Investigating the “Deep Earth” with long-period seismology and gravity

Alpine-Carpathian Gravimetry Workshop

Bratislava, 22.05.24

Wolfgang Szwillus,

Kiel University, Department of Geosciences

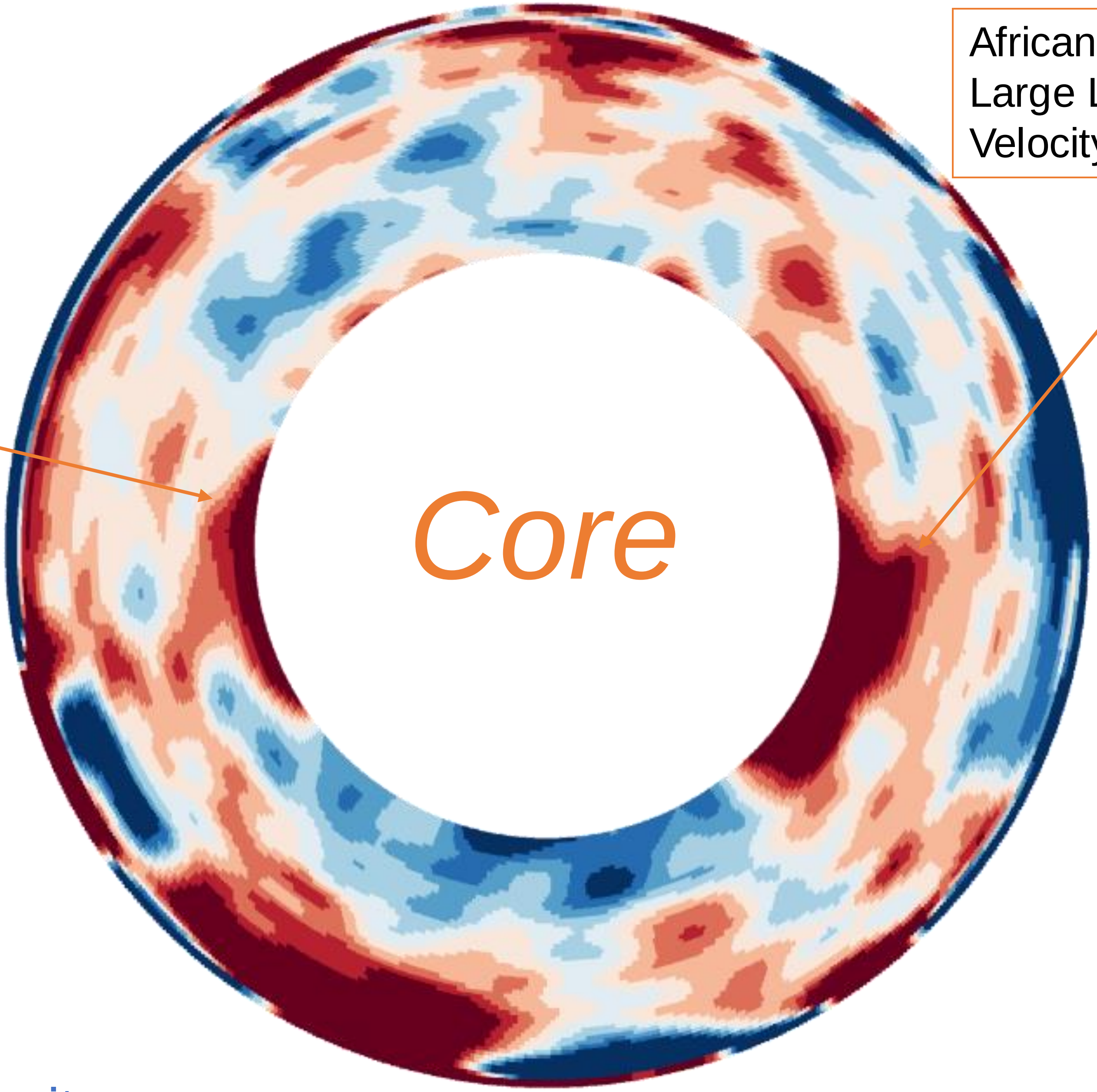
C | A | U

Christian-Albrechts-Universität zu Kiel

esa

Shear wave Velocity inside Earth‘s mantle

Pacific
Large Low Shear Wave
Velocity Province (LLSVP)



African
Large Low Shear Wave
Velocity Province (LLSVP)

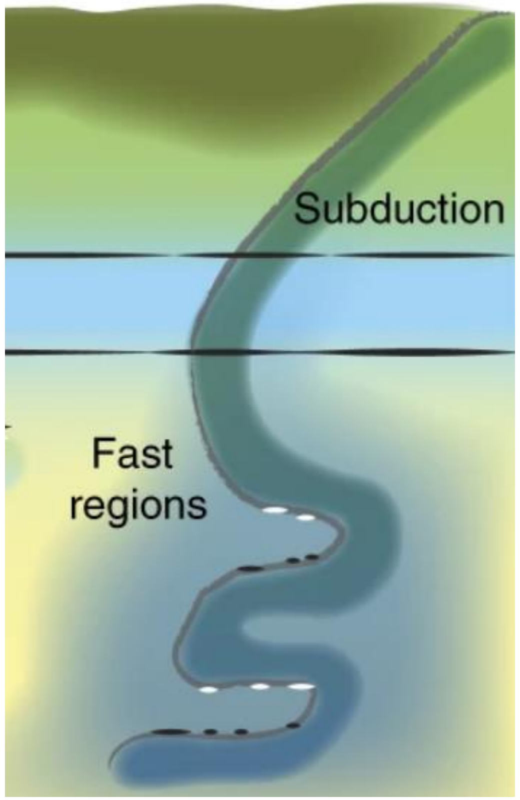
Red = Slower seismic velocity

Blue = Faster seismic velocity

SMEAN 2 (Becker and Boschi)

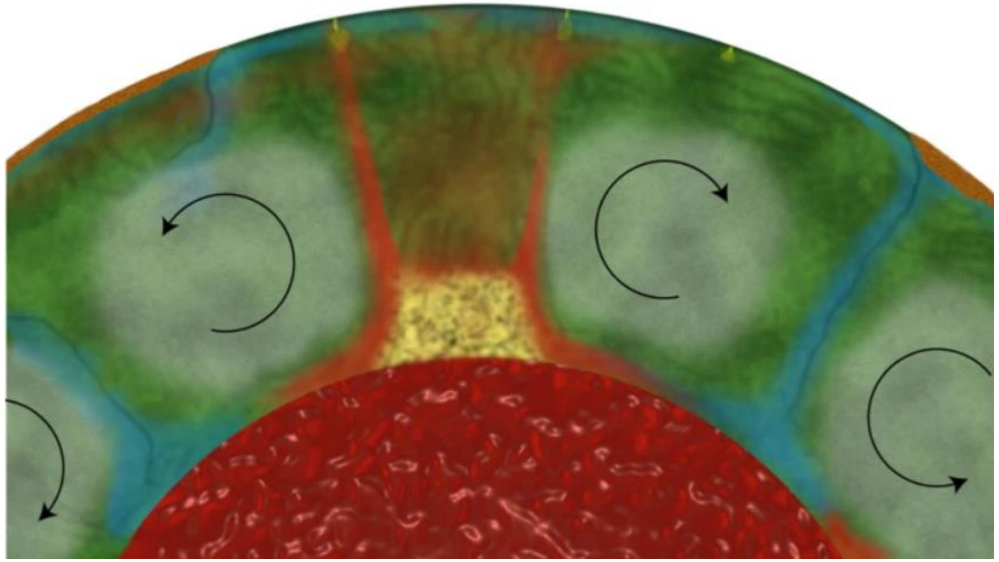
Possible thermochemical scenarios in the deep mantle

Subducted slabs



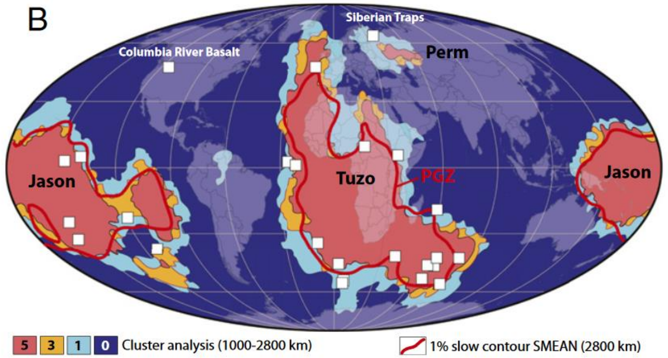
From Waszek et al. 2021

BEAMS



From Ballmer et al. 2017

LLVSP



From Torsvik et al. 2014

Is density in the (lower) mantle just velocity rescaled?

If it is, what is the correct scaling?

