

Splitting Scheme and Convergence of Stochastic Loewner Curves

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July 2021

Abstract

In this paper we study the approximations of the SLE_κ traces via the Ninomiya-Victoir splitting scheme. We prove a strong convergence in probability *w.r.t.* the *sup*-norm to the distance between the SLE trace and the output of the Ninomiya-Victoir splitting scheme when applied in the context of the Loewner Differential Equation. We show also that an L^p convergence of the scheme can be achieved under a set of assumptions. In the last section we show the uniform convergence of the approximation of the SLE trace obtained using a different scheme that is based on the linear interpolation of the Brownian driver.

1 Introduction

The Loewner equation was introduced by Charles Loewner in 1923 and it was one of the important ingredients in the proof of the Bieberbach Conjecture that was done by Louis de Branges, years later in 1985. In 2000, Oded Schramm introduced a stochastic version of the Loewner equation. The stochastic version of the Loewner evolution, i.e. the Schramm-Loewner evolution, SLE_κ , generates a one parameter family of random fractal curves that are proved to describe scaling limits of a number of discrete models that appear in two-dimensional statistical physics.

In the last years, results on numerical schemes to approximate the SLE_κ traces, along with mathematical proofs of their convergence, appeared in the body of literature on the topic. For example, V. Beffara used a Euler Scheme to produce approximations of the SLE_κ hulls.

There are various versions of Loewner equations. This article focuses on the forward Loewner equations defined in the upper half-plane \mathbb{H} and a fixed time

interval $[0, T]$

$$\partial_t g_t(z) = \frac{2}{g_t(z) - \lambda(t)}, \quad (1.1)$$

with the initial condition $g_0(z) = z$, for all $z \in \mathbb{H}$ and the continuous driving force $\lambda : [0, T] \rightarrow \mathbb{R}$.

The family of maps $(g_t)_{0 \leq t \leq T}$ is called the Loewner chain. For all $z \in \mathbb{H}$, the solution of the above forward Loewner equation is uniquely defined up to $T_z = \inf\{t \geq 0, g_t(z) = \lambda(t)\}$. Over time, the set $K_t = \{z \in \mathbb{H}, T_z \leq t\}$, called the hull, grows. It is also known that for all $t \in [0, T]$, $g_t : \mathbb{H} \setminus K_t \rightarrow \mathbb{H}$ is the unique conformal map satisfying the hydrodynamic normalization at ∞

$$\lim_{z \rightarrow \infty} [g_t(z) - z] = 0. \quad (1.2)$$

In addition, we work with Loewner chains $(g_t)_{0 \leq t \leq T}$ parametrized by upper half-plane capacity

$$g_t(z) = z + \frac{2t}{z} + o(1/|z|), \text{ as } |z| \rightarrow \infty, \quad (1.3)$$

where by ([1], *Lem.* 4.1), the coefficient of the z -term is 1 and each coefficient a_k of the term z^{-k} , $k \in \mathbb{N}_+$ is real.

We are particularly interested in the case when the Loewner chain $(g_t)_{0 \leq t \leq T}$ is generated by a curve $\gamma : [0, T] \rightarrow \mathbb{H} \cup \{\lambda(T)\}$. In other words, the domain of $g_t(z)$ is the unbounded component of $\mathbb{H} \setminus \gamma([0, t])$. By ([2], *Thm.* 4.1), this is equivalent to the existence and continuity in $0 < t < T$ of

$$\gamma(t) = \lim_{\epsilon \rightarrow 0^+} g_t^{-1}(\lambda(t) + i\epsilon). \quad (1.4)$$

Even though the piecewise linear interpolation method is independent to our main topic on splitting scheme, let us briefly discuss that idea to simulate the driving force $\lambda(t)$ and its corresponding hull K_t for all $t \in [0, T]$. The interpolation algorithm is based on the following observations. Fix $s > 0$, let $(\tilde{g}_t)_{0 \leq t \leq T}$ be the Loewner chain generated by the continuous driving force $\tilde{\lambda}(t) = \lambda(s + t)$ with $0 \leq t \leq T - s$. In fact, this solution admits the form

$$\partial_t g_{s+t} \circ g_s^{-1}(z) = \frac{2}{g_{s+t} \circ g_s^{-1}(z) - \lambda(s+t)} = \frac{2}{g_{s+t} \circ g_s^{-1}(z) - \tilde{\lambda}(t)}, \quad (1.5)$$

and $g_s \circ g_s^{-1}(z) = z$ with $z \in \mathbb{H} \setminus K_s$. The uniqueness property of Loewner chains implies that $\tilde{g}_t(z) = g_{s+t} \circ g_s^{-1}(z)$. And we denote \tilde{K}_t to be the hull associated

with the Loewner chain \tilde{g}_t , indeed

$$\mathbb{H} \cap g_s(K_{s+t}) = \tilde{K}_t \text{ and } K_{s+t} = K_s \cup g_s^{-1}(\tilde{K}_t). \quad (1.6)$$

Hence, computing K_s and g_s^{-1} and \tilde{K}_t would enable us to compute \tilde{K}_{s+t} .

There are methods interpolating $\lambda(t)$ with discretized force $\lambda^n(t)$. Using square-root ([11], *Sec. 2.*) or linear interpolation, there is usually an easier form of $\lambda^n(t)$, which endows computational convenience. The driving force $\lambda^{(n)}$ in the context of square-root and linear interpolation is written below

$$\lambda_{square-root}^n(t) := \sqrt{n}(\lambda(t_{k+1}) - \lambda(t_k))\sqrt{t - t_k} + \lambda(t_k) \text{ on } [t_k, t_{k+1}], \quad (1.7a)$$

$$\lambda_{linear}^n(t) := n(\lambda(t_{k+1}) - \lambda(t_k))(t - t_k) + \lambda(t_k) \text{ on } [t_k, t_{k+1}]. \quad (1.7b)$$

We will briefly discuss the linear interpolation method in the last section.

Acknowledgements We would like to acknowledge Lukas Schoug from the University of Cambridge for his valuable comments and for reading preliminary versions of the manuscript. VM acknowledges the support of the NYU-ECNU Mathematical Institute at NYU Shanghai.

2 Splitting scheme

In this section we propose an algorithm to simulate SLE_κ with $\kappa \neq 8$, which are *stochastic* Loewner chains generated by Brownian motions.

Throughout our paper, we work with $(\Omega, \mathcal{F}, \mathbb{P})$ that is a standard probability space, where the Brownian motion is defined.

The motivation to study SLE_κ comes from Statistical Physics. In ([17], *Sec. 1.1*) it is shown that the scaling limit of loop erased random walk, with the loops erased in a chronological order, converges in the scaling limit to SLE_κ with $\kappa = 2$. Moreover, other two dimensional discrete models from statistical mechanics including Ising model cluster boundaries, Gaussian free field interfaces, percolation on the triangular lattice at critical probability, and uniform spanning trees were proved to converge in the scaling limit to SLE_κ for values of $\kappa = 3$, $\kappa = 4$, $\kappa = 6$, and $\kappa = 8$ respectively in the series of works by Chelkak, Duminil-Copin, Hongler, Izyurov, Smirnov, Schramm, and Lawler.

SLE_κ traces are generated by the Loewner chains driven by Brownian motions $\sqrt{\kappa}B_t$ with $t \in [0, 1]$

$$\partial_t g_t(z) = \frac{2}{g_t(z) - \sqrt{\kappa}B_t}, \quad (2.1)$$

with $g_0(z) = z$ for all $z \in \mathbb{H} \setminus K_t$. In the following discussion of SLE_κ , we focus on the case where the hulls K_t are generated by curves $\gamma : [0, 1] \rightarrow \mathbb{H} \cup \{0\}$. Throughout the proof we will use the backward Loewner equation which is related to the forward version *Eqn.* (2.1) and admits the form

$$\partial_t h_t(z) = \frac{-2}{h_t(z) - \sqrt{\kappa} B_{1-t}}, \quad (2.2)$$

with $h_0(z) = z$. This backward equation generates a Loewner curve $\eta : [0, 1] \rightarrow \mathbb{H} \cup \{0\}$. Notice that $g_t(z)$ and $h_t(z)$ are both driven by Brownian motions with different time directions. In fact, there is a correspondence ([13], *Sec.* 1.1) between the dynamics constrained by *Eqn.* (2.1) and *Eqn.* (2.2): The random set $\eta([0, 1])$ has the same law as the chordal SLE_κ trace $\gamma([0, 1])$ modulo a real scalar shift $\sqrt{\kappa} B_{T=1}(\omega)$ with $\omega \in \Omega$. For convenience, we call $\eta(t)$ the shifted Loewner curve.

There are many schemes to simulate SLE_κ traces. This article focuses on the Ninomiya-Victoir scheme.

