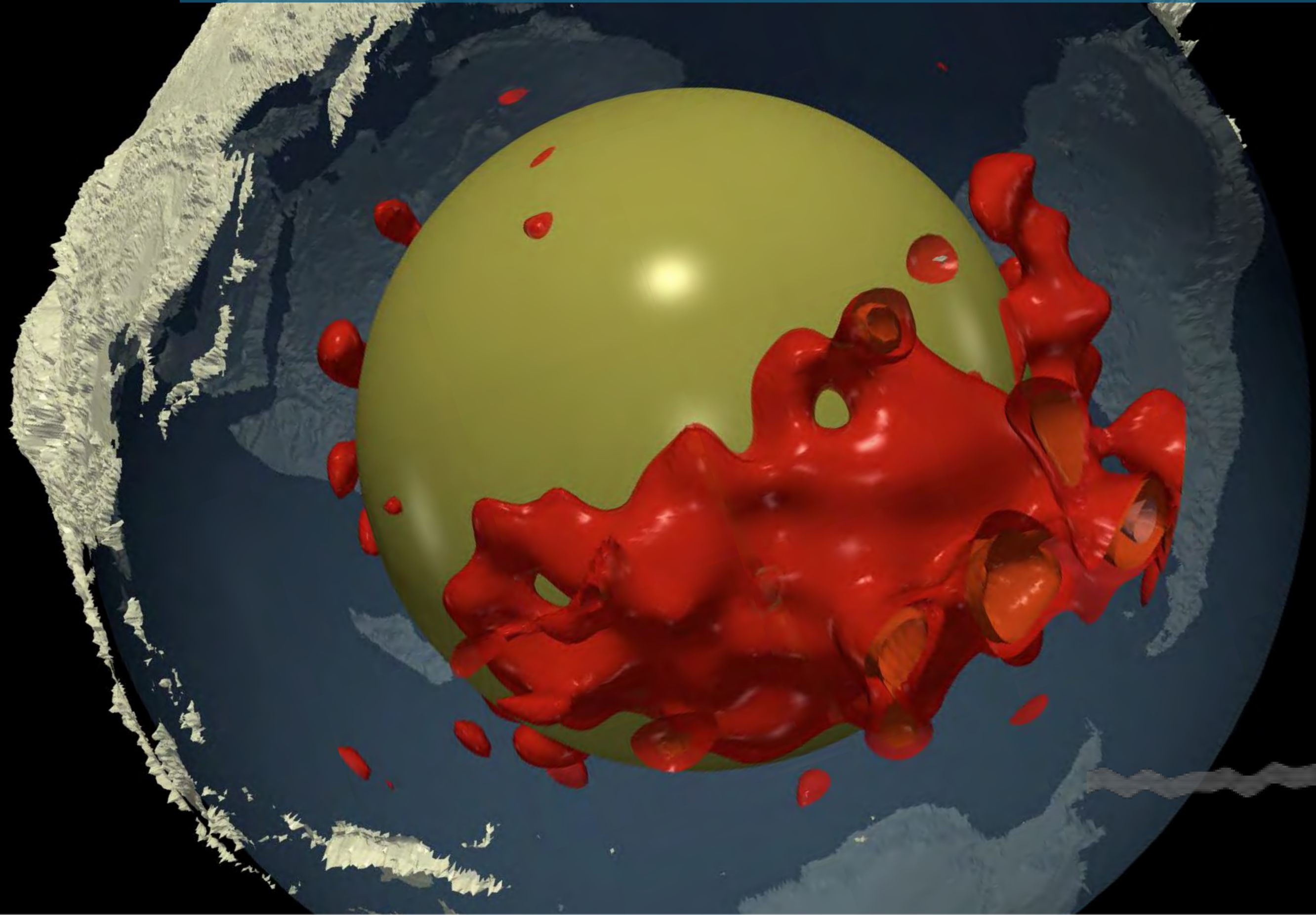
Illuminating Earth's Dynamic Deep Interior:
Multi-Scale Structures and Their Significance

Ed Garnero

Arizona State University

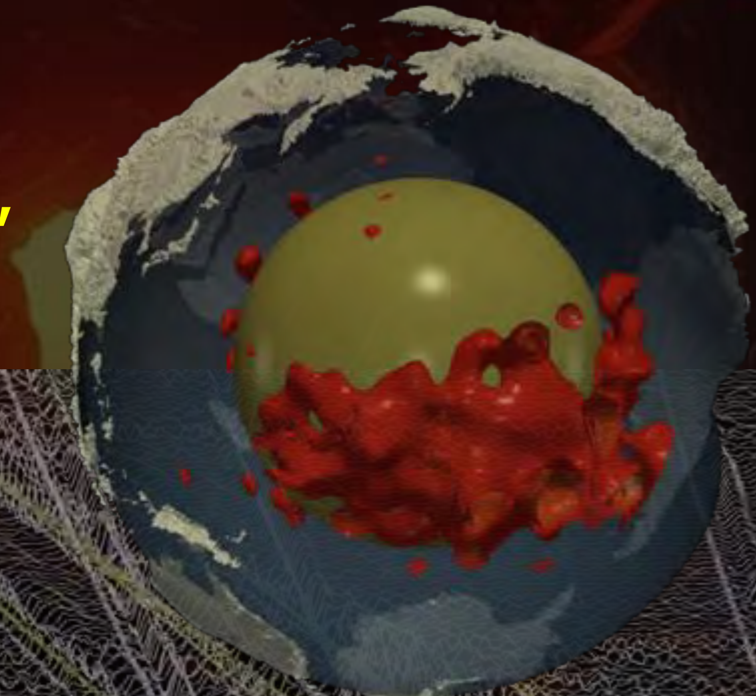


Forefront Physics and Mathematics Program to Drive Transformation
Feb 17, 2025

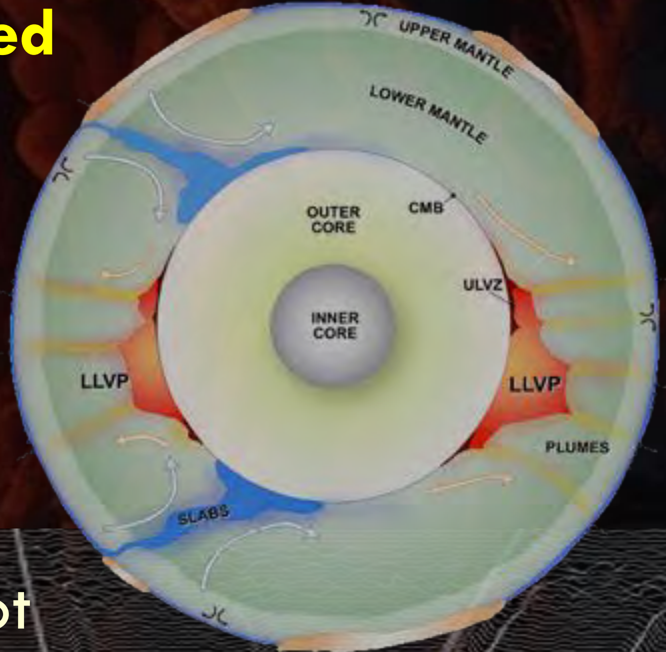
ASU School of Earth and Space Exploration

I will start with my take-home messages

Seismologists have mapped
a diverse **multi-scale** heterogeneity field
that relates to
Earth's **evolution, composition, and present-day dynamics.**

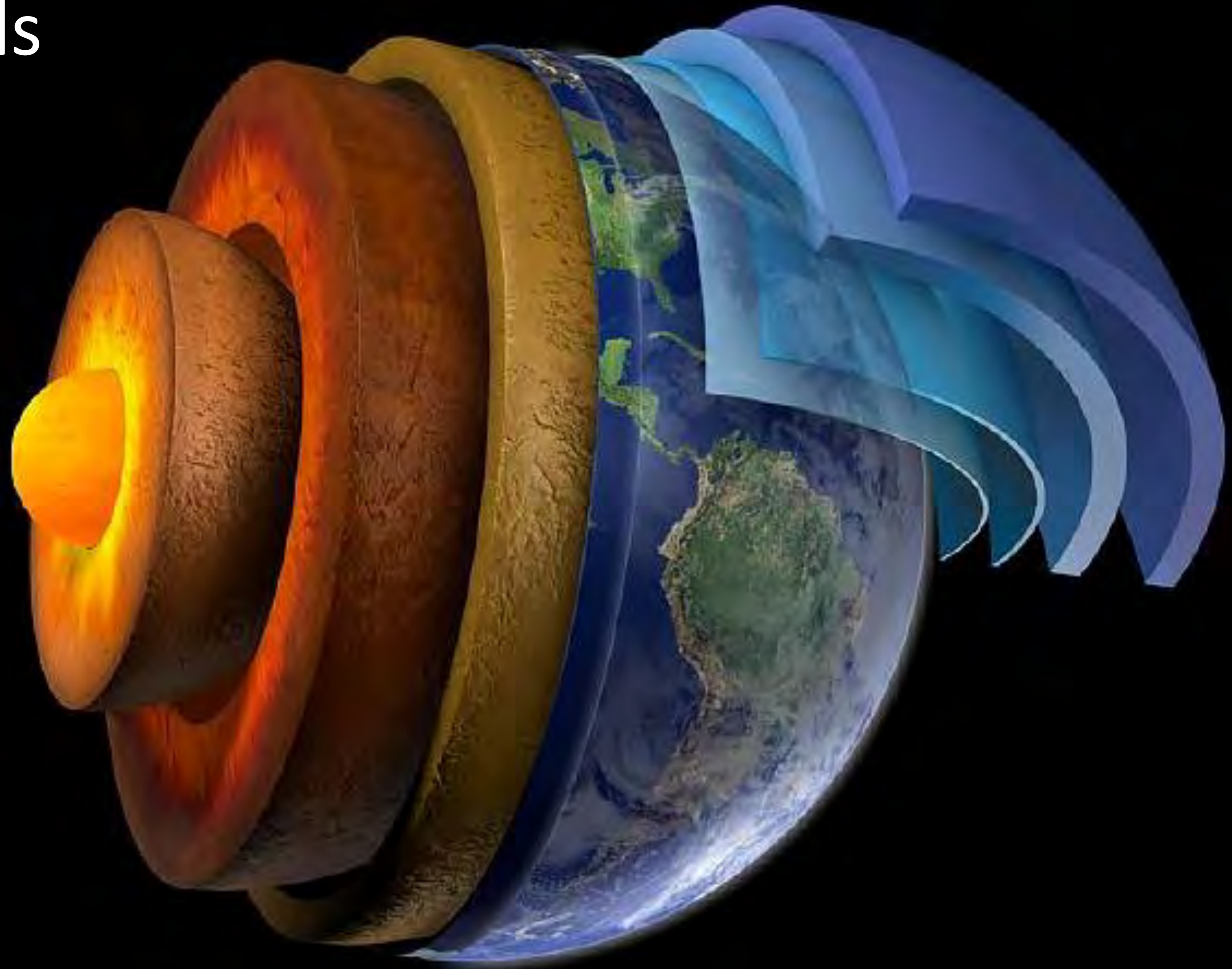


However, significant **uncertainties** give rise to **unconstrained interpretations.**



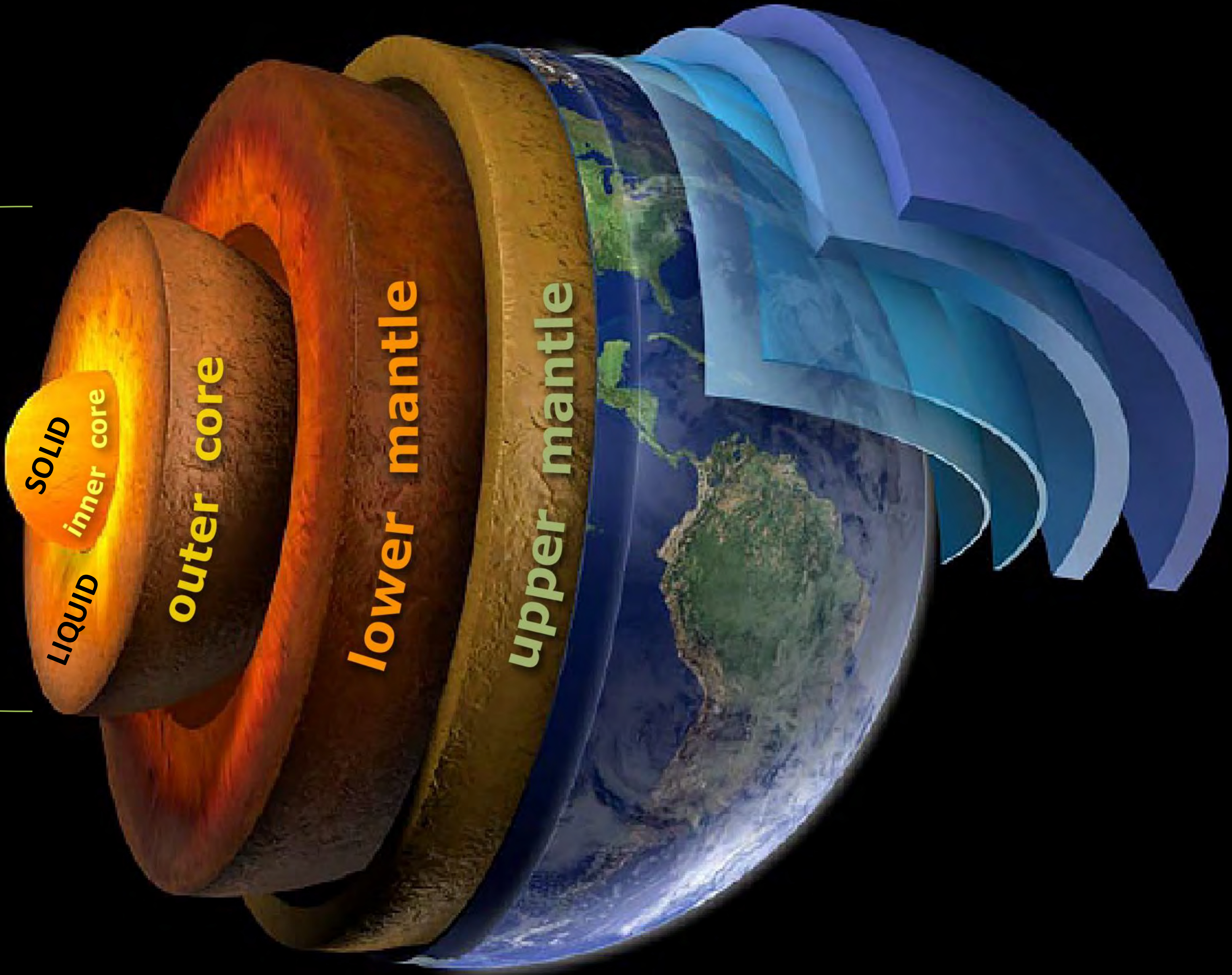
But… **big data** exist and are not all being utilized: fundamental progress ***and discovery* awaits**!

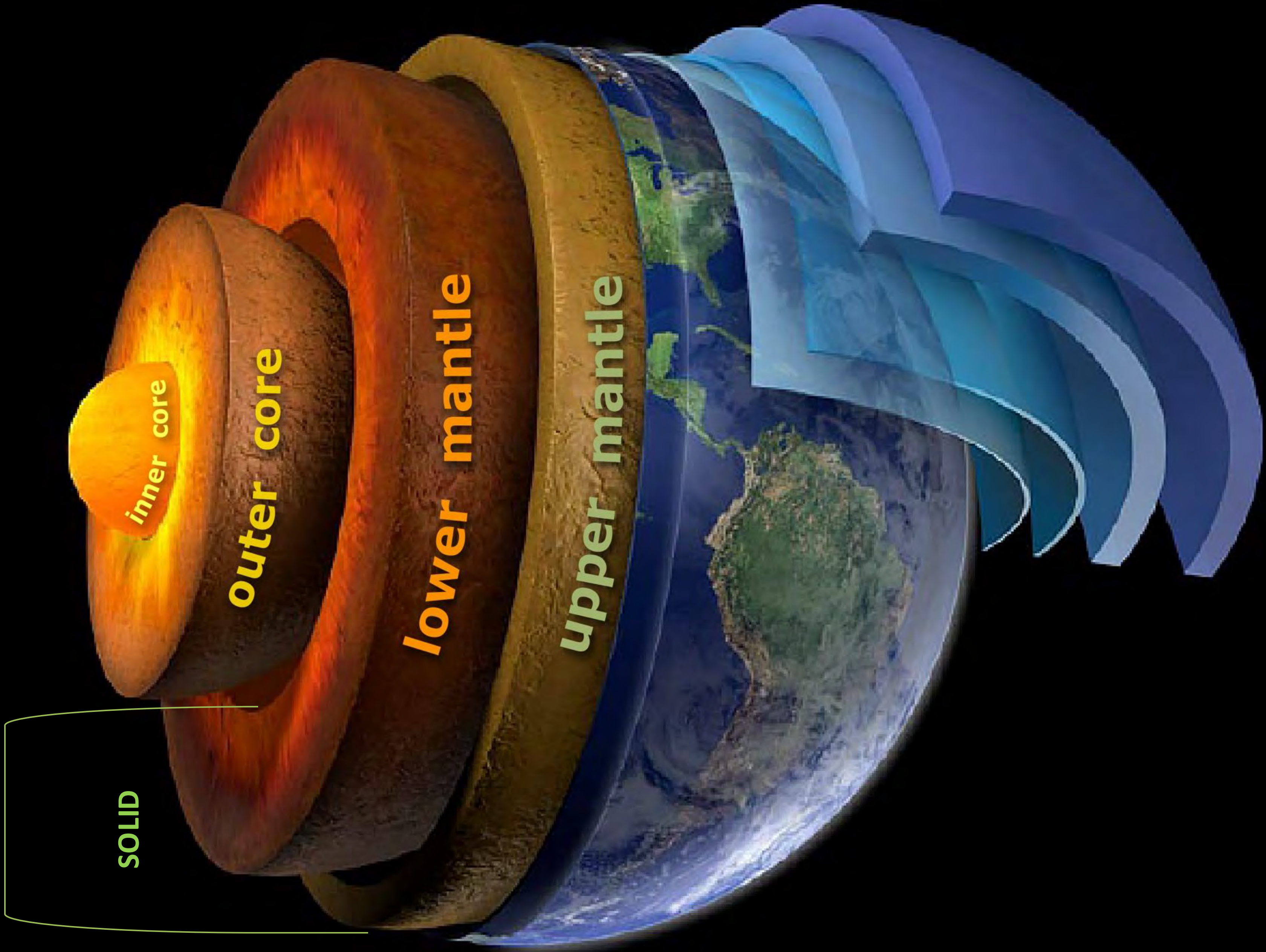
1-D Earth: shells



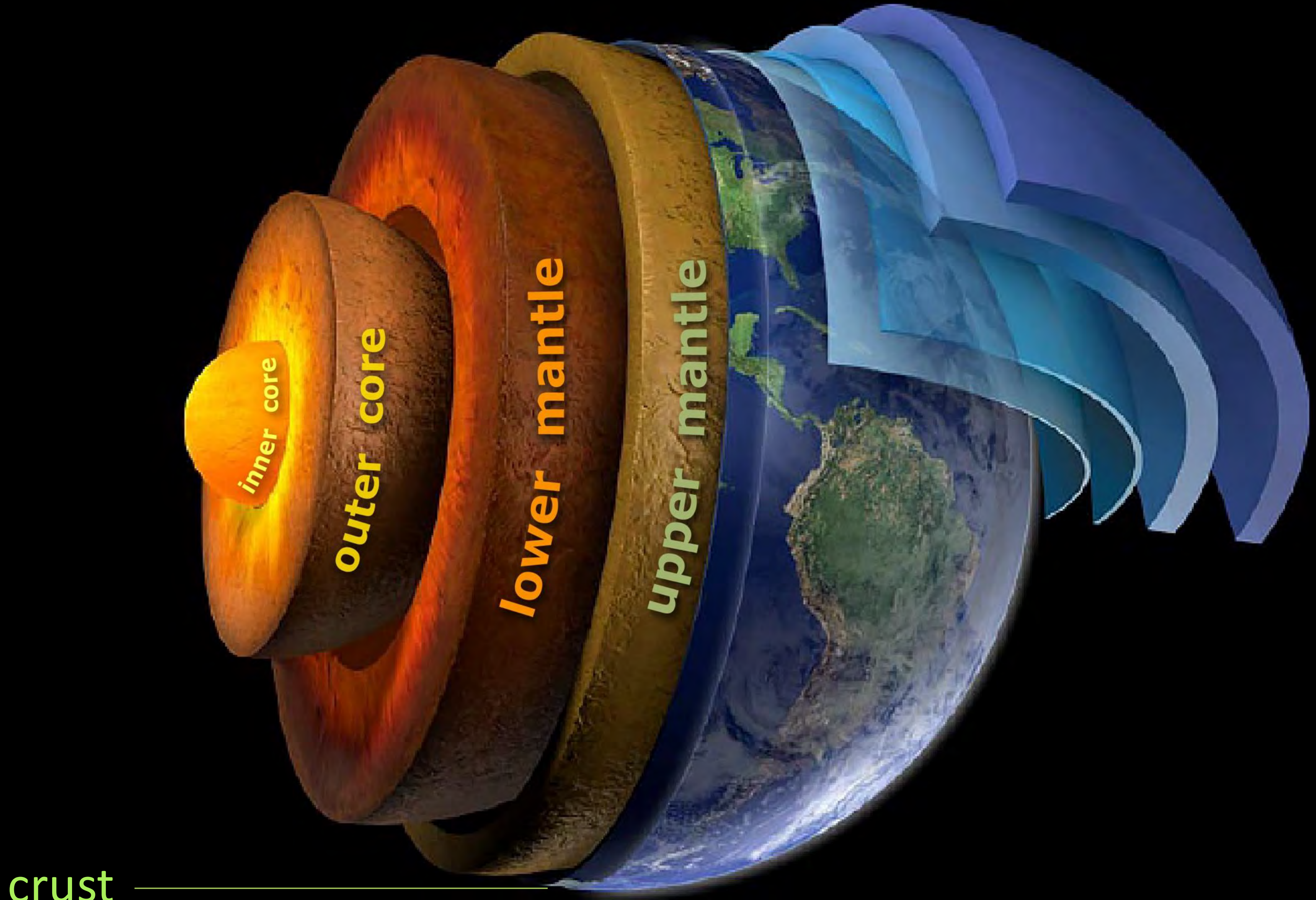
(Image: Hernan Canellas)

