Cracking the crack: What do the scaling properties of fracture surfaces tell us about material failure?

Laurent Ponson

Institut Jean le Rond d'Alembert
CNRS – Université Pierre et Marie Curie
Paris, France

Tate gallery of modern art, London

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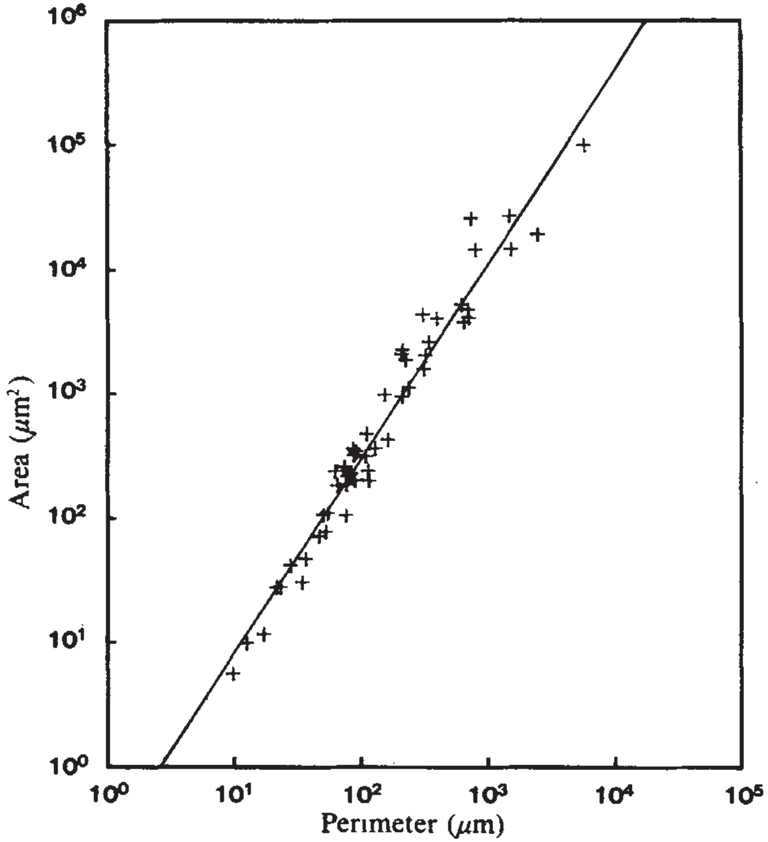
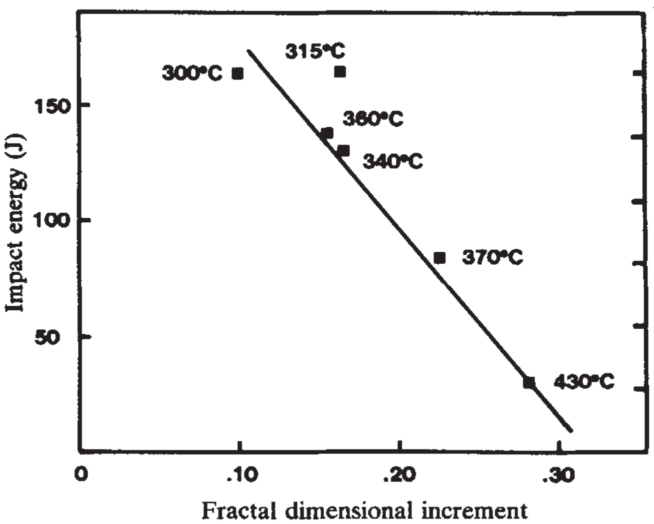
Fractal character of fracture surfaces of metals

Benoit B. Mandelbrot*, Dann E. Passoja† & Alvin J. Paullay‡

Measurement of the fractal dimension of fracture surfaces

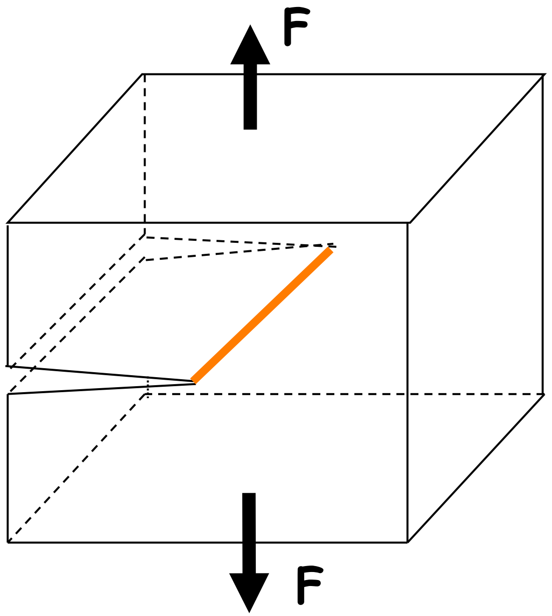


Fracture energy vs fractal dimension



A powerful predictive theory:
Linear Elastic Fracture Mechanics

Predicting the stability of cracks in an idealized elastic homogeneous solid



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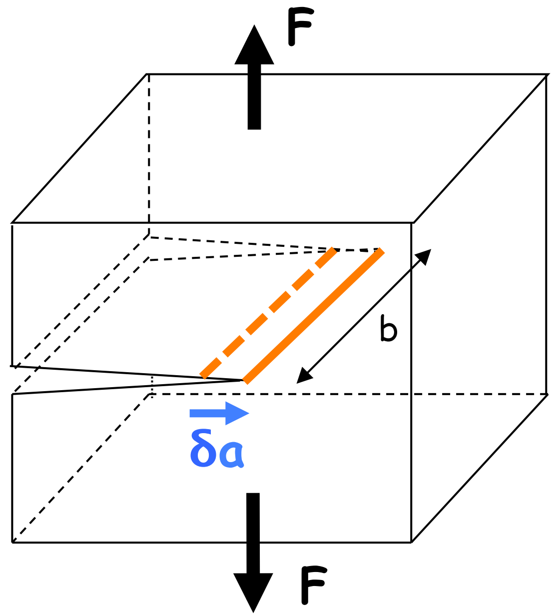

Energy balance:

δW_F	=	δE_{el}	+	δE_s
Work of the external force		Variation of elastic energy		Variation of surface energy

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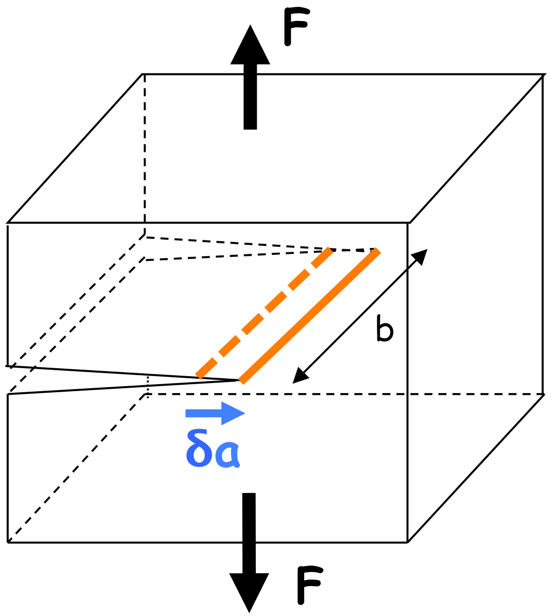

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Griffith's criterion:

Mechanical energy release rate	vs	Fracture energy
$G = \delta(W_F - \delta E_{el})/(\delta a.b)$		$G_c = \delta E_s/(\delta a.b)$

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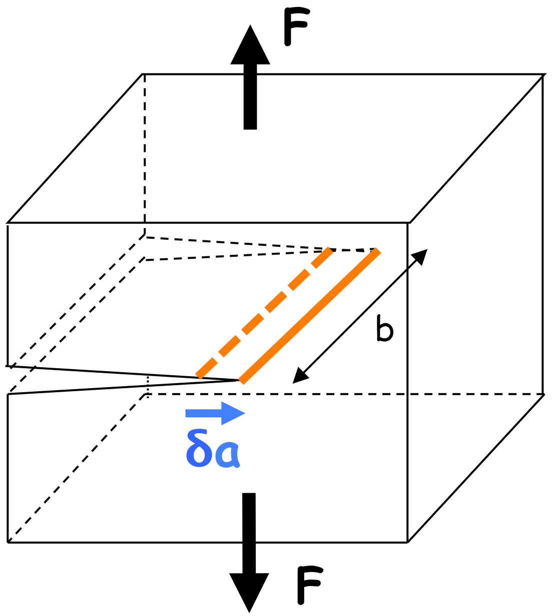

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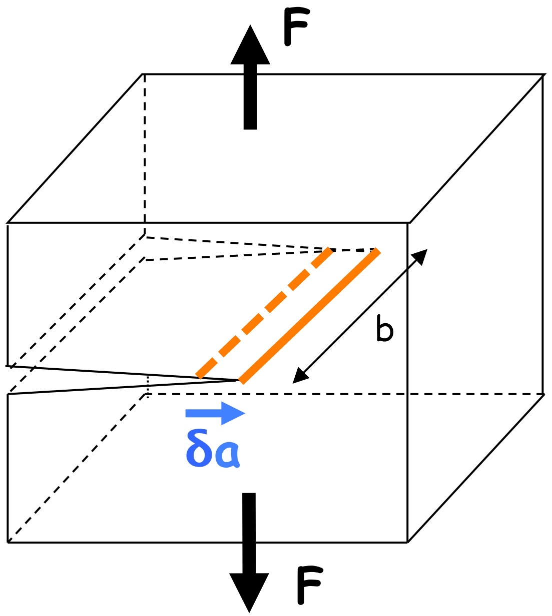

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$G < G_c$ → **Stable crack**

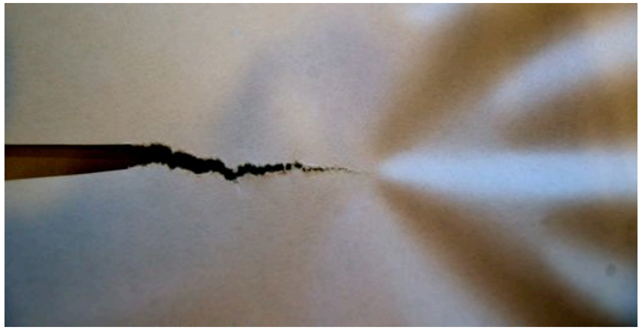
$G = G_c$ → **Propagating crack**

→ **But no hint on the actual value of fracture energy G_c**

	Silica glass	Paper	Aluminum
Fracture energy	7 J/m^2	100 J/m^2	10 kJ/m^2

Let's have a closer look at the tip of cracks

Crack in a paper sheet



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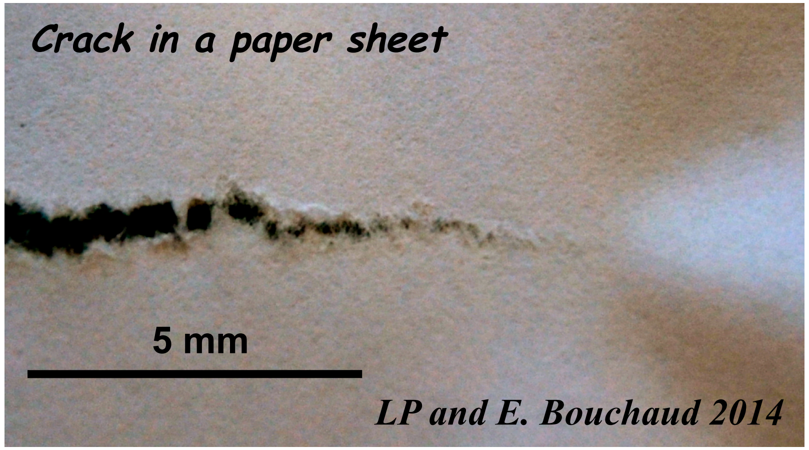

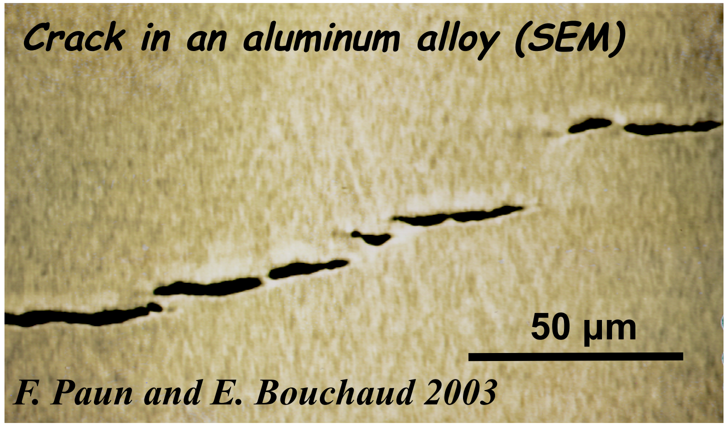

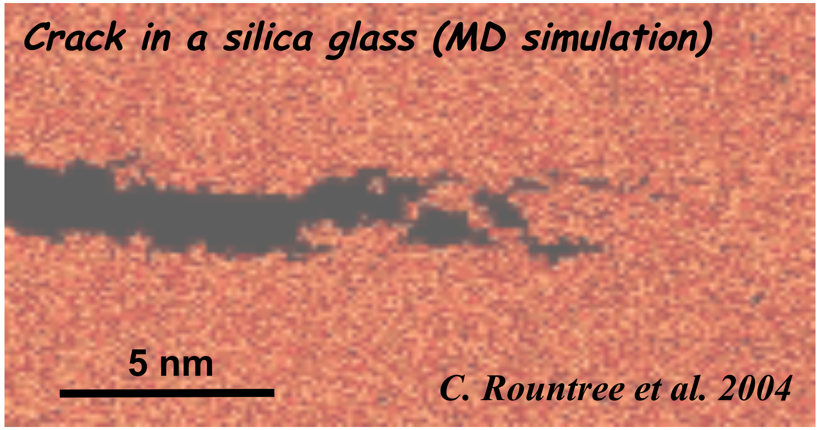

→ Crack propagation as a damage coalescence process taking place within some fracture process zone at the crack tip

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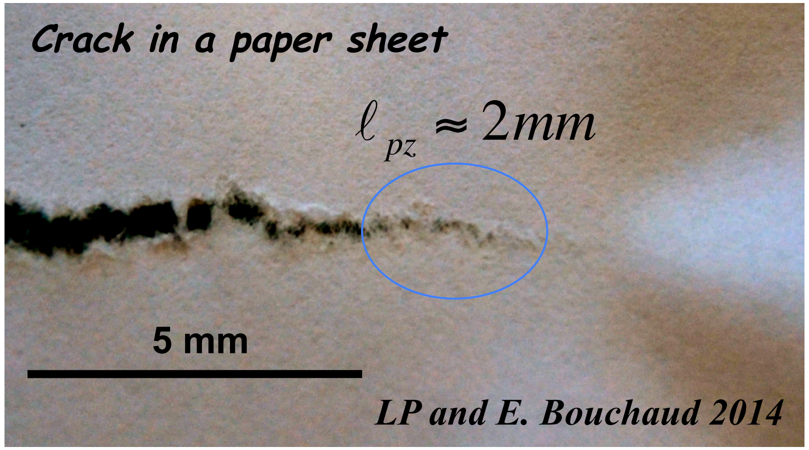

