Probing Stellar Structure with Pressure & Gravity modes – the Sun and Red Giants

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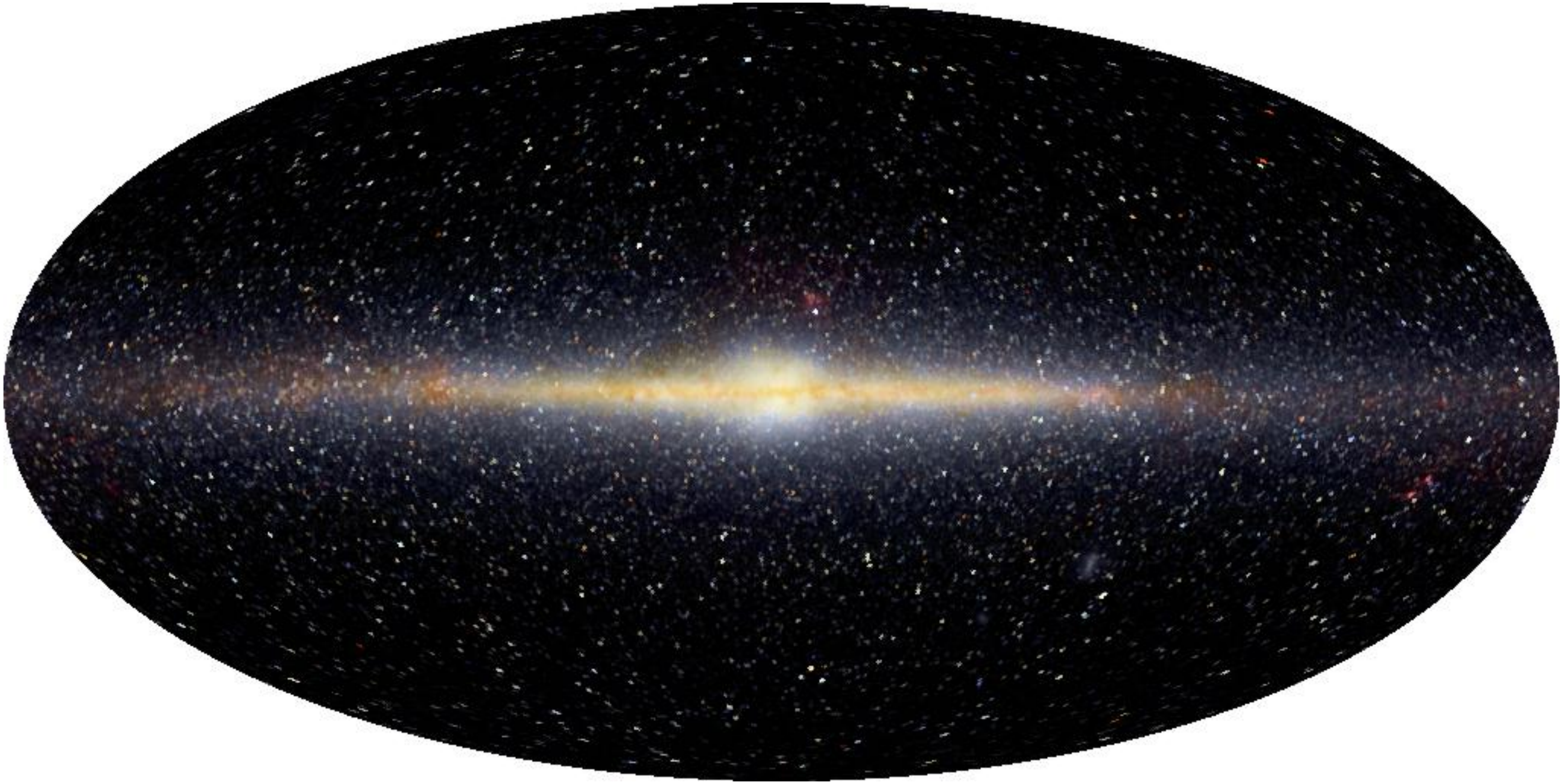
Science on the Sphere 14/15 July 2014

Evolving stars are building blocks of the galaxy and their cores are the power houses…



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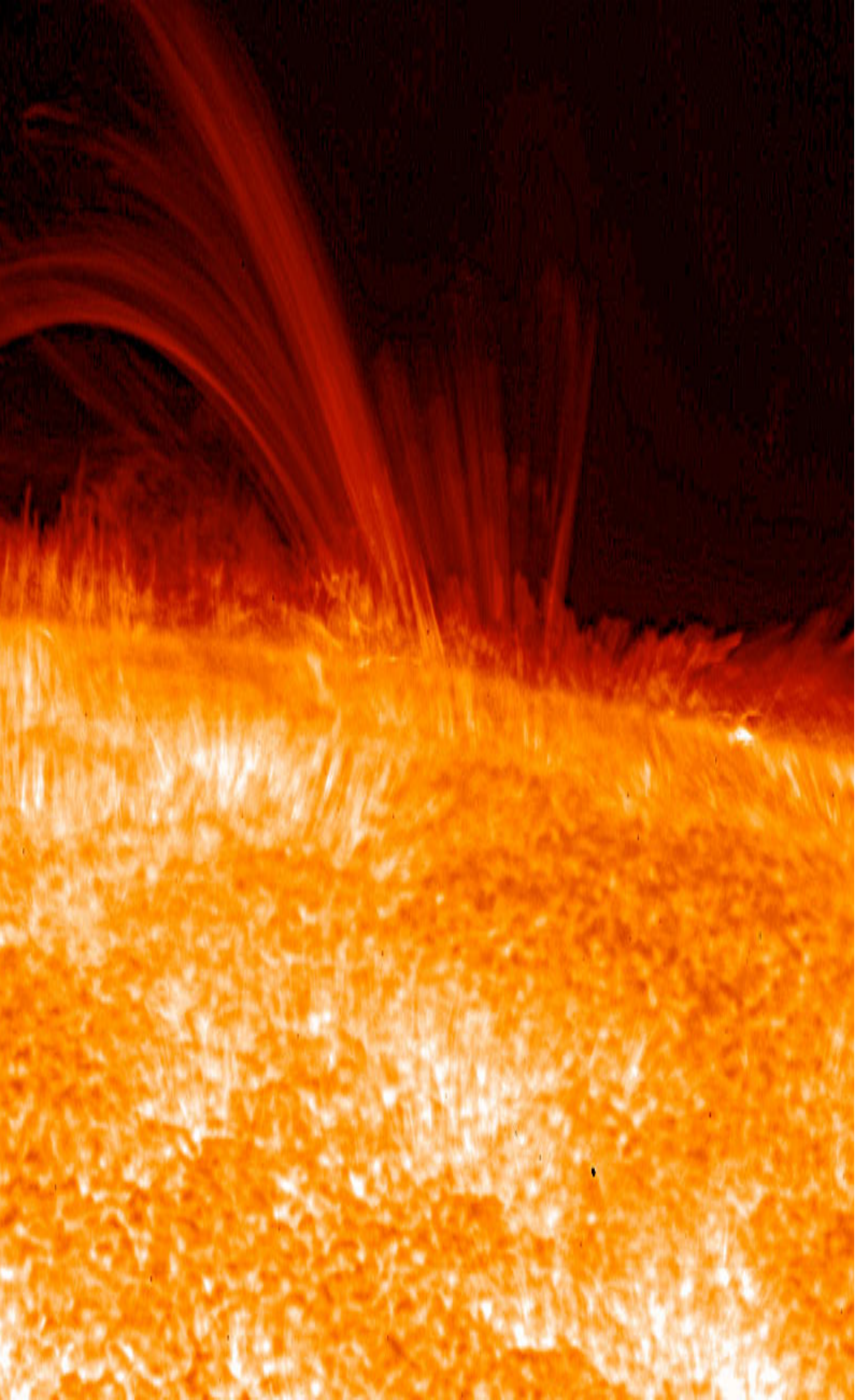
Introduction

This talk…..

- Getting beyond the surface
- Different sorts of modes
- Key discoveries of recent years
- What next
- Thanks to Andrea Miglio for many of the figures in this talk



- We have learnt a lot about the Sun and other stars from observations of their (almost spherical) surfaces

- Astrophysics theory is very powerful

- We learn a huge amount more by being able to make measurements of the conditions in the interior

- Oscillations open up that possibility

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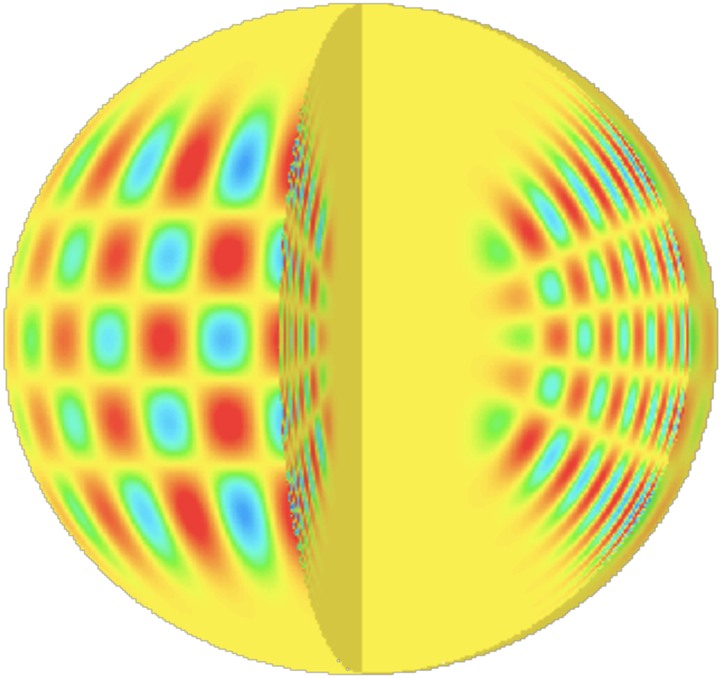
For p-modes the star resonates like a (3-dimensional) musical instrument



- Motion in the volume of the Sun due to sound (or pressure) waves inside it
- Viewed as Doppler velocity or as intensity change
- Driven by the outer convection zone and present in all stars with similar characteristics

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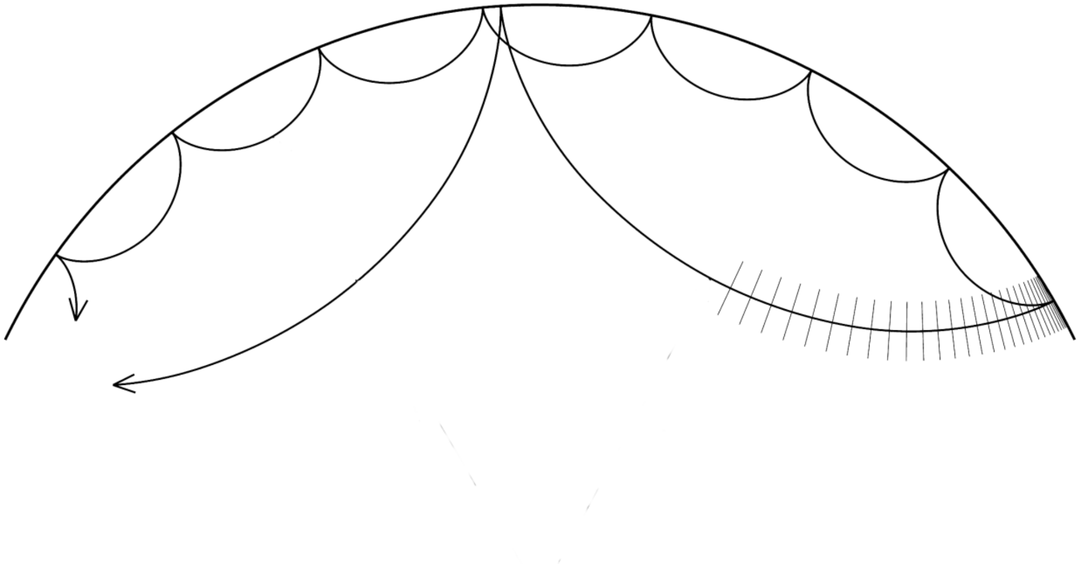
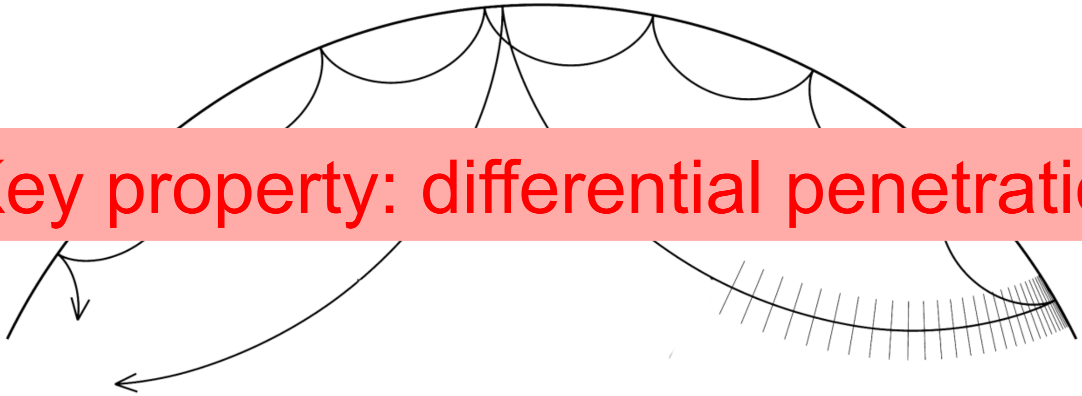
Trajectories of acoustic waves in interior



Waves travel to different depths!