mostly iron

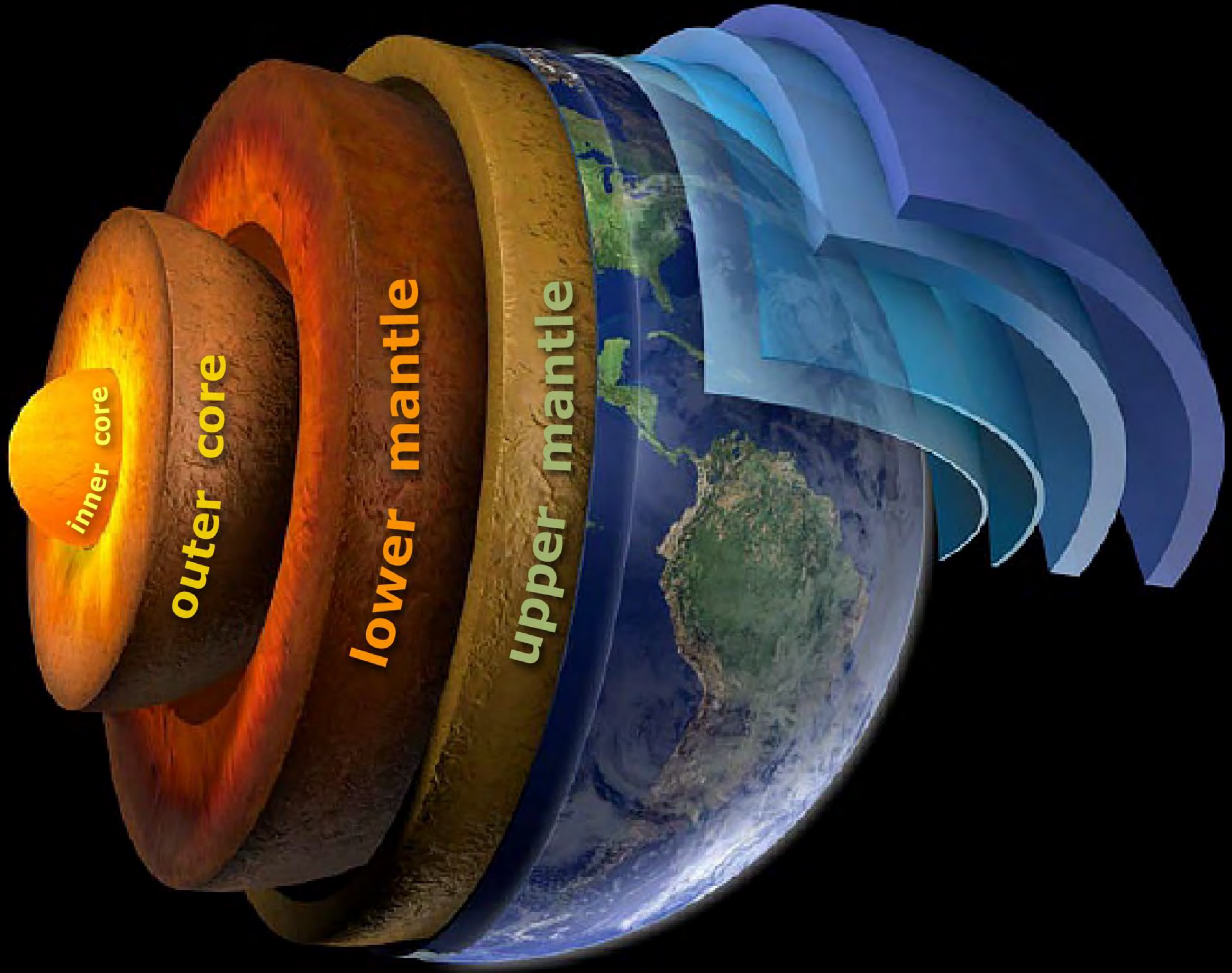

SOLID
inner core
LIQUID
outer core
lower mantle
upper mantle

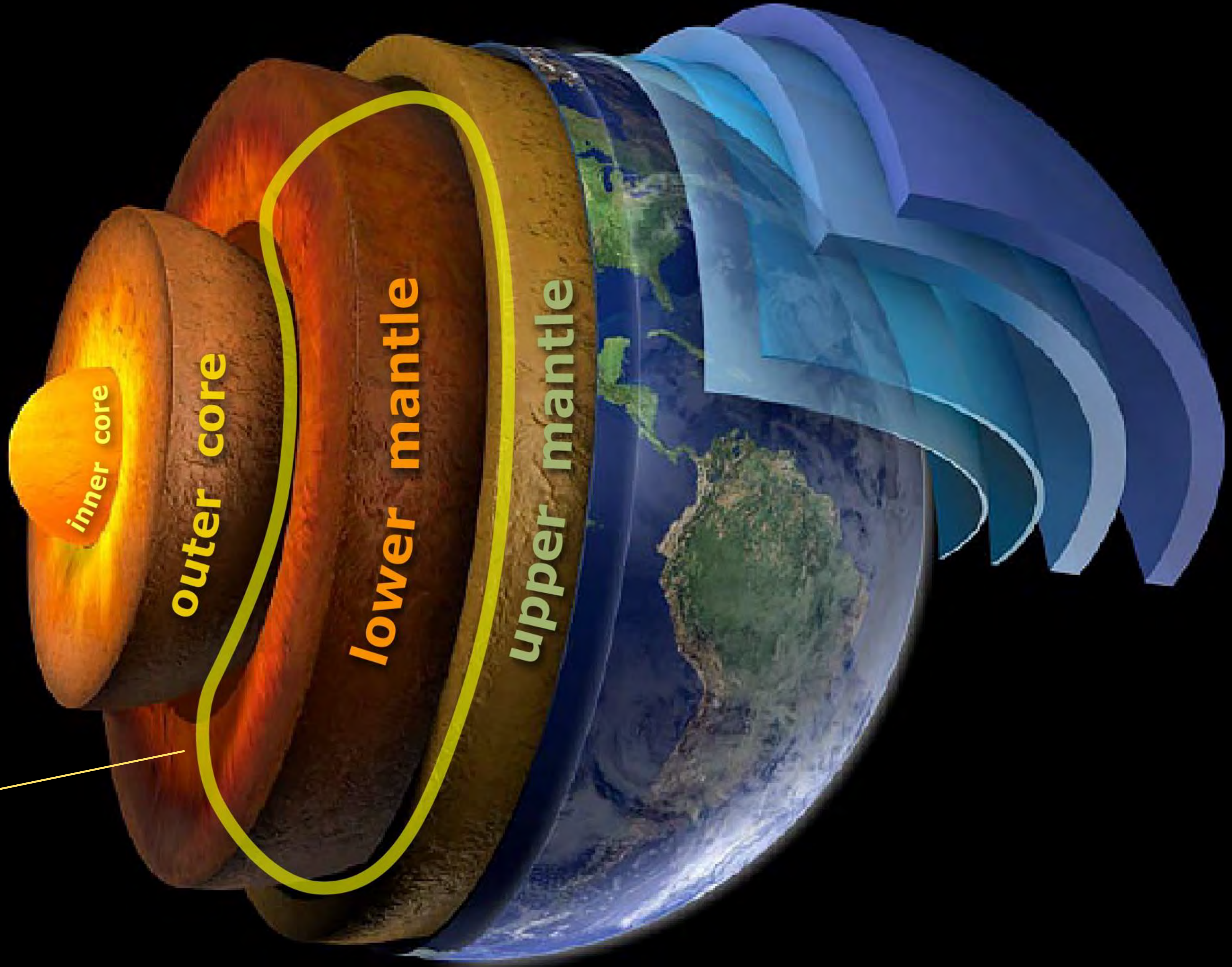


mostly silicate rock


inner core
outer core
lower mantle
upper mantle
crust

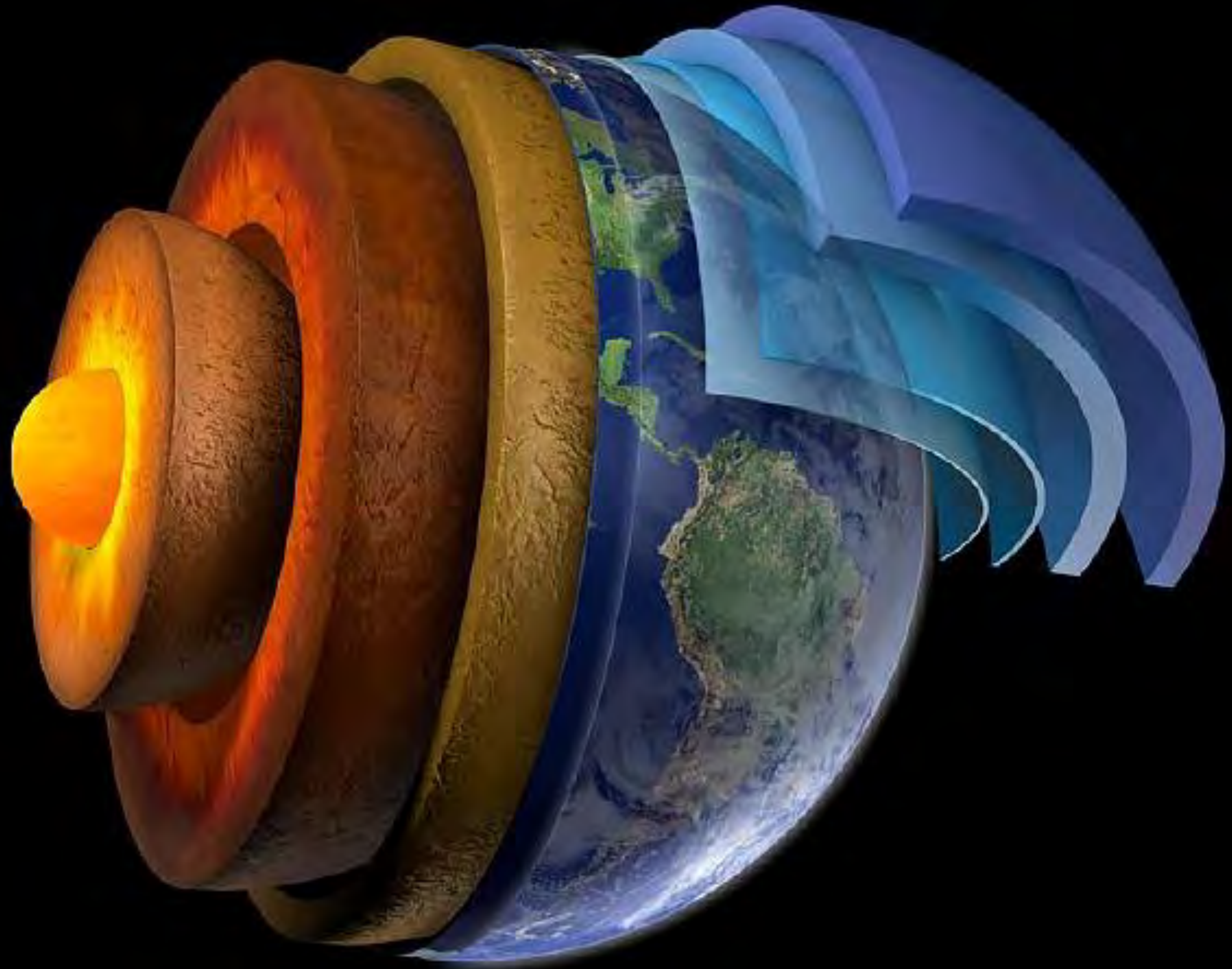
Earth's depiction of radially symmetric layering from >100 years of discoveries





Today I will mainly focus here

As more and more data became incorporated in models over the most recent decades, a picture beyond these homogenous shells has emerged



But first, why care?

Seismic wave behavior depends upon density, composition, temperature, state (fluid, solid), phase, mineralogy, convective flow (anisotropy)

They thus provide insight into Earth structure, composition, dynamics, evolution, in other words, geologic processes from crust to core.

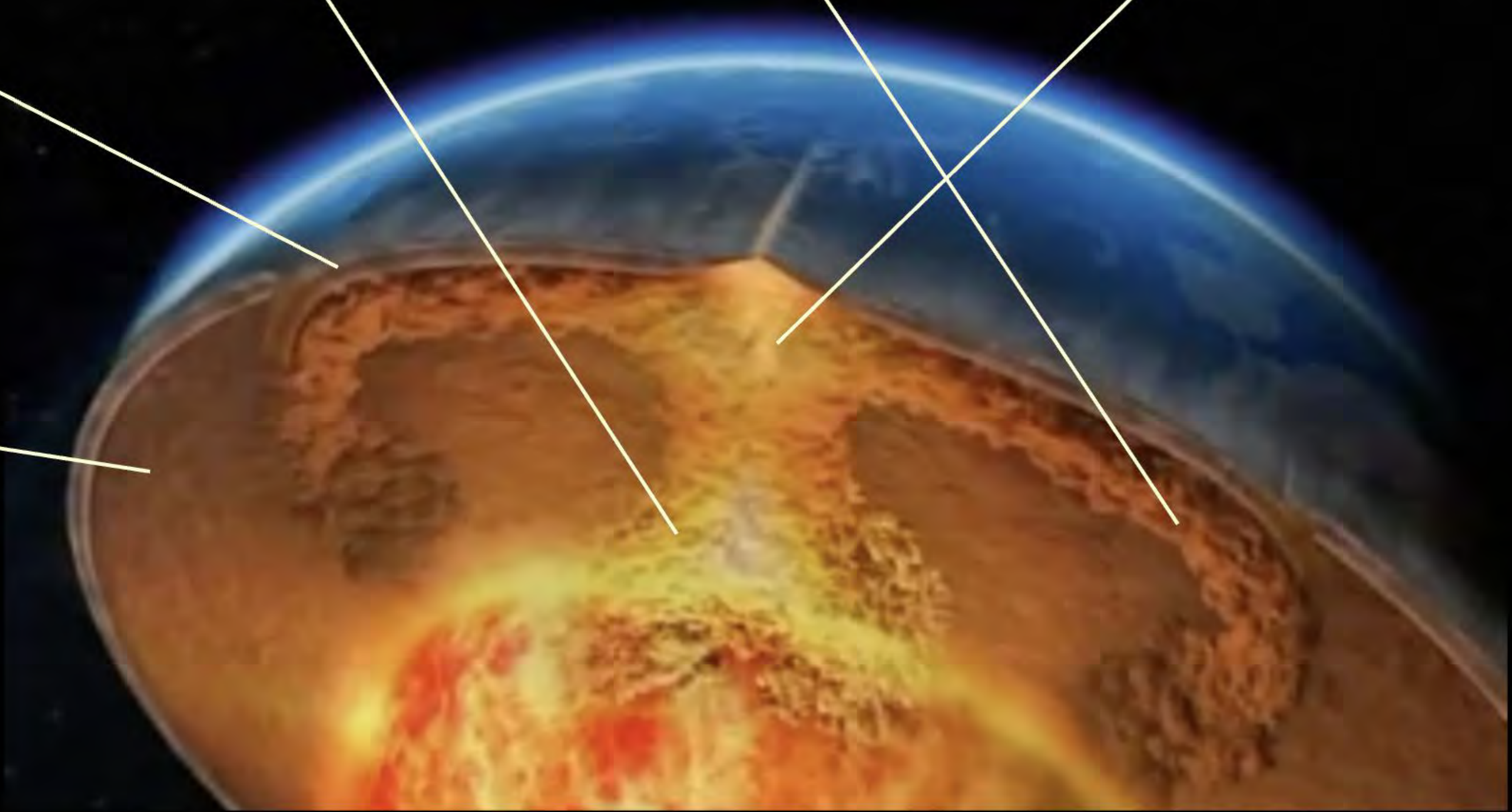
How does convection affect heat flow from the core, and our magnetic field?

How does subduction drive mantle flow patterns? Can we map them?

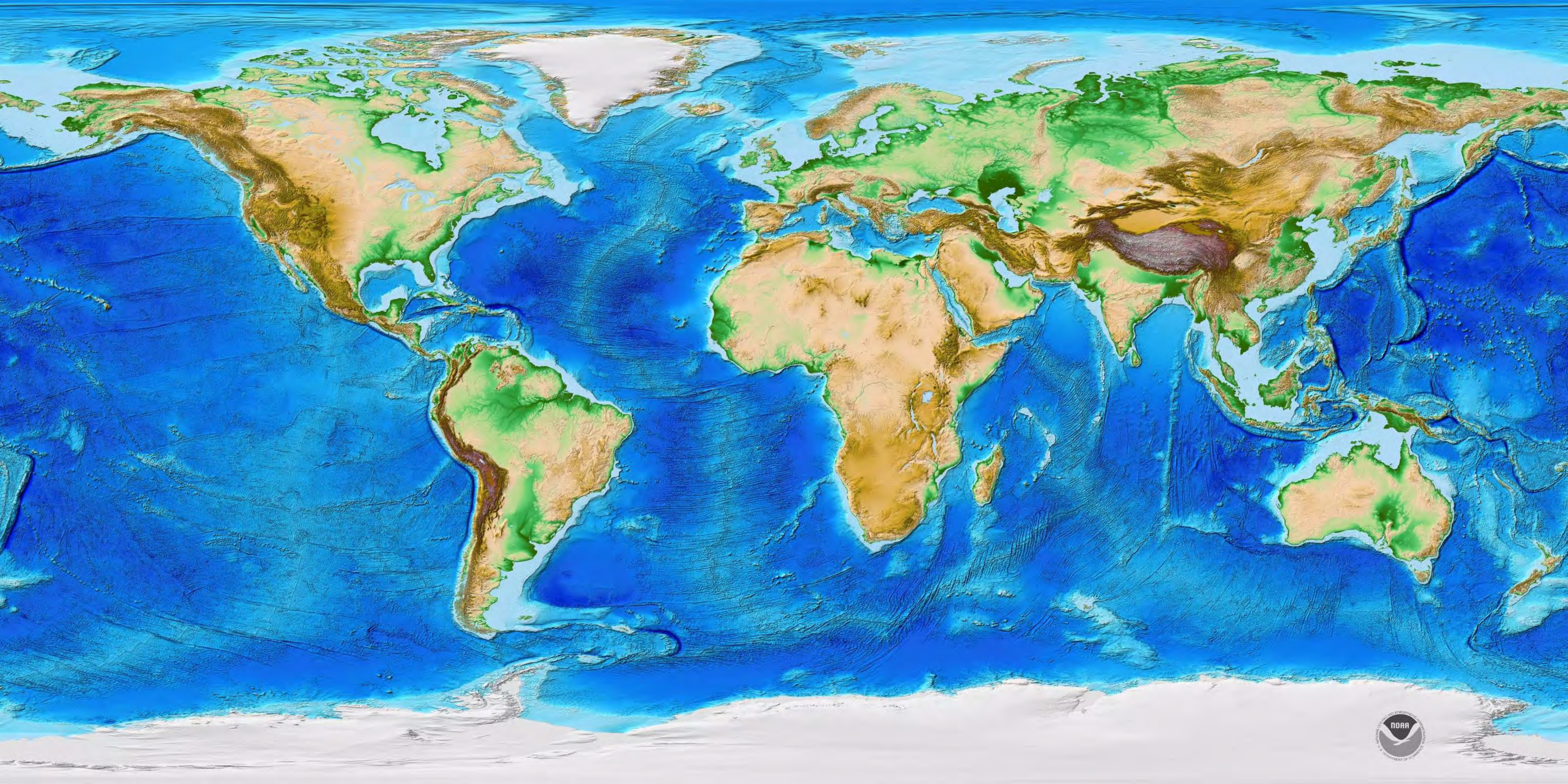
Can we map melting processes that relative to plumes, volcanism?

What is the relationship between internal convection and plate tectonics?

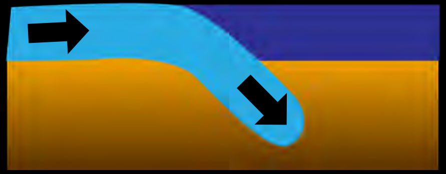
Mapping the interior holds clues for Earth's chemical and dynamical evolution

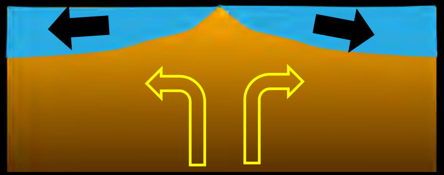


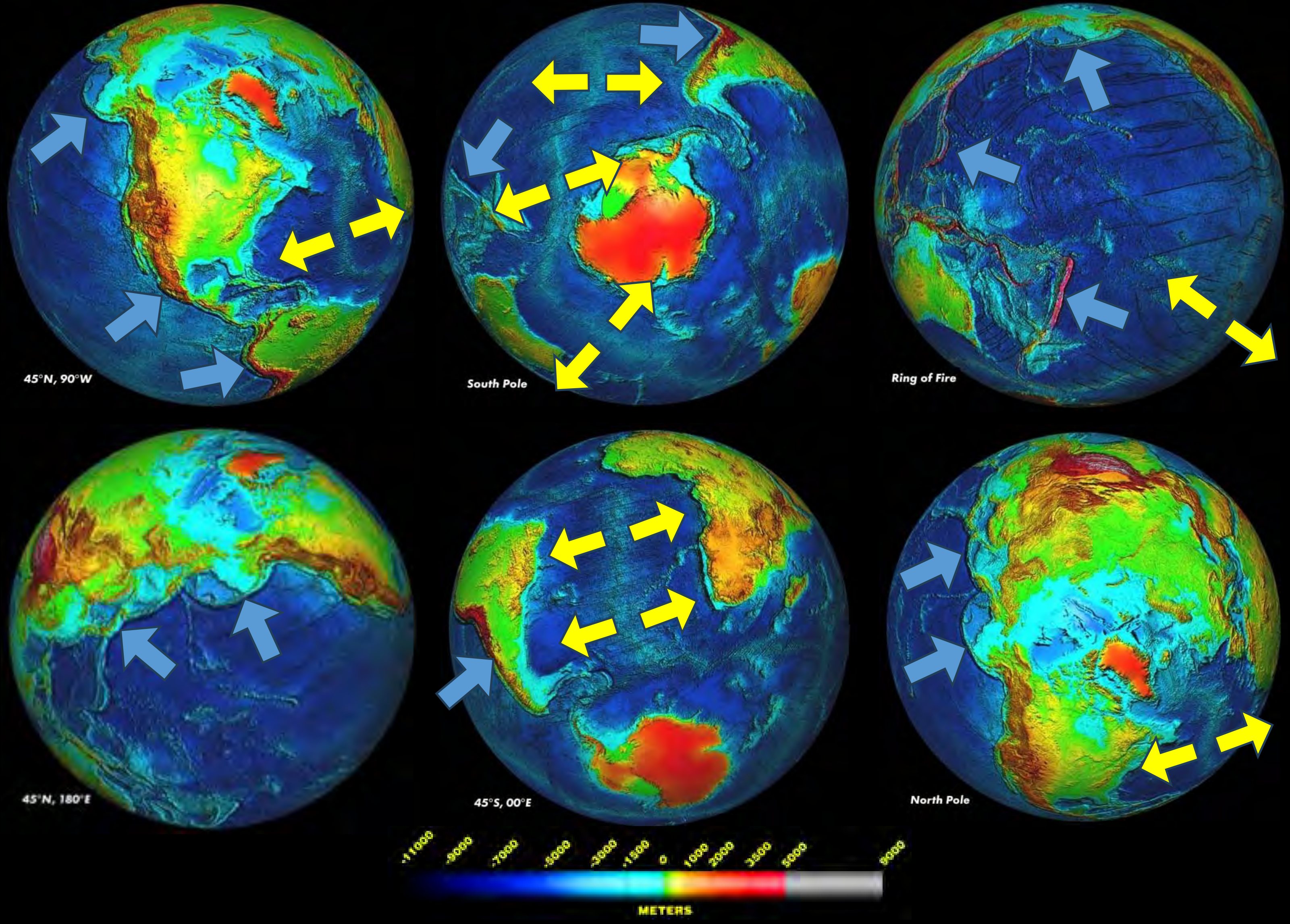
(Cartoon animation from National Geographic X-ray Earth)

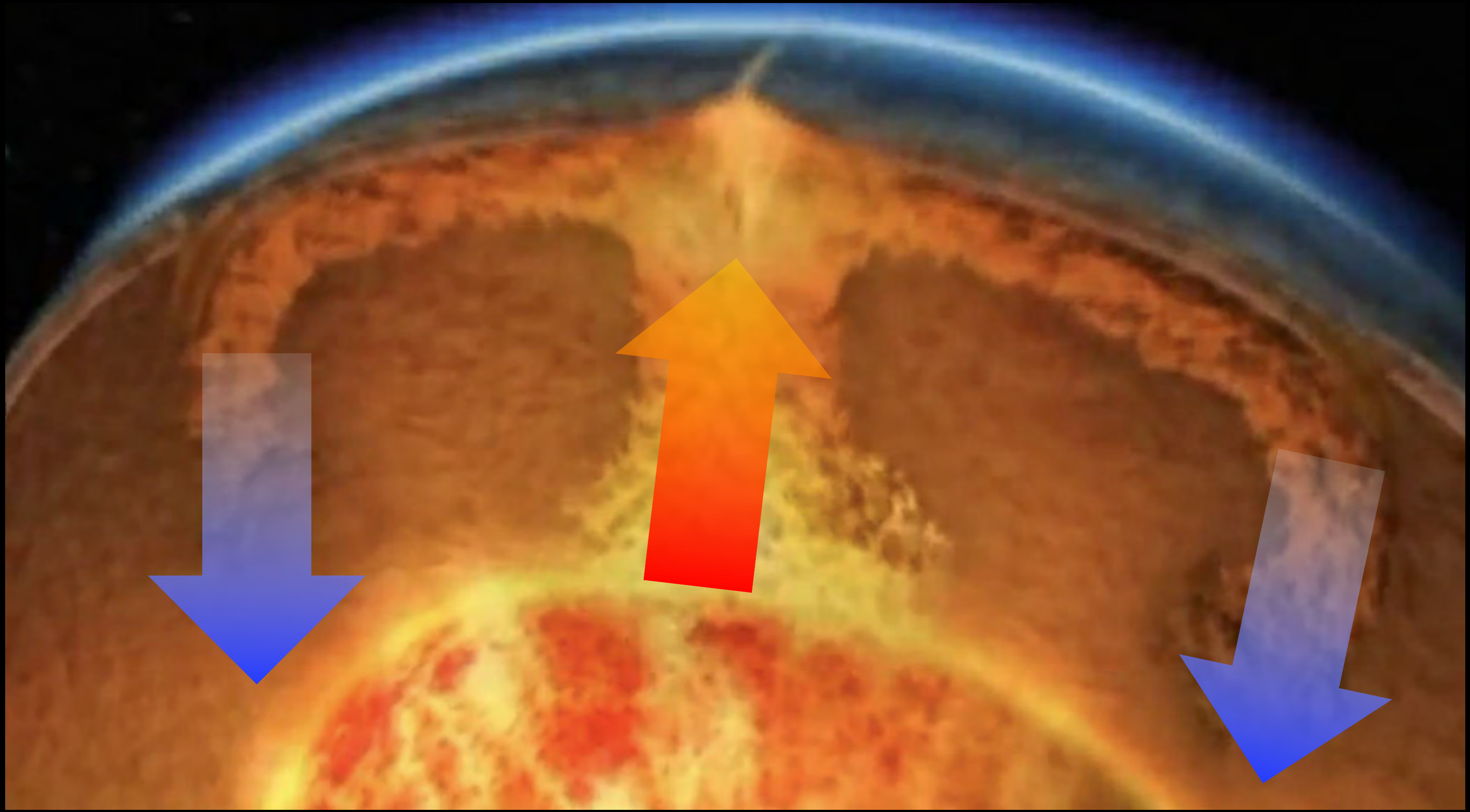


Creation and destruction of tectonic plates





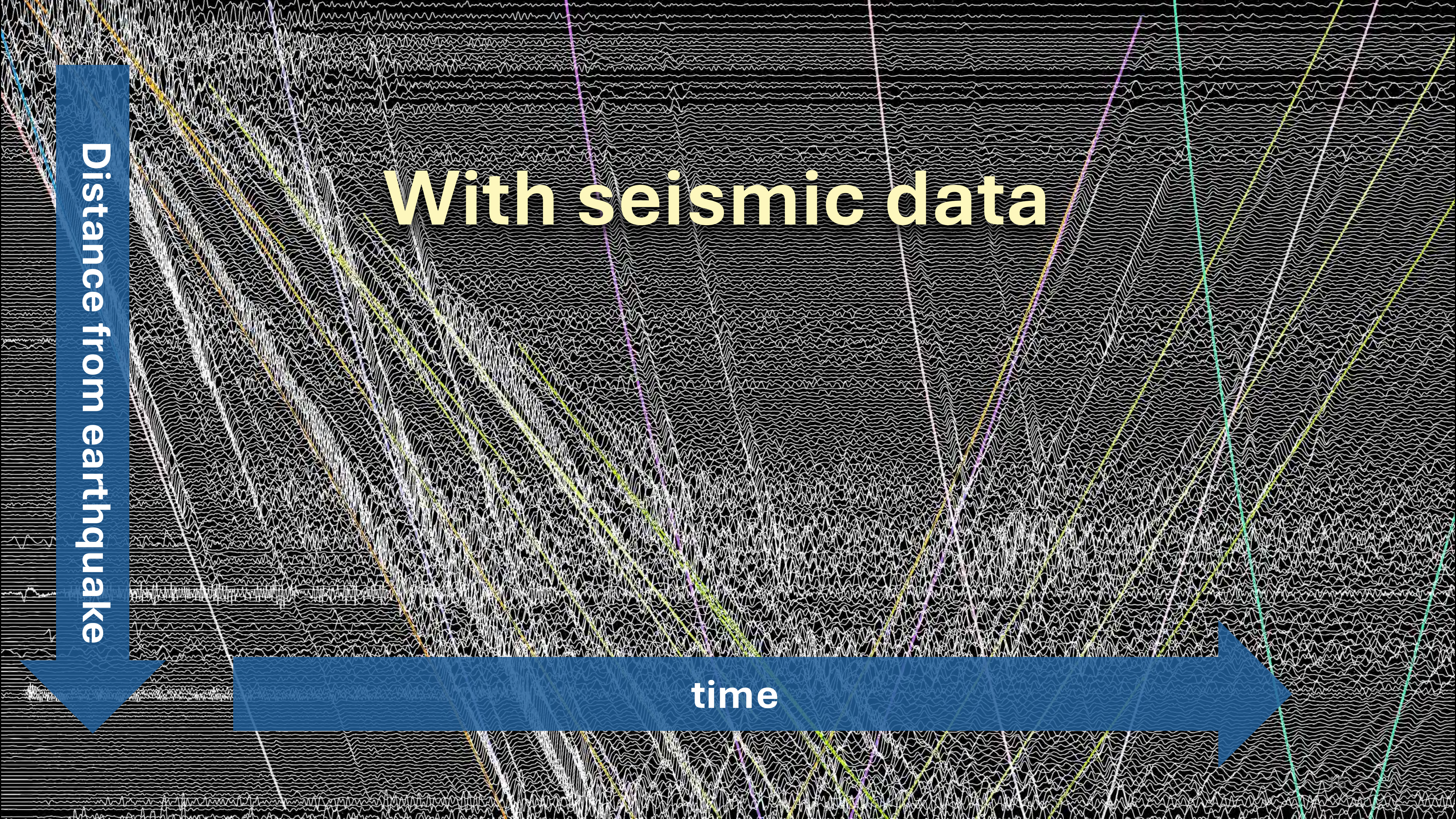


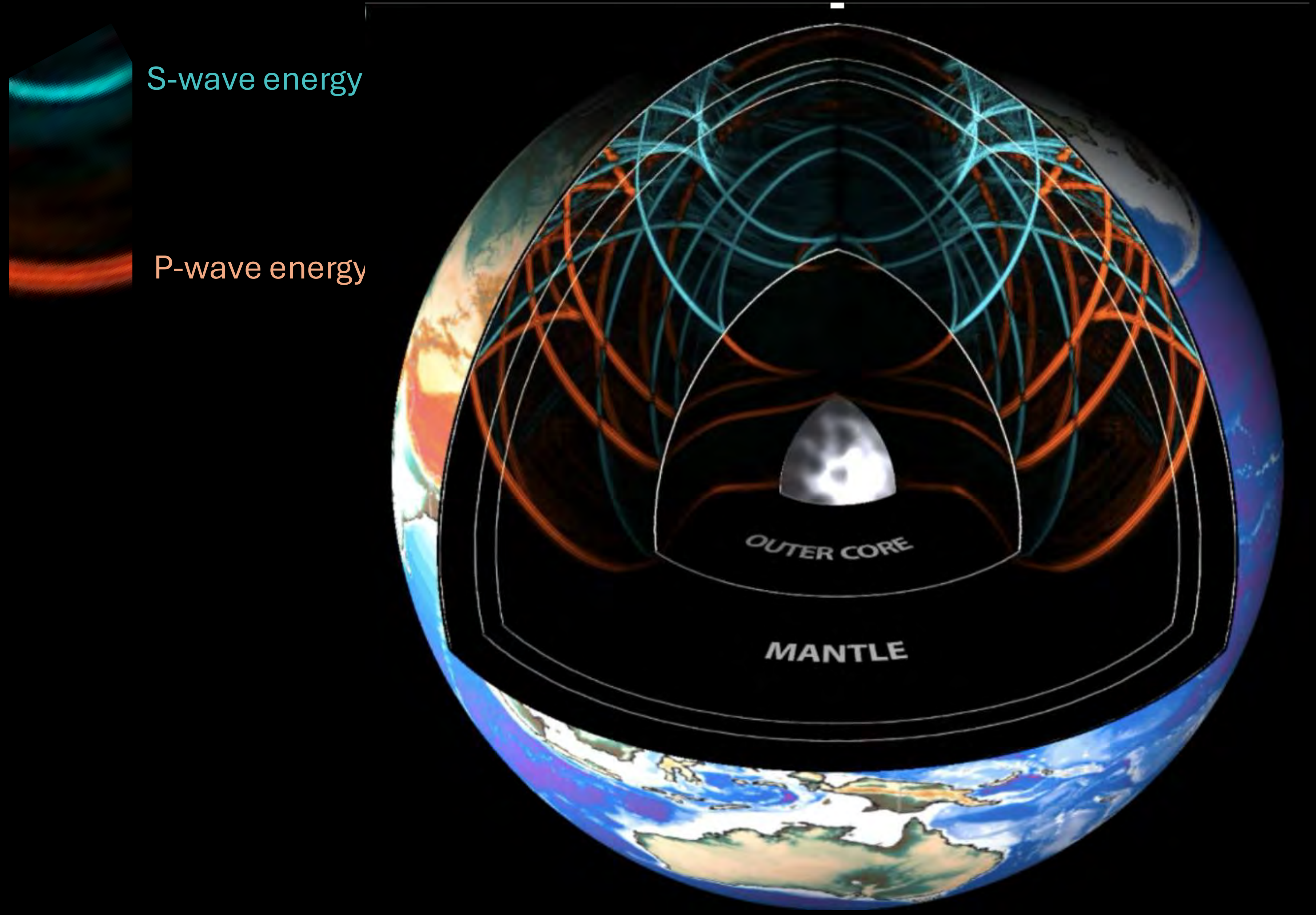


These surface motions relate to Earth's internal "ups and downs" but how do we move beyond cartoons?

