New Directions in Computational Earthquake Physics

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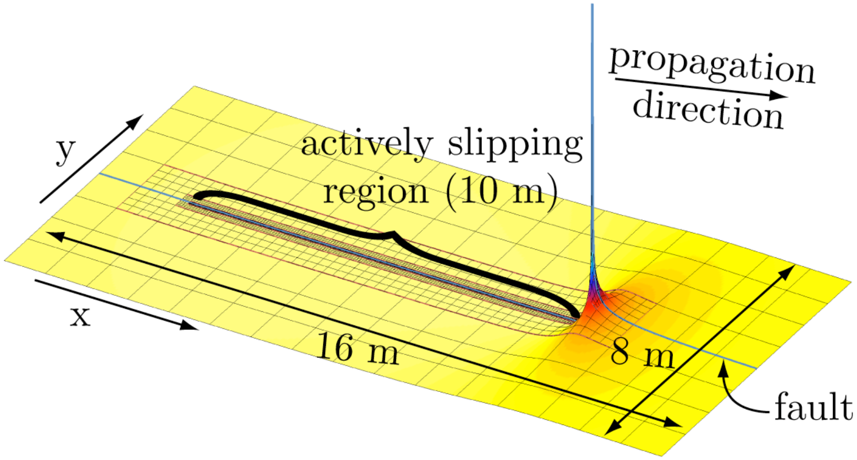
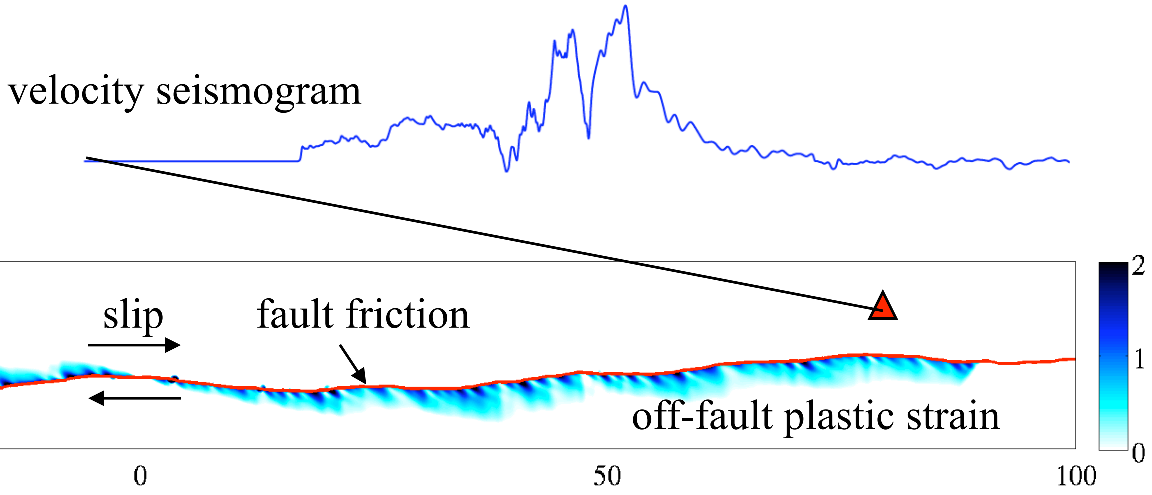
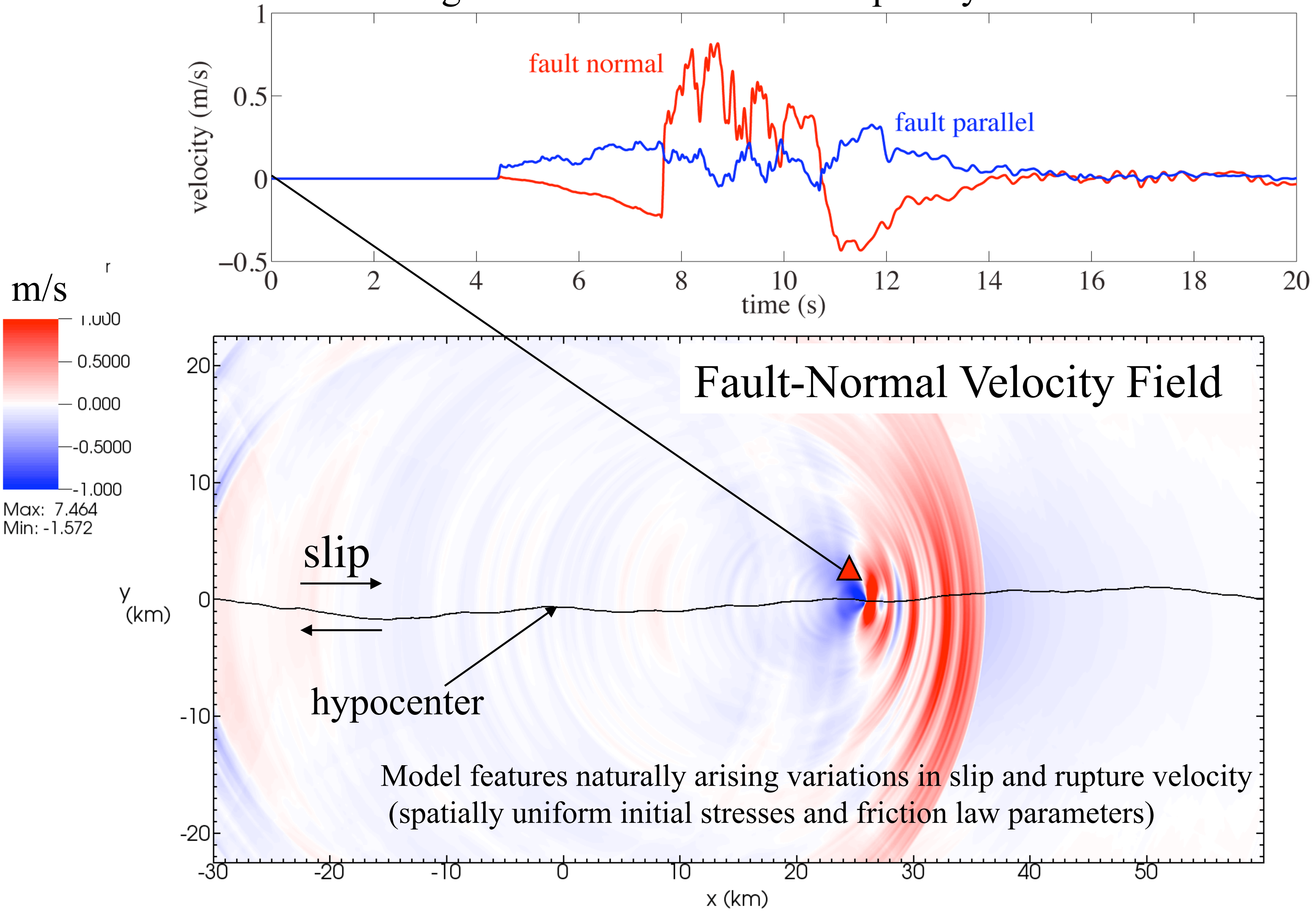
Extending SCEC's expertise in computational science from large-scale scenario earthquake simulations to more sophisticated earthquake physics

