Asteroseismology over the HR Diagram – Kepler results

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Jeremiah Horrocks Institute
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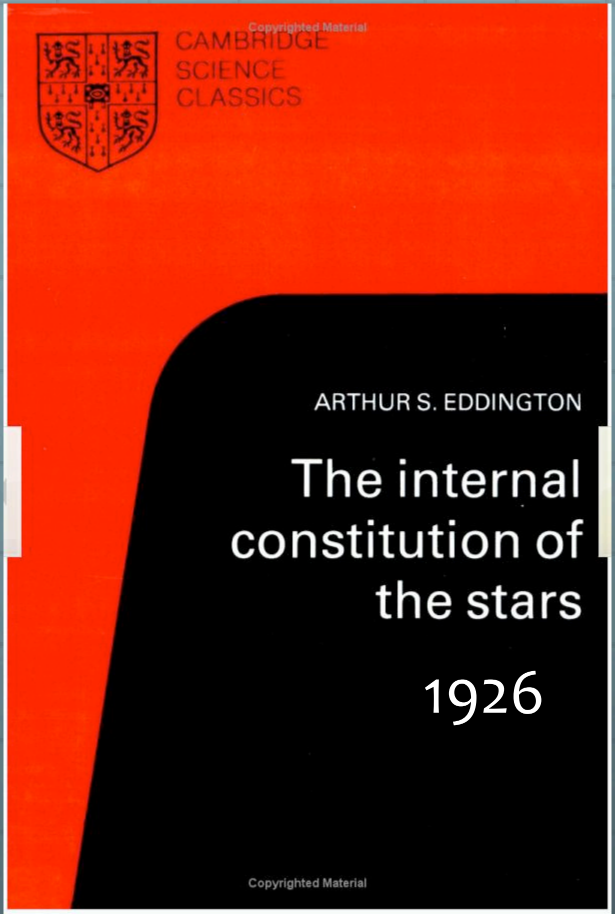
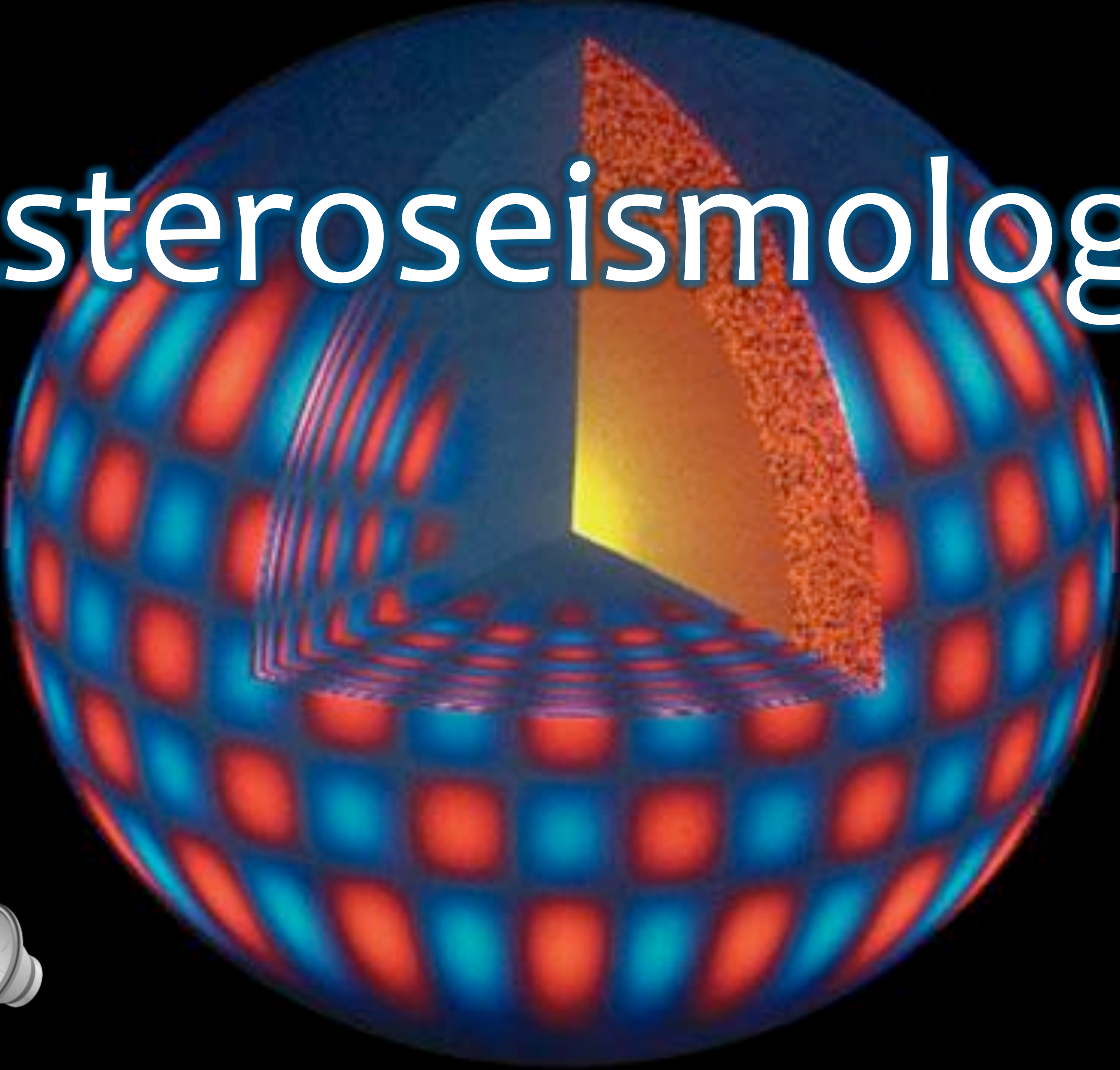


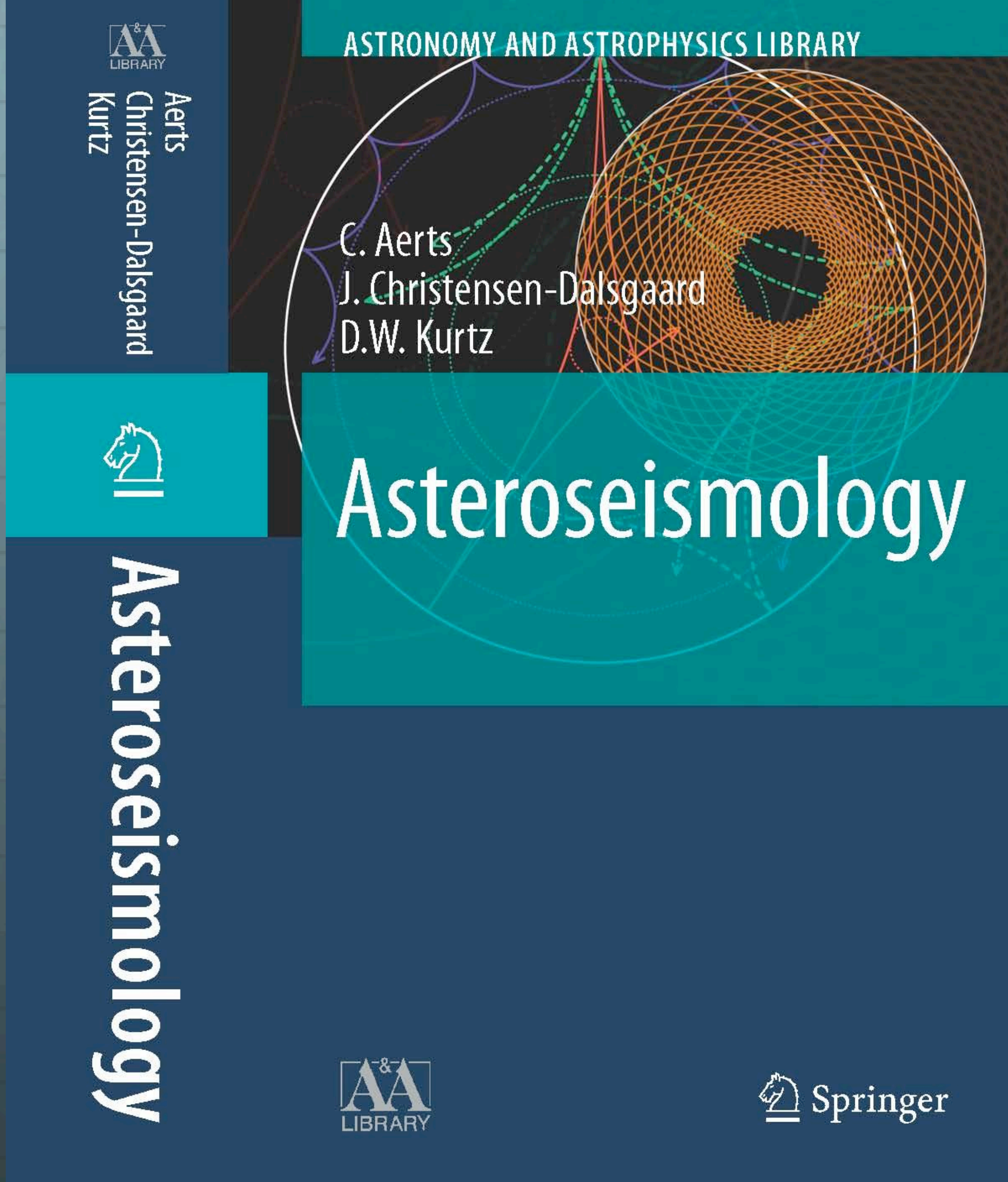
At first sight it would seem
that the deep interior
of the Sun and stars
is less accessible
to scientific investigation
than any other region of the universe.

Our telescopes may probe
farther and farther
into the depths of space;
but how can we ever obtain
certain knowledge
of that which is hidden
behind substantial barriers?

What appliance
can pierce through
the outer layers of a star
and test
the conditions within?

Asteroseismology

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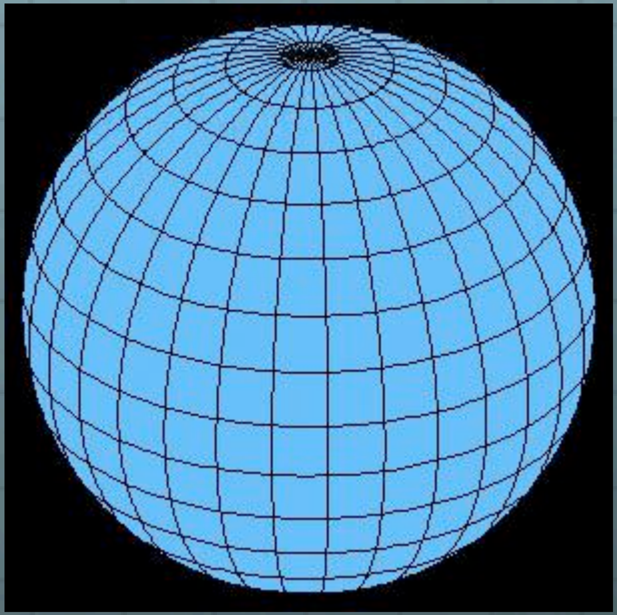
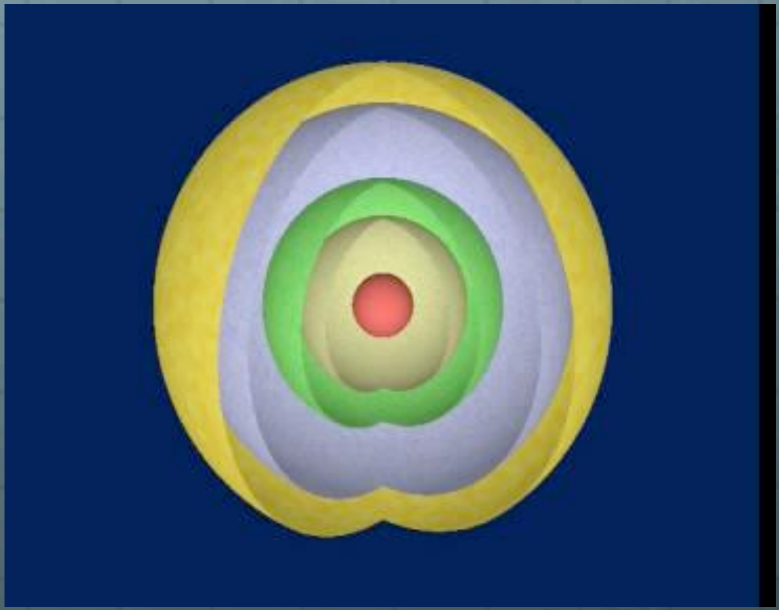
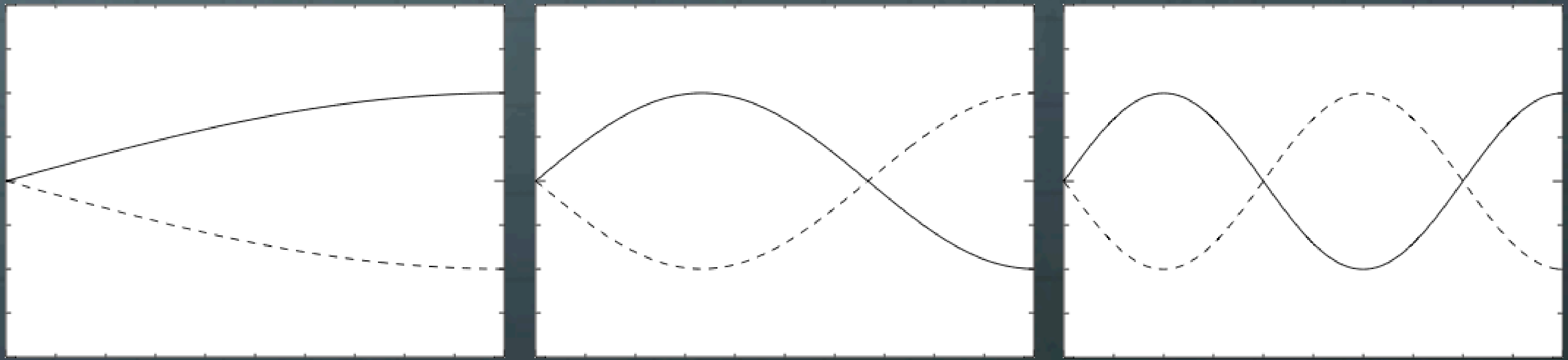
Radial modes