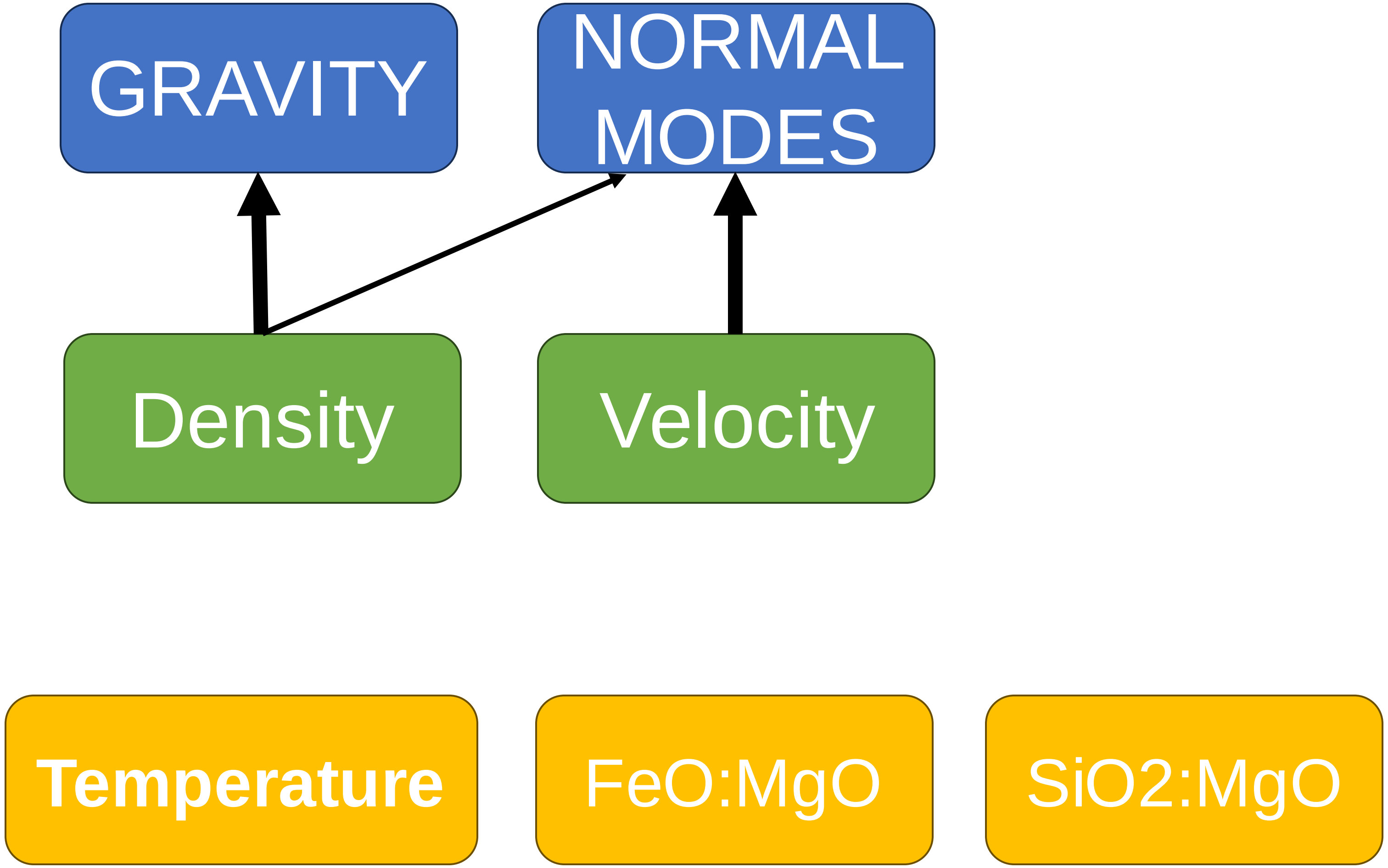
What happens if we use the ‚wrong' scaling?

GRAVITY

If it isn't, could we detect that?

If it isn't, what is the reason for that? (Composition?)

Joint inversion concept



- Inversion trade-offs
  - Volume vs. Anomaly
  - Roughness vs. Anomaly
- Depends on regularization choices
- Explore solution space with trandimensional inversion

Overview

Method

- Assumption: Normal modes = surface waves
- Transdimensional ‚inversion‘ (optimization) approach

Data

- Synthetic forward calculated from SP12-RTS

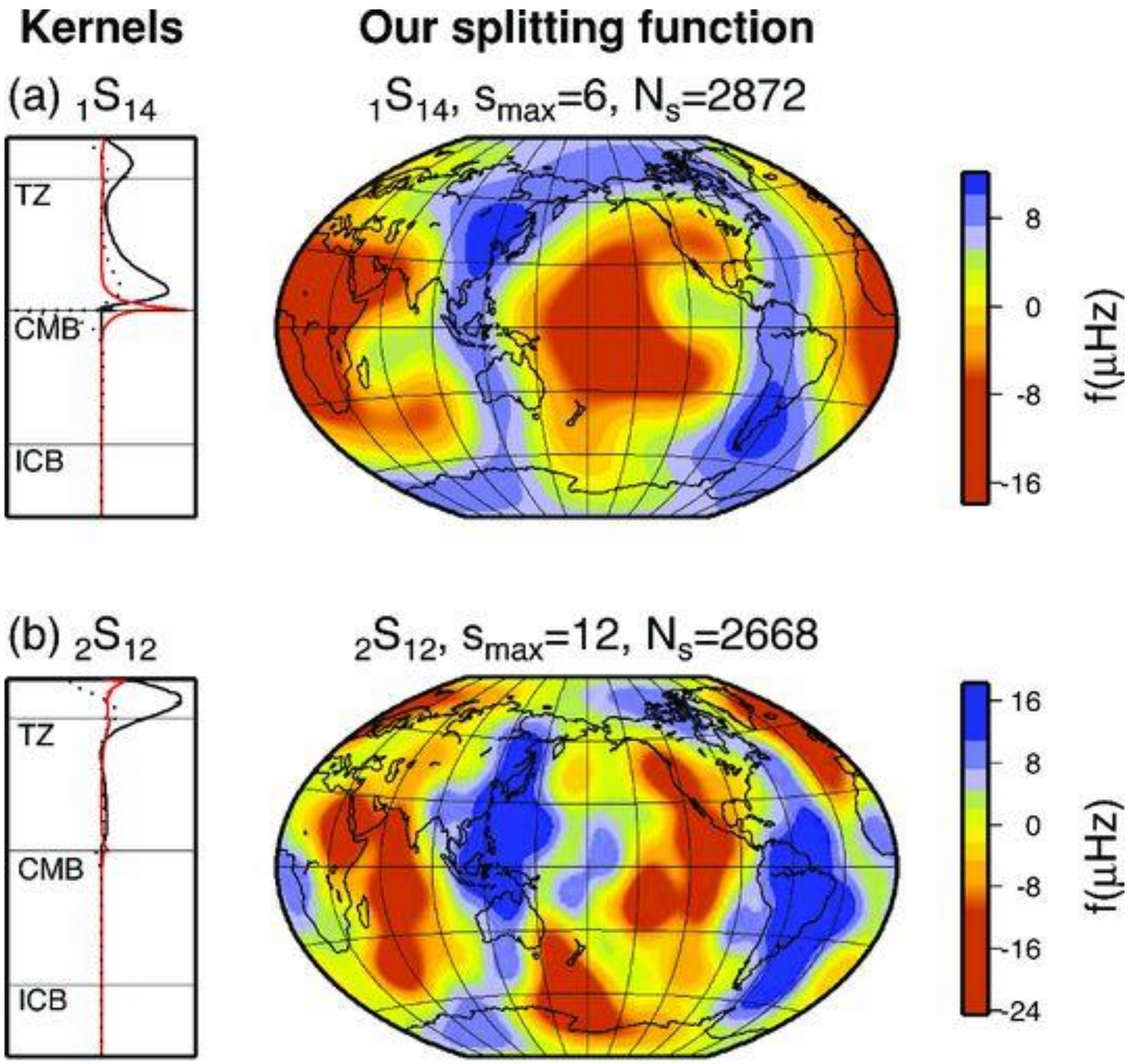
An additional complication

- „Dynamic“ gravity kernels

Methods and synthetic data

Normal modes

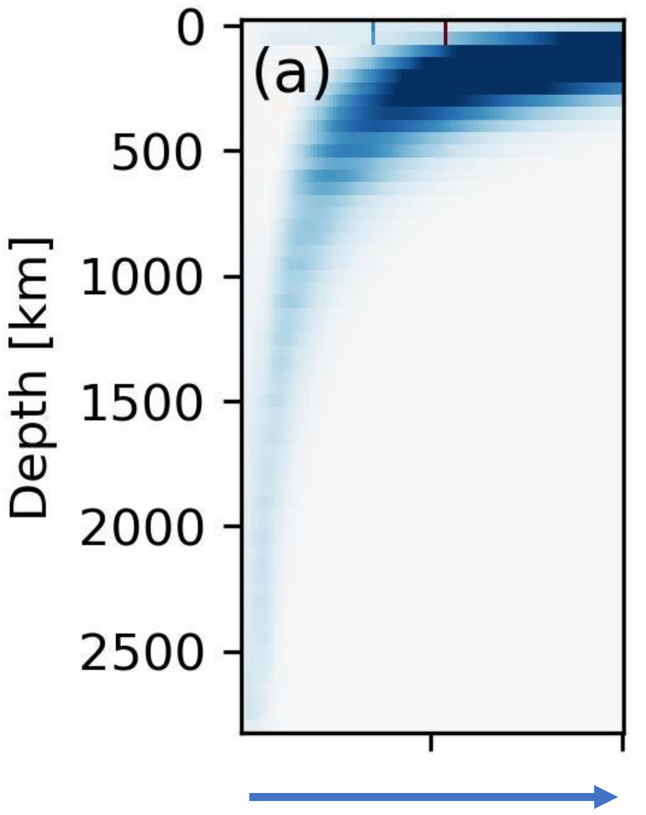
- Equivalent *in some sense* to surface wave phase velocity (?)
- Different periods
- Different orders (overtones)
- 2 recent data sets
  - Deuss et. 2013
  - Koelemeijer et al. 2018



