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## A renewal version of the Sanov theorem

Mauro Mariani\*      Lorenzo Zambotti†

### Abstract

Large deviations for the local time of a process  $X_t$  are investigated, where  $X_t = x_i$  for  $t \in [S_{i-1}, S_i[$  and  $(x_j)$  are i.i.d. random variables on a Polish space,  $S_j$  is the  $j$ -th arrival time of a renewal process depending on  $(x_j)$ . No moment conditions are assumed on the arrival times of the renewal process.

**Keywords:** Large deviations; Renewal processes, Sanov Theorem, Heavy tails.

**AMS MSC 2010:** 60K05; 60F10.

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## 1 Main results

### 1.1 Outline of the result

Consider an i.i.d. sequence  $(x_i)_{i \in \mathbb{N}^+}$  in a Polish space  $\mathcal{X}$ , with marginal distribution  $\bar{\mu}$ . One may define a stochastic process  $(X_t)_{t \geq 0}$  on  $\mathcal{X}$  by setting  $X_t = x_i$  for  $t \in [i-1, i[$ , and consider its empirical measure  $\pi_t := \frac{1}{t} \int_{[0, t]} ds \delta_{X_s}$ . The ergodic theorem then states that  $\pi_t \rightarrow \bar{\mu}$  as  $t \rightarrow +\infty$ , while the Sanov theorem yields a finer estimate for the probability that  $\pi_t$  is found in a small neighborhood of a given Borel probability measure  $\bar{\nu}$  on  $\mathcal{X}$ . Such probability is estimated, in the sense of large deviations, as  $\exp(-tH(\bar{\nu}|\bar{\mu}))$ , where  $H(\bar{\nu}|\bar{\mu})$  is the relative entropy of  $\bar{\nu}$  with respect to  $\bar{\mu}$ .

In this paper, we want to provide a similar result, in the case in which the time spent by the process  $X_t$  at the point  $x_i$  may depend on the process itself. In particular, for  $\tau: \mathcal{X} \rightarrow [0, +\infty]$  a measurable map, define  $\mathcal{N}_t := \inf\{n \in \mathbb{N}^+ : \sum_{i=1}^{n+1} \tau(x_i) \geq t\}$ , and  $X_t := x_{\mathcal{N}_t+1}$ . In the next section, the precise mathematical setting for the study of the large deviations of the empirical measure of  $X_t$  is recalled, and a large deviations result is established in Section 1.4. While for  $\tau \equiv 1$  one gets the classical Sanov theorem, we are mainly interested in the case where the law of  $\tau$  under  $\bar{\mu}$  features heavy tails. In such a case the Markov process  $(X_t, t - \sum_{i=1}^{\mathcal{N}_t} \tau(x_i))$  does not have good ergodic properties, and the classical Donsker-Varadhan theorem is violated.

### 1.2 Mathematical setting

In the following  $\mathbb{N} = \{0, 1, \dots\}$ ,  $\mathbb{N}^+ = \mathbb{N} \setminus \{0\}$ ;  $\mathcal{X}$  is a Polish space, that is a separable, completely metrisable topological space; a general element of  $\mathcal{X}^{\mathbb{N}^+}$  will be denoted  $\mathbf{x} = (x_1, x_2, \dots)$ ;  $C_b(\mathcal{X})$  and  $C_c(\mathcal{X})$  are respectively the spaces of bounded continuous

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functions and compactly supported continuous functions on  $\mathcal{X}$ .  $\mathcal{M}_1(\mathcal{X})$  is the space positive Radon measure on  $\mathcal{X}$  with total variation bounded by 1, while  $\mathcal{P}(\mathcal{X}) \subset \mathcal{M}_1(\mathcal{X})$  is the set of Borel probability measures on  $\mathcal{X}$ . For  $\mu \in \mathcal{M}_1(\mathcal{X})$  and  $f$  a  $\mu$ -integrable function, we write  $\mu(f) := \int d\mu f$ . For  $\mu, \nu \in \mathcal{P}(\mathcal{X})$ ,  $\mathbf{H}(\nu|\mu)$  denotes the relative entropy of  $\nu$  with respect to  $\mu$ :

$$\mathbf{H}(\nu|\mu) := \sup_{\varphi \in C_b(\mathcal{X})} \nu(\varphi) - \log \mu(e^\varphi) = \begin{cases} \int \mu(dx) h\left(\frac{d\nu}{d\mu}\right) & \text{if } \nu \ll \mu; \\ +\infty & \text{otherwise;} \end{cases} \quad (1.1)$$

where the positive convex function  $h$  is defined as  $h(\varrho) = \varrho(\log \varrho - 1) + 1$ .

We always consider  $\mathcal{P}(X)$  equipped with the narrow (or weak) topology, namely the weakest topology such that  $\mu \mapsto \mu(f)$  is continuous for all  $f \in C_b(\mathcal{X})$ . In the particular case in which  $\mathcal{X}$  is locally compact, we will also regard  $\mathcal{M}_1(\mathcal{X})$  as a topological space, equipped with the vague topology, namely the weakest topology such that  $\mu \mapsto \mu(f)$  is continuous for all  $f \in C_c(\mathcal{X})$ .  $\mathcal{P}(X)$  is then a Polish space, and if  $\mathcal{X}$  is locally compact  $\mathcal{M}_1(\mathcal{X})$  is a compact Polish space.

Fix a reference probability  $\bar{\mu} \in \mathcal{P}(\mathcal{X})$  and a measurable function  $\tau: \mathcal{X} \rightarrow [0, +\infty]$ ;  $\tau(x)$  has to be interpreted as the time elapsed at  $x$ .  $\bar{\mu}$  and  $\tau$  are the only 'inputs' of the problem.

Define  $\xi: \mathcal{X} \rightarrow [0, +\infty]$  and  $\xi^\infty \in [0, +\infty]$  as

$$\begin{aligned} \xi(x) &= \inf_{\delta > 0} \sup \{c \geq 0 : \bar{\mu}(e^{c\tau} \mathbb{1}_{B_\delta(x)}) < +\infty\} \\ \xi^\infty &:= \sup_{K \subset \mathcal{X}, K \text{ compact}} \sup \{c \geq 0 : \bar{\mu}(e^{c\tau} \mathbb{1}_{K^c}) < +\infty\} \end{aligned} \quad (1.2)$$

where  $B_\delta(x) \subset \mathcal{X}$  is the ball of radius  $\delta$  centered at  $x$ , see (2.4) for another characterisation of  $\xi$ . Note  $\xi^\infty = +\infty$  if  $\mathcal{X}$  is compact.

The role of the auxiliary function  $\xi$  and of the assumptions below are discussed at the end of this section. In particular it is remarked that (A2) below is implied by regularity assumptions on  $\tau$  (e.g. upper semicontinuity at infinity). Hereafter (A1) and (A2) will *always* be assumed, while our main results are proved whenever at least one of (A3) or (A4) holds (with somehow different statements in the two cases).

(A1)  $\bar{\mu}(\{\tau = 0\}) = \bar{\mu}(\{\tau = +\infty\}) = 0$ .

(A2)  $\bar{\mu}(\{\xi < +\infty\}) = 0$ .

(A3)  $\xi^\infty = +\infty$ .

(A4)  $\mathcal{X}$  is locally compact.

