

# The Loewner-Kufarev Energy and Foliations by Weil-Petersson Quasicircles

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June 10, 2021

## Abstract

We study foliations by chord-arc Jordan curves of the twice punctured Riemann sphere  $\mathbb{C} \setminus \{0\}$  using the Loewner-Kufarev equation. We associate to such a foliation a function on the plane that describes the “local winding” along each leaf. Our main theorem is that this function has finite Dirichlet energy if and only if the Loewner driving measure  $\rho$  has finite Loewner-Kufarev energy, defined by

$$S(\rho) = \frac{1}{2} \iint_{S^1 \times \mathbb{R}} \nu'_t(\theta)^2 d\theta dt$$

whenever  $\rho$  is of the form  $\nu_t(\theta)^2 d\theta dt$ , and set to  $\infty$  otherwise. Moreover, if either of these two energies is finite they are equal up to a constant factor, and in this case, the foliation leaves are Weil-Petersson quasicircles.

This duality between energies has several consequences. The first is that the Loewner-Kufarev energy is reversible, that is, invariant under inversion and time-reversal of the foliation. Furthermore, the Loewner energy of a Jordan curve can be expressed using the minimal Loewner-Kufarev energy of those measures that generate the curve as a leaf. This provides a new and quantitative characterization of Weil-Petersson quasicircles. Finally, we consider conformal distortion of the foliation and show that the Loewner-Kufarev energy satisfies an exact transformation law involving the Schwarzian derivative. The proof of our main theorem uses an isometry between the Dirichlet energy space on the unit disc and  $L^2(2\rho)$  that we construct using Hadamard’s variational formula expressed by means of the Loewner-Kufarev equation. Our results are related to  $\kappa$ -parameter duality and large deviations of Schramm-Loewner evolutions coupled with Gaussian random fields.

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# 1 Introduction

Methods involving monotone evolution of simply connected domains in the plane have been successfully applied to a range of problems in complex analysis. The Riemann mapping theorem and the notion of Carathéodory convergence allow to encode the dynamics by a continuous family of conformal maps from a reference domain such as the unit disk  $\mathbb{D}$  onto the evolving domains. Loewner proved in 1923 [40] that the family of maps generated by progressively slitting a domain along a simple curve satisfies a differential equation with a real-valued control function. Loewner's work was motivated by the Bieberbach conjecture and was ultimately instrumental in its resolution by de Branges about sixty years later [16]. This method was extended by Kufarev [35] and further developed by Pommerenke [49] to cover general evolution families beyond slitted domains. In this case, the dynamics is described by the Loewner-Kufarev equation which is controlled by a family of measures.

Besides the analysis of univalent functions in geometric function theory, the Loewner equation has in recent years played an important part in the rigorous analysis of conformally invariant random systems with the introduction of the Schramm-Loewner evolution (SLE) by Schramm in the late 1990s using Brownian motion as the control function, see, e.g., [37, 58, 59, 65]. While these applications of the Loewner equation are to essentially static problems, the Loewner-Kufarev equation provides a rather general device for generating and describing shape evolution and it has been employed to study physical systems as well. Examples include aggregation processes and models related to Laplacian growth as well as integrable systems, see, e.g., [5, 14, 28, 41], the last of which has many additional references and historical remarks. The recently introduced Quantum Loewner evolution [43], of importance in Liouville quantum gravity, is a stochastic version of Laplacian growth-type dynamics.

In this paper, we study the Loewner-Kufarev equation driven by members of a class of measures defined by the requirement to have finite Loewner-Kufarev energy, a quantity that arises as a large deviation rate function for  $SLE_\kappa$  when  $\kappa \rightarrow \infty$  [8]. We show that the Loewner-Kufarev energy is attached to certain families of Jordan curves and that it can be considered dual to the Loewner energy of a single Jordan curve, a quantity that also appears in the context of large deviations for  $SLE_\kappa$ , but this time when  $\kappa \rightarrow 0+$  [54, 70, 71]. (Our methods and conclusions are entirely deterministic, however, and no results from probability are needed in this paper.) More precisely, the boundaries of the evolving domains are Weil-Petersson quasicircles (equivalent to having finite Loewner energy) that foliate the twice punctured Riemann sphere  $\mathbb{C} \setminus \{0\}$ . Starting from Hadamard's variational formula we prove that the Dirichlet energy of a natural observable for a more general class of foliations – the winding function – is equal to a constant times the Loewner-Kufarev energy, including in the case when either quantity is infinite. This energy duality leads to a complete description of measures generating Weil-Petersson quasicircles. We are not aware of any other example where there is an equivalent description of the generated non-smooth Jordan curve interfaces in terms of the driving measure. (See [10, 27] for a sufficient condition to generate quasicircles via the Loewner-Kufarev equation. In this case no necessary condition is known however.) As further consequences of energy duality, we will see that the induced family of Weil-Petersson quasicircles sweeping out the sphere exhibits several remarkable features and symmetries.

In addition to the introduction and analysis of this natural class of foliations and the

implications to the theory of planar growth processes, another purpose of this paper is to provide large deviation counterparts to recent key results from the theory of SLE processes and Liouville quantum gravity, including SLE duality and the Mating of Trees theorem. We will discuss the links to random conformal geometry and open questions concerning further connections to, e.g., hyperbolic geometry at the end of the paper.

## 1.1 Loewner energy and Weil-Petersson quasicircles

Let  $\gamma$  be a Jordan curve in  $\mathbb{C}$  which separates  $0$  from  $\infty$  and write  $D$  and  $D^*$  for the bounded and unbounded component, respectively, and set  $\mathbb{D}^* = \mathbb{C} \setminus \overline{D}$ . If  $f : \mathbb{D} \rightarrow D$  and  $h : \mathbb{D}^* \rightarrow D^*$  are conformal maps fixing  $0$  and  $\infty$  respectively, then the Möbius invariant *Loewner energy* of  $\gamma$  can be defined as

$$I^L(\gamma) = \mathcal{D}_D(\log |f'|) + \mathcal{D}_{D^*}(\log |h'|) + 4 \log |f'(0)/h'(\infty)|, \quad (1.1)$$

where

$$\mathcal{D}_D(u) = \frac{1}{\pi} \int_D |\nabla u|^2 dA$$

is the Dirichlet integral. (Here and below we write  $dA$  for two-dimensional Lebesgue measure.) The quantity  $I^L$  was originally introduced in a different form [54, 70], see also Section 10. The identity (1.1) is established in [71]<sup>1</sup>.

A Jordan curve  $\gamma$  has finite Loewner energy if and only if it belongs to the set of Weil-Petersson quasicircles [67], a class of non-smooth chord-arc Jordan curves that has a number of equivalent characterizations from various different perspectives, see, e.g., [15, 62, 63, 67, 69], and [11] and the references therein.

One way to characterize Weil-Petersson quasicircles is to say that their welding homeomorphisms  $h^{-1} \circ f|_{S^1}$  (more precisely, the equivalence class modulo left-action by the group of Möbius transformations preserving  $S^1$ ) belong to the Weil-Petersson Teichmüller space  $T_0(1)$ , defined as the completion of  $\text{Möb}(S^1) \setminus \text{Diff}(S^1)$  using its unique homogeneous Kähler metric. The space  $T_0(1)$  carries an infinite dimensional Kähler-Einstein manifold structure and the Loewner energy itself is a Kähler potential for the Weil-Petersson metric, see [67] for definitions and a thorough discussion. The effort to find a mathematical foundation for non-perturbative string theory seems to have motivated the initial interest in  $\text{Möb}(S^1) \setminus \text{Diff}(S^1)$  and its Kähler structure, see, e.g., [12, 30, 46, 72] as well as the survey [47]. More recently, Weil-Petersson Teichmüller space has served as a fundamental building block in a construction of conformal field theory interpreted in the sense of Segal, as proposed in [52]. Other applications include analysis of the periodic KdV equation [57] and work by Sharon and Mumford on computer vision [61] both of which consider geodesics in  $T_0(1)$  that correspond to dynamical processes of Weil-Petersson quasicircles.

## 1.2 Loewner-Kufarev energy

Let  $\mathcal{N}$  be the set of Borel measures  $\rho$  on the cylinder  $S^1 \times \mathbb{R}$  with the property that  $\rho(S^1 \times I)$  equals  $|I|$  for any interval  $I$ . Each  $\rho \in \mathcal{N}$  can be disintegrated into a measurable family of probability measures  $(\rho_t)_{t \in \mathbb{R}}$  on  $S^1$ .

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<sup>1</sup>The right-hand side of (1.1) was introduced in [67] and there referred to as the universal Liouville action (up to a constant factor  $\pi$ ). As we will discuss connections to random conformal geometry, we choose to use the term Loewner energy.

Let  $(D_t)_{t \in \mathbb{R}}$  be a family of simply connected domains such that  $0 \in D_t \subset D_s$  for all  $s \leq t$ . We assume that for each  $t$ , the conformal radius of  $D_t$  at 0 equals  $e^{-t}$  which implies  $\bigcup_{t \in \mathbb{R}} D_t = \mathbb{C}$ . Let  $(f_t : \mathbb{D} \rightarrow D_t)_{t \in \mathbb{R}}$  be the associated family of conformal maps normalized so that  $f_t(0) = 0$  and  $f_t'(0) = e^{-t}$ . (Here and below we write  $'$  for  $\partial_z$ .) By a result of Pommerenke [49], there exists  $\rho \in \mathcal{N}$  such that  $(f_t)_{t \geq s}$  satisfies the *Loewner-Kufarev equation*

$$\partial_t f_t(z) = -z f_t'(z) H_t(z), \quad H_t(z) = \int_{S^1} \frac{e^{i\theta} + z}{e^{i\theta} - z} d\rho_t(\theta).$$

The Herglotz integral  $H_t$  is holomorphic in  $\mathbb{D}$  with positive real part. The equation is interpreted in the sense that  $t \mapsto f_t(z)$  is absolutely continuous. Conversely, for any  $\rho \in \mathcal{N}$  the monotone family of simply connected domains  $(D_t)_{t \in \mathbb{R}}$  and the corresponding family of conformal maps  $(f_t)_{t \in \mathbb{R}}$  can be recovered via the Loewner-Kufarev equation. We say that  $(f_t)_{t \in \mathbb{R}}$  is the *Loewner chain* driven by  $\rho$ . It is sometimes convenient to work with the family of inverse maps  $(g_t = f_t^{-1} : D_t \rightarrow \mathbb{D})_{t \in \mathbb{R}}$ , referred to as the *uniformizing Loewner chain*. See Sections 2.2 and 7.1 for more details.

For  $\rho \in \mathcal{N}$ , the *Loewner-Kufarev energy*  $S(\rho)$  introduced in [8] is defined by

$$S(\rho) = \int_{\mathbb{R}} L(\rho_t) dt, \quad \text{where} \quad L(\rho_t) = \frac{1}{2} \int_{S^1} \nu_t'(\theta)^2 d\theta,$$

whenever  $d\rho_t(\theta) = \nu_t^2(\theta)d\theta$  and  $L(\rho_t)$  is set to  $\infty$  otherwise. Notice that  $L(\rho_t)$  is the Dirichlet energy of  $\nu_t$  on  $S^1$ . We refer to measures with finite Loewner-Kufarev energy simply as *finite energy measures*. We will discuss how the Loewner-Kufarev energy relates to conformally invariant random systems in Section 10.

### 1.3 Main results

We call a monotone and continuous<sup>2</sup> family  $(\gamma_t)_{t \in \mathbb{R}}$  of chord-arc Jordan curves whose union covers  $\mathbb{C} \setminus \{0\}$  (or  $\overline{\mathbb{D}} \setminus \{0\}$ ) a *foliation*, see Section 2.3. Individual curves in a foliation are called *leaves*. Our definition allows more than one leaf passing through a given point  $z \in \mathbb{C} \setminus \{0\}$ . If the family of interfaces  $(\gamma_t = \partial D_t)_{t \in \mathbb{R}}$  arising from the Loewner-Kufarev equation driven by the measure  $\rho$  form a foliation, we say that  $\rho$  *generates a foliation*.

**Theorem 1.1** (Weil-Petersson leaves). *If  $S(\rho) < \infty$ , then  $\rho$  generates a foliation of  $\mathbb{C} \setminus \{0\}$  in which every leaf is a Weil-Petersson quasicircle.*

See Corollary 5.12 and Section 7.2. Theorem 1.1 shows that any  $\rho$  with  $S(\rho) < \infty$  gives rise to a dynamical process in  $T_0(1)$ , see Section 10.

We next associate to a foliation  $(\gamma_t)_{t \in \mathbb{R}}$  a real-valued function  $\varphi$  as follows. Given the leaf  $\gamma_t$ , let  $g_t$  be the conformal map of the bounded component of  $\hat{\mathbb{C}} \setminus \gamma_t$  onto  $\mathbb{D}$ , fixing 0 and with positive derivative there. Given  $z$  at which  $\gamma_t$  has a tangent, we define  $\varphi(z)$  to be the non-tangential limit at  $z$  of the function  $\arg[wg_t'(w)/g_t(w)]$ . (We choose the continuous branch that equals 0 at 0.) This defines  $\varphi$  arclength-a.e. on  $\gamma_t$ . Monotonicity of  $(\gamma_t)_{t \in \mathbb{R}}$  implies that there is no ambiguity in the definition of  $\varphi(z)$  if  $z \in \gamma_t \cap \gamma_s$ . See Section 2.3 for more details. Modulo  $2\pi$ ,  $\varphi(z)$  equals the difference of the argument of the tangent of

<sup>2</sup>Monotone is meant in the following sense: if  $s < t$  then  $D_t \subset D_s$  where  $D_t$  is the bounded connected component of  $\mathbb{C} \setminus \gamma_t$ . Continuous is meant in the sense of the supremum norm modulo increasing reparametrization.

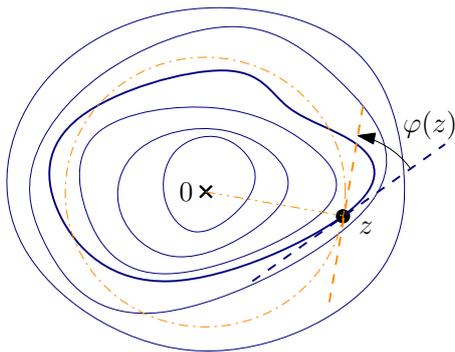


Figure 1.1: Illustration of the winding function  $\varphi$ .

$\gamma_t$  at  $z$  and that of the tangent to the circle centered at 0 passing through  $z$ . See Figure 1.1. We call  $\varphi$  the *winding function* associated with a foliation  $(\gamma_t)_{t \in \mathbb{R}}$ . The simplest example of winding function is when the measure  $\rho$  has zero energy, namely when  $\rho_t$  is the uniform probability measure on  $S^1$  for a.e.  $t \in \mathbb{R}$ . In this case, the associated foliation is the family of concentric circles centered at 0, and the winding function is identically 0. We discuss additional examples in Section 4.3.

In the present non-smooth foliation setting, a function defined on each leaf arclength-a.e. is not necessarily defined Lebesgue-a.e. in  $\mathbb{C}$ , see Section 2.3. However, we prove that if it is possible to extend the winding function  $\varphi$  to an element in  $W_{\text{loc}}^{1,2}$ , then the extension is unique. (This is one main reason why we choose to work in the setting of chord-arc curves.) See Proposition 3.6. Statements about the Dirichlet energy of  $\varphi$  will be understood in terms of this extension whose existence is implicitly part of any such statement.

The following is our main theorem, which shows that the dynamically defined Loewner-Kufarev energy can be expressed by a purely geometric and static quantity.

**Theorem 1.2** (Energy duality). *Assume that  $\rho \in \mathcal{N}$  generates a foliation and let  $\varphi$  be the associated winding function on  $\mathbb{C}$ . Then  $\mathcal{D}_{\mathbb{C}}(\varphi) < \infty$  if and only if  $S(\rho) < \infty$  and*

$$\mathcal{D}_{\mathbb{C}}(\varphi) = 16 S(\rho).$$

The proof of Theorem 1.2 is completed in Section 7.2.

*Remark.* The factor 16 in Theorem 1.2 is consistent with the SLE duality relation  $\kappa \leftrightarrow 16/\kappa$  [20, 73]. See Section 10.

Theorem 1.2 has several consequences. The first is the reversibility of the Loewner-Kufarev energy. Consider  $\rho \in \mathcal{N}$  and the corresponding evolution family of domains  $(D_t)_{t \in \mathbb{R}}$ . Applying  $z \mapsto 1/z$  to the complementary domains  $\hat{\mathbb{C}} \setminus D_t$ , we obtain an evolution family of domains  $(\tilde{D}_t)_{t \in \mathbb{R}}$  upon time-reversal and reparametrization, which may be described by the Loewner-Kufarev equation with an associated driving measure  $\tilde{\rho}$ . While there is no known simple description of  $\tilde{\rho}$  in terms of  $\rho$ , energy duality implies remarkably that the Loewner-Kufarev energy is invariant under this transformation.

**Theorem 1.3** (Energy reversibility). *We have  $S(\rho) = S(\tilde{\rho})$ .*

See Theorem 8.2.

The Loewner energy of a simple chord connecting two boundary points in a simply connected domain also satisfies a form of reversibility, see [70]. We will comment on the relation between these results and relevant probabilistic models in Section 10.

By Theorem 1.1, every leaf in the foliation generated by a measure with  $S(\rho) < \infty$  satisfies  $I^L(\gamma) < \infty$ . Conversely, the next result shows that if  $I^L(\gamma) < \infty$ , then  $\gamma$  can always be realized as a leaf in a foliation generated by Loewner evolution driven by a measure with  $S(\rho) < \infty$ . We obtain a new and quantitative characterization of Weil-Petersson quasicircles.

**Theorem 1.4** (Characterization of Weil-Petersson quasicircles). *A Jordan curve  $\gamma$  separating 0 from  $\infty$  is a Weil-Petersson quasicircle if and only if  $\gamma$  can be realized as a leaf in the foliation generated by a measure  $\rho$  with  $S(\rho) < \infty$ . Moreover, the Loewner energy of  $\gamma$  satisfies the identity*

$$I^L(\gamma) = 16 \inf_{\rho} S(\rho) + 2 \log |f'(0)/h'(\infty)|,$$

where the infimum, which is attained, is taken over all  $\rho \in \mathcal{N}$  such that  $\gamma$  is a leaf of the generated foliation.

See Theorem 8.4 and Corollary 8.6. The infimum is realized for the measure generating the family of equipotentials on both sides of  $\gamma$ . (By equipotential we mean the image of a circle about 0 under the Riemann map from  $\mathbb{D}$  to a component of  $\mathbb{C} \setminus \gamma$  fixing 0 or taking 0 to  $\infty$ .) In this case, the winding function is harmonic in  $\mathbb{C} \setminus \gamma$ , see Section 8.2. This minimum is zero if and only if  $\gamma$  is a circle centered at 0, whereas  $I^L(\gamma)$  is zero for all circles. This explains the presence of the derivative terms. Corollary 8.7 of Theorem 1.4 shows that the Loewner energies of the leaves in a foliation generated by  $\rho$  with  $S(\rho) < \infty$  are uniformly bounded by  $16S(\rho)$ .

Another consequence of Theorem 1.4 is the following identity that simultaneously expresses the interplay between Dirichlet energies under “welding” and “flow-line” operations in a similar spirit as [68, Cor. 1.6] which in turn combines the main results of [68]. In our setup, given a chord-arc curve  $\gamma$  separating 0 and  $\infty$ , we define a winding function on  $\gamma$  arclength-a.e. as above. We say that a Weil-Petersson quasicircle  $\gamma$  is compatible with  $\varphi \in W_{\text{loc}}^{1,2}$ , if the winding function of  $\gamma$  coincides with the trace  $\varphi|_{\gamma}$  arclength-a.e.

**Proposition 1.5** (Complex identity). *Let  $\psi$  be a complex valued function on  $\mathbb{C}$  with  $\mathcal{D}_{\mathbb{C}}(\psi) = \mathcal{D}_{\mathbb{C}}(\text{Re } \psi) + \mathcal{D}_{\mathbb{C}}(\text{Im } \psi) < \infty$  and  $\gamma$  a Weil-Petersson quasicircle separating 0 from  $\infty$  compatible with  $\text{Im } \psi$ . Let*

$$\zeta(z) := \psi \circ f(z) + \log \frac{f'(z)z}{f(z)}; \quad \xi(z) := \psi \circ h(z) + \log \frac{h'(z)z}{h(z)}. \quad (1.2)$$

Then  $\mathcal{D}_{\mathbb{C}}(\psi) = \mathcal{D}_{\mathbb{D}}(\zeta) + \mathcal{D}_{\mathbb{D}^*}(\xi)$ .

See Section 8.3.

Finally, we study the change of the Loewner-Kufarev energy under local conformal distortion of the foliation. We consider the following setup. Let  $\rho \in \mathcal{N}$  be a measure such that  $\rho_t$  is the uniform measure for  $t < 0$  and

$$S_{[0,1]}(\rho) := \int_0^1 L(\rho_t) dt < \infty.$$

(The choice of the upper bound  $t = 1$  is only for notational simplicity and the result is easily generalized to other bounded time intervals.)

We have  $D_0 = \mathbb{D}$  and write  $K_t = \overline{\mathbb{D}} \setminus D_t$ . Let  $\psi$  be a conformal map from a neighborhood  $U$  of  $K_1$  in  $\mathbb{D}$  to a neighborhood  $\tilde{U}$  of  $\tilde{K}_1$ , another compact hull in  $\mathbb{D}$ , such that  $\psi(K_1) = \tilde{K}_1$ . The family of compact hulls  $(\tilde{K}_t := \psi(K_t))_{t \in [0,1]}$  can be generated by a measure  $\tilde{\rho}$  with the associated uniformizing Loewner chain  $\tilde{g}_t : \mathbb{D} \setminus \tilde{K}_t \rightarrow \mathbb{D}$ .

**Theorem 1.6** (Conformal distortion). *We have the formulas*

$$L(\tilde{\rho}_t) - L(\rho_t) = \frac{1}{4} \int_{S^1} e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) \rho_t(\theta) d\theta + \frac{1}{8} (|\tilde{\rho}_t| - |\rho_t|)$$

and

$$S_{[0,1]}(\tilde{\rho}) - S_{[0,1]}(\rho) = \frac{1}{4} \int_0^1 \int_{S^1} e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) \rho_t(\theta) d\theta dt + \frac{1}{8} (\log \tilde{g}'_1(0) - \log g'_1(0)),$$

where  $\psi_t = \tilde{g}_t \circ \psi \circ g_t^{-1}$ ,  $\mathcal{S}\psi = (\psi''/\psi')' - (\psi''/\psi')^2/2$  is the Schwarzian derivative, and  $|\tilde{\rho}_t| = \tilde{\rho}_t(S^1)$ .

The proof is given in Section 9. Theorem 1.6 is related in spirit to the notion of conformal restriction [38]. We will relate the formulas in Theorem 1.6 to Brownian loop measures (see [38, 39]) in a forthcoming paper with Lawler.

## 1.4 Core argument for Theorem 1.2

We now indicate the key ideas for the proof of the energy duality Theorem 1.2 and along the way discuss some of the tools we use and develop. We will deduce Theorem 1.2 from the analogous result for the unit disk and a limiting argument. To prepare for the statement, let  $\mathcal{N}_+$  be defined analogously to  $\mathcal{N}$  but considering measures on  $S^1 \times \mathbb{R}_+$  and we define the corresponding Loewner-Kufarev energy  $S_+(\rho) = \int_0^\infty L(\rho_t) dt$ . The Loewner-Kufarev equation with the initial condition  $f_0(z) = z$  generates a Loewner chain  $(f_t : \mathbb{D} \rightarrow D_t)_{t \geq 0}$ , where  $(D_t)_{t \geq 0}$  is a monotone family of simply connected domains in  $\mathbb{D} = D_0$ . It can be viewed as a special case of the whole-plane Loewner chain by extending the measure  $\rho$  to a measure on  $S^1 \times \mathbb{R}$ , where  $\rho_t$  is the uniform probability measure on  $S^1$  when  $t < 0$ , which implies  $D_t = e^{-t}\mathbb{D}$  for all  $t \leq 0$ .

**Theorem 1.7** (Disk energy duality). *Assume  $\rho \in \mathcal{N}_+$  generates a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$  and let  $\varphi$  be the associated winding function. Then  $\mathcal{D}_{\mathbb{D}}(\varphi) < \infty$  if and only if  $S_+(\rho) < \infty$  and  $\mathcal{D}_{\mathbb{D}}(\varphi) = 16 S_+(\rho)$ .*

*Remark.* This result is a special case of Theorem 1.2 using the extension by the uniform measure for  $t < 0$  discussed above.

The proof of Theorem 1.7 is completed in Section 6.

The starting point of the proof is Hadamard's classical formula for the variation of the Dirichlet Green's function. We express Hadamard's formula using the Loewner-Kufarev equation:

$$-\partial_t G_{D_t}(z, w) = \int_{S^1} P_{\mathbb{D}}(g_t(z), e^{i\theta}) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta),$$

where  $P_{\mathbb{D}}$  is the Poisson kernel for  $\mathbb{D}$  and  $\rho \in \mathcal{N}_+$ , see Lemma 3.1. The Sobolev space  $\mathcal{E}_0(\mathbb{D}) = W_0^{1,2}(\mathbb{D})$  is a Hilbert space when endowed with the Dirichlet inner product. Hadamard's formula and the orthogonal decomposition with respect to the Dirichlet inner product along the Loewner evolution lead to a correspondence between  $\mathcal{E}_0(\mathbb{D})$  and  $L^2$ -integrable functions on the cylinder  $S^1 \times \mathbb{R}_+$ . More precisely, setting  $L^2(2\rho) := L^2(S^1 \times \mathbb{R}_+, 2\rho)$ , we define an operator

$$\iota : C_c^\infty(\mathbb{D}) \rightarrow L^2(2\rho), \quad \phi \mapsto \frac{1}{2\pi} \int_{\mathbb{D}} \Delta(\phi \circ f_t)(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z). \quad (1.3)$$

We prove the following theorem which is an important step in the proof of our main result and which we also believe to be of independent interest.

**Theorem 1.8** (Foliation disintegration isometry). *If  $\rho \in \mathcal{N}_+$  generates a foliation of  $\mathbb{D} \setminus \{0\}$ , then (1.3) extends to a bijective isometry  $\iota : \mathcal{E}_0(\mathbb{D}) \rightarrow L^2(2\rho)$  with the inverse mapping  $\varkappa : L^2(2\rho) \rightarrow \mathcal{E}_0(\mathbb{D})$*

$$\varkappa[u](w) = 2\pi \int_0^{\tau(w)} P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt, \quad u_t(\cdot) := u(\cdot, t).$$

See Lemma 3.2, Proposition 3.3, and Theorem 3.5. We show that  $P_{\mathbb{D}}[u_t \rho_t] \in \mathfrak{h}^1$  (the harmonic Hardy space on  $\mathbb{D}$ ), and Theorem 1.8 can be interpreted as a disintegration of finite Dirichlet energy functions into  $\mathfrak{h}^1$  functions. This implies the formula

$$\phi_t^0 \circ g_t = \varkappa[\iota[\phi] \mathbf{1}_{S^1 \times [t, \infty)}] \quad (1.4)$$

where  $\phi_t^0 \in \mathcal{E}_0(\mathbb{D})$  is the zero-trace part of the function  $\phi_t = \phi \circ f_t$  (so that  $\phi_t - \phi_t^0$  is harmonic). See Corollary 3.4.

