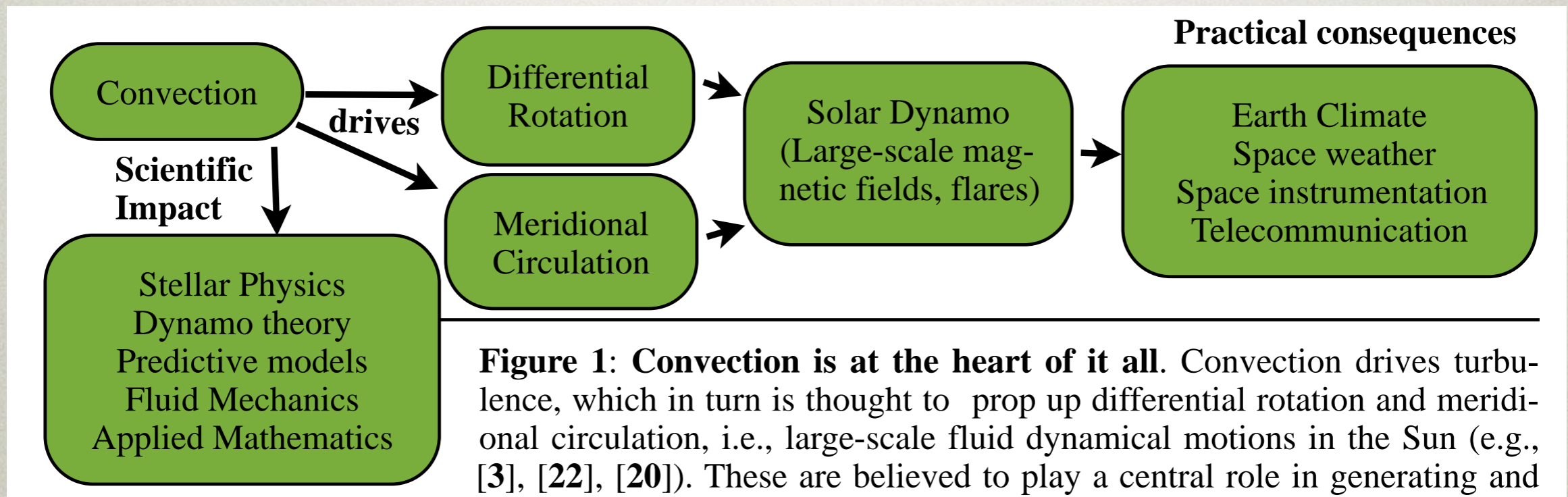


# Imaging Convection in the Solar Interior

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# THE STUDY OF CONVECTION

