Friction is Fracture: A New Paradigm for the onset of Friction

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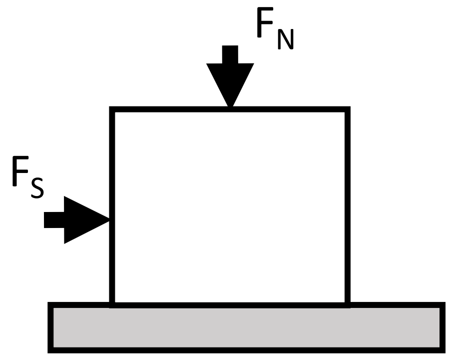
Why is there a “friction coefficient”?



$F_S < \mu_S F_N \Rightarrow$ no motion

$F_S = \mu_S F_N \Rightarrow$ motion starts

μ_S independent of the area of contact

Bowden and Tabor picture

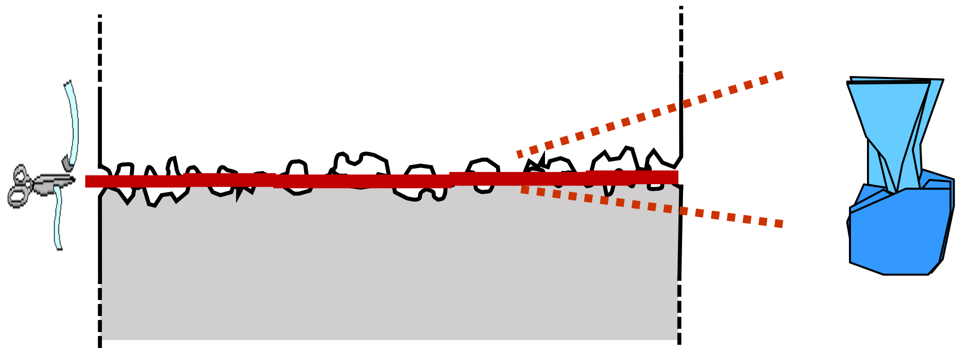
Net contact area = A << **Nominal** contact area

Huge pressures at the contact points **deform the contacts**

➔ $F_N = A \cdot$ **yield stress**

Slip starts when $F_S = A \cdot$**shear strength**

➔ $\mu_S = F_S / F_N =$ **shear strength / yield stress**



~~All the contacts break **simultaneously**~~ ➔ **Things don’t break that way**

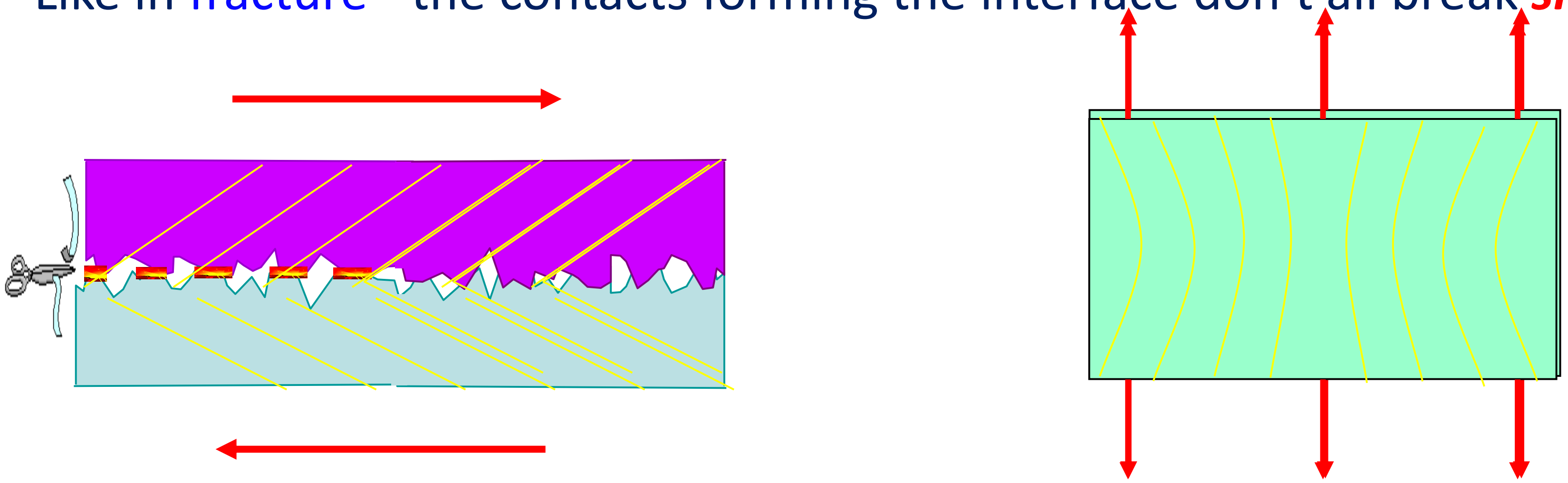
Fracture ⇔ propagating cracks!

The onset of friction ⇔ how/when/why cracks propagate….

So… how do things break?

Materials fracture via ***crack propagation***

Like in fracture - the contacts forming the interface don’t all break ***simultaneously***



In materials under shear/tension:

Cracks **focus** elastic energy into a **stress field singularity** at their tip.

- Material is preferentially ruptured at the tip of a crack
- ***Failure***: Loads << theoretical strength of “homogeneous” media

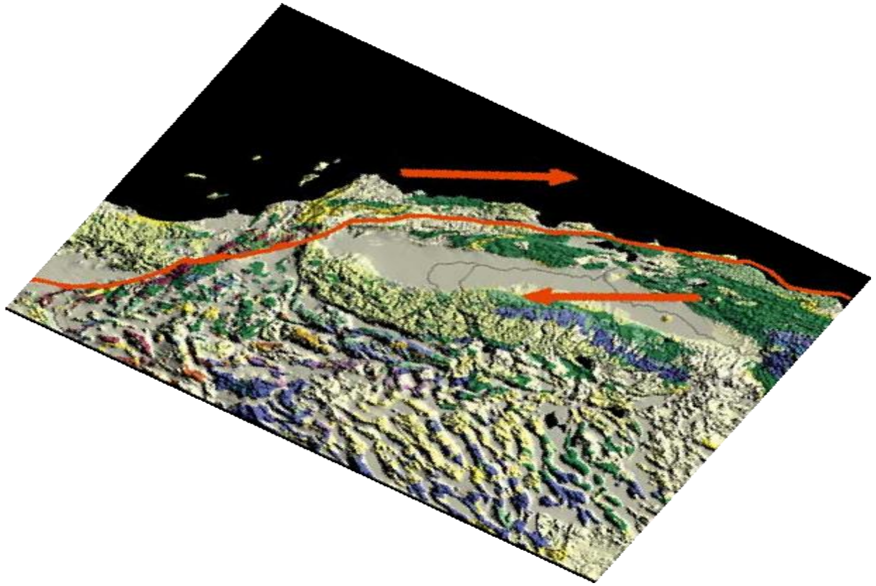
Therefore… like a crack:

Interface slip is mediated by crack-like rupture fronts

We’ll show that:

The ***stresses*** driving these fronts are described by ***Fracture Mechanics***

Earthquakes *are* Friction



San Andreas fault
California (USGS)

Kostrov, Eshelby, Freund, Rice, Aki, Andrews, Burridge….

Different modes of natural earthquakes have been predicted/observed/deduced … These include:

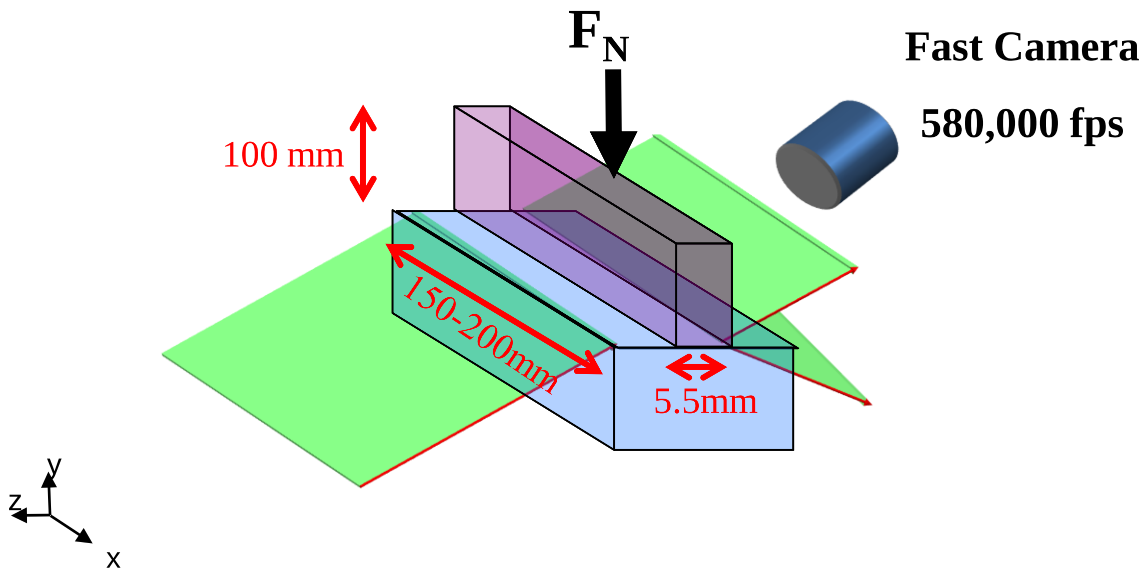
Anomalously slow, crack-like “sub-Rayleigh”, Supershear earthquakes

