AxiSEM

High-frequency global wavefields for forward and inverse modeling

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July 15, 2013
Carl's workshop

Fairbanks, Alaska

Overview

1. **Motivations & background**

2. **Methodology & validation**

3. **Applications: Forward modeling**

4. **Applications: Data & inverse modeling**

Overview

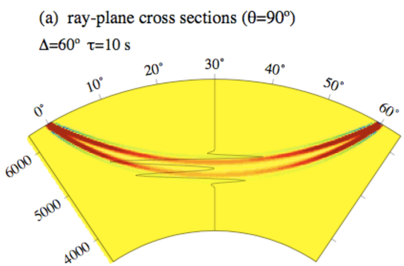
1. **Motivations & background**
   (a) Geophysical context
   (b) Physical, structural, computational complexity

2. **Methodology & validation**

3. **Applications: Forward modeling**

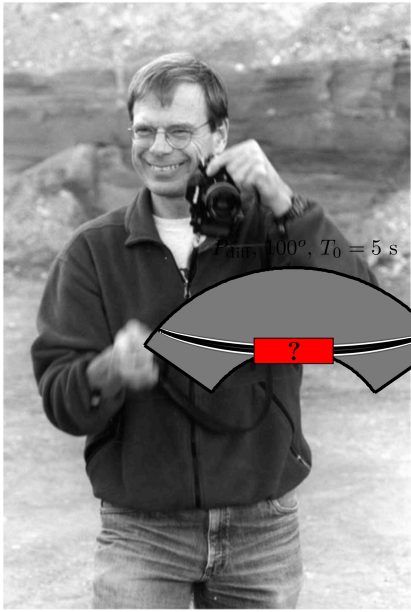
4. **Applications: Data & inverse modeling**

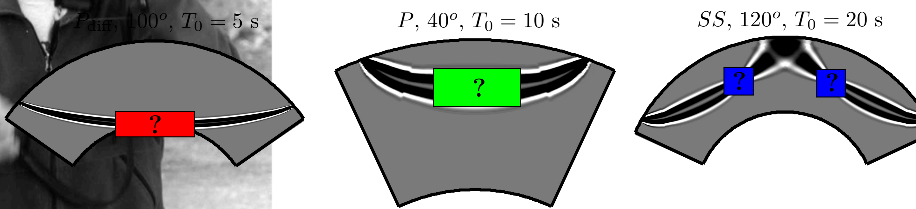
Early days



Finite-frequency
by ray tracing

Tony Dahlen





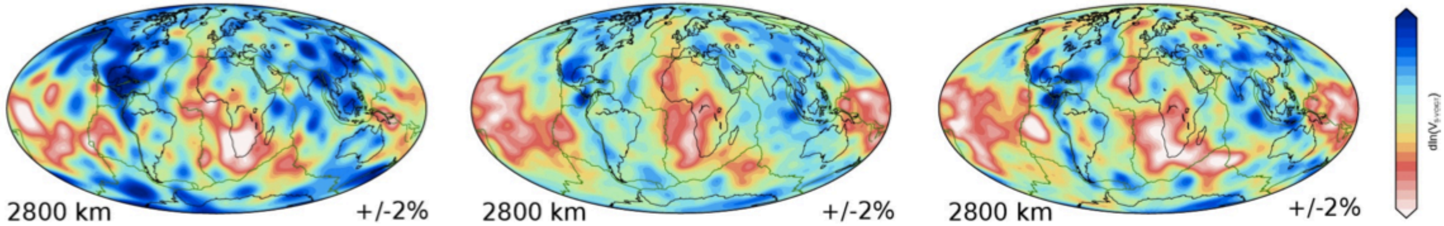
Full-wave effects

A full-wave solution to capture the entire frequency band for tomography

motivated by:
(1) Structure & dynamics, (2) Broadband data, (3) Computational constraints

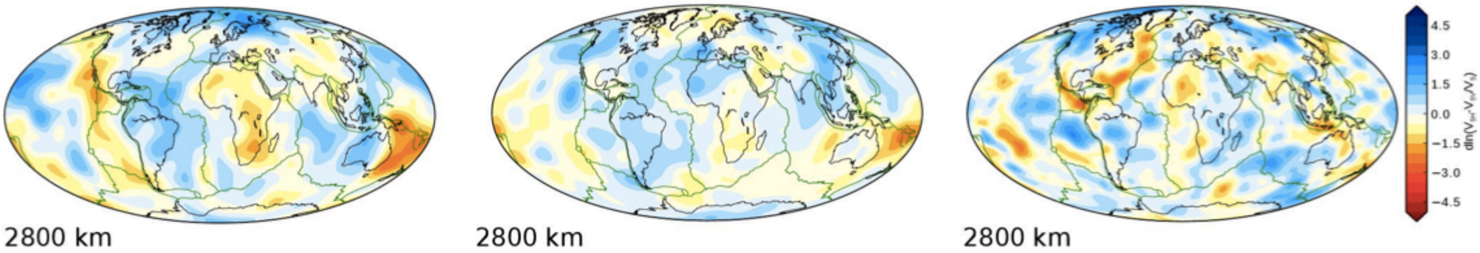
Large-scale structures

Isotropic S



Berkeley Michigan ETH

Relative anisotropic S variations ln((VSH - VSV)/VS)

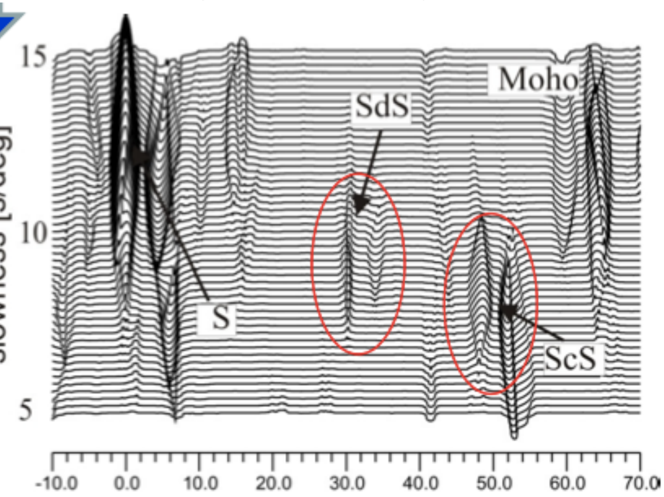


Berkeley Harvard ETH

(Auer et al. 2013, to be subm..)