- *Small-scale fault-zone physics* (in large-scale simulations)
- *Multicycle dynamics* (self-consistent initial conditions; role of slow slip)
- *High frequency ground motion* (geometrical complexities)





Source Processes Causing Incoherent High Frequency Ground Motion: Fault Roughness and Geometric Complexity

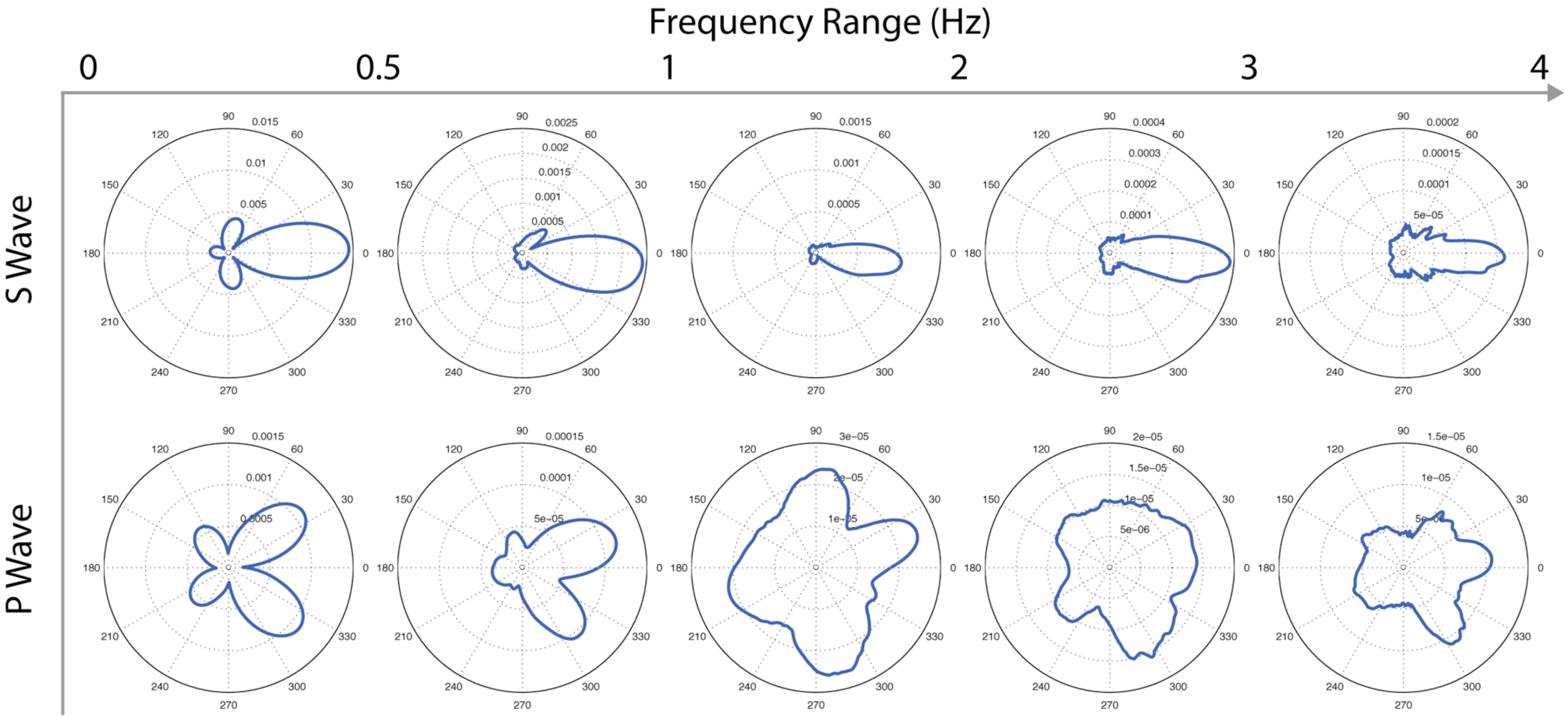


Fault-Normal Velocity Field

Model features naturally arising variations in slip and rupture velocity (spatially uniform initial stresses and friction law parameters)

[Dunham et al., 2010]

Frequency-Dependent Radiation Pattern and Directivity Effects
(In Far-Field Body Waves)

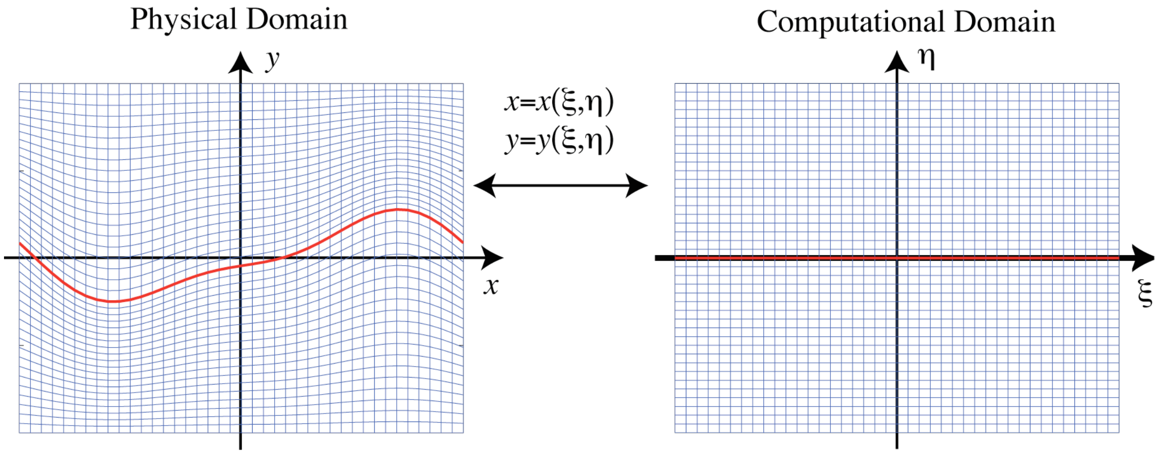


Caused by variations in local radiation pattern from nonplanarity
(*can never be captured with standard method of heterogeneous stresses on planar faults*)