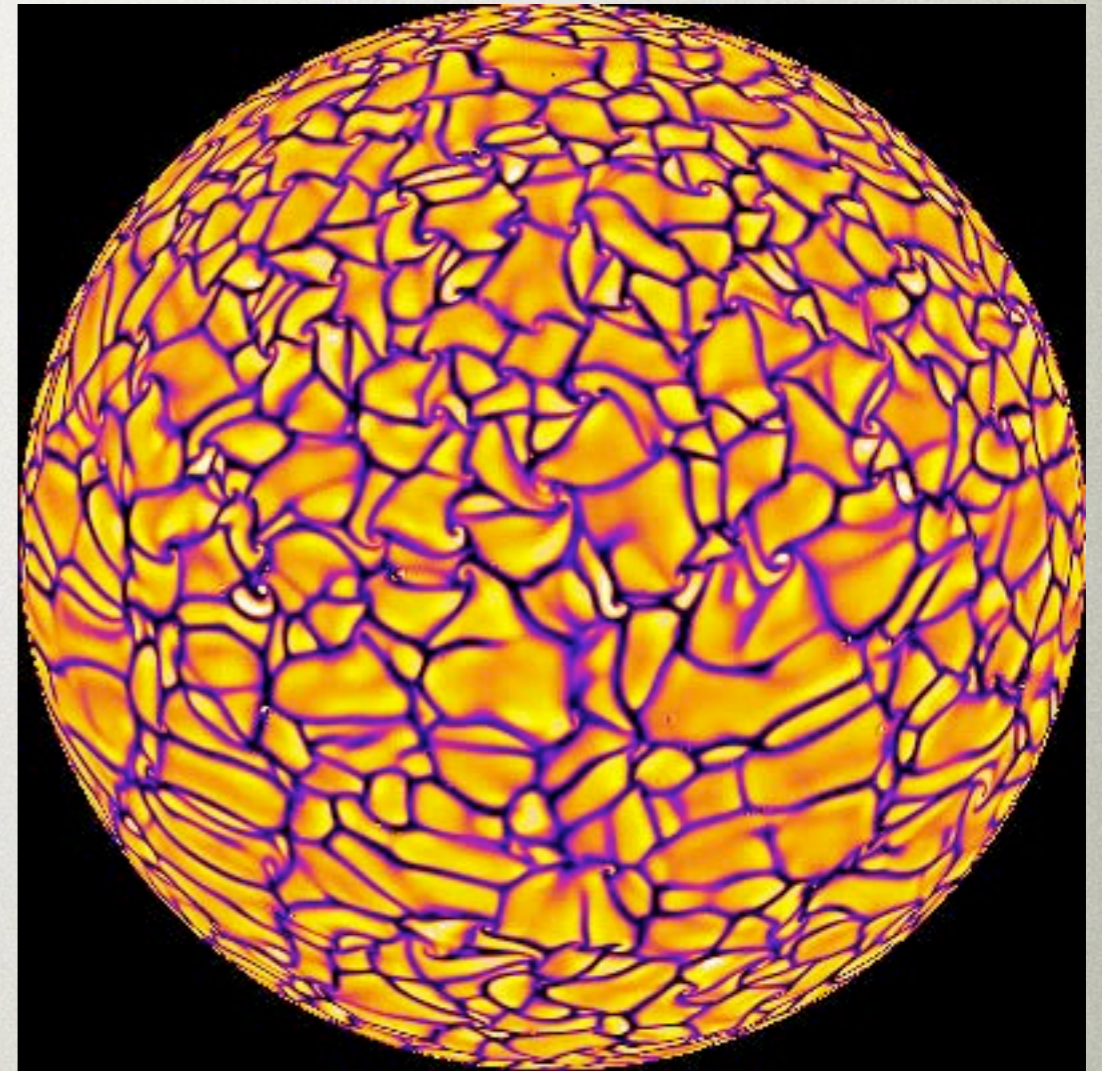


Convection is one of the least understood aspects of stellar models

# NUMERICAL SIMULATIONS

