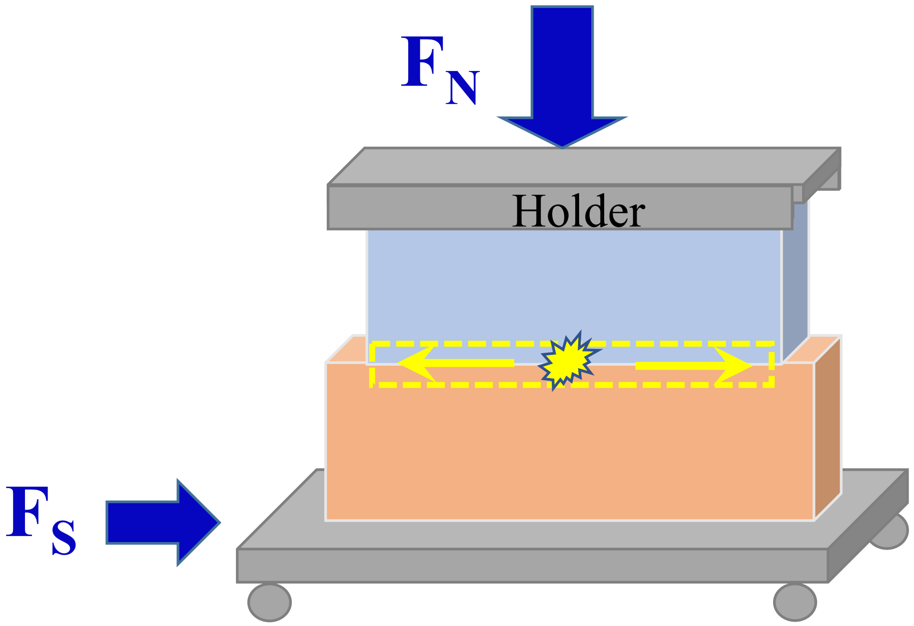
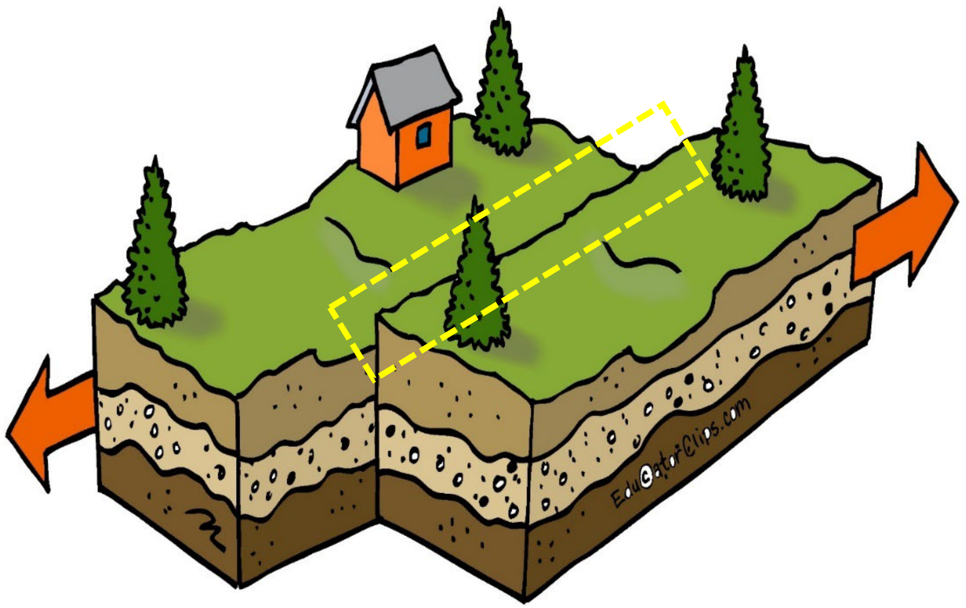
האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Israel Science Foundation





Inducing friction with friction…

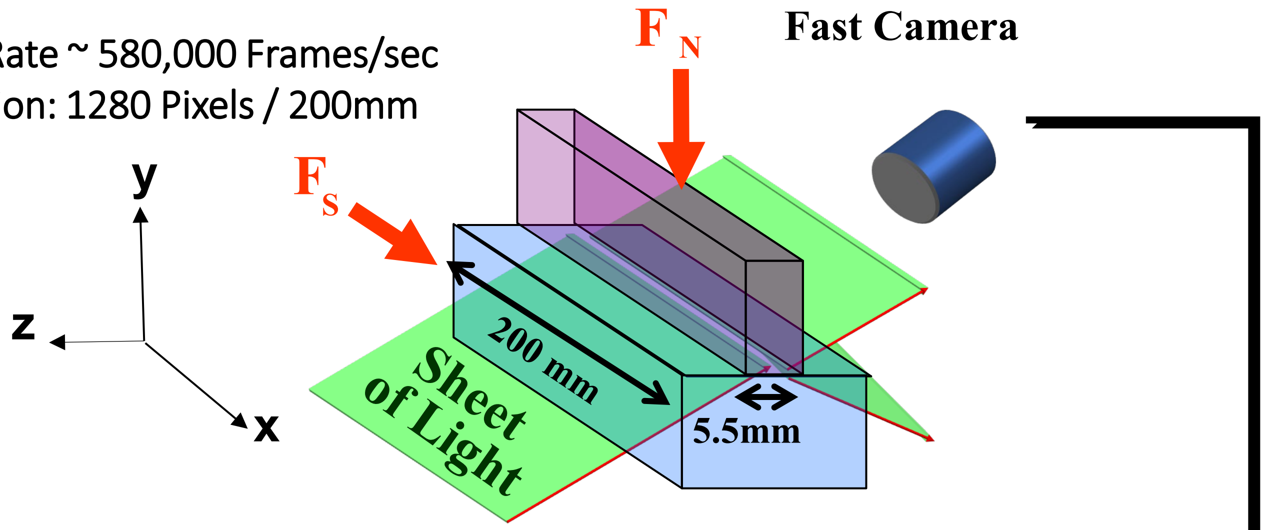
Songlin Shi , Jay Fineberg

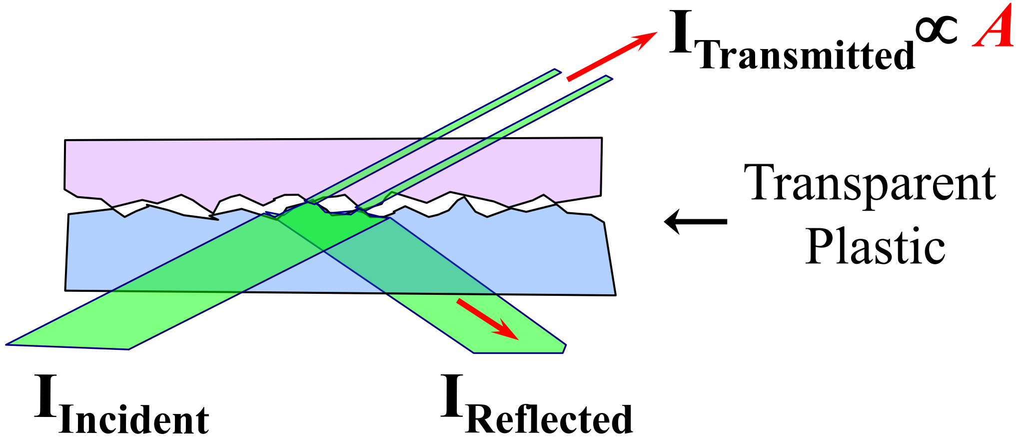
The Racah Institute of Physics,
The Hebrew University of Jerusalem

S. Shi, M. Wang, Y. Poles and J. Fineberg. *Nature Communications* **14**, 8291 (2023)
S. Shi and J. Fineberg, to appear (2025)

