Investigating Earth's deep mantle buoyancy and frequency dependent behavior using Earth tides

Harriet C.P. Lau (hcplau@berkeley.edu)

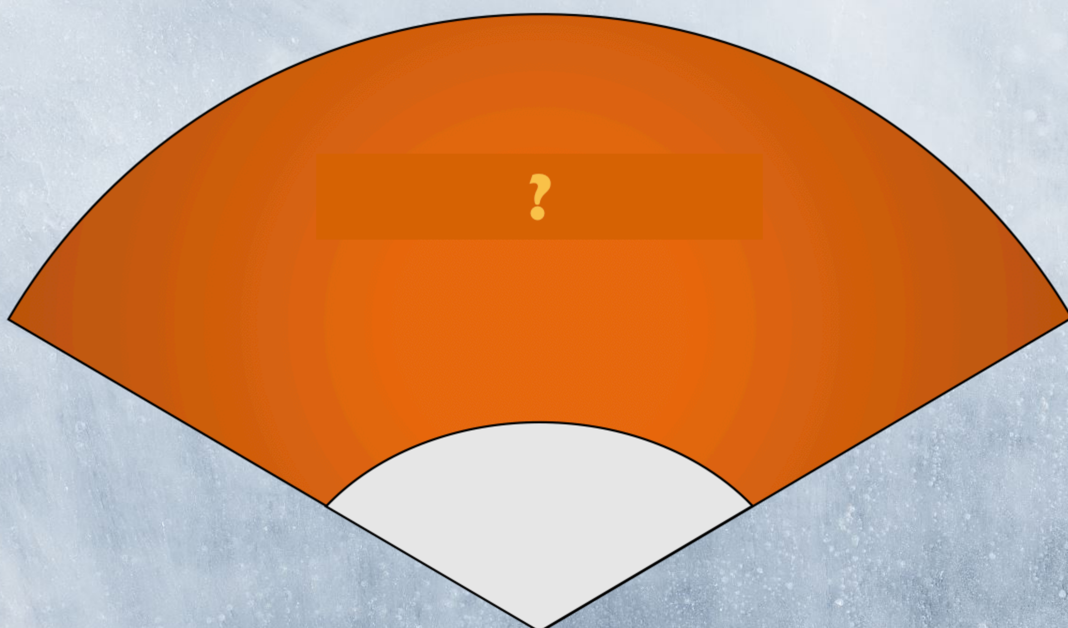
Hsin-Ying Yang, Jerry X. Mitrovica, Jeroen Tromp, David Al-Attar, Jim Davis, Konstantin Latychev, Ulrich Faul

2019 SAGE/GAGE: Earth Rheology and Structure:

New Approaches, Applications, and Implications for Dynamics

10th October, Portland OR

What's in the mantle?



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- Geochemistry
- Mineral Physics

(2) Indirectly look at rocks
- Geophysical Imaging

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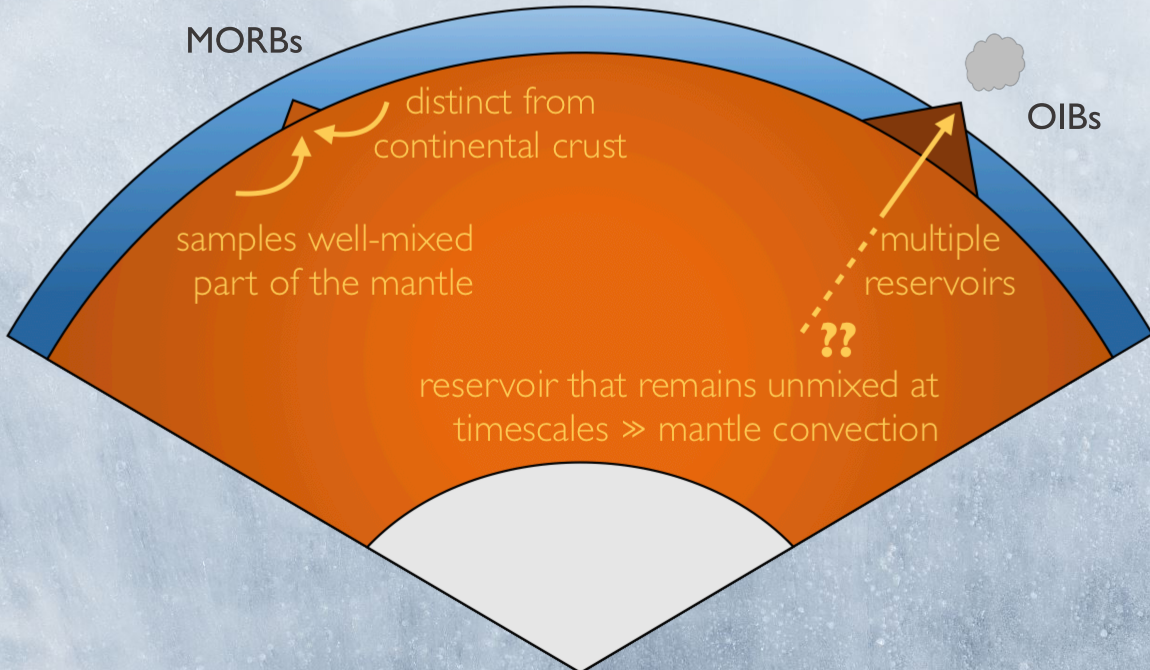

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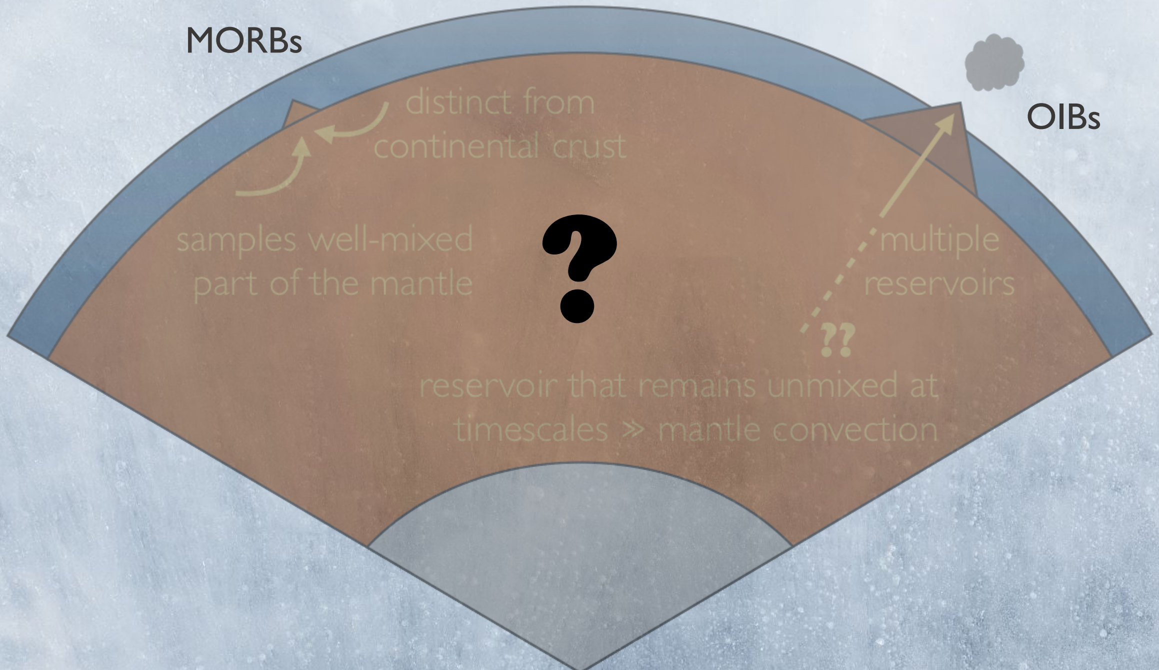

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no information on geometry

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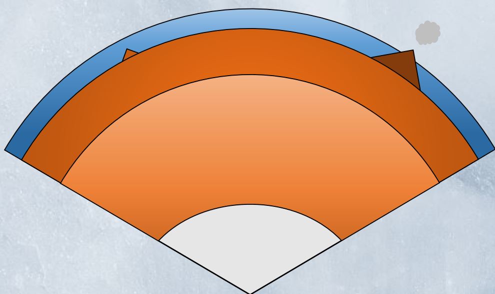
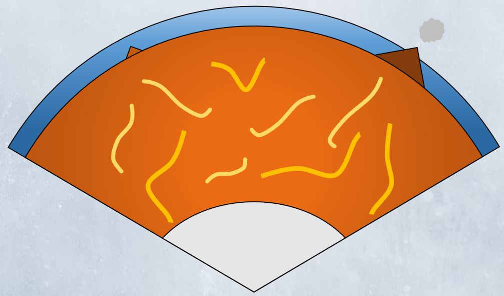


e.g., Hoffman (1997)



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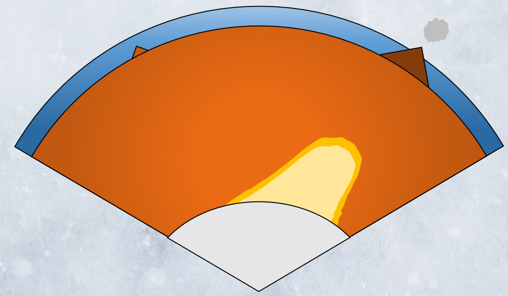

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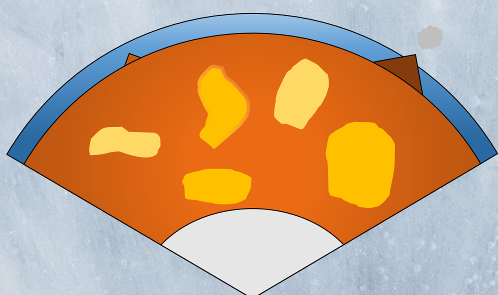

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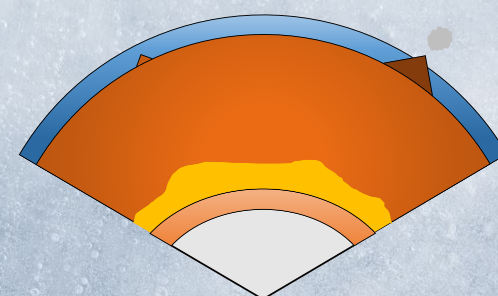

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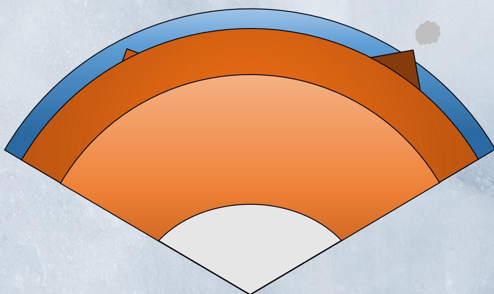

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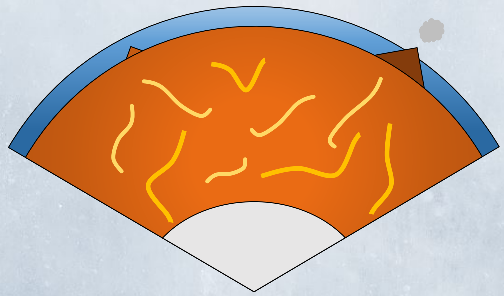

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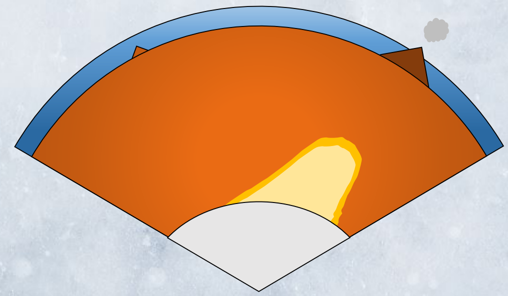

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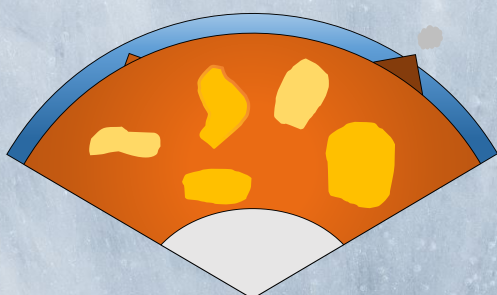

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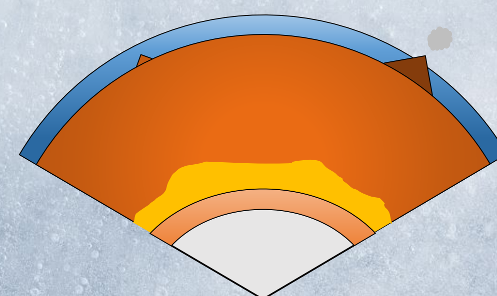

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All satisfy geochemical constraints!

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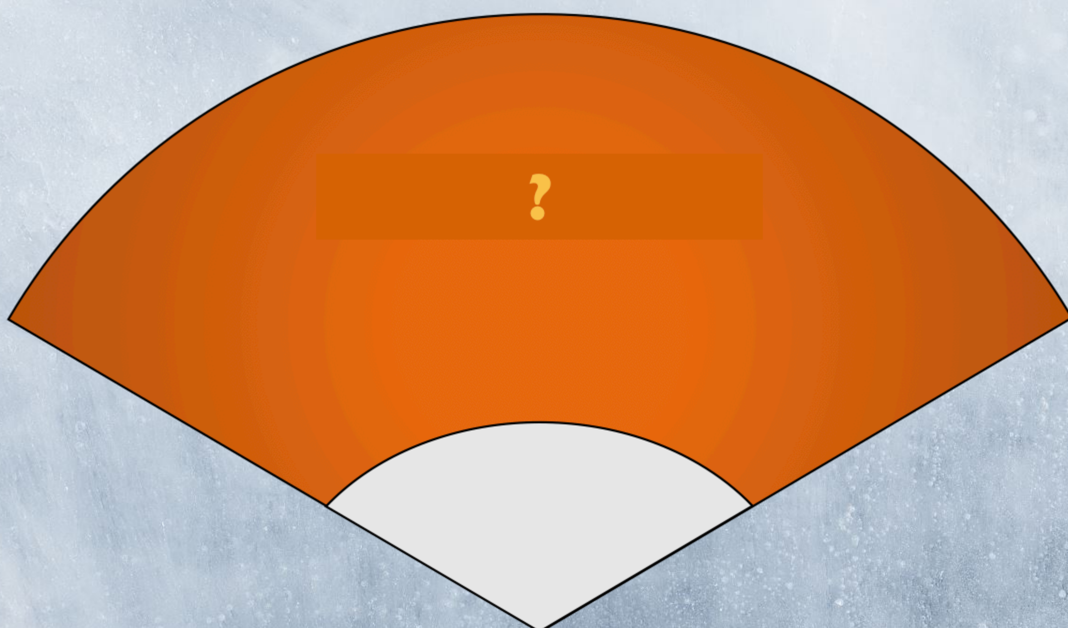

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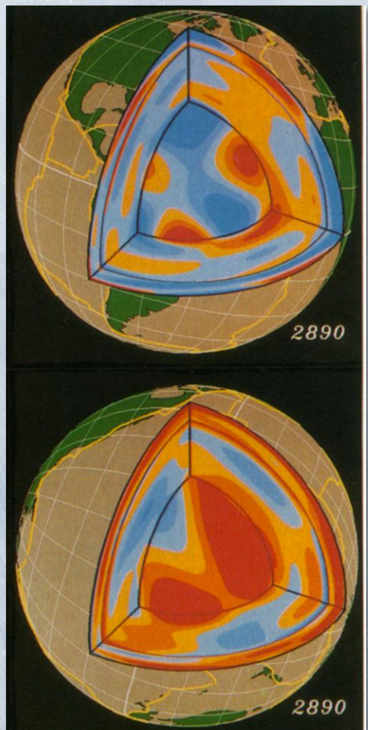
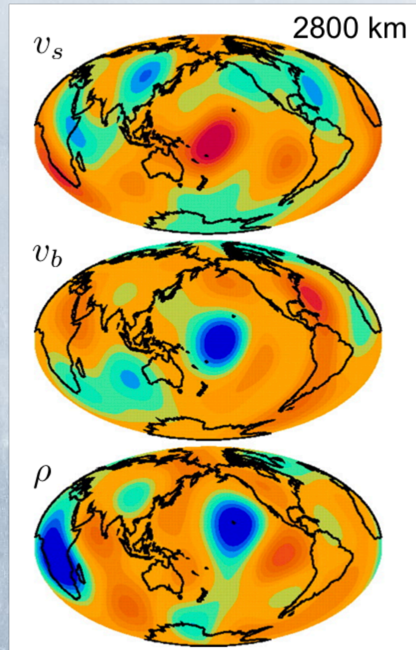
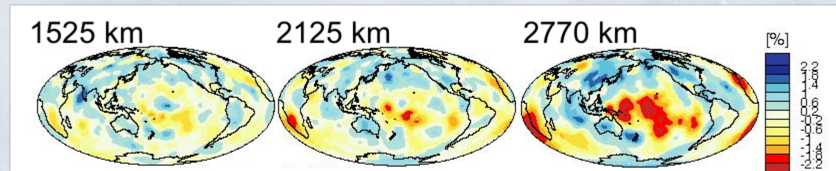
Seismic Tomography Provides Geometry

