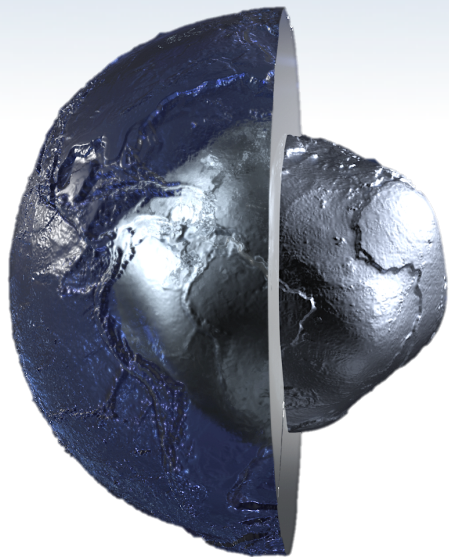


# Towards consistent seismological models of the core-mantle boundary landscape

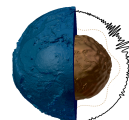


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05-05-2020, EGU2020-3518

EGU 2020 Sharing Geoscience Online

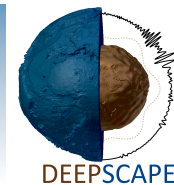


DEEPSCAPE



THE ROYAL SOCIETY

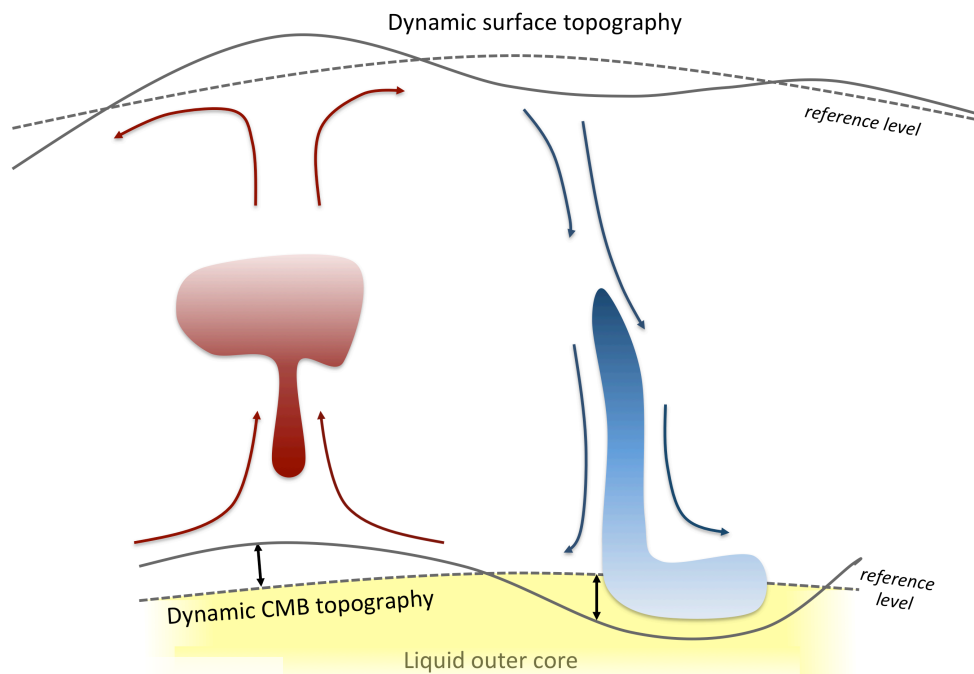




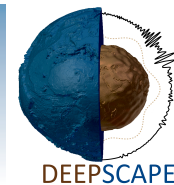
# Core-mantle boundary topography is important

**Reflects dynamic processes within the Earth, similar as on the Earth's surface**

- Provides insights into core and mantle dynamics
- Aids in constraining mantle viscosity
- Helps to constrain lower mantle density
- Affects interpretation of seismic observations
- Changes mechanical core-mantle coupling
- Influences length-of-day variations



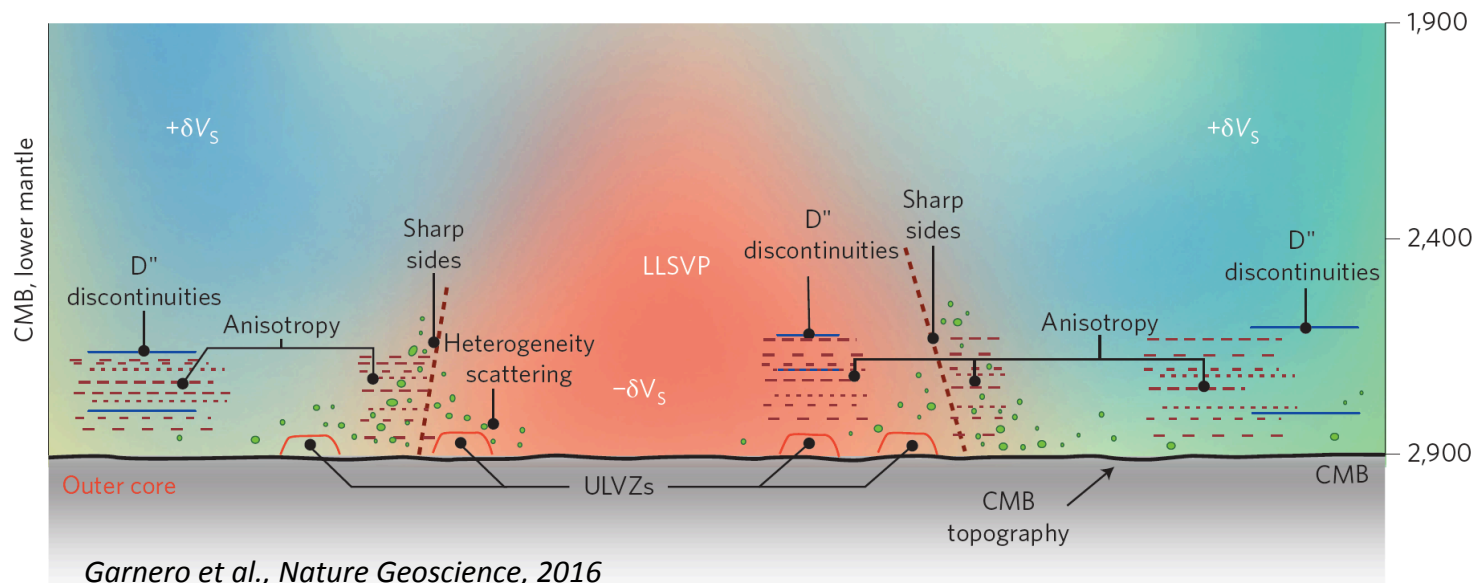
CMB = core-mantle boundary



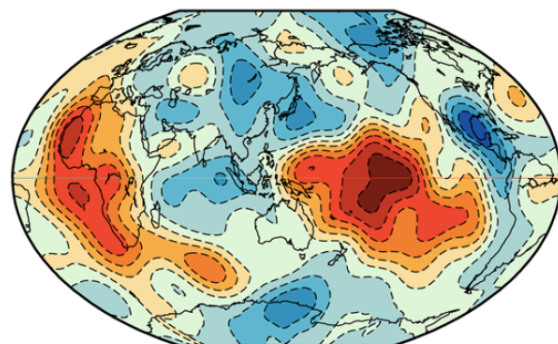
# But remains hard to constrain...

- Due to heterogeneous body-wave coverage: interpolation may cause spurious amplitudes
- Due to sensitivity of normal-mode data: only constraints on large-scale structure
- Due to trade-offs with strongly heterogeneous lower mantle structure (velocity, density, etc)

*The lower mantle shows heterogeneity on a range of scale lengths, with small-scale ultra-low-velocity-zones (ULVZs) and scatterers, D'' discontinuity reflections and anisotropy, and large-low-seismic-velocity-provinces (LLSVPs or LLVPs) on the large-scale*



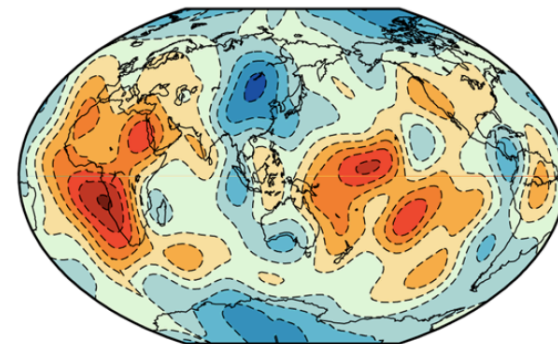
# ...leaving many questions unanswered:



$d\ln V_s$

$\pm 1.5\%$

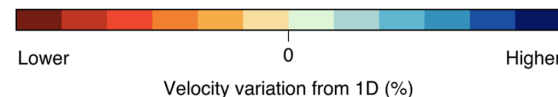
- What is the origin of the Large-Low-Velocity Provinces (LLVPs) imaged consistently in the lower mantle?
- Are they dominantly thermal or thermochemical structures?
- What is their role in mantle dynamics?



