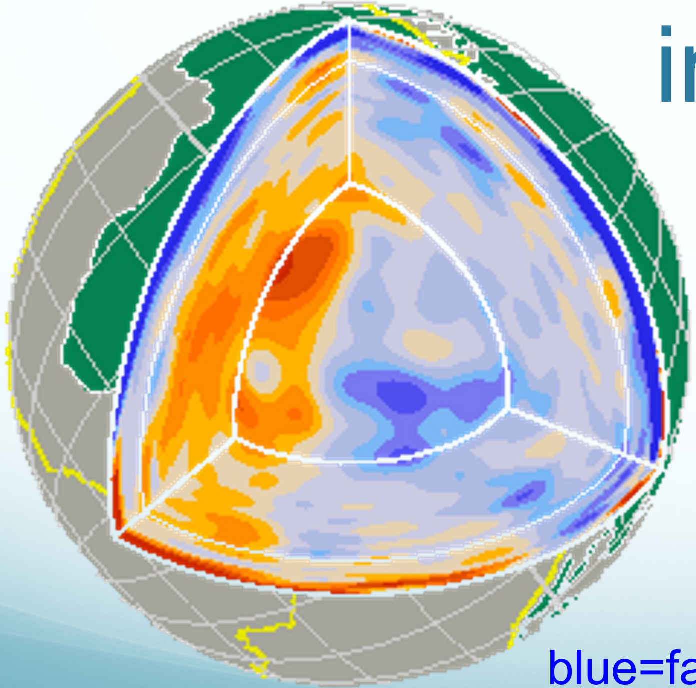
Whole Earth oscillations: Thé key to imaging density in Earth's deep interior using seismic data



blue=fast
red=slow

Model S40RTS
Ritsema, Deuss *et al.*, 2011

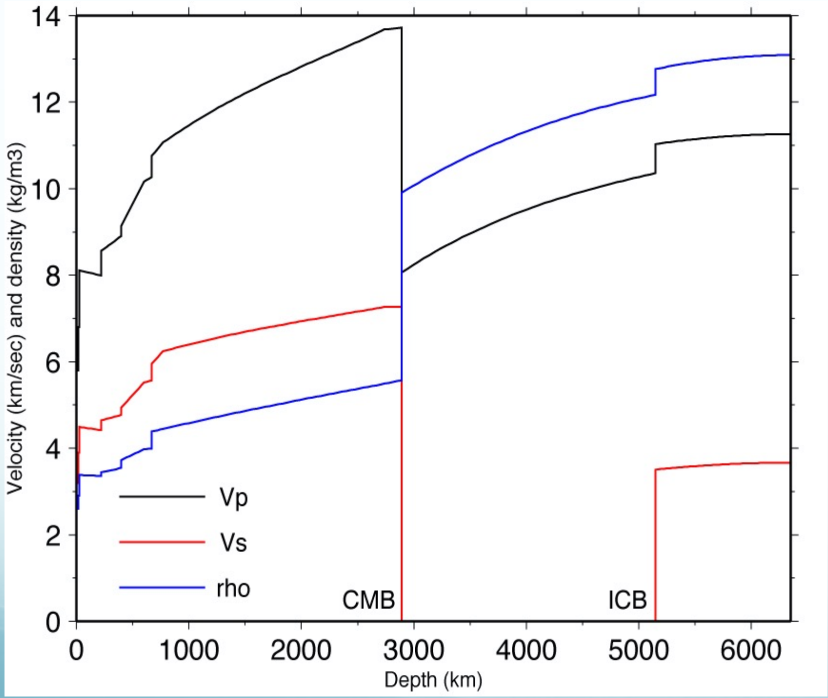
Arwen Deuss

Runa van Tent, Ashim Rijal, Laura Cobden

Universiteit Utrecht

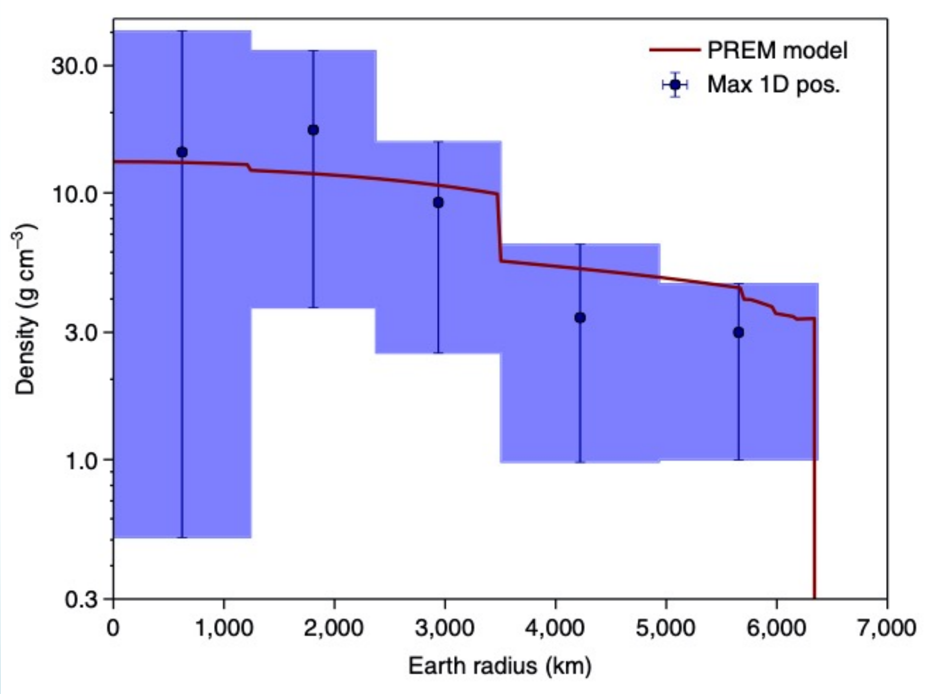
1D density profile

Seismic tomography



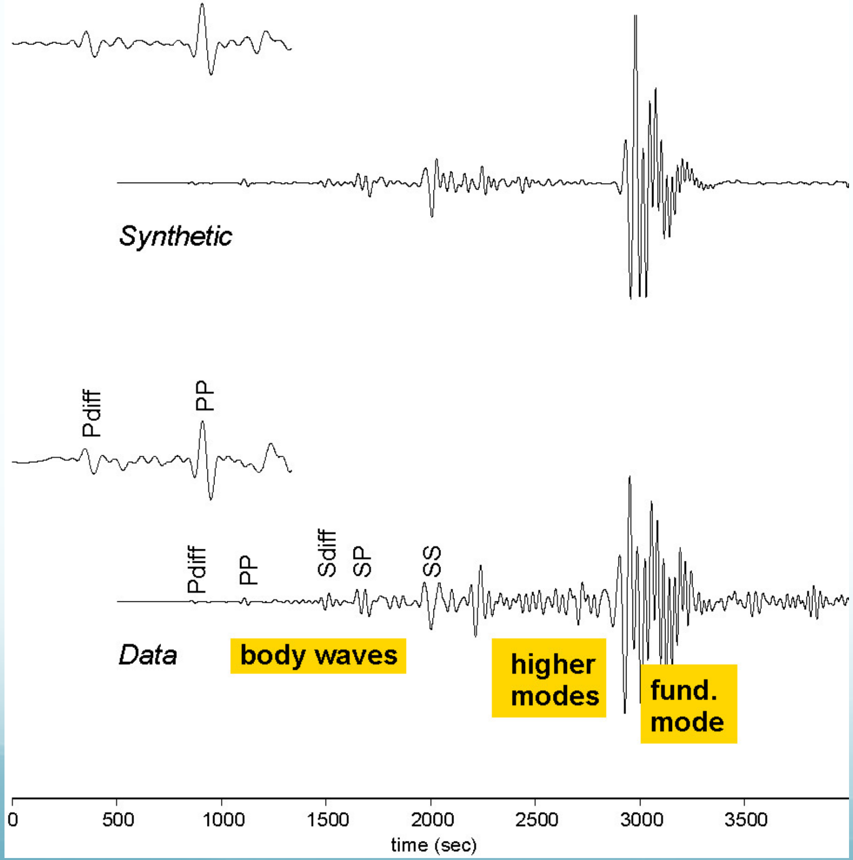
PREM, Dziewonski & Anderson (1981)

Neutrino tomography



Donini *et al* (2019)

Seismological Data



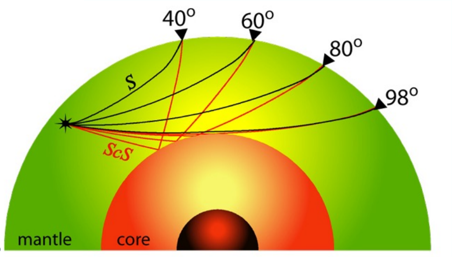
Synthetics computed using normal mode summation up to 6 seconds for PREM

Event 21 May 1998 (Indonesia) at TSUM (Tsumeb, Namibia)

Depth = 28km,
Mw= 6.6, Mb=6.3,
Δ =101.5

(1) Body waves

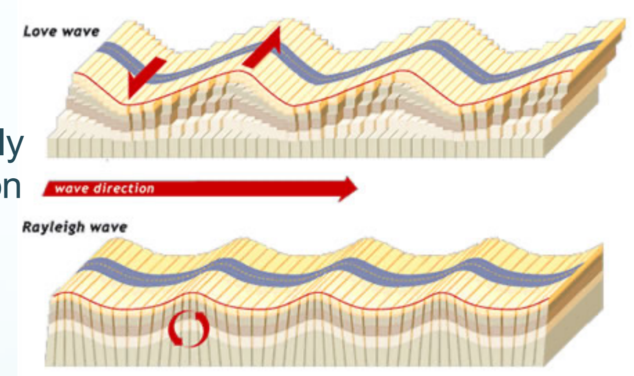
Imaging small scale structure and discontinuities
Only velocity information
Ray theoretical approximations



