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Self-interacting random walks : aging, exploration and first-passage times

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Self-interacting random walks are endowed with long range memory effects that emerge from the interaction of the random walker at time t with the territory that it has visited at earlier times $t' < t$. This class of non Markovian random walks has applications in a broad range of examples, ranging from insects to living cells, where a random walker modifies locally its environment – leaving behind footprints along its path, and in turn responds to its own footprints. Because of their inherent non Markovian nature, the exploration properties of self-interacting random walks have remained elusive. Here we show that long range memory effects can have deep consequences on the dynamics of generic self-interacting random walks ; they can induce aging and non trivial persistence and transience exponents, which we determine quantitatively, in both infinite and confined geometries. Based on this analysis, we quantify the search kinetics of self-interacting random walkers and show that the distribution of the first-passage time (FPT) to a target site in a confined domain takes universal scaling forms in the large domain size limit, which we characterize quantitatively. We argue that memory abilities induced by attractive self-interactions provide a decisive advantage for local space exploration, while repulsive self-interactions can significantly accelerate the global exploration of large domains.

I. INTRODUCTION

Random walk theory provides a natural framework to model transport processes at all scales. Beyond the historical examples provided by particle transport in simple fluids at the molecular and supramolecular scales [1–3], it has also proved more recently to powerfully describe the dynamics of more complex, passive or active, larger scale systems – ranging from polymers, molecular motors or self-propelled colloids to cells or animals, whose dynamics take place in potentially complex environments [4–10]. In the latter case, the coupling of the internal degrees of freedom of the random walker to those of the environment generically leads to complex correlations and require a non Markovian description of the evolution over time of the position $X(t)$ of the random walker. Taking into account such memory effects remains a theoretical challenge even if several examples of model systems have been analyzed [11–18].

In this paper we focus on a broad class of such non Markovian random walkers, where memory effects emerge from the interaction of the random walker at time t with the territory that it has visited at earlier times $t' < t$ [19–27]. This class of self-interacting random walks has clear applications in a broad range of examples where a random walker modifies locally its environment – leaving behind footprints along its path, and in turn responds to its own footprints [28, 29]. Such behaviours have been reported for ants depositing pheromones along their path [30], larger territorial animals [31], and have been identified quantitatively in the case of living cells

that chemically modify and remodel the extra-cellular matrix [32, 33].

More precisely, self-interacting random walks can be defined as nearest neighbor random walks on a d -dimensional lattice, for which the probability to jump to a neighboring site i at time t is proportional to a weight function $w(n_i)$ that depends on the number of previous visits n_i of the random walker to site i up to time t (see Fig.1). Writing $w(n) = e^{-V(n)}$, the process has the following clear interpretation : upon visiting site i , the random walker deposits a signal that in turn modifies the local energy landscape V experienced by the walker. Of note, in contrast to autochemotactic or autophoretic systems [34, 35], the deposited signal is assumed to be static and permanent, but not diffusive, which leads as we argue below to long lived memory effects. To cover a broad spectrum of possible behaviours, we will consider both attractive (V decreasing) and repulsive (V increasing) self-interacting random walks, with effective potentials ranging from linear ($V(n) = \beta n$) to bounded ($V(n) = \beta H(n)$), where $H(n)$ denotes the Heaviside function [22, 24–27, 36].

Despite their relevance in various contexts, the properties of self-interacting random walks remain poorly understood, even if significant results have been obtained in the mathematical [22, 24, 27, 37] and physical communities [19–21, 23, 25, 26, 28, 29, 38–41]. This stems from the strongly non Markovian nature of self-interacting random walks, whose dynamics depends on the set of number of visits (or local times) $\{n_i\}_{i \in \mathbb{Z}^d}$ at all sites i of the lattice at time t , and therefore on the full trajectory $\{X(t')\}_{t' \leq t}$ of the random walker up to time t . This dependence leads

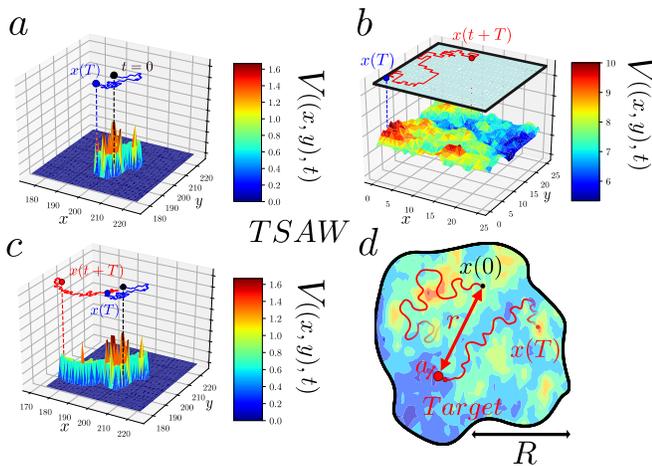


Figure 1. Aging and first-passage times for self-interacting random walks in infinite space and in confined domains. Examples of $2d$ self-interacting trajectories (TSAW model, see text) **a**. The random path from $t = 0$ to T generates the local energy landscape $V((x, y), t)$ (proportional to the total number of visits to (x, y) until t), plotted along the vertical axis z . This dynamics can lead to long range memory effects and aging at all time scales : the trajectory after T plotted in **c**, explicitly depends on the full territory visited by the walker until T . In confined domains **b**., the statistics of visits to a given site is radically modified by confinement : the dynamics of self-interacting random walks is thus geometry dependent. **d**. In this article, we aim at quantifying space exploration and search kinetics of confined self-interacting random walks.

to memory effects at all time scales, which can have important consequences depending on the potential $V(n)$ and space dimension d , such as anomalous diffusion – defined as the anomalous scaling of the mean squared displacement (MSD) :

$$\langle X^2(t) \rangle \underset{t \rightarrow \infty}{\propto} t^{2/d_w} \quad (1)$$

with the walk dimension $d_w \neq 2$, or aging – that can be defined as the dependence of increments

$$\Delta^2(T, t) \equiv \langle (X(T+t) - X(T))^2 \rangle \equiv 2D(T, t)t^{2/d_w} \quad (2)$$

on the observation time T , where $D(T, t)$ is the effective time dependent diffusion coefficient. As we recapitulate below, the analytical determination of d_w remains a theoretical challenge ; so far it has been obtained analytically or numerically for different examples of $V(n)$ and d , but even its numerical determination remains debated for attractive linear $V(n)$ for $d = 2$. In turn, the aging properties of $\Delta^2(T, t)$ have not been studied until recently [40] and will be analyzed in this paper.

A central question that arises in random walk theory is the quantification of space exploration by a random walker [42–45]. Beyond the MSD and increments of the position, which provide a first quantification of the dynamics of spreading in space, several observables have been proposed to quantify space exploration. Among

those, the first-passage time (FPT) and its distribution have proved to play a key role [17, 42, 43, 46–51]. Indeed, beyond being a prominent technical tool of random walk theory that gives access to various observables, it quantifies the kinetics of general target search problems at all time scales, and as such has a broad range of applications from diffusion limited reactions to animal foraging behaviour.

In infinite space, the first-passage statistics to a target follow two very distinct behaviours depending on the so-called type of the random walk [2]. In the compact or recurrent case, the survival probability $S(t)$, *i.e.* the probability that the target has not been found until time t typically vanishes at long time scales as

$$S(t) \underset{t \rightarrow \infty}{\propto} t^{-\theta}, \quad (3)$$

where θ is the persistence exponent, which has been the focus of numerous studies [52]. In the non compact or transient case, the survival probability admits a non zero large time limit, which defines the hitting probability Π [2, 42] according to $S \xrightarrow{t \rightarrow \infty} 1 - \Pi$. In turn, the hitting probability is expected to decrease with the distance r from the starting position of the random walk and the target radius a according to

$$\Pi \underset{r \rightarrow \infty}{\propto} (a/r)^\psi. \quad (4)$$

The corresponding transience exponent ψ was recently introduced in [50, 53] and parallels the persistence exponent of recurrent processes. In spite of their pivotal role in quantifying first-passage properties of random walks, determining analytically the exponents θ, ψ for general non Markovian, aging processes remains a theoretical challenge [52, 54]. In particular, they remain unknown analytically for most examples of self-interacting processes, with the exception of [40] ; they will be analyzed numerically and analytically in this paper.

In the case of geometrically confined spaces, which is relevant to most of practical situations where the space accessible to the random walker is ultimately bounded, space exploration is known to be radically different. In particular, a target is eventually found with probability one for both compact and non compact processes, and the broad tails of the FPT distribution are generally suppressed [47, 48, 50, 55]. FPT statistics in confinement has been the subject of intense activity over the last decade, and general results have been obtained for general scale-invariant Markovian processes [47, 55] or Gaussian non Markovian processes [17]. Notably, more recently a universal scaling form of the FPT distribution was derived in the limit of large confining volume for a class of scale-invariant non Markovian processes that display power law aging [50] ; importantly, the scaling of the FPT distribution in confinement was found in this case to be fully determined asymptotically by the exponents d_w, θ, ψ (in addition to the space dimension d), which are all defined *in infinite space* and independent of the geometric confinement.

