Hölder continuity of measures for heavy tail potentials

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Abstract

For a class of potentials ψ satisfying a condition depending on the roof function of a suspension (semi)flow, we show an EKP inequality, which can be interpreted as a Hölder continuity property in the weak* norm of measures, with respect to the pressure of those measures, where the Hölder exponent depends on the L^q-space that ψ belongs to. This also captures a new type of phase transition for intermittent (semi)flows (and maps).

1 Introduction

There exists a wide range of dynamical systems having a unique measure of maximal entropy. That is, there exists a unique measure μ_0 satisfying $h(\mu_0) = \sup\{h(\mu) : \mu \in \mathcal{M}\}$, where $h(\mu)$ denotes the entropy of the measure μ and $\mathcal{M}$ the space of invariant probability measures. Assume that the phase space is compact and the entropy map is upper semi-continuous (with respect to the weak* topology). In this setting, if $(\mu_n)_n$ is a sequence in $\mathcal{M}$ such that $\lim_{n\to\infty} h(\mu_n) = h(\mu)$, then $(\mu_n)_n$ converges to μ. In particular, for any Lipschitz function ψ, we have $\int \psi \, d\mu_n \to \int \psi \, d\mu_0$. Polo [P, Theorem 4.1.1] made this statement effective for hyperbolic automorphisms of the tori and its corresponding measure of maximal entropy μ_0 (the Haar measure). Indeed, he proved that there exists a constant $C > 0$ such that for any invariant probability measure μ and any Lipschitz function ψ, with Lipschitz constant L,

$$\left| \int \psi \, d\mu - \int \psi \, d\mu_0 \right| \le CL \left(h(\mu_0) - h(\mu) \right)^{1/3}. \tag{1.1}$$

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This result can be thought of as a Hölder continuity property in the weak* norm of measures. According to Polo [P, p.6] it was Einsiedler who outlined the argument for the proof of equation (1.1) in the case of $\times 2$ map. Kadyrov [K, Theorem 1.1] later extended this result to sub-shifts of finite type (defined over finite alphabets). In his case, instead of a cubic root, he had a quadratic root. Inequalities as (1.1) are now called EKP-inequalities after these authors. The case of countable Markov shifts has been studied recently. In that setting the phase space is no longer compact and the entropy map is not always upper semi-continuous. Moreover, there are cases in which there is no measure of maximal entropy. Therefore, further of assumptions are required in order for EKP-inequalities to make sense. For example, Rühr [R, Theorem 1.1] studied countable Markov shifts satisfying a combinatorial assumption (the BIP-property). This class of systems shares many properties with sub-shifts of finite type. However, they have infinite entropy, thus EKP-inequalities do not make sense for the measures of maximal entropy. Instead, he considered the Gibbs measure associated to a locally Hölder function of finite pressure. In that setting the right hand side of the EKP-inequality has the free energy of the measures (instead of the entropy) and a square root. Since systems having the BIP property are similar to subshifts of finite type, the arguments in the proof are close to those developed by Kadyrov. Sarig and Rühr recently studied finite entropy countable Markov shifts. In this case, instead of making a strong assumption on the system, they consider strongly positive recurrent (SPR) functions. Potentials in this class have unique equilibrium measures and the corresponding transfer operator acts with spectral gap in appropriate Banach spaces [CS, Theorem 2.1]. They proved [RS, Theorem 6.1] that if ϕ is an SPR regular function, μ_ϕ is the associated equilibrium measure and ψ a regular function, then for any invariant measure μ with sufficiently large free energy $P_\mu(\phi)$ (see Section 2.1) we have

$$\left| \int \psi \, d\mu - \int \psi \, d\mu_0 \right| \leq C\sigma \sqrt{P(\phi) - P_\mu(\phi)}, \tag{1.2}$$

where $P(\phi)$ is the pressure of ϕ and σ^2 is the asymptotic variance of ψ with respect to μ_0 (which in turn is related to the second derivative of the pressure).

In this article we prove EKP-inequalities for continuous time dynamical systems. Indeed, we study suspension (semi)flows over Gibbs Markov maps $T : Y \to Y$, and unbounded roof function $\tau : Y \to (0, \infty)$ with $\inf \tau > 0$ satisfying certain additional assumptions. Our main focus is towards systems with weak hyperbolicity properties. We denote the (semi)flow by $(F_t)_t$ and the suspension space by Y^τ. We refer to Section 2 for details. Consider a regular potential ϕ and its corresponding positive entropy equilibrium state ν_ϕ. In our main results we establish several EKP-inequalities for ν_ϕ, for a regular function ψ and for invariant measures ν satisfying $\int \psi \, d\nu > \int \psi \, d\nu_\phi$. We bound the difference $\int \psi \, d\nu - \int \psi \, d\nu_\phi$ with terms of form $(P(\phi) - P_\nu(\phi))^\rho$. The values of ρ are related to dynamical properties of the system.

In order to be more precise, we have two basic assumptions. The first (GM0) describes the decay of the tail of the measure on the base map T. It essentially says that there exists $\beta > 1$ such that $\mu(\tau > x) \leq cx^{-\beta}$. In order to state our second assumption (GM1), recall that every potential ψ for the (semi)flow has an induced version $\bar{\psi}$ defined on Y. The assumptions of our results are in terms of the induced potentials. It states that $\bar{\psi} = C_0 - \psi_0$, where $0 \leq \psi_0 \leq C_1\tau^\gamma$ and $\gamma \in (\beta - 1, \beta)$. We stress that this assumptions are fulfilled by a wide range of functions ψ.

In our first result, Theorem 2.6, we assume that $\beta/\gamma > 3$. We show that there exists $\epsilon > 0$ such that for any $\nu \in \mathcal{M}_F$, with $\int \psi \, d\nu \in \left(\int \psi \, d\nu_\phi, \int \psi \, d\nu_\phi + \epsilon\right)$, we have

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \leq C_{\phi,\psi}\sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)},$$

where σ^2 is the asymptotic variance of ψ with respect to ν_ϕ and where $C_{\phi,\psi} \geq 1$ tends to 1 as $\int \psi \, d\nu \to \int \psi \, d\nu_\phi$.

We note that in the expression above, as well as those in (a) and (b) below are only useful when $\int \psi \, d\nu > \int \psi \, d\nu_\phi$. It can be shown in the main examples of this theory that this is intrinsically necessary[1], rather than an artefact of the proof, i.e., we can not put absolute value signs on the left hand side of these equations and allow $\int \psi \, d\nu < \int \psi \, d\nu_\phi$. A natural example of this, as in Section 7.1, is in the intermittent map case with an absolutely continuous equilibrium state ν_ϕ (with an extension to suspensions over these) where there is a parabolic fixed point at 0 so that δ_0 is also an equilibrium state. In this case, by assuming ψ is strictly negative around 0 and positive away from that we can produce a ψ as above such that $\int \psi \, d\mu_\phi > 0$ and $\psi(0) < 0$, so $P_{\nu_\phi}(\phi) - P_{\delta_0}(\phi) = 0$ and $|\int \psi \, d\delta_0 - \int \psi \, d\nu_\phi| > 0$.

In our second main result, Theorem 2.7, we consider the cases in which $\beta/\gamma \in (1, 2]$ and $\beta/\gamma \in (2, 3)$ (with some additional assumptions). This result captures a new type of phase transition. Indeed, while item (b) below shows a EKP inequality in the case $\beta/\gamma \in (2, 3)$ (when CLT is present), item (a) gives a new type of EKP inequality with the exponent changing from 1/2 to one depending on the ratio β/γ. Interestingly, this result captures the transition form stable law to CLT in terms of the Hölder continuity of the pressure (see Remark 2.8.)

(a) If $\beta/\gamma \in (1, 2]$, then

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \leq c_2(P_{\nu_\phi}(\phi) - P_\nu(\phi))^{\frac{\beta-\gamma}{\beta-\gamma+1}}$$

(b) If $\beta/\gamma \in (2, 3)$, then

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \leq c_3\sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)}.$$

[1] though if $\mu(\tau > x)$ decays exponentially then the proofs can be rewritten to recover a statement like (1.2).

The proof of our results is based on asymptotic estimates of the pressure function $s \mapsto P_F(\phi + s\psi)$. For example, in Proposition 2.2 we prove, under the assumptions (GM0) and (GM1), that if $q_1 \in [1, \beta/\gamma]$ then $P_F(\phi + s\psi)$ is of class C^{q_1}. In Proposition 2.4, under (GM0) and an assumption on the decay of the tail of the measure, we establish estimates of the type: if $\beta/\gamma \in (1, 2]$, then $P''_F(\phi + s\psi) = Cs^{\beta-\gamma-1}(1 + o(1))$. Moreover, if $\beta/\gamma \in (2, 3)$, then $P''_F(\phi + s\psi) = -Cs^{\beta-2\gamma-1}(1 + o(1))$. These estimates are essential in the proofs of the main results and are obtained building up from [BTT1, BTT2, MT]. With these in hand we make use of the restricted pressure in a similar way as [RS].

In Section 7, examples of dynamical systems for which the results obtained in the article apply are provided. We construct suspension flows over maps exhibiting weak forms of hyperbolicity. Indeed, the class of interval maps we consider have parabolic fixed points. This shows the strength of our main results.

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2 Suspension flows over Gibbs Markov (GM) maps with unbounded roof τ

2.1 Thermodynamic formalism for suspension flows

Let $T : Y \to Y$ be a map and $\tau : Y \to (0, \infty)$ a positive function with $\inf \tau > 0$. Consider the space $Y^\tau = Y \times [0, \infty)/ \sim$ where $(y, \tau(y)) \sim (T(y), 0)$. The suspension (semi)flow over T with roof function τ is the (semi)flow $(F_t)_t$ defined by $F_t(y, t) = (y, t + t')$ for $t' \in [0, \tau(y))$.

Denote by $\mathcal{M}_F$ and by $\mathcal{M}_T$ the spaces of F-invariant and $T-$invariant probability measures correspondingly. There is a close relation between these spaces. Indeed, consider the subset of $\mathcal{M}_T$ for which τ is integrable. That is,

$$\mathcal{M}_T(\tau) := \left\{ \mu \in \mathcal{M}_T : \int \tau \, d\mu < \infty \right\}. \tag{2.1}$$

Let m denote the one-dimensional Lebesgue measure and $\mu \in \mathcal{M}_T(\tau)$, it follows directly from classical results by Ambrose and Kakutani [AK] that

$$\nu = \frac{(\mu \times m)|_Y}{(\mu \times m)(Y)} = \frac{(\mu \times m)|_Y}{\int \tau \, d\mu} \in \mathcal{M}_F. \tag{2.2}$$

Actually, under the assumption that $\inf \tau > 0$, equation (2.2) establishes a one-to-one correspondence between measures in $\mathcal{M}_F$ and measures in $\mathcal{M}_T(\tau)$. We say that μ is the *lift* of ν and that ν is the *projection* of μ. In the setting of this article, every measure in $\mathcal{M}_F$ lifts to some measure in $\mathcal{M}_T$.

The entropies of measures as in equation (2.2) are related. Indeed, for $\mu \in \mathcal{M}_T$ and $\nu \in \mathcal{M}_F$ denote by $h_T(\mu)$ and $h_F(\nu)$ the corresponding entropies. Abramov [Ab] proved that $h_F(\nu) = \frac{h_T(\mu)}{\int \tau \, d\mu}$.

It is also possible to relate the integral of a function on the flow to a corresponding one on the base. Let $\phi : Y^\tau \to \mathbb{R}$, we define its induced version $\bar{\phi}(x) : Y \to \mathbb{R}$ by $\bar{\phi}(x) = \int_0^{\tau(x)} \phi \circ F_t(x, 0) \, dt$. Let $\mu \in \mathcal{M}_T$ and $\nu \in \mathcal{M}_F$ be related as in equation (2.2). Kac's formula establishes the following relation, $\int \phi \, d\nu = \frac{\int \bar{\phi} \, d\mu}{\int \tau \, d\mu}$.

Having related the spaces of invariant measures, the corresponding entropies and integrals, it should come as no surprise that thermodynamic formalism on the flow is related to that on the base. Given a regular function $\phi : Y^\tau \to \mathbb{R}$, we define the *pressure* of ϕ (with respect to the (semi)flow F) by

$$P_F(\phi) := \sup \left\{ h_F(\nu) + \int \phi \, d\nu : \nu \in \mathcal{M}_F \text{ and } \int \phi \, d\nu > -\infty \right\}.$$

It will be convenient to write $P_{F,\nu}(\phi) = h_F(\nu) + \int \phi \, d\nu$ for $\nu \in \mathcal{M}_F$, when this sum makes sense. We call $\nu \in \mathcal{M}_F$ an *equilibrium state* for ϕ if $P_{F,\nu}(\phi) = P_F(\phi)$, and write $\nu = \nu_\phi$. Similarly, the *pressure* of $\bar{\phi} : Y \to \mathbb{R}$ (with respect to the map T) is defined by

$$P_T(\bar{\phi}) := \sup \left\{ h_T(\mu) + \int \bar{\phi} \, d\mu : \mu \in \mathcal{M}_T \text{ and } \int \bar{\phi} \, d\mu > -\infty \right\}.$$

Again, it will be convenient to write $P_{T,\mu}(\bar{\phi}) = h_T(\mu) + \int \bar{\phi} \, d\mu$ for $\mu \in \mathcal{M}_T$, when this sum makes sense. We call $\mu \in \mathcal{M}_T$ an *equilibrium state* for $\bar{\phi}$ if $P_{T,\mu}(\bar{\phi}) = P_T(\bar{\phi})$ and write $\mu = \mu_{\bar{\phi}}$.

Remark 2.1 Note that, under the assumptions we have considered here, Abramov and Kac's formula imply that,

$$P_F(\phi) = \sup \left\{ \frac{h_T(\mu) + \int \bar{\phi} \, d\mu}{\int \tau \, d\mu} : \mu \in \mathcal{M}_T(\tau) \text{ and } \int \bar{\phi} \, d\mu > -\infty \right\}.$$

We will assume that $P_F(\phi) = 0$ (otherwise we can shift the potential by a constant). This implies that $P_T(\bar{\phi}) \leq 0$. Moreover, in this paper liftability of all measures implies that in fact that $P_T(\bar\phi) = 0$. Under an integrability condition equilibrium states for ϕ and $\bar\phi$ are also related. Indeed, if $\mu_{\bar\phi} \in \mathcal{M}_T(\tau)$ then the equilibrium state for ϕ is

$$\nu_\phi = \frac{(\mu_{\bar\phi} \times m)|_Y}{\int \tau \, d\mu_{\bar\phi}}.$$

We conclude this section with the following definition which is analogous to [RS, Definition 3.1],

$$p(t) := P_F(\phi + t\psi) = \sup\left\{ \frac{P_{T,\mu}(\overline{\phi + t\psi})}{\int \tau \, d\mu} : \mu \in \mathcal{M}_T(\tau) \text{ and } \int \overline{\phi + t\psi} \, d\mu > -\infty \right\}.$$

2.2 Gibbs Markov maps and the main assumptions

Roughly speaking, Gibbs-Markov maps are infinite branch uniformly expanding maps with bounded distortion and big images. We recall the definitions in more detail. Let (Y, μ_Y) be a probability space, and let $T : Y \to Y$ be an ergodic measure-preserving transformation. Define $s(y, y')$ to be the least integer $n \geq 0$ such that $T^n y$ and $T^n y'$ lie in distinct partition elements. Assuming that $s(y, y') = \infty$ if and only if $y = y'$ one obtains that $d_\theta(y, y') = \theta^{s(z,z')}$ for $\theta \in (0, 1)$ is a metric.

Let $g = \frac{d\mu}{d\mu \circ T} : Y \to \mathbb{R}$. We say that T is a Gibbs-Markov map if there is an at most countable measurable partition $\{a\}$

- $T(a)$ is a union of partition elements and $T|_a : a \to T(a)$ is a measurable bijection for each $j \geq 1$ such that $T(a)$ is the union of elements of the partition modμ;
- $\inf_a \mu(T(a)) > 0$;
- There are constants $C > 0$, $\theta \in (0, 1)$ such that $|\log g(y) - \log g(y')| \leq C d_\theta(y, y')$ for all $y, y' \in a$, $j \geq 1$.

See, for instance, [A1, Chapter 4] and [AD] for background on Gibbs-Markov maps. Note that under these assumptions, μ_Y must have positive entropy.

Given $v : Y \to \mathbb{R}$, let

$$D_a v = \sup_{y, y' \in a, \, y \neq y'} |v(y) - v(y')|/d_\theta(y, y'), \qquad |v|_\theta = \sup_{j \geq 1} D_a v.$$

Te space $\mathcal{B}_\theta \subset L^\infty$ consisting of the functions $v : Y \to \mathbb{R}$ such that $|v|_\theta < \infty$ with norm $\|v\|_{\mathcal{B}_\theta} = |v|_\infty + |v|_\theta < \infty$ is a Banach space.