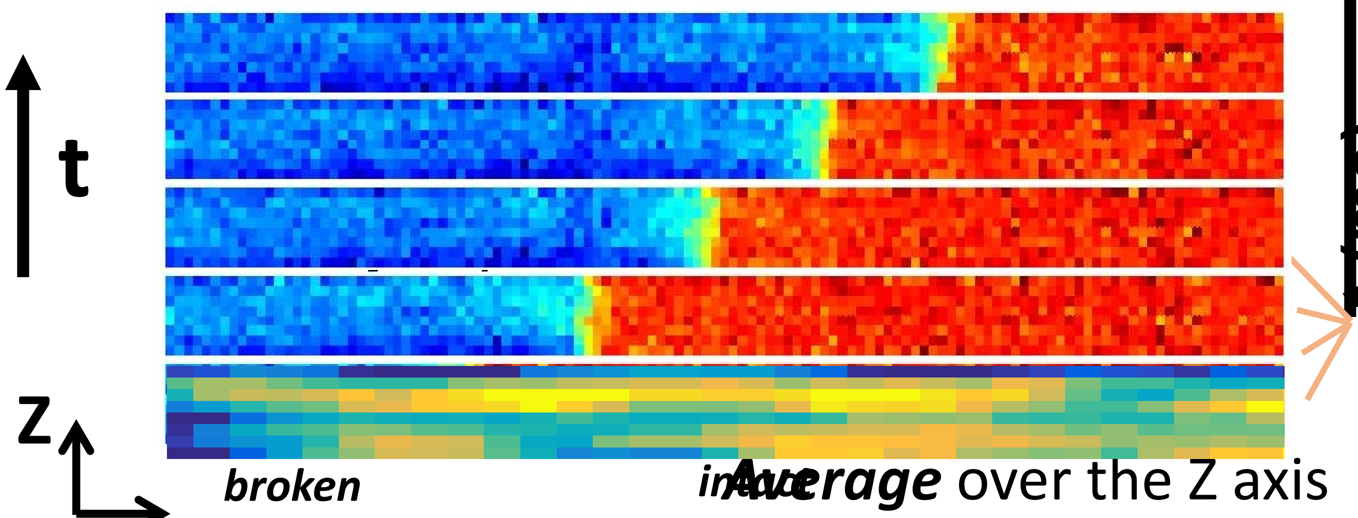
Tracking rupture fronts – or watching (lab) earthquakes unfold

Frame Rate ~ 580,000 Frames/sec
Resolution: 1280 Pixels / 200mm



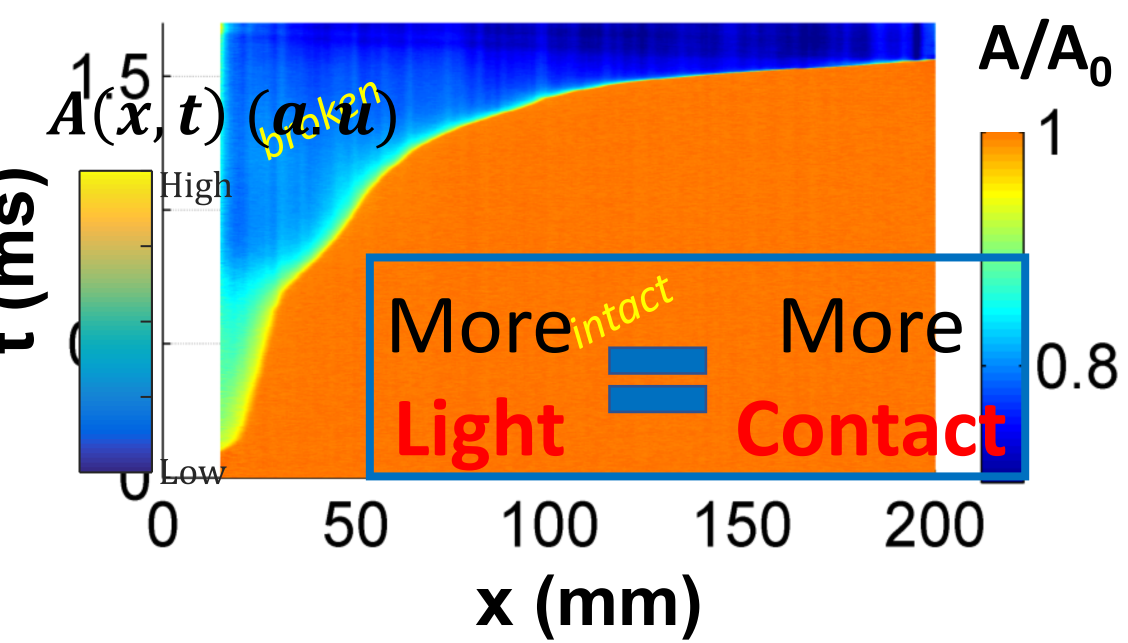


$C_f \sim 1000\ m/s$



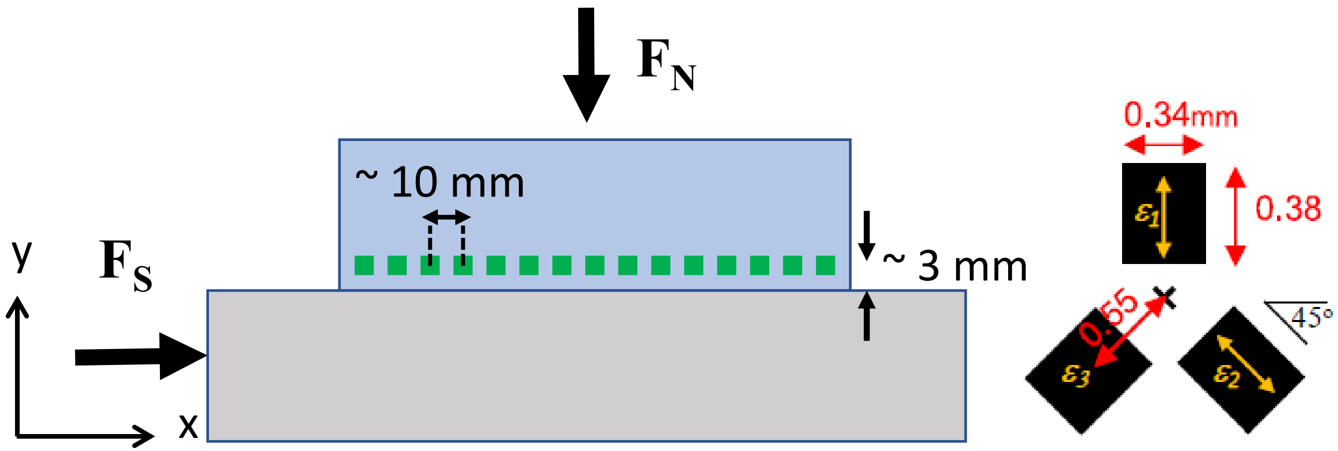
Average over the Z axis
to get **1D interface A**(x,t)

Continuous measurements

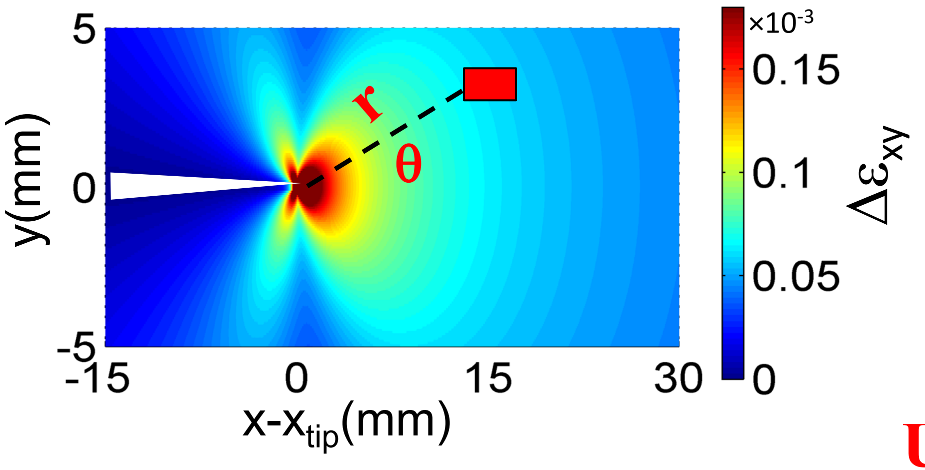


S. M. Rubinstein, G. Cohen, and J. Fineberg, *Nature* (2004)

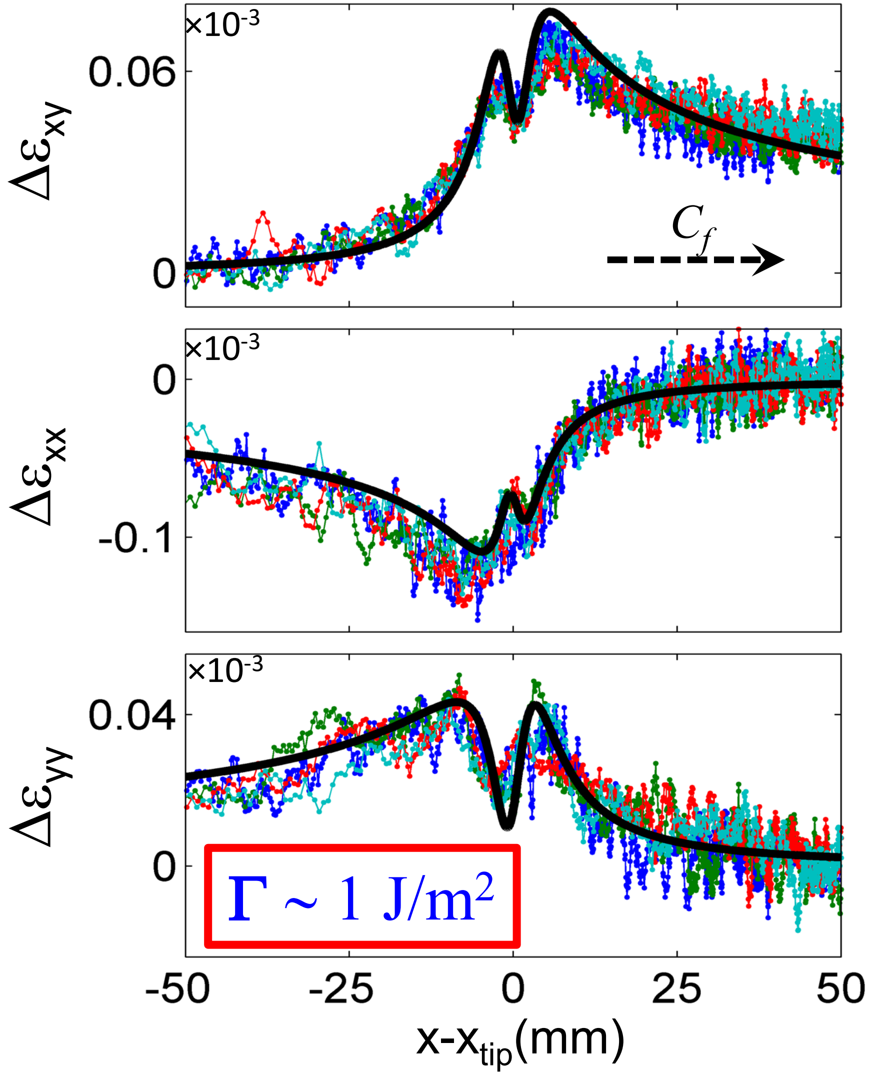
Fracture mechanics describes interface ruptures