[Cho and Dunham, work in progress, 2010]

Numerical Method: Simultaneous Solution of Elastodynamics and Friction Law

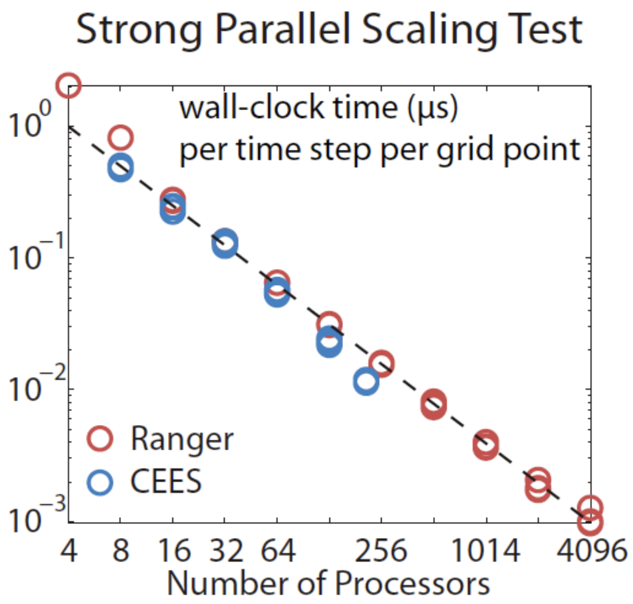
- Block-structured curvilinear meshes
- Artificial dissipation to control oscillations
- SBP+SAT finite differences
- Provably stable and high-order accurate



Parallelized FD code, currently in 2D with roughness wavelengths > 100 m (using ~100-500 cores routinely)

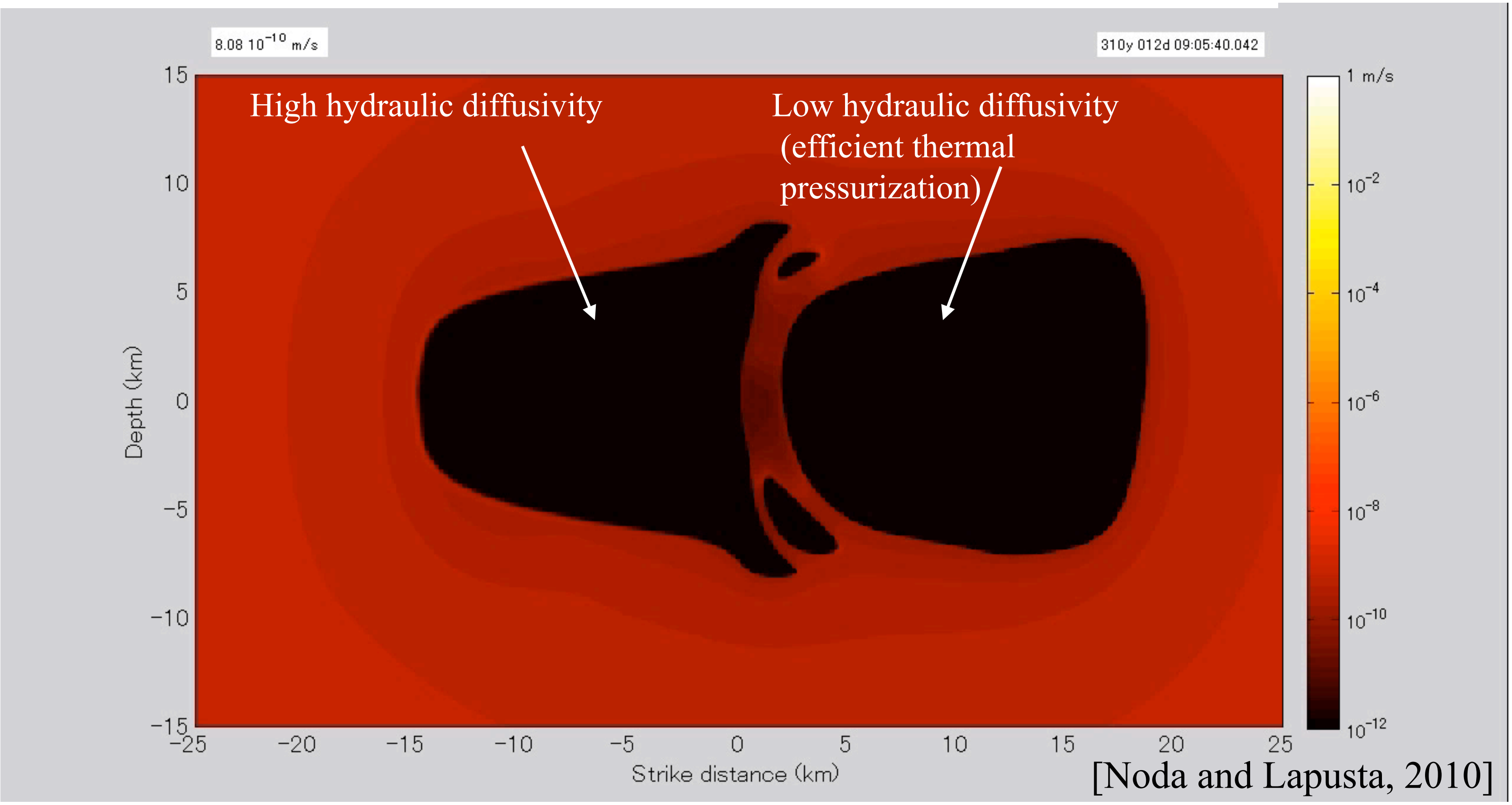
Main bottleneck now is lack of expertise visualizing large-scale simulation results

