Transdimensional Seismic Tomography, High Performance Computing solutions and applications

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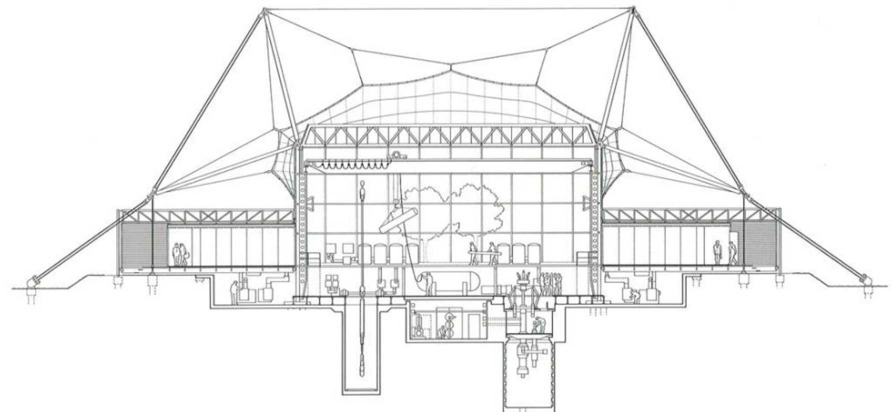
Geophysics Modelling and Inversion Seminar



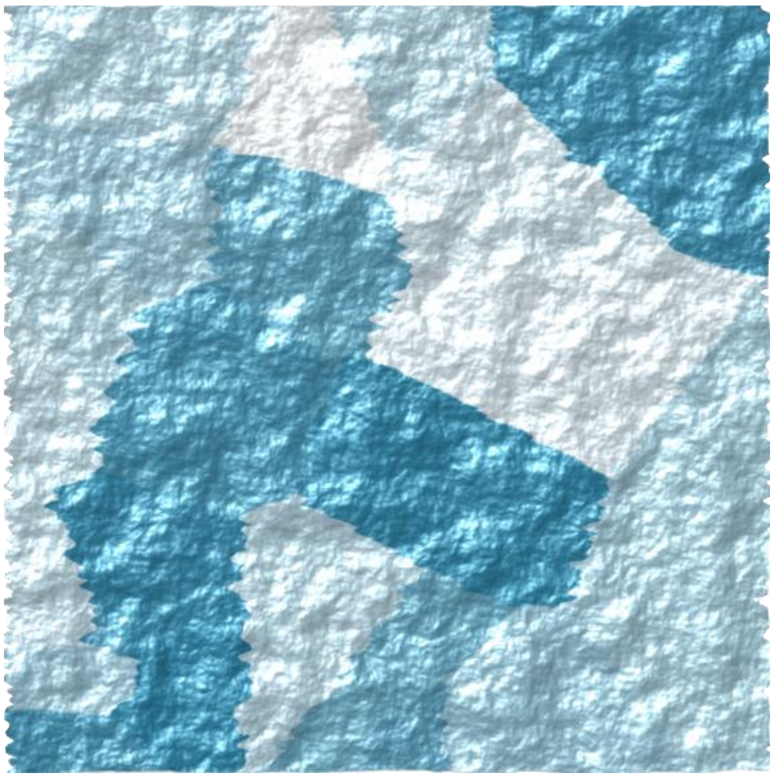
Schlumberger Gould Research

Schlumberger Geophysics Research

University of Edinburgh

Seismic Tomography

- Invert for a physical property of the medium…



Rock's seismic velocity…

Seismic Tomography

- Invert for a physical property of the medium…

…approximated by a Voronoi tesselation

Tomography ⇨ Transdimensional

- Invert for a physical property of the medium…

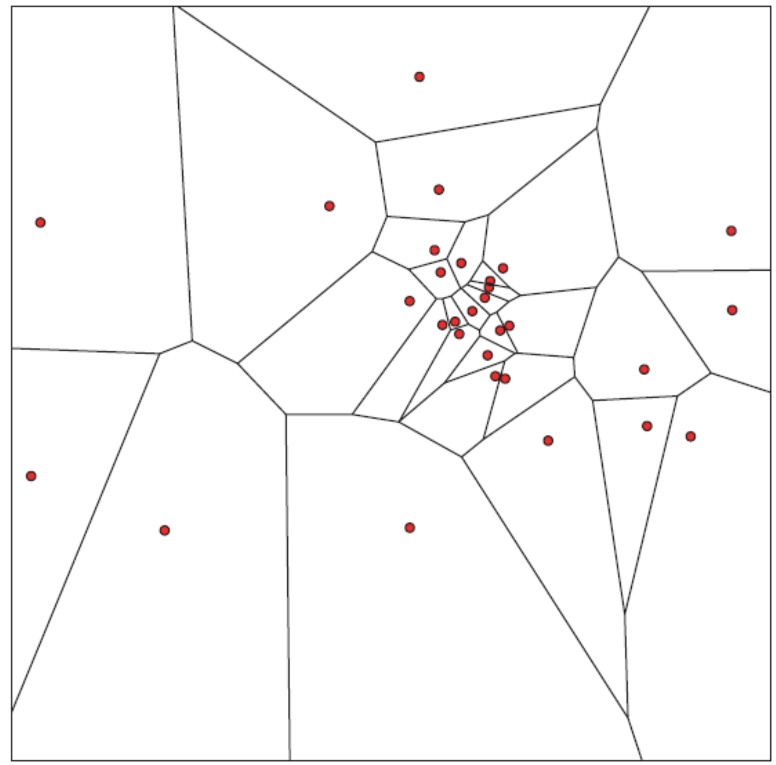
Voronoi grid of seismic velocity

Transdimensional Tomography

- Invert for a physical property of the medium… and for the dimension of the parameter space.

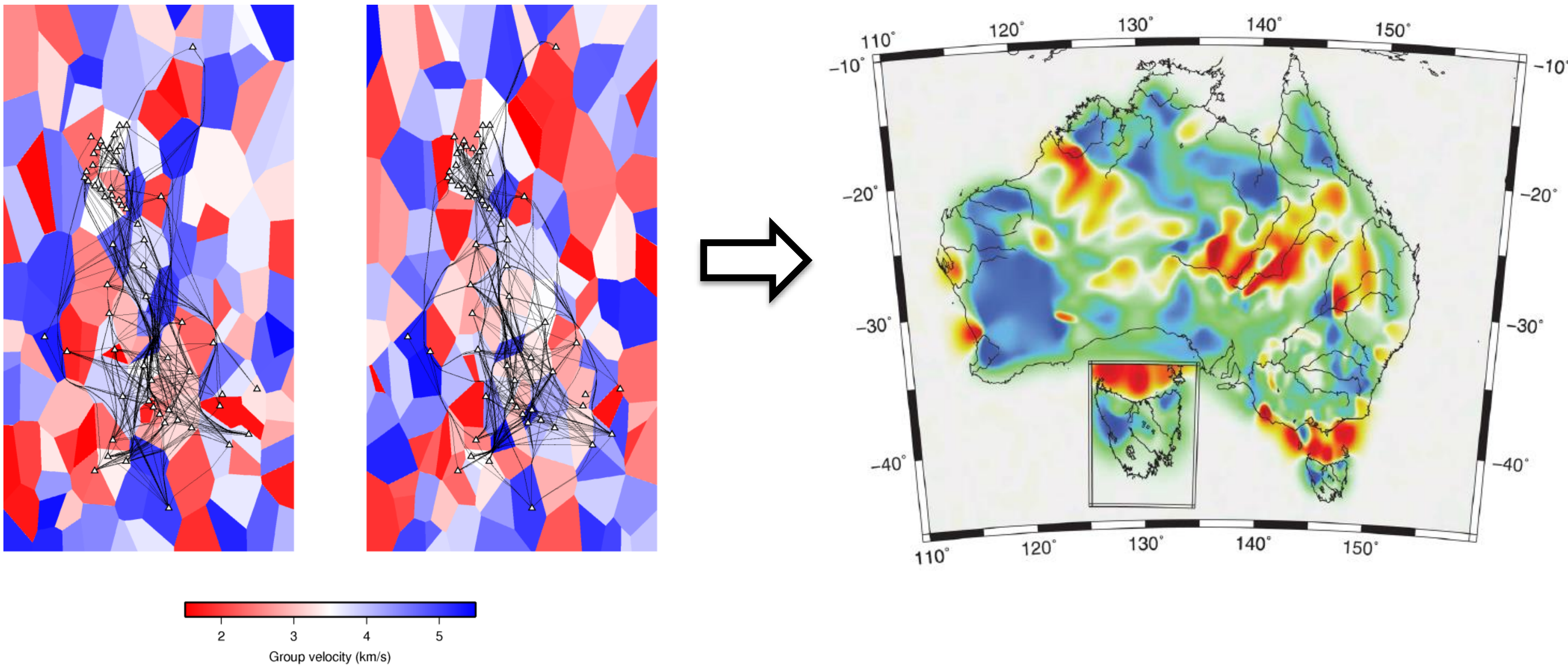
  – Extra parameter: Number of Voronoi cells for a 2-D physical model

Voronoi grid of seismic velocity



Transdimensional Tomography

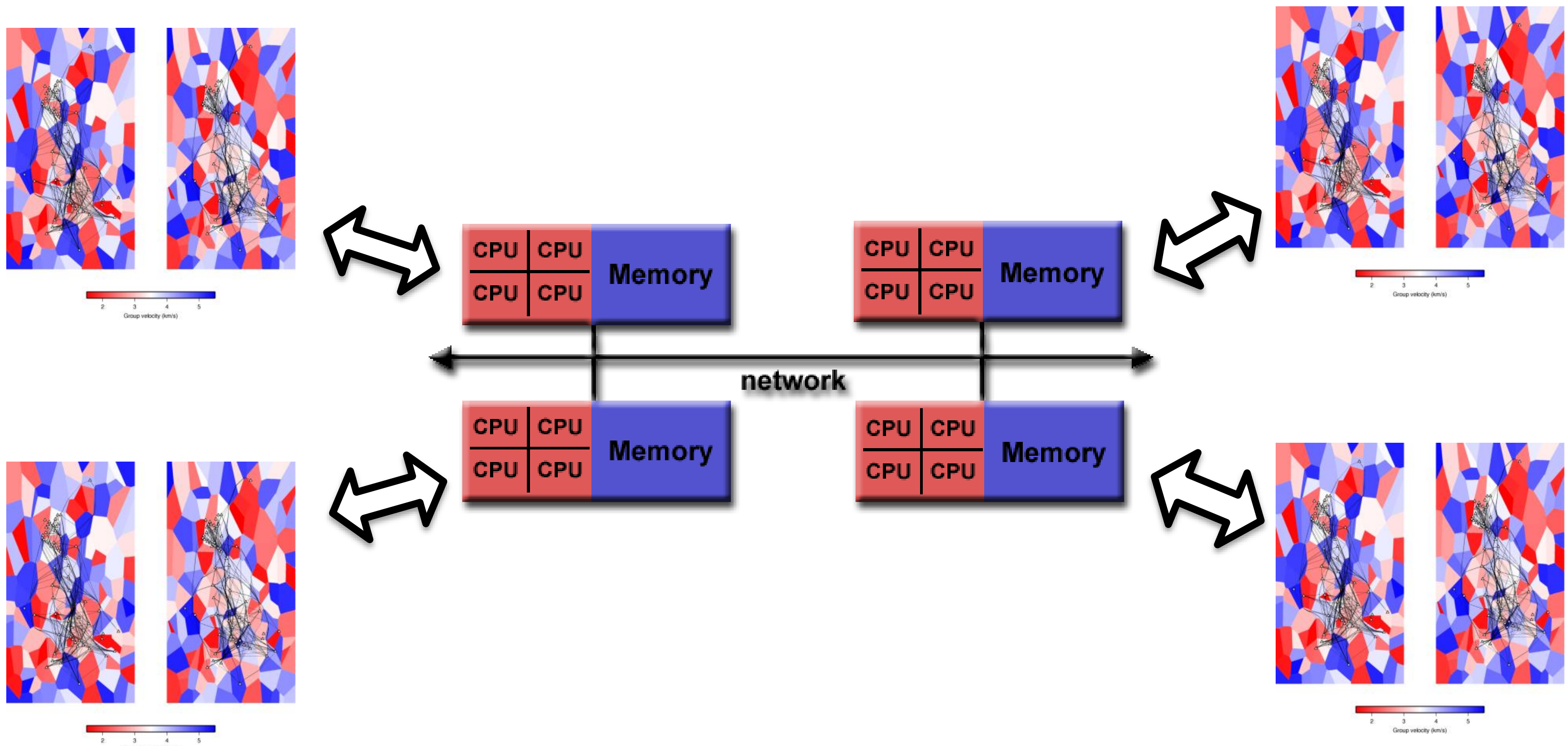
- Solutions as “ensembles” of accepted samples along MCMC chains.



Transdimensional Tomography

- Fast Marching Method is computationally expensive!

- Here we show how we used HPC solutions for increasing the performance of travel-time tomography.



Literature and history

- Green, P. J. (1995). *Reversible jump Markov chain Monte Carlo*.

  4403 Citations!

  – Transdimensional inverse theory.

- Sambridge, Bodin, Rawlinson, Gallagher et al.(2006-present)

  – Transdimensional Seismic Tomography, Geochronology, Hierarchical Bayes and Unknown data noise.

- Galleti and Curtis (2014)

  – MPI Non-linear Transdimensional Tomography: RJTOMO code.