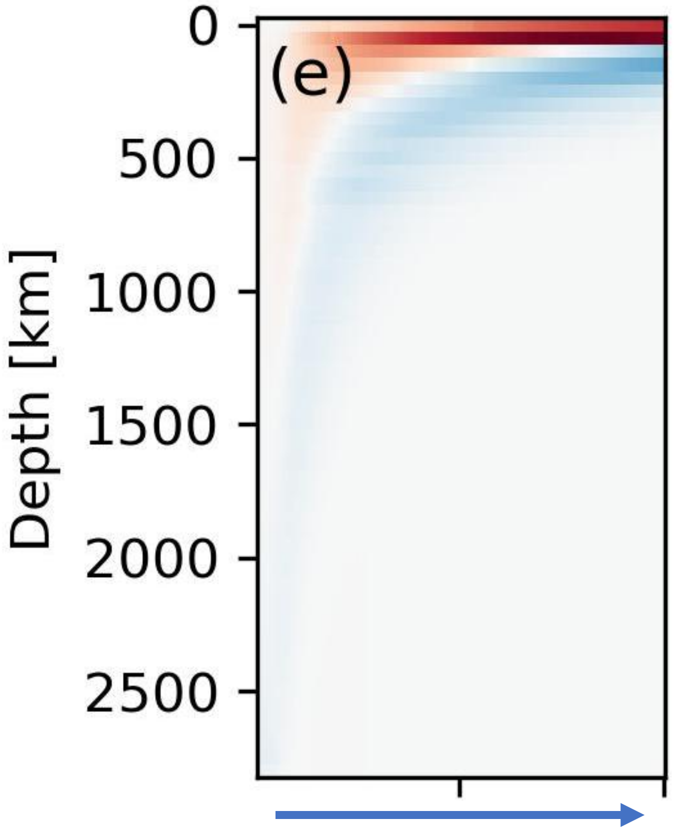
From Deuss et al. 2013

Normal mode sensitivity to velocity and density

Sensitivity to vs



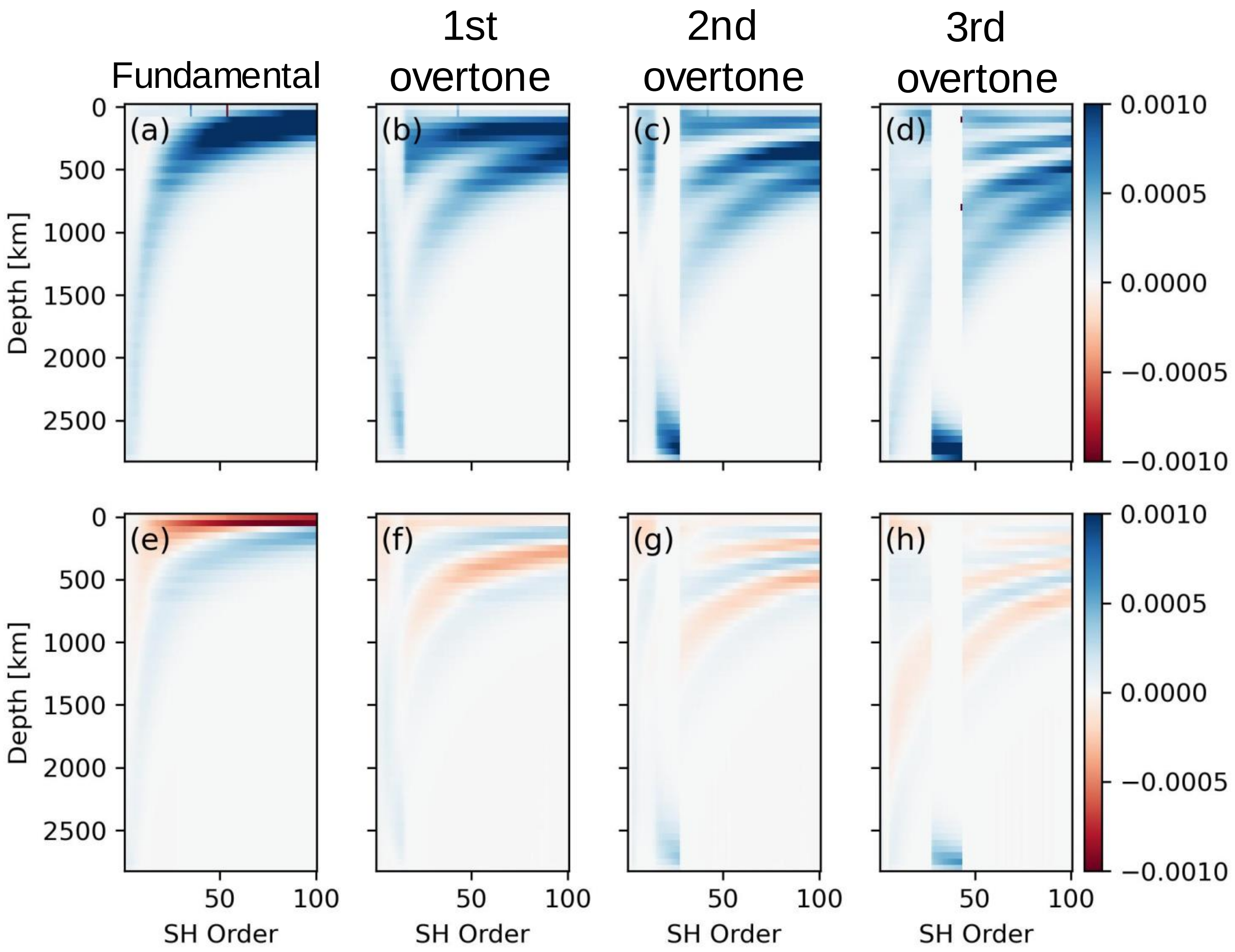
Sensity to density



Normal mode overtones

Sensitivity to vs

Sensity to density

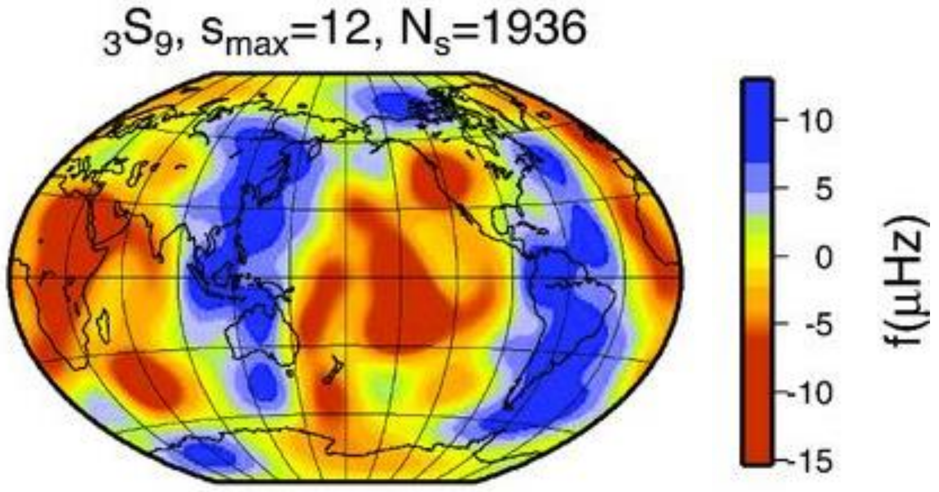


Normal modes = Surface waves?

- Normal modes described by splitting functions (frequency changes)
- Surface waves described by phase velocities
- Theoretically (asymptotically):

$$\frac{\delta\omega}{\omega} = \frac{\delta c}{c}\frac{u}{c}$$

  - ω: frequency, $\delta\omega$: frequency change
  - c: phase velocity, δc: velocity change
  - u: group velocity

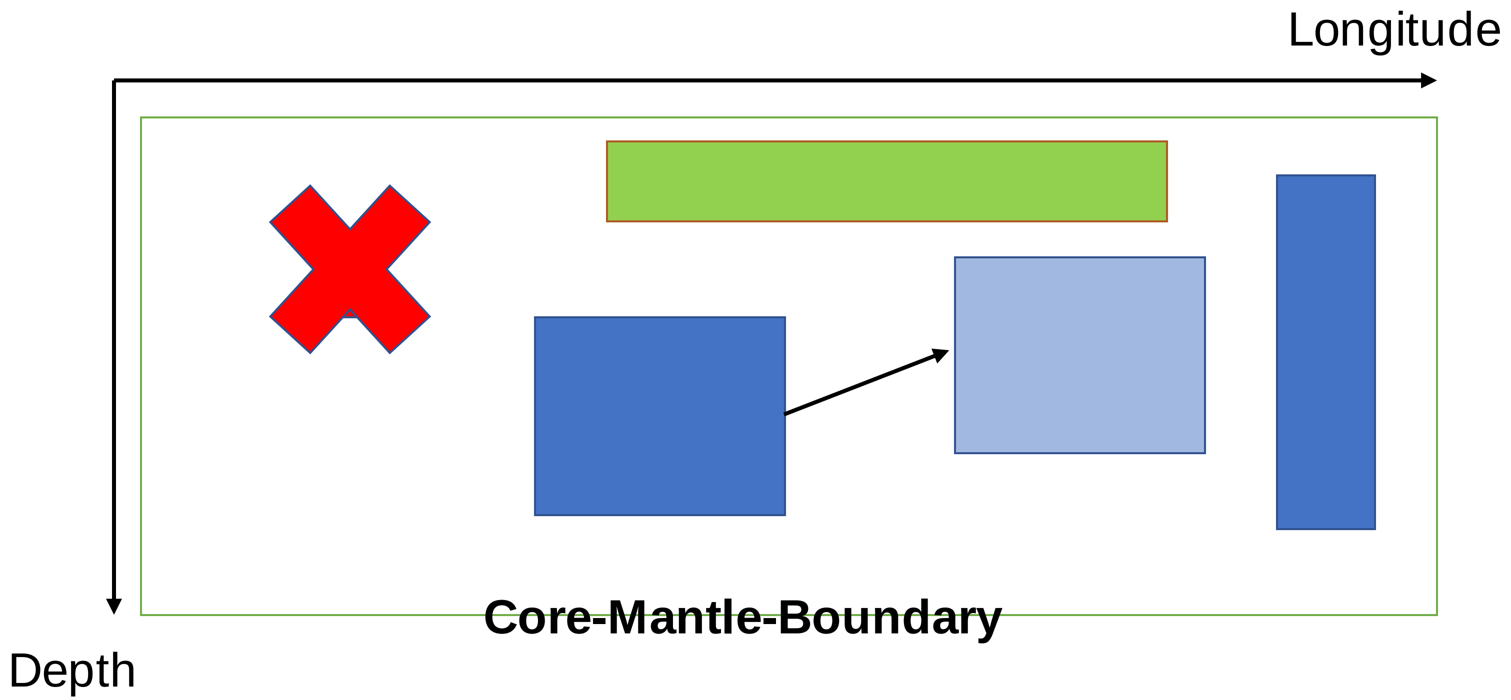


From Deuss et al. 2013

Transdimensional inversion

- Randomly change model and accept change based on posterior probability
- Changes
  - Add (Birth)
  - Remove (Death)
  - Move
  - Change
- Repeated for many iterations (>100,000)

*MCMC = Monte Carlo Markov Chain



Problem in 3-D: Gravity calculation with Tesseroids is too slow!