Courtesy J. Christensen-Dalsgaard

Trajectories of acoustic waves in interior

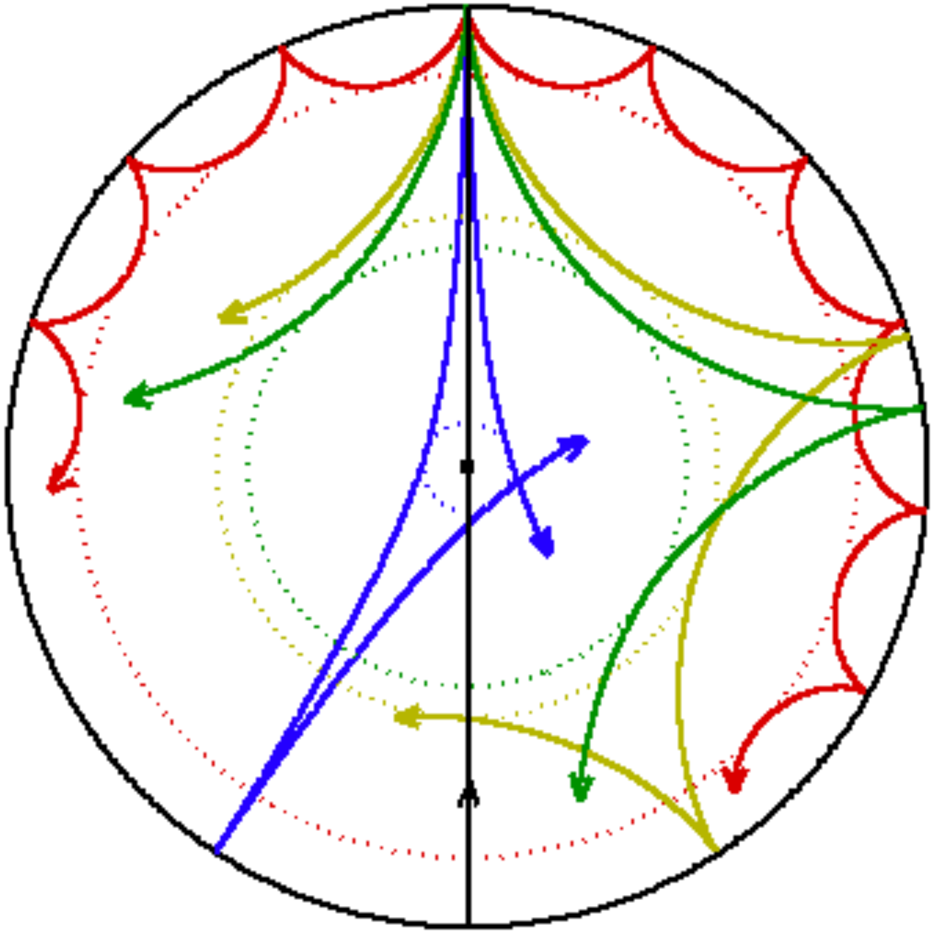


Key property: differential penetration

Waves launched at steeper angle to radial direction penetrate more deeply!

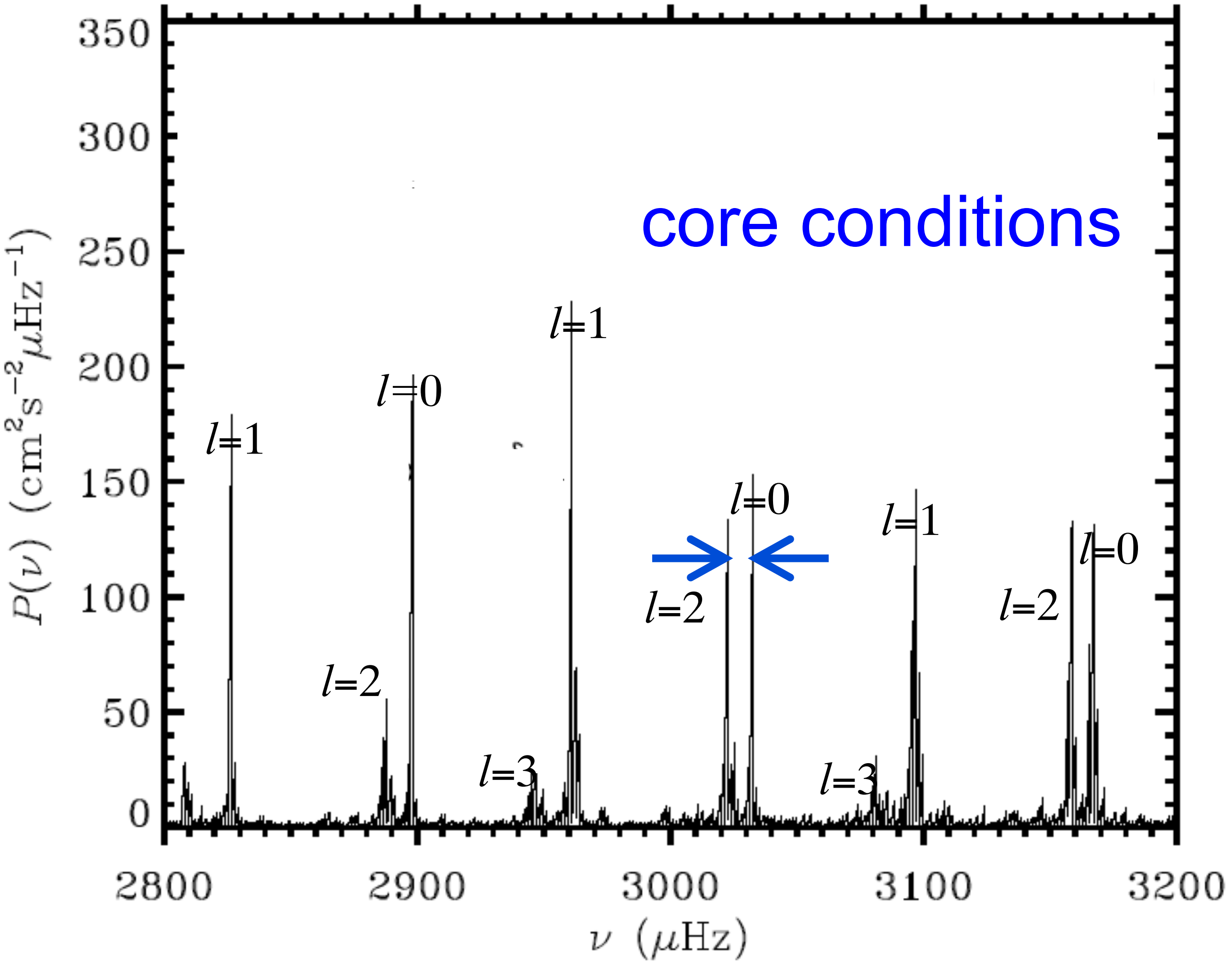
Courtesy J. Christensen-Dalsgaard

A simple spherical Sun



- The mode degree ℓ
- Low degree modes probe the core
- All that is (normally) observable without spatial resolution

As seen before: ℓ=0,2 splitting is sensitive to core conditions



BiSON data

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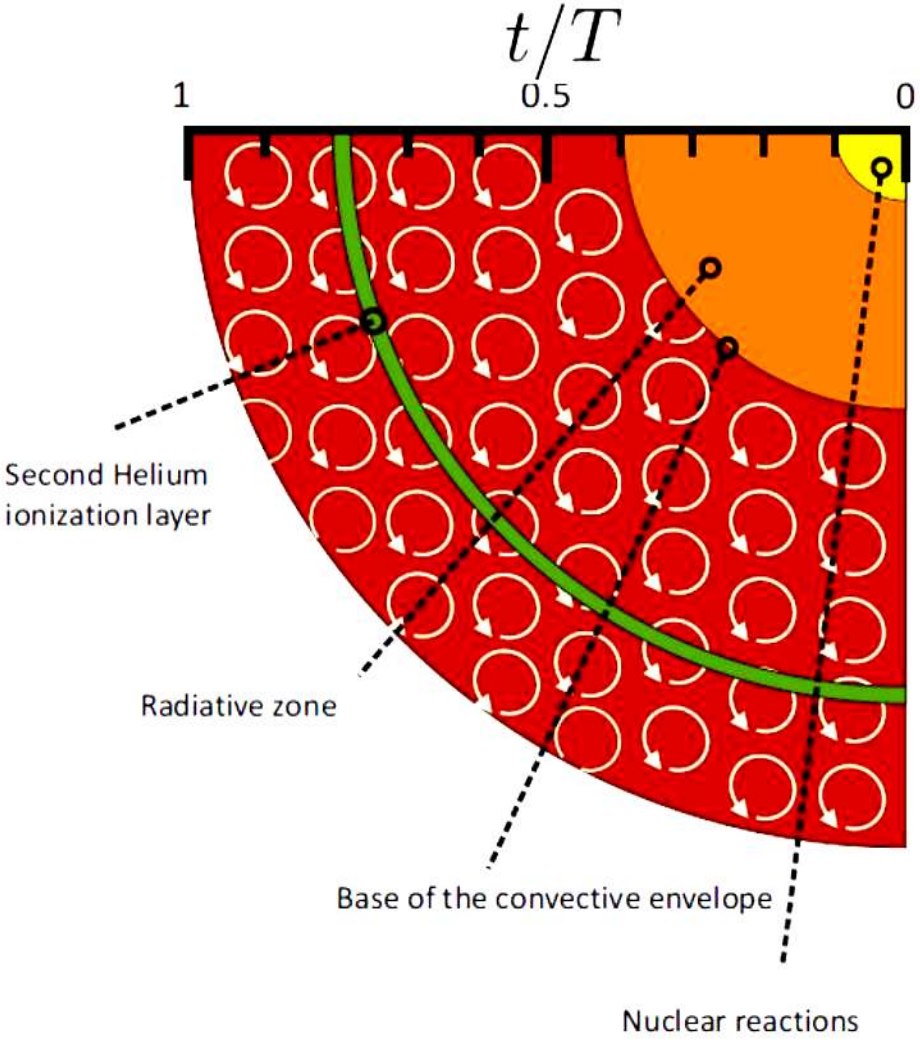
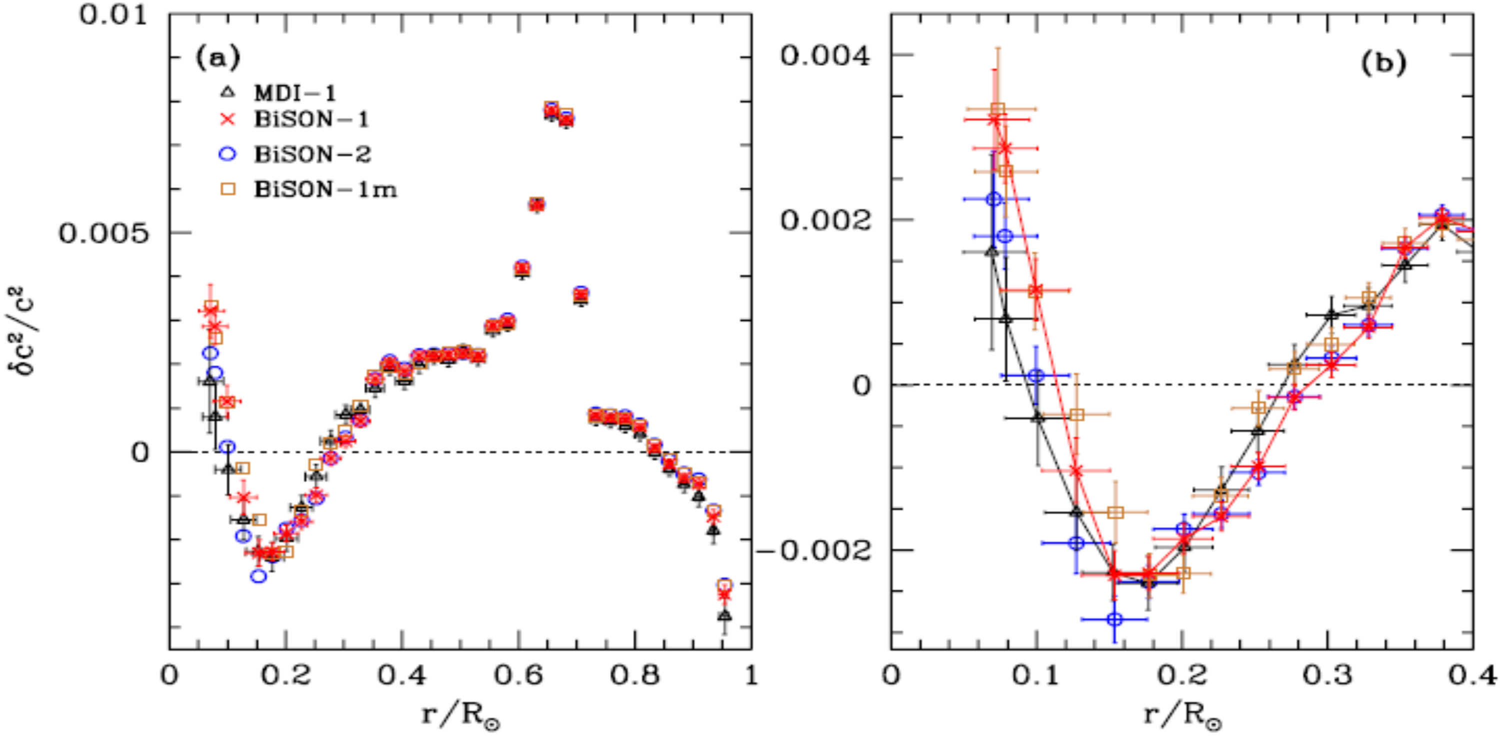
The structure of the Sun in terms of acoustic travel times



- nuclear reactions in Core
- Radiative zone
- Convection zone
- Note acoustic size of the core is small

Fractional (sound-speed)^2 differences: observed minus model BiSON + MDI data



Note that the uncertainties are larger towards centre and there is no information about the inner 5%.

Basu et al., 2009, ApJ, 699, 1403 (different lines are slightly different

Limitations of p modes in Sun……..

- In general it is very hard to get a view of the very centre because the sensitivity of the measurement in a zone is dependent on the time it takes a mode to travel through that zone. Sound speed is very high in the centre.

- For rotation the situation is worse because no information can be got from the $\ell=0$ modes that have most sensitivity to the centre.