$d\ln V_p$

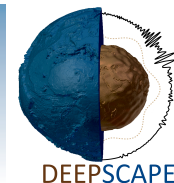
$\pm 1.0\%$

**To answer these questions, it is crucial to determine their **density** structure, which is intrinsically linked to **CMB topography****



*Model SP12RTS (Koelemeijer et al., GJI, 2016) @ 2850 km depth*





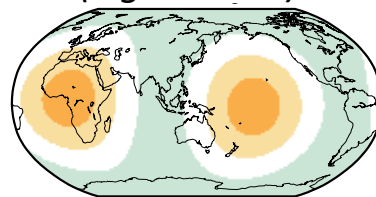
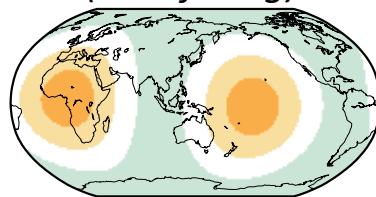
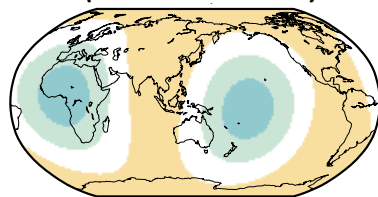
# LLVP density & CMB topography trade-offs

**KDR2017-pos**  
(Dense LLVPs)

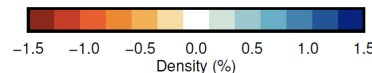
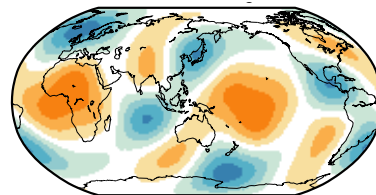
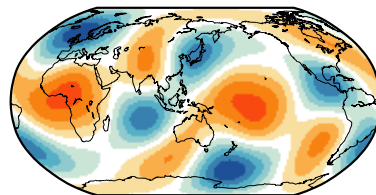
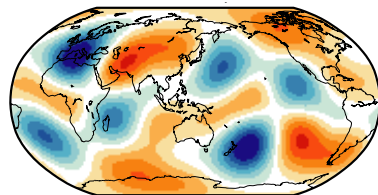
**KDR2017**  
(Best fitting)

**KDR2017-neg**  
(Light LLVPs)

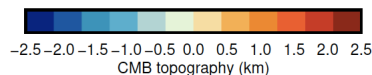
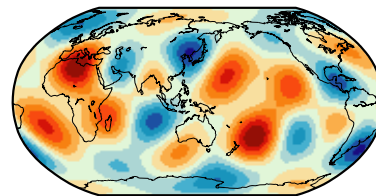
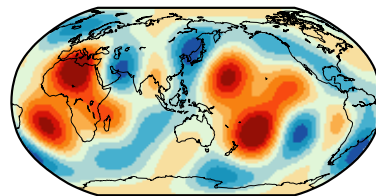
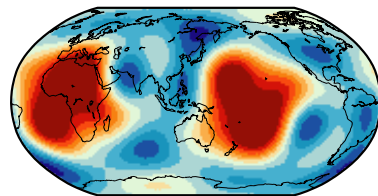
Density ( $l=2$ )



Density



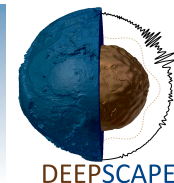
CMB topo



Koelemeijer et al. (2017) found two model classes with opposite relationship between density and CMB topography, which both fit normal mode data:

- KDR2017-pos (left, dense LLVPs)
- KDR2017-neg (right, light LLVPs)

However, larger CMB topography amplitudes and higher degree structure are required to cancel out the dense LLVPs in KDR2017-pos, while the overall best fitting model KDR2017 features light LLVPs and moderate topography.

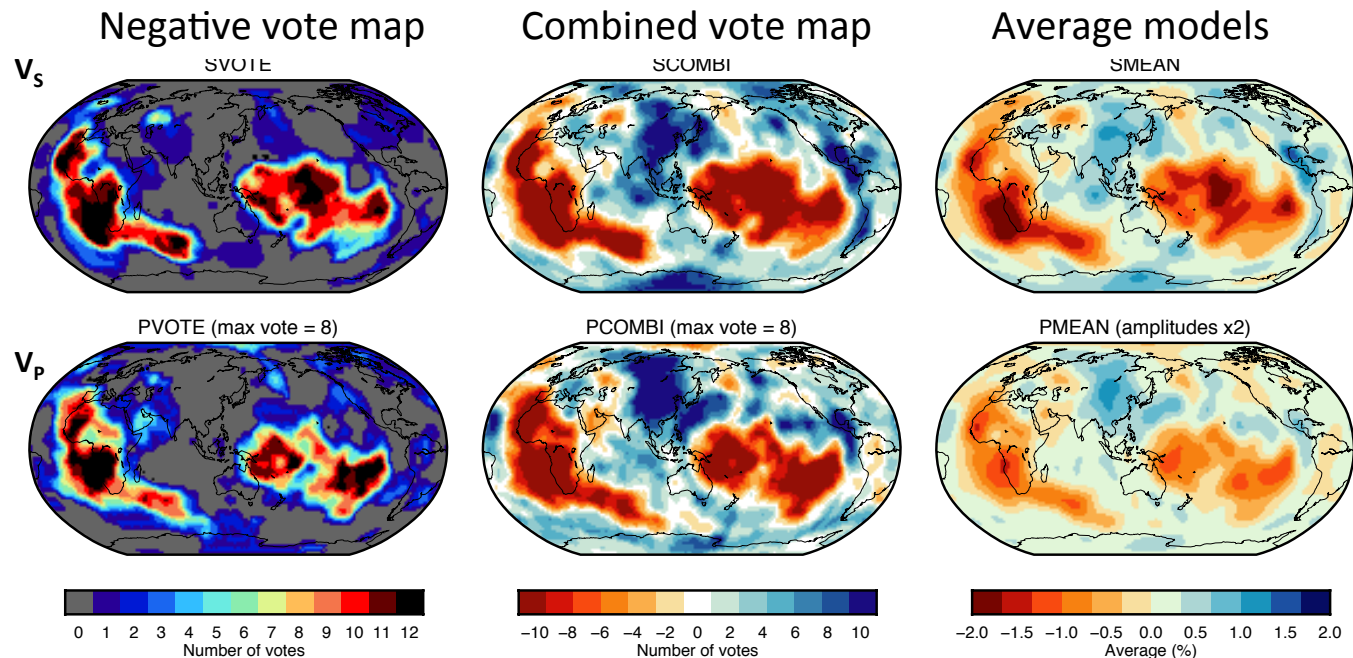


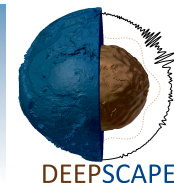
# Motivation and aims

There is **increasing consensus on large-scale lower mantle velocity** structure (both  $V_s$  and  $V_p$ ), as evidenced by the agreement between average models and vote maps.

Average models (SMEAN / PMEAN) and vote maps (SVOTE / PVOTE and SCOMBI / PCOMBI) were constructed based on 12 recent S-wave and 8 recent P-wave models.

For the vote maps, the negative and positive mean were used as threshold, with a high number of votes indicating that models agree on the presence of slow or fast velocities.





# Motivation and aims

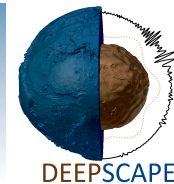
**Given the current agreement on large-scale lower mantle velocity structure, this study reviews and compares the progress towards our understanding of lower mantle density and CMB topography.**

Specifically, I seek to address the following questions:

- Are there any consistencies between current models?
- What can we already learn from these?

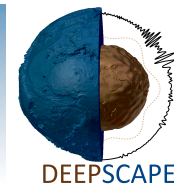
The approach taken consists of:

- Reviewing existing seismological models
- Analysing these in a quantitative way to identify consistent features
- Discussing the insights these provide about deep mantle structures



# Summary of findings

- For **density**, average models and vote maps agree on **two areas of dense anomalies** centered below Angola and close to Hawaii, but the relationship with seismic velocity differs.
- Considering both model classes of Koelemeijer et al. (2017) allows to **resolve recent results** based on Stoneley modes and tidal measurements (Lau et al., 2017). The correlation between Letal2017 and KDR2017-pos is particularly high as both studies employ a similar density scaling.
- **CMB topography** models mostly show **elevated topographies under locations of LLVPs**, but details differ between average models and vote maps.
- All topography models have a peak-to-peak amplitude **below 4.7 km for degree 2** except IT1999.
- A **discrepancy exists between body-wave and normal-mode models** of CMB topography, with normal-mode models showing a clearer relationship with velocity structure.
- The correlation between models of CMB topography and  $V_s$  tends to be **mostly negative**.
- **A comparison with recent geodynamic models** by Deschamps et al. (2018) suggests that **strongly thermochemical models are inconsistent with current seismological models**.



