

# Rate/state frictional nucleation and dynamic rupture on low-stress faults with thermal weakening effects

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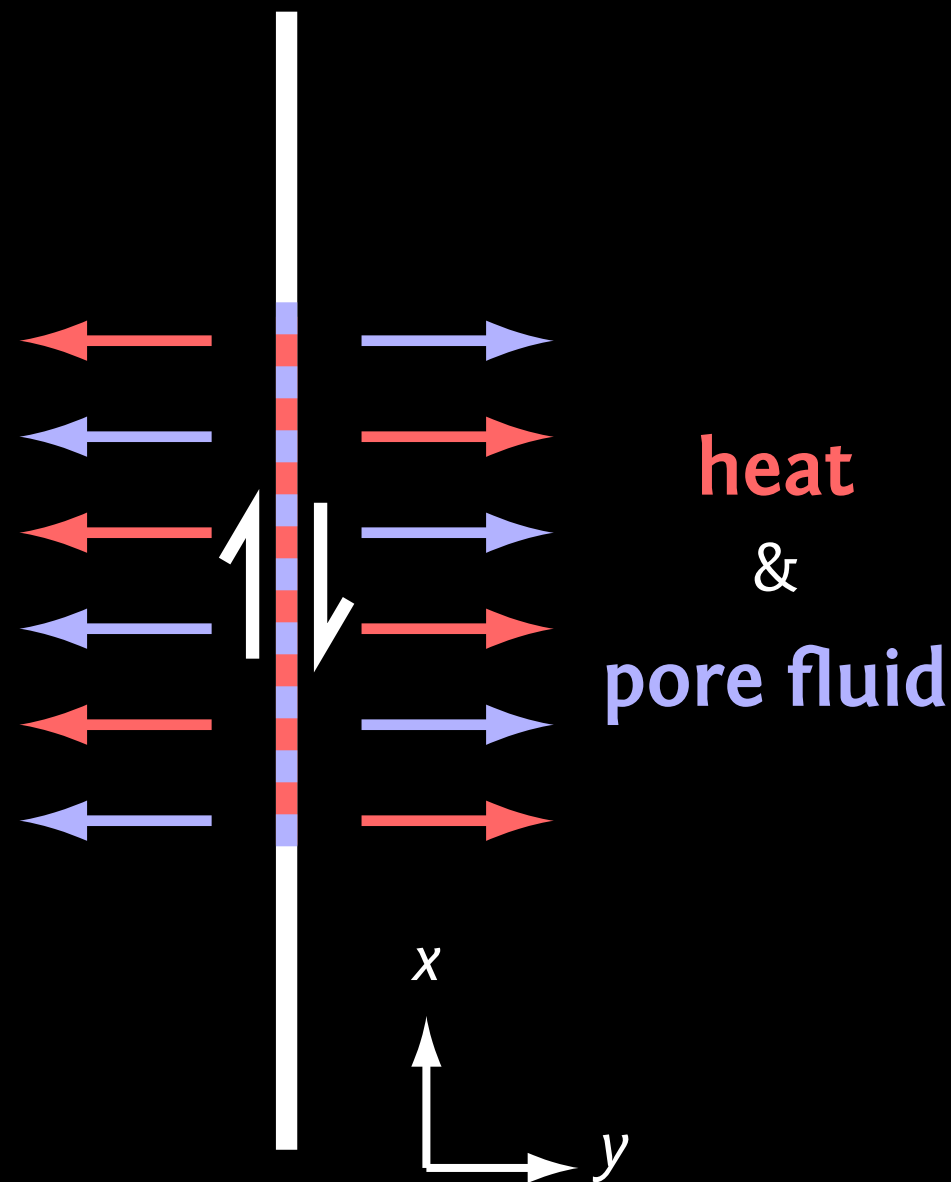
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1. For an earthquake to nucleate, a fault must locally be loaded to its static strength.
2. Thermal pressurization leads to a near total stress drop.
3. With lithostatic stress and laboratory friction values, total strength loss is larger than observed earthquake stress drops.
4. Earthquakes must occur on faults with low average stress, but nucleate at heterogeneities where stress  $\approx$  strength.

# Thermal pressurization

1. Frictional sliding generates heat.
2. Pore fluid expands more than rock.
3. Pore pressure increases if rate of heat production exceeds rate of fluid and heat transport.
4. Effective normal stress decreases, weakening the fault.



References: Sibson (1973); Lachenbruch (1980); Mase & Smith (1985, 1987); Andrews (2002); Noda & Shimamoto (2005); Wibberley & Shimamoto (2005); Rice (2006); Bizzari & Cocco (2006); Segall & Rice (2006); Noda, Dunham, & Rice (2009); Schmitt *et al.* (2011).

# Governing equations

Equation of motion

$$\underbrace{\left[ \mu_0 + a \ln \frac{v}{v_0} + b \ln \frac{\theta v_0}{d_c} \right]}_{\text{friction \& thermal pressurization}} [\sigma - p(t)] = \tau_0 + \underbrace{\phi(x, t) - \frac{G}{2v_s} v}_{\text{elasticity \& radiation}}$$

Slip law state evolution:  $\frac{d\theta}{dt} = -\frac{v\theta}{d_c} \ln \frac{v\theta}{d_c}$

Thermal diffusion:  $\frac{\partial T}{\partial t} = c_{th} \frac{\partial^2 T}{\partial y^2} + \frac{\tau}{\rho c_v} \frac{d\gamma(y)}{dt}$ , with  $\frac{\partial T}{\partial y} \Big|_{y=0} = 0$

Shear heating:  $\gamma(y, t) = \frac{\sqrt{2\tau v}}{\sqrt{\pi h}} \exp\left(-\frac{2y^2}{h^2}\right)$

Pore pressure diffusion:  $\frac{\partial p}{\partial t} = c_{hyd} \frac{\partial^2 p}{\partial y^2} + \Lambda \frac{\partial T}{\partial t}$ , with  $\frac{\partial p}{\partial y} \Big|_{y=0} = 0$

Thermal pressurization factor:  $\Lambda = \frac{\lambda_f - \lambda_\phi}{\beta_f + \beta_\phi}$

# Numerical simulations

1D fault in a 2D elastic, diffusive medium.

Finite difference thermal diffusion and pore pressure diffusion.

Remote, uniform stressing rate.