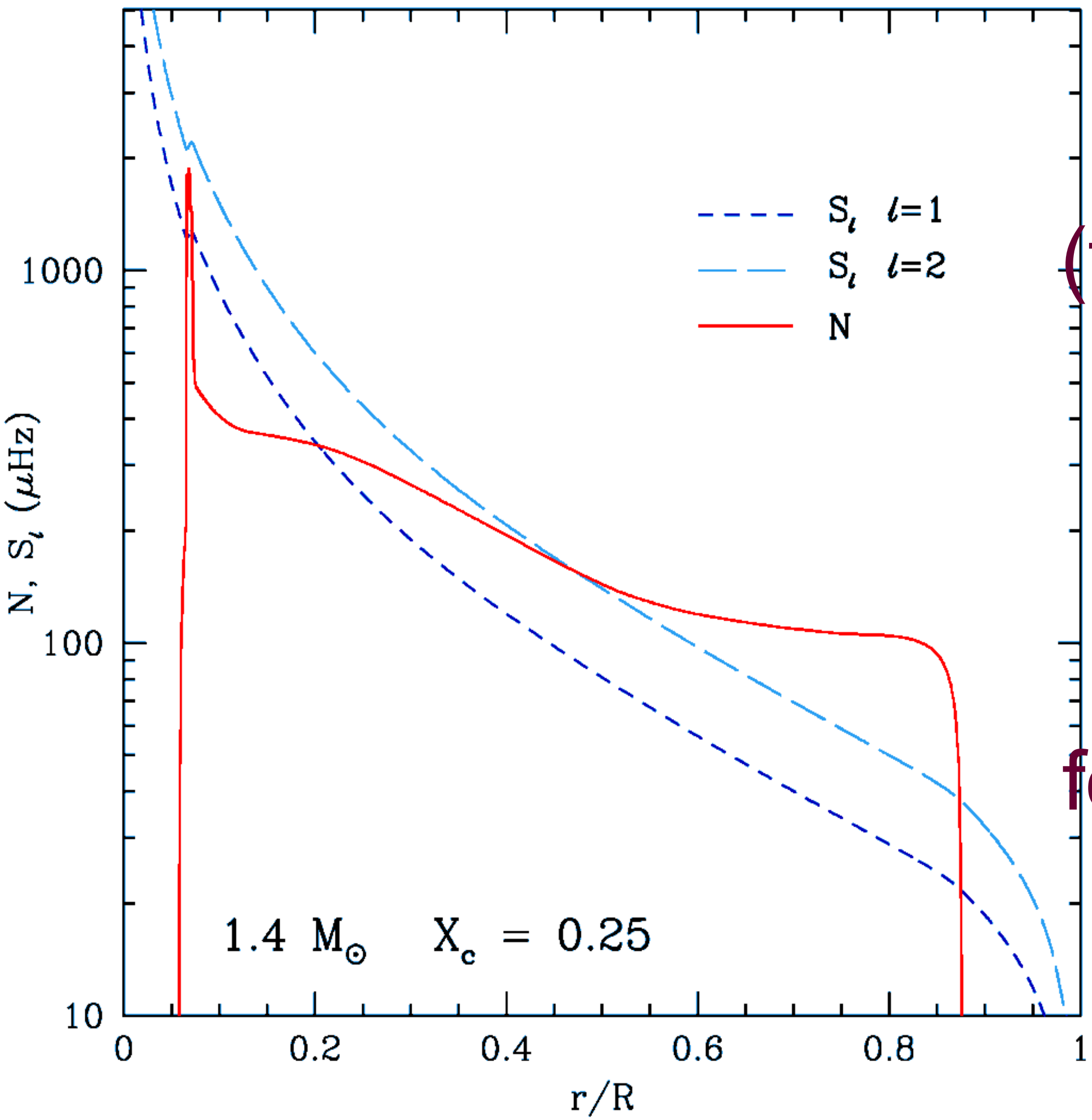
- We can do better with Red Giants

g modes

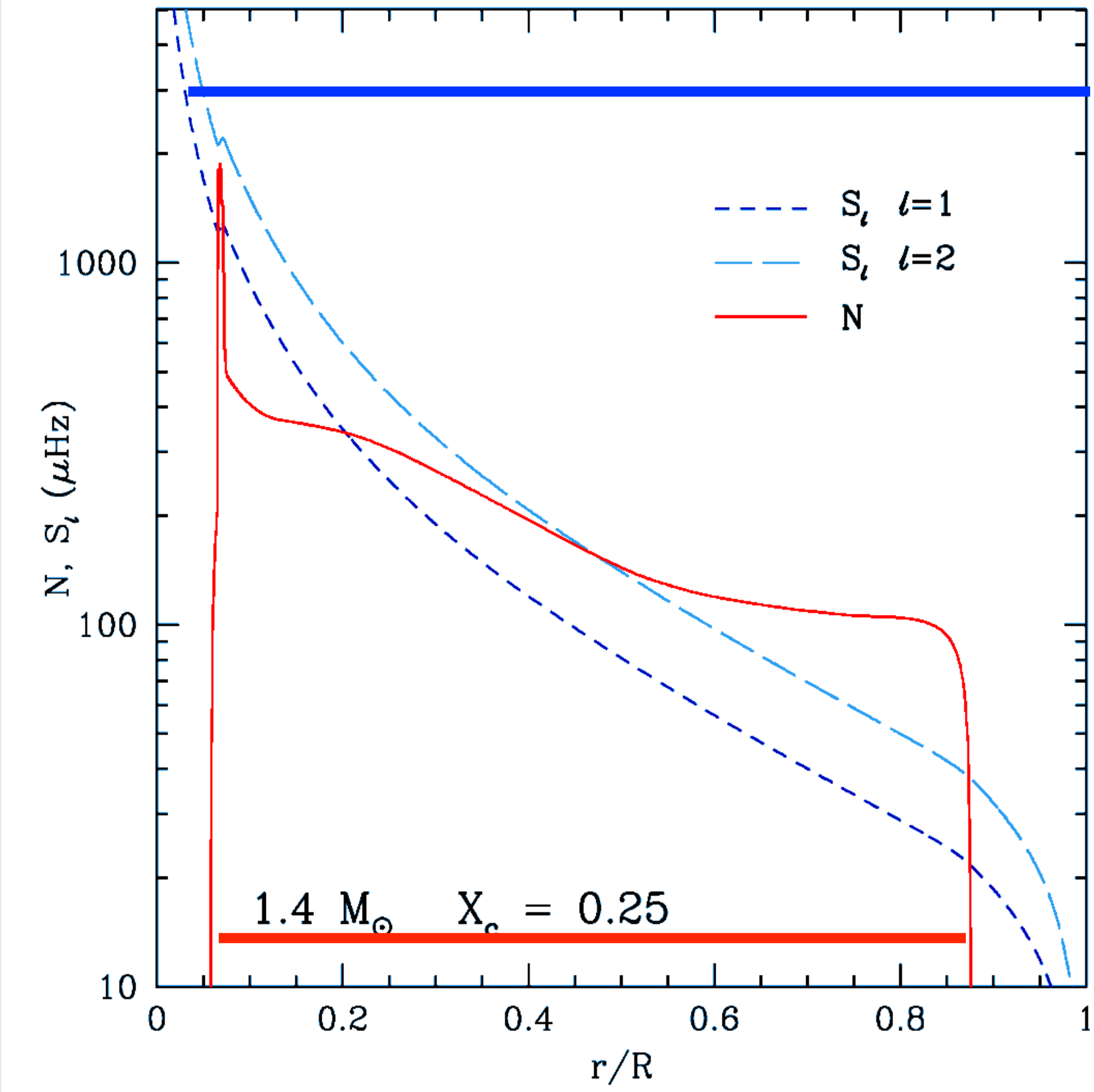
- Buoyancy is the restoring force
- The opposite of convection
- Have most of their sensitivity in the core
- Potentially very good for probing the core
- But very small amplitude at the surface of the Sun

Lamb and Buoyancy frequency

- Two key frequencies
- Lamb $S_\ell = \ell(\ell+1)c^2/r^2$ for p modes
- Buoyancy $N^2 = g(1/\Gamma_1 \rho\, (dp/dr) - 1/\rho\, (d\rho/dr))$ for g modes
- Both these vary through the star
- To get propagation, the mode frequency^2 must be less than both^2 or higher than both^2
- Otherwise, evanescant



Lamb
(for two values of ℓ)
&
Buoyancy
frequencies
vs. radius
for a 1.4$M\downarrow\odot$ star



- p mode (blue)

modes strongest where period similar to convective turn over time

- g mode (red)

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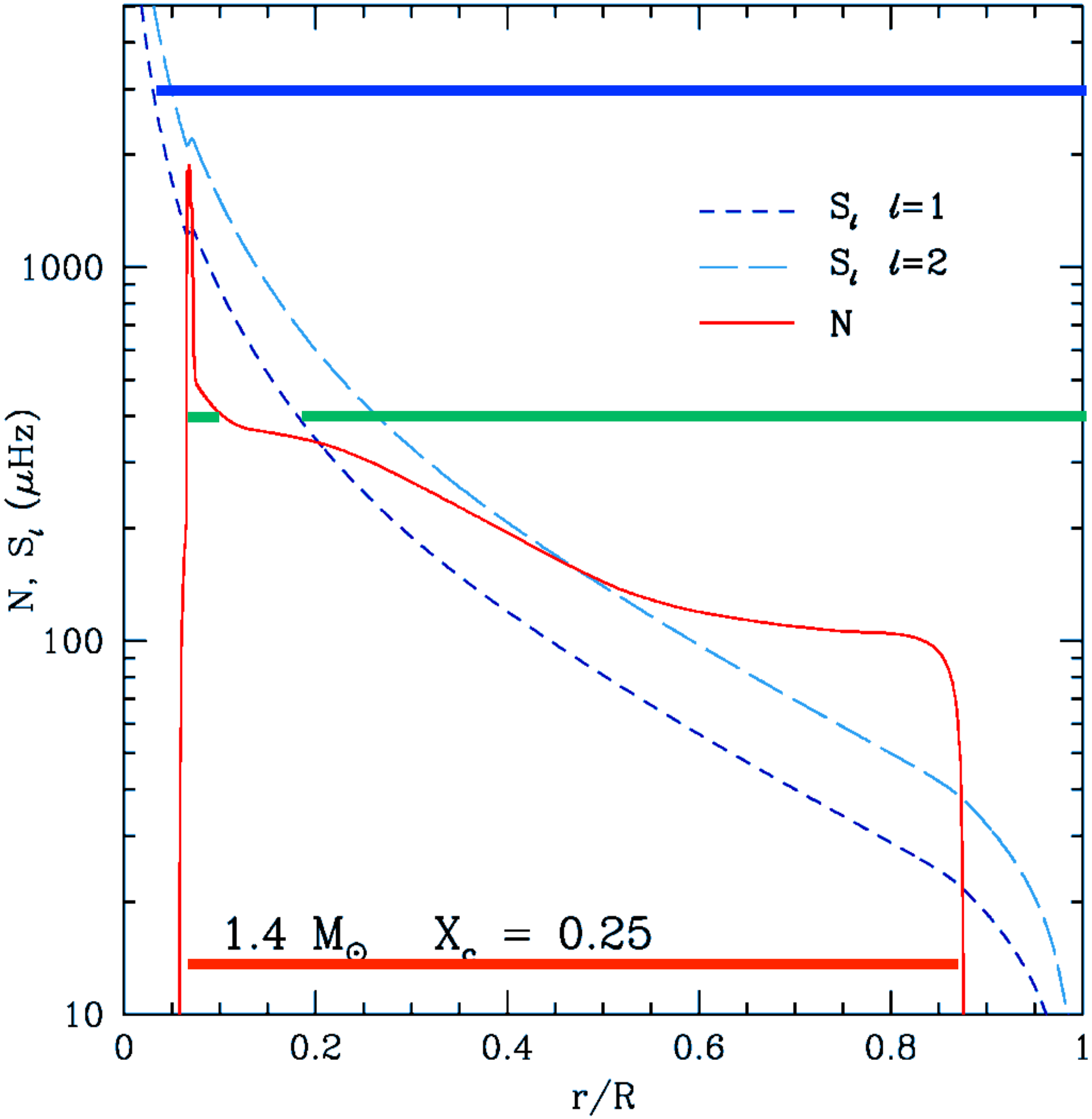

p mode

g mode

Mode that has a component in inner and outer cavities.

- mixed mode

Different types of mode are in different frequency regimes.

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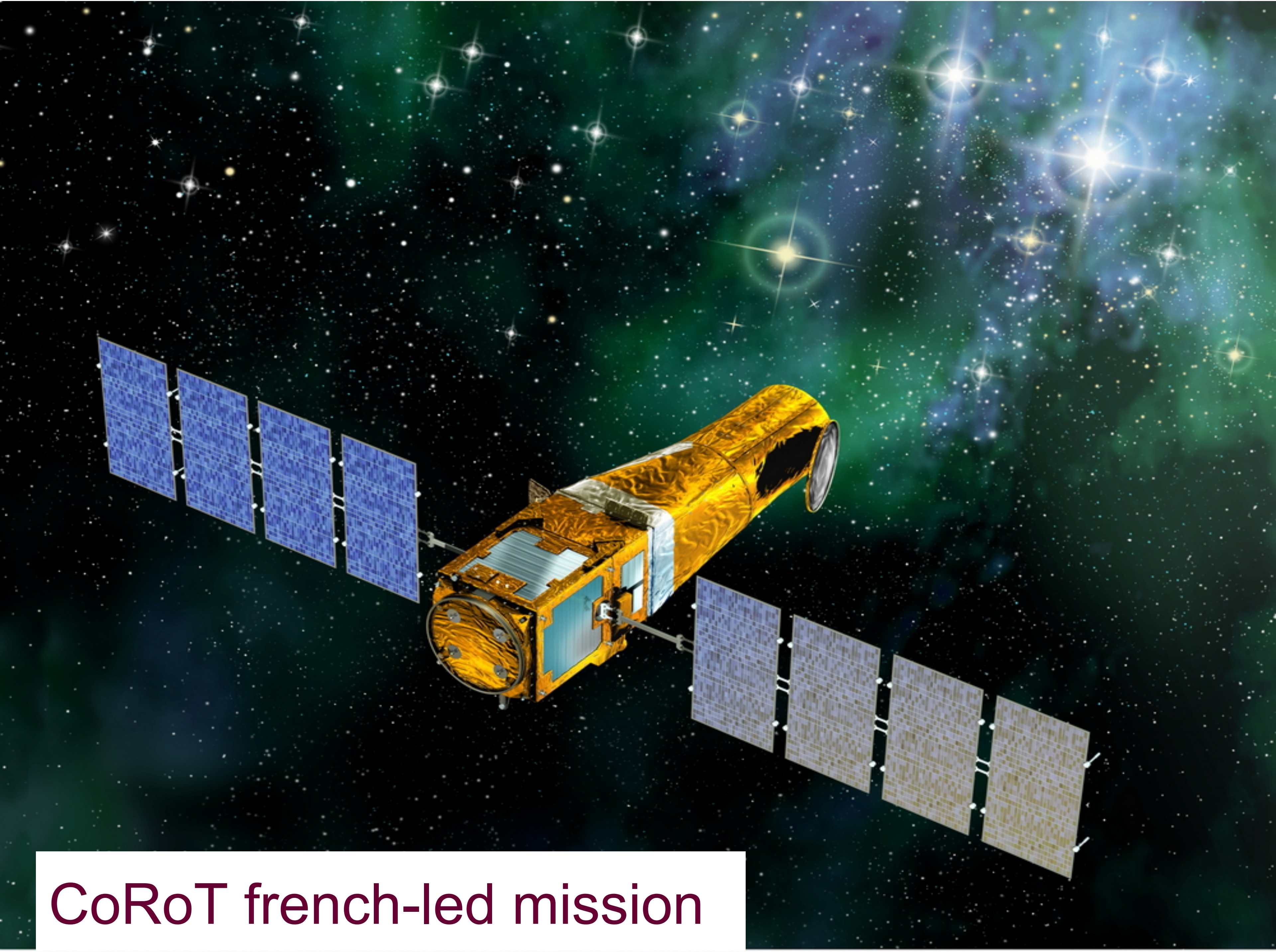
Mixed Modes

