Scattered wave and coda reliability in 3D elastic seismic simulation: new insights for the advancement of imaging studies

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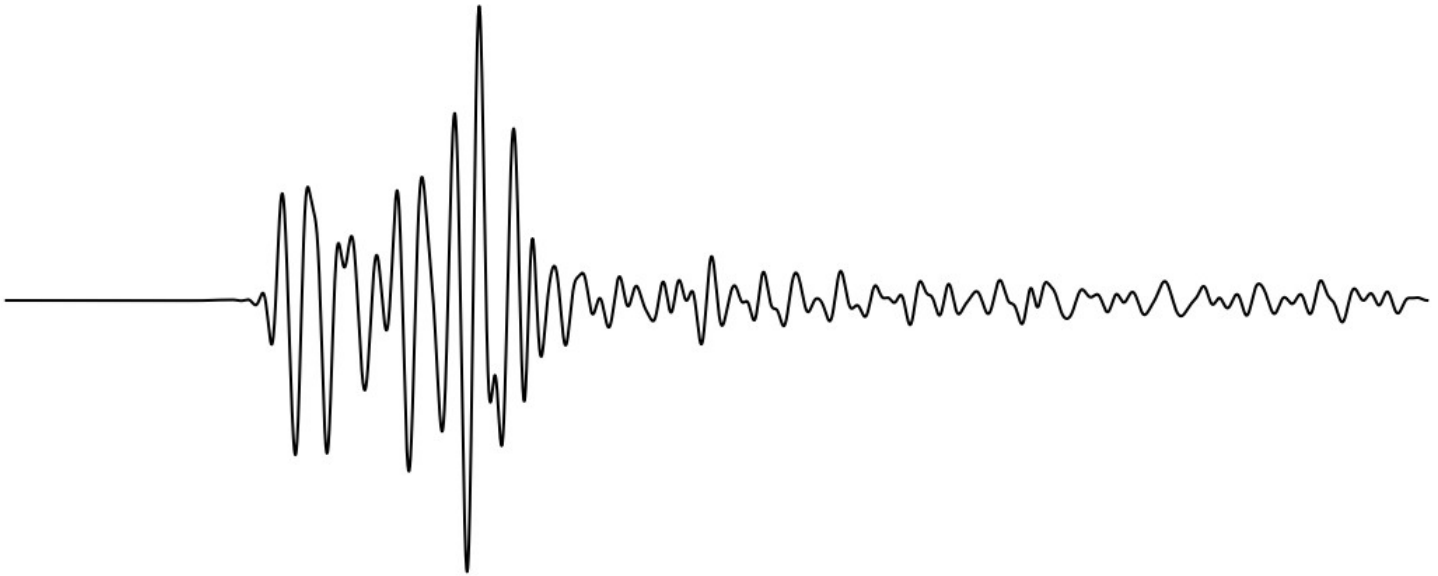

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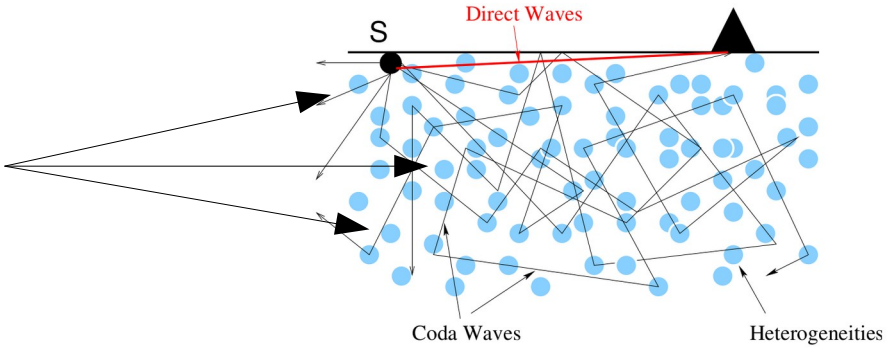
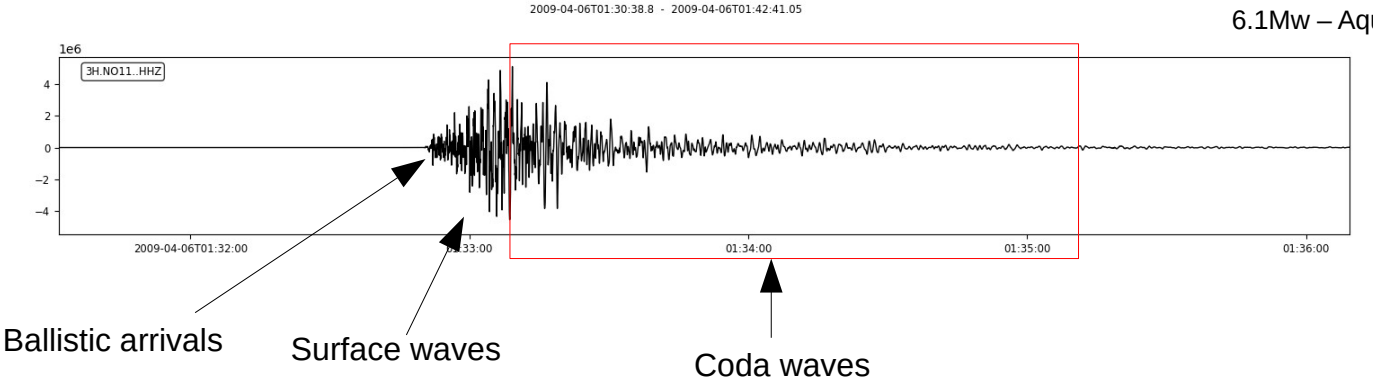
How are coda waves generated?

