Transition of Dynamic Rupture Modes in Elastic Media

EGU
07.04.2011

Alice Gabriel[1], Jean-Paul Ampuero[2], Luis A. Dalguer[1], P. Martin Mai[3]

[1] ETH Zürich

[2] California Institute of Technology

[3] King Abdullah University of Science & Technology

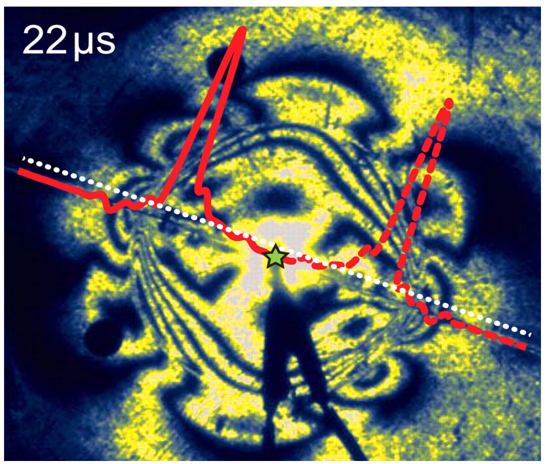
Why study rupture modes ?

- **Self-healing Pulse** vs. **Expanding Crack**

Why study rupture modes ?

- **Self-healing Pulse** vs. Expanding Crack

  Narrow slip-velocity pulse



Lu,Lapusta,Rosakis,2007

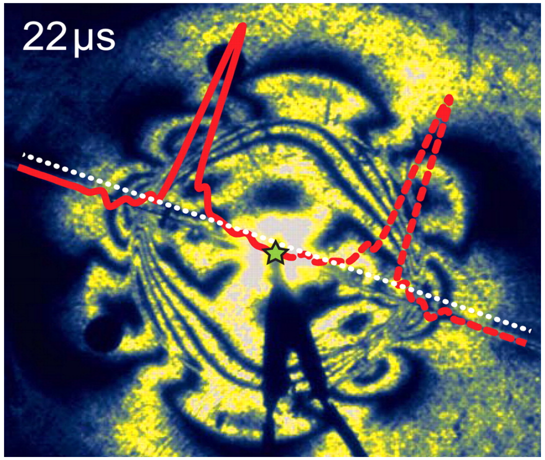
- Seismic inversions:
  → short rise times (T.H. Heaton 1990)
- Numerical simulations:

  → velocity weakening & background stress
  (e.g. Zheng & Rice 1998)
- High speed laboratory experiments:
  → strong friction drop & recovery

Why study rupture modes ?

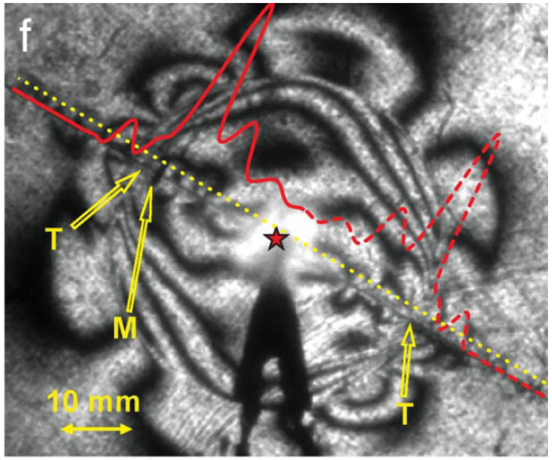
- **Self-healing Pulse** vs. **Expanding Crack**

  Narrow slip-velocity pulse vs. fault sliding on entire length



Lu,Lapusta,Rosakis,2007

- Seismic inversions:
  → variabel slip duration
  (e.g. Mw 8.8 2010 Chile Earthquake, Madariaga et al. 2010)
- Numerical simulations:
  → velocity-independent fault strength
  & background stress
- Laboratory experiments



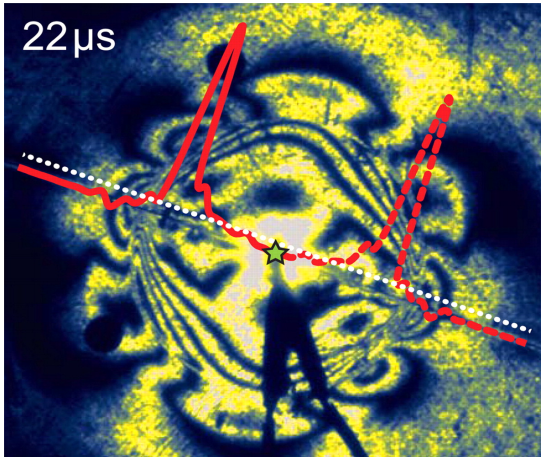
Lu,Lapusta,Rosakis,2007

Motivation

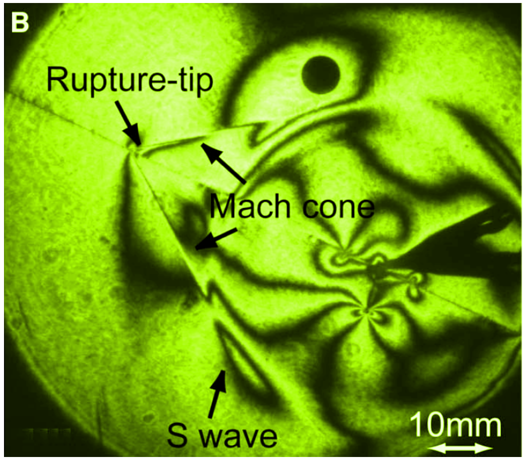
Why study rupture modes ?

- **Self-healing Pulse** vs. **Expanding Crack**

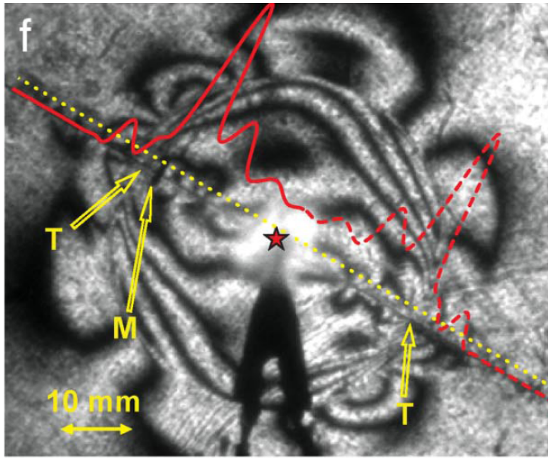
  Narrow slip-velocity pulse vs. fault sliding on entire length



Lu,Lapusta,Rosakis,2007



Xia, Rosakis, Kanamori,2004



Lu,Lapusta,Rosakis,2007

- **Subshear** vs. **Supershear**

  Rupture speeds larger than S-wave speed

  → background stress & constitutive relation

  (1979 Imperial Valley , 1992 Landers,
  1999 Izmit, Kunlunshan 2001, 2002 Denali)

Why study rupture modes ?

- **Self-healing Pulse** vs. **Expanding Crack**

  Narrow slip-velocity pulse vs. fault sliding on entire length

→ **Earthquakes may not be restricted to one singular rupture mode but show multiple rupture patterns**

