Mechanics of surface damage:
A new look at the old problem of wear

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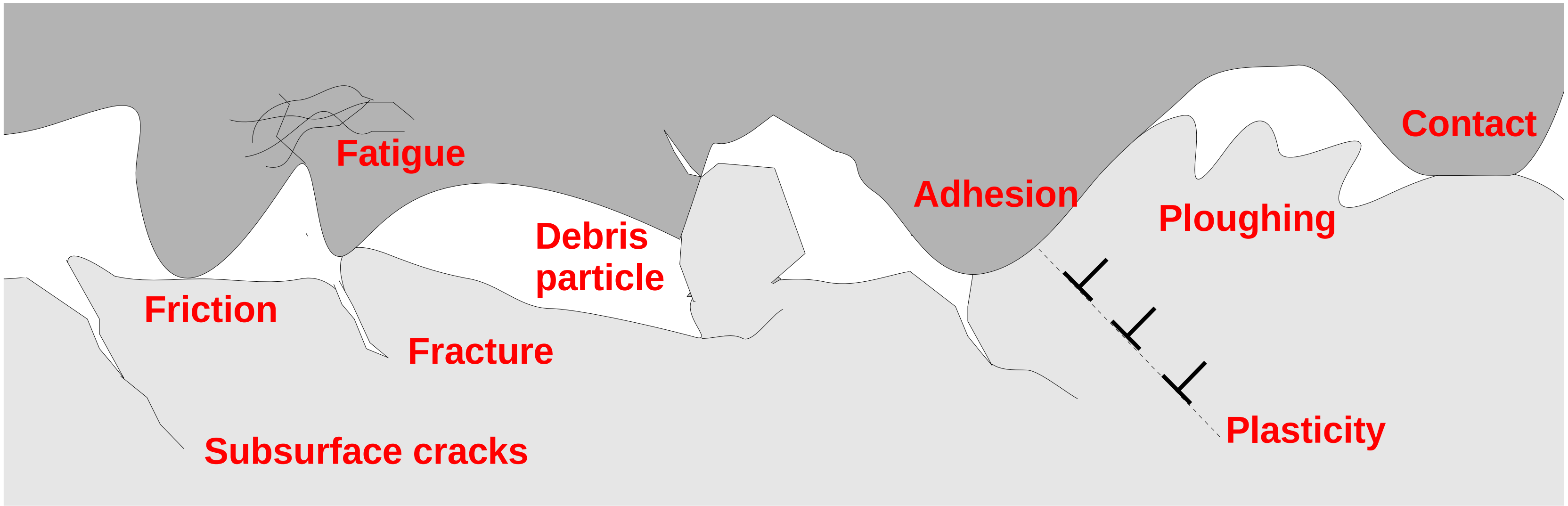
Aarhus University, Denmark (from September)

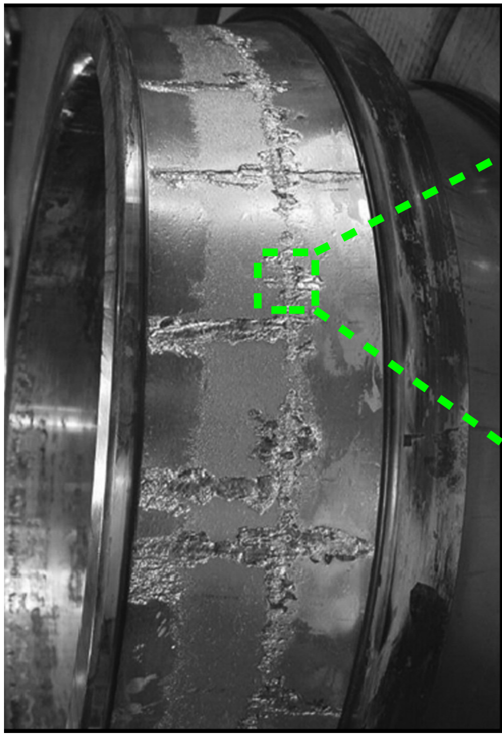


Collaborators: J.-F. Molinary (EPFL) and D.W. Warner (Cornell)

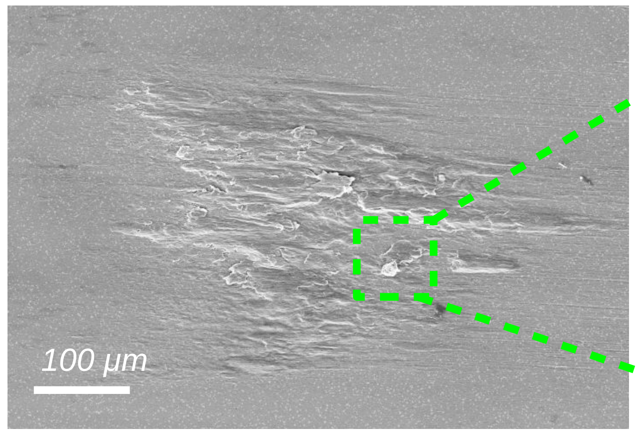
Wear is Extreme

The process of surface damage and eventual material degradation

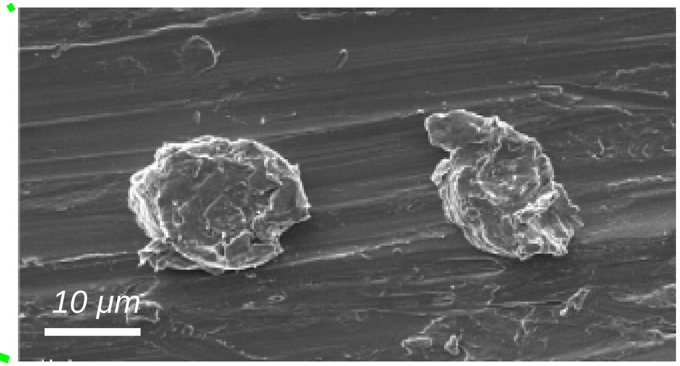
Wear in a shaft bearing



Surface damage



Wear debris

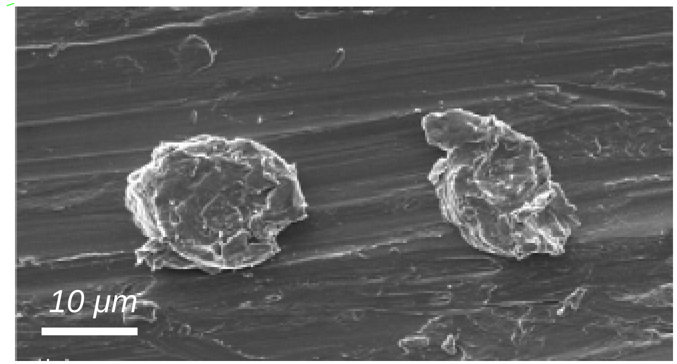


Farias et al (2007) Wear, Kotzalas and Doll (2010) Phil. Trans. R. Soc. A

Wear is Extreme

The process of surface damage and eventual material degradation

Wear debris



Extreme

- **Mechanics**
- **Temperature**
- **Environment**
- **Velocity**

Wear importance in energy systems

A major source of materials and energy loss

with serious *economic*, *environmental* and *industrial* impacts.

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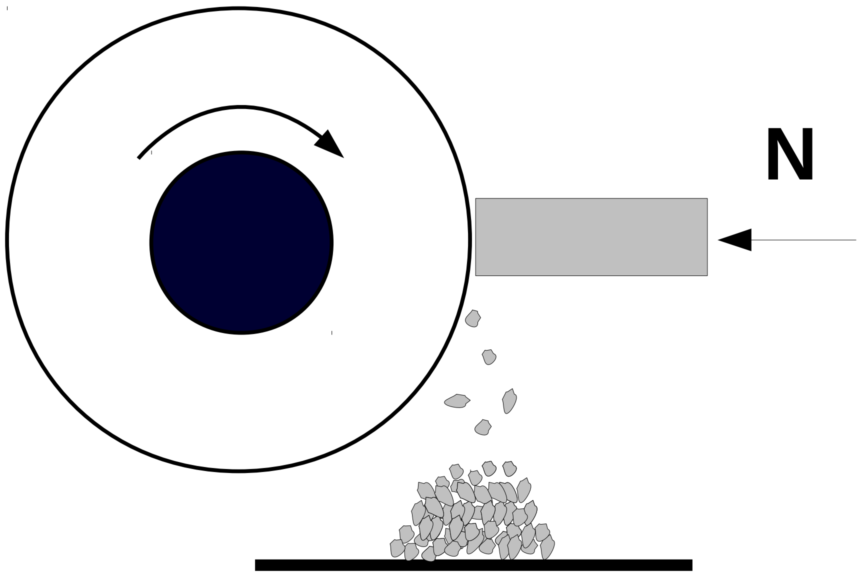
with serious *economic*, *environmental* and *industrial* impacts.

Cause: **wear in brake system**

Archard's wear law (1953)

$$V = K \frac{N \times S}{H}$$

Wear coefficient: *(10^{-10} - 1)*
The probability of particle detachment



J.F. Archard (1953) *JAP*

Archard's wear law (1953)