Short period (~ 0.05-1Hz)

(2) Surface waves

Imaging upper mantle only
Mainly velocity information
(limited density)



(0.3-40 mHz)

(3) Whole Earth oscillations

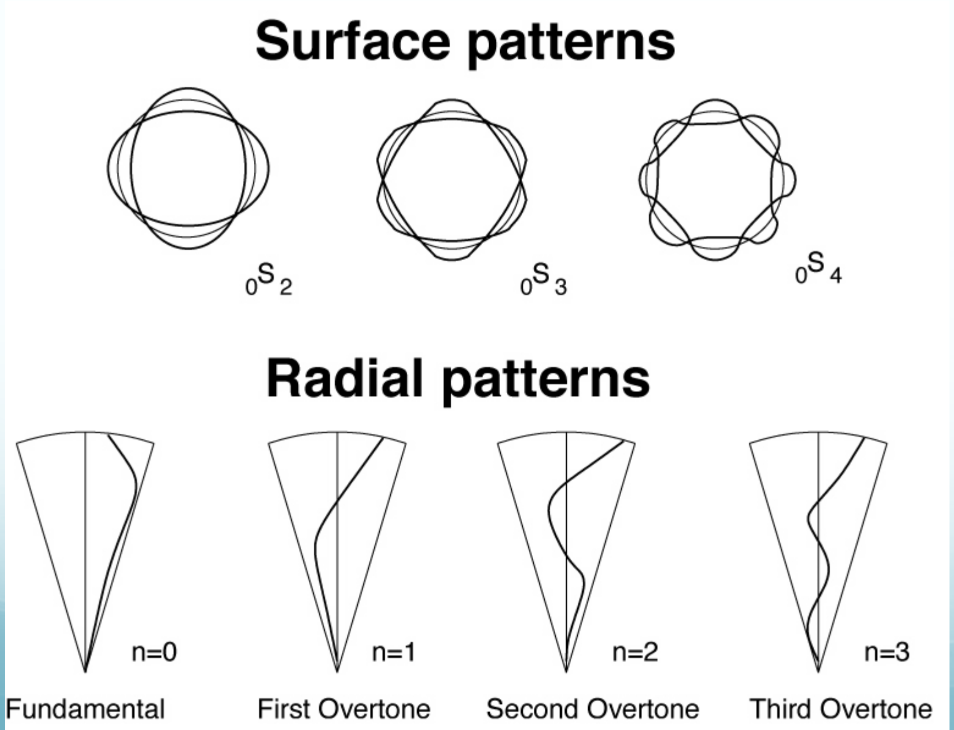
Density and velocity information
Only large scale structure
Complete theory

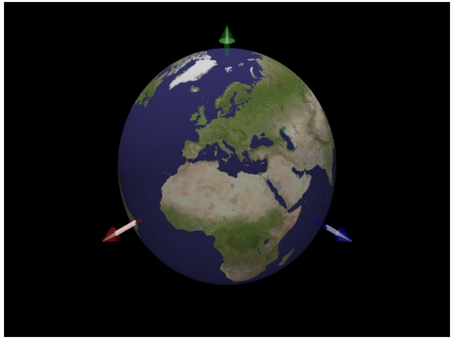
Long period (0.2-10 mHz)

Whole Earth oscillations

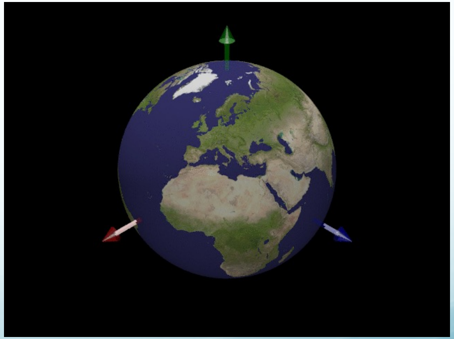
Spheroidal modes ${}_nS_l$

n = radial order, l = angular order





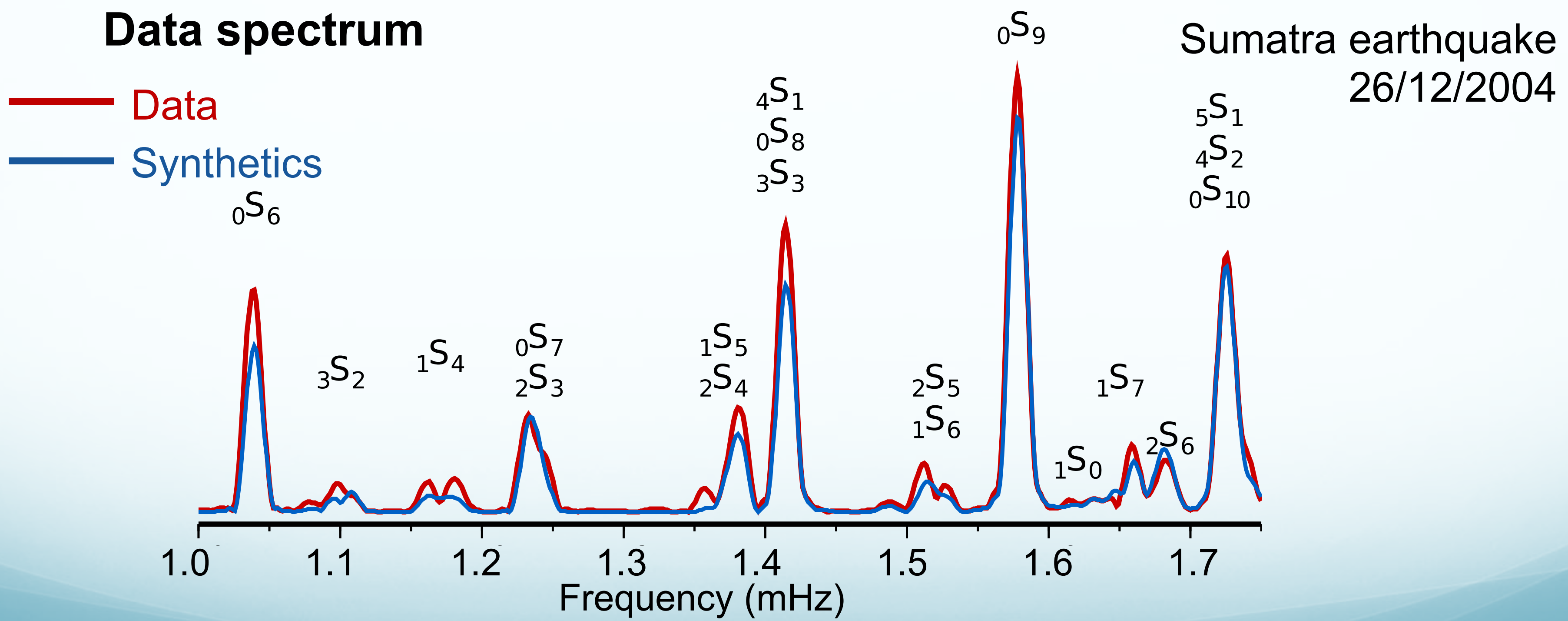
${}_0S_2$: 54 minutes
"football mode"



${}_0S_0$: 20 minutes
"breathing mode"

http://lucien.saviot.free.fr/terre/index.en.html

Normal mode data

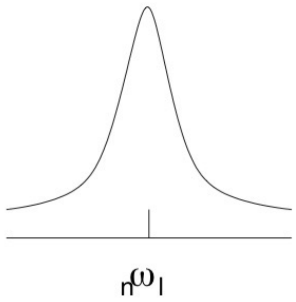


Deuss et al (2013)

SNREI

* spherical symmetric,
* non–rotating,
* isotropic Earth

degeneracy:
2l+1 singlets have same frequency



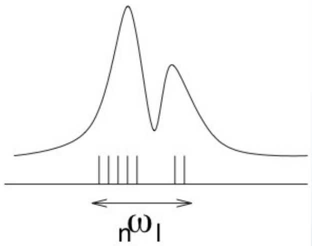
Real Earth

* Rotation
* Ellipticity
* Heterogeneity
* Anisotropy

degeneracy removed:
2l+1 singlets have different frequency

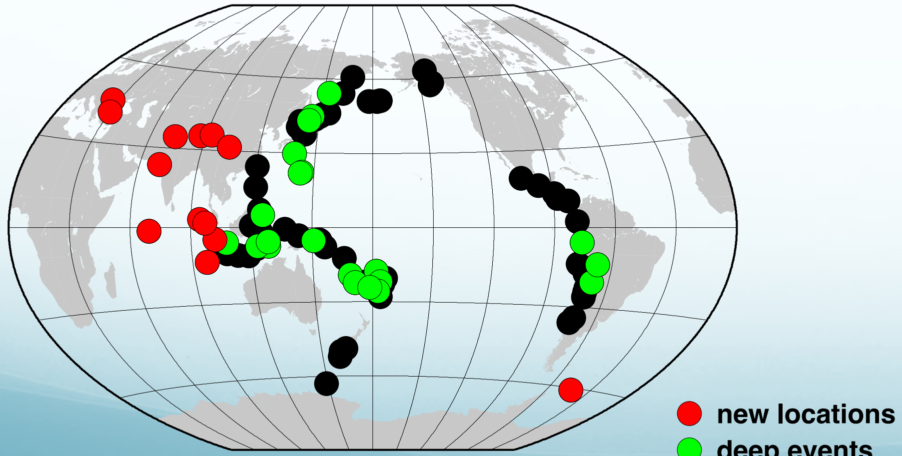
↓

splitting and coupling



Normal mode observations

- Data set of 93 events with Mw>7.4 since 1978
- Select frequency window for specific normal mode
- Combine all spectra for one splitting function
- Start from PREM predictions
- Iterative least squares spectral fitting



