Imaging Convection in the Solar Interior

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The Study of Convection

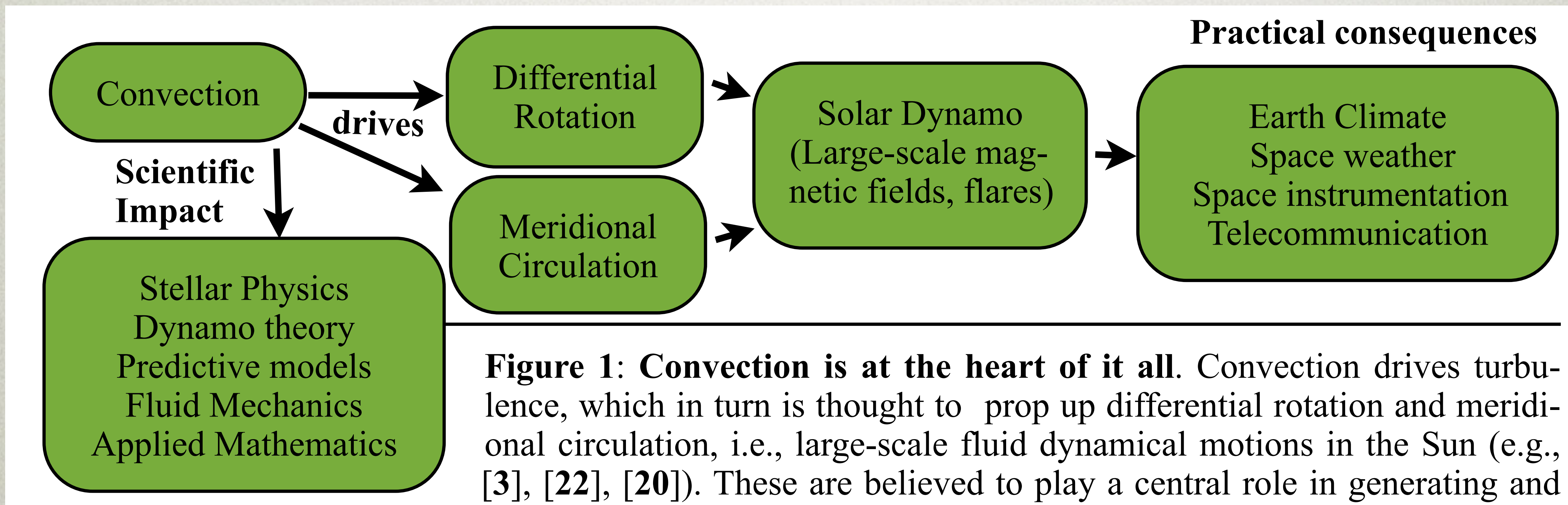
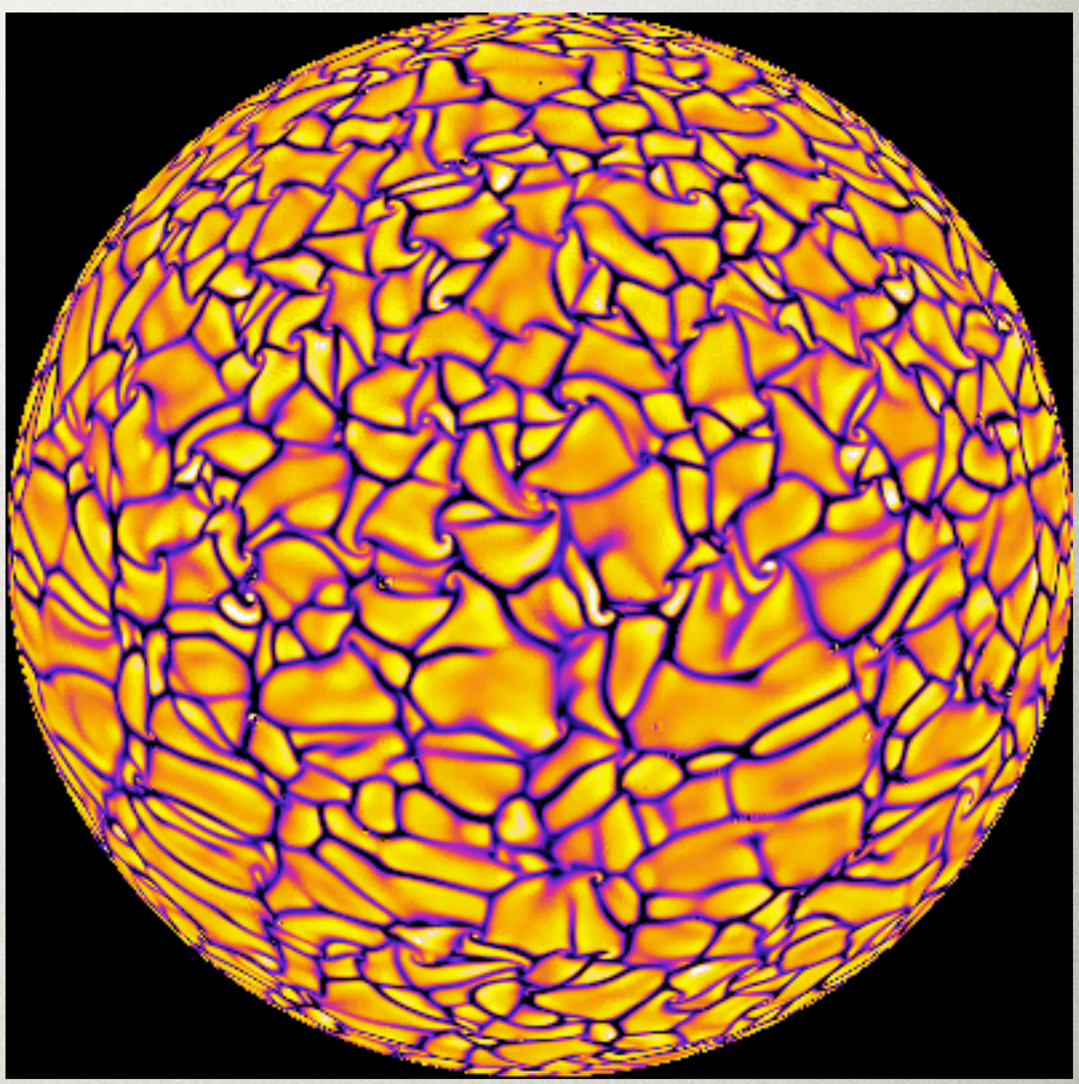


