Helioseismology Overview and Solar Orbiter

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Why Studying the Sun?

Because it is there!

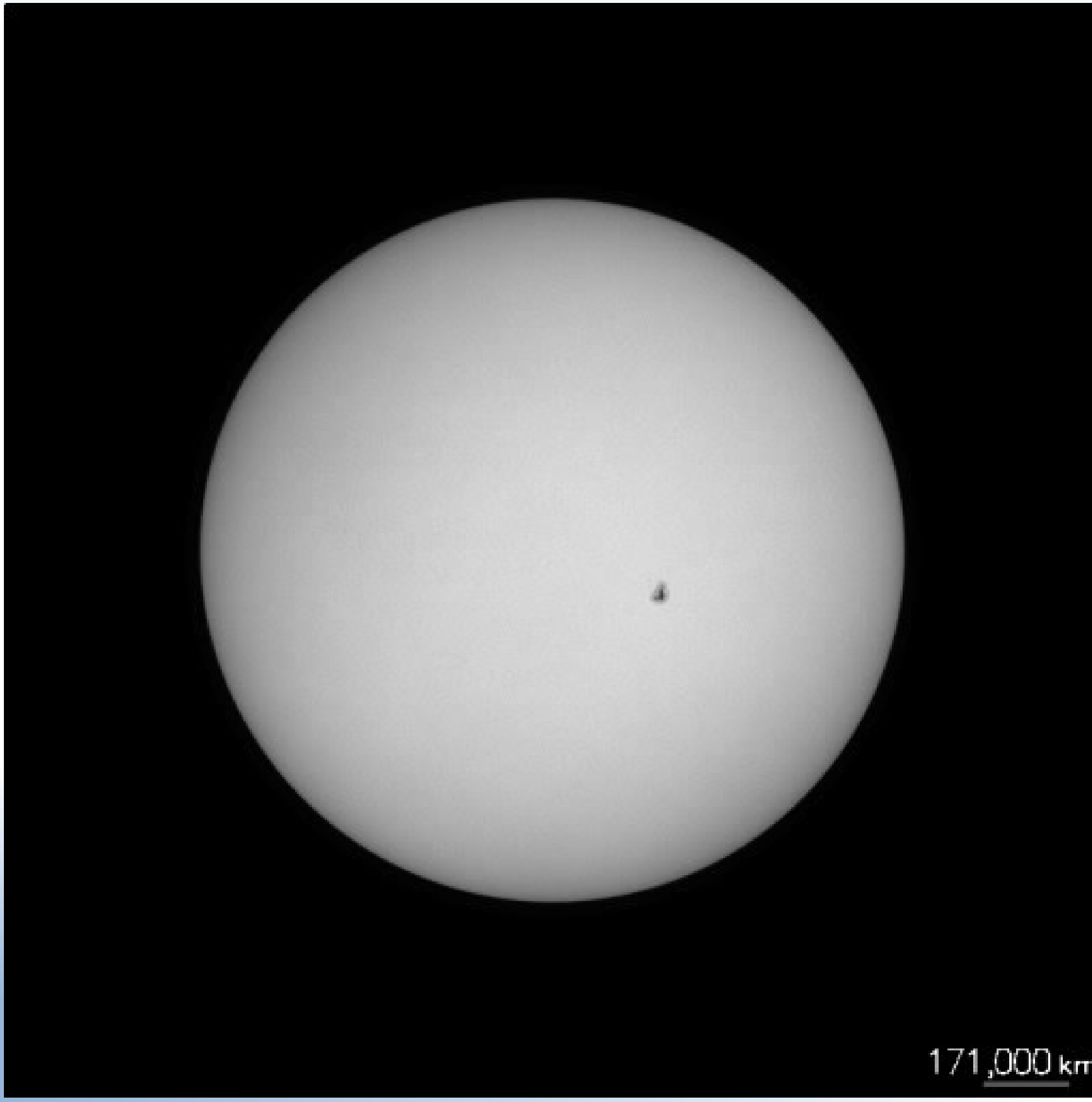
The Sun is the only star which is close enough, that we can study it with high resolution

?**Paradigm for astrophysics**

Surface temperature: 5800 K
(melting point of iron: 1811 K)

Granulation
Size of one granule: 1000 km
Life time: ca. 10 min

Sunspots
Size: several 10'000 km
Life time: days to weeks

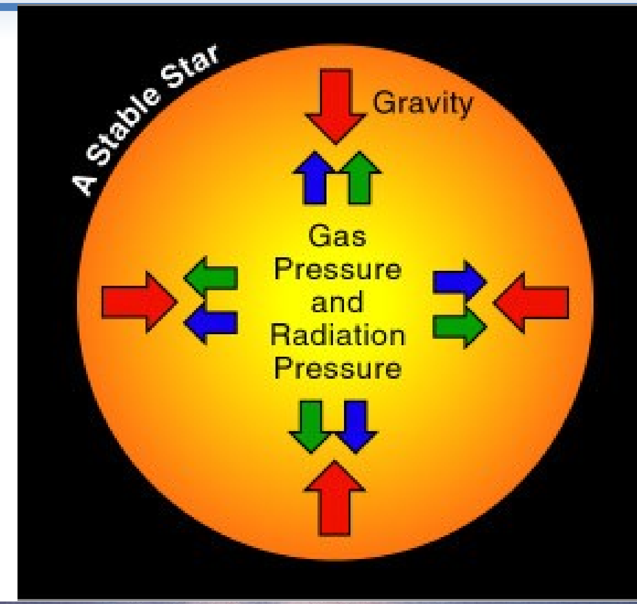


Theoretical Knowledge about the Solar Interior

What is the structure of the Sun?

Theory of the internal structure of the stars is based on the fundamental principles of physics:

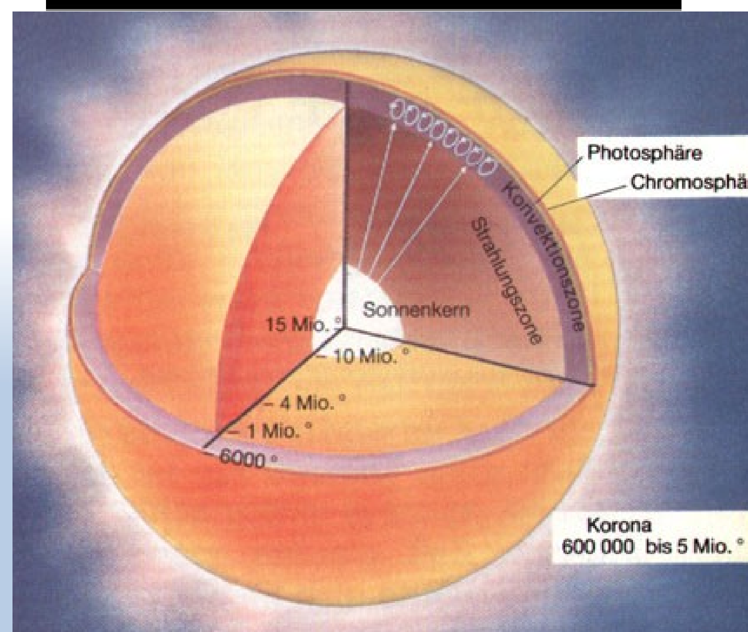
Energy conservation,
Mass conservation,
Momentum conservation



Pressure and gravity are in balance; hydrostatic equilibrium
→ *the Sun is stable*

A theoretical model of the Sun can be built on these physical laws.

Is there a possibility to „look inside" the Sun?

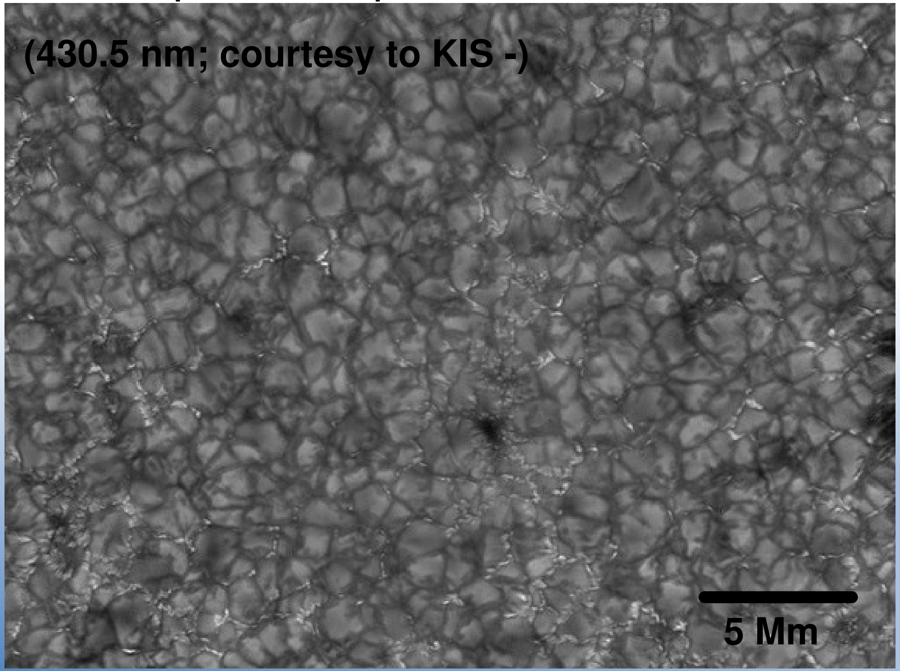


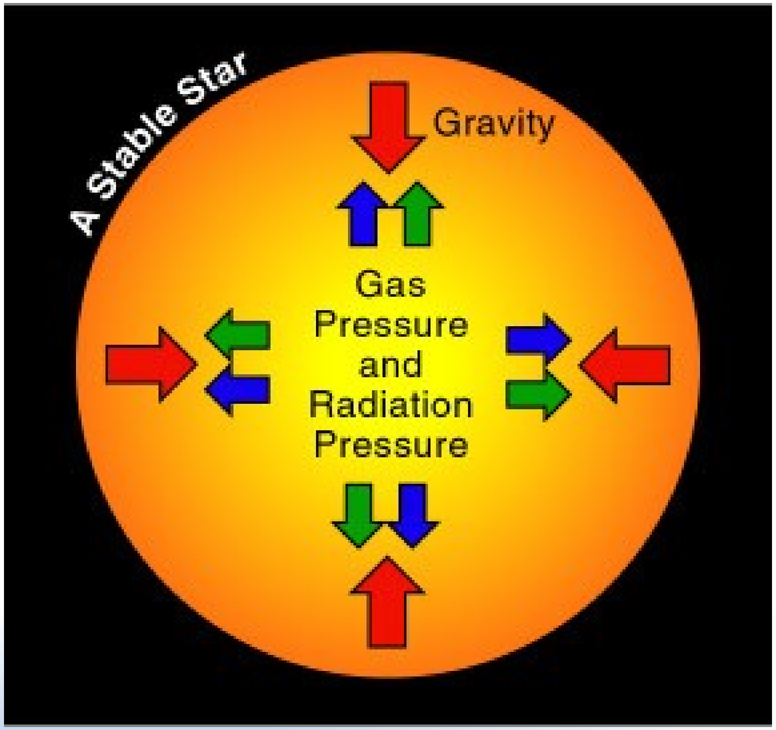
Oscillations in the Sun and the Stars

The Sun and the stars exhibit resonance oscillations!

Excitation Mechanism:
Small perturbations of the equilibrium lead to oscillations

Origin:
Granulation (turbulences) that generate sound waves, i.e. pressure perturbations





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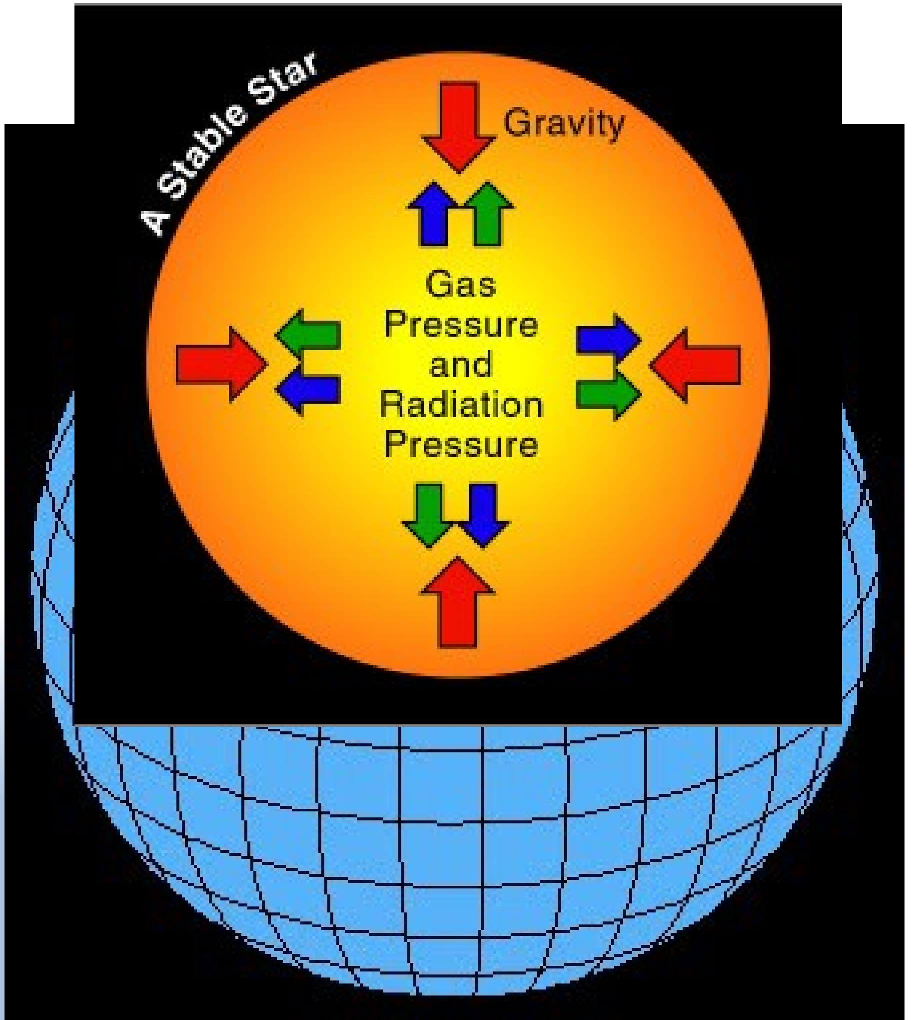
The superposition of sound waves lead to interferences: amplifications or annihilations.

! Sun and stars act as resonators

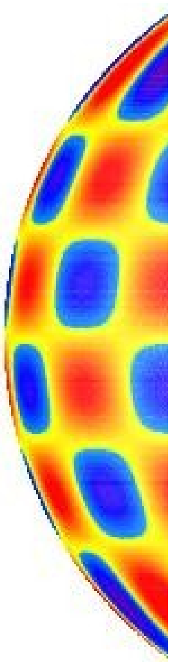
? Fundamental mode and higher harmonics are possible

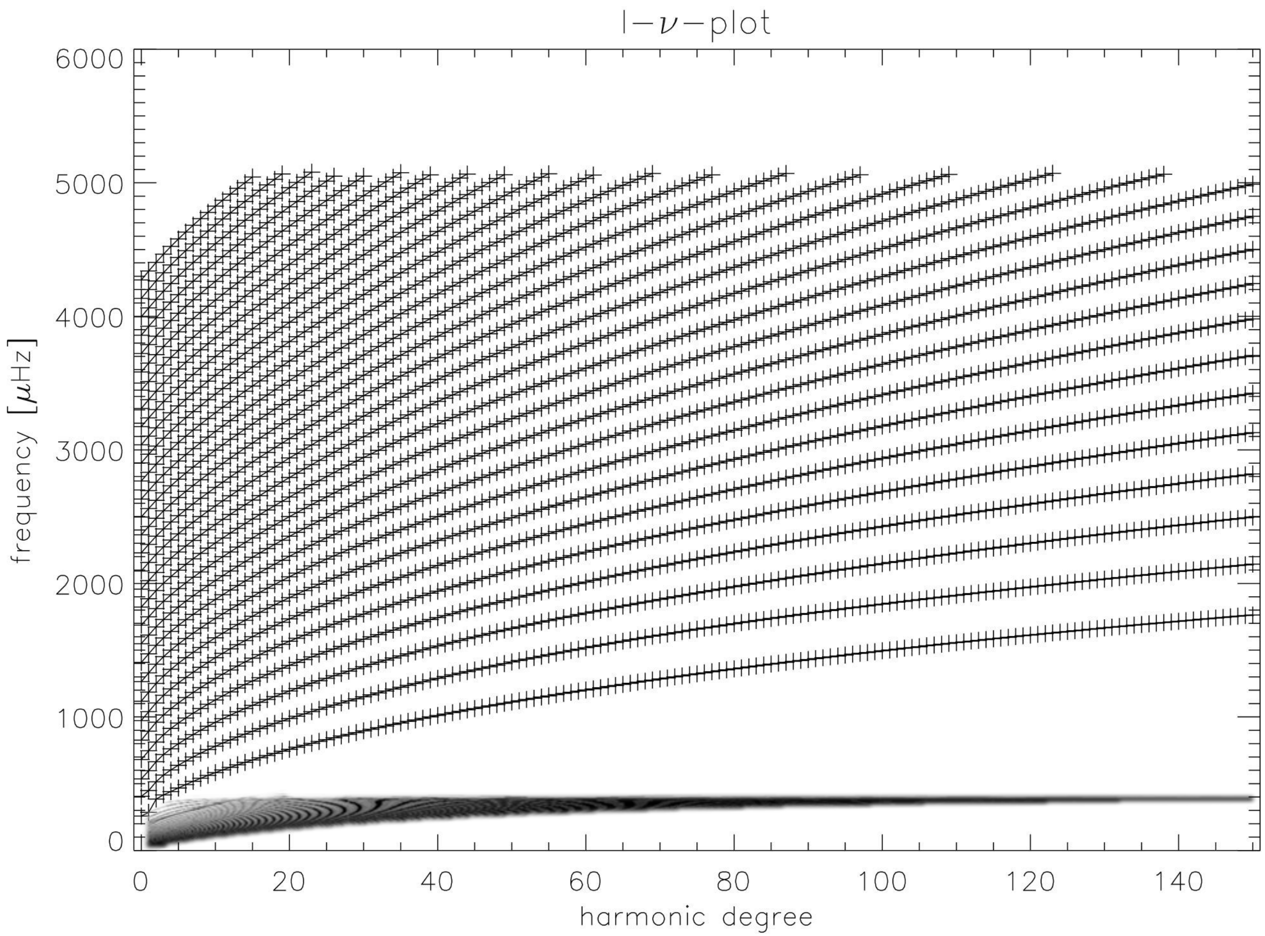


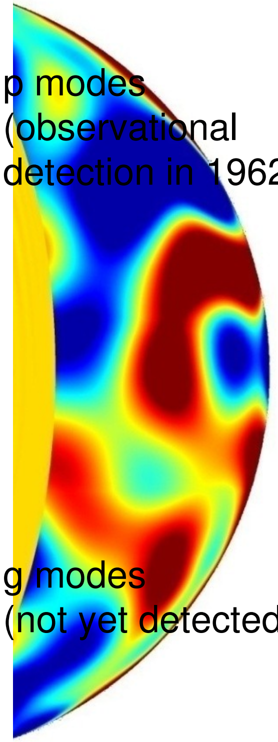
Solar Resonance Oscillations

Perturbation of hydrostatic equilibrium results in eigenmodes

The „sounds“ of a spherically symmetric Sun (theory, small cutout)







p modes
(observational
detection in 1962)

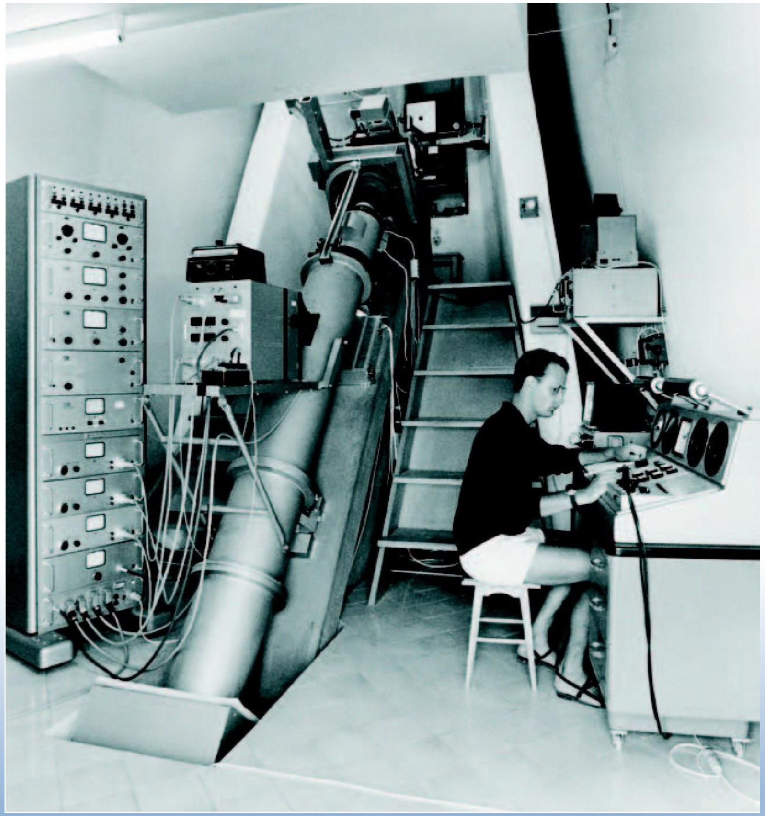
g modes
(not yet detected)

Roth, 2004, SuW 8, 24

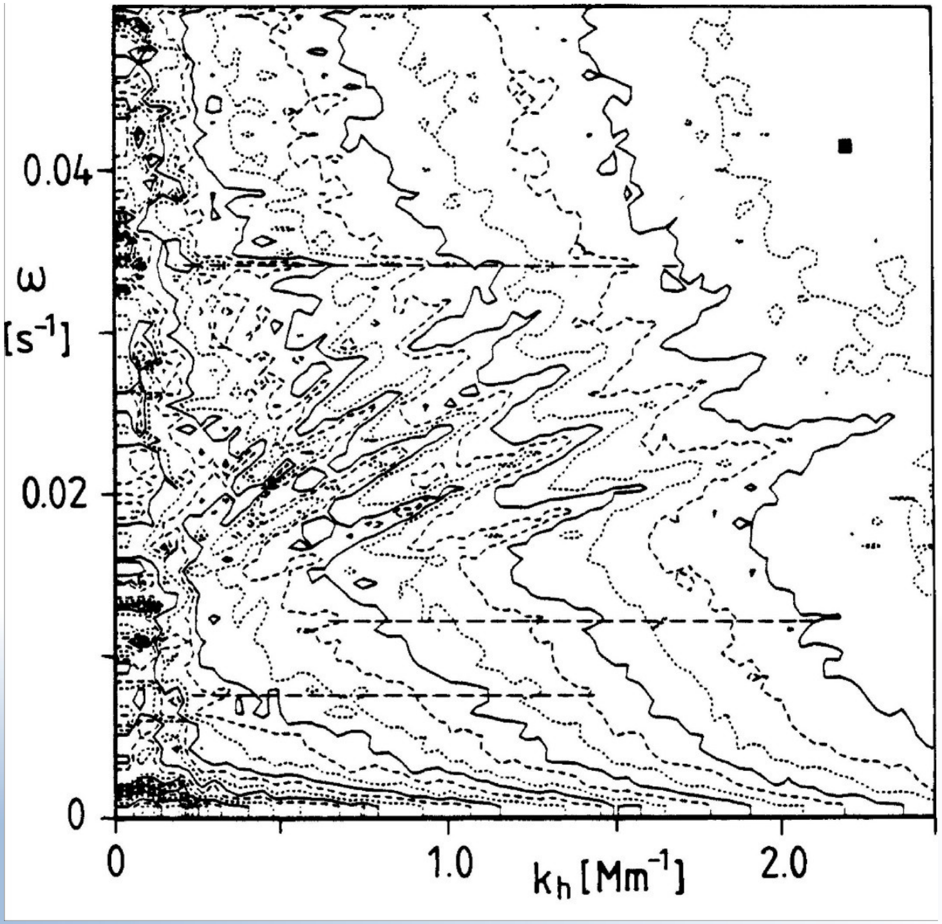
Each mode is 2l+1-fold degenerate

Experimental Proof

Measuring Doppler shifts of spectral lines



Franz-Ludwig Deubner, 1974



Seismology of the Sun

Different waves propagate through different areas inside the Sun
Waves are refracted due to increasing sound speed
? **Information from different depths**

Seismology of the Sun is possible

„Helioseismology“

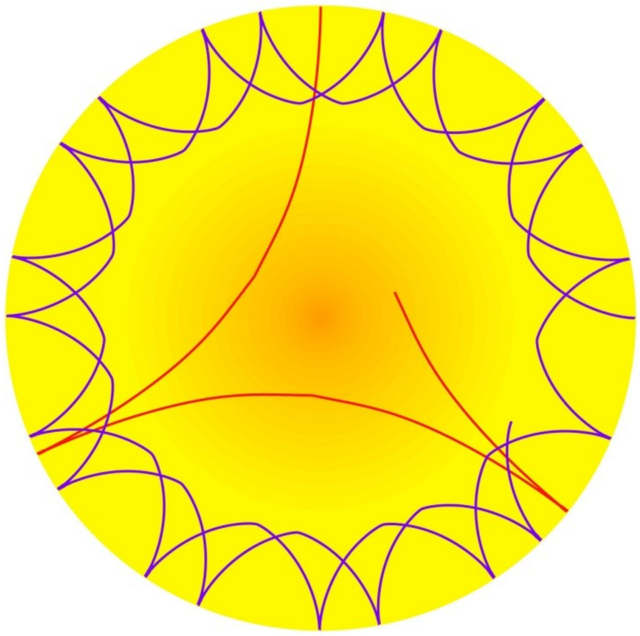
Concluding from its sounds about the internal structure of an instrument

Preconditions:

- Precise measurements of frequencies in order to separate waves

? long and uninterrupted measurements

Frequency resolution: $\Delta\nu = \frac{1}{T}$

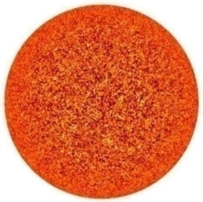


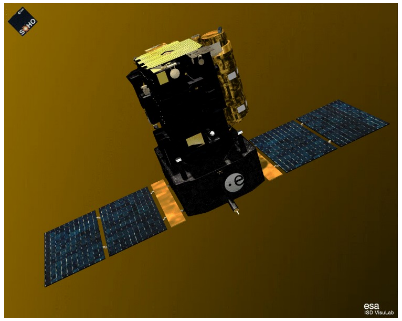
(Roth, 2004, SuW 8, 24)

Helioseismology Instrumentation

Dopplergrams of the Sun – Rotation removed

GONG
Global Oscillation Network Group
ground-based network
since 1995
1 Megapixel CCD