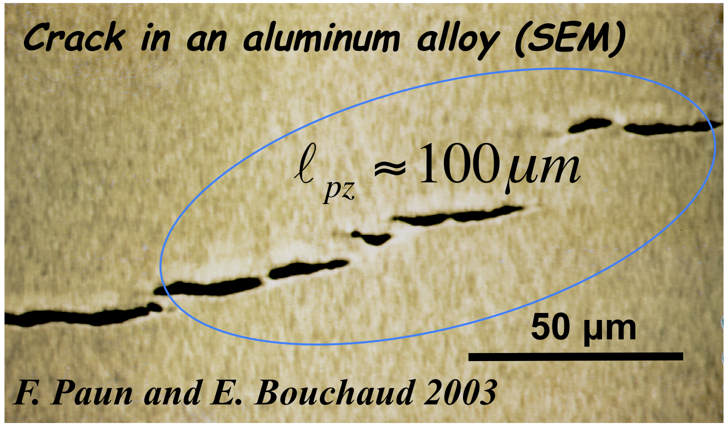

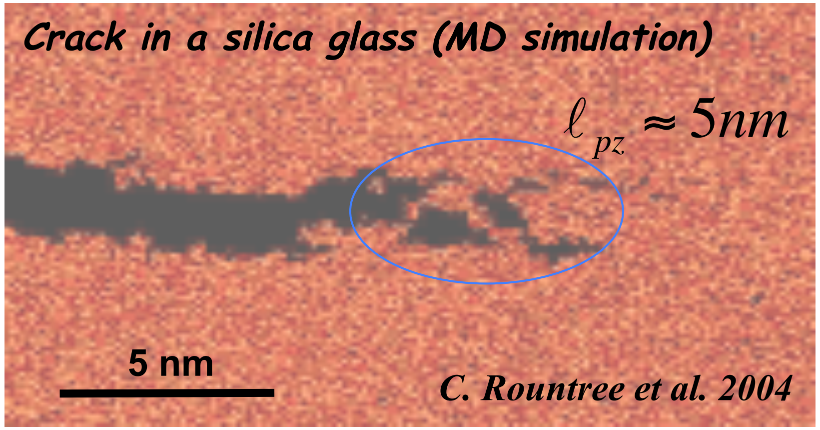

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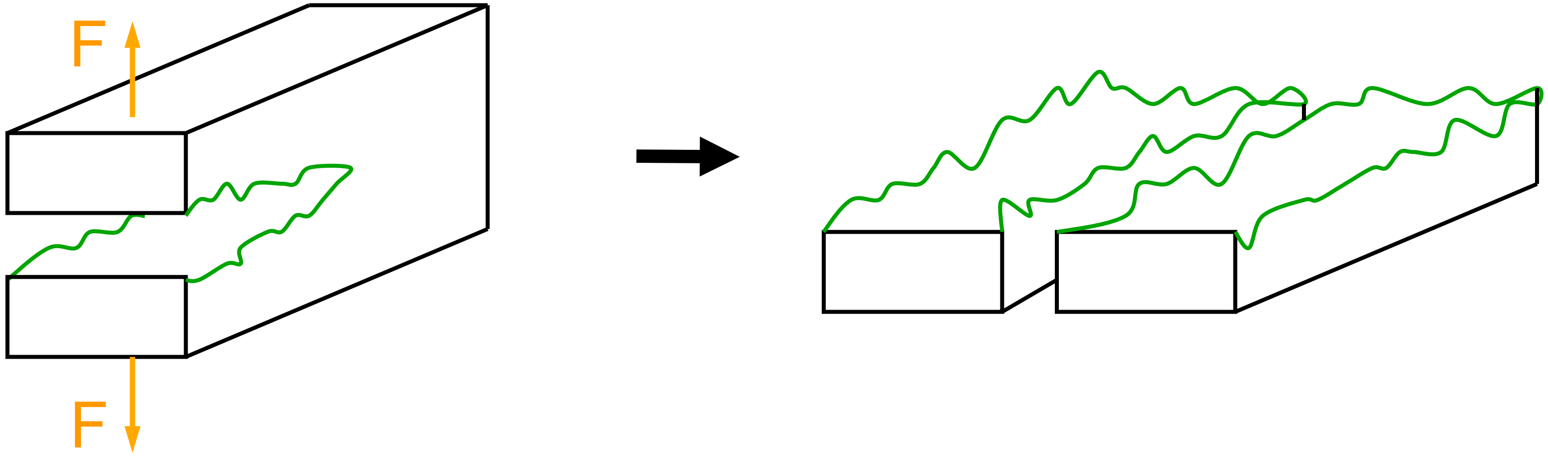
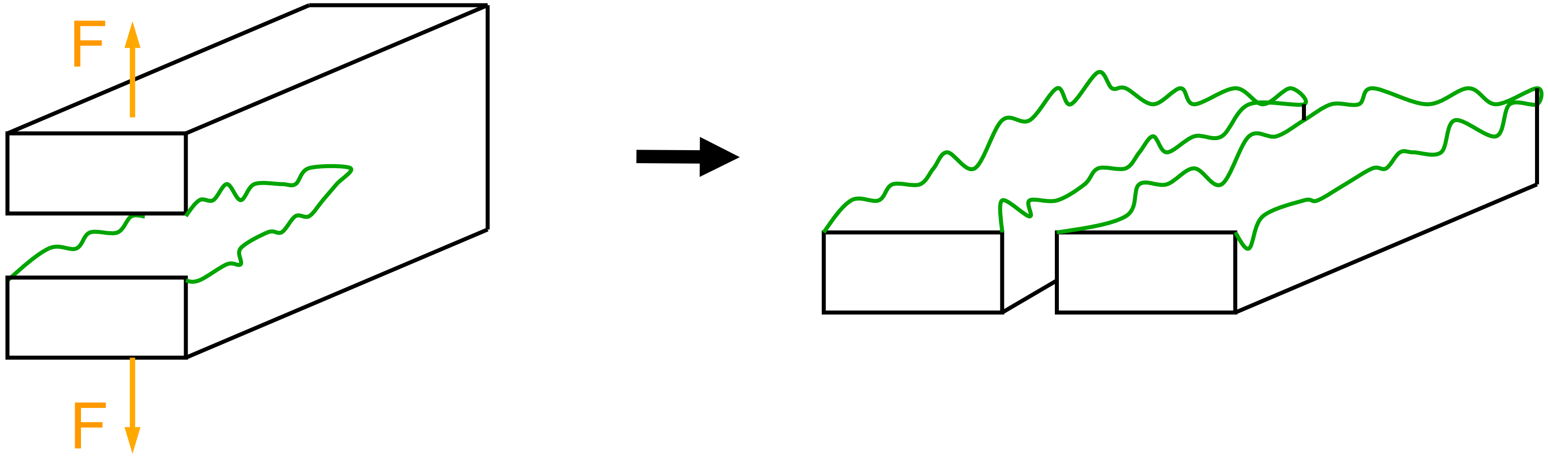
Statistical properties of crack roughness as a probe of the microscopic failure processes…

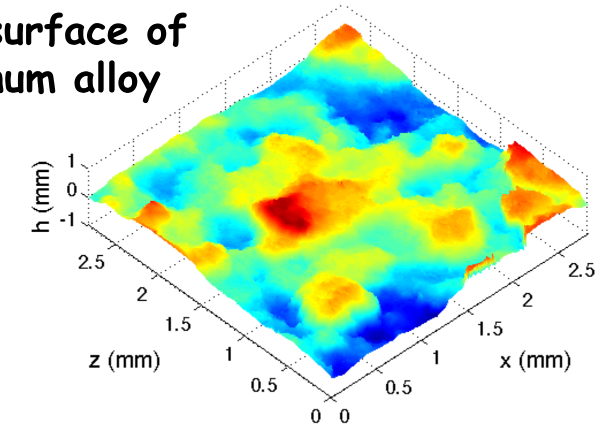


Statistical properties of crack roughness as a probe of the microscopic failure processes…



…if their complex geometry can be deciphered

Fracture surface of
an aluminum alloy



Rosetta stone

Goal: Providing a statistical description of the roughness of cracks

Using it for (i) exploring the dissipative failure mechanisms
(ii) tracing back the history of the failure of a material

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→ Persitent vs anti-persitent crack paths

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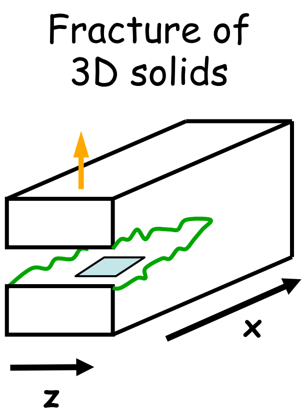
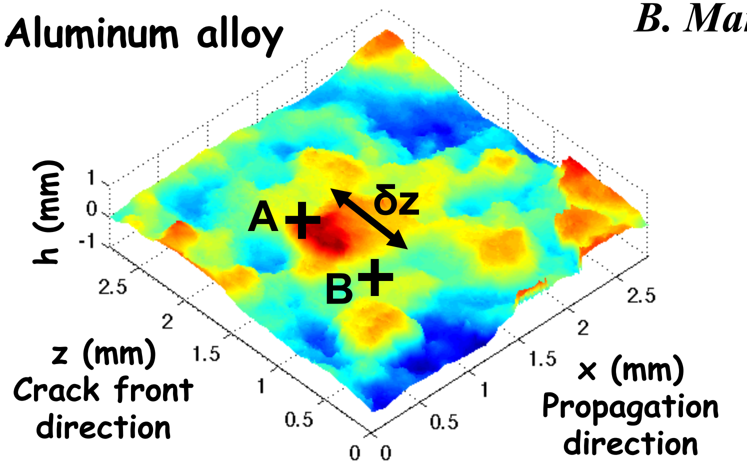
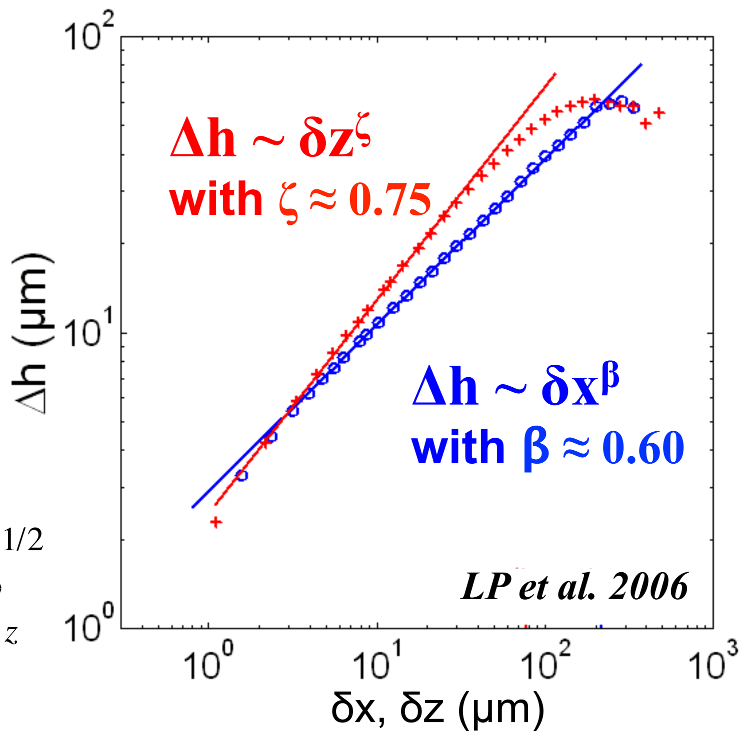
3- Application: Measuring material toughness from the *post-mortem* analysis of fracture surfaces

The roughness exponent as a signature of the failure mechanisms





B. Mandelbrot et al. 1984, E. Bouchaud et al. 1990



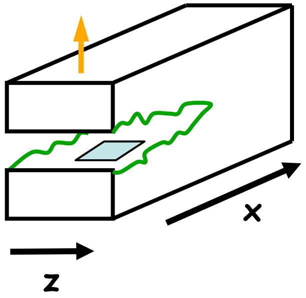
Height-height correlation function:

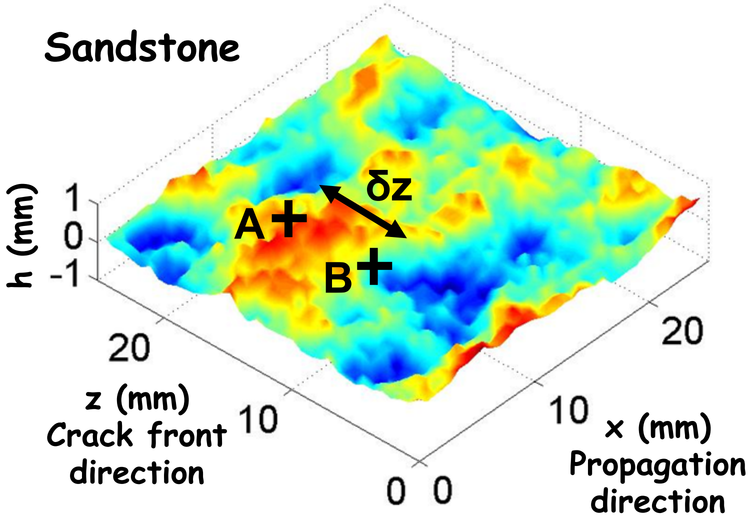
$$\Delta h(\delta z) = \left\langle \left(h(z+\delta z)-h(z)\right)^2 \right\rangle_z^{1/2} = \left\langle \left(\delta h(z,\delta z)\right)^2 \right\rangle_z^{1/2}$$

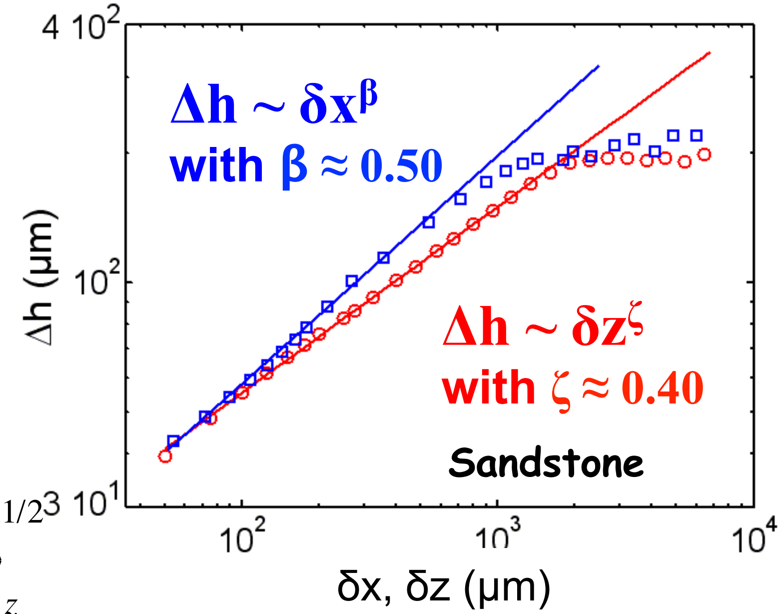
The roughness exponent as a signature of the failure mechanisms

J.M. Boffa et al. 1998, LP et al. 2007

Fracture of 3D solids







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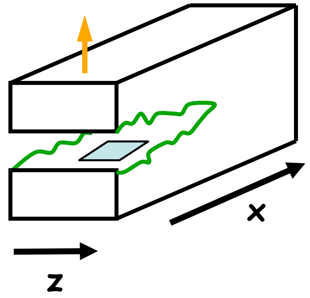

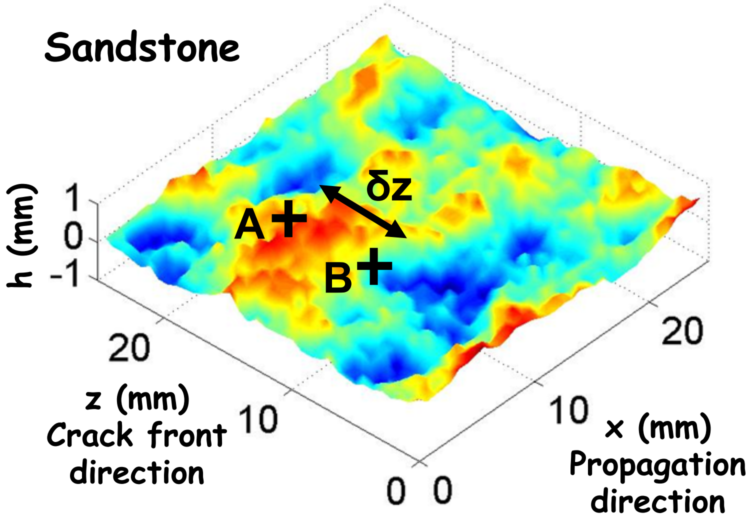

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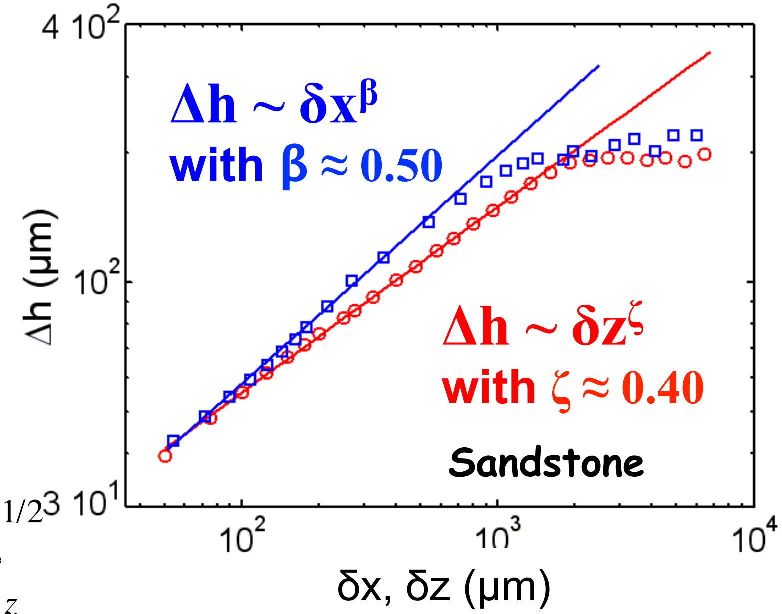

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→ **Two distinct classes of roughness**