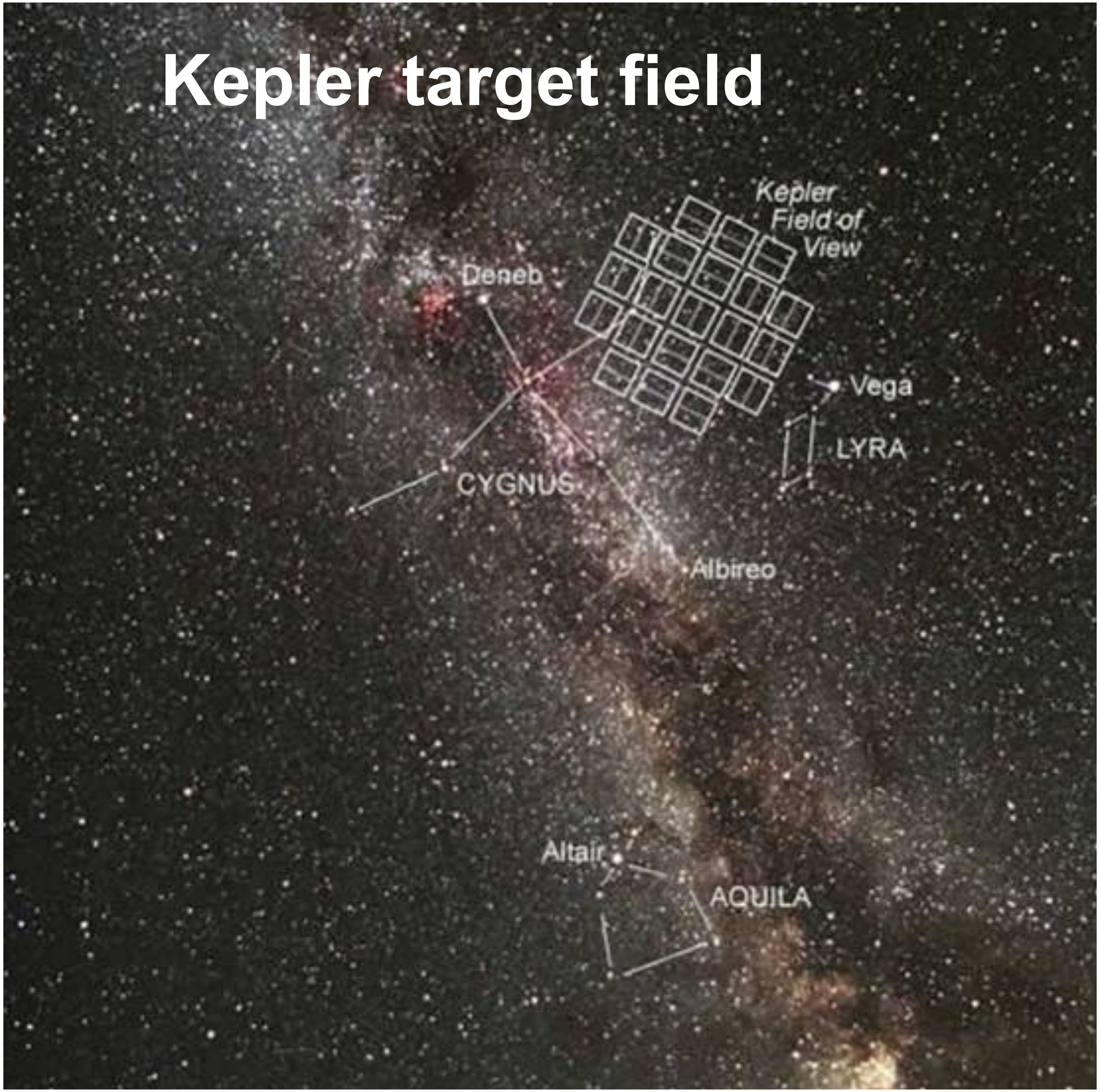
- Coupling between modes gives rise to mixed modes
- Why mixed modes are so useful
- Concept of $\nu\downarrow max$ = where p-mode power peaks
- Can we see them on the Sun? not easy
- But have been detected on other stars……..



CoRoT french-led mission

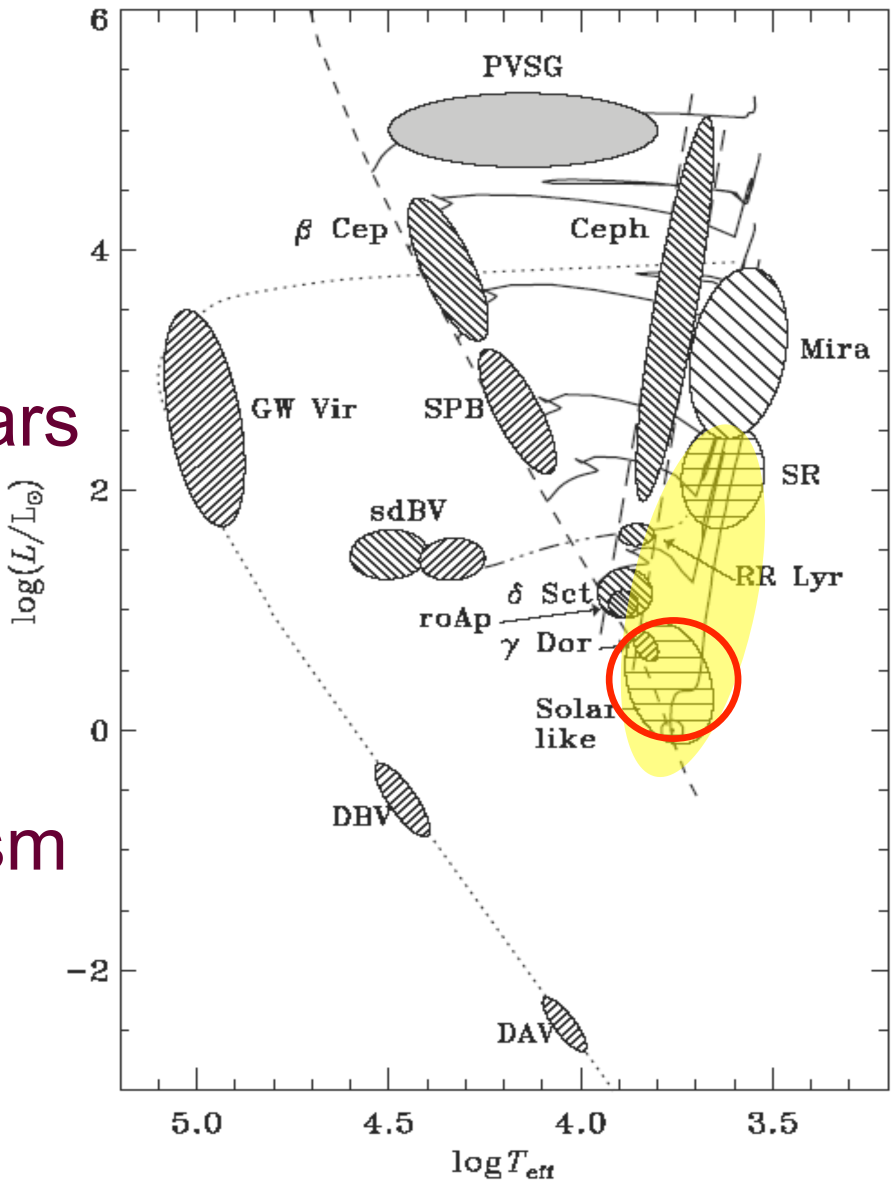
Kepler designed to search for planets by the transit method. Also picks up oscillations in the observed intensity.

Kepler target field

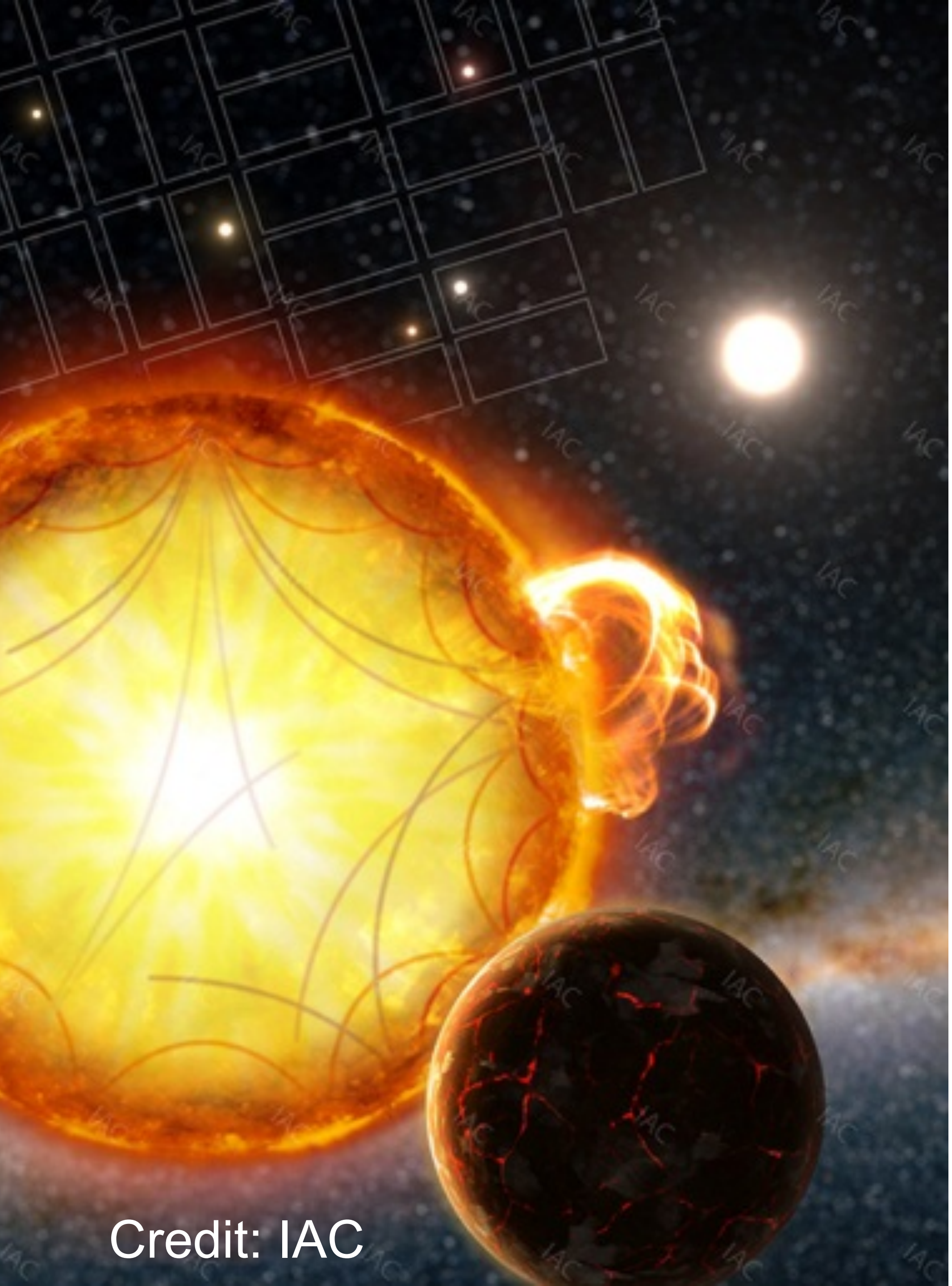


Pulsations across the HR diagram

- Bill Chaplin concentrated mostly on the solar-like stars
- I will move up the HR diagram to include more evolved stars
- Same excitation mechanism for p modes
- g (mixed) modes evident



Aerts, Christensen-Dalsgaard & Kurtz (2009)


Credit: IAC

Red Giants

Evolved low mass stars
No longer burning
Hydrogen in core
Shell hydrogen burning
May burn Helium in core

- Fundamental period of radial pulsation:

$$\Pi \propto \langle \rho \rangle^{-1/2}$$

Ritter 1880; Shapley, 1914

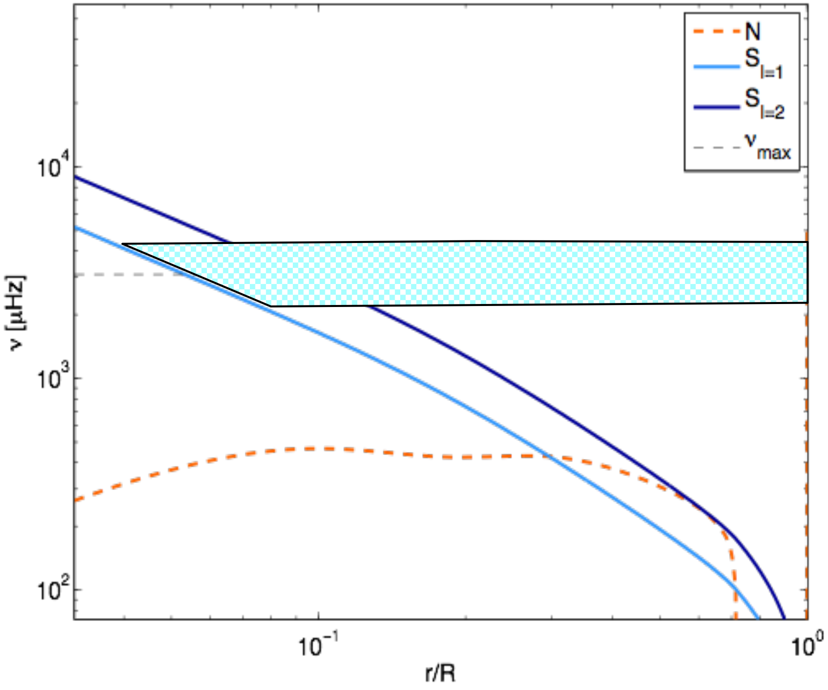
Changes with evolution as a star becomes a Red Giant ……………

- Typical frequency gets smaller as star gets larger.
- The core collapses and gets much denser and the envelope expands.
- Outer convection zone drives p modes.
- g modes in the core.
- But because of the relative densities in the zones, the frequencies are similar and the modes can couple ➔ mixed modes.
- Observable easily.
- Mixed modes very sensitive to core conditions

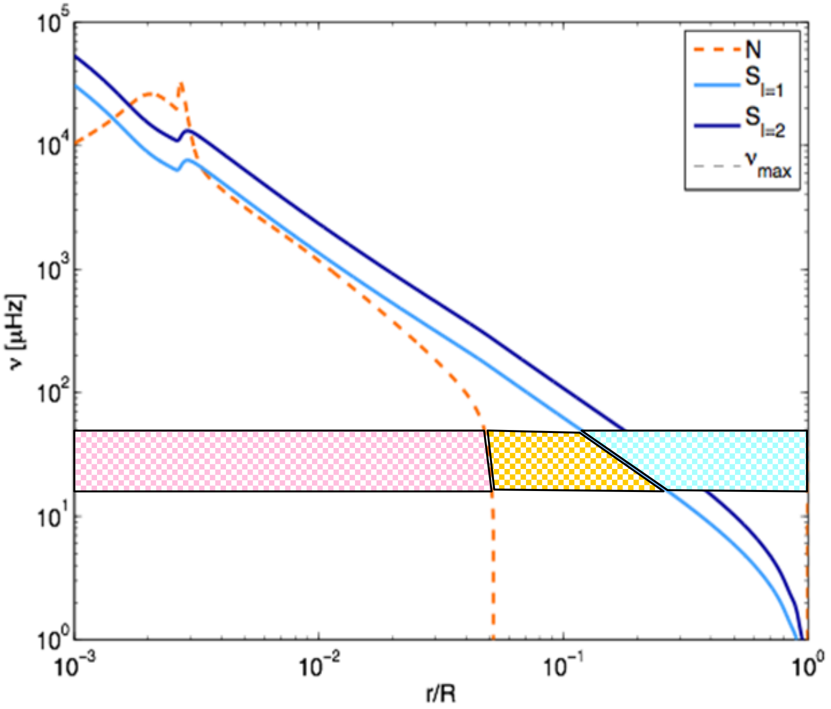
Propagation diagrams for a solar-mass star on Main Sequence and on Red-Giant Branch

