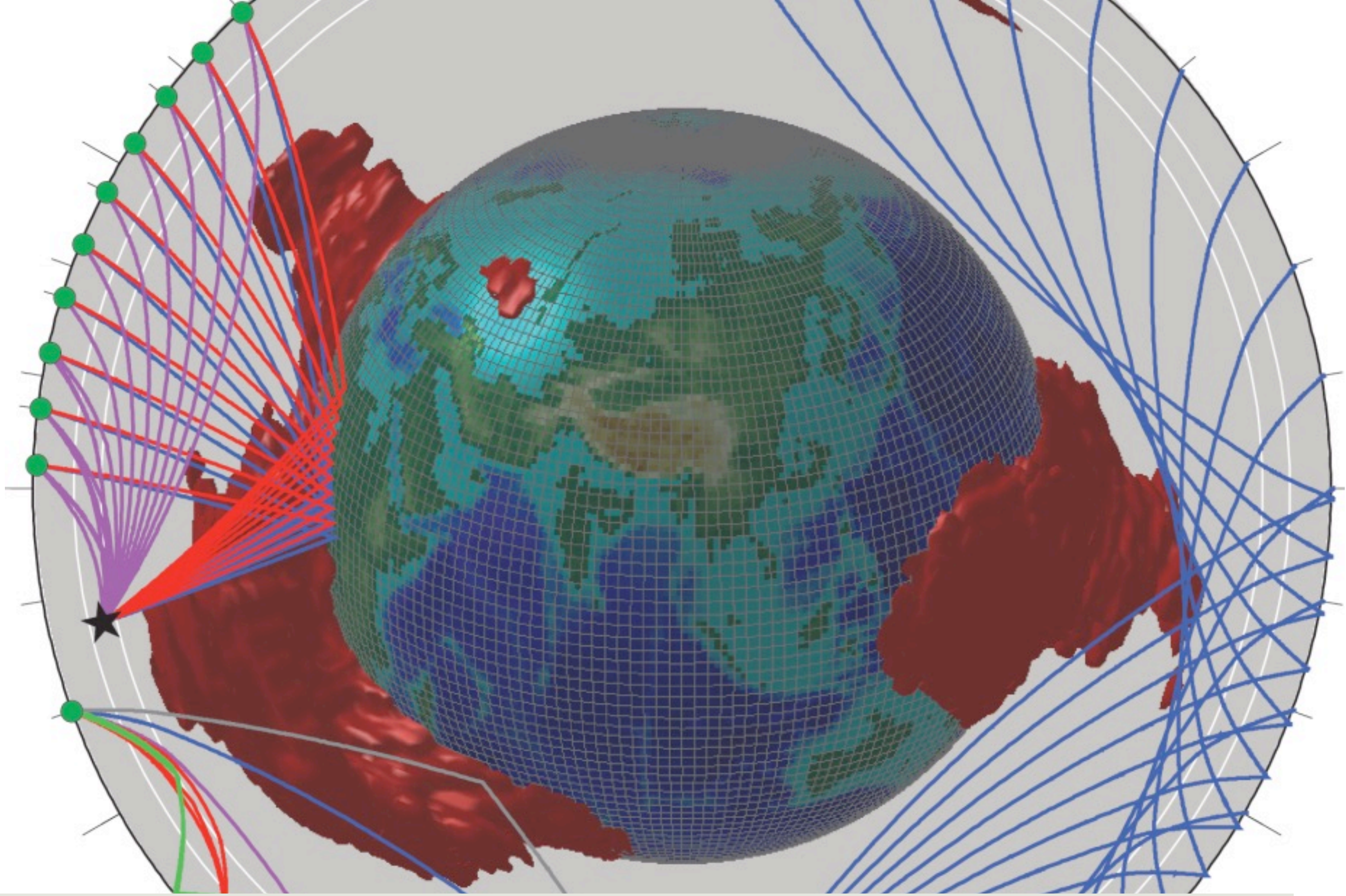
A Seismically Sound Foundation: Reference Models and Datasets



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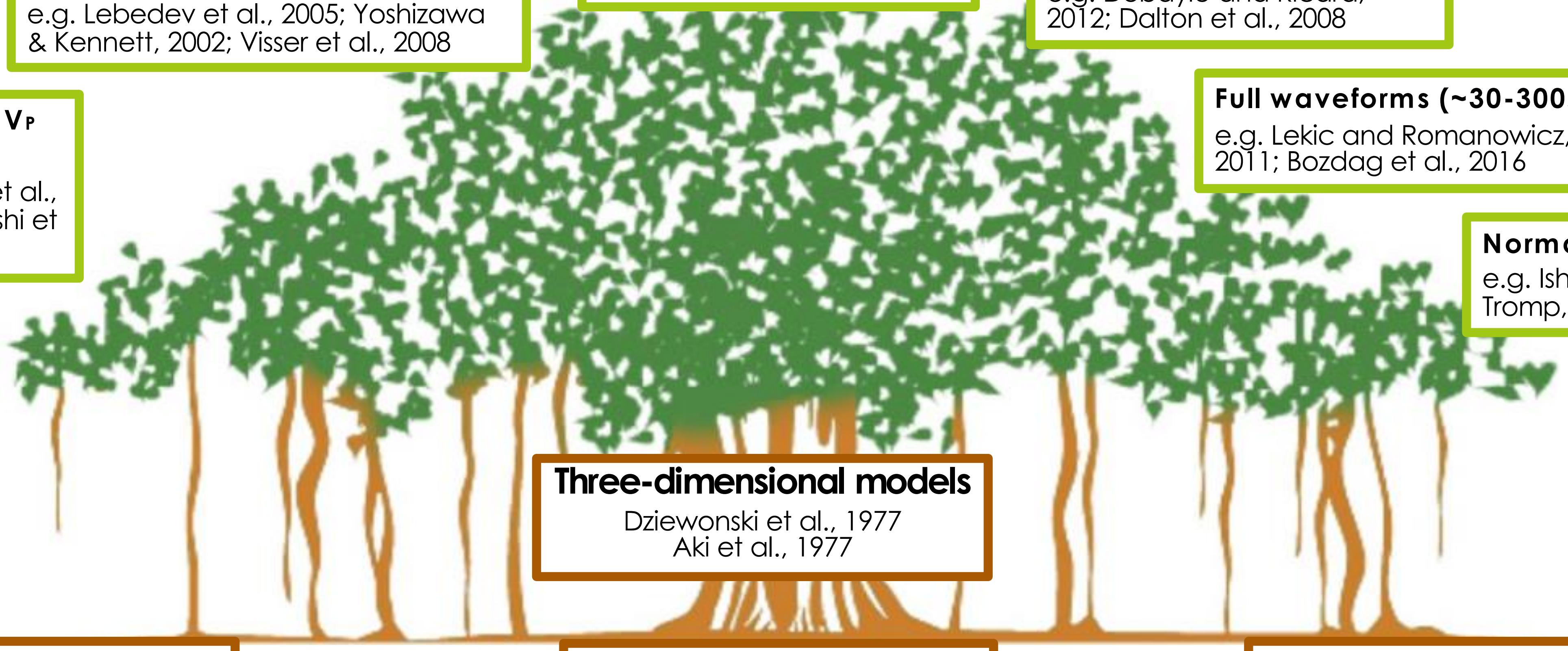
Contributing Authors: Eric Beucler, Scott Burdick, Stephanie Durand, Tak Ho, Paula Koelemeijer, Zhitu Ma, Keith Priestley, Andrew Schaeffer, Jeannot Trampert

Evolution of global models



Multiple data types
e.g. Ritsema et al., 2011; Moulik and Ekström, 2014

Multi-mode waveform inversions
e.g. Lebedev et al., 2005; Yoshizawa & Kennett, 2002; Visser et al., 2008

Surface waves
e.g. Debayle and Ricard, 2012; Dalton et al., 2008

Body wave V_P models
e.g. Burdick et al., 2017; Obayashi et al., 2013

Full waveforms (~30-300s)
e.g. Lekic and Romanowicz, 2011; Bozdag et al., 2016

Normal modes
e.g. Ishii and Tromp, 1999

Three-dimensional models
Dziewonski et al., 1977
Aki et al., 1977

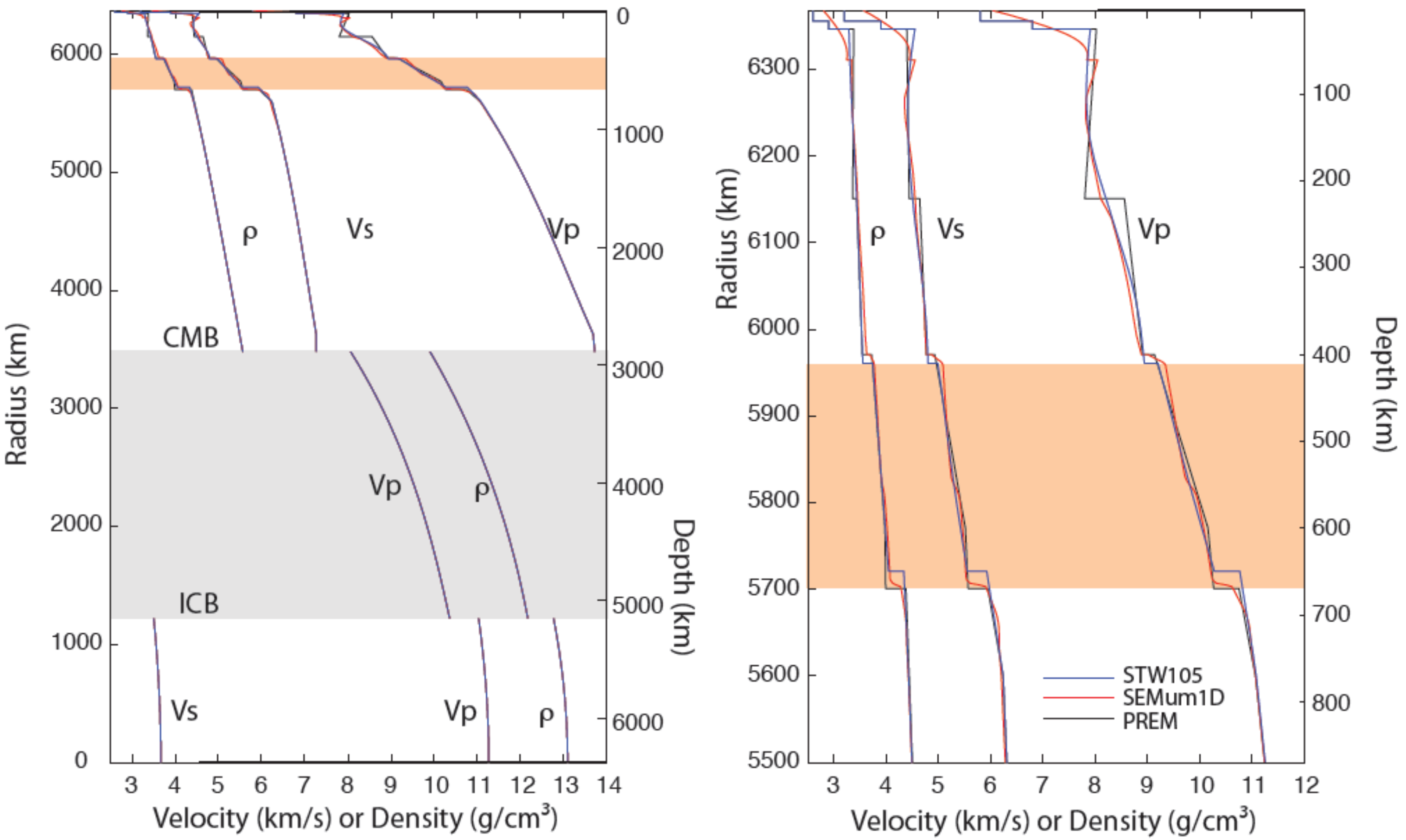
Body waves
Jeffreys and Bullen, 1940
SP6 Morelli and Dziewonski, 1993
AK135 Kennett et al., 1995

PREM
Dziewonski and Anderson, 1981
AK135
Kennett et al., 1995

Normal mode & Surface Waves
Gilbert and Dziewonski, 1975
Widmer et al., 1991
QL6 Durek and Ekström, 1996