Geophysical methods can shed light on these and many other phenomena

But how?

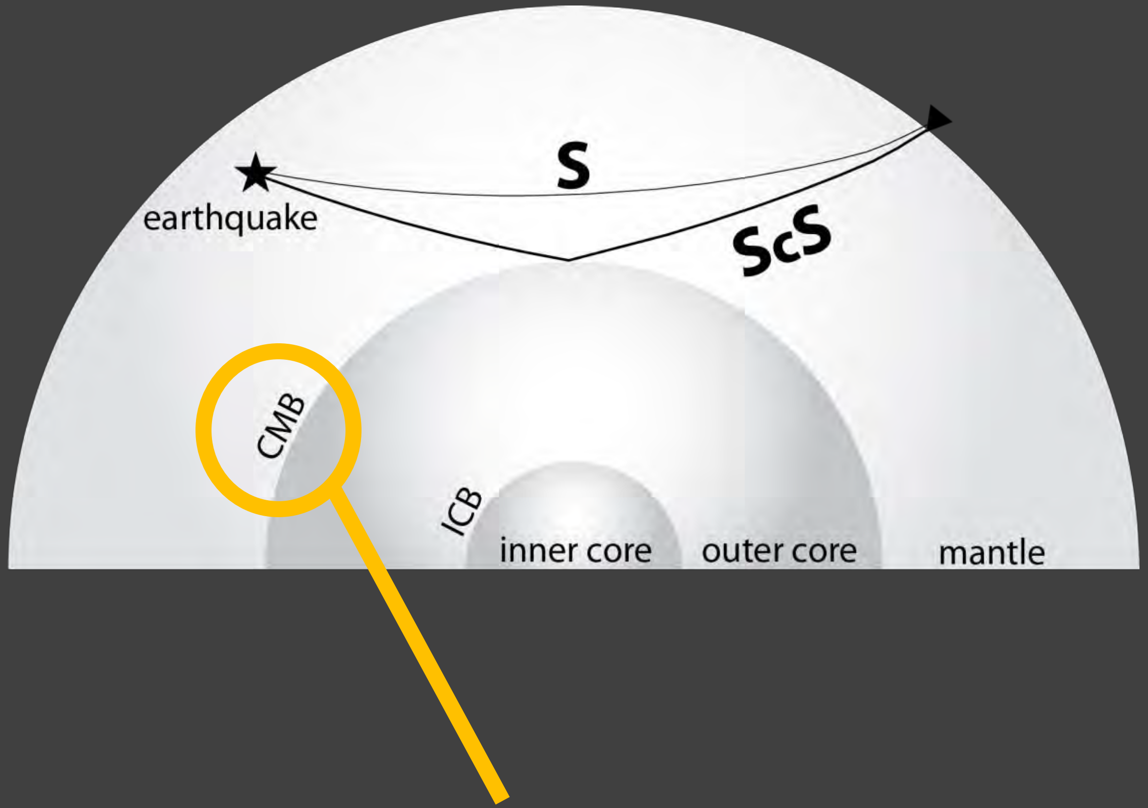

With seismic data
Distance from earthquake
time



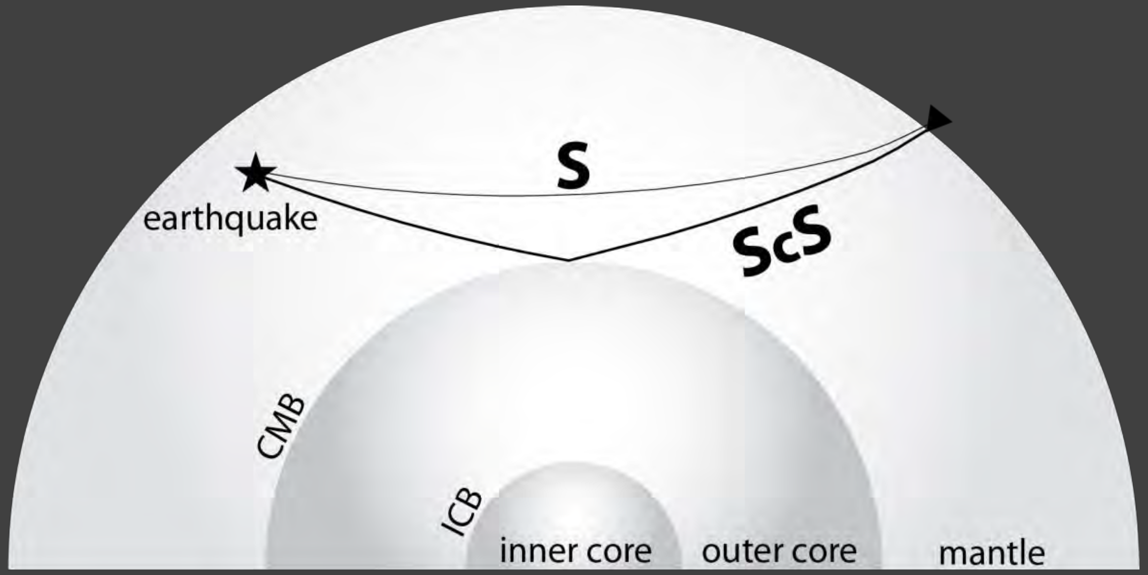
Prof. Mike Thorne
University of Utah

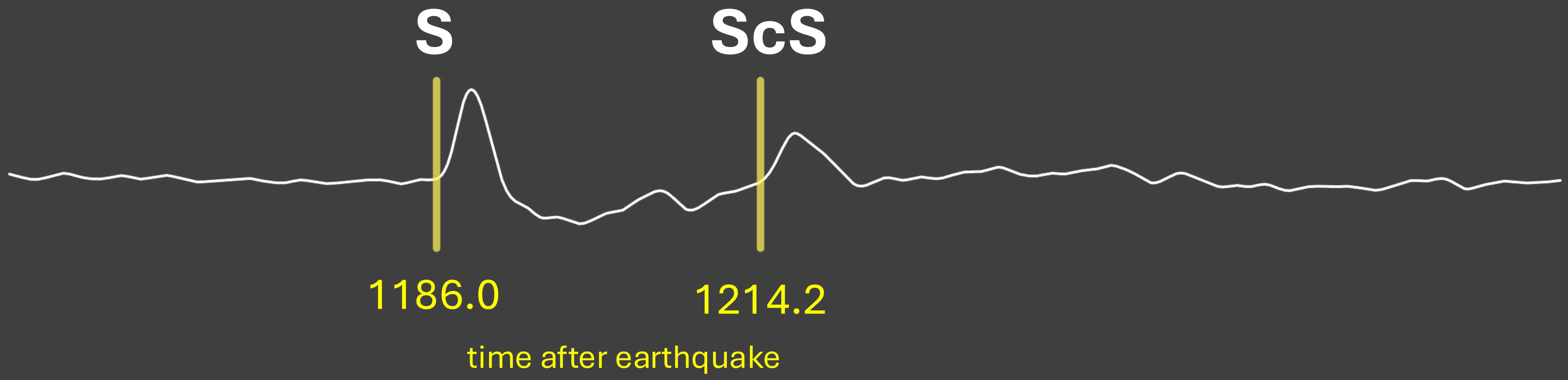
Let’s look at an example

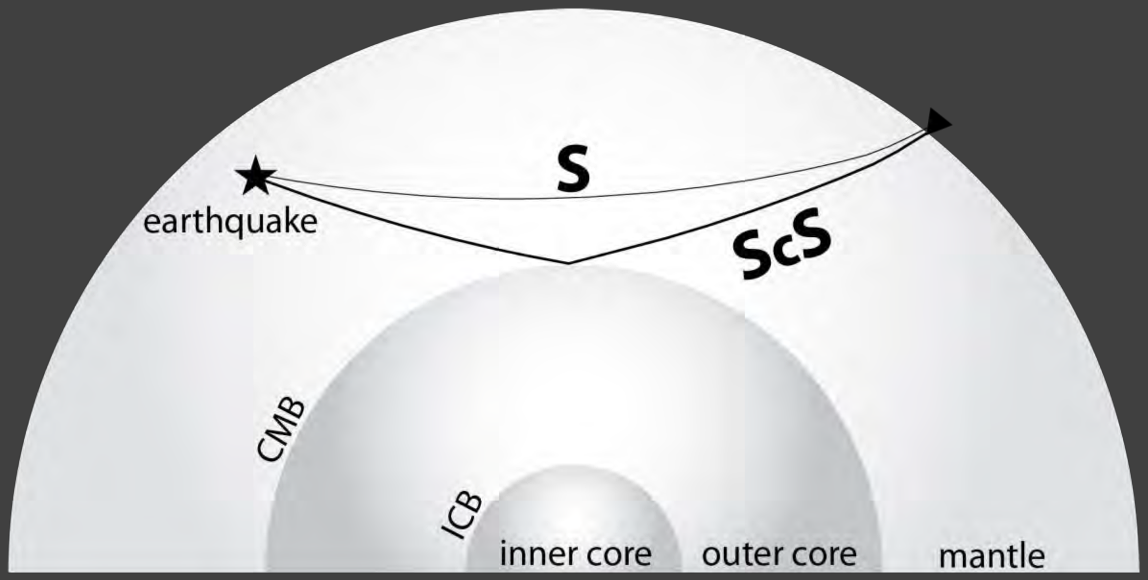
Seismologists measure, document and predict seismic wave timing, amplitude, waveform and frequency content

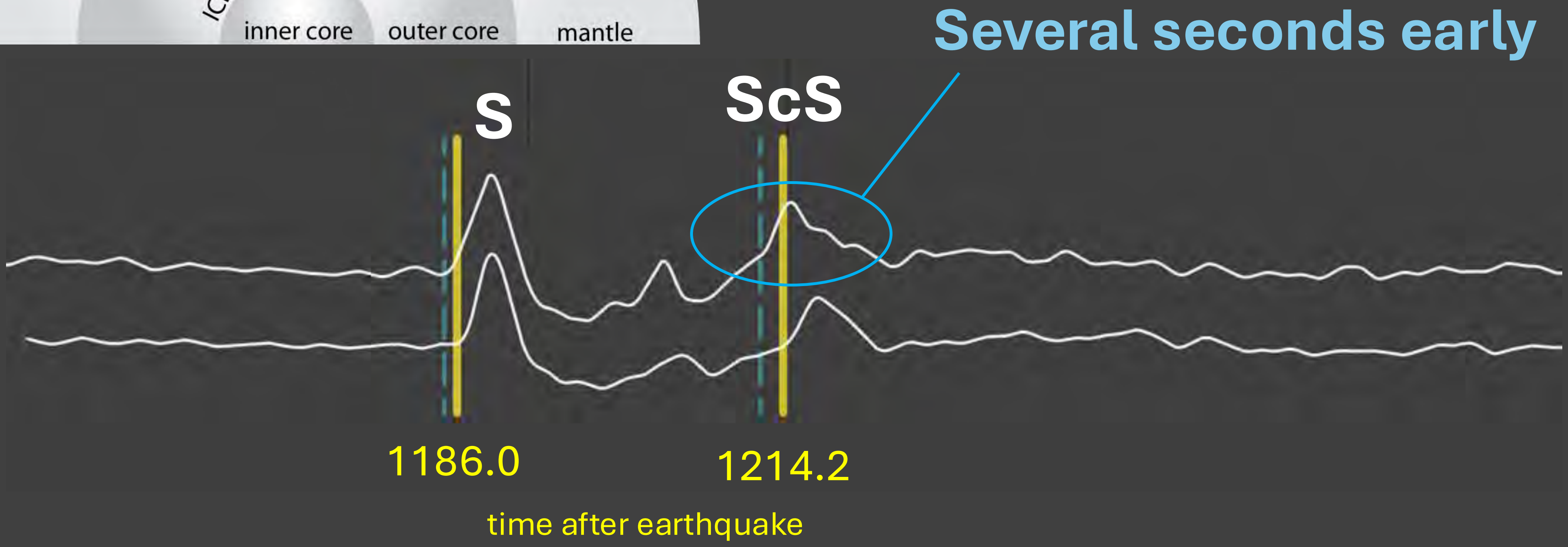


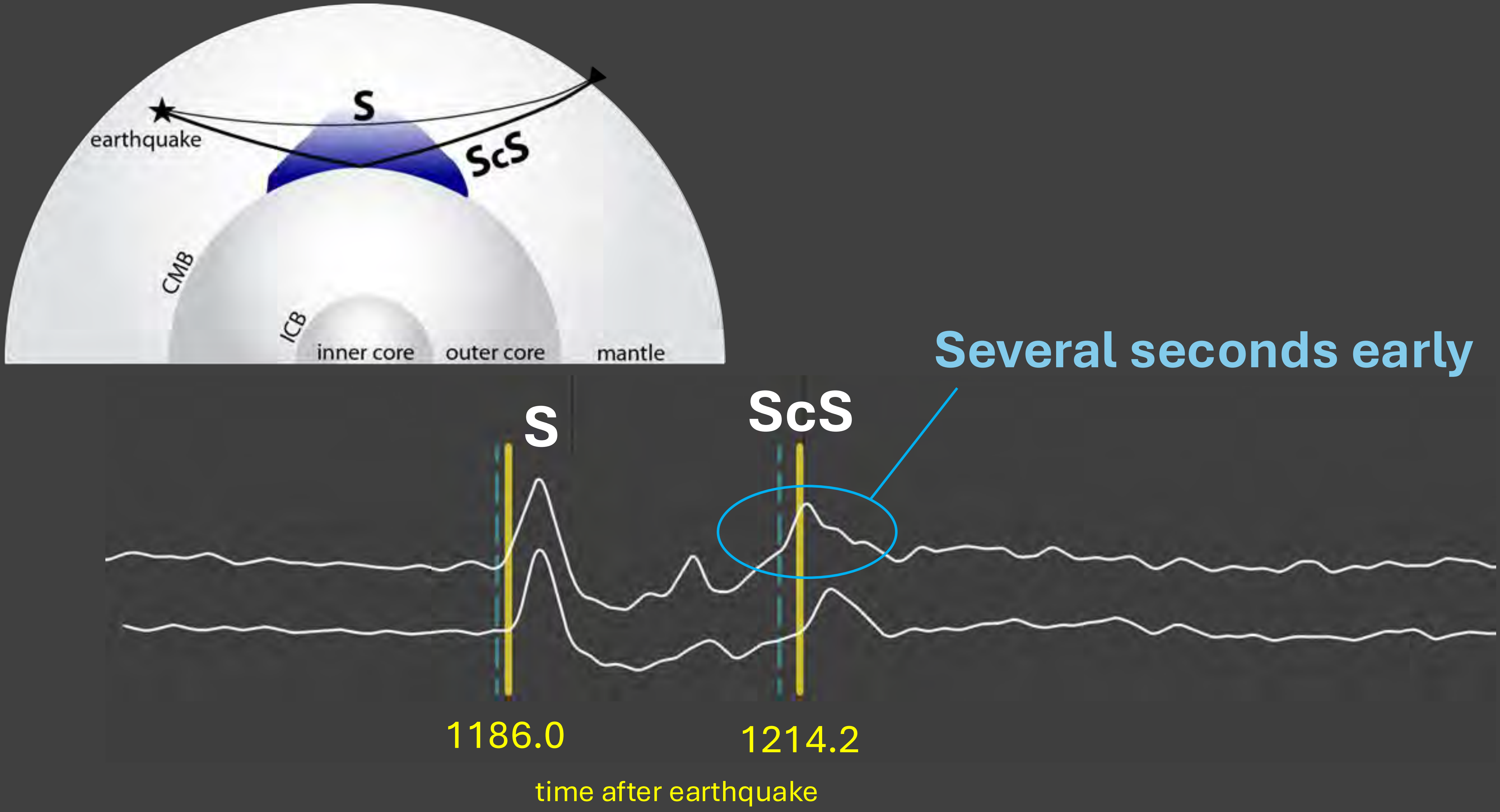
Core-Mantle Boundary

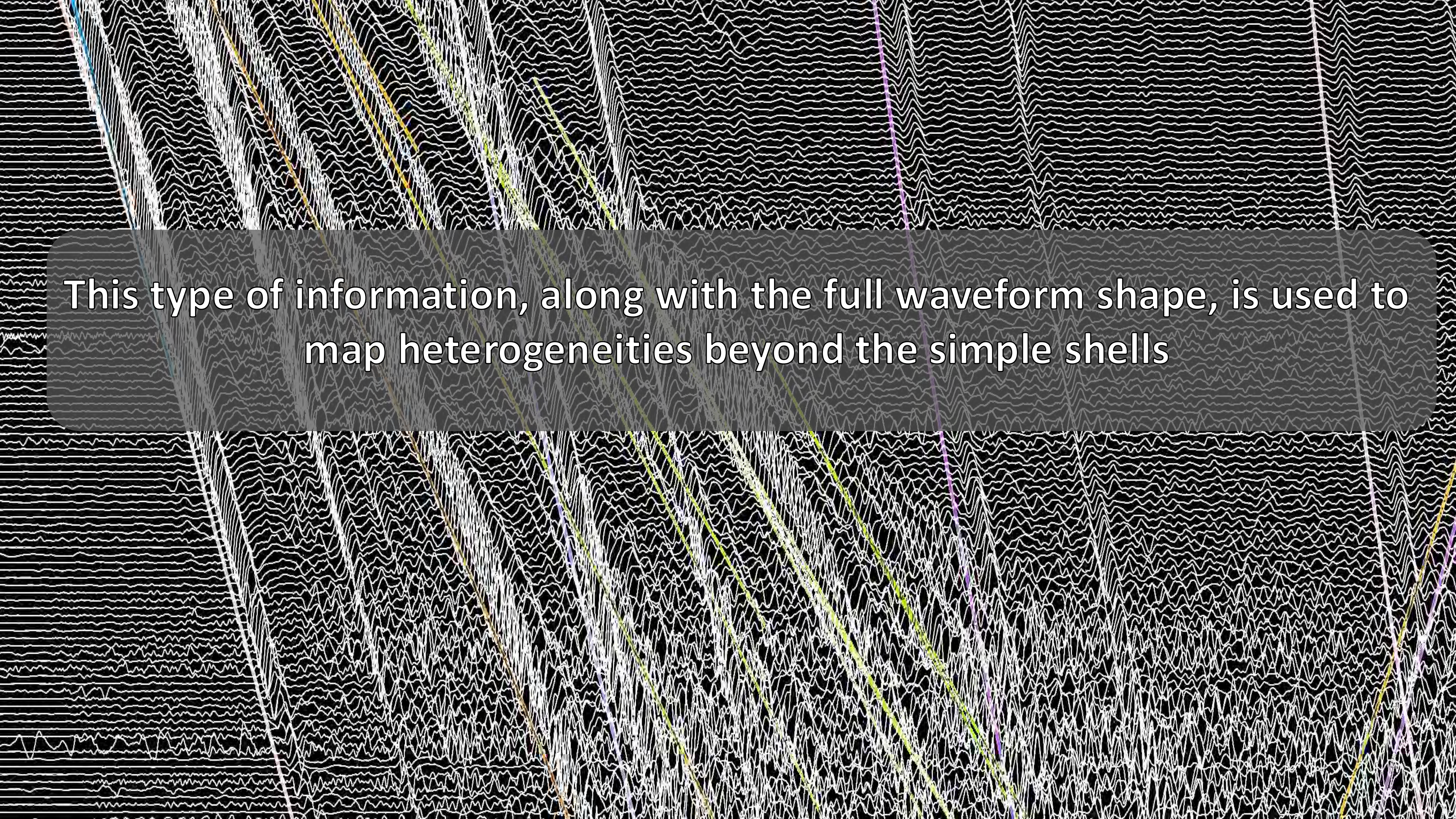

S
earthquake
ScS
CMB
ICB
inner core
outer core
mantle


S
ScS
1186.0
1214.2
time after earthquake


S
ScS
earthquake
CMB
ICB
inner core
outer core
mantle

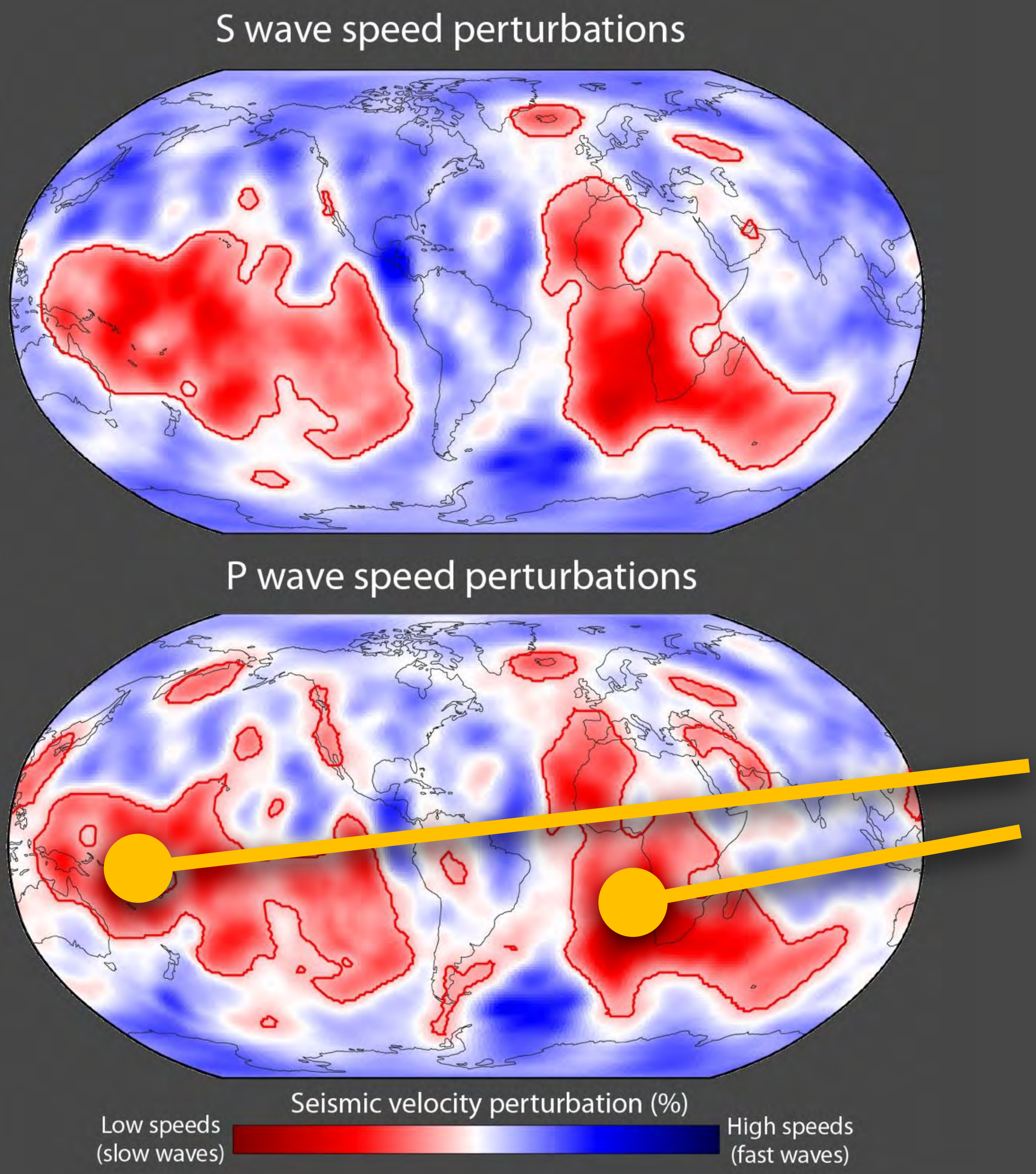

Several seconds early
S
ScS
1186.0
1214.2
time after earthquake

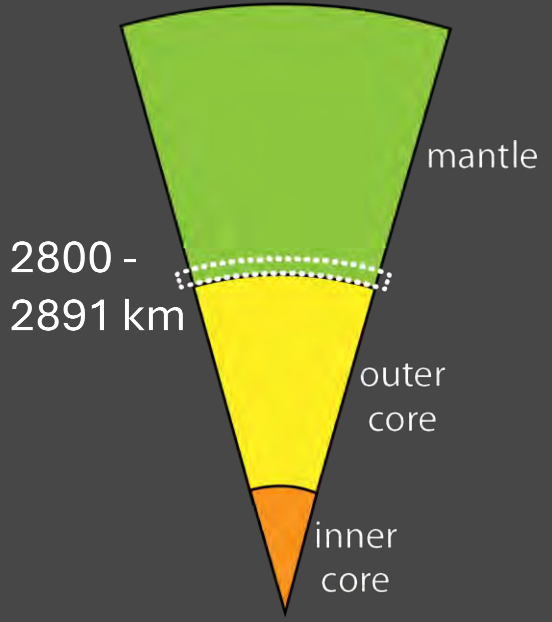

S
earthquake
ScS
CMB
ICB
inner core
outer core
mantle
Several seconds early
S
ScS
1186.0
1214.2
time after earthquake



