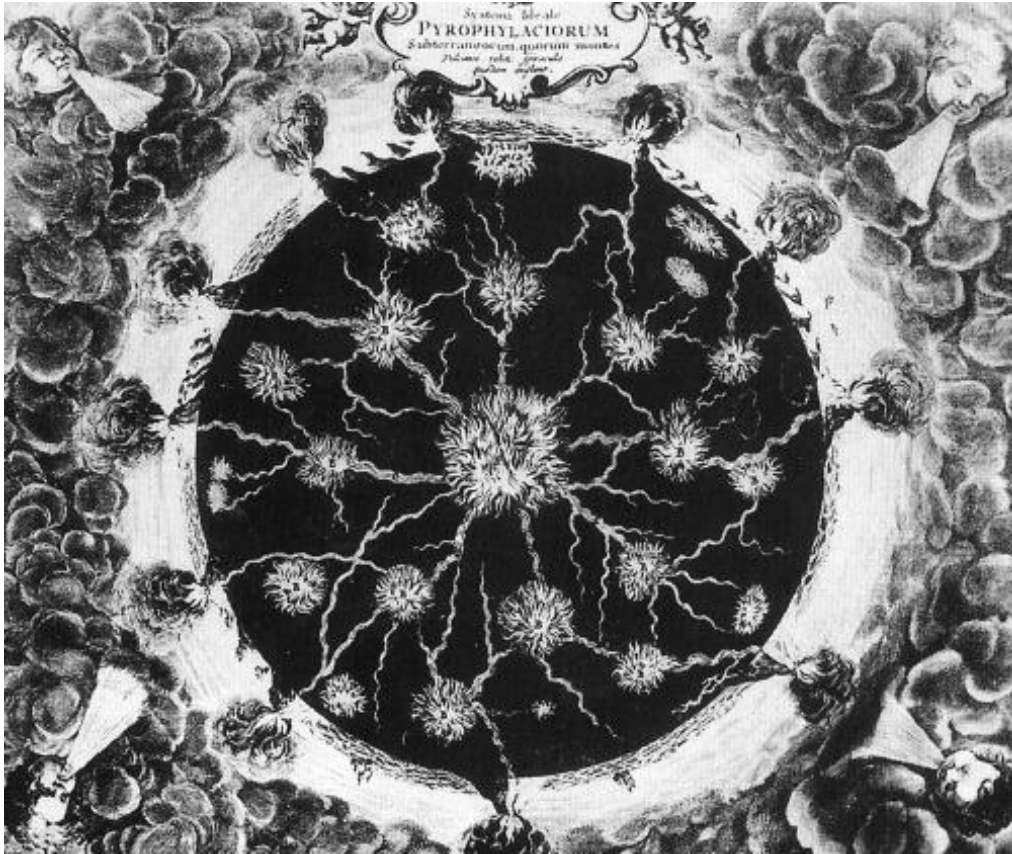


Look into Planetary Interiors with A Single Seismometer

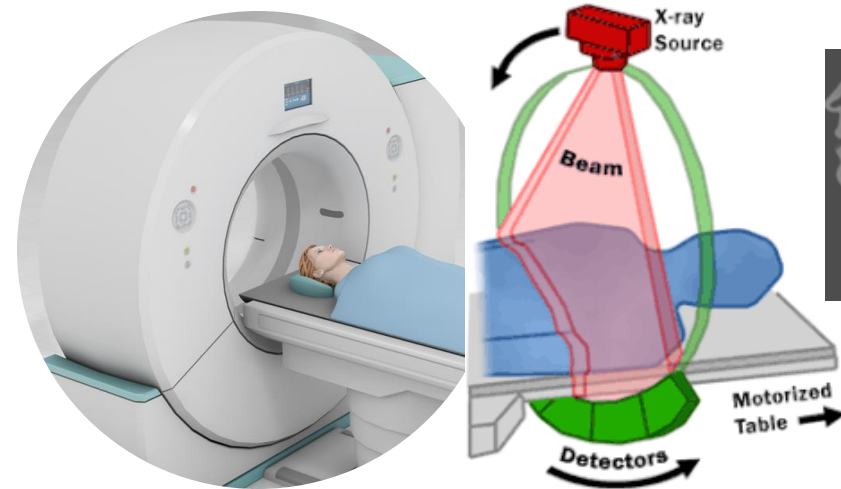
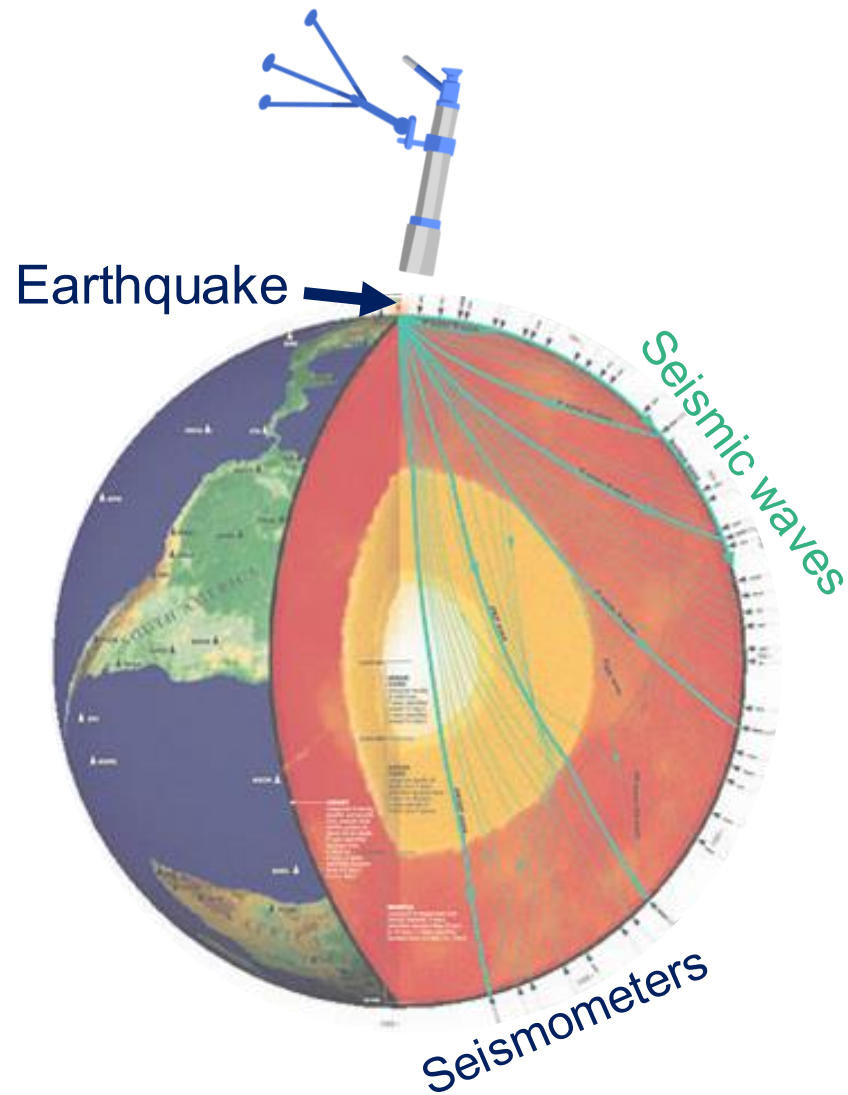
Sheng Wang
D-EAPS, ETH Zurich



Kircher's model of Earth's internal fires, *Mundus Subterraneus* (1665)



Athanasius Kircher (1602-1680)



Looking into the Earth's and planetary interiors is as "simple" as X-ray imaging of your body!

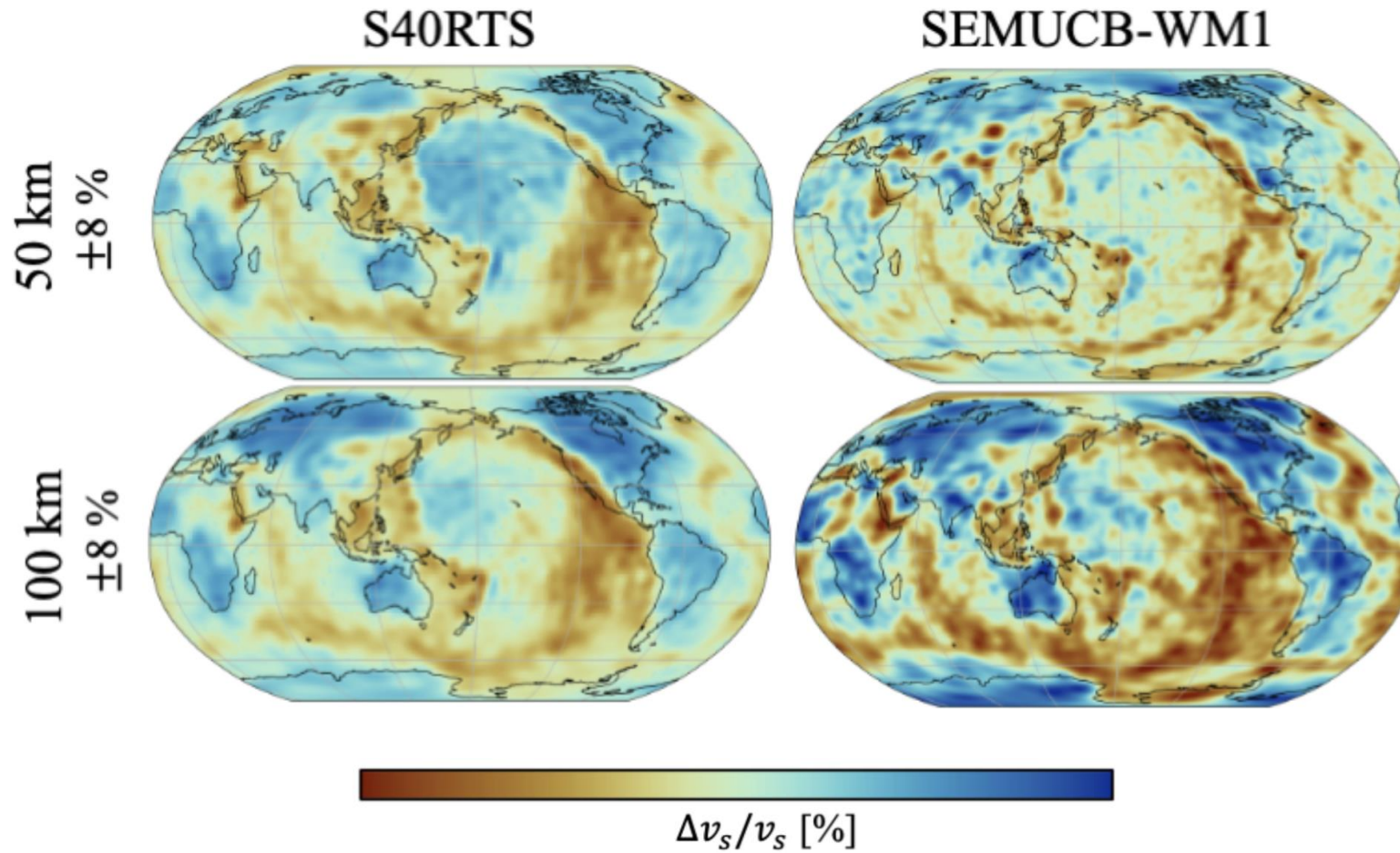
Global proliferation of seismographs



Seismometers available on Earth (Mar/31/25)

(http://www.iris.washington.edu/gmap/#network=_REALTIME&planet=earth)

Tomographic images of the Earth's interior



(e.g., Ritsema et al., 2011; French and Romanowicz, 2014; Simmons et al., 2021; Thrastarson et al., 2024;...)

Seismometers On Mars and the Moon



1969-1977 Lunar Seismometers, **Apollo program**

1976 Viking 1 (**Failed** to unlock) & Viking 2 (~19 months **operation on deck**)

1993 Mars94, **Cancelled**

1996 Mars96 (OPTIMISM seismometer), **Failed**

1996 InterMarsnet proposal, **Not selected** by ESA/NASA

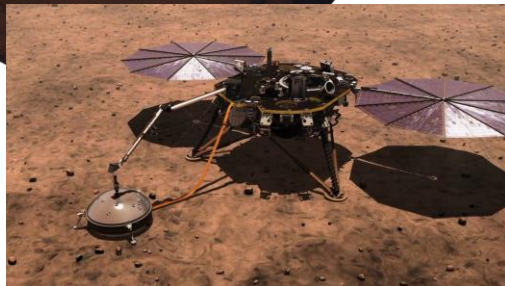
1990s MESUR (Mars Environmental SURvey), **Abandoned**

1990s-2000s NetLander mission (SEISM seismometer), **Shelved**

2000s ExoMARS mission, **Cancelled**

2018-2022 Mars SEIS seismometer, **InSight mission**

The ~\$1 Billion InSight Station on Mars



Spacecraft Development	\$596.3 million
Launch Vehicle (Atlas V 401)	\$163.4 million
Mission Operations (2 years)	\$53.9 million
U.S. Total	\$813.6 million
International Contributions	\$180 million
Total	\$993.6 million

Planetary Exploration Budget Dataset

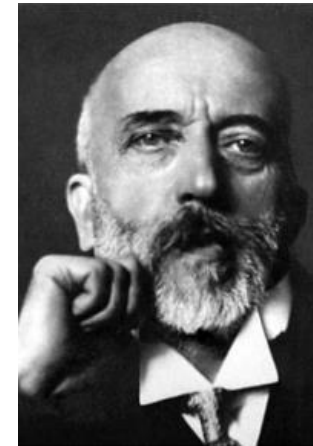
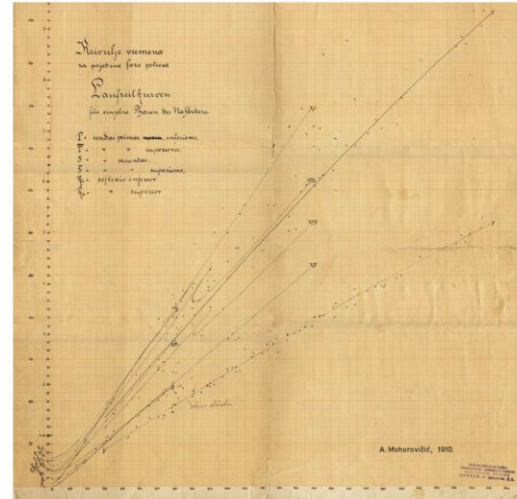
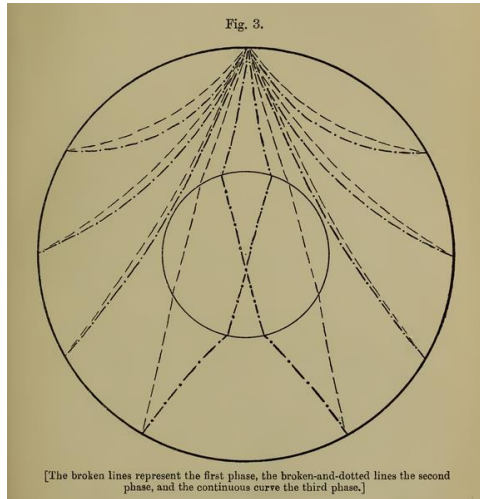
<https://www.planetary.org/space-policy/cost-of-mars-insight>



What can we do with a single instrument?