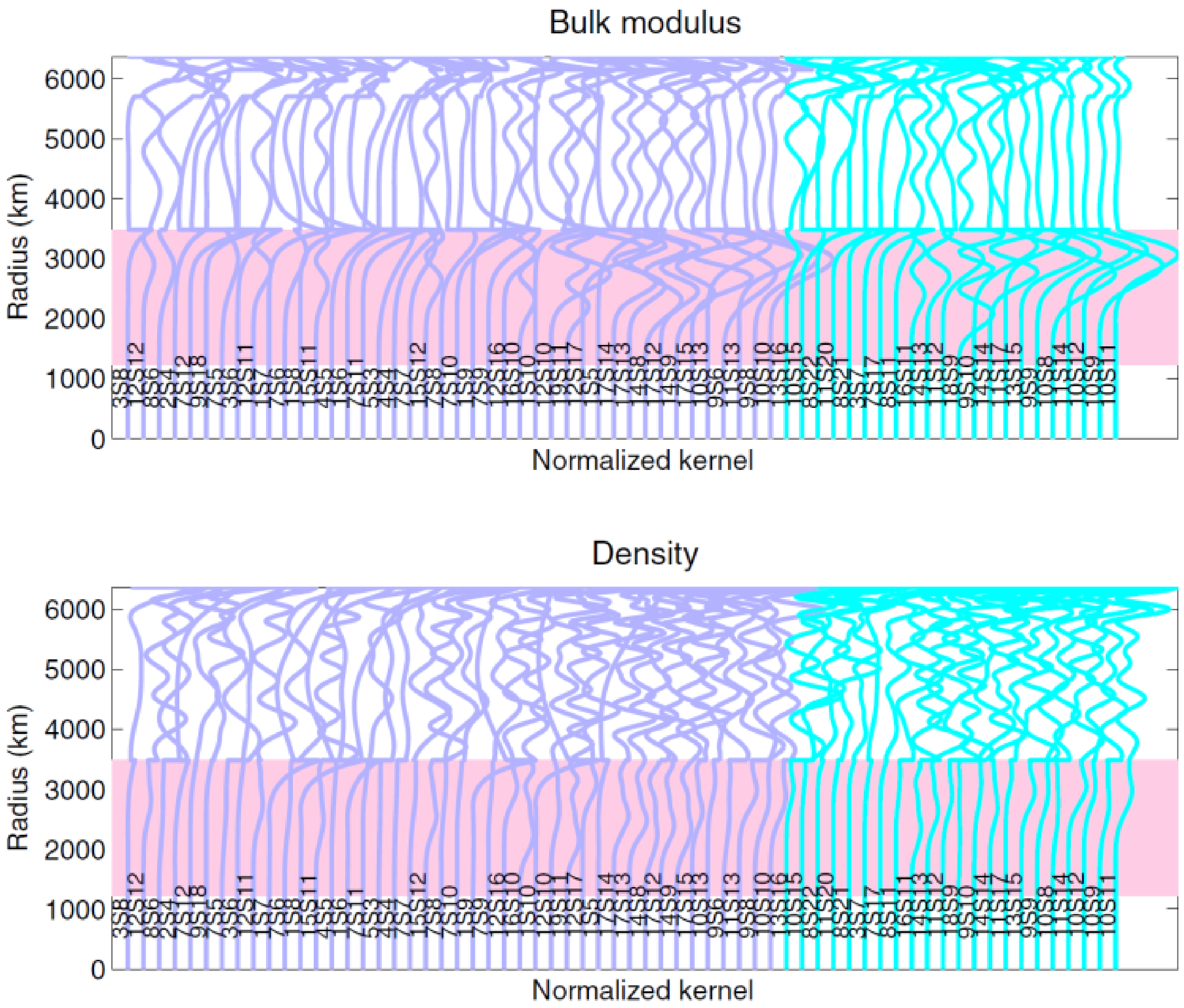
Why not existing 1D models?

- Existing 1D reference models: PREM (Dziewonski and Anderson, 1981), ak135 (Kennett et al., 1995), IASP91 (Kennett and Engdahl, 1991).
- Uneven distribution of earthquakes and seismometers means that:
  - Models that fit travel times as much as possible (e.g. ak135, IASP91) are not true global averages → biased toward continental structure, and should be used with caution;
  - Models that attempt an unbiased global average (e.g. PREM), cannot fit travel times as successfully.
- A 3D reference model could fit data better without biasing our view of the "average" Earth.



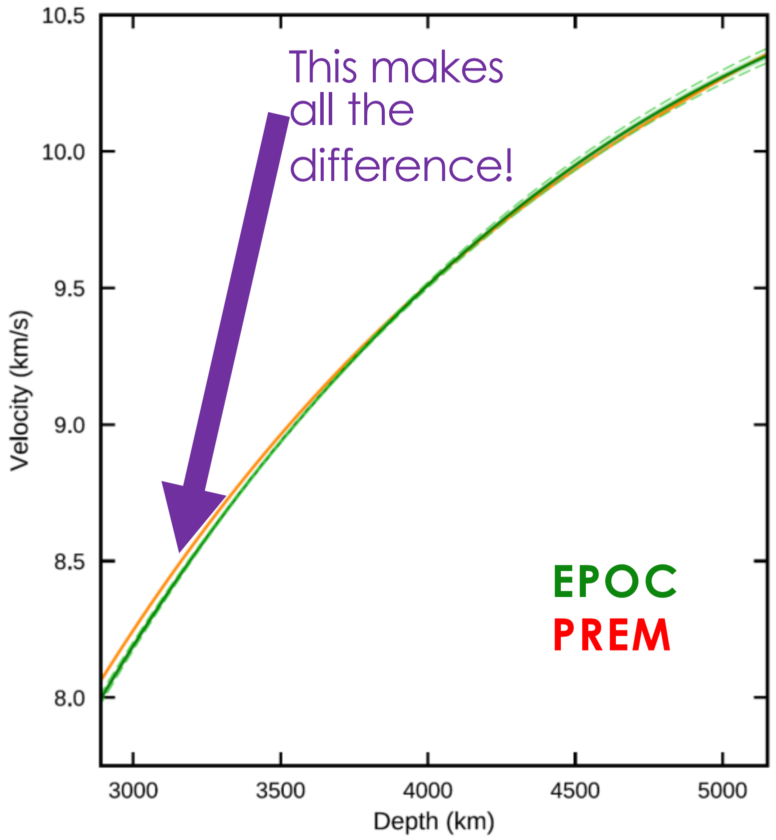
Importance of 1D reference models

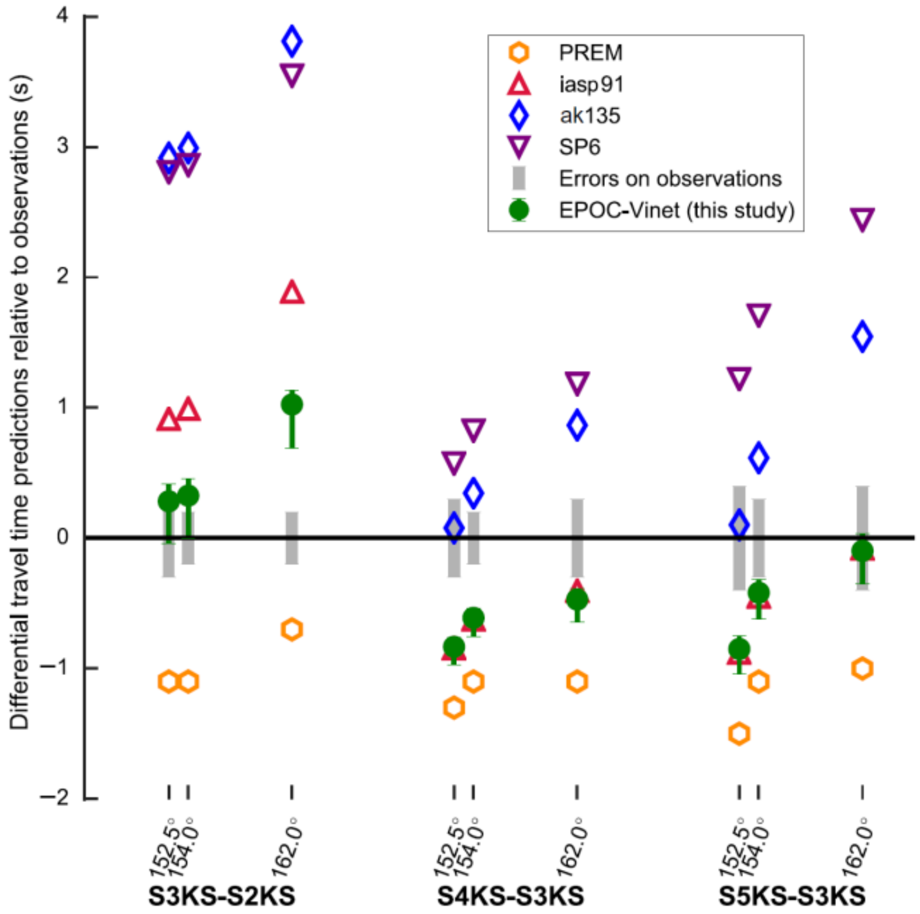
- Irving et al. (*in press at Sci. Adv.*) revisit 1D reference model of outer core:
  - Equation-of-state parameterization
  - Model-space search approach → improved quantification of uncertainty
  - **Expanded** dataset of normal mode center frequencies compared to **PREM**
- EPOC model fits mode data better than PREM
- See poster A1



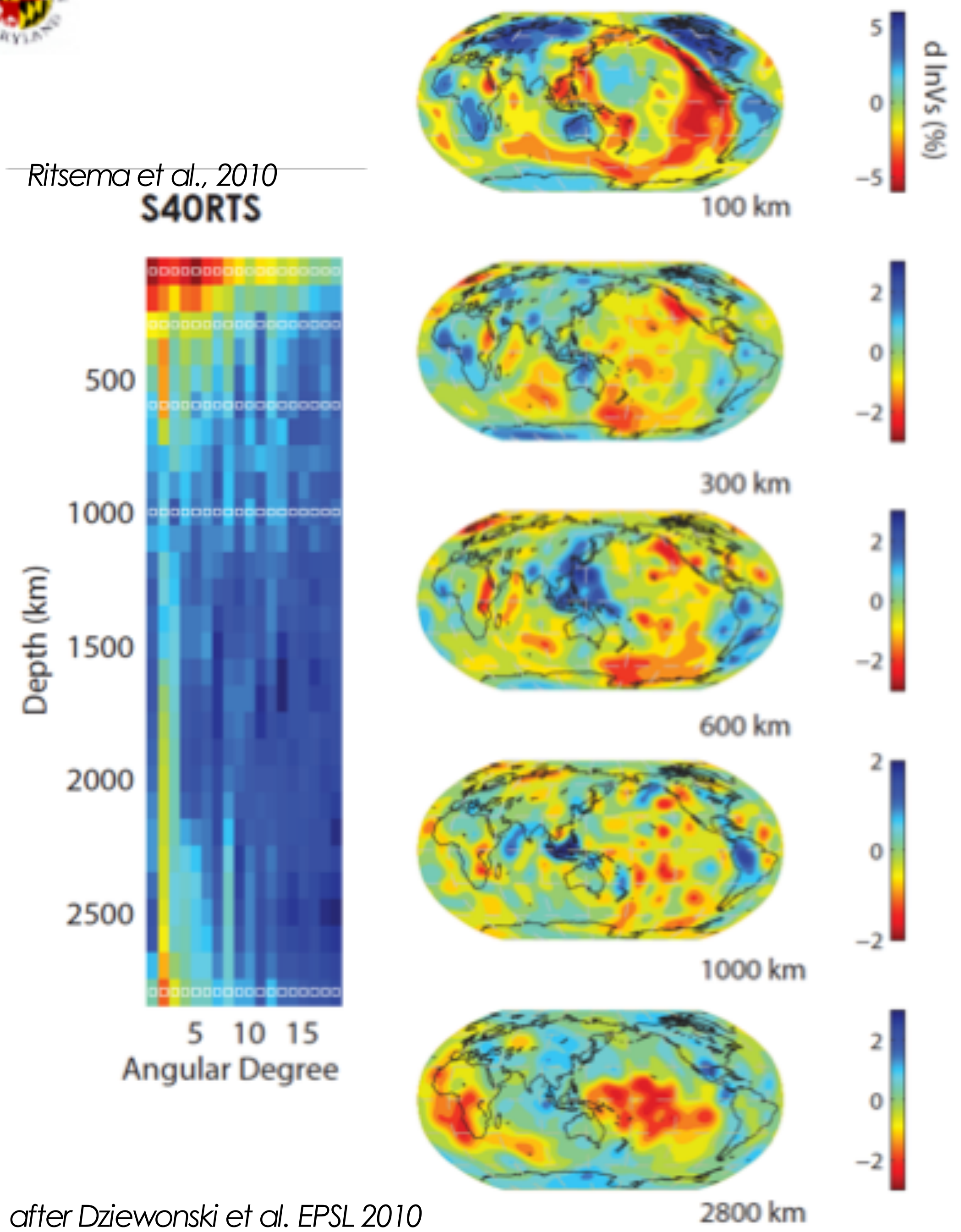
Importance of 1D reference models

- EPOC model fits mode data better than PREM
- EPOC fits body wave travel times better than PREM
- Reconciles body-wave and normal-mode models
- Reduces the need for slow layer (E') at the top of the outer core
- See poster A1





