Lower Mantle Structure & Geo-neutrinos

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Motivation

- Variations of material properties (rigidity, incompressibility, and density) in the Earth's interior relate to compositional variations, and may represent a reservoir enriched in heat producing elements (U,Th, K)

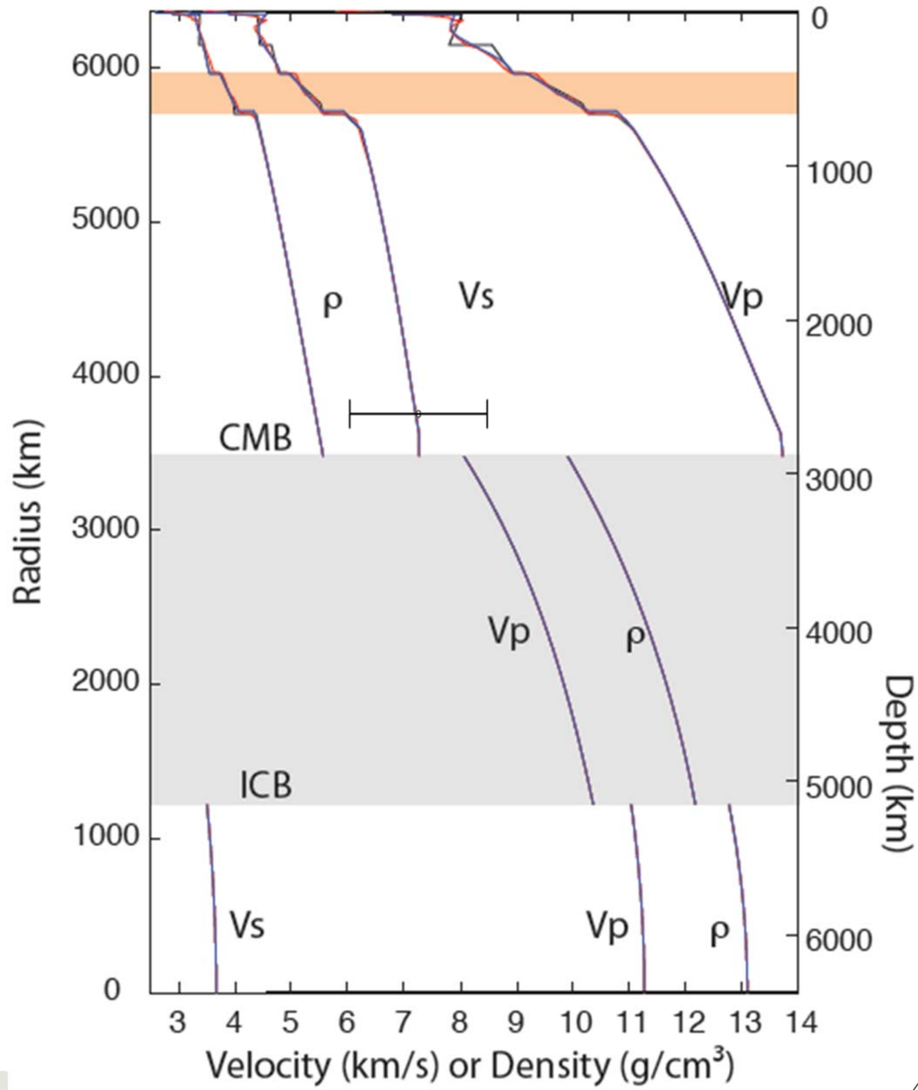
- Three main types of lower mantle structure:
  - Large-scale lower mantle structure: Large Low Shear Velocity Provinces (LLSVPs, a.k.a. "superplumes")
  - Small-scale lower mantle structure: Ultra Low Velocity Zones (ULVZs)
  - Meso-scale lower mantle structures: Permian Anomaly and Mega-ULVZs.

Structure of Earth's deep interior

- Seismic waves emitted by earthquakes, explosions, and/or ocean waves travel across and through the Earth.
- Velocities of the two basic types of waves – compressional (P) and shear (S) – are affected by variations in density, rigidity (shear modulus) and incompressibility (bulk modulus).
- Travel-times and waveforms of waves taking various paths through the Earth can be used to image the structure of the deep interior.

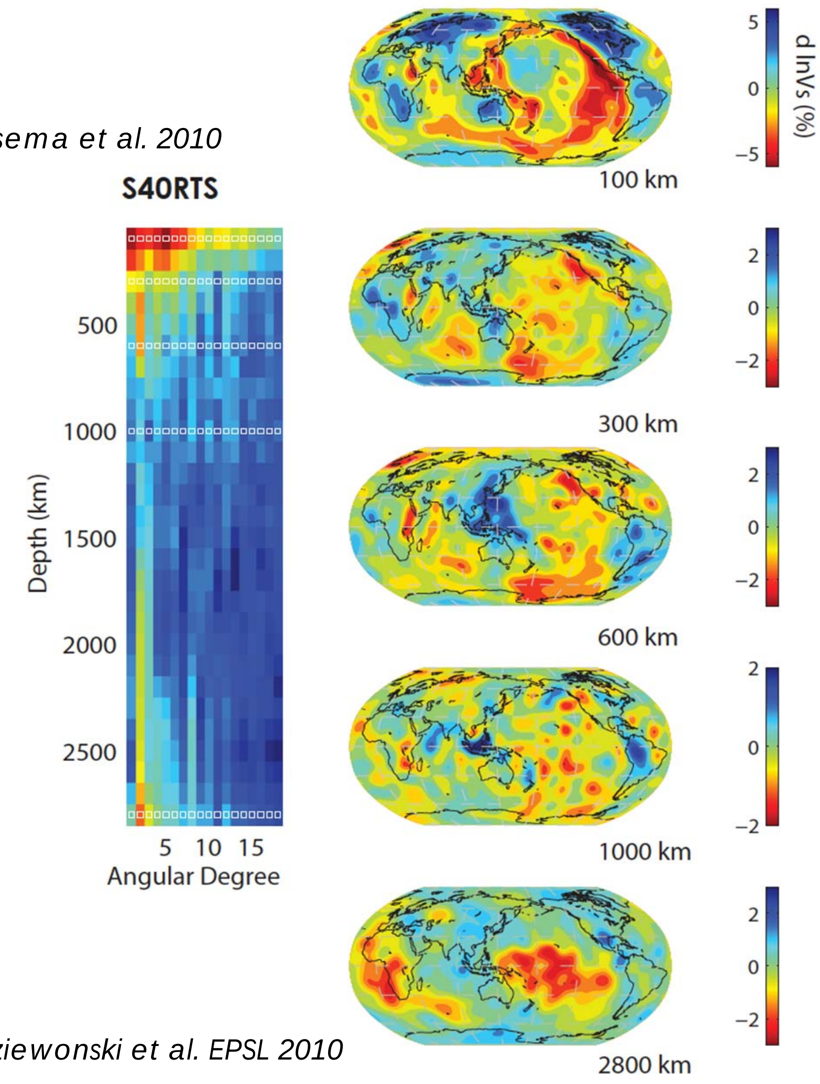
Radial structure

- A number of 1D Earth models have been developed: PREM (Dziewonski and Anderson, 1981), ak135 (Kennett et al., 1995), IASP91 (Kennett and Engdahl, 1991).
- None of these models have well-quantified uncertainties
- Lateral variations in structure are larger than uncertainties on average structure at a given depth:
  - Some models (e.g. ak135, IASP91) are not true global averages → biased toward continental structure, and should be used with caution;
  - 3D models are better suited for mineralogical / thermal interpretation



Large scale mantle structure

Ritsema et al. 2010



after Dziewonski et al. EPSL 2010

- Different depths in the mantle have distinct spatial characteristics in Vs global tomographic models:
- **Heterosphere** – upper 250 km where tectonic signals dominate: ±10% Vs variations
- **Transition Zone** – signal of slabs in Western Pacific and slow anomalies related to hot spots: ±3% Vs variations
- **Mid mantle** – smaller amplitudes and lengthscales of heterogeneity: ±1% Vs variations
- **Lower-most mantle** – dominance of degree 2 structure consisting of pair of antipodal LLSVPs surrounded by a ring of faster-than-average Vs: ±5% Vs variations