# Data used to study CMB topography

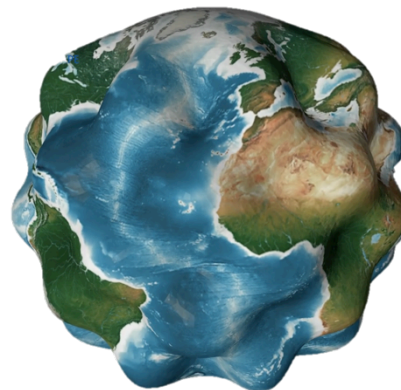
- Body waves (right, since 1970s):

- PKP / PKKP
- PcP, PcP - P
- $P_{\text{diff}}$
- PnKP, P4KP – PcP

- Normal modes (left, since 1991)

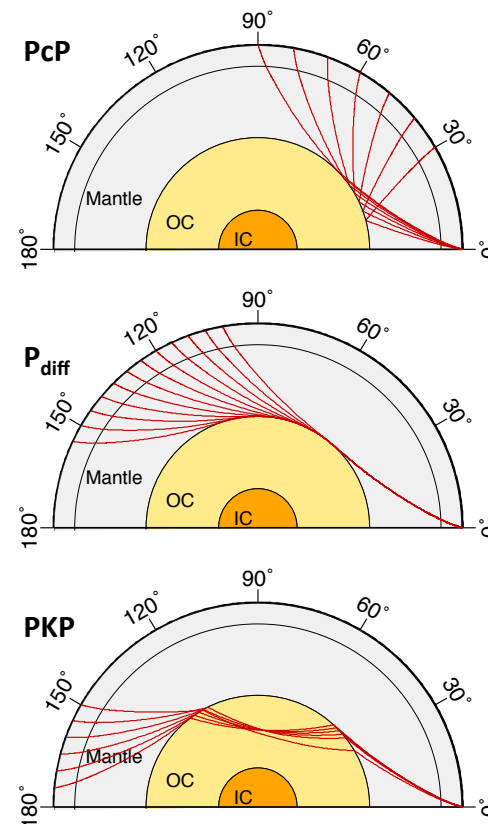
- Nutation data (since 1986)
- Geoid (since 1968)

(and predictions based on geodynamic simulations)



Whole-Earth oscillations arising after large earthquakes that distort the gravity field of the Earth and are also affected by topography

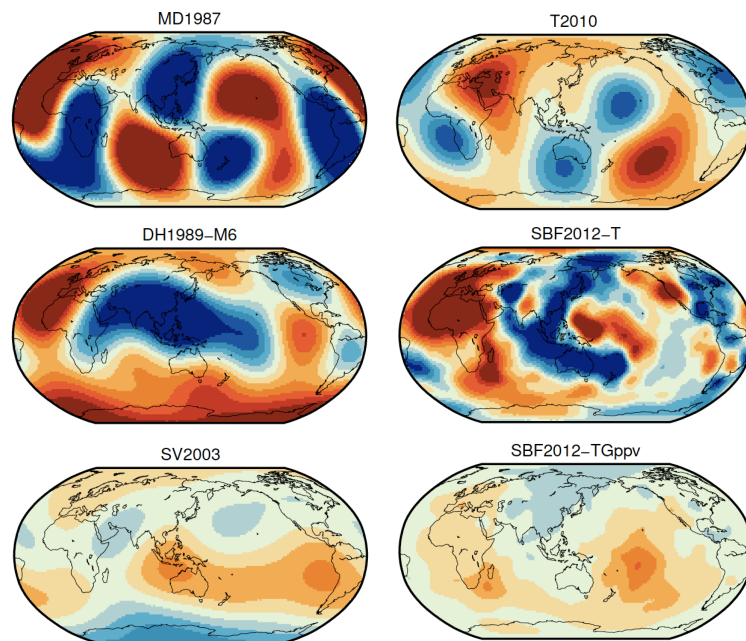
Different body wave phases are used that reflect, refract and diffract at the CMB





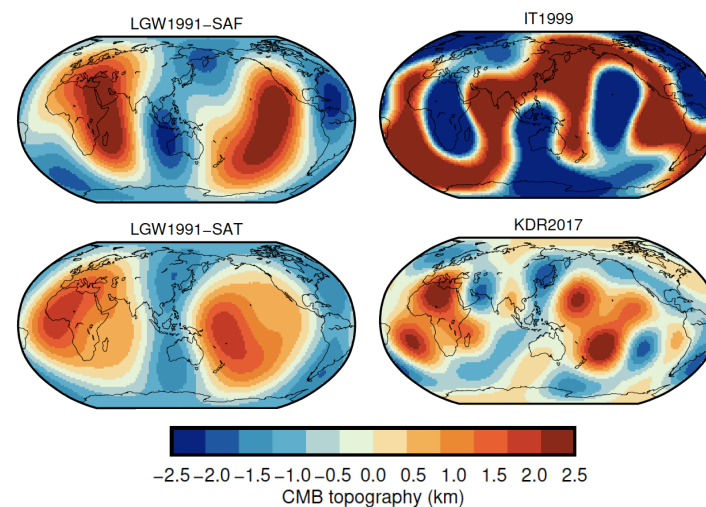
# Existing CMB topography models

## Using body wave data



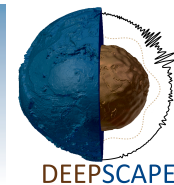
Model names consist of authors and year of publication.  
Note that the maximum degree varies between models.

## Using normal mode data

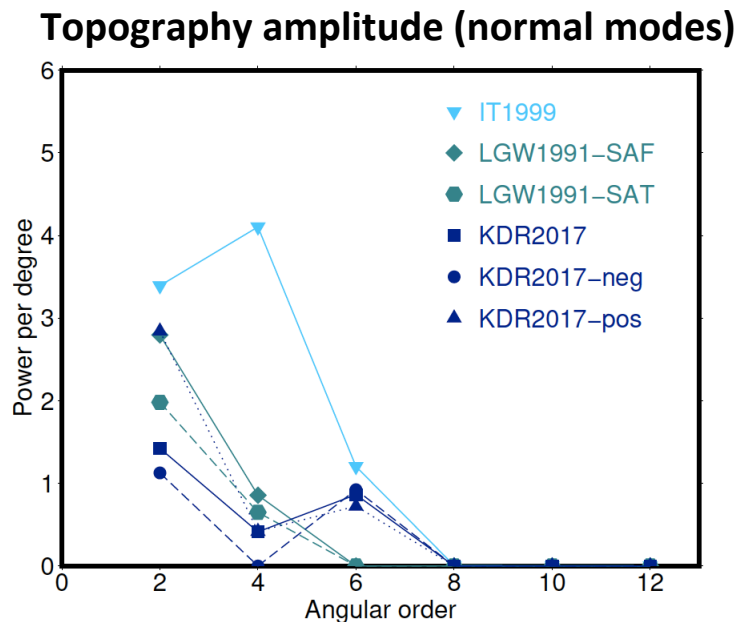
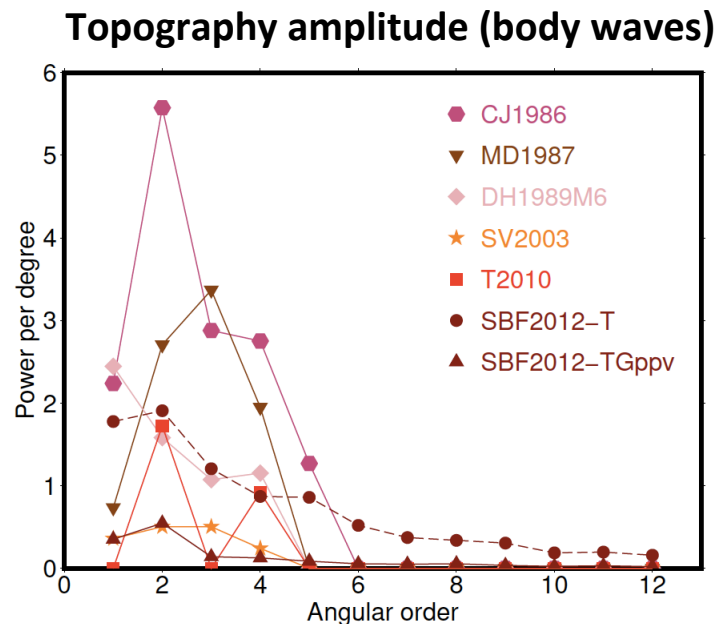


Global models of CMB topography have been developed for > 30 years, but **amplitudes and patterns continue to vary widely!**

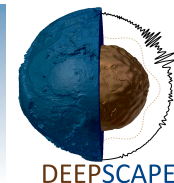




# Existing CMB topography models

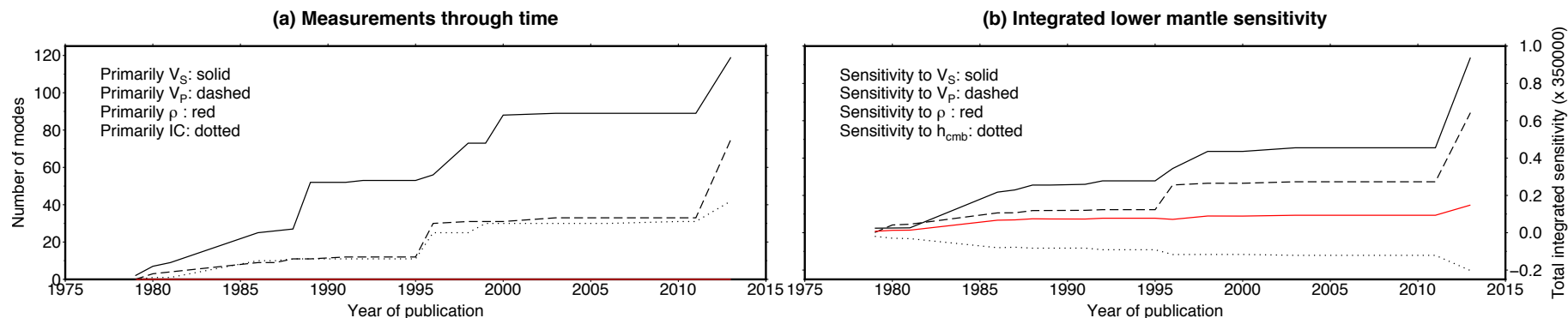


- **Body-wave models** (left) contain **larger amplitudes** and vary widely.
- **Normal mode models** (right) show **some consistency**, except for model IT1999 (Ishii & Tromp, 1999).