In the following  $\mathbf{x}$  is sampled as an i.i.d. sequence with marginal law  $\bar{\mu}$  and  $\mathbf{E}$  will denote the expectation of functions of  $\mathbf{x}$  with respect to  $\bar{\mu}^{\otimes \mathbb{N}^+}$ . By (A1), for each  $n \in \mathbb{N}$ ,  $t \geq 0$  and a.e.  $\mathbf{x}$ , the following random variables are well defined

$$\begin{aligned} S_0 &\equiv S_0(\mathbf{x}) := 0, & S_n &\equiv S_n(\mathbf{x}) := \sum_{i=1}^n \tau(x_i), & n &\geq 1, \\ \mathcal{N}_t &\equiv \mathcal{N}_t(\mathbf{x}) := \inf\{n \in \mathbb{N} : S_{n+1} \geq t\} = \sum_{n=1}^{+\infty} \mathbb{1}_{(S_n \leq t)}, \\ X_t &\equiv X_t(\mathbf{x}) := x_{\mathcal{N}_t+1}, \\ \pi_t &\equiv \pi_t(\mathbf{x}) = \frac{1}{t} \int_{[0,t[} ds \delta_{X_s} \in \mathcal{P}(\mathcal{X}). \end{aligned} \quad (1.3)$$

In other words,  $X_t = x_1$  for  $t \in [0, \tau(x_1)[$ ,  $X_t = x_2$  for  $t \in [\tau(x_1), \tau(x_1) + \tau(x_2)[$  and so on, while  $\pi_t: \mathcal{X}^{\mathbb{N}^+} \rightarrow \mathcal{P}(\mathcal{X})$  is the local time or the empirical measure of  $X_t$ . Let  $\mathbf{P}_t := \bar{\mu}^{\otimes \mathbb{N}^+} \circ \pi_t^{-1}$  be the law of  $\pi_t$ .

From the ergodic theorem, one expects  $\pi_t$  to concentrate on a deterministic limit as  $t \rightarrow +\infty$  (this is easily established, for instance, whenever  $\bar{\mu}(\tau) < +\infty$ ). Large deviations of  $\mathbf{P}_t$  are then relevant, and subject of investigation of this paper.

### 1.3 Some examples

Taking advantage of the general metric setting, one is able to fit in this framework also the case of a process with random waiting time, see the examples (b) and (c) below.

- (a) If  $\tau(x) \equiv 1$ , then we are in the framework of the classical Sanov theorem, [2, Chapter 6.2]. Here  $\xi(x) = \xi^\infty = +\infty$  for all  $x \in \mathcal{X}$ .
- (b) Assume  $\mathcal{X} = \mathcal{Y} \times [0, +\infty[$  for some Polish space  $\mathcal{Y}$ . Let  $p$  be a Borel probability on  $\mathcal{Y}$  and for  $p$ -a.e.  $y$  let  $\phi_y$  be a probability on  $[0, +\infty[$  concentrated on  $]0, +\infty[$ , with  $y \mapsto \phi_y$  measurable. Set  $d\bar{\mu}((y, t)) = dp(y) d\phi_y(t)$  and  $\tau(y, t) = t$ . Then we are in the framework of a pure jump process, jumping on  $\mathcal{Y}$  with law  $p$  and spending a random time at a visited point  $y$  with law  $\phi_y$ . In this case

$$\xi(y, t) = \begin{cases} \sup\{c \geq 0 : \int \phi_y(ds) e^{cs} < +\infty\} & \text{if } t = +\infty \text{ and } y \in \text{Supp}(\nu) \\ +\infty & \text{otherwise.} \end{cases}$$

$$\xi^\infty = \sup_{K \subset \mathcal{Y}, K \text{ compact}} \inf_{y \in K^c} \xi(y, +\infty)$$

- (c) As a special case of (b), take  $\mathcal{X} := [0, +\infty[ \times [0, +\infty[$  and for  $\bar{\mu}(d(r, s)) = \nu(dr)\phi(ds)$ , where  $\nu$  is any probability measure on  $]0, +\infty[$  and  $\phi$  is the exponential law with mean 1. Set  $\tau((y, s)) = \theta(y)s$ , so that, conditionally on  $y$ ,  $\tau$  is an exponential random variable with mean  $\theta(y)$ . In this setting,  $\mathcal{N}_t$  is an inhomogeneous Poisson random process, and the empirical measure  $\pi_t$  keeps track of the rates of the interarrival times. In this case  $\xi(y, t) = +\infty$  for  $t < +\infty$  or  $y \notin \text{Supp}(\nu)$ , while  $\xi(y, +\infty) = 1/\theta(y)$  for  $y \in \text{Supp}(\nu)$ , and  $\xi^\infty = \lim_{y \rightarrow +\infty} \xi(y, +\infty)$ .
- (d) An interesting example in which  $\tau$  is 'truly' deterministic is the following.  $\mathcal{X} = ]0, +\infty[^n$ ,  $\bar{\mu}(dx) = \prod_{i=1}^n \bar{\mu}_i(dx_i)$  for some probabilities  $\bar{\mu}_i \in \mathcal{P}([0, +\infty[)$  and  $\tau(x) = \frac{1}{n} \sum_{i=1}^n \frac{1}{x_i}$ . This is a model for a particle moving on 1-dimensional torus of length 1. During its motion the particle touches some fixed *hot* points equi-spaced on the torus, and it changes its speed by sampling a new one with law  $\bar{\mu}_i$  at the hot point  $i$ .  $\tau(x)$  is then the time elapsed to complete a tour of the torus.

One can derive the large deviations of some physical quantities (e.g. kinetic energy of the particle) from the large deviations of the empirical measure of  $X_t$ . The physically relevant case is  $\bar{\mu}_i(x_i) = x_i e^{-\beta_i x_i^2} dx_i$  for some  $\beta_i > 0$ . Then  $\xi^\infty = +\infty$  and  $\xi(x) = +\infty$  unless one the  $x_i$  is 0, in which case  $\xi(x) = 0$ . As remarked below, when  $\{\xi = 0\}$  is non-empty, the large deviations rate functional is not strictly convex. For  $n = 1$ , this moving particle dynamics has been used as a building block of a toy model of out-of-equilibrium statistical mechanics in [6], where the absence of strict convexity of the rate causes a dynamic phase transition in the model.

### 1.4 Large deviations results

We recall the following standard definition.

**Definition 1.1.** *Let  $\mathcal{Y}$  be Polish space and  $(\mathbf{Q}_t)_{t>0}$  a family of Borel probability measures on  $\mathcal{Y}$  and  $I: \mathcal{Y} \rightarrow [0, +\infty]$ . Then:*

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- $I$  is good if  $\{y \in \mathcal{Y} : I(y) \leq M\}$  is compact in  $\mathcal{Y}$  for all  $M > 0$  and  $I \neq +\infty$ .
- $(\mathbf{Q}_t)_{t>0}$  satisfies a large deviations upper bound with good rate  $I$  if

$$\overline{\lim}_{t \rightarrow +\infty} \frac{1}{t} \log \mathbf{Q}_t(\mathcal{C}) \leq - \inf_{u \in \mathcal{C}} I(u) \quad \text{for all } \mathcal{C} \subset \mathcal{Y} \text{ closed.}$$

- $(\mathbf{Q}_t)_{t>0}$  satisfies a large deviations lower bound with good rate  $I$ , if

$$\underline{\lim}_{t \rightarrow +\infty} \frac{1}{t} \log \mathbf{Q}_t(\mathcal{O}) \geq - \inf_{u \in \mathcal{O}} I(u) \quad \text{for all } \mathcal{O} \subset \mathcal{Y} \text{ open.}$$

$(\mathbf{P}_t)_{t>0}$  is said to satisfy a good large deviations principle if both the upper and lower bounds hold with the same good rate  $I$ .

