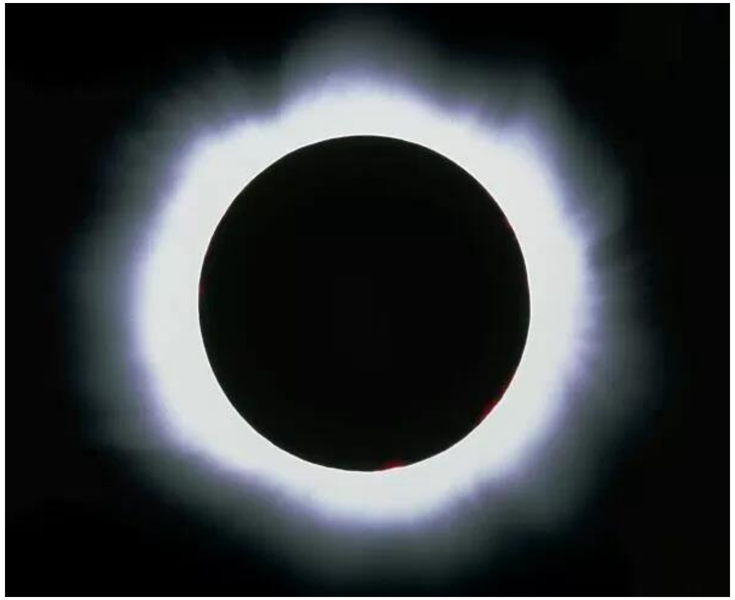
Solar interior and helioseismology

Anne-Marie Broomhall
(Centre for Fusion, Space, and Astrophysics, University of Warwick)

A bit about me

- Decided to study astronomy following eclipse in 1999.
- Masters in Maths and Astronomy from Univ. of Sheffield in 2004.
- PhD in solar physics from Univ. of Birmingham in 2008.
- My 1st daughter was born in 2009, my 2nd in 2012.
- Moved to Univ. of Warwick in 2012 for fellowship.
- Now Associate prof

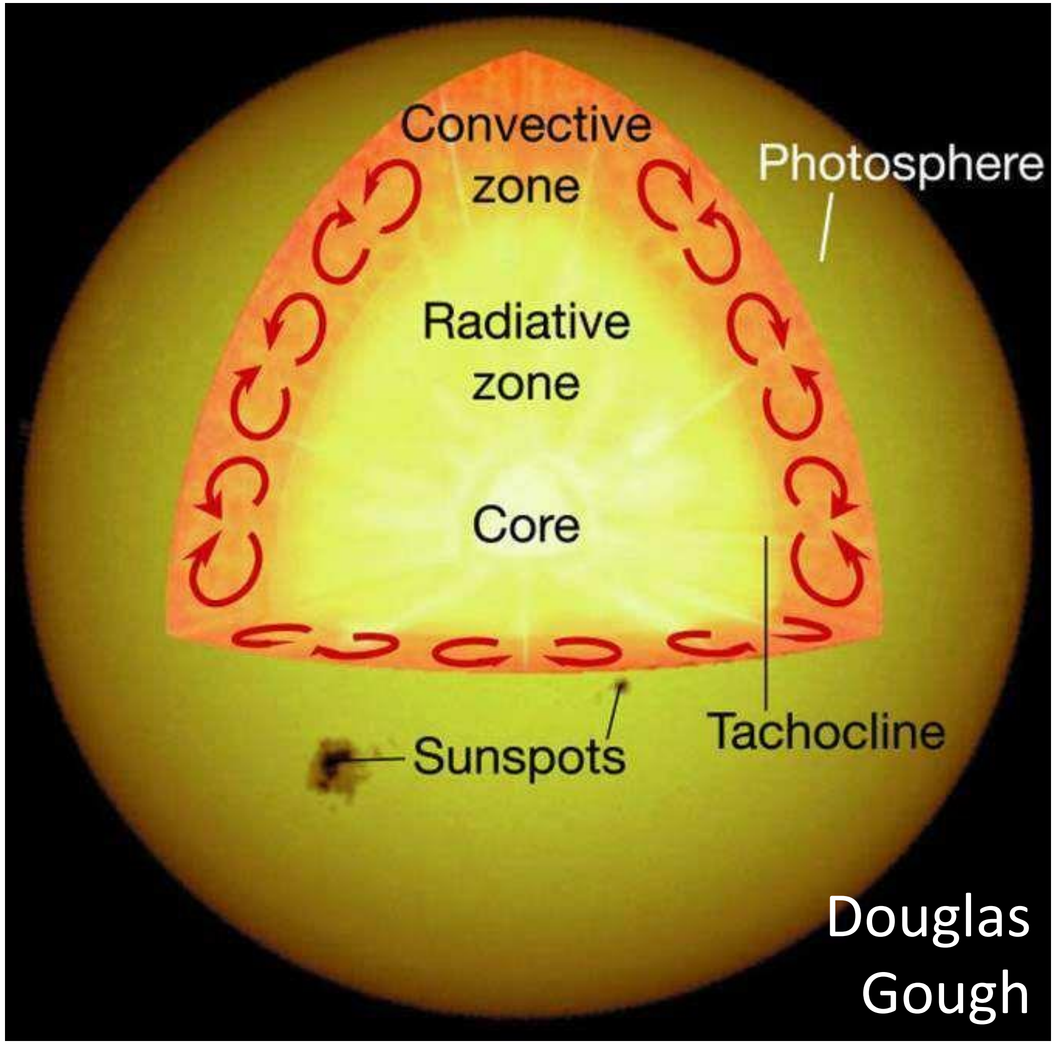


Structure

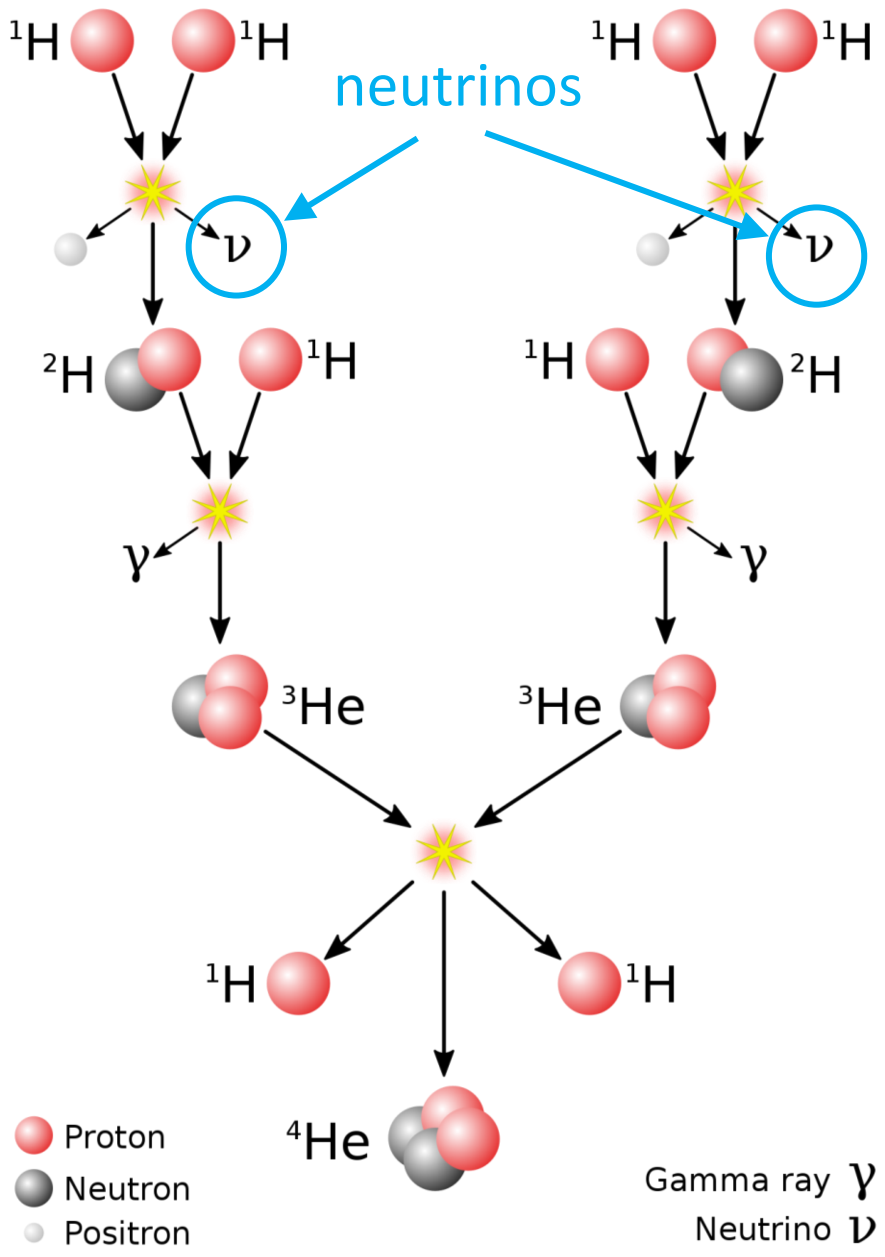
- Introduction to structure of the solar interior
- What is helioseismology?
- Interesting, important helioseismic results.

Basic structure of the solar interior

- **Core**
  - $0.25R_{\odot} \lesssim \mathrm{R}$
  - Where energy generated through nuclear fusion.
- **Radiative zone**
  - $0.25R_{\odot} \lesssim \mathrm{R} \lesssim 0.71R_{\odot}$.
  - Energy transported by radiation.
- **Tachocline**
  - Thin interface layer
  - Possible location of magnetic dynamo
- **Convection zone**
  - $0.71R_{\odot} \lesssim \mathrm{R} \lesssim R_{\odot}$.



Fusion: pp chain



- Dominant mechanism of energy production in Sun.
- Inefficient process
  - $\Delta m \sim 0.7\%$ of 4 ^{1}H → 26.7 MeV
  - It is slow
    - 1st reaction requires weak interaction & takes about 1 billion years.
  - Some of energy carried away by neutrinos.

By Sarang - Own work, Public Domain, https://commons.wikimedia.org/w/index.php?curid=51118538

Solar-neutrino problem

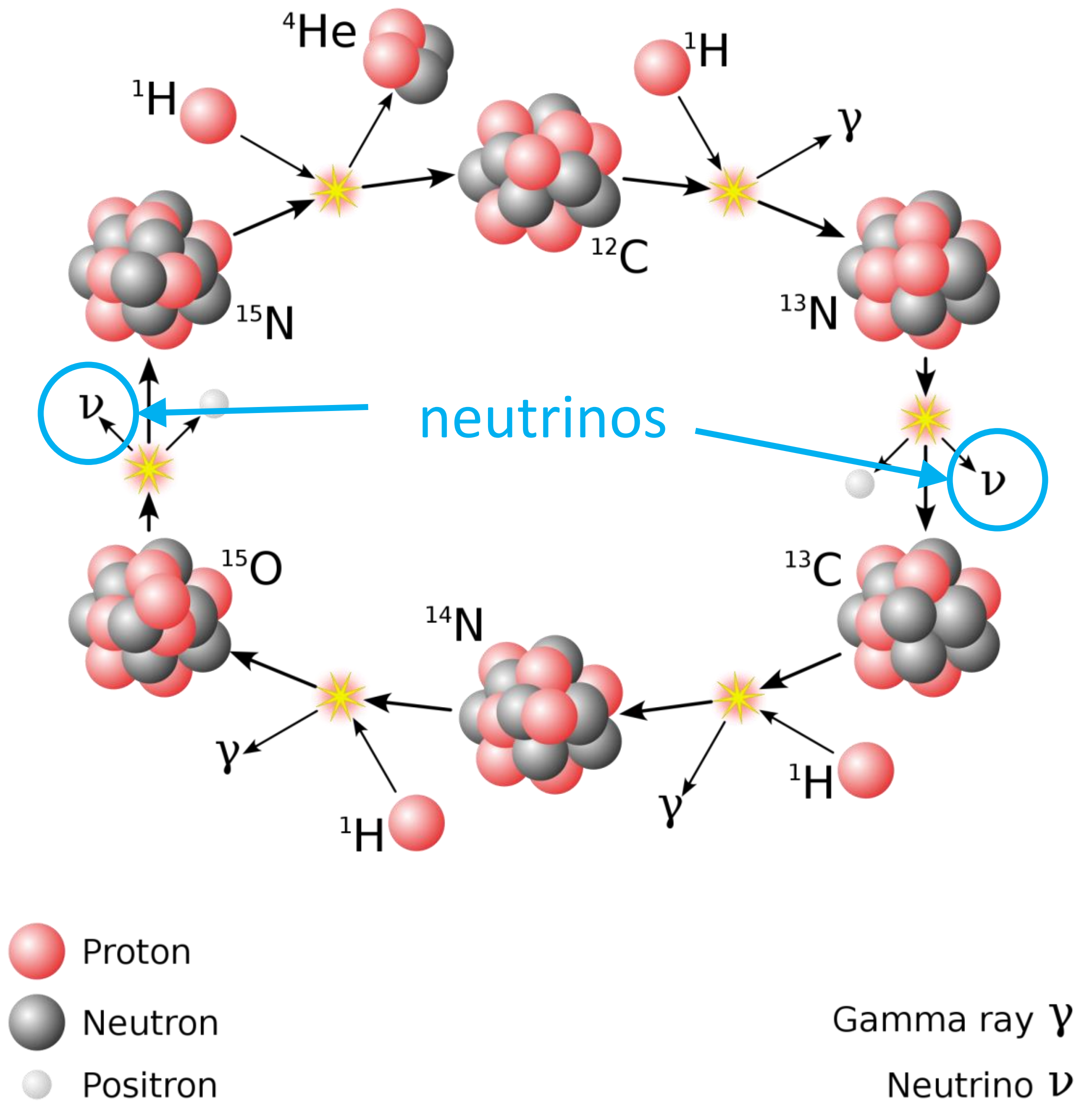
WARWICK

- Early solar neutrinos only detected around one third of predicted number of neutrinos from Sun.
- Neutrino physicists thought models of solar interior were wrong and core was cooler.
- Helioseismology showed core temperature was 15million degrees as predicted.
- Solution: neutrinos able to change flavour.

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Fusion: CNO cycle

WARWICK

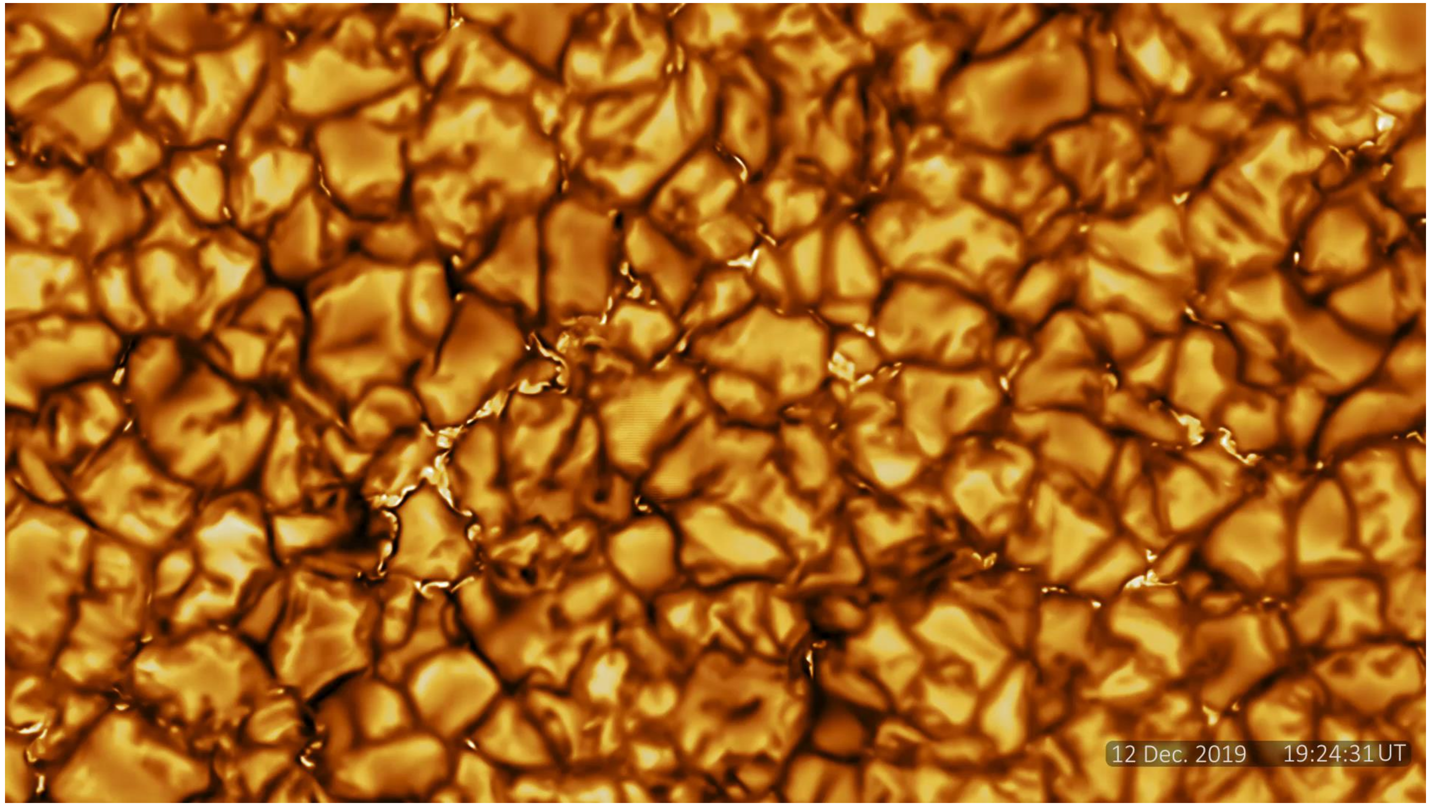


- Each reaction outputs more energy than pp chain.
- BUT only accounts for around 1% of energy generated.
- AND this % is uncertain as solar metallicity poorly constrained.
- Recent results from Borexino neutrino experiment (The Borexino Collaboration, *Nature*, 2020) have reduced this uncertainty substantially.

By Borb - Own work based on: Fusion in the Sun.svg:, Public Domain, https://commons.wikimedia.org/w/index.php?curid=691758

Convection

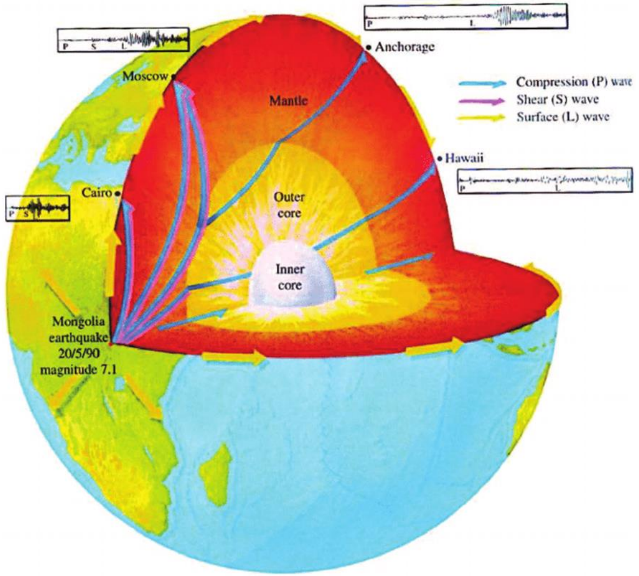
- At base of convection zone, T~2mill K → heavier ions hold on to electrons → more opaque to radiation → temperature gradient > adiabatic gradient → convection.
- Timescale for energy to rise through CZ ~ weeks.
- Granulation cells: size~1-2Mm, lifetime~5-8min, ~1km/s.
- Supergranulation cells: size~20-30Mm, lifetime ~ days, ~400m/s

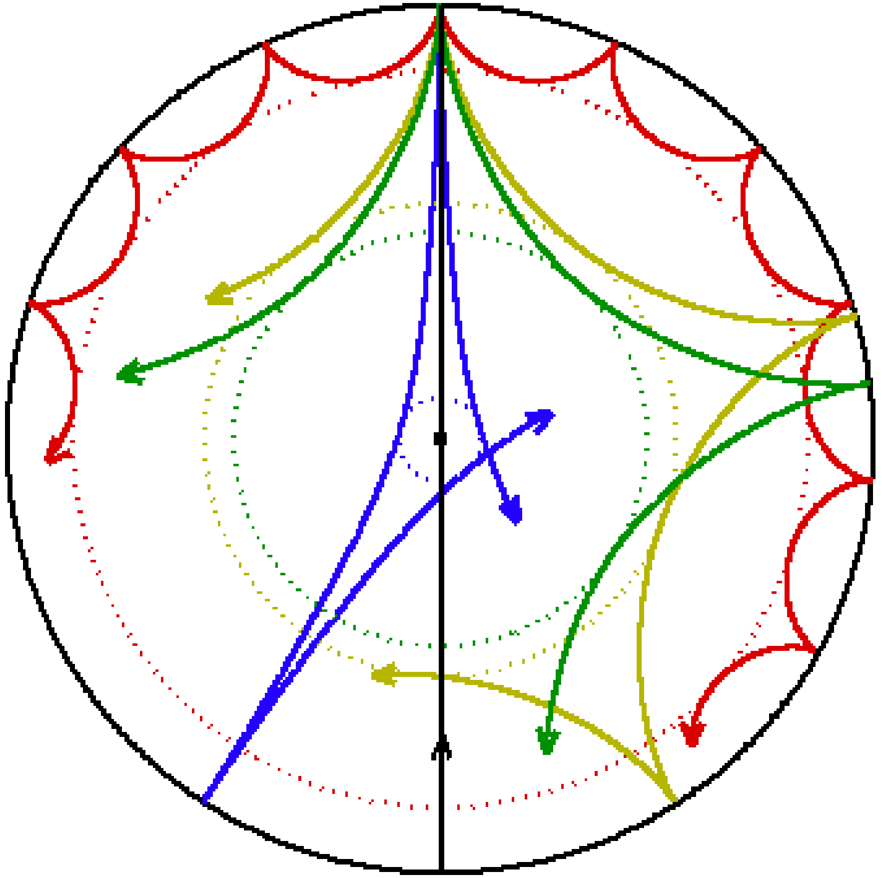


Courtesy of DKIST

What is helioseismology?

- Helioseismology allows conditions beneath the surface of the Sun to be probed.
- Each mode samples a different but overlapping region of the solar interior.





Stanford Solar Center

Types of oscillation

WARWICK

- p modes:
  - restoring force is pressure differential
  - amplitude largest at surface
  - main focus of this talk
- g modes:
  - restoring force is buoyancy
  - small amplitude at surface
  - not yet observed in the Sun

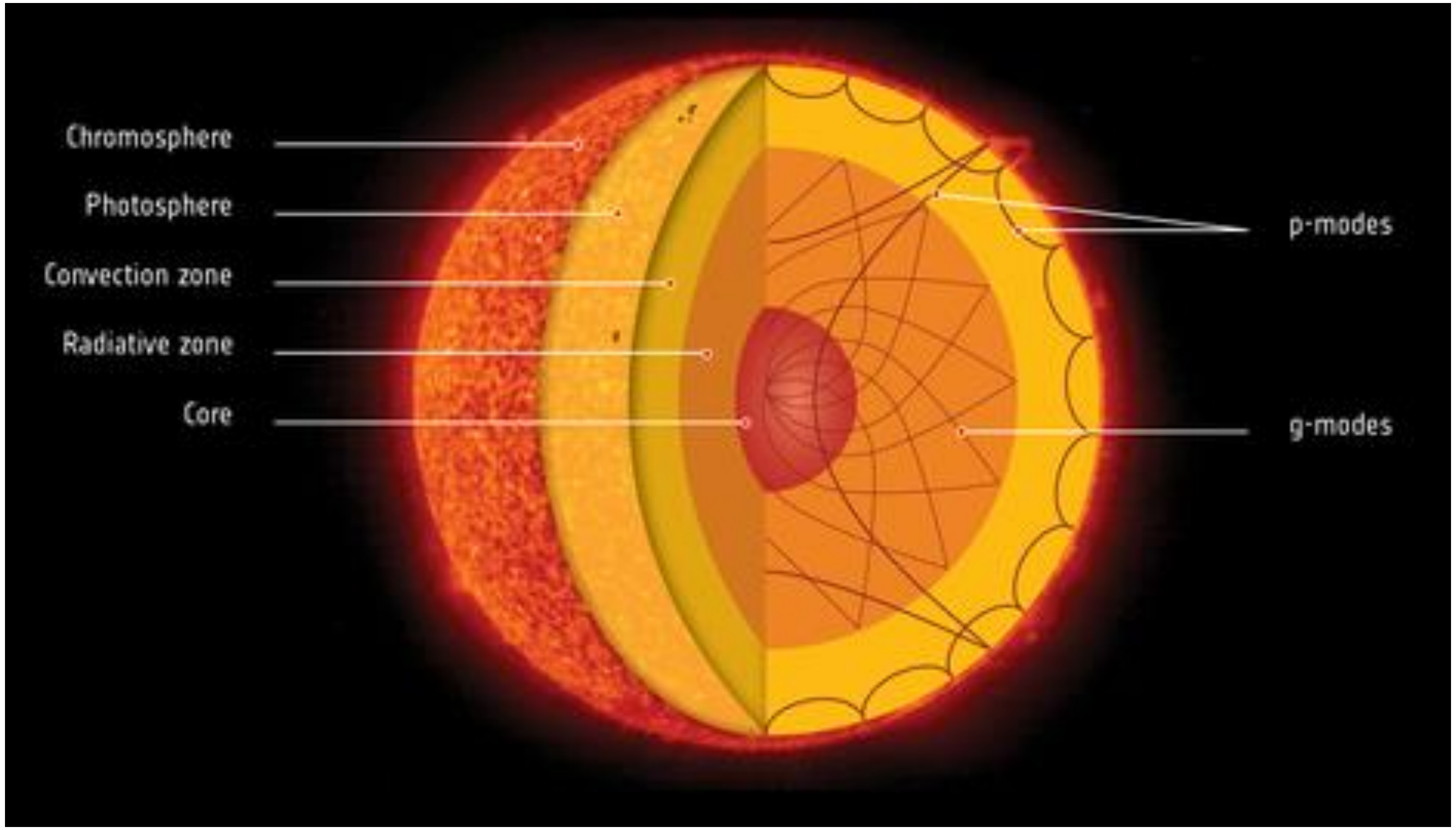


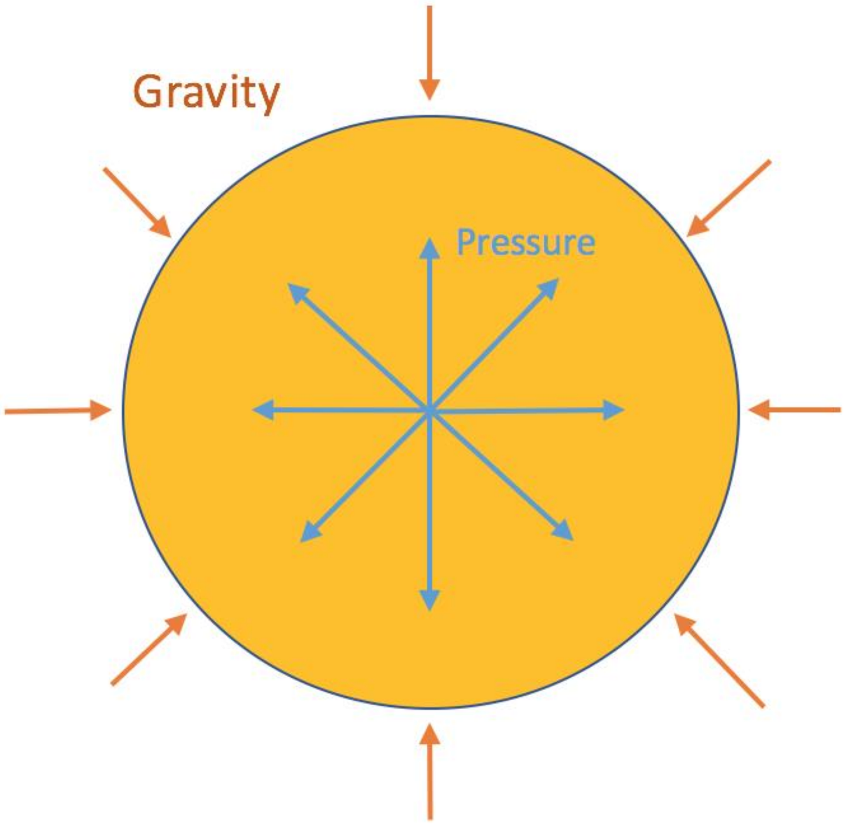
Image credit: SOHO (ESA & NASA)