"The direct S-wave is followed by waves trains (coda) whose phases look random but whose amplitude decrease smoothly with increasing lapse time"

Seismic waves interact with heterogeneities by scattering and mode conversion

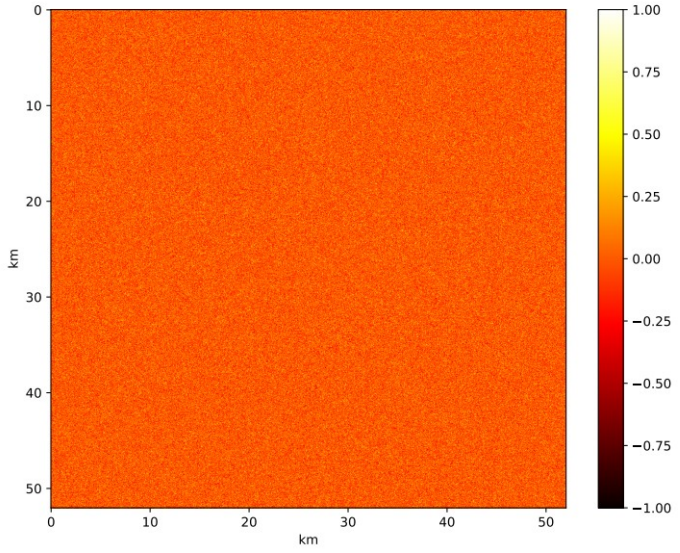


6.1Mw – Aquila 2009



[1]"Seismic Wave Propagation and Scattering in the Heterogenous Earth", Sato et al 2012

How to build a realistic scattering medium?

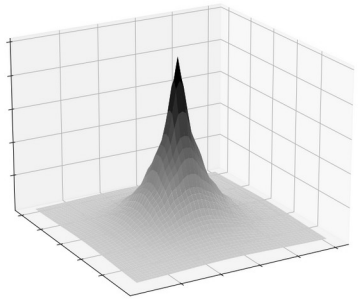


Random normally distributed values

*

Filtering

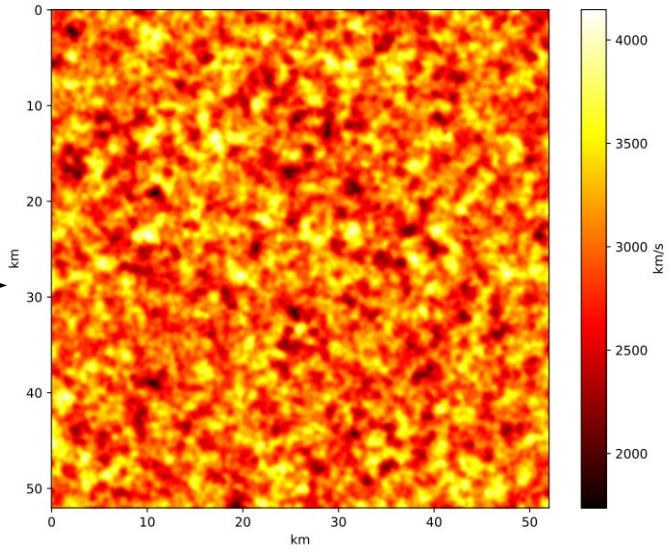
- Shape
- Correlation length



Laplacian filter

→

Vp



Laplacian correlated heterogeneities

Simulation details	
Element size	Elements number
200m	260x260x260

Medium details	
Correlation length	Std heterogeneity
300m	10% - 17% - 25%

Properties of a scattering medium come out of statistical analysis

Ensemble average

Average over thousands of realizations

A lot of realizations!

Spatial average

Average over thousands of receivers

Just one realization!