Large scale mantle structure

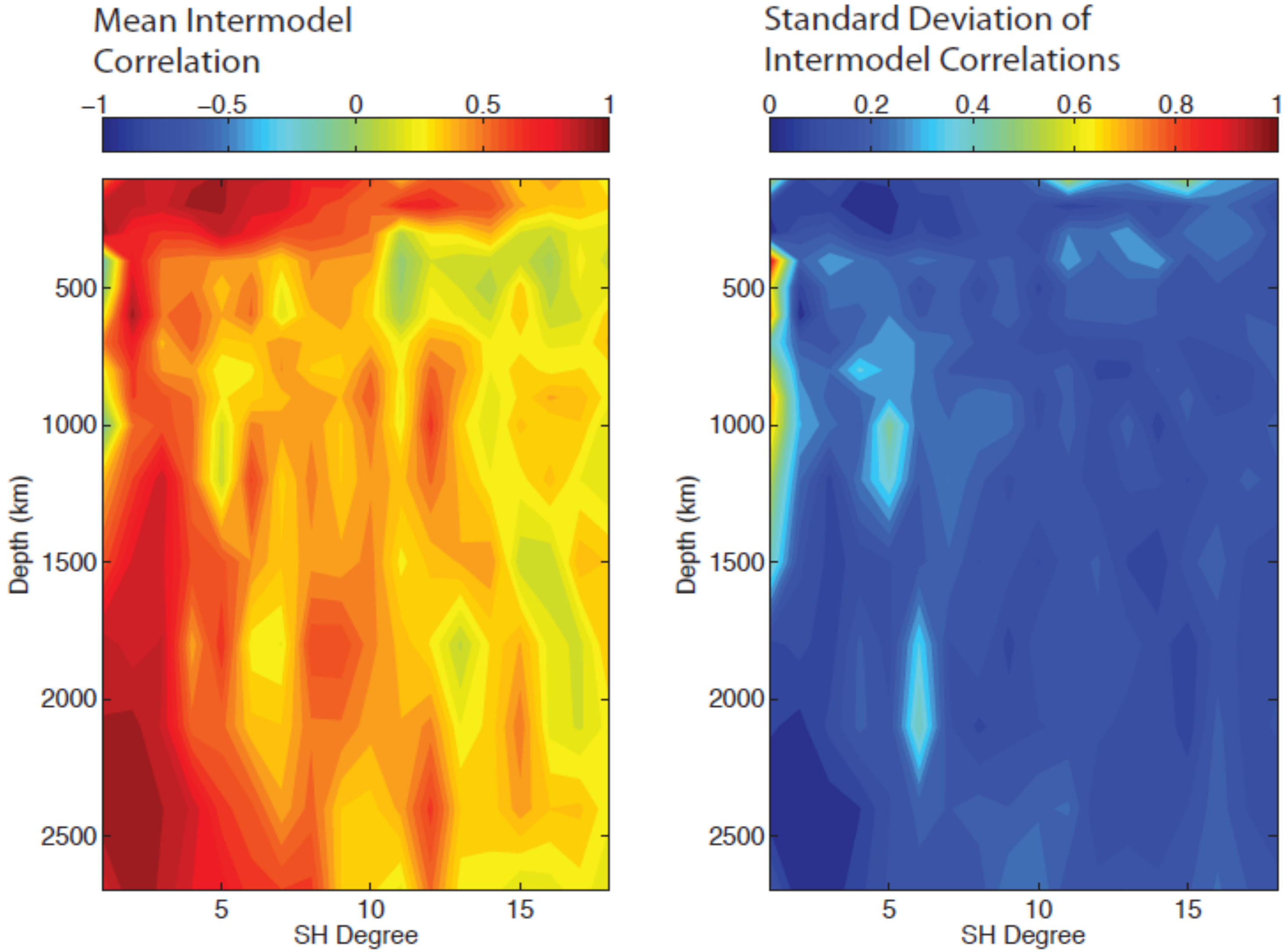


after Dziewonski et al. EPSL 2010

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

Reliability of tomographic models

- The large-scale structure of the mantle is robust
- Models similar throughout the uppermost and lower mantle
  - Regions with strongest lateral heterogeneity also have strongest inter-model consistency
- Inter-model consistency motivates new analyses of the models themselves



A Community Effort

- Community workgroups advise, oversee and evaluate the reference model development and compilation / reconciliation of reference datasets
- Pritwiraj Moulik carries out the primary tasks of the REM-3D project, together with Ved Lekic and Barbara Romanowicz
- **Reference Dataset WG:** Surface wave dispersion, normal mode frequencies and splitting, body wave travel times
- **Reference Model WG:** Physical parameterization (smooth and regionalized versions), depths of major discontinuities (410 and 660), and scaling factors for parameters about which consensus does not exist (e.g. Q).

TYPE	DATA
Surface Waves	Dispersion curves*
	Rayleigh phase velocities
	Love phase velocities
Waveforms	Body Waveforms
	Mantle Waveforms
Body Waves	Time-distance curves*
	Arrival times
Free Oscillations	Eigenfrequencies*
	Quality Factors*
	Spheroidal splitting functions
	Toroidal splitting functions

REM3D Framework

→

Moulik and Ekström, (2014, 2016)

HETEROGENEITY
Isotropic S-velocity (3D)
SH-SV anisotropy (3D)
410 & 650 km, CMB Topography
Isotropic P-velocity (3D)
Density (3D)
Shear attenuation (1D)

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This talk →

HETEROGENEITY
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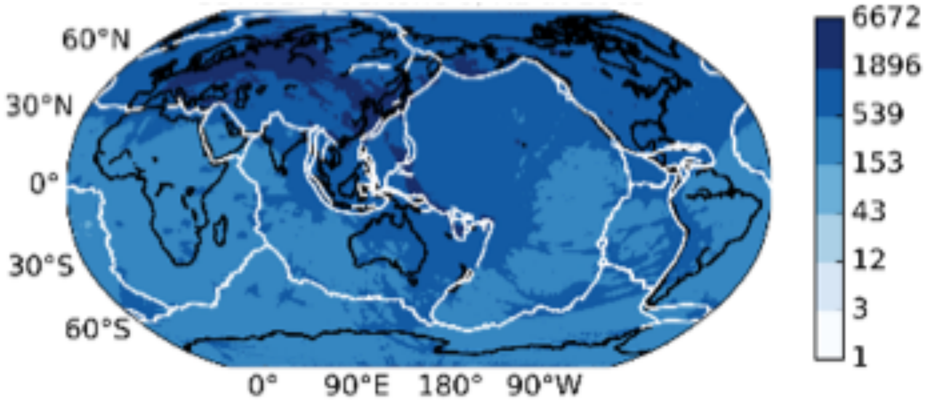
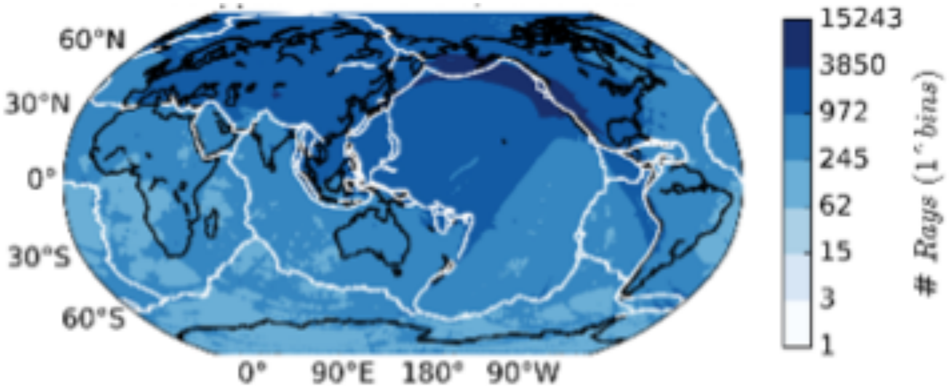
Shear attenuation (1D)

