Creep motion of elastic interfaces in a disordered landscape

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- V. Ros (LPTMS)
- G. Russo (LPTMS)
- V. Schimmenti (Dresda)
- M. Wyart (Hopkins)

Creep motion of elastic interfaces in a disordered landscape

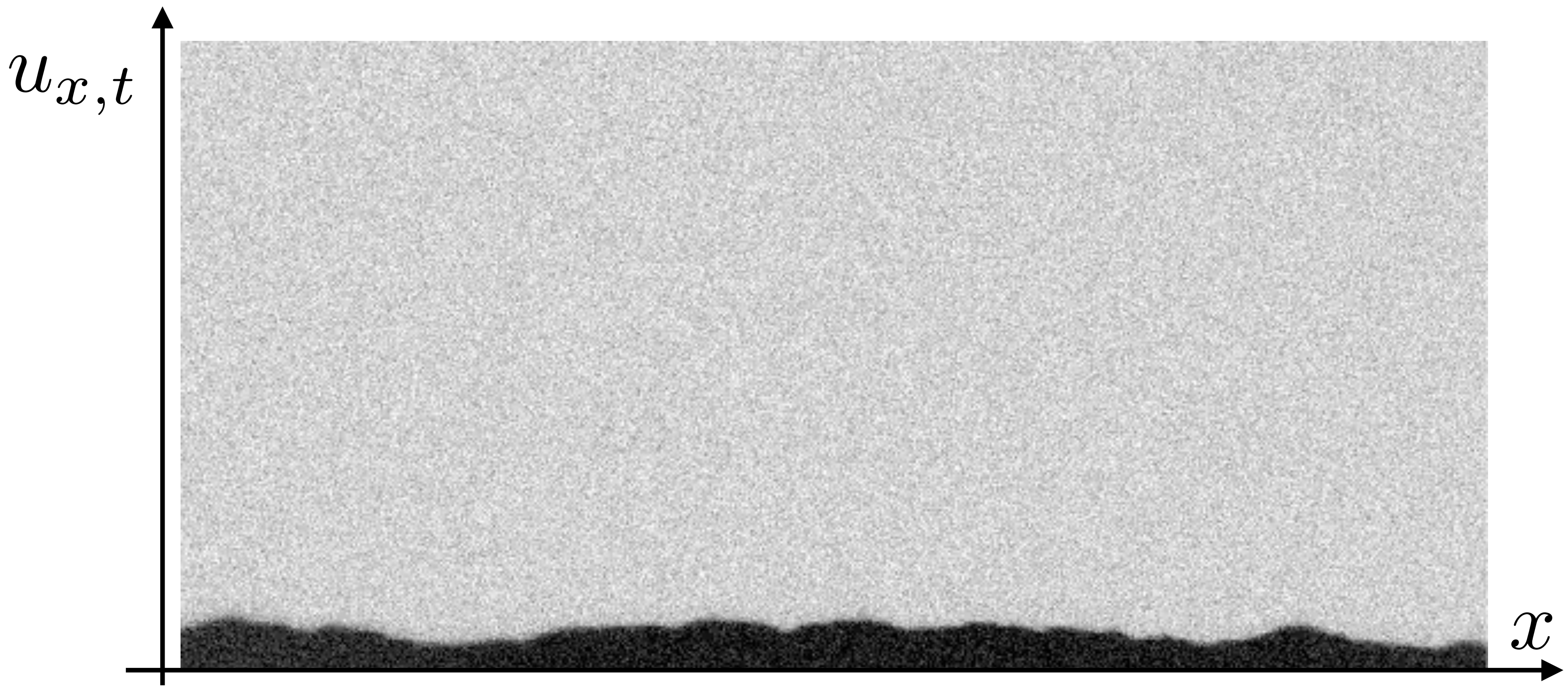
E. Ferrero, L. Foini, T. Giamarchi, A. Kolton, Ann Rev CondMat (2021)

G. Durin, V. Schimmenti, M. Baiesi, L. Foini, Phys. Rev. B (2024)

A. Pacco & V. Ros, JSTAT (2025)

T. de Geus, M Wyart, Phys. Rev. E (2025) + G. Russo (Phd)

Interface Driven Dynamics: Disorder and Elasticity



$$\partial_t u_{x,t} = \partial_x^2 u_{x,t} + \eta\left(x, u_{x,t}\right) + f + \xi_T(x,t)$$

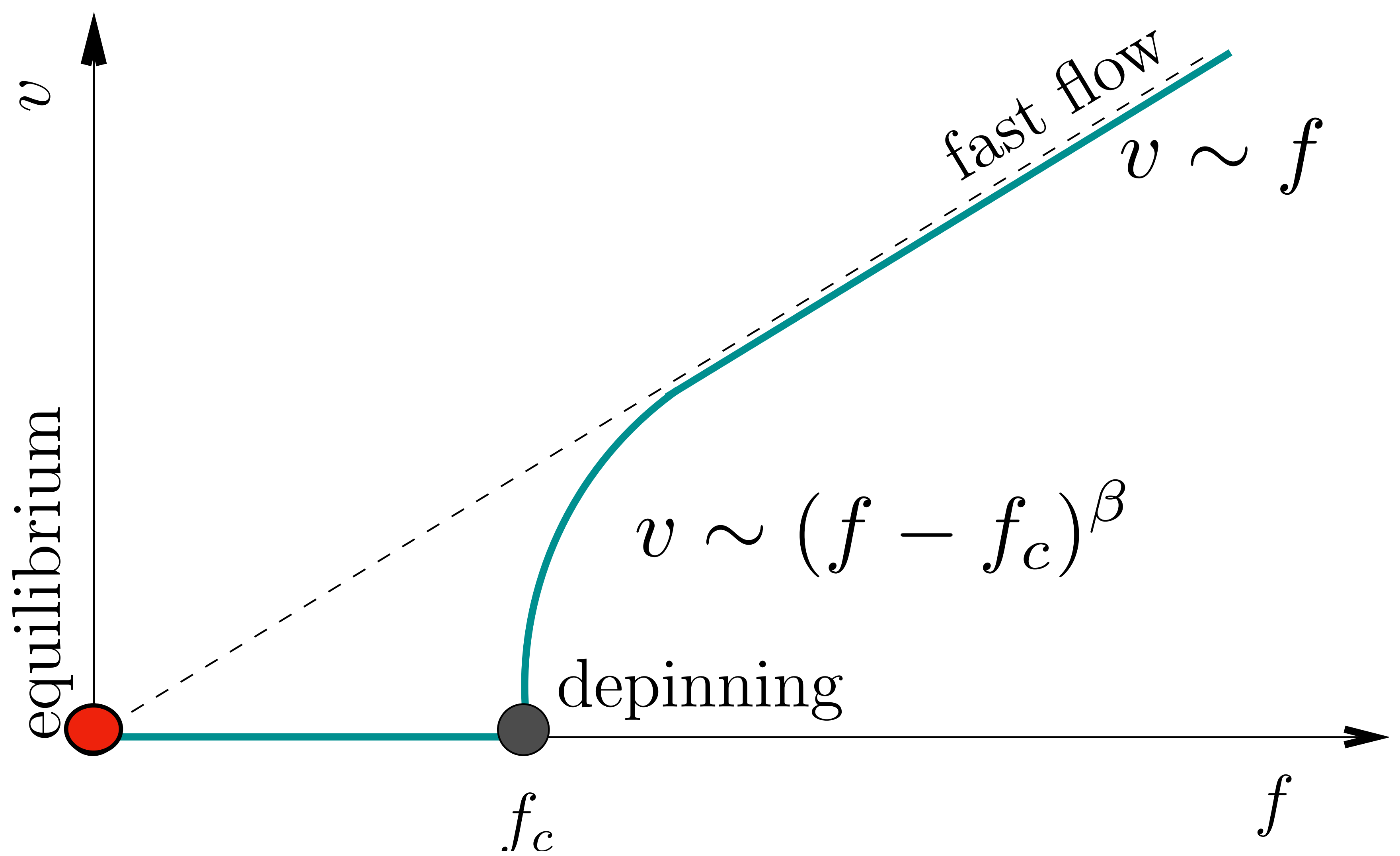
magnetic domain wall dynamics
by V. Jeudy & A. Mougin (Paris-Saclay)

Interface Driven Dynamics: Zero Temperature

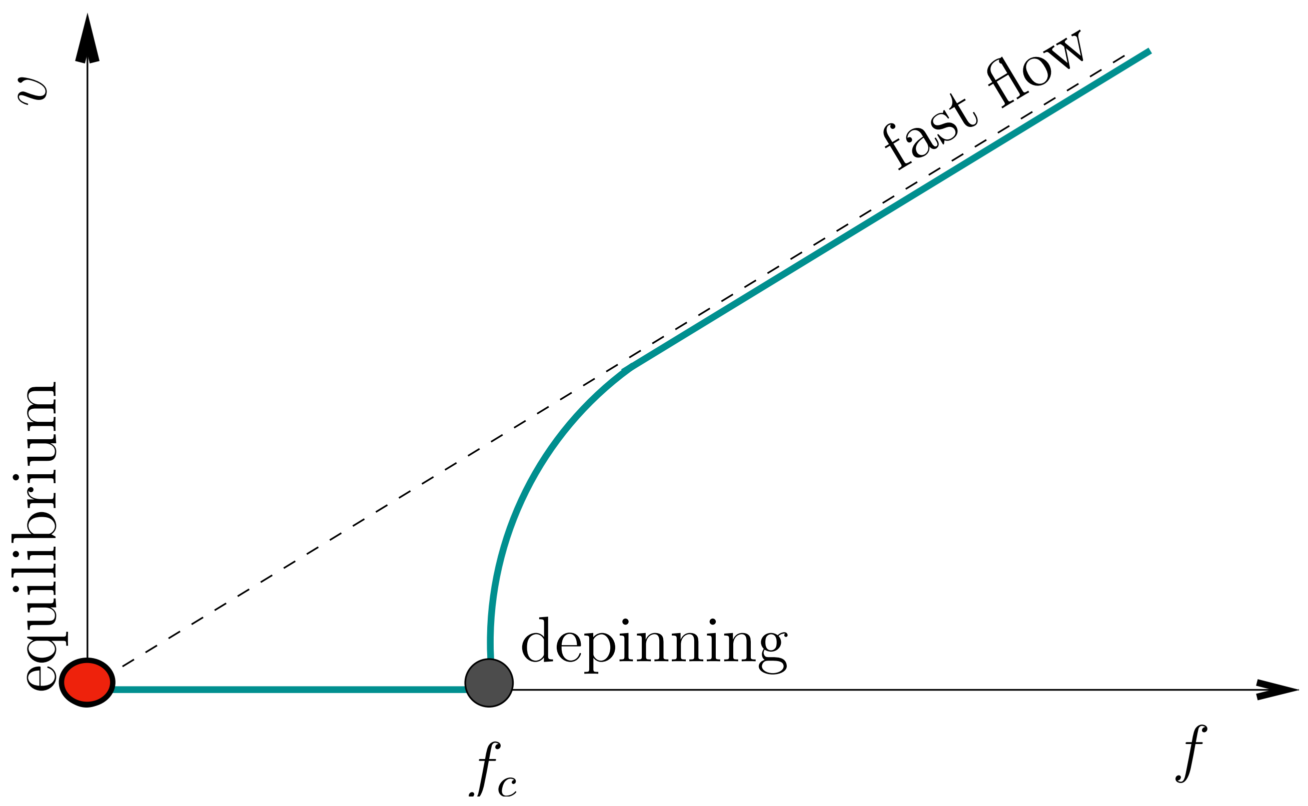
$$\partial_t u_{x,t} = \partial_x^2 u_{x,t} + \eta\left(x, u_{x,t}\right) + f + \xi_T(x,t)$$

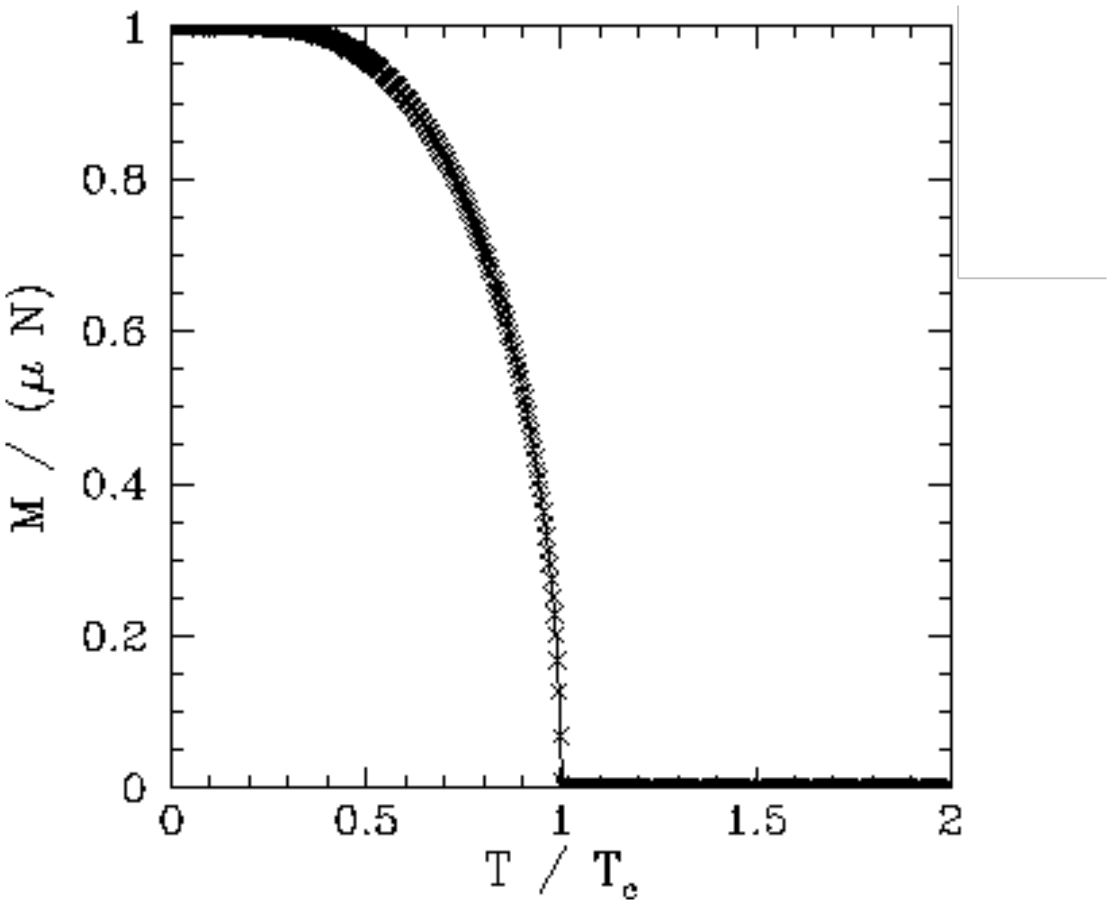
- Pinning - Depinning
- Shape of the interface
- Avalanches