→ **What controls the initiation and transition of rupture modes ?**

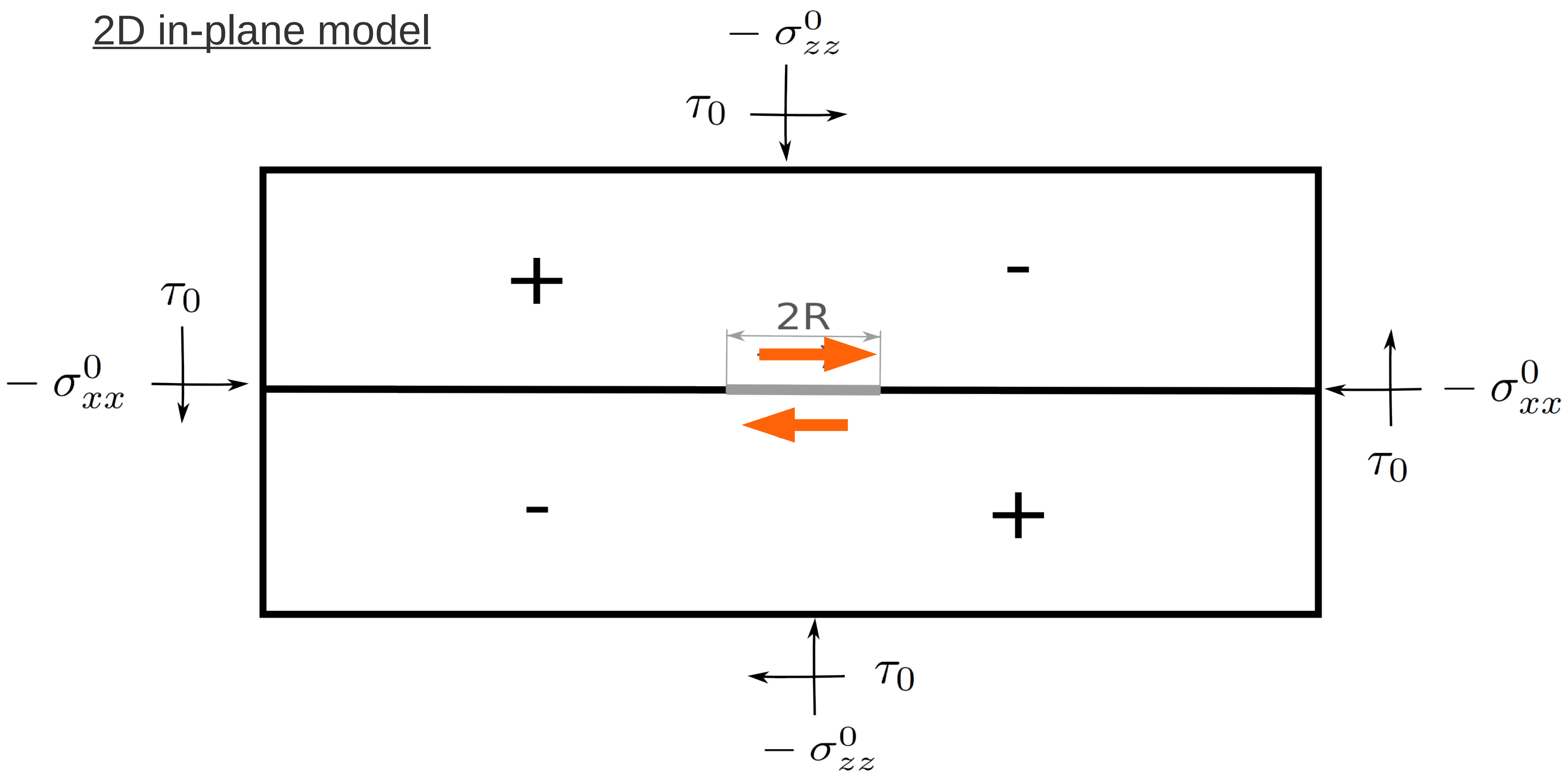
→ **What are the dynamics of rupture pulses ?**