Synthetic data

- Use SP12-RTS as input model
  - Scale velocity to density (factor 0.5)
  - Blank the top 200 km of model (remove lithosphere)
- Derive phase velocities
  - Maximum degree 30, fundamental, first, second and third overtone
  - Filtered to spatial degree 14
- Derive synthetic gravity field
  - Filtered to spatial degree 14

Inversion setup

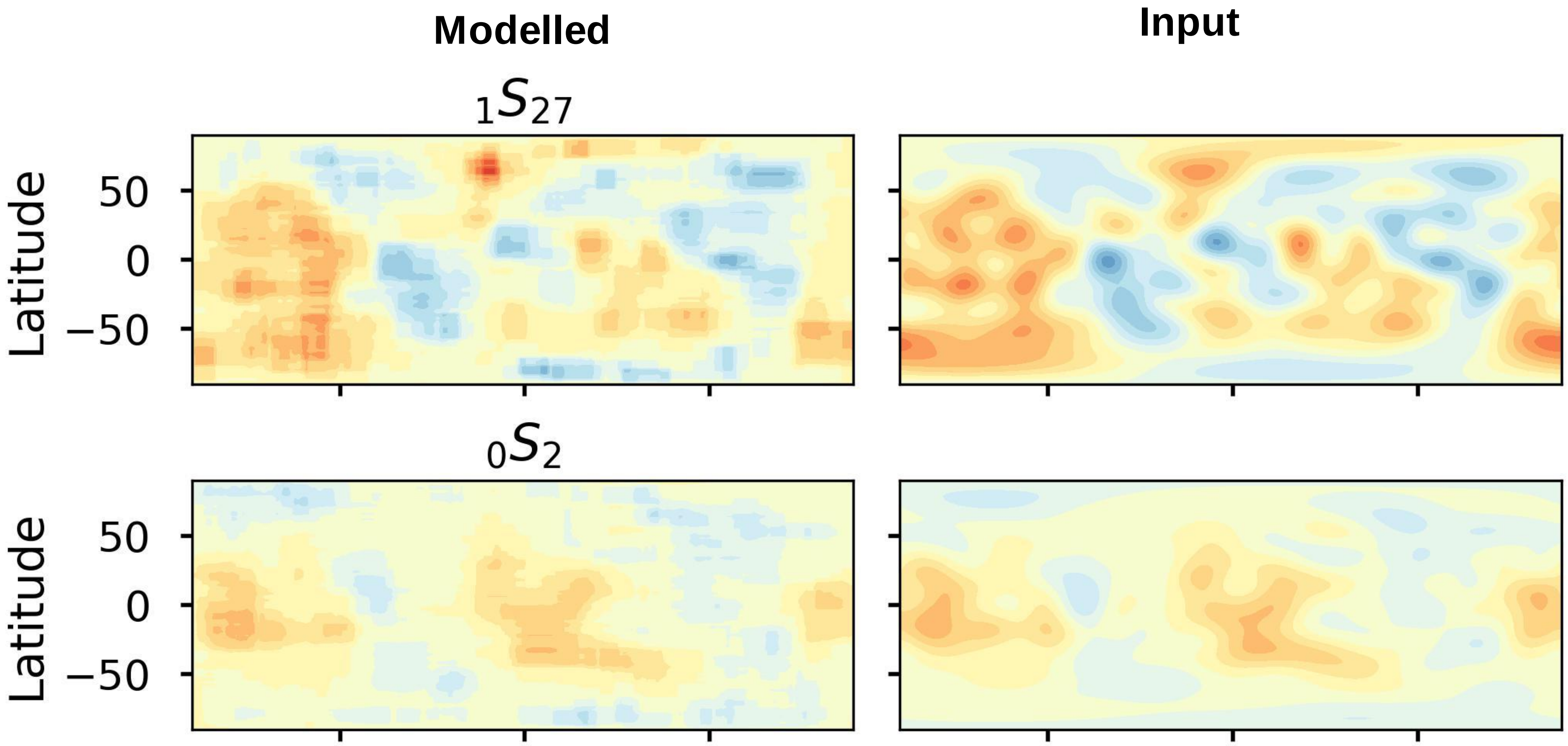
Prior	Type	Range
Velocity	Uniform	-5 to 5 % rel. To PREM
Density	Uniform	-5 to 5 % rel. To PREM
East-West size	Uniform	10° to 90°
North-south size	Uniform	10° to 45°
Radial size	Uniform	100 km to 1000 km

Parameter	
Iterations	48000
Parallel runs	8
Runtime	1 h

Scenario	Notes
Normal mode only	Only uses even degrees
Normal mode only with velocity-density constraint	Force $\lvert\rho - v_s\rvert < 1\%$
Normal mode + gravity with velocity-density constraint	
Normal mode + gravity without velocity-density constraint	
Normal mode + gravity with velocity-density constraint and include odd degrees	

Inversion results

Data fit examples(normal modes)

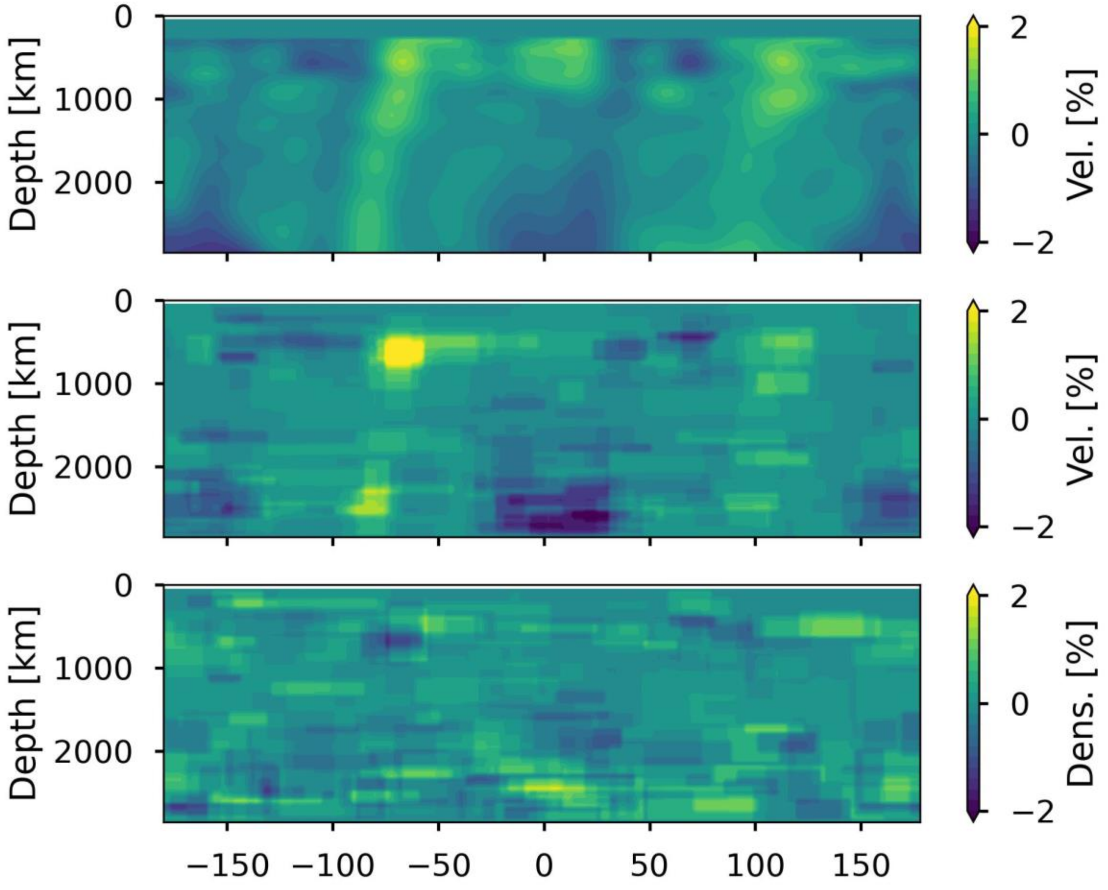


Model recovery (equatorial slice)