2D-strain tensor measurement at 1 MSamples/s



Strain field of rupture (crack)



Universal *singularity* □ $_{ij} = \frac{K}{\sqrt{2\pi r}}\Sigma_{ij}(\theta, C_f)$

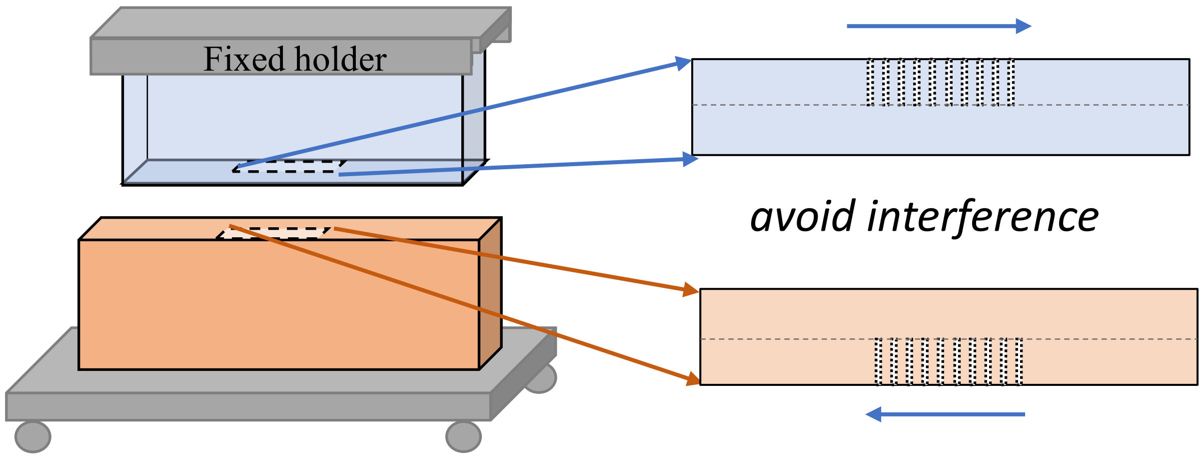
One free parameter K fits ***all*** of the data well ⇔ **Γ**

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

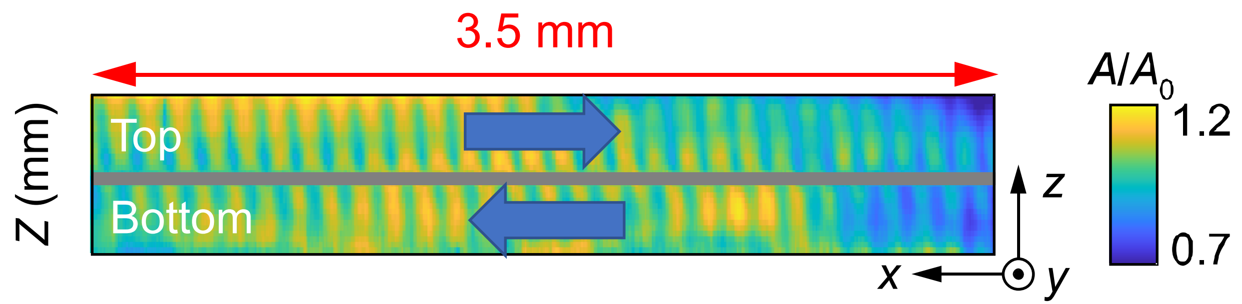
Tracking rupture **slip ON** the interface

*(**as** lab earthquakes **unfold**)*

Directly tracking the slip at interface

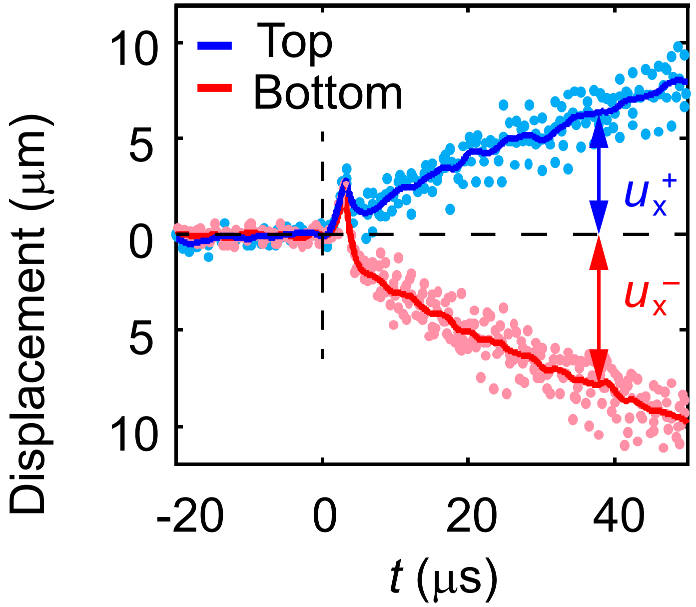


We require precise slip measurement on the interface, that are fast …



2 sets of ***grooves*** engraved on ***both*** sides of the interface

- Slip = $u_x = (u_x^+ - u_x^-)$



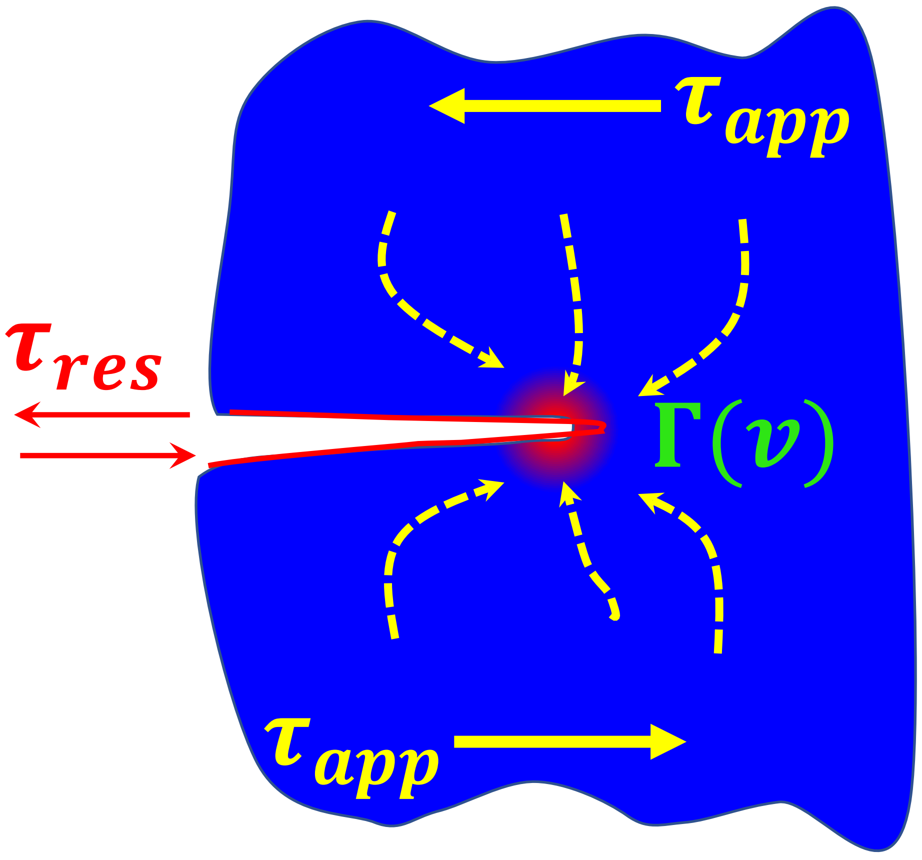
S. Shi, M. Wang, Y. Poles and J. Fineberg. Nature Communications. (2023)