# Data used to constrain density

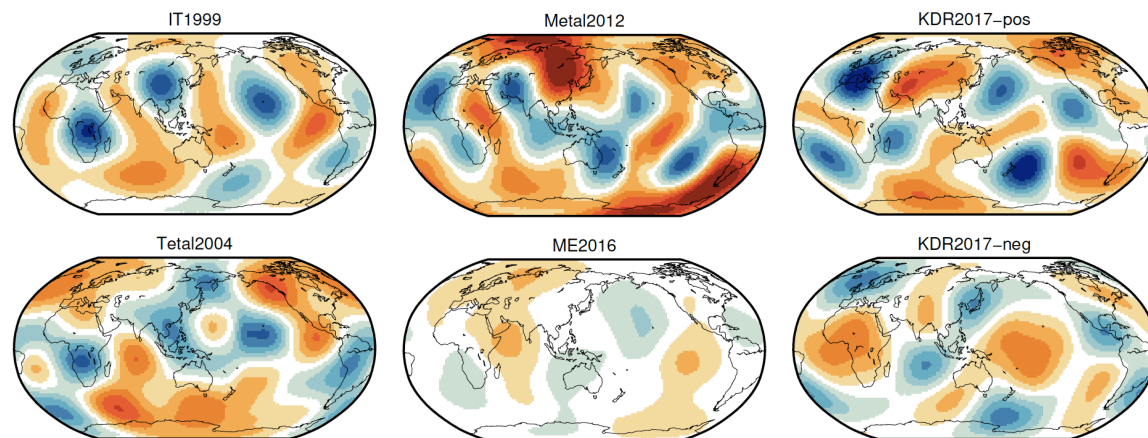
- Normal modes
  - Modes dominantly sensitive to  $V_S$  or  $V_P$  or inner core (IC) structure
  - Sensitivity to lower mantle density slowly increasing over time
  - No modes primarily sensitive to density, so difficult to extract robust constraints



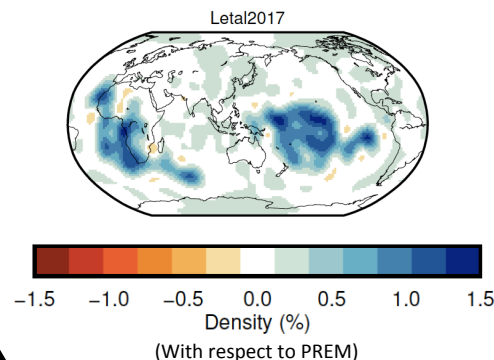
- Tidal tomography (GPS measurements)
- Geoid / gravity (satellite measurements)

# Existing lower mantle density models

## Using normal mode data



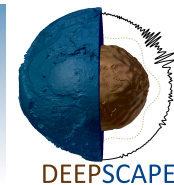
## Using tidal tomography



2 model classes from Koelemeijer et al. (2017)

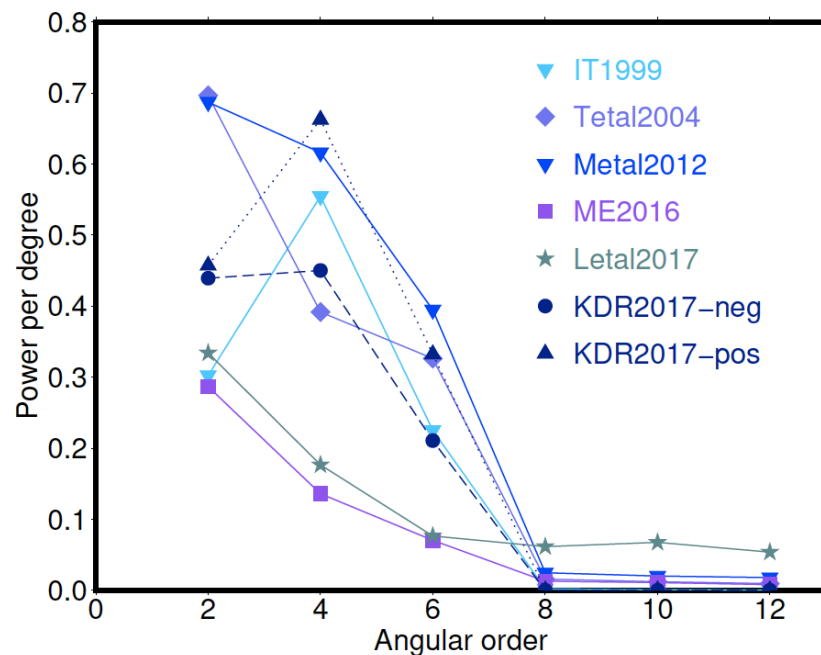
- Density models have now been developed for 20 years, **generally concluding the LLVPs are dense**.
- However, **models show a lot of variation** in where exactly dense material is present and what the relationship to velocity structure is.

*Model names consist of authors and year of publication.  
Note that the maximum degree varies between models.*

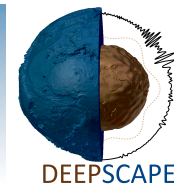


# Existing lower mantle density models

Density amplitudes

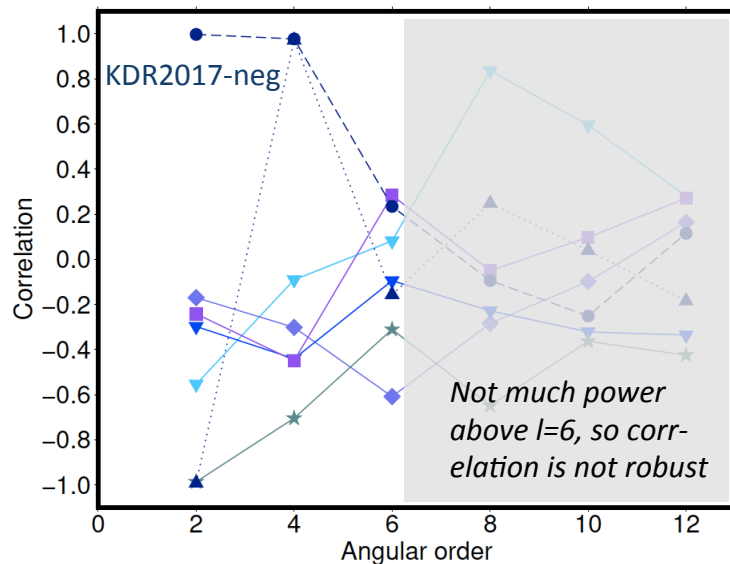


- Amplitudes of existing density models vary significantly.
- Particularly, models ME2016 (Moulik & Ekstrom, 2016) and Letal2017 (Lau et al., 2017) show low power in degree 4.
- Interestingly, not all models show a dominant degree 2.
- The two model classes of Koelemeijer et al. (2017) show similar degree 2 amplitudes, even though the sign is opposite.

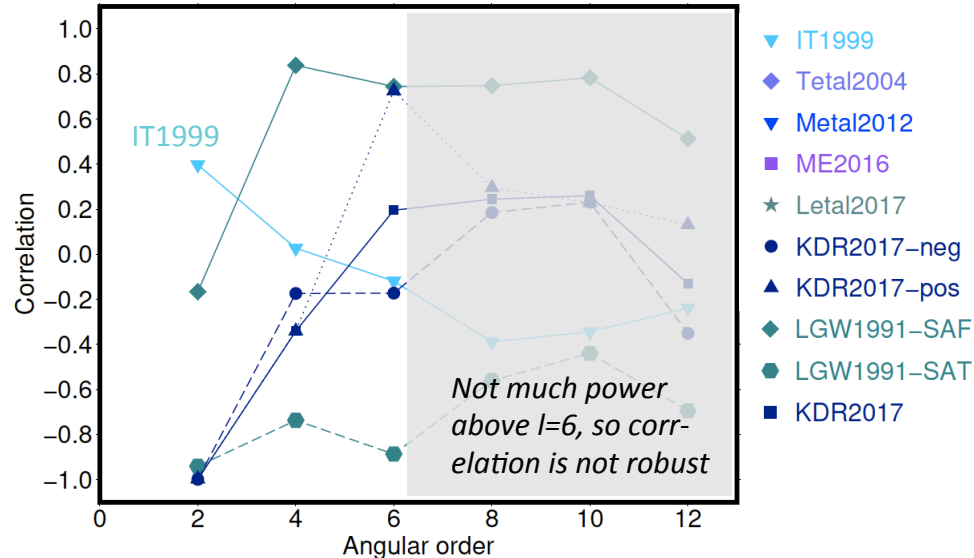


# Relationships between parameters

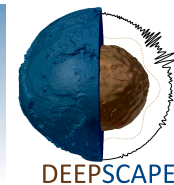
Correlation density -  $V_s$



Correlation  $V_s$  - CMB topography



- Density models correlate negatively with  $V_s$  at degree 2 & 4 (i.e. dense LLVPs), except KDR2017-neg (left).
- The  $V_s$  – CMB topography correlation is negative for degree 2 (i.e. elevated CMB), except for IT1999.