Including:

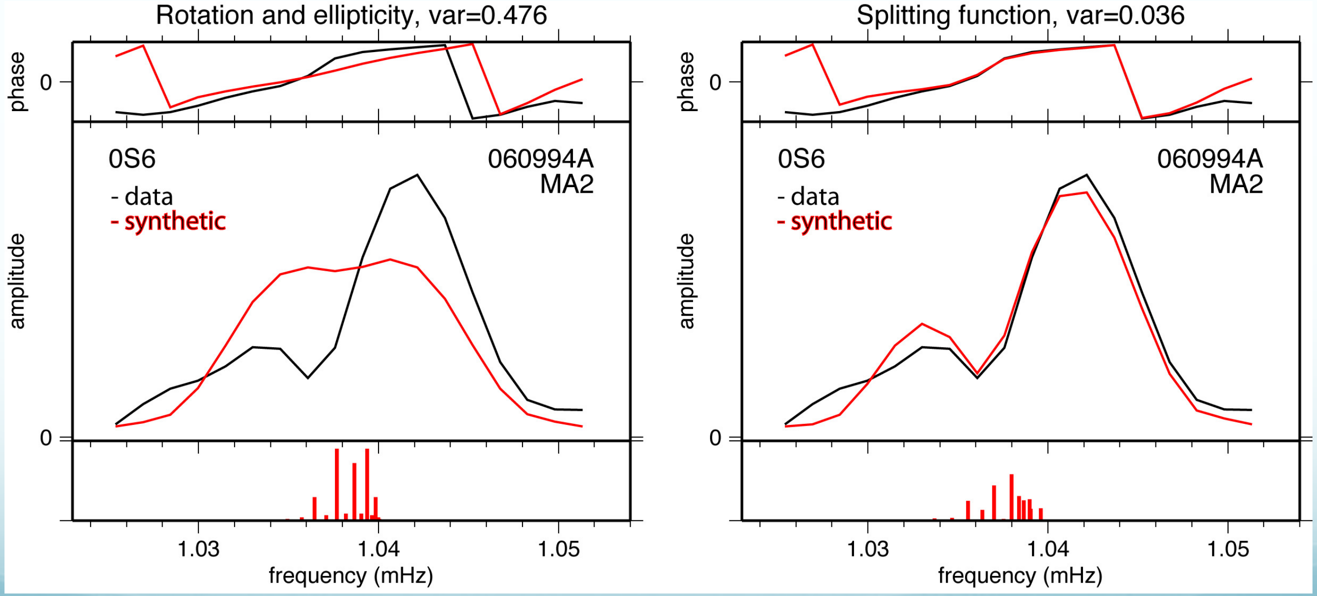
- 2004 Sumatra (Mw=9.0)
- 2010 Chile (Mw=8.8)
- 2011 Japan (Mw=9.0)

(Deuss et al., *GJI*, 2013)

Normal mode spectra

Before splitting function measurement:

After splitting function measurement:



Woodhouse & Deuss, *Treatise on Geophysics*, 2015

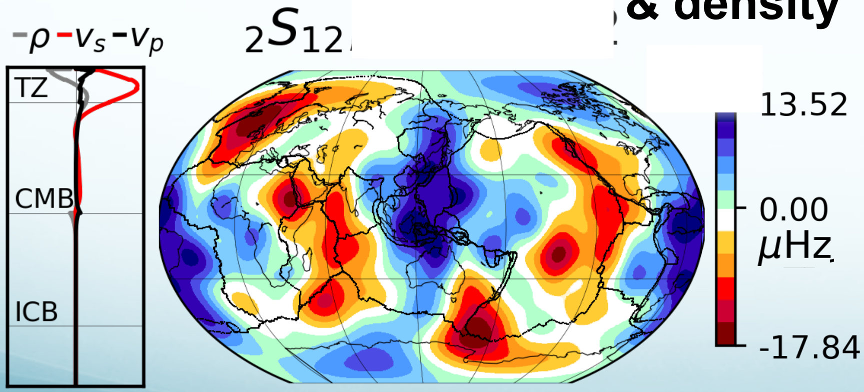
Splitting functions

$$F(\theta,\phi) = \Sigma\, c_{st}\, Y_s^t(\theta,\phi)$$

s=angular order
t=azimuthal order

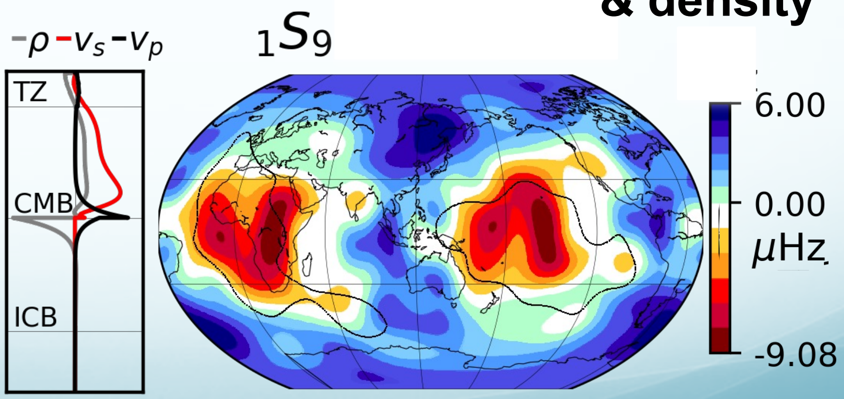
Upper mantle

Elastic splitting function – **3D velocity & density**



Lower mantle

Elastic splitting function – **3D velocity & density**



Deuss et al, *GJI*, 2013

Splitting functions

$$F(\theta,\phi) = \Sigma\, c_{st}\, Y_s^t(\theta,\phi)$$

s=angular order
t=azimuthal order

Coefficients c_{st} depend on Earth structure

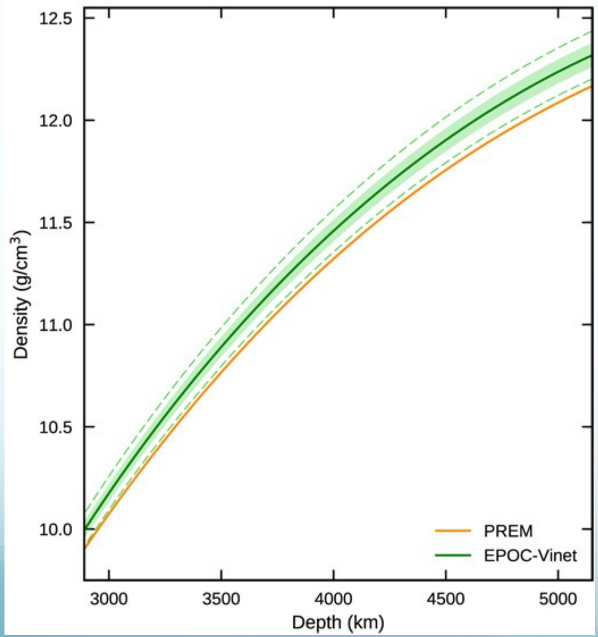
$$c_{st}=\int_0^a \delta m_{st}(r) K_s(r)\,dr$$

$\delta m_{st}(r)$ are model parameters (v_s, v_p, ρ)
$K_s(r)$ are the kernels

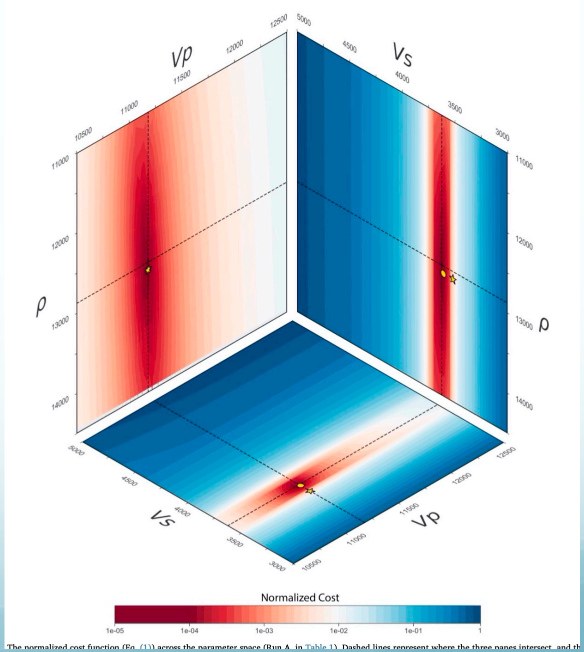
s=0 'center frequencies' $\longrightarrow$ 1D structure
s > 0 'splitting function' $\longrightarrow$ 3D structure

1D structure

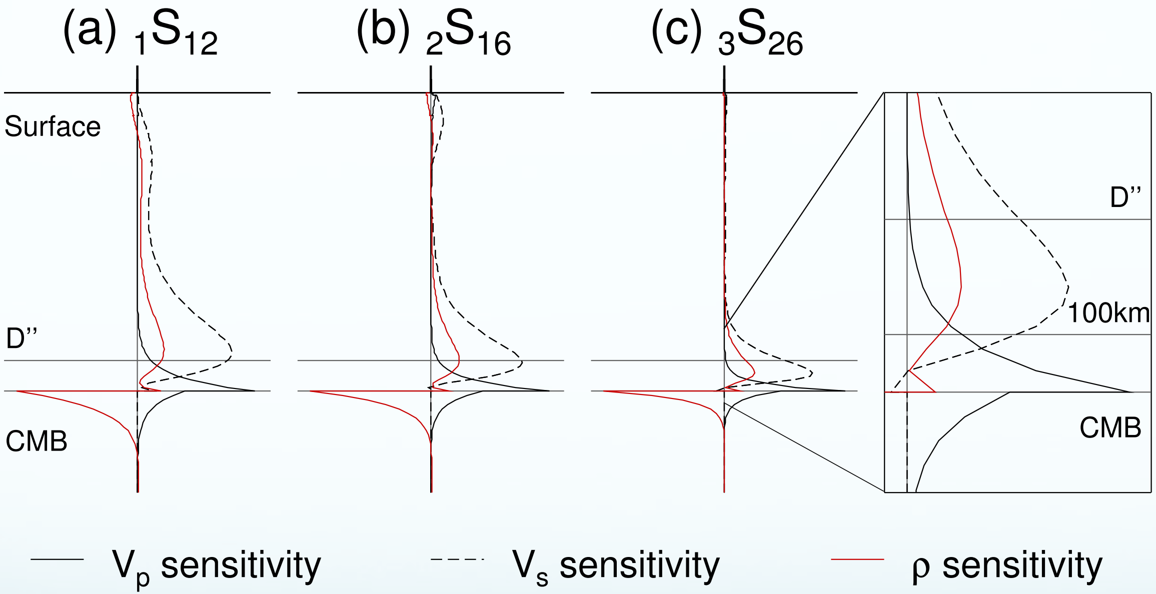
- Outer core is denser than PREM (Irving et al, 2018)



