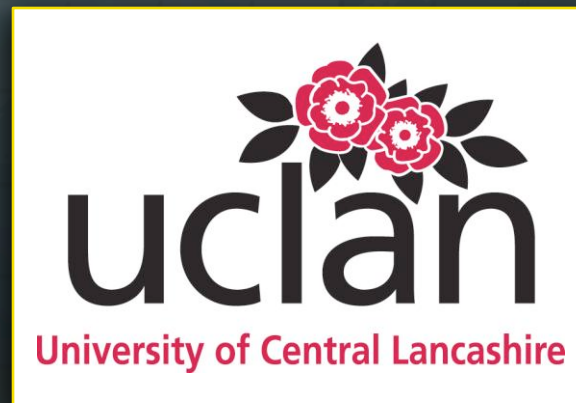
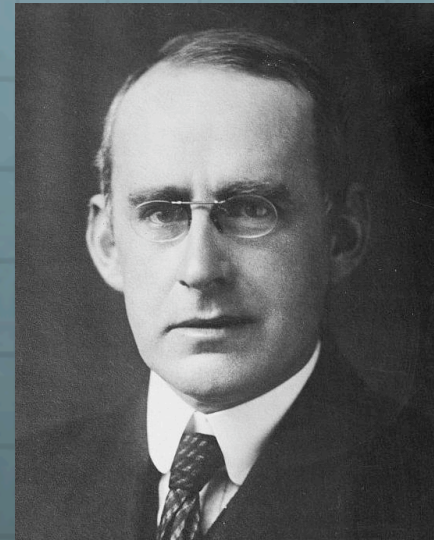
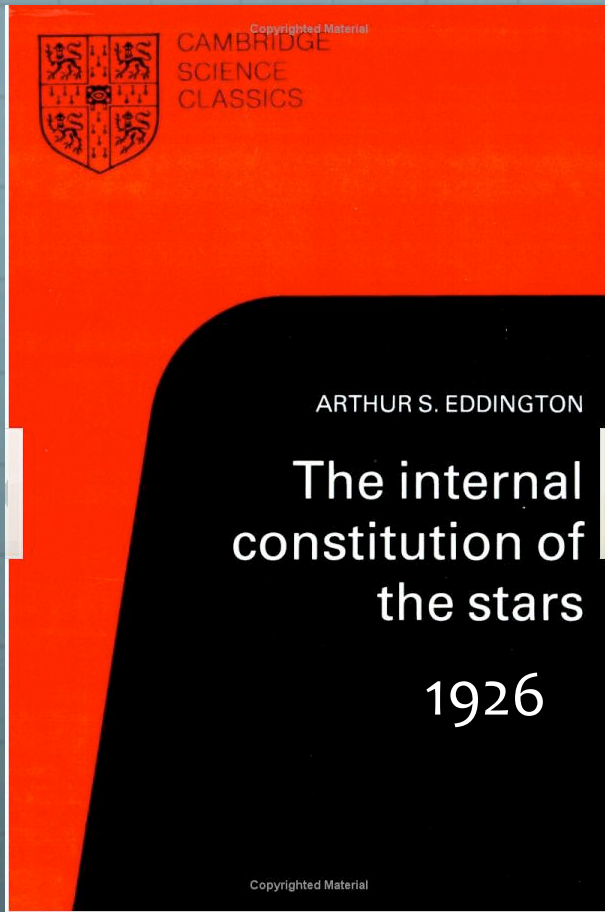