Improved coverage of data

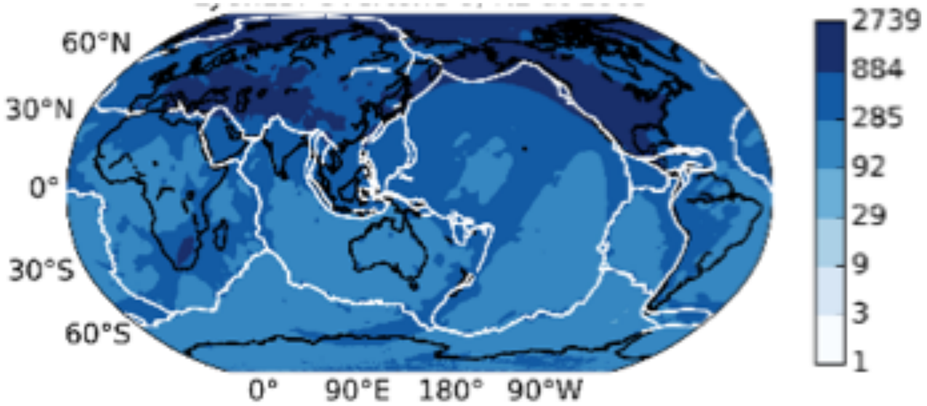
GDM52: Ekström, 2011



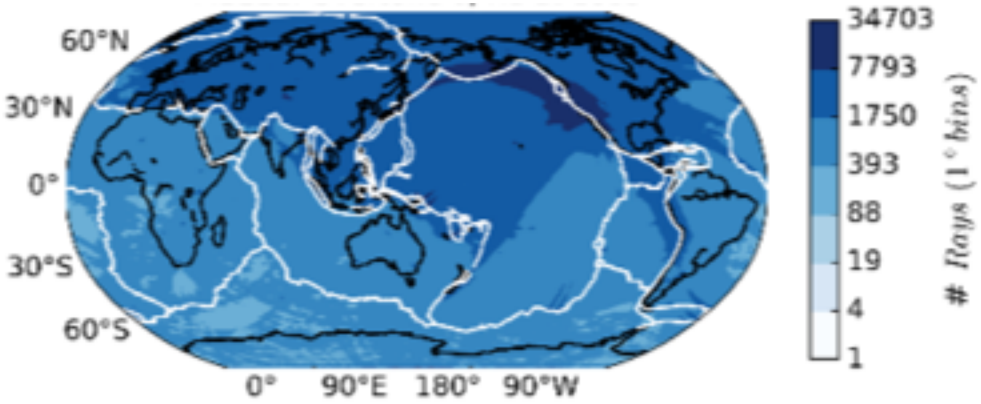
Scripps14: Ma et al. 2014



Lyon14: Durand et al., 2014



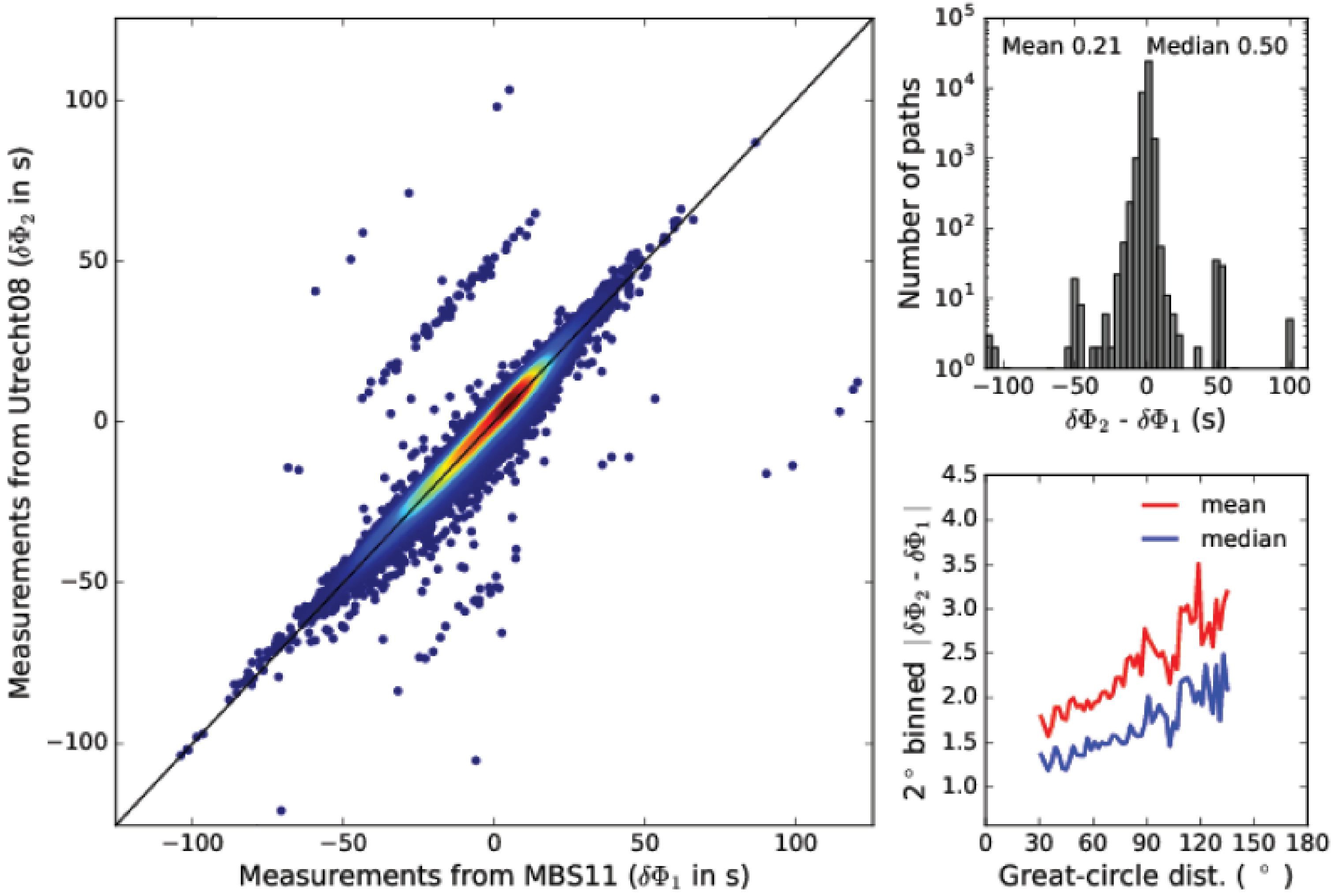
MBS11: Ritsema et al., 2011



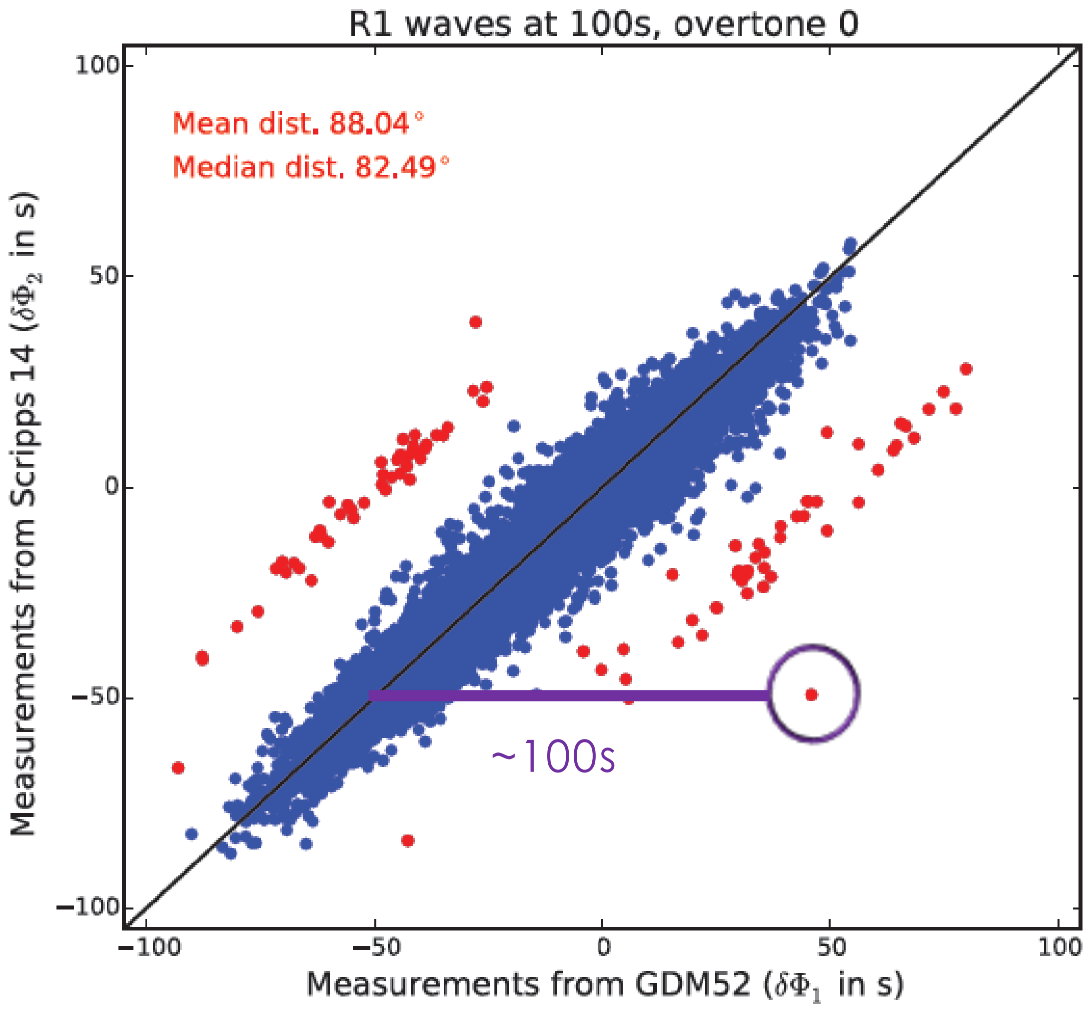
Measurement-by-measurement

We systematically assess measurement uncertainty:

- → On identical paths
- → On summary rays
- → Both across datasets and within datasets
- → Account for different source locations and reference to standard station locations

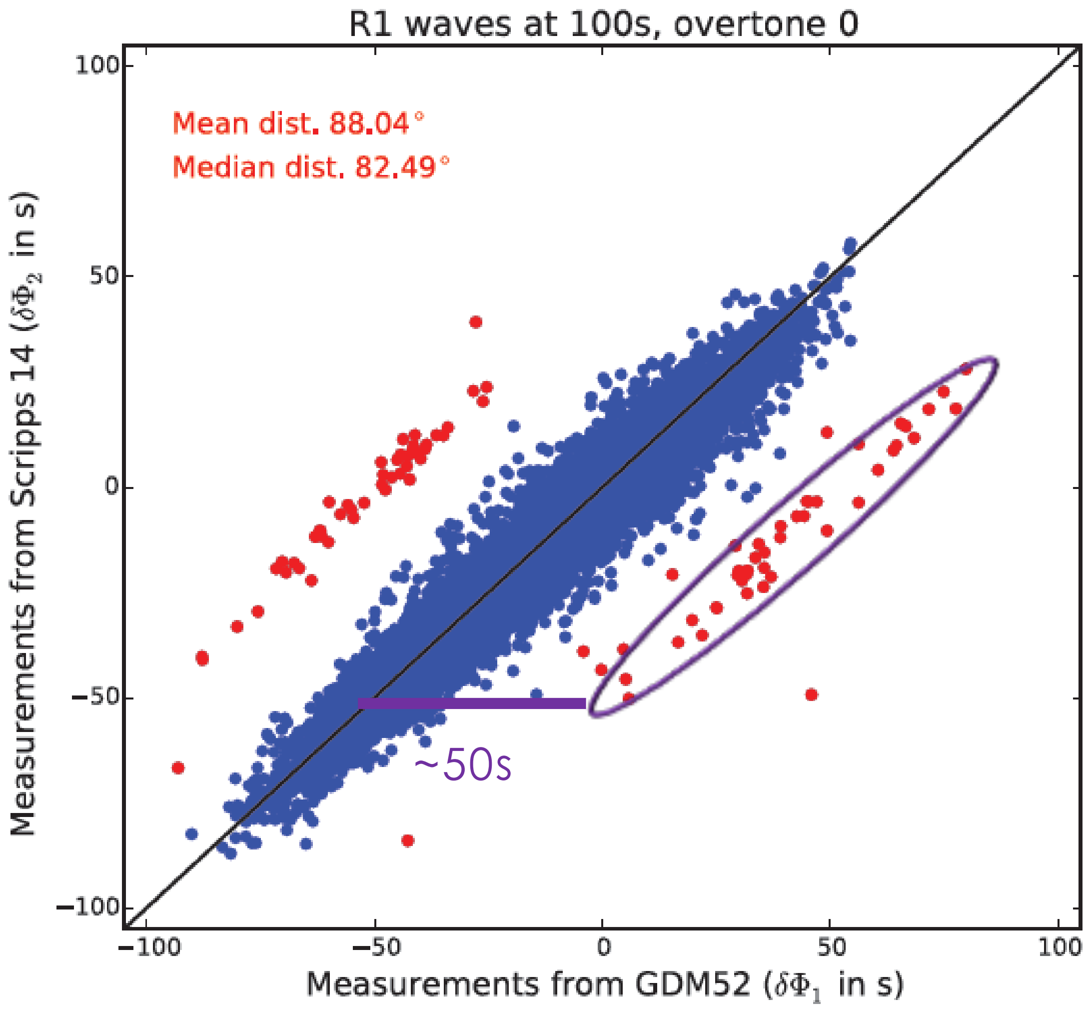


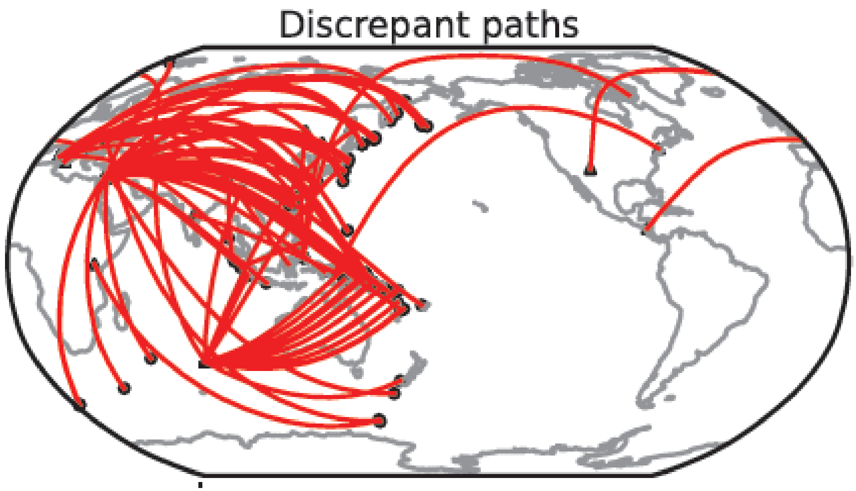
Tracking down outliers

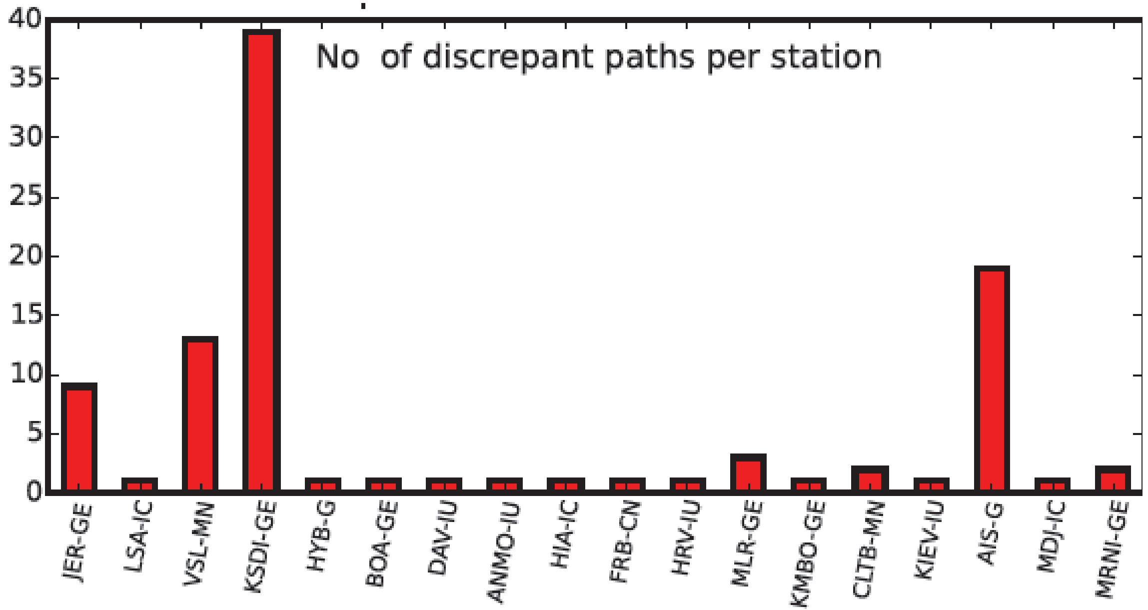


- Path-by-path analysis allows us to track down the cause of discrepancies between datasets
- Surface wave phase dispersion measurements are susceptible to cycle skips when the accumulated travel-time anomaly is bigger than a period
- We identify and remove cycle skips when constructing the reference dataset
- REM-3D will dramatically decrease likelihood of cycle skips by predicting the reference travel-time anomaly much more precisely than a 1D model can