Quantifying space exploration of self-interacting random walks in confined geometry brings in this context a new conceptual challenge. Indeed, qualitatively it is expected that geometric confinement will modify the statistics of the numbers of visits $\{n_i\}$ at the sites i of the confined domain over time and thus the effective potential $V(n_i)$ experienced by the walker, thereby impacting the very dynamics of the process, as compared to that in infinite space. This can be illustrated by the simple example of the normal random walk for $d = 3$: in infinite space, the mean number of visits $\langle n_i \rangle$ to any site i converges to a finite value for $t \rightarrow \infty$, whereas it diverges as $\langle n_i \rangle \propto t$ in a confined domain. In the case of self-interacting random walks, the kinetics of space exploration thus directly feeds-back to the dynamics of the process *in a geometry dependent manner*, which suggests that key intrinsic features of the dynamics, such as increments (quantified by $D(T, t)$ and d_w), persistence and transience exponents d_w, d_f could in fact be different in confined and infinite geometries. This in particular makes earlier approaches to determine FPT statistics inapplicable, and calls for new theoretical tools to quantify the space exploration of confined self-interacting random walks ; this is at the core of this paper.

Our findings can be summarized as follows. We show that universal scaling forms of the FPT distributions of general self-interacting random walks in confinement can be derived in the large volume limit, by generalizing the approach introduced in [50]. Because of the intrinsic aging properties of self-interacting random walks, different cases emerge depending on the preparation protocol. For "fresh" initial conditions, for which the random walker starts the search for a target in a domain that has never been explored, we find that the exponents d_w, θ, ψ that determine the FPT distribution are generally identical to those defined in infinite space : in other words, the FPT distribution in confinement can be asymptotically predicted from the knowledge of the process in infinite space only. This is quite remarkable because, as we show, geometric confinement ultimately deeply modifies the dynamics of the process and can even change the corresponding exponents $d_{w,c}, \theta_c, \psi_c$ defined in confinement. In contrast, for aged initial conditions, for which the random walker has been extensively wandering in the domain before the search starts, the exponents that determine the FPT distribution are those defined in confinement $d_{w,c}, \theta_c, \psi_c$, and can thus be different from the classical infinite space exponents d_w, θ, ψ . In that case, the process in confinement must therefore be characterized to determine the FPT distribution. In all cases, scaling functions are not universal and are process dependent. This analysis is made possible by a systematic quantitative characterization of the aging properties (quantified by $D(T, t)$ and d_w) and exponents θ or ψ of self-interacting random walks in both confined and infinite geometries, which highlights the impact of geometric confinement on their dynamics. Finally, this paper thus proposes a unified, quantitative analysis of aging,

exploration and FPT statistics of self-interacting random walks in confined and infinite geometries.

The paper is organized as follows. First, we briefly define the main classes of attractive and repelling self-interacting walks and recall their walk dimension d_w when it is known. In particular we provide a general criterion for attractive walks that leads to bounded exploration ($d_w = \infty$), or to the regime of strong attraction ($\theta = \infty$, to be defined below) ; in this case the FPT problem in confinement is trivially equivalent in the large volume limit to the problem in infinite space. Second, we characterize quantitatively the increments and their aging behavior, as well as the persistence and transience exponents θ, ψ in both confined and infinite geometries. Third, based on this analysis, we derive the asymptotic FPT distribution in confinement for both compact and non compact self-interacting random walks for fresh initial conditions. Last, we discuss the impact of aging on FPT statistics by analyzing the case of aged initial conditions, which allows us to assess the impact of memory effects on target search kinetics of self-interacting random walks.

II. DEFINITIONS AND MAIN CLASSES OF SELF-INTERACTING RANDOM WALKS

As stated above, self-interacting random walks can be defined as nearest neighbor random walks on a d -dimensional lattice, for which the probability to jump to a neighboring site i at time t is proportional to a weight function $w(n_i)$ that depends on the number of previous visits n_i of the random walker to site i up to time t . Denoting $w(n) = e^{-V(n)}$, the process has the following clear interpretation : upon visiting site i , the random walker deposits a signal that in turn modifies the local energy landscape V experienced by the walker. Different classes of random walks are obtained depending on the choice of weight function $w(n)$; we remind below the main known results concerning the MSD of these processes.

A. The True Self Avoiding Walk (TSAW) :

$$w(n) \propto e^{-\beta n}$$

In this model [19, 22, 56, 57] the effective potential $V(n)$ depends linearly on the local time n . For $\beta < 0$ the interaction is attractive, and leads (almost surely), as we show below, to the complete trapping of the random walker on a finite set of sites for all d , and thus formally to $d_w = \infty$:

$$\langle X(t)^2 \rangle \xrightarrow[t \rightarrow \infty]{} C, \quad (5)$$

where C is a d dependent constant. For $\beta > 0$ the interaction is repulsive and the random walker qualitatively avoids its own path. It has been shown that this leads to the following scaling of the MSD for $t \rightarrow \infty$ [19, 38, 56, 57]:

- $d = 1$: $\langle X(t)^2 \rangle \propto t^{\frac{4}{3}}$, $d_w = \frac{3}{2}$
- $d = 2$: $\langle X(t)^2 \rangle \propto t \ln(t)^\alpha$, $d_w = 2$, $\alpha \approx 0.5$
- $d = 3$: $\langle X(t)^2 \rangle \propto t$, $d_w = 2$

Of note, the scaling of the MSD is thus anomalous (superdiffusive) for $d \leq 2$ because of self-repulsion, while it is diffusive for $d > 2$.

B. The Sub-Exponential Self Repelling Walk (SESRW) : $w(n) \propto e^{-\beta n^k}$

This model [21, 22, 58] extends the TSAW to effective potentials $V(n)$ that depend sublinearly on the local time n : $V(n) = \beta n^k$ with $0 < k < 1$. Similarly to the TSAW, in the attractive case ($\beta < 0$), the random walker is (almost surely) trapped for all d , and thus $d_w = \infty$. For $\beta > 0$, the effect of self avoidance is clearly weaker than for the TSAW ; it has however been shown to still lead to superdiffusion for $d = 1$ [21, 58]. This can be summarized as follows :

- $d = 1$: $\langle X(t)^2 \rangle \propto t^{\frac{2(1+k)}{(2+k)}}$, $d_w = \frac{2+k}{1+k}$
- $d = 2$: $\langle X(t)^2 \rangle \propto t \ln(t)^{\alpha_k}$, $d_w = 2$, $\alpha_k \geq 0$
- $d = 3$: $\langle X(t)^2 \rangle \propto t$, $d_w = 2$

C. The self attractive random walk (SATW) : $w(n) \propto e^{-\beta H(n)}$

In this model [23–27, 59, 60], the effect of self interaction is assumed to saturate with the number of visits, so that the effective potential $V(n)$ is bounded for $n \rightarrow \infty$. For the sake of simplicity, it is assumed in the SATW model that $V(n) = \beta H(n)$, with $H(0) = 0$ and $H(n \geq 1) = 1$. Note that the SATW can thus be seen as the $k \rightarrow 0$ limit of the SESRW defined above. For $\beta > 0$, self-avoidance is insufficient to modify the scaling of the MSD, which remain diffusive for all d :

$$\langle X(t)^2 \rangle \propto t, \quad d_w = 2. \quad (6)$$

In the attractive case $\beta < 0$, the random walker is never trapped. For $d = 1$ the MSD satisfies [23, 59] :

$$\langle X(t)^2 \rangle \propto t, \quad d_w = 2, \quad (7)$$

while for $d = 3$ different behaviors emerge depending on the value of the parameter β

- $|\beta| < |\beta_c|$: $\langle X(t)^2 \rangle \propto t$, $d_w = 2$
- $|\beta| > |\beta_c|$: $\langle X(t)^2 \rangle \propto t^{1/2}$, $d_w = 4$.

For $d = 2$, the scaling of the MSD is still debated [25, 26]; while the existence of a subdiffusive regime with $d_w = 3$ is consistently observed numerically, the existence of a transition for a critical value $\beta'_c \neq 0$ to a diffusive regime with $d_w = 2$ for $|\beta| < |\beta'_c|$ has been proposed, but was later questioned in [25].

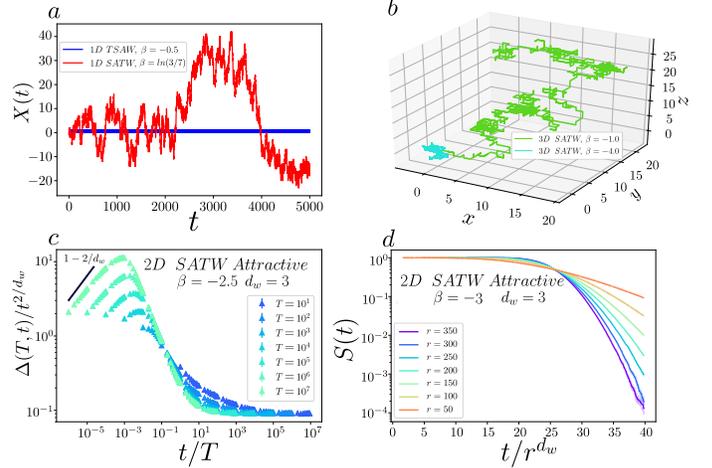


Figure 2. General properties of attractive self-interacting random walks. **a.** Example of trapped trajectory performed by a 1d attractive TSAW random walker (blue), compared to a diffusive trajectory of a 1d attractive SATW random walker (red). **b.** For $d > 1$, the SATW is subdiffusive for $|\beta| > |\beta_c|$ (blue sample trajectory), and diffusive for $|\beta| < |\beta_c|$ (green sample trajectory). Here $d = 3$ and thus $|\beta_c| \neq 0$ [25]. **c.** Aging of the increments for the subdiffusive SATW ($d_w = 3$ for $d = 2$) normalized by the expected subdiffusive scaling at long times. Each curve corresponds to a fixed value of T . Note that the increments are diffusive for $t \ll T$. **d.** In the subdiffusive regime, the SATW performs an extremely compact exploration of space : the survival probability $S(t)$ decays faster than any powerlaw ($\theta = \infty$).