This type of information, along with the full waveform shape, is used to map heterogeneities beyond the simple shells

Seismic wave velocity variations at the base of Earth's mantle



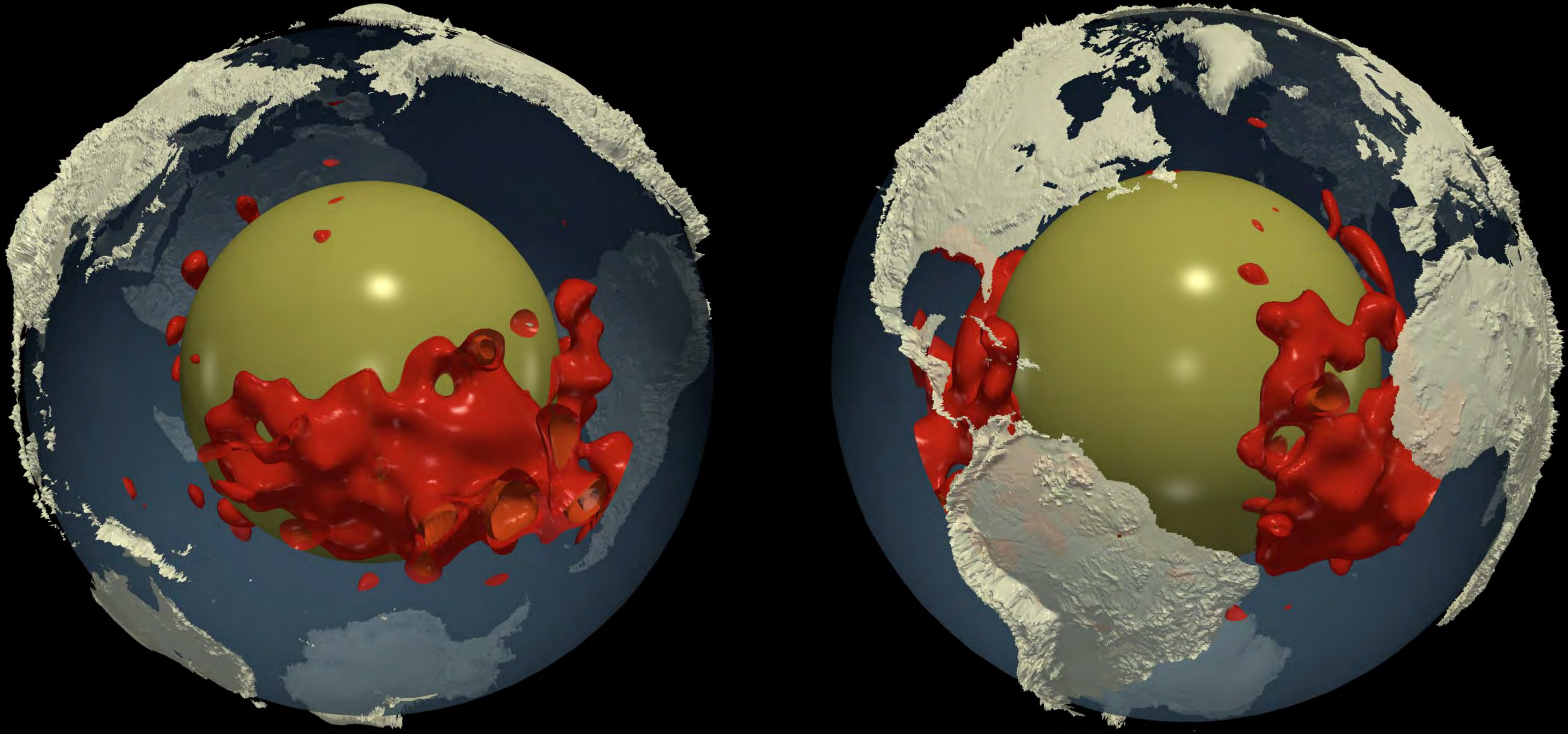


Large
Low
Velocity
Provinces

LLVPs

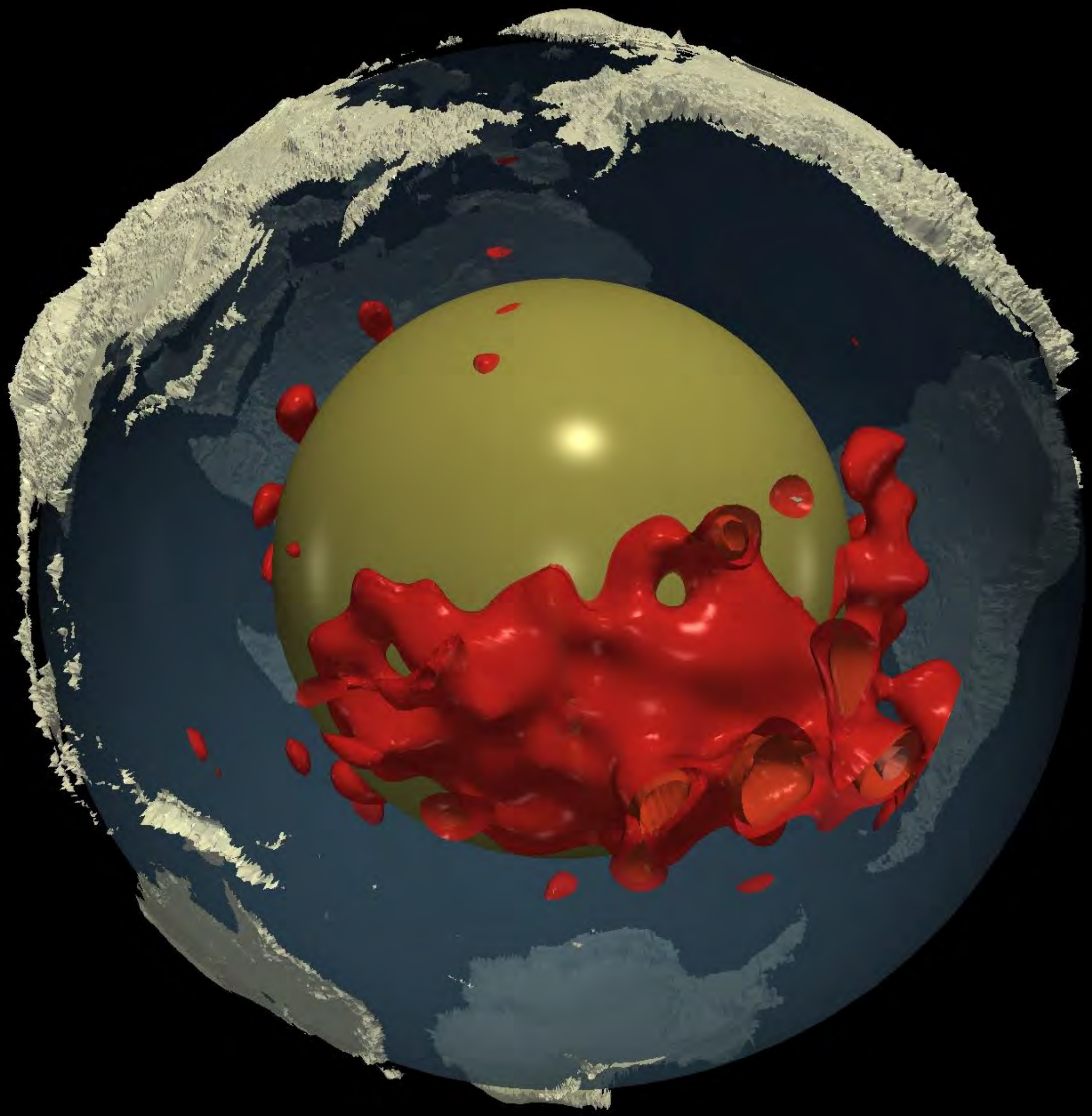
MODEL: GLAD-M25 (Lei et al., 2020)

LLVPs



Tomography model: French and Romanowicz (2014)
Free plotting software: paraview.org