- **Subshear** vs. **Supershear**

  Rupture speeds larger than S-wave speed

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

2D in-plane model



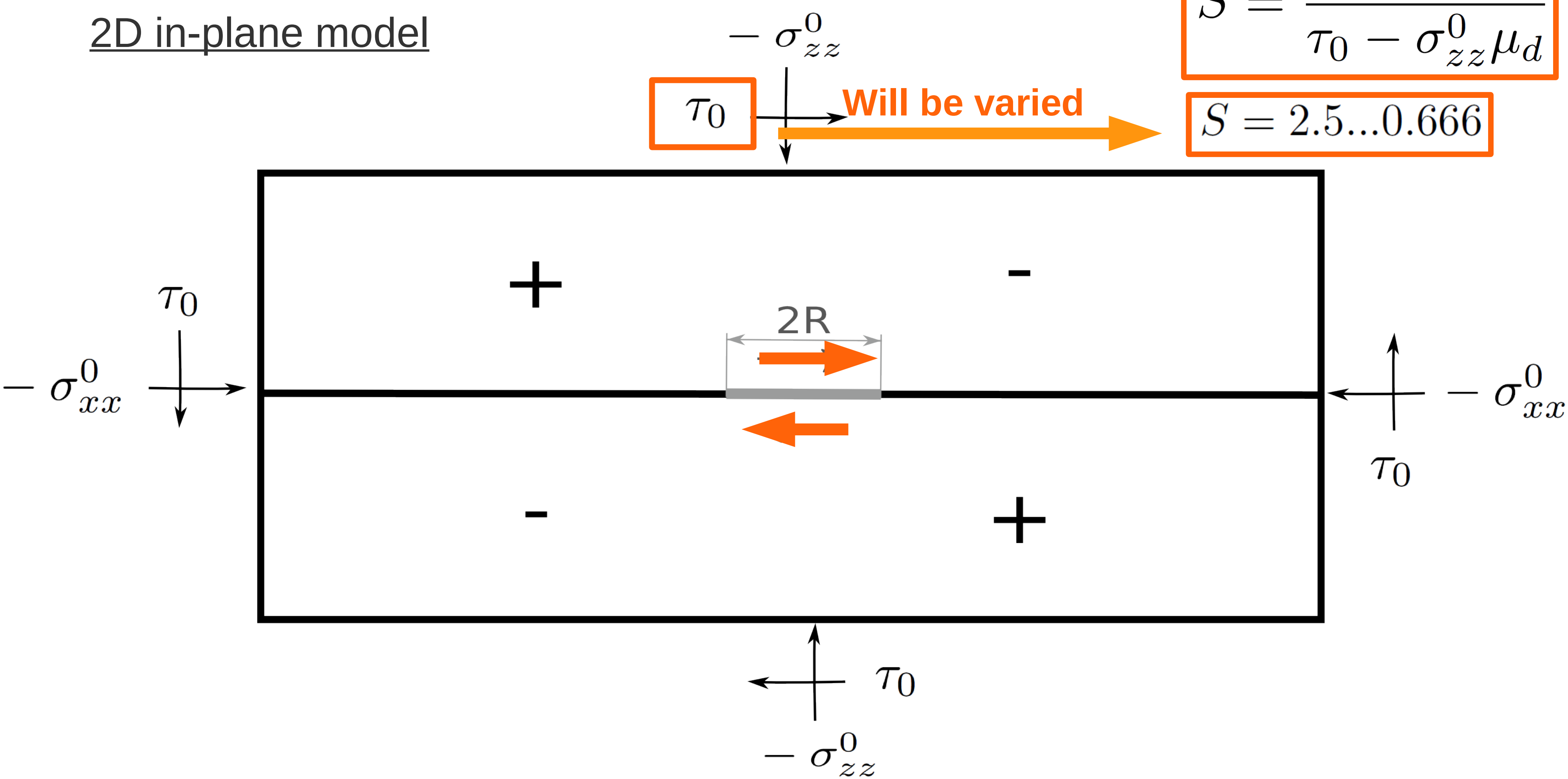
Andrews,1976

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

$$S = \frac{\sigma^0_{zz}\mu_s - \tau_0}{\tau_0 - \sigma^0_{zz}\mu_d}$$

<u>2D in-plane model</u>

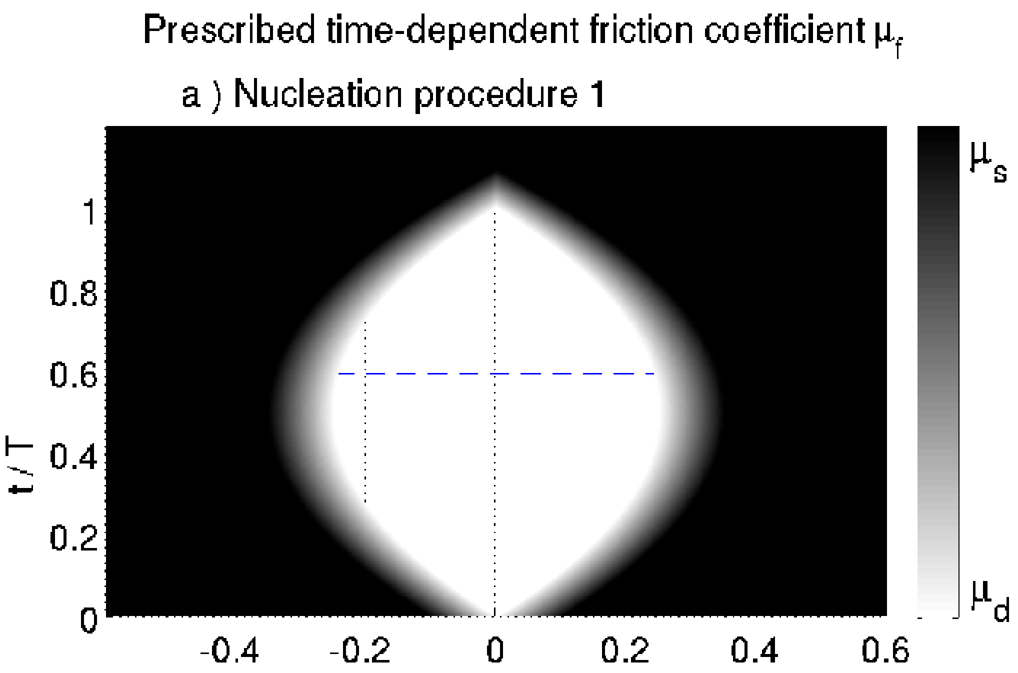


Andrews,1976

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

  + 2 Nucleation procedures: representing 2 extreme cases of frictional behavior



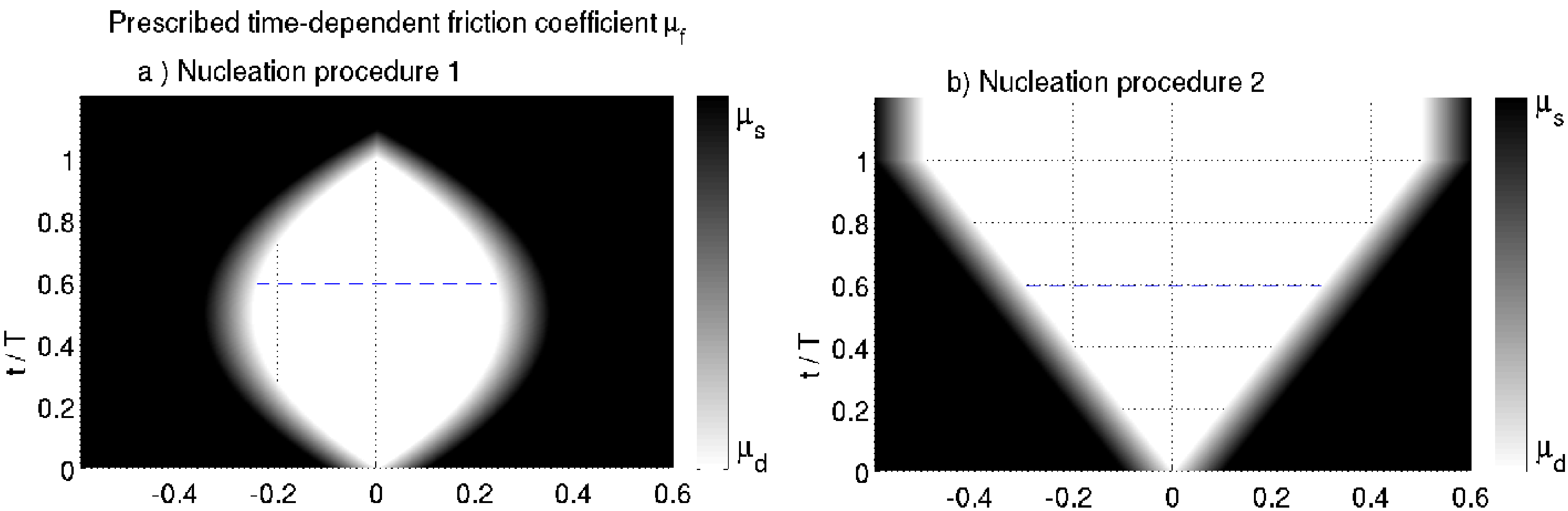
  - Self-healing time-weakening

    (Andrews and Ben-Zion,97)

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

  + 2 Nucleation procedures: representing 2 extreme cases of frictional behavior



- Self-healing time-weakening

  (Andrews and Ben-Zion,97)

- Non-healing time-weakening

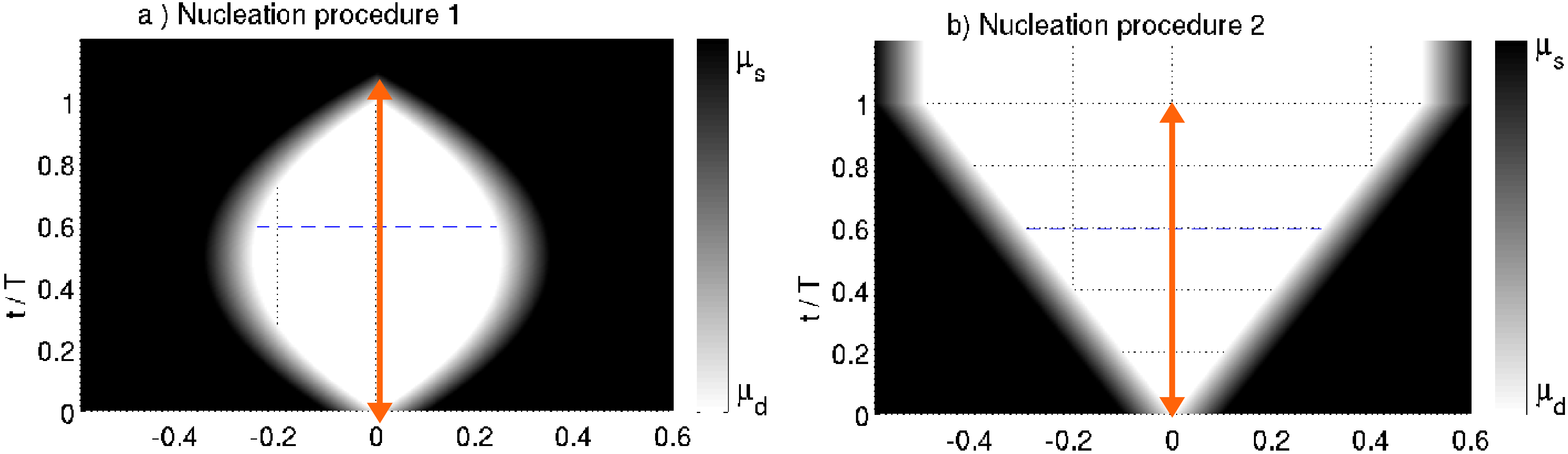
  (Andrews)

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

+ 2 Nucleation procedures: representing 2 extreme cases of frictional behavior

Prescribed time-dependent friction coefficient μ_f



Nucleation duration *T*: Will be varied