- p modes ▨
- g modes ▨
- evanescent ▨

Get mixed (coupled) modes in Red Giants



Main Sequence



Red Giant

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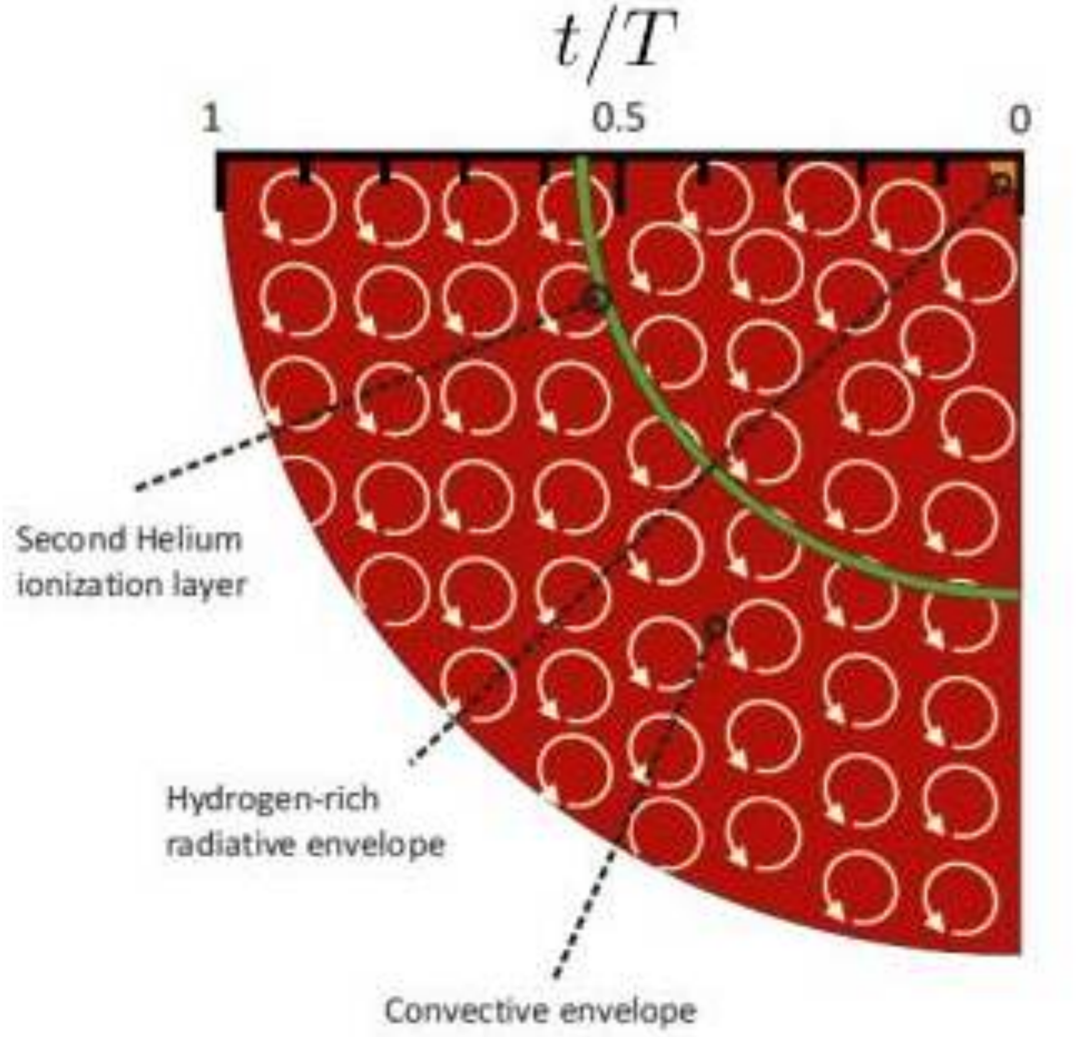
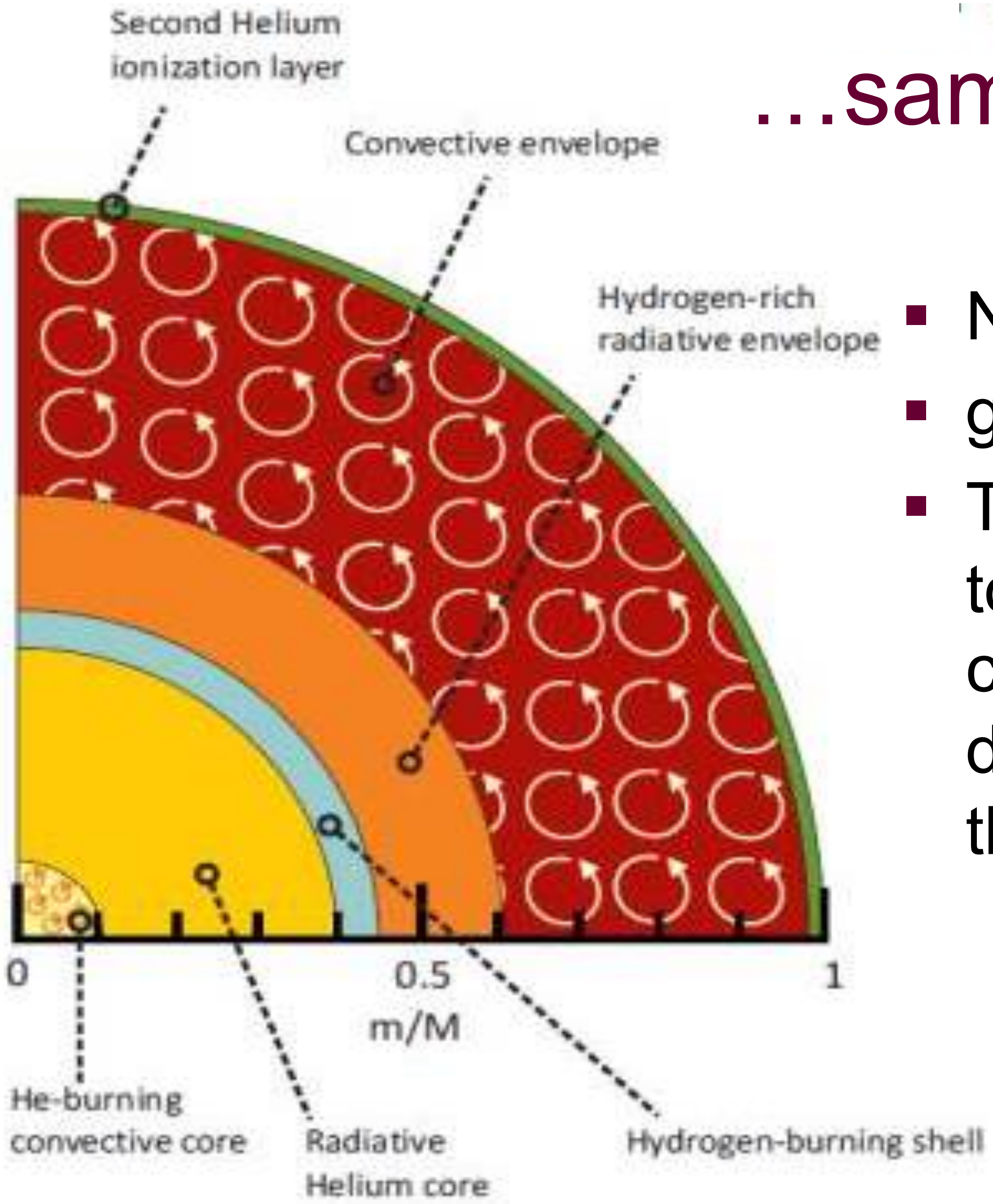
Acoustic structure of a 1.2 solar mass Red Giant



- For p modes the core is irrelevant

…same but by mass



- Now we see the core
- g modes sense this
- This star has started to burn Helium in the core but difficult to determine that from the surface

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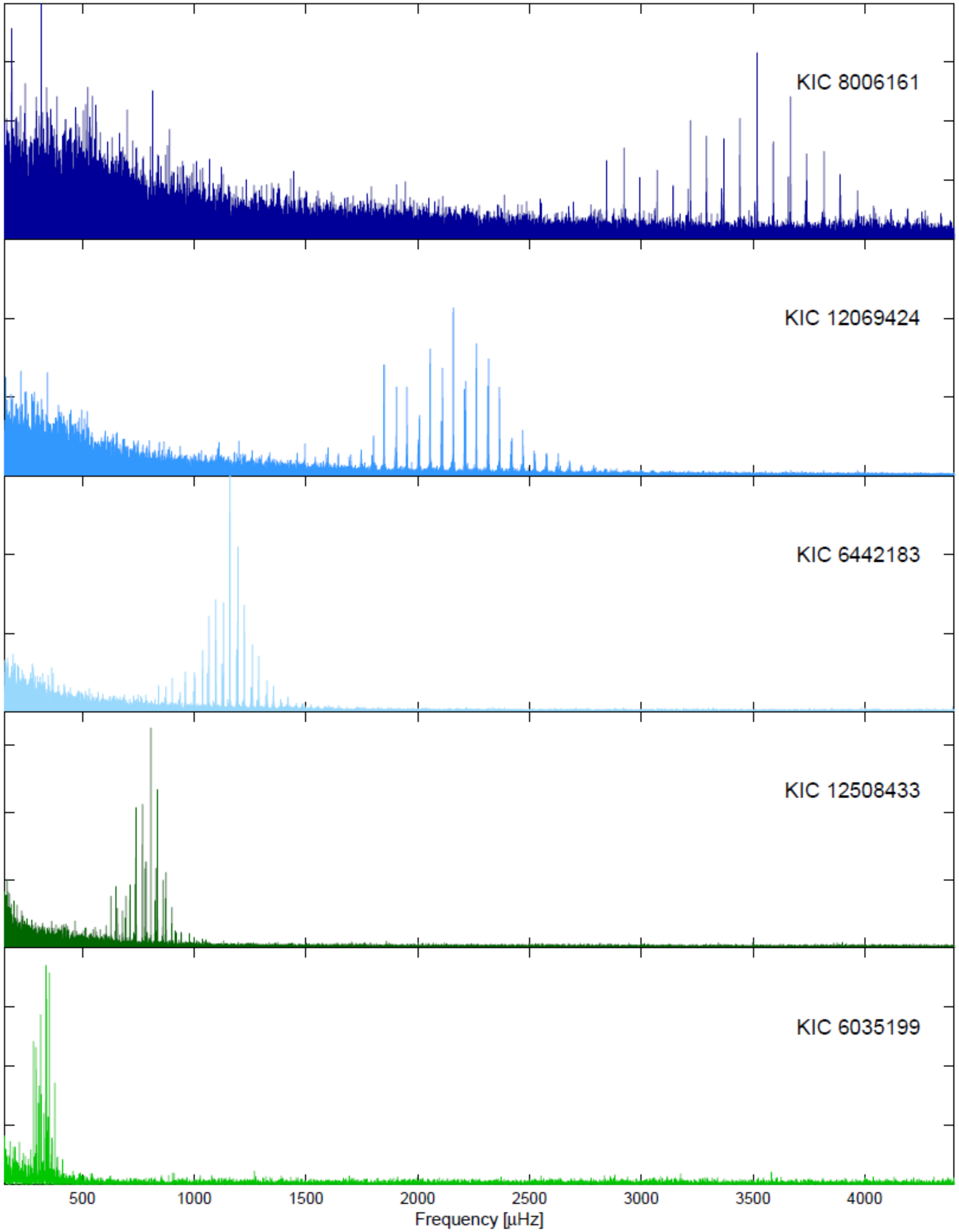
Evidence in the spectra

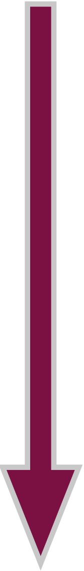
- We observe the luminosity of the star.
- In *Kepler* data Red Giants are observed with a cadence of about 30 minutes.
- Fourier spectra are made from these.
- Peak of the spectrum at frequency ν_{max}
- Backed up by traditional methods giving surface temperature and composition.