Dynamical timescale of Sun

WARWICK

- The dynamical timescale is essentially the freefall time of the star.
- Suppose the internal outward pressure of the Sun is removed. The outer radius, R, would collapse under gravity.
- The gravitational acceleration of the star at the surface is given by

$$g = \frac{GM_{\odot}}{R_{\odot}^2}.$$



Source: J. Stayner

Dynamical timescale of Sun

WARWICK

- The equations of motion tell us that

$$t = \sqrt{\frac{2s}{a}}$$

- Say that the star collapses to a radius of $R_\odot/2$ in the dynamical timescale then

$$\tau_{\mathrm{dyn}} = \sqrt{\frac{R_\odot^3}{GM_\odot}}$$

- i.e. ~20min for the Sun – upper limit for p mode periods.
- Dominant period for p modes is around 5mins (I'll show this later)

p modes

WARWICK

- In the adiabatic case the speed of sound is

$$c_s^2 = \frac{\Gamma_1 p}{\rho},$$

where Γ_1 is the first adiabatic exponent

- For an ideal gas

$$p = \frac{k_B}{\mu m_p}\rho T,$$

where μ is the mean molecular weight, m_p is the mass of a proton

- Giving

$$c_s^2 = \frac{\Gamma_1 k_B T}{\mu m_p}$$

Profiles of the solar interior

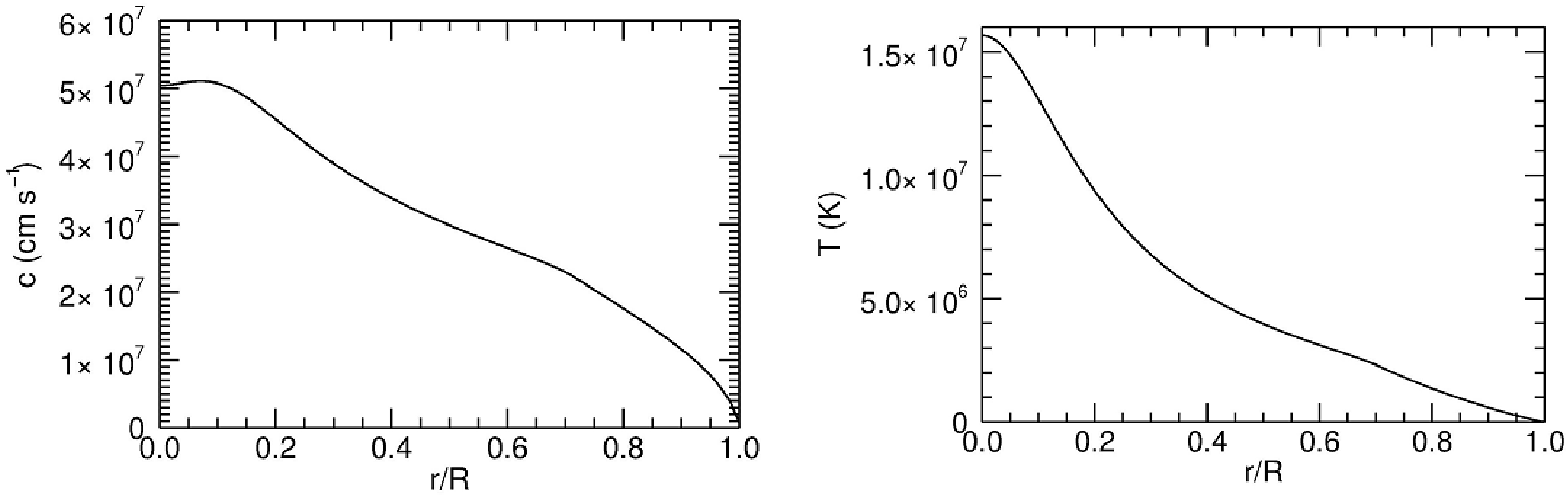
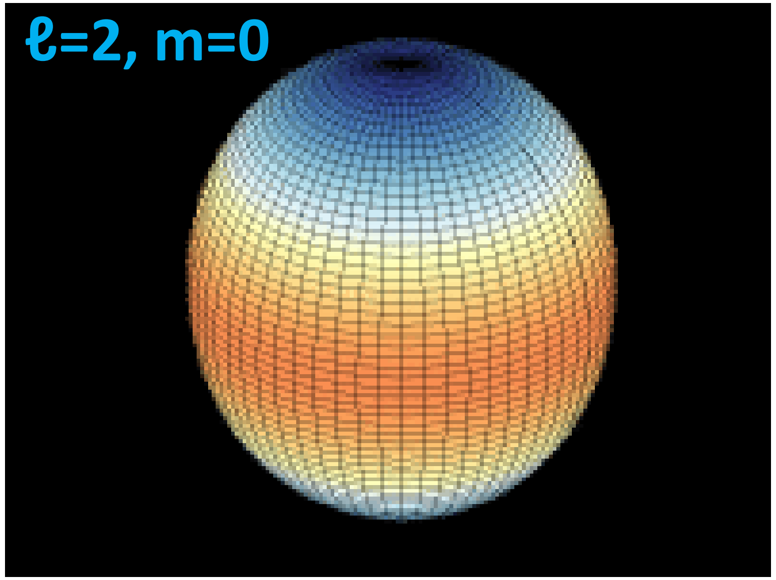
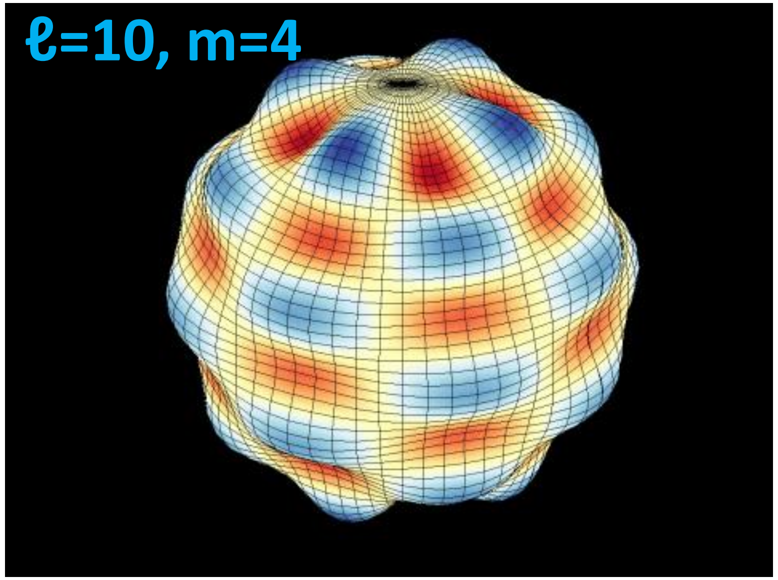


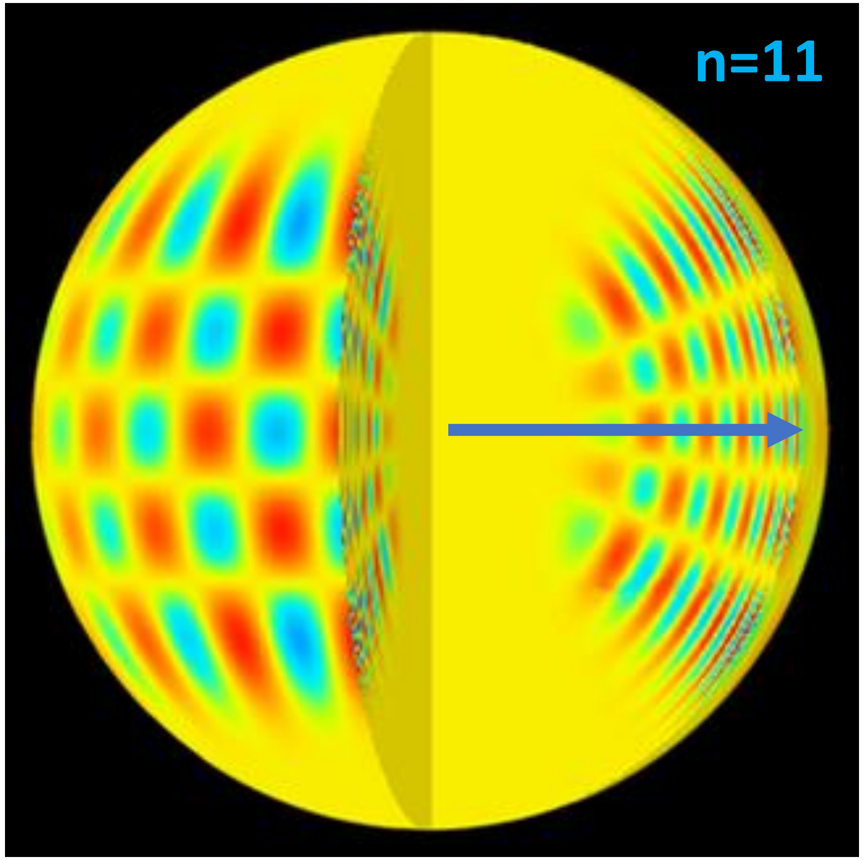
Figure 1: Sound speed (left) and temperature (right) as a function of radius predicted by Model S of Christensen-Dalsgaard et al. (1996, Science, 272, 1286).

Standing waves in 3 dimensions

- Described by stationary slices through sphere.
- Needs three numbers
  - Two for surface structure
    - ℓ determines the total number of node lines on surface
    - m determines number through equator
  - n for number of nodes from centre to surface

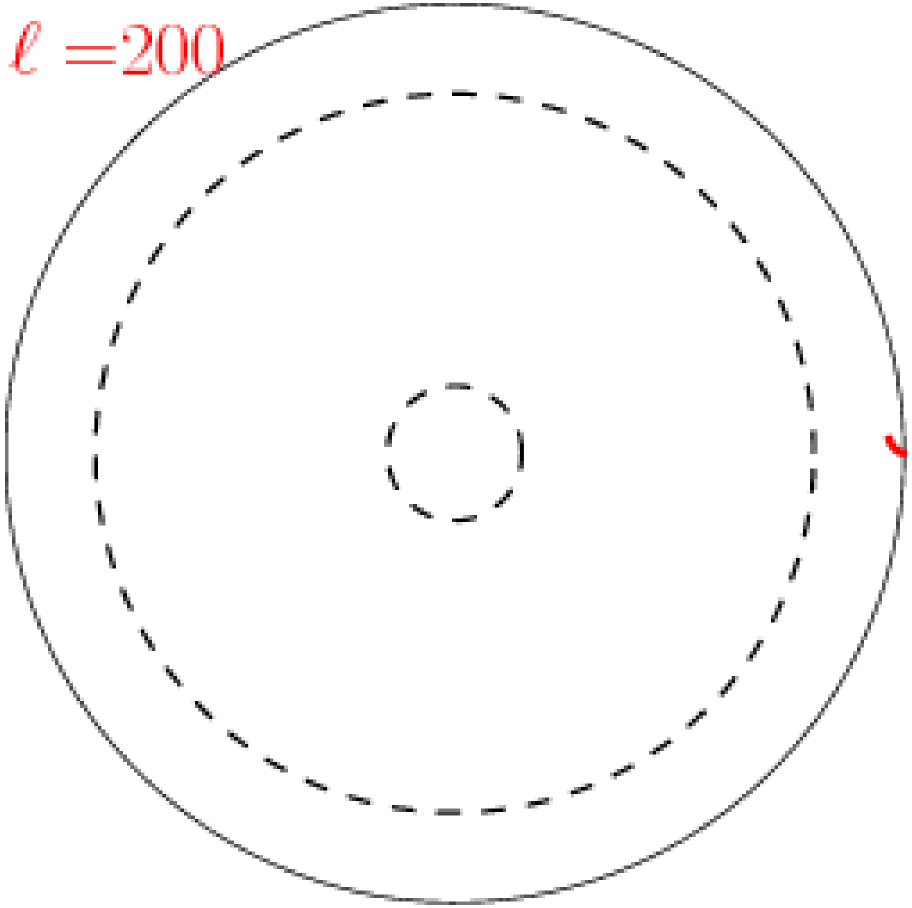






Different depths

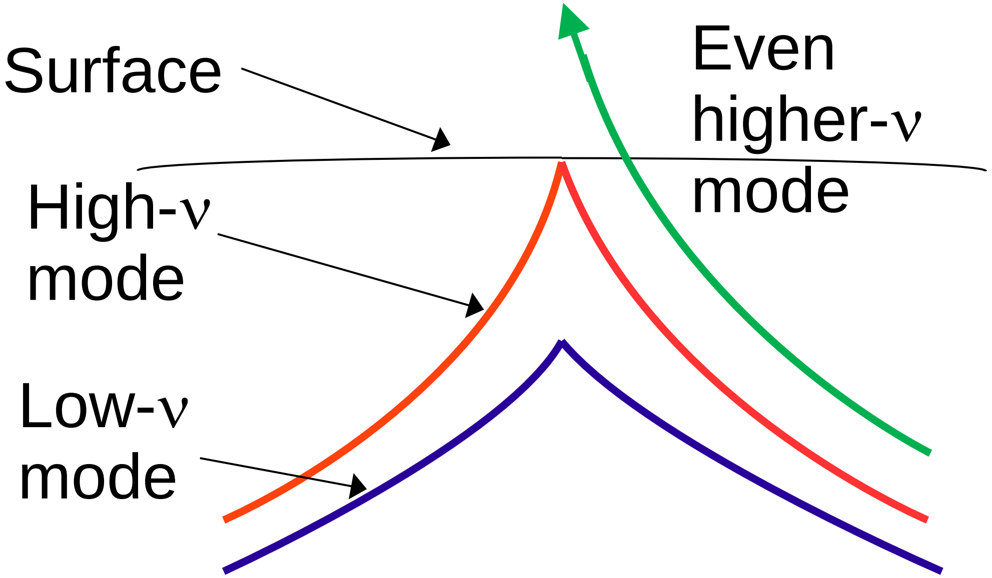
- The oscillations travel to different depths in the solar interior.
- As they travel inwards they are refracted by the increasing temperatures and pressures.
- Low-ℓ travel deeper than high-ℓ
- The frequencies of the oscillations are determined by the properties of the plasma they travel through.



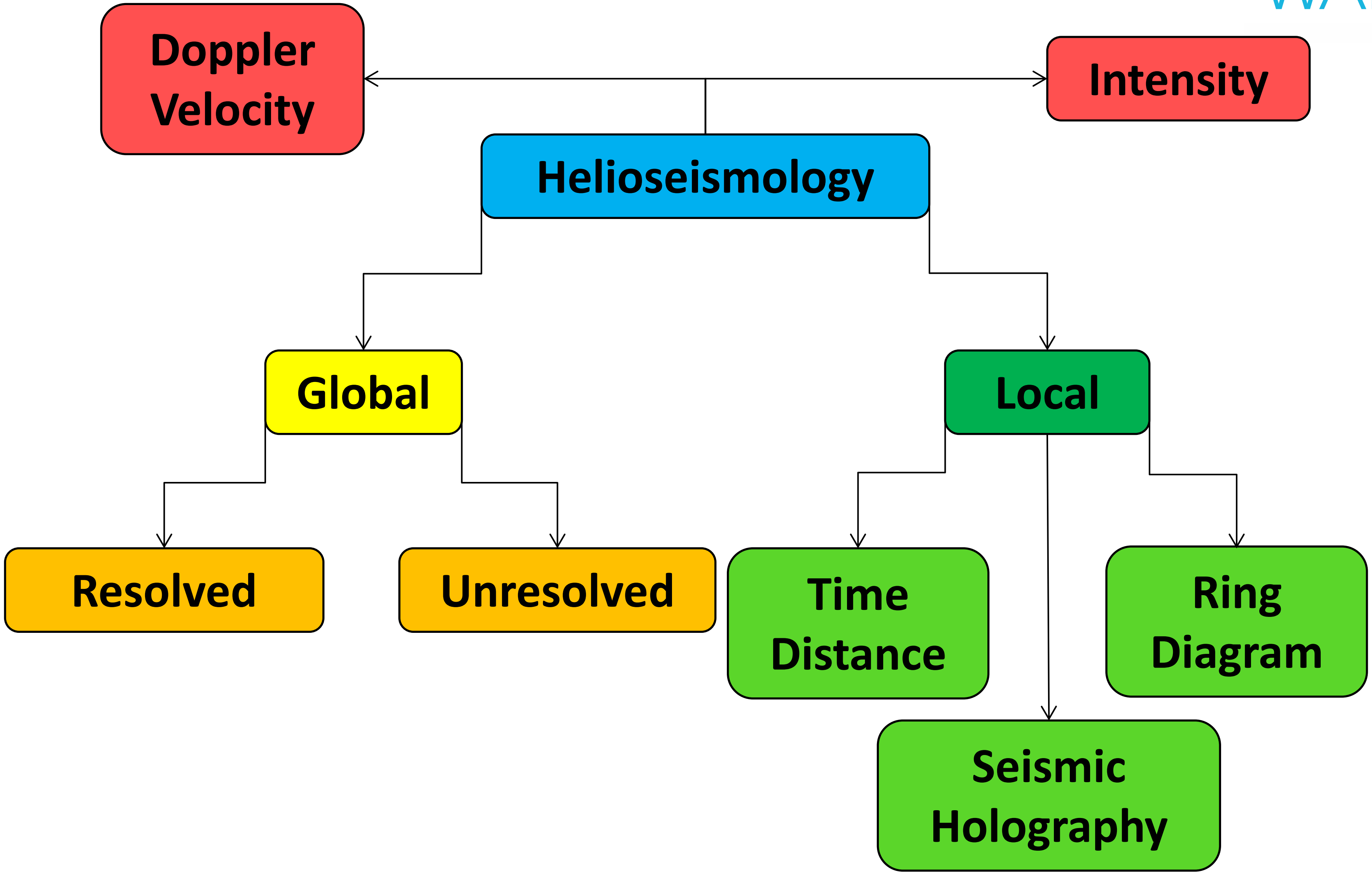
http://astronomy.nmsu.edu/jasonj/HELIO/outline.html

Upper turning points of modes

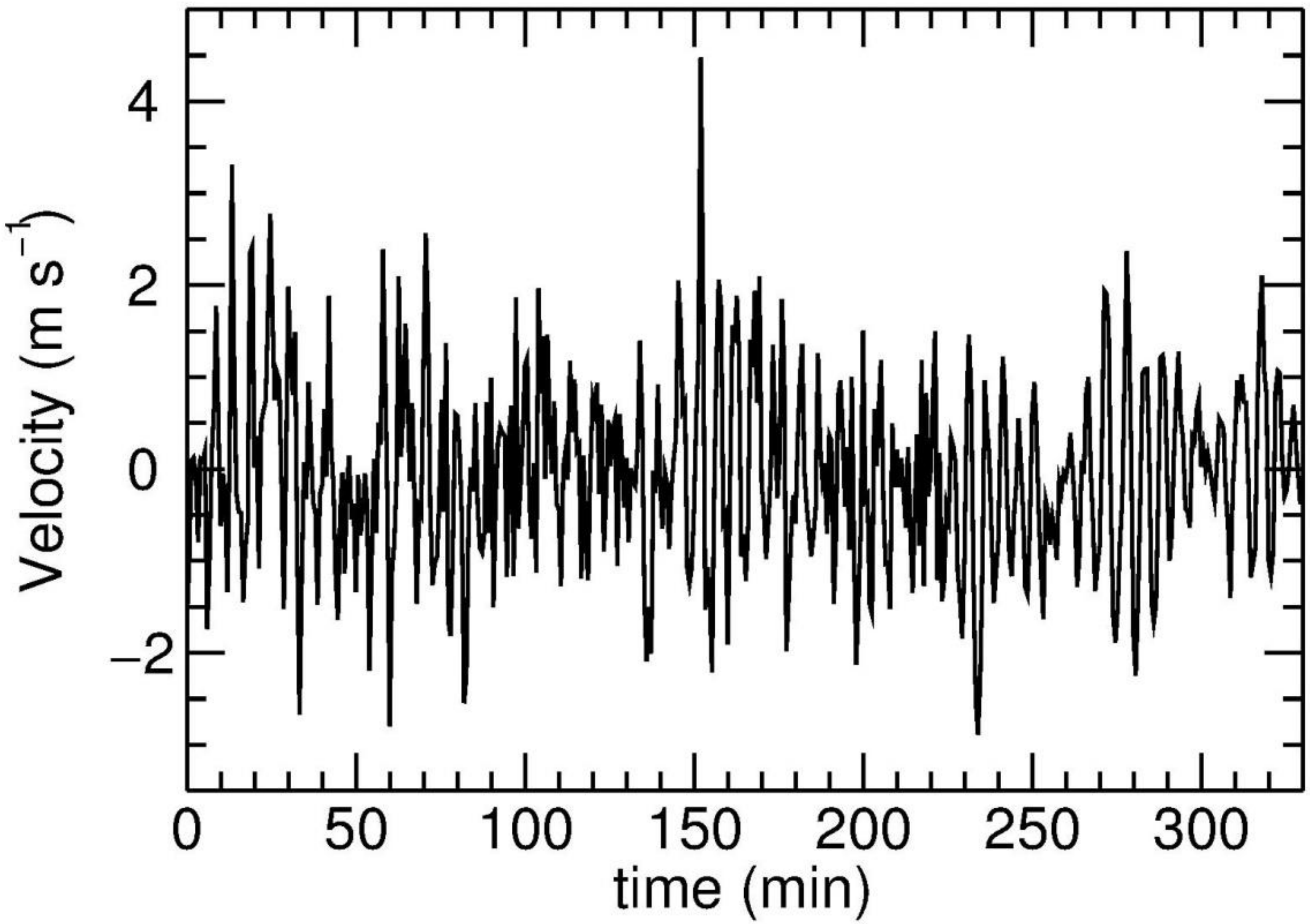
- Modes are reflected by the sharp drop in density at the Sun's surface.
- Modes are trapped in a cavity and so can become standing waves.
- Modes only reflected if density scale height < length scale of mode → pressure changes required to make the wave cannot be maintained over mode period.
- Density scale height reaches a minimum just above surface → maximum frequency above which modes no longer reflected.
- Known as acoustic cut-off, $\approx 5100\mu\text{Hz}$ (≈3 min).