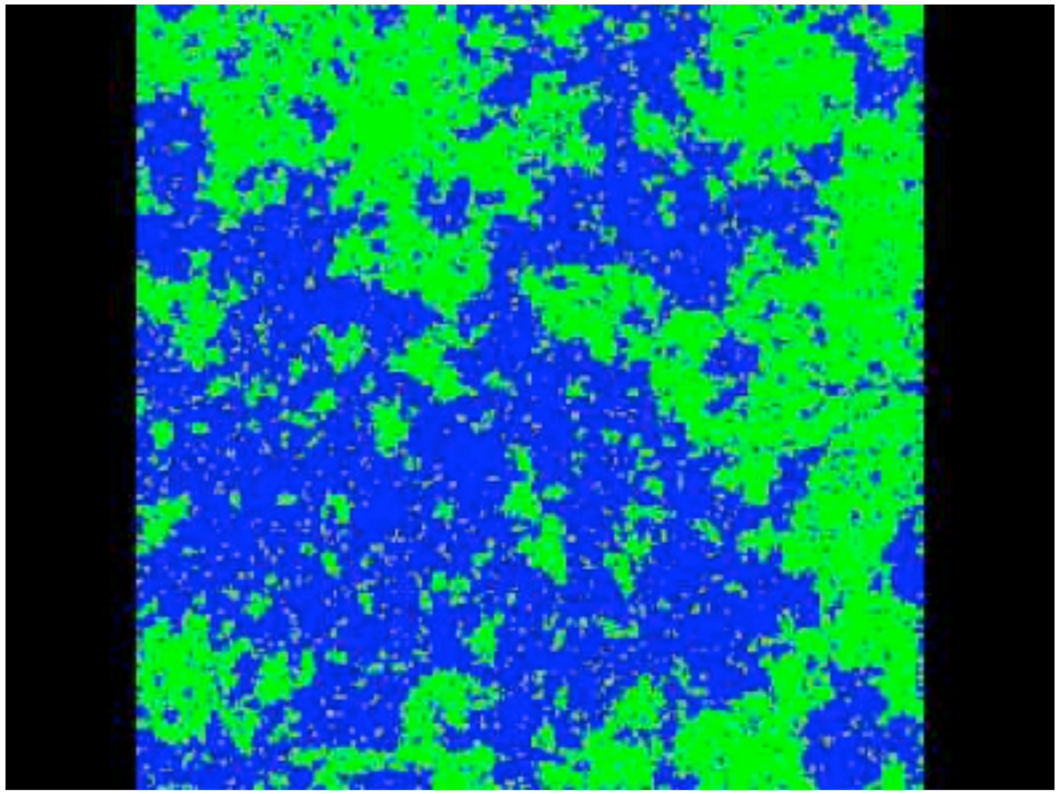
Pinning - Depinning



Depinning as critical point

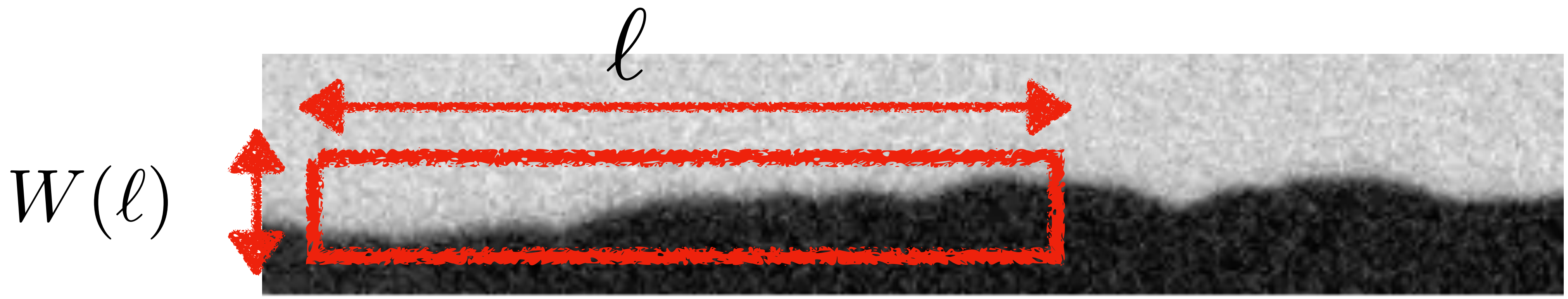






- correlation length
- scale invariance

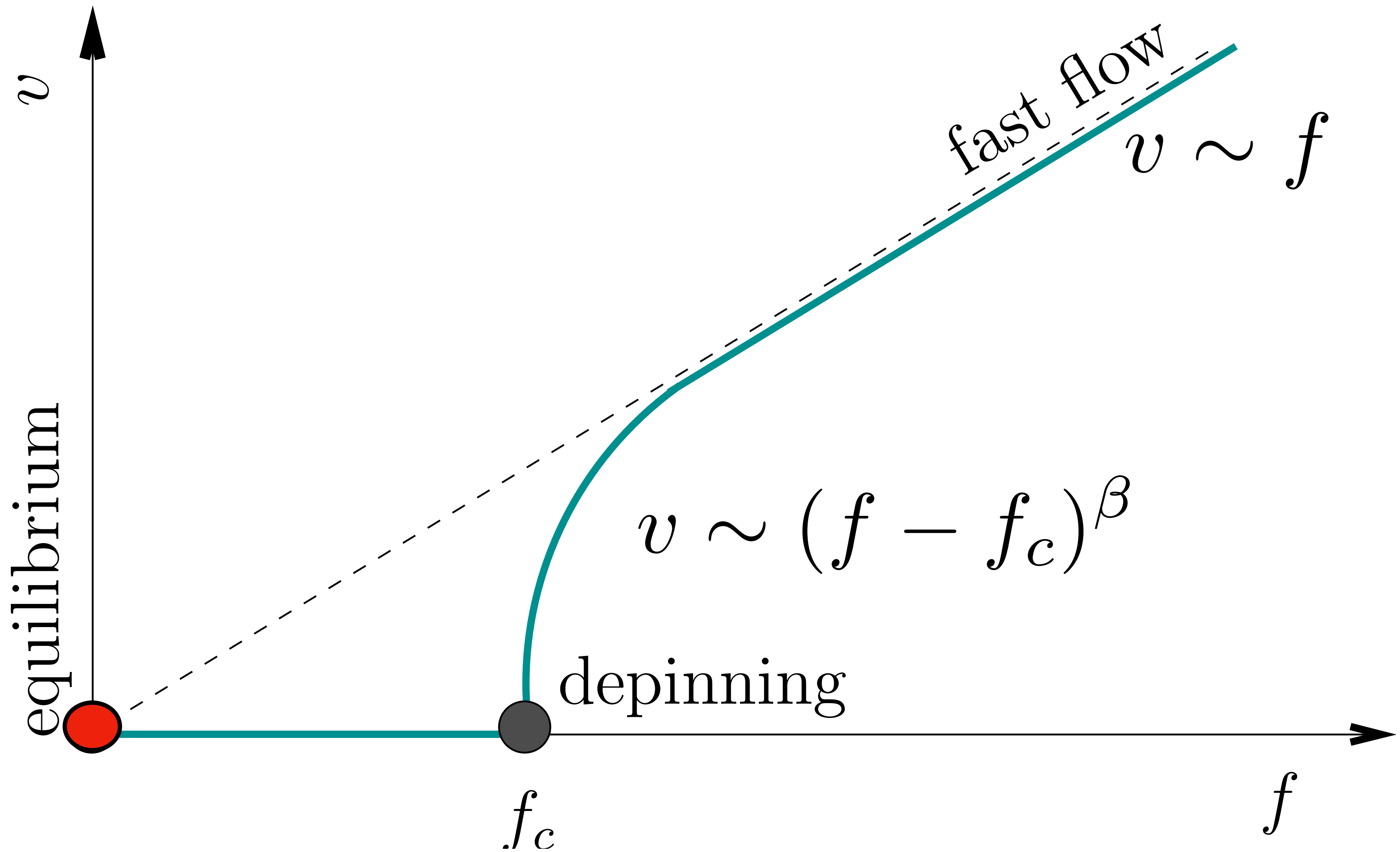
Shape of Driven Interfaces



$$W(\ell) \sim \ell^{\zeta} \qquad \zeta \text{ Roughness exponent}$$

- self similar interfaces (random fractal)
- Family-Vicsek scaling $W(\ell, t) \sim \ell^{\zeta} f\left(\frac{t}{L^z}\right)$

Shape of Driven Interfaces

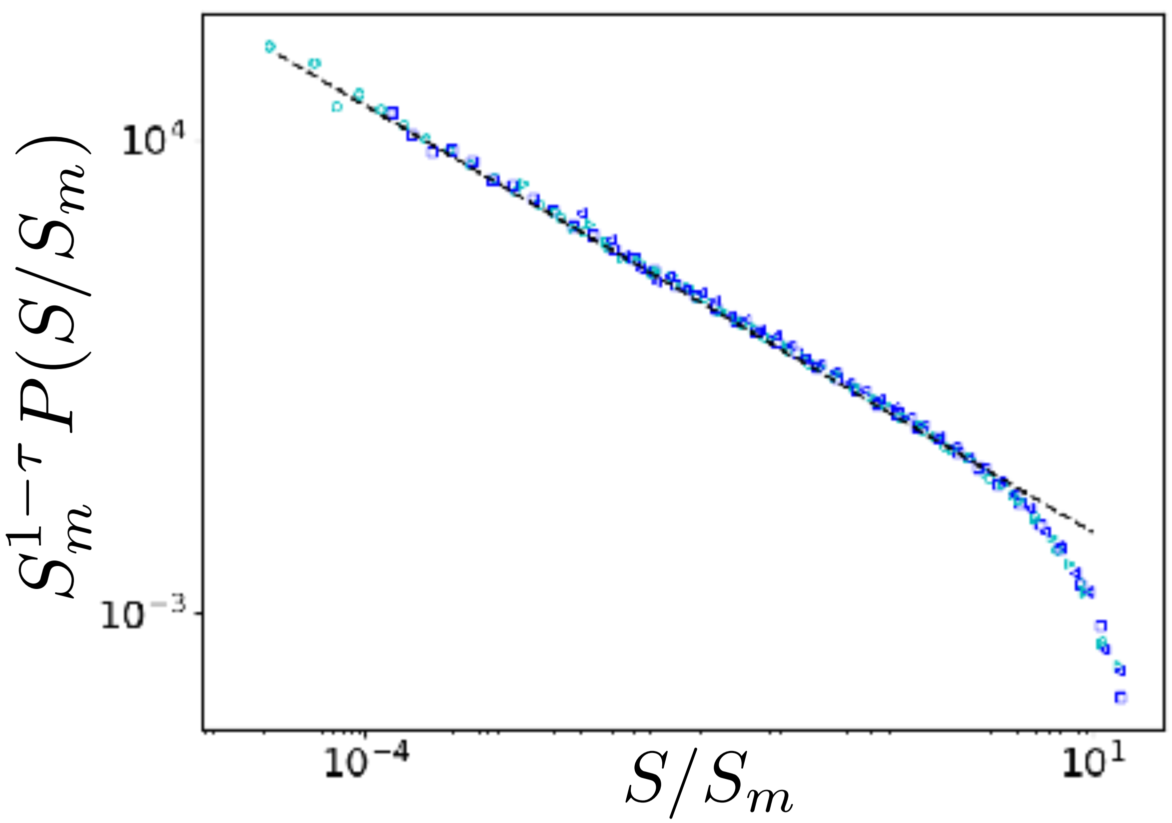


Three roughness exponents:

- Equilibrium $\zeta_{eq} = 2/3$
- Depinning $\zeta_{dep}^{(1)} = 1.25$ or $\zeta_{dep}^{(2)} = 0.63$
- Fast Flow $\zeta_{FF} = 0.5$

Depinning Avalanches

$$P(S) = S^{-\tau} g_S(S/S_m)$$

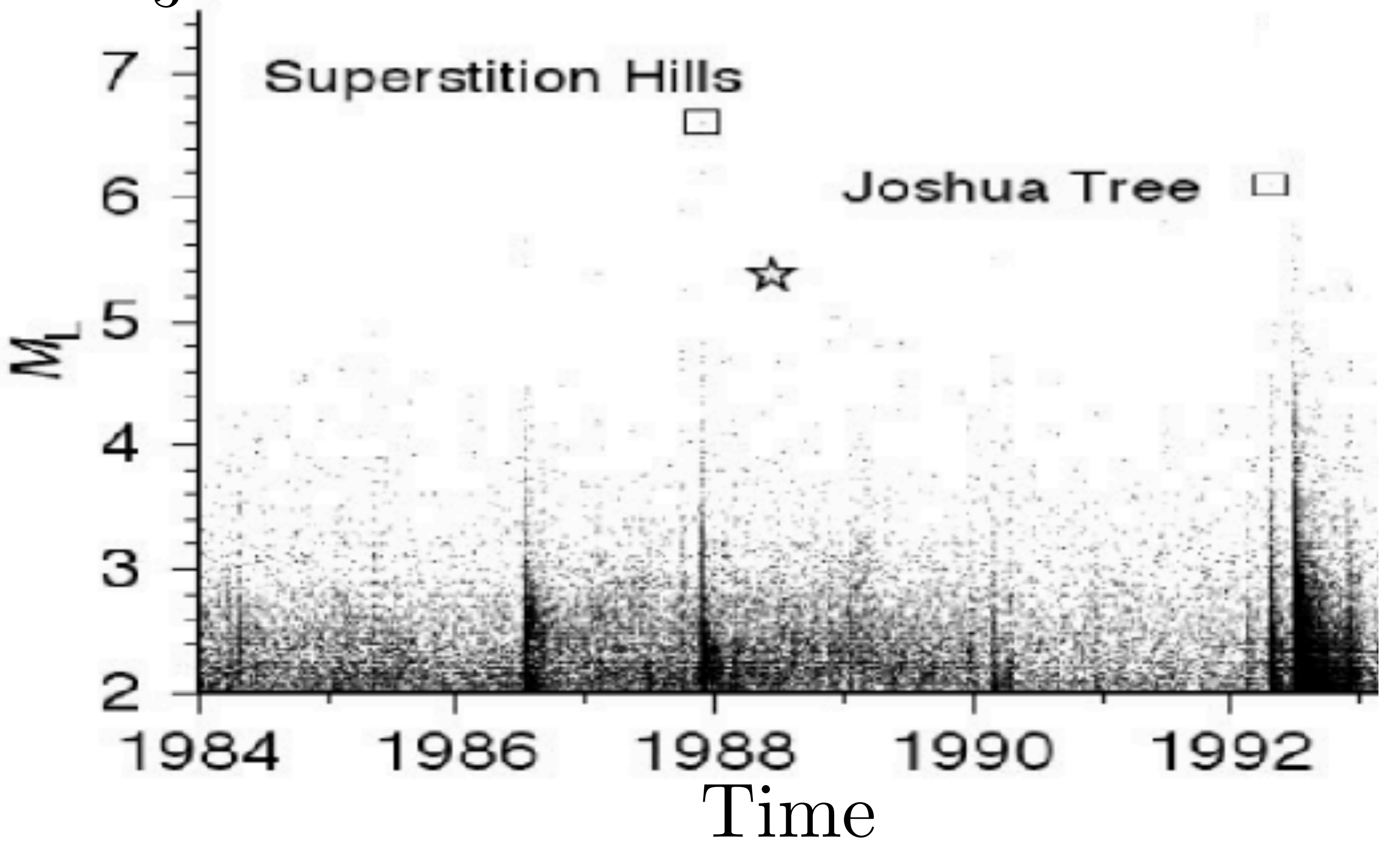


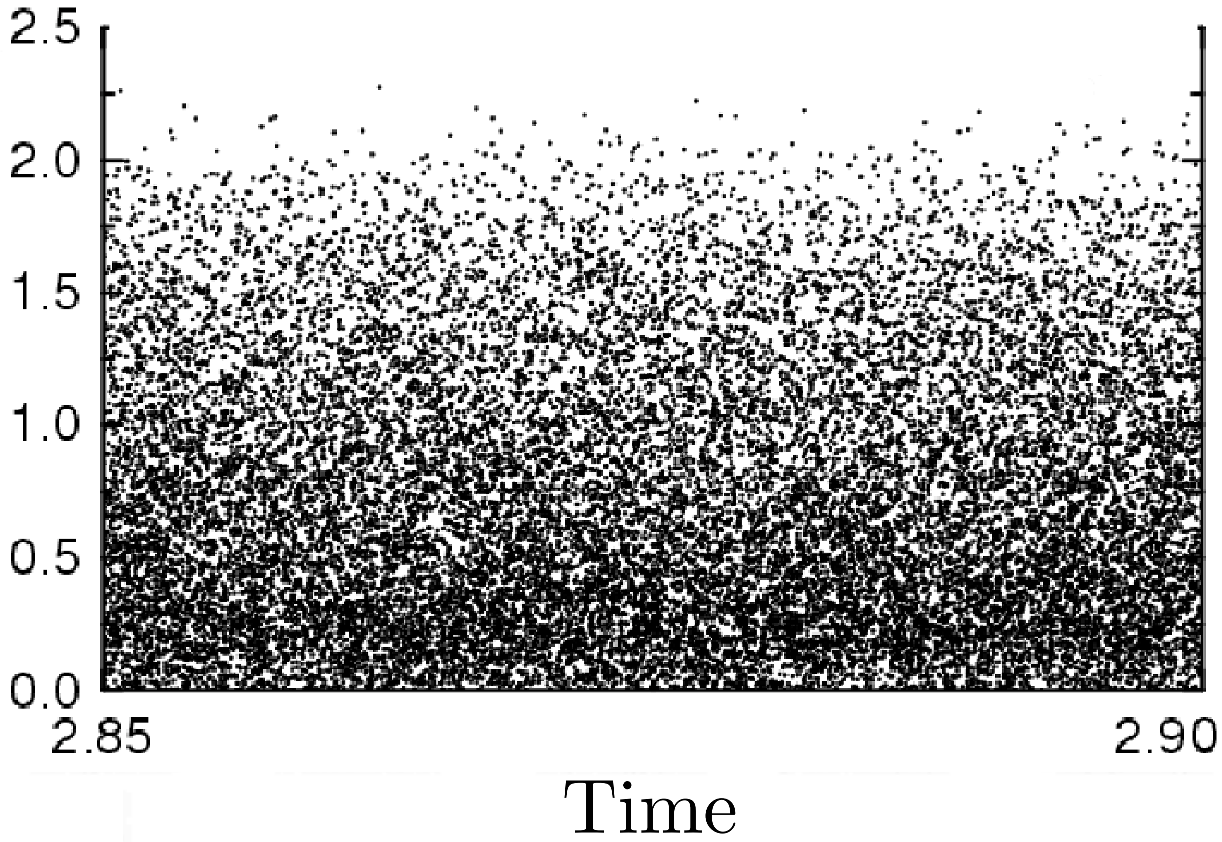
$$S_m \sim \ell_m^{d+\zeta} \qquad \ell_m \sim |f - f_c|^{-\nu}$$

by Alejandro Kolton (Bariloche)