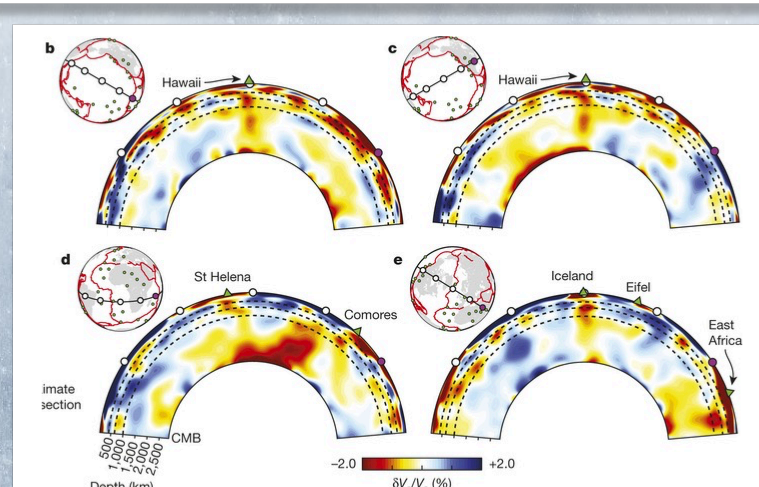




Ishii & Tromp (1999)

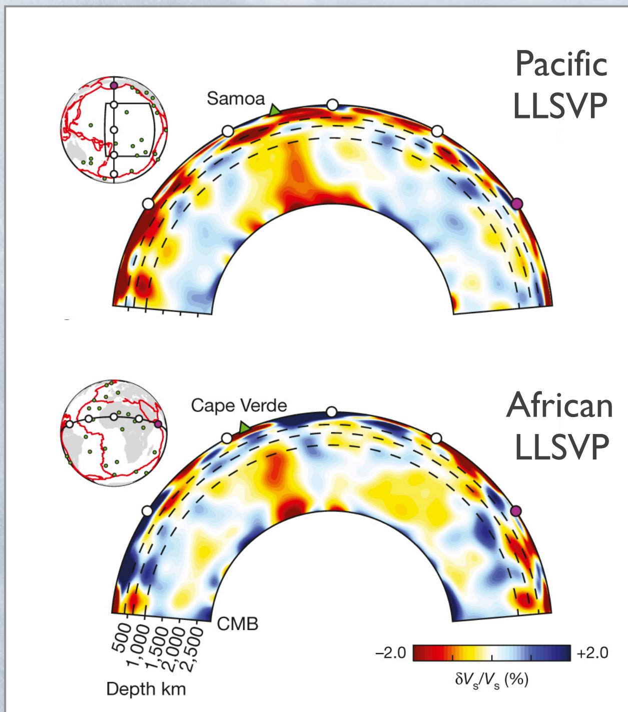


Masters *et al.* (2000)



French & Romanowicz (2015)

LLSVPs prominent feature



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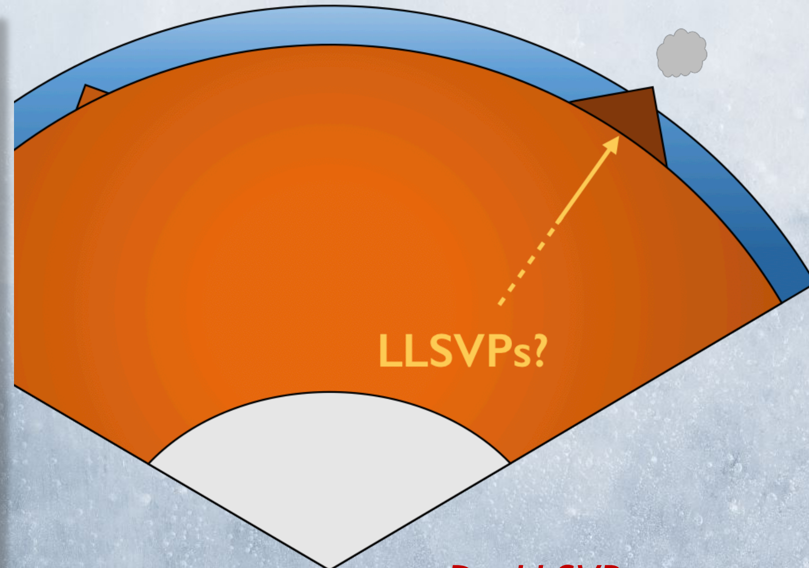
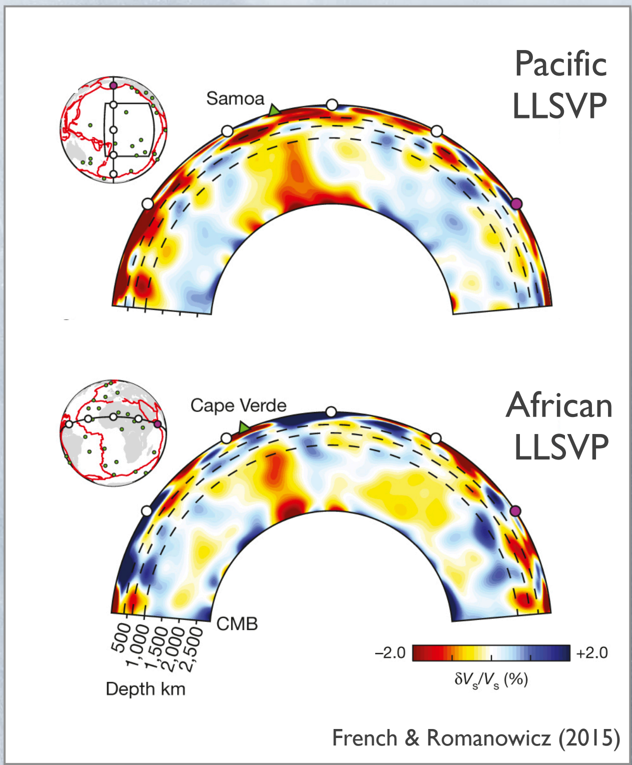
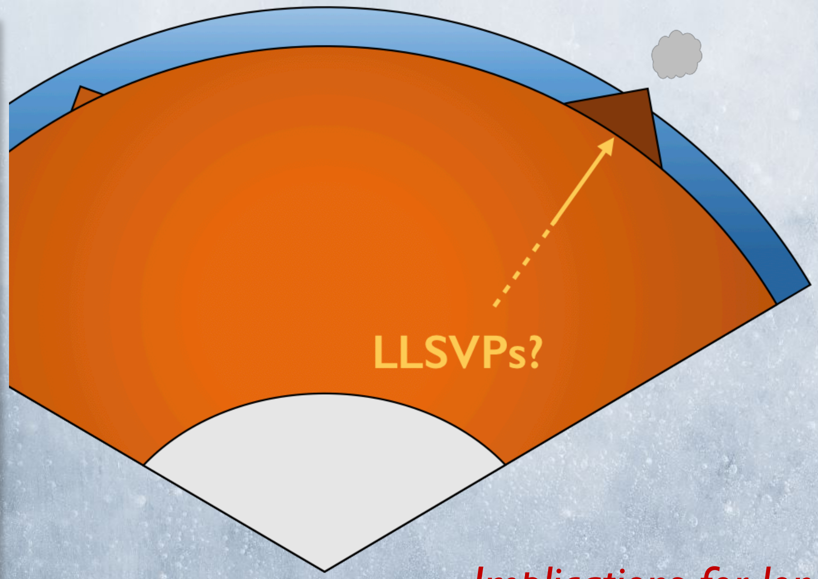


Do LLSVPs store compositional heterogeneity?
Are these just thermal structures?

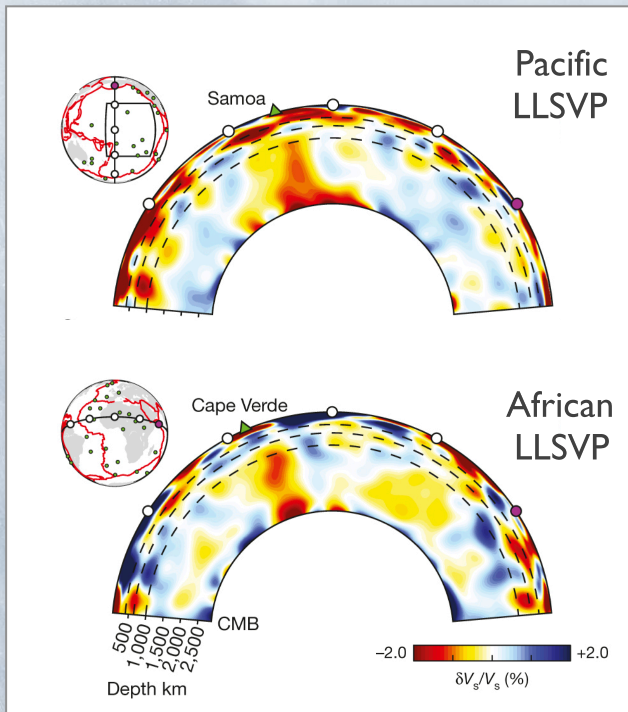
LLSVPs prominent feature





Implications for longevity of LLSVPs, energetics of mantle convection, thermal and compositional evolution of the Earth system

LLSVPs prominent feature



French & Romanowicz (2015)

Why is this so difficult?

Lowering seismic v can be achieved by:

Thermal anomaly → positive buoyancy
Compositional anomaly → negative buoyancy

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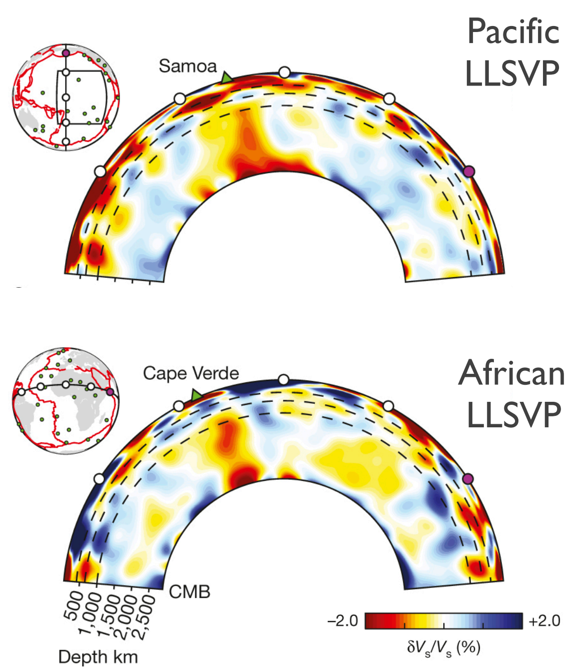

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Results in different modes of convection

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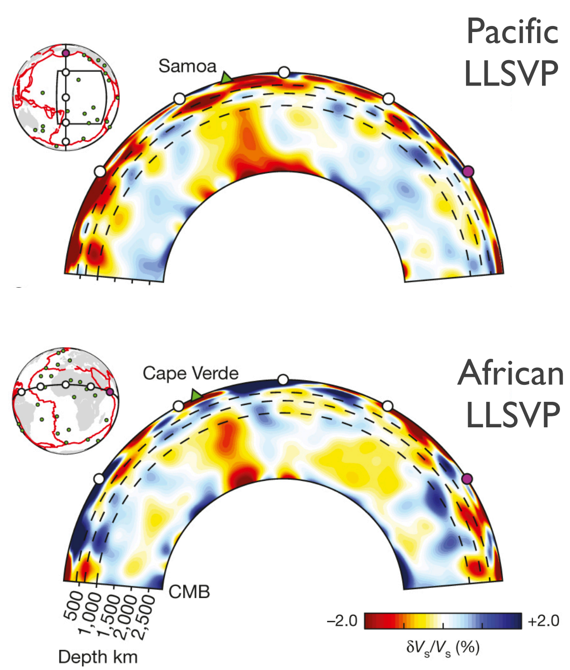

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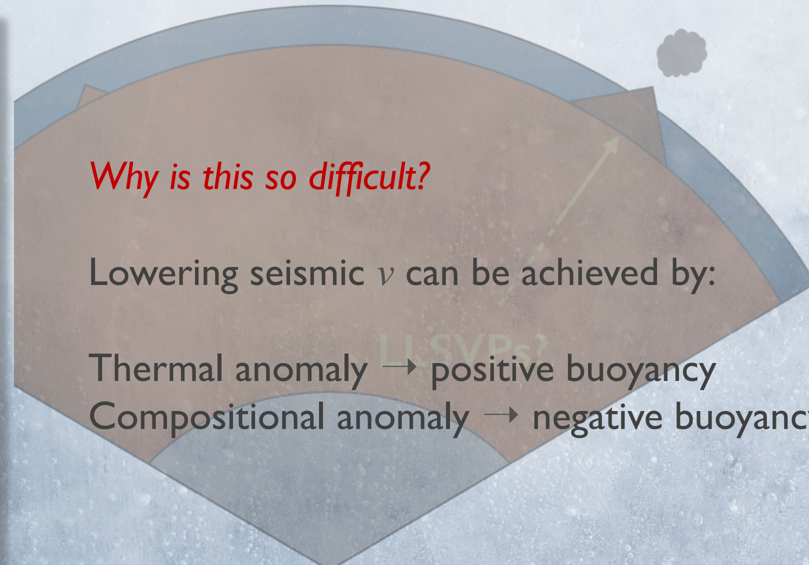

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Results in different modes of convection

Key parameter: Buoyancy!

Constraints on LLSVP buoyancy

Positive Buoyancy:
Geoid highs (e.g., Hager *et al*, 1985)
Surface and CMB dynamic tomography (Gurnis *et al*, 2000; Forte & Mitrovica, 2001)
Stoneley Modes (e.g., Koelemeijer *et al*, 2017)

Negative Buoyancy:
Normal mode and gravity inersions (e.g., Ishii & Tromp, 1999)
Probabilistic normal mode approaches (Resovsky & Trampert, 2003)
Fundamental normal mode (e.g., Moulik & Ekstrom, 206)

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Imply compositional source:
v_S anomalies very large
(e.g., Wang & Wen, 2007)
sharp gradients at margins
(Ni et al., 2002; Sun et al., 2007)
v_S and v_B anomalies anti-correlated
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Add a new constraint: Earth/ Body tides

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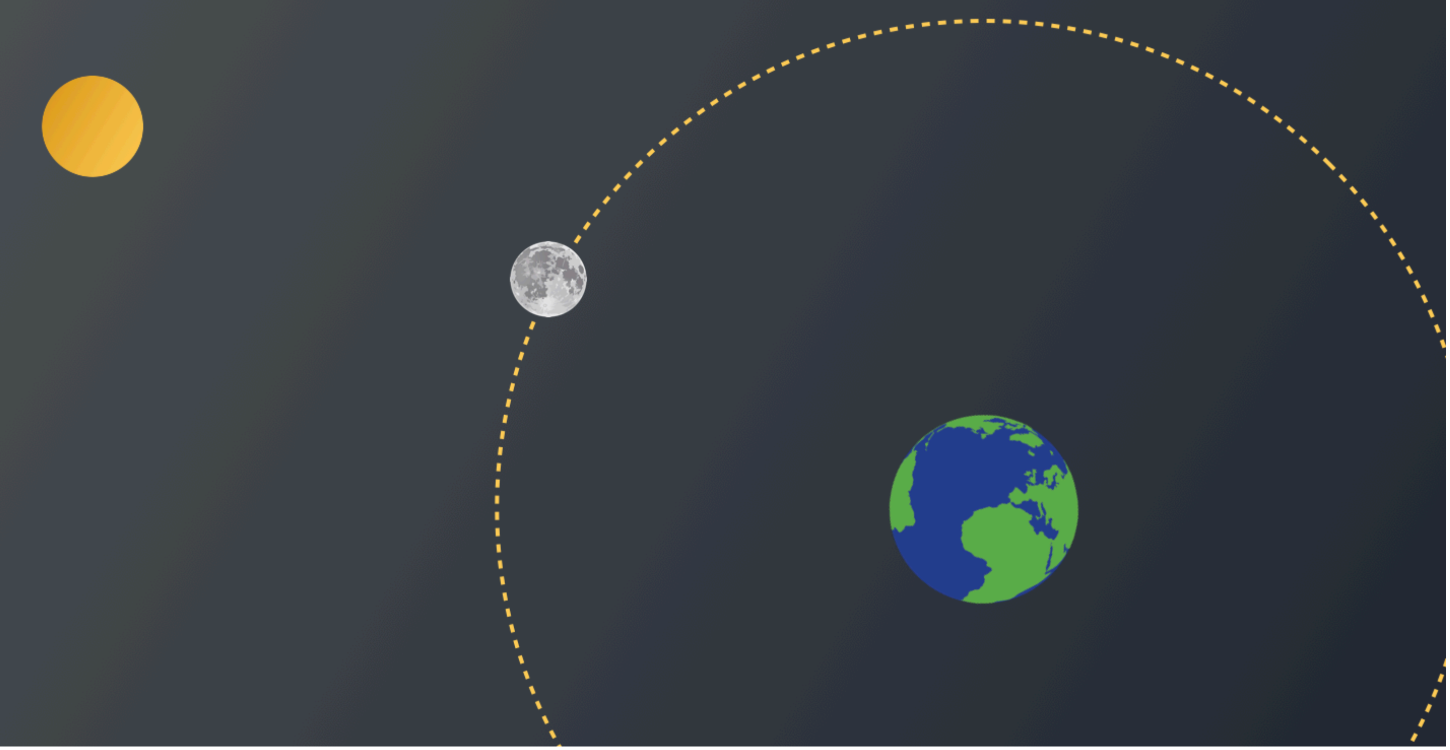
Body tides: Solid Earth deformation under luni-solar stresses