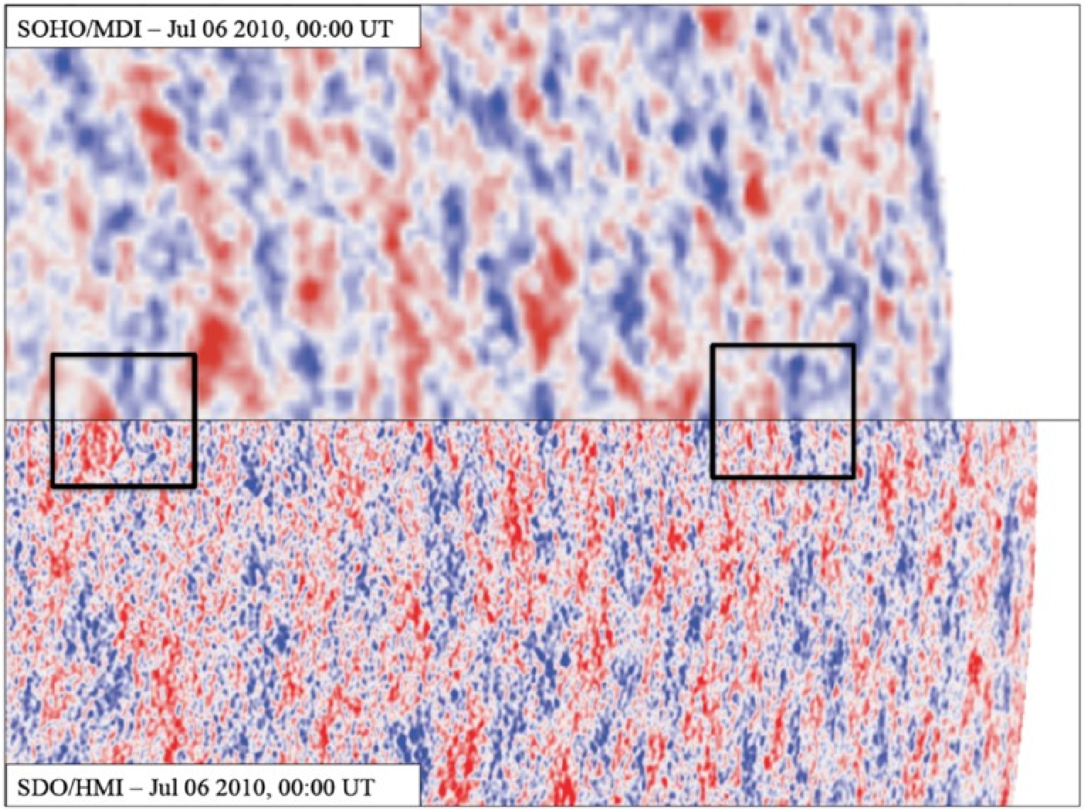
SOHO
Solar Heliospheric Observatory
1996 – 2010
with high duty cycle
1 Megapixel CCD

SDO
Solar Dynamics Observatory
solar oscillations in high resolution
since 2010
16 Megapixel CCD (8xFullHD)

From SoHO/MDI to SDO/HMI

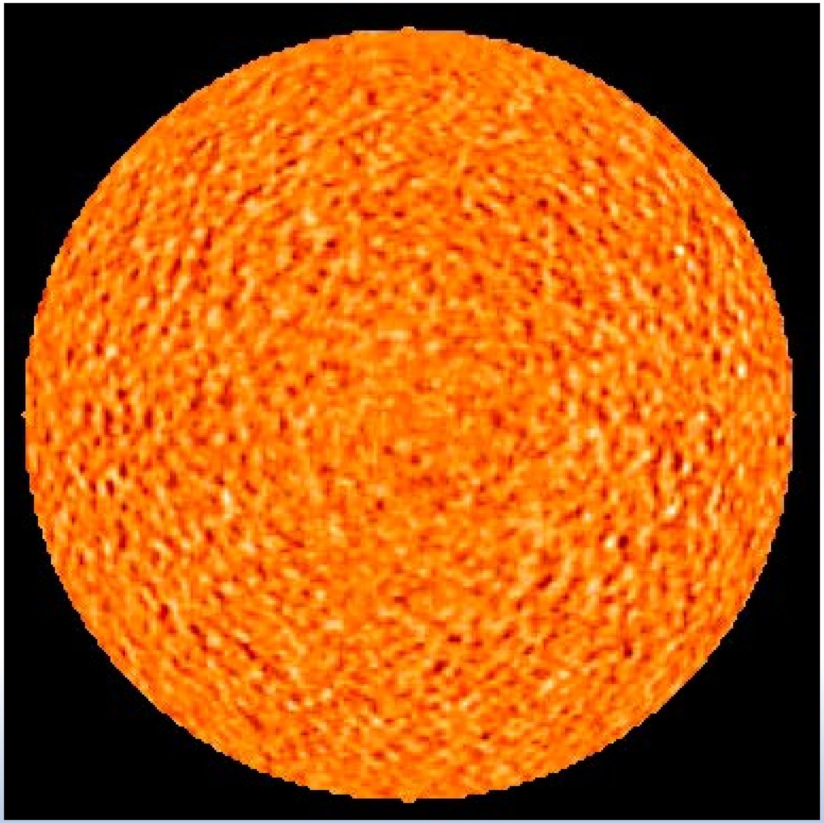
- Since 2010, SDO/HMI with higher resolution (4kx4k CCD, angular resolution < 1.5‘‘, 45s cadence)
- Ongoing improvement of accurate determination of helioseismic observables, mode parameters (e.g. Korzennik et al. 2013, Reiter et al. 2015, Larson & Schou 2015,...)

Supergranulation (Williams et al. 2015)



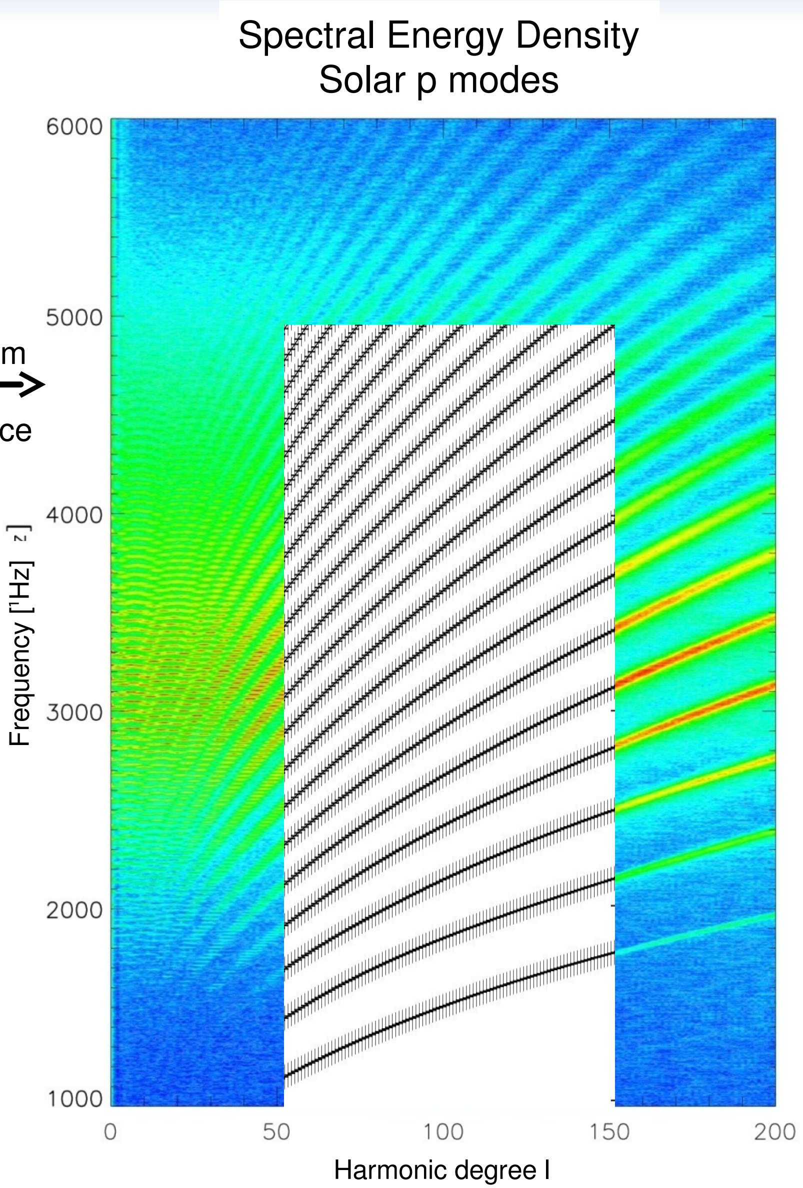
Modern Era of Helioseismology

10 million oscillations, simultaneously excited



Fourier transform

in time and space



Roth, 2004, SuW 8, 24

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First Successes of Helioseismology: Internal Structure of the Sun

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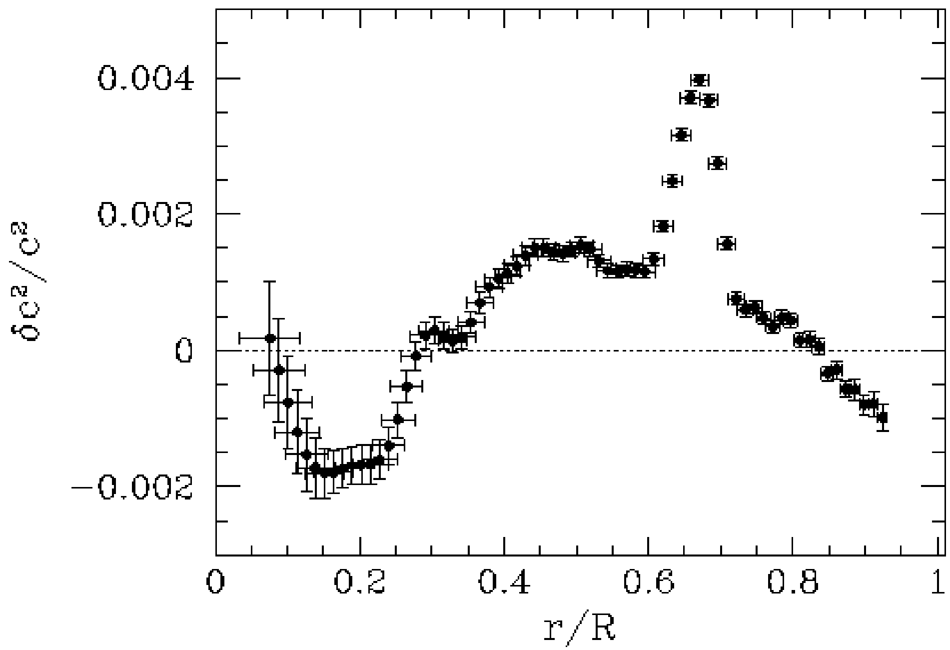
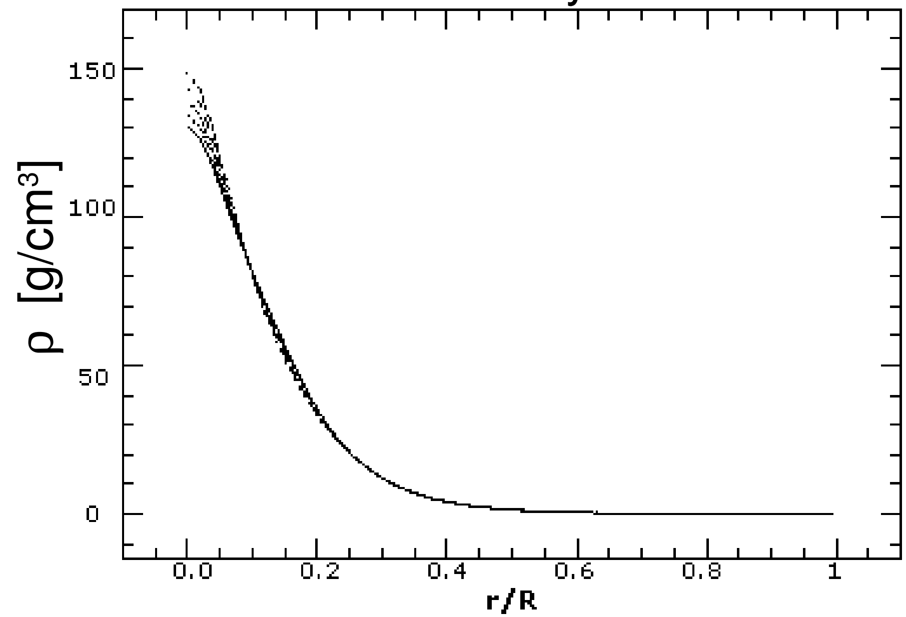
Sound Speed



Density



Difference between theoretical model on the Sun's internal structure and helioseismology: **approximately 3%**

(Kosovichev et al., 1997, Solar Phys.170, 43)

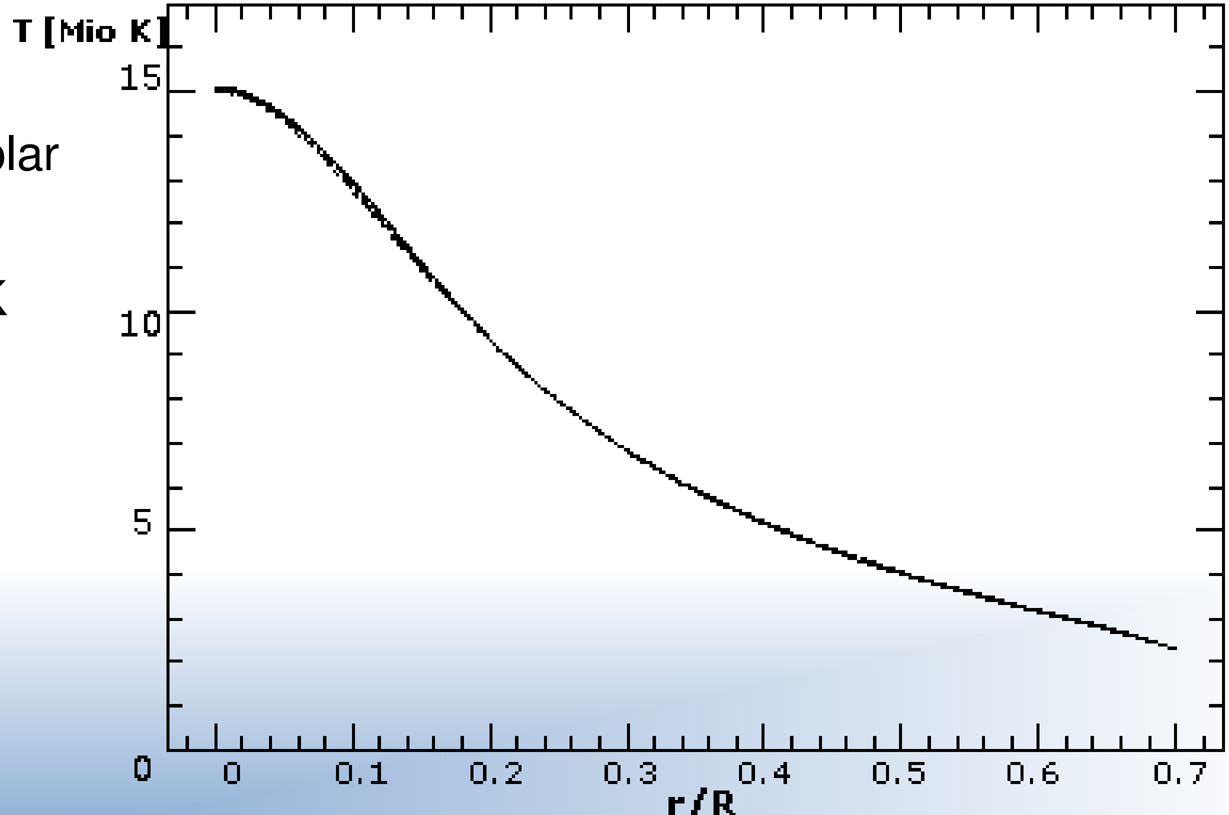
(Christensen-Dalsgaard et al., 1985, Nature 315, 378)
Antia & Chitre, 1995, Astrophys. J. 442, 434)

Central Temperature of the Sun

The temperature in the solar center is:

15,6 ± 0.4 Million K

? Neutrino problem



(Vorontsov, 2002)

The Solar Neutrino Problem

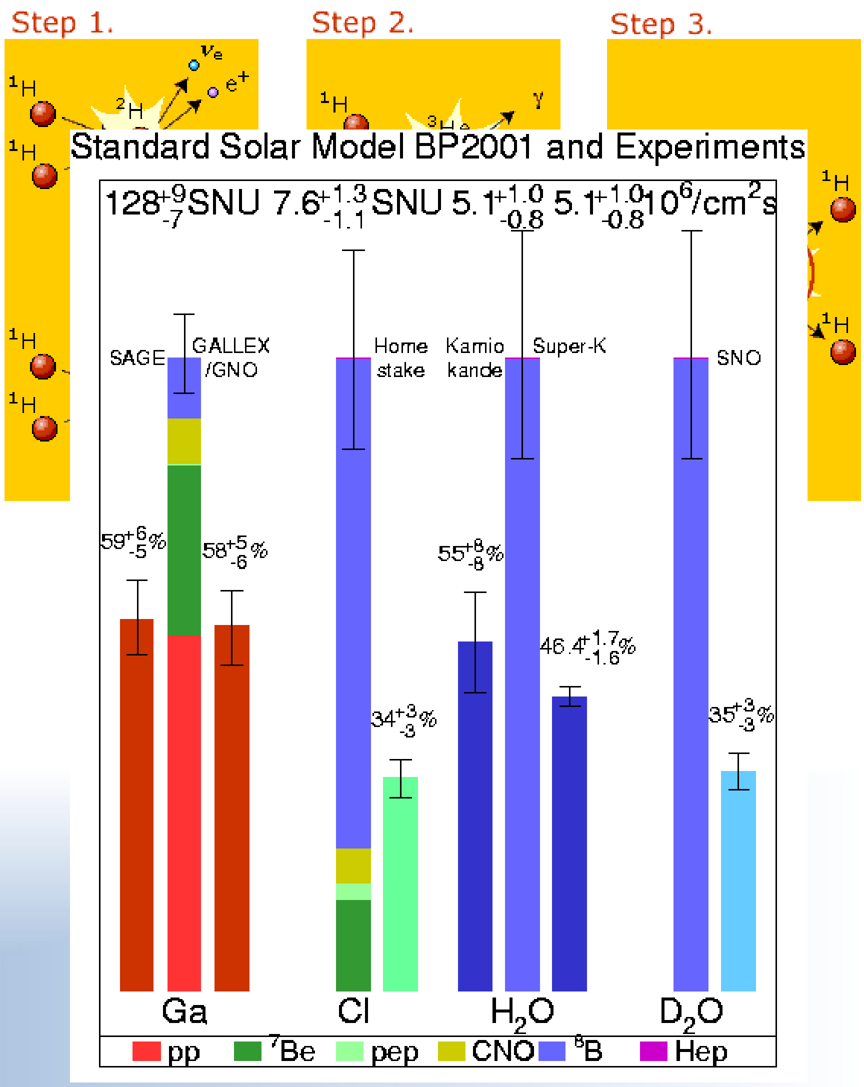
Fusion reactions are taking place in the solar core

Released neutrinos (ν_e) could be detected on Earth.

Problem: ***Less neutrinos are detected than predicted by theory of internal structure of the Sun (1/3 – 1/2).***

But: Helioseismology confirmed the theoretically expected core temperature of the Sun
→ ***Solar model is correct***

Solution by Particle Physics: Neutrino Oscillations



One Possibility to "look inside": Neutrino Detection

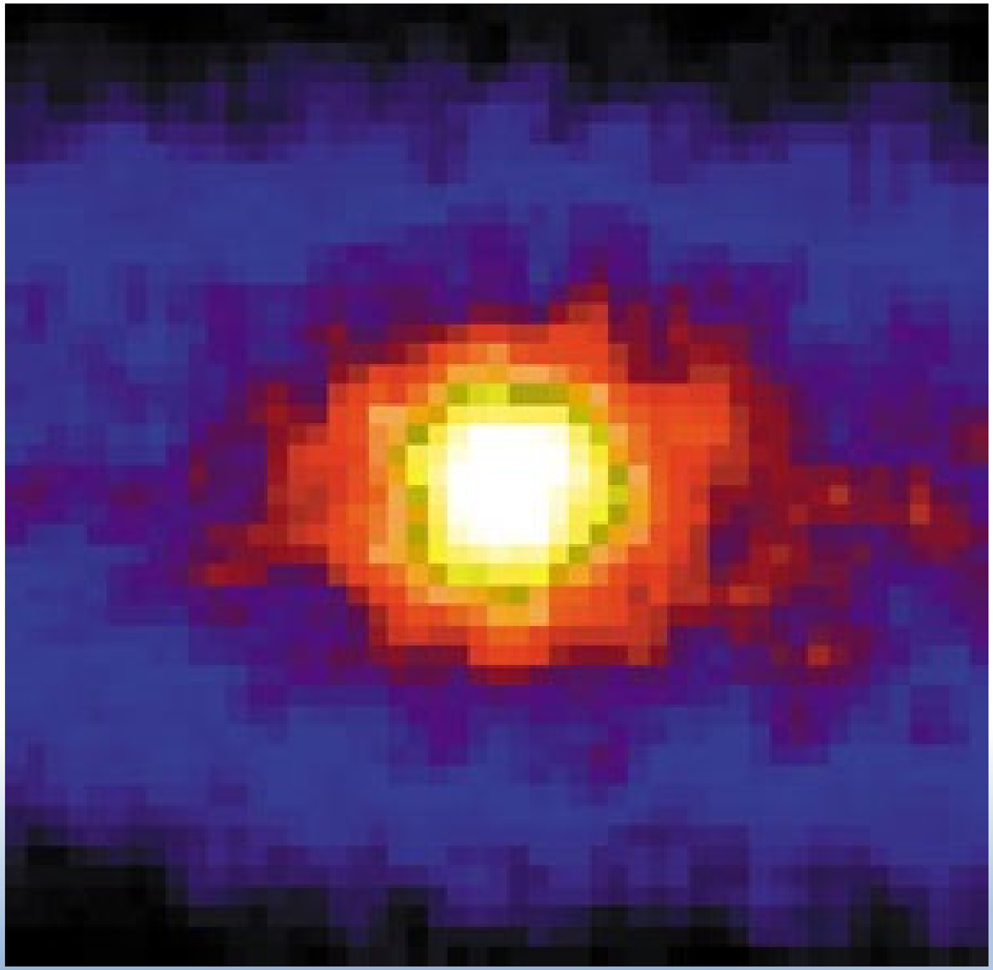


Image of the Sun recorded by the Super-Kamiokande-Detector in "neutrino light"

Exposure time: 540 days

1 Pixel corresponds to 1 degree on the sky

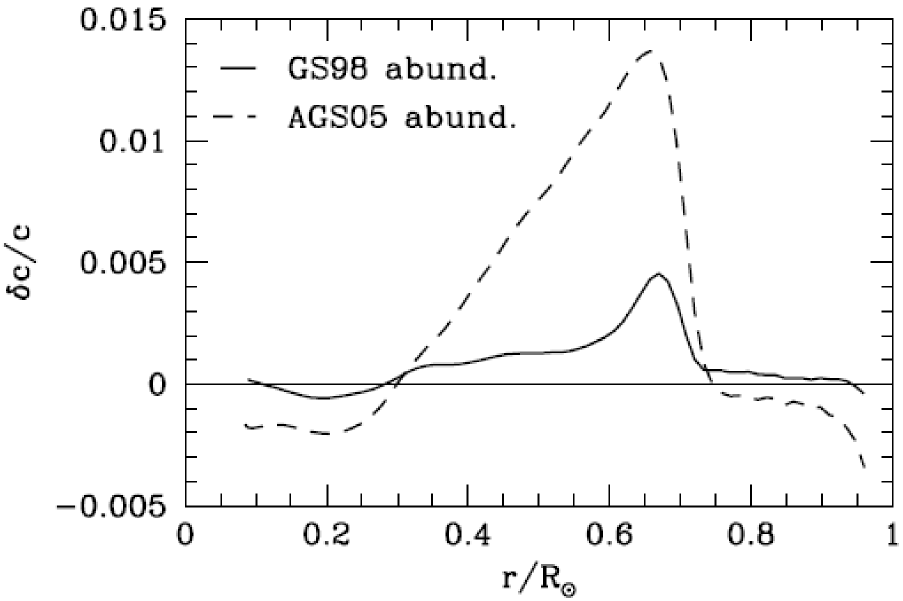
Proof of nuclear reactions in the solar core:

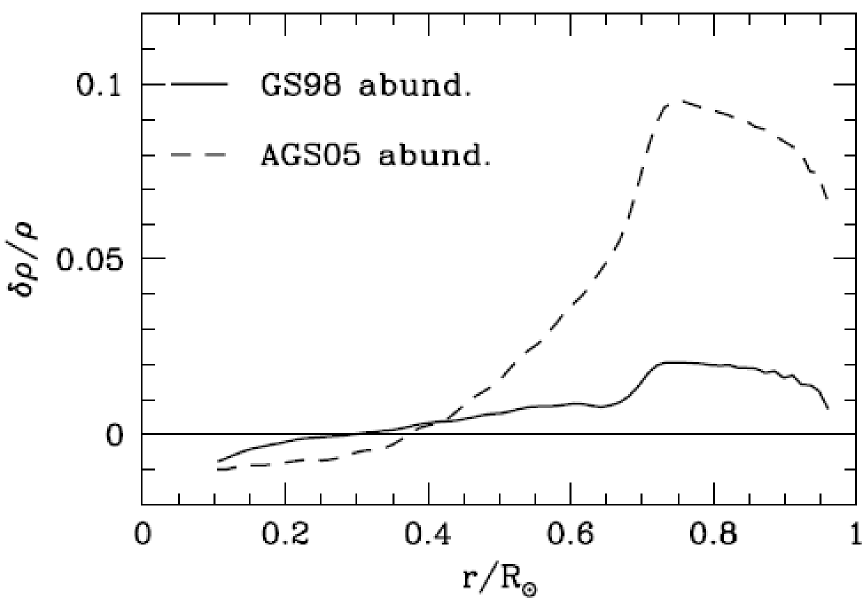
- Neutrinos are an almost direct measurement (8 min delay)
- Visible light is delayed by 10 Mio years

Fly in the Ointment: Revised Abundances

Element	Anders & Grevesse (1989)	Asplund et al. (2009)	Difference
Carbon	8.56+/-0.06	8.42+/-0.05	-28%
Nitrogen	8.05+/-0.04	7.83+/-0.05	-40%
Oxygen	8.93+/-0.03	8.70+/-0.05	-41%

Note: logarithmic scale with H defined to have 12.00





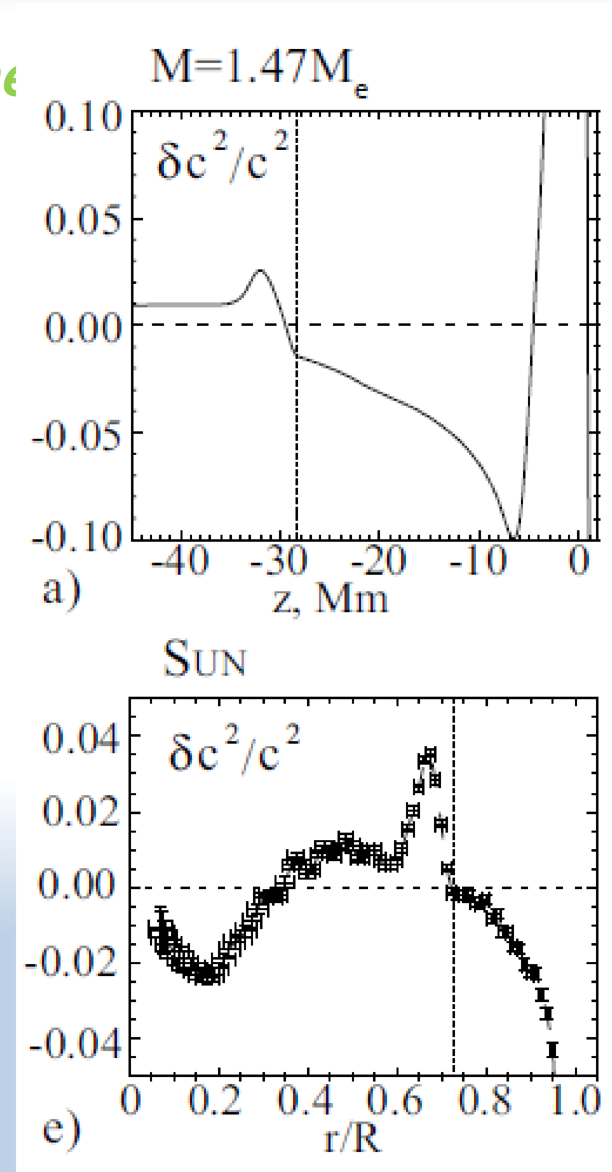
Result: Greater disagreement between solar model and seismic results