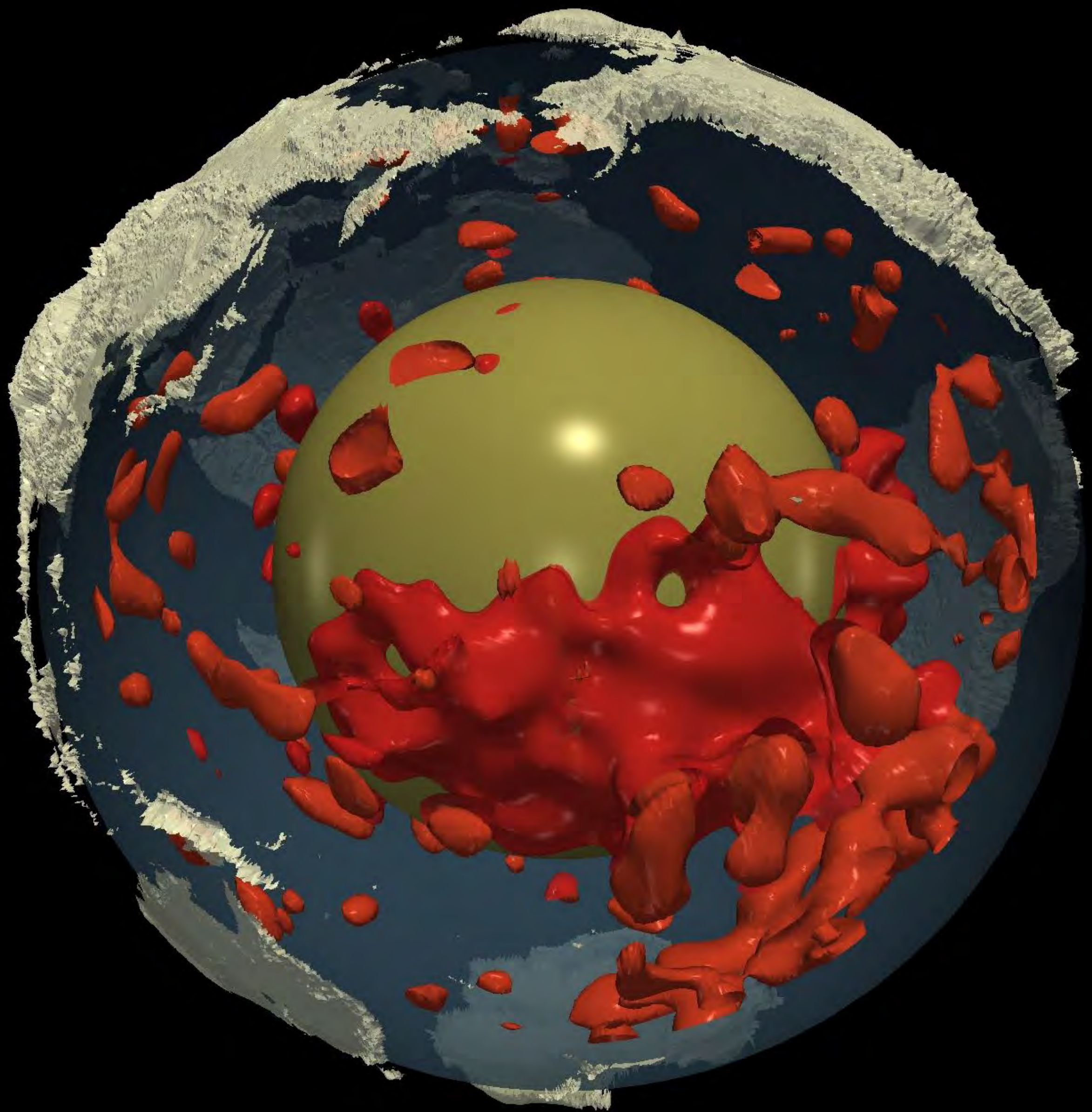
Plotting choices



$\delta Vs <= -0.8\%$

Z > 1350 km

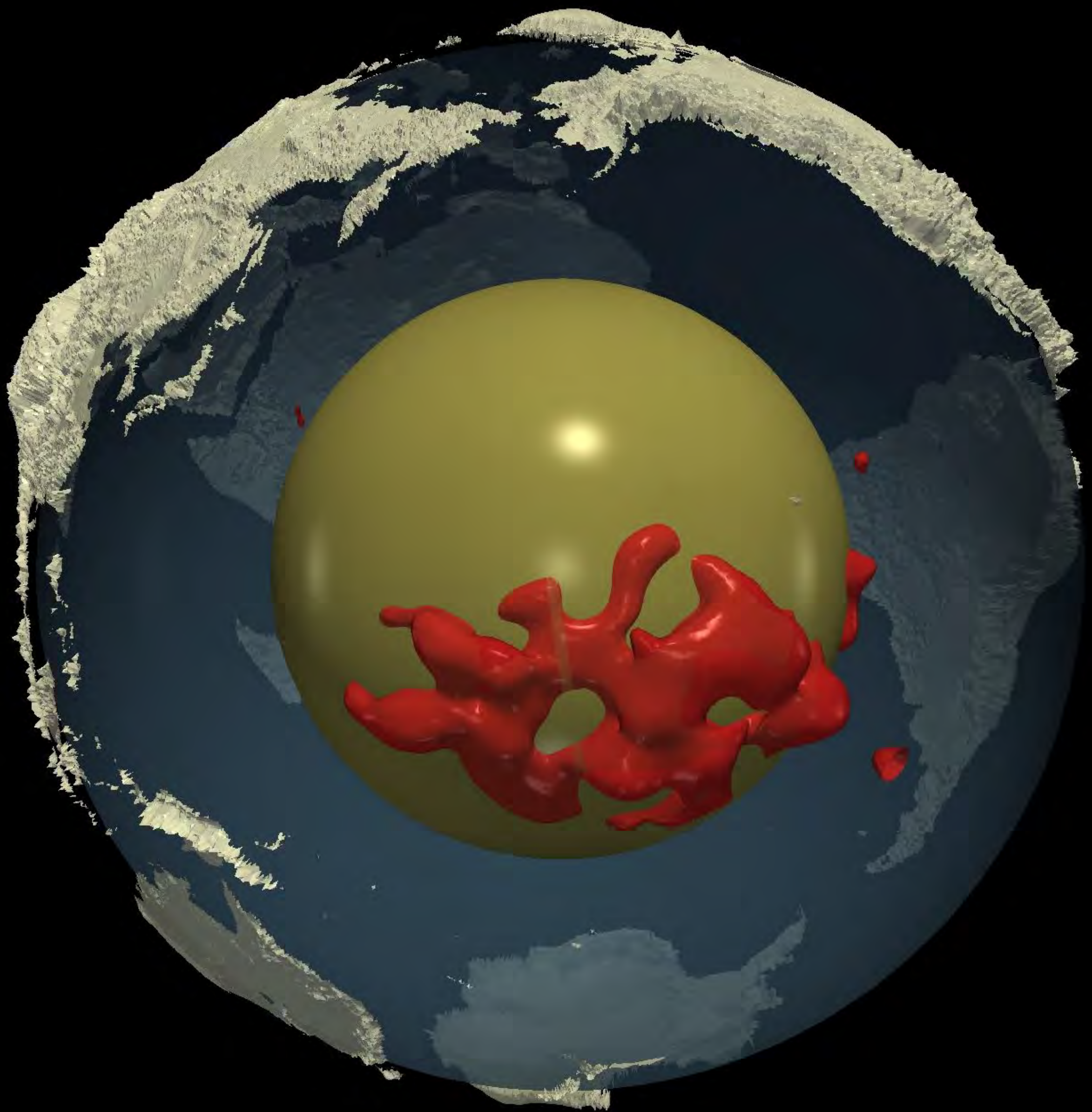
Plotting choices



δVs <= -0.8%

Z > 700 km

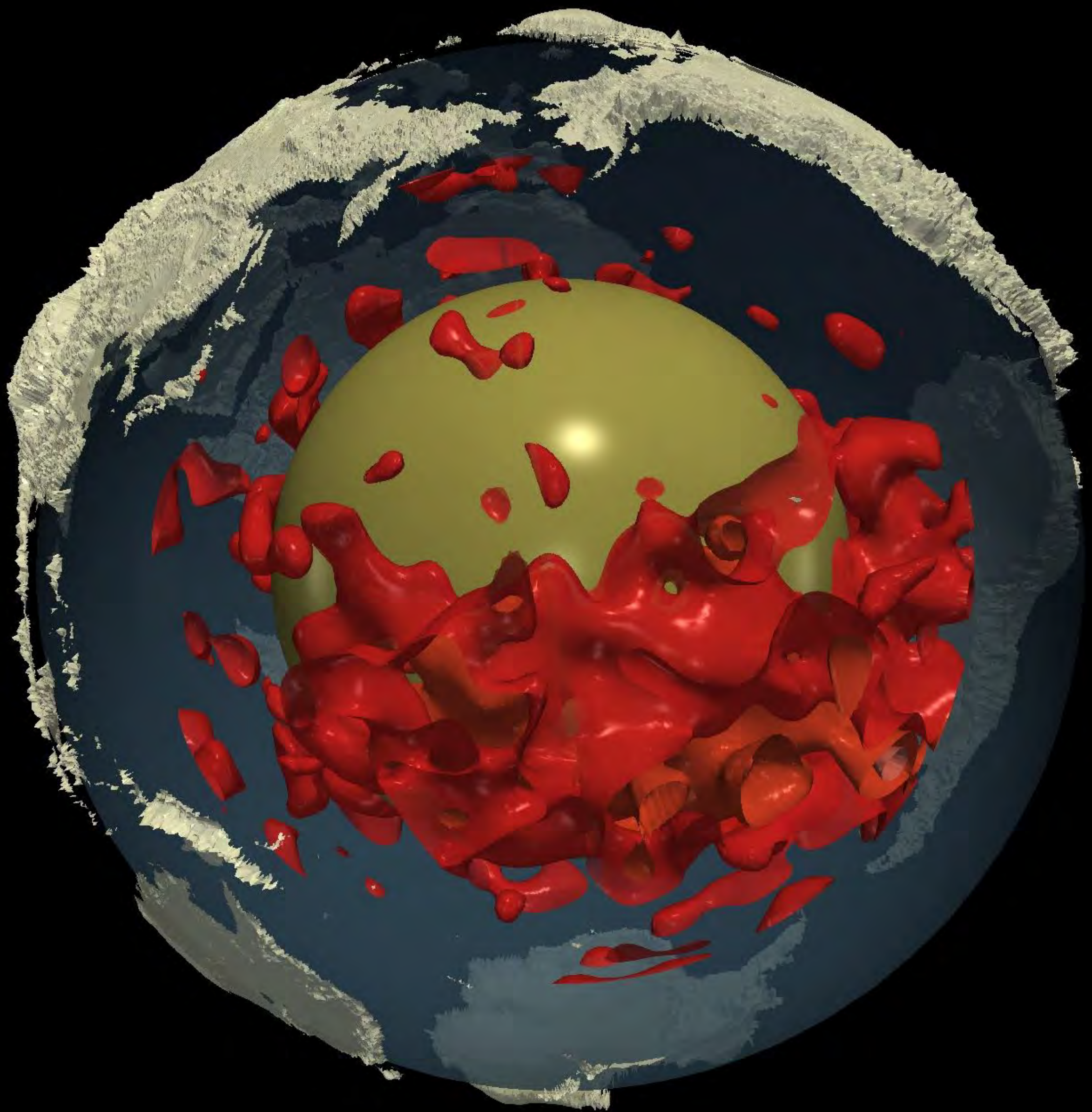
Plotting choices



δVs <= -1.5%

Z > 1350 km

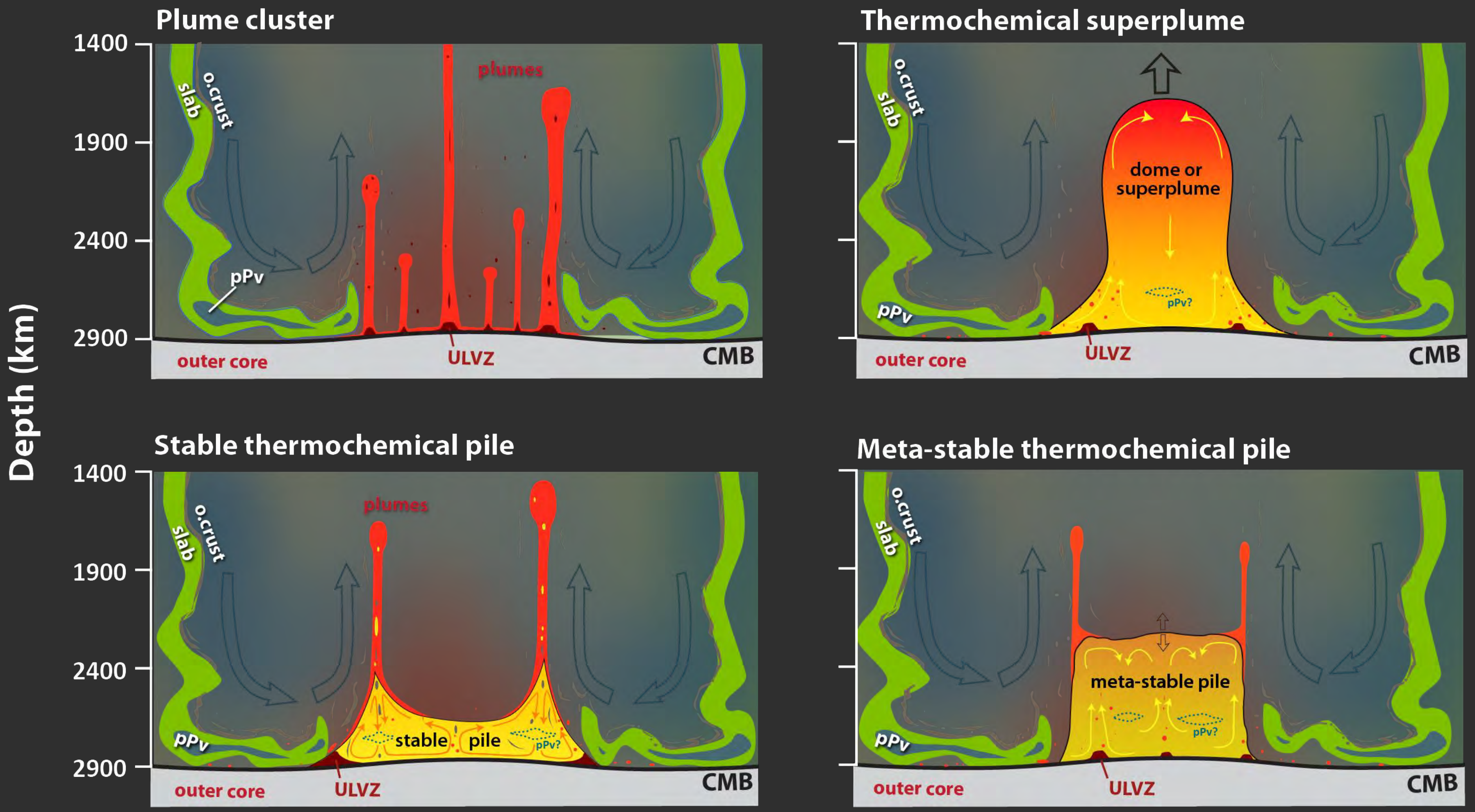
Plotting choices



δVs <= -0.5%

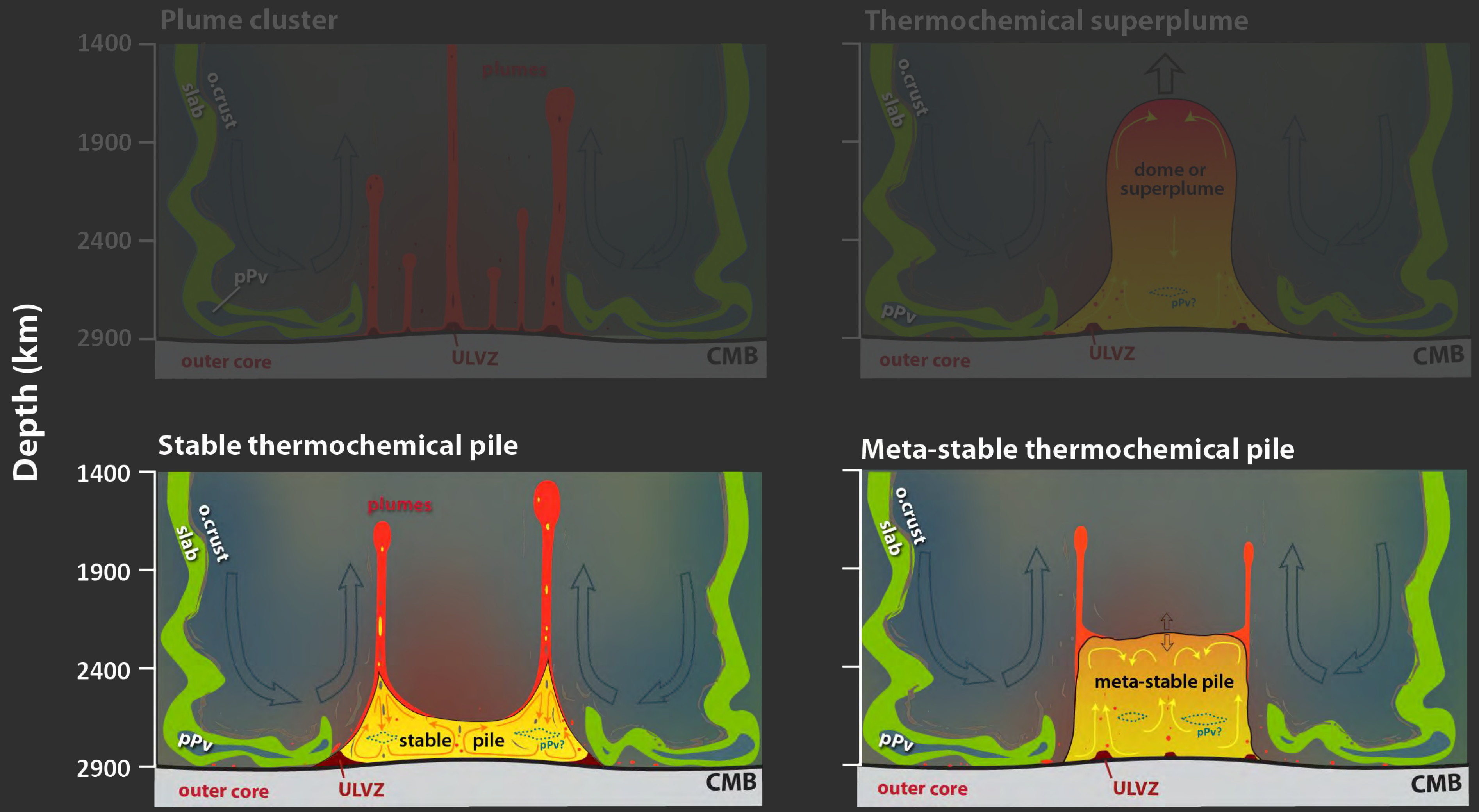
Z > 1350 km

LLVP interpretations

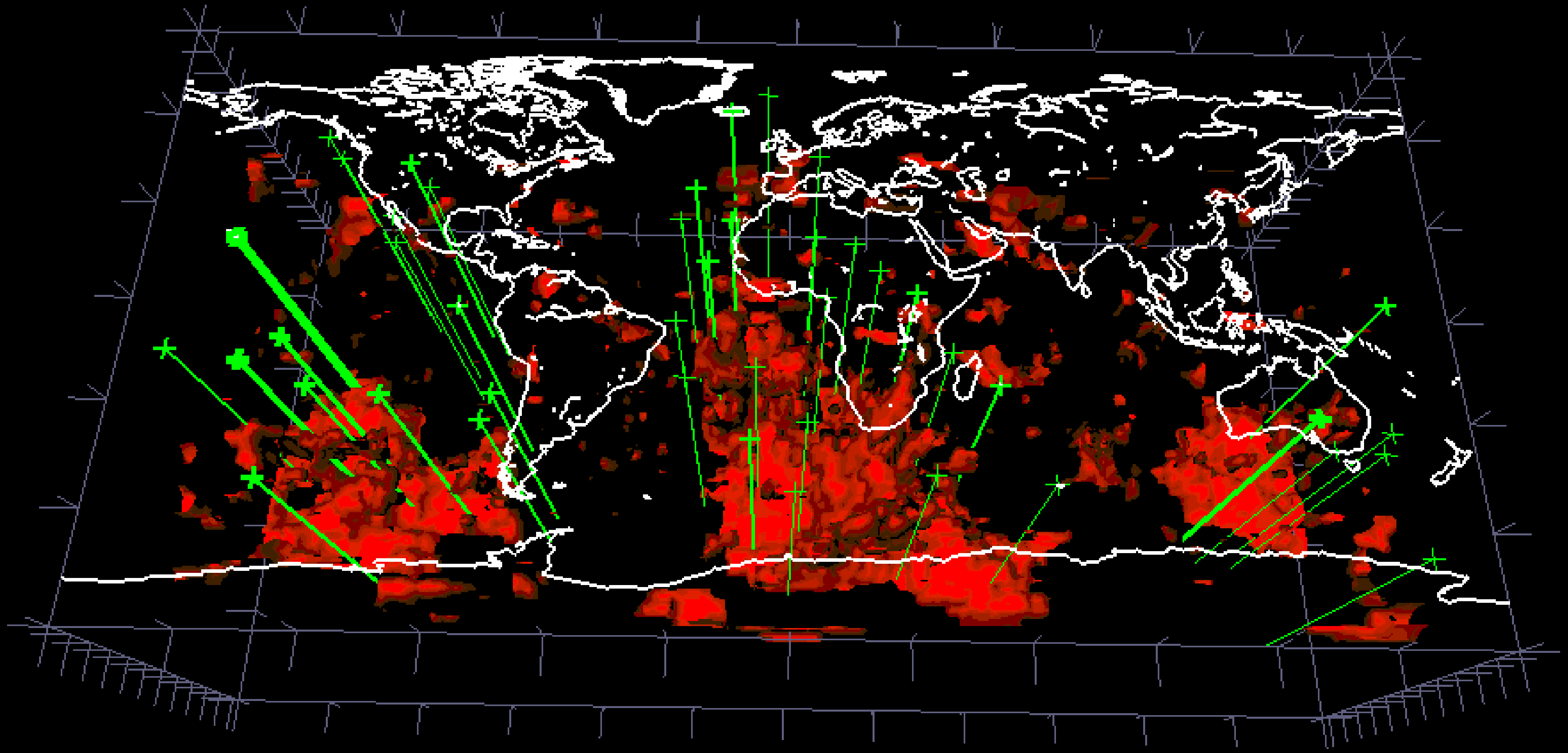


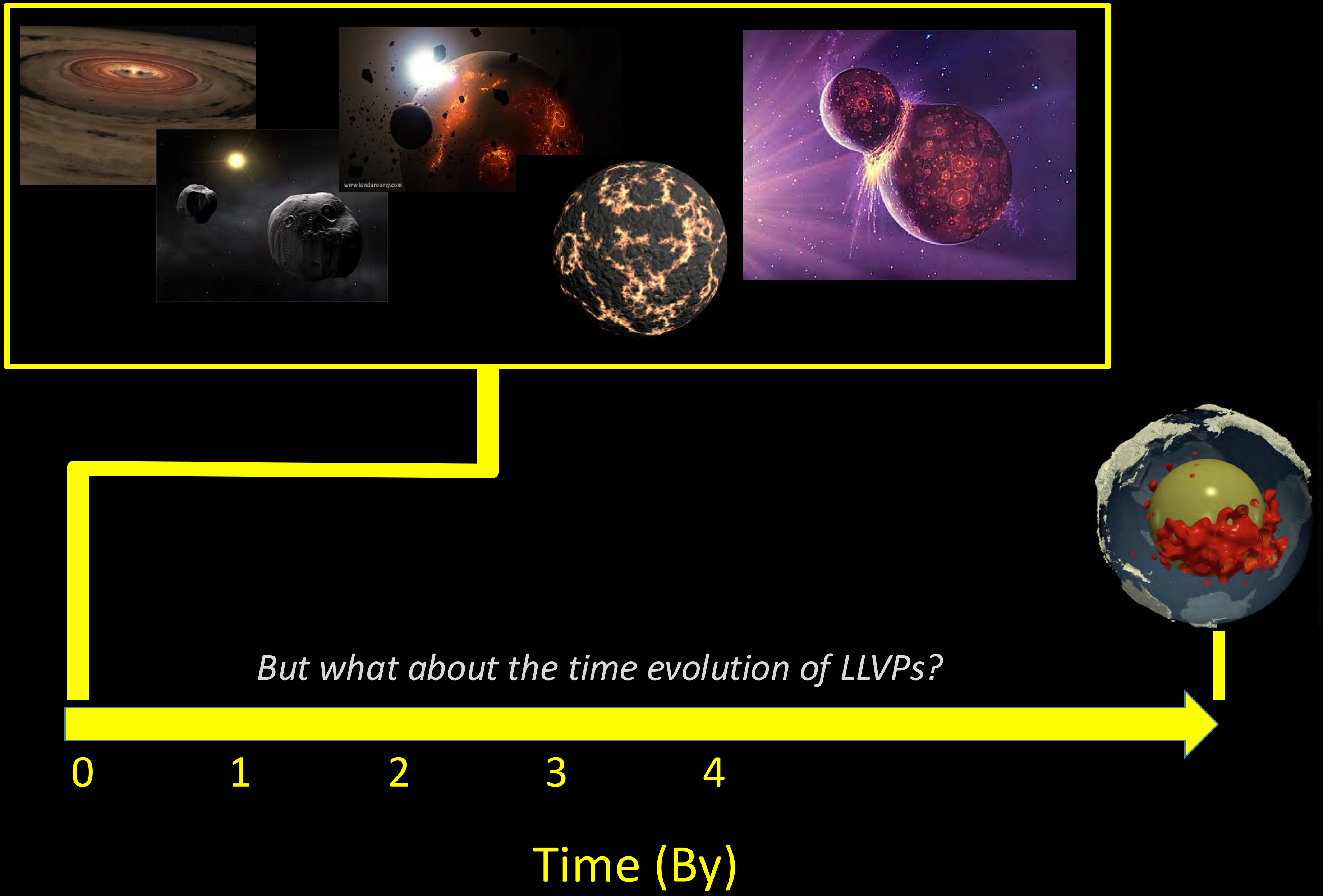
Garnero et al. (2016)

LLVP interpretations



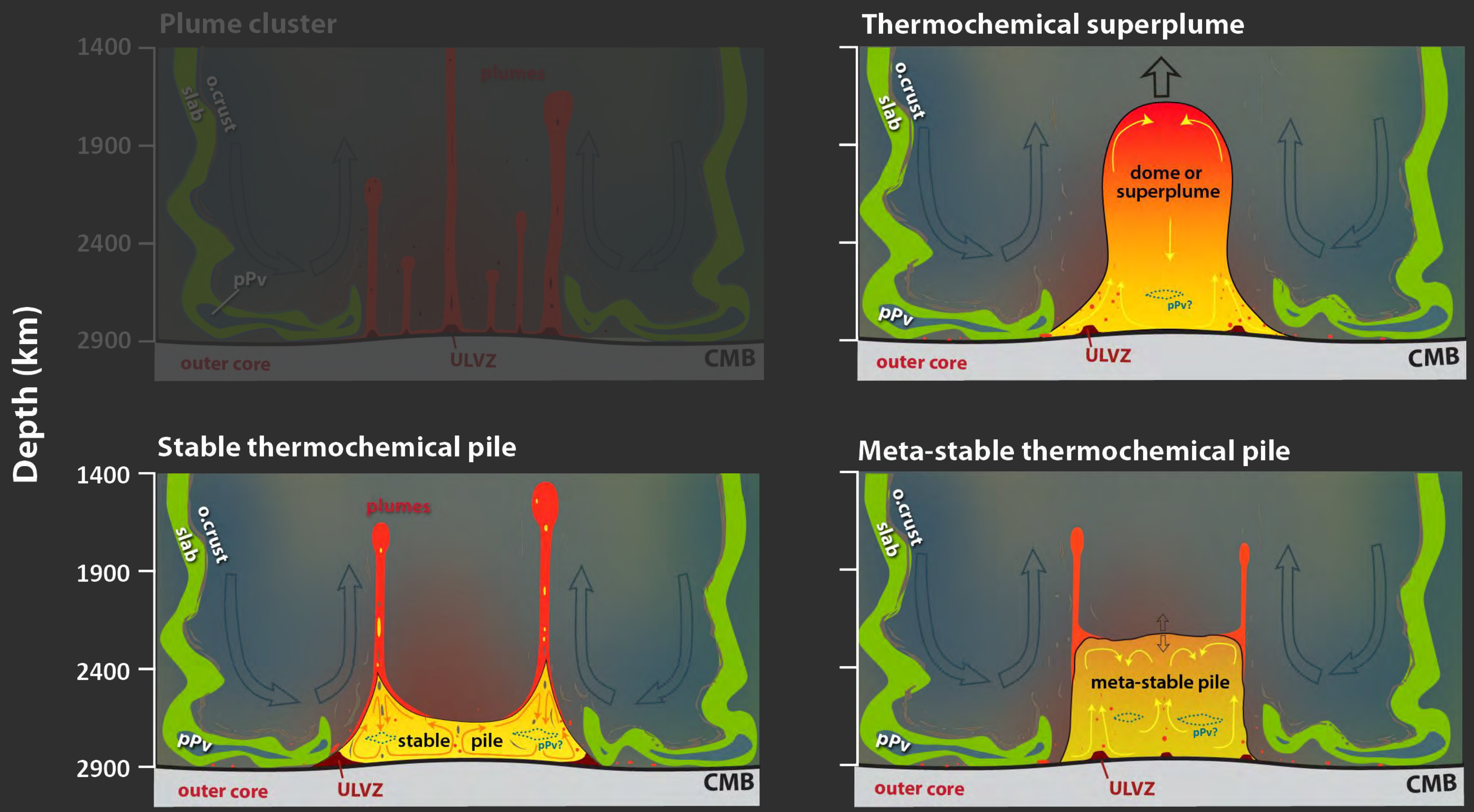
LLVP edges correlate with hotspot locations at Earth's surface



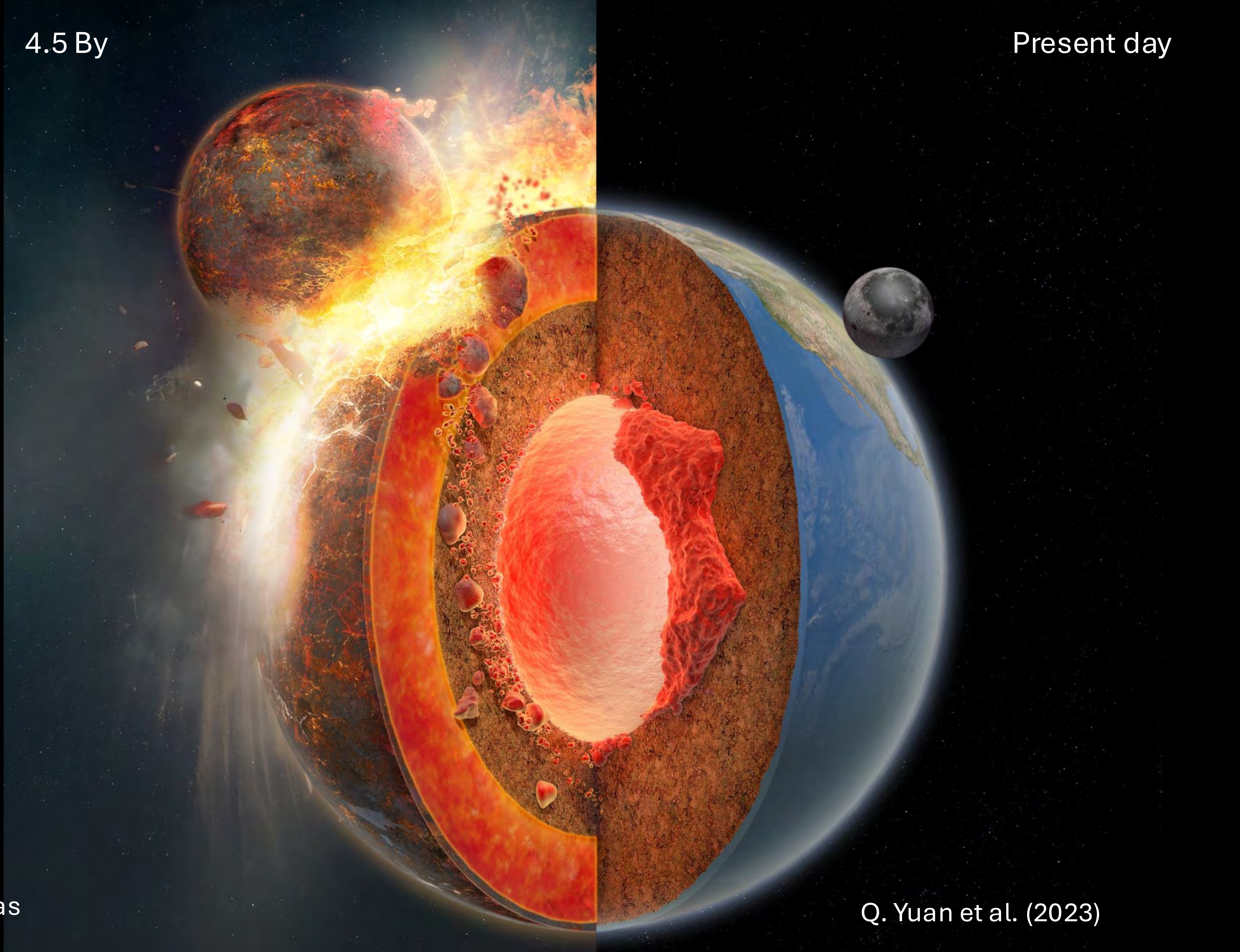


But what about the time evolution of LLVPs?
0
1
2
3
4
Time (By)

LLVP interpretations

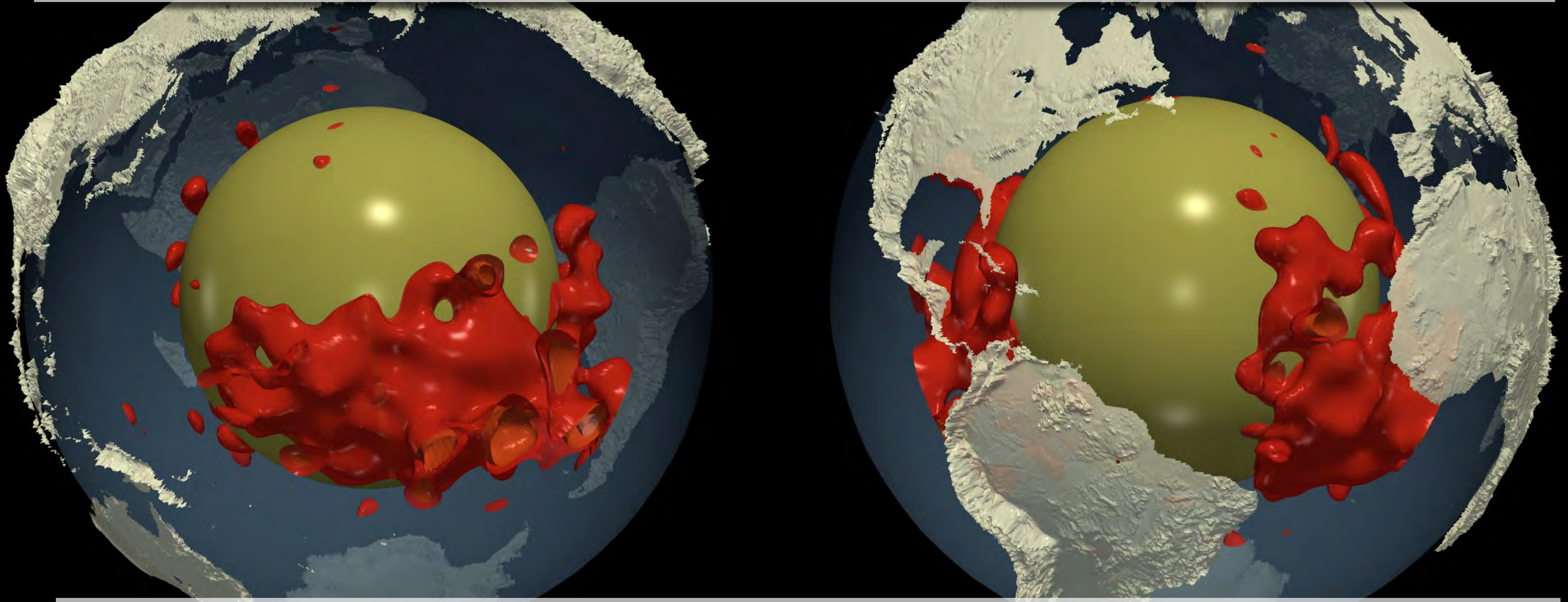


Remnants of the Moon-forming impact of Theia with proto-Earth

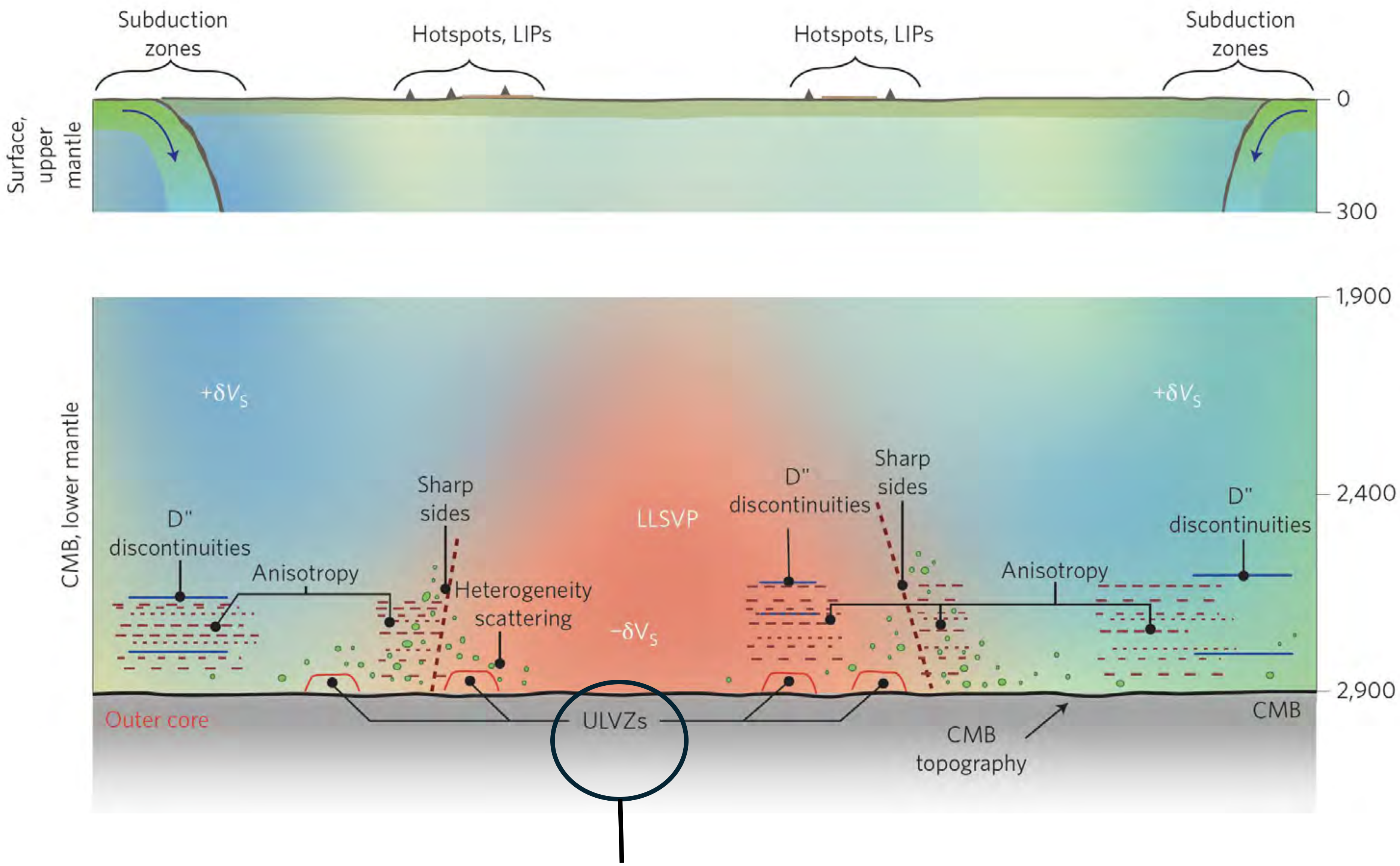


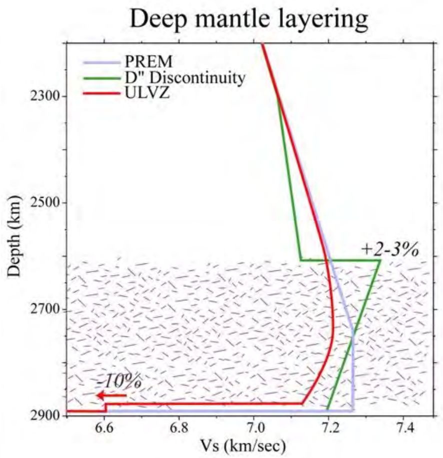
Artwork: H. Canellas

All geophysicists accept the existence of these massive structures, though discussion about their origin continues



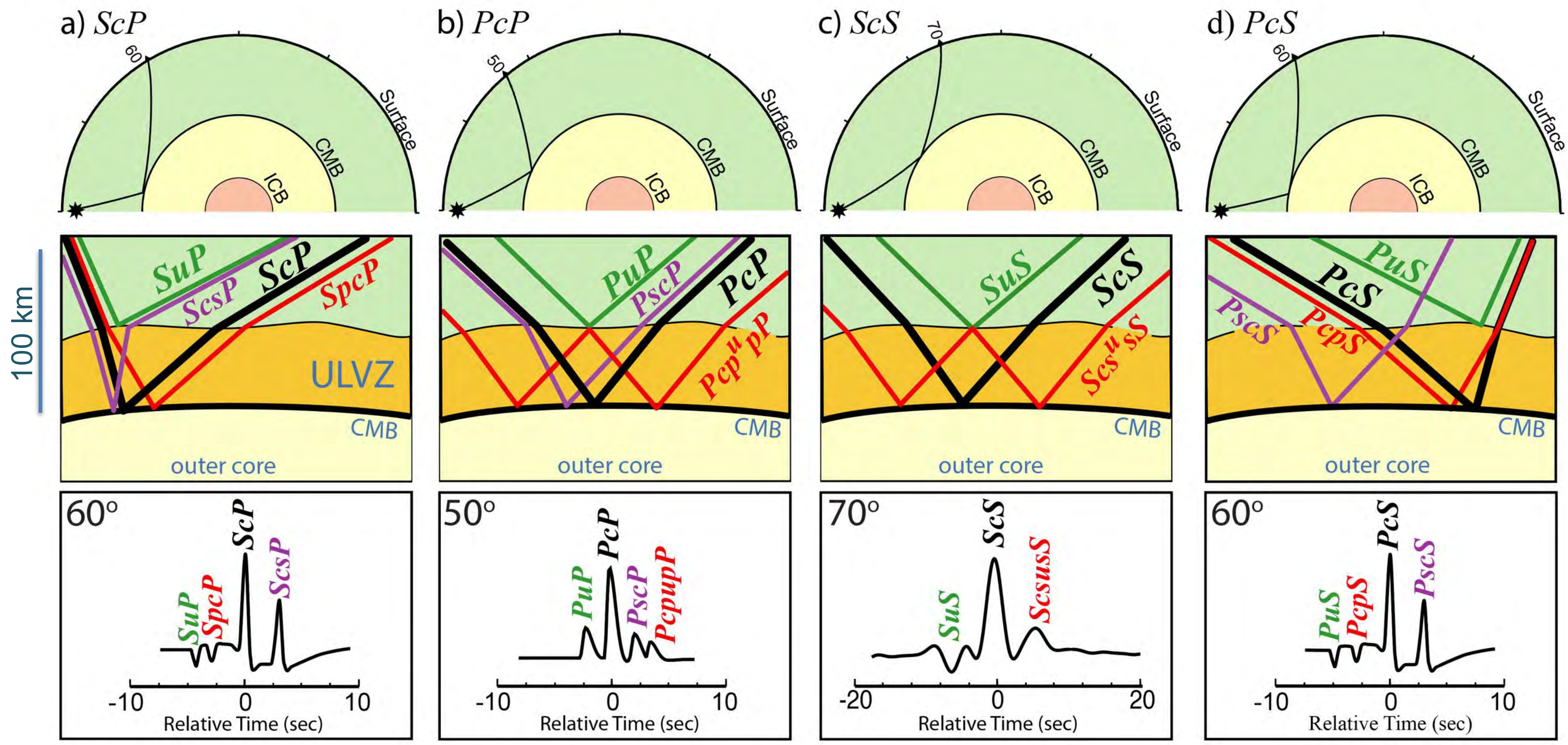
Let’s look at smaller scale things mapped by seismologists