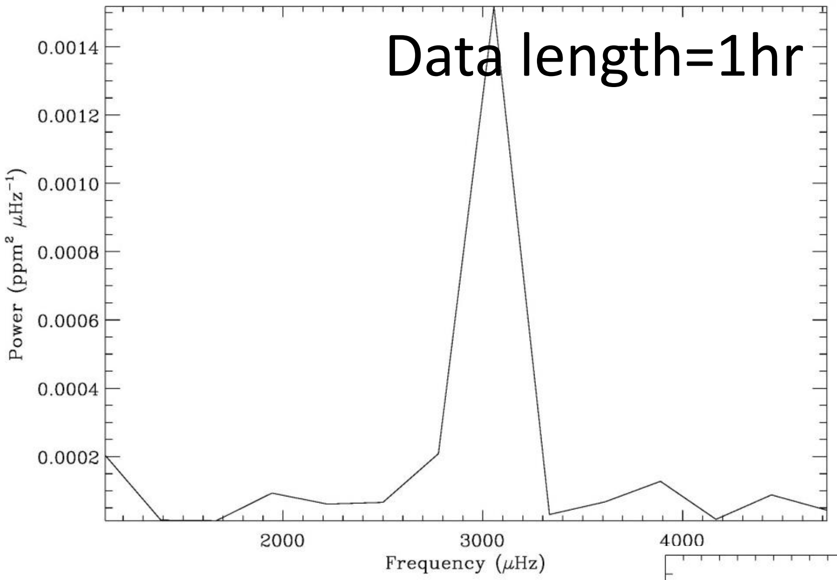
Different types of data

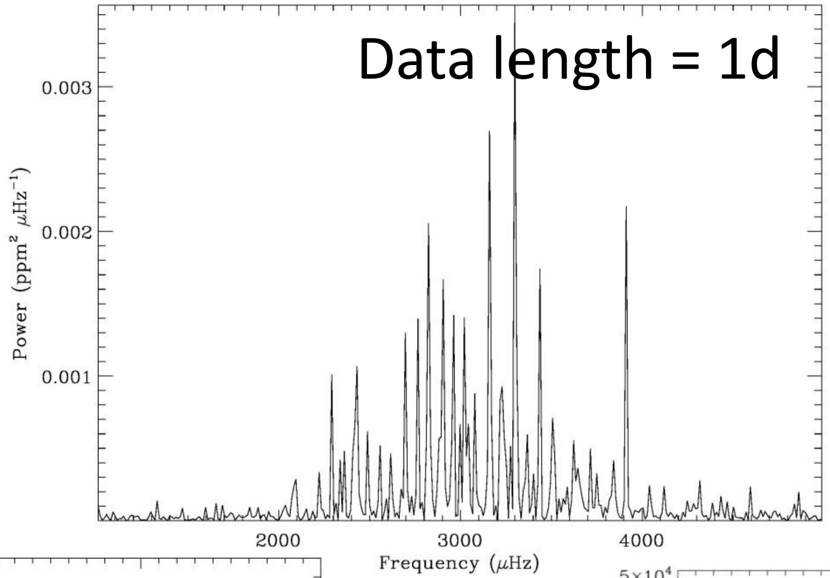


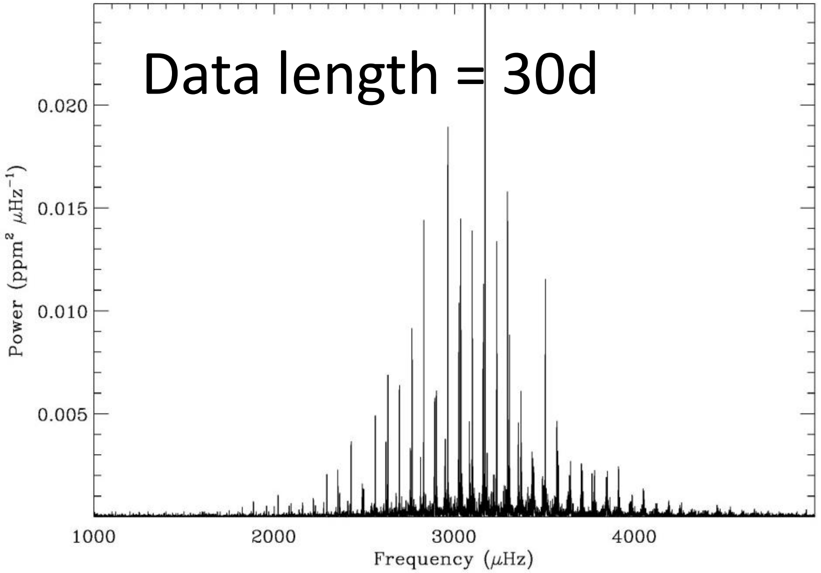
Global velocity timeseries

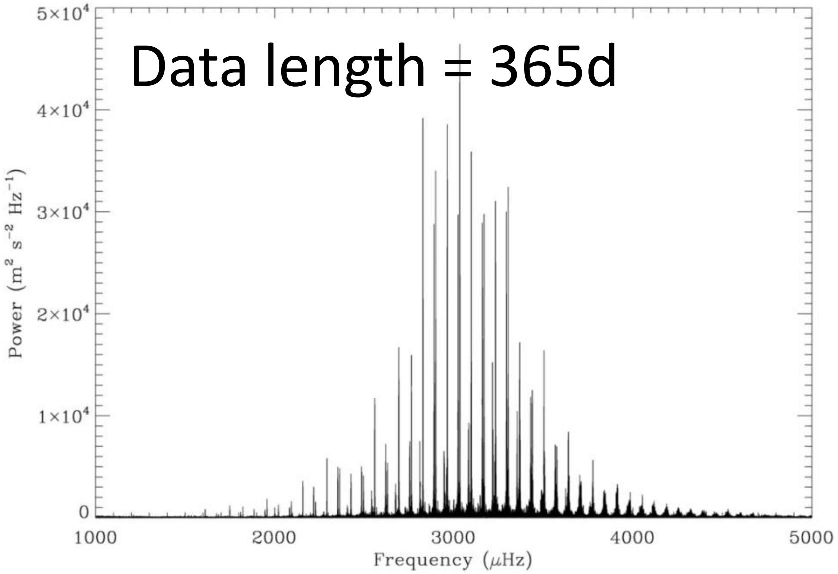


Global power spectra



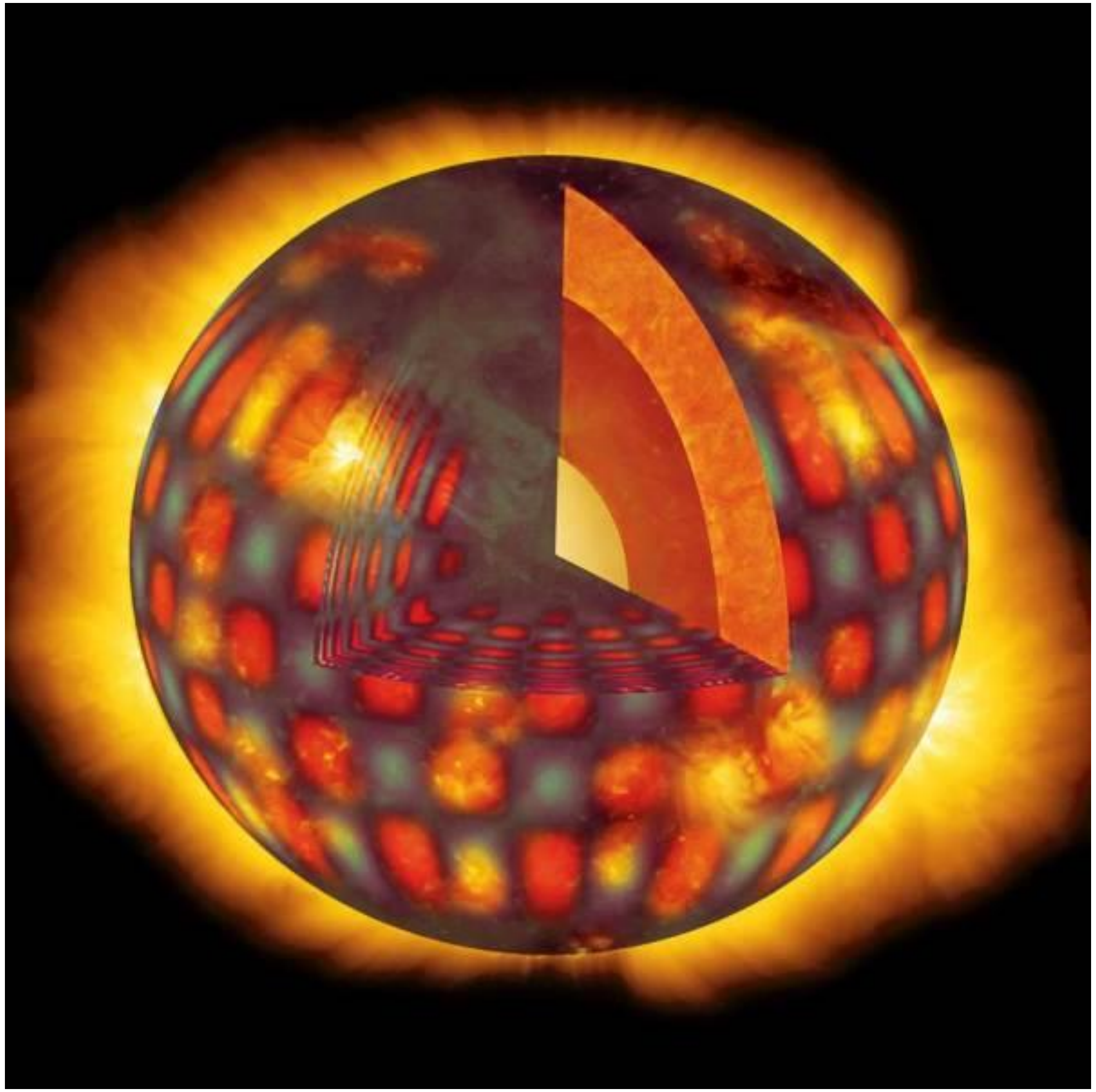






But what do they sound like

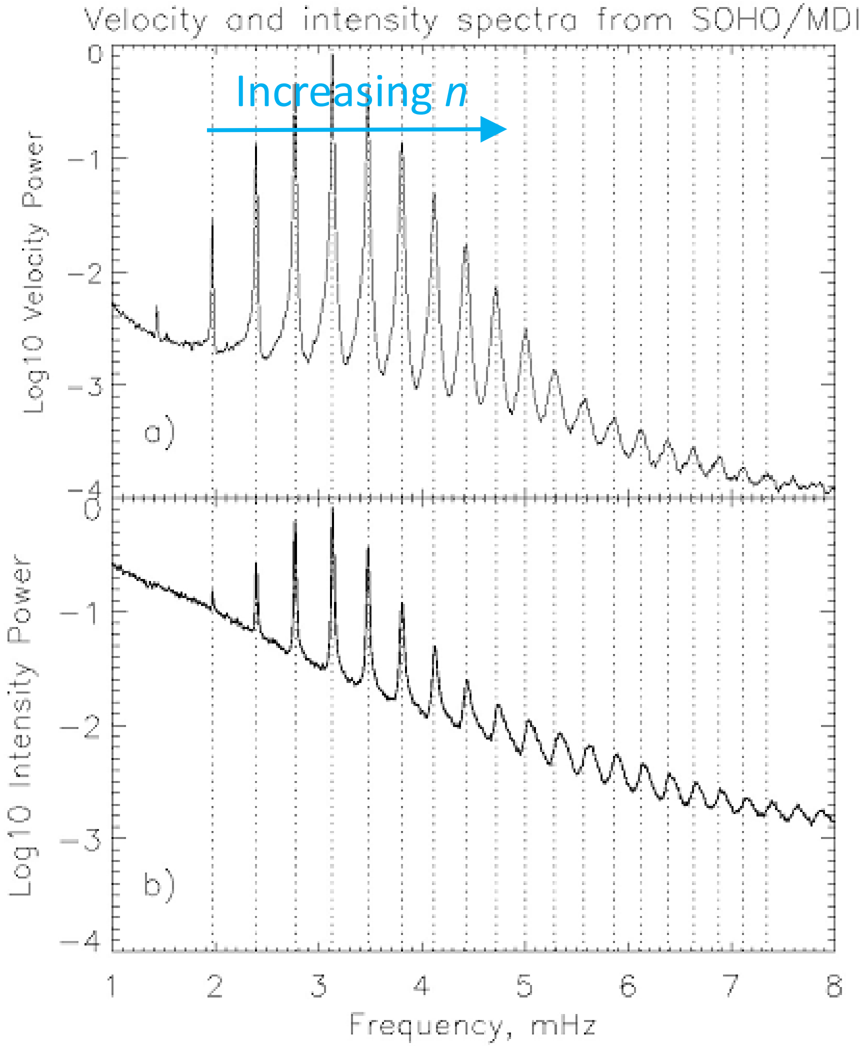
One wave scaled to middle C

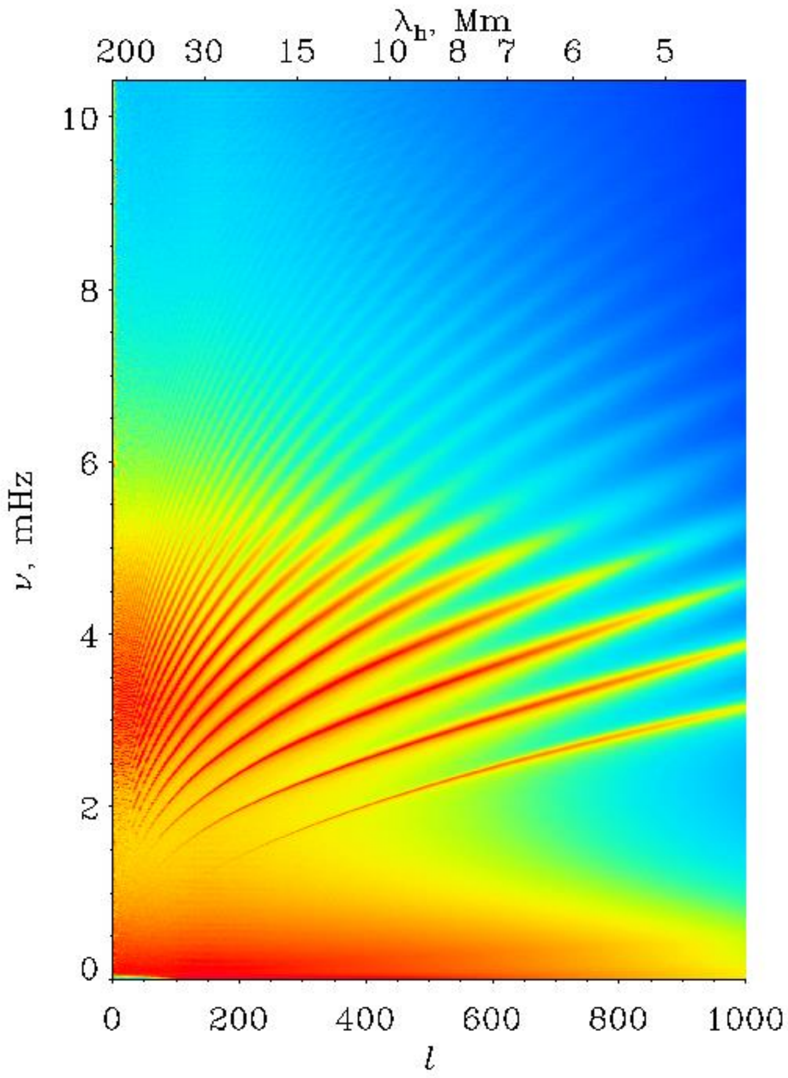


All waves

Global resolved power spectra

Power spectra of specific ℓ and m

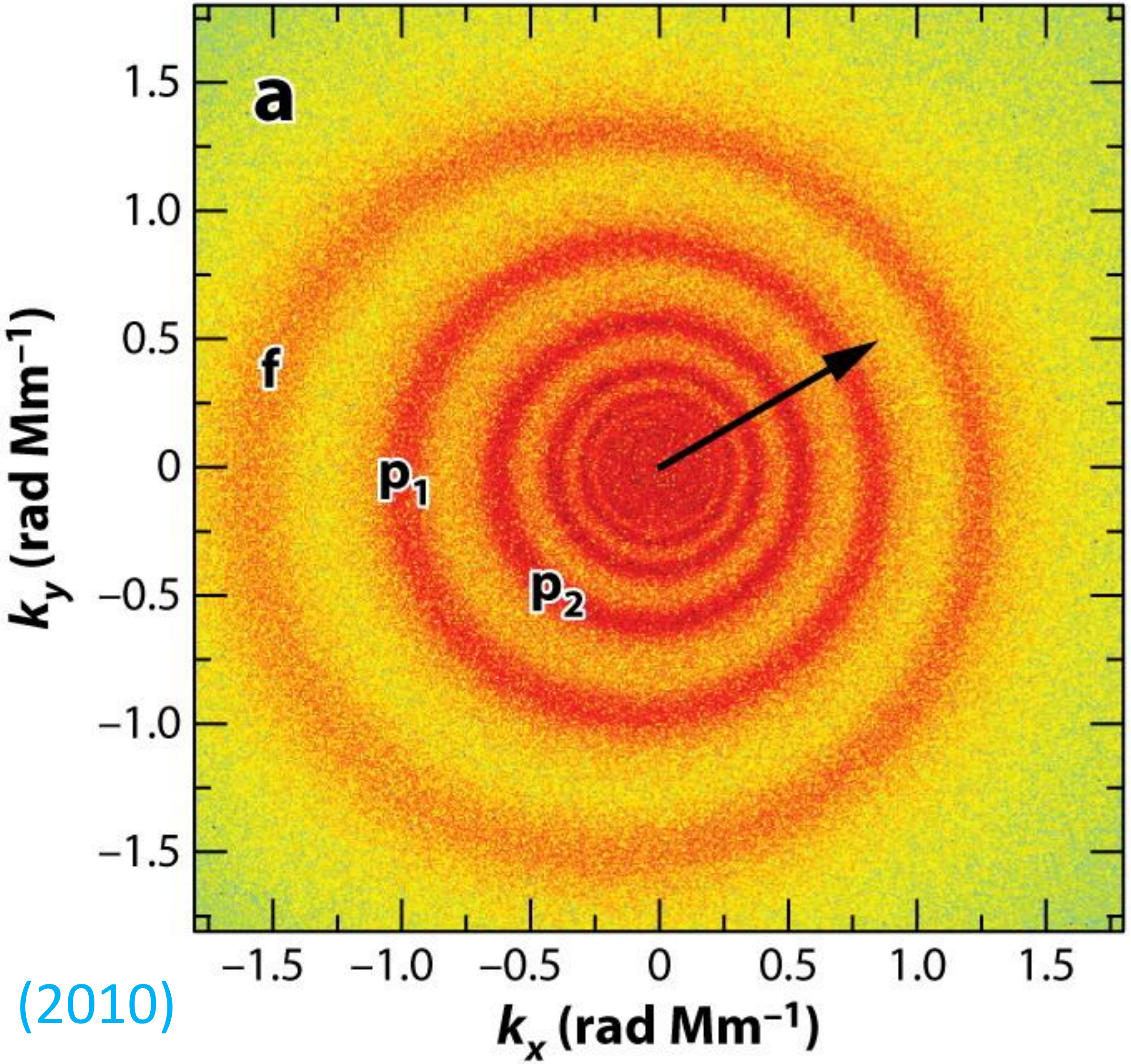




Local helioseismology: Ring diagrams

WARWICK

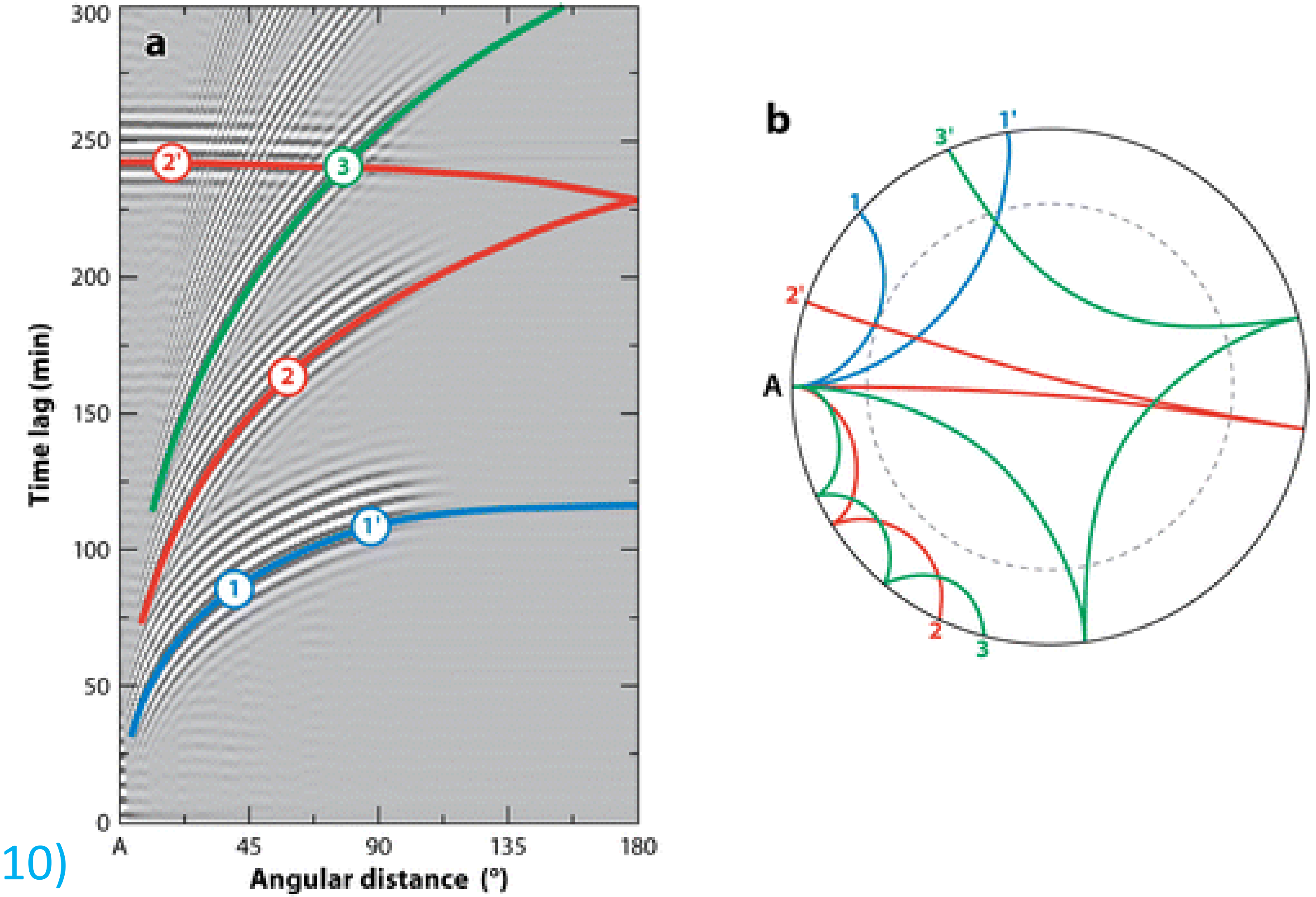
- Track patches of surface with radius 2-30°.
- Produce 3D power spectra.
- When no flow, radius of each ring is wavenumber.
- Flows distort the rings.



Gizon et al. (2010)

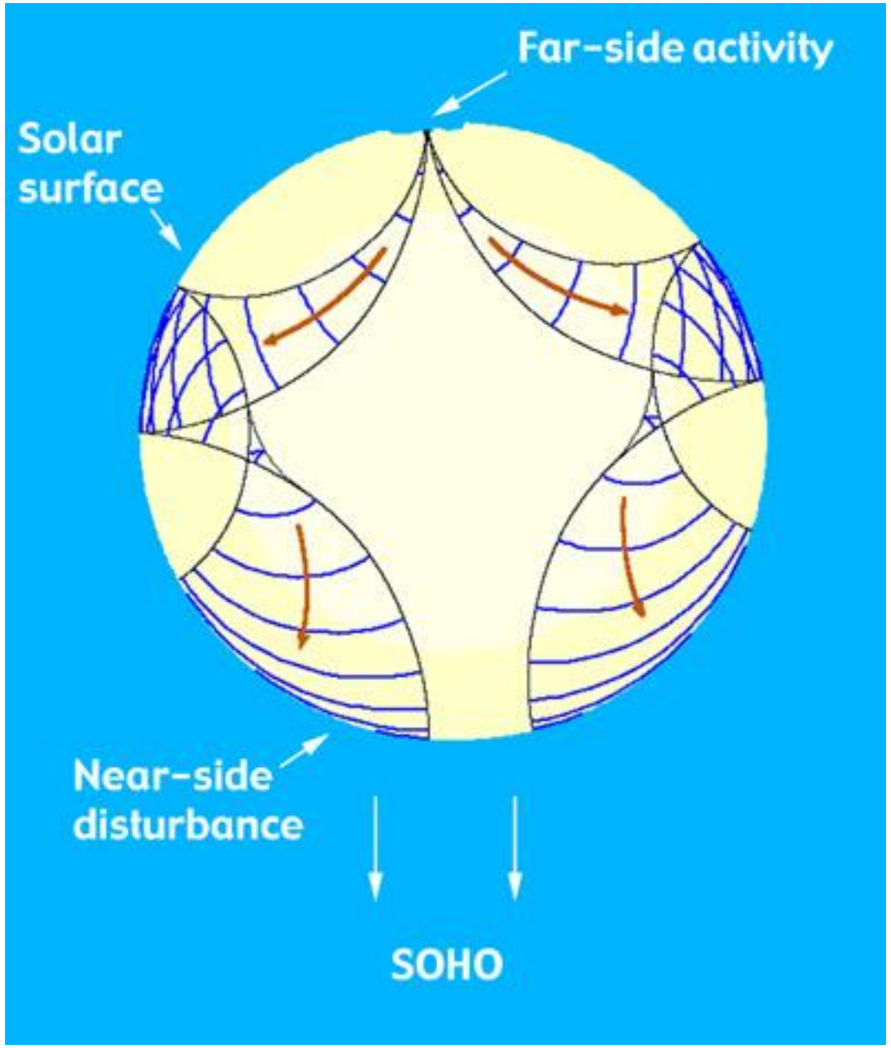
Local Helioseismology: Time-distance

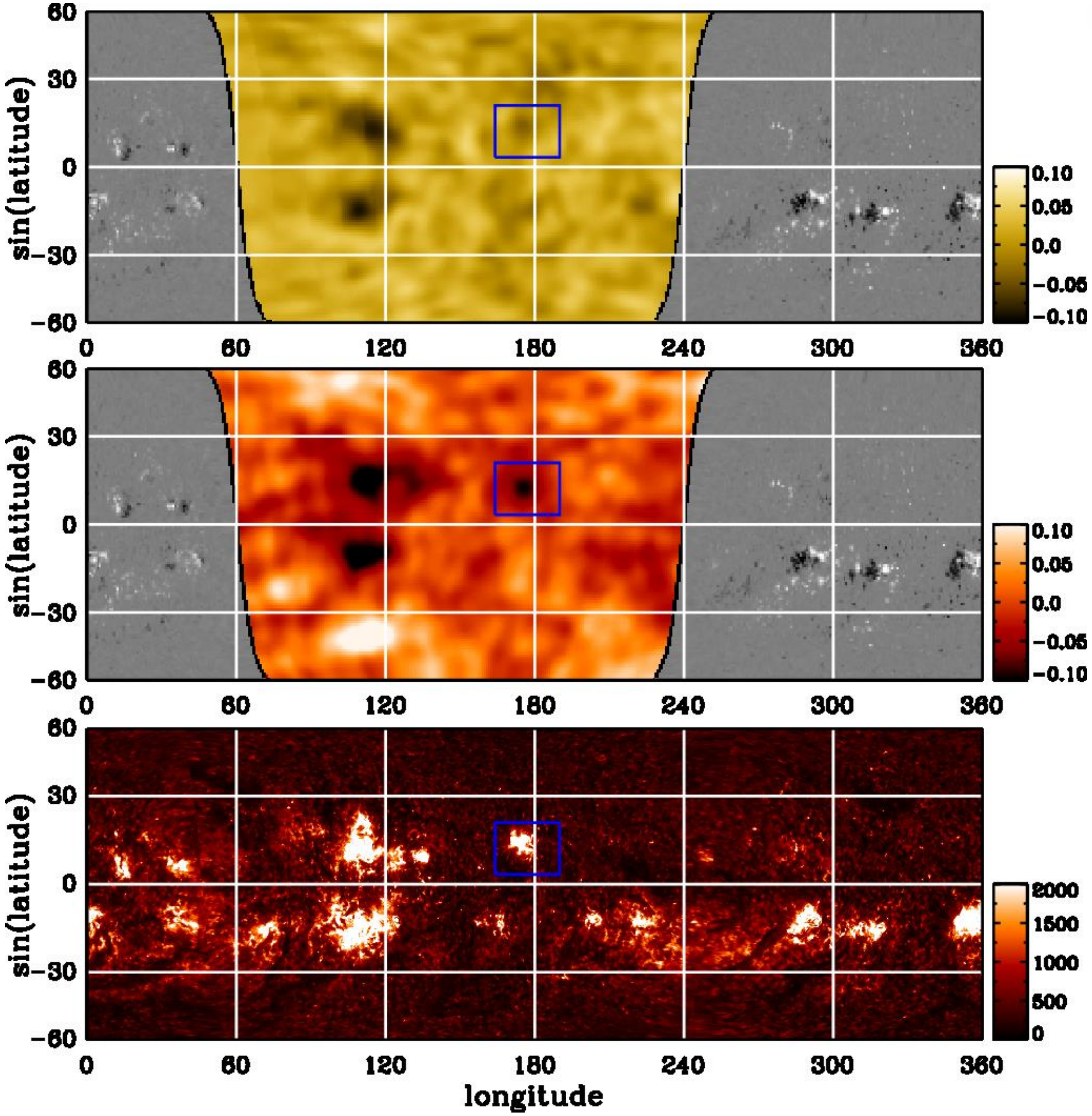
- Measure cross-covariance between two points.
- Ridges correspond to different paths taken by the wave energy.
- Flows obtained by inverting cross-covariance observations.