Outline

- Transdimensional inversion in the Geosciences
- Preliminaries in Transdimensional Inversion
- Love-wave Tomography of the British Isles
- High Performance Computing Solutions
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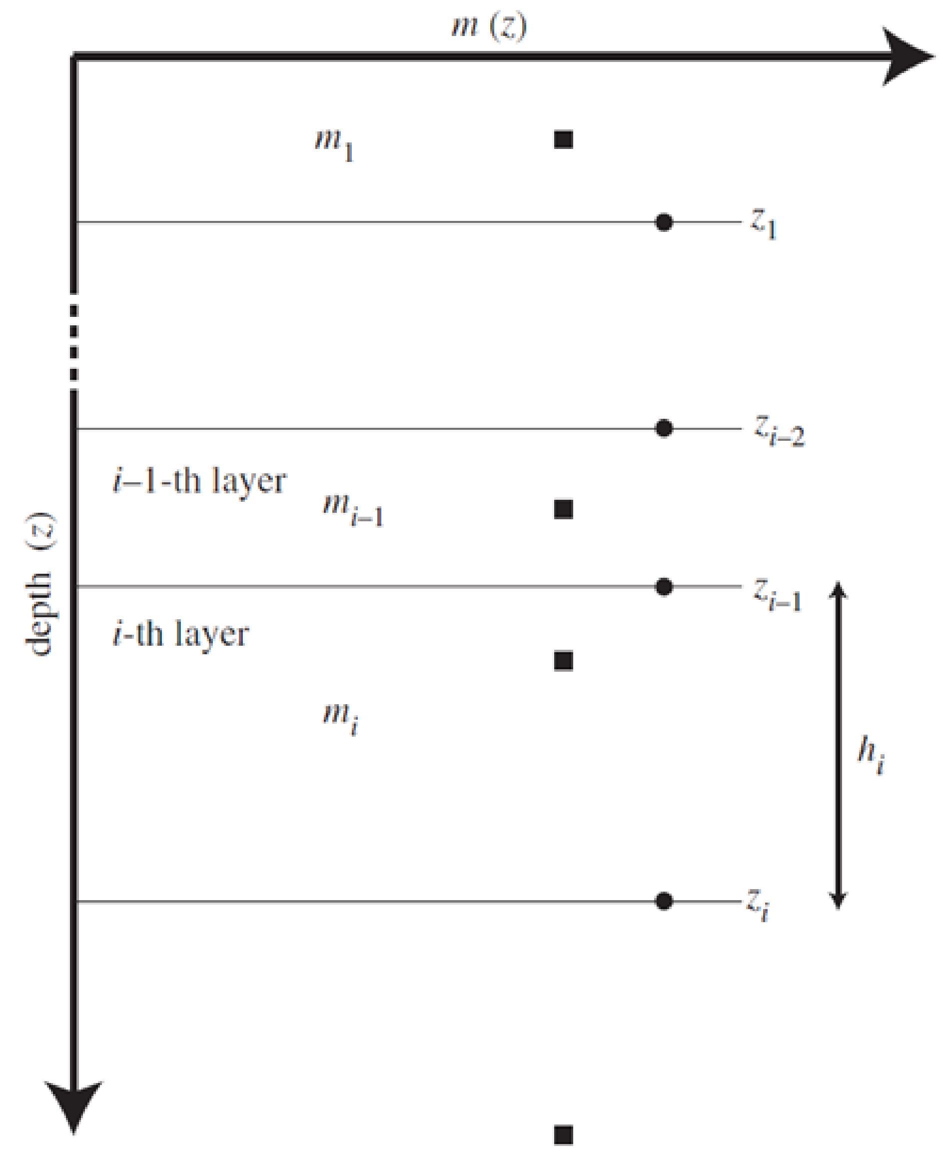
Transdimensional inversion in the Geosciences

- Application: Rock's property identification in stratified media

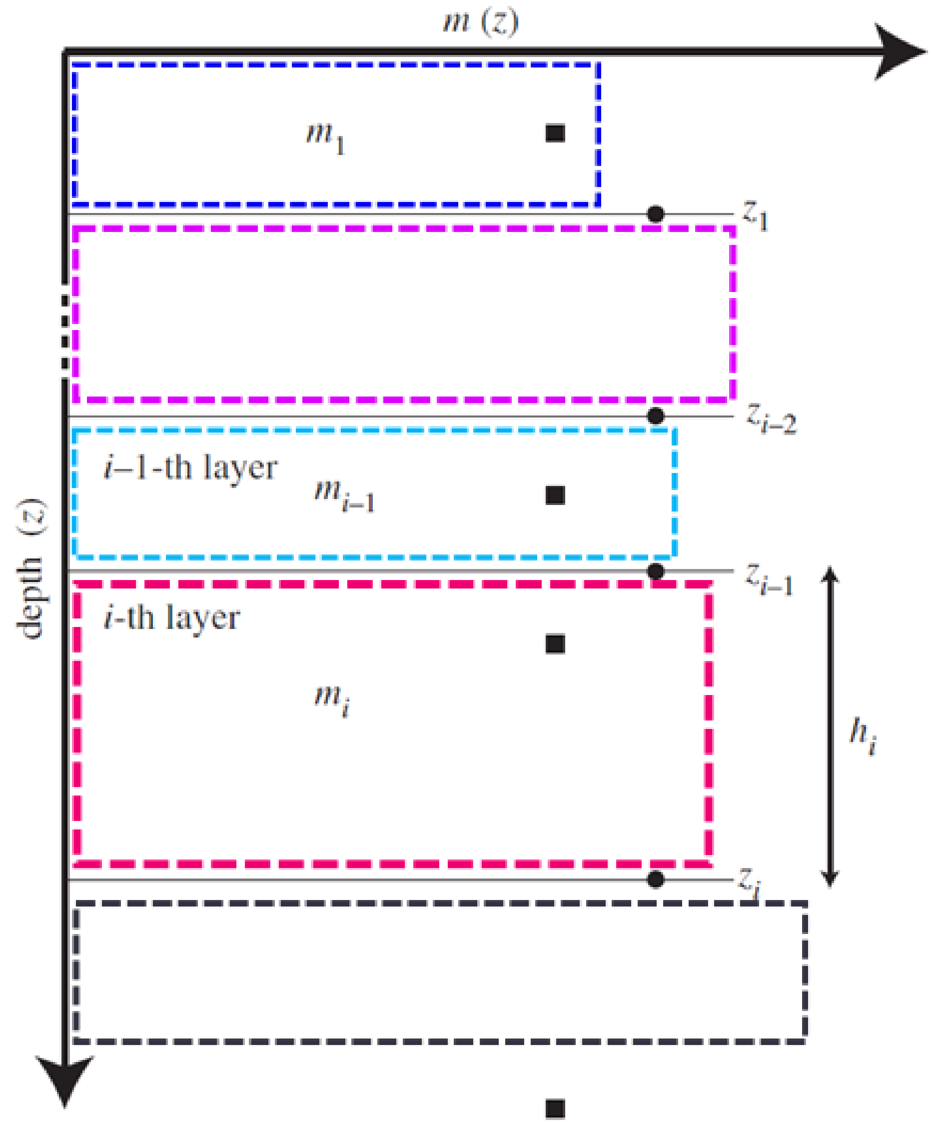
Transdimensional inversion in the Geosciences

- Parameter space dimension is unknown.
- Number of layers varies along inversion.



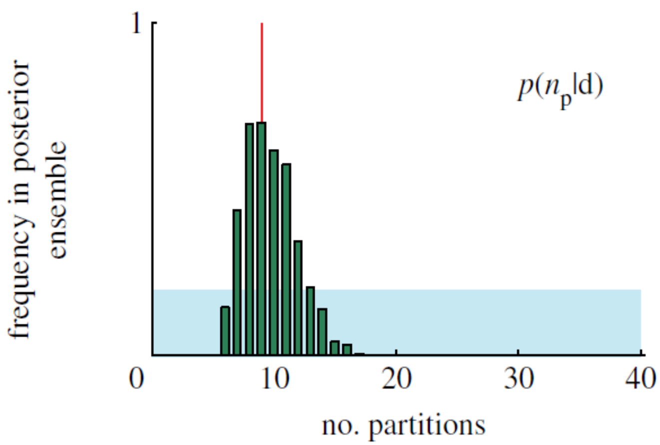
Transdimensional inversion in the Geosciences

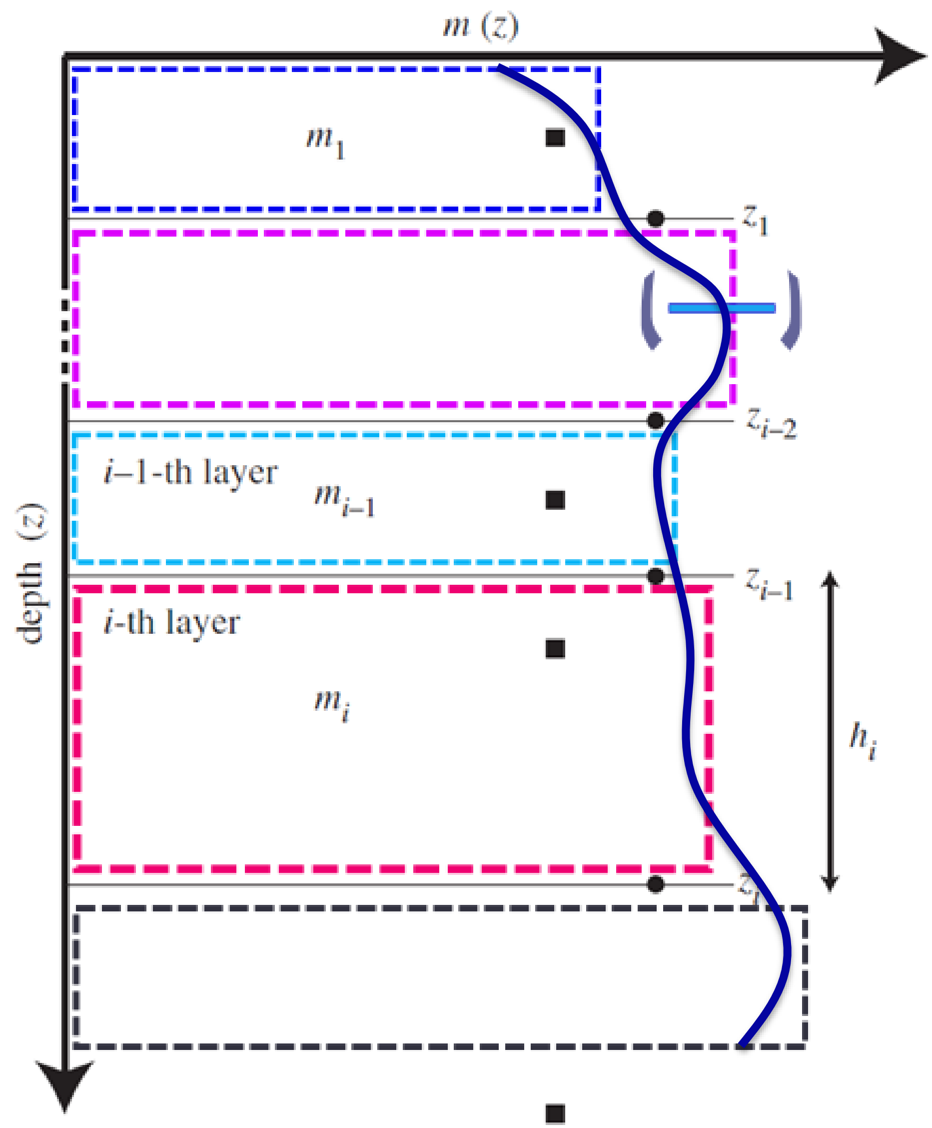
- Size of grid as well as the rock property in each layer is unknown.



Transdimensional inversion in the Geosciences

- Solution is built from the average of the accepted solutions.
- We obtain as well a posterior in the number of partitions.