Synthetic input model

Velocity output

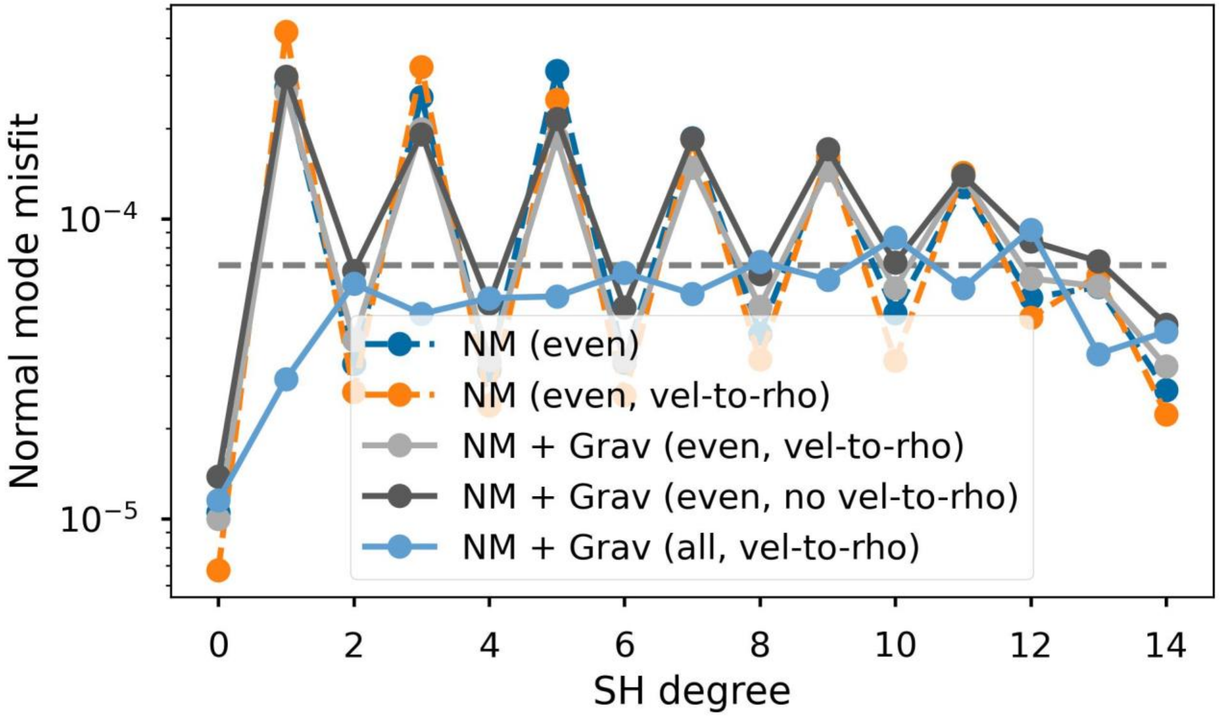
Density output



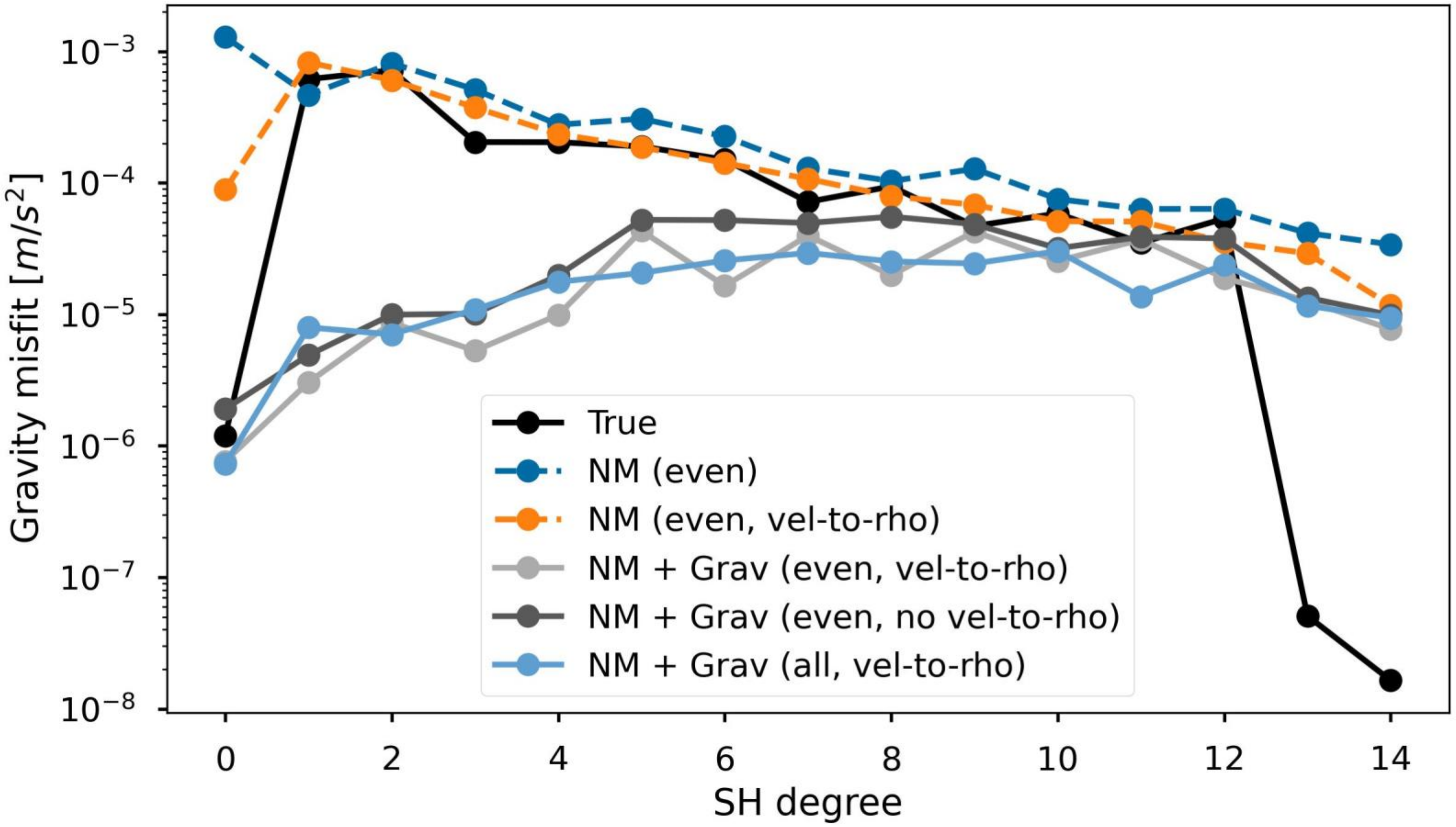
Normal modes only

Average misfit (normal modes)