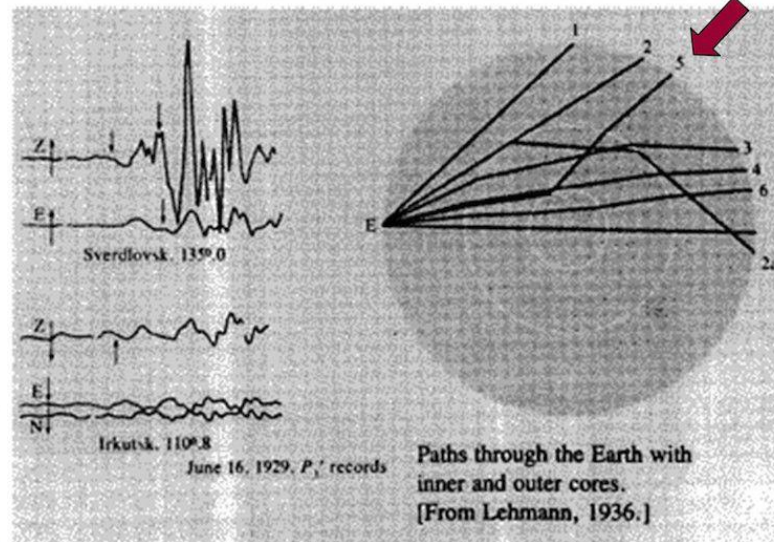
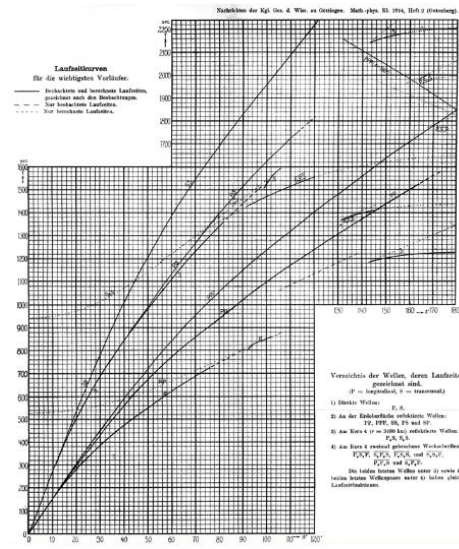
Spacecraft Development	\$596.3 million
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On-orbit Operations (2 years)	\$53.9 million
International Contributions	\$180 million
Total	\$993.6 million



Andrija Mohorovičić
1857-1936



Richard Dixon Oldham
1858-1936

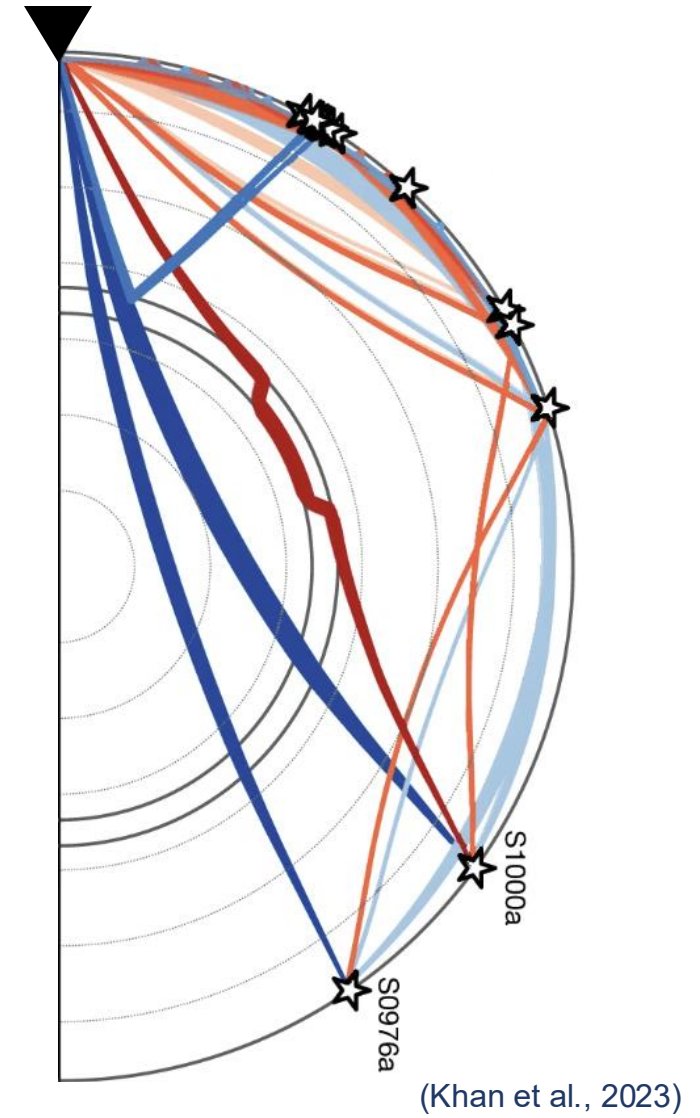
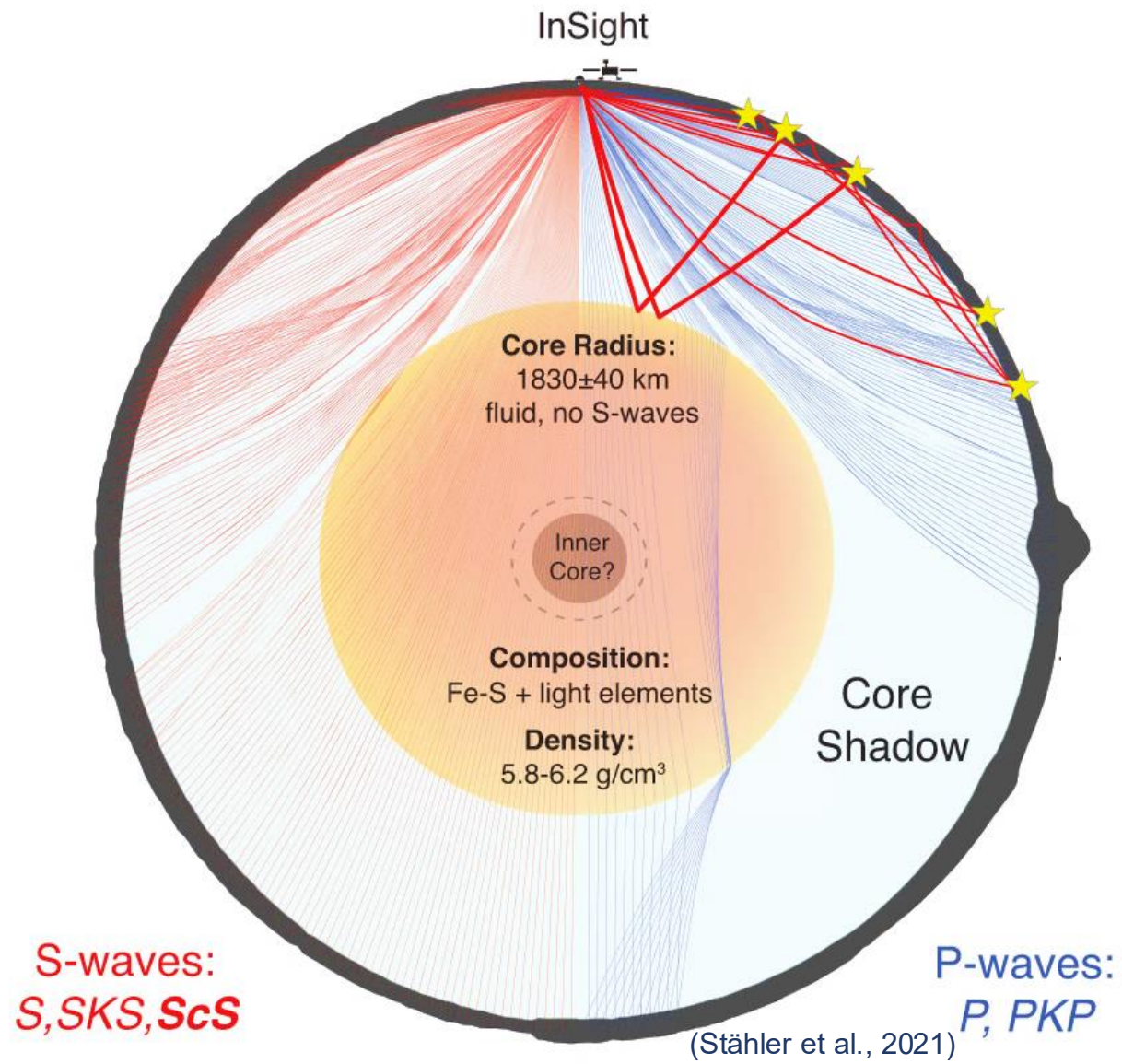


Inge Lehmann
1888-1993



Beno Gutenberg
1889-1960

(Mohorovičić 1909; Gutenberg 1913; Oldham 1906; Lehmann 1936; ...)



*... a single instrument ...
... the entire interior of a planet ...?*

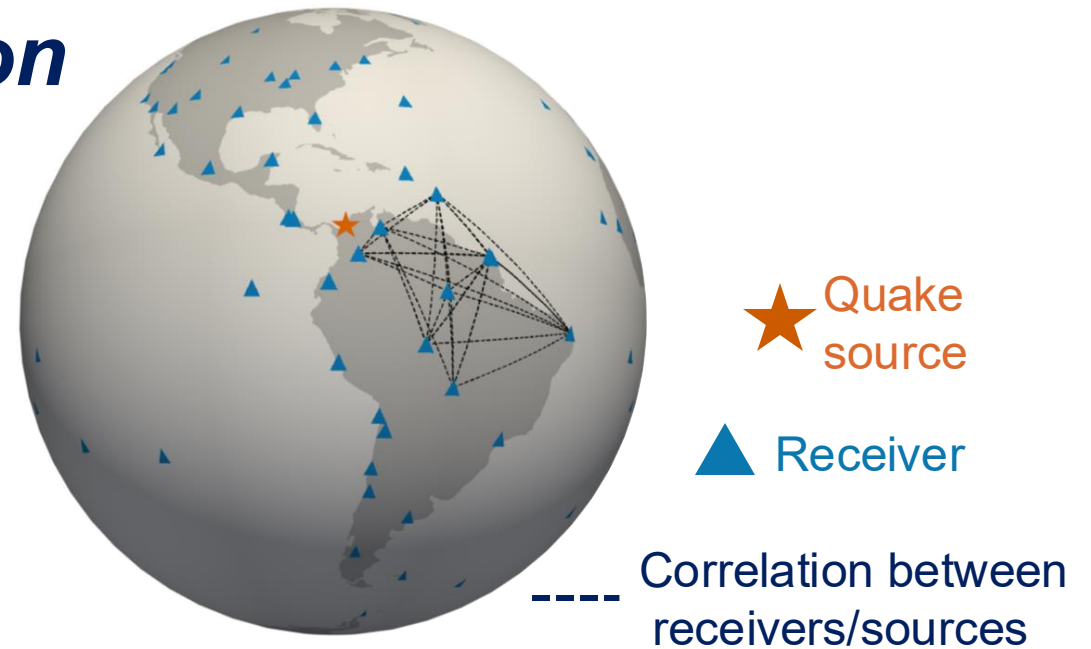
Spacecraft Development	\$596.3 million
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U.S. Total	\$813.6 million
European Space Agency Contribution	\$180 million
Total	\$993.6 million

Global Inter-Source Correlation

- Cross-correlation of seismic waveform records **between source events** on a global scale.

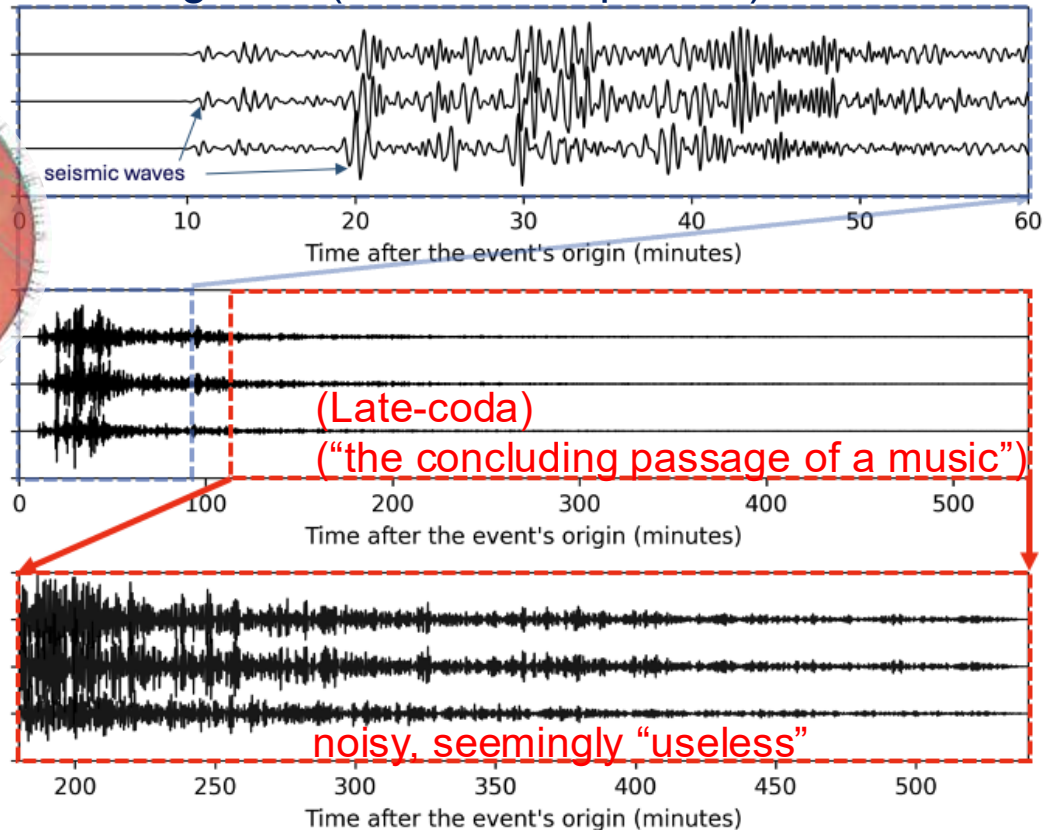
Global Inter-Receiver Correlation

- Cross-correlation of seismic waveform records **between receivers** on a global scale.



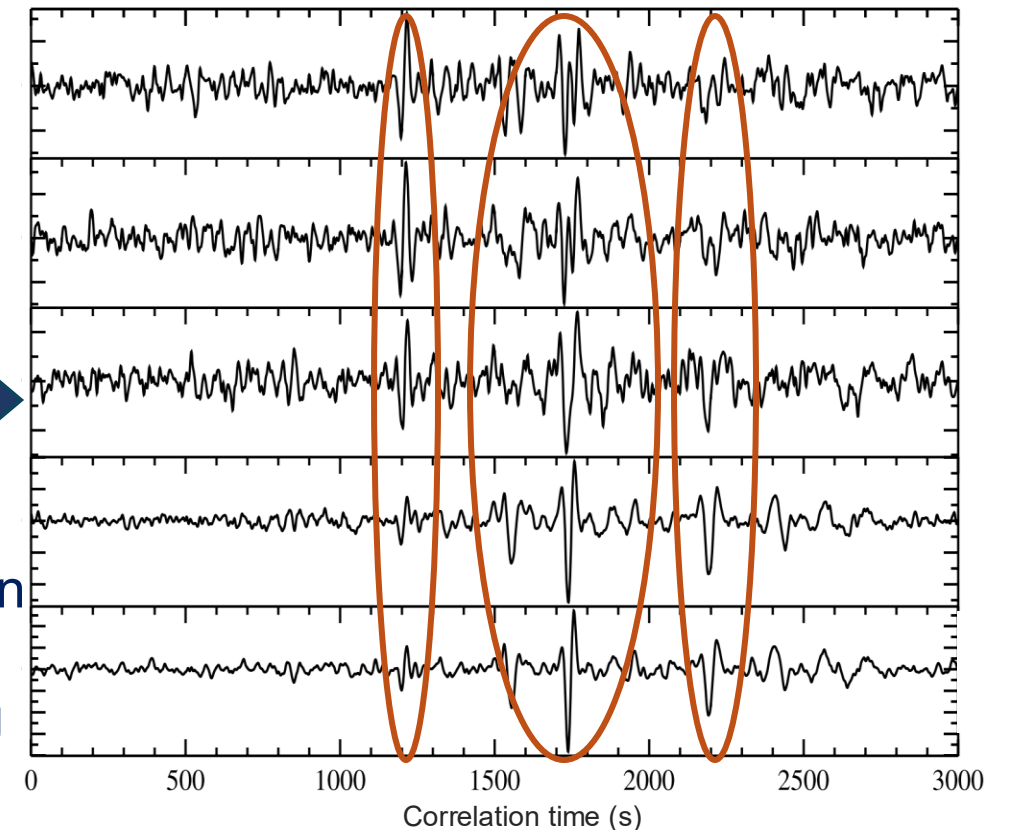
Global Inter-Receiver Correlation

Seismograms (vertical component)