Asteroseismology over the HR Diagram – Kepler results

Don Kurtz

Jeremiah Horrocks Institute
University of Central Lancashire





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



ASTRONOMY AND ASTROPHYSICS LIBRARY

C. Aerts
J. Christensen-Dalsgaard
D.W. Kurtz

Asteroseismology



Aerts
Christensen-Dalsgaard
Kurtz

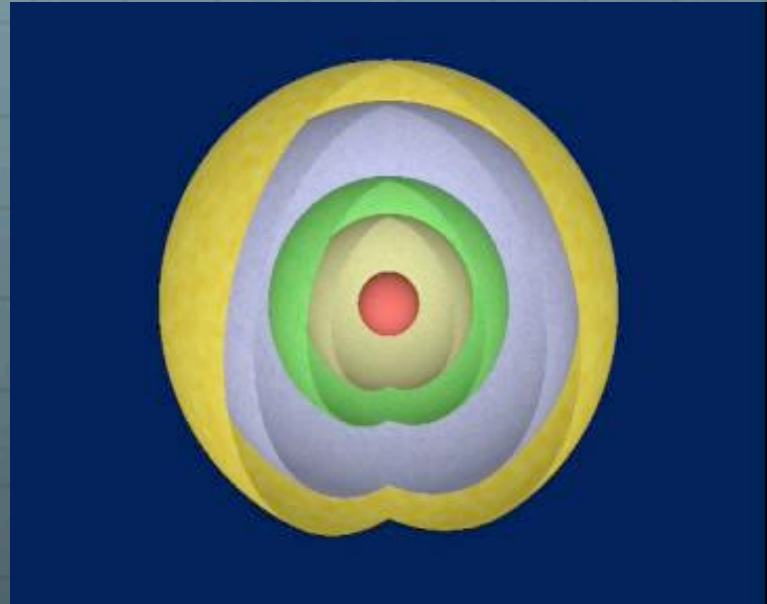
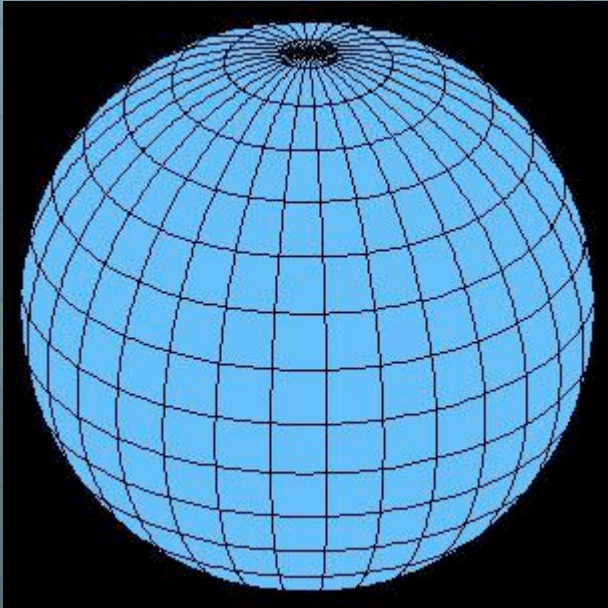


Asteroseismology



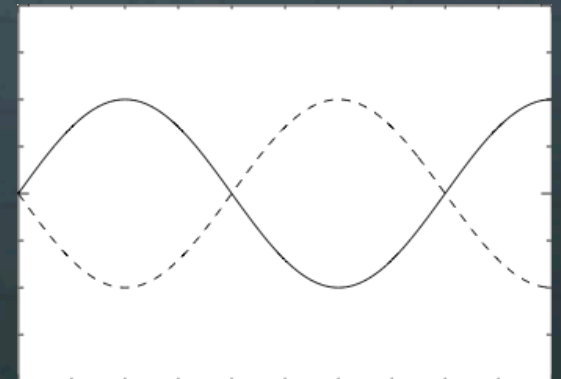
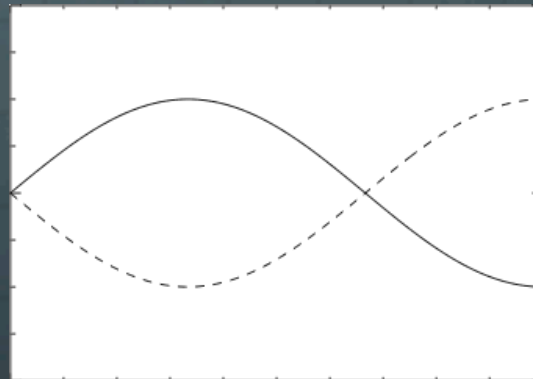
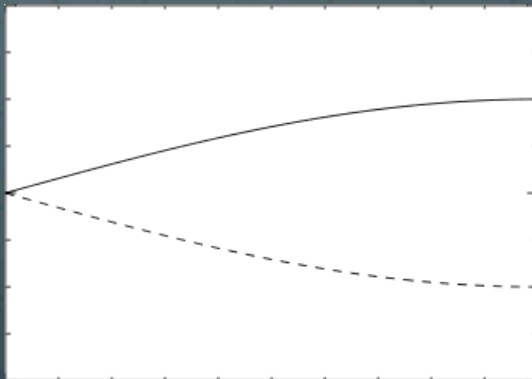
 Springer