Parameters used in all simulations shown:

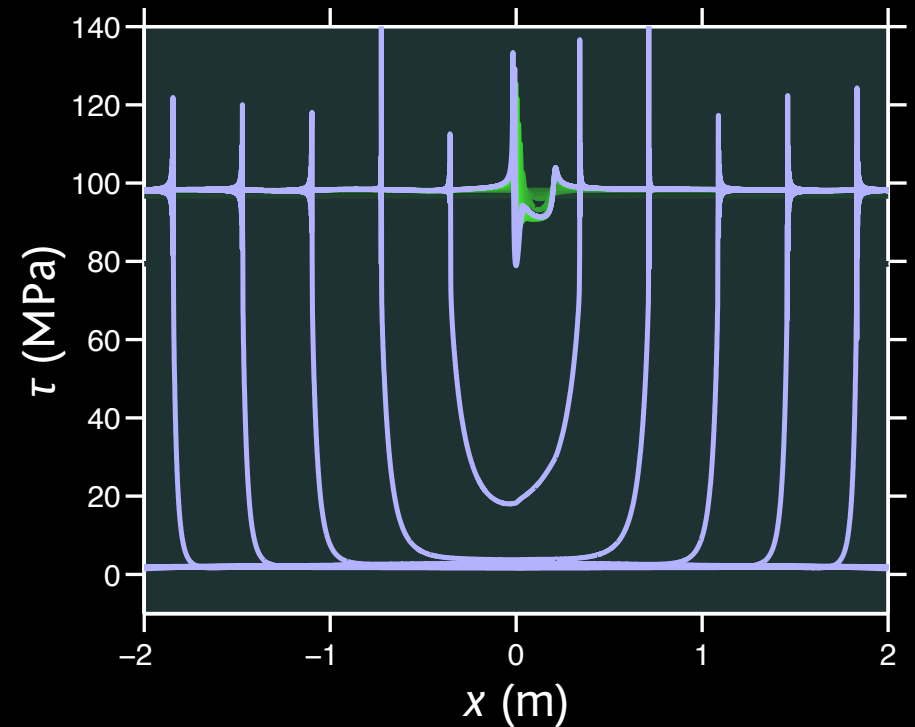
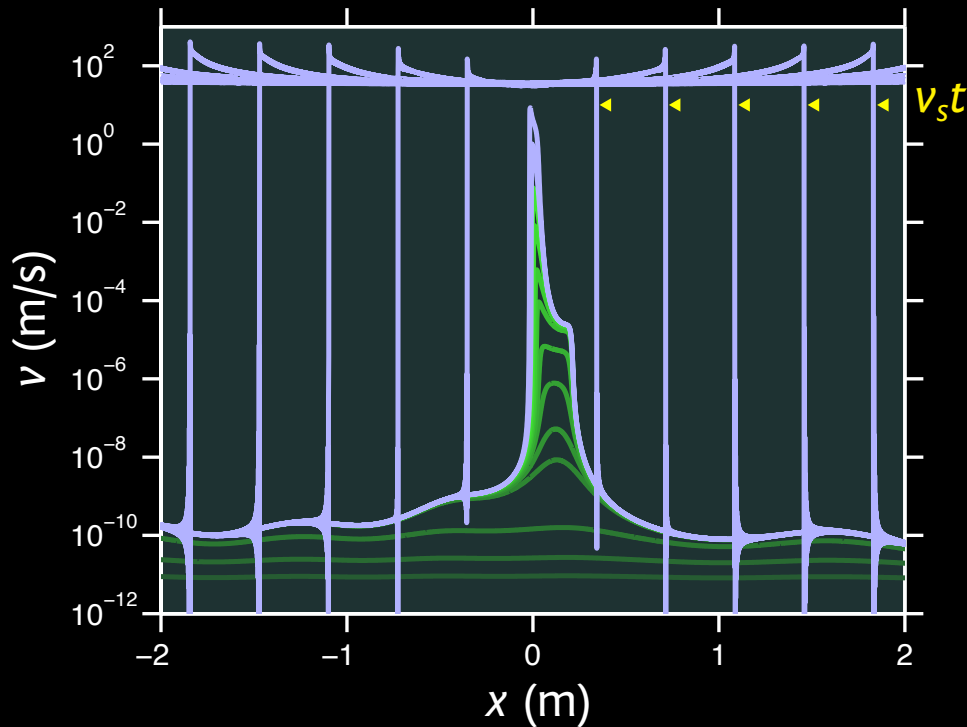
$$a/b = 0.8; \quad d_c = 20 \mu\text{m}; \quad h = 100 \mu\text{m}; \quad (\sigma - p_\infty) = 126 \text{ MPa};$$

$$\Lambda = 0.468 \text{ MPa/K}; \quad c_{\text{th}} = 0.7 \text{ mm}^2/\text{s}; \quad c_{\text{hyd}} = 3 \text{ mm}^2/\text{s};$$

$$\dot{\tau} = 0.01 \text{ Pa/s}; \quad \text{mode 3 antiplane slip.}$$

# Nucleation and rupture under uniform stress

High slip speed. Fast rupture growth. Near total stress drop.



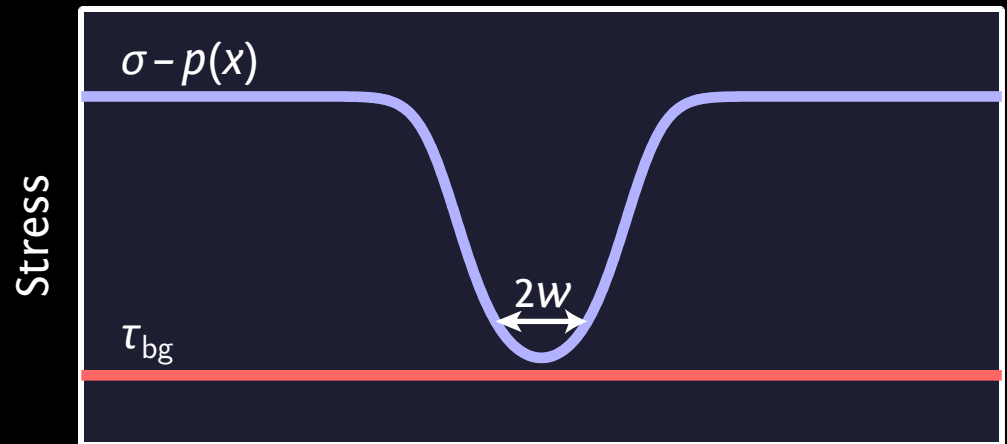
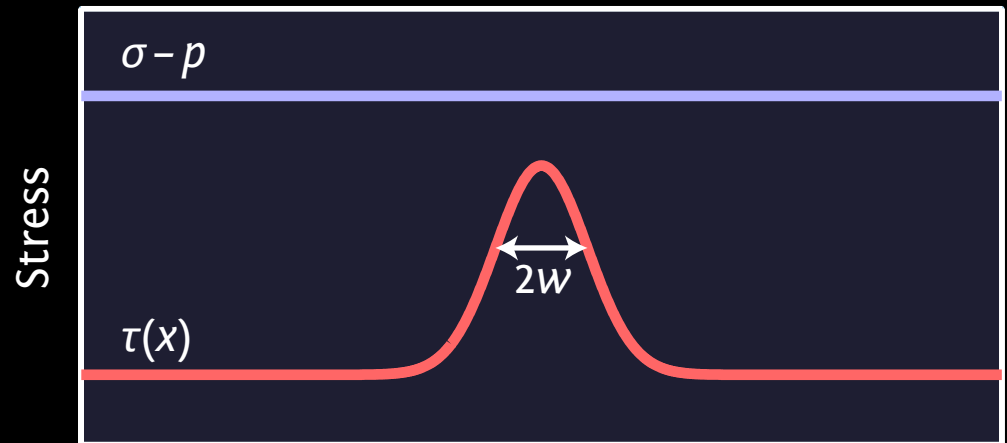
**Problem:** this is an unrealistic earthquake!

