Exploring Thermal Avalanches in the Creep Regime

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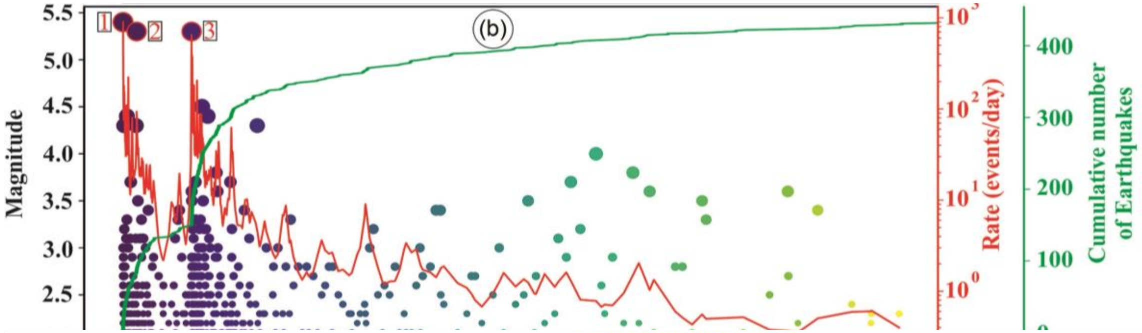
Part 1: Introduction

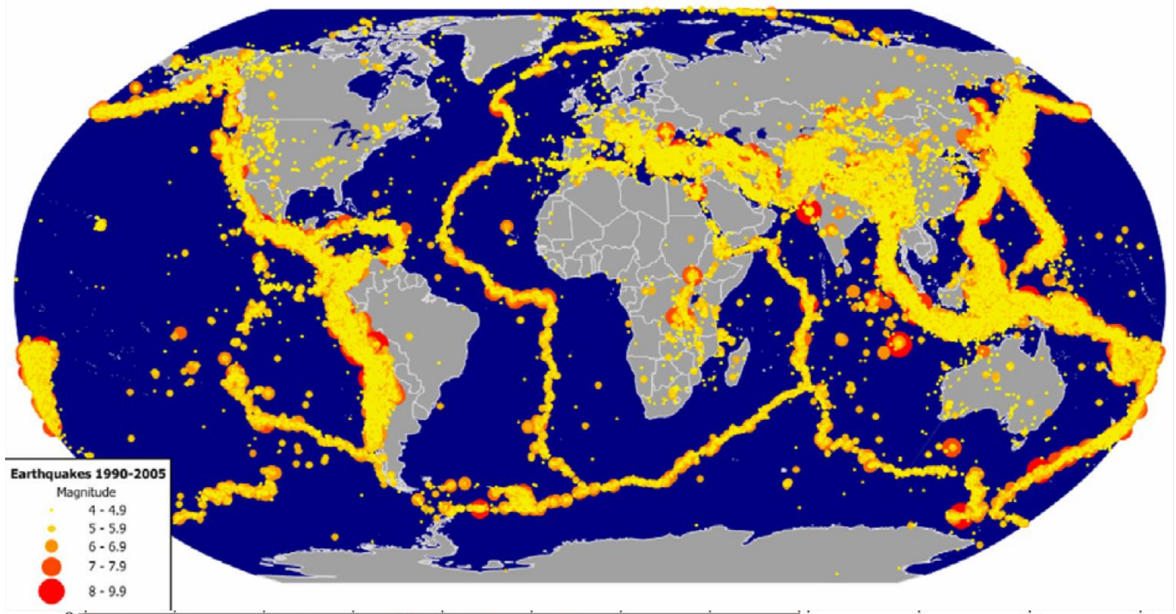
- Earthquakes in general and their phenomenology
- Model: driven elastic interface in a disordered medium
- Depinning and Creep

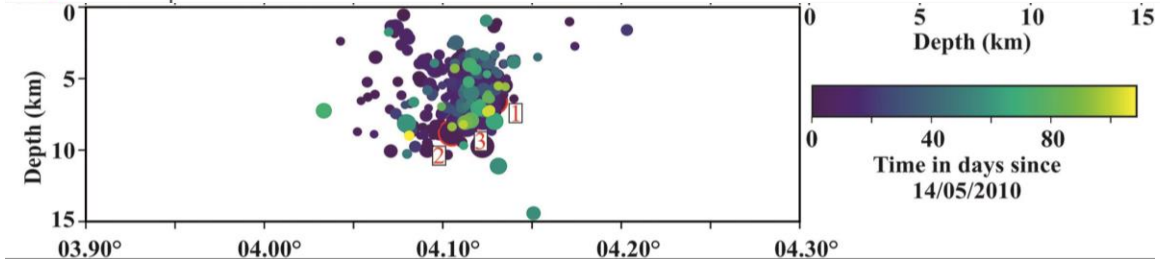
Motivation

- Causes of earthquakes?
  - Stick – Slip
- Global localization
  - Interface between tectonic plates
- Local observations
  - Mainshocks and aftershocks
  - Aftershocks seem to be correlated with mainshock in space and time
  - Stake: aftershock forecasting
- Phenomenological laws?

Rahmani, S., et al. "Time-dependent and spatio-temporal statistical analysis of seismicity: application on the complete data set of the 2010 Beni–Ilmane earthquake sequence," in *Geophysical Journal International*, vol. 236, no. 3, pp. 1246-1261, 2023.