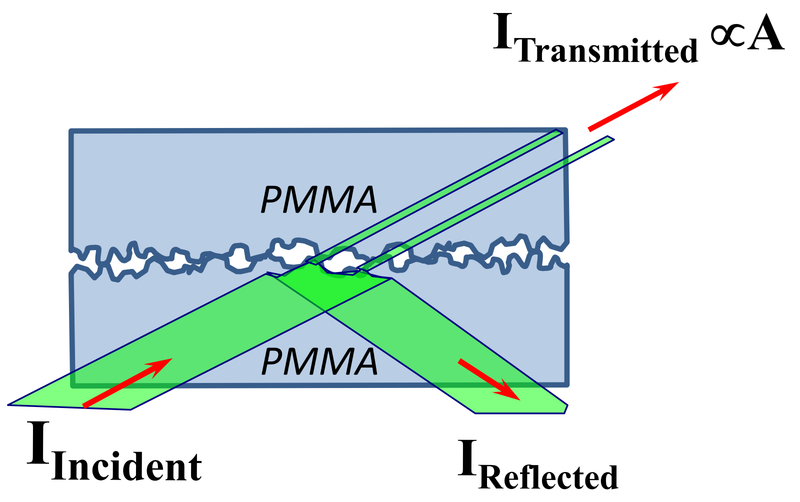
Along a natural fault collective “rupture” modes (earthquakes) exist…

How are these related to known fracture processes or friction??

Experimental setup

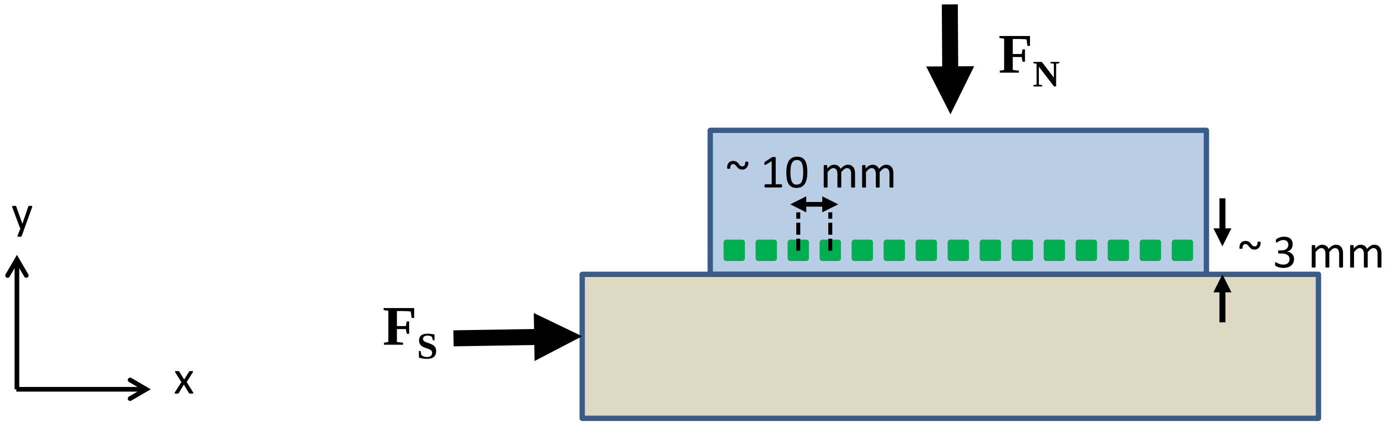
Real contact area measurement

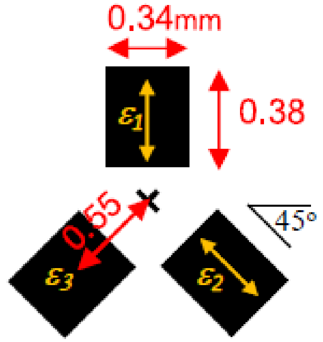




S. M. Rubinstein and J. Fineberg, Nature (2004)

2D-strain tensor measurement at 1 MSamples/s



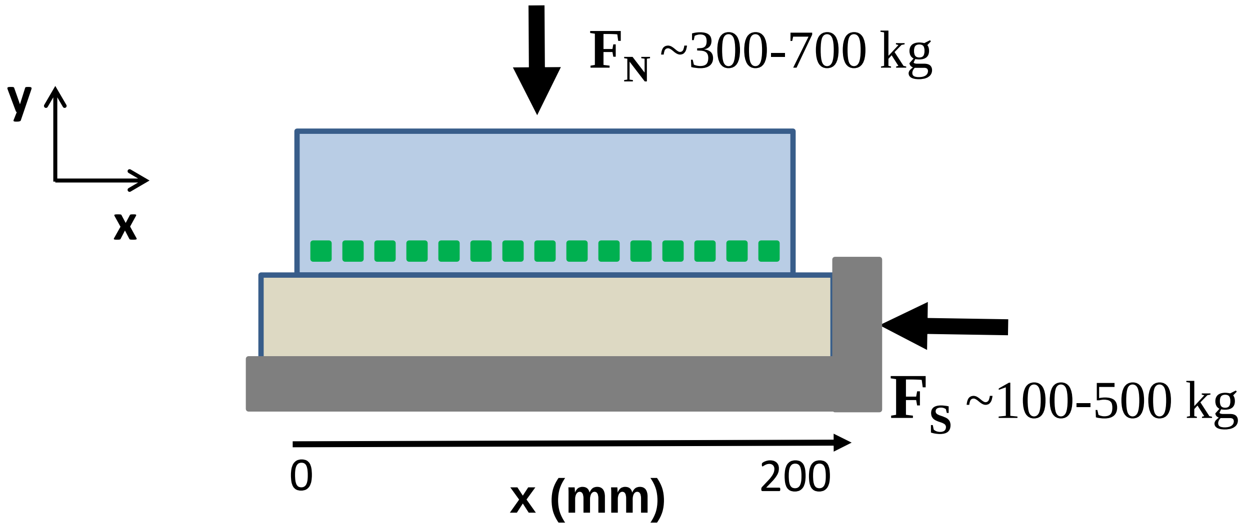


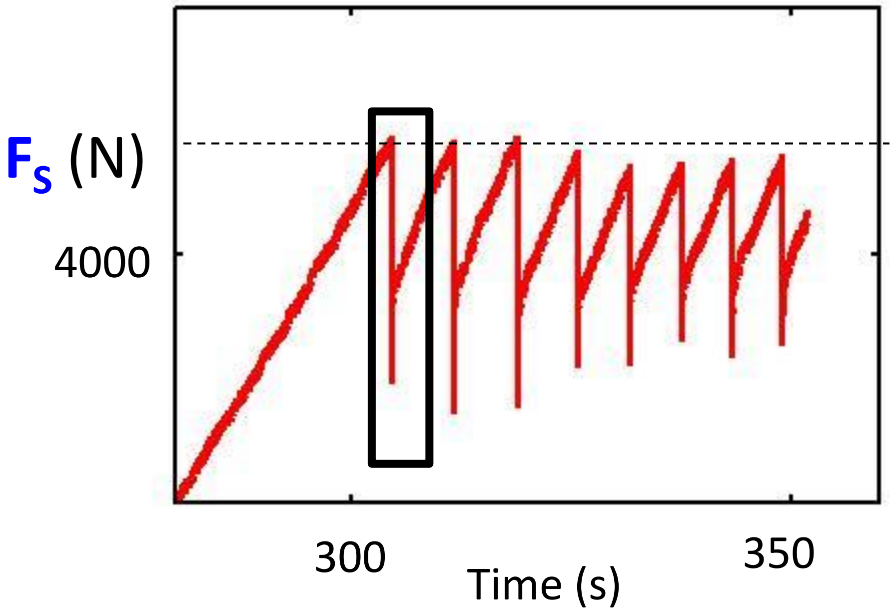
I. Svetlizky and J. Fineberg Nature ***509****, 205* (2014)

Brief Outline

1. Friction **is** Fracture (earthquakes break interfaces)
2. Boundary lubrication: (slippery) Friction **is still** Fracture
3. Predicting (lab) earthquake ***arrest*** and ***dynamics*** using Fracture Mechanics