# Methodology

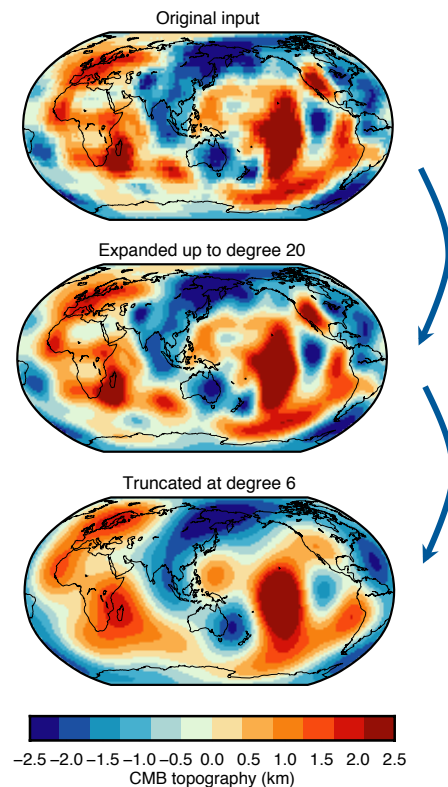
I analyse existing models quantitatively before building:

- Average models: RMEAN / TMEAN (following Becker & Boschi, 2002)
- Vote maps: RVOTE / TVOTE (following Shephard et al., 2017)
- Combined vote maps: RCOMBI / TCOMBI (combined vote maps)

*"R" indicates density / "T" indicates CMB topography*

For this, I first of all:

- Focus on structures at 2800 km depth (representative for the LLVPs)
- Expand each model into spherical harmonics up to degree 20
- Only consider long wavelengths (cut the models at degree 6)
- Only consider lateral variations (do not include degree 0)
- Only include mean / best fitting model from probabilistic studies





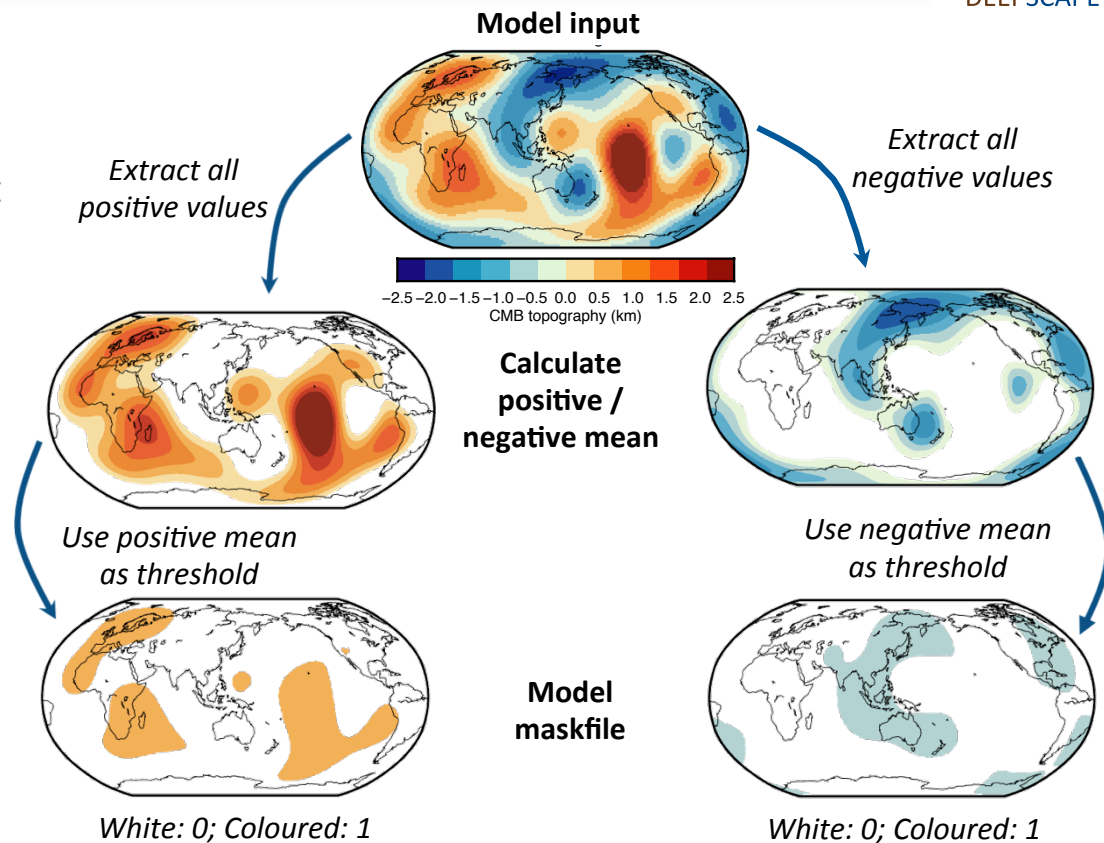
# Vote map procedure

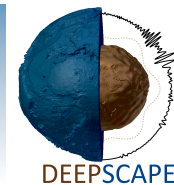
After preparing each model, maskfiles are constructed using the positive & negative mean as threshold (following Shephard et al. (2017)):

- Extract all positive or negative values
- Computing positive or negative mean
- Using this mean as threshold to mask out all other structure

This procedure is applied to:

- 10 CMB topography models
- 7 density models



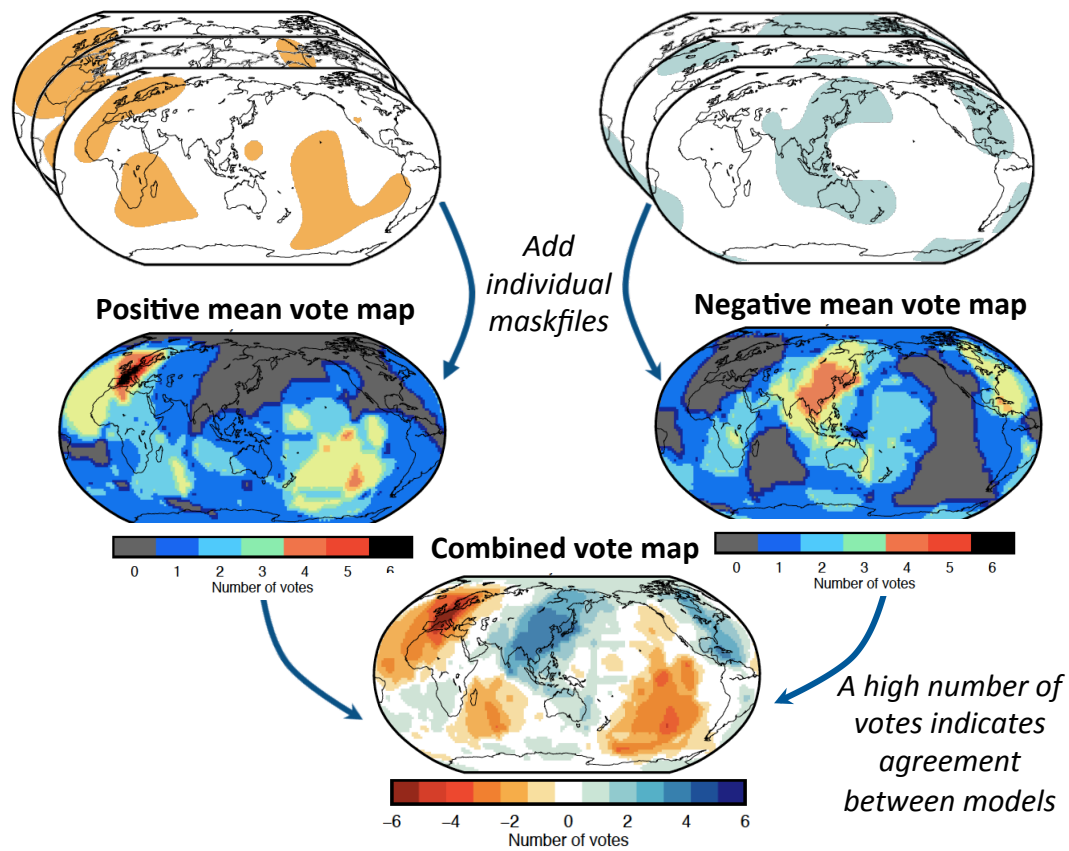


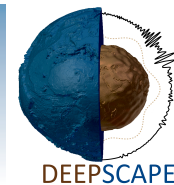
# Vote map procedure

Individual model maskfiles are added together to construct a positive or negative mean vote map, which are combined to produce the combined vote map. These are compared to simple average models.