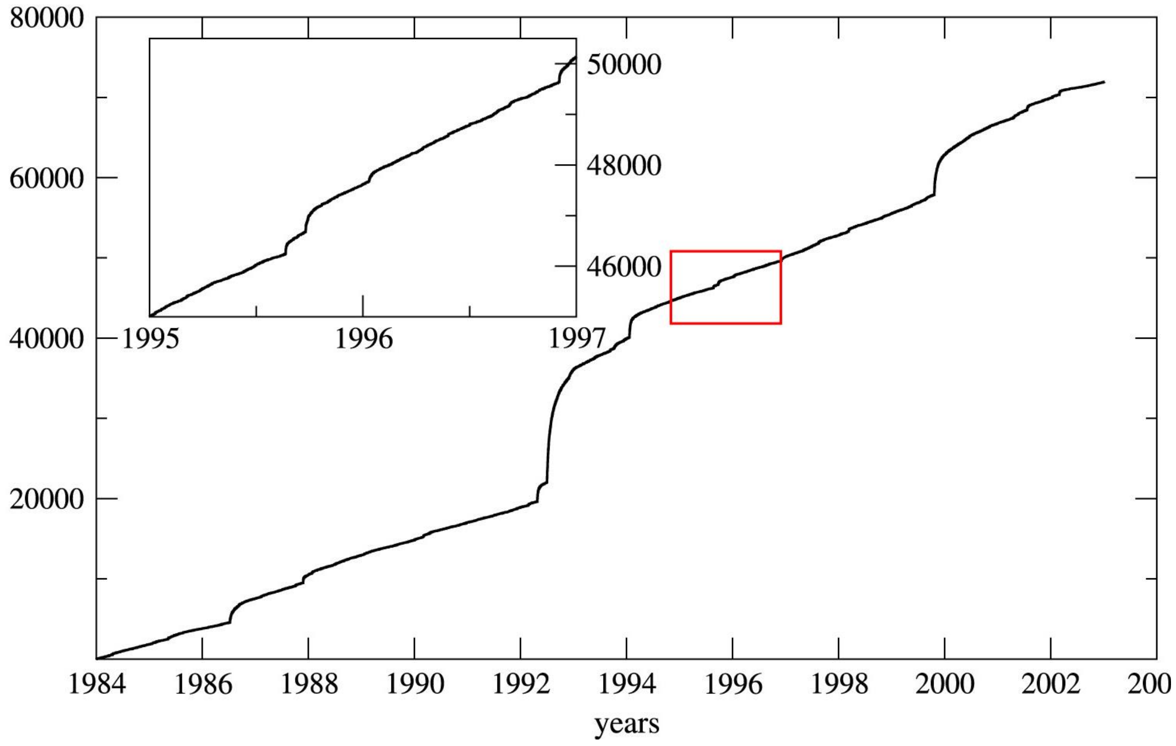




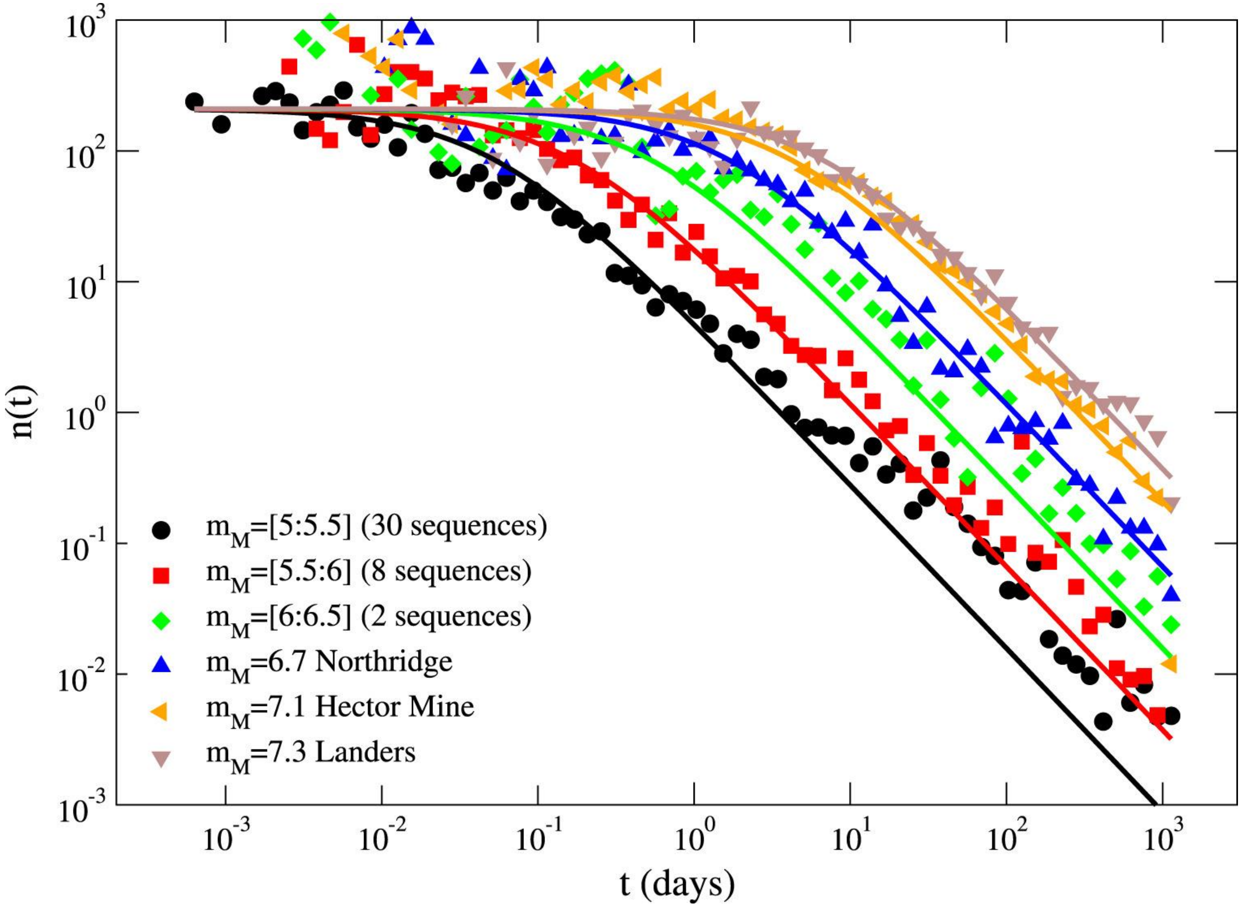


Omori-Utsu law

Decay rate $n(t) = \frac{k}{(c+t)^p}, \ p \approx 1$



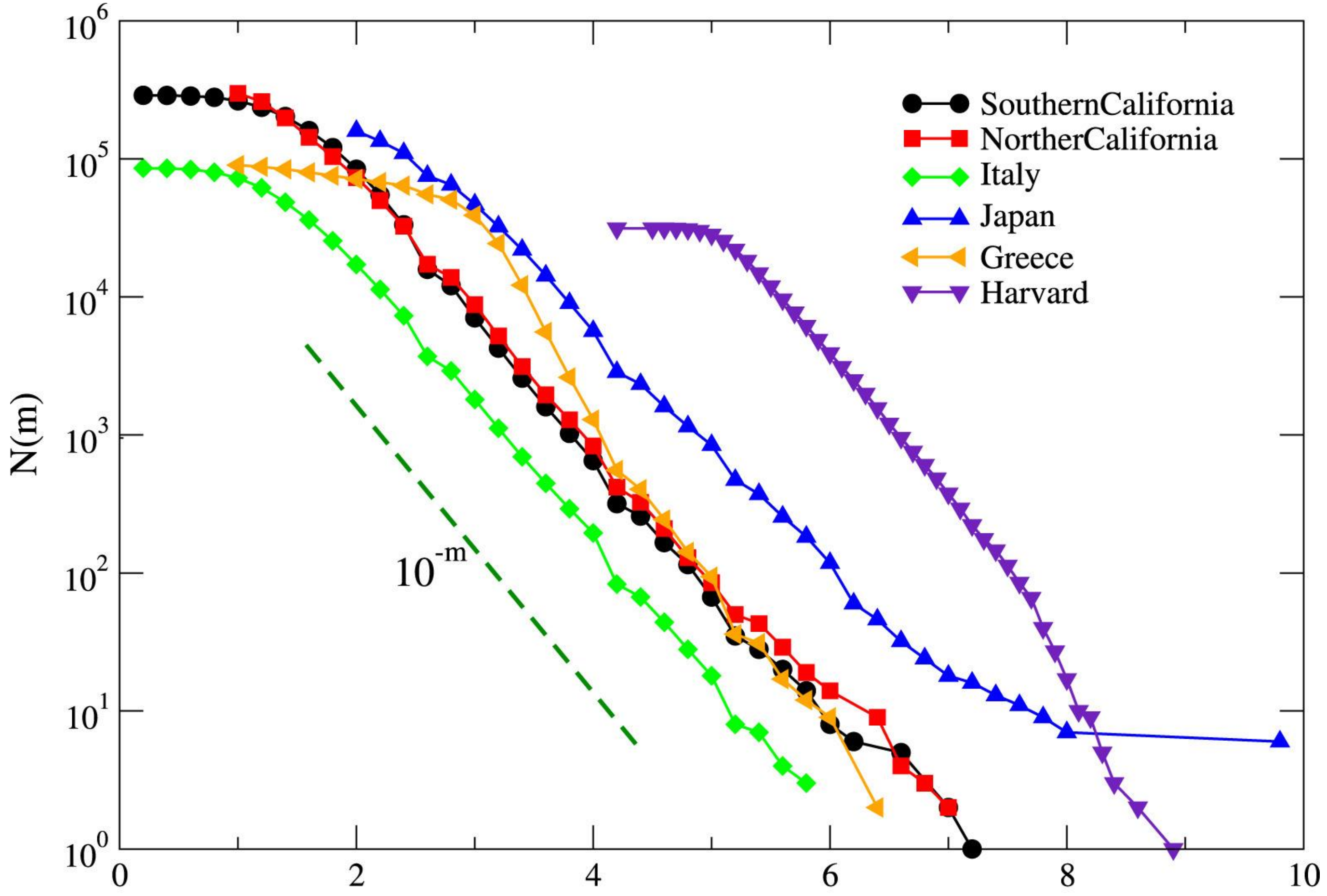
Lucilla de Arcangelis, et al. "Statistical physics approach to earthquake occurrence and forecasting," in *Physics Reports*, vol. 628, pp. 1-91, 2016.



Gutenberg-Richter law

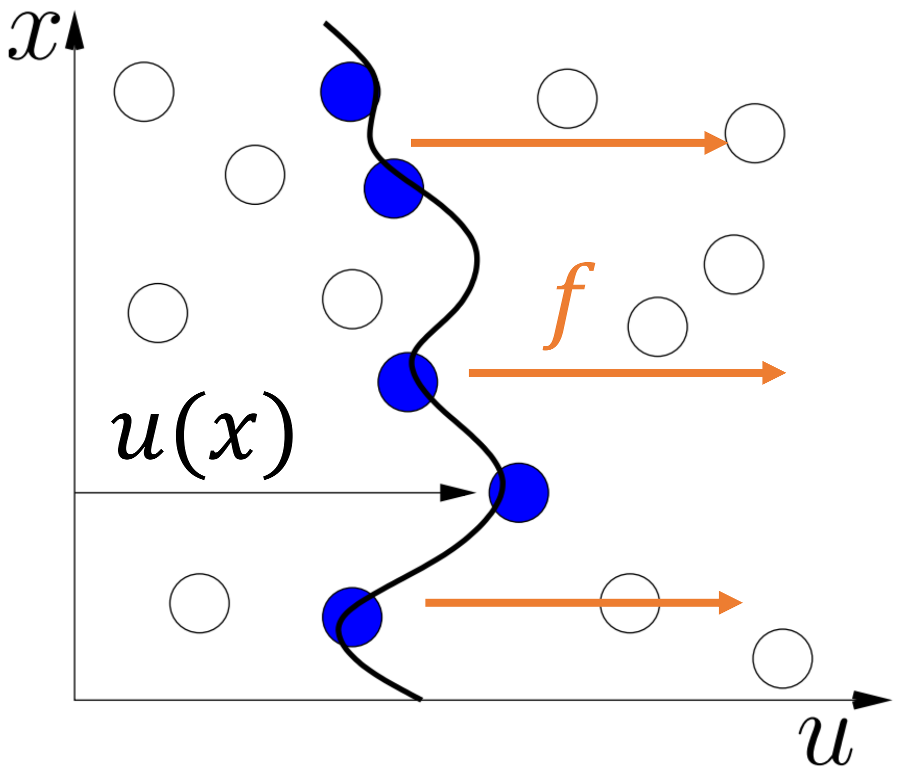
- $\log_{10} N(m) = a - bm$

→**How to model earthquakes?**



Lucilla de Arcangelis, et al. "Statistical physics approach to earthquake occurrence and forecasting," in *Physics Reports*, vol. 628, pp. 1-91, 2016.

Classical model



Kolton, A., et al. "Creep dynamics of elastic manifolds via exact transition pathways," in *Phys. Rev. B*, vol. 79, pp. 184207, 2009.