Large scale lower mantle structure

(a) S362ANI – *Kustowski et al 2008*

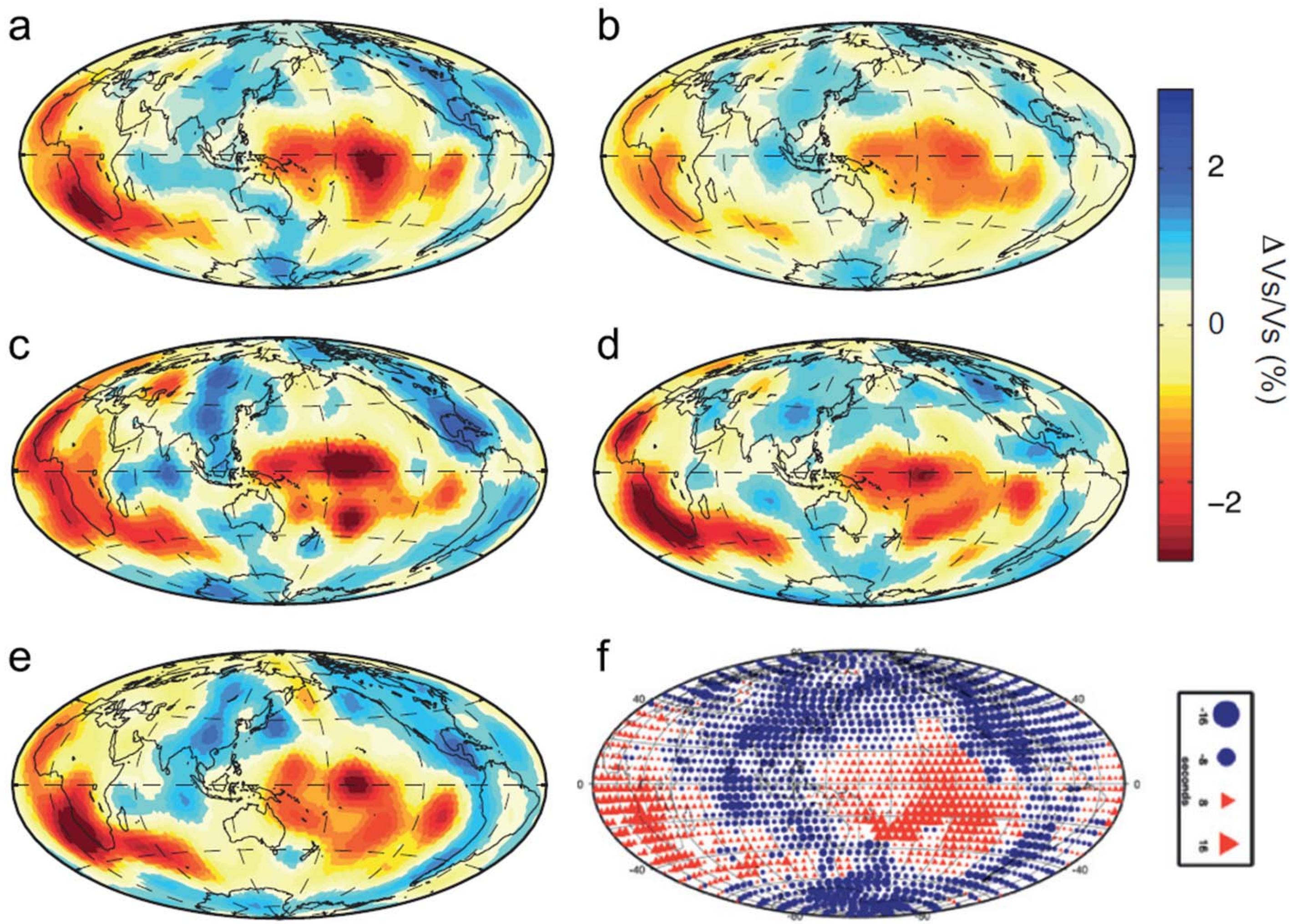
(b) S40RTS – *Ritsema et al 2011*

(c) SAW24B16 – *Megnin & Romanowicz 2000*

(d) HMSL-S – *Houser et al 2008*

(e) GyPSuM – *Simmons et al 2010*

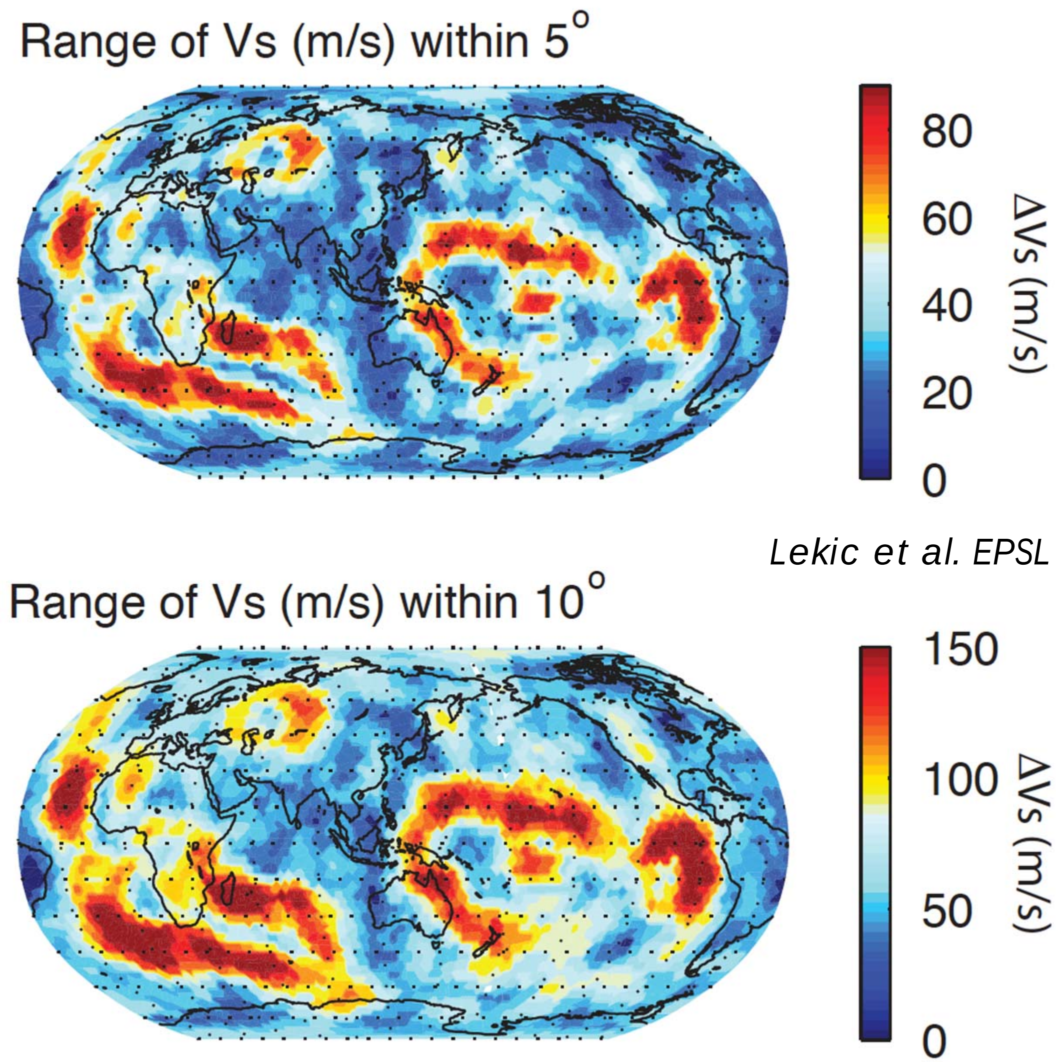
(f) Data – *Manners 2008*



Horizontal Gradients of Vs

LLSVPs appear to be bounded by steep lateral gradients in Vs

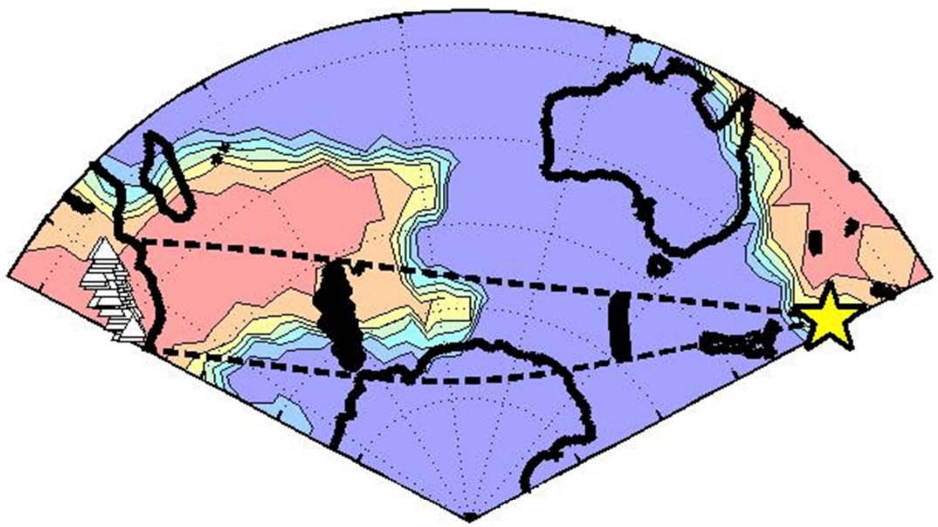
Remarkable uniformity of large-scale structure both within the LLSVPs and within the faster-than-average regions



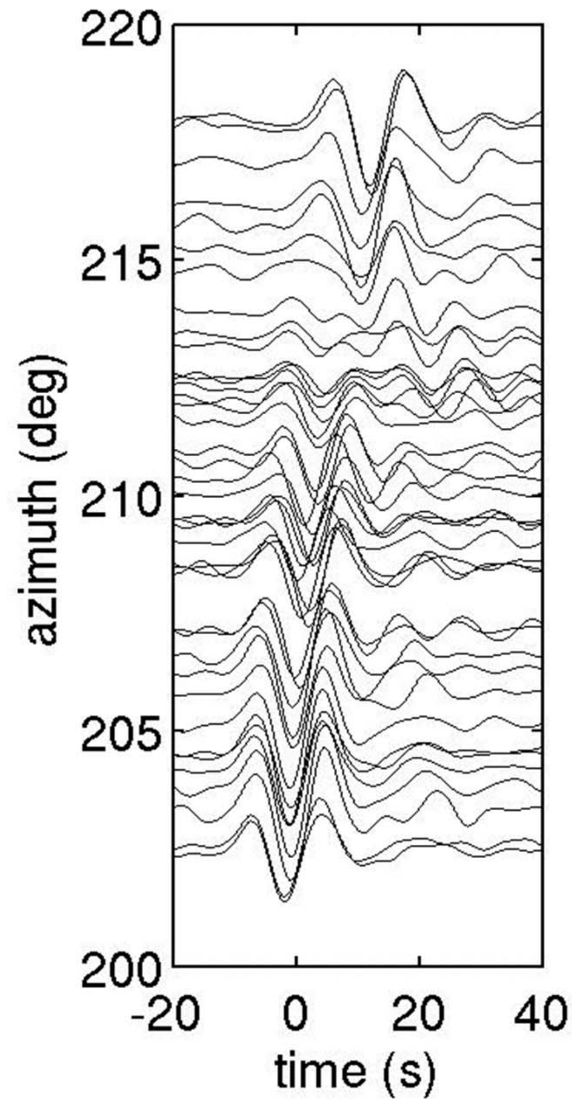
Lekic et al. EPSL 2012

LLSVPs have sharp boundaries

- Deep event in Fiji recorded at Kaapvaal Array in Southern Africa

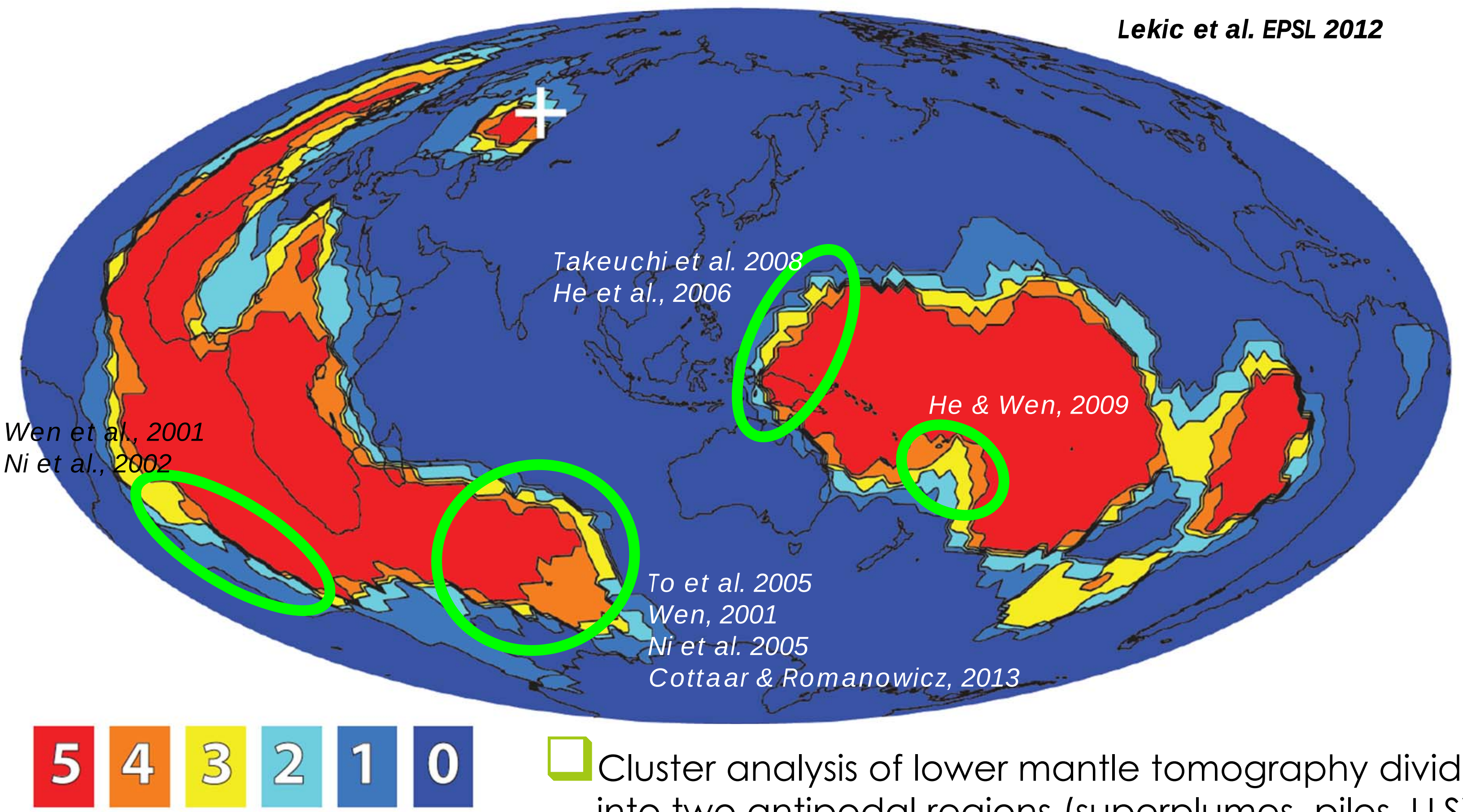


- Boundary modeled with an abrupt ~4.5% velocity jump



[To et al. 2005]

