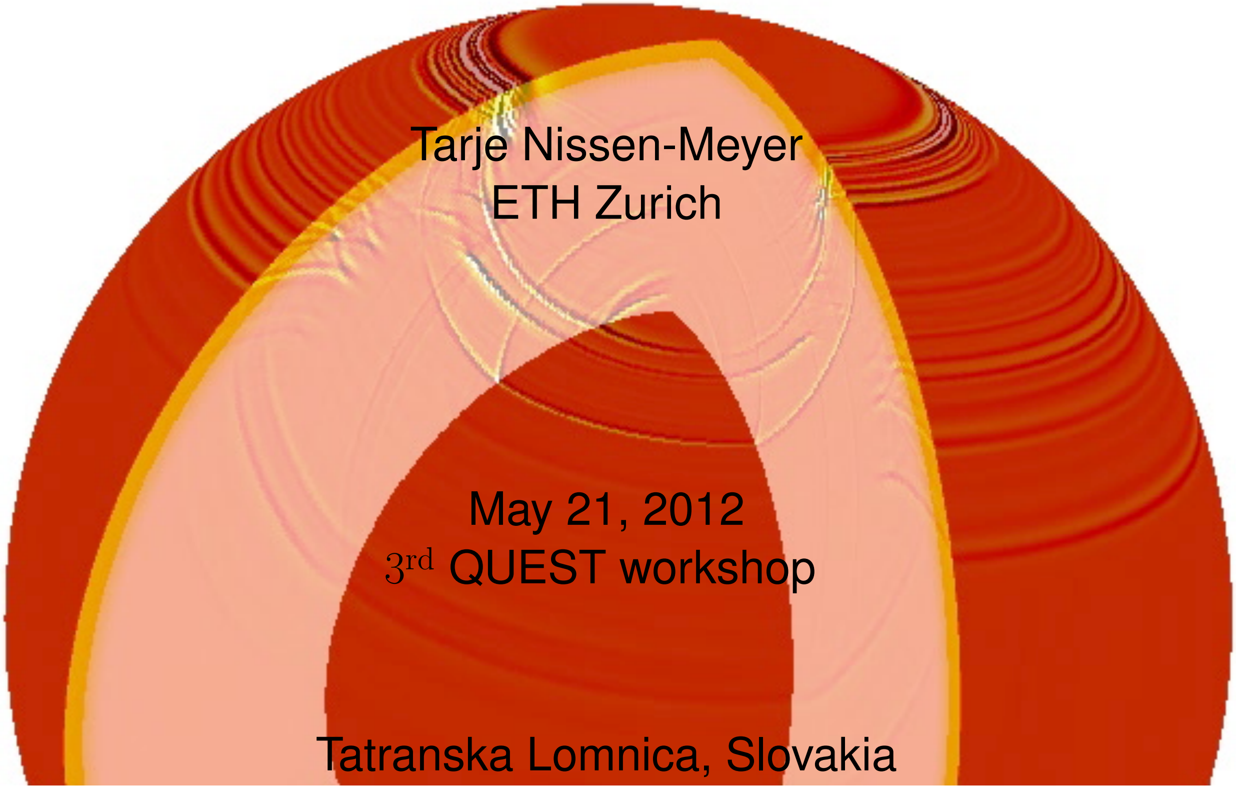
Forward modeling

A hang/hands - on/over tour of seismic wave propagation

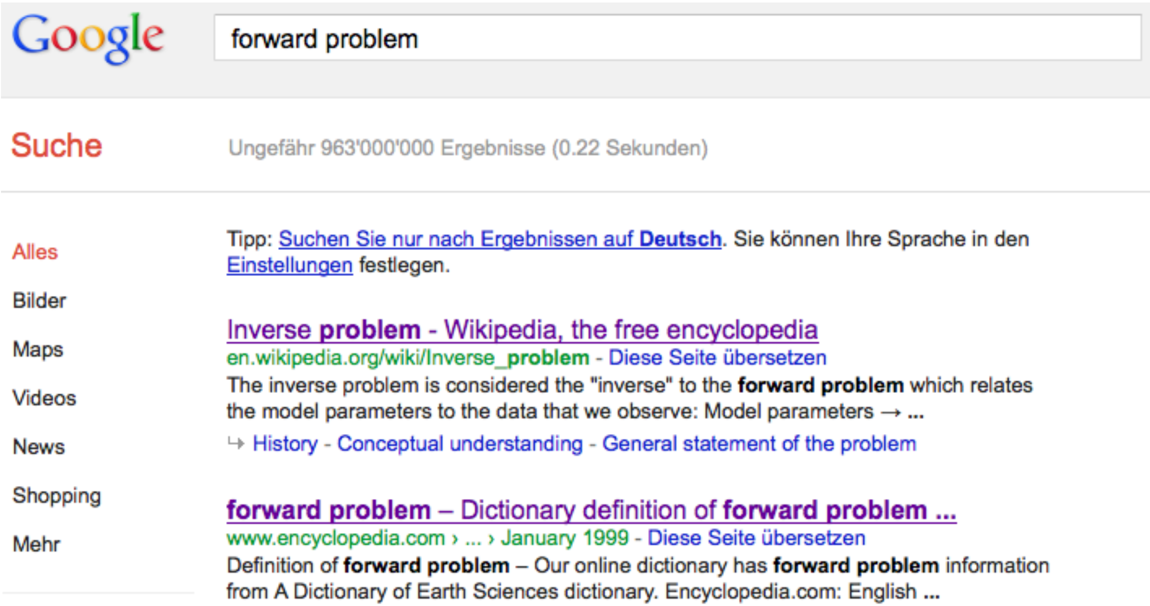


Tarje Nissen-Meyer
ETH Zurich

May 21, 2012
3rd QUEST workshop

Tatranska Lomnica, Slovakia

The forward problem


Google

forward problem

Suche

Ungefähr 963'000'000 Ergebnisse (0.22 Sekunden)

Alles

Bilder

Maps

Videos

News

Shopping

Mehr

Tipp: Suchen Sie nur nach Ergebnissen auf **Deutsch**. Sie können Ihre Sprache in den Einstellungen festlegen.

Inverse **problem** - Wikipedia, the free encyclopedia

en.wikipedia.org/wiki/Inverse_**problem** - Diese Seite übersetzen

The inverse problem is considered the "inverse" to the **forward problem** which relates the model parameters to the data that we observe: Model parameters → ...

↳ History - Conceptual understanding - General statement of the problem

forward problem – Dictionary definition of **forward problem** ...

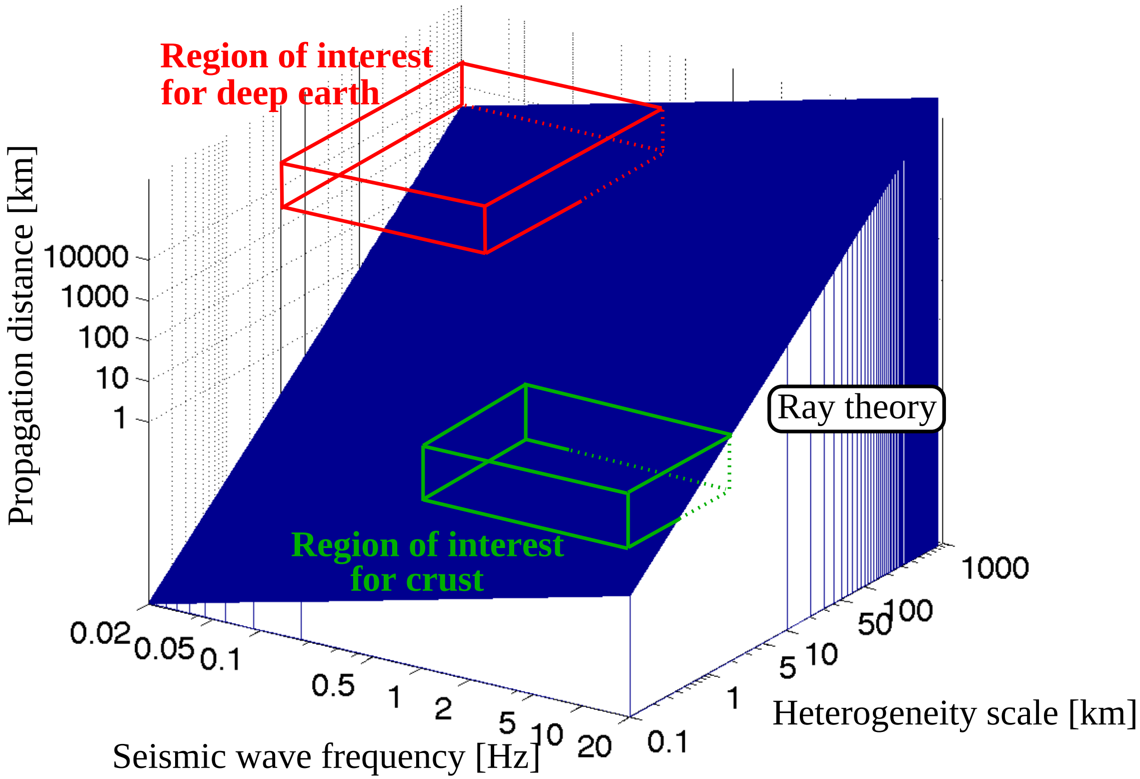
www.encyclopedia.com › ... › January 1999 - Diese Seite übersetzen

Definition of **forward problem** – Our online dictionary has **forward problem** information from A Dictionary of Earth Sciences dictionary. Encyclopedia.com: English ...

The possibility of conveniently solving non-linear inverse problems will then depend on the possibility of solving the forward problem a large enough number of times.