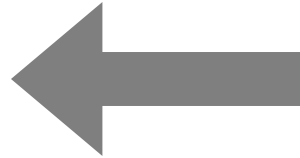
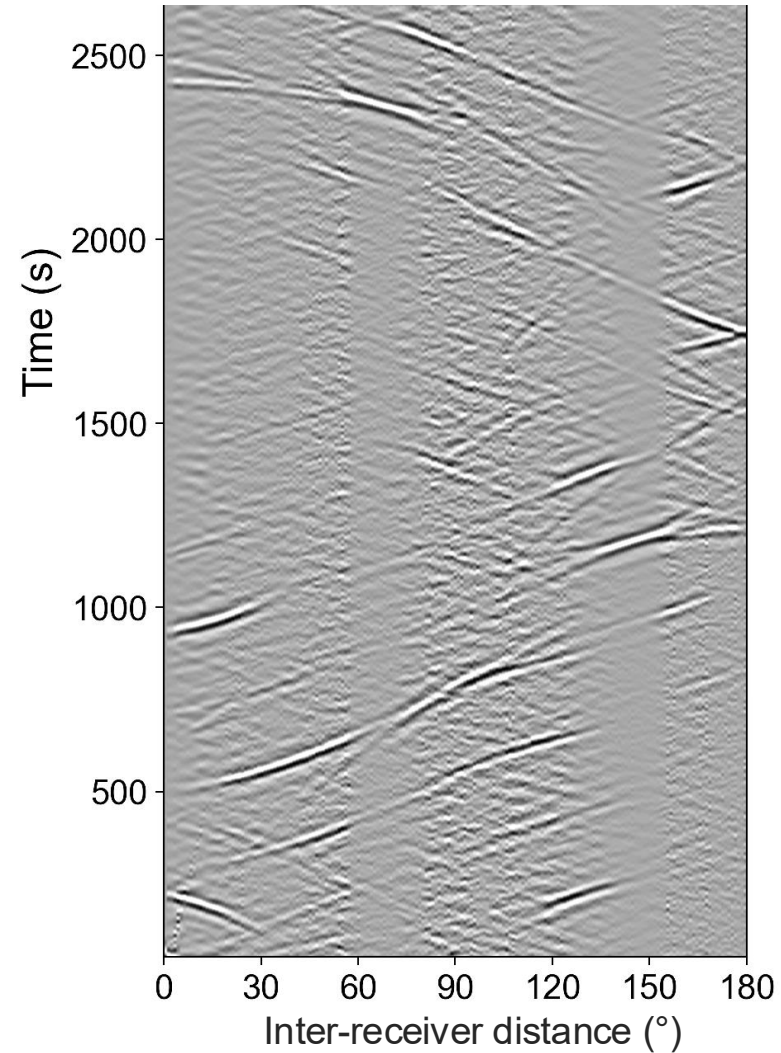
➔
Cross-
correlation
&
Stacking

Vertical-to-vertical cross correlation

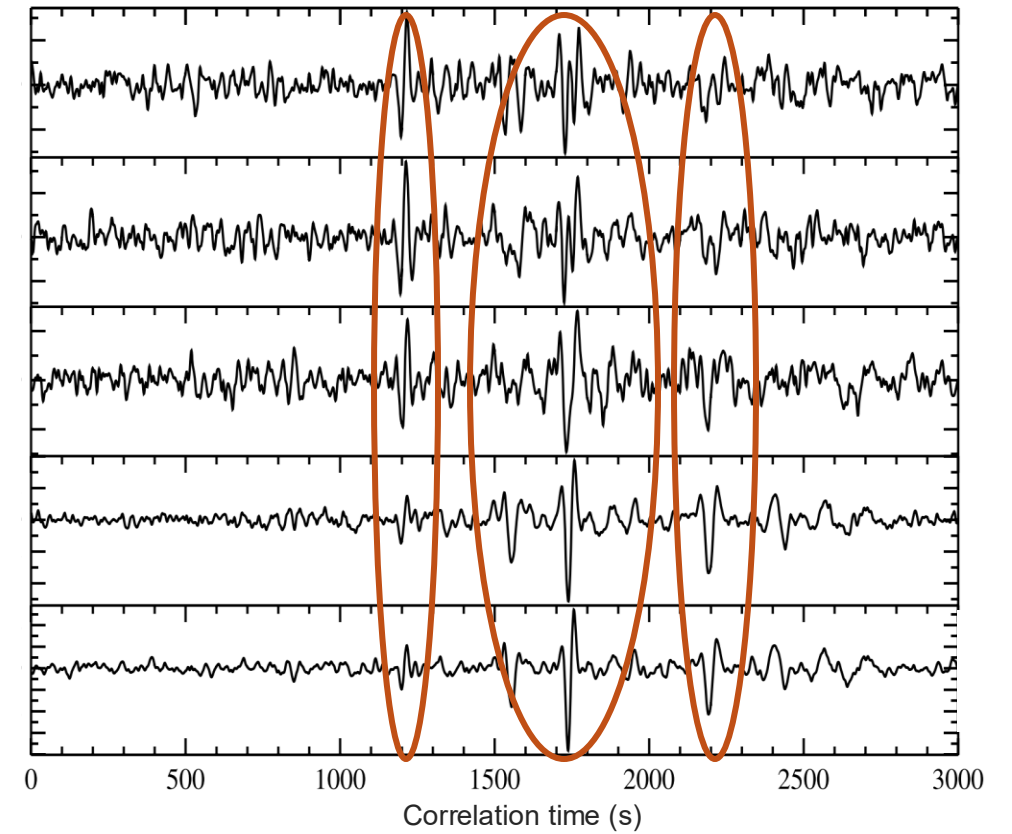


(Boué et al., 2013; Lin and Tsai, 2013; Nishida, 2013;
Wang et al., 2015; Poli et al., 2017; Phạm et al., 2018; ...)

Global correlogram (correlation wavefield)

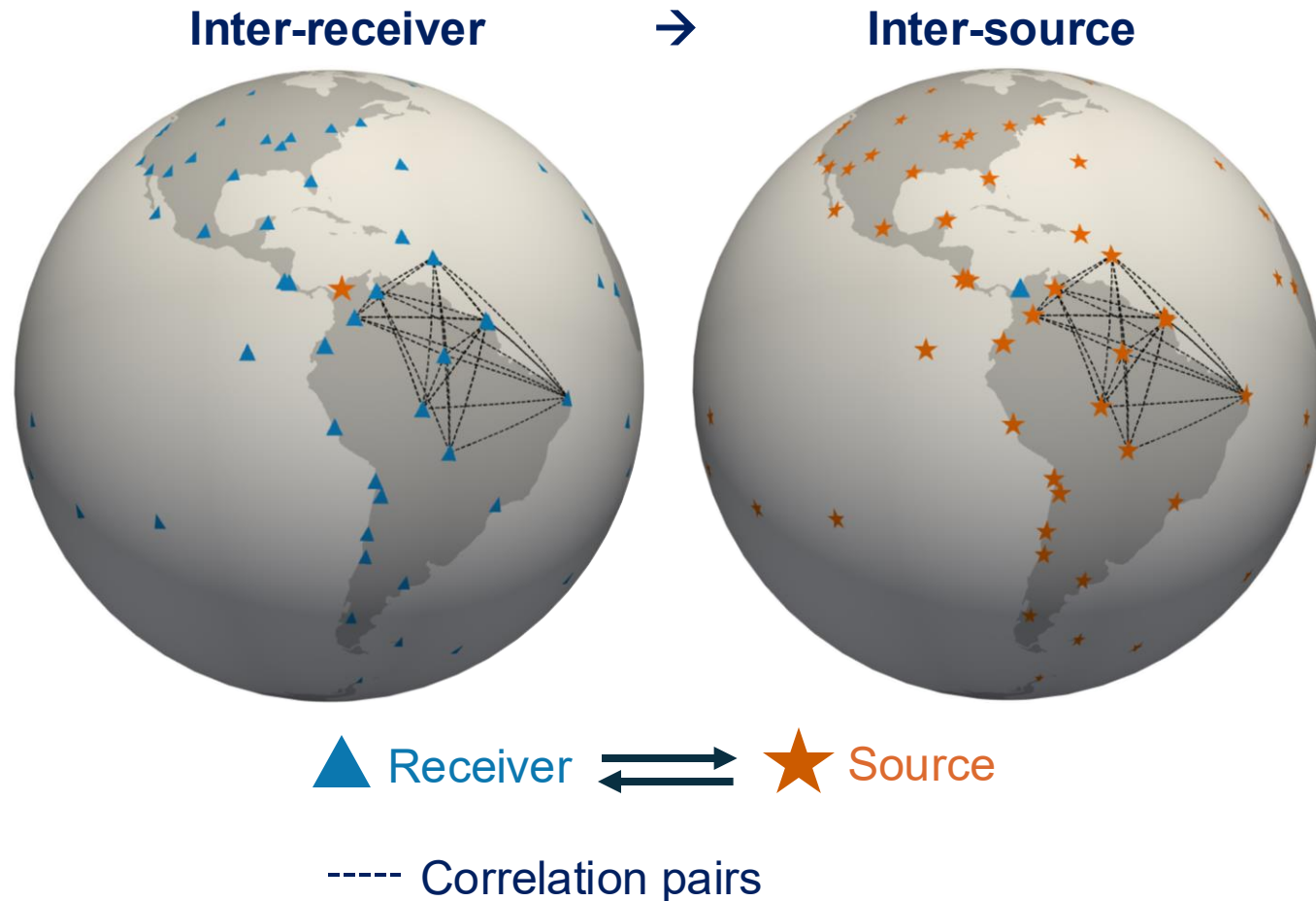


Vertical-to-vertical cross correlation

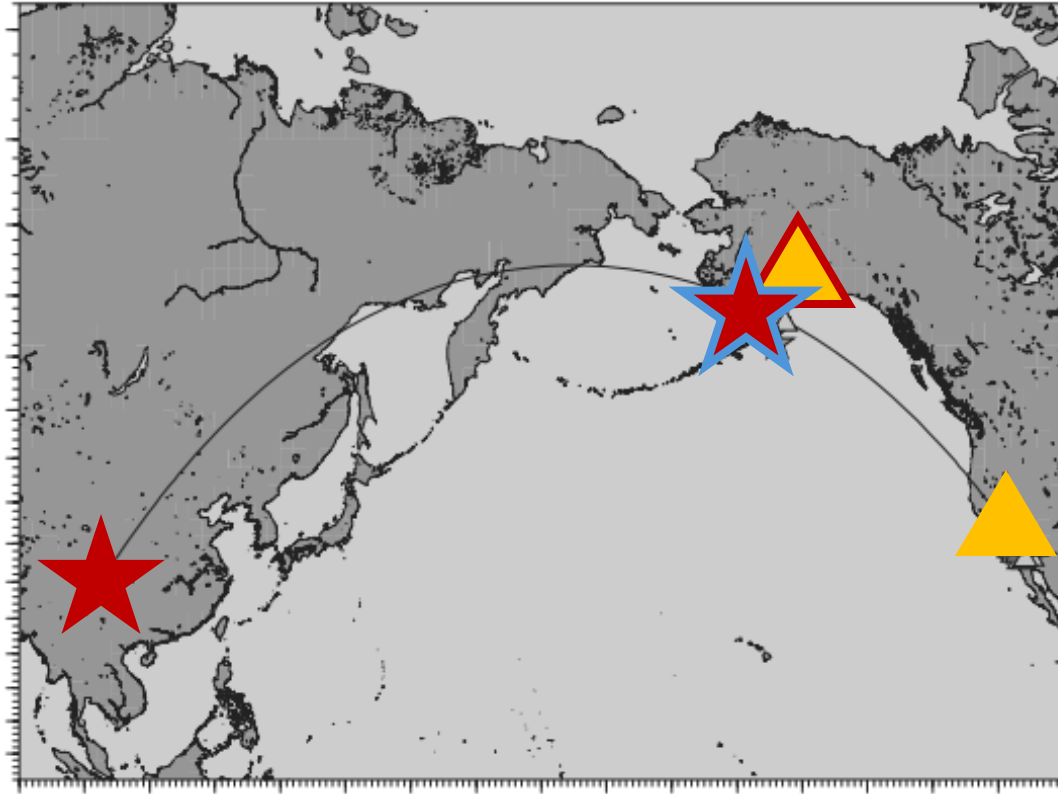


Global Inter-Source Correlation

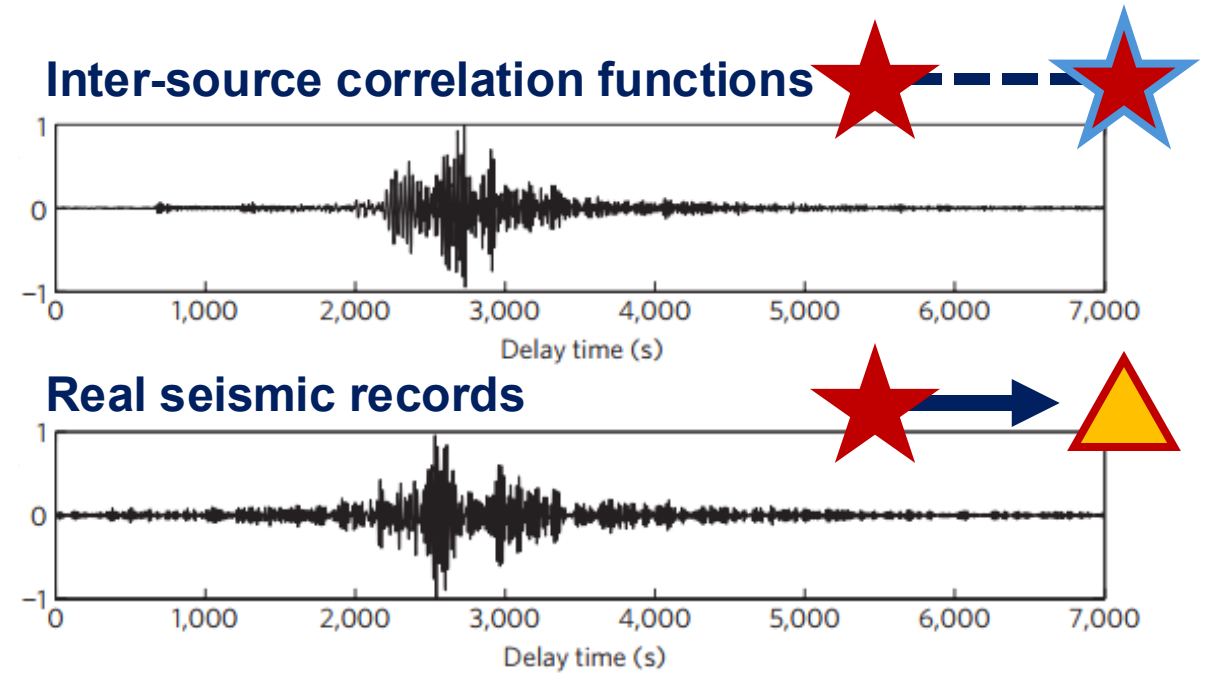
- Inter-source correlations can be theoretically derived from the inter-receiver correlations via **exchanging the locations of sources and receivers**.