For  $\nu \in \mathcal{M}_1(\mathcal{X})$ , let  $\nu_a$  and  $\nu_s$  be respectively the absolutely continuous and singular parts of  $\nu$  with respect to  $\bar{\mu}$ . If  $\nu$  is such that  $\nu(1/\tau) \in ]0, +\infty[$  define  $\bar{\nu} \in \mathcal{P}(\mathcal{X})$  as

$$\bar{\nu}(dx) = \frac{\frac{1}{\tau(x)}\nu(dx)}{\nu(1/\tau)}. \quad (1.4)$$

**Proposition 1.2.** Define  $I: \mathcal{P}(\mathcal{X}) \rightarrow [0, +\infty]$  as

$$I(\nu) = \begin{cases} \nu_a(1/\tau)\mathbf{H}(\bar{\nu}_a|\bar{\mu}) + \nu_s(\xi) & \text{if } \nu_a(1/\tau) < +\infty, \\ +\infty & \text{otherwise,} \end{cases}$$

where we define  $\nu_a(1/\tau)\mathbf{H}(\bar{\nu}_a|\bar{\mu}) = 0$  whenever  $\nu_a(1/\tau) = 0$ . If (A3) holds, then  $I$  is a good and convex functional on  $\mathcal{P}(\mathcal{X})$ .

**Theorem 1.3.** If (A3) holds, then  $(\mathbf{P}_t)_{t>0}$  satisfies a good large deviations principle on  $\mathcal{P}(\mathcal{X})$  with rate  $I$ .

In the following remark some features of the functional  $I$  are investigated. In particular we characterise the cases where  $I$  is strictly convex and those in which it features affine stretches.

**Remark 1.4.** Assume (A3). Since  $\xi(x) = +\infty$  for  $x \notin \text{Supp}(\bar{\mu})$ ,  $I(\nu) = +\infty$  if  $\text{Supp}(\nu) \not\subset \text{Supp}(\bar{\mu})$ . However, contrary to classical Sanov theorem, in general  $I(\nu) < +\infty$  does not imply that  $\nu$  is absolutely continuous with respect to  $\bar{\mu}$ , unless  $\xi \equiv \infty$ . In general, the nature of  $I(\nu)$  depends on the values of  $\xi$  and  $\bar{\mu}(\tau)$ . Indeed let

$$E := \{x \in \mathcal{X} : \xi(x) = 0\}$$

be the set of points around which  $\tau$  has no local exponential moments. Then

- (1) If  $E = \emptyset$ , namely if  $\xi(x) > 0$  for all  $x \in \mathcal{X}$ , then a fortiori  $\bar{\mu}(\tau) < +\infty$  and  $I(\nu) = 0$  iff  $\nu = \mu$ , where (consistently with (1.4))

$$\mu(dx) := \frac{\tau(x)\bar{\mu}(dx)}{\bar{\mu}(\tau)}. \quad (1.5)$$

- (2) If  $E \neq \emptyset$ , there are two possibilities

- (2A) If  $\bar{\mu}(\tau) < +\infty$ , then  $I(\nu) = 0$  iff  $\nu = \alpha\mu + (1 - \alpha)\lambda$  for some  $\alpha \in [0, 1]$  and some  $\lambda \in \mathcal{P}(X)$  such that  $\lambda(E) = 1$ , where  $\mu$  is given by (1.5).  
 (2B) If  $\bar{\mu}(\tau) = +\infty$  then  $I(\nu) = 0$  iff  $\nu$  is concentrated on  $E$ .

In particular, Theorem 1.3 implies the convergence in law of  $\pi_t$  to  $\mu$  in case (1), and in case (2B) if  $E$  is a singleton. In all other cases, a nontrivial second order large deviations may hold, see [10] where moderate deviations are discussed in a particular case. Finally, if  $E \neq \emptyset$ , then the subdifferential of  $I$  is nontrivial.

If  $\xi^\infty < +\infty$ ,  $(\mathbf{P}_t)_{t>0}$  is not exponentially tight on  $\mathcal{P}(\mathcal{X})$ , and large deviations need to be investigated on  $\mathcal{M}_1(\mathcal{X})$ . However, in this case we need  $\mathcal{X}$  to be locally compact in order to have good topological properties of  $\mathcal{M}_1(\mathcal{X})$ .

**Proposition 1.5.** Define  $I' : \mathcal{M}_1(\mathcal{X}) \rightarrow [0, +\infty]$  as

$$I'(\nu) = \begin{cases} \nu_a(1/\tau)\mathbf{H}(\bar{\nu}_a|\bar{\mu}) + \nu_s(\xi) + (1 - \nu(\mathcal{X}))\xi^\infty & \text{if } \nu_a(1/\tau) < +\infty, \\ +\infty & \text{otherwise,} \end{cases}$$

If (A4) holds, then  $I'$  is a good and convex functional on  $\mathcal{M}_1(\mathcal{X})$ .

**Theorem 1.6.** If (A4) holds, then  $(\mathbf{P}_t)_{t>0}$  satisfies a good large deviations principle on  $\mathcal{M}_1(\mathcal{X})$  with rate  $I'$ .

Under (A1), the key assumption (A2) is satisfied whenever

$$\bar{\mu}(\cap_{M>0} \text{Closure}(\{\tau \geq M\})) = 0.$$

In particular (A2) holds if  $\tau$  is upper semicontinuous at infinity. Since all the results stated above make sense even dropping (A2), one may wonder whether it is a merely technical condition. While one can prove the large deviations upper bound even dropping this assumption, the lower bound is in general false if (A2) does not hold.

### 1.5 Outlook

With the same notation as above, one may also introduce the Markov process  $Y_t = (X_t, \frac{t - \sum_{i=1}^{N_t} \tau(x_i)}{\tau(x_{N_t+1})}) \in \mathcal{X} \times [0, 1[$ . Large deviations for the empirical measure of  $Y_t$  would give large deviations of  $X_t$  by a standard contraction argument. Moreover, the Donsker-Varadhan theory [3] and its extensions provide general large deviations results for the empirical measure of a Markov process. However, this approach fails in this case. On the one hand, standard Donsker-Varadhan theorems cannot be applied here, since  $Y_t$  only enjoys weak ergodic properties. On the other hand, even formally, the Donsker-Varadhan rate functional does not provide the right answer, a feature already remarked in [5] for renewal processes. Indeed, it has been proved in [7] that in general the empirical measure of  $Y_t$  does not satisfy a large deviations principle, and in the special case it does (which depends on the law of  $\tau$  under  $\bar{\mu}$ ), the rate functional does not correspond to the Donsker-Varadhan functional. Similarly, the large deviations rate functional for  $\pi_t$  does not correspond in general to the one predicted by applying contraction to the Donsker-Varadhan functional for the empirical measure of  $Y_t$  (unless  $\tau$  has all exponential moments bounded). In this respect, it may be remarkable that the law of  $\pi_t$  satisfies a large deviations principle at all.

## 2 The functional $I$

This section is devoted to prove Proposition 1.2, Proposition 1.5 and general properties of the functional  $I$ , which will play a key role in the proof of the main theorems. First we remark that one can reduce to the case of a compact state space  $\mathcal{X}$ .

**Proposition 2.1.** Suppose that Proposition 1.2 and Theorem 1.3 hold with the additional hypotheses of  $\mathcal{X}$  being a compact Polish space. Then Proposition 1.2, Theorem 1.3, Proposition 1.5 and Theorem 1.6 hold.