At this point, some new notations are necessary before we formally present the Ninomiya-Victoir scheme. If we set $\hat{g}_t(z) := g_t(z) - \sqrt{\kappa} B_t$ for all $z \in \mathbb{H} \setminus K_t$, from the existence and continuity of $\gamma(t)$ discussed in *Sec.* 1, we write

$$\gamma(t) = \lim_{y \rightarrow 0^+} g_t^{-1}(\sqrt{\kappa} B_t + iy) = \lim_{y \rightarrow 0^+} \hat{g}_t^{-1}(iy), \quad (2.3)$$

and the stochastic differential equation

$$\begin{aligned} d\hat{g}_t(z) &= \frac{2}{\hat{g}_t(z)} dt - \sqrt{\kappa} dB_t, \\ \hat{g}_0(z) &= z, \end{aligned} \quad (2.4)$$

with $z \in \mathbb{H} \setminus K_t$. Remember that the Loewner curve $\eta(t)$ has the same law as $\gamma(t)$ up to a translation $\sqrt{\kappa} B_{T=1}(\omega)$ with $\omega \in \Omega$. In fact, we will simulate the Loewner curve $\eta(t)$ instead of $\gamma(t)$ for convenience, since the former curve preserves statistical properties of the latter curve. Let us consider

$$\begin{aligned} dZ_t &= -\frac{2}{Z_t} dt + \sqrt{\kappa} dB_t, \\ Z_0 &= iy, \end{aligned} \quad (2.5)$$

where $y > 0$ is taken sufficiently small and we avoid the choice $Z_0 = 0$, due to the singularity at 0 inherent in the boundary condition of *Eqn.* (2.5). The format of (2.5) follows from $Z_t(z) := h_t(z) - \sqrt{\kappa} B_t$, for all $z \in \mathbb{H}$ (see [3], *Eqn.* 6.5).

Then with the choice of initial value $Z_0 = iy$, we employ the Ninomiya-Victoir splitting scheme to derive a numerical solution.

Definition 2.1. *Ninomiya-Victoir Scheme*

Consider n -dimensional SDE on \mathbb{R}_+ with the form

$$\begin{aligned} dW_t &= L_0(W_t)dt + L_1(W_t)dB_t, \\ W_0 &= \xi, \end{aligned} \quad (2.6)$$

where $\xi \in \mathbb{R}^n$ and $L_i : \mathbb{R}^n \rightarrow \mathbb{R}^n$ are smooth vector fields. For all $t \in \mathbb{R}_+$ and $x \in \mathbb{R}^n$, let the flow $\exp(tL_i)x$, $i = 1, 2$, denote the unique solution at time $u = 1$ to the ODE

$$\begin{aligned} \frac{dy}{du} &= tL_i(y), \\ y(0) &= x. \end{aligned} \quad (2.7)$$

For a fixed iteration step $n \in \mathbb{N}$, we choose an arbitrary, possibly non-uniform, partition $\{t_0 = 0, t_1, \dots, t_n = 1\}$ with step-size $h_k = t_{k+1} - t_k$. We approximate a numerical solution $\{\widetilde{W}_{t_k(t)}\}_{0 \leq k \leq n}$ in the sense that $\widetilde{W}_0 = \xi$ and

$$\widetilde{W}_{t_{k+1}} = \exp\left(\frac{1}{2}h_k L_0\right) \exp\left(B_{t_k(t), t_{k+1}} L_1\right) \exp\left(\frac{1}{2}h_k L_0\right) \widetilde{W}_{t_k(t)}, \quad (2.8)$$

for all $k = 0, 1, \dots, n$ and where $B_{t_k(t), t_{k+1}}$ is the abbreviation for $B_{t_{k+1}} - B_{t_k(t)}$. In fact, the approximation $\{\widetilde{W}_{t_k(t)}\}_{0 \leq k \leq n}$ enjoys an integral form between every two discretization points

$$\widetilde{W}_t = \xi + \frac{1}{2} \int_0^t L_0(\widetilde{W}_s^{(2)})ds + \int_0^t L_1(\widetilde{W}_s^{(1)})dB_s + \frac{1}{2} \int_0^t L_0(\widetilde{W}_s^{(0)})ds, \quad (2.9)$$

where the above three discretization processes defined on each time interval $[t_k(t), t_{k+1}]$ admit the form

$$\begin{aligned} \widetilde{W}_t^{(0)} &:= \exp\left(\frac{1}{2}(t - t_k(t))L_0\right) \widetilde{W}_{t_k(t)}, \\ \widetilde{W}_t^{(1)} &:= \exp\left(B_{t_k(t), t} L_1\right) \widetilde{W}_{t_{k+1}}^{(0)}, \\ \widetilde{W}_t^{(2)} &:= \exp\left(\frac{1}{2}(t - t_k(t))L_0\right) \widetilde{W}_{t_{k+1}}^{(1)}. \end{aligned} \quad (2.10)$$

Looking back to our Loewner equation, we write $L_0(z) = -2/z$ and $L_1(z) =$

$\sqrt{\kappa}$. Hence, by ([3], *Thm.* 6.2) the following form is immediate

$$\begin{aligned}\exp(tL_0)z &= \sqrt{z^2 - 4t}, \\ \exp(tL_1)z &= z + \sqrt{\kappa}t.\end{aligned}\tag{2.11}$$

Given the above arbitrary partition $\{t_0 = 0, t_1, \dots, t_n = 1\}$, we could formulate an approximated solution $\{\tilde{Z}_{t_k(t)}\}_{0 \leq k \leq n}$ via the Ninomiya-Victoir splitting scheme

$$\tilde{Z}_{t_{k+1}} := \sqrt{\left(\sqrt{\tilde{Z}_{t_k(t)}^2 - 2h_k} + \sqrt{\kappa}B_{t_k(t), t_{k+1}}\right)^2 - 2h_k}, \tag{2.12}$$

with the initial value $\tilde{Z}_0 = iy$ specified at each n^{th} iteration.

3 Strong convergence in probability

In the following, we use $\|\cdot\|_{[0,1],\infty}$ for the sup-norm on the interval $[0,1]$. In this section we give a strong convergence in probability to the decay rate of the $\|\cdot\|_{[0,1],\infty}$ norm (*i.e. supremum norm*) between the original Loewner curve and our scheme. In the next section, we are going to alternatively discuss the general formalism to prove the L^p convergence of our splitting scheme, which is the same object *w.r.t.* a different topology.

Definition 3.1. *Let $Z_t(iy_n)$ be the solution to Eqn. (2.5) started from $iy_n \in \mathbb{H}$, and $\tilde{Z}_t(iy_n)$ be its approximation following Ninomiya-Victoir Scheme, and let $\eta(t)$ be the shifted Loewner curve defined above.*

Notice that at each iteration step $n \in \mathbb{N}$, we specify an initial condition $y \in \mathbb{R}_+$ and let the approximated sample paths $(\tilde{Z}_t(iy))_{0 \leq t \leq 1}$ evolve according to the backward Loewner equation (2.5). To ensure a decent $\|\cdot\|_{[0,1],\infty}$ convergence result, we not only require the mesh of the partition tends to 0, but also choose a sequence $\{y_n\} \subset \mathbb{R}_+$ so that $y_n \rightarrow 0^+$ strictly monotonically.

Remark 3.2. *Notice that we cannot let $y_n \equiv y$ for some $y > 0$, otherwise the convergence pattern breaks down and hence strict monotonicity of $\{y_n\}$ is necessary. On the other hand, the decay rate of $\{y_n\}$ should not be too fast to destroy the probability inequality w.r.t. the $\|\cdot\|_{[0,1],\infty}$ norm, which we will see in the following context.*

In this section, we manually set $y_n = n^{-1/2}$ for all $n \in \mathbb{N}$. This choice of $\{y_n\}$ actually satisfies the requirements in the above *Rmk.* 3.2 for the initial conditions.

For now we choose a prior uniform partition \mathcal{D}_n on $[0,1]$ at each step $n \in \mathbb{N}$.

To reach our main object, we make the following observation.

Definition 3.3. For all $t \in [0, 1]$, given an arbitrary uniform partition \mathcal{D}_n , we define $\{t_k(t), t_{k+1}(t)\} \subset \mathcal{D}_n$ to be the neighboring two points in the partition \mathcal{D}_n between which t resides, i.e. $t_k(t) \leq t < t_{k+1}(t)$.

We are now reaching our main object: an upper bound for the probability of $\|\cdot\|_{[0,1],\infty}$ norm of $(\eta(t) - \tilde{Z}_t(iy_n))_{0 \leq t \leq 1}$ to be small in the sense given by the following theorem, which is the main result of the paper

Theorem 3.4. Let $\eta(t)$ be the backward SLE trace for $\kappa \neq 8$. There exist two non-increasing functions $\varphi_i : \mathbb{Z}_+ \rightarrow \mathbb{R}_+$ such that $\lim_{n \rightarrow \infty} \varphi_i(n) = 0^+$ with $i = 1, 2$. If the mesh $\|D_n\| \rightarrow 0^+$ with $n \rightarrow \infty$, faster than a proper rate $\|D_n\| = o(n^{-3})$, then

$$\mathbb{P}\left(\left\|\eta(t) - \tilde{Z}_t(iy_n)\right\|_{[0,1],\infty} \leq \varphi_1(n)\right) \geq 1 - \varphi_2(n). \quad (3.1)$$

To prove this theorem, we use

$$\begin{aligned} \left|Z_t(iy_n) - \tilde{Z}_t(iy_n)\right| &\leq \left|Z_t(iy_n) - Z_{t_k(t)}(iy_n)\right| \\ &\quad + \left|Z_{t_k(t)}(iy_n) - \tilde{Z}_{t_k(t)}(iy_n)\right| + \left|\tilde{Z}_{t_k(t)}(iy_n) - \tilde{Z}_t(iy_n)\right|, \end{aligned} \quad (3.2a)$$

in addition to estimate

$$\left|\eta(t) - \tilde{Z}_t(iy_n)\right| \leq |\eta(t) - Z_t(iy_n)| + \left|Z_t(iy_n) - \tilde{Z}_t(iy_n)\right|. \quad (3.2b)$$

We study *Ineq. (3.3a)* and *Ineq. (3.3b)*. In the following, we investigate *Ineq. (3.3a)*. This inequality follows from the lemma below.