Earthquakes versus Depinning Avalanches

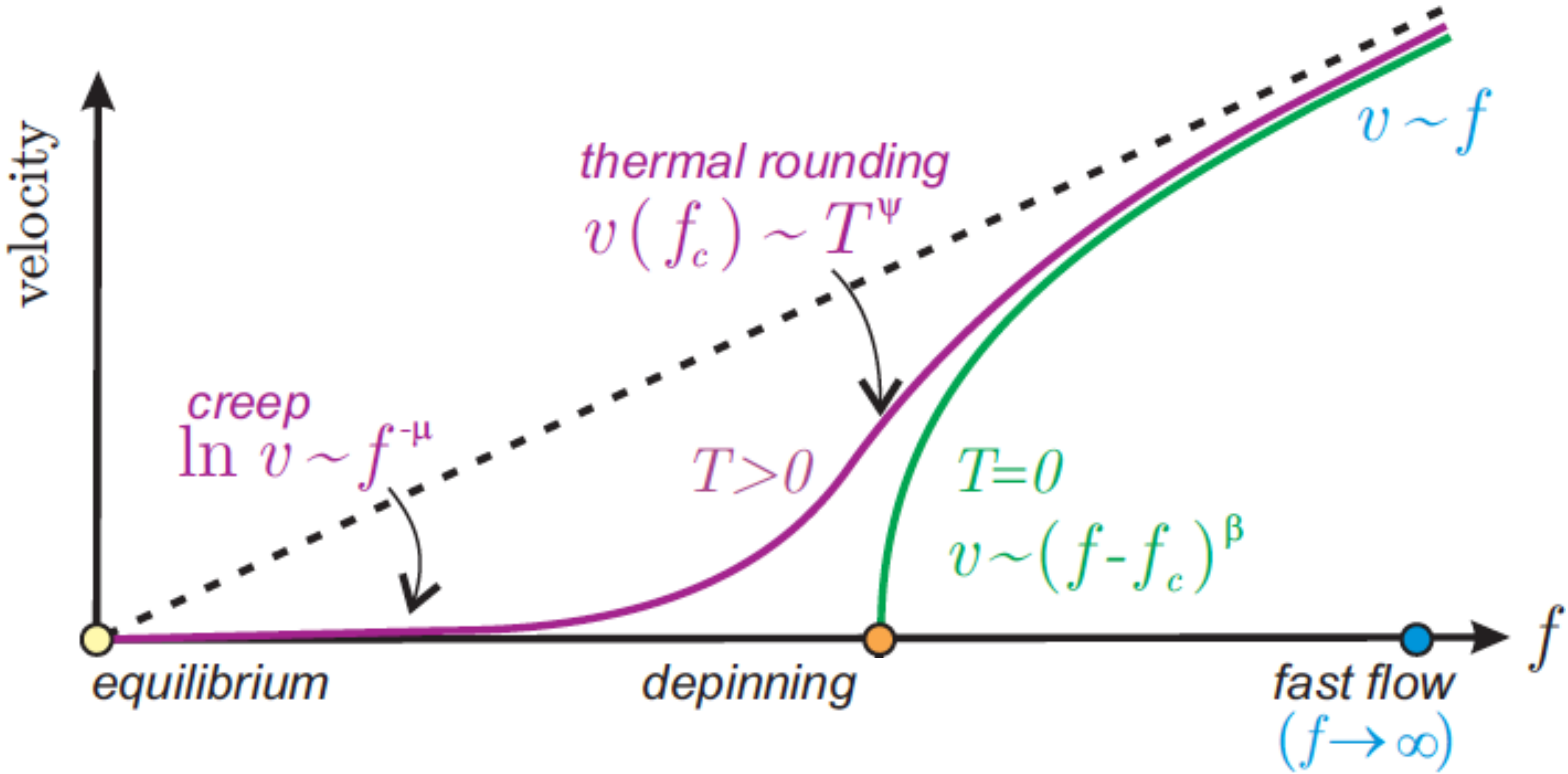
$$M = \frac{2}{3}\log S$$





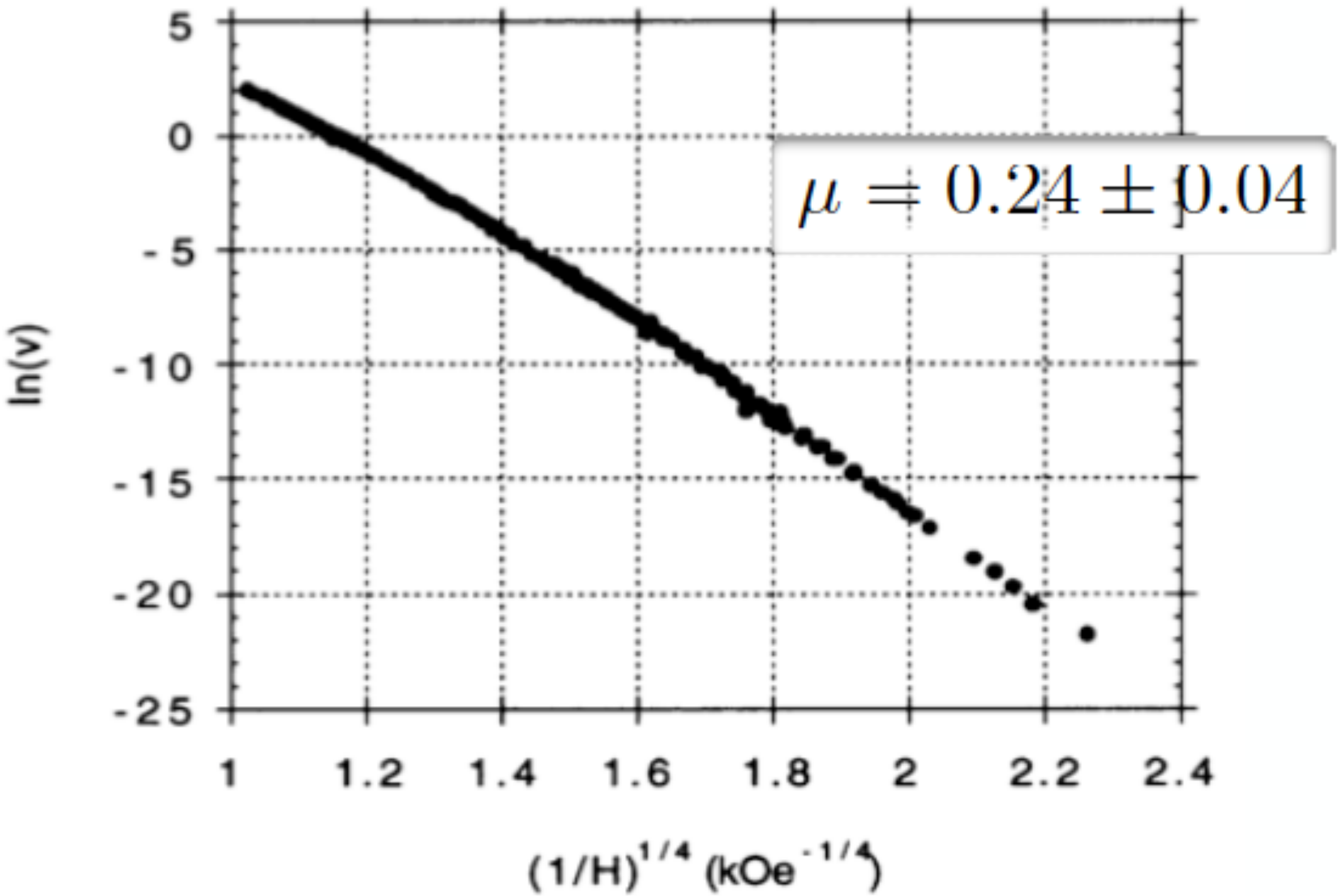
No Spatio-Temporal patterns for depinning avalanches

Interface Driven Dynamics: Finite Temperature



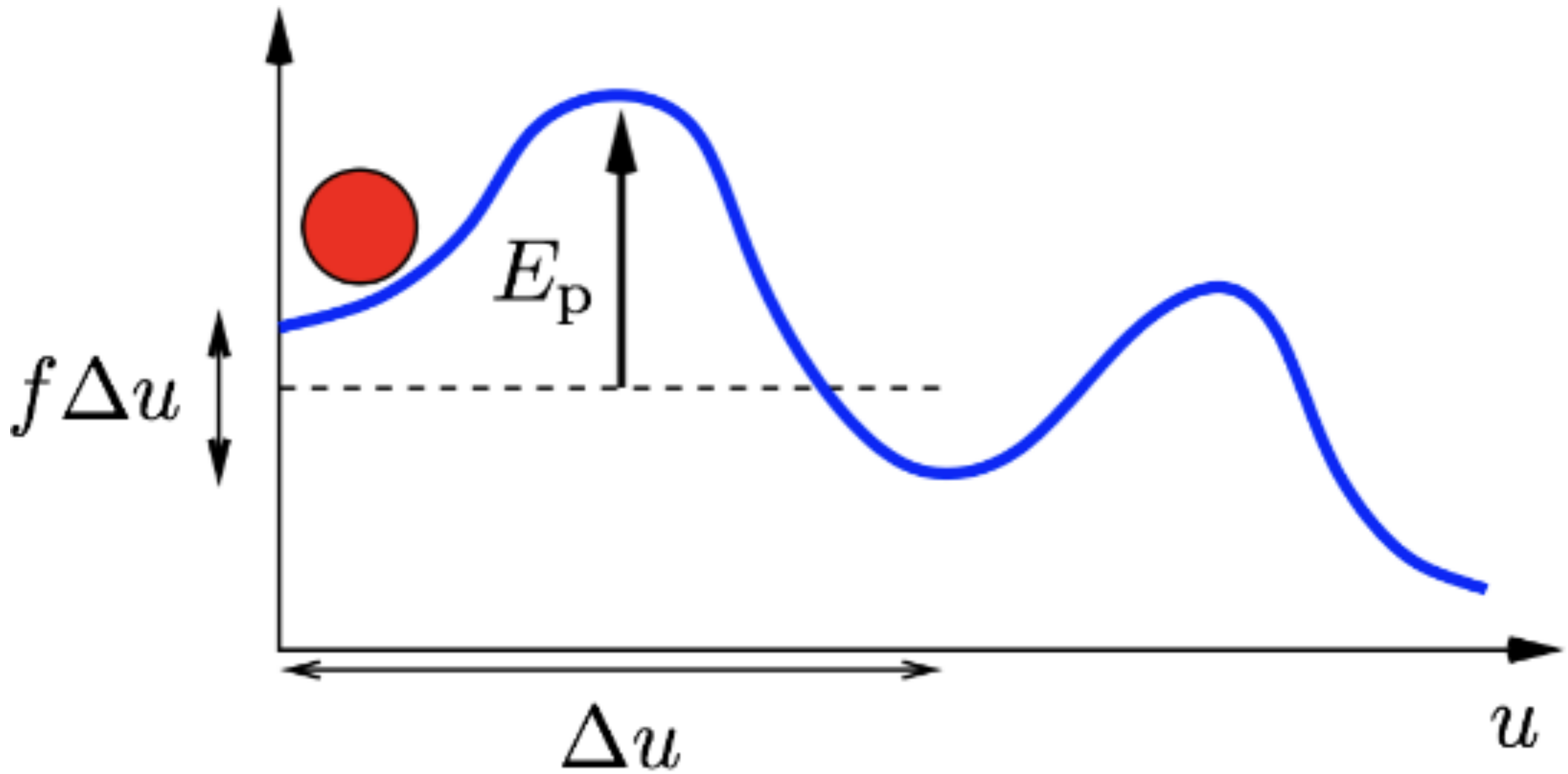
Creep formula (Experiment)

Velocity $\ln v \sim f^{-\mu}$ $\mu(d=1) = \frac{1}{4}$



Lemerle et al. PRL (1998)

Thermally assisted flux flow (TAFF model)



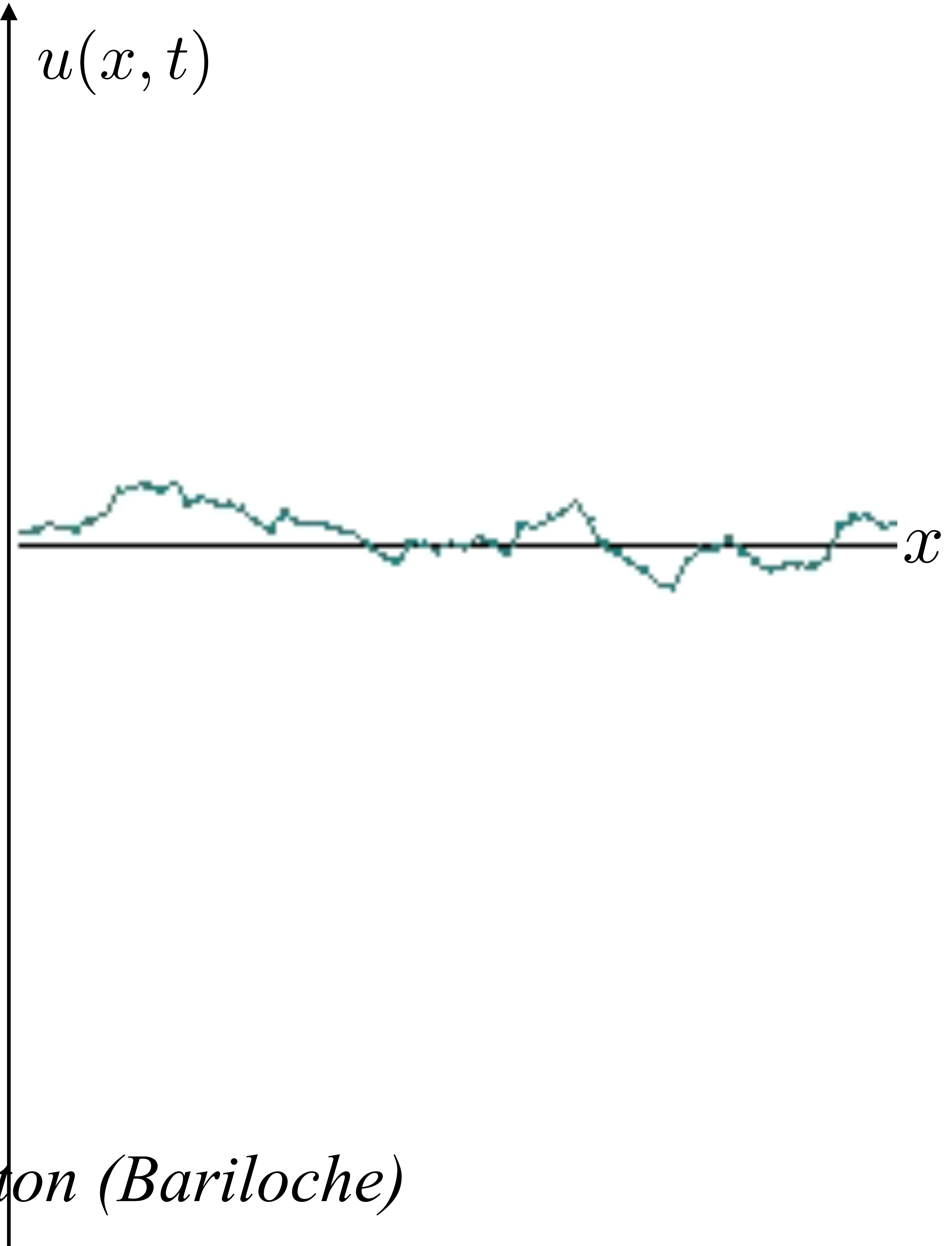
$$v \propto e^{-\beta(E_p - f\Delta u/2)} - e^{-\beta(E_p + f\Delta u/2)} \simeq e^{-\beta E_p} \Delta u f$$

TAFF $\Longrightarrow$ Linear response (even if exponentially suppressed)

Creep formula $\Longrightarrow \quad E_p = E_p(f) \propto 1/f^\mu$

Creep: $f \ll f_c$ and $T \to 0^+$

- small scales: thermal fluctuations
- large scales: forward motion



by Alejandro Kolton (Bariloche)

Creep: $f \ll f_c$ and $T \to 0^+$

- small scales: thermal fluctuations
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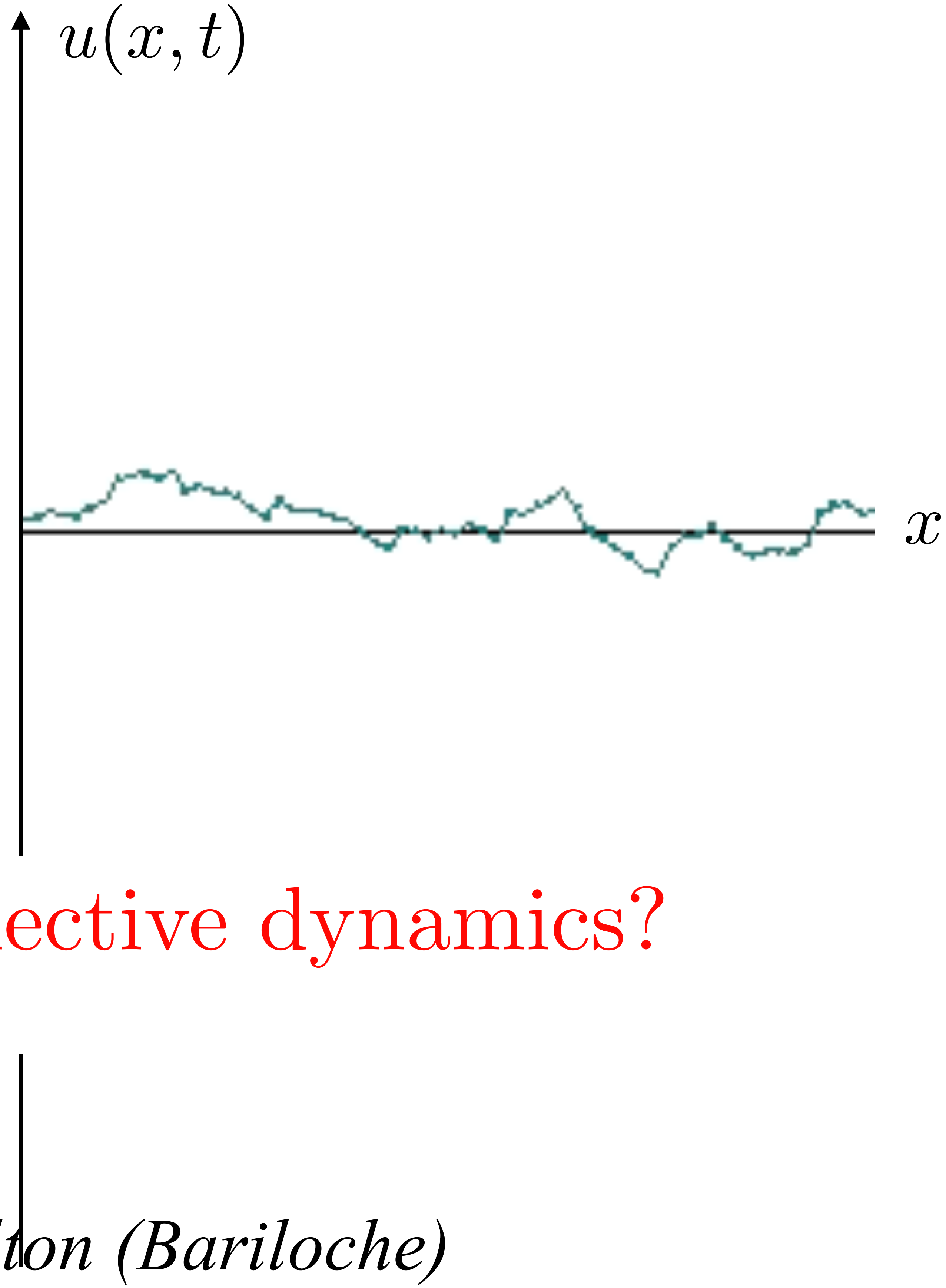
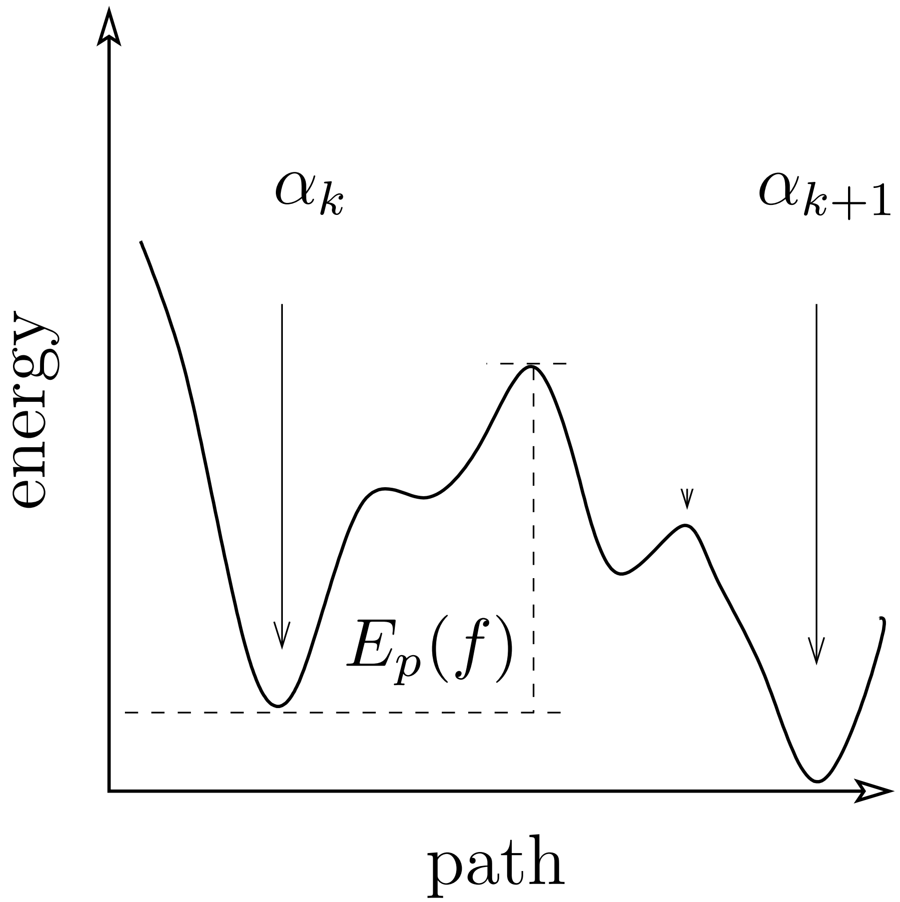