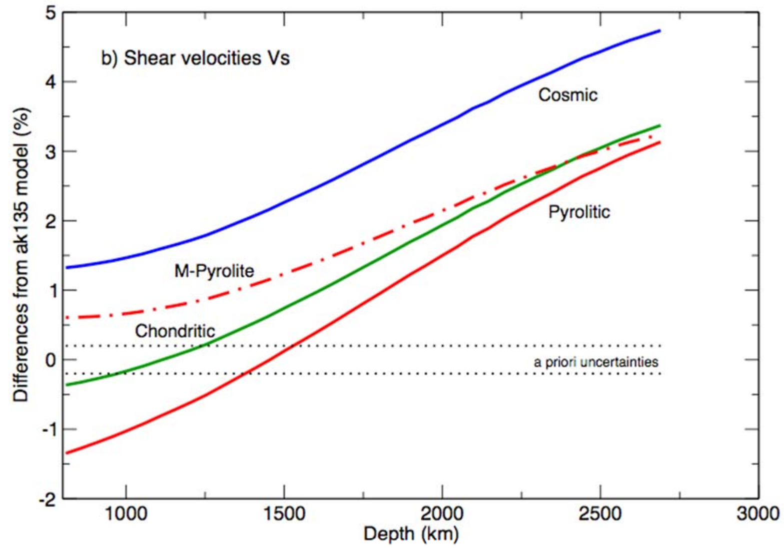
Cluster analysis of lower mantle



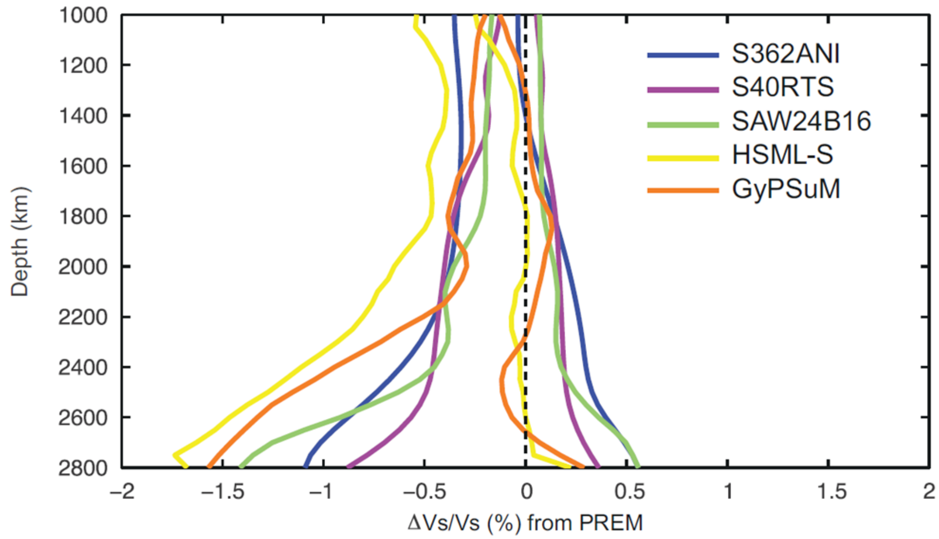
- Cluster analysis of lower mantle tomography divides mantle into two antipodal regions (superplumes, piles, LLSVPs) and a contiguous circumpolar torus of faster-than-average Vs.
- Remarkable inter-model consistency, especially along LLSVP boundaries

Vs characteristics of clusters

- Average Vs profiles of fast and slow clusters differ by >0.5% 1200 km up from the CMB.
- Differences increase abruptly starting at ~2200 km depth.
- Deviation of slow clusters is more pronounced resulting in significantly reduced dVs/dz w.r.t PREM.
- Differences between average Vs profiles span the range of predictions for end-member mantle compositions (at the same T conditions)



Matas et al. 2007



Volume of LLSVPs

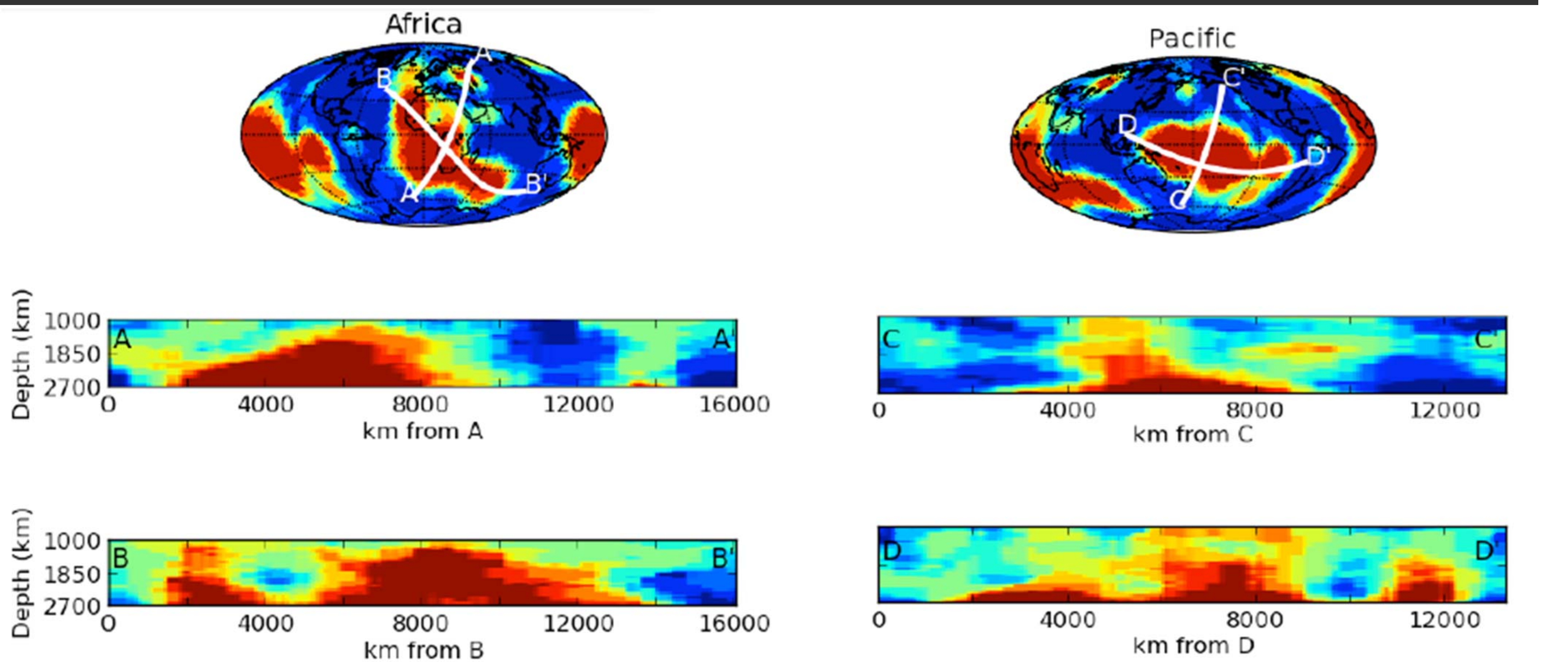
- Estimates of LLSVP volume vary:
  - Waveform analyses limited in depth and lateral coverage: 1.2 % of mantle volume (Wang & Wen, 2004)
  - Volume from tomographic models depends on Vs isocontour one chooses to define the LLSVPs.

Šrámek et al. 2012 (EPSL)

Table 5
Mass fraction and enrichment factors for the enriched mantle reservoir obtained for various δV_s cut-off contours in the TOMO model.

δV_s cut-off (%)	EM mass. frac. (%)	Enrichment factor		
	F^{EM}	E_U	E_{Th}	E_K
−0.25	9.5	6.3	12	3.8
−0.50	4.4	13	26	7.0
−0.75	1.8	30	63	16
−1.00	0.71	72	155	38

Volume of LLSVPs

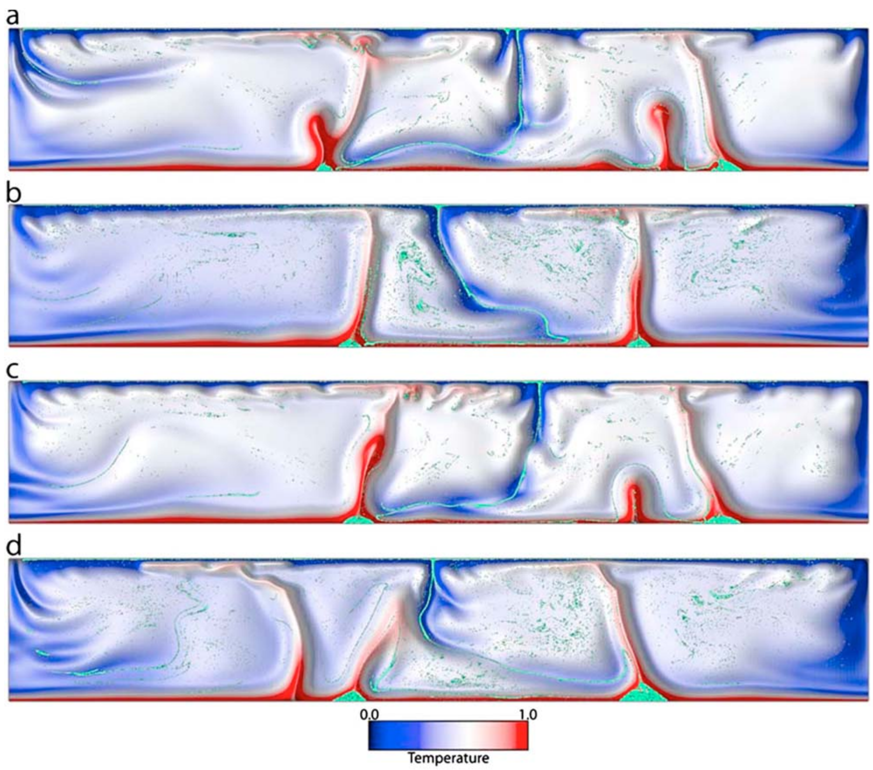


Model name	LLSVP (%)	Pacific LLSVP (%)	African LLSVP (%)
S362ANI	6.3	1.5	4.8
S40RTS	7.0	3.6	3.4
SAW24B16	5.9	2.0	3.8
HMSL-S	4.7	2.4	2.3
GyPSuM	5.0	2.3	2.7

