ENS DE LYON

The Complex Morphology & Dynamics of Interfacial Cracks

Universality Classes in Fracture Front Roughness Scaling & Avalanche Dynamics

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in collaboration essentially with :

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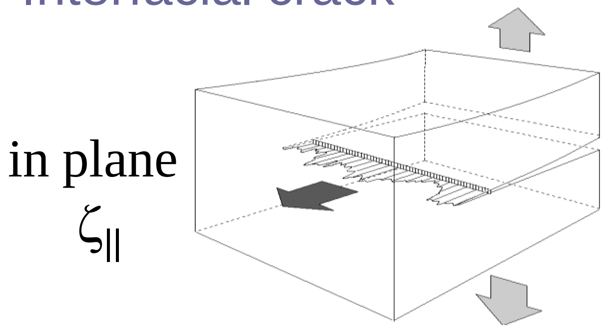
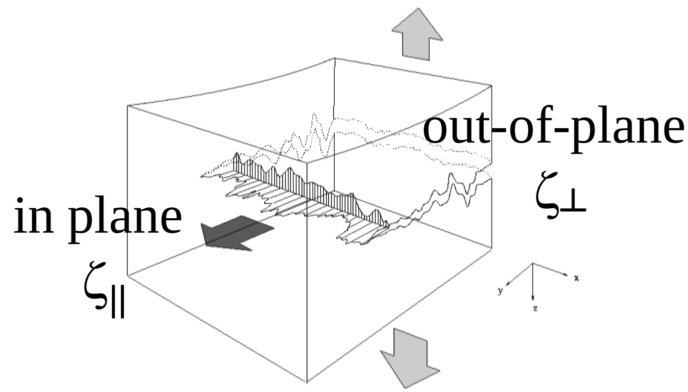
A model experiment

Interfacial crack

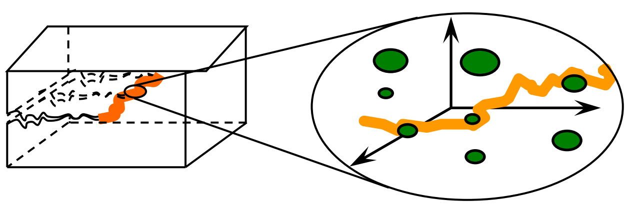


Schmittbuhl and Måløy (97)



Propagation of an elastic line through a disordered interface

Bouchaud et al (93)



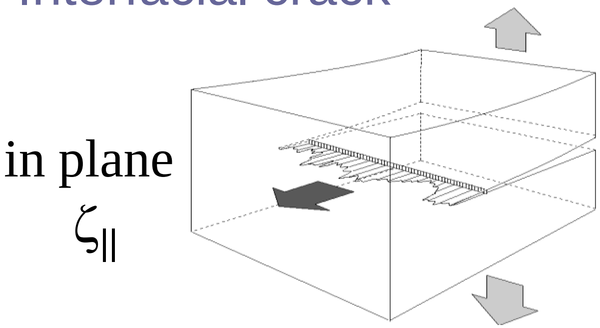
Schmittbuhl, Roux, Vilotte and Måløy (95)

- Quasi-static limit
- Linear elastic material, weakly heterogeneous using long-range elastic kernel of Gao & Rice (89)

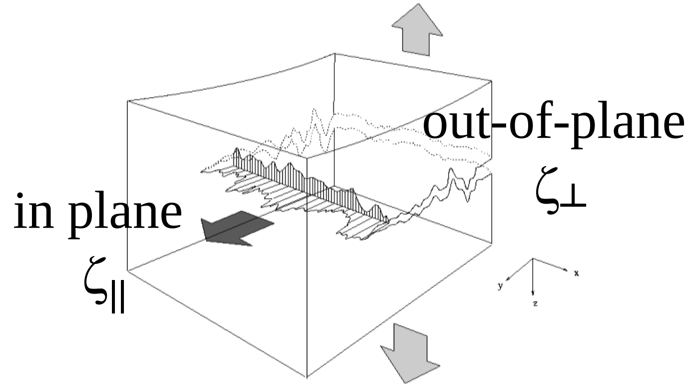
→ Non-Local approach !

A model experiment

Interfacial crack

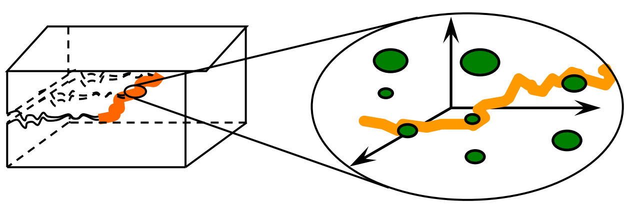


Schmittbuhl and Måløy (97)



Propagation of an elastic line through a disordered landscape

Bouchaud et al (93)



Vortex lines in superconductors,
Ertas and Kardar (92),

Contact lines of liquid menisci on rough substrates,
Ertas and Kardar (94), Rolley (98)

Crack propagation in solids,
Schmittbuhl, Roux et al. (95), Ramanathan et al. (97)

Magnetic domain wall in disordered ferromagnets,
Zapperi, Durin et al (98)

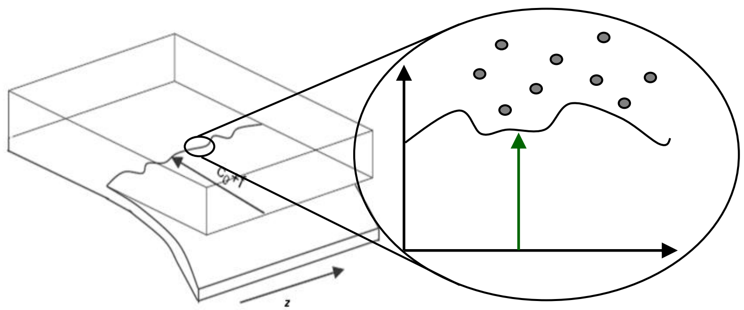
BUT : disagreement between predictions and experimental measurements

$\zeta^{\|}_{exp} \sim 0.5\text{-}0.6$ $\neq$ $\zeta^{\|} \sim 0.35 / 0.38,$

Schmittbuhl and Måløy(97), Delaplace et al (99) *Schmittbuhl, Roux et al. (95), Rosso et al (02)*

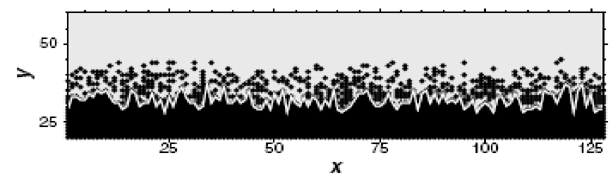
→ Long-standing controversy

"Elastic line" model *vs* "Damage coalescence" model



Bonamy, Santucci, Ponson (08)
Laurson, Santucci, Zapperi (10)

→ $\zeta^{\|} \sim 0.6$



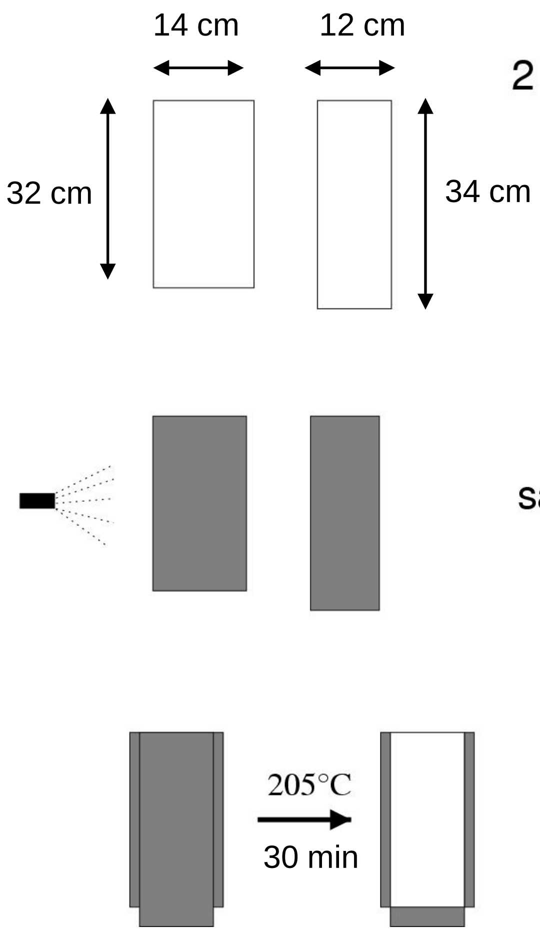
Hansen and Schmittbuhl, (03)

Goal : Clarify the apparent disagreement and controversy

Morphology of interfacial cracks
Avalanche Dynamics of interfacial cracks

Experimental setup

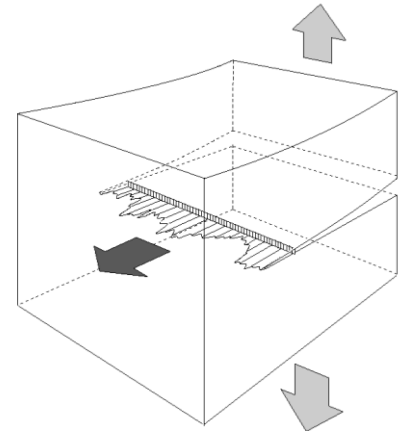
Sample preparation



2 plexiglas plates
(PMMA)

sand blasting

annealing



Key points

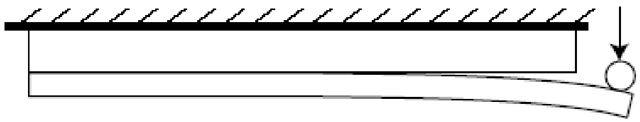
- Transparent block
→ direct observation

- Heterogeneities, toughness fluctuations

→ rough crack front →
burst dynamics

Experimental setup

Optical and mechanical set-up



A press imposes a normal displacement

- creep conditions
- constant low speed ~ μm/s :

→ Crack front propagating in quasi-mode I in the annealing plane of the 2 sandblasted plates

Optical tracking

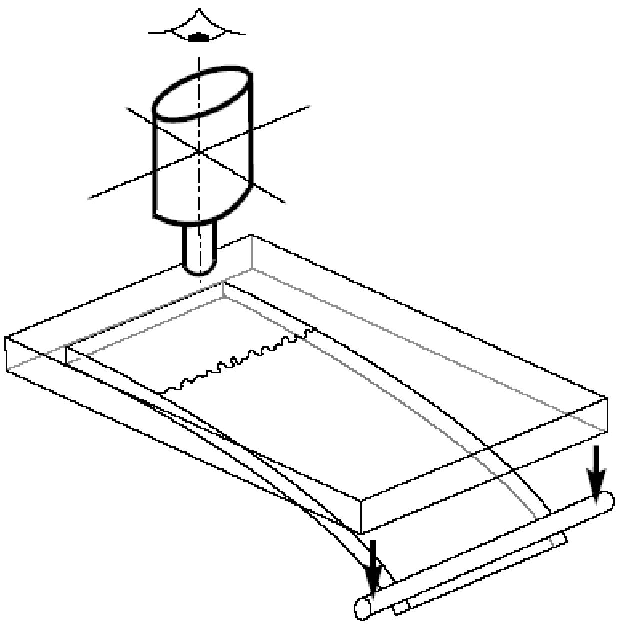
high speed & high resolution camera

•*high frame rate vs the average crack velocity*

Acoustic tracking

2 microphones, Wide Band (100 kHz-1 MHz)

•*Sampling rate : 1 MHz*

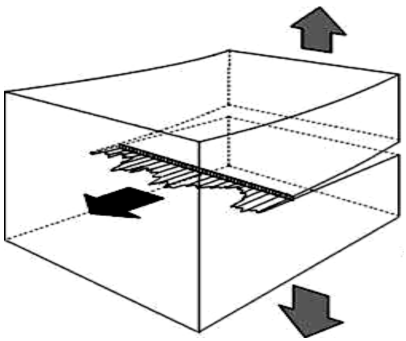


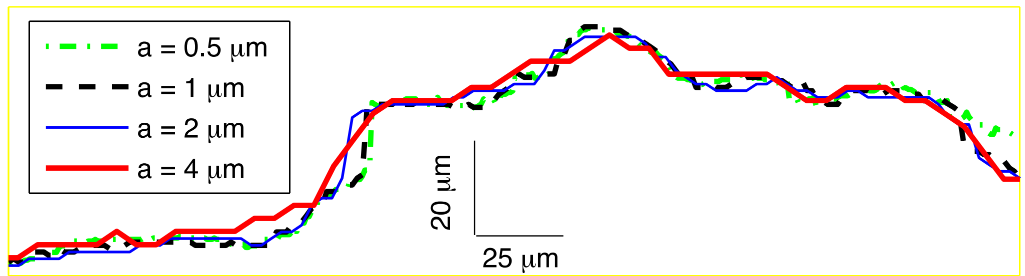
$0.03\ \mu m.s^{-1} < \langle V \rangle < 300\ \mu m.s^{-1}$