- Misfit averaged over all periods and overtones but for a given spectral degree



Gravity misfit

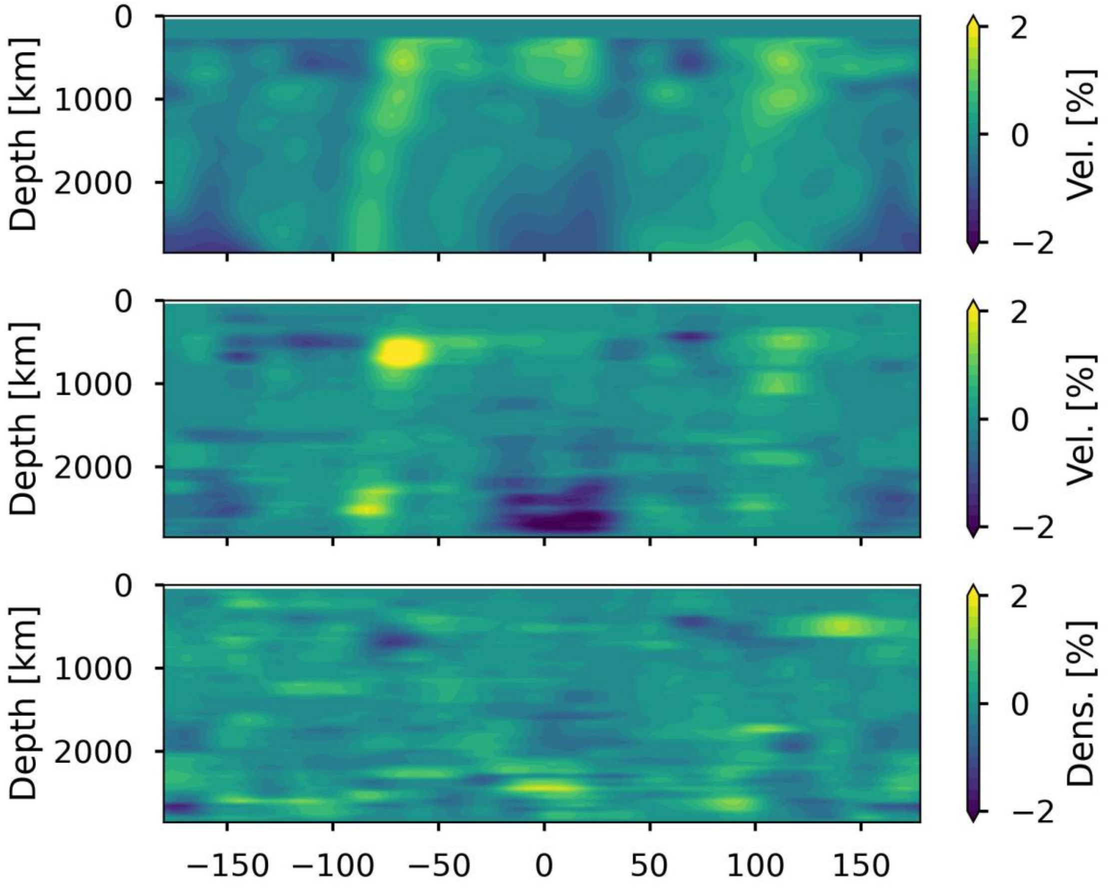


Using only normal mode data

Synthetic input model

Velocity output

Density output



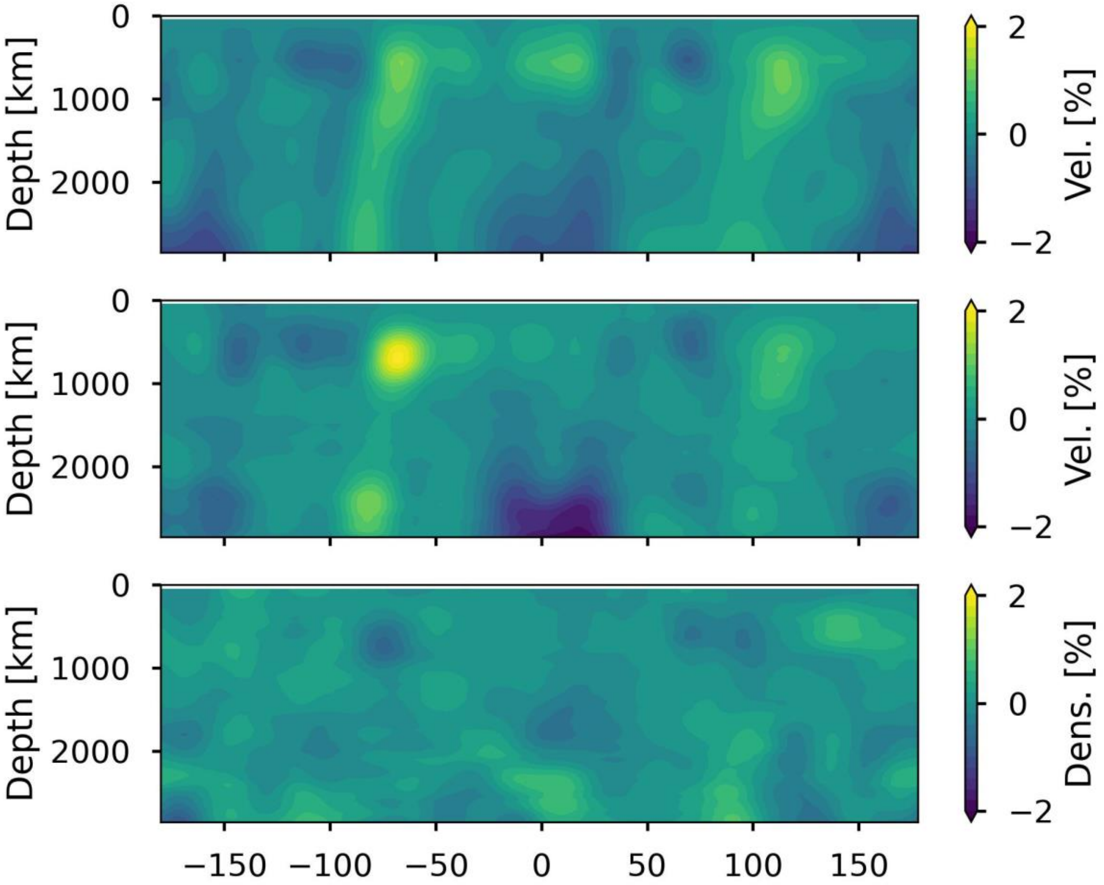
Filtered to degree 14 (like data)

Model recovery (equatorial slice)

Synthetic input model

Velocity output

Density output



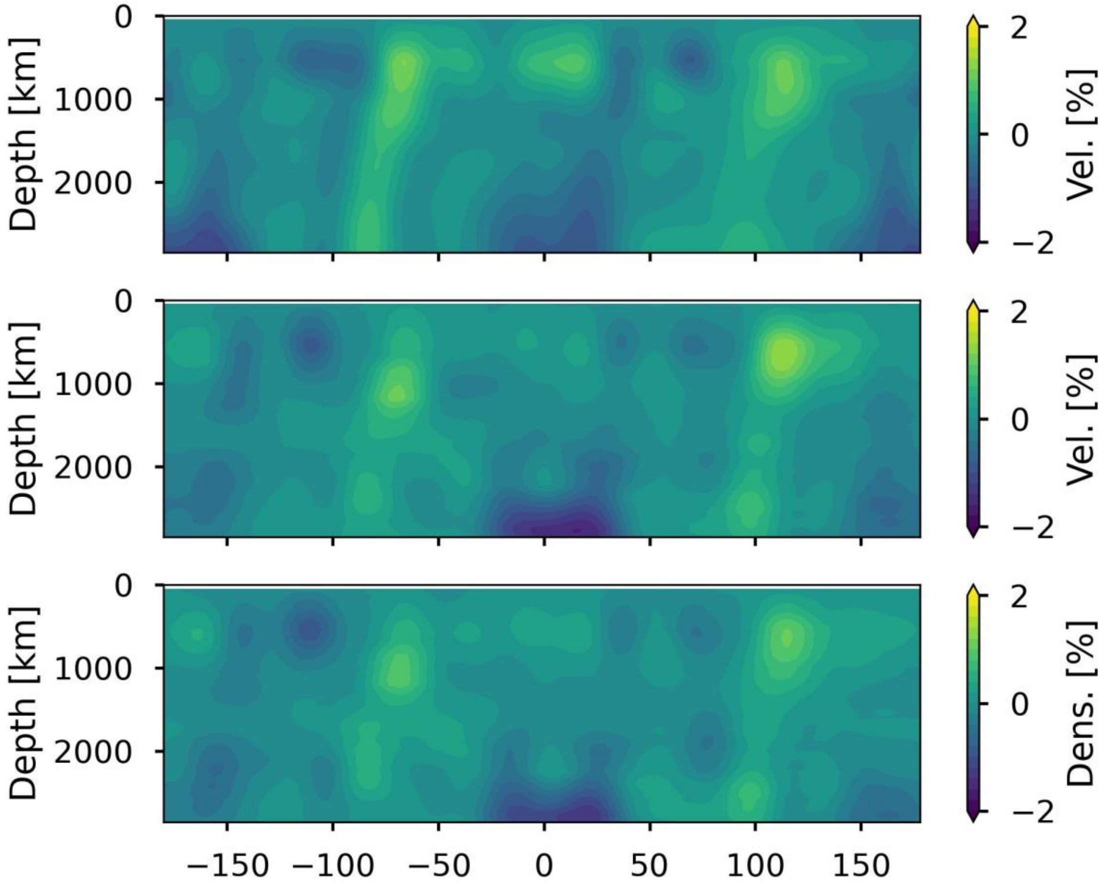
Filtered to degree 14 (like data) and 500 km vertical smoothing

Model recovery (equatorial slice)

Synthetic input model

Velocity output

Density output



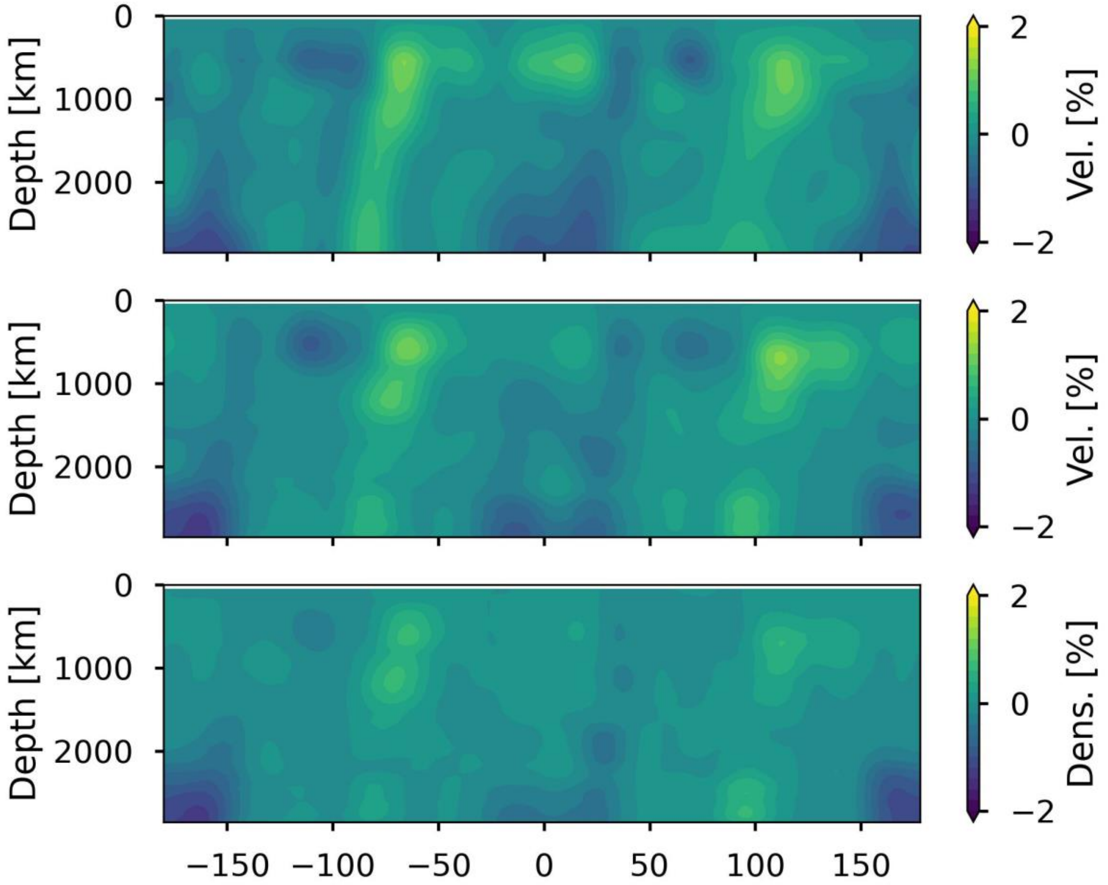
Include (correct) velocity-density scaling