# Stress heterogeneity for nucleation at low mean $\tau$

Two simple stress states satisfy a given  $\tau / (\sigma - p)$ .

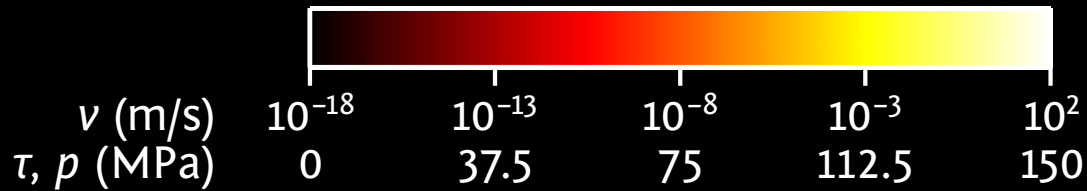
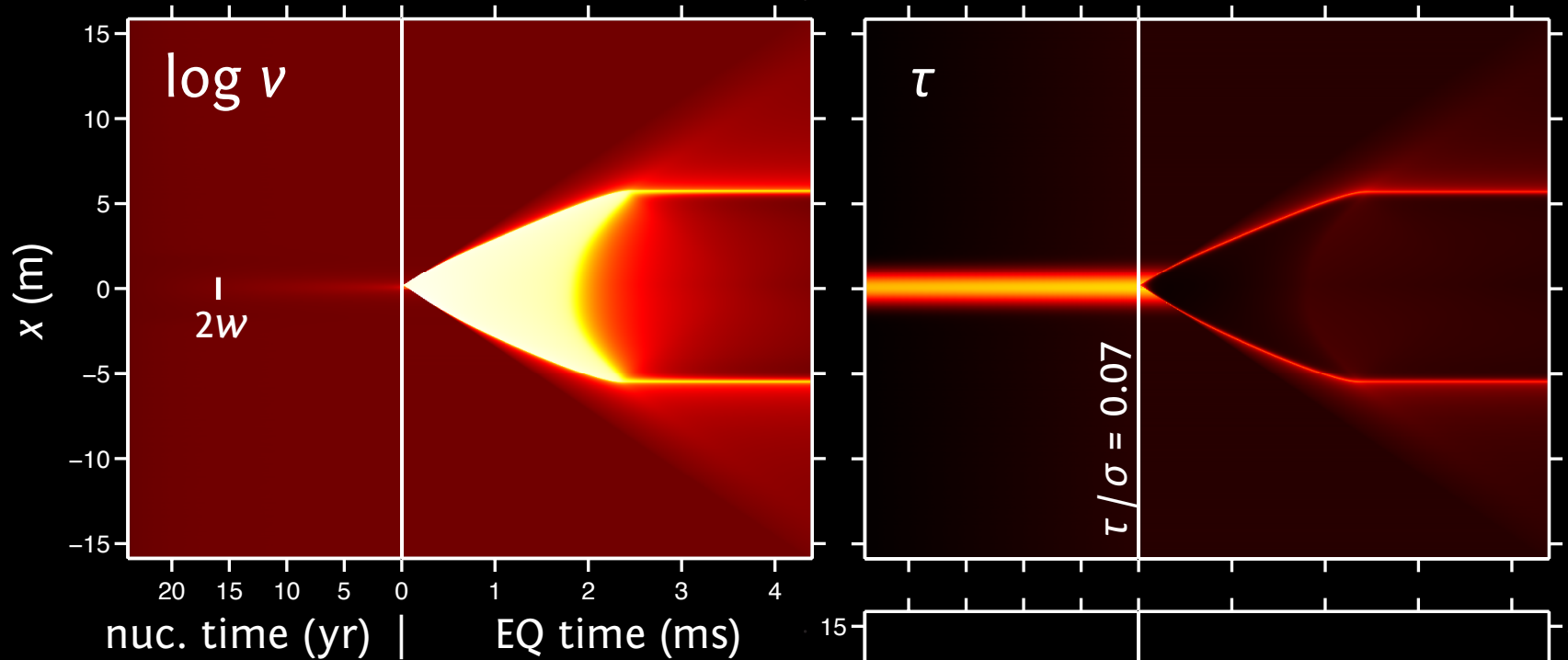
A **high-stress** model, where there is a concentration of shear stress.

A **low-strength** model, where effective normal stress is locally low.