We will also be interested in functions $v : Y \to \mathbb{R}$ such that there is some $C > 0$ so that

$$D_a v \leq C \inf(1_a v), \qquad \forall a \in \{a\}. \tag{2.3}$$

In this section, we assume that the roof function $\tau : Y \to \mathbb{R}_+$ is unbounded and so that

(GM0) $\mu_Y(\tau > x) \le cx^{-\beta}$, $\beta > 1$ for some $c > 0$ depending on the map T. Moreover, we assume that $\operatorname{essinf} \tau > 0$ and that τ satisfies (2.3).

The class of potentials we shall work with is as in [BTT1, BTT2], which is very natural in the unbounded roof function case. Given the suspension Y^τ and the suspension flow $F : Y^\tau \to Y^\tau$, consider the potential $\psi : Y^\tau \to \mathbb{R}$. Our assumptions are in terms of the induced potentials $\overline{\psi}(x)$.

(GM1) Under (GM0), we further assume that $\overline{\psi} = C_0 - \psi_0$, where $0 \le \psi_0(y) \le C_1 \tau^\gamma(y)$, for $C_0, C_1 > 0$ and $\gamma \in (\beta - 1, \beta)$. Moreover, we assume ψ_0 is piecewise C^η, $\operatorname{essinf} \psi_0 > 0$ and ψ_0 satisfies (2.3).

We note that under (GM0),

$$\tau \in L^{q_0}(\mu_{\overline{\phi}}), \text{ for any } 1 \le q_0 < \beta. \tag{2.4}$$

and under (GM1),

$$\psi_0 \in L^{q_1}(\mu_{\overline{\phi}}), \text{ for any } 1 \le q_1 < \beta/\gamma. \tag{2.5}$$

We note that for $q_1 > 2$ (so, $\beta/\gamma > 2$) and ψ is not cohomologous to a constant, $\frac{\bar{\psi}_n - n\mu_{\overline{\phi}}(\bar{\psi})}{\sqrt{n}}$ converges in distribution to a Gaussian random variable with zero mean and variance $\bar{\sigma}^2 = \int_Y \left(\bar{\psi} - \int_Y \bar{\psi}\, d\mu_{\overline{\phi}}\right)^2 d\mu_{\overline{\phi}}$. A classical lifting scheme [MTo] ensures that the CLT holds for the original potential $\psi : Y^\tau \to Y^\tau$ with mean zero and non zero variance σ^2. In this case, given that $\nu_\phi = \frac{\mu_{\overline{\phi}} \times m|_Y}{\int_Y \tau\, d\mu_{\overline{\phi}}}$ is the unique equilibrium state for ϕ (this is a classical lifting scheme: see, for instance, the review in [BTT2, Section 3]). Let

$$\sigma^2 = \lim_{T\to\infty} \frac{1}{T} Var(\psi_T), \quad \psi_T = \int_0^T \psi \circ F_t \, dt, \quad Var(\psi) = \int_{Y^\tau} \left(\psi - \int_{Y^\tau} \psi \, d\nu_\phi\right)^2 d\nu_\phi.$$

It follows from [MTo] that, for $\tau^* := \int_Y \tau \, d\mu_{\bar{\phi}}$,

$$\sigma^2 = \frac{\bar{\sigma}^2}{\tau^*} = \frac{\int_Y \left(\bar{\psi} - \int_Y \bar{\psi}\, d\mu_{\overline{\phi}}\right)^2 d\mu_{\overline{\phi}}}{\tau^*}. \tag{2.6}$$

For non-integer $q_* \in \mathbb{R}_+$, we write $[q_*]$ for the integer part and say that a function $g : \mathbb{R} \to \mathbb{R}$ is C^{q_*} if $|g|_{C^{[q_*]}} < \infty$ and $\sup_{x_1 \ne x_2} |x_1 - x_2|^{-(q_* - [q_*])} |\frac{d}{d^{[q_*]}} g(x_1) - \frac{d}{d^{[q_*]}} g(x_2)| < \infty$.

2.3 Key propositions

Combining and adapting arguments from [BTT1, BTT2, MT], we obtain

Proposition 2.2 *Assume (GM0) and (GM1). Assume that* $q_0 \in [1, \beta)$ *and* $q_1 \in [1, \beta/\gamma)$*. Then there exists* $\delta_0 > 0$ *so that for all* $u, s \in [0, \delta_0)$*,*

(i) $\bar{p}(u, s) := P_T(\overline{\phi + s\psi - u})$ *is* C^{q_0} *in* u *and* C^{q_1} *in* s*.*

(ii) Define $p(s) := P_F(\phi + s\psi)$ *and assume* $p(s) > 0$ *for* $s > 0$*. Then*

$$p(s) = \frac{\bar{p}(0, s)}{\tau^*}(1 + o(1)), \text{ as } s \to 0$$

and $p(s)$ *is* C^{q_1}*.*

Writing $p'(s)$ *for the first derivative,* $p'(0) = \frac{\overline{\psi}^*}{\tau^*} := \frac{\int_Y \overline{\psi}\, d\mu_{\bar{\phi}}}{\int_Y \tau\, d\mu_{\bar{\phi}}}$*.*

(iii) Suppose $q_1 > 2$ *and write* $p''(s)$ *for the second derivative. Then* $p''(0) = \sigma^2$*, where* $\sigma^2 = \sigma_{\nu_\phi}(\psi)^2$ *is as in* (2.6)*.*

Remark 2.3 We note that the restrictions posed on the class of potentials considered in (GM1) is not just a matter of simplification. Hypothesis (GM1) or variants of it are needed to ensure that the transfer operators perturbed with real valued potentials defined in Section 3 are well defined in $\mathcal{B}_\theta$. This is a necessary ingredient for the relation between eigenvalues and pressure function: see Section 3 below.

As we will show in Section 3, item (ii) of Proposition 2.2 follows from item (i) together with the Implicit Function Theorem (IFT). For the case of LSV maps (as in [LSV]; they are a type of AFN maps, see Section 7) with infinite measure, an implicit equation was exploited in the proof of [BTT1, Proof of Theorem 4.1]. For the proof of item i), we adapt the arguments in [BTT1] to the case of finite measure. For the proof of item ii), we combine the 'implicit' equation in [BTT1, Proof of Theorem 4.1] with the IFT, which is natural since here we are interested in the smoothness of $P_T(\overline{\phi + s\psi})$.

While Proposition 2.2 will allow us to obtain the expected EKP inequality for $q_1 > 3$ (so $\beta/\gamma > 3$, see (2.5)), in the case $\beta/\gamma < 3$, we need a refined version under stronger assumptions. The next proposition tells us how the second derivative of $p(s)$ blows up as $s \to 0$ when $\beta/\gamma \in (1, 2]$ and, how the third derivative blows up as $s \to 0$ when $\beta/\gamma \in (2, 3)$, respectively. (It also gives the speed of covergence of the first and second derivatives to $p'(0)$ and $p''(0)$, respectively.)

Proposition 2.4 *Assume (GM0) with* $\mu_Y(\tau > x) = cx^{-\beta}(1 + o(1))$ *for* $\beta \in (1, 2)$*. Suppose that (GM1) holds with* $\psi_0 = C_1\tau^\gamma$ *with* $\gamma \in (\beta - 1, 1)$*. There exist* $C_2, C_3 > 0$ *depending only on* c, β, γ *and* τ^* *so that the following hold as* $s \to 0$*.*

(i) If $\beta/\gamma \in (1, 2]$*, then* $p''(s) = C_2 s^{\beta-\gamma-1}(1 + o(1))$*.*

(ii) If $\beta/\gamma \in (2, 3)$*, then* $p'''(s) = -C_3 s^{\beta-2\gamma-1}(1 + o(1))$*.*

Remark 2.5 (i) It is also possible to change the assumption on β and γ, but we need a definite assumption to state a final result. When $\gamma > 1$, the asymptotics are different. We do not consider other cases here as this would make the analysis even more tedious, though most of the calculations can be easily be adapted to fit this case.

(ii) If $\gamma = 1$ and $\beta > 1$, then we have the following scenario: (a) $p''(s) = C_2 s^{\beta-2}(1+o(1))$ if $\beta \in (1,2)$, (b) $p''(s) = C_3 \log(1/s)(1+o(1))$ if $\beta = 2$ and (c) $p'''(s) = C_4 s^{\beta-3}(1+o(1))$ if $\beta \in (2,3)$. We do not display the calculations in this case mainly because it does not lead to any interesting phase transition in the corresponding version of Theorem 2.7.

2.4 Main Theorems

Using Propositions 2.2 and 2.4, we obtain an interesting generalization of [RS] for the restricted pressure $q_{\phi,\psi}$. Though our class of potentials is, naturally, much more restricted than in (GM1). Theorems 2.6 and 2.7 below show the existence of a new *phase transition* in terms of whether ψ_0 is in $L^2(\mu_{\bar{\phi}})$ or not. In particular, when $\beta/\gamma > 2$ then ψ_0 is L^2 (recall (2.5)). The new phase transition is captured in Theorem 2.7.

The result below gives the EKP inequality when $q_1 > 3$ (with q_1 as in (2.5)) when CLT holds. Before the statement we recall that σ defined in (2.6) depends linearly on ψ.

Theorem 2.6 *Assume (GM0) and (GM1). Assume that $q_1 > 3$ (so $\beta/\gamma > 3$), assume that ψ is not cohomologous to a constant and let $\sigma = \sigma_{\nu_\phi}(\psi)$ be as defined in* (2.6) *and non-zero. There exists $\epsilon > 0$ so that for any F-invariant probability measure ν with $\int \psi \, d\nu \in \left(\int \psi \, d\nu_\phi, \int \psi \, d\nu_\phi + \epsilon\right)$, we have*

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \le C_{\phi,\psi}\sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)},$$

where $C_{\phi,\psi} \ge 1$ tends to 1 as $\int \psi \, d\nu \to \int \psi \, d\nu_\phi$.

For the equilibrium state ν_s of $\phi + s\psi$, we have

$$\left| \frac{\int \psi \, d\nu_s - \int \psi \, d\nu_\phi}{\sqrt{P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)}} - \sqrt{2}\sigma \right| = O\left(\sqrt{P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)}\right) \qquad \text{as } s \to 0. \tag{2.7}$$

The first result below addresses the case $q_1 < 3$. We consider two main cases for the ratio β/γ. It is precisely this result that captures the new type of phase transition. While item (b) of the result below shows a (familiar) EKP inequality in the case $\beta/\gamma \in (2,3)$ (when CLT is present), item (a) gives a new type of EKP inequality with the exponent changing from $1/2$ to one depending on the ratio β/γ. The transition is natural (see Remark 2.8).

Theorem 2.7 *Assume (GM0) with $\mu_Y(\tau > x) = cx^{-\beta}(1 + o(1))$, with $\beta \in (1, 2)$. Suppose that (GM1) holds with $\psi_0 = C_1\tau^\gamma$ with $\gamma \in (\beta - 1, 1)$.*

There exist $c_2, c_3 > 0$ so that the following hold for any F-invariant probability measure ν with $\int \psi\, d\nu > \int \psi\, d\nu_\phi$.

(a) If $\beta/\gamma \in (1, 2]$, then

$$\int \psi\, d\nu - \int \psi\, d\nu_\phi \le c_2(P_{\nu_\phi}(\phi) - P_\nu(\phi))^{\frac{\beta-\gamma}{\beta-\gamma+1}}$$

For the equilibrium states ν_s of $\phi + s\psi$, there is a constant[2] *$C_2 > 0$ such that*

$$\left| \frac{\int \psi\, d\nu_s - \int \psi\, d\nu_\phi}{(P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi))^{\frac{\beta-\gamma}{\beta-\gamma+1}}} - \frac{\beta}{\gamma} C_2^{-\frac{1}{\beta-\gamma}} \right| = o(1) \qquad \text{as } s \to 0. \tag{2.8}$$

(b) If $\beta/\gamma \in (2, 3)$, then

$$\int \psi\, d\nu - \int \psi\, d\nu_\phi \le c_3\sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)}.$$

For the equilibrium states ν_s of $\phi + s\psi$, we have

$$\left| \frac{\int \psi\, d\nu_s - \int \psi\, d\nu_\phi}{\sqrt{P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)}} - \sqrt{2}\sigma \right| = O\left((P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi))^{\frac{\beta-2\gamma}{2}} \right) \qquad \text{as } s \to 0. \tag{2.9}$$

Remark 2.8 (a) We recall that in the setup of Theorem 2.7 (a), $\psi_T = \int_0^T \psi \circ F_t\, dt$ satisfies a stable law of index β/γ. More precisely, $\frac{\psi_T - \int_{Y^\tau} \psi\, d\nu}{T^{\gamma/\beta}} \to^d M_{\beta/\gamma}$, where $M_{\beta/\gamma}$ is a random variable in the domain of a stable law with index $\beta/\gamma < 2$. But in item (b) we speak of CLT. Theorem 2.7 captures the transition from stable law to CLT in terms of the Hölder continuity of the pressure (in the weak* norm): the change in the Hölder exponent makes this precise.

(b) We believe that some version of item (a) persists if one weakens the assumption to $\psi_0 \in (C_1\tau^\gamma, C_2\tau^\gamma)$ with $C_1, C_2 > 0$, and even under weaker assumptions on the tail of τ. In addition to the need to control the precise upper and lower bounds for $p'(s) - p'(0)$ in Proposition 2.4(a) (which make the calculations seriously more cumbersome), one needs to ensure that $p''(s) > 0$. This is very heavy in terms of calculations without assumptions that ensure regular variation of ψ_0. We do not pursue this here.

[2] for C_2 as in Proposition 2.4(i).

Remark 2.9 We can interpret (2.8) and (2.9) in Theorem 2.7 (b) as follows: the pressure function has a polynomial (in fact quadratic) form for $\beta/\gamma \in (2,3)$, but as β/γ drops below 2, then the Hölder exponent jumps to $(\beta-\gamma+1)/(\beta-\gamma) > 1+1/\gamma > 2$. This gives a kink in the second derivative of the pressure as function of the weak*-norm of the measures. This represents a phase transition of order 3 if $(\beta-\gamma+1)/(\beta-\gamma) \in (2,3)$ or of higher order if $(\beta-\gamma+1)/(\beta-\gamma) \geq 3$.

3 Proof of Proposition 2.2

As customary in the literature, due to Ruelle-Perron-Frobenius (RPF) Theorem, in the setup of GM maps $F = f^\tau : Y \to Y$ (see, for instance, [BTT1, Section 3.3]), the study of the pressure function $P_T(\overline{\phi + s\psi})$ comes down to the study of a perturbed version of the transfer operator $R : L^1(\mu_{\bar\phi}) \to L^1(\mu_{\bar\phi})$. In particular, we identify $P_T(\overline{\phi + s\psi - u})$, $u \in [0,\delta)$, $s \in (0,\delta)$ for some $\delta > 0$ with $\log \lambda(u,s)$, where $\lambda(u,s)$ is the leading eigenvalue of the perturbed transfer operator

$$R(u,s)v = R(e^{-u\tau} e^{s\overline{\psi}} v), \qquad u,s \in [0,\delta_0),\ v \in L^1(\mu_{\bar\phi}).$$

We briefly recall the application of the RPF Theorem. Note that $R(0,0) = R$ for $u = s = 0$. We already know that R has a spectral gap in $\mathcal{B}_\theta$; in particular, this means that 1 is a simple eigenvalue, isolated in the spectrum of R. Under (GM1), there exists $\delta_0 > 0$ so that $\|R(u,s) - R(u,0)\|_{\mathcal{B}_\theta} \ll s^\epsilon$, for some $\epsilon > 0$ and all $u,s \in [0,\delta_0)$. The proof of this fact is standard; for instance, it is an easier version of [BTT1, Proof of Lemma 5.2] ($\beta < 1$ there gives some $\epsilon > 0$ here). In fact, much more is true: see Lemma 3.1 below. Since also $u \mapsto R(u,0)$ is analytic in $u \in [0,\delta_0)$, there exists a family of eigenvalues $\lambda(u,s)$ analytic in $u \in [0,\delta_0)$ and C^1 in $s \in [0,\delta_0)$ with $\lambda(0,0) = 1$. By the RPF Theorem,

$$\bar p(u,s) = P_T(\overline{\phi + s\psi - u}) = \log \lambda(u,s), \qquad u,s \in [0,\delta_0). \tag{3.1}$$

To study the smoothness of $\lambda(u,s)$, we need to recall some facts about the smoothness of $R(u,s)$. Let q_0 and q_1 be as in (2.4) and (2.5). Throughout, we write

$$G_{[q_0]}(u,s) = \frac{\partial^{[q_0]}}{\partial u^{[q_0]}} R(u,s), \quad H_{[q_1]}(u,s) = \frac{\partial^{[q_1]}}{\partial s^{[q_1]}} R(u,s) \tag{3.2}$$

and

$$K_{[q_1]}(u,s) = \frac{\partial^{[q_1]}}{\partial s^{[q_1]}} \frac{\partial}{\partial u} R(u,s). \tag{3.3}$$

Lemma 3.1 *Assume (GM0) and (GM1). Let q_0 and $q_1 \in [1,\beta/\gamma)$ be so that* (2.4) *and* (2.5) *hold.*

Let G, H and K as in (3.2) *and* (3.3). *Let $u,s \in [0,\delta_0)$. Then $\|G_{[q_0]}(u,s)\|_{\mathcal{B}_\theta} < \infty$ and $\|H_{[q_1]}(u,s)\|_{\mathcal{B}_\theta} < \infty$. Moreover, there exists $C > 0$ so that* *(i) for all* $u_1, u_2, s_1, s_2 \in [0, \delta_0)$,

$$\|G_{[q_0]}(u_1, s) - G_{[q_0]}(u_2, s)\|_{\mathcal{B}_\theta} \le C|u_1 - u_2|^{q_0 - [q_0]},$$

$$\|H_{[q_1]}(u, s_1) - H_{[q_1]}(u, s_2)\|_{\mathcal{B}_\theta} \le C|s_1 - s_2|^{q_1 - [q_1]}.$$

(ii) for all $u > 0$ *and* $s_1, s_2 \in [0, \delta_0)$, $\|K_{[q_1]}(u, s)\|_{\mathcal{B}_\theta} \le C u^{\beta - q_1\gamma - 1}$ *and*

$$\|K_{[q_1]}(u, s_1) - K_{[q_1]}(u, s_2)\|_{\mathcal{B}_\theta} \le C|s_1 - s_2|^{q_1 - [q_1]} \cdot u^{\beta - q_1\gamma - 1}.$$

Remark 3.2 Recall that under (GM1), $\gamma > \beta - 1$. Hence, $q_1 \in [1, \beta/\gamma)$ is so that $\beta - q_1\gamma < 1$. This means that in Lemma 3.1(ii), the factor in u blows up as $u \to 0$, but in a controlled way.