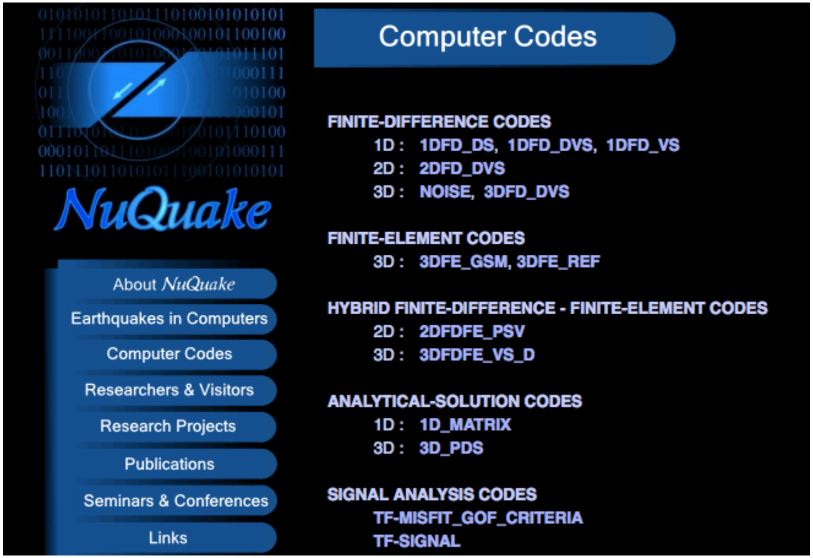
Tarantola & Valette, 1982.
Inverse Problems = Quest for Information, J. Geoph.

Scales of waves and structure



Code availability

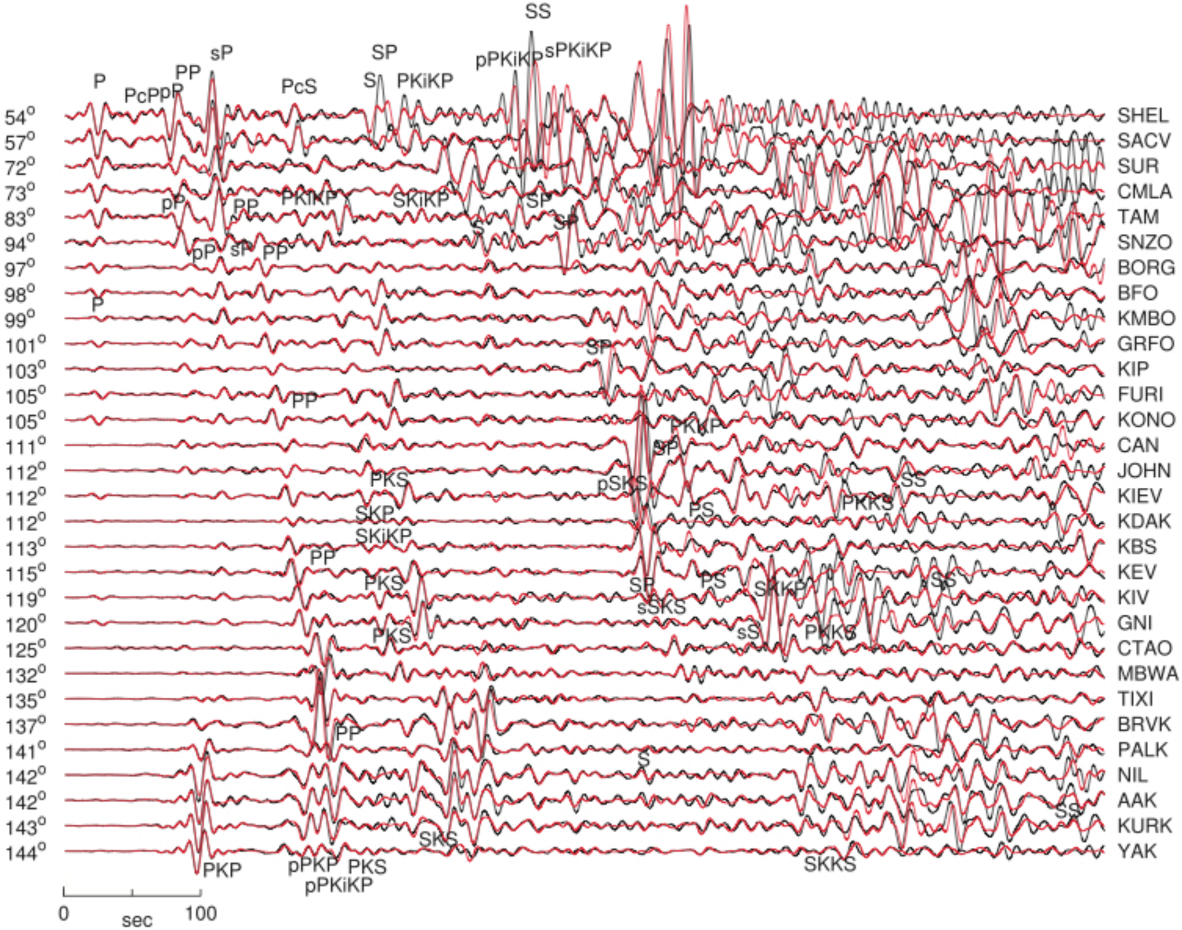
SPICE legacy: Code libraries, quantitative comparison



Comenius University, Slovak Academy of Sciences

We're all done.

SPECFEM GLOBE vs data (*Tromp et al., 2010*)



Wait a minute...who's paying the bill?

Seismic computability

Computability:

Algorithmic solution in an effective manner

What are bandpass and error constraints in data and model?

$\hookrightarrow$ signal-to-noise in data

$\hookrightarrow$ target resolution

Can I simulate?

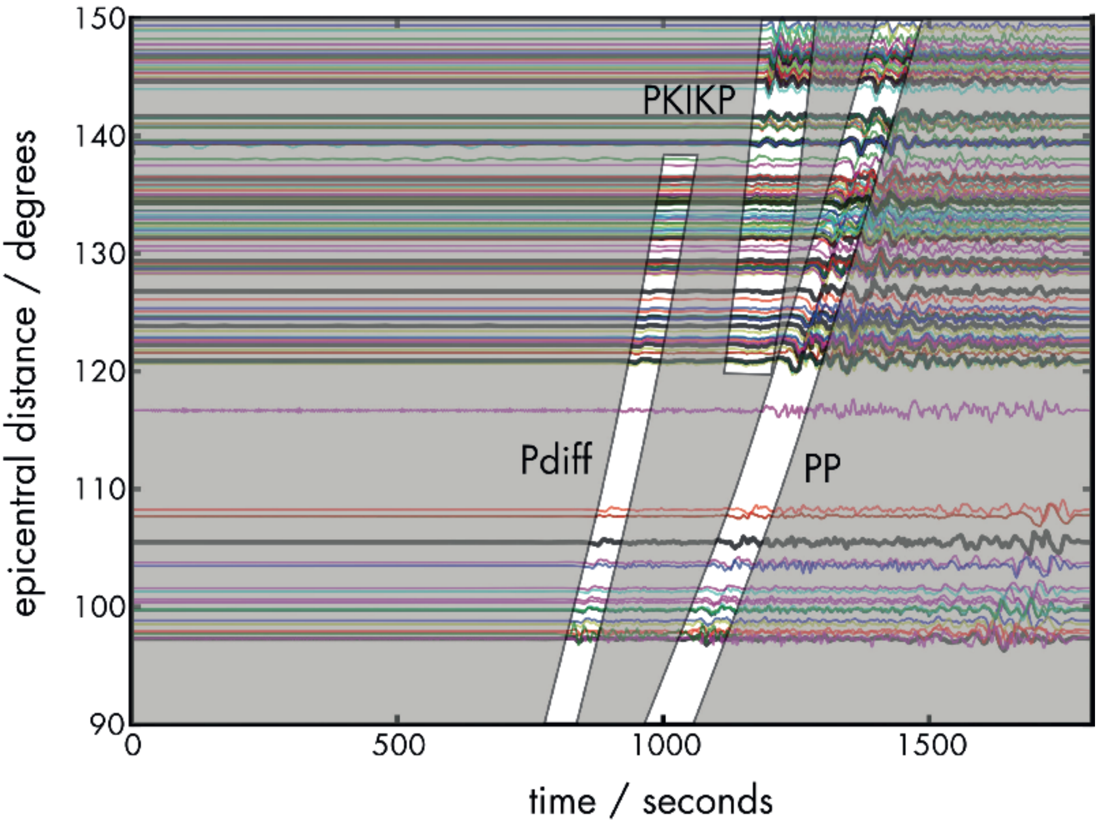
$\hookrightarrow$ possible & necessary accuracy of forward & inverse modeling

Two fundamental issues at large:

Computational cost of realistic scenarios

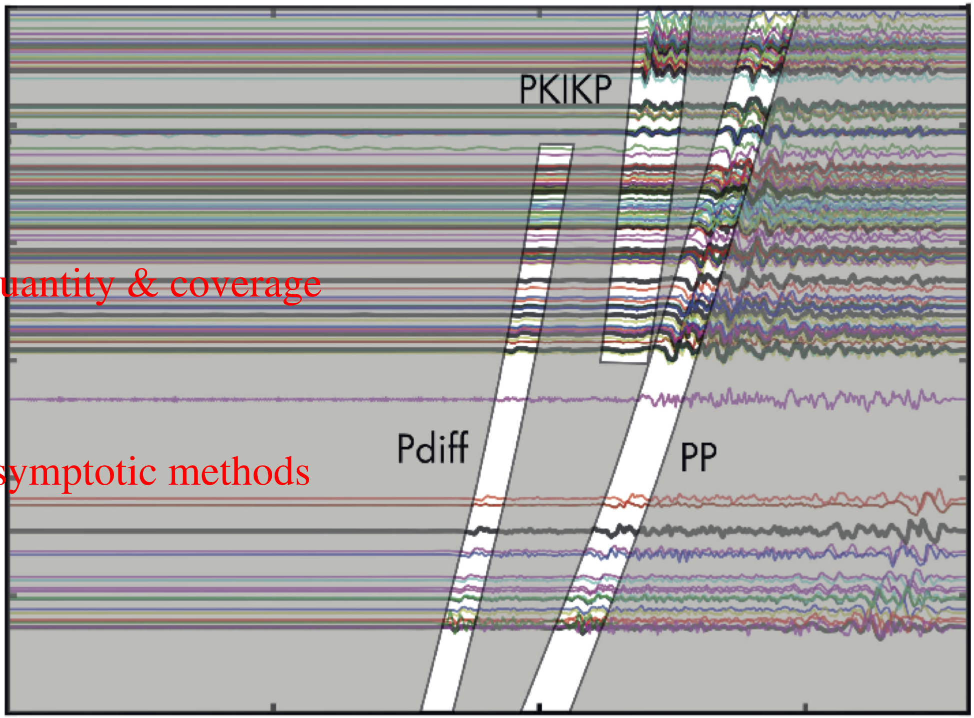
Reliability of assumptions on source and model parameters

Seismologist's veins & viewpoints



↪ maps to source radiation & Earth structure
↪ links to geodynamics (temperature, composition) via mineral physics
↪ links to geology (hydrocarbon deposits) via stratigraphy

Seismologist's veins & viewpoints



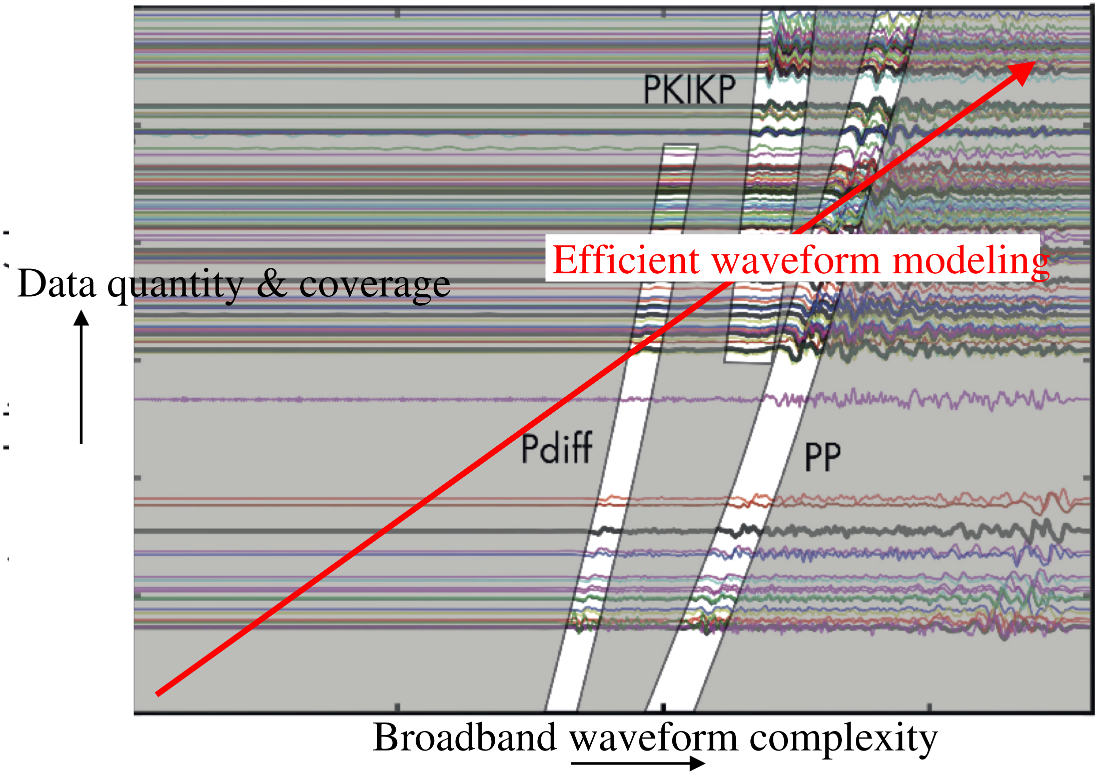
Data quantity & coverage

Fast asymptotic methods

Broadband waveform complexity

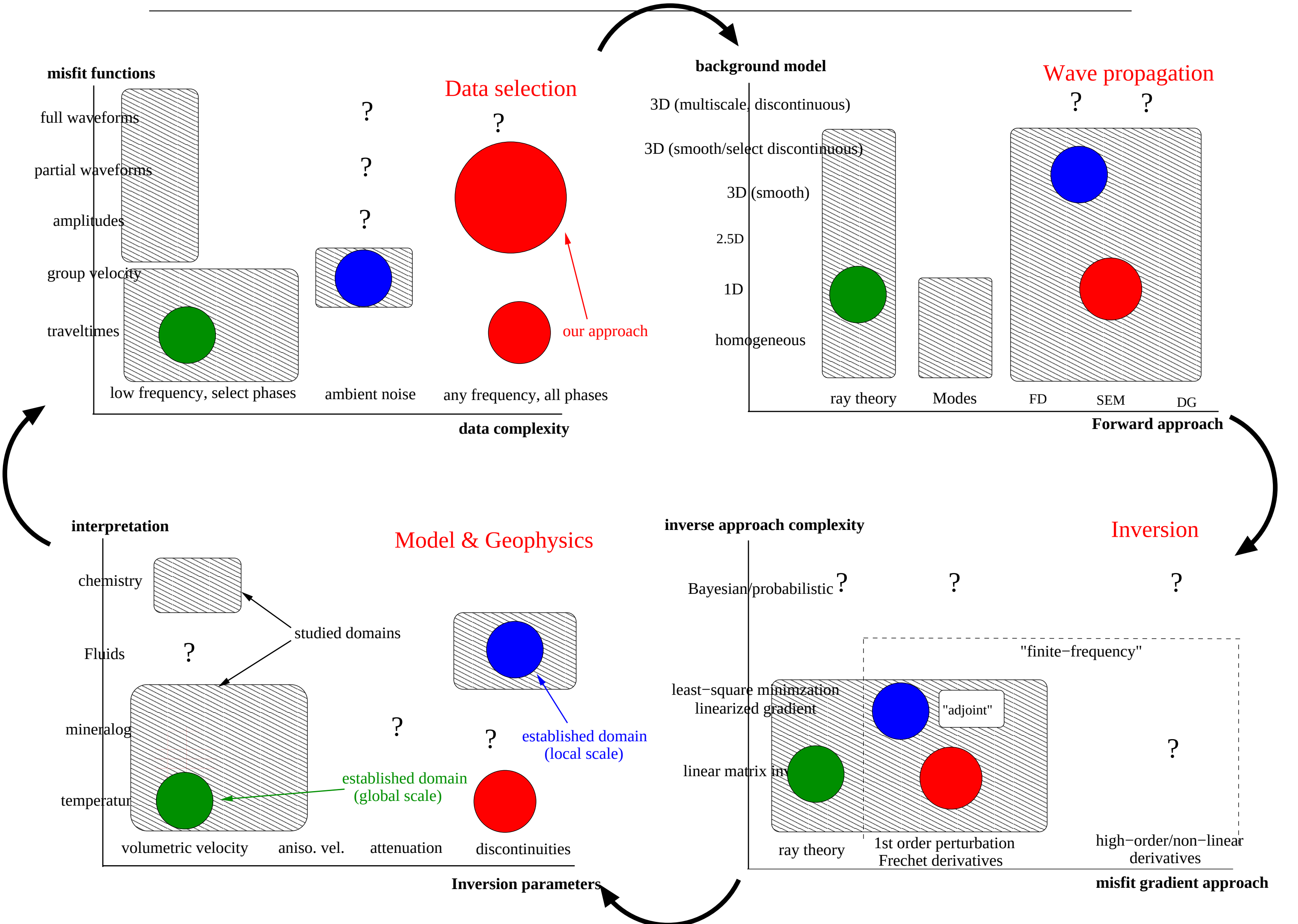
Full 3D waveform modeling

Seismologist's veins & viewpoints



↪ Maximize data computability in time, frequency, quantity

... a spatially downward spiral?