- Elastic interface in a disordered media
  - Elastic energy: minimal for flat interface
  - Disorder potential energy
  - External force f
- Equation of motion ($d = 1$):

$$\underbrace{\eta}_{\text{Friction coefficient}}\partial_t u = \underbrace{c\partial_x^2 u}_{\text{Elastic force}} + \underbrace{F_{\text{dis}}(u,x)}_{\text{Pinning force}} + \underbrace{f}_{\text{External force}}$$

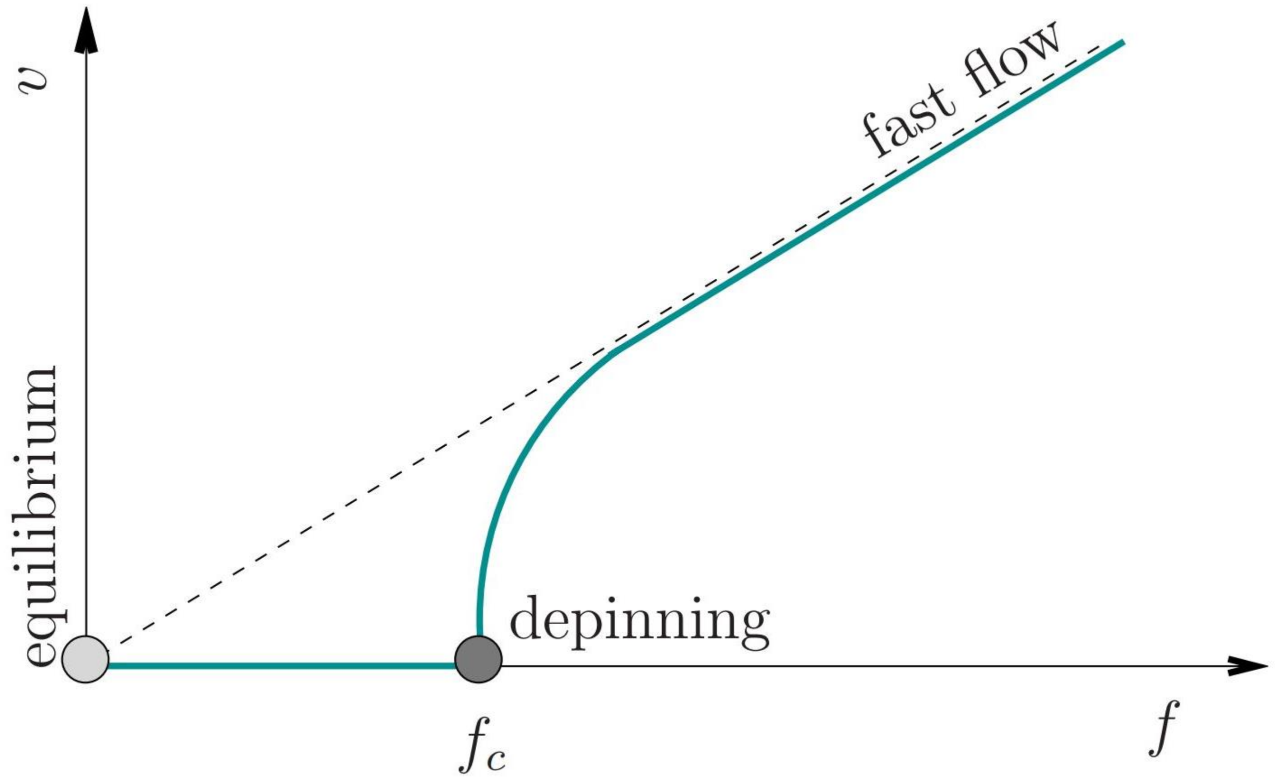
Velocity — force characteristics at $T = 0$

3 regimes for the interface:

- $f < f_c$: pinned
- $f > f_c$: moves with finite v
- $f = f_c$: critical behaviour

Velocity → order parameter of the "depinning" transition:

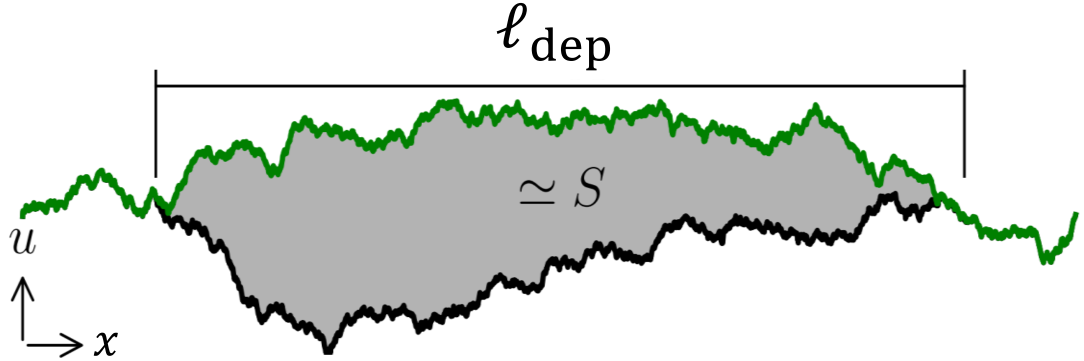
$$v \sim (f - f_c)^{\beta}$$



Kolton, A., et al. "Creep dynamics of elastic manifolds via exact transition pathways," in *Phys. Rev. B*, vol. 79, pp. 184207, 2009.

Interface response for $f \sim f_c$ and $T = 0$

T. Geus, M. Wyart. "Scaling theory for the statistics of slip at frictional interfaces," in *Phys. Rev. E*, vol. 106, pp. 065001, 2022.



- Intermittent dynamics with large and fast reorganisations: avalanches
- Avalanches: divergent typical extent

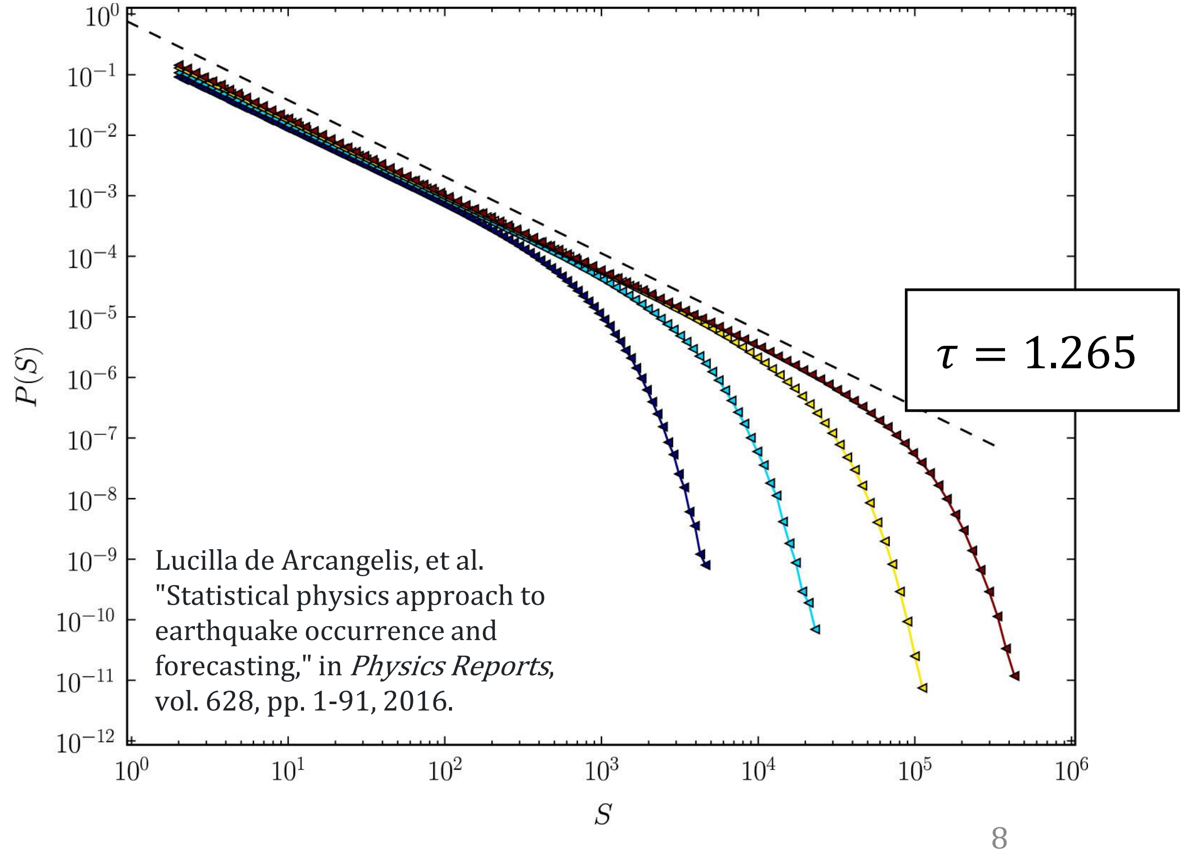
$$\ell_{\text{dep}} \sim |f - f_c|^{-\nu_{\text{dep}}}$$

- Interface morphology: self-similar with roughness exponent ζ_{dep}

$$S \sim \ell^{d+\zeta_{\text{dep}}}$$

- Sizes S: power law distributed

$$P(S) \sim S^{-\tau_{\text{dep}}}$$



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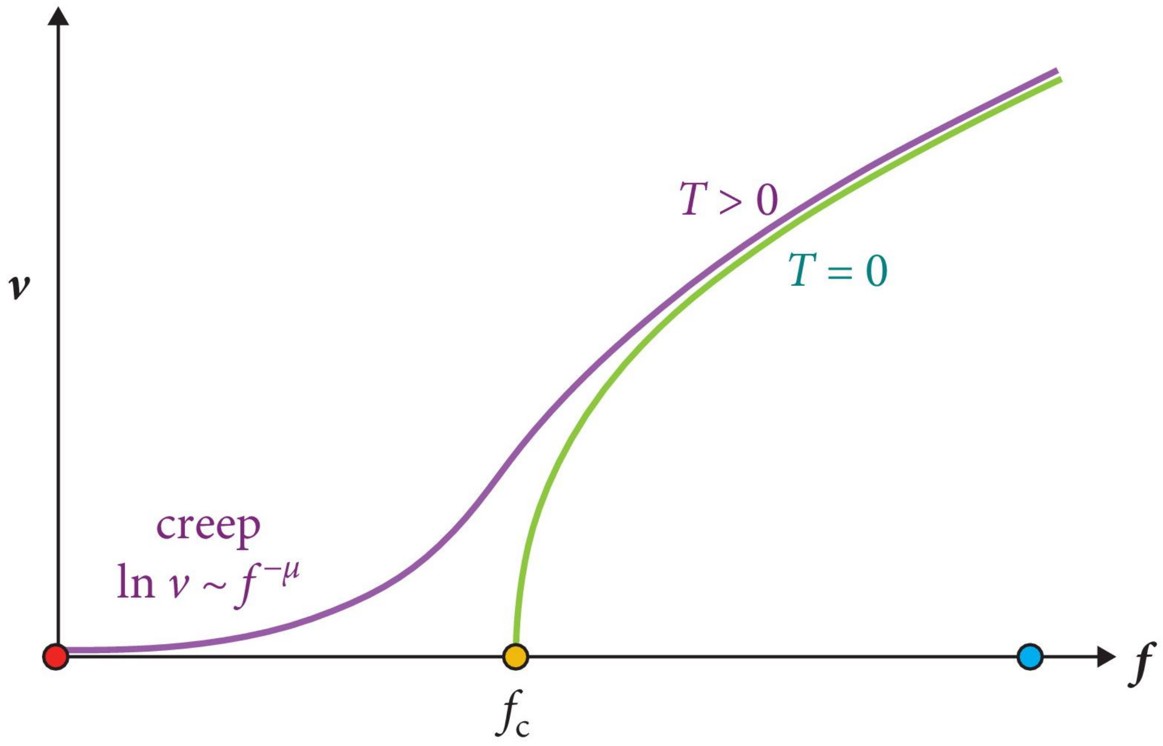
Velocity — force characteristics at $T > 0$