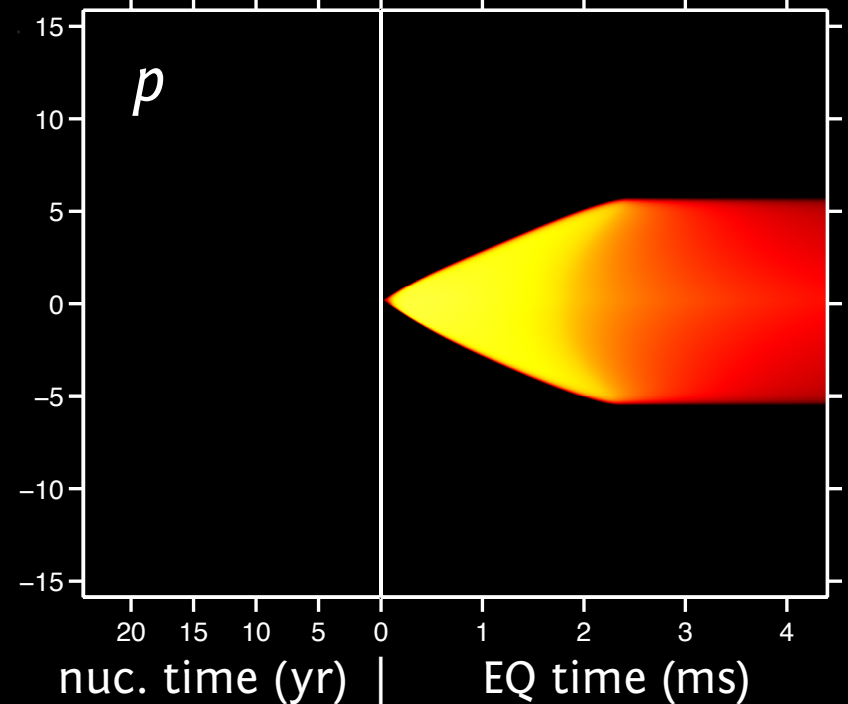
Position on fault

# High stress model with very low $\tau_{bg}$

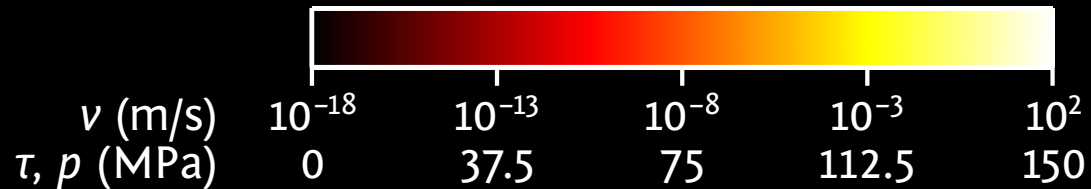
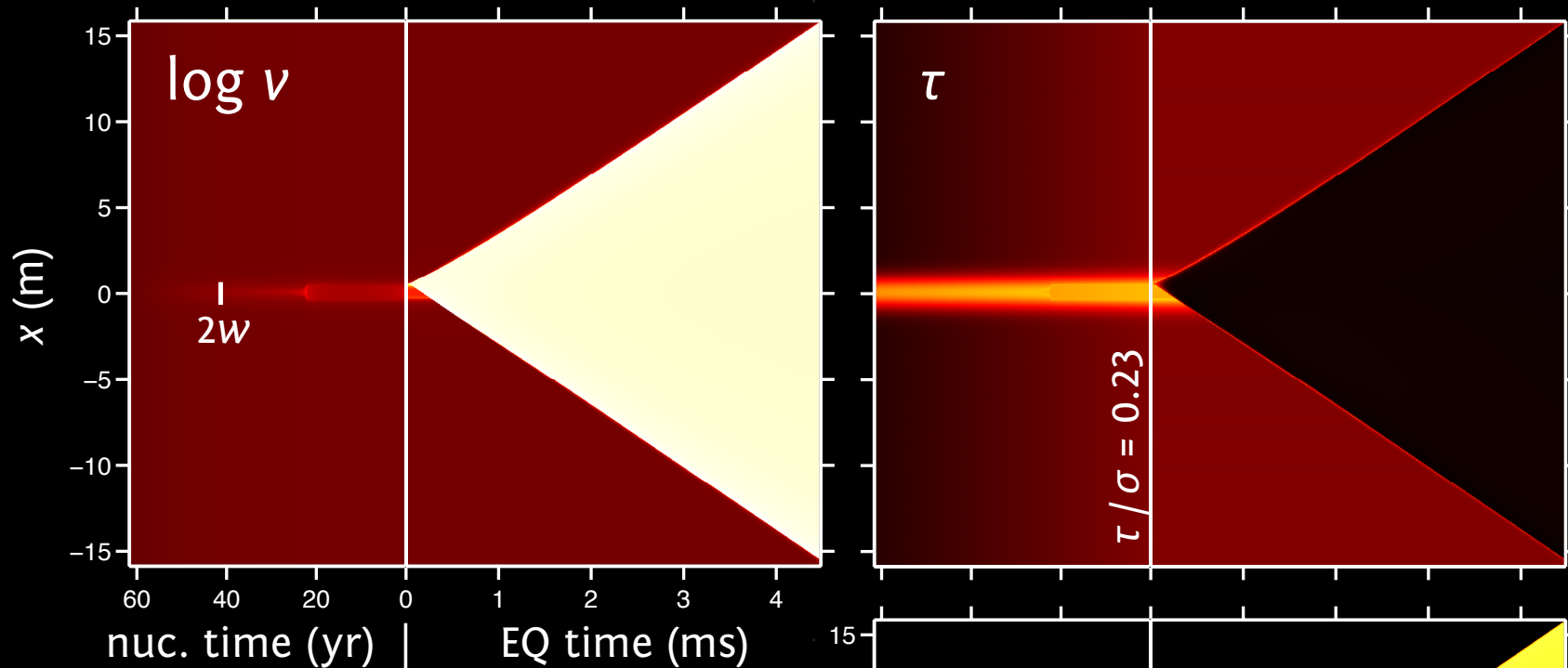