Sub-Rayleigh rupture – *first 50 μs*

Energy balance

Equation of motion (LEFM infinite medium):

$$\Gamma(v) = G(v) = G_S\, g(v) \rightarrow \frac{v}{C_R} = 1 - \frac{\Gamma(v)\cdot f(t)}{\left[\tau_{app}(t) - \tau_{res}(v)\right]^2 l(t)/E}$$



Elastic energy focused to tip

Stars of our show:

$\tau_{app}(t)$ = **applied** shear

(stress at Nucleation)

$\tau_{res}(v)$ = **residual** shear

(local dynamic friction)

$\Gamma(v)$ = **fracture energy**

= **$\Delta A(v)$ contact area** drop

$f(t)$ = **aging**

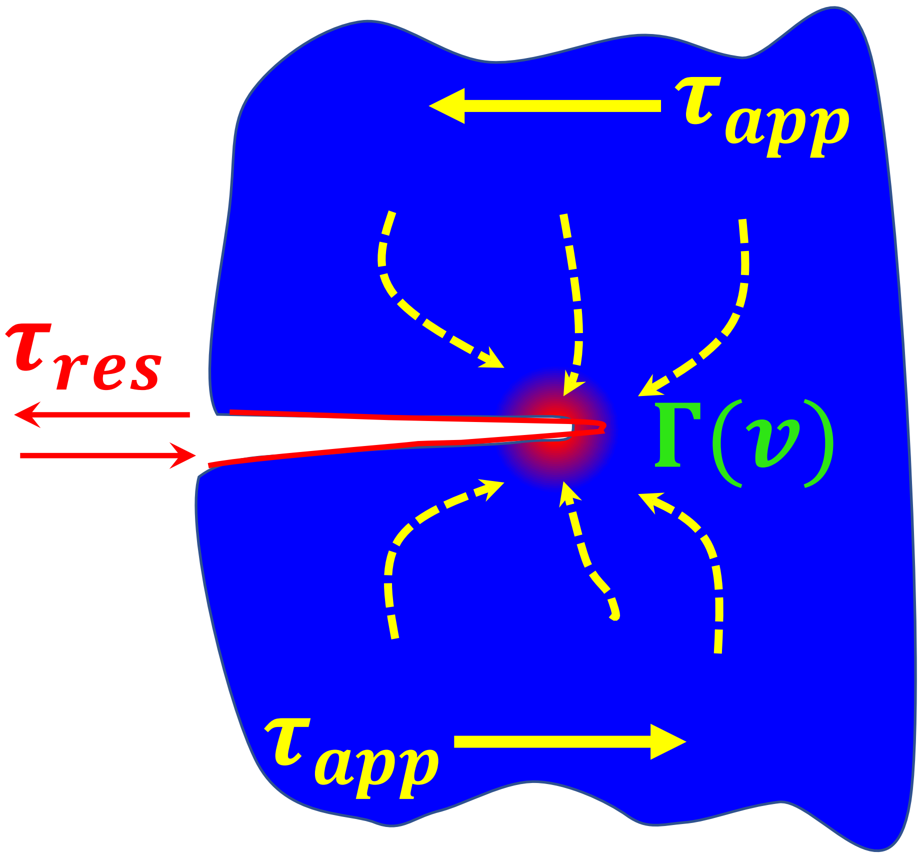
(healing of ΔA after rupture)

Energy balance

$$\Gamma(v) = G(v) = G_S\, g(v) \rightarrow$$

Equation of motion (LEFM infinite medium):

$$\frac{v}{C_R} = 1 - \frac{\Gamma(v) \cdot f(t)}{\left[\tau_{app}(t) - \tau_{res}(v)\right]^2 l(t)/E}$$



Elastic energy focused to tip

Case #1:

$\tau_{app}(t)$ = **applied** shear = ***const***

$\tau_{res}(v)$ = **residual** shear = ***const***

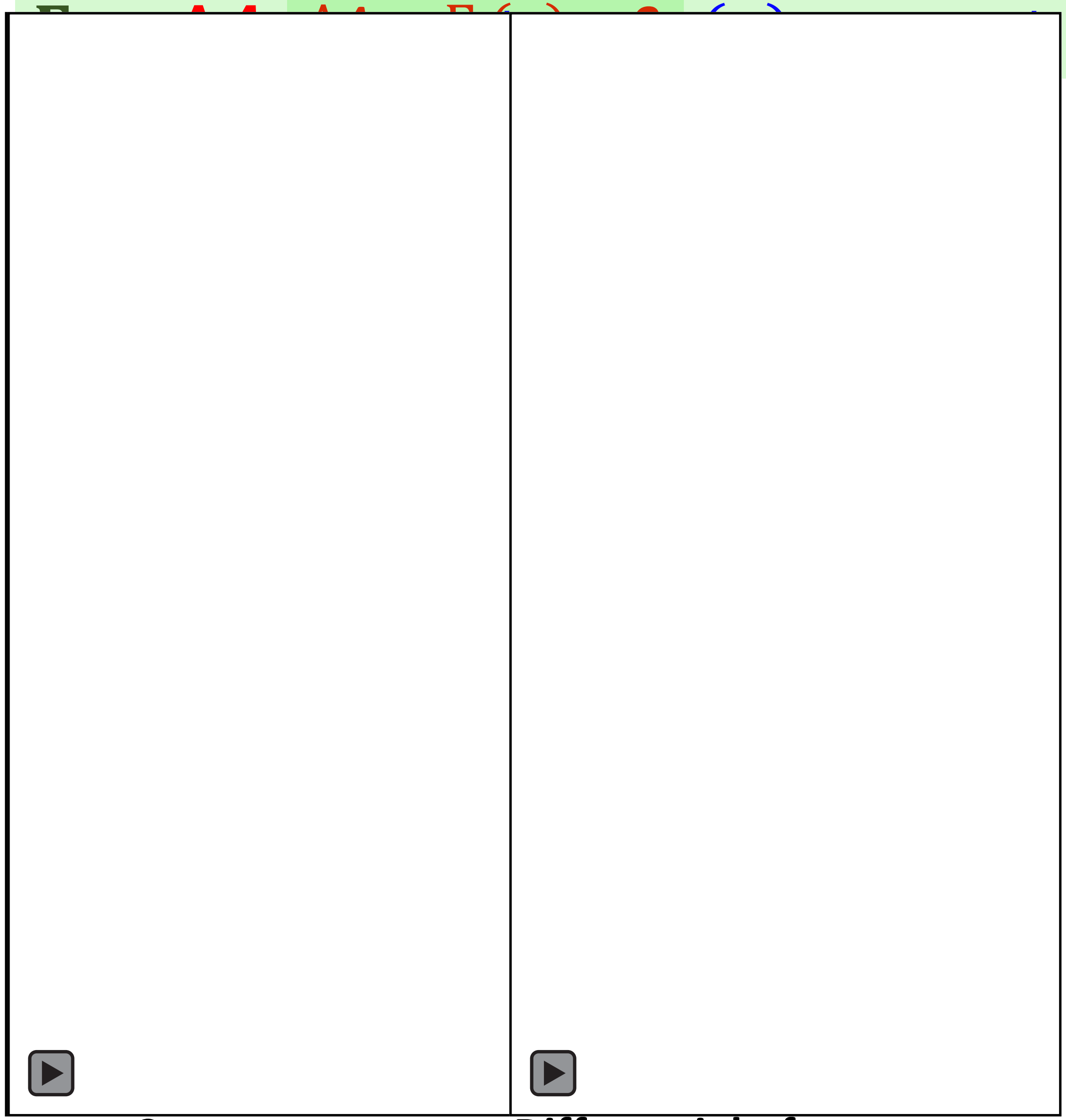
Γ = **fracture energy** = $\Gamma(t)$

= $\Delta A(t)$ **contact area** drop

$f(t)$ = **aging**

(healing of ΔA after rupture)