Model recovery (equatorial slice)

Synthetic input model

Velocity output

Density output



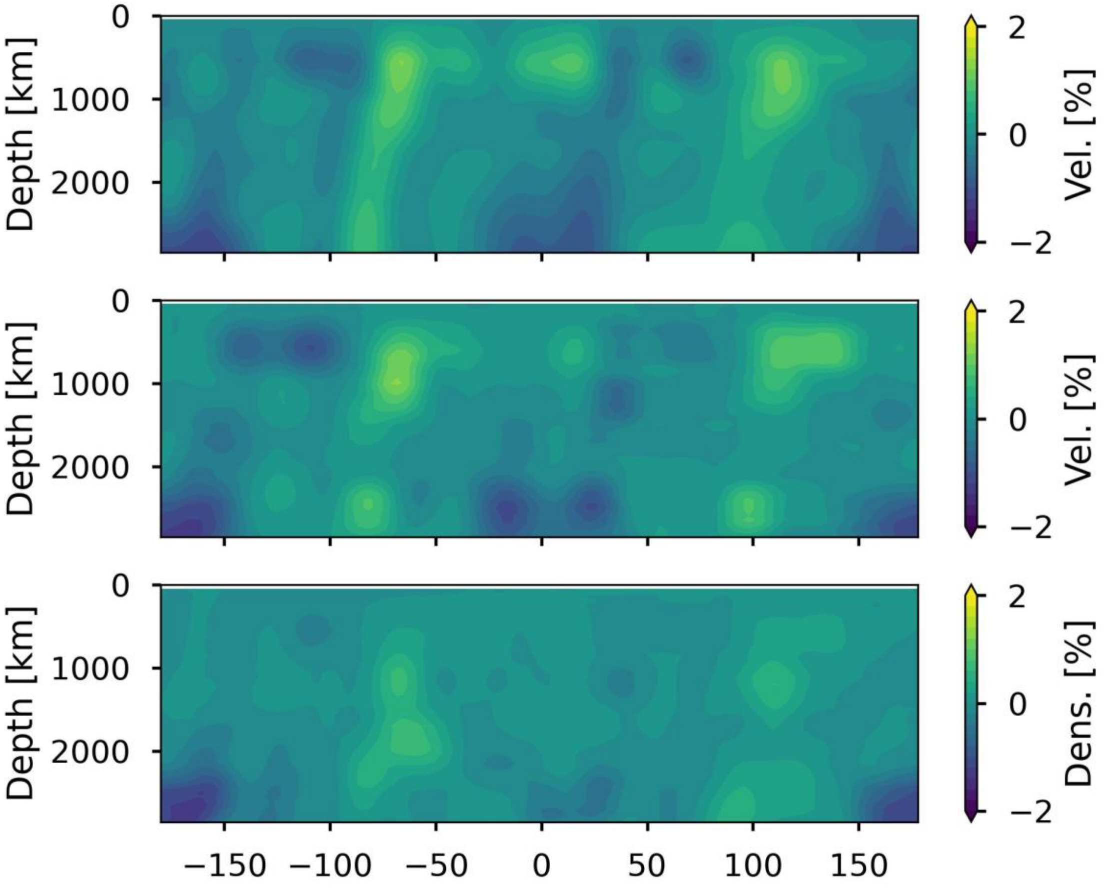
Include (correct) velocity-density scaling and gravity data

Model recovery (equatorial slice)

Synthetic input model

Velocity output

Density output



Gravity data only, no velocity-density constraint

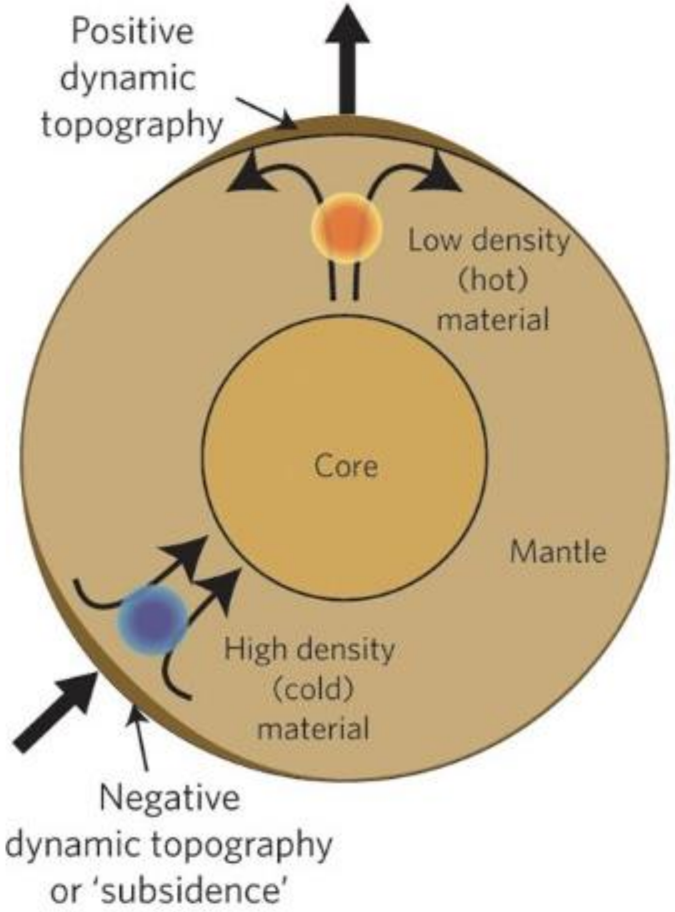
Outcomes of inversion

- First 3-D transdimensional inversion using tesseroidal mantle elements
- „Push and pull“ between different data sets in inversion
- Sometimes additional data lead to worse recovery -> optimize settings

Challenges

- **Transdimensional inversion struggles with upper and lower boundary (!)**
- How to treat lithosphere?
- How approriate are my assumptions?