Lemma 3.5. ([4], *Thm. 3.4.2*) There exist $c_1, c_2 > 0$ such that if we consider the event

$$E'_{n,1} := \left\{ \text{osc}(\sqrt{\kappa}B_t, \frac{1}{n}) \leq c_1 \sqrt{\frac{\log(n)}{n}} \right\}, \quad (3.3)$$

then we have

$$\mathbb{P}(E'_{n,1}) \geq 1 - \frac{c_2}{n^2}. \quad (3.4)$$

Lemma 3.6. ([11], *Eqn. 21.*) There exist $c_3, c_4 > 0$ and $\beta_1 \in (0, 1)$ such that if we consider the event

$$E''_{n,1} := \left\{ |\partial_z \widehat{g}_t^{-1}(iv)| \leq c_3 \cdot v^{-\beta_1} \text{ for all } t \in [0, 1] \text{ and } v \in [0, \frac{1}{\sqrt{n}}] \right\}, \quad (3.5)$$

then we have

$$\mathbb{P}(E''_{n,1}) \geq 1 - \frac{c_4}{n^{c_3/2}}. \quad (3.6)$$

We have an estimate to the first term to *Ineq.* (3.3a) with the form

$$\begin{aligned} |Z_t(iy_n) - Z_{t_k(t)}(iy_n)| &\leq |Z_t(iy_n) - \eta(t)| + |Z_{t_k(t)}(iy_n) - \eta(t_k(t))| \\ &\quad + |\eta(t) - \eta(t_k(t))|. \end{aligned} \quad (3.7)$$

To proceed our discussion, we remind our readers of the following definition.

Definition 3.7. A continuous function $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is called a subpower function if it is non-increasing and satisfies

$$\lim_{x \rightarrow \infty} x^{-\nu} \phi(x) = 0, \text{ for all } \nu > 0. \quad (3.8)$$

Remark 3.8. A typical subpower function is $\phi(x) = (\log x)^\alpha$, for all real $\alpha > 0$.

With the notion of a subpower function, we have the following result.

Proposition 3.9. Let $\beta_1 \in (0, 1)$. There exists a subpower function $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that if we consider the event

$$E_{n,1}^* := \left\{ \|\eta(t) - \eta(t_k(t))\|_{[0,1],\infty} \leq \frac{2\phi(\sqrt{n})}{(1-\beta_1)n^{(1-\beta_1)/2}} \right\}, \quad (3.9)$$

and if $\|\mathcal{D}_n\| \leq n^{-1}$, then

$$\mathbb{P}(E_{n,1}^*) \geq 1 - \frac{c_2}{n^2} - \frac{c_4}{n^{c_3/2}}. \quad (3.10)$$

Proof. In the proof we omit the bracket in $t_k(t)$ and simply write this term as $t_k(t)$, which will be clear from the context. In the proof, we follow the statement in ([11], Lem. 2.5) with some obvious changes of notations. Since $\eta([0, 1])$ has identical distribution to $\gamma([0, 1])$ modulo a scalar shift $\sqrt{\kappa}B_1$, it is immediate that $\mathbb{P}(E_{n,1}^*)$ is equal to the probability of the event with an expression which we substitute $\gamma(t)$ (and resp. $\gamma(t_k(t))$) into $\eta(t)$ (and resp. $\eta(t_k(t))$). By ([11], Lem. 2.5) there exists a subpower function $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that, on the event $E'_{n,1} \cap E''_{n,1} \subset \Omega$, provided $0 \leq t - t_k(t) \leq n^{-1}$ for all $t \in [0, 1]$, we have

$$\begin{aligned} |\gamma(t) - \gamma(t_k(t))| &\leq \phi(\sqrt{n}) \left(\int_0^{n^{-1/2}} |\partial_z \widehat{g}_t^{-1}(ir)| dr + \int_0^{n^{-1/2}} |\partial_z \widehat{g}_t^{-1}(ir)| dr \right) \\ &\leq \phi(n) \cdot \frac{2}{1-\beta_1} n^{-(1-\beta_1)/2}, \end{aligned} \quad (3.11)$$

where $\beta_1 \in (0, 1)$. Hence $\mathbb{P}(E_{n,1}^*) \geq \mathbb{P}(E'_{n,1} \cap E''_{n,1})$ and the conclusion follows. \square

To finish the evaluation of *Eqn.* (3.8) and then finishing the first term in

Ineq. (3.3a), we have the following result

Proposition 3.10. *Let $\epsilon_0 \in (0, 1)$. If we choose $M_n = n^{(1-\epsilon_0)/4}$ and consider the event*

$$E_{n,1}^{**} := \left\{ \|Z_t(iy_n) - \eta(t)\|_{[0,1],\infty} \leq M_n \cdot y_n^{1-\epsilon_0} = \frac{1}{n^{(1-\epsilon_0)/4}} \right\}, \quad (3.12)$$

then there exists $\epsilon_n \rightarrow 0^+$ monotonically such that

$$\mathbb{P}(E_{n,1}^{**}) \geq 1 - \epsilon_n. \quad (3.13)$$

Proof. It is stated in ([3], Lem. 6.7) that there exists $\epsilon_0 \in (0, 1)$ so that *almost surely*, we have

$$\sup_{t \in [0,1]} |Z_t(iy_n) - \eta(t)| \leq C'_1(\omega) \cdot y_n^{1-\epsilon_0}, \quad (3.14)$$

where $C'_1(\omega)$ is *almost surely* finite. Guaranteed with the existence of at least one $C'_1(\omega) \in \mathbb{R}_+$ for almost all $\omega \in \Omega$, we define the collection $\mathcal{A}(\omega) \subset \mathbb{R}_+$ for those $\omega \in \Omega$ with which there exists at least one $C'_1(\omega)$ satisfying Ineq. (3.15). Notice that the collection $\mathcal{A}(\omega)$ is defined except for a *measure-zero* event. The well-ordering principle tells us that $\mathcal{A}(\omega)$ has a lower bound. Hence it is legitimate to define

$$C_1(\omega) := \inf \mathcal{A}(\omega), \quad (3.15)$$

which is *almost surely* defined. Hence, we could simply assume $C(\omega)$ exists and is finite everywhere via subtracting a *measure-zero* event from Ω . With our choice of $M_n \rightarrow \infty$, there exists $\epsilon_n \in [0, 1]$ with $\epsilon_n := \min\{\epsilon_1, \dots, \epsilon_{n-1}, \mathbb{P}(\Omega - E_{n,1}^{**})\}$ such that

$$\mathbb{P}\left(\sup_{t \in [0,1]} |Z_t(iy_n) - \eta(t)| \leq M_n \cdot y_n^{1-\epsilon_0}\right) \geq 1 - \epsilon_n. \quad (3.16)$$

On the event $E_{n,1}^{**} \subset \Omega$, we know then

$$\sup_{t \in [0,1]} |Z_t(iy_n) - \eta(t)| \leq C_1(\omega) \cdot y_n^{1-\epsilon_0} \text{ and } \sup_{t \in [0,1]} |Z_t(iy_n) - \eta(t)| \leq M_n \cdot y_n^{1-\epsilon_0}. \quad (3.17)$$

By the definition of $C_1(\omega)$, it is then clear that on the event $E_{n,1}^{**}$, we have

$$C_1(\omega) \leq M_n. \quad (3.18)$$

Hence, on the event $E_{n,1}^{**}$, it is immediate that

$$\sup_{t \in [0,1]} |Z_t(iy_{n+1}) - \eta(t)| \leq C_1(\omega) \cdot y_{n+1}^{1-\epsilon_0} \leq M_n \cdot y_{n+1}^{1-\epsilon_0} \leq M_{n+1} \cdot y_{n+1}^{1-\epsilon_0}. \quad (3.19)$$

Hence the event $E_{n+1,1}^{**}$ occurs and

$$\mathbb{P}(E_{n+1,1}^{**}) \geq \mathbb{P}(E_{n,1}^{**}), \quad (3.20)$$

which justifies our choice of definition of ϵ_n , from which the monotonicity of $\{\epsilon_n\} \subset \mathbb{R}_+$ is easily seen. To show that $\epsilon_n \rightarrow 0^+$, we notice that $C_1(\omega)$ is *almost surely* finite. Suppose $\epsilon_n \rightarrow \sigma > 0$. Then with probability σ , the constant $C_1(\omega)$ is greater than any M_n , $n \in \mathbb{N}_+$. Since $M_n \rightarrow \infty$, we are forced to conclude that $C_1(\omega) = \infty$ with positive probability, which is impossible. \square

We have now discussed every term in Eqn. (3.8), it is time to finalize the estimate of the first term in Ineq. (3.3a).