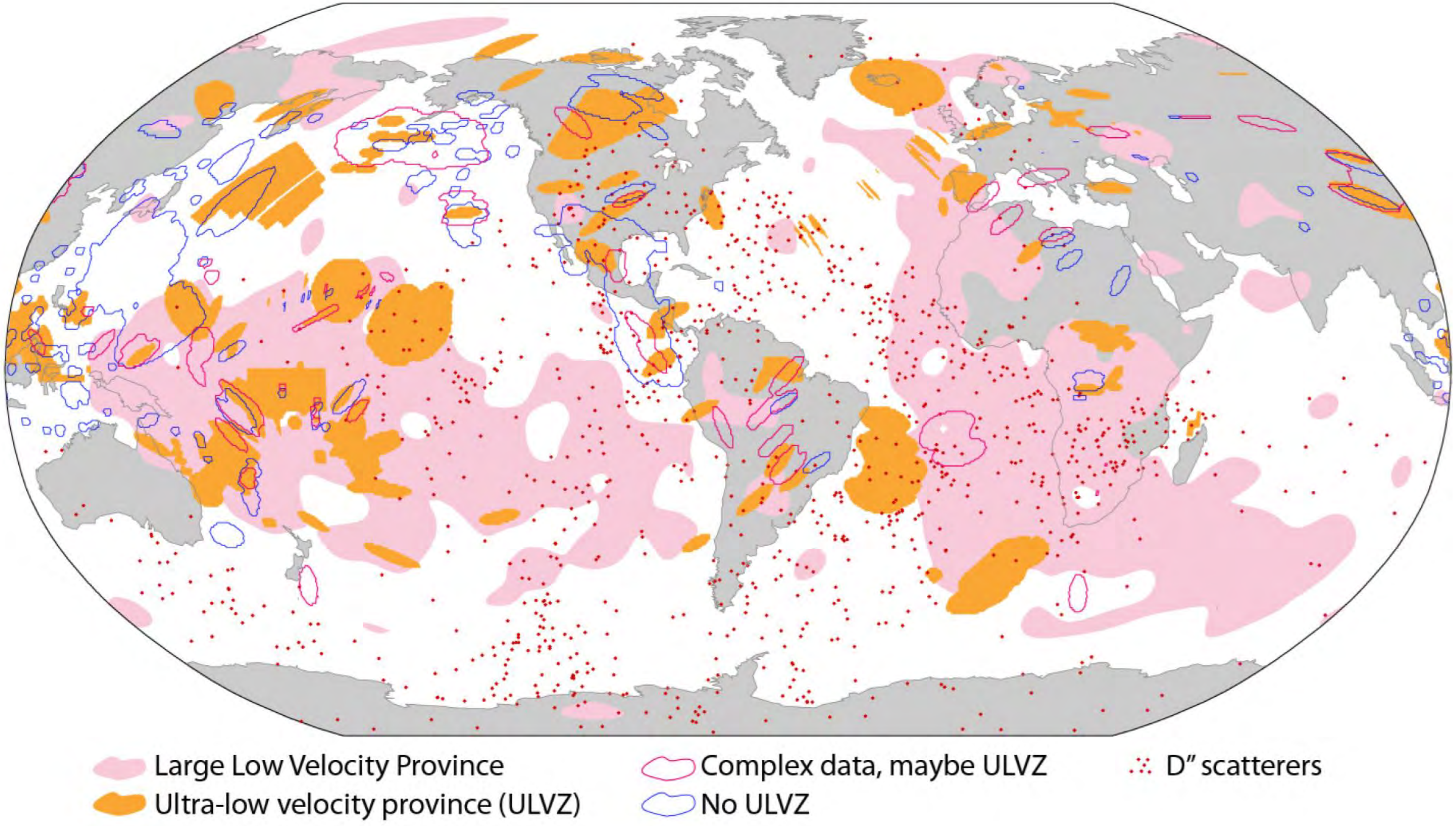


These have been imaged by unexpected pulses of seismic energy

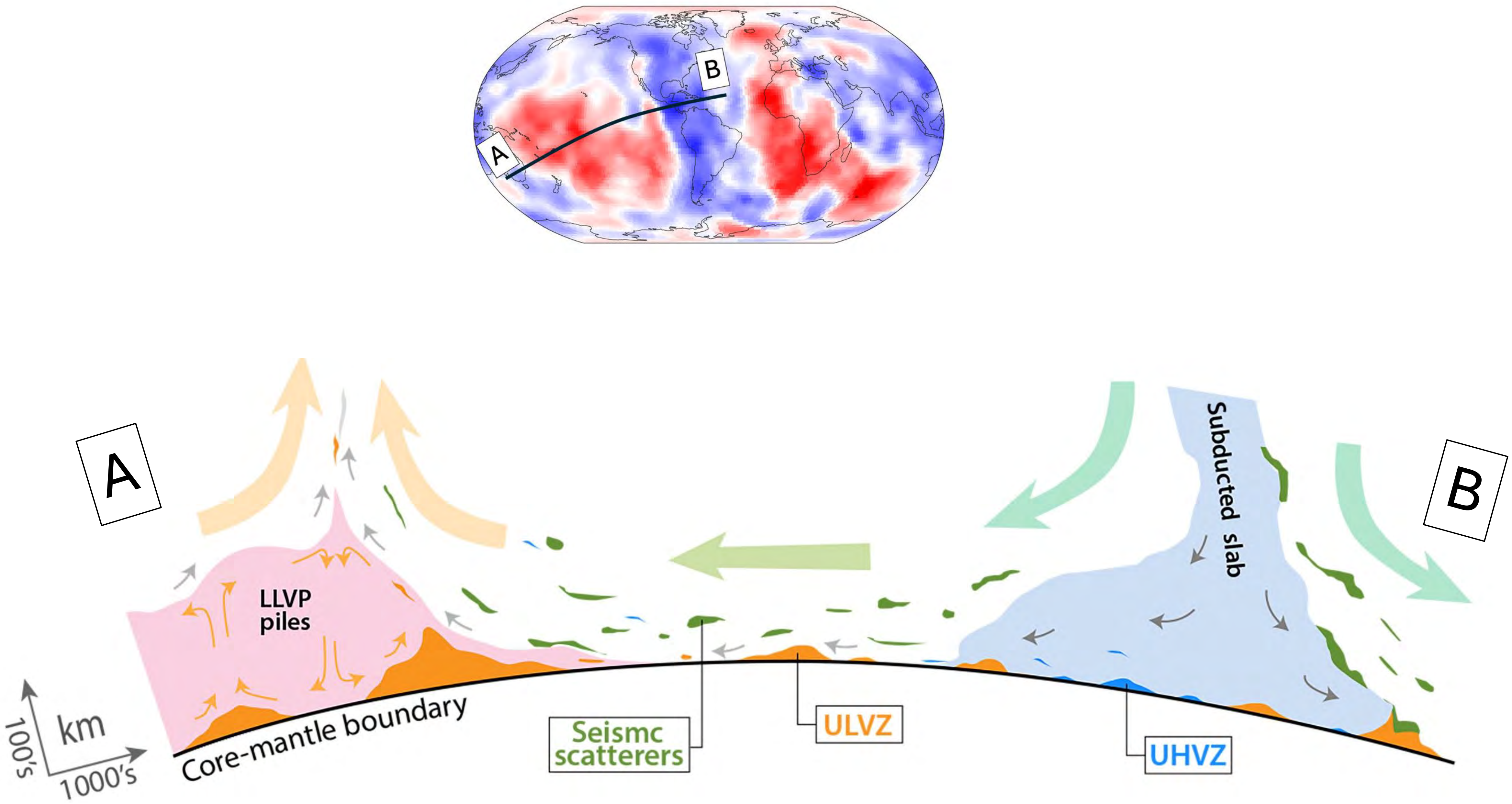
Unexpected pulses due to ULVZ structure



Phenomena at the base of Earth’s mantle



Hansen et al. Sci. Adv. 2023

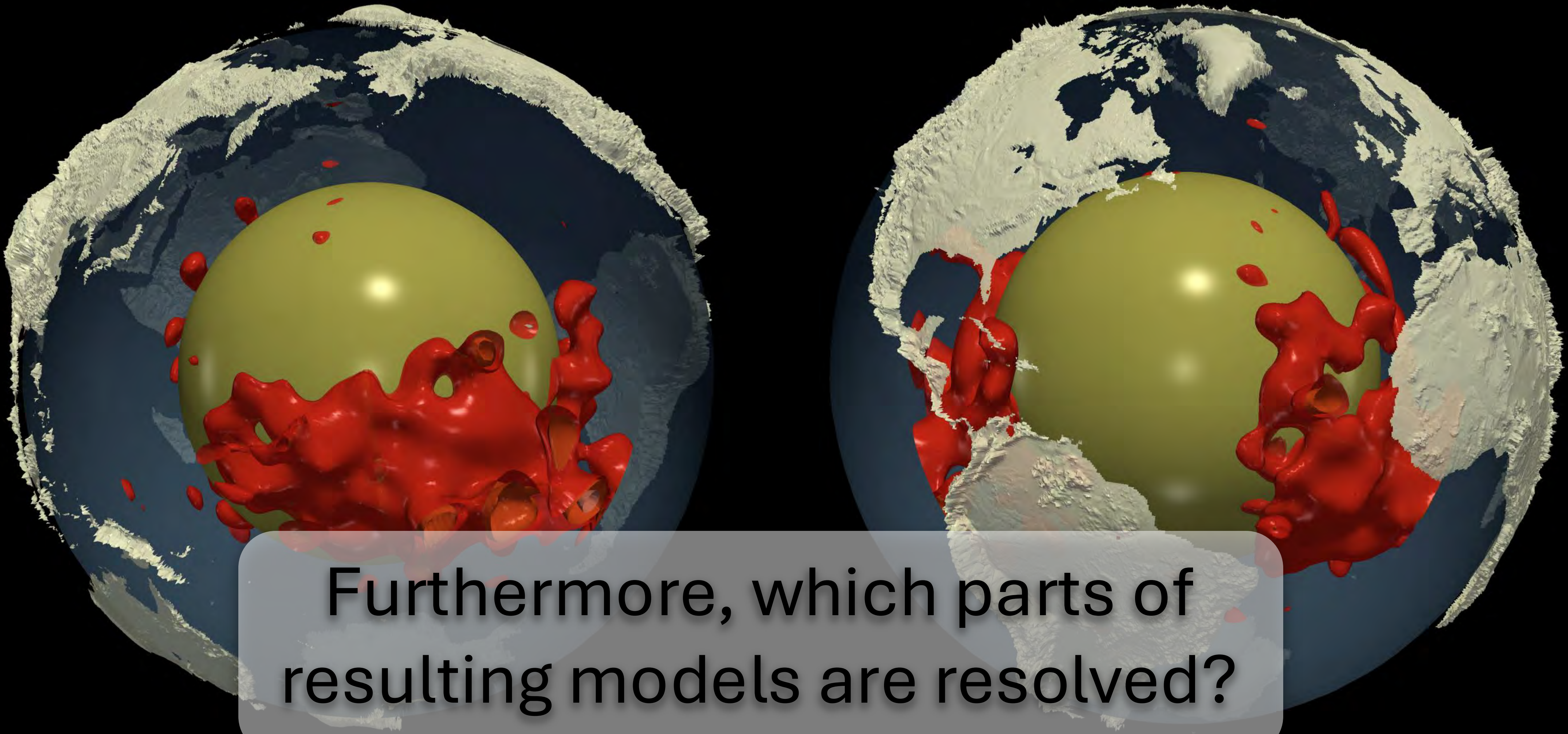


Hansen et al. (2023)

Models are only as good as their data quality and sampling coverage

So let's take a step back and ask

how well is the interior sampled by data?



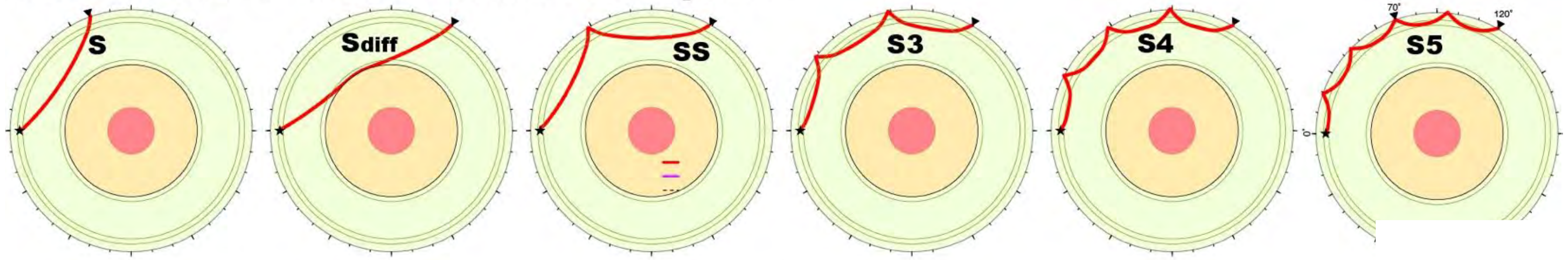
Furthermore, which parts of resulting models are resolved?

We assess Earth sampling from 3 independent travel time datasets

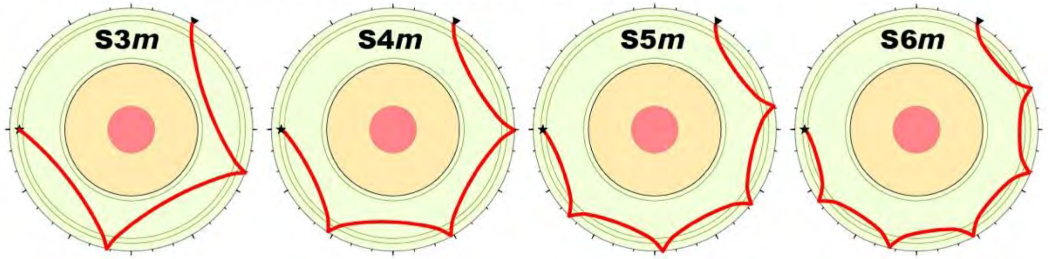
Researcher	# travel times
J. Ritsema	378,568
S. Grand	51,349
H. Lai	250,193 8,623 *(VS)*
TOTAL	**688,733**

Richardson et al (2025a, in prep)

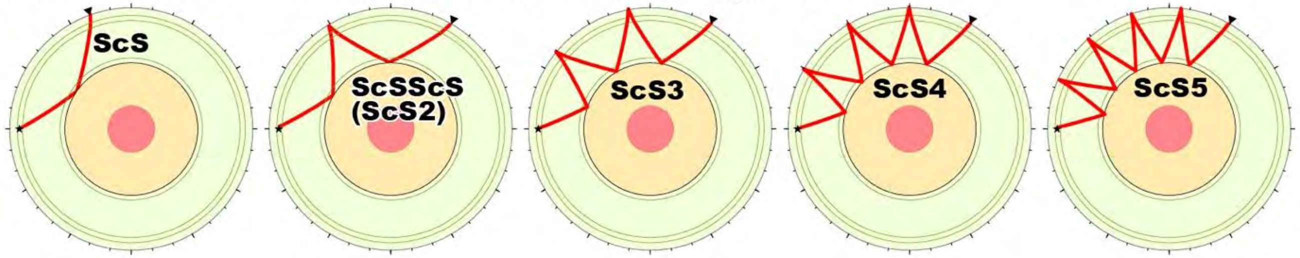
Minor arc S-waves and multiples



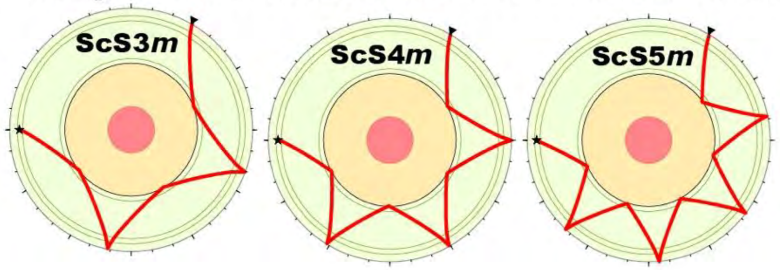
Major arc multi-bounce S-waves

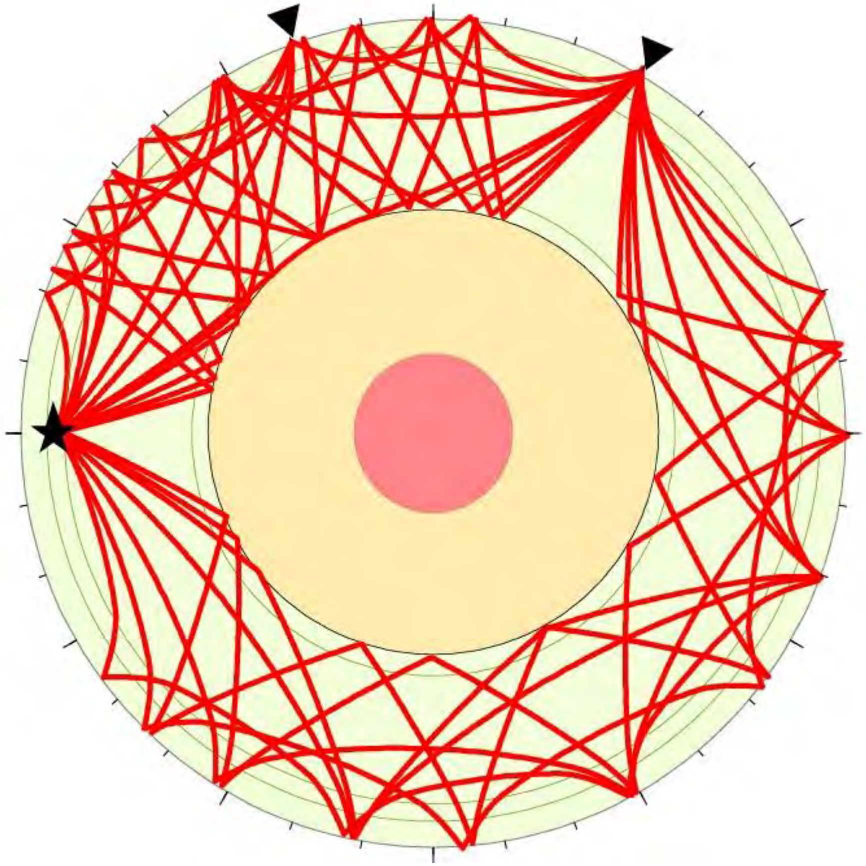


Minor arc ScS-waves and multiples

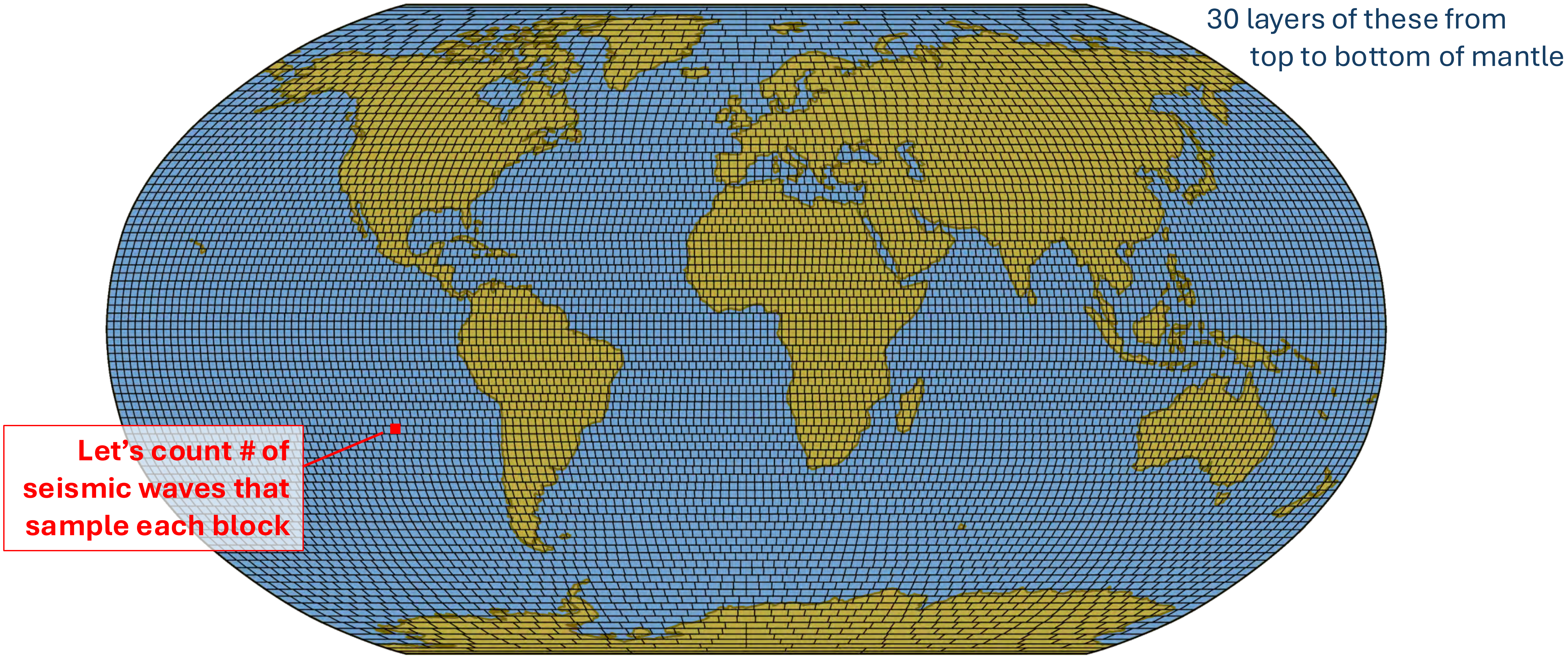


Major arc multi-bounce ScS-waves





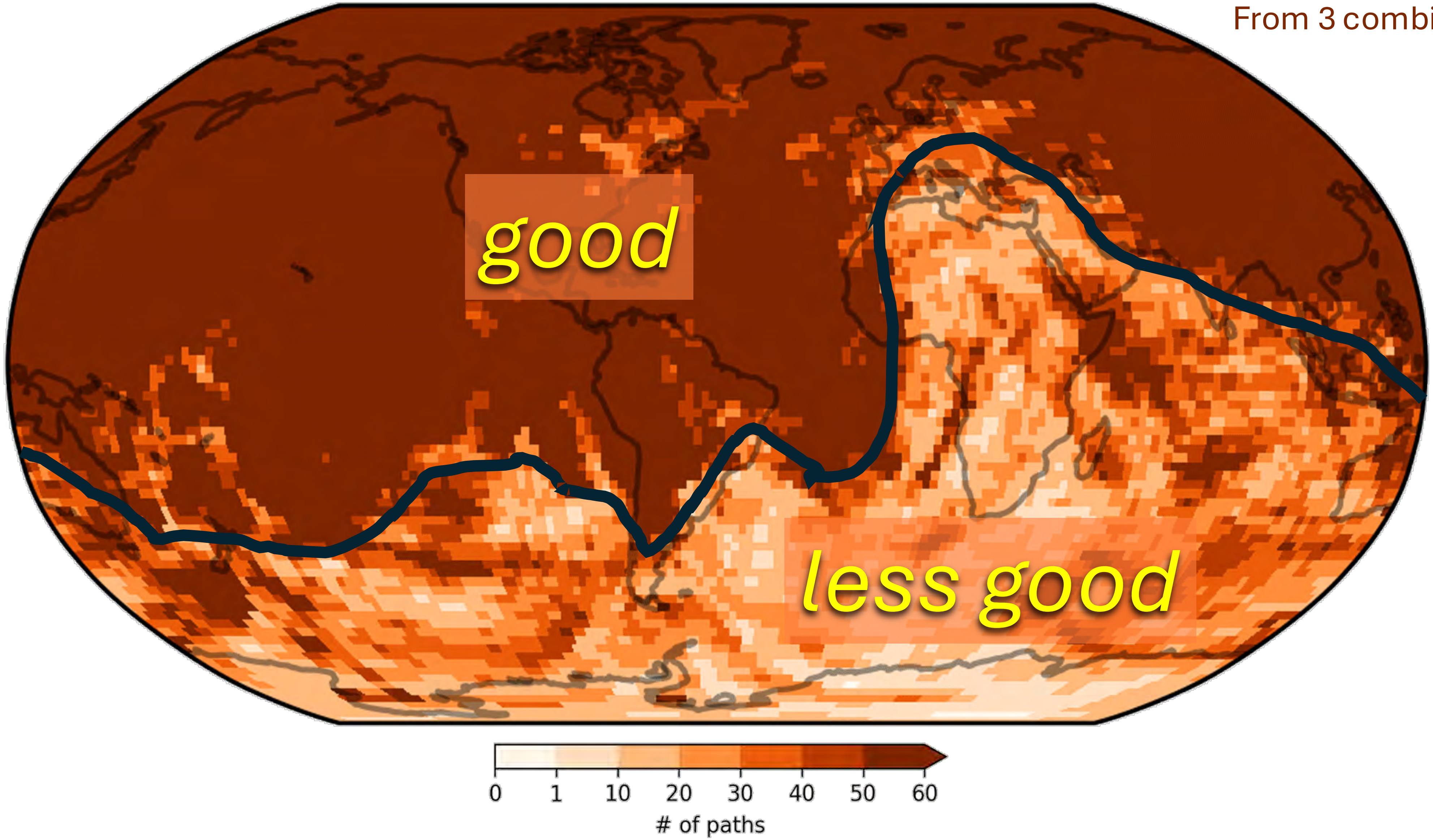
First, divide the Earth up into ~220 km^2 equal area blocks



Richardson et al (2025a, in prep)

Wave sampling in deepest 100 km of mantle

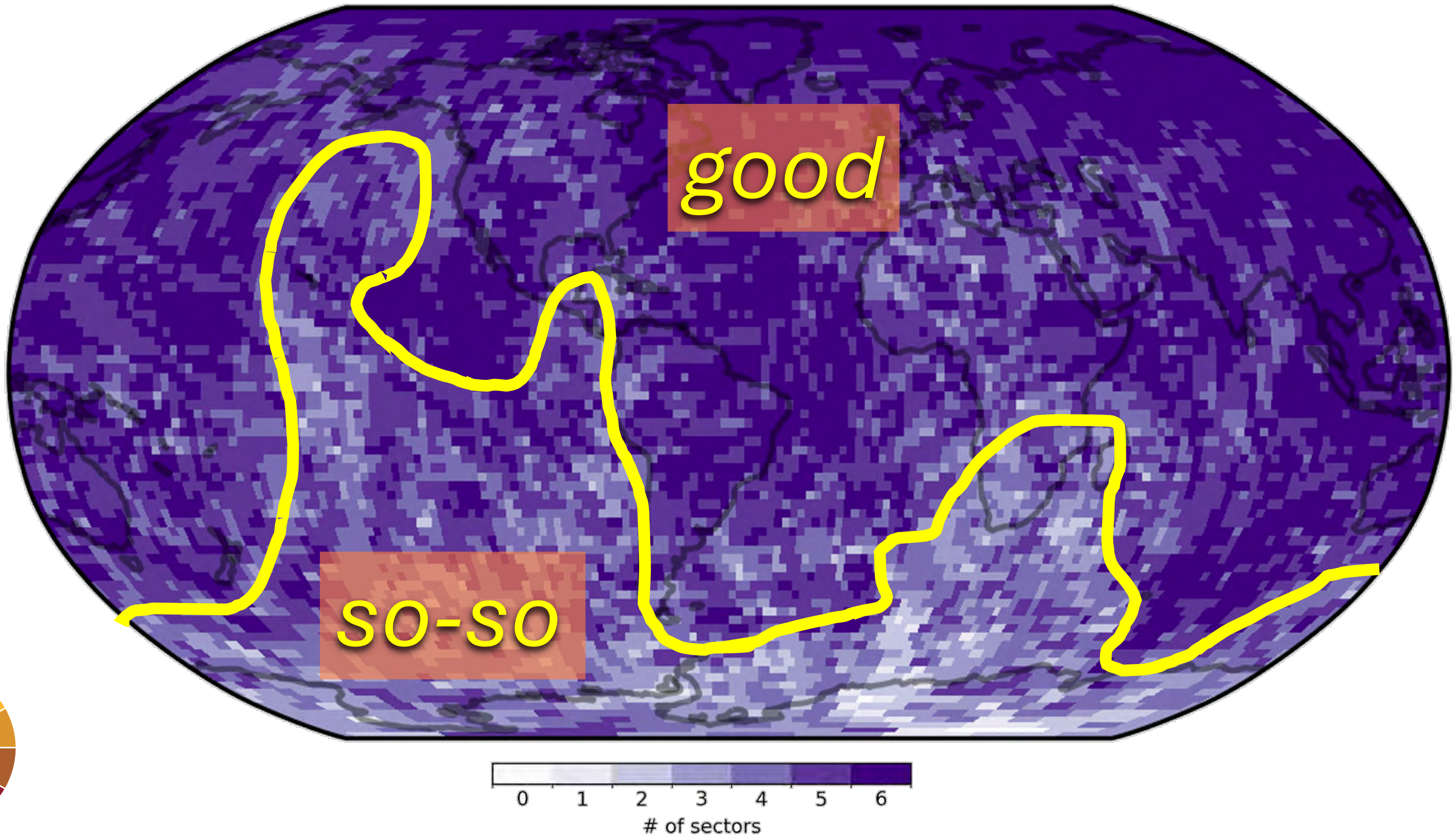
From 3 combined datasets



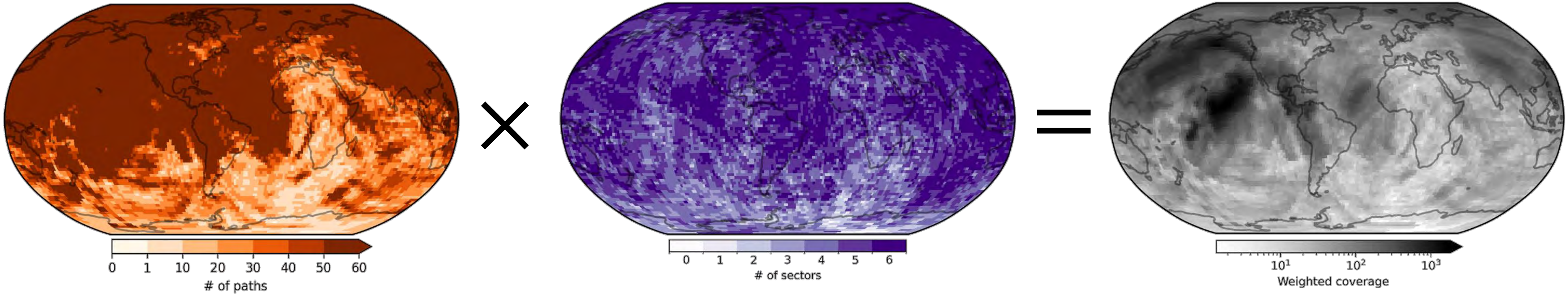
Azimuthal (directional) sampling

Block-by-block, we count how many of 6 directional sectors are sampled by wave paths from the 3 combined datasets