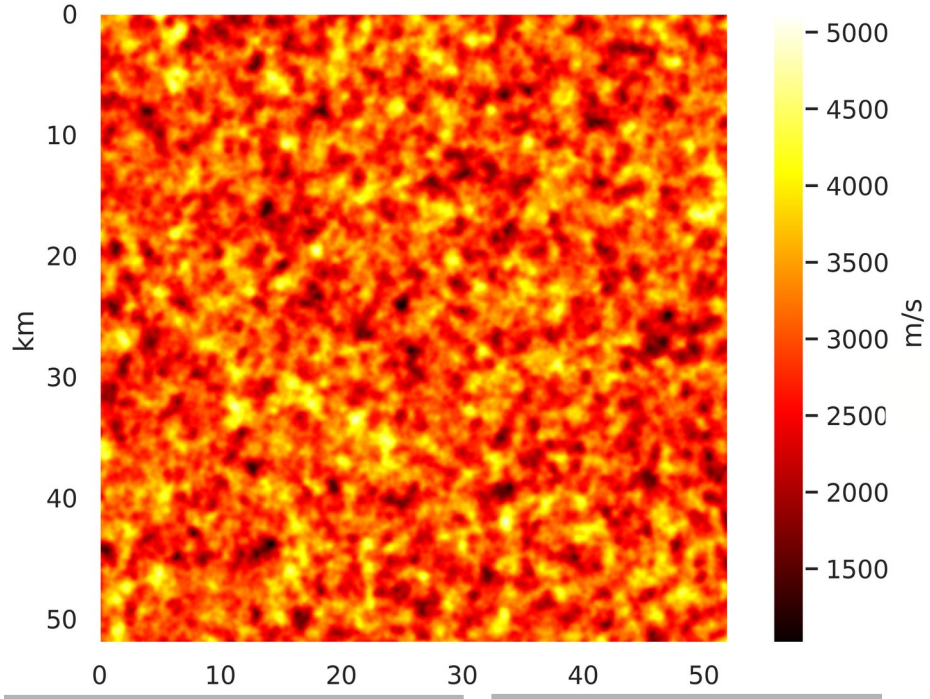
Conditions

1) Isotropic
2) Receivers must be sufficiently spaced

Assumption: At each receiver location, the waves interacted with heterogeneities with which other receivers did not interact or interacted poorly. Receiver must be sufficiently spaced

Full space elastic simulation with continuous heterogeneity

P-wave velocity



Medium details	
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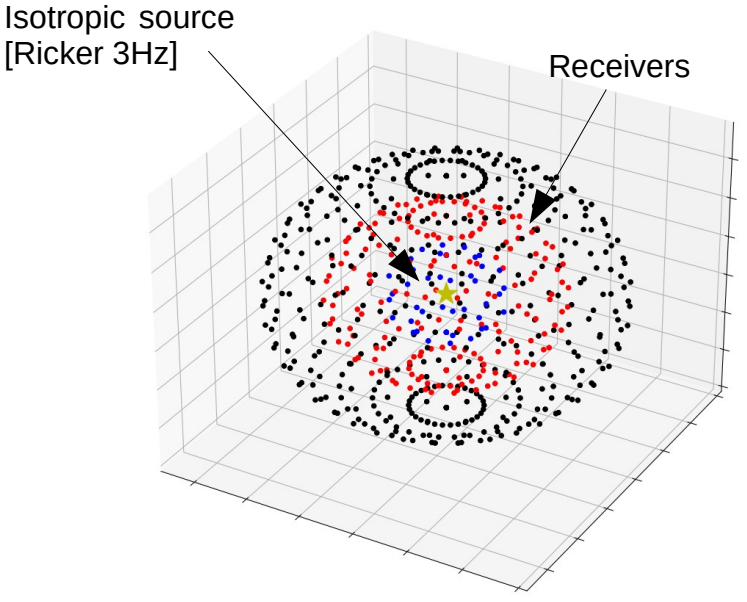
Simulation details	
Element size	Elements #
200m	260x260x260