Small-scale structures

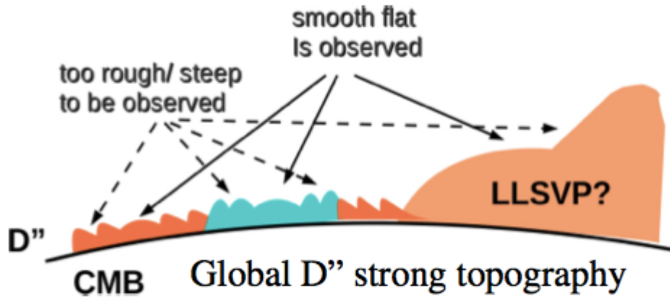
High-frequency (1Hz) waveforms



Kito, Rost,, Thomas, Garnero, 2007

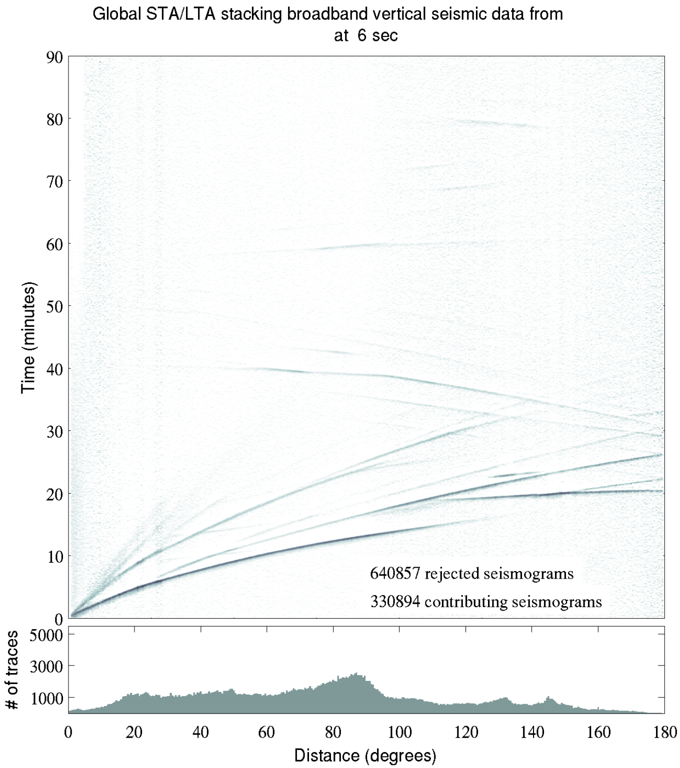
Needed to resolve structures

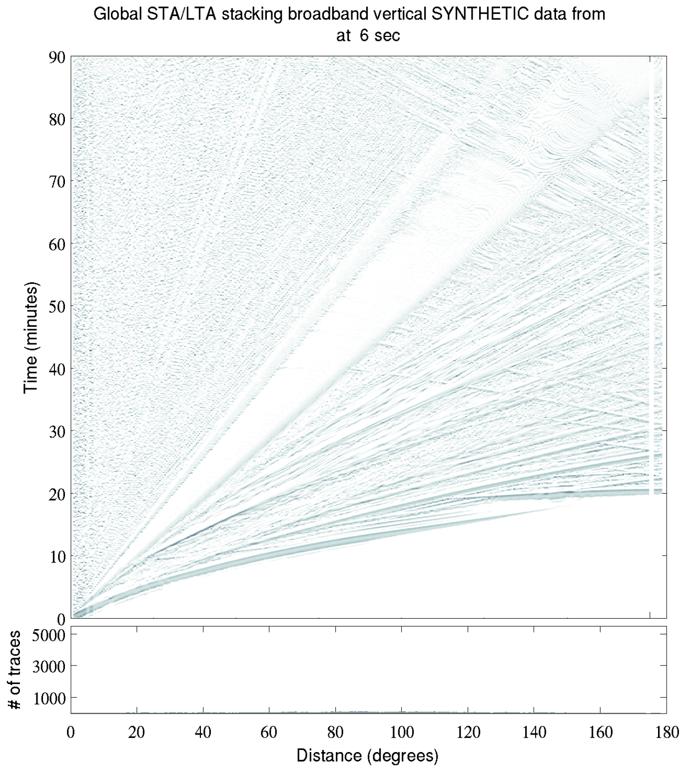
Small-scale D” topography



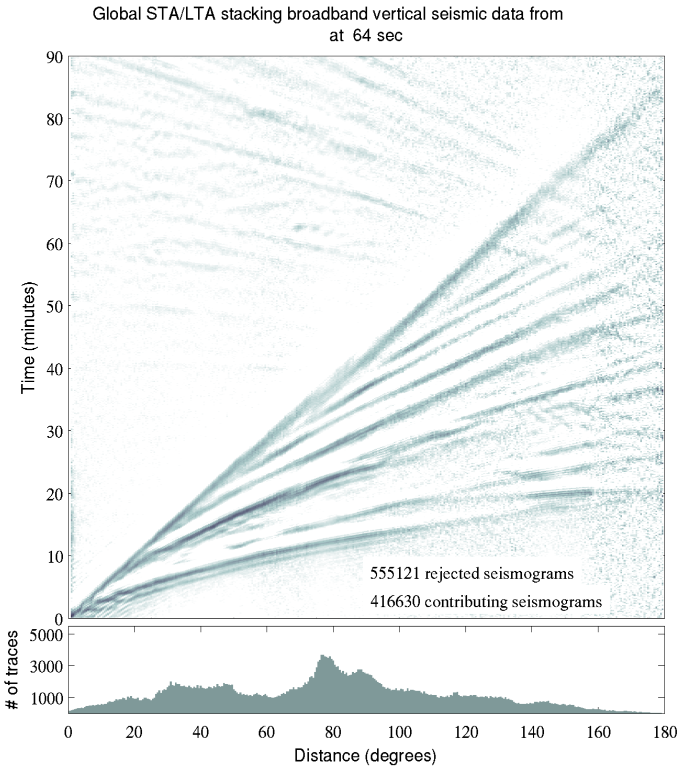
satisfies data, but trades off

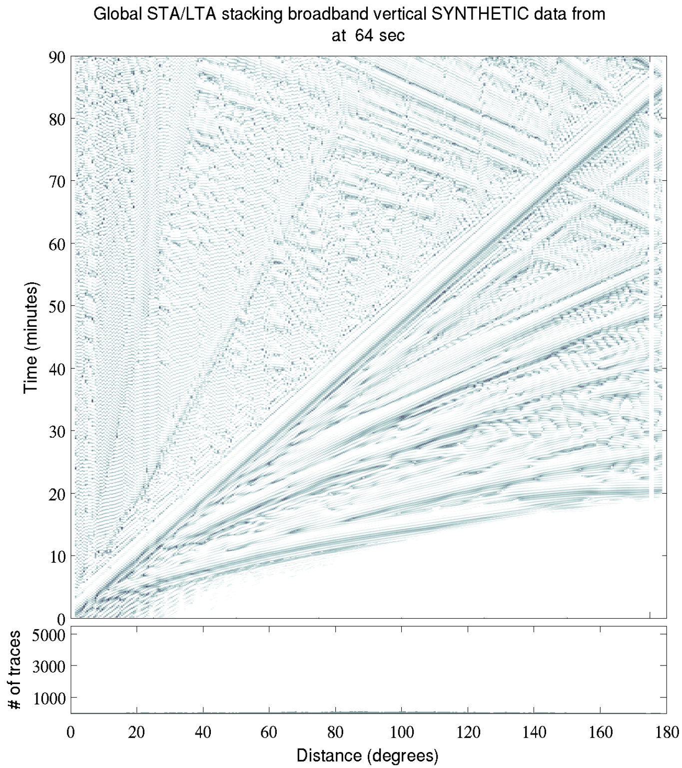
Waveform stacks at 6 seconds



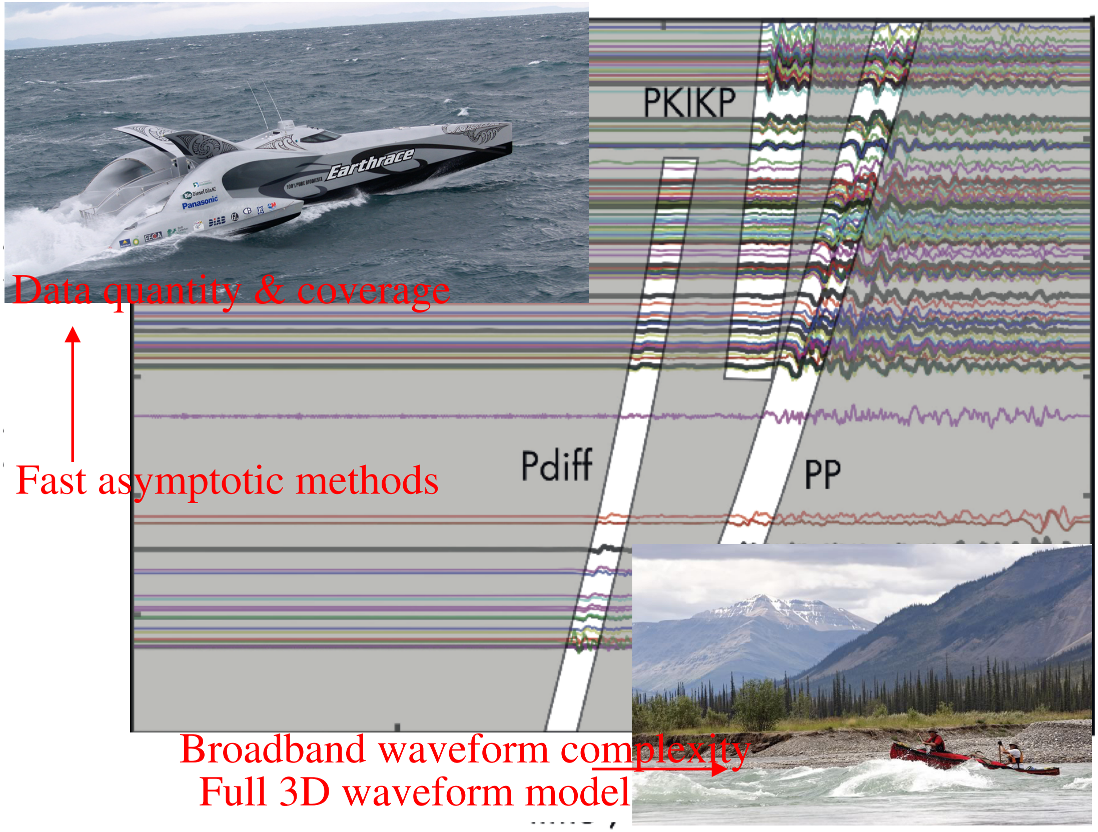


Waveform stacks at 64 seconds

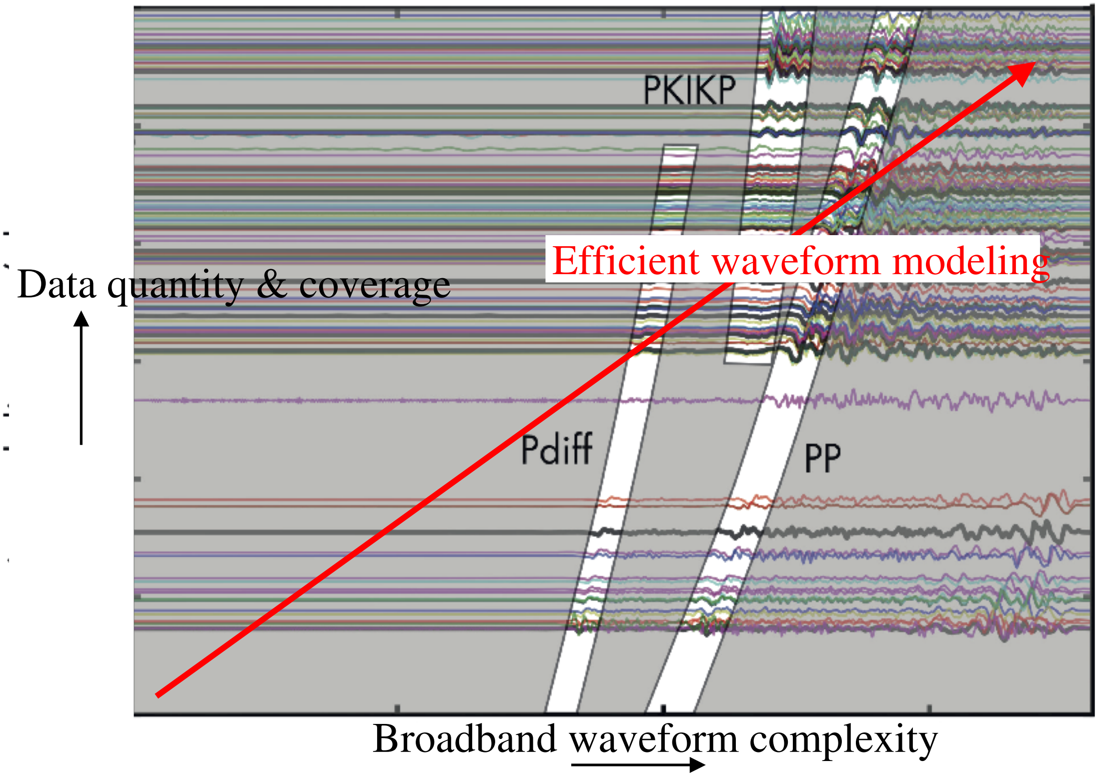




Wave modeling end-members



Modeling quantity & complexity



↪ Jointly accommodate data complexity in time, frequency, quantity

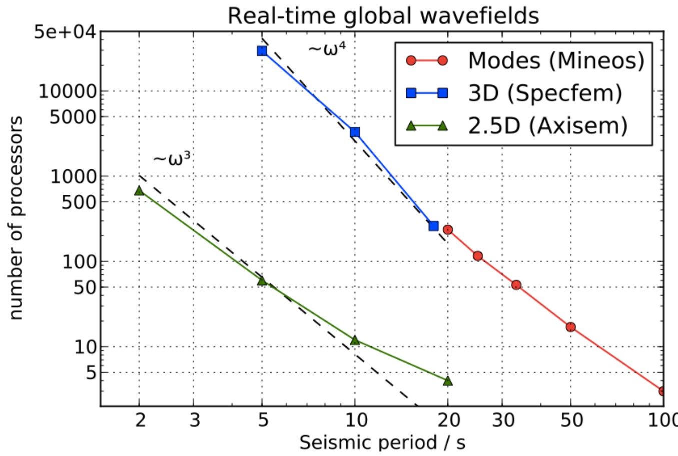
Computability

Computable processes

✍ *algorithmic solution in effective manner*

✍ *a sequence of simple, local steps*

✍ *on computer bits, atoms in matter*



(TNM & Fournier, 2013, tbs, GJI)

Two types of computations:

(1) nature itself... forward modeling!