*Remark.* If  $\rho$  is smooth and  $t$  is fixed, the function  $\theta \mapsto \iota[\phi](\theta, t)$  can be interpreted as the inward pointing normal derivative in  $\mathbb{D}$  at  $e^{i\theta}$  applied to  $\phi_t^0$ . The foliation disintegration isometry is closely related to the ‘‘Hadamard operators’’ considered in [29] in a  $C^2$ -smooth and strictly monotone setting, see Section 3 for further discussion. Here, we consider chord-arc foliations which in general have leaves that are not  $C^1$ , and are not even locally Lipschitz graphs. Moreover,  $t \mapsto \gamma_t$  is only continuous and monotone but not strictly monotone. Theorem 1.8 allows us to work under such rather weak regularity assumptions and this level of generality is needed in order to include Weil-Petersson quasicircles and to obtain optimal statements as in Theorem 1.2 and Theorem 1.7. While not needed in this paper, the conclusions of Theorem 1.8 hold under even weaker regularity assumptions on the interfaces of the evolution. We will discuss this elsewhere.

*Remark.* By considering the Gaussian measures associated to the Hilbert spaces  $\mathcal{E}_0(\mathbb{D})$  and  $L^2(2\rho)$ , Theorem 1.8 immediately entails a decomposition of the Dirichlet Gaussian free field on  $\mathbb{D}$  into white-noise on the cylinder  $S^1 \times \mathbb{R}_+$  weighted by  $2\rho$ , generalizing the main result of [29].

The next step is to prove that  $\rho \in \mathcal{N}_+$  with  $S_+(\rho) < \infty$  generates a foliation so that Theorem 1.8 can be applied. For this, we first derive a preliminary, weak energy duality result: under the strong assumption that  $\rho$  is piecewise constant in time and the disintegration measures are all strictly positive and smooth, we prove in Proposition 5.3 that the winding function is defined, continuous and piecewise smooth in  $\overline{\mathbb{D}}$ . By essentially

explicit computation, the identity  $16S_+(\rho) = \mathcal{D}_{\mathbb{D}}(\varphi)$  follows. This result combined with an approximation argument is then used to prove that  $\rho$  with  $S_+(\rho) < \infty$  generates a foliation by Weil-Petersson quasicircles, see Corollary 5.12. At this point the proof of Theorem 1.1 is completed in the case when  $\rho \in \mathcal{N}_+$ . Then in Section 6 we prove disk energy duality in full generality. From the work in Section 5 we know that  $\rho$  with  $S_+(\rho) < \infty$  generates a foliation. Using the inverse operator  $\varkappa$  we prove that the winding function  $\varphi = -\varkappa[2\nu'_t/\nu_t]$  from which it follows immediately that  $\varphi \in \mathcal{E}_0(\mathbb{D})$  and that  $\mathcal{D}_{\mathbb{D}}(\varphi) = 16S_+(\rho)$ .

The final step assumes that  $\rho \in \mathcal{N}_+$  generates a foliation whose winding function can be extended so that  $\mathcal{D}_{\mathbb{D}}(\varphi) < \infty$ . To point to the difficulty, at this stage we do not know that  $\rho_t$  is absolutely continuous. However, applying Theorem 1.8, we have that  $\iota[\varphi] \in L^2(2\rho)$ . Using the integrability information we deduce that  $H'_t$  is in the Hardy space  $\mathcal{H}^1$  and this implies that  $\rho_t$  is absolutely continuous and that the density is differentiable a.e. It then follows that  $S_+(\rho) < \infty$  using Theorem 1.8.

**Structure of the paper.** We recall basic definitions in Section 2. The foliation disintegration isometry, Theorem 1.8, which is a key step in our proof of the energy duality, is established in Section 3. In Section 4 we define the Loewner-Kufarev energy, derive a few basic properties, and discuss examples of finite energy measures and associated foliations. Section 5 is devoted to the proof of energy duality in the disk under strong regularity assumptions and here we obtain the important *a priori* result that finite energy measures generate foliations whose leaves are Weil-Petersson quasicircles, see Corollary 5.12. The general energy duality result for the unit disk, Theorem 1.7, is proved in Section 6. We work in the set-up of the Loewner-Kufarev equation in the unit disk in Sections 2-6 and we introduce the whole-plane Loewner-Kufarev equation only in Section 7, where we prove whole-plane energy duality, see Theorems 1.1 and 1.2. In Section 8 we derive the consequences of energy duality, see Theorem 1.3, 1.4, and Proposition 1.5. Section 9 is devoted to the proof of the conformal distortion formula, Theorem 1.6. Section 10 collects further comments, including a discussion of additional interpretations of our results as well as open problems.

## Acknowledgments

We are very grateful to Håkan Hedenmalm for pointing out the reference [29], which helped us improve and simplify our argument considerably. We thank David Jerison and Greg Lawler for discussions and helpful input, Paul Laurain and Andrea Seppi for discussions on the implication to minimal surfaces, and Steffen Rohde and Wendelin Werner for useful comments on an earlier version of our paper. F.V. is supported by the Knut and Alice Wallenberg Foundation, the Swedish Research Council, and the Ruth and Nils-Erik Stenbäck Foundation. Y.W. is supported by NSF grant DMS-1953945.

## 2 Preliminaries

### 2.1 Basic definitions

For a bounded simply connected domain  $D \subset \mathbb{C}$ , we write  $G_D(z, w)$  for the Green's function associated to the positive Laplacian  $\Delta = -(\partial_{xx} + \partial_{yy})$  with Dirichlet boundary

condition, where  $z = x + iy$ . It is convenient to normalize the Green's function so that  $G_D(z, w) - \log|z - w|$  is harmonic in each variable, that is, so that  $G_D = 2\pi\Delta^{-1}$ .

For sufficiently regular domains  $D$ , the Poisson kernel is defined for  $z \in D, \zeta \in \partial D$ , by

$$P_D(z, \zeta) := \partial_{n(\zeta)} G_D(z, \zeta),$$

where  $\partial_{n(\zeta)}$  is the inward normal derivative at  $\zeta$ . If  $D = \mathbb{D}$  we have

$$G_{\mathbb{D}}(z, w) = -\log \left| \frac{z - w}{1 - \bar{w}z} \right|, \quad P_{\mathbb{D}}(z, e^{i\theta}) = \frac{1 - |z|^2}{|z - e^{i\theta}|^2}.$$

If  $\sigma$  is a finite measure on the unit circle  $S^1$ , identified with  $[0, 2\pi]_{/0 \sim 2\pi}$ , we write

$$P_{\mathbb{D}}[\sigma](z) = \frac{1}{2\pi} \int_0^{2\pi} P_{\mathbb{D}}(z, e^{i\theta}) d\sigma(\theta)$$

for its Poisson integral. If  $d\sigma = u d\theta$  for  $u \in L^1(S^1)$  we write simply  $P_{\mathbb{D}}[u](z)$ . By Fatou's theorem,  $P_{\mathbb{D}}[u]$  has non-tangential limit  $u$  Lebesgue-a.e. on  $S^1$ .

If  $D$  is an open set, the Dirichlet energy of an almost everywhere defined function  $\phi : D \rightarrow \mathbb{R}$  is given by

$$\mathcal{D}_D(\phi) := \langle \phi, \phi \rangle_{\nabla} := \frac{1}{\pi} \int_D |\nabla \phi|^2 dA(z)$$

whenever  $\phi$  has weak first derivatives in  $L^2(D)$ . Here and below we write  $dA$  for two-dimensional Lebesgue measure. Let  $W^{1,2}(D)$  be the Sobolev space of real-valued functions  $\phi$  such that both  $\phi$  and its weak first derivatives are in  $L^2(D)$  with norm  $\|\phi\|_{W^{1,2}(D)} = \|\phi\|_{L^2(D)} + \|\nabla \phi\|_{L^2(D)}$  and write  $W_0^{1,2}(D)$  for the closure of smooth and compactly supported functions in  $D$ ,  $C_c^\infty(D)$ , in  $W^{1,2}(D)$ .

When  $D$  is bounded,  $\mathcal{D}_D^{1/2}$  is a norm equivalent to  $\|\cdot\|_{W^{1,2}}$  on  $W_0^{1,2}(D)$  by the Poincaré inequality. In this case, we write  $\mathcal{E}_0(D)$  for  $W_0^{1,2}(D)$  equipped with the norm  $\mathcal{D}_D^{1/2}$  which is a Hilbert space endowed with the Dirichlet inner product  $\langle \cdot, \cdot \rangle_{\nabla}$ . Every  $\phi$  with  $\mathcal{D}_{\mathbb{C}}(\phi) < \infty$  has a unique decomposition with respect to  $D$

$$\phi = \phi^0 + \phi^h \quad \text{and} \quad \langle \phi^0, \phi^h \rangle_{\nabla} = 0 \quad (2.1)$$

such that  $\phi^0 \in \mathcal{E}_0(D)$  and  $\phi^h$  with  $\mathcal{D}_{\mathbb{C}}(\phi^h) < \infty$  is harmonic in  $D$ , see, e.g., [1, P. 77] and [68, Appx. B].

The Hardy space  $\mathcal{H}^p$  (resp. harmonic Hardy space  $\mathfrak{h}^p$ ) for  $p > 0$  consists of functions  $f$  holomorphic (resp. harmonic) in  $\mathbb{D}$  satisfying

$$\sup_{0 \leq r < 1} \int_0^{2\pi} |f(re^{i\theta})|^p d\theta < \infty.$$

Let  $\gamma$  be a Jordan curve in  $\mathbb{C}$ , and write  $D$  and  $D^*$  for the connected components of  $\mathbb{C} \setminus \gamma$ . Let  $f$  be a conformal map from  $\mathbb{D}$  onto the bounded component  $D$ , and  $h$  a conformal map from  $\mathbb{D}^*$  onto the unbounded component  $D^*$  fixing  $\infty$ . The Loewner energy of  $\gamma$  is defined as

$$I^L(\gamma) = \mathcal{D}_{\mathbb{D}}(\log |f'|) + \mathcal{D}_{\mathbb{D}^*}(\log |h'|) + 4 \log |f'(0)| - 4 \log |h'(\infty)|, \quad (2.2)$$

where  $h'(\infty) := \lim_{z \rightarrow \infty} h'(z) = \tilde{h}'(0)^{-1}$  and  $\tilde{h}(z) := 1/h(1/z)$ . The Loewner energy  $I^L$  is finite if and only if either Dirichlet integral on the right-hand side in (2.2) is finite. We summarize this as a lemma.

**Lemma 2.1.** *Suppose  $\gamma$  is a bounded Jordan curve. Then the following statements are equivalent:*

1.  $I^L(\gamma) < \infty$ ;
2.  $\mathcal{D}_{\mathbb{D}}(\log |f'|) = \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f''(z)}{f'(z)} \right|^2 dA(z) < \infty$ ;
3.  $\mathcal{D}_{\mathbb{D}^*}(\log |h'|) < \infty$ .

There are several additional equivalent ways to define the Loewner energy, and the class of Jordan curves with finite Loewner energy coincides with the class of Weil-Petersson quasicircles, see [71]. Henceforth we will refer to Jordan curves with finite Loewner energy as Weil-Petersson quasicircles.

## 2.2 The Loewner-Kufarev equation

We consider first the version for the unit disc and then later in Section 7 the whole-plane version. Let  $\mathcal{M}(\Omega)$  (resp.  $\mathcal{M}_1(\Omega)$ ) be the space of Borel measures (resp. probability measures) on  $\Omega$  endowed with the topology induced by weak convergence on compact subsets. Let

$$\mathcal{N}_+ = \{\rho \in \mathcal{M}(S^1 \times \mathbb{R}_+) : \rho(S^1 \times I) = |I| \text{ for any interval } I\}.$$

Any  $\rho \in \mathcal{N}_+$  can be disintegrated into a family of measures  $(\rho_t)_{t \geq 0}$  measurable in  $t$ , such that  $\rho(d\theta dt) = \rho_t(d\theta)dt$  and  $\rho_t \in \mathcal{M}_1$ . The disintegration is unique in the sense that any two disintegrations  $(\rho_t), (\tilde{\rho}_t)$  of  $\rho$  must satisfy  $\rho_t = \tilde{\rho}_t$  for a.e.  $t$ . See, e.g., [17, Sec. 70]. We will work with the Loewner-Kufarev equation driven by measures  $\rho \in \mathcal{N}_+$  and we now review some of the relevant definitions and facts. See, e.g., [55, Ch. 8] for proofs and a detailed discussion in this general setting.

Given  $\rho \in \mathcal{N}_+$ , consider the associated Herglotz integrals

$$H_t(z) := H[\rho_t](z) = \int_0^{2\pi} \frac{e^{i\theta} + z}{e^{i\theta} - z} d\rho_t(\theta). \quad (2.3)$$

The mapping  $z \mapsto H_t(z)$  is a holomorphic function in  $\mathbb{D}$  with positive real part and  $t \mapsto H_t(z)$  is measurable. In this setting, the Loewner-Kufarev partial differential equation for  $\mathbb{D}$  reads

$$\partial_t f_t(z) = -z f'_t(z) H_t(z), \quad f_0(z) = z. \quad (2.4)$$

The equation (2.4) is understood in the sense that  $t \mapsto f_t(z)$  is absolutely continuous, and (2.4) is required to hold for a.e.  $t \geq 0$ . The exceptional set can be taken to be the same for all  $z \in \mathbb{D}$ . Throughout the paper, all differential equations are interpreted in a similar manner. The unique solution to (2.4) gives rise to a family of conformal maps  $(f_t)_{t \geq 0}$  fixing 0 such that for each  $t$ ,  $f_t : \mathbb{D} \rightarrow D_t = f_t(\mathbb{D})$  where if  $s < t$ , then  $D_t \subset D_s$ . In the present case where the disintegrated measures are probability measures we have  $f'_t(0) = e^{-t}$ . (Indeed,  $\partial_t \log f'_t(0) = -H_t(0) = -|\rho_t| \equiv -1$ .) We refer to the family  $(f_t)_{t \geq 0}$  as the *Loewner chain* driven by  $\rho$ . We call the family of compact sets  $(K_t = \overline{\mathbb{D}} \setminus D_t)_{t \geq 0}$  the *hulls* associated to the Loewner chain.

A converse statement is also true. Consider a monotone family of simply connected domains  $(D_t)_{t \geq 0}$  containing 0:  $D_0 = \mathbb{D}$ ,  $0 \in D_t$  for all  $t$ , and if  $s < t$  then  $D_t \subset D_s$ . Let  $f_t : \mathbb{D} \rightarrow D_t$

be the conformal map normalized by  $f_t(0) = 0$ ,  $f_t'(0) > 0$ . According to a theorem of Pommerenke [49, Satz 4] (see also [50, Thm. 6.2] and [55]), if  $t \rightarrow f_t'(0)$  is a decreasing homeomorphism of  $\mathbb{R}_+ \rightarrow (0, 1]$ , one can reparametrize  $(D_t)_{t \geq 0}$  so that  $f_t'(0) = e^{-t}$ , and there exists a measurable family of holomorphic functions  $(H_t)_{t \geq 0}$  in  $\mathbb{D}$ , uniquely defined for a.e.  $t \geq 0$ , with positive real part such that (2.5) holds. The measurable family of probability measures  $(\rho_t)_{t \geq 0}$  is obtained from the Herglotz-Riesz representation of  $(H_t)_{t \geq 0}$ . The upshot of the discussion is that the measure  $\rho \in \mathcal{N}_+$ , Loewner chain  $(f_t)_{t \geq 0}$ , uniformizing Loewner chain  $(g_t)_{t \geq 0}$ , the monotone family of simply connected domains  $(D_t)_{t \geq 0}$ , and the increasing family of hulls  $(K_t)_{t \geq 0}$  each determine the others.

Let  $\mathcal{L}_+$  be the set of Loewner chains  $(f_t)_{t \geq 0}$ , and change notation by writing  $f(z, t) = f_t(z)$ . We endow  $\mathcal{L}_+$  with the topology of uniform convergence of  $f$  on compact subsets of  $\mathbb{D} \times \mathbb{R}_+$ . In this setting, the continuity of the Loewner transform is well-known.

**Lemma 2.2** (See e.g., [43, Prop. 6.1] and [32]). *The Loewner transform  $\rho \in \mathcal{N}_+ \mapsto f \in \mathcal{L}_+$  is a homeomorphism.*

The *uniformizing Loewner chain*  $(g_t := f_t^{-1} : D_t \rightarrow \mathbb{D})_{t \geq 0}$  driven by  $\rho$  satisfies a similar equation

$$\partial_t g_t(z) = g_t(z) H_t(g_t(z)), \quad g_0(z) = z, \quad (2.5)$$

for a.e.  $t < \tau(z)$  where for  $z \in \mathbb{D}$ ,

$$\tau(z) = \sup\{t \geq 0, \text{ the solution of (2.5) exists for all } s < t\} = \sup\{t \geq 0 : z \in D_t\}, \quad (2.6)$$

and we set by convention  $\tau(z) = 0$  for  $z \in S^1$ . Further, we can write

$$D_t = \{z \in \mathbb{D}, \tau(z) > t\}.$$

An important property which follows immediately from (2.5) is the *domain Markov property* of the Loewner transform.

**Lemma 2.3.** *Let  $\rho \in \mathcal{N}_+$  and  $(g_t)_{t \geq 0}$  the associated uniformizing Loewner chain. Fix  $T \geq 0$ , then  $(\tilde{g}_s := g_{s+T} \circ g_T^{-1})_{s \geq 0}$  is the uniformizing Loewner chain driven by the measure  $\tilde{\rho} \in \mathcal{N}_+$  with disintegration  $\tilde{\rho}_s = \rho_{s+T}$ .*

### 2.3 Chord-arc foliations and the winding function

Let  $\gamma$  be a rectifiable Jordan curve. We say that  $\gamma$  is chord-arc if there exists a constant  $A < \infty$  such that for all  $z, w \in \gamma$ , we have the inequality  $|\gamma^{z,w}| \leq A|z - w|$ , where  $\gamma^{z,w}$  is the subarc of  $\gamma \setminus \{z, w\}$  of smaller length.

Consider a monotone family of simply connected domains  $(D_t)_{t \geq 0}$  that can be described by Loewner evolution as in Section 2.2. We call the family  $(\gamma_t := \partial D_t)_{t \geq 0}$  a *non-injective chord-arc foliation* of  $\overline{\mathbb{D}} \setminus \{0\}$  if

1. For all  $t \geq 0$ ,  $\gamma_t$  is a chord-arc Jordan curve.
2. It is possible to parametrize each curve  $\gamma_t, t \geq 0$ , by  $S^1$  so that the mapping  $t \mapsto \gamma_t$  is continuous in the supremum norm.
3. For all  $z \in \overline{\mathbb{D}} \setminus \{0\}$ ,  $\tau(z) < \infty$ , where  $\tau$  is defined in (2.6).

For convenience we shall say simply foliation in what follows, but we stress that the chord-arc assumption is always in effect. We refer to the Jordan curves  $\gamma_t$  as *leaves*. Non-injective here means that we do not require that there is a unique leaf that passes through each point in  $\overline{\mathbb{D}}$ . The following lemma shows that a foliation in the above sense indeed foliates the punctured unit disk.

**Lemma 2.4.** *Assume that  $(\gamma_t)_{t \geq 0}$  is a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$ . Then for all  $z \in \overline{\mathbb{D}} \setminus \{0\}$ , we have  $z \in \gamma_{\tau(z)}$ . In particular,  $\bigcup_{t \geq 0} \gamma_t = \overline{\mathbb{D}} \setminus \{0\}$ .*

This lemma shows that the definition of foliation in  $\overline{\mathbb{D}} \setminus \{0\}$  and  $\tau$  coincide with the definitions in Section 1.3.

*Proof.* From the monotonicity of  $(D_t)$  and the continuity of  $t \mapsto \gamma_t$ , we have  $\bigcup_{t > \tau(z)} D_t = D_{\tau(z)}$ . Since  $z \notin D_t$  for all  $t > \tau(z)$ , we have  $z \notin D_{\tau(z)}$ . It remains to show that  $z \in \overline{D_{\tau(z)}}$ . Since  $(\overline{D}_t^c := \hat{\mathbb{C}} \setminus D_t)$  is also a monotone family of domains bounded by a continuous family of Jordan curves, we have

$$\bigcap_{t < \tau(z)} \overline{D}_t = \left( \bigcup_{t < \tau(z)} (\overline{D}_t)^c \right)^c = \left( (\overline{D_{\tau(z)}})^c \right)^c = \overline{D_{\tau(z)}}.$$

The monotonicity shows that for all  $t < \tau(z)$ ,  $z \in D_t$ . Therefore  $z \in \bigcap_{t < \tau(z)} \overline{D}_t = \overline{D_{\tau(z)}}$  and this completes the proof.  $\square$

If  $\rho \in \mathcal{N}_+$  and the family of interfaces  $(\gamma_t = \partial D_t)_{t \geq 0}$  produced by Loewner evolution forms a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$ , we say that  $\rho \in \mathcal{N}_+$  *generates a foliation*. We will often choose the conformal parametrization for each  $\gamma_t$ , obtained by continuously extending  $f_t : \mathbb{D} \rightarrow D_t$  to  $\overline{\mathbb{D}}$  by Carathéodory's theorem and then restricting to  $S^1$ .

We will now define the winding function  $\vartheta$  associated with a foliation  $(\gamma_t = \partial D_t)_{t \geq 0}$ . It will be convenient to use the notation

$$\vartheta[f](z) = \arg \frac{zf'(z)}{f(z)} = \int_0^z d \arg \frac{f(w) - f(z)}{w - z}, \quad (2.7)$$

when  $f$  is a conformal map (defined on a simply connected domain) fixing 0. Here and elsewhere, the continuous branch of  $\arg(zf'/f)$  is chosen to equal 0 at the origin. The integral is taken along any continuous path from 0 to  $z$ . The function  $\vartheta$  satisfies a chain rule

$$\vartheta[f \circ g](z) = \vartheta[f] \circ g + \vartheta[g] \quad (2.8)$$

if  $f, g, f \circ g$  are all conformal maps defined on simply connected neighborhoods of the origin which  $f, g$  fix. Given a curve  $\gamma$  with some parametrization  $\gamma(s)$ , we say that  $\gamma$  has a tangent at  $\gamma(s_0)$  if there exists  $\alpha$  such that

$$\lim_{s \rightarrow s_0 \pm} \frac{\gamma(s) - \gamma(s_0)}{|\gamma(s) - \gamma(s_0)|} = \pm e^{i\alpha}.$$

The existence of a tangent does not depend on the chosen parametrization.

**Lemma 2.5.** *Suppose  $\gamma = \partial D$  is a chord-arc curve where  $D$  contains 0 and let  $f : \mathbb{D} \rightarrow D$  be the conformal map such that  $f(0) = 0, f'(0) > 0$ . Let  $\mathcal{T}_\gamma \subseteq \gamma$  be the set of points at which a tangent exists. Then  $|\gamma \setminus \mathcal{T}_\gamma| = 0$  and the following statements are equivalent.*

- (i)  $f(e^{i\theta}) \in \mathcal{T}_\gamma$ .
- (ii) The unrestricted limit of  $\arg(f(z) - f(e^{i\theta}))/z - e^{i\theta}$  in  $\overline{\mathbb{D}}$  exists at  $e^{i\theta}$  and is finite.
- (iii) The non-tangential limit of  $\arg(f(z) - f(e^{i\theta}))/z - e^{i\theta}$  exists at  $e^{i\theta}$  and is finite.
- (iv) The non-tangential limit of  $\arg f'(z)$  exists at  $e^{i\theta}$  and is finite.

In this case, the limits are equal modulo  $2\pi$ .

*Proof.* The equivalence of (i) and (ii) is the first part of [25, Thm. II.4.2] and this equivalence holds without the chord-arc assumption. Next, (ii) trivially implies (iii) and the converse implication is given in [51, Thm. 5.5] since  $\gamma$  is chord-arc so in particular  $D$  is a John domain. The equivalence of (iii) and (iv) is [51, Prop. 4.11]. Finally, since  $\gamma$  is rectifiable  $|\gamma \setminus \mathcal{T}_\gamma| = 0$  by [51, Thm. 6.8].  $\square$

*Remark.* Note that non-tangential approach regions are preserved under conformal mapping between  $\mathbb{D}$  and a quasidisk, see [31, Prop. 1.1].

**Lemma 2.6.** *Suppose  $f : \mathbb{D} \rightarrow D \subset \mathbb{D}$  is a conformal map satisfying  $f(0) = 0$  and assume  $\partial D \cap \partial \mathbb{D} \neq \emptyset$ . If  $z \in \partial \mathbb{D}$  is such that the non-tangential limit  $\arg f'(z)$  exists and  $f(z) \in \partial \mathbb{D}$ , then  $\vartheta[f](z) = 0$ .*

*Proof.* If  $z, f(z) \in \partial \mathbb{D}$ ,  $w \mapsto (f(w) - f(z))/(w - z)$  takes value in the slit domain  $\mathbb{C} \setminus \{-tf(z)/z, t \geq 0\}$ . We can therefore define  $w \mapsto \arg(f(w) - f(z))/(w - z)$  continuously and unambiguously for  $w \in \mathbb{D}$  by choosing a branch of  $\arg$  on this slit domain. Consider the path  $s \mapsto sz$ ,  $s \in [0, 1]$ . Equation (2.7) and Lemma 2.5 show that

$$\vartheta[f](z) = \lim_{s \rightarrow 1^-} \arg \frac{f(sz) - f(z)}{sz - z} - \arg \frac{f(z)}{z} = 0$$

which completes the proof.  $\square$

Let  $\mathcal{T}_t = \mathcal{T}_{\gamma_t}$  be the set of  $z \in \gamma_t$  at which  $\gamma_t$  has a tangent. By Lemma 2.5 and the remark following it,  $\gamma_t \setminus \mathcal{T}_t$  has arclength 0 and if  $z \in \mathcal{T}_t$ , the harmonic function  $\vartheta[g_t](w)$  has a non-tangential limit  $\vartheta[g_t](z)$  as  $w$  tends to  $z$  inside  $D_t$ . We define

$$\hat{\varphi}(t, z) = \vartheta[g_t](z), \quad z \in \mathcal{T}_t, \quad t \geq 0. \quad (2.9)$$

**Lemma 2.7.** *Suppose  $s < t$  and  $z \in \mathcal{T}_s \cap \mathcal{T}_t$ . Then  $\hat{\varphi}(s, z) = \hat{\varphi}(t, z)$ .*

*Proof.* By the chain rule (2.8) and Lemma 2.3, it is enough to assume that  $s = 0$  and verify that  $\hat{\varphi}(t, z) = 0$  if  $z \in S^1$ . This follows from Lemma 2.6 which shows that  $\vartheta[g_t](z) = -\vartheta[f_t](g_t(z)) = 0$ .  $\square$

Let  $\mathcal{T} := \cup_{t \geq 0} \mathcal{T}_t \subset \overline{\mathbb{D}}$ . We define the *winding function*  $\varphi : \mathcal{T} \rightarrow \mathbb{R}$  by forgetting the leaf in  $\hat{\varphi}$ , namely  $\varphi(z) := \hat{\varphi}(t, z)$  if  $z \in \mathcal{T}_t$ . We set by convention  $\varphi(0) = 0$ . By Lemma 2.7  $\varphi$  is well-defined.

*Remark.* Geometrically, modulo  $2\pi$ , the winding function at  $z \in \mathcal{T}_t$  is the angle between the tangent to  $\gamma_t$  and that of the circle passing through  $z$  centered at 0 as described in Section 1.3.

*Remark.* If the leaves are all  $C^1$ ,  $\varphi$  is defined everywhere since  $\mathcal{T} = \overline{\mathbb{D}} \setminus \{0\}$  by Lemma 2.4. In the general case of a chord-arc foliation, a function defined arclength-a.e. on all leaves need not be defined on  $\overline{\mathbb{D}} \setminus \{0\}$  Lebesgue-a.e. To illustrate the subtlety, it is possible to construct a subset  $X$  of  $\mathbb{D}$  of full Lebesgue measure and a foliation of piecewise smooth curves such that each leaf intersects  $X$  in exactly one point, see, e.g., [45]. On the other hand, we shall prove in Proposition 3.6 that a function in  $\mathcal{E}_0(\mathbb{D})$  is determined by its “values” (interpreted appropriately) on the leaves if the curves are chord-arc.