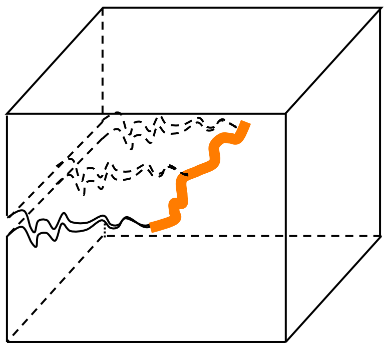
D. Bonamy et al. 2006, LP 2007

Brittle failure

$\zeta \approx 0.40$

$\beta \approx 0.50$

→ Ceramics, sandstone…

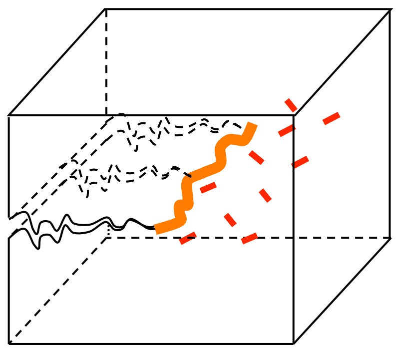


Failure by damage coalescence

$\zeta \approx 0.75$

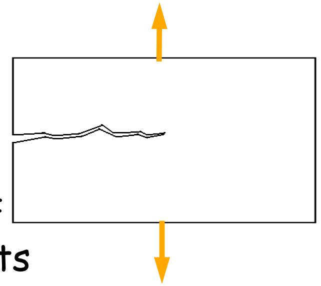
$\beta \approx 0.60$

→ Metallic alloys, mortar, granite…



Interpretation of the value of the exponents: Crack paths in 2D thin sheets

J. Kertész et al. 1993, T. Engøy et al. 1994, S. Santucci et al. 2007



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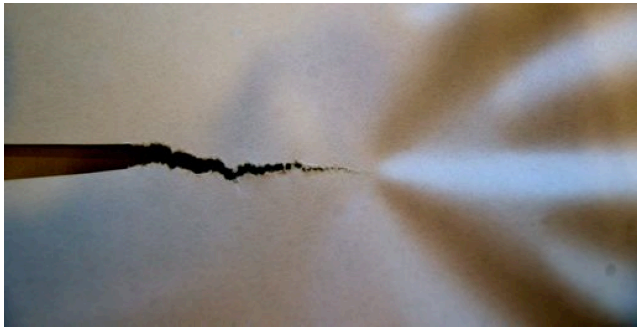
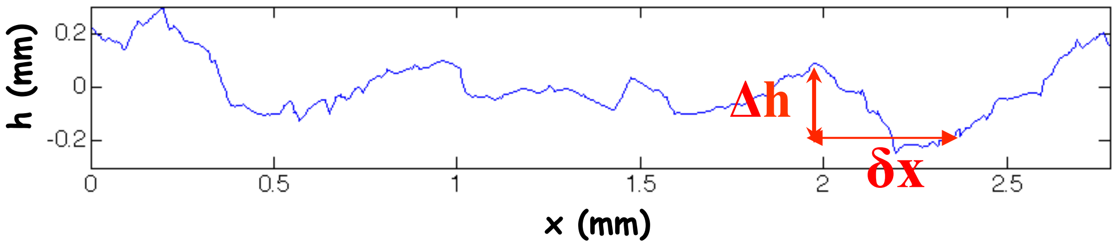
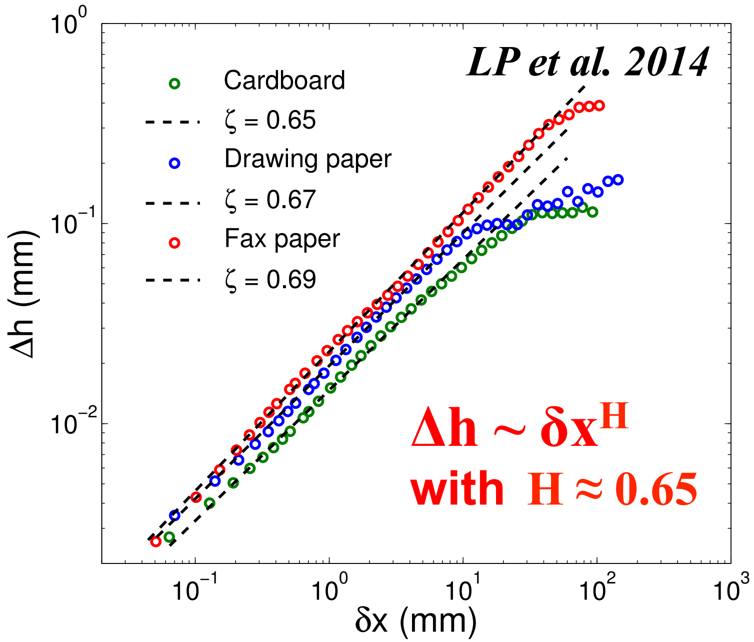


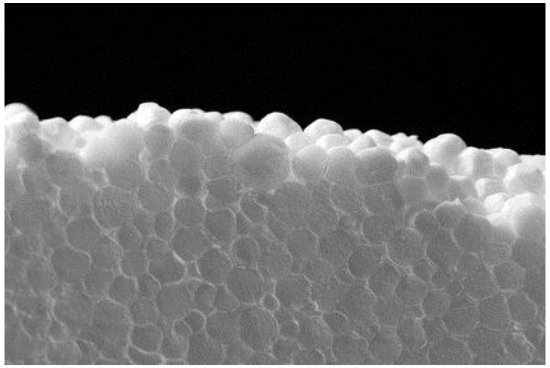




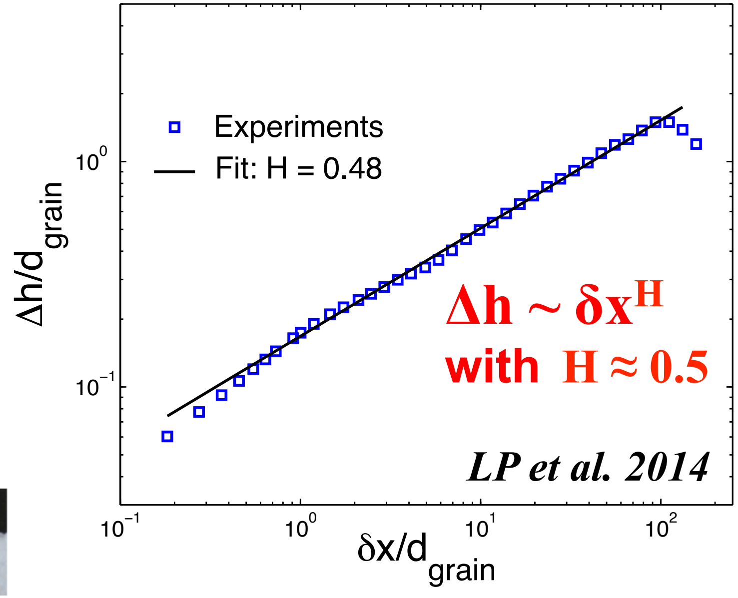
Interpretation of the value of the exponents: Crack paths in 2D thin sheets

Key assumption:

$\ell_{pz} << d_{grain}$



Fracture profile of a sheet of expanded polystyrene



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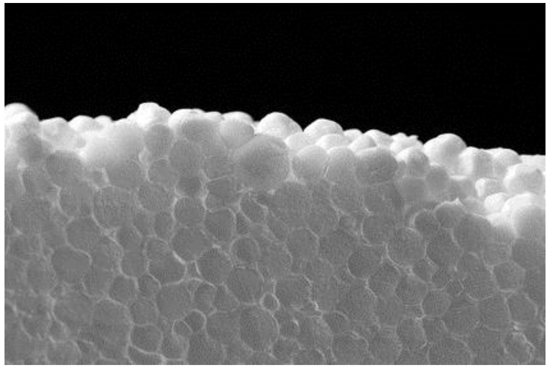
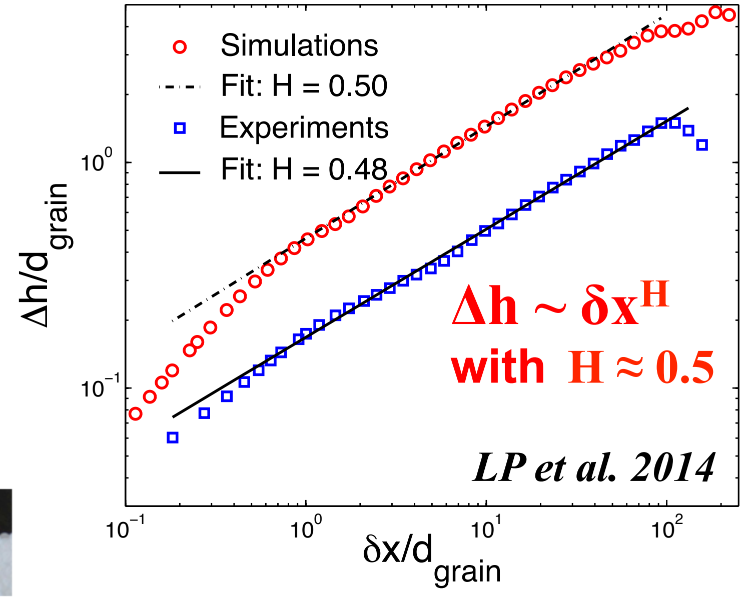
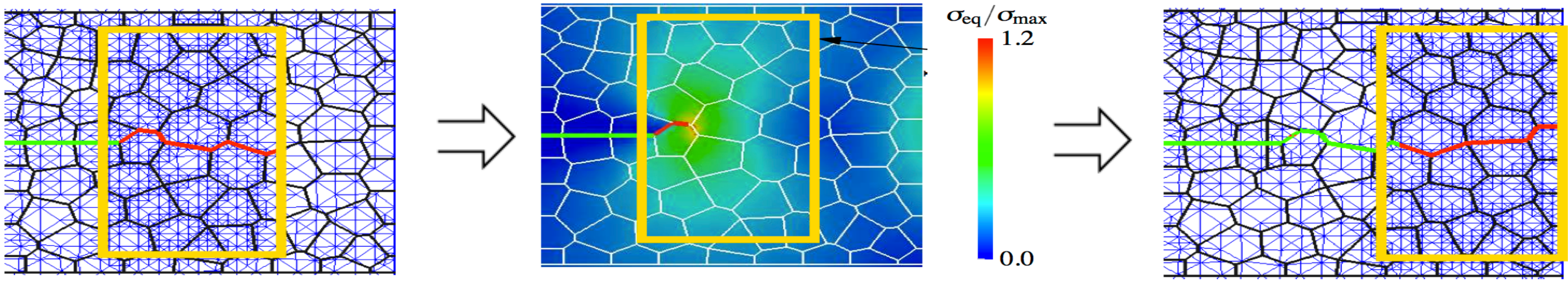
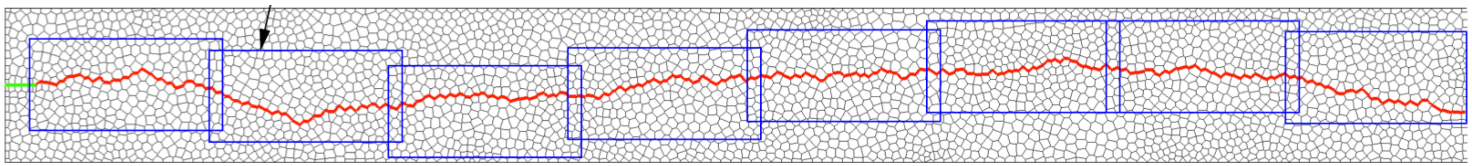




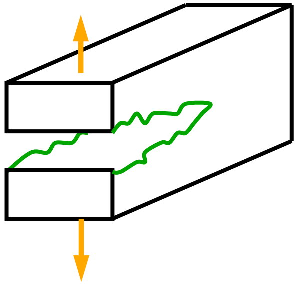
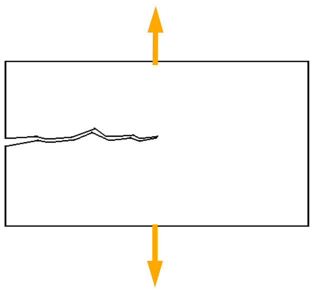
Fracture profile of a sheet of expanded polystyrene

→ Simulation of the process of crack propagation via cohesive zone model





Roughness exponent vs failure mechanisms: A tentative scenario

	Anti-persistent crack path	*Persistent* crack path
Fracture of *3D solids* 	$\zeta \approx 0.40$ $\beta \approx 0.50$	$\zeta \approx 0.75$ $\beta \approx 0.60$
Fracture of *2D thin sheets* 	$H \approx 0.50$	$H \approx 0.65$

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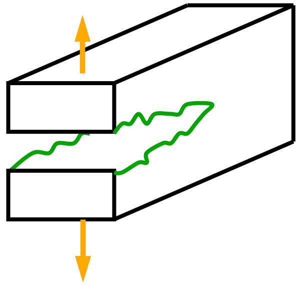
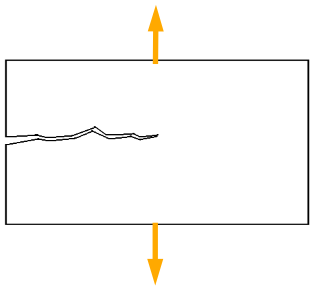
Fracture of *3D solids* 	$\zeta \approx 0.40$ $\beta \approx 0.50$	$\zeta \approx 0.75$ $\beta \approx 0.60$
	Brittle failure	**Failure by damage coalescence**
Fracture of *2D thin sheets* 	$H \approx 0.50$	$H \approx 0.65$
	→ **2D and 3D: Exponents captured by fracture mechanics based models**	→ **2D: Exponent captured by damage coalescence based models**
	D. Bonamy et al. 2006, E. Katzav et al. 2007, L. Konate et al. 2014	*M. Alava, S. Zapperi et al. 2006, E. Bouchbinder et al. 2007*

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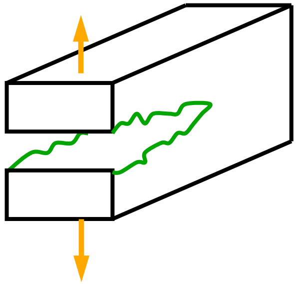
Fracture of *3D solids* 	$\zeta \approx 0.40$ $\beta \approx 0.50$	$\zeta \approx 0.75$ $\beta \approx 0.60$
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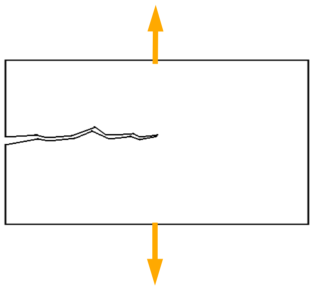
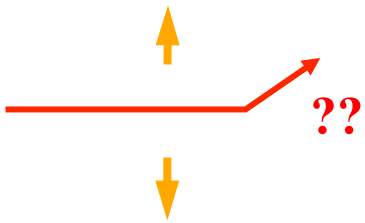
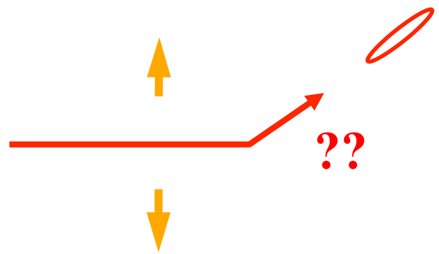
Fracture of *2D thin sheets* 	$H \approx 0.50$ 	$H \approx 0.65$ 

	Crack growth direction governed by elasticity	Crack growth direction governed by damage nucleation

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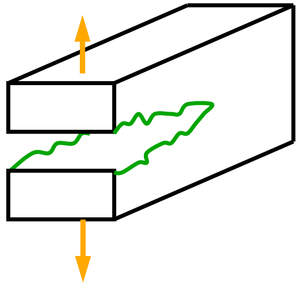
Fracture of *3D solids* 	$\zeta \approx 0.40$ $\beta \approx 0.50$	$\zeta \approx 0.75$ $\beta \approx 0.60$
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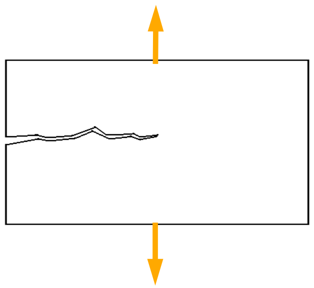
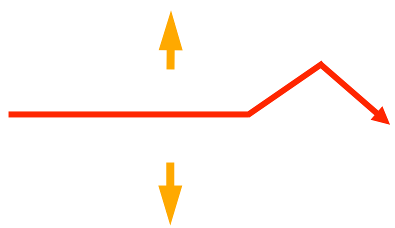
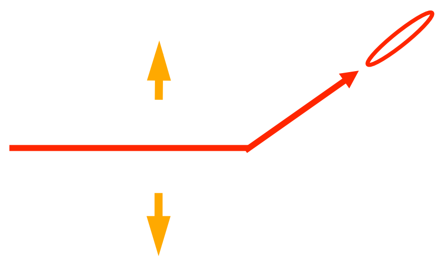
Fracture of *2D thin sheets* 	$H \approx 0.50$	$H \approx 0.65$