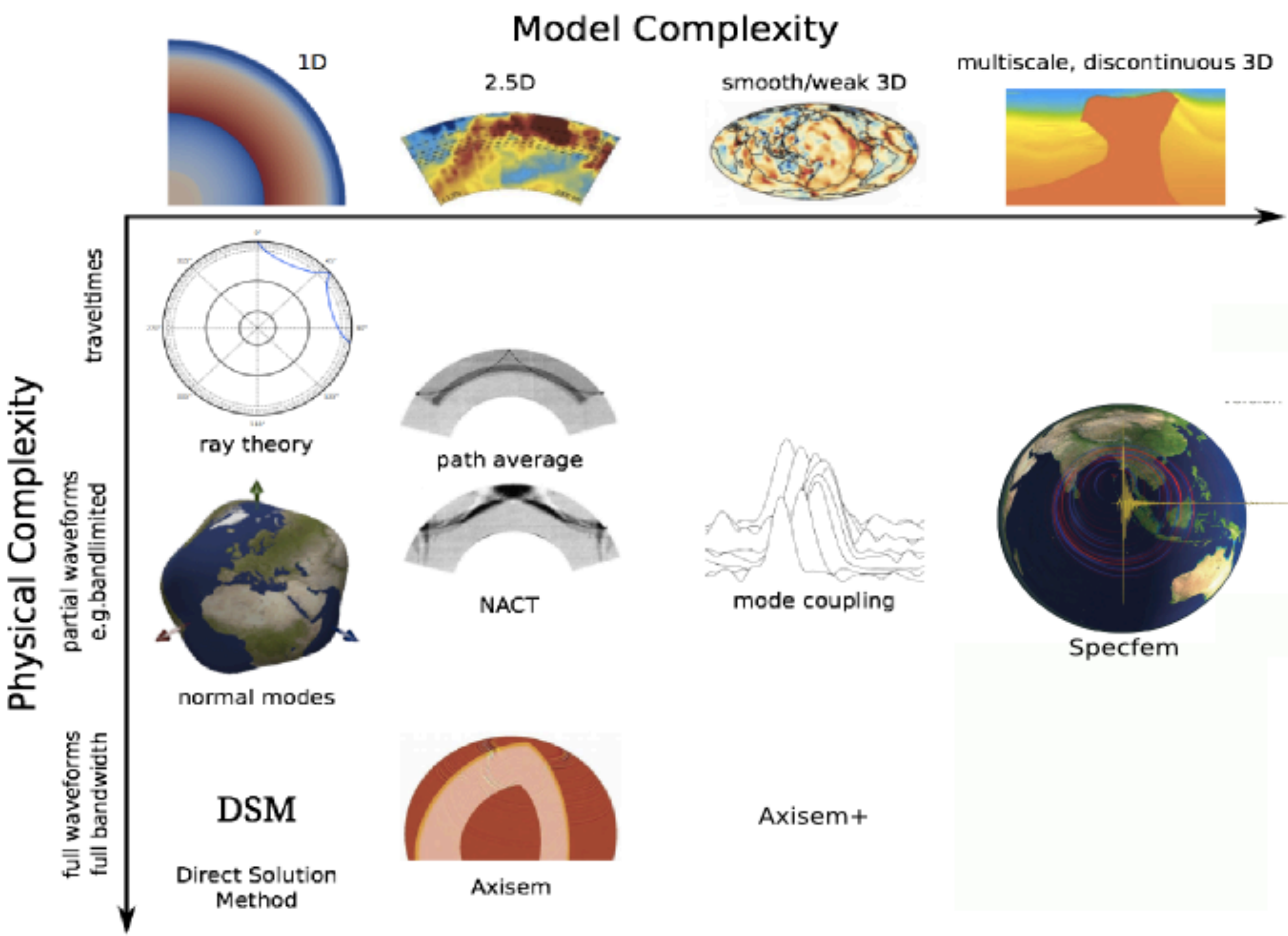
(2) subjects (humans) attempting to replicate nature... inverse modeling!

Two factors matter in seismic modeling:

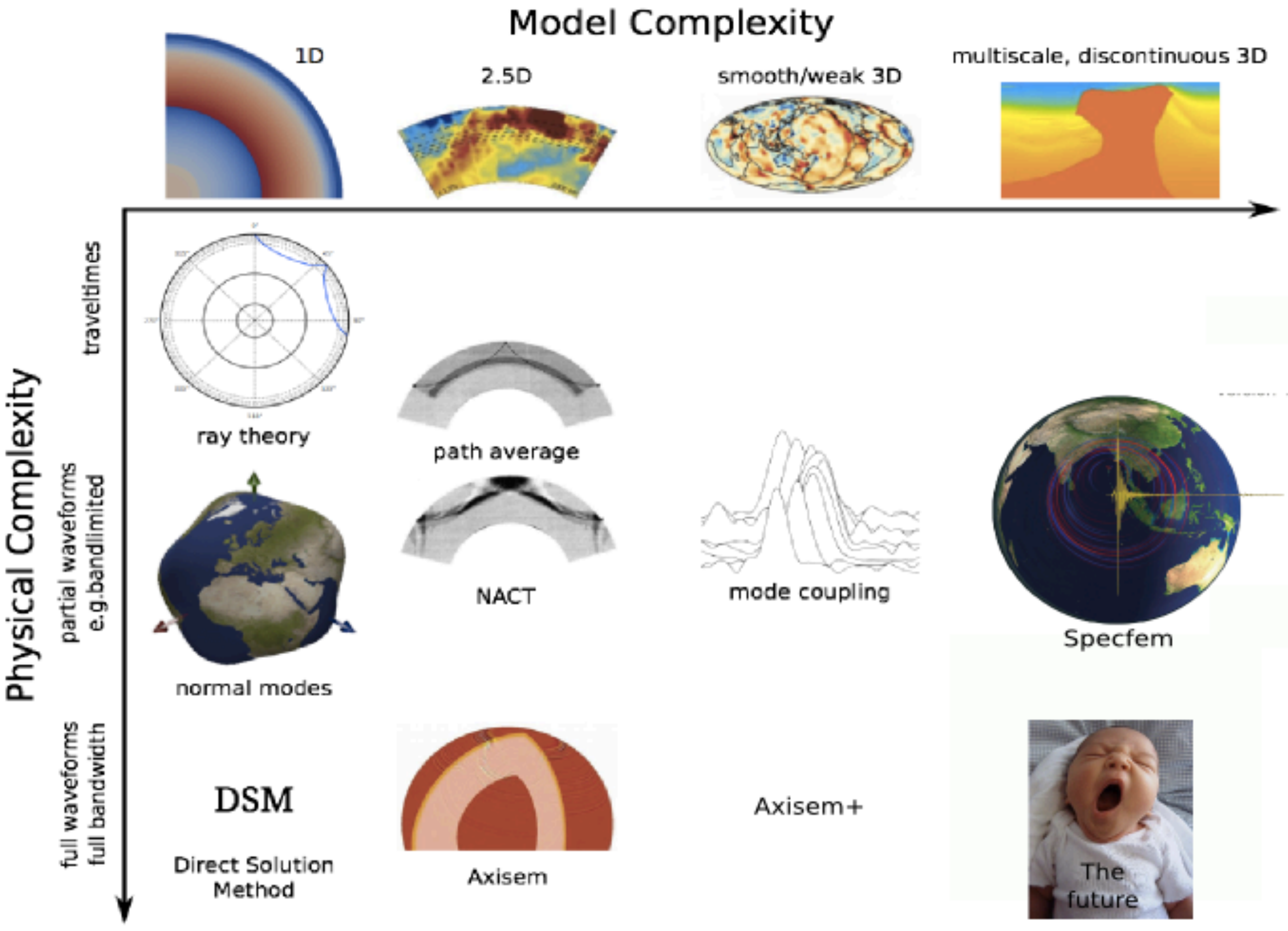
(1) Computational cost ⇒ 1 hour or 1 month?

(2) Reliability of assumptions ⇒ Occam's Razor

Structural vs. physical complexity



Structural vs. physical complexity



Overview

1. **Motivations & background**

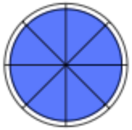
2. **Methodology & validation**
   (a) Axisymmetric collapse & discretization
   (b) Broadband validation & wavefields

3. **Applications: Forward modeling**

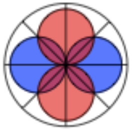
4. **Applications: Data & inverse modeling**

Flat Earth

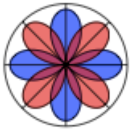
Axisymmetric source radiation:



$\mathbf{u} = \mathbf{u}(s, z)$



$\mathbf{u} = \mathbf{u}(s, z) \cdot f(\sin\phi, \cos\phi)$

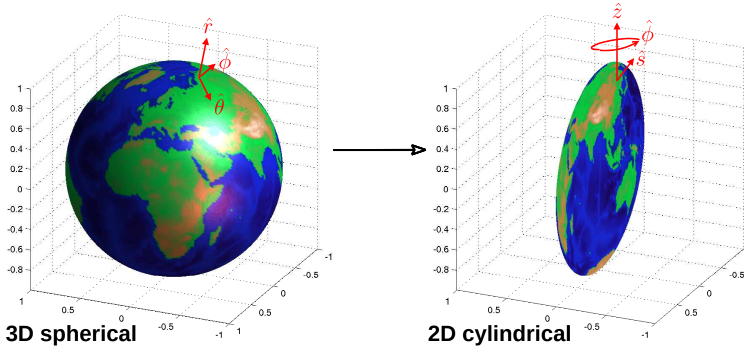


$\mathbf{u} = \mathbf{u}(s, z) \cdot f(\sin(2\phi), \cos(2\phi))$

4 simulations per **earthquake**

Azimuthal integration (weak form):

$$\int_0^{2\pi} \cos^2 2\phi \, d\phi = \pi$$



3-D system in a **2-D domain**

☞Axisymmetric spectral-element method ☜

Less than Moore: AxiSEM

Axisymmetric Earth models $\Longrightarrow$ numerical spheroid, analytical toroid

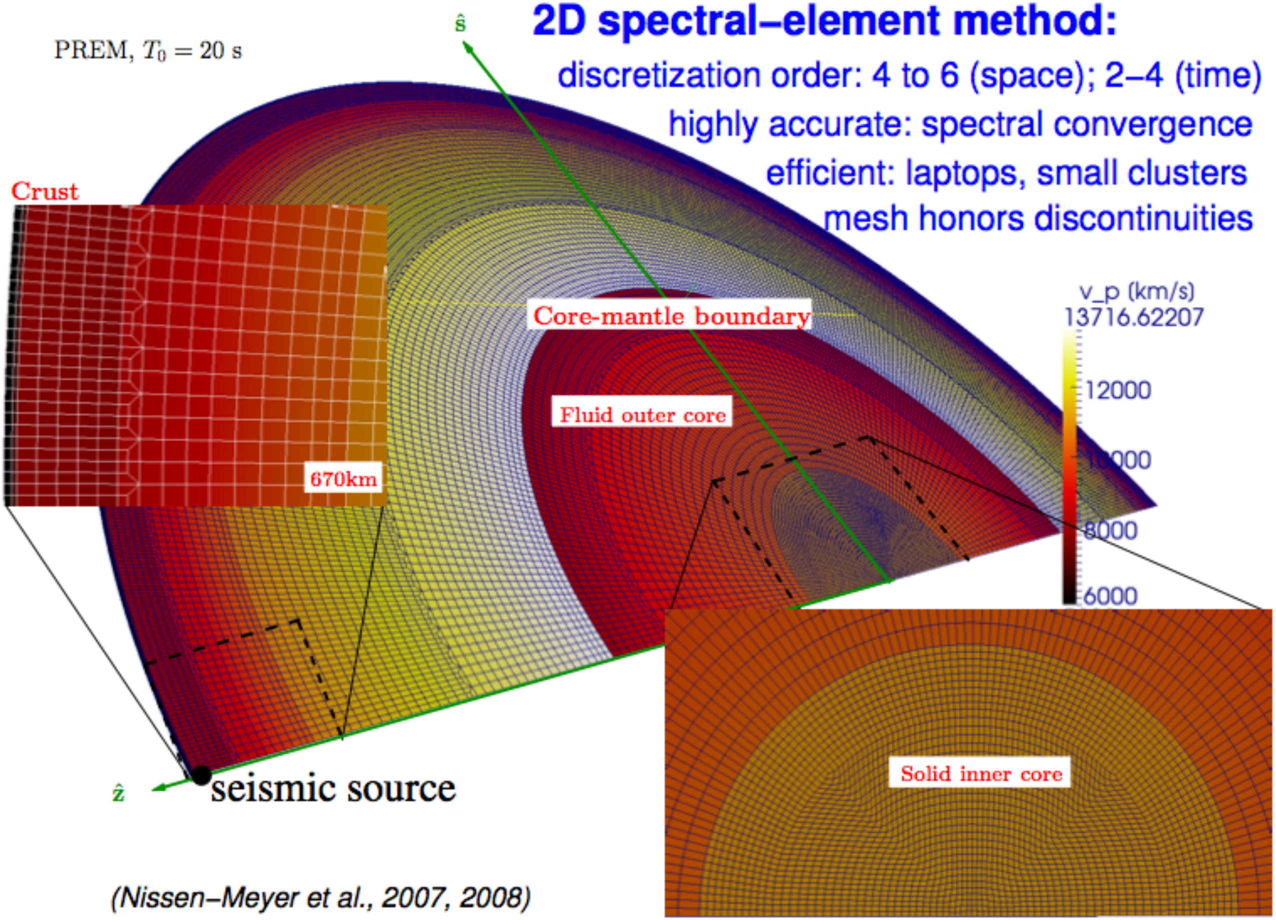
2D spectral–element method:

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

highly accurate: spectral convergence

efficient: laptops, small clusters

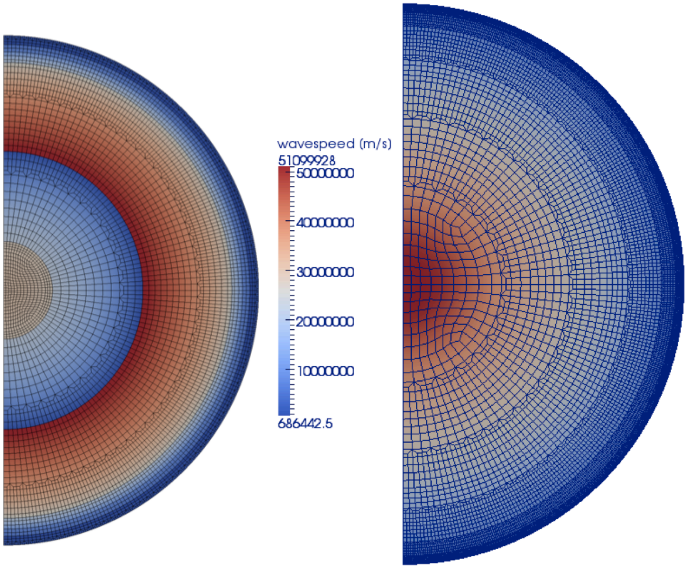
mesh honors discontinuities



(Nissen–Meyer et al., 2007, 2008)

Background models

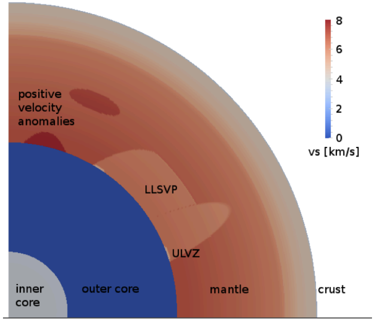
Spherical symmetry:



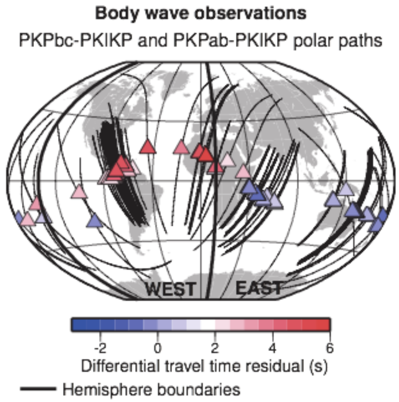
Solid-fluid Earth

Fluid Sun

2.5D axisymmetric structures:



Arbitrary geometry & structure



(Deuss et al, 2010)

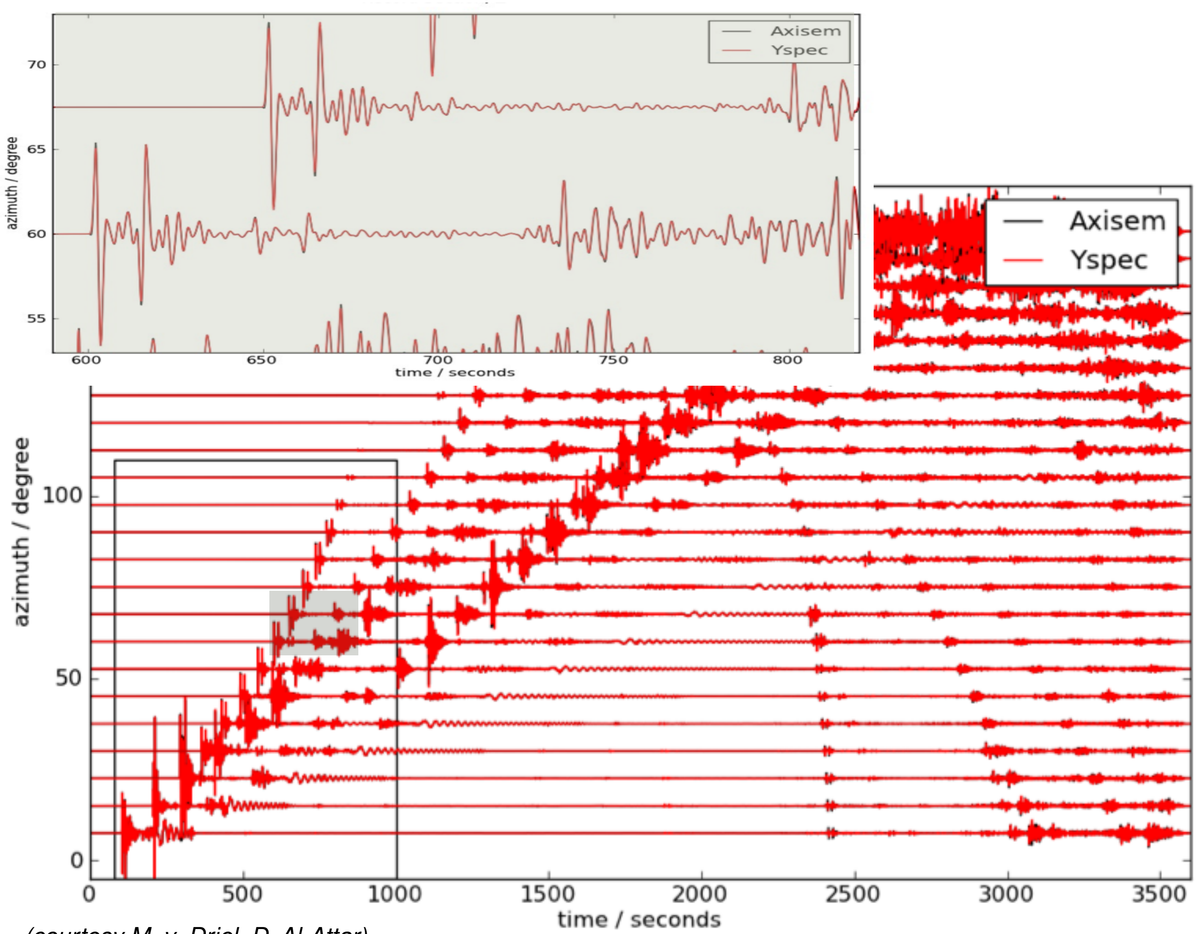
Inner-core anisotropy (tilted)

Rheologies:

Acoustic, elastic, viscoelastic
fully anisotropic

1D model, 2D domain, 3D waves

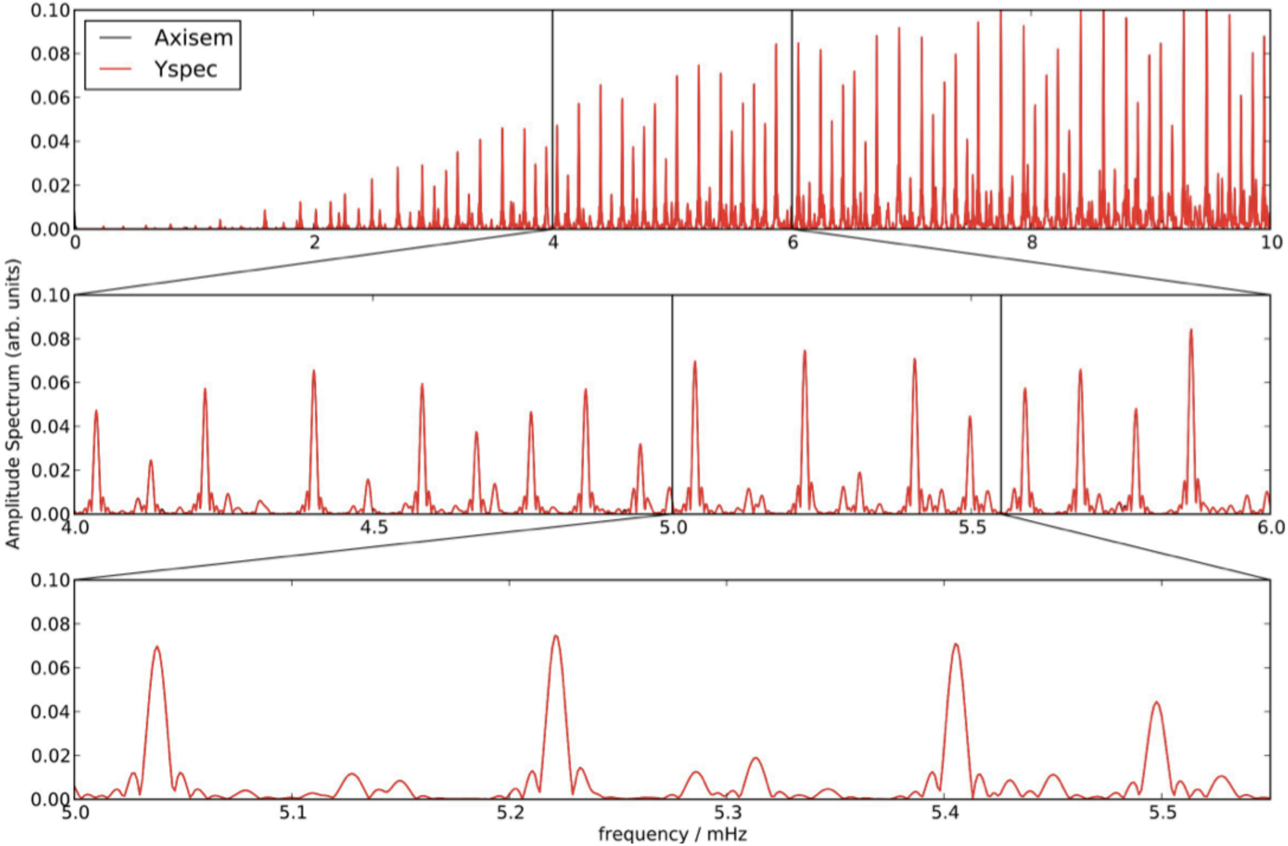
(anisotropic) PREM, dominant period: 2s, explosion at 100km depth



(courtesy M. v. Driel, D. Al-Attar)

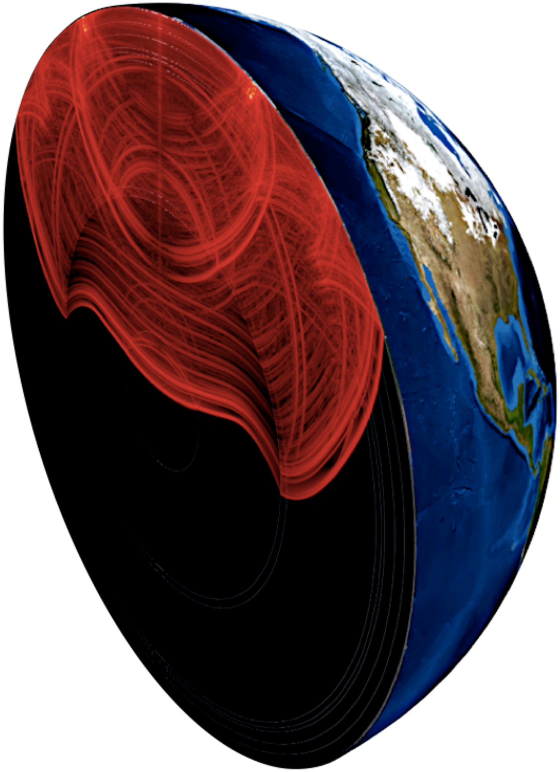
Amplitude spectra benchmark

(anisotropic) PREM, 48 hours (1.7 million timesteps)