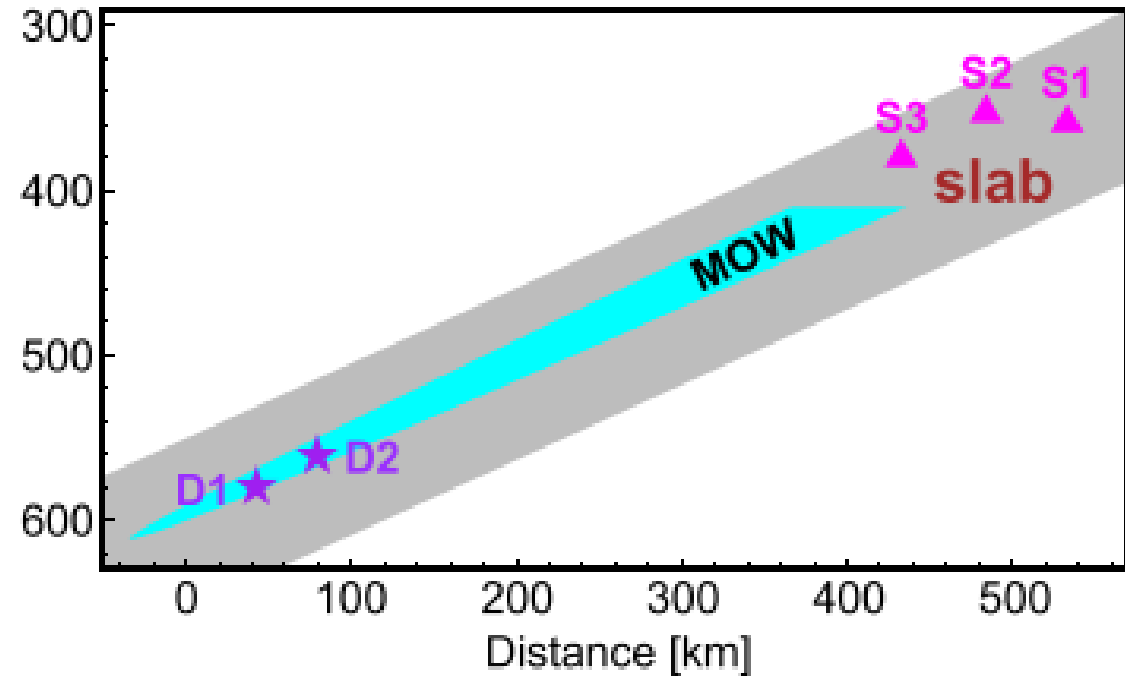
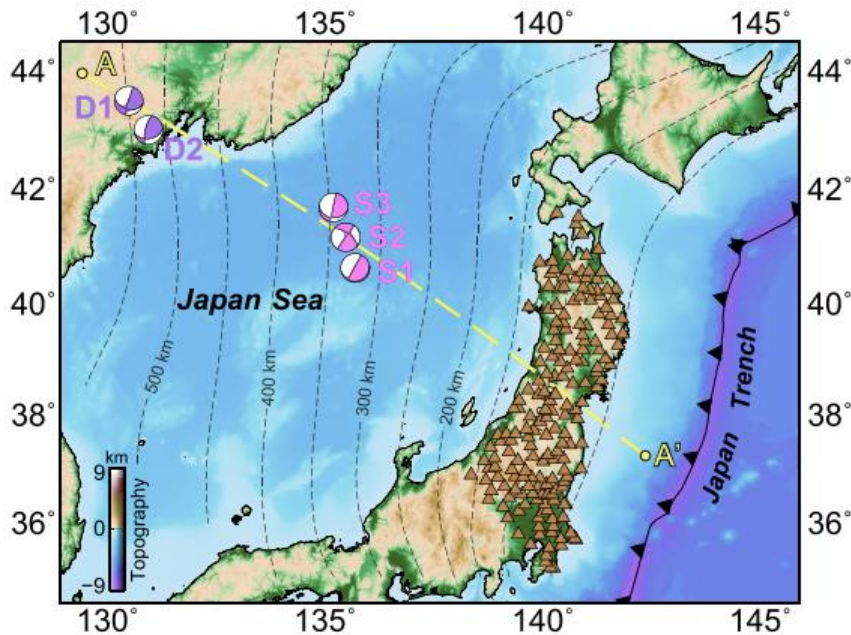
Inter-source correlation creates “virtual receivers”



(Curtis et al., 2009)



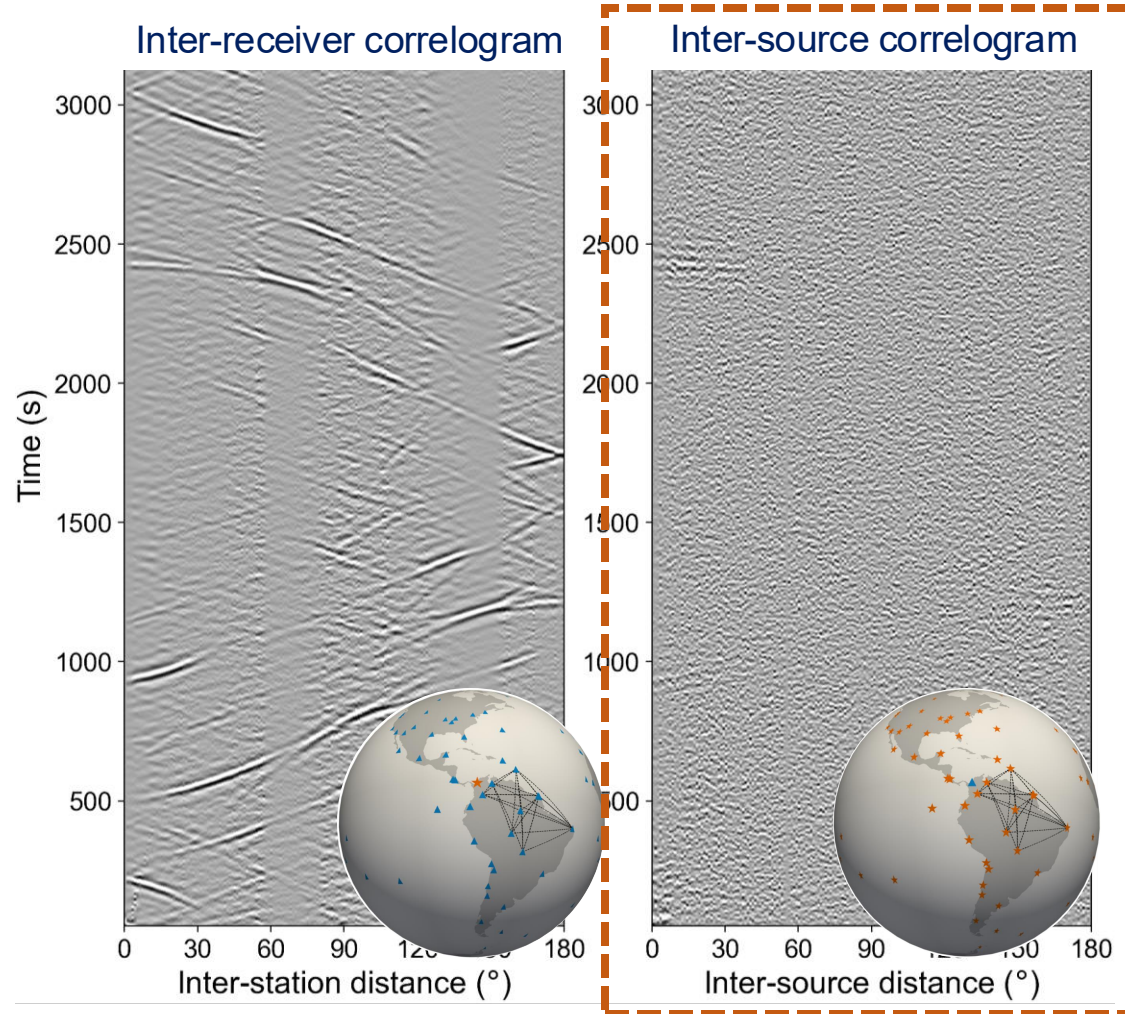
Inter-source correlation creates “virtual receivers”



(Shen and Zhan 2020; Shen et al, 2021)

However...

- Realistic attempts **fail to present theoretical expectations.**



Observation contradicts theory!

However...

- **Fewer publications** on inter-source correlation than on inter-receiver ones.

Inter-source correlation

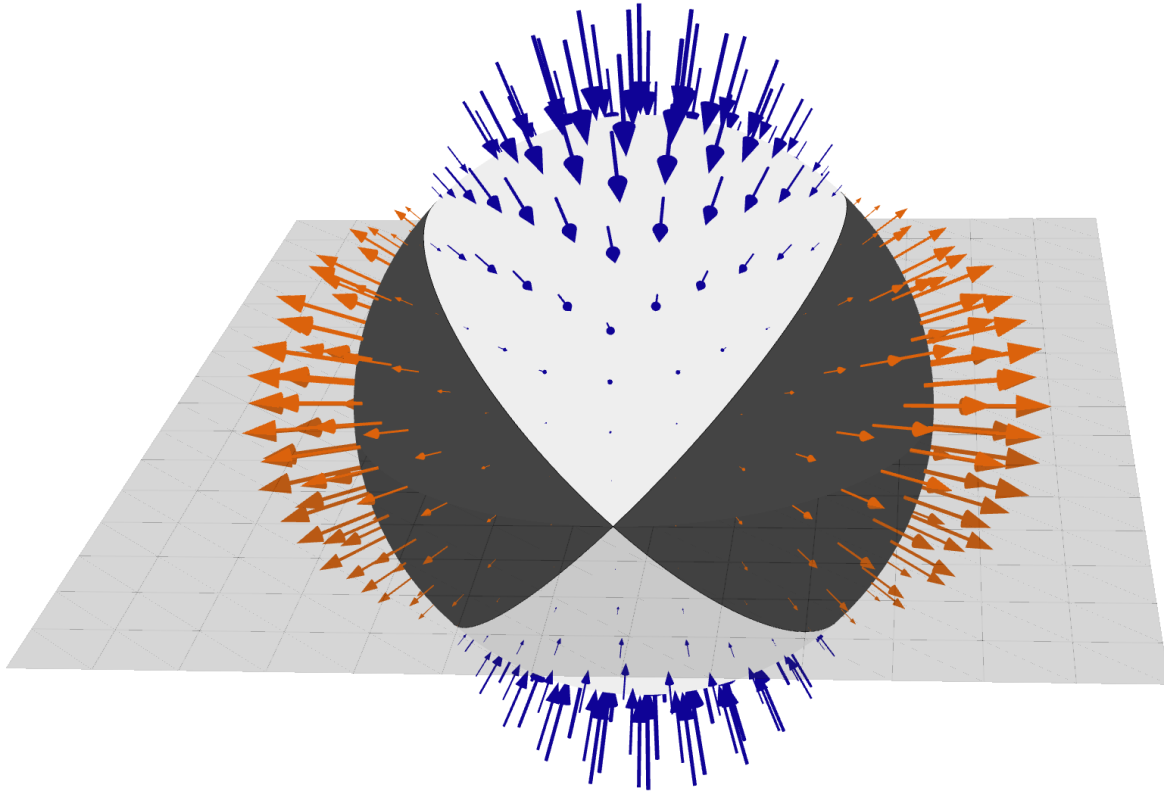
- 1 Hong and Menke, 2006;
- 2 Curtis, 2009;
- 3 Tonegawa & Nishida, 2010;
- 4 Morency & Matzel, 2017
- 5 Shirzad et al., 2019
- 6 Eulenfeld, 2020
- 7 Shen and Zhan, 2020;
- 8 Shen et al., 2021;
- 9 Saengduean et al., 2021

VS.

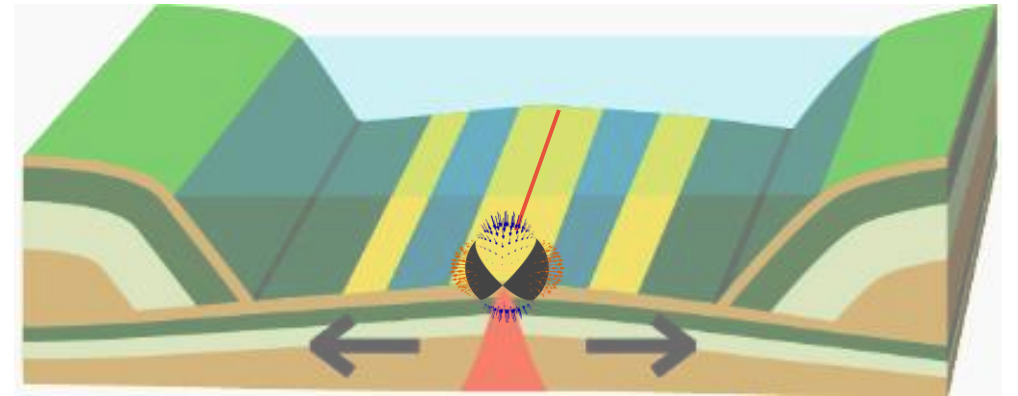
Inter-receiver correlation

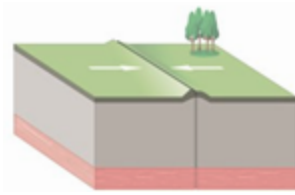
A VREY LARGE NUMBER OF ...

≡	Google Scholar	seismic inter station interferometry
📖	Articles	About 18'100 results (0.13 sec)
≡	Google Scholar	seismic inter station correlation
📖	Articles	About 11'200 results (0.13 sec)

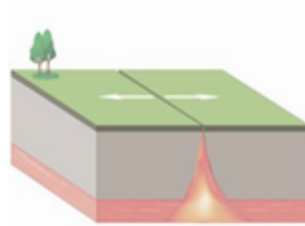


Beachball representation of a quake source

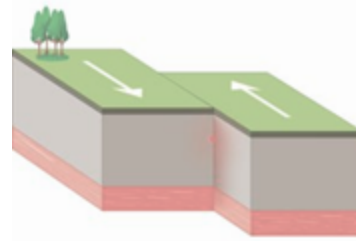




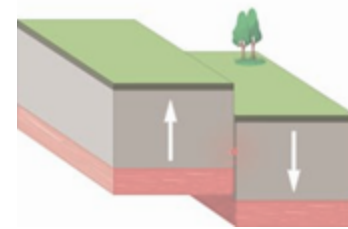
Thrust



Normal



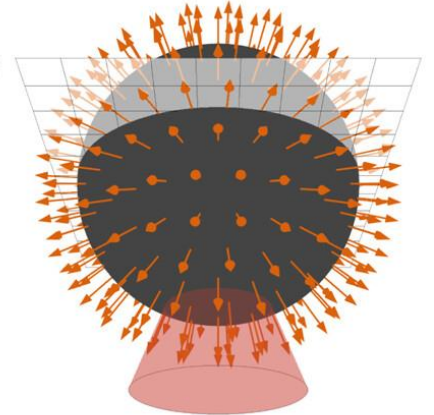
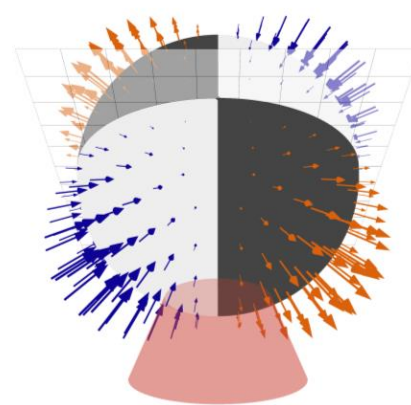
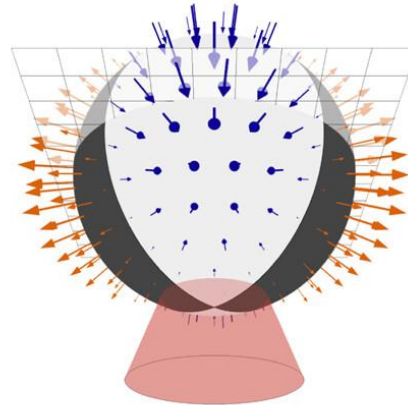
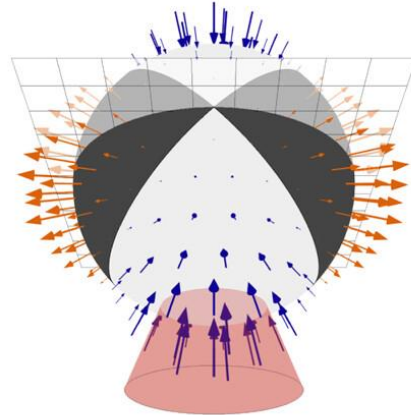
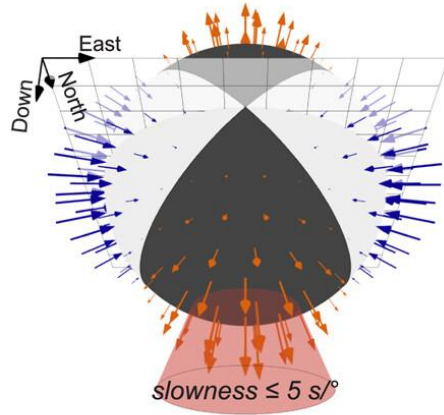
Strike-slip