III. ATTRACTIVE SELF-INTERACTING RANDOM WALKS: TRAPPING AND SUBDIFFUSION

Qualitatively, attractive self-interacting random walks are attracted by their own path. Strikingly, this can lead to the full trapping of the walker within a finite set of sites in the $t \rightarrow \infty$ limit, and therefore to a bounded MSD. This effect was demonstrated mathematically [27, 61] for 1-dimensional attractive self-interacting random walks and later generalized to arbitrary d [36, 62–64] : more precisely, these results state that if $\sum_{n=1}^{\infty} w(n)^{-1} = \infty$ the random walker is free and will visit infinitely many sites of the lattice (note that the limit case $w(n) \propto 1/n$ must be discussed independently). Conversely, for $\sum_{n=1}^{\infty} w(n)^{-1} < \infty$, the random walker visits only a finite set of sites and the MSD is bounded (see Supplementary Information SI). This yields immediately that attractive TSAW and SESRW lead to the full trapping of the ran-

dom walker and to a bounded MSD for all d (see Fig.2). Among the classes of attractive self-interacting random walks introduced above, the only case that leads to a non trivial exploration of space is thus the SATW, for which the MSD diverges for $t \rightarrow \infty$ (see Fig.2). Despite the diverging MSD, the effect of attractive self interactions can still have important consequences on the dynamics of space exploration; in particular, for $d = 2$ and $d = 3$ (for $|\beta| > |\beta_c|$) the process is subdiffusive [25] and we find that the survival probability $S(t)$ in infinite space decays faster than any power-law, so that $\theta = \infty$ (see Fig.2 and SI). In this case, determining the FPT distribution starting at a distance r from the target $F(t, r, R)$ in confined domains of volume $V \propto R^d$ is straightforward in the large volume limit because all moments of $F(t, r, R)$ have a finite limit, so that:

$$F(t, r, R) \underset{t \rightarrow \infty}{\sim} -\frac{dS}{dt}. \quad (8)$$

$F(t, r, R)$ is thus asymptotically independent of R . Defining the rescaled variable $\eta = t/r^{d_w}$, a scaling argument finally indicates that its asymptotic distribution can be simply written:

$$\bar{F}(\eta, r, R) = h(\eta) \quad (9)$$

where h is an undetermined scaling function. In the rest of this paper, we thus focus on diffusive attractive and all repulsive self-interacting random walks, for which determining the FPT distribution $F(t, r, R)$ in confined domains is non trivial.

IV. IMPACT OF CONFINEMENT ON INCREMENTS, θ, ψ

In this section, we characterize quantitatively the exploration properties of diffusive attractive self-interacting random walks and repulsive self-interacting random walks. We focus on the following observables : increments, and survival probability characterized by θ (for compact processes) and ψ (for non compact processes) in both infinite and confined geometries. We show numerically and provide heuristic arguments to justify that geometric confinement can deeply and non locally modify the dynamics of the process, beyond imposing locally reflecting boundary conditions. As can be expected, it is useful to analyse separately compact and non compact processes. While this property is known to impact many properties of random walks, it is expected to play a prominent role in the case of self-interacting random walks, whose dynamics is controlled by the number of visits n at each site.

A. Compact (recurrent) processes

The compact case is exemplified by the 1d (repulsive) TSAW, the 1d (repulsive) SERW and the 1d (attractive

or repulsive) SATW. In the compact case, the mean number of visits $\langle n_i \rangle$ to a given site diverges with time T by definition even in infinite space. The local energy landscape $V(n_i)$ experienced by the random walker therefore depends on the observation time T at all time scales. We argue below that this leads to aging of the increments in infinite space at all time scales, ie a dependence on T of the effective diffusion coefficient $D(T, t)$ defined in (2) for all T . In a confined domain, the dynamics of the random walk starting typically from the bulk is not modified by confinement up to an observation time $T \sim R^{d_w}$, where R is the typical linear size of the domain; in this regime we therefore expect the increments to be identical in both confined and infinite geometries (note that for the same reason, in confined domains the analysis of increments is restricted to $t \ll R^{d_w}$). For $T \gtrsim R^{d_w}$, confinement does modify the statistics of visits to a given site; however the number of visits to a given site still diverges with time T , even if the explicit dependence on T is different in confinement and in infinite space. Aging of the increments is thus expected in confinement as well.

To make this analysis quantitative, it is useful to write $V(n_i)$ as a Taylor series:

$$V(n_i) = V(\bar{n}) + \sum_{p \geq 1} V^{(p)}(\bar{n}) \frac{(\delta n_i)^p}{p!}, \quad (10)$$

where \bar{n} denotes the number of visites to a given site averaged over a spatial scale $l \ll T^{1/d_w}$ and $n_i = \bar{n} + \delta n_i$. The very definition of the dynamics of self-interacting random walks shows that it depends only on the spatial fluctuations of V ; increments are thus independent of the site independent contribution $V(\bar{n})$ for $t \lesssim l^{d_w} \ll T$. In the case of the SATW and the SESRW, one has $V^{(p)}(\bar{n}) \propto \bar{n}^{k-p}$ by definition (we remind that for the SESRW $V \propto n^k$, where $k \rightarrow 0$ yields the SATW) ; in addition, a mean field argument (see SI) yields the scaling $\delta n_i \propto \bar{n}^{(1-k)/2}$. This shows that in the regime $1 \ll t \ll T$ all site dependent terms $V^{(p)}(\bar{n})(\delta n_i)^p/p!$ for $p \geq 1$ appearing in (10) vanish in the limit $T \rightarrow \infty$ in both confined and infinite geometries because $\bar{n} \rightarrow \infty$. Self-interactions are thus eventually negligible in this limit: the SATW and the SESRW are equivalent to a simple random walk and one has identically $\Delta^2(T, t) \sim t$ in both confined and infinite geometries. In the case of the TSAW, one has $V'(\bar{n}) = \beta$ and $V^{(p)}(\bar{n}) = 0$ for $p > 1$, independently of \bar{n} . Using in addition the fact that the spatial fluctuations δn_i reach a steady state in the limit $\bar{n} \rightarrow \infty$ (see [39] and SI), this shows that in the regime $1 \ll t \ll T$ the dynamics of increments is identical in both confined and infinite cases ; it can be shown to satisfy $\Delta^2(T, t) \propto t^{2/d_w}$. Last, in the regime $1 \ll T \ll t$, one recovers the scaling of the MSD in all cases : $\Delta^2(T, t) \propto t^{2/d_w}$.

These results can be recapitulated for all examples by the following scaling forms, which are identical in con-

finned and infinite geometries :

$$\begin{aligned} 1 \ll t \ll T & : \Delta^2(T, t) \sim 2D_{<}(t)t^{2/d_w} \\ 1 \ll T \ll t & : \Delta^2(T, t) \sim 2D_{>}t^{2/d_w}, \end{aligned} \quad (11)$$

where the constant $D_{>}$ and function $D_{<}(t)$ are process dependent. Numerical simulations confirm this analysis in all examples of compact self-interacting random walks (see Fig.3) : increments display aging (as seen by a dependence of Δ^2 on the observation time T), and their dynamics is found to be the same in infinite space and in confined domains in both regimes $t, T \ll R^{d_w}$ and $T \gtrsim R^{d_w}, t \ll R^{d_w}$.

In contrast to the dynamics of increments, we now argue that the persistence exponent θ can be modified by confinement. Following [65], we introduce here the persistence exponent θ_c in confinement that can be defined by

$$S(t|T) \propto t^{-\theta_c} \quad (12)$$

for $T \gg R^{d_w}$ and $1 \ll t \ll R^{d_w}$, where $S(t|T)$ denotes the (survival) probability that the random walker has not reached the target between T and $T+t$. It is known that θ depends on the dynamics of increments at all time scales [52], and not only on their long time asymptotics. The exponents θ and θ_c can thus be different, as was earlier found in [65] for models of fluctuating interfaces, because θ involves the dynamics of increments at all time scales T, t , while the definition of θ_c only involves the time scales $t \ll R^{d_w}$ and $T \gg R^{d_w}$. This is straightforwardly confirmed in the case of the $1d$ SATW. It is clear that for $T \gg R^{d_w}$, the confined SATW is equivalent to a simple random walk (in this regime all sites have been visited and $V(n_i) = \beta$ for all sites), so that $\theta_c = 1/2$; in contrast, it was shown recently that in infinite space one has $\theta = e^{-\beta}/2$ [40]. In the case of the SERW, the above analysis shows that in the regime $T \gg 1$, the process is also equivalent to a simple random walk, so that $\theta_c = 1/2$; in contrast, we find numerically $\theta \neq \theta_c$. Note however that it is found numerically that $\theta_c \approx \theta \approx 1 - 1/d_w$ for the TSAW for all $\beta > 0$.

B. Non compact (transient) processes

The non compact case is exemplified by the $3d$ (repulsive) TSAW, the $3d$ (repulsive) SERW and the $3d$ (diffusive attractive or repulsive) SATW. In the non compact case, in infinite space, a random walker visits only a fraction of sites, and ultimately only makes on average a finite number of visits to a given site i . The local energy landscape $V(n_i)$ therefore reaches a stationary state at large observation time T , so that aging, if any, is expected to be transient : $D(T, t)$ is asymptotically independent of T for $T \gg 1$. This is indeed observed numerically in all examples of non compact self-interacting random walks: increments display weak aging at short time scales t , and cross-over to diffusive increments with numerically close

diffusion coefficients at larger t for all observation times T (see Fig.4). The effect of self-interaction is thus moderate for non compact self-interacting random walks, which are all eventually diffusive. This can be heuristically justified as follows: at time t , the typical volume covered scales as t^{d/d_w} , while the number of visited sites scales as t , so that the local fraction of sites where the local energy landscape is non zero eventually vanishes for $t \rightarrow \infty$ as t^{1-d/d_w} . Self interactions are thus negligible in the large time limit for non compact processes, which are diffusive in this limit (note however that the diffusion coefficient is non trivial and depends on the small t dynamics).