Gizon et al. (2010)

Helioseismic holography: Far-side imaging

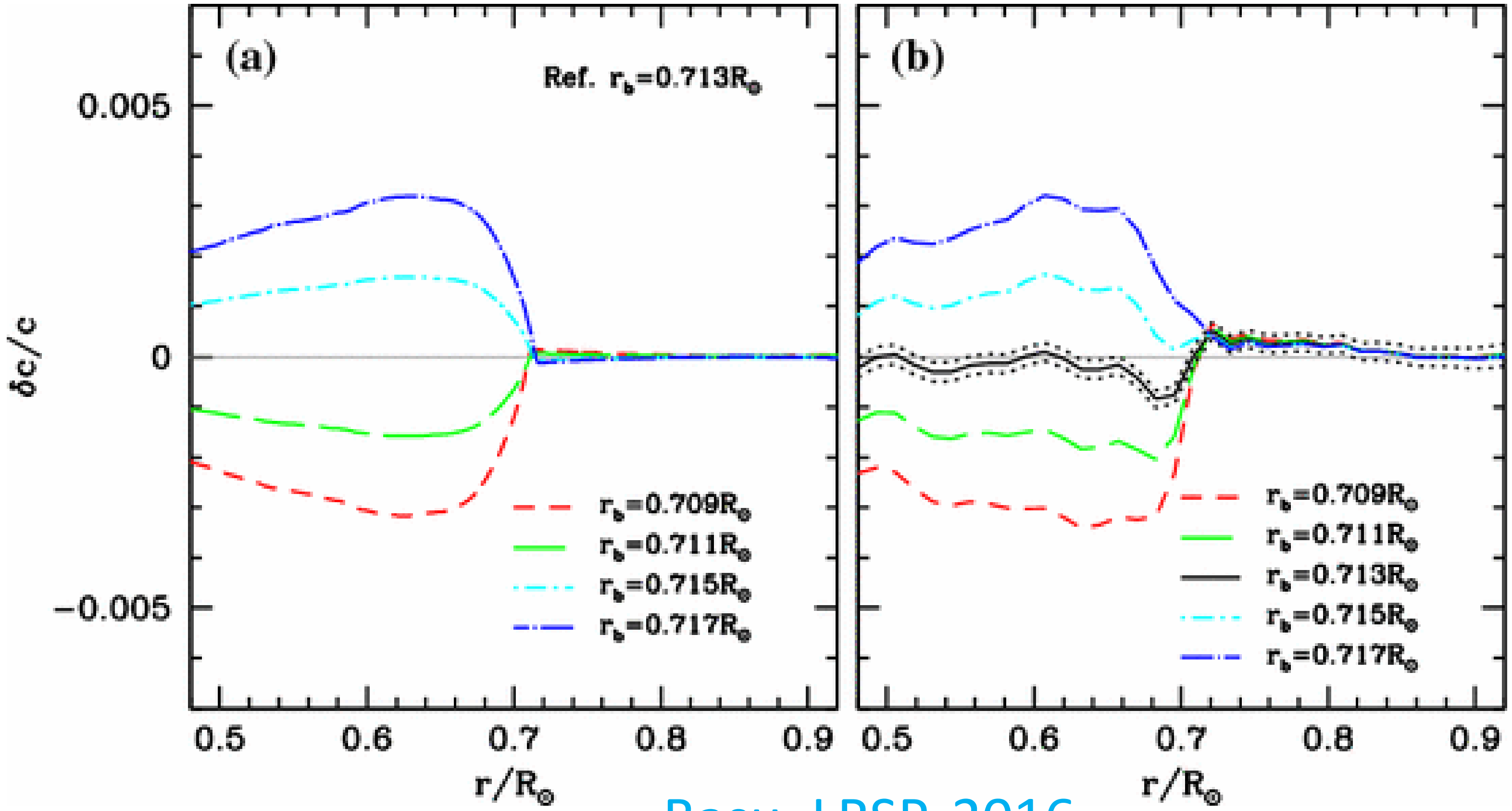




http://jsoc.stanford.edu/data/timed/

Depth of the convection zone

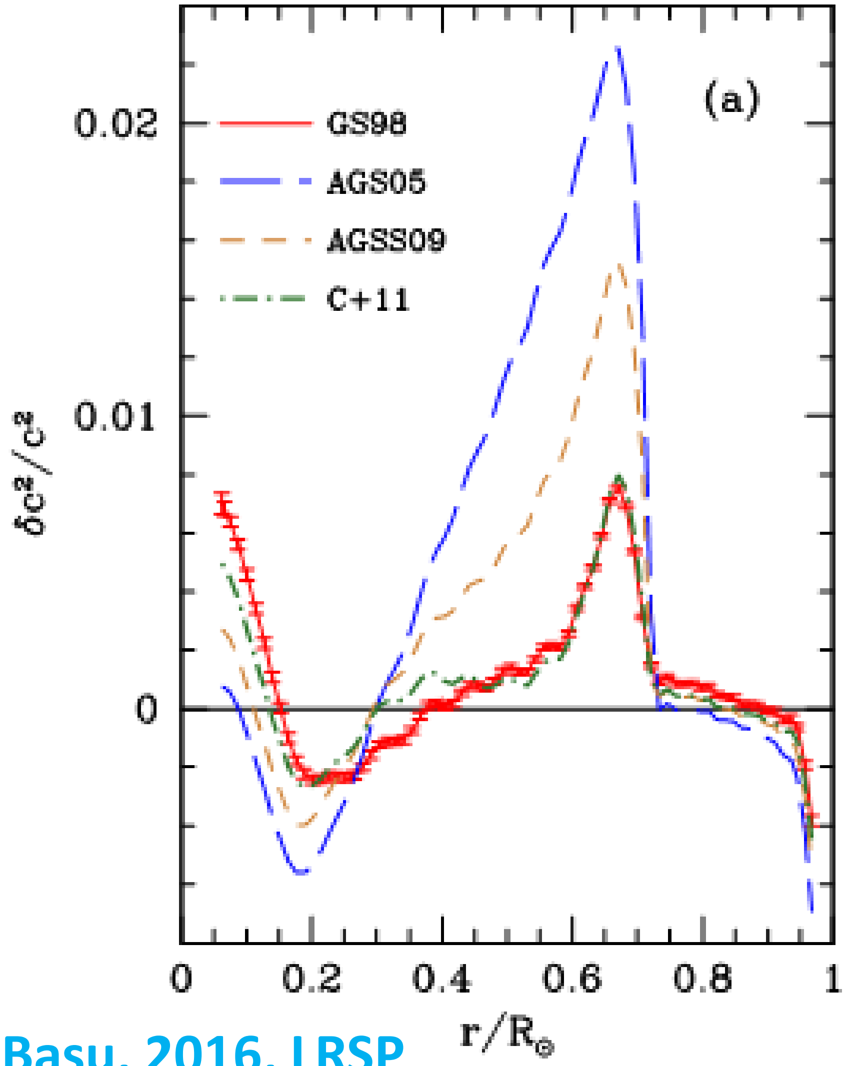
- Sharp change in temperature gradient impacts sound speed
- Helioseismology determined the radius of the base of the Sun's convection zone is $0.713 \pm 0.001 R_{sun}$.
- What is the impact of overshoot?



Basu, LRSP, 2016

Abundances within the Sun

- Difficult to measure with spectroscopy.
- Remember $c_s^2 \propto \mu^{-1}$
- Helioseismology → helium abundance, Y=0.25.
- Research ongoing into solar abundance problem



Basu, 2016, LRSP

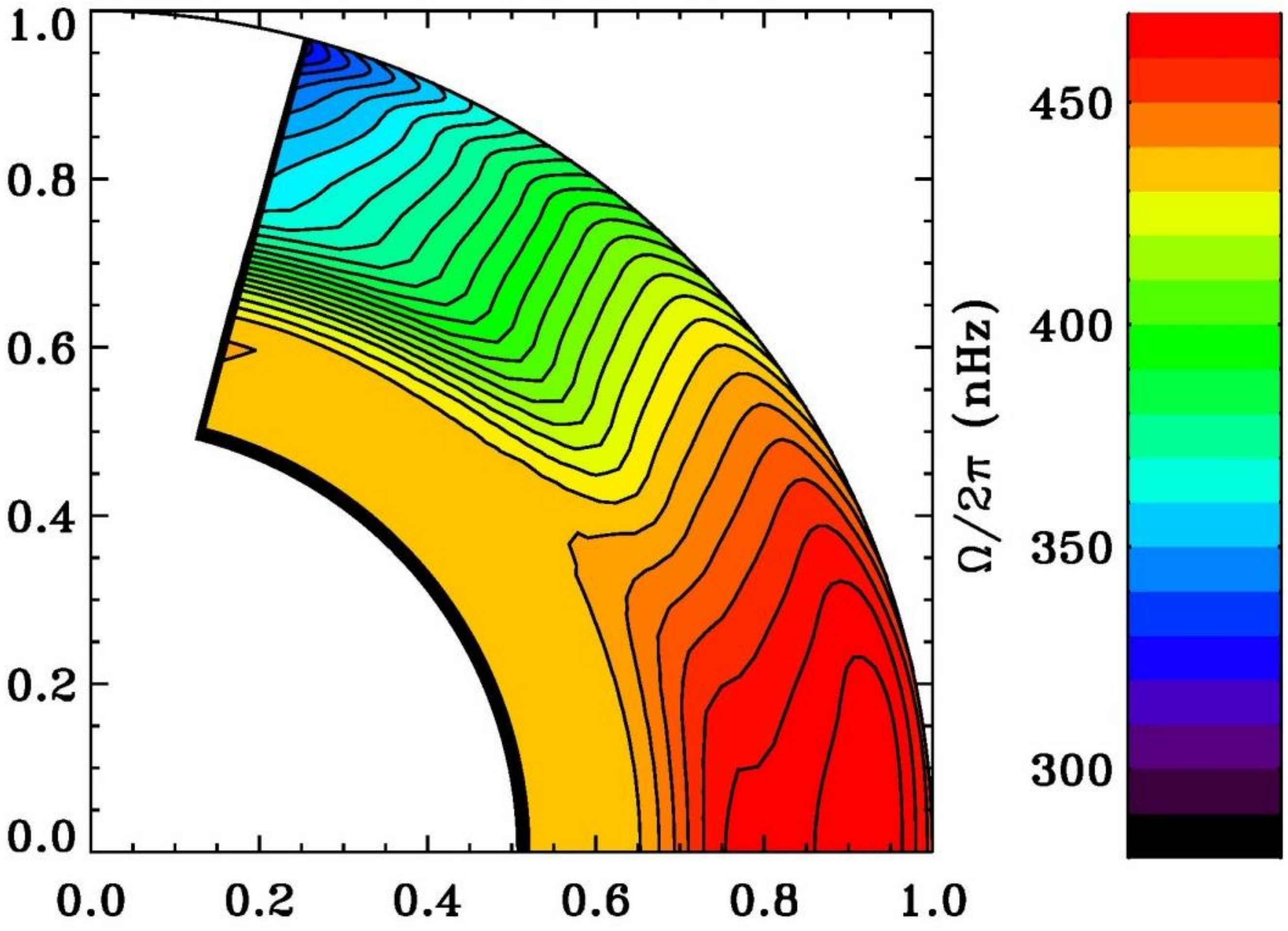
Z/X: GS98 – 0.023
AGS05 – 0.016
AGSS09 – 0.018
C+11 – 0.0209

Internal rotation profile

- Rotation splits frequencies of *m* components.
  $\delta\nu_{\mathrm{rot}} = \nu_{\ell,n,m+1} - \nu_{\ell,n,m}$
- For the Sun, $\delta\nu_{\mathrm{rot}} \sim 0.4\mu\mathrm{Hz}$,

$$\Omega_{\mathrm{rot}} = \frac{1.0}{\delta\nu_{\mathrm{rot}}},$$

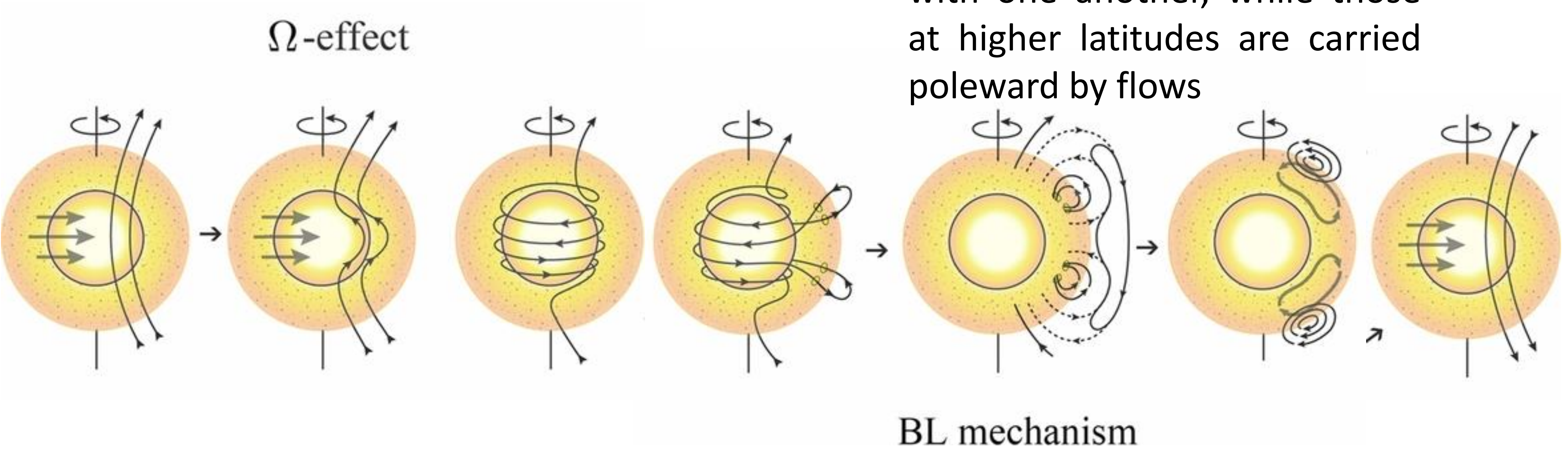
  or ~29d.
- Why is there a near-surface shear layer?
- Why doesn't the tachocline diffuse?



Courtesy of Michael Thompson

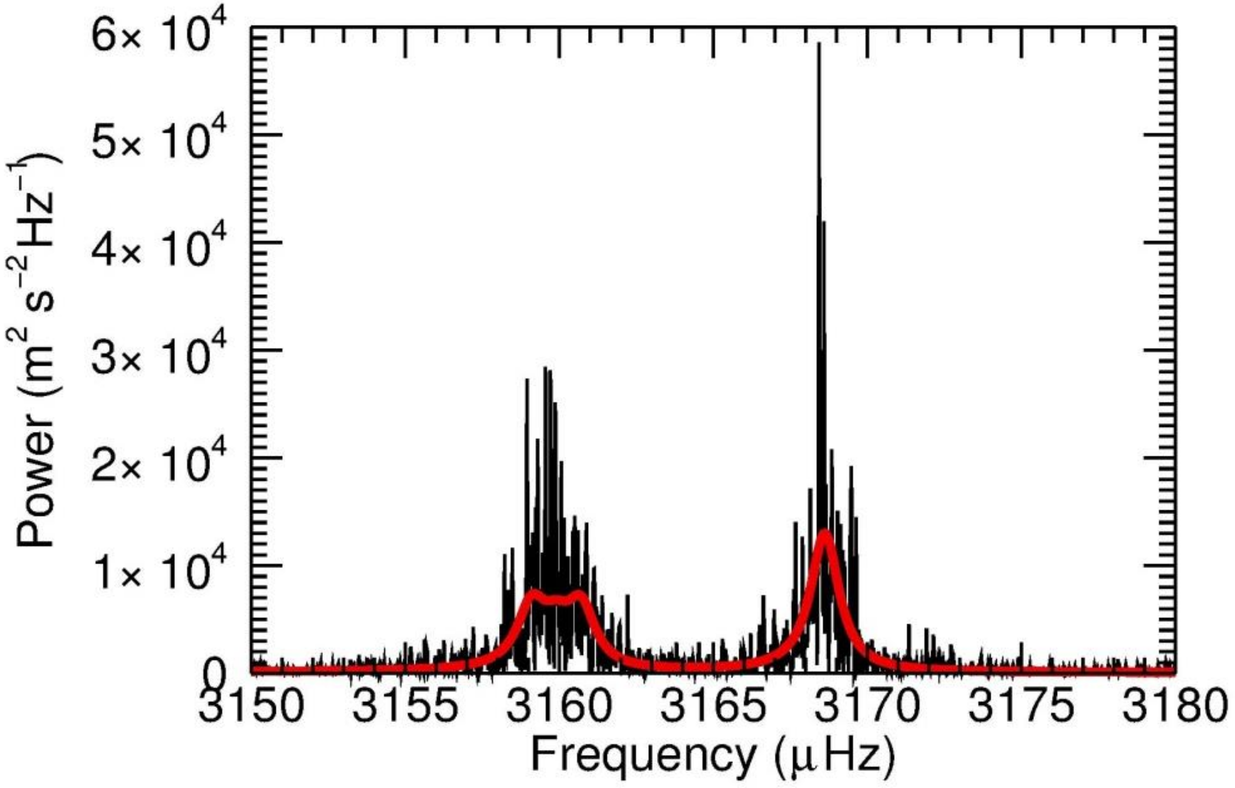
The solar dynamo

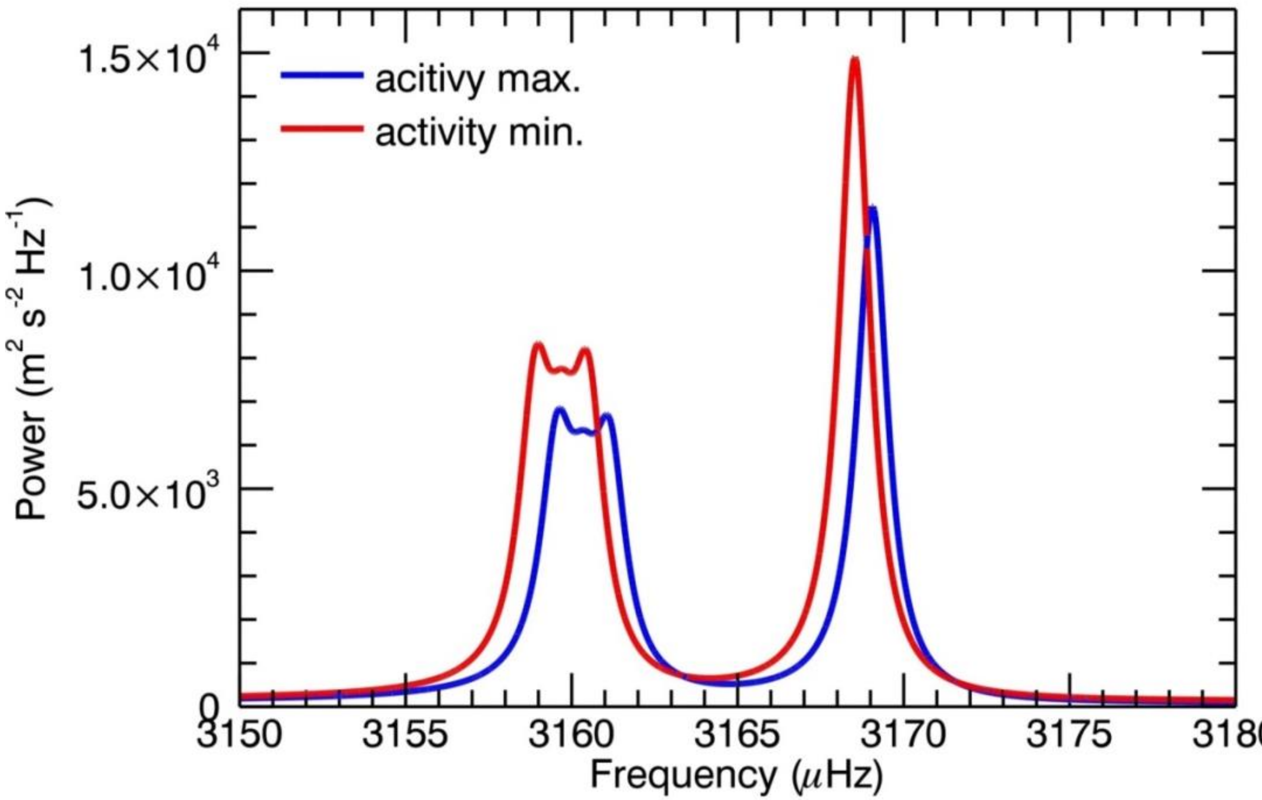
Spots near the equator connect with one another, while those at higher latitudes are carried poleward by flows



Sanchez et al (2014)

Solar cycle variations in p modes

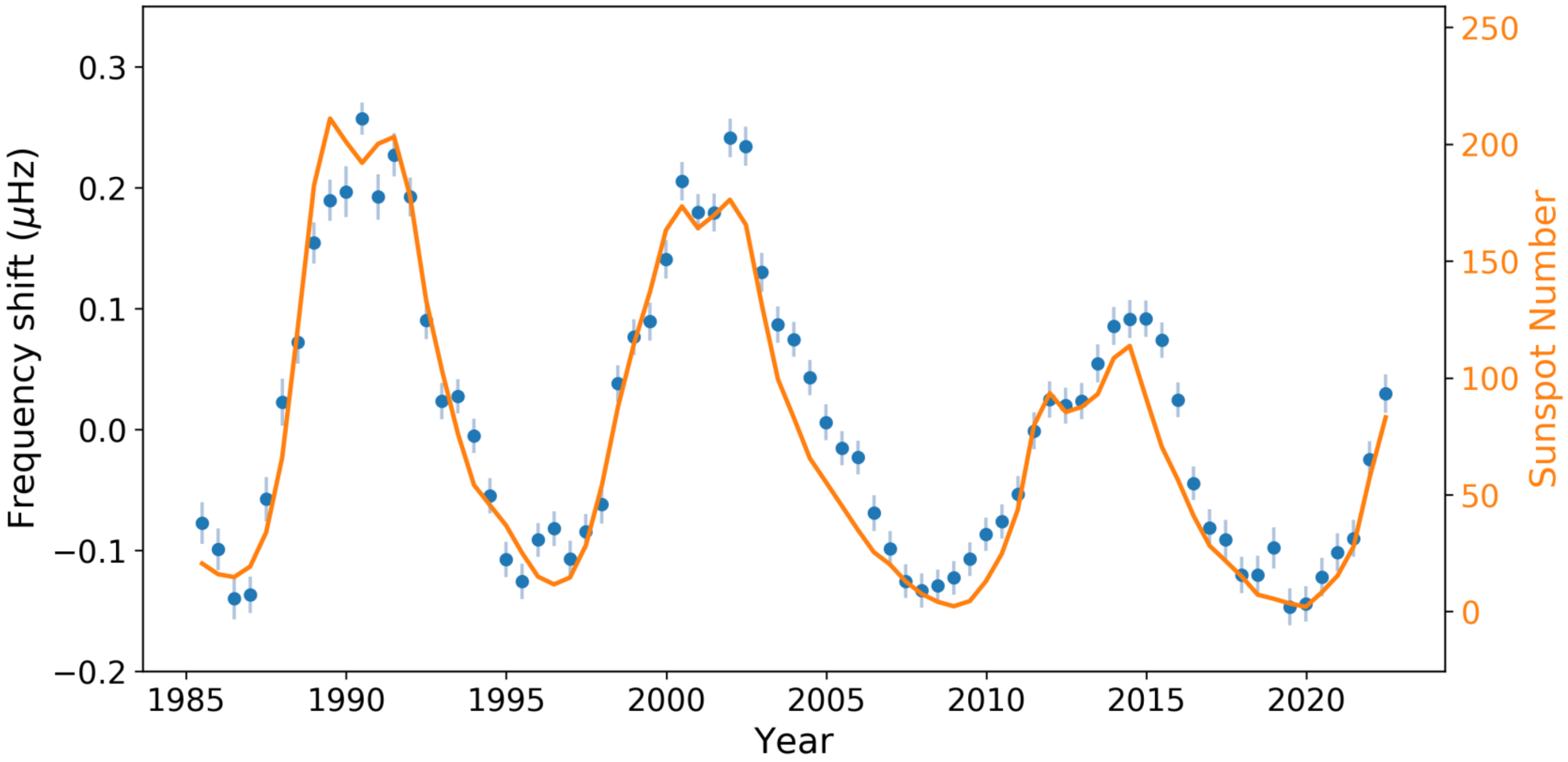




Seismic frequencies and the solar cycle

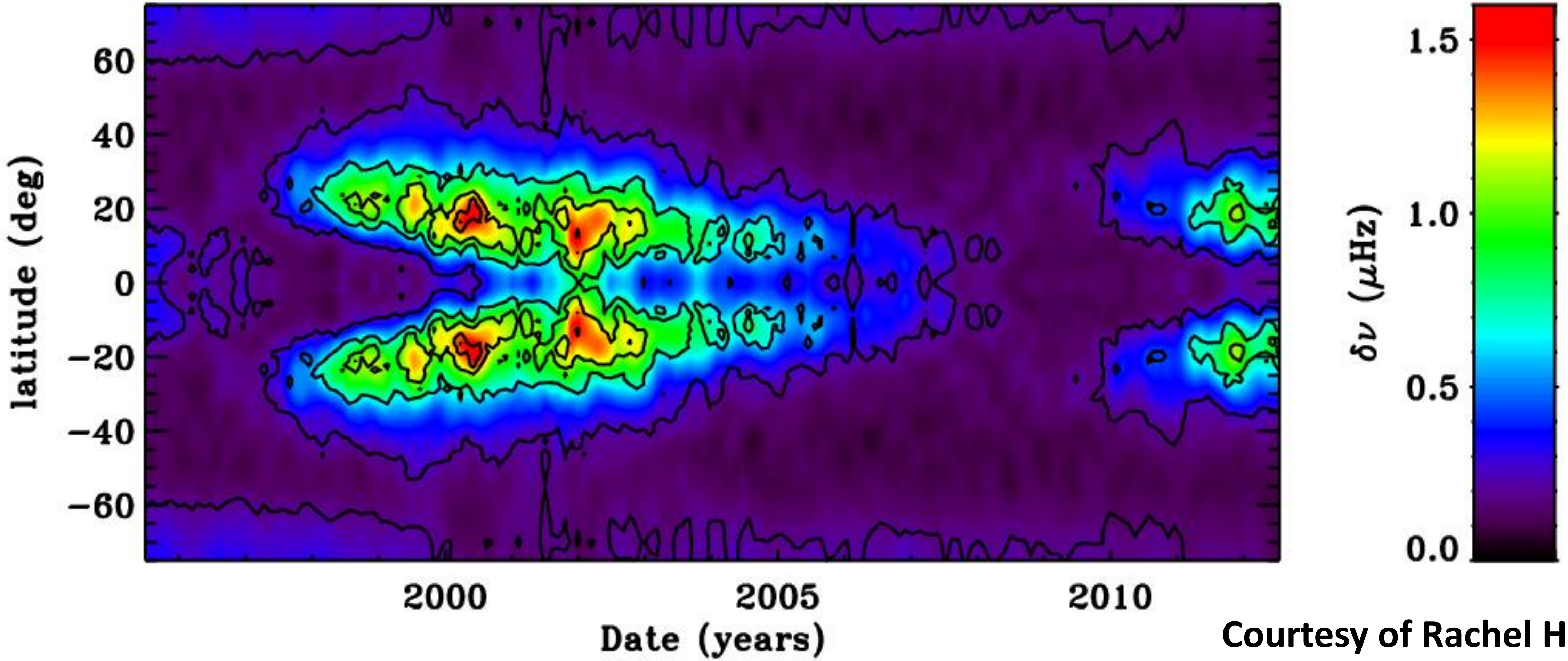
WARWICK

- Seismic frequencies respond to changes in the surface activity (Woodard & Noyes ,1985).
- Causes:
  - Direct – Lorentz force.
  - Indirect – change in cavity properties.
- Shift ≈ 0.01% of mode frequency
- Shift of ≈ 0.03μHz G^{-1}



Frequency shift inversions

- Howe et al. (2002) localized the frequency shifts in latitude.