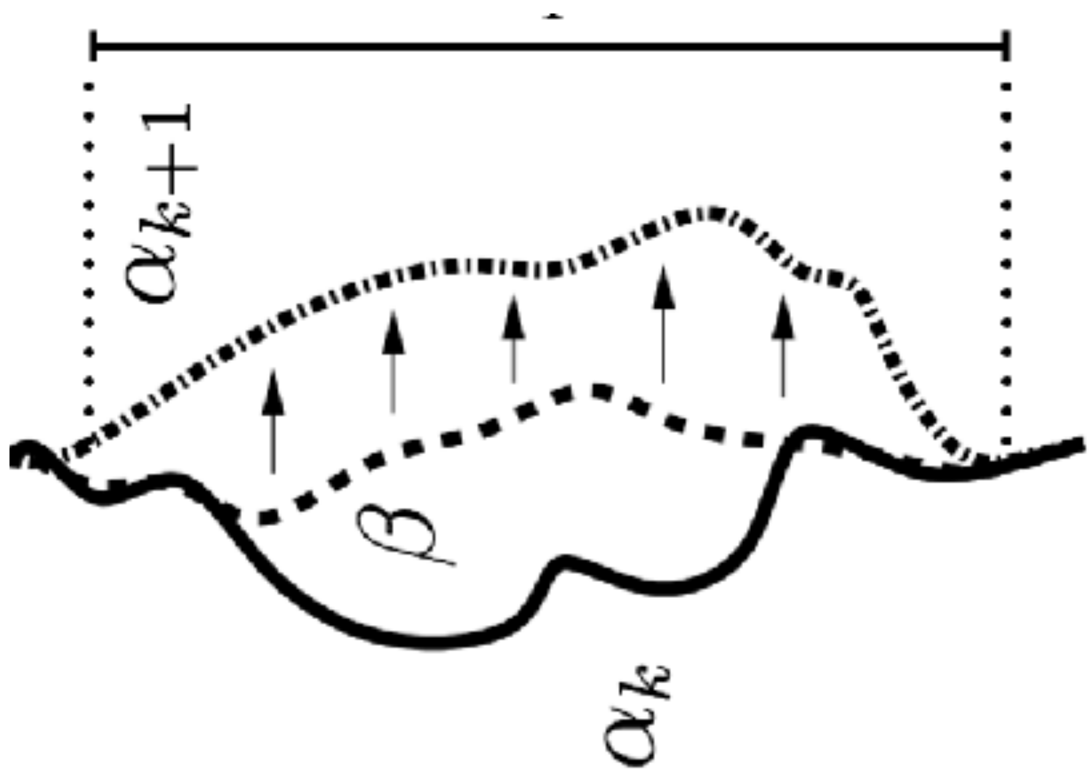
Emergence of collective dynamics?

by Alejandro Kolton (Bariloche)

Creep formula and equilibrium

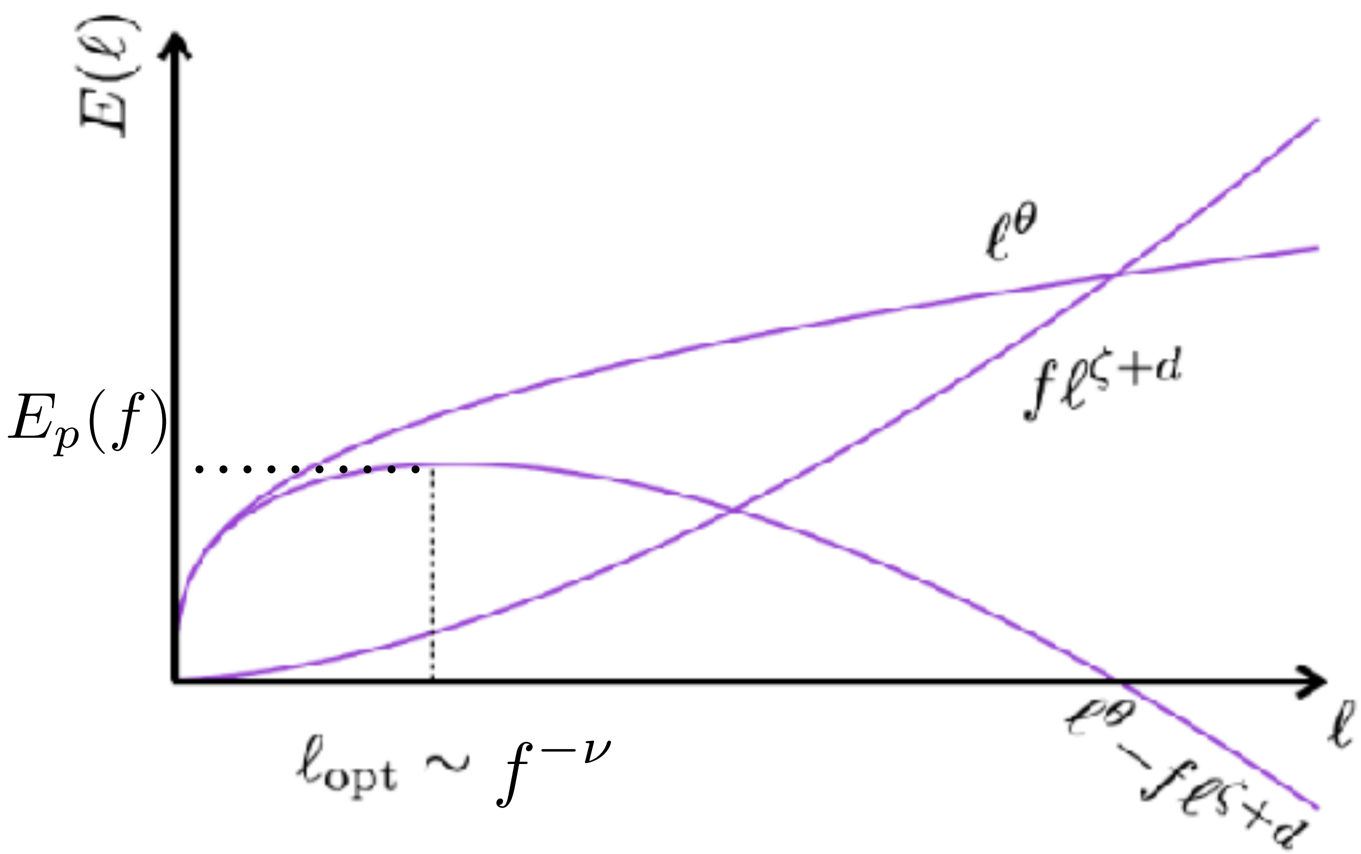
$$E[u] = \int d^d x \ \left[(\nabla u_{x,t})^2 + V(x, u_{x,t})\right] \quad - \quad f \cdot \int d^d x \, u_{x,t}$$





by Ioffe, Vinokur 1987

$$E[u] = \underbrace{\int d^d x \ \left[(\nabla u_{x,t})^2 + V(x, u_{x,t})\right]}_{E_{eq}(\ell)\sim\ell^\theta} \quad - \quad \underbrace{f \cdot \int d^d x \ u_{x,t}}_{E_f(\ell)\sim f\cdot\ell^{d+\zeta}}$$



$$E_p(f) \sim \ell_{\text{opt}}^\theta \sim f^{-\mu}$$

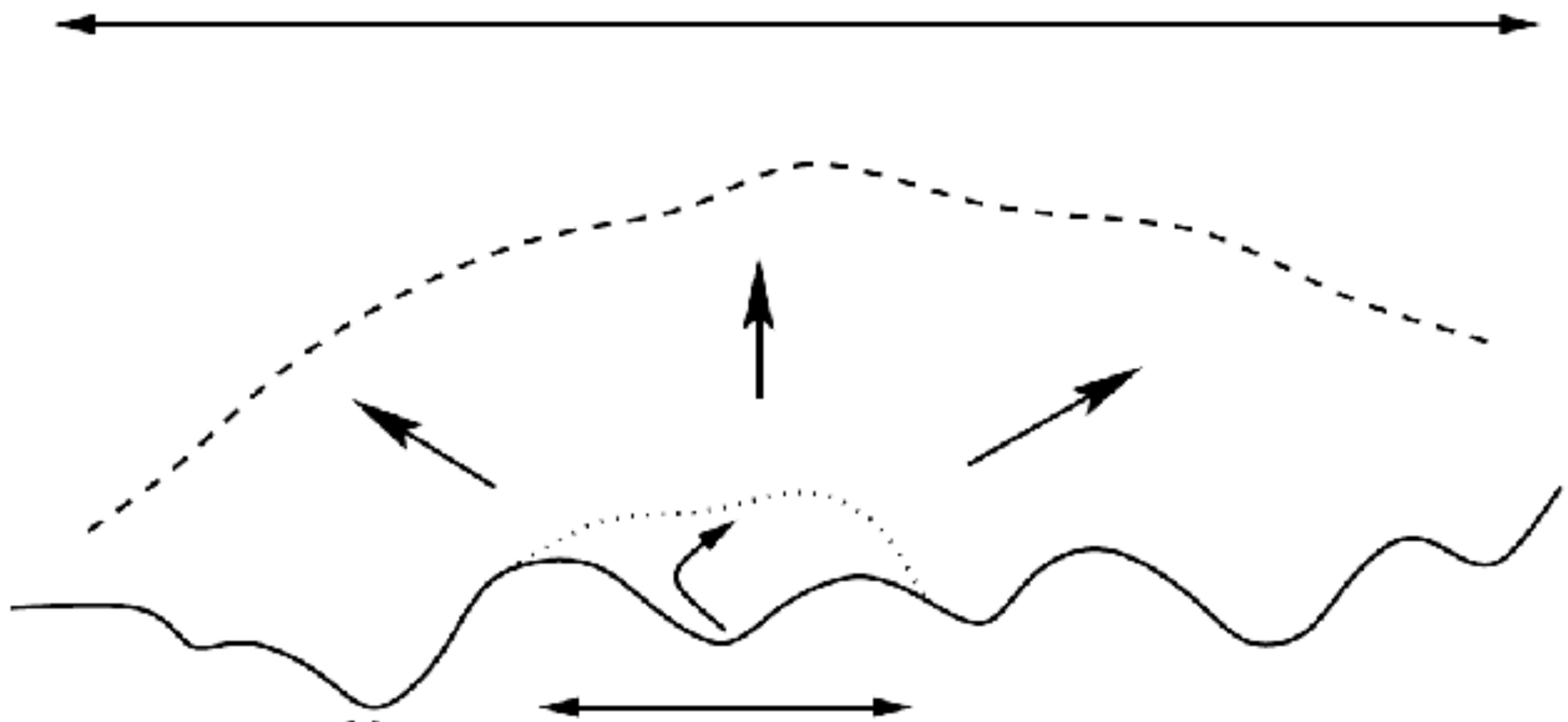
At equilibrium, in $d = 1$

$\ell_{\text{opt}}(f) \sim f^{-3/4}$ and $E_p(f) \sim f^{-1/4}$

FRG approach (P. Chauve, T. Giamarchi and P. Le Doussal)

- Confirm creep formula
- Predict depinning-like motion up to ℓ_{av}
- the latter has no impact on the creep formula

$$\ell_{\mathrm{av}}(f,T) \sim T^{-\sigma} f^{-\lambda}$$

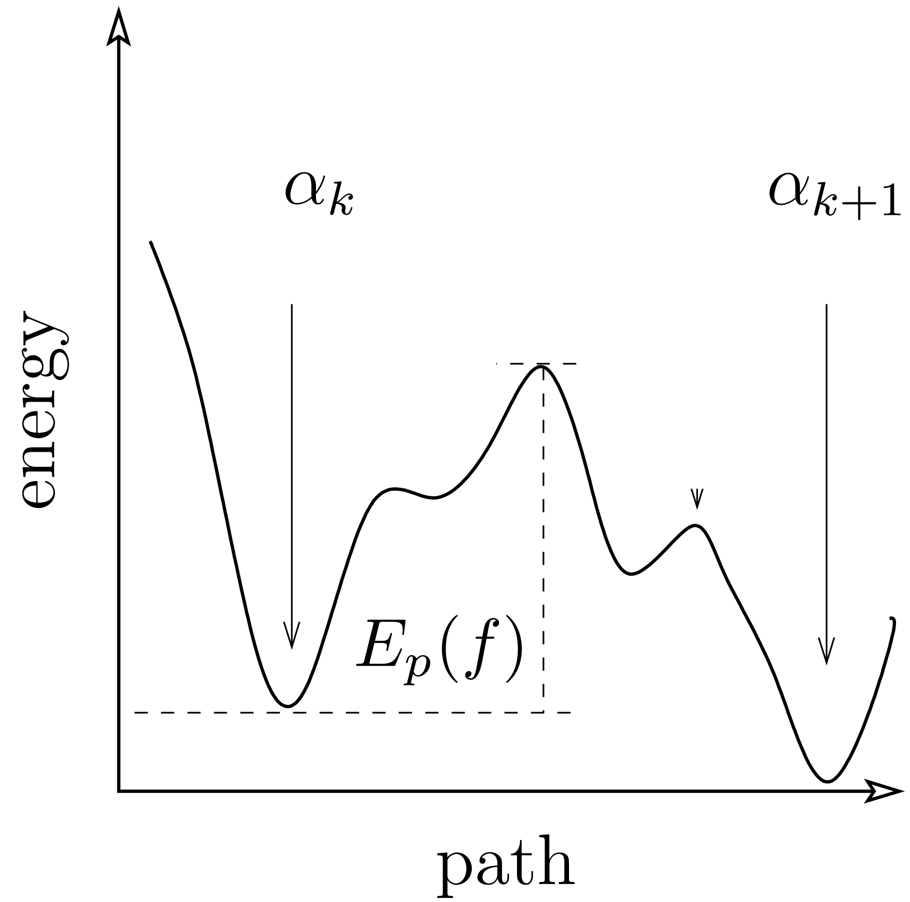


$$\ell_{\mathrm{opt}}(f) \sim f^{-\mu_{\mathrm{eq}}}$$

Algorithms to unveil creep

Molecular dynamics
huge problems of futility

Coarse grained dynamics
sequence of metastable states
$\alpha_1 \to \alpha_2 \to \ldots \to \alpha_t$

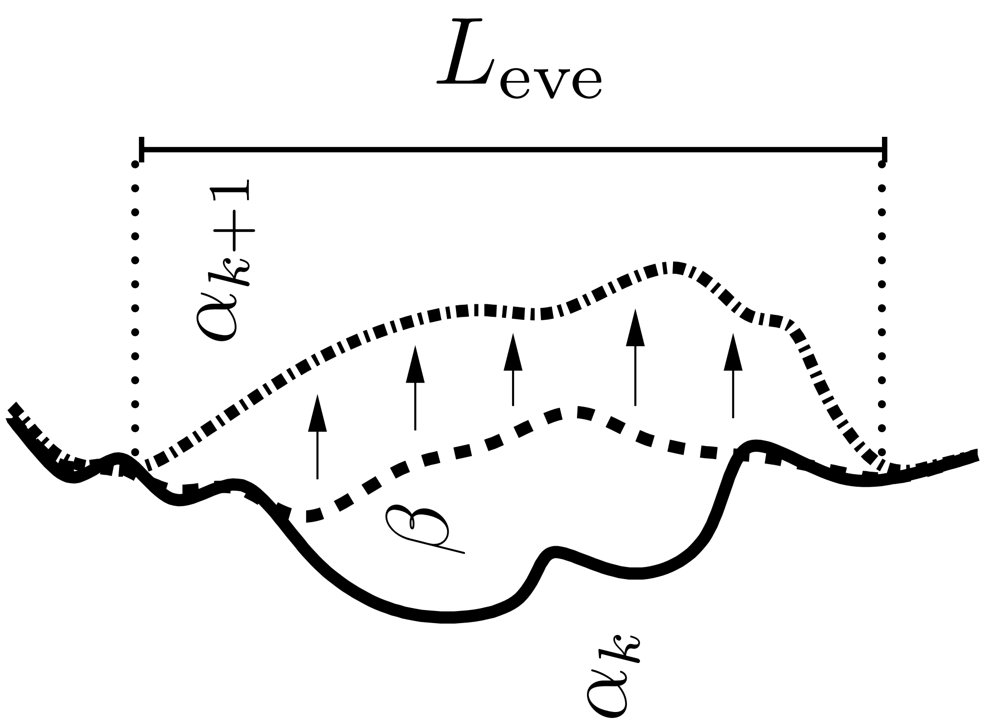


Decreasing energy:

$$E(\alpha_1) > E(\alpha_2) > \ldots$$

Exact algorithms for the sequence of metastable states (T=0+)