Proof The first statements on $G_{[q_0]}(u, s)$ and $H_{[q_1]}$ follow immediately from [MT, Proposition 12.1]. Assumption (A1) there is part of (GM0), (GM1) here and the involved constants depend on the L^{q_0}, L^{q_1} norm of $\tau, \bar{\psi}$ respectively, on $\theta \in (0, 1)$ and on the constants in (GM0), (GM1).

We sketch the argument for the statement on $H_{[q_1]}$ and as a consequence, the somewhat easier fact that $G_{[q_0]}(u, s)$ is C^{q_1} in s. By the argument used in the proof of [MT, Proposition 12.1], for $w \in L^1(\mu_{\bar{\phi}})$ with $\operatorname{essinf} w > 0$ and satisfying (2.3), we obtain

$$\|R(w\, v)\|_{\mathcal{B}_\theta} \le C|w|_{L^1(\mu_{\bar{\phi}})}|v|_\theta, \tag{3.4}$$

for some $C > 0$ depending on the constant appearing in (2.3).

Under (GM1), $\psi_0 \in L^{q_1}(\mu_{\bar{\phi}})$. Since $H_{[q_1]}(u, s)\tilde{v} = R(\bar{\psi}^{[q_1]} e^{-u\tau} e^{sC_0} e^{-s\psi_0}\tilde{v})$, the first statement on $H_{[q_1]}$ follows immediately from (3.4) with $w = \bar{\psi}^{[q_1]}$ and $v = e^{-u\tau} e^{sC_0} e^{-s\psi_0}\tilde{v}$. Throughout the rest of the proof, we will heavily exploit (3.4), but we will not write down the explicit form of w and v.

Proof of item (i) Using (3.4), we compute that

$$\begin{aligned}
\|(H_{[q_1]}(u, s_1) - H_{[q_1]}(u, s_2))v\|_{\mathcal{B}_\theta} &\le \left\|R\left(\bar{\psi}^{[q_1]}(e^{s_1 C_0} - e^{s_2 C_0})e^{-s_1\psi_0} e^{-u\tau} v\right)\right\|_{\mathcal{B}_\theta} \\
&\quad + \left\|R(\bar{\psi}^{[q_1]}(e^{-s_1\psi_0} - e^{-s_2\psi_0})e^{s_2 C_0} e^{-u\tau} v)\right\|_{\mathcal{B}_\theta} \\
&\le C_0|s_1 - s_2| \left\|R(\bar{\psi}^{[q_1]} e^{-s\psi_0} v)\right\|_{\mathcal{B}_\theta} + C\left|\bar{\psi}^{[q_1]}(e^{-s_1\psi_0} - e^{-s_2\psi_0})e^{-u\tau}\right|_{L^1(\mu_{\bar{\phi}})} |v|_\theta \\
&\le C'|s_1 - s_2|\, |\bar{\psi}^{[q_1]}|_{L^1(\mu_{\bar{\phi}})}|v|_\theta + C\left|\bar{\psi}^{[q_1]}(e^{-s_1\psi_0} - e^{-s_2\psi_0})e^{-u\tau}\right|_{L^1(\mu_{\bar{\phi}})} |v|_\theta,
\end{aligned}$$

for some $C, C' > 0$.

The second statement on $H_{[q_1]}$ follows since

$$|\bar{\psi}^{[q_1]}(e^{-s_1\psi_0} - e^{-s_2\psi_0})e^{-u\tau}\|_{L^1(\mu_{\bar{\phi}})} \ll |s_1 - s_2|^{q_1 - [q_1]}\, |\psi_0^{q_1}|_{L^1(\mu_{\bar{\phi}})} \ll |s_1 - s_2|^{q_1 - [q_1]}.$$

Proof of item (ii) First, $K_{[q_1]}(u,0) = -R(\bar\psi^{[q_1]}\tau e^{-u\tau})$. Using (3.4), $\|(K_{[q_1]}(u,0)v\|_{\mathcal{B}_\theta} \le C\left|\bar\psi^{[q_1]}\tau e^{-u\tau}\right|_{L^1(\mu_{\bar\phi})}$. To estimate this quantity, let $S(x)=\mu_{\bar\phi}(\tau > x)$ and recall from Remark 3.2 that $\beta - q_1\gamma < 1$. Integrating by parts and using (GM0),

$$\begin{aligned}
\int_Y \tau^{q_1\gamma+1}e^{-u\tau}\,d\mu_{\bar\phi} &= -\int_0^\infty x^{q_1\gamma+1}e^{-ux}\,d(1-S(x))\\
&= (q_1\gamma+1)\int_0^\infty x^{q_1\gamma}(1-S(x))e^{-ux}\,dx - u\int_0^\infty x^{q_1\gamma+1}(1-S(x))e^{-ux}\,dx\\
&\ll \int_0^\infty x^{-(\beta-q_1\gamma)}e^{-ux}\,dx + u\int_0^\infty x^{-(\beta-q_1\gamma+1)}e^{-ux}\,dx\\
&\ll u^{\beta-q_1\gamma-1}\left(\int_0^\infty \sigma^{-(\beta-q_1\gamma)}e^{-\sigma}\,d\sigma + \int_0^\infty \sigma^{-\beta+q_1\gamma+1}e^{-\sigma}\,d\sigma\right)\\
&\ll u^{\beta-q_1\gamma-1}. \qquad (3.5)
\end{aligned}$$

Hence, $\|(K_{[q_1]}(u,0)v\|_{\mathcal{B}_\theta} \le Cu^{\beta-q_1\gamma-1}$, as claimed.

Using that $K_{[q_1]}(u,s) = -R(\bar\psi^{[q_1]}\tau e^{-u\tau}e^{sC_0}e^{-s\psi_0})$, we compute that

$$\begin{aligned}
\left\|(K_{[q_1]}(u,s_1)-K_{[q_1]}(u,s_2))v\right\|_{\mathcal{B}_\theta} &\le \left\|R\left(\bar\psi^{[q_1]}\tau(e^{s_1C_0}-e^{s_2C_0})e^{-s_1\psi_0}e^{-u\tau}\,v\right)\right\|_{\mathcal{B}_\theta}\\
&\quad + \left\|R\left(\bar\psi^{[q_1]}\tau(e^{-s_1\psi_0}-e^{-s_2\psi_0})e^{s_2C_0}e^{-u\tau}\,v\right)\right\|_{\mathcal{B}_\theta}
\end{aligned}$$

Using (3.4) we obtain that there exists $C>0$ so that

$$\begin{aligned}
\|K_{[q_1]}(u,s_1)-K_{[q_1]}(u,s_2)\|_{\mathcal{B}_\theta} &\le C_0|s_1-s_2|\,\left|\bar\psi^{[q_1]}\tau e^{-u\tau}\right|_{L^1(\mu_{\bar\phi})}\\
&\quad + C\left|\bar\psi^{[q_1]}\tau(e^{-s_1\psi_0}-e^{-s_2\psi_0})e^{-u\tau}\right|_{L^1(\mu_{\bar\phi})}. \qquad (3.6)
\end{aligned}$$

Regarding the first term in (3.6), recall (GM1) and note that $|\bar\psi^{[q_1]}\tau e^{-u\tau}|_{L^1(\mu_{\bar\phi})} \ll |\tau^{q_1\gamma+1}e^{-u\tau}|_{L^1(\mu_{\bar\phi})}$. This together with (3.5) implies that the first term in (3.6) is bounded by $|s_1-s_2|\,u^{\beta-q_1\gamma-1}$.

It remains to estimate the second term in (3.6). Using (GM1), compute that

$$\begin{aligned}
\left|\psi_0^{[q_1]}\tau(e^{-s_1\psi_0}-e^{-s_2\psi_0})e^{-u\tau}\right|_{L^1(\mu_{\bar\phi})} &\ll |s_1-s_2|^{q_1-[q_1]}\cdot|\psi_0^{q_1}\,\tau e^{-u\tau}|_{L^1(\mu_{\bar\phi})}\\
&\ll |s_1-s_2|^{q_1-[q_1]}\cdot|\tau^{q_1\gamma+1}e^{-u\tau}|_{L^1(\mu_{\bar\phi})}.
\end{aligned}$$

By (3.5), $|\tau^{q_1\gamma+1}e^{-u\tau}|_{L^1(\mu_{\bar\phi})} \ll u^{\beta-q_1\gamma-1}$ and the conclusion follows. ∎

A consequence of Lemma 3.1 is that the family of eigenvalues $\lambda(u,s)$ has 'good' smoothness properties. Recall that $\tau^*, \bar\psi^*$ are as in Proposition 2.2 (ii).

Corollary 3.3 *The following hold in the setup of Lemma 3.1. Let $u,s\in[0,\delta_0)$.*

(i) $\lambda(u,s) = 1 + g(u,s)$*, where* $g(u,s) \to 0$ *as* $u, s \to 0$ *and* $g(u,s)$ *is* C^{q_0} *in* u *and* C^{q_1} *in* s*.*

(ii) $\frac{\partial}{\partial u}\lambda(u,s) = -\tau^* + d(u,s)$*, where* $d(u,s)$ *is* C^{q_0-1} *in* u *and* C^{q_1} *in* s *and* $d(u,0) \to 0$ *as* $u \to 0$*. Moreover,* $\frac{\partial}{\partial s}\lambda(u,s) = \bar{\psi}^* + e(u,s)$*, where* $e(u,s)$ *is* C^{q_0} *in* u *and* C^{q_1-1} *in* s*.*

(iii) Let $\kappa(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)$*. Then for all* $u, s \in [0, \delta_0)$*,* $|\kappa(u,s)| \le Cu^{\beta - q_1\gamma - 1}$ *and* $\kappa(u,s)$ *is* C^{q_1-1} *in* s*.*

Proof (i). Given that $v(u,s)$ is the normalized eigenvector corresponding to $\lambda(u,s)$,

$$\begin{aligned}
1 - \lambda(u,s) &= \int_Y (1 - e^{-u\tau}e^{s\bar{\psi}})\, d\mu_{\bar{\phi}} - \int_Y (1 - e^{-u\tau}e^{s\bar{\psi}})(v(0,0) - v(u,s))\, d\mu_{\bar{\phi}} \\
&:= \int_Y (1 - e^{-u\tau}e^{s\bar{\psi}})\, d\mu_{\bar{\phi}} - V(u,s) \\
&= \int_Y (1 - e^{-u\tau})\, d\mu_{\bar{\phi}} + \int_Y (1 - e^{s\bar{\psi}})\, d\mu_{\bar{\phi}} + \int_Y (1 - e^{-u\tau})(1 - e^{s\bar{\psi}})\, d\mu_{\bar{\phi}} - V(u,s)
\end{aligned} \tag{3.7}$$

By Lemma 3.1, $V(u,s) \to 0$, as $u, s \to 0$ and item (i) follows.

(ii). Using (3.7), compute that

$$\begin{aligned}
-\frac{\partial}{\partial u}\lambda(u,s) &= \int_Y \tau\, d\mu_{\bar{\phi}} - \int_Y \tau(1 - e^{-u\tau})\, d\mu_{\bar{\phi}} - \int_Y \tau e^{-u\tau}(1 - e^{s\bar{\psi}})\, d\mu_{\bar{\phi}} - \frac{\partial}{\partial u}V(u,s) \\
&:= \int_Y \tau\, d\mu_{\bar{\phi}} + d(u,s).
\end{aligned}$$

A calculation similar to the one used in obtaining (3.5) (via (GM0) and (GM1)) shows that the functions $\int_Y \tau(1 - e^{-u\tau})\, d\mu_{\bar{\phi}}$ and $\int_Y \tau e^{-u\tau}(1 - e^{s\bar{\psi}})\, d\mu_{\bar{\phi}}$ are C^{q_0-1} in u and also that $\int_Y \tau e^{-u\tau}(1 - e^{s\bar{\psi}})\, d\mu_{\bar{\phi}}$ is C^{q_1} in s. Note that

$$\frac{\partial}{\partial u}V(u,s) = \int_Y \tau e^{-u\tau}e^{s\bar{\psi}}(v(0,0) - v(u,s))\, d\mu_{\bar{\phi}} - \int_Y (1 - e^{-u\tau}e^{s\bar{\psi}})\, \frac{\partial}{\partial u}v(u,s))\, d\mu_{\bar{\phi}}.$$

The required smoothness properties of $\frac{\partial}{\partial u}v(u,s)$ in u and then in s, and as a consequence on $\frac{\partial}{\partial u}V(u,s)$, follow from the statement on G in Lemma 3.1(i) and from the statement on K in Lemma 3.1(iii). The statement on the smoothness of $\frac{\partial}{\partial u}\lambda(u,s)$ in u and s follows by putting all these together. Also, $d(u,0) = -\int_Y \tau(1 - e^{-u\tau})\, d\mu_{\bar{\phi}} + O(u)$ and (by, for instance, the Dominated Convergence Theorem applied to $\int_Y \tau(1 - e^{-u\tau})\, d\mu_{\bar{\phi}}$) we have $d(u,0) \to 0$ as $u \to 0$.

The statement on the smoothness of $\frac{\partial}{\partial s}\lambda(u,s)$ in u and s follows by a similar argument.

Item **(iii)** is an immediate consequence of Lemma 3.1(ii). ∎

We can now proceed to

Proof of Proposition 2.2. Throughout we will use Corollary 3.3 and the relation (3.1).

Proof of item (i). Since $\bar{p}(u,s) = \log \lambda(u,s)$, using Corollary 3.3 (i) and (ii),

$$\frac{\partial}{\partial u}\bar{p}(u,s) = \frac{\frac{\partial}{\partial u}\lambda(u,s)}{\lambda(u,s)} = -\tau^* + D(u,s), \quad \frac{\partial}{\partial s}\bar{p}(u,s) = \frac{\frac{\partial}{\partial s}\lambda(u,s)}{\lambda(u,s)} = \bar{\psi}^* + E(u,s), \tag{3.8}$$

where

(a) $D(u,s)$ is C^{q_0-1} in u and C^{q_1} in s. Also, $D(u,0) \to 0$ as $u \to 0$.

(b) $E(u,s)$ is C^{q_0} in u and C^{q_1-1} in s. Also, $D(u,0) \to 0$ as $u \to 0$.

In particular, $\bar{p}(0,s) = \lambda(0,s) - 1 + O(|1-\lambda(0,s)|^2)$ and

$$\frac{\partial}{\partial s}\bar{p}(0,s) = \frac{\frac{\partial}{\partial s}\lambda(0,s)}{\lambda(0,s)} = \bar{\psi}^* + E(0,s), \tag{3.9}$$

where $E(0,s)$ is C^{q_1-1} in s.