Dip-slip

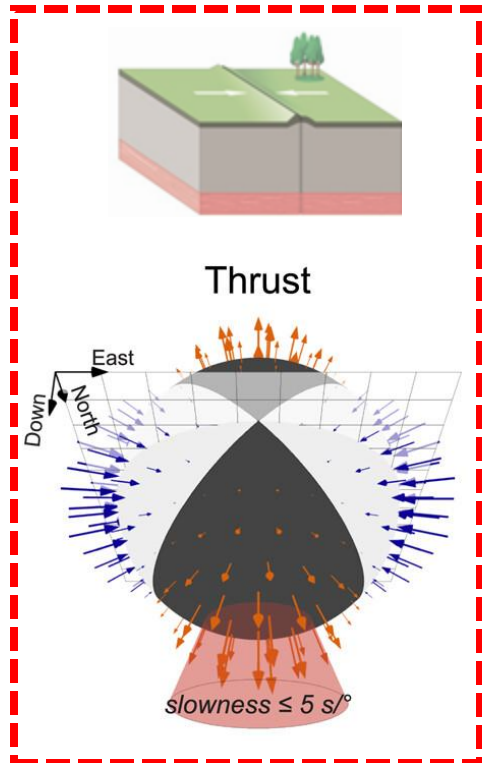


Explosive

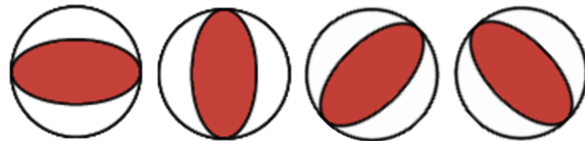


Deep-traveling waves

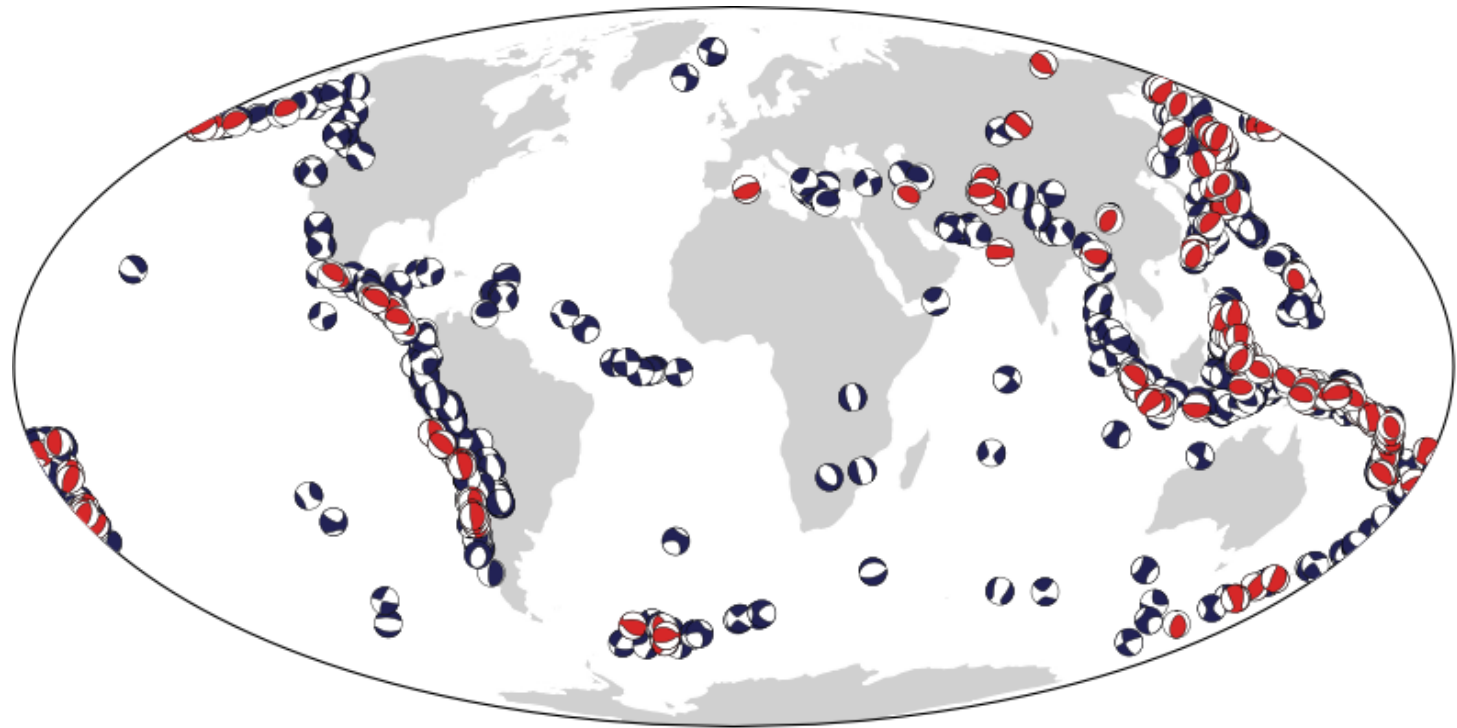
Selecting quake sources



Selected quakes (Thrust)



(Wang and Tkalčić, 2023)



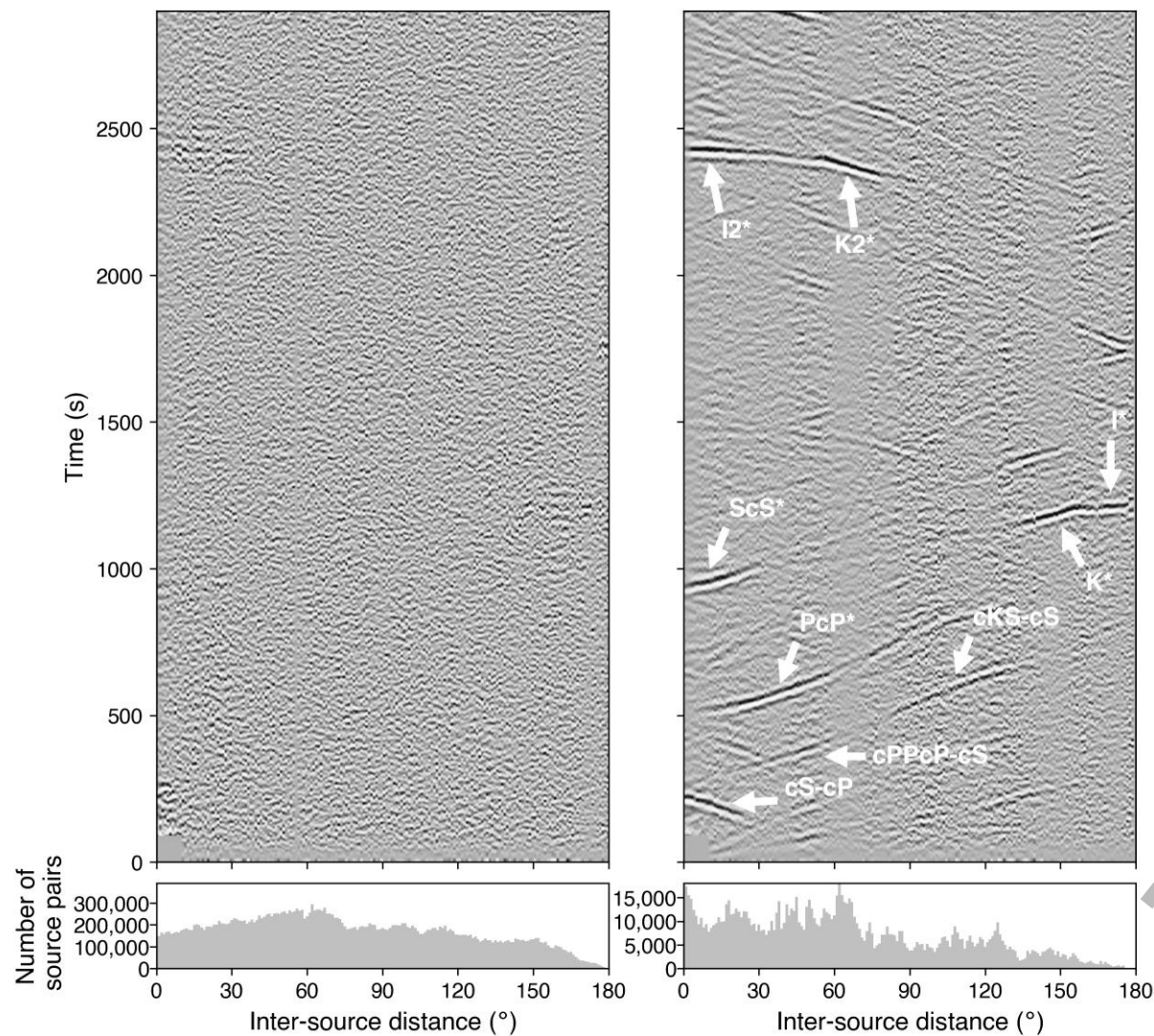
Discarded quakes

○ Normal ⊗ Strike-slip ◐ Dip-slip

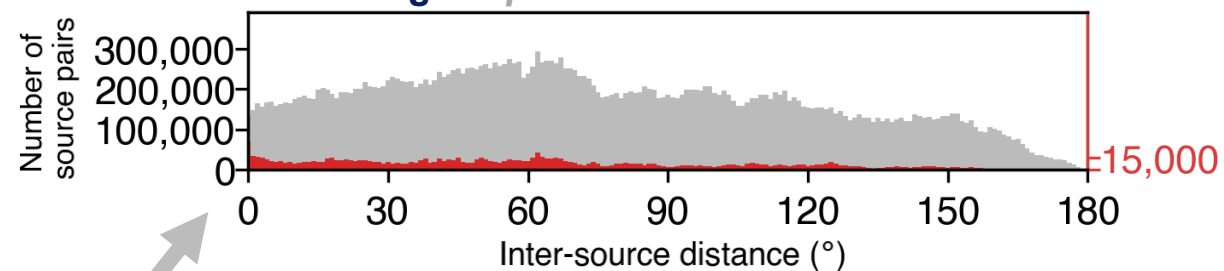
(Ekström et al., 2012; Global Centroid-Moment-Tensor [GCMT] Project, <https://www.globalcmt.org/>)

Using all quakes

Using the selected quakes

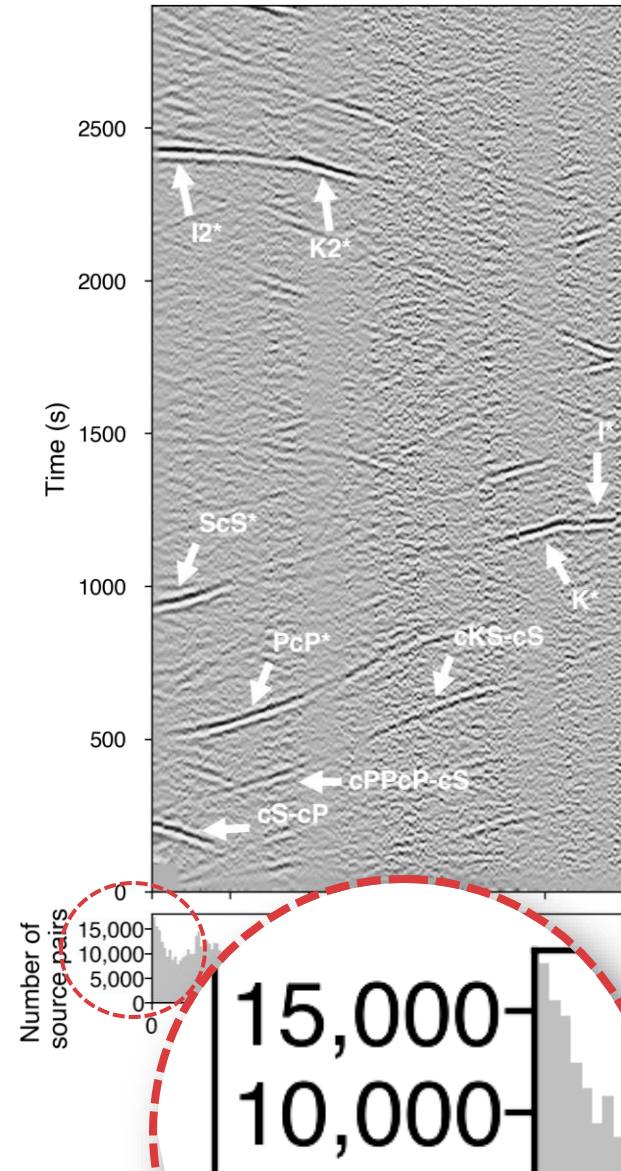


Number of correlation pairs for
using *all quakes* versus *the selected*



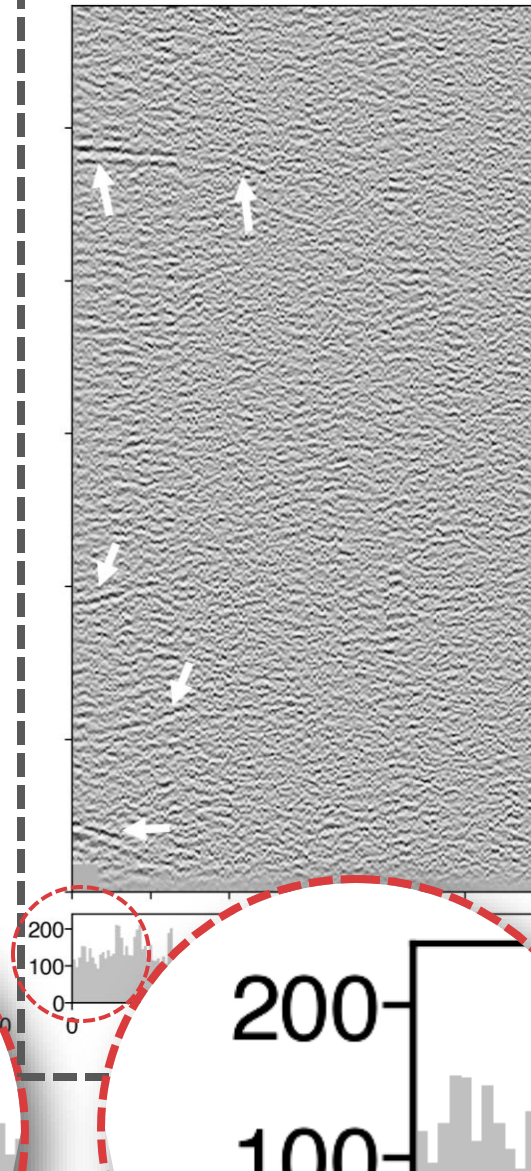
***The selection removed
>90% source-to-source pairs***

Inter-source correlogram
(stacked with many receivers)