Transdimensional inversion in the Geosciences

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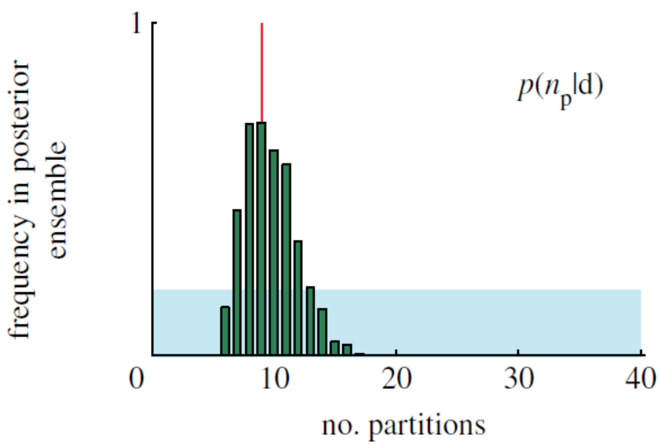
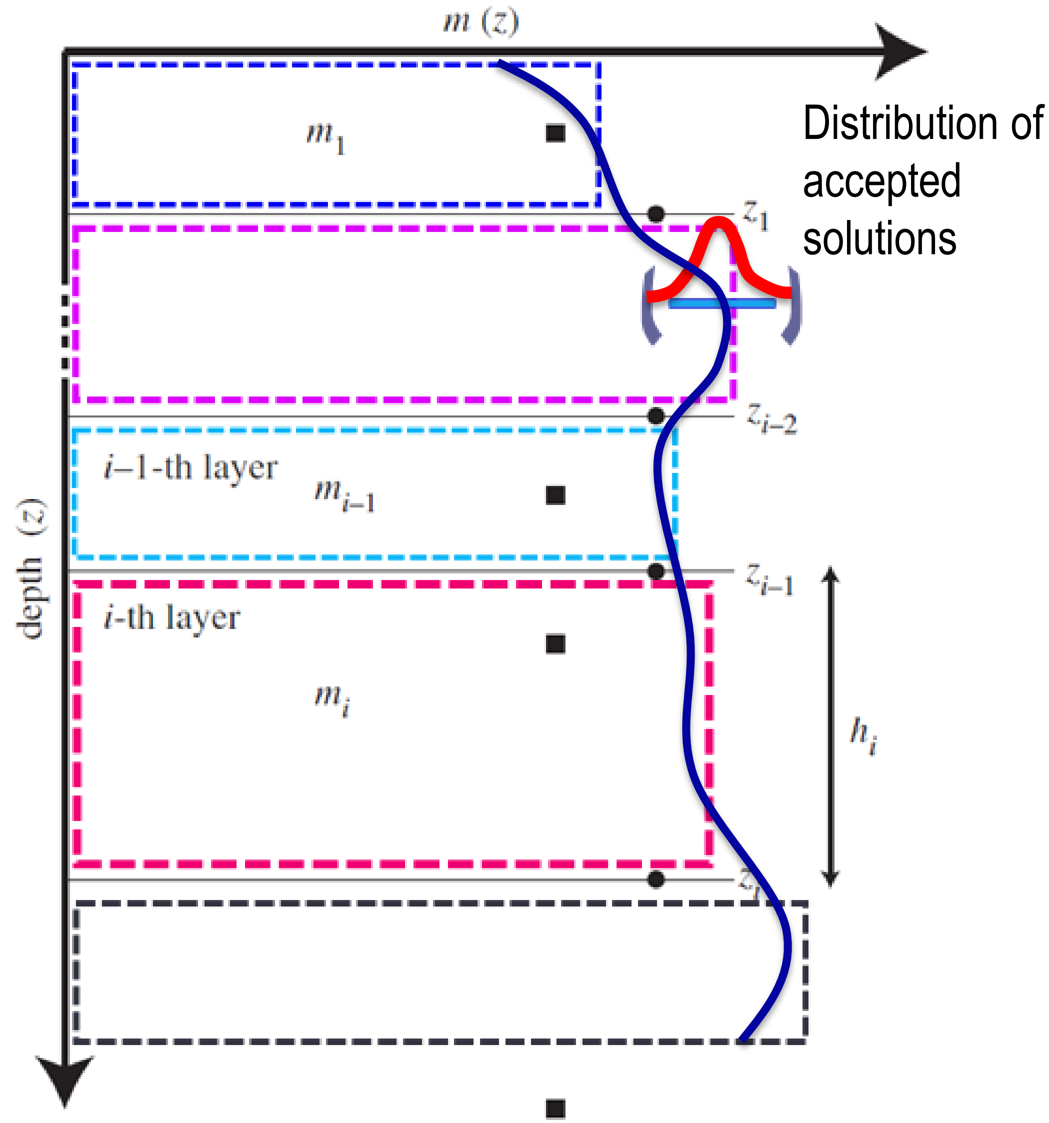
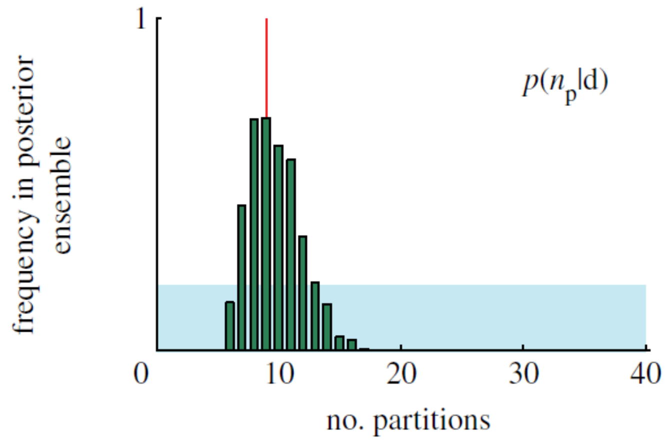
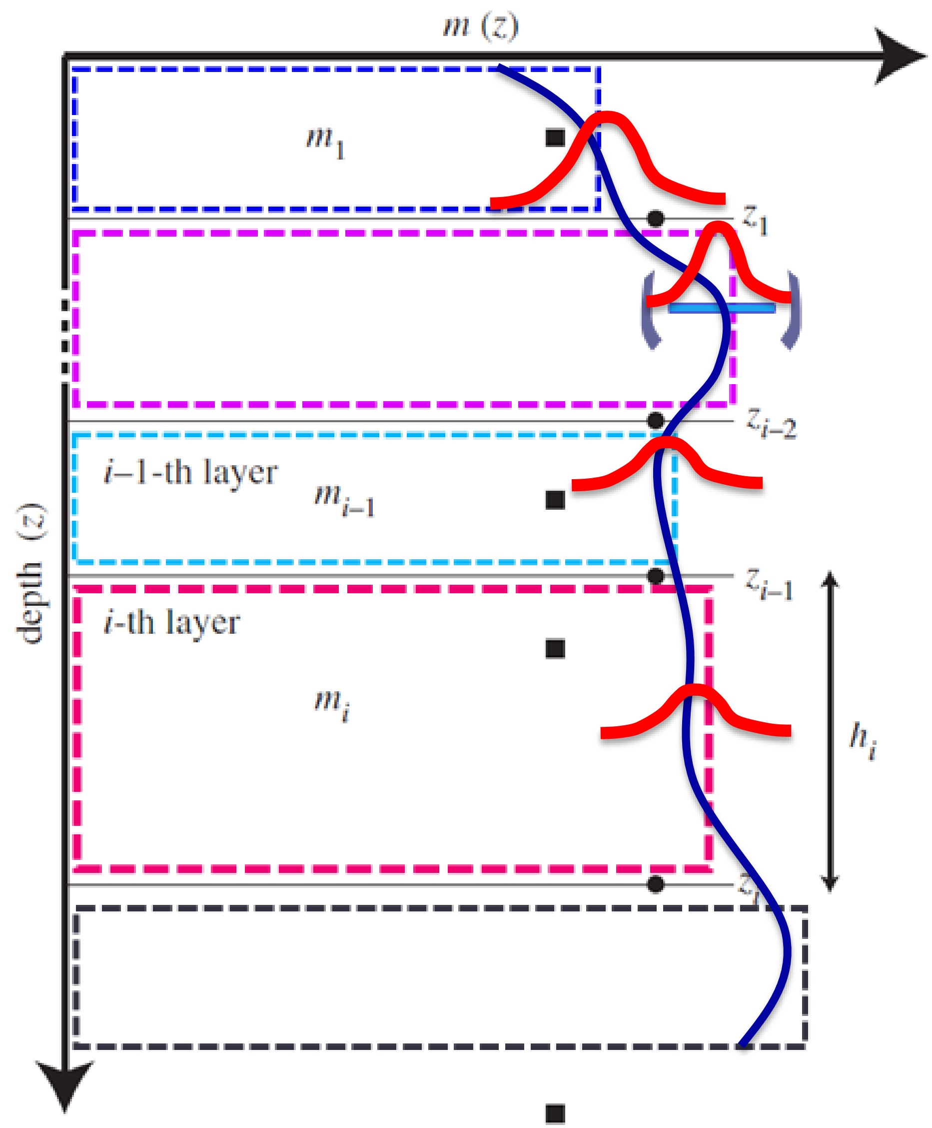




Transdimensional inversion in the Geosciences

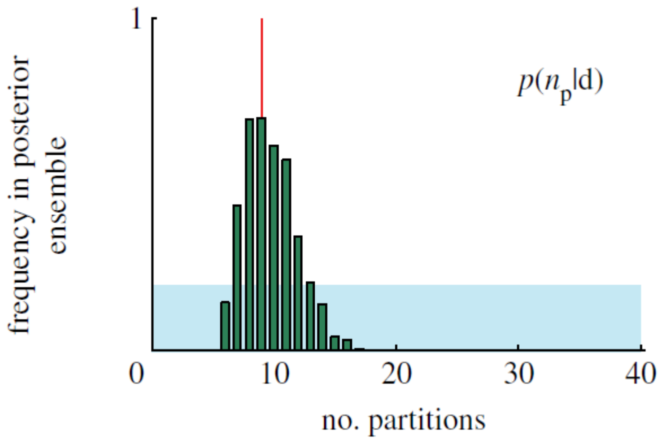
- Solution is built from the average of the accepted solutions.
- We obtain as well a posterior in the number of partitions…
- …and posteriors for all depths…

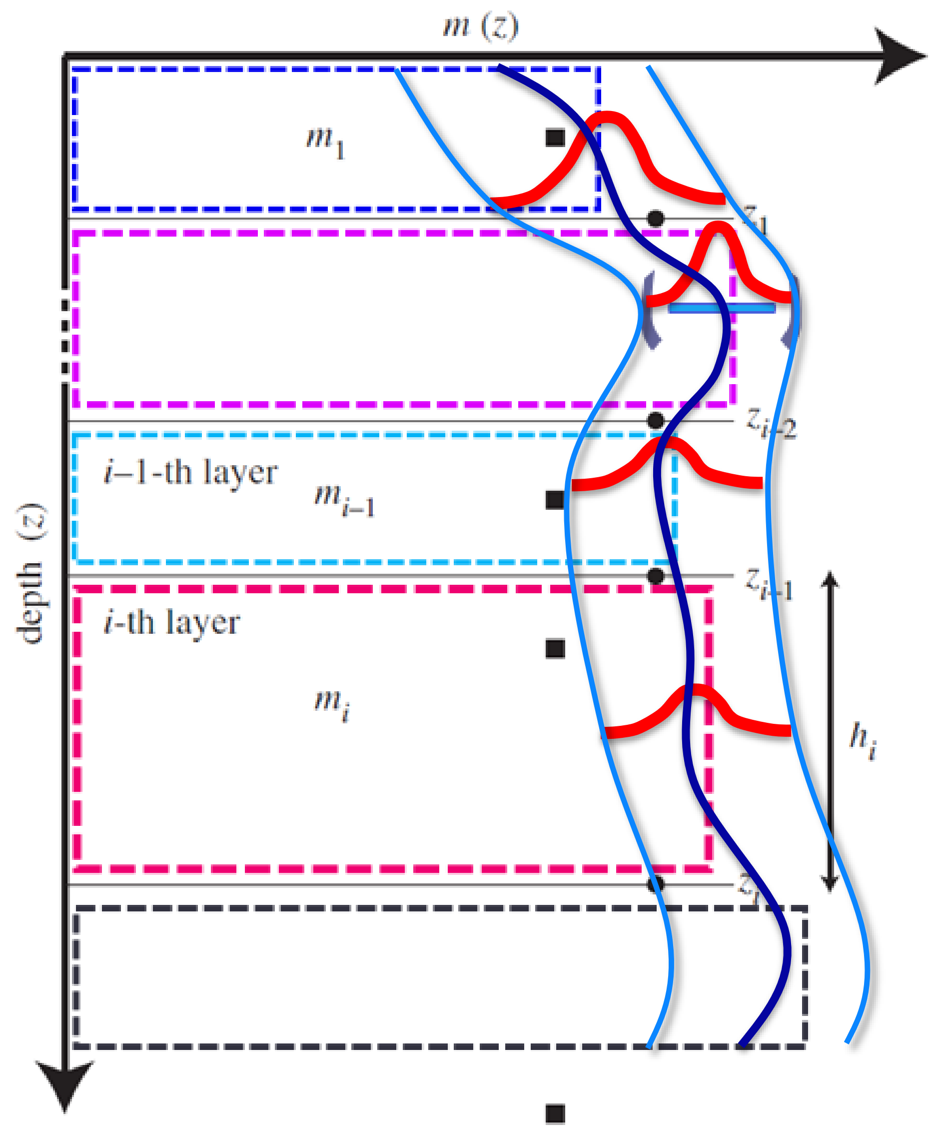




Transdimensional inversion in the Geosciences

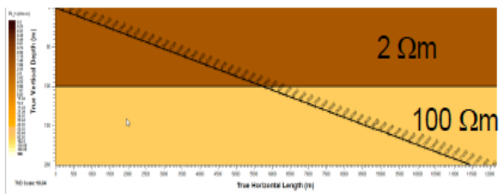
- Solution is built from the average of the accepted solutions.
- We obtain as well a posterior in the number of partitions…
- …and posteriors for all depths…
- i.e., the overall statistics.

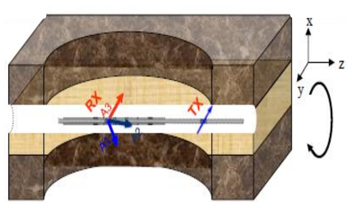


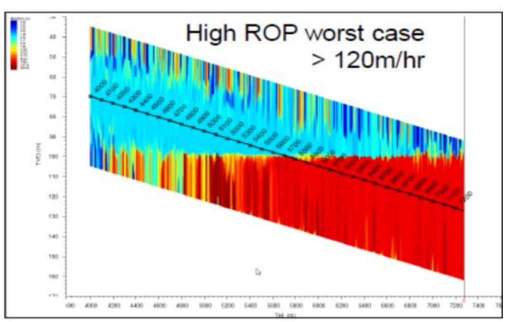


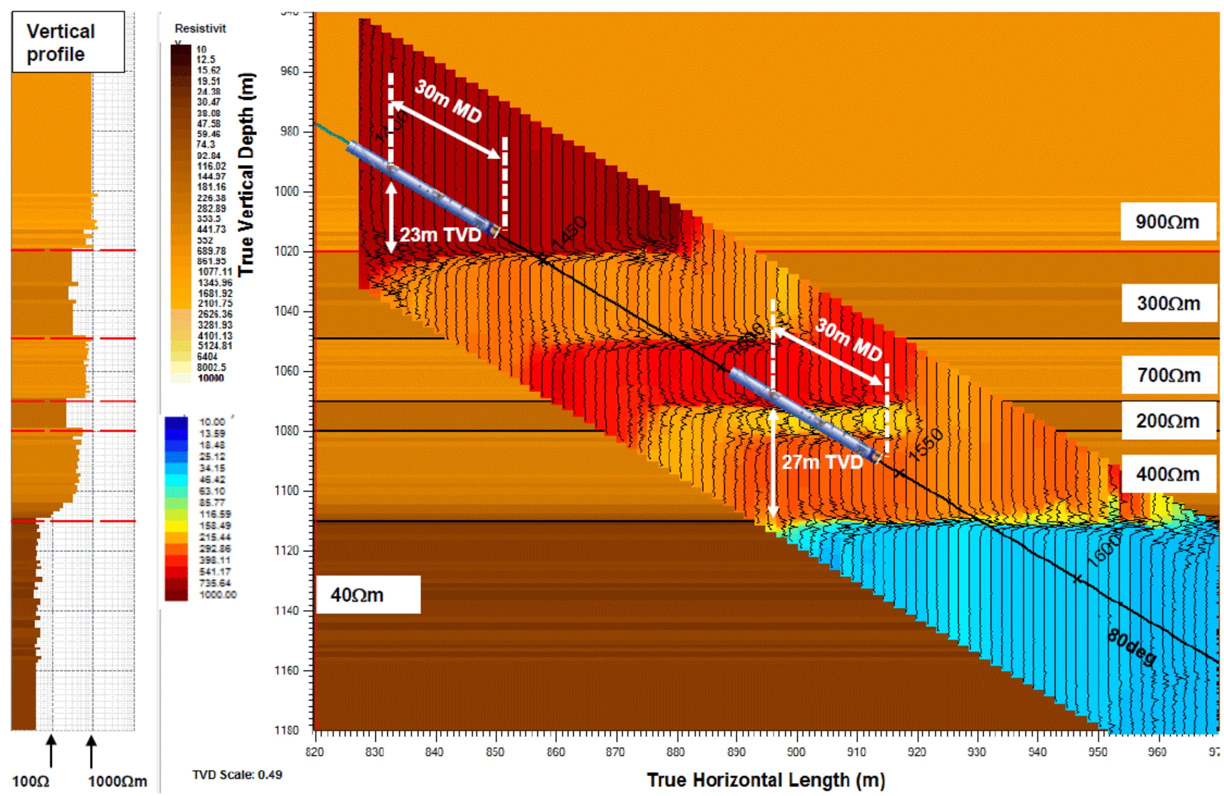
Well Placement: Direction Resistivity example

- Inversion done in 1D parameter space, at each depth.
- Fixed noise, but calibrated for acceptance ratio above 35%.