After first earthquake The first earthquake … slip ***continues***



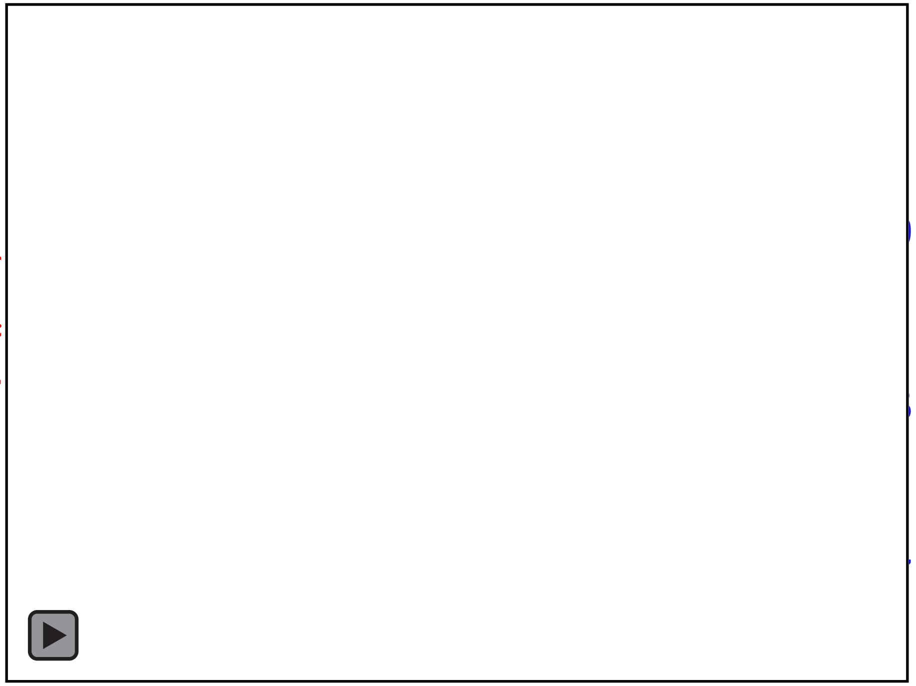
$\overline{\partial_t A(x,t)} = [\partial_t A(x,t) - \partial A_c]/(\partial A)$

Numerous *finite* slip-steps

'invisible'* lab-quakes *after the first event

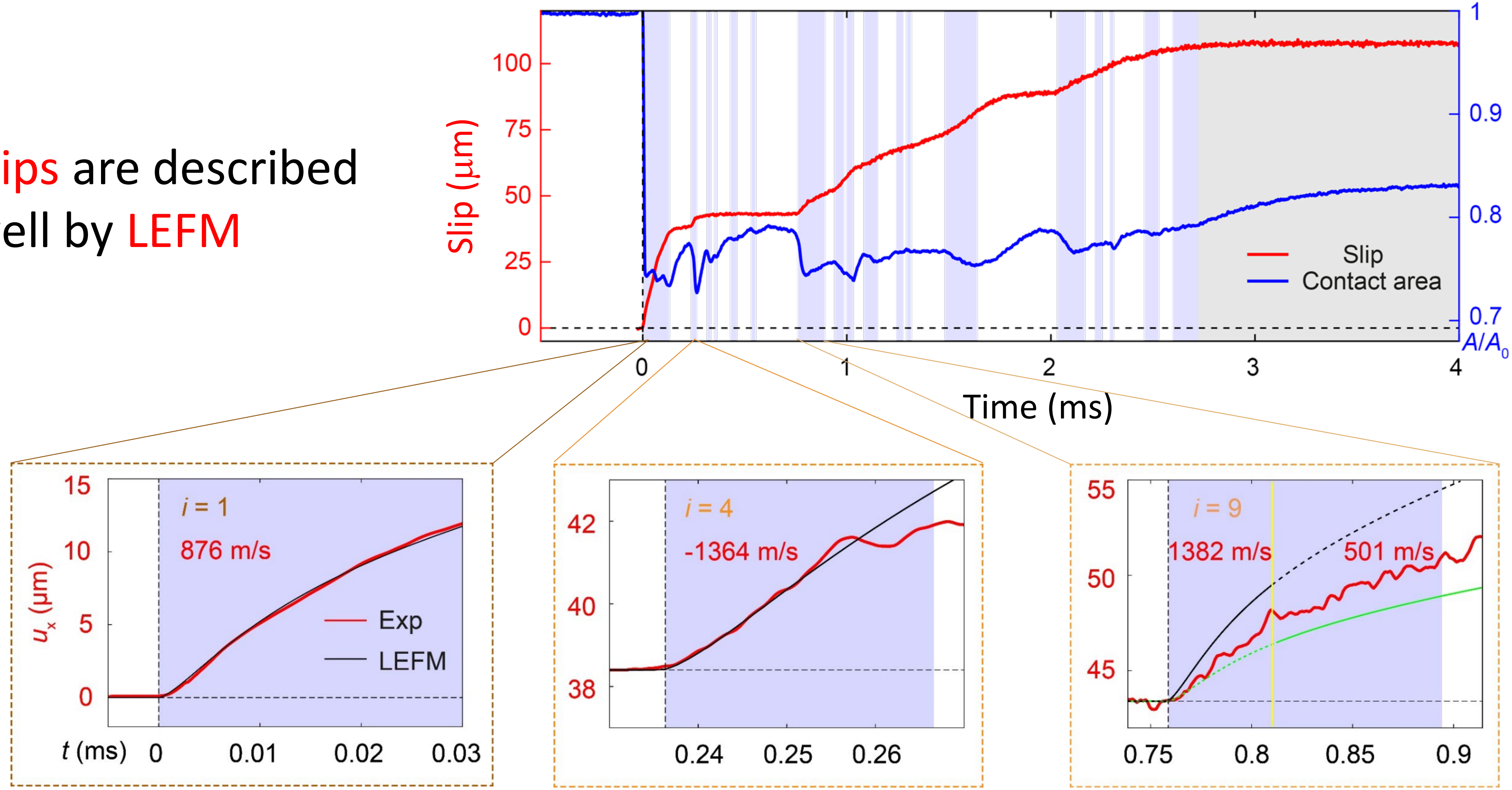
⇕

- Almost **zero** Γ (no time for aging) – but ***finite slip***!