Cepheids
$P_1/P_0 = 0.7$

organ pipe
$P_1/P_0 = 0.33$



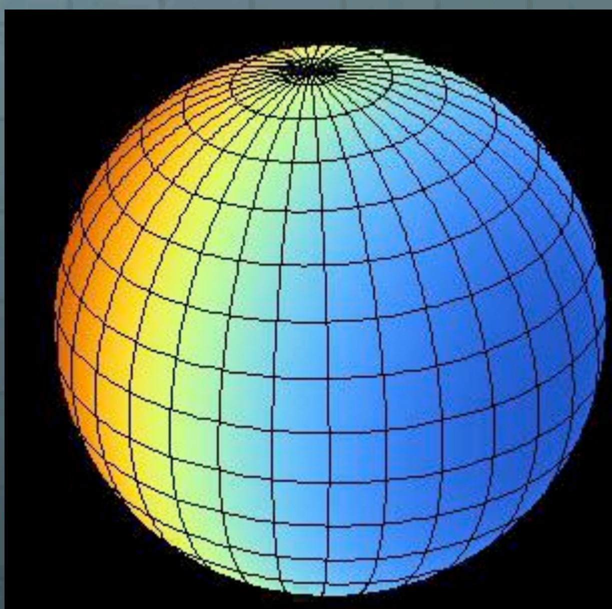
Structure of stellar pulsation modes

$$Y_l^m(\theta,\varphi) = N_l^m P_l^{|m|}(\cos\theta)\, e^{im\varphi}$$

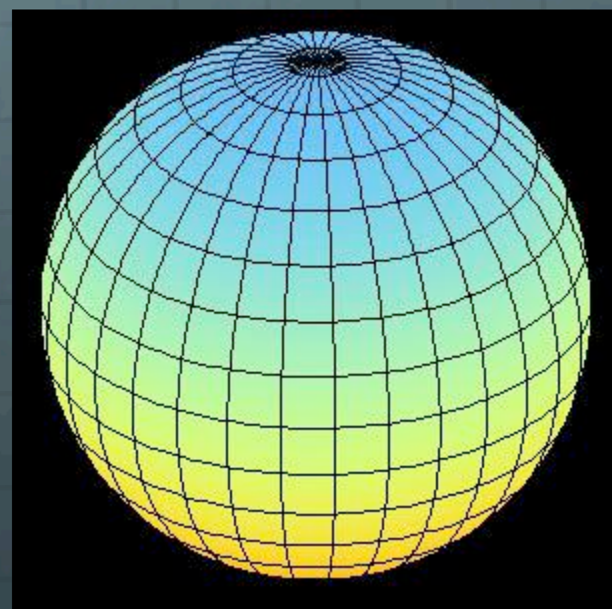
- *n = number of radial nodes*
- *l = total number of surface nodes*
- *m = number of surface nodes that are lines of longitude*
- *l – m = number of surface nodes that are lines of latitude*

Nonradial modes-
Dipole modes

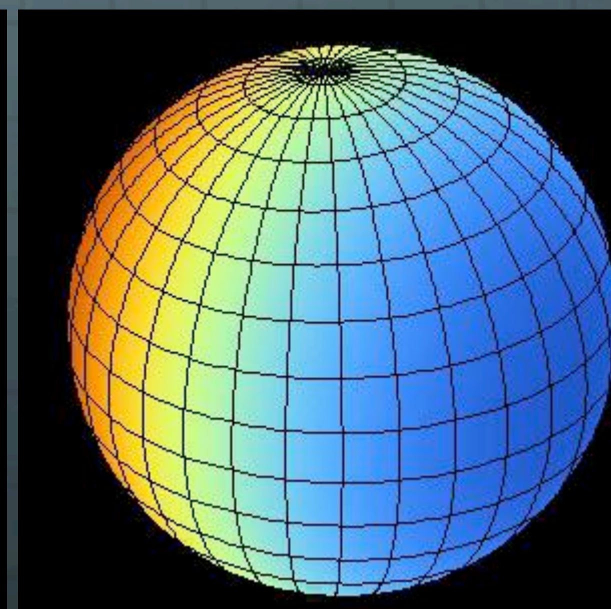
$$Y_1^m(\theta,\varphi) \propto P_1^{|m|}(\cos\theta)\, e^{im\varphi}$$



l = 1, m = -1



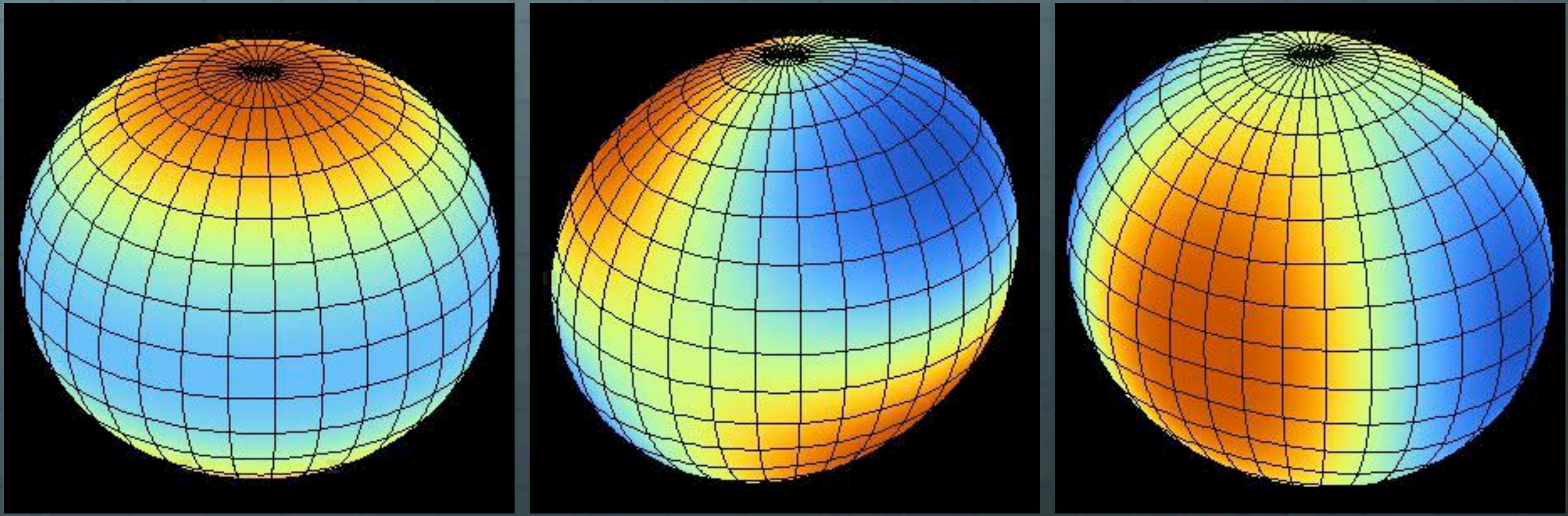
l = 1, m = 0



l = 1, m = +1

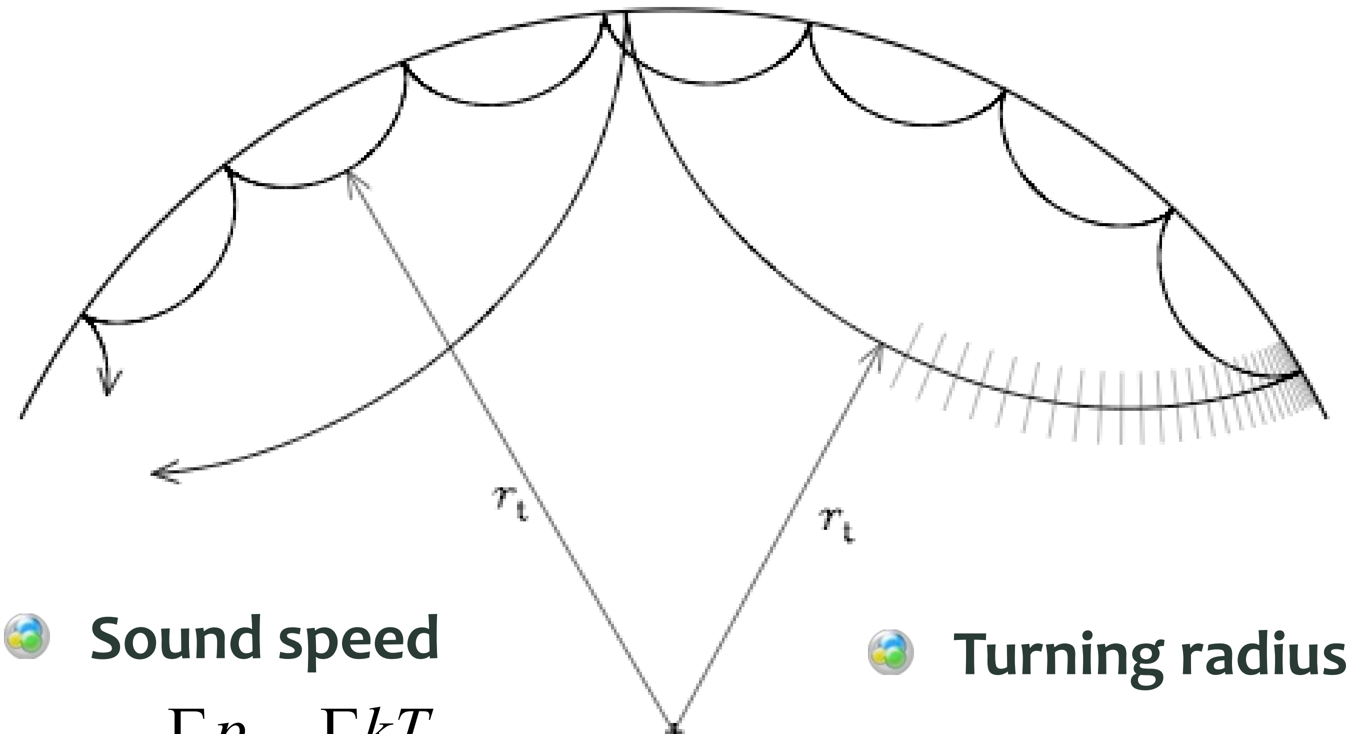
Nonradial modes- Quadrupole modes

$$Y_2^m(\theta,\varphi) \propto P_2^{|m|}(\cos\theta)\, e^{im\varphi}$$



l = 2, m = 0   l = 2, m = -1   l = 2, m = -2

Asteroseismology – how does it work?