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Transdimensional Math Background

“Conventional” Bayes:

$$p(\mathbf{m}|\mathbf{d}) = \lambda p(\mathbf{d}|\mathbf{m})p(\mathbf{m})$$

$$p(\mathbf{m}|\mathbf{d}, k) \propto p(\mathbf{d}|\mathbf{m}, k)p(\mathbf{m}|k)$$

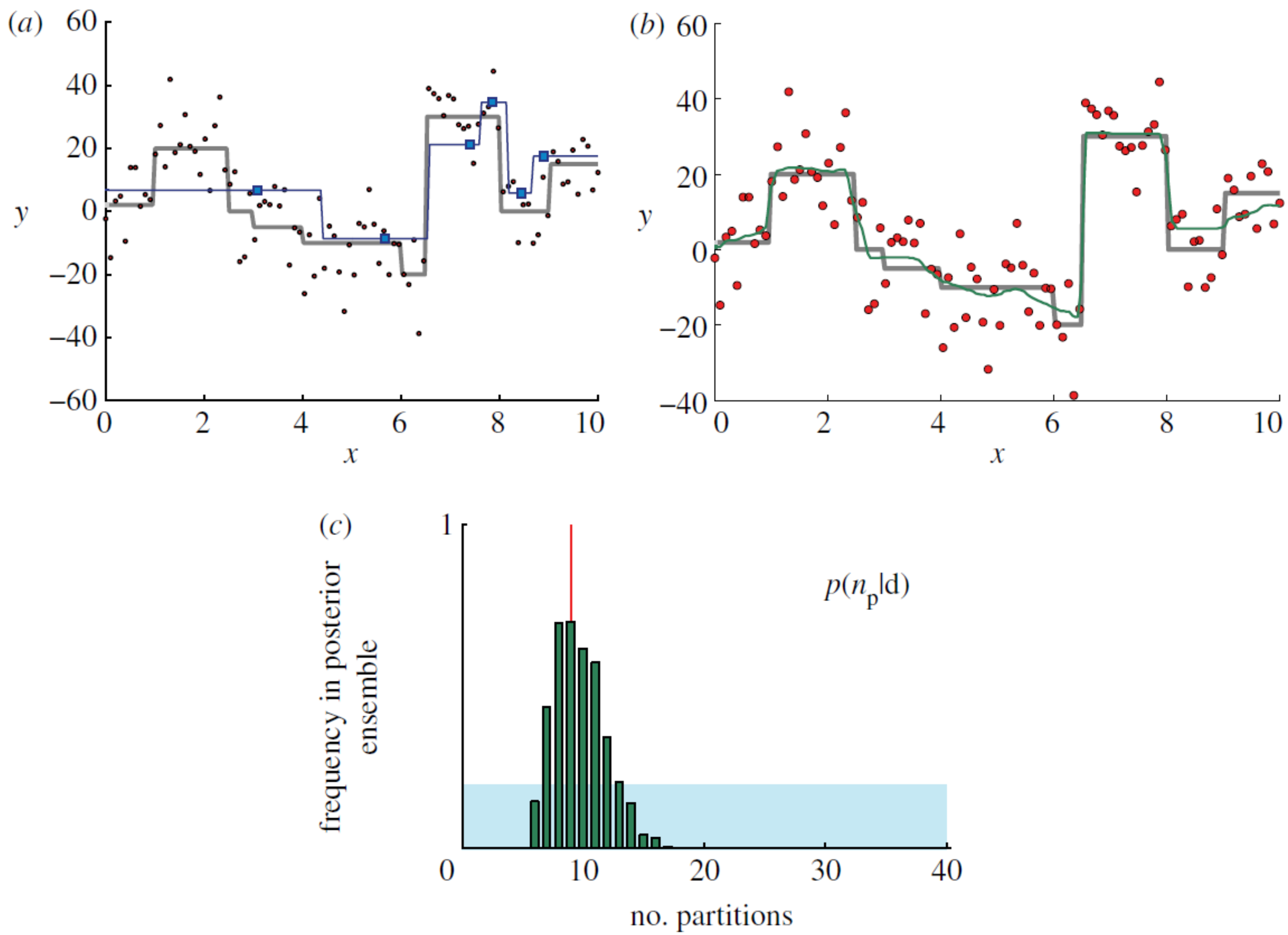
Transdimensional (Hierarchical Bayes):

$$p(\mathbf{m}, k|\mathbf{d}) \propto p(\mathbf{d}|\mathbf{m}, k)p(\mathbf{m}|k)p(k)$$

$$p(\mathbf{m}, k|\mathbf{d}) = p(\mathbf{m}|\mathbf{d}, k)p(k|\mathbf{d})$$

$$p(k|\mathbf{d}) = \int p(\mathbf{m}, k|\mathbf{d})\, \mathrm{d}\mathbf{m}$$

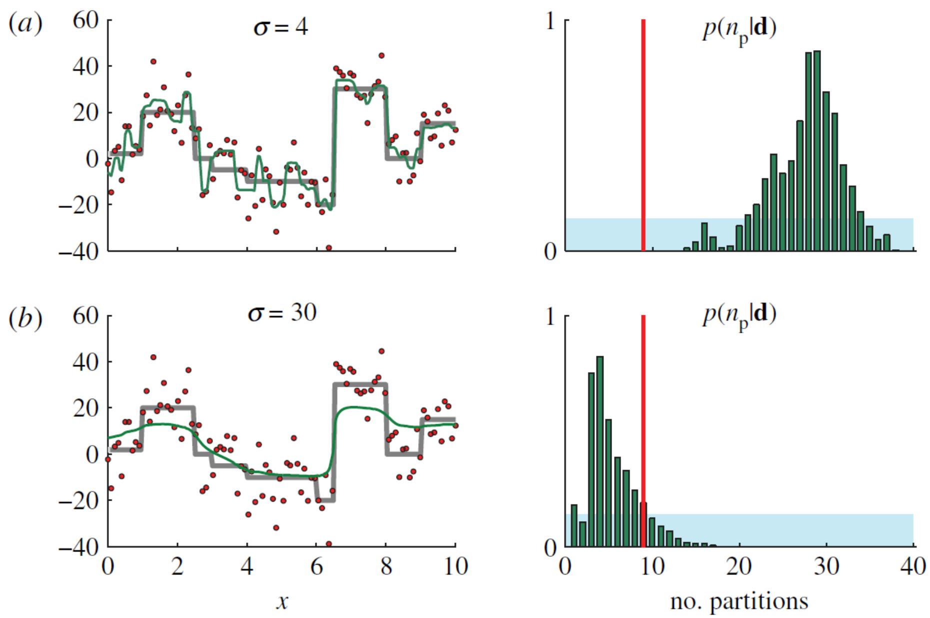
Discretization as a variable in Monte-Carlo

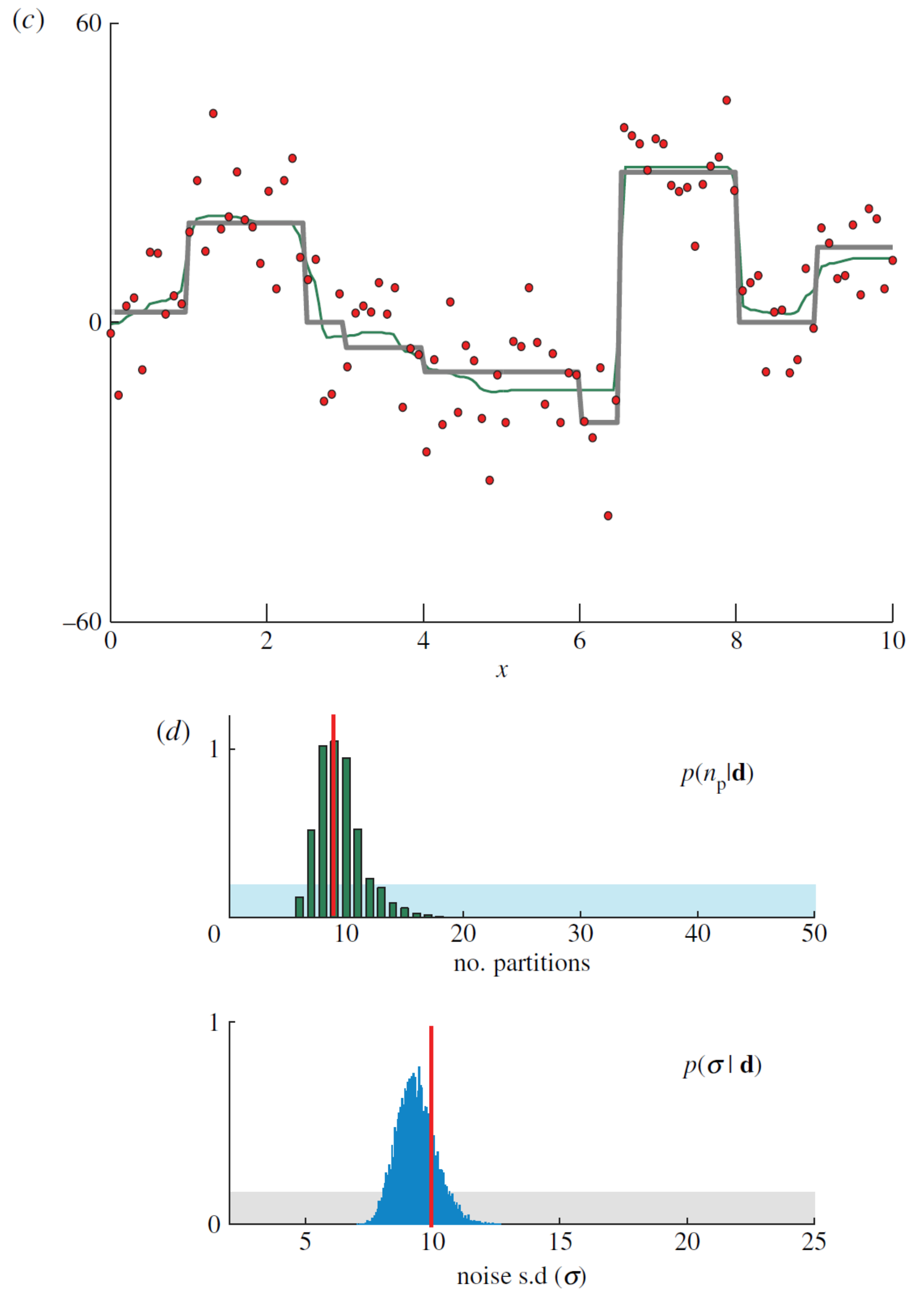


What if the data noise is another unknown

- How is the noise solved for in the solution of the inverse problem?
- Fixed vs variable noise.
- Mathematical principles of Hierarchical Bayes.
- Other filters, and advantages of “not knowing” noise.

Unknown data noise





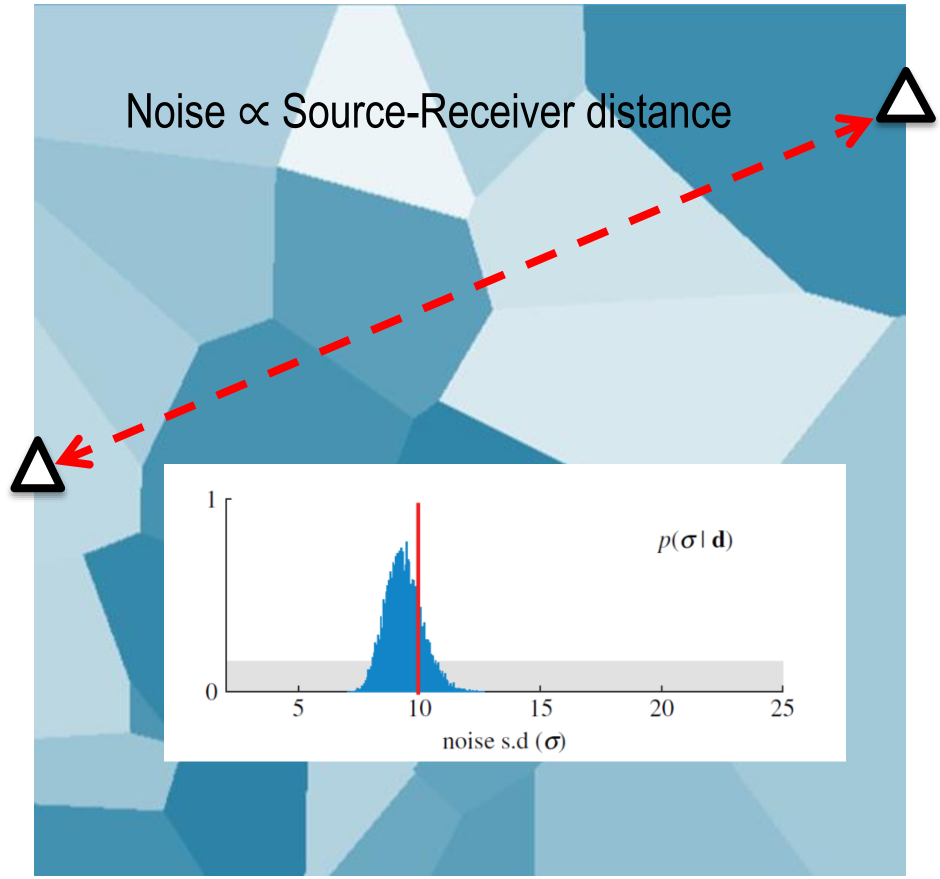
Transdimensional Seismic Tomography

Problem Setup: Data

- Setup hypotheses.
  - Number of Voronoi Cells
  - Coordinates of seismometers
  - Travel-times.
  - Other considerations

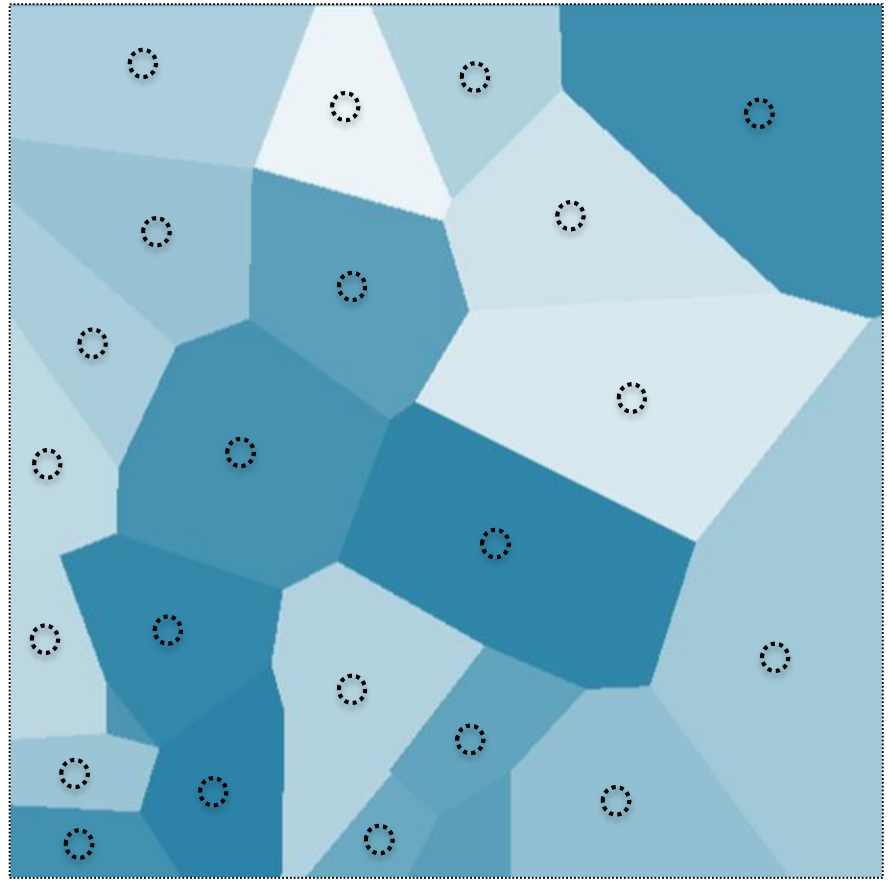
Problem Setup: How is the noise treated and included.