For use below in the proof of (ii), we also note that

$$\begin{aligned}\frac{\partial}{\partial s}D(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s) &= -\frac{\frac{\partial}{\partial u}\lambda(u,s)\frac{\partial}{\partial s}\lambda(u,s)}{\lambda(u,s)^2} + \frac{\frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)}{\lambda(u,s)} \\ &= -\bar{\psi}^*\tau^* - E_0(u,s) + \frac{\frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)}{\lambda(u,s)},\end{aligned} \tag{3.10}$$

where, using again Corollary 3.3 (i) and (ii), $E_0(u,s)$ is C^{q_0-1} in u and C^{q_1-1} in s. Moreover, $\kappa(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)$ satisfies the properties listed in Corollary 3.3 (iii). In particular, for all $u \in (0,\delta)$ and $s \in [0,\delta)$, we have $|\kappa(u,s)| \ll u^{\beta-q_1\gamma-1}$ and $\kappa(u,s)$ is C^{q_1-1} in s. It follows that

$$\frac{\partial}{\partial s}D(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s) = -\bar{\psi}^*\tau^* - E_1(u,s), \tag{3.11}$$

where $|E_1(u,s)| \ll u^{\beta-q_1\gamma-1}$ and $E_1(u,s)$ is C^{q_1-1} in s.

Proof of item (ii). We proceed via an 'implicit equation' exploited in [BTT1, Proof of Theorem 4.1] for the case $\beta < 1$ (infinite equilibrium states). By (i), $r(u,s) := \frac{\partial}{\partial u}\bar{p}(u,s)$ is well defined. For any small $u_0 > 0$,

$$\bar{p}(u_0,s) - \bar{p}(0,s) = \int_0^{u_0} r(u,s)\,du = -\tau^* u_0 + \int_0^{u_0} D(u,s)\,du, \tag{3.12}$$

where $D(u,s)$ is as in item (a) after (3.8).

By liftability, for $u_0 = u_0(s) = p(s) = P_F(\phi+s\psi)$, we obtain $P_T(\overline{\phi + s\psi - u_0}) = 0$. Hence the LHS of (3.12) is $-P_T(\overline{\phi + s\psi})$. By assumption, $u_0(s) > 0$ for all $s > 0$. The continuity of the pressure function gives that $u_0(s) \to 0$ as $s \to 0$. Thus, (3.12) holds for $u_0 = u_0(s)$ and

$$-\bar{p}(0, s) = -\tau^* u_0 + \int_0^{u_0} D(u, s)\, du := -\tau^* u_0 + L(u_0, s). \tag{3.13}$$

At this point we can conclude that

$$p(s) = u_0(s) = \frac{\bar{p}(0, s)}{\tau^*} = s\frac{\bar{\psi}^*}{\tau^*}(1 + o(1)), \text{ as } s \to 0. \tag{3.14}$$

The first equality follows immediately from (3.13), using the smoothness of $D(u, s)$ in s and the fact that $D(u, 0) \to 0$ (as in item (a) after (3.8)). The second equality follows immediately from (3.13). The third equality follows immediately from (3.9).

We continue with the study of the derivative in s of $u_0(s)$ via (3.13). Since $D(u, s)$ is uniformly continuous in u (since it is C^{q_0-1} in u), $\frac{\partial}{\partial u_0} L(u_0, s) = D(u_0, s)$, for all s. Set

$$M(u_0, s) := L(u_0, s) + \bar{p}(0, s),$$

and note that $\frac{\partial}{\partial u_0} M(u_0, s) = D(u_0, s) \neq 0$, for all u_0, s small enough. Since $M(u_0, s) - \tau^* u_0(s) \equiv 0$ and we also know that $|\frac{\partial}{\partial u_0} L(u_0, s)| < \infty$ and $|\frac{\partial}{\partial s} L(u_0, s)| < \infty$ (because $D(u_0, s)$ is C_1^q in s), the IFT ensures that $u_0(s)$ is differentiable in s and

$$u_0'(s) = \frac{\frac{\partial}{\partial s} M(u_0, s)}{\tau^* - \frac{\partial}{\partial u_0} M(u_0, s)}. \tag{3.15}$$

We first estimate the numerator in (3.15). Using (3.9),

$$\frac{\partial}{\partial s} M(u_0, s) = \frac{\partial}{\partial s} L(u_0, s) + \bar{\psi}^* + E(0, s),$$

where $E(0, s)$ is C^{q_1-1} in s. Using the definition of $L(u_0, s)$ in (3.13) and (3.11),

$$\begin{aligned} \left|\frac{\partial}{\partial s} L(u_0, s)\right| &= \left|\int_0^{u_0} \frac{\partial}{\partial s} D(u, s)\, du\right| = \left|\int_0^{u_0} \frac{\partial}{\partial s}\frac{\partial}{\partial u} \bar{p}(u, s)\, du\right| \\ &= \left|\bar{\psi}^* \tau^* u_0 + \int_0^{u_0} E_1(u, s)\, du\right| \ll u_0 + u_0^{\beta - q_1\gamma}. \end{aligned} \tag{3.16}$$

Moreover, using the smoothness properties of E_1, we obtain that $\frac{\partial}{\partial s} L(u_0, s)$ is C^{q_1-1} in s. Thus,

$$\frac{\partial}{\partial s} M(u_0, s) = \bar{\psi}^* + \hat{E}(u_0, s), \tag{3.17}$$

where $\hat{E}$ is well-defined in u_0 and C^{q_1-1} in s.

We continue with estimating the denominator in (3.15). Recall that $\frac{\partial}{\partial u_0}M(u_0,s) = D(u_0,s)$, where D is as in item (a) after (3.8). In particular, $D(u_0,s)$ is C^{q_1} in s. By (3.14), $u_0(s) = O(s)$. Using the smoothness of $D(u_0,s)$ in s, we note that

$$\frac{1}{\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)} = \frac{1}{\tau^* - D(u_0,s)} = \frac{1}{\tau^*}\left(1 + O(D(u_0,s))\right)^{-1} = \frac{1+o(1)}{\tau^*} \quad \text{as } s \to 0.$$

Recalling the smoothness properties of $\hat{E}(u_0,s)$ in (3.17), we obtain $p'(0) = \frac{\bar{\psi}^*}{\tau^*}$.

Proof of item (iii). When $q_1 > 2$, differentiating (3.15) once more in s,

$$u_0''(s) = \frac{\frac{\partial^2}{\partial s^2}M(u_0,s)(\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)) + \frac{\partial}{\partial s}M(u_0,s)\frac{\partial^2}{\partial s \partial u_0}M(u_0,s)}{\left(\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)\right)^2}. \tag{3.18}$$

A very lengthy but straightforward[3] calculation using the smoothness properties of the function $D(u_0,s)$ (after differentiating (3.16) once more in s) together with the fact that $u_0'(0) = \frac{\bar{\psi}^*}{\tau^*}$ and also with (3.11) shows that the numerator of (3.18) evaluated at 0 is $\bar{\sigma}^2\tau^*$, where $\bar{\sigma}^2 = \int_Y \left(\bar{\psi} - \int_Y \bar{\psi}^2\, d\mu_{\bar{\phi}}\right)^2 d\mu_{\bar{\phi}}$. As in the proof of item (ii), $\left(\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)\right)^{-2} = \frac{1}{(\tau^*)^2}(1+o(1))$ as $s \to 0$ and the result $p''(0) = \frac{\bar{\sigma}^2}{\tau^*} = \sigma^2$ follows. ∎

4 Refined estimates in the setup of Proposition 2.4

We start with a refined version of Lemma 3.1. Recall from (3.2) and (3.3) that $H_{[q_1]}(u,s)v = \frac{\partial}{\partial s^{[q_1]}}R(u,s)v = R(\bar{\psi}^{[q_1]}e^{-u\tau}e^{s\bar{\psi}}v)$ and that $K_{[q_1]}(u,s)v = \frac{\partial}{\partial s^{[q_1]}}\frac{\partial}{\partial u}R(u,s)v = -R(\bar{\psi}^{[q_1]}\tau e^{-u\tau}e^{s\bar{\psi}}v)$. The first result below tells us how the derivatives in s of H, K go to ∞ as $u,s \to 0$.

Lemma 4.1 *Assume the setup of Proposition 2.4, in particular $\gamma \in (\beta-1,\beta)$. Let $u,s \in [0,\delta_0)$.*

(i) If $[q_1] = 1$ and $\beta/\gamma \in (1,2]$ then $\|H_1(u,s)\|_{\mathcal{B}_\theta} < \infty$ and $\|K_1(u,0)\|_{\mathcal{B}_\theta} \le Cu^{\beta-\gamma-1}$, for some $C > 0$.

Furthermore, if $\beta/\gamma \in (1,2)$, there exists $C_2, C_3, C_4 > 0$ so that

$$\left\|\frac{\partial}{\partial s}H_1(u,s)\right\|_{\mathcal{B}_\theta} \le C_2 u^{\beta-2\gamma}, \quad \left\|\frac{\partial}{\partial s}K_1(u,s)\right\|_{\mathcal{B}_\theta} \le C_3 u^{\beta-2\gamma-1}.$$

[3]A refined version of this calculation is covered inside the proof of Proposition 2.4.

and

$$\left\|\frac{\partial}{\partial s}H_1(0,s)\right\|_{\mathcal{B}_\theta} \le C_4 s^{\beta/\gamma-2}.$$

If $\beta/\gamma = 2$, then there exists $C_2, C_3, C_4 > 0$ so that

$$\left\|\frac{\partial}{\partial s}H_1(u,s)\right\|_{\mathcal{B}_\theta} \le C_2\log(1/u), \quad \left\|\frac{\partial}{\partial s}K_1(u,s)\right\|_{\mathcal{B}_\theta} \le C_3 u^{-1}.$$

and

$$\left\|\frac{\partial}{\partial s}H_1(0,s)\right\|_{\mathcal{B}_\theta} \le C_4\log(1/s).$$

(ii) If $[q_1] = 2$ and $\beta/\gamma \in (2,3)$ then $\|H_2(u,s)\|_{\mathcal{B}_\theta} < \infty$ and $\|K_2(u,0)\|_{\mathcal{B}_\theta} \le Cu^{\beta-2\gamma-1}$, for some $C > 0$. Furthermore, there exists $C_2, C_3, C_4 > 0$ so that

$$\left\|\frac{\partial}{\partial s}H_2(u,s)\right\|_{\mathcal{B}_\theta} \le C_2 u^{\beta-3\gamma}, \quad \left\|\frac{\partial}{\partial s}K_2(u,s)\right\|_{\mathcal{B}_\theta} \le C_3 u^{\beta-3\gamma-1}.$$

and

$$\left\|\frac{\partial}{\partial s}H_2(0,s)\right\|_{\mathcal{B}_\theta} \le C_4 s^{\beta/\gamma-3}.$$

4.1 Some general type of integrals

Before the proving Lemma 4.1, we provide estimates of some general type of integrals. This or variants of it that will be used throughout the proofs of the technical results in this section. Let $S(x) = \mu_{\overline{\phi}}(\tau < x)$ and recall from (GM1) that $\gamma > \beta - 1$, so $\beta - \gamma < 1$. Since $1 - S(x) = cx^{-\beta}(1 + o(1))$,

$$\begin{aligned}\int_Y \tau^{\gamma+1}e^{-u\tau}\,d\mu_{\overline{\phi}} &= -\int_0^\infty x^{\gamma+1}e^{-ux}\,d(1-S(x))\\ &= (\gamma+1)\int_0^\infty x^\gamma(1-S(x))e^{-ux}\,dx - u\int_0^\infty x^{\gamma+1}(1-S(x))e^{-ux}\,dx\\ &= c(\gamma+1)(1+o(1))\int_0^\infty e^{-ux}x^{-\beta+\gamma}\,dx - u(1+o(1)\,c\int_0^\infty e^{-ux}x^{\gamma+1-\beta}\,dx\\ &= cu^{\beta-\gamma-1}(1+o(1))\left((\gamma+1)\int_0^\infty e^{-\sigma}\sigma^{-\beta+\gamma}\,d\sigma - \int_0^\infty e^{-\sigma}\sigma^{-\beta+\gamma+1},d\sigma\right)\\ &= Cu^{\beta-\gamma-1}(1+o(1)),\end{aligned} \tag{4.1}$$

for a positive C depending only on c, β, γ.

By a similar argument, if $\beta/\gamma \neq 2$, then

$$\begin{cases}\int_Y \tau^{2\gamma}e^{-u\tau}\,d\mu_{\overline{\phi}} = Cu^{\beta-2\gamma}(1+o(1)),\\ \int_Y \tau^{2\gamma+1}e^{-u\tau}\,d\mu_{\overline{\phi}} = C'u^{\beta-2\gamma-1}(1+o(1))\end{cases} \tag{4.2}$$

for some $C, C' > 0$, whereas if $\beta/\gamma = 2$ then

$$\begin{cases} \int_Y \tau^{2\gamma} e^{-u\tau}\, d\mu_{\overline{\phi}} = \int_Y \tau^{\beta} e^{-u\tau}\, d\mu_{\overline{\phi}} = C\log(1/u)(1+o(1)), \\ \int_Y \tau^{2\gamma+1} e^{-u\tau}\, d\mu_{\overline{\phi}} = \int_Y \tau^{\beta+1} e^{-u\tau}\, d\mu_{\overline{\phi}} = Cu^{-1}(1+o(1)). \end{cases} \tag{4.3}$$

Recall that $\bar{\psi} = C_0 - \psi_0 = C_0 - C_1\tau^\gamma$. Similar calculations, this time with $S(x) = \mu_{\overline{\phi}}(\psi_0 < x) = \mu_{\overline{\phi}}(C_1\tau^\gamma < x)$ show that if $\beta/\gamma < 2$, $\int_Y \psi_0^2 e^{-s\psi_0}\, d\mu_{\overline{\phi}} = Cs^{\beta/\gamma-2}(1+o(1))$ for some $C > 0$ and that if $\beta/\gamma \in (2,3)$, $\int_Y \psi_0^3 e^{-s\psi_0}\, d\mu_{\overline{\phi}} = -Cs^{\beta/\gamma-3}(1+o(1))$ for some $C > 0$. The involved constants depend only on c, β, γ. If $\beta/\gamma = 2$ then $\int_Y \psi_0^2 e^{-s\psi_0}\, d\mu_{\overline{\phi}} = C\log(1/s)(1+o(1))$. The involved constants (denoted by C here) depend only on c, β, γ.

Next, note that $\bar{\psi}^2 = C_0^2 + \psi_0^2 - 2C_0\psi_0$ and that $\bar{\psi}^3 = C_0^3 - \psi_0^3 + 3C_0^2\psi_0 - 3C_0\psi_0^2$. Thus, there exist C_2, C_3, C_4 depending only on c, β, γ so that

$$\begin{cases} \int_Y \bar{\psi}^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = C_2 s^{\beta/\gamma-2}(1+o(1)), & \text{if } \beta/\gamma < 2, \\ \int_Y \bar{\psi}^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = C_3\log(1/s)(1+o(1)), & \text{if } \beta/\gamma = 2, \\ \int_Y \bar{\psi}^3 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = -C_4 s^{\beta/\gamma-3}(1+o(1)) & \text{if } \beta/\gamma \in (2,3). \end{cases} \tag{4.4}$$

Proof of Lemma 4.1 We provide the argument for item (i). Item (ii) follows by a similar argument after taking one more derivative in s.

The first estimate on H_1 follows directly from Lemma 3.1 with $[q_1] = 1$.

Next, note that if $\beta/\gamma \in (1,2)$,

$$\left\| \frac{\partial}{\partial s} H_1(u,s) \right\|_{\mathcal{B}_\theta} \ll \|R(\bar{\psi}^2 e^{-u\tau})\|_{\mathcal{B}_\theta} \ll |\tau^{2\gamma} e^{-u\tau}|_{L^1(\mu_{\overline{\phi}})} \ll u^{\beta-2\gamma},$$

where we used (4.2). The estimate for the case $\beta/\gamma = 2$ follows similarly using (4.3). Also, if $\beta/\gamma \in (1,2)$,

$$\left\| \frac{\partial}{\partial s} H_1(0,s) \right\|_{\mathcal{B}_\theta} \ll \|R(\bar{\psi}^2 e^{s\bar{\psi}})\|_{\mathcal{B}_\theta} \ll |\bar{\psi}^2 e^{s\bar{\psi}}|_{L^1(\mu_{\overline{\phi}})} \ll s^{\beta/\gamma-2},$$

where we have used the first estimate of (4.4) for s. The estimate for the case $\beta/\gamma = 2$ follows similarly using the corresponding estimate of (4.4) for this case.

Regarding K_1, if $\beta/\gamma \in (1,2)$,

$$\left\| \frac{\partial}{\partial s} K_1(u,s) \right\|_{\mathcal{B}_\theta} \ll \|R(\bar{\psi}^2 \tau e^{-u\tau})\|_{\mathcal{B}_\theta} \ll |\tau^{2\gamma+1} e^{-u\tau}|_{L^1(\mu_{\overline{\phi}})} \ll u^{\beta-2\gamma-1},$$

where the second estimate after (4.1). The estimate for the case $\beta/\gamma = 2$ follows similarly using the corresponding estimates for this case. ∎

We shall also need the following refined version of Corollary 3.3 (ii) and (iii). Item (i) of Corollary 3.3 remains unchanged. Again, the derivatives in s of several quantities in the lemma below blow up as $u, s \to 0$ but in a controlled way.