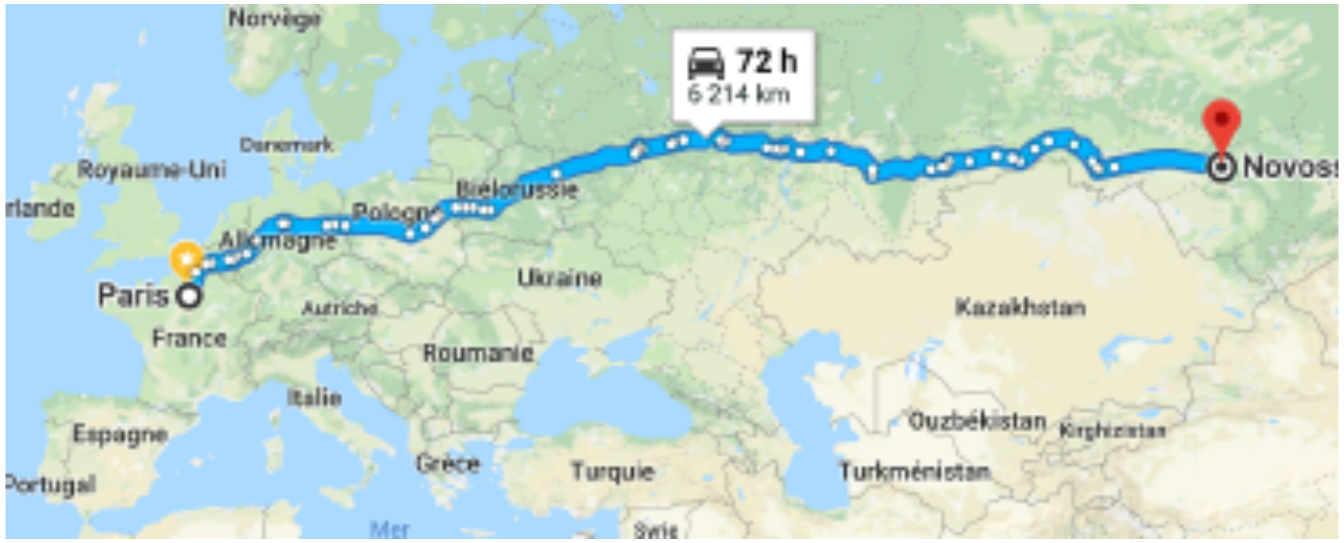
Minimal rearrangement



Performance: f up to $0.002 f_c$

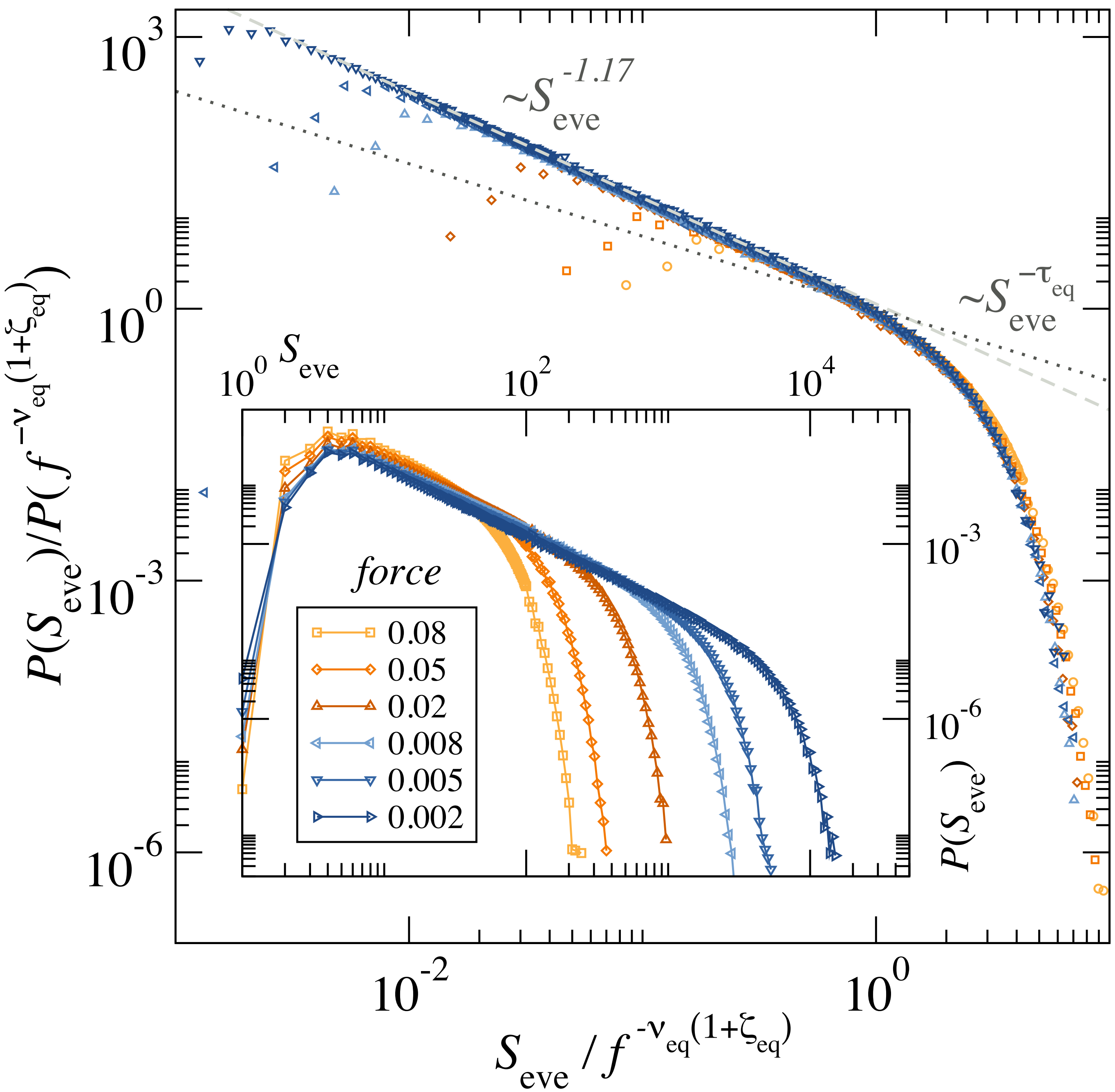
$L \approx 4000$

Polynomial cost (Dijkstra algorithm)



by Ferrero, Foini, Kolton, Giamarchi, Rosso

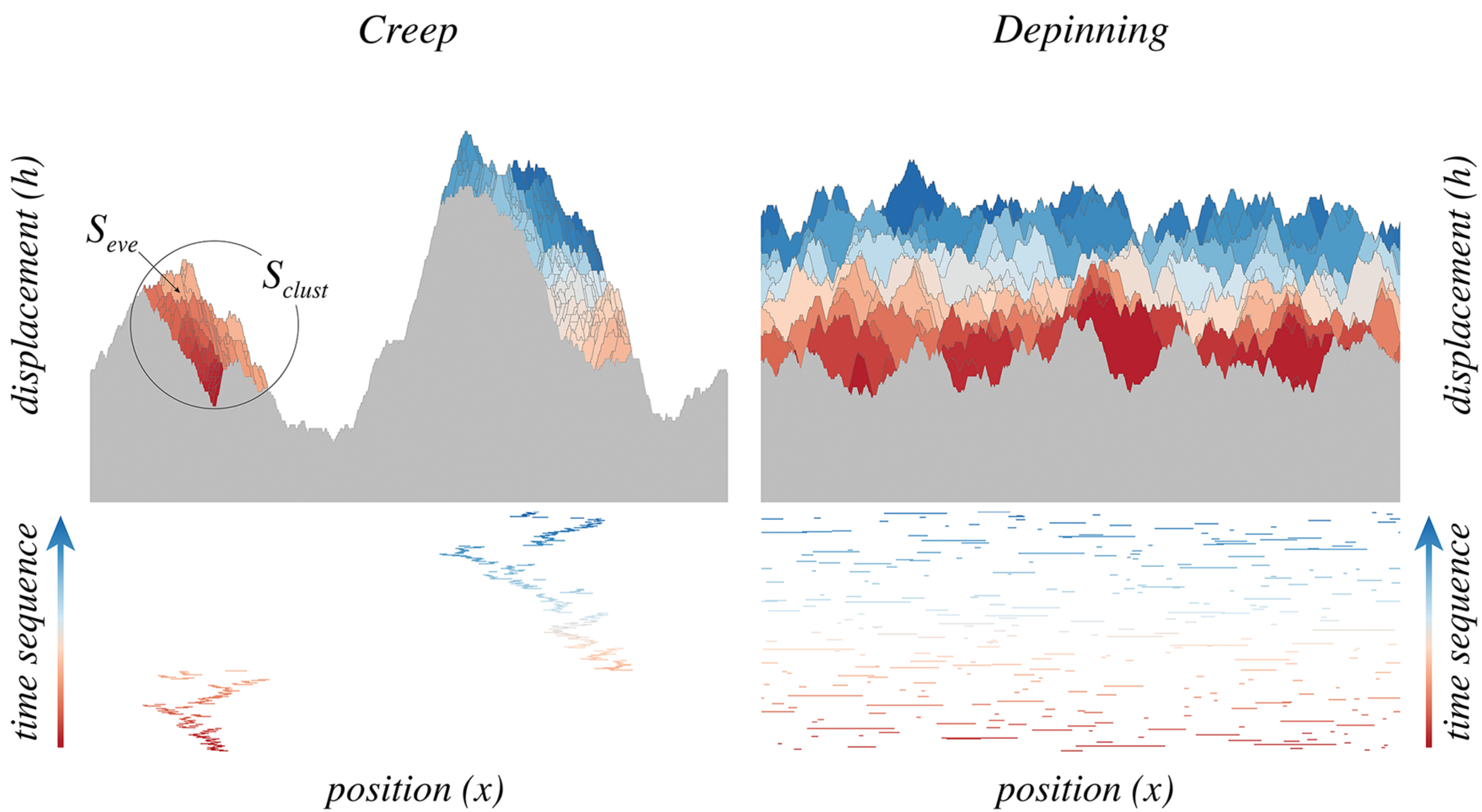
Creep : events statistics



- Scale free when $f \to 0$
- Collapse of $S_{\max} \sim L_{\text{opt}}^{1+\zeta_{\text{eq}}}$
- Anomalous $\tau > \tau_{\text{eq}}$

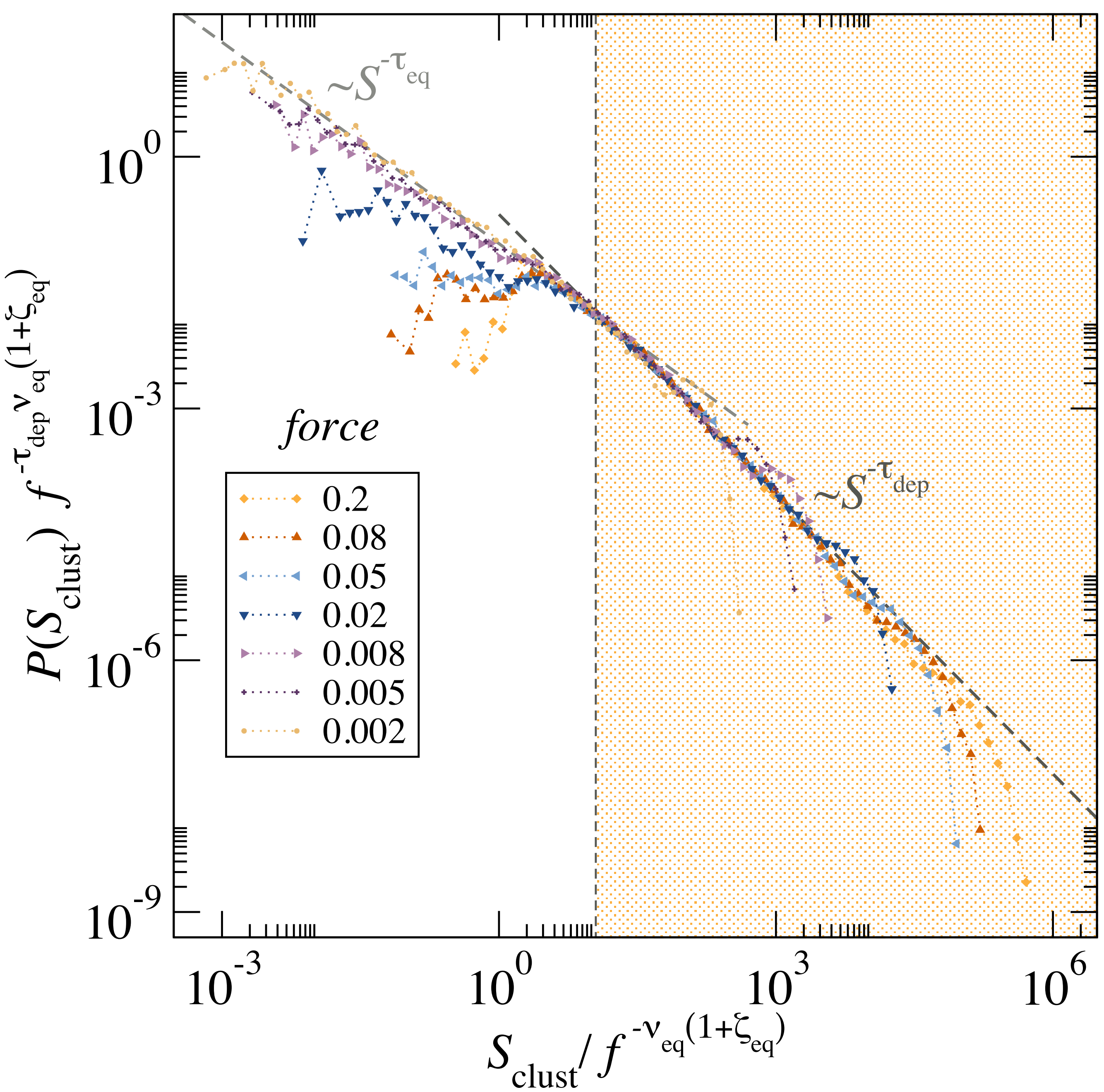
- creep law is saved
- Gutenberg Richter anomaly