- Hierarchical Bayes in the Transdimensional Tomography case.
- Levels of noise:
  - Perturbations
  - Noise prior
  - Tool noise, measurement noise, line non-linear, associated to source-receiver pairs, and source-receiver distances.
- How is the noise posterior calculated?



Problem Setup: the Markov Chain

- Objective: invert for Voronoi grid slowness, number and location of grid nodes, and data noise.
- New samples of Markov Chain created with new velocity values, by creating new nodes, or by deleting nodes.
- Misfit is calculated with ray paths traveltimes.
- (TODO: new nodes or nodes deletion in figure, change velocity values).

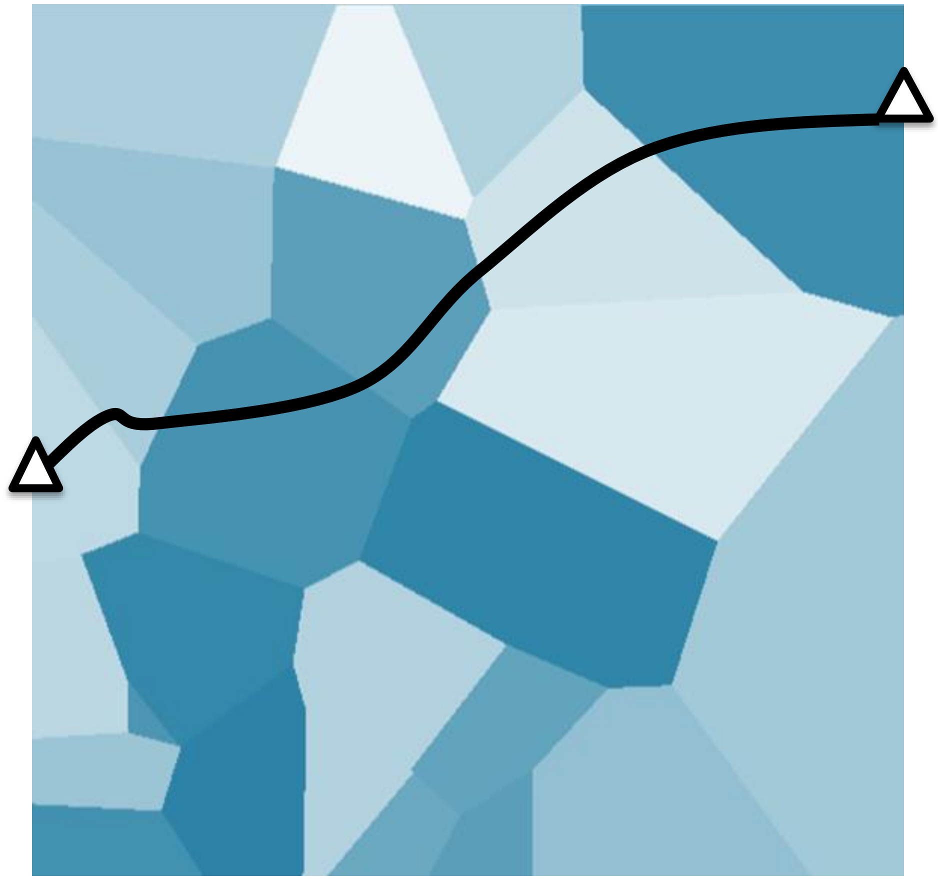


First arriving travel-times through FMM

- FMM is used for calculating first-arrival travel-times through a 2-D continuous velocity medium in spherical shell coordinates.

- We interpolate the Voronoi grid velocity values with B-splines in order to use FMM.

- Inter-seismometer ray path geometries are updated from fine grid of FMM trave times, and the corresponding ray path travel-times are calculated.



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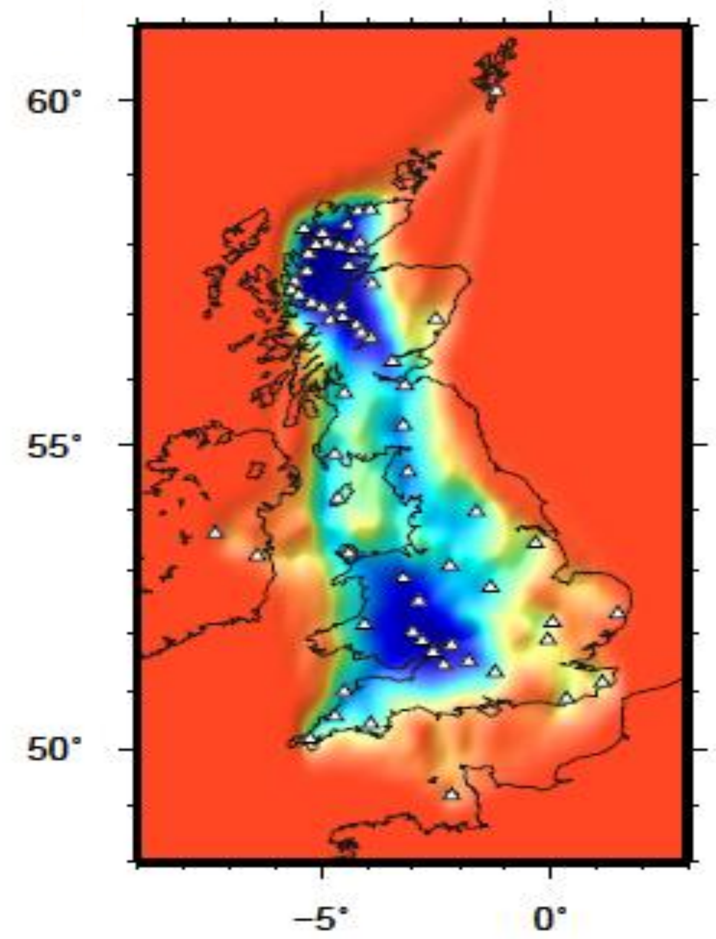
Tomography of the British Isles

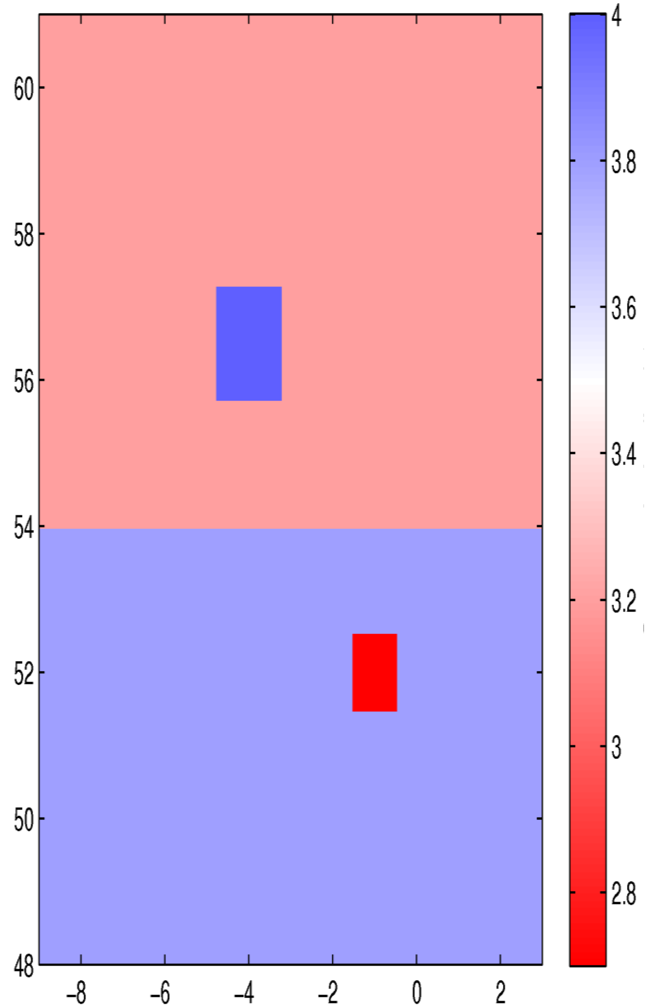
- Seismometer disposition.
- Retrieval of Love-waves traveling between pairs of seismometers calculated from ambient noise using Greens function approach (explain how).
- Authors: Galletti, Curtis, Angelo Meles. University of Edinburgh.
- (TODO: Change figure).

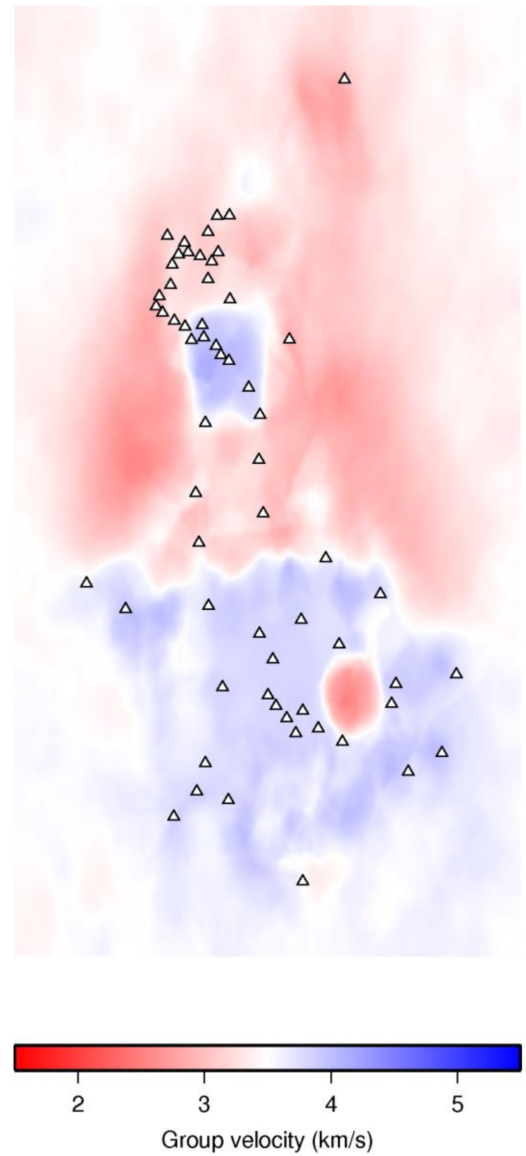


The Love-wave Synthetic Tomography

- Synthetic case design

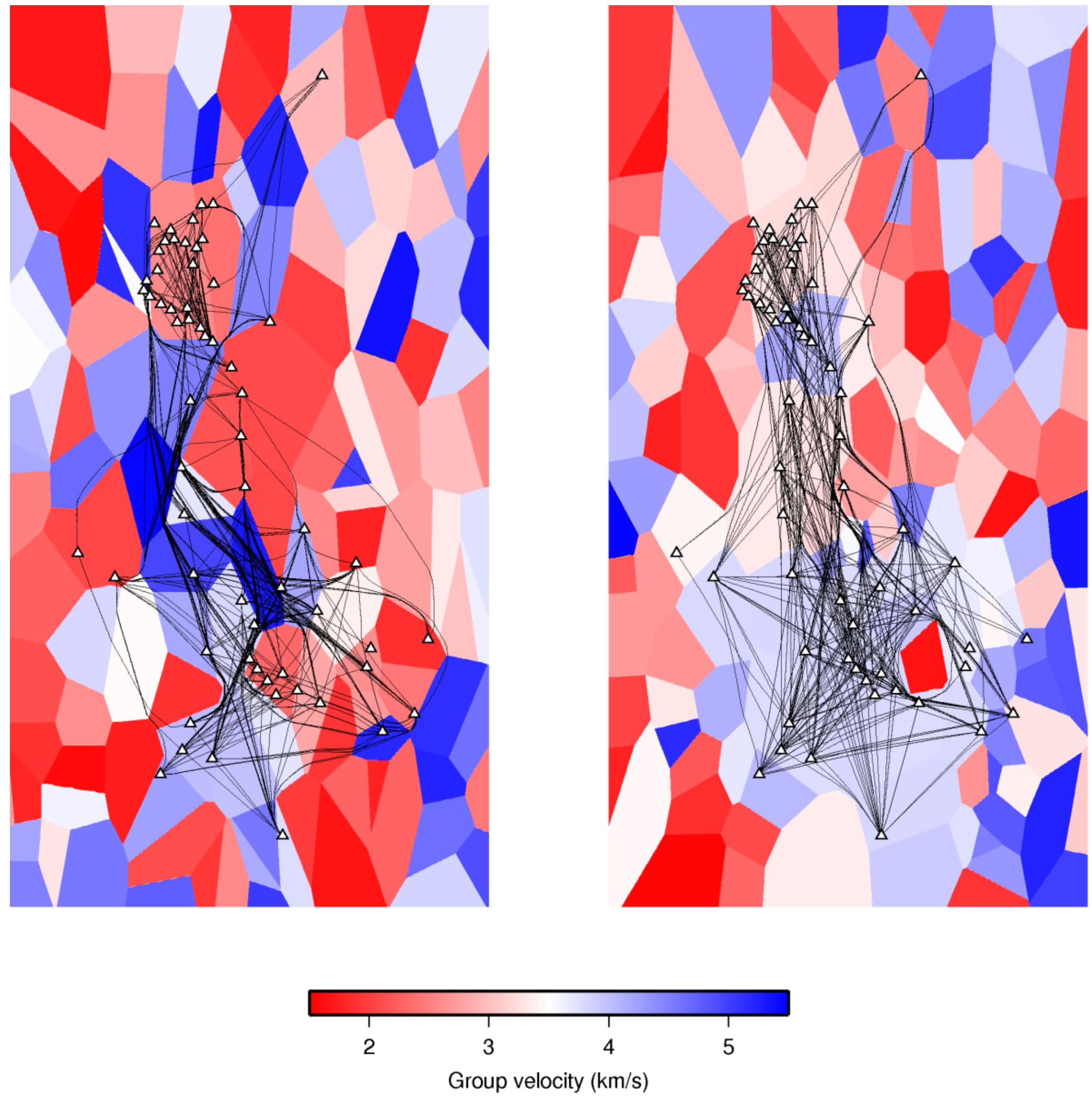
- We ran synthetic seismic velocity case keeping geographical dispositions of the seismometers.