*Proof.* An arbitrary Polish space  $\mathcal{X}$  embeds continuously in the compact Polish space  $[0, 1]^{\mathbb{N}}$ , see [9, Lemma 3.1.2]. Regard  $\mathcal{X}$  as a subset of  $[0, 1]^{\mathbb{N}}$  and let  $\mathcal{Y}$  be the closure of  $\mathcal{X}$ . Then  $\mathcal{Y}$  is compact. Extend  $\bar{\mu}$  to  $\mathcal{Y}$  setting  $\bar{\mu}(\mathcal{Y} \setminus \mathcal{X}) = 0$  and extend  $\tau$  to  $\mathcal{Y}$  setting  $\tau(x) = +\infty$  for  $x \in \mathcal{Y} \setminus \mathcal{X}$ . We denote  $\xi_{\mathcal{Y}}$  and  $I_{\mathcal{Y}}$  the object corresponding to  $\xi$  and  $I$  on

$\mathcal{Y}$ . Then (A1), (A2) hold on  $\mathcal{Y}$  since they hold on  $\mathcal{X}$ , while *refa3* is trivially satisfied on  $\mathcal{Y}$ . Thus, by the hypotheses of this proposition, the extension of  $\mathbf{P}_t$  to  $\mathcal{P}(\mathcal{Y})$  satisfies a large deviations principle with good rate  $I_{\mathcal{Y}}$ . We then separate the two cases, whether (A3) or (A4) hold on  $\mathcal{X}$ .

If (A3) holds (on  $\mathcal{X}$ ), then  $\xi_{\mathcal{Y}}(x) = +\infty$  for  $x \in \mathcal{Y} \setminus \mathcal{X}$  (since neighborhoods of such points  $x$  in  $\mathcal{Y}$  are exactly complements of compact subsets of  $\mathcal{X}$ ). Thus the map  $\Pi: \mathcal{P}(\mathcal{Y}) \rightarrow \mathcal{P}(\mathcal{X})$  defined as

$$\Pi(\nu) = \begin{cases} \nu(\cdot|\mathcal{X}) := \frac{\nu(\cdot \cap \mathcal{X})}{\nu(\mathcal{X})} & \text{if } \nu(\mathcal{X}) > 0 \\ \bar{\mu} & \text{otherwise} \end{cases}$$

is continuous on the domain of  $I_{\mathcal{Y}}$ . Since  $\Pi$  is just the restriction map for probabilities concentrated on  $\mathcal{X}$ , the extension of  $\mathbf{P}_t$  to  $\mathcal{P}(\mathcal{Y})$  is mapped to  $\mathbf{P}_t$  by  $\Pi$ . Then by contraction principle [2, Chapter 4.2],  $I$  is good and  $\mathbf{P}_t$  satisfies a good large deviations principle on  $\mathcal{P}(\mathcal{X})$  with rate  $I$ . It is immediate to check that  $\Pi$  preserves the convexity, so  $I$  is convex.

Suppose now (A4) holds (but not (A3)). Consider the map  $\Pi': \mathcal{P}(\mathcal{Y}) \rightarrow \mathcal{M}_1(\mathcal{X})$  defined by

$$\Pi'(\nu)(f) = \nu(f) \quad \forall f \in C_c(\mathbf{X})$$

where we also identified  $f$  with its unique continuous extension on  $\mathcal{Y}$  (namely  $f(x) = 0$  for  $x \in \mathcal{Y} \setminus \mathcal{X}$ ). Then  $\Pi'$  is continuous, and we conclude again by contraction principle.  $\square$

Motivated by the previous remark, hereafter we assume  $\mathcal{X}$  to be compact, with no loss of generality.

For  $\delta > 0$ , define  $\xi_{\delta}: \mathcal{X} \rightarrow [0, +\infty]$  as

$$\xi_{\delta}(x) = \sup \{c : \bar{\mu}(e^{c\tau} \mathbb{1}_{B_{\delta}(x)}) < +\infty\} \tag{2.1}$$

In particular  $\xi = \sup_{\delta>0} \xi_{\delta}$ . Let  $\hat{\xi}_{\delta}$  be the lower semicontinuous envelope of  $\xi_{\delta}$ .

**Lemma 2.2.** *For all  $x \in \mathcal{X}$ ,  $\xi(x) = \sup_{\delta>0} \hat{\xi}_{\delta}(x)$ . In particular  $\xi$  is lower semicontinuous.*

*Proof.* By the very definition of  $\xi_{\delta}$ , if  $y \in B_{\delta}(x)$ , then  $\xi_{2\delta}(x) \leq \xi_{\delta}(y)$ . Therefore

$$\xi_{\delta}(x) \geq \hat{\xi}_{\delta}(x) := \sup_{\varepsilon>0} \inf_{y \in B_{\varepsilon}(x)} \xi_{\delta}(y) \geq \inf_{y \in B_{\delta}(x)} \xi_{\delta}(y) \geq \xi_{2\delta}(x)$$

The lemma follows taking the supremum in  $\delta > 0$ .  $\square$

Let  $LSC(\mathcal{X})$  be the set of lower semicontinuous functions  $f: \mathcal{X} \rightarrow ]-\infty, +\infty]$ . If  $f \in LSC(\mathcal{X})$  then  $f$  is bounded from below.

**Lemma 2.3.** *Recall (2.1). For all  $M < +\infty$  and  $\varepsilon, \delta > 0$  (hereafter  $a \wedge b := \min(a, b)$ )*

$$\bar{\mu}(e^{(\xi_{\delta} \wedge M - \varepsilon)\tau}) < +\infty. \tag{2.2}$$

*On the other hand, if  $f \in LSC(\mathcal{X})$  is such that*

$$\bar{\mu}(e^{\tau f}) < +\infty, \tag{2.3}$$

*then  $f(x) \leq \xi(x)$  for all  $x \in \mathcal{X}$ . In particular*

$$\xi(x) = \sup \{f(x), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) < +\infty\}. \tag{2.4}$$

*Proof.* Fix  $M, \varepsilon, \delta > 0$  and let  $\{B_{\delta/2}(y_1), \dots, B_{\delta/2}(y_n)\}$  be a finite covering of the compact space  $\mathcal{X}$  with balls of radius  $\delta/2$ . Since  $\xi_\delta(x) \leq \xi_{\delta/2}(y_i)$  for  $x \in B_{\delta/2}(y_i)$

$$\bar{\mu}(e^{(\xi_\delta \wedge M - \varepsilon)\tau}) \leq \sum_{i=1}^n \bar{\mu}(e^{(\xi_\delta \wedge M - \varepsilon)\tau} \mathbb{1}_{B_{\delta/2}(y_i)}) \leq \sum_{i=1}^n \bar{\mu}(e^{(\xi_{\delta/2}(y_i) \wedge M - \varepsilon)\tau} \mathbb{1}_{B_{\delta/2}(y_i)}).$$

Since  $\xi_{\delta/2}(y_i) \wedge M - \varepsilon < \xi_{\delta/2}(y_i)$ , each term in the summation in the last line of the above formula is finite by the very definition of  $\xi_{\delta/2}(y_i)$ . Thus (2.2) holds.

Let now  $f \in LSC(\mathcal{X})$ , and suppose that for some  $x \in \mathcal{X}$  and  $\varepsilon > 0$ ,  $f(x) \geq \xi(x) + 2\varepsilon$ . Since  $f$  is lower semicontinuous, there exists  $\delta > 0$  such that  $\inf_{y \in B_\delta(x)} f(y) \geq \xi(x) + \varepsilon$ . Then

$$\bar{\mu}(e^{\tau f}) \geq \bar{\mu}(e^{\tau f} \mathbb{1}_{B_\delta(x)}) \geq \bar{\mu}(e^{\tau[\xi(x) + \varepsilon]} \mathbb{1}_{B_\delta(x)}) \geq \bar{\mu}(e^{\tau[\xi_\delta(x) + \varepsilon]} \mathbb{1}_{B_\delta(x)}) = +\infty.$$

Therefore if (2.3) holds, then  $f \leq \xi$  everywhere. □

**Proposition 2.4.** For each  $\nu \in \mathcal{P}(\mathcal{X})$

$$I(\nu) = \sup \{ \nu(f), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) \leq 1 \} =: \tilde{I}(\nu). \tag{2.5}$$

In particular Proposition 1.2 holds.