Proposition 3.11. *Let $\beta_1 \in (0, 1)$. Given the assumptions that $\|\mathcal{D}_n\| \leq n^{-1}$ and $y_n = n^{-1/2}$, if we define the event*

$$E_{n,1} := \left\{ \|Z_t(iy_n) - Z_{t_k(t)}(iy_n)\|_{[0,1],\infty} \leq \frac{2\phi(\sqrt{n})}{(1-\beta_1)n^{(1-\beta_1)/2}} + \frac{2}{n^{(1-\epsilon_0)/4}} \right\}, \quad (3.21)$$

then the following inequality holds

$$\mathbb{P}(E_{n,1}) \geq 1 - \frac{c_2}{n^2} - \frac{c_4}{n^{c_3/2}} - 2\epsilon_n. \quad (3.22)$$

Proof. On the event $E_{n,1}^* \cap E_{n,1}^{**}$, we know that for $\beta_1 \in (0, 1)$, we have

$$\begin{aligned} \sup_{t \in [0,1]} |Z_t(iy_n) - \eta(t)| &\leq \frac{1}{n^{(1-\epsilon_0)/4}}, \\ \sup_{t \in [0,1]} |\eta(t) - \eta(t_k(t))| &\leq \frac{2\phi(\sqrt{n})}{(1-\beta_1)n^{(1-\beta_1)/2}}. \end{aligned} \quad (3.23)$$

Looking back to Eqn. (3.8), we see $\mathbb{P}(E_{n,1}) \geq \mathbb{P}(E_{n,1}^* \cap E_{n,1}^{**}) \geq 1 - c_2 n^{-2} - c_4 n^{-c_3/2} - 2\epsilon_n$. \square

Hence we have estimated the $\|\cdot\|_{[0,1],\infty}$ norm of the first term in Ineq. (3.3a). This is in fact the most complicated term among these three terms. Next, we will estimate the $\|\cdot\|_{[0,1],\infty}$ norm of the second term.

Inspecting Eqn. (2.12), we observe that the evolution $\tilde{Z}_{t_k} \mapsto \tilde{Z}_{t_{k+1}}$ resembles a forward Loewner map driven by constant forces on the local time interval $[t_k(t), t_{k+1}]$. In fact, this is the case. We are going to split the total time interval $[0, 1]$ into time sub-intervals $[t_k(t), t_{k+1}]$. On each time sub-interval, the evolution $\tilde{Z}_{t_k} \mapsto \tilde{Z}_{t_{k+1}}$ is a composition of two local backward Loewner maps driven by constant forces with an intermediate parallel translation.

Lemma 3.12. ([10], Sec. 2.) *Given a constant driving force $t \mapsto A$ on the time interval $[0, T]$, the forward Loewner chain admits the form*

$$g_t(z) = A + [(z - A)^2 + 4t]^{\frac{1}{2}}. \quad (3.24)$$

And this forward Loewner chain induces a time-reversed (i.e. backward) Loewner chain at the final moment $t = T$ with the form

$$h_T(z) = A + [(z - A)^2 - 4T]^{\frac{1}{2}}. \quad (3.25)$$

Proof. We know $g_T(z) \circ h_T(z) = z$, for all $z \in \mathbb{H}$ by ([1], Lem. 4.10). The result immediately follows. \square

Lemma 3.13. *On each local time interval $[t_k(t), t_{k+1}]$, we consider the constant force $t \mapsto 0$ on time interval $[t_k(t), t_k(t) + \frac{h_k}{2}]$ and the constant force given by the corresponding value of the Brownian path at the end of the time sub-interval on $[t_k(t) + \frac{h_k}{2}, t_{k+1}]$. We denote the time-reversed (i.e. backward) Loewner chain driven by these constant forces as $\iota'_{k,1}$ and $\iota''_{k,1}$, respectively. Consider the parallel translation $z \xrightarrow{\iota_{k,2}} z + \sqrt{\kappa}B_{t_k(t), t_{k+1}}$. Then we have the composition*

$$\tilde{Z}_{t_{k+1}}(iy_n) = \iota''_{k,1} \circ \iota_{k,2} \circ \iota'_{k,1} \tilde{Z}_{t_k}(iy_n). \quad (3.26)$$

Proof. Inspect Eqn (2.12) and Eqn. (3.26) and the conclusion follows. \square

The above perspective in Lem. 3.14 endows us convenience because now we can introduce some discretized force with the form of a step-function to estimate the second term in Ineq. (3.3a). In fact, we have the following proposition.

Proposition 3.14. *If we consider the perturbation event*

$$E_{n,2} := \left\{ \left\| Z_{t_k(t)}(iy_n) - \tilde{Z}_{t_k(t)}(iy_n) \right\|_{[0,1],\infty} \leq \frac{1}{\sqrt{4n+1}} \right\}, \quad (3.27)$$

and if we further restrict $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n+1)^{-3}$, then

$$\mathbb{P}(E_{n,2}) \geq 1 - 2e^{-(4n+1)/\kappa}. \quad (3.28)$$

Proof. From Sec. 2. we already know $Z_t(iy_n) = h_t(iy_n) - \sqrt{\kappa}B_t$. If we further choose $\widehat{B}_t := B_{1-t} - B_1$, then Eqn. (2.2) can be written as

$$\partial_t h_t(z) = \frac{-2}{h_t(z) - \sqrt{\kappa}\widehat{B}_t}, \quad (3.29)$$

with $h_0(z) = z$ and where \widehat{B}_t has the law of a standard Brownian motion. We also comment that our splitting scheme could be formulated in a similar fashion. Define the driver

$$\widetilde{\lambda}(t) := 0 \cdot \mathbb{1}_{[0, \frac{t_1}{2})} + \sum_{k \geq 1} \sqrt{\kappa} B_{t_k(t)} \cdot \mathbb{1}_{[t_k(t) - \frac{h_k}{2}, t_k(t) + \frac{h_k}{2} \wedge 1)}. \quad (3.30)$$

The random process $\widetilde{\lambda}(t)$ can be viewed as a step-function interpolation to the sample paths of Brownian motion $\sqrt{\kappa} B_t$ on $[0, 1]$. In this regard, we denote by $\widetilde{Z}_t^*(iy_n)$ the trajectory driven by the above driver similar to $Z_t(iy_n)$ being driven by $\sqrt{\kappa} \widehat{B}_t$ in the following sense

$$\widetilde{Z}_t^*(iy_n) = \widetilde{h}_t(iy_n) - \widetilde{\lambda}(t), \quad (3.31)$$

due to *Lem. 3.13* and where $(\widetilde{h}_t)_{t \in [0, 1]}$ is a backward Loewner chain constrained by

$$\partial_t \widetilde{h}_t(z) = \frac{-2}{\widetilde{h}_t(z) - \widehat{\lambda}_t}, \quad (3.32)$$

with $\widetilde{h}_0(z) = z$ and $\widehat{\lambda}_t := \widetilde{\lambda}(1 - t) - \widetilde{\lambda}(1)$. The above scheme brings us some consistency to some perturbation term $Z_t(iy_n) - \widetilde{Z}_t^*(iy_n)$. And our first goal is to estimate

$$\left| Z_t(iy_n) - \widetilde{Z}_t^*(iy_n) \right| \leq \left| h_t(iy_n) - \widetilde{h}_t(iy_n) \right| + \left| \sqrt{\kappa} B_t - \widetilde{\lambda}(t) \right|. \quad (3.33)$$

Define $\epsilon := \sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_t - \widetilde{\lambda}(t) \right|$, then it follows that

$$\left| Z_t(iy_n) - \widetilde{Z}_t^*(iy_n) \right| \leq \left| h_t(iy_n) - \widetilde{h}_t(iy_n) \right| + \epsilon. \quad (3.34)$$

To achieve this goal, we further define $H(t) := h_t(iy_n) - \widetilde{h}_t(iy_n)$. And we will first estimate $|H(t)|$. Differentiate $H(t)$ *w.r.t.* $t \in [0, 1]$ and use *Eqn. (2.2)* and *Eqn. (3.33)* to obtain

$$\frac{d}{dt} H(t) - H(t) \zeta(t) = (\sqrt{\kappa} \widehat{B}_t - \widehat{\lambda}_t) \zeta(t), \quad (3.35)$$

where we define $\zeta(t) := (h_t(iy_n) - \sqrt{\kappa} \widehat{B}_t)^{-1} \cdot (\widetilde{h}_t(iy_n) - \widehat{\lambda}_t)^{-1}$. Notice that the derivative of $H(t)$ *w.r.t.* time t is defined except for finitely many points because the driving force $\widetilde{\lambda}(t)$ is piecewise continuous. Integrating the above differential

equation and choose $u(t) := e^{-\int_0^t \zeta(s) ds}$, we find

$$H(t) = u(t)^{-1} \left[H(0) - \int_0^t (\sqrt{\kappa} \widehat{B}_s - \widehat{\lambda}_s) u(s) \zeta(s) ds \right]. \quad (3.36)$$

Since $H(0) = 0$, we obtain

$$|H(t)| \leq \int_0^t \left| \sqrt{\kappa} \widehat{B}_s - \widehat{\lambda}_s \right| e^{\int_s^t \operatorname{Re} \zeta(r) dr} |\zeta(s)| ds. \quad (3.37)$$