Figure 1: **Convection is at the heart of it all**. Convection drives turbulence, which in turn is thought to prop up differential rotation and meridional circulation, i.e., large-scale fluid dynamical motions in the Sun (e.g., [**3**], [**22**], [**20**]). These are believed to play a central role in generating and

Convection is one of the least understood aspects of stellar models

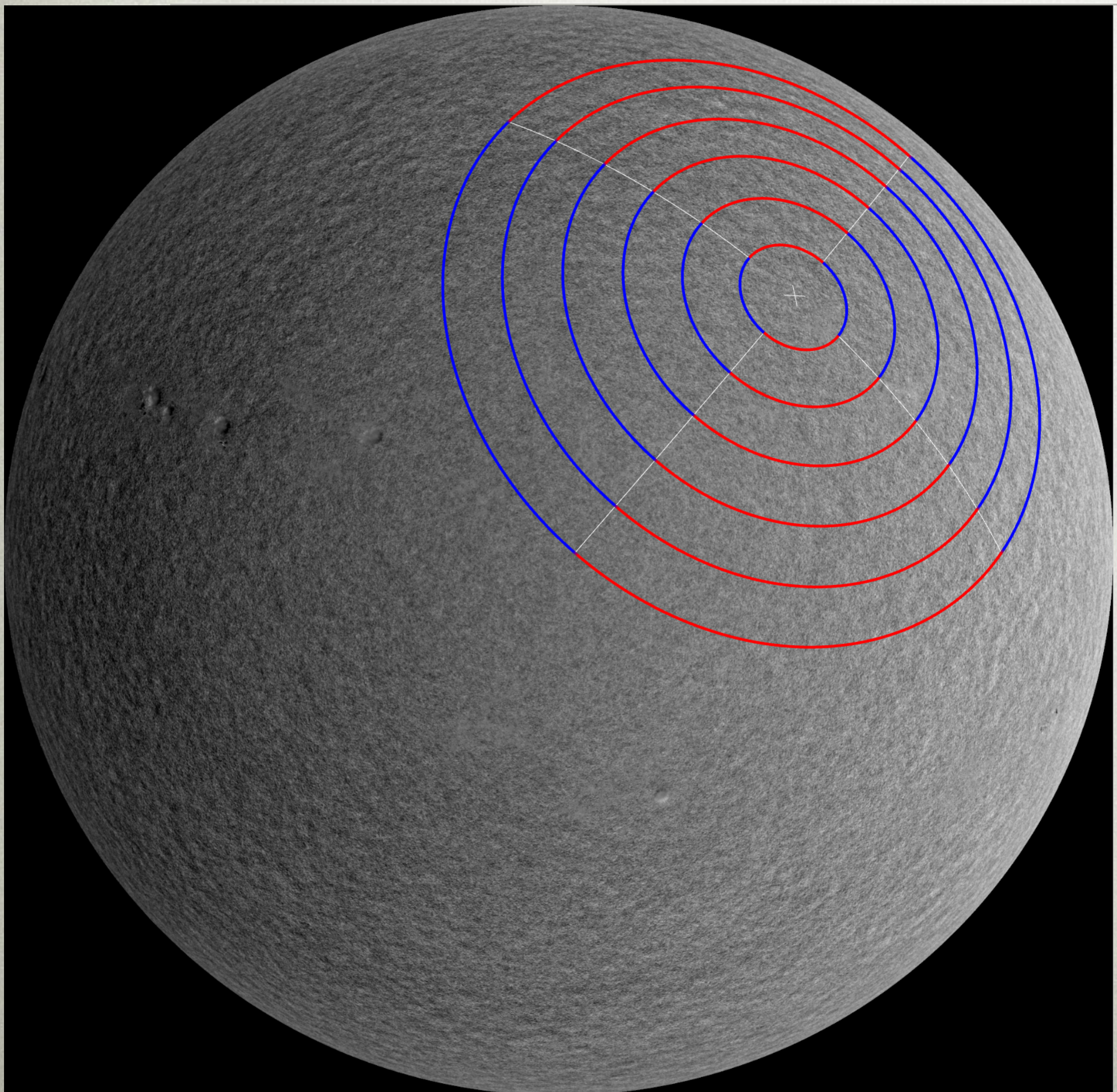
Numerical Simulations

- Detailed physics (anelastic/ compressible dynamics)
- Hypothesis testing



e.g., ASH, from Miesch (2005)
radial velocity

Measurements: Wave travel times as proxies



HMI dopplergrams

900 billion wavefield measurements

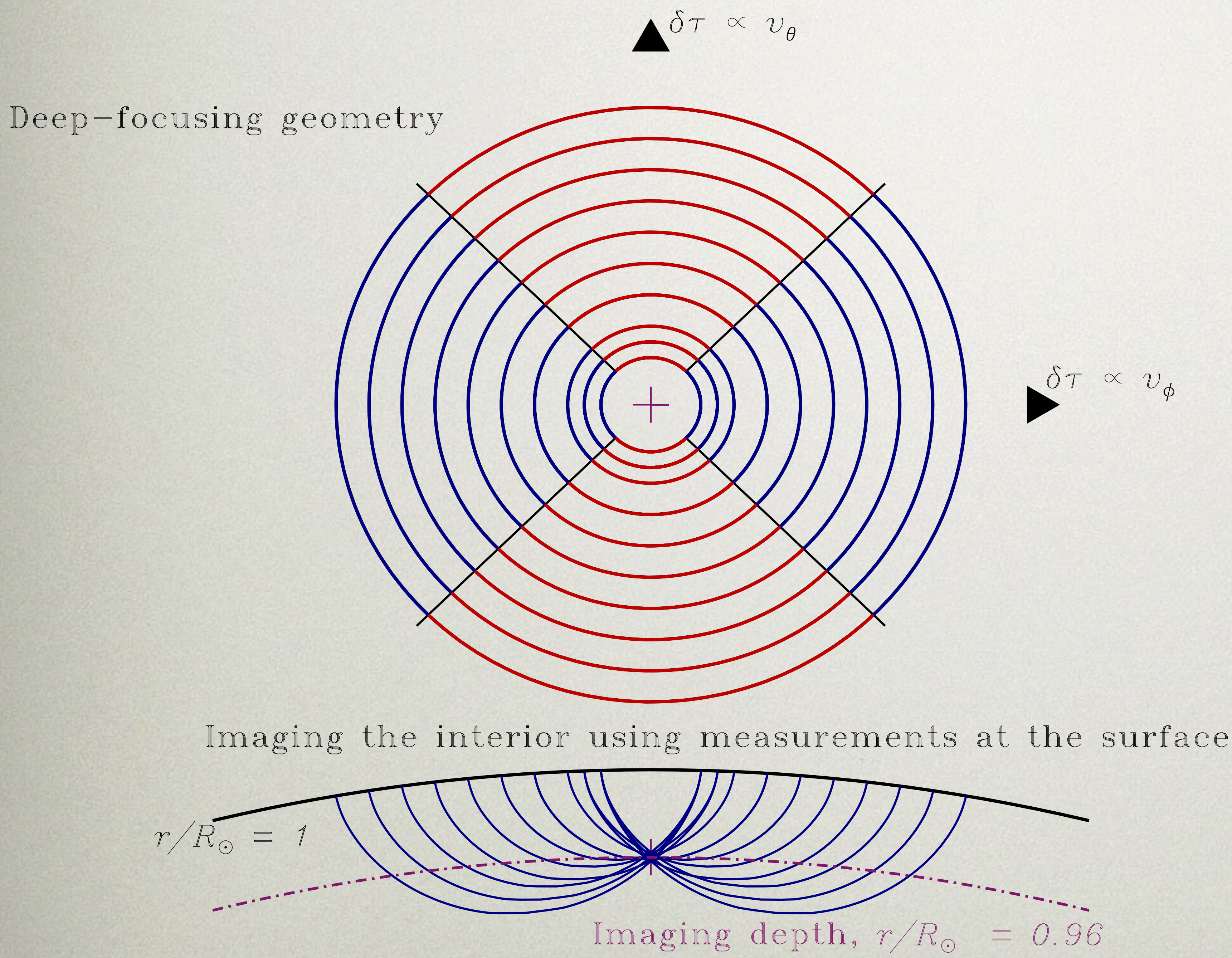
Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA

~ 3 billion cross correlations

~ 5 million travel times

Sensitive to 3-flows

Imaging



Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA

Aperture at the surface through which interior dynamics are observed

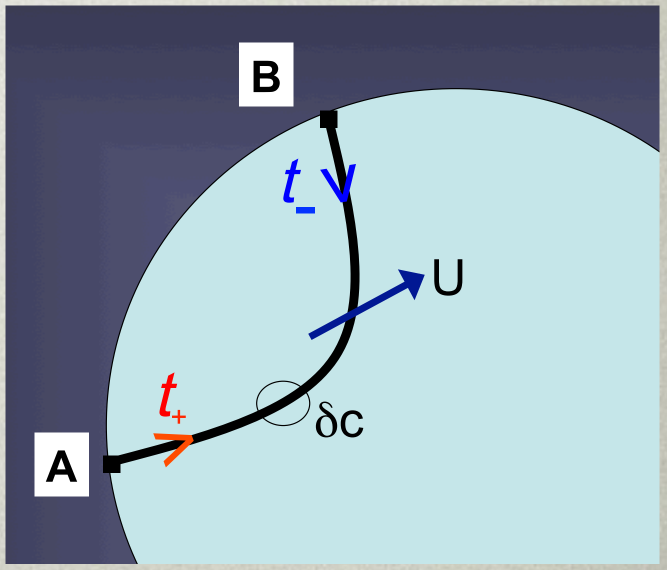
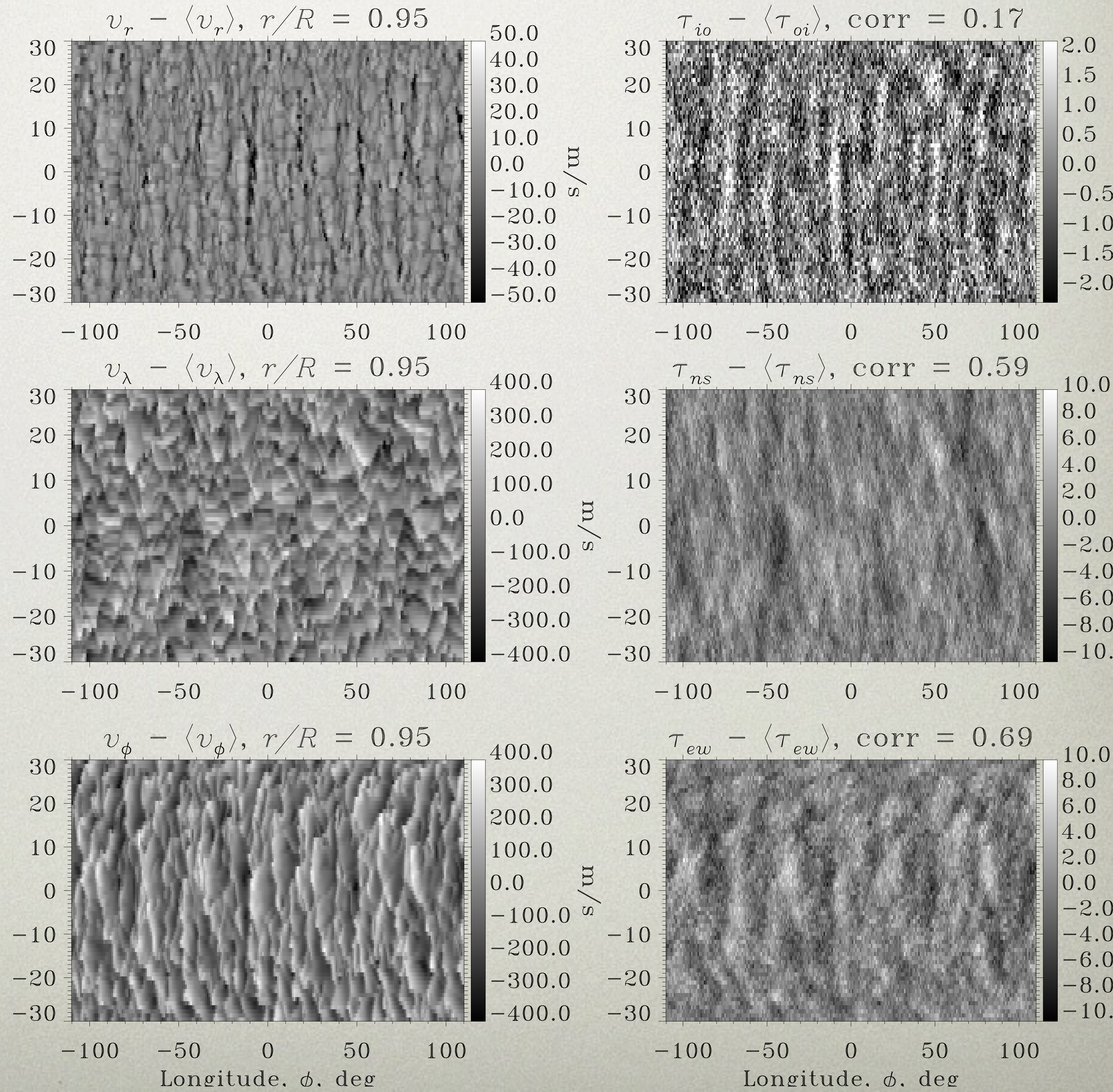