**Lemma 2.8.** *Suppose  $\rho \in \mathcal{N}_+$  generates a foliation and let  $T \geq 0$ . If  $\rho_t$  is the uniform measure for all  $t \geq T$ , then for all  $z \in D_T$ ,*

$$\varphi(z) = \vartheta[g_T](z). \quad (2.10)$$

*In particular,  $\varphi$  is defined and harmonic in  $D_T$ . Moreover,  $(\gamma_t)_{t \geq T}$  are the equipotentials in  $D_T$ .*

*Proof.* If  $T = 0$ ,  $\rho_t$  is the uniform measure for all  $t \geq 0$  which implies that  $g_t(z) = e^t z$  and  $\varphi = 0 = \vartheta[g_0]$ . Now let  $t > T \geq 0$ . By Lemma 2.3, we have  $g_t \circ f_T(z) = e^{t-T} z$ . It follows from  $g_t = (g_t \circ f_T) \circ g_T$ , (2.8) and  $\vartheta[z \mapsto e^{t-T} z] = 0$  that

$$\varphi(z) = \vartheta[g_t](z) = \vartheta[g_T](z) \quad \forall z \in \partial D_t,$$

and we have  $(\gamma_t = f_T(e^{T-t} S^1))_{t > T}$  which is by definition the family of equipotentials in  $D_T$ . We conclude the proof of (2.10) using  $\cup_{t > T} \gamma_t = \cup_{t > T} g_T^{-1}(e^{T-t} S^1) = g_T^{-1}(\mathbb{D} \setminus \{0\}) = D_T \setminus \{0\}$  (and by convention,  $\varphi(0) = 0 = \vartheta[g_T](0)$ ).  $\square$

**Lemma 2.9.** *Suppose  $\rho \in \mathcal{N}_+$  generates a foliation and let  $\varphi$  be the corresponding winding function. For every  $T \geq 0$ , let  $\varphi^{(T)}$  denote the winding function associated to the truncated measure  $\rho^{(T)}$  defined by  $\rho_t^{(T)} := \rho_t$  for  $t \leq T$  and  $\rho_t^{(T)}$  is uniform for  $t > T$ . Then  $(\varphi - \varphi^{(T)}) \circ f_T$  is the winding function generated by the measures  $(\tilde{\rho}_s := \rho_{T+s})_{s \geq 0}$ .*

*Proof.* From Lemma 2.3, the winding function  $\tilde{\varphi}$  associated to  $\tilde{\rho}$  is obtained from

$$\vartheta[\tilde{g}_s] = \vartheta[g_{s+T} \circ f_T] = \vartheta[g_{s+T}] \circ f_T - \vartheta[g_T] \circ f_T$$

where  $(\tilde{g}_s)_{s \geq 0}$  is the Loewner chain of  $\tilde{\rho}$ . We conclude the proof using Lemma 2.8.  $\square$

In other words, decomposing the driving measure  $\rho$  into the truncated (and extended by uniform measure) measure on  $S^1 \times [0, T]$ , and the measure  $\tilde{\rho} : s \mapsto \rho_{T+s}$  amounts to decomposing the winding function into  $\varphi^{(T)}$  which is defined and harmonic in  $D_T$  and  $\varphi - \varphi^{(T)}$  which vanishes (arclength-a.e.) on every  $\gamma_t$  for  $t \leq T$ .

## 3 The foliation disintegration isometry

### 3.1 Hadamard’s formula

In this section we use the Loewner-Kufarev equation to derive a formula for the dynamics of the Green’s function. The resulting expression is a version of the classical Hadamard formula in a smooth setting. We fix  $\rho \in \mathcal{N}_+$  and let  $(g_t : D_t \rightarrow \mathbb{D})_{t \geq 0}$  be the associated uniformizing Loewner chain.

For each  $t \geq 0$ , we let  $G_t(z, w)$  be the Green's function for  $D_t$ . For  $z, w$  fixed, we extend the definition of  $G_t(z, w)$  to  $t \geq \min\{\tau(z), \tau(w)\}$  by 0. We will show that with this definition,  $t \mapsto G_t(z, w)$  is absolutely continuous under the assumption that  $\rho$  generates a foliation. Note that  $t \mapsto G_t(z, w)$  is always absolutely continuous for  $t \in [0, \min\{\tau(z), \tau(w)\})$  but need not be continuous at  $\min\{\tau(z), \tau(w)\}$ , e.g., in the case when  $\partial D_t$  disconnects an open set containing  $z, w$  from 0 as  $t \rightarrow \tau = \tau(z) = \tau(w)$ .

**Lemma 3.1.** *Consider the Loewner-Kufarev equation driven by  $\rho \in \mathcal{N}_+$ . Then for a.e.  $t < \min\{\tau(z), \tau(w)\}$  and all  $z, w \in D_t$ ,*

$$-\partial_t G_{D_t}(z, w) = \int_0^{2\pi} P_{\mathbb{D}}(g_t(z), e^{i\theta}) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta).$$

If in addition  $\rho$  is assumed to generate a foliation, then  $t \mapsto G_t(z, w)$  is absolutely continuous for all  $t$ .

See also [56, Thm. 4] for a similar result.

*Proof.* First note that for  $z, w \in D_t$ , by conformal invariance of the Green's function,

$$G_t(z, w) = G_{D_t}(z, w) = -\log \left| \frac{g_t(z) - g_t(w)}{1 - \overline{g_t(w)}g_t(z)} \right|. \quad (3.1)$$

Setting  $z_t = g_t(z), w_t = g_t(w)$ , the Loewner-Kufarev equation (2.5) implies that for a.e.  $t < \min\{\tau(z), \tau(w)\}$ ,  $\partial_t z_t = z_t H_t(z_t)$ ,  $\partial_t w_t = w_t H_t(w_t)$  and so

$$\begin{aligned} -\partial_t G_t(z, w) &= \operatorname{Re} \partial_t \log \frac{z_t - w_t}{1 - \overline{w_t}z_t} \\ &= \operatorname{Re} \frac{\overline{w_t}z_t (H_t(z_t) + \overline{H_t(w_t)})}{1 - \overline{w_t}z_t} + \operatorname{Re} \frac{z_t H_t(z_t) - w_t H_t(w_t)}{z_t - w_t}. \end{aligned}$$

Next, note that

$$\begin{aligned} \operatorname{Re} \frac{\overline{w_t}z_t (H_t(z_t) + \overline{H_t(w_t)})}{1 - \overline{w_t}z_t} &= \int_0^{2\pi} \operatorname{Re} \frac{\overline{w_t}z_t \cdot 2(1 - z_t \overline{w_t})}{(1 - z_t \overline{w_t})(e^{i\theta} - z_t)(e^{-i\theta} - \overline{w_t})} d\rho_t(\theta) \\ &= \int_0^{2\pi} \operatorname{Re} \frac{2z_t \overline{w_t}}{(e^{i\theta} - z_t)(e^{-i\theta} - \overline{w_t})} d\rho_t(\theta) \\ &= \int_0^{2\pi} \operatorname{Re} \frac{2z_t \overline{w_t} (e^{-i\theta} - \overline{z_t})(e^{i\theta} - w_t)}{|e^{i\theta} - z_t|^2 |e^{i\theta} - w_t|^2} d\rho_t(\theta). \end{aligned} \quad (3.2)$$

Moreover,

$$\begin{aligned} \operatorname{Re} \frac{z_t H_t(z_t) - w_t H_t(w_t)}{z_t - w_t} &= \int_0^{2\pi} \operatorname{Re} \left( \frac{e^{i\theta} + z_t}{e^{i\theta} - z_t} + \frac{2w_t e^{i\theta}}{(e^{i\theta} - z_t)(e^{i\theta} - w_t)} \right) d\rho_t(\theta) \\ &= \int_0^{2\pi} \operatorname{Re} \frac{(e^{i\theta} + z_t)(e^{-i\theta} - \overline{z_t})|e^{i\theta} - w_t|^2 + 2w_t e^{i\theta} (e^{-i\theta} - \overline{z_t})(e^{-i\theta} - \overline{w_t})}{|e^{i\theta} - z_t|^2 |e^{i\theta} - w_t|^2} d\rho_t(\theta). \end{aligned} \quad (3.3)$$

Adding (3.2) and (3.3) and simplifying,

$$-\partial_t G_t(z, w) = \int_0^{2\pi} \frac{1 - |z_t|^2}{|e^{i\theta} - z_t|^2} \cdot \frac{1 - |w_t|^2}{|e^{i\theta} - w_t|^2} d\rho_t(\theta) = \int_0^{2\pi} P_{\mathbb{D}}(z_t, e^{i\theta}) P_{\mathbb{D}}(w_t, e^{i\theta}) d\rho_t(\theta),$$

as claimed.

Let us now assume  $\rho \in \mathcal{N}_+$  generates a foliation and prove that  $t \mapsto G_t(z, w)$  is absolutely continuous for all  $t \geq 0$ . For all  $z, w \in \mathbb{D}$ ,  $z \neq w$ , we need to show that  $G_t(z, w) \rightarrow 0$  as  $t \nearrow \min\{\tau(z), \tau(w)\}$ . Without loss of generality, we assume that  $\tau(z) \leq \tau(w)$ . If  $\tau(z) < \tau(w)$ , it is clear from (3.1) that  $G_t(z, w) \rightarrow 0$  as  $t \rightarrow \tau(z)$  since  $|g_t(w)|$  is bounded away from 1 for  $t \in [0, \tau(z)]$ . Assume now that  $\tau = \tau(z) = \tau(w)$ . Lemma 2.4 implies that  $z, w \in \partial D_\tau$ . Since  $g_\tau : D_\tau \rightarrow \mathbb{D}$  is a conformal map between two Jordan domains,  $g_\tau$  extends to a homeomorphism  $\overline{D}_\tau \rightarrow \overline{\mathbb{D}}$  and  $g_\tau(z) \neq g_\tau(w) \in S^1$ . We claim that

$$\lim_{t \rightarrow \tau^-} g_t(z) = g_\tau(z).$$

Assuming this, it follows that  $|g_t(z) - g_t(w)|$  is bounded away from 0 on  $[0, \tau]$ . Therefore  $G_t(z, w) \rightarrow 0$  as  $t \rightarrow \tau^-$  using (3.1). To prove the claim, let  $t_n, n = 1, 2, \dots$ , be any sequence such that  $t_n \nearrow \tau$  and such that  $\zeta := \lim_{n \rightarrow \infty} g_{t_n}(z)$  exists. Pick  $\varepsilon > 0$  and let  $v \in D_\tau$  be such that the interior distance between  $z$  and  $v$  in  $D_\tau$  is at most  $\varepsilon$ . By the Beurling estimate there is a constant  $C$  that does not depend on  $z, v$  such that  $|g_\tau(z) - g_\tau(v)| \leq C\sqrt{\varepsilon}$  and by monotonicity of the domains the same estimate holds with  $\tau$  replaced by any  $t_n < \tau$ . Let  $n_0$  be large such that if  $n > n_0$  then  $|g_{t_n}(v) - g_\tau(v)| + |g_{t_n}(z) - \zeta| < \varepsilon$ . Such  $n_0$  exists by definition of  $\zeta$  and since  $t \mapsto g_t(v)$  is continuous on  $[0, \tau(v))$  and  $\tau(v) > \tau(z)$ . Combining these estimates with the triangle inequality it follows that  $|g_\tau(z) - \zeta| \leq 2C\sqrt{\varepsilon}$ .  $\square$

### 3.2 Disintegration isometry

We assume in this section that  $\rho \in \mathcal{N}_+$  generates a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$ . We will write

$$L^2(2\rho) := L^2(S^1 \times \mathbb{R}_+, 2\rho)$$

and  $\langle \cdot, \cdot \rangle_{L^2(2\rho)}$  for the corresponding inner product. Recall also that we write  $\mathcal{E}_0(\mathbb{D})$  for  $W_0^{1,2}(\mathbb{D})$  equipped with the Dirichlet energy norm.

**Lemma 3.2.** *Suppose  $\rho \in \mathcal{N}_+$  generates a foliation and that  $\phi \in C_c^\infty(\mathbb{D})$ . Then*

$$\iota[\phi](\theta, t) := \frac{1}{2\pi} \int_{\mathbb{D}} \Delta(\phi \circ f_t)(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z) \quad (3.4)$$

is an element of  $L^2(2\rho)$ . Moreover, for all  $T > 0$ ,

$$\mathcal{D}_{\mathbb{D}}(\phi) - \mathcal{D}_{\mathbb{D}}(\phi_T^0) = \|\iota[\phi] \mathbf{1}_{S^1 \times [0, T]}\|_{L^2(2\rho)}^2$$

where  $\phi_T^0 \in \mathcal{E}_0(\mathbb{D})$  is the zero-trace part of  $\phi \circ f_T \in W^{1,2}(\mathbb{D})$  as in (2.1).

In particular, the operator  $\iota : \mathcal{E}_0(\mathbb{D}) \cap C_c^\infty(\mathbb{D}) \rightarrow L^2(2\rho)$  is norm-preserving.

*Proof.* Let  $\phi \in C_c^\infty(\mathbb{D})$  set  $\mu = \Delta\phi$  and write  $G_0 = 2\pi\Delta^{-1}$ , where we recall that we consider the positive Laplacian. (We write  $G_0$  for both the operator and function.) For  $z \in \mathbb{D}$ ,

$$\phi(z) = \frac{1}{2\pi} G_0 \mu(z) = \frac{1}{2\pi} \int_{\mathbb{D}} G_0(w, z) \mu(w) dA(w).$$

Using integration by parts, since  $\phi$  is smooth and has compact support,

$$\int_{\mathbb{D}} |\nabla\phi(z)|^2 dA(z) = \int_{\mathbb{D}} \phi(z) \Delta\phi(z) dA(z)$$

$$= \frac{1}{2\pi} \int_{\mathbb{D}} \int_{\mathbb{D}} G_0(w, z) \mu(w) \mu(z) dA(w) dA(z).$$

As before we set  $G_t(z, w) = G_{D_t}(z, w) = G_0(z_t, w_t)$  for  $z, w \in D_t$  (recall that  $z_t = g_t(z)$  and  $w_t = g_t(w)$ ) and 0 otherwise. Let

$$\phi_t := \phi \circ f_t, \quad \mu_t := \Delta \phi_t = |f_t'|^2 \mu \circ f_t$$

and note that the zero-trace part of  $\phi_t$  satisfies  $\phi_t^0 = G_0 \mu_t / 2\pi$ . Moreover, performing a change of variable,

$$\begin{aligned} \int_{\mathbb{D}} |\nabla \phi_t^0(z)|^2 dA(z) &= \frac{1}{2\pi} \int_{\mathbb{D}} \int_{\mathbb{D}} G_0(w, z) \mu_T(w) \mu_T(z) dA(w) dA(z) \\ &= \frac{1}{2\pi} \int_{\mathbb{D}} \int_{\mathbb{D}} G_0(w, z) \mu \circ f_T(w) \mu \circ f_T(z) |f_T'(z)|^2 |f_T'(w)|^2 dA(w) dA(z) \\ &= \frac{1}{2\pi} \int_{D_T} \int_{D_T} G_T(w, z) \mu(w) \mu(z) dA(w) dA(z). \end{aligned} \quad (3.5)$$

Next, note that by Lemma 3.1  $-\partial_t G_t(z, w) = \int_0^{2\pi} P_{\mathbb{D}}(g_t(z), e^{i\theta}) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta) \geq 0$  for  $z, w \in \mathbb{D}$  and that  $P_{\mathbb{D}}(g_t(w), e^{i\theta}) \geq 0$ . Since the singularity of the Green's function is logarithmic (and therefore integrable), we obtain

$$\begin{aligned} \int_0^T \int_{D_t} \int_{D_t} -\partial_t G_t(z, w) dA(z) dA(w) dt &= \int_0^T \int_{\mathbb{D}} \int_{\mathbb{D}} -\partial_t G_t(z, w) dA(z) dA(w) dt \\ &= \int_{\mathbb{D}} \int_{\mathbb{D}} \int_0^T -\partial_t G_t(z, w) dt dA(z) dA(w) \\ &= \int_{\mathbb{D}} \int_{\mathbb{D}} G_0(z, w) - G_T(z, w) dA(z) dA(w) < \infty. \end{aligned}$$

Therefore, using the smoothness of  $h$ , we can apply Fubini's theorem (repeatedly) and (3.5) to compute

$$\begin{aligned} &\int_{\mathbb{D}} |\nabla \phi(z)|^2 dA(z) - \int_{\mathbb{D}} |\nabla \phi_T^0(z)|^2 dA(z) \\ &= \frac{1}{2\pi} \int_{\mathbb{D}} \int_{\mathbb{D}} (G_0(z, w) - G_T(z, w)) \mu(z) \mu(w) dA(z) dA(w) \\ &= \frac{1}{2\pi} \int_{\mathbb{D}} \int_{\mathbb{D}} \int_0^T -\partial_t G_t(z, w) \mu(z) \mu(w) dt dA(w) dA(z) \\ &= \frac{1}{2\pi} \int_0^T \int_{D_t} \int_{D_t} -\partial_t G_t(z, w) \mu(z) \mu(w) dA(w) dA(z) dt \\ &= \frac{1}{2\pi} \int_0^T \int_{D_t} \int_{D_t} \mu(z) \mu(w) \int_0^{2\pi} P_{\mathbb{D}}(g_t(z), e^{i\theta}) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta) dA(w) dA(z) dt \\ &= \frac{1}{2\pi} \int_0^T \int_0^{2\pi} \int_{D_t} \int_{D_t} \mu(z) \mu(w) P_{\mathbb{D}}(g_t(z), e^{i\theta}) P_{\mathbb{D}}(g_t(w), e^{i\theta}) dA(w) dA(z) d\rho_t(\theta) dt \\ &= \frac{1}{2\pi} \iint_{S^1 \times [0, T]} \left( \int_{\mathbb{D}} \mu_t(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z) \right) \left( \int_{\mathbb{D}} \mu_t(w) P_{\mathbb{D}}(w, e^{i\theta}) dA(w) \right) d\rho(\theta, t) \\ &= 2\pi \iint_{S^1 \times [0, T]} |\iota[\phi](\theta, t)|^2 d\rho(\theta, t), \end{aligned}$$

as claimed. Letting  $T \rightarrow \infty$ , by monotone convergence, we obtain that the operator  $\iota : \mathcal{E}_0(\mathbb{D}) \cap C_c^\infty(\mathbb{D}) \rightarrow L^2(2\rho)$  is norm-preserving.  $\square$

*Remark.* Given a signed measure  $\mu$  supported on  $\overline{\mathbb{D}}$ , the *balayage* of  $\mu$  to  $\partial\mathbb{D}$  is a measure  $\nu$  on  $\partial\mathbb{D}$  such that the logarithmic potentials of  $\mu$  and  $\nu$  agree on  $\mathbb{D}^*$ . Viewing  $\mu$  as a charge density,  $\nu$  represents the optimal way (with respect to logarithmic energy) to redistribute charge to  $\partial\mathbb{D}$  while keeping the potential fixed in the complementary domain. In our setting, for  $t$  fixed, one can see that  $\iota[\phi](\theta, t)$  in fact equals the (density of) the balayage of the “charge density”  $\Delta\phi_t dA$  to  $\partial\mathbb{D}$ . See, e.g., [36, Ch. IV].

*Remark.* The disintegration isometry is closely related to the general approach of [29], see in particular Section 3 of that paper. Hedenmalm and Nieminen consider  $C^2$ -smooth, strictly monotone deformations of domains, and do not employ the Loewner equation. In the smooth, strictly monotone case, a version of our Lemma 3.2 can be deduced from results of [29] via a “polar coordinates” change of variable which also relies on strong regularity assumptions of the interfaces.

Since  $C_c^\infty(\mathbb{D})$  is dense in  $\mathcal{E}_0(\mathbb{D})$ , the operator  $\iota$  extends to  $\mathcal{E}_0(\mathbb{D})$  and we have

$$\mathcal{D}_{\mathbb{D}}(\phi) = \|\iota[\phi]\|_{L^2(2\rho)}^2, \quad \phi \in \mathcal{E}_0(\mathbb{D}).$$

We will now construct an inverse operator  $\varkappa : L^2(2\rho) \rightarrow \mathcal{E}_0(\mathbb{D})$  as follows. For  $u \in L^2(2\rho)$  and  $\phi \in C_c^\infty(\mathbb{D})$ , we consider

$$\Phi_u : \quad \phi \mapsto 2 \iint_{\mathbb{R}_+ \times S^1} u(t, \theta) \iota[\phi](\theta, t) d\rho(t, \theta) = \langle u, \iota[\phi] \rangle_{L^2(2\rho)}$$

which extends to a bounded linear operator  $\mathcal{E}_0(\mathbb{D}) \rightarrow \mathbb{R}$ . Indeed, the Cauchy-Schwarz inequality and Lemma 3.2 show that

$$\left| \langle u, \iota[\phi] \rangle_{L^2(2\rho)} \right| \leq \|u\|_{L^2(2\rho)} \|\iota[\phi]\|_{L^2(2\rho)} = \|u\|_{L^2(2\rho)} \mathcal{D}_{\mathbb{D}}(\phi)^{1/2}. \quad (3.6)$$

By the Riesz representation theorem there exists a unique  $\varkappa[u] \in \mathcal{E}_0(\mathbb{D})$  with the property that for all  $\phi \in C_c^\infty(\mathbb{D})$ ,

$$\frac{1}{\pi} \int_{\mathbb{D}} \varkappa[u] \Delta\phi dA(z) = \frac{1}{\pi} \int_{\mathbb{D}} \nabla \varkappa[u] \nabla \phi dA(z) = \Phi_u(\phi). \quad (3.7)$$

It follows immediately that  $\varkappa \circ \iota = \text{Id}_{\mathcal{E}_0(\mathbb{D})}$ . We now give the explicit formula for  $\varkappa$ . In this statement and below we use the notation  $u_t(\cdot) := u(\cdot, t)$  for  $u \in L^2(2\rho)$ .

**Proposition 3.3.** *Suppose  $\rho \in \mathcal{N}_+$  generates a foliation. Let  $u \in L^2(2\rho)$ . Then for a.e.  $w \in \mathbb{D}$ ,*

$$\varkappa[u](w) = 2\pi \int_0^{\tau(w)} P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt,$$

and  $t \mapsto P_{\mathbb{D}}[u_t \rho_t](g_t(w)) \in L^1([0, \tau(w)], dt)$ .

*Proof.* By linearity and splitting  $u = u^+ - u^-$  with  $u^+ = \max\{u, 0\}$  and  $u^- := \max\{-u, 0\}$ , it suffices to prove the proposition when  $u \geq 0$ . We let

$$\tilde{\varkappa}[u](w) := 2\pi \int_0^{\tau(w)} P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt = \int_0^{\tau(w)} \int_{S^1} P_{\mathbb{D}}(g_t(w), e^{i\theta}) u(\theta, t) d\rho_t(\theta) dt.$$

We first prove that for all  $\phi \in C_c^\infty(\mathbb{D})$ ,

$$2 \int_0^\infty \int_{S^1} u(\theta, t) \iota[\phi](\theta, t) d\rho_t(\theta) dt = \frac{1}{\pi} \int_{\mathbb{D}} \Delta\phi(w) \tilde{\varkappa}[u](w) dA(w). \quad (3.8)$$

For this, we will interchange repeatedly the order of integration in the following computation. To justify this, we let

$$\phi^+ := \Delta^{-1} \max\{\Delta\phi, 0\} \quad \text{and} \quad \phi^- := \Delta^{-1} \max\{-\Delta\phi, 0\}.$$

We have  $\phi = \phi^+ - \phi^-$ . Since  $\phi$  is smooth,  $\max\{\Delta\phi, 0\}$  is Lipschitz continuous. By elliptic regularity (see, e.g., [26, Sec. 4.3]),  $\phi^+, \phi^- \in \mathcal{E}_0(\mathbb{D}) \cap C^{2,\alpha}(\mathbb{D})$  for any  $\alpha < 1$  and clearly  $\Delta\phi^\pm \geq 0$ . Moreover, recalling that  $\phi_t^\pm = \phi \circ f_t$ , we have  $\Delta\phi_t^\pm = \Delta(\phi^\pm \circ f_t) = |f_t'|^2(\Delta\phi^\pm) \circ f_t \geq 0$ . So it follows that

$$u[\phi^\pm](\theta, t) = \frac{1}{2\pi} \int_{\mathbb{D}} \Delta\phi_t^\pm(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z) \geq 0.$$

Since  $u, u[\phi^\pm] \in L^2(2\rho)$ , the Cauchy-Schwarz inequality shows that  $u \cdot u[\phi^\pm] \in L^1(2\rho)$ . Using Fubini's theorem, this implies that  $u(\theta, t) \Delta\phi_t(z) P_{\mathbb{D}}(z, e^{i\theta})$  is in  $L^1(\mathbb{D} \times S^1 \times \mathbb{R}_+, dA \times d\rho_t(\theta) \times dt)$ . Therefore the left-hand side of (3.8) equals

$$\begin{aligned} & 2 \int_0^\infty \int_{S^1} u(\theta, t) \left[ \frac{1}{2\pi} \int_{\mathbb{D}} \Delta\phi_t(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z) \right] d\rho_t(\theta) dt \\ &= \frac{1}{\pi} \int_0^\infty \int_{\mathbb{D}} \Delta\phi_t(z) \int_{S^1} u(\theta, t) P_{\mathbb{D}}(z, e^{i\theta}) d\rho_t(\theta) dA(z) dt \\ &= \frac{1}{\pi} \int_0^\infty \int_{\mathbb{D}} (\Delta\phi) \circ f_t(z) |f_t'(z)|^2 \int_{S^1} u(\theta, t) P_{\mathbb{D}}(z, e^{i\theta}) d\rho_t(\theta) dA(z) dt \\ &= \frac{1}{\pi} \int_0^\infty \int_{D_t} \Delta\phi(w) \int_{S^1} u(\theta, t) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta) dA(w) dt \\ &= \frac{1}{\pi} \int_{\mathbb{D}} \Delta\phi(w) \int_0^{\tau(w)} \int_{S^1} u(\theta, t) P_{\mathbb{D}}(g_t(w), e^{i\theta}) d\rho_t(\theta) dt dA(w) \end{aligned}$$

which proves (3.8). Given this, (3.7) implies that  $\varkappa[u] - \tilde{\varkappa}[u]$  is weakly harmonic, and by Weyl's lemma it is harmonic in  $\mathbb{D}$ . Since we know that  $\varkappa[u] \in \mathcal{E}_0(\mathbb{D})$ , to complete the proof, it is therefore enough to show that  $\tilde{\varkappa}[u] \in \mathcal{E}_0(\mathbb{D})$ . For this, we show that  $\tilde{\varkappa}[u]$  can be extended to a function  $\psi \in W^{1,2}(e\mathbb{D})$  where  $\psi(w) = 0$  for all  $1 < |w| < e$  (see, e.g., [13, Prop. 9.18]). To construct the extension, we define a measure  $\hat{\rho} \in \mathcal{N}_+$  with  $\hat{\rho}_t = \rho_{t-1}$  for  $t \geq 1$  and uniform for  $t \in [0, 1)$ . Similarly, let  $\hat{u}(\theta, t) := u(\theta, t-1)$  for  $t \geq 1$ , and  $\hat{u}(\theta, t) = 0$  for  $t \in [0, 1)$ .

We clearly have  $\hat{u} \in L^2(2\hat{\rho})$ , and  $\psi(w) := \tilde{\varkappa}[\hat{u}](e^{-1}w) = 0$  if  $1 < |w| < e$ . By construction, we have  $\psi \in \mathcal{E}_0(e\mathbb{D})$  from the proof above. Moreover, if  $\hat{g}_t$  is the uniformizing Loewner chain of  $\hat{\rho}$ , then for  $t \in [0, 1)$  we have  $\hat{g}_t(z) = e^t z$  and for  $t \geq 1$ ,  $\hat{g}_t(z) = g_{t-1}(ez)$ . It follows that  $\tilde{\varkappa}[u](w) = \tilde{\varkappa}[\hat{u}](e^{-1}w) = \psi(w)$  for  $w \in \mathbb{D}$ , and this shows that  $\varkappa = \tilde{\varkappa}$  in  $\mathcal{E}_0(\mathbb{D})$ .