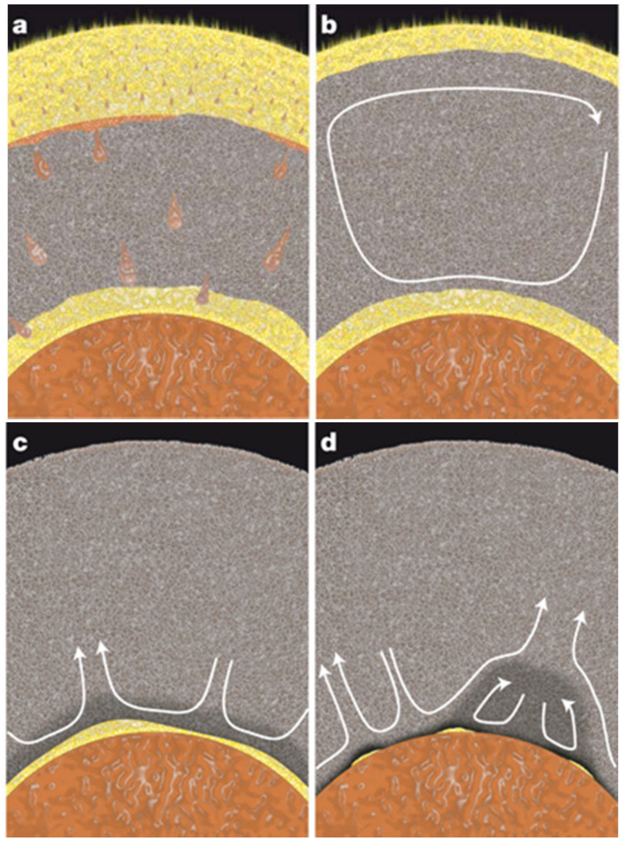
Cottaar & Lekić, 2014

Origin of LLSVPs

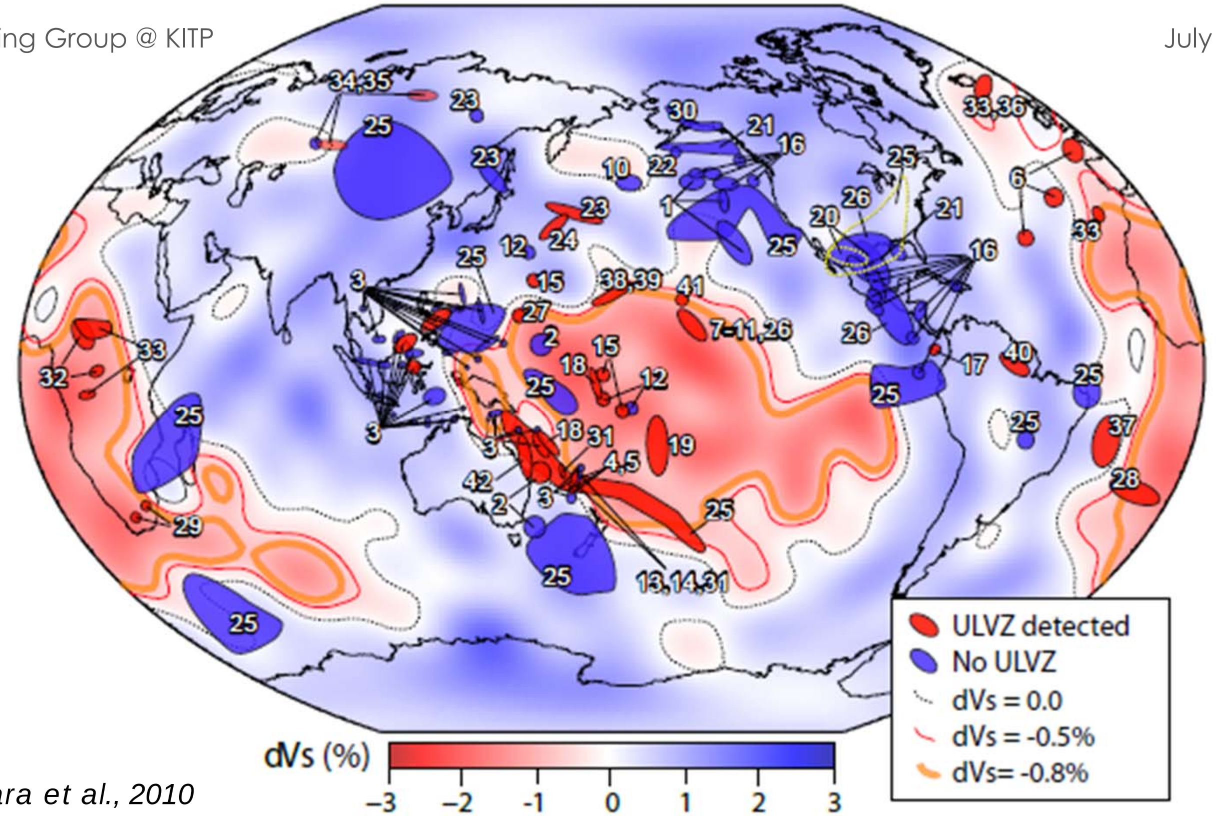
- Accumulation of subducted oceanic crust
- Remnants of a basal magma ocean



[Li and McNamara, 2013]



[Labrosse et al. 2007]



McNamara et al., 2010

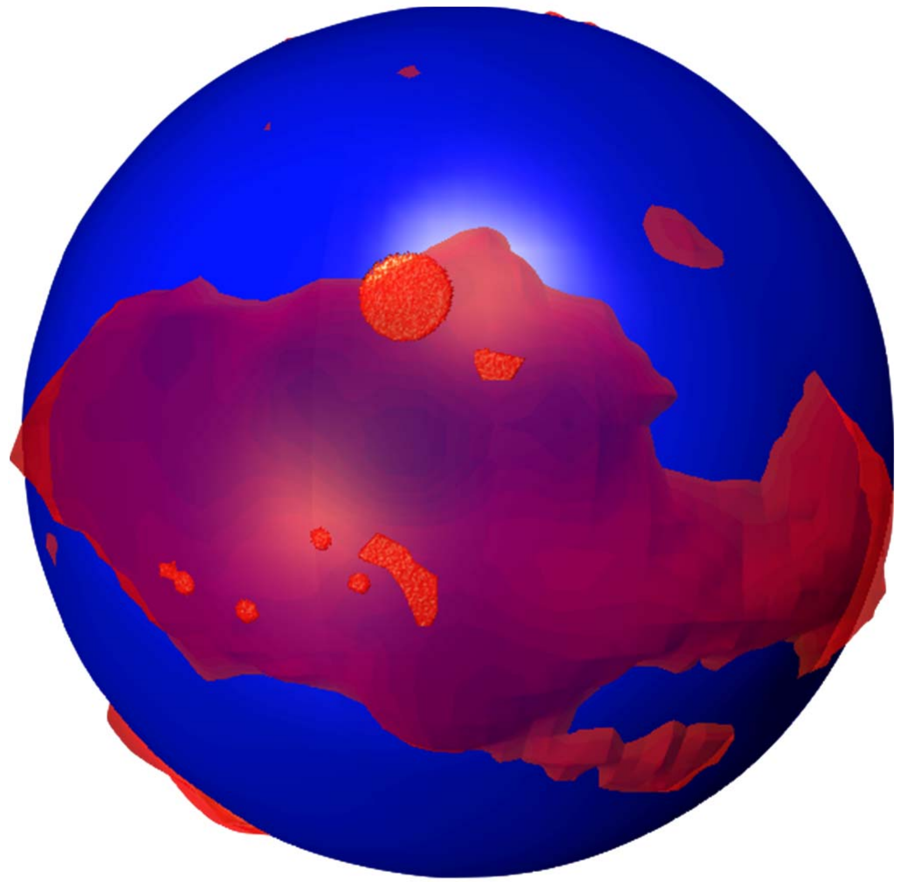
Ultra Low Velocity Zones

ULVZs are small (~10 km tall, ~100 km across) dense (~10%), slow (>10% reduction) anomalies

Might be preferentially associated with the edges of the LLSVPs

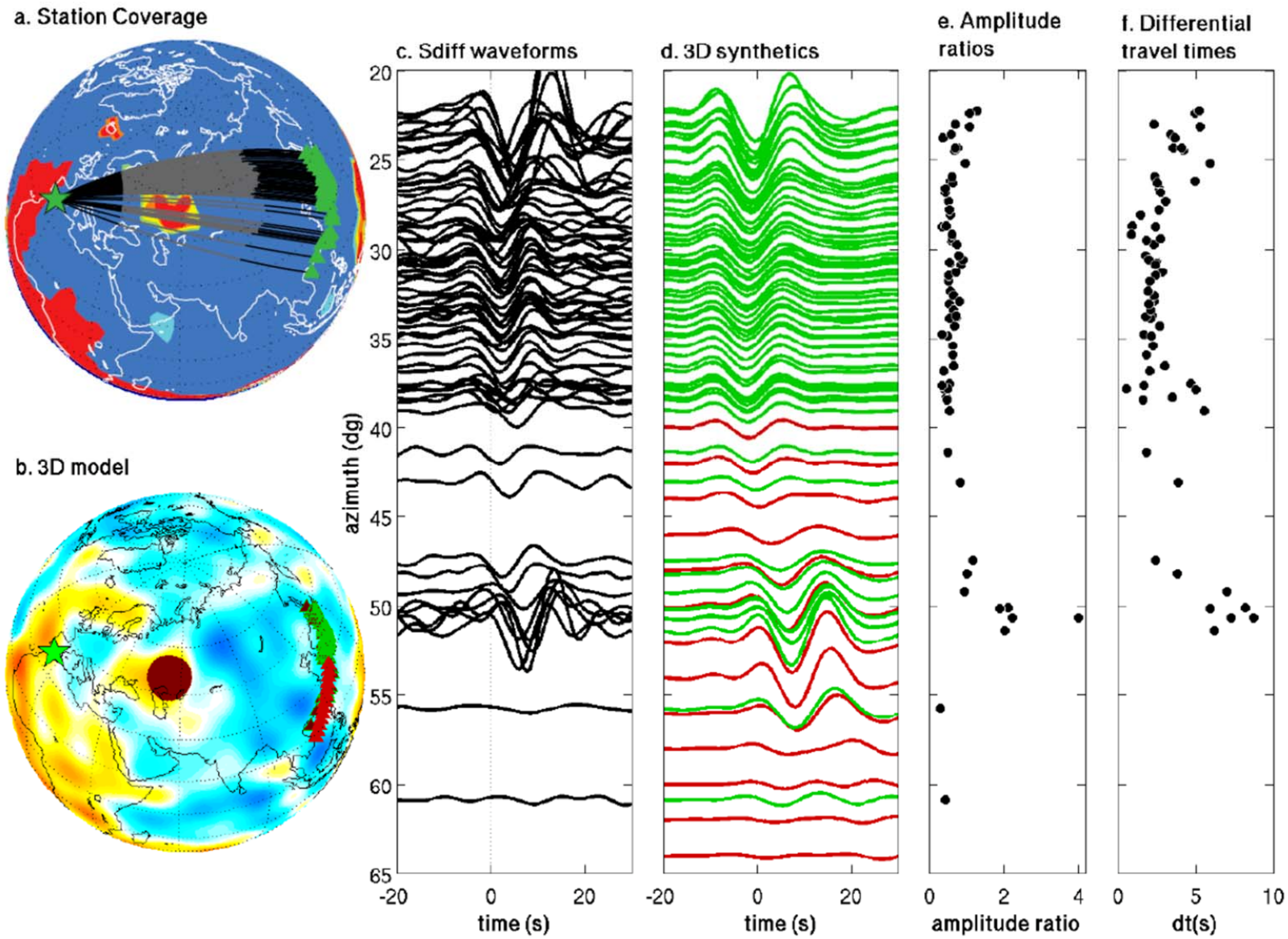
Origin of ULVZs

- Iron enrichment (Wicks et al. 2010), partial melt (Williams & Garnero 1996), or both
- Possible remnant from a basal magma ocean (Labrosse et al. 2007) or could be from the outer core (Otsuka & Karato, 2012)
- What processes lead to differences in size?