$$W = 2.5L_{\min}$$

$$(\tau_0/\sigma_0)^{\text{peak}} = 1.1\mu_0$$

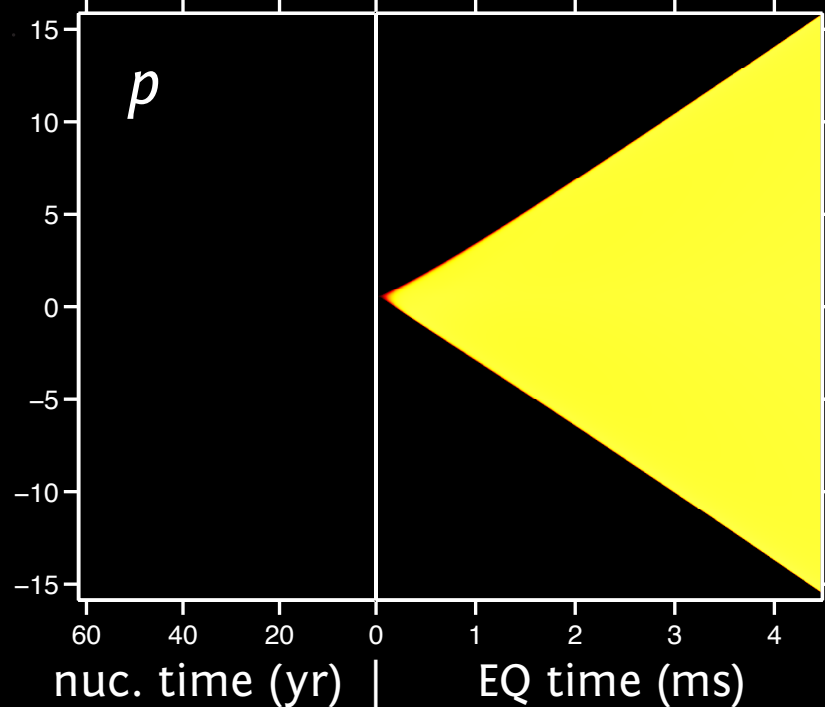


# High stress model: sustained rupture

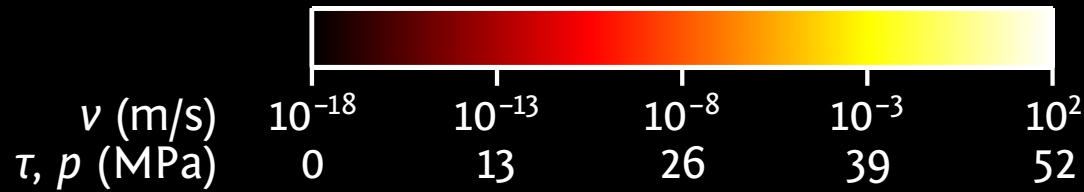
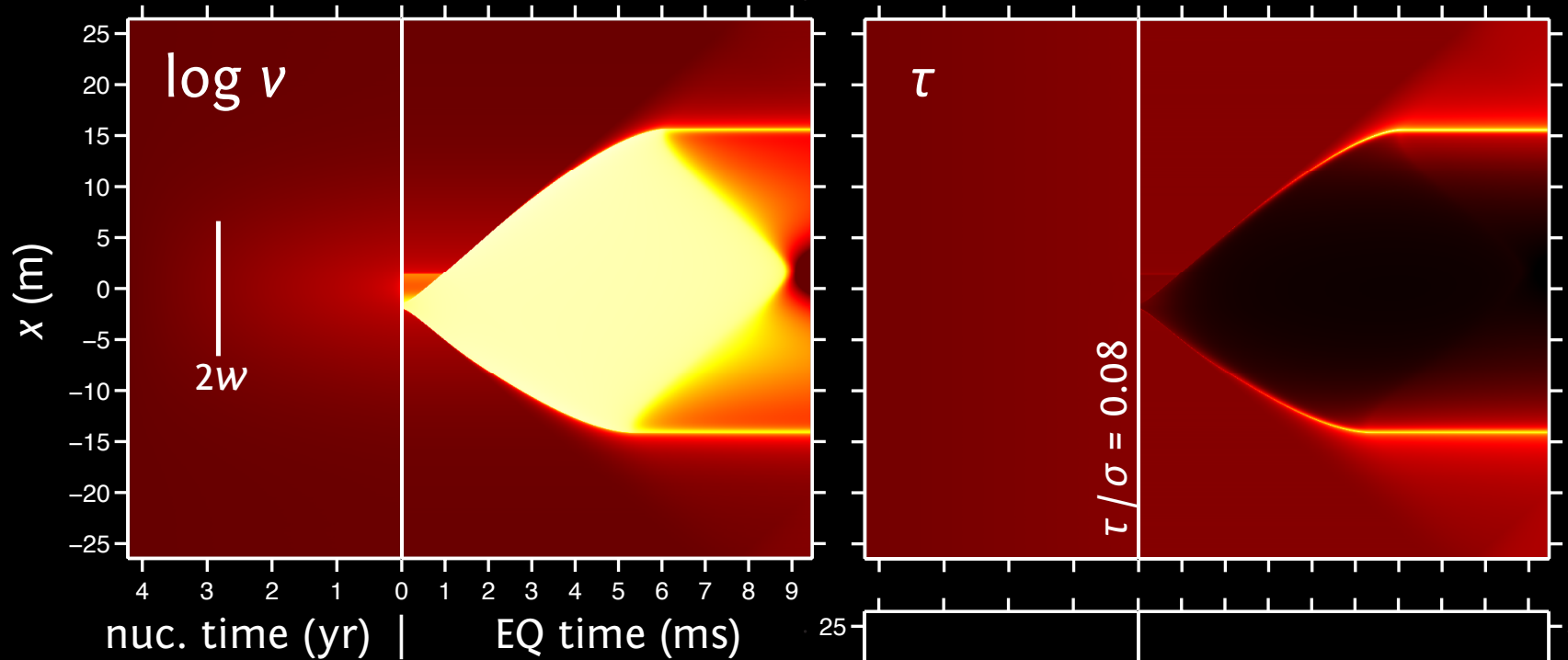