Secondary ruptures generate discrete slip

- Slips are described well by LEFM

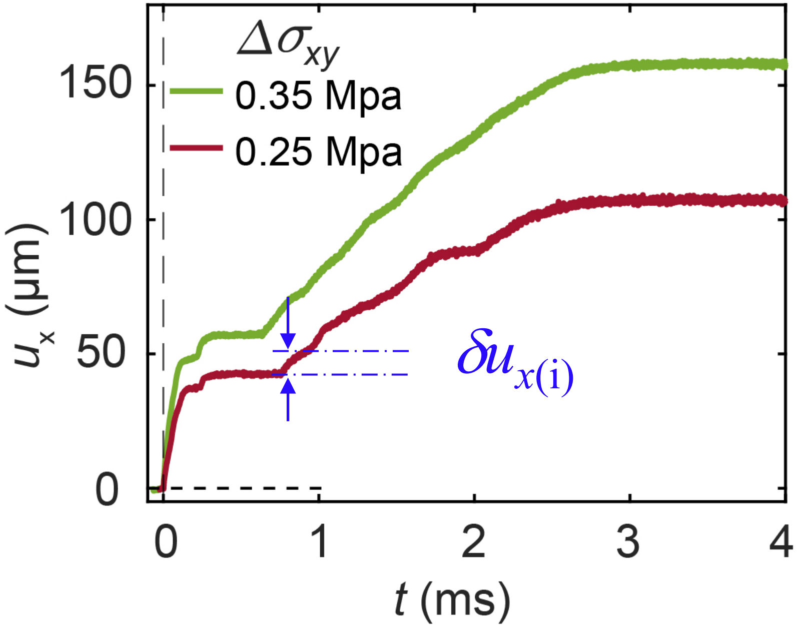


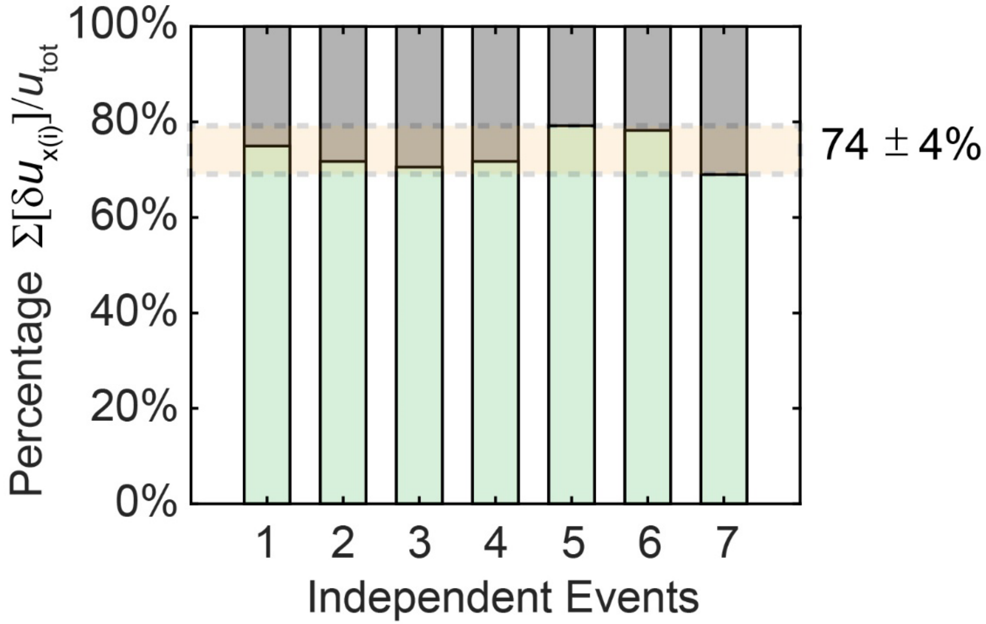
Sub-Rayleigh ~ $0.9C_R$

Supershear ~ $1.4C_R$

Transition to sub-Rayleigh

Total stress drop & the slip budget





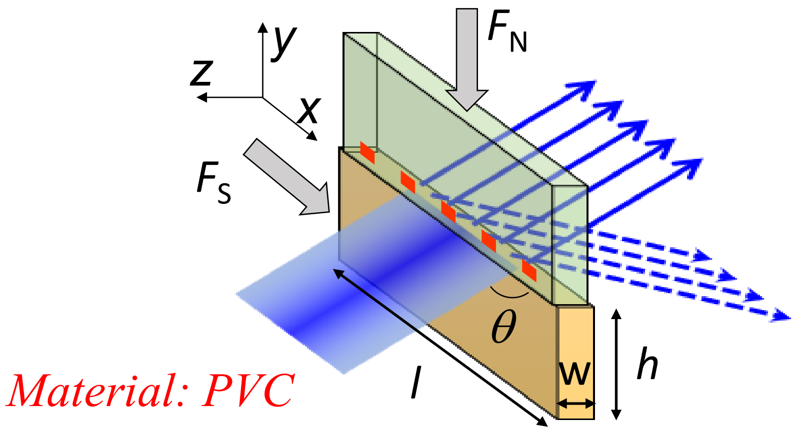
- Total stress drop linearly related to total slip, $\boldsymbol{u_{tot}}$, as in natural earthquakes
- The main and secondary ruptures account for approximately **74% of *total slip*, $\boldsymbol{u_{tot}}$**

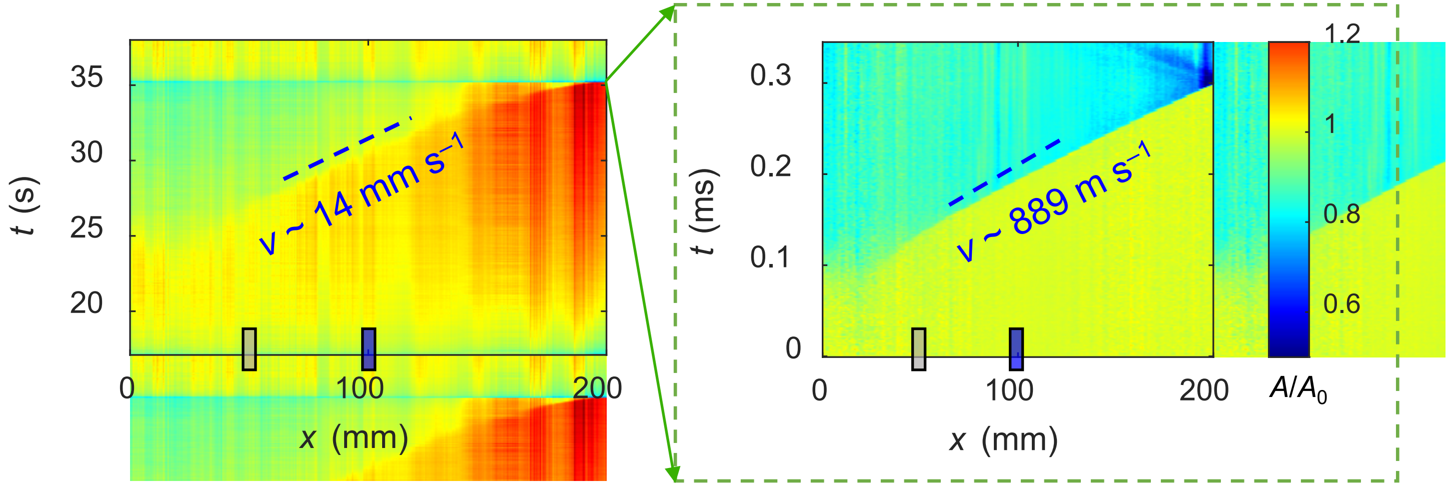
Most slip is caused by the discrete invisible ruptures.

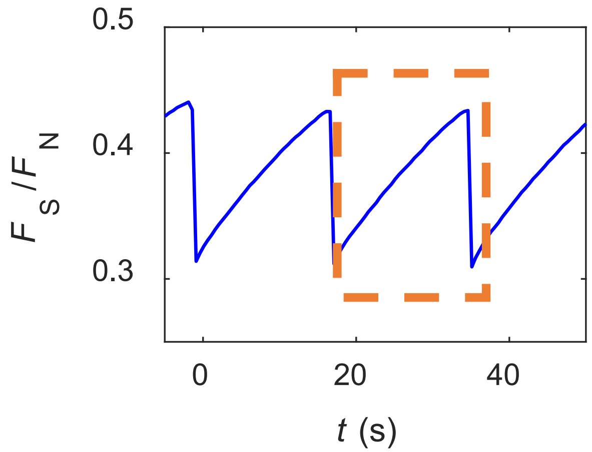
H. Kanamori and E. E. Brodsky. '*The physics of earthquakes*'. Reports on Progress in Physics. 67(8).2004

Slow ruptures in 'ductile' materials can induce rapid ruptures…

Shi, S. and Fineberg, J. (to appear.)







In PVC (a ***ductile*** material):

- ***Super-slow*** ruptures ($C_f \sim 10^{-5} C_R$) trigger ***fast*** ($\sim C_R$) ruptures
- ***Periodic sequences*** of slow-fast-slow-fast ….
- ***Not*** observed in ***brittle*** materials

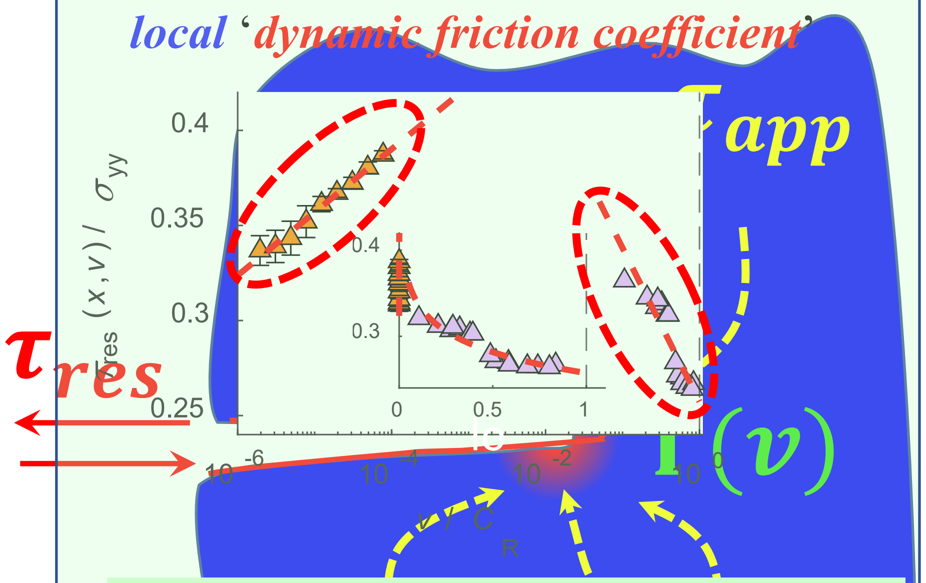
Why? What is ***special*** about ***this*** material?

Energy balance

Equation of motion (LEFM infinite medium):

$$\Gamma(v) = G(v) = G_S\, g(v) \rightarrow \frac{v}{C_R} = 1 - \frac{\Gamma(v)\cdot f(t)}{\left[\tau_{app}(t) - \tau_{res}(v)\right]^2 l(t)/E}$$

$\tau_{res}(v)$, v-dependent residual strength



Velocity strengthening for *small v*:

$$\tau_{res}(x,v)/\sigma_{yy} = a_s + b_s \log(v/C_R)$$

+

Velocity weakening for *high v*:

$$\tau_{res}(x,v)/\sigma_{yy} = a_w + b_w \log(v/C_R)$$

Elastic energy focused to tip

Case #2:

$\tau_{app}(t)$ = **applied** shear $\neq$ ***const***

$\tau_{res}(v)$ = **residual** shear

Γ = **fracture energy** = $\Gamma(v)$

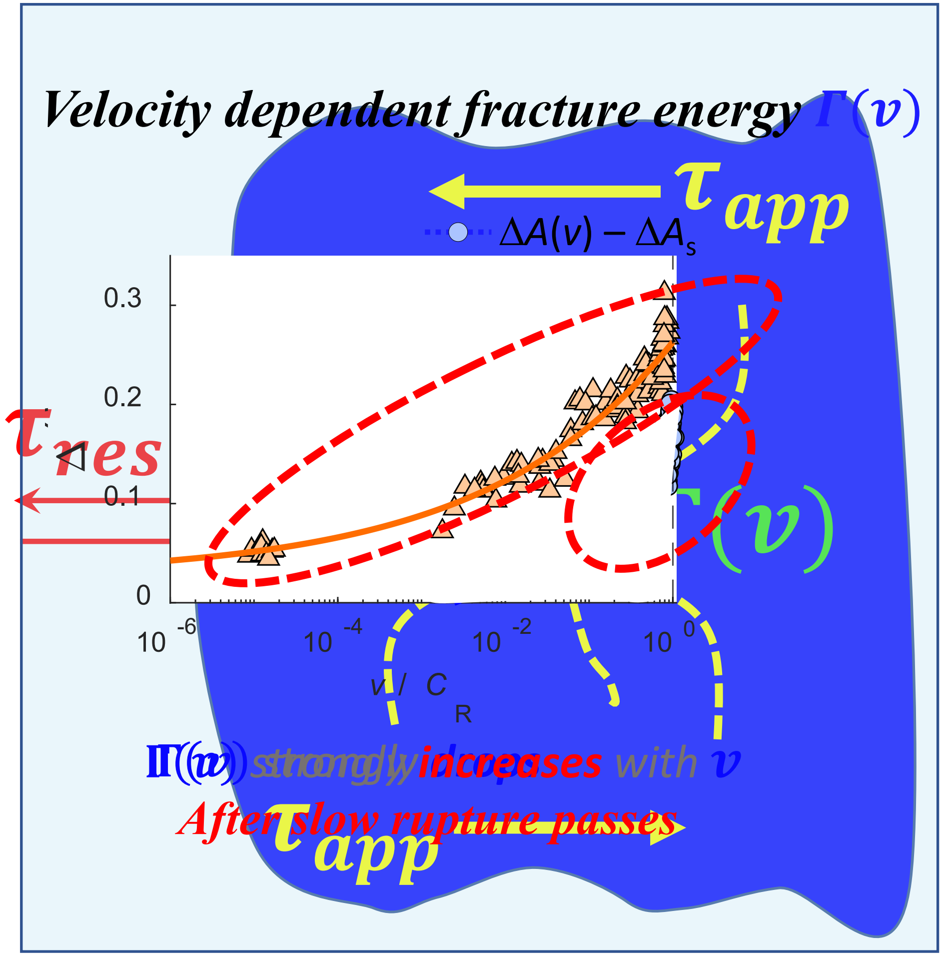
= $\Delta A(v)$ **contact area** drop

$f(t)$ = **aging**

(healing of ΔA after rupture)

Energy balance

$$\Gamma(v) = G(v) = G_S\, g(v) \rightarrow$$



Equation of motion (LEFM infinite medium):

$$\frac{v}{C_R} = 1 - \frac{\Gamma(v)\cdot f(t)}{\left[\tau_{app}(t) - \tau_{res}(v)\right]^2 l(t)/E}$$

Case #2:

$\tau_{app}(t)$ = **applied** shear $\neq$ *const*

$\tau_{res}(v)$ = **residual** shear

Γ = **fracture energy** = $\Gamma(v)$

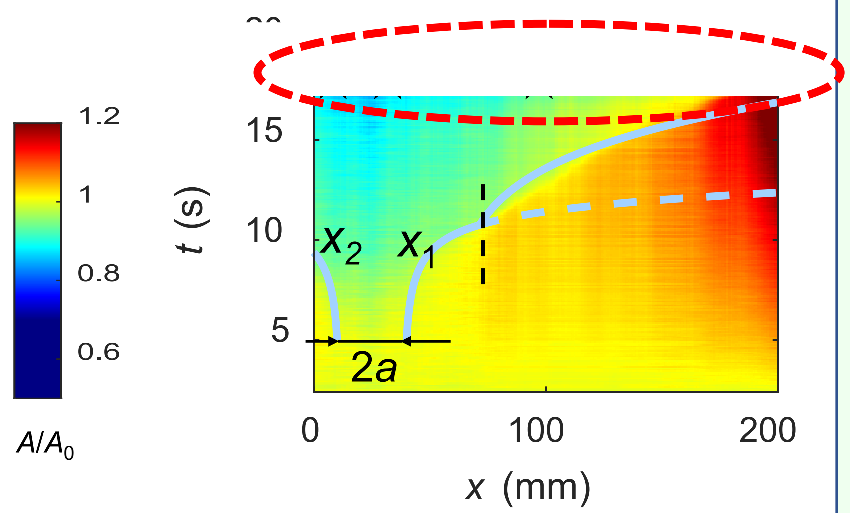
= $\Delta A(v)$ **contact area** drop

$f(t)$ = **aging**

(healing of ΔA after rupture)

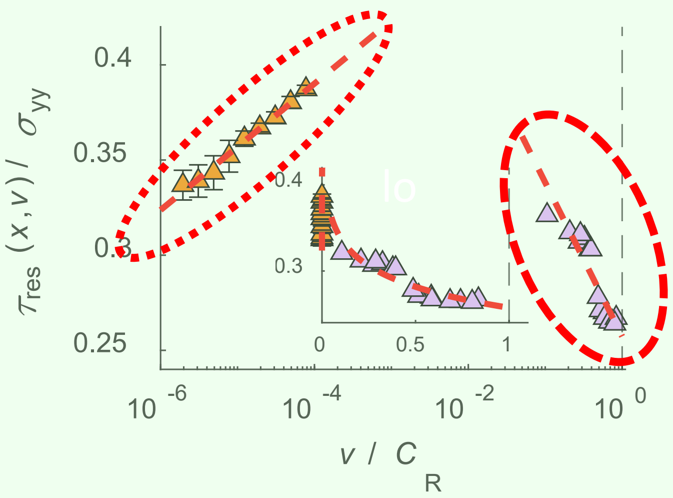
LEFM *also* describes the propagation of slow ruptures

$$\frac{v}{C_R} = 1 - \frac{\Gamma(v)\cdot f(t)}{\left[\tau_{app}(t) - \tau_{res}(v)\right]^2 l(t)/E}$$

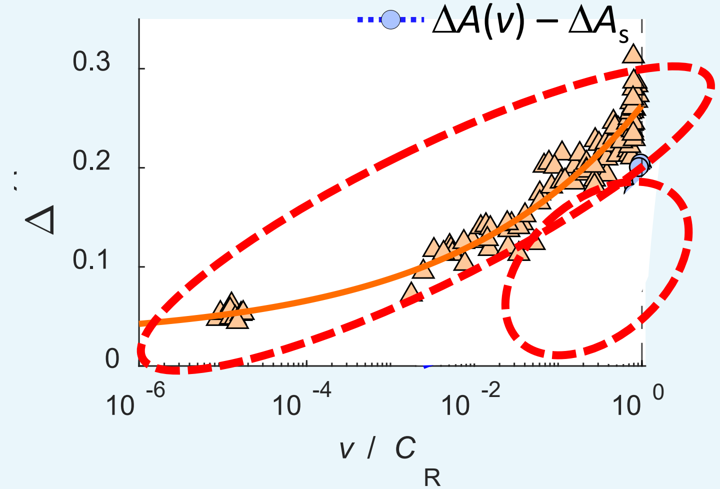


$\tau_{res}(v)$, v-dependent residual strength

local '*dynamic friction coefficient*'



v −dependent $\Gamma(v)$



$\Gamma(v)$ strongly increases with v

After slow rupture passes

- **Slow ruptures:** 'Uphill climb' in $[\tau_{app}(t) - \tau_{res}(v)]$ and $\Gamma(v)$
- **Fast ruptures:** Increased $[\tau_{app}(t) - \tau_{res}(v)]$, decreased $\Gamma(v)$

Colored stars ⇔ nucleation rapid ruptures following different slow ruptures.

Conclusion

- Both **extremely slow (cm/sec) and fast (km/sec) ruptures** can repeatably propagate within the same frictional interface.
- Dynamic equilibrium between **loading rates and velocity-dependences of both interface resistance and fracture energy** enable slow ruptures to nucleate and propagate at very low applied shear stresses.
- Fast ruptures also occur, but only when their nucleation becomes possible at higher stress conditions.
- Dynamics and structure of both rupture classes are well-described by Fracture Mechanics.
- These results help us understand what drives slow and fast ruptures and how they transition, while also giving key insights into fault mechanics and frictional motion.