Source receivers configuration

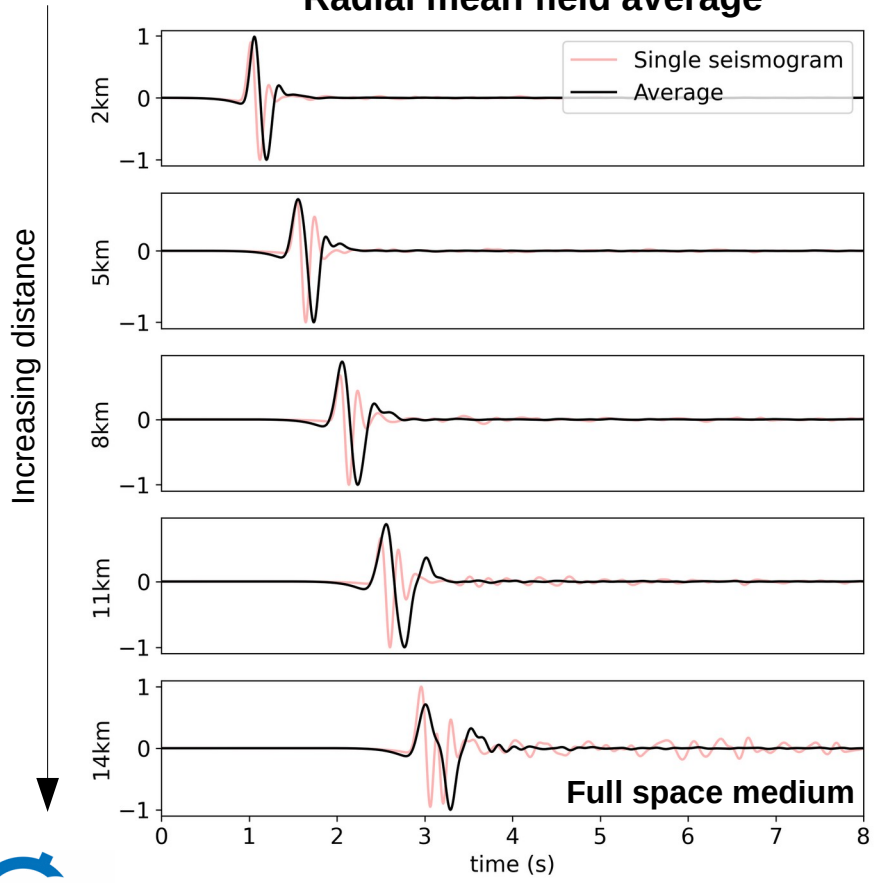


Assuming the receivers are sufficiently spaced and there is isotropy, **spatial averaging** can replace ensemble averaging

Comparison of numerical simulation and scattering theory

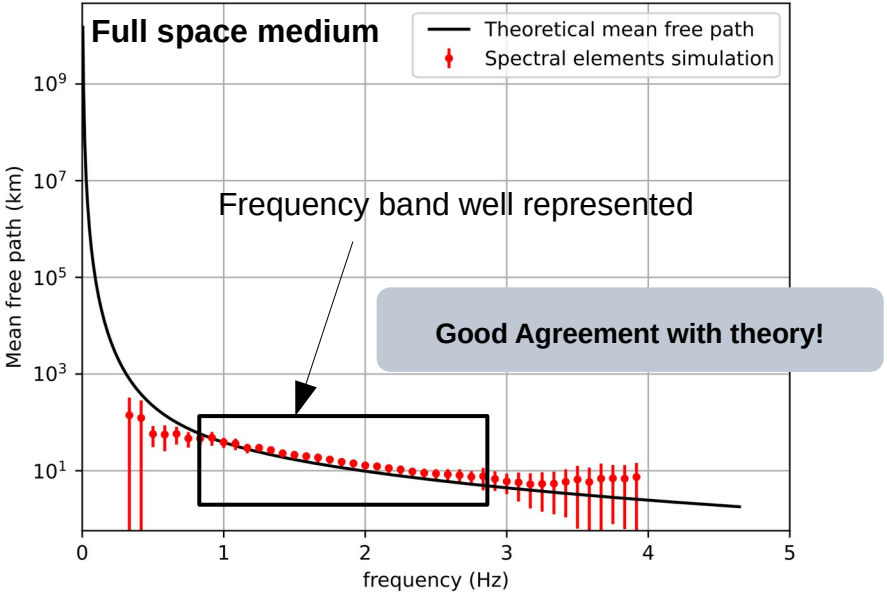
Scattering mean free path

Radial mean field average



Mean free path computation

Exponential fitting of the mean field frequency components' amplitude as a function of distance.



The limits of the well-represented frequencies are determined by the medium size and short decay of high frequencies

Comparison of numerical simulation and scattering theory

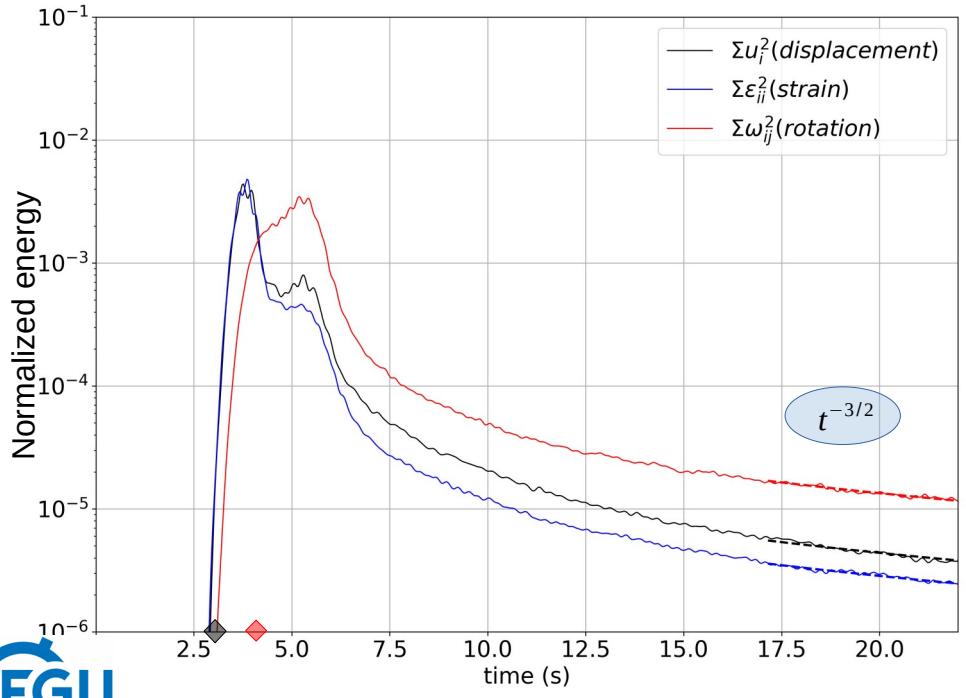
Transition to diffusion and asymptotic decay of the energy