Tracking down outliers







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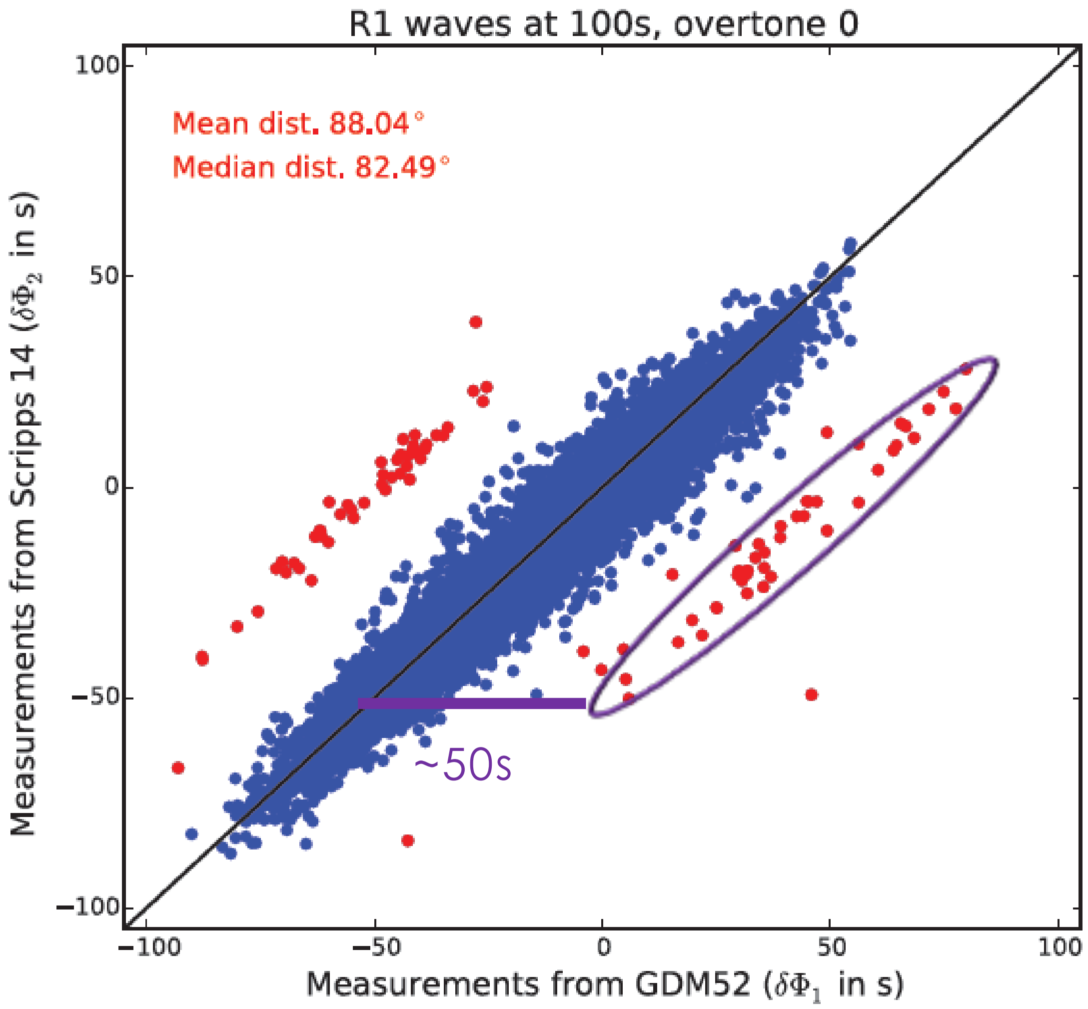
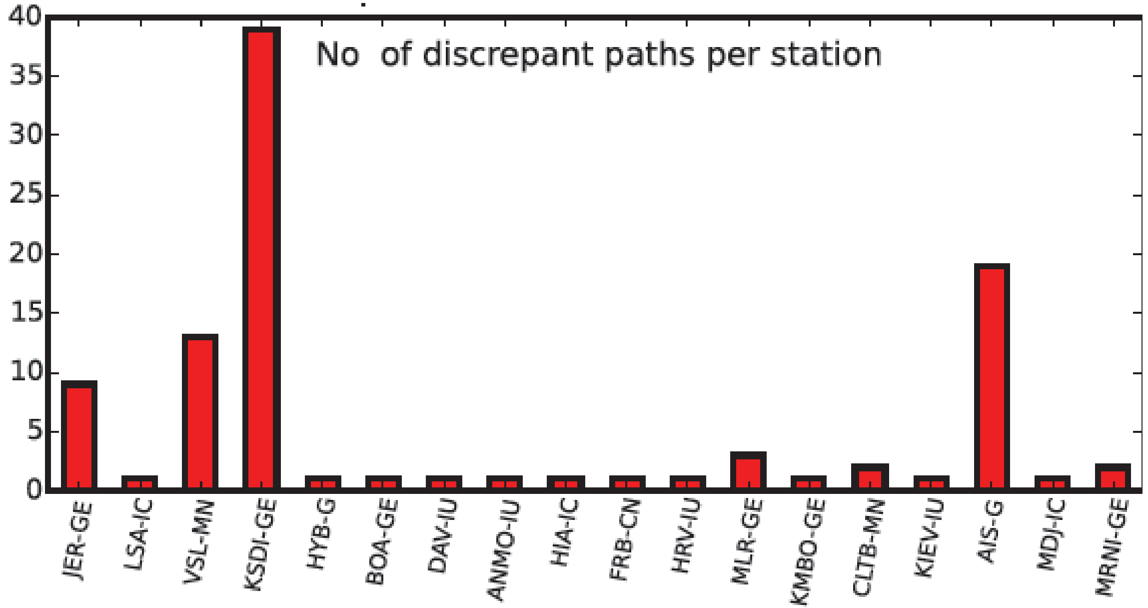
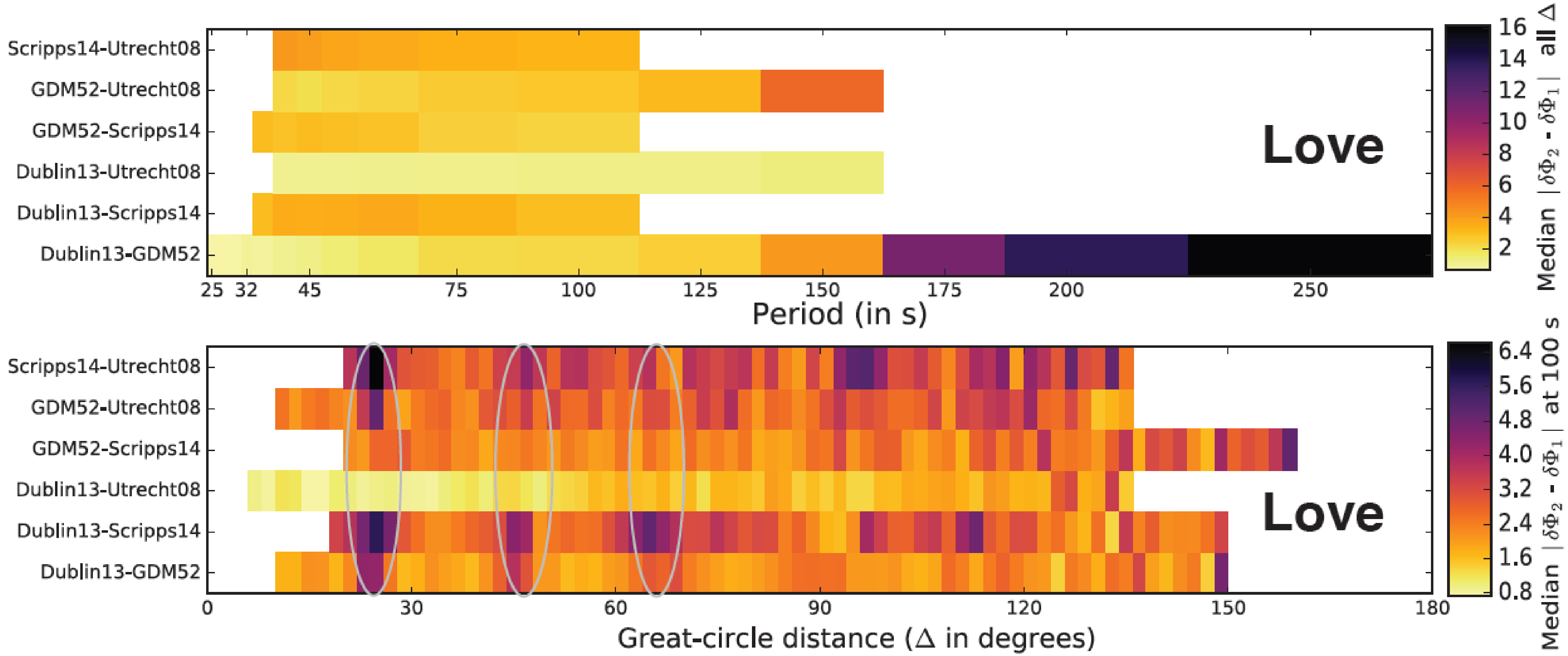


- Travel-time discrepancies of T/2 are due to polarity reversals at a few stations
- Currently, individual groups store polarity reversal information
  - incomplete and not synced with IRIS DMS
  - Metadata update warning would be helpful!





Fundamental mode Love waves

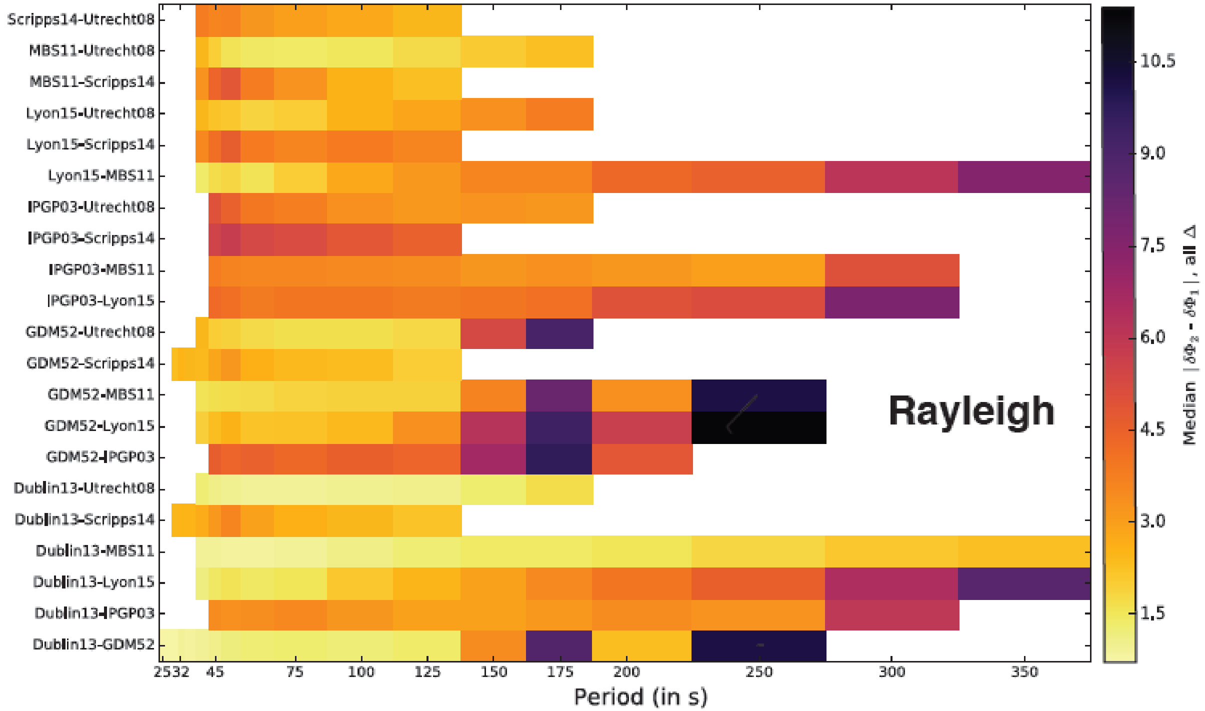
- → Excellent inter-dataset agreement
- → Increasing errors at long periods (due to tilt noise?)
- → Inter-model discrepancies vary with distance, with a periodicity of ~25° -30°