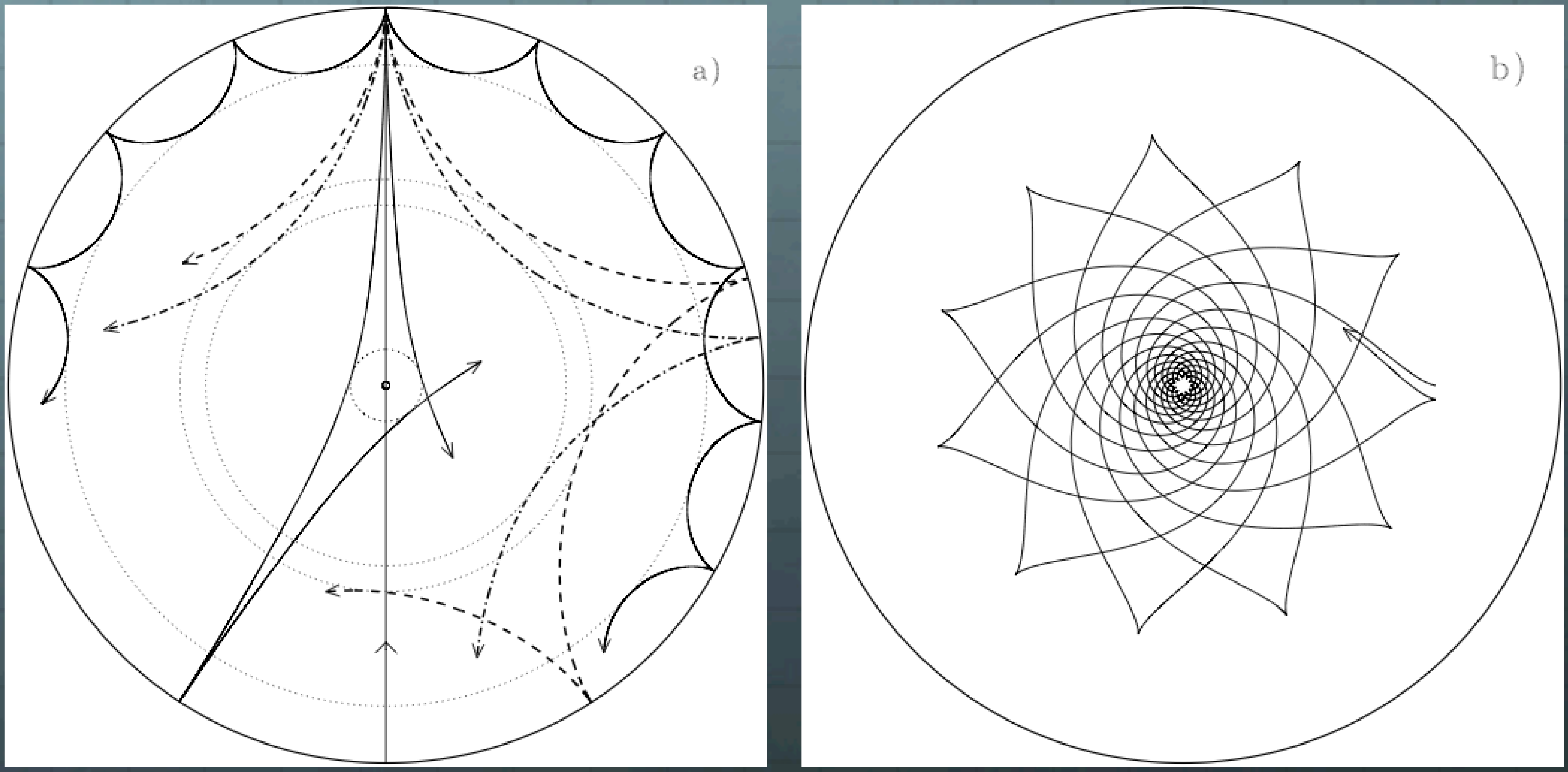


- **Sound speed**

$$c^2 = \frac{\Gamma_1 p}{\rho} = \frac{\Gamma_1 kT}{\mu}$$

- **Turning radius**
- **Acoustic cavity**

p modes and g modes



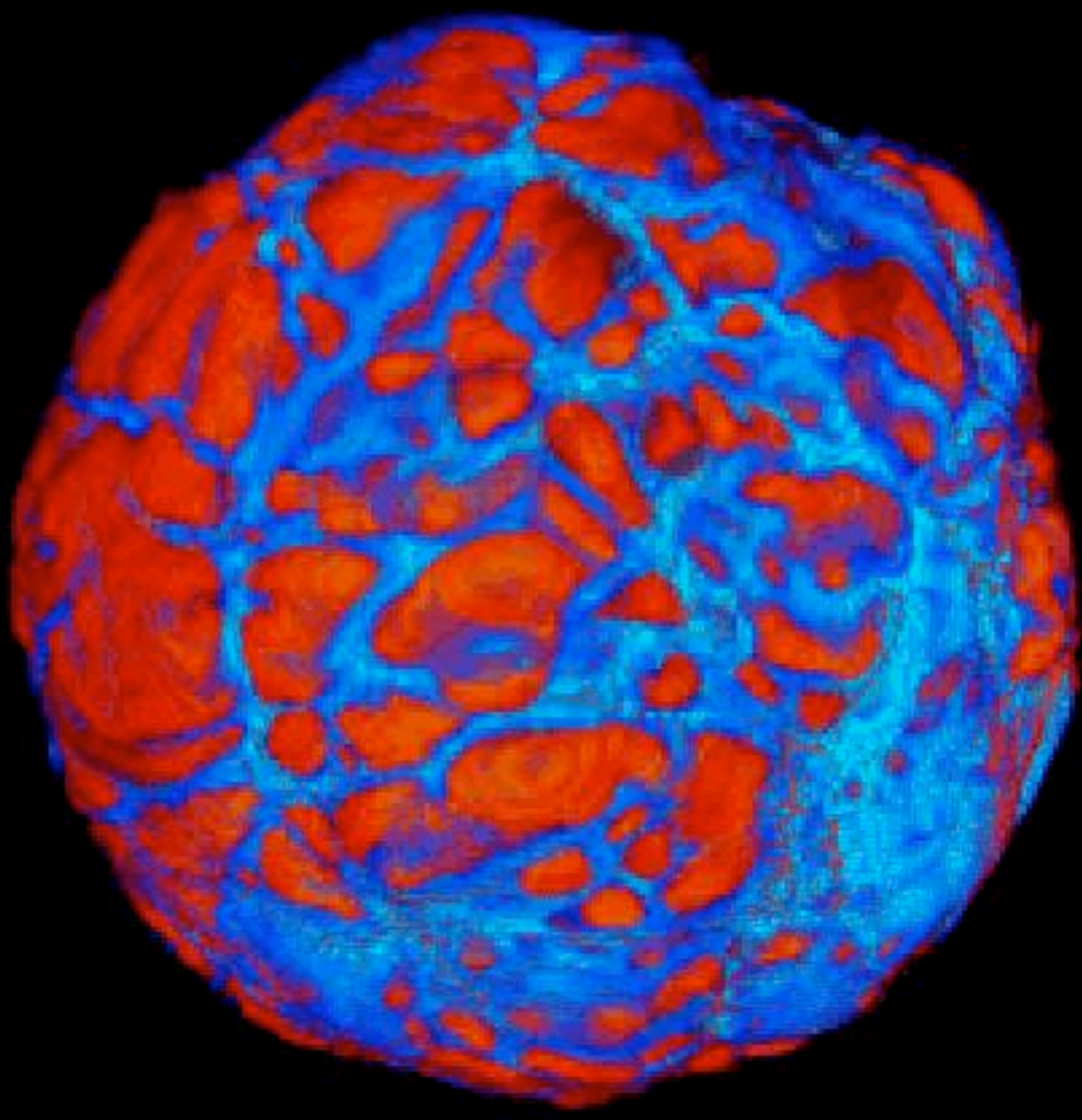
Driving mechanisms

Heat engine mechanism

- Gains heat on compression
- κ-mechanism (κappa = opacity)
- H, He, Fe main drivers
- Cepheids, RR Lyr stars, δ Sct stars, β Cep stars, SPB stars, roAp stars, pulsating white dwarfs, …

Stochastic driving

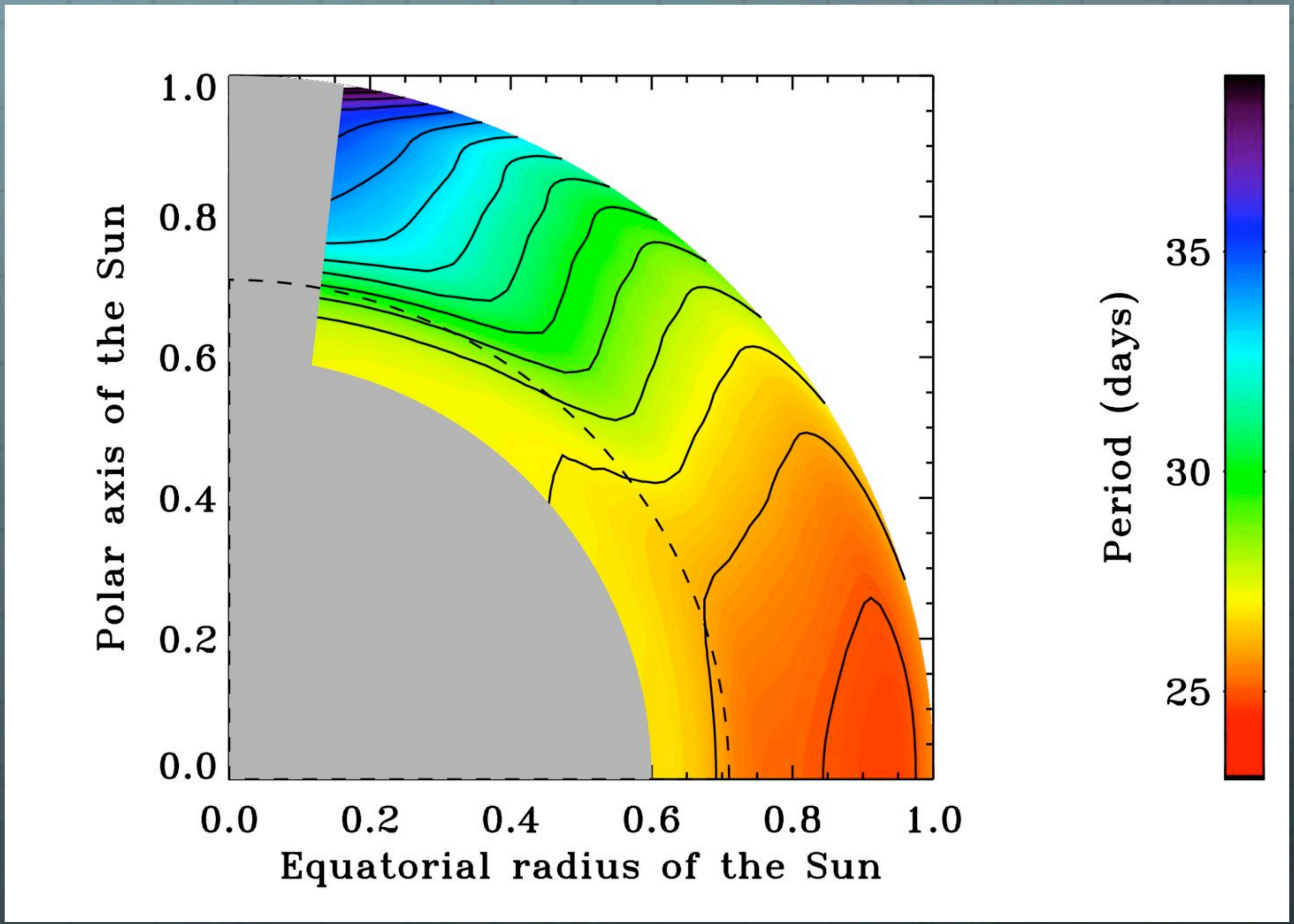
- Star resonates with acoustic noise
- Solar-like oscillators
- Main interest in exoplanet finding



LCSE
University
of
Minnesota

“… the deep interior of the Sun … is less accessible … than any other region of the universe.”

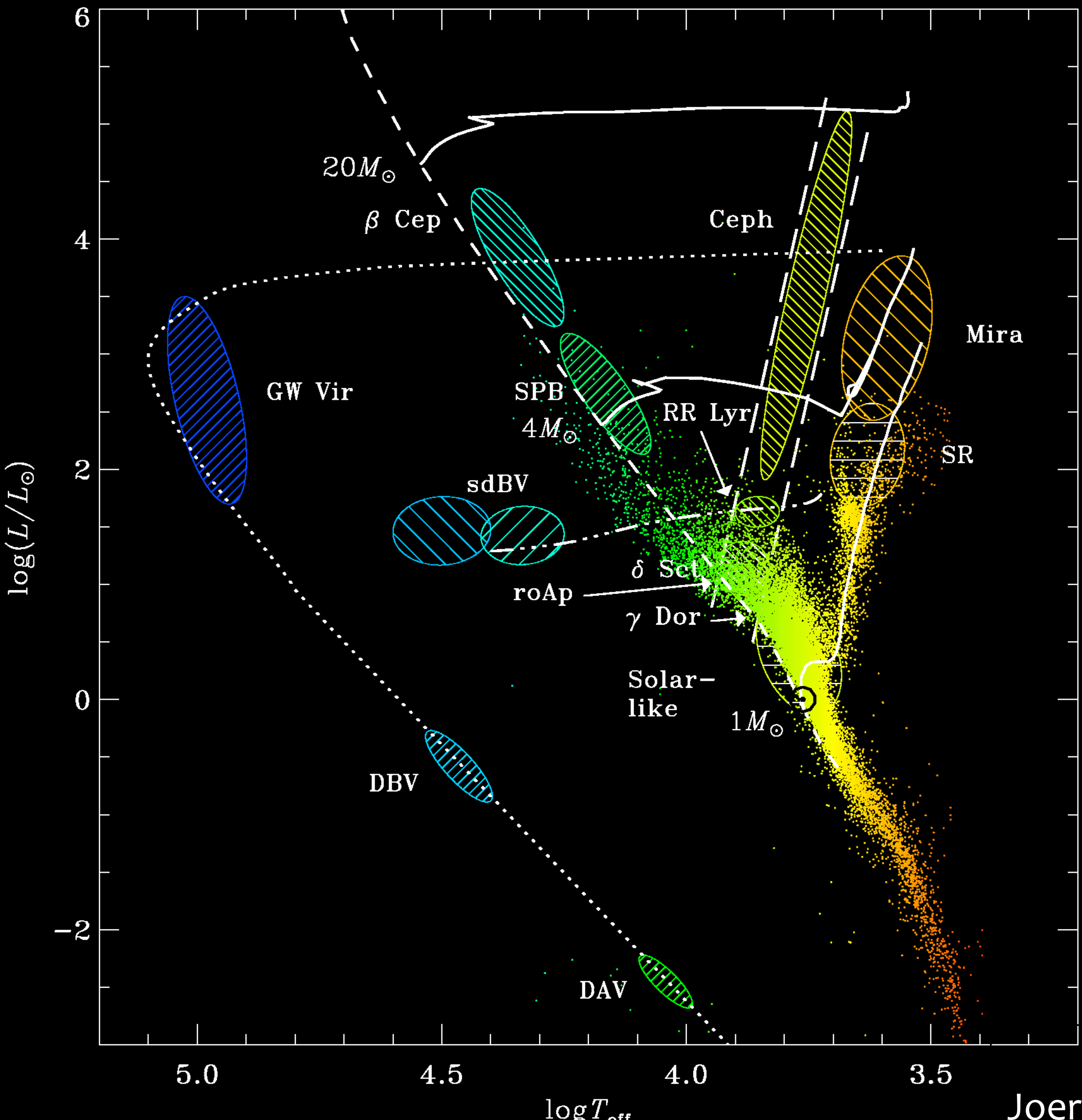
Eddington 1926



Helioseismology:

The solar interior is accessible now!