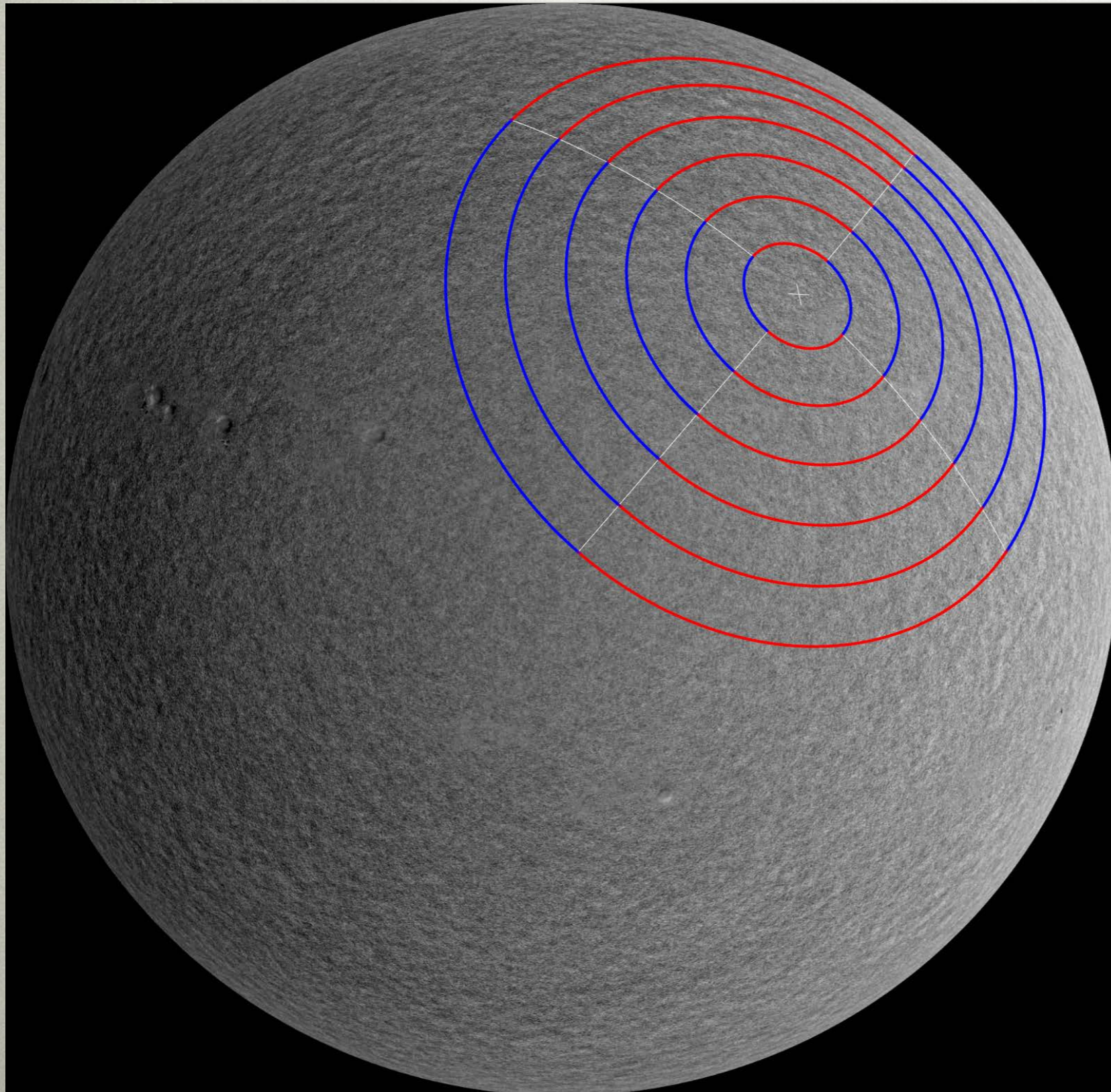
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- Detailed physics (anelastic/compressible dynamics)
- Hypothesis testing