We recall that in the setup of Proposition 2.4, $\gamma < 1$ and $\beta < 2$.

Lemma 4.2 *The following hold in the setup of Proposition 2.4. Let $u, s \in [0, \delta_0)$.*

(i) $\frac{\partial}{\partial u}\lambda(u,s) = -\tau^* + d(u,s)$, *where $d(u,s)$ is as follows.*

There exists $C > 0$ depending only on c, β so that $d(u,0) = Cu^{\beta-1}(1+o(1))$. Moreover, there exist $C_2, C_3 > 0$ depending only on c, β, γ so that as $u, s \to 0$,

$$\frac{\partial}{\partial s} d(u,s) = C_2 u^{\beta-\gamma-1}(1+o(1)), \text{ if } \beta/\gamma \in (1,2],$$

$$\frac{\partial^2}{\partial s^2} d(u,s) = C_3 u^{\beta-\gamma-2}(1+o(1)), \text{ if } \beta/\gamma \in (2,3).$$

(ii) The following holds for some $C, C' > 0$ depending only on $c, \beta/\gamma$.

$$\frac{\partial}{\partial s}\lambda(u,s) = \bar{\psi}^* + e(u,s) + \begin{cases} h(s) + h_0(s), & \text{if } \beta/\gamma \in (1,2], \\ -s\int_Y \bar{\psi}^2\, d\mu_{\bar{\phi}} + Cs^{\beta/\gamma-1} + h_1(s), & \text{if } \beta/\gamma \in (2,3), \end{cases}$$

where $h(s) = Cs^{\beta/\gamma-1}$ if $\beta/\gamma \in (1,2)$, $h(s) = C\log(1/s)$ if $\beta/\gamma = 2$ and where h_0, h_1 and e are as follows:

(a) $h_0(s) = o(s^{\beta/\gamma-1})$, $h_0'(s) = o(s^{\beta/\gamma-2})$ *if* $\beta/\gamma \in (1,2)$ *and* $h_0'(s) = o(\log(1/s))$ *if* $\beta/\gamma = 2$.

(b) $h_1(s) = o(s^{\beta/\gamma-1})$, $h_1'(s) = C's^{\beta/\gamma-2}(1+o(1))$ *and* $h_1''(s) = C's^{\beta/\gamma-3}(1+o(1))$;

(c) $e(0,s) = O(s)$, $e(u,0) = o(1)$ *as* $u, s \to 0$ *and*

(*) *If* $\beta/\gamma \in (1,2)$, *then* $\frac{\partial}{\partial s}e(u,s) = o(u^{\beta-\gamma-1}) + o(s^{\beta/\gamma-2})$. *Also,* $\frac{\partial}{\partial s}e(0,s) = o(s^{\beta/\gamma-2})$.

(**) *If* $\beta/\gamma = 2$, *then* $\frac{\partial}{\partial s}e(u,s) = o(u^{\beta-\gamma-1}) + o(\log(1/s))$. *Also,* $\frac{\partial}{\partial s}e(0,s) = o(\log(1/s))$.

(***) *If* $\beta/\gamma \in (2,3)$, *then* $\frac{\partial}{\partial s}e(u,s) = o(u^{\beta-\gamma-2}) + o(s^{\beta/\gamma-3})$. *Also,* $\frac{\partial}{\partial s}e(0,s) = o(s^{\beta/\gamma-3})$.

(iii) Let $\kappa(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)$. Then there exist $C, C' > 0$ depending only on c, β, γ,

$$\begin{cases} \kappa(u,0) = Cu^{\beta-\gamma-1} + O(u^{\beta-\gamma-1+\epsilon_0}), & \text{if } \beta/\gamma \in (1,2], \\ \frac{\partial}{\partial s}\kappa(u,s)\Big|_{s=0} = C'u^{\beta-2\gamma-1} + O(u^{\beta-2\gamma-1+\epsilon_0}), & \text{if } \beta/\gamma \in (2,3), \end{cases}$$

as $u \to 0$ and for any $\epsilon_0 > 0$.

Also, the following hold for some $\hat{C}_2, \hat{C}_3 > 0$ depending only on c, β, γ, as $u, s \to 0$.

(*) If $\beta/\gamma \in (1, 2]$, then $\frac{\partial}{\partial s}\kappa(u,s) = \hat{C}_2 u^{\beta-2\gamma-1}(1 + o(1))$.

(**) If $\beta/\gamma \in (2, 3)$, then $\frac{\partial^2}{\partial s^2}\kappa(u,s) = -\hat{C}_3 u^{\beta-3\gamma-1}(1 + o(1))$.

Proof of Lemma 4.2 We continue from the proof of Corollary 3.3 (ii) with the same notation.

Proof of item (i) Recall that

$$\begin{aligned}
-\frac{\partial}{\partial u}\lambda(u,s) &= \int_Y \tau\, d\mu_{\overline{\phi}} - \int_Y \tau(1 - e^{-u\tau})\, d\mu_{\overline{\phi}} - \int_Y \tau e^{-u\tau}(1 - e^{s\bar{\psi}})\, d\mu_{\overline{\phi}} \\
&\quad - \int_Y \tau e^{-u\tau} e^{s\bar{\psi}}(v(0,0) - v(u,s))\, d\mu_{\overline{\phi}} + \int_Y (1 - e^{-u\tau}e^{s\bar{\psi}})\, \frac{\partial}{\partial u} v(u,s)\, d\mu_{\overline{\phi}} \\
&:= \int_Y \tau\, d\mu_{\overline{\phi}} - \int_Y \tau(1 - e^{-u\tau})\, d\mu_{\overline{\phi}} - W_0(u,s) - W_1(u,s) - W_2(u,s).
\end{aligned} \tag{4.5}$$

Recall $\mu_Y(\tau > x) = cx^{-\beta}(1 + o(1))$. A standard calculation (mostly similar to the one used in obtaining (4.1)) shows that there exists $C > 0$ depending on c and β so that

$$-\int_Y \tau(1 - e^{-u\tau})\, d\mu_{\overline{\phi}} = Cu^{\beta-1}(1 + o(1)).$$

Set $d(u,s) = \int_Y \tau(1 - e^{-u\tau})\, d\mu_{\overline{\phi}} - W_0(u,s) - W_1(u,s) - W_2(u,s)$ with W_0, W_1, W_2 as defined in (4.5). Note that $W_0(u,0) = 0$, $|W_1(u,0)| \ll u$ and $|W_2(u,0)| \ll u$ and that so far we obtained the expression for $d(u,0)$.

Note that $\frac{\partial}{\partial s}d(u,s) = -\frac{\partial}{\partial s}(W_0(u,s) + W_1(u,s) + W_2(u,s))$. We continue with the derivatives in s of W_0, W_1, W_2 by considering each of the two cases.

The term $W_0(u,s)$. First, $\frac{\partial}{\partial s}W_0(u,s) = \int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = \int_Y \tau\bar{\psi}e^{-u\tau}\, d\mu_{\overline{\phi}} + \int_Y \tau\bar{\psi}e^{-u\tau}(e^{s\bar{\psi}} - 1)\, d\mu_{\overline{\phi}}$.

If $\beta/\gamma \in (1, 2]$, then $\beta - \gamma \in (0, 1)$. Since $\bar{\psi} = C_0 - C_1\tau^\gamma$,

$$\begin{aligned}
\int_Y \tau\bar{\psi}e^{-u\tau}\, d\mu_{\overline{\phi}} &= C_0 \int_Y \tau e^{-u\tau}\, d\mu_{\overline{\phi}} - C_1 \int_Y \tau^{\gamma+1}e^{-u\tau}\, d\mu_{\overline{\phi}} \\
&= -Cu^{\beta-\gamma-1}(1 + o(1)),
\end{aligned} \tag{4.6}$$

for some $C > 0$ depending on c and β, γ. In the last equality we have used that (4.1) holds as soon as $\beta - \gamma \in (0, 1)$. This together with the fact that $e^{s\bar{\psi}} - 1 \to 0$ as $s \to 0$

and the Dominated Convergence Theorem implies that $\int_Y \tau\bar{\psi}e^{-u\tau}(e^{s\bar{\psi}}-1)\,d\mu_{\overline{\phi}} = o(u^{\beta-\gamma-1})$. So, if $\beta/\gamma \in (1,2]$ then $\frac{\partial}{\partial s}W_0(u,s) = -Cu^{\beta-\gamma-1}(1+o(1))$.

If $\boldsymbol{\beta/\gamma \in (2,3)}$, then $\beta-2\gamma < \gamma < 1$ and $\beta-2\gamma \in (0,1)$. Note that $\frac{\partial^2}{\partial s^2}W_0(u,s) = \int_Y \tau\bar{\psi}^2 e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\overline{\phi}}$. Proceeding similarly to the argument above in the case $\beta/\gamma \in (1,2]$, we compute that if $\beta-2\gamma \in (0,1)$, then $\frac{\partial^2}{\partial s^2}W_0(u,s) = Cu^{\beta-2\gamma-1}(1+o(1))$ for some C depending on c and β,γ, where we use an analogue of (4.1) for the case $\beta-2\gamma \in (0,1)$. So, if $\beta/\gamma \in (2,3)$ then $\frac{\partial}{\partial s}W_0(u,s) = -Cu^{\beta-2\gamma-1}(1+o(1))$.

The term $\boldsymbol{W_1(u,s)}$. Start from

$$\frac{\partial}{\partial s}W_1(u,s) = \int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}(v(u,0)-v(u,s))\,d\mu_{\overline{\phi}} - \int_Y \tau e^{-u\tau}e^{s\bar{\psi}}\frac{\partial}{\partial s}v(u,s))\,d\mu_{\overline{\phi}}.$$

Recall that **if $\boldsymbol{\beta/\gamma \in (1,2]}$**, then $\beta-\gamma \in (0,1)$. Since

$$\|v(0,0)-v(u,s)\|_{\mathcal{B}_\theta} \le \|v(0,s)-v(u,s)\|_{\mathcal{B}_\theta} + \|v(u,0)-v(u,s)\|_{\mathcal{B}_\theta} \le u+s,$$

using (4.6), we obtain $\int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}(v(u,0)-v(u,s))\,d\mu_{\overline{\phi}} = o(u^{\beta-\gamma-1})$, as $u,s\to 0$. Also, by Lemma 4.1(i) (statement on H_1), $\|\frac{\partial}{\partial s}v(u,s)\|_{\mathcal{B}_\theta} < \infty$. Thus,

$$\left|\int_Y \tau e^{-u\tau}e^{s\bar{\psi}}\frac{\partial}{\partial s}v(u,s))\,d\mu_{\overline{\phi}}\right| \ll \int_Y \tau e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\overline{\phi}} = O(1).$$

Thus, if $\beta/\gamma \in (1,2]$, $\frac{\partial}{\partial s}W_1(u,s) = o(u^{\beta-\gamma-1})$, as $u,s\to 0$.

Next, recall that **if $\boldsymbol{\beta/\gamma \in (2,3)}$**, then $\beta-2\gamma \in (0,1)$. In this case, taking one more derivative,

$$\begin{aligned}\frac{\partial^2}{\partial s^2}W_1(u,s) &= \int_Y \tau\bar{\psi}^2 e^{-u\tau}e^{s\bar{\psi}}(v(u,0)-v(u,s))\,d\mu_{\overline{\phi}} - \int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\frac{\partial}{\partial s}v(u,s))\,d\mu_{\overline{\phi}} \\ &\quad - \int_Y \tau e^{-u\tau}e^{s\bar{\psi}}\frac{\partial^2}{\partial s^2}v(u,s))\,d\mu_{\overline{\phi}} = I_1+I_2+I_3\end{aligned}$$

Using the analogue of (4.6) for the case $\beta-2\gamma \in (0,1)$,

$$|I_1| \ll \|v(0,0)-v(u,s)\|_{\mathcal{B}_\theta}\int_Y \tau\bar{\psi}^2 e^{-u\tau}\,d\mu_{\overline{\phi}} \ll u^{\beta-2\gamma-1}(u+s) = o(u^{\beta-2\gamma-1})$$

as $u,s\to 0$.

Next, we already know that $\|\frac{\partial}{\partial s}v(u,s)\|_{\mathcal{B}_\theta} < \infty$. Thus, $|I_2| \ll \int_Y \tau^{\gamma+1}e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\overline{\phi}} \ll u^{\beta-\gamma-1}$. Also, by Lemma 4.1(ii) (the statement on H_2),$\|\frac{\partial^2}{\partial s^2}v(u,s))\|_{\mathcal{B}_\theta} < \infty$ and thus, $|I_3| \ll \int_Y \tau e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\overline{\phi}} = O(1)$. Thus, if $\beta/\gamma \in (2,3)$, $\frac{\partial}{\partial s}W_1(u,s) = o(u^{\beta-2\gamma-1})$, as $u,s\to 0$.

The term $W_2(u,s)$.
Note that

$$\frac{\partial}{\partial s}W_2(u,s) = -\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar\phi} + \int_Y (1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial^2}{\partial s\,\partial u}v(u,s)\,d\mu_{\bar\phi}.$$

If $\beta/\gamma\in(1,2]$, by Lemma 3.1 (statement on $G_{[q_0]}$ with $[q_0]=1$), $\|\frac{\partial}{\partial u}v(u,s)\|_{\mathcal{B}_\theta}<\infty$. Thus, $\left|\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar\phi}\right|=O(1)$. By Lemma 4.1(i) (statement on K_1), $\|\frac{\partial^2}{\partial s\,\partial u}v(u,s)\|_{\mathcal{B}_\theta}\ll u^{\beta-\gamma-1}$. So, $\left|\int_Y (1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial^2}{\partial s\,\partial u}v(u,s)\,d\mu_{\bar\phi}\right|\ll u^{\beta-\gamma-1}\int_Y(1-e^{-u\tau}e^{s\bar\psi})\,d\mu_{\bar\phi}=o(u^{\beta-\gamma-1})$, as $u,s\to 0$. Thus, if $\beta/\gamma\in(1,2]$, $\frac{\partial}{\partial s}W_2(u,s)=o(u^{\beta-\gamma-1})$, as $u,s\to0$.

If $\beta/\gamma\in(2,3)$, then we differentiate once more.

$$\begin{aligned}\frac{\partial^2}{\partial s^2}W_2(u,s) &= -\int_Y \bar\psi^2 e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar\phi} - \int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial^2}{\partial s\partial u}v(u,s)\,d\mu_{\bar\phi}\\ &\quad -\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial^2}{\partial u\,\partial s}v(u,s)\,d\mu_{\bar\phi} + \int_Y(1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial^3}{\partial s^2\,\partial u}v(u,s)\,d\mu_{\bar\phi}\\ &= I_1+I_2+I_3+I_4.\end{aligned}$$

Since $\bar\psi\in L^2$ for $\beta/\gamma\in(2,3)$, and since $\|\frac{\partial}{\partial u}v(u,s)\|_{\mathcal{B}_\theta}<\infty$, $|I_1|=O(1)$. Also, it is easy to see that $|I_2|=O(1)$ and $|I_3|=O(1)$. For I_4, we note that by Lemma 4.1(ii) (statement on K_2), $\|\frac{\partial^3}{\partial s^2\,\partial u}v(u,s)\|_{\mathcal{B}_\theta}\ll u^{\beta-2\gamma-1}$. Thus, $|I_4|=o(u^{\beta-2\gamma-1})$, as $u,s\to0$. So, when $\beta/\gamma\in(2,3)$, $\frac{\partial^2}{\partial s^2}W_2(u,s)=o(u^{\beta-2\gamma-1})$, as $u,s\to0$.

The statement on $\frac{\partial}{\partial s}d(u,s)$ for $\beta/\gamma\in(1,2]$ and for $\frac{\partial^2}{\partial s^2}d(u,s)$ for $\beta/\gamma\in(2,3)$ follows by putting all the above estimates on W_0,W_1,W_2 together.