*Proof.* Fix  $\nu \in \mathcal{P}(\mathcal{X})$ , and let  $f: \mathcal{X} \rightarrow \mathbb{R}$  be Borel measurable,  $\nu$ -integrable, such that  $\bar{\mu}(e^{\tau f}) < 1$  and  $f \leq (\hat{\xi}_\delta \wedge M - \varepsilon)$  for some  $M, \delta, \varepsilon > 0$ . Since continuous functions are dense in  $L_1(\nu + \bar{\mu})$ , there exists a sequence  $(f_n)$  in  $LSC(\mathcal{X})$  such that  $f_n \rightarrow f$  in  $L_1(d\nu)$  and (up to passing to a subsequence) also  $\bar{\mu}$ -almost everywhere. Moreover one can assume  $f_n \leq \hat{\xi}_\delta \wedge M - \varepsilon$ , since the sequence  $f_n \wedge (\hat{\xi}_\delta \wedge M - \varepsilon)$  is in  $LSC(\mathcal{X})$  and enjoys the aforementioned properties as well. Dominated convergence and (2.2) imply  $\lim_n \bar{\mu}(e^{\tau f_n}) = \bar{\mu}(e^{\tau f}) < 1$ . Therefore  $\bar{\mu}(e^{\tau f_n}) \leq 1$  for  $n$  large enough. Thus

$$\tilde{I}(\nu) \geq \sup_{M, \delta, \varepsilon > 0} \sup \{ \nu(f), f \nu\text{-integrable such that } \bar{\mu}(e^{\tau f}) < 1, f \leq \hat{\xi}_\delta \wedge M - \varepsilon \}. \tag{2.6}$$

By (A2), the Borel set  $A = \{\xi = +\infty\} \setminus \text{Supp}(\nu_s)$  is such that  $\bar{\mu}$  and  $\nu_a$  are concentrated on  $A$  and  $\nu_s$  is concentrated on  $A^c$ . Fix  $M, \delta, \varepsilon > 0$  and take  $\varphi \in C(\mathcal{X})$  such that  $\bar{\mu}(e^\varphi) \leq 1$ . In the right hand side of (2.6) consider a  $f$  of the form

$$f = \left(\frac{\varphi}{\tau} \wedge \hat{\xi}_\delta \wedge M\right) \mathbb{1}_A + (\hat{\xi}_\delta \wedge M) \mathbb{1}_{A^c} - \varepsilon. \tag{2.7}$$

Then  $\bar{\mu}(e^{\tau f}) = \bar{\mu}(e^{\tau f} \mathbb{1}_A) \leq \bar{\mu}(e^{\varphi - \varepsilon}) \leq e^{-\varepsilon} < 1$ .

If  $\nu_a(1/\tau) = +\infty$ , take  $\varphi \equiv 1$  in (2.7). Then  $f$  is  $\nu$ -integrable and by monotone convergence  $\nu(f) \rightarrow +\infty$  as one lets  $M \rightarrow +\infty$  and  $\delta \downarrow 0$ , so that  $\tilde{I}(\nu) = +\infty$  by (2.6). Thus  $\tilde{I}(\nu) = I(\nu) = +\infty$  whenever  $\nu_a(1/\tau) = +\infty$ .

Consider then the case  $\nu_a(1/\tau) < +\infty$ . Since  $\varphi$  is bounded, any  $f$  of the form (2.7) is  $\nu$ -integrable, and thus by (2.6)

$$\tilde{I}(\nu) \geq \nu(f) = \nu_a\left(\frac{\varphi}{\tau} \wedge \hat{\xi}_\delta \wedge M\right) + \nu_s(\hat{\xi}_\delta \wedge M) - \varepsilon.$$

Take the limit  $M \rightarrow +\infty, \delta \downarrow 0, \varepsilon \downarrow 0$ . Monotone convergence and Lemma 2.2 then yield

$$\tilde{I}(\nu) \geq \nu_a\left(\frac{\varphi}{\tau}\right) + \nu_s\left(\sup_{\delta > 0} \hat{\xi}_\delta\right) = \nu_a\left(\frac{\varphi}{\tau}\right) + \nu_s(\xi) = \nu_a(1/\tau) \bar{\nu}_a(\varphi) + \nu_s(\xi)$$

where the last equality is a direct consequence of (1.4). Now optimize over  $\varphi$  to get

$$\begin{aligned} \tilde{I}(\nu) &\geq \nu_a(1/\tau) \sup \{ \bar{\nu}_a(\varphi), \varphi \in C(\mathcal{X}) : \bar{\mu}(e^\varphi) \leq 1 \} + \nu_s(\xi) \\ &\geq \nu_a(1/\tau) \sup \{ \bar{\nu}_a(\varphi) - \log \bar{\mu}(e^\varphi), \varphi \in C(\mathcal{X}) : \bar{\mu}(e^\varphi) = 1 \} + \nu_s(\xi) \end{aligned}$$



Notice that the condition  $\bar{\mu}(e^\varphi) = 1$  can now be dropped in the supremum in the last line above, since for any  $c \in \mathbb{R}$  the change  $\varphi \mapsto \varphi + c$  leaves the quantity  $\bar{\nu}_a(\varphi) - \log \bar{\mu}(e^\varphi)$  invariant. Therefore the supremum over  $\varphi$  equals the relative entropy as defined in (1.1), so that  $\tilde{I} \geq I$ .

In order to prove  $I(\nu) \geq \tilde{I}(\nu)$ , one only needs to consider the case  $\nu_a(1/\tau) < +\infty$ , the inequality being trivial otherwise. Then for  $\varphi \in L_1(d\bar{\nu}_a)$  such that  $\bar{\mu}(e^\varphi) \leq 1$ ,

$$\nu_a(1/\tau)\mathbf{H}(\bar{\nu}_a|\bar{\mu}) \geq \nu_a(1/\tau)[\bar{\nu}_a(\varphi) - \log \bar{\mu}(e^\varphi)] \geq \nu_a(\varphi/\tau) = \nu_a(f),$$

where  $f := \varphi/\tau$  and the above conditions on  $\varphi$  translates into  $f \in L_1(d\nu_a)$  and  $\bar{\mu}(e^{\tau f}) \leq 1$ . Therefore, optimizing over  $f \in LSC(\mathcal{X})$  satisfying these two conditions, and noting that Lemma 2.3 implies  $f \leq \xi$  for such a  $f$

$$\begin{aligned} I(\nu) &= \nu_a(1/\tau)\mathbf{H}(\bar{\nu}_a|\bar{\mu}) + \nu_s(\xi) \\ &\geq \sup\{\nu_a(f), f \in LSC(\mathcal{X}) \cap L_1(d\nu_a) : \bar{\mu}(e^{\tau f}) \leq 1\} + \nu_s(\xi) \\ &= \sup\{\nu_a(f) + \nu_s(\xi), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) \leq 1\} \\ &\geq \sup\{\nu_a(f) + \nu_s(f), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) \leq 1\} = \tilde{I}(\nu). \end{aligned}$$

Now (2.5) states in particular that  $I$  is the supremum of a family of linear lower semi-continuous mappings, thus Proposition 1.2 follows.  $\square$

**Lemma 2.5.** For  $A \subset \mathcal{X}$  a Borel set, define

$$\begin{aligned} \xi^A &:= \sup\{c \geq 0 : \bar{\mu}(e^{c\tau} \mathbb{1}_A) < +\infty\}, \\ \underline{\xi}^A &:= -\overline{\lim}_{L \rightarrow +\infty} \frac{1}{L} \log \bar{\mu}(\{\tau \geq L\} \cap A). \end{aligned}$$

Then  $\xi^A = \underline{\xi}^A$ .