The case of confined geometries is radically different for non compact processes, because confinement leads to a divergence of the number of visits to a given site, and has thus important consequences at time scales $T \gtrsim R^{d_w}$. In this regime, the above reasoning developed after (10) for compact processes in fact applies also to confined non compact processes, because the locally averaged number of visits \bar{n} diverges in both cases. In particular, this yields similarly that in the regime $1 \ll t \ll T$ both the non compact SATW and the non compact SESRW are equivalent to a simple random walk, so that $\Delta^2(T, t) \sim t$. In the case of the confined non compact TSAW, one finds numerically (see also [19, 37] and SI for an heuristic argument) that the spatial fluctuations δn_i reach a steady state in the limit $T \rightarrow \infty$. This, together with (10), allows us to conclude that in this limit increments are similar (scaling wise) to the infinite space case and thus diffusive and independent of T (see SI).

Finally, for all confined non compact self-interacting random walks, these results can be recapitulated as follows for $R \gg 1$:

$$\begin{aligned} T \lesssim R^{d_w} & : \Delta^2(T, t) \underset{T \gg 1}{\sim} 2D_{<}(t)t, \quad D_{<}(t) \underset{t \gg 1}{\rightarrow} D_{<} \\ T \gtrsim R^{d_w} & : \Delta^2(T, t) \underset{t \gg 1}{\sim} 2D_{>}(T)t, \quad D_{>}(T) \underset{T \gg 1}{\rightarrow} D_{>} \end{aligned} \quad (13)$$

where $D_{<}, D_{>}$ are constants. The first regime $T \lesssim R^{d_w}$ is the same in confined and infinite geometries, while the second regime $T \gtrsim R^{d_w}$ is controlled by geometric confinement. Numerical simulations confirm this analysis in all examples of non compact self-interacting random walks (see Fig.4) : increments, even if always asymptotically diffusive, are found numerically in all examples to be quantitatively different for confined and non confined non compact self-interacting random walks.

Last, for the sake of completeness, we note that similarly to the persistence exponent in the compact case (see (12)), the transience exponent ψ_c can be defined in confinement according to :

$$S(t|T) \underset{a \rightarrow 0}{\propto} \left(\frac{a}{r}\right)^{\psi_c} \quad (14)$$

for $T \gg R^{d_w}$ and $a^{d_w} \ll t \ll R^{d_w}$. While, in principle ψ_c can be different from its infinite space counterpart ψ , our above analysis showed that all examples of non compact self-interacting processes that we analysed are diffusive

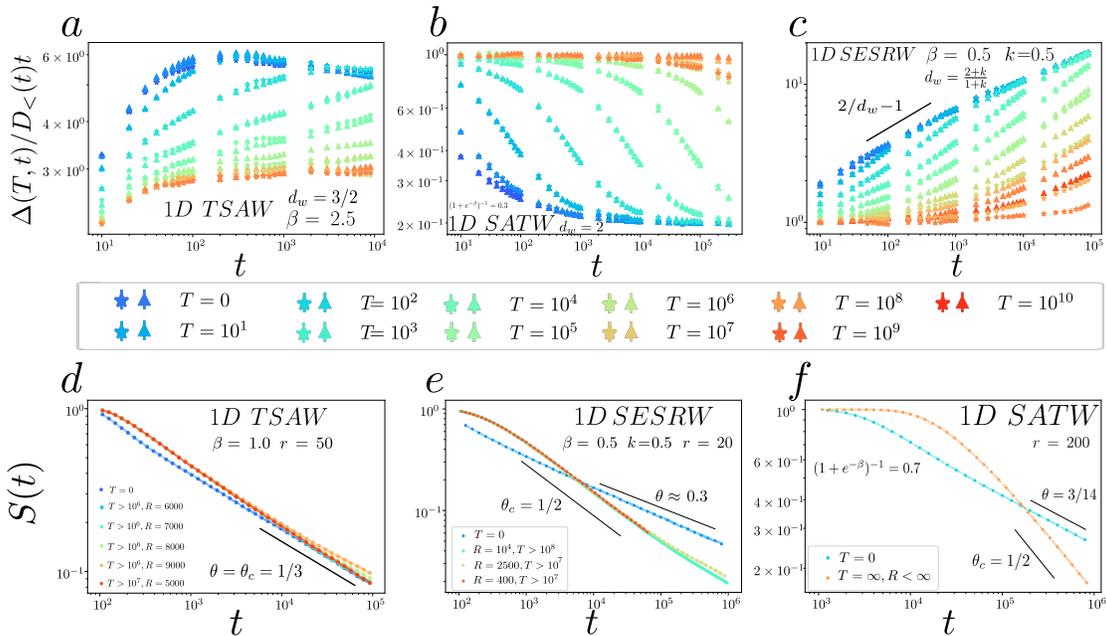


Figure 3. aging and first-passage properties for compact self-interacting random walks in infinite space and in confined geometries. aging of the increments for the 1d TSAW (a.), the 1d SATW (b.) and the 1d SESRW (c.) in both infinite space and confined domains (increments are normalized by the expected scaling for $T \gg t$). The dynamic is found to be identical in infinite space (triangle) and in confined domains (stars) in both regimes $t, T \ll R^{d_w}$ and $T \gtrsim R^{d_w}, t \ll R^{d_w}$. The TSAW is superdiffusive at all times scales and displays aging ; the SATW is diffusive at all times scales and displays aging. In contrast, the SESRW is diffusive for $T \gg t$, but superdiffusive for $t \gg T$ with $d_w = (2 + k)/(k + 1)$. Persistence exponents in infinite space (θ) and in confined domains (θ_c) for the 1d TSAW (d.), the 1d SESRW (e.) and for the 1d SATW (f.). The persistence exponent is modified by confinement for the SATW and the SESRW models, but is found numerically to be unchanged for the TSAW.

and independent of T for $t \gg 1$ in the limit $T \rightarrow \infty$ in both confined and non confined cases; this suggests that $\psi = \psi_c = 1$, which is consistent with our numerical simulations (see Fig.4).

To summarize this section, we have showed quantitatively that geometric confinement can deeply and non locally modify the dynamics of self-interacting random walks, beyond imposing locally reflecting boundary conditions. In the compact case, increments remain unchanged (in the regime $t \ll R^{d_w}$) in confined and unconfined geometries, but the persistence exponent can be modified. In the non compact case, increments remain asymptotically diffusive in both cases, but their dynamics is quantitatively modified by geometric confinement ; in turn, it is found that the transience exponent is unchanged.

V. FPT DISTRIBUTION IN CONFINED DOMAINS

The above analysis of increments and exponents θ and ψ shows that these observables can be impacted by confinement. Turning to the analysis of FPT properties of self-interacting random walks in confinement, one therefore needs to develop a new methodology. Indeed, so far,

available methods to determine FPT statistics in confinement [50] rely implicitly on the hypothesis that increments and exponents θ and ψ , which are the key quantities defining the universality classes of FPT statistics in confinement, are not modified by confinement. Below, we extend the method developed originally in [50] to the case of self-interacting random walks by taking explicitly into account the impact of confinement on the dynamics. In this section, we consider the case of "fresh" initial conditions : at $t = 0$ the random walker, confined in a domain of volume $V = R^d$ with reflecting walls, starts at a distance r from the target of radius a , and the number of visits to all sites i of the domain is set to $n_i = 0$. As stated in introduction, we focus on diffusive attractive and repulsive self-interacting random-walks, and consider separately the cases of compact processes (for which the survival probability $S(t)$ has a power-law decay in infinite space) and non compact processes ; the case of marginal exploration ($2d$ processes with $d_w = 2$) is discussed in SI.

A. Compact (recurrent) case

We sketch in this section the derivation of the asymptotic FPT distribution $F(t, r, R)$ for compact self-interacting random walks in the large volume limit $R \rightarrow$