[McNamara et al. 2010, Hutko et al. 2009, Rost et al. 2010, Thorne et al. 2013]

"Perm Anomaly" – a mini LLSVP



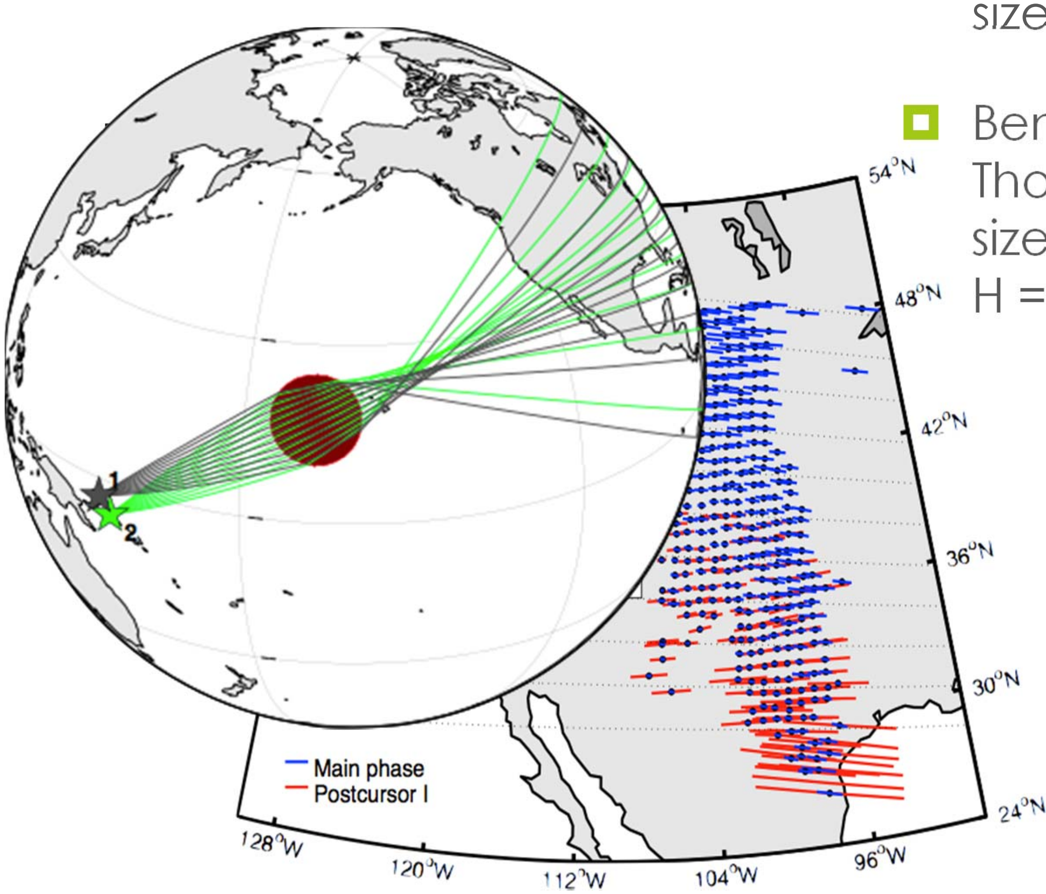
Lekic et al. EPSL 2012

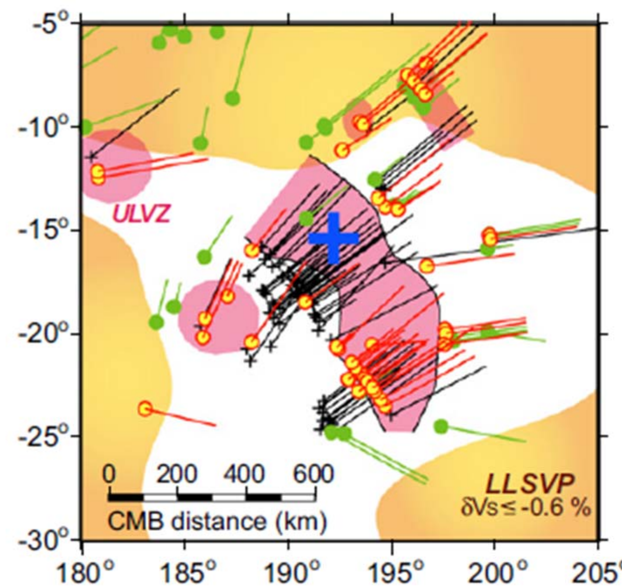
- Transverse-component velocity waveforms from the 4/11/2010 Spain event
- Stations in 91° -102° epicentral distance range
- S/Sdiff waveforms show amplitude focusing and travel-time delays
- Lack of anomalous amplitudes/travel-times to the North confirms that Perm Anomaly is not connected to the African LLSVP

Mega Ultra LVZs!

- Beneath Hawai'i, Cottaar and Romanowicz (2012) find a Texas-size ULVZ

- Beneath the central Pacific LLSVP, Thorne et al. (2013) find a Florida-size ULVZ: Vs -45%, Vp -15%, ρ +10%, H = 10-15 km.





Thorne et al. (2013)

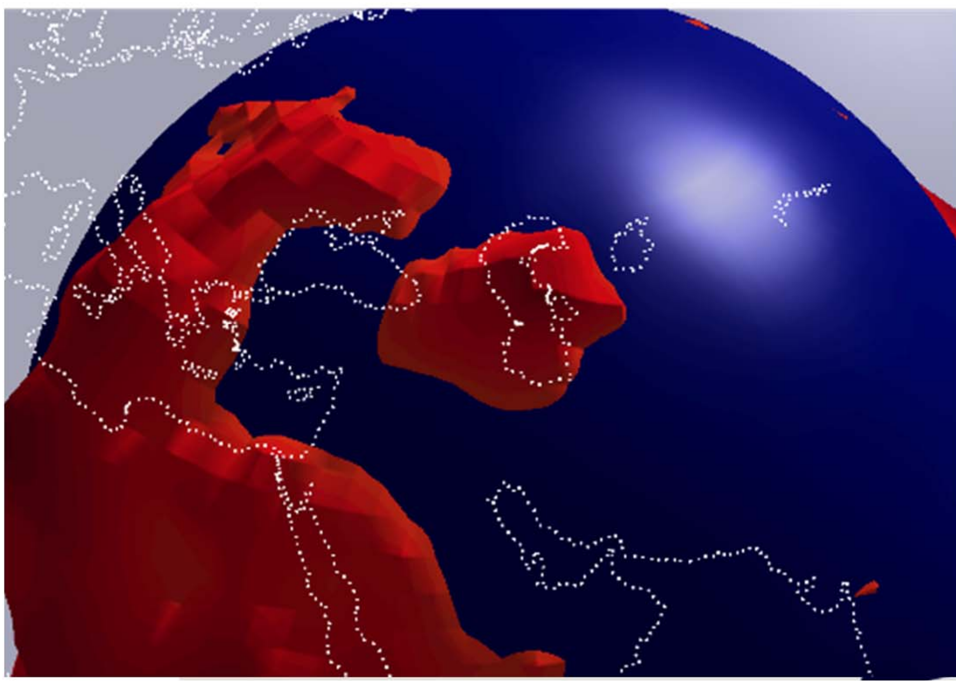
Mesoscale Archetypes

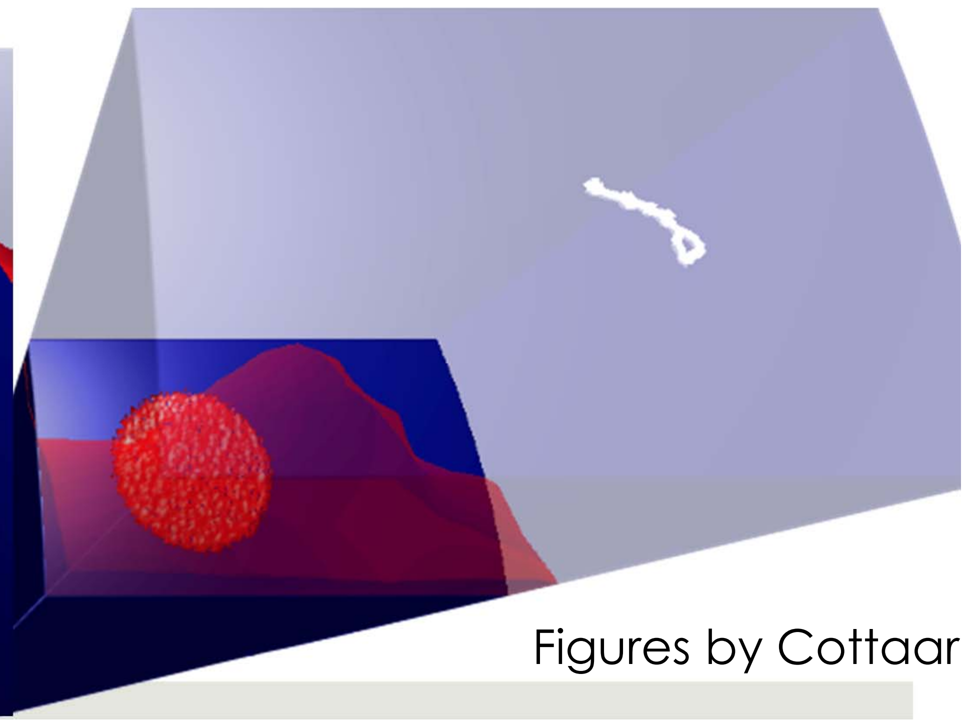
Perm Anomaly – "SLSVP"

- Size of Texas
- ~6% Vs reduction
- Hundreds of km high
- Visible in all tomographic models

Hawaiian Puddle – "HULVZ"

- Size of Texas
- ~20% Vs reduction
- Tens of km high
- Only visible at shorter periods (+hints!)