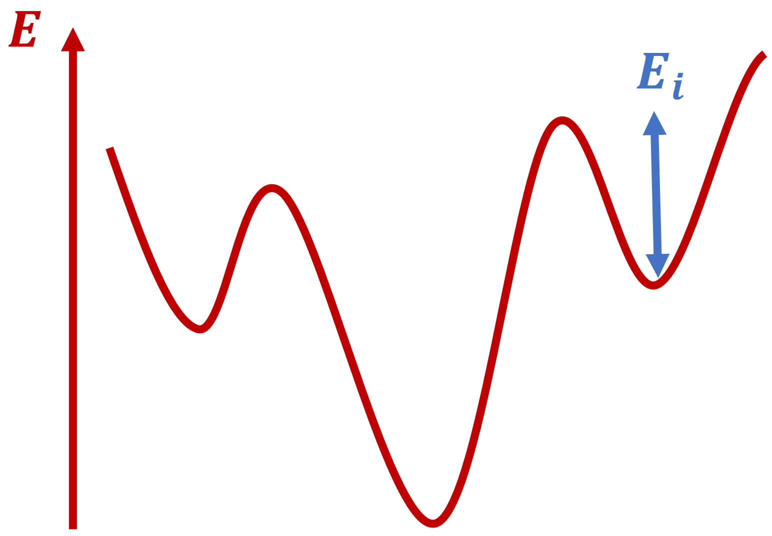


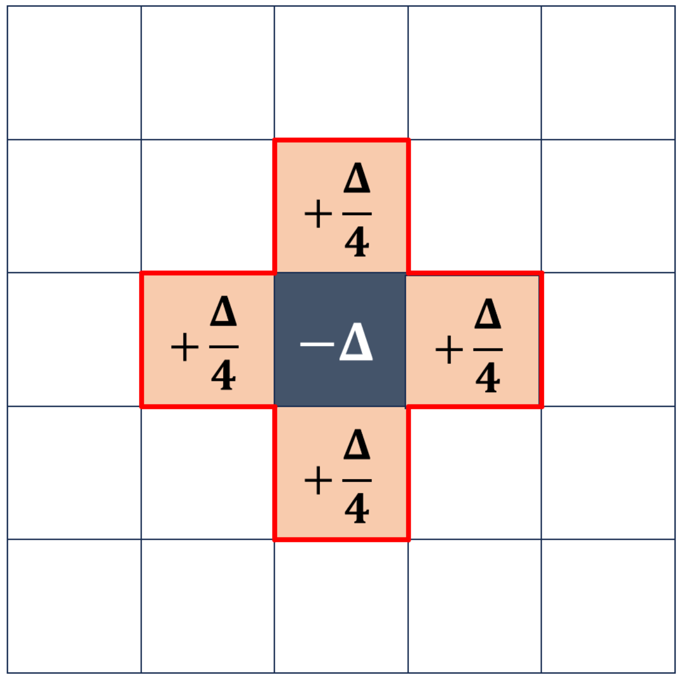
Ferrero EE, et al. 2021
Annu. Rev. Condens. Matter Phys. 12:111–34

- Even for $f < f_c$, interface moves with finite v
- Thermal activations over the pinning potential
- 2 length scales:
  - $\ell_{\mathrm{opt}}(f)$: elementary excitations (small)
  - $\ell_{\mathrm{c}}(T, f)$: thermal avalanches (cascades of elementary excitations).
- Below ℓ_{c} avalanches are depinning-like $(\zeta_{\mathrm{dep}}, \nu_{\mathrm{dep}}, \tau_{\mathrm{dep}})$

Model for $T > 0$

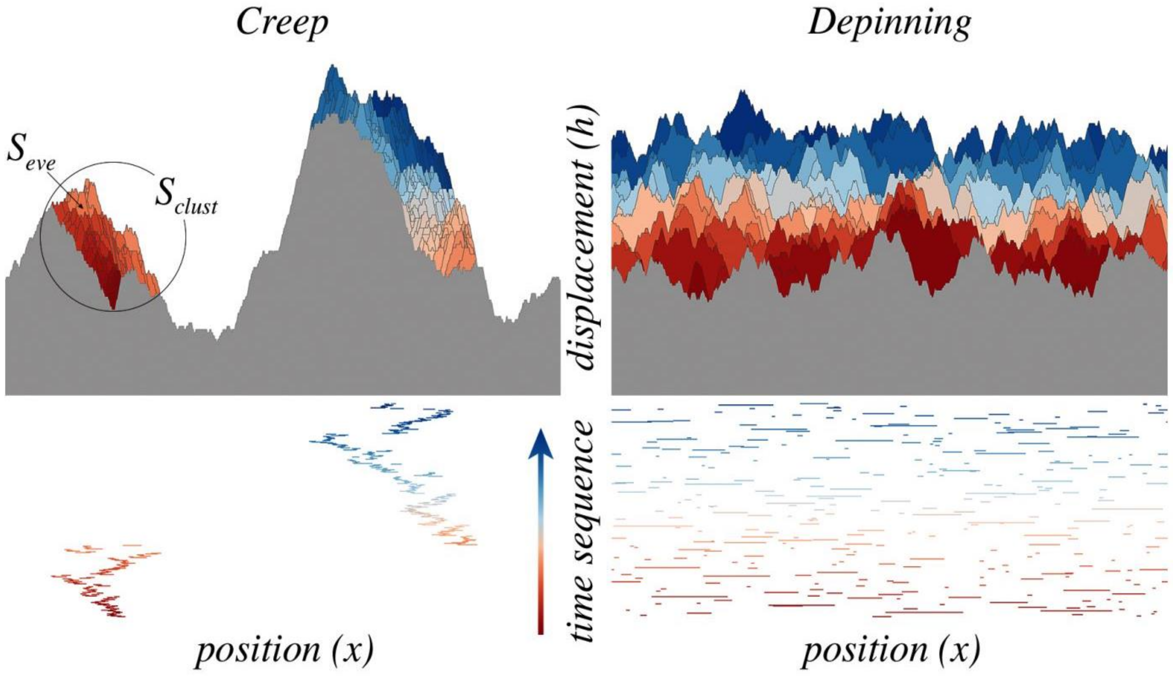
- Lattice of L^d mesoscopic blocks
- Block i has an applied force f_i and a yielding threshold f_i^{yield}
  - Distance to yielding $x_i \coloneqq f_i^{\text{yield}} - f_i$
  - Local energy barrier: $E_i = |x_i|^\alpha \text{sign}(x_i) \begin{cases} \geq 0 \text{ stable,} \\ < 0 \text{ unstable} \end{cases}$
  - Characteristic time: $\tau_i = \begin{cases} \tilde{\tau} \exp\left(\frac{E_i}{T}\right), & \text{if } i \text{ stable} \\ \tilde{\tau}, & \text{if } i \text{ unstable} \end{cases}$
  - Time to failure: $P(\tau) = \frac{1}{\tau_i} \exp\left(-\frac{\tau}{\tau_i}\right)$
- When block i fails:
  - Force drops to small $\varepsilon = f_i - \Delta$
  - Uniform stress kick to nearest neighbours
  - Facilitation can lead to avalanches





Comparing depinning and creep

Creep exhibit spatio-temporal patterns like aftershocks following a mainshock



Ferrero, E., et al. "Spatiotemporal Patterns in Ultraslow Domain Wall Creep Dynamics," in *Physical Review Letters*, vol. 118, no. 14, 2017.