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

# MEASUREMENTS: WAVE TRAVEL TIMES AS PROXIES



HMI dopplergrams

900 billion wavefield  
measurements

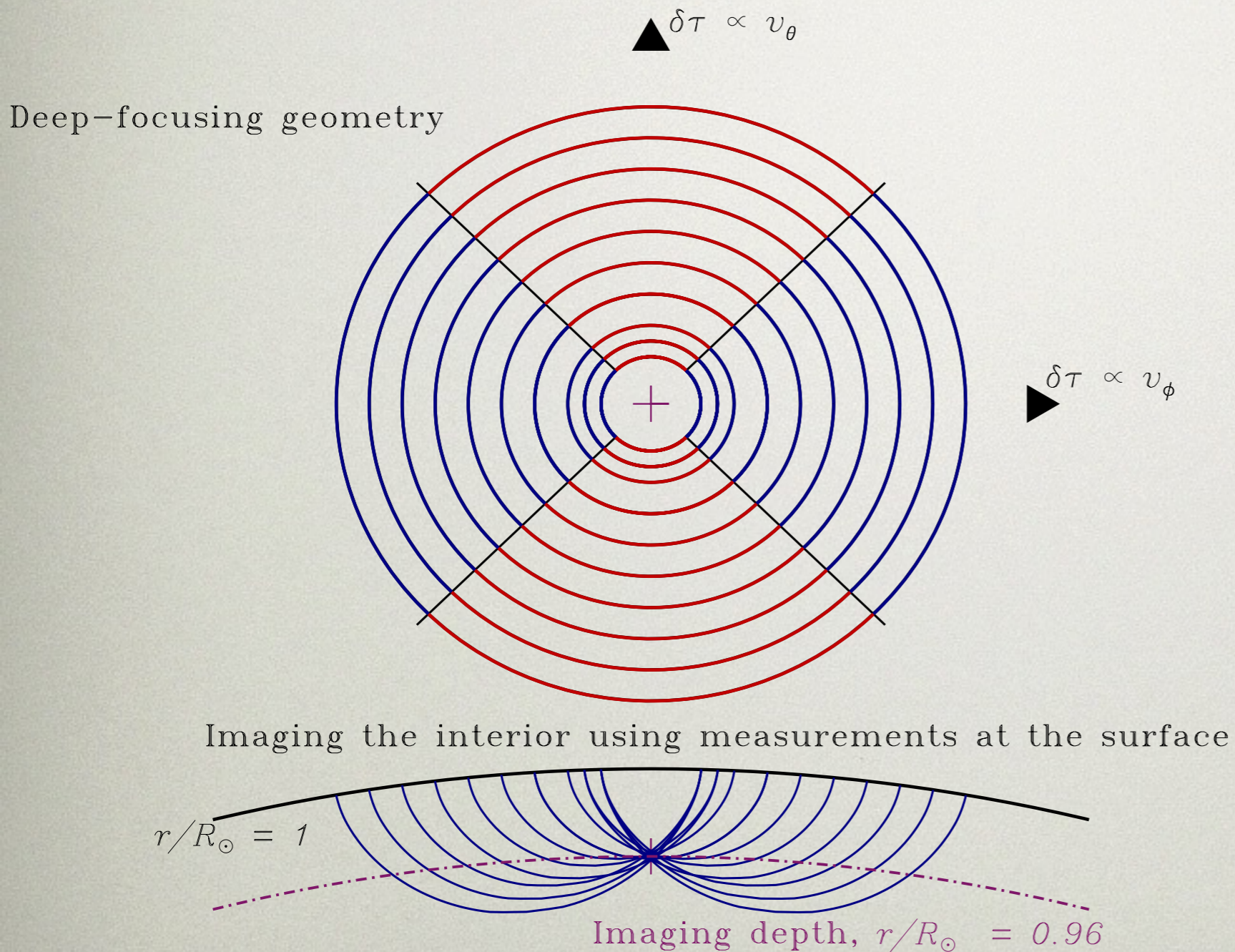
Hanasoge, Duvall & Sreenivasan (2012)  
Proceedings of the Natl. Acad. Sciences, USA