$0.5\ \mu m <$ pixel size: $a < 10\ \mu m$

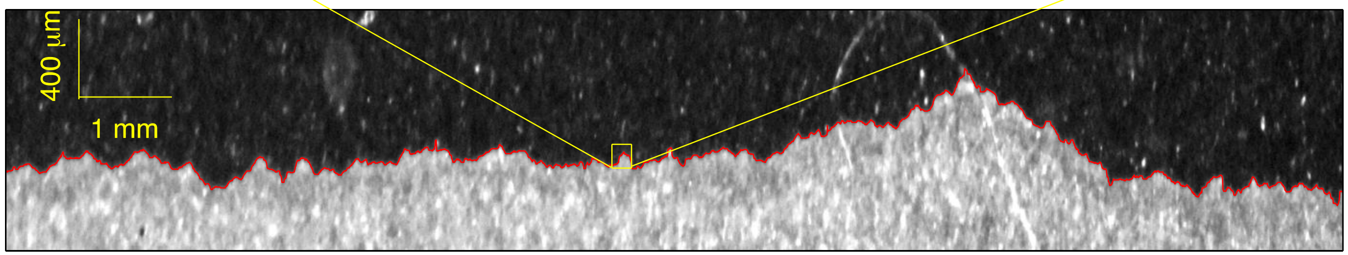
Interfacial crack fronts morphology

Crack at rest → Multi - High resolution description





Sand-blasting
with glass beads
Ø ~ 50 μm



1 picture; x 6.5; pixel size ~ 3.9 μm ~ 4 000 pixels

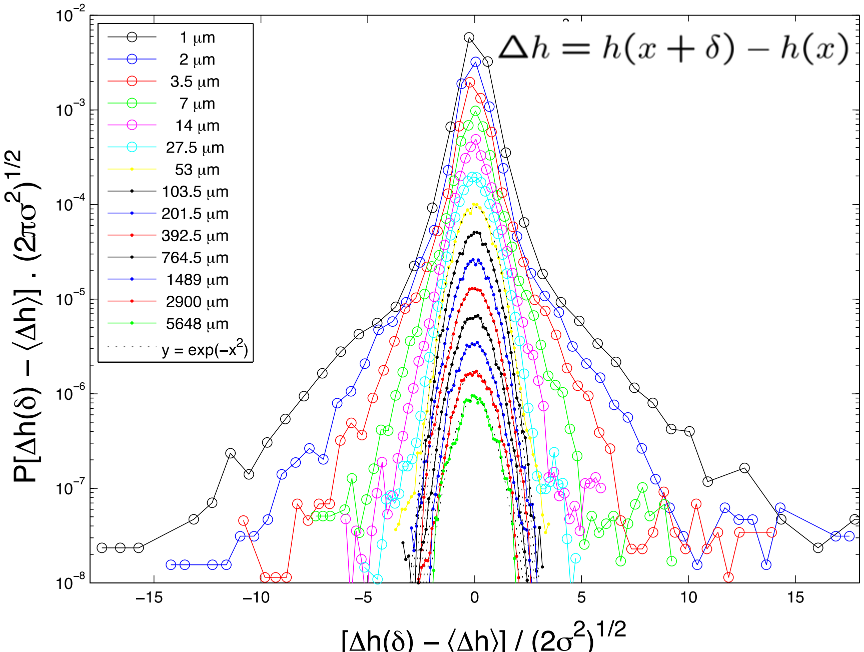
-assembling pictures for a crack at rest-

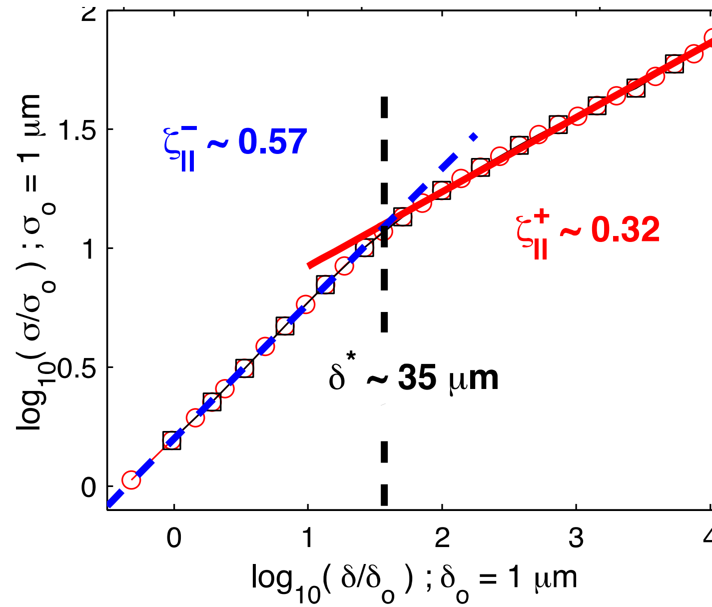
assembling 3 pictures; x 12.5; pixel size ~ 2 μm ~ 8 000 pixels
assembling 7 pictures; x 25; pixel size ~ 1 μm ~ 16 000 pixels
assembling 11 pictures; x 50; pixel size ~ 0.48 μm; ~ 25 000 pixels

‹ 20 fronts ›
for each set

Interfacial crack fronts morphology

Statistical distribution of the height fluctuations $P(\Delta h)$





2 ≠ scaling regimes

$\delta > \delta^*$ Gaussian distribution $P(\Delta h) \sim \delta^{-\zeta} G(\Delta h/\delta^{\zeta}) \sim \frac{e^{-(\Delta h)^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}}$ $\sigma \propto \delta^{\zeta}$

$\zeta^+ \sim 0.35$ in agreement with elastic line model

$\delta < \delta^*$ Non-Gaussian distribution with large tails ← multi-scaling behavior

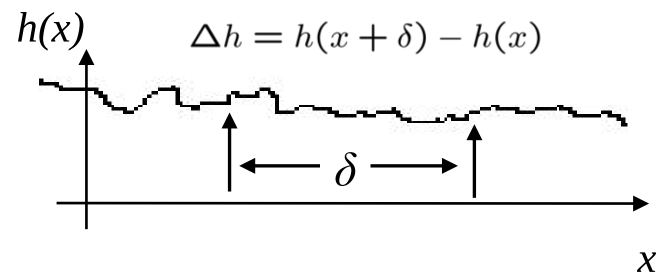
$\zeta^- \sim 0.6$ in agreement with coalescence model

Santucci et al, EPL (10)

Interfacial crack fronts morphology

Multi-scaling analysis

(Coll.: A. Hansen)



- Structure functions

$$C_k(\delta) = \langle |h(x+\delta) - h(x)|^k \rangle_x^{1/k}$$

- Normalized Structure Functions by a Gaussian Statistics

$$C_k^N(\delta) = \frac{C_k(\delta)}{R_k^G} \qquad R_k^G = \sqrt{2}\left(\Gamma\left(\frac{k+1}{2}\right)/\sqrt{\pi}\right)^{1/k}$$

Set of “Universal numbers” independent of σ and δ

Structure Functions Ratios $\quad R_k(\delta) = \frac{C_k(\delta)}{C_2(\delta)}$

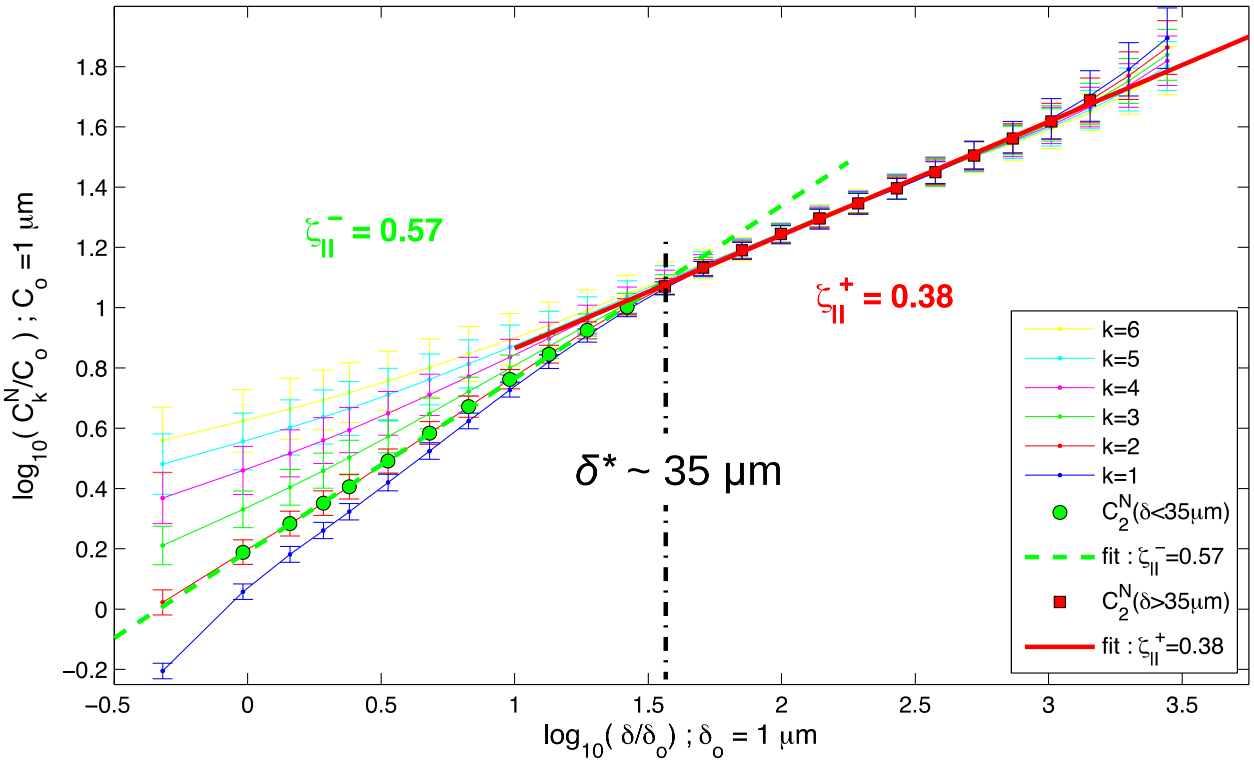
Gaussian statistics with a self-affine scaling $\quad P(\Delta h) = \frac{e^{-(\Delta h)^2/2\sigma^2}}{\sqrt{2\pi\sigma^2}} \; ; \; \sigma^2 \propto \delta^{2\zeta}$

Santucci et al, EPL (10)

exple: Brownian motion $\zeta = 1/2$

Interfacial crack fronts morphology

Scaling behavior the structure functions C_k/R_k^G



For $\delta < \delta^*$ Fanning of the structure functions C_k/R_k^G :

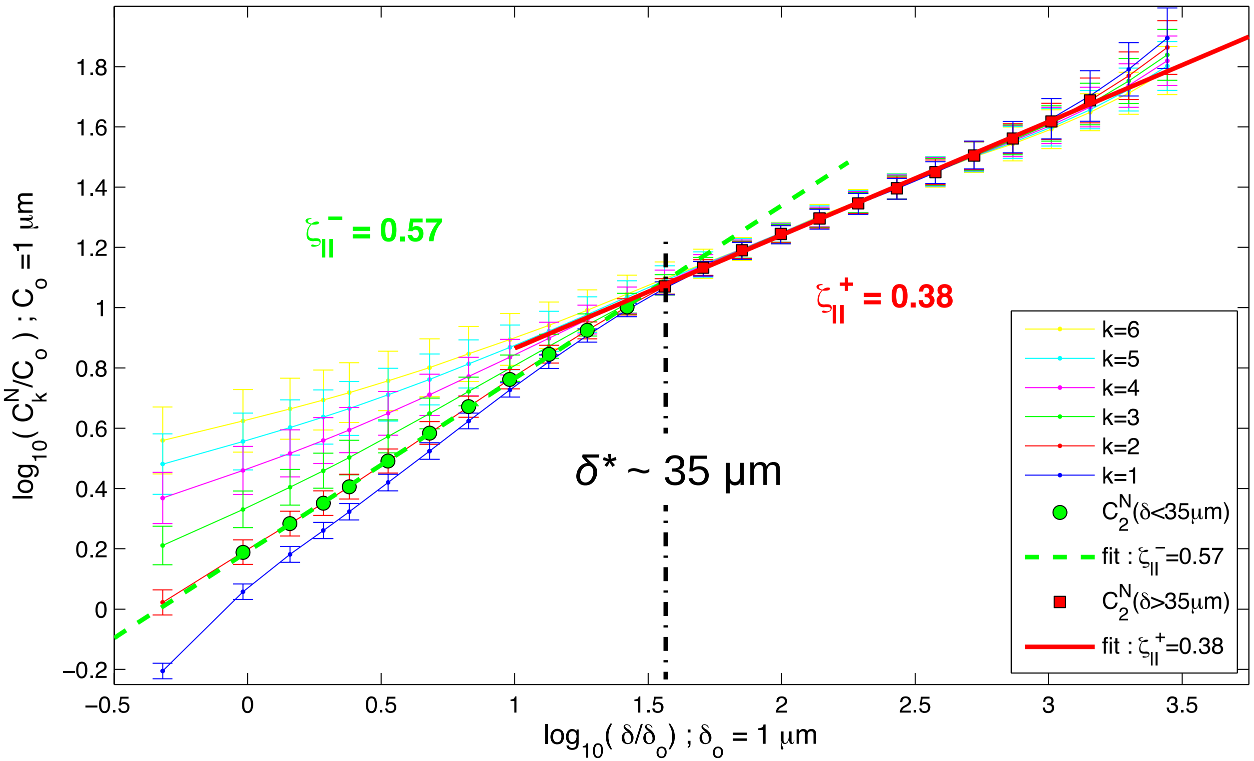
→ Non-Gaussian statistics

→ Non-unique roughness exponent : multiscaling ζ (k)