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Wear coefficient: *(10^-10 - 1)*
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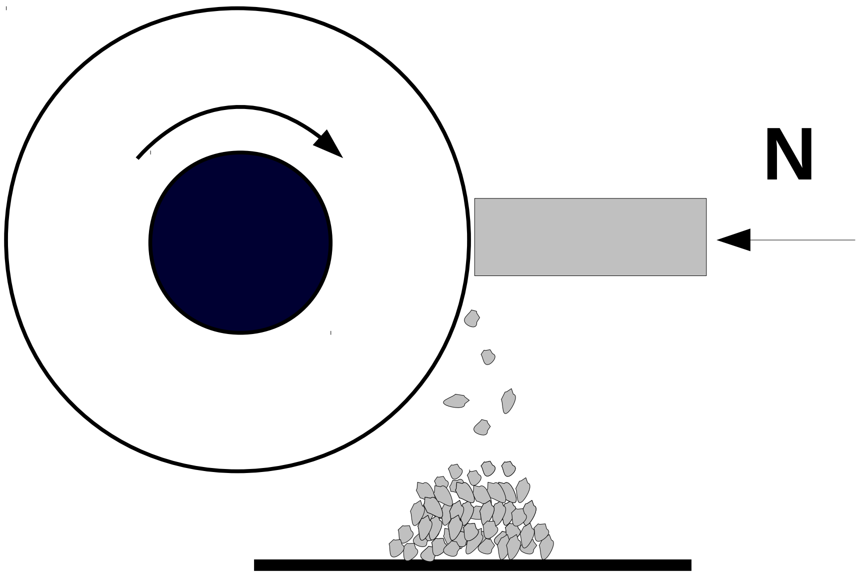
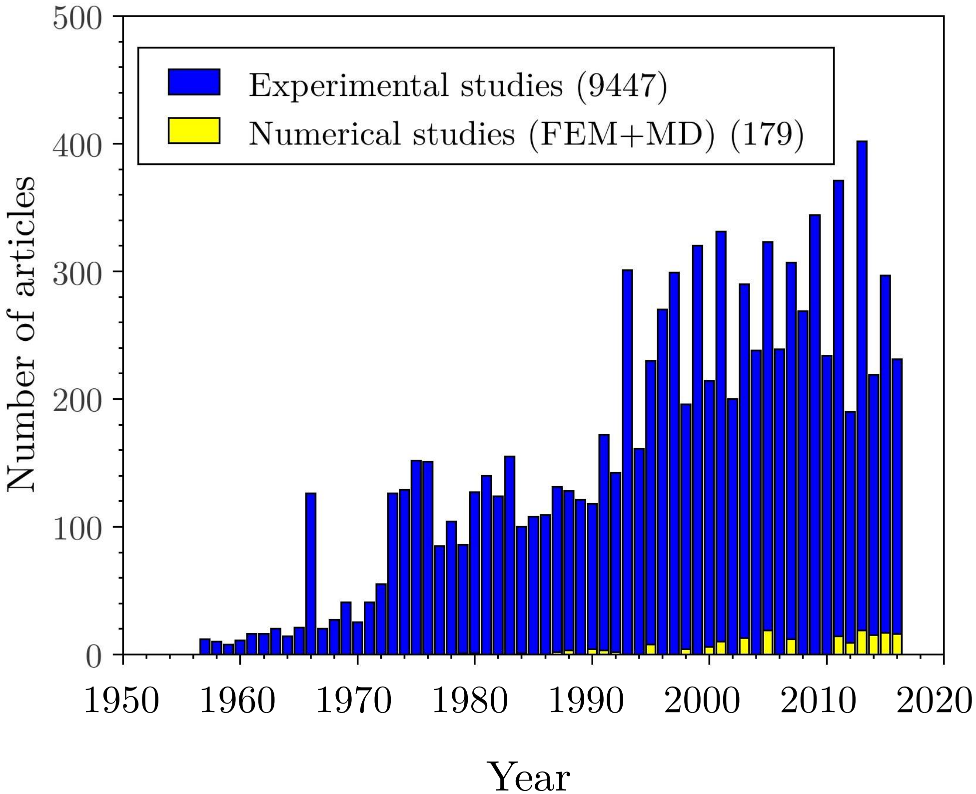


J.F. Archard (1953) *JAP*



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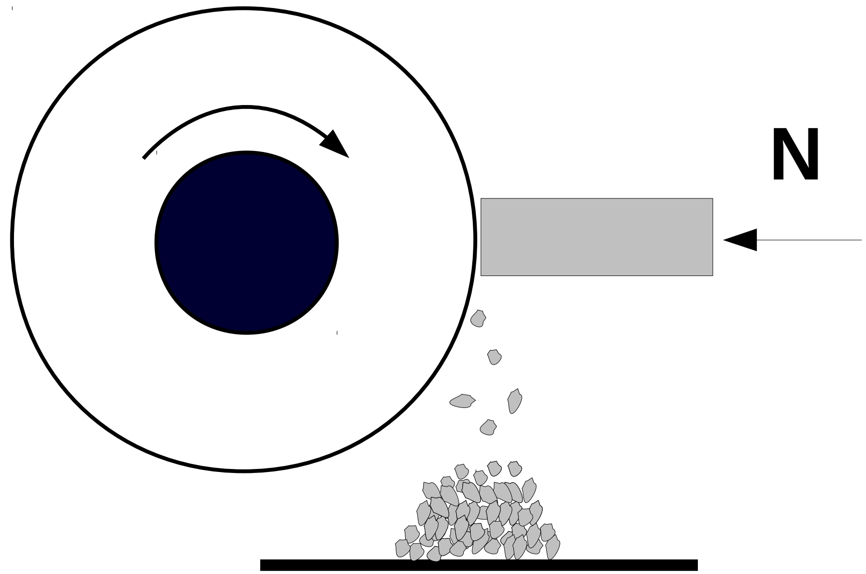

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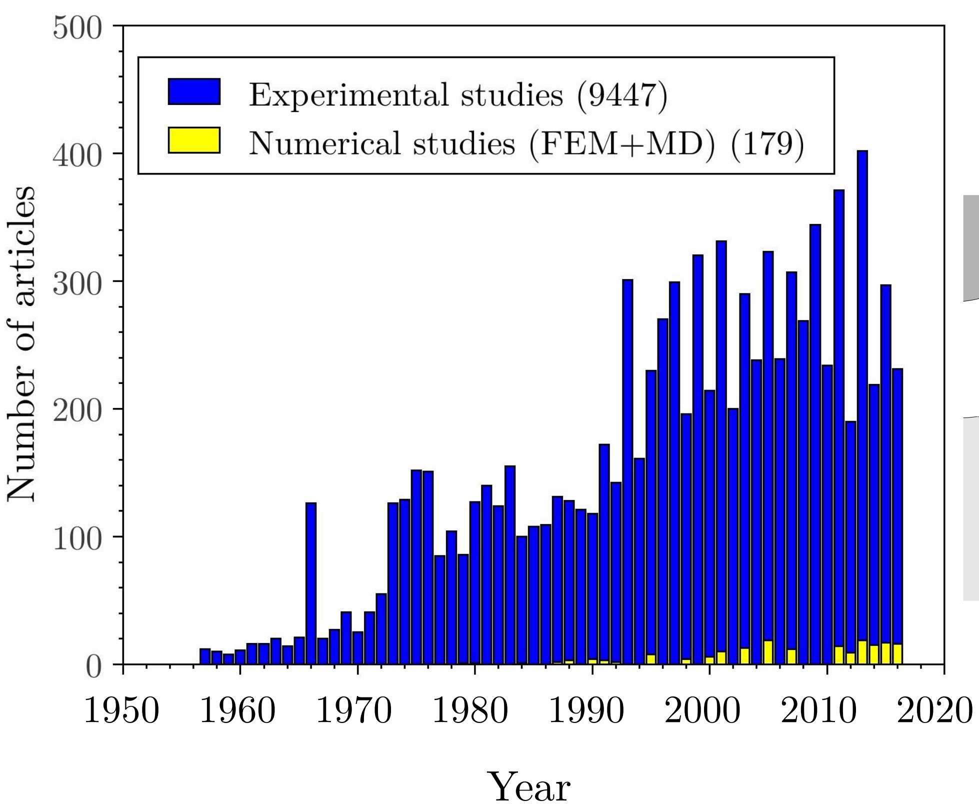

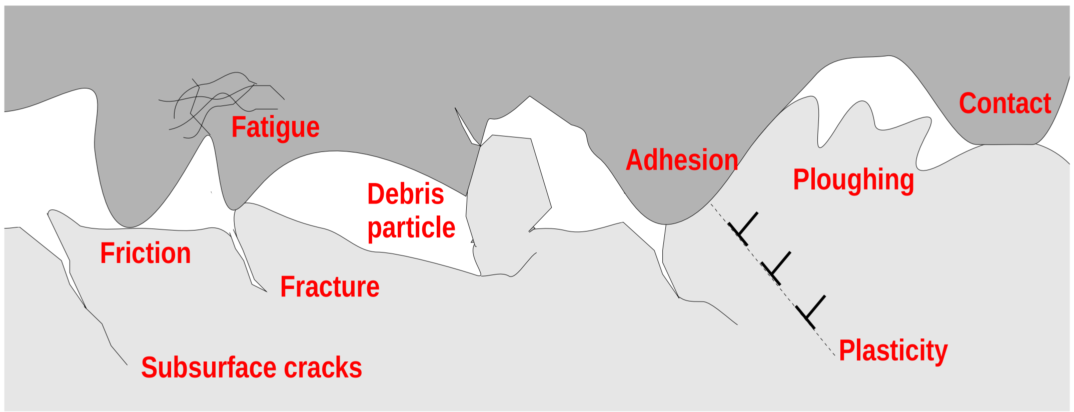

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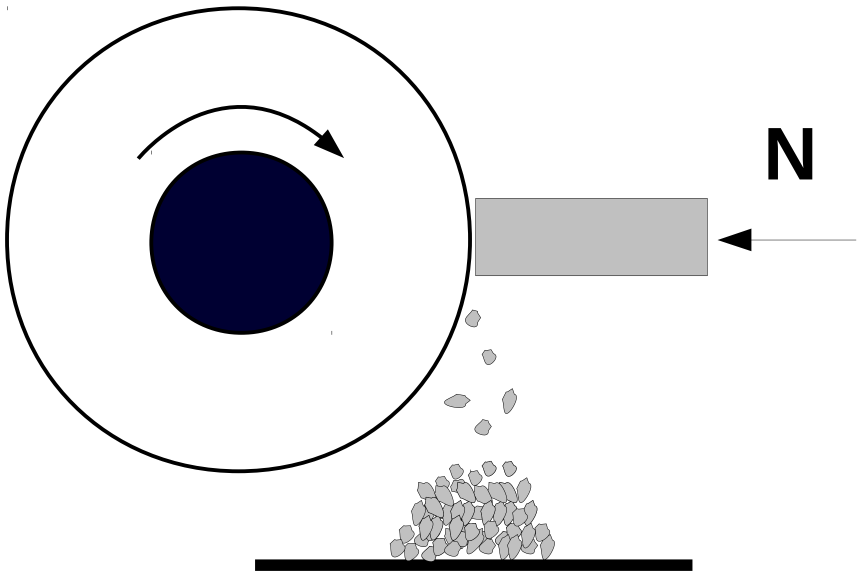


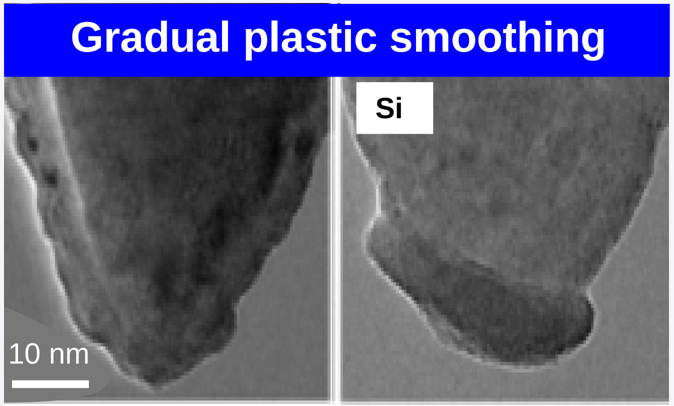
J.F. Archard (1953) *JAP*

How and when do wear particles arise?