Average of the energy of displacement, strain and rotation at 7km distance

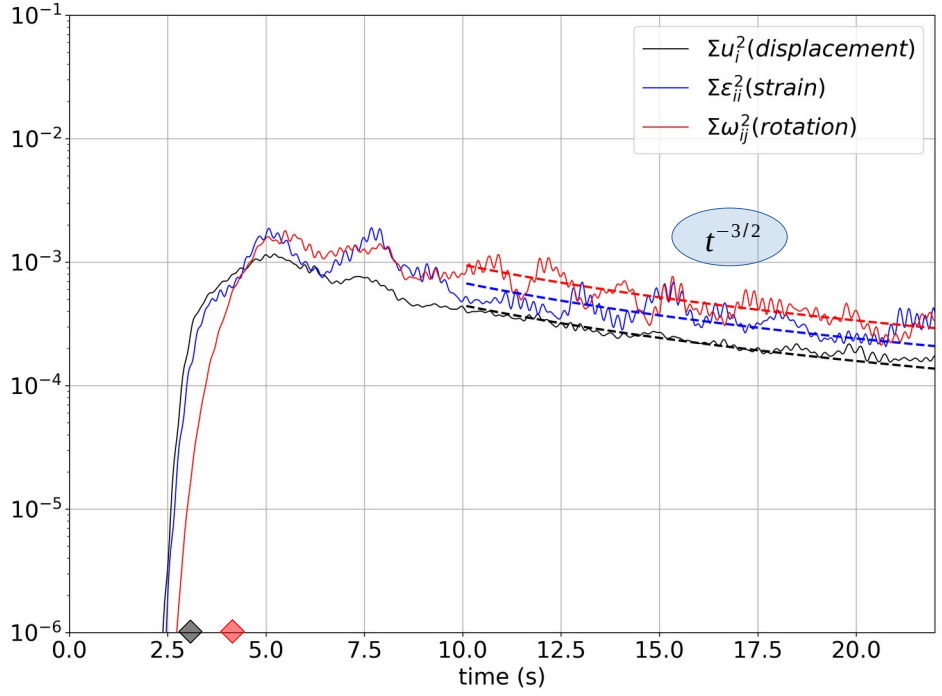
Travel times: P-wave, S-wave

$$\frac{\partial E}{\partial t} - D\nabla^2 E = W\,\partial(x)\partial(t) \xrightarrow{t\to\infty} E(t) \propto t^{-3/2}$$