Method can be extended and coupled to unstructured finite volume mesh (for arbitrarily complex geometries) with provable stability and accuracy



Multicycle Dynamics

- Inertial dynamics as well as quasi-static loading (rate-and-state friction)
- Self-consistent initial conditions for single event simulations



High hydraulic diffusivity

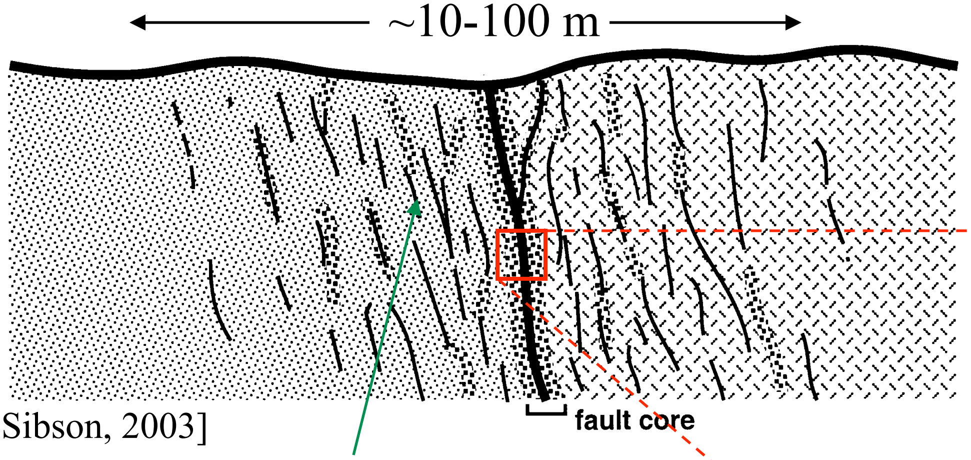
Low hydraulic diffusivity (efficient thermal pressurization)

[Noda and Lapusta, 2010]

- Current methodologies limited to simplest geometries, linear elasticity
- Computational challenge: quasi-static elasticity (equations are elliptic, not hyperbolic) requires *scalable parallel iterative solvers* for volume-discretized (FD, FE, FV) codes

Physics-Based Description of Fault-Zone Processes

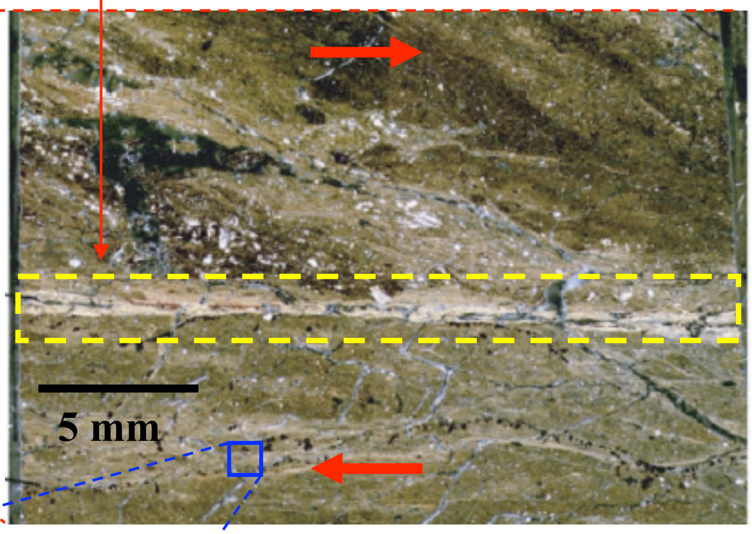
Fault strength governed by small-scale processes, many of which have only recently been introduced into dynamic rupture models (usually in idealized 2D geometries)



[Sibson, 2003]

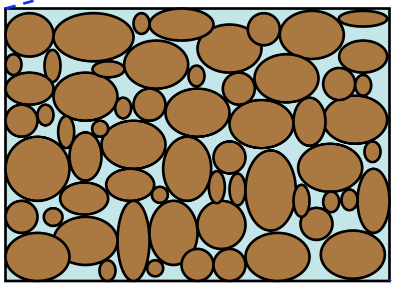
fracturing and inelastic deformation in damage zone

slip accommodated by thin shear zone (frictional heating, melting?)



[Chester and Chester, 1998]