$\nu_{max} = (M T^{-0.5} / R^{2})$:related to surface gravity



As stars age they increase in size

Kepler sequence of 1 solar-mass stars



Increasing size, age

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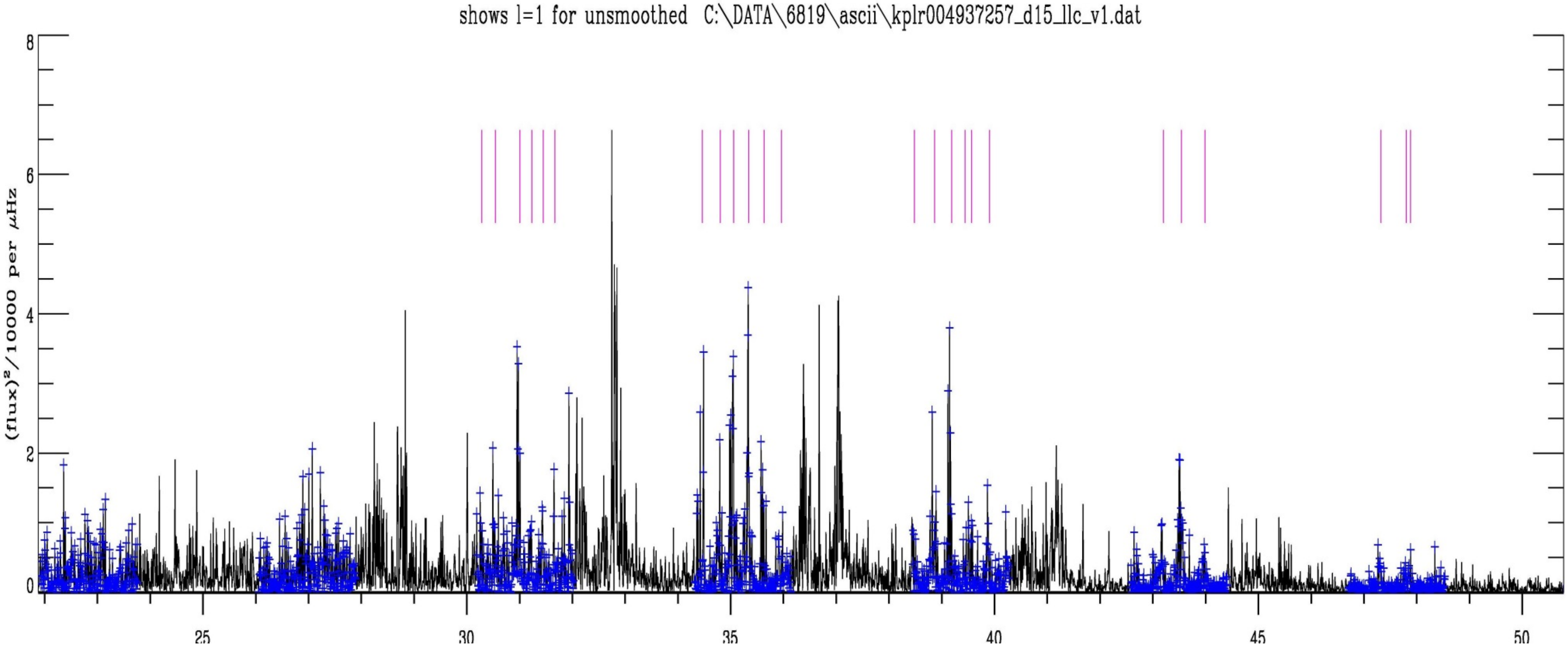
Part of spectrum of a Red Clump star that is burning Helium in its core



- Blue shows ℓ=1 mixed modes
- Black ℓ=0 (p modes) & 2 (p dominated)

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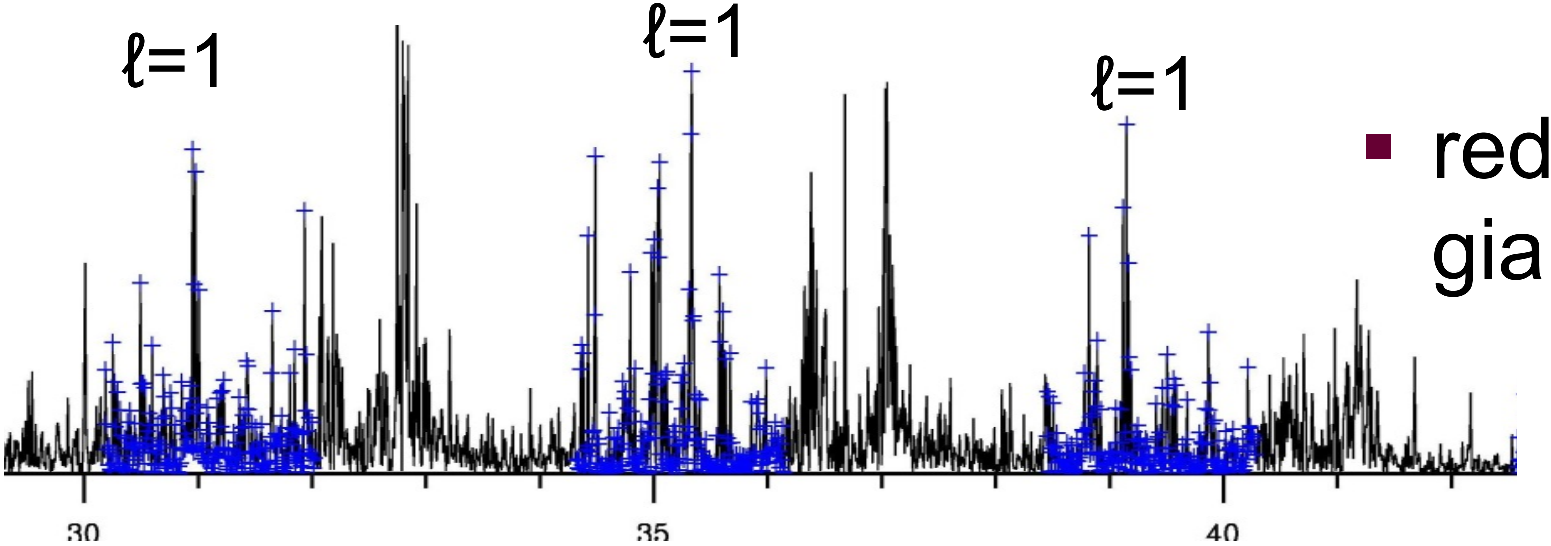
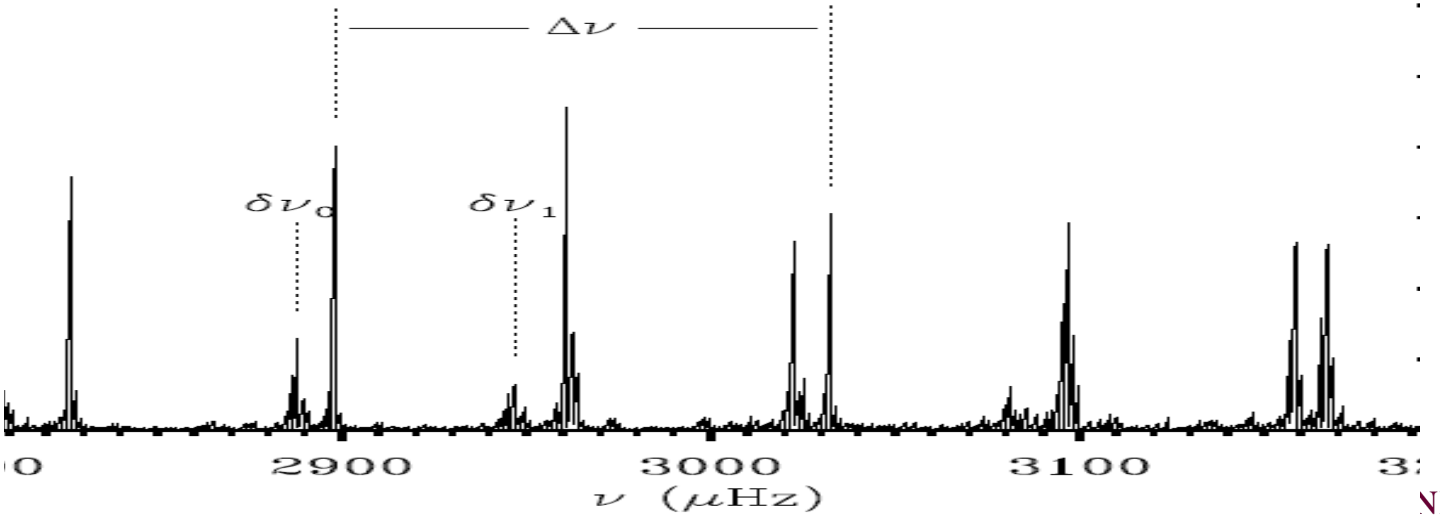
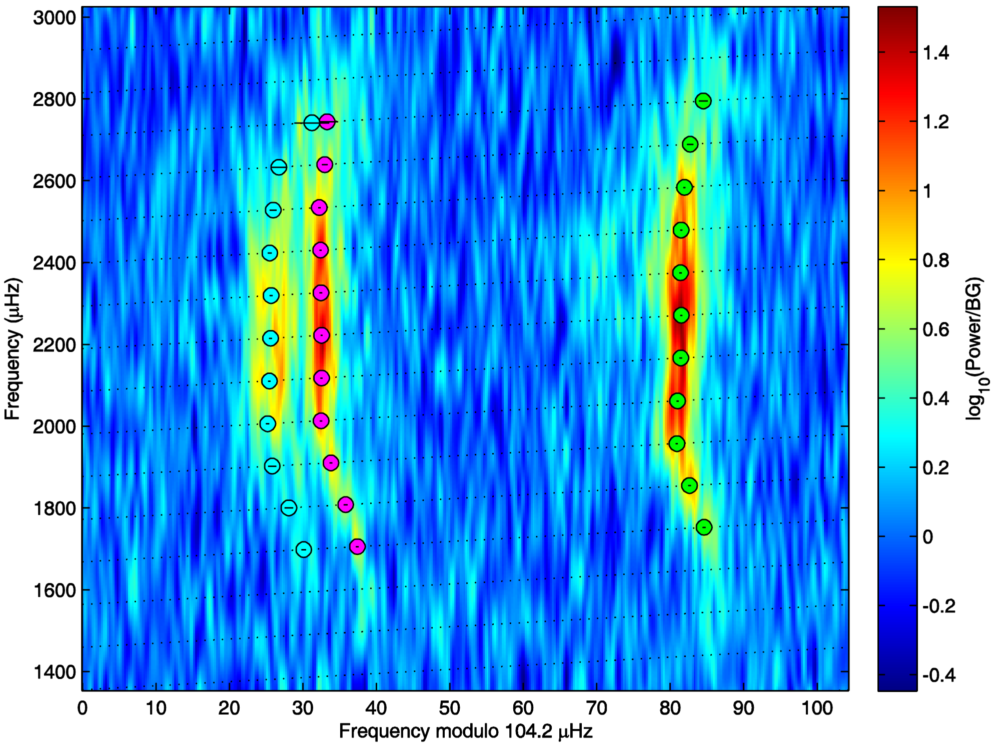
Compare with solar spectrum



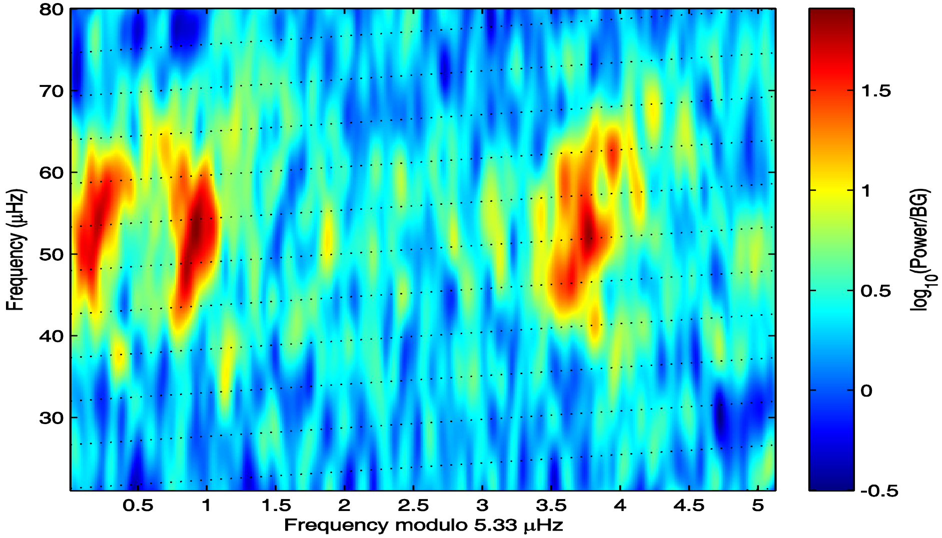
- red giant



Compare main sequence and red giant spectrum



- Red giants oscillate at lower frequencies because much bigger 30μHz vs. 3000μHz
- Relatively stronger oscillations
- Many fewer orders
- High signal to noise
- Complicated spectra
- Extra features



What we have learnt about Red Giants

- Great success stories of *CoRoT* and *Kepler*
- Showed non-radial modes present *Nature* 2009 **459**
- Detected 'mixed' modes which are sensitive to both the core and the outer regions. *Science 2011* ***332***
- Have been able to detect evolutionary state of stars – have they reached helium-core burning yet? *Nature 2011* ***471***
- Measure rotation and able to show centre rotating much fast then surface – unlike the Sun. Can we track changes with evolution? *Nature 2012* ***481***

Giants oscillate in radial and non-radial modes

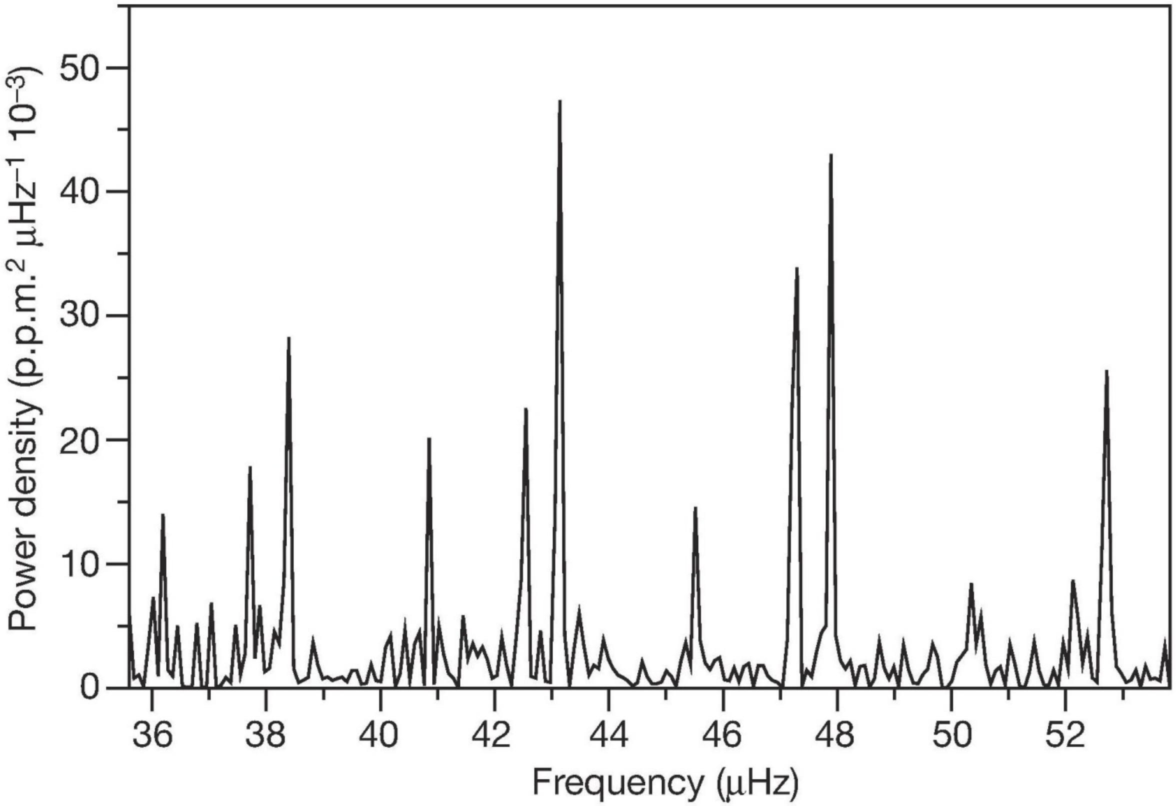
A major problem with the observation of the giants is typical period of the oscillations at a few hours – hard to fit into a night and interrupted observations give sidebands.

Amplitudes are parts per thousand so need low noise – also hard from the ground because of the atmosphere.