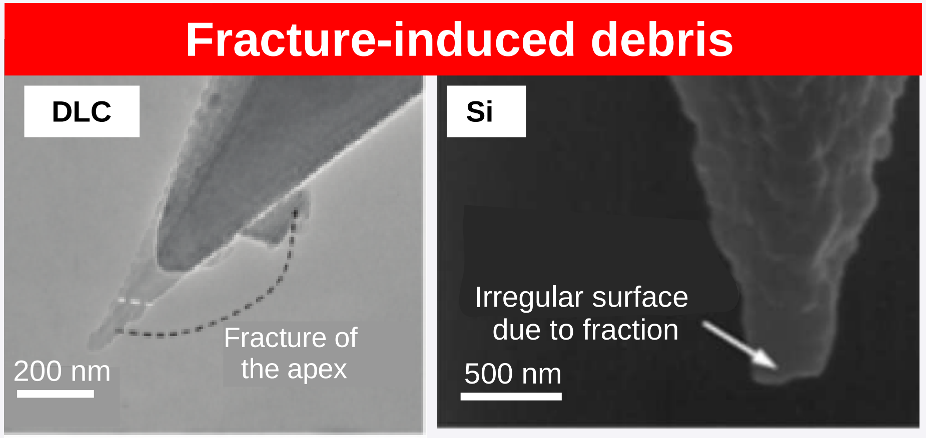
Archard (1953) JAP, Archard and Hirst (1957)

Wear Experiments vs. Simulations

Experiments



Bhaskaran et al., (2010) Nat. Nanotech
Vahdat et al., (2013) ACS Nano

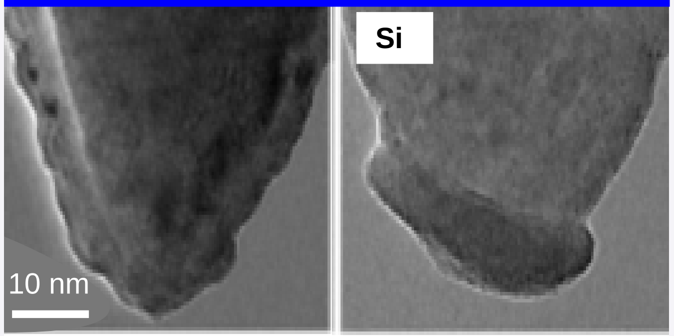


Liu et al.,(2010) ACS Nano Chung and Kim, (2014) Tri. Let.

Wear Experiments vs. Simulations

Experiments

Gradual plastic smoothing



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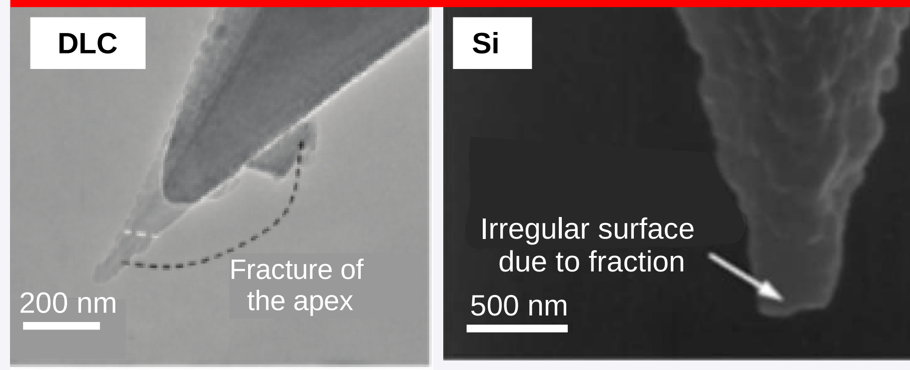
Fracture-induced debris



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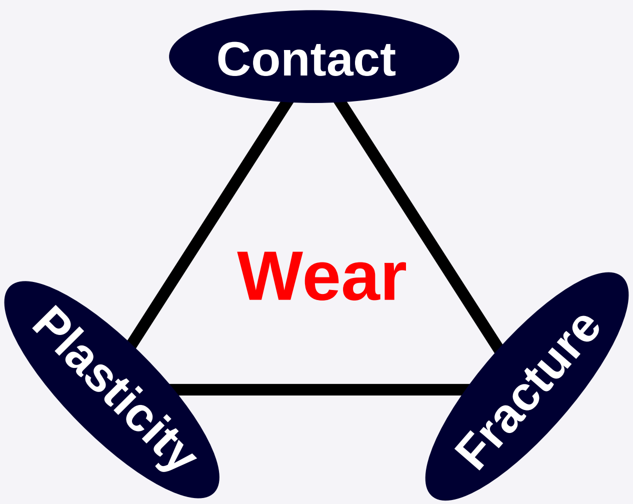
Simulations



Too complex for continuum approach

Wear Experiments vs. Simulations

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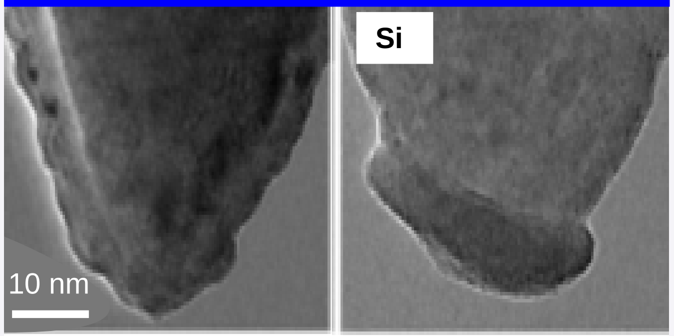

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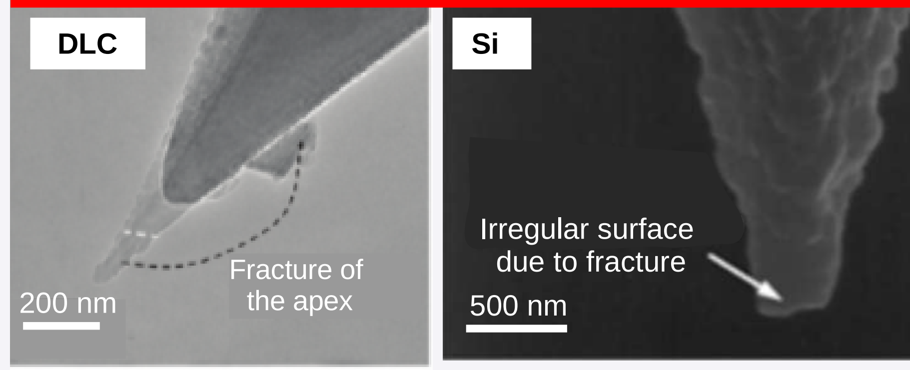

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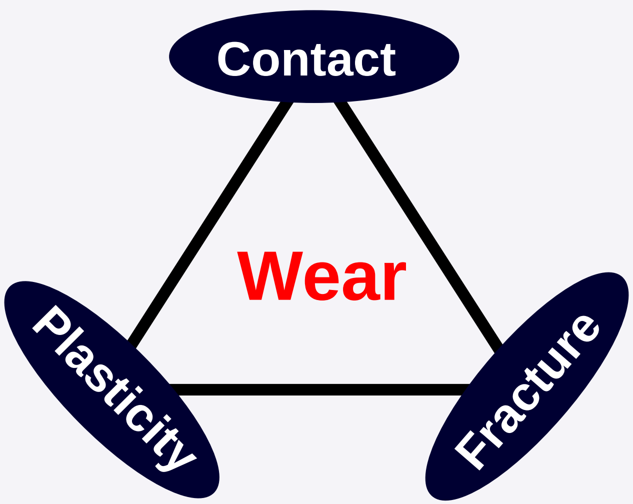
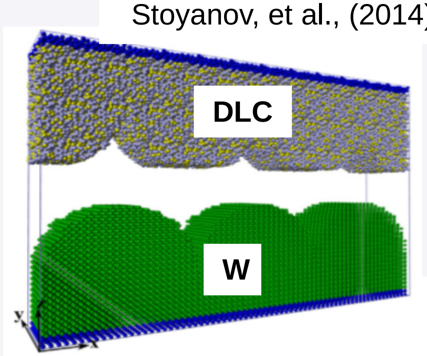
Simulations

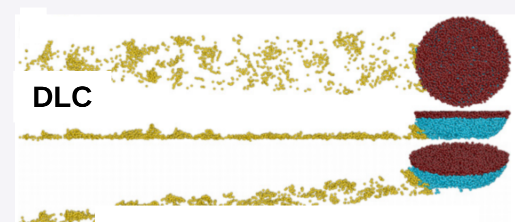
Gradual plastic smoothing



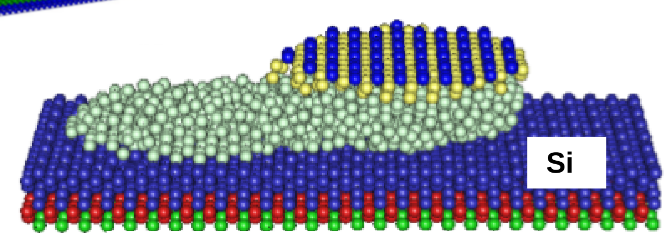
Too complex for continuum approach

Stoyanov, et al., (2014) Acta Mat.