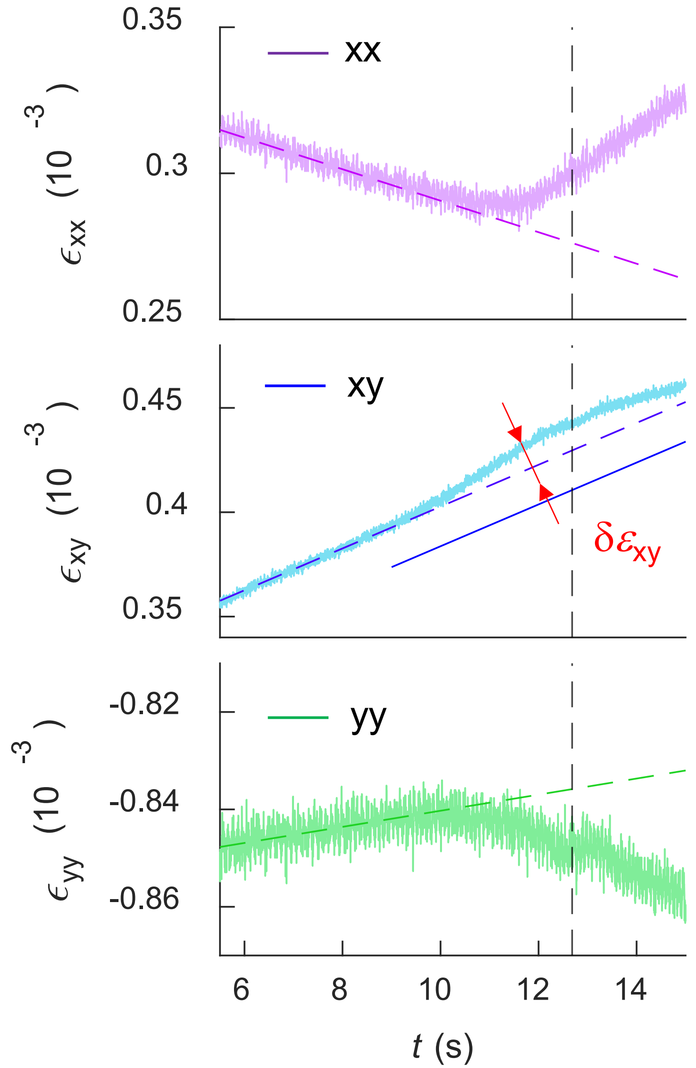
Shi, S. and Fineberg, J. (Submitted.)

Conclusion

- Numerous **weak-secondary ruptures** are observed after the main ruptures. These are still described by linear elastic fracture mechanics (LEFM).
- Secondary ruptures with **finite size slip** occur under almost **'free' fracture energy** ➔ supershear occurs easily.
- Slip budget : over 70% of slip contributed by the main and secondary ruptures
  - Invisible ruptures have a huge effect
  - Slip *looks* like steady sliding (*dynamic friction*), but slip is ***actually*** composed of **discrete steps** caused by **secondary ruptures**.
- Secondary ruptures suggest a connection to after-slip/aftershocks in statistics

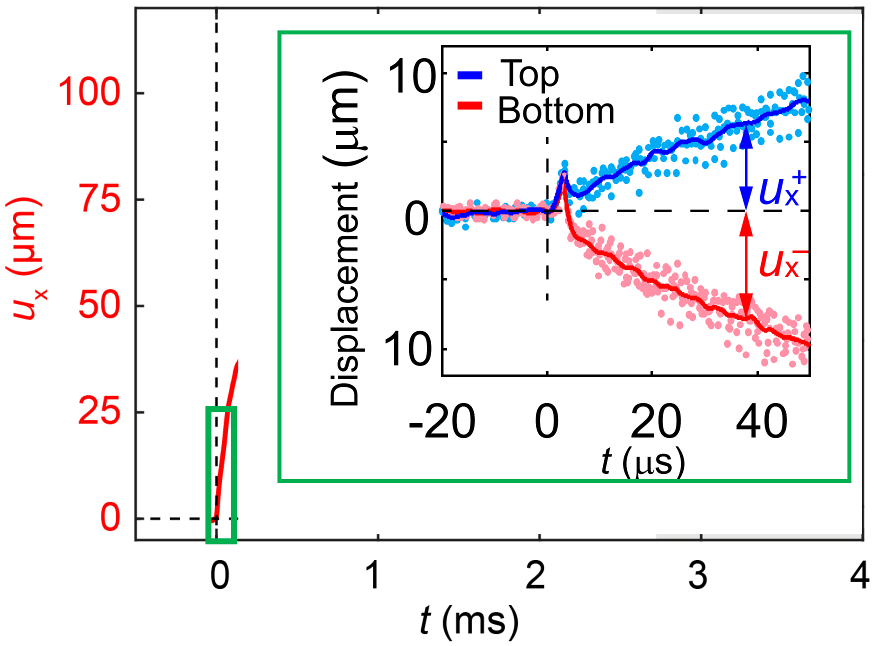
Thank you!

S. Shi, M. Wang, Y. Poles and J. Fineberg. Nature Communications. (2023)



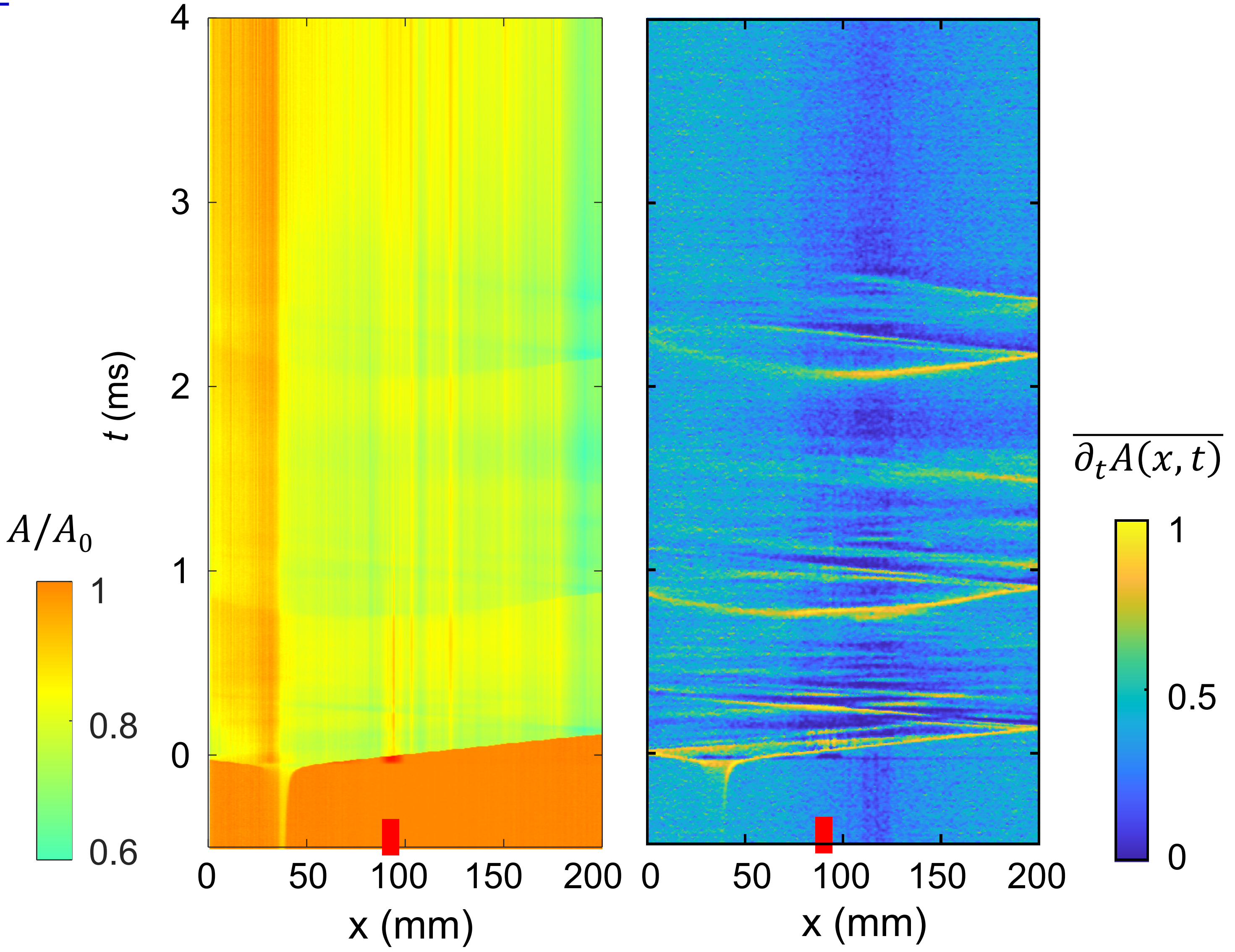
0.35
0.3
0.25
ϵ_{xx} (10^{-3})
xx
0.45
0.4
0.35
ϵ_{xy} (10^{-3})
xy
$\delta\varepsilon_{xy}$
-0.82
-0.84
-0.86
ϵ_{yy} (10^{-3})
yy
6
8
10
12
14
t (s)

Slip & Contact Area at long times



- **Numerous slip-steps**
- **Weak secondary ruptures exist!**

$$\overline{\partial_t A(x,t)} = [\partial_t A(x,t) - \partial A_c]/(\partial A)$$



What is the connection between slip and the ruptures?