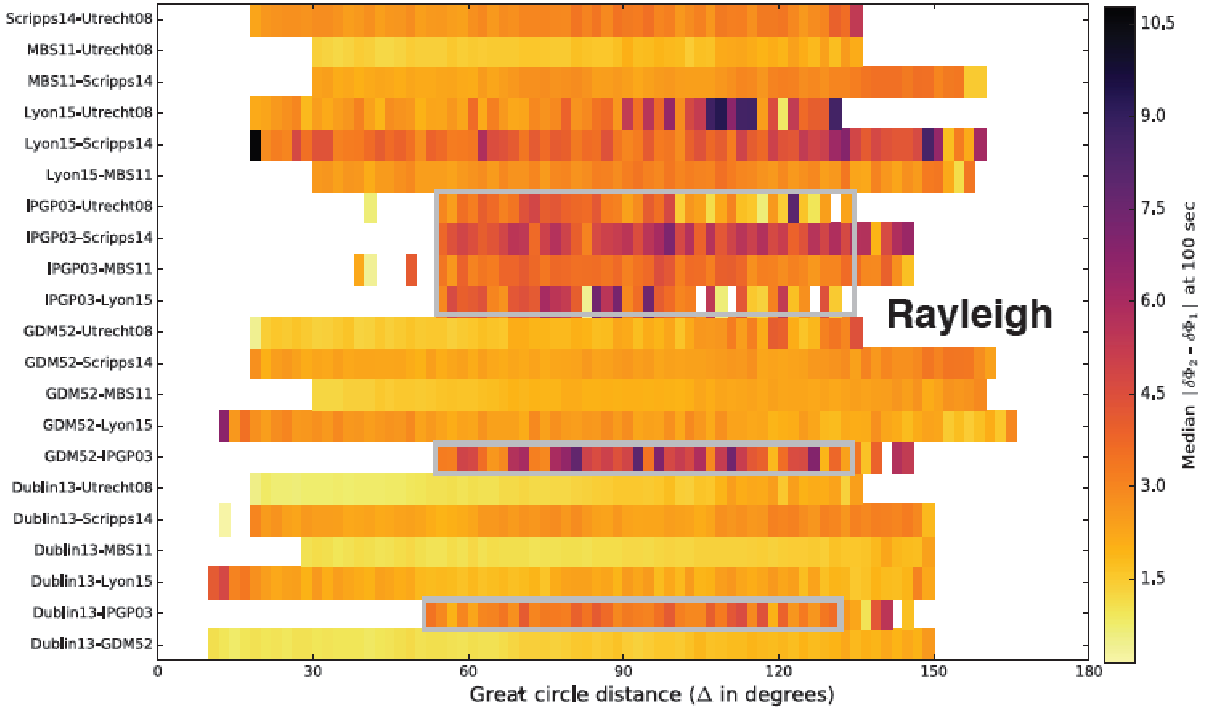
Rayleigh waves

→ Excellent inter-dataset agreement

→ Increasing errors at long periods for some datasets

→ Inter-model discrepancies suggest outlier datasets

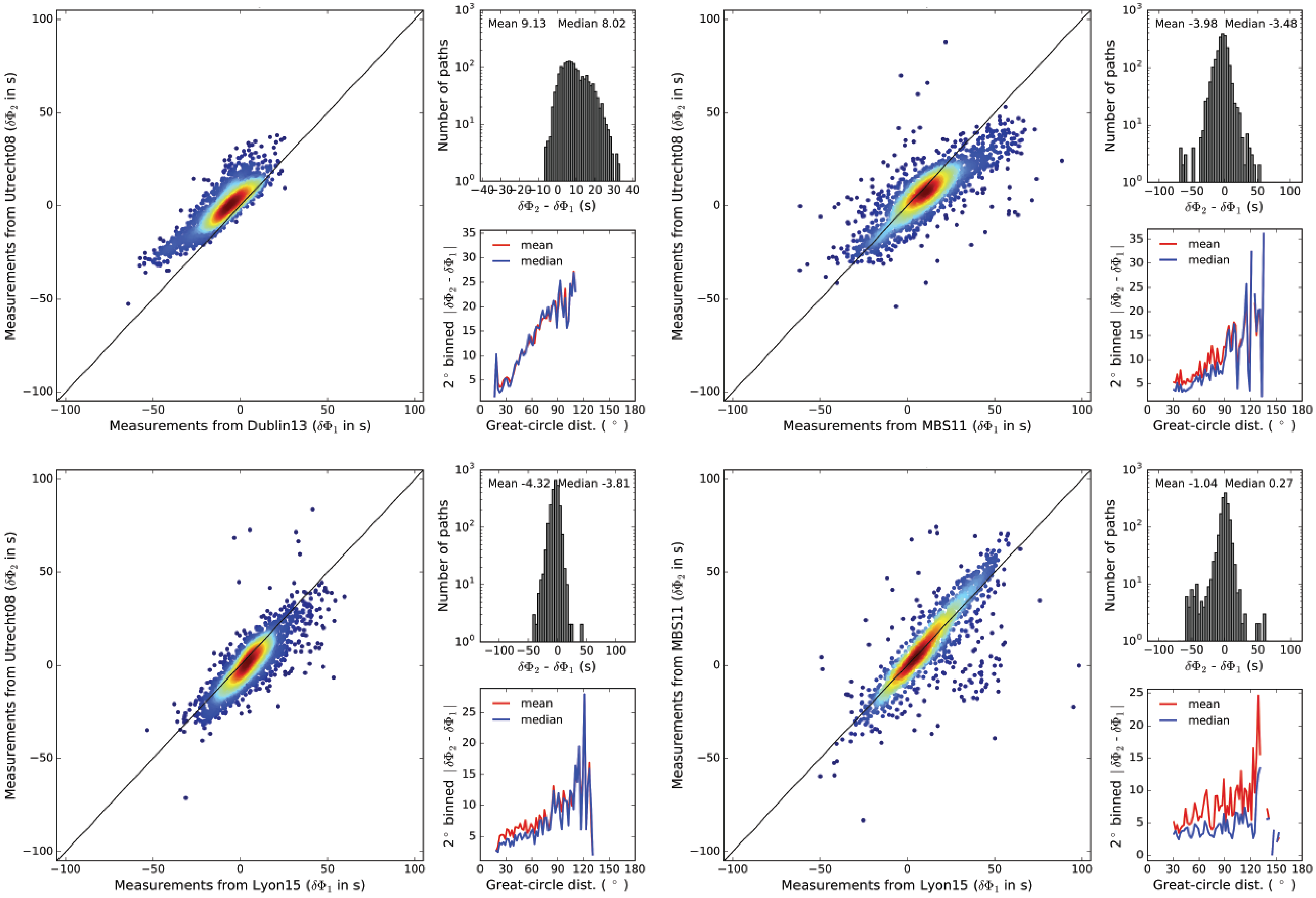


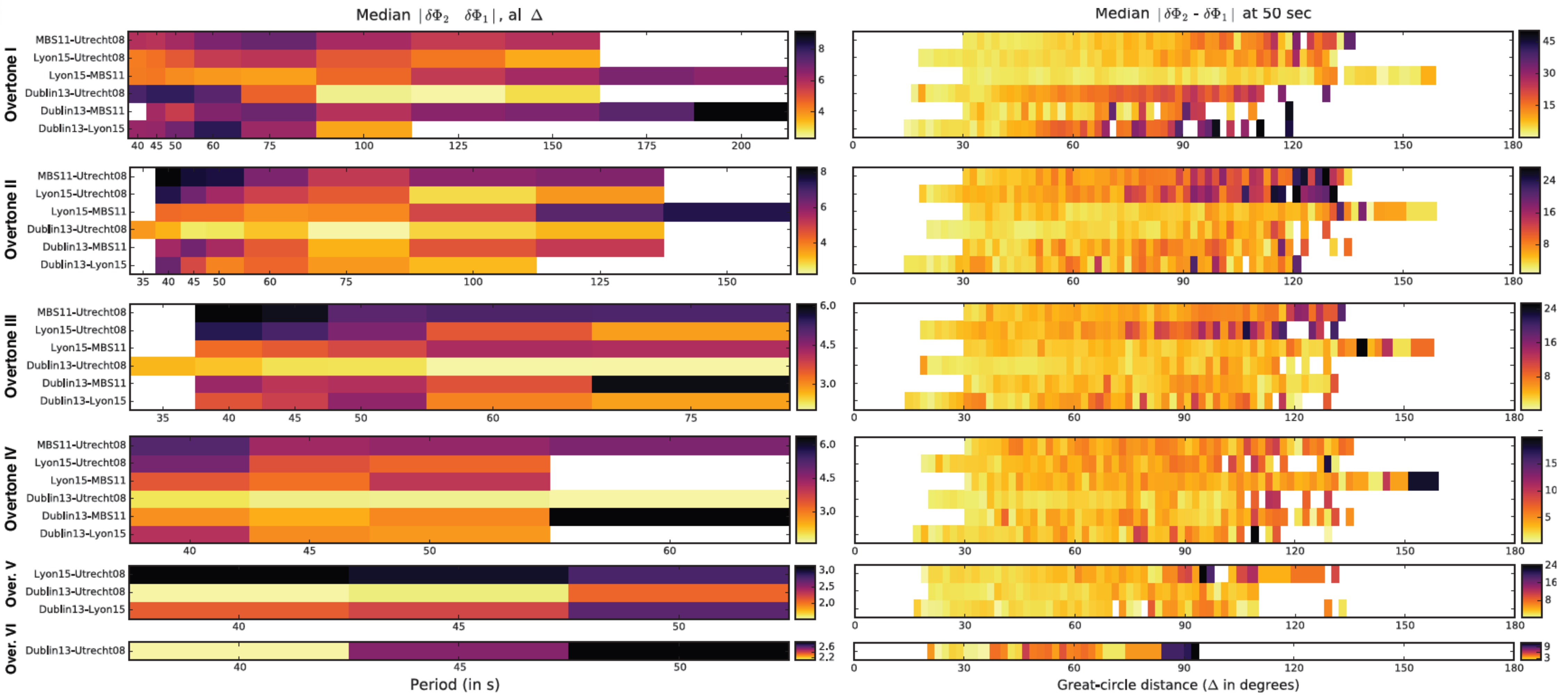


Overtones

- Overtone measurements are less consistent
- Biases and trends among datasets exist
- Measurements from different groups should be combined with caution