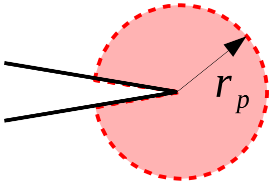


Sha, J. et al., (2013) APL



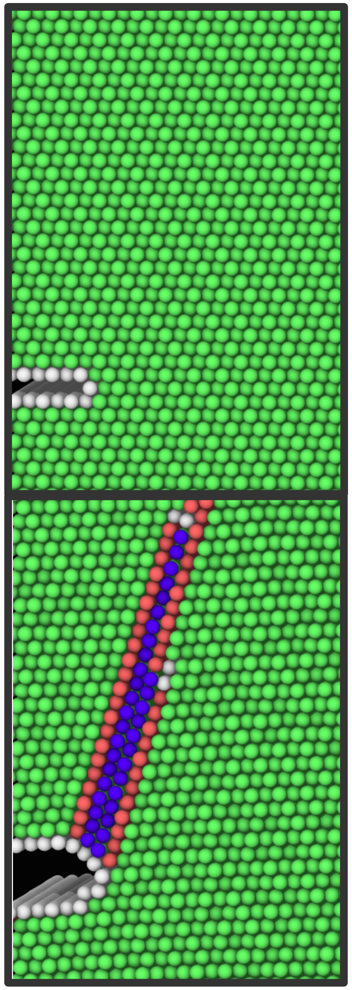
Kim and Falk (2010) PRB

Fracture at the atomic scale



$$r_p = \beta \frac{K_c^2}{\pi \sigma_y^2}$$

Plastic zone size, Rice (1972)



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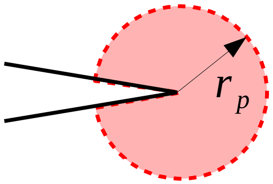

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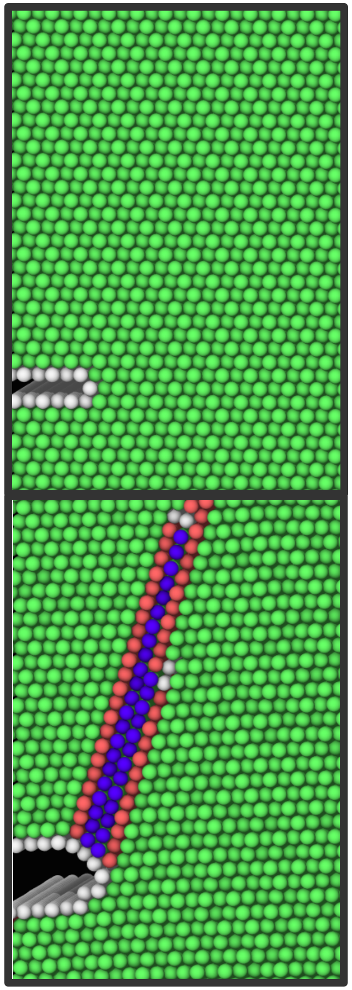
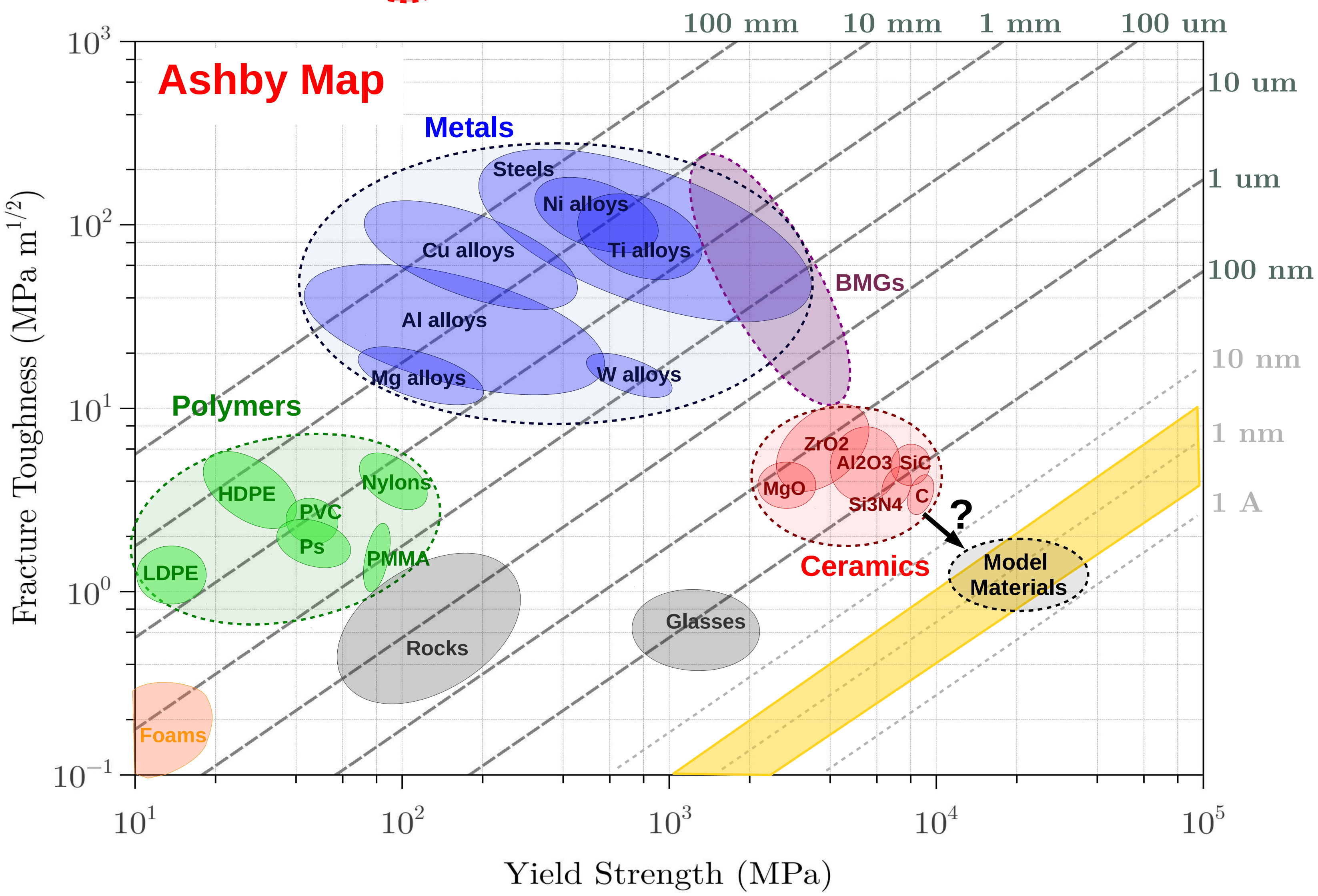
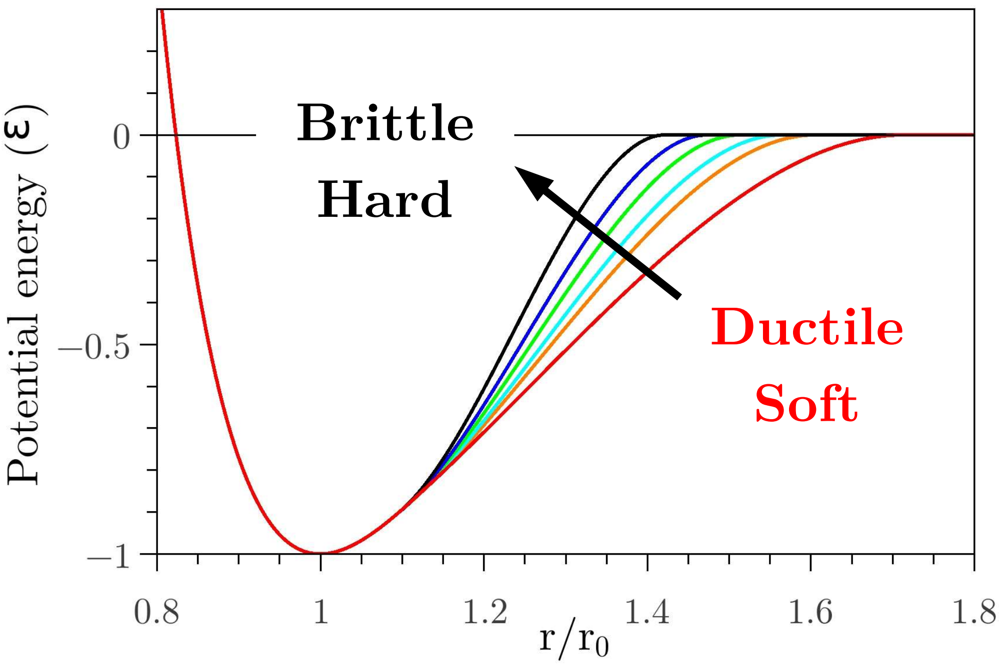
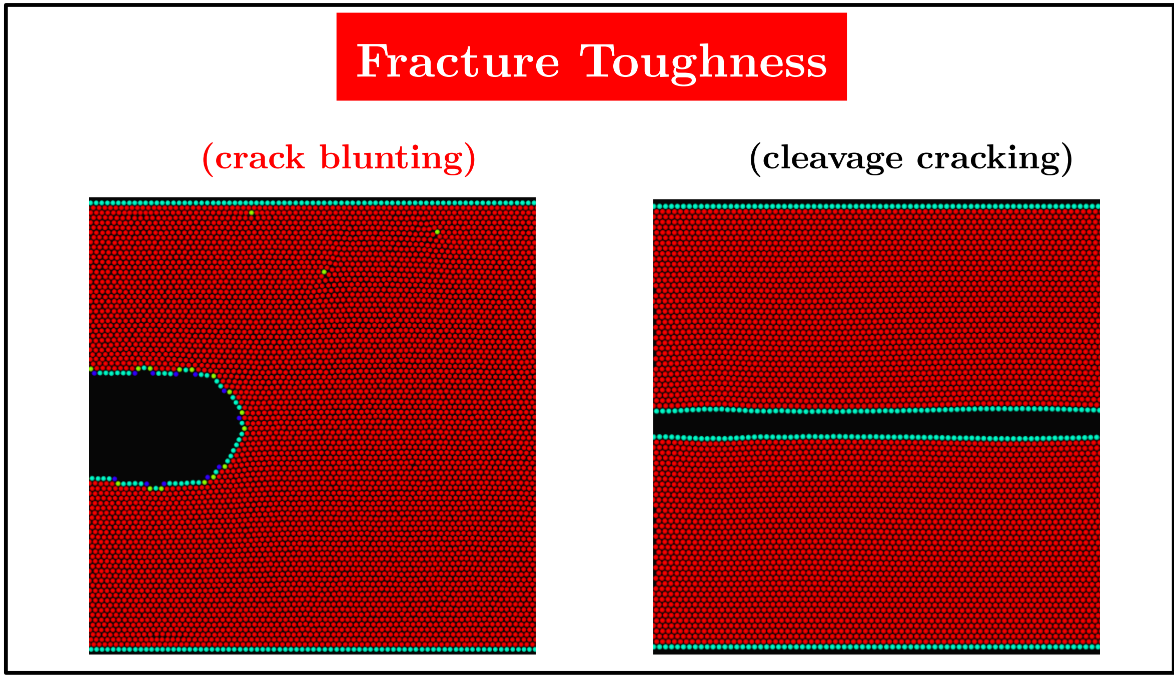