Voronoi grid Geometry and Raypath Geometry update

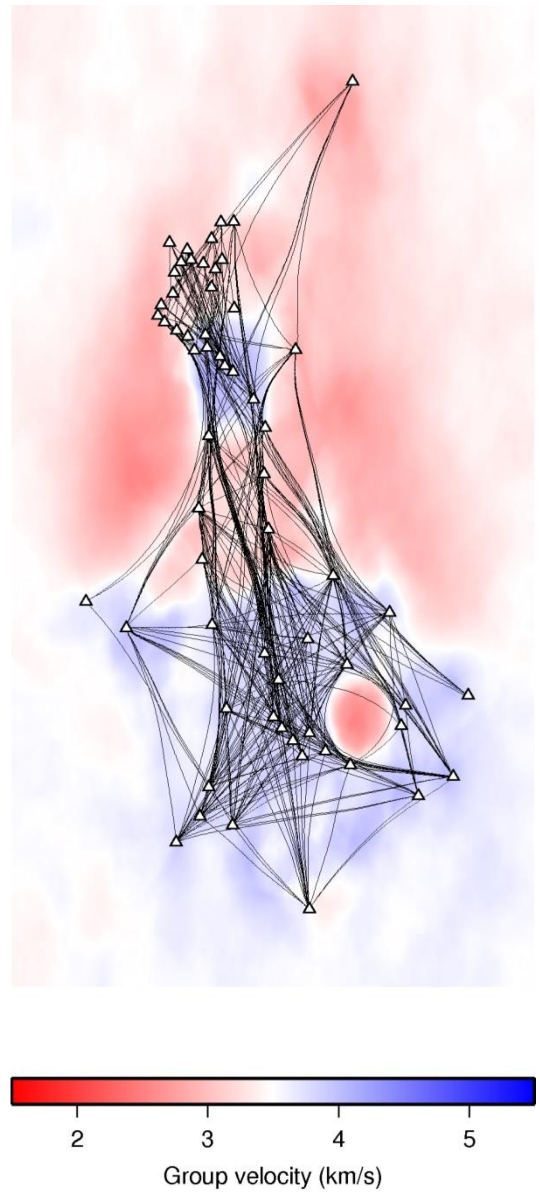
- Raypaths are updated at each step of the Markov chain, and Ray paths travel-times calculated.
- Voronoi grids of low complexity: [100, 300] cells, or high complexity [300-600] can be chosen.
- Figure: First and Last samples of Markov Chain Monte Carlo.

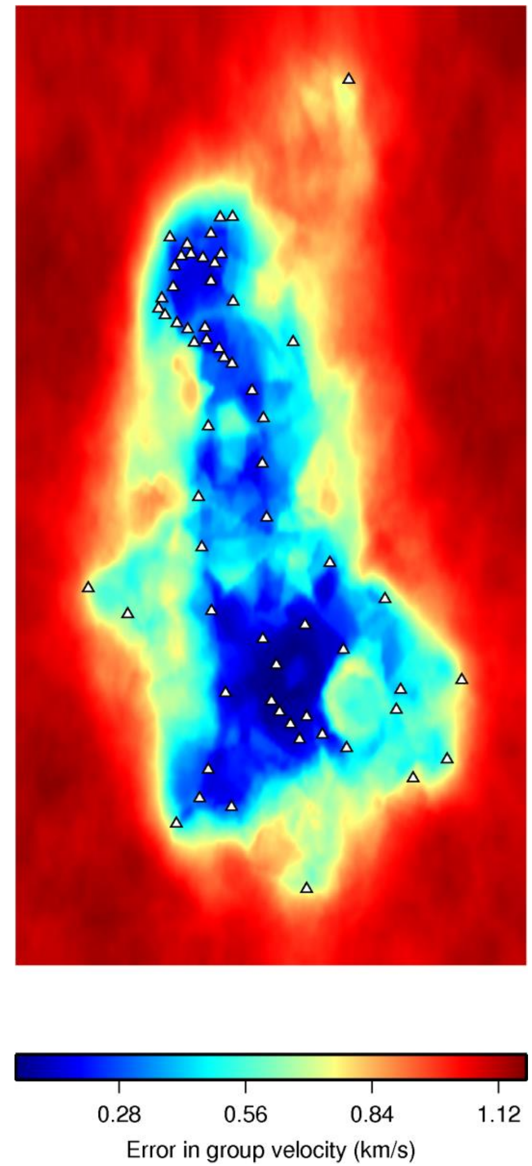


Results

- Average along the accepted samples across all chains is a statistical solution of the inverse problem.

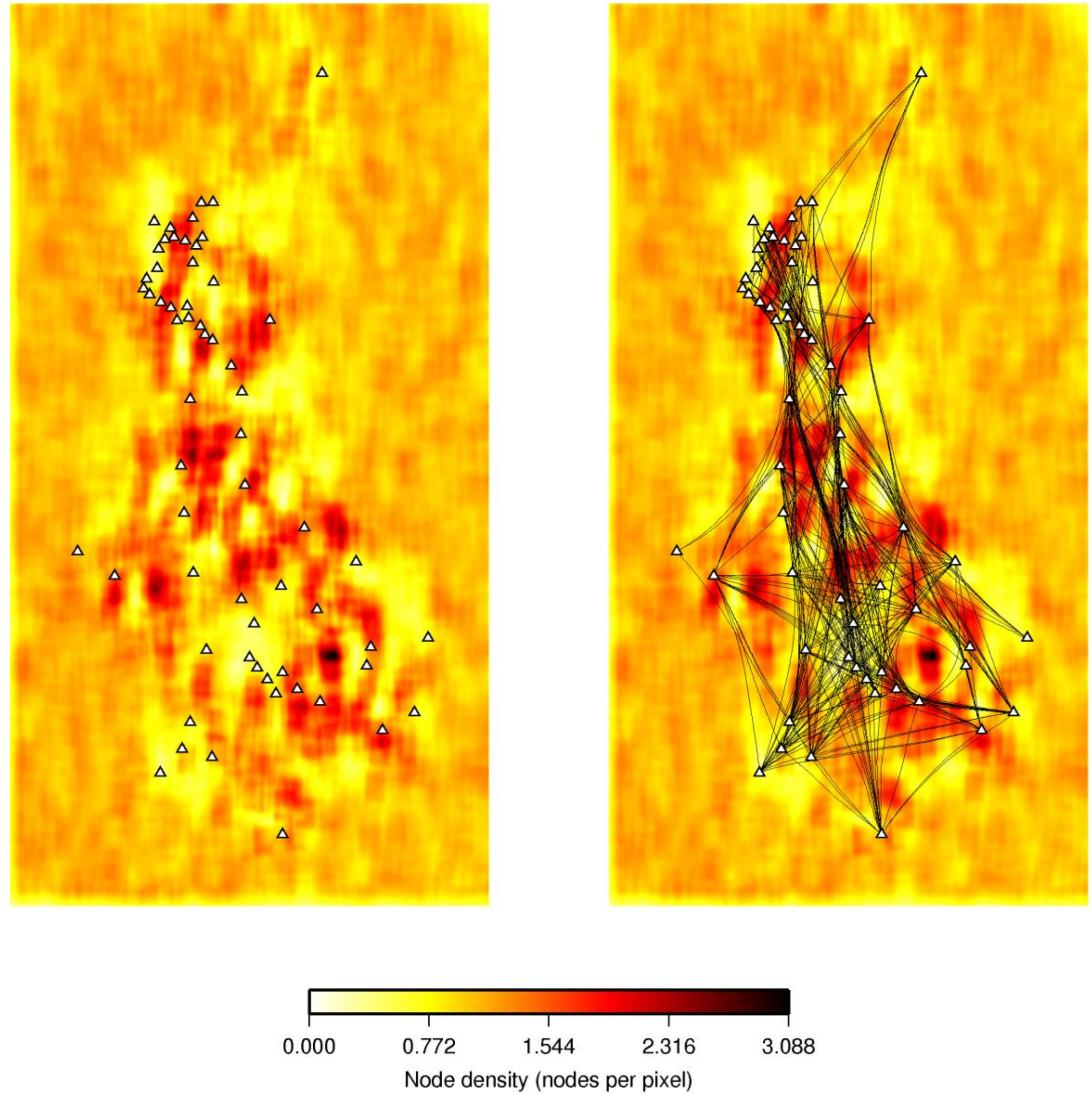
- Uncertainty can be evaluated along the accepted samples, across all chains.





Resolution of Voronoi nodes

- The transdimensional approach "resolves" the node density according to the seismometer sampling!



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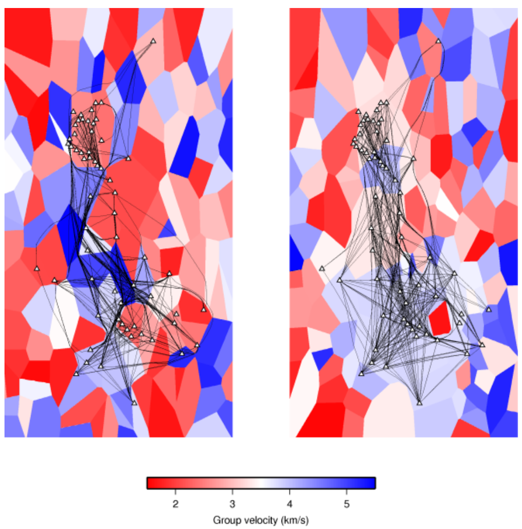
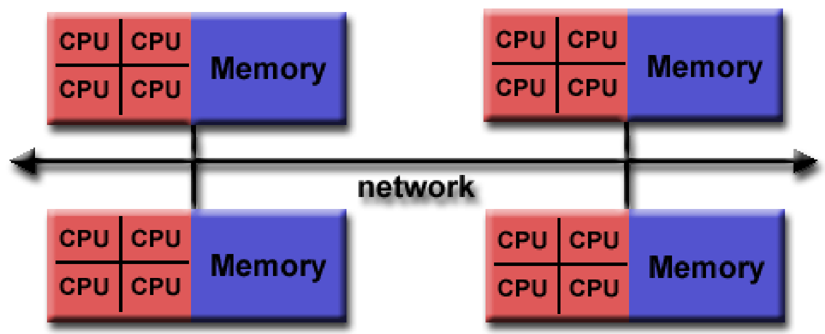
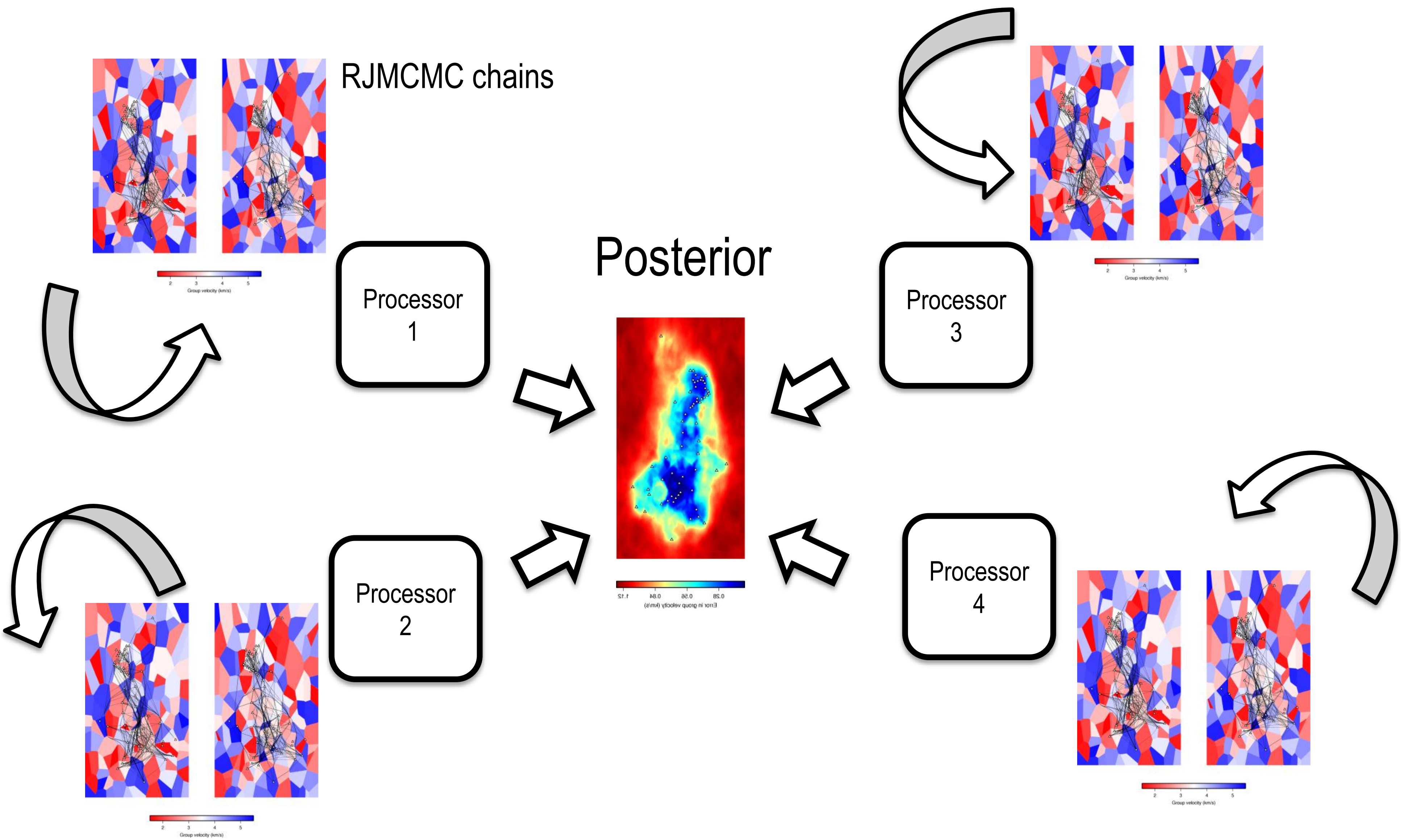
MPI architecture 1

- MPI design 1: Galletti, Curtis. We ran synthetic case design.
- Several Markov Chains (up to 16) run in parallel MPI process.
- No interaction between chains except for Message-blocking MPI commands, e.g. error messages.
- FMM is run (serially) for ALL seismometer-pairs at each MCMC samples, for EACH chains.