Finally, since  $u \geq 0$ , it follows that  $P_{\mathbb{D}}[u_t \rho_t](g_t(w)) \in L^1([0, \tau(w)], dt)$  for a.e.  $w \in \mathbb{D}$ .  $\square$

**Corollary 3.4.** *Let  $\phi \in \mathcal{E}_0(\mathbb{D})$  and  $T \geq 0$ . The orthogonal decomposition of  $\phi$  into a function in  $\mathcal{E}_0(D_T)$  and a function in  $\mathcal{E}_0(\mathbb{D})$  harmonic in  $D_T$  (2.1) is given by*

$$\phi^{0,T} := \varkappa[u[\phi] \mathbf{1}_{S^1 \times [T, \infty)}] \in \mathcal{E}_0(D_T) \quad \text{and} \quad \phi^{h,T} := \varkappa[u[\phi] \mathbf{1}_{S^1 \times [0, T)}].$$

*Remark.* Using the notation of Lemma 3.2, a consequence of the corollary is that  $\phi^{0,T} = \phi_T^0 \circ g_T$ .

*Proof.* Since  $\varkappa \circ \iota[\phi] = \phi$ , we have  $\phi^{0,T} + \phi^{h,T} = \phi$ . Consider the Loewner chain driven by  $(\hat{\rho}_t := \rho_{T+t})_{t \geq 0}$  and the associated operator  $\hat{\varkappa}$ . We obtain from Lemma 2.3 and Proposition 3.3 that

$$\phi^{0,T} \circ f_T = \hat{\varkappa}[\iota[\phi](\cdot, \cdot + T)] \in \mathcal{E}_0(\mathbb{D}).$$

Using conformal invariance, this yields  $\phi^{0,T} \in \mathcal{E}_0(D_T)$ . For  $z \in D_T$ , by definition,

$$\phi^{h,T}(z) = 2\pi \int_0^T P_{\mathbb{D}}[\iota[\phi]_t \rho_t](g_t(z)) dt.$$

Note that  $P_{\mathbb{D}}[\iota[\phi]_t \rho_t](g_t(\cdot))$  is harmonic in  $D_T$  for  $t < T$ . Therefore, by the characterization of harmonic functions in terms of the mean value property and Fubini's theorem we obtain that  $\phi^{h,T}$  is harmonic in  $D_T$ .  $\square$

**Theorem 3.5.** *The operator  $\iota : \mathcal{E}_0(\mathbb{D}) \rightarrow L^2(2\rho)$  is a (bijective) isometry.*

*Proof.* We already know that  $\varkappa \circ \iota = \text{Id}_{\mathcal{E}_0(\mathbb{D})}$ . To check that  $\iota \circ \varkappa = \text{Id}_{L^2(2\rho)}$ , it suffices to show that  $\text{Ker}(\varkappa) = \{0\}$  in  $L^2(2\rho)$ . Indeed, for all  $u \in L^2(2\rho)$ , we have  $\varkappa[u] = \varkappa \circ \iota \circ \varkappa[u]$ . Then  $\text{Ker}(\varkappa) = \{0\}$  implies that  $u = \iota \circ \varkappa[u]$ .

Now let  $u \in \text{Ker}(\varkappa)$ . Fix  $T \geq 0$ . By Corollary 3.4,  $\varkappa[u \mathbf{1}_{S^1 \times [0,T]}] \in \mathcal{E}_0(\mathbb{D})$  and  $\varkappa[u \mathbf{1}_{S^1 \times [T,\infty)}]$  give the orthogonal decomposition (2.1) of  $\varkappa[u] = 0$  with respect to  $D_T$ . We have therefore for all  $w \in D_T$ ,

$$\varkappa[u \mathbf{1}_{S^1 \times [0,T]}](w) = 2\pi \int_0^T P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt = 0.$$

Taking the derivative in  $T$ , we obtain that the function  $P_{\mathbb{D}}[u_T \rho_T]$  vanishes in  $\mathbb{D}$ . (One can choose a dense and countable family  $J$  of points in  $\mathbb{D}$ , we have for a.e.  $T \geq 0$  and  $w \in D_T \cap J$ ,  $P_{\mathbb{D}}[u_T \rho_T](g_T(w)) = 0$ . Since the latter integral is harmonic thus continuous, it vanishes for a.e.  $T \geq 0$  and all  $w \in D_T$ .) But this implies that the measure  $u_T \rho_T$  on  $S^1$  is the zero measure. Therefore,  $u(\theta, T) = 0$  for  $\rho_T$ -a.e.  $\theta \in S^1$ . It follows that

$$\iint_{S^1 \times \mathbb{R}_+} |u(\theta, t)|^2 d\rho(\theta, t) = 0,$$

which shows  $\text{Ker}(\varkappa) = \{0\}$  and concludes the proof.  $\square$

We will now discuss the relation between  $\mathcal{E}_0(\mathbb{D})$  and functions defined on the leaves of a foliation. We will consider a generalization of the standard trace operator for  $W^{1,2}$  on Lipschitz domains to chord-arc domains, see [33] and [68, Appx. A]. Suppose  $\phi \in W_{\text{loc}}^{1,2}(\mathbb{C})$  and  $\gamma$  is a chord-arc curve in  $\mathbb{C}$ . The *Jonsson-Wallin trace* of  $\phi$  on  $\gamma$  is defined for arclength-a.e.  $z \in \gamma$  by the following limit of averages on balls  $B(z, r) = \{w : |w - z| < r\}$

$$\phi|_{\gamma}(z) := \lim_{r \rightarrow 0^+} \int_{B(z,r)} \phi dA. \quad (3.9)$$

A function  $\varphi$  defined arclength-a.e. on all leaves of a foliation ( $\gamma_t = \partial D_t$ ) is said to have an extension  $\phi$  in  $\mathcal{E}_0(\mathbb{D})$  if for all  $t$ , the Jonsson-Wallin trace of  $\phi$  on  $\gamma_t$  (denoted  $\phi|_{\gamma_t}$ ) coincides with  $\varphi$  arclength-a.e. (Here and below we identify  $\phi \in \mathcal{E}_0(\mathbb{D})$  with the function in  $W^{1,2}(\mathbb{C})$  that is equal to  $\phi$  in  $\mathbb{D}$  and 0 in  $\mathbb{D}^*$ .)

**Proposition 3.6.** *If a function  $\varphi$  defined arclength-a.e. on each leaf of a foliation of  $\mathbb{D}$  has an extension to  $\mathcal{E}_0(\mathbb{D})$ , then the extension is unique.*

*Proof.* Let  $\phi$  be an extension of  $\varphi$  in  $\mathcal{E}_0(\mathbb{D})$ . For a fixed  $T \geq 0$ , the orthogonal decomposition  $\phi = \phi^{0,T} + \phi^{h,T}$  where  $\phi^{0,T} \in \mathcal{E}_0(D_T)$  and  $\phi^{h,T} \in \mathcal{E}_0(\mathbb{D})$  is harmonic in  $D_T$  is given by

$$\phi^{0,T} = \varkappa[\iota[\phi]\mathbf{1}_{S^1 \times [T, \infty)}] \quad \text{and} \quad \phi^{h,T} = \varkappa[\iota[\phi]\mathbf{1}_{S^1 \times [0, T)}],$$

by Corollary 3.4. We have that  $\phi|_{\partial D_T} = \phi^{h,T}|_{\partial D_T}$  arclength-a.e. since they coincide in  $\mathbb{C} \setminus D_T$ , see [68, Lem. A.2]. Hence,  $\varphi$  determines  $\phi^{h,T}|_{D_T}$  since arclength and harmonic measure are mutually absolutely continuous on chord-arc curves. Assume that  $\tilde{\phi}$  also extends  $\varphi$ . Then we have for all  $w \in D_T$ ,

$$0 = \phi^{h,T}(w) - \tilde{\phi}^{h,T}(w) = \varkappa\left[(\iota[\phi] - \iota[\tilde{\phi}])\mathbf{1}_{S^1 \times [0, T)}\right](w) = 2\pi \int_0^T P_{\mathbb{D}}[\iota[\phi - \tilde{\phi}]_t \rho_t](g_t(w)) dt.$$

The proof of Theorem 3.5 shows that  $\iota[\phi] = \iota[\tilde{\phi}]$  in  $L^2(2\rho)$ . Therefore  $\phi = \tilde{\phi}$  in  $\mathcal{E}_0(\mathbb{D})$  and this completes the proof.  $\square$

## 4 Loewner-Kufarev energy

### 4.1 Definitions

For each measure  $\sigma \in \mathcal{M}(S^1)$  we define

$$L(\sigma) = \frac{1}{2} \int_{S^1} \nu'(\theta)^2 d\theta \tag{4.1}$$

if  $d\sigma(\theta) = \nu^2(\theta) d\theta$  with the non-negative square-root density  $\nu \in W^{1,2}(S^1)$  and, by convention,  $L(\sigma) = \infty$  otherwise. With this definition,  $L(\sigma)$  is the usual Dirichlet energy of  $\nu$  on  $S^1$ .

*Remark.* Note that  $L(\sigma) = 0$  if and only if  $\sigma$  is the uniform measure on  $S^1$ .

Then for  $\rho \in \mathcal{N}_+$  (see Section 2.2), we define

$$S_+(\rho) = \int_0^\infty L(\rho_t) dt, \tag{4.2}$$

where  $(\rho_t)_{t \geq 0}$  is a disintegration of  $\rho$ . We call  $S_+(\rho)$  the *Loewner-Kufarev energy* of the measure  $\rho$ . When  $L(\rho_t) < \infty$ , we write  $d\rho_t = \rho_t(\theta) d\theta = \nu_t^2(\theta) d\theta$ .

It is also useful to define

$$S_{[a,b]}(\rho) = \int_a^b L(\rho_t) dt.$$

### 4.2 First properties

We now record a few simple properties that will be used in our proofs.

**Lemma 4.1.** *Suppose  $S_+(\rho) < \infty$  and define the time-changed family of measures  $(\tilde{\rho}_s = t'(s)\rho_{t(s)})_{s \geq 0}$ , where*

$$t(s) = \int_0^s |\tilde{\rho}_u| du.$$

*Then  $S_+(\tilde{\rho}) = S_+(\rho)$ . Moreover, if  $(g_t^\rho)_{t \geq 0}$  and  $(g_s^{\tilde{\rho}})_{s \geq 0}$  are the corresponding uniformizing Loewner chains, then  $g_s^{\tilde{\rho}} = g_{t(s)}^\rho$ .*

*Proof.* We have

$$S_+(\tilde{\rho}) = \int_0^\infty L(\tilde{\rho}_t) dt = \int_0^\infty L(t'(s)\rho_t) ds = \int_0^\infty L(\rho_t)t'(s) ds = S_+(\rho).$$

On the other hand, the Loewner flow driven by  $(\tilde{\rho}_s)$  is the solution  $s \mapsto g_s^{\tilde{\rho}}(z)$  to

$$\partial_s g_s^{\tilde{\rho}}(z) = g_s^{\tilde{\rho}}(z) H[\tilde{\rho}_s](g_s^{\tilde{\rho}}(z)) \quad g_0^{\tilde{\rho}}(z) = z.$$

Using the definition of  $\tilde{\rho}$ , we therefore get

$$\partial_t g_t^{\tilde{\rho}}(z) = g_t^{\tilde{\rho}}(z) H[\rho_t](g_t^{\tilde{\rho}}(z))$$

and this implies  $g_s^{\tilde{\rho}} = g_{t(s)}^\rho$ . □

One should thus view  $\tilde{\rho}$  as a time-reparametrization of  $\rho$  and the solution to the Loewner equation associated with the measure  $\tilde{\rho}$  is a reparametrization of the solution associated to  $\rho$ . The invariance property of the Loewner-Kufarev energy suggests that it is intrinsic to the foliation (once we know that finite energy measures generate foliations) and does not depend on the time-parametrization. This is further reflected in the energy duality Theorem 1.7 expressing  $S_+$  in terms of the winding function.

**Lemma 4.2.** *If  $S_+(\rho) < \infty$ , then for every  $z \in \overline{\mathbb{D}} \setminus \{0\}$  we have  $\tau(z) < \infty$ .*

*Proof.* We claim that there exists  $\varepsilon > 0$  such that for all  $t \geq 0$ ,  $L(\rho_t) < \varepsilon$  implies  $\min_\theta \nu_t^2(\theta) > 1/4\pi$ . Indeed, suppose without loss in generality that  $\nu_t^2(0) \leq 1/4\pi$ . Then by the mean value theorem and that  $\rho_t \in \mathcal{M}_1(S^1)$ , there is  $\theta_0$  such that  $\nu_t^2(\theta_0) \geq 1/2\pi$  and we obtain easily by interpolating linearly  $\nu_t$  on  $[0, \theta_0]$  that  $L(\rho_t) \geq (3 - 2\sqrt{2})/16\pi^2 =: \varepsilon$ . Let  $E := \{t \geq 0 : L(\rho_t) > \varepsilon\}$ . For  $t \notin E$  the Poisson integral of  $\rho_t$  is continuous on  $\overline{\mathbb{D}}$  and by the maximum principle,  $P_{\mathbb{D}}[\rho_t] \geq 1/4\pi$ .

Now fix  $z \in \overline{\mathbb{D}} \setminus \{0\}$ . Using (2.5), for  $t < \tau(z)$ ,

$$\begin{aligned} \log |g_t(z)/z| &= \int_0^t \partial_s \operatorname{Re} \log g_s(z) ds = \int_0^t \operatorname{Re} H_s(g_s(z)) ds \\ &= 2\pi \int_0^t P_{\mathbb{D}}[\rho_s](g_s(z)) ds \geq |[0, t] \setminus E|/2 \end{aligned}$$

since the Poisson integral is non-negative. Since  $\log |g_t(z)/z| \leq -\log |z|$  it follows that

$$\tau(z) \leq -2 \log |z| + |E| \leq -2 \log |z| + S_+(\rho)/\varepsilon < \infty$$

where we also used Markov's inequality and that  $S_+(\rho) = \int_0^\infty L(\rho_t) dt$ . □

### 4.3 Examples and energy minimizers

We discussed the simple but important example of a Loewner chain driven by the constant zero-energy measure in the introduction and Section 2.2. Here we give another example of a time-homogeneous driving measure, this time vanishing at  $\theta = 0$ , and minimizing the Loewner-Kufarev energy among all such measures. We compute explicitly the winding function of the corresponding non-injective foliation and verify energy duality by hand.

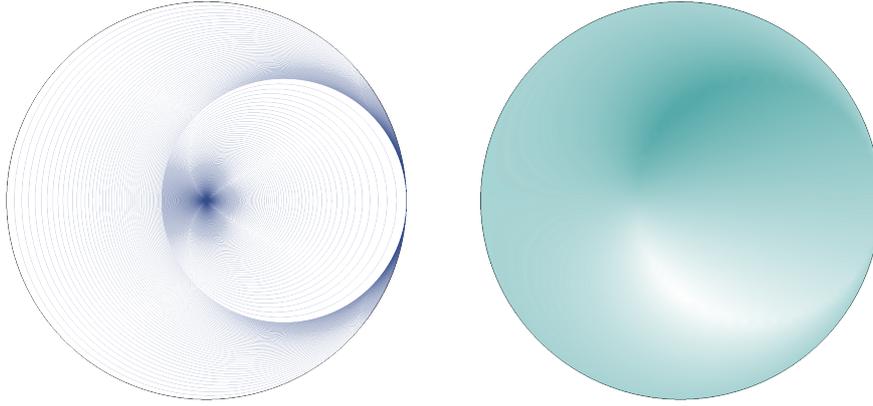


Figure 4.1: *Left*: Leaves of the foliation corresponding to the measure that equals  $\pi^{-1} \sin^2(\theta/2) d\theta dt$  for  $0 \leq t < 1$  and is uniform for  $t \geq 1$ , drawn at equidistant times. *Right*: Density plot of the winding function corresponding to the same measure, where lighter color represents a larger value. The winding function is harmonic, but non-zero, in the part foliated after time 1.

Even for this simple example, while the computation is straightforward it is not entirely trivial.

Let  $T > 0$  and  $\nu \in W^{1,2}([0, 2\pi])$  with  $\nu(0) = \nu(2\pi) = 0$  and  $\int_{S^1} \nu^2(\theta) d\theta = 1$ . Consider the measure  $\rho \in \mathcal{N}_+$  such that  $d\rho_t(\theta) = \nu^2(\theta) d\theta$  for  $t \in [0, T]$ , and that is equal to the uniform measure on  $S^1$  otherwise. Among all such measures,  $\nu^2(\theta) d\theta$  minimizes  $L$  if and only if  $\nu$  is the first eigenfunction of the Dirichlet Laplacian on  $[0, 2\pi]$ , namely,  $\nu^2(\theta) = \sin^2(\theta/2)/\pi$ . In this case, we have  $L(\rho_t) \equiv 2$  so  $S_+(\rho) = \int_0^T L(\rho_t) dt = 2T$ . The corresponding Herglotz integral can be evaluated explicitly and the Loewner-Kufarev equation in this case is simply

$$\partial_t f_t(z) = -z f_t'(z) (1 - z), \quad z \in \mathbb{D},$$

see, e.g., [66] where solutions to Loewner equations of this form were studied. We have

$$f_t(z) = \frac{e^{-t} z}{1 - (1 - e^{-t})z}.$$

The leaf  $\partial D_t$  is a circle of radius  $1/(2 - e^{-t})$  centered at  $(1 - e^{-t})/(2 - e^{-t})$  and the hull  $K_t$  at time  $t$  is a crescent-shaped compact set, see Figure 4.1. In particular,  $z = 0$  and  $z = 1$  are fixed points of the evolution. We now compute the corresponding winding function. Suppose  $z \in K_T$  and let  $t = \tau(z)$ . Then

$$\varphi(z) = \arg \frac{z g_t'(z)}{g_t(z)} = -\arg(z(1 - e^{-t}) + e^{-t}) = \arg \frac{z}{(z - 1)^2} + \pi.$$

Moreover, for  $z \in D_T$ , we have

$$\varphi(z) = -\arg(z(1 - e^{-T}) + e^{-T}),$$

which is harmonic in  $D_T$ . From these formulas one can verify directly that  $\mathcal{D}_{\mathbb{D}}(\varphi) = 32T = 16S_+(\rho)$ , which is the statement of energy duality in this case. We note that

the computation of  $\mathcal{D}_{\mathbb{D}}(\varphi)$  is slightly technical as  $\nabla\varphi$  has a singularity at 1 (which is  $L^2$ -integrable).

*Remark.* Conjugating  $f_t$  by  $z \mapsto z^m$ , it is also possible carry out similar explicit computations for measures of the form  $\pi^{-1} \sin^2(m\theta/2)d\theta dt$  that correspond to Laplace eigenfunctions on  $S^1$  of higher eigenvalues.

## 5 Weak energy duality and Weil-Petersson interfaces

In this section we prove energy duality in the disk, for measures satisfying a strong smoothness assumption. We then use this result and an approximation argument to prove that any  $\rho$  with  $S_+(\rho) < \infty$ , produces interfaces that are Weil-Petersson quasicircles which form a foliation of  $\mathbb{D} \setminus \{0\}$ .

### 5.1 Weak energy duality

Let  $\mathcal{N}_+^\infty$  denote the set of  $\rho \in \mathcal{N}_+$  such that:

1. There exists  $T < \infty$ , such that for  $t > T$ ,  $\rho_t = d\theta/2\pi$  is the uniform measure on  $S^1$ .
2. The mapping  $t \mapsto \rho_t$  is piecewise constant (on finitely many time intervals).
3. For all  $t \geq 0$ ,  $\rho_t$  has  $C^\infty$ -smooth and strictly positive density with respect to  $d\theta$ .

**Lemma 5.1.** *Any  $\rho \in \mathcal{N}_+^\infty$  generates a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$  in which each leaf is a smooth Jordan curve. The corresponding winding function  $\varphi$  is continuous and piecewise smooth on  $\overline{\mathbb{D}}$ .*

*Proof.* We assume first  $\rho \in \mathcal{N}_+^\infty$  and that  $\rho_t$  is constant on  $[0, T]$ . Let  $H := H[\rho_t]$  which is constant for  $t \leq T$ . The family  $(f_t)_{t \in [0, T]}$  solves the equation  $\partial_t f_t(z) = -z f_t'(z) H(z)$  with  $f_0(z) = z$  and forms a semigroup of conformal maps with fixed point 0. (See Lemma 2.3.) The solution therefore enjoys the following representation: there exists a starlike<sup>3</sup> domain  $D$  and a conformal map  $\psi : \mathbb{D} \rightarrow D$  fixing 0 such that

$$f_t(z) = \psi^{-1}(e^{-t}\psi(z)), \quad \psi(z) = z \exp\left(\int_0^z \frac{1}{w} \left(\frac{1}{H(w)} - 1\right) dw\right).$$

See, e.g., [64, Sec. 3] and the references therein. Since  $H$  is the Herglotz integral of a smooth, positive function, the maximum principle implies that it is non-zero on  $\overline{\mathbb{D}}$  and the smoothness implies that all derivatives exist and extend continuously to  $\overline{\mathbb{D}}$ . (See, e.g., [25, Cor. II.3.3].) It follows that  $\psi$  is smooth on  $\overline{\mathbb{D}}$ . The foliation generated by  $\rho$  is given by the family  $(\gamma_t = \psi^{-1}(e^{-t}\psi(S_1)))$  for  $t \leq T$ , and for  $t > T$ , the leaves  $\gamma_t$  are equipotential curves in  $D_T$  by Lemma 2.8. We now verify the smoothness of the winding function  $z \mapsto \varphi(z)$  in  $K_T$ . For this, consider  $(\theta, t) \in S^1 \times [0, T]$  and set  $z(\theta, t) = f_t(e^{i\theta})$ . Then  $\varphi(z(\theta, t)) = -\arg e^{i\theta} f_t'(e^{i\theta})/f_t(e^{i\theta})$ . We have

$$\begin{aligned} \partial_\theta z &= i e^{i\theta} f_t'(e^{i\theta}) \\ \partial_t z &= \partial_t f_t(re^{i\theta}) = e^{i\theta} f_t'(e^{i\theta}) H(e^{i\theta}). \end{aligned}$$

<sup>3</sup>Starlike here means that  $D$  contains 0 and for every  $z \in D$ , the line segment  $[0, z] \subset D$ .

Since  $\operatorname{Re} H > 0$  the Jacobian is non-zero. Further differentiation using the Loewner equation shows that  $z(\theta, t)$  is smooth and by the inverse function theorem, the inverse is also smooth in  $K_T$ , and so is  $\varphi$ . Since  $\varphi|_{D_T} = \vartheta(g_T)$  by Lemma 2.8 and is continuous on  $\overline{D_T}$ , we obtain that  $\varphi$  is continuous on  $\overline{\mathbb{D}}$  and smooth in  $\overline{\mathbb{D}} \setminus \gamma_T$ .

Using Lemma 2.3 and the fact the smoothness is preserved under composition of smooth conformal mappings, the statement immediately generalizes to arbitrary  $\rho \in \mathcal{N}_+^\infty$ .  $\square$

**Lemma 5.2.** *If  $\rho \in \mathcal{N}_+$  and  $z \in \mathbb{D}$ , then  $-\partial_t \vartheta[f_t](z)|_{t=0} = \operatorname{Im} z H'_0(z)$ .*

*Proof.* Using (2.4), we have for  $t \geq 0$ ,

$$\partial_t \log f_t(z) = -z \frac{f'_t(z)}{f_t(z)} H_t(z).$$

and

$$\partial_t \log f'_t(z) = -\frac{\partial_z(z f'_t(z) H_t(z))}{f'_t(z)} = -\left(1 + z \frac{f''_t(z)}{f'_t(z)}\right) H_t(z) - z H'_t(z).$$

Hence,

$$\partial_t \log \frac{z f'_t(z)}{f_t(z)} = -\left(1 + z \frac{f''_t(z)}{f'_t(z)} - z \frac{f'_t(z)}{f_t(z)}\right) H_t(z) - z H'_t(z).$$

Since  $f_0(z) = z$ , we have  $f''_0(z) = 0$  and the claimed expression when evaluated at  $t = 0$  follows by taking the imaginary part.  $\square$

**Proposition 5.3** (Weak energy duality). *Suppose  $\rho \in \mathcal{N}_+^\infty$  and let  $\varphi$  be the associated winding function. Then  $\mathcal{D}_{\mathbb{D}}(\varphi) = 16 S_+(\rho)$ .*

*Proof.* By Lemma 5.1 the winding function  $\varphi$  is continuous and piecewise smooth on  $\overline{\mathbb{D}}$ . Moreover,  $\varphi|_{S^1} = 0$  and therefore  $\varphi \in \mathcal{E}_0(\mathbb{D})$  [13, Thm. 9.17] and we may apply the foliation disintegration isometry to  $\varphi$ . We claim that for  $t \in [0, T]$ ,  $\iota[\varphi](\theta, t) = -2\nu'(\theta)/\nu(\theta)$ . Given this, we can apply Theorem 3.5 to conclude the proof. To prove the claim, set  $\varphi_t = \varphi \circ f_t$  and recall that by definition

$$\iota[\varphi](\theta, t) = \frac{1}{2\pi} \int_{\mathbb{D}} \Delta \varphi_t(z) P_{\mathbb{D}}(z, e^{i\theta}) dA(z) = \frac{1}{2\pi} \int_{\mathbb{D}} \Delta \varphi_t(z) \partial_n(e^{i\theta}) G_{\mathbb{D}}(z, e^{i\theta}) dA(z). \quad (5.1)$$

On the other hand, by Lemma 5.1,  $\Delta \varphi_t$  is smooth, so the last term in (5.1) equals

$$\frac{1}{2\pi} \partial_n \int_{\mathbb{D}} \Delta \varphi_t(z) G_{\mathbb{D}}(z, e^{i\theta}) dA(z) = \partial_n \varphi_t^0(e^{i\theta}).$$

Recall from Lemma 2.8 and Lemma 2.9 that  $z \mapsto \varphi_t^0(z)$  is the winding function generated by the measures  $s \mapsto \rho_{t+s}$  for  $s \geq 0$ . Hence, it suffices to consider  $t = 0$  and show that for a.e.  $\theta \in [0, 2\pi)$ ,

$$\partial_n \varphi_0^0(e^{i\theta}) = \partial_n \varphi_0(e^{i\theta}) = -2\nu'_0(\theta)/\nu_0(\theta). \quad (5.2)$$

We know that  $\partial D_t$  is  $C^\infty$  for all  $t$ , and all (complex) derivatives of  $f_t$  are continuous on  $\overline{\mathbb{D}}$  and since the Herglotz integral  $H_t$  is also continuous on  $\overline{\mathbb{D}}$ , so is  $\partial_t f_t(z) = -z f'_t(z) H_t(z)$ . It follows that the normal velocity (with respect to  $\partial D_t$ ) of the interface at the point  $f_t(e^{i\theta})$  can be written

$$\operatorname{vel}_n(t, \theta) = -\operatorname{Re} \left( \frac{\partial_t f_t(e^{i\theta}) \overline{e^{i\theta} f'_t(e^{i\theta})}}{|f'_t(e^{i\theta})|} \right)$$

$$\begin{aligned}
&= \operatorname{Re} \left( \frac{e^{i\theta} f'_t(e^{i\theta}) H_t(e^{i\theta}) \overline{e^{i\theta} f'_t(e^{i\theta})}}{|f'_t(e^{i\theta})|} \right) \\
&= |f'_t(e^{i\theta})| \operatorname{Re} H_t(e^{i\theta}) = 2\pi |f'_t(e^{i\theta})| \nu_t(\theta)^2 > 0.
\end{aligned}$$

In particular, at  $t = 0$  the normal velocity of the interface at  $e^{i\theta}$  equals  $2\pi\nu_0(\theta)^2$ . On the other hand, using the chain rule (2.8)

$$2\pi\nu_0(\theta)^2 \partial_n \varphi_0(e^{i\theta}) = \partial_t [\varphi_0(f_t(e^{i\theta}))]_{t=0} = \partial_t [\vartheta[g_t](f_t(e^{i\theta}))]_{t=0} = -\partial_t (\vartheta[f_t](e^{i\theta}))|_{t=0}.$$

It follows from Lemma 5.2 that

$$-\partial_t (\vartheta[f_t](e^{i\theta}))|_{t=0} = \operatorname{Im}(e^{i\theta} H'_0(e^{i\theta})) = -4\pi\nu_0(\theta) \nu'_0(\theta).$$

The last identity is not hard to verify by hand, using integration by parts and the smoothness of  $\nu_0$ , see also Lemma 6.1. This proves (5.2) and concludes the proof.  $\square$

Let us cite the following special case of the generalized Grunsky inequality, which provides a useful bound to control  $\mathcal{D}_{\mathbb{D}}(\arg f'_t)$  in terms of  $\mathcal{D}_{\mathbb{D}}(\vartheta[f_t])$  (see Corollary 5.6).