Figure courtesy of L. Gizon

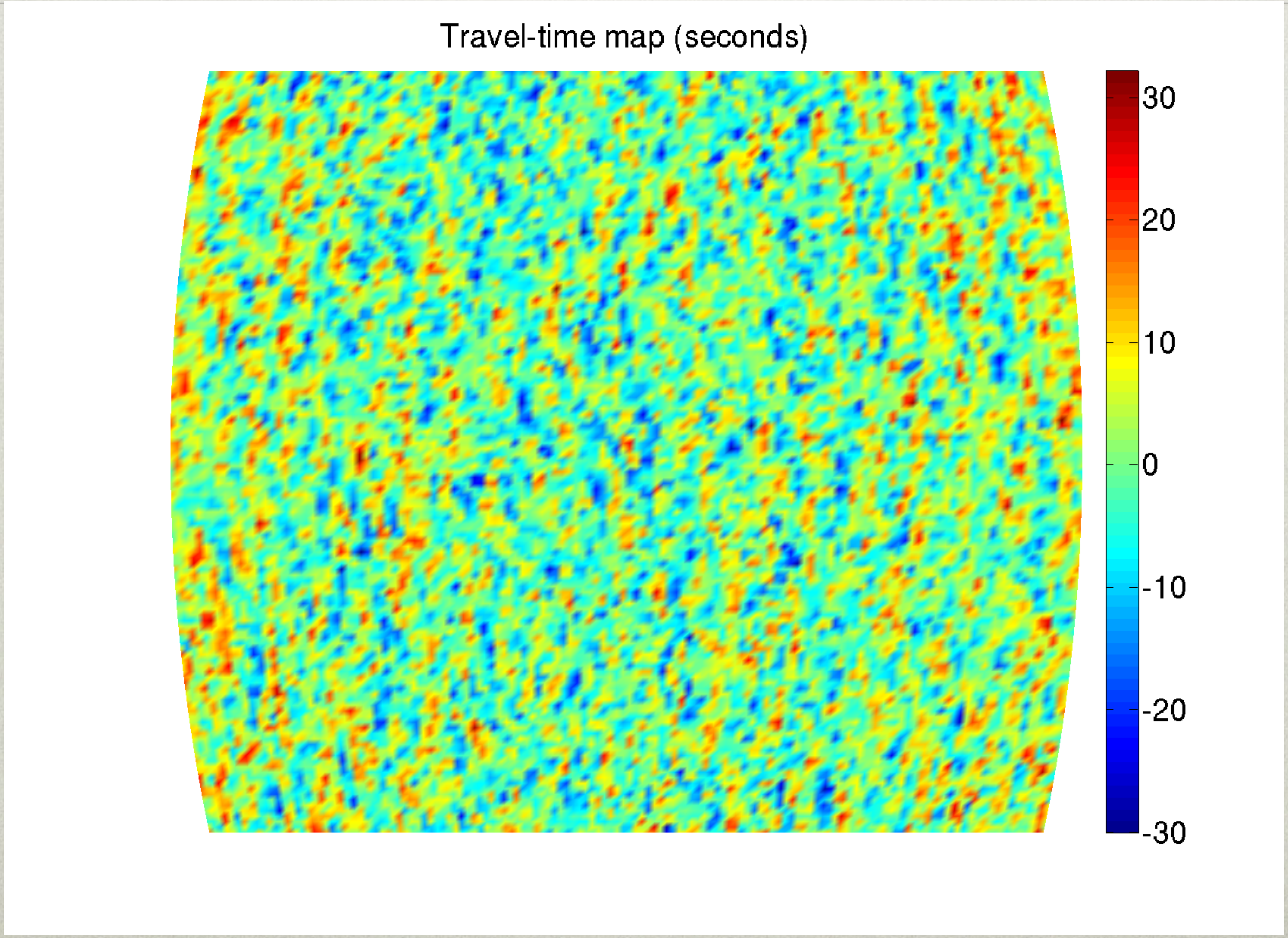
ASH Convective flows

- Test: How do waves perceive a snapshot of anelastic convection (from the ASH code)
- To determine signatures, we simulate wave propagation through these complex flows in spherical geometry (Hanasoge et al. 2006)
- Figure from Hanasoge, Duvall, & DeRosa (2010)
- Are observations as striking?