~ 3 billion cross  
correlations

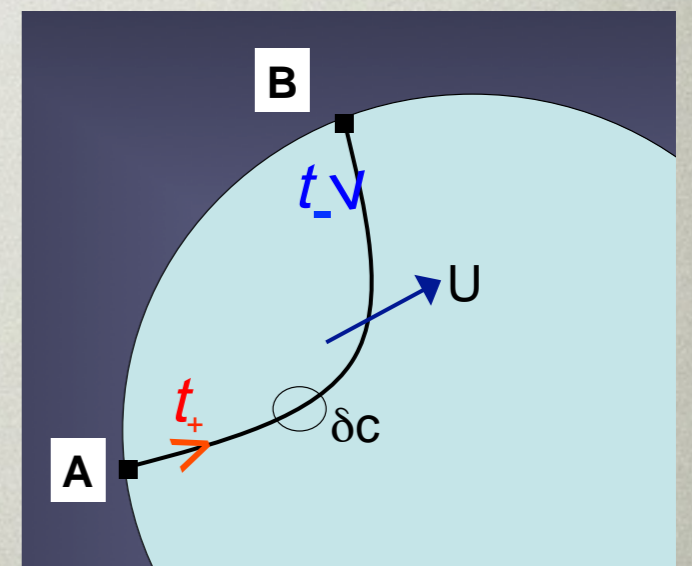
~ 5 million travel  
times

Sensitive to 3-flows

# IMAGING



Aperture at the surface through which interior dynamics are observed

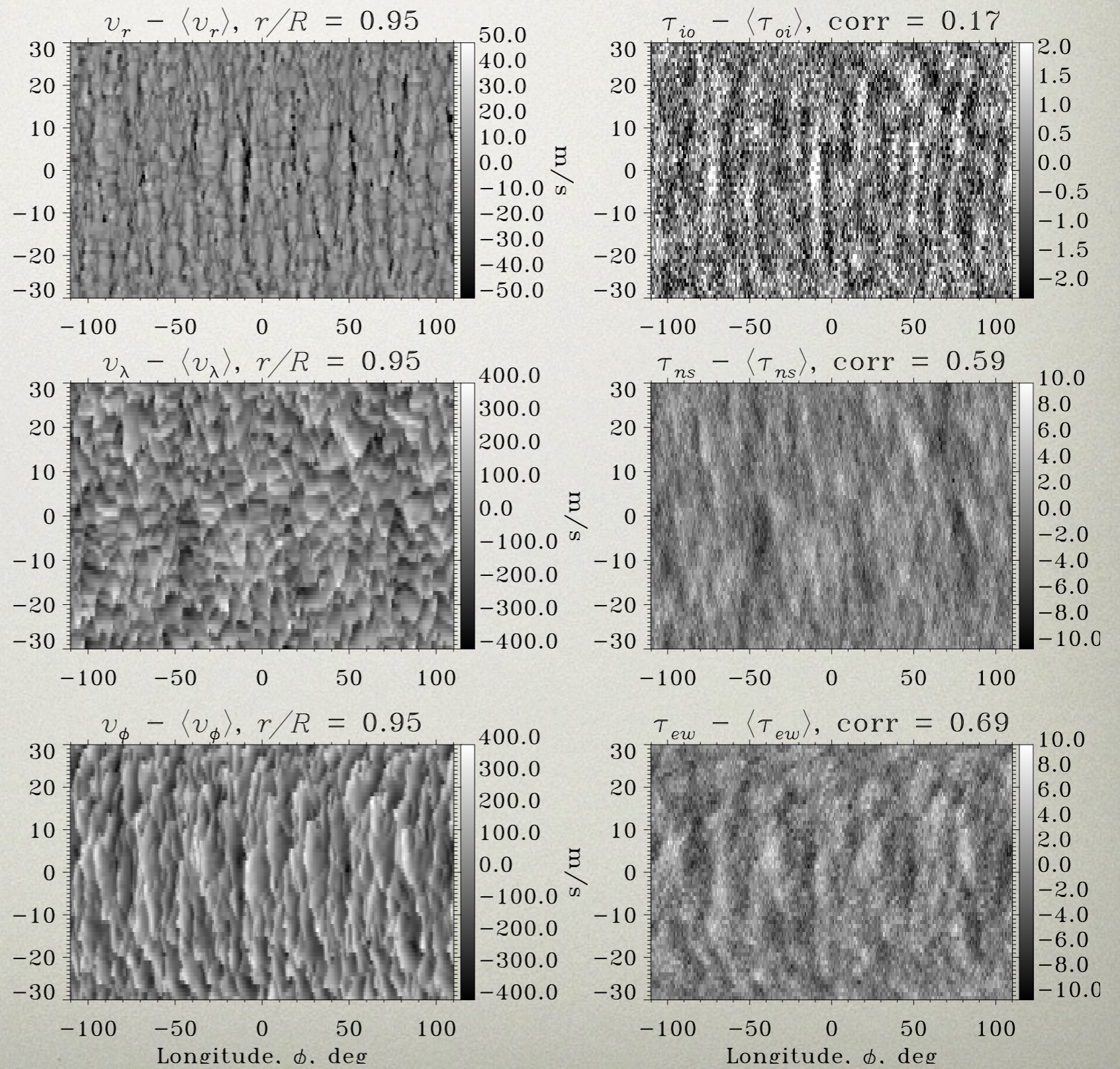


Hanasoge, Duvall & Sreenivasan (2012)  
Proceedings of the Natl. Acad. Sciences, USA