Then, it is immediate that

$$\begin{aligned} |h_t(iy_n) - \widetilde{h}_t(iy_n)| &\leq \epsilon \cdot \int_0^t e^{\int_s^t \operatorname{Re} \zeta(r) dr} |\zeta(s)| ds \\ &\leq \epsilon \cdot \left(e^{\int_s^t |\zeta(r)| dr} - 1 \right), \end{aligned} \quad (3.38)$$

where the last inequality is due to ([15], *Lem.* 2.3) and ([15], *Eqn.* 2.12). Now turning attention to *Eqn.* (3.34), we have

$$\left| Z_t(iy_n) - \widetilde{Z}_t^*(iy_n) \right| \leq \left| h_t(iy_n) - \widetilde{h}_t(iy_n) \right| + \epsilon \leq \epsilon \cdot e^{\int_s^t \operatorname{Re} \zeta(r) dr}. \quad (3.39)$$

Furthermore, ([15], *Eqn.* 2.12) tells us that $\int_0^t |\zeta(s)| ds \leq \log(\sqrt{4 + y_n^2}/y_n)$. Consequently, we have

$$\left| Z_t(iy_n) - \widetilde{Z}_t^*(iy_n) \right| \leq \epsilon \cdot \sqrt{4 + y_n^2}/y_n = \epsilon \cdot \sqrt{4n + 1}. \quad (3.40)$$

Notice that

$$\epsilon = \sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_t - \widetilde{\lambda}(t) \right| \leq \bigvee_{t_k(t) \in \mathcal{D}_n} \sup_{t \in [0, h_k]} \sqrt{\kappa} |B_t|, \quad (3.41)$$

where the notation “ \vee ” indicates we take the maximal value over all $t_k(t) \in \mathcal{D}_n$. By ([9], *Cor.* 2.2), for the supremum Brownian motion $S_t := \sup_{0 \leq s \leq t} B_s$ we have that

$$\mathbb{P}\left(S_t \leq x\right) = 2\Phi\left(\frac{x}{\sqrt{t}}\right) - 1, \quad (3.42)$$

for all $x \geq 0$ and where $\frac{d}{dx}\Phi(x) := e^{-x^2/2}/\sqrt{2\pi}$ is the law of standard normal variable. It follows from the reflection principle that

$$\mathbb{P}\left(\sup_{0 \leq t \leq h_k} |\sqrt{\kappa} B_t| \geq \frac{1}{4n+1}\right) = 2\mathbb{P}\left(S_{h_k} \geq \frac{1}{\sqrt{\kappa} \cdot (4n+1)}\right) \leq 2\sqrt{\frac{2}{\pi}} e^{-\frac{(4n+1)^{-2}}{2h_k \cdot \kappa}}, \quad (3.43)$$

if we restrict $h_k \leq n^{-1} \wedge (4n+1)^{-3}$ for all $t_k(t) \in \mathcal{D}_n$. Then

$$\left\{ \epsilon > \frac{1}{4n+1} \right\} \leq \bigcup_{t_k(t) \in \mathcal{D}_n} \left\{ \sup_{0 \leq t \leq \frac{h_k}{2}} |\sqrt{\kappa} B_t| > \frac{1}{4n+1} \right\}, \quad (3.44a)$$

and we see

$$\begin{aligned} \mathbb{P}\left(\epsilon > \frac{1}{4n+1}\right) &\leq \sum_{t_k(t) \in \mathcal{D}_n} \mathbb{P}\left(\sup_{0 \leq t \leq \frac{h_k}{2}} |\sqrt{\kappa} B_t| > \frac{1}{4n+1}\right) \\ &\leq 2(4n+1)^3 \cdot e^{-(4n+1)/2\kappa}. \end{aligned} \quad (3.44b)$$

Conditioned on the event $\{\epsilon > (4n+1)^{-1}\}^c \in \Omega$, following Eqn. (3.41), we have

$$\sup_{t \in [0,1]} \left| Z_t(iy_n) - \tilde{Z}_t^*(iy_n) \right| \leq \frac{1}{\sqrt{4n+1}}. \quad (3.45)$$

Hence, by the strict inclusion of events in probability space, we have our estimate to the perturbation term

$$\mathbb{P}\left(\sup_{t \in [0,1]} \left| Z_t(iy_n) - \tilde{Z}_t^*(iy_n) \right| \leq \frac{1}{\sqrt{4n+1}}\right) \geq 1 - 2(4n+1)^3 \cdot e^{-(4n+1)/2\kappa}. \quad (3.46a)$$

We further observe that the splitting scheme $\tilde{Z}_t(iy_n)$ coincides with the trajectory $\tilde{Z}_t^*(iy_n)$ at the times $t_k(t) \in \mathcal{D}_n$, by virtue of Lem. 3.13. Hence we have the desired result

$$\mathbb{P}(E_{n,2}) \geq 1 - 2(4n+1)^3 \cdot e^{-(4n+1)/2\kappa}. \quad (3.46b)$$

□

Remark 3.15. *The perturbation in Prop. 3.14 in our splitting scheme is estimated via a probabilistic argument using ([15], Lem. 2.2). Notice that the time-reversed Loewner map $h_t(z)$ is different from the inverse of the forward map $g_t^{-1}(z)$, even though we do have the equality $h_{T=1}(z) = g_{T=1}^{-1}(z)$. In Sec. 5. we are going to briefly discuss the linear interpolation of driving force. To prove its convergence, we will need ([15], Lem. 2.2) again under a different context.*

Hence we have estimated the sup-norm on $[0,1]$ of the second term in Ineq. (3.3a). Next, we will estimate the $\|\cdot\|_{[0,1],\infty}$ norm of the third term. Following Eqn. (2.10) with $L_0(z) = -2/z$ and $L_1(z) = \sqrt{\kappa}$, we could explicitly

calculate, with $t_k(t) \leq s < t_{k+1}$

$$\begin{aligned}\tilde{Z}_s^{(0)} &= \exp\left(\frac{1}{2}(s - t_k(t))L_0\right)\tilde{Z}_{t_k(t)} = \sqrt{\tilde{Z}_{t_k(t)}^2 - 2(s - t_k(t))}, \\ \tilde{Z}_s^{(1)} &= \exp\left(B_{t_k(t),s}L_1\right)\tilde{Z}_{t_{k+1}}^{(0)} = \sqrt{\tilde{Z}_{t_k(t)}^2 - 2h_k + B_{t_k(t),s}}, \\ \tilde{Z}_s^{(2)} &= \exp\left(\frac{1}{2}(s - t_k(t))L_0\right)\tilde{Z}_{t_{k+1}}^{(1)} = \sqrt{(\tilde{Z}_{t_{k+1}}^{(1)})^2 - 2(s - t_k(t))},\end{aligned}\tag{3.47}$$

which could be written into the form via solving Eqn. (2.9)

$$\begin{aligned}\tilde{Z}_t(iy_n) - \tilde{Z}_{t_k(t)}(iy_n) &= \frac{1}{2} \int_{t_k(t)}^t L_0(\tilde{Z}_s^{(2)})ds + \int_{t_k(t)}^t L_1(\tilde{Z}_s^{(1)})dB_s + \frac{1}{2} \int_{t_k(t)}^t L_0(\tilde{Z}_s^{(0)})ds, \\ &= \int_{t_k(t)}^t \sqrt{\kappa}dB_s - \int_{t_k(t)}^t \frac{1}{\sqrt{(\tilde{Z}_{t_k(t)}^2 - 2(s - t_k(t)))}}ds - \int_{t_k(t)}^t \frac{1}{\sqrt{(\tilde{Z}_{t_{k+1}}^{(1)})^2 - 2(s - t_k(t))}}ds.\end{aligned}\tag{3.48a}$$

Solving these integrals, we have

$$\begin{aligned}\tilde{Z}_t(iy_n) - \tilde{Z}_{t_k(t)}(iy_n) &= \sqrt{\kappa}B_{t_k(t),t} - \frac{2(t - t_k(t))}{\sqrt{\tilde{Z}_{t_k(t)}^2 - 2(t - t_k(t)) + \tilde{Z}_{t_k(t)}^2}} \\ &\quad - \frac{2(t - t_k(t))}{\sqrt{(\sqrt{\tilde{Z}_{t_k(t)}^2 - 2h_k + \sqrt{\kappa}B_{t_k(t),t_{k+1}}})^2 - 2(t - t_k(t)) + \sqrt{\tilde{Z}_{t_k(t)}^2 - 2h_k + \sqrt{\kappa}B_{t_k(t),t_{k+1}}}}},\end{aligned}\tag{3.48b}$$

where $t_k(t)$ abbreviates $t_k(t)$ in the above expression. Eqn. (3.49b) provides an exact form of the approximated process \tilde{Z}_t , which leads us to the following result.