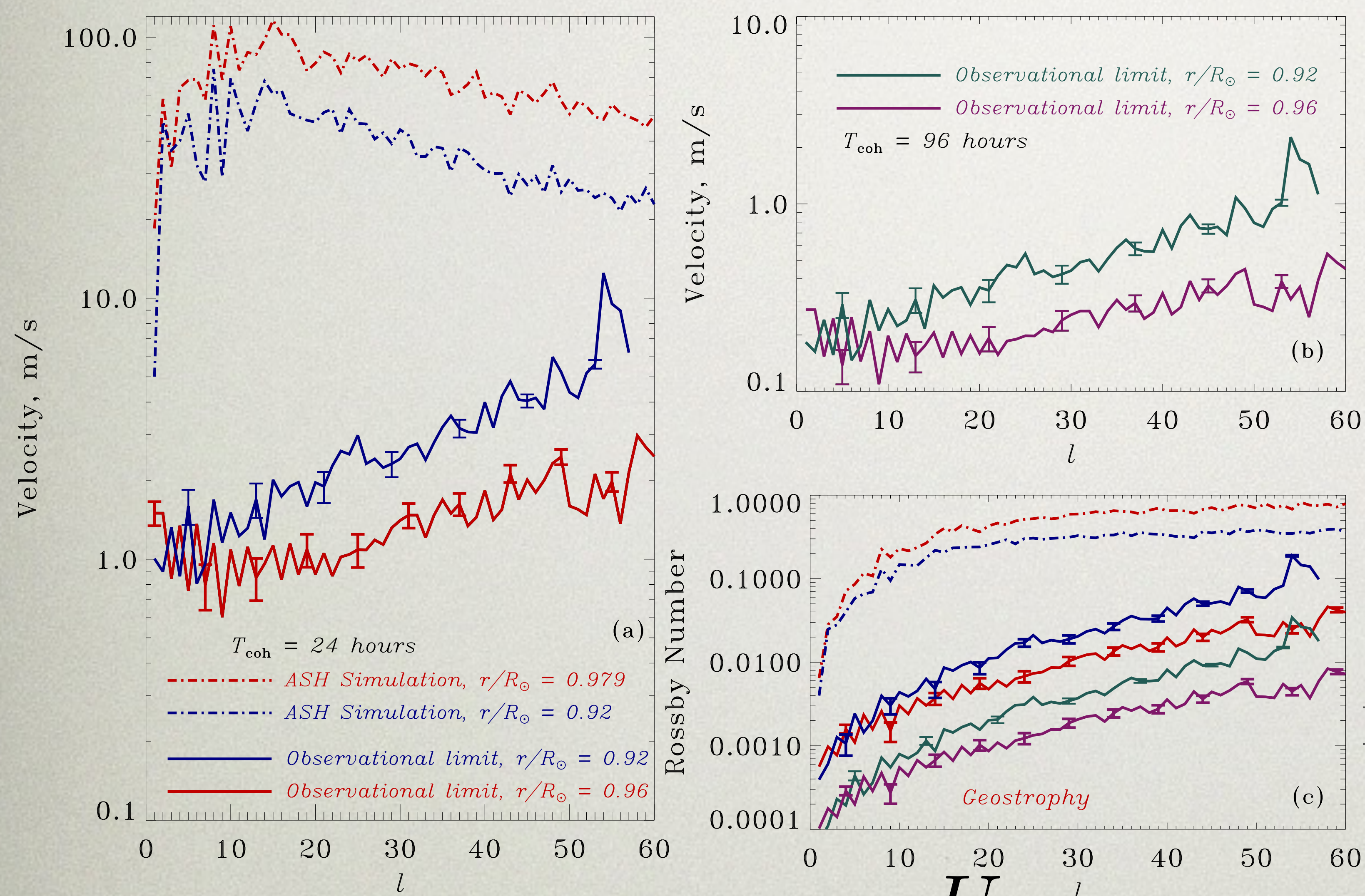
OBSERVED MAPS OF TRAVEL TIMES

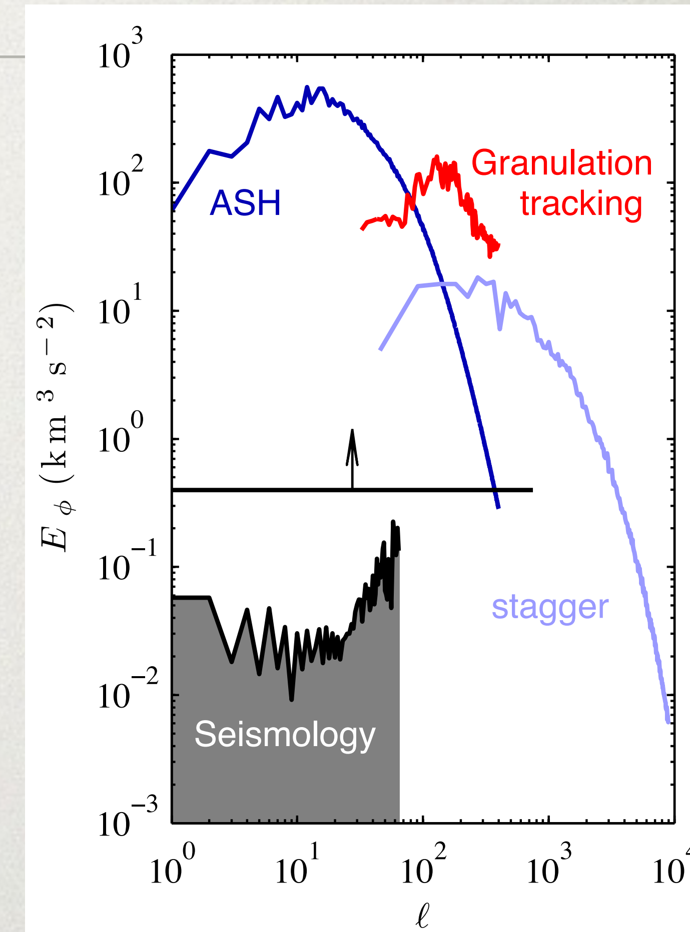
Hanasoge, Duvall & Sreenivasan (2012)
Proceedings of the Natl. Acad. Sciences, USA



No obvious large-scale structure (noise)

Upper bounds





Hanasoge et al. (2012; PNAS)

Gizon & Birch

Comment, PNAS:

`Helioseismology Challenges Models of Solar Convection'

$$Ro = \frac{U}{2\Omega L}$$

Finite frequency effects are accounted for

Wave ``PSF'' deconvolved from the measurement

The Nature of the Result

- Non-detections are hard to explain
- The analysis is complicated
- The recognition that non-detections can be profound too (e.g., Birch, Braun, Cameron, Duvall , Gizon, Hanasoge)
- It is ultimately not vastly surprising; few prior detections (notable exception of Hathaway et al. 2013)

Thermal and Momentum transport

- How to transport a solar luminosity with very low turbulent kinetic energy?
- How is differential rotation sustained? i.e., how is angular momentum transported? Reynolds' stresses not high enough? Meriodional circulation? (Miesch et al. 2012)

The excess low wavenumber power we find in both our simplified model and realistic simulations adds to other recent evidence that large scale flows deep in the solar convection zone are weaker than previously thought. It supports suggestions that numerical simulations more generally may have difficulty matching solar observations if they