Not to scale

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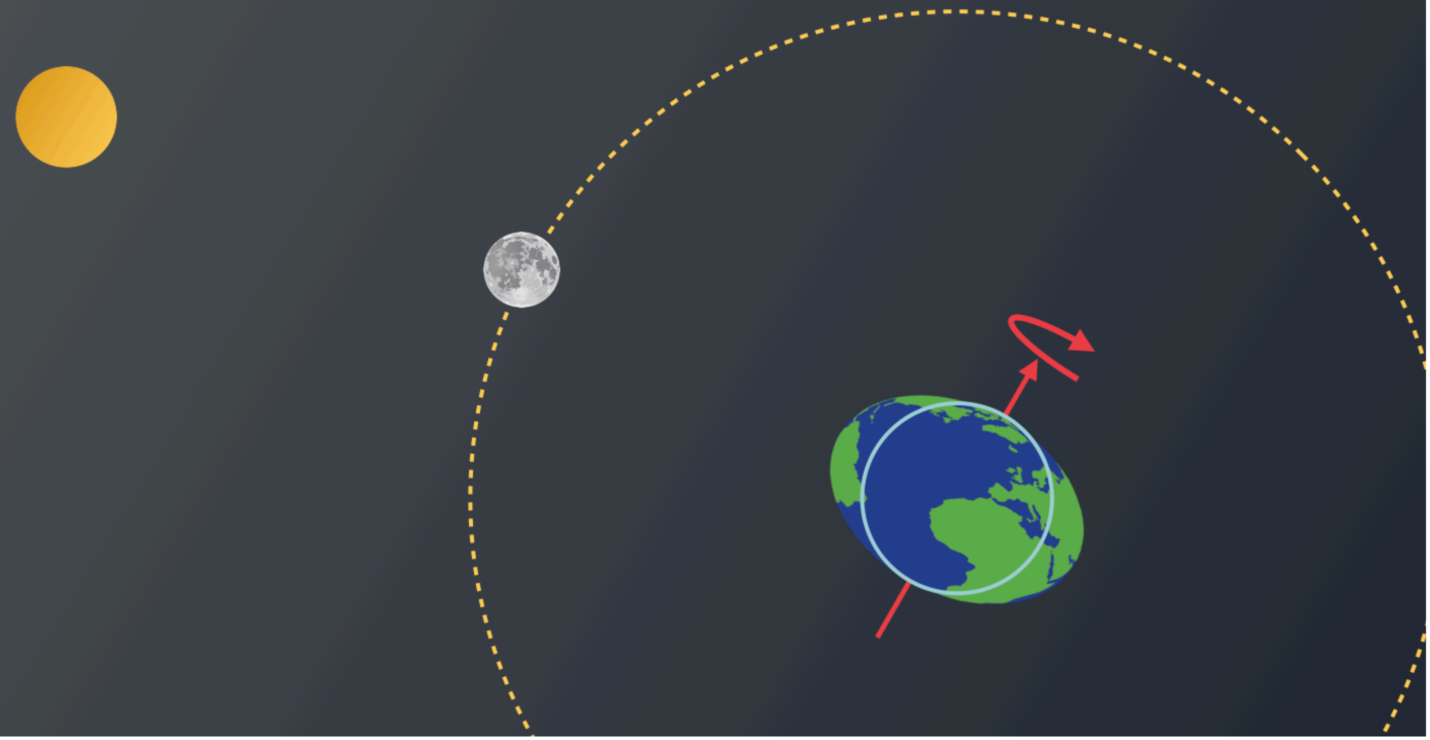

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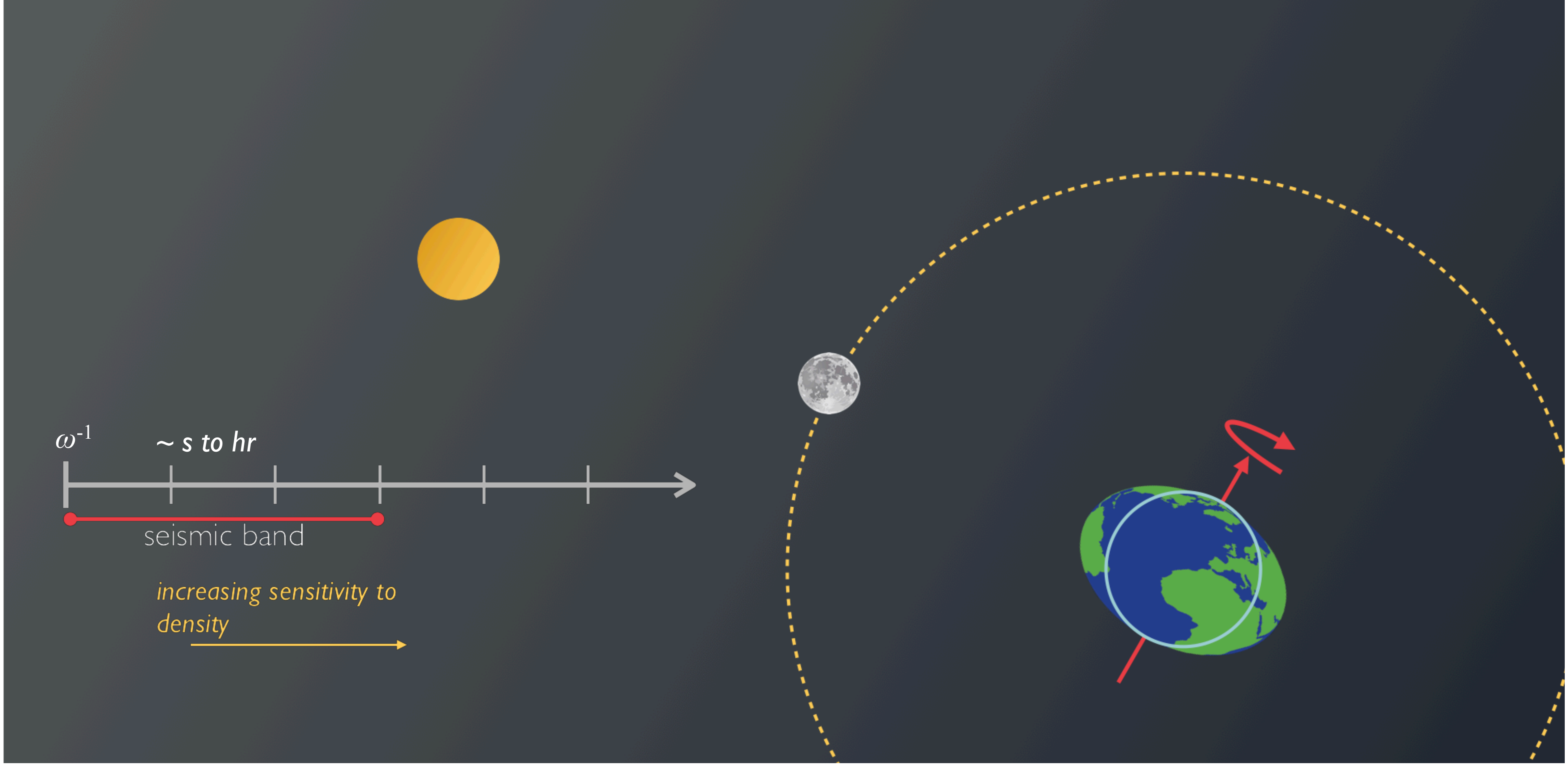

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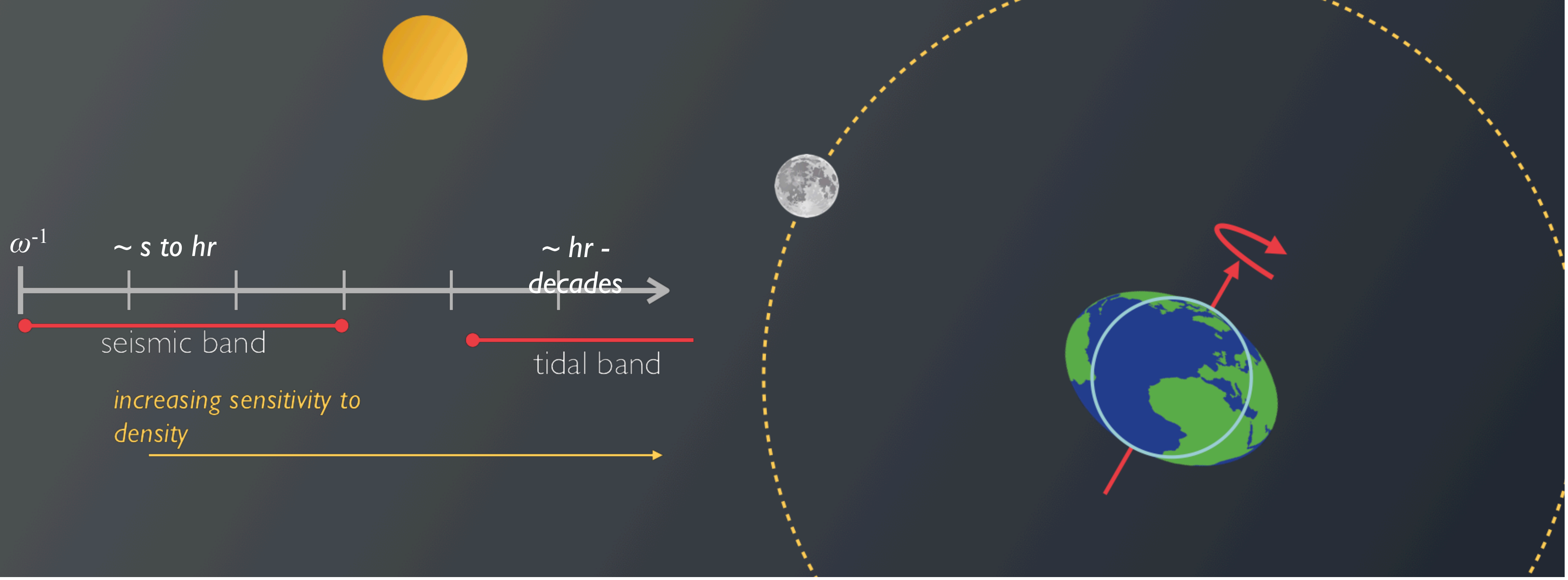

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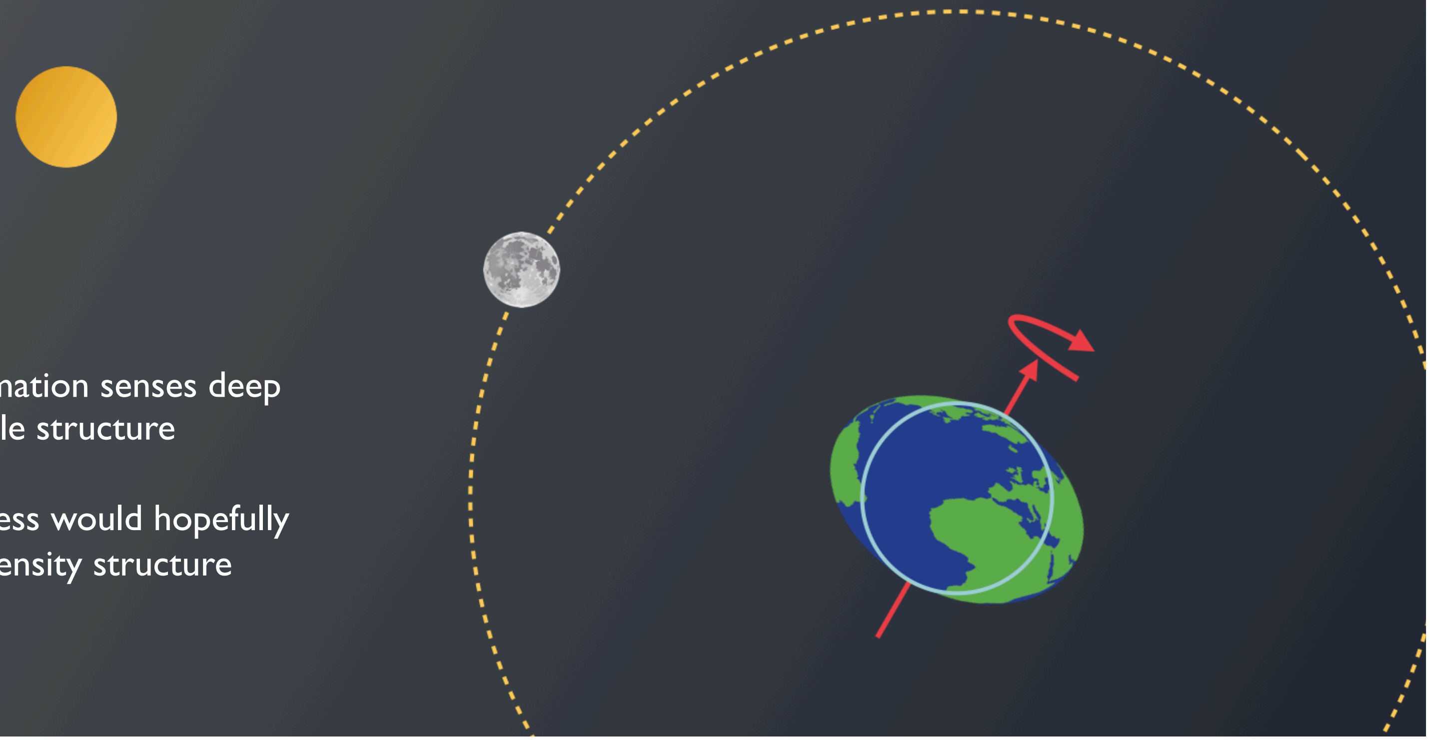
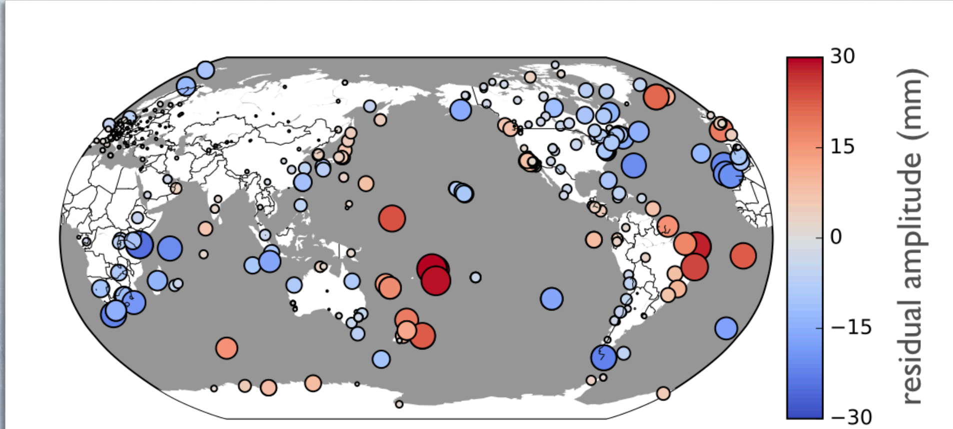


Whole earth deformation senses deep
and large-scale structure

Low frequency process would hopefully
be sensitive to density structure

Global GPS measurements show sub-mm level variability in body tide

deformation amplitude after 1D effects removed

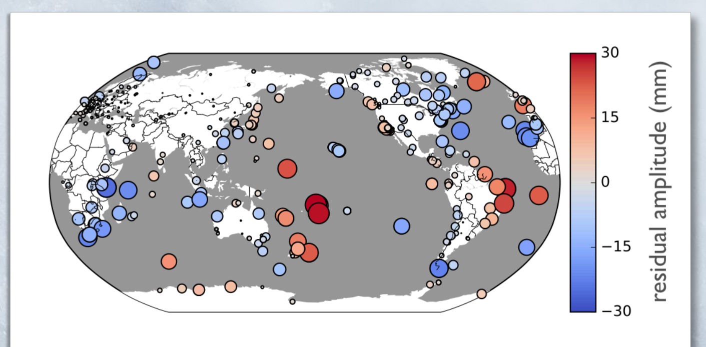


Yuan *et al* (2014)

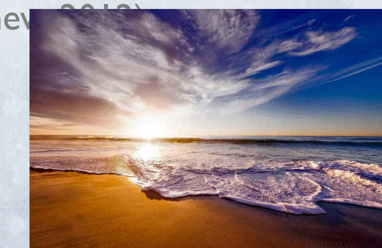
Sub-mm precision of semi-diurnal body tide measurement
Highly non-uniform response
Use this data for tidal tomography

Lau *et al* (2015; 2017)

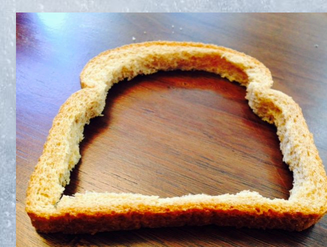
3D corrections to be made



(1) Ocean Tidal
Loading (Agne



(2) Boundary
Topography
(Bassin *et al*, 2000,
Mathews *et al*, 2002)



Lau *et al* (2015; 2017)

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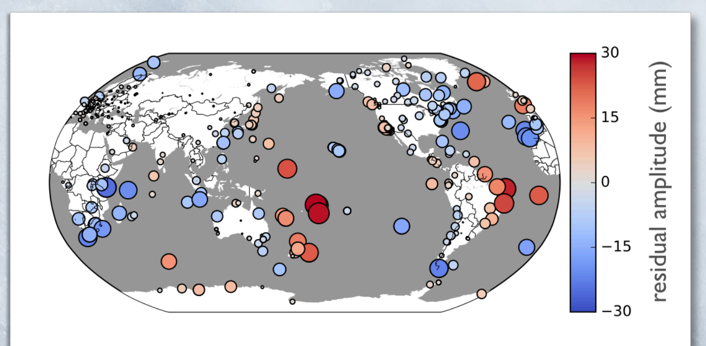
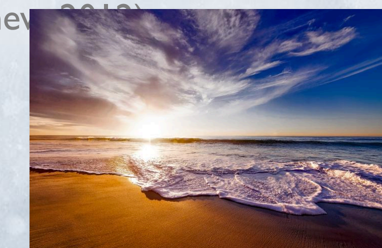