Computational accelerators

data-space: infinite frequencies, direct waves

model-space: 1D/2.5D models, weak/localized heterogeneities

data-model relations: effective media, upscaling, far-/near-field

hardware-tailored software: GPU, stencil tuning

accuracy: forward/inverse error quantification, data noise

methodology: local timestepping, flexible meshing, polygrid

interpretation: "extrapolating experience"

Overview

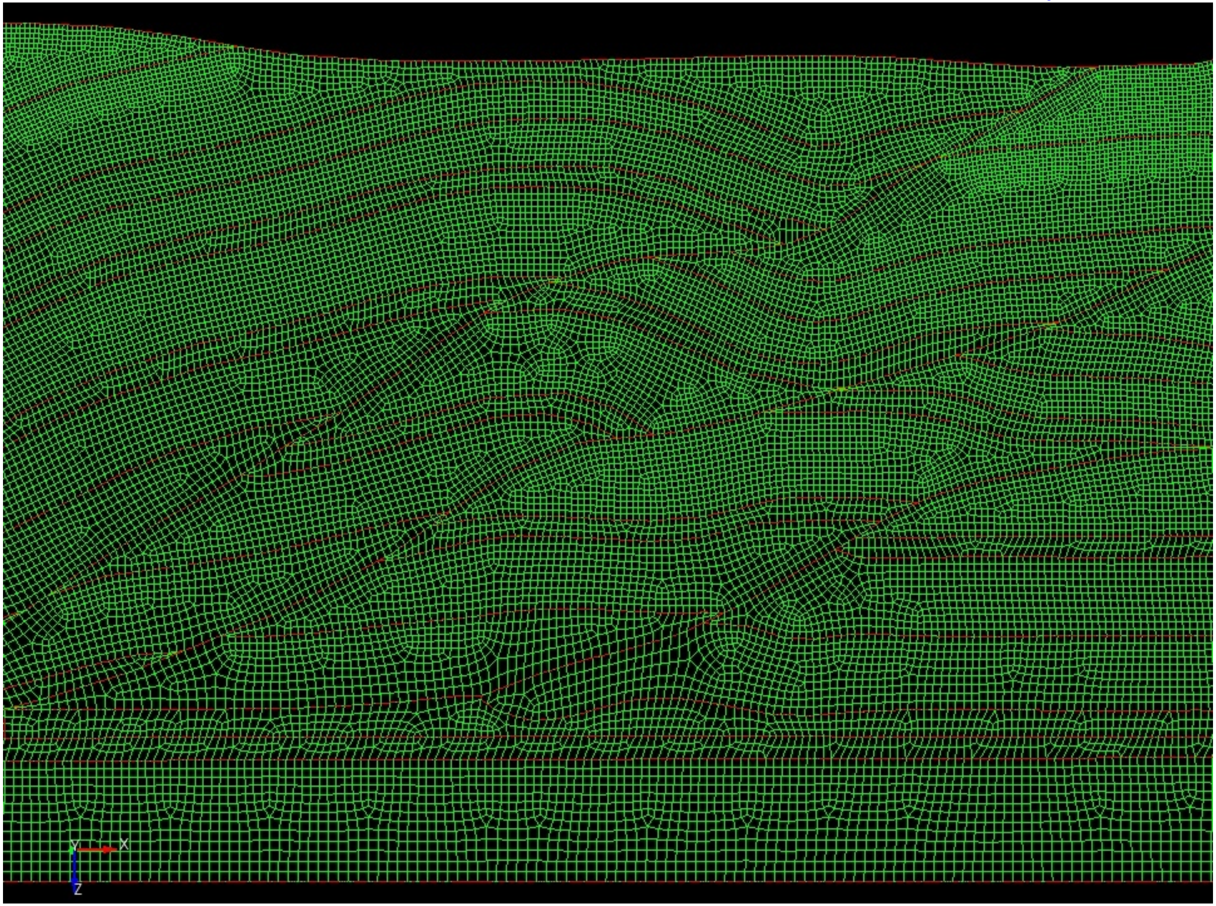
1. **Models: Chang Su (& village de Capdeville)**
   (a) **Meshing complex domains**
   (b) **Up-/Downscaling (Homogenization session)**
   (c) **Dependency on a priori information**

2. **Accelerators: Martin v. Driel, Yder Masson**

3. **Parametors: noone and everyone?**

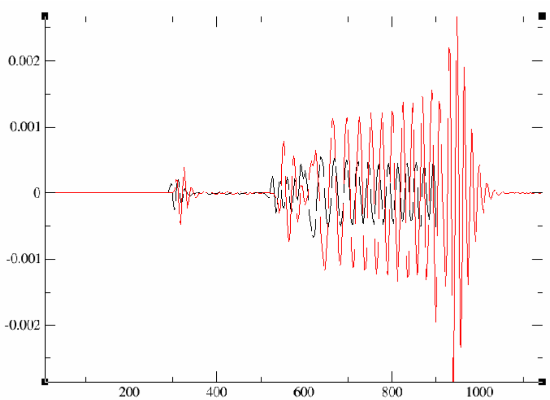
... says Earth*: Accept my faults!

* in Bayes' view

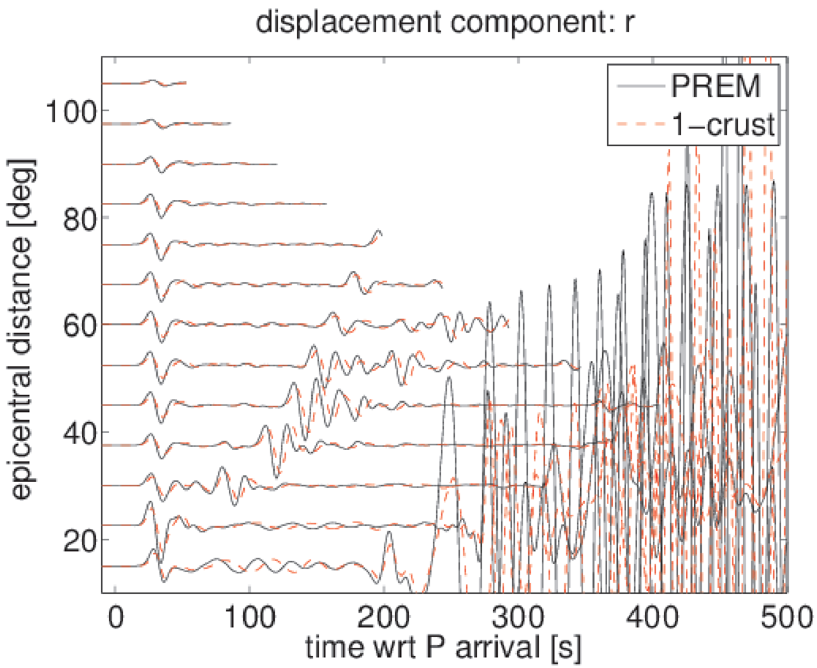


☞**Chang Su: Polygrid for heterogeneous domains** ☜

Source & crustal assumptions



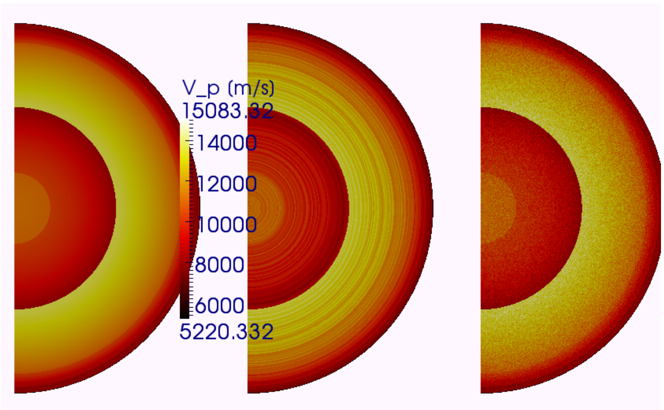
source mislocation 20 vs 28km

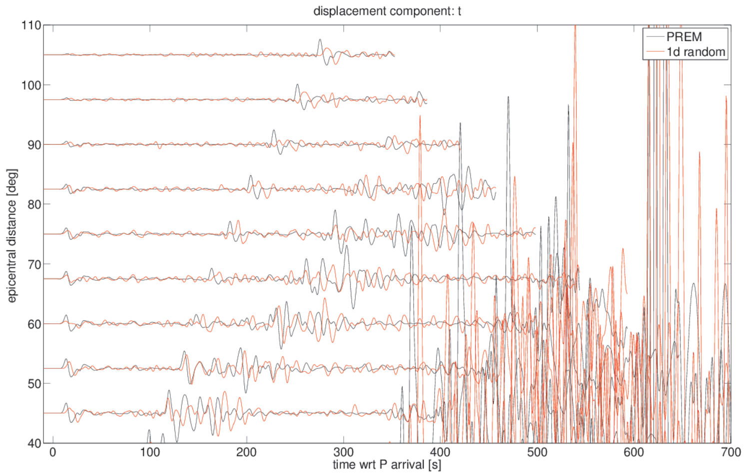


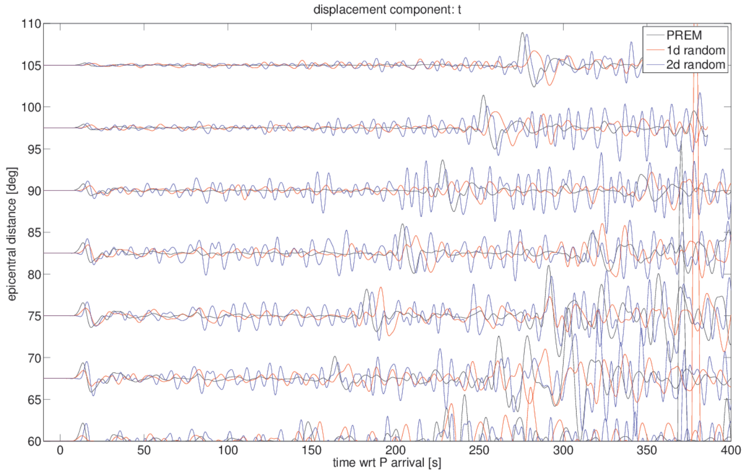
PREM crust vs. one crustal layer

☞ Whence the source of trouble? ☜

Global structural model







PREM v_p (left) superimposed with random v_p variations up to ±5% in 1D (middle),and up to ±10% in 2.5D (right).