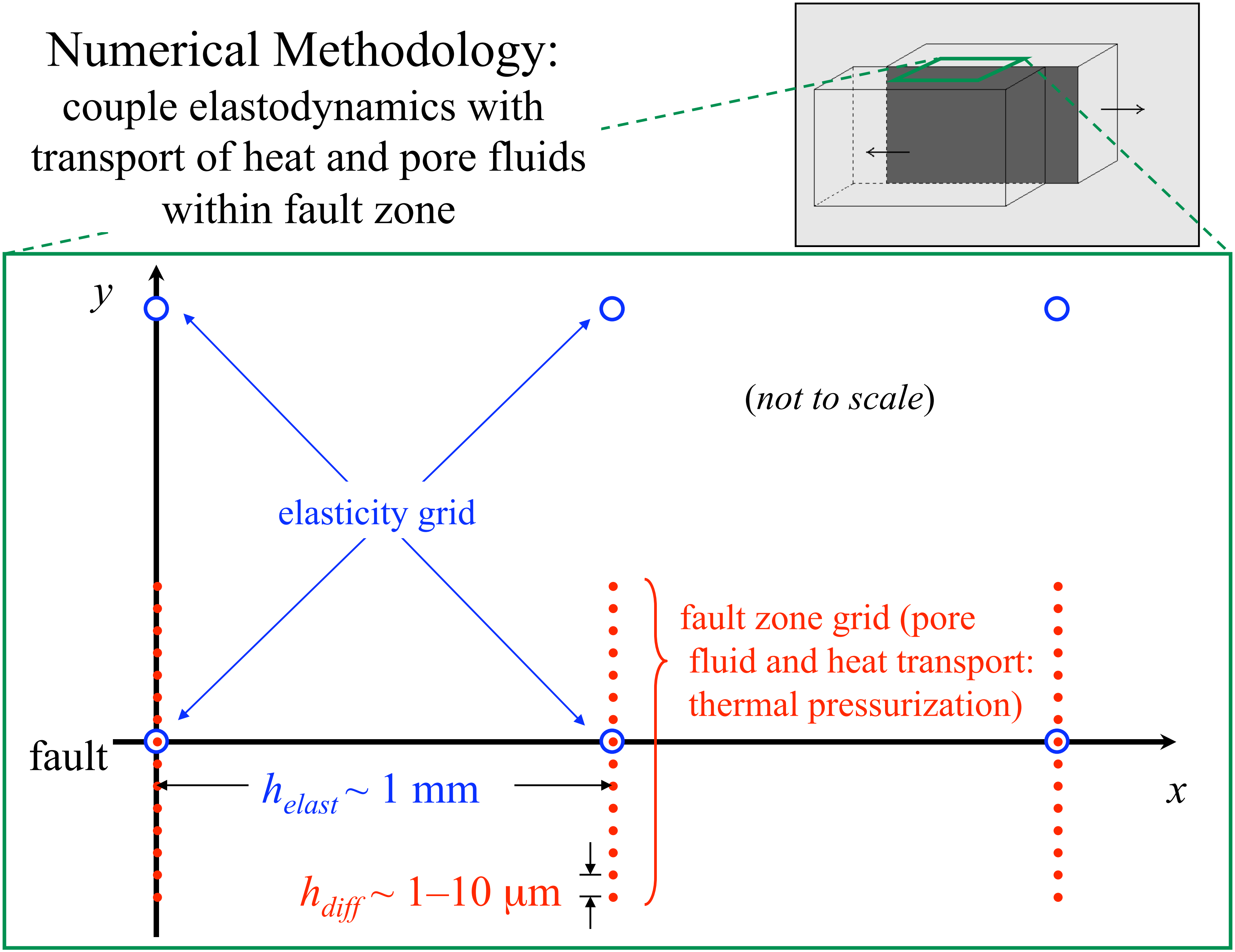
Equations describe transport of heat and pore fluids, thermodynamics of porous media, friction, etc., at scales of ~1-10 mm



fluid-saturated fault gouge (thermal pressurization of pore fluids)

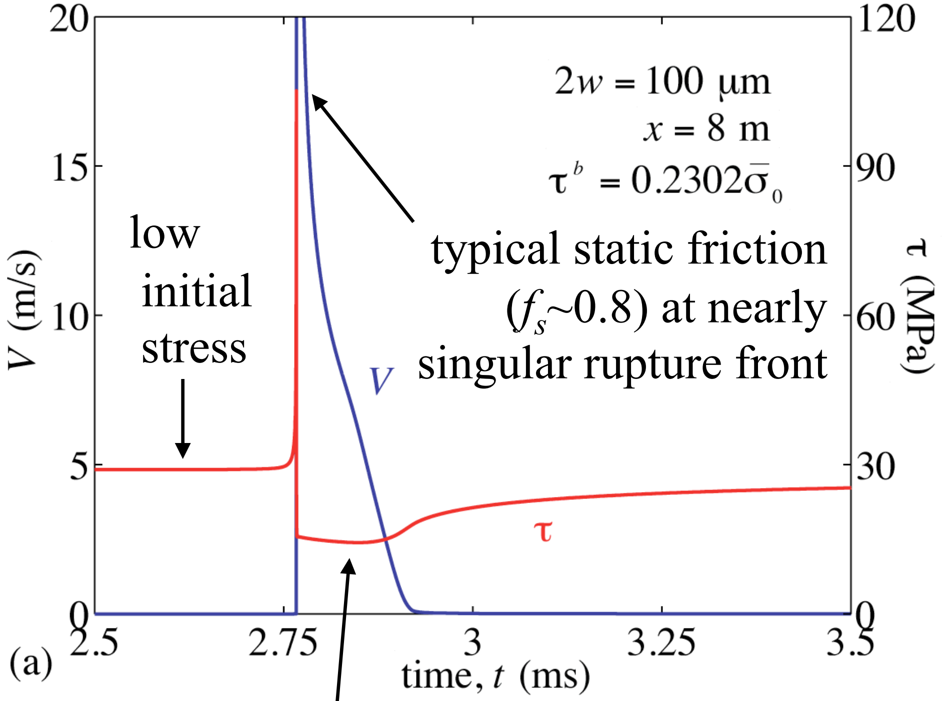
Numerical Methodology:

couple elastodynamics with transport of heat and pore fluids within fault zone



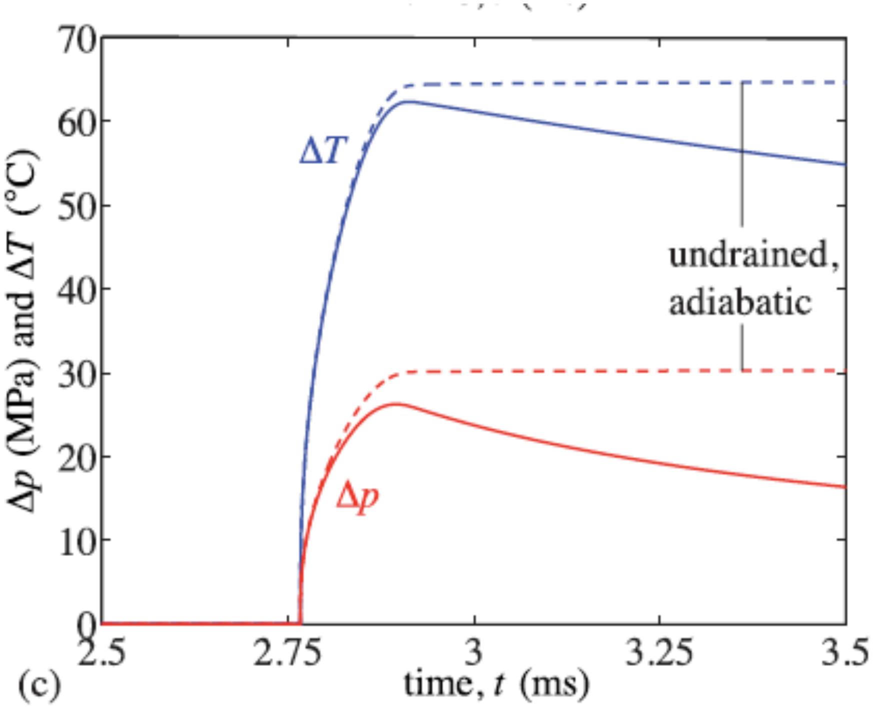
Earthquake Simulations with Dynamic Weakening