$$W = 2.5L_{\min}$$

$$(\tau_0/\sigma_0)^{\text{peak}} = \mu_0$$

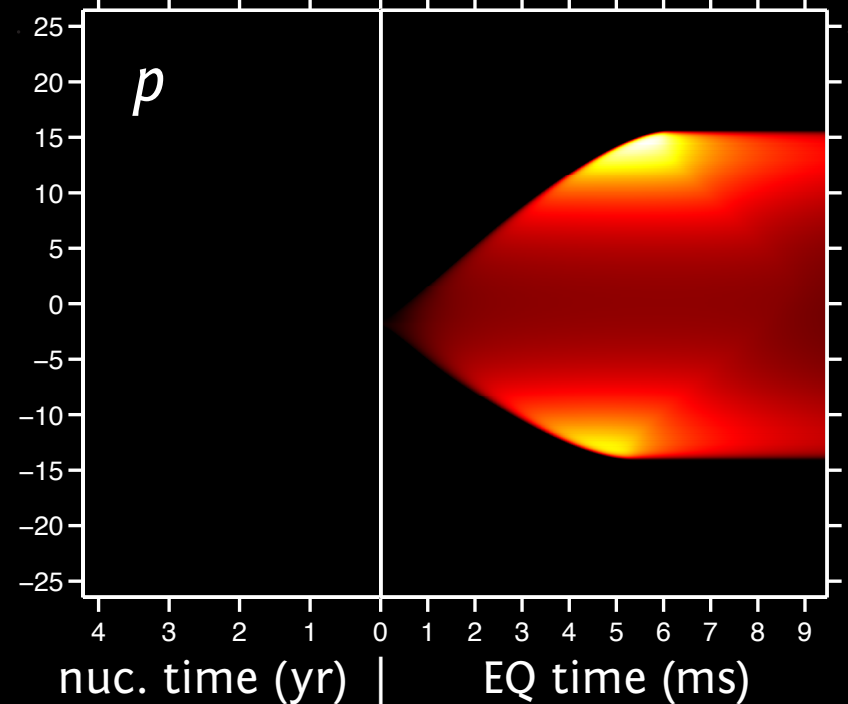


# Low strength model



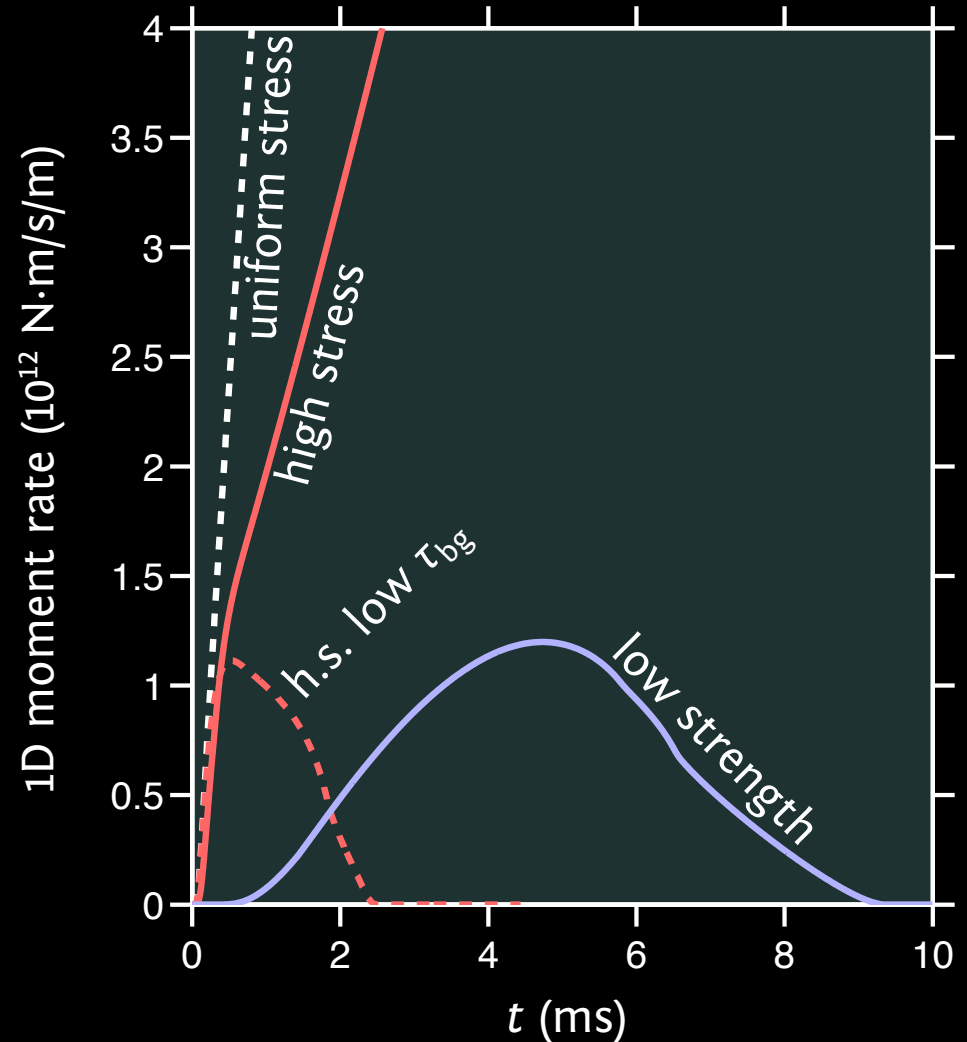
$$w = 2.5L_{\min}$$

$$(\tau_0/\sigma_0)^{\text{peak}} = \mu_0$$



# Moment rate comparison

High stress earthquakes are more impulsive than low strength earthquakes.



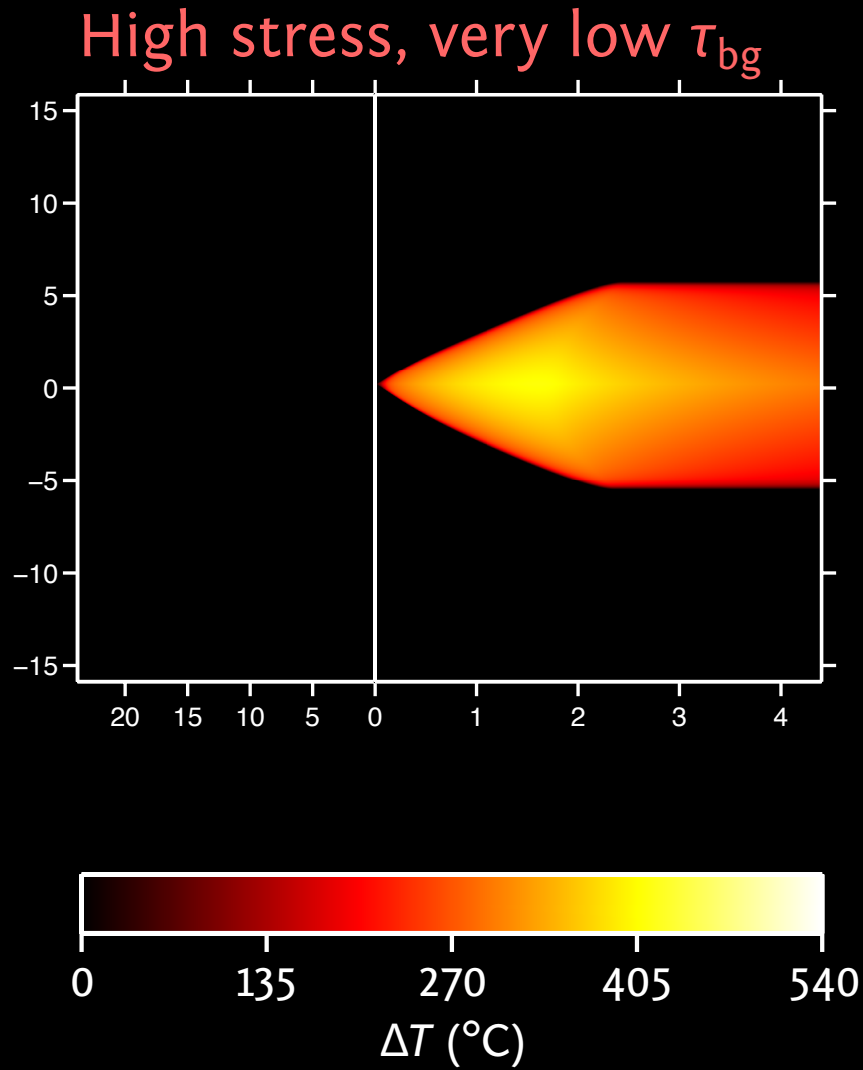
## Conclusion

Earthquakes on low-stress faults nucleate in regions of locally elevated  $\tau / (\sigma - p)$ .