Proposition 3.16. *Let $\kappa \in (0, 4)$. Let us consider the event*

$$E_{n,3} := \left\{ \left\| \tilde{Z}_t(iy_n) - \tilde{Z}_{t_k(t)}(iy_n) \right\|_{[0,1],\infty} \leq \frac{2}{n^{1/2}} + \frac{1}{n^{1/4}} \right\}.\tag{3.49}$$

Then as long as $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n + 1)^{-3}$, we have

$$\mathbb{P}(E_{n,3}) \geq 1 - \frac{1}{n} - 2e^{-\sqrt{n}/2\kappa}.\tag{3.50}$$

Proof. By ([3], Sec. 6.1), we have two general results $\text{Im}(z) \leq \text{Im}(\sqrt{z^2 - c})$ and $\text{Im}(z) = \text{Im}(z + c)$ for all $z \in \mathbb{H}$ and $c \in \mathbb{R}$. Applying this two results to

Eqn. (3.49b), we have

$$\begin{aligned} \left| \tilde{Z}_t(iy_n) - \tilde{Z}_{t_k(t)}(iy_n) \right| &\leq \left| \sqrt{\kappa} B_{t_k(t),t} \right| + \frac{h_k}{\operatorname{Im} \tilde{Z}_{t_k(t)}(iy_n)} + \frac{h_k}{\operatorname{Im} \tilde{Z}_{t_k(t)}(iy_n)}, \\ &\leq \left| \sqrt{\kappa} B_{t_k(t),t} \right| + \frac{2h_k}{y_n}, \end{aligned} \quad (3.51)$$

where the last inequality follows from ([1], Lem. 4.9), where it is shown that the map $t \mapsto \operatorname{Im} \tilde{Z}_t(iy)$ is strictly increasing. Using ([9], Cor. 2.2), we obtain that

$$\mathbb{P} \left(\sup_{0 \leq t \leq h_k} \left| \sqrt{\kappa} B_t \right| \geq \frac{1}{n^{1/4}} \right) = 2\mathbb{P} \left(S_{h_k} \geq \frac{1}{\sqrt{\kappa} \cdot n^{1/4}} \right) \leq 2\sqrt{\frac{2}{\pi}} e^{-\frac{n^{-1/2}}{2h_k \cdot \kappa}}, \quad (3.52)$$

by reflection principle. Note that we have restricted $h_k \leq n^{-1} \wedge (4n+1)^{-3}$ for all $t_k(t) \in \mathcal{D}_n$. In this regard

$$\mathbb{P} \left(\sup_{t \in [0,1]} \left| \sqrt{\kappa} B_{t_k(t),t} \right| \geq \frac{1}{n^{1/4}} \right) \leq 2e^{-\sqrt{n}/2\kappa}, \quad (3.53)$$

and

$$\mathbb{P}(E_{n,3}) \geq 1 - \frac{1}{n} - 2e^{-\sqrt{n}/2\kappa}. \quad (3.54)$$

□

At this point, we have evaluated the $\|\cdot\|_{[0,1],\infty}$ norm *w.r.t.* all the three terms in Ineq. (3.3a). Therefore, we come to prove the main result.

Proof. (of Thm. 3.4) Denote $E_{n,4} := E_{n,1}^{**}$. On the event $E_{n,1} \cap E_{n,2} \cap E_{n,3} \cap E_{n,4} \subset \Omega$, we observe from Prop. 3.10, Prop. 3.11, Prop. 3.14, and Prop. 3.16 that

$$\begin{aligned} \|\eta(t) - Z_t(iy_n)\|_{[0,1],\infty} &\leq \frac{1}{n^{(1-\epsilon_0)/4}}, \\ \|Z_t(iy_n) - Z_{t_k(t)}(iy_n)\|_{[0,1],\infty} &\leq \frac{2\phi(\sqrt{n})}{(1-\beta_1)n^{(1-\beta_1)/2}} + \frac{2}{n^{(1-\epsilon_0)/4}}, \\ \|Z_{t_k(t)}(iy_n) - \tilde{Z}_{t_k(t)}(iy_n)\|_{[0,1],\infty} &\leq \frac{1}{(4n+1)^{1/2}}, \\ \|\tilde{Z}_{t_k(t)}(iy_n) - \tilde{Z}_t(iy_n)\|_{[0,1],\infty} &\leq \frac{2}{n^{1/2}} + \frac{1}{n^{1/4}}, \end{aligned} \quad (3.55)$$

given $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n+1)^{-3}$ and $\beta_1 \in (0, 1)$. If we define

$$\begin{aligned}\varphi_1(n) &:= \frac{2\phi(\sqrt{n})}{(1-\beta_1)n^{(1-\beta_1)/2}} + \frac{3}{n^{(1-\epsilon_0)/4}} + \frac{1}{(4n+1)^{1/2}} + \frac{2}{n^{1/2}} + \frac{1}{n^{1/4}} \rightarrow 0, \\ \varphi_2(n) &:= \frac{1}{n} + \frac{c_2}{n^2} + \frac{c_4}{n^{c_3/2}} + 2(4n+1)^3 \cdot e^{-(4n+1)/2\kappa} + 2e^{-\sqrt{n}/2\kappa} + 3\epsilon_n \rightarrow 0,\end{aligned}\tag{3.56}$$

as $n \rightarrow \infty$. Then the following inequality proves our result

$$\mathbb{P}\left(\left\|\eta(t) - \tilde{Z}_t(iy_n)\right\|_{[0,1],\infty} \leq \varphi_1(n)\right) \geq \mathbb{P}\left(E_{n,1} \cap \dots \cap E_{n,4}\right) \geq 1 - \varphi_2(n).\tag{3.57}$$

□

Corollary 3.17. *For almost all $\omega \in \Omega$, we have that*

$$\left\|\eta(t) - \tilde{Z}_t(iy_n)\right\|_{[0,1],\infty} \rightarrow 0, \text{ with } n \rightarrow \infty.\tag{3.58}$$

Proof. This corollary immediately follows from the strong convergence in probability in *Thm. 3.4*. □

Remark 3.18. *From a practical view-point, for a fixed level $n \in \mathbb{N}$, in order to achieve better precision one can choose a constant $\tau > 0$, called tolerance, to ensure that*

$$\left|\tilde{Z}_{t_{k+1}} - \tilde{Z}_{t_k}\right| \leq \tau\tag{3.59}$$

for each k . To achieve this, we start by computing \tilde{Z}_t along a prior uniform partition until $\left|\tilde{Z}_{t_{k+1}} - \tilde{Z}_{t_k}\right| > \tau$. If this event occurs, we reduce the step size h_k of the SLE_κ discretization, that is we insert the mid-point of this interval $[t_k(t), t_{k+1}]$ into the partition.

In other words, we refine the prior partition via mid-point insertion whenever necessary. Notice that the choice of a refined partition actually depends on $\omega \in \Omega$ because the evolution $(\tilde{Z}_t)_{0 \leq t \leq 1}$ contains Brownian motion.

4 Convergence in L^p norm

Following *Ineq. (3.3a)* and *Ineq. (3.3b)*, we are going to estimate the L^p norm to $(\eta(t) - \tilde{Z}_t(iy_n))$ with $p \geq 2$, given some technical assumptions. This approach can be thought of as a variant of the convergence, under the mentioned assumptions. We plan to investigate the proof of these in future work. Similar to the proof of strong convergence in probability, the first step is to estimate each of the four terms in *Eqn. (3.56)* individually.

Assumption 4.1. *There exists $p_1 \geq 2$ and $\epsilon_0 \in (0, 1)$ such that*

$$\sup_{t \in [0, 1]} |\eta(t) - Z_t(iy_n)| \leq C_1(\omega) \cdot y_n^{1-\epsilon_0}, \quad (4.1)$$

where the constant $C_1(\omega)$ is almost surely finite as in ([3], Lem. 6.7). Moreover, we assume that $C_1(\omega)$ is p_1 -integrable, i.e. $C_1(\omega) \in L^{p_1}(\mathbb{P})$.

Assumption 4.2. *There exists $p_2 \geq 2$ and $\beta_2 \in (0, 1)$ such that the SLE_κ Loewner chain is generated by a curve when $\kappa \neq 8$ with the following modulus of continuity*

$$|\eta(t+s) - \eta(t)| \leq C_2(\omega) s^{(1-\beta_2)/2} \quad (4.2)$$

where the constant $C_2(\omega)$ is almost surely finite as in ([5], Prop. 4.3). And moreover $C_2(\omega)$ is p_2 -integrable, i.e. $C_2(\omega) \in L^{p_2}(\mathbb{P})$.

Assumption 4.3. *The Ninomiya-Victoir splitting scheme satisfies the various regularity assumptions, including the ellipticity condition in ([7], Rmk. 4.1) and then admits the inequality*

$$\mathbb{E} \left[\sup_{t \in [0, 1]} \left| Z_t(iy_n) - \tilde{Z}_t(iy_n) \right|^p \right] \leq \frac{c_6}{n^p}, \quad (4.3)$$

for some constant $c_6 > 0$, and for all $p \geq 2$.

If these assumptions hold as expected, we could take a crucial step near the idea of L^p convergence of our splitting scheme. In this section, we choose $p := p_1 \wedge p_2 \geq 2$. We have the following propositions.