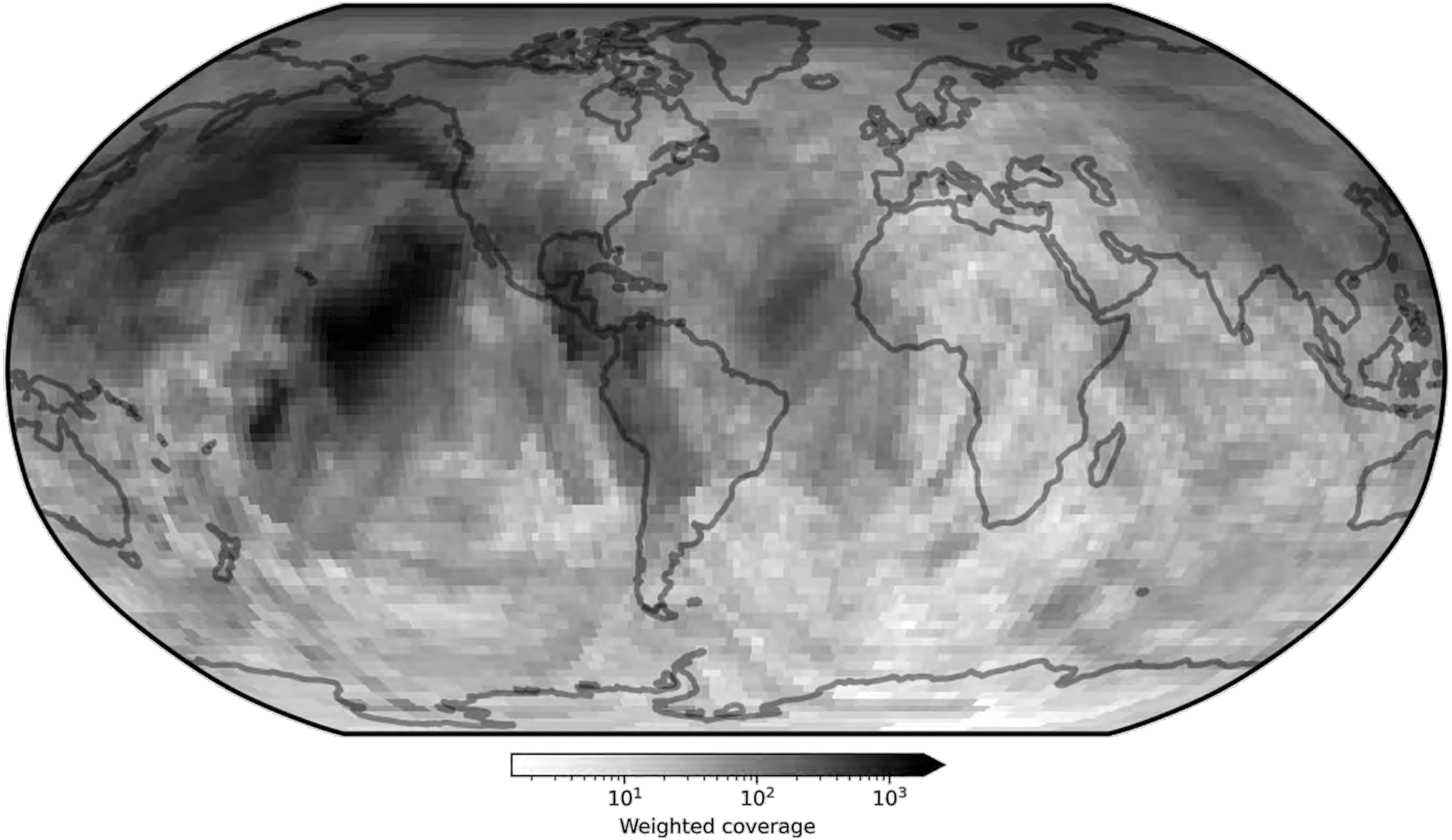
Azimuthal (directional) sampling of the deepest 100 km of mantle



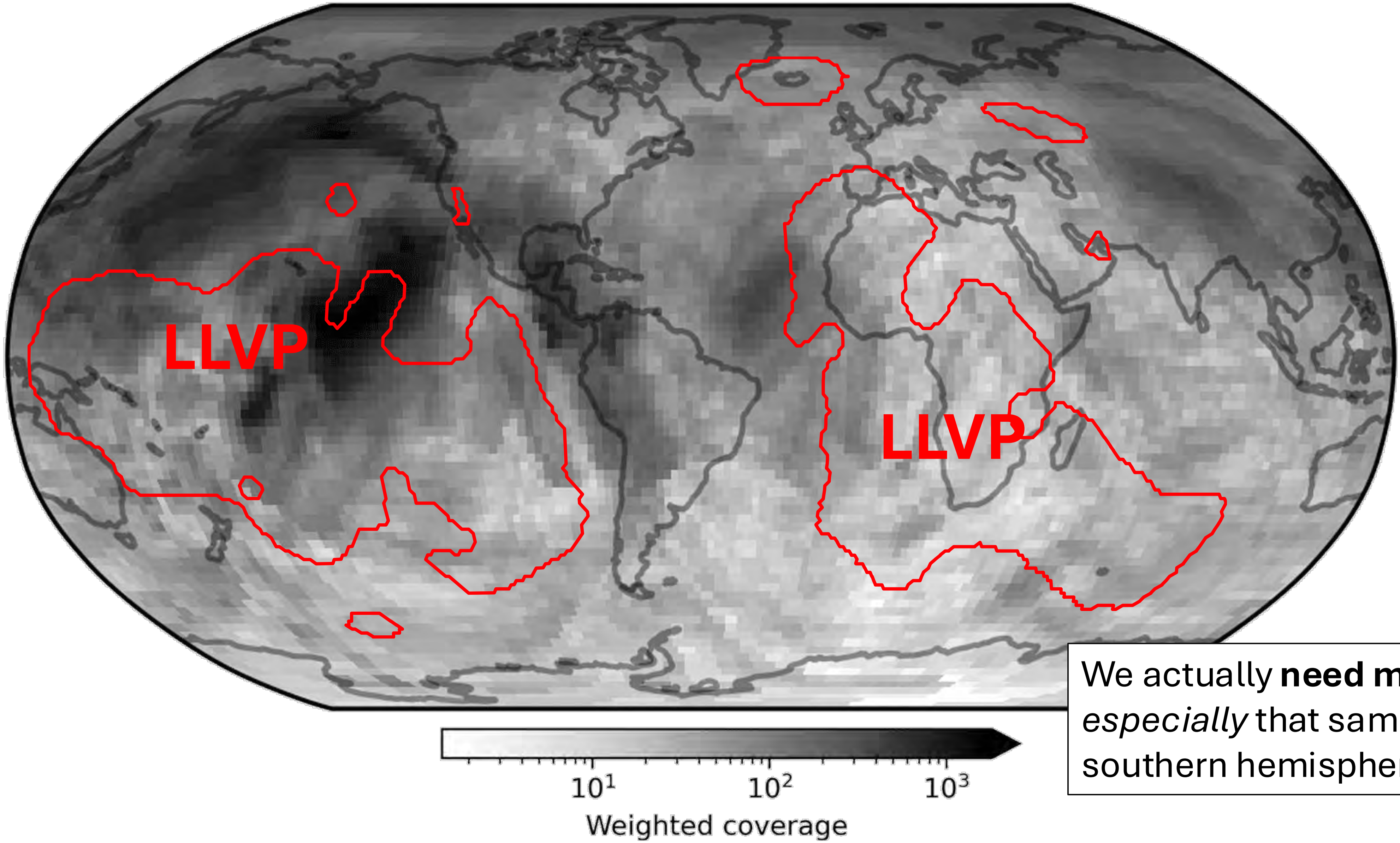
Combine path coverage measurements



Combined coverage measures



Combined coverage measures



We actually **need more data,** *especially* that samples the southern hemisphere

We experiment by "updating" tomography models using these data

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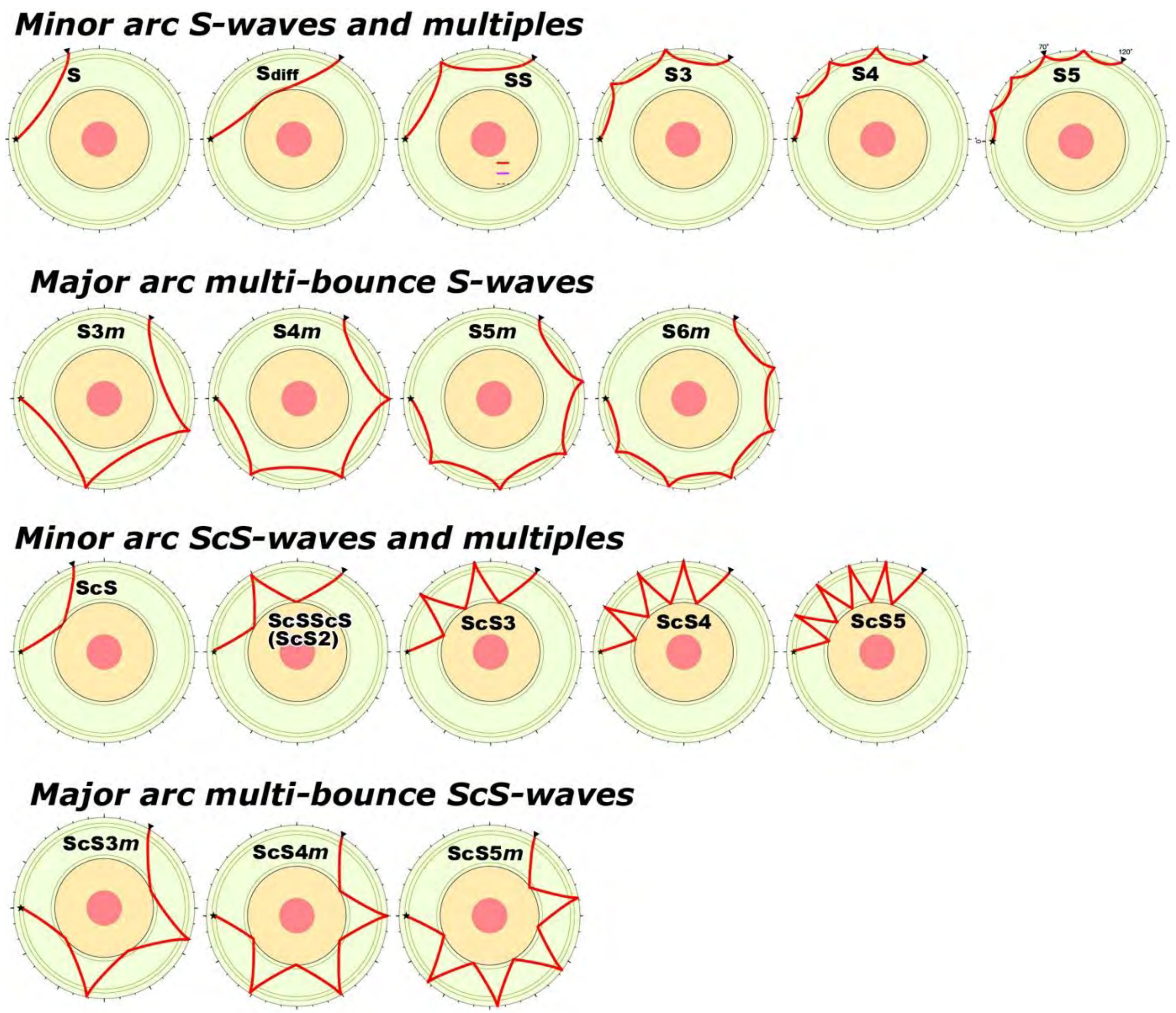
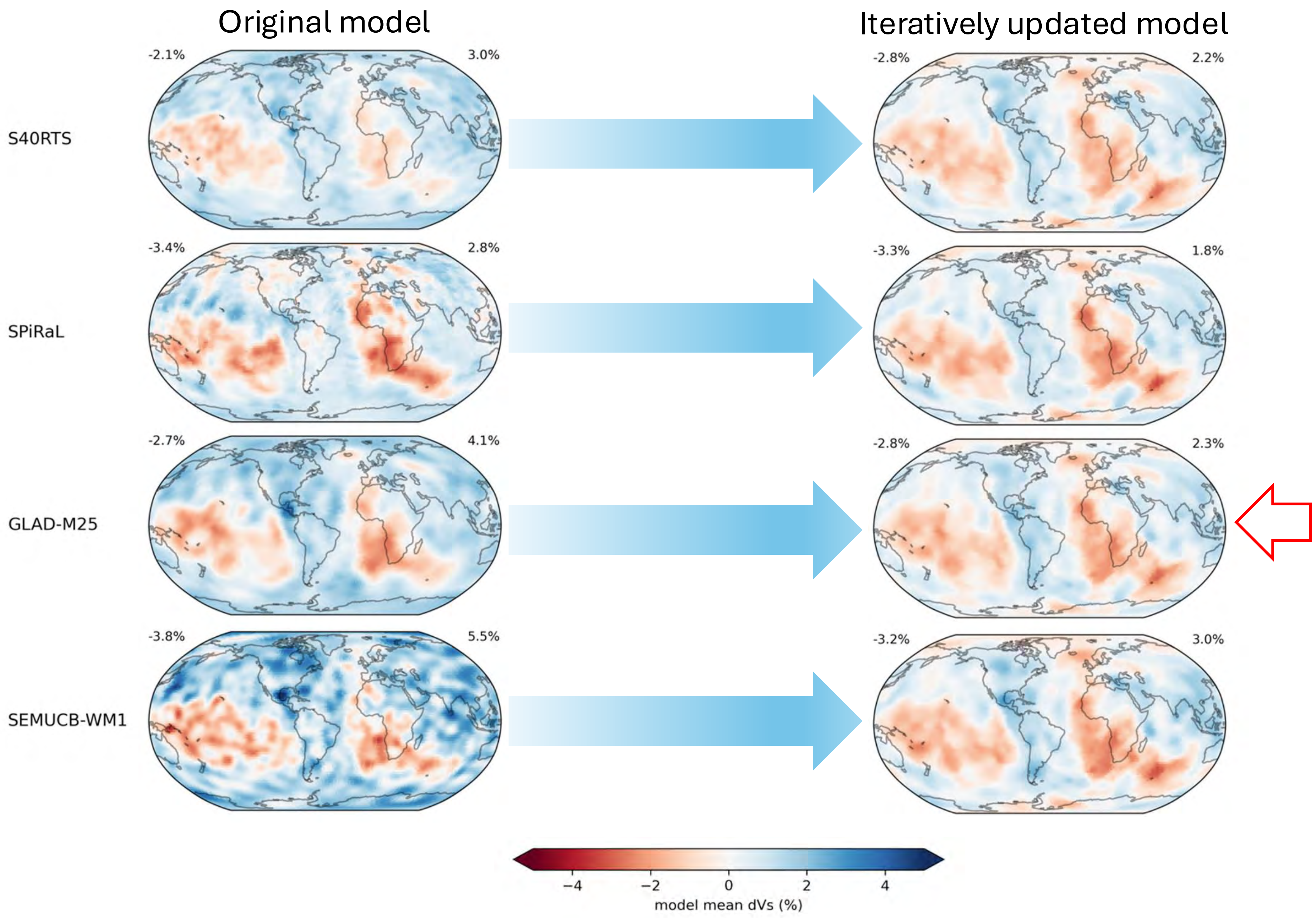
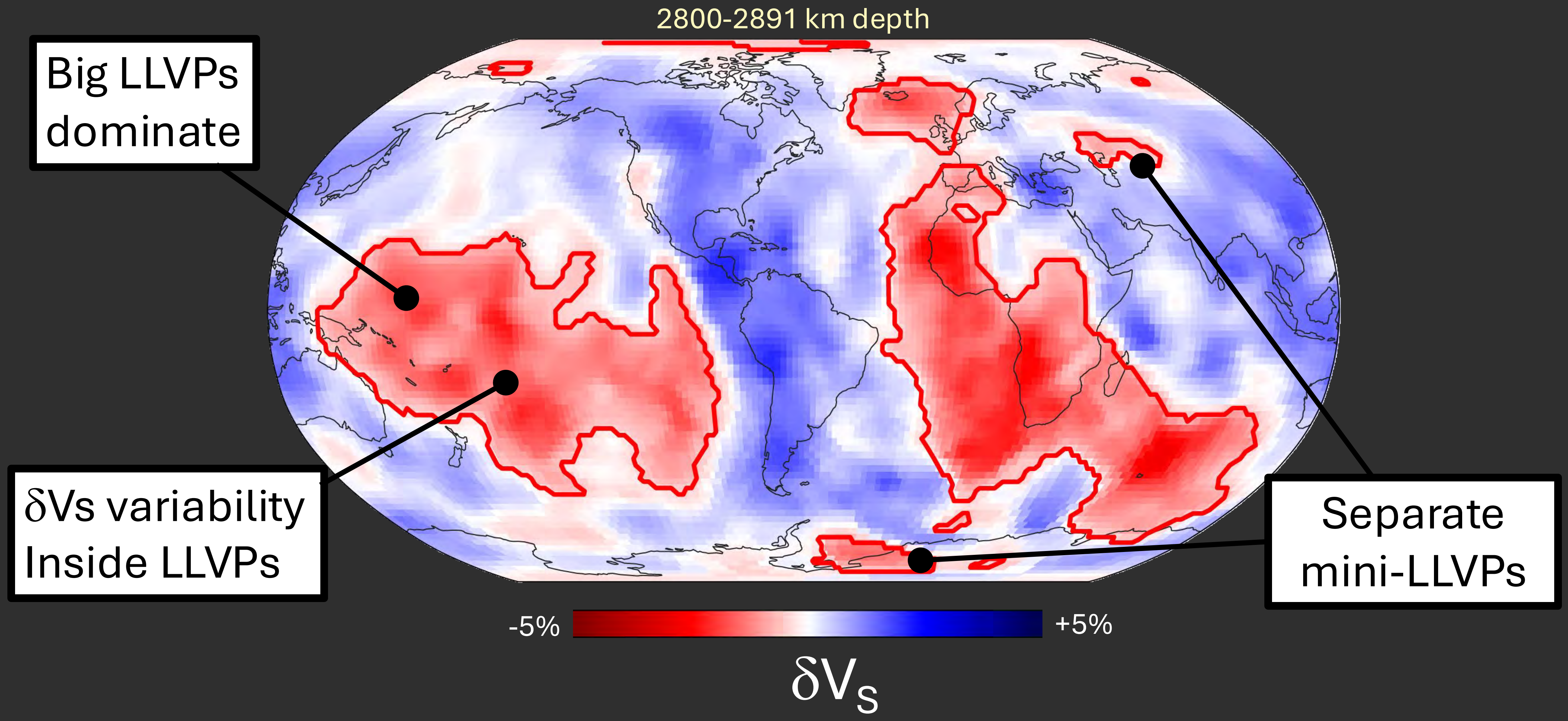




C.Richardson (in prep, 2025)

Updated S wave velocity model



***UPDATED MODEL**: GLAD-M25 (Lei et al., 2020)*

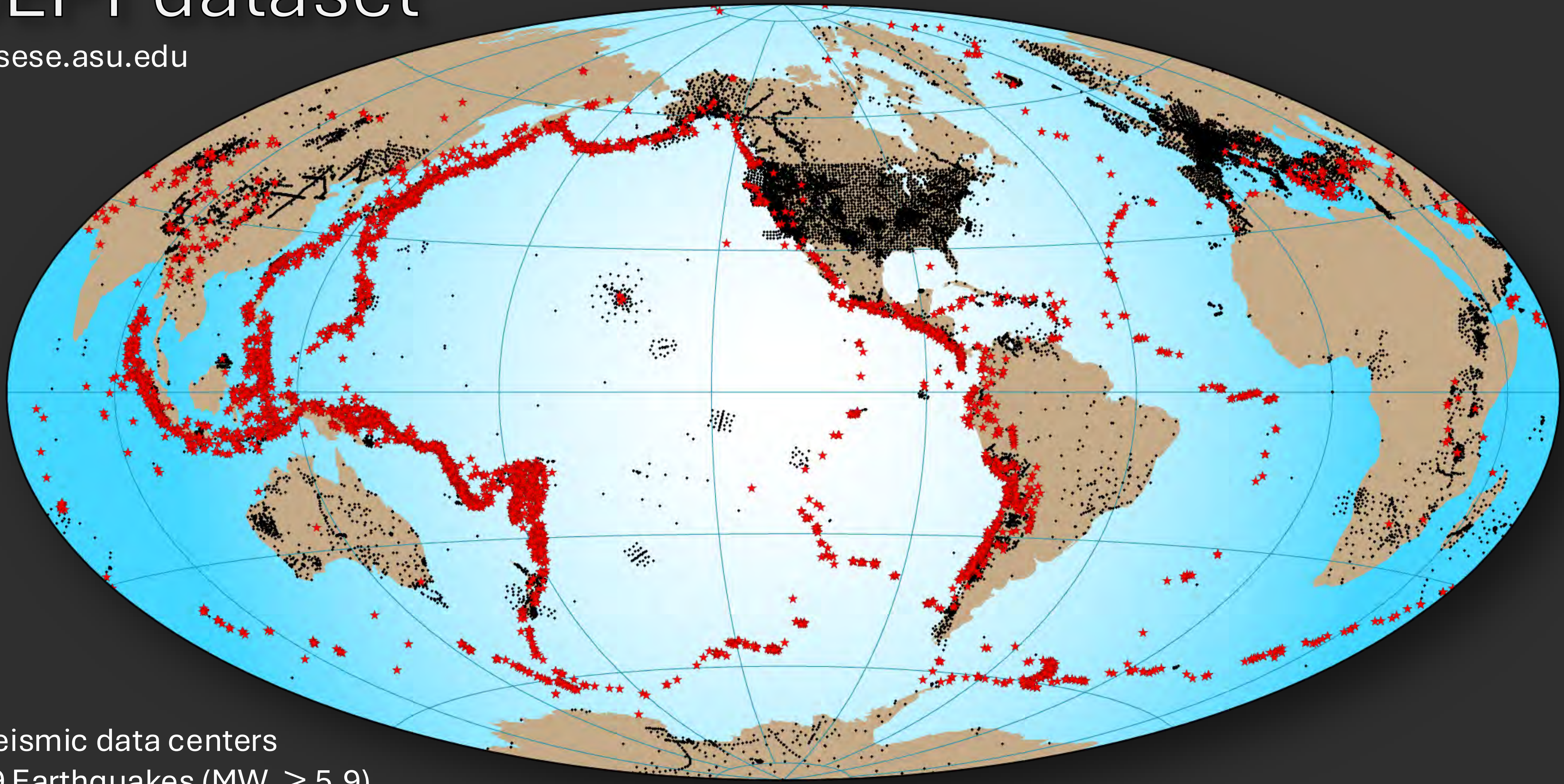
Now what?

Can we improve sampling of Earth's interior?