Figures by Cottaar

Predicting Geo-ν Flux

- Start with bulk silicate Earth abundance of U, Th, K
- Subtract out the contribution of the continental crust
- Assume mantle contains two reservoirs:
  - Depleted Mantle from Salters & Stracke (2004)
  - Enriched reservoir that makes up the difference in heat production between BSE and DM
- Predict geo-ν flux for three candidate enriched reservoirs
  - LLSVPs – as defined by different tomographic models and different isocontours
  - ULVZs – as defined by waveform studies
  - "Aureoles" – as defined by boundaries of LLSVPs

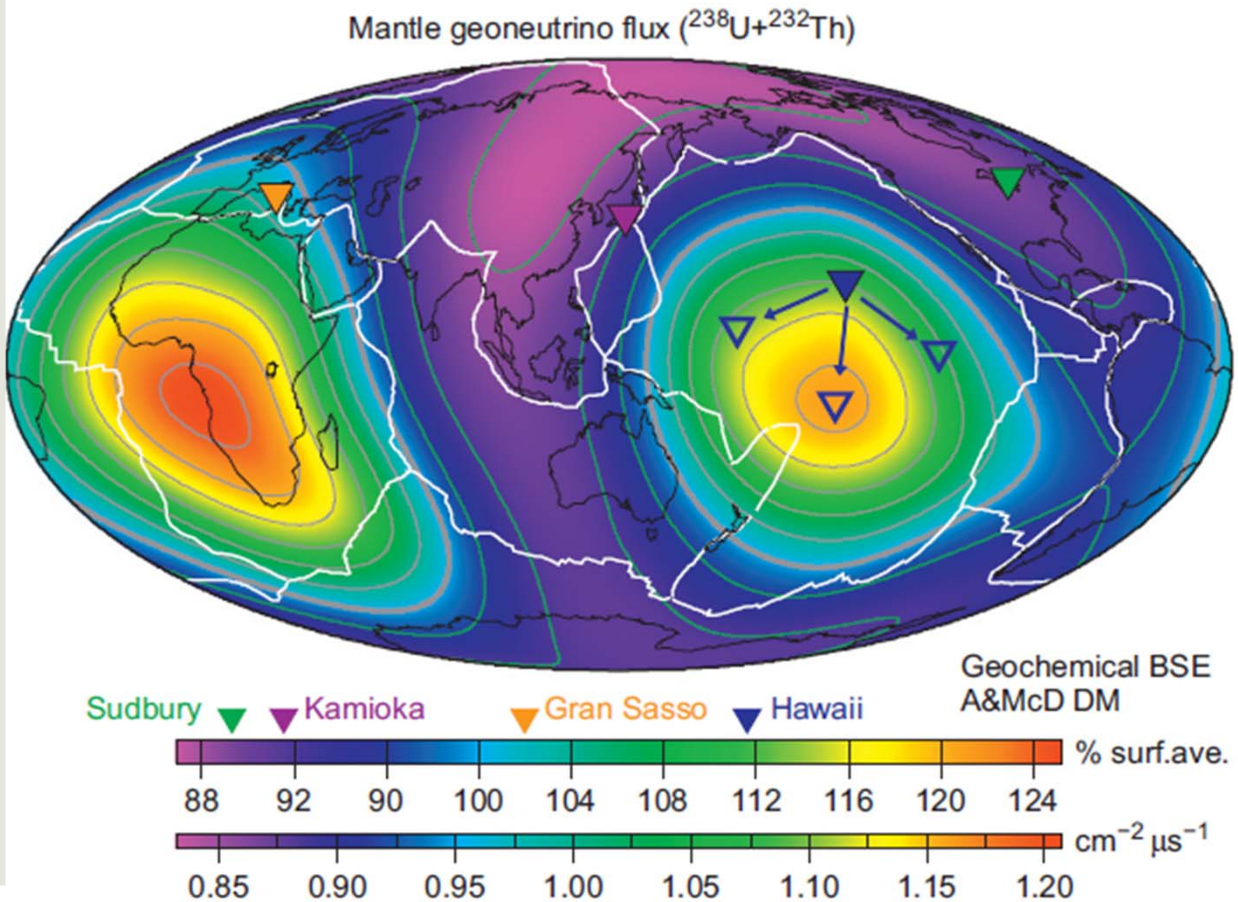
Geo-ν Signature of LLSVPs

U, Th, and K enrichment in LLSVPs introduces lateral variations in geo-ν flux

Variations are ~20% of surface mean

Largest fluxes on top of LLSVPs

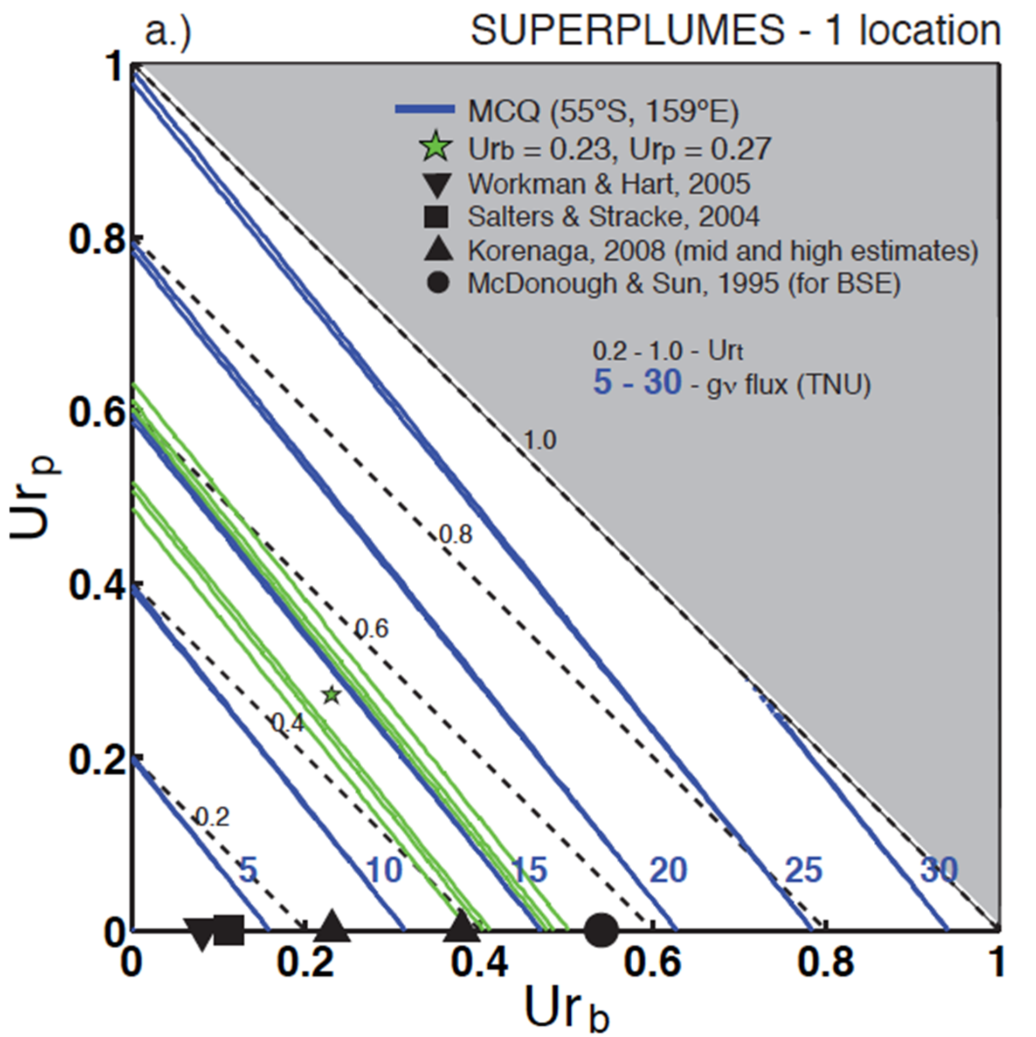
Sramek et al. 2012 (EPSL)



Where to site a geo-νdetector?

- Substantial lateral variations in geo-ν flux at the surface due to spatial variations in U, Th, and K enrichment may:
  - Bias estimates of Earth's budget of heat producing elements
  - Offer a means of constraining the origin of lower mantle structures
- Uncertainty in seismic imaging of structure introduces uncertainty in the pattern of predicted geo-ν flux
- Locations with small inter-model variability in predicted geo-νflux are ideal
- Locations with small bias & variability are ideal for constraining average heat budget (many exist)
- Locations with high bias & low variability are ideal for constraining LLSVP / ULVZ enrichments (none exist)

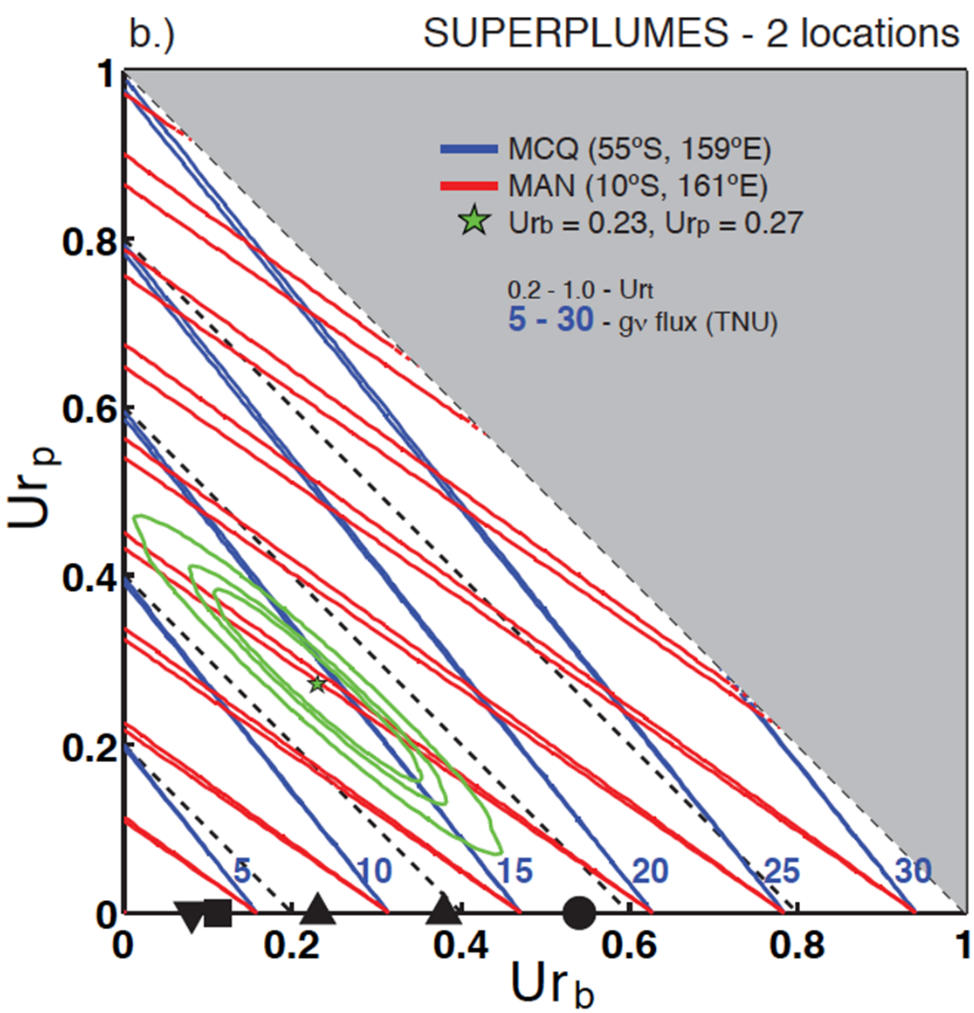
Single Detector – LLSVPs



- At a single detector, there is trade-off between geo-ν flux from LLSVPs and the "background" mantle
- Blue lines define the tradeoff at a single, low variability, location
- No matter how long you count, you will not eliminate the trade-off (green ellipses)
- Don't pay attention to numbers ☺