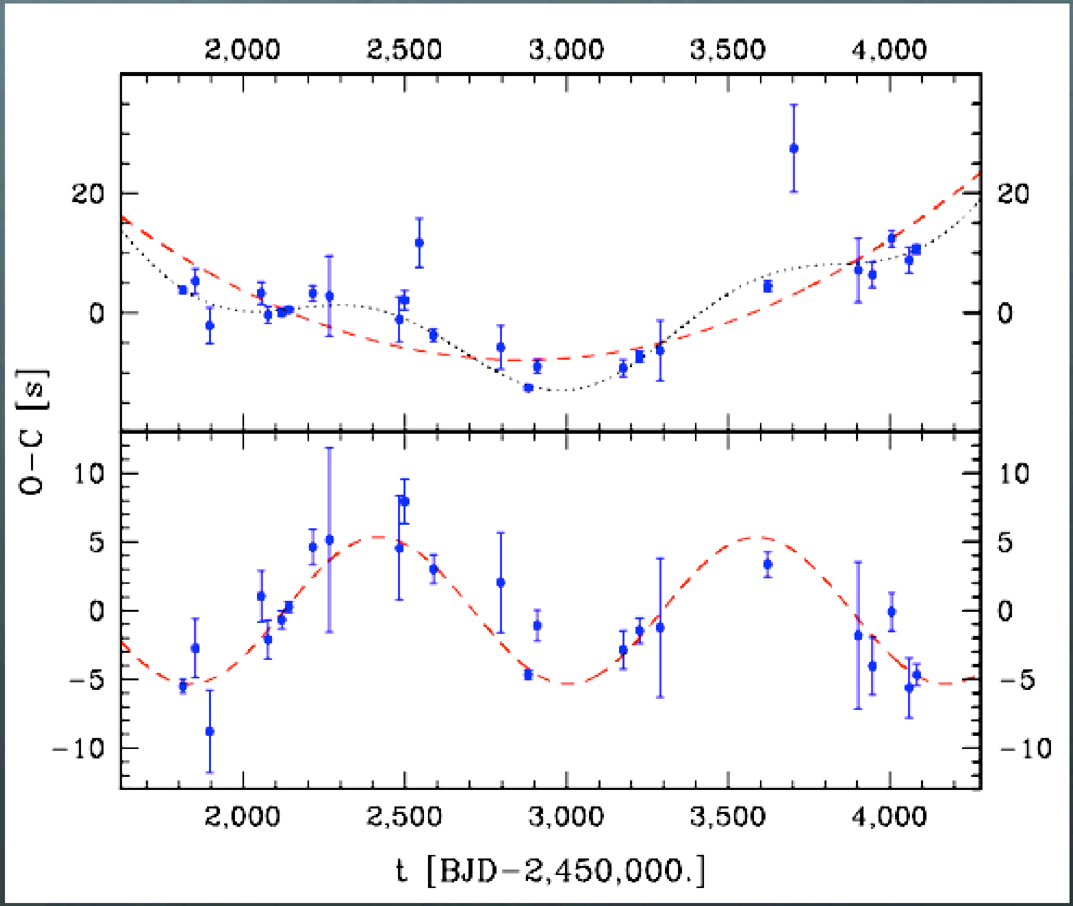
courtesy of Rachel Howe



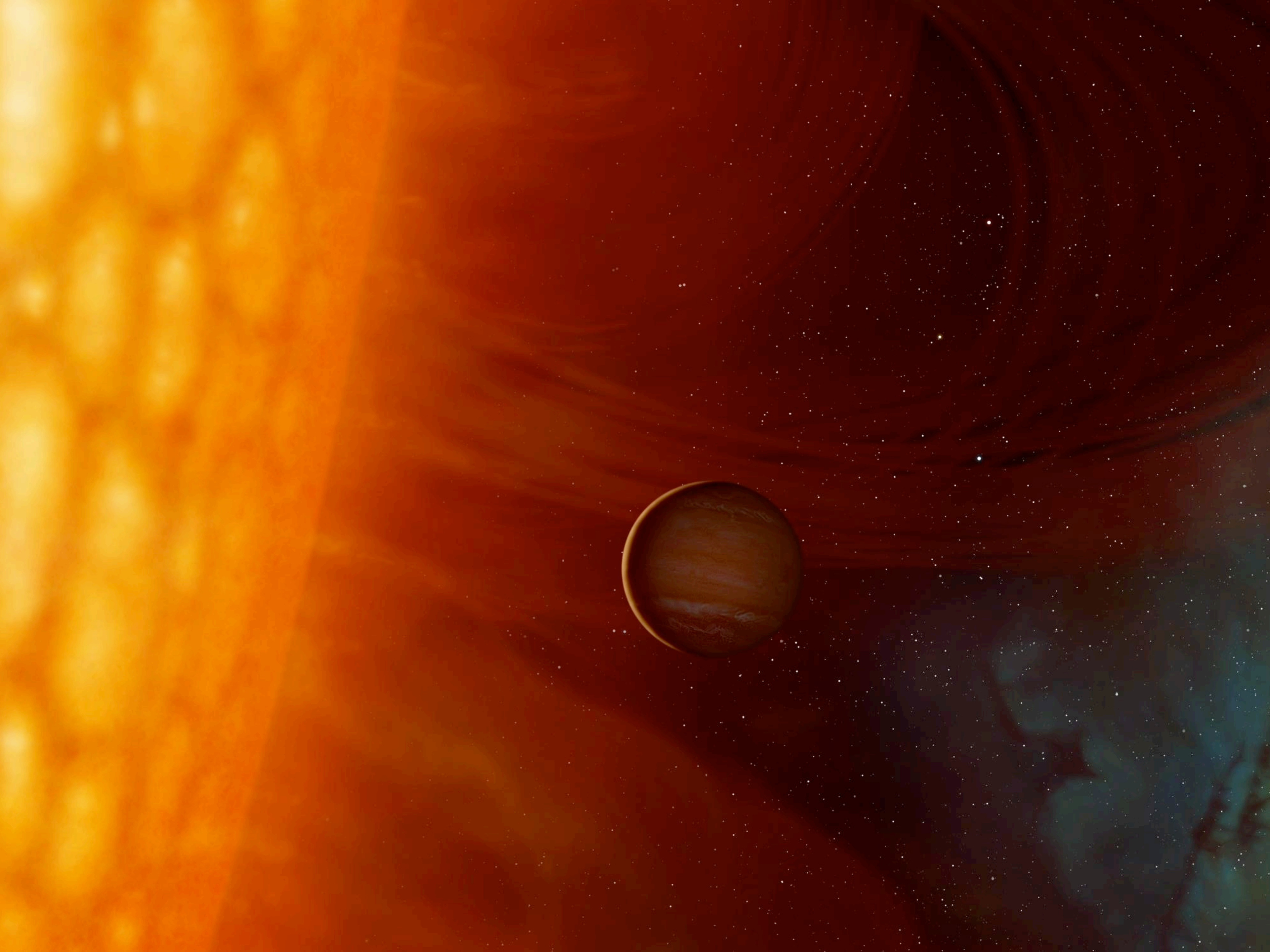
courtesy of
Joergen Christensen-Dalsgaard

Planet-finding: the timing method

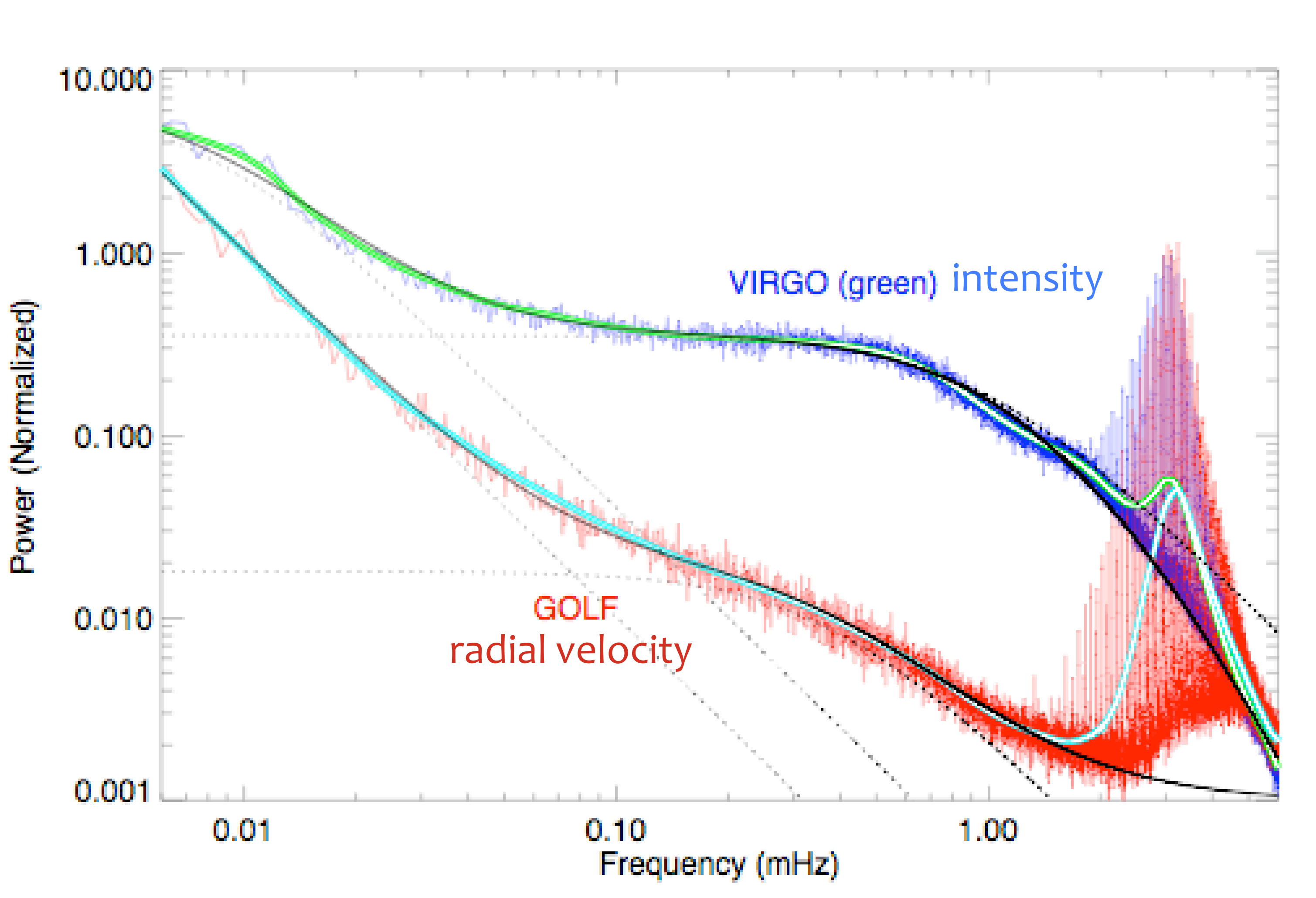
- V391 Peg
  - sdBV star
  - Excellent clock
  - 7 years with WET
- V391b Peg
  - $3\ M_j$
  - a = 1.7 au
  - a = 1 au
    in red giant stage



Silvotti et al., 2007, Nature, 449, 189



The era of Kepler:
Why do asteroseismology from the ground?