*Proof.* For  $c > 0$

$$\bar{\mu}(e^{c\tau} \mathbb{1}_A) = \int_{\mathbb{R}^+} d\eta \bar{\mu}(\{e^{c\tau} \geq \eta\} \cap A) = c \int_{\mathbb{R}^+} dL \bar{\mu}(\{\tau \geq L\} \cap A) e^{cL}.$$

It is then easy to check that, for  $c > \xi^A$ ,  $\bar{\mu}(e^{c\tau} \mathbb{1}_A) = +\infty$ , while if  $\xi^A > 0$  and  $0 < c < \xi^A$ , then  $\bar{\mu}(e^{c\tau} \mathbb{1}_A) < +\infty$ . It follows  $\xi^A = \underline{\xi}^A$ .  $\square$

**Proposition 2.6.** Define  $J : \mathcal{P}(\mathcal{X}) \rightarrow [0, +\infty]$  as

$$J(\nu) = \begin{cases} I(\nu) & \text{if } \nu = \nu_a, \\ +\infty & \text{otherwise.} \end{cases} \tag{2.8}$$

$I$  is the lower semicontinuous envelope of  $J$ .

Notice that in the classical case  $\tau \equiv 1$ ,  $J$  coincides with  $I$ . However, in this general case,  $I = J$  iff  $\xi \equiv +\infty$ .

*Proof of Proposition 2.6.* Since  $J \geq I$  and  $I$  is lower semicontinuous, the lower semicontinuous envelope of  $J$  is greater than  $I$ . Therefore it is enough to show that for each  $\nu \in \mathcal{P}(\mathcal{X})$  such that  $I(\nu) < +\infty$ , there exists a sequence  $\nu^n \rightarrow \nu$  such that  $\lim_n J(\nu^n) \leq I(\nu)$ .

Let  $\nu = \nu_a + \nu_s$  satisfy  $I(\nu) < +\infty$ . Since  $\mathcal{X}$  is compact, for each  $\delta \in (0, 1)$  there exist  $n^\delta \in \mathbb{N}^+$  and a finite Borel partition  $(A_1^\delta, \dots, A_{n^\delta}^\delta)$  of  $\mathcal{X}$  such that each  $A_i^\delta$  has

diameter bounded by  $\delta$ , has nonempty interior, and satisfies  $\nu_s(\partial A_i^\delta) = 0$ . For  $\delta > 0$  and  $M > L \geq 0$ , define

$$A_i^{\delta,L,M} := \{L \leq \tau \leq M\} \cap A_i^\delta.$$

Fix a  $j \in \{1, \dots, n^\delta\}$ . We claim that

$$\text{if } \nu_s(A_j^\delta) > 0 \text{ then } \forall L \geq 0, \exists M^L \geq L \text{ such that } \bar{\mu}(A_j^{\delta,L,M}) > 0 \text{ for all } M \geq M^L. \quad (2.9)$$

Indeed  $\nu_s(\xi) \leq I(\nu) < +\infty$ , thus  $\nu_s$  is concentrated on  $\{\xi < +\infty\}$ . Since  $\nu_s(\partial A_j^\delta) = 0$ , there exists a point  $x_j^\delta$  in the interior of  $A_j^\delta$  such that  $\xi(x_j^\delta) < +\infty$ . Then, for each  $c > \xi(x_j^\delta)$  and  $\varepsilon > 0$

$$\lim_{M \rightarrow +\infty} \bar{\mu}(e^{c\tau} \mathbb{1}_{B_\varepsilon(x_j^\delta)} \mathbb{1}_{L \leq \tau \leq M}) = \bar{\mu}(e^{c\tau} \mathbb{1}_{B_\varepsilon(x_j^\delta)} \mathbb{1}_{\tau \geq L}) = +\infty.$$

Hence for  $M$  large enough  $\{L \leq \tau \leq M\}$  has positive  $\bar{\mu}$ -measure in each neighbourhood of  $x_j^\delta$ , including  $A_j^\delta$ . The claim (2.9) is thus proved.

By (2.9), for each  $\mathbf{L} = (L_1, L_2, \dots) \in [0, +\infty[^{\mathbb{N}}$  there exists  $\mathbf{M}^{\mathbf{L}} \in [0, +\infty[^{\mathbb{N}}$ , such that the probability measure

$$\nu^{\delta,\mathbf{L},\mathbf{M}}(dx) := \nu_a(dx) + \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) \frac{\tau(x) \bar{\mu}(dx|A_i^{\delta,L_i,M_i})}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})} \quad (2.10)$$

is well defined whenever  $\mathbf{M} \geq \mathbf{M}^{\mathbf{L}}$ , provided the terms in the summation are understood to vanish whenever  $\nu_s(A_i^\delta)$  does. It follows straightforwardly from this definition that for each  $\varphi \in C_b(\mathcal{X})$

$$\begin{aligned} & \lim_{\delta \downarrow 0} \sup_{\mathbf{L} \in [0, +\infty[^{\mathbb{N}}, \mathbf{M} \geq \mathbf{M}^{\mathbf{L}}} |\nu^{\delta,\mathbf{L},\mathbf{M}}(\varphi) - \nu(\varphi)| \\ & \leq \overline{\lim}_{\delta \downarrow 0} \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) \left[ \sup_{x \in A_i^\delta} \varphi(x) - \inf_{x \in A_i^\delta} \varphi(x) \right] = 0. \end{aligned} \quad (2.11)$$

Note that for each  $\delta > 0$  and  $\mathbf{L}, \mathbf{M} \in [0, +\infty[^{\mathbb{N}}$  with  $\mathbf{M} \geq \mathbf{M}^{\mathbf{L}}$ ,  $\nu^{\delta,\mathbf{L},\mathbf{M}}$  is absolutely continuous with respect to  $\bar{\mu}$ . By the convexity of  $I$  proved in Proposition 2.4

$$\begin{aligned} J(\nu^{\delta,\mathbf{L},\mathbf{M}}) &= I(\nu^{\delta,\mathbf{L},\mathbf{M}}) \leq \nu_a(\mathcal{X}) I\left(\frac{1}{\nu_a(\mathcal{X})} \nu_a\right) \\ & \quad + \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) I\left(\frac{\tau(x) \bar{\mu}(dx|A_i^{\delta,L_i,M_i})}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})}\right) \\ &= I(\nu) - \left[ \nu_s(\xi) - \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) I\left(\frac{\tau(x) \bar{\mu}(dx|A_i^{\delta,L_i,M_i})}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})}\right) \right] \end{aligned} \quad (2.12)$$

where the corresponding terms above are understood to vanish whenever  $\nu_a(\mathcal{X})$  or  $\nu_s(A_i^\delta)$  do. By direct computation

$$\begin{aligned} I\left(\frac{\tau(x) \bar{\mu}(dx|A_i^{\delta,L_i,M_i})}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})}\right) &= -\frac{1}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})} \log \bar{\mu}(A_i^{\delta,L_i,M_i}) \\ &\leq -\frac{1}{L_i} \log \bar{\mu}(\{L_i \leq \tau \leq M_i\} \cap A_i^\delta). \end{aligned}$$

Thus, from Lemma 2.5

$$\overline{\lim}_{L_i \rightarrow +\infty} \overline{\lim}_{M_i \rightarrow +\infty} \left(\frac{\tau(x) \bar{\mu}(dx|A_i^{\delta,L_i,M_i})}{\bar{\mu}(\tau|A_i^{\delta,L_i,M_i})}\right) \leq \xi^{A_i^\delta}.$$

Now, since  $\xi \geq \xi^{A_i^\delta}$  on  $A_i^\delta$

$$\overline{\lim}_{L \rightarrow +\infty} \overline{\lim}_{M \rightarrow +\infty} \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) I\left(\frac{\tau(x)\bar{\mu}(dx|A_i^{\delta,L_i,k})}{\bar{\mu}(\tau|A_i^{\delta,L_i,k})}\right) \leq \sum_{i=1}^{n^\delta} \nu_s(A_i^\delta) \xi^{A_i^\delta} \leq \nu_s(\xi).$$