Proof of item (ii). Recalling (3.7) and differentiating in s,

$$\frac{\partial}{\partial s}\lambda(u,s)=\int_Y\bar\psi\,d\mu_{\bar\phi}+\int_Y\bar\psi(e^{s\bar\psi}-1)\,d\mu_{\bar\phi}+e(u,s),$$

for

$$\begin{aligned}e(u,s) &= \int_Y\bar\psi e^{s\bar\psi}(1-e^{-u\tau})\,d\mu_{\bar\phi}+\int_Y\bar\psi e^{-u\tau}e^{s\bar\psi}(v(0,0)-v(u,s))\,d\mu_{\bar\phi}\\ &\quad+\int_Y(1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial}{\partial s}v(u,s)\,d\mu_{\bar\phi}\\ &= Z_0(u,s)+Z_1(u,s)+Z_2(u,s).\end{aligned}\tag{4.7}$$

A standard calculation (already used in showing (4.1)) shows that, given that $\bar\psi=C_0-C_1\tau^\gamma$ and that $\mu_Y(\tau>x)=cx^{-\beta}(1+o(1))$, there exists $C,C'>0$ depending on c and β/γ so that

$$\int_Y \bar{\psi}(e^{s\bar{\psi}} - 1)\, d\mu_{\overline{\phi}} = \begin{cases} h(s) + h_0(s), & \text{if } \beta/\gamma \in (1,2], \\ -s\int_Y \bar{\psi}^2\, d\mu_{\overline{\phi}} + Cs^{\beta/\gamma-1} + h_1(s), & \text{if } \beta \in (2,3), \end{cases} \tag{4.8}$$

where $h(s) = Cs^{\beta/\gamma-1}$ if $\beta/\gamma \in (1,2)$, $h(s) = C\log(1/s)$ if $\beta/\gamma = 2$ and where h_0 and h_1 are as follows: (a) $h_0(s) = o(s^{\beta/\gamma-1})$, $h_0'(s) = o(s^{\beta/\gamma-2})$ if $\beta/\gamma \in (1,2)$ and $h_0'(s) = o(\log(1/s))$ if $\beta/\gamma = 2$; (b) $h_1(s) = o(s^{\beta/\gamma-1})$, $h_1'(s) = C's^{\beta/\gamma-2}(1+o(1))$ and $h_1''(s) = C's^{\beta/\gamma-3}(1+o(1))$;

We continue with the study of $e(u,s)$. It is easy to see that taking $u = 0$ in (4.7), $|e(0,s)| = O(s)$ and $|e(u,0)| = o(1)$. Also, it is easy to see that if $\beta/\gamma \in (1,2]$ then

$$\begin{aligned} \left|\frac{\partial}{\partial s} e(0,s)\right| &\ll \|v(0,0) - v(0,s)|\|_{\mathcal{B}_\theta} \int_Y \bar{\psi}^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} + \|\frac{\partial^2}{\partial s^2} v(0,s)\|_{\mathcal{B}_\theta} \int_Y (1 - e^{s\bar{\psi}})\, d\mu_{\overline{\phi}} \\ &\ll s\, s^{\beta/\gamma-2} + s^{\beta/\gamma-2} s \int_Y \bar{\psi}\, d\mu_{\overline{\phi}} \ll s^{\beta/\gamma-1}, \end{aligned}$$

where in the previous to last inequality we have used Lemma 4.1 (i) (statement on $\frac{\partial}{\partial s} H_1(0,s)$) and the estimate in s in (4.4). If $\beta/\gamma = 2$, then, again due to used Lemma 4.1 (i), the same statement holds with $s^{\beta/\gamma-2}$ replace by $\log 1/s$. In this case, $\left|\frac{\partial}{\partial s} e(0,s)\right|$ is bounded by $s \log 1/s$.

We continue with the derivatives of Z_0, Z_1, Z_2 in (4.7), when $u \neq 0$, by considering each of the two cases.

The term $\boldsymbol{Z_0(u,s)}$. Differentiating in s, we obtain

$$\frac{\partial}{\partial s} Z_0(u,s) = \int_Y \bar{\psi}^2 e^{s\bar{\psi}} (1 - e^{-u\tau})\, d\mu_{\overline{\phi}}, \quad \frac{\partial^2}{\partial s^2} Z_0(u,s) = \int_Y \bar{\psi}^3 e^{s\bar{\psi}} (1 - e^{-u\tau})\, d\mu_{\overline{\phi}}$$

Using the estimates (4.4) in s in (4.4), as $s \to 0$, $\int_Y \bar{\psi}^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = Cs^{\beta/\gamma-2}(1+o(1))$ if $\beta/\gamma \in (1,2)$, $\int_Y \bar{\psi}^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = C\log(1/s)(1+o(1))$ if $\beta/\gamma = 2$ and $\int_Y \bar{\psi}^3 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} = Cs^{\beta/\gamma-3}(1+o(1))$ if $\beta/\gamma \in (2,3)$ for some $C > 0$ (varying from estimate to estimate).

Thus, as $u, s \to 0$, $\frac{\partial}{\partial s} Z_0(u,s) = o(s^{\beta/\gamma-2})$, **if $\boldsymbol{\beta/\gamma \in (1,2)}$**, $\frac{\partial}{\partial s} Z_0(u,s) = o(\log(1/s))$, **if $\boldsymbol{\beta/\gamma = 2}$** and $\frac{\partial^2}{\partial s^2} Z_0(u,s) = o(s^{\beta/\gamma-3})$, **if $\boldsymbol{\beta/\gamma \in (2,3)}$**.

The term $\boldsymbol{Z_1(u,s)}$. Differentiating in s, we obtain

$$\frac{\partial}{\partial s} Z_1(u,s) = \int_Y \bar{\psi}^2 e^{-u\tau} e^{s\bar{\psi}} (v(0,0) - v(u,s))\, d\mu_{\overline{\phi}} - \int_Y \bar{\psi} e^{-u\tau} e^{s\bar{\psi}} \frac{\partial}{\partial s} v(u,s)\, d\mu_{\overline{\phi}}.$$

Recall that $\|v(0,0) - v(u,s)\|_{\mathcal{B}_\theta} \ll u + s$. Thus, **if $\boldsymbol{\beta/\gamma \in (1,2)}$**,

$$\left|\int_Y \bar{\psi}^2 e^{-u\tau} e^{s\bar{\psi}} (v(0,0) - v(u,s))\, d\mu_{\overline{\phi}}\right| \ll (u+s) \int_Y \psi^2 e^{s\bar{\psi}}\, d\mu_{\overline{\phi}} \ll (u+s) s^{\beta/\gamma-2},$$

where we have used that $\int_Y \bar\psi^2 e^{s\bar\psi}\,d\mu_{\bar\phi} = Cs^{\beta/\gamma-2}(1+o(1))$.

Recall that by Lemma 4.1(i) (statement on H_1), $\|\frac{\partial}{\partial s}v(u,s)\|_{\mathcal{B}_\theta} < \infty$. Thus, $\left|\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial s}v(u,s))\,d\mu_{\bar\phi}\right| = O(1)$. Therefore,

If $\beta/\gamma \in (1,2)$, $\frac{\partial}{\partial s}Z_1(u,s) = O((u+s)s^{\beta/\gamma-2})$.

If $\boldsymbol{\beta/\gamma = 2}$, then we proceed the same using that $\int_Y \bar\psi^2 e^{s\bar\psi}\,d\mu_{\bar\phi} = C\log(1/s)(1+o(1))$, which gives $\frac{\partial}{\partial s}Z_1(u,s) = O((u+s)\log(1/s))$.

If $\boldsymbol{\beta/\gamma \in (2,3)}$, differentiating once more in s and using a similar argument to the case $\beta/\gamma \in (1,2)$ above (exploiting that $\int_Y \bar\psi^3 e^{s\bar\psi}\,d\mu_{\bar\phi} = Cs^{\beta/\gamma-3}(1+o(1)))$ we obtain $\frac{\partial^2}{\partial s^2}Z_1(u,s) = O((u+s)s^{\beta/\gamma-3})$.

The term $\boldsymbol{Z_2(u,s)}$. Differentiating in s,

$$\frac{\partial}{\partial s}Z_2(u,s) = -\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial s}v(u,s)\,d\mu_{\bar\phi} + \int_Y (1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial^2}{\partial s^2}v(u,s)\,d\mu_{\bar\phi}.$$

We already know that $\|\frac{\partial}{\partial s}v(u,s)\|_{\mathcal{B}_\theta} < \infty$. Hence, $\left|\int_Y \bar\psi e^{-u\tau}e^{s\bar\psi}\,\frac{\partial}{\partial s}v(u,s)\,d\mu_{\bar\phi}\right| = O(1)$. Also, **if** $\beta/\gamma \in (1,2]$, by Lemma 4.1(i) (statement on H_1), $\|\frac{\partial^2}{\partial s^2}v(u,s)\|_{\mathcal{B}_\theta} \ll u^{\beta-\gamma-1}$. Thus, $\left|\int_Y (1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial^2}{\partial s^2}v(u,s)\,d\mu_{\bar\phi}\right| = o(u^{\beta-\gamma-1})$, as $u,s\to 0$. Thus, if $\beta/\gamma \in (1,2]$, then $\frac{\partial}{\partial s}Z_2(u,s) = o(u^{\beta-\gamma-1})$, as $u,s\to 0$.

If $\boldsymbol{\beta/\gamma \in (2,3)}$, differentiating once more in s and using a similar argument to the case $\beta/\gamma \in (1,2]$ above (but using the statement on H_2 in Lemma 4.1(ii)), we obtain $\frac{\partial^2}{\partial s^2}Z_2(u,s) = o(u^{\beta-2\gamma-1})$, as $u,s\to 0$.

The statement on $\frac{\partial}{\partial s}e(u,s)$ for $\beta/\gamma \in (1,2]$ and for $\frac{\partial^2}{\partial s^2}e(u,s)$ for $\beta/\gamma \in (2,3)$ follows by putting all the above estimates on Z_0, Z_1, Z_2 together.

Proof of item (iii). We continue from (4.5) and compute that

$$\begin{aligned}\kappa(u,s) &= \int_Y \tau\bar\psi e^{-u\tau}e^{s\bar\psi}\,d\mu_{\bar\phi} - \int_Y \tau\bar\psi e^{-u\tau}e^{s\bar\psi}(v(0,0)-v(u,s))\,d\mu_{\bar\phi}\\ &+ \int_Y \tau\bar\psi e^{-u\tau}e^{s\bar\phi}\frac{\partial}{\partial s}v(u,s0\,d\mu_{\bar\phi} - \int_Y \tau e^{-u\tau}e^{s\bar\phi}\frac{\partial}{\partial u}v(u,s0\,d\mu_{\bar\phi}\\ &+ \int_Y (1-e^{-u\tau}e^{s\bar\psi})\,\frac{\partial}{\partial s}\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar\phi}\end{aligned}$$

and

$$\frac{\partial}{\partial s}\kappa(u,s) = \int_Y \tau\bar{\psi}^2 e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\bar{\phi}} - \int_Y \tau\bar{\psi}^2 e^{-u\tau}e^{s\bar{\psi}}(v(0,0)-v(u,s))\,d\mu_{\bar{\phi}} \tag{4.9}$$
$$+ 2\int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\frac{\partial}{\partial s}v(u,s)\,d\mu_{\bar{\phi}} - 2\int_Y \bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\frac{\partial}{\partial s}\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar{\phi}}$$
$$+ \int_Y \tau e^{-u\tau}e^{s\bar{\phi}}\frac{\partial^2}{\partial s^2}v(u,s)\,d\mu_{\bar{\phi}} - \int_Y \tau^2 e^{-u\tau}e^{s\bar{\phi}}\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar{\phi}}$$
$$+ \int_Y (1-e^{-u\tau}e^{s\bar{\psi}})\,\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}v(u,s)\,d\mu_{\bar{\phi}}$$
$$= \kappa_1(u,s)+\kappa_2(u,s)+\kappa_3(u,s)+\kappa_4(u,s)+\kappa_5(u,s)+\kappa_6(u,s)+\kappa_7(u,s).$$

We provide the argument for the case $\beta/\gamma \in (1,2]$. The case $\beta/\gamma \in (2,3)$ follows by a similar argument after differentiating (4.9) once more in s.

Using Lemma 4.1 (i),

$$\kappa(u,s) = \int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\bar{\phi}} + O\left((u+s)\int_Y \tau\bar{\psi}e^{-u\tau}e^{s\bar{\psi}}\,d\mu_{\bar{\phi}}\right) + O\left(u^{\beta-\gamma-1}(u+s)\right).$$

Taking $s=0$ in this equation, we get that there exists $C>0$ so that

$$\kappa(u,0) = \int_Y \tau\bar{\psi}e^{-u\tau}\,d\mu_{\bar{\phi}} + O\left(u\int_Y \tau\bar{\psi}e^{-u\tau}\,d\mu_{\bar{\phi}}\right) + O\left(u^{\beta-\gamma}\right).$$
$$= Cu^{\beta-\gamma-1}(1+o(1)),$$

where in the last equality we have used (4.1).

We estimate $\kappa_1,\dots,\kappa_7$ in (4.9). Note that differentiating once more in (4.6) and using the estimates in Section 4.1, $\int_Y \tau\bar{\psi}^2 e^{-u\tau}\,d\mu_{\bar{\phi}} = Cu^{\beta-2\gamma-1}(1+o(1))$. Thus, as $u,s\to 0$,

$$\kappa_1(u,s) = \int_Y \tau\bar{\psi}^2 e^{-u\tau}\,d\mu_{\bar{\phi}} + \int_Y \tau\bar{\psi}^2(e^{s\bar{\psi}}-1)e^{-u\tau}\,d\mu_{\bar{\phi}} = Cu^{\beta-2\gamma-1}(1+o(1)).$$

By arguments already used in estimating quantities in proof of items (i) and (ii) above, $\kappa_2(u,s), \kappa_3(u,s), \kappa_4(u,s), \kappa_6(u,s) = o(u^{\beta-2\gamma-1})$, as $u,s\to 0$. Finally, by Lemma 4.1(i) (statement on K_2), $\|\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}v(u,s)\|_{\mathcal{B}_\theta} \ll u^{\beta-2\gamma-1}$. Thus, $\kappa_5(u,s), \kappa_7(u,s) = o(u^{\beta-2\gamma-1})$, as $u,s\to 0$. ∎

5 Proof of Proposition 2.4

Using the technical results in Section 4 we can proceed to the proof of Proposition 2.4. We recall that this is a refined version of Proposition 2.2 under stronger assumptions.

In this sense, the task of this section is to go over the steps of the proof of Proposition 2.2 and obtain higher order expansions. From this proof, we recall that a first step is to refine the estimate on $\frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s)$ (see (3.10)). For the proof of Proposition 2.4, we shall need $\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s)$

Lemma 5.1 *Assume the setup of Proposition 2.4 with larger range of γ, namely $\gamma \in (\beta-1,\beta)$. There exists $C_2, C_3, C_4, C_5 > 0$(varying from line to line) so that the following hold as $u, s \to 0$.*

(i) If $\beta/\gamma \in (1,2)$ then $\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s) = -C_2 s^{\beta/\gamma-2}(1+o(1) + C_3 u^{\beta-2\gamma-1}(1+o(1))$. Also, $\frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s) = C_4 u^{\beta-\gamma-1}(1+o(1)) + C_3 s u^{\beta-2\gamma-1}(1+o(1))$.

(ii) If $\beta/\gamma = 2$ then $\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s) = -C_2\log(1/s)(1+o(1) + C_3 u^{-1}(1+o(1))$. Also, $\frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s) = C_4 u^{\beta-\gamma-1}(1+o(1)) + C_3 s u^{-1}(1+o(1)) - C_2 s\log(1/s)(1+o(1)$.

(ii) If $\beta/\gamma \in (2,3)$ then $\frac{\partial^3}{\partial s^3}\frac{\partial}{\partial u}\bar{p}(u,s) = -C_2 s^{\beta/\gamma-3}(1+o(1)) - C_3 u^{\beta-3\gamma-1}(1+o(1))$. Also, $\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s)\Big|_{s=0} = -C_4 u^{\beta-2\gamma-1}(1+o(1)) + C_3 s u^{\beta-3\gamma-1}(1+o(1))$.

Proof First we recall from (3.10) that

$$\frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s) = -\frac{\frac{\partial}{\partial u}\lambda(u,s)\frac{\partial}{\partial s}\lambda(u,s)}{\lambda(u,s)^2} + \frac{\frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)}{\lambda(u,s)}.$$

Set $A(u,s) := \frac{\partial}{\partial u}\lambda(u,s)\frac{\partial}{\partial s}\lambda(u,s)$ and recall (for instance, from Lemma 4.2(iii)) that $\kappa(u,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\lambda(u,s)$. Compute that

$$\begin{aligned}\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s) &= -\frac{\frac{\partial}{\partial s}A(u,s)}{\lambda(u,s)^2} - 2\frac{A(u,s)\frac{\partial}{\partial s}\lambda(u,s)}{\lambda(u,s)^3} + \frac{\frac{\partial}{\partial s}\kappa(u,s)}{\lambda(u,s)} - \frac{\kappa(u,s)}{\lambda(u,s)^2}\\ &= N_1(u,s) + N_2(u,s) + N_3(u,s) + N_4(u,s)\end{aligned}$$

We provide the proof of item (i). Item (ii) follows by the same argument using the statements for the case $\beta/\gamma = 2$ in Lemma 4.2 (i) and (ii). Item (iii) follows by a similar argument after differentiating once more and using the statements for the case $\beta/\gamma \in (2,3)$ in Lemma 4.2 (i) and (ii).

From a quick look at the estimates of Lemma 4.2 (i) and (ii) (the statements for the case $\beta/\gamma \in (1,2)$), it is easy to see that N_2 and N_4 do not contribute to the main asymptotic(because they go to a constant as $u, s \to 0$). We need to look at N_1 and N_3.