Crack growth direction governed by elasticity



Crack growth direction governed by damage nucleation

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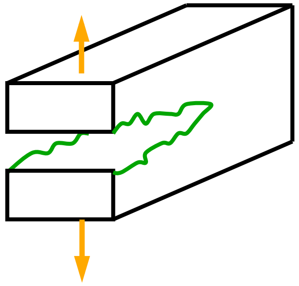
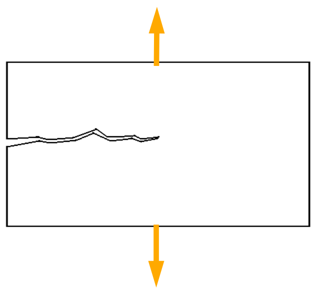
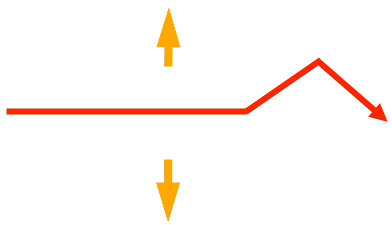
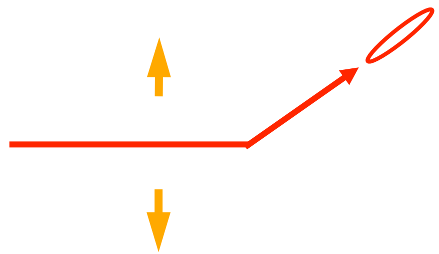
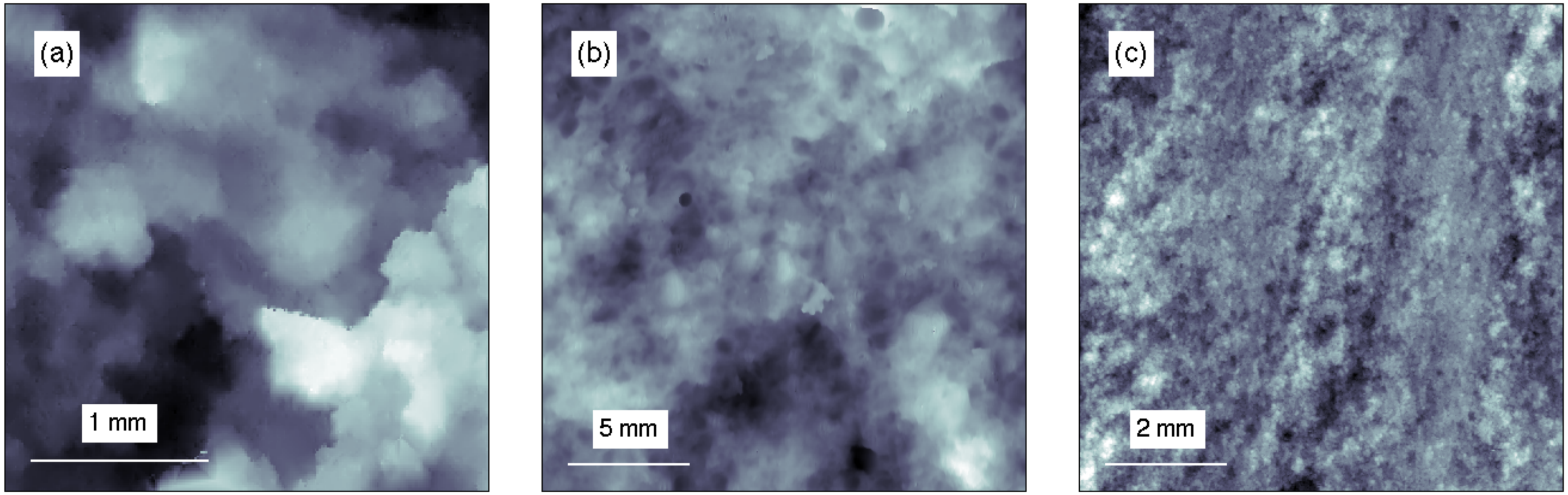
Fracture of *3D solids* 	$\zeta \approx 0.40$ $\beta \approx 0.50$	? ↔	$\zeta \approx 0.75$ $\beta \approx 0.60$
	Brittle failure		**Failure by damage coalescence**
Fracture of *2D thin sheets* 	$H \approx 0.50$ $\ell_{pz} << d_{\mu structure}$  Crack growth direction governed by elasticity		$H \approx 0.65$ $\ell_{pz} >> d_{\mu structure}$  Crack growth direction governed by damage nucleation

Beyond the value of the roughness exponent: Full statistics of fracture surfaces

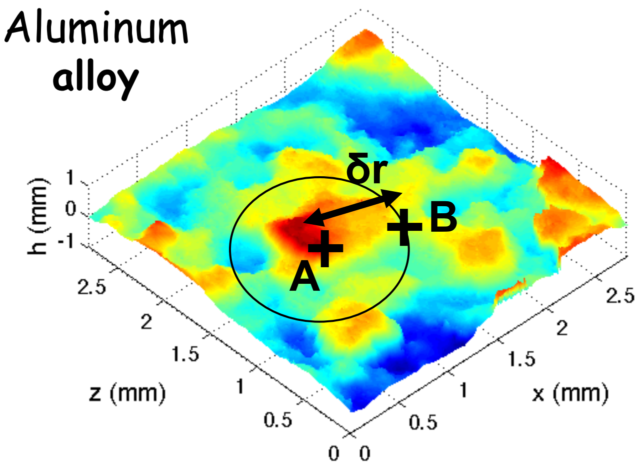
The materials

One representative sample of each major class of failure mechanisms



(a) Ductile: aluminum alloy (4% copper)
(b) Quasi-brittle: Mortar
(c) Brittle: Glass ceramics

Statistics of height fluctuations



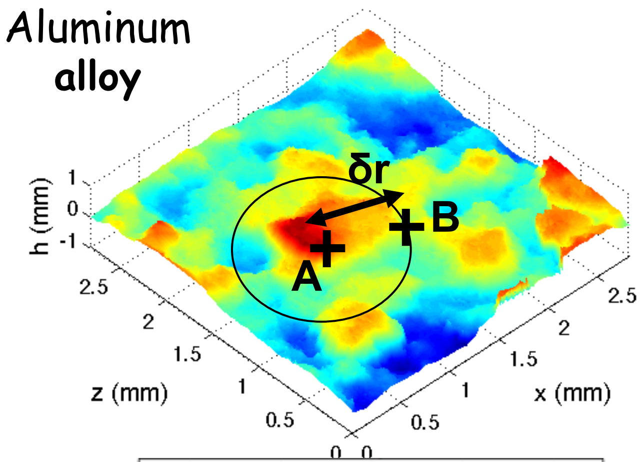
Distribution of height variations:

$P(\delta h \mid \delta r)$ with $\delta h = h(\vec{r} + \delta\vec{r}) - h(\vec{r})$

where $|\delta\vec{r}| = \delta r$

→ Fracture surfaces treated as isotropic

Statistics of height fluctuations



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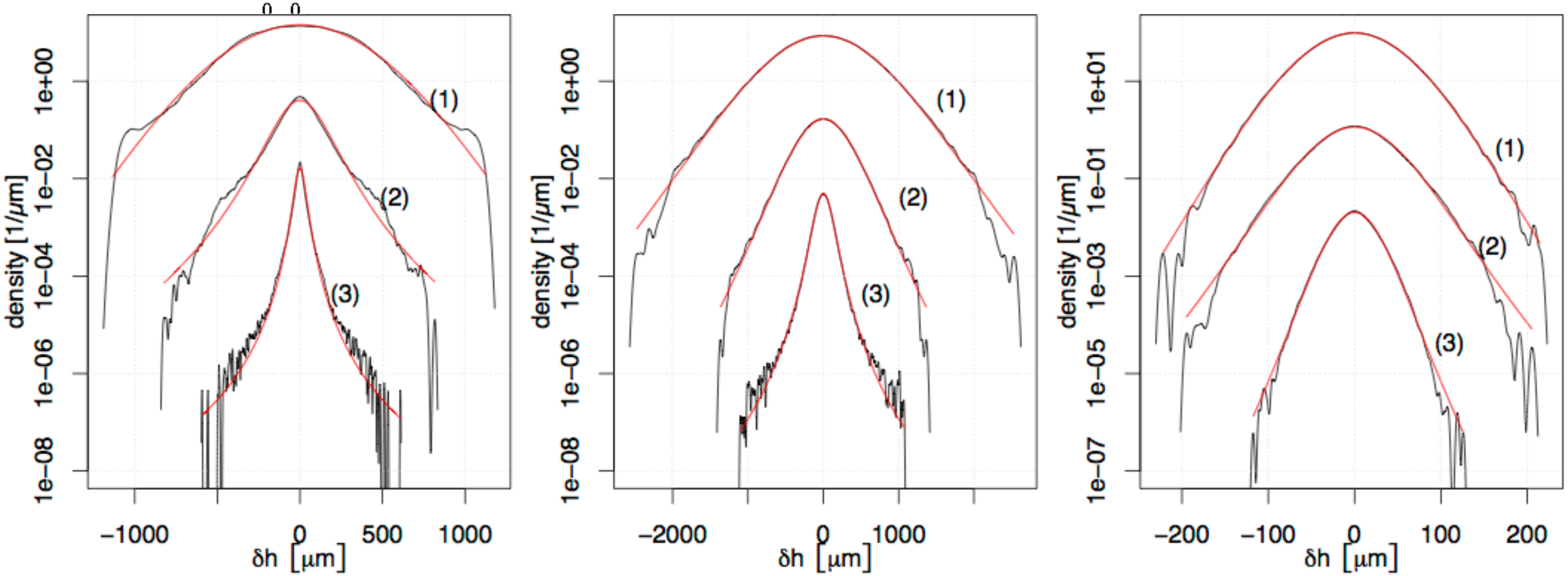


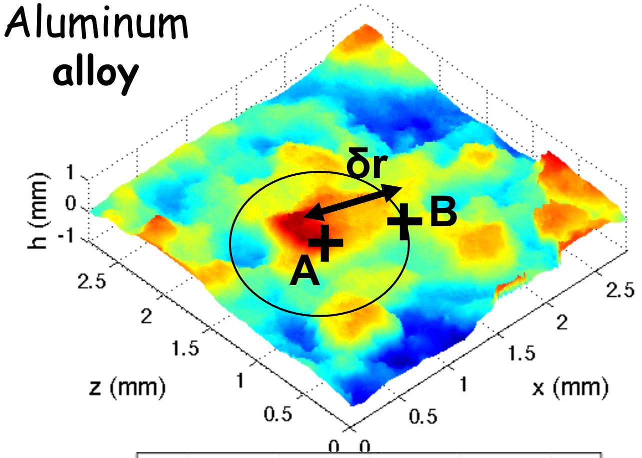
Aluminum
1: 550 μm, 2: 115 μm, 3: 25 μm

Mortar
1: 3.8mm, 2: 915 μm, 3: 225 μm

Ceramic
1: 1.5mm, 2: 310 μm, 3: 60 μm

Statistics of height fluctuations

Aluminum
alloy



Distribution of height variations:

$P(\delta h \,|\, \delta r)$ with $\delta h = h(\vec{r} + \delta\vec{r}) - h(\vec{r})$

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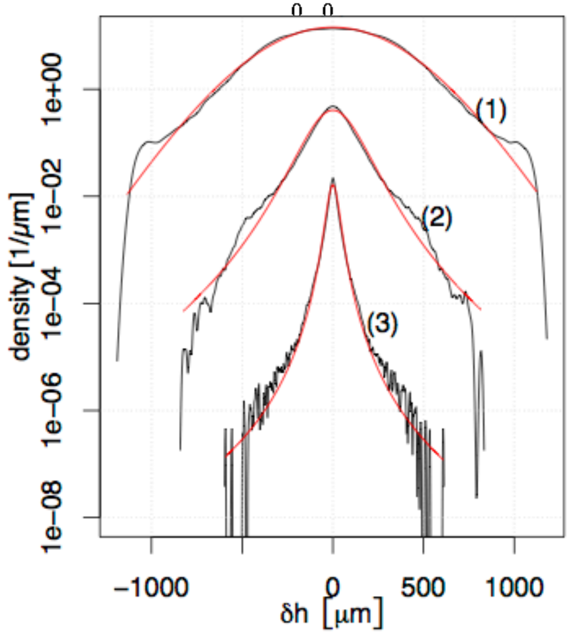
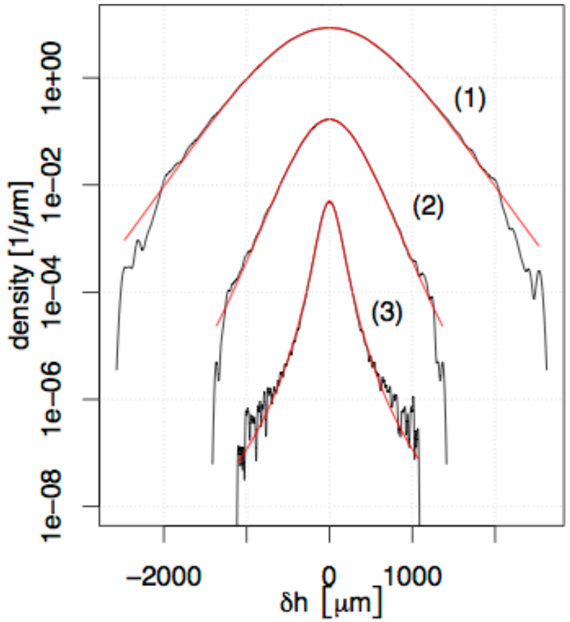
→ Fracture surfaces treated as isotropic



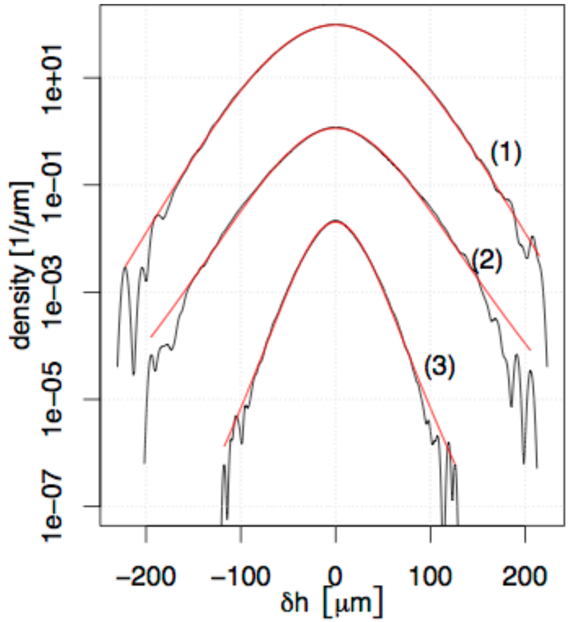
Aluminum

1: 550 μm, 2: 115 μm, 3: 25 μm



Mortar

1: 3.8mm, 2: 915 μm, 3: 225 μm

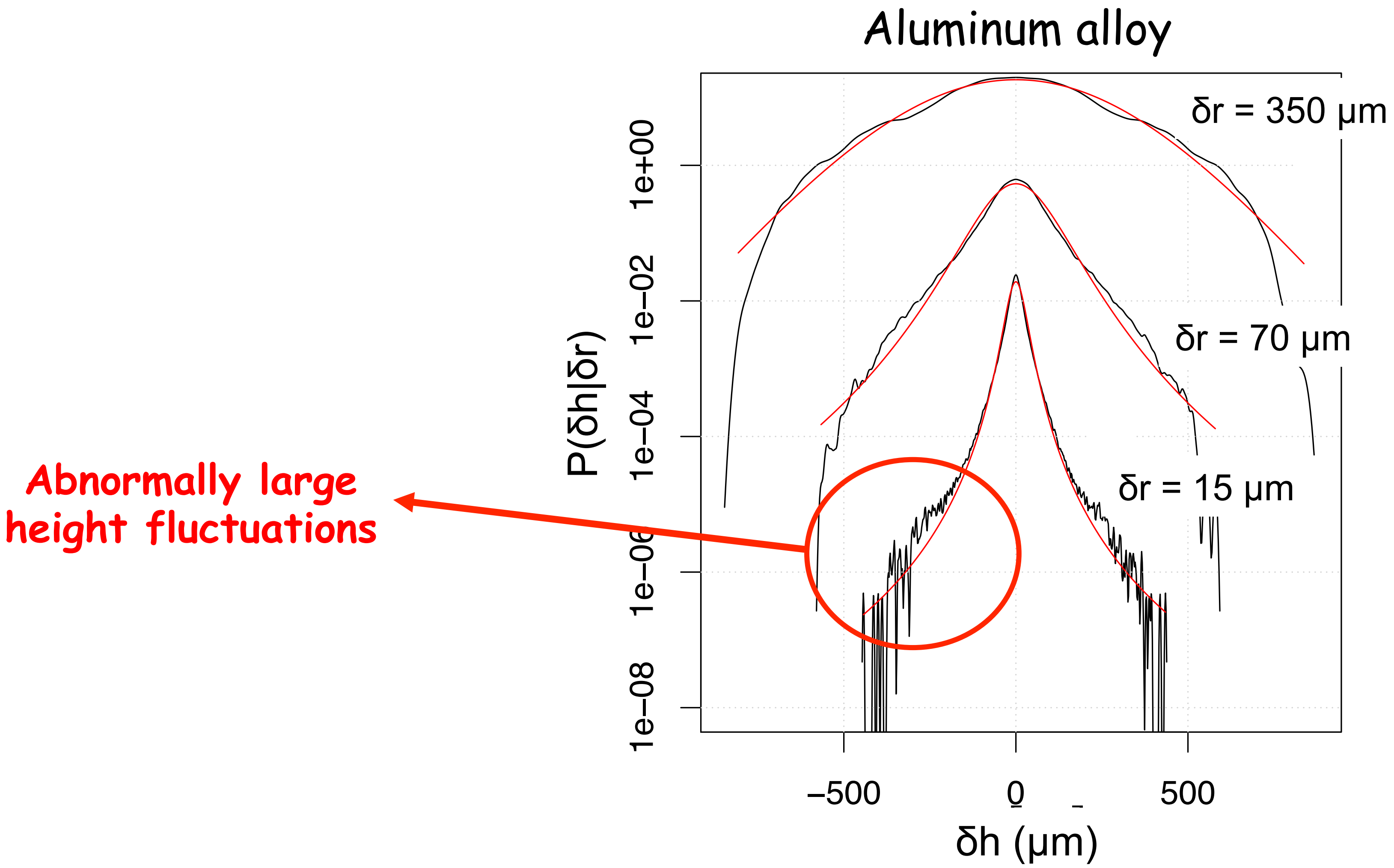


Ceramic

1: 1.5mm, 2: 310 μm, 3: 60 μm

Aluminum and mortar: non-Gaussian at small scales → One exponent only insufficient to fully describe their statistics