Overtone 1, 50s





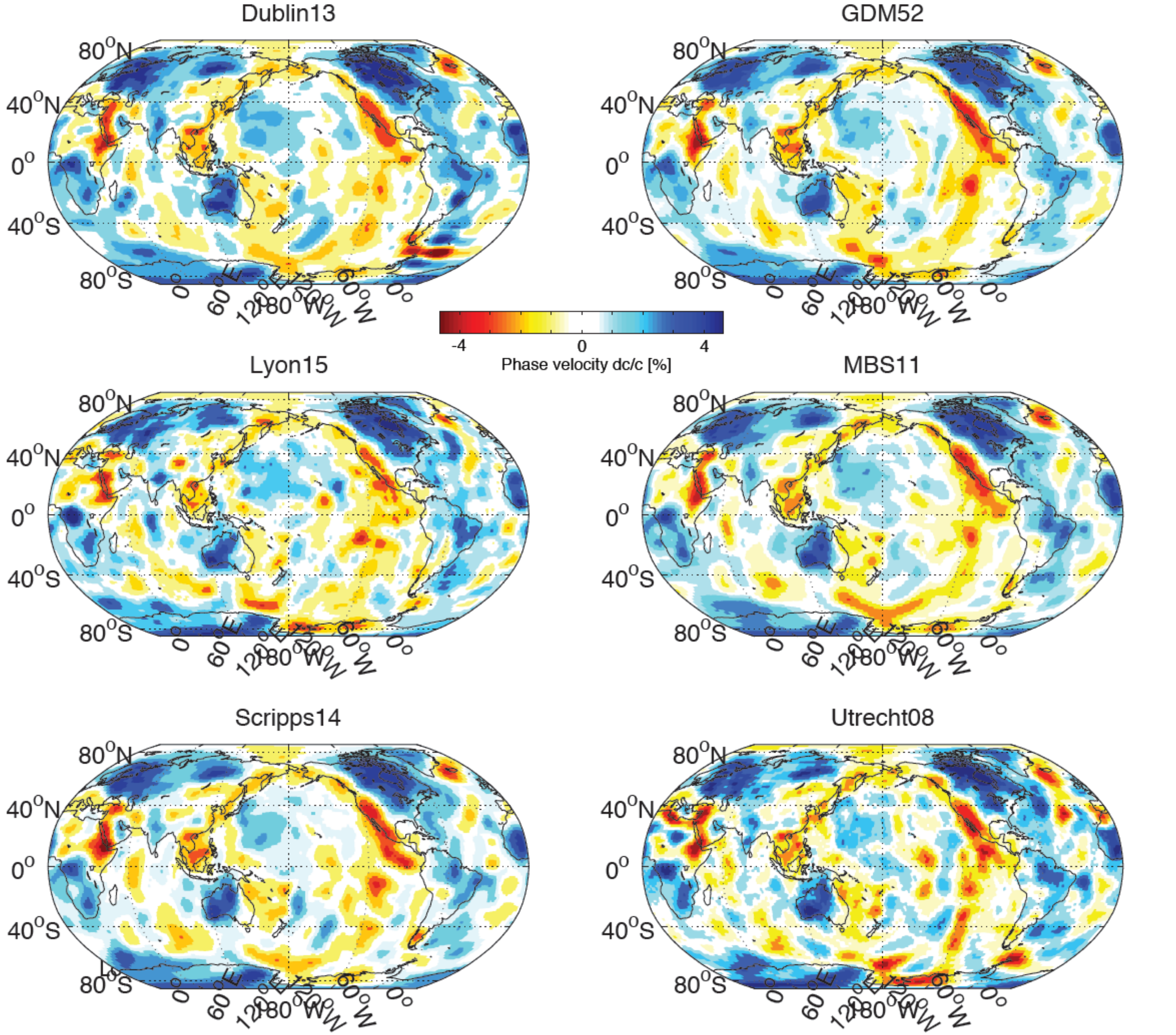
Overtones – systematics with period and distance

Inter-dataset discrepancies grow with epicentral distance

Median errors are on the order of 2-10 seconds

How detailed should REM-3D be?

- We construct phase velocity maps from 6 contributing datasets (e.g. 100s Rayleigh)
- Identical parameterization / similar regularization
- Compare correlation vs. spherical harmonic degree



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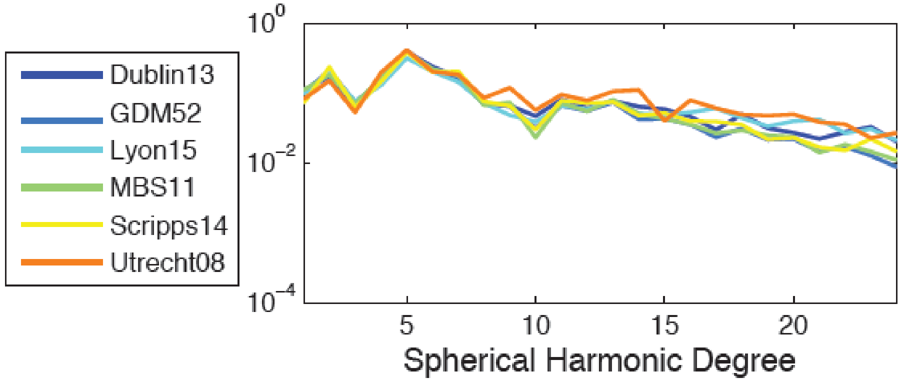
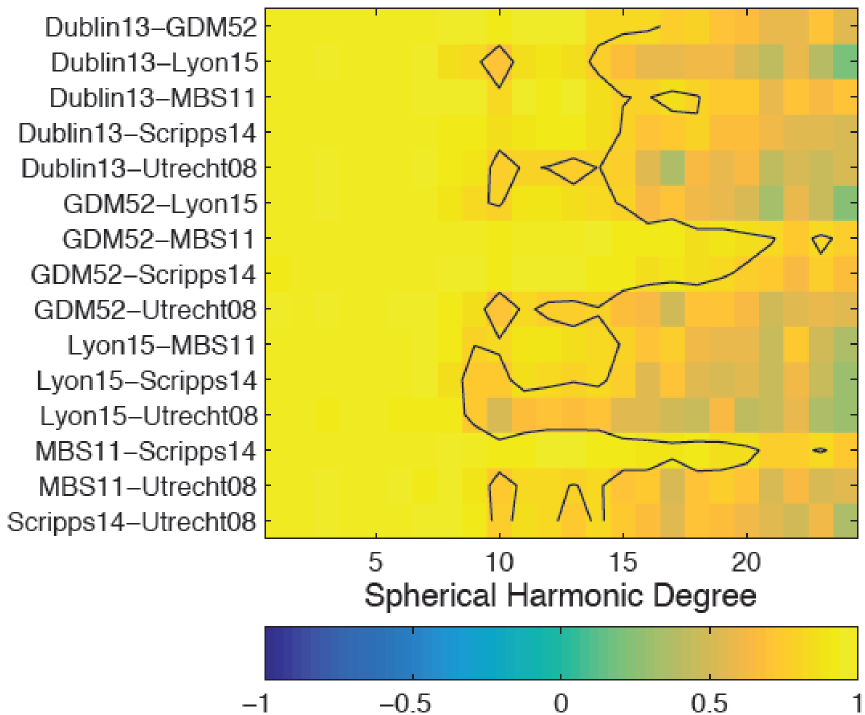
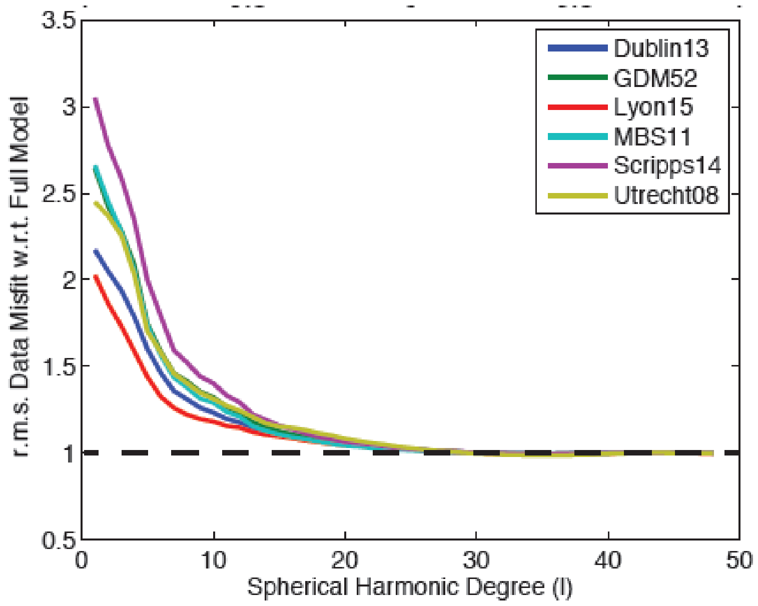


Rayleigh waves at 100s





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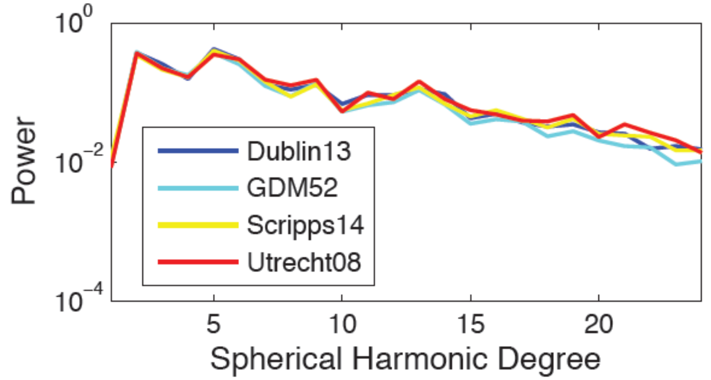
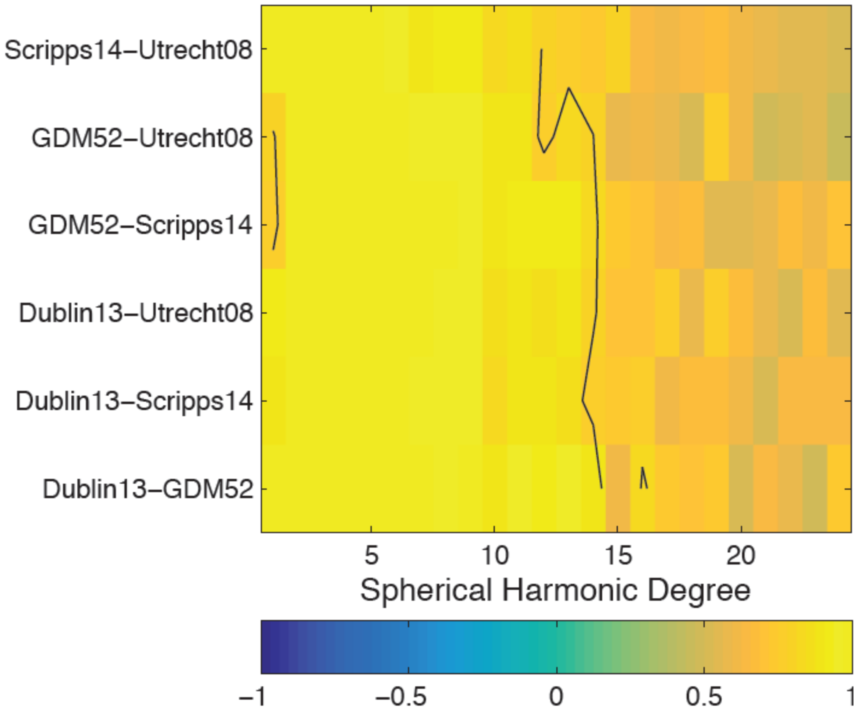
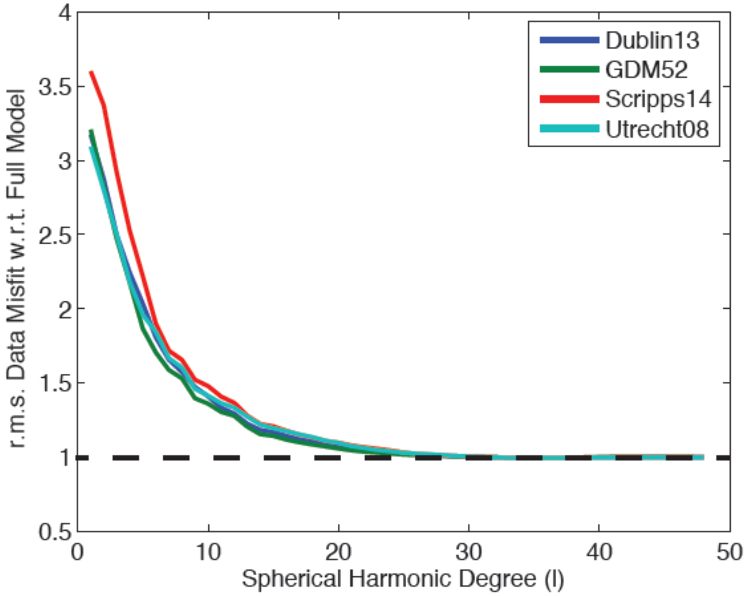