A typical experiment



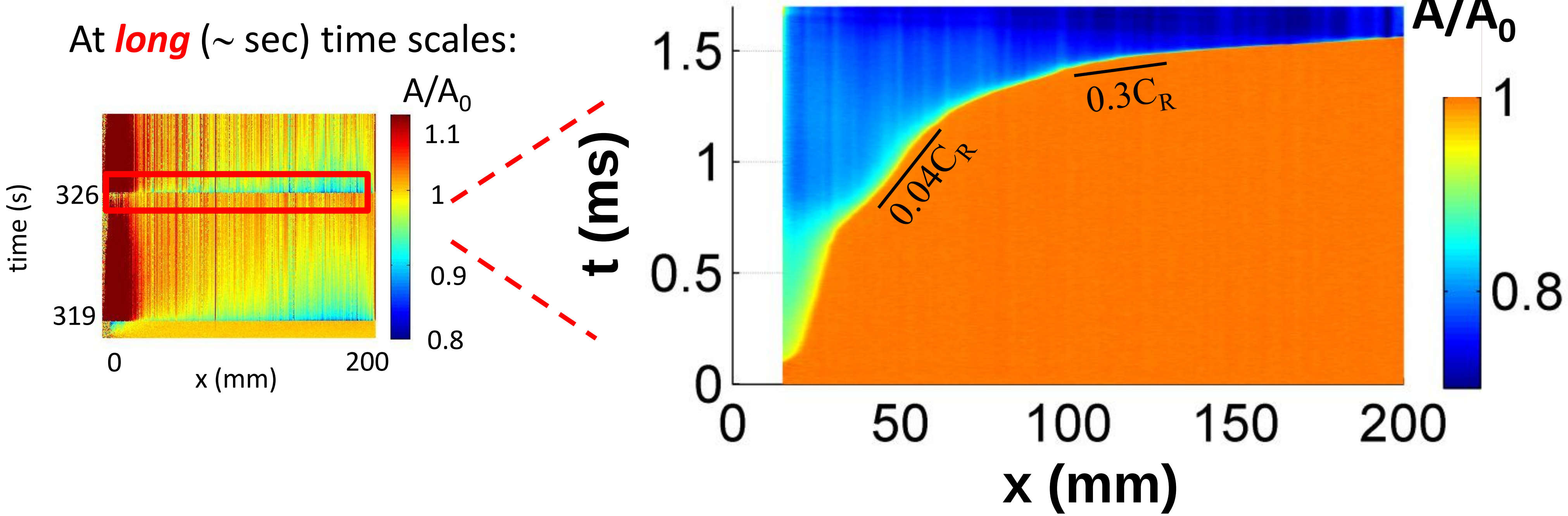


We focus on the fast processes at the ***onset*** of a sliding event

Rupture Fronts

At *long* (~ sec) time scales:

At *shorter* time scales:



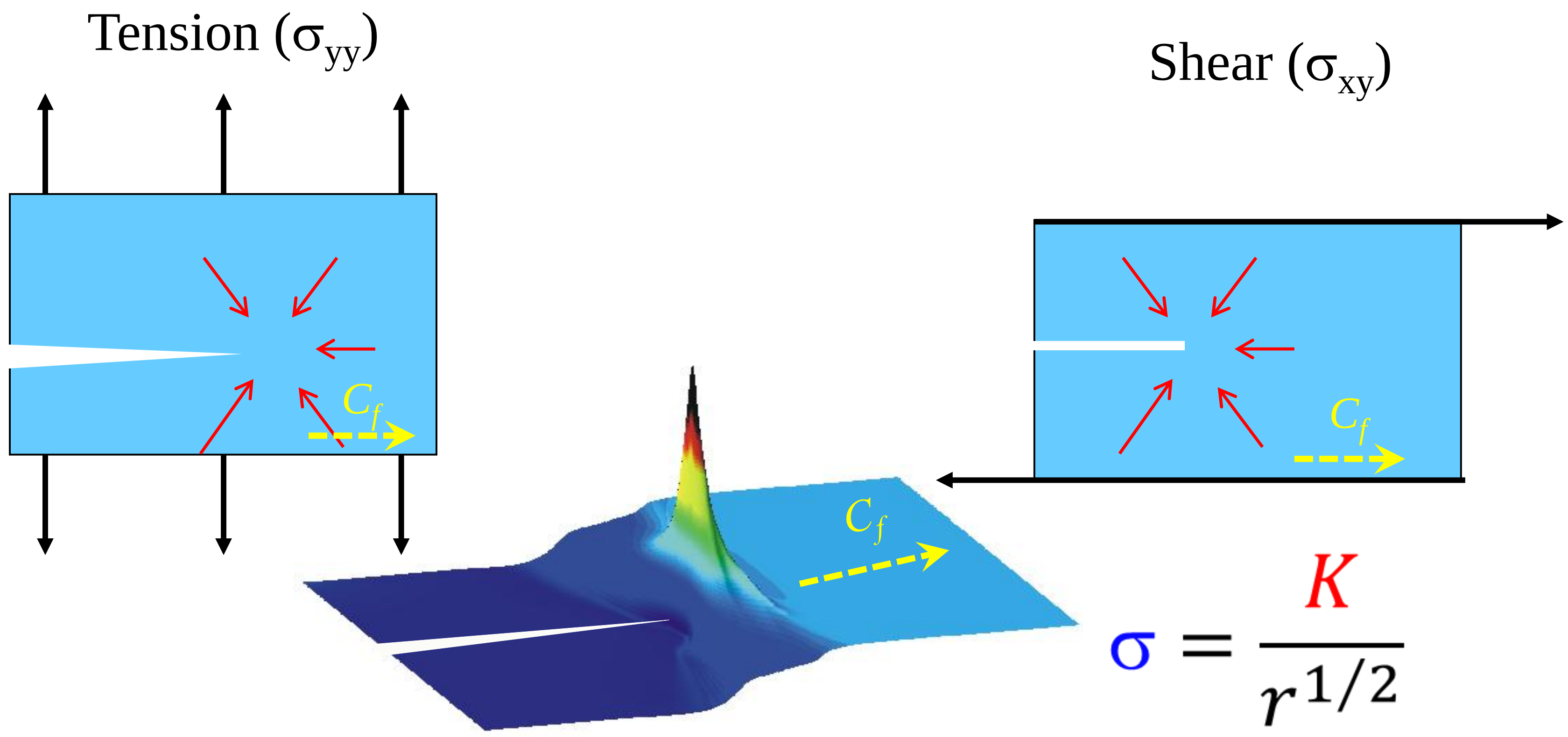
C_R: Rayleigh wave speed (1255m/s for PMMA)

Each line = snapshot of the real area of contact along the entire interface (1.5μsec between lines)

The onset of friction is mediated by propagating crack-like fronts

Short Primer: Fracture Mechanics

Linear Elastic Fracture Mechanics (LEFM)