(1) Ocean Tidal Loading (Agnew



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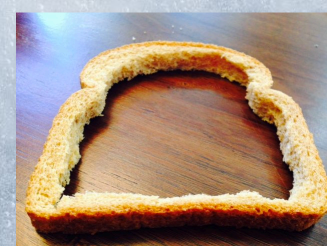
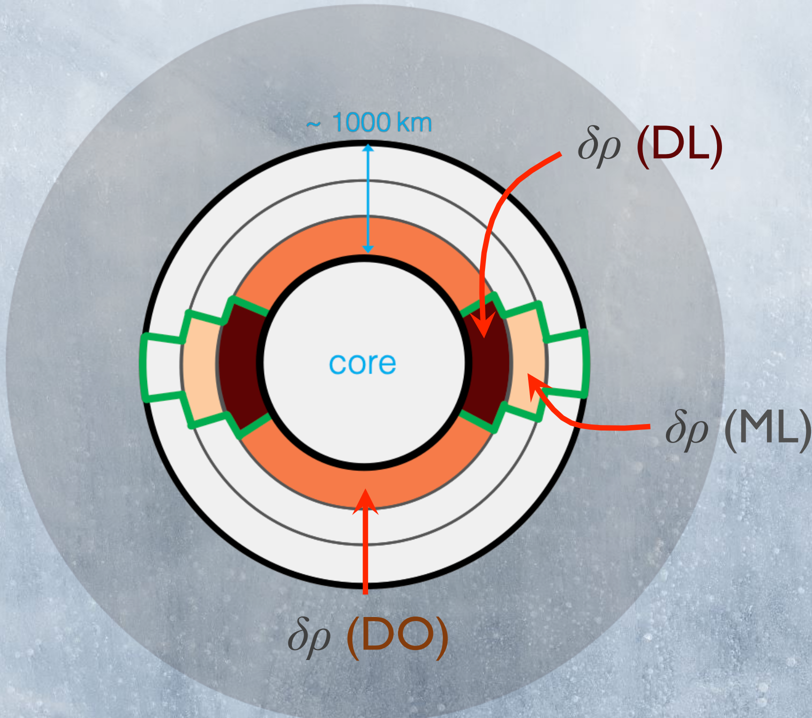


3D elastic and density structure of the mantle

Lau *et al* (2015; 2017)

Tidal Tomography



Consider bottom 700 km of deep mantle

Impose v_S and v_B structure from selection of seismic tomography models.
Isolate 3 regions:

Deep LLSVP (DL)
Deep Outside (DO)
Mid LLSVP (ML)

Lau *et al* (2015; 2017)

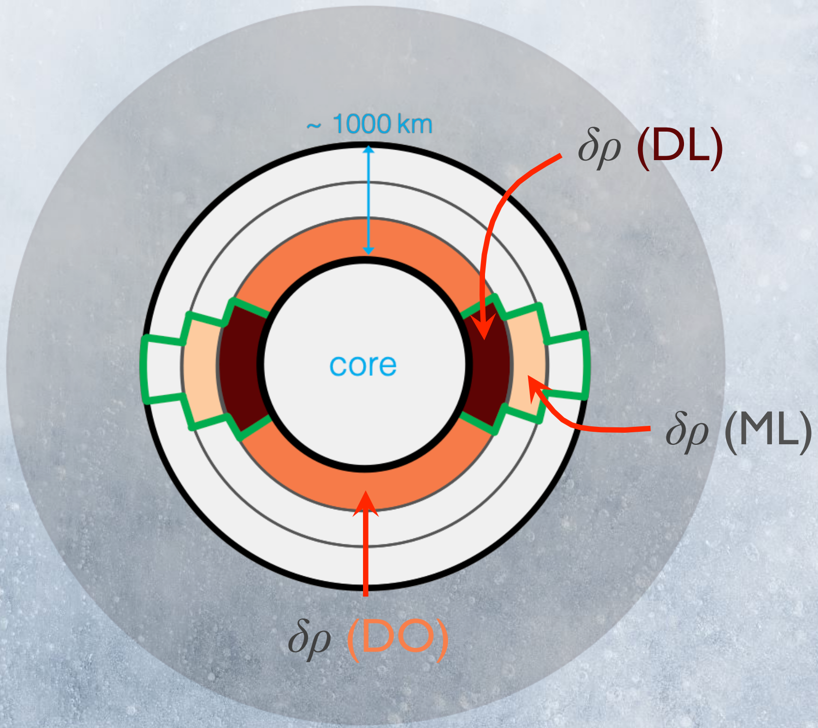
Tidal Tomography

Take Monte Carlo approach and test many models.

Each model will impose randomly selected v_S and v_B structure:
HMSL (Houser *et al*, 2006); GYPSUM (Simmons *et al*, 2010); S362MANI (Kustowski *et al*, 2008); S40RTS (Ritsema *et al*, 2008) SAW24B16 (Megnin *et al*, 2000)

Forward calculate many models with varying excess densities:
$\delta\rho$ (DL), $\delta\rho$ (DO), $\delta\rho$ (ML)

Test for statistical significant against GPS measurements for body tide



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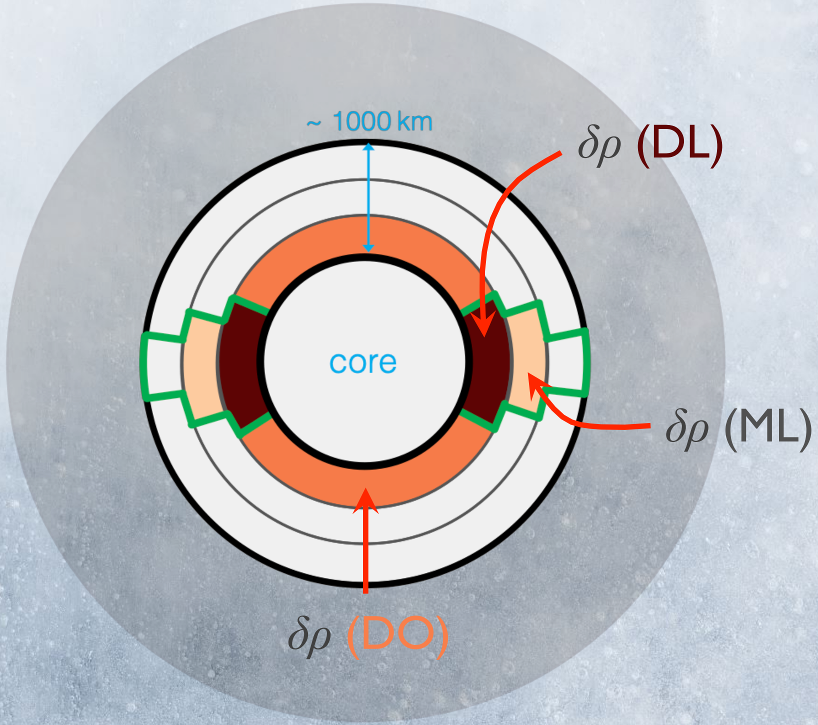

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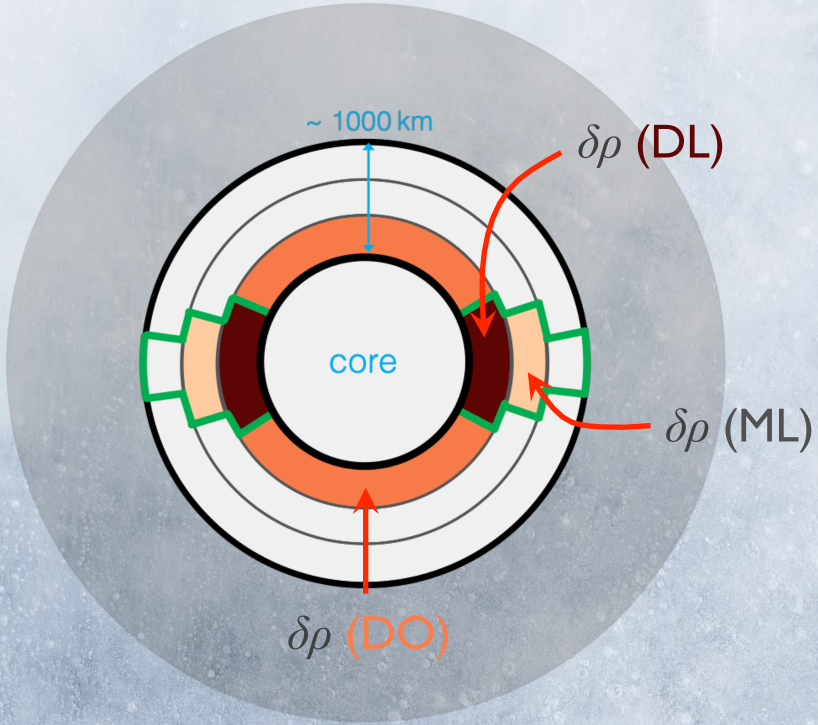

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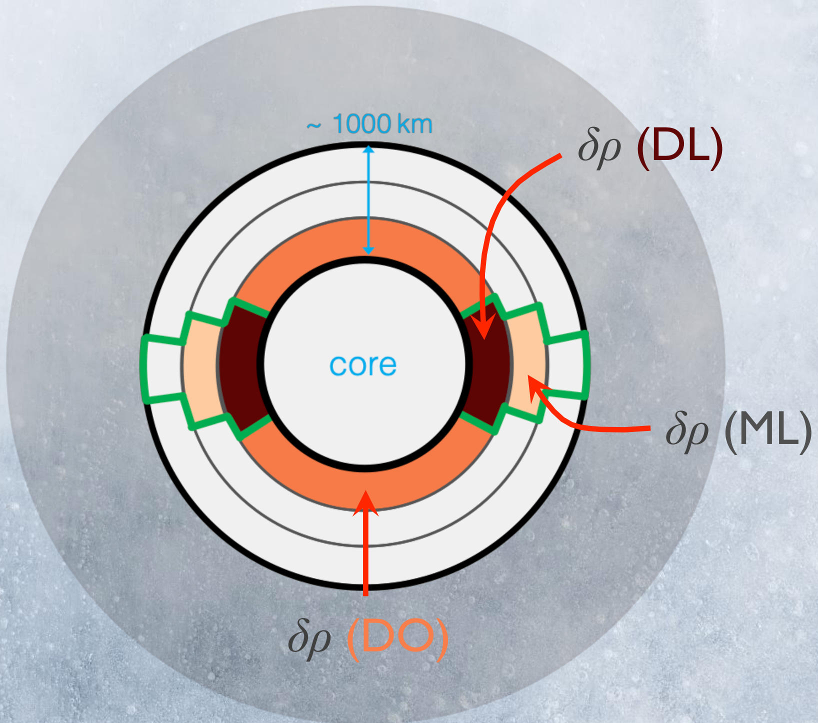
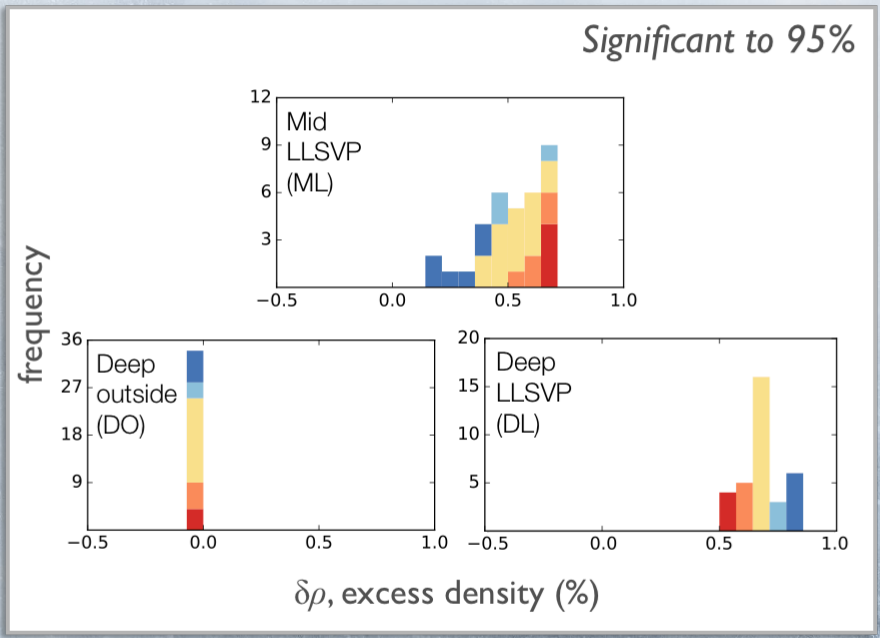


Lau *et al* (2015; 2017)

Results: Buoyancy of Deep Mantle



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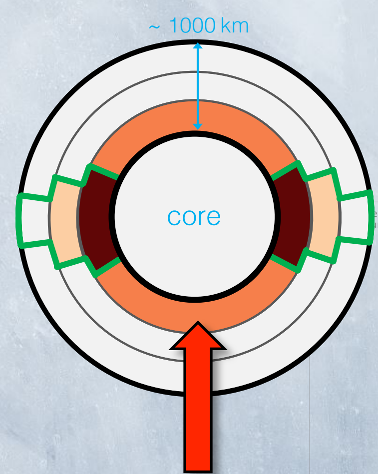

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Above the core, surrounding the LLSVP, the mantle is slightly buoyant

Lau *et al* (2015; 2017)

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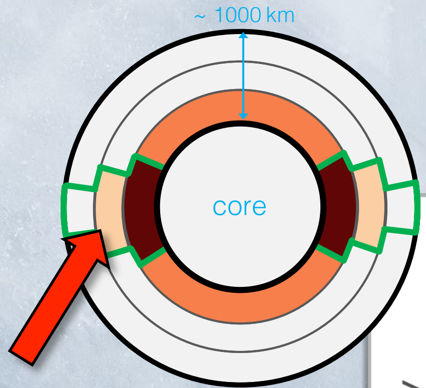

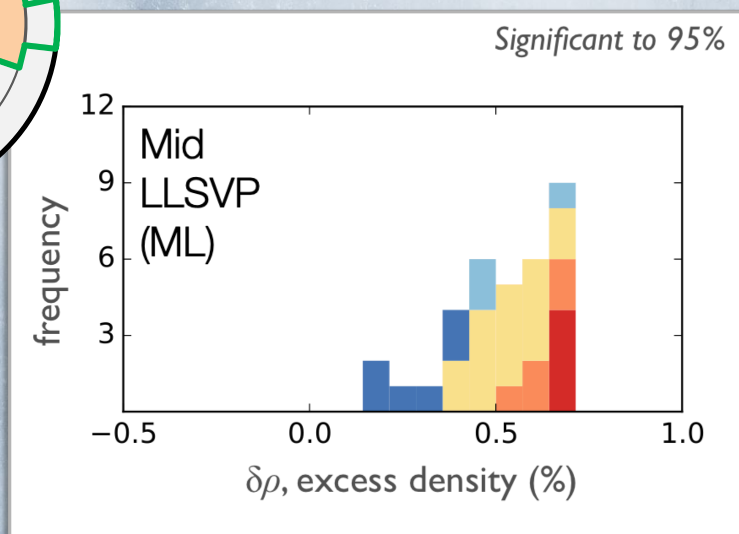

The ML region shows positive excess density

Lau *et al* (2015; 2017)

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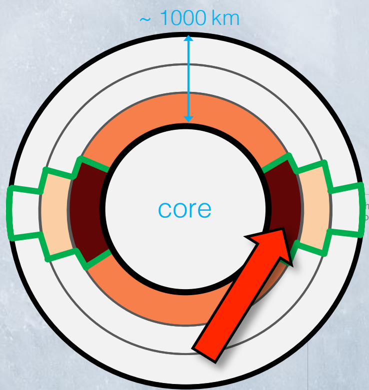

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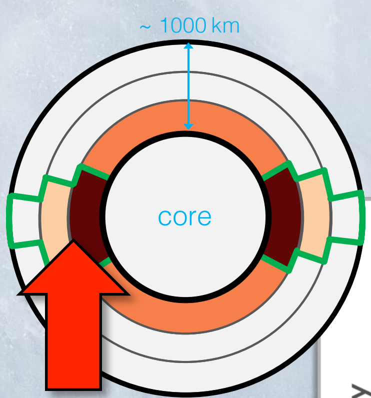
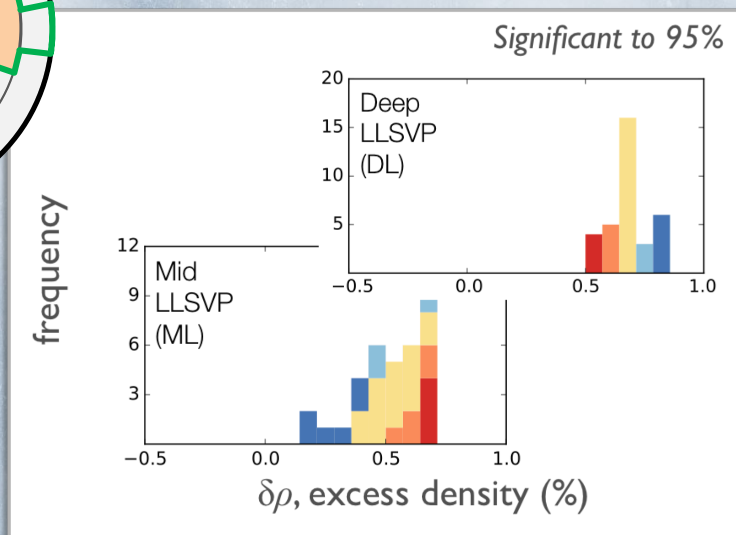
The ML region shows positive excess density to a greater degree

Lau *et al* (2015; 2017)

Results: Buoyancy of Deep Mantle





LLSVPs represent regions of negative buoyancy

Covariance between DL and ML

Reduces our ability to resolve $\delta\rho$ independently within these layers

Lau *et al* (2015; 2017)