3D Modelling of Turbulent Convection

3D simulations of a full convection zone a 1.47 $M_\odot$ star

- *Difference in sound speed between simulation and 1D stellar model shows functional behavior*

- *Clear similarity to the difference between helioseismic measurements and 1D model of the Sun*



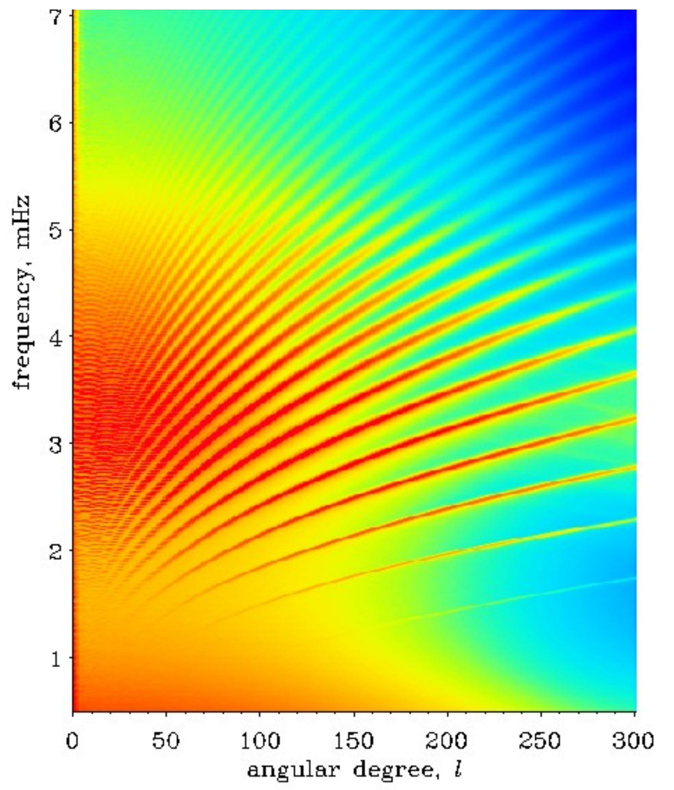
(Kitiashvili et al. 2016)

Local Helioseismology Techniques

- *Ring Diagrams &*
  Fourier–Hankel Decomposition
  - Local analysis of oscillatory power

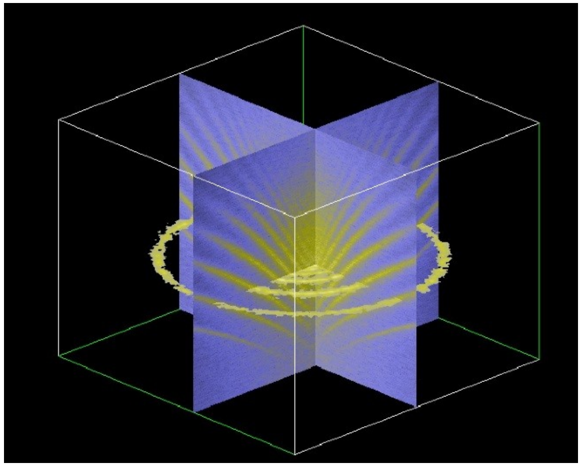
- *Time–Distance Helioseimology & Holography*
  - Analysis of travelling waves

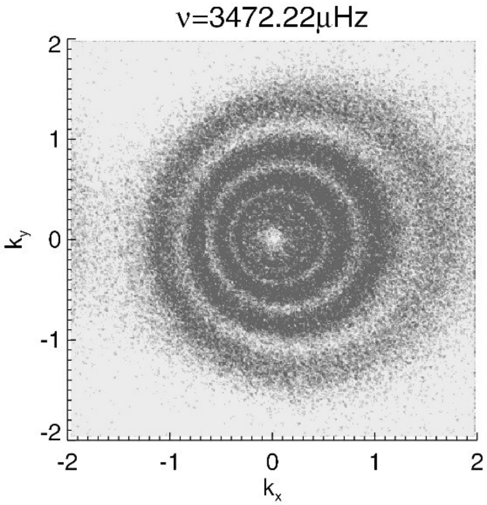
Ring Diagrams



Power of oscillations as determined from the whole visible solar surface

(Hill, 1988)





2D power spectrum of small patch of solar surface

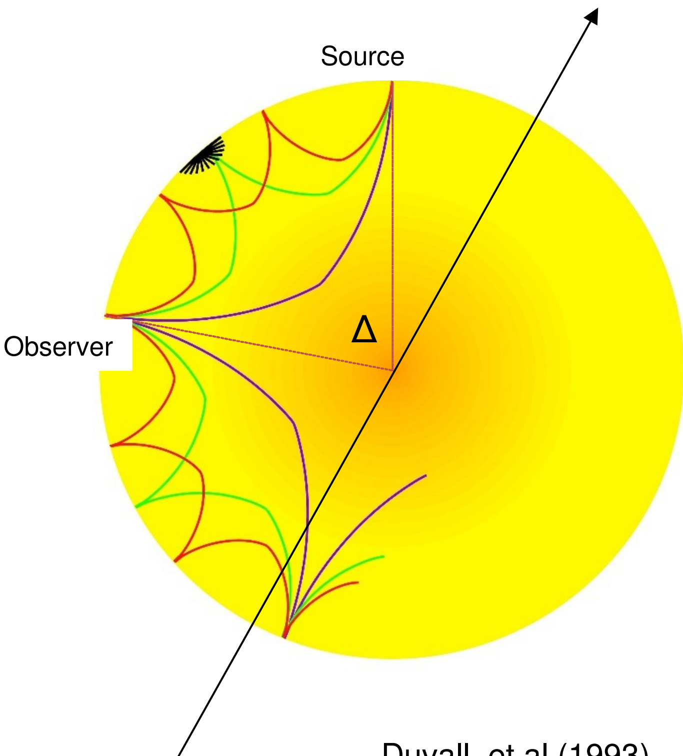
Horizontal section through power spectrum give rings.

Flows advect modes:

? Rings are ellipses
(direction dependent eigenmode perturbations)

Time-Distance Helioseismology

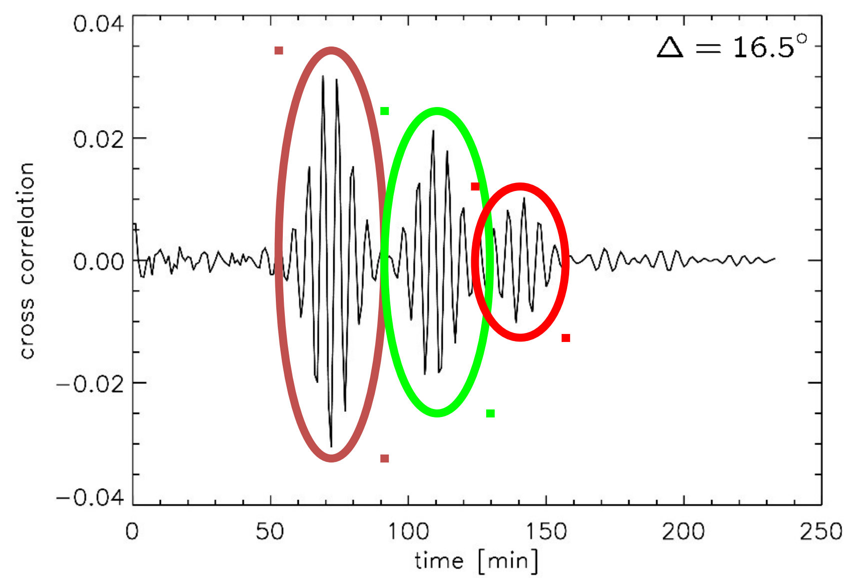
Observation of oscillation signal at two locations on the Sun



Duvall et al (1993)

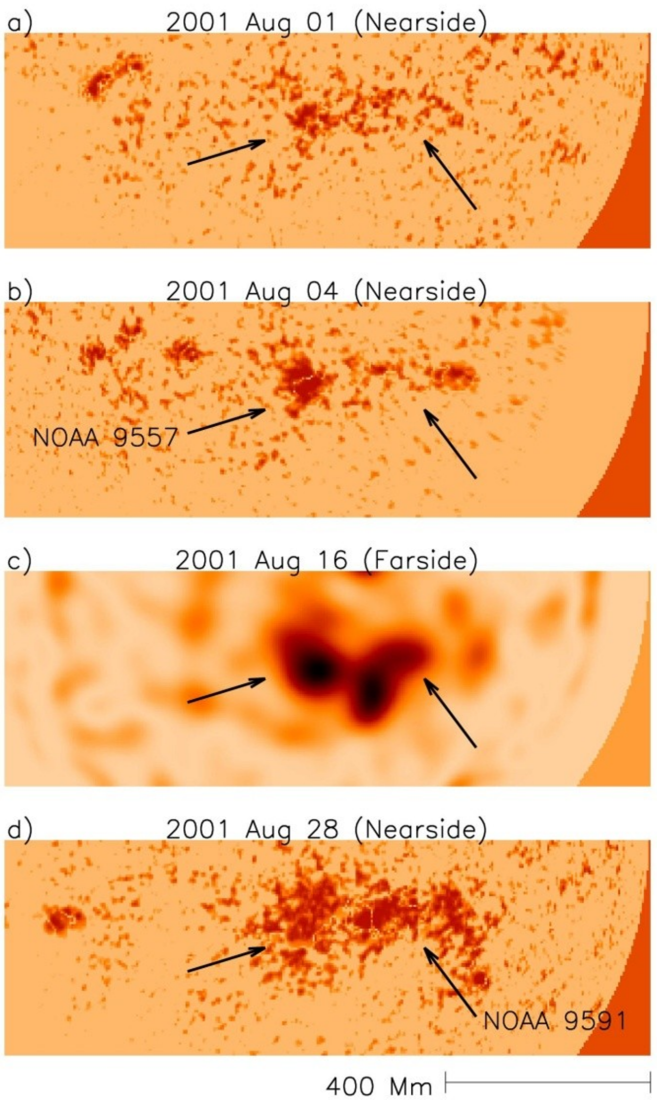
Calculation of the Cross Correlation of the observed signals as function of travel-distance and time lag:

$$C(\tau,\Delta) = \int_0^T \psi(0,t)\psi(\Delta,t+\tau)\,dt$$



Travel time of incoming and outgoing wave
average: sound speed
difference: flows

Farside Imaging



Acoustic holography was developed by Lindsey and Braun (1990)

Waves from the backside appear on the frontside of the Sun

In turn: Waves from the frontside can reach to a point on the backside

Difference between incoming and outgoing amplitudes

and

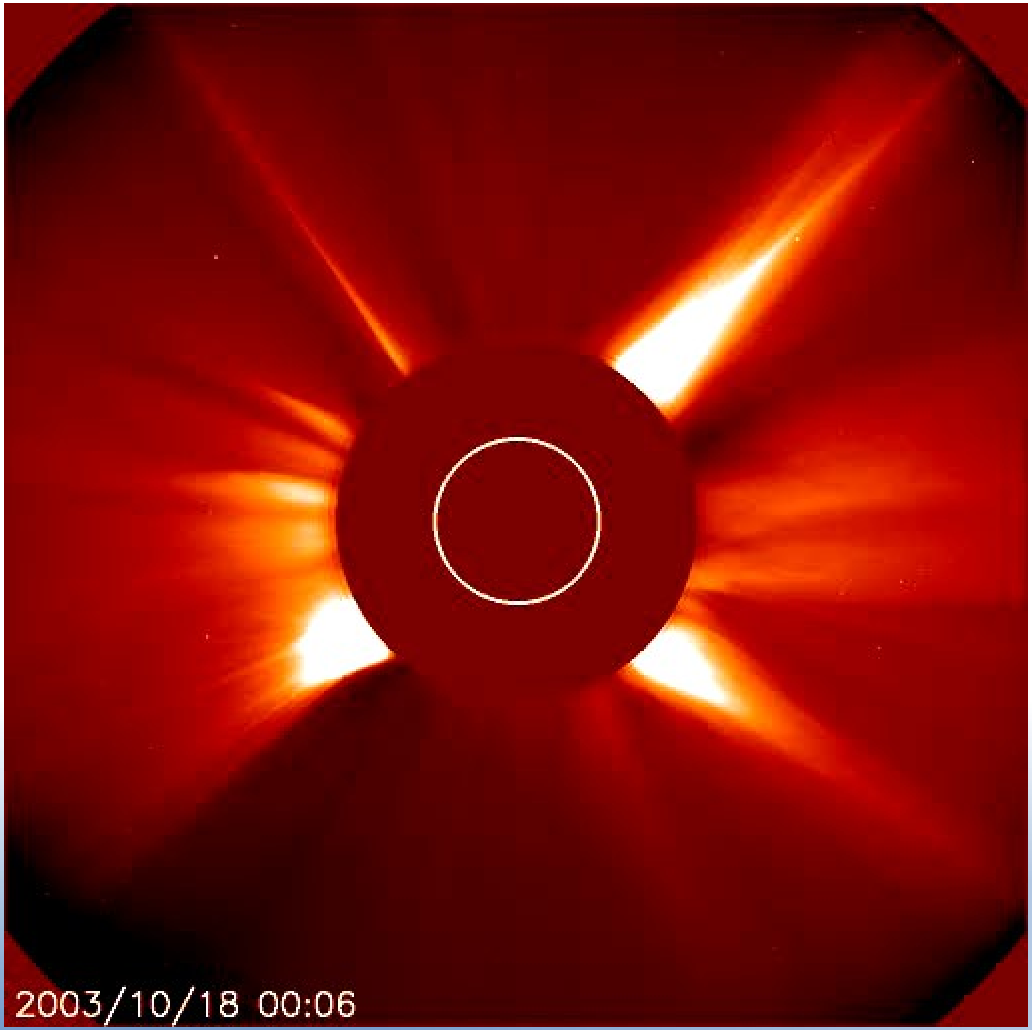
the *travel time shift between the waves* results in

Acoustic image of the solar farside

(courtesy D. Braun & C. Lindsey)

Current Research: The Active Sun

(SOHO/LASCO)



Enormeous eruptions on the Sun accelerate material into space.

Solar activity affects:
e.g., climate, satellites, space flights, technological systems on Earth

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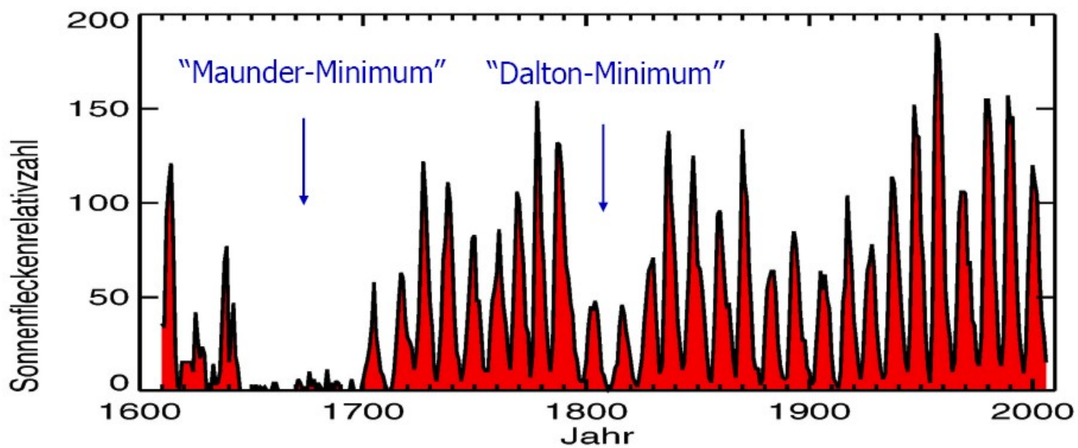
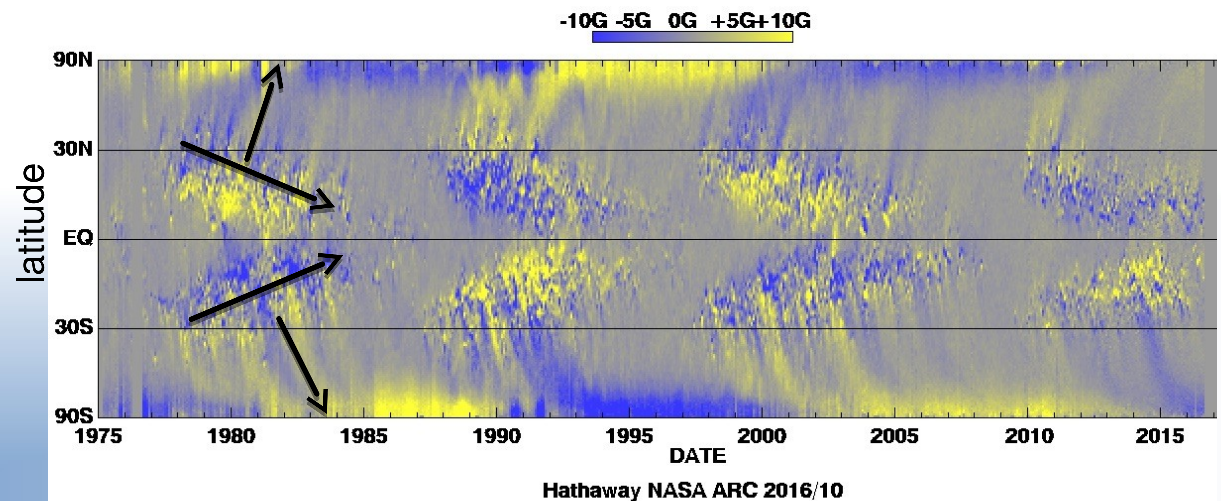
Sunspot Cycle

Solar Maximum

Solar Minimum

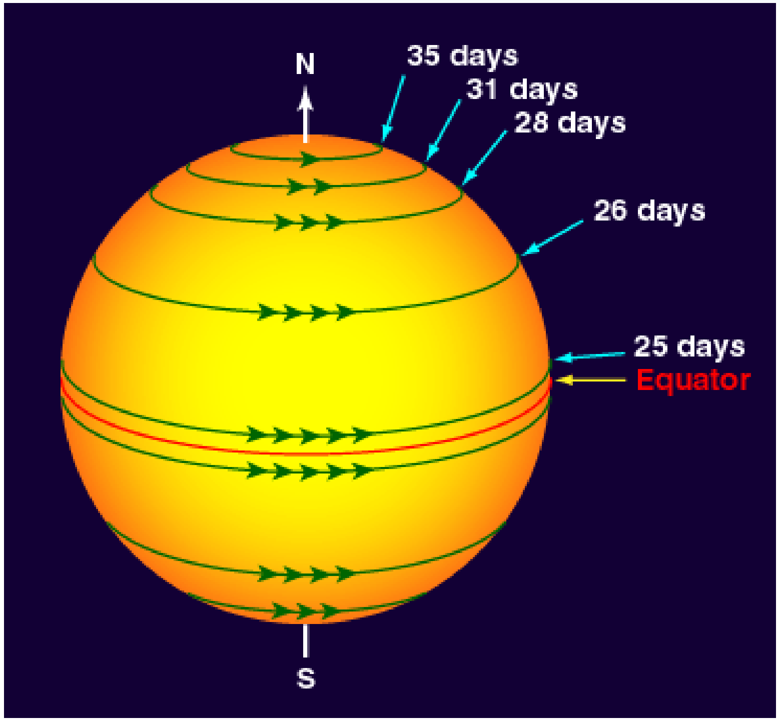
Number of sunspots varies within ~11 years

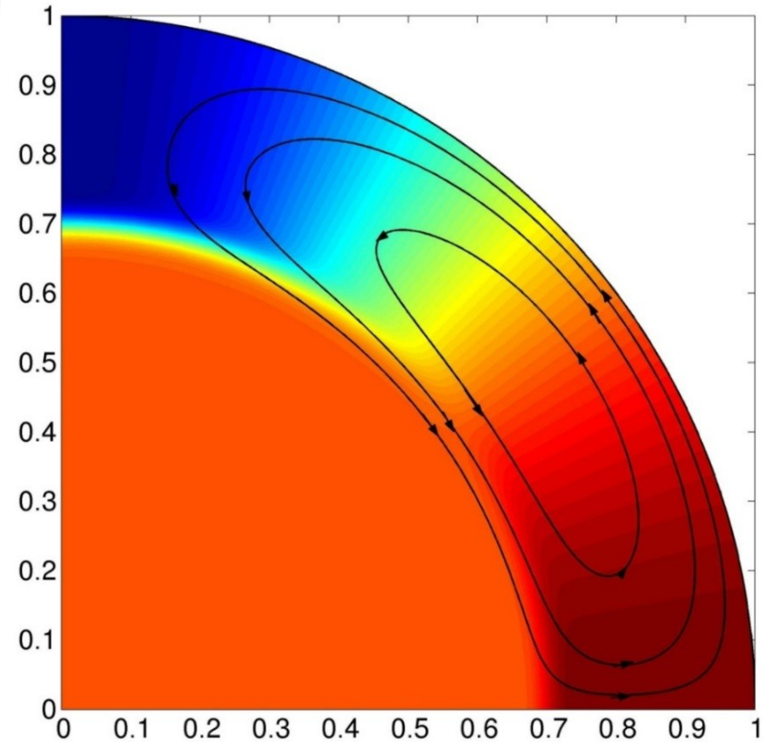




How does the solar dynamo work?

Large-scale Flows: Differential Rotation & Meridional Flow





The Sun rotates differentially:

Equator rotates faster than the polar regions

The Sun has a meridional flow:

On the surface the flow is poleward v ¼ 15 m/s

Surface flow must sink inward at poles and return to the equator at some depth

The Solar Dynamo

Flows inside the Sun are important for solar dynamo action:

A possible solar/stellar dynamo

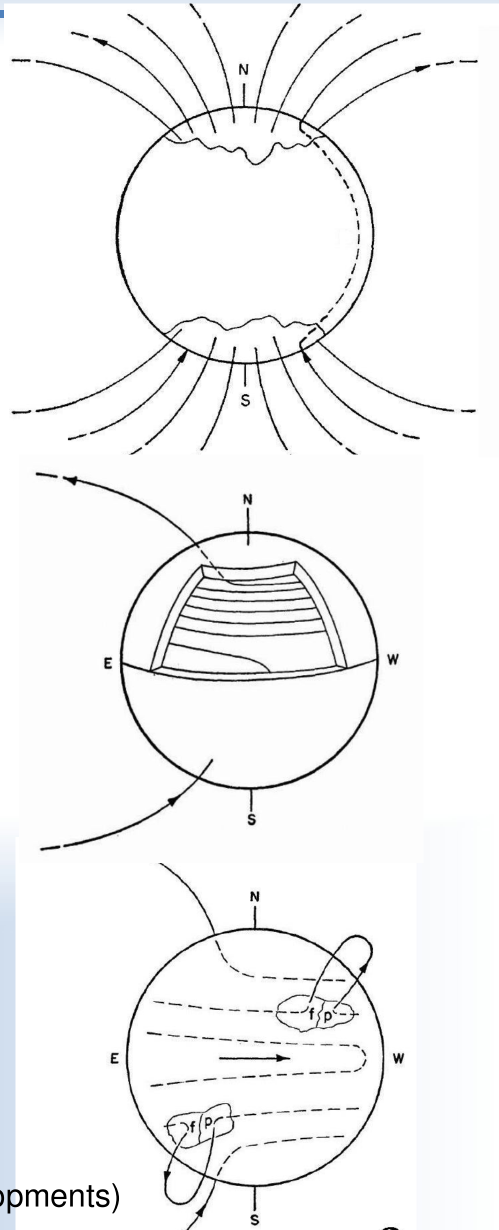
- *At cycle minimum:*
  a dipolar field threads through a shallow layer below the surface.

- *Differential rotation shears out this dipolar field*
  to produce a strong toroidal field
  (first at the mid-latitudes then progressively lower latitudes).

- *Around solar maximum:*
  Buoyant fields erupt through the photosphere forming,
  e.g. sunspots and active regions

- *The meridional flow away from the mid-latitudes*
  gives reconnection at the poles and equator.