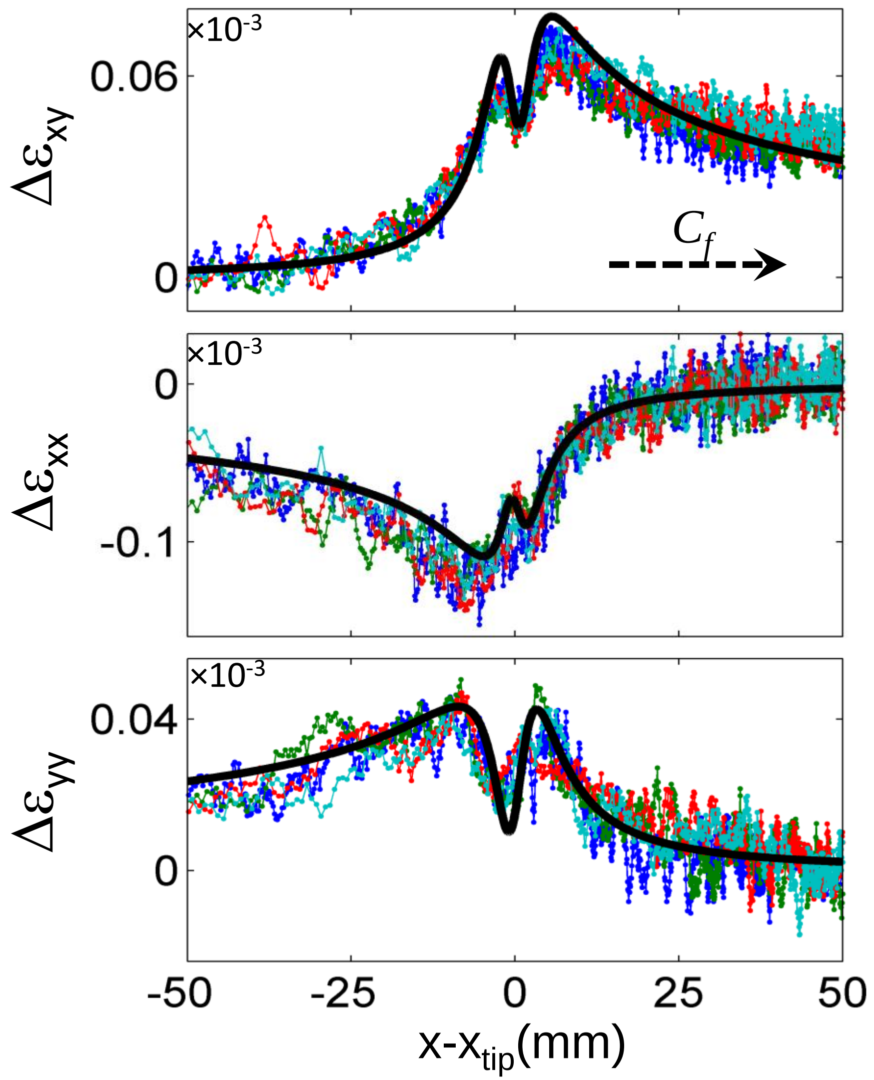
$$\sigma = \frac{K}{r^{1/2}}$$

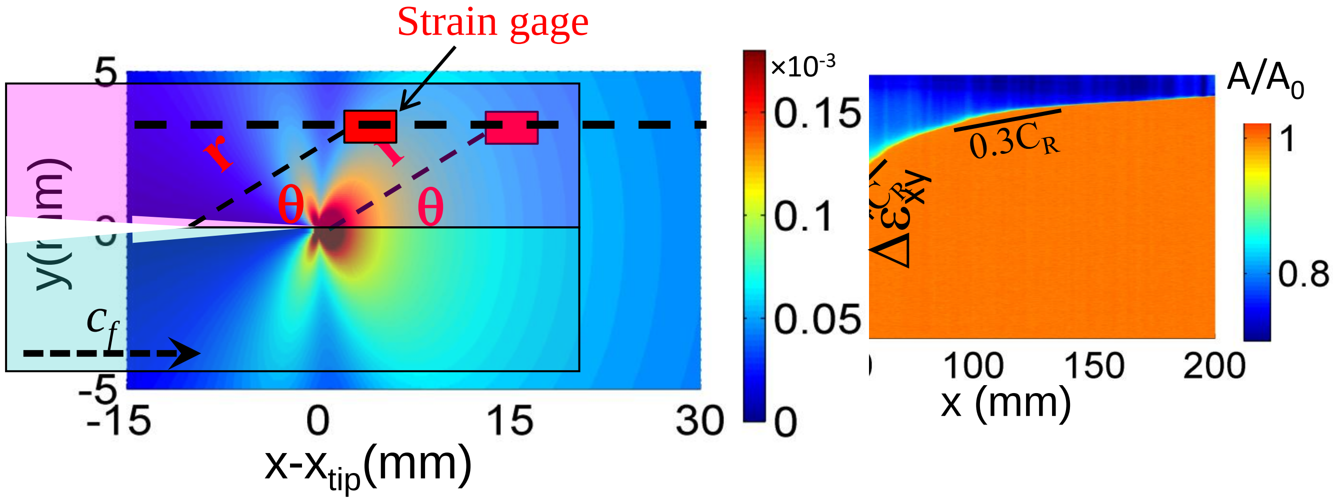
- Linear elasticity → singular stress at a crack’s tip
- Energy balance → Dissipation = Energy flux into the crack tip
- Speed limit: C_R, Rayleigh wave speed (1255m/s for PMMA)

(shear cracks can also surpass C_R but not today…)

Comparing Strain Measurements To LEFM

$0.04C_R<C_f<0.3C_R$





$$\Delta\varepsilon_{i,j} = \frac{K}{r^{1/2}}\Sigma'_{i,j}(\theta,c_f)$$

One free parameter K fits ***all*** of the data well

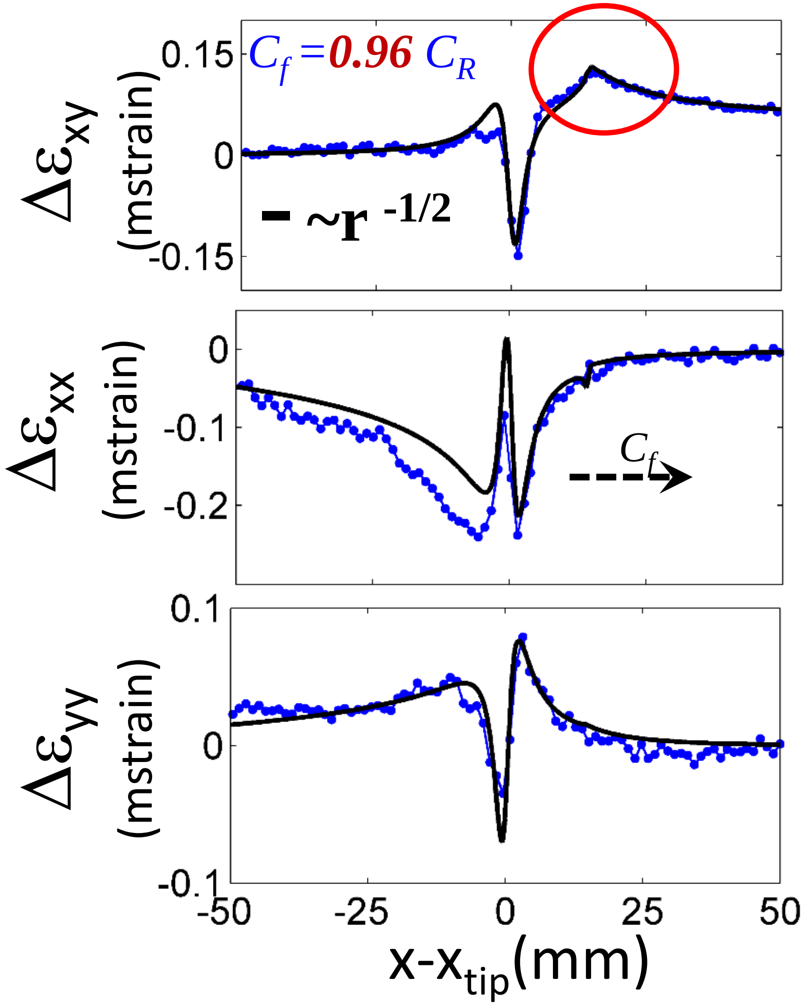
Fracture Mechanics:

$$K=K(C_f) \Leftrightarrow \Gamma\binom{\text{Fracture}}{\text{Energy}}$$

Γ= energy to break a unit area of contacts

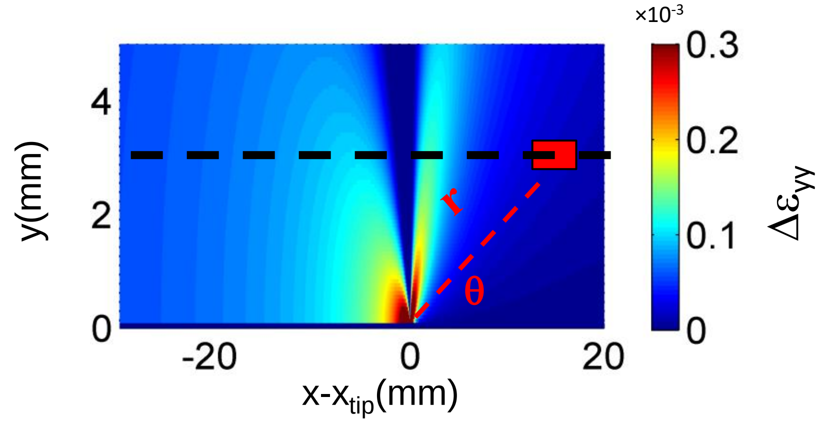
$\Gamma \sim 1\ \mathrm{J/m^2}$

Using the same fracture energy of $\Gamma = 1\ \mathrm{J/m^2}$



$$\Delta\varepsilon_{i,j} = \frac{K}{r^{1/2}}\,\Sigma'_{i,j}(\theta, c_f)$$

$K = K(c_f, \Gamma)$



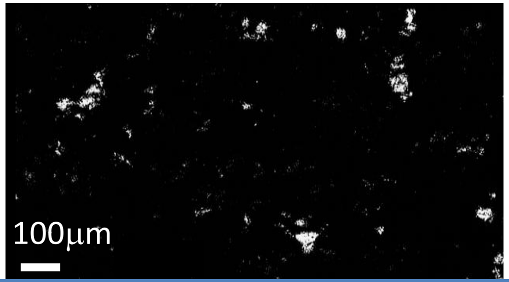
Frictional ruptures are true shear cracks!

Excellent agreement with ***Fracture Mechanics*** for ***all*** velocities with ***no*** adjustable parameters

Radiation of accelerating ruptures:
I.Svetlizky, D. Pino Munoz, M. Radiguet , D. S. Kammer , J. F. Molinari and J. Fineberg, PNAS **113**,542-7 (2016)

Why does the *measured* fracture energy $\Gamma = 1\ \mathrm{J/m^2}$?

Real area of contact - PMMA

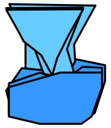


For our conditions: A ~ 0.005A_0

J.H. Dieterich, B.D. Kilgore Tectonophysics 256 (1996)

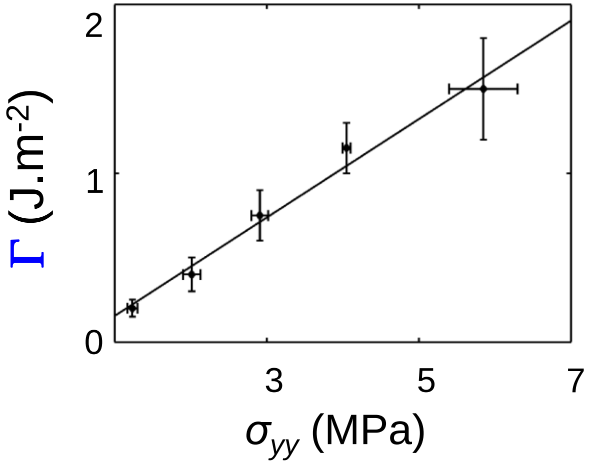
➡ Γ is proportional to A

➡ A is proportional to σ_{yy}



(Bowden and Tabor picture)

➡ Γ is proportional to σ_{yy} !