Together with (2.12) this implies

$$\sup_{\delta > 0} \overline{\lim}_{L \rightarrow +\infty} \overline{\lim}_{M \rightarrow +\infty} J(\nu^{\delta,L,M}) \leq I(\nu).$$

Combining this with (2.11), by a standard diagonal argument, there exists a sequence  $\nu^n = \nu^{\delta^n, L^n, M^n}$  converging to  $\nu$  such that  $\overline{\lim}_n I(\nu^n) \leq I(\nu)$ .  $\square$

### 3 Large deviations of the empirical measure

The following identity follows immediately from (1.3), and will come handy in this section.

$$\pi_t = \frac{1}{t} \sum_{i=1}^{\mathcal{N}_t} \tau(x_i) \delta_{x_i} + \frac{t - S_{\mathcal{N}_t}}{t} \delta_{x_{\mathcal{N}_t+1}}. \tag{3.1}$$

**Lemma 3.1.** *Let  $f: \mathcal{X} \rightarrow [-\infty, +\infty]$  be a measurable function such that  $\bar{\mu}(e^{\tau f}) \leq 1$ . Then*

$$\sup_{t \geq 1} \frac{1}{t} \mathbf{E} \exp[t \pi_t(f)] < +\infty.$$

*Proof.* It is enough to prove the result in the case  $\bar{\mu}(e^{\tau f}) = 1$ . Then define  $\bar{\mu}_f \in \mathcal{P}(\mathcal{X})$  as

$$\bar{\mu}_f(dx) := e^{\tau(x)f(x)} \bar{\mu}(dx).$$

Thus

$$\begin{aligned} \mathbf{E} \exp[t \pi_t(f)] &= \sum_{n=0}^{\infty} \mathbf{E} \exp\left[\sum_{i=1}^n \tau(x_i) f(x_i) + (t - S_n) f(x_{n+1})\right] \mathbb{1}_{\mathcal{N}_t=n} \\ &= \sum_{n=0}^{\infty} \int_{\mathcal{X}^{n+1}} \left(\prod_{i=1}^n \bar{\mu}_f(dx_i)\right) \bar{\mu}(dx_{n+1}) \exp[(t - S_n) f(x_{n+1})] \mathbb{1}_{\mathcal{N}_t=n}. \end{aligned}$$

Note that  $\{\mathcal{N}_t = n\} = \{S_n < t\} \cap \{\tau(x_{n+1}) \geq t - S_n\}$ , so that denoting  $\zeta_{n,f} \in \mathcal{P}([0, +\infty])$  the law of  $S_n = \tau(x_1) + \dots + \tau(x_n)$  with respect to  $\prod_{i=1}^n \bar{\mu}_f(dx_i)$

$$\mathbf{E} \exp[t \pi_t(f)] = \sum_{n=0}^{\infty} \int_{[0,t]} \zeta_{n,f}(ds) \int_{\{\tau \geq t-s\}} \bar{\mu}(dx) e^{(t-s)f(x)}.$$

The rightest integral is bounded by 2, since  $e^{(t-s)f(x)} \leq 1 + e^{\tau(x)f(x)}$  on  $\{\tau \geq t-s\}$ . Thus

$$\frac{1}{t} \mathbf{E} \exp[t \pi_t(f)] \leq \frac{2}{t} \sum_{n=0}^{\infty} \zeta_{n,f}([0, t]) = \frac{2}{t} \sum_{n=0}^{\infty} \mathbf{E}_f \mathbb{1}_{\mathcal{N}_t \geq n} = 2 \mathbf{E}_f \frac{\mathcal{N}_t}{t},$$

where  $\mathbf{E}_f$  denotes expectation with respect to  $\bar{\mu}_f^{\otimes \mathbb{N}^+}$ . By general renewal theory [1, Chapter V.4],  $\mathbf{E}_f \mathcal{N}_t/t \rightarrow \frac{1}{\bar{\mu}_f(\tau)} < +\infty$  as  $t \rightarrow +\infty$ .  $\square$

*Proof of Theorem 1.3, upper bound.* Fix  $\mathcal{O}$  an open subset of  $\mathcal{P}(\mathcal{X})$ . Then for each  $f \in LSC(\mathcal{X})$  such that  $\bar{\mu}(e^{\tau f}) \leq 1$

$$\begin{aligned} \frac{1}{t} \log \mathbf{P}_t(\mathcal{O}) &= \frac{1}{t} \log \mathbf{E} e^{-t\pi_t(f)} e^{t\pi_t(f)} \mathbb{1}_{\pi_t \in \mathcal{O}} \\ &\leq \frac{1}{t} \log \left[ e^{-t \inf_{\nu \in \mathcal{O}} \nu(f)} \mathbf{E} e^{t\pi_t(f)} \right] = - \inf_{\nu \in \mathcal{O}} \nu(f) + \frac{1}{t} \log \mathbf{E} e^{t\pi_t(f)}. \end{aligned}$$

By taking the limsup  $t \rightarrow \infty$ , the last term in the above formula vanishes by Lemma 3.1. Optimizing over  $f$

$$\overline{\lim}_t \frac{1}{t} \log \mathbf{P}_t(\mathcal{O}) \leq -\sup\{\inf_{\nu \in \mathcal{O}} \nu(f), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) \leq 1\}. \quad (3.2)$$

Since (3.2) holds true for each open set  $\mathcal{O} \subset \mathcal{X}$ , and  $\nu \mapsto \nu(f)$  is lower semicontinuous for  $f \in LSC(\mathcal{X})$ , the minimax lemma [4, Appendix 2, Lemma 3.3] yields

$$\overline{\lim}_t \frac{1}{t} \log \mathbf{P}_t(\mathcal{K}) \leq -\inf_{\nu \in \mathcal{K}} \sup\{\nu(f), f \in LSC(\mathcal{X}) : \bar{\mu}(e^{\tau f}) \leq 1\}$$

for each compact  $\mathcal{K} \subset \mathcal{P}(\mathcal{X})$ . By Lemma 2.4, the large deviations upper bound then holds true on compact sets. But closed sets are compact since  $\mathcal{P}(\mathcal{X})$  is compact.  $\square$

The following remark provides a standard approach for proving large deviations lower bounds, see for instance [8] and references therein.

**Remark 3.2.** If for each  $\nu \in \mathcal{P}(\mathcal{X})$  there exists a sequence  $(\mathbf{Q}_t)$  in  $\mathcal{P}(\mathcal{P}(\mathcal{X}))$  such that  $\lim_t \mathbf{Q}_t = \delta_\nu$  narrowly in  $\mathcal{P}(\mathcal{P}(\mathcal{X}))$  and

$$\overline{\lim}_t \frac{1}{t} \mathbf{H}(\mathbf{Q}_t | \mathbf{P}_t) \leq J(\nu),$$

then  $(\mathbf{P}_t)_{t>0}$  satisfies a large deviations lower bound with rate given by the lower semicontinuous envelope of  $J$ .

For  $t > 0$  let  $\mathfrak{F}_t$  be the smallest  $\sigma$ -algebra on  $\mathcal{X}^{\mathbb{N}^+}$  such that the map

$$\mathcal{X}^{\mathbb{N}^+} \ni \mathbf{x} \mapsto (x_1, \dots, x_{N_t(\mathbf{x})+1}) \in \cup_{n \in \mathbb{N}^+} \mathcal{X}^n \hookrightarrow \mathcal{X}^{\mathbb{N}^+}$$

is Borel measurable. Note in particular that  $\mathcal{N}_t: \mathcal{X}^{\mathbb{N}^+} \rightarrow \mathbb{N}$  and  $\pi_t: \mathcal{X}^{\mathbb{N}^+} \rightarrow \mathcal{P}(\mathcal{X})$  are  $\mathfrak{F}_t$  measurable (with respect to the discrete  $\sigma$ -algebra of  $\mathbb{N}$  and the Borel  $\sigma$ -algebra on  $\mathcal{P}(\mathcal{X})$  respectively).