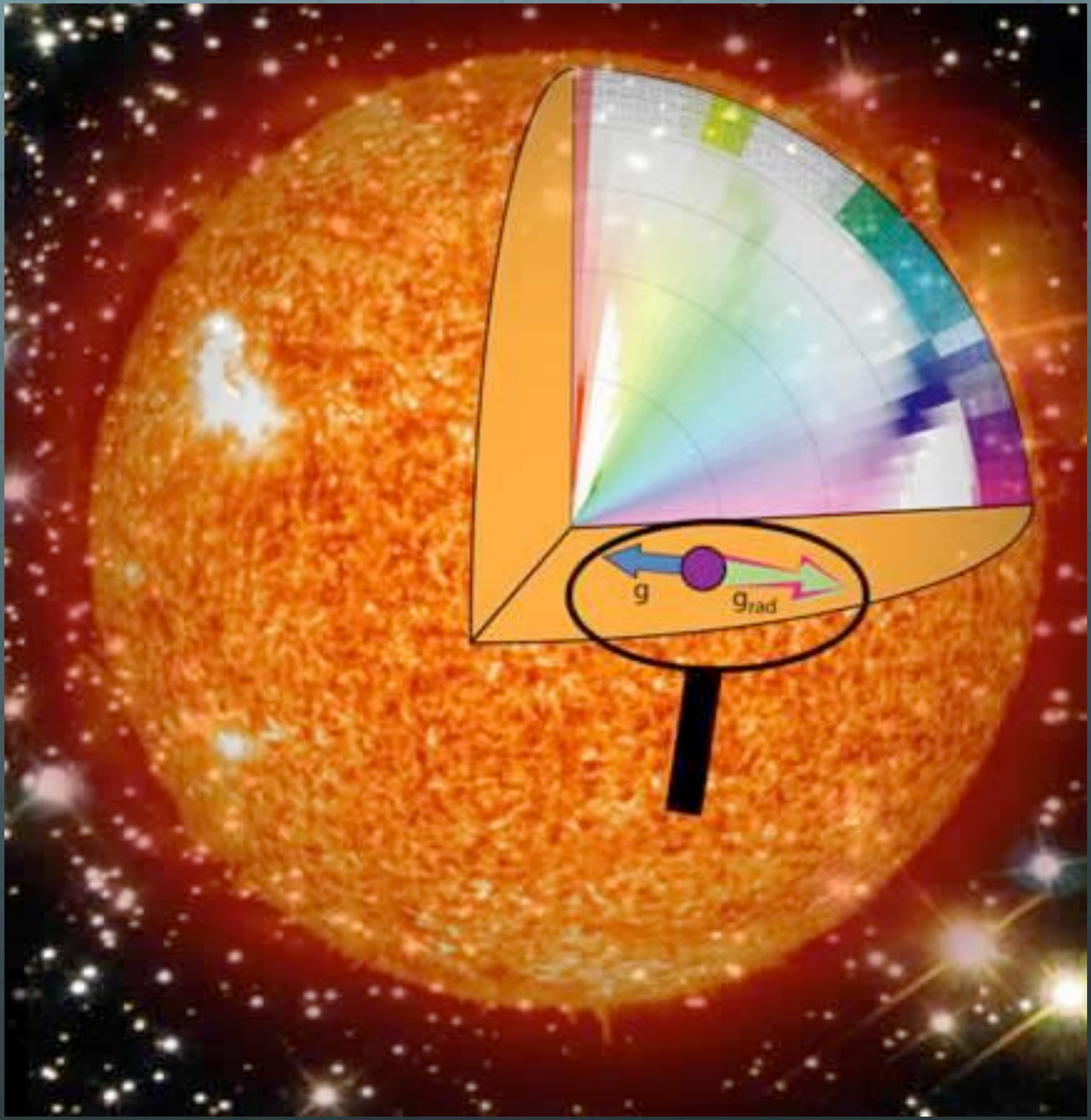


courtesy of
Hans Kjeldsen

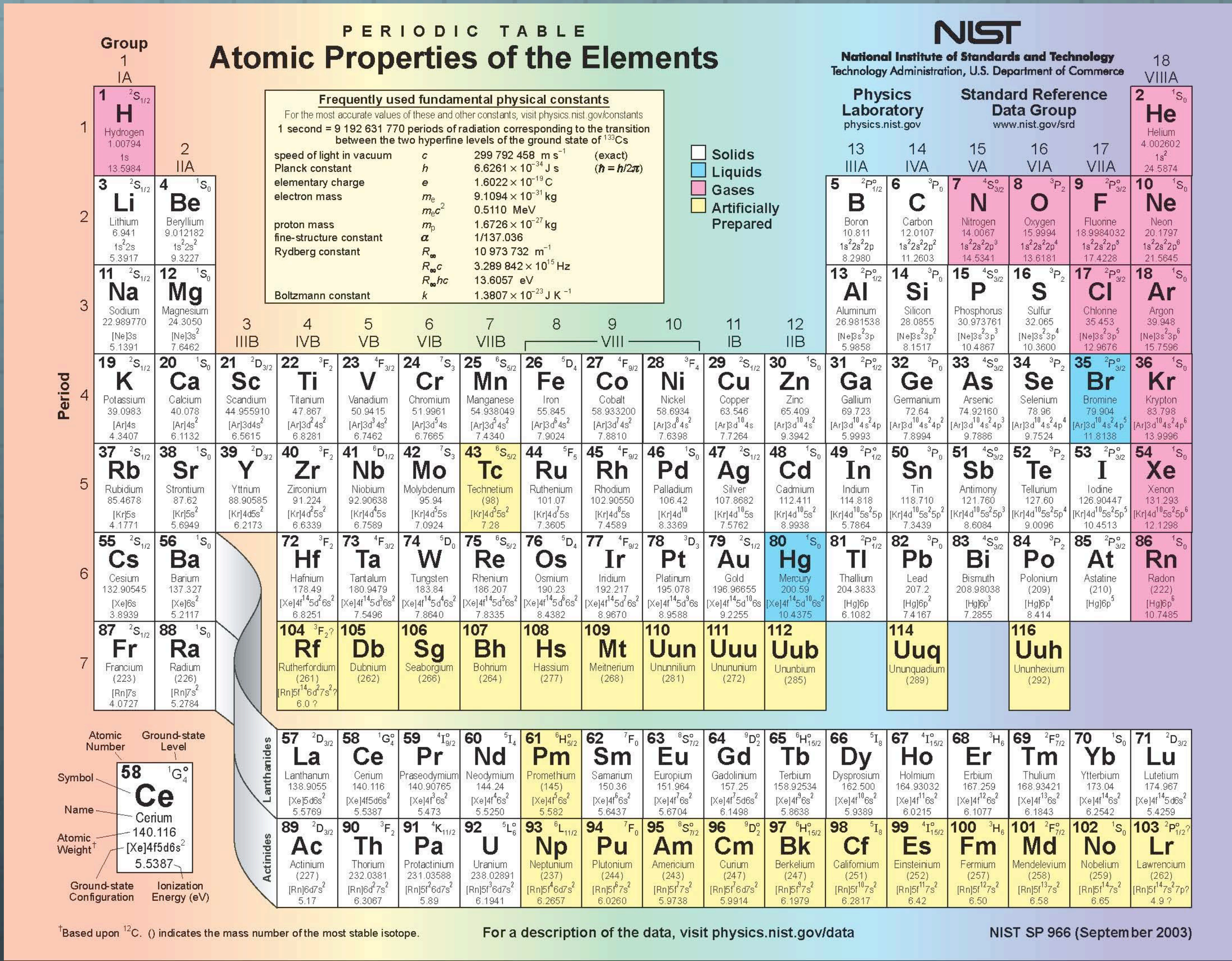
Atomic diffusion

- Radiative levitation
- Gravitational settling

  - Solar model
  - White dwarf stucture
  - Pulsation driving
  - Stellar cluster ages

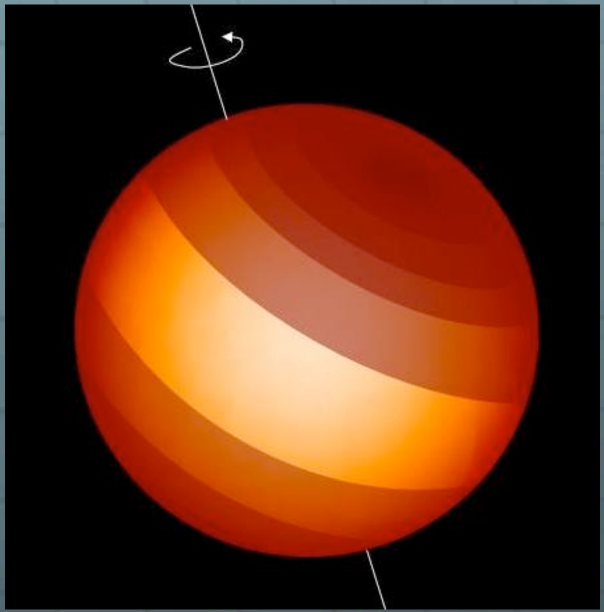


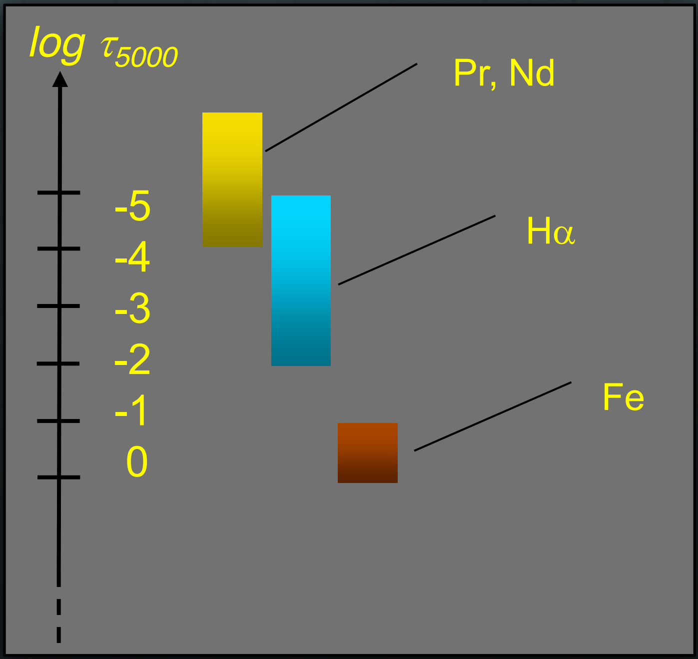
The roAp stars



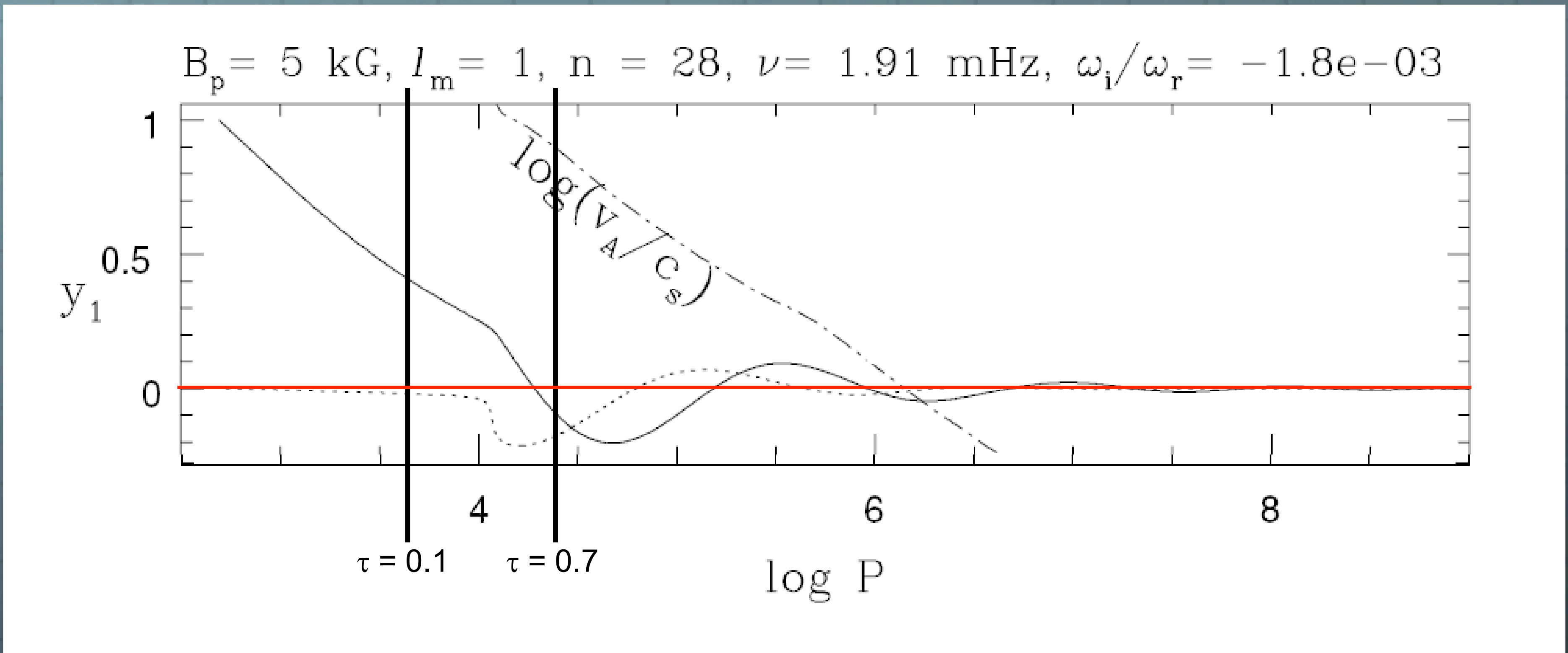
The roAp stars

- T_{eff}: 6600 – 8500 K
- P_{pul}: 5.65 – 21.2 min
- A_{phot}: < 10 mmag
- A_{rv}: < 8000 m s^{-1}
- B_s: < 30 kG
- Very peculiar: atomic diffusion
- Oblique pulsators
- Chemically stratified atmospheres