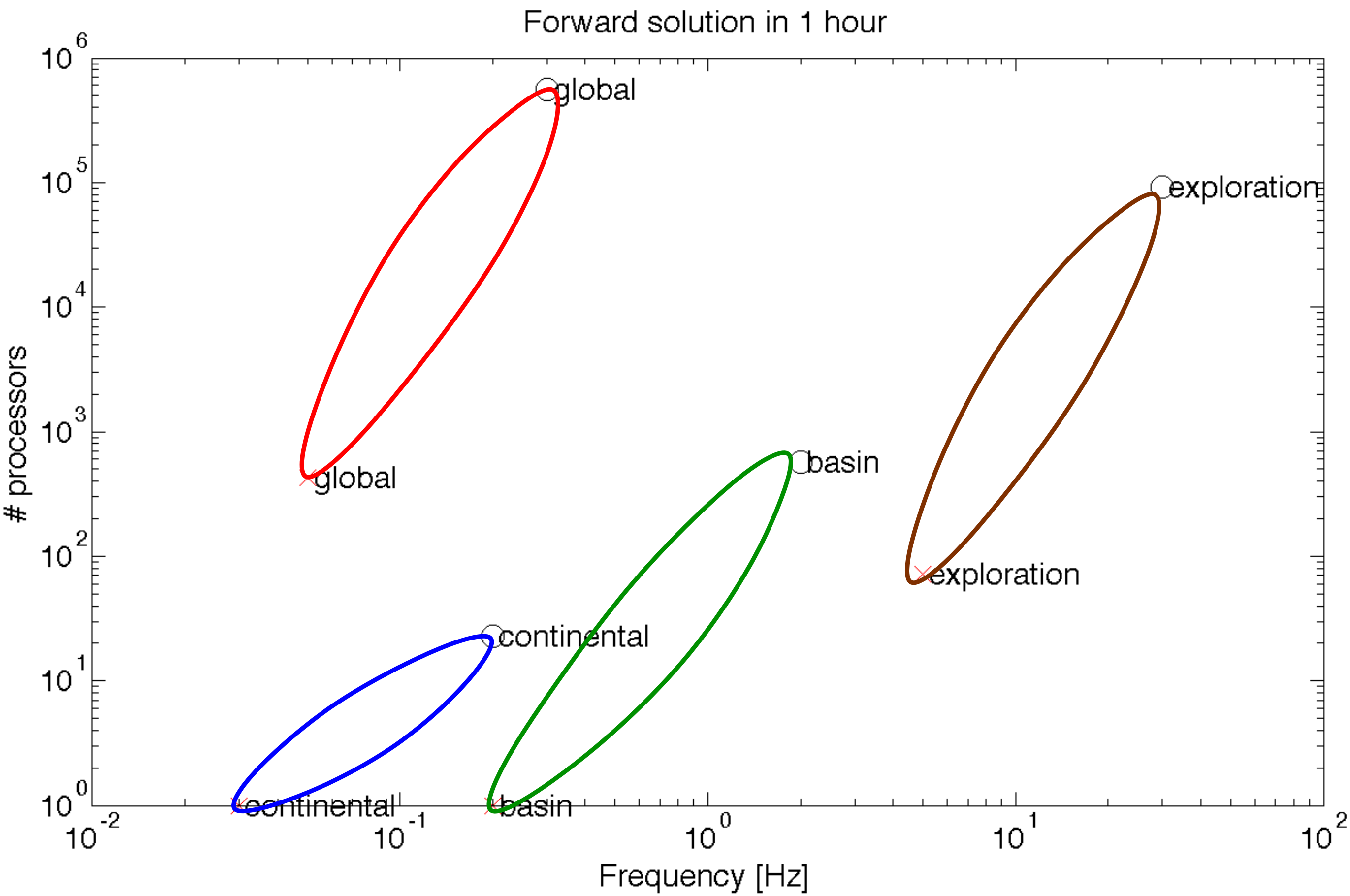
Overview

1. Models: Chang Su (& village de Capdeville)

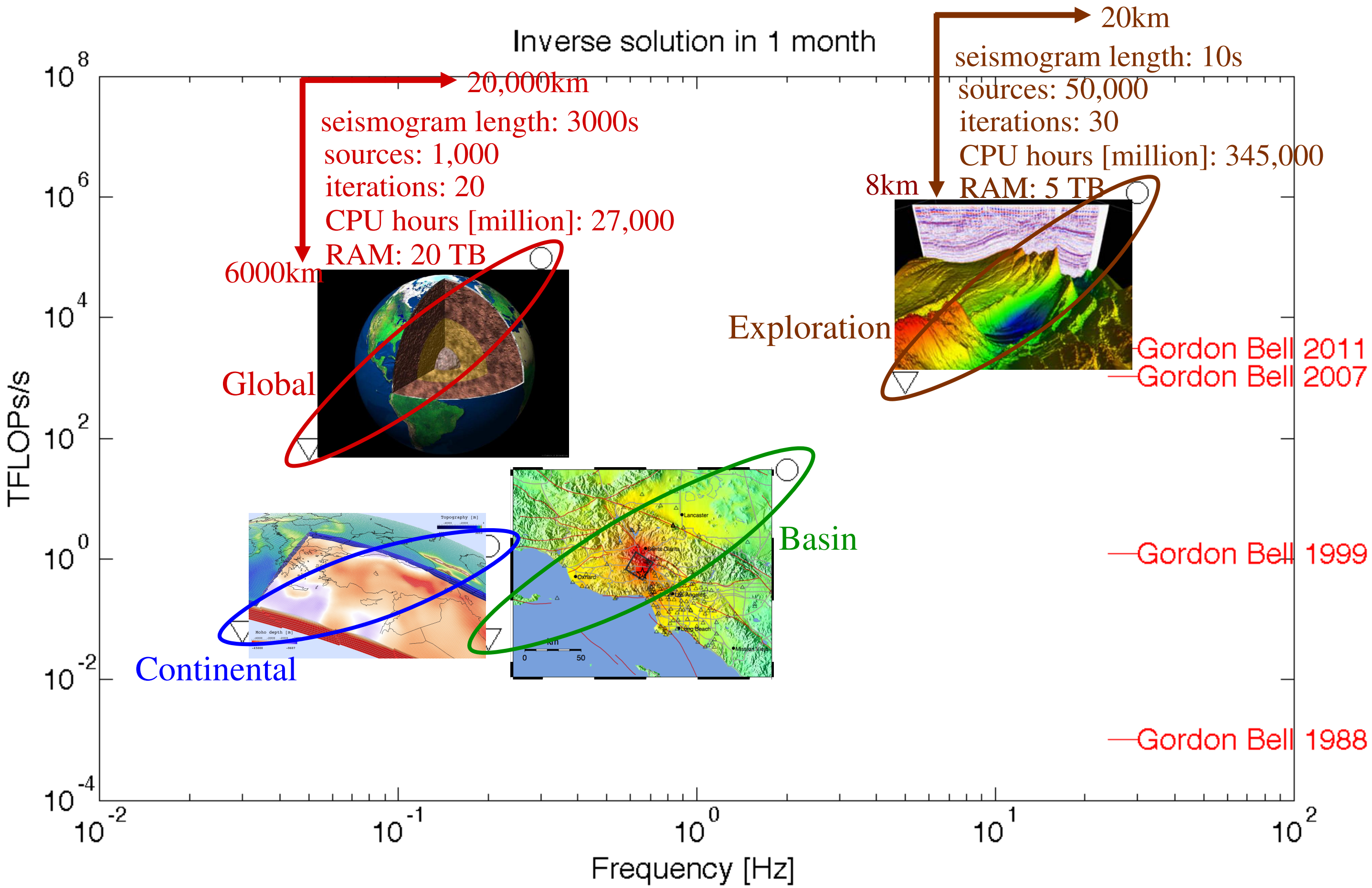
2. Accelerators: Martin v. Driel, Yder Masson
   (a) Computational cost
   (b) Exploiting model-/data-space complexity
   (c) GPU hardware
   (d) (FD stencil autotuning, local timestepping)

3. Parameters: noone and everyone?

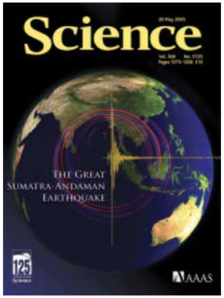
Computational cost: forward

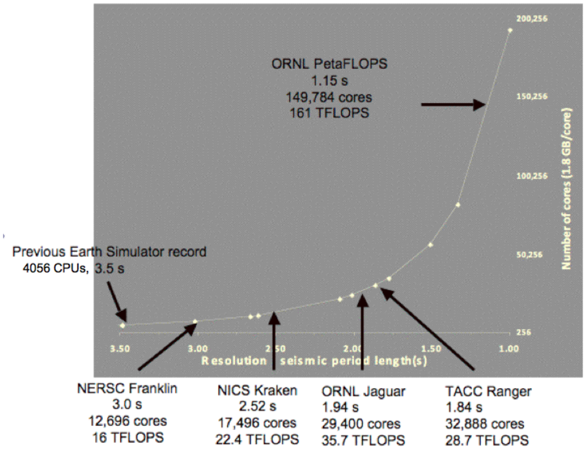


Computational inverse challenges

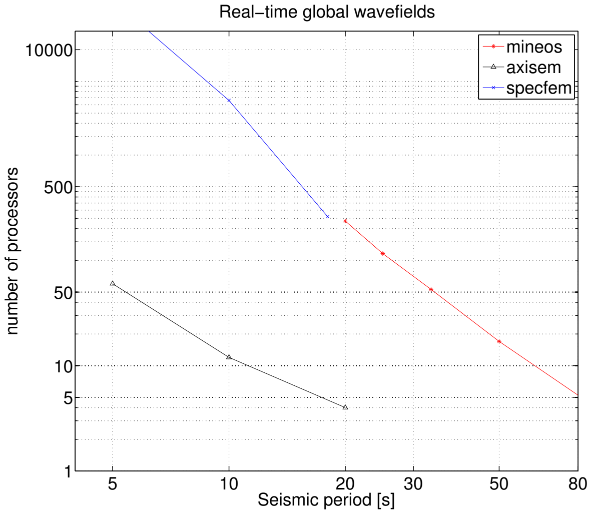


The cost of global waves





Carrington et al. (SC'08)



3D modeling cost complexity:

Are actual seismic problems computable[1] ?