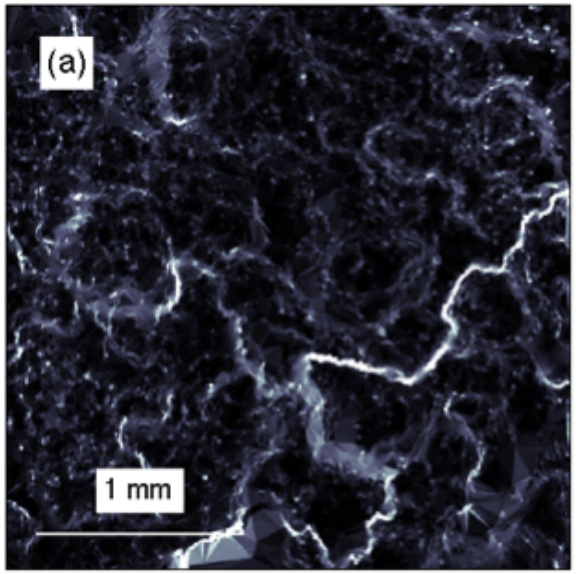
Origin of the fat tail statistics?



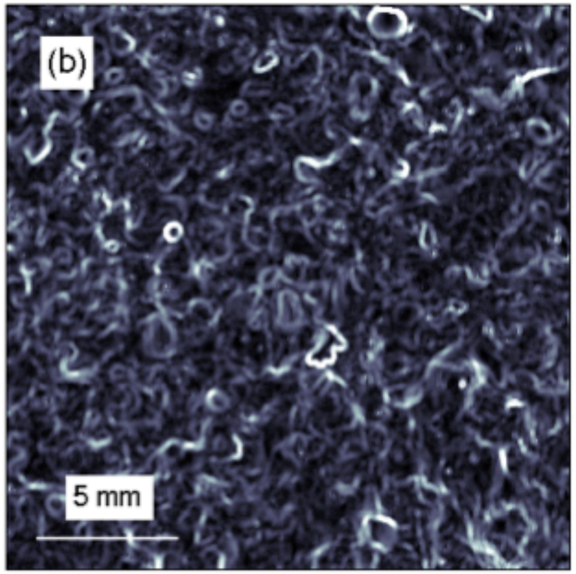
Where are these steep cliffs located on the fracture surface?

Spatial organization of the largest fluctuations

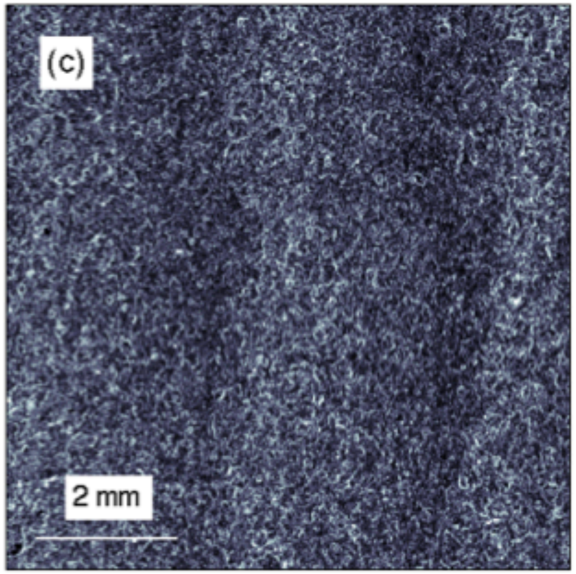
Operator $\omega_\epsilon(\mathbf{x}) = \frac{1}{2}\log\left(\langle \delta h(\mathbf{x}, \delta\mathbf{x})^2 \rangle_{|\delta\mathbf{x}|=\epsilon}\right)$



Aluminum (ε = 3μm)



Mortar (ε = 50μm)



Ceramics (ε = 50μm)

Spatial organization of the largest fluctuations

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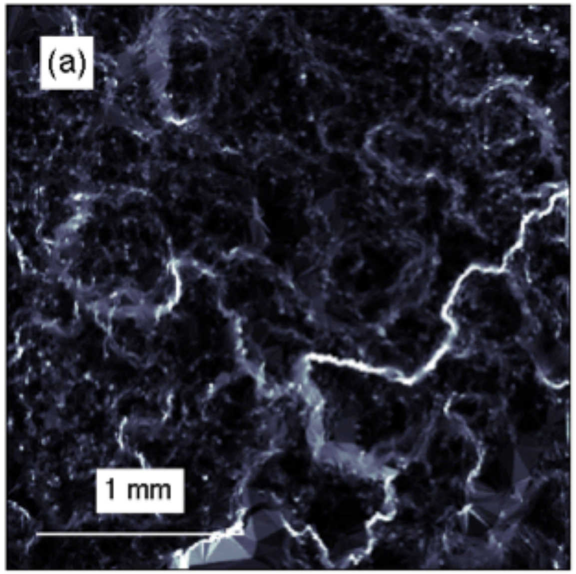

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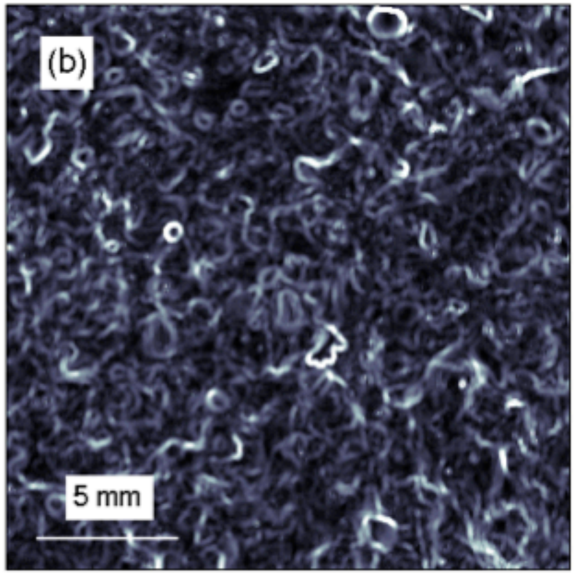
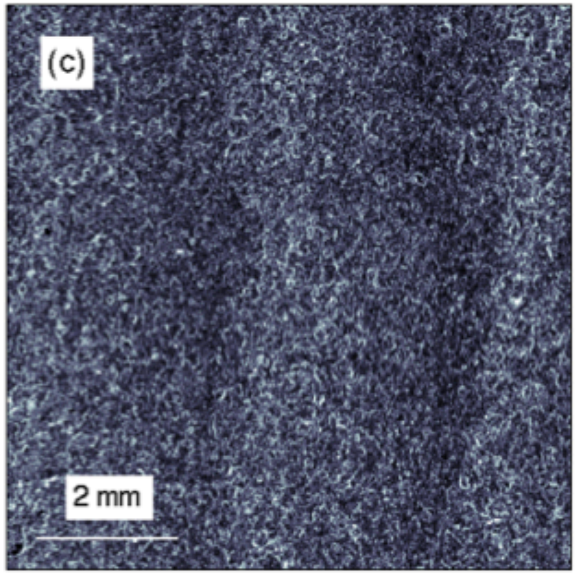


Mortar (ε = 50μm)



Ceramics (ε = 50μm)

Qualitatively: For the aluminum and mortar

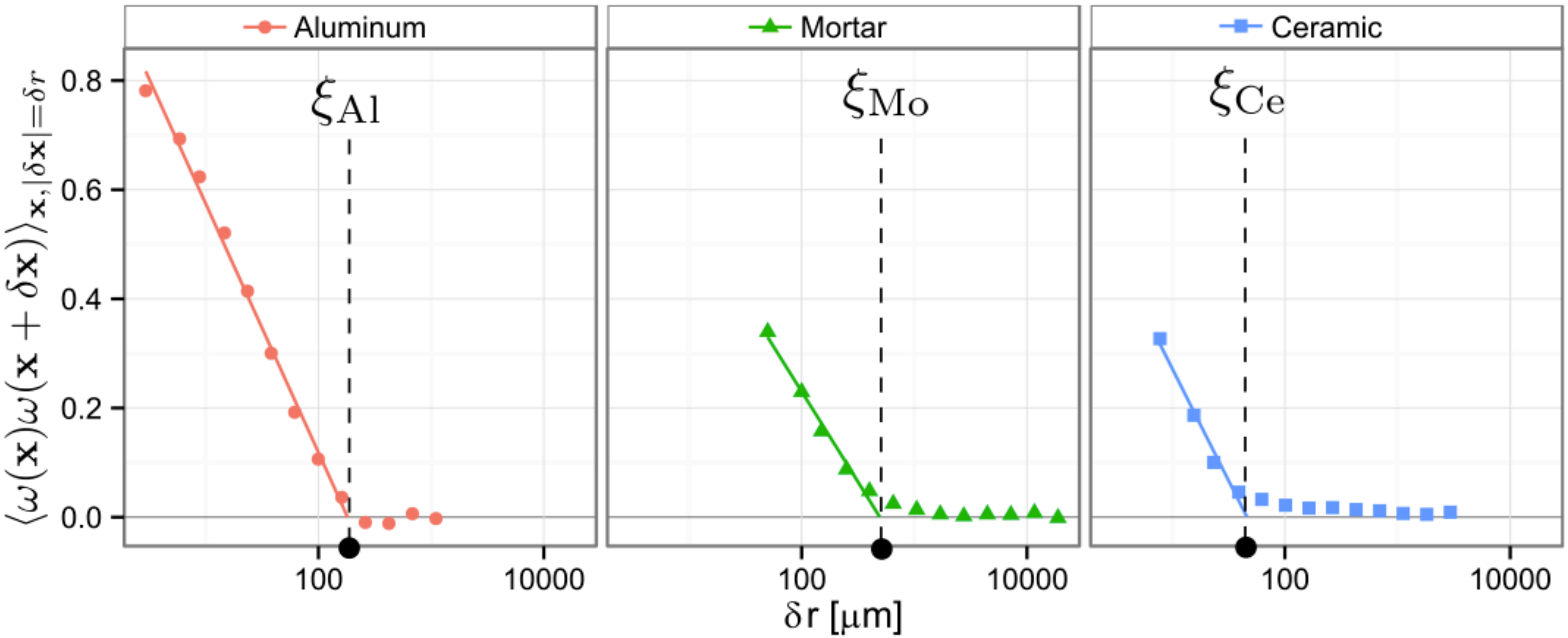
→ Large scale features, long-range correlation of ω

For the ceramics

→ Absence of large scale features

Spatial correlations of ω

Characterized by its correlation function $C(\delta r) = \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r}$



→ Revealing a cut-off length

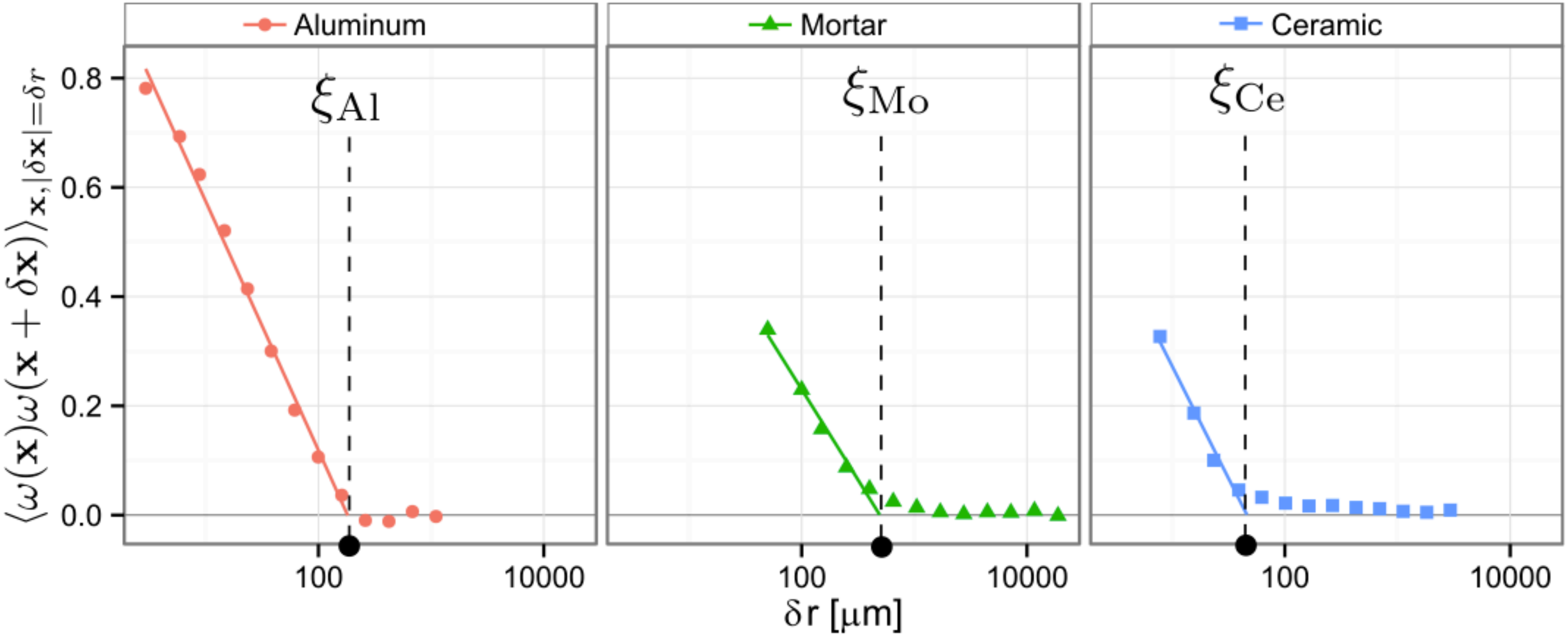
→ Aluminum $\xi_{Al} \approx 180\mu m$

→ Mortar $\xi_{Mortier} \approx 500\mu m$

→ Ceramics $\xi_{Céramique} \approx 50\mu m$

Spatial correlations of ω

Characterized by its correlation function $C(\delta r) = \left\langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \right\rangle_{\vec{r},|\delta\vec{r}|=\delta r}$