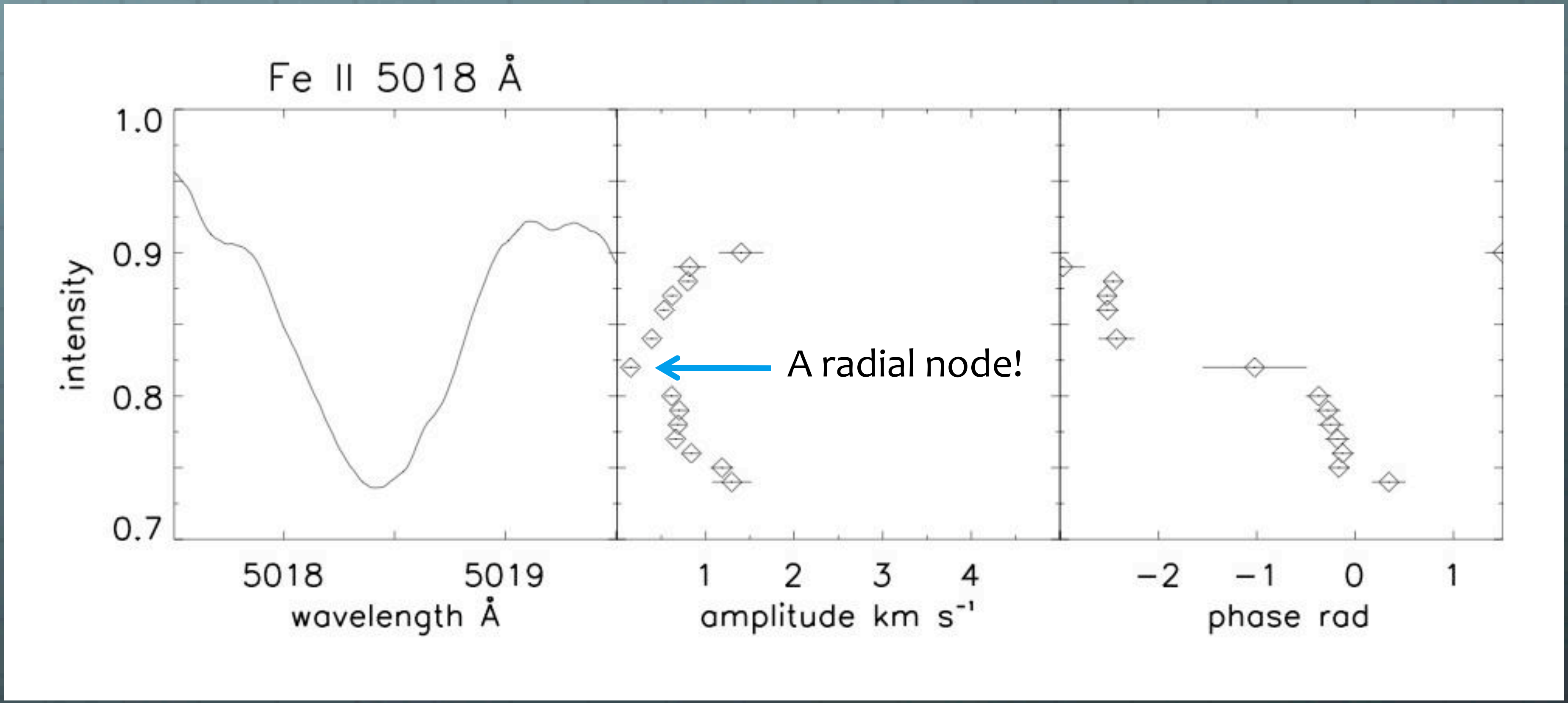


Theoretical expectation



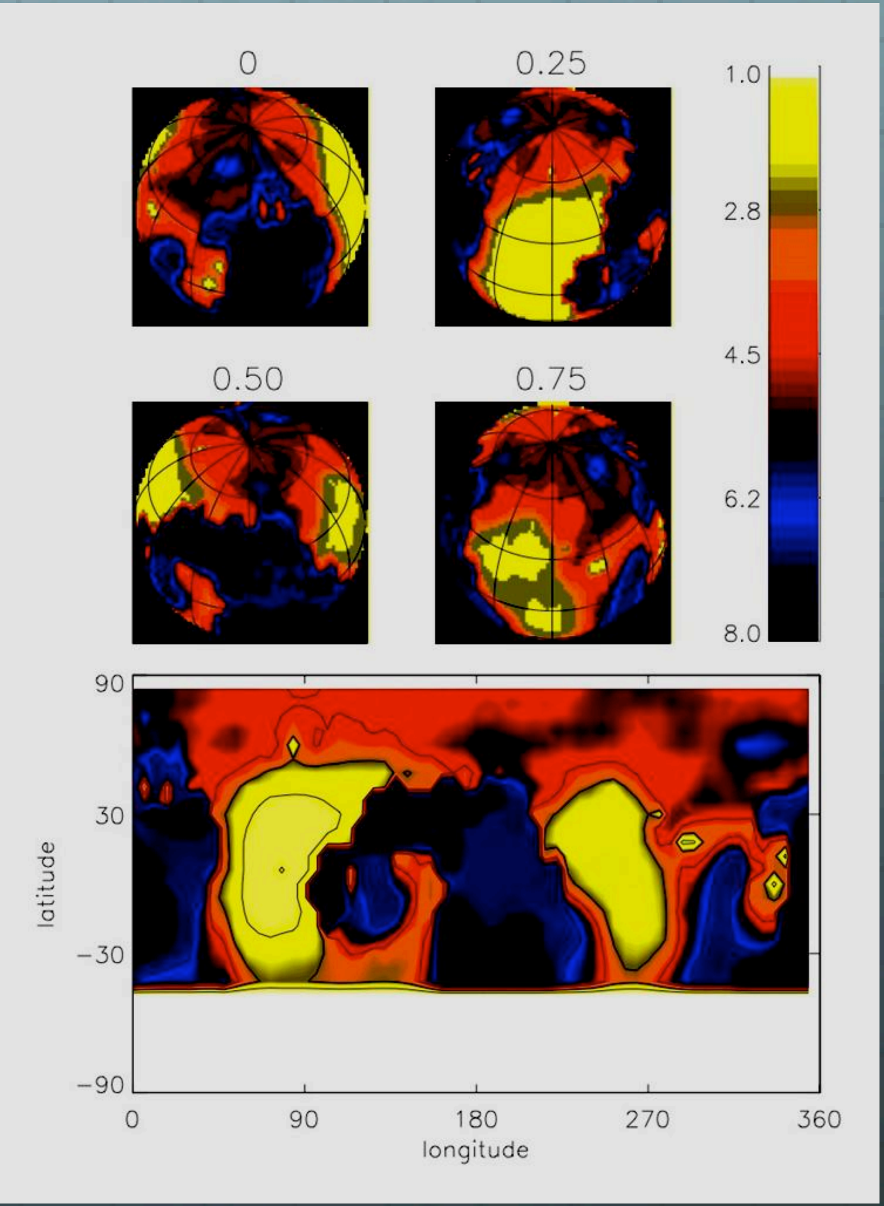
Saio, H. 2005, MNRAS, 360, 1022

Resolving the third dimension – HD99563



Elkin, Kurtz, Mathys, 2005, MNRAS, 364, 864

Doppler imaging of HD99563



NdIII spots

VLT UVES +
Subaru HDS
3 nights

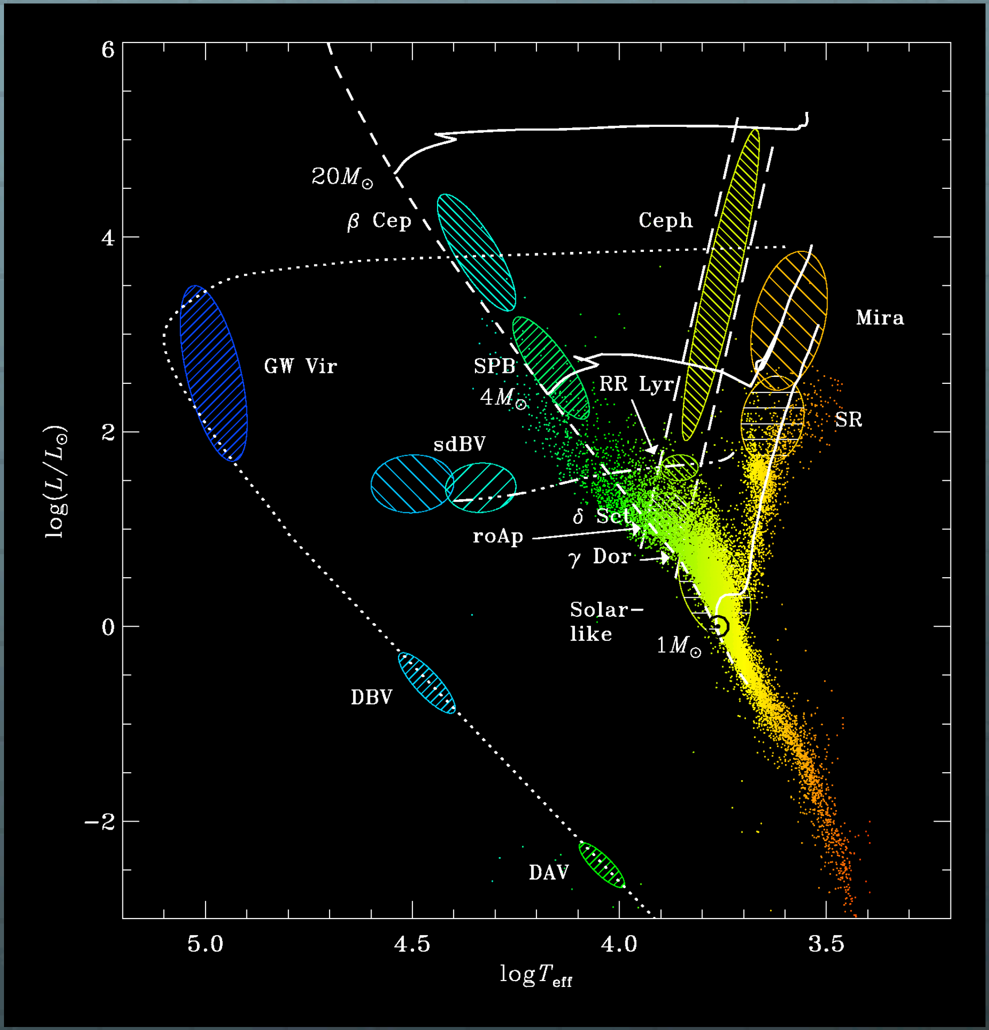
Freyhammer, Kurtz, Elkin, Mathys, Savanov, Zima, Shibahashi & Sekiguchi, 2009, MNRAS, 396, 325

roAp stars test:

- Atmospheric structure in 3D
- Pulsation mode geometry in 3D
- Interaction of pulsation with rotation and strong magnetic fields
  - Relevant to solar p mode interaction with sunspots
- Atomic diffusion

BPM 37093

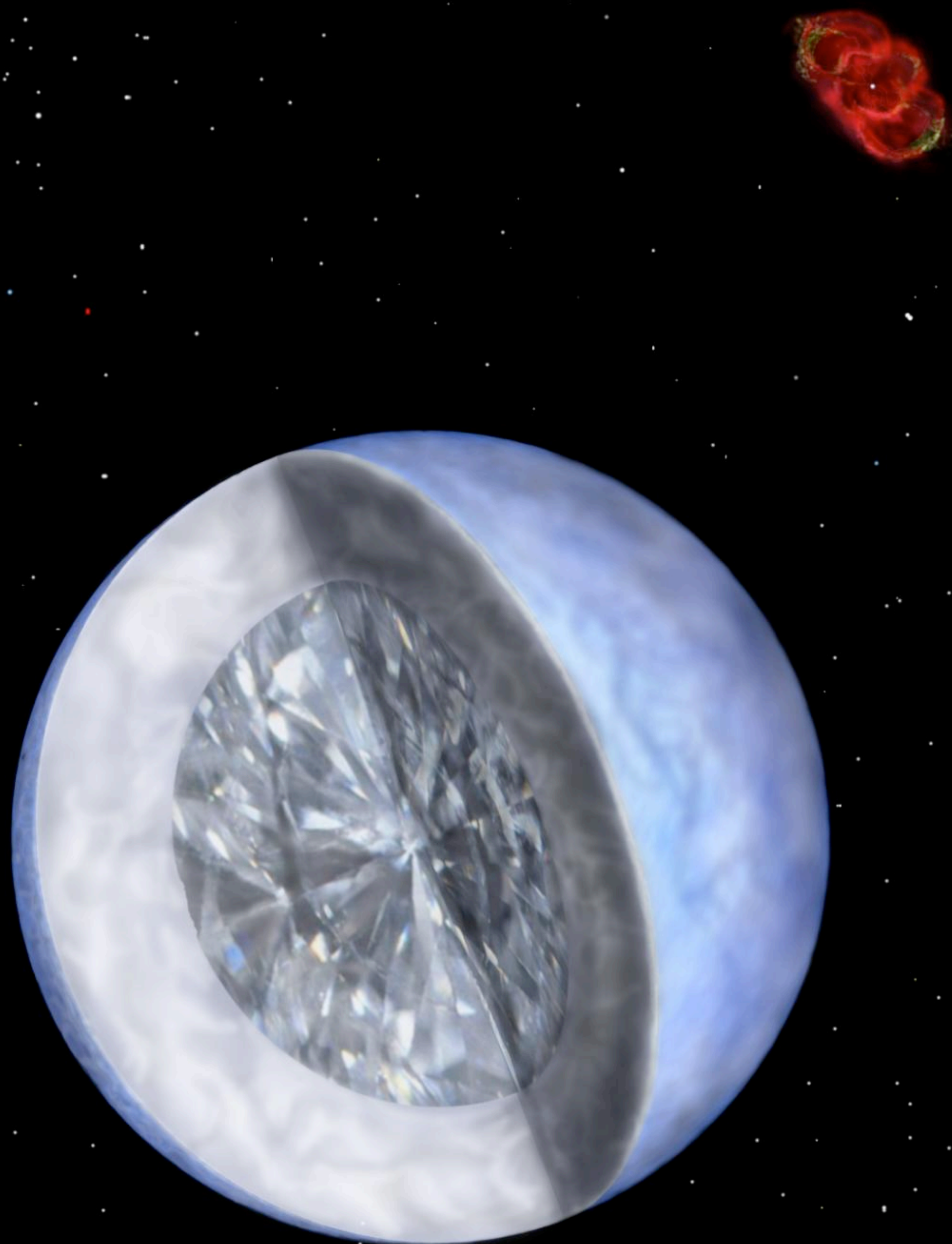
- DAV
- $M = 1.09\ M_\odot$
- $T_{eff} = 11730$ K
- Partially crystallized C-O core