Model combinations consist of:

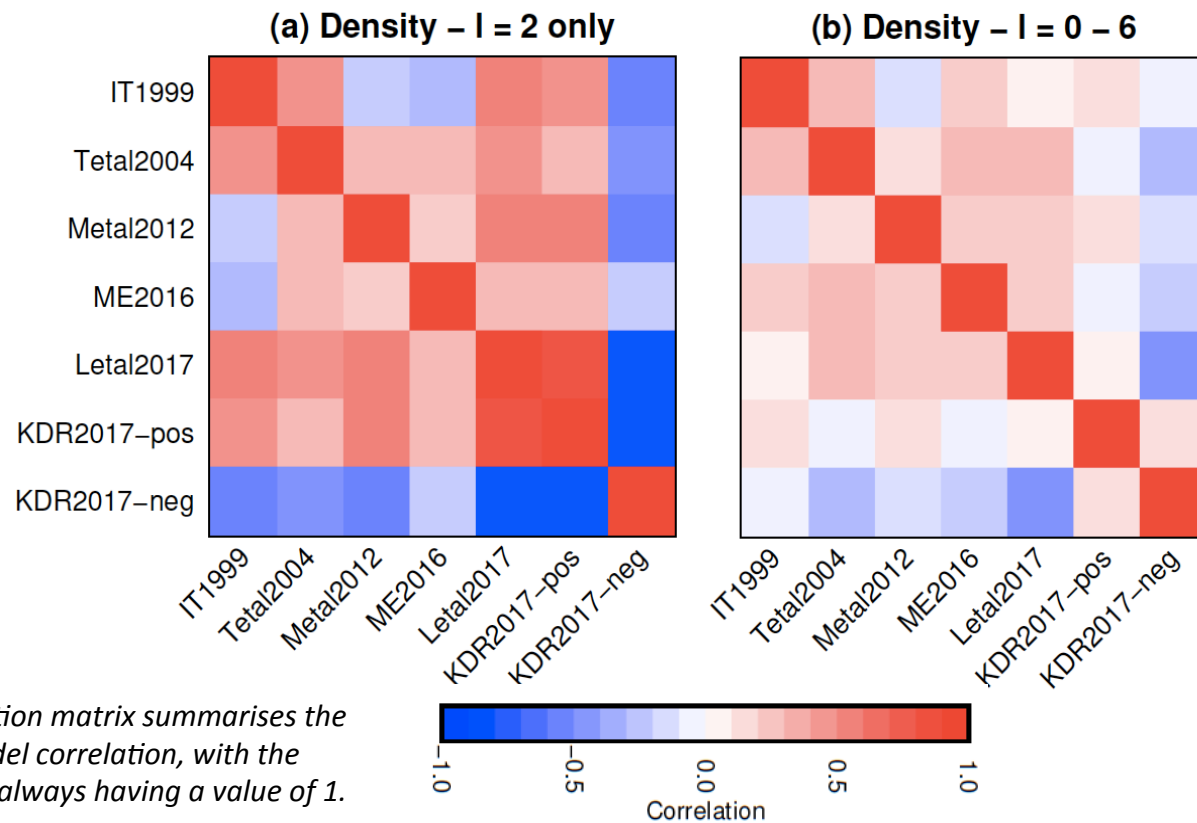
- 4 normal-mode CMB topography models (using model KDR2017)
- 6 body-wave CMB topography models
- All 10 CMB topography models
- 6 density models (using KDR2017-pos)
- 6 density models (using KDR2017-neg)



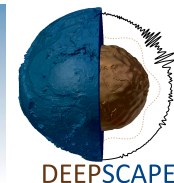


# Density: correlation matrices

- For degree 2, there is strong agreement between density models, except KDR2017-neg that features light LLVPs.
- Letal217 (based on tidal tomography) and KDR2017-pos (based on Stoneley modes) show a strong correlation of 0.96.
- Agreement is however less clear for higher degrees.



A correlation matrix summarises the intra-model correlation, with the diagonal always having a value of 1.



# Density: average models and vote maps

For density structure, average models (right) and combined vote maps (middle) agree, **showing consistently two focused areas of dense anomalies** beneath South Africa (LLVP core) and the North Pacific (LLVP edge).

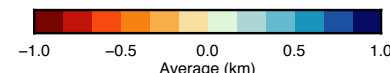
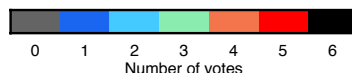
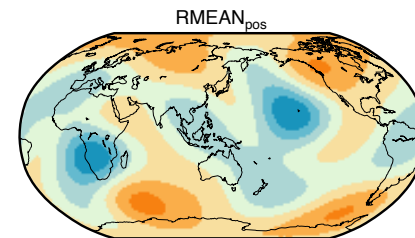
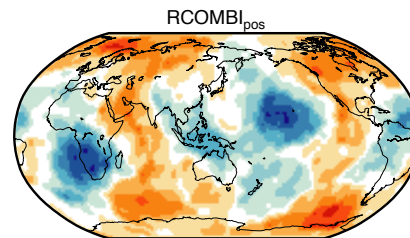
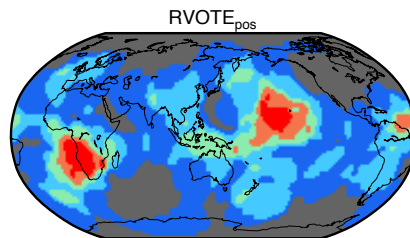
Overall, the vote count is only high in a few patches, indicating that **exact locations differ between models**.

**Positive vote map**

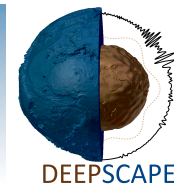
**Combined vote map**

**Average model**

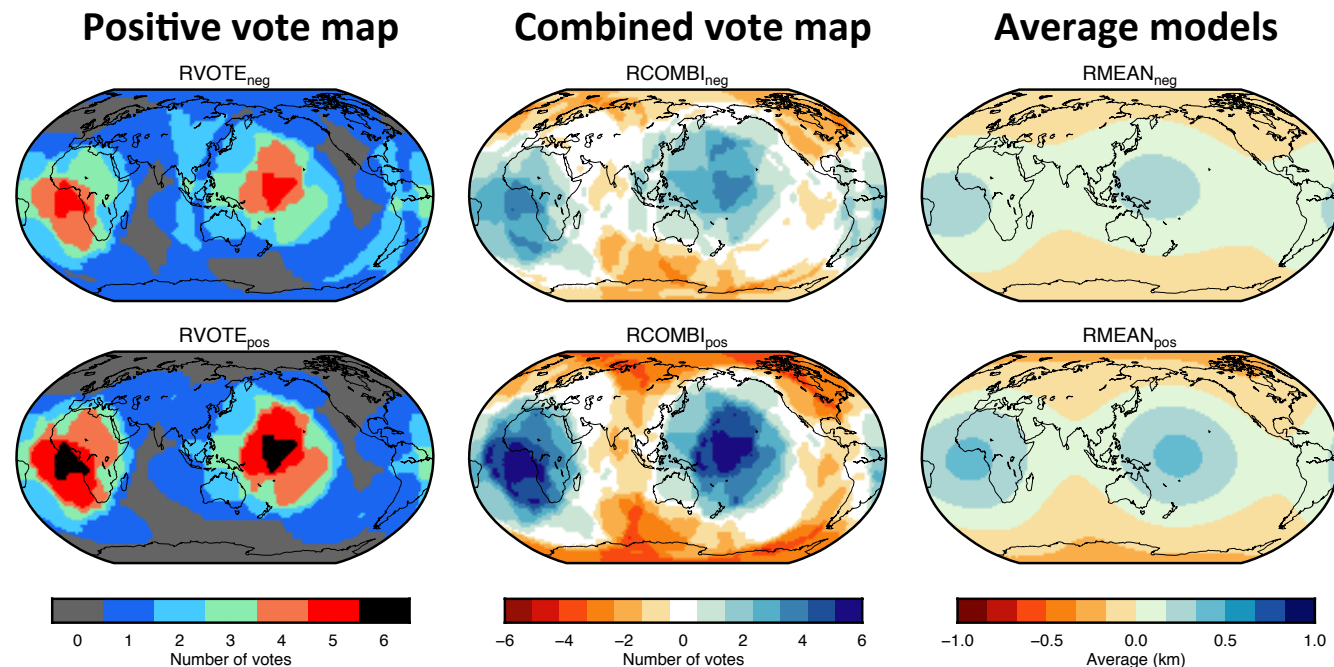
*Grey or red areas (high vote) indicate all models agree that the density structure is significantly light or dense respectively.*



*Dark red or blue areas (high vote) indicate all models agree that the density structure is significantly light or dense respectively.*



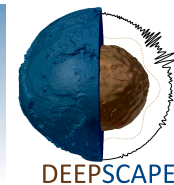
# Density: average models and vote maps



*Note that these are for degree 2 structure only, comparing the influence of the two model classes of Koelemeijer et al. (2017).*

Including model KDR2017-pos (bottom) with dense LLVPs instead of model KDR2017-neg (top) with light LLVPs helps to **resolve differences between studies based on Stoneley modes and tidal data**, evidenced by the higher vote for degree 2.

This demonstrates the **strong influence of CMB topography on the retrieved density**.