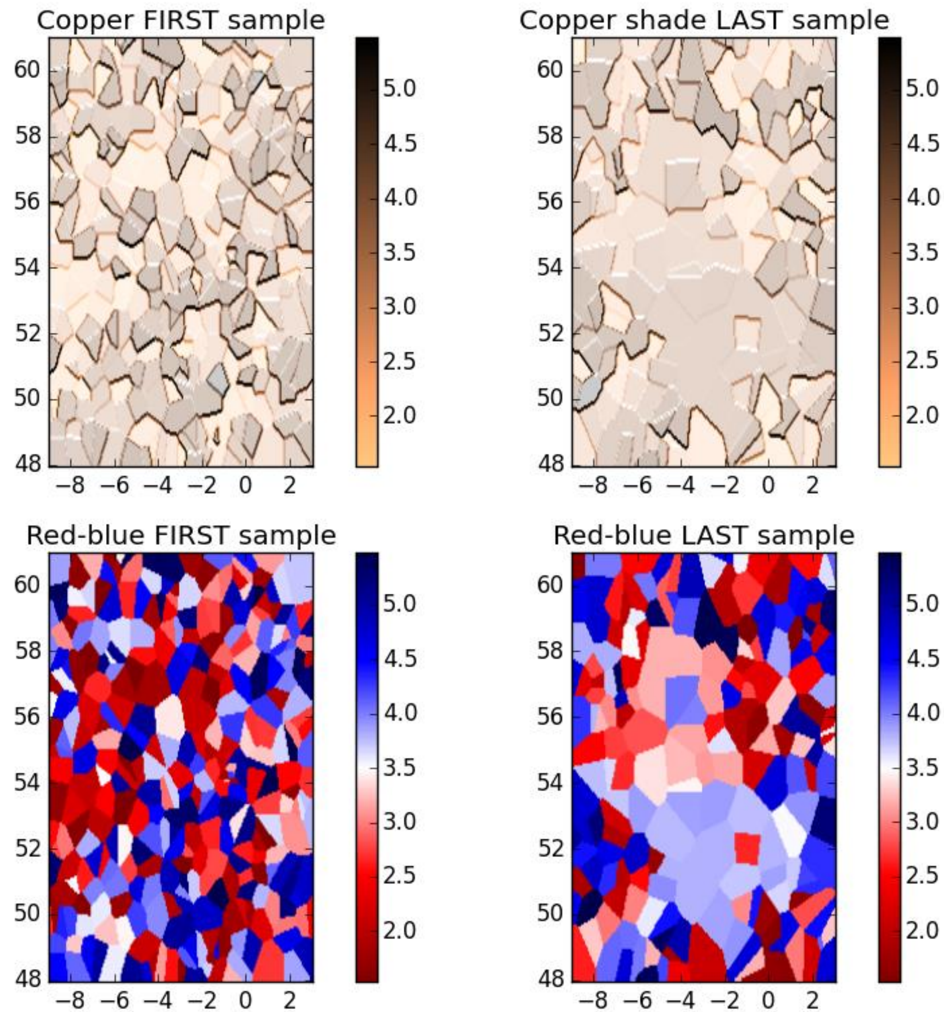


MPI architecture 1



MPI architecture 1: Expensive!

- Markov chain: 100,000 samples.
- 12 chains, acceptance, approx. 44%
- Time: approx. 24 hours
- Computationally expensive!



Computing time

- Serial code = 24 hours (Galdor) per 100,000 samples.

MPI architecture 1: Profiling the code

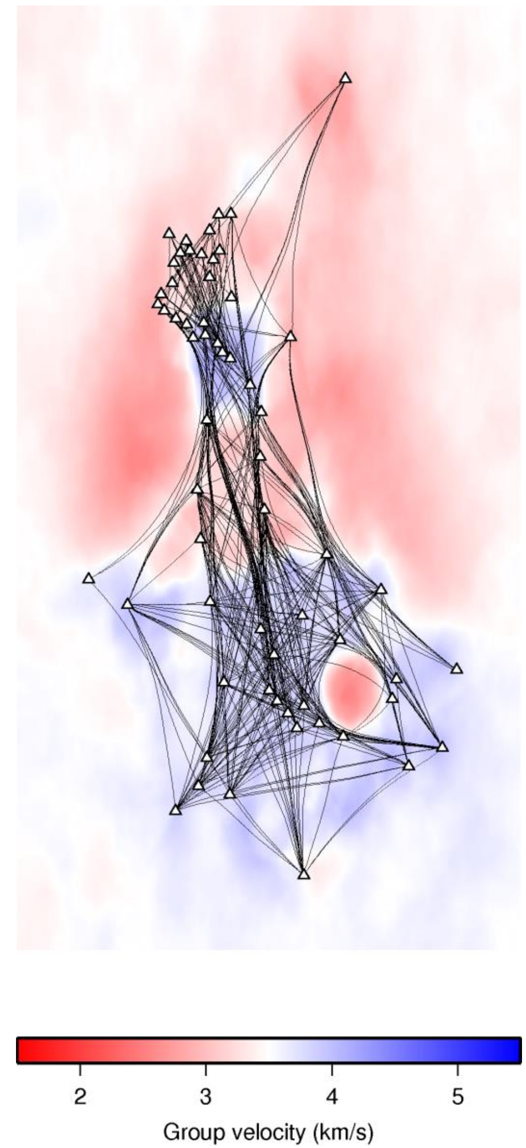
- **Code profiling results: TODO table of results.**

- Ray modifier (i.e. FMM + raypath tracers + raypath geometry calculation) spends more than 90% of code time.

- Why is the raypath modifier the perfect candidate for MPI parallelization? Is this the only candidate?

Increasing performance with HPC

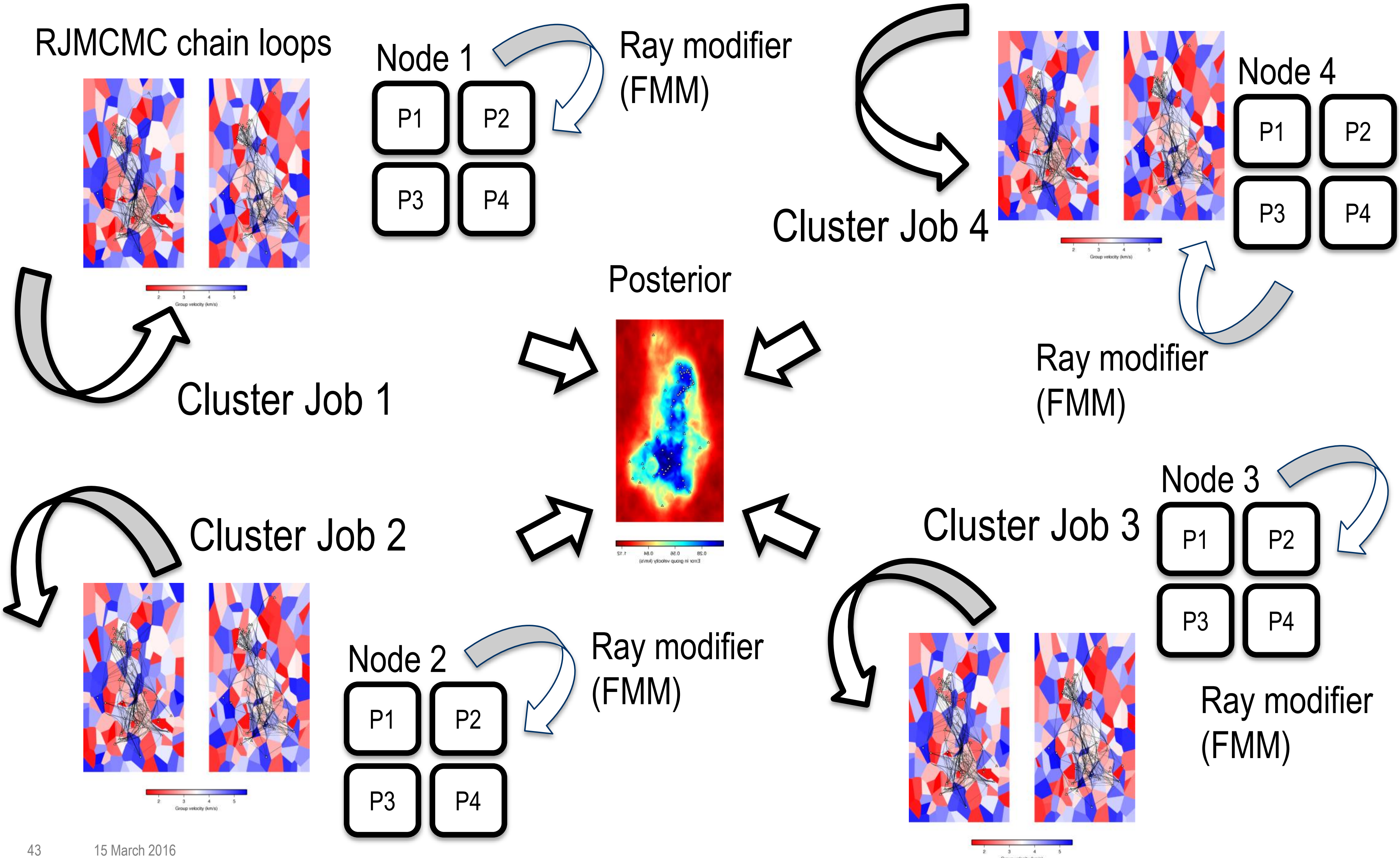
- Ray modifier is computationally expensive!
- FFM can be parallelized: Examples from the literature for HPC applications to seismic tomography?
- Proposal: HPC solutions through hybrid embarrassingly parallel Markov Chains and MPI at the ray-modifier level!



New MPI design

- Hybrid Embarrasingly Parallel Process and internal FMM and Ray modifier MPI loop.
- Candidates: places where an update in the ray-paths is used in the inverse problem solution.
- FFM can be divided for sub-groups of seismometer pairs.
- Size of group varies according to number of nodes available in the Cluster.
- Size of sub-array= Number of pairs MOD(number of nodes).
- Our case: number of pairs = 61. Number of nodes = 2 to 16 (up to 32 but not good for SGR-HPC group.
- Number of processors per node: approx 8.

MPI architecture 2: Faramir and Galdor



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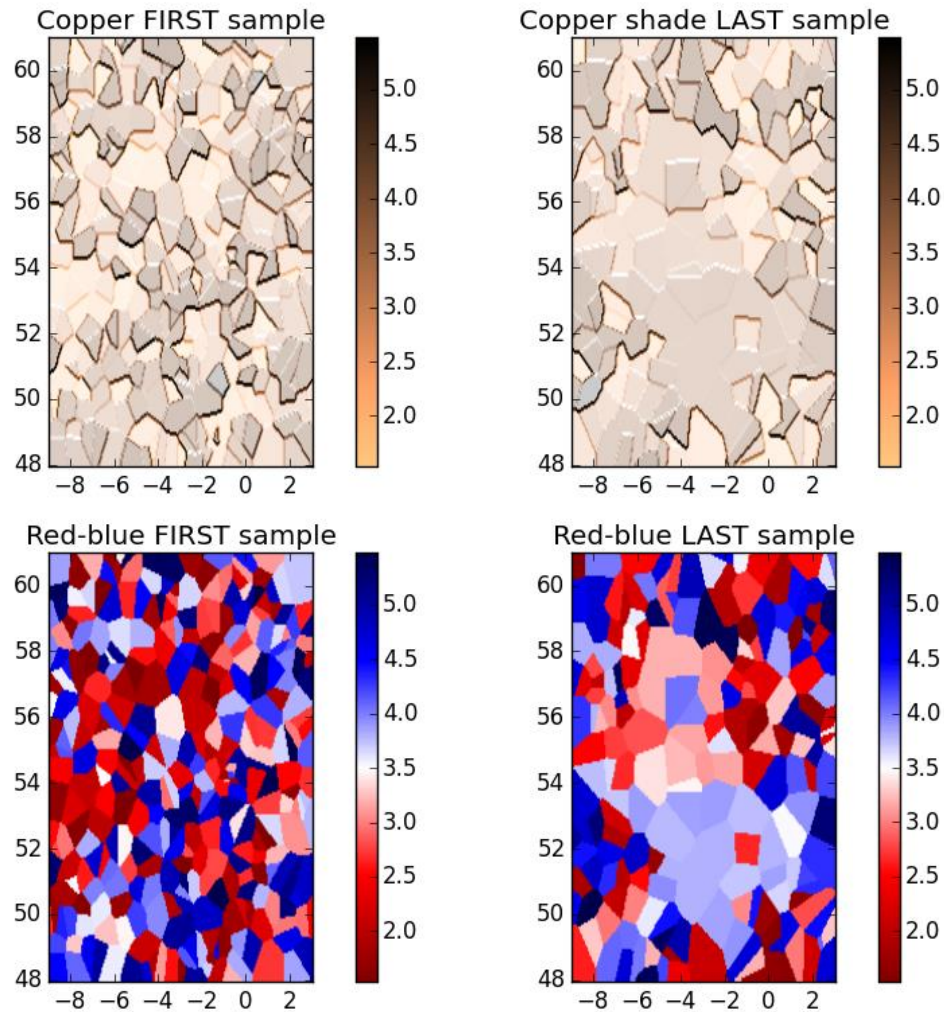
Speed-up comparison.