Santucci et al, EPL (10)

Interfacial crack fronts morphology

Scaling behavior the structure functions C_k/R_k^G



For $\delta > \delta^*$ Collapse of the structure functions C_k/R_k^G :

→ underlying distribution Gaussian

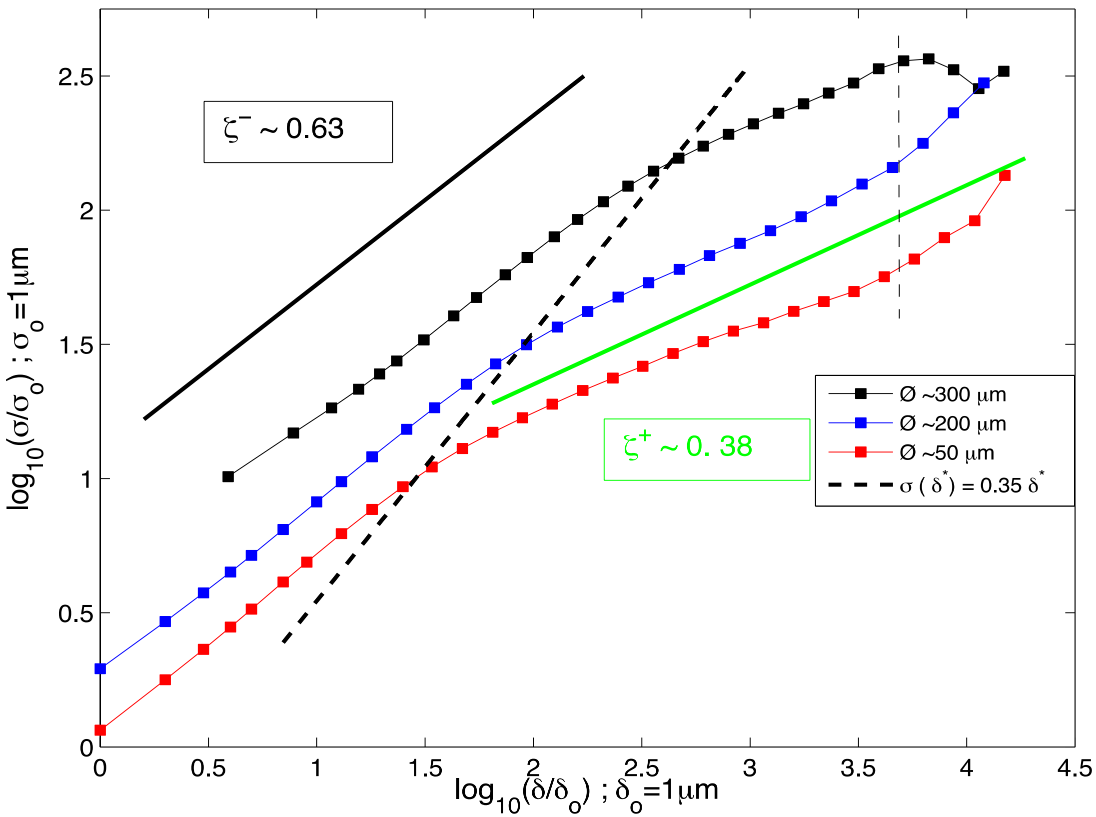
→ extraction of a unique roughness ζ exponent : ζ (k) ~ 0.38

Santucci et al, EPL (10)

Interfacial crack fronts morphology

What controls the cross-over length scale δ^* ?

Effect of the disorder and material heterogeneities



Blasting with ≠ glass beads

Ø ~ 300 μm

Ø ~ 100/200 μm

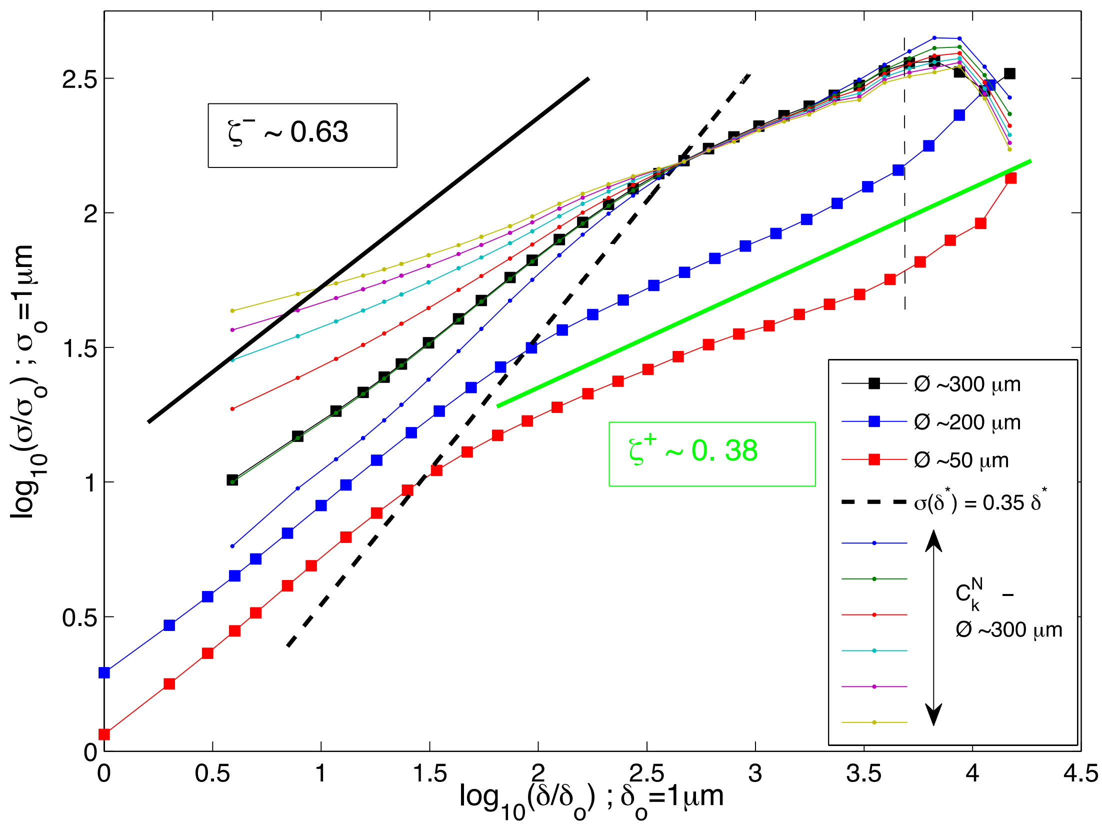
Ø ~ 50 μm

Santucci et al, EPL (10)

Interfacial crack fronts morphology

What controls the cross-over length scale δ^* ?

Effect of the disorder and material heterogeneities



Blasting with ≠ glass beads

Ø ~ 300 μm

Ø ~ 100/200 μm

Ø ~ 50 μm

Local slope of the front

$$\frac{\sigma(\delta)}{\delta} \sim 0.3$$

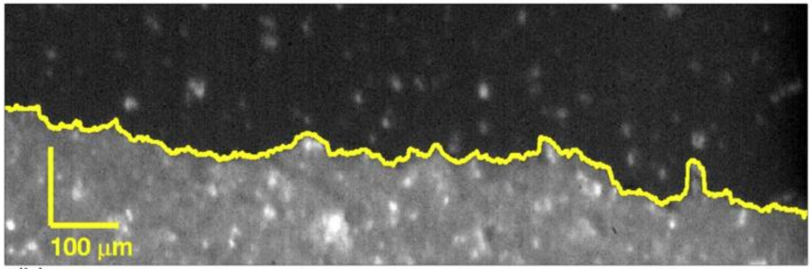
Santucci et al, EPL (10)

Interfacial crack fronts morphology

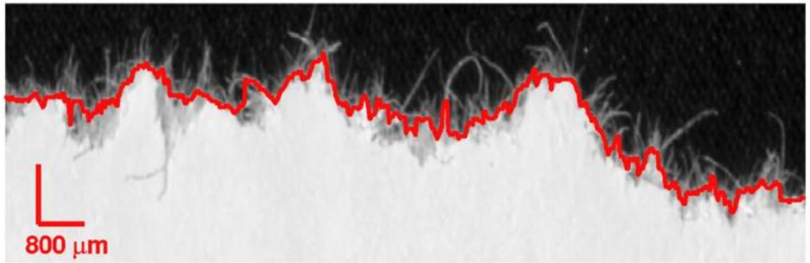
What controls the cross-over length scale δ^* ?

Effect of the disorder and material heterogeneities

High Local slope of the front $s = \dfrac{\sigma(\delta_c)}{\delta_c} \gg 1$



(b)



(a)

→ Deviations to Mono-affine scaling observed for various crack fronts and surfaces

→ Limit for elastic line model using the Kernel of Gao & Rice assuming small deviations

Also in agreement with numerical simulations *Laurson & Zapperi (2010)*

⚠ way fronts are extracted / lack of resolution

Santucci et al, PRE (07), Santucci et al, EPL (10)

Partial Conclusion

A detailed statistical description of the morphology of interfacial crack fronts

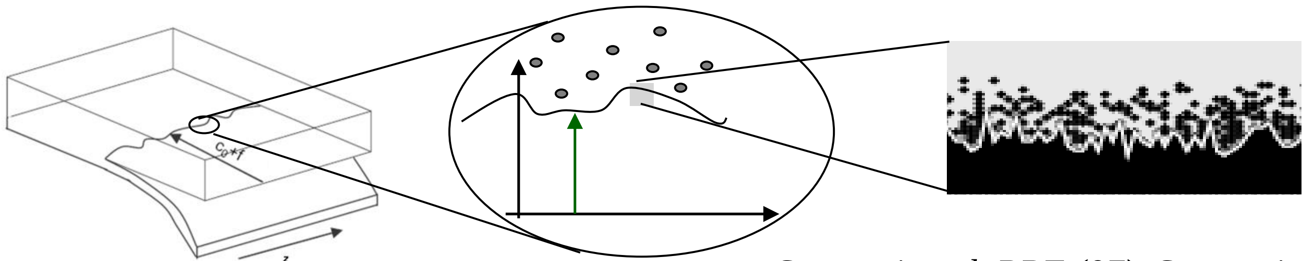
δ^* cross-over length scale *microstructure, toughness fluctuations,*
could depend on loading, sample geometry…

$\delta > \delta^*$:

- The height fluctuations follow a Gaussian statistics
- Self-affine behavior with a unique roughness exponent $\zeta^+ \sim 0.35$
- Agreement with the predictions of elastic line model

$\delta < \delta^*$:

- Separation of the structure functions at small scales Multi-scaling; $C_k(\delta) \sim \delta^{\zeta(k)}$
- Deviation to a Gaussian statistics
- $C_2(\delta) \sim \delta^{\zeta-}$ with $\zeta^- \sim 0.6$
- Agreement with the prediction of a coalescence model



Santucci et al, PRE (07), Santucci et al, EPL (10)

Interfacial crack fronts dynamics

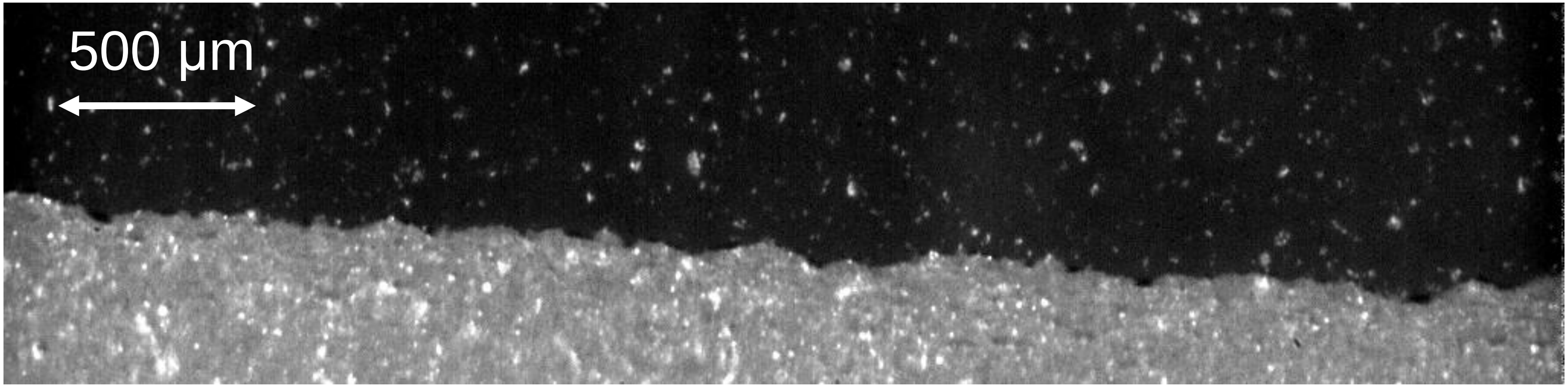
Forced expt.