Kite & Lekic, in revision

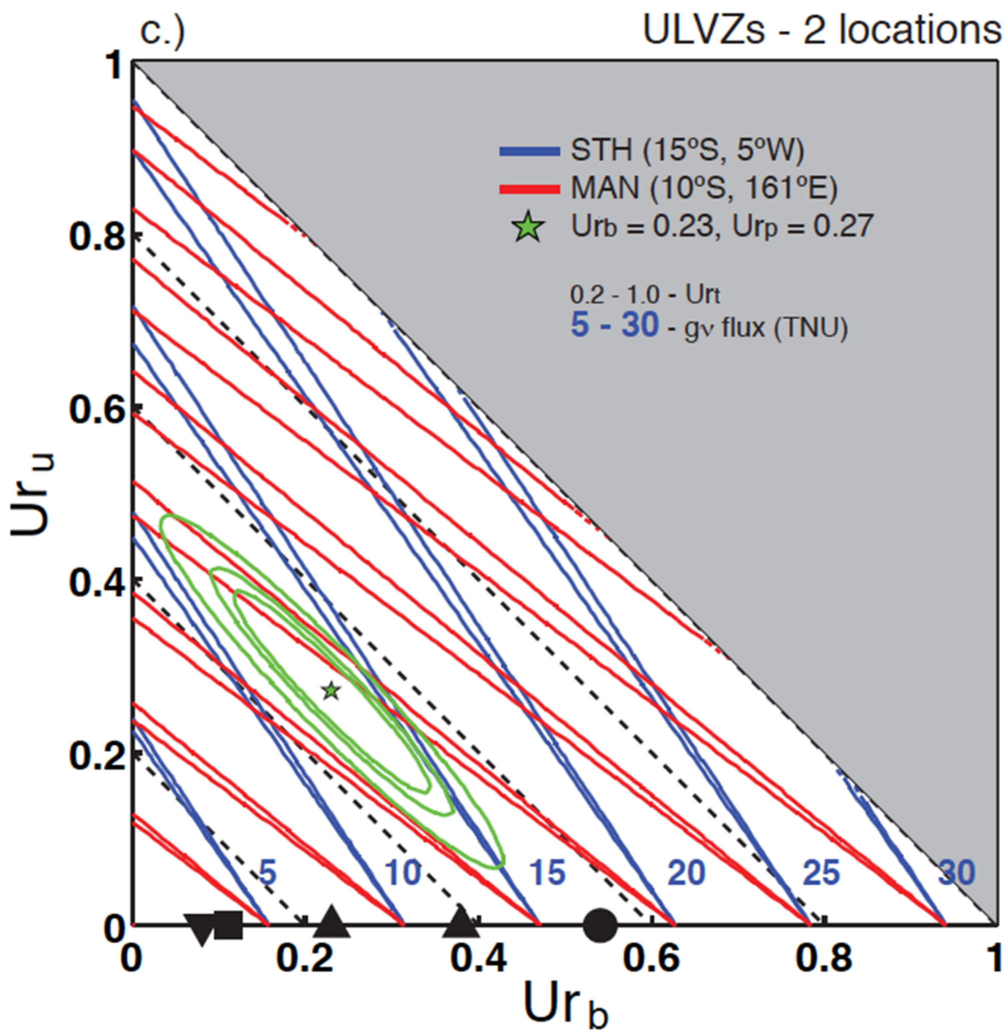
Two Detectors - LLSVPs



Kite & Lekic, in revision

- Multiple, well-sited detectors can reduce the trade-off between geo-ν flux from LLSVPs and the "background" mantle
- Blue (Macquarie) and red (Manihiki) lines define different tradeoffs
- As you count more geo-ν, you can separate the LLSVP vs "background" mantle signal
- Don't pay attention to numbers ☺

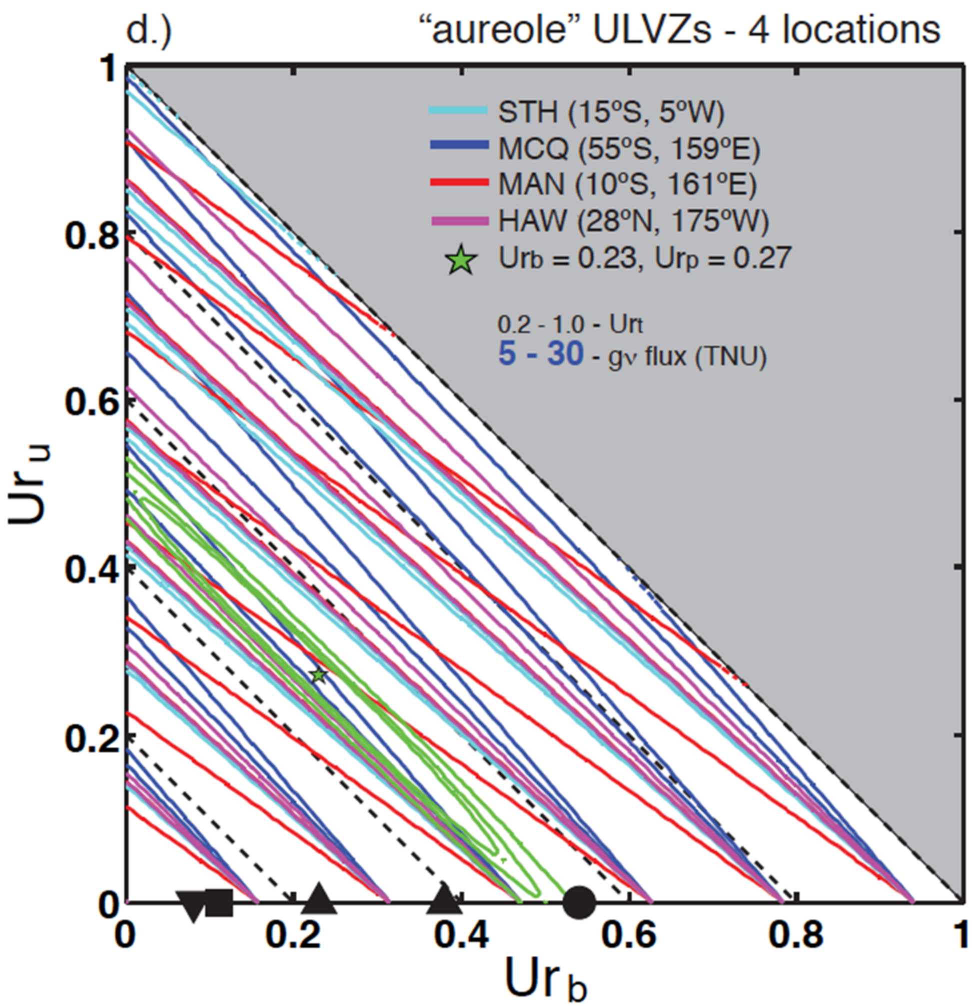
Two Detectors - ULVZs



Kite & Lekic, in revision

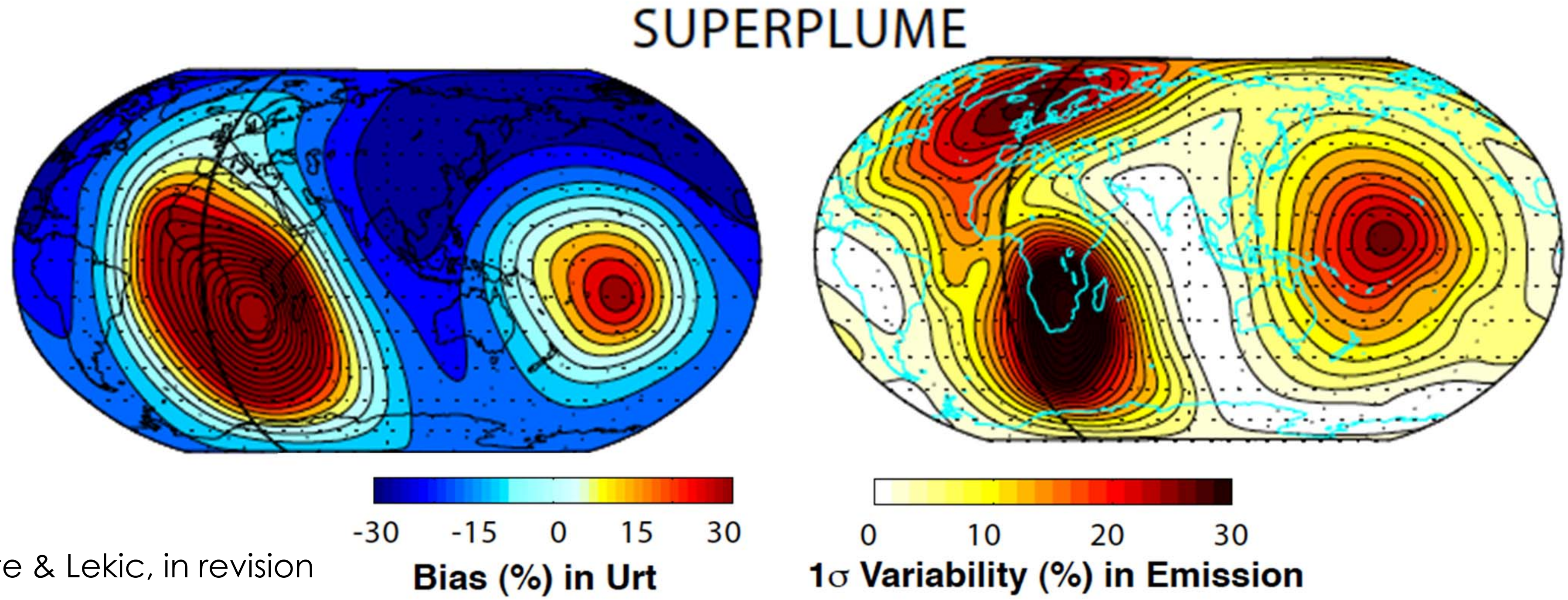
- Multiple, well-sited detectors can reduce the trade-off between geo-ν flux from ULVZs and the "background" mantle
- Blue (St. Helena) and red (Manihiki) lines define different tradeoffs
- As you count more geo-ν, you can separate the ULVZ vs "background" mantle signal
- Don't pay attention to numbers ☺

Four Detectors – "Aureoles"



- Even multiple, well-sited detectors canNOT reduce the trade-off between geo-ν flux from "aureole" model and the "background" mantle
- Colored lines define similar tradeoffs and high variability at all locations
- As you count more geo-ν, you CANNOT separate the "aureole" vs "background" mantle signal
- Don't pay attention to numbers ☺