The Sun's internal rotation
and meridional flow need to be measured

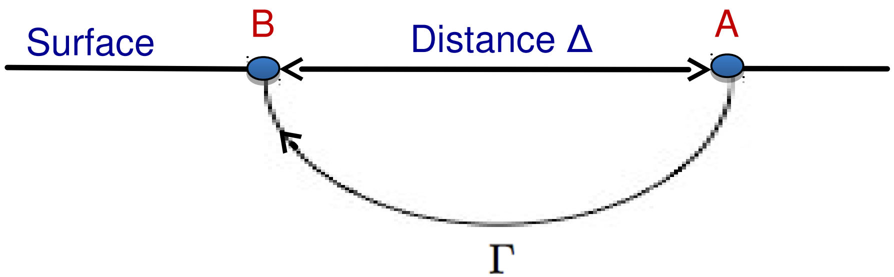


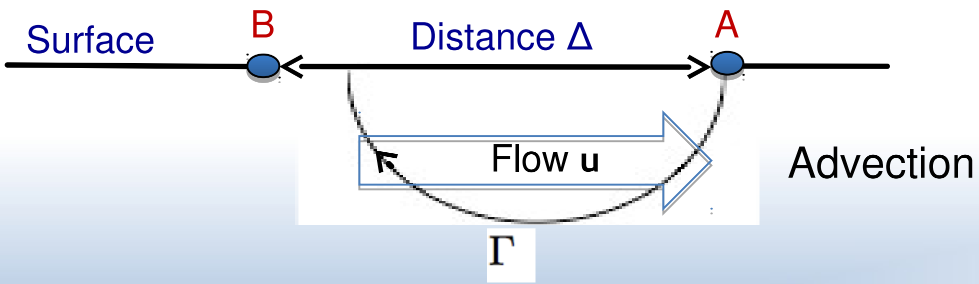
(Babcock, 1961; and later developments)

Perturbation of Waves by Flows

Equation of motion for sound waves: $$\mathcal{L}\boldsymbol{\xi}_k = -\rho_0\omega_k^2\boldsymbol{\xi}_k$$

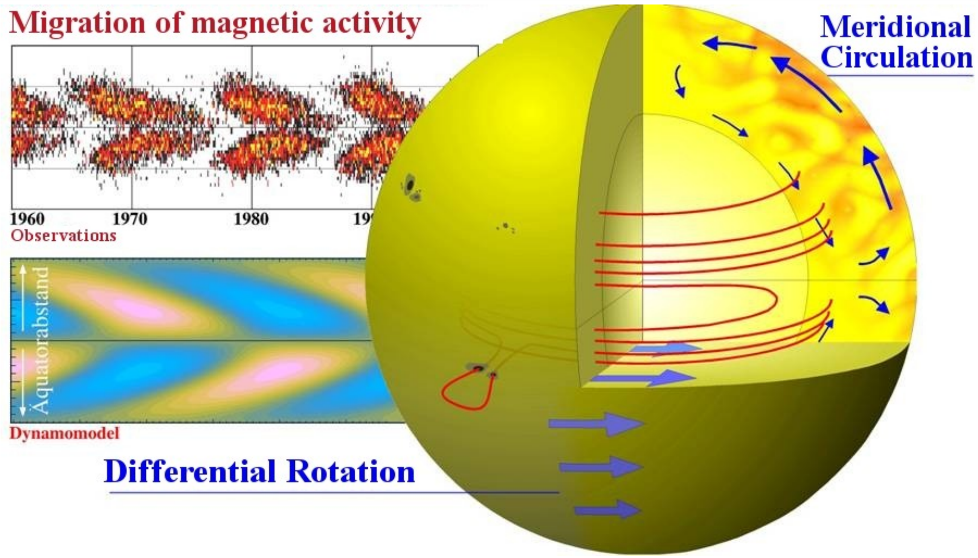
Flow induces advection of the sound wave: $$\mathcal{L}_1\boldsymbol{\xi}_k = -2\mathrm{i}\omega_k\rho_0(\mathbf{u}\cdot\nabla)\boldsymbol{\xi}_k$$





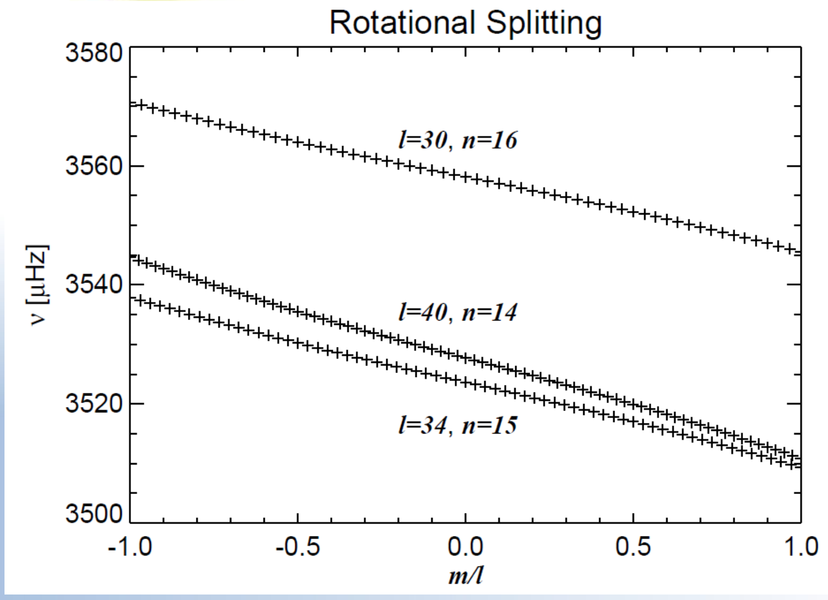
! **Perturbation of wave eigenfunction and eigenfrequency**

Global Diagnostics for Different Flow Geometries

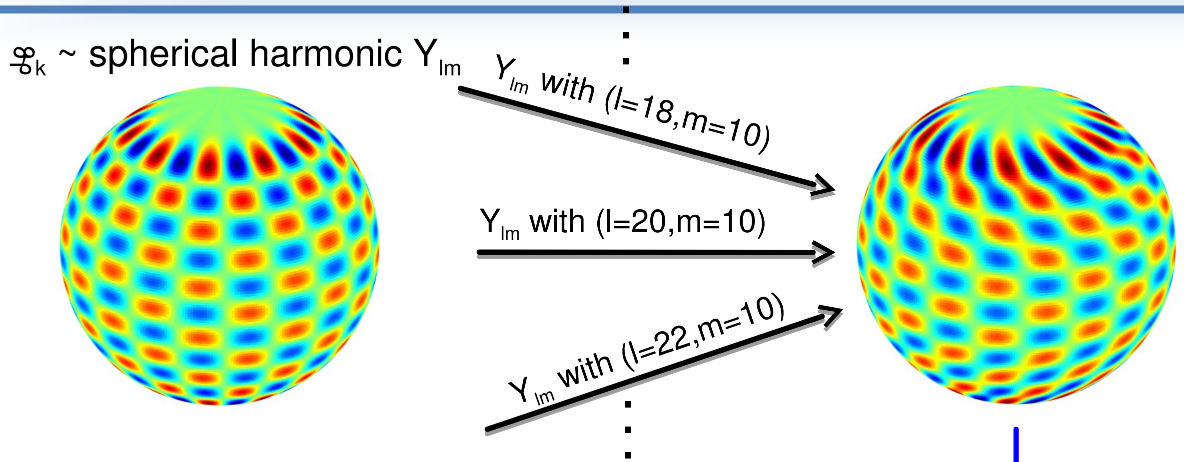


(Figure: R. Arlt)

- *Classical helioseismic approach: Toroidal axissymmetric flows (differential rotation) measured from frequency splittings*

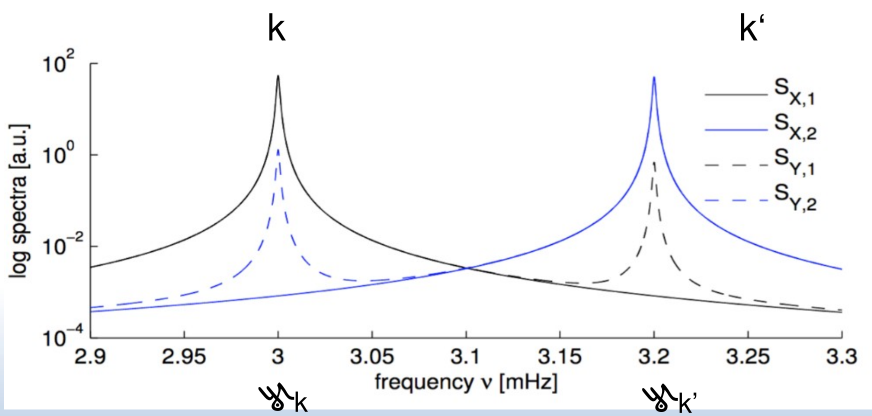


Analysis of Eigenfunction Perturbations



Wave „shape" deformation

$$\boldsymbol{\xi}_k(r,\theta,\phi) = \sum_{k' \in K_k} c_{kk'} \boldsymbol{\xi}^0_{k'}(r,\theta,\phi)\,,$$



SHT + Spectralanalysis

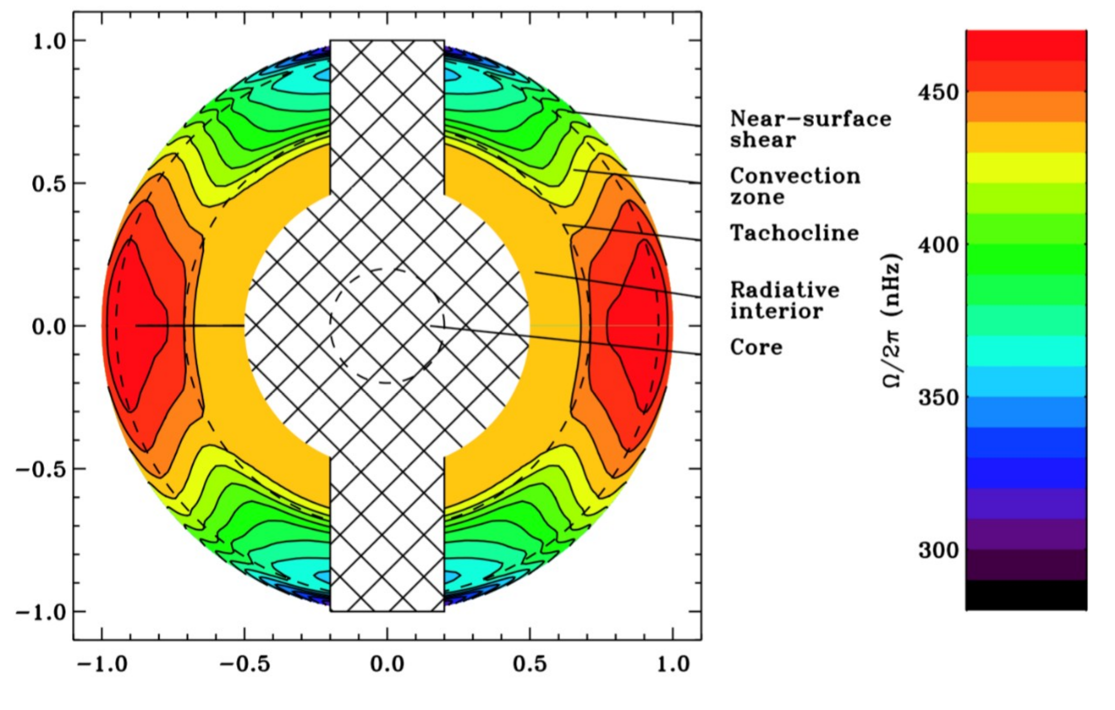
Cross-talk between SH time series of adjacent (l,m)

Cross-spectral analysis of Dopplergrams

New:
Toroidal & Poloidal flows to be measured by measuring eigenfunction perturbations

Rotation in the Solar Interior

Long-term North-South average derived from 12 years of SoHO/MDI observations of “frequency splittings” (Howe 2009):



Below the surface:
Extended area of fast rotation

Depth: ca. 200.000 km
Width: ca. 500.000 km

Red areas move faster than the blue areas by approximately 2000 km/h

Indication for solid body rotation in the core
Shear layer at the bottom of the convection zone is important for generation of toroidal magnetic field

Higher latitudes & deep interior?

Solar Rotation & Zonal Flows – Temporal Evolution

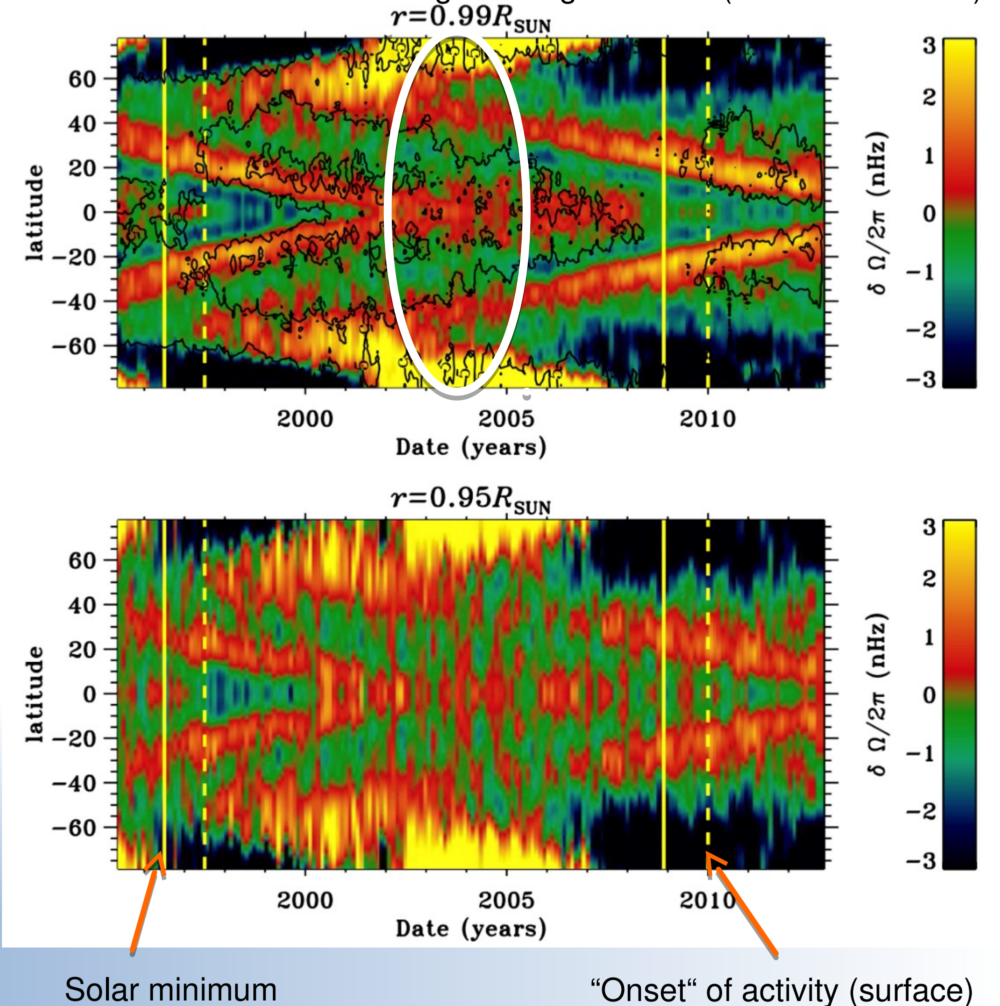
Torsional oscillations

•Temporal variations around mean rotation - equator/poleward propagating branches
•1% of mean rotation
•Extends to the bottom of the convection zone
(e.g. Vorontsov et al. 2002)

Precursor for upcoming surface activity?
(Howe et al. 2011, 2013,
Komm et al. 2014)

Connection to merdional flow?

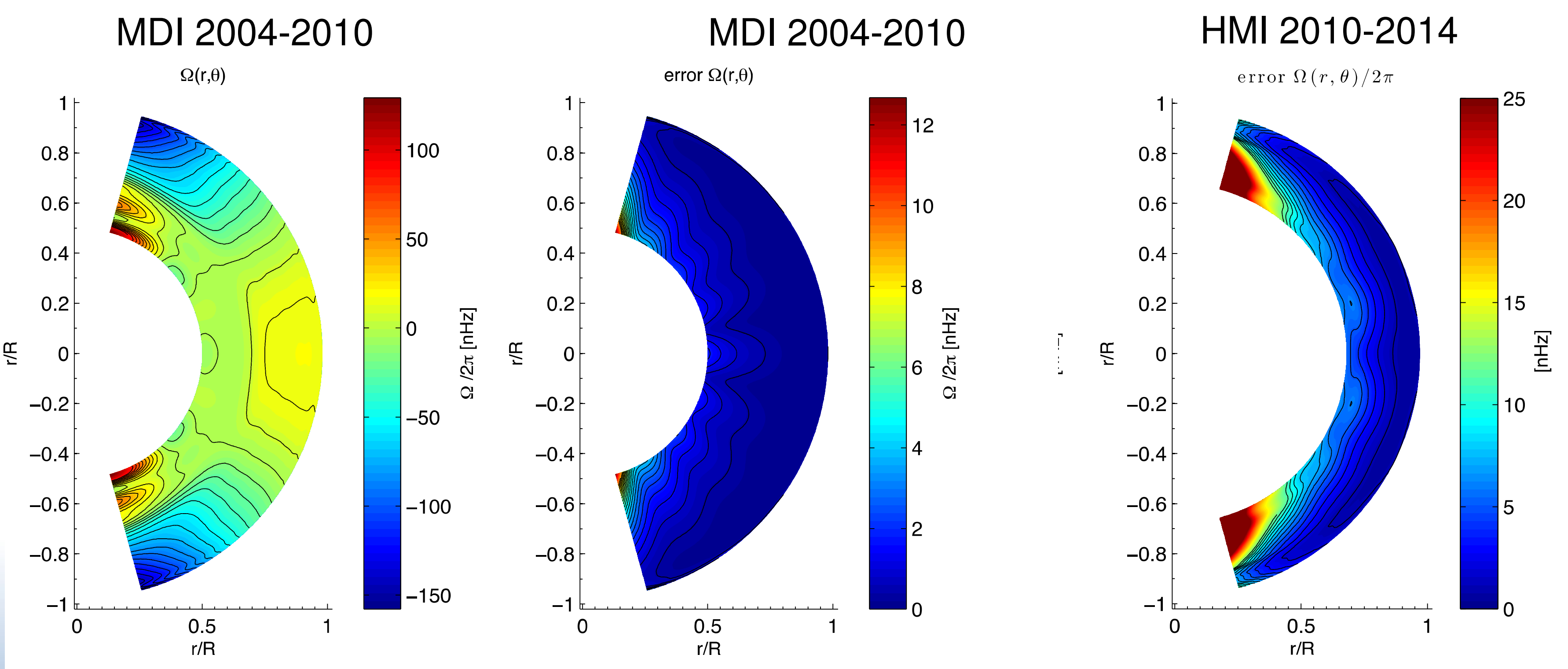
Flow residuals + unsigned magnetic field (Howe et al. 2013)



Differential Rotation from Eigenfunction Perturbations

$$\Omega(r,\theta) r \sin\theta = -\sum_s w_s(r) \partial_\theta Y_s^0(\theta,\phi)$$

inversion of splitting coeff. for w_3-w_9

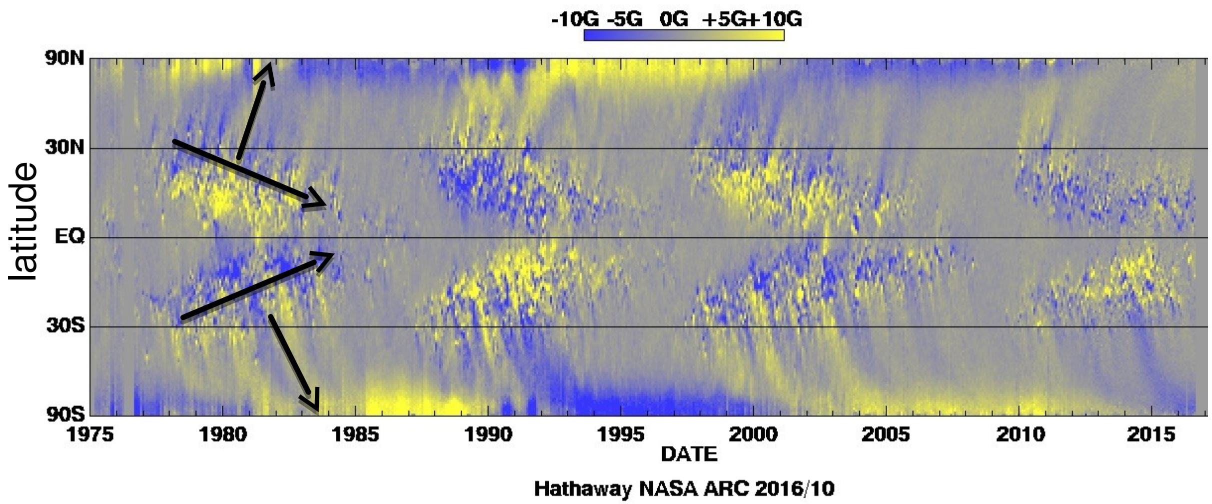


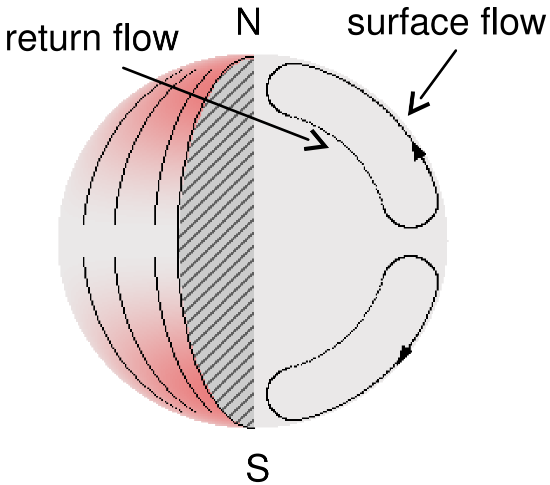
- Sensitive to **antisymmetric rotation rate component** (“frequency splittings“ are not!)
- Interesting for zonal flow studies in depth

(Schad & Roth., in prep.)

The Solar Meridional Flow

Magnetic butterfly diagram





(Figure: Hathaway, NASA)

- Essential element of **flux transport dynamo models** (Wang & Sheeley 1991, Choudhuri et al. 1995, Dikpati & Schüssler 1999,...)
- Location & amplitude of return flow determines timing and strength of solar activity cycle (Hathaway et al. 2003, Dikpati et al. 2004,...)

- **Where is the return flow?**

➢ Measurement of the flow profile in depth helps to constrain models/simulations of dynamo & convection zone (Dikpati et al. 2006, Miesch et al. 2012,...)

Meridional flow measurements from tracking of supergranules

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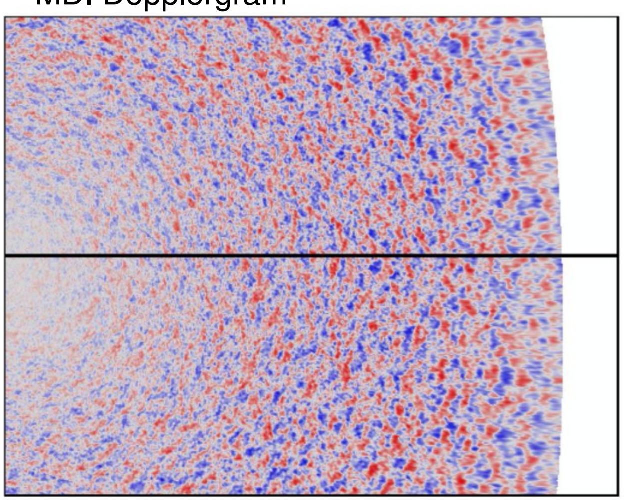
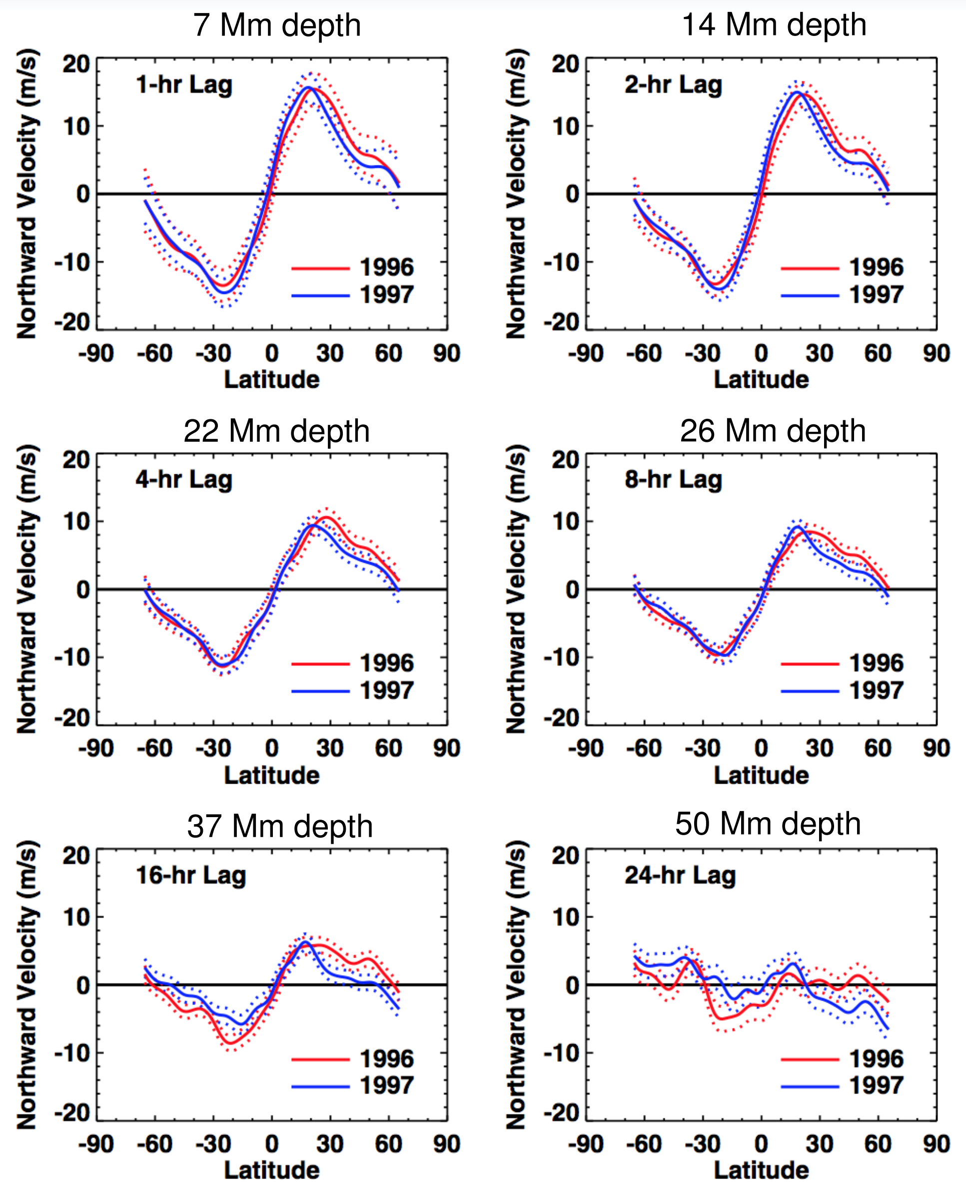
Hathaway 2012:
•MDI 60d in1996,1997
•assuming supergranules anchored in a depth equal to their width

> Shallow poleward flow –
weak return flow below 50Mm (~0.93R)

MDI Dopplergram





Time-Distance Helioseismology of Meridional Flow

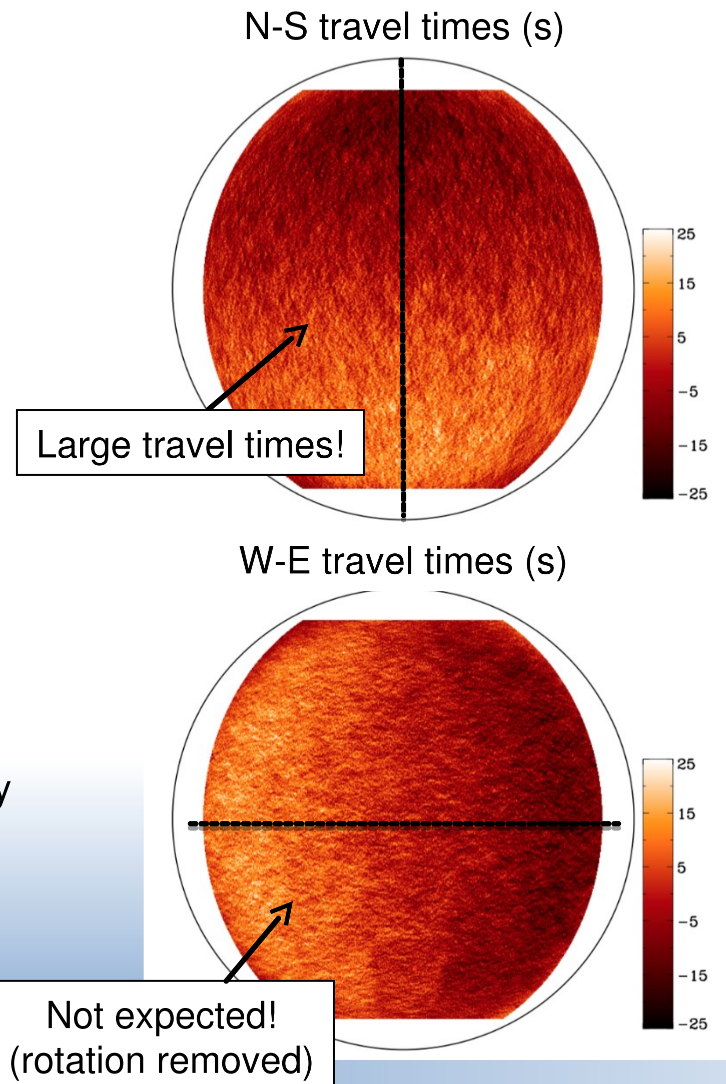
Solar Orbiter SAP#4 Meeting Göttingen

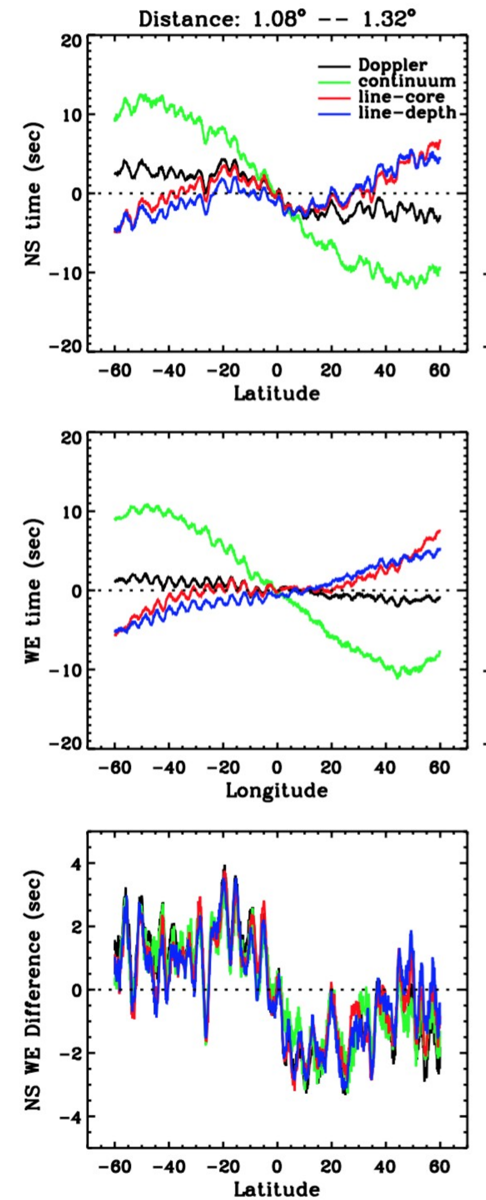
- Finding: travel times suspiciously large - increase with “depth”
- Dependency on observation quantity
- Systematic effect mimics a radial outflow from center toward limb
- Effect much stronger than signal (flow ~1s)!
- **Origin unknown**