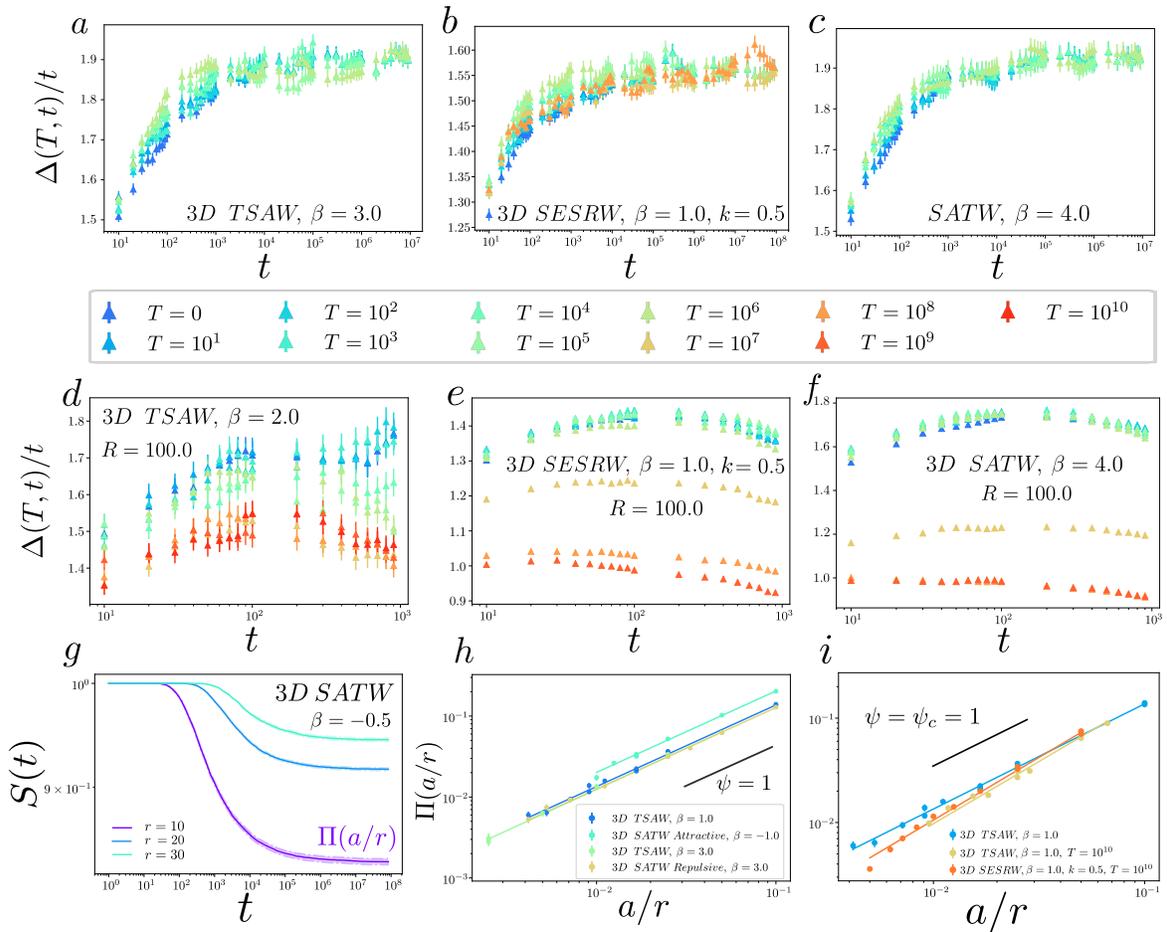


Figure 4. Aging and first-passage properties for non-compact self-interacting random walks in infinite space and in confined geometries. Aging of the increments for the 3d TSAW (a.), the 3d SESRW (b.) and the 3d SATW (c.) in infinite space (increments are normalized by the expected diffusive scaling at long times). Of note, the increments are stationary at timescales $T \gg 1$. In contrast, in confined geometries, aging occurs at longer time scales $\gtrsim R^d$, for the TSAW (d.), the SESRW (e.) and the SATW (f.) (increments are normalized by the expected diffusive scaling at long times). g. For non-compact random walks (here the 3d diffusive SATW), the survival probability tends for $t \rightarrow \infty$ to a non-zero value $1 - \Pi$, which defines the hitting probability that depends on the initial distance to the target r and the target radius a . Hitting probability and transience exponent in infinite space (h.) and in confined domains (i.). Numerical simulations (symbols) and power law fits (plain lines). Our numerical results indicate $\psi = \psi_c = 1$ for the TSAW, the SESRW and the SATW, in agreement with the asymptotic diffusive behaviour of non compact self-interacting random walks.

∞ . For compact processes the FPT distribution is independent of the target linear size a for $r \gg a$; we focus on this regime below. Following [50], $F(t, r, R)$ can be written as a partition over trajectories that either hit the reflecting boundary before the target (with probability $\pi(r, R)$ and conditional FPT distribution to the target $F_b(t, r, R)$) or hit the target before the boundary (with probability $1 - \pi(r, R)$ and conditional FPT distribution to the target $F_t(t, r, R)$):

$$F(t, r, R) = \pi F_b(t, r, R) + (1 - \pi) F_t(t, r, R). \quad (15)$$

Importantly, the weight $1 - \pi$ of trajectories that hit the target first can be expressed in the limit $R \rightarrow \infty$ (with r fixed) in terms of the FPT distribution in infinite space

$F_\infty(t, r)$:

$$\pi(r, R) \underset{R \gg r}{\propto} \int_{R^{d_w}}^{\infty} F_\infty(t, r) dt, \quad (16)$$

which expresses the fact that most trajectories that hit the target before the boundary yield a FPT smaller than the timescale R^{d_w} . Making use of the definition of θ for processes in infinite space, we then obtain from dimensional analysis

$$F_\infty(t, r) \propto \frac{r^{d_w \theta}}{t^{\theta+1}} \quad (17)$$

in the regime $1 \ll t \ll R^{d_w}$, which yields from (16):

$$\pi(r, R) \underset{R \gg r}{\propto} \left(\frac{r}{R} \right)^{d_w \theta}. \quad (18)$$

We stress that here the persistence exponent θ is defined in infinite space, and not in confined geometry. Next, the above argument leading to (16) also implies that

$$F_t(t, r, R) \propto \Theta(t/R^{d_w}) F_\infty(t, r) \propto \Theta(t/R^{d_w}) \frac{r^{d_w \theta}}{t^{\theta+1}}, \quad (19)$$

where Θ denotes a step function with $\Theta(x \ll 1) = 1$ and $\Theta(x \gg 1) = 0$. At this stage, the conditional FPT distribution $F_b(t, r, R)$ remains to be determined. By definition, this quantity involves trajectories that interact with the domain boundary. However, our analysis above shows that the increments of compact processes are identical in confined and infinite geometries. In the limit $R \rightarrow \infty$ with r fixed, $F_b(t, r, R)$ can thus depend only on the time scales t and R^{d_w} ; dimensional analysis then yields the following scaling form:

$$F_b(t, r, R) \sim g(t/R^{d_w})/t, \quad (20)$$

where g is an undetermined function that depends on the process. Finally, it is convenient to introduce the rescaled variable $\eta = t/R^{d_w}$, and write, from (15),(18),(19), (20) its asymptotic distribution for $R \rightarrow \infty$ for $\eta > 0$ with r fixed :

$$\bar{F}(\eta, r, R) = \left(\frac{r}{R}\right)^{d_w \theta} h(\eta) \quad (21)$$

where h is an undetermined function that depends on the process. Finally, this explicitly captures the dependence of the FPT distribution on the geometrical parameters r, R , and therefore of all its moments (when they exist). In particular, the mean FPT can be readily derived and satisfies:

$$\langle T \rangle \propto R^{d_w(1-\theta)} r^{d_w \theta}. \quad (22)$$

The mean FPT thus scales non linearly with the confining volume $V \sim R^d$ (because one has $\theta \neq 1 - d/d_w$) for SESRW and SATW, as was found for other examples of aging processes ; notably, this scaling is linear for the TSAW. Strikingly, the asymptotic form of the FPT distribution (21) is comparable to that obtained in [50], and can be determined solely from the knowledge of d_w, θ , which are defined in infinite space. This holds even if the dynamics of the process is ultimately impacted by the geometric confinement, as we have shown above – this result is in particular independent of the persistence exponent in confinement θ_c . Fig.5 shows an excellent quantitative agreement between numerical simulations and this analytical result. The data collapse of the properly rescaled FPT distribution shows that our approach fully captures its dependence on both r and R for all examples of compact self-interacting random walks that we have studied.

B. Non compact (transient) case

We now turn to the non-compact case. As opposed to the compact case, in the regime $r \gg a$ that we consider

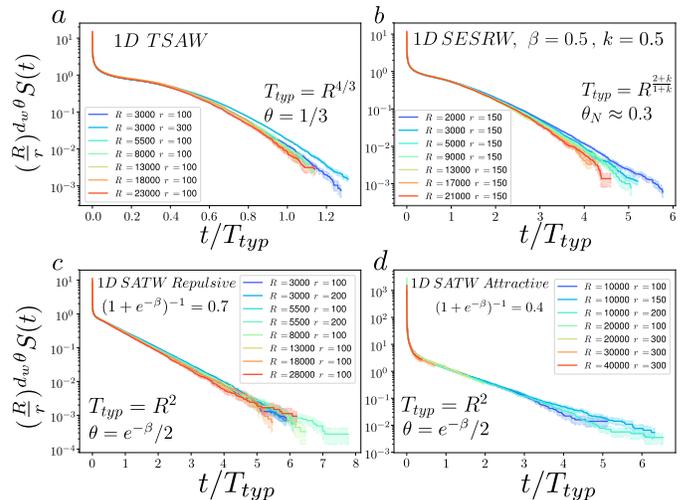


Figure 5. Asymptotic FPT distribution of compact self-interacting random walks in confined domains for fresh initial conditions. Here $S(t)$ is the survival probability of the random walker, whose scaling with geometrical parameters is deduced from (21). The collapse of numerical simulations after rescaling for different values of geometric parameters captures the dependence of the FPT distribution on the geometric parameters r, R . Simulations are performed in 1D boxes of size R with reflecting boundary conditions. **a.** 1D TSAW with $d_w = 3/2$ (independent of β). **b.** 1d SESRW with $\beta = 0.5$ and $k = 0.5$. 1d repulsive SATW with $(1 + e^{-\beta})^{-1} = 0.7$ (**c.**) and $(1 + e^{-\beta})^{-1} = 0.4$ (**d.**).

below, the FPT distribution depends on a . Following [50], we call excursion a fraction of trajectory that starts from the sphere S of radius $R/2$ centered on the target, next hits the boundary and eventually returns to S . The FPT distribution can then be written as a partition over the number n of excursions before the first-passage to the target, where we introduce $\Phi_n(t)$ as the corresponding conditional FPT distribution :

$$F(t, a, r, R) = p_0 \Phi_0(t) + (1 - p_0) \sum_{n=1}^{\infty} \Phi_n(t) P(n). \quad (23)$$