Only ~30 m propagation distance (magnitude 1-2, mapping 2D simulations to 3D) but no compromises in lab-based parameters



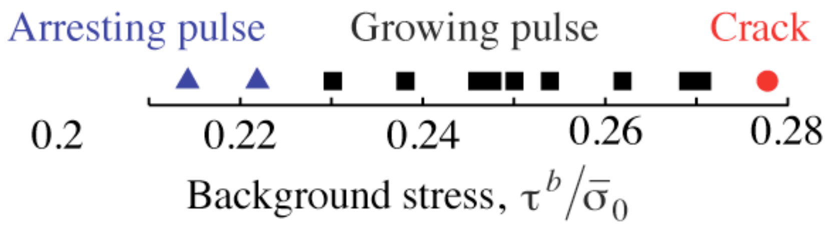
low initial stress

typical static friction (f_s~0.8) at nearly singular rupture front



low stress during slip (minimizes heat production)

Operation of mature faults (like SAF) at low stresses

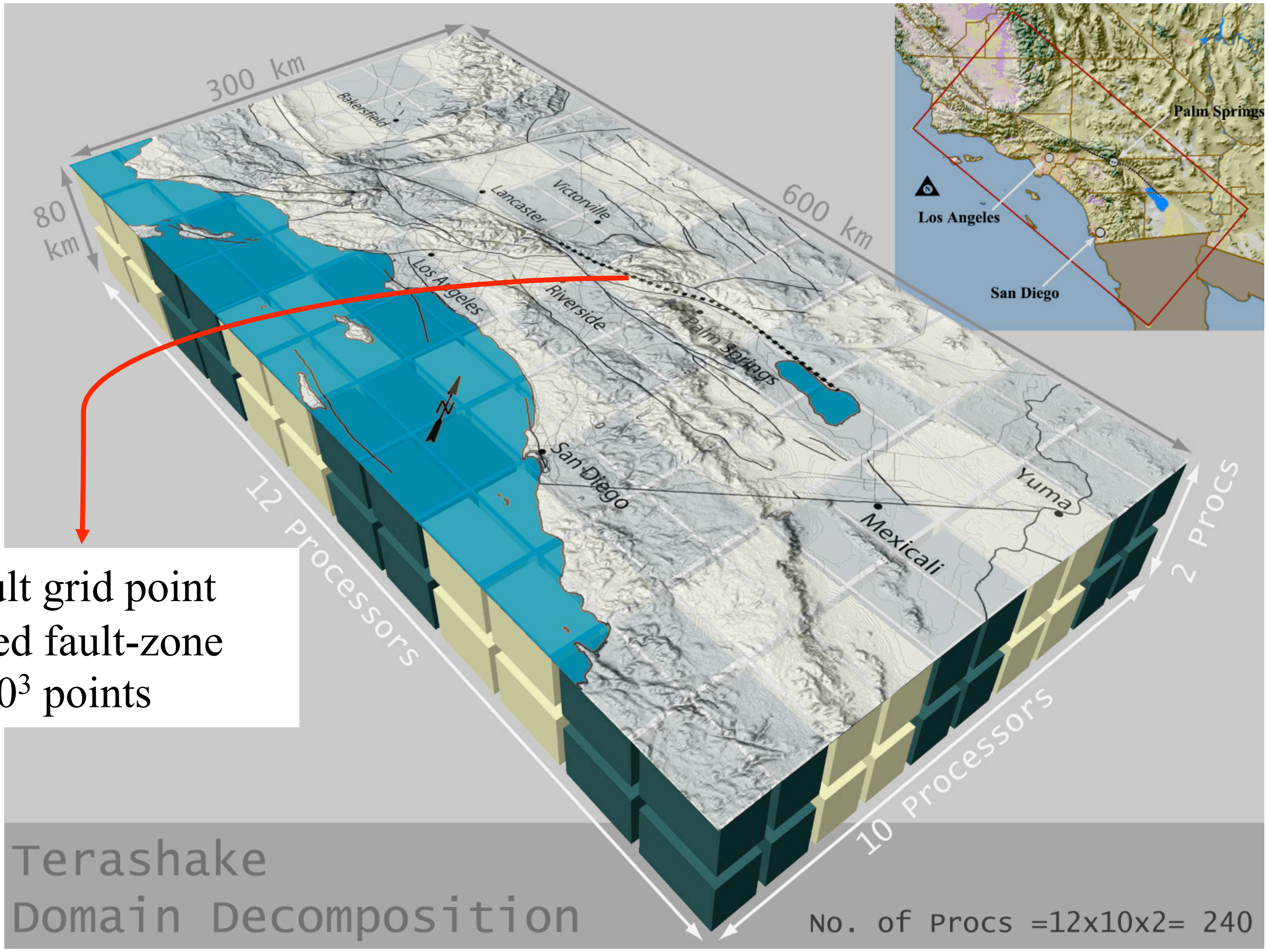


[Noda, Dunham, and Rice, 2009]

Computational Challenges

Numerical methods: Multiphysics (diffusion + wave propagation)