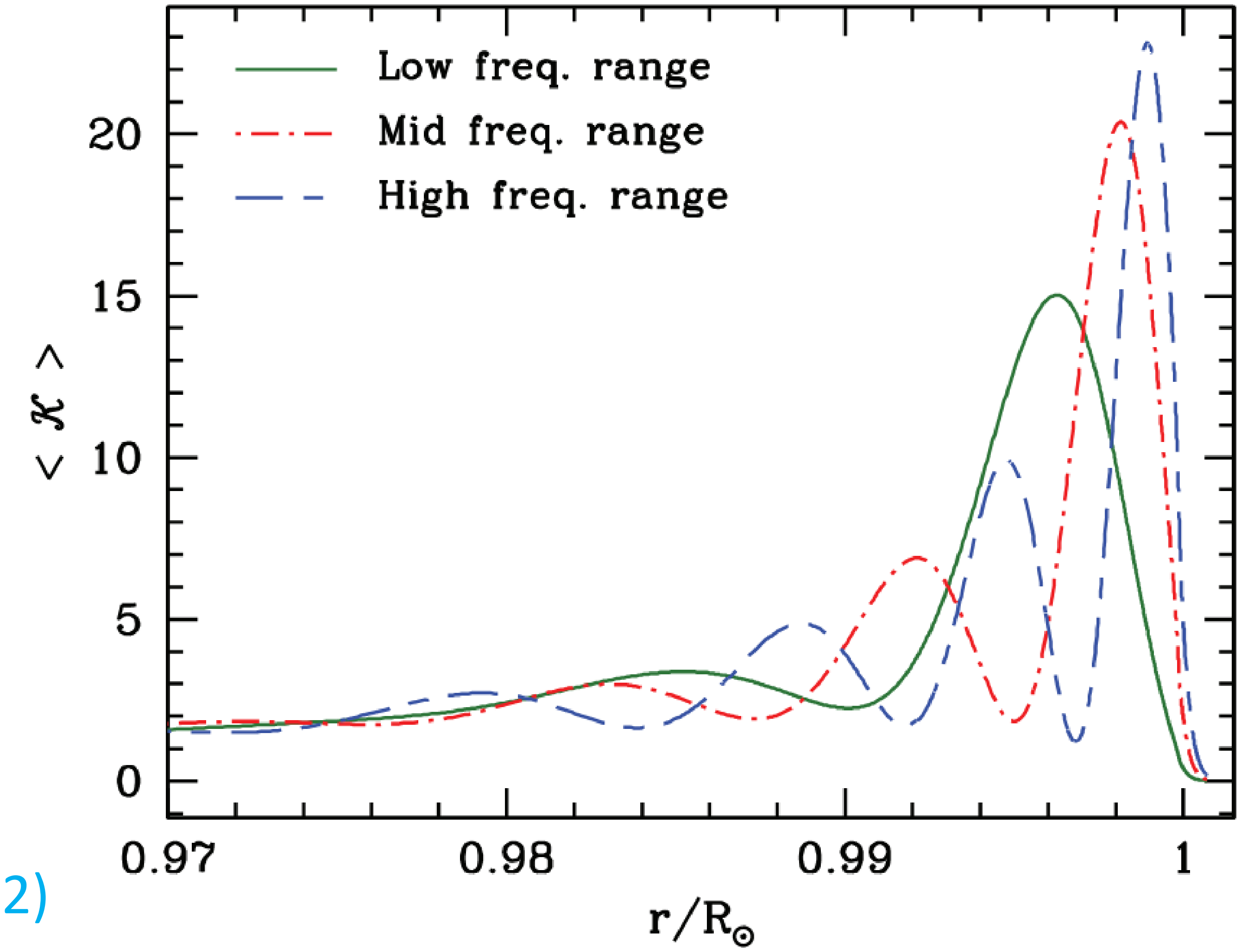


Courtesy of Rachel Howe

Can we probe deeper regions?

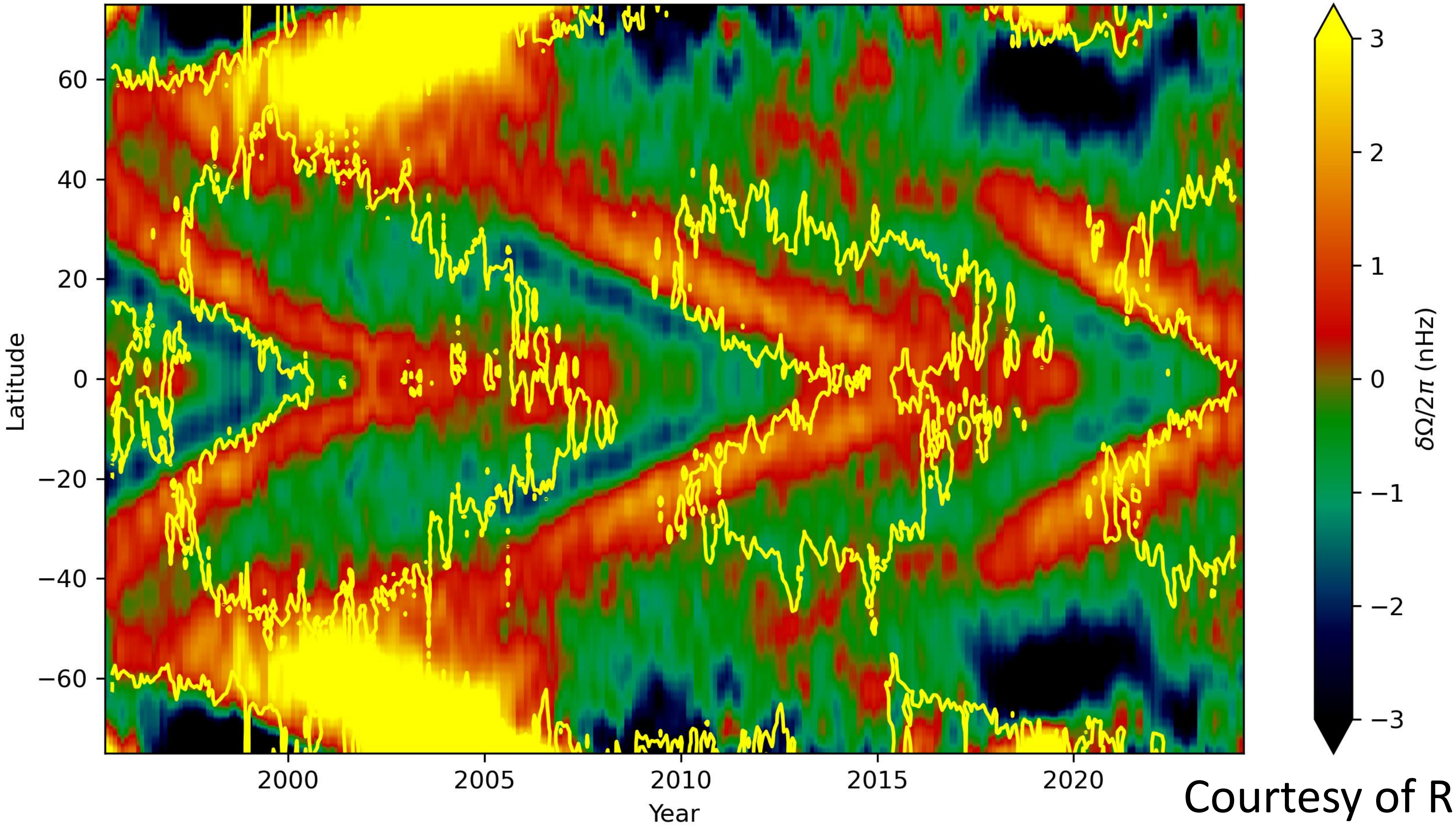
- high sound speed ⇒ limited influence on oscillations.
- plasma-β $= p_{plasma}/p_{magnetic} >> 1$
- Short answer: Not very well at the moment

Increased sensitivity



Basu et al. (2012)

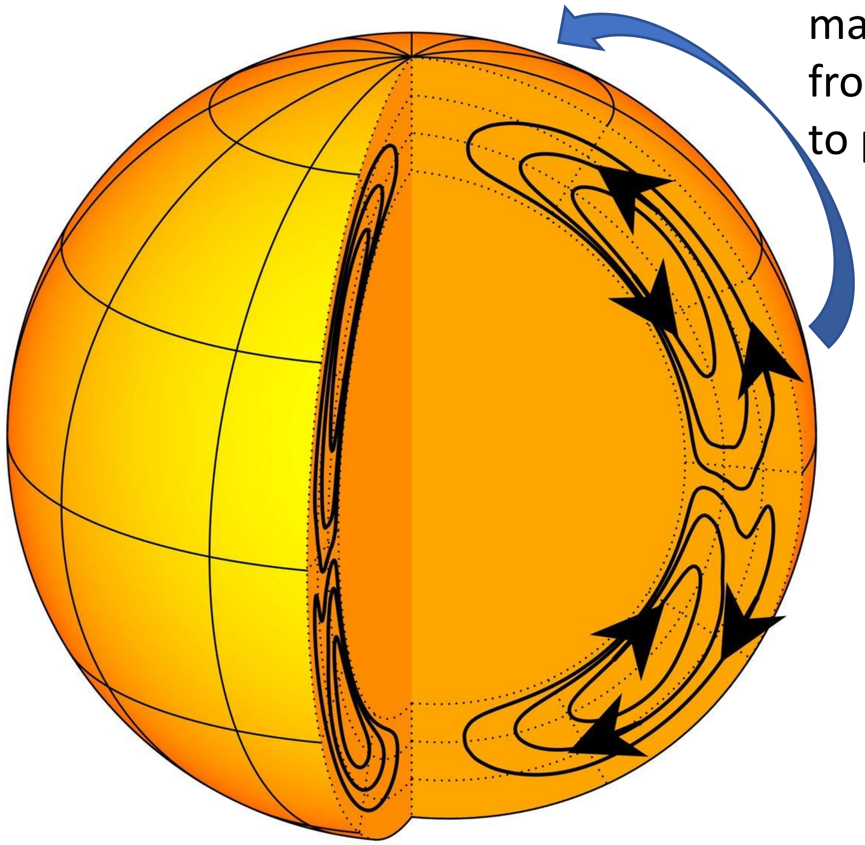
Torsional Oscillation



Courtesy of Rachel Howe

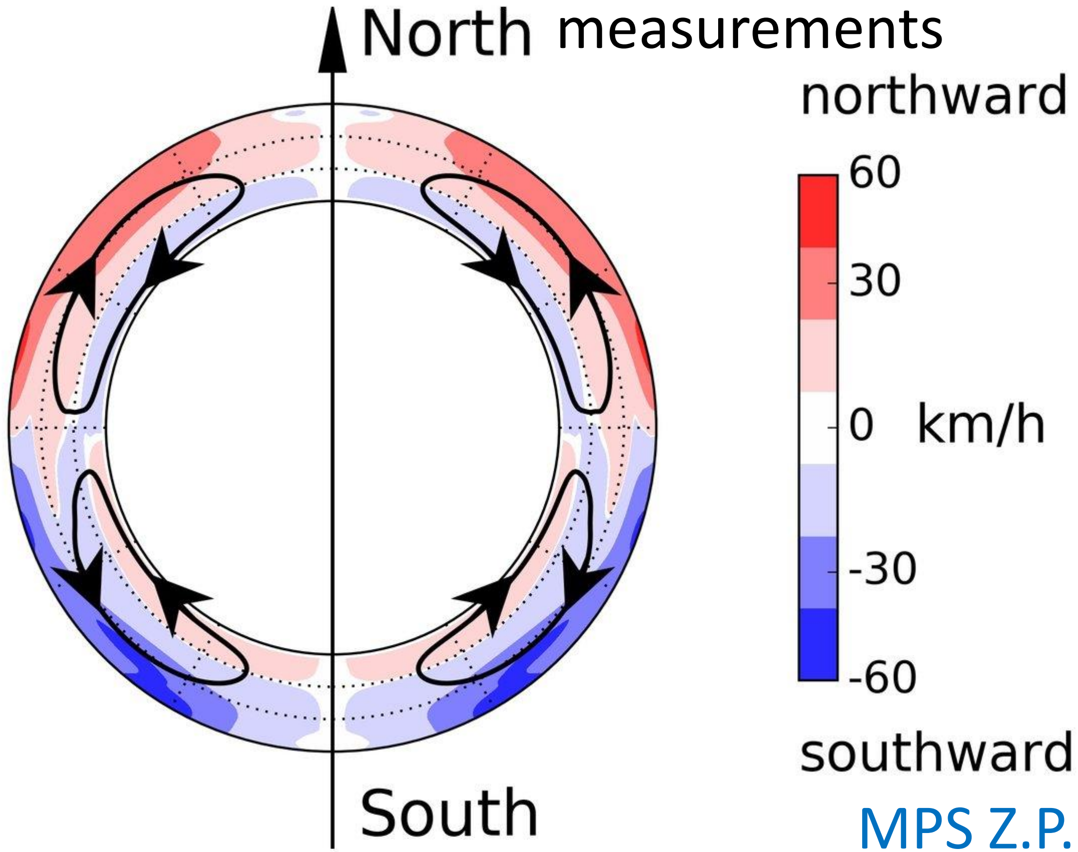
Meridional circulation

WARWICK



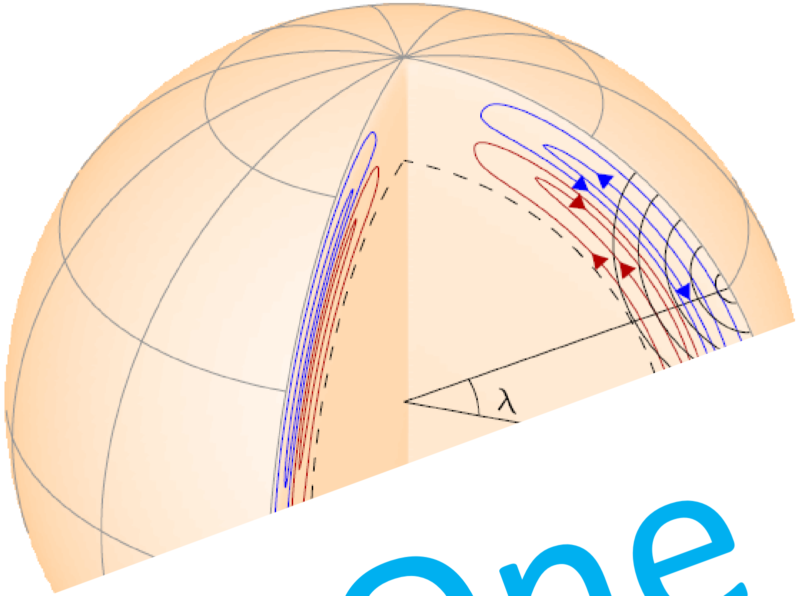
Drags magnetic flux from equator to poles

Helioseismology measurements

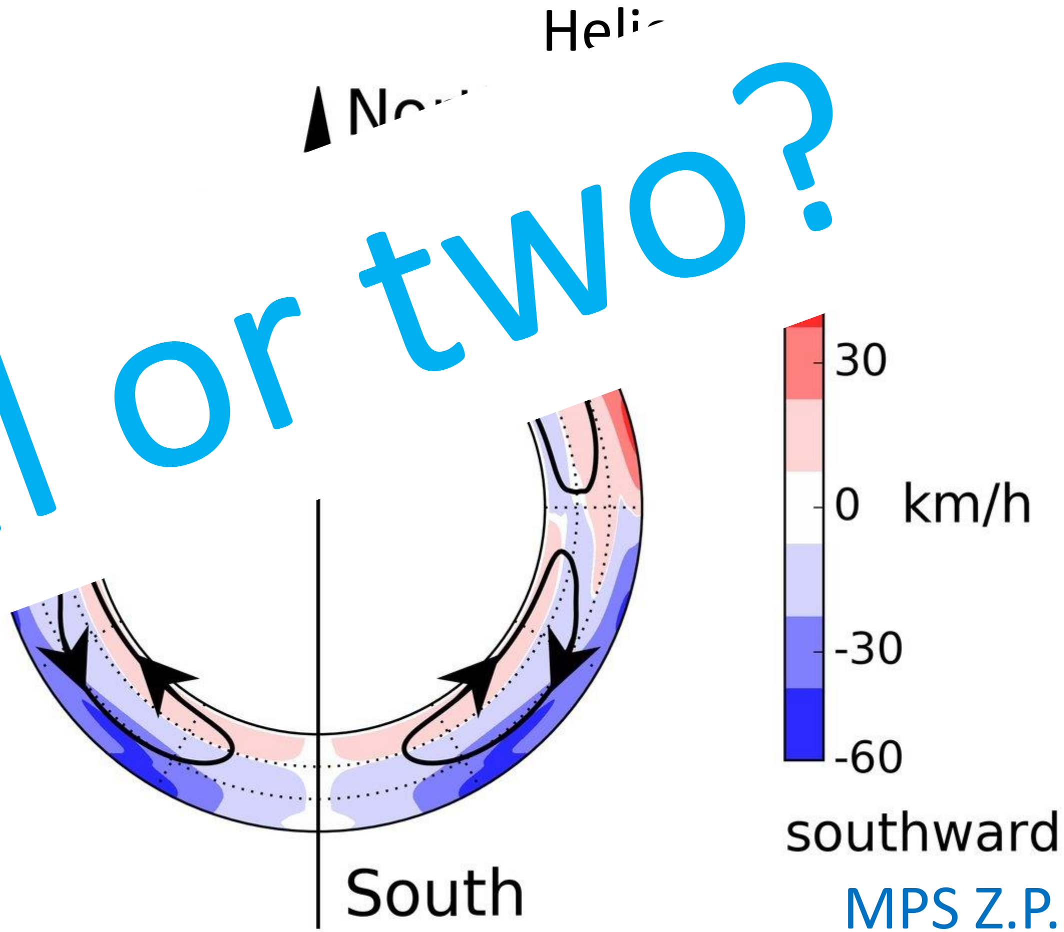


MPS Z.P. Liang
Gizon et al. (2020)

Meridional circulation



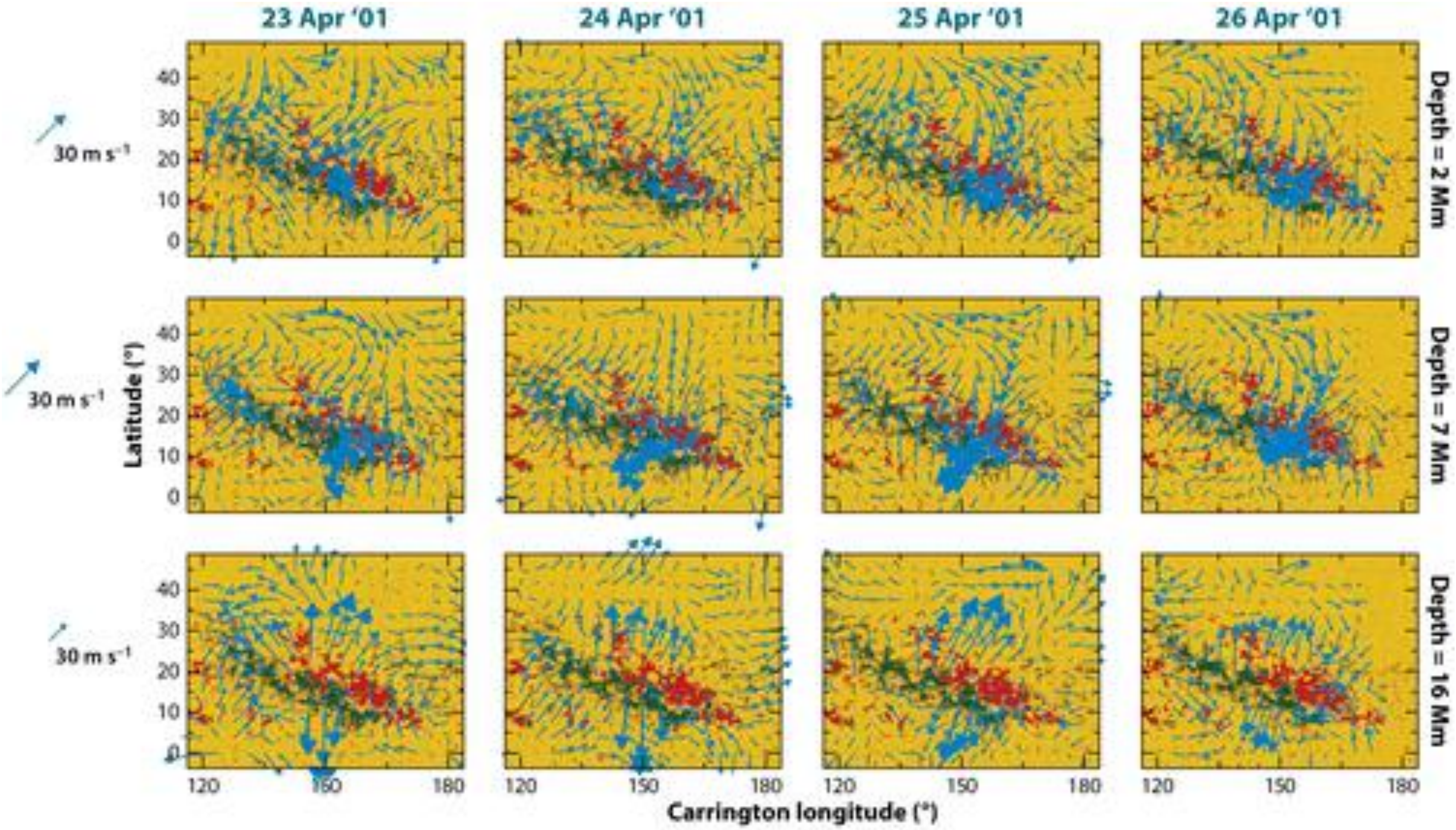
One cell or two?