Here $p_0 \sim (a/r)^\psi$ is the probability to hit the target before the boundary starting from r , and $P(n)$ the probability that the target is reached for the first time during the n^{th} excursion. This can be written

$$P(n) = p_n \prod_{k=1}^{n-1} (1 - p_k) \quad (24)$$

where p_k is the probability that the target is found during the k^{th} excursion, knowing that it has not been found before. Our analysis of increments and transience exponents ψ, ψ_c above (see (13)) shows that, in confinement, non compact self-interacting random walks are diffusive for $t \gg 1$ in both regimes $T \ll R^{d_w}$ (with diffusion coefficient $D_<$) and $T \gg R^{d_w}$ (with diffusion coefficient $D_>$). We thus denote by $D_n \equiv D_> + \delta D_n$ the

effective diffusion coefficient during the n^{th} excursion, which verifies $|\delta D_n| \leq |D_{<} - D_{>}|$ and $\delta D_n \rightarrow 0$ for $n \gg 1$. In addition, one has $\psi_c = \psi$. We can thus write $p_k \sim (C_{>} + \delta C_k)(a/R)^\psi$, where $\delta C_k \rightarrow 0$ for $k \gg 1$. Note that here we have implicitly assumed (and checked numerically, see SI) that the conditional probability p_k behaves as the unconditional probability that the target is found during the k^{th} excursion. Last, a scaling argument (see SI) shows that

$$\Phi_n(t) = \frac{1}{t} \phi(t/t_n), \quad (25)$$

where t_n is the typical time elapsed before the n^{th} excursion, which verifies

$$t_n = R^{d_w} \sum_{k=1}^{n-1} \frac{1}{D_k}. \quad (26)$$

Finally, taking the $R \rightarrow \infty$ limit in (23) with r, a fixed, one finds that the rescaled variable $\eta = t/R^d$ admits asymptotically the following distribution for $\eta \neq 0$ (see SI):

$$\bar{F}(\eta, r, R) = \left(1 - C \left(\frac{a}{R}\right)^\psi\right) h(\eta) \quad (27)$$

where h is an undetermined process dependent scaling function – not necessarily exponential – and C a process dependent constant. Similarly to the compact case, this explicitly captures the dependence of the FPT distribution on the geometrical parameters r, R , and therefore of all its moments (when they exist). In particular, the mean FPT is given by :

$$\langle T \rangle \sim \frac{R^d}{a^\psi} \left(1 - C \left(\frac{a}{R}\right)^\psi\right). \quad (28)$$

In contrast to the compact case, the mean FPT thus scales linearly with the confining volume $V \sim R^d$. Remarkably, the asymptotic form of the FPT distribution (21) is comparable to that obtained in [50] in absence of power-law aging, and can be determined solely from the knowledge of d_w, ψ , which are defined in infinite space. This holds even if the dynamics of the process is impacted by the geometric confinement, as we have shown above. However, geometric confinement does not change the diffusive scaling of non compact self-interacting walks ; (27) shows that this is sufficient to preserve the dependence on r, R of the FPT distribution in confinement. Fig.6 shows an excellent quantitative agreement between numerical simulations and this analytical result. The data collapse of the properly rescaled FPT distribution shows that our approach fully captures its dependence on both r and R for all examples of non compact self-interacting random walks that we have studied.

VI. AGED INITIAL CONDITIONS

In this section, we analyse the impact of initial conditions on the FPT statistics of confined self-interacting

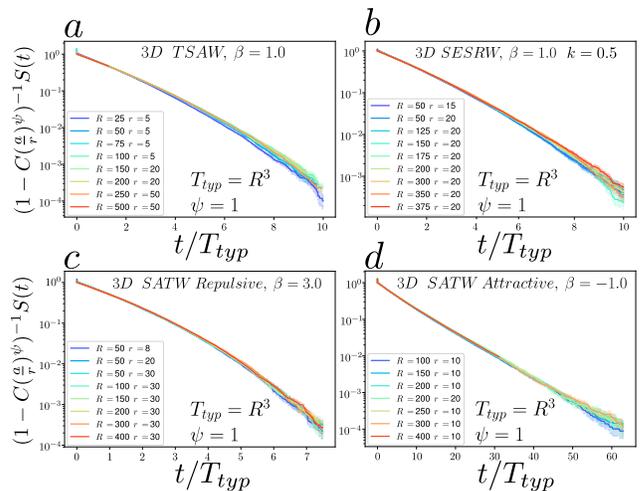


Figure 6. Asymptotic FPT distribution of non compact self-interacting random walks in confined domains for fresh initial conditions. Here $S(t)$ is the survival probability of the random walker, whose scaling with geometrical parameters is deduced from (27). The collapse of numerical simulations after rescaling for different values of the geometrical parameters captures the dependence of the FPT distribution on r, R . Simulations are performed in 3d boxes of size R with reflecting boundary conditions and the constant C is measured numerically. **a.** 3d TSAW with $\beta = 1.0$. **b.** 3d SESRW with $\beta = 1.0$ and $k = 0.5$. 3d SATW repulsive with $\beta = 3.0$ (c) and with $\beta = -1.0$ (d).

random walks. As we have shown above, the dynamics of self-interacting random walks display aging properties, which can depend on geometric confinement. In other words, the dynamics is different if the random walk starts at $T = 0$ (fresh initial conditions studied above, for which the number of visits to any site i of the domain is set to $n_i = 0$) or at $T \gg R^{d_w}$ (aged initial conditions, for which $n_i \gg 1$). We show that the FPT distribution can be readily obtained for aged initial conditions by adapting the approach developed above for fresh initial conditions, and highlight the impact of initial conditions.

A. Compact (recurrent) case

For aged initial conditions, because $T \gg R^{d_w}$, the only relevant regime is $t \ll T$. In this regime we have found the following behaviour of the increments:

$$\Delta^2(T, t) \sim 2D_{<}(t)t^{2/d_w} \propto t^{2/d_{w,c}} \quad (29)$$

where the effective walk dimension $d_{w,c}$ can be different from d_w (see SESRW in Fig.3). The relevant persistent exponent is clearly θ_c in this regime. All steps leading to the derivation of the FPT distribution (see previous section) can then be reproduced. It is found that the rescaled variable $\eta = t/R^{d_{w,c}}$ is asymptotically distributed according to :

$$\bar{F}_c(\eta, r, R) = \left(\frac{r}{R}\right)^{d_{w,c}\theta_c} h_c(\eta) \quad (30)$$

where h_c is an undetermined function that depends on the process. Initial conditions can thus deeply impact the FPT distribution, and even its scaling form : they can modify the walk dimension $d_{w,c}$, the persistence exponent θ_c , and the scaling function h_c . This result is confirmed by numerical simulations (see Fig.7). For the SATW, one has $\theta_c \neq \theta$ and $d_{w,c} = d_w = 2$ while for the SESRW one has $\theta_c \neq \theta$ and $d_{w,c} \neq d_w$; the scaling of the FPT distribution is thus modified by initial conditions for these processes. In contrast, for the TSAW one has $\theta_c = \theta$ and $d_{w,c} = d_w$ and the scaling of the FPT distribution is not modified by initial conditions.

B. Non compact (transient) case

In the regime $T \gg R^{d_w}$ and $1 \ll t \ll T$, we have found the following diffusive scaling of increments for non compact self-interacting random walks:

$$\Delta^2(T, t) \underset{t \gg 1}{\sim} 2D_{>}t. \quad (31)$$

In addition, we have shown that $\psi_c = \psi$. All steps leading to the derivation of the FPT distribution (see previous section) can then be straightforwardly reproduced. It is found that

$$\bar{F}_c(\eta, r, R) = \left(1 - C \left(\frac{a}{R}\right)^\psi\right) h_c(\eta) \quad (32)$$

where $\eta = t/R^d$ and h_c is an undetermined function that depends on the process. In the case of non compact self-interacting random walks, initial conditions thus do not modify the scaling of the FPT distribution ; they however can change the scaling function h_c . This result is confirmed by numerical simulations (see Fig.7).

VII. DISCUSSION AND CONCLUSION

A. Summary of the results

Our joint analytical and numerical analysis shows finally that long range memory effects can have deep consequences on the dynamics of generic self-interacting random walks ; they can induce aging (quantified by $D(T, t)$ and d_w) and non trivial persistence and transience exponents θ and ψ , which we characterized quantitatively. In striking contrast with other non Markovian processes, we have shown that geometric confinement can strongly modify the dynamic properties of self-interacting random walks, beyond imposing locally reflecting boundary conditions : the dynamics of increments can be modified (in the non compact case), as well as persistent exponents (in the compact case).

Based on this systematic quantitative analysis, we have shown that universal scaling forms of the FPT distributions of general self-interacting random walks in confinement can be derived in the large volume limit, by generalizing the approach introduced in [50]. For "fresh" initial

conditions, we find that the FPT distribution in confinement can be asymptotically predicted from the knowledge of the process in infinite space only (via the infinite space exponents d_w, θ, ψ) : geometric confinement ultimately does modify the dynamics of the process and even changes the corresponding exponents $d_{w,c}, \theta_c, \psi_c$ defined in confinement, but this occurs only at timescales larger than the typical FPT, and thus only mildly impacts the FPT statistics. In contrast, for aged initial conditions the exponents that determine the FPT distribution are those defined in confinement $d_{w,c}, \theta_c, \psi_c$, and can thus be different from the classical infinite space exponents d_w, θ, ψ . In that case, the process in confinement must therefore be characterized to determine the FPT distribution.

B. Search efficiency of self-interacting random walkers

These results allow us to assess the efficiency of space exploration of self-interacting random walks, and in particular to discuss the impact of memory effects on target search kinetics.