High-frequency wave propagation

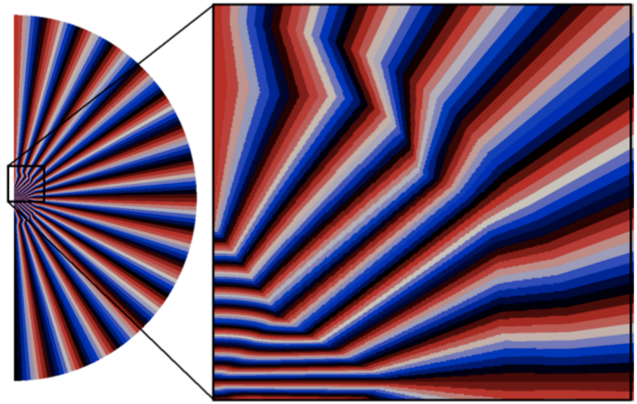
Moment-tensor source, PREM (anisotropic, attenuated), dominant period $5s$

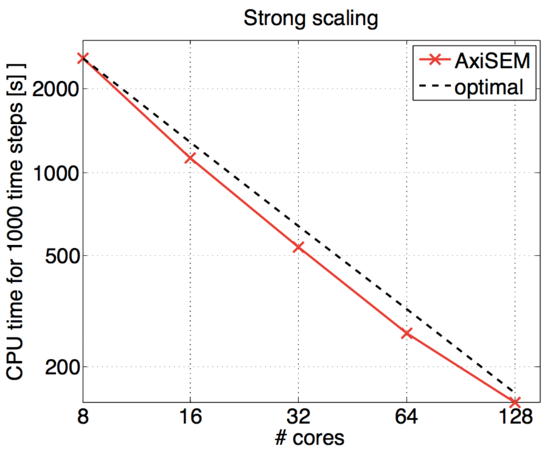


Simulated on a workstation, 16 CPU hours

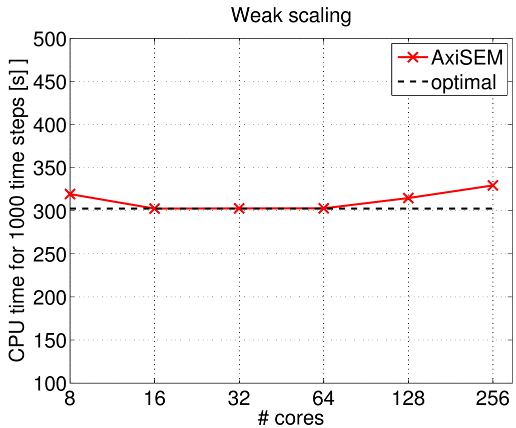
Parallelization & scalability

- Automated internal mesher
- Domain decomposition: 272 CPUs
- Exactly load balanced
- Small domain interfaces
- Max. 2 neighbors





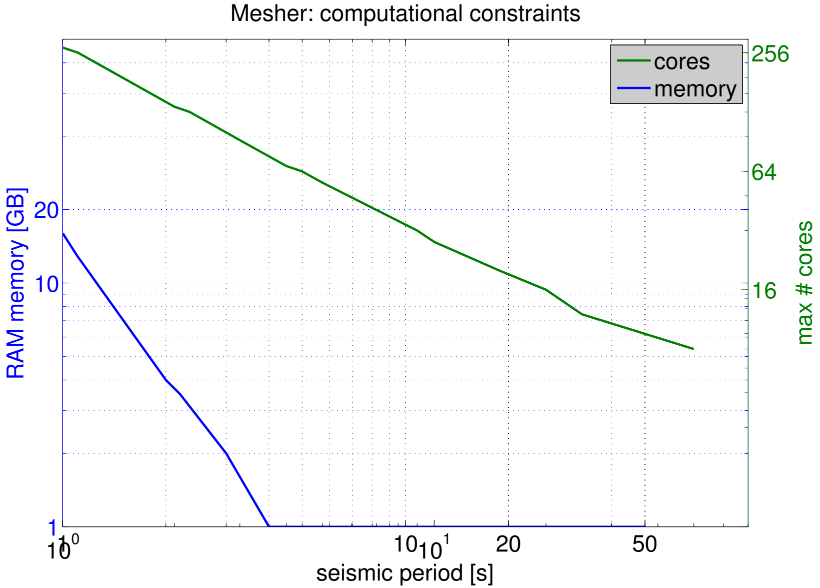
(fixed overall problem)



(fixed problem per core)

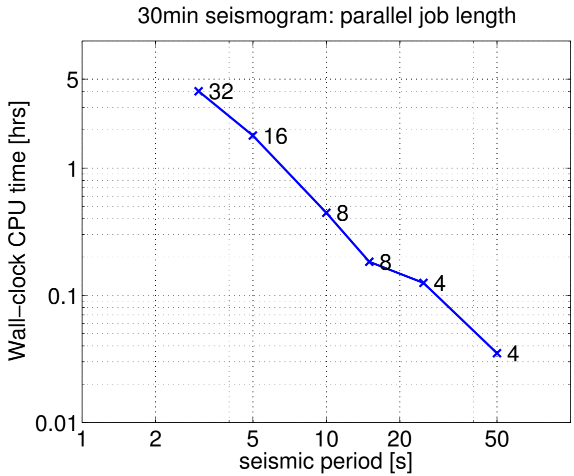
Computational cost

How many processors can/must I use?



What is the memory?

Wall-clock time?



(Nissen-Meyer et al., 2013, t.b. subm.)

Overview

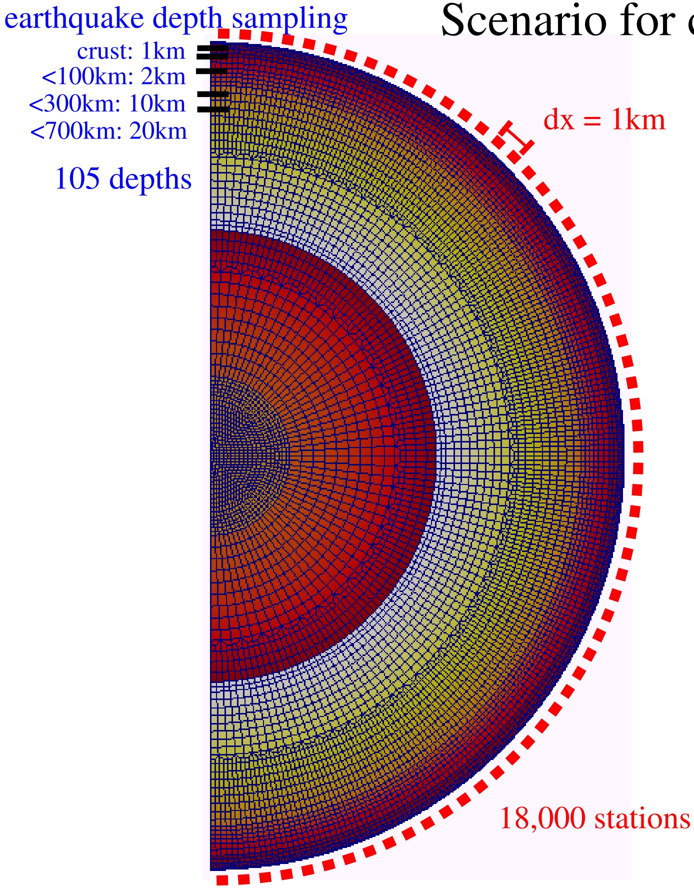
1. **Motivations & background**

2. **Methodology & validation**

3. **Applications: Forward modeling**
   (a) 1D: Once-and-for-all solutions
   (b) 2.5D: High-frequency wavefields
   (c) 3D: Scattering approaches

4. **Applications: Data & inverse modeling**

A comprehensive database



Scenario for corner frequency 0.5 Hz

Sources:
- point sources (finite also possible)
- response for each moment tensor element
- requires 4 simulations per depth

Background models:
- (an−)elastic, (an−)isotropic PREM
- IASP91
- ak135

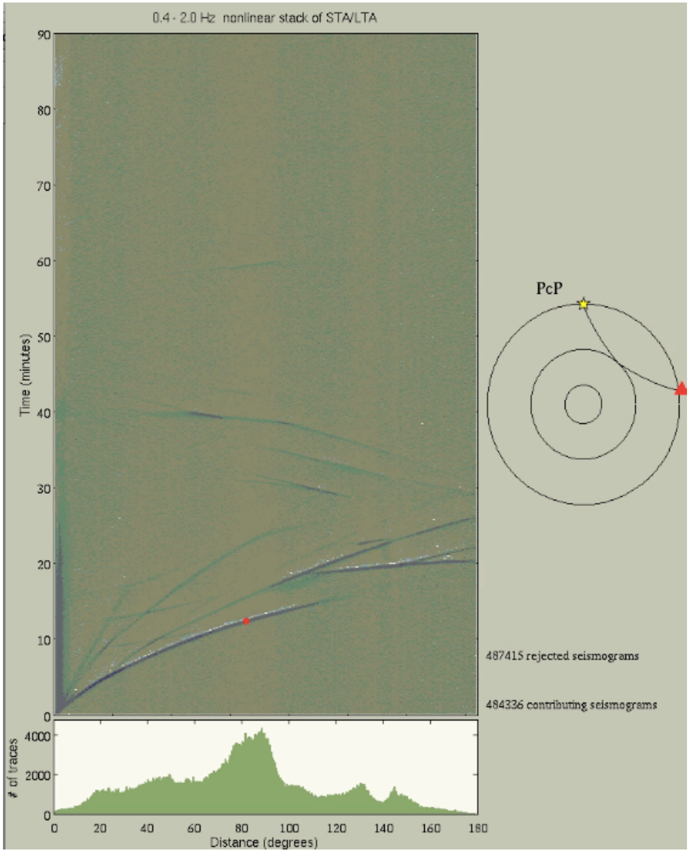
Seismograms:
- length: 50min
- sampling rate: 0.1s