Zhao et al. (2013)

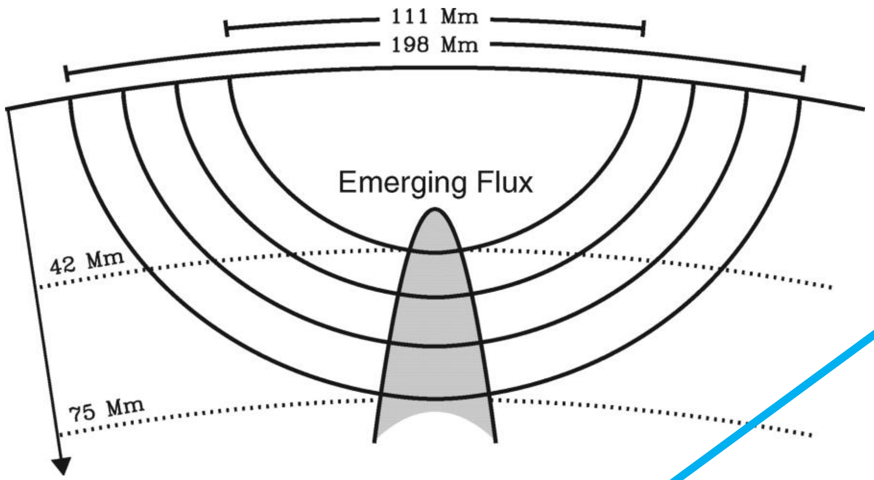
MPS Z.P. Liang
Gizon et al. (2020)

Flows around active regions/sunspots



Gizon L, et al. 2010.
Annu. Rev. Astron. Astrophys. 48:289–338

Emerging active regions

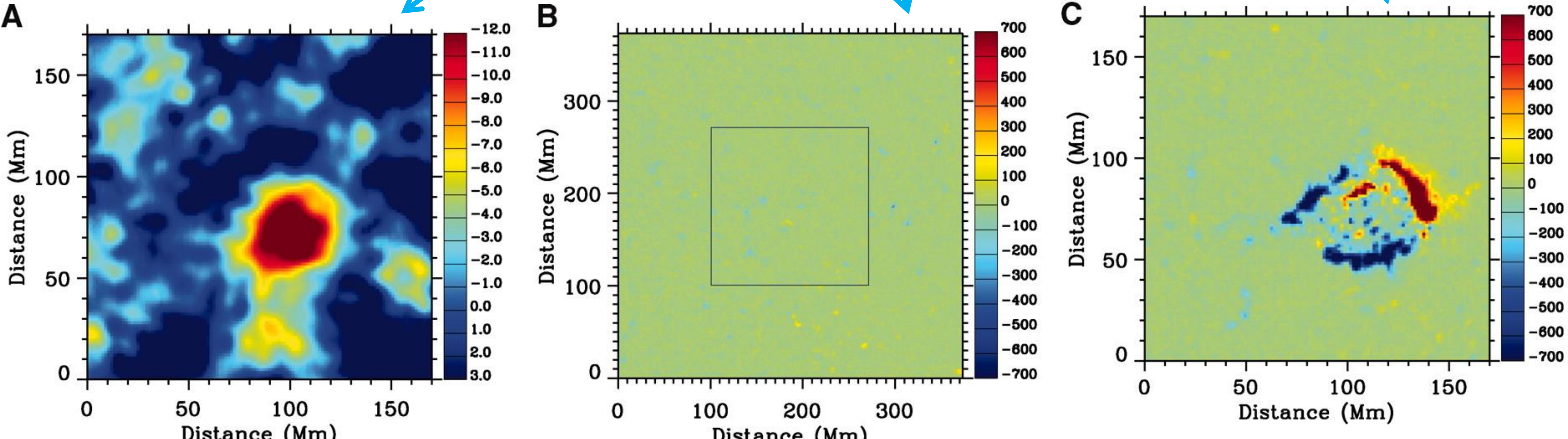


Mean travel time

Surface flux at same time

Surface flux 24h later

Ilonidis et al (2011)



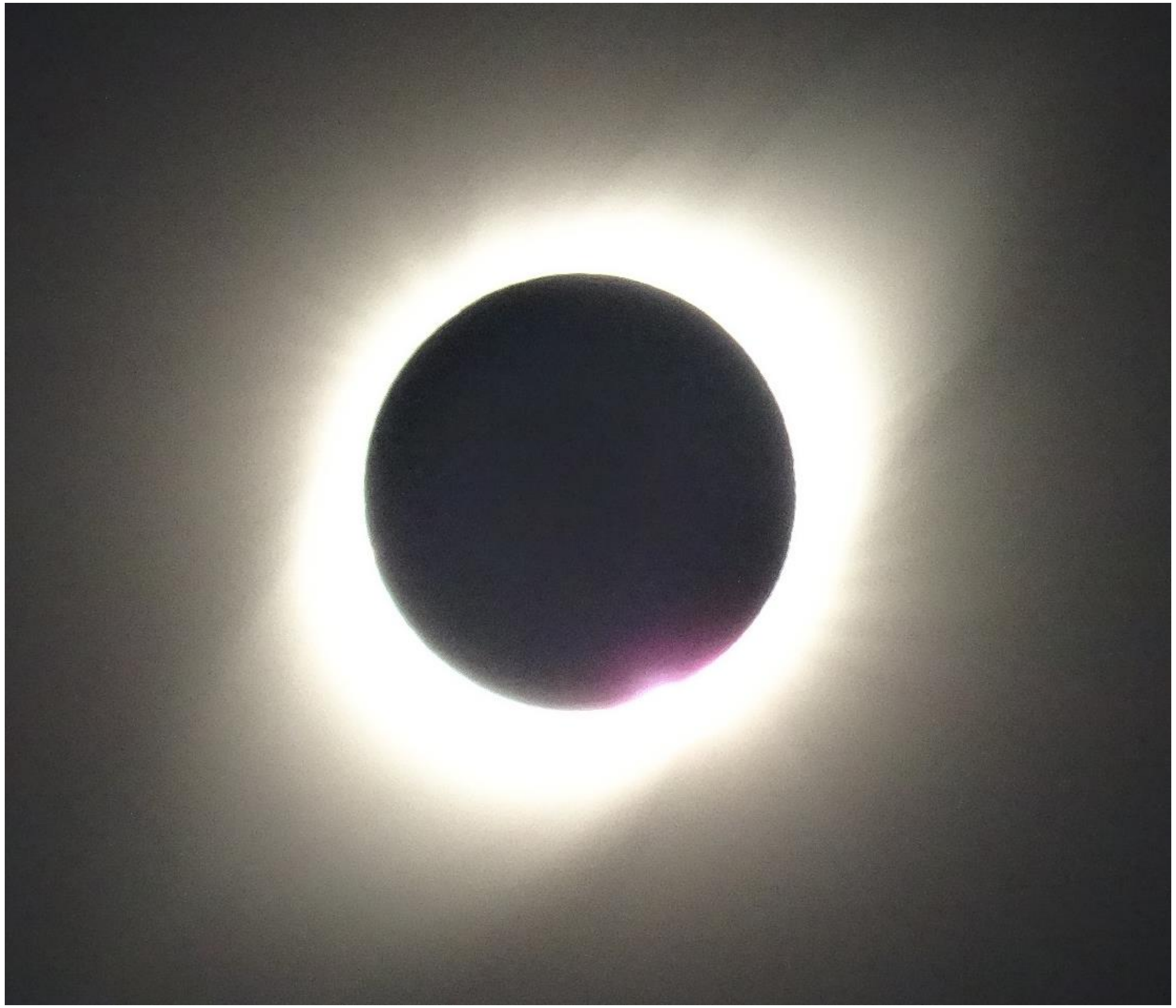
Summary

WARWICK

- We know a great deal about the interior of the Sun even though we can't actually see it.
- Helioseismology allows us to infer conditions in the solar interior.
  - Primarily looks at acoustic p modes.
  - These can then be used to infer properties & flows in interior and how they vary.
  - Can inform understanding of e.g. abundances, dynamo, flux emergence, far-side.
- The Sun is just 1 star and can now do asteroseismology on many, many other stars.

- Thanks for listening
- Any questions?

Credit: Me, Chile, 2019

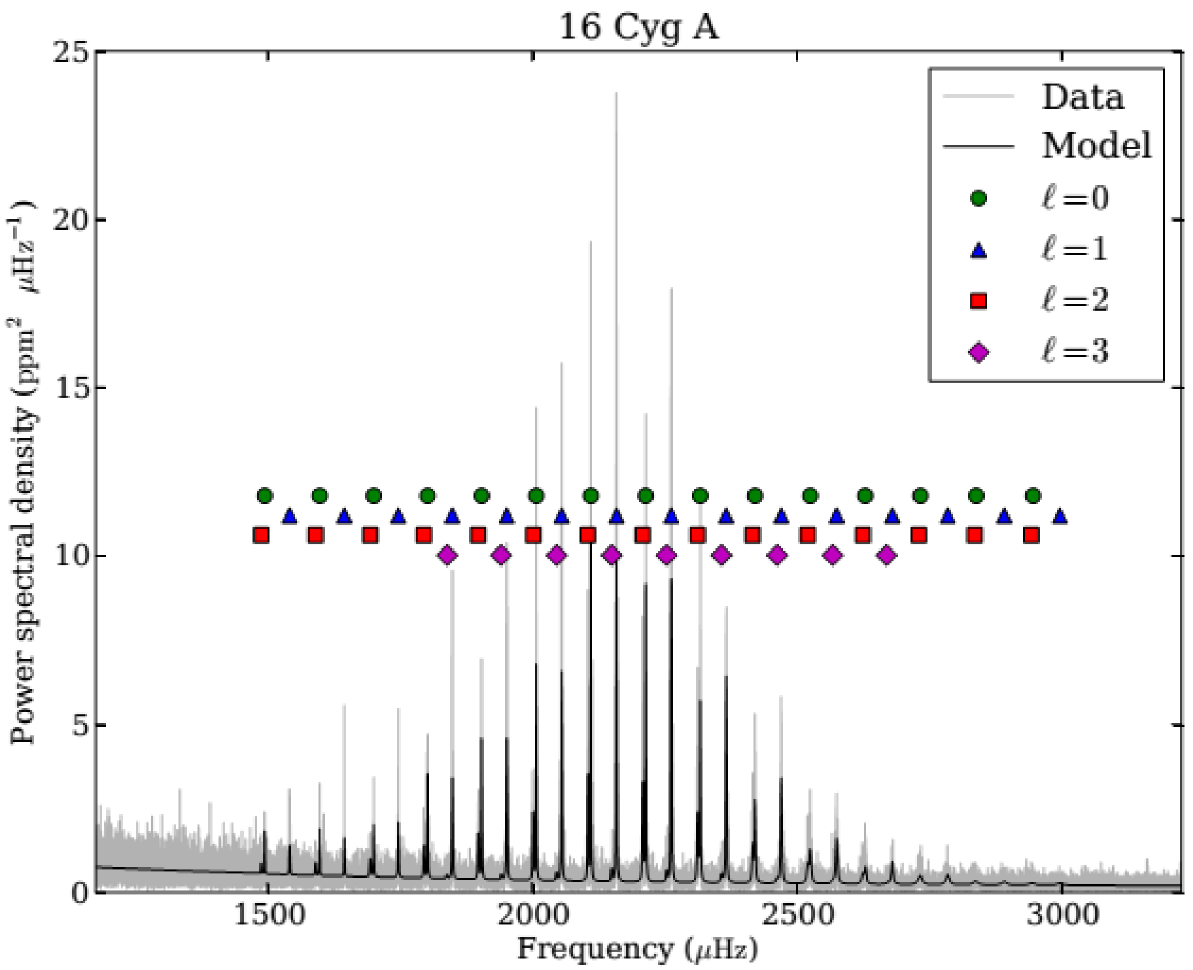


Asteroseismology

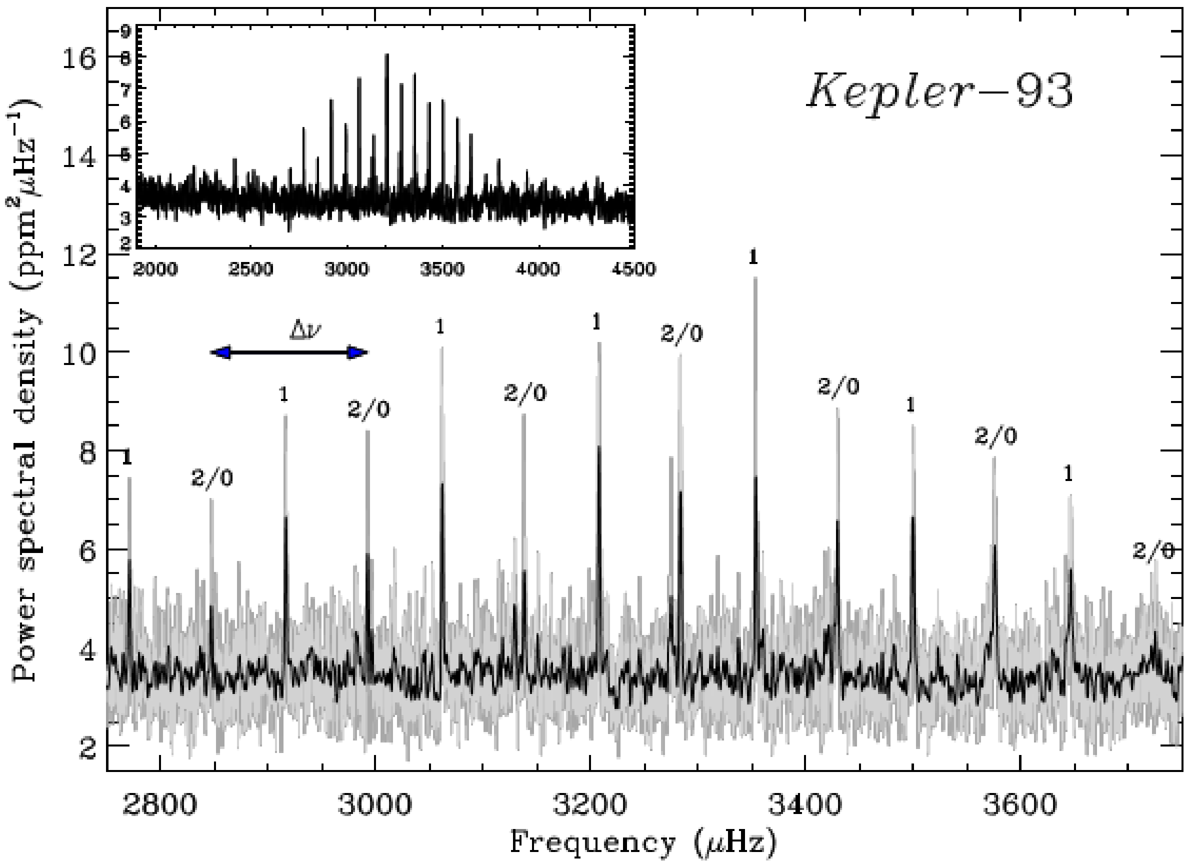
WARWICK

- Uses natural resonant oscillations of stars to learn about their interiors.
- Kepler and CoRoT missions made asteroseismic observations.
- Now TESS
- Coming soon: PLATO

Asteroseismic power spectra



Davies et al., 2015, MNRAS



Ballard et al., 2014, ApJ

Summary of main results

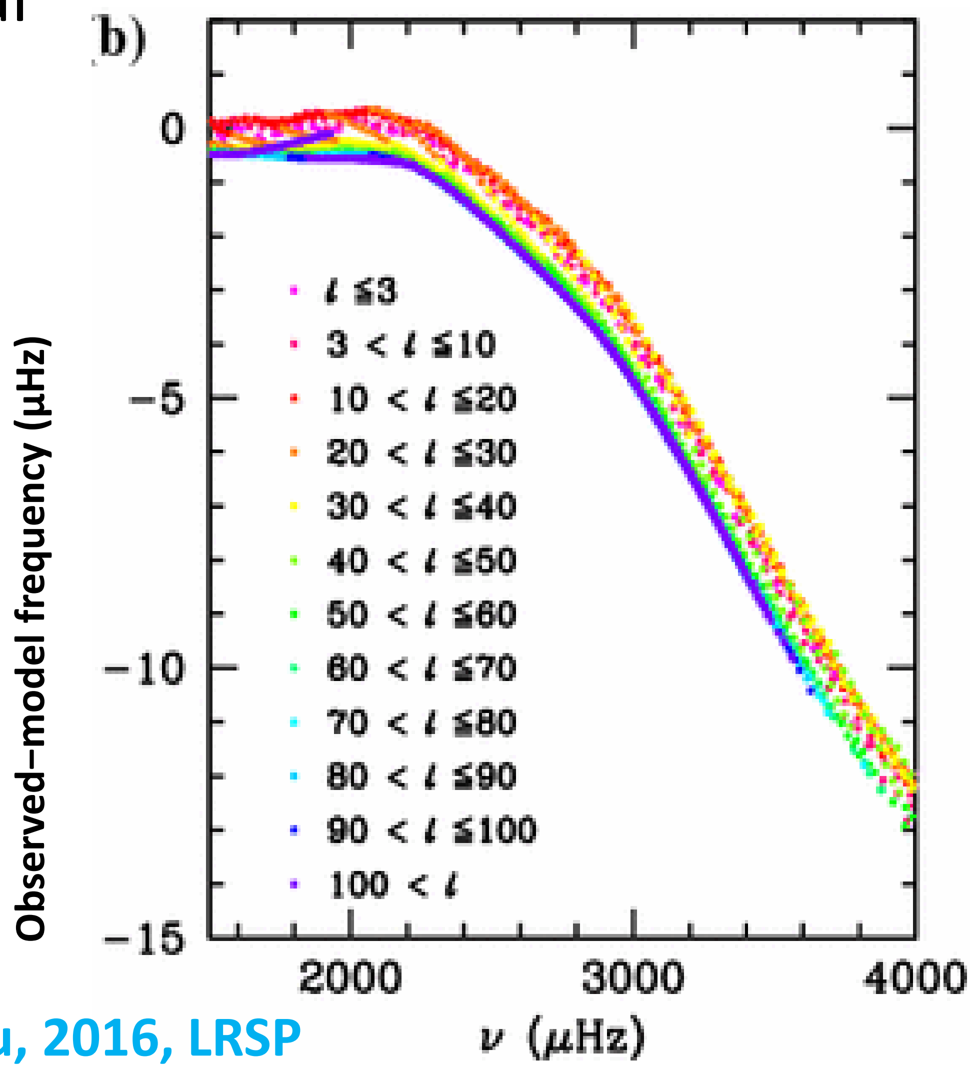
WARWICK

- Helioseismology results can constrain models of the interior
  - Don’t forget neutrino observations, especially for deep interior.
- Helioseismology can infer small and large scale flows in solar interior
  - Particularly important for understanding and modelling small and large scale magnetic fields.

- Thanks for listening… any questions?

Testing solar models

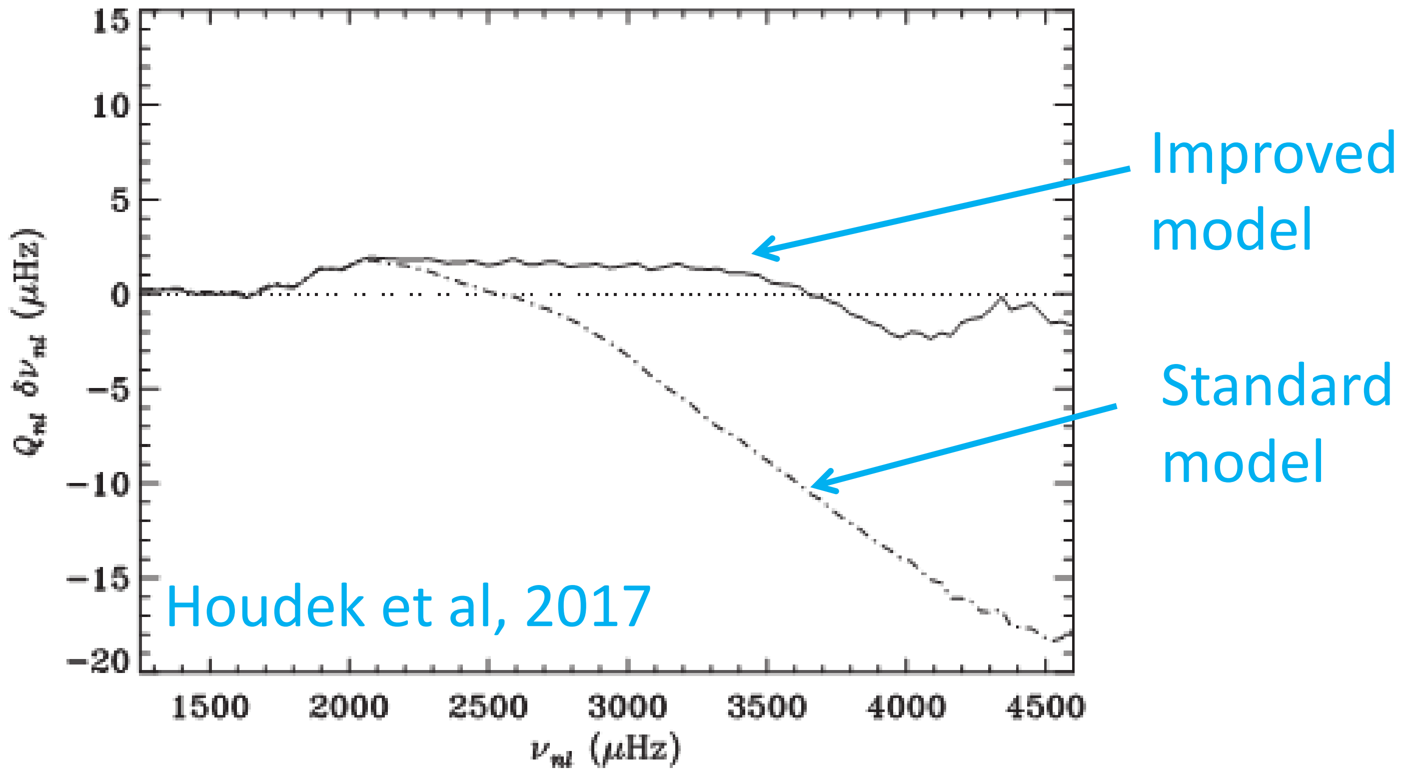
- When using helioseismology to infer internal conditions we compare models and observations.
- ‘Surface term’ discrepancies are due to e.g.
  - Poor modelling of temperature gradients in superadiabatic layer.
  - Use of adiabatic approx. when calculating frequencies.
  - Interactions between convection and oscillations not accounted for.

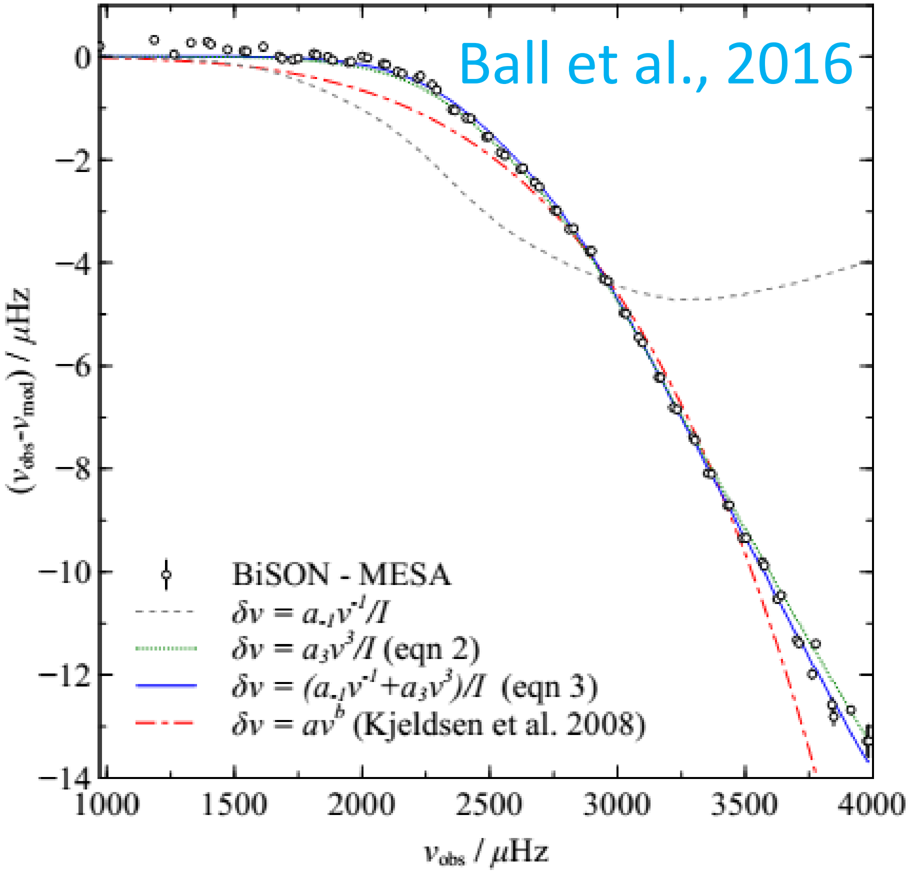


Basu, 2016, LRSP

The ‘surface term’

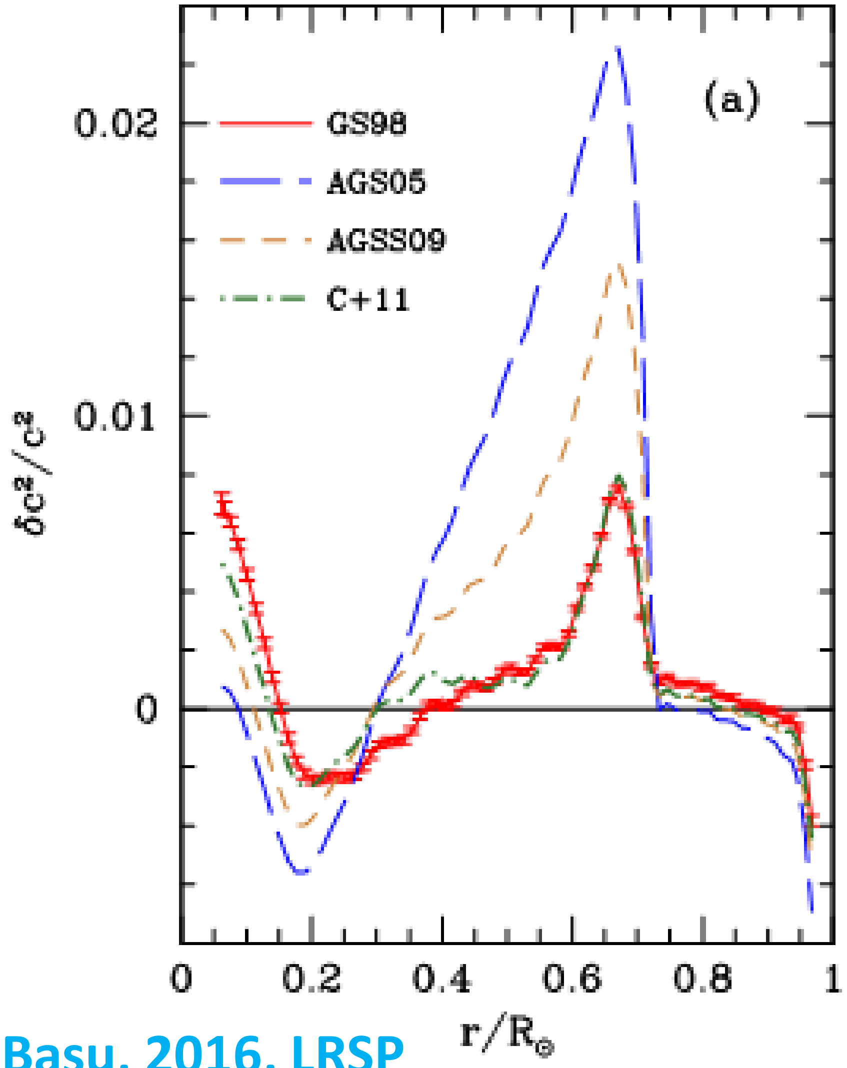
- Corrections based on parametric fit to frequencies e.g. Gough, 1990, Ball et al., 2016.
- 3D hydrodynamical simulation, nonadiabatic effects, and a consistent treatment of the turbulent pressure e.g. Houdek et al, 2017





Solar abundance problem

- Heavy element abundance is important input into solar models
- To determine need to use model atmosphere.
- Conversion to 3D models and non-LTE effects reduced Z/X.
- Numerous attempted solutions include modified opacities, gravitational settling, enhanced diffusion, dark matter…