→ Revealing a cut-off length

ξ of the order of the process zone size ↔ $\xi \approx \ell_{pz}$

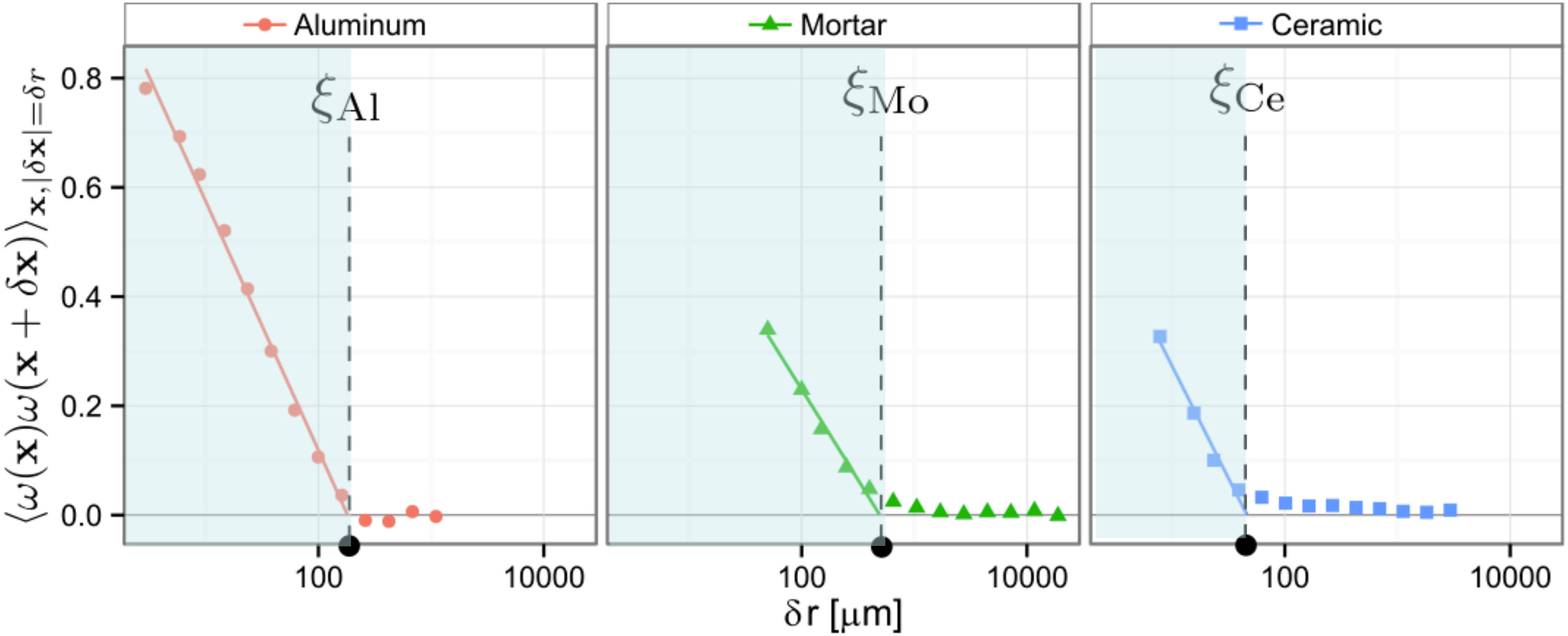
→ Aluminum $\xi_{Al} \approx 180\,\mu m$

→ Mortar $\xi_{Mortier} \approx 500\,\mu m$

→ Ceramics $\xi_{Céramique} \approx 50\,\mu m$

Spatial correlations of ω

Characterized by its correlation function $C(\delta r) = \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r}$



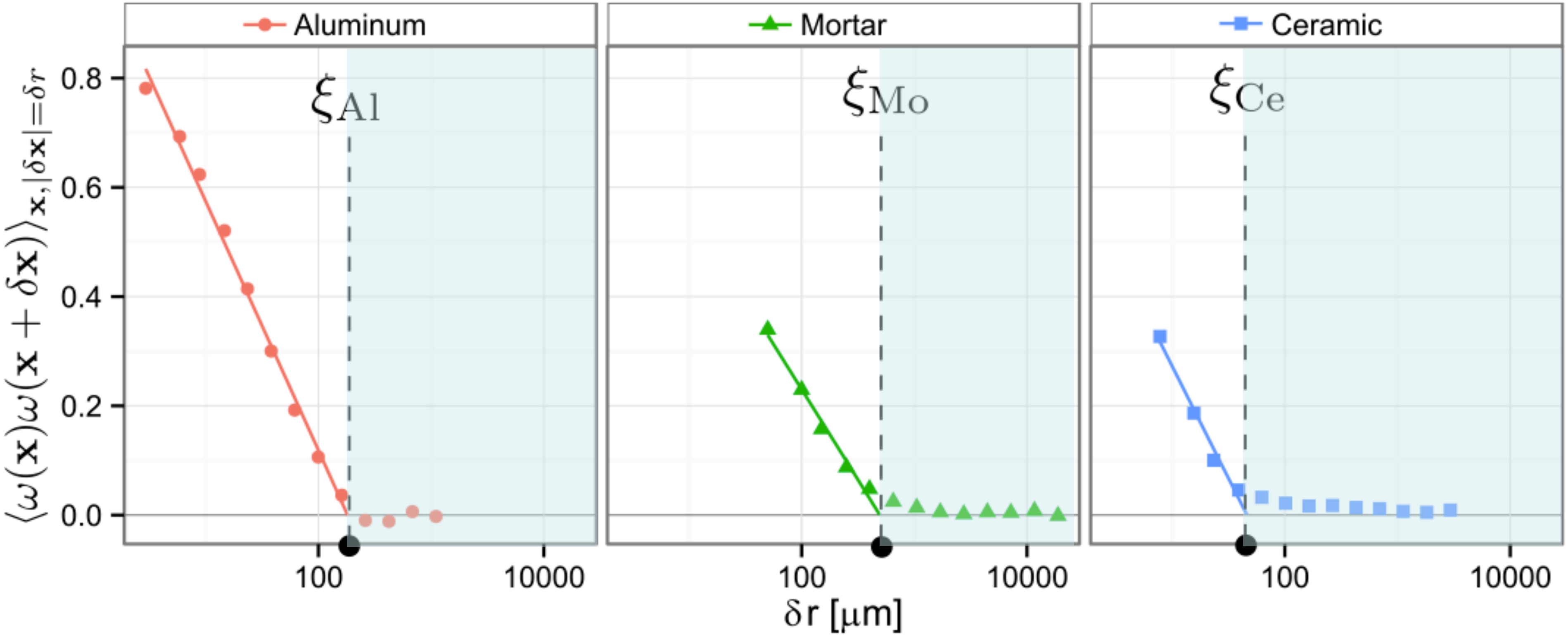
Defining two distinct ranges of length scales:

→ $\delta r < \xi$ → $\langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r} \approx -\lambda \log(\delta r / \xi)$

Typical scales of damage processes

Spatial correlations of ω

Characterized by its correlation function $C(\delta r) = \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r}$



Defining two distinct ranges of length scales:

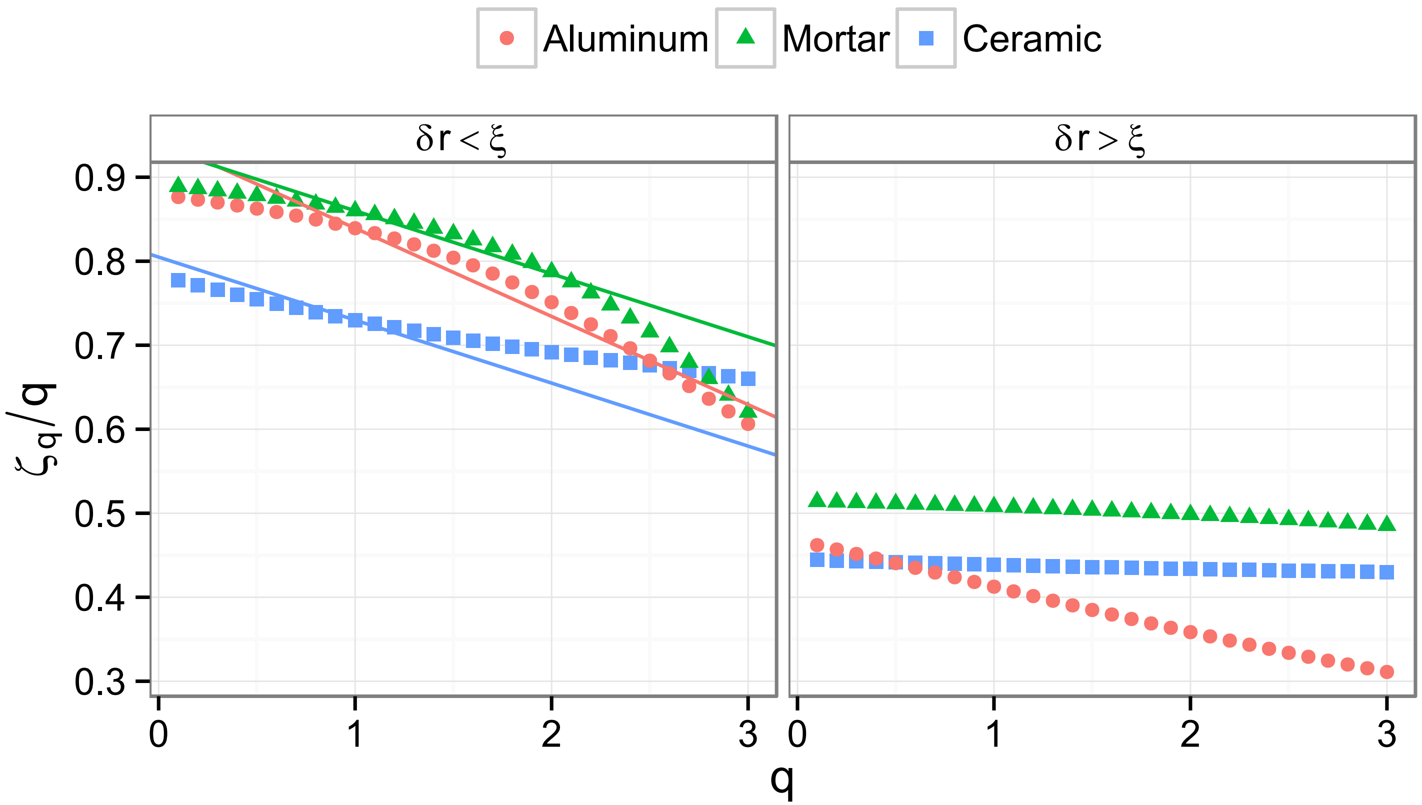
$\delta r < \xi \longrightarrow \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r} \approx -\lambda \log(\delta r / \xi)$

$\delta r > \xi \longrightarrow \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r} \approx 0$

Roughness exponents

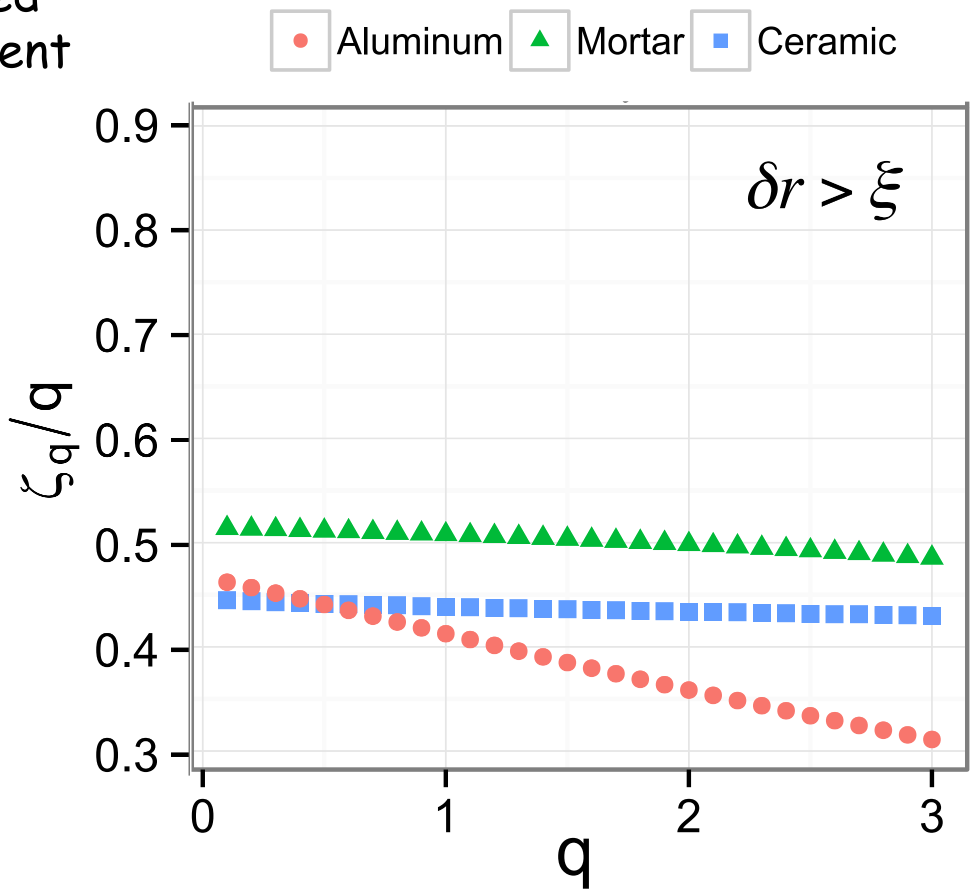
Natural extension of the roughness exponent: $\left\langle \left|\delta h(\vec{r},\delta\vec{r})\right|^{q} \right\rangle_{\vec{r},|\delta\vec{r}|=\delta r} \sim \delta r^{\zeta_q}$

Computed for the two ranges of length scales → $\delta r < \xi$ → $\delta r > \xi$



Roughness exponents at large scales

One well-defined
roughness exponent

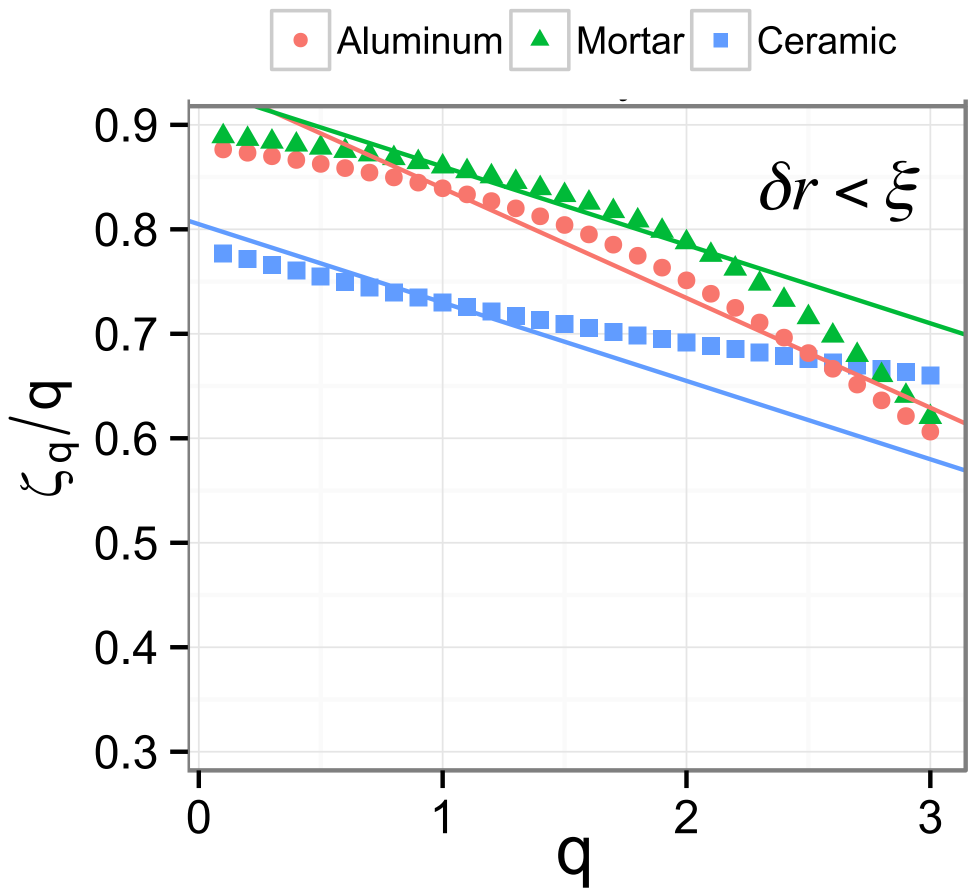


Mortar and ceramics: $\zeta_q / q \approx 0.45$

Low variations with q ⟶ Consistent with (i) a mono-affine behavior
(ii) a Gaussian distribution

Roughness exponents at small scales

Multi-affine Spectrum:



Slope consistent with the spatial correlations of height fluctuations

Simple multi-affine model:

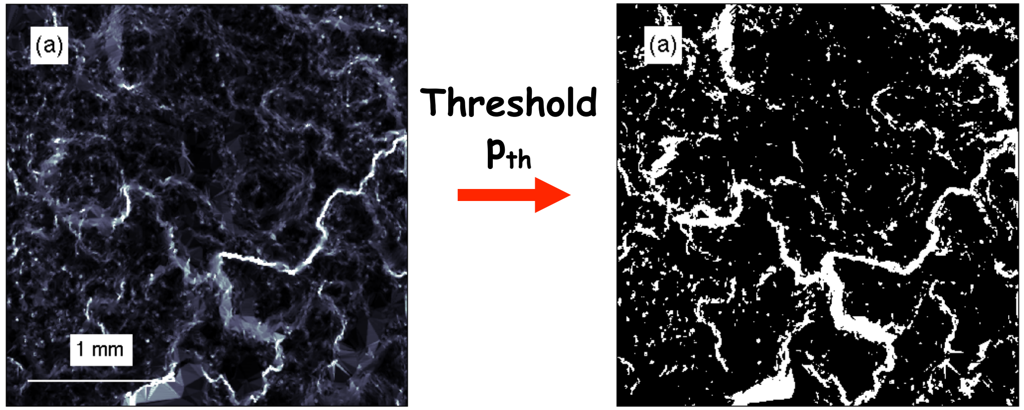
J.F. Muzy and E. Bacry 2002

Multi-affine spectrum ⟷ Spatial correlation of slopes

$$\zeta_q / q \sim H - \frac{\lambda}{2}(q-1) \quad \text{where } \lambda \text{ given by } \langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \rangle_{\vec{r},|\delta\vec{r}|=\delta r} \approx -\lambda \log(\delta r)$$

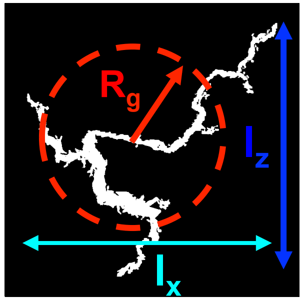
Cluster and spatial organization of the largest fluctuations

Aluminum



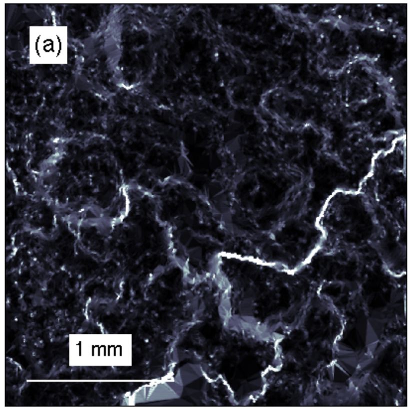
Cluster and spatial organization of the largest fluctuations

→ Fractal geometry of clusters

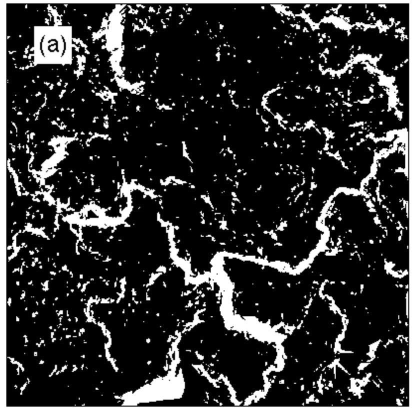


D ≈ 1.7
independent of
the material

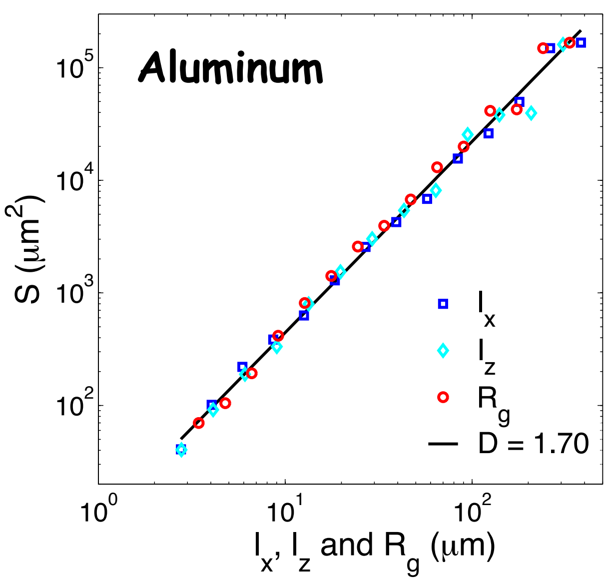
Aluminum

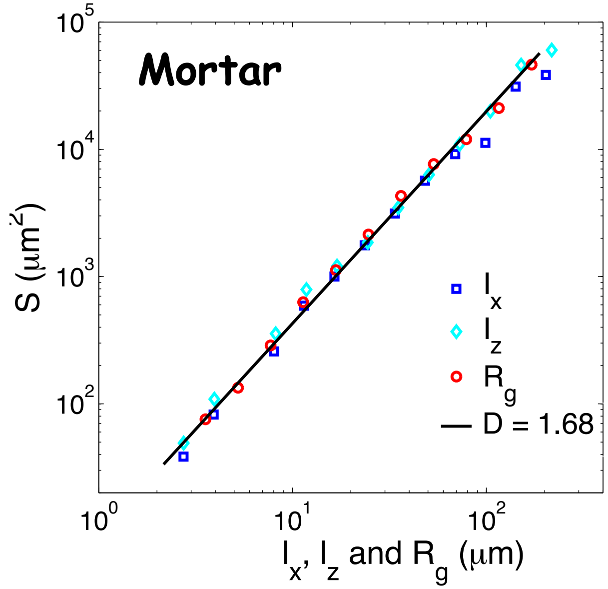


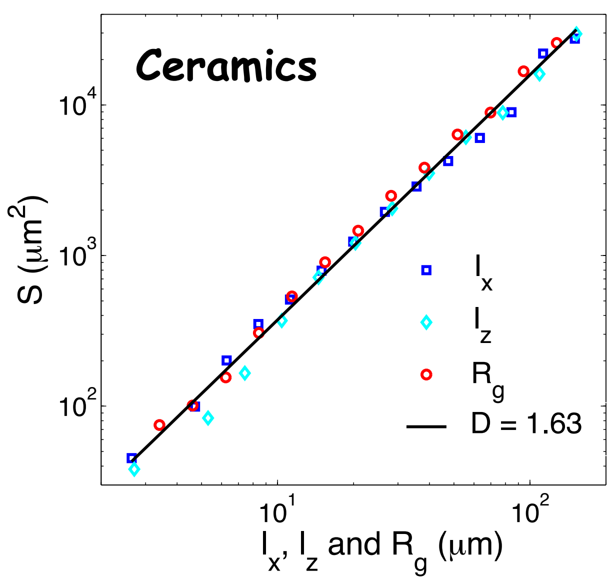
Threshold p_{th}



Surface vs caracteristic length of clusters

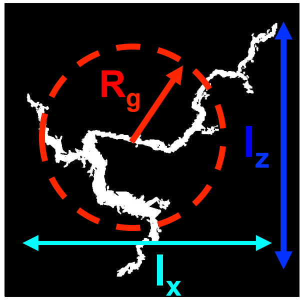






Cluster and spatial organization of the largest fluctuations

→ Fractal geometry of clusters



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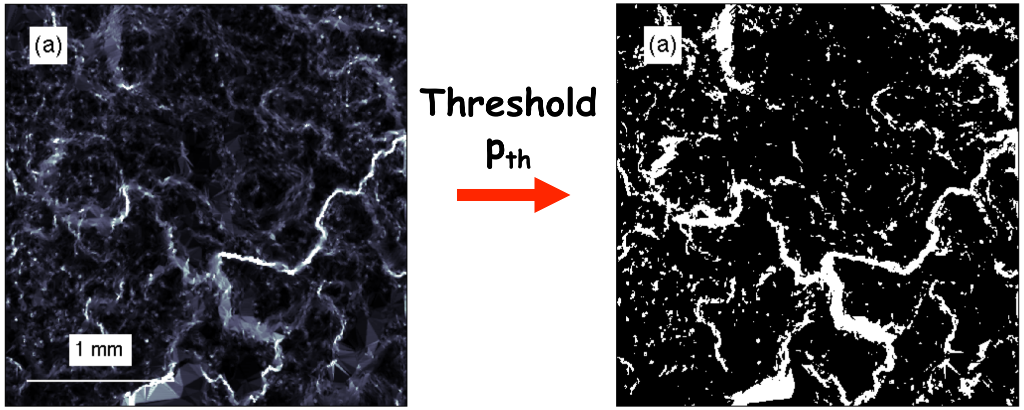
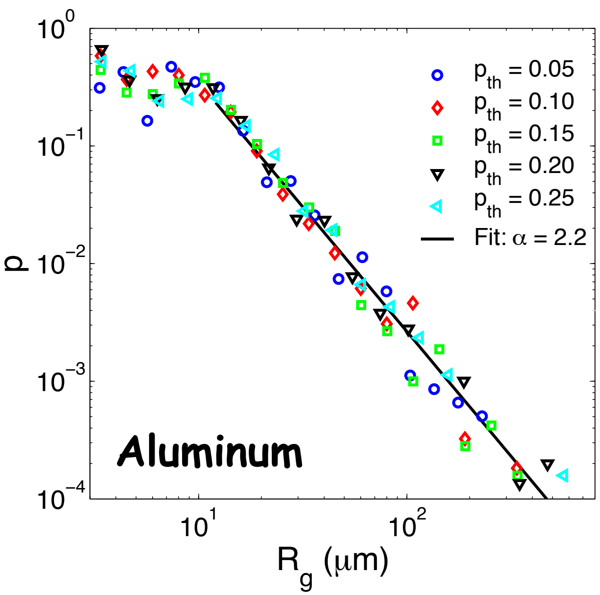
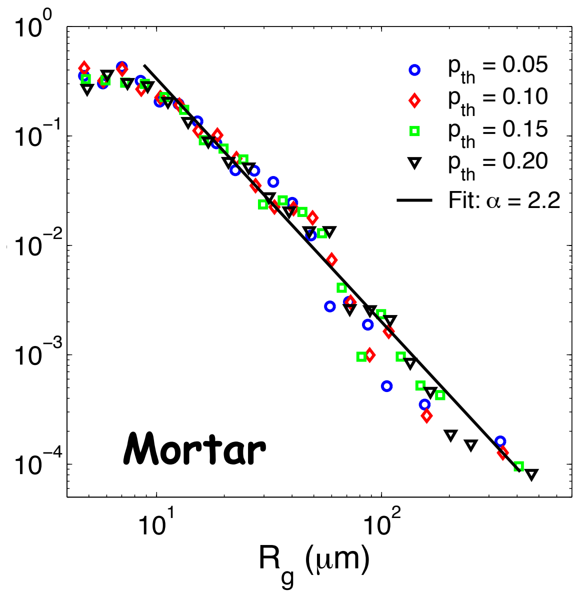
Aluminum

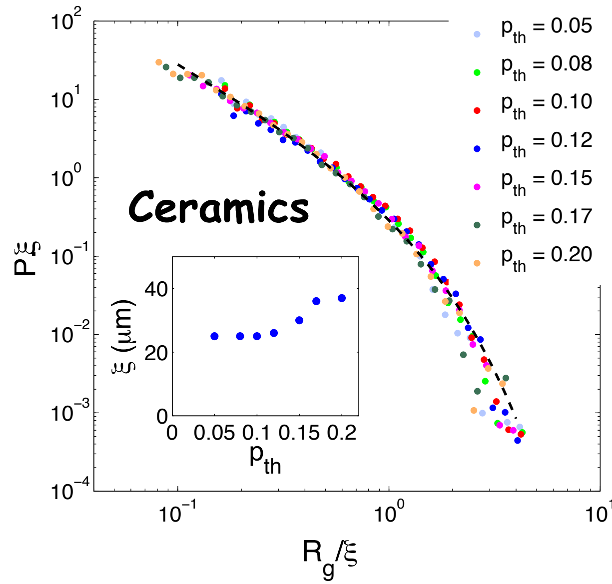


→ Power law distributed clusters

$P(S) \sim S^{-\alpha}$ with $\alpha \approx 2.2$
independent of the material

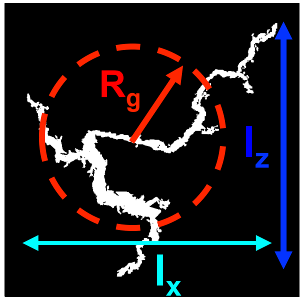






Cluster and spatial organization of the largest fluctuations

→ **Fractal geometry of clusters**



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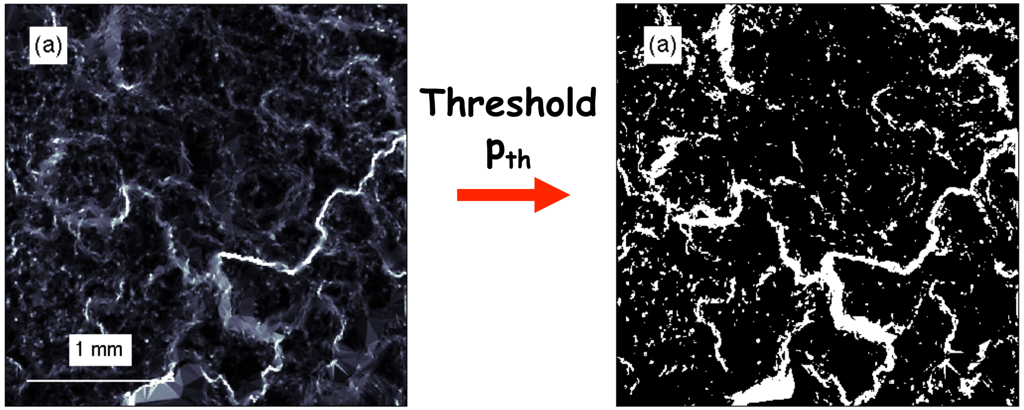
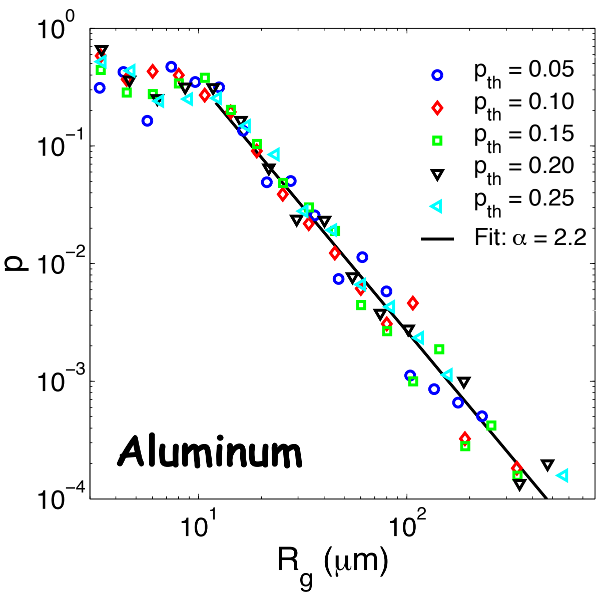
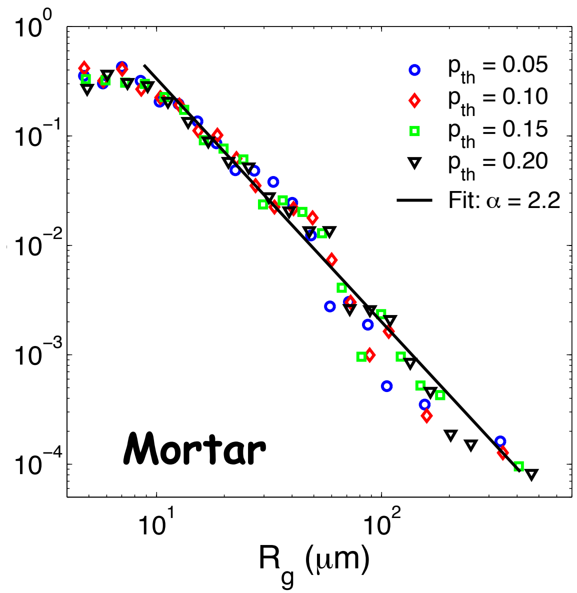