Figure courtesy of L. Gizon

# ASH CONVECTIVE FLOWS

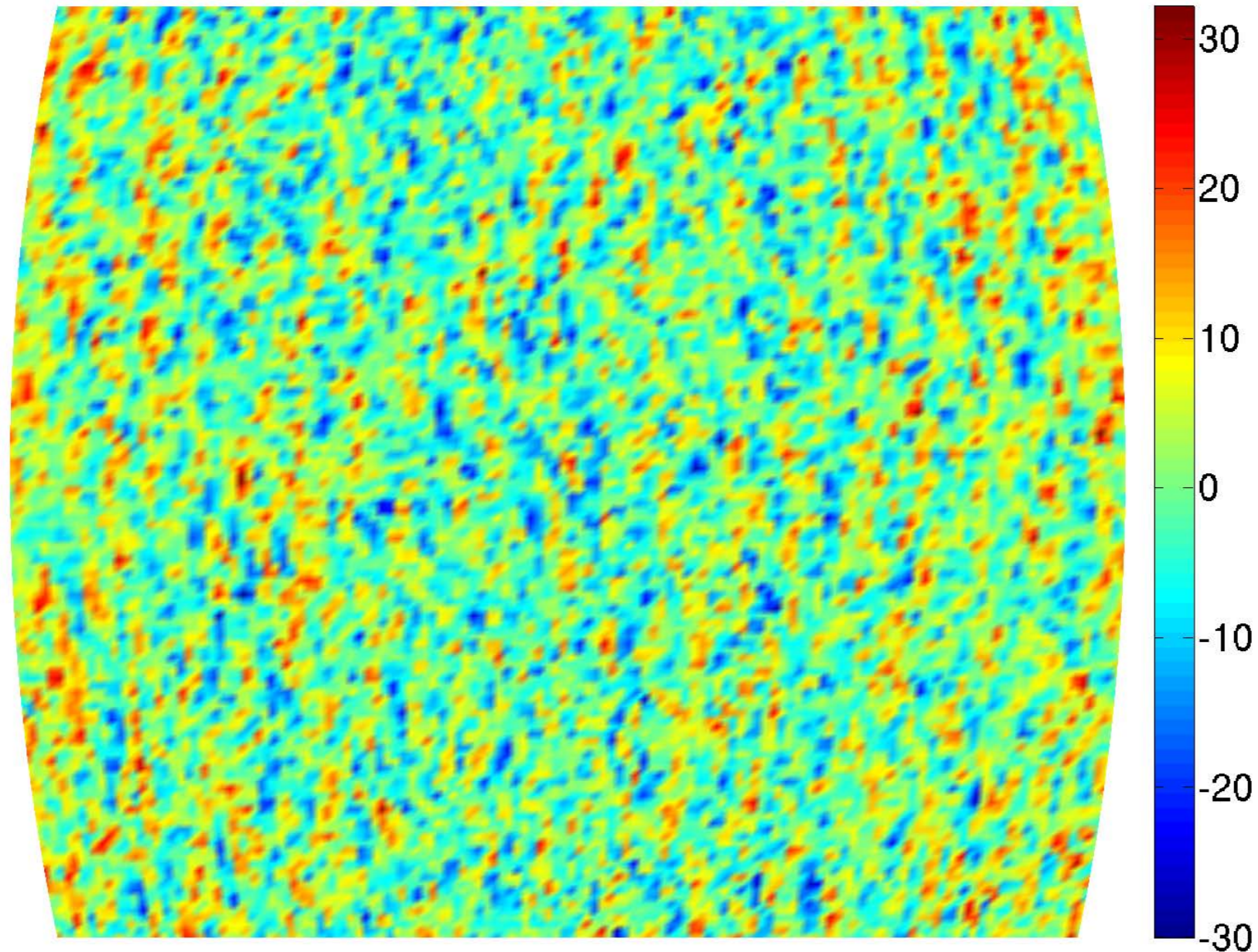
- Test: How do waves perceive a snapshot of anelastic convection (from the ASH code)
- To determine signatures, we simulate wave propagation through these complex flows in spherical geometry (Hanasoge et al. 2006)
- Figure from Hanasoge, Duvall, & DeRosa (2010)
- Are observations as striking?