Load balancing: Processors holding fault have significantly higher work loads

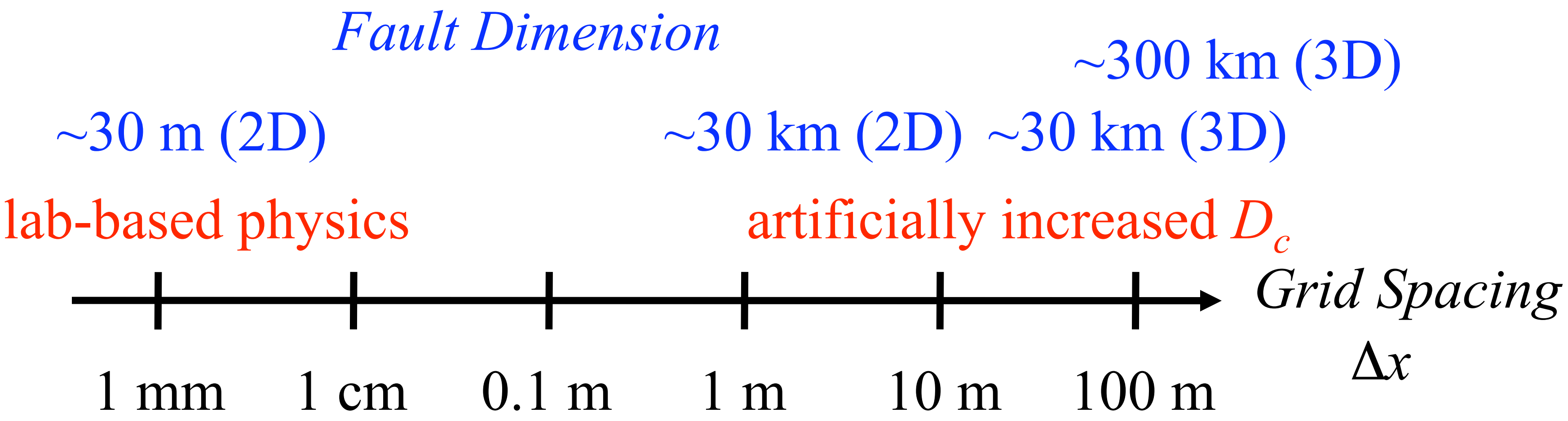


Imagine: Each fault grid point now has associated fault-zone grid with ~10^2–10^3 points

[Olsen et al., 2006]

Resolution, Resolution, Resolution

Current state-of-the-art with marginally
resolved rupture fronts on uniform grids



Fault Dimension

~300 km (3D)

~30 m (2D)

~30 km (2D) ~30 km (3D)

lab-based physics

artificially increased D_c

Grid Spacing Δx

1 mm 1 cm 0.1 m 1 m 10 m 100 m

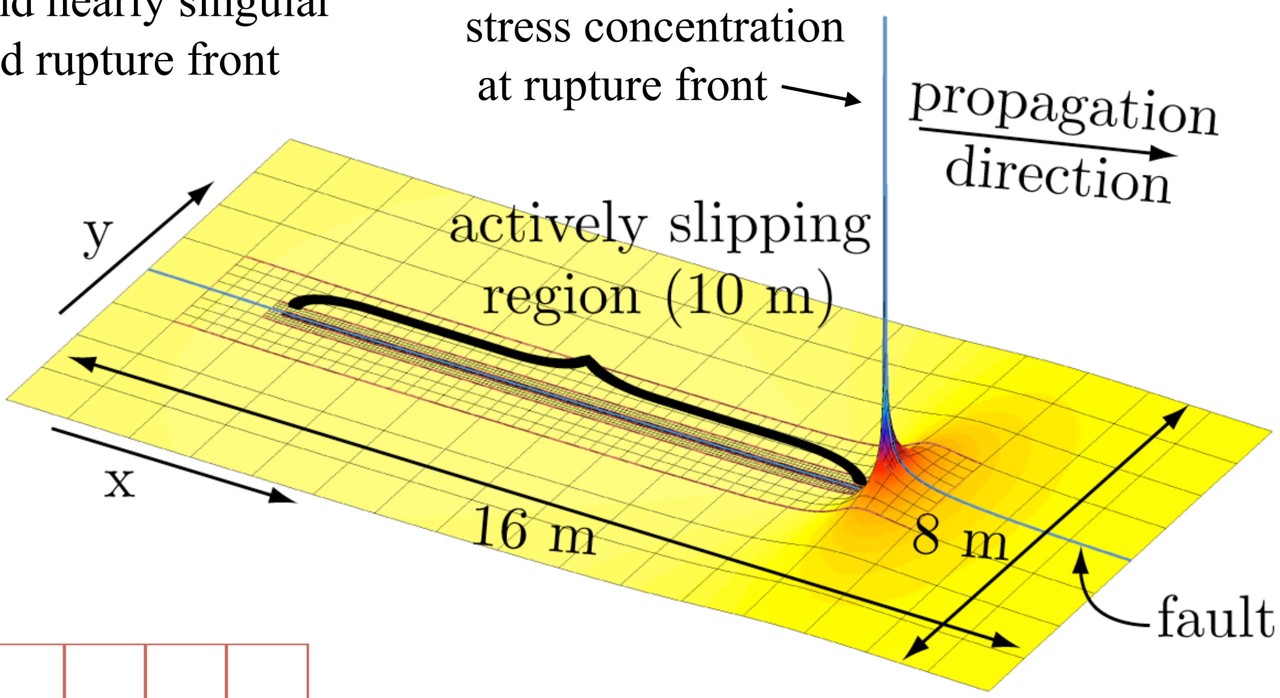
5 orders of magnitude difference!!!

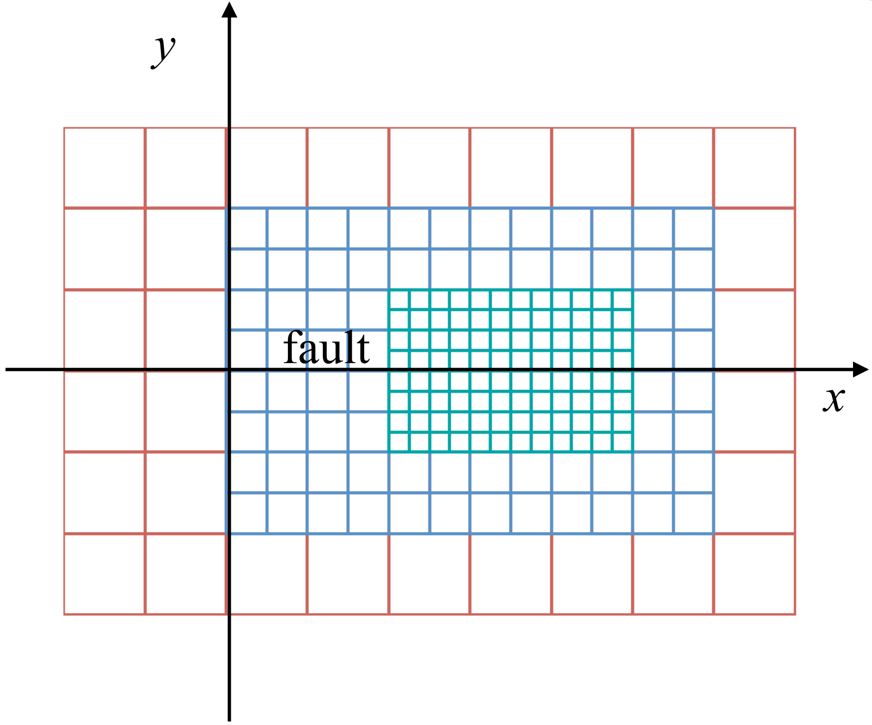
Alternative approaches:

- Parameterization of unmodeled small-scale processes
- Adaptive Mesh Refinement (AMR) to resolve rupture front and wavefronts

Adaptive Mesh Refinement

resolve sharp wavefronts and nearly singular stress/velocity fields around rupture front





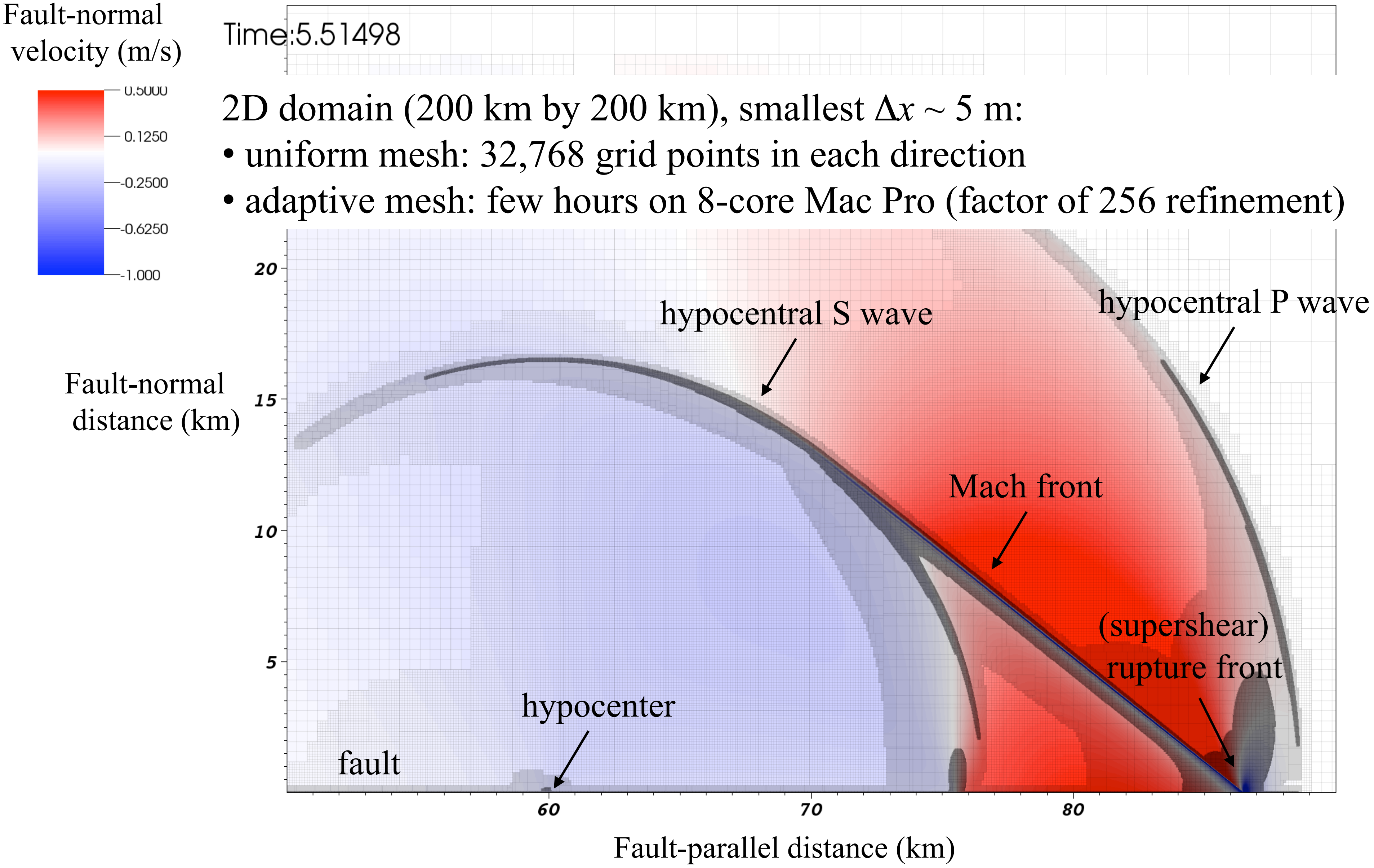
2D domain (10 km by 10 km), smallest $\Delta x \sim 1$ mm:

- uniform mesh: 10^{14} grid points
- adaptive mesh: 10^{8} grid points (identical numerical error approximating spatial derivatives)

Adaptive Mesh Refinement

2D domain (200 km by 200 km), smallest $\Delta x \sim 5$ m:

- uniform mesh: 32,768 grid points in each direction
- adaptive mesh: few hours on 8-core Mac Pro (factor of 256 refinement)



[Kozdon and Dunham, work in progress, 2010]

High frequency ground motion

- Five causes:
    - Site/Path: (1) site effects, (2) scattering off material heterogeneities
    - Source: variations in (3) slip, (4) rupture velocity, (5) local radiation pattern
- Computational tasks: Select code (options: SORD, FEM, *FDM with mapping*)
    - Our FD code scales to 4096 cores (most tested), but needs optimization
    - Add roughness waves to scale of slip in 2D
    - Extend to 3D

Multicycle simulations (quasi-static loading, dynamic ruptures)

- Currently only in BIEM codes (flat faults in uniform whole-spaces)
- Extension to general geometries and material response with FEM/FDM/FVM
- Computational tasks:
    - Optimize BIEM codes (parallel FFT)
    - Scalable parallel iterative solver for volume-discretized methods

Dynamic weakening mechanisms and detailed fault-zone models

- Thermal pressurization, velocity-weakening friction, off-fault plasticity
- Computational tasks:
    - Load balancing or enlisting off-fault processes to help update fault physics
    - AMR to resolve nearly singular fields at rupture front