YES

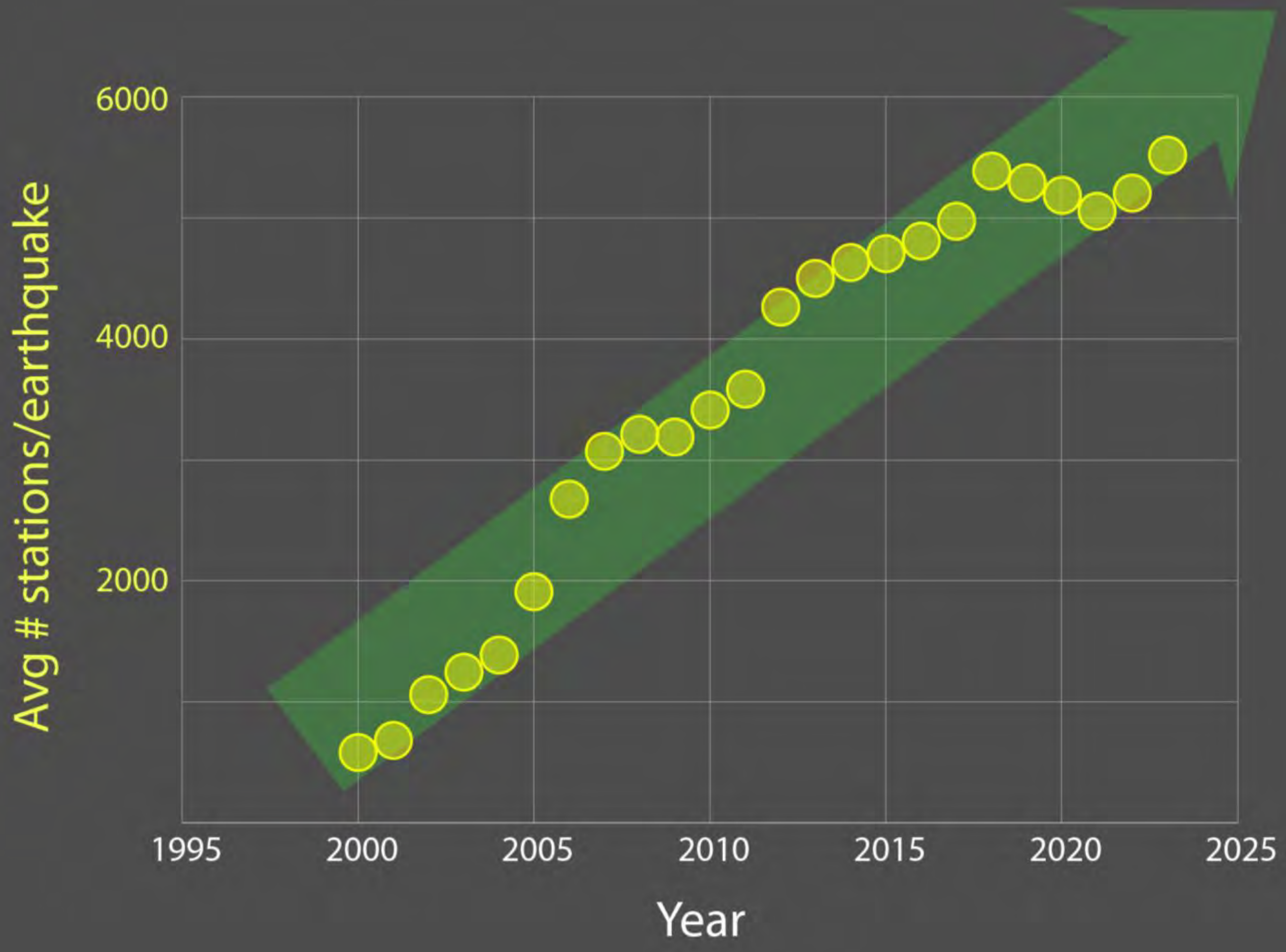
ADEPT dataset

adept.sese.asu.edu



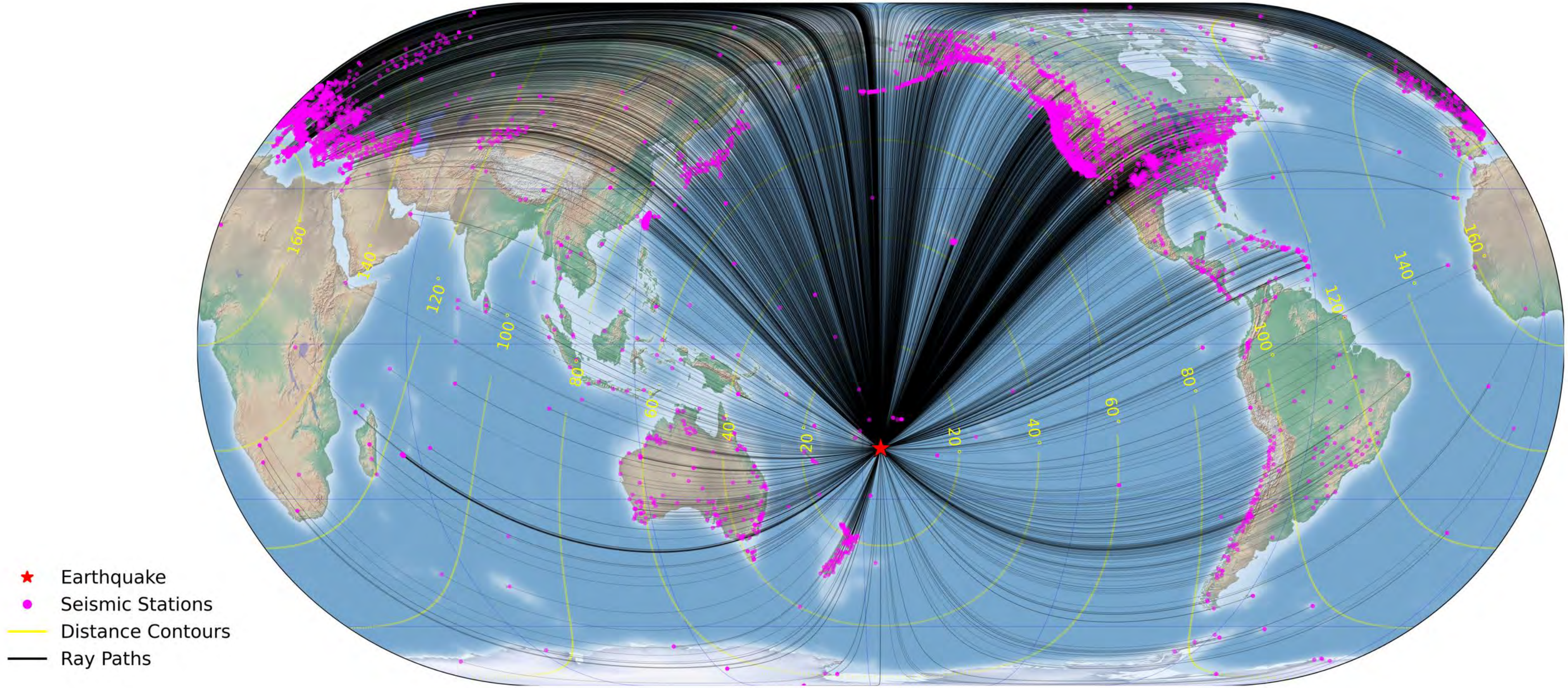
24 seismic data centers
5709 Earthquakes (MW $\geq$ 5.9)
24521 Stations (3-comp broadband)
~50,000,000 seismograms (and counting...)

J. Wolf et al. (2025, in rev.)

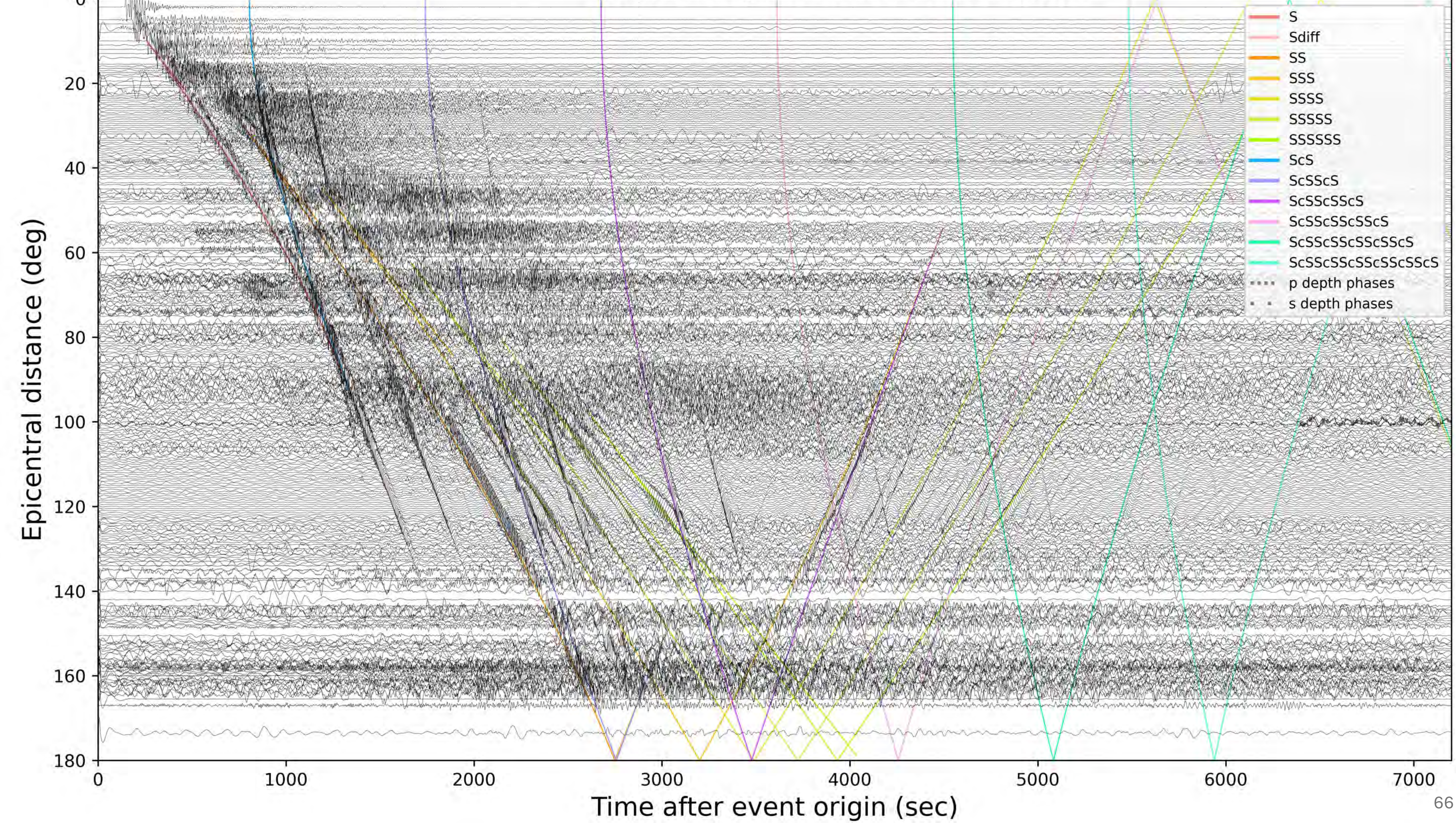


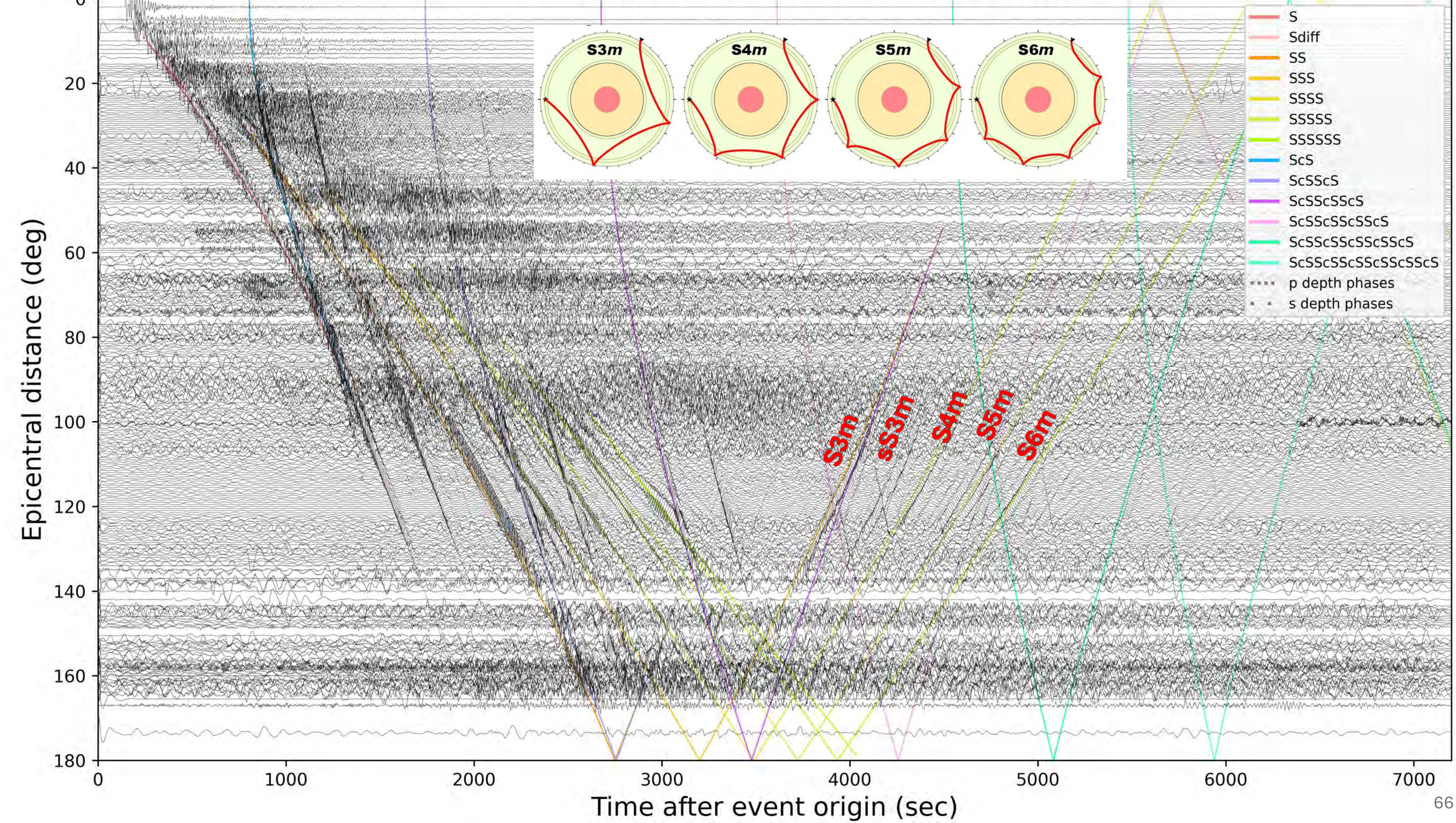
Avg # stations/earthquake
6000
4000
2000
1995
2000
2005
2010
2015
2020
2025
Year

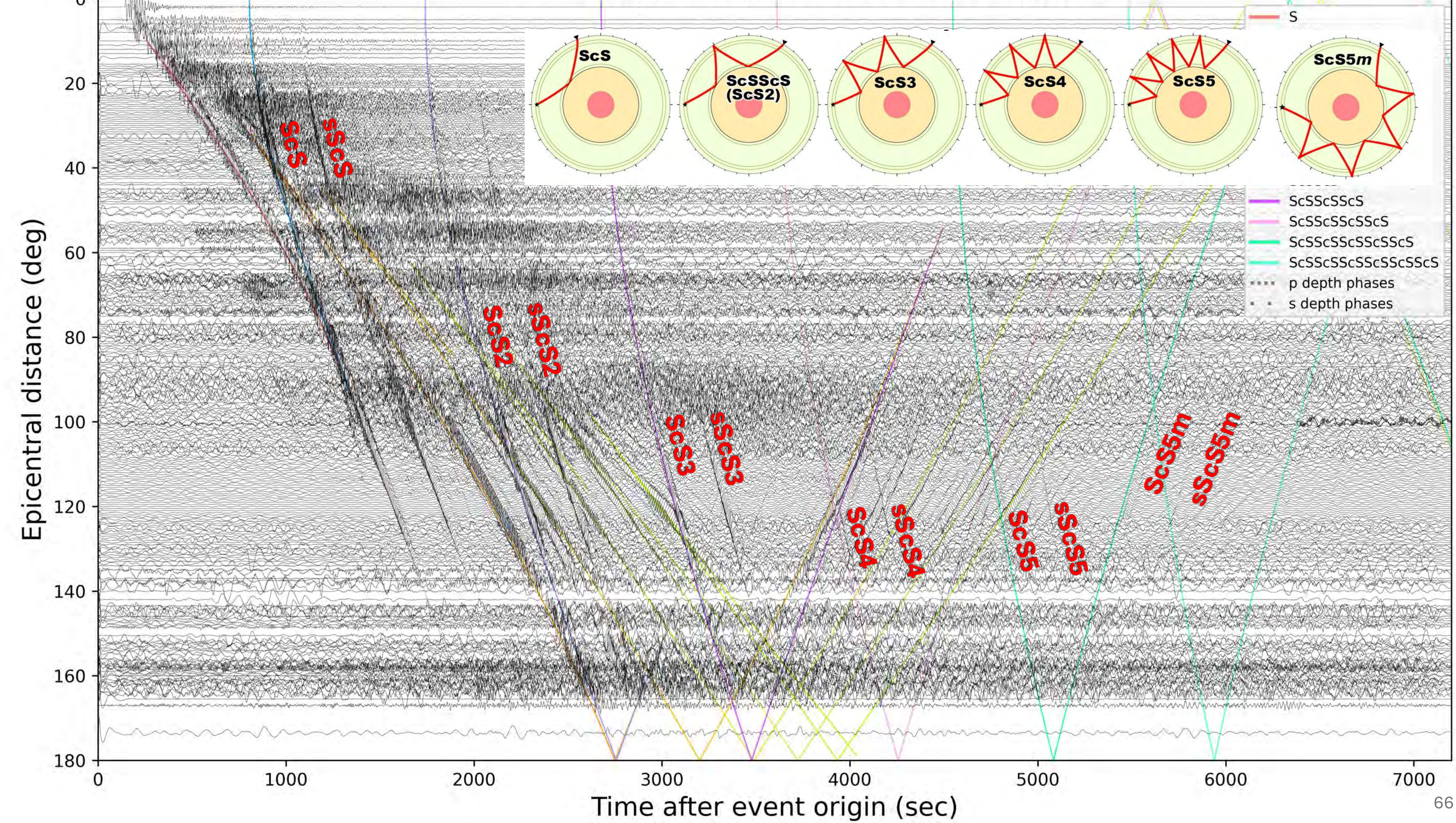
Event 202408252329   M6.9   5182 stations
75 km W of Pangai, Tonga
Lat=-19.8125 Lon=-175.0711 Depth=96 km
Azimuth 0.0-360.0, Distance 0.0-180.0



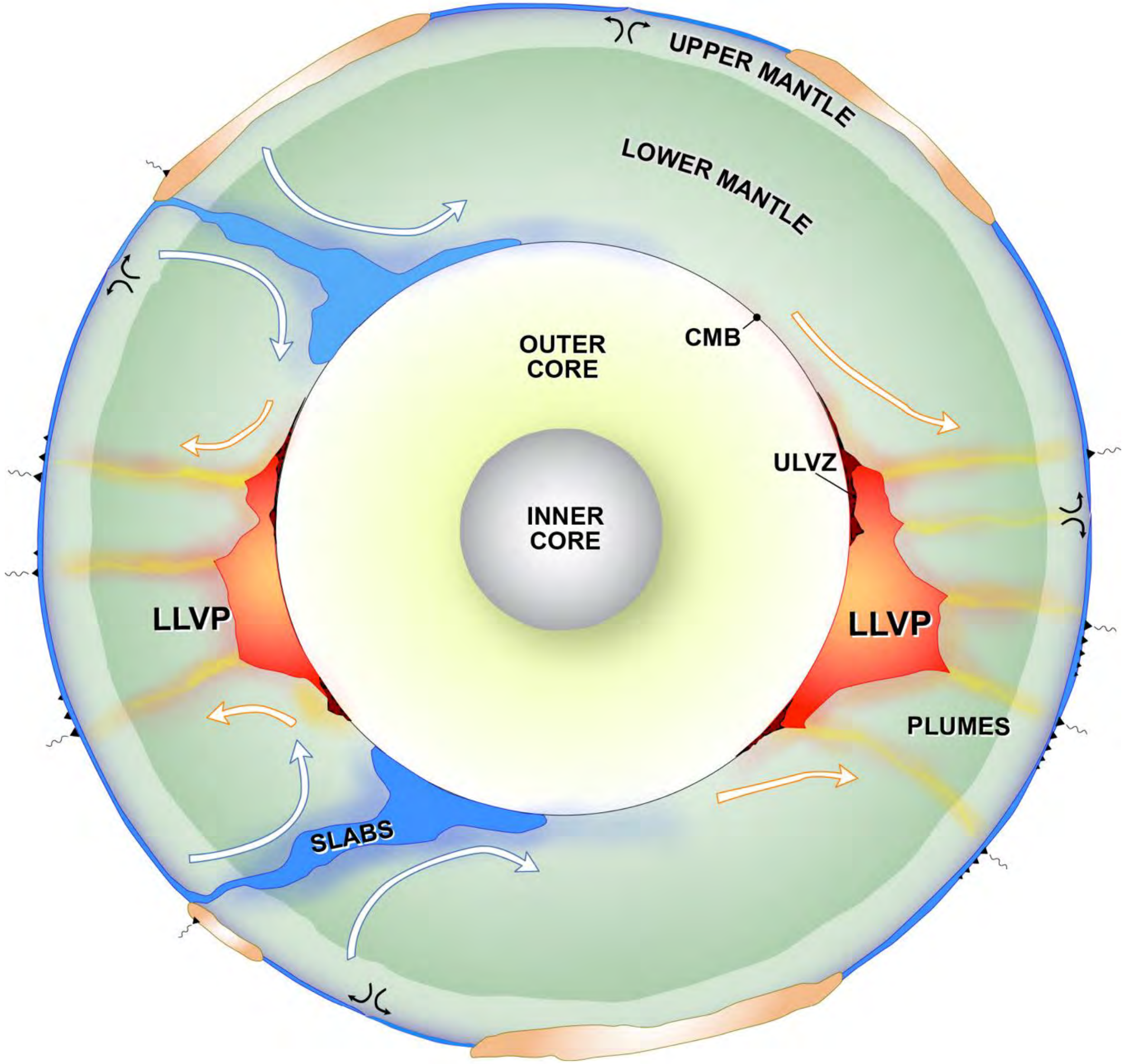
Plotted 11/23/24 by JD West at ASU SWAT project


S
Sdiff
SS
SSS
SSSS
SSSSS
SSSSSS
ScS
ScSScS
ScSScSScS
ScSScSScSScS
ScSScSScSScSScS
ScSScSScSScSScSScS
p depth phases
s depth phases
Epicentral distance (deg)
Time after event origin (sec)
0
20
40
60
80
100
120
140
160
180
0
1000
2000
3000
4000
5000
6000
7000


S3m
S4m
S5m
S6m
S
Sdiff
SS
SSS
SSSS
SSSSS
SSSSSS
ScS
ScSScS
ScSScSScS
ScSScSScSScS
ScSScSScSScSScS
ScSScSScSScSScSScS
p depth phases
s depth phases
S3m
sS3m
S4m
S5m
S6m
Epicentral distance (deg)
Time after event origin (sec)


ScS
ScSScS (ScS2)
ScS3
ScS4
ScS5
ScS5m
S
ScSScSScS
ScSScSScSScS
ScSScSScSScSScS
ScSScSScSScSScSScS
p depth phases
s depth phases
ScS
sScS
ScS2
sScS2
ScS3
sScS3
ScS4
sScS4
ScS5
sScS5
ScS5m
sScS5m
Epicentral distance (deg)
Time after event origin (sec)

Interpretive cartoon



Using massive data sets we can move towards better determining these phenomena (and discover new things!)

There are great opportunities for using AI and unsupervised machine learning

Garnero and Richardson (2025)

Chat GPT’s AI Image Generator

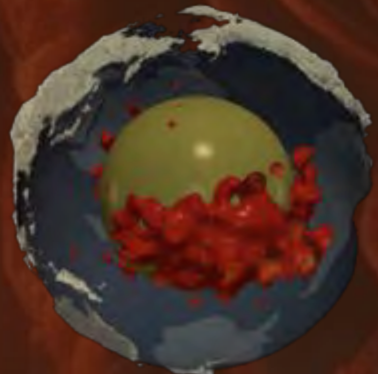
Prompt: **too many seismograms**

These are obviously not seismic data. Thus, we have to proceed cautiously with AI tools

Take-home messages

Seismologists are mapping diverse multi-scale heterogeneity inside Earth that relates to Earth's planetary evolution, composition, and present-day dynamics

→Earth beyond the 1-D shells



Significant uncertainties are present giving rise to uncertainties in models and interpretations

→Better constraints needed

Big data exist, but are not all being utilized: fundamental progress is imminent

→Exciting discoveries await!

Huge thanks to these curious scientists I regularly interact with!

Adeolu Aderoju: Seismologist (finishing PhD @ ASU, array processing / outer core imaging)

Sam Hansen: Seismologist (U. Alabama, ULVZ collaborations, Antarctica seismo)

Mingming Li: Geodynamicist (ASU, Mantle flow/convection)

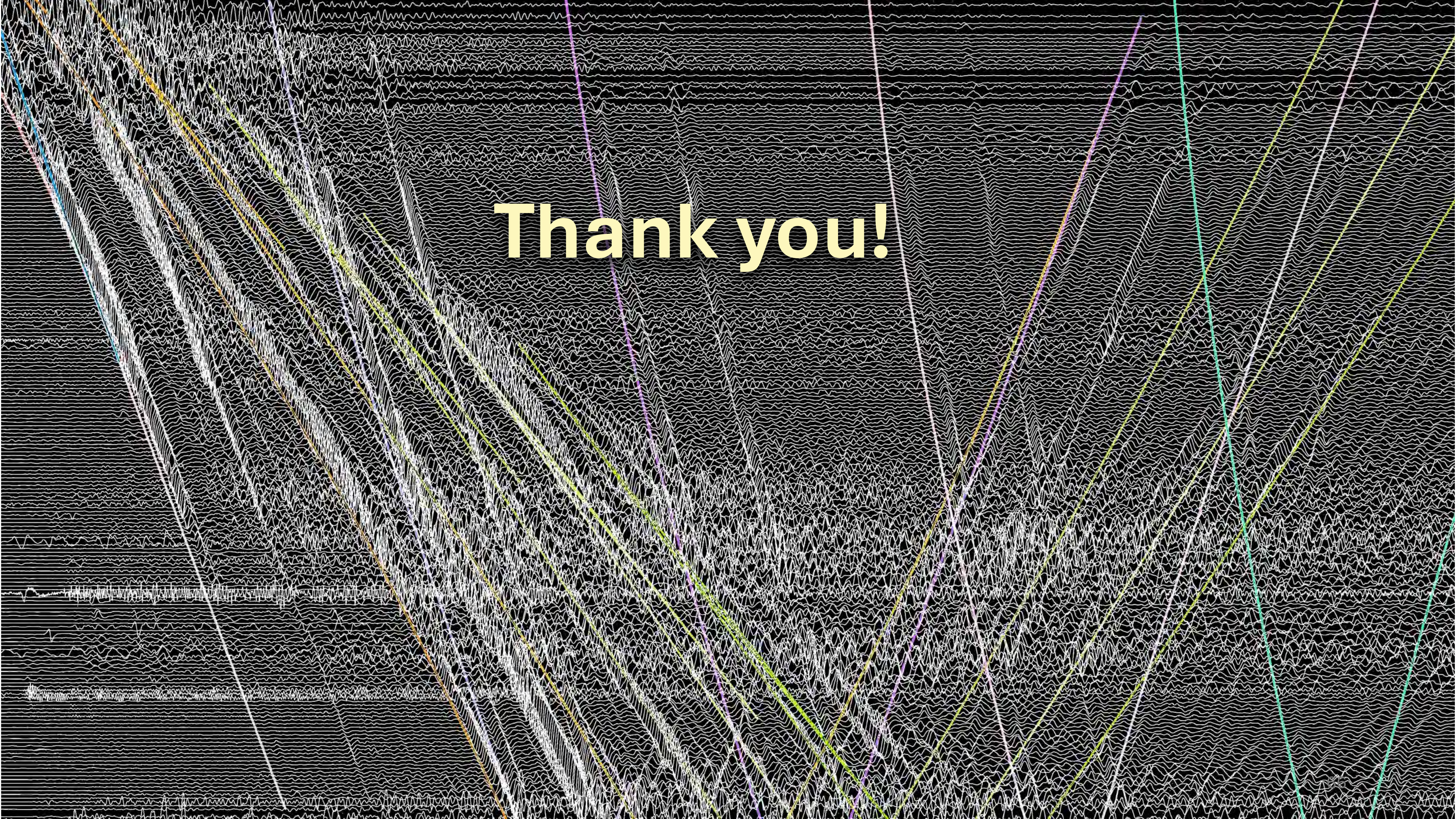
Claire Richardson: Seismologist (finishing PhD @ ASU, SITRUS tomography updating)

Dan Shim: Mineral physics (deep mantle mineralogy)

John West: Seismologist, coder extraordinaire (ASU, ADEPT data set, SWAT)

Jonathan Wolf: Seismologist (U. California, Berkeley, Anisotropy, ULVZ, SmKS)

The SmKS crew!


Thank you!