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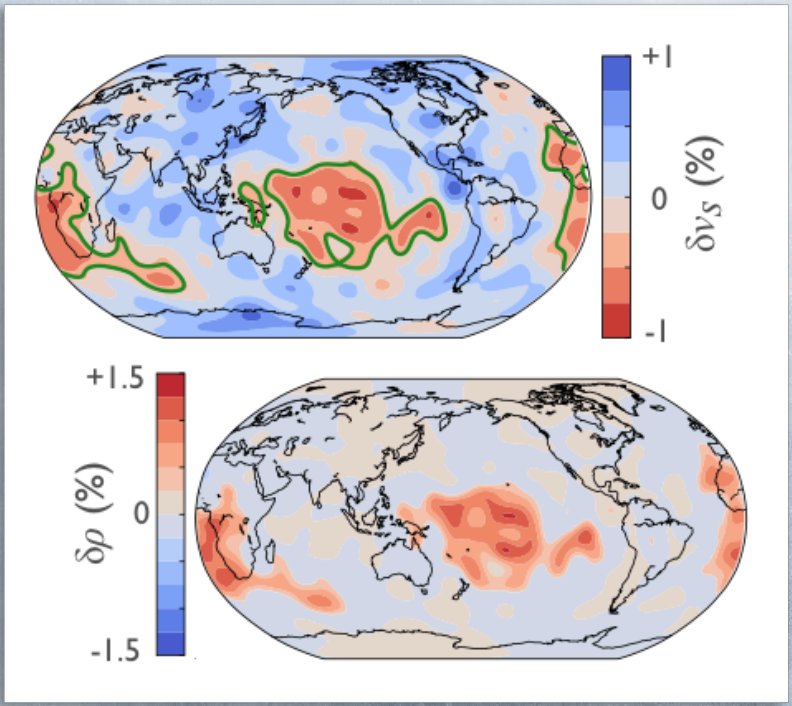


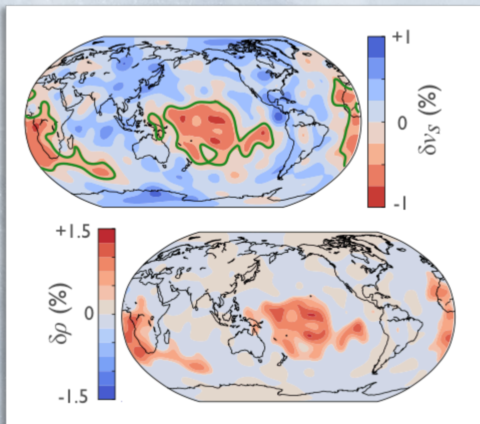
The source of negative buoyancy must be due to chemical heterogeneity

Negative buoyancy also provides a mechanism to stably preserve chemically distinct reservoirs implied by geochemistry

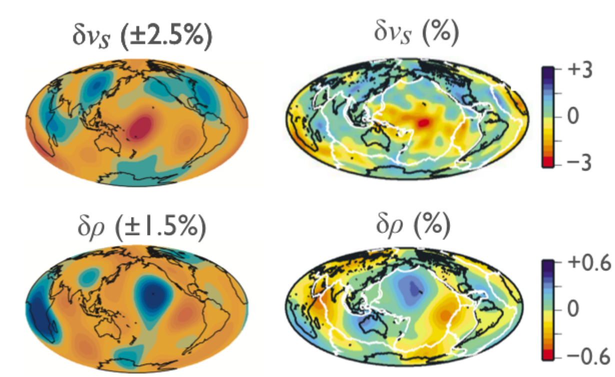
The depth distribution of this excess density cannot be resolved

Lau *et al* (2015; 2017)

Moving forwards:

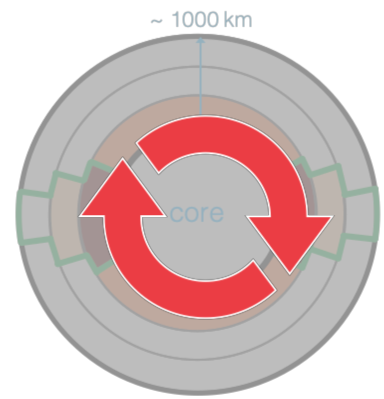


This study (Lau *et al*, 2017)



Ishii & Tromp (1999) Moulik & Ekström (2016)

Stoneley mode study

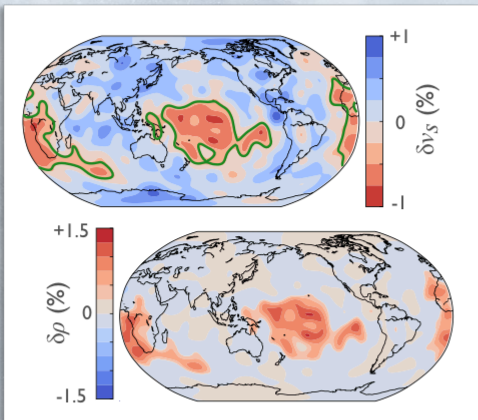


Prefer lighter LLSVPs and denser surroundings

Seemingly contradictory …
But no sensitivity in the lowest 100 km mantle

Koelemeijer *et al* (2017)

Moving forwards:



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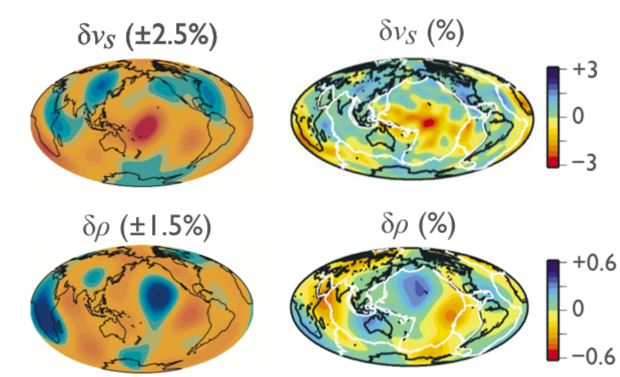
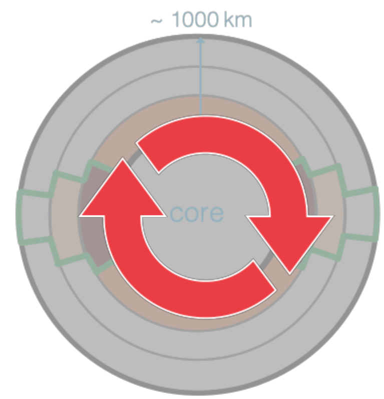


Ishii & Tromp (1999) Moulik & Ekström (2016)

Joint tides-Stoneley mode study?

Stoneley mode study



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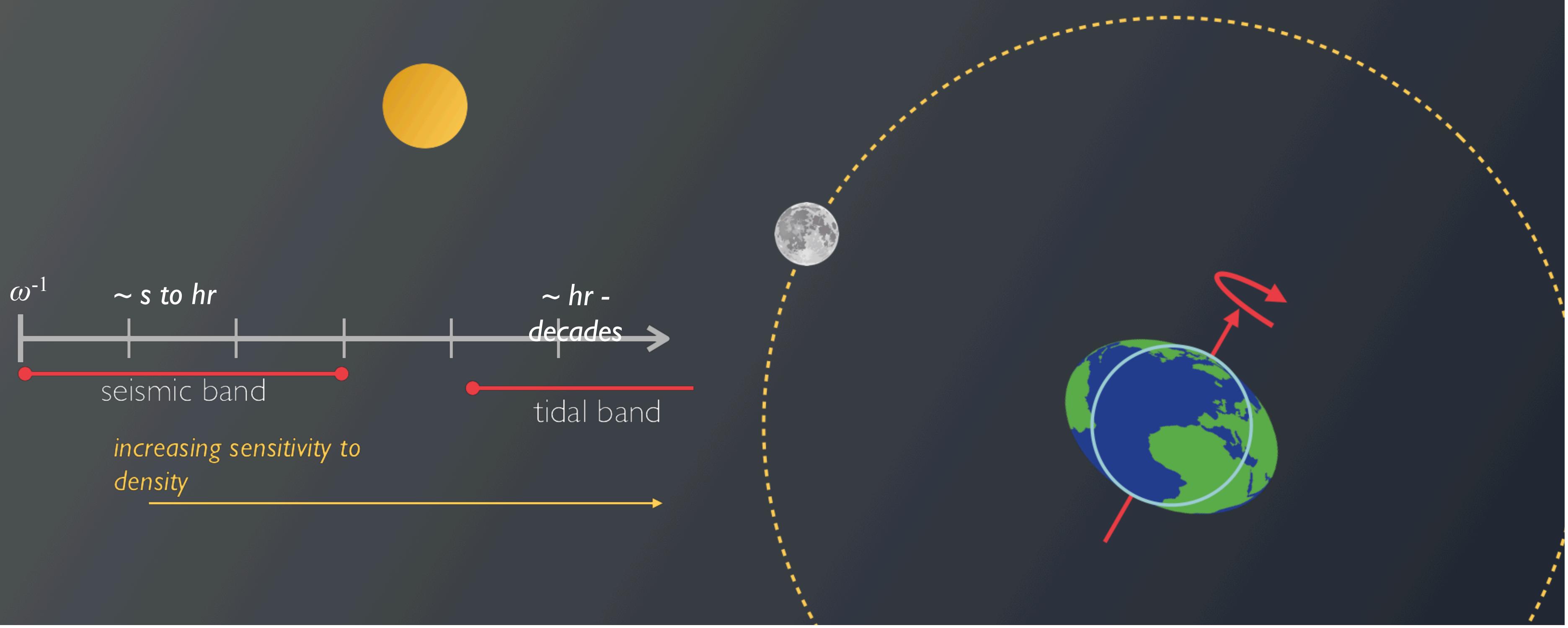
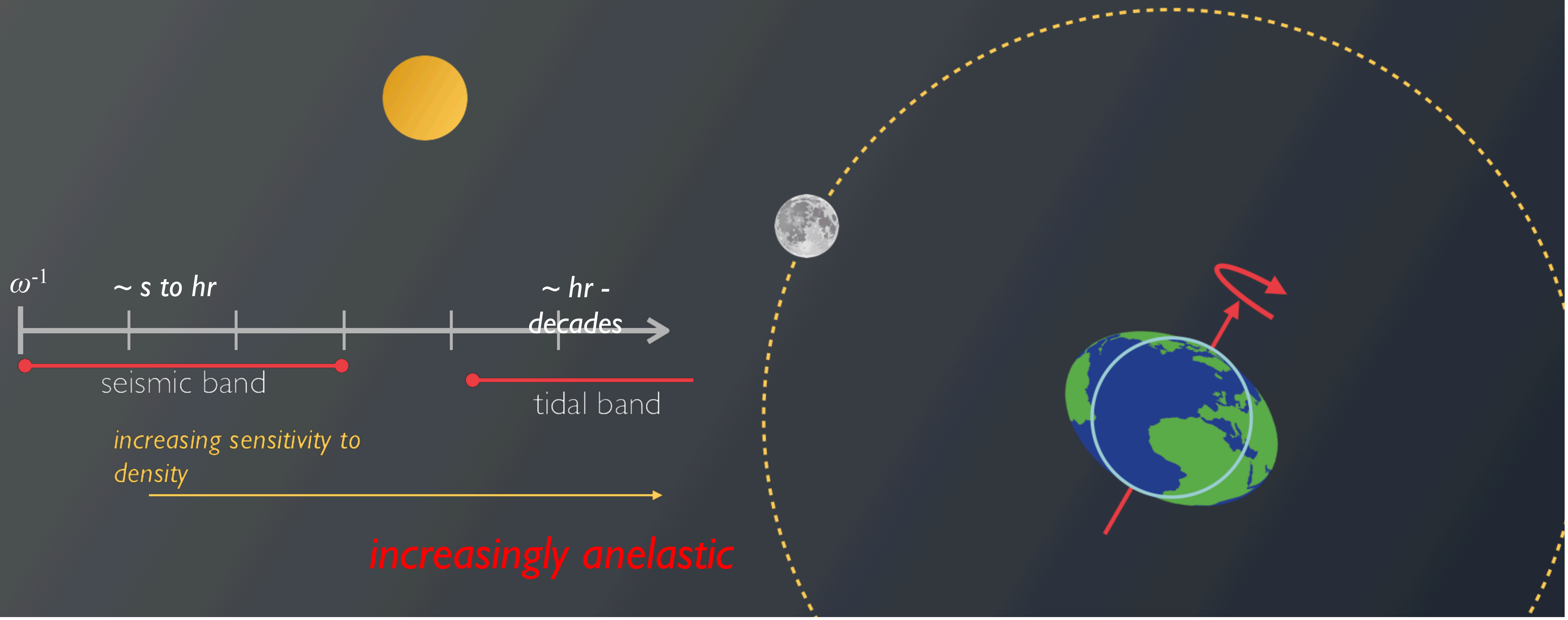
Frequency dependence?



Frequency dependence?



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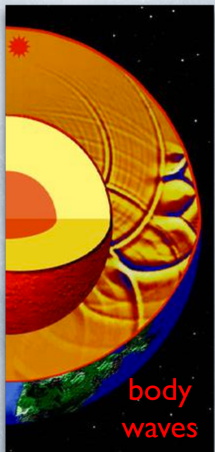
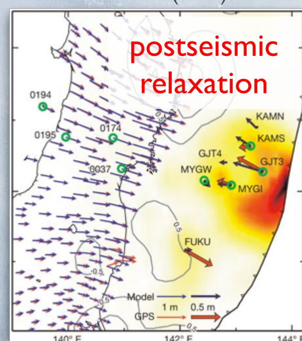


sub-sec

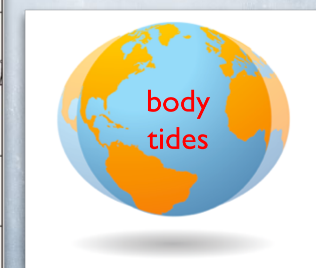
from Harvard seismology

min - hr

Sun et al. (2014)

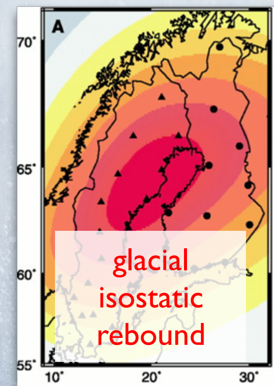


hr - months



hr - decades

Milne et al. (2001)

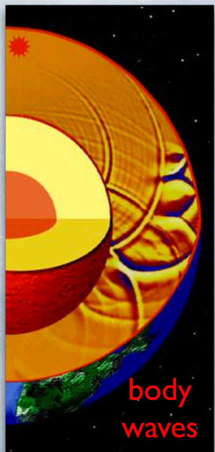


100y- 100ky

> 10 My

increasing timescale

Frequency dependence?



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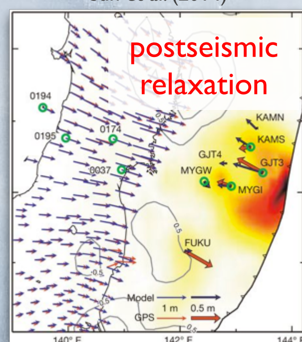
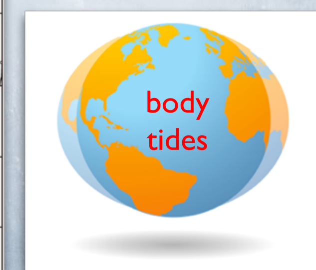


hr - months



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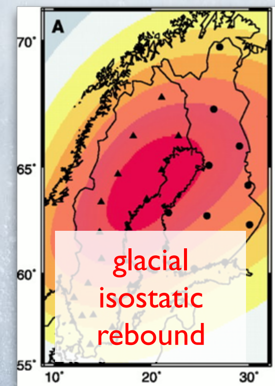


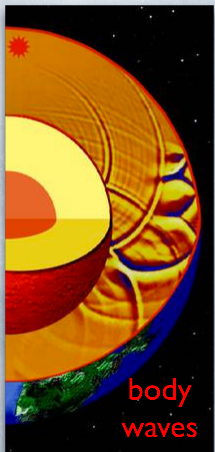
100y- 100ky

> 10 My

increasing timescale

increasingly viscous

Frequency dependence?



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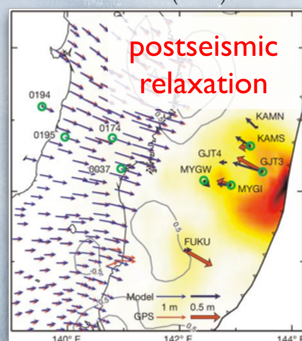
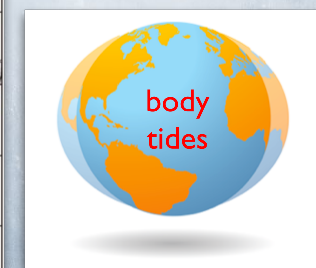


hr - months



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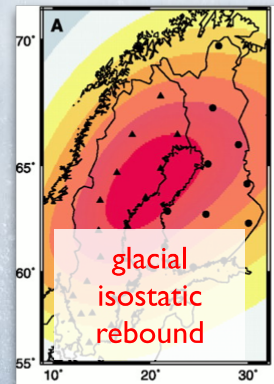


100y- 100ky

> 10 My

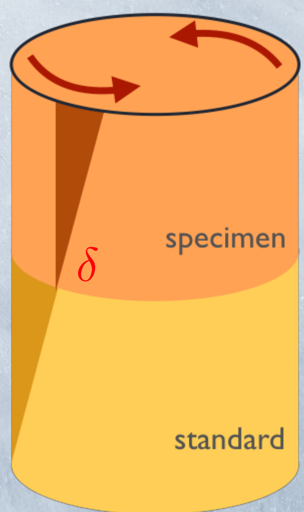
increasing timescale

increasingly viscous

minutes to decades

Measures of intrinsic dissipation, Q^{-1}?