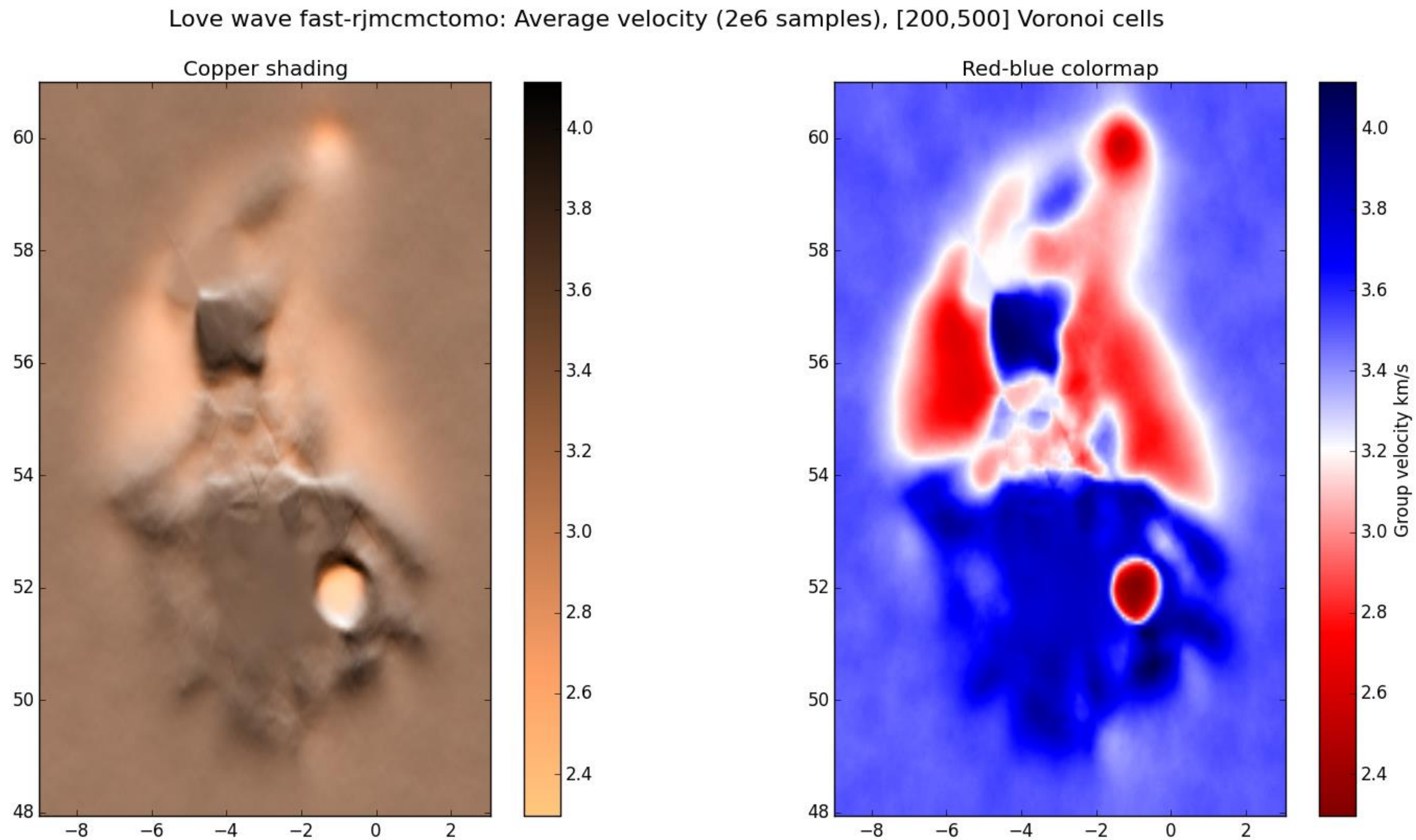
- Markov chain: 2 million samples.
- 16 chains, acceptance ~ 38%
- Fast computation!
- TODO: Table or graph with speed-up.



Computing time

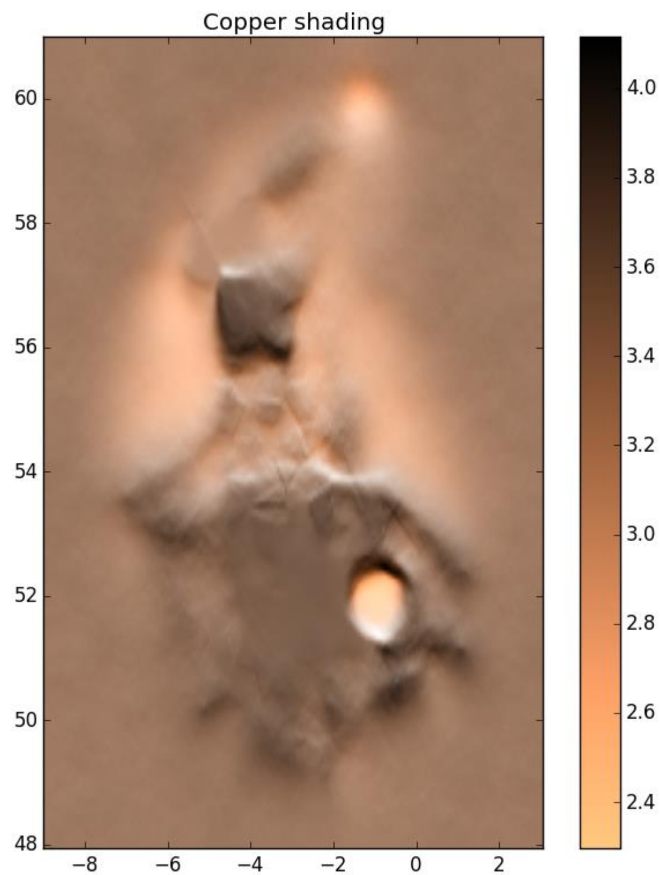
- **(before)** Semi-serial code = 480 hours for 2 million samples.
- **(after)** MPI Raytracer 24 processors, 2 million samples = 33 hours (Galdor).

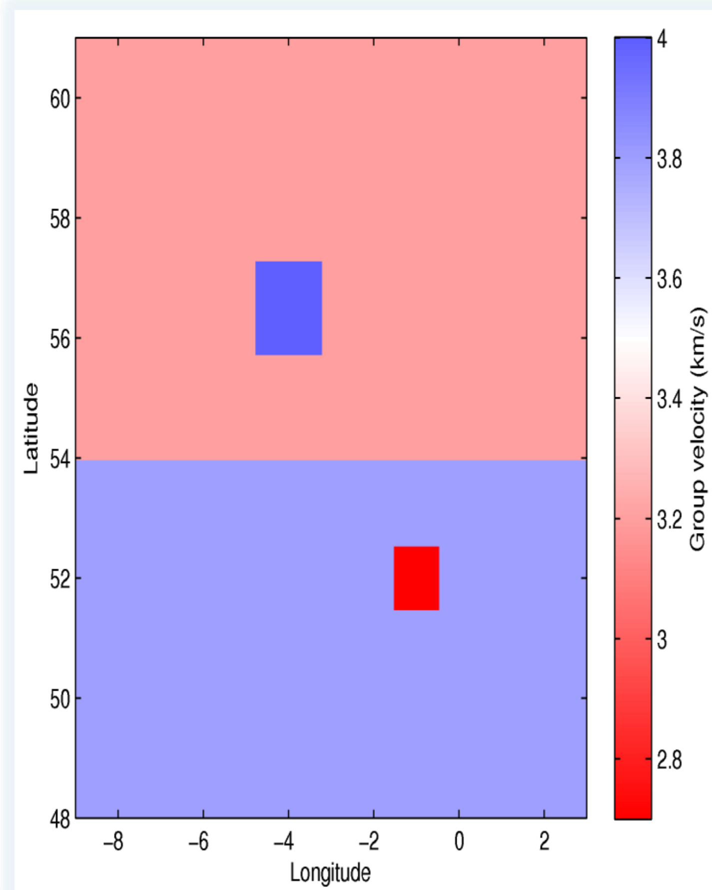
Results for Synthetic Case Average seismic velocity



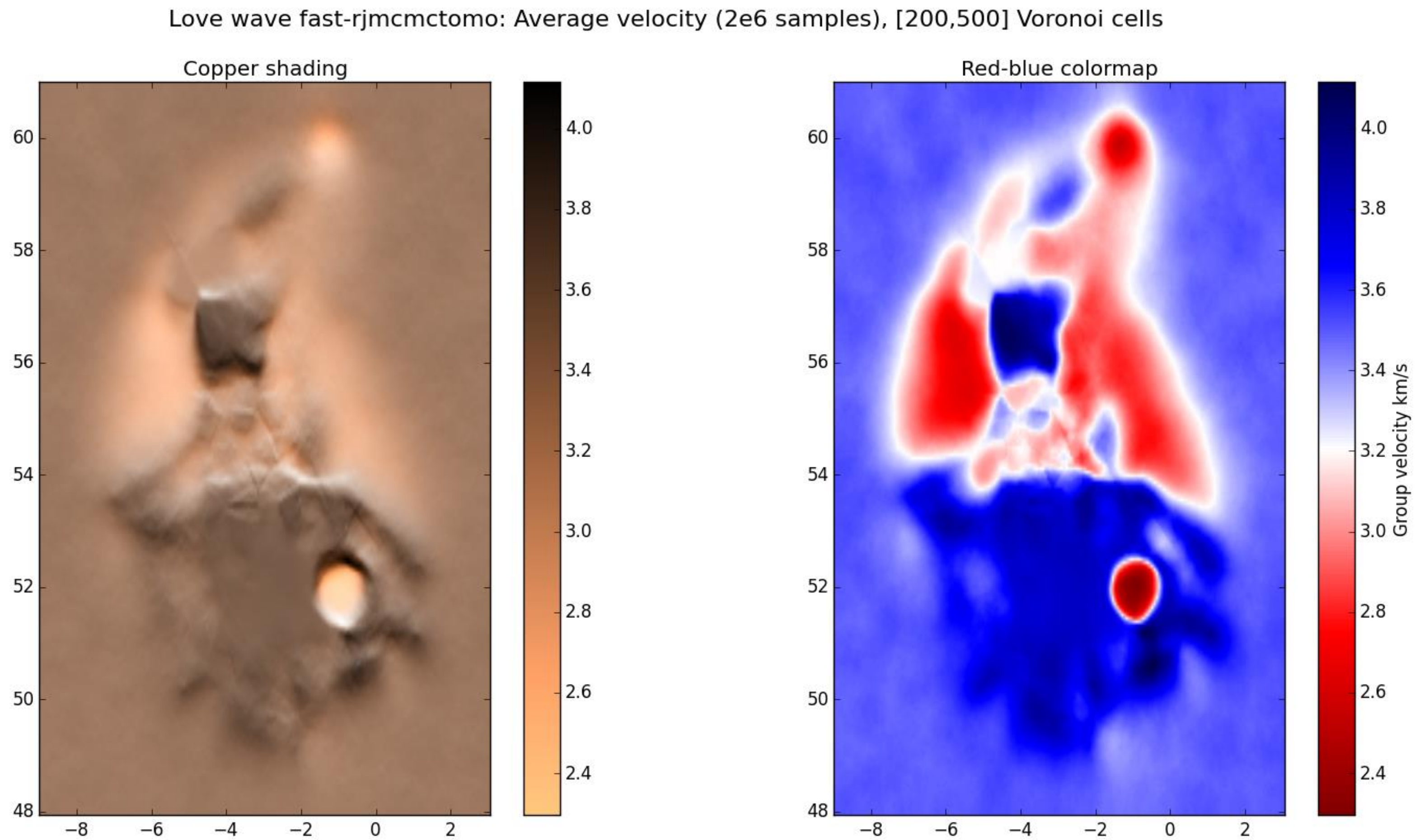
Average seismic velocity

Love wave fast-rjmcmctomo: Average velocity (2e6 samples), [200,500] Voronoi cells



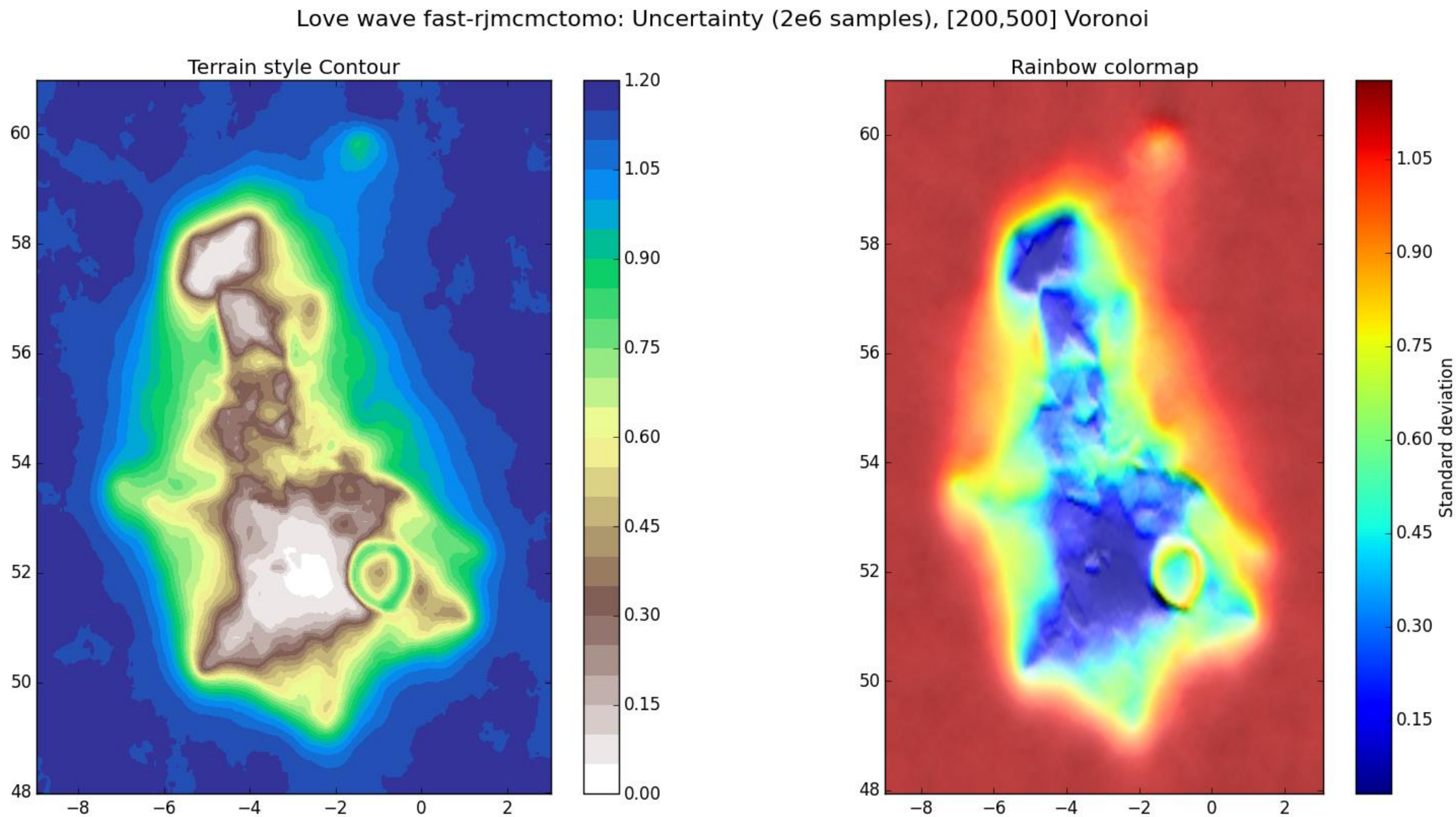


Average seismic velocity



Inversion is good for highly sampled regions!

Uncertainty quantification



Uncertainty is low for highly sampled regions!