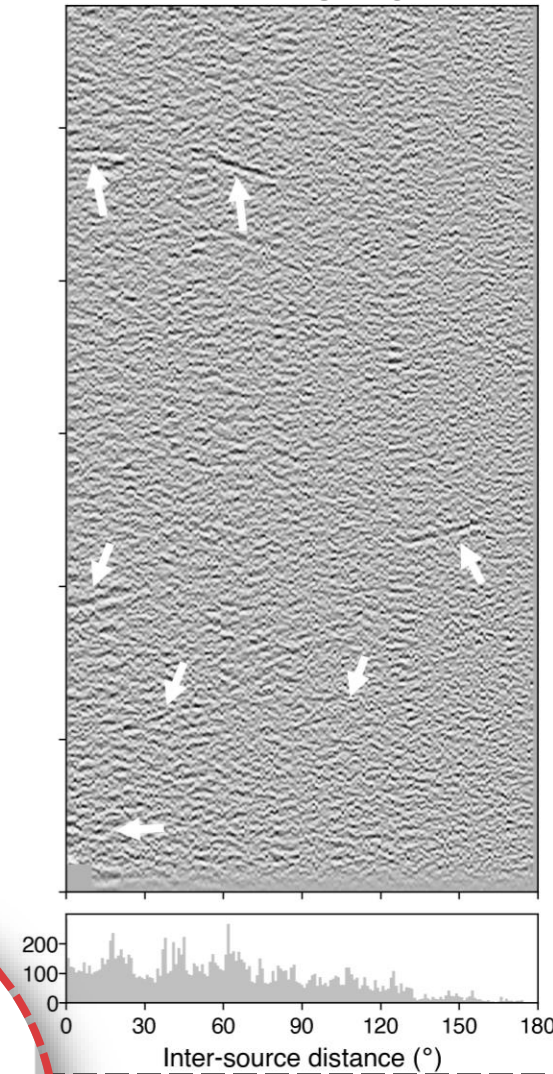


Single-receiver inter-source correlograms

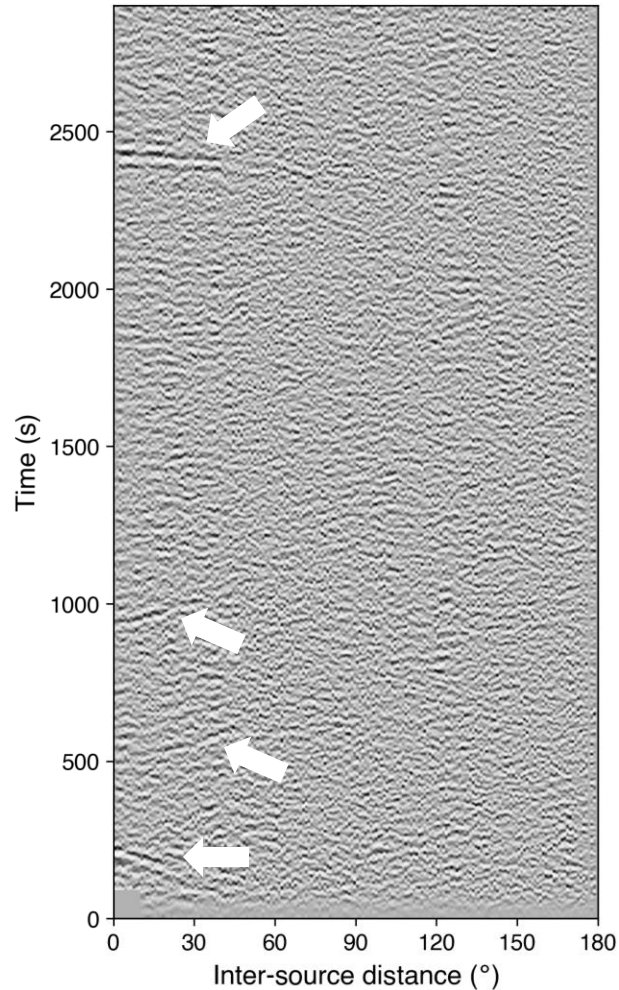
Station II.NNA



Station IU.PFO

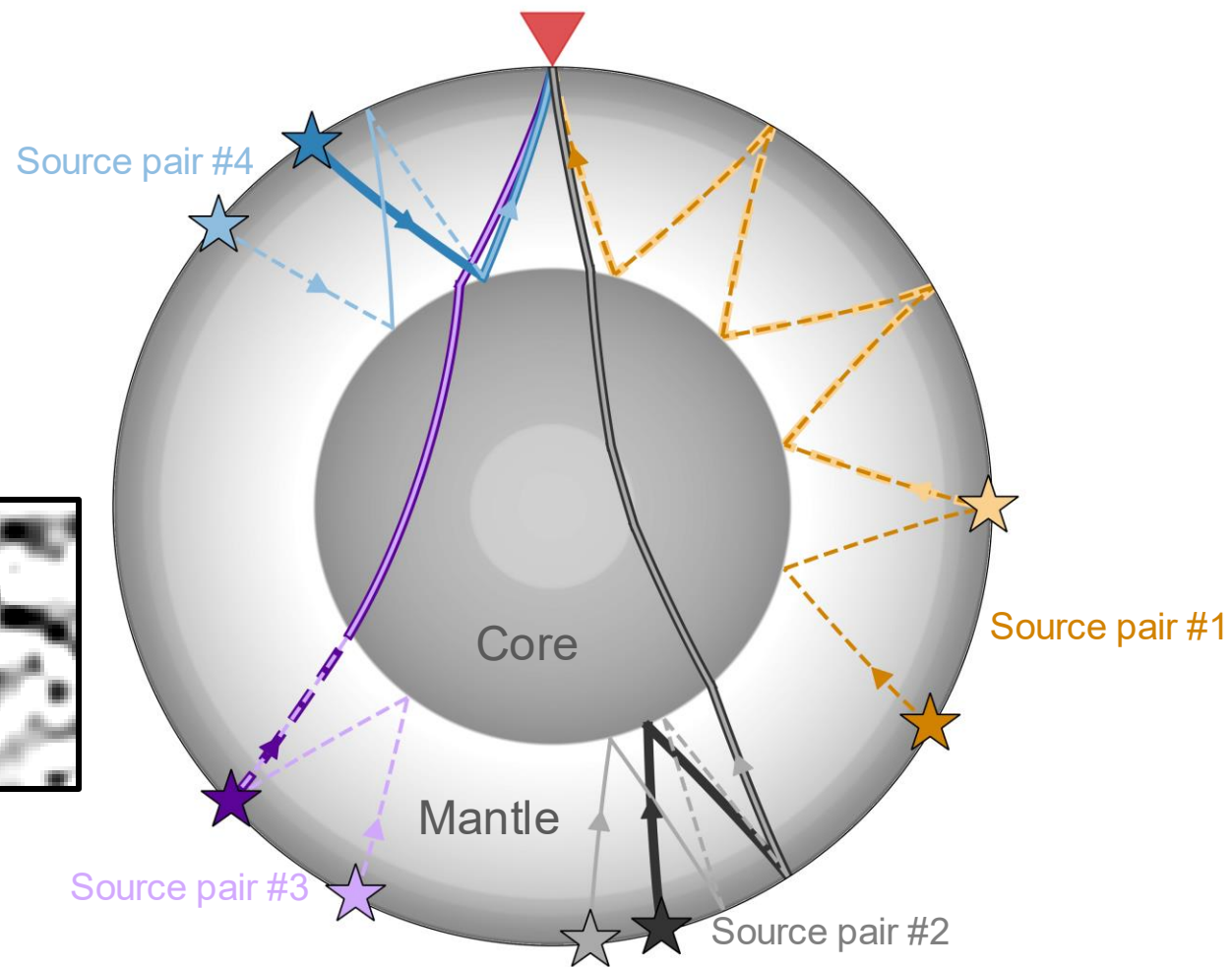
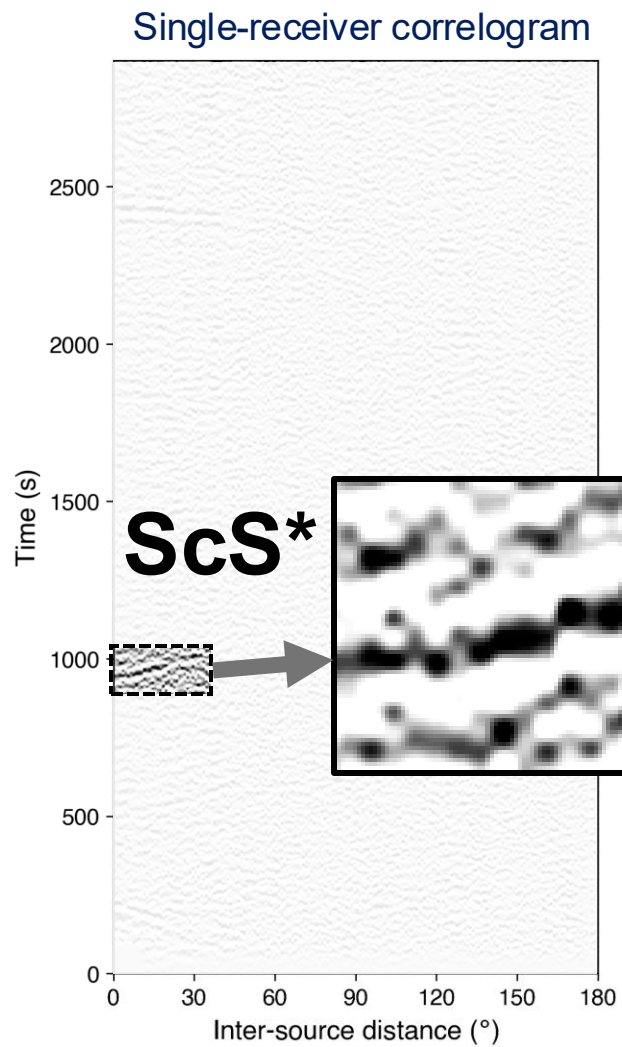


Single-receiver correlogram

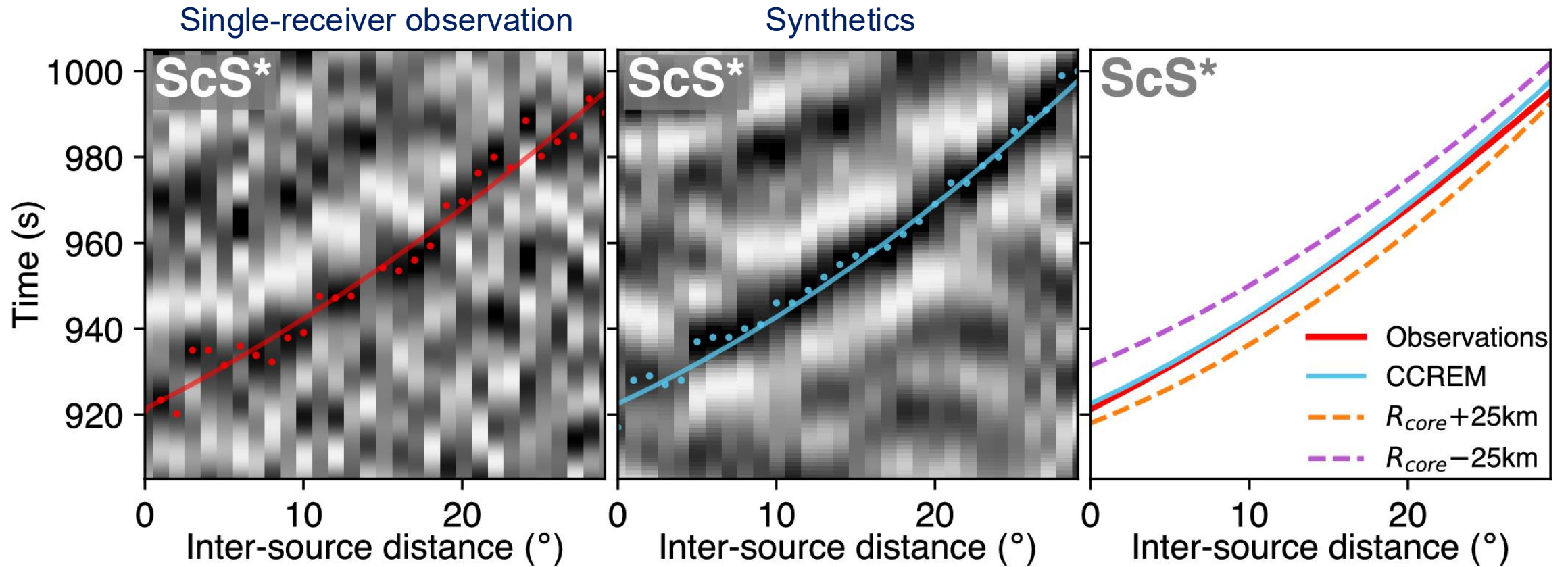


Single-receiver correlogram can be used to constrain internal structures based on:

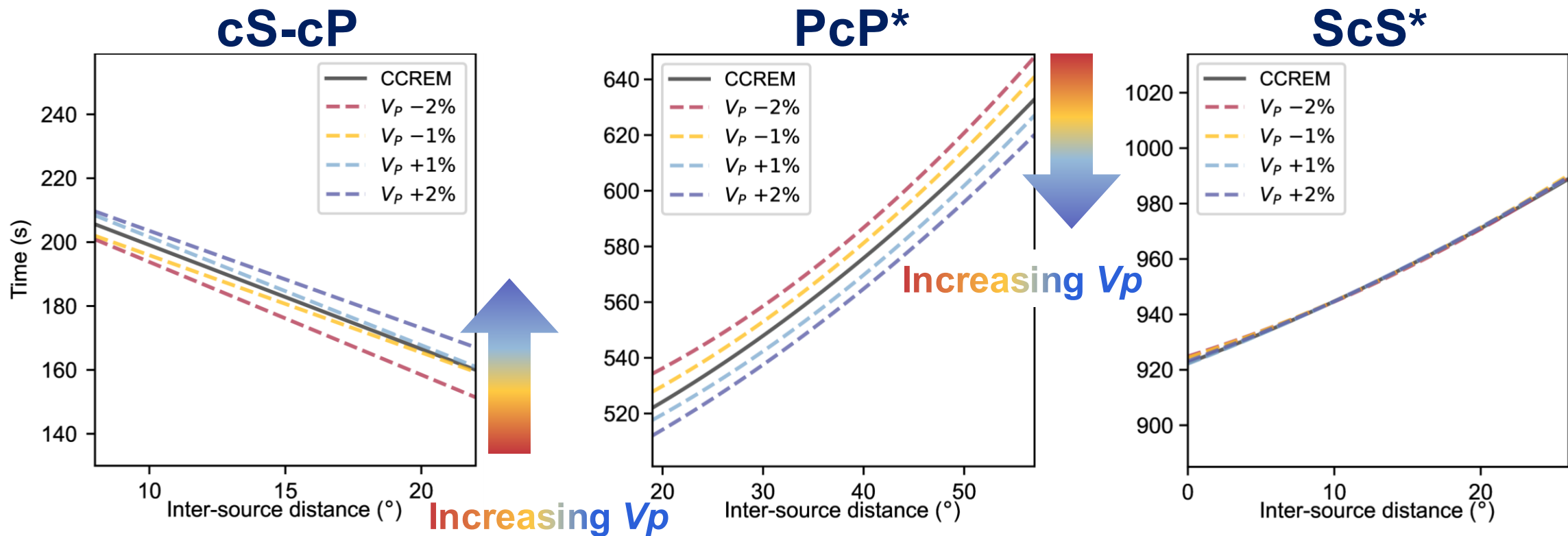
- *the emergence of specific correlation features;*
- *timing;*
- *amplitude;*
- *distance-time relationship;*
- *waveforms;*
- *... ..*



Sampling of internal structures by ScS*



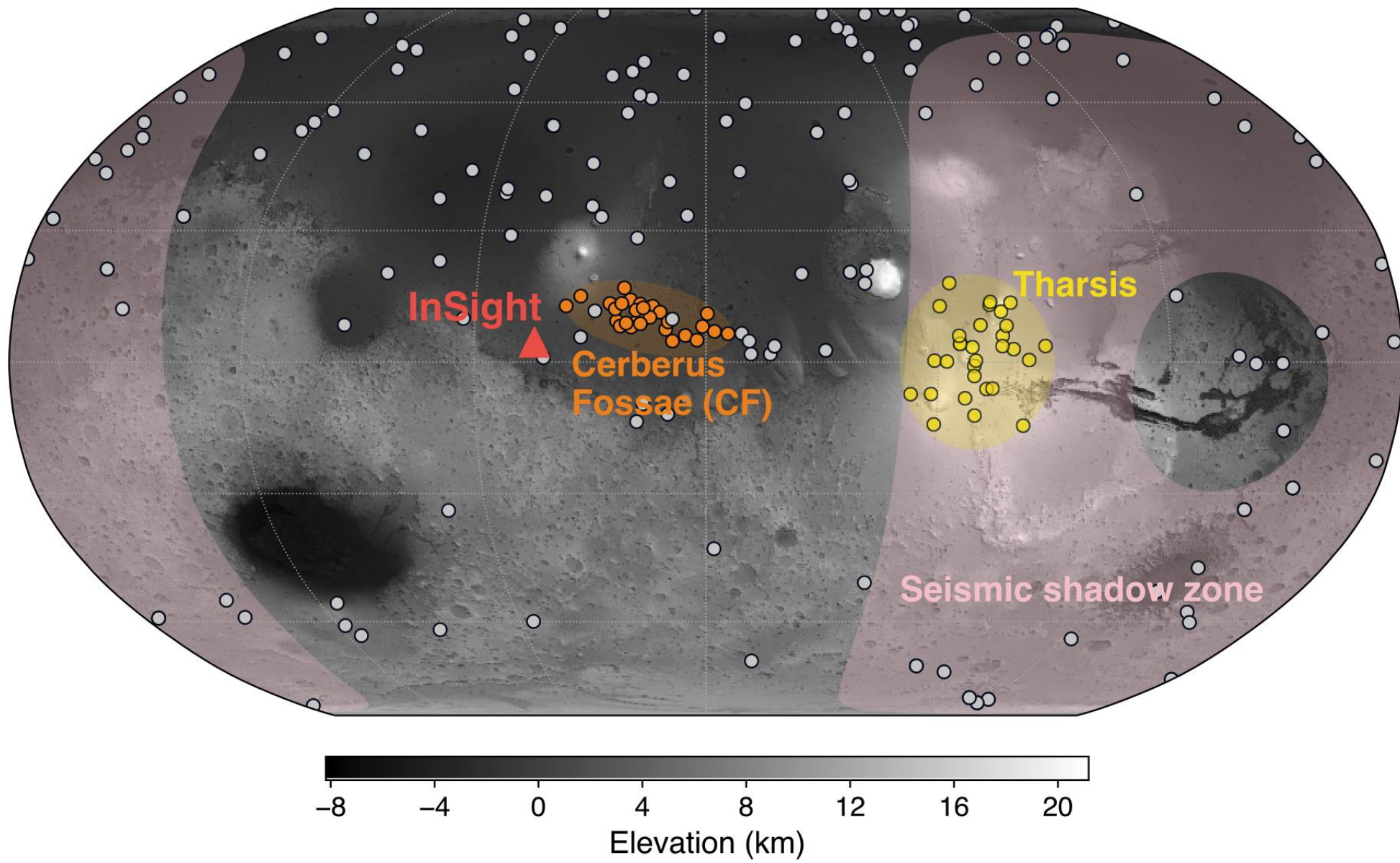
*Constrain the existence of the Earth's core and **measure its size.***