Let’s now ***use*** this new paradigm for friction

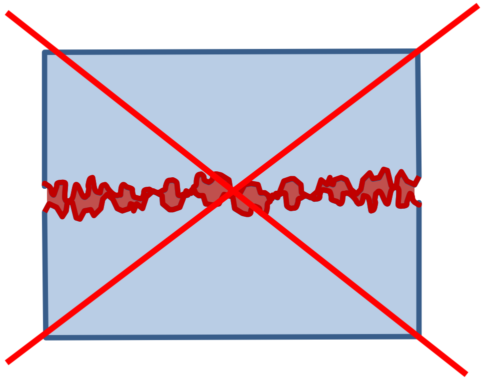
Two examples:

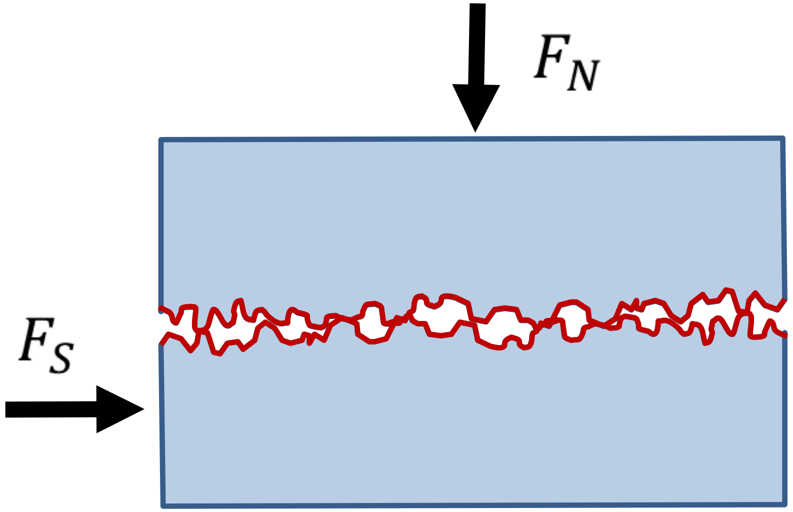
- Lubricating the interface
- Predicting Earthquake **arrest** and ***dynamics***

First example: what is the ***strength*** of *lubricated* interfaces ?

Coated lubricated interfaces = Interfaces coated with a film of lubricant

(boundary lubrication regime)

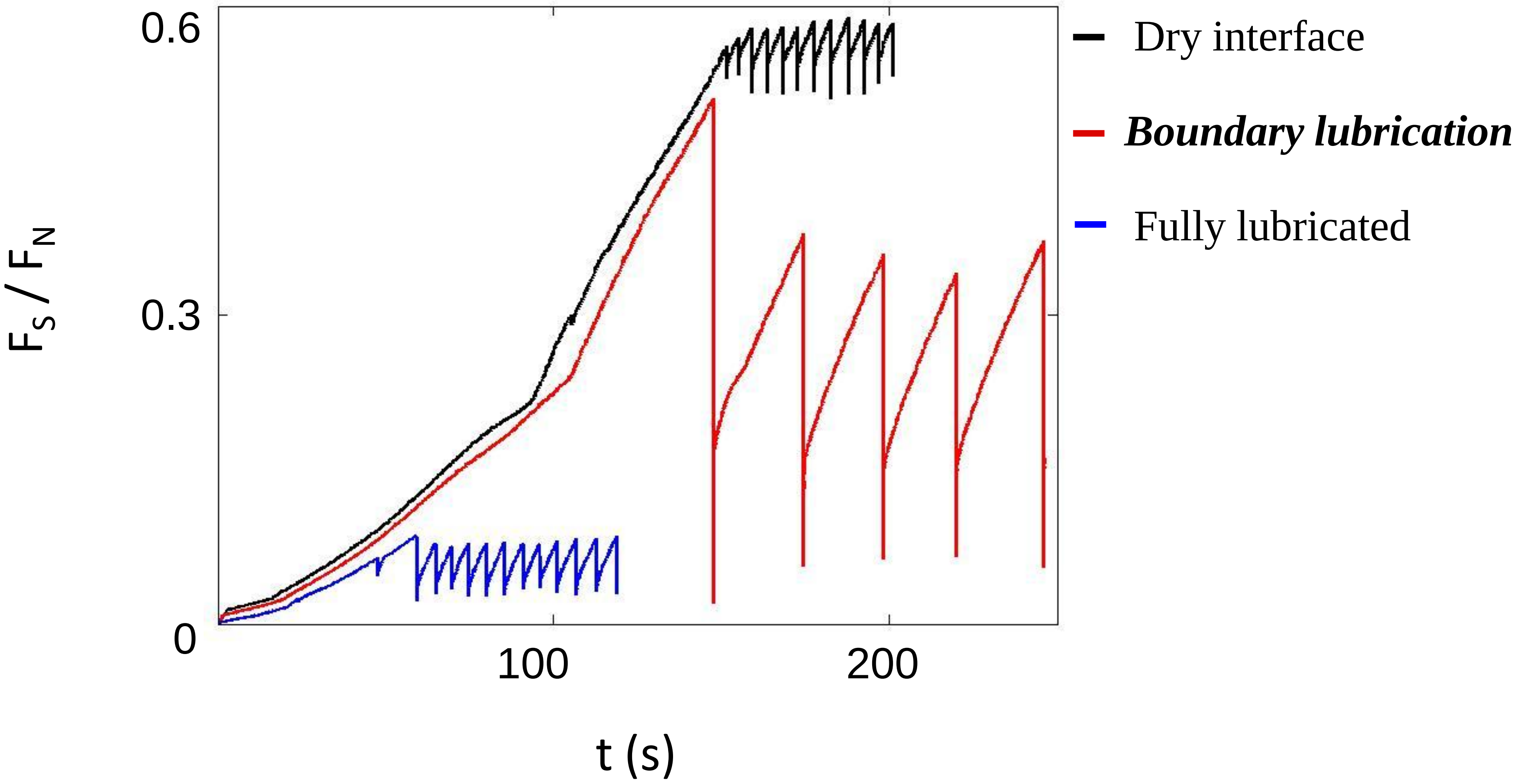




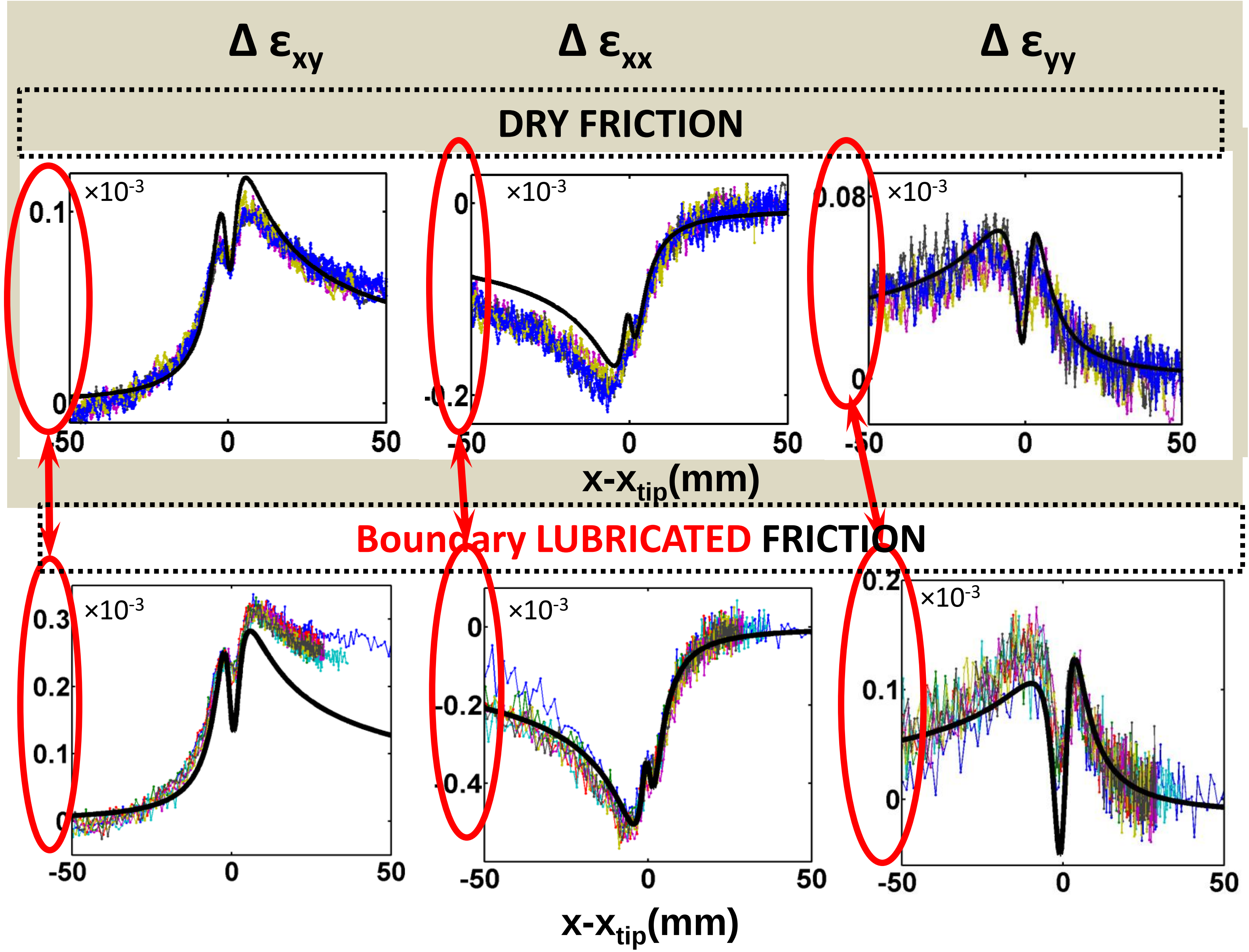
LUBRICANT	KINEMATIC VISCOSITY (cSt)
Silicone oil	5
Silicone oil	100
Silicone oil	10^4
Hydrocarbon oil (TKO-77)	200

The lubricated interface is more slippery

…



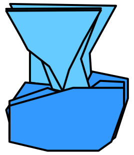
… BUT 10 times tougher!!