- Inner core is lighter than PREM (Robson & Romanowicz, 2019)



Core Mantle Boundary Stoneley modes

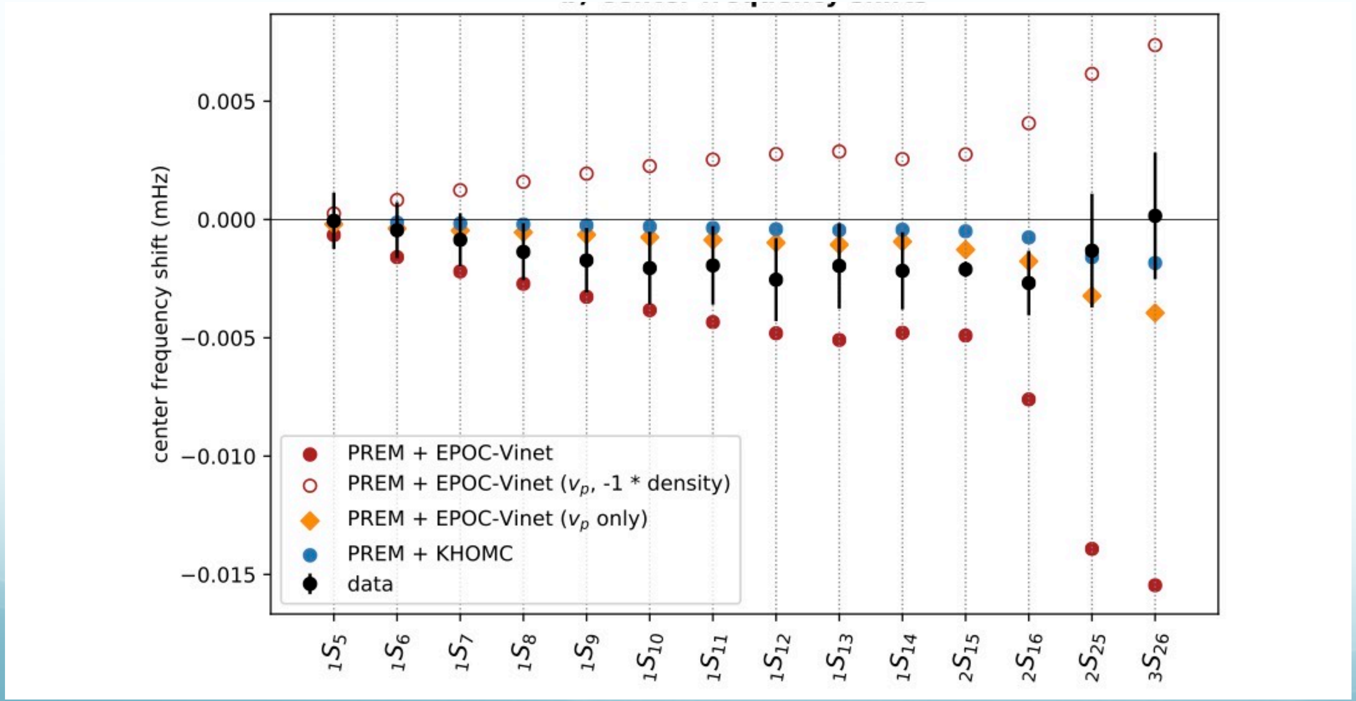


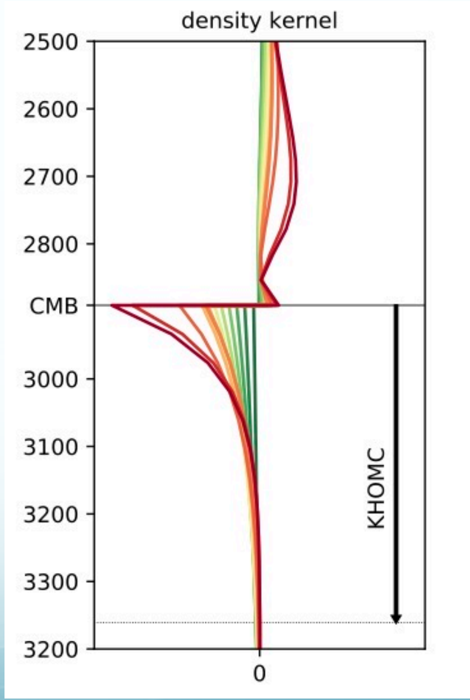
- Strong sensitivity to the Core Mantle Boundary
- Difficult to observe, as almost no surface expression!

(Koelemeijer & Deuss, *GJI*, 2013)

1D structure

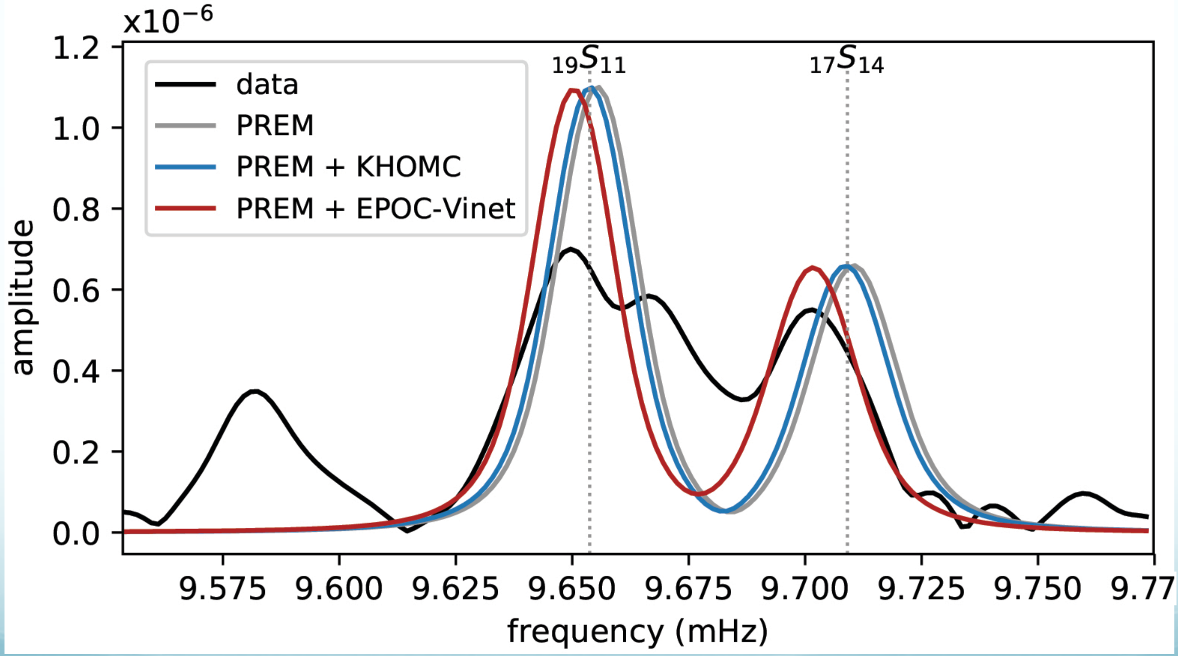
Outer core density – center frequency shifts





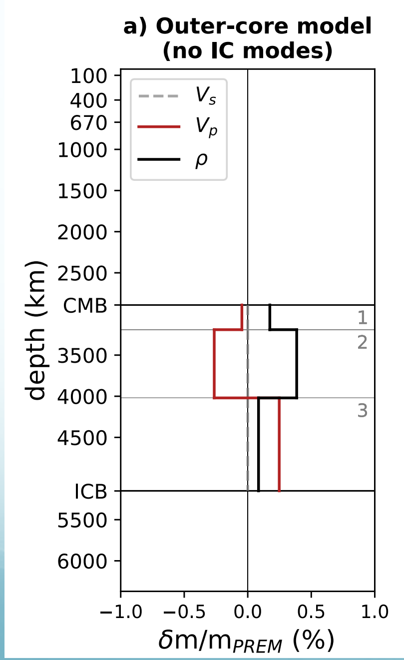
1D structure

Normal mode spectra– outer core density



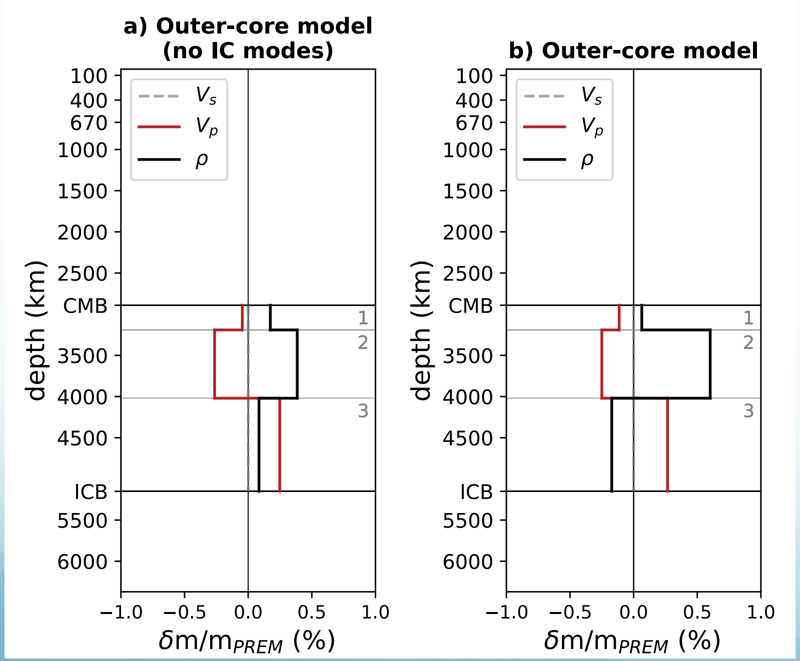
1D structure

- Outer core is denser then PREM?
- Inner core is lighter than PREM?