- Self-healing time-weakening (Andrews and Ben-Zion,97)
- Non-healing time-weakening (Andrews)

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

+ 2 Nucleation procedures: representing 2 extreme cases of frictional behavior

+ Rate-and-state dependent friction law with fast velocity-weakening

(Ampuero, Ben-Zion (2008))

$$\mu_f = \mu_s + a\frac{V}{V+V_c} - b\frac{\Theta}{\Theta + D_c} \qquad \dot{\Theta} = V - \Theta\frac{V_c}{D_c}$$

Model setup

- 2D spectral element method SEM2DPACK (Ampuero, 2008)

+ 2 Nucleation procedures: representing 2 extreme cases of frictional behavior

+ Rate-and-state dependent friction law with fast velocity-weakening
(Ampuero, Ben-Zion (2008))

→ **Parameter space study :**

Nucleation procedure and duration (*T*) / background shear stress (*S*)

General rupture modes

- **In elastic media rupture approaches distinct**

(Stable) self-similar and **(sensitive) transitional** regimes

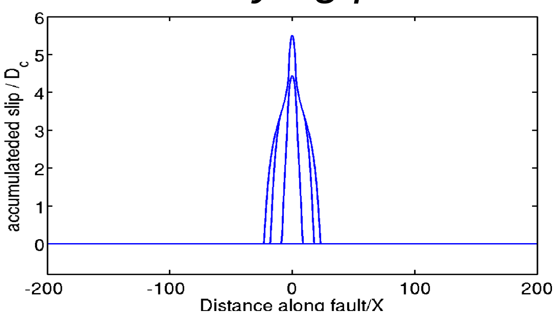
General rupture modes

- **In elastic media rupture approaches distinct**

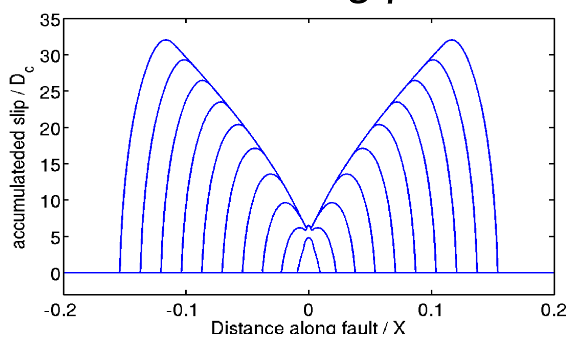
(Stable) self-similar and **(sensitive) transitional** regimes