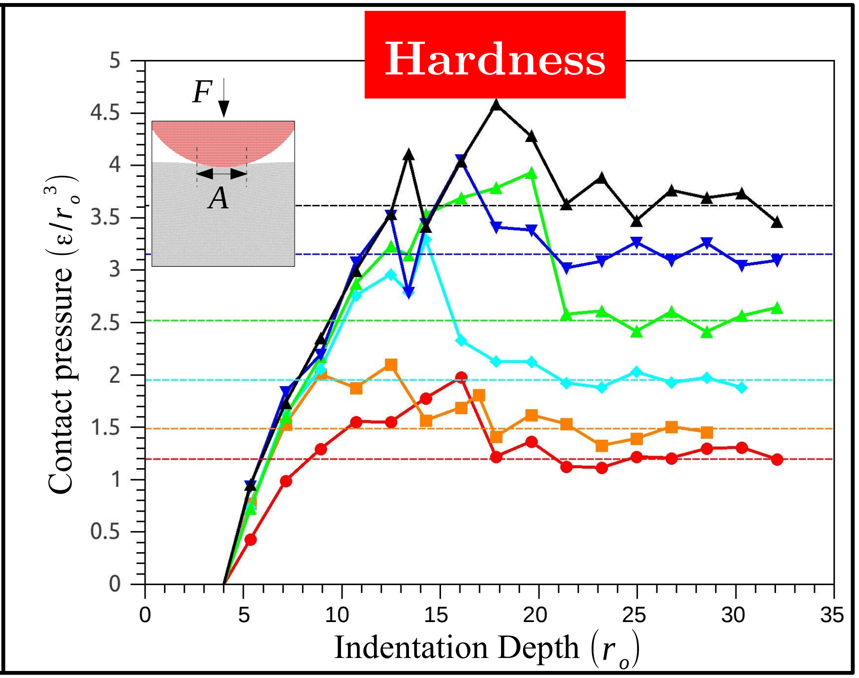


Model inter-atomic potential

- Identical lattice structure
- Identical elastic properties
- Tunable inelastic properties

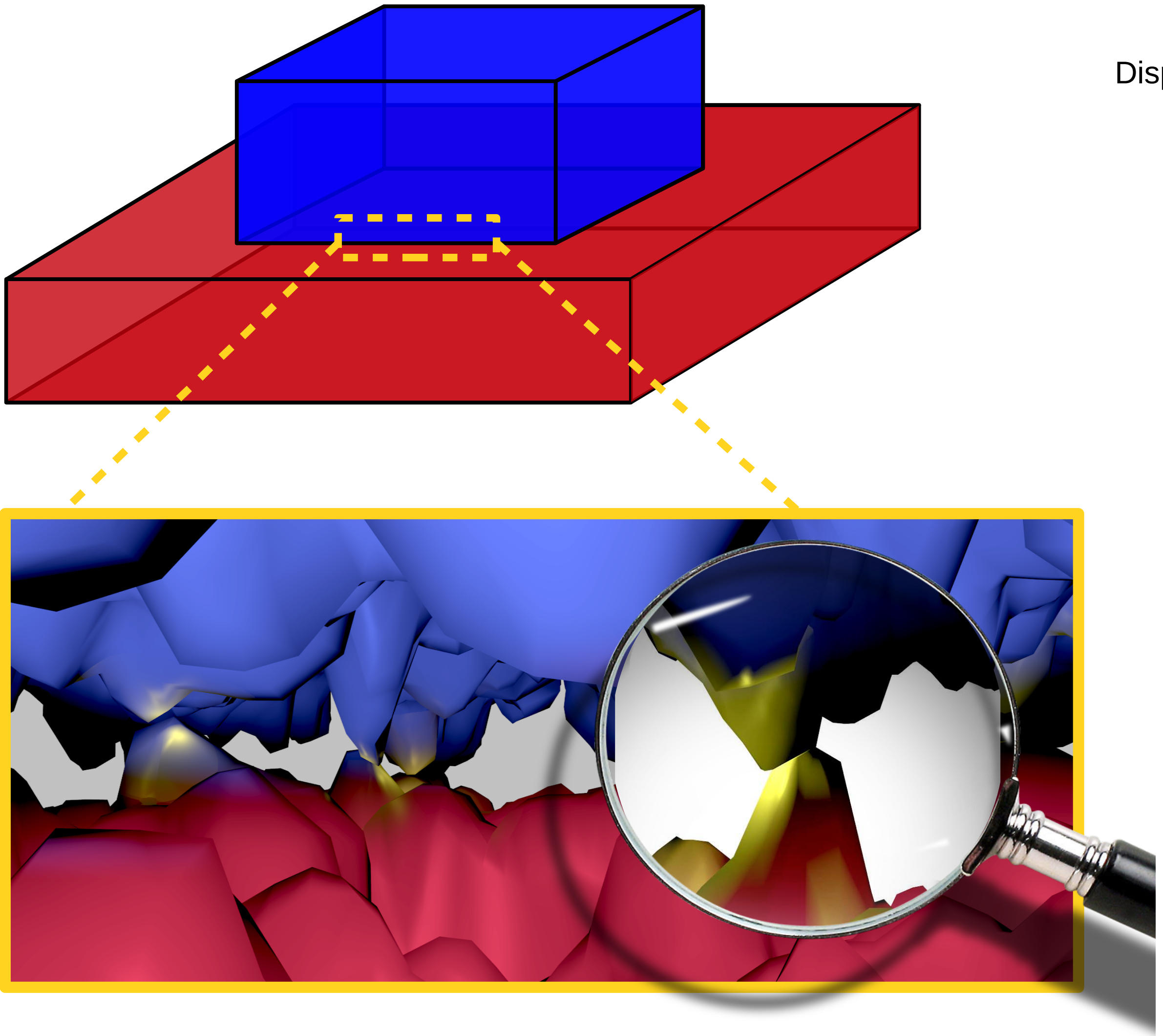


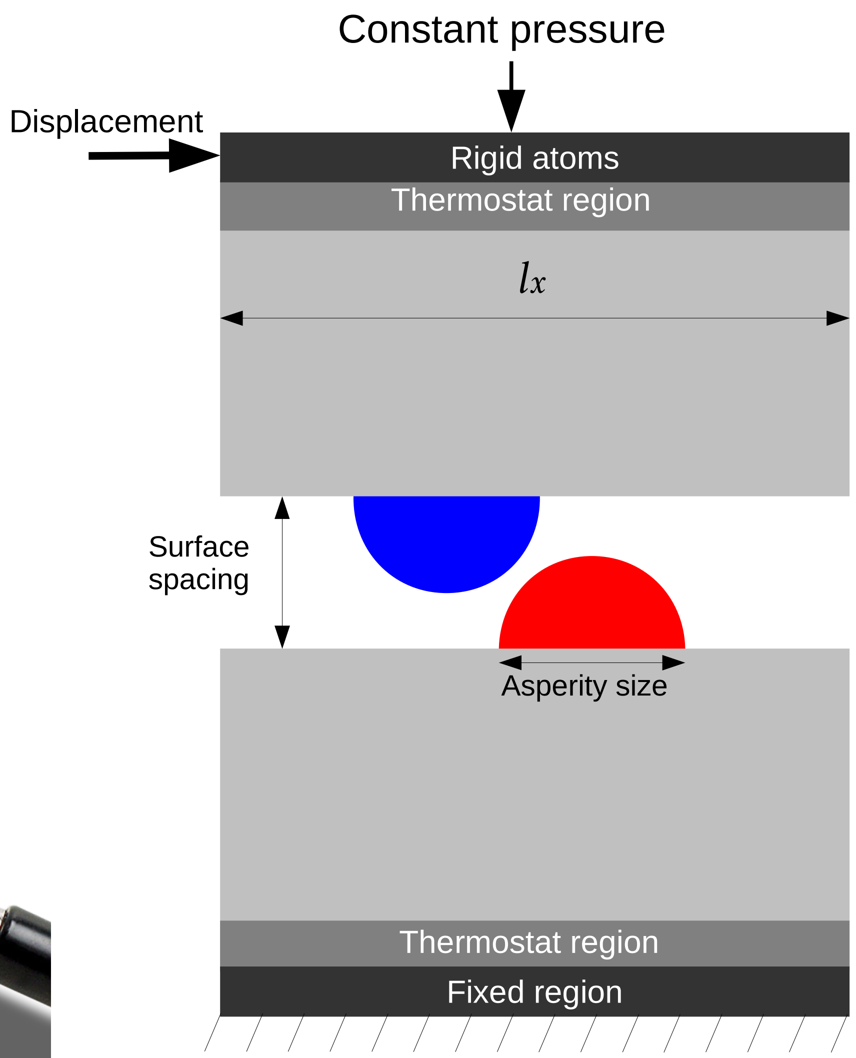




Aghababaei et al., (2016) Nat. Comm.