In infinite space, attractive self-interactions ($\beta < 0$) can have drastic consequences on space exploration : for bounded effective interaction potentials $V(n)$ (SATW), the random walk is subdiffusive for $d = 2, 3$ and $|\beta| > |\beta|_c$ and characterised by $\theta = \infty$, so that all moments of the FPT to a target are finite. In this case memory effects thus give a decisive advantage to attractive SATW ($|\beta| > |\beta|_c$) as compared to normal random walks ($\beta = 0$) or repulsive self-interacting walks ($\beta > 0$).

In confined domains, the discussion is very different. If no prior information on the target position is available, the relevant observable to quantify the search kinetics is the position averaged mean FPT $\langle \bar{T} \rangle$. For compact processes, our results yield $\langle \bar{T} \rangle \propto R^{d_w}$. Search kinetics is thus enhanced by lowering d_w , which amounts to maximising the scaling of the MSD with time. In that case, memory effects give a decisive advantage to repulsive $1d$ TSAW and $1d$ SESRW, which both show a superdiffusive exponent $d_w < 2$ for all values of $\beta > 0$. For non compact processes, we obtained $\langle \bar{T} \rangle \propto R^d$, which is consistent with the large time diffusive limit of non compact (repulsive or attractive) self-interacting random walks. The scaling of $\langle \bar{T} \rangle$ with R is thus independent of memory effects, which however modify the effective diffusion coefficient and are thus favorable in the repulsive case.

If the starting distance r from the target is known, the full FPT distribution is needed to analyse the search kinetics. For compact processes, our results (21) show that the set of trajectories that hit the target can be decomposed into a set of fast trajectories, with timescale $\propto r^{d_w}$ and weight $1 - \alpha(r/R)^{d_w\theta}$ (where α is a constant), and a set of slow trajectories that typically hit the domain boundaries before the target, with timescale $\propto R^{d_w}$ and weight $\propto (r/R)^{d_w\theta}$. The exponents d_w, θ thus appear as key parameters that control the respective weight of fast

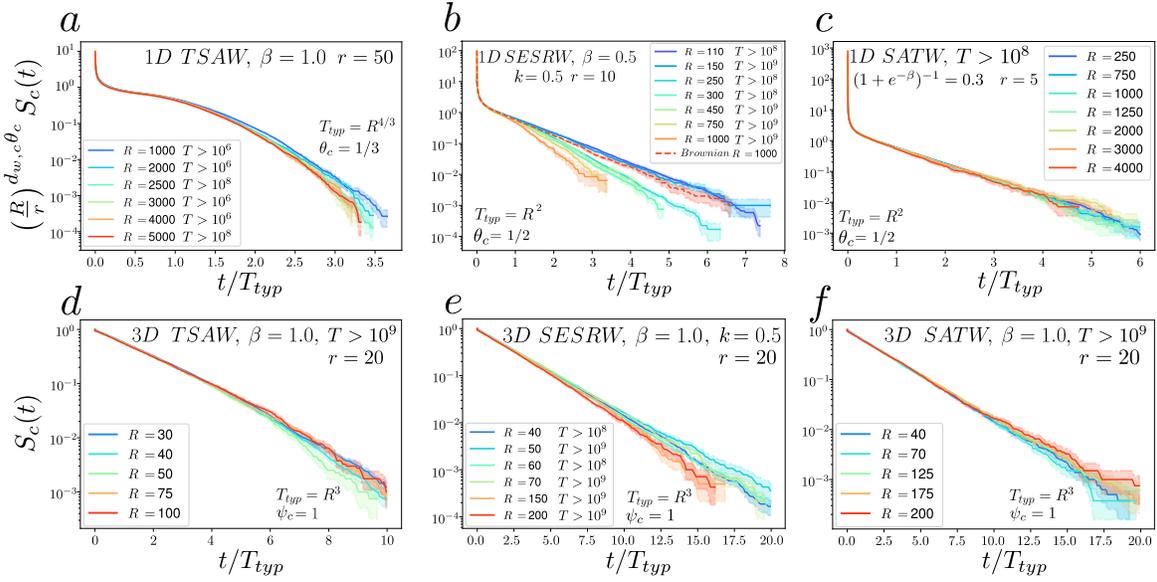


Figure 7. Asymptotic FPT distribution of self-interacting random walks in confined domains for aged initial conditions. The search process starts at $t = 0$, but the random walker is assumed to have explored the domain from $t = -T$ to $t = 0$. $S(t)$ is the survival probability of the random walker at time t . The scaling of $S(t)$ with geometrical parameters is deduced from (30) and (32), for compact and non-compact processes respectively. The collapse of numerical simulations after rescaling captures the dependence of the FPT distribution on geometrical parameters. Simulations are performed in 1d and 3d boxes of size R with reflecting boundary conditions for fixed r and a . Compact cases : **a.** 1d TSAW with $\beta = 1.0$; **b.** 1d SESRW with $\beta = 1.0$ and $k = 0.5$. The FPT distribution of the simple random walk is added for comparison (dashed curve); **c.** 1d SATW repulsive with $\beta = 3.0$ Non-compact cases : **d.** 3d TSAW with $\beta = 1.0$; **e.** 3d SESRW with $\beta = 1.0$ and $k = 0.5$; **f.** 3d SATW with $\beta = 1.0$.

and slow trajectories, as well as the typical timescale of slow trajectories. For random processes with stationary increments, it has been proposed that both exponents are not independent and satisfy $\theta = 1 - d/d_w$ [50, 52, 66] ; in that case, increasing the weight of direct, fast trajectories by increasing d_w comes at the cost of increasing the timescale of indirect trajectories. This is also the case of the 1d repulsive TSAW, for which we found numerically $\theta = 1 - d/d_w$. In the case of the 1d SESRW and the 1d SATW however, we found that d_w and θ are independent, with a dependence of θ only on the coupling parameter β . This shows that repulsive self-interactions can be favorable for large starting distances because they diminish the timescale of indirect trajectories by lowering d_w (1d TSAW and 1d SESRW) ; they however in all cases reduce the weight of direct trajectories and are thus detrimental at short distances. In turn, attractive interactions (SATW) are detrimental for $d = 2, 3$ because they increase the timescale of indirect trajectories by increasing d_w (subdiffusive SATW), while they preserve the diffusive scaling for $d = 1$; they can however significantly

increase the weight of direct trajectories by increasing θ ($d = 1, 2, 3$), and are thus favorable at short distances. Finally, in the non compact case, our results (27) show that the FPT statistics is characterized by the single time scale R^d as long as $r \gg a$. As in the case of the position averaged mean FPT, memory effects modify only the effective diffusion coefficient ; they are thus favorable in the repulsive case, but do not impact scaling properties of the FPT distribution.

Finally, this analysis shows that memory effects induced self-interactions can have a deep impact on space exploration, as quantified by various observables. Qualitatively, attractive self-interactions have dramatic effects and can lead to subdiffusion with compact exploration, which is favorable for local exploration, and even to self-trapping. Repulsive self-interactions have important effects for compact random walks, for which they modify the walk dimension d_w and thus the scaling of the position averaged mean FPT with the size of the confining domain ; this is thus favorable for global exploration of confined domains with no prior informations on the target position.

- [1] N. G. van Kampen, *Stochastic Processes in Physics and Chemistry* (North-Holland, Amsterdam, 1992).
 [2] B. Hughes, *Random Walks and Random Environments*

- (Oxford University Press, New York, 1995).
 [3] J. Klafter and I. M. Sokolov, *First steps in random walks: From Tools to Applications* (Oxford University Press,