Radial modes



Cepheids
 $P_1/P_0 = 0.7$

organ pipe
 $P_1/P_0 = 0.33$



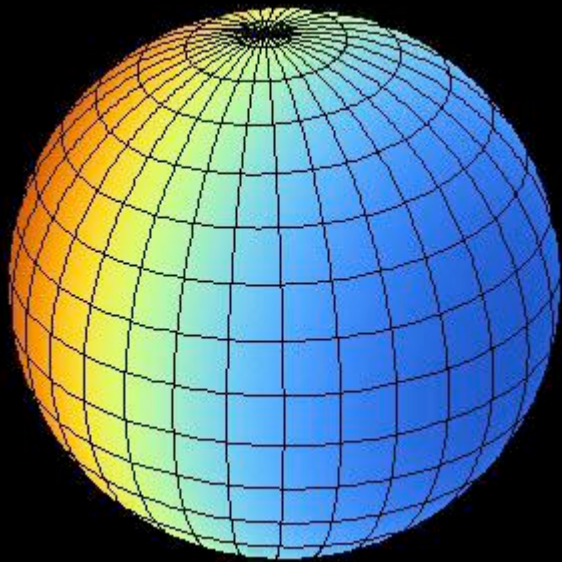
Structure of stellar pulsation modes

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

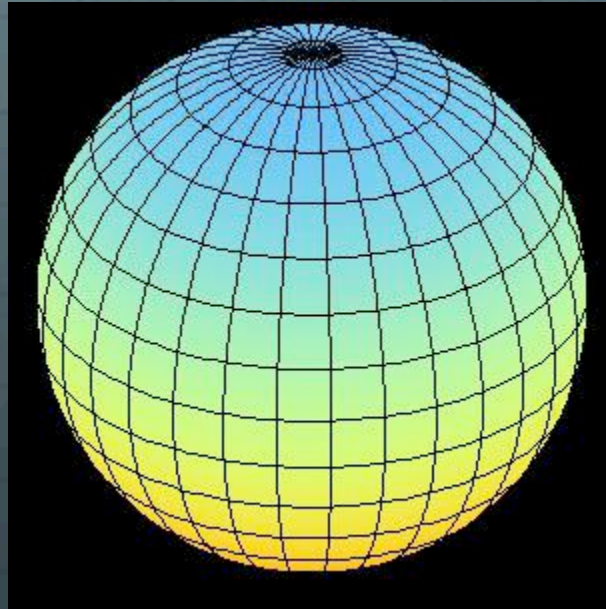
- n = number of radial nodes
- l = total number of surface nodes
- m = number of surface nodes that are lines of longitude
- $l - m$ = number of surface nodes that are lines of latitude