Superstacks

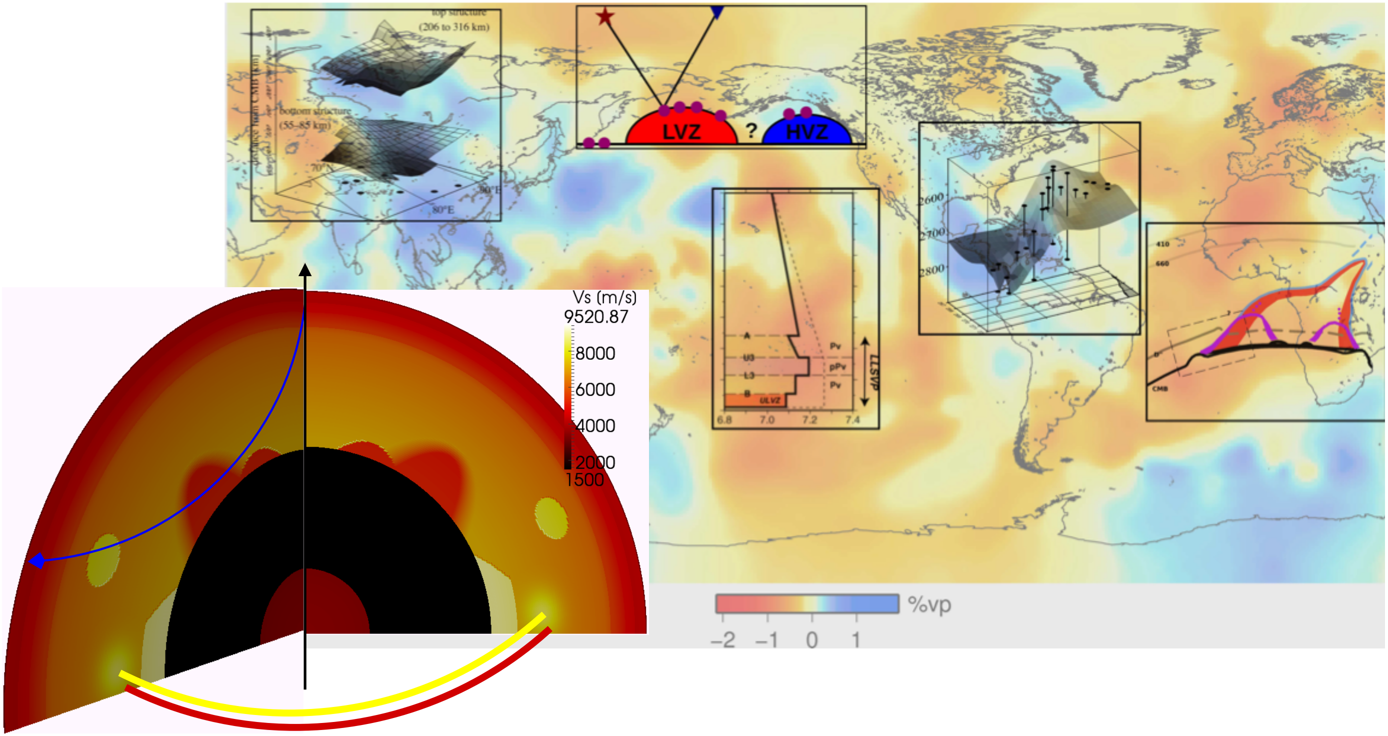
- ☞ Nonlinear STA/LTA stacks
- ☞ 500’000 seismograms
- ☞ Filtered at 0.4-2Hz
- ☞ SNR-based rejection

Courtesy Data Products IRIS-DMC

... phase identification by modelling?



2.5D structures

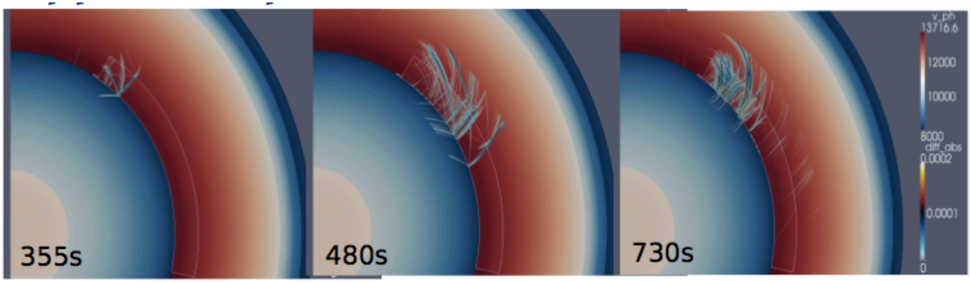


↪ Torus-like structures
↪ High-frequency waves only see small Fresnel zone
↪ Waveform modeling often on 2.5D structural parameters

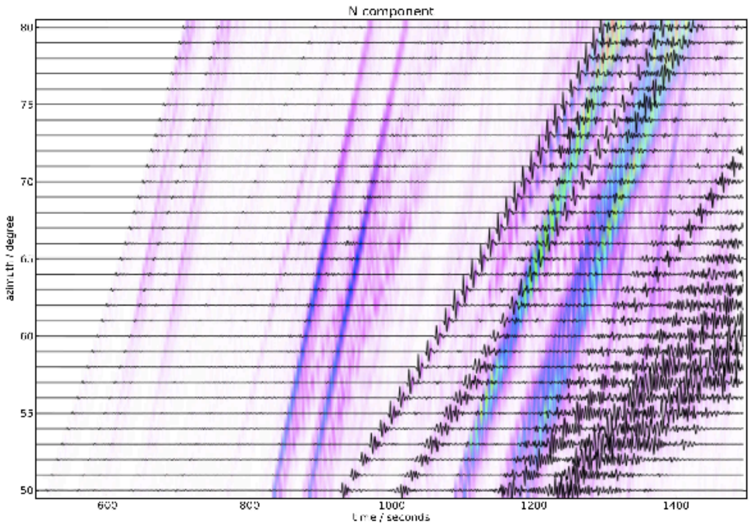
(TNM et al., 2013, in prep.)

Large low shear velocity provinces

Question: Thermal versus compositional anomaly
Proxy: Boundary sharpness (sharp ☞ compositional)

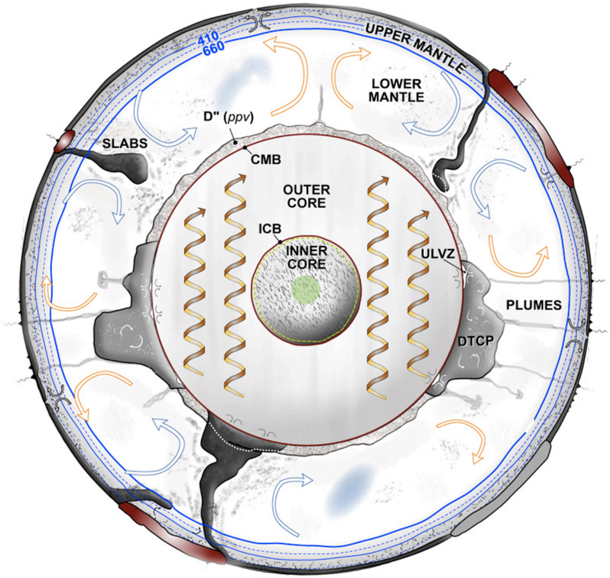


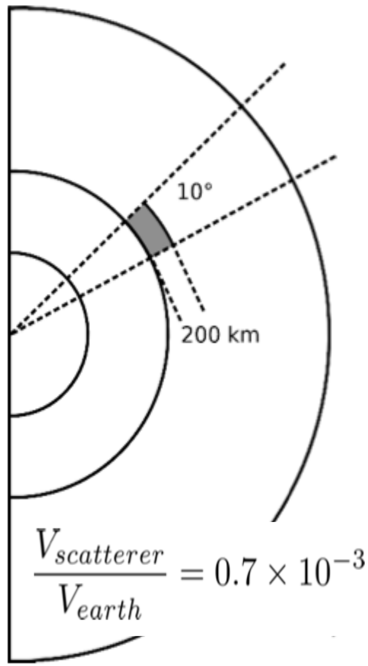
Differential wavefields for sharp vs. gradational LLSVP boundary.



(TNM et al. 2013, to be submitted)

Parsimonious 3D modeling



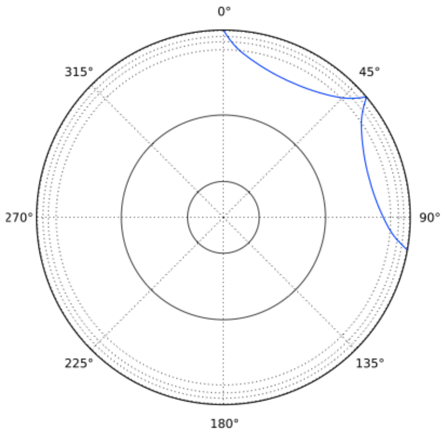


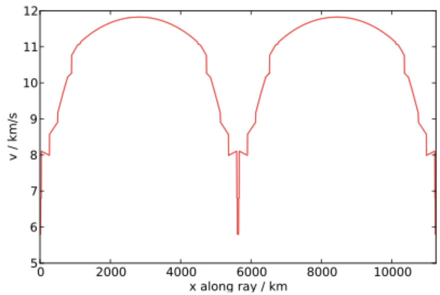
- Exploit weak & sparse heterogeneities
- Exploit 1/(curse of dimensionality)
- Link **computational cost** to **model complexity**
- Iterative inversions: local adjustments

Wavefield injection: Hybrid methods, exact boundary conditions

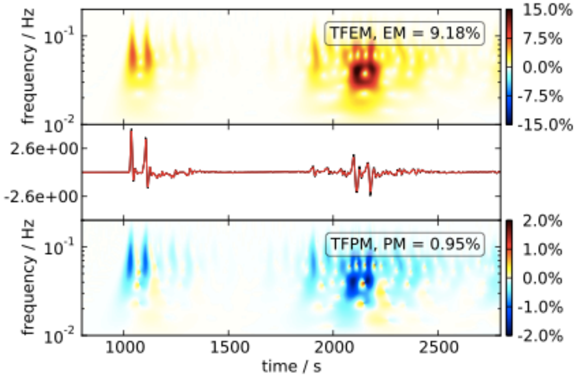
Scattering integrals: Born modeling, modified Neumann series

First-order scattering

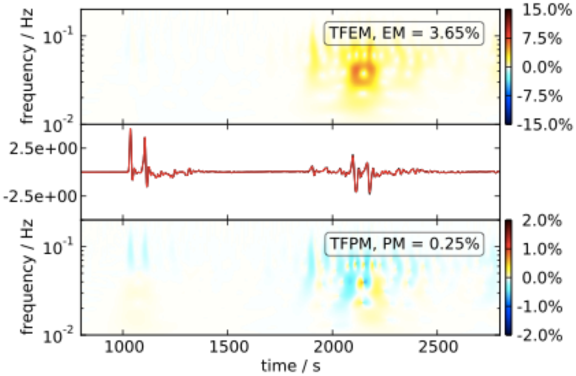




Born:



Rytov:



Simulation time per event and 3D model: 1 second

Reality check

ARE YOU LIVING IN A COMPUTER SIMULATION?

BY NICK BOSTROM

[Published in *Philosophical Quarterly* (2003) Vol. 53, No. 211, pp. 243-255. (First version: 2001)]

This paper argues that *at least one* of the following propositions is true: (1) the human species is very likely to go extinct before reaching a "posthuman" stage; (2) any posthuman civilization is extremely unlikely to run a significant number of simulations of their evolutionary history (or variations thereof); (3) we are almost certainly living in a computer simulation. It follows that the belief that there is a significant chance that we will one day become posthumans who run ancestor-simulations is false, unless we are currently living in a simulation. A number of other consequences of this result are also discussed.

The End of Theory: The Data Deluge Makes the Scientific Method Obsolete

By Chris Anderson 06.23.08

.... let big data take control!