Currently: Empirical correction

Possible Explanation

Baldner & Schou (2012): Effect partly due to interaction of waves with asymmetric, convective motions near surface + formation height variation





(Zhao et al. 2012)

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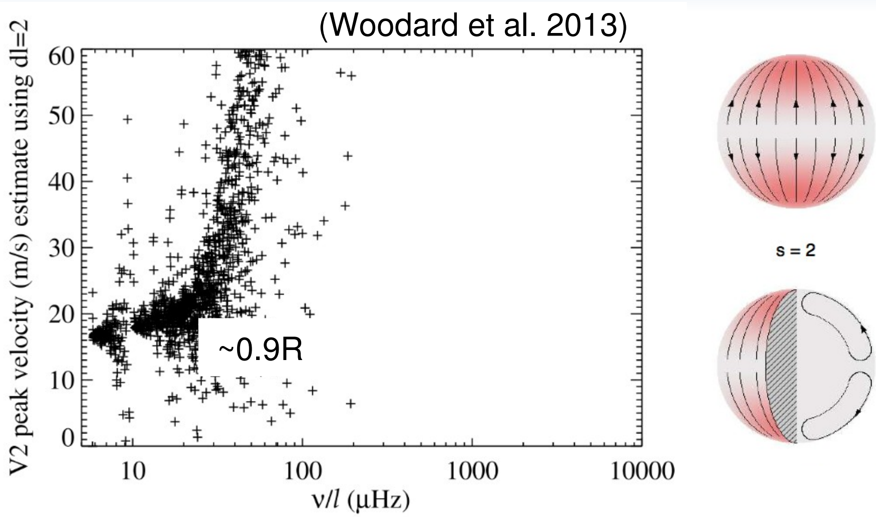
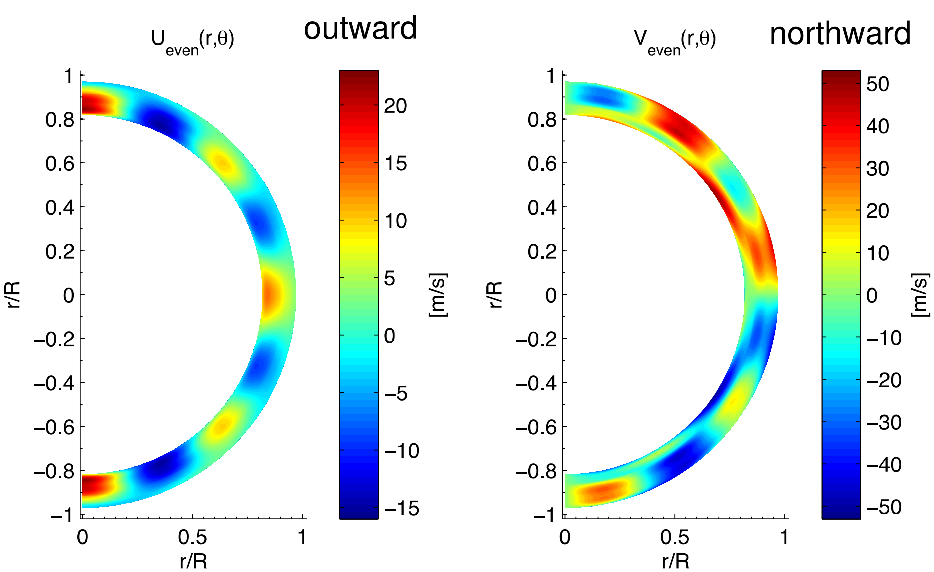
Mode eigenfunction perturbation analysis - results



Woodard et al. 2013:

- Early HMI data, 500d
- Fitting of cross-spectra, model incorporates rotation and meridional flow
- Suspicious increase of horizontal peak velocities V below 0.9R

Authors assume systematic effect distorting the phase of mode eigenfunction



(Schad et al. 2013)

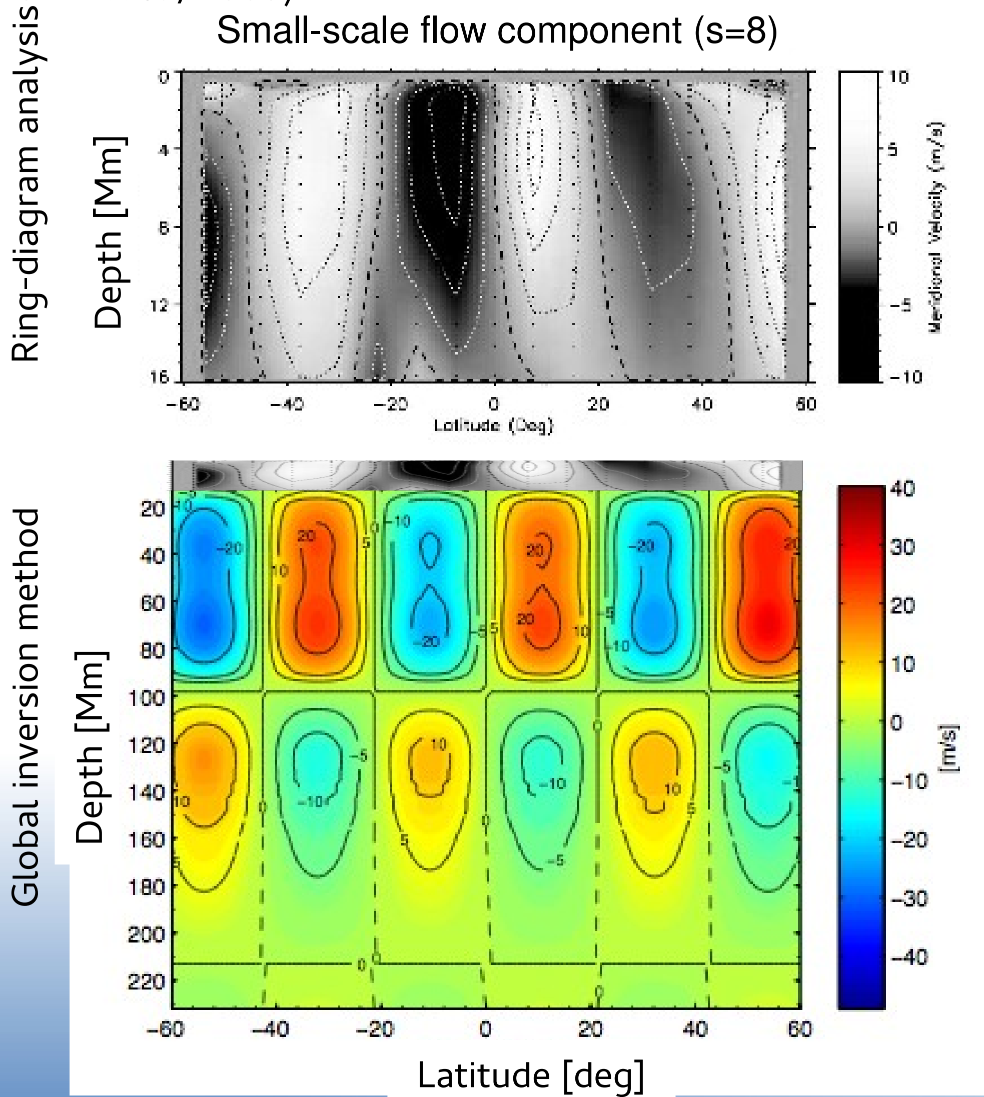
Schad, Timmer, Roth: 2013:

- MDI data 2004-2010
- s=1,...,8
- Shown is a composite of even s

Complex flow pattern in latitude & depth dominated by s=2 (20 – 125 Mm depth) and s=8 (13 – 188 Mm depth) component

Comparison with local helioseismology measurements

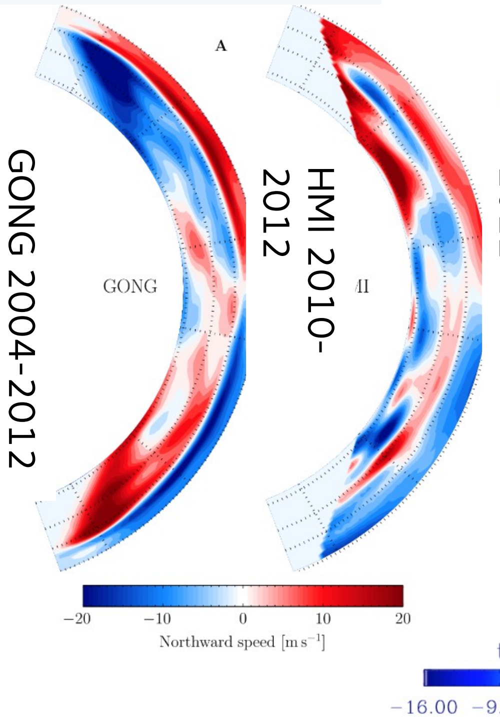
(Komm et al., 2005)



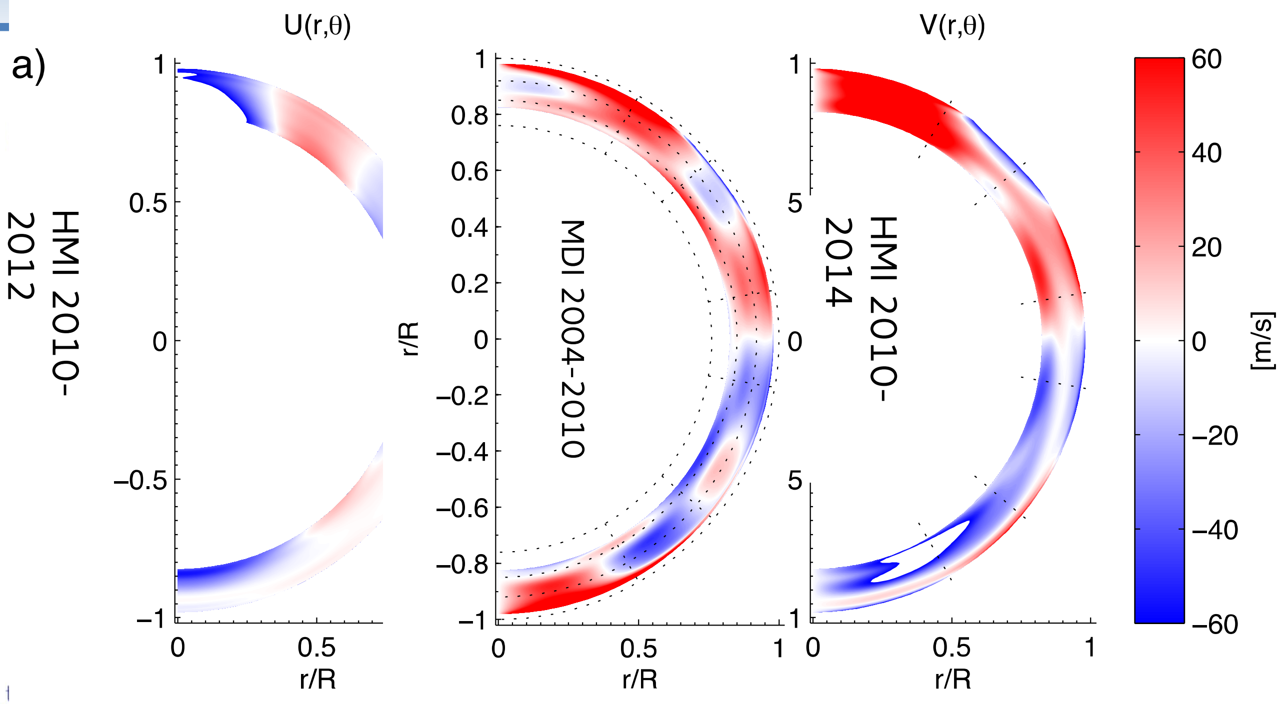
- Ring-diagram analysis by Komm et al. 2005 (0.6 – 16 Mm) agrees with deep meridional flow measurements
- Small-scale component reaches down to the base of CZ (200Mm)

(Schad, Timmer, Roth, 2013)

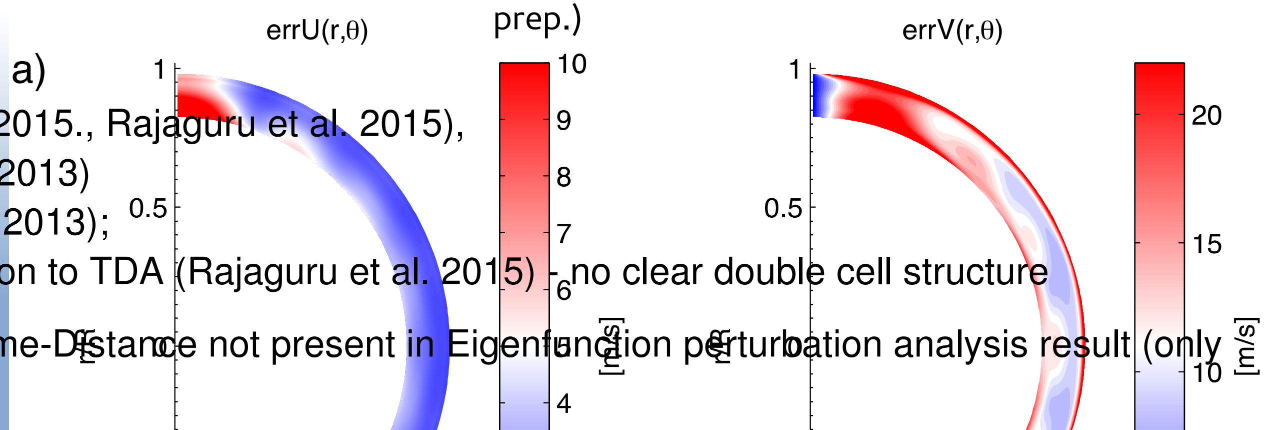
Comparison of TDA and EFPA flow measurements



(Jackiewicz et al. 2015; Zhao et al. 2(2015)



(Schad et al. 2013; Schad & Roth 2016 in prep.)

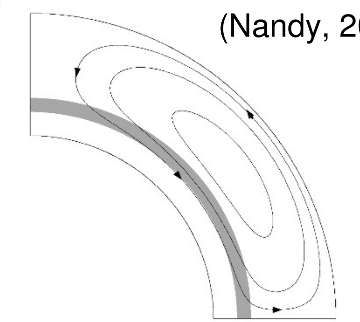


Various Results:

•**Single cell** (Jackiewicz et al 2015., Rajaguru et al. 2015),
Double-cell flow (Zhao et al. 2013)
Multiple "cells" (Schad et al. 2013);
incorporating mass conservation to TDA (Rajaguru et al. 2015) - no clear double cell structure

•Flow reversal at 0.93 R by Time-Distance not present in Eigenfunction perturbation analysis result (only weakening)

Consequences of Helioseismic Results on Dynamo Models

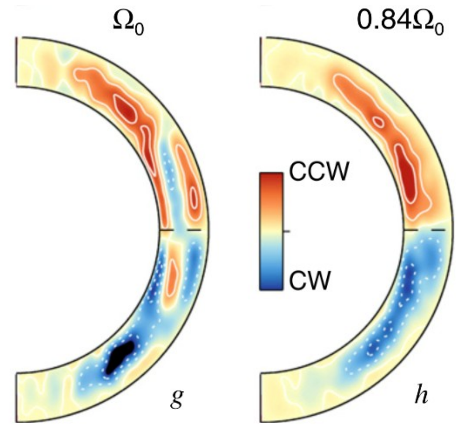


(Nandy, 2004)

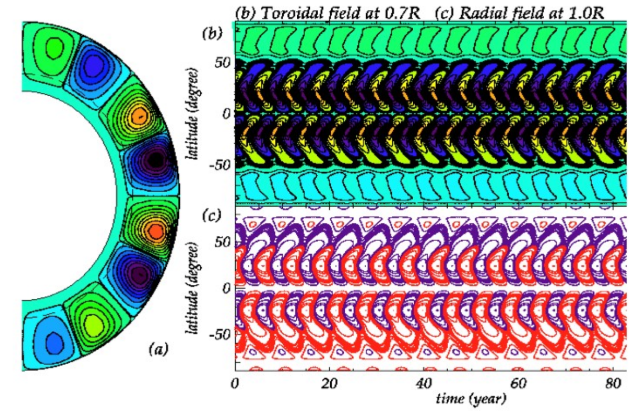
- Helioseismic results with multiple cells (depth, latitude) have inspired new dynamo simulations
  (e.g. Hazra et al. 2014, Belucz et al., 2015)

- Multiple cells produce solar-like dynamos given there is an equatorward flow near BCZ
  (Jouve et al. 2007, Hazra et al. 2014, Choudhuri 2015, Passos et al. 2016)

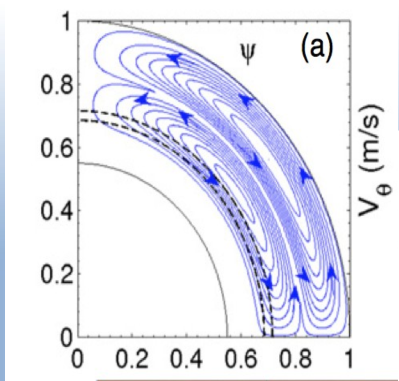
- HD convection simulations – Sun at transition from single to multiple meridional flow cells with anti-solar (poles faster) to solar rotation (poles slower) profile
  (e.g., Featherstone et al., 2015)

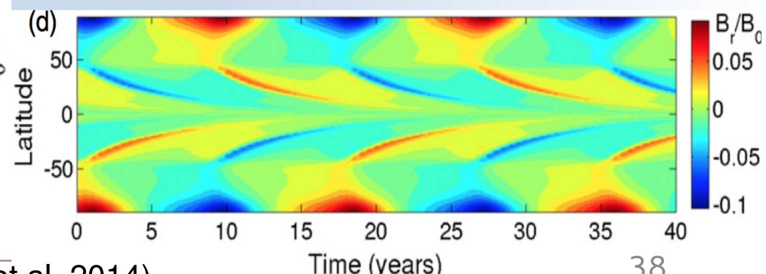


(Featherstone et al. 2015)



(Belucz et al., 2015)



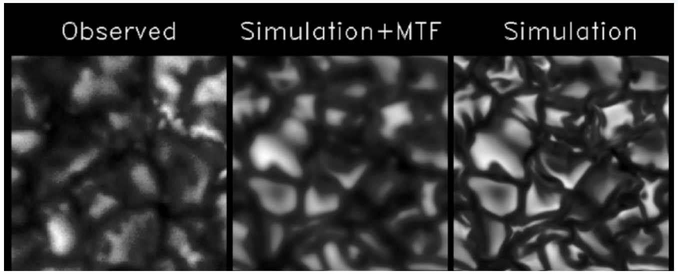


(Hazra et al. 2014)

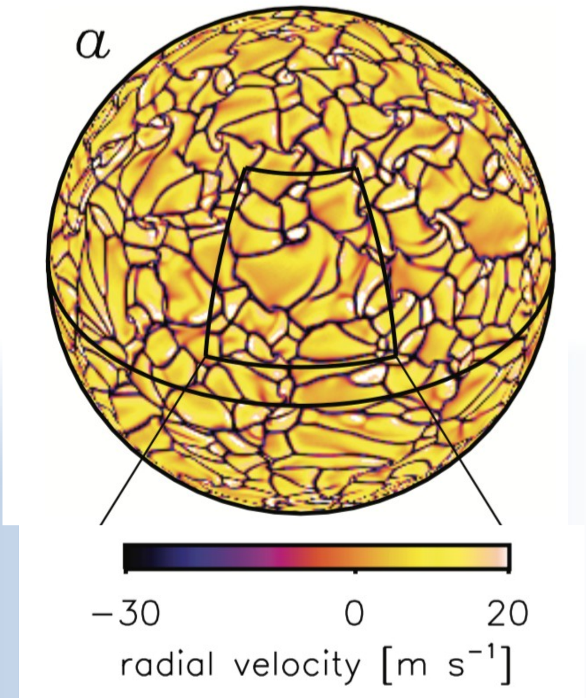
Convection

- Participates in redistribution of angular momentum
  ? differential rotation
- Generation & amplification/weakening of magnetic fields

- Observations near surface
  - **Granulation** ø~1000 km, lifetime ~10 min
  - **Supergranulation** ø~35,000 km, lifetime ~24 h
- **Theoretical insights:**
  sophisticated 3D simulations, e.g., Stein & Nordlund 1998, Rempel et al. 2009, Brun et al. 2004, Miesch et al. 2008,...
- Probing the deep convection is a challenge for helioseismology (low SNR, averaging effects)



(Stein & Nordlund 1998)



(Miesch et al 2008)

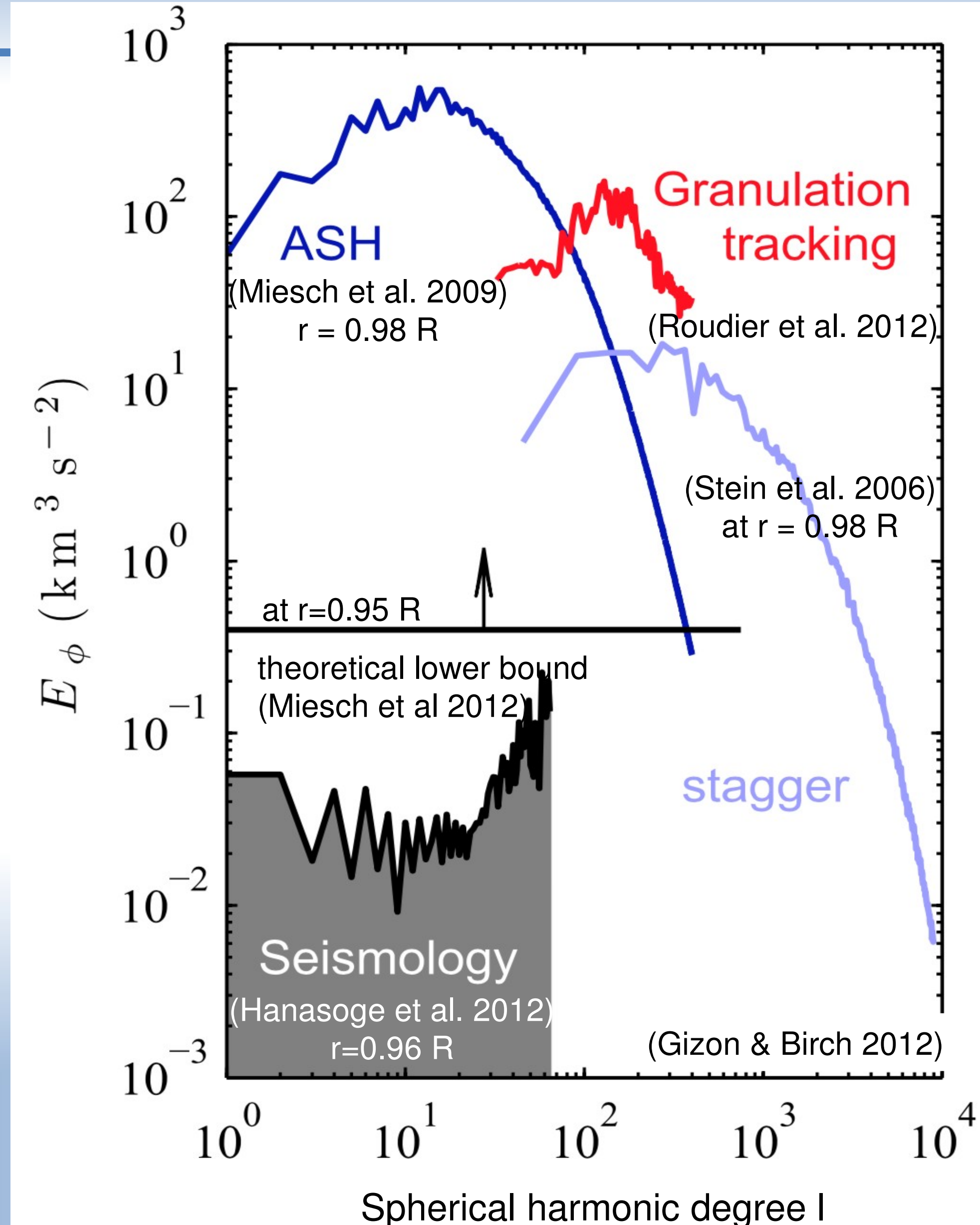
Open Questions:

- How reliable are simulations?
- Energy spectrum, maximum velocity amplitudes, spatial profile?

Convective Kinetic Energy Spectrum

Upper bounds for longitudinal velocities v_ϕ (kinetic energy E_ϕ)

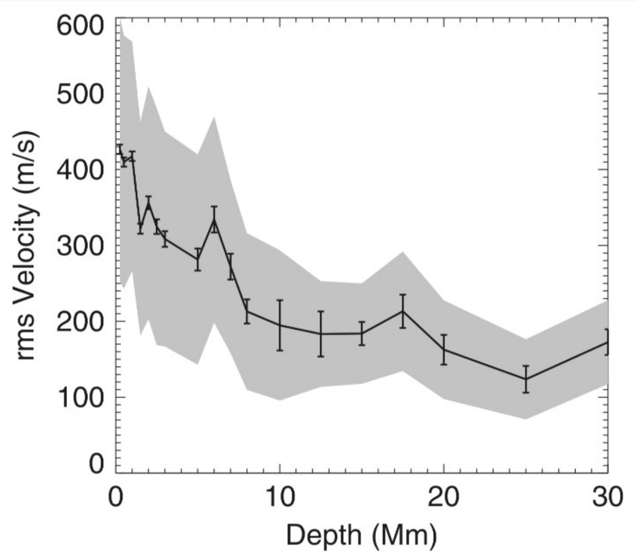
•**Hanasoge et al. 2012:** Time-distance analysis,
Miesch et al 2012: theoretical lower limit (scaling arguments); at r=0.95 R ampltiude ≥ 30m/s needed to sustain mean flows
•**Miesch et al. 2009**: 3D simulation
•**Roudier et al 2012:** Granulation tracking



Time-distance result is orders of magnitude below theory & simulations!