‹V› ~ 30 μm.s^{-1}

resolution : 3.5 μm

acquisition rate :1000 fps

expt ~ 10 s



Complex dynamics

- large scale : stable slow crack propagation
- locally : pinning ← heterogeneities, toughness fluctuations

→ rough crack front

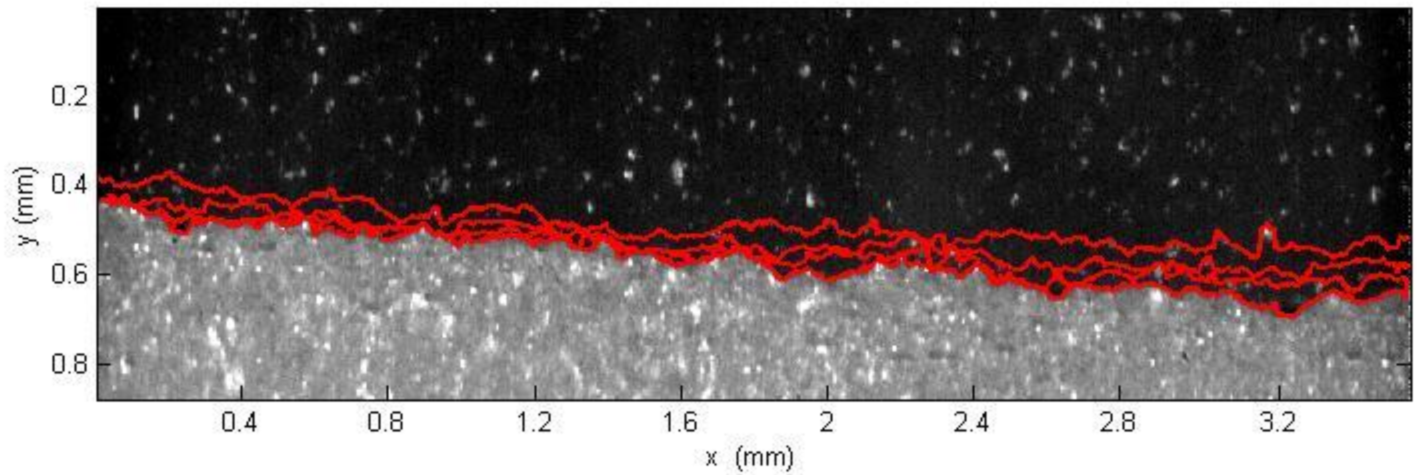
→ avalanches

large velocity and size fluctuations

Analysis procedure

Image analysis

Raw image → front extraction



Waiting time matrix **M** ← front dynamics

M_2

0	0	0	1	0	0
0	2	1	0	1	0
2	0	1	1	0	2
0	0	0	0	1	0
0	0	0	0	0	0

waiting time matrix obtained by adding fronts F_i

$$\mathbf{M} = \sum F_i \,.\delta t$$

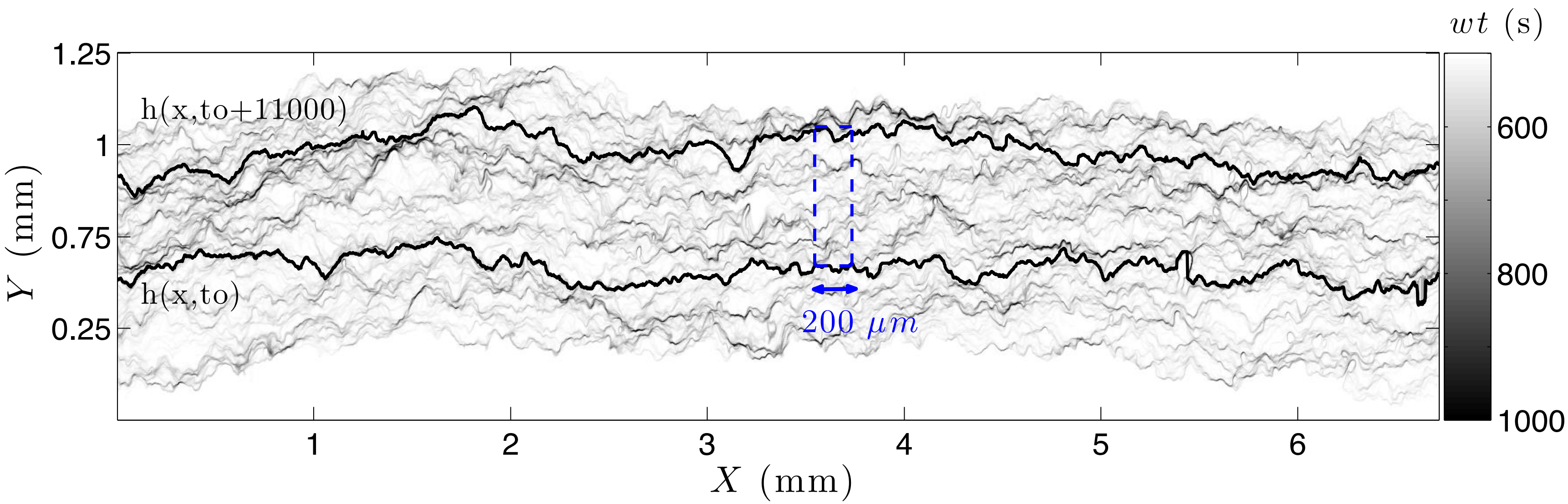
Results

- local front velocity field

Creep expts

⟨V⟩ ≈ 1 μm.s⁻¹

the darker parts the longer waiting times



M → V :

local front velocity

image recording so fast

→ no holes in M

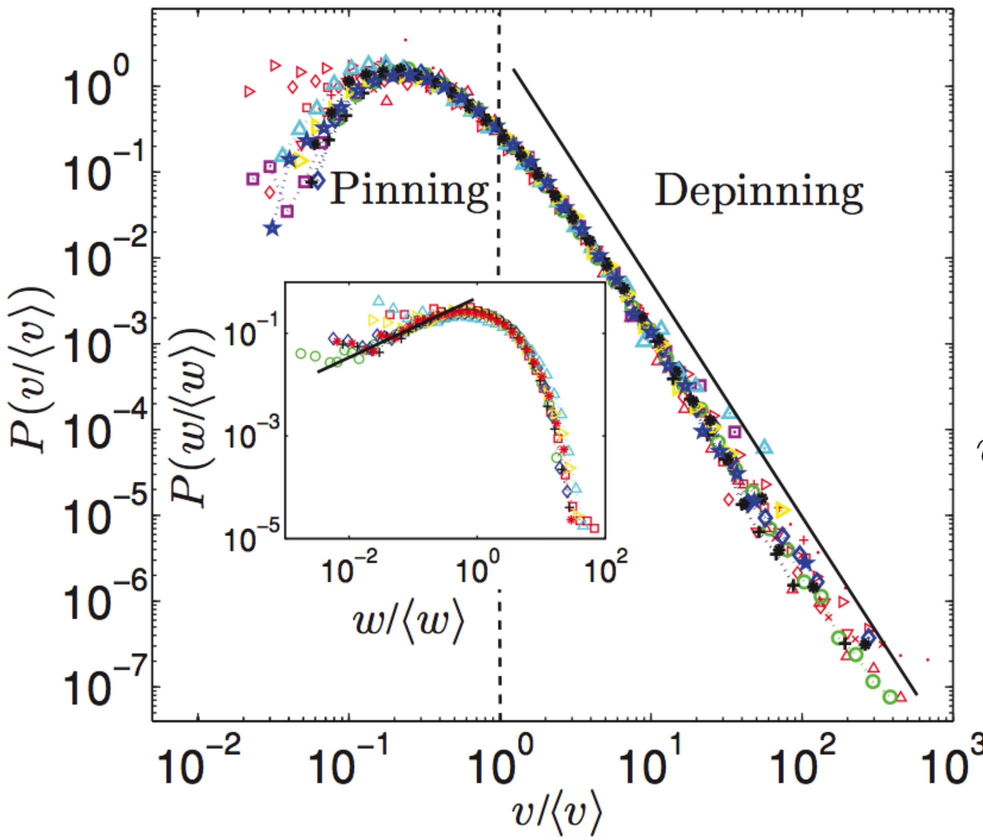
$$v = \frac{a}{w.\delta t}$$

a   pixel size
δt time delay between 2 pictures
w element in waiting time matrix

Santucci et al, (06), Måløy et al, PRL (06)

Results

- local front velocity distribution



Distribution independent of loading regime : creep or forced

0.03 μm.s^{-1} < ‹V› < 300 μm.s^{-1}

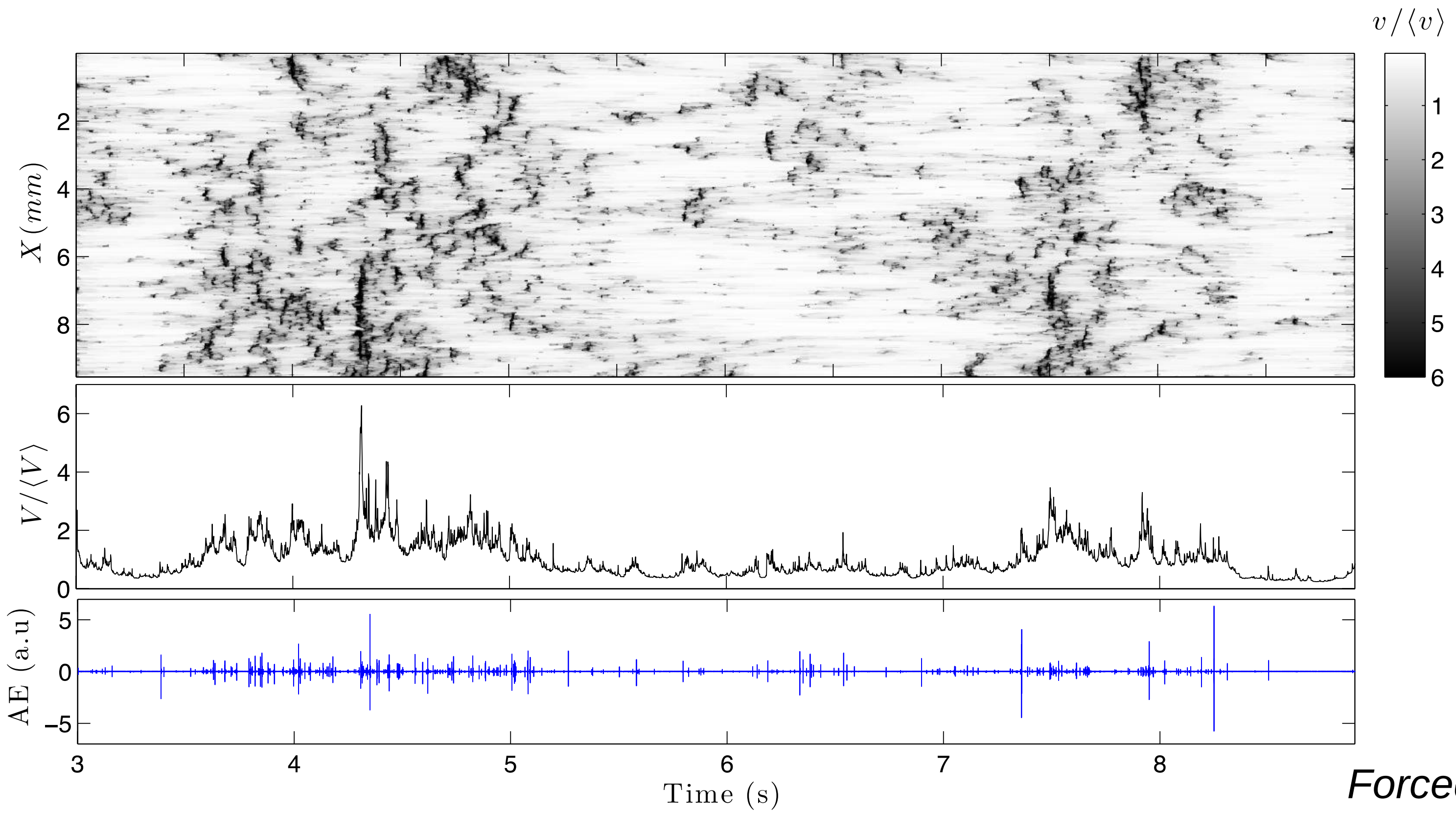
$$v > \langle v\rangle \; : \; P\left(\frac{v}{\langle v\rangle}\right) \sim \left(\frac{v}{\langle v\rangle}\right)^{-(\alpha+1)}$$

$$\alpha + 1 = 2.6 \pm 0.15$$

Santucci et al, (06), Måløy et al, PRL (06), Tallakstad et al, PRE (11)