Overview

1. **Motivations & background**

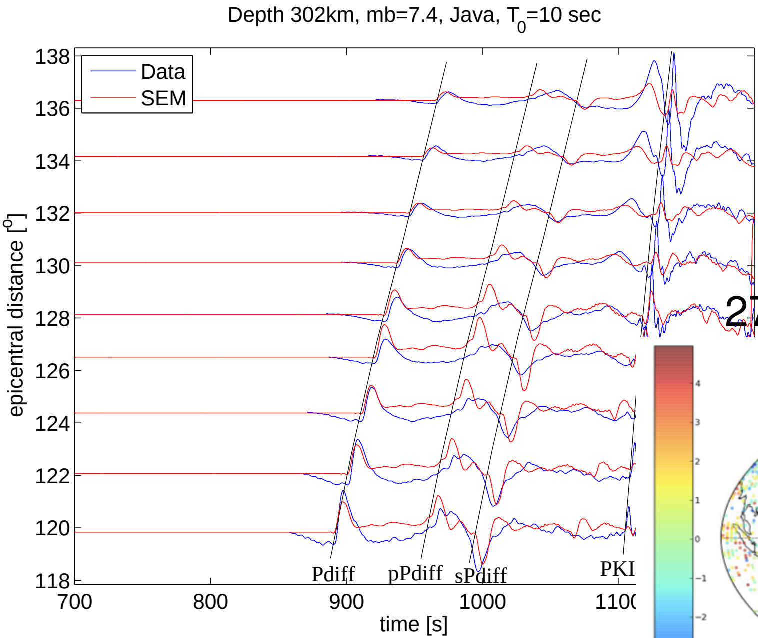
2. **Methodology & validation**

3. **Applications: Forward modeling**

4. **Applications: Data & inverse modeling**
   (a) Data & modelling
   (b) Forensic sensitivity
   (c) CMB topography

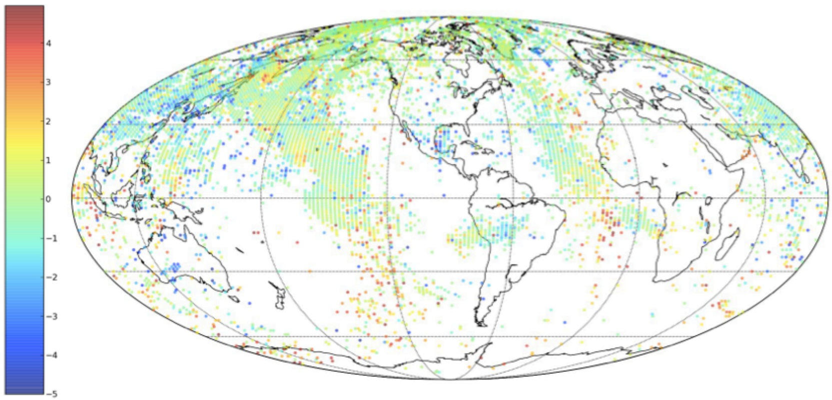
$P_{\rm diff}$ tomography

Observations & modeling



Pdiff sensitivity

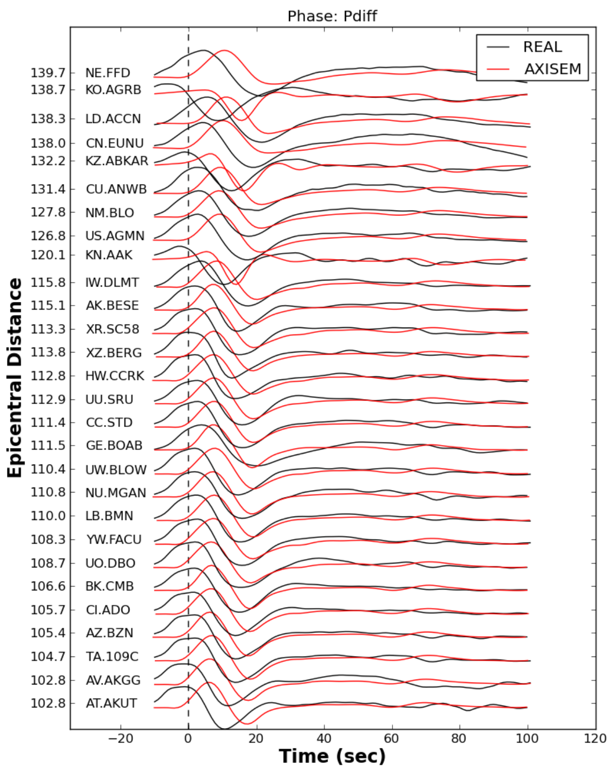
27k CMB traveltime anomalies (10s)



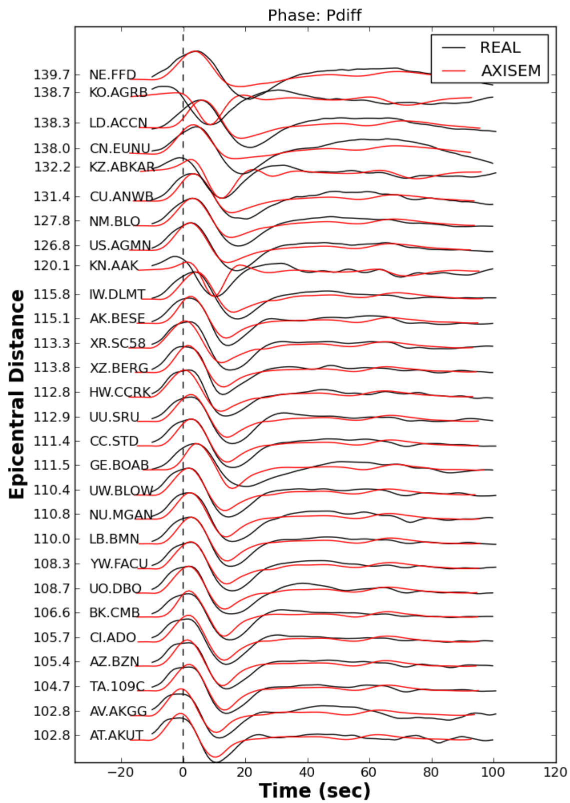
(Hosseini et al. 2013, in prep)

P_{diff}: 10 seconds

Raw



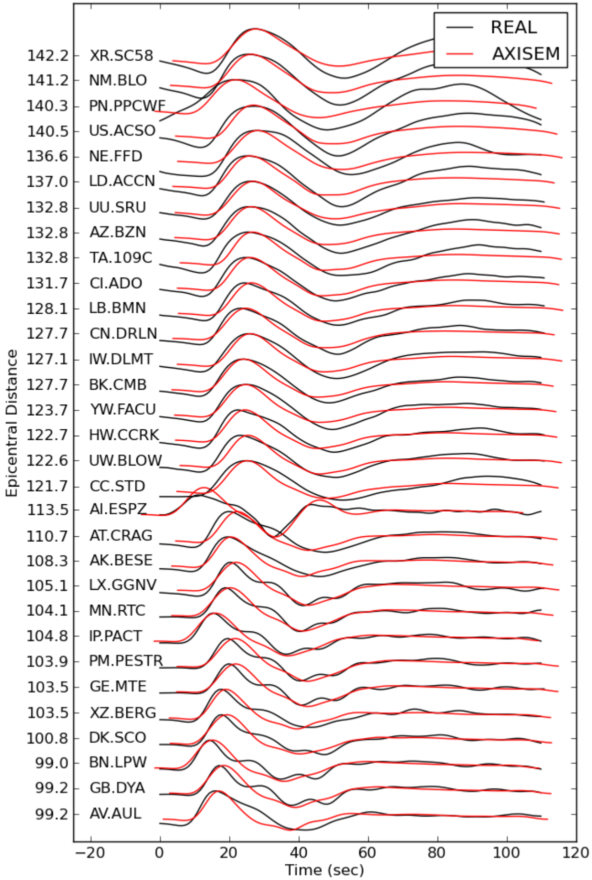
Shifted (xcorr)



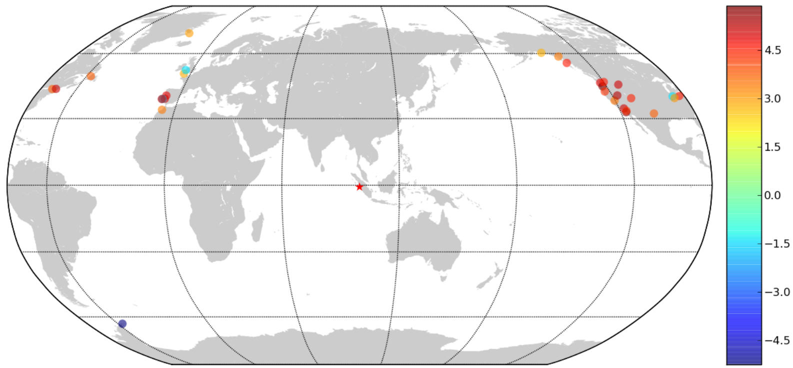
(Hosseini et al. 2013, in prep)

P_{diff}: 10 seconds

Shifted (event2)



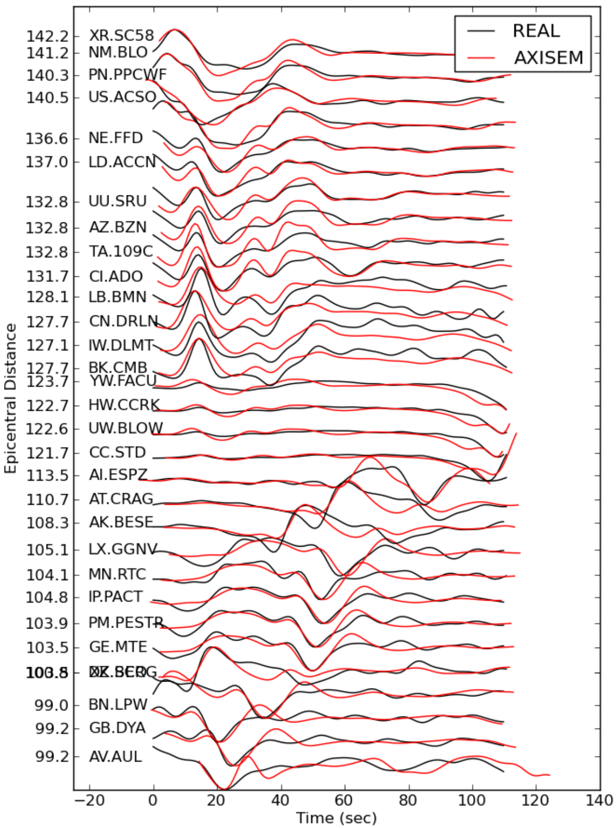
Mapped traveltimes



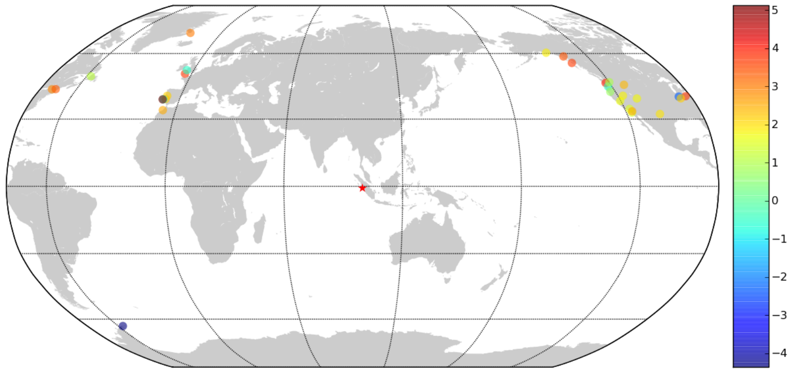
(Hosseini et al. 2013, in prep)

$PKiKP$: 10 seconds

Shifted (event2)