Increasing shear stress-
Decreasing S

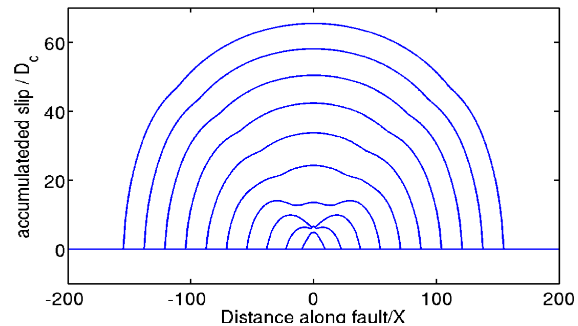
Decaying pulse



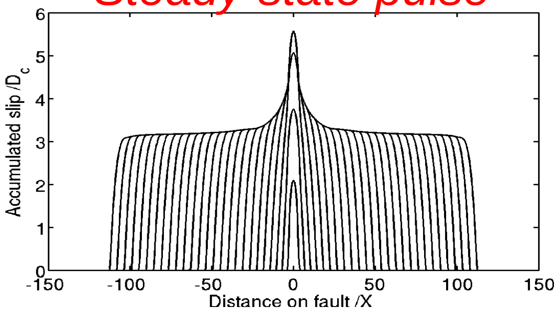
Growing pulse



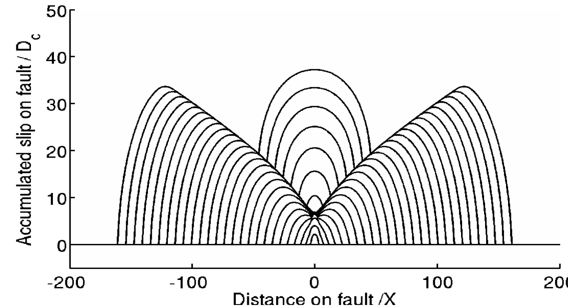
Crack-like



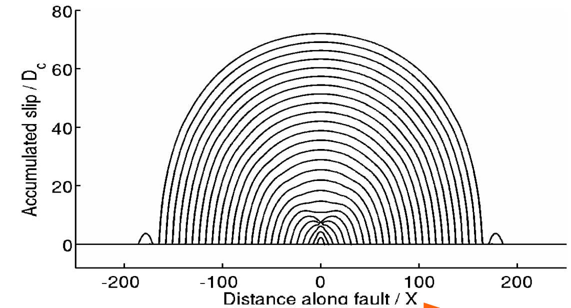
Steady-state pulse



Pulse-crack transition



Supershear transition

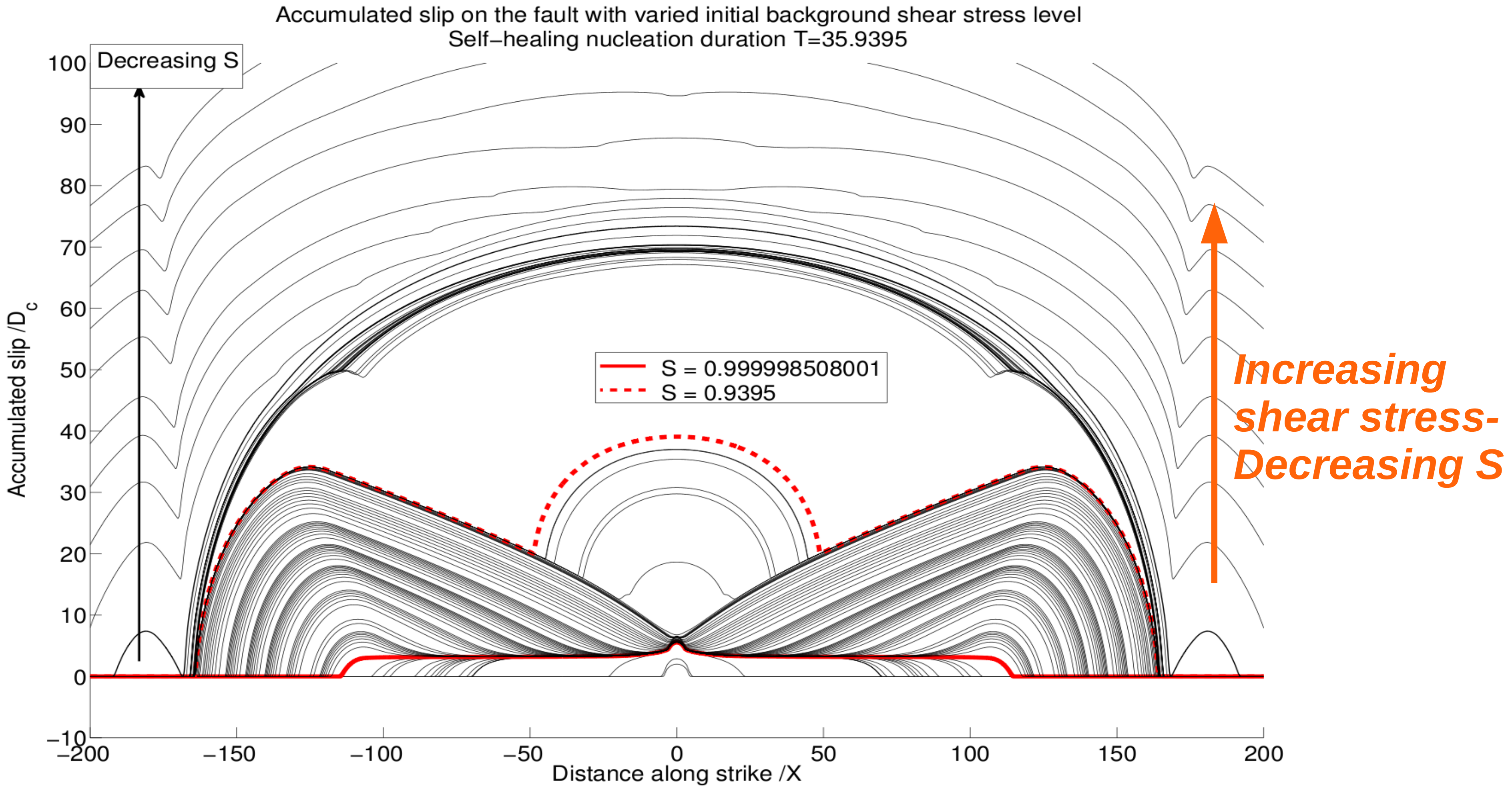


Increasing Nucleation duration T

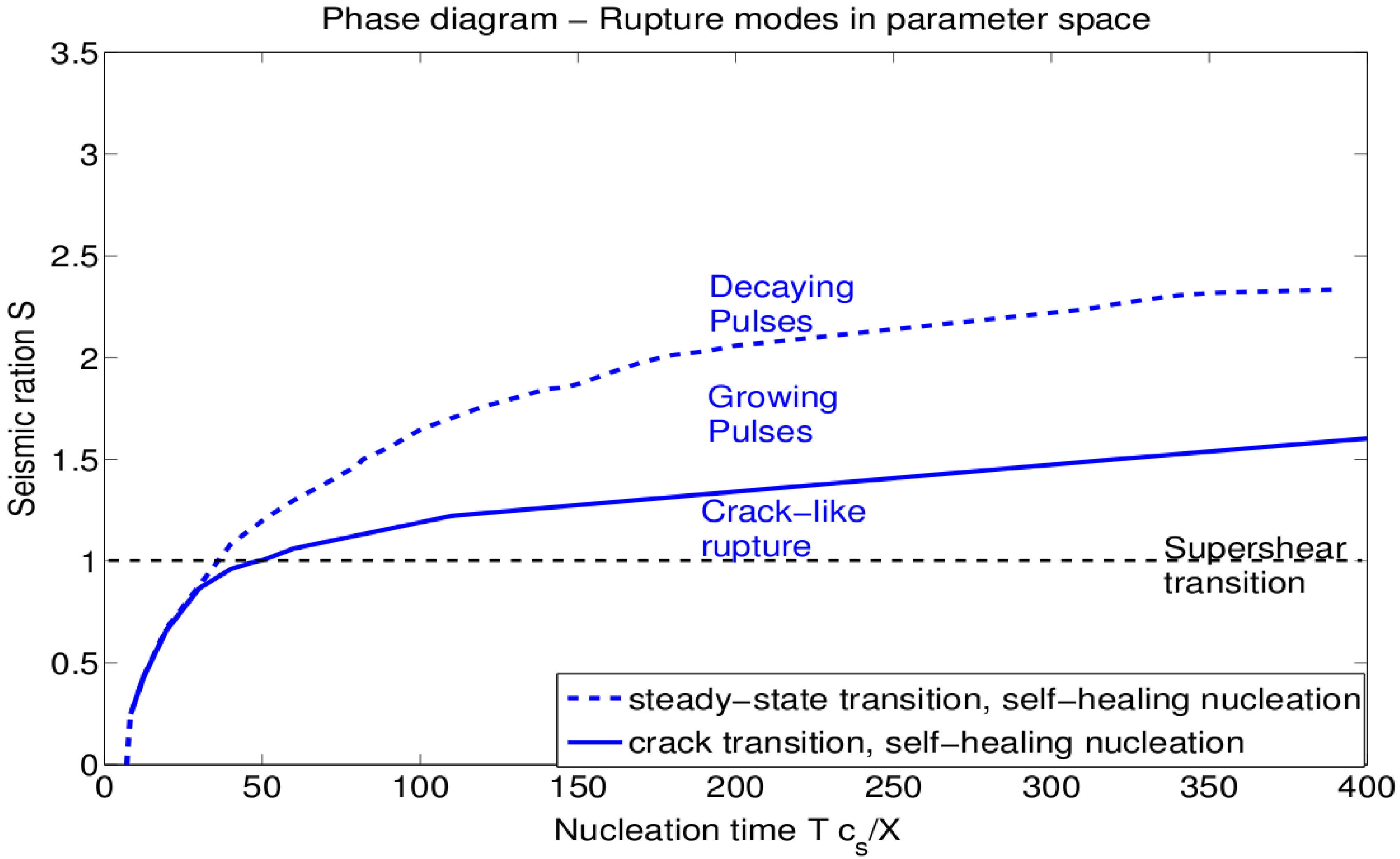
General rupture modes

- **In elastic media rupture approaches distinct**

(Stable) self-similar and **(sensitive) transitional** regimes



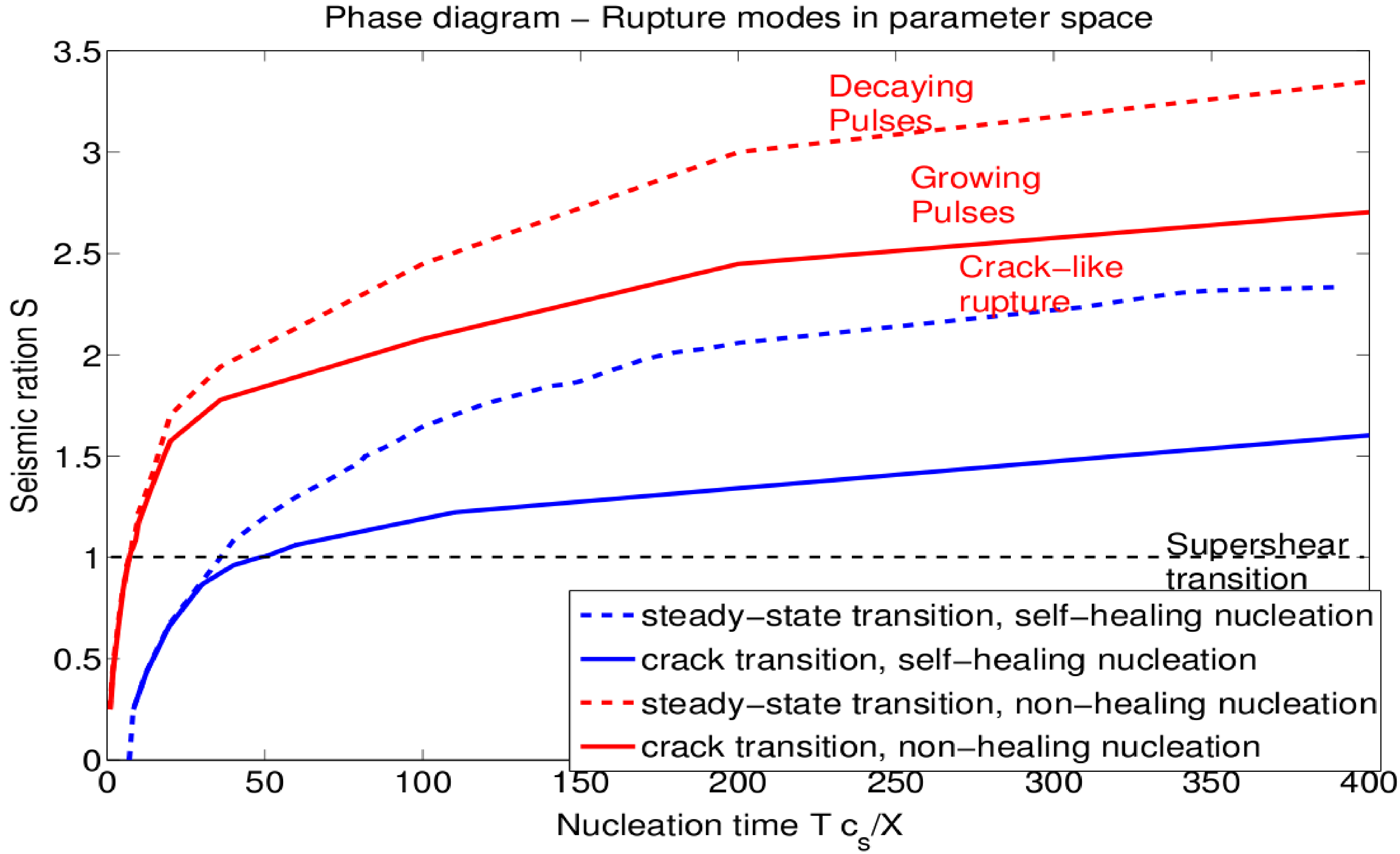
Phase diagram – S, T



- **Changes in initial stress state and nucleation shift rupture modes**
- **Higher stress states ⇆ shorter nucleation**