Results

- Crackling Noise $V_l(t) = \langle v(x,t) \rangle_l \equiv \frac{1}{l} \sum_{i=1}^{l} v(x_i, t)$



Forced expts

$\langle V \rangle \approx 200\ \mu m.s^{-1}$

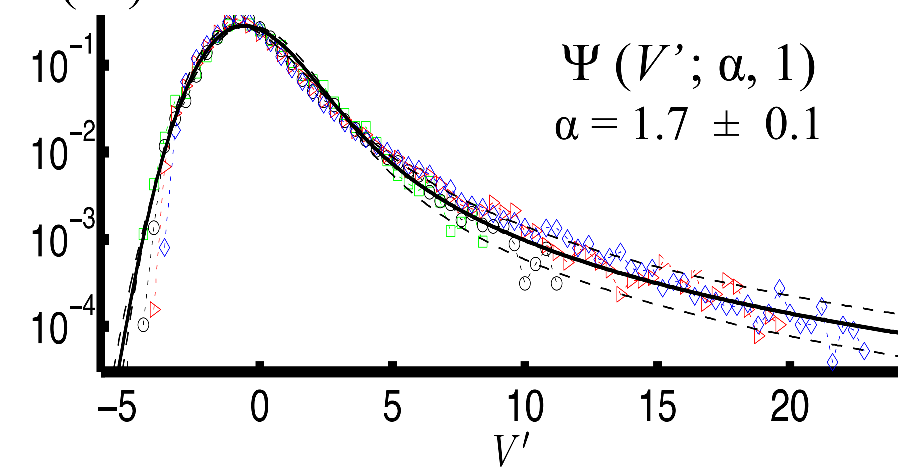
Santucci et al, ICF (09),

Results

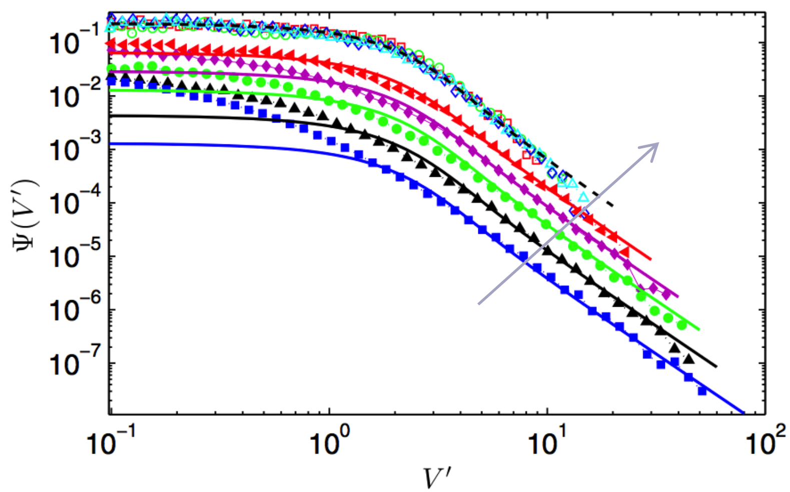
- Crackling Noise $V_l(t) = \langle v(x,t)\rangle_l \equiv \frac{1}{l}\sum_{i=1}^{l} v(x_i, t)$

$$P(v/\bar{v}) \propto (v/\bar{v})^{-(\alpha+1)} \qquad \alpha = 1.7 \pm 0.1 < 2$$

→ *Generalized Central Limit Theorem*
Alpha Stable Levy Distribution



$$V' = \frac{V_l - \langle V_l \rangle_T}{b_l}$$



→ Fat tail survives the upscaling

Tallakstad et al PRL (13)

Results

- Burst dynamics : spatial distribution of clusters

Creep expts

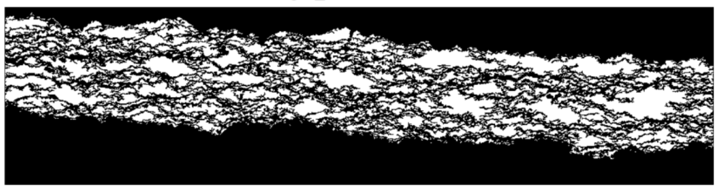
⟨V⟩ = 1.4 μm.s^{-1}

Clipped velocity map V_C :

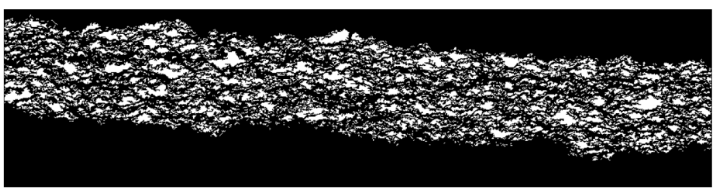
$$V_C = \begin{cases} 1 & \text{for } v \geq C \langle v \rangle \\ 0 & \text{for } v < C \langle v \rangle \end{cases}$$

$$V_C = \begin{cases} 1 & \text{for } v \leq \frac{1}{C} \langle v \rangle \\ 0 & \text{for } v > \frac{1}{C} \langle v \rangle \end{cases}$$

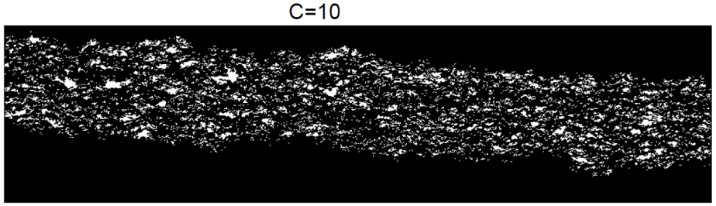
C=2



C=4

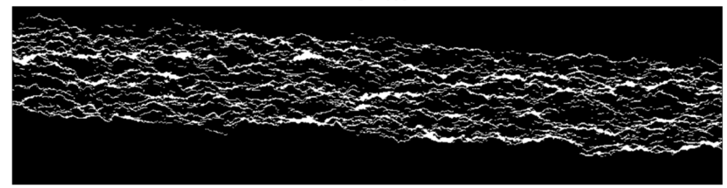


C=10

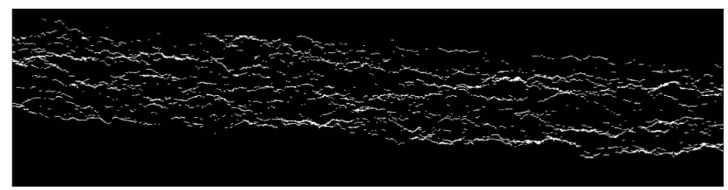


Depinning Bursts

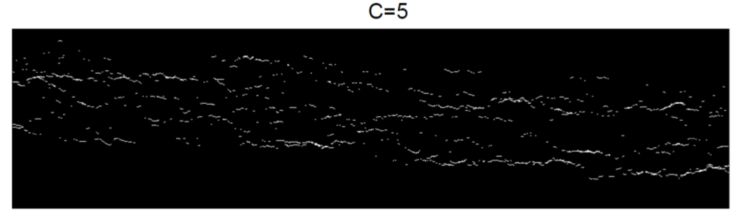
C=1.5



C=3



C=5

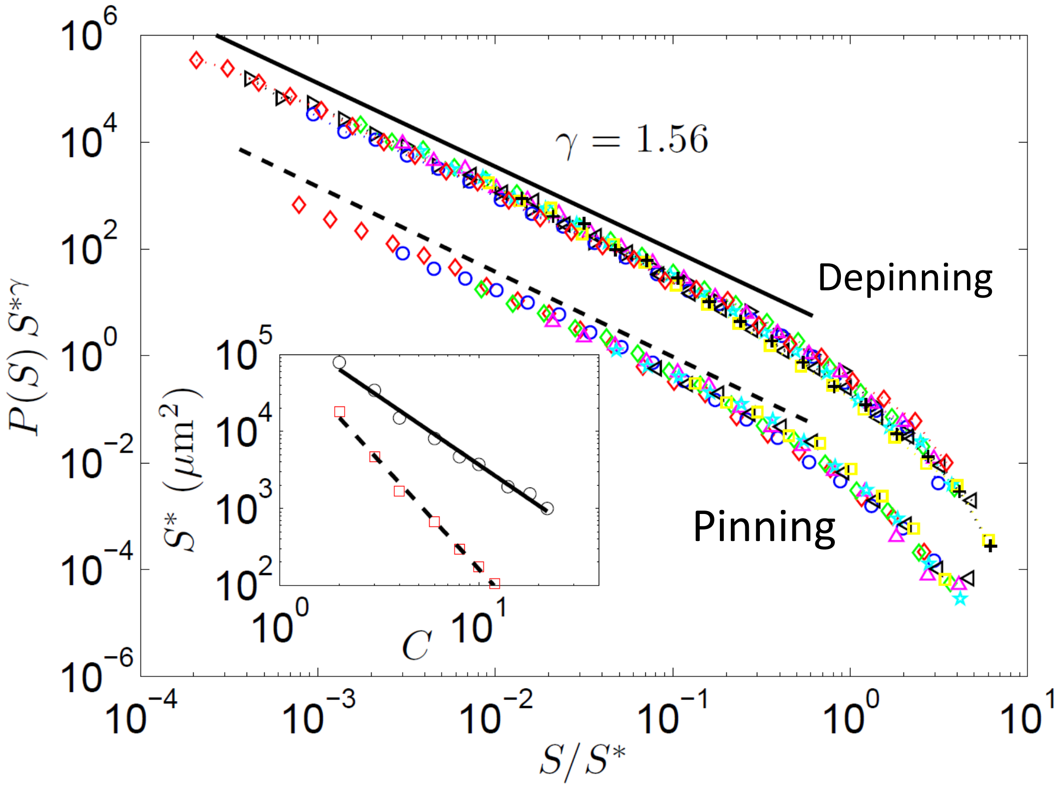


Pinning Clusters

Tallakstad et al, PRE (11)

Results

- Clusters size distribution



$$P(S) \propto S^{-\gamma} \exp(-S/S^*)$$

Distributions independent of loading regime : creep or forced

For both Pinning / Depinning

$$\gamma = 1.56 \pm 0.04$$

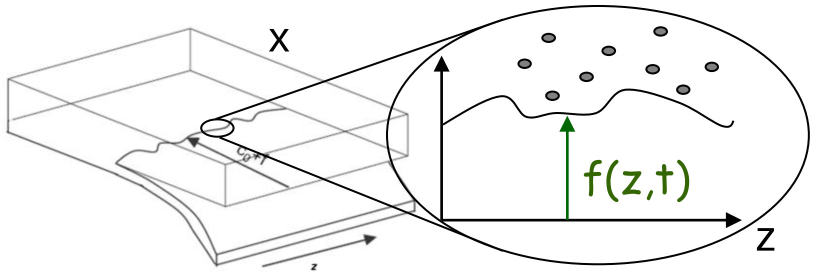
Extremely robust
wide range of exp. conditions
thresholds *C*

Tallakstad et al, PRE (11)

Results

Propagation of an elastic line through a disordered landscape

(Coll.: D. Bonamy, L. Ponson)



- Quasi-static limit
- Linear elastic material and weakly heterogeneous

→ long-range elastic kernel

Gao & Rice (89)