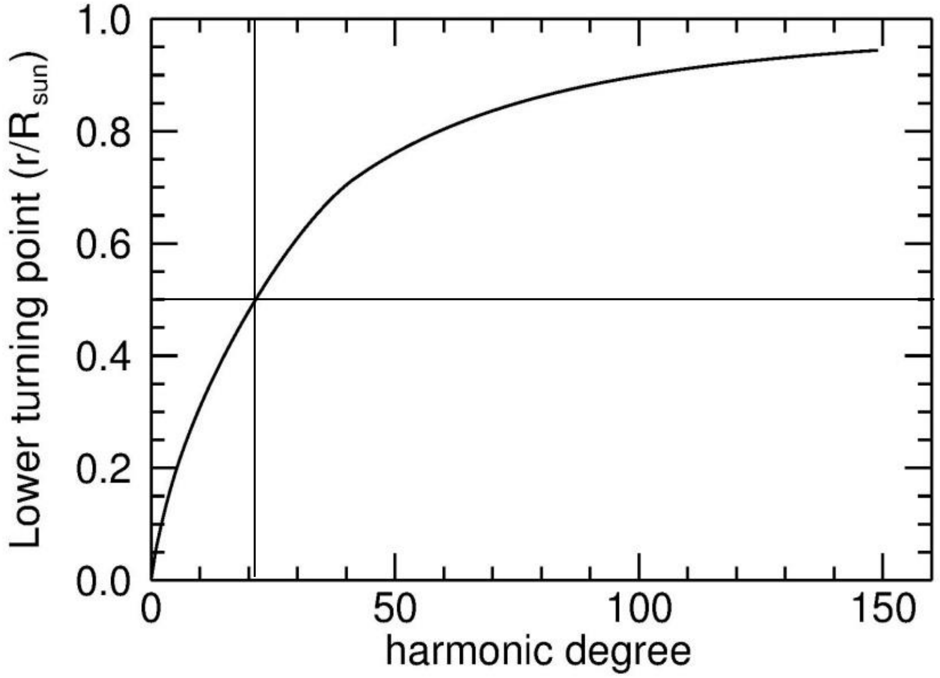


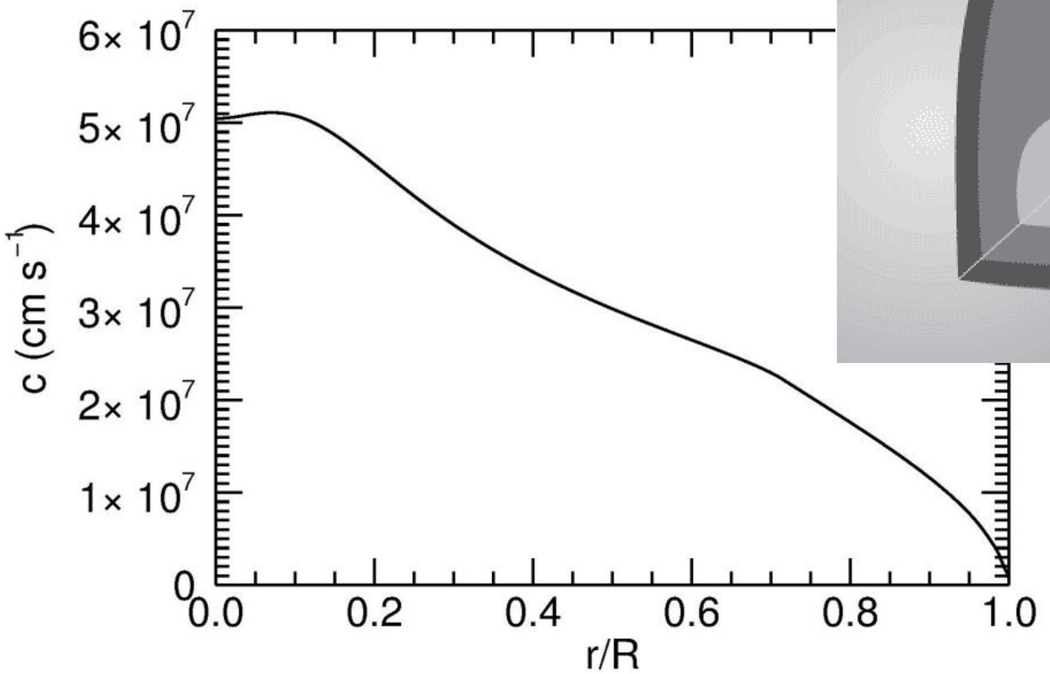
Basu, 2016, LRSP

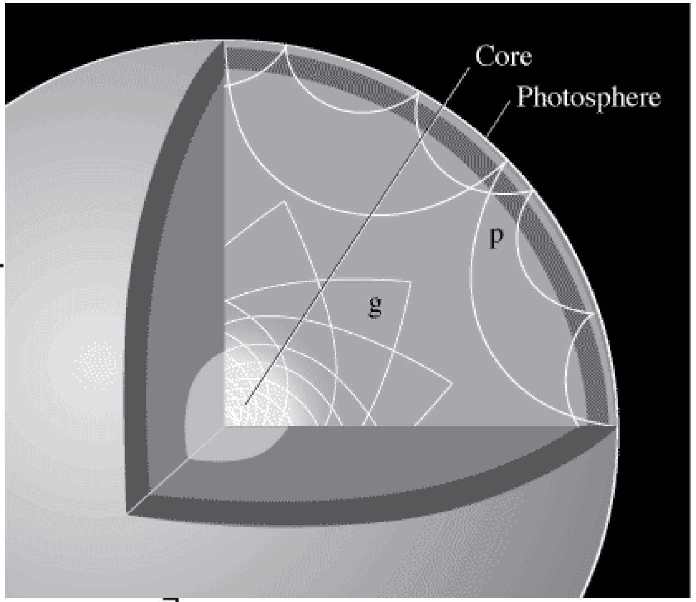
Z/X: GS98 – 0.023
AGS05 – 0.016
AGSS09 – 0.018
C+11 – 0.0209

Limitations of p modes

- Inversions of core conditions poorly constrained by p modes.
- Gravity modes far more sensitive to solar core.

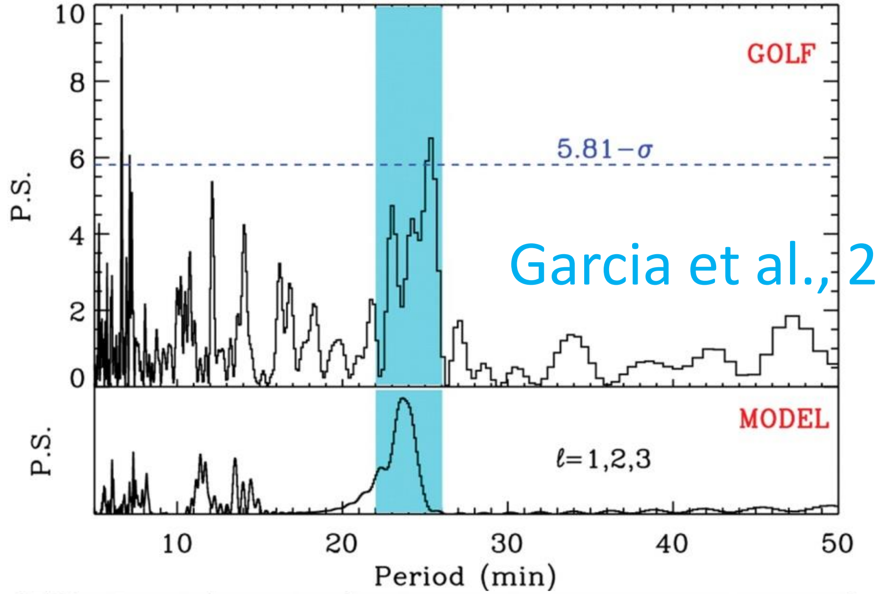




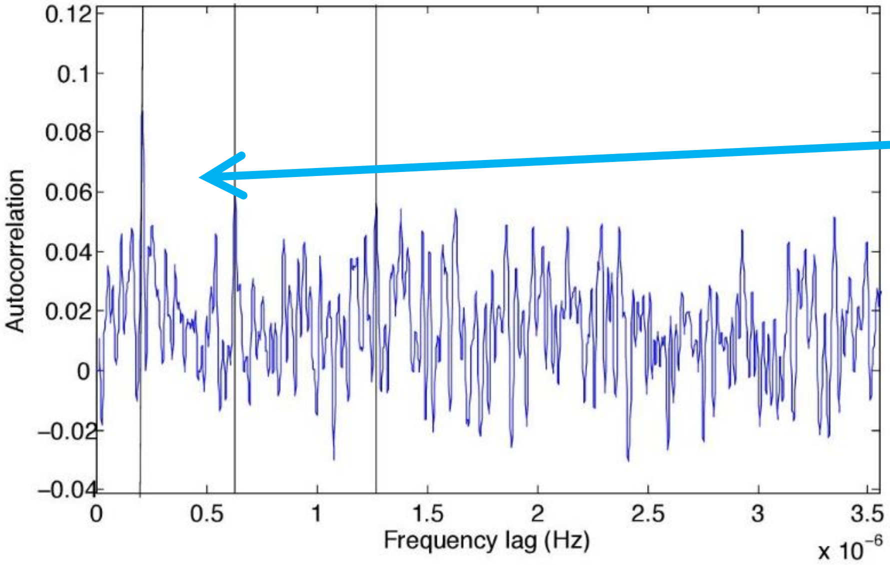


Detections of gravity modes

- No independently confirmed detections of individual g modes.
- Some evidence but controversial.
- Garcia and Fossat results both imply rapidly rotating core.

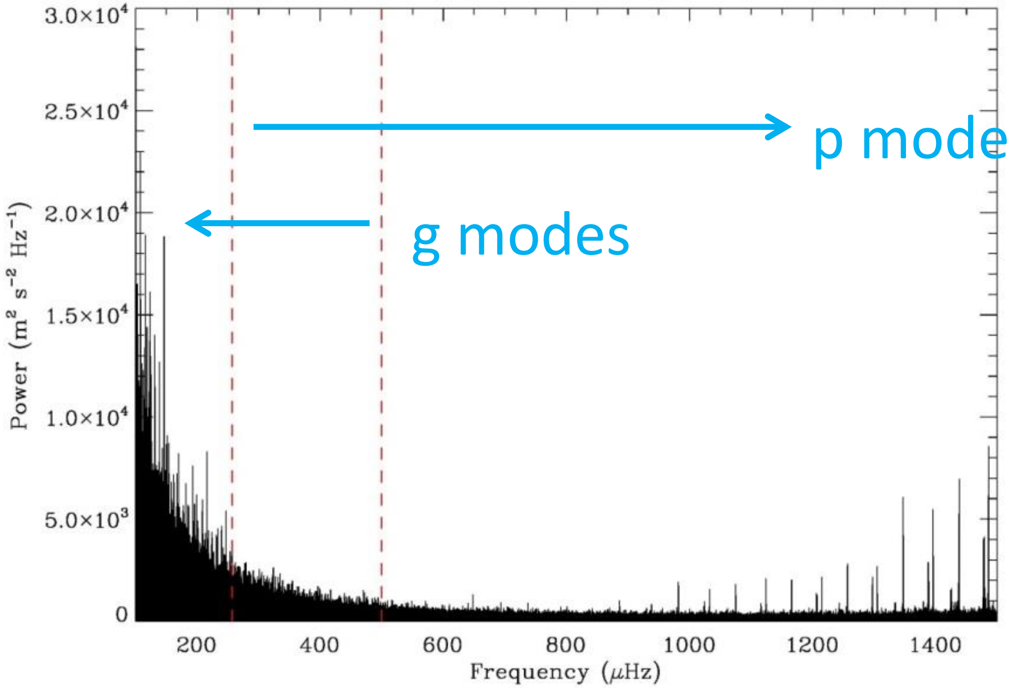


Garcia et al., 2007



210nHz (prob $< 10^{-3}$)

Fossat et al (2017)

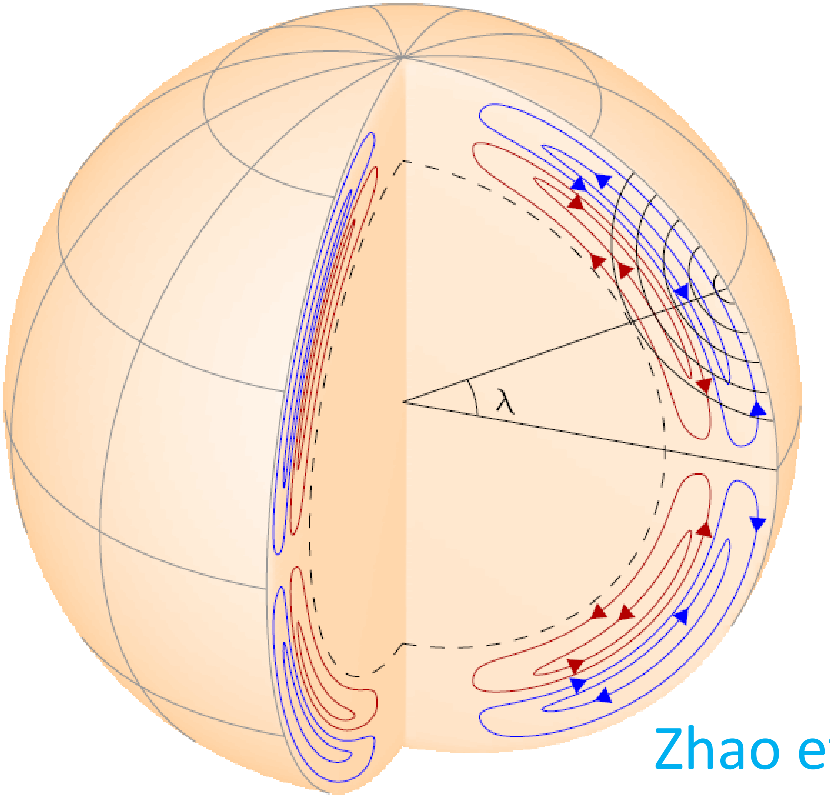


p modes

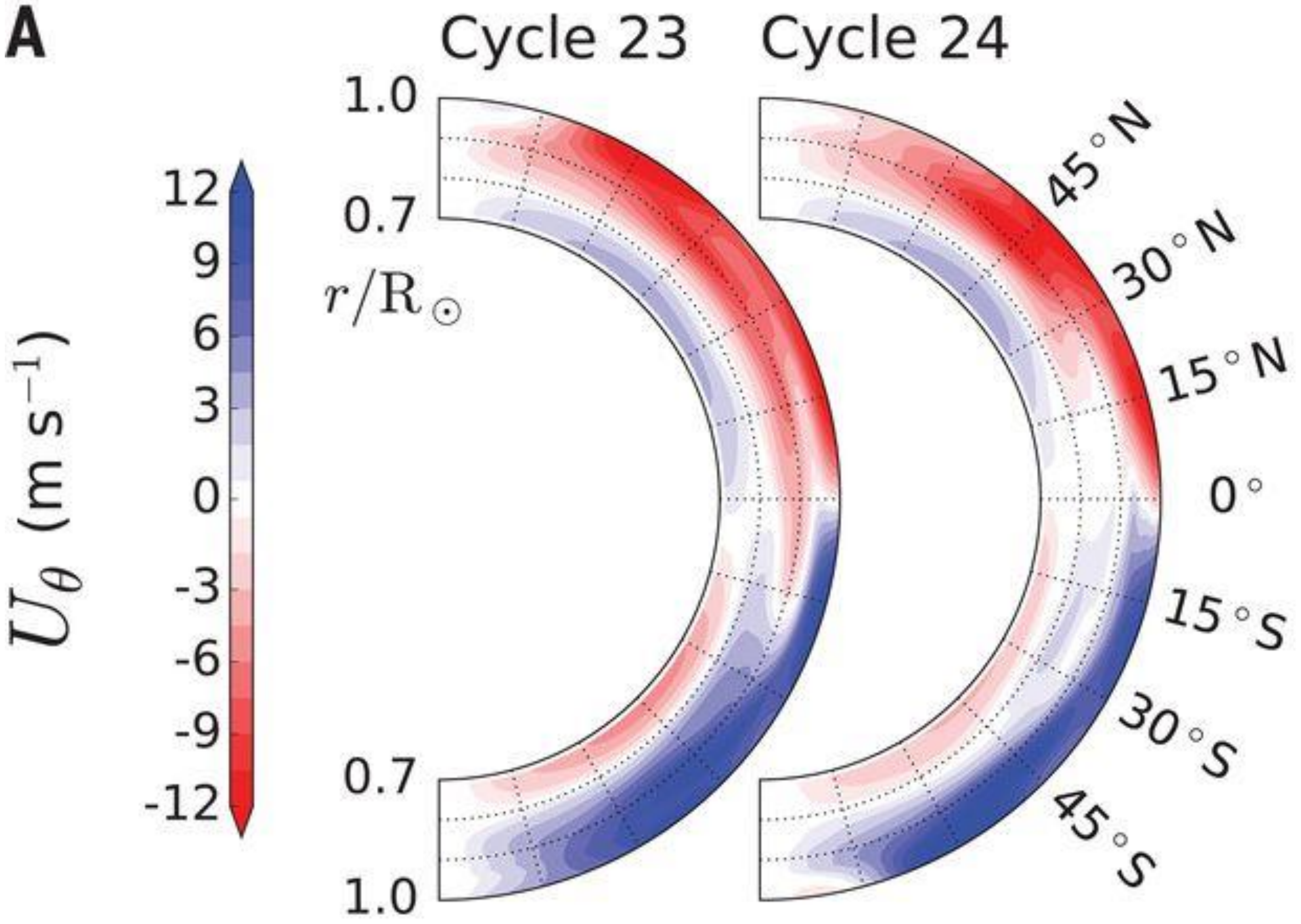
g modes

One cell or two?

- Zhao et al. (2013) found hint of two cells.
- But large uncertainties and other results disagree

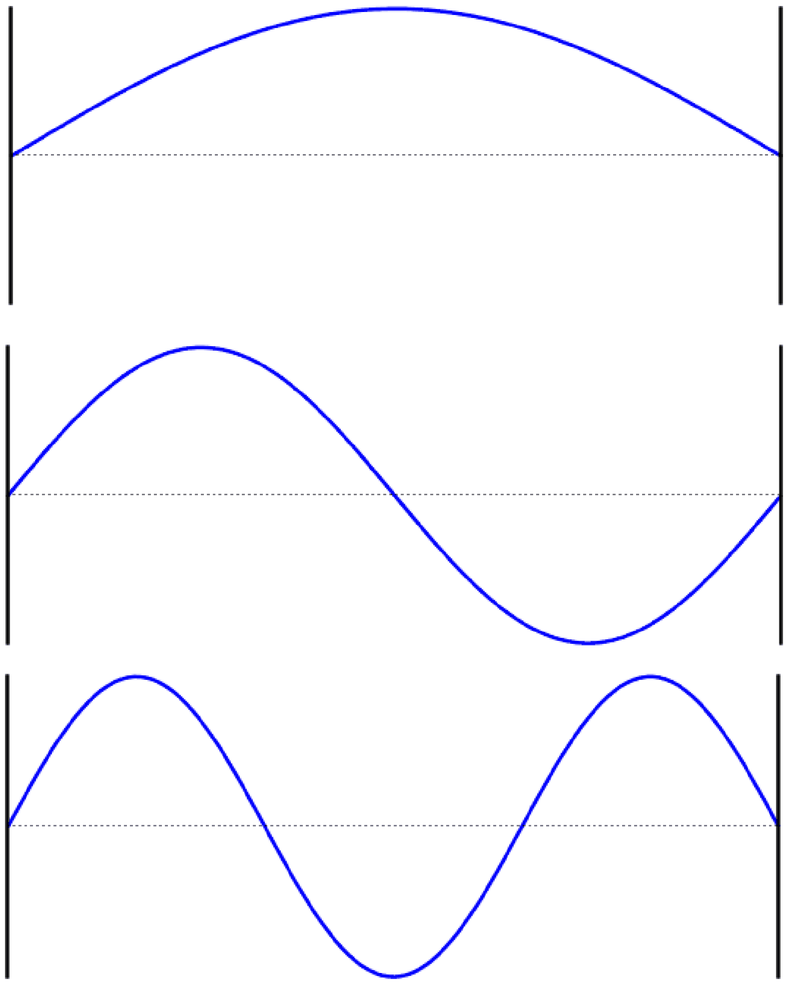


Zhao et al. (2013)

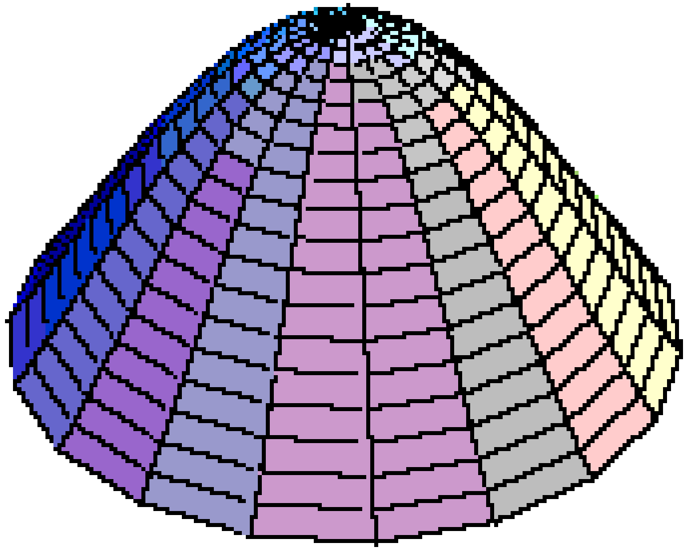


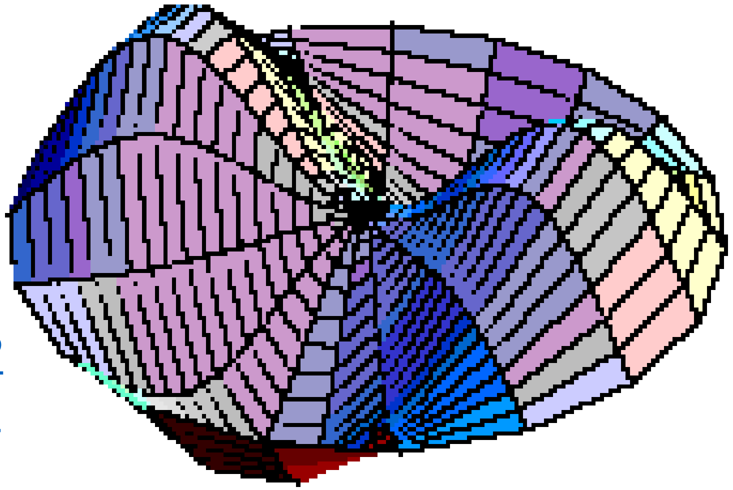
Gizon et al. (2020)

1D and 2D standing waves



Nodes described by location on x axis



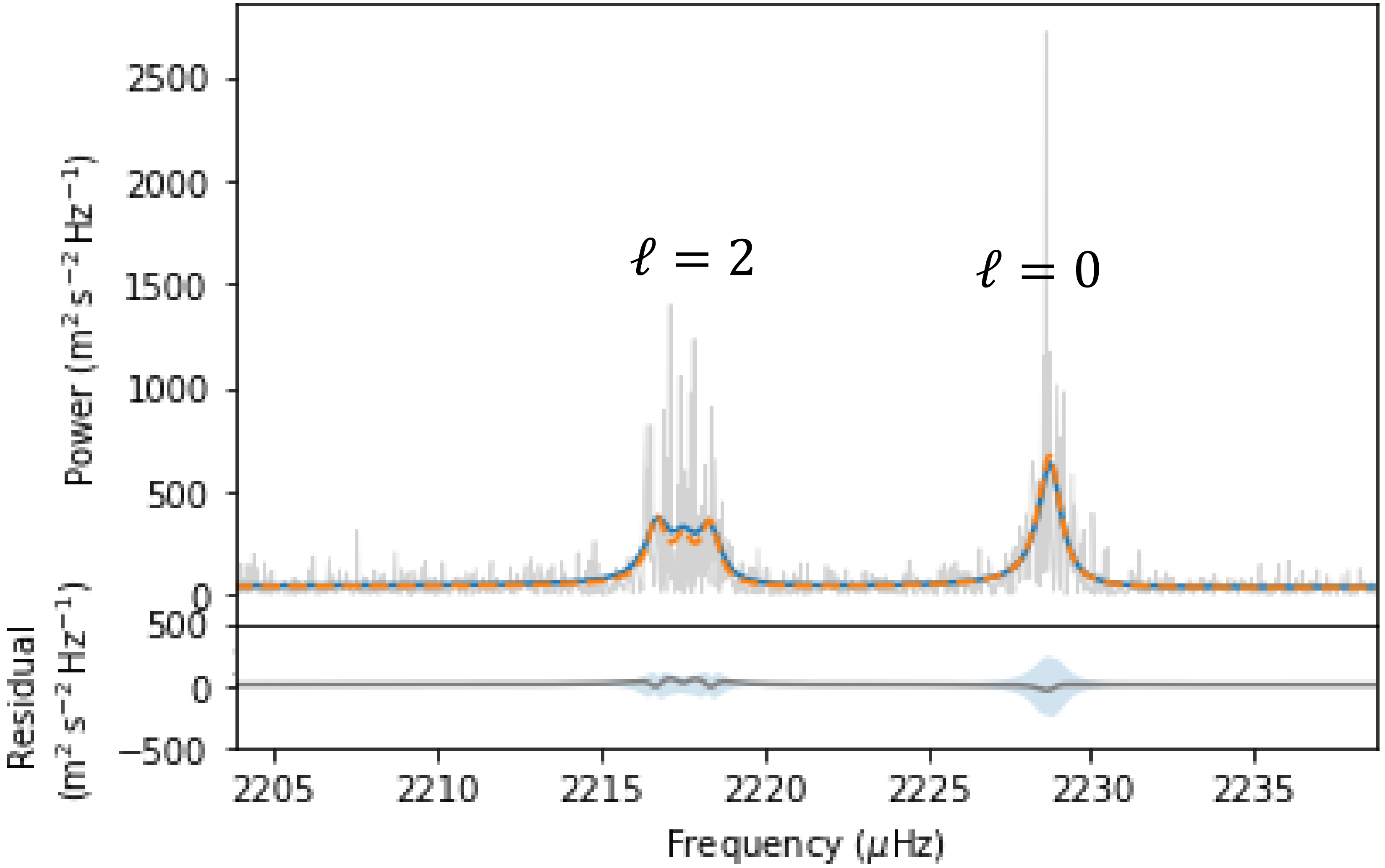


Nodes described by lines on membrane

https://www.ophysics.com/waves/waves6.html

https://faraday.physics.utoronto.ca/PVB/Harrison/Vibrations/Vibrations.html

Fitting frequency-power spectra



Doppler Velocity

Global

Unresolved

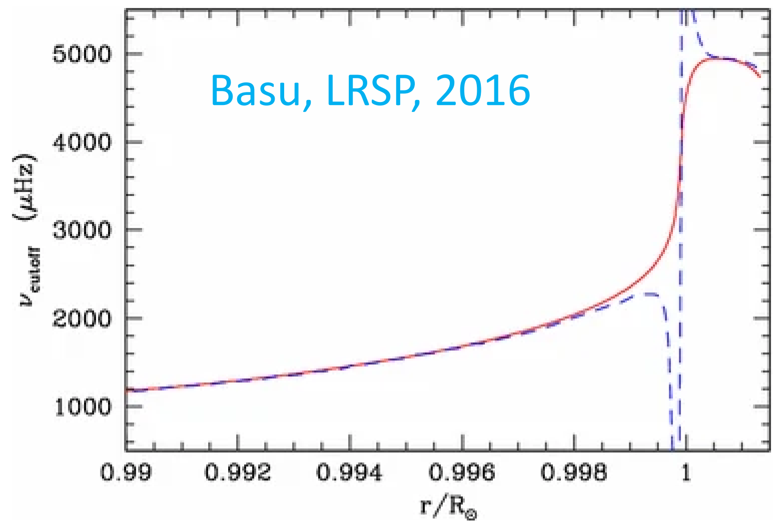
Acoustic cut-off frequency

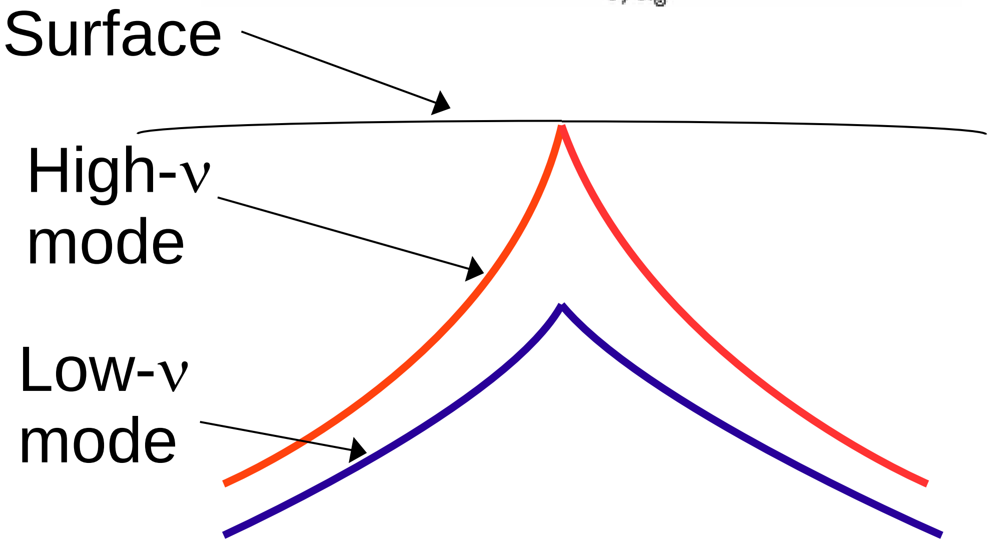
- The acoustic cut-off frequency is given by

$$\omega_a^2 = \frac{c_s^2}{4H_\rho^2}\left(1 - 2\frac{\mathrm{d}H_\rho}{\mathrm{d}r}\right),$$

where H_ρ is density scale height

- But equation of state says $H_\rho \propto T$.
- T decreases with r until it reaches a minimum, $T = T_{\mathrm{min}}$.
- Here $H_\rho = H_{\rho,\,\mathrm{min}}$, and $\omega_a = \omega_{a,\mathrm{max}}$.
- In the Sun $\nu_{a,\mathrm{max}} \approx 5100\mu\mathrm{Hz}$.