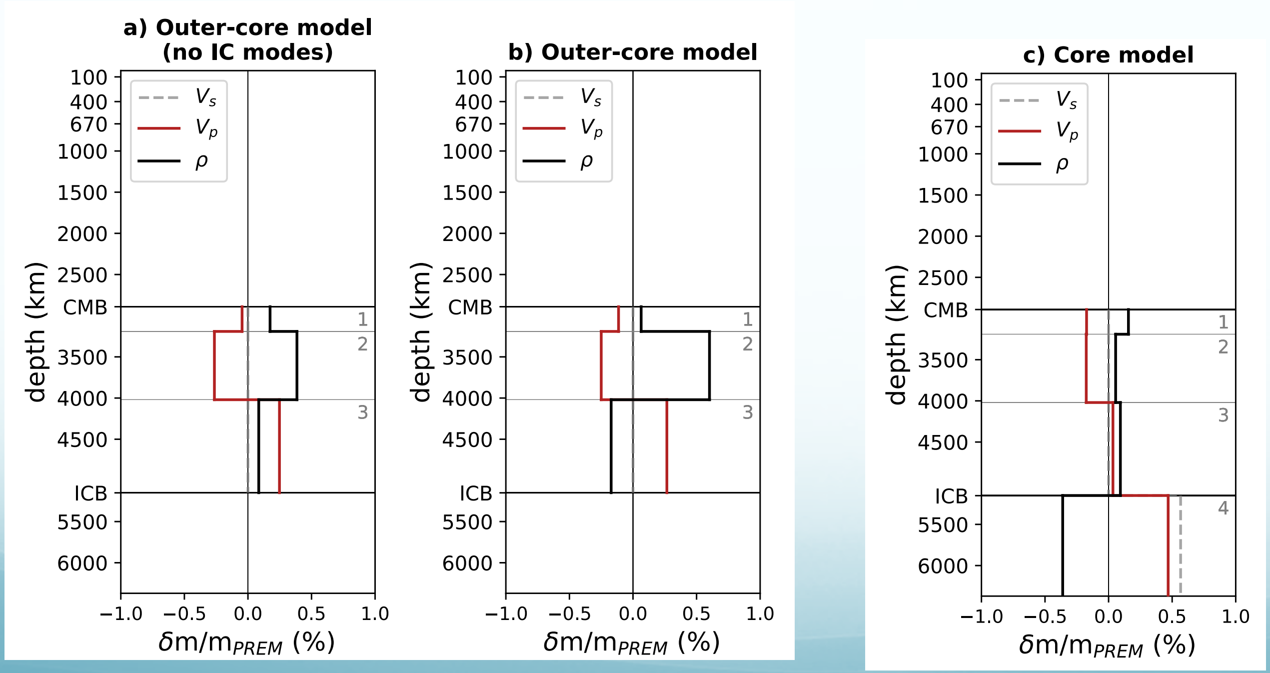
1D structure

- Outer core is denser then PREM?
- Inner core is lighter than PREM?



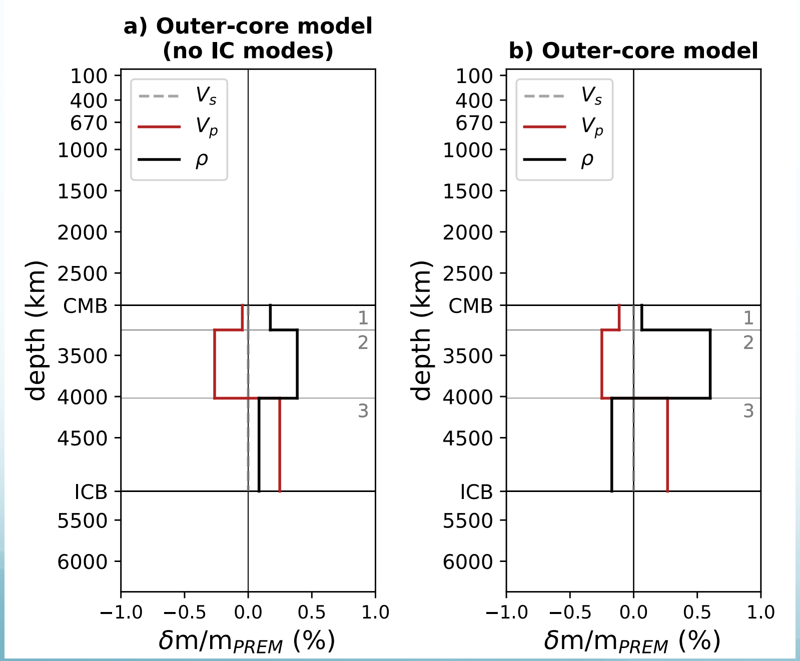
1D structure

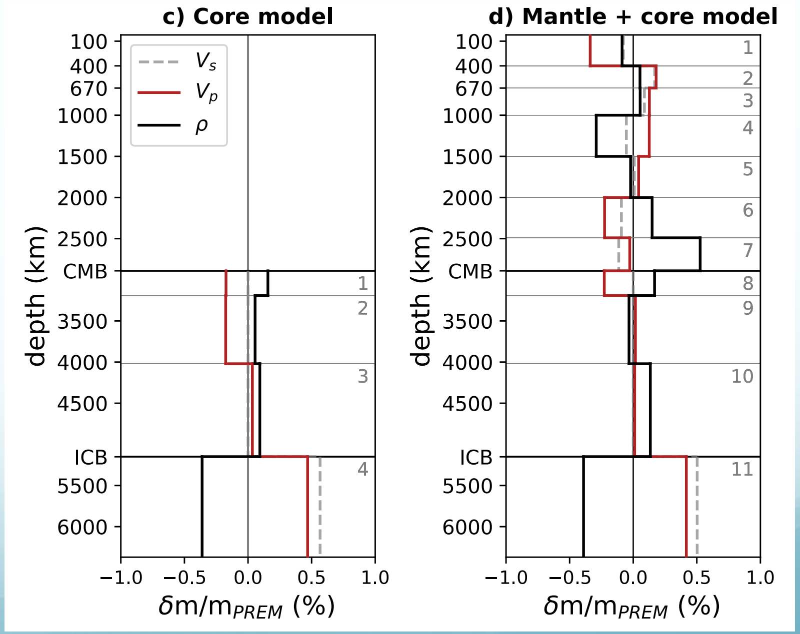
- Outer core is denser then PREM?
- Inner core is lighter than PREM?



1D structure

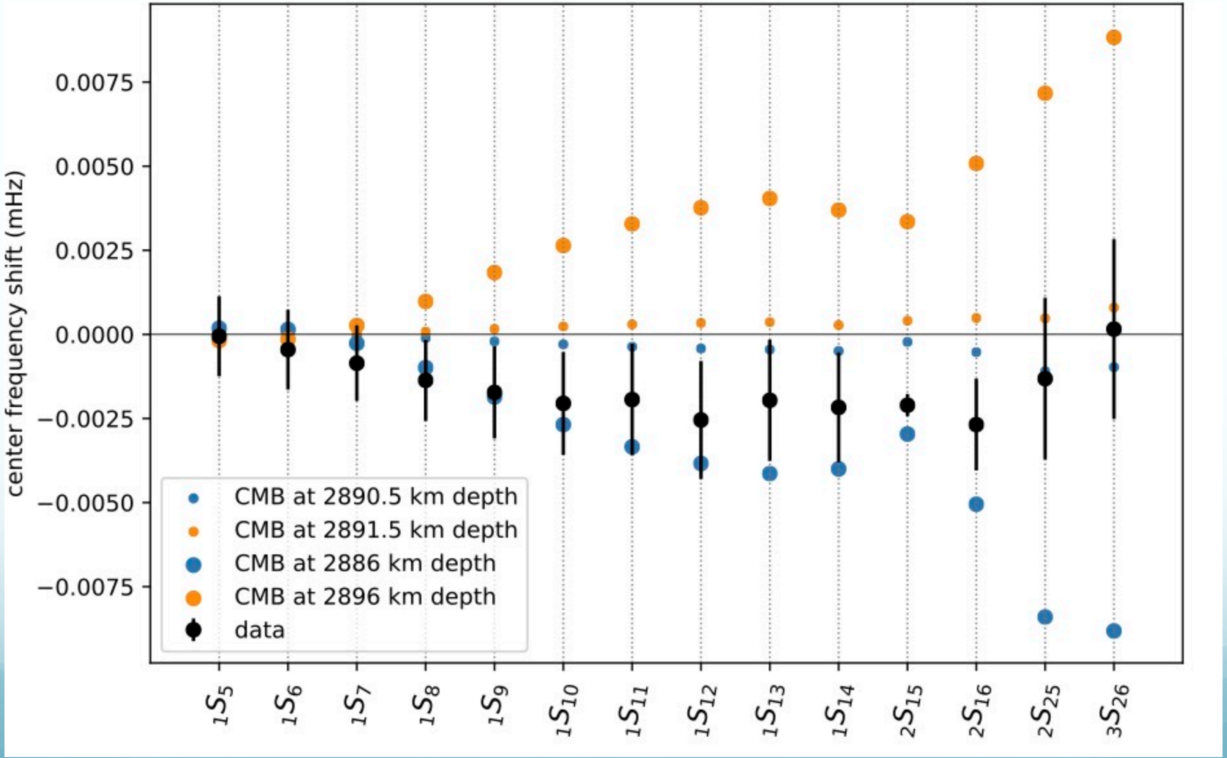
- Outer core is denser then PREM?
  0.2% denser near the top
- Inner core is lighter than PREM?
  0.4% lighter