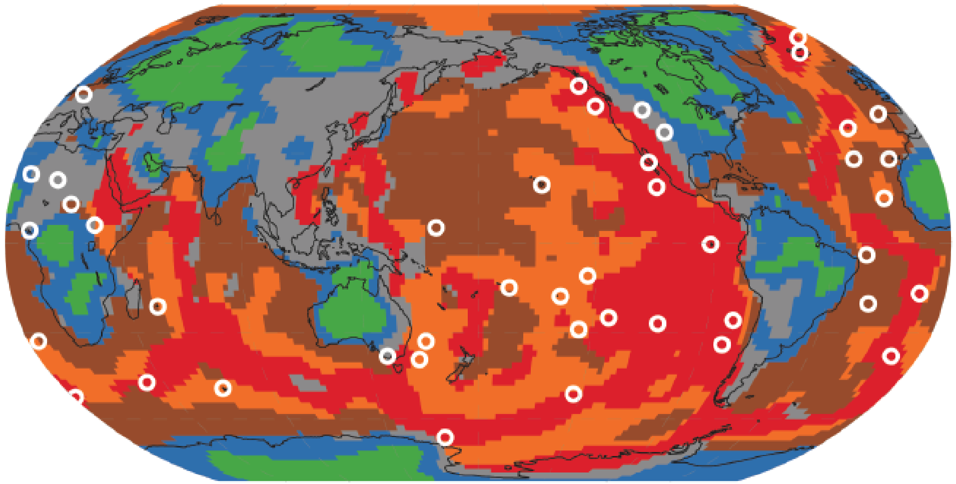
Love waves
at 100s

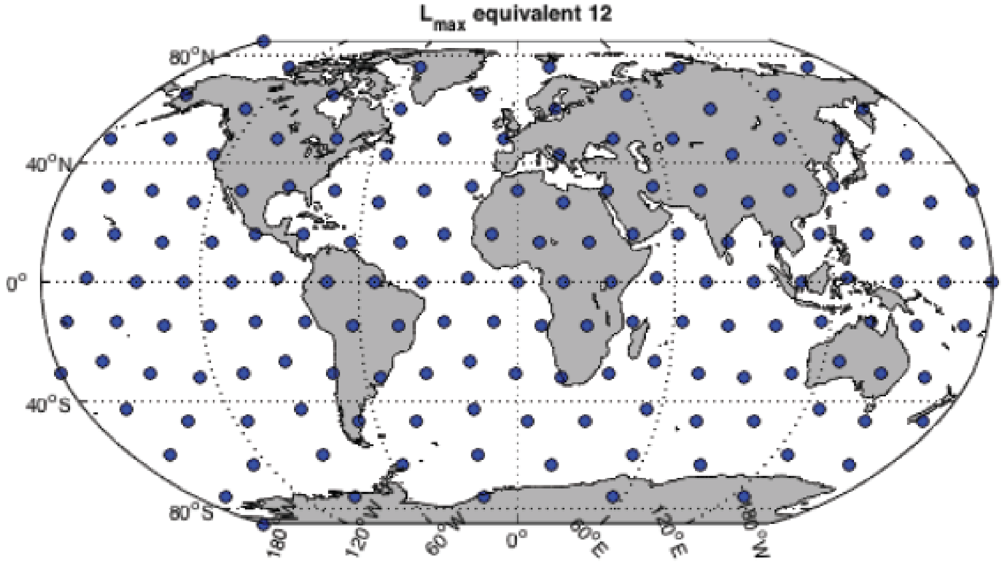




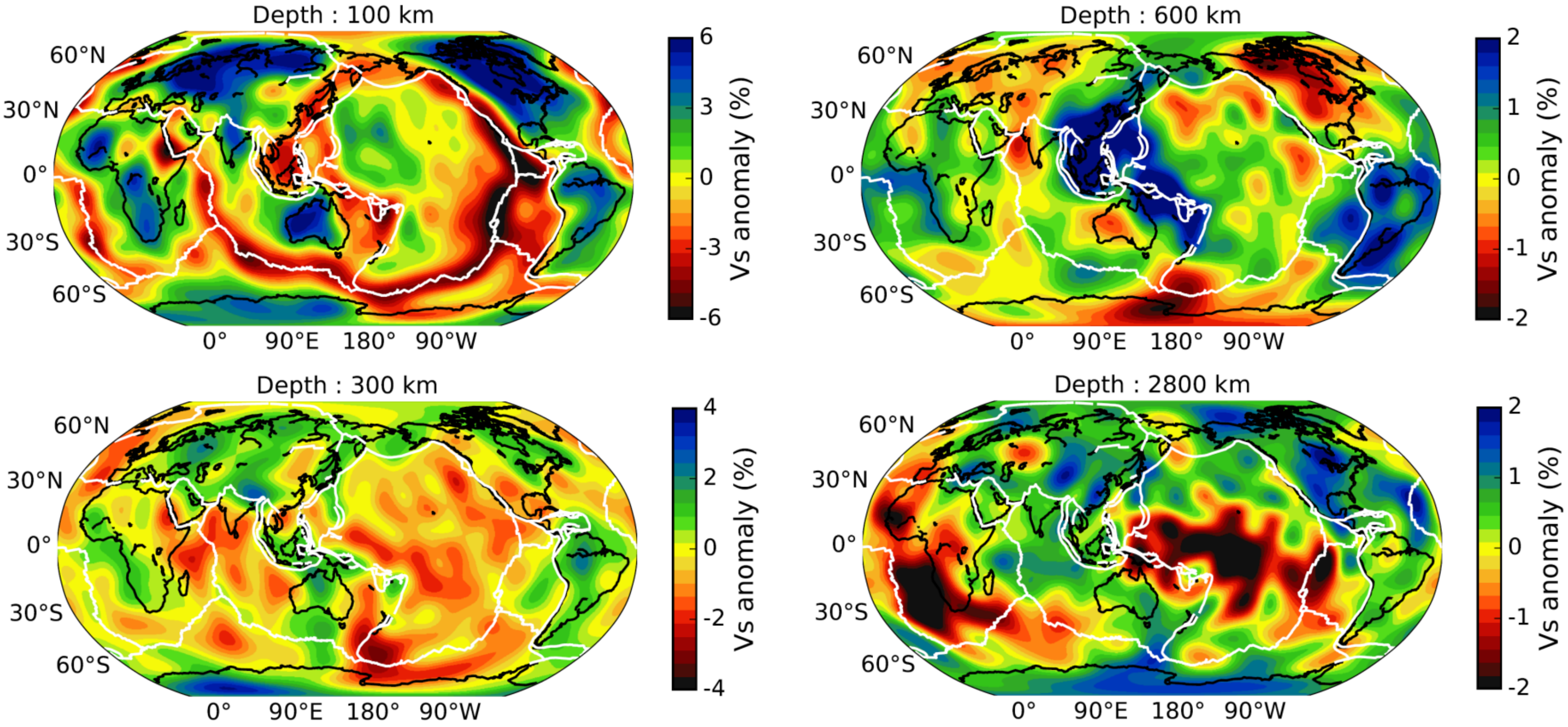
Parameterization and uncertainty

- 3D REM will come in two flavors:
  - **Regionalization** – Reference profiles of Vp, Vs, r for each of 6 regions in the upper mantle and 2 in the lower mantle
  - **Smooth parameterization** – Lateral variations parameterized in spherical splines
- Preliminary analysis suggests that L_{MAX} = 12-18 is justified in the upper mantle by inter-dataset consistency
- Relatively small number of model parameters enable use of model-space search to quantify uncertainty.





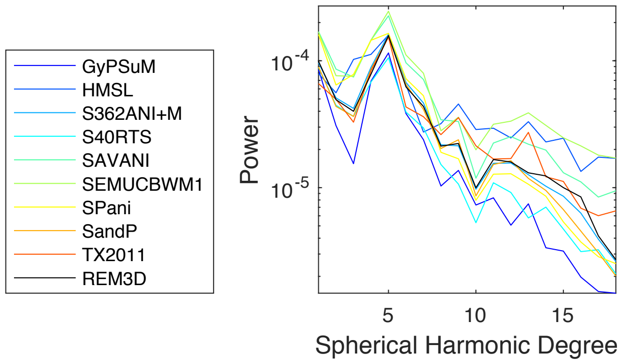
Preliminary REM-3D

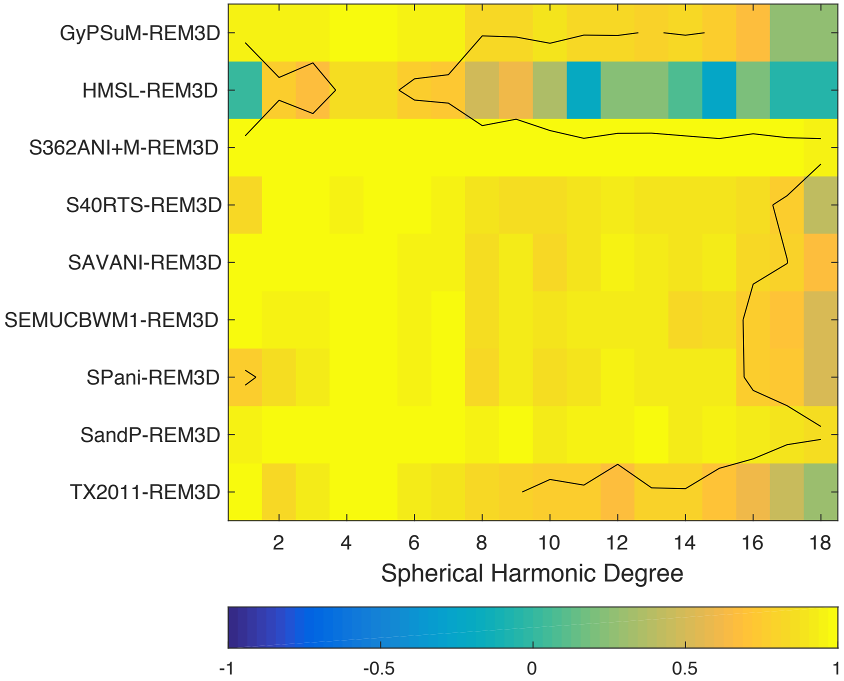


High consistency with Vs models

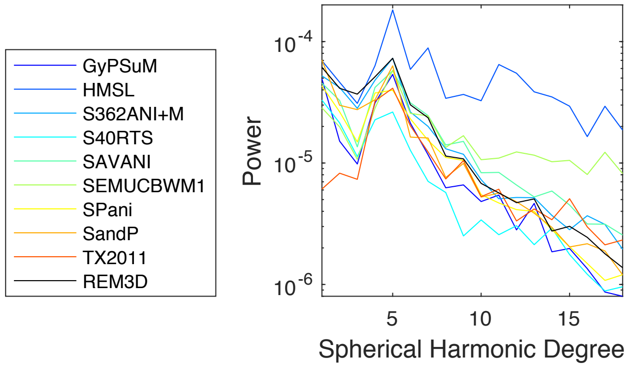
- Preliminary REM-3D correlates strongly with existing tomographic models (often r > 0.8)
- High correlations extend to Lmax 14-18

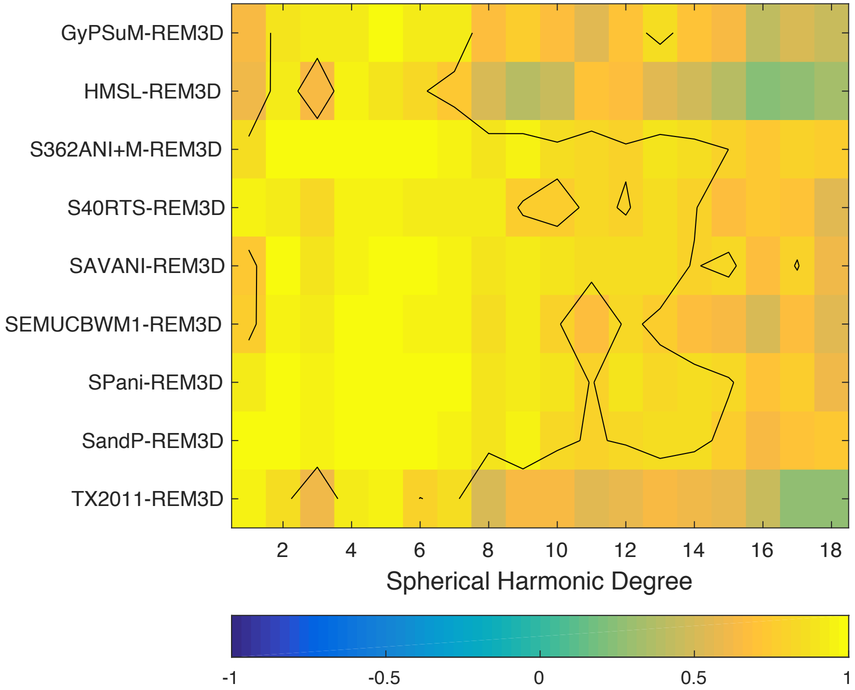
100 km





200 km





Reference Datasets and Models

- 1D reference Earth model is due for an update:
  - Small changes to 1D reference have profound implications for structure inferences (*e.g. Irving et al., in press and Poster A1 here*)
  - Moulik and Ekström (in prep) have created a new 1D reference model incorporating latest normal mode and body wave constraints (and eliminating 220-discontinuity)
- 3D reference Earth model effort is underway:
  - Metadata is crucial: polarity reversals, source location, reference model for measurements
  - Fundamental mode dataset: 8 contributed datasets,100 million measurements are reconciled, uncertainties estimated within and across models
  - Overtone dataset: 4 contributed datasets, systematic differences between datasets warrant further study and caution when combining datasets
  - Preliminary mantle REM-3D:
    - Parameterized in ~362 spherical splines
    - Summary ray data coverage of entire reference dataset