Idealized wear simulation





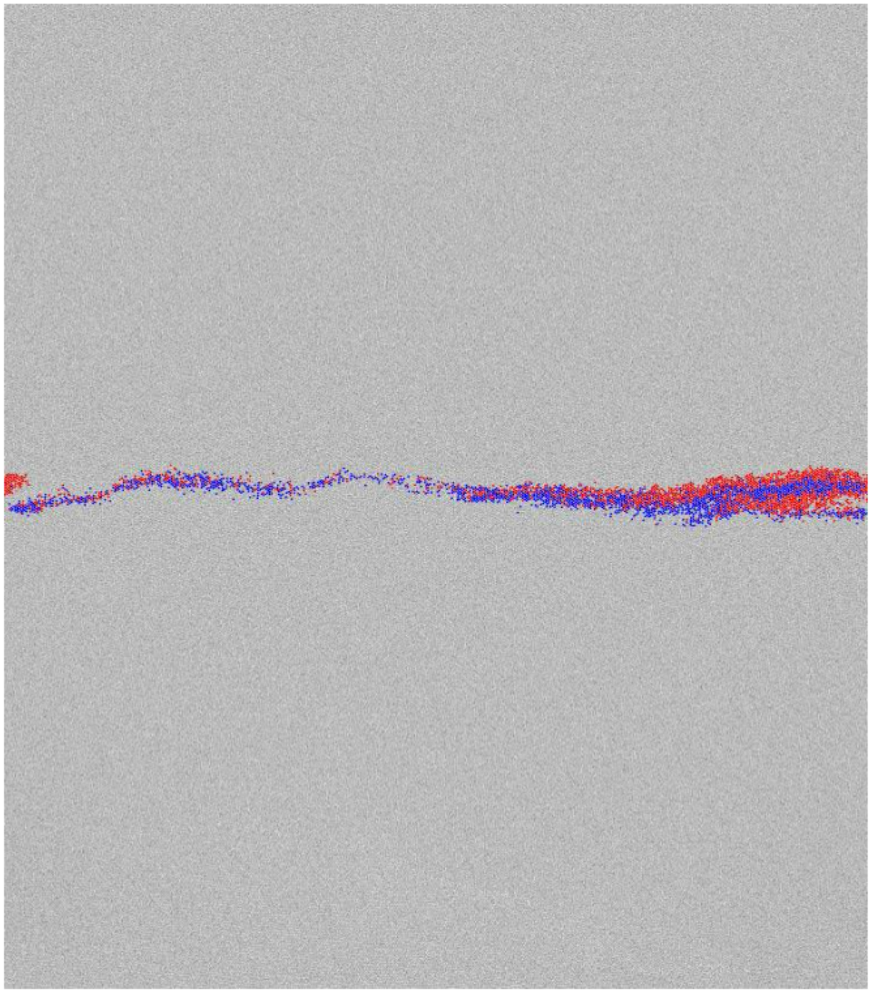
Idealized wear simulation

***Ductile* potential**

Gradual plastic smoothing

Idealized wear simulation

***Ductile* potential**



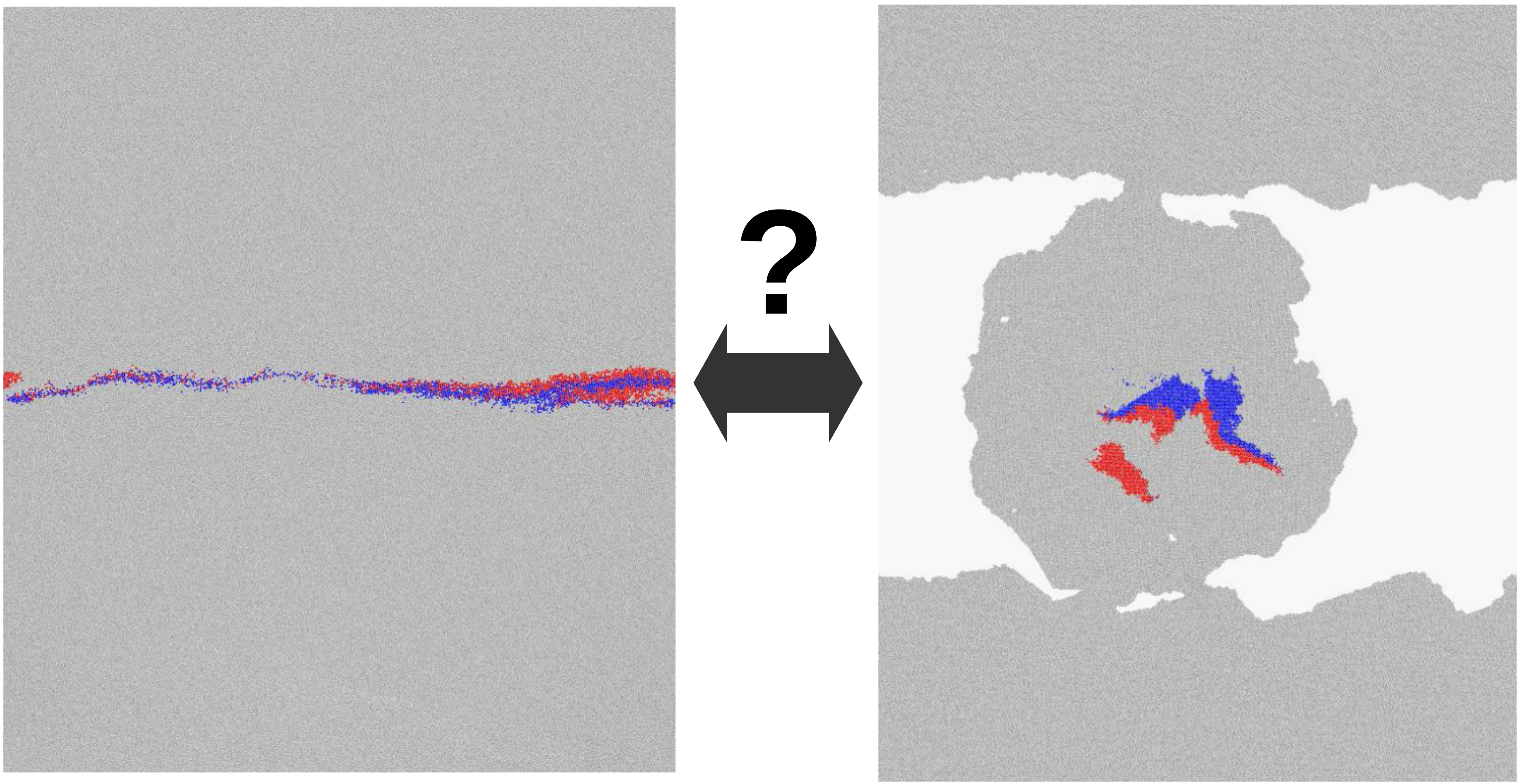
Gradual plastic smoothing

***Brittle* potential**

Fracture-induced debris

Idealized wear simulation

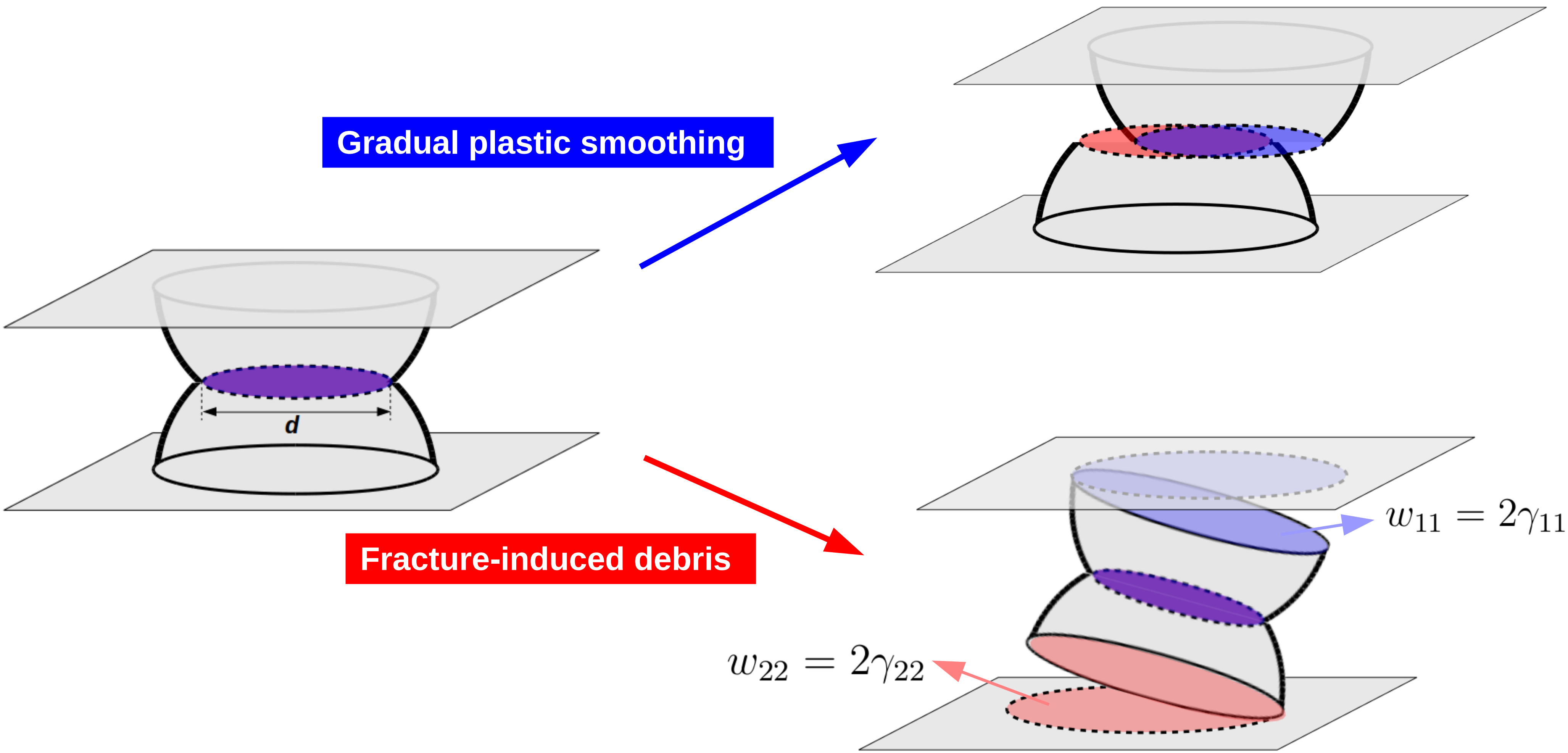
***Ductile* potential** | ***Brittle* potential**