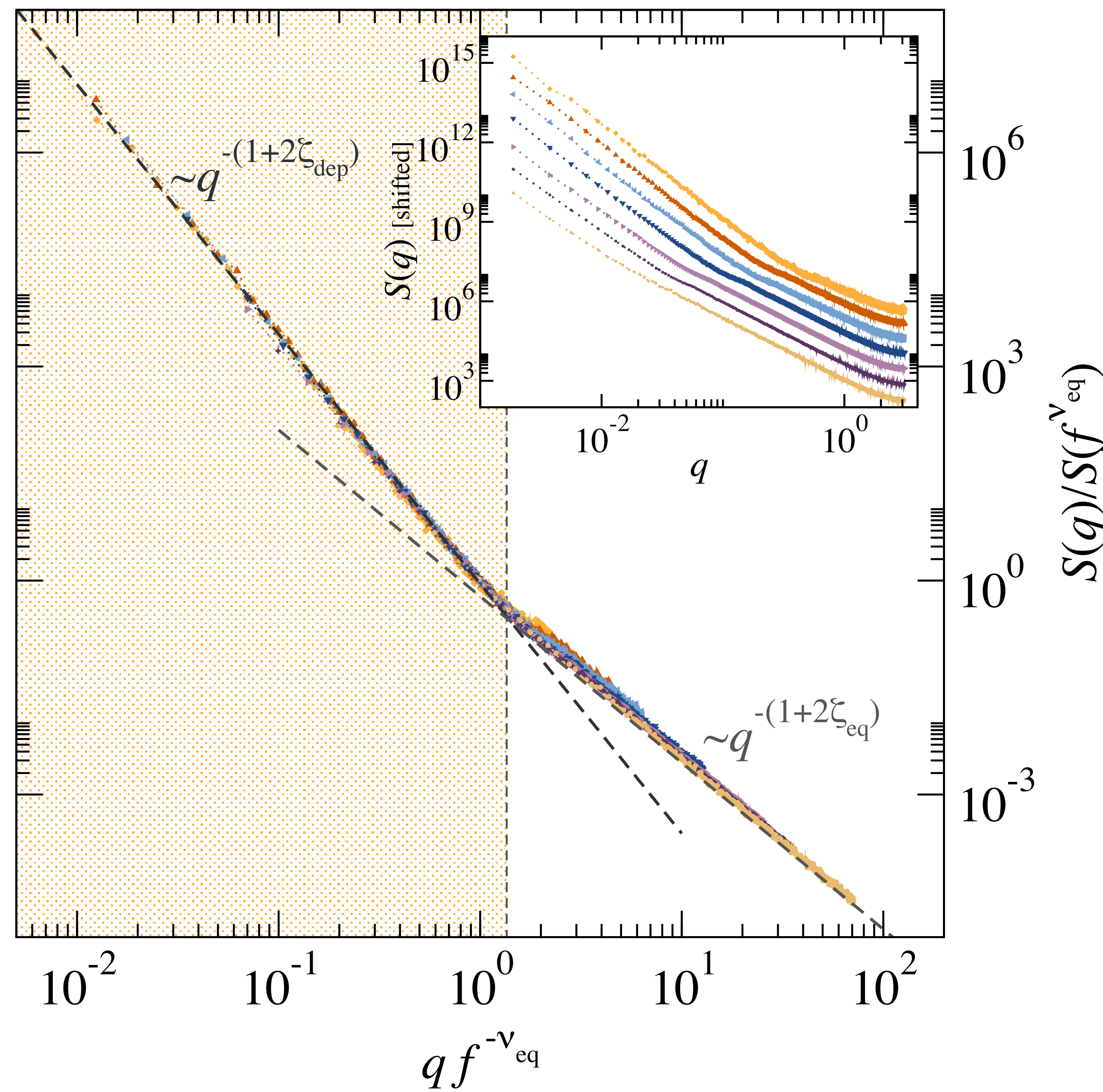
Creep versus Depinning



Clear Spatio-Temporal patterns among events

Depinning-like behaviour above Lopt

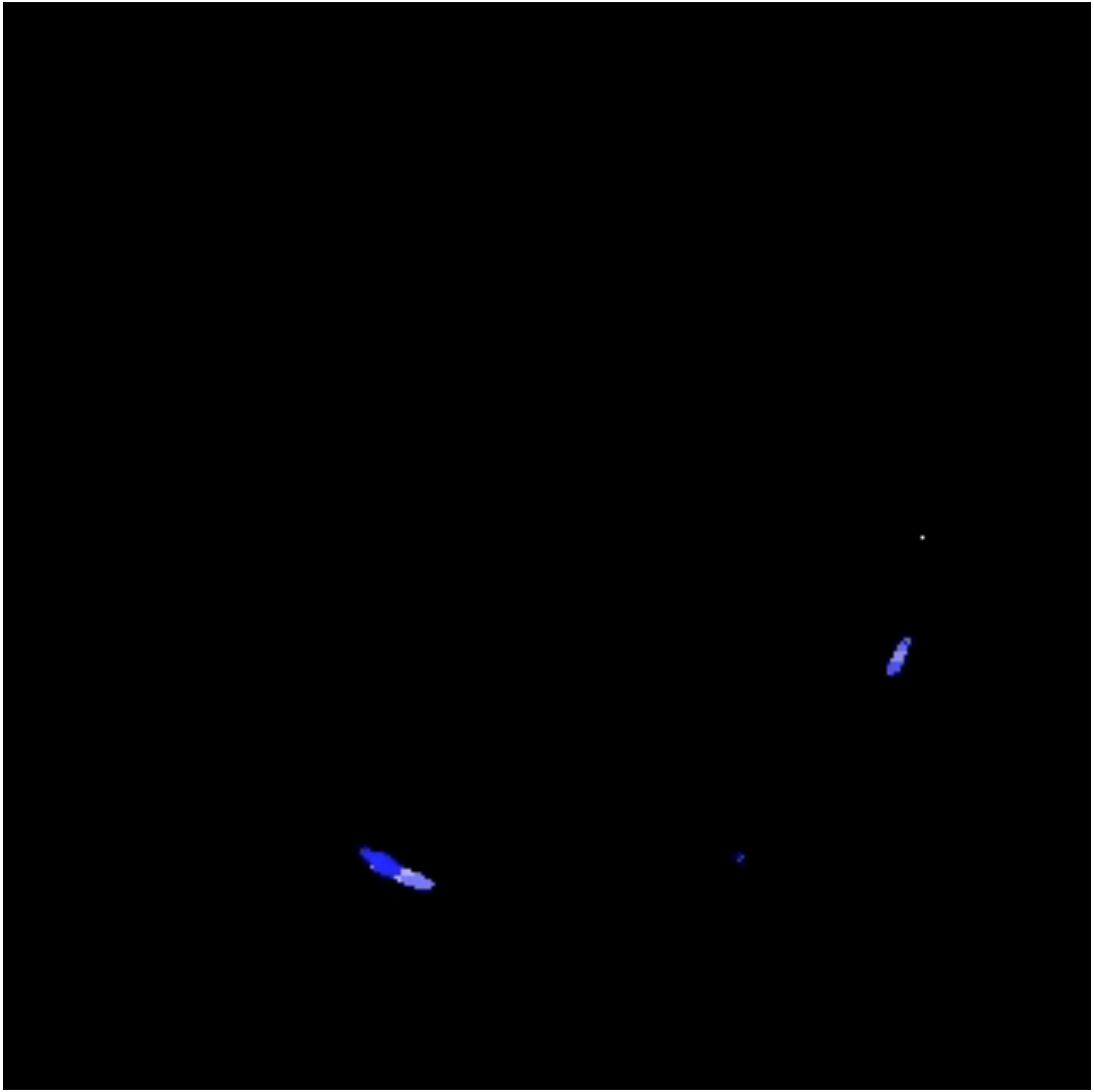




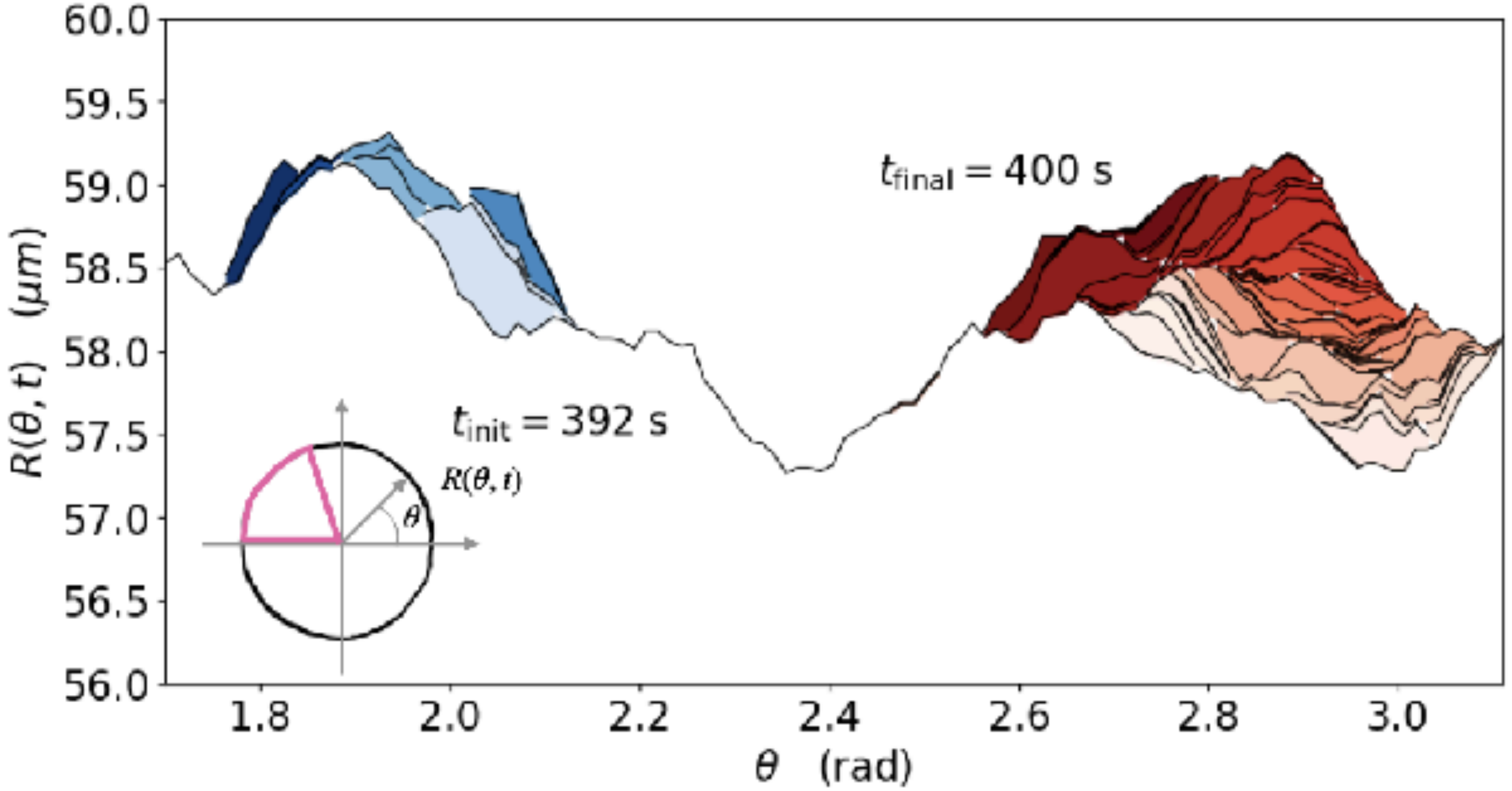
Clusters like depinning avalanches

Roughness
Short distance: Equilibrium
Long distance: Depinning

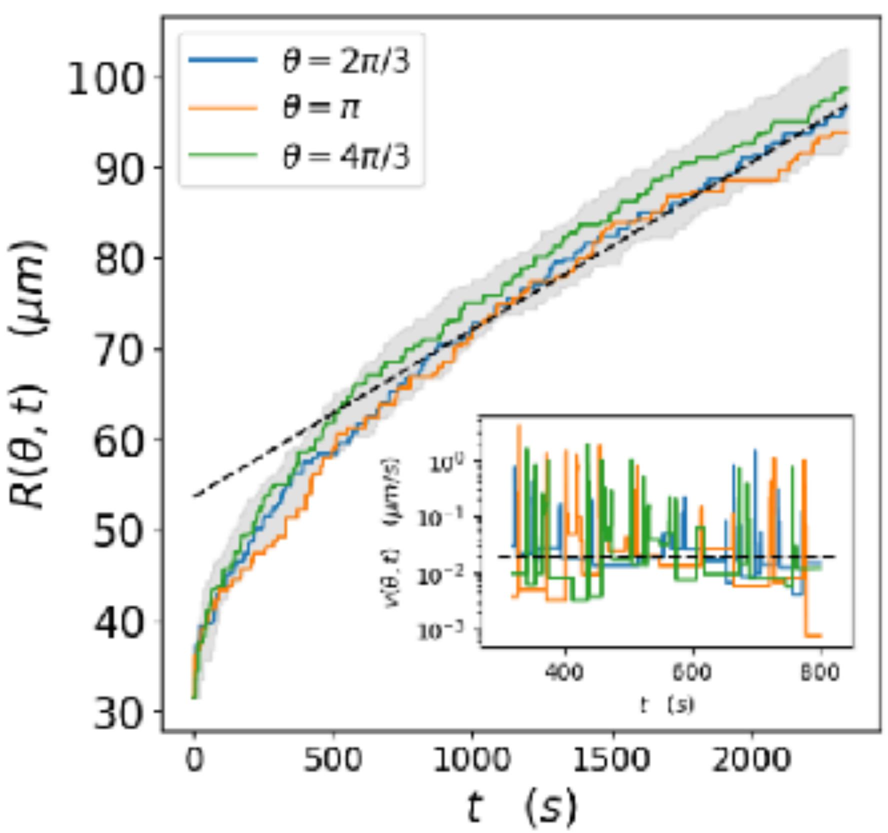
Gianfranco Durin experiment



Clustering and intermittency

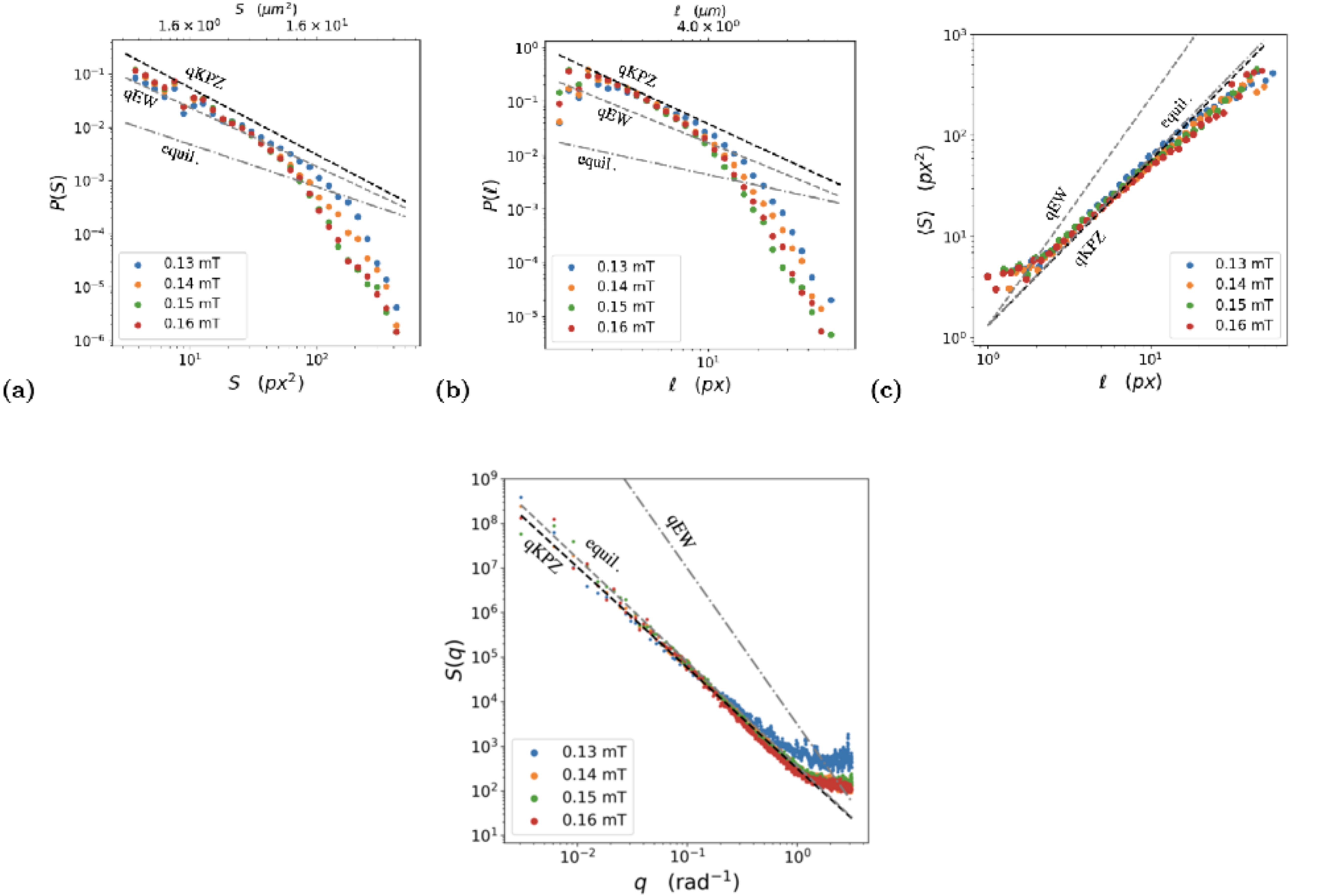


(a)

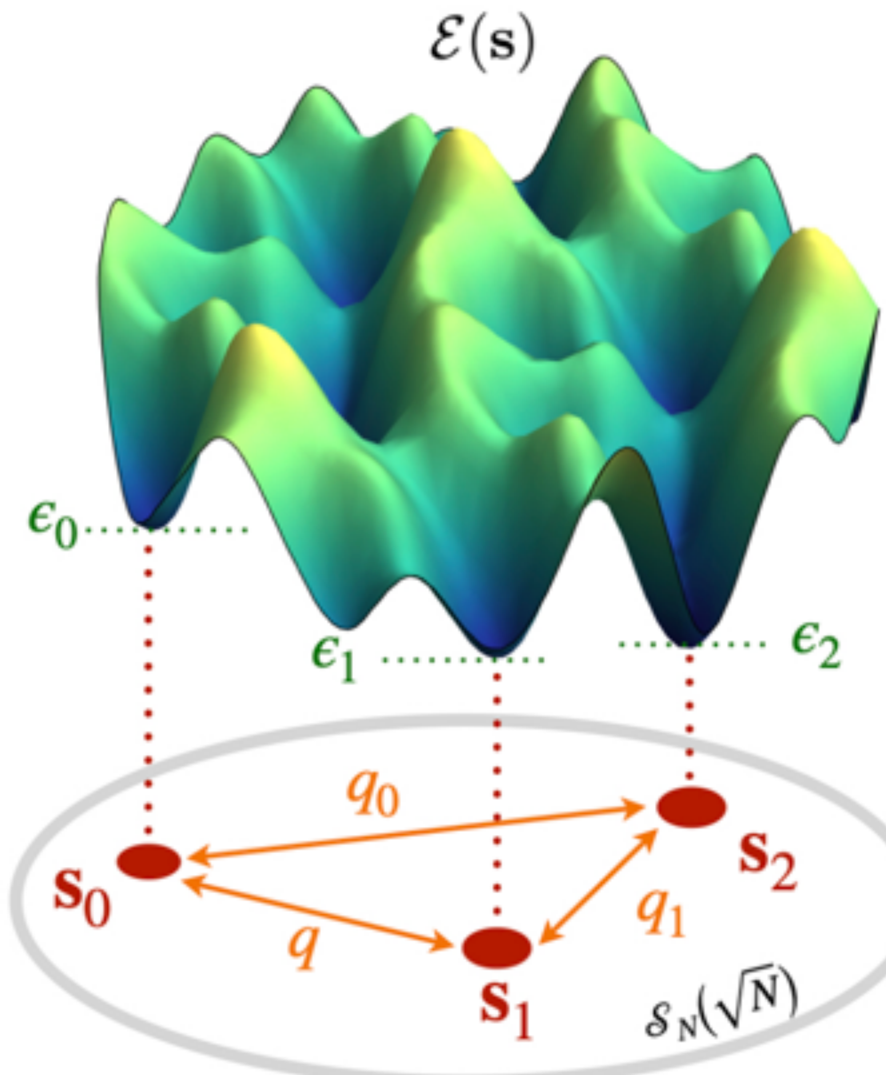


(b)