**Lemma 5.4** (See [67, P. 70-71]). *Suppose that  $f : \mathbb{D} \rightarrow \mathbb{C}$  and  $h : \mathbb{D}^* \rightarrow \mathbb{C}$  are univalent functions on  $\mathbb{D}$  and  $\mathbb{D}^*$  such that  $f(0) = 0$  and  $h(\infty) = \infty$ , and  $f(\mathbb{D}) \cap h(\mathbb{D}^*) = \emptyset$ . Then we have*

$$\int_{\mathbb{D}} \left| \frac{f'(z)}{f(z)} - \frac{1}{z} \right|^2 dA(z) + \int_{\mathbb{D}^*} \left| \frac{h'(z)}{h(z)} - \frac{1}{z} \right|^2 dA(z) \leq 2\pi \log \left| \frac{h'(\infty)}{f'(0)} \right|.$$

*Equality holds if the omitted set  $\mathbb{C} \setminus \{f(\mathbb{D}) \cup h(\mathbb{D}^*)\}$  has Lebesgue measure zero.*

**Lemma 5.5.** *Let  $\rho \in \mathcal{N}_+$  and  $(f_t)_{t \geq 0}$  is the associated Loewner chain. Then*

$$\mathcal{D}_{\mathbb{D}}(\arg[f_t(z)/z]) = \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f'_t(z)}{f_t(z)} - \frac{1}{z} \right|^2 dA(z) \leq 2t. \quad (5.3)$$

*Proof.* Since  $D_t$  and  $\mathbb{D}^*$  are disjoint, and since  $f'_t(0) = e^{-t}$ , Lemma 5.4 applied to the pair  $(f_t, \operatorname{Id}_{\mathbb{D}^*})$  shows that

$$\int_{\mathbb{D}} \left| \frac{f'_t(z)}{f_t(z)} - \frac{1}{z} \right|^2 dA(z) \leq -2\pi \log |f'_t(0)| = 2\pi t$$

as claimed.  $\square$

**Corollary 5.6.** *Suppose  $\rho \in \mathcal{N}_+^\infty$ . Then for all  $t \geq 0$ ,  $\mathcal{D}_{\mathbb{D}}(\arg f'_t) \leq 32S_{[0,t]}(\rho) + 4t$ .*

*Proof.* Fix  $t \geq 0$ . Without loss of generality, we assume that  $\rho_s$  is the uniform measure for all  $s > t$ . Combining Proposition 5.3, Lemma 5.5, and the Cauchy-Schwarz inequality, we obtain

$$\begin{aligned}
\mathcal{D}_{\mathbb{D}}(\arg f'_t) &= \mathcal{D}_{\mathbb{D}}(\vartheta[f_t] + \arg[f_t(z)/z]) \leq 2\mathcal{D}_{D_t}(\vartheta[g_t]) + 2\mathcal{D}_{\mathbb{D}}(\arg[f_t(z)/z]) \\
&\leq 2\mathcal{D}_{\mathbb{D}}(\varphi) + 4t = 32S_{[0,t]}(\rho) + 4t
\end{aligned}$$

as claimed.  $\square$

## 5.2 Weil-Petersson interfaces

This section proves that the interfaces in Loewner evolution driven by a finite energy measure are Weil-Petersson quasicircles and produces a foliation (Corollary 5.12). We give first a quantitative upper bound for  $\mathcal{D}_{\mathbb{D}}(\arg f'_t)$  that depends only on  $S_+(\rho)$  and  $t$ .

**Lemma 5.7.** *It  $S_+(\rho) < \infty$ , then for all  $t \geq 0$ ,  $\mathcal{D}_{\mathbb{D}}(\arg f'_t) \leq 32S_{[0,t]}(\rho) + 4t$ .*

*Proof.* Fix  $t > 0$ . We will approximate  $\rho$  by a sequence of measures  $\rho^{(k)} \in \mathcal{N}_+^\infty$  which converges to  $\rho$  weakly, and such that  $S_{[0,t]}(\rho^{(k)}) \leq S_{[0,t]}(\rho)$ . The corresponding sequence of conformal maps  $f_t^{(k)}$  then converges uniformly on compacts to  $f_t$  by Lemma 2.2, which, by Corollary 5.6, implies

$$\mathcal{D}_{\mathbb{D}}(\arg f'_t) \leq \liminf_{k \rightarrow \infty} \mathcal{D}_{\mathbb{D}}(\arg (f_t^{(k)})') \leq 32 S_{[0,t]}(\rho^{(k)}) + 4t \leq 32 S_{[0,t]}(\rho) + 4t.$$

We construct the approximation in two steps. We first let  $\rho^{(n)}$  be the “time-averaged” measure, which is piecewise constant on dyadic time intervals  $[jt/2^n, (j+1)t/2^n)$  and is defined by

$$\rho_s^{(n)} := \sigma^j := \frac{2^n}{t} \int_{jt/2^n}^{(j+1)t/2^n} \rho_r \, dr \in \mathcal{M}_1(S^1), \quad \forall s \in \left[ \frac{jt}{2^n}, \frac{(j+1)t}{2^n} \right).$$

To see that  $S_{[0,t]}(\rho^{(n)}) \leq S_{[0,t]}(\rho)$ , the key observation is that the map  $\sigma \mapsto L(\sigma)$  from  $\mathcal{M}_1(S^1)$  to  $[0, \infty]$  is convex [19] (see also [8, Thm. 3.4]). We can therefore apply Jensen’s inequality:

$$S_{[0,t]}(\rho^{(n)}) = \frac{t}{2^n} \sum_{j=0}^{2^n-1} L \left( \frac{2^n}{t} \int_{jt/2^n}^{(j+1)t/2^n} \rho_r \, dr \right) \leq \sum_{j=0}^{2^n-1} \int_{jt/2^n}^{(j+1)t/2^n} L(\rho_t) \, dt = S_{[0,t]}(\rho).$$

It is clear that  $\rho^{(n)}$  restricted to  $S^1 \times [0, t]$  converges weakly to  $\rho$ : integrating against a continuous function  $u$  on  $S^1 \times [0, t]$ , which is then uniformly continuous,  $\int u \, d\rho^{(n)}$  converges to  $\int u \, d\rho$ .

Since  $\rho^{(n)}$  might not be strictly positive and smooth, the second step is to approximate each  $\sigma = \sigma^j$  of the  $2^n$  measures in  $\mathcal{M}_1(S^1)$  on dyadics by

$$d\sigma_r(\theta) := \frac{d\theta}{2\pi} \int_{\xi \in S^1} P_{\mathbb{D}}(re^{i\theta}, e^{i\xi}) d\sigma(\xi)$$

where  $r < 1$ , which has positive and smooth density with respect to  $d\theta$ .

Now we prove that  $L(\sigma_r) \leq L(\sigma)$ . Let  $f \in C^0(S^1)$ ,

$$\begin{aligned} \sigma_r(f) &:= \int_{S^1} f(\theta) d\sigma_r(\theta) = \frac{1}{2\pi} \int_{\theta \in S^1} f(\theta) \int_{\xi \in S^1} P_{\mathbb{D}}(re^{i\theta}, e^{i\xi}) d\sigma(\xi) d\theta \\ &= \frac{1}{2\pi} \int_{\xi \in S^1} \int_{\theta \in S^1} f(\theta) P_{\mathbb{D}}(re^{i(\theta-\xi)}, 1) d\theta d\sigma(\xi) \\ &= \frac{1}{2\pi} \int_{\xi \in S^1} \int_{\eta \in S^1} f(\eta + \xi) P_{\mathbb{D}}(re^{i\eta}, 1) d\eta d\sigma(\xi) \\ &= \frac{1}{2\pi} \int_{\eta \in S^1} P_{\mathbb{D}}(re^{i\eta}, 1) \int_{\xi \in S^1} f(\eta + \xi) d\sigma(\xi) d\eta \end{aligned}$$

$$= \frac{1}{2\pi} \int_{\eta \in S^1} P_{\mathbb{D}}(r, e^{i\eta}) \eta_* \sigma(f) d\eta,$$

where  $\eta_* \sigma$  is the pull-back measure  $\sigma$  by the rotation  $\xi \mapsto \xi + \eta$ . In particular,  $L(\sigma) = L(\eta_* \sigma)$ . We obtain

$$\sigma_r = \frac{1}{2\pi} \int_{\eta \in S^1} P_{\mathbb{D}}(r, e^{i\eta}) \eta_* \sigma d\eta.$$

Since  $\frac{1}{2\pi} \int_{\eta \in S^1} P_{\mathbb{D}}(r, e^{i\eta}) d\eta = 1$ ,  $\sigma_r$  is a probability measure. Using convexity and Jensen's inequality once again,

$$L(\sigma_r) \leq \frac{1}{2\pi} \int_{\eta \in S^1} P_{\mathbb{D}}(r, e^{i\eta}) L(\eta_* \sigma) d\eta = L(\sigma).$$

Finally, note that since  $f$  is continuous,  $\eta \mapsto \eta_* \sigma(f)$  is continuous on  $S^1$  and equal to  $\sigma(f)$  for  $\eta = 0$ . Therefore, since  $\sigma_r(f)$  is the Poisson integral of  $\eta \mapsto \eta_* \sigma(f)$  evaluated at  $r$ , we have that  $\lim_{r \rightarrow 1} \sigma_r(f) = \sigma(f)$ . Hence  $\sigma_r$  converges to  $\sigma$  weakly and this completes the proof.  $\square$

We would now like to use Lemma 5.7 to conclude that  $\partial D_t$  is a Weil-Petersson quasicycle. However, we cannot directly apply Lemma 2.1 since we do not know *a priori* that  $\partial D_t$  is a Jordan curve. In fact, it is not hard to construct an example of a simply connected domain for which the boundary is self-touching, while  $\mathcal{D}_{\mathbb{D}}(\log f') < \infty$  where  $f$  is the “one-sided” conformal map onto the domain. In the present case, however, we can use the fact that  $\partial D_t$  arises from Loewner evolution: we will consider the evolution for a small time interval and use estimates on the Schwarzian combined with a result of Ahlfors-Weill. We can then complete the proof using Lemma 2.3.

For a function  $f$  holomorphic at  $z$  such that  $f'(z) \neq 0$ , recall that the Schwarzian derivative of  $f$  at  $z$  is defined by

$$\mathcal{S}f(z) = \frac{f'''(z)}{f'(z)} - \frac{3}{2} \left( \frac{f''(z)}{f'(z)} \right)^2 = \left( \frac{f''(z)}{f'(z)} \right)' - \frac{1}{2} \left( \frac{f''(z)}{f'(z)} \right)^2.$$

**Lemma 5.8** (See [67, Lem. I.2.1, Lem. II.1.3 and Lem. II.1.5]). *There exists  $\delta > 0$  such that if  $\mathcal{D}_{\mathbb{D}}(\log f') < \delta$ , then  $f$  is univalent and  $f(\mathbb{D})$  is a Jordan domain bounded by a Weil-Petersson quasicycle.*

*Proof.* By Lemma 2.1 and the assumption that  $\mathcal{D}_{\mathbb{D}}(\log f') < \delta < \infty$ , it is enough to prove that  $f(\mathbb{D})$  is a Jordan domain. We will prove more and show that  $f(\mathbb{D})$  is a quasidisk. By a theorem of Ahlfors-Weill (see [51, Cor. 5.24]), to show that  $f(\mathbb{D})$  is a quasidisk it suffices to show that for small enough  $\delta$ ,

$$\sup_{z \in \mathbb{D}} (1 - |z|^2)^2 |\mathcal{S}f(z)| < 2. \tag{5.4}$$

We will estimate the left-hand side of (5.4) in terms of  $\mathcal{D}_{\mathbb{D}}(\log f')$ . The required estimate is a combination of two bounds. First we claim that if  $f$  is holomorphic on  $\mathbb{D}$  and  $f' \neq 0$ , then,

$$\int_{\mathbb{D}} |\mathcal{S}f(z)|^2 (1 - |z|^2)^2 dA(z) \leq \pi \mathcal{D}_{\mathbb{D}}(\log f') + \frac{\pi}{8} (\mathcal{D}_{\mathbb{D}}(\log f'))^2.$$

Indeed, this follows from the proof of [67, Lem. II.1.5] where the bound depends on a constant from [67, Lem. II.1.3]. On the other hand, it follows directly from [67, Lem. I.2.1] that

$$\sup_{z \in \mathbb{D}} (1 - |z|^2)^2 |\mathcal{S}f(z)| \leq \sqrt{\frac{12}{\pi}} \left( \int_{\mathbb{D}} |\mathcal{S}f(z)|^2 (1 - |z|^2)^2 dA(z) \right)^{1/2}.$$

Combining these bounds we see that (5.4) indeed holds provided  $\delta$  is chosen sufficiently small.  $\square$

**Proposition 5.9.** *If  $S_+(\rho) < \infty$ , then for all  $t \geq 0$ ,  $\partial D_t$  is a Weil-Petersson quasicircle.*

*Proof.* Let  $\delta > 0$  be the small constant from Lemma 5.8. Pick  $t_1 > 0$  such that  $32S_{[0, t_1]}(\rho) + 4t_1 < \delta$ . For  $t \leq t_1$ , Lemma 5.7 and Lemma 5.8 show that  $\partial D_t$  is a Weil-Petersson quasicircle.

Now we consider the general case  $t \geq 0$ . Lemma 5.7 shows that  $\mathcal{D}_{\mathbb{D}}(\arg f'_t) < \infty$ , it suffices to show  $D_t$  is a Jordan domain to conclude that it is Weil-Petersson by Lemma 2.1. For this, let  $0 = t_0 < t_1 < t_2 < \dots$  be a sequence tending to  $\infty$  such that  $32S_{[t_j, t_{j+1}]}(\rho) + 4(t_{j+1} - t_j) < \delta$ . We show by induction that  $f_t$  is a homeomorphism from  $\overline{\mathbb{D}}$  onto  $\overline{D}_t$  for all  $t \leq t_j$ . We have already proved this in the case  $j = 1$ . Assume it is true for all  $t \leq t_j$ . Using Lemma 2.3 and the choices of  $\delta$  and  $|t_{j+1} - t_j|$  we obtain that  $g_{t_j}(\partial D_t)$  is a Weil-Petersson quasicircle for each  $t_j \leq t \leq t_{j+1}$ , in particular a Jordan curve. Since by assumption  $f_{t_j}$  is a homeomorphism of  $\overline{\mathbb{D}}$ ,  $\partial D_t = f_{t_j} \circ g_{t_j}(\partial D_t)$  is also a Jordan curve and this completes the induction.  $\square$

Notice that the next lemma does not assume that  $D$  is a Jordan domain.

**Lemma 5.10.** *Suppose  $D$  is a simply connected domain containing 0 and let  $f : \mathbb{D} \rightarrow D$  be a conformal map with  $f(0) = 0$  and assume that  $\mathcal{D}_{\mathbb{D}}(\log f') < \infty$ . There exists a constant  $C < \infty$  depending only on  $\mathcal{D}_{\mathbb{D}}(\log f')$  such that*

$$|f'(re^{i\theta})| \leq C |f'(0)| \exp \sqrt{C \log(1-r)^{-1}}. \quad (5.5)$$

*Remark.* The estimate (5.5) easily implies that  $f$  is continuous on  $\overline{\mathbb{D}}$ .

*Proof.* We may assume  $f'(0) = 1$ . Any  $\phi$  that is holomorphic in  $\mathbb{D}$  and such that  $\mathcal{D}_{\mathbb{D}}(\phi) < \infty$  has non-tangential limits a.e. on  $S^1$ , and writing  $\phi$  for that function as well we have the following weak-type estimate: there exist universal constants  $C_1, C_2$  such that  $|\{\theta \in S^1 : |\phi| > \lambda\}| \leq C_1 e^{-C_2 \lambda^2 / (|\phi(0)|^2 + \mathcal{D}_{\mathbb{D}}(\phi))}$ . See [24, Cor. 3.3.2] for a proof. We apply this estimate with  $\phi = \log f'$  which is normalized so that  $\log f'(0) = 0$ . Hence the upper bound in the weak-type estimate depends only on  $\mathcal{D}_{\mathbb{D}}(\log f')$  and implies there exist  $C_1, C_2$  depending only on  $\mathcal{D}_{\mathbb{D}}(\log f')$  (but which, in what follows, are allowed to change from line to line) such that

$$\int_0^{2\pi} \exp \left( C_1 |\log |f'(e^{i\theta})||^2 \right) d\theta \leq C_2.$$

Since  $\log |f'(z)|$  is harmonic,  $\exp(C_1 |\log |f'(z)||^2)$  is subharmonic and it follows that for  $0 \leq r < 1$

$$\int_0^{2\pi} \exp \left( C_1 |\log |f'(re^{i\theta})||^2 \right) d\theta \leq C_2.$$

Therefore, if  $r_n = 1 - 2^{-n}$  and  $z_{k,n} = r_n e^{i2\pi k/2^n}$ , using Koebe's distortion theorem (see, e.g., [23, Ch. 2.3]), there is a universal constant  $C_3 < \infty$  such that, taking  $C_2$  larger if necessary,

$$\frac{1}{2^n} \sum_{k=1}^{2^n} \exp\left(C_1(|\log |f'(z_{k,n})||)^2\right) \leq \int_0^{2\pi} \exp\left(C_1(|\log |f'(r_n e^{i\theta})|| + C_3)^2\right) d\theta \leq C_2.$$

Whence,

$$|f'(z_{k,n})| \leq \exp \sqrt{C_1^{-1} \log(C_2 2^n)}.$$

Using the distortion theorem again we deduce

$$|f'(r e^{i\theta})| \leq C \exp \sqrt{C \log(1-r)^{-1}},$$

where  $C$  depends only on  $\mathcal{D}_{\mathbb{D}}(\log f')$ , as claimed.  $\square$

If  $(f_t)_{t \geq 0}$  is the Loewner chain generated by a finite energy measure  $\rho$  then by Lemma 5.7 we have  $\mathcal{D}_{\mathbb{D}}(\log |f'_t|) \leq 32S_+(\rho) + 4T$  for all  $t \leq T$ . Therefore, by Lemma 5.10, there is a subpower function  $\sigma(x) := C \exp \sqrt{C \log(x)}$  (that is, for every  $\varepsilon > 0$ ,  $\lim_{x \rightarrow \infty} \sigma(x)/x^\varepsilon = 0$ ) that depends only on  $S_+(\rho)$  and  $T$ , such that

$$|f'_t(r e^{i\theta})| \leq |f'_t(0)| \sigma(1/(1-r)) \leq \sigma(1/(1-r)). \quad (5.6)$$

In the rest of the section we use the conformal parametrization of the leaves, namely  $\gamma_t(\theta) := f_t(e^{i\theta})$ .

**Proposition 5.11.** *Suppose  $S_+(\rho) < \infty$ . Then the function  $t \mapsto (\gamma_t : S^1 \rightarrow \mathbb{C}) : [0, \infty) \rightarrow (C^0, \|\cdot\|_\infty)$  is continuous.*

*Proof.* Throughout  $C$  denotes a constant whose value is allowed to change from line to line. Fix any  $T < \infty$ . Then if  $0 \leq s \leq t \leq T$ , for any  $0 \leq r < 1$ ,

$$|\gamma_s(\theta) - \gamma_t(\theta)| \leq |\gamma_s(\theta) - f_s(r e^{i\theta})| + |\gamma_t(\theta) - f_t(r e^{i\theta})| + |f_s(r e^{i\theta}) - f_t(r e^{i\theta})|. \quad (5.7)$$

By integrating (5.6) we have

$$|\gamma_s(\theta) - f_s(r e^{i\theta})| + |\gamma_t(\theta) - f_t(r e^{i\theta})| \leq C(1-r)\sigma(1/(1-r)), \quad (5.8)$$

where  $\sigma$  is a subpower function depending only on  $S_+(\rho)$  and  $T$ . Using the Loewner equation and once again (5.5), we have

$$|f_s(r e^{i\theta}) - f_t(r e^{i\theta})| = \left| \int_s^t z f'_u(z) H_u(z) du \right| \leq C \sigma(1/(1-r)) \int_s^t |H_u(z)| du, \quad z = r e^{i\theta}.$$

Since for a.e.  $t$ ,  $d\rho_t(\theta) = \nu_t(\theta)^2 d\theta$ , we can estimate using the Cauchy-Schwarz inequality

$$|\nu_t(\theta_1)^2 - \nu_t(\theta_2)^2| \leq 2 \|\nu_t\|_\infty \|\nu'_t\|_{L^2} |\theta_1 - \theta_2|^{1/2} \leq M_t |\theta_1 - \theta_2|^{1/2},$$

where

$$M_t := 2(1/\sqrt{2\pi} + \sqrt{2\pi} \|\nu'_t\|_{L^2}) \|\nu'_t\|_{L^2}.$$

Indeed, since  $\nu_t$  is continuous and  $\int \nu_t^2 = 1$ , we can assume that  $\nu_t(0) < 1/\sqrt{2\pi}$ . Then  $|\nu_t(\theta) - \nu_t(0)| \leq \sqrt{\theta} \|\nu'_t\|_{L^2} \leq \sqrt{2\pi} \|\nu'_t\|_{L^2}$ , so  $\|\nu_t\|_\infty \leq 1/\sqrt{2\pi} + \sqrt{2\pi} \|\nu'_t\|_{L^2}$ . We claim that

for a.e.  $t$ ,  $\sup_{z \in \overline{\mathbb{D}}} |H_t(z)| \leq CM_t$ . Since  $\operatorname{Re} H_t(z) = 2\pi P_{\mathbb{D}}[\rho_t](z)$ , we have  $|H'_t(re^{i\theta})| \leq CM_t(1-r)^{-1/2}$ . (See, e.g., [22, Thm. 5.8 and 5.1].) So by integration, the claim follows. Consequently  $\int_s^t |H_u(z)| du \leq C \int_s^t M_u du$ . Hence

$$|f_s(re^{i\theta}) - f_t(re^{i\theta})| \leq C\sigma(1/(1-r)) \int_s^t M_u du. \quad (5.9)$$

Now we choose  $r$  so that  $1-r = \int_s^t M_u du \wedge 1$  and plug in (5.8) and (5.9) into (5.7) to conclude that

$$\sup_{\theta \in [0, 2\pi)} |\gamma_s(\theta) - \gamma_t(\theta)| = o(1)$$

as  $|t-s| \rightarrow 0$ . Since  $T < \infty$  was arbitrary, this completes the proof.  $\square$

*Remark.* Under the stronger assumption that  $L(\rho_t)$  is uniformly bounded, the proof of Lemma 5.10 shows that the mapping  $t \mapsto (\gamma_t : S^1 \rightarrow \mathbb{C}) : [0, \infty) \rightarrow (C^0, \|\cdot\|_\infty)$  is *weakly Lipschitz continuous*, that is, it admits a modulus of continuity of the form  $|\cdot| \sigma(1/|\cdot|)$ , where  $\sigma$  is a subpower function.

We are now ready to prove the main result of this section.

**Corollary 5.12.** *If  $S_+(\rho) < \infty$ , then  $\rho$  generates a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$  by Weil-Petersson quasircles.*

*Proof.* Proposition 5.9 shows  $\gamma_t$  is a Weil-Petersson quasircle for each  $t$  and  $t \mapsto \gamma_t$  is continuous in the supremum norm for the conformal parametrization by Proposition 5.11. Lemma 4.2 shows that  $\tau(z) < \infty$  for all  $z \in \overline{\mathbb{D}} \setminus \{0\}$  and this completes the proof.  $\square$

The next result is not used in the rest of the paper, but as it is an interesting and immediate consequence of Lemma 5.10, we choose to state it here.

**Corollary 5.13.** *Suppose  $D$  is a simply connected domain containing 0 and let  $f : \mathbb{D} \rightarrow D$  be a conformal map with  $f(0) = 0$  and assume that  $\mathcal{D}_{\mathbb{D}}(\log f') < \infty$ . Then the conformal parametrization of  $\partial D$  is weakly Lipschitz continuous on  $S^1$  with subpower function depending only on  $\mathcal{D}_{\mathbb{D}}(\log f')$ .*

*Remark.* The condition  $\mathcal{D}_{\mathbb{D}}(\log f') < \infty$  allows  $f'$  to be unbounded and the conformal parametrization is not Lipschitz in general in this setting, so up to the exact form of the subpower function this modulus of continuity is sharp.

*Proof.* We have already noted that  $f$  is continuous on  $\overline{\mathbb{D}}$ . By Lemma 5.10, we have for  $0 < r < 1$ ,

$$\begin{aligned} |f(e^{i\theta_1}) - f(e^{i\theta_2})| &\leq |f(e^{i\theta_1}) - f(re^{i\theta_1})| + |f(e^{i\theta_2}) - f(re^{i\theta_2})| + |f(re^{i\theta_1}) - f(re^{i\theta_2})| \\ &\leq 2 \int_r^1 \sigma(1/(1-u)) du + \sigma(1/(1-r)) |\theta_1 - \theta_2| \\ &\leq ((1-r) + |\theta_1 - \theta_2|) \tilde{\sigma}(1/(1-r)), \end{aligned}$$

where  $\tilde{\sigma}$  is a subpower function that depends only on  $\mathcal{D}_{\mathbb{D}}(\log f')$ . Now choose  $r = 1 - |\theta_1 - \theta_2|$  and we obtain the desired estimate.  $\square$

## 6 Disk energy duality: proof of Theorem 1.7

The proof of Theorem 1.7 is completed at the end of the section. We assume that  $\rho \in \mathcal{N}_+$  generates a foliation of  $\overline{\mathbb{D}} \setminus \{0\}$  throughout. The proof is carried out in two steps: in Section 6.1 we assume  $S_+(\rho) < \infty$  and derive energy duality. Then in Section 6.2 we assume  $\mathcal{D}_{\mathbb{D}}(\varphi) < \infty$  and prove that this implies  $S_+(\rho) < \infty$ . An overview of the argument presented in this section was provided in Section 1.4.

### 6.1 $S_+(\rho) < \infty$ implies $\mathcal{D}_{\mathbb{D}}(\varphi) = 16S_+(\rho)$

For  $\rho \in \mathcal{N}_+$ , we define (for a.e.  $t$ )

$$\alpha_t(z) = \operatorname{Im}(zH'_t(z)), \quad z \in \mathbb{D},$$

where  $H_t$  is the Herglotz integral of  $\rho_t$ . In this section, we assume  $S_+(\rho) < \infty$ , and write as before  $d\rho_t = \nu_t^2(\theta)d\theta$ . In this case, we have

$$H_t(z) = \int_0^{2\pi} \frac{e^{i\theta} + z}{e^{i\theta} - z} \nu_t^2(\theta) d\theta.$$

**Lemma 6.1.** *If  $H'_t \in \mathcal{H}^1$  then for a.e.  $\theta \in S^1$ ,*

$$\operatorname{Im}(e^{i\theta} H'_t(e^{i\theta})) = -4\pi \nu_t(\theta) \nu'_t(\theta), \quad (6.1)$$

where the left-hand side is understood in terms of radial limits and  $\alpha_t = -4\pi P_{\mathbb{D}}[\nu_t \nu'_t]$ . In particular, this holds if  $L(\rho_t) < \infty$ .