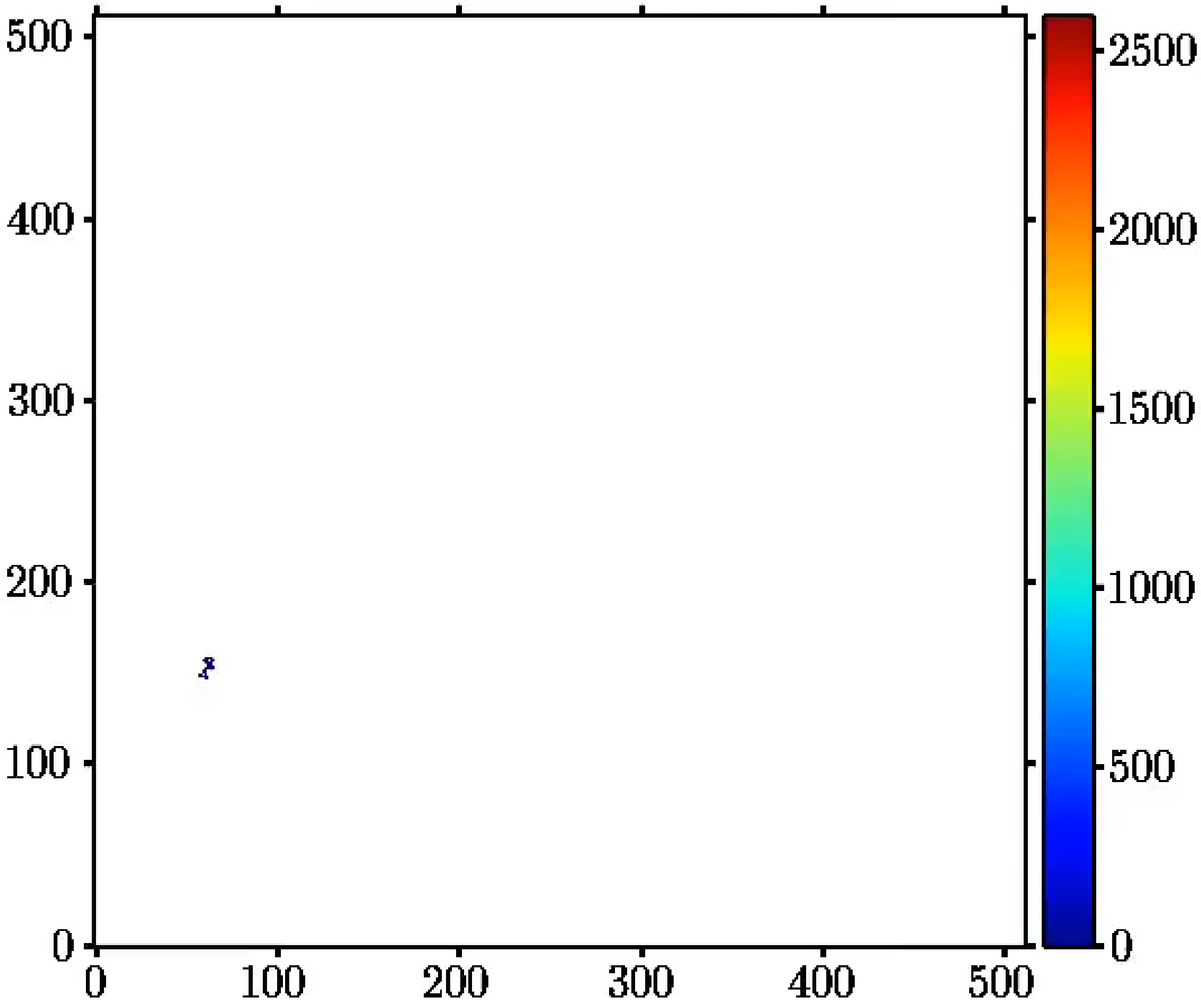
Part 2: Exploring Thermal Avalanches

Are there aftershocks-like sequences after big thermal avalanches?

- Numerical model
- Avalanches, Mainshocks, Aftershocks
- Spatio-temporal clusterings

Observations at $T > 0$

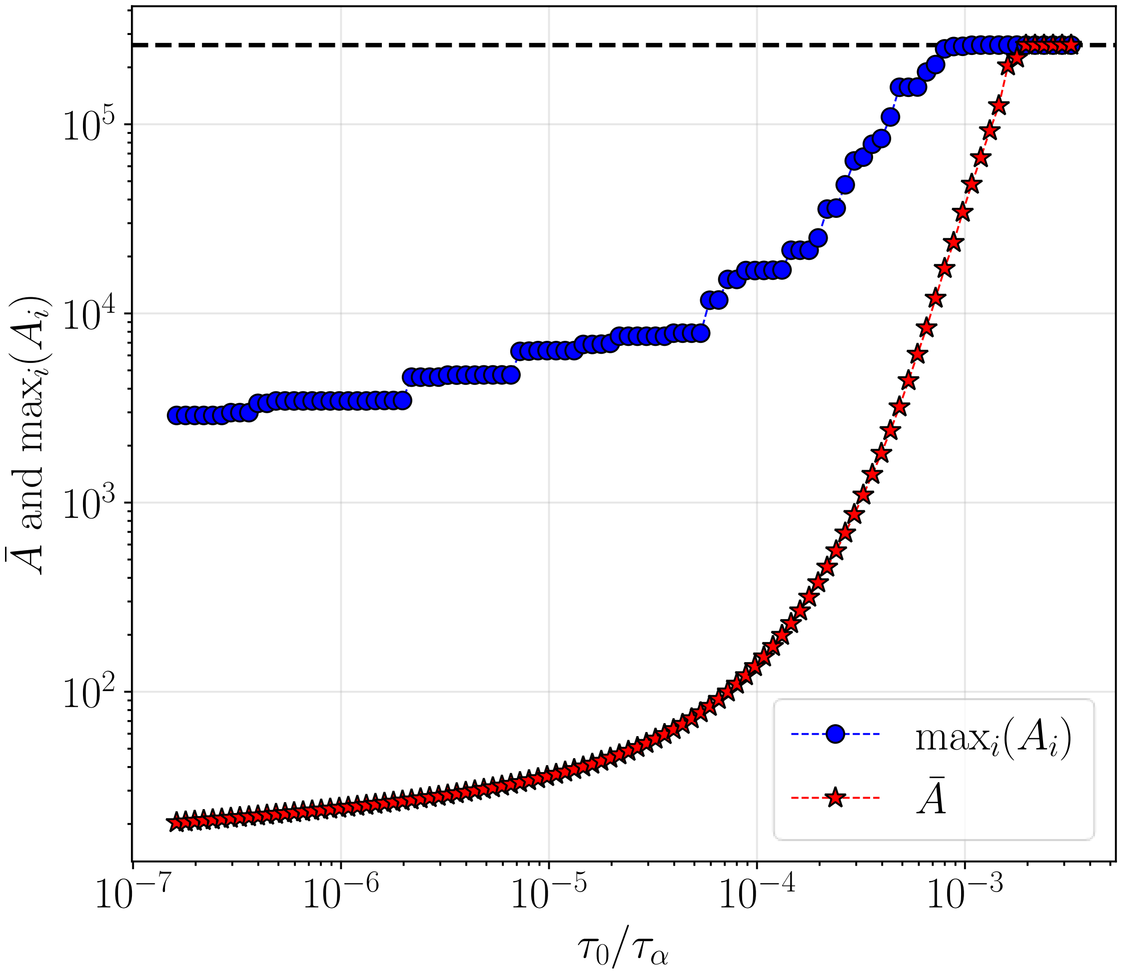
- Rapidly failing connected regions → Avalanches
- Various sizes



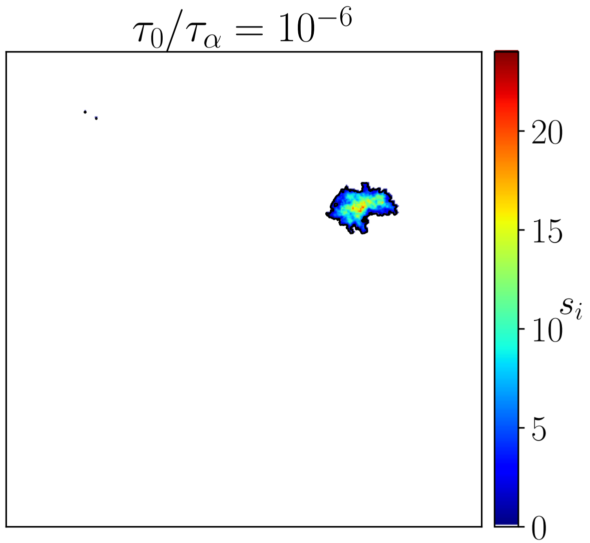
Avalanche definition

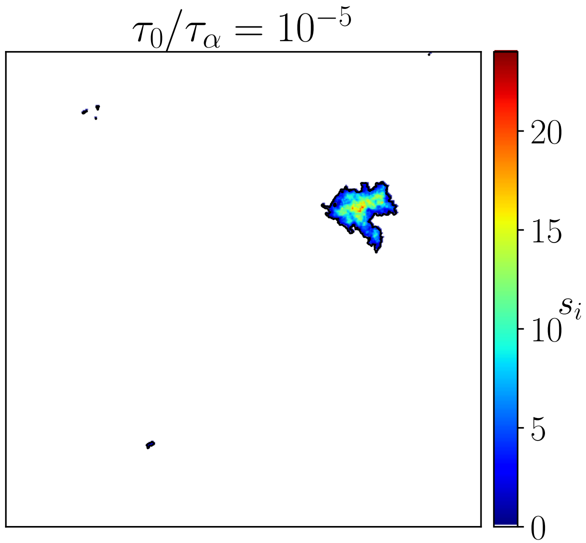
- Simple criterion:
  - Two consecutive block failures are part of a same avalanche if the time difference Δt between them is smaller than a **temporal threshold $\boldsymbol{\tau_0}$**