**Lemma 3.3.** Let  $\mathcal{Y}$  be a Polish space,  $F: \mathcal{X}^{\mathbb{N}^+} \rightarrow \mathcal{Y}$  a  $\mathfrak{F}_t$ -Borel measurable map,  $(\bar{\mu}_i)_{i \in \mathbb{N}^+}$ ,  $(\bar{\nu}_i)_{i \in \mathbb{N}^+}$  be sequences in  $\mathcal{P}(\mathcal{X})$  and set  $\Omega^\mu := \prod_{i \in \mathbb{N}^+} \bar{\mu}_i$ ,  $\Omega^\nu := \prod_{i \in \mathbb{N}^+} \bar{\nu}_i$ . Let  $\mathbf{P}^F, \mathbf{Q}^F \in \mathcal{P}(\mathcal{Y})$  be the laws of  $F$  under  $\Omega^\mu$  and  $\Omega^\nu$  respectively. Then

$$\mathbf{H}(\mathbf{Q}^F | \mathbf{P}^F) \leq \sum_{j=1}^{\infty} \mathbf{H}(\bar{\nu}_j | \bar{\mu}_j) \Omega^\nu(\mathcal{N}_t \geq j - 1).$$

In particular, if  $\bar{\mu}_i = \bar{\mu}$  and  $\bar{\nu}_i = \bar{\nu}$ , then

$$\mathbf{H}(\mathbf{Q}^F | \mathbf{P}^F) \leq \mathbf{H}(\bar{\nu} | \bar{\mu}) \Omega^\nu(\mathcal{N}_t + 1).$$

*Proof.* For  $r > 0$  let (as above)  $h(r) = r(\log r - 1) + 1$ , and let  $\mathfrak{F}^F \subset \mathfrak{F}_t$  be the  $\sigma$ -algebra generated by  $F$ . Then for  $\Omega^\mu$ -a.e.  $\mathbf{x}$

$$\frac{d\mathbf{Q}^F}{d\mathbf{P}^F}(F(\mathbf{x})) = \frac{d\Omega^\nu \circ F^{-1}}{d\Omega^\mu \circ F^{-1}}(F(\mathbf{x})) = \Omega^\nu\left(\frac{d\Omega^\nu}{d\Omega^\mu} \Big| \mathfrak{F}^F\right)(\mathbf{x}).$$

Therefore changing variables in the integration and using the convexity of  $h$

$$\begin{aligned} \mathbf{H}(\mathbf{Q}^F | \mathbf{P}^F) &= \int_{\mathcal{Y}} \mathbf{P}^F(dy) h\left(\frac{d\mathbf{Q}^F}{d\mathbf{P}^F}(y)\right) \\ &= \int_{\mathcal{X}^{\mathbb{N}^+}} \Omega^\mu(d\mathbf{x}) h\left(\Omega^\mu\left(\frac{d\Omega^\nu}{d\Omega^\mu} \Big| \mathfrak{F}^F\right)(\mathbf{x})\right) \leq \int_{\mathcal{X}^{\mathbb{N}^+}} \Omega^\mu(d\mathbf{x}) h\left(\Omega^\mu\left(\frac{d\Omega^\nu}{d\Omega^\mu} \Big| \mathfrak{F}_t\right)(\mathbf{x})\right). \end{aligned}$$

For  $n \in \mathbb{N}$ , and  $\mathbf{x}$  such that  $\mathcal{N}_t(\mathbf{x}) = n$  one has  $\Omega^\mu \left( \frac{d\Omega^\nu}{d\Omega^\mu} \middle| \mathfrak{F}_t \right) (\mathbf{x}) = \prod_{j=1}^{n+1} \frac{d\nu_j}{d\mu_j}(x_j)$   
and thus

$$\begin{aligned} \mathbf{H}(\mathbf{Q}^F | \mathbf{P}^F) &\leq \sum_{n \in \mathbb{N}} \int_{\mathcal{X}^{n+1}} \prod_{i=1}^{n+1} \mu_i(dx_i) h \left( \prod_{j=1}^{n+1} \frac{d\nu_j}{d\mu_j}(x_j) \right) \mathbb{1}_{\mathcal{N}_t(\mathbf{x})=n} \\ &= \sum_{n \in \mathbb{N}} \int_{\mathcal{X}^{n+1}} \prod_{i=1}^{n+1} \nu_i(dx_i) \log \left( \prod_{j=1}^{n+1} \frac{d\nu_j}{d\mu_j}(x_j) \right) \mathbb{1}_{\mathcal{N}_t(\mathbf{x})=n} \\ &= \sum_{j \in \mathbb{N}^+} \int_{\mathcal{X}^j} \prod_{i=1}^j \nu_i(dx_i) \log \frac{d\nu_j}{d\mu_j}(x_j) \mathbb{1}_{\mathcal{N}_t(\mathbf{x}) \geq j-1}. \end{aligned}$$

The event  $\{\mathcal{N}_t(\mathbf{x}) \geq j-1\}$  only depends on  $(x_1, \dots, x_{j-1})$ . Therefore the last integral in the above formula splits into a product as

$$\mathbf{H}(\mathbf{Q}^F | \mathbf{P}^F) \leq \sum_{j \in \mathbb{N}^+} \int_{\mathcal{X}^{j-1}} \prod_{i=1}^{j-1} \nu_i(dx_i) \mathbb{1}_{\mathcal{N}_t(\mathbf{x}) \geq j-1} \int_{\mathcal{X}} \nu_j(dx_j) \log \frac{d\nu_j}{d\mu_j}(x_j)$$

which is easily rewritten as in the statement. □

*Proof of Theorem 1.3, lower bound.* In view of Proposition 2.6, and Remark 3.2, for each  $\nu \in \mathcal{P}(\mathcal{X})$  such that  $J(\nu) < +\infty$ , one needs to find a sequence  $(\mathbf{Q}_t)$  in  $\mathcal{P}(\mathcal{P}(\mathcal{X}))$  such that  $\mathbf{Q}_t \rightarrow \delta_\nu$  narrowly and  $\overline{\lim}_t \frac{1}{t} \mathbf{H}(\mathbf{Q}_t | \mathbf{P}_t) \leq J(\nu)$ .

Fix a  $\nu \in \mathcal{P}(\mathcal{X})$  absolutely continuous with respect to  $\bar{\mu}$  and such that  $\nu(1/\tau) \in ]0, +\infty[$ , and let  $\Omega^\nu(dx) := \prod_{i \in \mathbb{N}^+} \bar{\nu}(dx_i)$  as in Lemma 3.3. Set  $\mathbf{Q}_t := \Omega^\nu \circ \pi_t^{-1}$ . Since  $\nu(1/\tau) < +\infty$ , ergodic theorem yields  $\lim_t \mathbf{Q}_t = \delta_\nu$ . On the other hand, since  $\pi_t$  is  $\mathfrak{F}_t$  measurable, one may apply Lemma 3.3 with  $F = \pi_t$  to get

$$\frac{1}{t} \mathbf{H}(\mathbf{Q}_t | \mathbf{P}_t) \leq \mathbf{H}(\bar{\nu} | \bar{\mu}) \frac{\Omega^\nu(\mathcal{N}_t + 1)}{t}. \tag{3.3}$$

The renewal theorem [1, Chapter V.4] implies  $\lim_t \Omega^\nu(\mathcal{N}_t)/t = \nu(1/\tau)$ , which concludes the proof. □

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