Current modeling of large-scale convection in the Sun is incomplete (Hanasoge 2016)?

Convective Kinetic Energy Spectrum

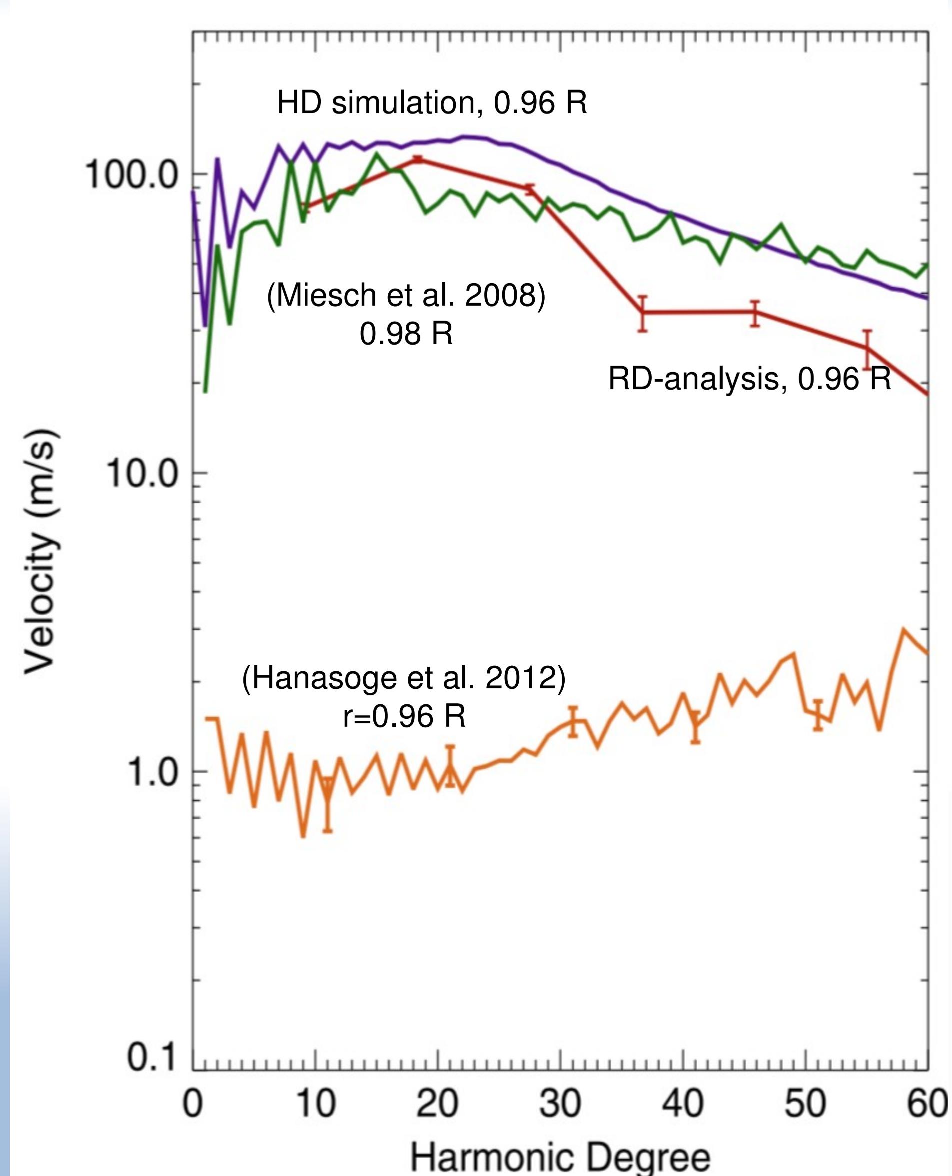


Greer et al. 2015:

improved ring-diagram analysis method,

inversion up to 30 Mm depth (0.96R)

- Convective flow > 120 m/s
- Ring-diagram inversion in agreement with simulations!
- TD result affected by averaging effects?

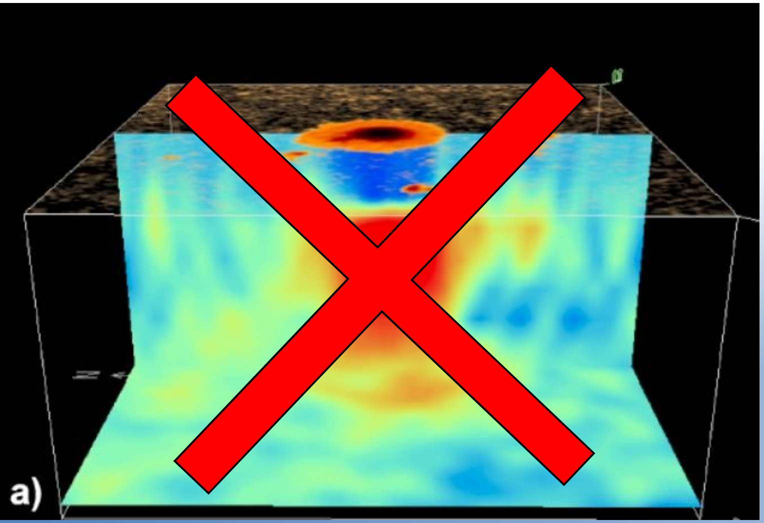


Helioseismology of Sunspots

Former helioseismic results of subsurface structure of sunspots are incorrect

Reason: strong interaction of seismic waves with magnetic field

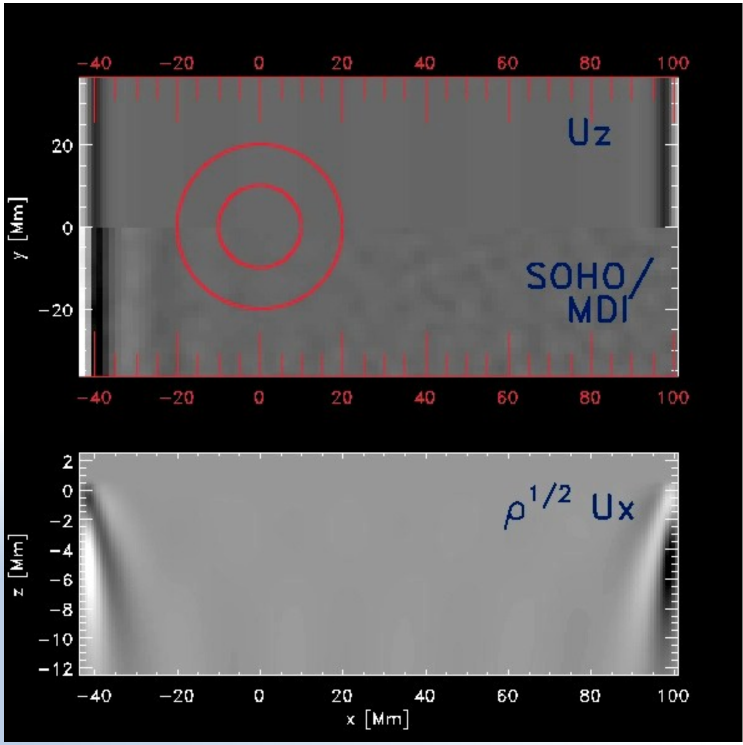
New approach:
Forward modelling and comparison with observations



Model sunspot

Helioseismic observations

Vertical cut

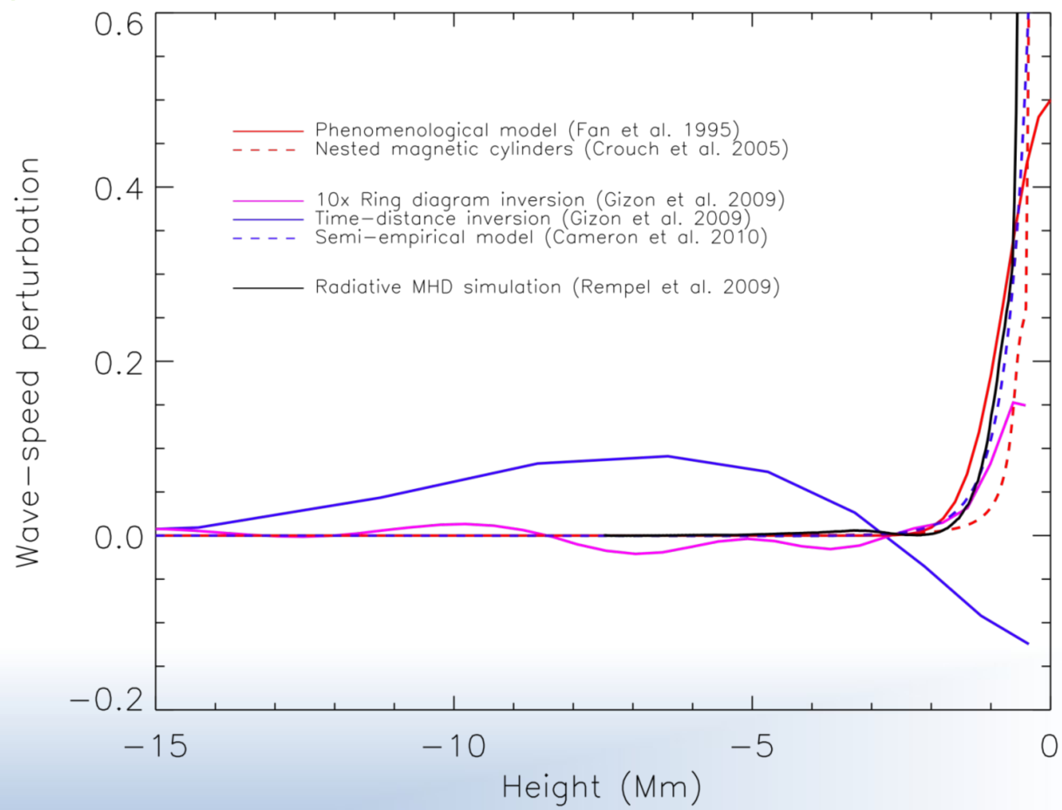


(Cameron, Gizon, Duvall, 2008)

Ring-Diagramm-Analysis vs. Time-Distance-Helioseismology: Structure of a Sunspot

Comparison of helioseismic methods and theoretical models

- *Agreement of several curves, indicating a positive perturbation of the wave speed down to 2 Mm depth*
- *Time–Distance:* *at great depths strong perturbation of the wave speed*
- *Problem:*
  - **Linearization?** sunspot affects p-Modes strongly
  - **Filtering in Time–Distance Helioseismology?**
- *Solution:*
  - Forward modelling
  - a "shallow" sunspot model reproduces actual observations very closely (Cameron et al., 2009)

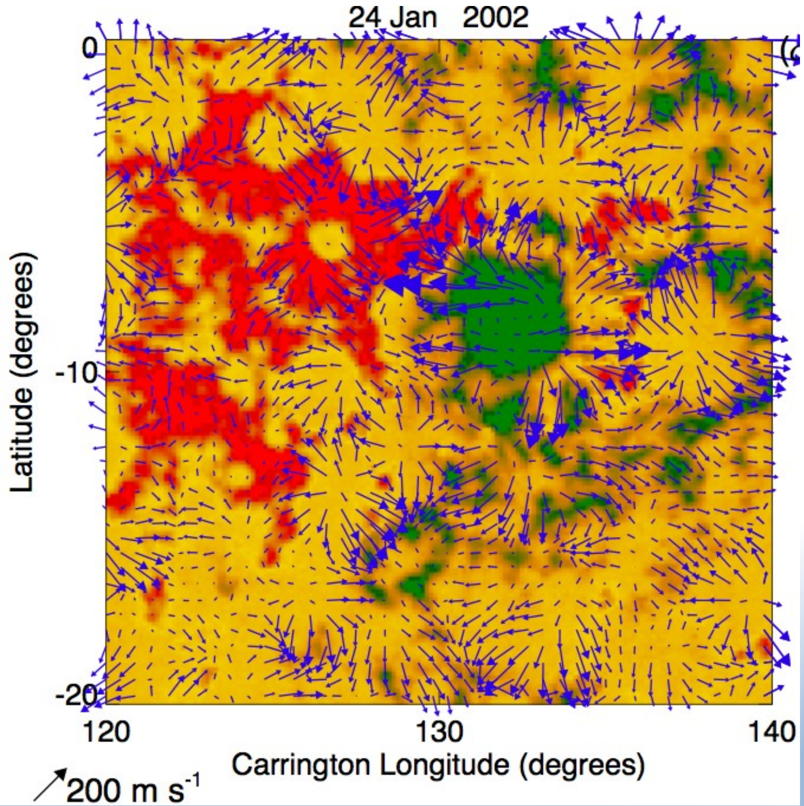


(Gizon et al., 2009

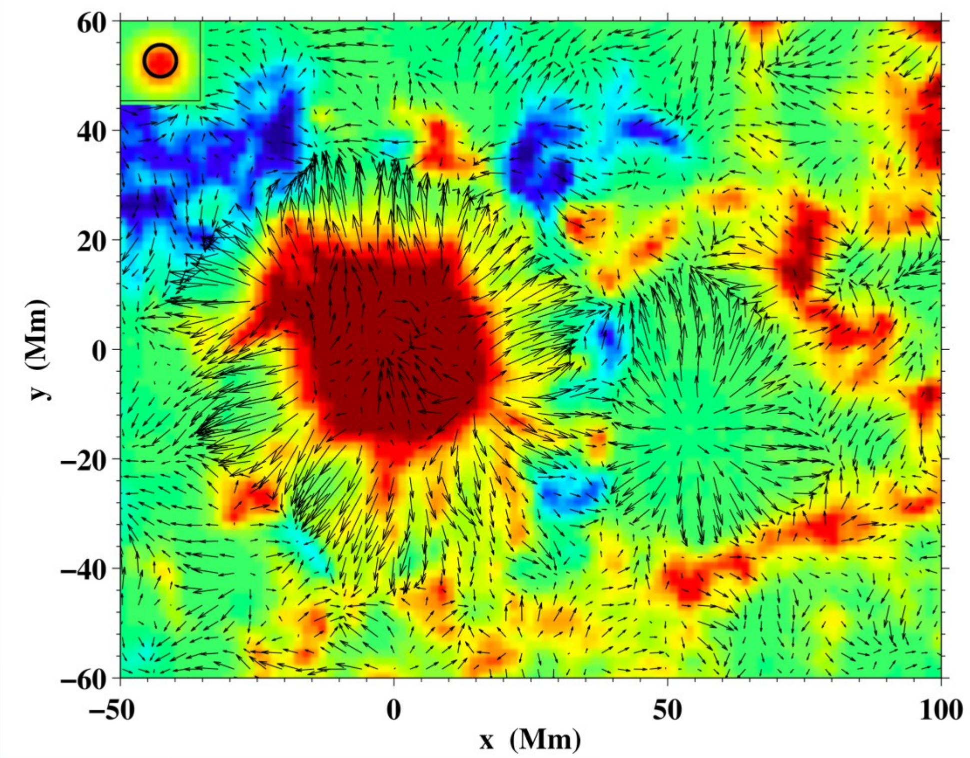
Ring-Diagramm-Analysis vs. Time-Distance-Helioseismology: Flows around Active Regions

Good agreement for both methods in measuring flows:
moat flow, outflow in supergranulation, ...

Ring-Diagramm-Analysis



Time-Distance-Helioseismology
(with ridge filter)

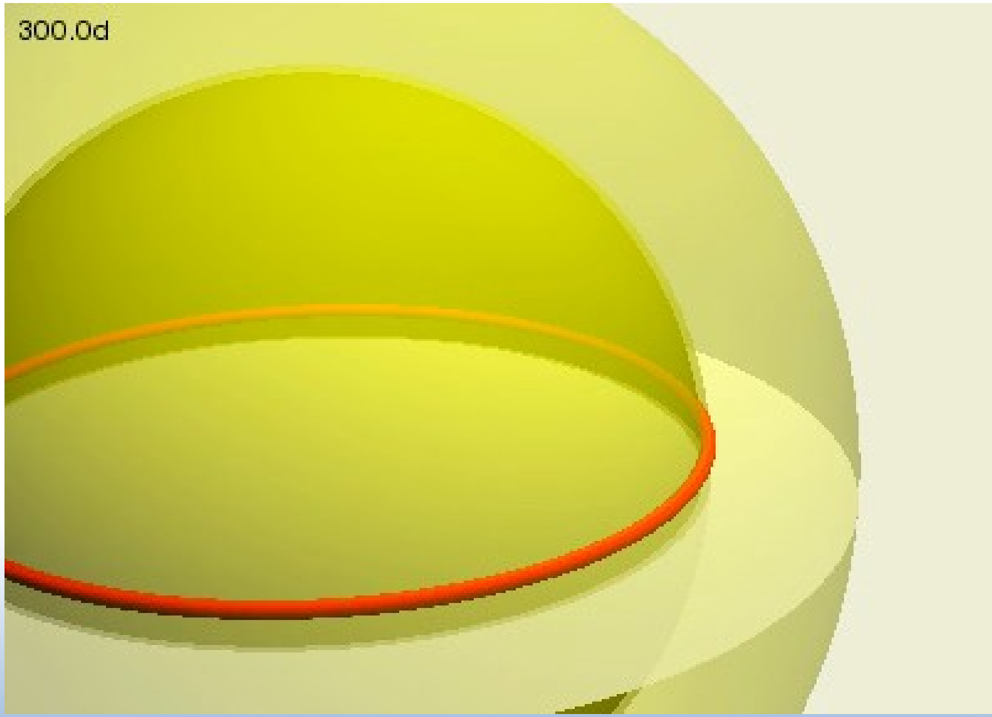


(Moradi et al., 2009)

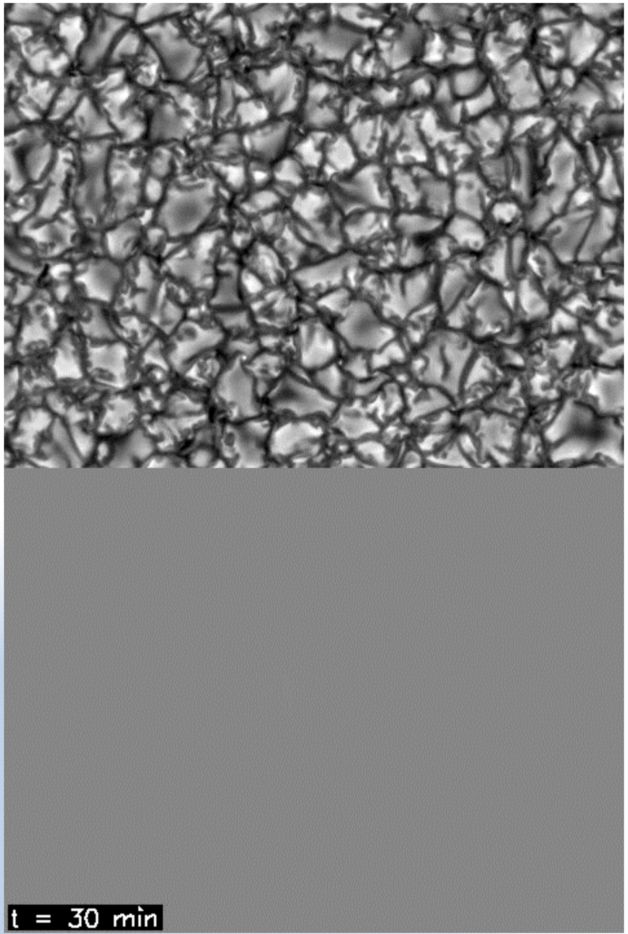
Origin of Activity: Rise of Magnetic Flux

Comparing simulations and helioseismic observations will greatly improve our understanding of the dynamo.

Rise of magnetic flux rope



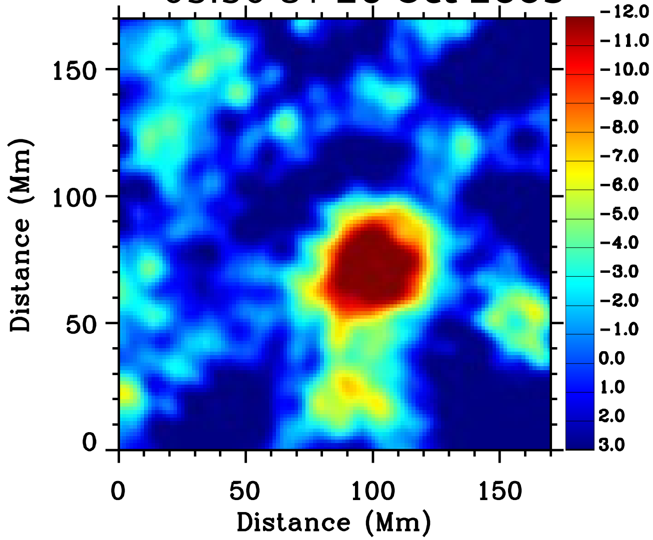
Emergence through the surface



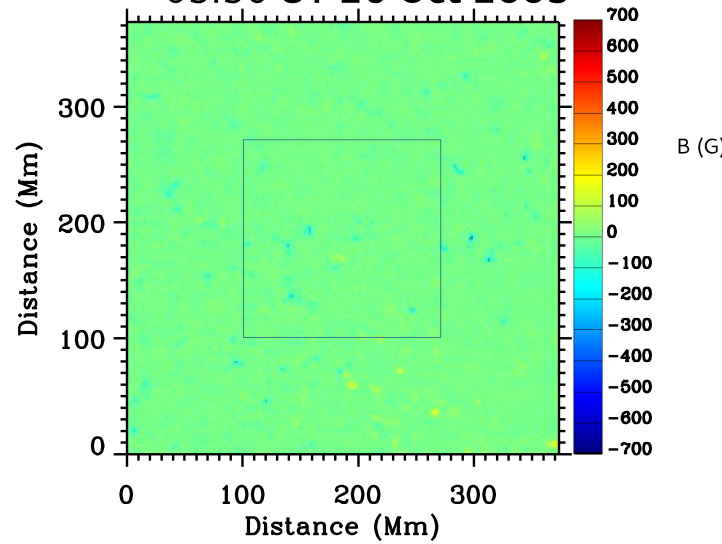
(Cheung et al. 2008)

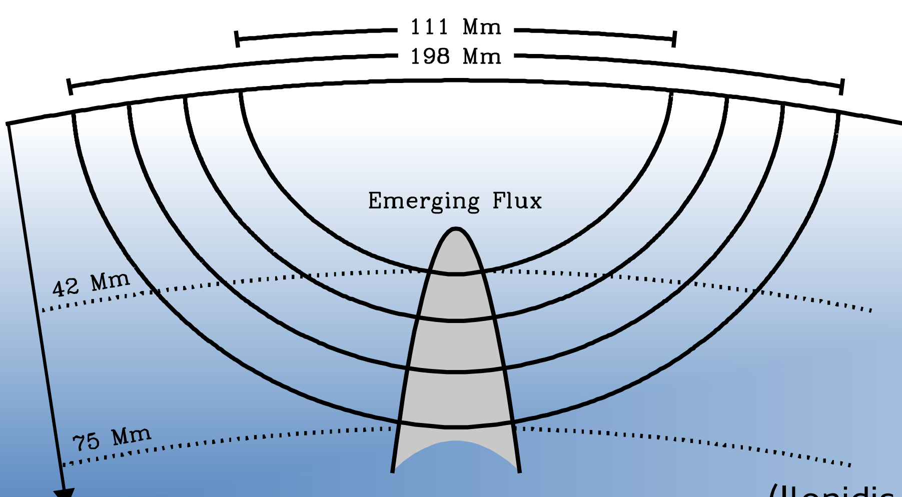
Emergence of Magnetic Flux: AR 10488

Wave travel time anomaly
03:30 UT **26 Oct 2003**

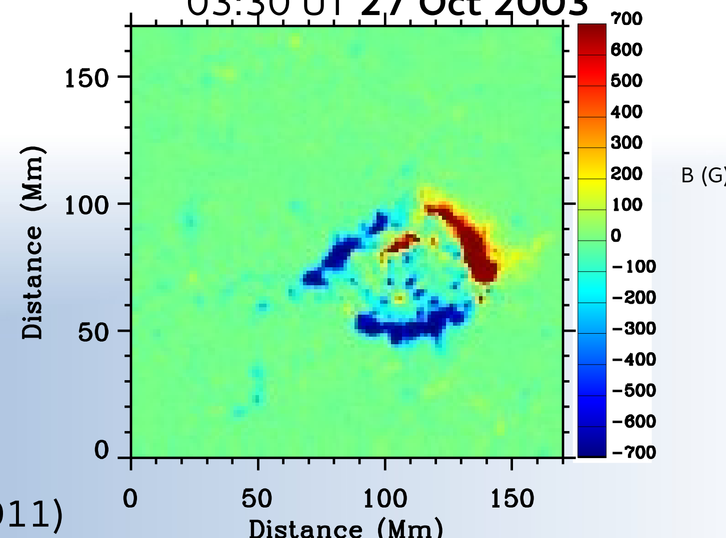


Magnetogram
03:30 **UT 26 Oct 2003**





03:30 UT **27 Oct 2003**



(Ilonidis et al., 2011)

Emergence of Magnetic Flux

- *Anomalies appear at the surface 1–2 days after their detection*
  □ Important for Space Weather applications?

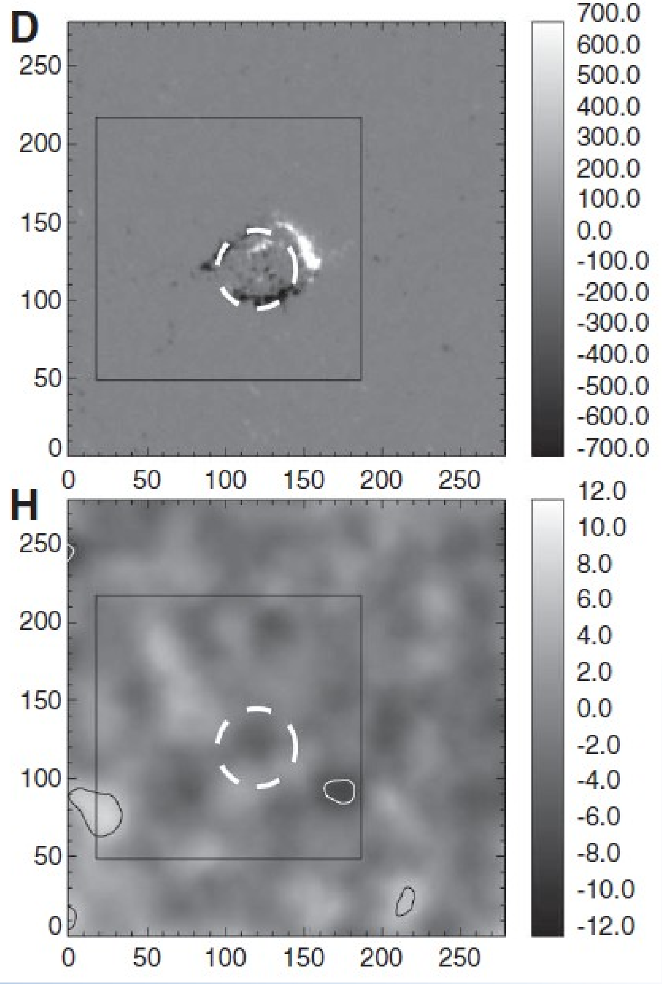
- *Average emergence speed:*
  0.6 and 0.3 km/s for the strongest and weakest analyzed events respectively.

- *Detected sub–surface structures are mostly circular with a typical size of 30–50 Mm*
  - Limitation: horizontal wavelength is ~35 Mm at 3.5 mHz

- ***Question:***
  - What causes the travel time perturbation of up to 12s?
  - Signal should be small (105 emerging active regions studied by Schunker et al. 2016)
  - Why not seen by Braun et al. 2012?