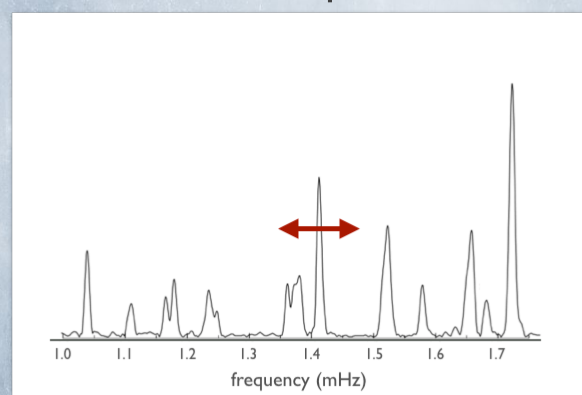
laboratory



$$Q^{-1} = \tan\delta$$

10^0 - 10^3 s
800 - 1200°C
cm-scale

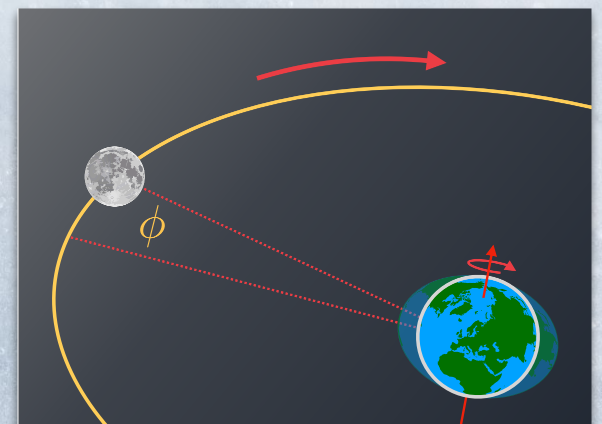
seismic spectra



$$Q^{-1} = f(\text{width of peak})$$

10^1 - 10^3 s
1200 -
4000°C
1000 km-scale

body tides

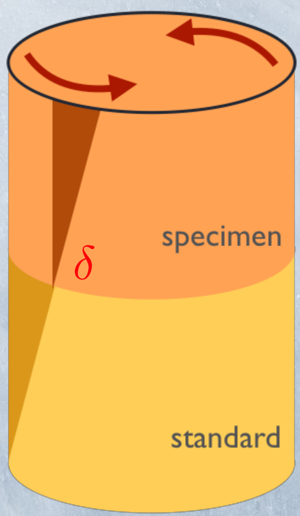


$$Q^{-1} = f(\phi)$$

10^5 - 10^8 s
1200 -
4000°C
1000 km-scale

Measures of intrinsic dissipation, Q^{-1}?

laboratory



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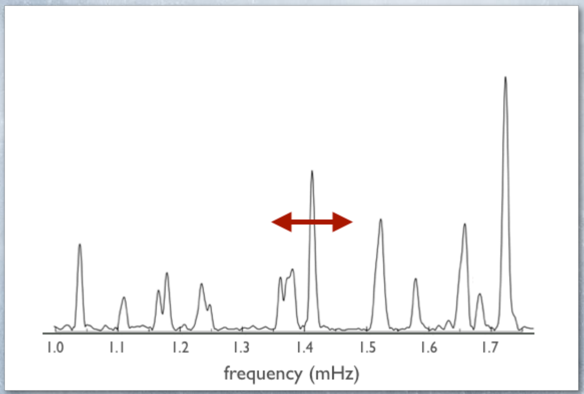

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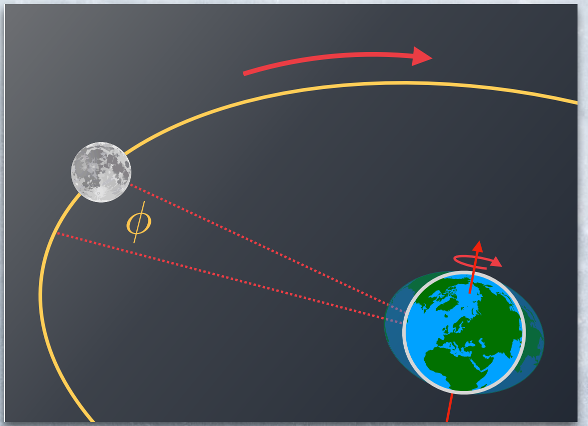

$$Q^{-1} = f(\phi)$$

10^5 - 10^8 s
1200 -
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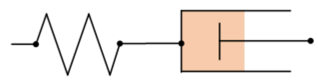
1000 km-scale

Affected by different sensitivities and dynamical effects

Phenomenological model

"Maxwell" visco-elastic model

$\omega \to \infty$

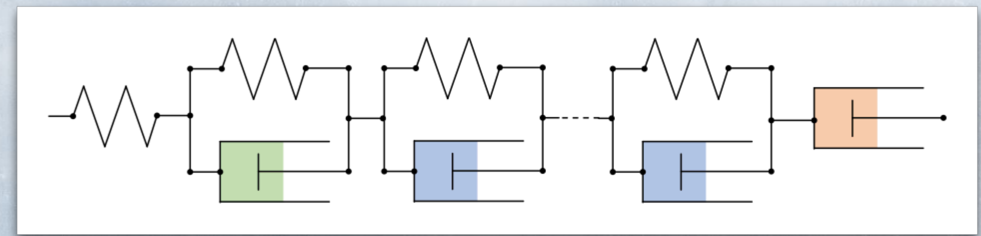


$\omega \to 0$

Insights from experiments: Phenomenological model

"Extended Burgers" visco-elastic model

$\omega \to \infty$



$\omega \to 0$

Jackson & Faul (2010)

Insights from experiments: Phenomenological model

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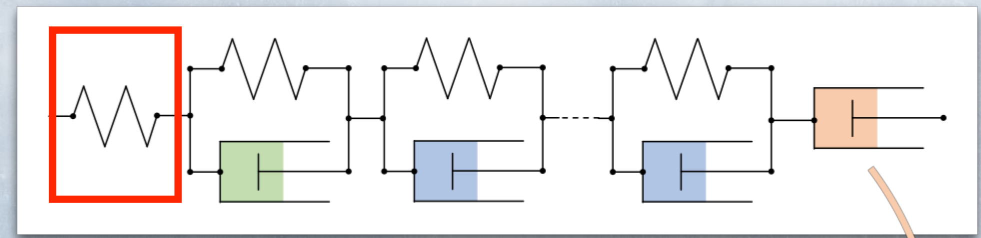

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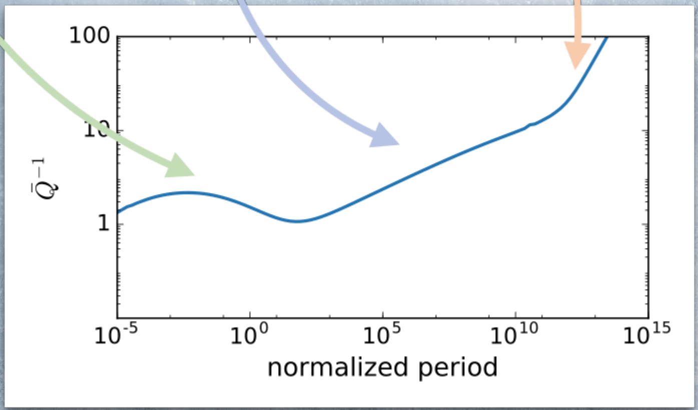


(1) No dissipation

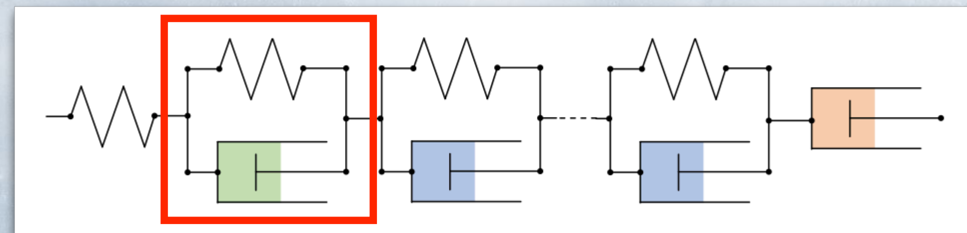
Elastic response

Jackson & Faul (2010)

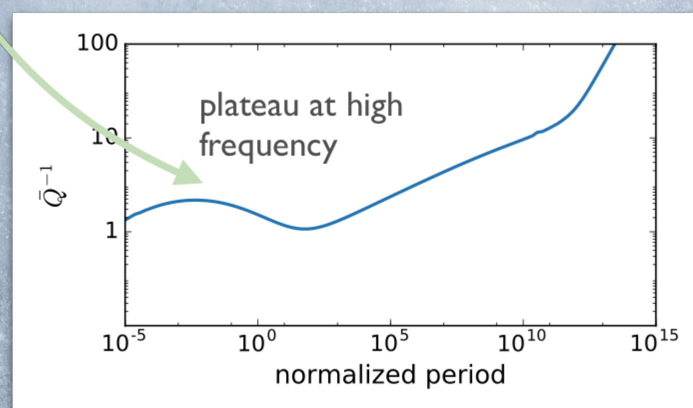
Insights from experiments: Phenomenological model

"Extended Burgers" visco-elastic model

$\omega \to \infty$



$\omega \to 0$



(2) broad, low strength, high frequency plateau

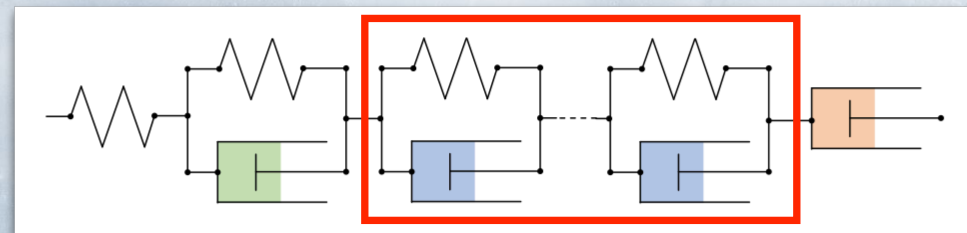
elastically accommodated grain boundary sliding, occurring at a distinct timescale

Jackson & Faul (2010)

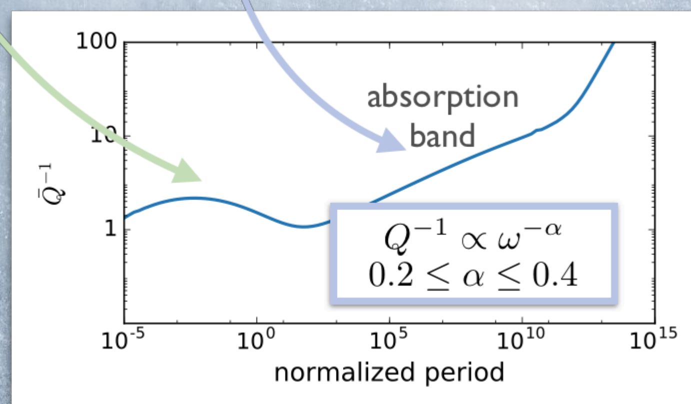
Insights from experiments: Phenomenological model

"Extended Burgers" visco-elastic model

$\omega \to \infty$



$\omega \to 0$



(3) mild constant frequency power law

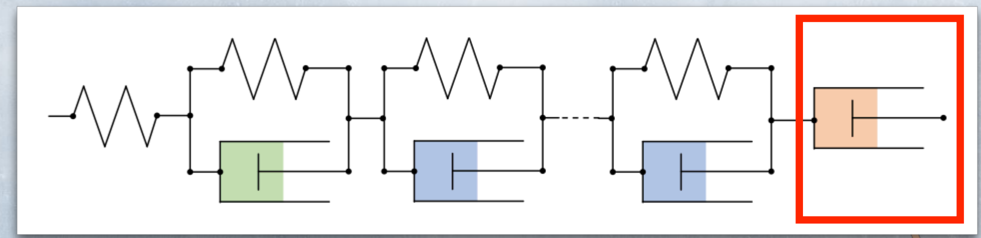
Diffusion along grain boundaries results in absorption band

Jackson & Faul (2010)

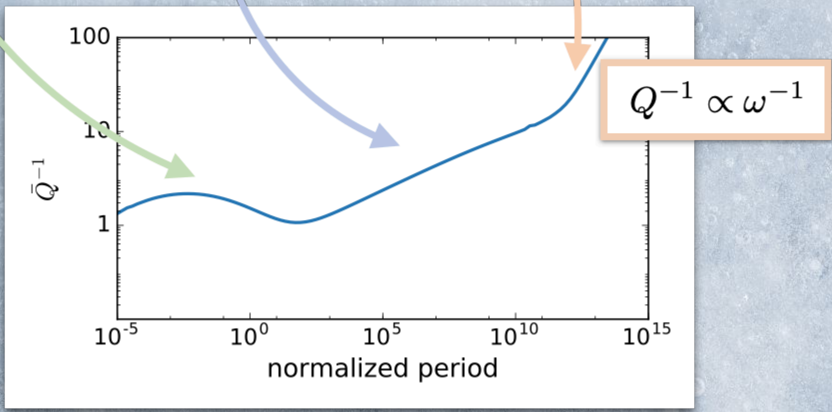
Insights from experiments: Phenomenological model

“Extended Burgers” visco-elastic model

$\omega \to \infty$



$\omega \to 0$

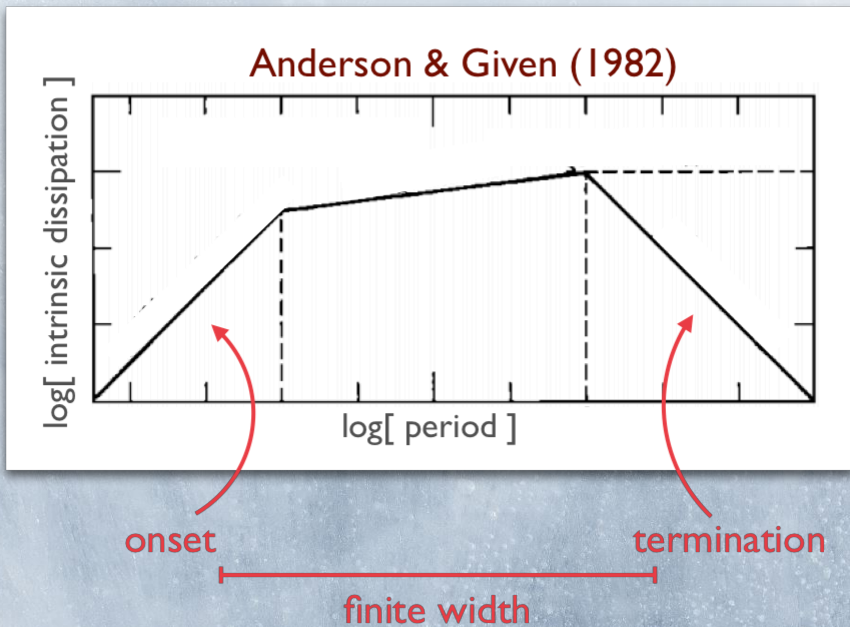


(4) Frequency dependence with dissipation becomes viscous fluid

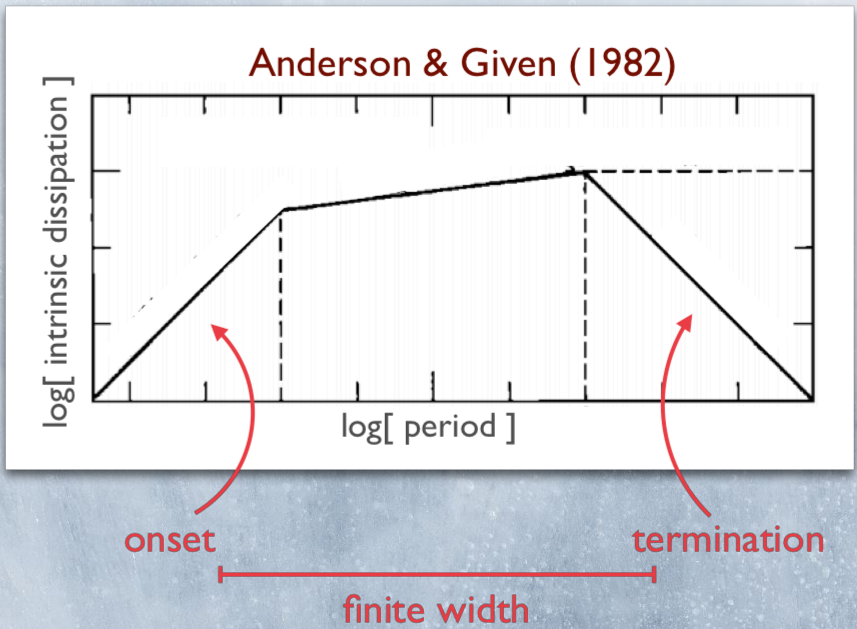
Seamless transition into steady state regime

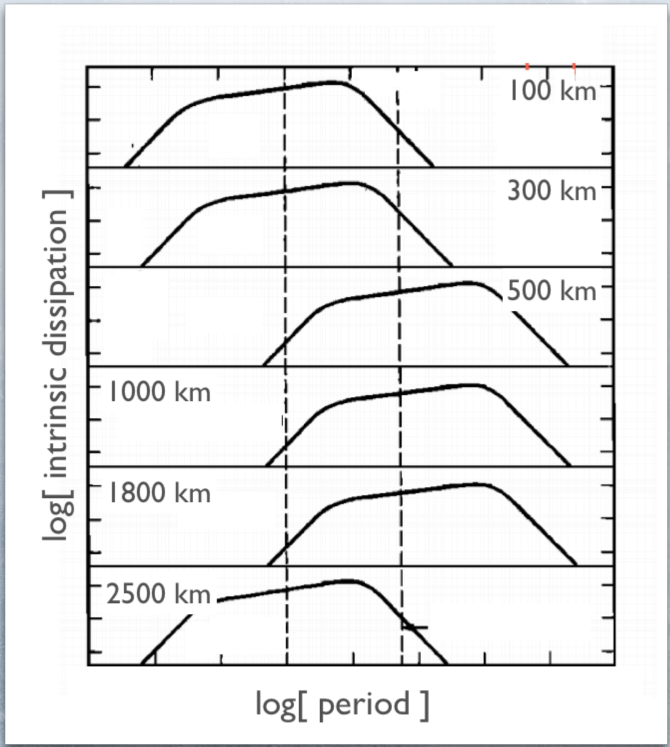
Jackson & Faul (2010)