# OBSERVED MAPS OF TRAVEL TIMES

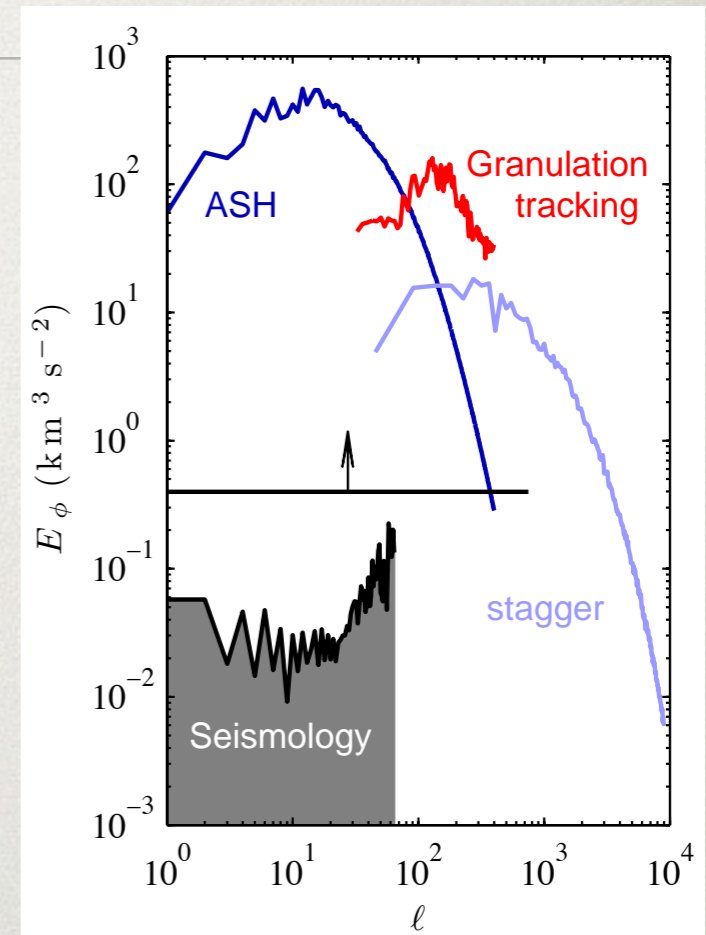
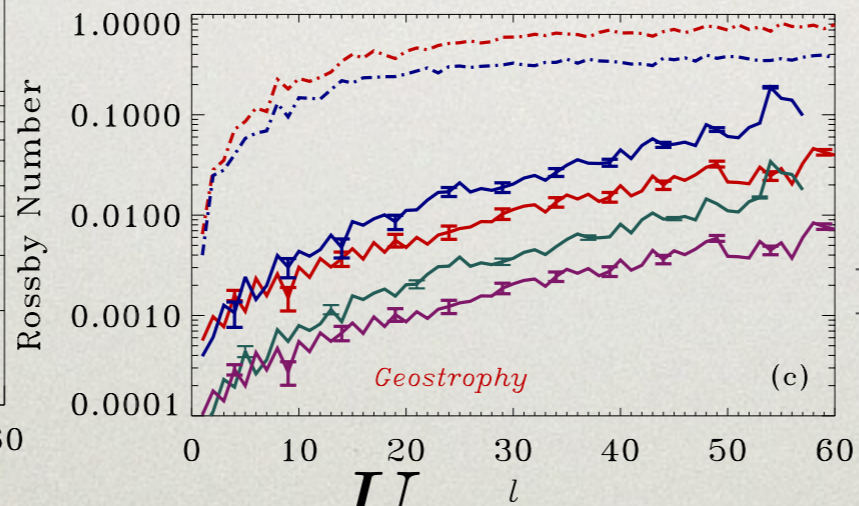
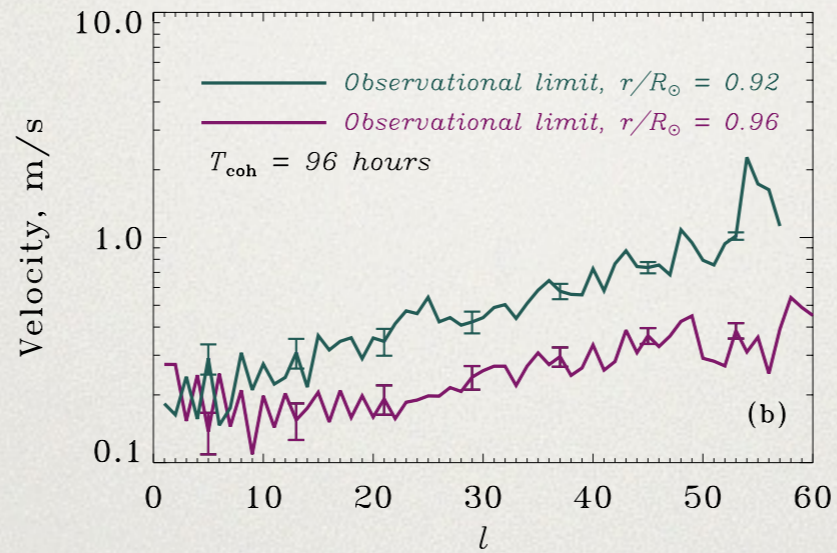
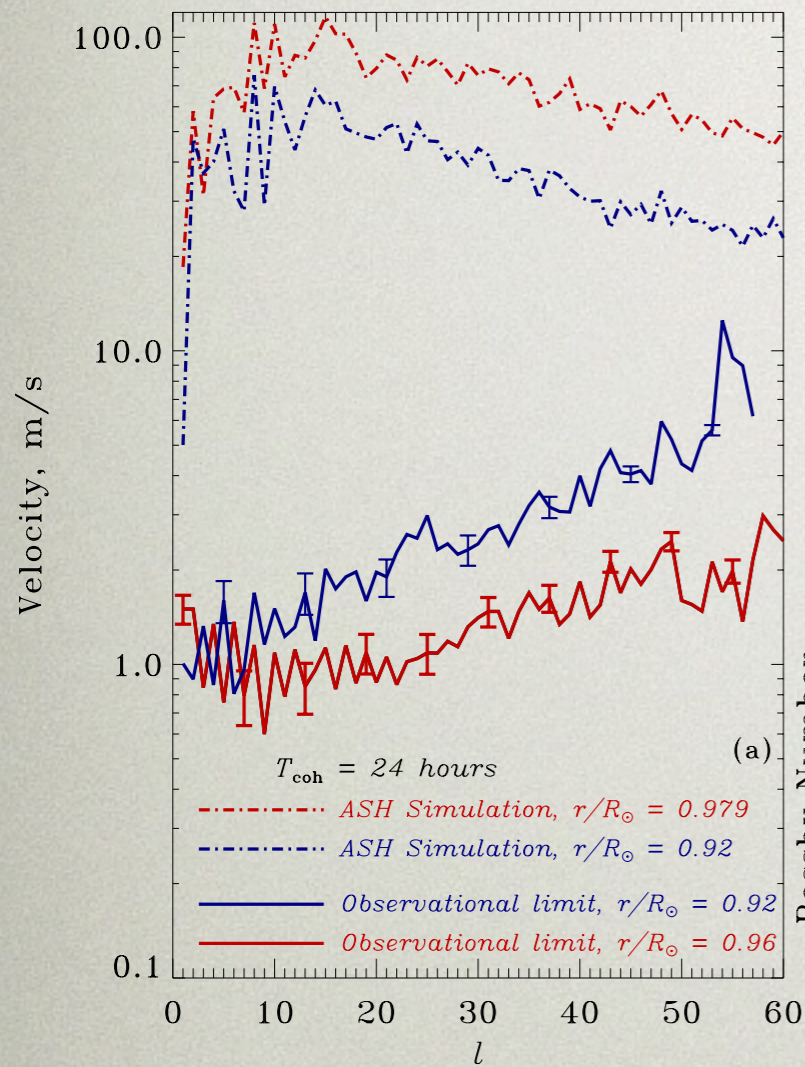
Hanasoge, Duvall & Sreenivasan (2012)  
Proceedings of the Natl. Acad. Sciences, USA

Travel-time map (seconds)



No obvious large-scale structure (noise)

# UPPER BOUNDS



Hanasoge et al. (2012; PNAS)

Gizon & Birch

Comment, PNAS:

'Helioseismology Challenges Models of Solar Convection'

Finite frequency effects are accounted for

Wave 'PSF' deconvolved from the measurement

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

# THE NATURE OF THE RESULT

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- 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

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- 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?  
Meridional 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  $\sim 10\text{Mm}$ .

# DIRECTIONS FORWARD

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- 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)