QKPZ (depinning) universality class



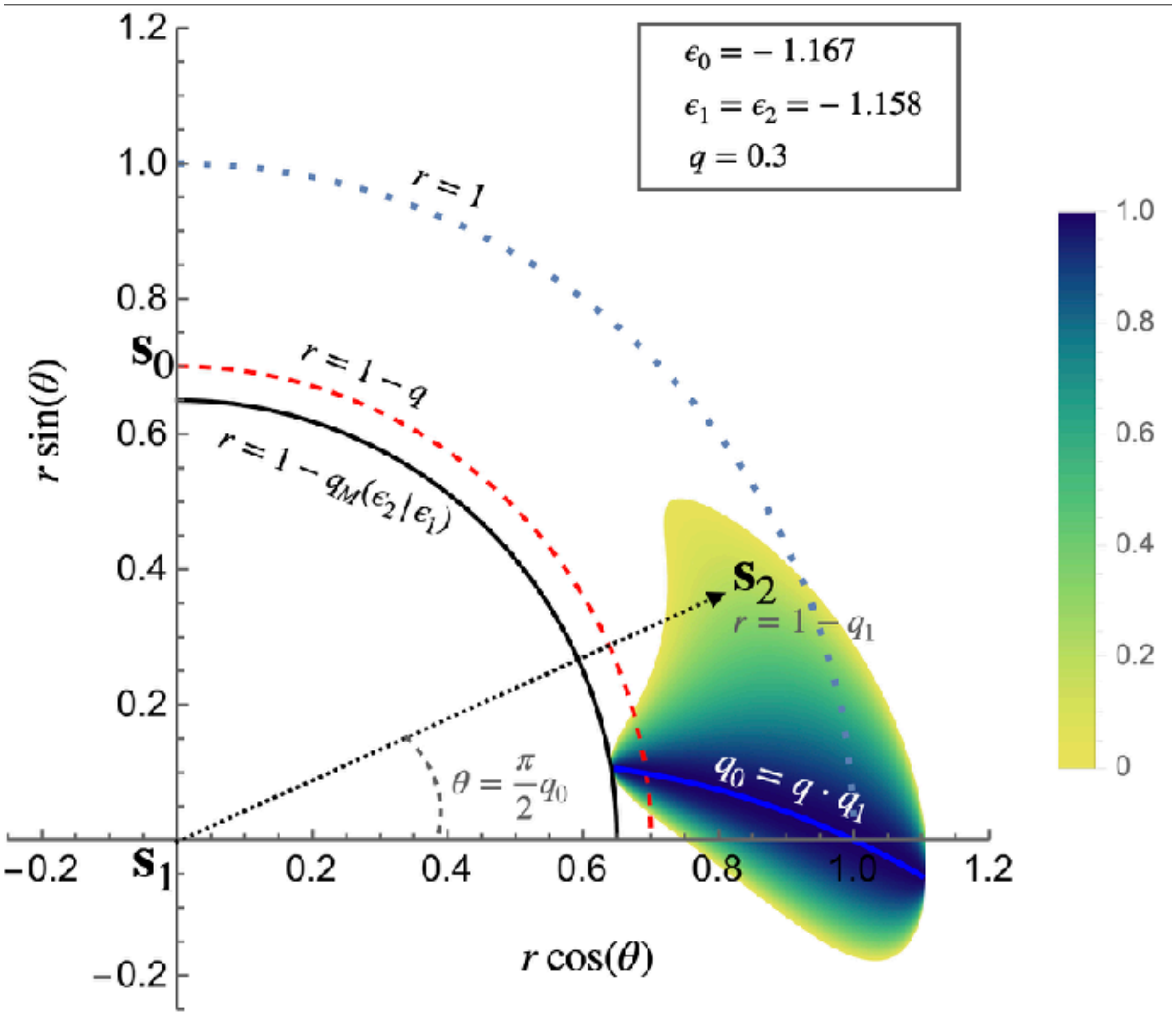
Landscape study of the p-spin model



$\mathbf{s} = (s_1, s_2, \ldots, s_N)$ point on the surface of an hypersphere of radius $\sqrt{N}$

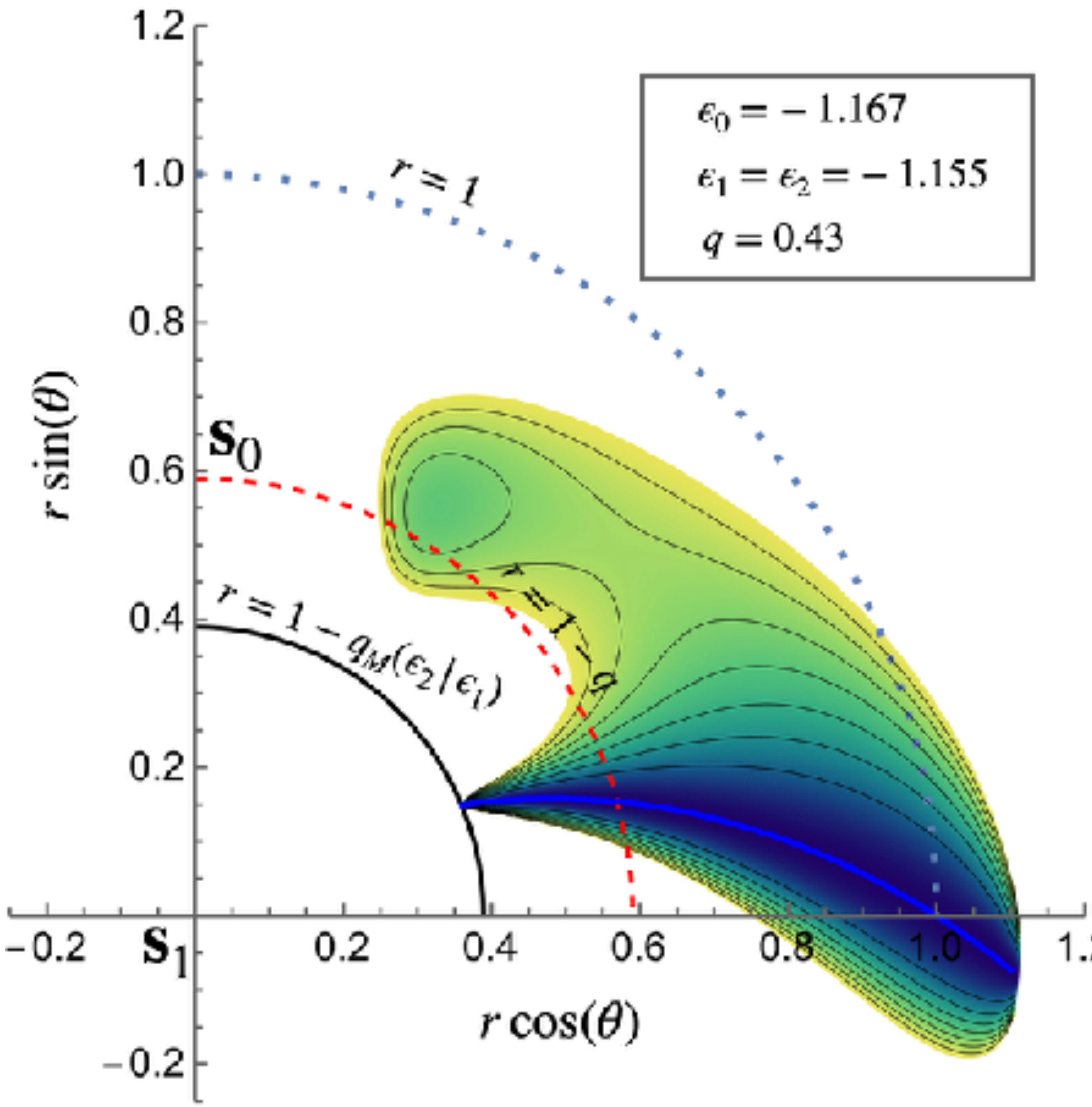
$$\epsilon(\mathbf{s}) = \frac{\sqrt{3}}{N^2} \sum_{i_1 < i_2 < i_3} a_{i_1 i_2 i_2} \cdot s_{i_1} s_{i_3} s_{i_3}$$