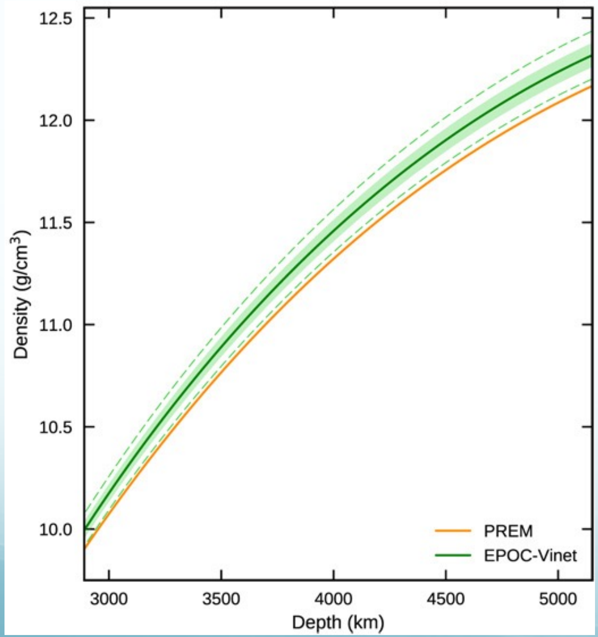
1D structure

CMB depth – 5km shift is already too much!

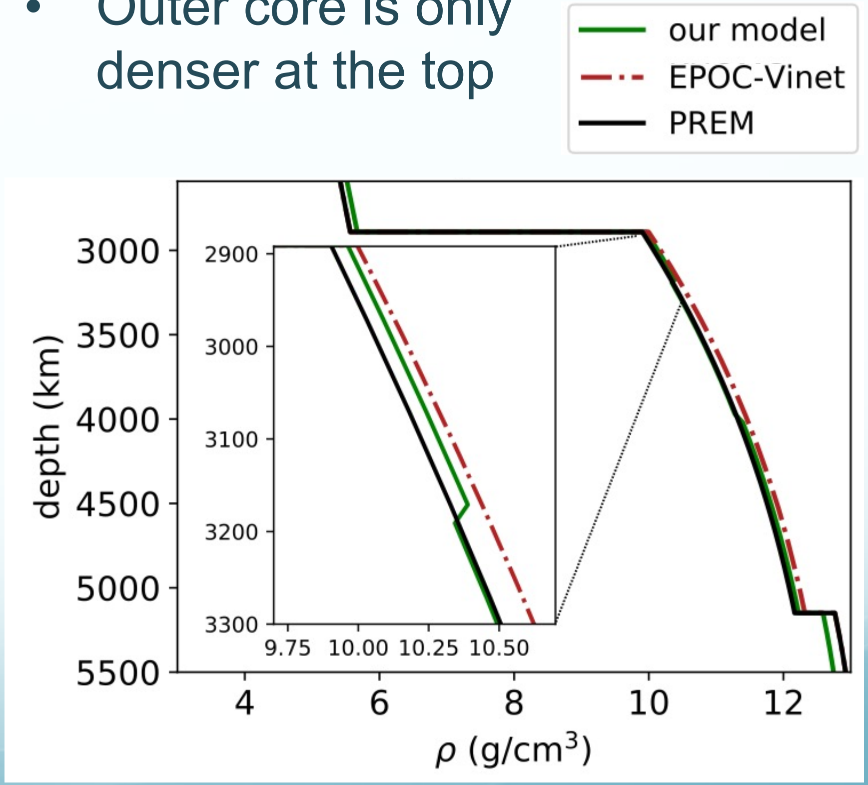


1D structure

- Outer core is denser than PREM (Irving et al, 2018)

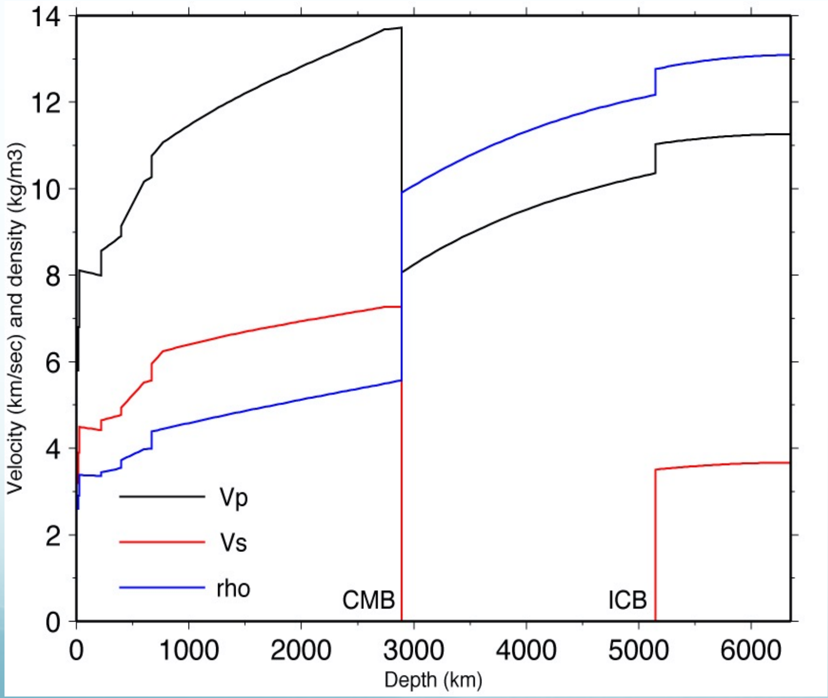


- Outer core is only denser at the top



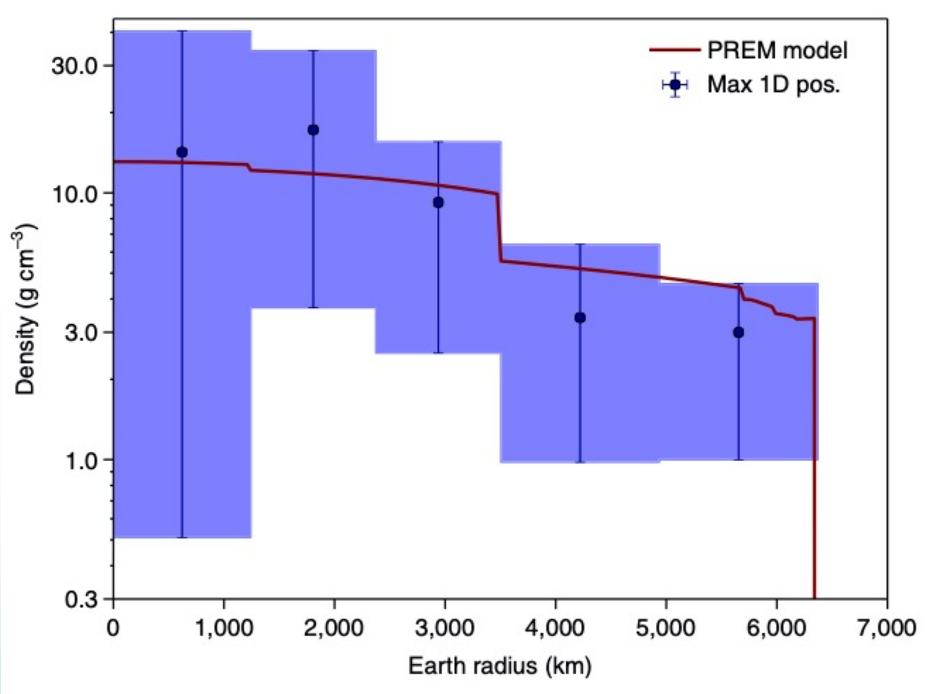
1D density profile

Seismic tomography



PREM, Dziewonski & Anderson (1981)