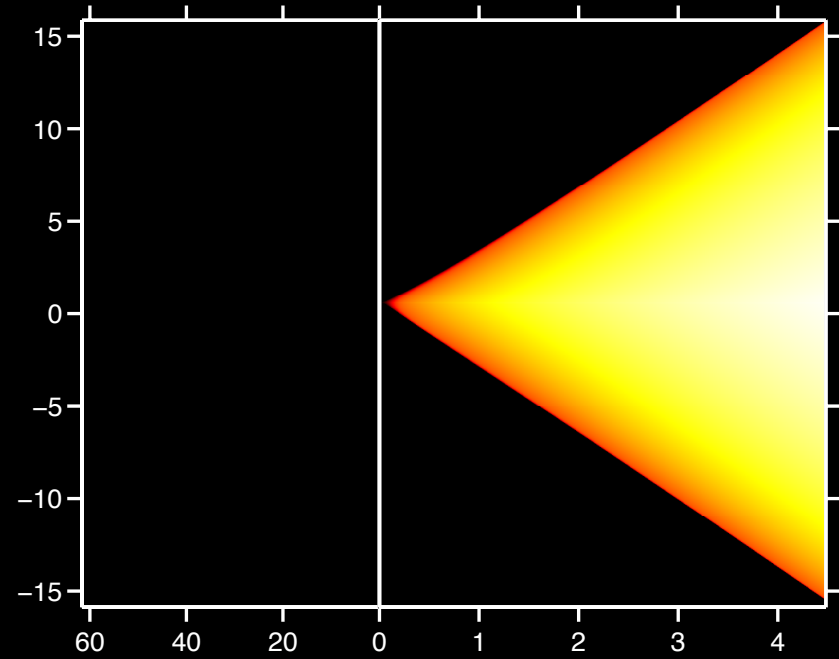
Thermal pressurization can allow slip to occur at low mean  $\tau$ .

Numerical simulations show that “high stress” nucleation has a larger early moment rate than “low strength” nucleation.

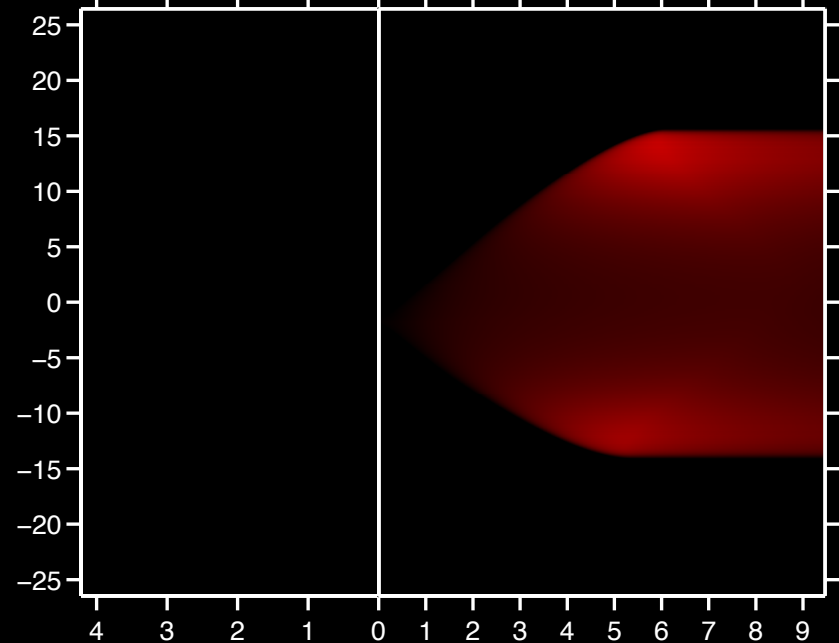
# Temperature rise



# High stress

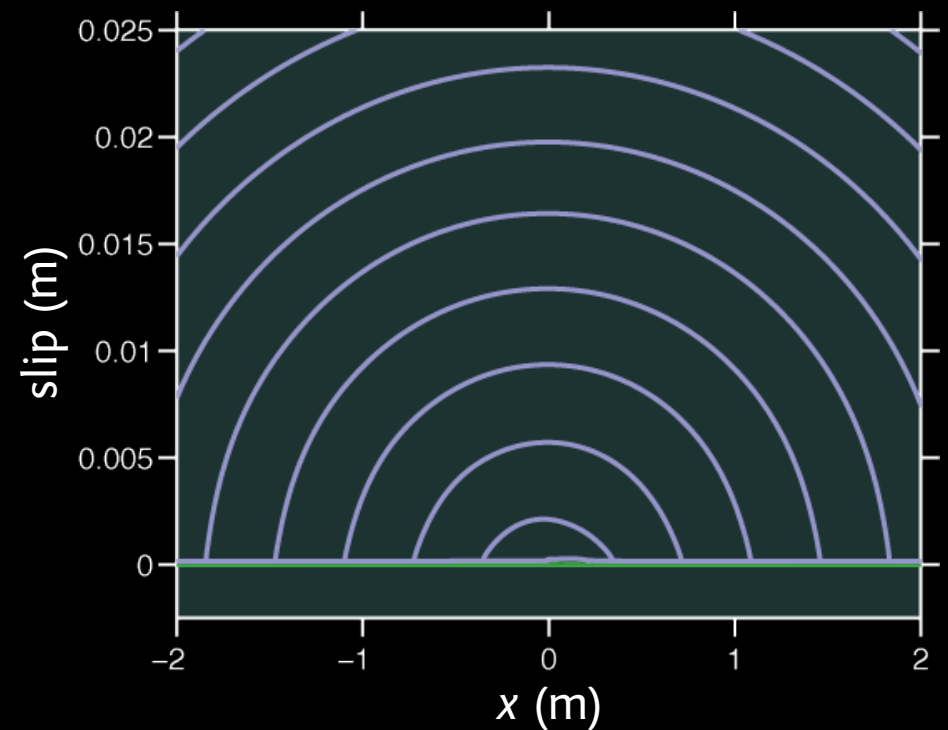
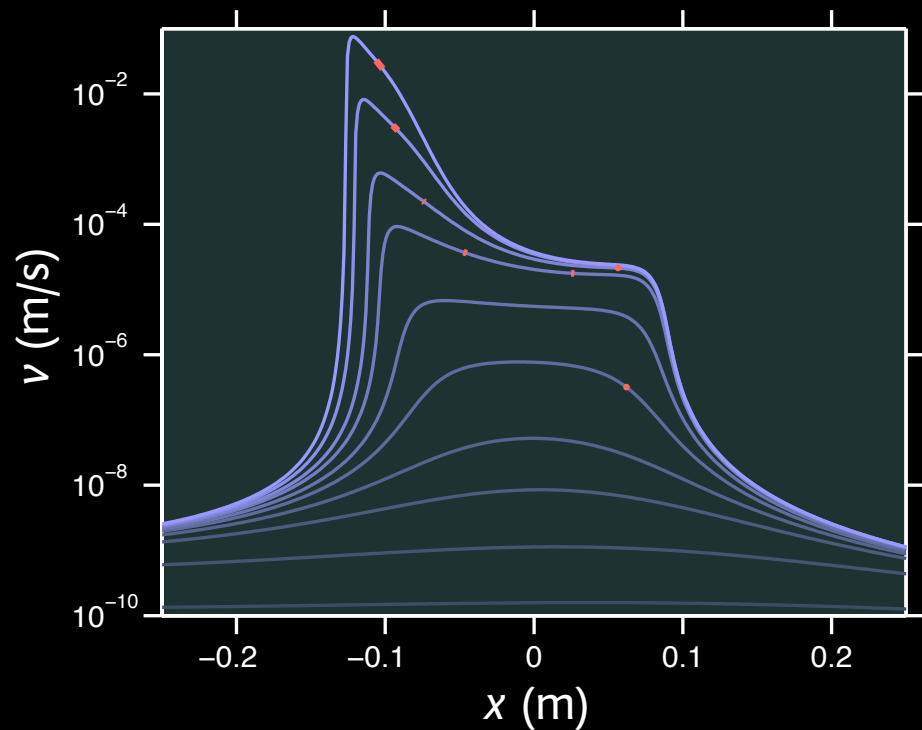