*Proof.* If  $H'_t \in \mathcal{H}^1$ , then by [22, Thm. 5.2] (see in particular the last paragraph of the proof),  $H_t$  is continuous on  $\overline{\mathbb{D}}$  and the boundary function  $H_t(e^{i\theta})$  is absolutely continuous on  $S^1$ . Since  $2\pi \nu_t^2(\theta) = \operatorname{Re} H_t(e^{i\theta})$ ,  $4\pi \nu_t(\theta) \nu'_t(\theta) = \partial_\theta \operatorname{Re} H_t(e^{i\theta})$  exists a.e. on  $S^1$ . Moreover,  $H'_t$  has radial limits a.e. on  $S^1$  and by [22, Thm. 3.11],  $\partial_\theta H_t(e^{i\theta}) = ie^{i\theta} \lim_{r \rightarrow 1} H'_t(re^{i\theta})$  a.e. on  $S^1$ . This gives the identity (6.1). Since  $H'_t \in \mathcal{H}^1$ ,  $\alpha_t(z) = \operatorname{Im} zH'_t(z)$  is the Poisson integral of its boundary values and this gives the second assertion.

Finally, if  $L(\rho_t) < \infty$  we have  $\rho'_t = 2\nu'_t \nu_t \in L^2(S^1, d\theta)$  since  $\nu_t$  is bounded and  $\nu'_t \in L^2(S^1, d\theta)$ . Writing the complex derivative in polar coordinates shows  $\operatorname{Im} zH'_t = -\partial_\theta \operatorname{Re} H_t$ . We claim  $\operatorname{Im} zH'_t(z) = -2\pi P_{\mathbb{D}}[\rho'_t](z)$ . Indeed, writing  $P_r(\theta - s) = P_{\mathbb{D}}(re^{i(\theta-s)}) = (1 - r^2)/|1 - re^{i(\theta-s)}|^2$  for the Poisson kernel, using integration by parts

$$\begin{aligned} \partial_\theta \operatorname{Re} H_t(z) &= \int_0^{2\pi} \partial_\theta P_r(\theta - s) \nu_t(s)^2 ds = \int_0^{2\pi} (-\partial_s P_r(\theta - s)) \nu_t(s)^2 ds \\ &= \int_0^{2\pi} P_r(\theta - s) [\nu_t(s)^2]' ds = 2\pi P_{\mathbb{D}}[\rho'_t](z). \end{aligned}$$

Therefore, since  $\rho'_t \in L^2$ , we get that  $\operatorname{Im} H'_t \in \mathfrak{h}^2$ . By [22, Thm. 4.1] this in turn implies  $\operatorname{Re} H'_t \in \mathfrak{h}^2$  and we conclude that  $H'_t \in \mathcal{H}^2$ .  $\square$

The following lemma holds for all  $\rho \in \mathcal{N}_+$ .

**Lemma 6.2.** *For all  $z \in D_T$ ,  $\vartheta[g_T](z) = \int_0^T \alpha_t(g_t(z)) dt$ .*

*Proof.* Since  $t \mapsto \vartheta[g_t](z)$  is absolutely continuous on  $[0, T]$ , we can use the Loewner equation (2.5) to see that for a.e.  $t$ ,

$$\begin{aligned} \partial_t \vartheta[g_t](z) &= \operatorname{Im} \left( \frac{\partial_t g'_t(z)}{g'_t(z)} - \frac{\partial_t g_t(z)}{g_t(z)} \right) \\ &= \operatorname{Im} \left( \frac{g'_t(z) H_t(g_t(z)) + g_t(z) H'_t(g_t(z)) g'_t(z)}{g'_t(z)} - H_t(g_t(z)) \right) \\ &= \operatorname{Im}(g_t(z) H'_t(g_t(z))) = \alpha_t(g_t(z)). \end{aligned}$$

Since  $g_0(z) = z$  we get the claim after integration.  $\square$

We define

$$\beta(z) = \int_0^{\tau(z)} \alpha_t(g_t(z)) dt, \quad z \in \mathbb{D}. \quad (6.2)$$

It is not obvious that this quantity is finite a.e. However, part of the conclusion of the next result is that  $\beta \in \mathcal{E}_0(\mathbb{D})$  and we shall later prove that  $\beta$  is the unique  $\mathcal{E}_0(\mathbb{D})$  extension of the winding function  $\varphi$ .

**Proposition 6.3.** *Suppose  $S_+(\rho) < \infty$ . Let  $u(\theta, t) := -2\nu'_t(\theta)/\nu_t(\theta)$  if  $\nu_t(\theta) \neq 0$ , and  $u(\theta, t) := 0$  otherwise. Then  $u \in L^2(2\rho)$  and  $\varkappa[u] = \beta$ . In particular,  $\beta \in \mathcal{E}_0(\mathbb{D})$  and  $\mathcal{D}_{\mathbb{D}}(\beta) = 16 S_+(\rho)$ .*

*Proof.* We verify directly that  $u \in L^2(2\rho)$  and

$$\|u\|_{L^2(2\rho)}^2 = 2 \int_0^\infty \int_{S^1} 1_{\nu_t \neq 0} \left[ \frac{2\nu'_t(\theta)}{\nu_t(\theta)} \right]^2 \nu_t^2(\theta) d\theta dt = 16 S_+(\rho) < \infty. \quad (6.3)$$

Corollary 5.12 shows that  $\rho$  generates a foliation, therefore the Hadamard disintegration isometry of Section 3.2 applies. Using Proposition 3.3 and Lemma 6.1,

$$\begin{aligned} \varkappa[u](z) &= 2\pi \int_0^{\tau(z)} P_{\mathbb{D}}[u_t \nu_t^2](g_t(z)) dt = -4\pi \int_0^{\tau(z)} P_{\mathbb{D}}[\nu_t \nu'_t](g_t(z)) dt \\ &= \int_0^{\tau(z)} \alpha_t(g_t(z)) dt = \beta(z). \end{aligned}$$

Moreover, by Theorem 3.5 and (6.3), we obtain  $16 S_+(\rho) = \|u\|_{L^2(2\rho)}^2 = \mathcal{D}_{\mathbb{D}}(\varkappa[u]) = \mathcal{D}_{\mathbb{D}}(\beta)$  as claimed.  $\square$

**Corollary 6.4.** *For  $T > 0$ , let  $\rho_t^T = \rho_t$  for  $t \leq T$  and let  $\rho_t^T$  be the uniform measure for  $t > T$ . Let  $\beta^T$  be the associated function as in (6.2). Then we have  $\vartheta[g_T] = \beta^T$  on  $D_T$ . In particular,*

$$\mathcal{D}_{D_T}(\vartheta[g_T]) \leq \mathcal{D}_{\mathbb{D}}(\beta^T) = 16 S_+(\rho^T) = 16 S_{[0, T]}(\rho).$$

*Proof.* We only need to note that for  $t \geq T$ ,  $\alpha_t \equiv 0$ . Therefore, for  $z \in D_T$ ,

$$\beta^T(z) = \int_0^{\min\{\tau(z), T\}} \alpha_t(g_t(z)) dt = \int_0^T \alpha_t(g_t(z)) dt,$$

since  $\tau(z) > T$ . Lemma 6.2 implies  $\vartheta[g_T] = \beta^T$  on  $D_T$ .  $\square$

We now show that  $\beta$  is the unique extension of the winding function (2.9)  $\varphi$  in  $\mathcal{E}_0(\mathbb{D})$ .

**Lemma 6.5.** *If  $S_+(\rho) < \infty$ , then for all  $t \geq 0$ ,*

$$\beta|_{\partial D_t} = \varphi|_{\partial D_t} \quad \text{arclength-a.e.},$$

where  $\beta$  is as in (6.2) and its trace is taken in the sense of Jonsson-Wallin (3.9).

In other words,  $\beta$  is the unique extension of  $\varphi$  in  $\mathcal{E}_0(\mathbb{D})$  by Proposition 3.6 (and from now on we will not distinguish  $\beta$  and  $\varphi$ ).

*Proof.* We will identify functions in  $\mathcal{E}_0(\mathbb{D})$  with their extension to  $W^{1,2}(\mathbb{C})$  by 0 in  $\mathbb{D}^*$ . By Corollary 6.4,  $\beta^t = \beta$  in  $\mathbb{C} \setminus D_t$  and the Jonsson-Wallin traces satisfy

$$\beta|_{\gamma_t} = \beta^t|_{\gamma_t} = \vartheta[g_t]|_{\gamma_t} = \varphi|_{\gamma_t} \quad \text{arclength-a.e.}$$

Here, the first equality is a property of the Jonsson-Wallin trace, see [68, Lem. A.2]. The second equality follows from Corollary 6.4, where we interpret  $\vartheta[g_t]|_{\gamma_t}$  as the non-tangential limit from inside  $D_t$  using [68, Lem. A.5]. The last equality is the definition of  $\varphi$ .  $\square$

**Corollary 6.6.** *If  $S_+(\rho) < \infty$ , then  $\varphi \in \mathcal{E}_0(\mathbb{D})$ . For  $\rho$ -a.e.  $(\theta, t)$ ,*

$$\iota[\varphi](\theta, t) = -2\nu'_t(\theta)/\nu_t(\theta).$$

and  $\mathcal{D}_{\mathbb{D}}(\varphi) = 16S_+(\rho)$ .

*Proof.* The proof is immediate by combining Proposition 6.3 and Lemma 6.5.  $\square$

## 6.2 $\mathcal{D}_{\mathbb{D}}(\varphi) < \infty$ implies $S_+(\rho) < \infty$

This section proves the following result.

**Proposition 6.7.** *Suppose  $\rho \in \mathcal{N}_+$  generates a foliation and assume that the winding function  $\varphi : \mathcal{T} \mapsto \mathbb{R}$  can be extended to a function in  $\mathcal{E}_0(\mathbb{D})$  (also denoted  $\varphi$ ). Then  $S_+(\rho) < \infty$ .*

Assuming this proposition, we can complete the proof of Theorem 1.7.

*Proof of Theorem 1.7.* Let  $\rho \in \mathcal{N}_+$ . If  $S_+(\rho) < \infty$ , Corollary 6.6 shows that  $\varphi \in \mathcal{E}_0(\mathbb{D})$  and  $\mathcal{D}_{\mathbb{D}}(\varphi) = 16S_+(\rho)$ . Conversely, Proposition 6.7 shows that if  $\varphi \in \mathcal{E}_0(\mathbb{D})$ , then  $S_+(\rho) < \infty$ . Therefore the identity also holds.  $\square$

To explain our present goal towards the proof of Proposition 6.7, note that we do not know *a priori* that  $\rho_t$  is absolutely continuous with respect to Lebesgue measure, nor that its density (if it exists) is differentiable almost everywhere. We need to show that this is the case.

Under the assumptions of Proposition 6.7, we let as before  $\varphi_s^0$  be the zero trace part of the function  $\varphi \circ f_s$  and recall that  $\alpha_t(z) = \text{Im}(zH'_t(z))$  for  $z \in \mathbb{D}$ . Since  $\rho$  generates a foliation and since  $\varphi \in \mathcal{E}_0(\mathbb{D})$  by assumption, using Theorem 3.5 we may consider

$$u := \iota[\varphi] \in L^2(2\rho).$$

**Lemma 6.8.** For a.e.  $t \geq 0$ , we have

$$\alpha_t(z) = 2\pi P_{\mathbb{D}}[u_t \rho_t](z), \quad u_t(\cdot) := u(\cdot, t). \quad (6.4)$$

*Proof.* Proposition 3.3 shows that a.e. in  $\mathbb{D}$ ,

$$\varphi(w) = \varkappa[u](w) = 2\pi \int_0^{\tau(w)} P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt. \quad (6.5)$$

Lemma 2.9 shows that the unique orthogonal decomposition of  $\varphi$  with respect to  $D_s$  is given by the zero-trace part  $\varphi_s^0 \circ g_s \in \mathcal{E}_0(D_s)$  and the harmonic part  $\varphi - \varphi_s^0 \circ g_s$  which equals  $\vartheta[g_s]$  in  $D_s$ . On the other hand, Corollary 3.4 shows that this decomposition is also given by  $\varkappa[u \mathbf{1}_{S^1 \times [0, s]}]$  and  $\varkappa[u \mathbf{1}_{S^1 \times [s, \infty)}]$ . Hence, for all  $w \in D_s$  (so that  $\tau(w) > s$ ),

$$\vartheta[g_s](w) = 2\pi \int_0^s P_{\mathbb{D}}[u_t \rho_t](g_t(w)) dt.$$

Taking a derivative in  $s$  in the above expression we obtain from Lemma 6.2 that for a fixed  $w \in \mathbb{D}$  and a.e.  $t < \tau(w)$ ,  $2\pi P_{\mathbb{D}}[u_t \rho_t](g_t(w)) = \alpha_t(g_t(w))$ . Indeed, by choosing a dense and countable family  $J$  of points in  $\mathbb{D}$ , we have for a.e.  $t \geq 0$  and all  $w \in D_t \cap J$ ,  $2\pi P_{\mathbb{D}}[u_t \rho_t](g_t(w)) = \alpha_t(g_t(w))$ . Since both  $\alpha_t$  and  $P_{\mathbb{D}}[u_t \rho_t]$  are continuous (actually harmonic) in  $\mathbb{D}$ , we therefore obtain a.e.  $t$ ,  $\alpha_t = 2\pi P_{\mathbb{D}}[u_t \rho_t]$  for all  $w \in \mathbb{D}$ .  $\square$

We are now ready to prove the main result of this section.

*Proof of Proposition 6.7.* Since  $u = \iota[\varphi] \in L^2(2\rho)$ , for a.e.  $t \in \mathbb{R}_+$ ,  $u_t \in L^2(S^1, 2\rho_t)$ . By the Cauchy-Schwarz inequality and the fact that  $\rho_t \in \mathcal{M}_1(S^1)$  is a probability measure, we also know that  $u_t \in L^1(S^1, 2\rho_t)$ . Hence  $\alpha_t = 2\pi P_{\mathbb{D}}[u_t \rho_t] \in \mathfrak{h}^1$  by Lemma 6.8. This implies  $H'_t \in \mathcal{H}^p$  for any  $p < 1$ . (See [22, Thm. 4.2], and use that an analytic function is in  $\mathcal{H}^p$  if and only if its real and imaginary parts are in  $\mathfrak{h}^p$ .) Using [22, Thm. 5.15] this in turn implies  $H_t \in \mathcal{H}^p$  for every  $p < \infty$ . (More precisely, if  $f' \in \mathcal{H}^p$  for some  $p < 1$ , then  $f \in \mathcal{H}^q$  with  $q = p/(1-p)$ .) Therefore, the radial limits of  $H_t$  exist a.e. and define a function in  $L^p(S^1, d\theta)$  for all  $p < \infty$ . It follows that the positive function  $\operatorname{Re} H_t / 2\pi$  is the Poisson integral of a function in  $L^p(S^1, d\theta)$  for all  $p < \infty$ , and we denote this function by  $\nu_t^2(\theta)$ . (See e.g., Corollary 2 to [22, Thm. 3.1].) In other words we have shown that the measure  $\rho_t$  is absolutely continuous and  $d\rho_t(\theta) = \nu_t^2(\theta) d\theta$ , where  $\nu_t^2 \in L^p(S^1, d\theta)$  for every  $p < \infty$ . Since  $u_t^2 \nu_t^2 \in L^1(S^1, d\theta)$  and  $\nu_t^2 \in L^p(S^1, d\theta)$  for all  $p < \infty$ , Hölder's inequality with  $p = 2/(2-\varepsilon)$ ,  $q = 2/\varepsilon$  implies  $u_t \nu_t^2 \in L^{2-\varepsilon}(S^1, d\theta)$  for any  $\varepsilon \in (0, 2)$ . This in turn implies that the Herglotz integral of  $u_t \nu_t^2$  is in  $\mathcal{H}^{2-\varepsilon}$  if  $\varepsilon \in (0, 1)$ . Lemma 6.8 then implies that  $H'_t \in \mathcal{H}^{2-\varepsilon}$ . It follows that  $H_t$  is continuous on  $\overline{\mathbb{D}}$  and absolutely continuous on  $S^1$  (see [22, Thm. 3.11]) and consequently so is the density  $\theta \mapsto \nu_t(\theta)$  and  $\nu'_t(\theta)$  is well-defined for Lebesgue-a.e.  $(\theta, t)$ .

Moreover, by taking radial limits in (6.4), we obtain using Lemma 6.1 and Fubini's theorem that for Lebesgue-a.e.,  $(\theta, t) \in S^1 \times \mathbb{R}_+$ ,

$$u_t(\theta) \nu_t^2(\theta) = \frac{1}{2\pi} \alpha_t(e^{i\theta}) = -2\nu'_t(\theta) \nu_t(\theta).$$

It follows that Lebesgue-a.e., when  $\nu_t(\theta) \neq 0$ ,  $u_t^2(\theta) \nu_t^2(\theta) = 4\nu'_t(\theta)^2$ , and both sides are equal to 0 otherwise. We conclude the proof by integrating over  $S^1 \times \mathbb{R}_+$ , and we obtain  $S_+(\rho) < \infty$  since  $u = \iota[\varphi] \in L^2(2\rho)$ .  $\square$

## 7 Whole-plane energy duality: proof of Theorem 1.2

In this section we deduce the whole-plane energy duality Theorem 1.2 from the disk energy duality Theorem 1.7.

### 7.1 Whole-plane Loewner evolution

We now describe the whole-plane Loewner chain. We define similarly as before a space of driving measures

$$\mathcal{N} := \{\rho \in \mathcal{M}(S^1 \times \mathbb{R}) : \rho(S^1 \times I) = |I| \text{ for all intervals } I\}.$$

The whole-plane Loewner chain driven by  $\rho \in \mathcal{N}$ , or equivalently by its measurable family of disintegration measures  $\mathbb{R} \rightarrow \mathcal{M}_1(S^1) : t \mapsto \rho_t$ , is the unique family of conformal maps  $(f_t : \mathbb{D} \rightarrow D_t)_{t \in \mathbb{R}}$  such that

- (i) For all  $s < t$ ,  $0 \in D_t \subset D_s$ .
- (ii) For all  $t \in \mathbb{R}$ ,  $f_t(0) = 0$  and  $f_t'(0) = e^{-t}$  (in other words,  $D_t$  has conformal radius  $e^{-t}$  seen from 0).
- (iii) For all  $s \in \mathbb{R}$ ,  $(f_t^{(s)} := f_s^{-1} \circ f_t : \mathbb{D} \rightarrow D_t^{(s)})_{t \geq s}$  is the Loewner chain driven by  $(\rho_t)_{t \geq s}$ , which satisfies (2.4) with the initial condition  $f_s^{(s)}(z) = z$ , as discussed in Section 2.2.

*Remark.* If  $\rho_t \in \mathcal{M}_1(S^1)$  is the uniform measure for all  $t \leq 0$ , then  $f_t(z) = e^{-t}z$  for  $t \leq 0$  and  $(f_t)_{t \geq 0}$  is the Loewner chain driven by  $(\rho_t)_{t \geq 0} \in \mathcal{N}_+$  as in Section 2.2. Indeed, we check directly that  $(f_t)_{t \in \mathbb{R}}$  satisfy the three conditions above. In other words, the Loewner chain in  $\mathbb{D}$  is a special case of the whole-plane Loewner chain.

Note that the range  $D_t^{(s)}$  of  $f_t^{(s)}$  has conformal radius  $e^{s-t}$  seen from 0 and the family  $(f_t^{(s)})_{t \geq s}$  is uniquely defined for all  $s \in \mathbb{R}$  and satisfies for  $t \geq s$  and  $z \in \mathbb{D}$ ,

$$\partial_t f_t^{(s)}(z) = -z f_t^{(s)'}(z) H_t(z), \quad H_t(z) = \int_{S^1} \frac{e^{i\theta} + z}{e^{i\theta} - z} d\rho_t(\theta),$$

with the initial condition  $f_s^{(s)}(z) = z$  (see Section 2.2). The condition (iii) is then equivalent to for all  $t \in \mathbb{R}$  and  $z \in \mathbb{D}$ ,

$$\partial_t f_t(z) = -z f_t'(z) H_t(z) \tag{7.1}$$

as described in the introduction. For the purposes of our proofs later on it is convenient to give a slightly more explicit construction of the family  $(f_t)_{t \in \mathbb{R}}$  and explain why it is uniquely determined by  $t \rightarrow \rho_t$ , even though this statement is well-known. For this, note that once we determine  $f_n$ , (7.1) gives  $f_t$  for all  $t \geq n$  by

$$f_t = f_n \circ f_t^{(n)}. \tag{7.2}$$

**Existence:** Consider for  $-\infty < s \leq t$ , the conformal map

$$F_t^{(s)}(z) := e^{-s} f_t^{(s)}(z)$$

which maps  $\mathbb{D}$  onto  $e^{-s} D_t^{(s)}$ . Since  $F_t^{(s)'}(0) = e^{-t}$ ,  $(F_t^{(s)})_{s \in (-\infty, t]}$  is a normal family for any  $t$ . We extract a sequence  $(s_k)$  converging to  $-\infty$ , such that for all  $n \in \mathbb{Z}$ ,  $F_n^{(s_k)}$  converges

uniformly on compacts to a univalent function that we call  $F_n$ . We construct  $(f_t)$  by taking  $f_n := F_n$  and generate the other  $f_t$  using (7.2). We need to verify compatibility, that is, that we have that  $F_{n+1} = F_n \circ f_{n+1}^{(n)}$ . To see this, notice that for  $s < t_1 < t_2$ ,

$$(F_{t_1}^{(s)})^{-1} \circ F_{t_2}^{(s)} = (f_{t_1}^{(s)})^{-1} \circ f_{t_2}^{(s)} = f_{t_2}^{(t_1)}$$

is independent of  $s$ . The last equality follows from the fact that as a function of  $t_2$  on  $[t_1, \infty)$ , both terms satisfy the same differential equation with same initial condition. Hence, we have  $F_n^{-1} \circ F_{n+1} = f_{n+1}^{(n)}$  as claimed.

**Uniqueness:** If there are two such families  $(f_t : \mathbb{D} \rightarrow D_t)_{t \in \mathbb{R}}$  and  $(\tilde{f}_t : \mathbb{D} \rightarrow \tilde{D}_t)_{t \in \mathbb{R}}$ . Let  $\psi_t := \tilde{f}_t \circ f_t^{-1} : D_t \rightarrow \tilde{D}_t$ . Since  $(f_t)$  and  $(\tilde{f}_t)$  are driven by the same process of measures, for all  $s \leq t$ ,

$$f_s^{-1} \circ f_t = \tilde{f}_s^{-1} \circ \tilde{f}_t.$$

And for  $z = f_t(w) \in D_t$ ,

$$\psi_s(z) = \tilde{f}_s \circ f_s^{-1} \circ f_t(w) = \tilde{f}_s \circ \tilde{f}_s^{-1} \circ \tilde{f}_t(w) = \tilde{f}_t \circ f_t^{-1}(z) = \psi_t(z).$$

That is,  $\psi_s|_{D_t} = \psi_t$ . Hence,  $\psi_t$  extends to a conformal map  $\cup_{t \in \mathbb{R}} D_t \rightarrow \cup_{t \in \mathbb{R}} \tilde{D}_t = \mathbb{C}$ . This shows that  $\psi_t$  is the identity map and  $D_t = \tilde{D}_t$ , since  $\psi_t(0) = 0$  and  $\psi_t'(0) = 1$  and completes the proof of the uniqueness.

We remark that for  $\rho \in \mathcal{N}$ , then  $\cup_{t \in \mathbb{R}} D_t = \mathbb{C}$ . Indeed,  $D_t$  has conformal radius  $e^{-t}$ , therefore contains the centered ball of radius  $e^{-t}/4$  by Koebe's 1/4 theorem. We define for all  $z \in \mathbb{C}$ ,

$$\tau(z) := \sup\{t \in \mathbb{R} : z \in D_t\} \in (-\infty, \infty].$$

Similar to the definition of foliations of  $\overline{\mathbb{D}} \setminus \{0\}$ , we say that  $\rho \in \mathcal{N}$  generates a foliation  $(\gamma_t := \partial D_t)_{t \in \mathbb{R}}$  of  $\mathbb{C} \setminus \{0\}$  if

1. For all  $t \in \mathbb{R}$ ,  $\gamma_t$  is a chord-arc Jordan curve.
2. It is possible to parametrize each curve  $\gamma_t, t \in \mathbb{R}$ , by  $S^1$  so that the mapping  $t \mapsto \gamma_t$  is continuous in the supremum norm.
3. For all  $z \in \mathbb{C} \setminus \{0\}$ ,  $\tau(z) < \infty$ .

We have the whole-plane version of Lemma 2.4:

**Lemma 7.1.** *Assume that  $\rho$  generates a foliation  $(\gamma_t)_{t \in \mathbb{R}}$  of  $\mathbb{C} \setminus \{0\}$ . For all  $z \neq 0$ , we have  $z \in \gamma_{\tau(z)}$ . In particular,  $\cup_{t \geq 0} \gamma_t = \mathbb{C} \setminus \{0\}$ .*

We associate similarly to a foliation of  $\mathbb{C} \setminus \{0\}$  its *winding function* defined by  $\varphi(0) = 0$ ,

$$\varphi(z) := \vartheta[g_t](z), \quad \text{for arclength-a.e. } z \in \gamma_t \text{ and } \forall t \in \mathbb{R},$$

where  $g_t = f_t^{-1}$ . We may also define  $\varphi(z)$  by  $\vartheta[g_{\tau(z)}](z)$ . We say that  $\varphi$  has an extension to  $W_{\text{loc}}^{1,2}$  if  $\varphi|_{\gamma_t}$  coincides a.e. with the Jonsson-Wallin trace of its extension on  $\gamma_t$ , for all  $t$ .

## 7.2 Proof of Theorem 1.1 and Theorem 1.2

Recall the definition of the Loewner-Kufarev energy in the whole-plane setting: for  $\rho \in \mathcal{N}$ ,

$$S(\rho) = \int_{\mathbb{R}} L(\rho_t) dt \quad \text{and} \quad S_{[a,b]}(\rho) = \int_a^b L(\rho_t) dt.$$

We use the notation from Section 7.1 and write for  $s \leq t$ ,

$$g_t^{(s)} := (f_t^{(s)})^{-1} = g_t \circ f_s, \quad g_t = f_t^{-1}.$$

Then  $(g_t^{(s)})_{t \geq s}$  is the uniformizing Loewner chain driven by  $\rho^{(s)} := (\rho_t)_{t \geq s}$ , mapping  $D_t^{(s)} = g_s(D_t)$  onto  $\mathbb{D}$ .

We are now ready to prove Theorem 1.1.

*Proof of Theorem 1.1.* By Conditions (i) and (iii) we have that

$$\bigcap_{t \in \mathbb{R}} D_t = \bigcap_{t \in \mathbb{R}_+} D_t = f_0(\bigcap_{t \geq 0} D_t^{(0)}) = \{0\},$$

where we used Lemma 4.2 and  $S_+(\rho) < \infty$ . Therefore  $\tau(z) < \infty$  for all  $z \neq 0$ .

Now we show that  $\partial D_t$  is a Weil-Petersson quasicircle. Note that on  $D_t$ ,

$$g_t = (g_t \circ f_s) \circ g_s = g_t^{(s)} \circ g_s, \quad \forall s \leq t.$$

Since  $S_{[s,\infty)}(\rho^{(s)}) < \infty$ , Proposition 5.9 shows that  $g_s(D_t) = g_s(f_t(\mathbb{D})) = f_t^{(s)}(\mathbb{D}) = D_t^{(s)}$  is bounded by a Weil-Petersson quasicircle. Moreover, from the proof of Lemma 4.2, we know that for all  $t \in \mathbb{R}$  there is  $s_0 < t$ , such that  $D_t^{(s_0)} \subset (1/2)\mathbb{D}$ . As  $f_{s_0} : \mathbb{D} \rightarrow D_{s_0}$  is conformal,  $\gamma_t = f_{s_0}(\partial D_t^{(s_0)})$  is also a Weil-Petersson quasicircle (e.g. by Lemma 2.1). We also obtain the continuity of  $t \mapsto \gamma_t$  from the continuity of  $t \mapsto \partial D_t^{(s_0)}$  by Corollary 5.12.  $\square$

We are now ready to prove whole-plane energy duality.