⇆ smaller range of growing pulses

Phase diagram – S, T

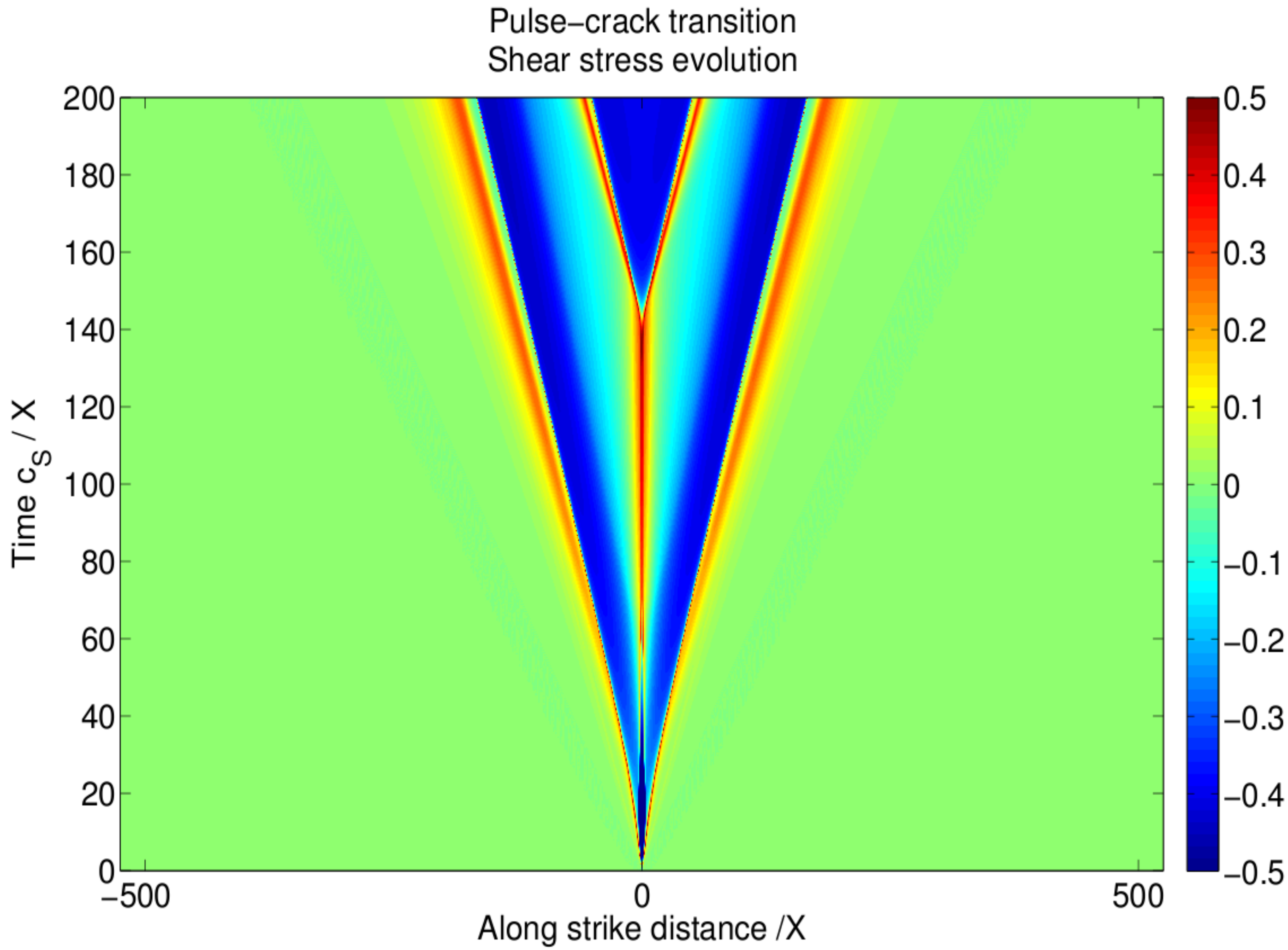


- **Change in nucleation procedure shifts rupture modes**
- **Non-healing nucleation ⇆ shorter nucleation**
  ⇆ lower initial stress state

Transitional rupture modes

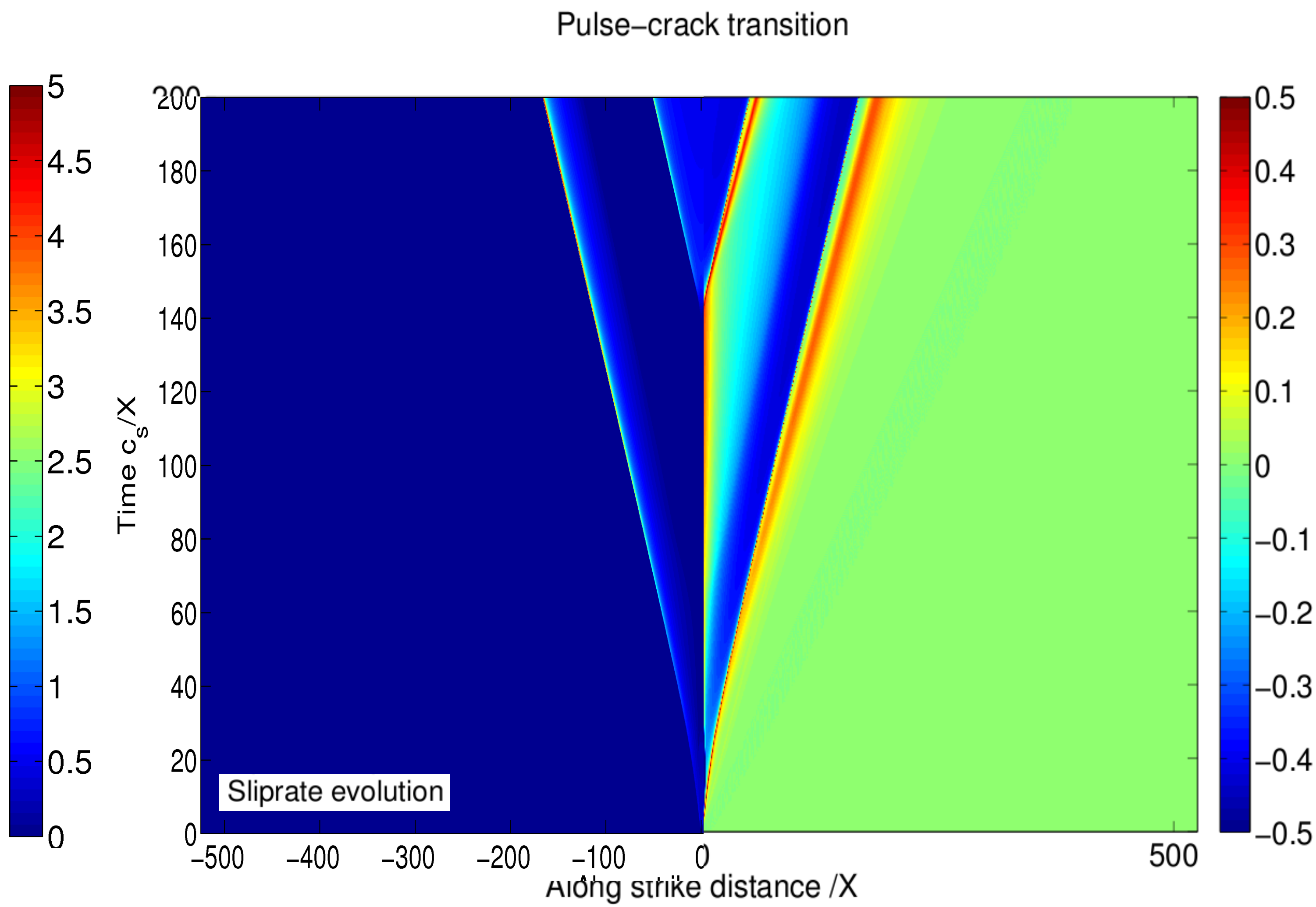
Pulse-crack transition → Gradual stress build-up at hypocenter

(Madariaga&Nielsen,2003)



Transitional rupture modes

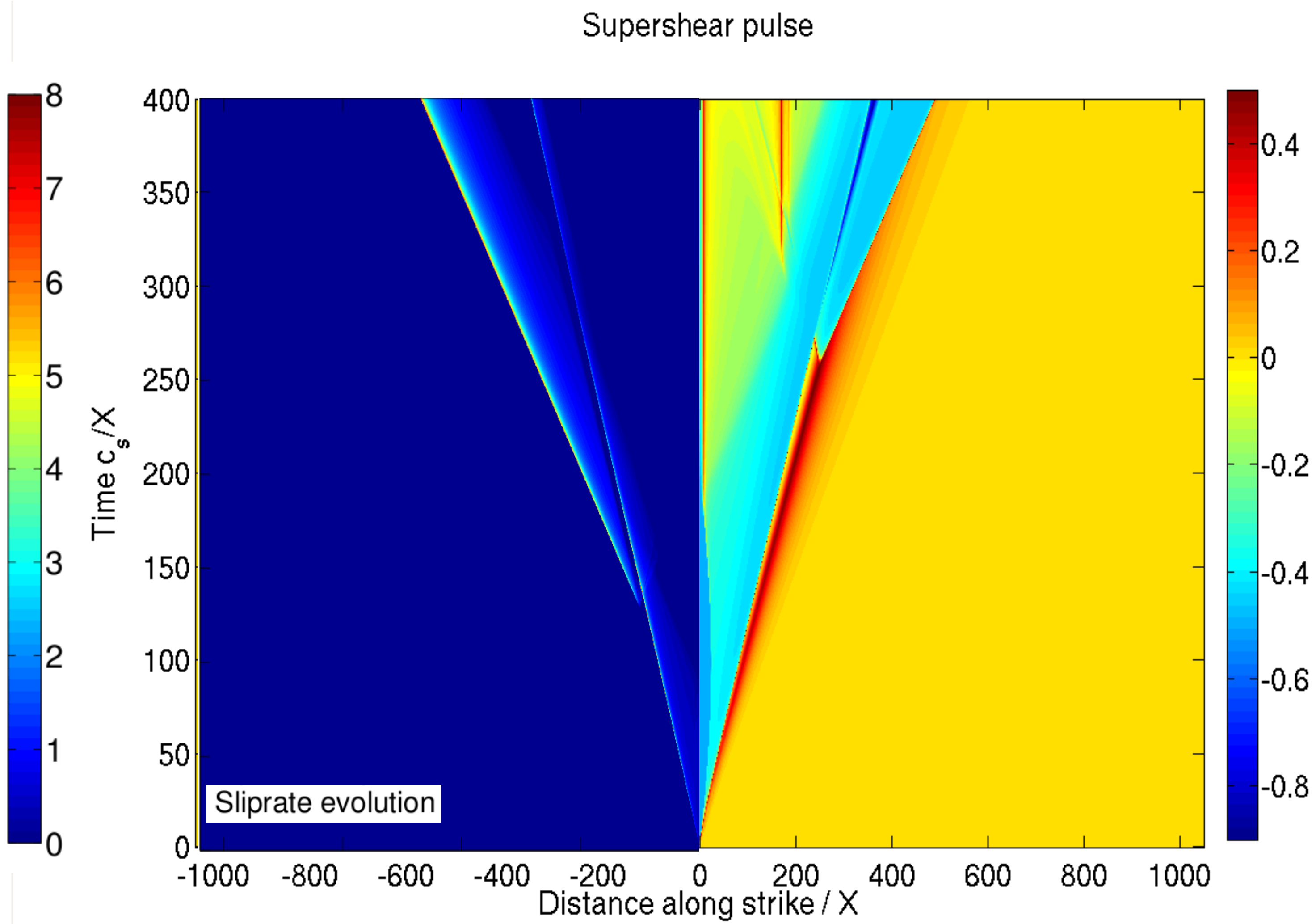
Pulse-crack transition → Gradual stress build-up at hypocenter
(Madariaga&Nielsen,2003) → Renucleation of secondary rupture