De Ridder et al. 2009, *Nature*, 459, 398 used *CoRoT* data to report the presence of radial and non-radial oscillations in more than 300 giant stars.

No-one knew if the mode lifetimes would be short or long – they showed them to be at least 1 month thus indicating that longer observations would show more structure.

Spectrum of CoRoT 101034881



from *Nature*, 459, 398

Figure 2 | Power density spectrum of the red giant candidate CoRoT-101034881 showing a frequency pattern with a regular spacing. This spacing is predicted by the theoretical asymptotic relation for high-order and low-degree oscillations[21]. Using the auto-correlation function of the power spectrum, we derive the large separation to be 4.8 μHz. This value is consistent with what is expected for red giants from scaling laws[19].

from *Nature*, 459, 398

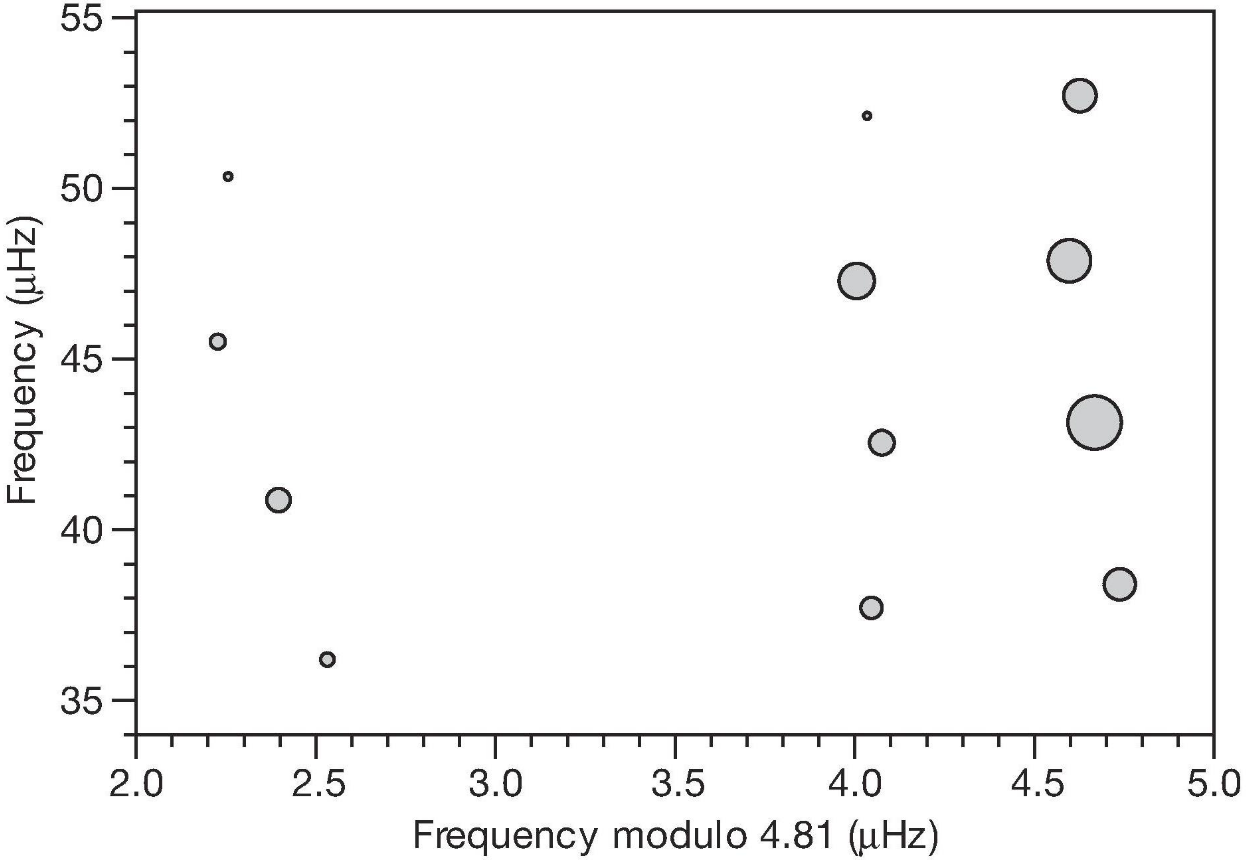


Figure 3 | Echelle diagram of the modes shown in Fig. 2, showing 'ridges' related to radial and non-radial modes. The folding frequency is 4.81 μHz. The size of the symbols is proportional to the height of the peak in the spectrum shown in Fig. 2. From the theoretical asymptotic relation for high-order and low-degree oscillations[21], we conclude that the three vertical ridges correspond to dipole modes (left), quadrupole modes (middle) and radial modes (right).

‘Mixed’ modes sensitive to both the core and the outer regions detected.

Beck et al. *Science* 2011, **322,** 205

Lifetime of g modes is long.

Multi-year datasets from *Kepler* allow extra structure to be revealed.

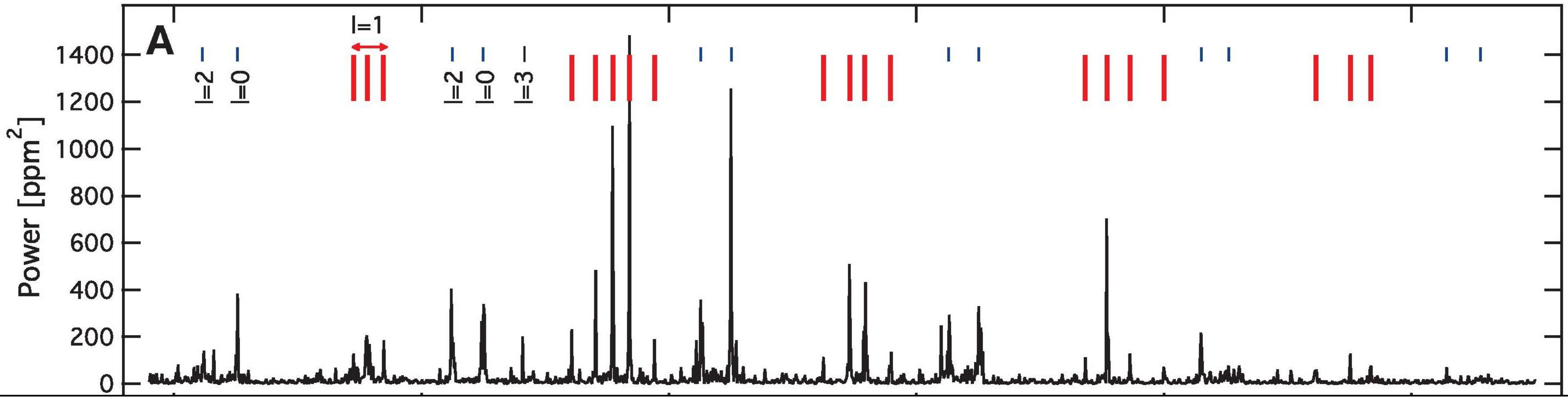
p-mode pattern is roughly equally spaced in frequency

but …………….

g-mode pattern equal in period except pulled when very close to nominal p-mode position

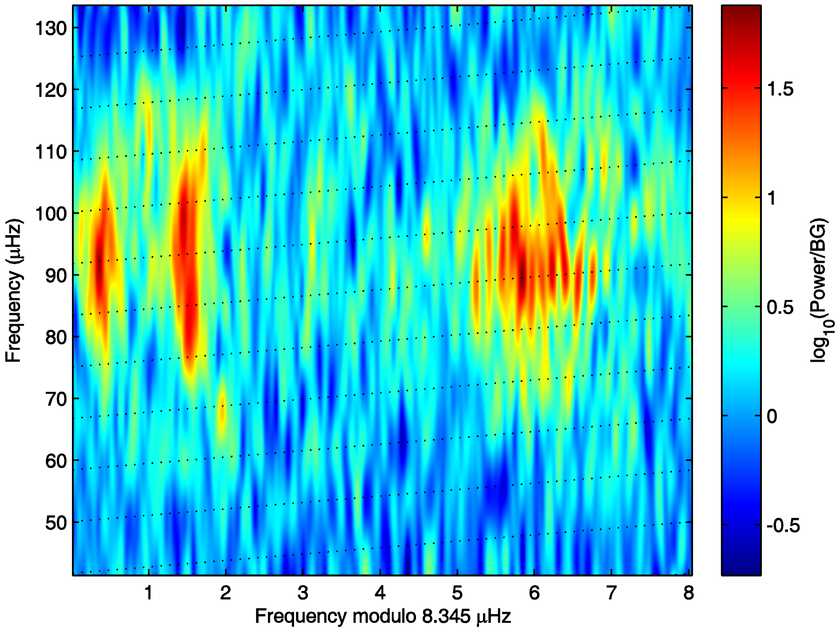
Mixed modes revealed in KIC 6928990 red-giant branch star

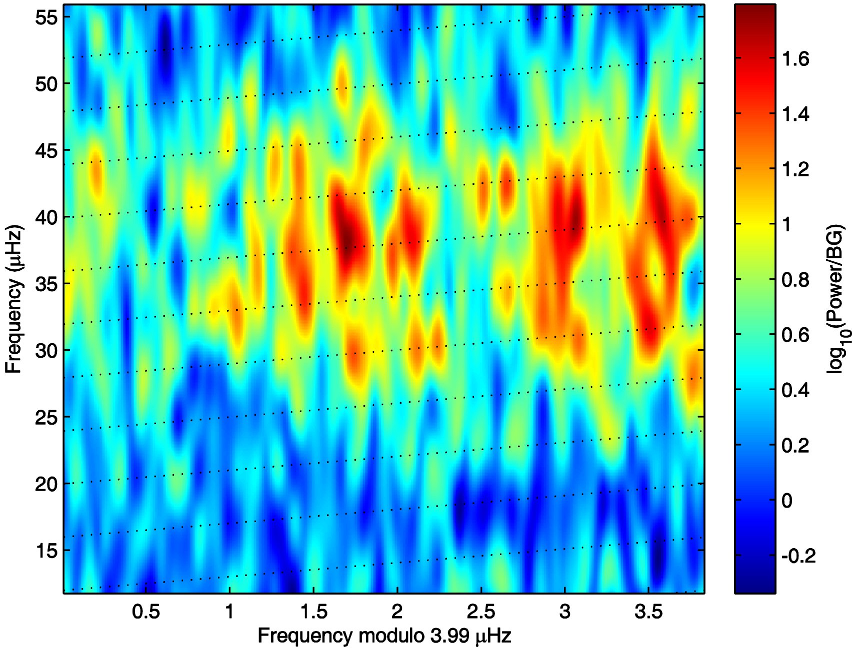
from *Science*, **322**, 205



What is happening deep inside - Red Giant branch or Helium core burning?

- Compare structure……





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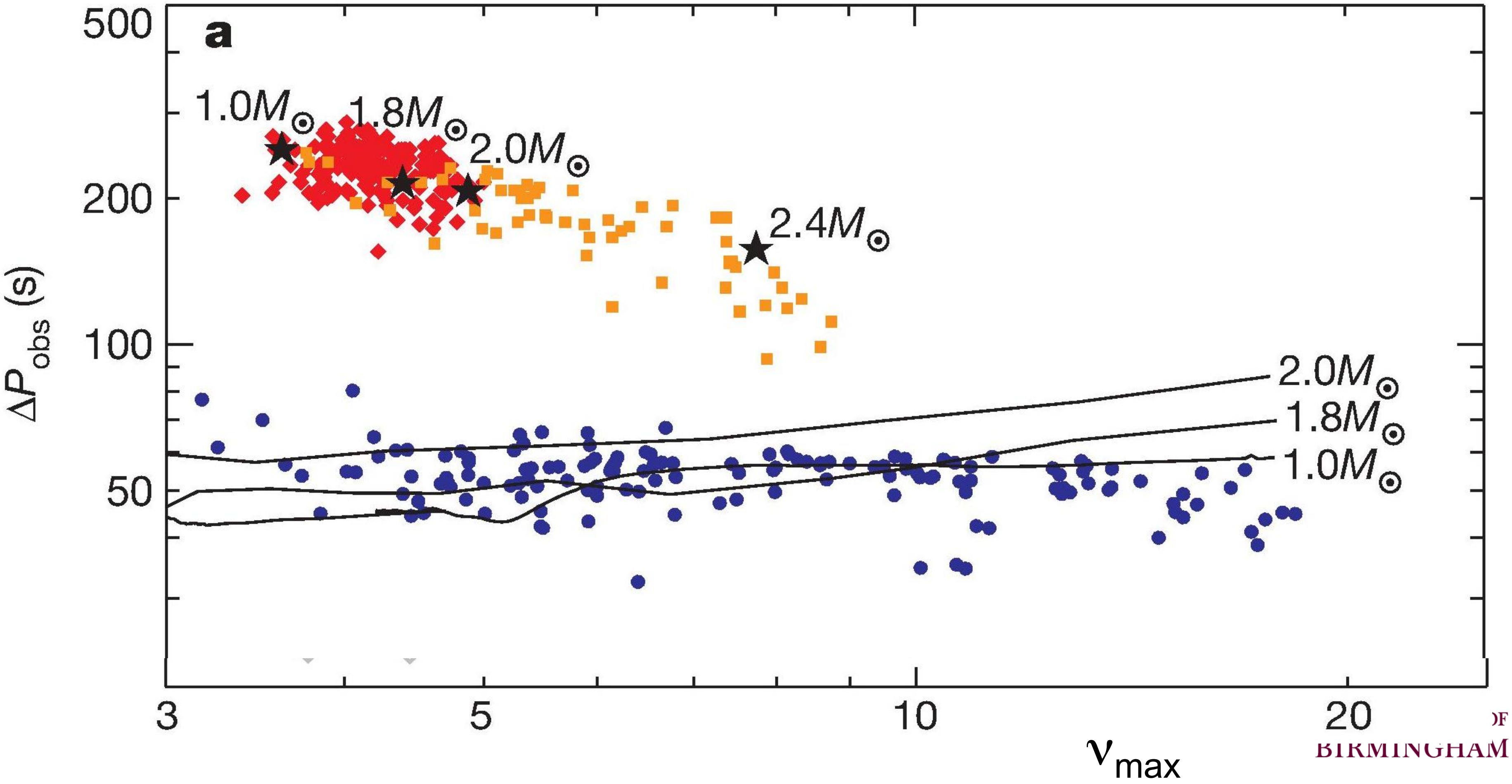
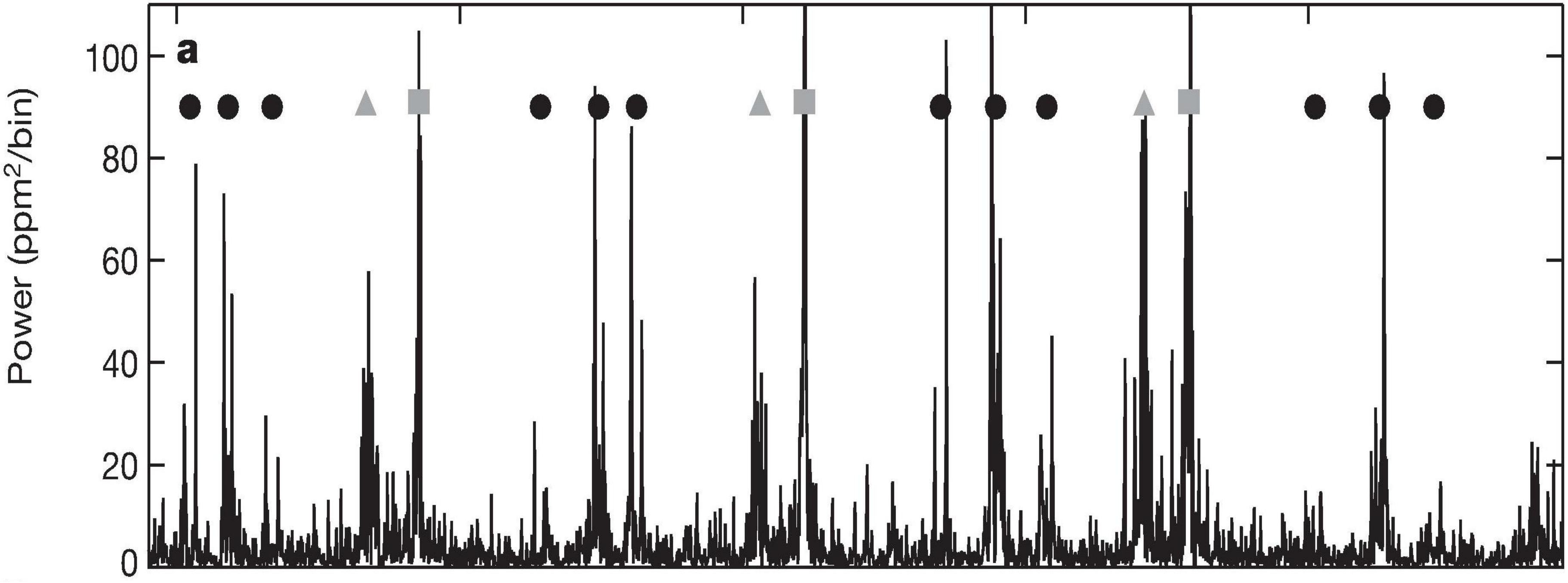
Helium-core burning (red and yellow) or RGB (blue)