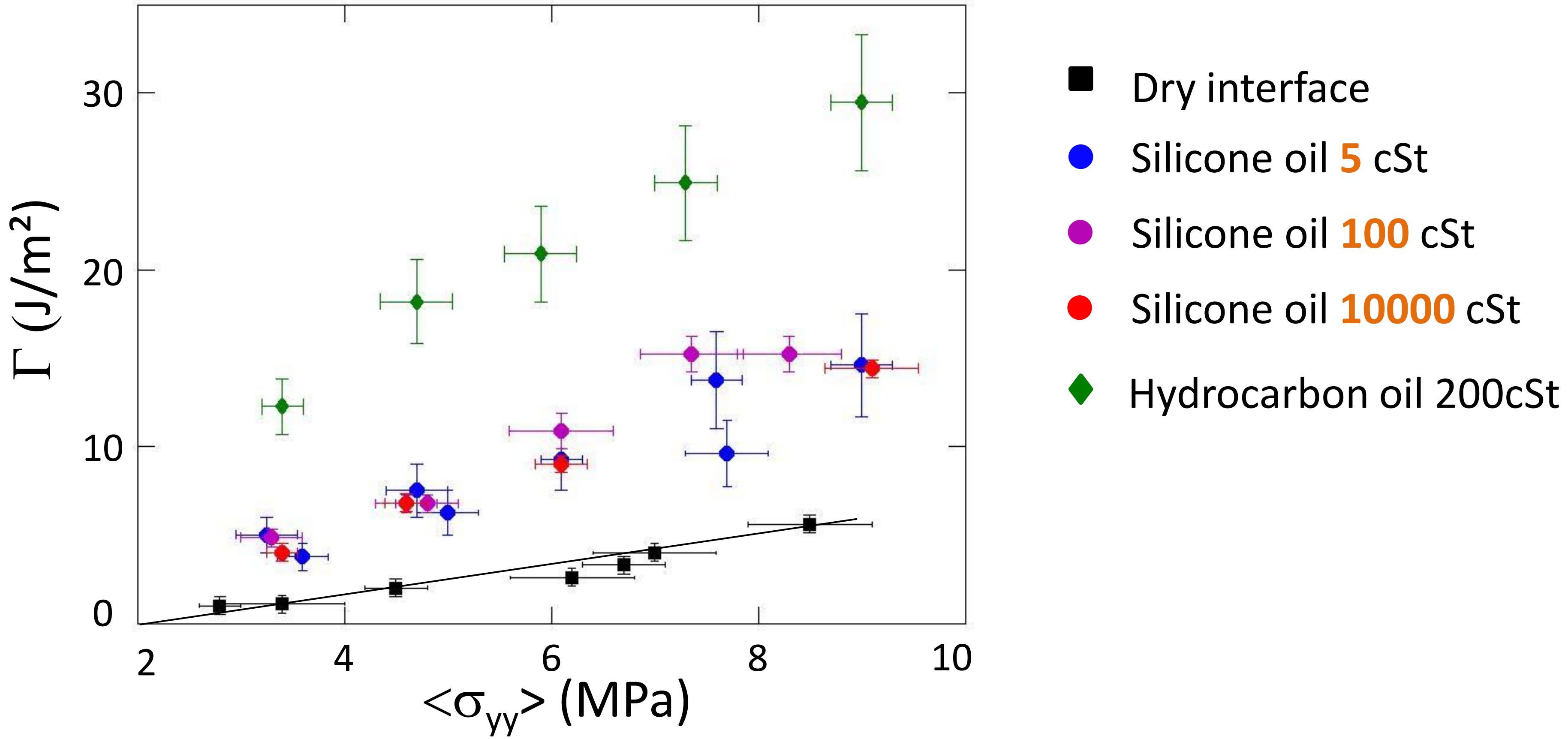
Γ_{coated}=20 J/m^2 >> Γ_{dry} ~ 2 J/m^2 !!

Fracture energy vs normal stress

$\mathbf{A} \propto \sigma_{yy}$



and $\Gamma \propto \mathbf{A}$



- Γ is always proportional to normal stress
- Viscosity does ***not*** affect Γ
- Different lubricants have different influence on Γ

Bayart, Svetlizky and Fineberg, Phys. Rev. Lett. **116**, 194301 (2016)

Why are (boundary) lubricated interfaces tougher than dry ones?

$\Gamma = (\sigma_{peak} - \sigma_{res}) \times slip$

- **Peak stress, σ_{peak}, at the contacts is not** reduced, even ***increased for lubricated interfaces***:

  Huge pressures at the contacts may cause Layering transition or effective elasticity

  ➔ **trapped** fluids **acquire shear strength**!

(e.g. layering -Israelachvili, Klein, Granick, elasticity of confined fluid: Charlaix...) ?

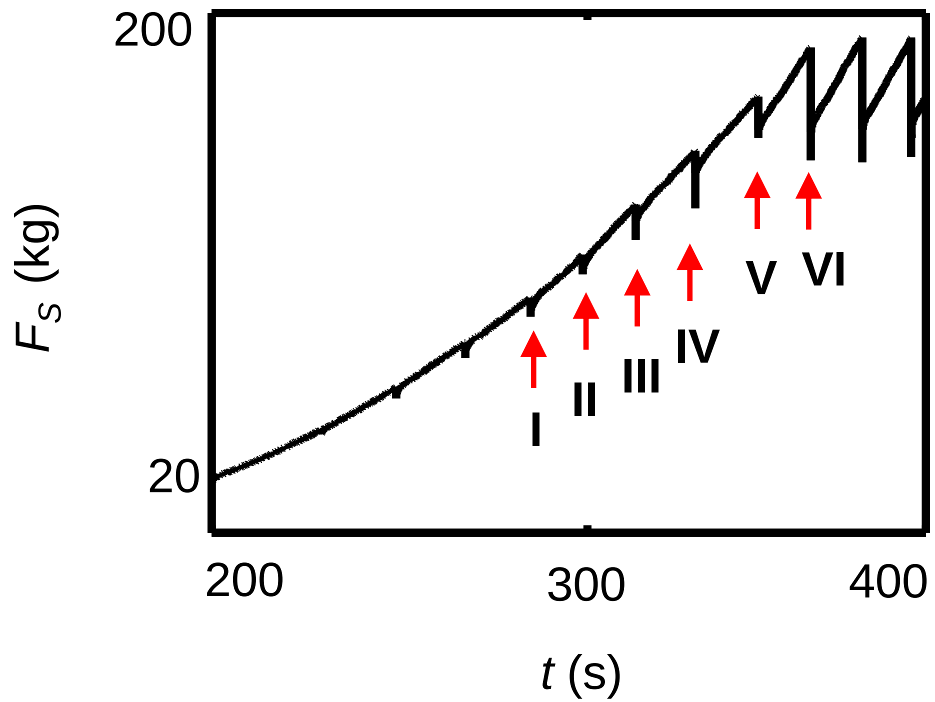
- **Once the front has passed...measured residual strengths, σ_{res} are** significantly ***reduced***.

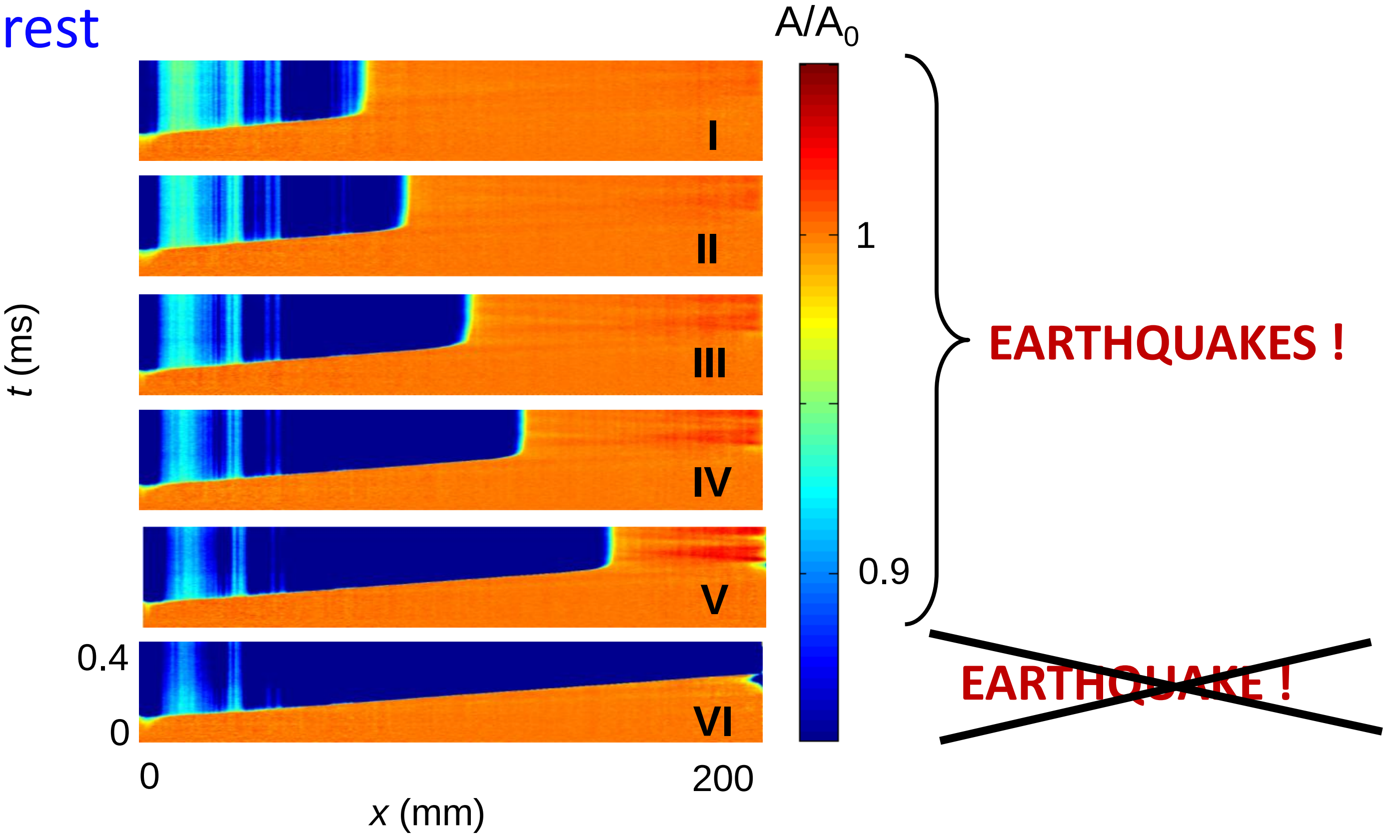
  ➔ **Once motion initiates...Lubricants may start to "lubricate"** (fluid behavior)