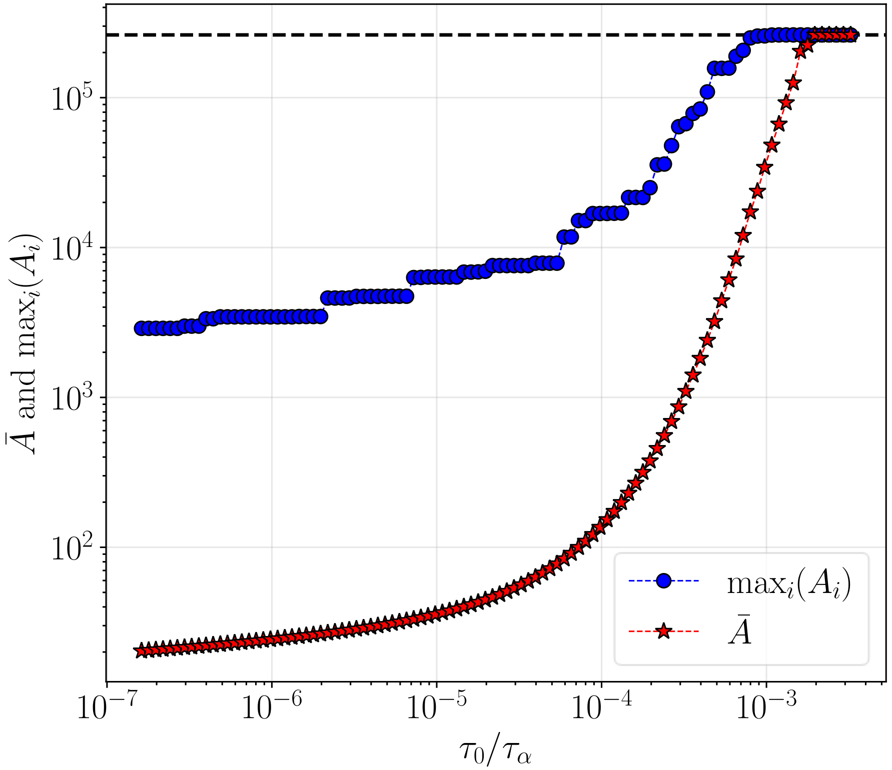
- Avalanche characterised by:
  - Number of block failures $\boldsymbol{S}$
  - Number of failing blocks $\boldsymbol{A}$ (counted uniquely)