Jumping on deep minima

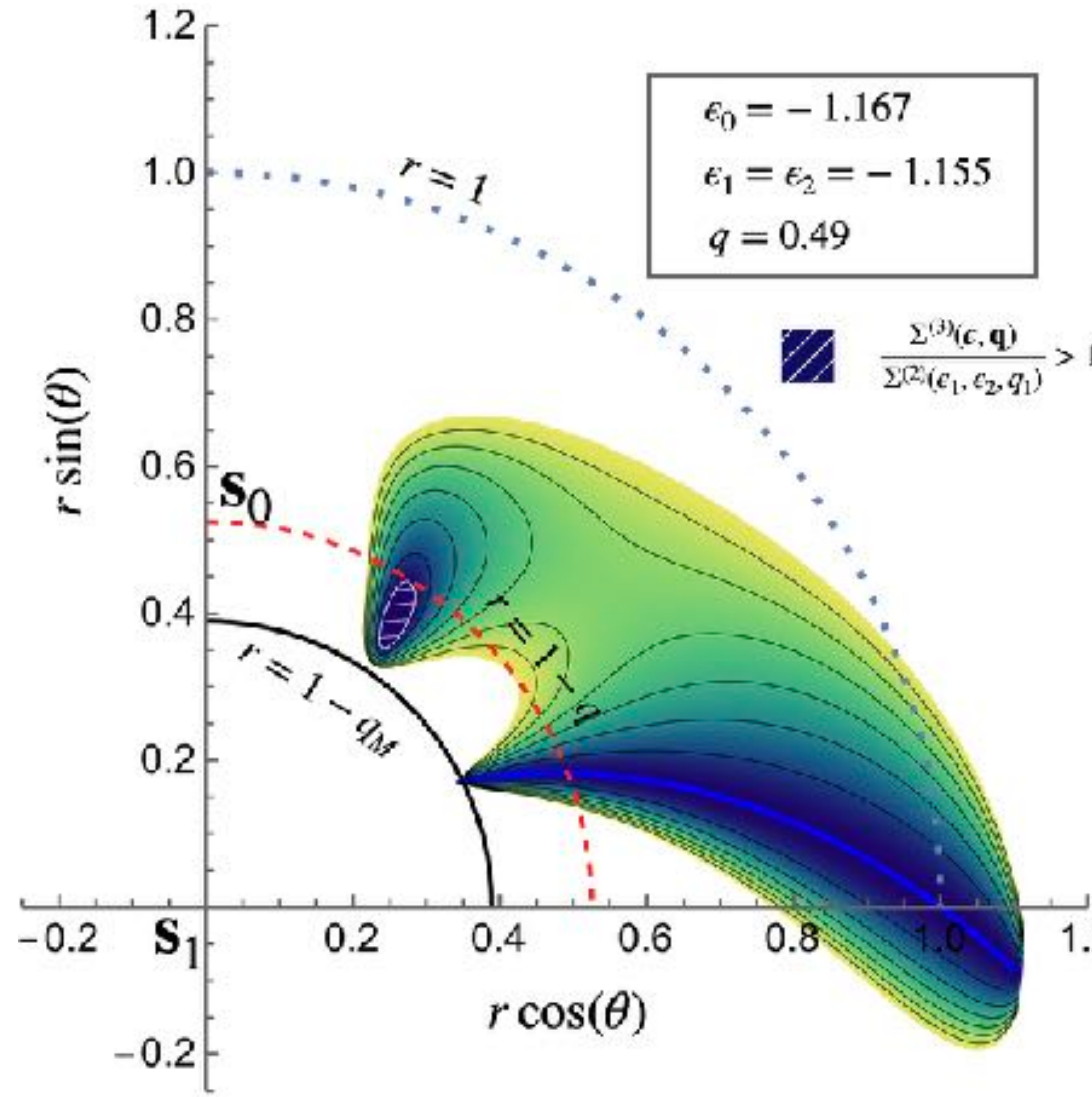


Jumping on shallow minima

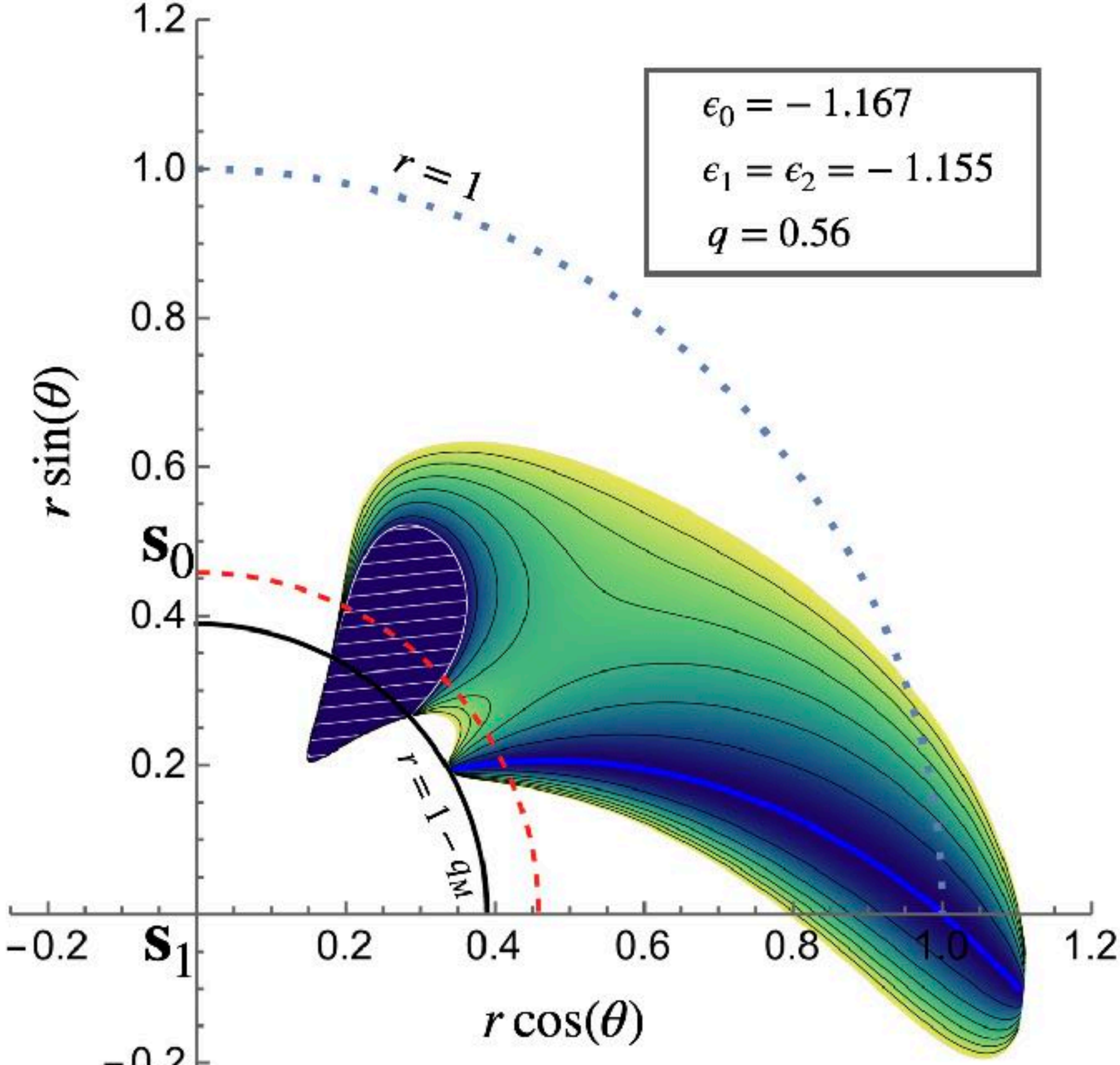
non monotonic regime



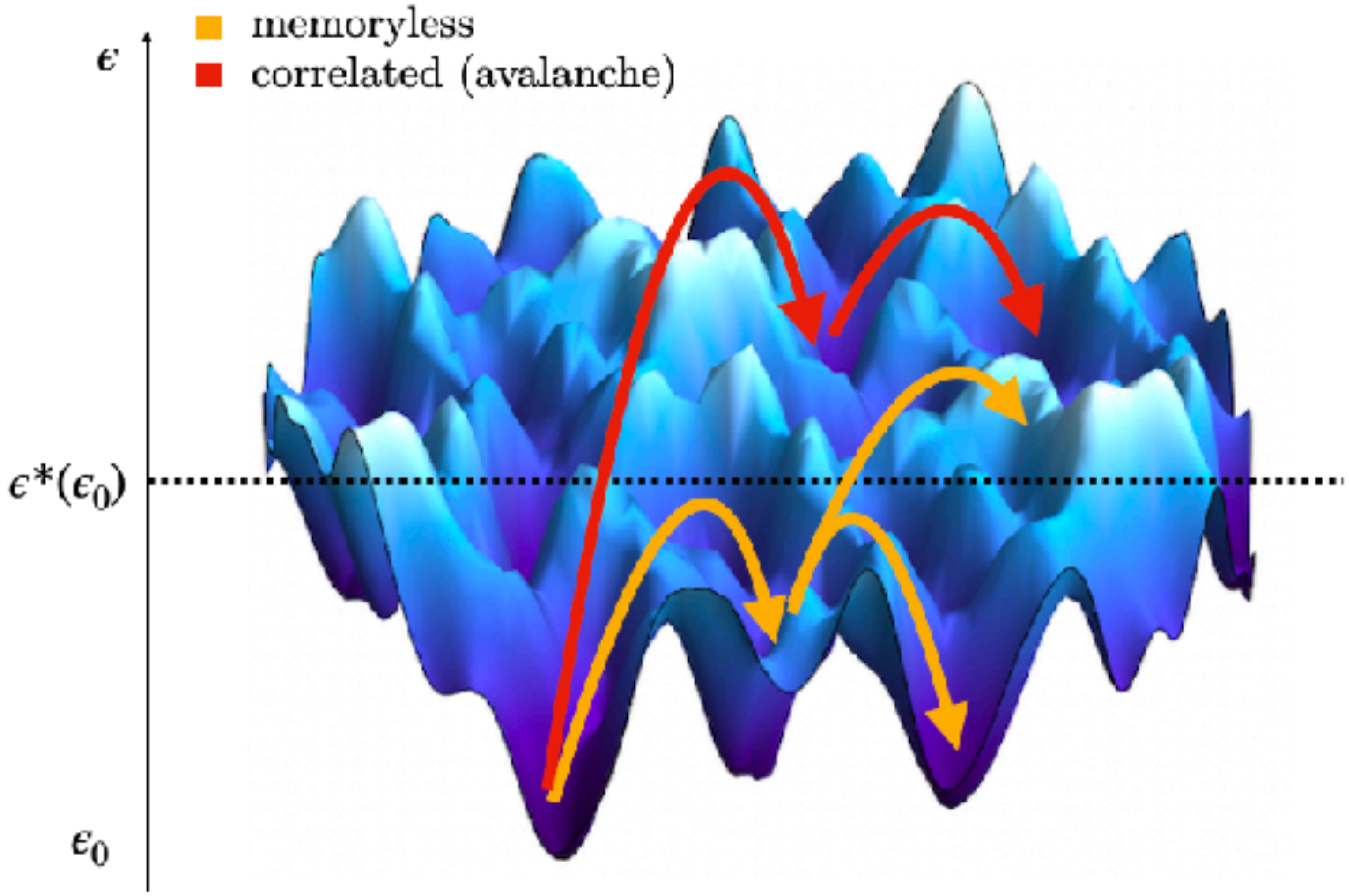
local accumulation regime



clustering of shallow minima



Two scenarios



Conclusions

- *Activation of slow events trigger thermal avalanches*

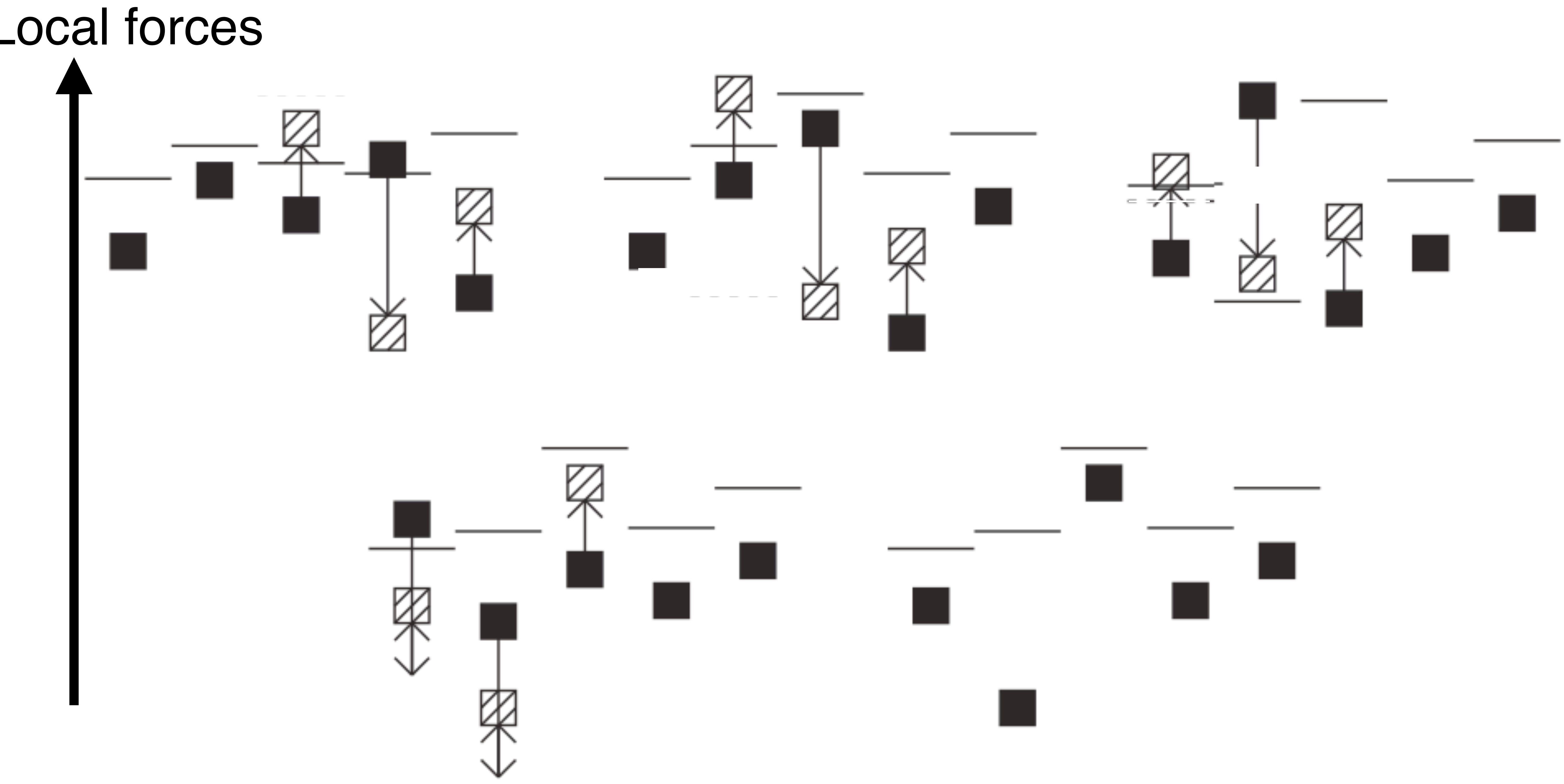
- *Experimental verification in QKPZ class*

- *p-spin landscape: clustering only for shallow minima*

Perspectives

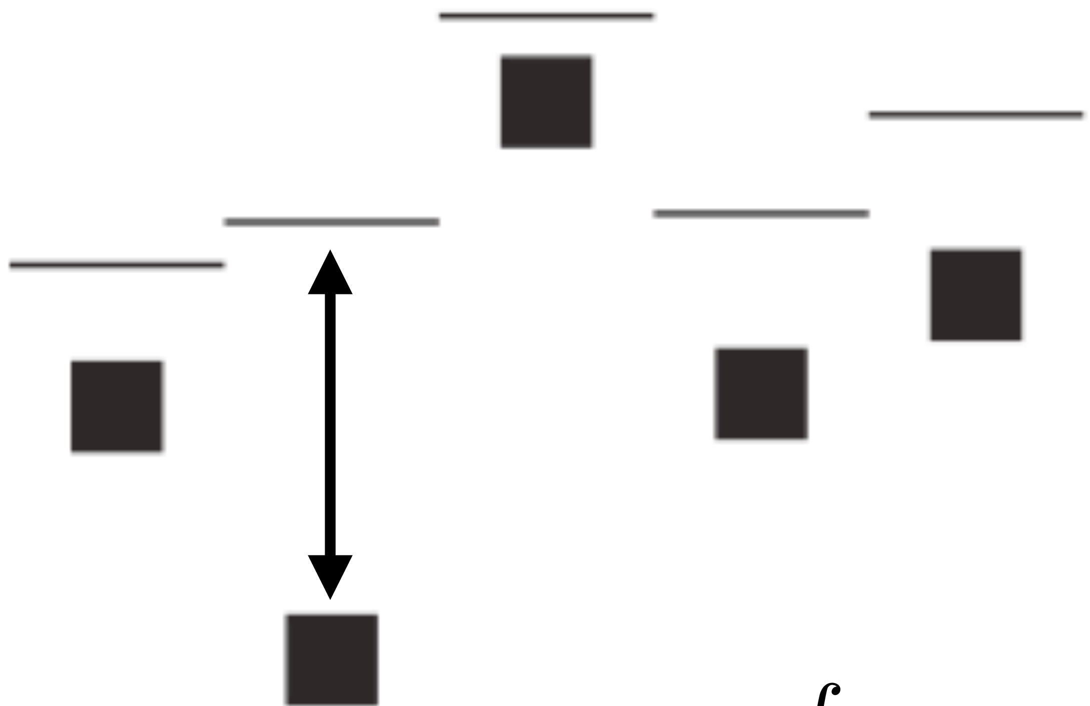
- *Beyond T=0+, finite temperature introduce a correlation length*

Depinning cellular automaton



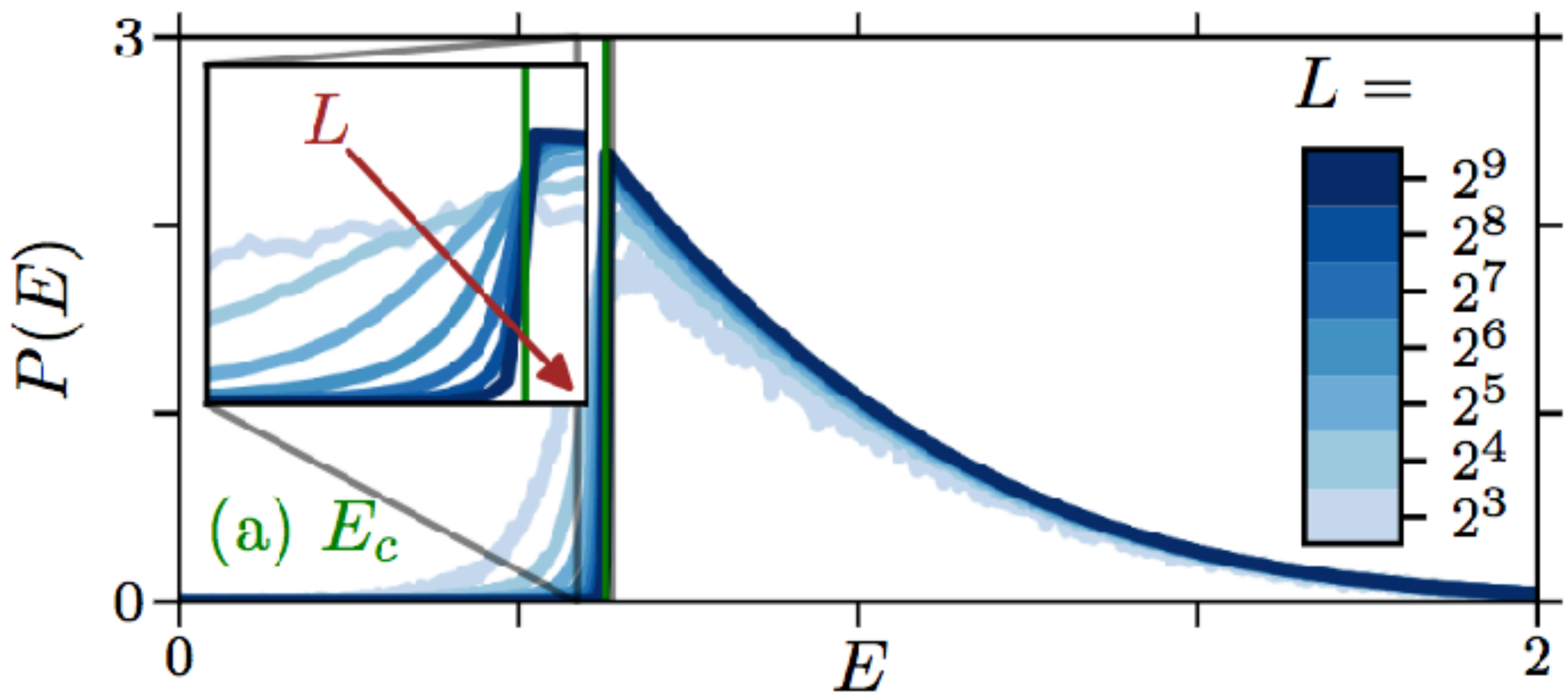
$$f = \overline{f_i}$$

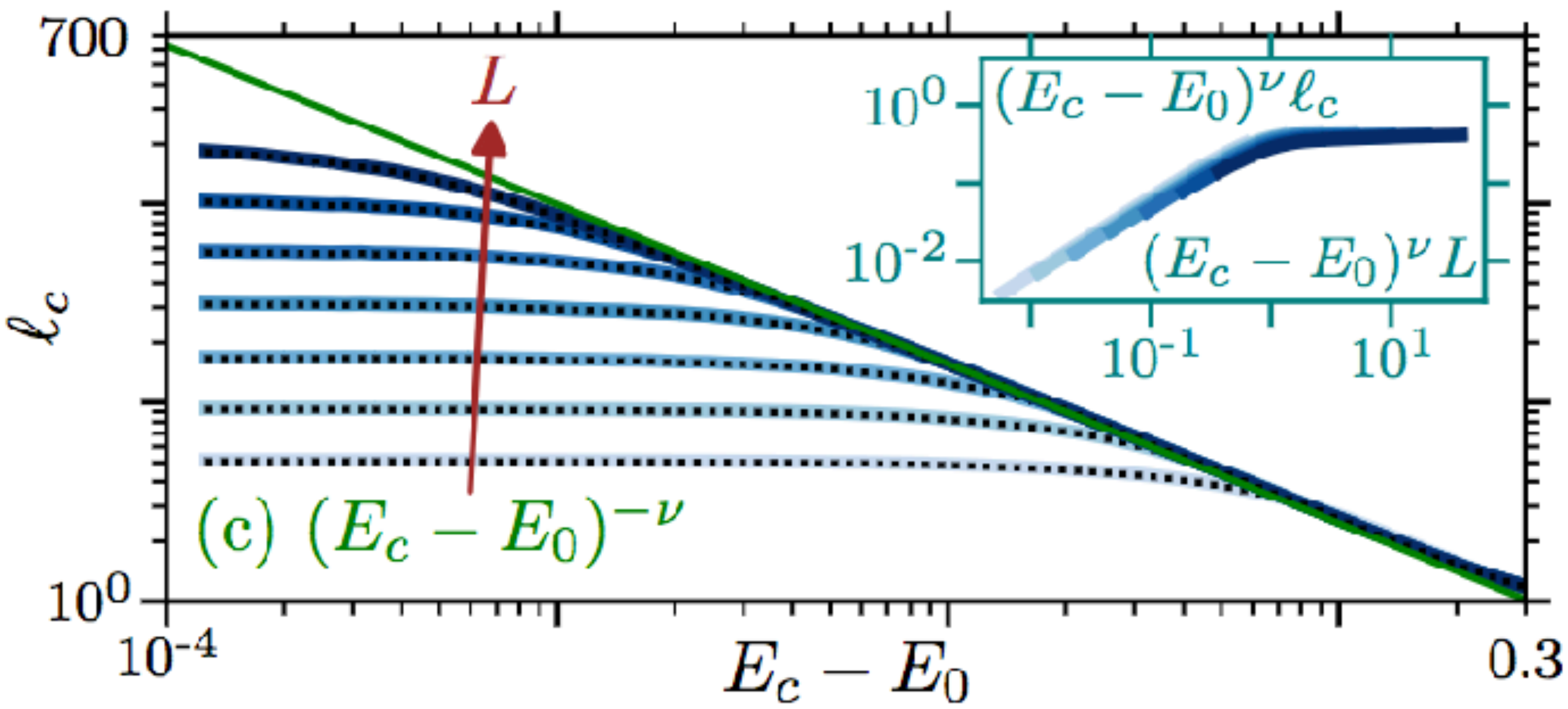
Stylised model, coarse grained at lopt



$$\tau_i \sim \exp(E_i/T)$$

$$f = \frac{f_c}{2}, T = 0^+$$





$$\ell_c(E_0) \sim (E_c - E_0)^{-\nu}$$

$$\Delta E_c(L) \sim L^{-1/\nu}$$

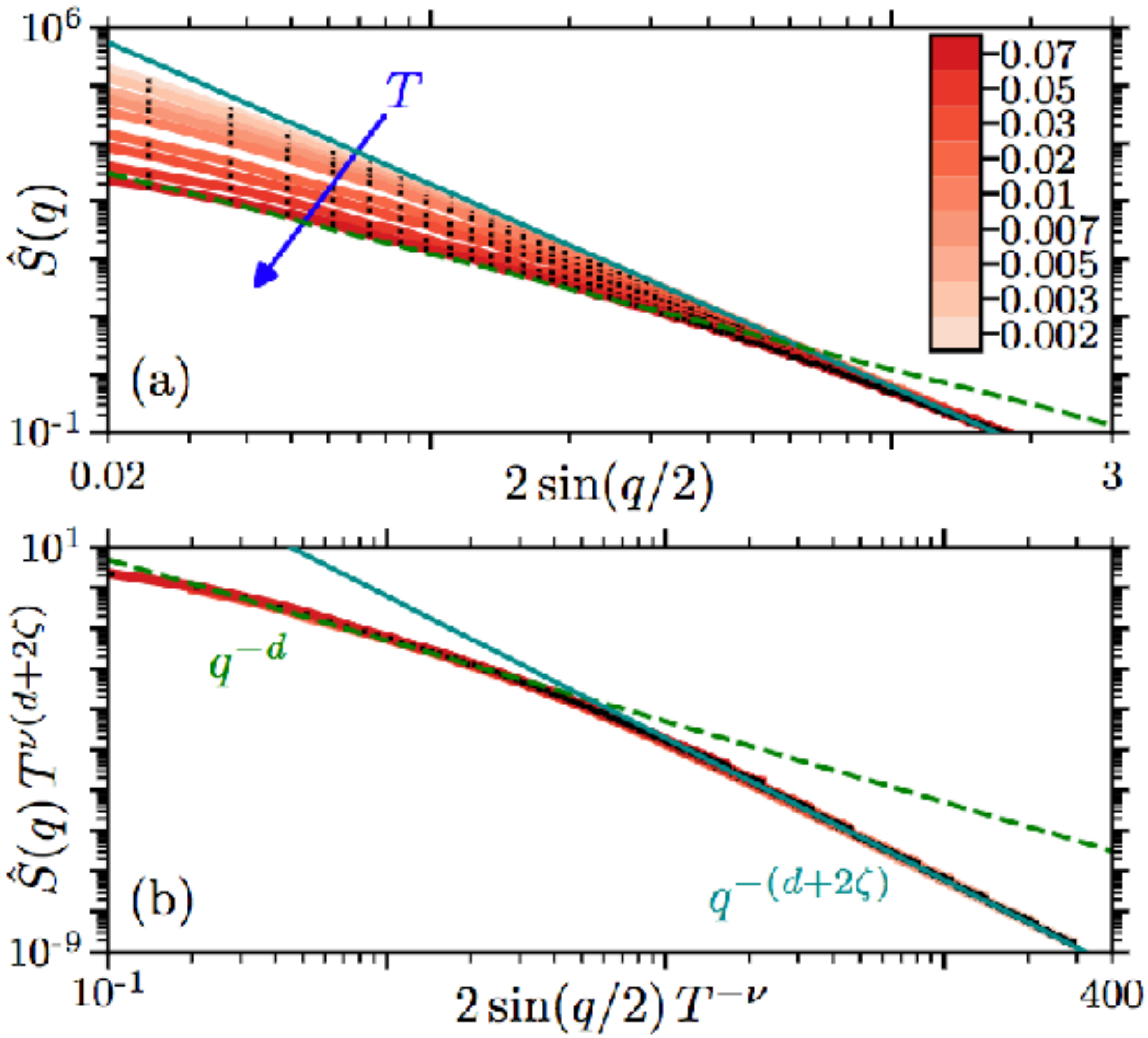
For $T \ll \Delta E_c(L)$ system heterogeneous

For $T \gg \Delta E_c(L)$ system homogeneous

$$\ell_c(T) \sim T^{-\nu}$$

$\sigma_{FRG} = \nu/\beta \simeq 1.23$ $\sigma_{CA} = \nu \simeq 0.8$

Stylised model at finite temperature



Ongoing project : G. Russo