Solidification (or stiffening) followed by ***effective melting*** may be the **explanation**

Bayart, Svetlizky and Fineberg, Phys. Rev. Lett. **116**, 194301 (2016)

second “Example”: Predicting Earthquake Arrest





Several **observations** of these partial ruptures: *Rubinstein* 2007, *Maegawa* 2010, *Katano* 2014

Numerical studies of the **existence** of such ruptures:

Braun 2009, *Scheibert* 2010, *Tromborg* 2011, *Taloni* 2015, *Bar-Sinai* 2015

- Transition from stick to slip is mediated by a rupture front
- Partial ruptures occur before the transition: no macroscopic sliding

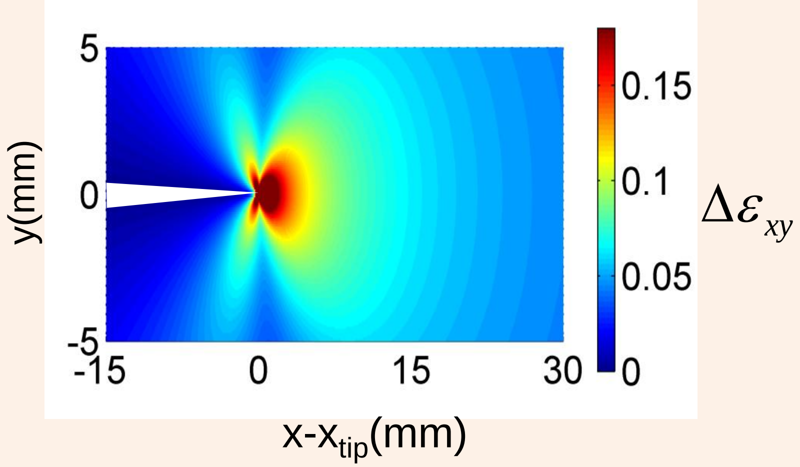
What controls the arrest of the rupture? ➔ ***use*** **Fracture Mechanics!**

D. S. Kammer, M. Radiguet, J. P. Ampuero, & J. F. Molinari, *Tribology Letters* 57, 23 (2015).

Definition of a crack arrest criterion

We have seen that stresses are ***singular*** at the crack tip

$$\Delta\sigma_{ij} = \frac{K}{r^{1/2}} f(\theta, \mathrm{v})$$



Propagation criterion: ***Energy balance***

Energy flux = Fracture energy

$$G \sim K^2/E = \Gamma$$

E is the Young's modulus

Arrest criterion: $G < \Gamma$ **GRIFFITH CRITERION**

Γ determined by the ***dynamic*** strain field

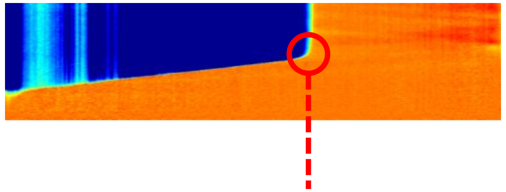
G calculated from stress drops induced by the crack

Griffith (1920)

Can fracture mechanics predict the rupture length? ***YES!***

Crack arrest criterion:

$$\frac{K^2_{stat}}{E} = G(C_f = 0) < \Gamma$$

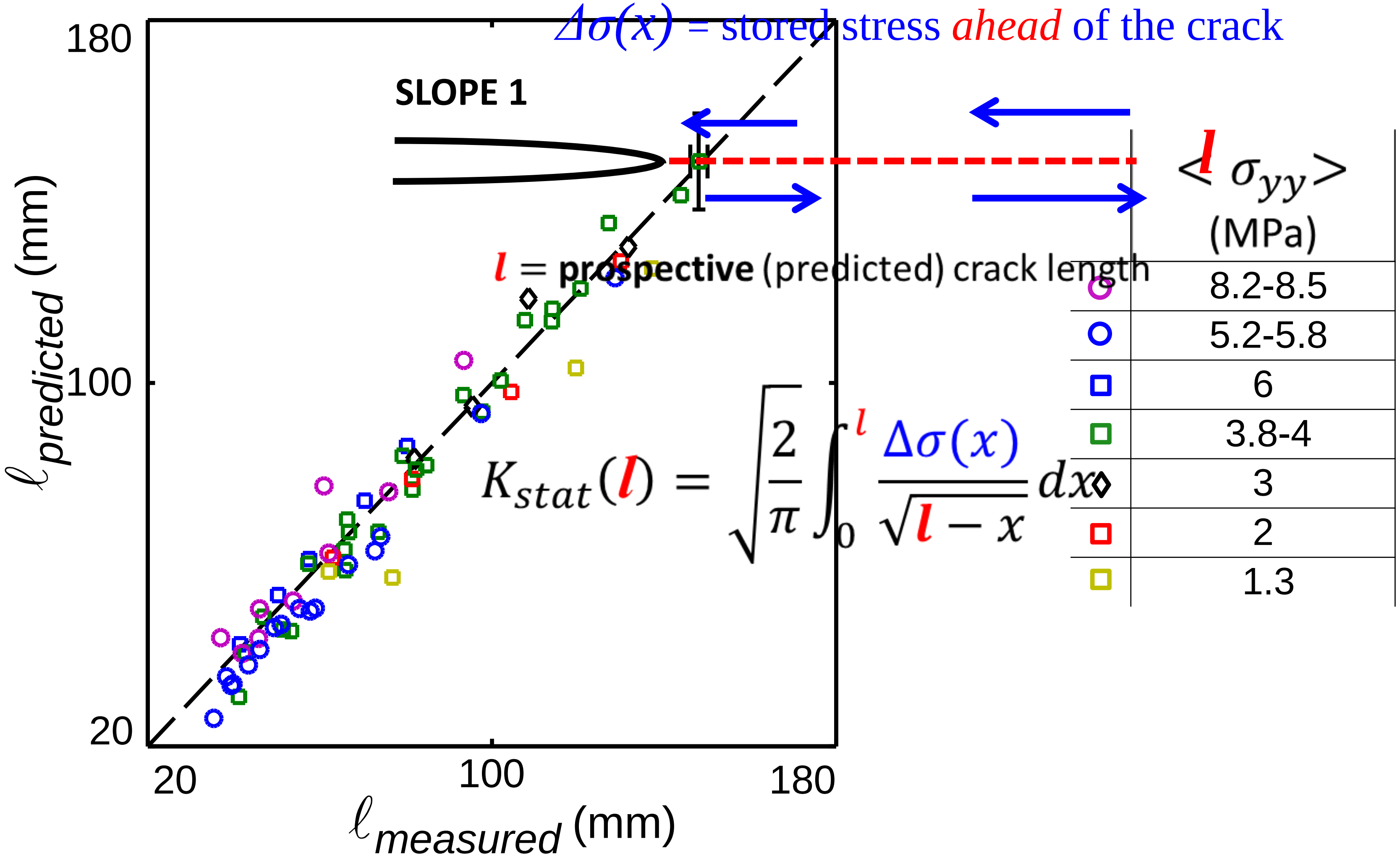


$$\boxed{K^2_{stat}(\ell)/E = G < \Gamma}$$

$\ell_{predicted}$

Fracture Mechanics:

K_{stat} is determined by the stress drop $\Delta\sigma(x)$ for all $x < l$



$\Delta\sigma(x)$ = stored stress *ahead* of the crack

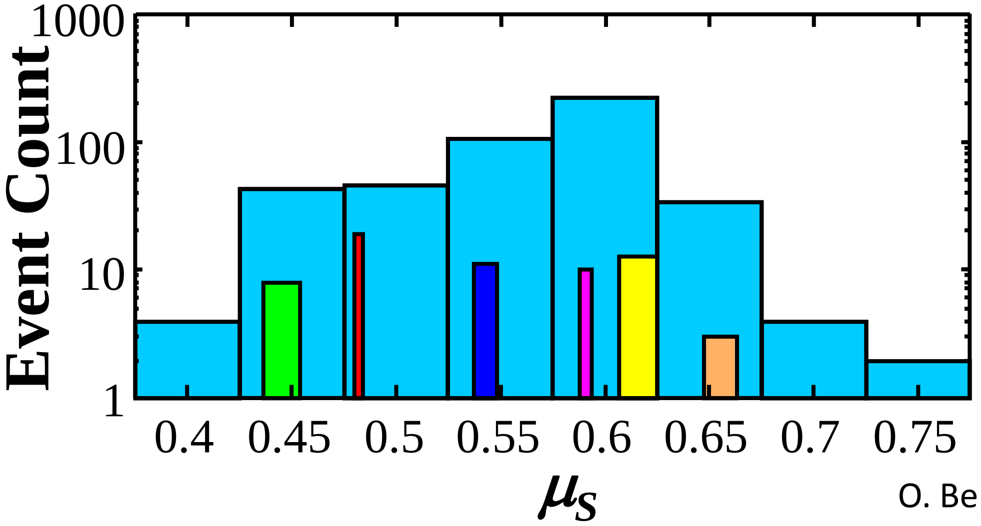
l = **prospective** (predicted) crack length

$$K_{stat}(l) = \sqrt{\frac{2}{\pi}} \int_0^l \frac{\Delta\sigma(x)}{\sqrt{l - x}}\, dx$$

	$<\sigma_{yy}>$ (MPa)
○	8.2-8.5
○	5.2-5.8
□	6
□	3.8-4
◇	3
□	2
□	1.3

Bayart, Svetlizky and Fineberg, Nature Physics ***12***, 166-170 (2016)

The static Friction coefficient is ***not*** a characteristic material property



O. Ben David and JF, Phys. Rev. Lett. (2011)

The onset of (dry) friction is governed by ***Fracture Mechanics***:

$\ell_{predicted}$ ***= System size***
+ rupture nucleation

➔ **We have a *different paradigm* for understanding friction.**

Svetlizky and Fineberg, Nature **509**, 205–208 (2014)

Bayart, Svetlizky and Fineberg, Phys. Rev. Lett. **116**, 194301 (2016)

Bayart, Svetlizky and Fineberg, Nature Physics ***12**,* 166-170 (2016)

The Equation of Motion for *Frictional Fractures*

Equation of motion ⇔ Energy Balance :

Energy flux
to the crack tip

⟺ $$G(l, C_f) = \Gamma$$ ⟺

Dissipated energy
at the crack tip

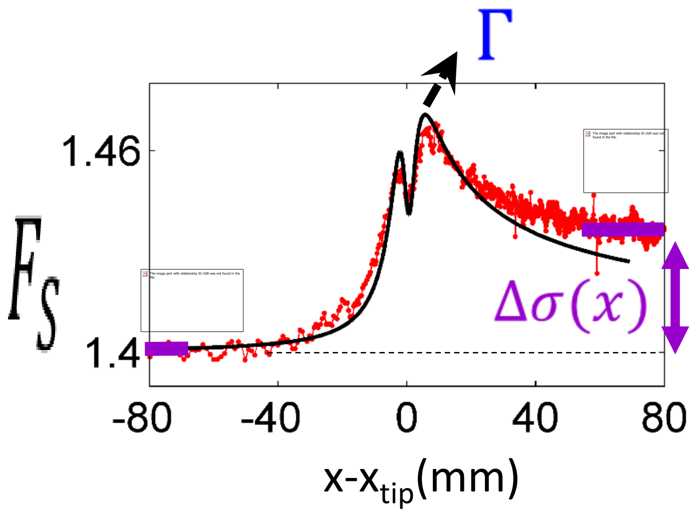
($C_f(l)$ is given implicitly)

⇓

$$G_s(l) \cdot g(C_f) = \Gamma$$

Universal Function

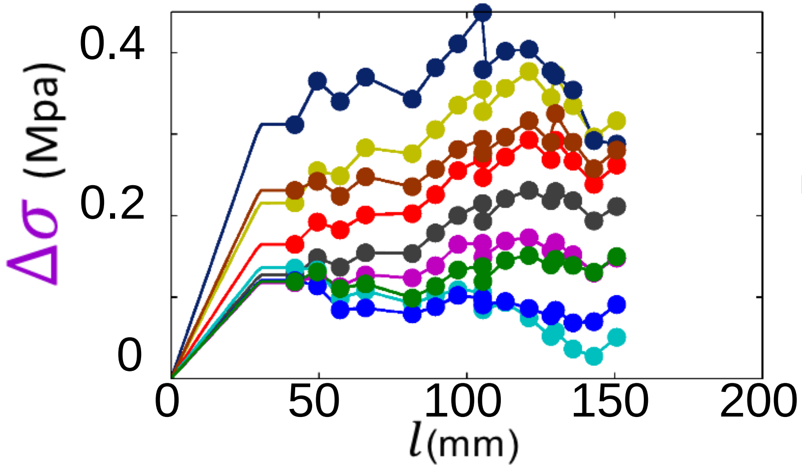
$$G_s(l) = G_s(l;\ \Delta\sigma) = K^2_{II\ static}(l, \Delta\sigma(l))/E$$

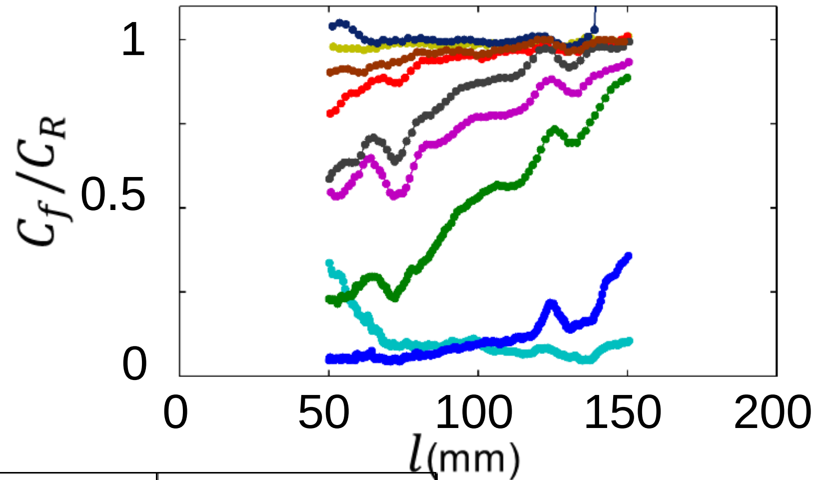


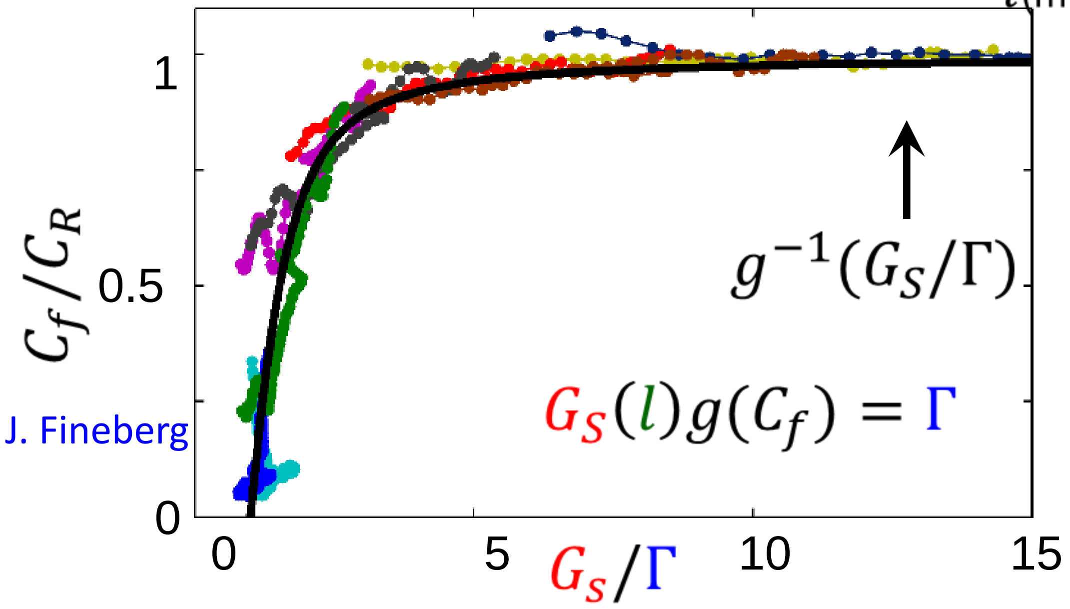
I. Svetlizsky, D. Kammer, E. Bayart, G. Cohen, and Jay Fineberg PRL **118,** 125501 (2017)

L. B. Freund, J. Mech. Phys. Solids, (1972)

In general – Do ***fracture mechanics*** **predict** crack **motion**? **Yes!**







I. Svetlisky, D. Kammer, E. Bayart, G. Cohen, J. Fineberg
PRL (2017).

All rupture velocity profiles collapse to a single LEFM predicted curve!

➔ Fracture Mechanics wholly describe rupture dynamics!

SUMMARY

At the onset of motion, ***true*** **SHEAR CRACKS** propagate within frictional interfaces

Fracture-paradigm for friction … completely different from classical view

Friction coefficient = force balance $\cancel{\mu_s}$

Fracture mechanics = energy balance

FRACTURE MECHANICS describe:

- When/if ruptures will **ARREST**
- Rupture (Earthquake) Dynamics

Along a **LUBRICATED** interface, fracture mechanics provide a ***window*** into the complex dynamics of the lubrication layer

Thank you