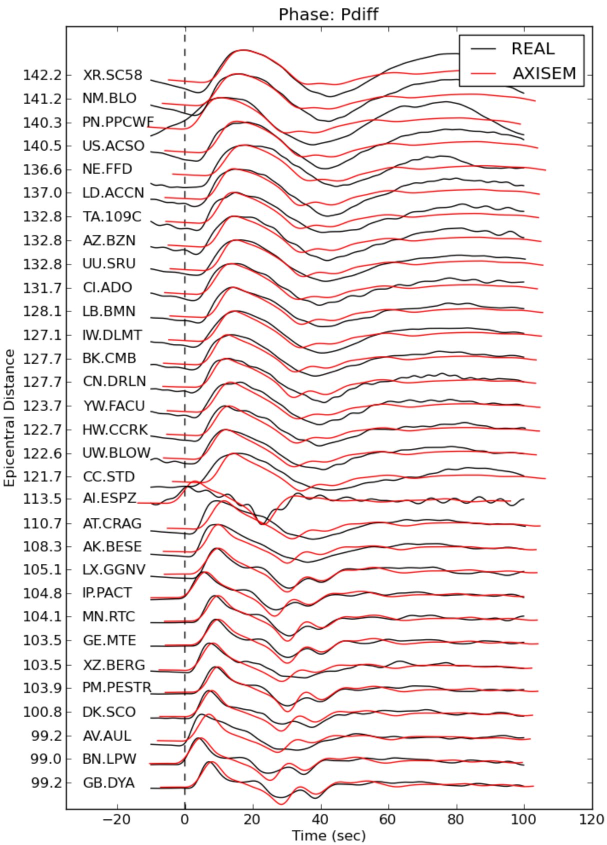
Mapped traveltimes



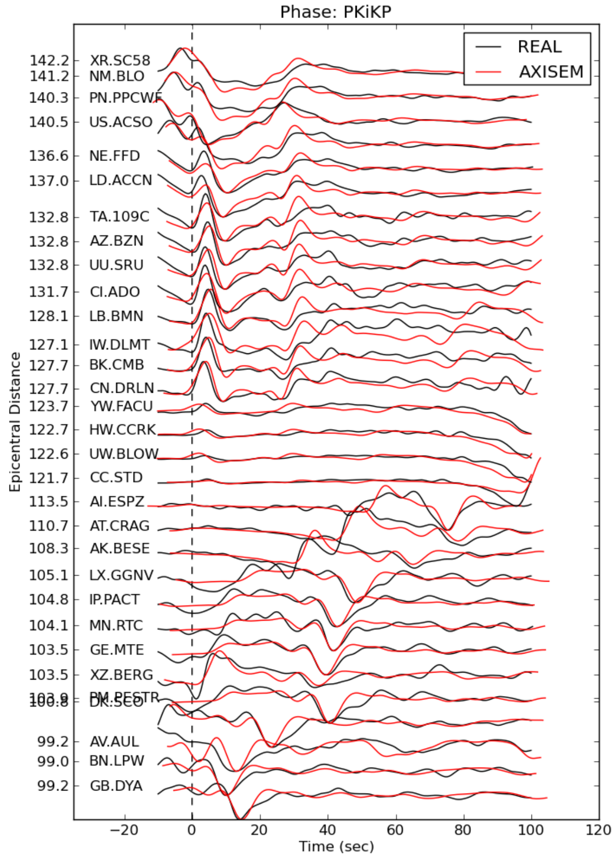
(Hosseini et al. 2013, in prep)

P_{diff}, $PKiKP$: 5 seconds

Pdiff

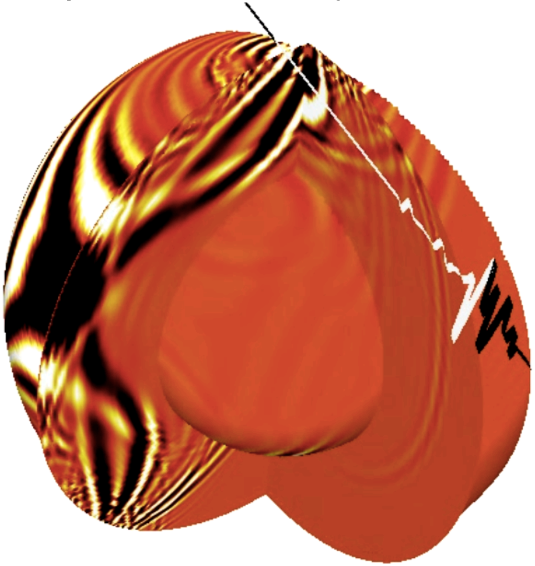


PKiKP

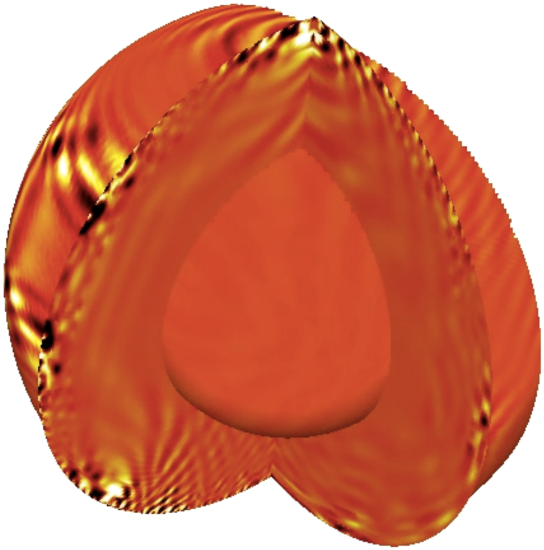


Sensible seismograms

Temporal sensitivity



Spectral sensitivity



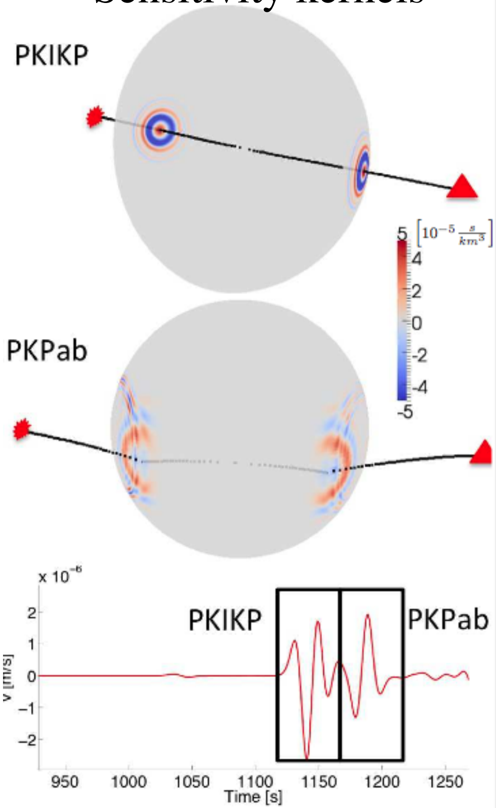
... with global wavefields $\mathbf{u}(\mathbf{x}, t)$ from AxiSEM

(TNM & Fournier, 2013, t.b. subm.)

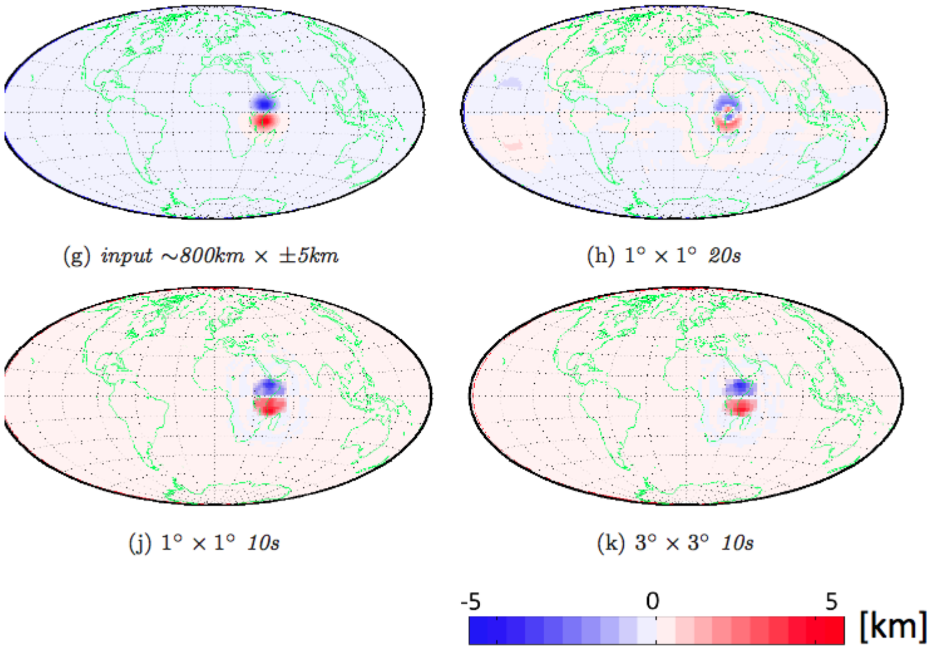
☞ Forensic sensing of seismograms ☜

PKP phase and CMB topography

Sensitivity kernels

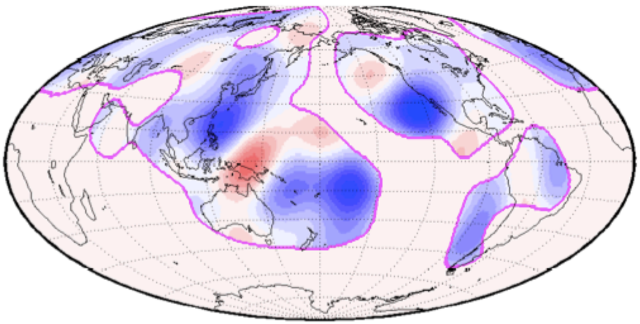


Synthetic inversions

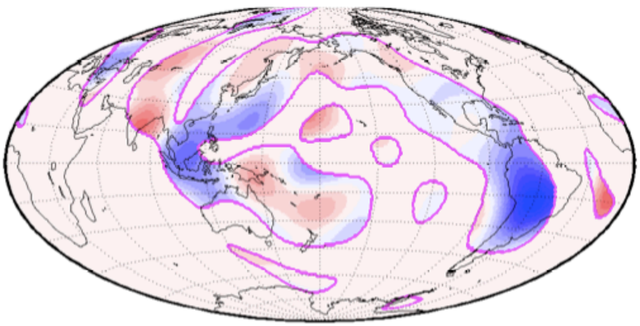


(Colombi, TNM, Boschi, 2013, to be submitted)

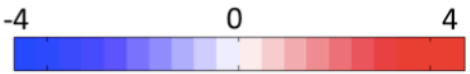
CMB topography models



(a) $SKSac$



(b) $PKIKP$



S40RTS traveltimes

$3^\circ \times 3^\circ$ grid

up to degree 12

contour lines: sufficient coverage

Inversion for topography only

☞Need joint inversion

(Colombi, TNM, Boschi, 2013, to be submitted)

Conclusions

Code works.

Full-range frequency global wavefields

Dimensional collapse: once-and-for-all solutions

Framekwork for scattering approaches

Data at 5-10s well suited for waveform tomography

Forensic sensitivity: Comprehensive data-model mining

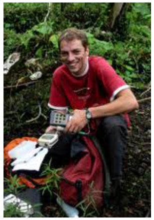
CMB topography: Poorly constrained without joint inversion

Onset-pick ⇒ traveltime ⇒ waveform ⇒ **wavefield seismology**

More information & tutorial

More info:
www.axisem.info

Kasra Hosseini Zad



Lion Krischer

Martin v. Driel

AxiSEM/ObsPy Tutorial

Aim: Familiarize users with code procedure and range of applications

Approach: Out-of-the-virtual box

Content: Obspy, AxiSEM, data and synthetics, scripts, manuals

1. Simulate at low-resolution: AxiSEM I/O procedures
2. Wavefields, record sections, source-receiver geometries
3. Load/plot event data (IRIS) with ObsPy scripts
4. Compare data with AxiSEM & SPECFEM synthetics
5. Change background models, filtering, source parameters
6. Cross-correlate traveltimes, plot delay times