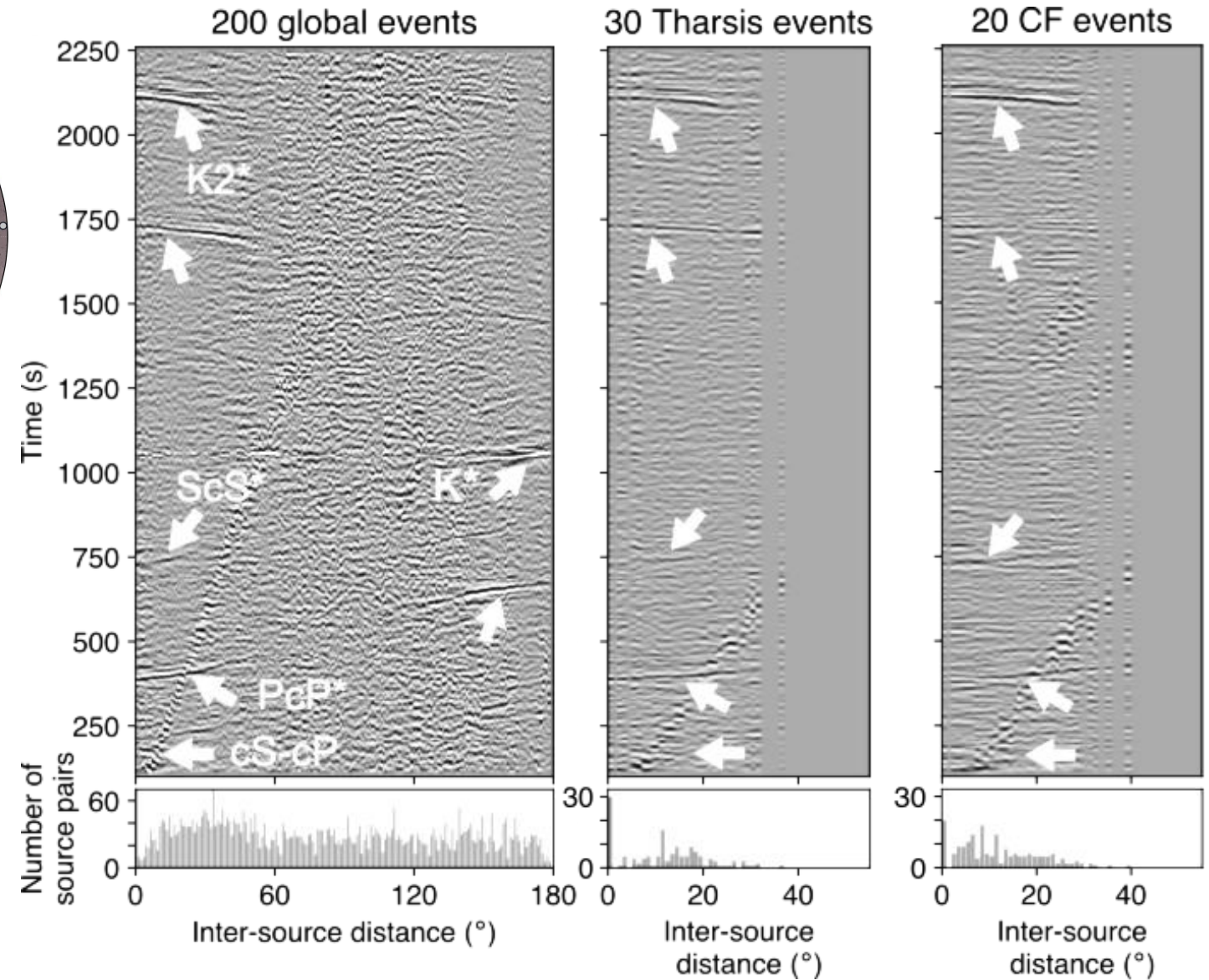
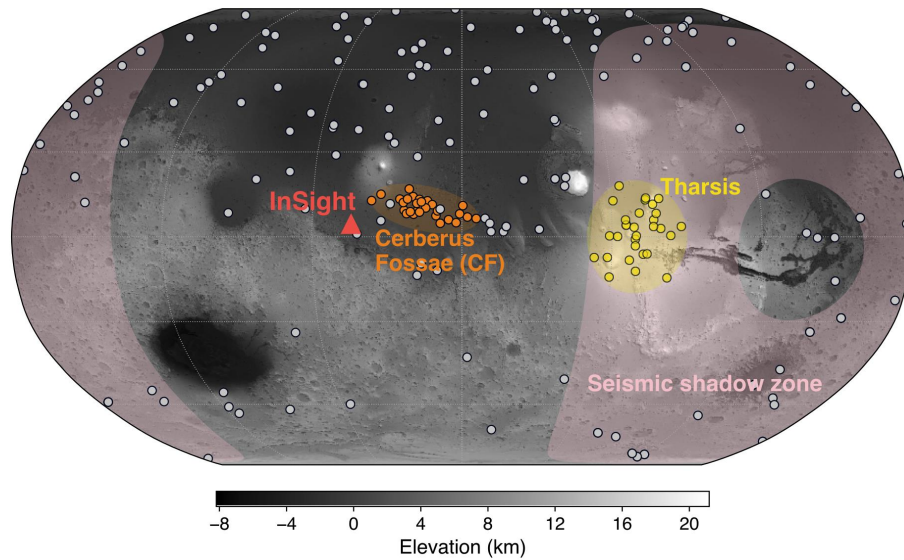
Varied sensitivities to Mantle structure by different correlation signals.

(Wang and Tkalčić, 2023)

Synthetic Marsquake Correlogram

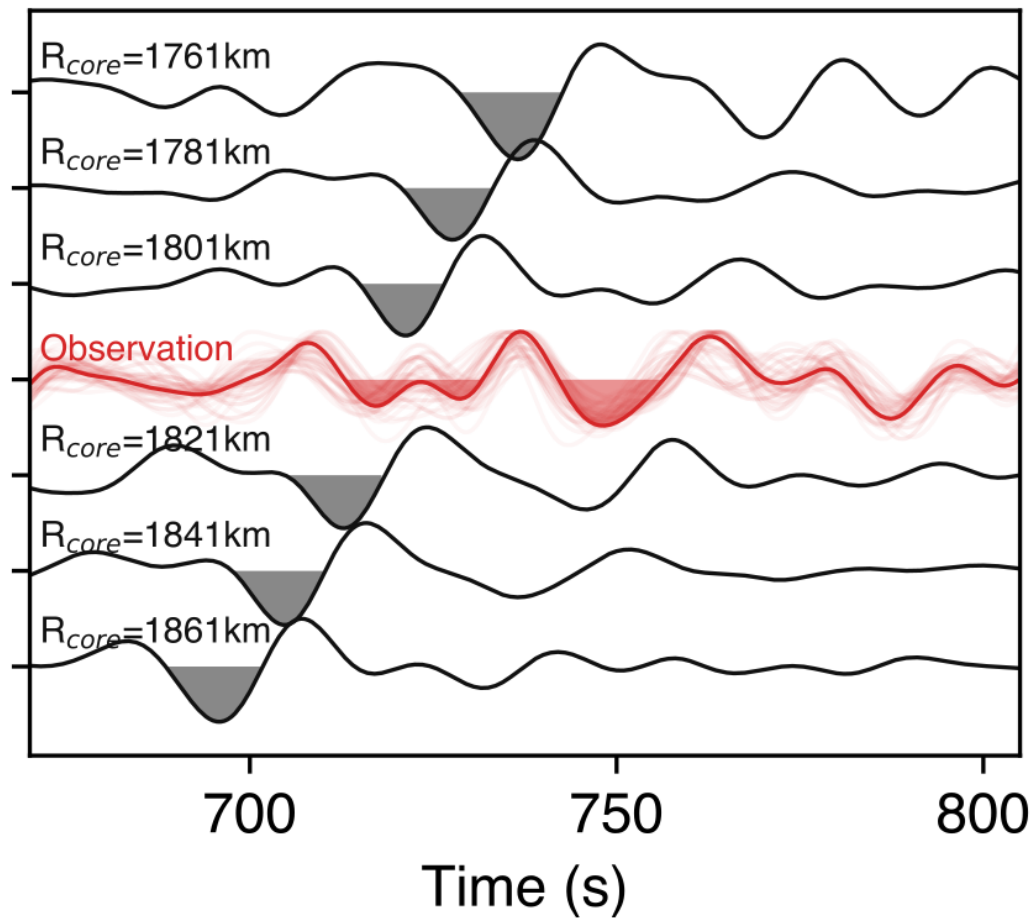


Synthetic Marsquake Correlogram

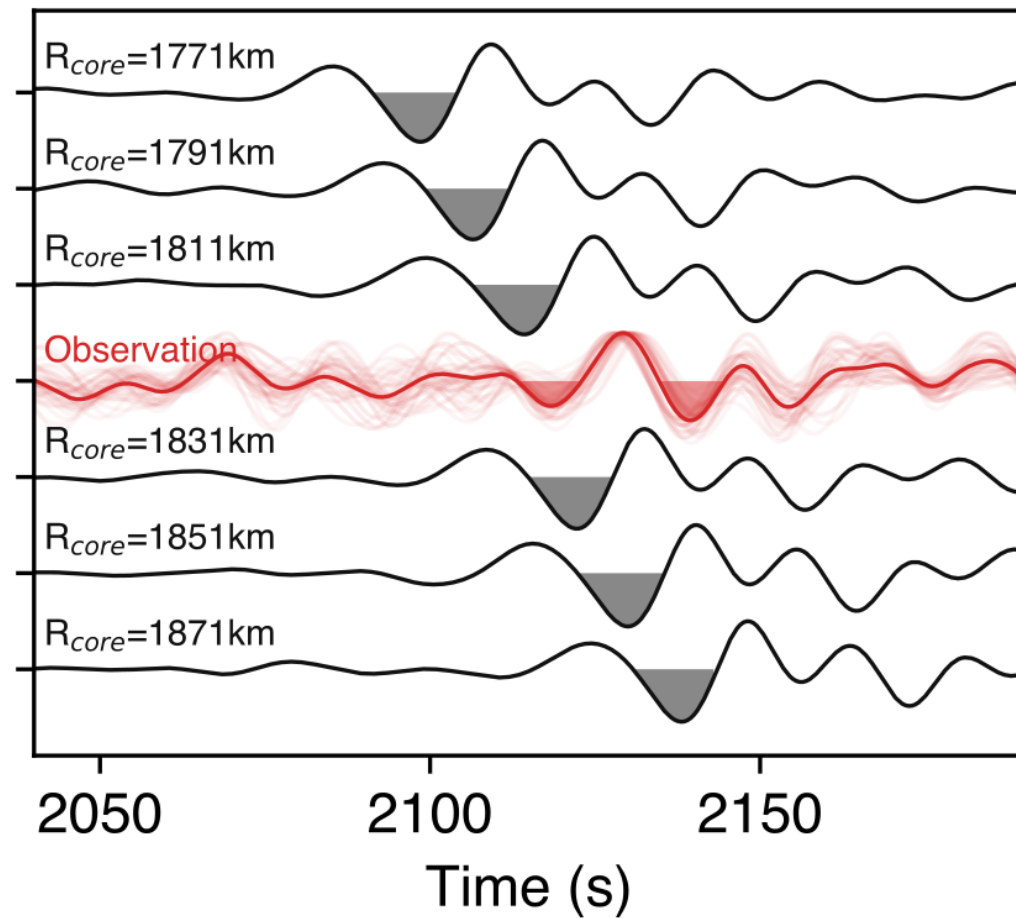


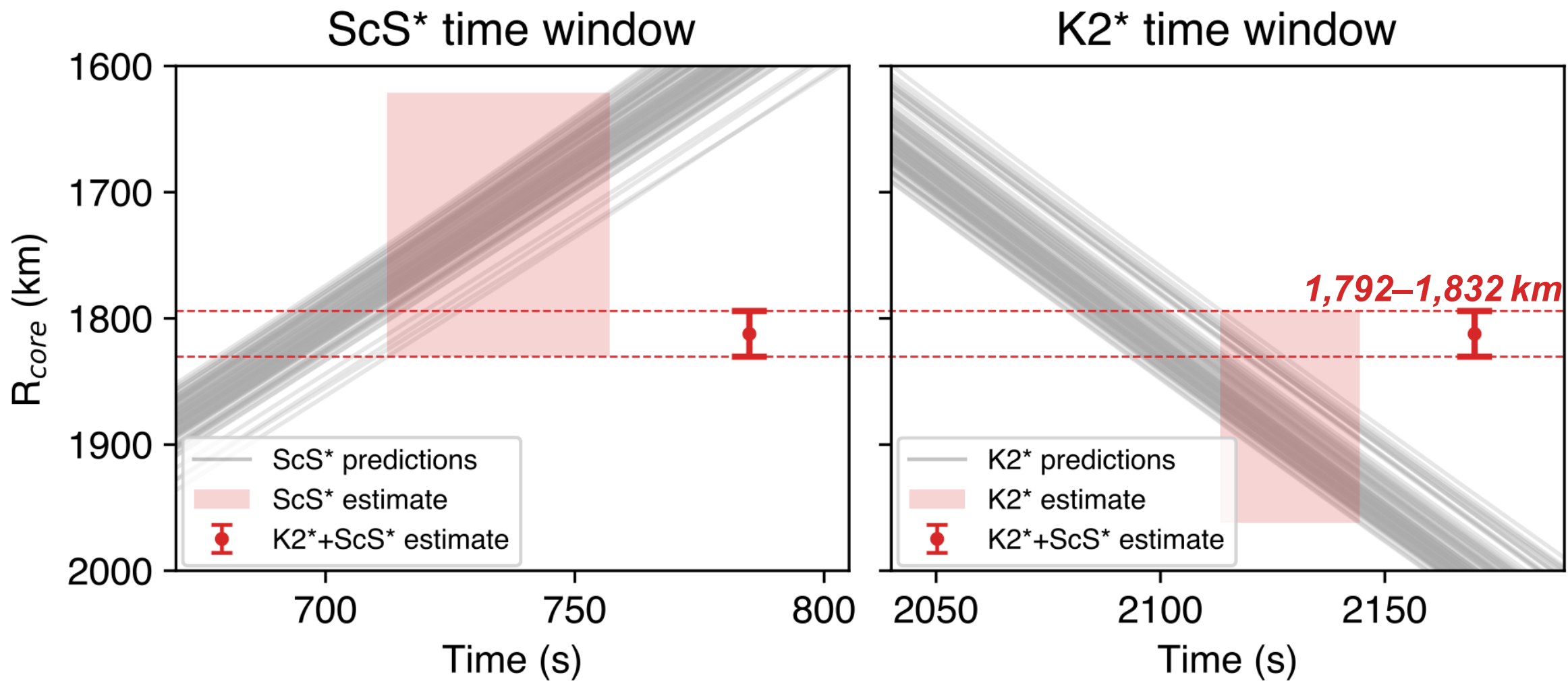
(Wang and Tkalčić, 2022)