Metcalfe, T. S., Montgomery, M. H., Kanaan, A. 2004, ApJ, 605, 133

Kanaan et al., 2005, A&A, 432, 219

Brassard & Fontaine, 2005, ApJ, 622, 572



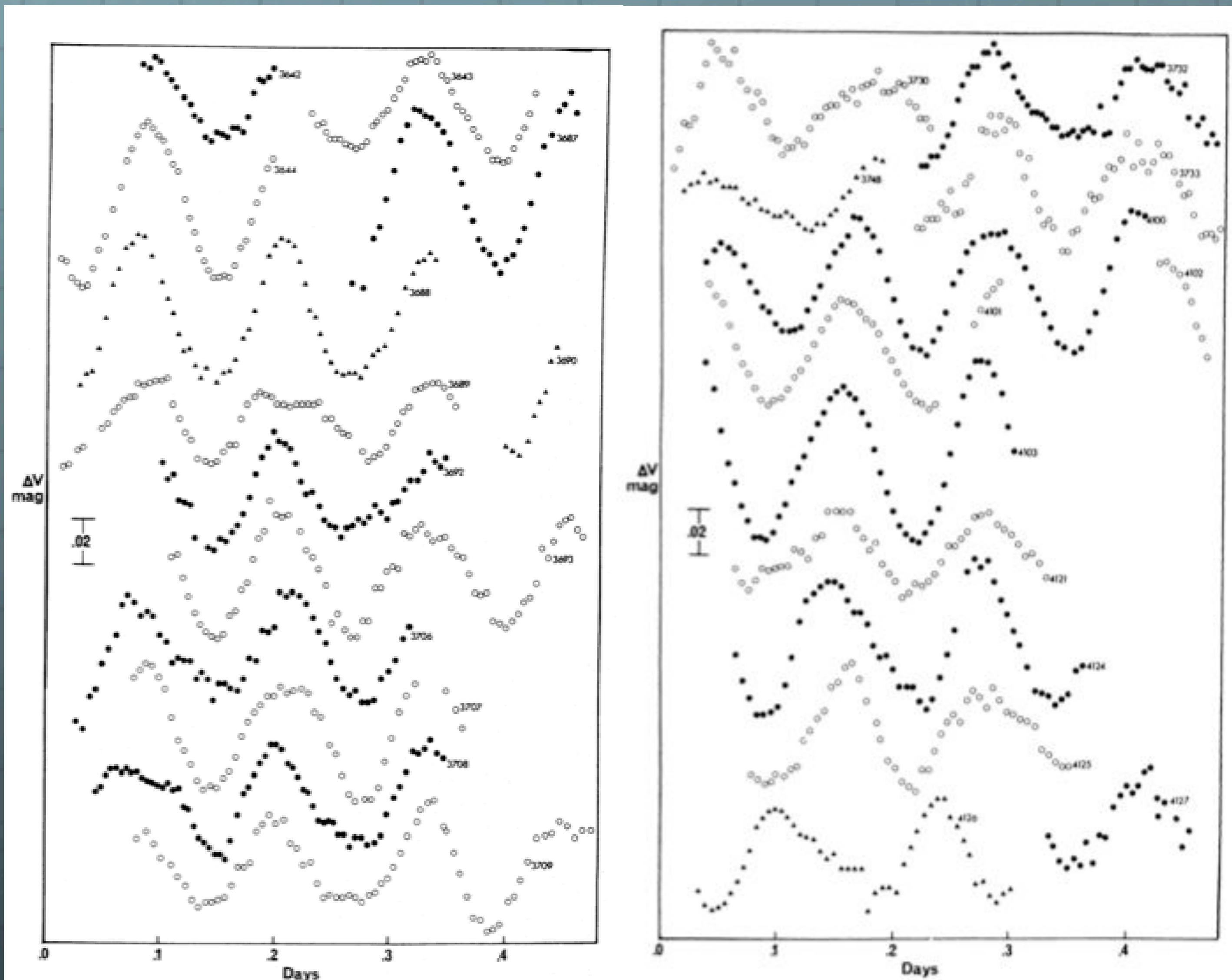
Harvard press release

courtesy of
Travis Metcalfe

Kepler

A Search for Terrestrial Planets

The μmag revolution



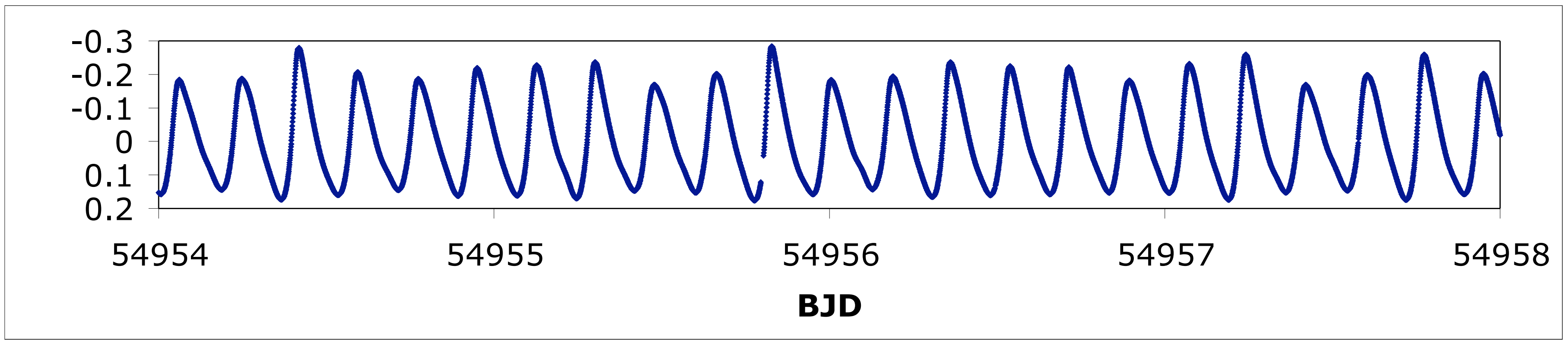
HD188136
δ Sct star

6 weeks of telescope time –

Grinding away on the ground

Kurtz, D., 1980, MNRAS, 193, 29

Kepler mission



Just four days of Kepler data for only one of >150,000 stars

The Tychonic principle

- Precision leads to discovery
- The Kepler data are 100 times higher precision than typical ground-based data
- The Kepler "duty cycle" is better than 90%
- Asteroseismic discoveries are pouring out of the Kepler data

Three selected examples (out of many!)

- RR Lyr:
  - The Blazhko effect
  - Period doubling

Szabó and the Kepler team, 2010, MNRAS, in press

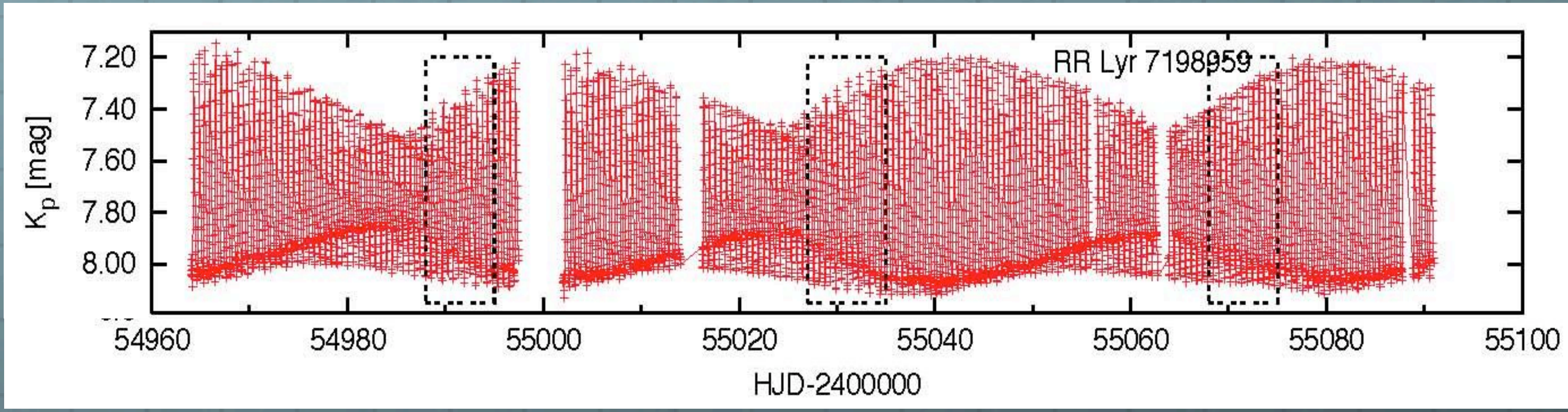
- KPD 1946 +4340
  - sdBV + WD eclipsing binary
  - Doppler beaming
  - Gravitional lensing

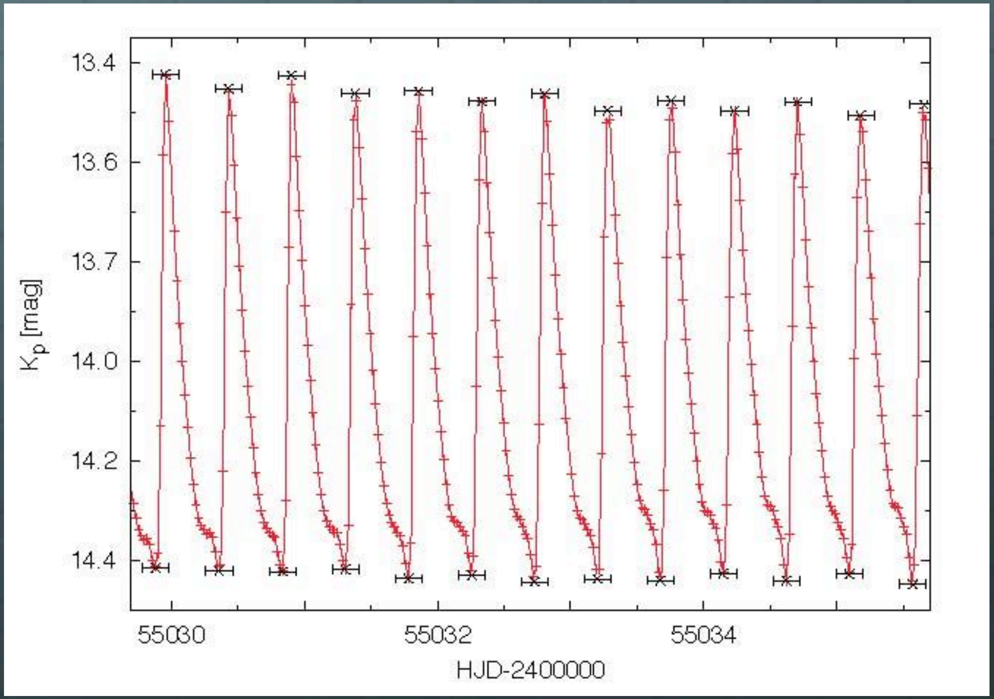
Bloemen and the Kepler team, 2010, MNRAS, in press