*Proof of Theorem 1.2.* Assume first  $S(\rho) < \infty$ , we show  $\mathcal{D}_{\mathbb{C}}(\varphi) < \infty$ . For this, note that the winding function  $\varphi^{(s)}$  of the foliation in  $\overline{\mathbb{D}} \setminus \{0\}$  driven by  $\rho^{(s)} = (\rho_t)_{t \geq s}$  is given by

$$\varphi^{(s)}(w) = \vartheta[g_{\tau(w)}^{(s)}](w) = \vartheta[g_{\tau(z)}](z) - \vartheta[g_s](z) = \varphi(z) - \vartheta[g_s](z)$$

where  $z = f_s(w) \in D_s$  and we used the chain rule (2.8). We have

$$\begin{aligned} \mathcal{D}_{D_s}(\varphi) &= \mathcal{D}_{D_s}(\varphi^{(s)} \circ g_s) + \mathcal{D}_{D_s}(\vartheta[g_s]) = \mathcal{D}_{\mathbb{D}}(\varphi^{(s)}) + \mathcal{D}_{D_s}(\vartheta[g_s]) \\ &= 16 S_{[s,\infty)}(\rho) + \mathcal{D}_{\mathbb{D}}(\vartheta[f_s]). \end{aligned} \tag{7.3}$$

The first equality follows from orthogonality of  $\vartheta[g_s]$  and  $\varphi^{(s)} \circ g_s$  in  $\mathcal{E}_0(\mathbb{D})$ , since  $\vartheta[g_s]$  is harmonic in  $D_s$  and  $\varphi^{(s)} \circ g_s \in \mathcal{E}_0(D_s)$ . The second equality follows from the conformal invariance of the Dirichlet energy, and the third from Theorem 1.7. We obtain immediately the lower bound

$$\mathcal{D}_{\mathbb{C}}(\varphi) \geq 16 S(\rho).$$

For the opposite inequality, since  $F_s^{(r)} := e^{-r} f_s^{(r)}$  (see Section 7.1) converges uniformly on compact subsets of  $\mathbb{D}$  to  $f_s$  as  $r \rightarrow -\infty$ , we have that  $\vartheta[F_s^{(r)}](z) = \vartheta[f_s^{(r)}](z)$  converges

uniformly on compact sets to  $\vartheta[f_s](z)$ . The lower semicontinuity of the Dirichlet energy then shows that for all compact  $K \subset \mathbb{D}$ ,

$$\mathcal{D}_K(\vartheta[f_s]) \leq \liminf_{r \rightarrow -\infty} \mathcal{D}_K(\vartheta[f_s^{(r)}]).$$

On the other hand, Corollary 6.4 shows that

$$\mathcal{D}_K(\vartheta[f_s^{(r)}]) = \mathcal{D}_{f_s^{(r)}(K)}(\vartheta[g_s^{(r)}]) \leq 16 S_{[r,s]}(\rho),$$

letting  $r \rightarrow -\infty$  yields

$$\mathcal{D}_{\mathbb{D}}(\vartheta[f_s]) \leq 16 \int_{-\infty}^s L(\rho_t) dt.$$

Combining this with (7.3) shows that  $\mathcal{D}_{D_s}(\varphi) \leq 16 S(\rho)$ . Letting  $s \rightarrow -\infty$  we obtain the upper bound and hence  $\mathcal{D}_{\mathbb{C}}(\varphi) = 16 S(\rho)$ .

For the converse, if  $\rho$  generates a foliation of  $\mathbb{C} \setminus \{0\}$  with  $\mathcal{D}_{\mathbb{C}}(\varphi) < \infty$ , Proposition 6.7 and (7.3) imply that

$$16 S_{[s,\infty)}(\rho^{(s)}) = \mathcal{D}_{\mathbb{D}}(\varphi^{(s)}) \leq \mathcal{D}_{D_s}(\varphi) \leq \mathcal{D}_{\mathbb{D}}(\varphi).$$

Letting  $s \rightarrow -\infty$  we obtain  $S(\rho) < \infty$  and this completes the proof.  $\square$

## 8 Applications of energy duality

In this section we derive several consequences of energy duality, Theorem 1.2.

### 8.1 Reversibility of the Loewner-Kufarev energy

Let  $(\gamma_t)_{t \in \mathbb{R}}$  be a foliation generated by  $\rho \in \mathcal{N}$  and let  $(D_t)_{t \in \mathbb{R}}$  be the corresponding family of domains. We will consider the evolution of its time-reversal, that is the Loewner chain corresponding to the family  $(\tilde{D}_{s(t)} := j(\hat{\mathbb{C}} \setminus D_t))_{t \in \mathbb{R}}$ , where  $j(z) := 1/z$  and  $e^{-s(t)}$  is the conformal radius of  $j(\hat{\mathbb{C}} \setminus D_t)$ . Let  $\tilde{f}_s$  be the conformal map from  $\mathbb{D}$  onto  $\tilde{D}_s$  with  $\tilde{f}_s(0) = 0$  and  $\tilde{f}'_s(0) = e^{-s}$ .

**Lemma 8.1.** *The function  $t \mapsto s(t)$  is a decreasing homeomorphism of  $\mathbb{R}$ .*

*Proof.* To show that  $t \mapsto s$  is decreasing, let  $t_1 < t_2$ . Since  $D_{t_2} \subsetneq D_{t_1}$ , we have  $\tilde{D}_{s(t_1)} \subsetneq \tilde{D}_{s(t_2)}$ . Schwarz' lemma then shows that  $s(t_2) < s(t_1)$ . We claim that  $s(t) \rightarrow \infty$  as  $t \rightarrow -\infty$ . In fact, Koebe's 1/4-theorem shows that  $D_t$  contains the centered disk of radius  $e^{-t}/4$ , therefore  $\tilde{D}_{s(t)}$  is contained in the centered disk of radius  $4e^t$ . Schwarz' lemma shows  $s(t) \geq -t - \log 4$  which goes to  $\infty$  as  $t \rightarrow -\infty$ . Since the diameter of  $D_t$  tends to 0 as  $t \rightarrow \infty$  by Lemma 4.2,  $\tilde{D}_{s(t)}$  has conformal radius tending to  $\infty$ . Therefore  $s(t) \rightarrow -\infty$  as  $t \rightarrow \infty$ . It remains to verify that  $s$  is continuous. To see this, note that the continuity of  $t \mapsto \gamma_t$  in the supremum norm shows that as  $t \rightarrow t_0 \in \mathbb{R}$ ,  $\tilde{D}_{s(t)}$  converges in the Carathéodory kernel sense to  $\tilde{D}_{s(t_0)}$ . Therefore,  $\tilde{f}'_{s(t)}(0)$  tends to  $\tilde{f}'_{s(t_0)}(0)$ , and equivalently,  $s(t)$  tends to  $s(t_0)$ .  $\square$

Lemma 8.1 implies that  $(\tilde{f}_s)_{s \in \mathbb{R}}$  is a whole-plane Loewner chain as defined in Section 7. Note that in Section 7 we took the measure  $\rho$  as starting point for the definition whereas

we have constructed the monotone family of domains here. However, using Pommerenke's theorem as discussed in Section 2.2 the existence of a measure  $\tilde{\rho}$  generating the family follows easily. Energy duality, Theorem 1.2, now implies the following reversibility of the Loewner-Kufarev energy.

**Theorem 8.2** (Energy reversibility). *Let  $\tilde{\rho} \in \mathcal{N}$  be the measure generating  $(\tilde{D}_s)_{s \in \mathbb{R}}$ . We have  $S(\rho) = S(\tilde{\rho})$ .*

*Proof.* It suffices to prove that the winding function  $\tilde{\varphi}$  associated to the foliation  $(\partial\tilde{D}_{s(t)})$  satisfies  $\tilde{\varphi} \circ j = \varphi$ . Energy reversibility then follows from Theorem 1.2 and conformal invariance of the Dirichlet energy, which implies  $\mathcal{D}_{\mathbb{C}}(\varphi) = \mathcal{D}_{\mathbb{C}}(\tilde{\varphi})$ .

Now let  $z$  be a differentiable point of  $\gamma_t = \partial D_t$ . The winding function  $\tilde{\varphi}$  at  $j(z)$  associated to the inverted foliation is geometrically the angle (modulo  $2\pi$ ) from  $j(\gamma_t)$  to the circle centered at 0 passing through  $j(z)$ . Since  $j$  is conformal and the family of circles centered at 0 is preserved under  $j$ , we have  $\tilde{\varphi} \circ j(z) = \varphi(z)$  modulo  $2\pi$ . To determine the  $2\pi$  branches from the analytic definition of  $\varphi$  and  $\tilde{\varphi}$  via  $\vartheta$  and to show that they actually coincide, we can use the equipotentials  $f_t(rS^1)$  inside  $D_t$  to continuously deform both winding functions to 0 as  $r \rightarrow 0$ .  $\square$

## 8.2 Characterization of Weil-Petersson quasicircles

Let  $\gamma$  be a Weil-Petersson quasicircle separating 0 from  $\infty$ . We will associate to  $\gamma$  a particular measure  $\rho = \rho^\gamma$  (and foliation) with  $S(\rho) < \infty$  and in this way prove Theorem 1.4. We assume for notational simplicity that the bounded component of  $\mathbb{C} \setminus \gamma$  has conformal radius 1<sup>4</sup>. Let  $f$  (resp.  $h$ ) be the conformal map from  $\mathbb{D}$  (resp.  $\mathbb{D}^*$ ) to the bounded component  $D_0$  (resp. unbounded component  $D_0^*$ ) of  $\mathbb{C} \setminus \gamma$  such that  $f$  (resp.  $h$ ) fixes 0 (resp.  $\infty$ ) and has derivative  $f'(0) = 1$  (resp.  $h'(\infty) > 0$ ). Consider the foliation  $(\gamma_t)_{t \in \mathbb{R}}$  that consists of  $\gamma$  together with the family of equipotentials on both sides of  $\gamma$ . By equipotential which we mean image of a circle  $rS^1$  under  $f$  (resp. under  $h$ ), and we include all equipotentials corresponding to  $r < 1$  (resp.  $r > 1$ ). The parametrization of  $(\gamma_t)_{t \in \mathbb{R}}$  by  $t$  is chosen so that the connected component  $D_t$  of  $\hat{\mathbb{C}} \setminus \gamma_t$  containing 0 has conformal radius  $e^{-t}$ .

Let  $\rho^\gamma \in \mathcal{N}$  be the measure associated with  $(\gamma_t)_{t \in \mathbb{R}}$  and let  $\varphi$  be the corresponding winding function. Along with the Loewner chain  $(f_t : \mathbb{D} \rightarrow D_t)_{t \in \mathbb{R}}$ , we consider also the conformal maps  $h_t : \mathbb{D}^* \rightarrow D_t^*$ , such that  $h_t(\infty) = \infty$  and  $h'_t(\infty) > 0$ . In particular,  $f = f_0$  and  $h = h_0$ . We also set  $g_t := f_t^{-1}$  and  $k_t := h_t^{-1}$  as before. For a conformal map  $k$  fixing  $\infty$ , we define similarly

$$\vartheta[k](z) = \arg \frac{zk'(z)}{k(z)} = \int_{\infty}^z d \left( \arg \frac{k(w) - k(z)}{w - z} + \arg \frac{w}{k(w)} \right),$$

namely, the continuous branch of argument is chosen so that  $\vartheta[k](z) \rightarrow 0$  as  $z \rightarrow \infty$ .

**Lemma 8.3.** *For a.e.  $t \geq 0$ ,  $\rho_t^\gamma$  is the uniform measure. Moreover,  $\varphi|_{\mathbb{C} \setminus \gamma}$  is harmonic, and we have*

$$\varphi|_{D_0} = \vartheta[g_0], \quad \text{and} \quad \varphi|_{D_0^*} = \vartheta[k_0].$$

<sup>4</sup>This assumption is only made for convenience, so that the curve  $\gamma$  corresponds to time-index 0 in the foliation. All results in this section hold for a general Weil-Petersson quasicircle  $\gamma$  separating 0 from  $\infty$ .

*Proof.* By our definition of equipotentials we have  $\gamma_t = f(e^{-t}S^1)$  for  $t \geq 0$ . The flow  $(g_t \circ f)_{t \geq 0}$ , driven by  $(\rho_t^\gamma)_{t \geq 0}$  equals  $(z \mapsto e^t z)$ , which shows that  $(\rho_t^\gamma)_{t \geq 0}$  is a.e. the uniform measure on  $S^1$ . The identity  $\varphi = \vartheta[g_0]$  on  $D_0$  and the harmonicity of  $\varphi|_{D_0}$  follow as in Lemma 2.8.

Now we consider  $D_0^*$ . Using the notation of Theorem 8.2, we have that the winding function in  $D_0^*$  is given by  $\varphi(z) = \tilde{\varphi} \circ j(z)$ . Since the family of equipotentials is preserved under the inversion  $j$ , it follows that  $\tilde{\varphi}$  is harmonic in  $j(D_0^*)$  and

$$\tilde{\varphi} = \vartheta[j \circ k_0 \circ j] = \vartheta[k_0] \circ j,$$

using the chain rule (2.8) and  $\vartheta[j] \equiv 0$ . Therefore  $\varphi|_{D_0^*} = \vartheta[k_0]$ .  $\square$

Recall that the Loewner energy of the curve  $\gamma$  is

$$I^L(\gamma) = \mathcal{D}_{\mathbb{D}}(\arg f') + \mathcal{D}_{\mathbb{D}^*}(\arg h') + 4 \log |f'(0)/h'(\infty)|. \quad (8.1)$$

(We have normalized so that  $f'(0) = 1$  but we will keep it in the notation since (8.1) holds more generally.)

**Theorem 8.4.** *Let  $\gamma$  be a Weil-Petersson quasicycle separating 0 from  $\infty$ . Let  $\rho^\gamma$  be the measure associated to  $\gamma$ . Then*

$$16 S(\rho^\gamma) = I^L(\gamma) - 2 \log |f'(0)/h'(\infty)| < \infty.$$

Moreover, if  $\rho \in \mathcal{N}$  generates  $\gamma$  as a leaf, then  $S(\rho^\gamma) \leq S(\rho)$ .

*Proof.* By Lemma 8.3, the winding function associated to  $\rho^\gamma$  satisfies

$$\begin{aligned} \mathcal{D}_{\mathbb{C}}(\varphi) &= \frac{1}{\pi} \int_{D_0} |\nabla \vartheta[g_0]|^2 dA(z) + \frac{1}{\pi} \int_{D_0^*} |\nabla \vartheta[k_0]|^2 dA(z) \\ &= \frac{1}{\pi} \int_{\mathbb{D}} |\nabla \vartheta[f]|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}^*} |\nabla \vartheta[h]|^2 dA(z) \\ &= \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f''}{f'} - \frac{f'}{f} + \frac{1}{z} \right|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{h''}{h'} - \frac{h'}{h} + \frac{1}{z} \right|^2 dA(z) \\ &= \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f''}{f'} \right|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{h''}{h'} \right|^2 dA(z) - \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f'}{f} - \frac{1}{z} \right|^2 dA(z) \\ &\quad - \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{h'}{h} - \frac{1}{z} \right|^2 dA(z) \\ &= \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f''}{f'} \right|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{h''}{h'} \right|^2 dA(z) + 2 \log |f'(0)/h'(\infty)| \\ &= I^L(\gamma) - 2 \log |f'(0)/h'(\infty)|, \end{aligned}$$

where we used (8.1) and Lemma 8.5 proved just below. Theorem 1.2 then implies the identity. The claim  $S(\rho^\gamma) \leq S(\rho)$  follows immediately from Lemma 8.3 since equipotentials are generated by the zero energy measure for  $t \geq 0$  and we complete the proof using Theorem 8.2.  $\square$

**Lemma 8.5.** *We have the identity*

$$\operatorname{Re} \left[ \int_{\mathbb{D}} \frac{f''}{f'} \left( \frac{\overline{f'}}{f} - \frac{1}{z} \right) dA(z) + \int_{\mathbb{D}^*} \frac{h''}{h'} \left( \frac{\overline{h'}}{h} - \frac{1}{z} \right) dA(z) \right]$$

$$= \int_{\mathbb{D}} \left| \frac{f'}{f} - \frac{1}{z} \right|^2 dA(z) + \int_{\mathbb{D}^*} \left| \frac{h'}{h} - \frac{1}{z} \right|^2 dA(z) = 2\pi \log \left| \frac{h'(\infty)}{f'(0)} \right|.$$

*Proof.* Consider  $\tilde{f} := j \circ h \circ j$  and  $\tilde{h} := j \circ f \circ j$ , the conformal maps associated to  $j(\gamma)$ . We have  $\tilde{f}'(0) = h'(\infty)^{-1}$  and

$$\frac{\tilde{f}''(z)}{\tilde{f}'(z)} = -\frac{1}{z^2} \left( \frac{h''(1/z)}{h'(1/z)} - \frac{2h'(1/z)}{h(1/z)} + 2z \right)$$

and similarly for  $\tilde{h}$ . We compute

$$\begin{aligned} I^L(j(\gamma)) &= \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{\tilde{f}''}{\tilde{f}'} \right|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{\tilde{h}''}{\tilde{h}'} \right|^2 dA(z) + 4 \log \left| \frac{\tilde{f}'(0)}{\tilde{h}'(\infty)} \right| \\ &= \frac{1}{\pi} \int_{\mathbb{D}^*} \left| \frac{h''}{h'} - \frac{2h'}{h} + \frac{2}{z} \right|^2 dA(z) + \frac{1}{\pi} \int_{\mathbb{D}} \left| \frac{f''}{f'} - \frac{2f'}{f} + \frac{2}{z} \right|^2 dA(z) + 4 \log \left| \frac{f'(0)}{h'(\infty)} \right| \\ &= I^L(\gamma) - \int_{\mathbb{D}^*} 4 \operatorname{Re} \left[ \frac{h''}{h'} \left( \frac{\overline{h'} - 1}{h} - \frac{1}{z} \right) \right] dA(z) - \int_{\mathbb{D}} 4 \operatorname{Re} \left[ \frac{f''}{f'} \left( \frac{f'}{f} - \frac{1}{z} \right) \right] dA(z) \\ &\quad + 4 \int_{\mathbb{D}^*} \left| \frac{h'}{h} - \frac{1}{z} \right|^2 dA(z) + 4 \int_{\mathbb{D}} \left| \frac{f'}{f} - \frac{1}{z} \right|^2 dA(z). \end{aligned}$$

Since the Loewner energy of a Jordan curve is Möbius invariant, we have  $I^L(\gamma) = I^L(j(\gamma))$ , we obtain the first equality. The second equality follows from Lemma 5.4 since  $\gamma$  has Lebesgue measure zero.  $\square$

Combining Theorem 1.1 and Theorem 8.4, we obtain a new characterization of Weil-Petersson quasicircles.

**Corollary 8.6.** *A Jordan curve  $\gamma$  separating 0 from  $\infty$  is a Weil-Petersson quasicircle if and only if  $\gamma$  can be realized as a leaf in the foliation generated by a measure  $\rho$  with  $S(\rho) < \infty$ .*

**Corollary 8.7.** *The Loewner energies of the leaves generated by  $\rho$  are uniformly bounded by  $16 S(\rho)$ .*

*Proof.* Using Theorem 1.2 and Theorem 8.4,

$$16 S(\rho) \geq 16 S(\rho^\gamma) = I^L(\gamma_t) - 2 \log |f'_t(0)| + 2 \log |h'_t(\infty)|,$$

where  $f_t, h_t$  are the conformal maps associated to  $\gamma_t$ . On the other hand, Lemma 5.4 shows that

$$2 \log |h'_t(\infty)| - 2 \log |f'_t(0)| \geq 0.$$

Thus,  $I^L(\gamma_t) \leq 16 S(\rho)$  for all  $t$  as claimed.  $\square$

*Remark.* Corollary 8.7 provides a way to generate and simulate Weil-Petersson quasicircles of bounded Loewner energy using a measure with controlled Loewner-Kufarev energy. In fact, we obtain infinitely many such quasicircles for any given measure.

*Remark.* The Loewner energy  $I^L(\gamma)$  is invariant under Möbius transformations, and is known to be a Kähler potential for the Weil-Petersson metric defined on a subspace  $T_0(1)$  of the universal Teichmüller space, see [67, Thm. II.4.1]. On the other hand,  $\log |f'(0)/h'(\infty)|$  is only invariant under scaling and rotation which is consistent with the fact that the Loewner-Kufarev equation has two marked points 0 and  $\infty$  on the Riemann sphere. We also point out that  $\log |f'(0)/h'(\infty)|$  is a Kähler potential for the Velling-Kirillov metric on the universal Teichmüller curve, a complex fiber bundle over  $T_0(1)$ , see [67, Thm. I.5.3].

### 8.3 Complex identity: Proof of Proposition 1.5

Recall that a Weil-Petersson quasicycle  $\gamma$  separating 0 from  $\infty$  is compatible with  $\varphi \in W_{\text{loc}}^{1,2}$  if the winding function of  $\gamma$  coincides with the trace  $\varphi|_{\gamma}$  arclength-a.e. Since  $\gamma$  is by assumption compatible with  $\text{Im } \psi$ ,

$$\vartheta[f](z) = -\text{Im } \psi^h(f(z)), \quad \forall z \in \mathbb{D},$$

where  $\text{Im } \psi^h + \text{Im } \psi^0$  is the orthogonal decomposition of  $\text{Im } \psi$  with respect to  $\mathbb{C} \setminus \gamma$  as in (2.1). In other words,  $\text{Im } \psi^h$  is the winding function associated to the foliation driven by  $\rho^\gamma$  described by Section 8.2. Hence we can write,

$$\begin{aligned} \zeta &= \left( \text{Re } \psi \circ f + \log \left| \frac{zf'(z)}{f(z)} \right| \right) + i (\text{Im } \psi \circ f + \vartheta[f](z)) = u + i \text{Im } \psi^0 \circ f; \\ \xi &= v + i \text{Im } \psi^0 \circ g, \end{aligned}$$

where

$$u := \text{Re } \psi \circ f + \log \left| \frac{zf'(z)}{f(z)} \right|, \quad v := \text{Re } \psi \circ h + \log \left| \frac{zh'(z)}{h(z)} \right|.$$

Notice that  $\log |zf'(z)/f(z)|$  is a harmonic conjugate of  $\vartheta[f]$ , so they have the same Dirichlet energy. Therefore

$$\begin{aligned} \mathcal{D}_{\mathbb{D}}(\zeta) + \mathcal{D}_{\mathbb{D}^*}(\xi) &= \mathcal{D}_{\mathbb{D}}(u) + \mathcal{D}_{\mathbb{D}}(v) + \mathcal{D}_{\mathbb{C}}(\text{Im } \psi^0) \\ &= \mathcal{D}_{\mathbb{C}}(\text{Re } \psi) + \mathcal{D}_{\mathbb{C}}(\text{Im } \psi^h) + \text{“cross-terms”} + \mathcal{D}_{\mathbb{C}}(\text{Im } \psi^0) \\ &= \mathcal{D}_{\mathbb{C}}(\text{Re } \psi) + \mathcal{D}_{\mathbb{C}}(\text{Im } \psi) + \text{“cross-terms”} \end{aligned}$$

where the “cross-terms” come from expanding the Dirichlet integrals of  $u$  and  $v$ . In fact, they equal 2 times

$$\int_{\mathbb{D}} \left\langle \nabla \text{Re } \psi \circ f, \nabla \log \left| \frac{f'(z)z}{f(z)} \right| \right\rangle dA(z) + \int_{\mathbb{D}^*} \left\langle \nabla \text{Re } \psi \circ h, \nabla \log \left| \frac{h'(z)z}{h(z)} \right| \right\rangle dA(z). \quad (8.2)$$

It suffices to show that (8.2) vanishes. We will only prove it assuming that  $\gamma$  is smooth. The general case of a Weil-Petersson quasicycle can be deduced using an approximation argument following exactly the same proof as [68, Thm. 3.1].

From Stokes' formula, the first term in (8.2) equals

$$\begin{aligned} &\int_{\partial\mathbb{D}} \text{Re } \psi \circ f(z) \partial_n \log \left| \frac{f'(z)z}{f(z)} \right| |dz| \\ &= \int_{\partial\mathbb{D}} \text{Re } \psi \circ f(z) \partial_n \log |f'(z)| |dz| + \text{Re} \left[ \int_{\partial\mathbb{D}} \text{Re } \psi \circ f(z) \partial_n \left( \log \frac{z}{f(z)} \right) |dz| \right] \end{aligned}$$

$$=: I_1 + I_2$$

where  $\partial_n$  is the normal derivative in the outward pointing direction. Using the formula  $\partial_n \log |f'(z)| = k_\Omega \circ f(z) |f'(z)| - k_{\mathbb{D}}(z) = k_\Omega \circ f(z) |f'(z)| - 1$ , where  $k_\Omega$  is the geodesic curvature of  $\partial\Omega$  (see, e.g., [71, Appx. A]), we obtain

$$I_1 = \int_{\partial\Omega} \operatorname{Re} \psi(w) k_\Omega(w) |dw| - \int_{\partial\mathbb{D}} \operatorname{Re} \psi \circ f(z) |dz|.$$

Using  $z|dz| = -idz$ , we have

$$\begin{aligned} I_2 &= \operatorname{Re} \int_{\partial\mathbb{D}} \operatorname{Re} \psi \circ f(z) z \left( -\frac{f'(z)}{f(z)} + \frac{1}{z} \right) |dz| \\ &= \operatorname{Re} \int_{\partial\mathbb{D}} i \operatorname{Re} \psi \circ f(z) \frac{f'(z)}{f(z)} dz + \int_{\partial\mathbb{D}} \operatorname{Re} \psi \circ f(z) |dz| \\ &= \operatorname{Re} \int_{\partial\Omega} \frac{i \operatorname{Re} \psi(w)}{w} dw + \int_{\partial\mathbb{D}} \operatorname{Re} \psi \circ f(z) |dz|. \end{aligned}$$

The sum of  $I_1$ ,  $I_2$  and those integrals coming from the second term of (8.2) vanishes since  $k_\Omega(y) = -k_{\Omega^*}(y)$  and the contour integral in  $I_2$  winds in the opposite direction for  $\Omega$  and  $\Omega^*$ . This concludes the proof.  $\square$

## 9 Conformal distortion formula

The goal of this section is to compute an explicit formula for the change of the Loewner-Kufarev energy under conformal transformation of the foliation and prove Theorem 1.6 which combines Proposition 9.2 and Corollary 9.3.

We consider the following set up. Let  $\rho \in \mathcal{N}_+$  be such that

$$S_{[0,1]}(\rho) = \int_0^1 L(\rho_t) dt < \infty.$$

We write as before  $\rho_t = \nu_t^2(\theta) d\theta$ . Suppose  $\psi$  is a conformal transformation that maps  $K_1$  onto another compact hull  $\psi(K_1) = \tilde{K}_1 \subset \overline{\mathbb{D}}$ , and is defined on a neighborhood  $U$  of  $K_1$  in  $\overline{\mathbb{D}}$  which is mapped onto a neighborhood  $\tilde{U}$  of  $\tilde{K}_1$  in  $\overline{\mathbb{D}}$ . Note that we always have  $S^1 \subset K_1$  by definition. See Figure 9.1. The image of the hulls ( $\tilde{K}_t := \psi(K_t)$ ), is driven by a measure  $t \mapsto \tilde{\rho}_t$ , where  $\tilde{\rho}_t$  is not necessarily a probability measure. Indeed,  $\tilde{D}_t := \mathbb{C} \setminus \tilde{K}_t$  may not have conformal radius  $e^{-t}$ , so the new Loewner chain is not necessarily normalized.