[1] Algorithmic solution in an *effective* manner

Less than Moore: AxiSEM

Radial earth models $\Longrightarrow$ 2D numerical, azimuth analytical

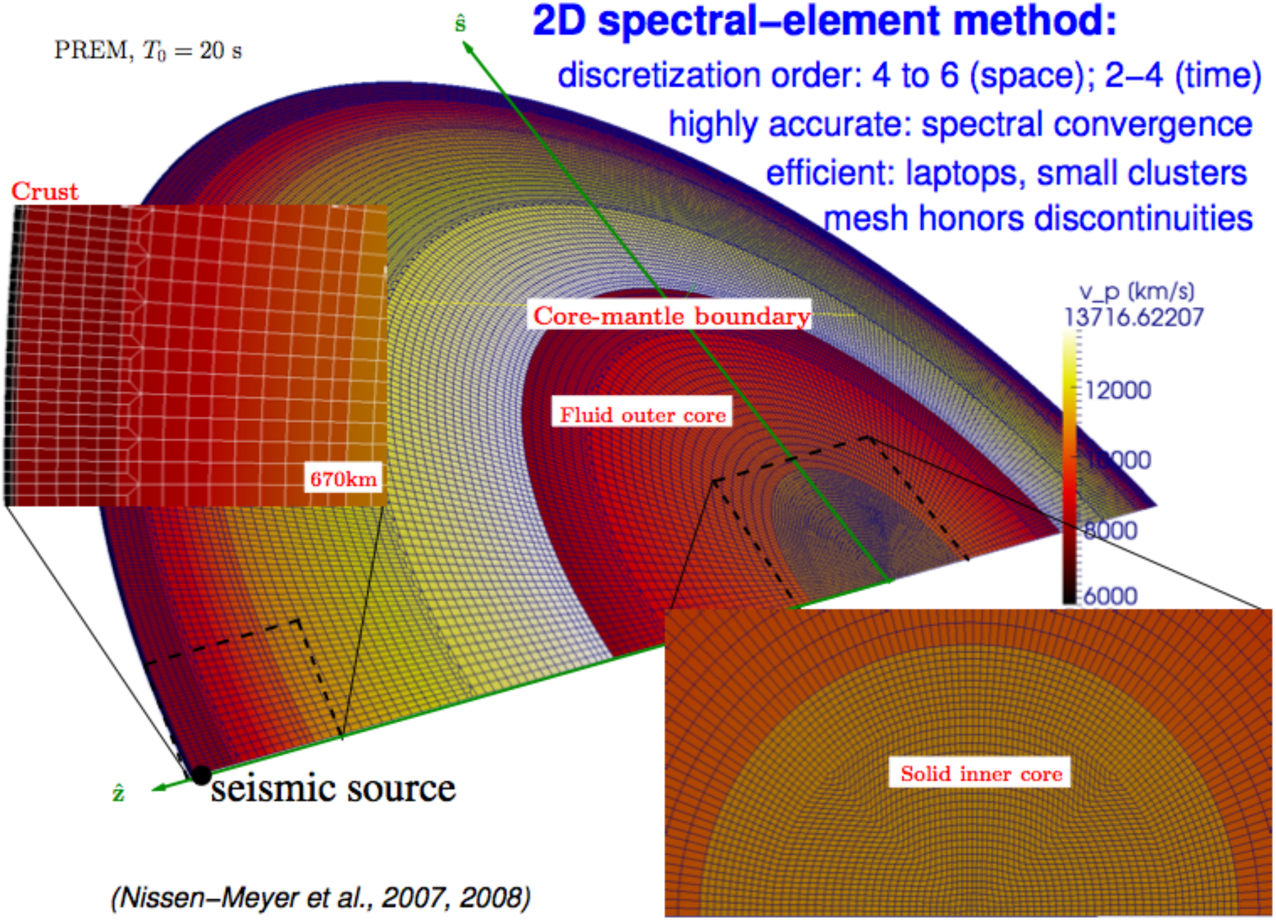
2D spectral–element method:

discretization order: 4 to 6 (space); 2–4 (time)

highly accurate: spectral convergence

efficient: laptops, small clusters

mesh honors discontinuities



(Nissen–Meyer et al., 2007, 2008)

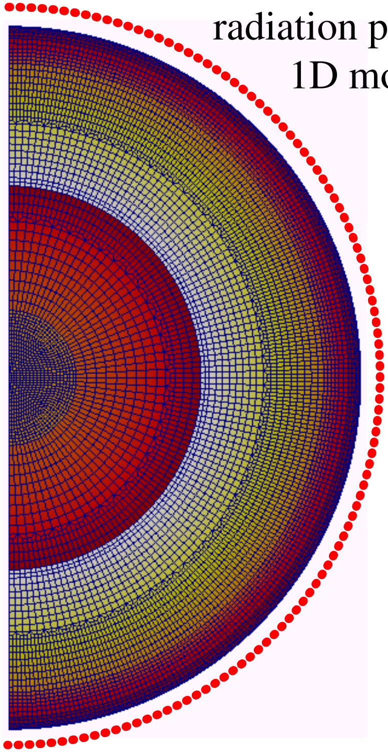
1D, modeled once-and-for-all

1. Seismogram database (1 Hz)

Simulate "all" depths

radiation patterns

1D models



Seismograms at 0–180 deg

2. Specify event/receiver details

CMT solution

receiver details

3. Post processing

Rotate to source–receiver geometry

Sum to full moment tensor

Filter & convolve with source function

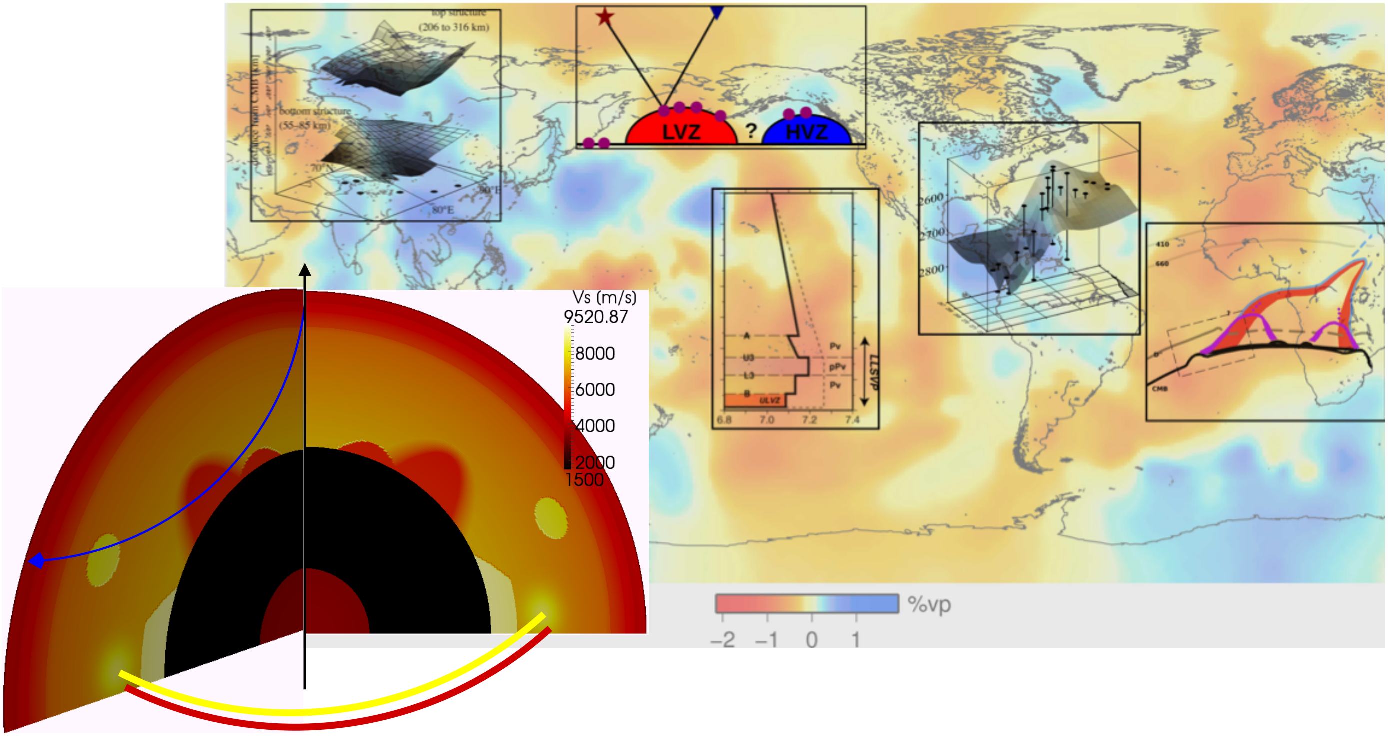
4. Instantaneous arbitrary seismogram

Done with and to be hosted at

IRIS

Incorporated Research Institutions for Seismology

2.5D structures

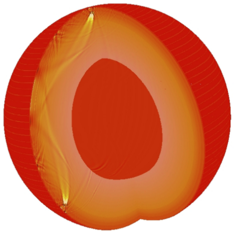


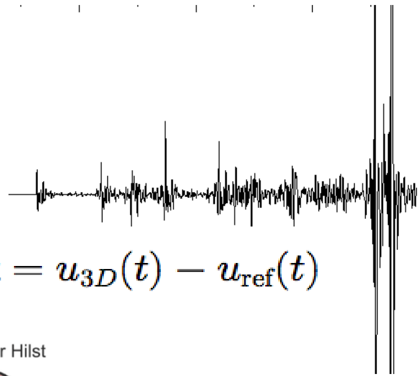
↪ Torus-like structures
↪ High-frequency waves only see small Fresnel zone
↪ Waveform modeling often on 2.5D structural parameters

(TNM et al., 2012, in prep.)