10% standard deviation heterogeneity



25% standard deviation heterogeneity

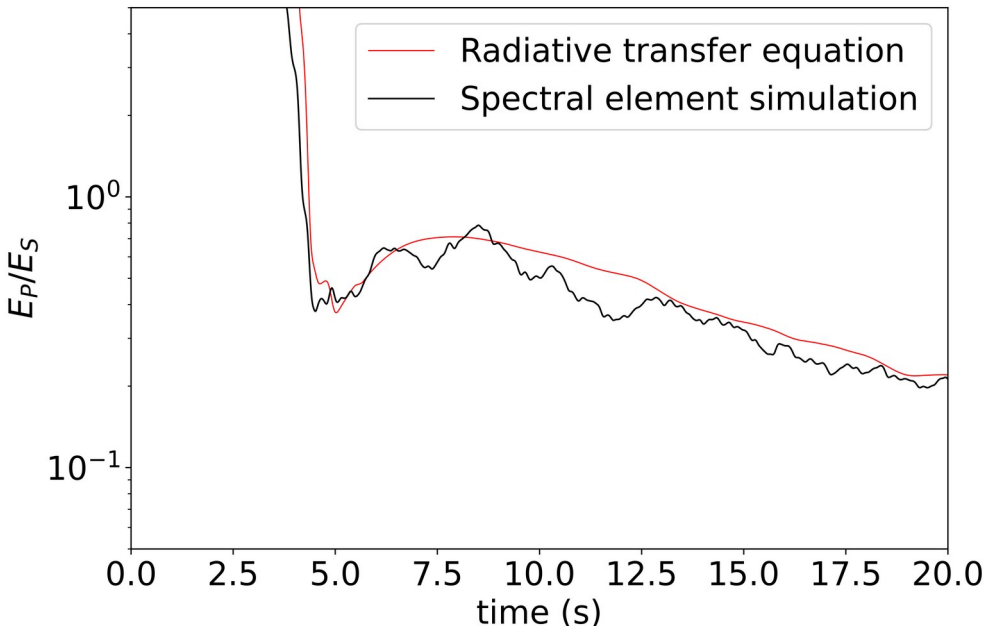


Comparison of numerical simulation and scattering theory

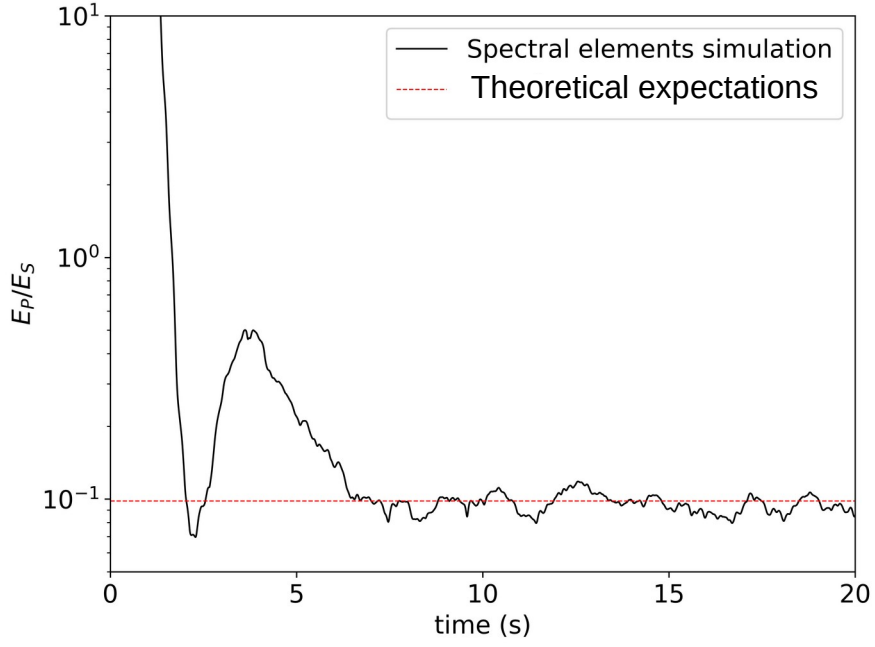
Energy partition ratio

The energy conversion leads to a state where shear and longitudinal wave energy is partitioned in a specific ratio