Insights from geophysics



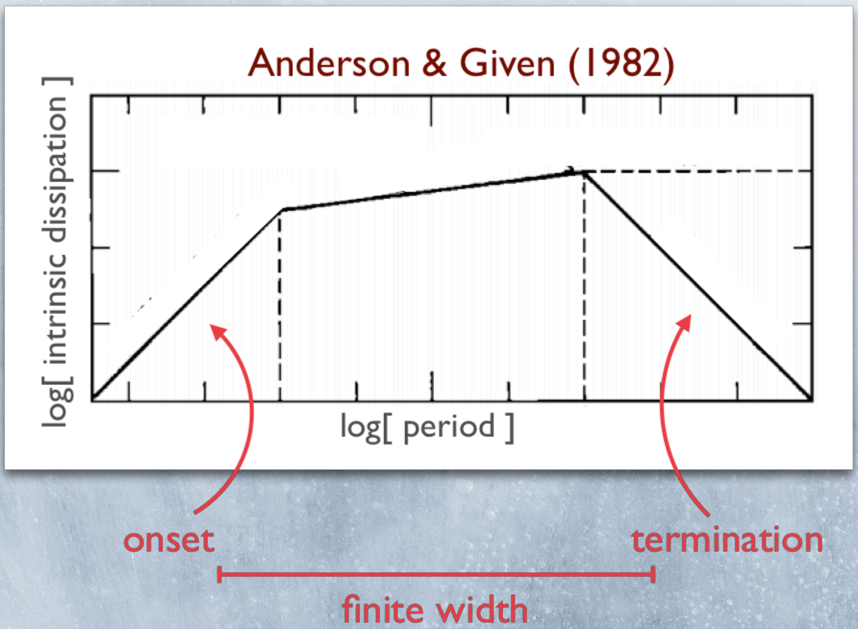
Insights from geophysics

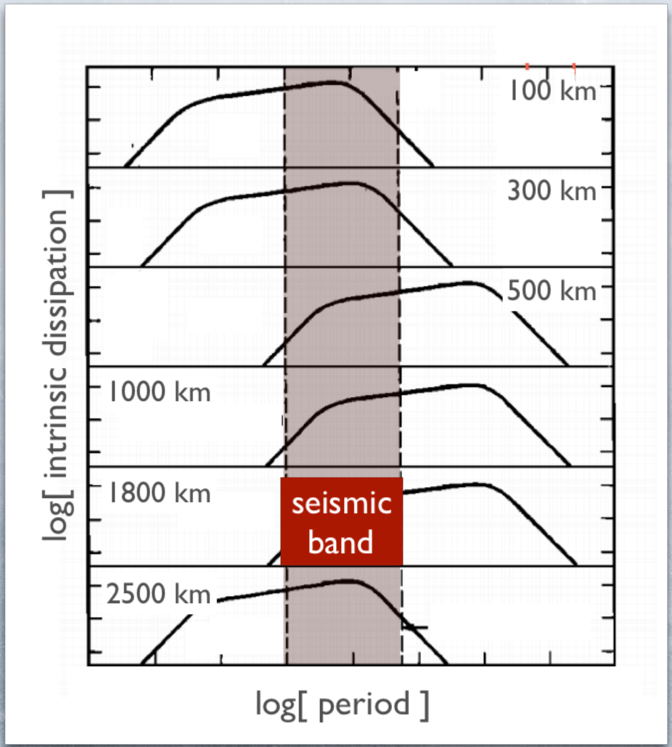




absorption band shifts with depth sensitivity of modes

Insights from geophysics





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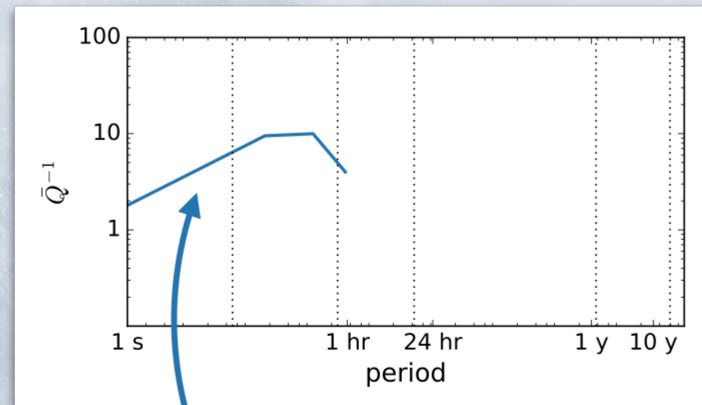
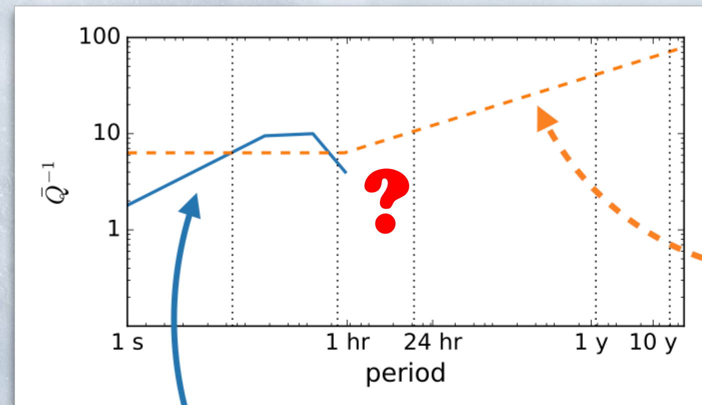


Lekic et al. (2009)
Surface and normal mode study

Insights from geophysics



Benjamin et al. (2006)
Geodetic study

Lekic et al. (2009)
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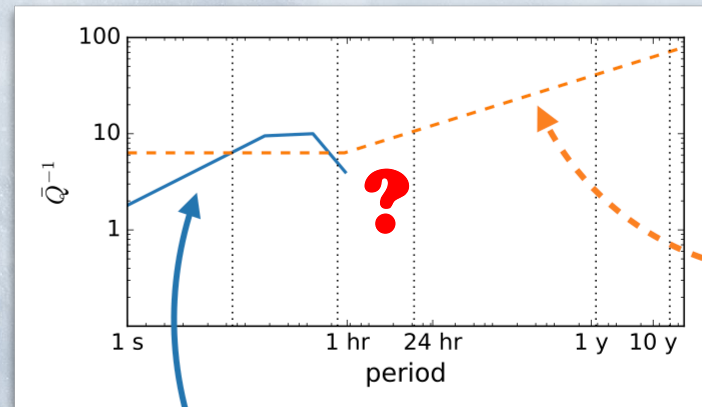

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Lekic et al. (2009)
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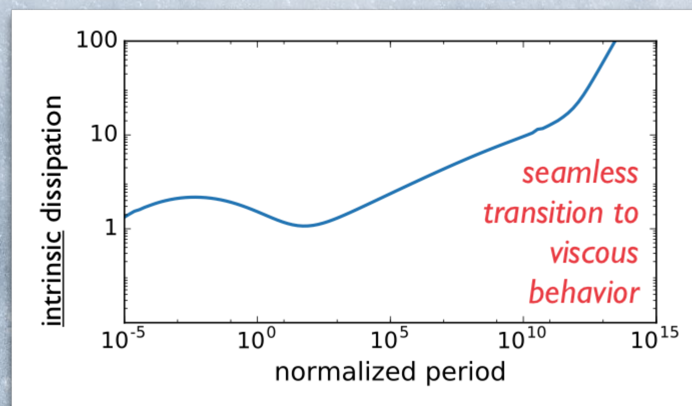
experimentally derived
(Jackson & Faul, 2010)



Our goal

Our task

Use most up to date tidal theory (Lau et al., 2015; 2017)

(2) Use a experimentally constrained viscoelastic model
(Jackson & Faul, 2010)

(3) Use the widest period band of data possible

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Use most up to date tidal theory (Lau et al., 2015; 2017)

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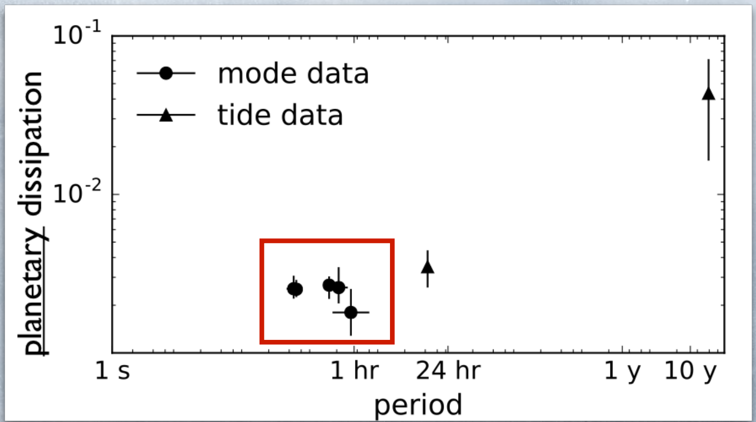
Is the absorption band finite?
If so, what is its range?
How consistent are planetary scale observations with laboratory models?

Are geophysical and experimental observations consistent?

Geophysical observations must:
sample the similar parts of Earth's mantle
span a wide enough frequency band



$Q^{-1}_{\oplus}$ = "planetary dissipation"
Planetary observation of dissipation that includes dynamical and depth sampling effects

Not the same as intrinsic dissipation

Allows mode and tide dissipation data to be placed on same figure

Seismic data: https://igppweb.ucsd.edu/~gabi/rem.html
Tidal data: Benjamin et al. (2006)

Lau & Faul (2019)

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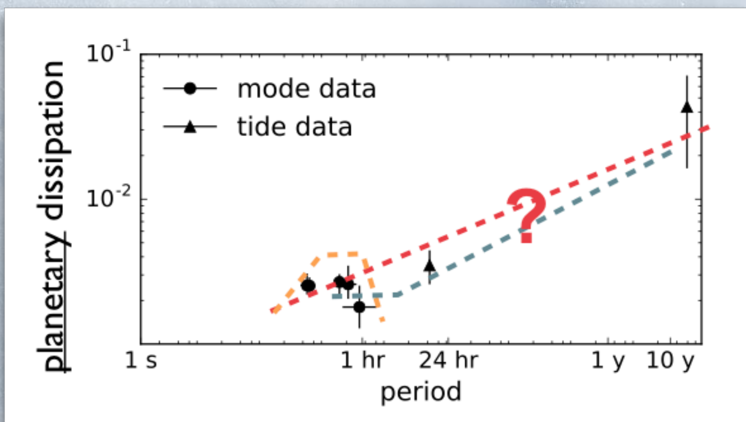
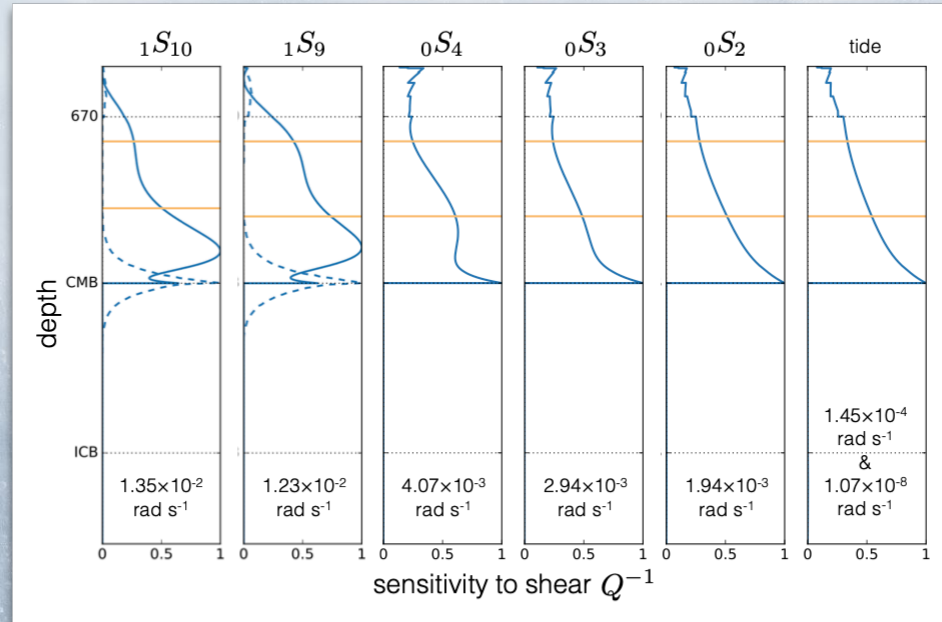




frequency dependence can't be fit by single straight line

Seismic data: https://igppweb.ucsd.edu/~gabi/rem.html
Tidal data: Benjamin et al. (2006)

Lau & Faul (2019)

Methodology

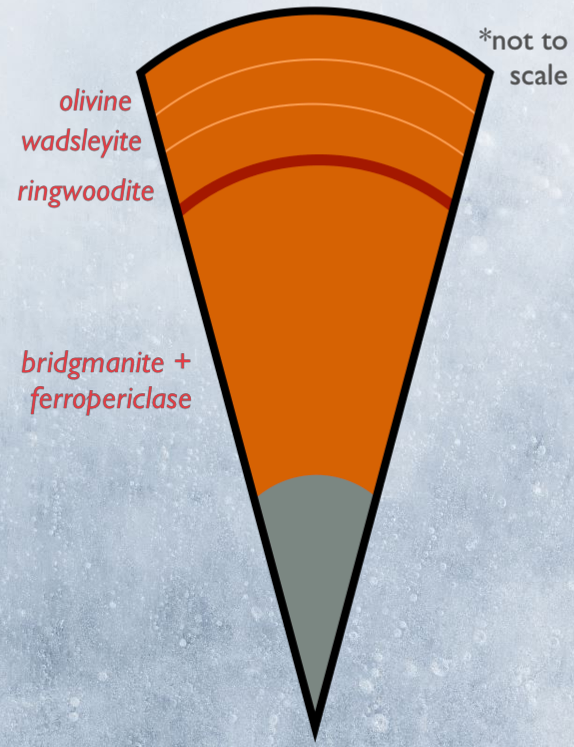
Modelling

(1)Take 4 major mantle mineral assemblages and assuming an adiabatic profile

(2) Impose viscoelastic model using the Extended Burgers model as in Jackson & Faul (2010)

(3) Leave 5 free parameters in the lower mantle:
Potential Temperature
Strength of high frequency plateau
Grain size
Strength of absorption band
Activation volume

(4) Predict normal mode and tidal planetary dissipation using updated theory



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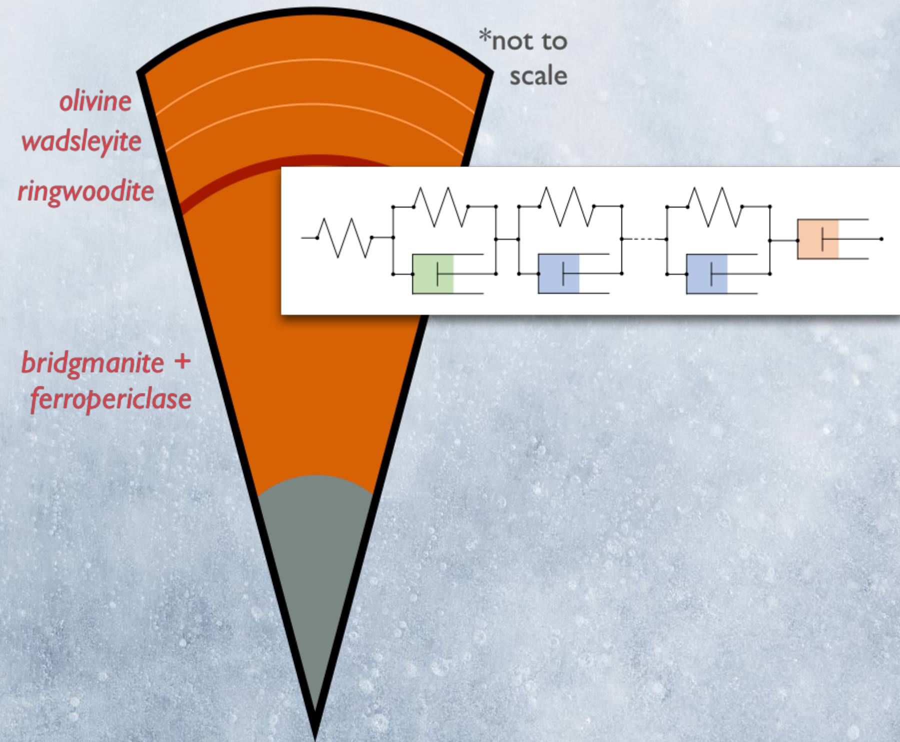

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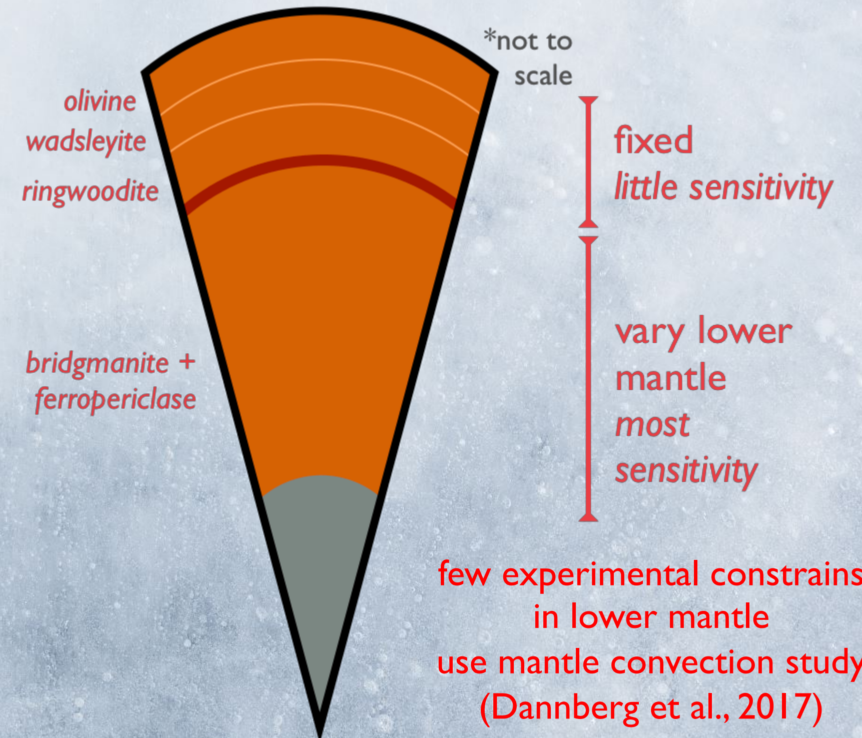