Efficient 3D modeling

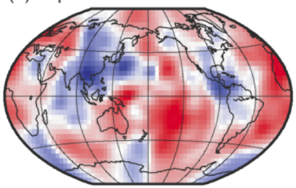
- Exploit weak and sparse heterogeneities
- Exploit 1/curse of dimensionality
- Scale computational cost with (differential) complexity





$$\int_V K(\mathbf{x},t)\Delta m(\mathbf{x})\ d^3\mathbf{x} = u_{3D}(t) - u_{\text{ref}}(t)$$

(d) dVp: Karason & van der Hilst

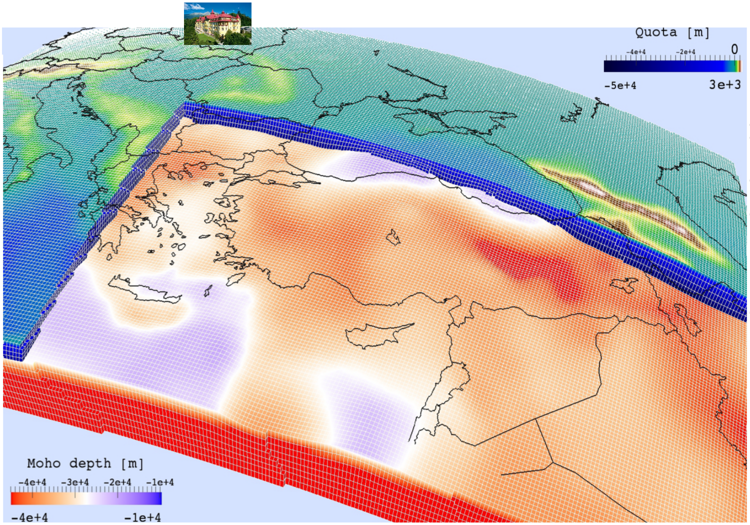


Wavefield injection: **Masson**, Monteiller/Chevrot/Liu, Robertsson/Curtis

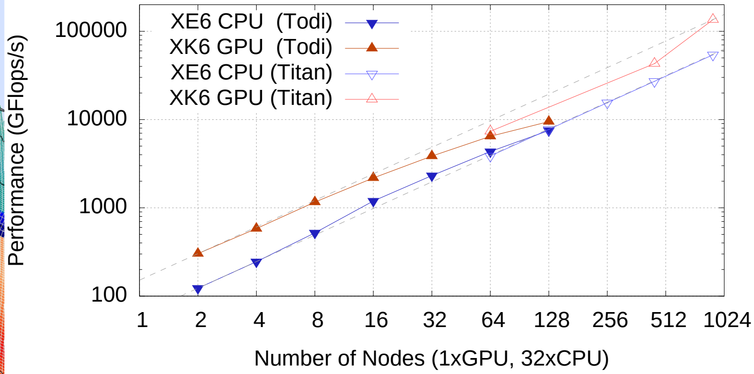
Scattering integrals: **v. Driel**, Panning/Romanowicz, Pollitz

“Extreme-scale” GPU modeling

- ☞New SPECFEM3D implementation for GPUs
- ☞Cuda kernels for forward/adjoint modeling



19 Mio elements (6×10^9 dof)
2hrs on 896 GPUs @ Oakridge’s Titan
sustained 135 TFLOP/s



Speedup... with respect to WHAT?
E.g. purchase cost GPU vs. CPU
⇒ speedup ∼ $1.7 - 2.5$

... worth it? When is the Big One?

(Rietmann et al. 2012, submitted to SC’12)

Overview

1. Models: Chang Su (& village de Capdeville)

2. Accelerators: Martin v. Driel, Yder Masson

3. Parametors: noone and everyone?

   (a) performance-based numerical design

   (b) high-order time schemes

   (c) dispersion error

Performance design & dispersion

Given an error tolerance, find scheme to minimize CPU time & memory

Numerical errors

Discretization $\Longrightarrow$ **dispersion** (waveform time delay)

dissipation (waveform amplitude attenuation)

Dispersion error:

$$\epsilon = \epsilon_{\text{space}} + \epsilon_{\text{time}} \sim (\Delta x/\lambda_0)^{2N} + (\Delta t/T_0)^K$$

Most seismic cases: $\epsilon_{\text{space}} < \epsilon_{\text{time}}$

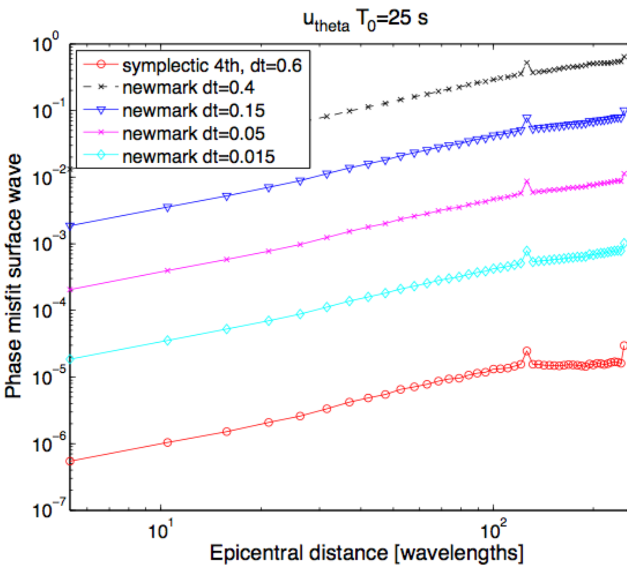
Refined task. Find time scheme to minimize cost given max. accuracy

Time discretization

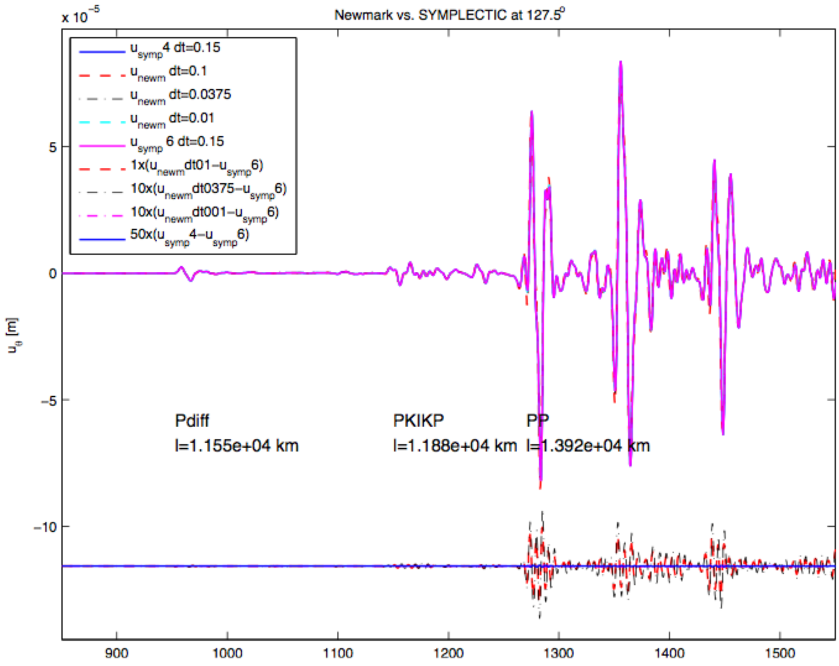
Temporal ODE system of the discretized weak form:

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t)$$

$\mathcal{O}^4$ symplectic scheme: 4-fold force evaluation per Δt

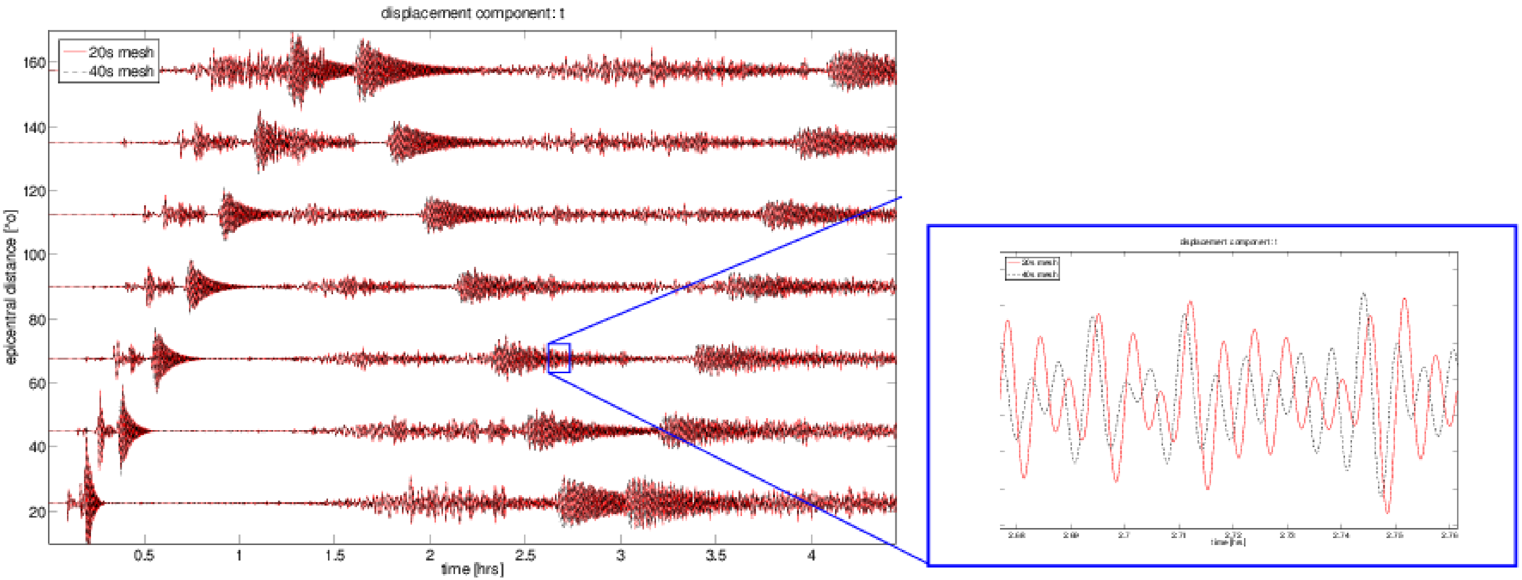


(Ampuero & Nissen-Meyer, to be submitted, 2012)



⇒ Symplectic scheme more cost-effective

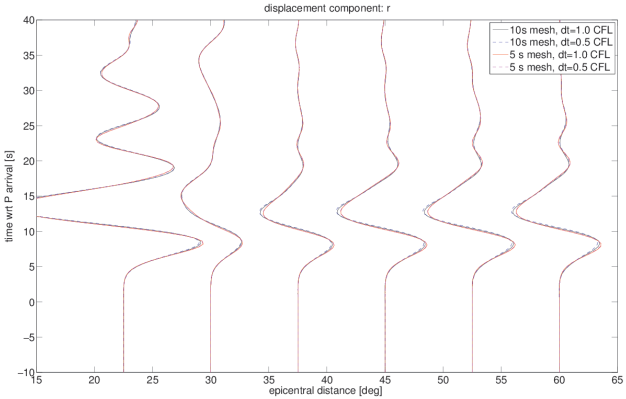
Major-arc cycle skips

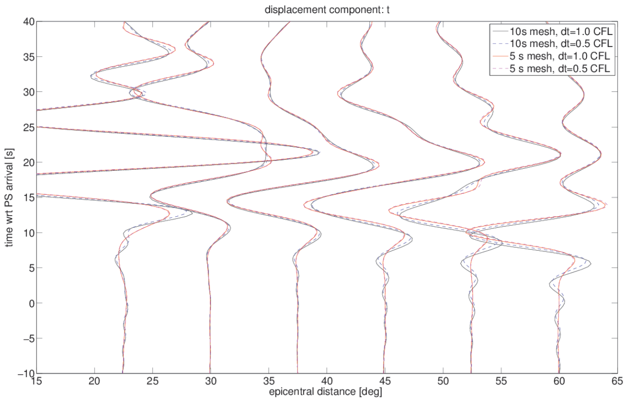


Surface waves over the globe (left), zoom: major-arc surface wave R2 at 65°

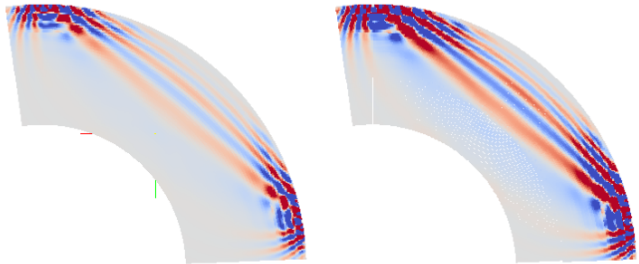
☞ Forget about doing anything with this. ☜

Body wave types





Dispersion in P-wave kernel

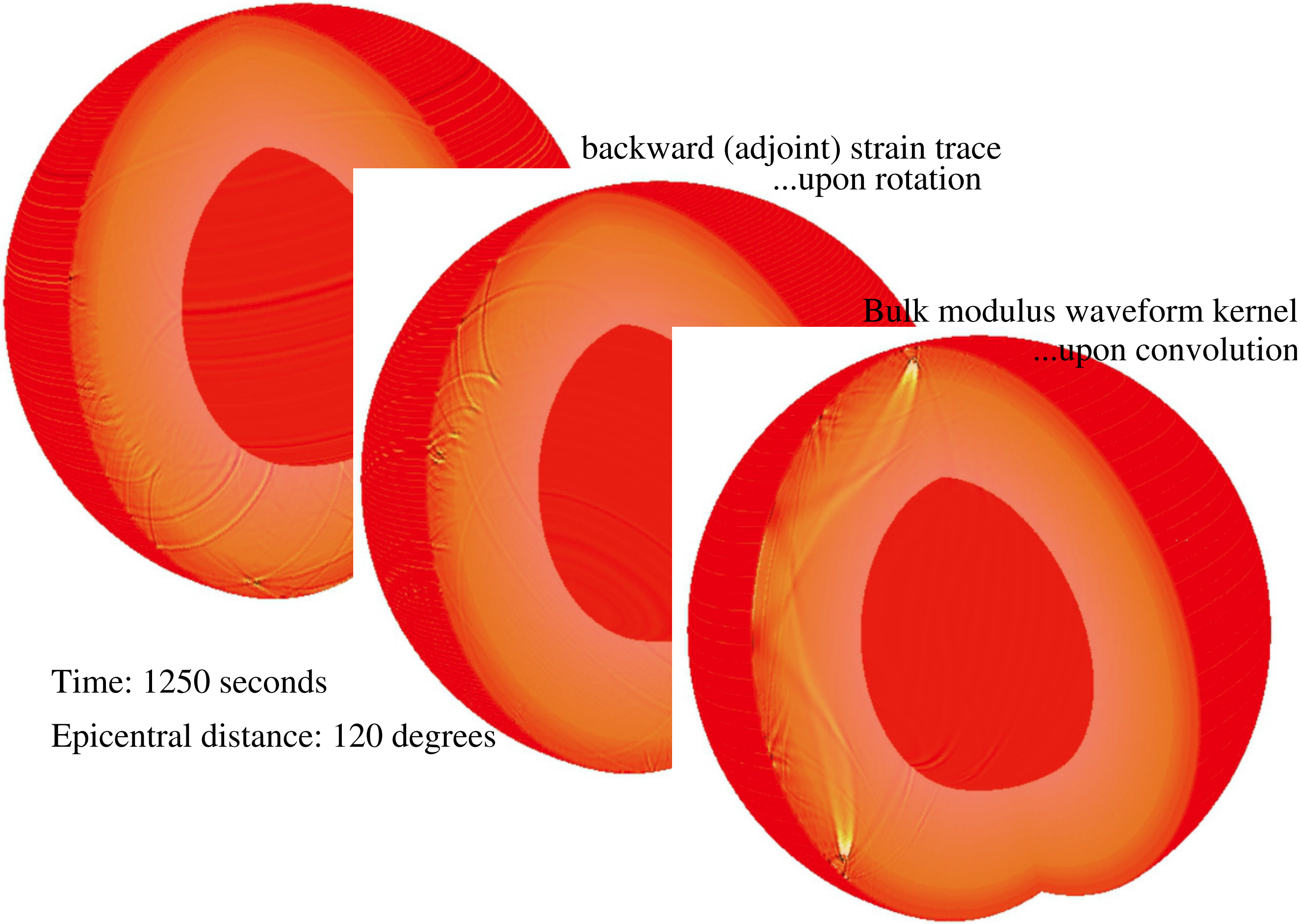


Meshes at 20s (left) and 40s (right)

P (top) and PS (bottom) for various dx & dt

Spatio-temporal sensitivity kernels

$$\mathcal{K}_\kappa(\mathbf{x}, t) = -\int_0^t \left[\nabla \cdot \overrightarrow{\mathbf{u}}(\mathbf{x}, \tau)\right]\left[\nabla \cdot \overleftarrow{\mathbf{u}}(\mathbf{x}, t-\tau)\right]\, d\tau$$



Time: 1250 seconds

Epicentral distance: 120 degrees

Software success stories

What makes a certain technique/implementation **popular**?

- Favorable cost-error function at various settings
- Inclusion of complexity in model and physics
- Flexibility to change/add anything
- Small code complexity (readability, good examples)
- Availability (open-source, feedback, manual)
- promotion (publications, talks)
- popularity/peer pressure ("STILL don't use AxiSEM??")

Remaining task:

popular (# downloads?) $\Rightarrow$ ***successful*** (# referenced publications?)...

Summary

Seismic forward modeling is somewhat solved if:

1. Linear elastodynamics, kinematic sources are sufficient
2. Models are piecewise smooth and not too discontinuous
3. Source & structural parameters are "well-chosen"
4. Numerical parameters are "well-chosen"
5. We hijack **global supercomputing**

Current developments include:

1. **Dimensional reduction:** New applications possible
2. **Subvolume methods:** Backbone for hi-res tomography
3. **Model discretization:** To honor or not to honor?

Remember: We're always constrained by our forward modeling capabilities!

Ďakujem...

QUESTions?