- KIC 8677585
  - roAp star
  - Unpredicted, unprecedented g mode

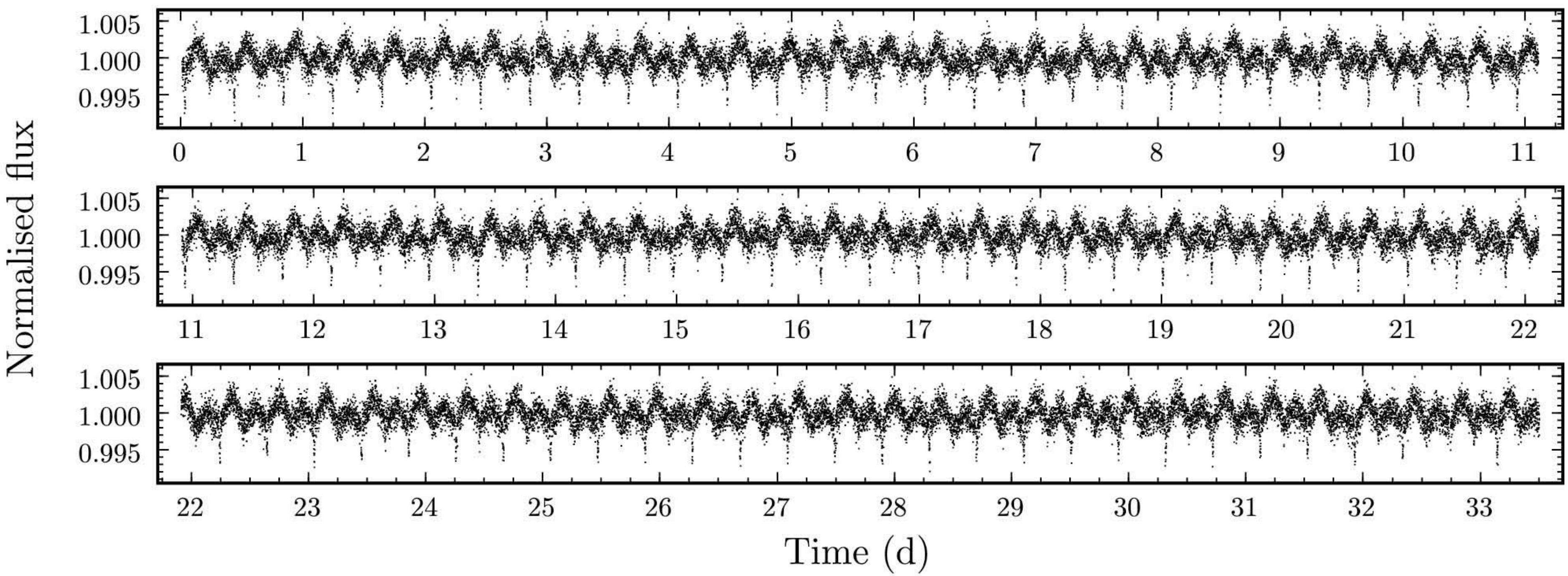
Balona and the Kepler team, 2010, MNRAS, submitted

RR Lyr


RR Lyr 7198959
K_p [mag]
7.20
7.40
7.60
7.80
8.00
54960
54980
55000
55020
55040
55060
55080
55100
HJD-2400000


K_p [mag]
13.4
13.6
13.7
14.0
14.2
14.4
55030
55032
55034
HJD-2400000

KPD 1946 +4340



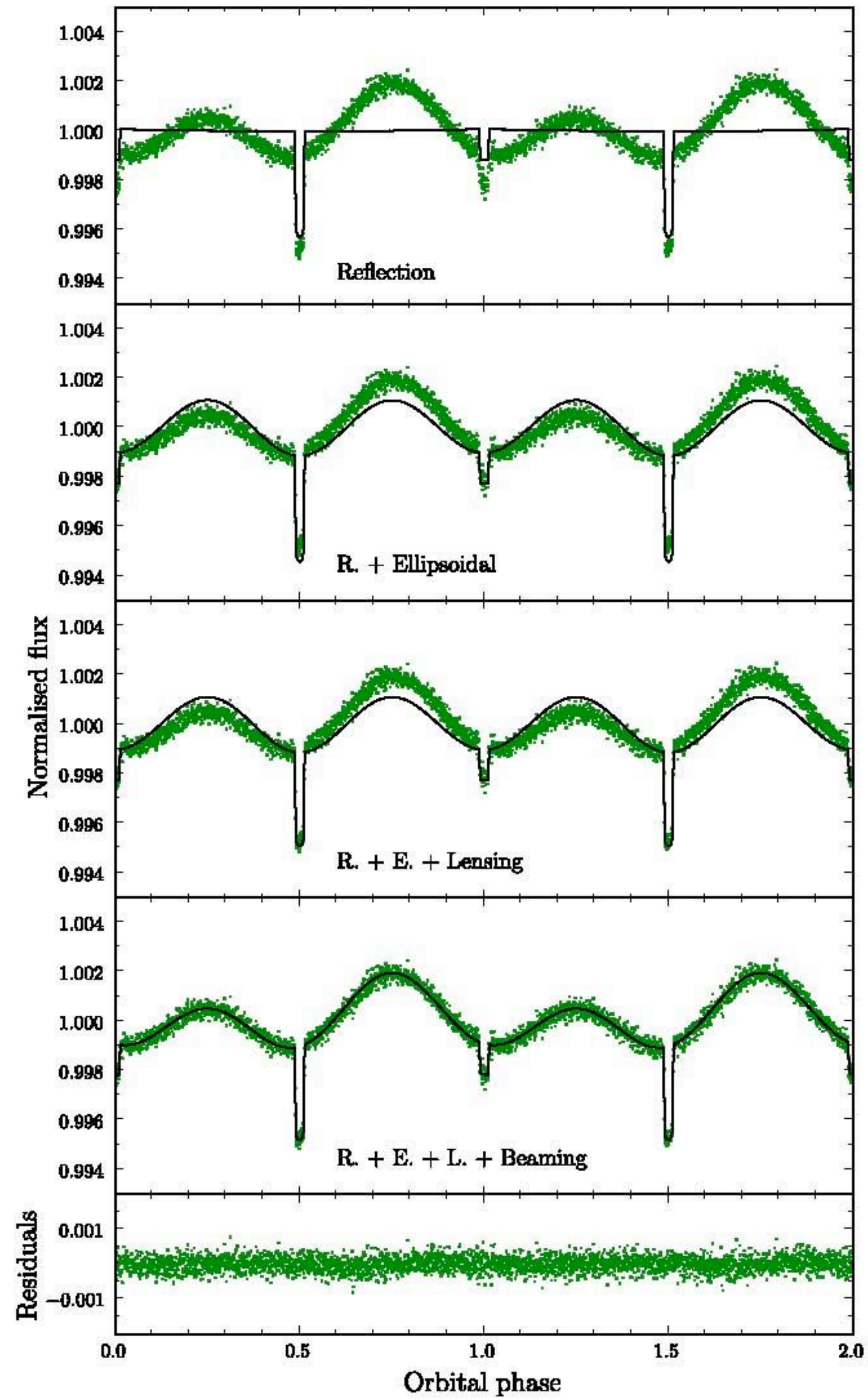
- The sdB star is an EHB star
  - He star
  - Mass probably 0.5 $M_\odot$
- P_{orb} = 0.403739 d
- V = 14.30; Kp = 14.65
- White dwarf companion
- Eclipsing binary

KPD 1946 +4340

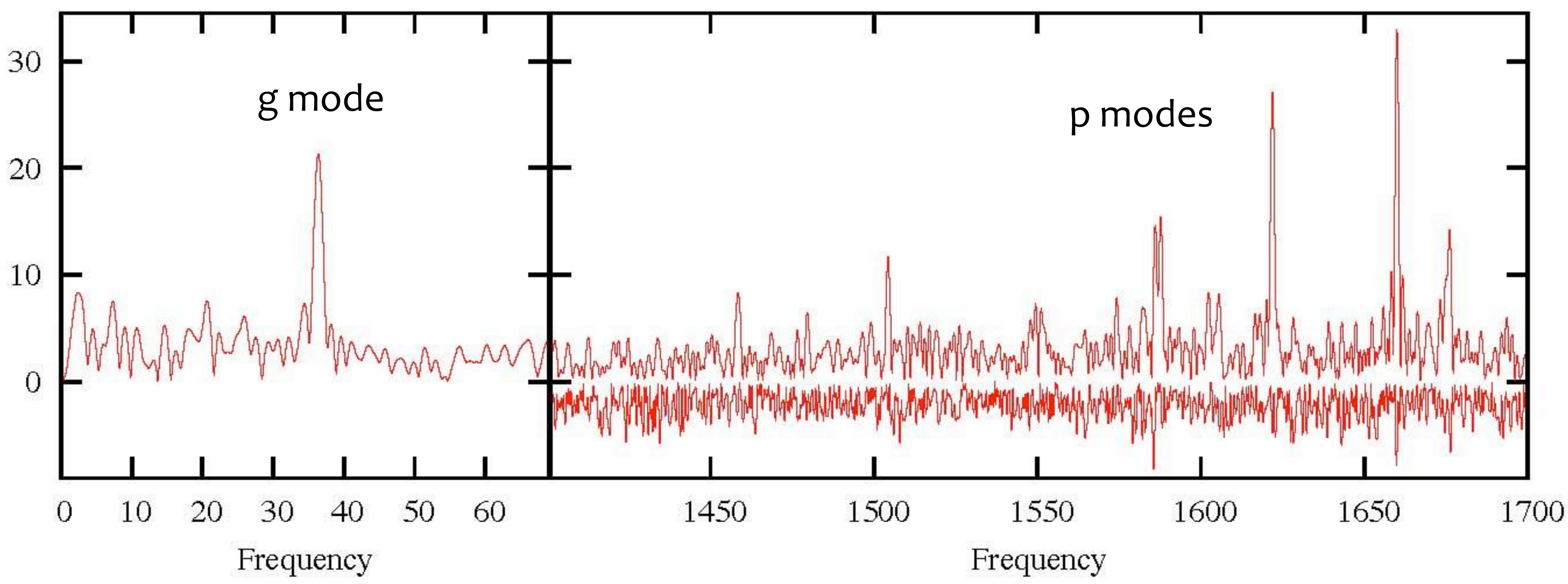
Distortion of the sdB star accounts for some of the ellipsoidal variability, but not all.

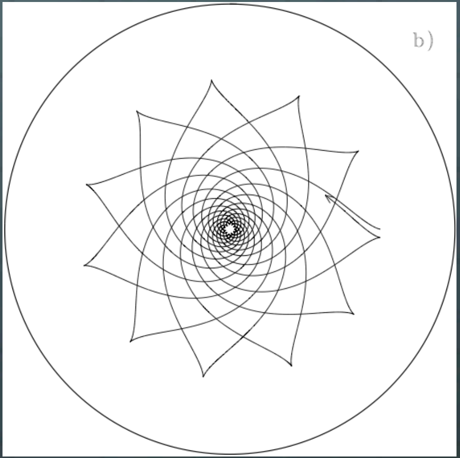
Gravitational lensing reduces the apparent geometrical cross-section of the white dwarf

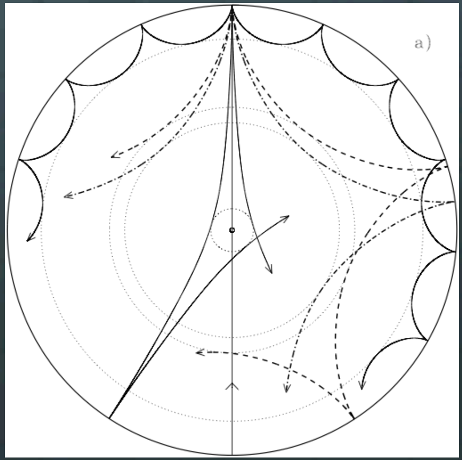
Doppler "beaming" makes the sdB star apparently hotter (thus brighter) when approaching and cooler (thus fainter) when receding.

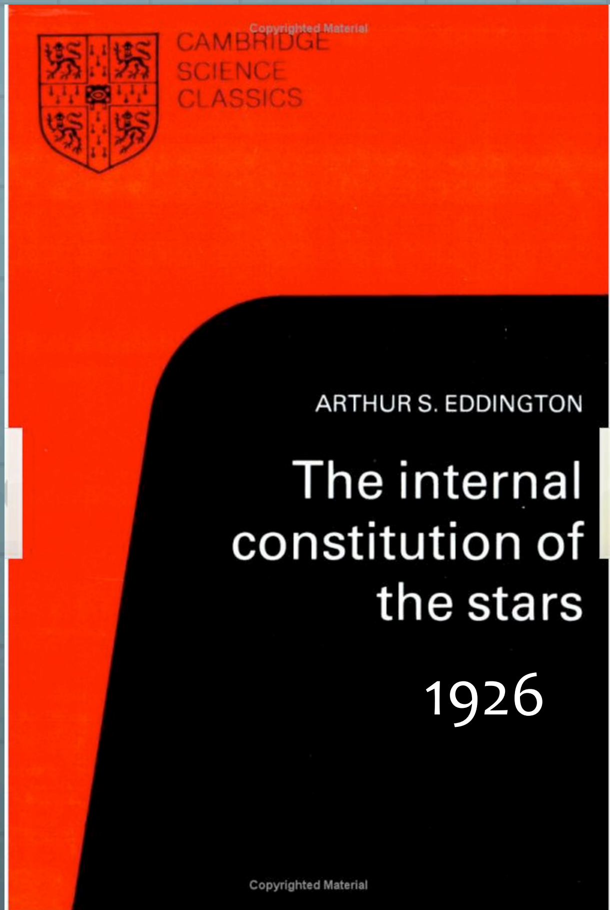


KIC 8677585


g mode
p modes
30
20
10
0
0
10
20
30
40
50
60
1450
1500
1550
1600
1650
1700
Frequency
Frequency


b)


a)



What appliance
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and test
the conditions within?

Asteroseismology: a new Keplerian revolution