Proposition 4.4. *Admitting Asmp. 4.1 with $||\mathcal{D}_n| \leq n^{-1} \wedge (4n+1)^{-3}$ where $||\mathcal{D}_n|$ is refined partition, then there exists a decreasing function $\psi_1 : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that $\psi_1(n) \rightarrow 0$ as $n \rightarrow \infty$, and*

$$\mathbb{E} \left[\int_0^1 |\eta(t) - Z_t(iy_n)|^p dt \right] \leq \psi_1(n). \quad (4.4)$$

Proof. By ([3], Lem. 6.7), there exists $\epsilon_0 \in (0, 1)$ such that almost surely

$$\sup_{t \in [0, 1]} |\eta(t) - Z_t(iy_n)| \leq C_1(\omega) \cdot y_n^{1-\epsilon_0}. \quad (4.5)$$

It is clear then

$$\begin{aligned} \mathbb{E} \left[\int_0^1 |\eta(t) - Z_t(iy_n)|^p dt \right] &\leq \mathbb{E} \left[\|\eta(t) - Z_t(iy_n)\|_{[0, 1], \infty}^p \right] \\ &\leq \mathbb{E} [C_1(\omega)^p] \cdot \frac{1}{n^{(1-\epsilon_0)p/2}} := \psi_1(n) \xrightarrow{n \rightarrow \infty} 0. \end{aligned} \quad (4.6)$$

□

Proposition 4.5. *Admitting Asmp. 4.2 with $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n+1)^{-3}$, there exists a decreasing function $\psi_2 : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that $\psi_2(n) \rightarrow 0$ as $n \rightarrow \infty$, and*

$$\mathbb{E} \left[\int_0^1 |Z_t(iy_n) - Z_{t_k(t)}(iy_n)|^p dt \right] \leq \psi_2(n). \quad (4.7)$$

Proof. ([5], Prop. 3.8) and ([5], Prop. 4.3) imply that there exists $\beta_2 \in (0, 1)$ such that

$$\sup_{t \in [0,1]} |\eta(t) - \eta(t_k(t))| \leq C_2(\omega) \cdot \frac{1}{n^{(1-\beta_2)/2}}. \quad (4.8)$$

By Prop. 4.4, it follows that

$$\sup_{t \in [0,1]} |Z_t(iy_n) - Z_{t_k(t)}(iy_n)| \leq \frac{2C_1(\omega)}{n^{(1-\epsilon_0)/2}} + \frac{C_2(\omega)}{n^{(1-\beta_2)/2}}. \quad (4.9)$$

It is clear then

$$\begin{aligned} \mathbb{E} \left[\int_0^1 |Z_t(iy_n) - Z_{t_k(t)}(iy_n)|^p dt \right] &\leq \mathbb{E} \left[\|Z_t(iy_n) - Z_{t_k(t)}(iy_n)\|_{[0,1],\infty}^p \right] \\ &\leq \mathbb{E}[C_1(\omega)^p] \cdot \frac{2^{2p-1}}{n^{(1-\epsilon_0)p/2}} + \mathbb{E}[C_2(\omega)^p] \cdot \frac{2^{p-1}}{n^{(1-\beta_2)p/2}} := \psi_2(n) \xrightarrow{n \rightarrow \infty} 0. \end{aligned} \quad (4.10)$$

□

Proposition 4.6. *Admitting Asmp. 4.3 with $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n+1)^{-3}$, it is immediate that*

$$\mathbb{E} \left[\sup_{t \in [0,1]} |Z_{t_k(t)}(iy_n) - \tilde{Z}_{t_k(t)}(iy_n)|^p \right] \leq \frac{c_6}{n^p}. \quad (4.11)$$

If we denote $\psi_3(n) := c_6/n^p$, then

$$\mathbb{E} \left[\int_0^1 |Z_{t_k(t)}(iy_n) - \tilde{Z}_{t_k(t)}(iy_n)|^p dt \right] \leq \psi_3(n) \xrightarrow{n \rightarrow \infty} 0. \quad (4.12)$$

Proof. The proposition follows from Eqn. (4.9). □

To give an estimate to the last term in Eqn. (3.56), we quote the known interpolation inequality from ([8], Sec. 6.5) for Lebesgue spaces and another inequality *w.r.t.* supremum Brownian motion.

Lemma 4.7. *For all $1 < p < r < q$, suppose $f \in L^p \cap L^q$. Then $f \in L^r$ with*

$$\|f\|_r \leq (\|f\|_p)^{(1/r-1/q)/(1/p-1/q)} (\|f\|_q)^{(1/r-1/q)/(1/p-1/q)}. \quad (4.13)$$

Lemma 4.8. *For all $m \in \mathbb{N}$, we have*

$$\mathbb{E} \left[\sup_{s \in [0, t]} |B_s|^{2m} \right] = \pi^{-\frac{1}{2}} \Gamma \left(\frac{1}{2} + m \right) 2^m \cdot t^m, \quad (4.14)$$

where B_t is a standard one-dimensional Brownian motion.

Proof. The proof follows if we revisit the supremum Brownian motion $S_t = \sup_{0 \leq s \leq t} B_s$ from ([9], Cor. 2.2), by computing all even order moments. \square

Proposition 4.9. *With $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n + 1)^{-3}$, there exists a decreasing function $\psi_4 : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that $\psi_4(n) \rightarrow 0$ with $n \rightarrow \infty$, and*

$$\mathbb{E} \left[\int_0^1 \left| \tilde{Z}_{t_k(t)}(iy_n) - \tilde{Z}_t(iy_n) \right|^p dt \right] \leq \psi_4(n). \quad (4.15)$$

Proof. By Prop. 3.14 and Eqn. (3.52), we know almost surely that

$$\left| \tilde{Z}_{t_k(t)}(iy_n) - \tilde{Z}_t(iy_n) \right|^p \leq 2 \left| \sqrt{\kappa} B_{t_k(t), t} \right|^p + \frac{2^{p+1}}{n^{p/2}}. \quad (4.16)$$

Since $p \geq 2$, there exists $\{m, m+1\} \subset \mathbb{N}$ so that $2m \leq p < 2(m+1)$. Remember that $t - t_k(t) \leq h_k \leq n^{-1}$. Then, by Lem. 4.8

$$\begin{aligned} \mathbb{E} \left[\sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_{t_k(t), t} \right|^{2m} \right] &\leq \frac{2^m \kappa^m \Gamma(\frac{1}{2} + m)}{\pi^{\frac{1}{2}} \cdot n^m}, \\ \mathbb{E} \left[\sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_{t_k(t), t} \right|^{2m+2} \right] &\leq \frac{2^{m+1} \kappa^{m+1} \Gamma(\frac{3}{2} + m)}{\pi^{\frac{1}{2}} \cdot n^{m+1}}. \end{aligned} \quad (4.17)$$

By Lem. 4.7, we use the interpolation inequality in Lebesgue spaces and have

$$\begin{aligned} &\mathbb{E} \left[\sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_{t_k(t), t} \right|^p \right] \\ &\leq \mathbb{E} \left[\sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_{t_k(t), t} \right|^{2m} \right]^{m+1-\frac{p}{2}} \mathbb{E} \left[\sup_{t \in [0, 1]} \left| \sqrt{\kappa} B_{t_k(t), t} \right|^{2m+2} \right]^{(m+1-\frac{p}{2}) \cdot \frac{m}{m+1}} \\ &\leq \frac{c_7}{n^{m(m+1-\frac{p}{2})}} := \psi_4(n) \xrightarrow{n \rightarrow \infty} 0, \end{aligned} \quad (4.18)$$

where $c_7 > 0$ is a constant depending only on $p \geq 2$. \square

We have, at this point, estimated the L^p norm *w.r.t.* the four terms in Eqn. (3.52) under several assumptions. Combining them together, under the specified assumptions, we obtain the following result.

Theorem 4.10. *Admitting Asmp. 4.1, 4.2, and 4.3, together with $\|\mathcal{D}_n\| \leq n^{-1} \wedge (4n + 1)^{-3}$, there exists a decreasing function $\psi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ such that*

$\psi(n) \rightarrow 0$ as $n \rightarrow \infty$, and

$$\mathbb{E} \left[\int_0^1 \left| \eta(t) - \tilde{Z}_t(iy_n) \right|^p \right] \leq \psi(n). \quad (4.19)$$

Proof. Define $\psi := \psi_1 + \psi_2 + \psi_3 + \psi_4$, then the result follows. \square

5 Linear interpolation of driving force

In *Sec. 2.* we have formulated a splitting scheme of SLE_κ traces via Ninomiya-Victoir Scheme. In *Sec. 3.* we proved the strong convergence in probability of the splitting scheme. In *Sec. 4.* we proposed an L^p convergence of the above splitting scheme under several assumptions (whose investigation will expand in future work). In this section, we diverge a little to see a variant simulating scheme: linearly interpolating the driving Brownian motion $\sqrt{\kappa}B_t$ pointwisely, and discuss its convergence.

Definition 5.1. In this section, $\mathcal{D}_n := \{t_0 = 0, t_1, \dots, t_n = 1\}$ will denote a uniform partition on the time interval $[0, 1]$.

Definition 5.2. Given the Brownian sample paths $B.(\omega) : [0, 1] \rightarrow \mathbb{R}$, we write our linear interpolation in the following form

$$\lambda^n(t) := n(\sqrt{\kappa}B_{t_{k+1}} - \sqrt{\kappa}B_{t_k(t)})(t - t_k(t)) + \sqrt{\kappa}B_{t_k(t)} \text{ on } [t_k(t), t_{k+1}]. \quad (5.1)$$

Definition 5.3. Following the convention in *Sec. 2.* and *Sec. 3.* we use the notation $\gamma : [0, 1] \rightarrow \mathbb{H} \cup \{\sqrt{\kappa}B_1\}$ for the forward Loewner curve generated by the forward Loewner chain $(g_t)_{t \in [0, 1]}$ with driving force $\sqrt{\kappa}B_t$. We further let $\gamma^n : [0, 1] \rightarrow \mathbb{H} \cup \{\sqrt{\kappa}B_1\}$ to denote the forward Loewner curve generated by the forward Loewner chain $(g_t^n)_{t \in [0, 1]}$, driven by the piecewise-linear force $\lambda^n(t)$.