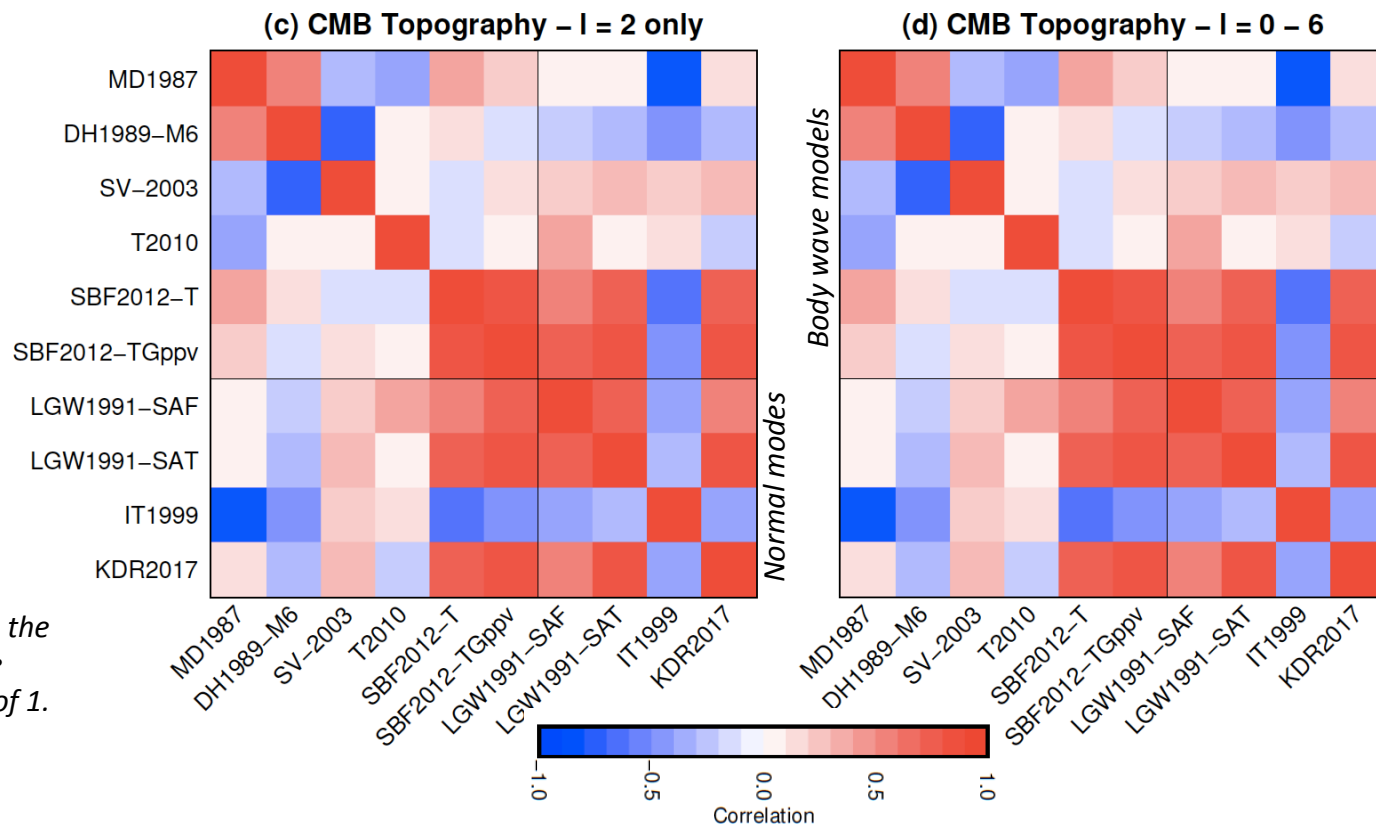


# CMB topography: correlation matrices

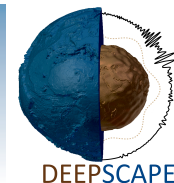
Body-wave models  
(top left) do **not** show  
much consistency at  
degree 2 or up to  
degree 6.

Normal mode models  
(bottom right)  
correlate well with  
each other, except for  
model IT1999.

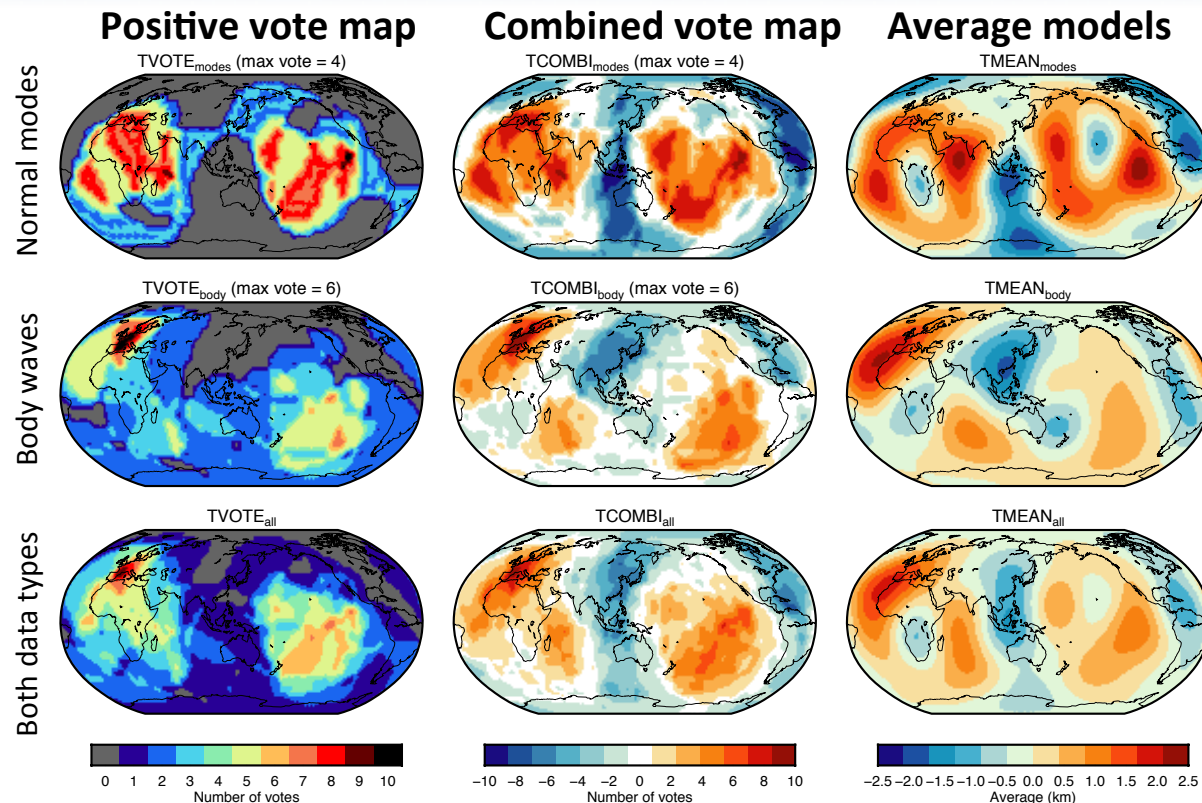
*A correlation matrix summarises the  
intra-model correlation, with the  
diagonal always having a value of 1.*







# CMB topography: average models and vote maps



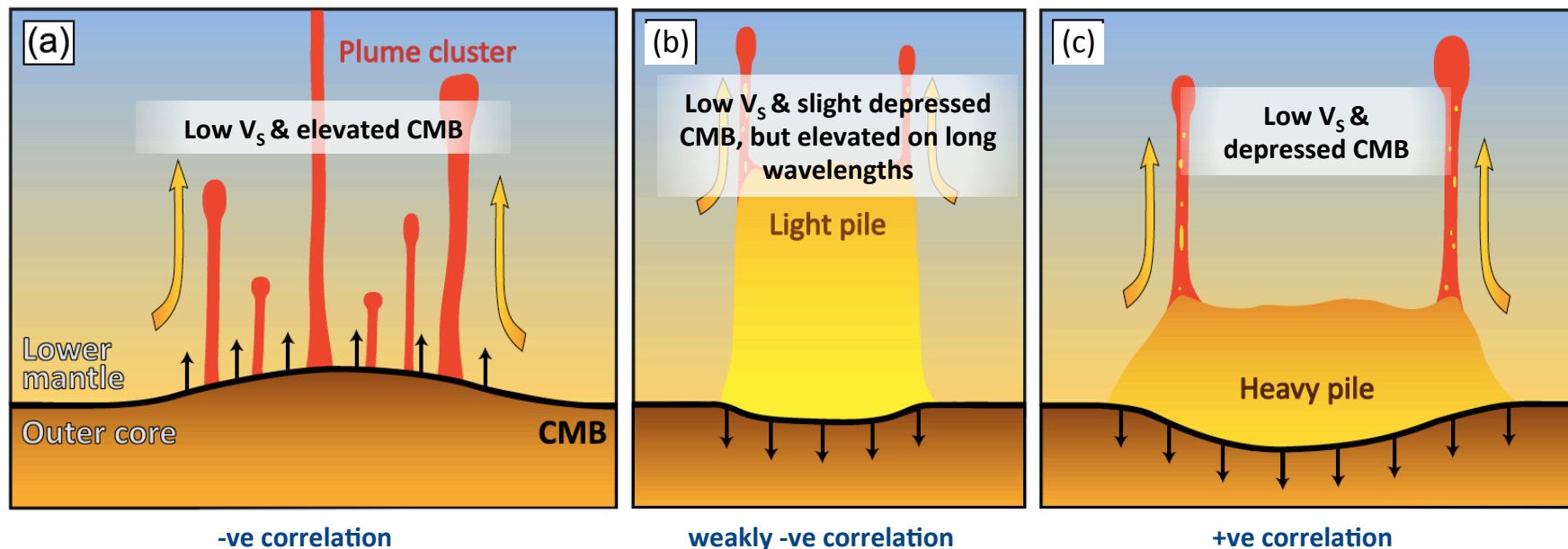
For CMB topography, **average models and vote maps do not agree**, indicating that particular large-amplitude models dominate the averages.

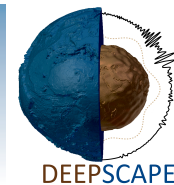
A **discrepancy** (evident as low overall vote) also exists between **models based on normal modes (top) and body waves (middle)**.

However, most models show **consistently elevated topography in the South Pacific and Central Africa**.