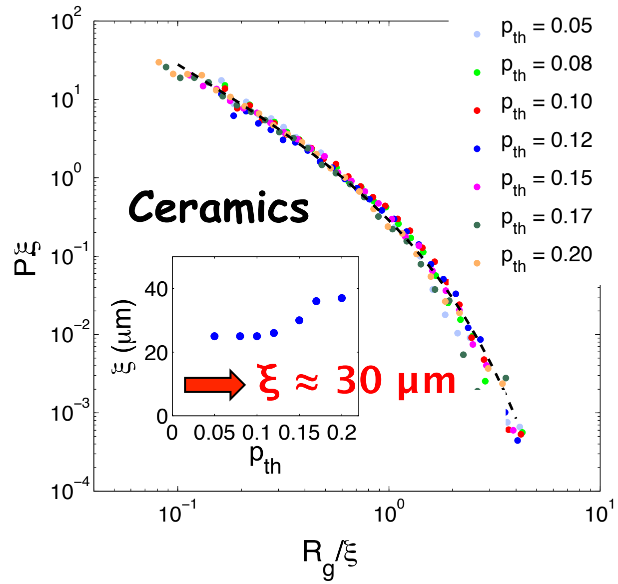
→ **Power law distributed clusters**

$P(S) \sim S^{-\alpha}$ with $\alpha \approx 2.2$
independent of the material

→ **Cut-off length of the cluster size distribution consistent with ξ**

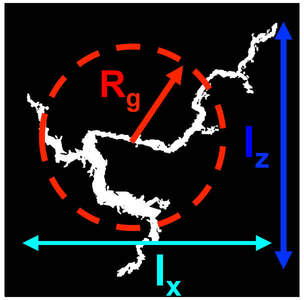






Cluster and spatial organization of the largest fluctuations

→ Fractal geometry of clusters



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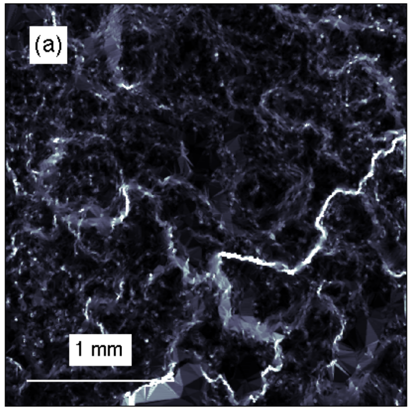
Aluminum



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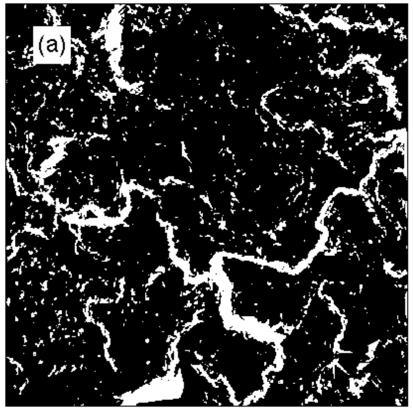

→ Cut-off length of the cluster size distribution consistent with ξ

Interpretation:

→ Clusters reminiscent of the process of damage coalescence

Full statistics of 2D fracture surfaces: Summary

S. Vernède, LP and J.P. Bouchaud, 2014

Operator ω

- Characterized the local intensity of height fluctuations δh
- Defined a cut-off length ξ

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δr > ξ
- ω uncorrelated: $\langle \omega(x)\omega(y) \rangle = 0$
- Mono-affine Gaussian roughness with $\zeta = 0.45$

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δr > ξ

- ω uncorrelated: ⟨ω(x)ω(y)⟩ = 0
- Mono-affine Gaussian roughness with $\zeta = 0.45$

δr < ξ

- Long range correlations of ω, with $\left\langle \omega(\vec{r})\omega(\vec{r}+\delta\vec{r}) \right\rangle_{\vec{r},|\delta\vec{r}|=\delta r} \approx -\lambda \log(\delta r)$
- Multi-affine spectrum of the roughness

  → Consistent with the spatial correlations of ω
- Universal geometrical properties of clusters of largest fluctuations

Towards a unified description of 2D fracture surfaces?

Three different failure behavior

Ductile – quasi-brittle - brittle

One description

- $\delta r < \xi$ ⟶ Roughness signature of damage
- $\delta r > \xi$ ⟶ Roughness signature of the propagation of a brittle crack front

Towards a unified description of 2D fracture surfaces?

Three different failure behavior

Ductile – quasi-brittle - brittle

One description

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Application ***S. Vernède and LP, French Patent 2014***

- Length ξ ⟶ characteristic size of the dissipative failure mechanisms

Towards a unified description of 2D fracture surfaces?

Three different failure behavior

Ductile – quasi-brittle - brittle

One description

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Application ***S. Vernède and LP, French Patent 2014***

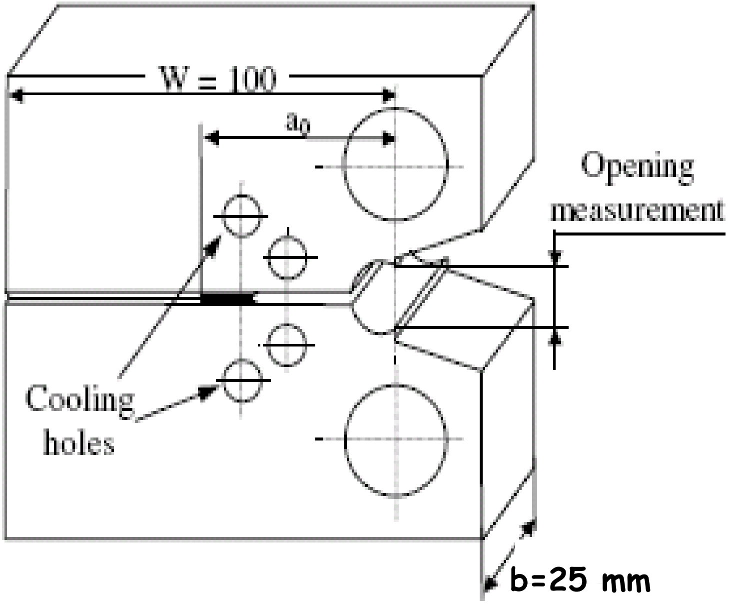
- Length ξ ⟶ characteristic size of the dissipative failure mechanisms
- *Post-mortem* measurement of the fracture energy

⟶ *See A. Needleman's talk*

Application: Post-mortem measurement of fracture toughness

S. Chapuliot et al. 2005

Same steel (A508) broken at different temperatures



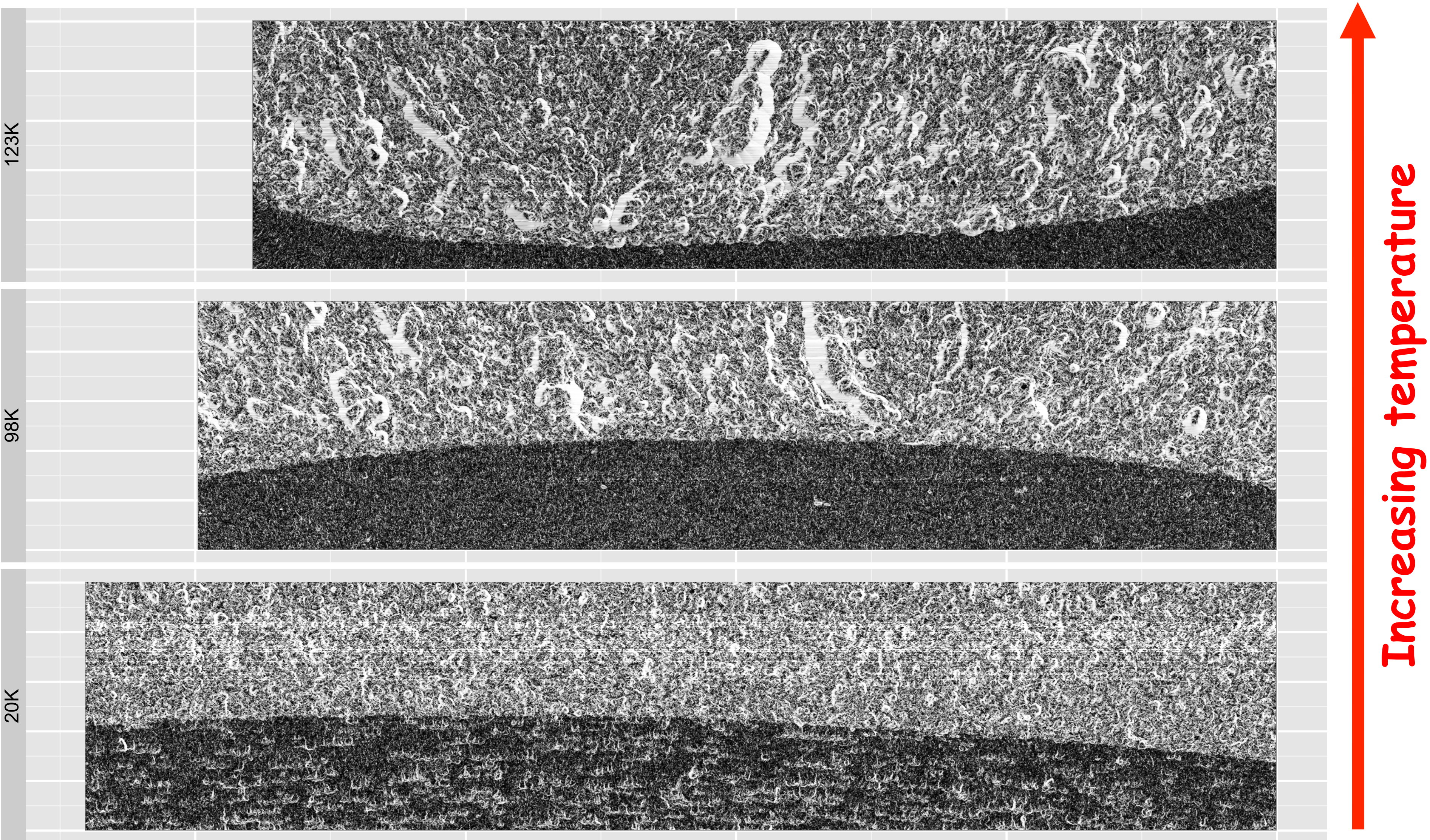
Effect of temperature on fracture properties

Temperature (°C)	**σ_Y (MPa) Yield Stress**	**J_{IC} (kJ/m²) Fracture energy**	**R_c (µm) Plastic process zone**
-253°	1300	2.5	16
-175°	770	11.3	215
-150°	680	16	380

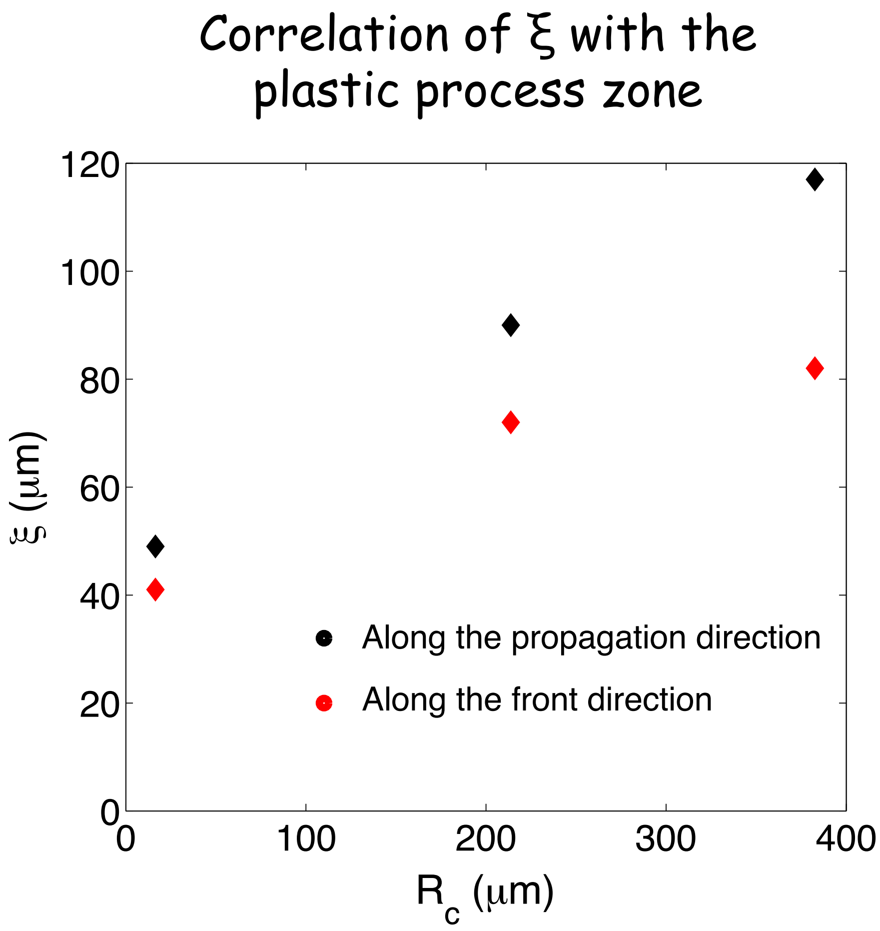
Plastic process zone:

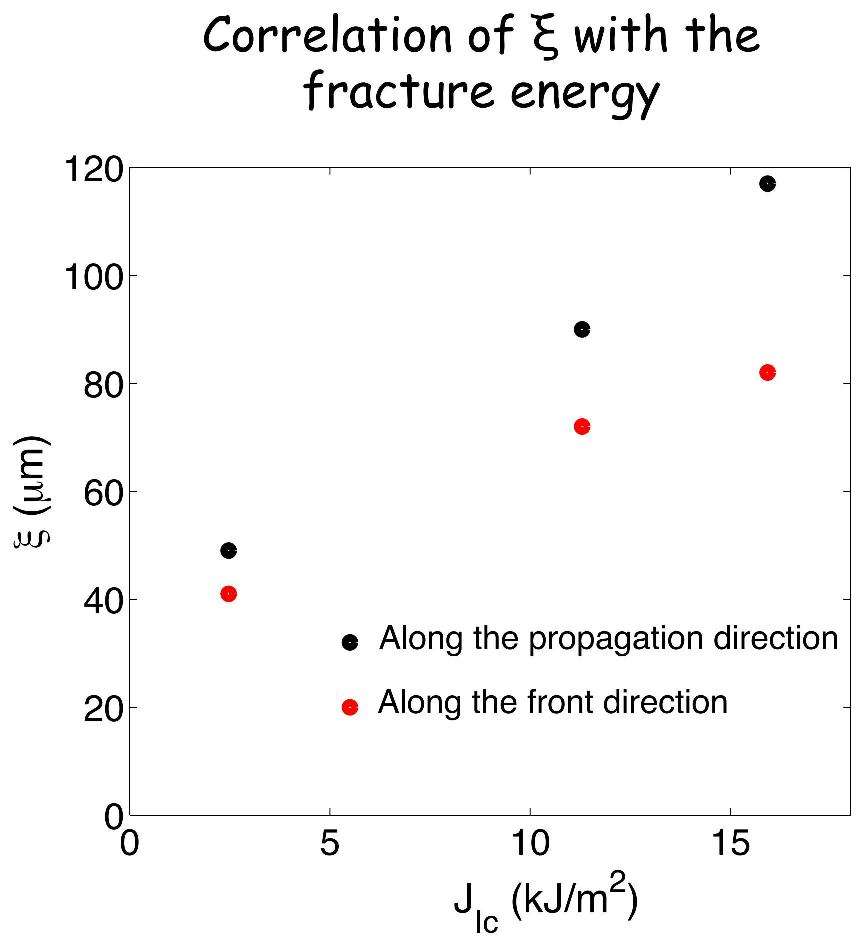
$$\longrightarrow R_c \sim \frac{J_{Ic}}{\sigma_Y^2}$$

Fields ω of local height fluctuations



Correlation of ξ with the material fracture properties





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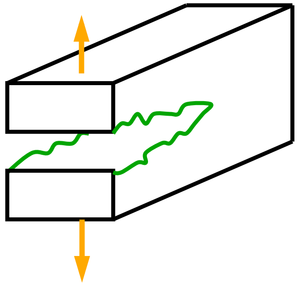
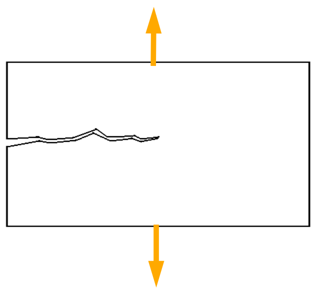
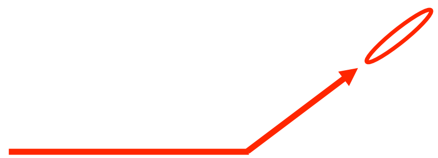
Towards a unified description of fracture surfaces?

	Anti-persistent crack path	*Persistent* crack path
Fracture of *3D solids* 	$\delta r < L_{pz}$ $\zeta \approx 0.40$ $\beta \approx 0.50$ **Roughness signature of the propagation of a brittle crack front**	$\delta r > L_{pz}$ $\zeta \approx 0.75$ $\beta \approx 0.60$ **Roughness signature of damage**
Fracture of *2D thin sheets* 	$\ell_{pz} << d_{\mu structure}$ $H \approx 0.50$  **Crack growth direction governed by elasticity**	$\ell_{pz} >> d_{\mu structure}$ $H \approx 0.65$  **Crack growth direction governed by damage nucleation**