Dynamic gravity kernels

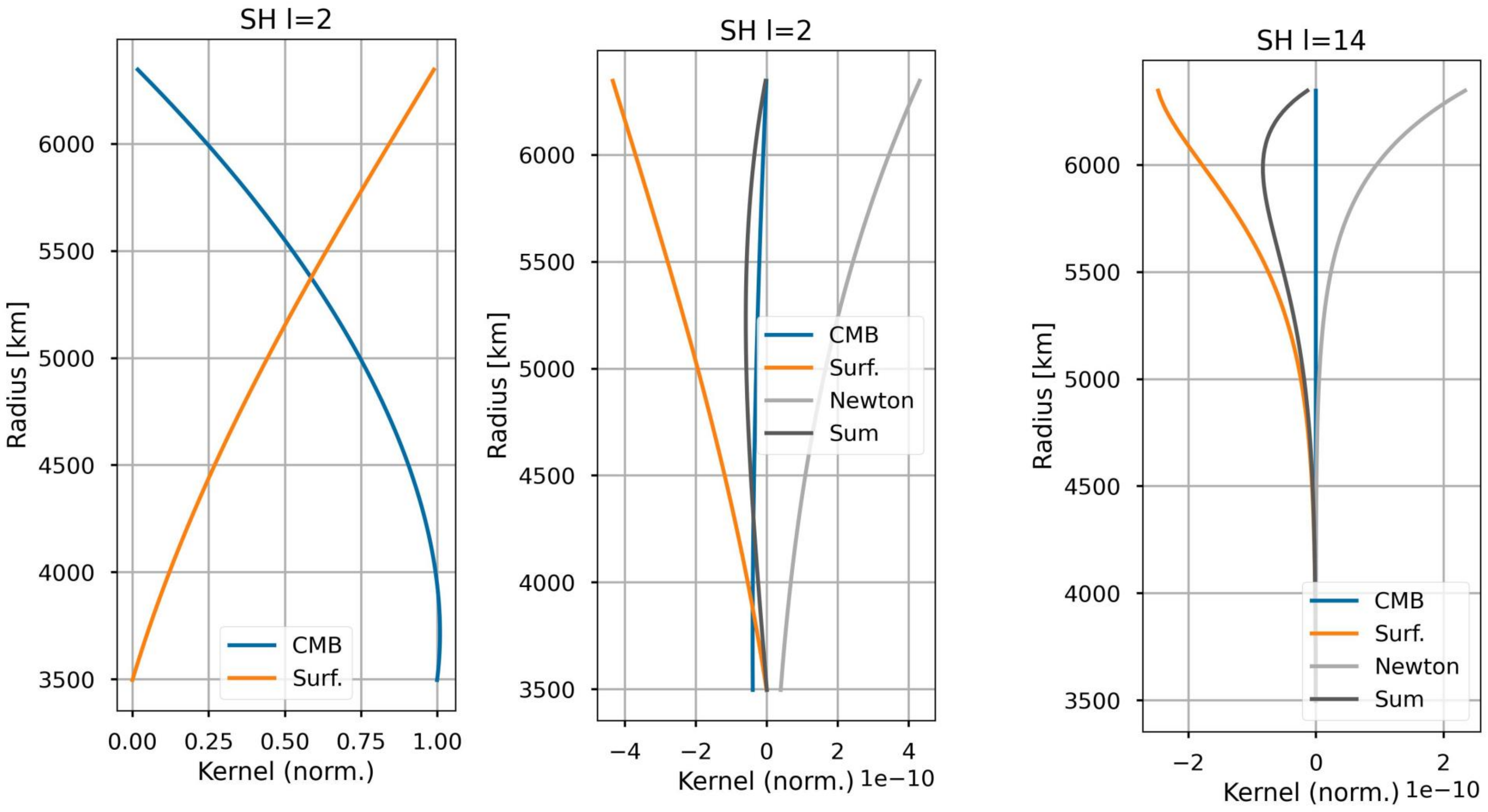


$$g_{dyn} = g_{newton} + g_{surface} + g_{CMB}$$

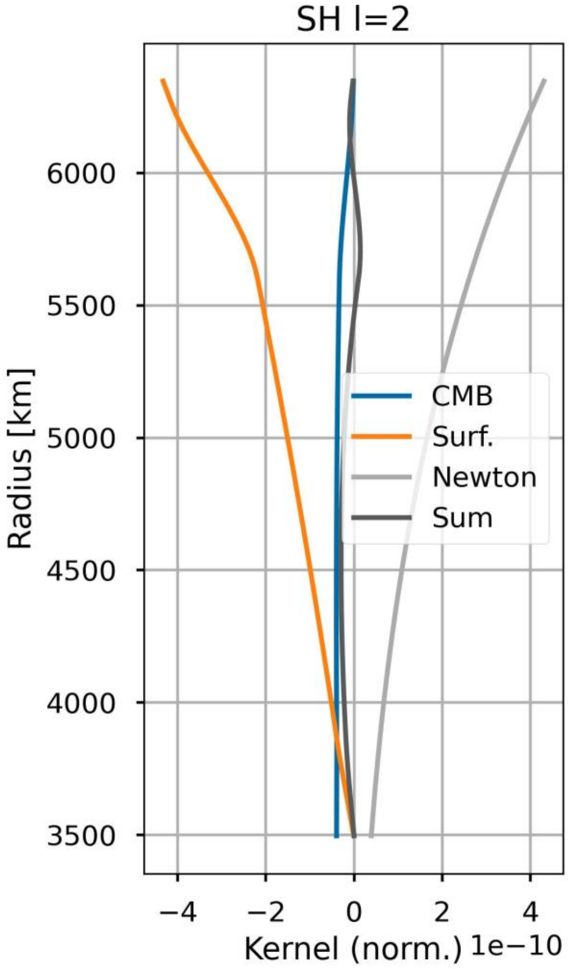
Gravity effect of dynamic surface topography

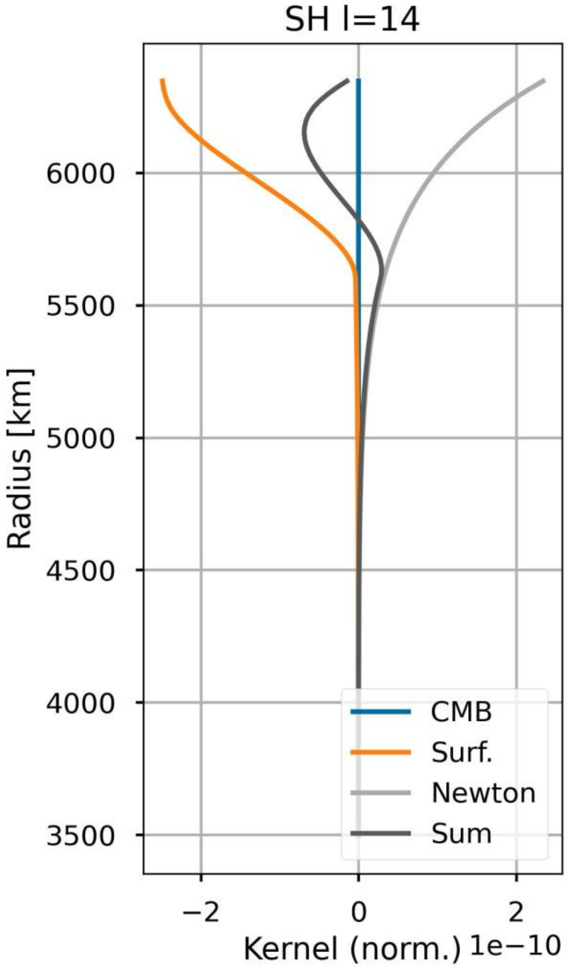
Depends on rheology, can be calculated assuming 1-D viscosity model

Constant viscosity



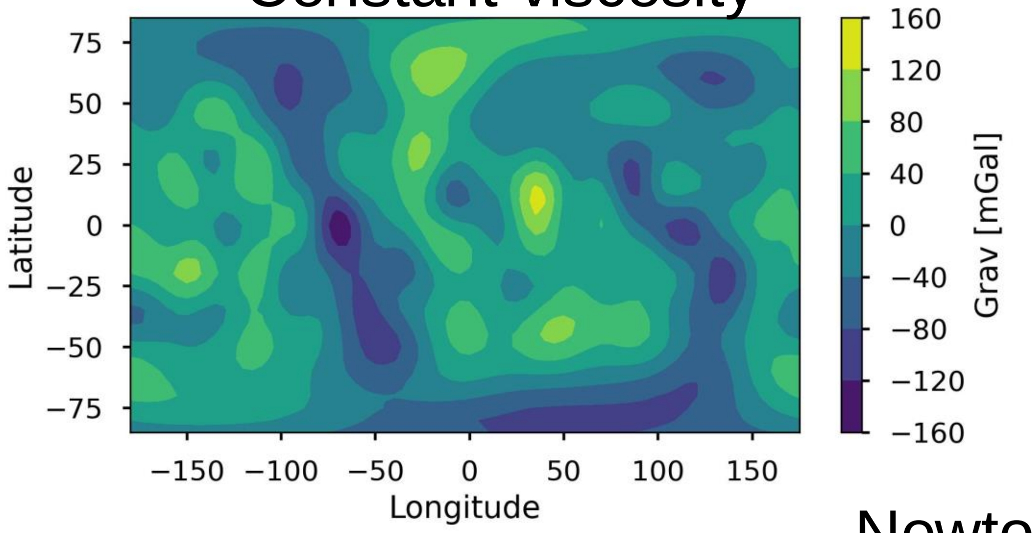
Layered viscosity



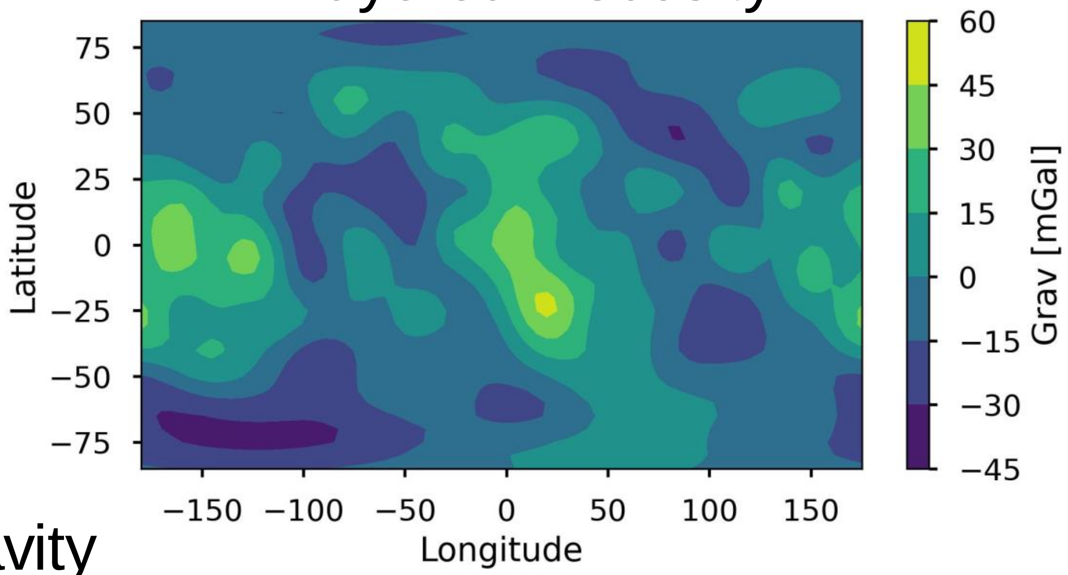


Gravity from tomography model

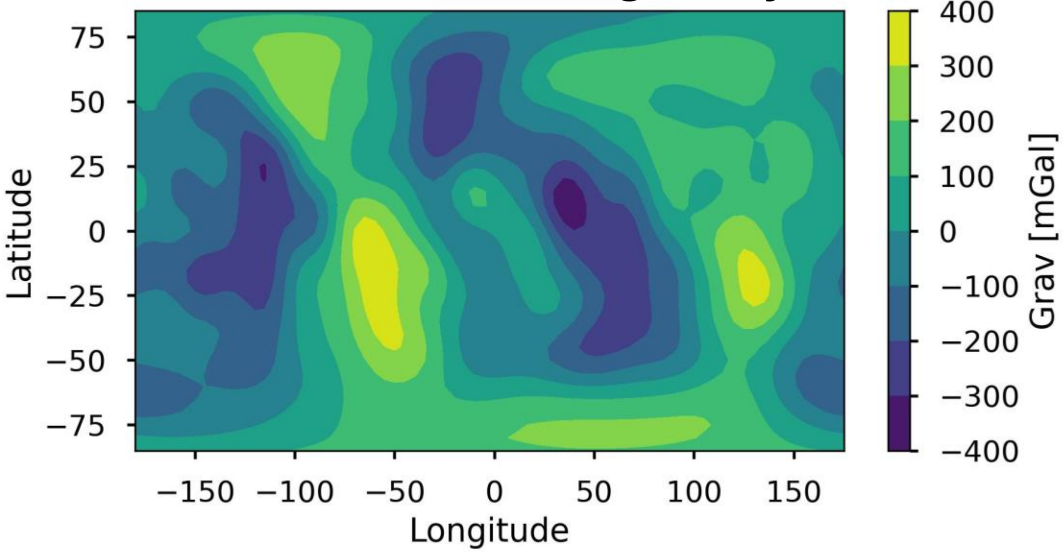
Constant viscosity



Layered viscosity



Newtonian gravity



Thank you for your attention!