are required to carry all of the solar energy flux in the resolved modes (Featherstone 2014). Helioseismic observations (Hanasoge et al. 2010, 2012) yield estimates of flow velocities that are an order of magnitude or two below those found in either global (e.g. Miesch et al. 2008) or local area (Lord et al. 2014) sim-

tra of the simulations and observations. These separate lines of evidence all suggest that the Sun transports energy through the convection zone while maintaining very low amplitude large scale motions. Something is missing from our current theoretical understanding of solar convection below $\sim$ 10Mm.

Lord et al. 2014

Directions Forward

- Address systematics more fully
- Comprehensive single study of near-surface and deeper layers (e.g., Gizon & Birch 2004)
- Homogenization (wave propagation through spatio-temporally fluctuating medium)
- Alternate phenomenology? (e.g., Spruit 1997, Miesch et al. 2012, Lord et al. 2014)

SEISMIC WAVES

- Excited by near-surface granulation
- Sources are band-limited spatio-temporally stochastic processes
- Finite samples of stochastic process, correlations contain intrinsic noise
- Waves have finite sizes, infinite frequency asymptotics do not apply

What Is A Detection?

- The seismic wavefield is all stochastic, so there is only noise
- Distinguish correlated and uncorrelated noise (Gizon & Birch 2004)
- Correlated noise could be a convective structure