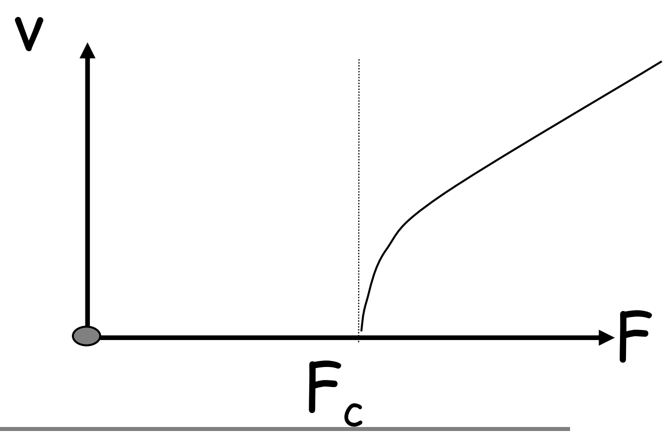
$$\frac{1}{\mu\Gamma^0}\frac{\partial f}{\partial t} = F(t,\{f\}) + \frac{1}{2\pi}\int_{-\infty}^{-\infty}\frac{f(z',t)-f(z,t)}{(z'-z)^2}dz' - \eta(z,f(z,t))$$

$$F(t,\{f\}) = \frac{4}{c_0}(v_m t - \langle f(z,t)\rangle_z)$$

F ≠ constant

Retro-action process: F ~ F_c

→Self-organized criticality



Bonamy et al, PRL (08)

Results

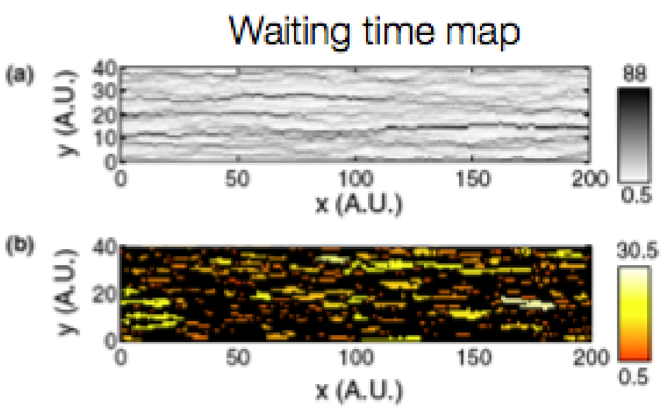
- Bursts size distribution / comparison with simulations

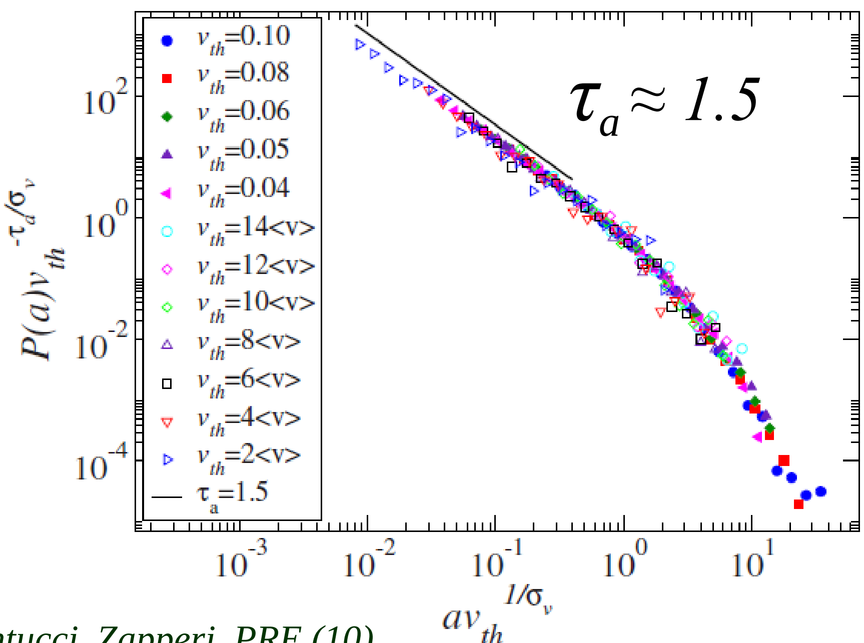
(Coll.: D. Bonamy, L. Ponson / L. Laurson, S. Zapperi)

Propagation of an elastic line through a disordered landscape

Quantitative agreement !!

size, duration & shapes of the clusters



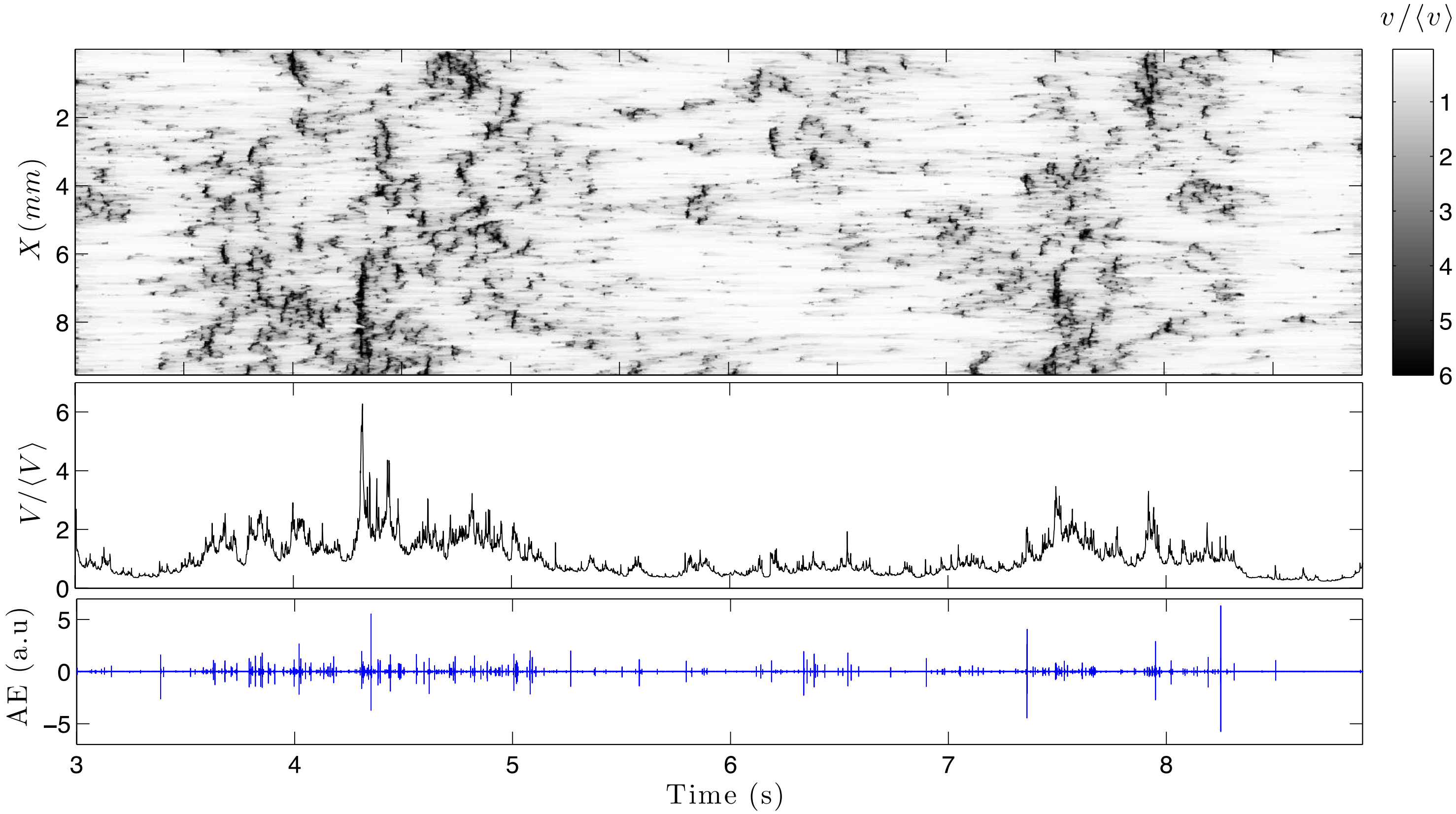


Bonamy, Santucci, Ponson, PRL (08), Laurson, Santucci, Zapperi, PRE (10)