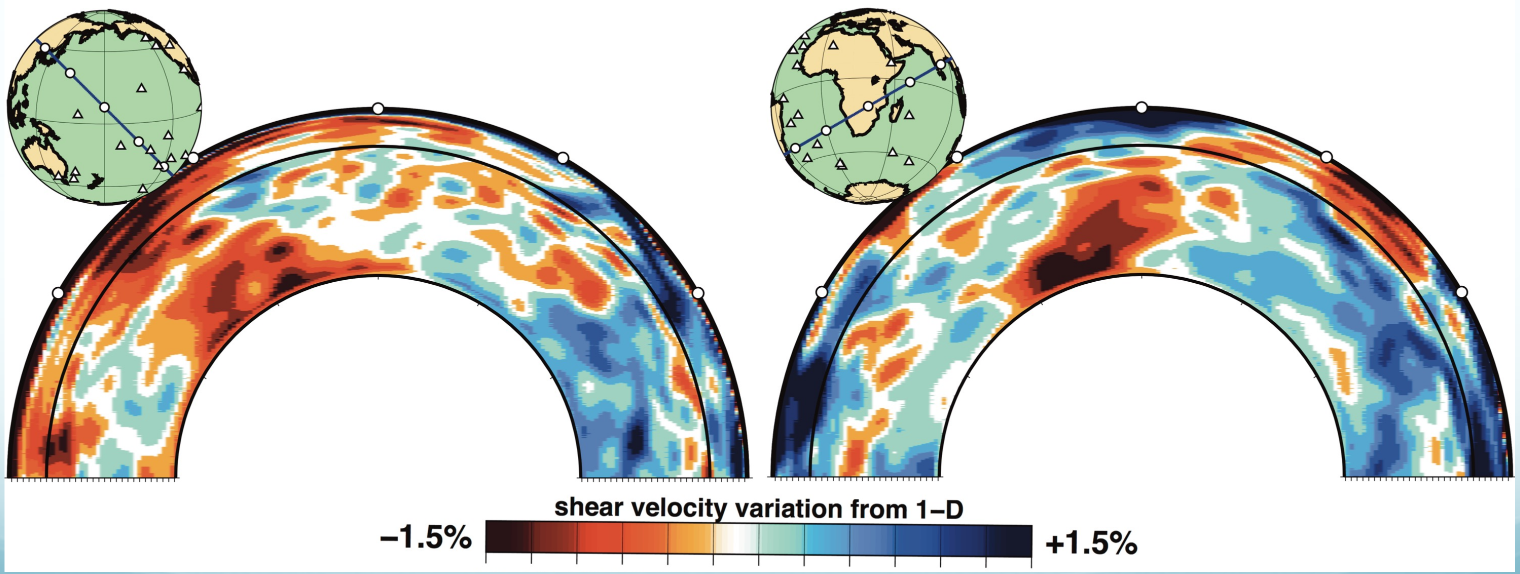
Neutrino tomography



Donini *et al* (2019)

3D structure

Large Low Shear Velocity Provinces (LLSVPs):
Hot superplume or stable mantle anchor?



Model S40RTS
Ritsema, Deuss *et al.*, 2011

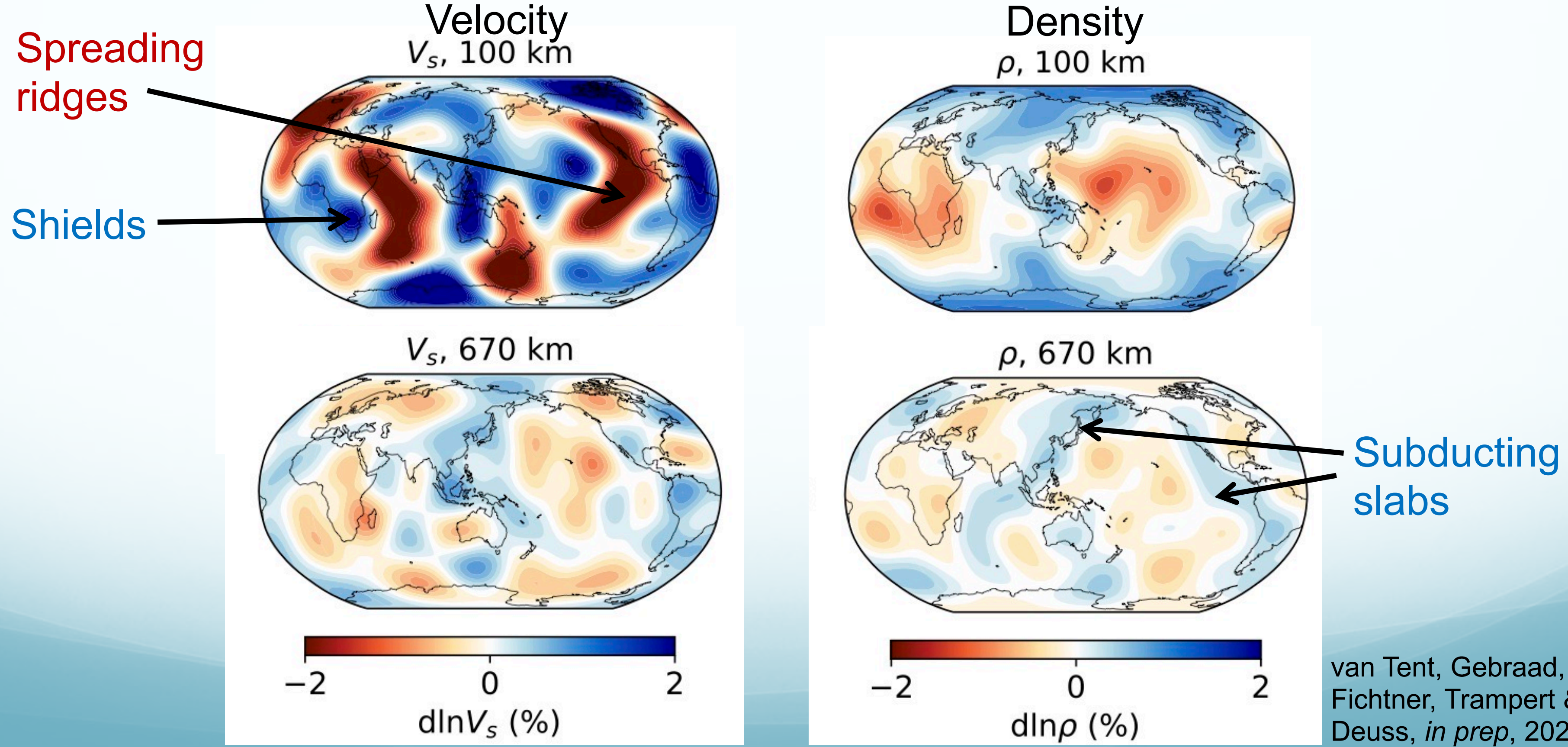
LLSVP density – previous studies

Seismic normal modes

Tomographic models	- LLSVPs are **dense**	Ishii & Tromp (1999) Trampert et al. (2004) Mosca et al. (2012)
Stoneley modes	- LLSVPs are **light**	Koelemeijer et al.(2017)
Geoid	- LLSVPs are **light**	Hager et al. (1985)
Tidal data	- LLSVPs are **dense**	Lau et al. (2017)

Density tomography

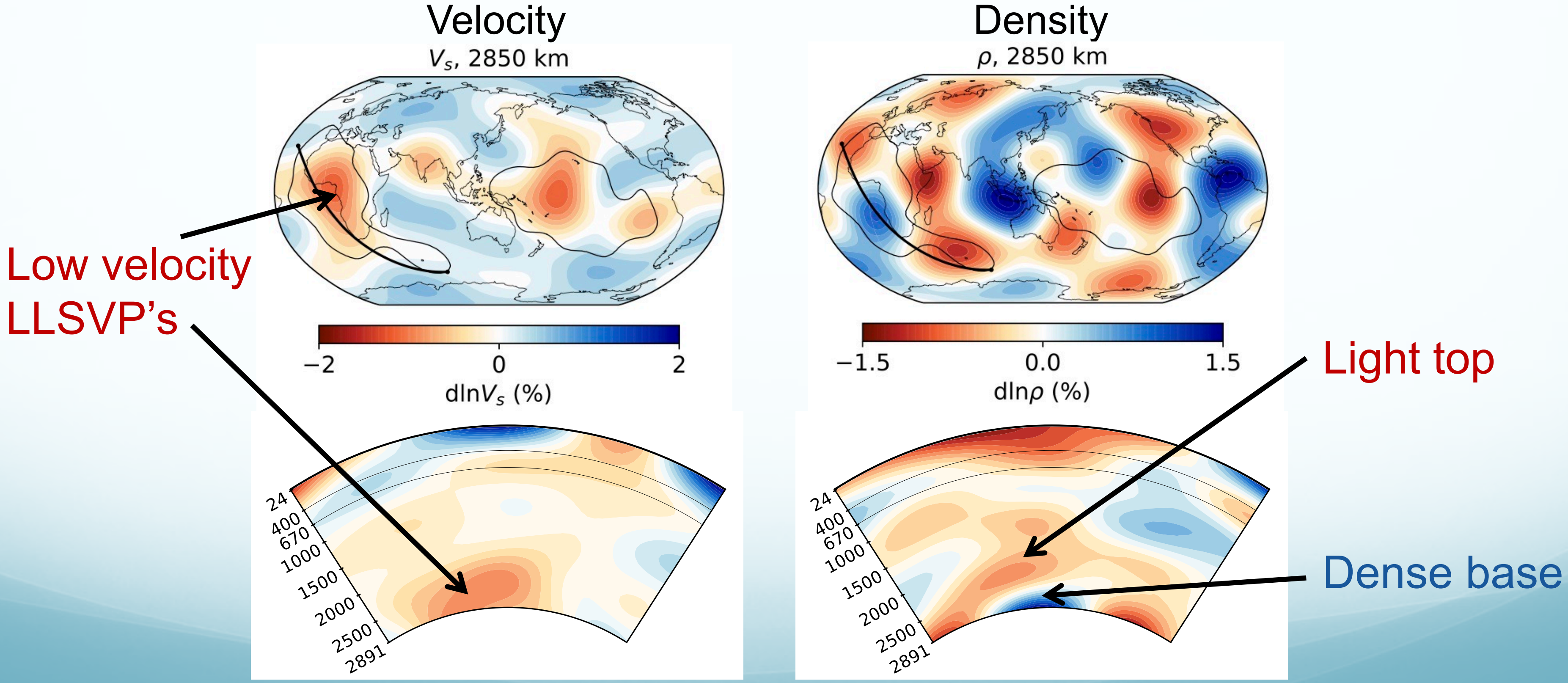
(Using Hamiltonian Monte Carlo sampling)



van Tent, Gebraad, Fichtner, Trampert & Deuss, *in prep*, 2022

Density tomography

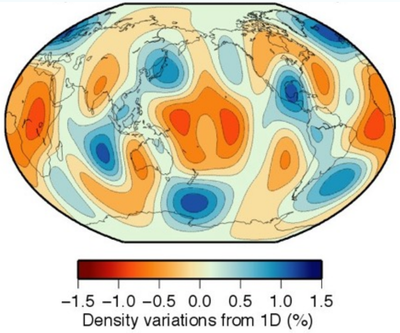
(Using Hamiltonian Monte Carlo sampling)