ScS* time window

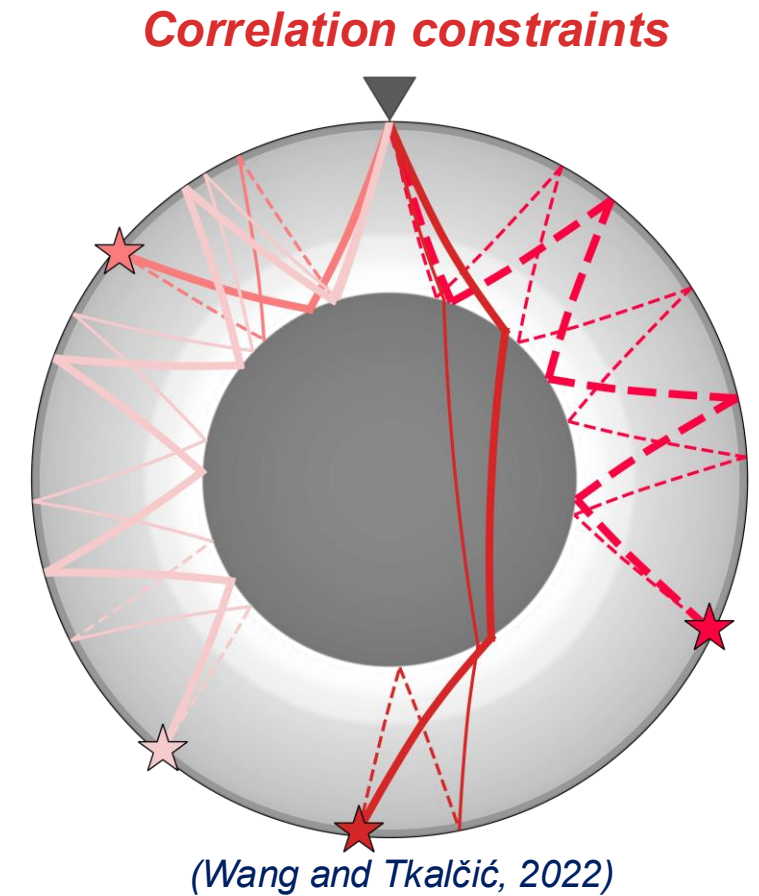
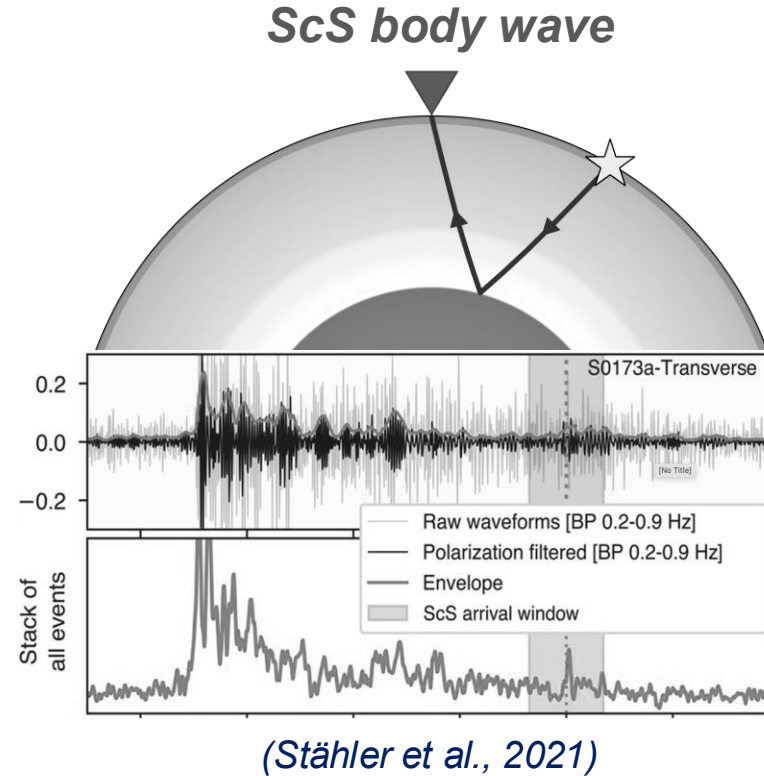
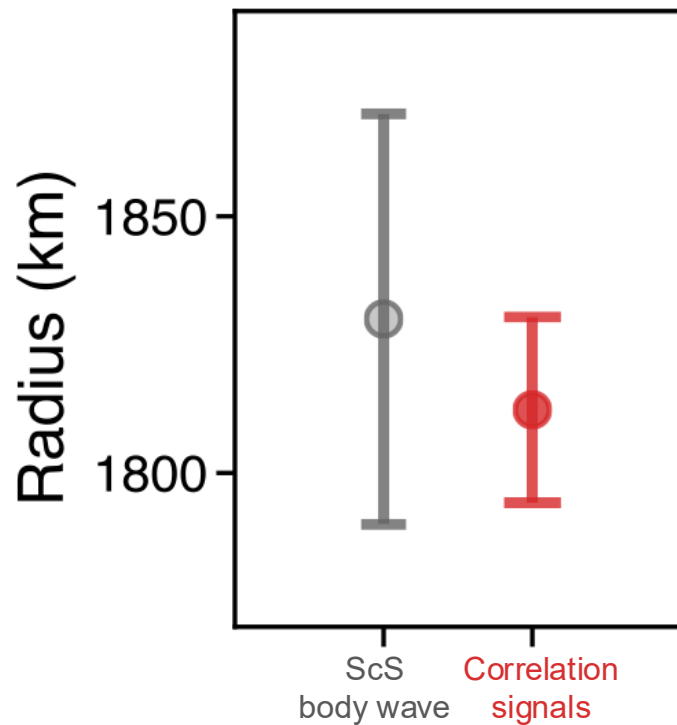


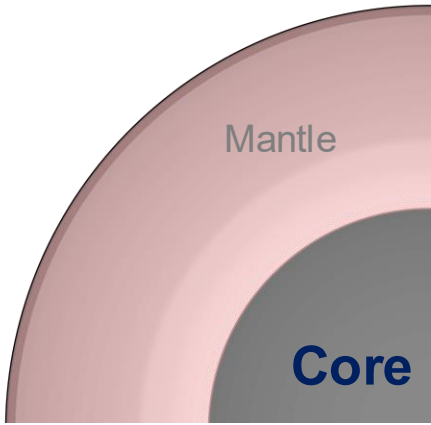
K2* time window





Different constraints on the Martian core



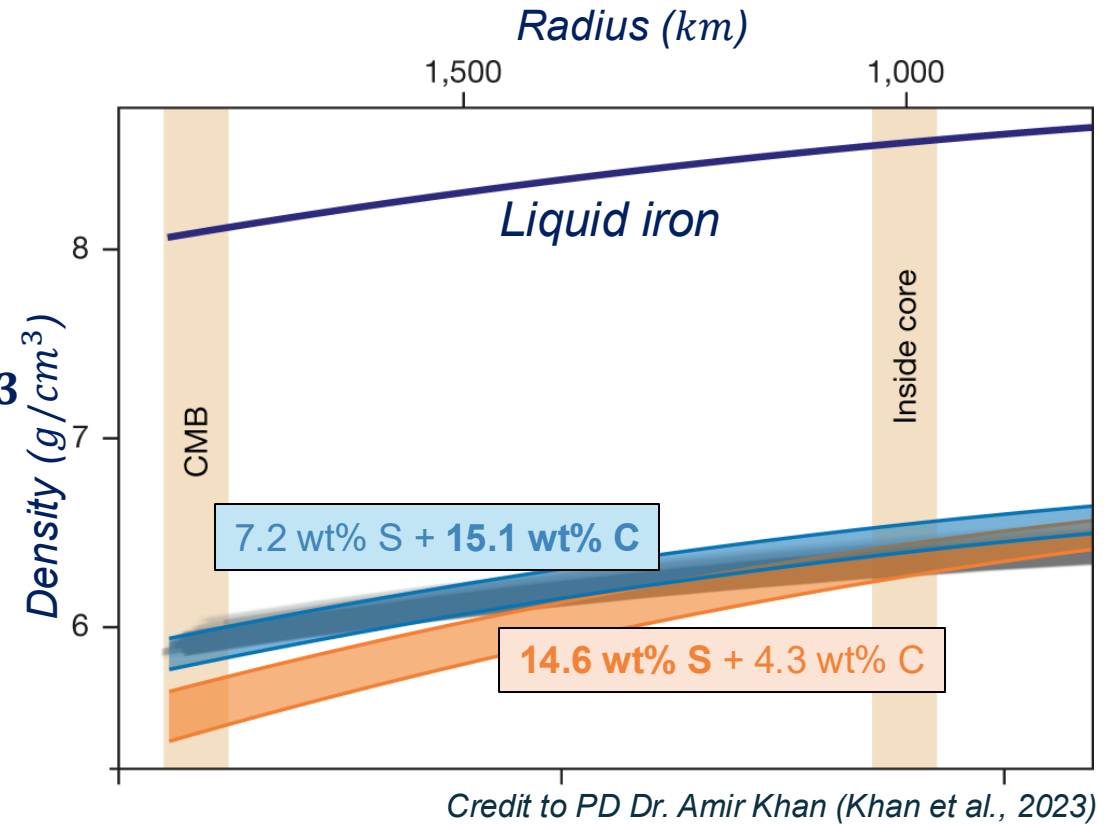


$$\rho_{\text{core}} = 6.0 \sim 6.3 \text{ g/cm}^3$$

vs.

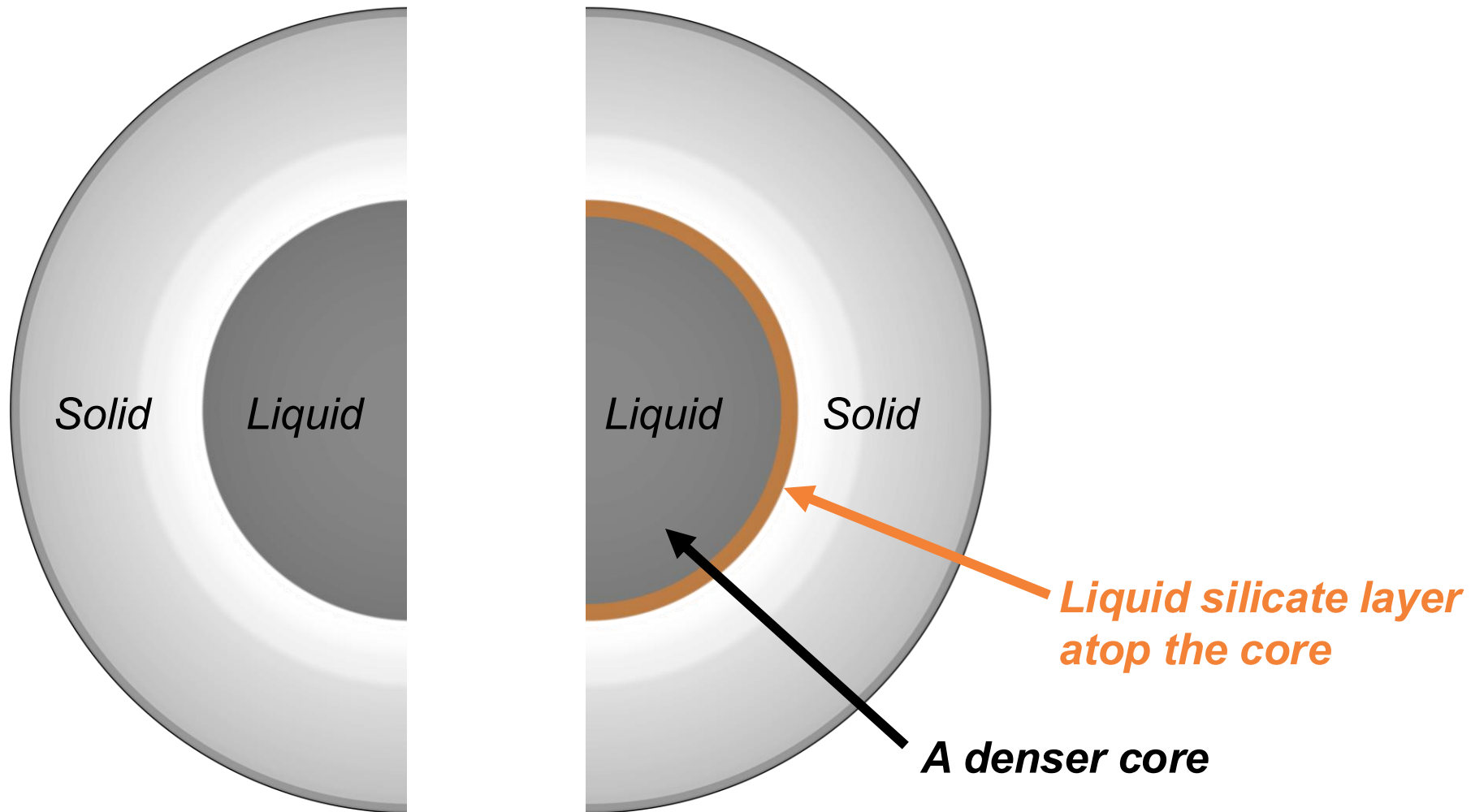
$$\text{Liquid iron} > 8 \text{ g/cm}^3$$

**Abundance of light elements (e.g., S, C)
in the Martian core?**



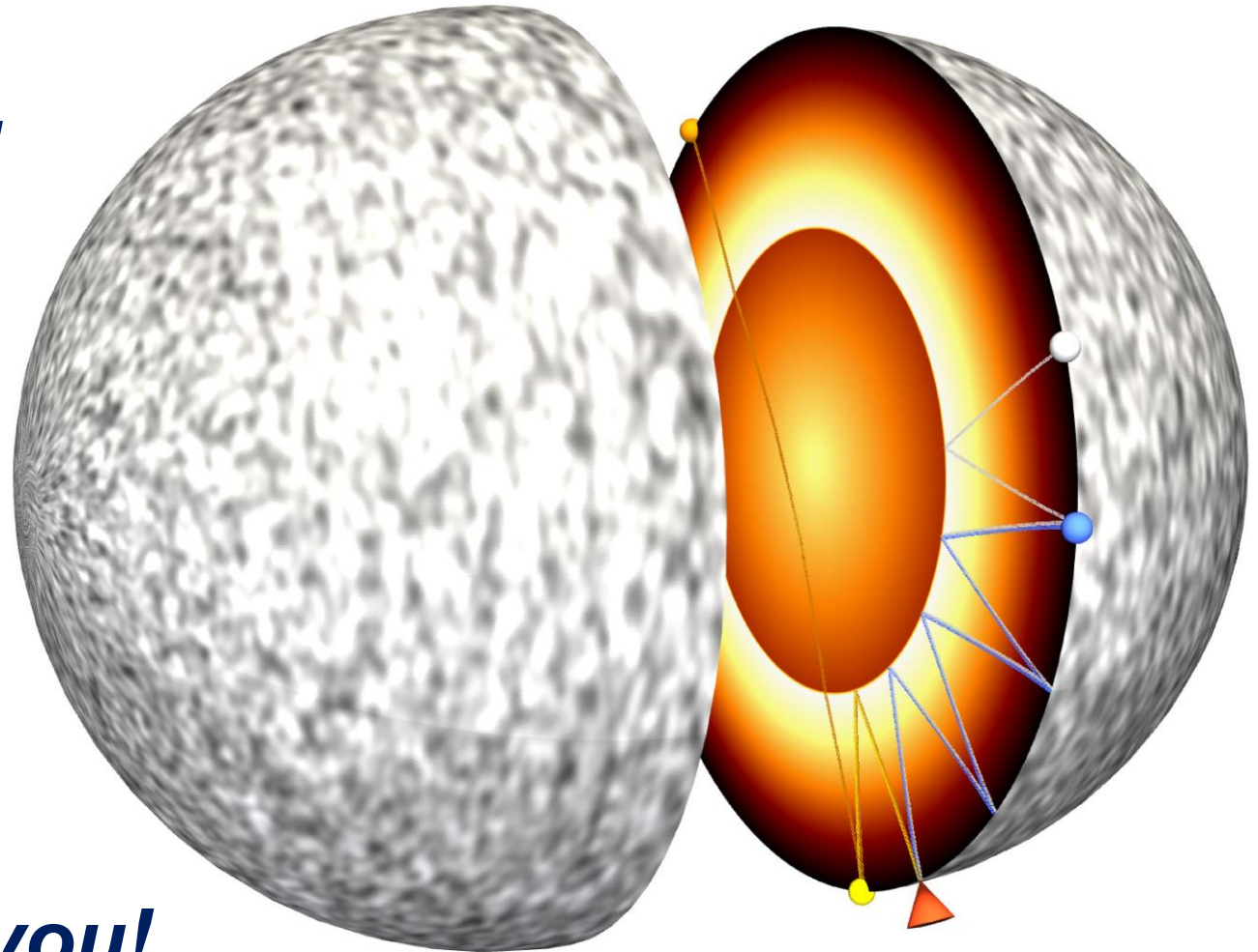
>20 wt% light elements in the core?

A smaller and denser core?



Conclusion

- *An "inverted telescope" for probing planetary interiors.*
- *A single station as powerful for illuminating the entire interior of a planetary body.*
- *New opportunities ahead!*



Thank you!
Comments & Questions!