Results

Crackling Noise

$$V_l(t) = \langle v(x,t)\rangle_l \equiv \frac{1}{l}\sum_{i=1}^{l} v(x_i,t)$$



Forced expts

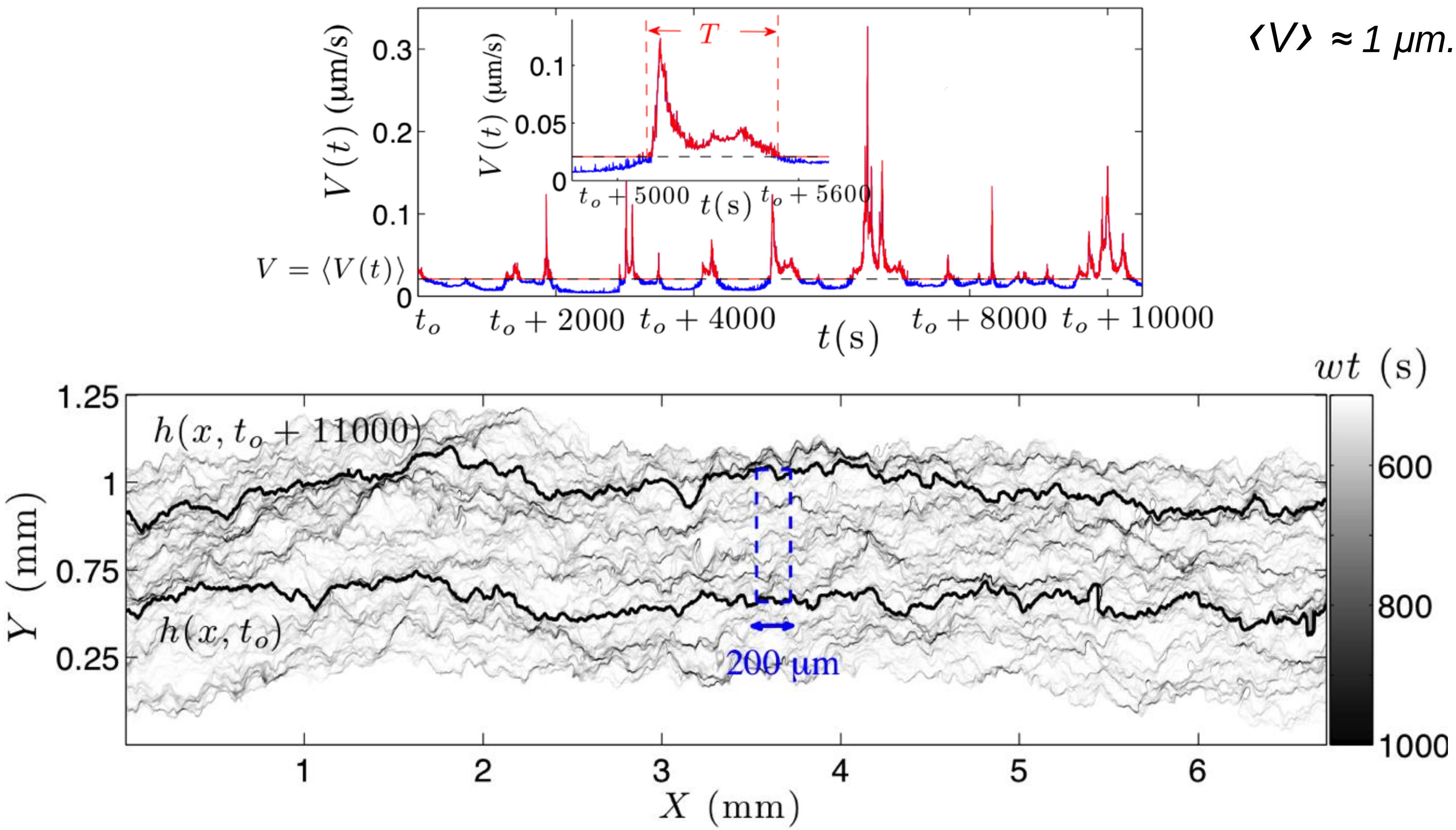
⟨V⟩ ≈ 200 μm.s^{-1}

Santucci et al, ICF (09),

Crackling Noise

Creep expts

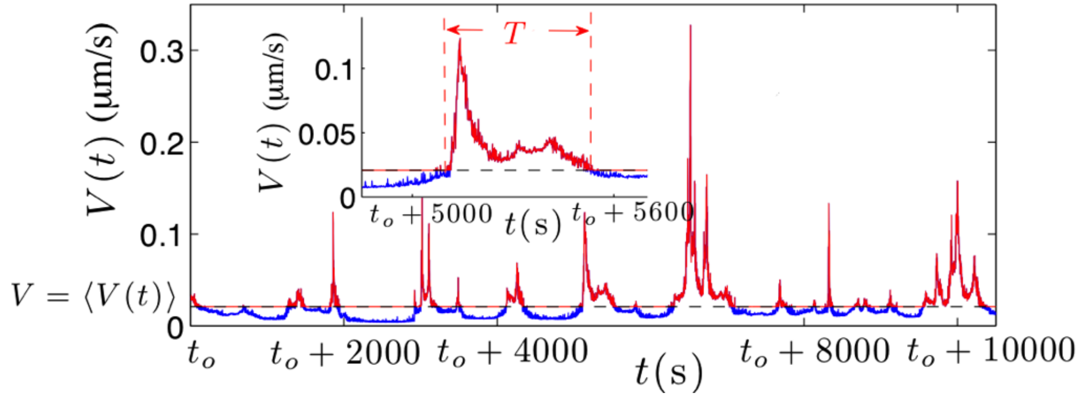
⟨V⟩ ≈ 1 μm.s⁻¹

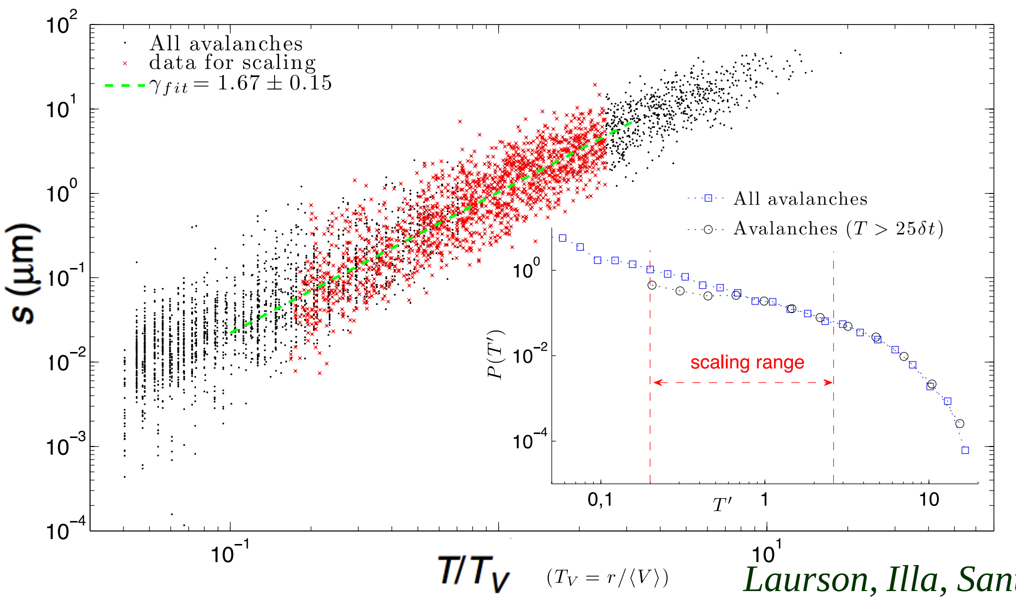


Laurson, Illa, Santucci, Tallakstad, Maloy, Alava, Nat. Comm (2013)

Results

Crackling Noise





$$\langle s(T) \rangle \equiv \int_0^T \langle V(t|T) \rangle dt \propto T^\gamma$$

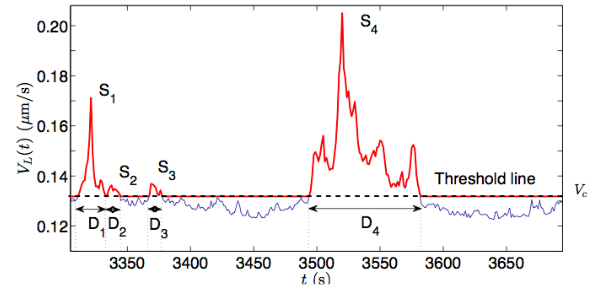
$$\gamma \approx 1.7$$

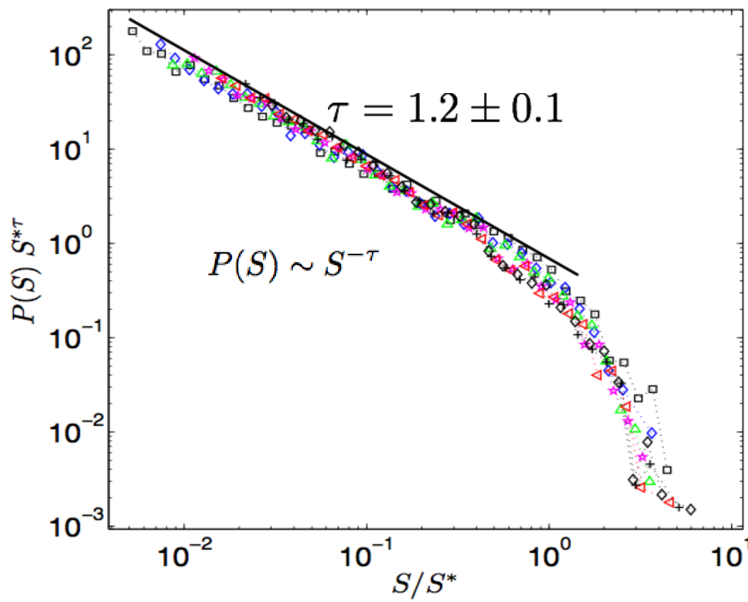
Laurson, Illa, Santucci, Tallakstad, Maloy, Alava, Nat. Comm (2013)

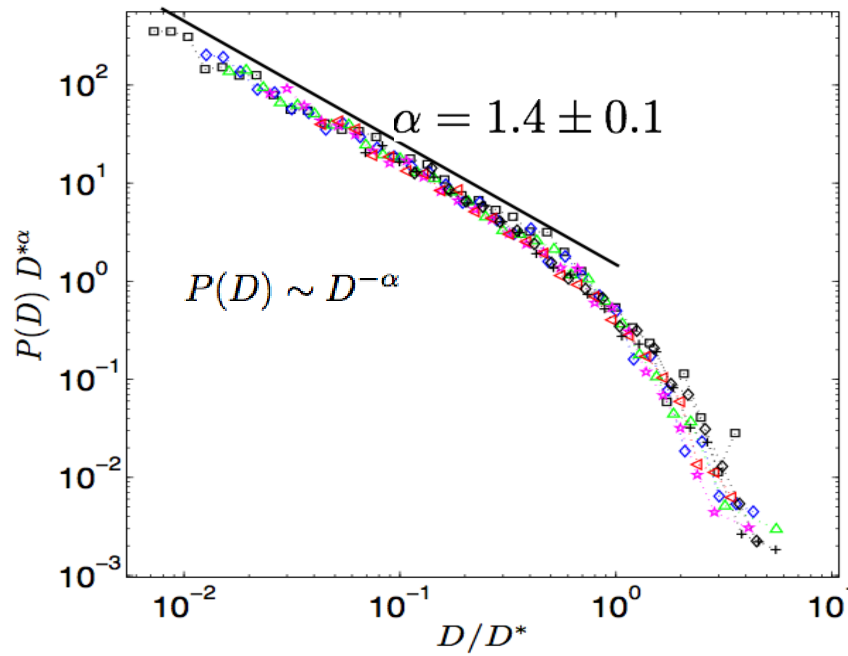
Results

Crackling Noise

Avalanche Statistics

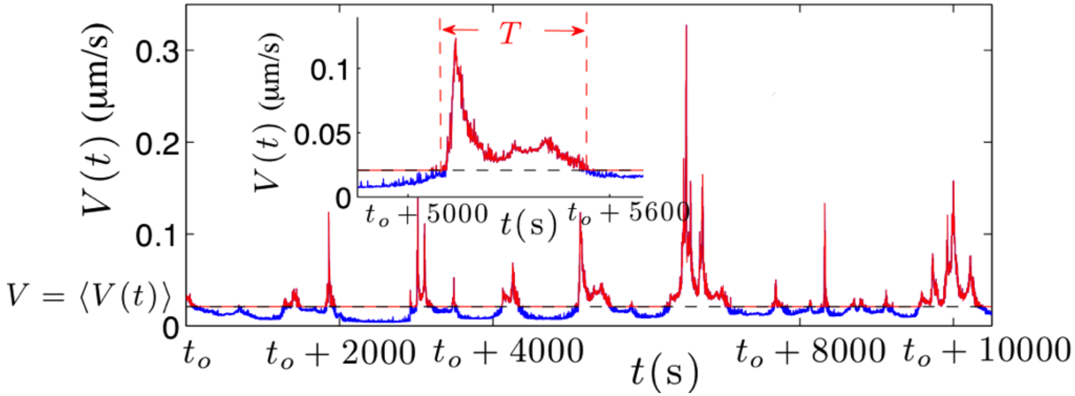


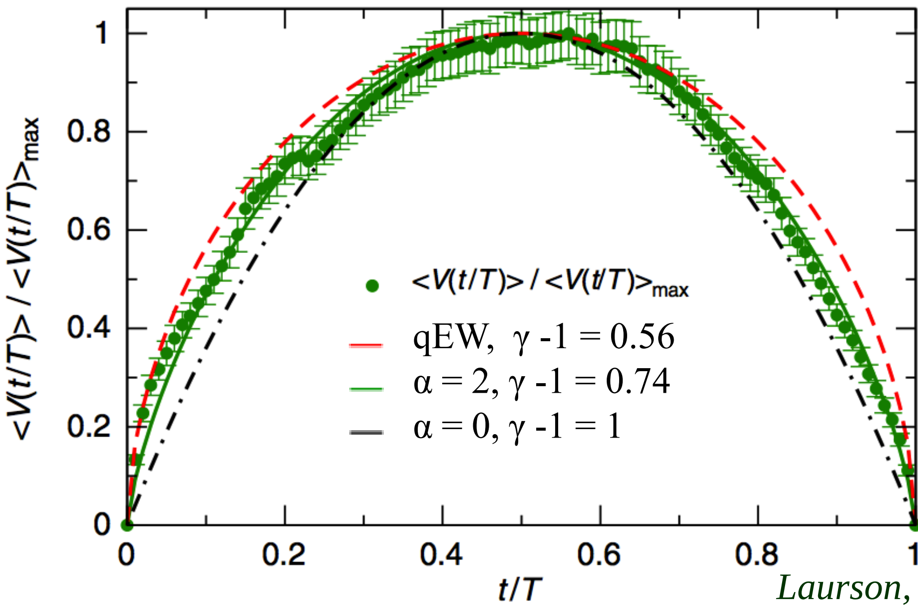




Results

Crackling Noise / Avalanche Shape





Average Avalanche Shape

$$\langle V(t|T) \rangle \propto T^{\gamma-1} \left[\frac{t}{T} \left(1 - \frac{t}{T} \right) \right]^{\gamma-1}$$

$$\gamma \approx 1.7$$

Laurson, Illa, Santucci, Tallakstad, Maloy, Alava, Nat. Comm (2013)

Summary

Propagation of an elastic crack line through a disordered landscape

A simple model with minimal ingredients :

Linear Elastic Material, weak disorder, quasi-static limit

Langevin equation with non local elastic term,

Quasi-static crack growth appears as a "self-organized" dynamic phase transition

Reproduce the Crackling dynamics

Quantitatively the scaling behavior at both local and global scales

Avalanches shape, size and duration distributions.

Måløy, Santucci, Schmittbuhl, Toussaint PRL (06),
Bonamy, Santucci, Ponson, PRL (08),
Laurson, Santucci, Zapperi, PRE (10),
Tallakstad, Toussaint, Santucci, Schmittbuhl, Måløy, PRE (11),
Laurson, Illa, Santucci, Tallakstad, Maloy, Alava, Nat. Comm (2013)

Interfacial depinning model

$v_i = \theta(F_i) \quad V(t) = \sum_i v_i(t)$

Control the universality class by tuning α.

Force acting on a segment of the interface:

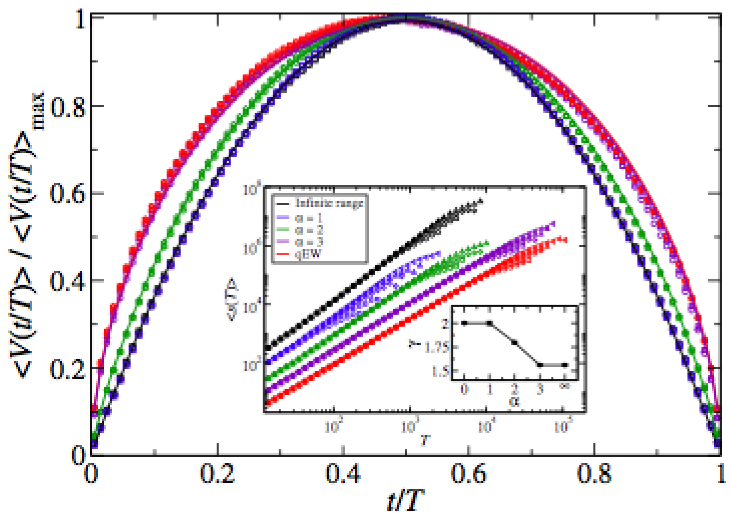
$$F_i = \Gamma_0 \sum_{j \neq i} \frac{h_j - h_i}{|x_j - x_i|^\alpha} + \eta(x_i, h_i) + F_{ext}$$

$\alpha \to \infty$: $\Gamma_0 \nabla^2 h_i$ — local qEW model.