- 2016).
- [4] J.-P. Bouchaud and A. Georges, Anomalous diffusion in disordered media: Statistical mechanisms, models and physical applications, *Physics Reports* **195**, 127 (1990).
 - [5] D. Ben-Avraham and S. Havlin, *Diffusion and reactions in fractals and disordered systems* (Cambridge University Press, 2000).
 - [6] R. Metzler and J. Klafter, The random walk's guide to anomalous diffusion: a fractional dynamics approach, *Phys. Rep.* **339**, 1 (2000).
 - [7] R. Burioni and D. Cassi, Random walks on graphs: ideas, techniques and results, *Journal of Physics A: Mathematical and General* **38**, R45 (2005).
 - [8] P. Romanczuk, M. Bar, W. Ebeling, B. Lindner, and L. Schimansky-Geier, Active brownian particles from individual to collective stochastic dynamics, *EPJE-ST* **202**, 1 (2012).
 - [9] R. Metzler, J.-H. Jeon, A. G. Cherstvy, and E. Barkai, Anomalous diffusion models and their properties: non-stationarity, non-ergodicity, and ageing at the centenary of single particle tracking, *Physical Chemistry Chemical Physics* **16**, 24128 (2014).
 - [10] C. Bechinger, R. Di Leonardo, H. Löwen, C. Reichhardt, G. Volpe, and G. Volpe, Active particles in complex and crowded environments, *Reviews of Modern Physics* **88**, 045006 (2016).
 - [11] J. Masoliver, K. Lindenberg, and B. J. West, First-passage times for non-markovian processes: Correlated impacts on bound processes, *Physical Review A* **34**, 2351 (1986).
 - [12] D. J. Bicut and T. W. Burkhardt, Absorption of a randomly accelerated particle: gambler's ruin in a different game, *Journal of Physics A: Mathematical and General* **33**, 6835 (2000).
 - [13] G. M. Schütz and S. Trimper, Elephants can always remember: Exact long-range memory effects in a non-markovian random walk, *Physical Review E* **70**, 045101 (2004).
 - [14] T. Guérin, O. Bénichou, and R. Voituriez, Non-markovian polymer reaction kinetics, *Nat Chem* **4**, 568 (2012).
 - [15] D. Boyer and J. C. R. Romo-Cruz, Solvable random-walk model with memory and its relations with markovian models of anomalous diffusion, *Physical Review E* **90**, 042136 (2014).
 - [16] A. Falcón-Cortés, D. Boyer, L. Giuggioli, and S. N. Majumdar, Localization transition induced by learning in random searches, *Physical Review Letters* **119**, 140603 (2017).
 - [17] T. Guérin, N. Levernier, O. Bénichou, and R. Voituriez, Mean first-passage times of non-markovian random walkers in confinement, *Nature* **534**, 356 (2016).
 - [18] H. Meyer and H. Rieger, Optimal non-markovian search strategies, *arXiv* **2105.10207** (2021).
 - [19] D. J. Amit, G. Parisi, and L. Peliti, Asymptotic behavior of the "true" self-avoiding walk, *Physical Review B* **27**, 1635 (1983), publisher: American Physical Society.
 - [20] L. Peliti and L. Pietronero, Random walks with memory, *La Rivista del Nuovo Cimento* (1978-1999) **10**, 1 (1987).
 - [21] H. C. Ottinger, The generalised true self-avoiding walk-a model with continuously variable exponent ν , *Journal of Physics A: Mathematical and General* **18**, L363 (1985), publisher: IOP Publishing.
 - [22] B. Tóth, *Self-Interacting Random Motions* (Birkhäuser Basel, 2001) pp. 555–564.
 - [23] V. B. Sapozhnikov, Self-attracting walk with $\nu < 1/2$, *Journal of Physics A: Mathematical and General* **27**, L151 (1994).
 - [24] R. Pemantle, A survey of random processes with reinforcement, *Probability Surveys* **4**, 1 (2007).
 - [25] J. G. Foster, P. Grassberger, and M. Paczuski, Reinforced walks in two and three dimensions, *New Journal of Physics* **11**, 023009 (2009).
 - [26] A. Ordemann, E. Tomer, G. Berkolaiko, S. Havlin, and A. Bunde, Structural properties of self-attracting walks, *Physical Review E* **64**, 046117 (2001).
 - [27] B. Davis, Reinforced random walk, *Probability Theory and Related Fields* **84**, 203 (1990).
 - [28] W. T. Kranz, A. Gelimison, K. Zhao, G. C. L. Wong, and R. Golestanian, Effective dynamics of microorganisms that interact with their own trail, *Physical Review Letters* **117**, 038101 (2016).
 - [29] W. T. Kranz and R. Golestanian, Trail-mediated self-interaction, *The Journal of Chemical Physics*, *The Journal of Chemical Physics* **150**, 214111 (2019).
 - [30] A. Dussutour, V. Fourcassié, D. Helbing, and J.-L. Deneubourg, Optimal traffic organization in ants under crowded conditions, *Nature* **428**, 70 (2004).
 - [31] L. Giuggioli, J. R. Potts, and S. Harris, Animal interactions and the emergence of territoriality, *PLOS Computational Biology* **7**, e1002008 (2011).
 - [32] J. d'Alessandro, A. Barbier-Chebbah, V. Cellerin, O. Benichou, R. Mège, R. Voituriez, and B. Ladoux, Cell migration guided by long-lived spatial memory, *Nature Communications* **12**, 4118 (2021).
 - [33] H. Flyvbjerg, Past attractions set future course, *Nature Physics* 10.1038/s41567-021-01298-w (2021).
 - [34] O. Pohl and H. Stark, Dynamic clustering and chemotactic collapse of self-phoretic active particles, *Physical Review Letters* **112**, 238303 (2014).
 - [35] I. Theurkauff, C. Cottin-Bizonne, J. Palacci, C. Ybert, and L. Bocquet, Dynamic clustering in active colloidal suspensions with chemical signaling, *Physical Review Letters* **108**, 268303 (2012).
 - [36] A. Stevens and H. G. Othmer, Aggregation, Blowup, and Collapse: The ABC's of Taxis in Reinforced Random Walks, *SIAM Journal on Applied Mathematics* **57**, 1044 (1997).
 - [37] I. Horváth, B. Tóth, and B. Vető, Diffusive limits for the true (or myopic) self-avoiding random walks and self-repellent brownian polymers in $d \geq 3$, *Probability Theory and Related Fields* **153**, 691 (2012).
 - [38] P. Grassberger, Self-Trapping Self-Repelling Random Walks, *Physical Review Letters* **119**, 10.1103/PhysRevLett.119.140601 (2017).
 - [39] H. Freund and P. Grassberger, How uniformly a random walker covers a finite lattice, *Physica A: Statistical Mechanics and its Applications* **192**, 465 (1993).
 - [40] A. Barbier-Chebbah, O. Benichou, and R. Voituriez, Anomalous persistence exponents for normal yet aging diffusion, *Physical Review E* **102**, 062115 (2020).
 - [41] D. Campos, J. Cristín, and V. Méndez, Minimization of spatial cover times for impaired self-avoiding random walks: the mirage effect, *Journal of Statistical Mechanics: Theory and Experiment* **2021**, 063404 (2021).
 - [42] S. Redner, *A Guide to First-Passage Processes* (Cambridge University Press, Cambridge, England, 2001).
 - [43] R. Metzler, G. Oshanin, and S. Redner, *First passage*

problems: recent advances (World Scientific, Singapore, 2014).

- [44] O. Bénichou, C. Loverdo, M. Moreau, and R. Voituriez, Intermittent search strategies, *Reviews of Modern Physics* **83**, 81 (2011).
- [45] G. M. Viswanathan, E. P. Raposo, and M. G. E. da Luz, Levy flights and superdiffusion in the context of biological encounters and random searches, *Physics of Life Reviews* **5**, 133 (2008).
- [46] S. Condamin, O. Bénichou, V. Tejedor, R. Voituriez, and J. Klafter, First-passage times in complex scale-invariant media., *Nature* **450**, 77 (2007).
- [47] O. Bénichou, C. Chevalier, J. Klafter, B. Meyer, and R. Voituriez, Geometry-controlled kinetics, *Nat Chem* **2**, 472 (2010).
- [48] T. G. Mattos, C. Mejía-Monasterio, R. Metzler, and G. Oshanin, First passages in bounded domains: When is the mean first passage time meaningful?, *Physical Review E* **86**, 031143 (2012).
- [49] O. Bénichou and R. Voituriez, From first-passage times of random walks in confinement to geometry-controlled kinetics, *From first-passage times of random walks in confinement to geometry-controlled kinetics*, *Physics Reports* **539**, 225 (2014).
- [50] N. Levernier, O. Bénichou, T. Guérin, and R. Voituriez, Universal first-passage statistics in aging media, *Physical Review E* **98**, 022125 (2018).
- [51] L. Giuggioli, Exact spatiotemporal dynamics of confined lattice random walks in arbitrary dimensions: A century after smoluchowski and polya, *Physical Review X* **10**, 021045 (2020).
- [52] A. J. Bray, S. N. Majumdar, and G. Schehr, Persistence and first-passage properties in nonequilibrium systems, *Advances in Physics*, *Advances in Physics* **62**, 225 (2013).
- [53] N. Levernier, O. Bénichou, and R. Voituriez, Universality classes of hitting probabilities of jump processes, *Physical Review Letters* **126**, 100602 (2021).
- [54] N. Levernier, M. Dolgushev, O. Bénichou, R. Voituriez, and T. Guérin, Survival probability of stochastic processes beyond persistence exponents, *Nat Commun* **10**, 2990 (2019).
- [55] B. Meyer, C. Chevalier, R. Voituriez, and O. Bénichou, Universality classes of first-passage-time distribution in confined media, *Physical Review E* **83**, 051116 (2011).
- [56] L. Pietronero, Critical dimensionality and exponent of the "true" self-avoiding walk, *Physical Review B* **27**, 5887 (1983).
- [57] S. P. Obukhov and L. Peliti, Renormalisation of the true self-avoiding walk, *Journal of Physics A: Mathematical and General* **16**, L147 (1983).
- [58] B. Toth, The "True" Self-Avoiding Walk with Bond Repulsion on \mathbb{Z} : Limit Theorems, *The Annals of Probability* **23**, 1523 (1995).
- [59] M. A. Prasad, D. P. Bhatia, and D. Arora, Diffusive behaviour of self-attractive walks, *Journal of Physics A: Mathematical and General* **29**, 3037 (1996).
- [60] E. Agliari, R. Burioni, and G. Uguzzoni, The true reinforced random walk with bias, *New Journal of Physics* **14**, 063027 (2012).
- [61] S. Volkov, Phase Transition in Vertex-Reinforced Random Walks on \mathbb{Z} with Non-linear Reinforcement, *Journal of Theoretical Probability* **19**, 691 (2006).
- [62] C. Cotar and D. Thacker, Edge- and vertex-reinforced random walks with super-linear reinforcement on infinite graphs, *The Annals of Probability* **45**, 2655 (2017).
- [63] T. Sellke, Reinforced random walk on the d-dimensional integer lattice, *Markov Processes and Related Fields* **2** (2008).
- [64] A.-L. Basdevant, B. Schapira, and A. Singh, Localization of a vertex reinforced random walk on \mathbb{Z} with sub-linear weight, *Probability Theory and Related Fields* **159**, 75 (2014).
- [65] J. Krug, H. Kallabis, S. N. Majumdar, S. J. Cornell, A. J. Bray, and C. Sire, Persistence exponents for fluctuating interfaces, *Physical Review E* **56** (1997).
- [66] Y. Meroz, I. M. Sokolov, and J. Klafter, Distribution of first-passage times to specific targets on compactly explored fractal structures, *Physical Review E* **83**, 020104 (2011).