# Comparison to geodynamic predictions

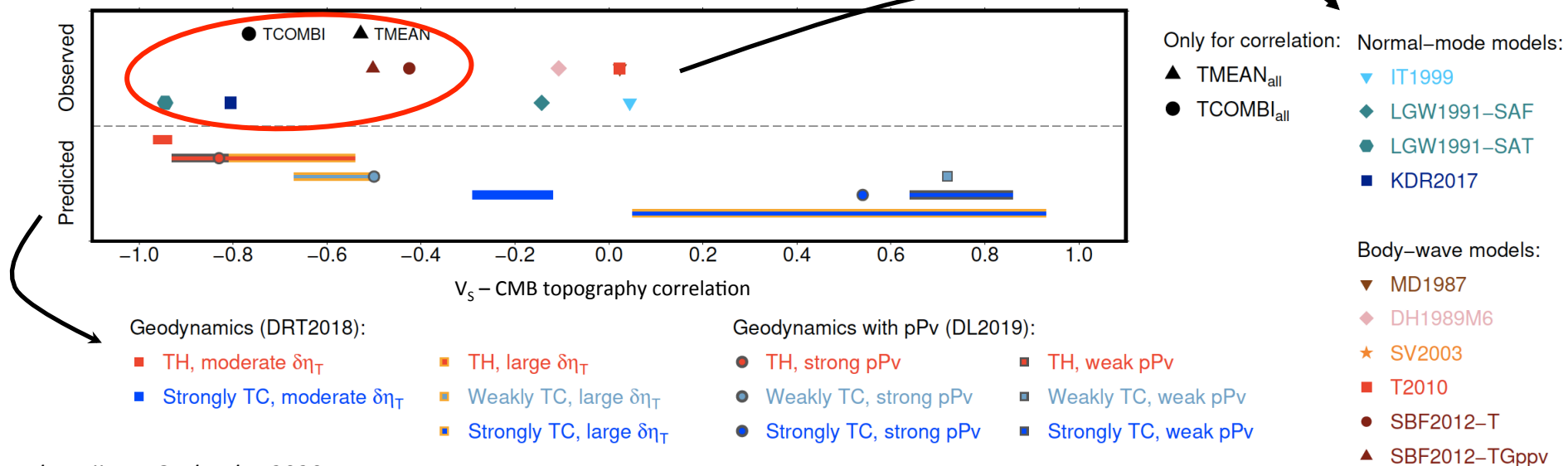
Deschamps et al. (2018) suggested the **correlation between  $V_s$  and CMB topography** allows to discriminate between thermal anomalies (-ve), light piles (weakly -ve) or heavy piles (+ve). Their predictions based on **geodynamic models can be compared to seismological results**.

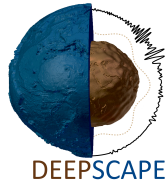




# Comparison to geodynamic predictions

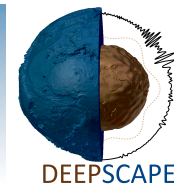
- The  $V_s$  – CMB topography correlation varies between observed models (top), but all that showed consistency with each other in the correlation matrix (red circle) have a correlation  $< -0.4$ .
- This comparison with geodynamic predictions (bottom) thus suggests strongly thermochemical models (blue bars, heavy piles) can be ruled out for the LLVPs.





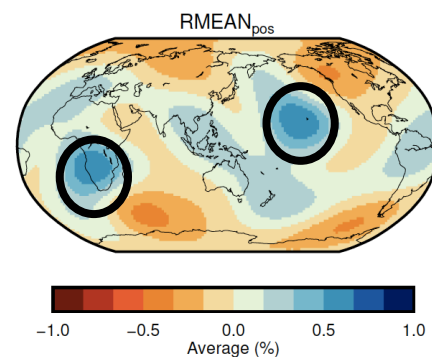
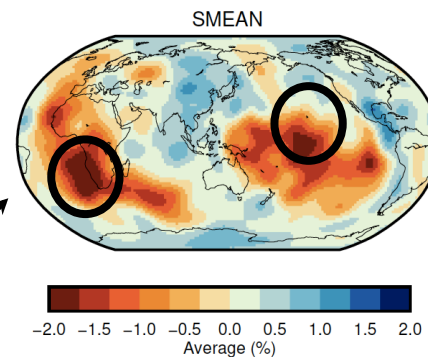
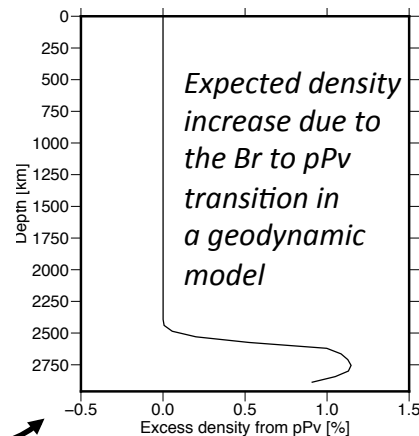
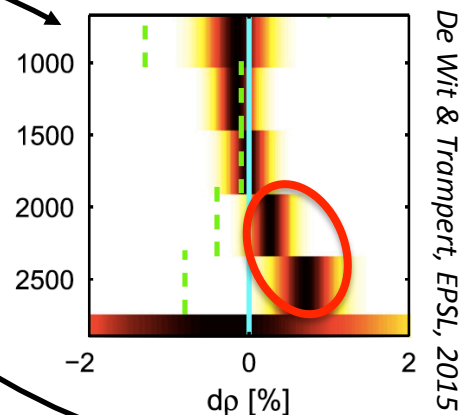
# Summary of findings

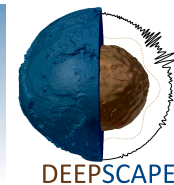
- For **density**, average models and vote maps agree on **two areas of dense anomalies** centered below Angola and close to Hawaii, but the relationship with seismic velocity differs.
- Considering both model classes of Koelemeijer et al. (2017) allows to **resolve recent results** based on Stoneley modes and tidal measurements (Lau et al., 2017). The correlation between Letal2017 and KDR2017-pos is particularly high as both studies employ a similar density scaling.
- **CMB topography** models mostly show **elevated topographies under locations of LLVPs**, but details differ between average models and vote maps.
- All topography models have a peak-to-peak amplitude **below 4.7 km for degree 2** except IT1999.
- A **discrepancy exists between body-wave and normal-mode models** of CMB topography, with normal-mode models showing a clearer relationship with velocity structure.
- The correlation between models of CMB topography and  $V_s$  tends to be **mostly negative**.
- A **comparison with recent geodynamic models** by Deschamps et al. (2018) suggests that **strongly thermochemical models are inconsistent with current seismological models**.



# Things to keep in mind when interpreting models

- All models considered here only show lateral variations, while the entire lower mantle may be denser than PREM (red circle, radial density structure).
- The transition from Bridgmanite (Br) to post-Perovskite (pPv) would also increase the density (mostly in fast regions, but radial average as well).
- Should we interpret the African and Pacific LLVP the same, given they seem to have a different relationship between velocity and density?
- Or has the use of even spherical harmonics lead to artifacts in density models?





# Future directions in density and CMB topography

In future density studies, it will be important to carefully consider the choice of:

- Theoretical approximation (e.g. self-coupling vs. full-coupling when using normal modes)
- Vertical parameterisation (refined in depth to see any possible dense basal layer)
- Lateral parameterisation (is scaling density with velocity physically sound?)
- Trade-offs with other complexities (anisotropy, CMB topography)
- Inverse framework (focus should be on Bayesian inferences)

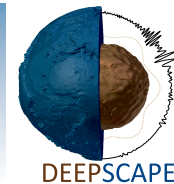
Future studies of CMB topography should:

- Exploit the existing normal mode data sets available
- Consider finite-frequency theory and carefully select body wave phases

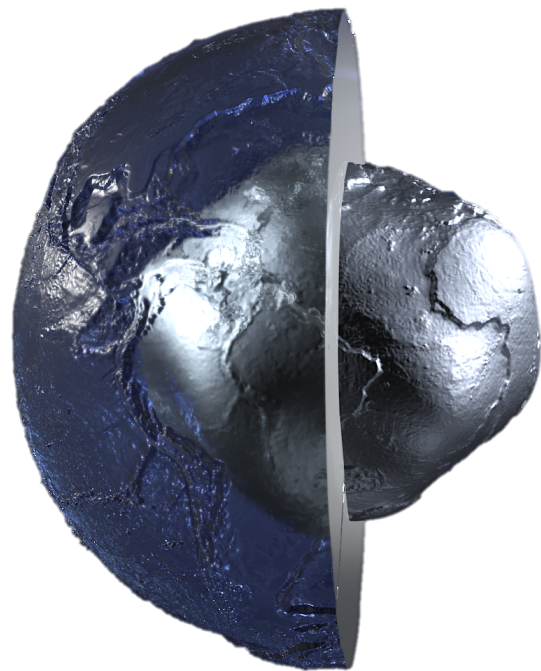
Efforts should focus on combining data sets:

- To jointly study CMB topography with lower mantle & outer core structure
- To develop models consistent with both body wave and normal mode data
- To include geodetic data and insights from geodynamics together with seismological observations





# Read more:



Koelemeijer, P. (2020). Towards consistent seismological models of the core-mantle boundary landscape. *In press, AGU monograph "Mantle Convection and Surface Expressions", edited by Marquardt, Ballmer, Cottaar & Konter.*

Download the preprint online:

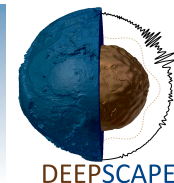
<https://www.essoar.org/doi/abs/10.1002/essoar.10502426.1>

Download the corresponding AGU 2019 poster:

<https://www.essoar.org/doi/abs/10.1002/essoar.10501794.1>

Attend the virtual press conference on 6<sup>th</sup> May 2020 (17:15 CEST):

[https://us02web.zoom.us/webinar/register/WN\\_udbT5DpRQJuSCq41DEtmKw](https://us02web.zoom.us/webinar/register/WN_udbT5DpRQJuSCq41DEtmKw)



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