10% standard deviation heterogeneity

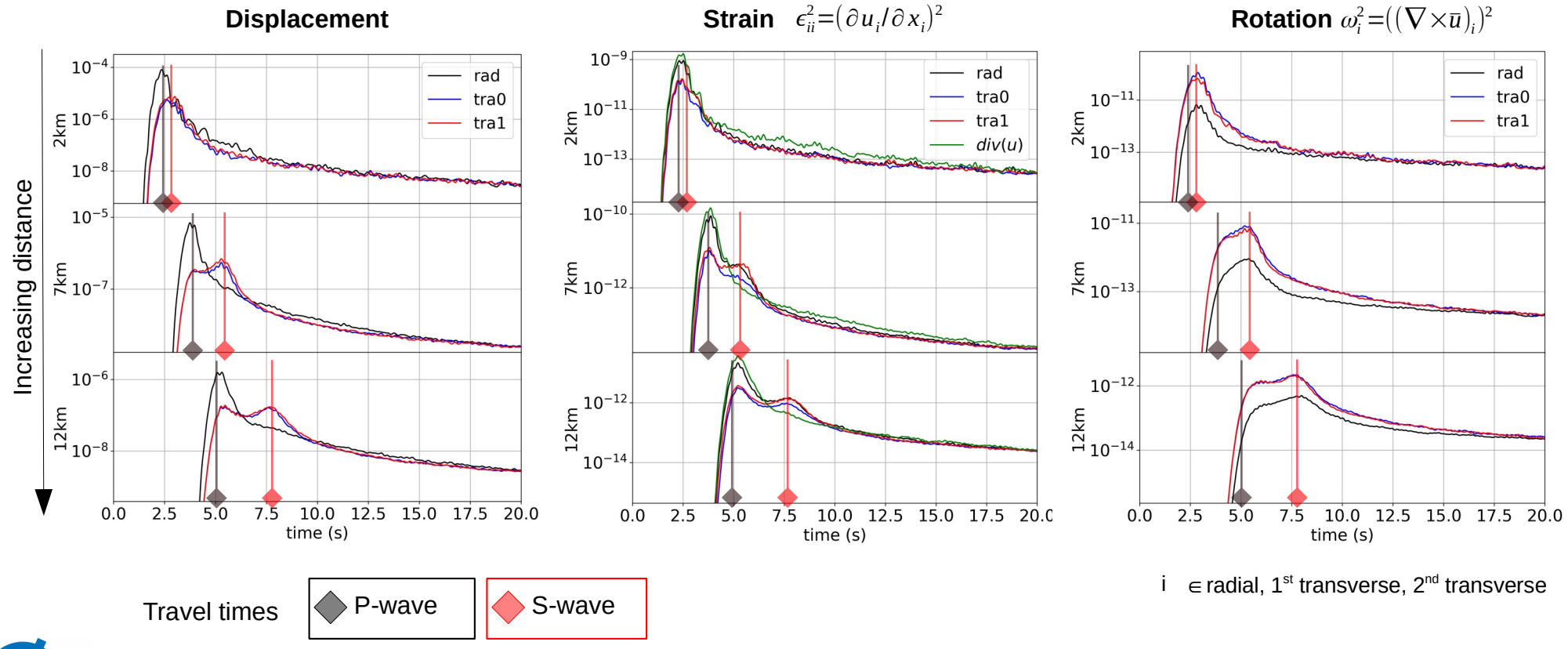


25% standard deviation heterogeneity



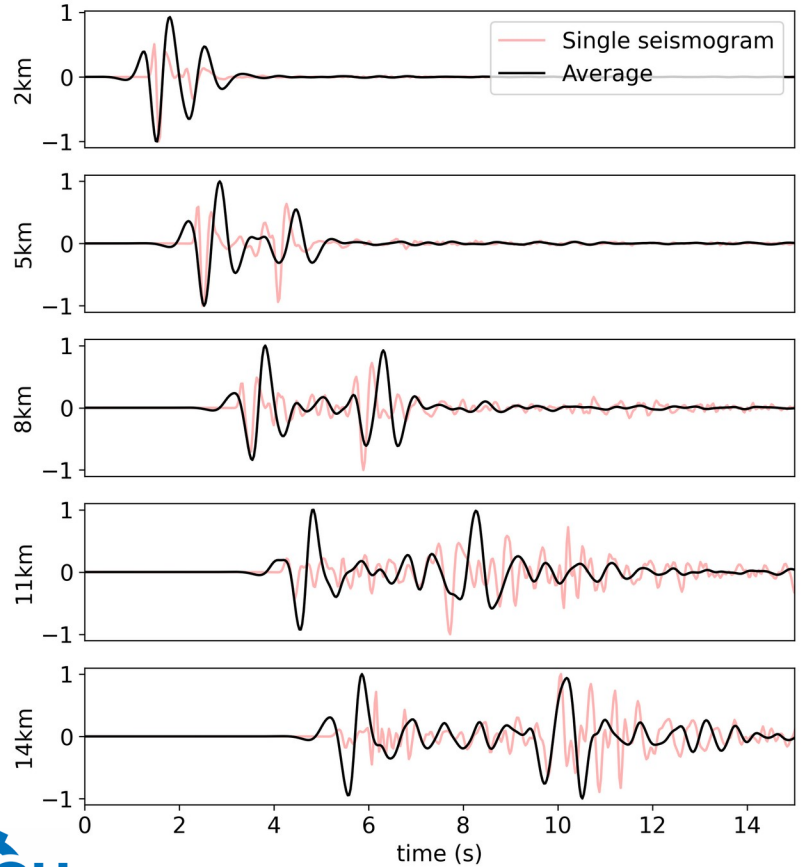
Average energy over a sphere

Energy of radial and transverse components of displacement, strain and rotation, smoothed by a moving window