Kite & Lekic, in revision

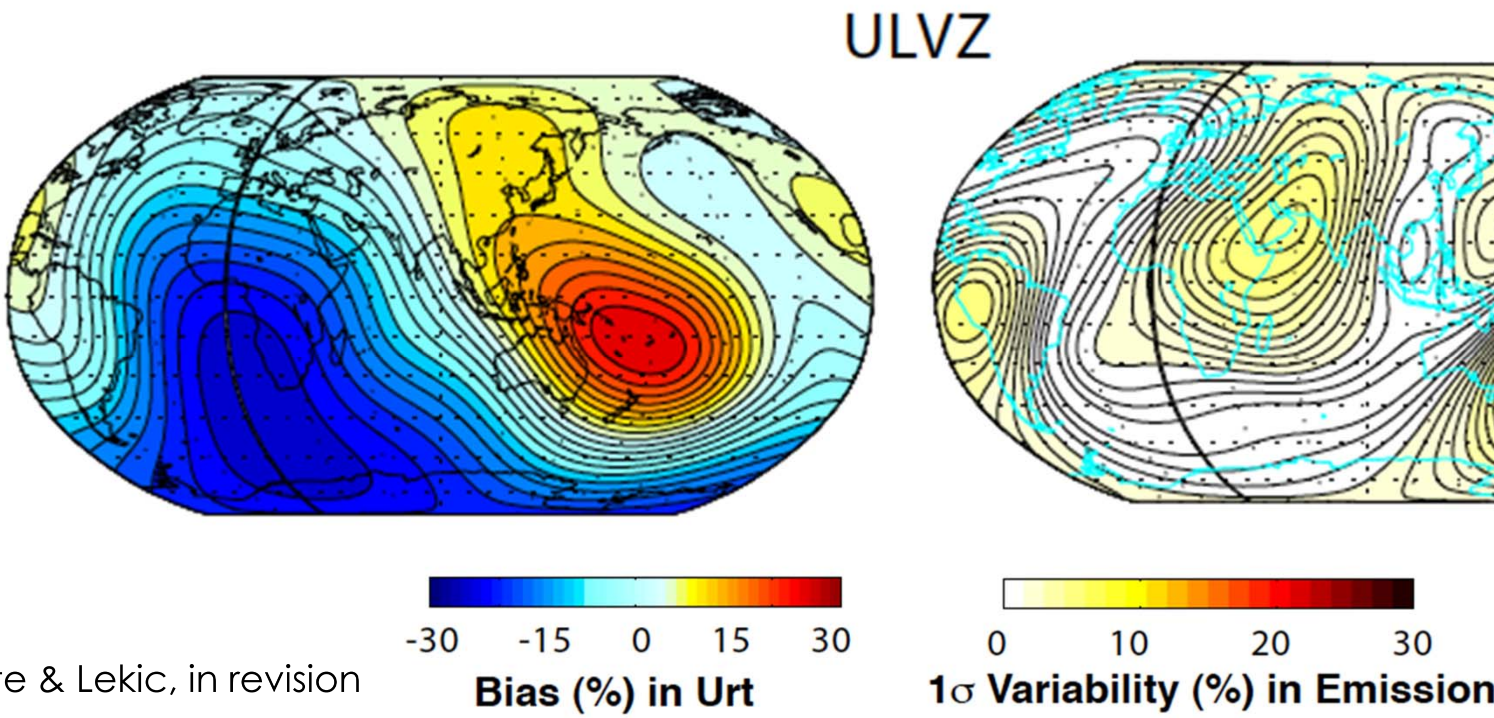


Kite & Lekic, in revision

LLSVP geo-neutrino signature

High geo-v flux above the African and Pacific superplumes requires measured fluxed to be corrected before interpretation in terms of average Earth values

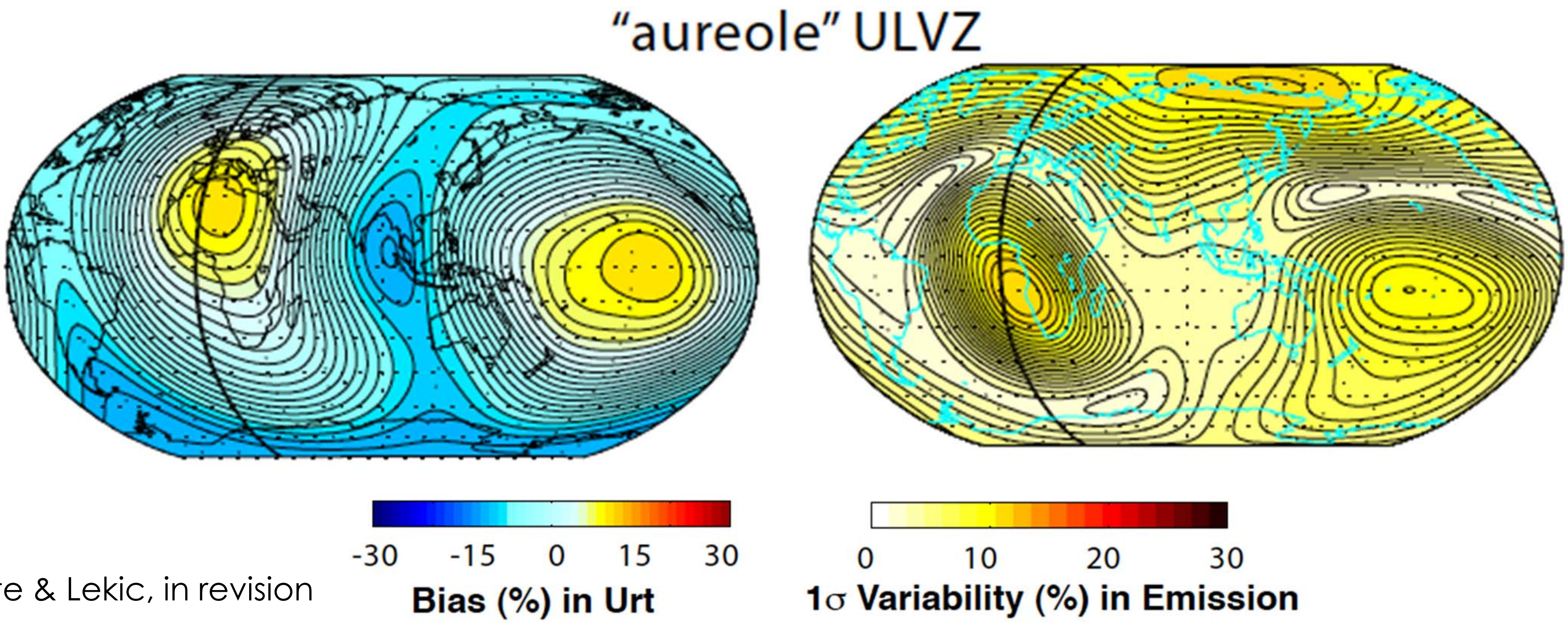
High variability regions (due to inter-model differences) are large on top of the LLSVPs



Kite & Lekic, in revision

ULVZ geo-neutrino signature

- Average signature is weaker and very different from that of the LLSVPs, with a pronounced peak in the Pacific and reduced emissions over the South Atlantic
- High variability regions (due to uncertainty in locations of ULVZs) are not co-located with high flux regions

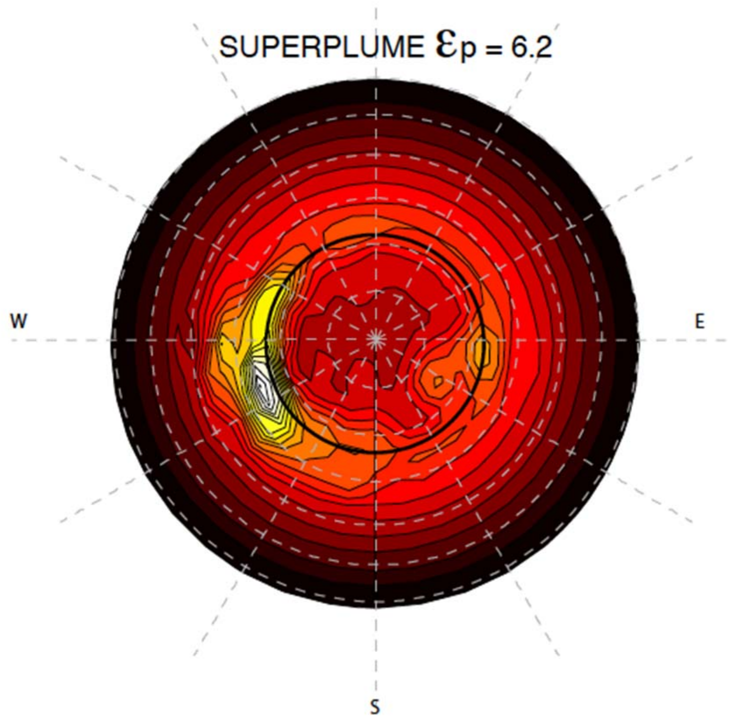


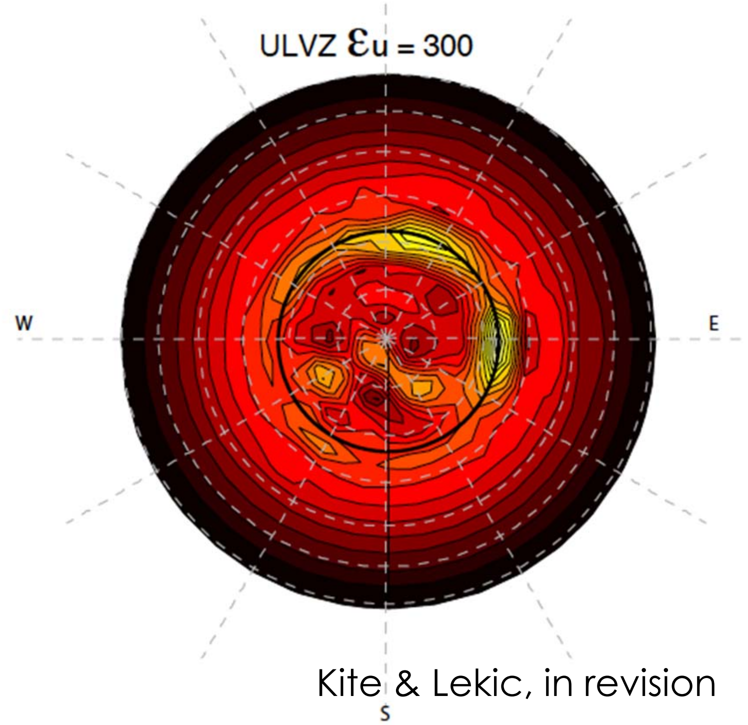
Kite & Lekic, in revision

"Aureole" geo-neutrino signature

Geo-ν signature of hypothesized "aureole" structures is weakest and has a pattern qualitatively similar to that of the LLSVPs

High variability (due to changing the location and width of the aureole regions) regions are co-located with high flux regions





Kite & Lekic, in revision

A seismologist's dream detector

A directional detector placed half-way between the superplumes would be ideal for discriminating between various hypotheses regarding lower mantle reservoirs.

Conclusions

- Lower mantle has large, small, and intermediate scale structures with reduced Vs that may be enriched in U, Th, and K
- Geo-ν signatures of these structures are large in comparison to average mantle flux
- Lateral variations in geo-ν flux may bias estimates of average radiogenic heat budget
  - To avoid this, a single detector must be sited in low bias / low variability areas
  - Or, multiple detectors must be sited in regions with different tradeoffs between average and enriched signatures
- Multiple (two) oceanic detectors can constrain ULVZ and LLSVP enrichment in U, Th