Nonradial modes- Dipole modes

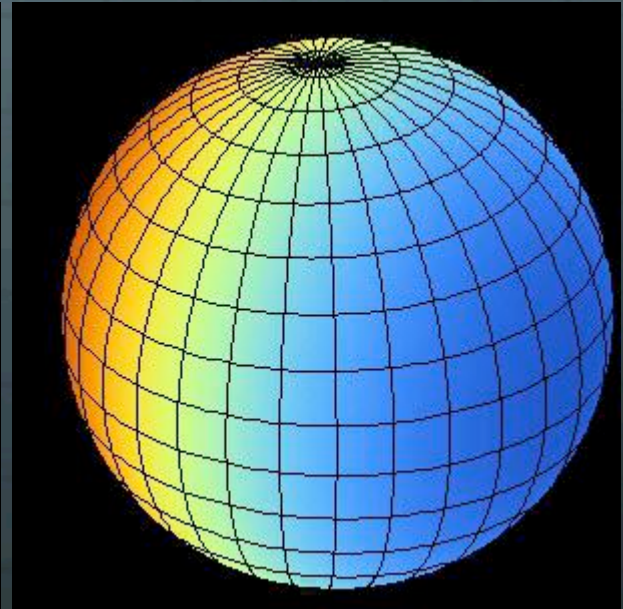
$$Y_1^m(\theta, \varphi) \propto P_1^{|m|}(\cos \theta) e^{im\varphi}$$