Sun-as-a-star power spectrum

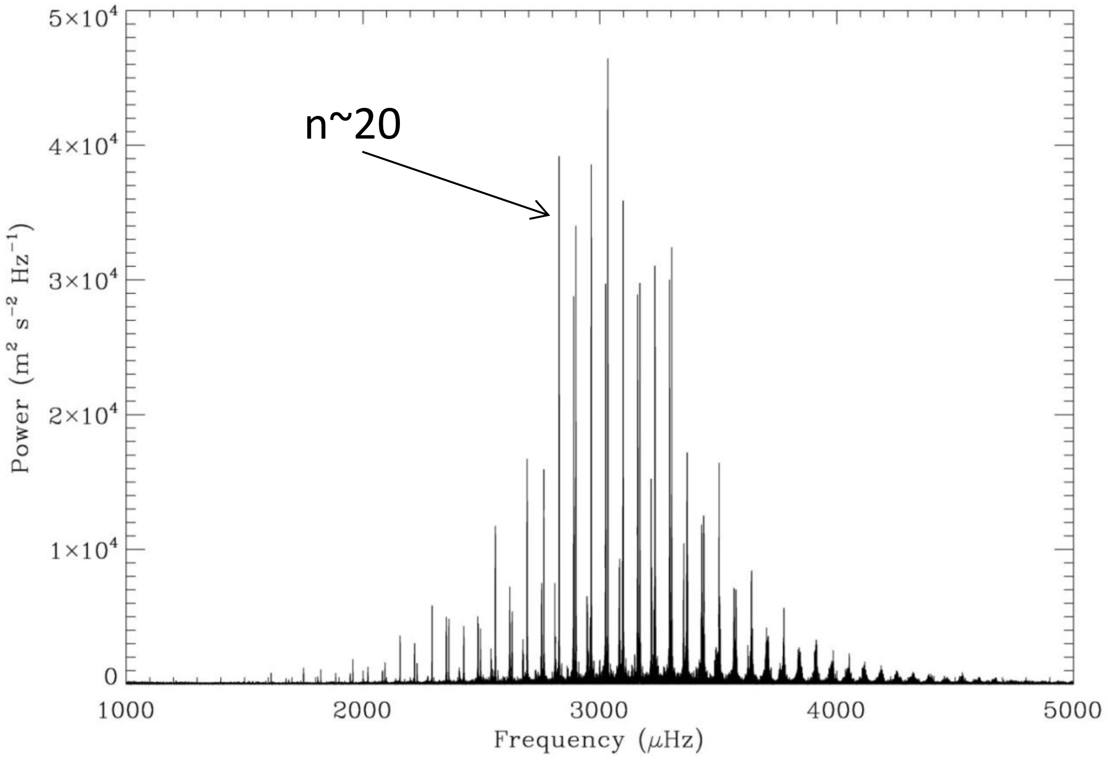
- Modes with largest amplitudes have frequencies around 3000μHz or periods ~5min.

Amplitudes of 1-10 cm s^{-1}

Doppler Velocity

Global

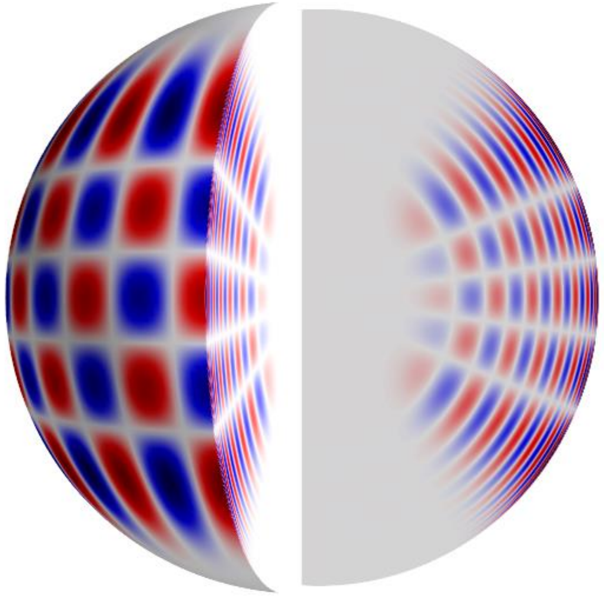
Unresolved

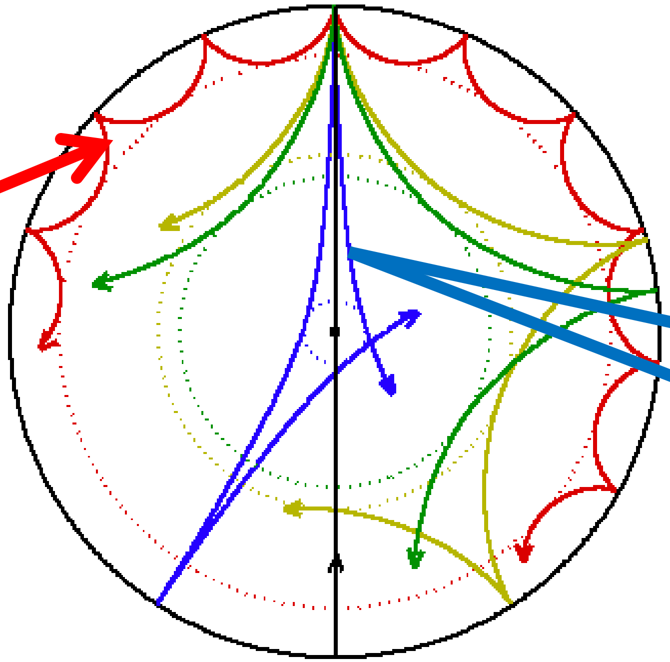


365d of BiSON data Unresolved/Sun-as-a-star data
l=0-3

Lower turning point: harmonic degree, ℓ

Intermediate or high degree (ℓ)

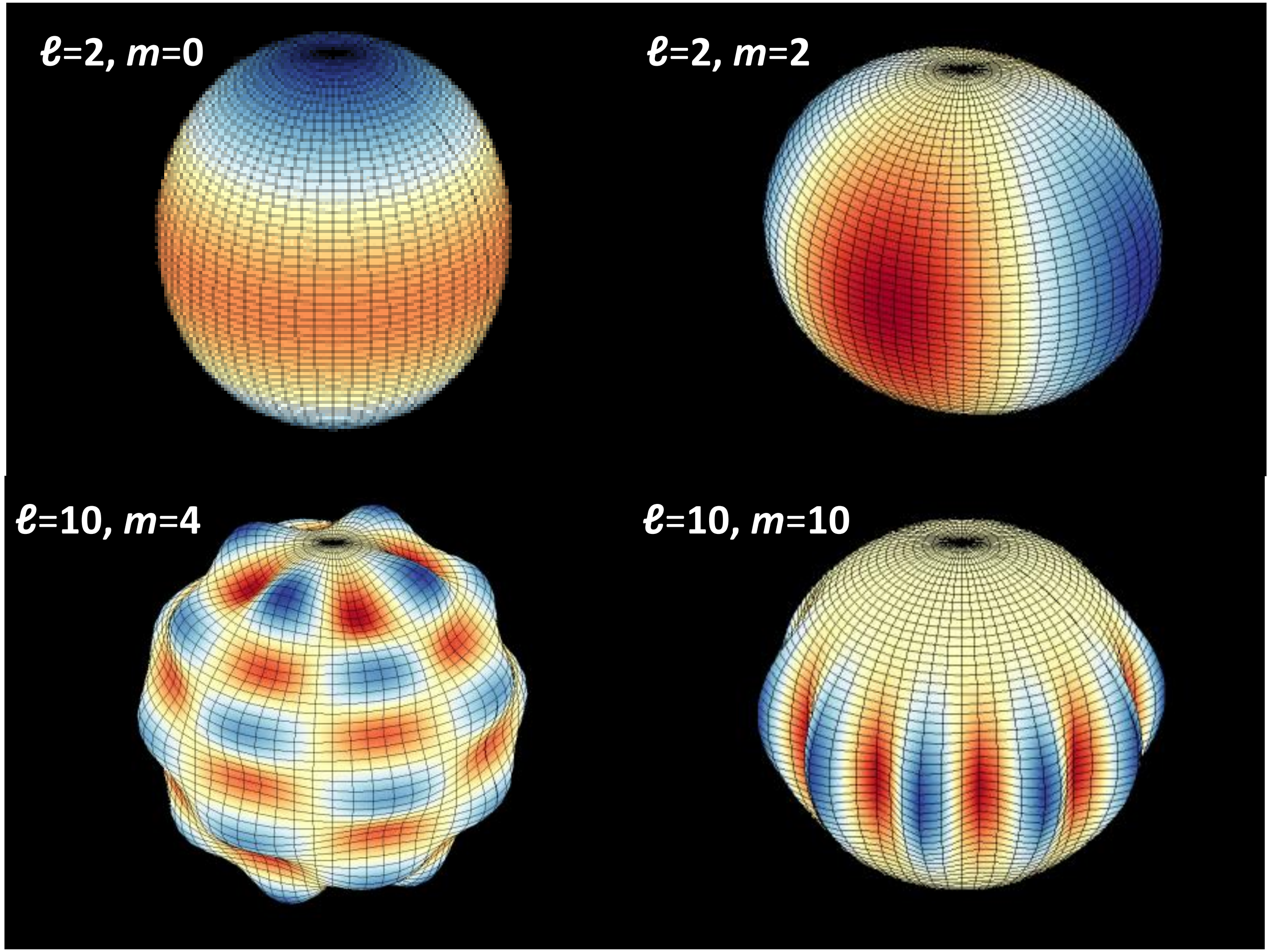




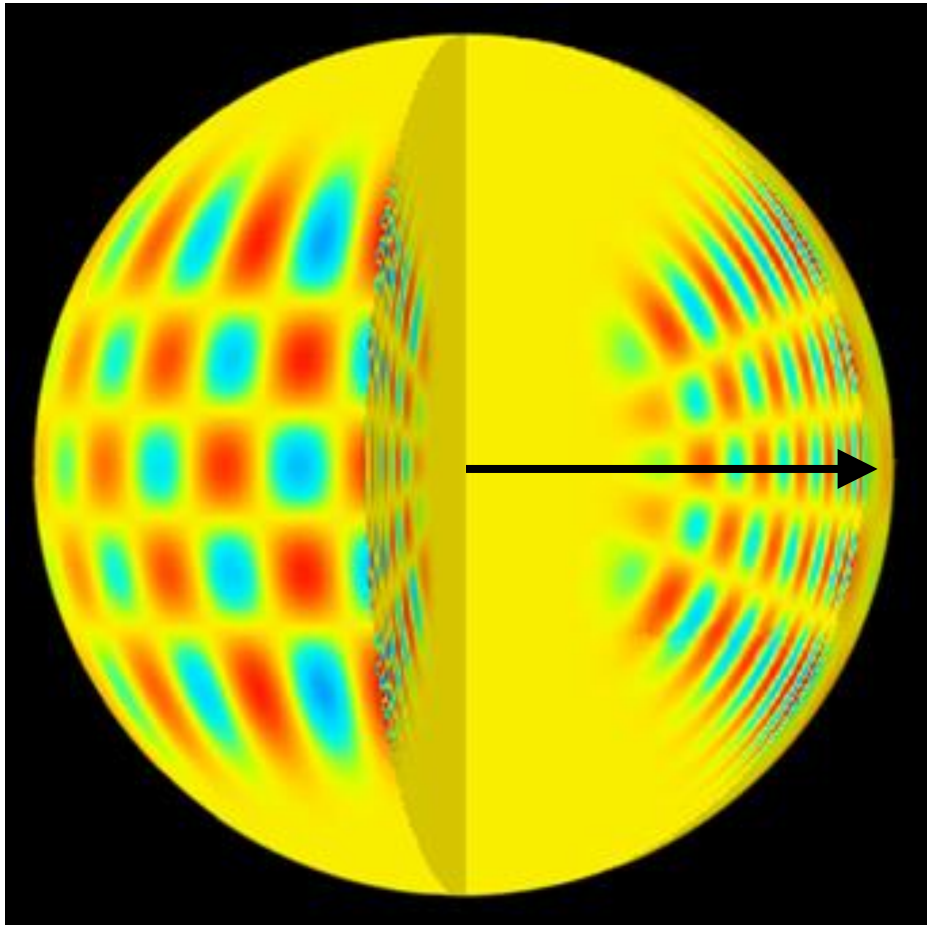
Low degree (ℓ)

https://github.com/warrickball/spherical-harmonics

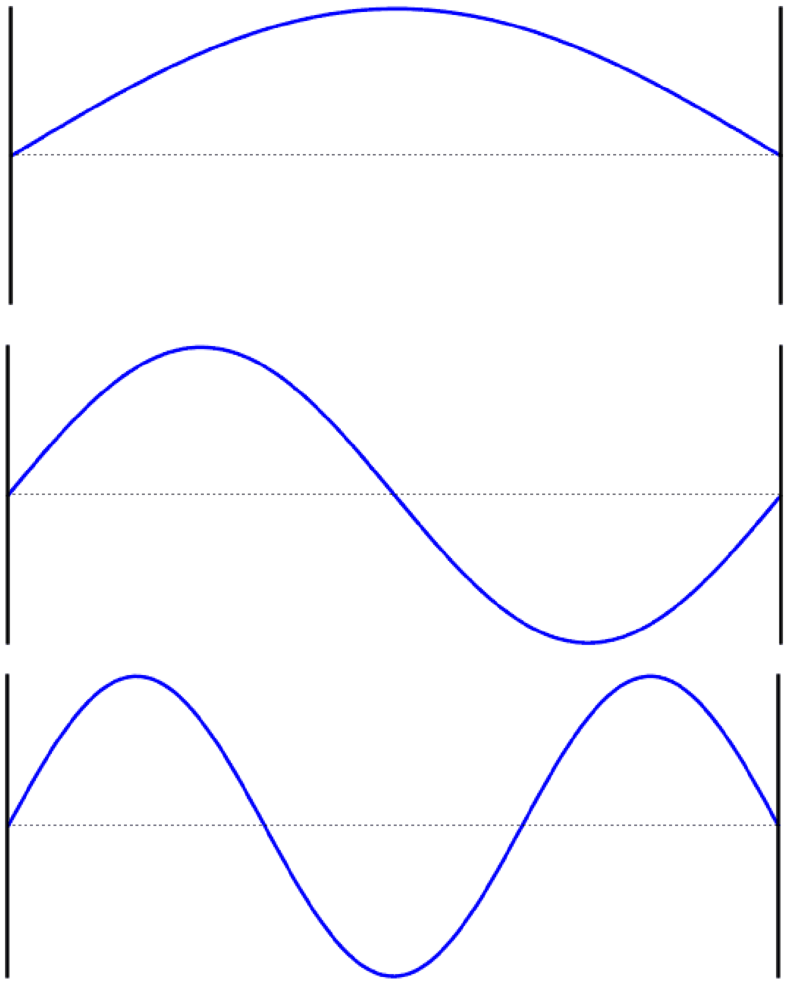
Azimuthal degree, *m*



Radial degree, *n*



1D and 2D standing waves



$$\lambda = 2L$$
$$f = v/2L$$

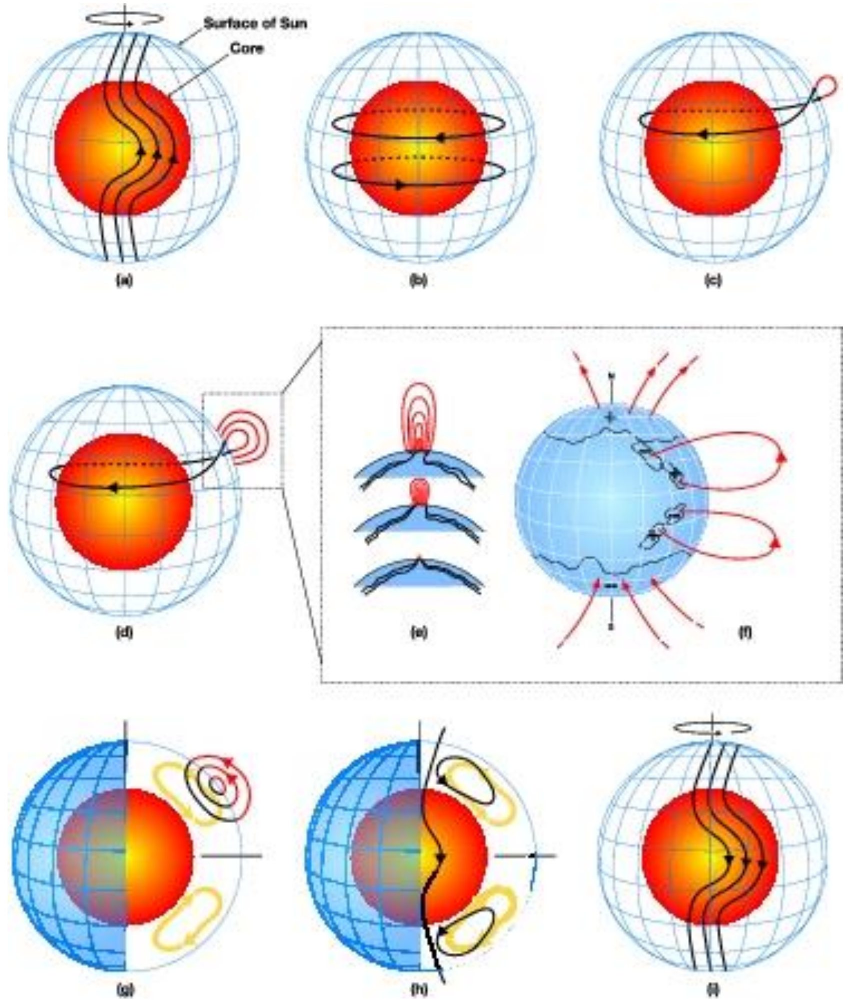
$$\lambda = L$$
$$f = v/L$$

$$\lambda = 2L/3$$
$$f = 3v/2L$$

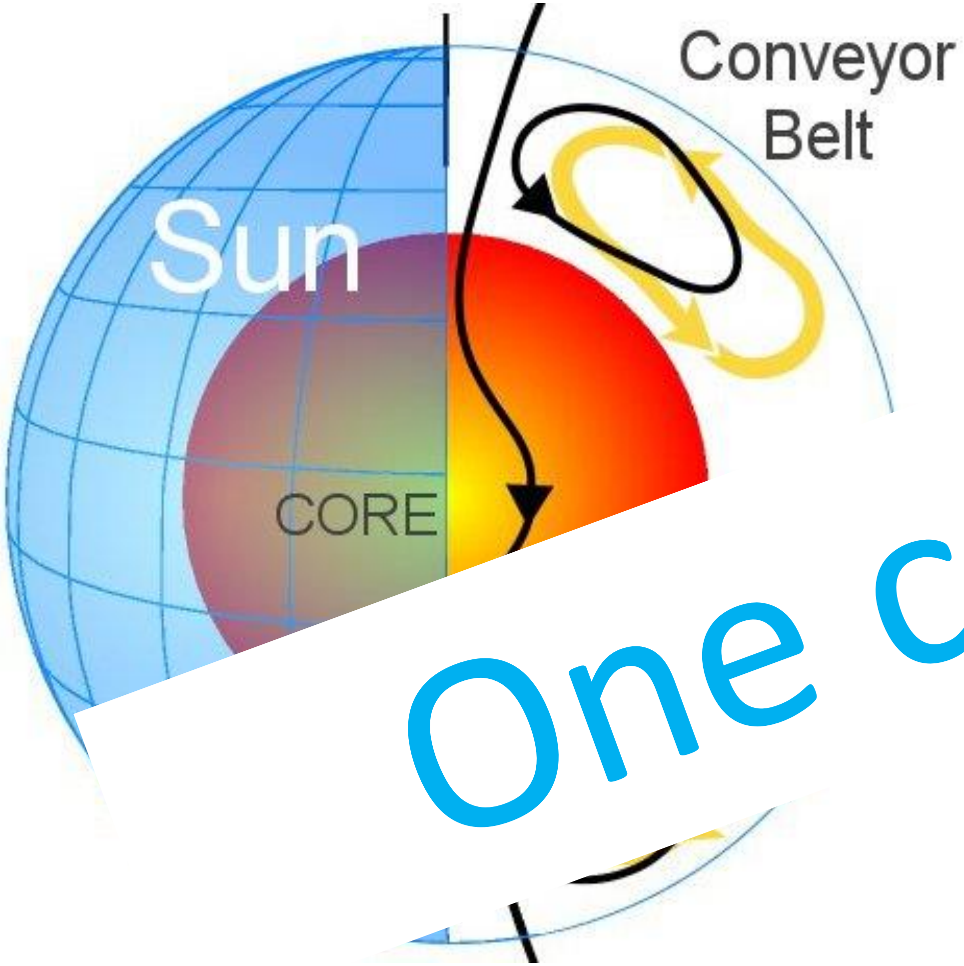
δf = v/2L=constant

https://www.ophysics.com/waves/waves6.html

The solar dynamo



Meridional flow

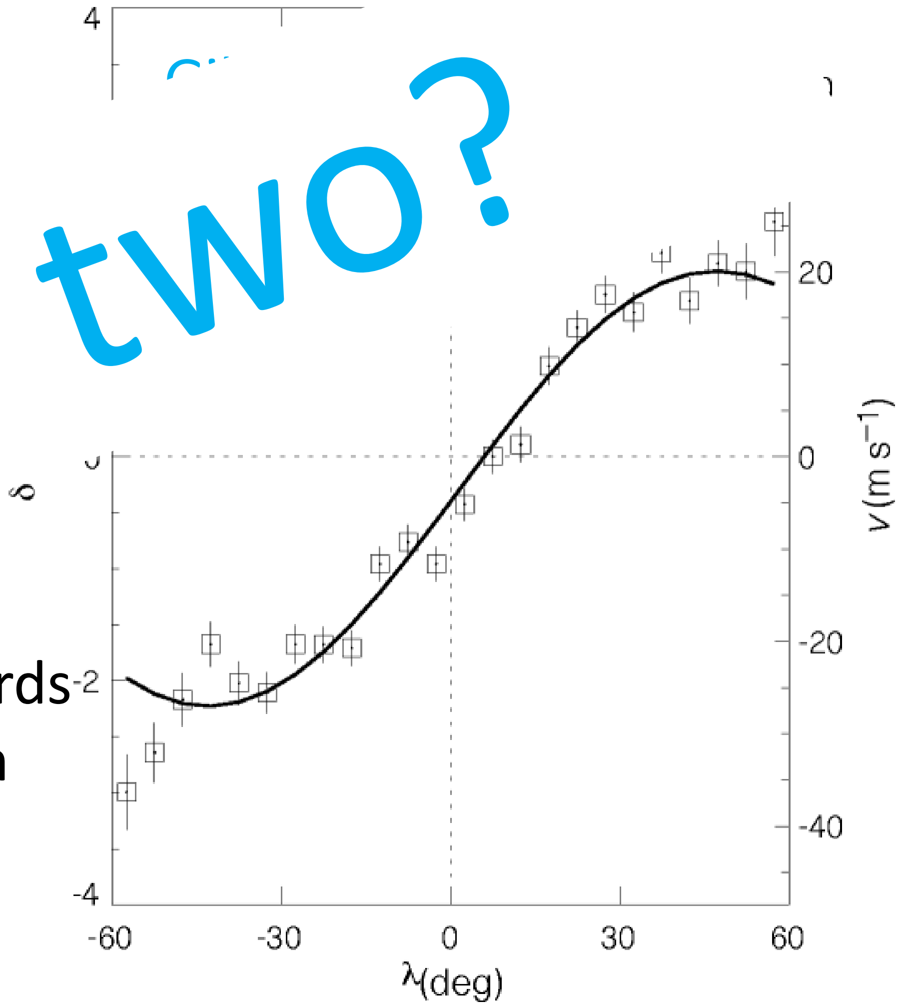


Courtesy of Science@NASA

Only sensitive t…

Flow to…

Flow towards south pole



One cell or two?