Transitional rupture modes

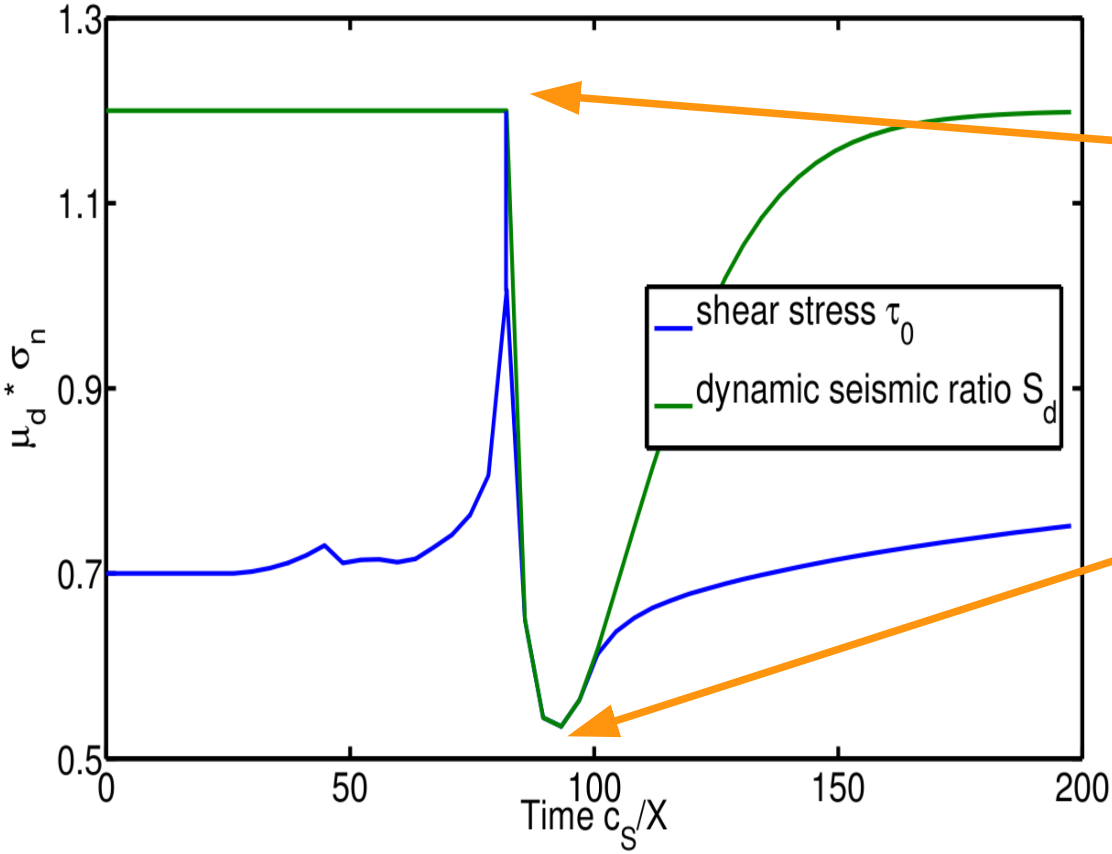
Pulse-crack transition vs **Supershear transition**

→ stress build-up at rupture front (Burridge-Andrews-Mechanism)



Dynamic seismic ratio S_d

- **Quantification** of closeness of rupture to Transitional Modes
  → **Dynamic strength excess** as part of solution
  → potentially **summarizing nucleation, initial stress & frictional** parameters