The term $N_1(u,s)$. Using the same notation as in Lemma 4.2 (i) and (ii),

$$A(u,s) = (-\tau^* + d(u,s))\left(\bar{\psi}^* + Cs^{\beta/\gamma-1} + h(s) + h_0(s) + e(u,s)\right)$$

and

$$\frac{\partial}{\partial s}A(u,s) = \frac{\partial}{\partial s}d(u,s)\ \left(\bar{\psi}^* + Cs^{\beta/\gamma-1} + h(s) + h_0(s) + e(u,s)\right)$$
$$+ (-\tau^* + d(u,s))\left(C(\beta/\gamma-1)s^{\beta/\gamma-2} + \frac{\partial}{\partial s}h(s) + h_0'(s) + \frac{\partial}{\partial s}e(u,s)\right).$$

Using all the estimates on d, h_0, e in Lemma 4.2 (i) and (ii) (the statements for the case $\beta/\gamma \in (1,2)$), we obtain that there exists $C_2, C_2' > 0$ so that

$$\frac{\partial}{\partial s}A(u,s) = -C_2 s^{\beta/\gamma-2}(1+o(1)) + C_2' u^{\beta-\gamma-1}(1+o(1)),$$

which gives the asymptotic for $N_1(u,s)$. In the previous displayed equation, apart from the estimates on $\frac{\partial}{\partial s}d(u,s)$ and on $\frac{\partial}{\partial s}e(u,s)$ we have used the immediate consequence of Lemma 4.2(ii) that $d(u,s) = O(su^{\beta-\gamma-1})$ and that $e(u,s) = o(su^{\beta-\gamma-1})$.

The term $N_3(u,s)$. By Lemma 4.2 (iii) (the statement for the case $\beta/\gamma \in (1,2)$), $\frac{\partial}{\partial s}\kappa(u,s) = C_3 u^{\beta-2\gamma-1}(1+o(1))$, for some $C_3 > 0$. This gives the same asymptotic for N_3.

Therefore,

$$N_1(u,s) + N_3(u,s) = -C_2 s^{\beta/\gamma-2}(1+o(1)) + C_3 u^{\beta-2\gamma-1}(1+o(1)),$$

which gives the first statement statement in item (i).

The second statement in item (i) follows immediately from the first together with the asymptotic of $\kappa(u,0)$ in Lemma 4.2 (iii). ∎

We can now proceed to

Proof of Proposition 2.4 We redo all steps in the proof of Proposition 2.2(ii) using Lemma 4.2.

Recall $\bar{p}(u,s) = \log\lambda(u,s)$. The analogue of (3.8) is

$$\frac{\partial}{\partial u}\bar{p}(u,s) = -\tau^* + D(u,s), \quad \frac{\partial}{\partial s}\bar{p}(u,s) = \bar{\psi}^* + E(u,s), \tag{5.1}$$

where

(a) $D(u,s)$ satisfies the same properties as $d(u,s)$ in Lemma 4.2(i).

(b) $E(u,s)$ satisfies the same properties as $e(u,s)$ in Lemma 4.2(ii).

By Lemma 4.2(i) and (ii), we have the following refined version of (3.9) (with C varying from line to line).

$$\frac{\partial^2}{\partial s^2}\bar{p}(0,s) = Cs^{\beta/\gamma-2}(1+o(1)), \qquad \text{if } \beta/\gamma \in (1,2) \tag{5.2}$$
$$\frac{\partial^2}{\partial s^2}\bar{p}(0,s) = C\log(1/s)(1+o(1)), \qquad \text{if } \beta/\gamma = 2$$
$$\frac{\partial^3}{\partial s^3}\bar{p}(0,s) = Cs^{\beta/\gamma-3}(1+o(1)), \qquad \text{if } \beta/\gamma \in (2,3).$$

The analogue of (3.12) for any small $u_0 > 0$ is

$$\bar{p}(u_0, s) - \bar{p}(0, s) = -\tau^* u_0 + \int_0^{u_0} D(u, s)\, du := -\tau^* u_0 + L(u_0, s),$$

where $D(u, s)$ satisfies the same properties as $d(u, s)$ in Lemma 4.2(i). Moreover, as in the proof of Proposition 2.2 (ii),

$$\frac{\partial}{\partial s} D(u, s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u, s). \tag{5.3}$$

By the argument used in the proof of Proposition 2.2 in deriving (3.15),

$$u_0'(s) = \frac{\frac{\partial}{\partial s} M(u_0, s)}{\tau^* - \frac{\partial}{\partial u_0} M(u_0, s)}, \tag{5.4}$$

where, as in the proof of Proposition 2.2,

$$M(u_0, s) = L(u_0, s) + \bar{p}(0, s) \qquad \text{with } \frac{\partial}{\partial u_0} L(u_0, s) = D(u_0, s). \tag{5.5}$$

Differentiating (5.4) once more in s (analogous formula of (3.18)),

$$\begin{aligned} p''(s) &= \frac{\frac{\partial^2}{\partial s^2} M(u_0, s)(\tau^* - \frac{\partial}{\partial u_0} M(u_0, s))}{\left(\tau^* - \frac{\partial}{\partial u_0} M(u_0, s)\right)^2} + \frac{\frac{\partial}{\partial s} M(u_0, s) \frac{\partial^2}{\partial u_0 \partial s} M(u_0, s)}{\left(\tau^* - \frac{\partial}{\partial u_0} M(u_0, s)\right)^2} \\ &= M_1(u_0, s) + M_2(u_0, s). \end{aligned} \tag{5.6}$$

We complete the proof of (i), that is we treat the case $\beta/\gamma \in (1, 2)$ using the estimates in Lemma 4.2. The precise asymptotics in (ii) for the case $\beta/\gamma = 2$ follow by the same argument using the corrsponding estimates in Lemma 4.2. Item (iii), the case $\beta/\gamma \in (2, 3)$, (after taking one more derivative in s) is similar and omitted.

Proof of (i), the case $\boldsymbol{\beta/\gamma \in (1, 2)}$.

The term $\boldsymbol{M_1(u_0, s)}$ defined in (5.6). Differentiating (5.5),

$$\frac{\partial}{\partial s} M(u_0, s) = \frac{\partial}{\partial s} L(u_0, s) + \frac{\partial}{\partial s}\bar{p}(0, s). \tag{5.7}$$

Using (3.11), (5.3) and Lemma 5.1(i),

$$\frac{\partial}{\partial s} L(u_0, s) = \int_0^{u_0} \frac{\partial}{\partial s} D(u, s)\, du = C_4 u_0^{\beta - \gamma}(1 + o(1)) + C_3 s\, u_0^{\beta - 2\gamma}(1 + o(1)).$$

By Proposition 2.2 (ii), $p(s) = u_0(s) = \frac{\bar{p}(0,s)}{\tau^*} = s\frac{\bar{\psi}^*}{\tau^*}(1+o(1))$, as $s \to 0$. Thus,

$$\frac{\partial}{\partial s}L(u_0,s) = C_4 s^{\beta-\gamma}(1+o(1)) + C_3 s^{\beta-2\gamma+1}(1+o(1)) = C_4 s^{\beta-\gamma}(1+o(1)),$$

where in the last equality we have used that $\gamma < 1$.

By Lemma 4.2(ii), $\frac{\partial}{\partial s}\bar{p}(0,s) = \bar{\psi}^* + Cs^{\beta/\gamma-1}(1+o(1))$. Since $\beta > \gamma$,

$$\frac{\partial}{\partial s}M(u_0,s) = \bar{\psi}^* + Cs^{\beta/\gamma-1}(1+o(1)) = \bar{\psi}^*(1+o(1)). \tag{5.8}$$

Differentiating (5.7) once more in s and using (5.2),

$$\frac{\partial^2}{\partial s^2}M(u_0,s) = \frac{\partial^2}{\partial s^2}L(u_0,s) + \frac{\partial^2}{\partial s^2}\bar{p}(0,s) = \frac{\partial^2}{\partial s^2}L(u_0,s) + Cs^{\beta/\gamma-2}(1+o(1)).$$

Next, recall (5.3) and note that $\frac{\partial^2}{\partial s^2}D(u,s) = \frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s)$. By Lemma 5.1(i), $\frac{\partial^2}{\partial s^2}\frac{\partial}{\partial u}\bar{p}(u,s) = -C_2 s^{\beta/\gamma-2}(1+o(1) + C_3 u^{\beta-2\gamma-1}(1+o(1))$. Also, recall that $u_0(s) = s\frac{\bar{\psi}^*}{\tau^*}(1+o(1))$, as $s \to 0$ for $C_2, C_3 > 0$. Thus,

$$\begin{aligned}\frac{\partial^2}{\partial s^2}L(u_0,s) &= \int_0^{u_0}\frac{\partial^2}{\partial s^2}D(u,s)\,du = -C_2 s^{\beta/\gamma-1}(1+o(1) + C_3 s^{\beta-2\gamma}(1+o(1))\\ &= C_3 s^{\beta-2\gamma}(1+o(1)).\end{aligned}$$

Putting the previous three displayed equations together and noticing that $s^{\beta-2\gamma} > s^{\beta/\gamma-2}$ (since $\gamma < 1$),

$$\frac{\partial^2}{\partial s^2}M(u_0,s) = C_3 s^{\beta-2\gamma}(1+o(1)). \tag{5.9}$$

We have $\frac{1}{\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)} = \frac{1}{\tau^* - D(u_0,s)} = \frac{1}{\tau^*}\left(1 + O(D(u_0,s)\right)^{-1}$ as in the proof of Proposition 2.2 (ii). Using the properties of $D_0(u,s)$ in item (a) after (3.8) (both smoothness in s and asymptotics of $D(u_0,0)$), and using that $u_0(s) = O(s)$, we have

$$\frac{1}{\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)} = \frac{1}{\tau^*}(1 + O(s^{\beta-1} + s))$$

as $s \to 0$. This together with (5.9) gives that as $s \to 0$,

$$M_1(u_0,s) = C_3 s^{\beta-2\gamma}(1+o(1)). \tag{5.10}$$

The term $M_2(u_0,s)$ defined in (5.6).

Differentiating (5.7) once more in u_0, $\frac{\partial^2}{\partial u_0 \partial s}M(u_0,s) = \frac{\partial^2}{\partial u_0 \partial s}L(u_0,s)$. Recall that $\frac{\partial}{\partial s}L(u_0,s) = \int_0^{u_0}\frac{\partial}{\partial s}D(u,s)\,du$ and that $D(u,s)$ is uniformly continuous in u. Thus, $\frac{\partial^2}{\partial u_0 \partial s}M(u_0,s) = \frac{\partial}{\partial s}D(u_0,s)$. Recalling (5.3),

$$\frac{\partial^2}{\partial u_0 \partial s}M(u_0,s) = \frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s)\Big|_{u=u_0}.$$

By Lemma 5.1(i),

$$\frac{\partial}{\partial s}\frac{\partial}{\partial u}\bar{p}(u,s)\Big|_{u=u_0} = C_4 u_0^{\beta-\gamma-1}(1+o(1)) + C_3 s\, u_0^{\beta-2\gamma-1}(1+o(1)).$$

for $C_3, C_4 > 0$. Since $u_0(s) = s\frac{\bar{\psi}^*}{\tau^*}(1+o(1))$, as $s \to 0$,

$$\frac{\partial^2}{\partial u_0 \partial s}M(u_0,s) = C_4 s^{\beta-\gamma-1}(1+o(1)) + C_3 s^{\beta-2\gamma}(1+o(1)) = C_4 s^{\beta-\gamma-1}(1+o(1)),$$

where in the last equation we have used again that $\gamma < 1$.

Recalling (5.8) and that $\frac{1}{\tau^* - \frac{\partial}{\partial u_0}M(u_0,s)} == \frac{1}{\tau^*}(1+o(1))$, we have $M_2(u_0,s) = \frac{\bar{\psi}^*}{\tau^*}C_4 s^{\beta-\gamma-1}(1+o(1))$. This together with (5.10) gives the conclusion after recalling again that $\gamma < 1$, which ensures that $s^{\beta-\gamma-1} > s^{\beta-2\gamma}$. ∎

6 Proofs of the main abstract results

The proofs of the main results will make use of the restricted pressure. Analogous to [RS, Definition 5.1], we define

$$\begin{aligned} q(a) = q_{\phi,\psi}(a) &:= \sup\left\{ P_{F,\nu}(\phi) : \nu \in \mathcal{M}_F, \int_{Y^\tau} \psi \, d\nu = a \right\} \\ &= \sup\left\{ \frac{P_{T,\mu}(\bar{\phi})}{\int \tau \, d\mu} : \mu \in \mathcal{M}_T(\tau), \frac{\int_Y \bar{\psi}\, d\mu}{\int \tau \, d\mu} = a \right\}. \end{aligned}$$

6.1 Proof of Theorem 2.6

Proof of Theorem 2.6 Given Proposition 2.2 with $q_1 > 3$, the details are very similar with those in [RS, Proof of Lemma 5.2] (and also the main line of the argument in [RS, Proof of Proposition 6.1]). We recall most of the details, partly for completeness, partly because our setup is different (unbounded potential but more restricted ψ).

By Proposition 2.2(ii), $p'(0) = \frac{\int_Y \bar{\psi}\, d\mu_{\bar{\phi}}}{\int_Y \tau \, d\mu_{\bar{\phi}}} = \int_{Y^\tau} \psi \, d\nu_\phi = a_0$. By assumption, ν_ϕ is the unique equilibrium measure for ϕ. Since $p''(s) \geq 0$ is continuous with $p''(0) = \sigma^2 > 0$ (by Proposition 2.2), p' is strictly monotonically increasing near 0.

Given $h \in (0, \delta_0)$, for δ_0 is as in Proposition 2.2, let $a \in (p'(0), p'(h))$. By the Intermediate Value Theorem, there exists $s \in (0,h)$ so that $p'(s) = a$. By Proposition 2.2(ii) and (iii), the second derivative is well-defined whenever $q_1 > 2$.

We next show that p is strictly convex in our domain of interest. Throughout the rest of the proof let $K > \sigma^2$, so $\delta_0 \frac{\sigma^2}{K} < \delta_0$. By the assumption $q_1 > 3$, the third derivative p''' is well-defined and we can assume $|p'''| < K$ by taking K larger if necessary. We use this to show strict convexity and that the solution to the equation (in s) $p'(s) = a$ is unique. To see this, we recall the argument by contradiction in [RS, Proof of Lemma 5.2]. As in [RS, Proof of Lemma 5.2], if there exists $s_0 \neq s, s \in \left(0, \delta_0 \frac{\sigma^2}{K}\right)$ so that $p'(s_0) = a$ then p'' would have vanished in this interval. This is not possible because for some $s' \in (0, s)$,

$$|p''(s) - \sigma^2| = |p''(s) - p''(0)| = s|p'''(s')| \leq K \cdot \left(\delta_0 \frac{\sigma^2}{K}\right) = \delta_0 \sigma^2 \neq 0.$$

For the unique s so that $p'(s) = a$, we know that $R(u, s)$ satisfies the spectral gap: this follows since $R(0, 0)$ has a spectral gap in $\mathcal{B}$ and $R(u, s)$ is continuous in u, s (by Lemma 3.1). Thus, the potential $\overline{\phi + s\psi - p(s)}$ has a unique equilibrium measure μ_s. This projects to an equilibrium state ν_s for the potential $\phi + s\psi$ (the unique such measure), as follows. First note that from the Gibbs property

$$\int \tau \, d\mu_s \ll \int \tau e^{s\bar{\psi} - \tau p(s)} \, d\mu_{\bar{\phi}} \ll \int \tau \, d\mu_{\bar{\phi}} < \infty,$$

so $\mu_s \in \mathcal{M}_T(\tau)$ and we obtain $\nu_s \in \mathcal{M}_F$ from (2.2). Moreover by the Abramov formula, $P_{F,\nu_s}(\phi + s\phi - p(s)) = 0$, which firstly implies that ν_s is an equilibrium state for $\phi + s\psi$. It is also standard to show that this is the unique equilibrium state for this potential and that $\int \psi \, d\nu_s = p'(s) = a$, as above. Moreover, if $\nu \in \mathcal{M}_F$ has $P_\nu(\phi) > P_{\nu_s}(\phi)$ and $\int \psi \, d\nu = a$, then

$$P_\nu(\phi + s\psi) = P_\nu(\phi) + sa > P_{\nu_s}(\phi) + sa = P_{\nu_s}(\phi + s\psi) = p(s),$$

a contradiction. Therefore,

$$P_\nu(\phi) \leq p(s) - s \int \psi \, d\nu_s = P_{\nu_s}(\phi) = q(a) \tag{6.1}$$

for any $\nu \in \mathcal{M}_F$ with $\int \psi \, d\nu = a$.