# Low strength



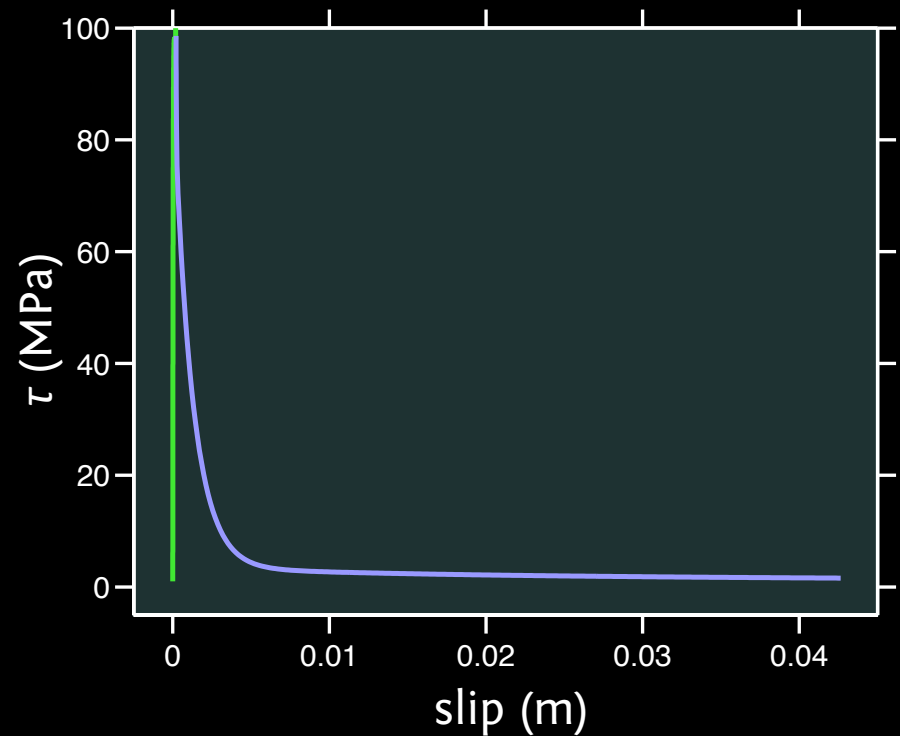
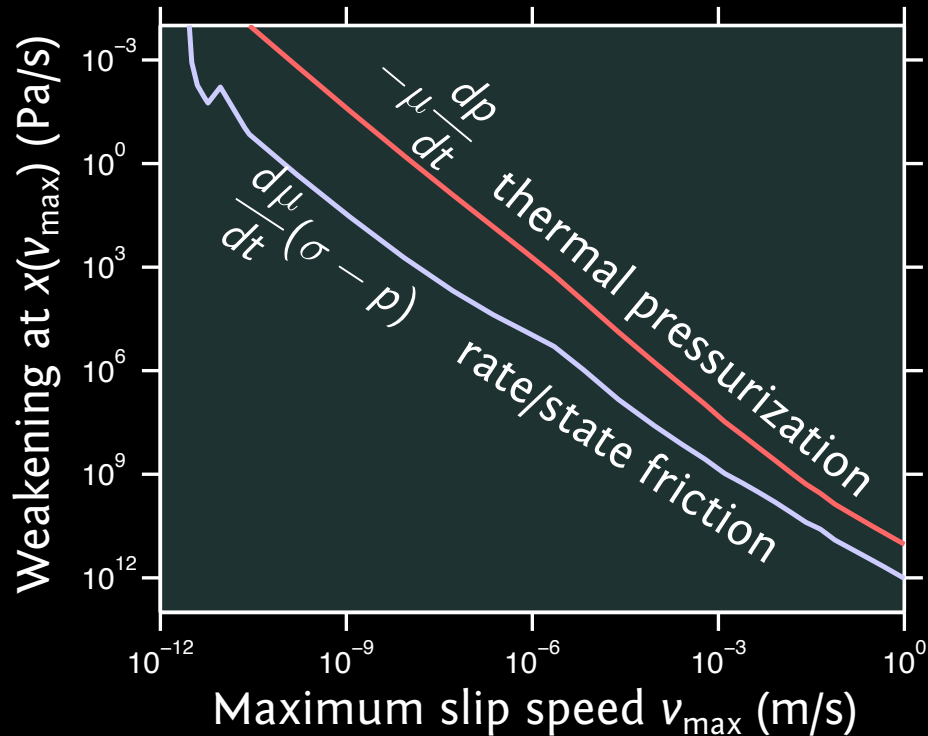
# Dynamic rupture under uniform stress

High slip speeds. Fast crack-like rupture growth.



# Uniform stress: slip weakening under t.p.

Shear stress rapidly approaches zero.



## Additional observations

Dynamic rupture grows bilaterally after nucleation.

For aging law nucleation, the nucleation zone size is different.

$$L_{\infty} = L_{\min} \times 2b / [\pi(b-a)]$$

$\sim 3.2L_{\min}$  for the values used here.