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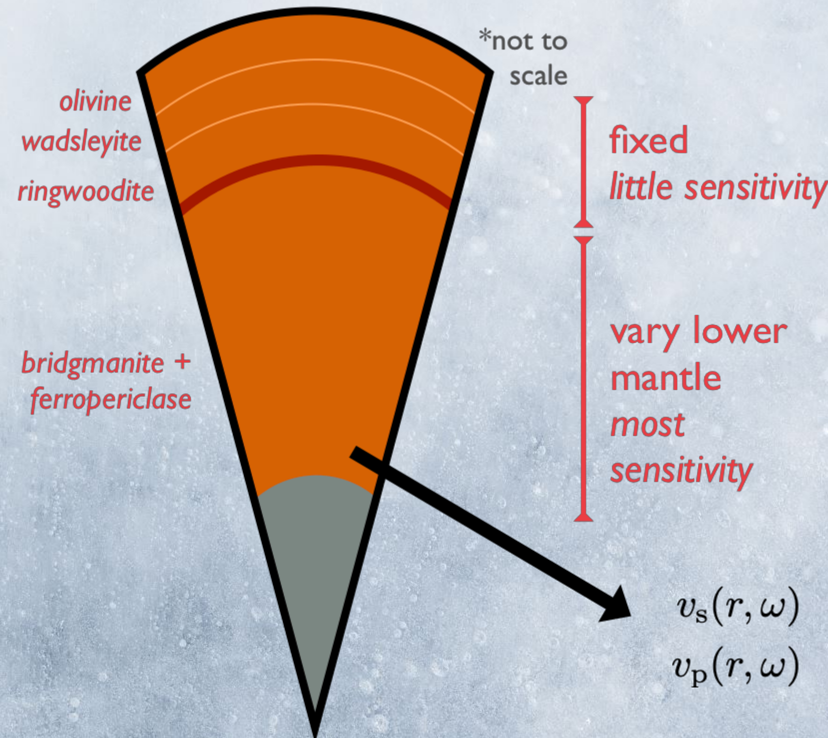
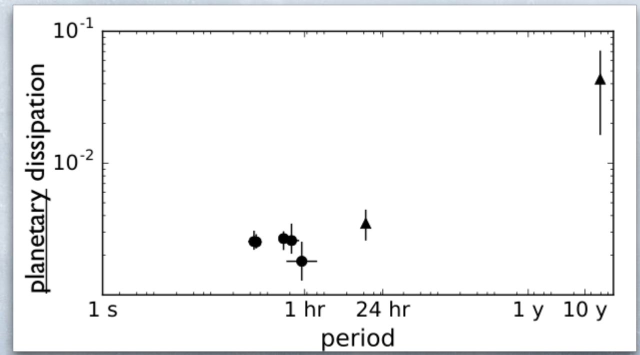


Lau & Faul (2019)

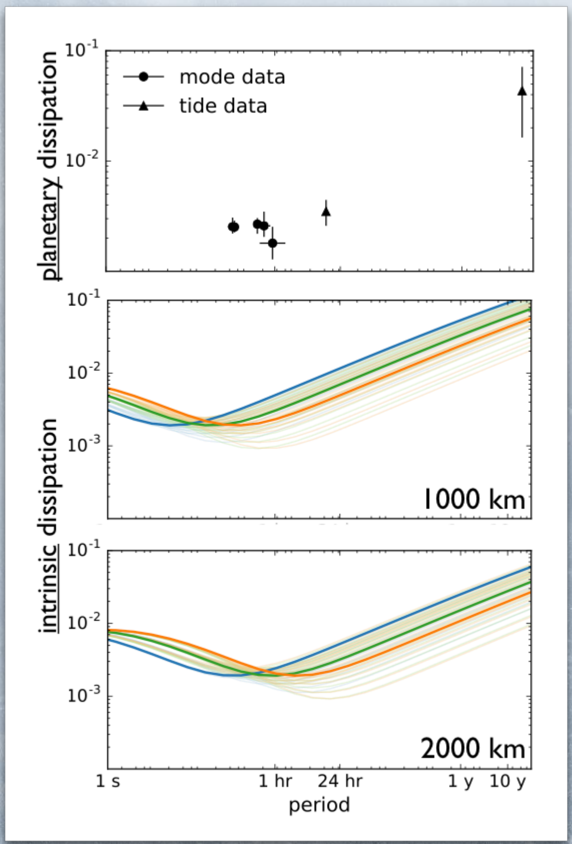
Results



No single slope can explain this trend

Lau & Faul (2019)

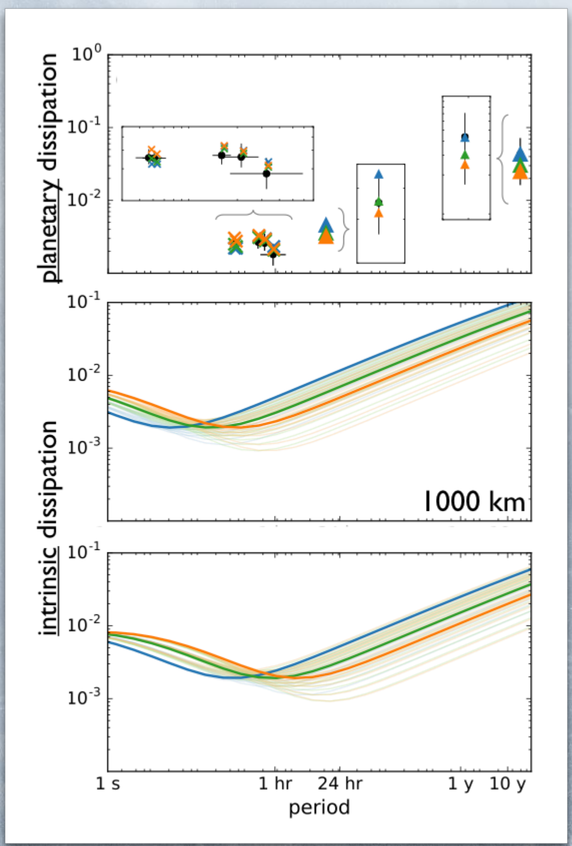
Results



intrinsic dissipation shows transitions in slope at the right periods …

Lau & Faul (2019)

Results



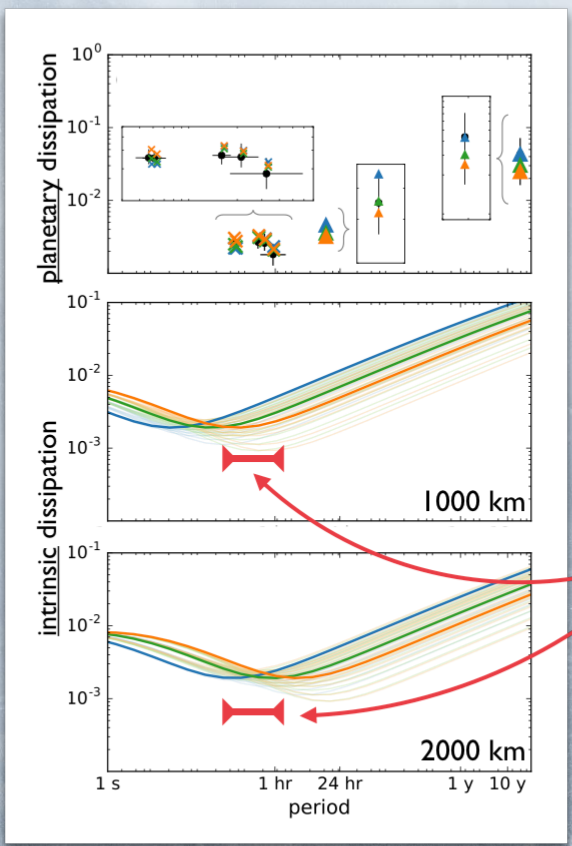
colored symbols: modeled planetary dissipation

intrinsic dissipation shows transitions in slope at the right periods …

…and planetary dissipation, when modeled correctly, can reproduce the data

Lau & Faul (2019)

Results

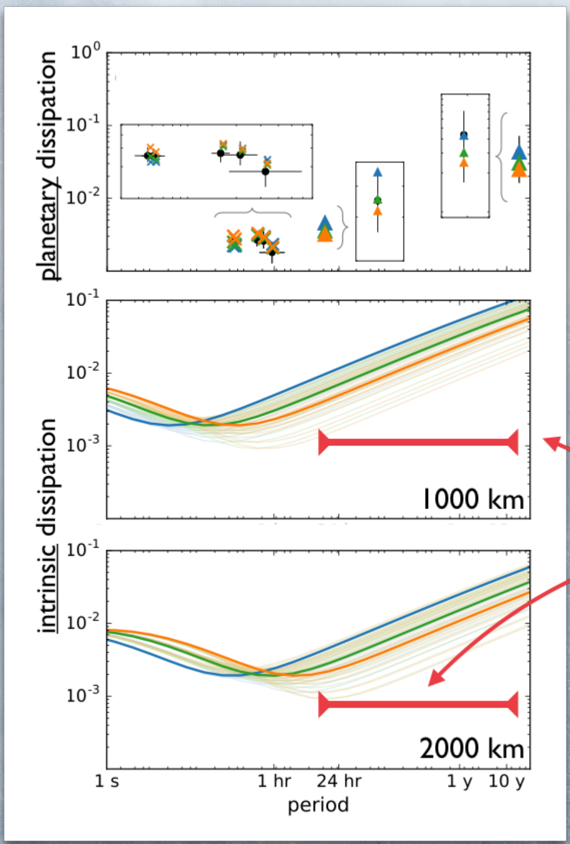


colored symbols: modeled planetary dissipation

modes sample transition between high frequency plateau and absorption band

Lau & Faul (2019)

Results

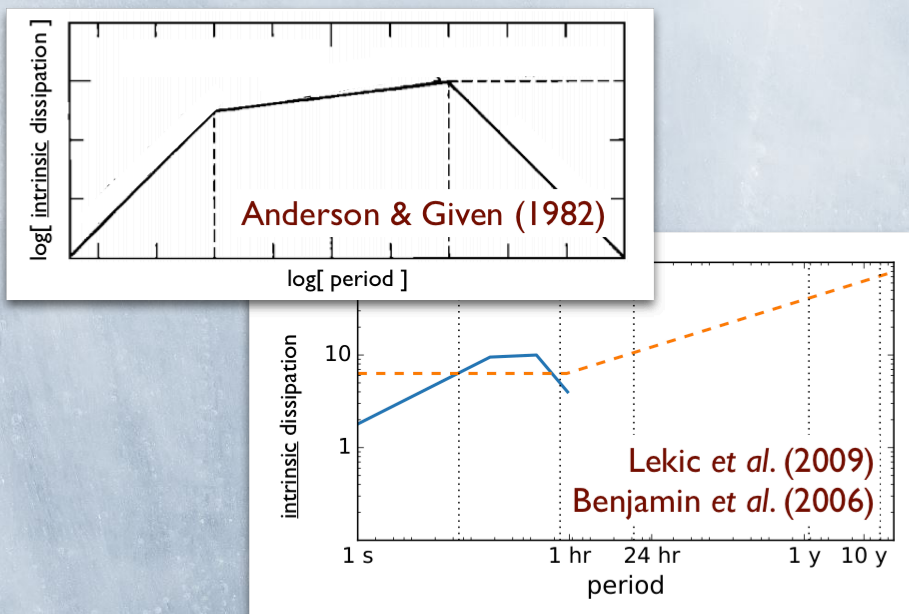


colored symbols: modeled planetary dissipation

Tides sample absorption band but periods are too short to sample viscous regime

Lau & Faul (2019)

Results

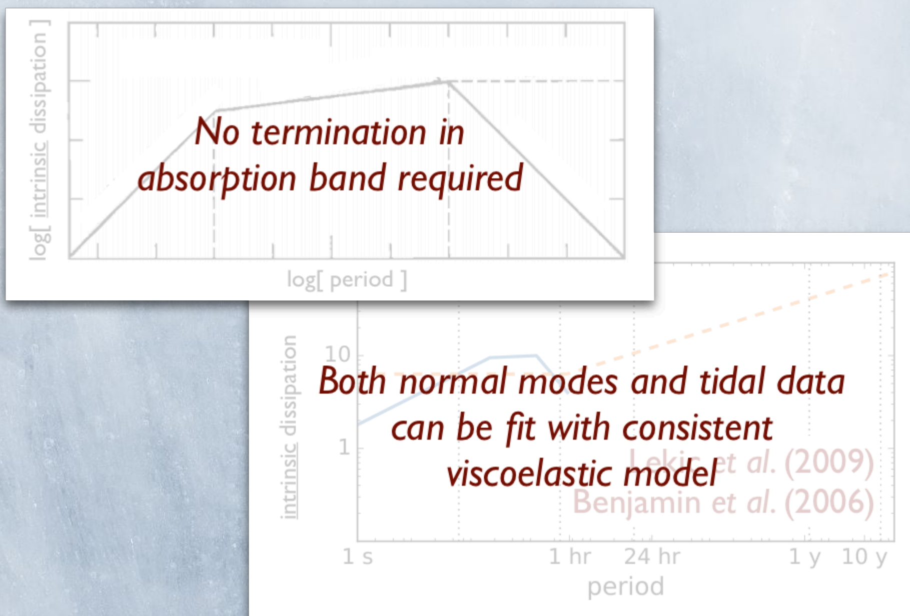


previous pictures of intrinsic dissipation

- finite absorption band
- conflicting trends between seismic and tidal data

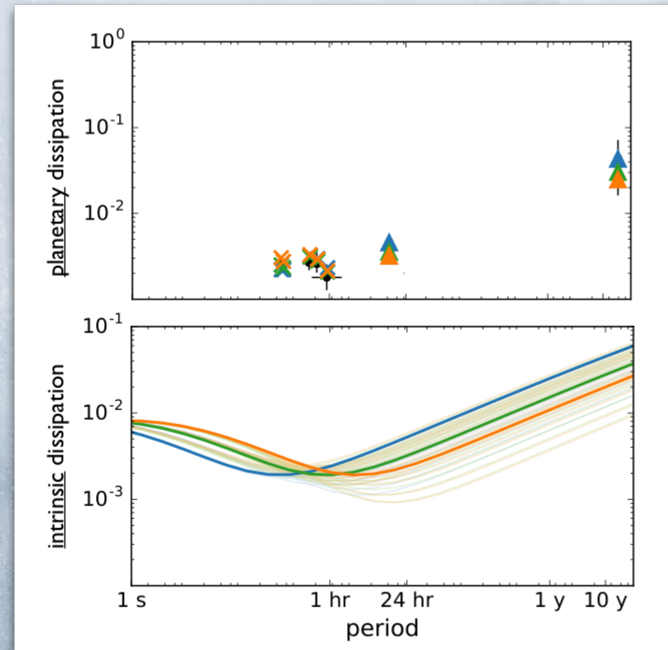
Lau & Faul (2019)

Results



No termination in absorption band required

Both normal modes and tidal data can be fit with consistent viscoelastic model



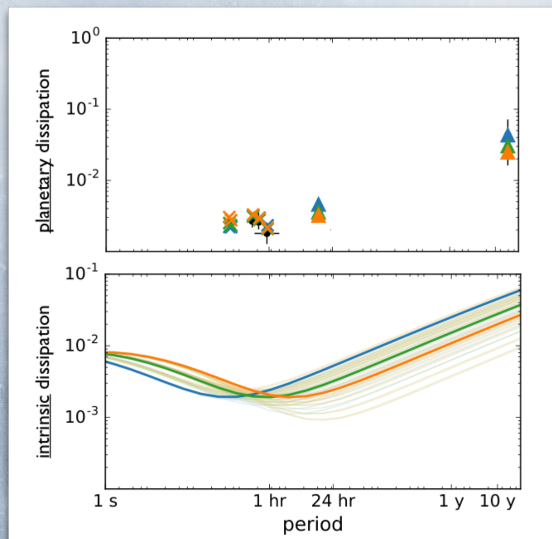
Lau & Faul (2019)

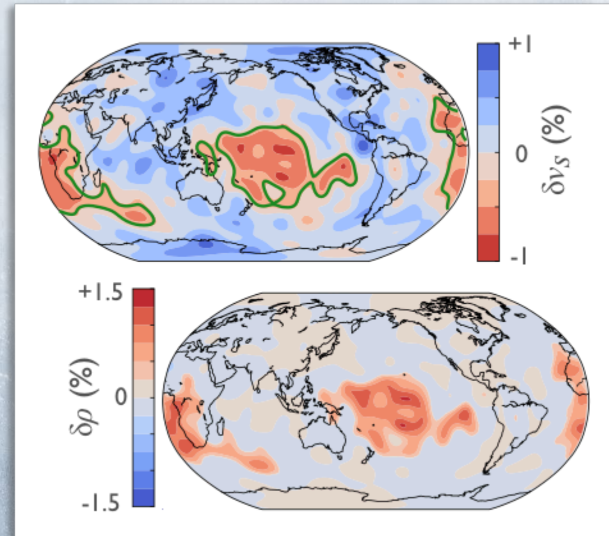
Thank you

Harriet C.P. Lau
(hcplau@berkeley.edu)

Hsin-Ying Yang
Jerry X. Mitrovica
Jeroen Tromp
David Al-Attar
Jim Davis
Konstantin Latychev
Ulrich Faul

Tidal constraints on frequency dependent rheology





Tidal constraints on deep mantle buoyancy

Lau *et* al. (2017); Lau & Faul (2019)