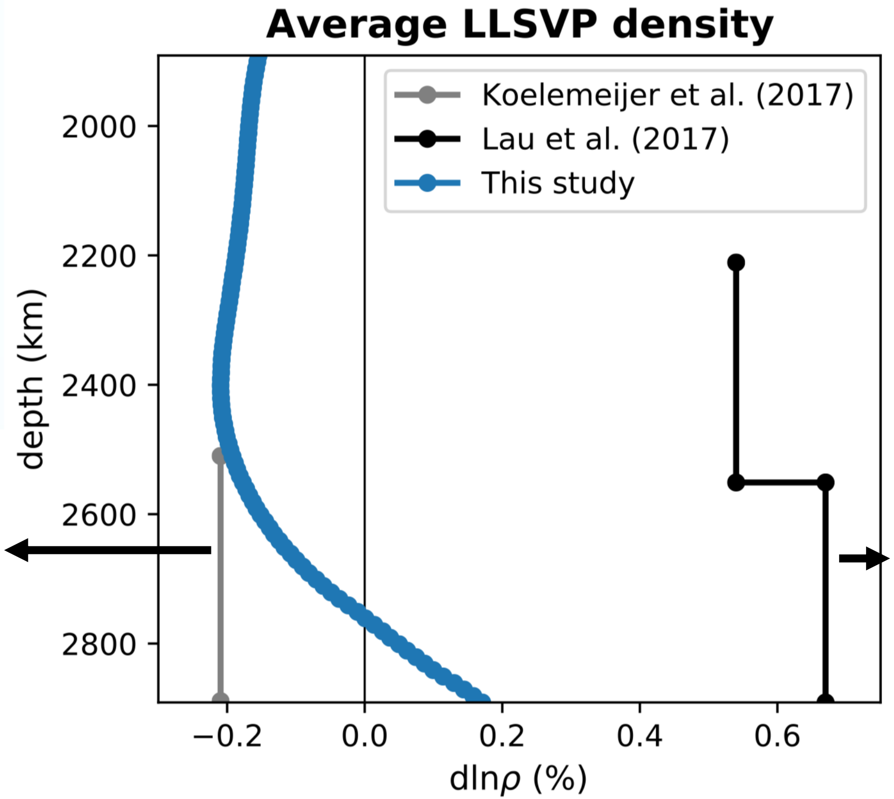


van Tent, Gebraad, Fichtner, Trampert & Deuss, *in prep*, 2022

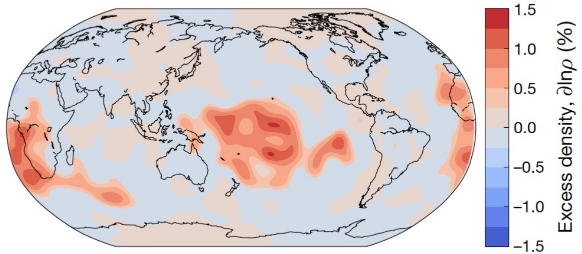
Comparing density models

Koelemeijer et al. (2017)

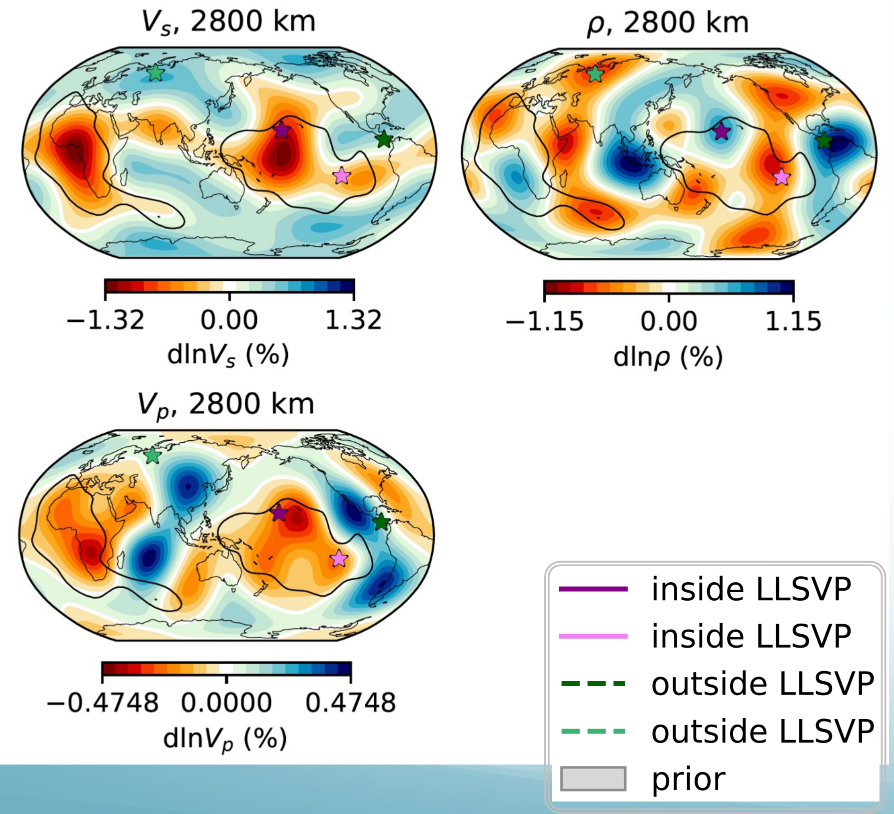


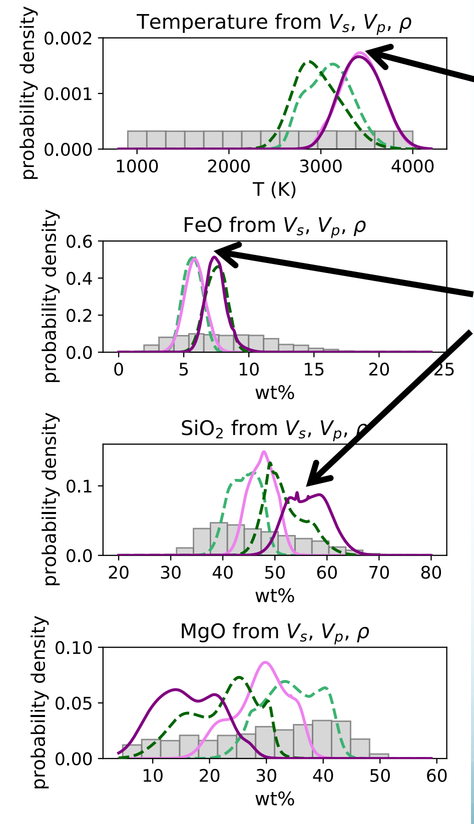


Lau et al. (2017)



Thermochemical inversion



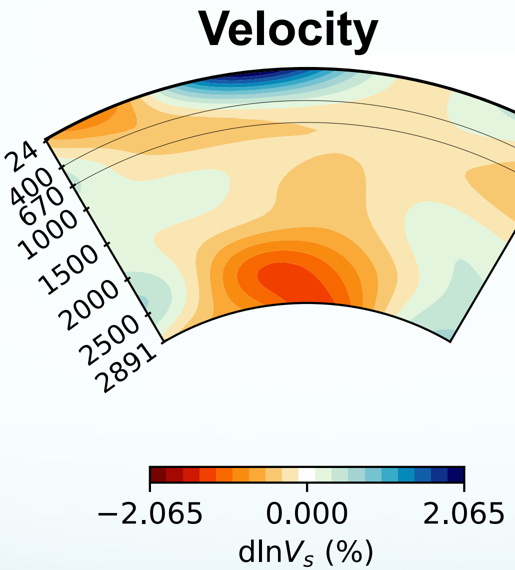


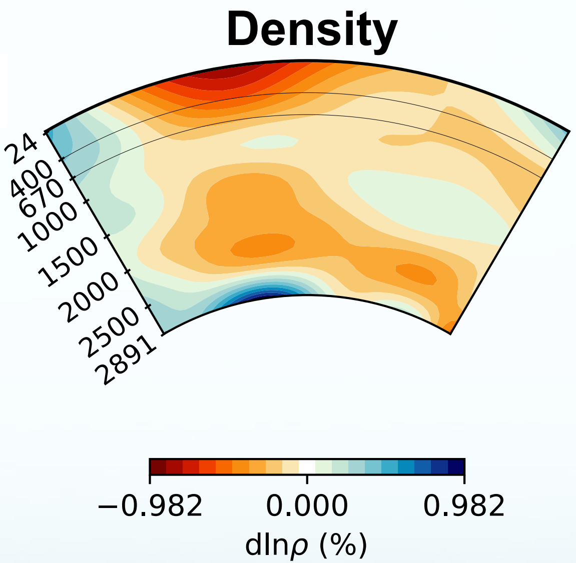
LLSVPs are hot

High density regions are enriched in FeO and SiO_2

In collaboration with
Ashim Rijal and Laura Cobden

Synthesis - LLSVPs





The continental sized LLSVPs are devided into a dense base and a light top. They have a high temperature; their higher density is due to increased iron content, which makes them rather stable.

Conclusions

- The outer core is 0.2% denser than PREM
- The inner core is 0.4% lighter than PREM.
- We find 1% denser regions at the base of otherwise light LLSVPs, reconciling apparently contradicting earlier constraints
- The dense base of the LLSVP regions correspond to a change in composition with an increase in **FeO and SiO_2**, within overall **high temperature** LLSVPs