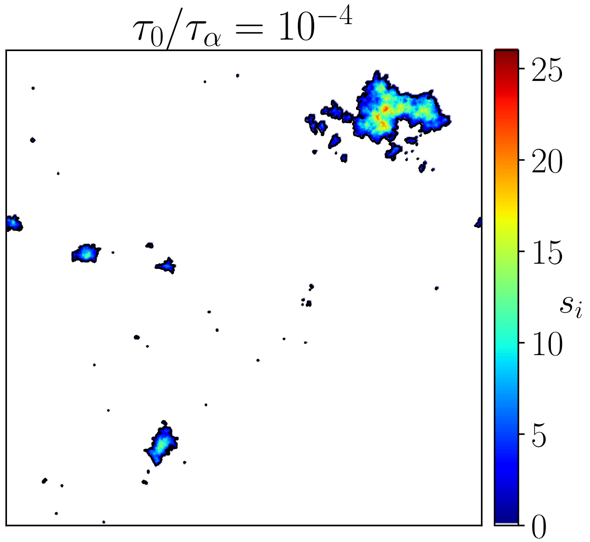


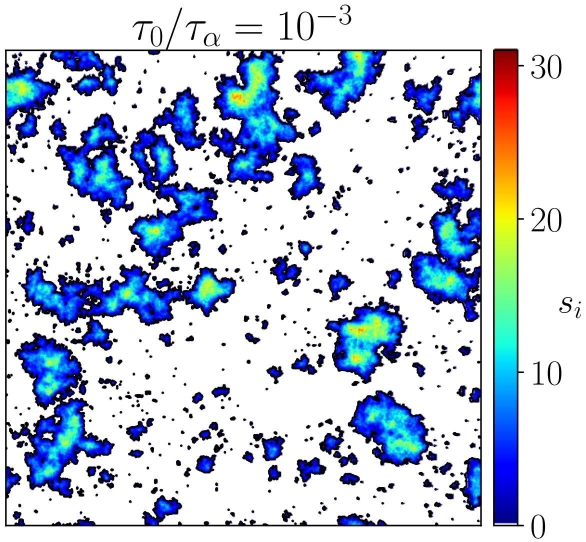
Choice of τ_0 matters

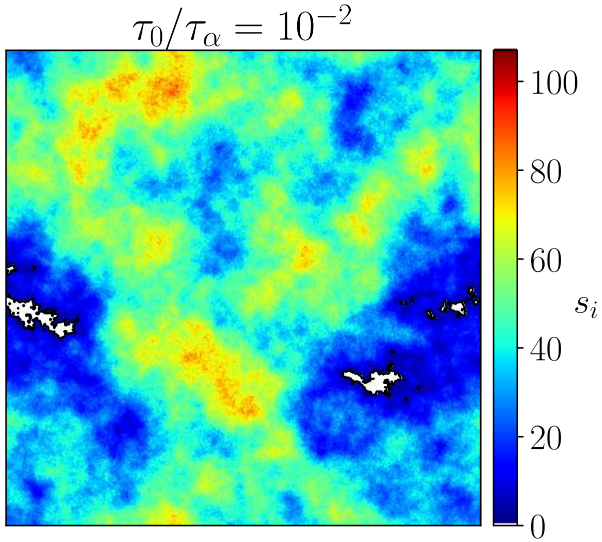




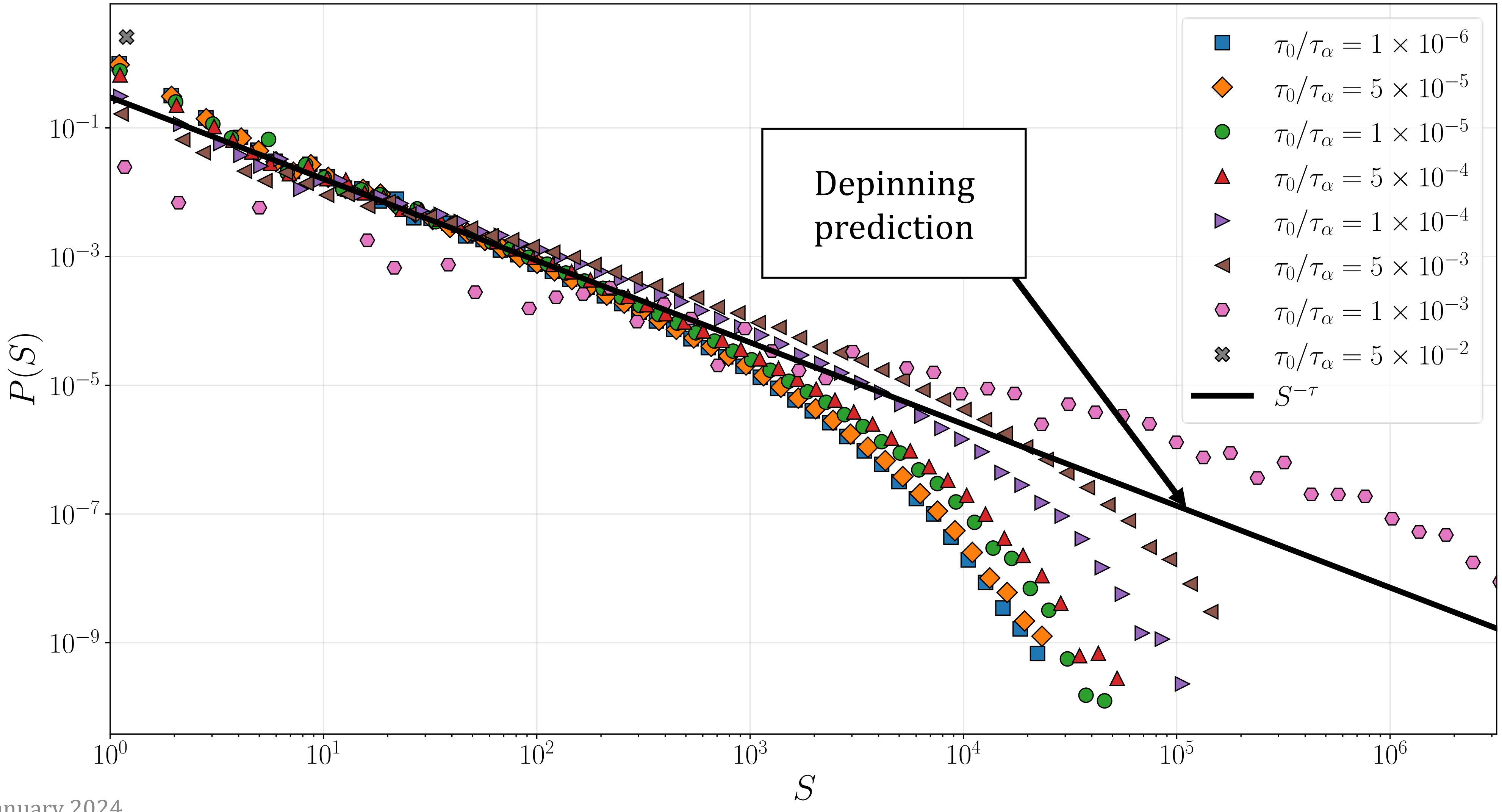




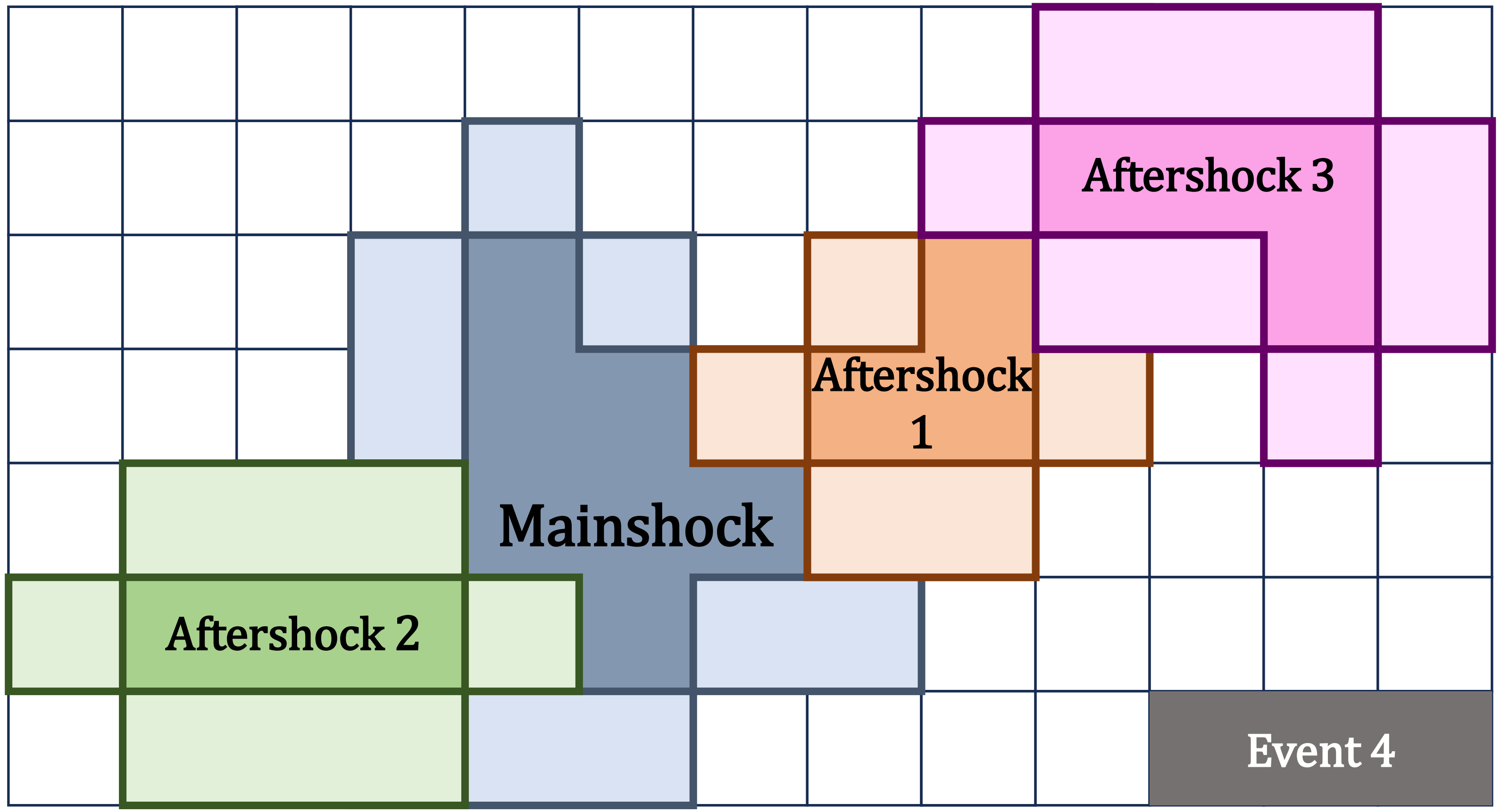




Avalanche Statistics for different τ_0



Mainshocks and Aftershocks



- Mainshocks: big avalanches s.t. $A > rL^d, r \in [0,1]$
- Aftershocks: subsequent events connected to the mainshock

➢ **Are there spatio-temporal clusterings?**

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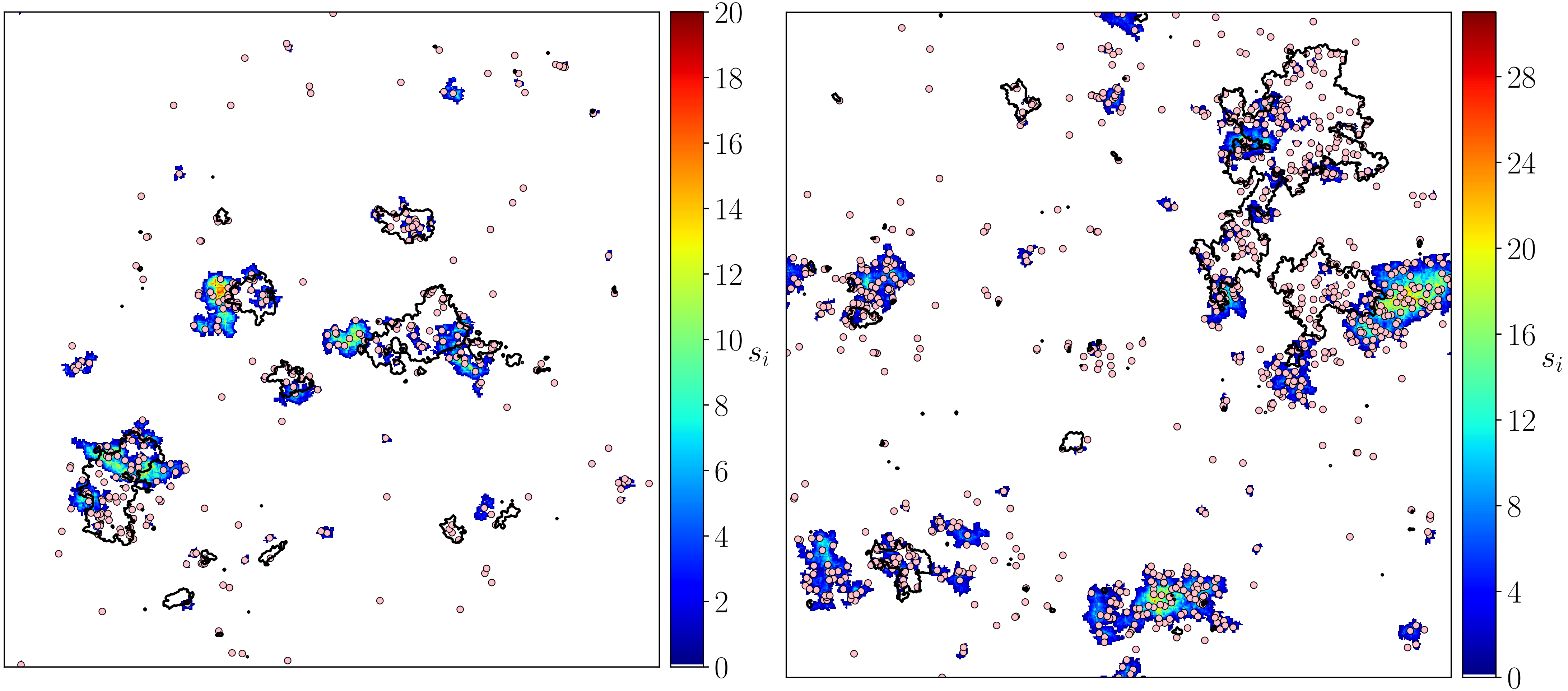