Results reported by Braun with helioseismic holography

03:00 UT **26 Oct 2003**



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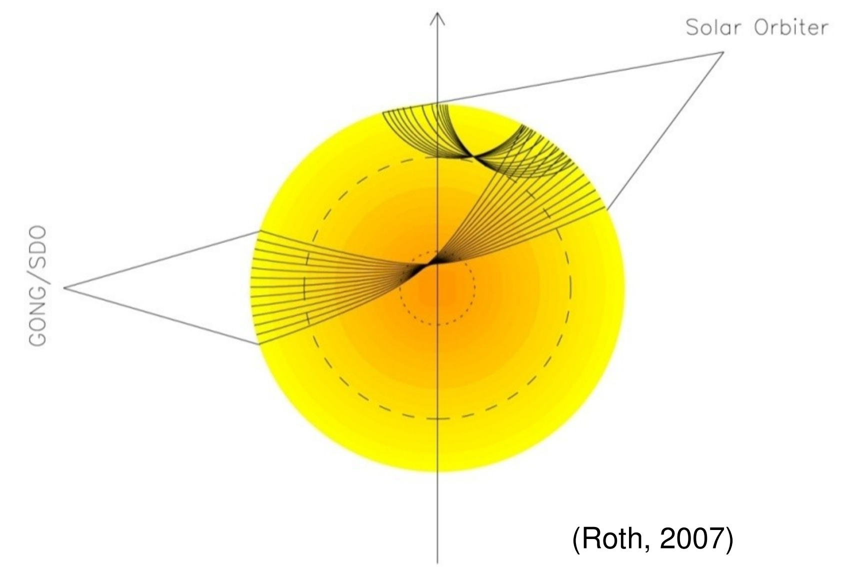
Open Question in Helioseismology

- *Functioning of the solar dynamo*
  - Structure of the tachocline
  - Sub-surface shear layer
- *Structure and temporal evolution of large–scale flows on the whole Sun*
  - Differential rotation & meridional Flows
  - Giant Cells
- *Sub–surface structure and evolution of active regions*
  - Currently the holy grail
- *Deep Solar Interior*
  - Rotation & magnetic field in the solar core

Solar Orbiter - Expectations

- *End of 24th and start of 25th cycle to be covered by helioseismic observations*
  - Changes in the internal dynamics between cylces
- *Seeing backside and higher latitudes*
  - Improvement in combined helioseismic data (back+front)
  - Large- and small-scale flow patterns at poles
- *Probing of the deep solar interior*
  - Improvement of meridional flow measurements
  - Systematic changes in the tachocline region?
  - Surprises in the deep interior?
- *Magnetoseismology / Atmospheric Seismology*
  - Sunspot seismology
  - Prediction of appearance of active regions
  - Space weather applications



(Roth, 2007)

Solar Orbiter Science Questions

Central Science Goal:
How does the Sun create and control the heliosphere?

- *How and where do the solar wind plasma and magnetic field originate in the corona?*
- *How do solar transients drive heliospheric variability?*
- *How do solar eruptions produce the energetic particle radiation that fills the heliosphere?*
- ***How does the solar dynamo work and drive the connections between the Sun and the heliosphere?***

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Solar Orbiter Instruments

Combination of remote-sensing and in-situ measurements

Field Package:
Radio and Plasma Waves Instrument (RPW) & Magnetometer (MAG).

Particle Package:
Energetic Particle Detector (EPD) & Solar Wind Plasma Analyzer (SWA).

Solar remote sensing instrumentation:
Polarimetric and Helioseismic Imager (PHI)
Extreme Ultraviolet Imager (EUI)
Multi Element Telescope for Imaging and Spectroscopy (METIS), Solar Orbiter Heliospheric Imager (SoloHI)
Spectral Imaging of the Coronal Environment (SPICE) Spectrometer/Telescope for Imaging X-Rays (STIX).

Solar Orbiter – Helioseismology Objectives

4.1 How is magnetic flux transported to and re-processed at high solar latitudes?

- Study the detailed solar surface flow patterns in the polar regions, including coronal hole boundaries.
- Study the subtle cancellation effects that lead to the reversal of the dominant polarity at the poles
- Explore the transport processes of magnetic flux from the activity belts towards the poles and the interaction of this flux with the already present polar magnetic field.
- Study the influence of cancellations at all heights in the atmosphere.

4.2 What are the properties of the magnetic field at high solar latitudes?

- Probability density function (PDF) of solar high-latitude magnetic field structures.
- Basic properties of solar high-latitude magnetic field structures.
- Probe the structure in deep layers of the Sun.

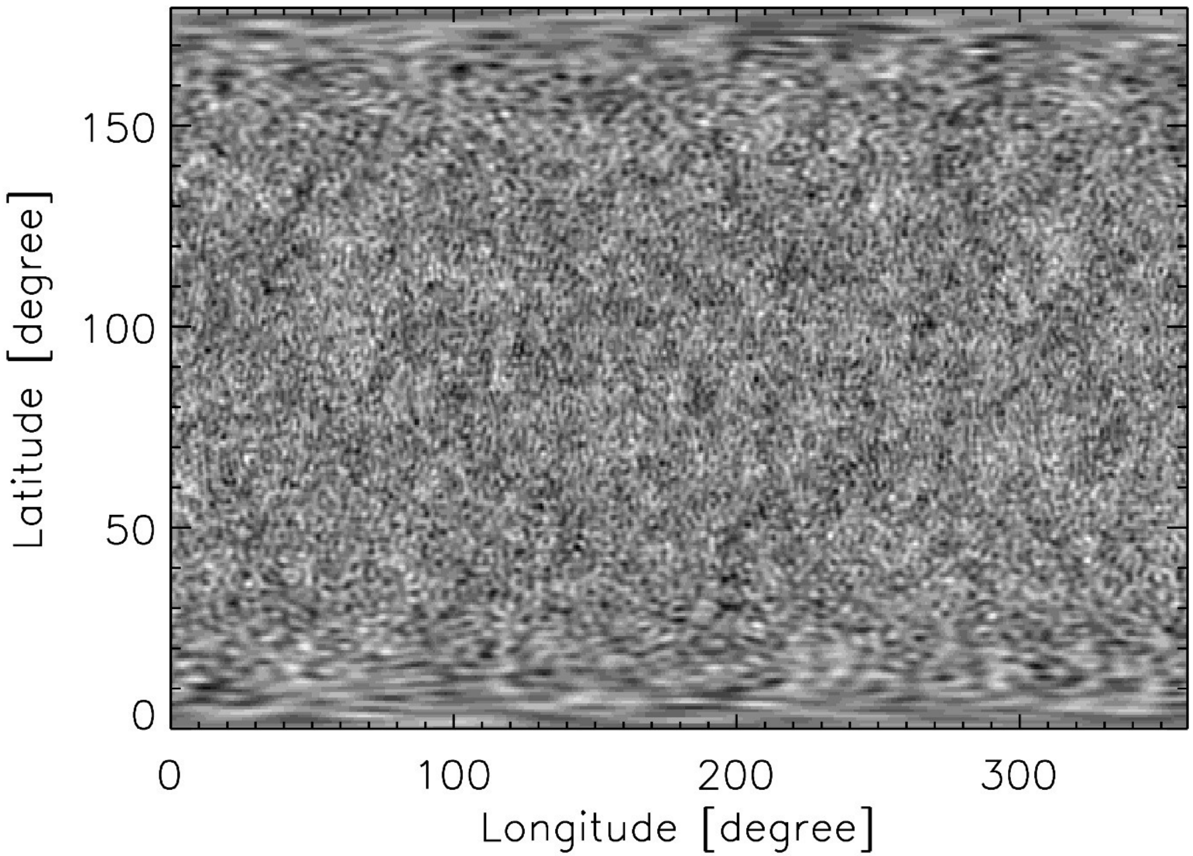
4.3 Are there separate dynamo processes acting in the Sun?

4.4 How are coronal and heliospheric phenomena related to the solar dynamo?

? What observables to expect from Solar Orbiter?

Very Simple Considerations: Artificial Data

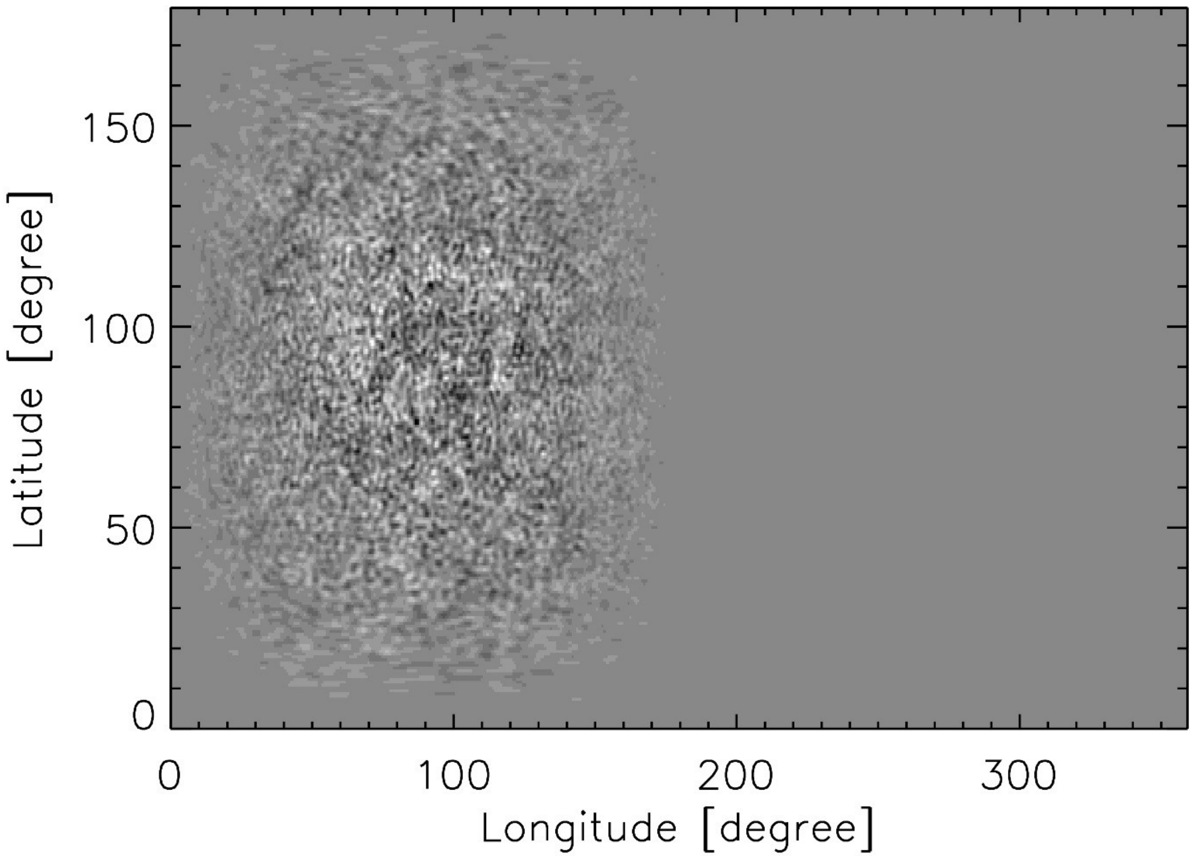
- *Optimal case observation of the full Sun*



(Wave simulation data provided by Hartlep, Univ. Stanford)

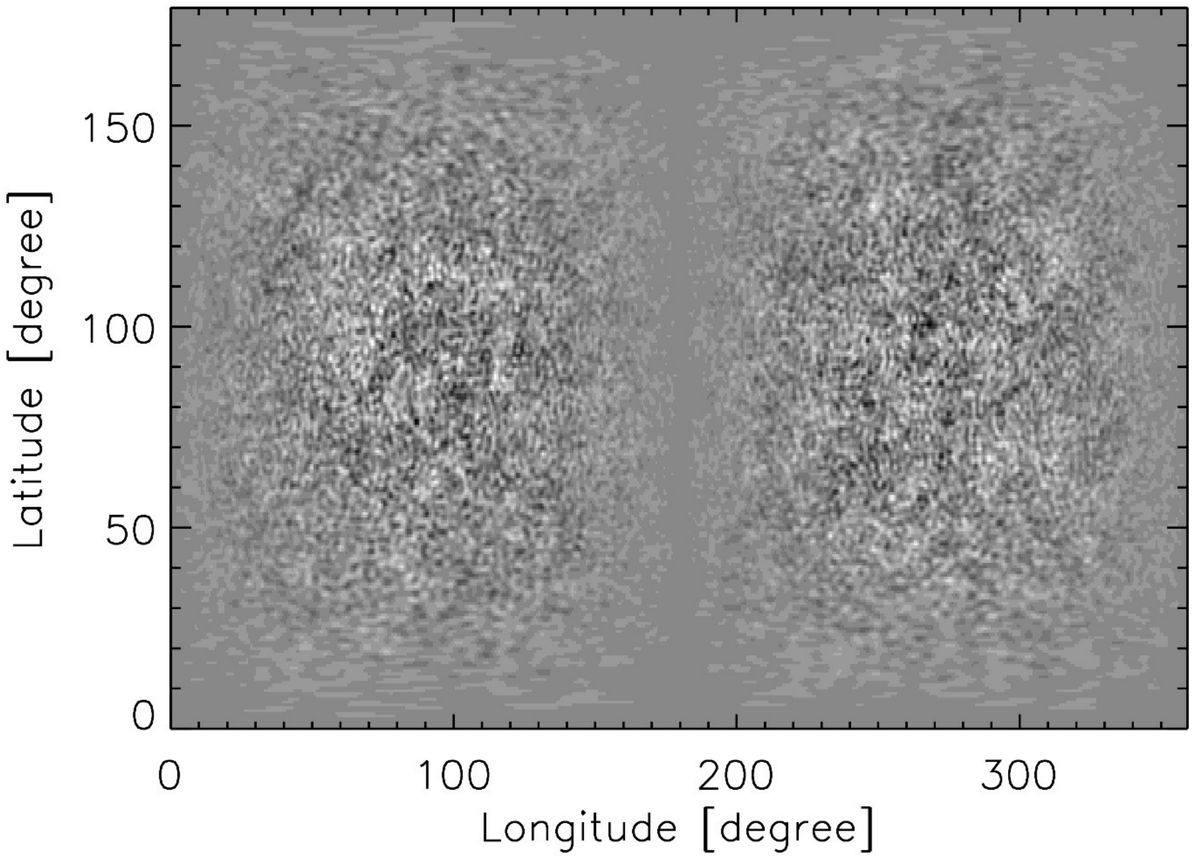
Artificial Data

- *Current Situation: front-side view only*

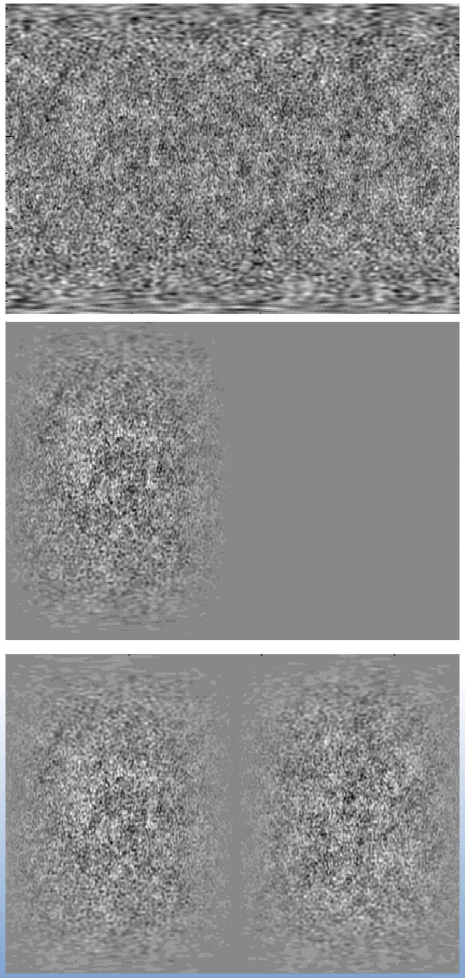


Artificial Data

- *Front-side data + Solar Orbiter Data (in ecliptic)*

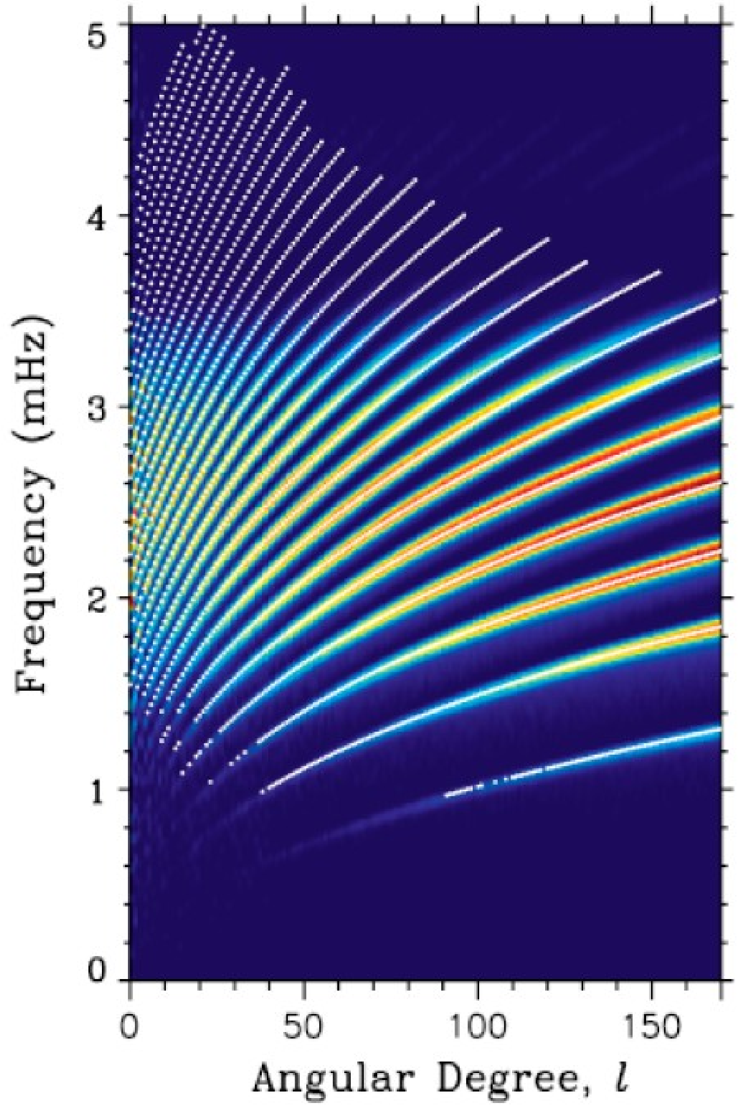


Global Helioseismology



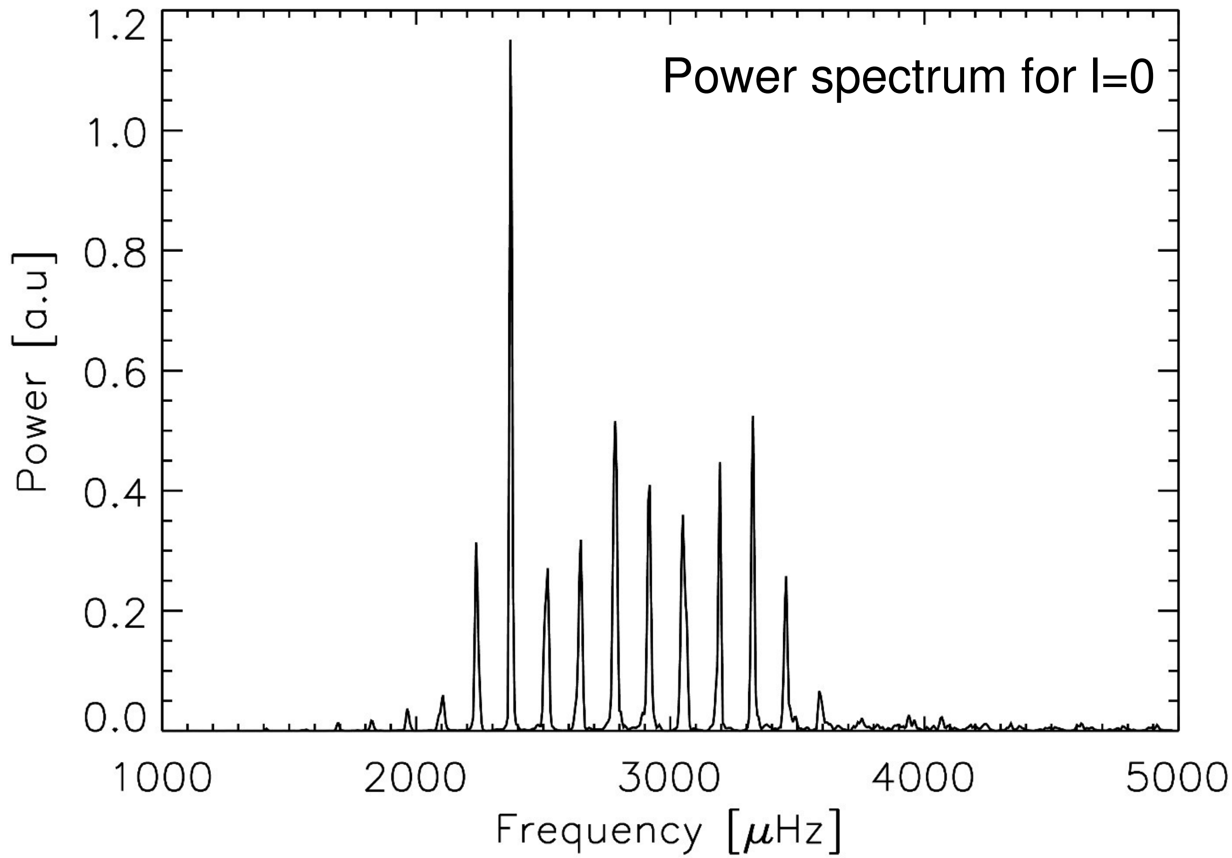
Fourier transform

in time and space



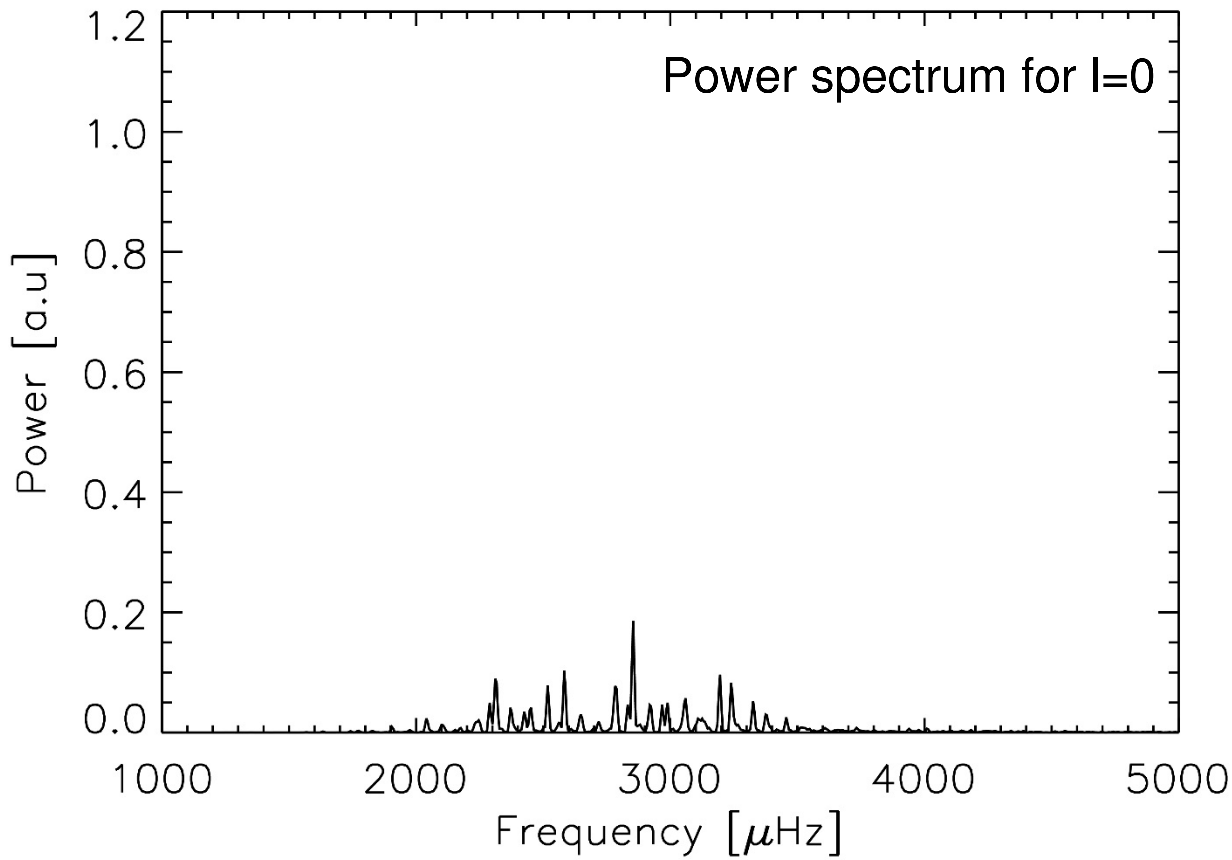
Global Helioseismology

- *Optimal case – observation of the full Sun (for 2 days)*



Global Helioseismology

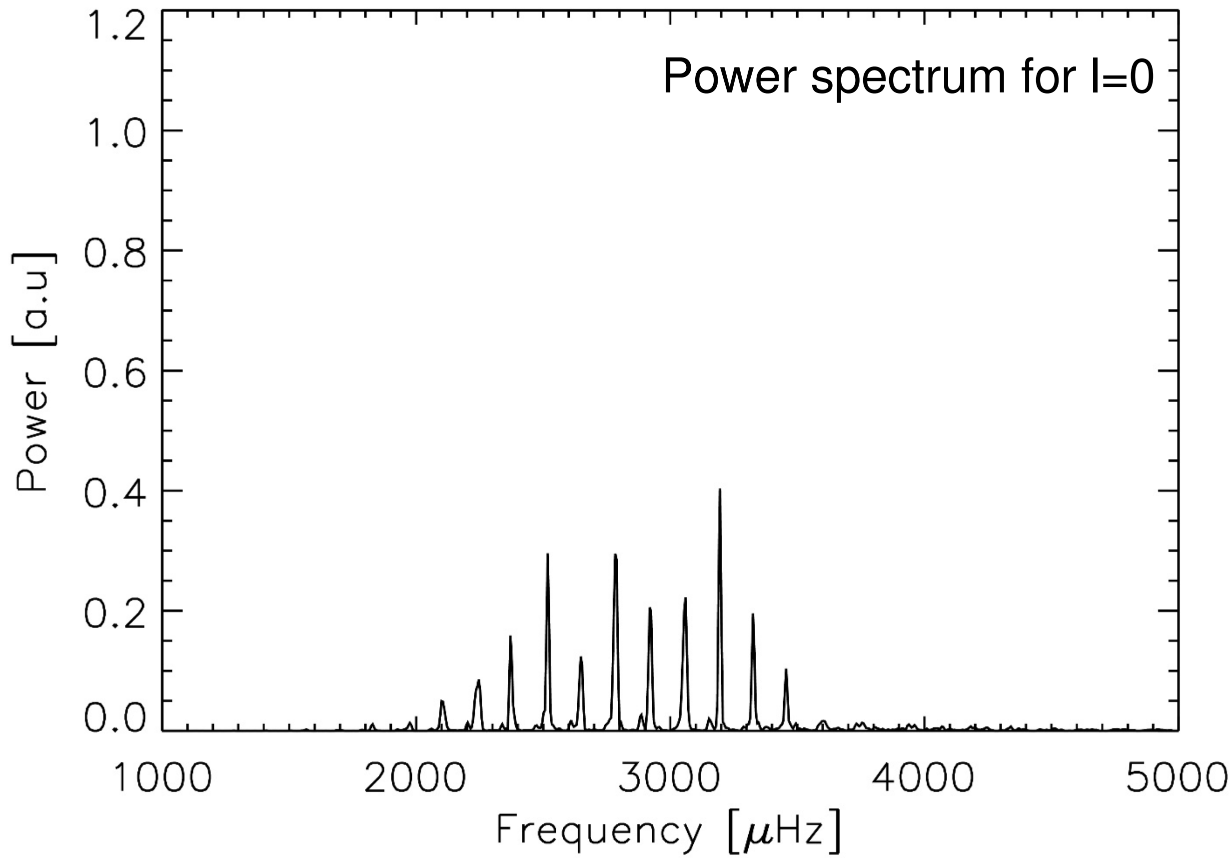
- *Front-side view only (for 2 days)*
  – leakage effect: side lobes!