Recall $q_1 > 3$. By Proposition 2.2(ii), p''' is $C^{q_1 - [q_1]}$. Thus,

$$p(s) = p(0) + sp'(0) + \frac{s^2}{2} p''(0) + \frac{s^3}{6} p'''(0) + O(s^{3+\epsilon}),$$

for some $\epsilon > 0$, so $p'(s) = p'(0) + sp''(0) + \frac{s^2}{2} p'''(0) + O(s^{2+\epsilon})$. Then for s so that $p'(s) = a$, and recalling that $p''(0) = \sigma^2$,

$$\begin{aligned} a - a_0 = p'(s) - p'(0) &= sp''(0) + \frac{s^2}{2} p'''(0) + O(s^{2+\epsilon}) \\ &= s\left(p''(0) + \frac{s}{2} p'''(0) + O(s^{2+\epsilon})\right) = s\sigma^2(1 + O(s\sigma^{-2}), \end{aligned}$$

where in the last step we have used that $s \in \left(0, \delta_0 \frac{\sigma^2}{K}\right)$ and that $|p'''(0)| < K$. Hence,

$$s = \frac{a - a_0}{\sigma^2}(1 + O(s^{1+\epsilon}\sigma^{-2})). \tag{6.2}$$

Next, arguing word for word as in the [RS, Proof of Lemma 5.2, item (4)], $q(a_0) = P_{\nu_\phi}(\phi)$ and since, by assumption, $P_{\nu_\phi}(\phi) = p(0) = 0$, we have $q(a_0) = 0$. This together with (6.1), the fact that $a = p'(s)$, the expansions of $p(s)$ and $p'(s)$ and (6.1), imply that for some $\epsilon > 0$,

$$q(a_0) - q(a) = sp'(s) - p(s) = \frac{s^2}{2}\sigma^2 + \frac{s^3}{6}p'''(0) + O(s^{3+\epsilon}).$$

This together with (6.2) gives

$$q(a_0) - q(a) = \frac{(a - a_0)^2}{2\sigma^2}(1 + O(\sigma^{-2}(a - a_0)).$$

So for $\nu \in \mathcal{M}_F$ with $\int \psi \, d\nu = a$, the above equation and (6.1) imply

$$P_{\nu_\phi}(\phi) - P_\nu(\phi) \geq P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi) = \frac{(a - a_0)^2}{2\sigma^2}(1 + O(\sigma^{-2}(a - a_0)) \tag{6.3}$$

Making $a - a_0 = \int \psi \, d\nu - \int \psi \, d\nu_\phi$ the subject of this equation gives

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \leq C_{\phi,\psi}\sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)}.$$

where the constant $C_{\phi,\psi} \geq 1$ tends to 1 as $\int \psi \, d\nu \to \int \psi \, d\nu_\phi$. Continuing with ν_s, the equilibrium state of $\phi + s\psi$, we get the more precise form

$$\int \psi \, d\nu_s - \int \psi \, d\nu_\phi = \sqrt{2}\sigma\sqrt{P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)} + O\left(P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)\right).$$

which can be rewritten as (2.7) as required. ∎

6.2 Proof of Theorem 2.7

We shall need the following fact, which relies on the positivity of $p''(s)$ given by Proposition 2.4.

Lemma 6.1 *Take $\beta/\gamma \in (1, 3)$ and $a \in (p'(0), p'(\delta_0))$, where δ_0 is as in Proposition 2.2. Then $p''(s) > 0$ for $s \in (0, \delta_0)$ and there exists a unique $s \in (0, \delta_0)$ satisfying $p'(s) = a$.*

Proof By Proposition 2.4, both for $\beta/\gamma \in (1, 2]$ and for $\beta/\gamma \in (2, 3)$, the first derivative p' is bounded. For $\beta/\gamma \in (1, 2)$, the positivity of $p''(s)$ is given by Proposition 2.4 (i). For the case $\beta/\gamma \in (2, 3)$, Proposition 2.2(iii) ensures that $p''(0) = \sigma^2$. This together with Proposition 2.4 (ii) gives the positivity of $p''(s)$ when $\beta/\gamma \in (2, 3)$. It follows that p' is a strictly increasing function and the conclusion follows. ∎

Proof of Theorem 2.7 Let $a_0 = \int \psi \, d\nu_\phi$ and $a = \int \psi \, d\nu$ and assume $a > a_0$. By Lemma 6.1, $p'(s) = a$ has a unique solution. This allows us to repeat the argument recalled in obtaining (6.1) and to obtain $q(a) = p(s) - sa$. As in the proof of Theorem 2.6, recall that $q(a_0) = P_{\nu_\phi}(\phi)$ and $q(a) = P_{\nu_s}(\phi)$, where ν_s is the unique equilibrium measure for $\psi + s\psi$. Let ν be any F-invariant probability measure so that $a = \int_{Y^\tau} \psi \, d\nu > a_0 = \int_{Y^\tau} \psi \, d\nu_\phi$.

Proof of item (a), the case $\boldsymbol{\beta/\gamma \in (1, 2]}$. Note that $a - a_0 = p'(s) - p'(0)$. Using Proposition 2.4(i),

$$a - a_0 = sp''(s)(1 + o(1)) = C_2 \, s \, s^{\beta-\gamma-1}(1 + o(1)) = C_2 s^{\beta-\gamma}(1 + o(1)).$$

and so,

$$s = \left(\frac{a - a_0}{C_2}\right)^{1/(\beta-\gamma)} (1 + o(1)). \tag{6.4}$$

Since $q(a_0) = 0$, $q(a_0) - q(a) = sp'(s) - p(s)$. By the Taylor expansion with remainder $p(y) = p(x) + p'(x)(y - x) + \int_x^y (y - \xi)p''(\xi) \, d\xi$. Taking $y = 0$ and $x = s$, $q(a_0) - q(a) = sp'(s) - p(s) = \int_0^s \xi p''(\xi) \, d\xi$. By Proposition 2.4(i), we have

$$\begin{aligned} q(a_0) - q(a) &= \int_0^s \xi \left(C_2 \xi^{\beta-\gamma-1}(1 + o(1)) \right) \, d\xi = \frac{\gamma}{\beta} C_2 s^{\beta-\gamma+1}(1 + o(1)) \\ &= \frac{\gamma}{\beta} C_2 \left(\frac{a - a_0}{C_2}\right)^{\frac{\beta-\gamma+1}{\beta-\gamma}} (1 + o(1)), \end{aligned} \tag{6.5}$$

where in the equality we have used (6.4). So, there is $c_2 > 0$ so that

$$a - a_0 = c_2 \left(q(a_0) - q(a)\right)^{\frac{\beta-\gamma}{\beta-\gamma+1}} (1 + o(1)),$$

Since for an arbitrary measure ν we have $P_{\nu_\phi}(\phi) - P_\nu(\phi) \geq P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)$ as in (6.3), we have

$$\int \psi \, d\nu - \int \psi \, d\nu_\phi \leq c_2 (P_{\nu_\phi}(\phi) - P_\nu(\phi))^{\frac{\beta-\gamma}{\beta-\gamma+1}}$$

as required. For the equilibrium state ν_s itself, we have the more precise estimate with $c_2 = \frac{\beta}{\gamma} C_2$:

$$\int \psi \, d\nu_s - \int \psi \, d\nu_\phi = c_2 (P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi))^{\frac{\beta-\gamma}{\beta-\gamma+1}} (1 + o(1)),$$

which can be rewritten to (2.8).

Proof of item (b), the case $\beta/\gamma \in (2,3)$. Using Proposition 2.4(ii) and Taylor's theorem, we have

$$a - a_0 = p'(s) - p'(0) = sp''(0) + \int_0^s \xi p'''(\xi)\, d\xi = s\sigma^2 + O(s^{\beta-2\gamma+1}). \tag{6.6}$$

Therefore

$$s = \frac{a-a_0}{\sigma^2}\left(1 + O(s^{\beta-2\gamma})\right). \tag{6.7}$$

By Taylor's theorem, $p(s) = p(0) + sp'(0) + \frac{s^2}{2}p''(0) + \int_0^s \xi^2 p'''(\xi)\, d\xi$. This together with Proposition 2.4(ii) (and recalling $p''(0) = \sigma^2$) gives

$$\begin{aligned} q(a_0) - q(a) &= sp'(s) - p(s) \\ &= sp'(s) - \left(p(0) + sp'(0) + \frac{s^2}{2}p''(0) + \int_0^s \xi^2 p'''(\xi)\, d\xi\right) \\ &= s(p'(s) - p'(0)) - \frac{s^2}{2}\sigma^2 - \int_0^s \xi^2 p'''(\xi)\, d\xi \\ &= s^2\sigma^2 + O(s^{\beta-2\gamma+2}) - \frac{s^2}{2}\sigma^2 + O(s^{\beta-2\gamma+2}) = \frac{s^2}{2}\sigma^2(1 + O(s^{\beta-2\gamma})), \end{aligned}$$

where we used (6.6) in the last line. This together with (6.7),

$$q(a_0) - q(a) = \frac{(a-a_0)^2}{2\sigma^2}\left(1 + O\left((a-a_0)^{\beta-2\gamma}\right)\right). \tag{6.8}$$

Since for an arbitrary measure ν we have again

$$\int \psi\, d\nu - \int \psi\, d\nu_\phi \le c_3\sqrt{P_{\nu_\phi}(\phi) - P_\nu(\phi)}$$

for some $c_3 \ge 1$. For the equilibrium state ν_s itself, we have the more precise estimate:

$$\int \psi\, d\nu_s - \int \psi\, d\nu_\phi = \sigma\sqrt{2}\sqrt{P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi)}\left(1 + O\left((P_{\nu_\phi}(\phi) - P_{\nu_s}(\phi))^{\frac{\beta-2\gamma}{2}}\right)\right).$$

This can be rewritten to (2.9) ∎

7 Applications

We provide examples of systems, both of discrete and continuous time, for which our main results apply. These are systems with weak forms of hyperbolicity that have not been studied before form this point of view.

7.1 Intermittent interval maps

Zweimüller [Z] introduced a class of interval maps $f : [0,1] \to [0,1]$ that he called AFN maps, i.e., non-uniformly expanding maps with finitely many branches, finitely many neutral fixed points, and satisfying Adler's distortion property (f''/f'^2 bounded). Note that AFN maps are, in general, non-Markov. We stress that these are maps with weak hyperbolicity properties. Let $\alpha \in (0,1)$ and $b \in (0,1]$ consider the family of AFN maps defined by

$$f(x) = f_{\alpha,b}(x) = \begin{cases} x(1 + 2^\alpha x^\alpha) & \text{if } x \in [0, 1/2], \\ b(2x-1) & \text{if } x \in (1/2, 1]. \end{cases}$$

It follows from [Z] that for this range of values of the parameters α and b, there exists an absolutely continuous probability measure μ. Moreover, the first return time map to $Y = (1/2, 1]$ is uniformly expanding, although it may not be Markov. In [BT, Section 9], a Gibbs-Markov inducing scheme for Y with return time τ is constructed. That is, there exists a countable partition of Y so that τ is constant on each of the elements of the partition and the map $T : Y \to Y$ defined by $T = f^\tau$ is Gibbs-Markov. The map T can be thought of as a discrete suspension of f with roof function τ. Moreover, for a potential $\psi : [0,1] \to \mathbb{R}$ its induced version $\bar{\psi} : Y \to \mathbb{R}$ is defined by $\bar{\psi} = \sum_{j=0}^{\tau-1} \psi \circ f^j$. In particular, our main results can be applied to this discrete time system. We now verify that under certain conditions the assumptions of our results are indeed satisfied. We begin with Theorem 2.6.

It was was established in [BT, Section 9] that for $\beta = 1/\alpha$ there exists $c > 0$ such that the following bound on the tails holds,

$$\mu_Y(\tau > n) \sim cn^{-\beta}.$$

That is, assumption (GM0) is fulfilled.

Note that if $\alpha \in (0, 1/2)$ then $\beta > 2$ and if $\alpha \in (1/2, 1)$ then $\beta \in (1, 2)$.

Recall that (GM1) is an assumption on the induced version of a potential ψ. It states that there exists $\gamma \in (\beta - 1, \beta)$ such that $\bar{\psi} = C_0 - \psi_0$ with $0 \leq \psi_0 \leq C_1 \tau^\gamma$. The last assumption in Theorem 2.6, besides (GM0) and (GM1), is that $q_1 > 3$, which in particular implies that $\beta/\gamma > 3$. Under the assumptions of (GM1) we have that $\beta/\gamma \in (1, \beta/(\beta-1))$. Also, for $\beta > 2$ we have $\beta/(\beta-1) < 2$. Thus, if $\alpha \in (0, 1/2)$ then the assumptions of Theorem 2.6 can not be satisfied (q_1 is always smaller than 3). However, for $\alpha \in (1/2, 1)$ the result holds.

Proposition 7.1 *The conclusions of Theorem 2.6 hold for the induced system (T, μ_Y) with $\alpha \in (1/2, 1)$ and $\psi : [0,1] \to \mathbb{R}$ a Hölder function such that $\psi(x) = -x^{(1-\gamma)\alpha}$ for $\gamma \in ((1-\alpha)/\alpha, \alpha/(\alpha+1))$, $\beta/\gamma > 3$ and x in a neighbourhood of 0.*

In the case $\beta > 3$ we can consider the case $\gamma = 1$ in this setting. Here we can for example choose ψ to be Hölder and negative (bounded below by $-C_1$) in Y^c and to be equal to C_0 and Theorem 2.6 holds.

Proof We already established that assumption (GM0) is satisfied. It was proved in [BTT1, Proposition 8.5] that if $\gamma \in (0, \alpha/(\alpha+1))$ then the induced potential satisfies $\bar{\psi}(x) \sim C - \tau(x)^\gamma$ as $x \to 1/2$. Thus, the parameter γ has to be chosen from the set $(\beta-1, \beta) \cap (0, \alpha/(\alpha+1))$ so as $\beta/\gamma > 3$. These conditions are compatible, so we can assume that $q_1 > 3$ and that (GM1) is fulfilled.

For the final statement note that in this setting $\bar{\psi}(x) = C_0 - \psi_0(x)$ where $0 \leq \psi_0(x) \leq C_1\tau(x)$. ∎

Similarly, we obtain a version of Theorem 2.7 in the same range of values of α, but for a different range of values of γ.

Proposition 7.2 *The conclusions of Theorem 2.7 hold for the induced system* (T, μ_Y) *with* $\alpha \in (1/2, 1)$ *and* $\psi : [0,1] \to \mathbb{R}$ *a function such that there exists* $\gamma \in (\beta - 1, 1)$ *for which* $\bar{\psi} = C_0 - C_1\tau^\gamma$. *Both cases,* $\beta/\gamma \in (1, 2]$ *and* $\beta/\gamma \in (2, 3)$, *occur.*

In the case $b = 1$ a construction to produce ψ as above is given as follows. Let $x_0 = 1$ and $x_n = f_L^{-n}(1/2)$, where f_L is the left branch of f. Then on the intervals $X_n := (x_n, x_{n-1}]$ define $\psi|_{X_1} = C_0 - C_1$ and $\psi|_{X_n} = C_1(-n^\gamma + (n-1)^\gamma)$, so for x having $\tau(x) = n$, $\bar{\psi} = C_0 + C_1 \sum_{k=1}^n(-n^\gamma + (n-1)^\gamma) = C_0 - C_1 n^\gamma$, as required.

Observe that for $\alpha \in (0, 1/2)$ we have $\beta > 2$ and for Theorem 2.7 to hold we require $\beta \in (1, 2)$. Therefore, the appropriate range of values of α in order to apply our main results is $(0, 1/2)$.

7.2 Suspensions over intermittent interval maps

In this section we consider suspension flows over the induced map T defined in Section 7.1. Essentially, this is a continuous time representation of T that preserves its main properties. Let $\rho : Y \to \mathbb{R}^+$ be a Hölder function bounded away from zero. Let $\bar{\tau} : Y \to \mathbb{R}^+$ be defined by $\bar{\tau}(x) = \sum_{j=0}^{\tau(x)-1} \rho(f^j x)$. Let $(F_t)_t$ be the suspension (semi)flow with base map T and roof function $\bar{\tau}$. Since ρ is bounded, assumption (GM0) is satisfied (as in Section 7.1) for the measure μ_Y.

A standard tool to construct examples in suspension flows is the following. Given a regular potential defined on the base space $g : Y \to \mathbb{R}$, construct a continuous potential $\psi : Y^{\bar{\tau}} \to \mathbb{R}$ so that its induced version coincides with g, that is $\bar{\psi} = g$. Details of this type of construction can be found in [BRW], minor adaptations are required in this setting. Since the assumptions of our main results are in terms of the induced potentials, this tool allows us to state flow versions of Propositions 7.1 and 7.2. Indeed, we just need to consider potentials $\psi : Y^{\bar{\tau}} \to \mathbb{R}$ so that its induced versions satisfy the properties of the induced potentials $\bar{\psi}$ in Propositions 7.1 and 7.2.

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