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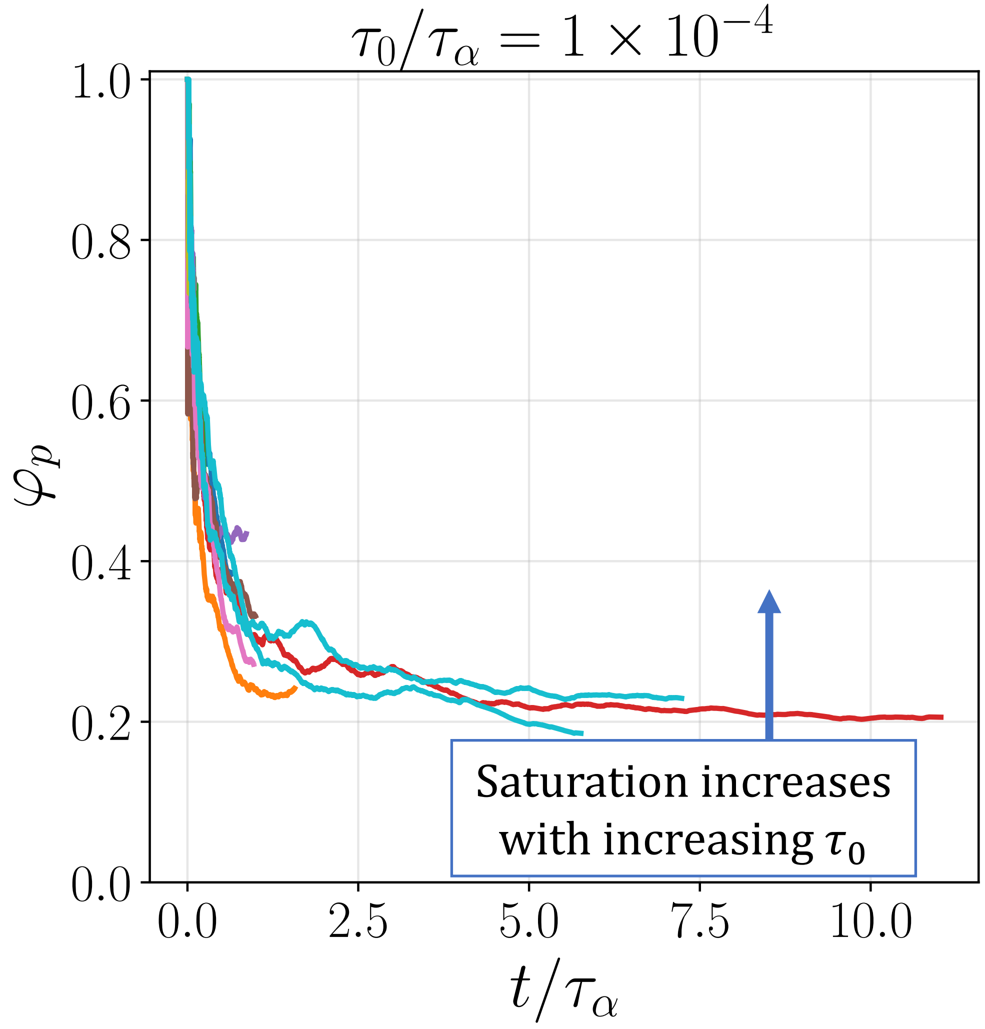
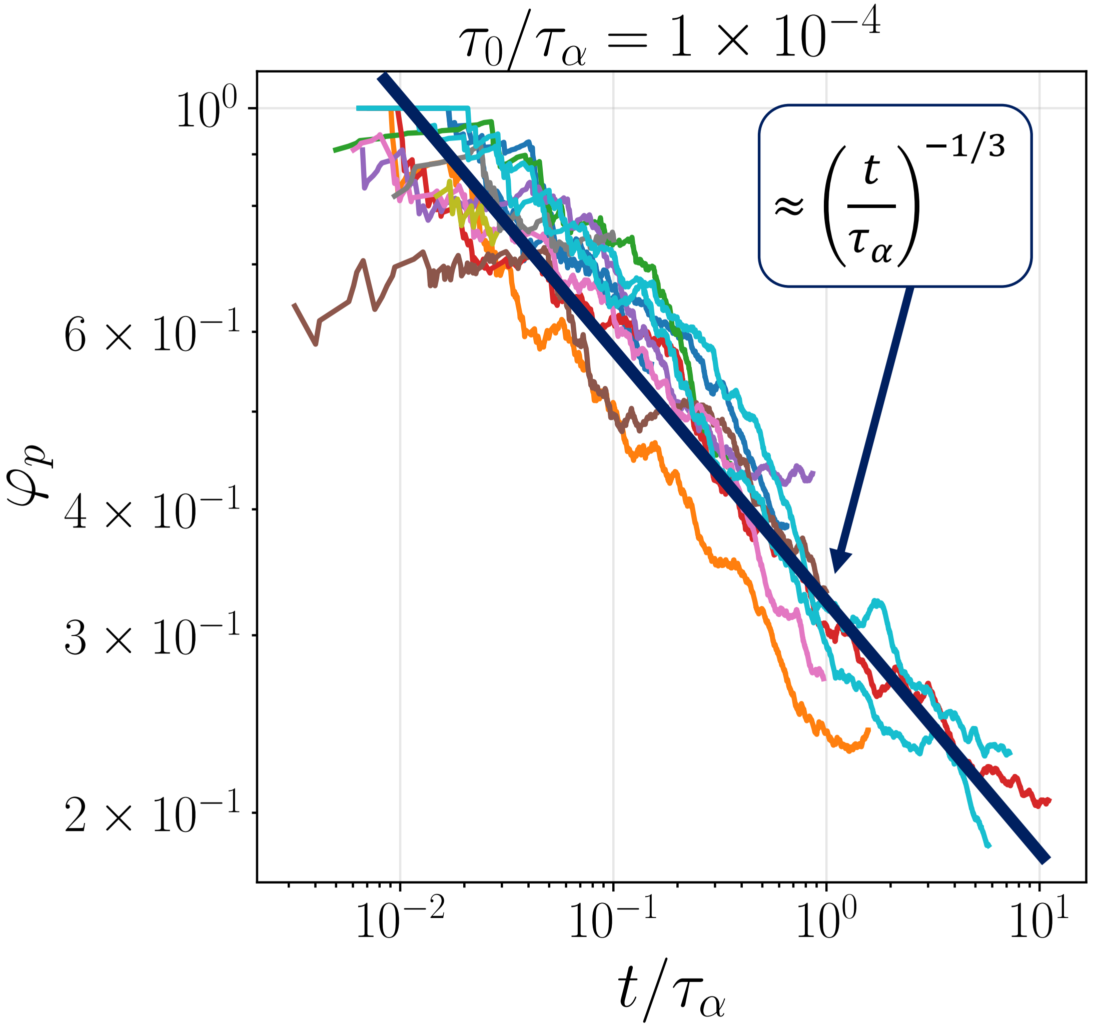
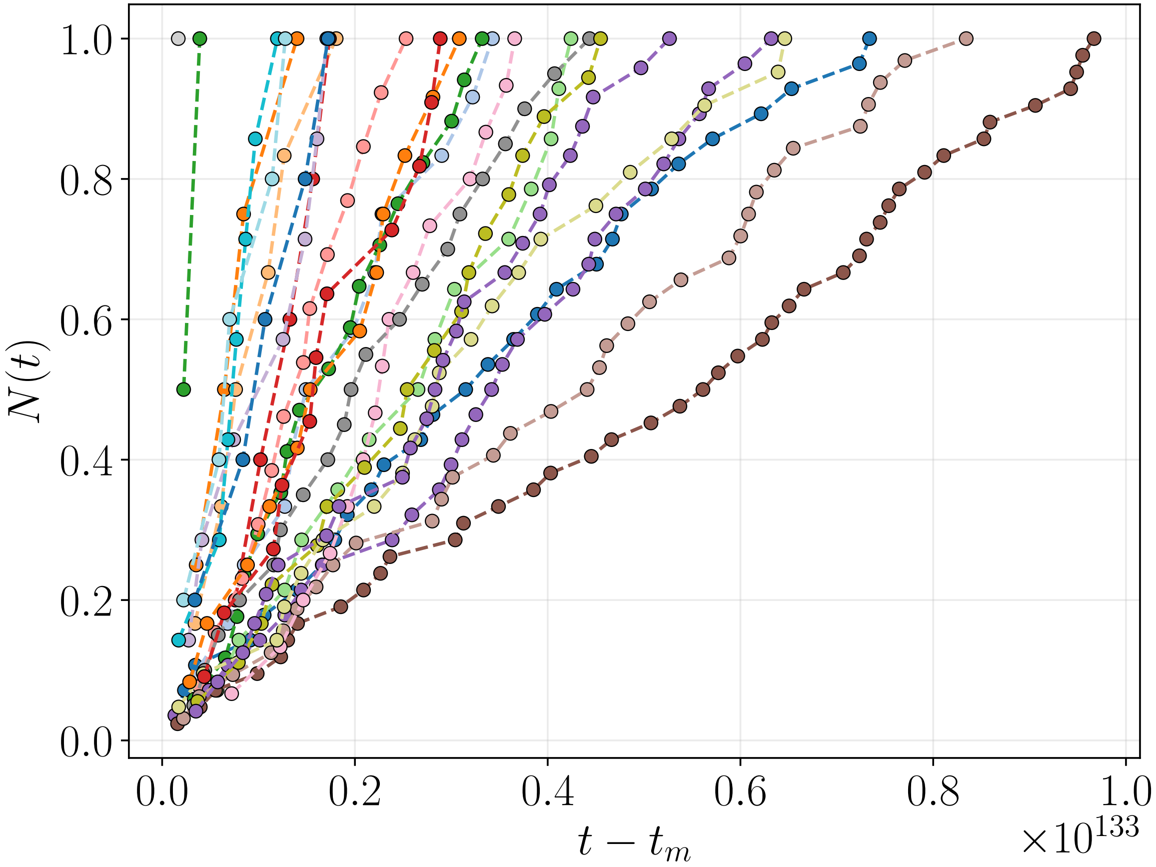
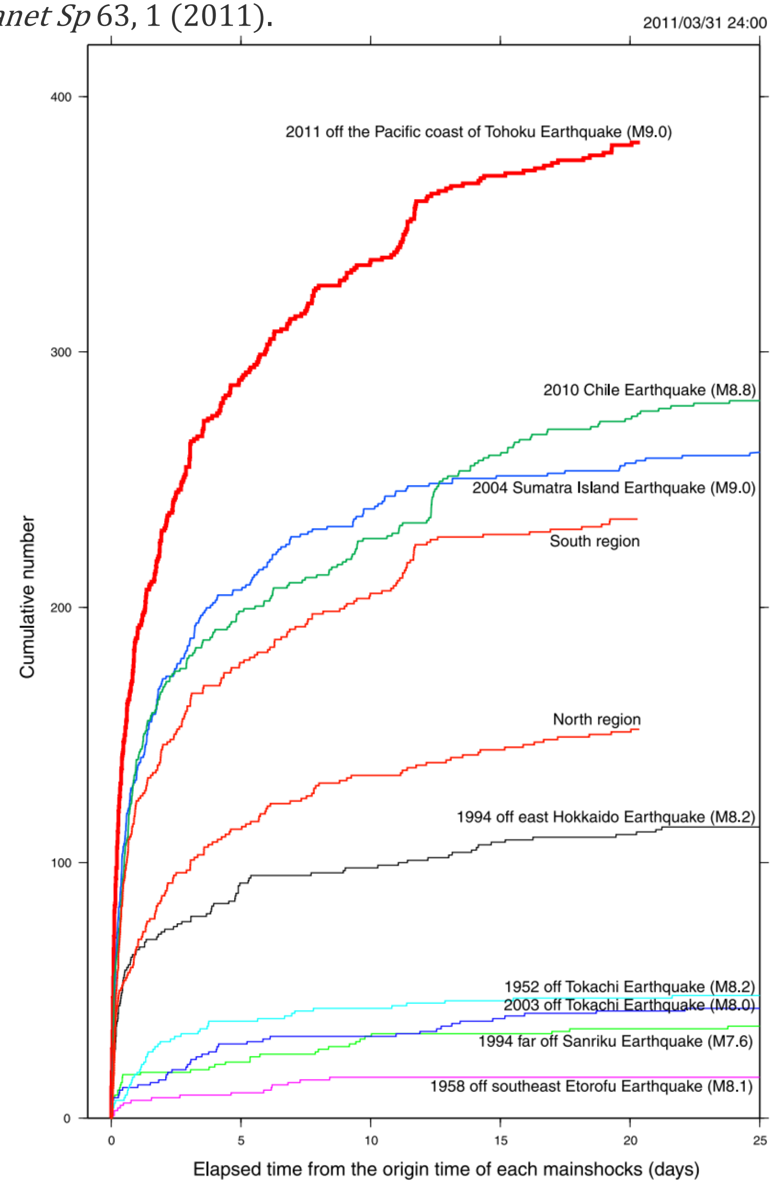




Comparison with real world data



Hirose, F., Miyaoka, K., Hayashimoto, N. *et al.* Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) —Seismicity: foreshocks, mainshock, aftershocks, and induced activity—. *Earth Planet Sp* 63, 1 (2011).



3. Questions?

Thank you for your attention!