$\alpha = 2$ — long-range elastic string (planar crack fronts, contact lines, grain boundaries).

$\alpha \to 0$: $\Gamma'_0(\bar{h} - h_i)$ — Infinite range mean field model.

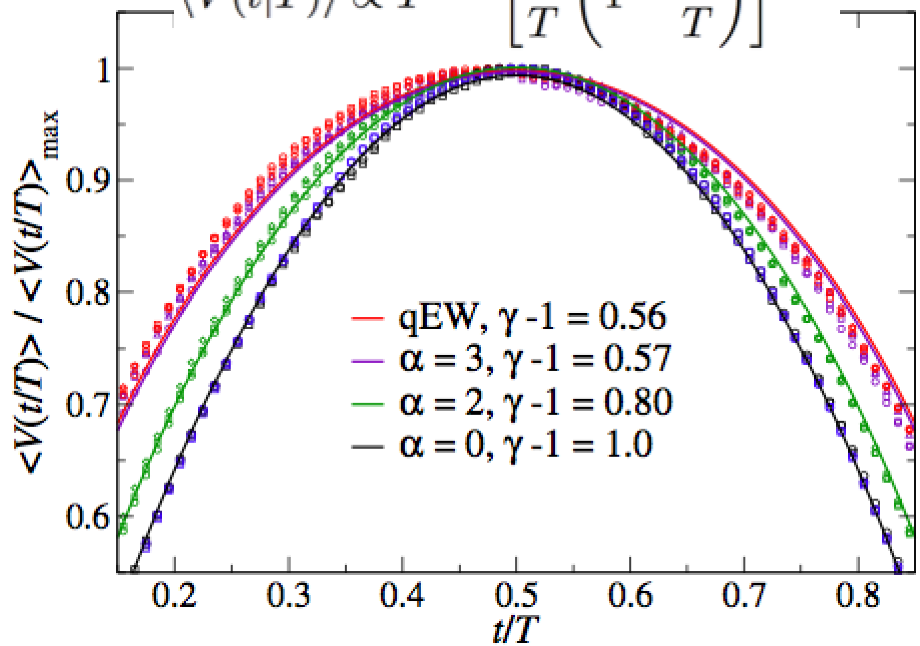
Average Avalanche Shape



Fitting the avalanche shapes reproduces the values of the γ-exponents.

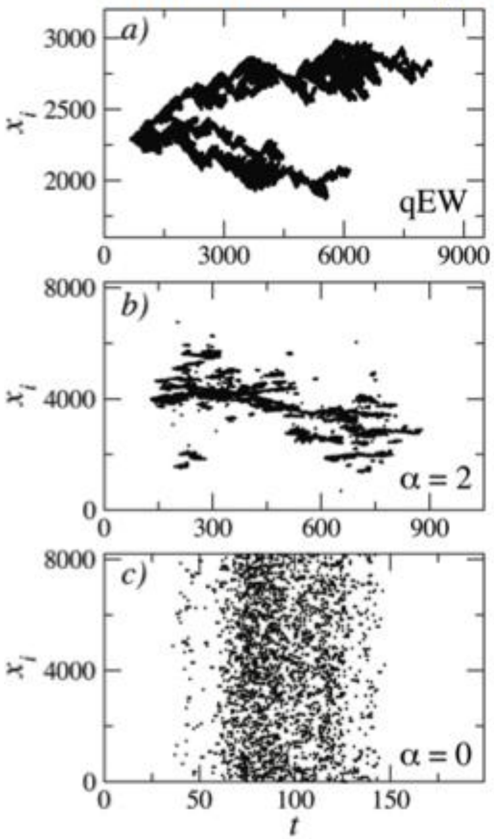
$$\langle V(t|T)\rangle \propto T^{\gamma-1}\left[\frac{t}{T}\left(1-\frac{t}{T}\right)\right]^{\gamma-1}$$

For localized interaction kernels, the symmetric function does not work.



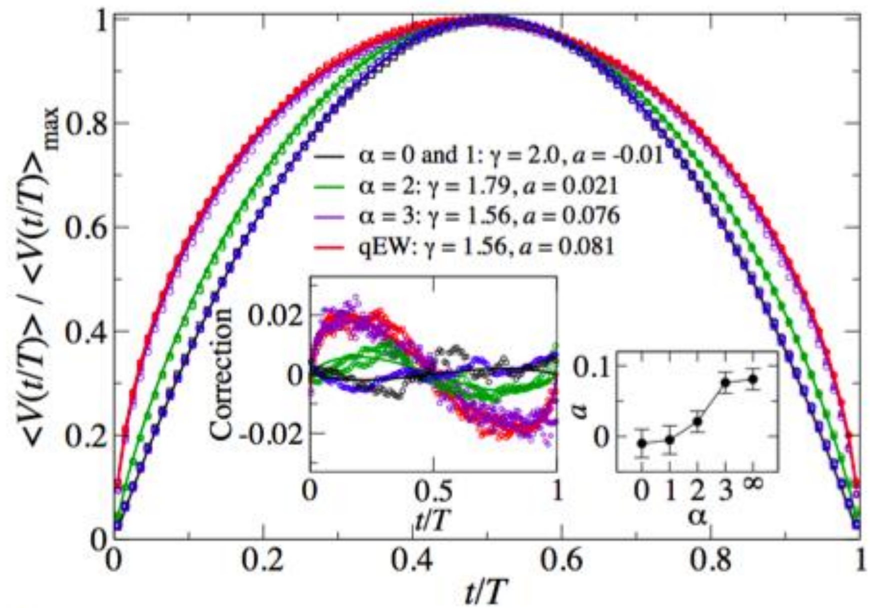
Broken Time symmetry

Space-time avalanche activity:



Introduce an asymmetry correction:

$$\langle V(t|T)\rangle \propto T^{\gamma-1}\left[\frac{t}{T}\left(1-\frac{t}{T}\right)\right]^{\gamma-1}\left[1-a\left(\frac{t}{T}-\frac{1}{2}\right)\right]$$



Asymmetry evolves with the interaction range.

More details in :

– L. Laurson, X. Illa, S. Santucci, K. T. Tallakstad, K.J. Måløy, and M. Alava, **Nature Comm., 4 : 2927 (2013)**, *Evolution of the average avalanche shape with the universality class*

– K. T. Tallakstad, R. Toussaint, S. Santucci, and K.J. Måløy, **Phys. Rev. Lett. 110, 154301 (2013)**, *Non-Gaussian nature of fracture and the survival of fat-tail exponent*

– K. Tallakstad, R. Toussaint, S. Santucci, J. Schmittbuhl, and K.J. Måløy, **Phys. Rev. E, 83, 046108 (2011)**, *Local Dynamics of a Randomly Pinned Crack Front during Creep and Forced Propagation,*

– L. Laurson, S. Santucci, S. Zapperi, **Phys. Rev. E, 81 (4), 046116, (2010)**, *Avalanches and clusters in planar crack front propagation,*

– S. Santucci, M. Grob, R. Toussaint, J. Schmittbuhl, A. Hansen and K.J. Måløy, **EPL 92, 44001, (2010),** *Fracture roughness scaling : a case study on planar cracks*

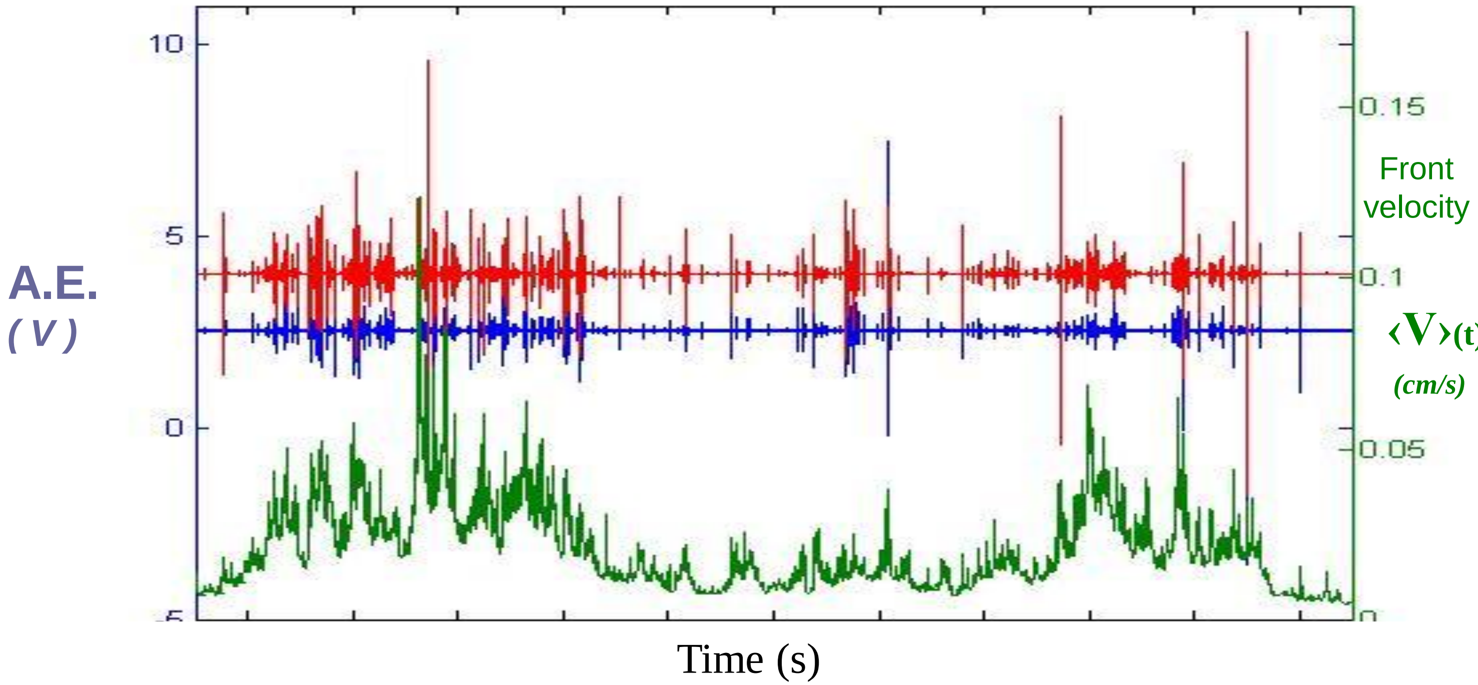
– D. Bonamy, S. Santucci, L. Ponson, **Phys. Rev. Lett. 101, 045501 (2008)** *Crackling dynamics in material failure as a self-organized dynamic phase transition,*

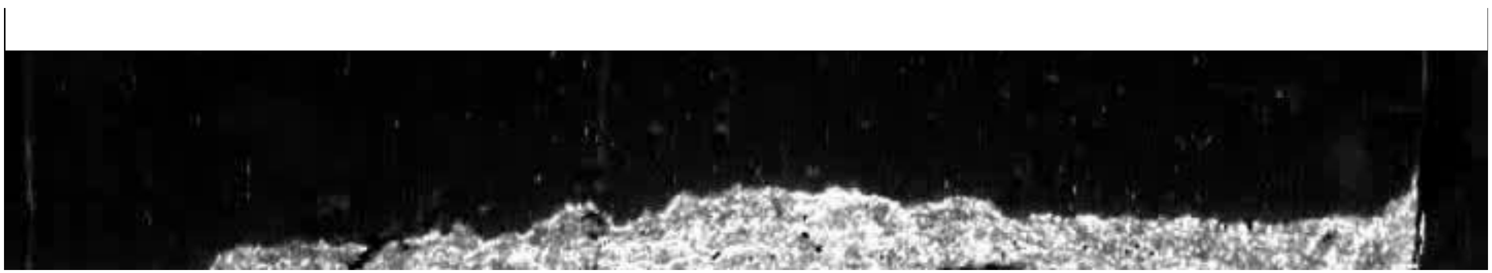
– S. Santucci et al, *Statistics of Fracture Surfaces,* **Phys. Rev. E 75, 016104 (2007)**

– K.J. Måløy, S. Santucci, J. Schmittbuhl, and R. Toussaint, **Phys. Rev. Lett., 96, 045501 (2006)** *Local waiting time fluctuations along a randomly pinned crack front,*

– S. Santucci, K.J. Måløy, R. Toussaint and J. Schmittbuhl, **NATO SCIENCE SERIES, 232, 49-59 (2006)** Dynamics of Complex Interconnected Systems, ASI Conference (Geilo, Norway) *Self-affine scaling during interfacial crack front propagation,*

"Crackling Noise"





Expt ~ 5 s, front length = 1 cm. - acquisition rate : movie : 1000 fps,
‹V› ~ 200 µm.s^{-1} ; resolution ~9µm sound : 1 MHz – (filtered at 10 kHz)