Bedding et al. *Nature 2011* ***471***

Period spacing vs. ν_{max} for a wide range of stars

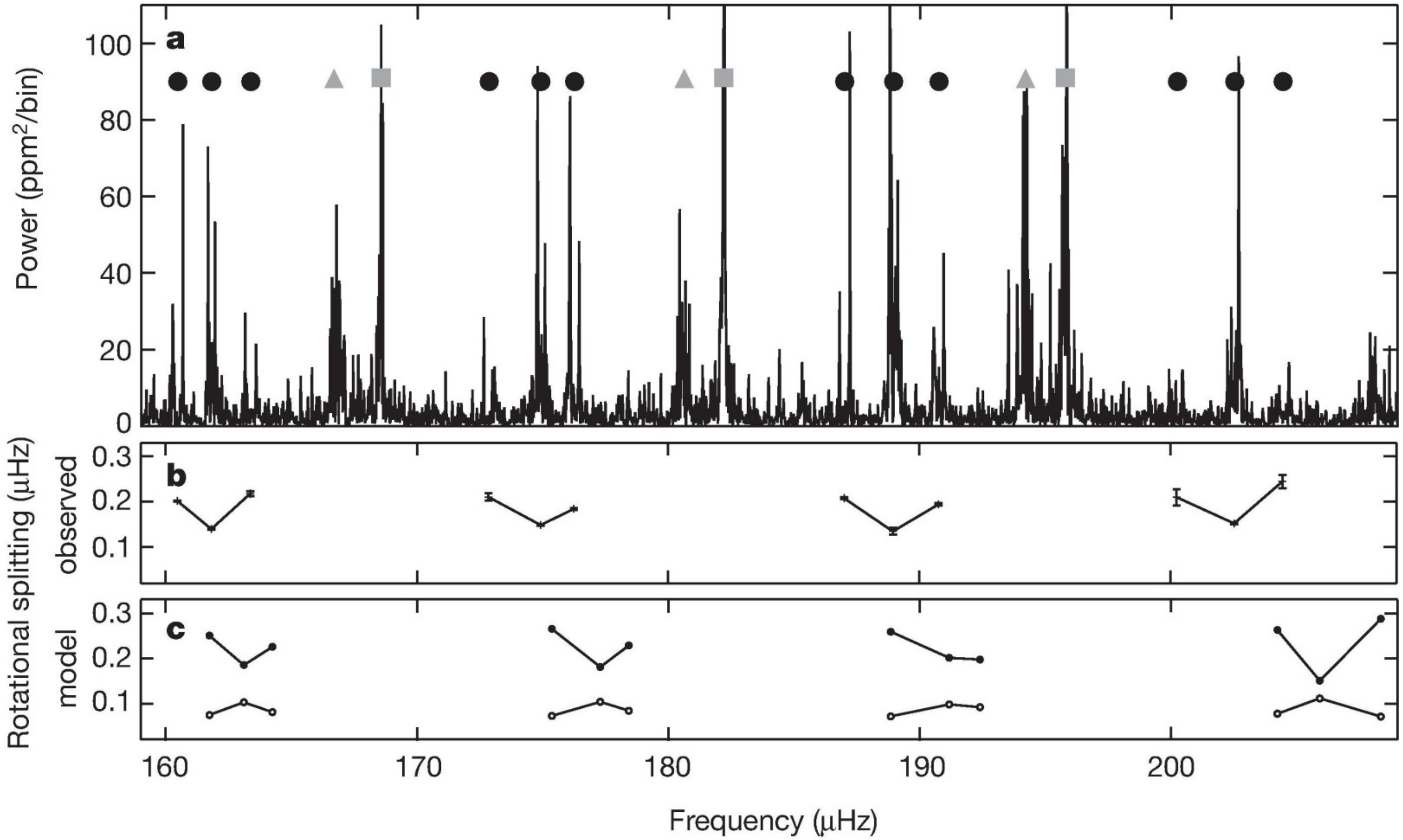


Rotational splitting of red giant branch star



Beck et al. *Nature* *2012* ***481***

The core of a red giant rotates faster than its surface

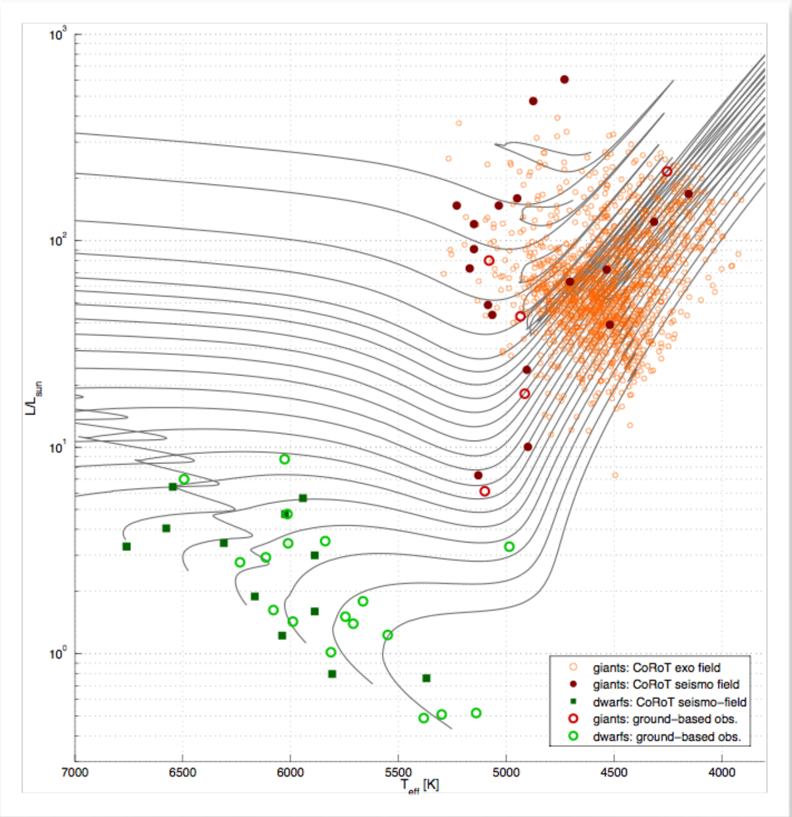


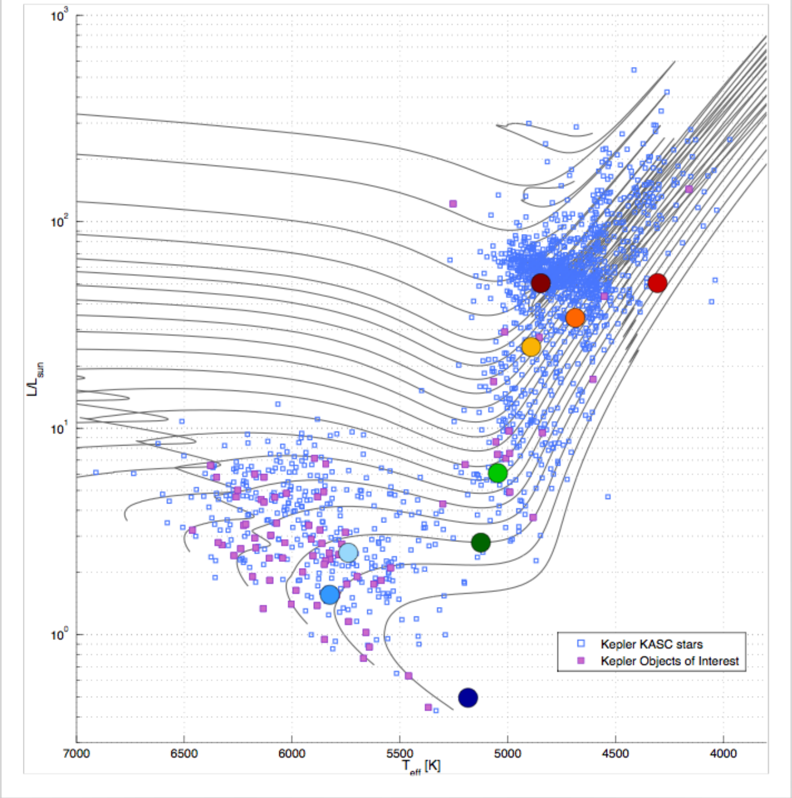
Beck et al.
Nature
2012 ***481***

Panel b: observation

Panel c: upper – fast core, lower – rigid rotation

CoRoT & Kepler



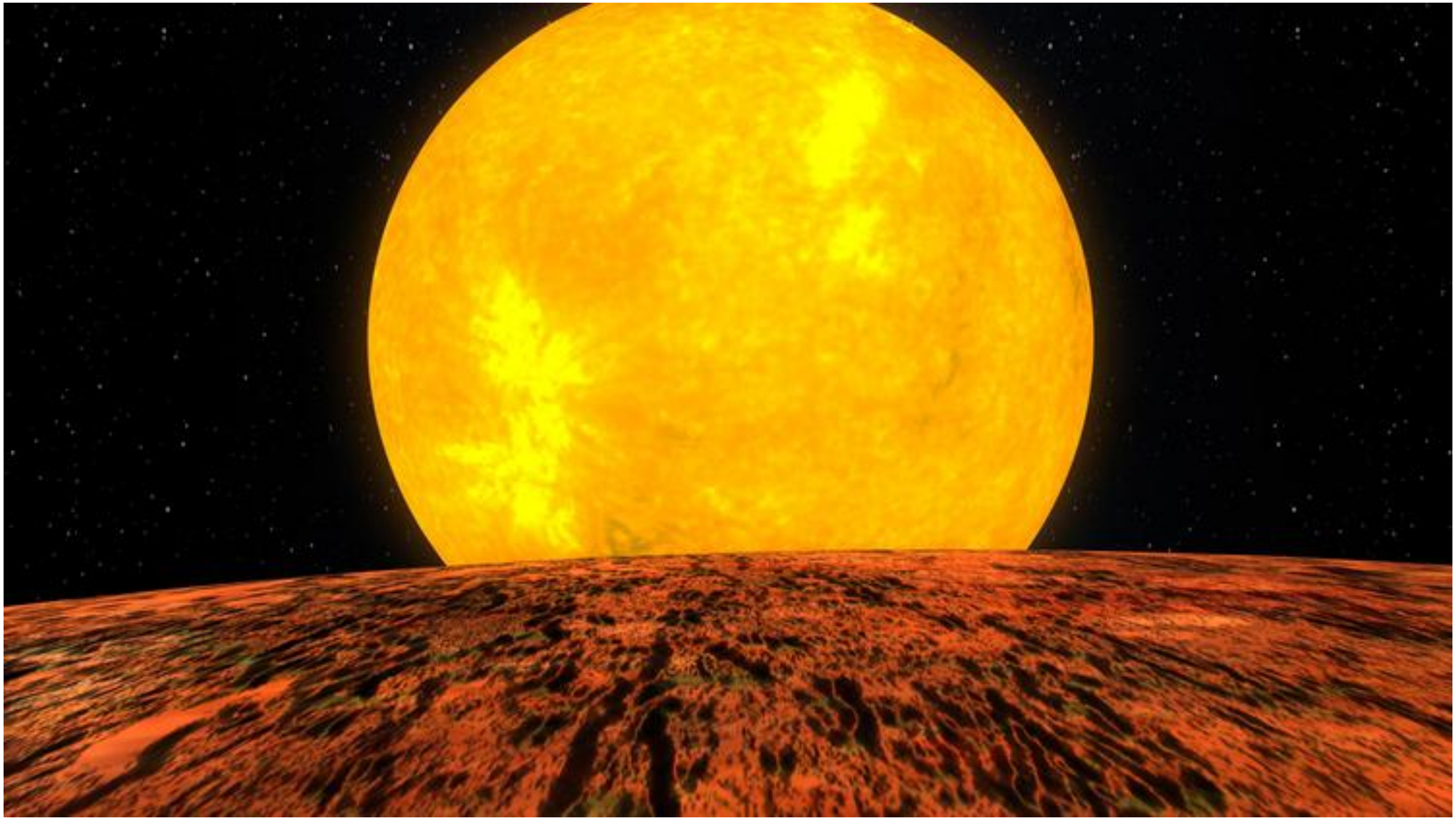


Chaplin & Miglio, ARAA, 2013

Challenges

- Develop good methods to compare observation and theory
- Average seismic parameters for very many stars – many methods exist for some of the parameters. Rotation and period spacing more difficult.
- Find the parameters of individual modes
- Automation
- Simulations – how good is the model?
- Improve the stellar models
- Population studies

Thanks



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