Global Helioseismology

- *Front-side + Solar Orbiter data (for 2 days) – side lobes reduced*

  - *helioseismology possible*



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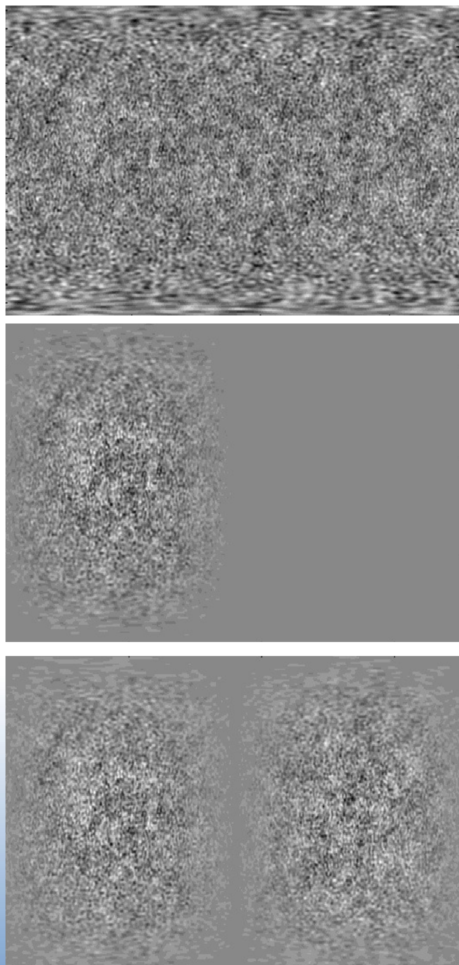
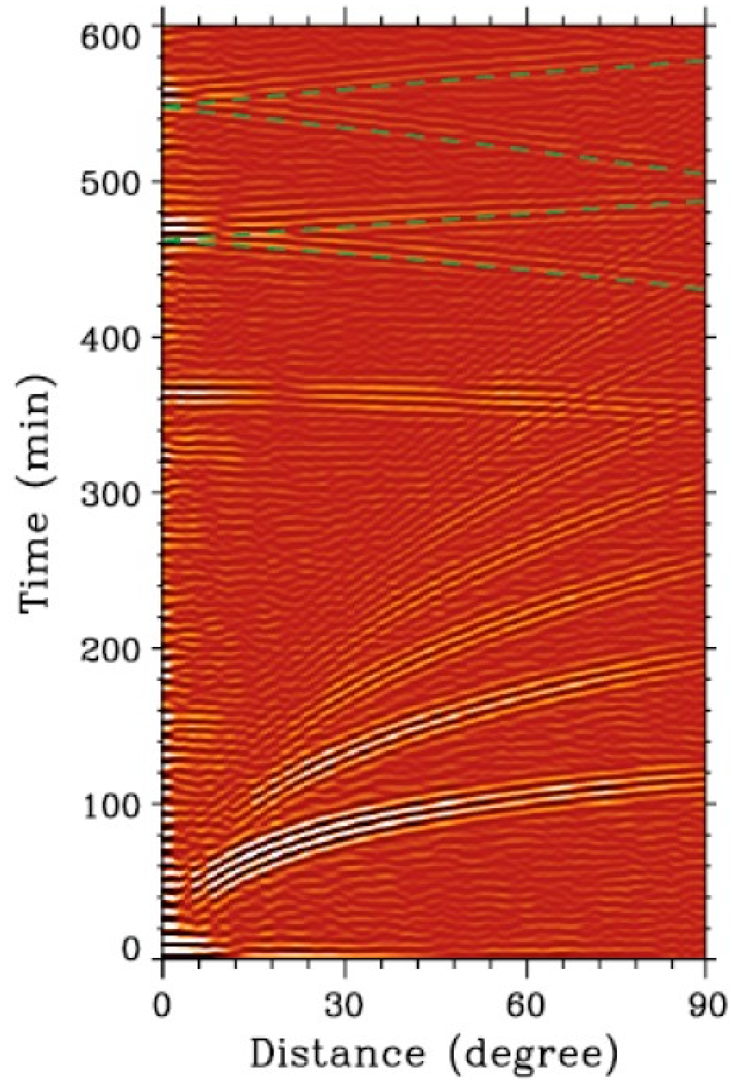
Local Helioseismology



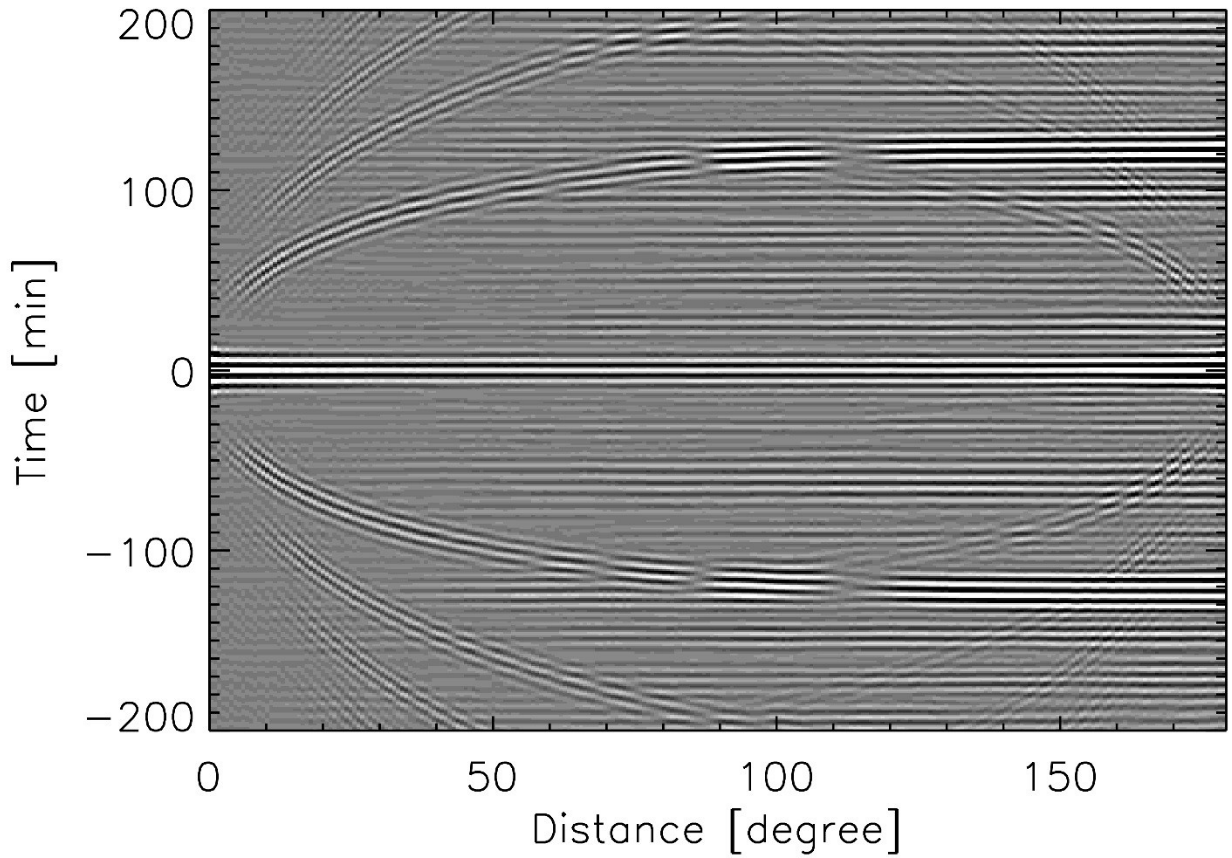
Cross-correlation

in time and space



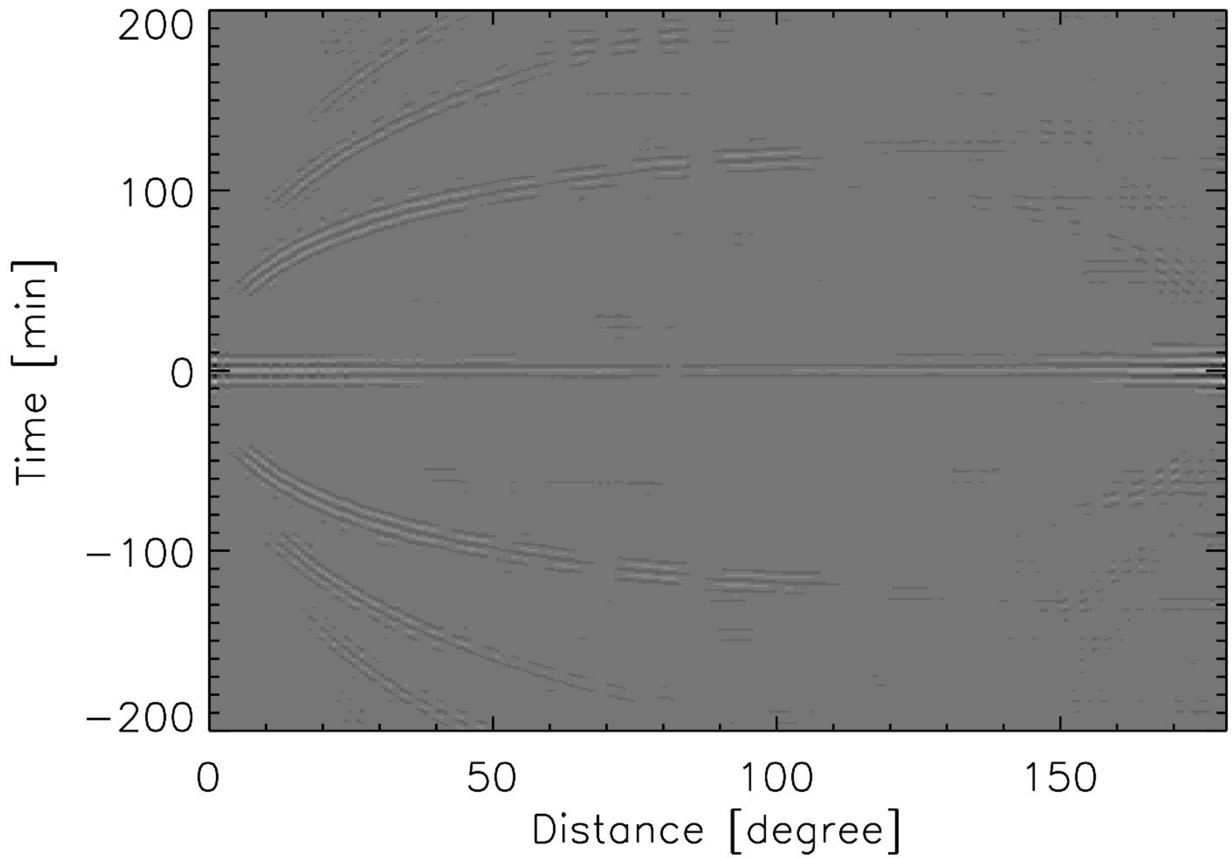
Time-Distance Diagrams

- *Optimal case – observation of the full Sun (for 2 days)*



Time-Distance Diagrams

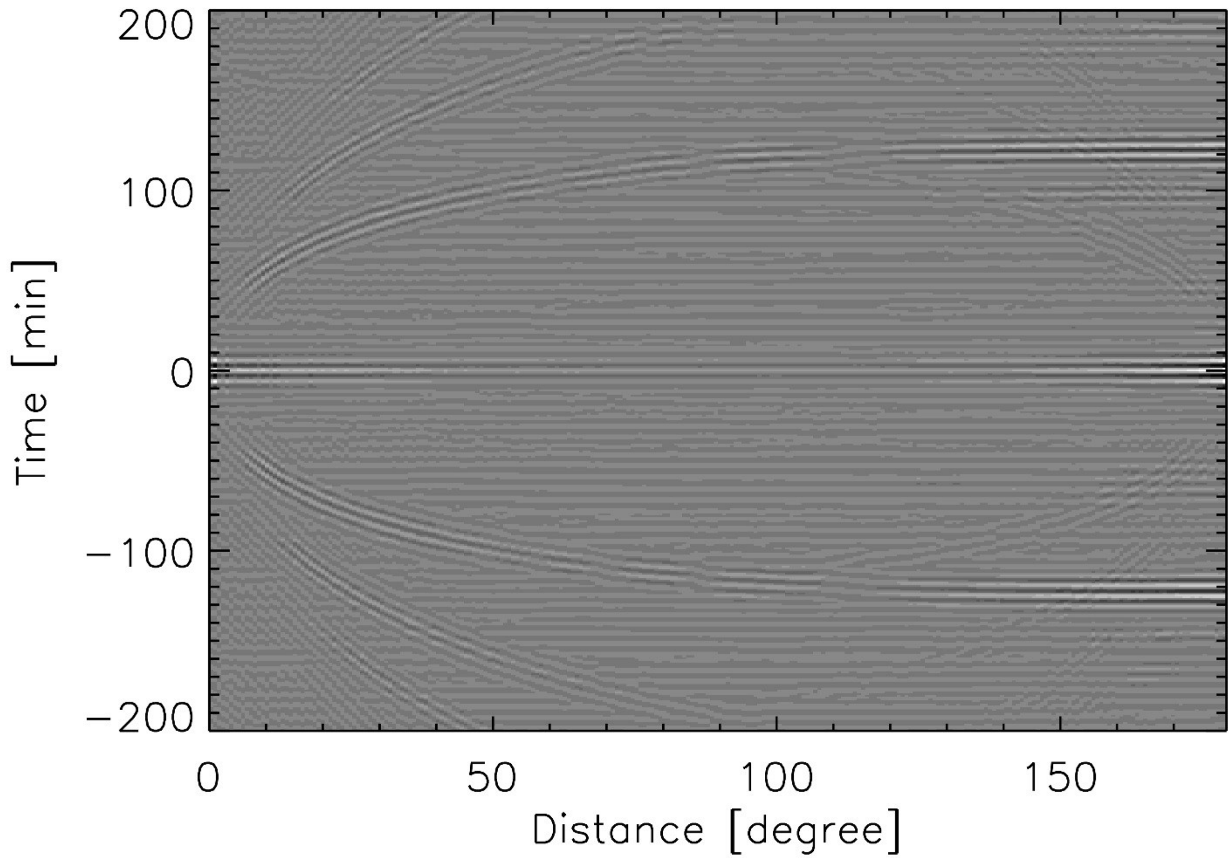
- *Front-side view only (for 2 days)*
  – only small distances can be used for seismology



Time-Distance Diagrams

- *Front-side + Solar Orbiter data (for 2 days) – signal improves at all angular distances*

□promise for stereoscopic helioseismology



Meridional Flow Measurements with Front and Backside Data

Tests with simulation data from Hartlep, Univ. Stanford):

Inversions for a meridional flow (artificially high amplitude) for the three observational setups

Red line: true input flow

Asteriks with error bars: helioseismic results

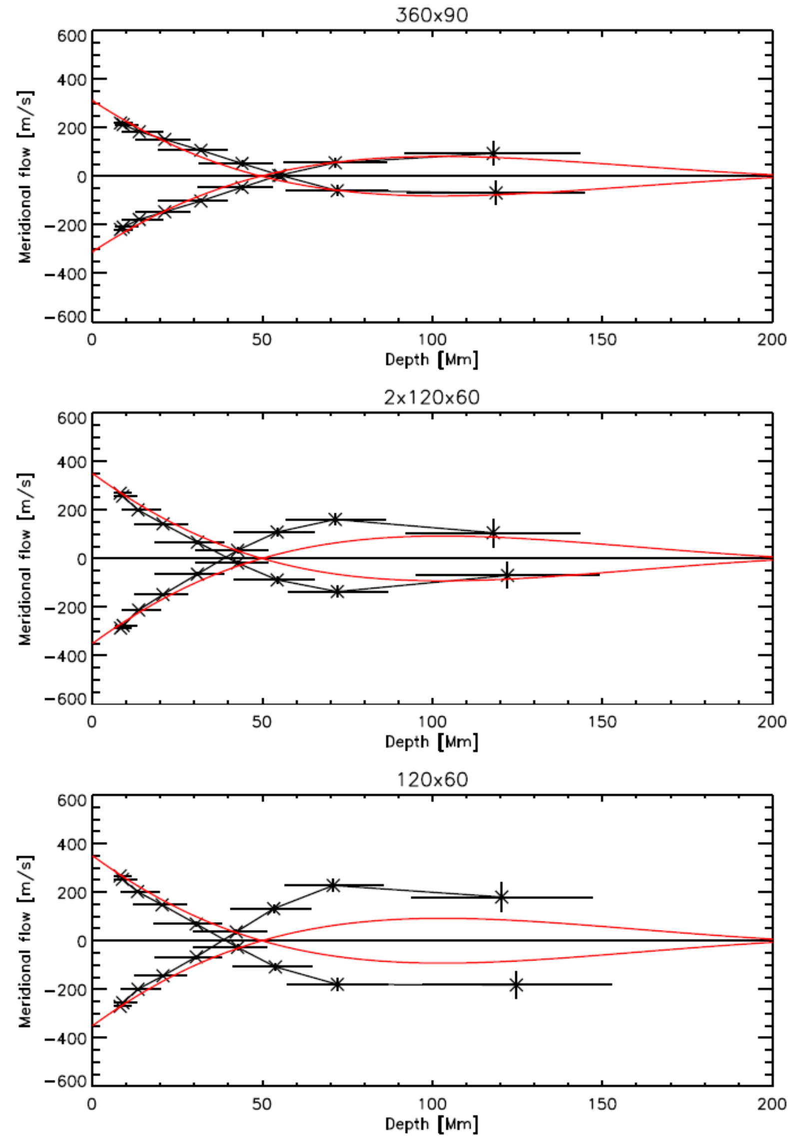
With smaller observation area measurements in the deeper layers get worse.

Agreement between inversion and actual flow is good down to ~30Mm.

Deep measurements improve with backside view.
Disagreement worst ~50-80 Mm due to missing side views

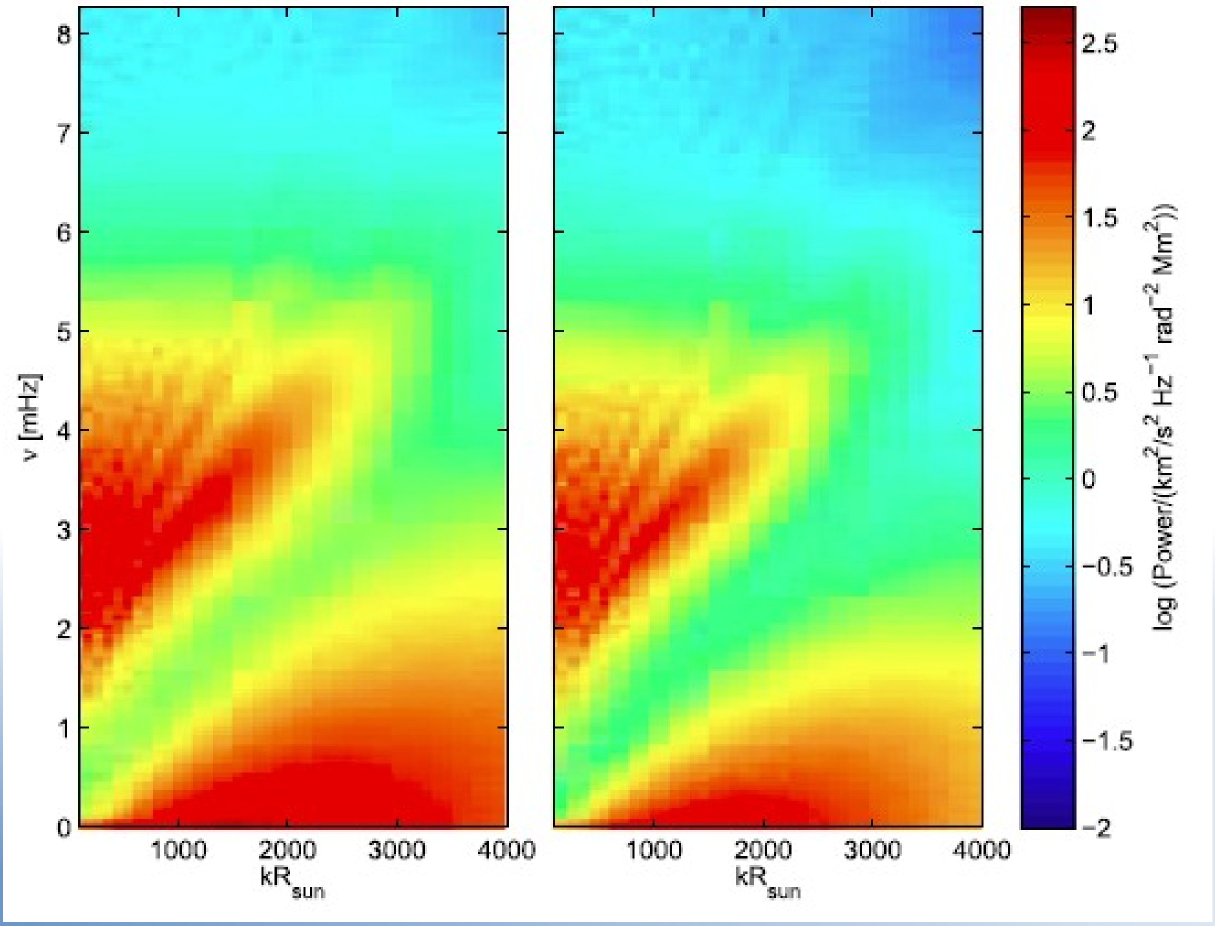
Required: > 3 years of Solar Orbiter data

(Roth et al. 2016)



More Sophisticated Analysis

- *Löptien et al., 2014*
- *Power spectrum of 6 hours of data*



What can be done with Solar Orbiter?

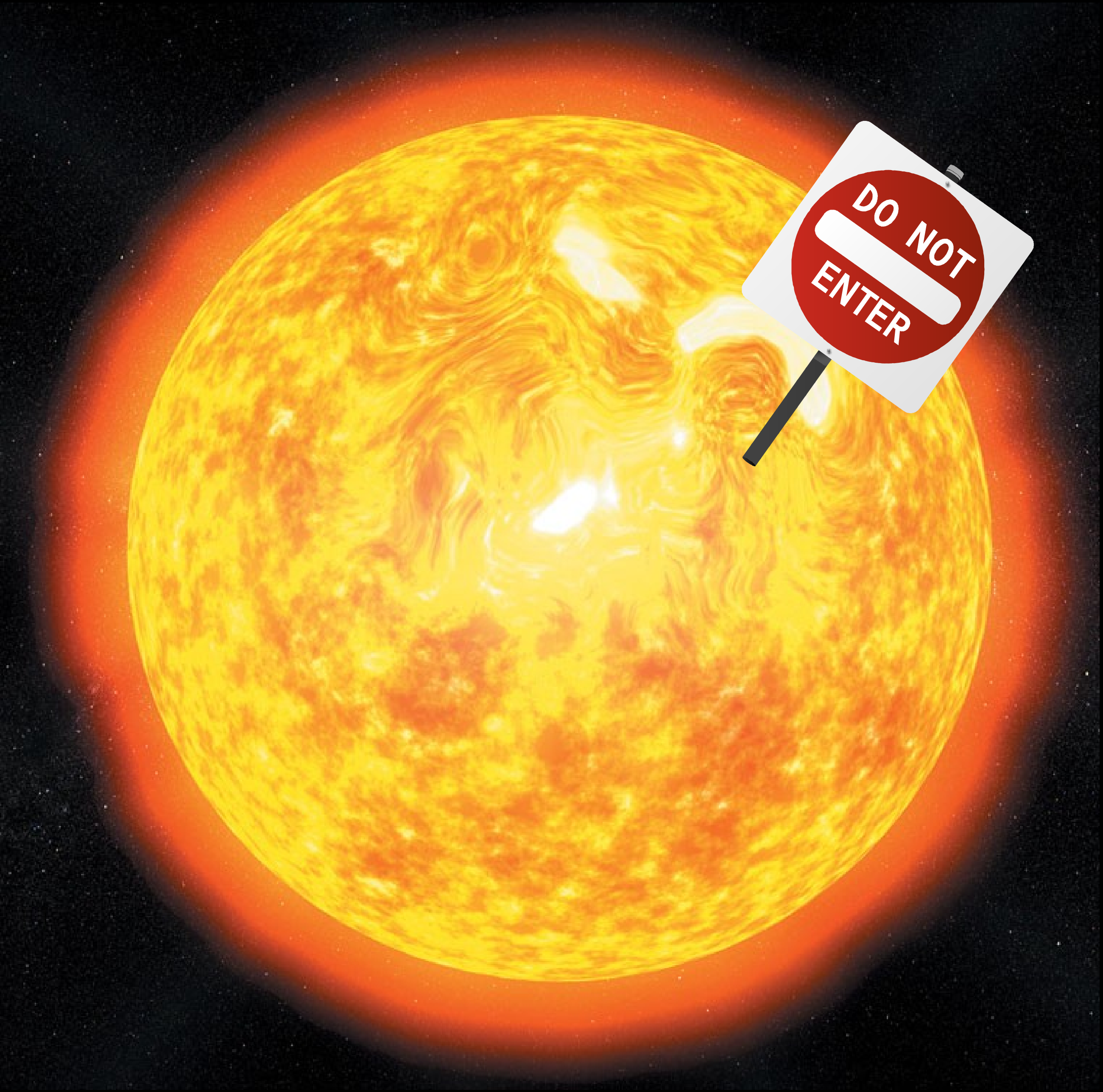
- *Global Helioseismology of structure and flows*
  needs long time series (example GONG: 36 days)
  Achievable only by combining Solar Orbiter data from different observing periods?
  Solar Orbiter can contribute to mode physics,
  e.g. vertical to horizontal displacement ratio (stereoscopy)
- *Meridional flow measurements in the deep interior*
  needs years of data; even if front and back are combined
- *Deep Convection*
  long time series required (years)
- *Subsurface layers with local techniques:*
  near-surface flows (low and high latitudes) & active regions
  Requires only days of data

 Talk by Björn Löptien

Summary

- *In the past:*
  - Helioseismology has revealed important insights on solar structure, rotation, and their variations
- *Presently:*
  - The origins of solar activity in the subsurface layers and the processes involved in the dynamo action are under study
- *Prospects for Solar Orbiter:*
  - The vantage point, the new instrument and new techniques promise in principle probing the Sun in a unique way

- ***Points for Reviewing and Discussion:***
  - Instrument properties (e.g. infer leakage matrix)
  - Telemetry & science windows to tailor seismic techniques
  - Sophisticated data modeling (noise estimates)
  - ***Instrumentation on the ground for, e.g., observing the front-side at the same time***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