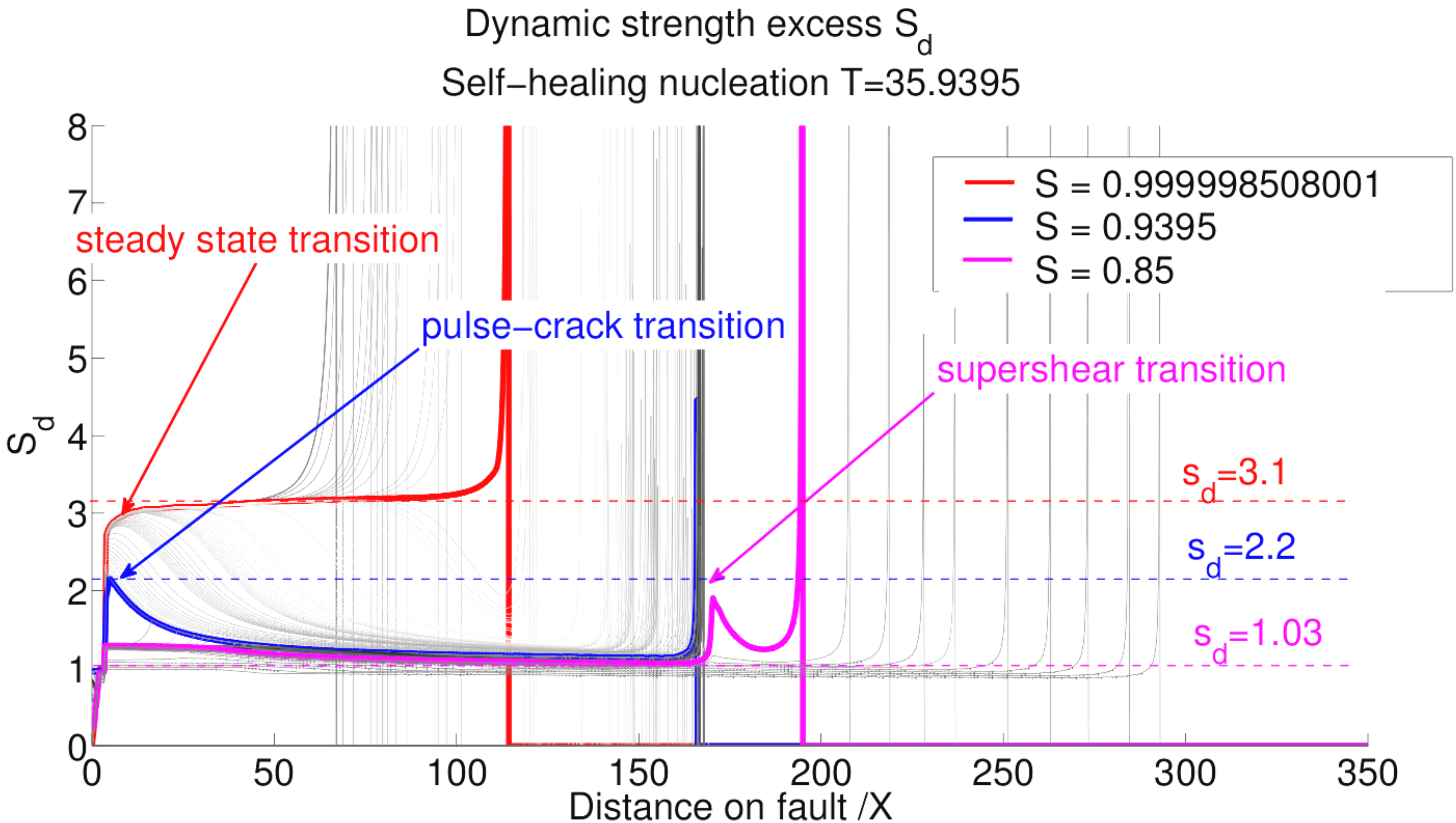
maximum shear stress initiating rupture

$$S_d = \frac{\tau_{max} - \tau_0}{\tau_0 - \tau_{min}}$$

minimum shear stress during sliding

Dynamic seismic ratio S_d

- **Quantification** of closeness of rupture to Transitional Modes



Summary

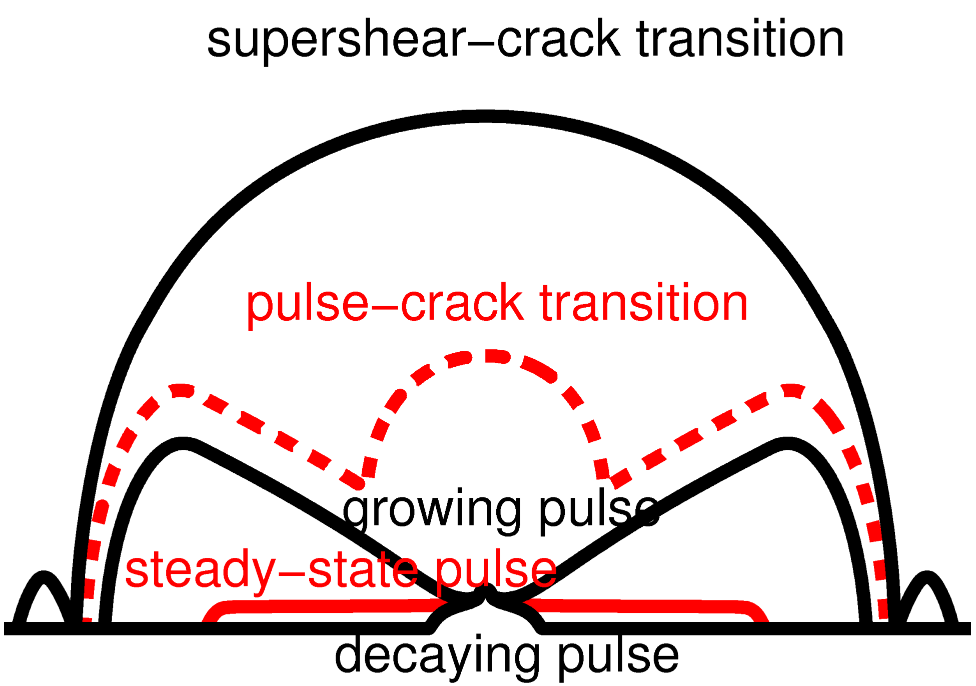
- Generalized dynamic rupture behavior in wide parameter space

  in self-similar and transitional zones of rupture between decaying , steady state , growing and crack-like ruptures

  in sub- and supershear regimes

- The asymptotic behavior of self-similar areas seems independent of the initial parameters,

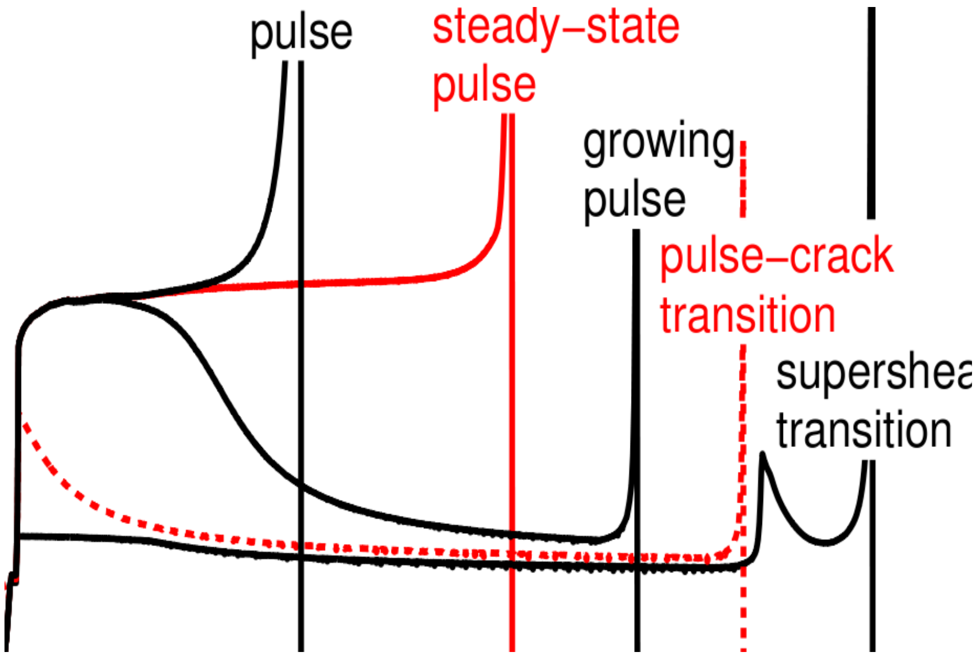
  unlike the details of the transient approach to that asymptotic solution



Summary

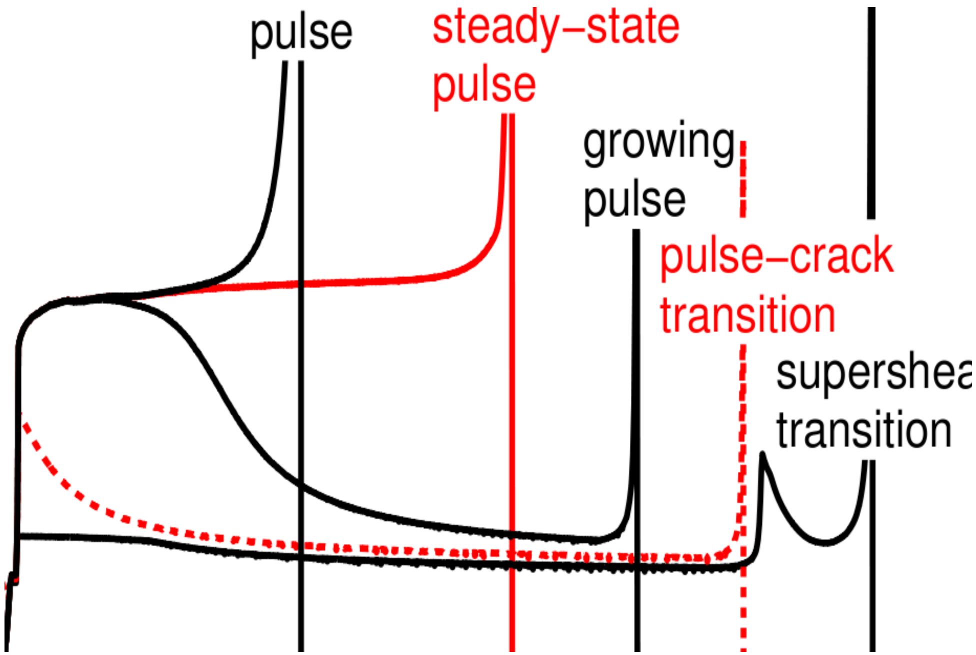
- Transitional modes are highly sensitive to initial conditions and nucleation procedure and depend on competing critical propagation length scales

- Dynamic seismic ratio S_d is quantifying the closeness of rupture mode to (supershear) transition



Summary

- Transitional modes are highly sensitive to initial conditions and nucleation procedure and depend on competing critical propagation length scales
- Dynamic seismic ratio S_d is quantifying the closeness of rupture mode to (supershear) transition



→ Under natural, non-homogeneous stress conditions, earthquakes can rupture in any dynamically stable rupture regime, or in combination of those, at sub- or supershear rupture velocities: depending on the actual dynamical stress state of the fault.

Thank you!

→ alice@sed.ethz.ch

→ For the effects of **off-fault plasticity on rupture modes and macroscopic source properties**

→ <u>POSTER: **XY499 Friday 10.30**</u>

EGU2011-11806

"Macroscopic Source Properties From Dynamic Rupture Simulations With Off-Fault Plasticity"