Half space simulation continuous heterogeneity

Displacement radial component average



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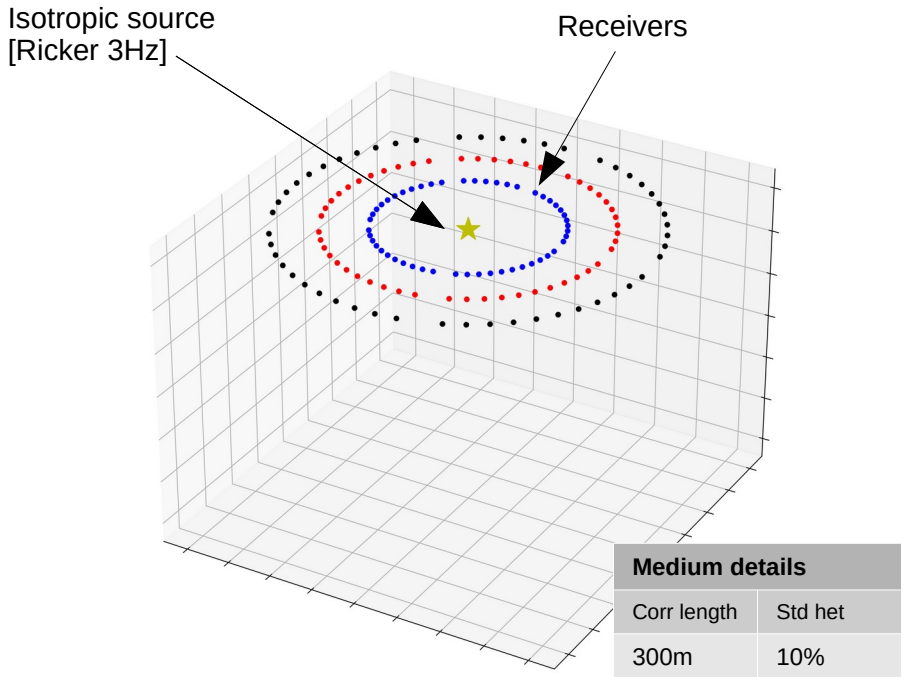
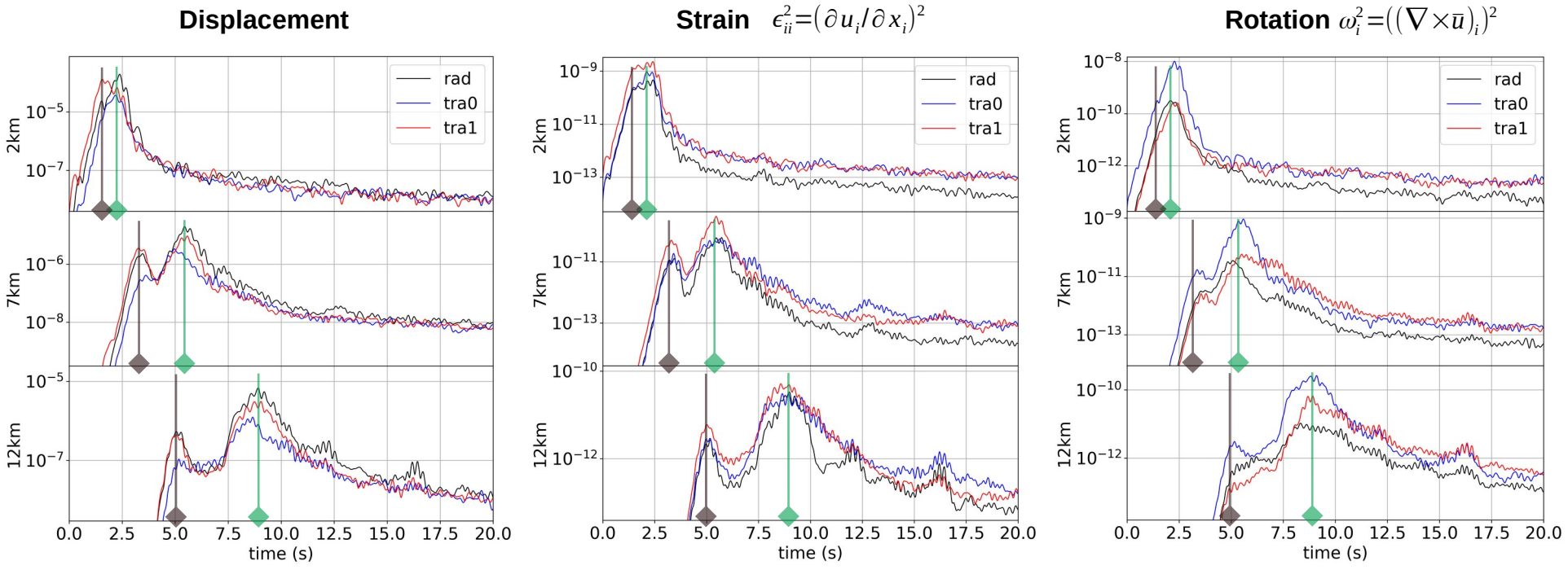


Medium details	
Corr length	Std het
300m	10%

Receivers positioned in concentric circles, with the source at the center.

Average energy over a circle

Radial and transverse components of displacement, strain and rotation, smoothed by a moving window



Conclusions and take-home message

We performed many simulations using a spectral element code in heterogeneous media

We compared our observations with scattering theory and found a perfect agreement in the following aspects:

- Scattering mean free path
- Transition to diffusion in both full and half space
- Partition of energy in both full and half space

Rotation and strain:

- Allow to separate the P and S energy in a wide range of frequency
- Show different behaviors in terms of evolution of energy compared to the displacement field

The results of this study demonstrate that it is possible to accurately simulate the physics of seismic wave scattering in heterogeneous media. **Such simulations can be a valuable tool for studying seismic wave scattering as well as for inversion purposes to derive the scattering parameters of a region.**

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