Gradual plastic smoothing | **Fracture-induced debris**

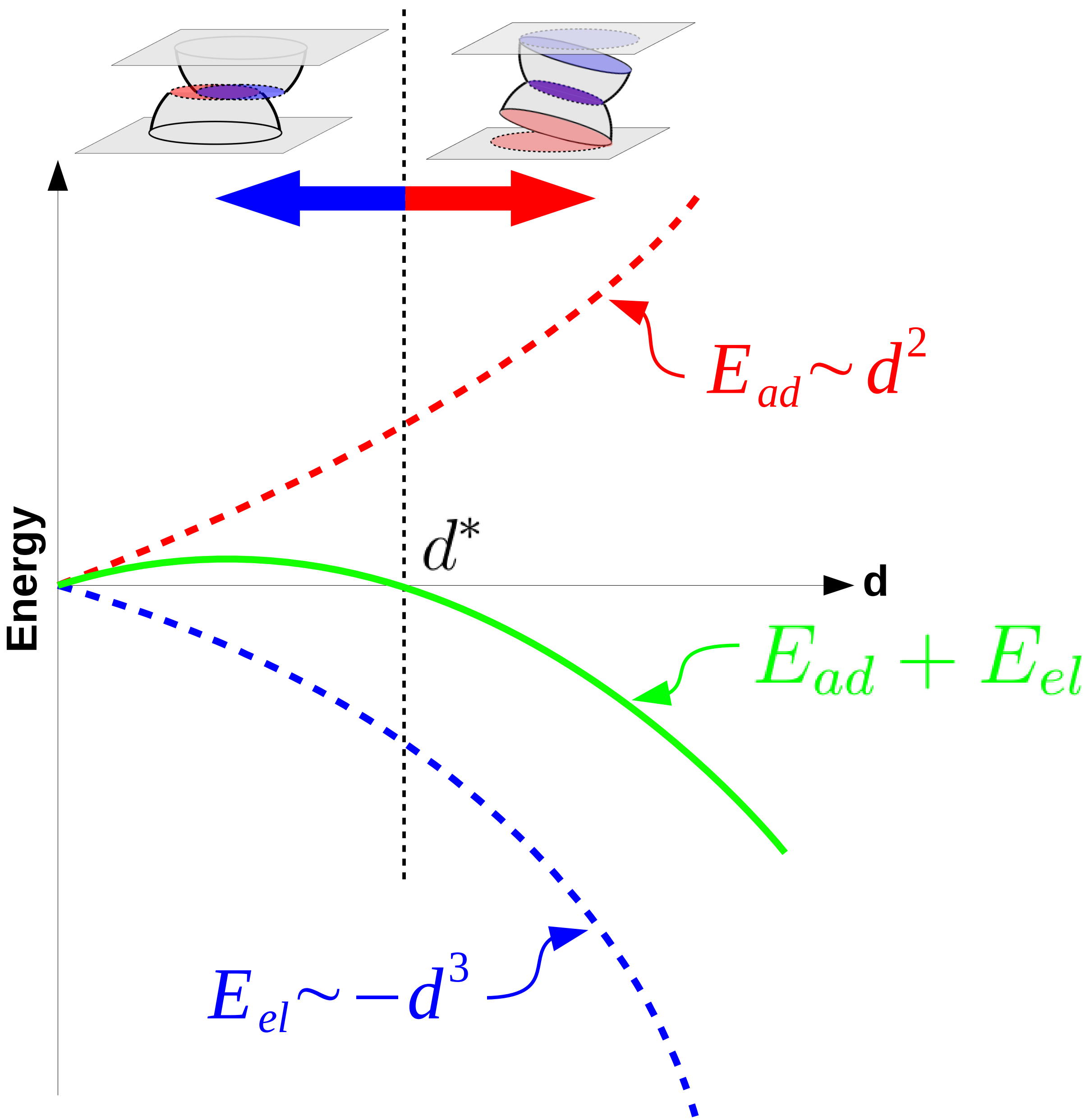
Energy balance criterion

$$E_{el} = \alpha \cdot \frac{\sigma_j^2}{2G} \cdot \frac{\pi d^3}{6}$$



$$E_{ad} = \beta \cdot \underbrace{(w_{11} + w_{22})}_{\Delta_w} \cdot \frac{\pi d^2}{4}$$

Energy balance criterion



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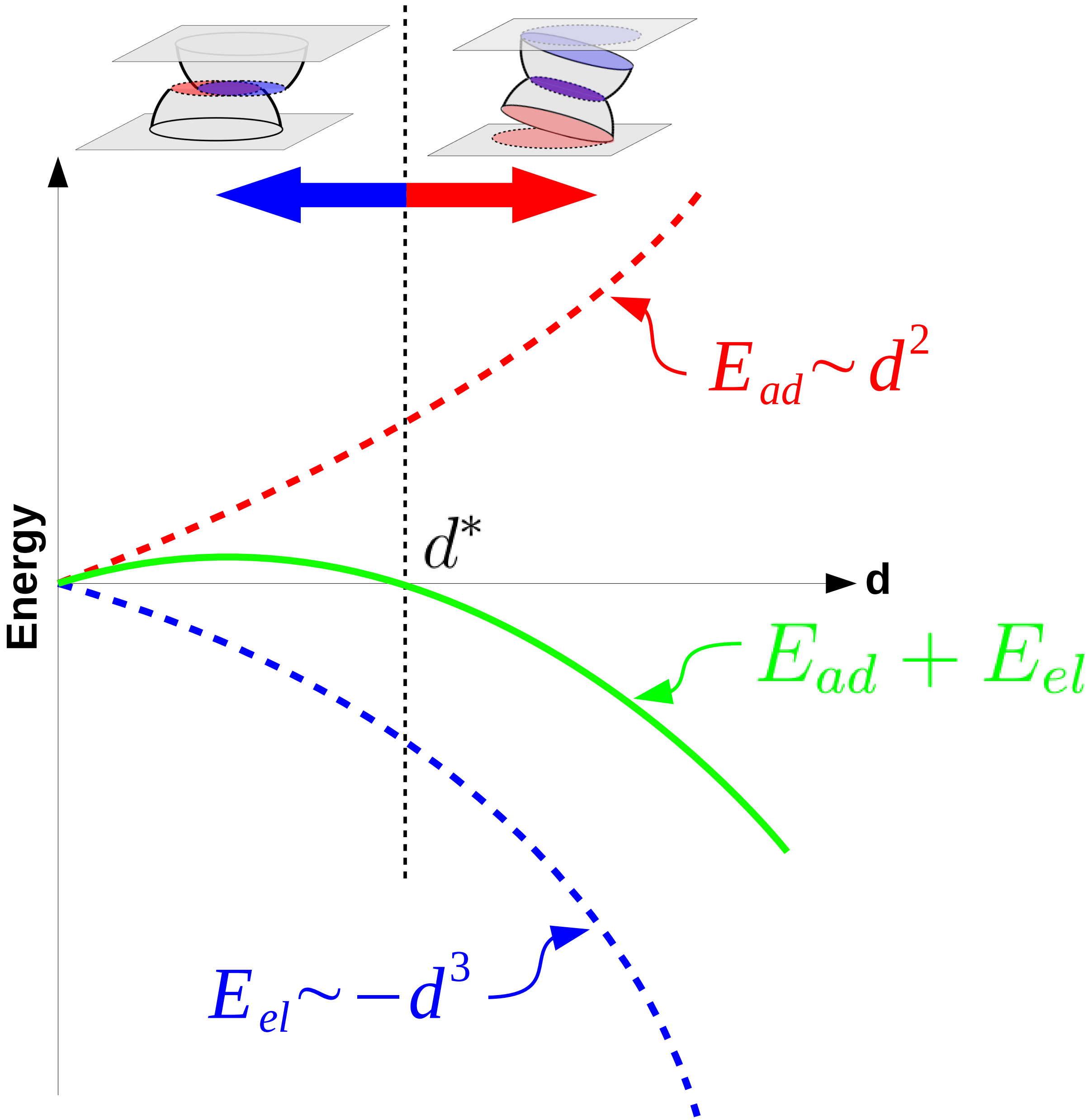


Wear transition occurs when:

$$E_{ad} + E_{el} <= 0$$

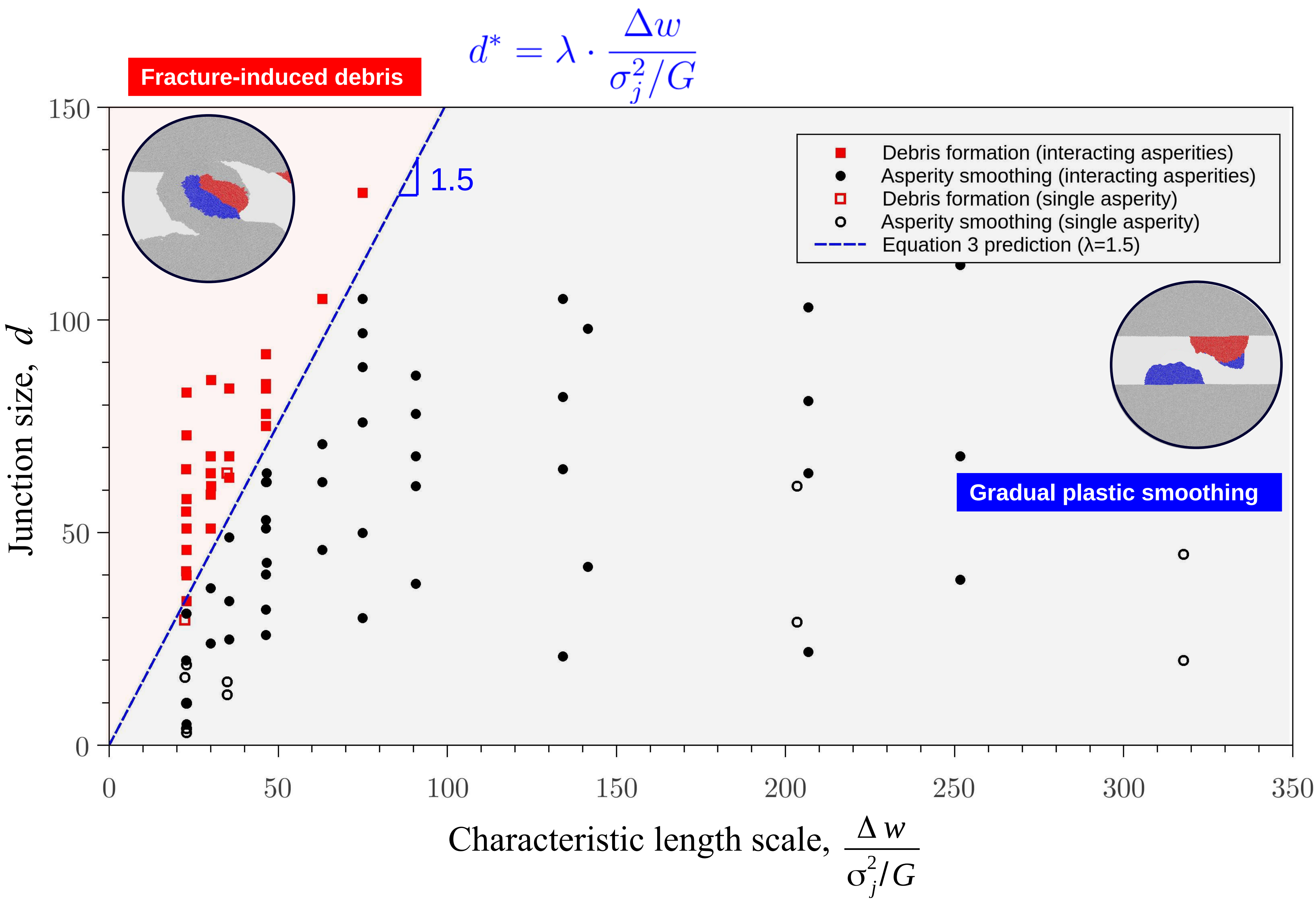
Critical junction size

$$d^* = \lambda \frac{\Delta w}{\sigma_j^2 / G}$$

Idealized case *(α=β=1)*

$\lambda = 8/\pi$	*in 2D*
$\lambda = 3$	*in 3D*

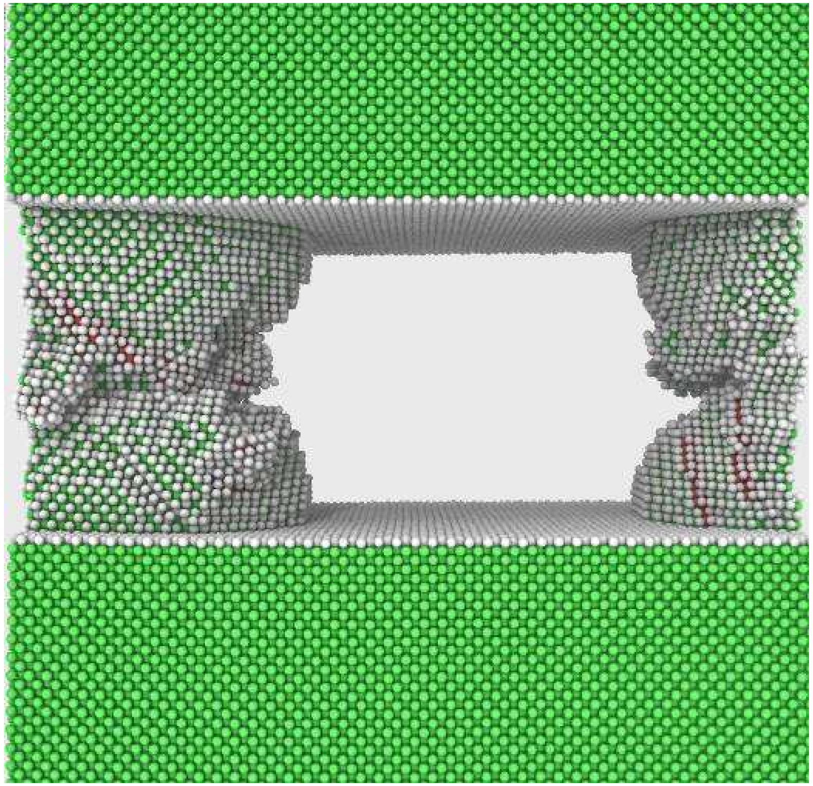
Model vs. Simulations



3D simulations

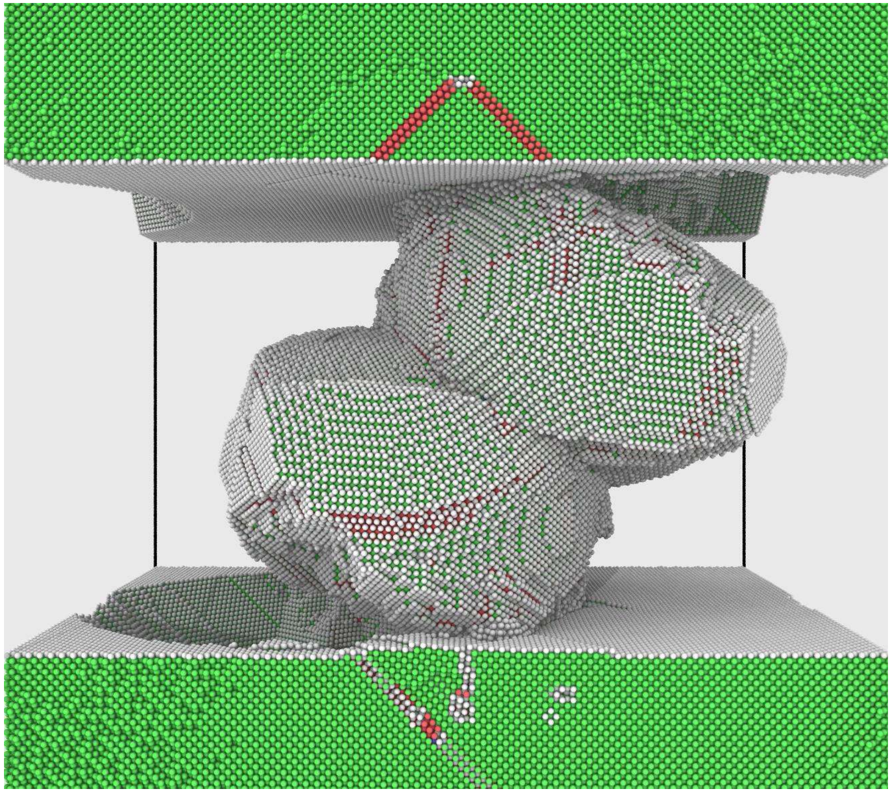
d < d*

Gradual plastic smoothing



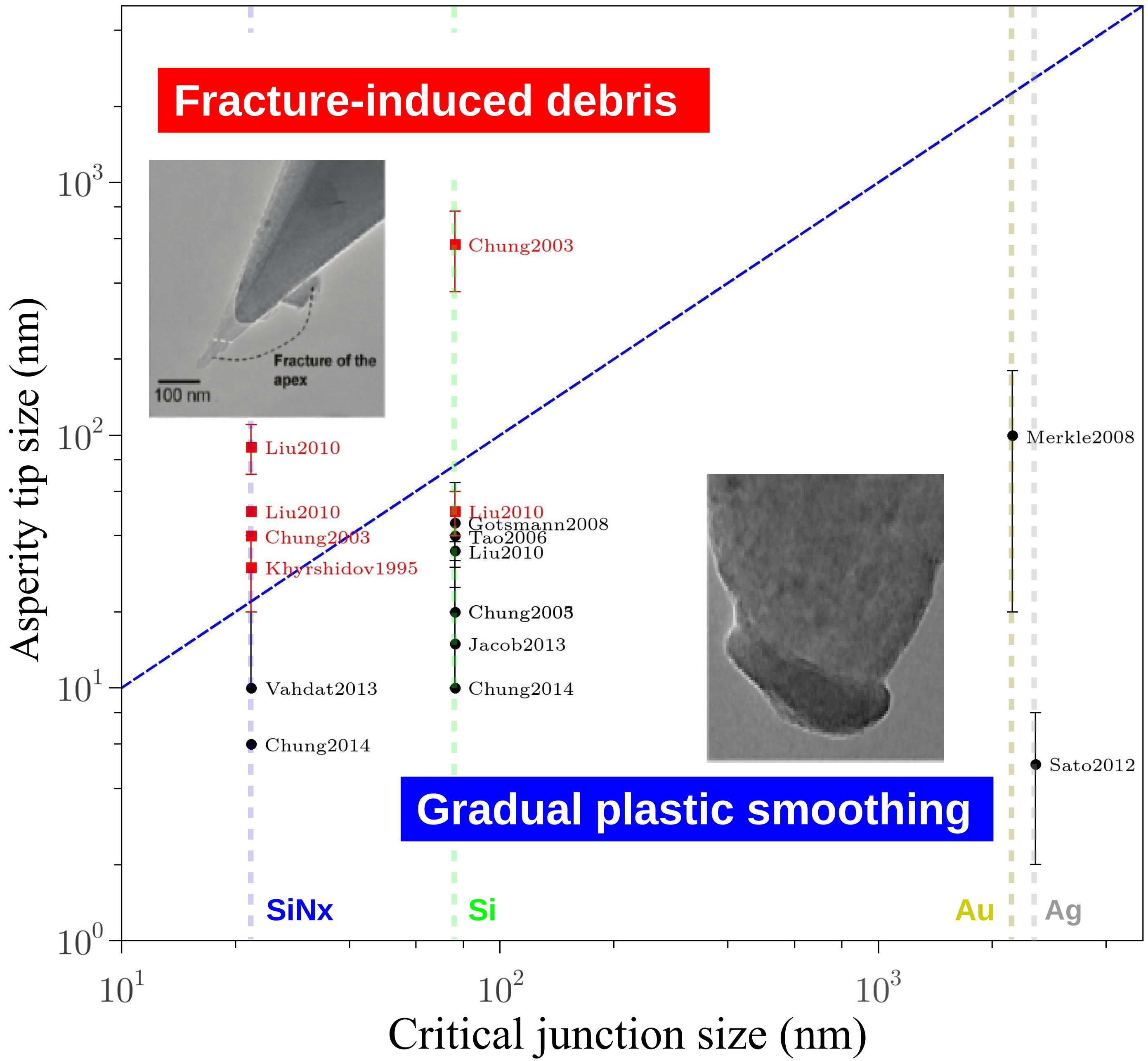
d > d*

Fracture-induced debris



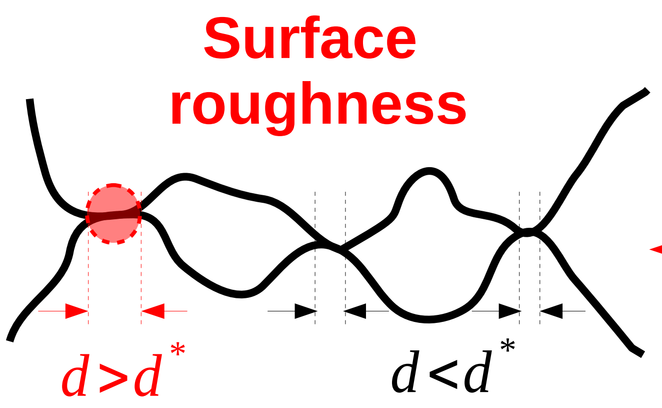
~ 4 Million atoms
~ 10 Millions time-steps
~ 2 *weeks* of calculation on 240 processors

Model vs. Experiments



New mechanistic look at wear

A *critical length scale* controls wear mechanisms at the asperity level



Bulk properties

$$d^* = \lambda \frac{G \times \Delta w}{\sigma_j^2}$$

Interface properties

Empirical fitting ➡ **Mechanics of interfaces**

Aghababaei et al., (2016) Nat. Comm.

Summary and outlook

- A new methodology to simulate wear phenomena
- A *critical length scale* controls adhesive wear mechanisms at the asperity level
- Revising empirical wear laws at different scale
- Develop new physics-based wear models

- R. Aghababaei et al, (2016) Critical length scale controls adhesive wear mechanisms, Nature Communications, 7, 11816.
- R. Aghababaei et al, (2017) On the debris-level origins of adhesive wear: Did Archard get it right?, appears in PNAS
- Frérot (2017) Emergence of wear law: from single-asperity to multi-asperity, Submitted.