Remark 5.4. Notice that in this section we will interpolate the forward Loewner chain and hence simulate the forward Loewner curve $\gamma(t)$, whereas we have simulated the backward Loewner curve $\eta(t)$ via Ninomiya-Victoir Scheme in *Sec. 2.*

Definition 5.5. With $(g_t^n)_{t \in [0, 1]}$ the Loewner chain corresponding to $\lambda^n(t)$, let $f_t^n : \mathbb{H} \rightarrow \mathbb{H} \setminus \gamma^n([0, t])$ be the inverse map of $g_t^n(z)$ and denote $\hat{f}_t^n(z) := f_t^n(z + \lambda^n(t))$. Choose $G_k^n := (\hat{f}_{t_k(t)}^n)^{-1} \circ \hat{f}_{t_{k+1}}^n$. Then

$$\hat{f}_{t_k(t)}^n = G_0^n \circ G_1^n \circ \dots \circ G_{k-1}^n. \quad (5.2)$$

Definition 5.6. Choose $\gamma_t^n(s) := g_t^n(\gamma^n(t+s))$ with $s \in [0, 1-t]$, for all $t \in [0, 1]$.

Lemma 5.7. Consider the event $F_{n,1} := E'_{n,1}$ and $F_{n,2} := E''_{n,1}$ as in Eqn. (3.4) and in Eqn. (3.6). Then we have

$$\mathbb{P}(F_{n,1}) \geq 1 - \frac{c_2}{n^2} \quad \text{and} \quad \mathbb{P}(F_{n,2}) \geq 1 - \frac{c_4}{n^{c_3/2}}, \quad (5.3)$$

where $c_2, c_3, c_4 > 0$ are constants depending only on $\kappa \neq 8$.

Theorem 5.8. Let γ be the SLE_κ trace and let γ^n be the trace obtained by the linear interpolation of the Brownian driver. There exist $c_6, c_7 > 0$ depending only on $\kappa \neq 8$ such that if we consider the event

$$F_n := \left\{ \|\gamma - \gamma^n\|_{[0,1],\infty} \leq \frac{c_6(\log n)^{c_7}}{n^{(1-\sqrt{(1+\beta_1)/2})/2}} \right\}. \quad (5.4)$$

Then we have $\mathbb{P}(F_n) \geq 1 - c_2 \cdot n^{-2} - c_3 \cdot n^{-c_4/2}$.

This theorem is our main result in the context of linearly interpolating Brownian driver. We will not give a detailed proof here because the proof is similar to the known result of square-root interpolation obtained in ([11], Sec. 2.). Instead, we outline the ideas to estimate the convergence in probability of the linear interpolation method.

On the event $F_{n,1} \cap F_{n,2}$, we want to give a uniform bound to $|\gamma(t) - \gamma^n(t)|$ with $t \in [0, 1]$. In fact, for all $t_k(t) \in \mathcal{D}_n$, we write

$$\begin{aligned} |\gamma(r + t_k(t)) - \gamma^n(r + t_k(t))| &\leq |\gamma(r + t_k(t)) - \gamma(s + t_k(t))| + \left| \widehat{f}_{t_k(t)}(z) - \widehat{f}_{t_k(t)}^n(w) \right| \\ &\leq |\gamma(r + t_k(t)) - \gamma(s + t_k(t))| + \left| \widehat{f}_{t_k(t)}(z) - \widehat{f}_{t_k(t)}(w) \right| + \left| \widehat{f}_{t_k(t)}(w) - \widehat{f}_{t_k(t)}^n(w) \right|, \end{aligned} \quad (5.5)$$

where $w := \gamma_k^n(r)$, r is arbitrarily fixed in $[\frac{1}{n}, \frac{2}{n}]$ and $z := \gamma_k(s)$ is chosen to be the highest point in the arc $\gamma_k([0, \frac{2}{n}])$. The first term in Eqn. (5.5) is bounded by the uniform continuity of $\gamma(t)$ on the event $F_{n,1}$.

The estimate of the second term in Eqn. (5.5) is comparing the images of nearby points in \mathbb{H} very close to the real and the imaginary axis, under a conformal map. To proceed our discussion, we introduce, for any subpower function $\phi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$, constant $c > 0$, and integer $n \in \mathbb{N}_+$ that

$$A_{n,c,\phi} := \left\{ x + iy \in \mathbb{H}; |x| \leq \frac{\phi(n)}{\sqrt{n}} \text{ and } \frac{1}{\sqrt{n}\phi(n)} \leq y \leq \frac{c}{\sqrt{n}} \right\}, \quad (5.6)$$

which is a box near the origin in the upper half-plane. The reason we introduce

this extra object is that the images of nearby points in $A_{n,c,\phi}$ will also be close to each other under certain conformal maps, in the sense of the following lemmas.

Lemma 5.9. ([11], Lem. 2.6) *There exist constants $\alpha > 0$, and $c' > 0$, depending only on $c > 0$ in the definition of the box $A_{n,c,\phi}$, such that for all $z_1, z_2 \in A_{n,c,\phi}$ and conformal map $f : \mathbb{H} \rightarrow \mathbb{C}$, we have*

$$\begin{aligned} |f'(z_1)| &\leq c' \phi(n)^\alpha \cdot |f'(i \operatorname{Im} z_1)|, \\ d_{\mathbb{H},hyp}(z_1, z_2) &\leq c' \log \phi(n) + c', \end{aligned} \tag{5.7}$$

where $d_{\mathbb{H},hyp}(z_1, z_2)$ denotes the hyperbolic distance between z_1 and z_2 in \mathbb{H} .

Lemma 5.10. ([16], Cor. 1.5) *Suppose $f : \mathbb{H} \rightarrow \mathbb{C}$ is a conformal map, then for all $z_1, z_2 \in \mathbb{H}$, we have*

$$|f(z_1) - f(z_2)| \leq 2|(\operatorname{Im} z_1)f'(z_1)| \cdot \exp(4d_{\mathbb{H},hyp}(z_1, z_2)). \tag{5.8}$$

Therefore, it is natural that we want to show $\{z, w\} \in A_{n,c,\phi}$ with proper parameters. Indeed, this is the case in the square-root interpolation ([11], Lem. 3.3). The only non-trivial remark is the following.

Remark 5.11. *In the linear interpolation, from ([10], Sec. 3.) we know that for a typical linear force $\lambda(t) = t$ on the time interval $[0, \infty)$, the Loewner curve admits the form*

$$t \mapsto 2 - 2\rho_t \cot \rho_t + 2i\rho_t, \tag{5.9}$$

where ρ_t increases monotonously from $\rho_0 = 0$ to $\rho_\infty = \pi$. Indeed, the Loewner curve of a general linear force $t \mapsto at + b$ requires some change of constant parameters depending on $a, b \in \mathbb{R}$, possibly with change in signs. Hence, we know the arc $\gamma_k^n : [0, \frac{1}{n}] \rightarrow \mathbb{H} \cup \{0\}$ corresponding to the piecewise-linear force $\lambda^n(t_k(t) + t) - \lambda^n(t_k(t))$ with $t \in [0, \frac{1}{n}]$ has an image which vertically stretches monotonically upward and horizontally either leftward or rightward. Hence, the images $\gamma_k^n([0, \frac{1}{n}])$ attains its maximal height at its tip $\gamma_k^n(\frac{1}{n})$, which justifies our choice of $z = \gamma_k(s)$.

In this regard we could use Lem. 5.9 and Lem. 5.10 to give an upper bound to the second term in Ineq. (5.5).

Now, let us turn our attention to the third term in Ineq. (5.5). This is actually a perturbation term: we need to measure the difference of one point in \mathbb{H} under two conformal maps. In order to estimate the third term in Ineq. (5.5), we use the following result.

Lemma 5.12. ([15], Lem. 2.2) *Let $0 < T < \infty$. Suppose $f_t^{(1)}$ and $f_t^{(2)}$ are the inverse map to the forward Loewner chain satisfying Eqn. (2.1) with driving force $W_t^{(1)}$ and $W_t^{(2)}$, respectively. Define $\epsilon := \sup_{s \in [0, T]} |W_s^{(1)} - W_s^{(2)}|$. Then if $u = x + iy \in \mathbb{H}$, we have*

$$|f_T^{(1)} - f_T^{(2)}| \leq \epsilon \exp \left\{ \frac{1}{2} \left[\log \frac{I_{T,y} |\partial_z f_T^{(1)}(u)|}{y} \log \frac{I_{T,y} |\partial_z f_T^{(2)}(u)|}{y} \right]^{\frac{1}{2}} + \log \log \frac{I_{T,y}}{y} \right\}, \quad (5.10)$$

where $I_{T,y} := \sqrt{4T + y^2}$.

Applying Lem. 5.12 to estimate the third term in Ineq. (5.5), combining the estimate to the first and the second terms, on the event $F_{n,1} \cap F_{n,2}$, we see that

$$\sup_{t \in [0,1]} |\gamma(t) - \gamma^n(t)| \leq \frac{c_6 (\log n)^{c_7}}{n^{(1 - \sqrt{(1+\beta_1)/2})/2}}, \quad (5.11)$$

for $\beta_1 \in (0, 1)$. By definition of the event $F_n \in \Omega$, we know $F_{n,1} \cap F_{n,2} \subset F_n$. Moreover using the probability bounds on the events $F_{n,1}$ and $F_{n,2}$ in Ineq. (5.3), we obtain Thm. 5.8.

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