Let  $(g_t = f_t^{-1})_{t \leq 1}$  and  $(\tilde{g}_t = \tilde{f}_t^{-1})_{t \leq 1}$  be the corresponding uniformizing Loewner chains. Let  $\psi_t := \tilde{g}_t \circ \psi \circ f_t$ . Then  $\psi_t$  is a conformal map of  $U_t := g_t(U \setminus K_t)$  onto  $\tilde{U}_t := \tilde{g}_t(\tilde{U} \setminus \tilde{K}_t)$ . By the Schwarz reflection principle,  $\psi_t$  extends to a holomorphic function in a neighborhood of  $S^1$ . For the next statement, recall that  $\mathcal{S}f$  denotes the Schwarzian of  $f$ .

**Lemma 9.1.** *For a.e.  $t \in [0, 1]$ ,  $\tilde{\rho}_t \ll d\theta$ . If we write  $\tilde{\rho}_t = \tilde{\nu}_t^2(\theta) d\theta$ , then*

$$\tilde{\nu}_t^2(\theta_t) = |\psi_t'(e^{i\theta})| \nu_t^2(\theta), \quad (9.1)$$

where  $\theta_t \in [0, 2\pi]_{/0 \sim 2\pi}$  satisfies  $e^{i\theta_t} = \psi_t(e^{i\theta})$ .

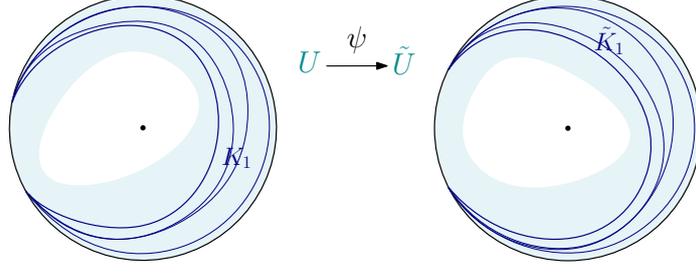


Figure 9.1: Conformal distortion of a foliation. The mapping  $\psi$  is conformal in a neighborhood of the hull  $K$  generated by  $\rho$ , which is mapped to another hull  $\tilde{K}$ , generated by a measure  $\tilde{\rho}$ . Proposition 9.2 computes the difference of the Loewner-Kufarev energies of  $\rho$  and  $\tilde{\rho}$ .

*Proof.* Let  $\tilde{H}_t$  be the Herglotz integral of  $\tilde{\rho}_t$ . Let  $0 < r < 1$  and consider for  $t \in [0, 1]$  the curve  $\gamma_t^r = f_t(rS^1)$  passing through  $f_t(re^{i\theta}) =: w$ . We can compute the normal velocity of  $\psi \circ \gamma_t^r$  at  $\psi(w)$  in two ways. First starting from the velocity at  $w$  using that  $\psi$  is conformal: this gives  $r|\psi'(w)||f'_t(re^{i\theta})|\operatorname{Re} H_t(re^{i\theta})$ ; and second, directly from the Loewner-Kufarev equation driven by  $\tilde{\rho}$ , which gives

$$|\tilde{f}'_t(\psi_t(re^{i\theta}))|\operatorname{Re} \overline{e^{i\theta} \psi'_t(re^{i\theta})} |\psi'_t(re^{i\theta})|^{-1} \psi_t(re^{i\theta}) \tilde{H}_t(\psi_t(re^{i\theta})).$$

Indeed, to see why these formulas hold, first note that a unit normal at  $w$  is

$$\mathbf{n}(\gamma_t^r(e^{i\theta})) = -e^{i\theta} \frac{f'_t(re^{i\theta})}{|f'_t(re^{i\theta})|}, \quad \theta \in [0, 2\pi).$$

Using the Loewner equation, we see that the normal velocity with respect to the curve  $\gamma_t^r(\theta)$  at time  $t$  at the point  $w$  is

$$\begin{aligned} -\operatorname{Re} \frac{\partial_t f_t(re^{i\theta}) \overline{e^{i\theta} f'_t(re^{i\theta})}}{|f'_t(re^{i\theta})|} &= \operatorname{Re} \frac{re^{i\theta} f'_t(re^{i\theta}) H_t(re^{i\theta}) \overline{e^{i\theta} f'_t(re^{i\theta})}}{|f'_t(re^{i\theta})|} \\ &= r |f'_t(re^{i\theta})| \operatorname{Re} H_t(re^{i\theta}). \end{aligned}$$

Next, by definition  $\psi_t = \tilde{g}_t \circ \psi \circ f_t$ , so  $\tilde{f}_t \circ \psi_t = \psi \circ f_t$ . Since  $w = f_t(re^{i\theta})$  we have  $\psi'(w) f'_t(re^{i\theta}) = \tilde{f}'_t(\psi_t(re^{i\theta})) \psi'_t(re^{i\theta})$  and the normal velocity of the image curve at  $\psi(w)$  is

$$\begin{aligned} -\operatorname{Re} \frac{(\partial_t \tilde{f}_t)(\psi_t(re^{i\theta})) \overline{e^{i\theta} \psi'(w) f'_t(re^{i\theta})}}{|\psi'(w)||f'_t(re^{i\theta})|} \\ &= \operatorname{Re} \frac{\psi_t(re^{i\theta}) \tilde{f}'_t(\psi_t(re^{i\theta})) \tilde{H}_t(\psi_t(re^{i\theta})) \overline{e^{i\theta} \psi'(w) f'_t(re^{i\theta})}}{|\psi'(w)||f'_t(re^{i\theta})|} \\ &= \operatorname{Re} \frac{\psi_t(re^{i\theta}) \tilde{f}'_t(\psi_t(re^{i\theta})) \tilde{H}_t(\psi_t(re^{i\theta})) \overline{e^{i\theta} \tilde{f}'_t(\psi_t(re^{i\theta})) \psi'_t(re^{i\theta})}}{|\tilde{f}'_t(\psi_t(re^{i\theta})) \psi'_t(re^{i\theta})|} \\ &= |\tilde{f}'_t(\psi_t(re^{i\theta}))| \operatorname{Re} \frac{\psi_t(re^{i\theta}) \tilde{H}_t(\psi_t(re^{i\theta})) \overline{e^{i\theta} \psi'_t(re^{i\theta})}}{|\psi'_t(re^{i\theta})|} \end{aligned}$$

We get

$$r|\psi'(w)||f'_t(re^{i\theta})|\operatorname{Re} H_t(re^{i\theta}) = |\tilde{f}'_t(\psi_t(re^{i\theta}))| \operatorname{Re} \left( \frac{e^{i\theta} \psi'_t(re^{i\theta})}{|\psi'_t(re^{i\theta})|} \psi_t(re^{i\theta}) \tilde{H}_t(\psi_t(re^{i\theta})) \right).$$

Note that  $H_t$  is continuous on  $\overline{\mathbb{D}}$  and  $\psi_t$  extends to be holomorphic on a neighborhood of  $S^1$ . Moreover, as  $r \rightarrow 1-$ ,  $e^{i\theta}\psi'_t(re^{i\theta})\psi_t(re^{i\theta})/|\psi'_t(re^{i\theta})| \rightarrow 1$ . Since  $\text{Re } \tilde{H}_t = 2\pi P_{\mathbb{D}}[\tilde{\rho}_t]$ , we obtain that  $\tilde{\rho}_t \ll d\theta$  and (9.1) by letting  $r \rightarrow 1-$  and using the definition  $\psi_t = (\tilde{f}_t)^{-1} \circ \psi \circ f_t$  and the chain rule.  $\square$

**Proposition 9.2.** *We have*

$$L(\tilde{\rho}_t) - L(\rho_t) = \frac{1}{4} \int_{S^1} e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) d\rho_t(\theta) + \frac{1}{8} (|\tilde{\rho}_t| - |\rho_t|).$$

Note that by conjugating  $\psi_t$  by a Möbius transformation mapping  $\mathbb{D}$  to  $\mathbb{H}$ , one sees that  $e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) \in \mathbb{R}$ .

*Proof.* We use the same notation as in Lemma 9.1. Differentiating (9.1) with respect to  $\theta$ , we obtain using  $\partial\theta_t/\partial\theta = |\psi'_t(e^{i\theta})|$  that

$$\tilde{\nu}'_t(\theta) \sqrt{|\psi'_t(e^{i\theta})|} = \nu'_t(\theta) + \frac{\partial_\theta |\psi'_t(e^{i\theta})|}{2|\psi'_t(e^{i\theta})|} \nu_t(\theta).$$

Plugging this into the expression for  $L(\tilde{\rho}_t)$ , we get

$$\begin{aligned} L(\tilde{\rho}_t) &= \frac{1}{2} \int_{S^1} \tilde{\nu}'_t(\theta)^2 d\theta = \frac{1}{2} \int_{S^1} \tilde{\nu}'_t(\psi_t(e^{i\theta}))^2 |\psi'_t(e^{i\theta})| d\theta \\ &= \frac{1}{2} \int_{S^1} \left( \nu'_t + \frac{\partial_\theta |\psi'_t|}{2|\psi'_t|} \nu_t \right)^2 d\theta \\ &= L(\rho_t) + \frac{1}{2} \int_{S^1} \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \nu'_t \nu_t d\theta + \frac{1}{8} \int_{S^1} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \nu_t^2 d\theta. \end{aligned}$$

Integrating

$$\partial_\theta \left[ \nu_t^2 \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right] = 2\nu'_t \nu_t \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} + \nu_t^2 \left[ \frac{\partial_\theta^2 |\psi'_t|}{|\psi'_t|} - \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \right],$$

over  $S^1$  against  $d\theta$  gives 0. It follows that  $L(\tilde{\rho}_t) - L(\rho_t)$  equals

$$\frac{1}{2} \int_{S^1} \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \nu'_t \nu_t d\theta + \frac{1}{8} \int_{S^1} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \nu_t^2 d\theta = -\frac{1}{4} \int_{S^1} \nu_t^2 \left[ \frac{\partial_\theta^2 |\psi'_t|}{|\psi'_t|} - \frac{3}{2} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \right] d\theta.$$

Using  $|\psi'_t(z)| = \psi'_t(z)z/\psi_t(z)$  and  $\partial_\theta = iz\partial_z$ , we compute

$$\frac{\partial_\theta |\psi'_t(z)|}{|\psi'_t(z)|} = iz\partial_z \log |\psi'_t(z)| = iz \left( \frac{\psi''_t}{\psi'_t} - \frac{\psi'_t}{\psi_t} + \frac{1}{z} \right)$$

and

$$\begin{aligned} -\frac{1}{2} \left( \frac{\partial_\theta |\psi'_t(z)|}{|\psi'_t(z)|} \right)^2 &= \frac{z^2}{2} \left[ \left( \frac{\psi''_t}{\psi'_t} \right)^2 + \left( \frac{\psi'_t}{\psi_t} \right)^2 + \frac{1}{z^2} - 2\frac{\psi''_t}{\psi_t} - 2\frac{\psi'_t}{z\psi_t} + 2\frac{\psi''_t}{z\psi'_t} \right] \\ &= \frac{z^2}{2} \left( \frac{\psi''_t}{\psi'_t} \right)^2 + \frac{z^2}{2} \left( \frac{\psi'_t}{\psi_t} \right)^2 + \frac{1}{2} - z^2 \frac{\psi''_t}{\psi_t} - \frac{z\psi'_t}{\psi_t} + \frac{z\psi''_t}{\psi'_t}. \end{aligned}$$

Moreover,

$$\begin{aligned}\partial_\theta \left( \frac{\partial_\theta |\psi'_t(z)|}{|\psi'_t(z)|} \right) &= iz \left[ i \left( \frac{\psi''_t}{\psi'_t} - \frac{\psi'_t}{\psi_t} + \frac{1}{z} \right) + iz \left( \left( \frac{\psi''_t}{\psi'_t} \right)' - \left( \frac{\psi'_t}{\psi_t} \right)' - \frac{1}{z^2} \right) \right] \\ &= -z^2 \left( \frac{\psi''_t}{\psi'_t} \right)' - z \left( \frac{\psi''_t}{\psi'_t} - \frac{\psi'_t}{\psi_t} + \frac{1}{z} \right) + z^2 \left( \frac{\psi''_t}{\psi_t} - \frac{(\psi'_t)^2}{\psi_t^2} \right) + 1.\end{aligned}$$

We obtain

$$\begin{aligned}\frac{\partial_\theta^2 |\psi'_t|}{|\psi'_t|} - \frac{3}{2} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 &= \partial_\theta \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right) - \frac{1}{2} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \\ &= -z^2 \mathcal{S}\psi_t - \frac{z^2}{2} \left( \frac{\psi'_t}{\psi_t} \right)^2 + \frac{1}{2} = -z^2 \mathcal{S}\psi_t + \frac{1 - |\psi'_t|^2}{2}.\end{aligned}$$

Combining these computations, we get

$$\begin{aligned}L(\tilde{\rho}_t) - L(\rho_t) &= -\frac{1}{4} \int_{S^1} \nu_t^2(\theta) \left[ \frac{\partial_\theta^2 |\psi'_t|}{|\psi'_t|} - \frac{3}{2} \left( \frac{\partial_\theta |\psi'_t|}{|\psi'_t|} \right)^2 \right] d\theta \\ &= \frac{1}{4} \int_{S^1} \nu_t^2(\theta) \left[ e^{2i\theta} \mathcal{S}\psi_t + \frac{|\psi'_t|^2 - 1}{2} \right] d\theta \\ &= \frac{1}{4} \int_{S^1} \nu_t^2(\theta) e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) d\theta + \frac{1}{8} \left( \int_{S^1} \tilde{\nu}_t^2(\theta) d\theta - \int_{S^1} \nu_t^2(\theta) d\theta \right),\end{aligned}$$

where we used (9.1) in the last equality and

$$\int_{S^1} \nu_t^2(\theta) |\psi'_t|^2 d\theta = \int_{S^1} \tilde{\nu}_t^2(\theta) |\psi'_t| d\theta = \int_{S^1} \tilde{\nu}_t^2(\theta) d\theta$$

which completes the proof.  $\square$

**Corollary 9.3.** *We have*

$$S_{[0,1]}(\tilde{\rho}) - S_{[0,1]}(\rho) = \frac{1}{4} \int_0^1 \int_{S^1} e^{2i\theta} \mathcal{S}\psi_t(e^{i\theta}) \rho_t(\theta) d\theta dt + \frac{1}{8} (\log \tilde{g}'_1(0) - 1). \quad (9.2)$$

*Proof.* The formula follows by integrating (9.1), using  $\int_0^1 |\rho_t| dt = 1$  and  $\int_0^1 |\tilde{\rho}_t| dt = \log \tilde{g}'_1(0)$ .  $\square$

*Remark.* The Brownian loop measure is a conformally invariant sigma finite measure on Brownian loops in the plane [38, 39]. The conformal distortion formula of Theorem 1.6 can be interpreted in terms of Brownian loop measures: namely,  $S_+(\rho) - S_+(\tilde{\rho})$  also equals the difference between the Brownian loop measure of those loops in  $\mathbb{D}$  that intersect both  $K_1$  and  $\mathbb{D} \setminus U$  and the measure of those loops in  $\mathbb{D}$  that intersect both  $\tilde{K}_1$  and  $\mathbb{D} \setminus \tilde{U}$ . We will prove this in a forthcoming paper with Lawler. For now we just remark that this interpretation immediately implies that the energy difference depends only on the hulls at time 1 and not on the foliation, a fact that is not immediately apparent from (9.2).

## 10 Further comments and open problems

We will now indicate further implications and interpretations as well as open problems suggested by our results.

### Random conformal geometry and mating-of-trees

We begin by discussing connections to ideas in random conformal geometry, see in particular [21, 44], which served as inspiration for the formulation of our main result, Theorem 1.2. We will also speculate on how to formulate stochastic versions of some of the results obtained in this paper but we do not make rigorous statements here.

Let  $(B_t)_{t \in \mathbb{R}}$  be the rotation-invariant two-sided Brownian motion on  $S^1$  and suppose  $\kappa \geq 0$ . Whole-plane  $\text{SLE}_\kappa$  is the random (whole-plane) Loewner chain generated by the measure  $\rho(d\theta dt) = \delta_{B_{\kappa t}}(\theta) dt \in \mathcal{N}$ , where  $\delta_{B_{\kappa t}}$  is the Dirac mass at  $B_{\kappa t}$  and  $dt$  is Lebesgue measure on  $\mathbb{R}$ . When  $\kappa \geq 8$ , the hull is generated by a space-filling curve growing in  $\mathbb{C}$  from  $\infty$  towards 0, see [53]. The Loewner-Kufarev energy is infinite in the case  $\text{SLE}$ , since a Dirac mass is not an absolutely continuous measure. However, an easy generalization of the main result of [8] shows that the Loewner-Kufarev energy is the large deviation rate function of whole-plane  $\text{SLE}_\infty$ . Roughly speaking, as  $\kappa \rightarrow \infty$ ,

$$\begin{aligned} \mathbb{P}\{\text{The complements of a whole-plane } \text{SLE}_\kappa \text{ process stay close to } (D_t)_{t \in \mathbb{R}}\} \\ \approx \exp(-\kappa S(\rho)) \end{aligned} \quad (10.1)$$

where  $(D_t)_{t \in \mathbb{R}}$  is the family of domains of any deterministic whole-plane Loewner chain with driving measure  $\rho$ . See [8, Thm. 1.2] for a precise statement in the unit disk setup. On the other hand, the Loewner energy  $I^L$  of a Jordan curve can be expressed in terms of Dirichlet energies, see (1.1), and it is believed to be the large deviation rate function of the  $\text{SLE}_{0+}$  loop: as  $\kappa \rightarrow 0+$ ,

$$\mathbb{P}\{\text{SLE}_\kappa \text{ loop stays close to } \gamma\} \approx \exp(-I^L(\gamma)/\kappa) \quad (10.2)$$

where  $\gamma$  is a given deterministic Jordan curve. See [48, 70] for precise statements in chordal settings. Furthermore, it is well-known that the Dirichlet energy is the large deviation rate function for the Gaussian free field, see [18, Thm. 3.4.12].

$\text{SLE}$  processes enjoy a duality property with respect to replacing  $\kappa$  by  $16/\kappa$  [20, 42, 73]. Roughly speaking, an  $\text{SLE}_\kappa$  curve describes locally the outer boundary of an  $\text{SLE}_{16/\kappa}$  hull when  $\kappa < 4$ . The mating-of-trees theorem [21] further explores this duality and the interplay with an underlying Liouville quantum gravity field. (See also, e.g., [7] and the references therein for some recent progress in this direction.) An impressionistic picture is as follows. A pair of “mated” space-filling trees whose branches are formed by  $\text{SLE}_\kappa$ -like curves are constructed as flowlines of a Gaussian field and a coupled whole-plane chordal space-filling  $\text{SLE}_{16/\kappa}$  curve from  $\infty$  to  $\infty$  traces the interface between the pair of trees. One can speculate that the union of the pair of trees degenerate to a foliation as  $\kappa \rightarrow 0+$  (and  $16/\kappa \rightarrow +\infty$ ) and the mating-of-trees coupling suggests that the large deviation rate functions of the coupled processes should match in this limit. Combining this with the heuristic formulas (10.1) and (10.2) led us to guess Theorem 1.2 where the factor 16 is consistent with the  $\text{SLE } \kappa \leftrightarrow 16/\kappa$  duality.

However, the setup of [21] uses whole-plane chordal Loewner evolution so the space-filling  $\text{SLE}$  there runs from  $\infty$  to  $\infty$ , whereas the whole-plane radial  $\text{SLE}$  runs from  $\infty$  to 0. A

coupling of radial SLE with the Gaussian free field is described in [44], but we are not aware of results similar to the mating-of-trees theorem in the current literature for the setting we work in. Our results, in particular Theorem 1.1, Theorem 1.2, and Proposition 1.5 provide analytical evidence for a “radial mating-of-trees” theorem.

Using the dictionary we outlined in [68, Sec. 1.3 and 3.4], we may speculate that the following statements should hold. For small  $\kappa > 0$ , run a space filling whole-plane  $\text{SLE}_{16/\kappa}$  on an appropriate “quantum sphere” assumed to be independent of the SLE. (A quantum sphere can be described by a Gaussian free field with additional logarithmic singularities and an attached transformation law.) If the SLE process is run up to time  $t$ , the unvisited part and visited part of the quantum sphere form two independent “quantum disks” (which are also defined starting from a Gaussian free field) conformally welded along the frontier of the whole-plane  $\text{SLE}_{16/\kappa}$ , which itself is an  $\text{SLE}_\kappa$ -type loop. The two “quantum disks” are each decorated with an independent radial  $\text{SLE}_{16/\kappa}$  curve, and the two  $\text{SLE}_{16/\kappa}$  curves are independent conditionally on the position of the tip at time  $t$ . Varying  $t$ , we expect the separating  $\text{SLE}_\kappa$ -type loops to form a (fractal) foliation-like family that sweeps out the twice punctured sphere. This foliation-like process also encodes the whole-plane  $\text{SLE}_{16/\kappa}$  evolution. The real part of the complex field in Proposition 1.5 reflects the metric/measure structure of the quantum sphere, whereas the imaginary part encodes the fractal foliation-like process, hence the trajectory of the space filling SLE.

### Whole-plane radial SLE Reversibility

Let us next comment on the reversibility of the Loewner-Kufarev energy, Theorem 1.3. An analogous result about the reversibility of the Loewner energy can be explained (and proved) by  $\text{SLE}_{0+}$  large deviations considerations combined with the fact that chordal SLE is reversible [74] for small  $\kappa$ , see [70]. However, it is not known whether whole-plane  $\text{SLE}_\kappa$  for  $\kappa > 8$  is reversible. (For  $\kappa \leq 8$ , reversibility was established in [44, 75].) Therefore Theorem 1.3 cannot be predicted from the SLE point of view given currently known results, but it does on the other hand suggest that reversibility for whole-plane radial SLE might hold for large  $\kappa$  as well.

### Whole-plane chordal Loewner-Kufarev energy

One can ask about a version of our results in chordal settings. The most natural one is the whole-plane chordal version, where the family of curves all pass through  $\infty$  and foliate the plane  $\mathbb{C}$  as  $t$  ranges from  $-\infty$  to  $\infty$ , as in the mating-of-trees theorem. When  $\kappa \rightarrow \infty$ , the whole-plane chordal  $\text{SLE}_\kappa$  Loewner chain converges to the constant identity map for all time  $t$ . Therefore, renormalization is needed to obtain both a non-trivial limit and a meaningful large deviation result. (This is one reason to work in the radial setup here as well as in [8].) One way to proceed is to conformally map the two punctures (0 and  $\infty$ ) in our whole-plane (radial) setup to  $y$  and  $\infty$  then let  $y \rightarrow \infty$ . The third complex degree of freedom (ranging in a non compact space) in the choice of conformal automorphism of the Riemann sphere needs to be chosen carefully to obtain a clean statement.

### Foliation loops in Weil-Petersson Teichmüller space

Recall that any quasicircle  $\gamma$  separating 0 from  $\infty$  can be identified with an element in universal Teichmüller space  $T(1) \simeq \text{Möb}(S^1) \backslash \text{QS}(S^1)$  via (the equivalence class of) its welding homeomorphism  $\phi_\gamma = h^{-1} \circ f|_{S^1}$ . The subspace  $T_0(1)$  corresponding to Weil-Petersson

quasicircles has an infinite dimensional Kähler-Einstein manifold structure equipped with the Weil-Petersson metric, see [67]. Theorem 1.1 shows that any  $\rho$  with  $S(\rho) < \infty$  generates a foliation  $(\gamma_t)_{t \in \mathbb{R}}$  of Weil-Petersson quasicircles which can be considered as elements of  $T_0(1)$  via their welding homeomorphisms. So the Loewner evolution of  $\rho$  generates a dynamical process on  $T_0(1)$ . Theorem 1.4 shows that there exists such a family (obtained by interpolating by equipotentials) passing through any given element of  $T_0(1)$ . It is not too hard to show that it corresponds to a continuous loop  $t \mapsto [\phi_{\gamma_t}]$  in  $T_0(1)$  starting and ending at the origin  $[\text{Id}_{S^1}]$ . We believe the class of loops in  $T_0(1)$  coming from measures with  $S(\rho) < \infty$  may be of interest to study. For instance, an interesting question concerns how the length of a loop is related to  $S(\rho)$ . The example in Section 4.3 shows that one can have  $S(\rho) > 0$  while the corresponding loop is trivial, so one can only hope for an upper bound in terms of  $S(\rho)$ . One can further ask for properties of the minimal energy (equipotential) path to a given element. Another question concerns how transformations on  $\rho$  affects a path in  $T_0(1)$ , and vice versa. We are currently investigating these and related questions.

### Unitarizing measures on $\text{Homeo}(S^1)$

Evolutions of random homeomorphisms of  $S^1$  have been studied by Airault, Malliavin and collaborators as part of a program to find certain unitarizing probability measures on the group of homeomorphisms of the unit circle that provide a unitary representation of the Virasoro algebra, see, e.g., [2–4]. See also [9] for analytic treatment of the conformal welding problem in a similar context involving rough random homeomorphism. It is shown in [2] that the Berezin quantization on the homogeneous space  $T_0(1)$  can be carried out given the existence of a unitarizing probability measure satisfying an integration by parts formula. In this quantization scheme, the Hilbert space consists of holomorphic square integrable sections over the trivial line bundle with respect to the measure and the quantized operators act unitarily on this Hilbert space. Kontsevich and Suhov alluded to potential links between SLEs and unitarizing measures in [34, Sec. 2.5.2]. This link is supported by the fact that the Loewner energy is the Kähler potential (which plays a central role in the Berezin quantization) on  $T_0(1)$  and recent developments establishing the connection between the Loewner energy and SLEs [71]. The results in the present paper may provide another angle of attack of this circle of problems from a dynamical point of view.

### “Foliations” in hyperbolic 3-space

Since Möbius transformations of  $\hat{\mathbb{C}}$  extend to isometries of the hyperbolic 3-space  $\mathbb{H}^3$  (whose boundary at  $\infty$  is identified with the Riemann sphere  $\hat{\mathbb{C}}$ ) and being a Weil-Petersson quasicircle is a Möbius invariant property, it is natural to try to relate our foliations by Weil-Petersson quasicircles to objects in  $\mathbb{H}^3$ . In [6], it is shown that every Jordan curve bounds at least one minimal disk in  $\mathbb{H}^3$ , and [11] shows that a Jordan curve is a Weil-Petersson quasicircle if and only if any such minimal disk in  $\mathbb{H}^3$  has finite total curvature. For example, when  $\gamma$  is a circle, the unique minimal surface is the totally geodesic surface, namely the hemisphere bounded by  $\gamma$ . Although the minimal disk for a given boundary curve may not be unique in general, [60, Thm. B] and a bound on the quasiconformal constant of the Weil-Petersson quasicircle together imply uniqueness when the Loewner energy of  $\gamma$  is small enough. Hence, for small enough  $S(\rho)$ , Theorem 1.1 and Corollary 8.7

imply that the foliation  $(\gamma_t)_{t \in \mathbb{R}}$  uniquely determines a family of minimal disks of finite total curvature  $(\Sigma_t)_{t \in \mathbb{R}}$  in  $\mathbb{H}^3$ , where  $\Sigma_t$  is bounded by the leaf  $\gamma_t$ . We believe that the family  $(\Sigma_t)_{t \in \mathbb{R}}$  forms a smooth foliation of  $\mathbb{H}^3$  in this case. Such families of minimal surfaces seem interesting to study in their own right and, by embedding into a dynamical family, could be useful in the analysis of minimal surfaces in  $\mathbb{H}^3$  bounded by Weil-Petersson quasicircles and in deriving a rigorous  $\text{AdS}_3/\text{CFT}_2$  holographic principle.

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