$l = 1, m = -1$



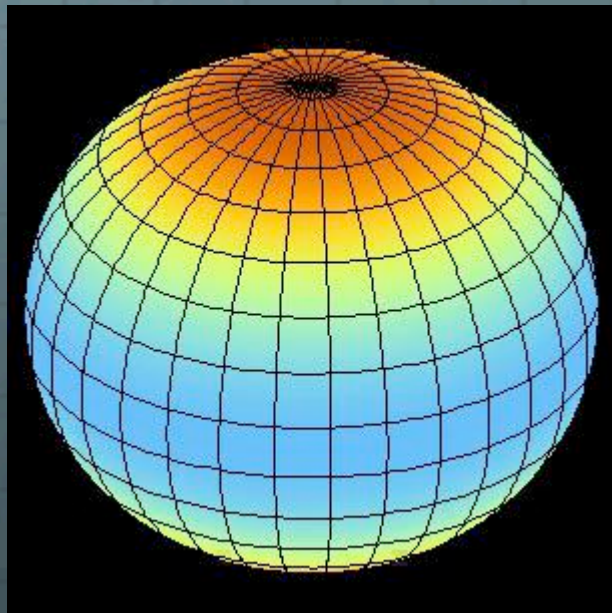
$l = 1, m = 0$



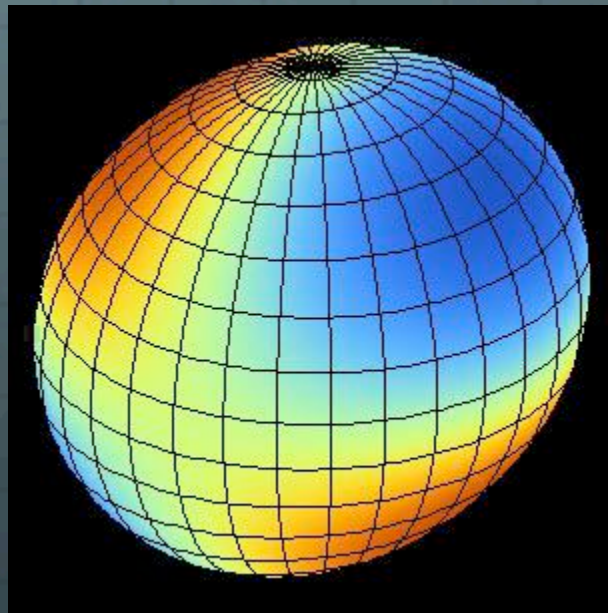
$l = 1, m = +1$

Nonradial modes- Quadrupole modes

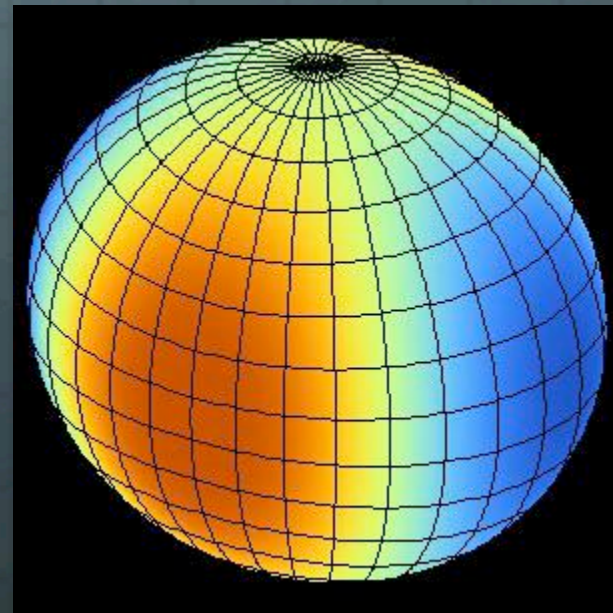
$$Y_2^m(\theta, \varphi) \propto P_2^{|m|}(\cos \theta) e^{im\varphi}$$



$l = 2, m = 0$

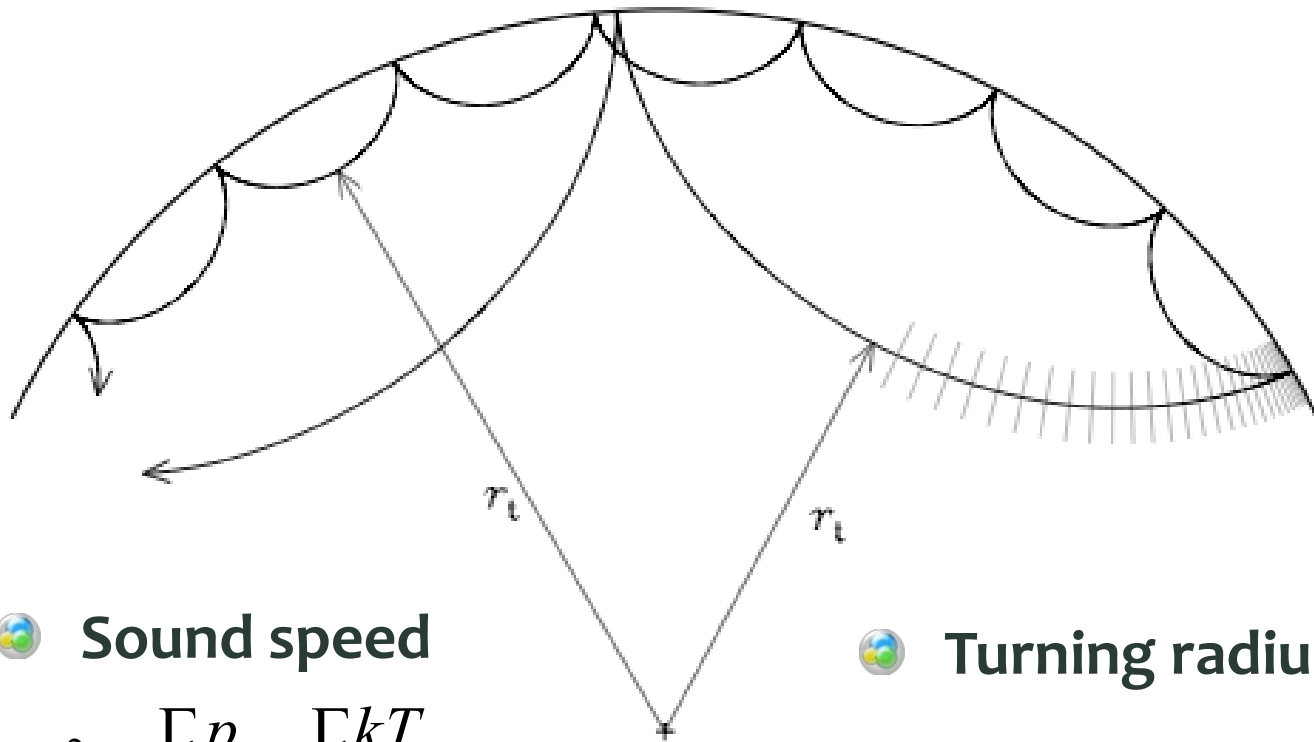


$l = 2, m = -1$



$l = 2, m = -2$

Asteroseismology – how does it work?



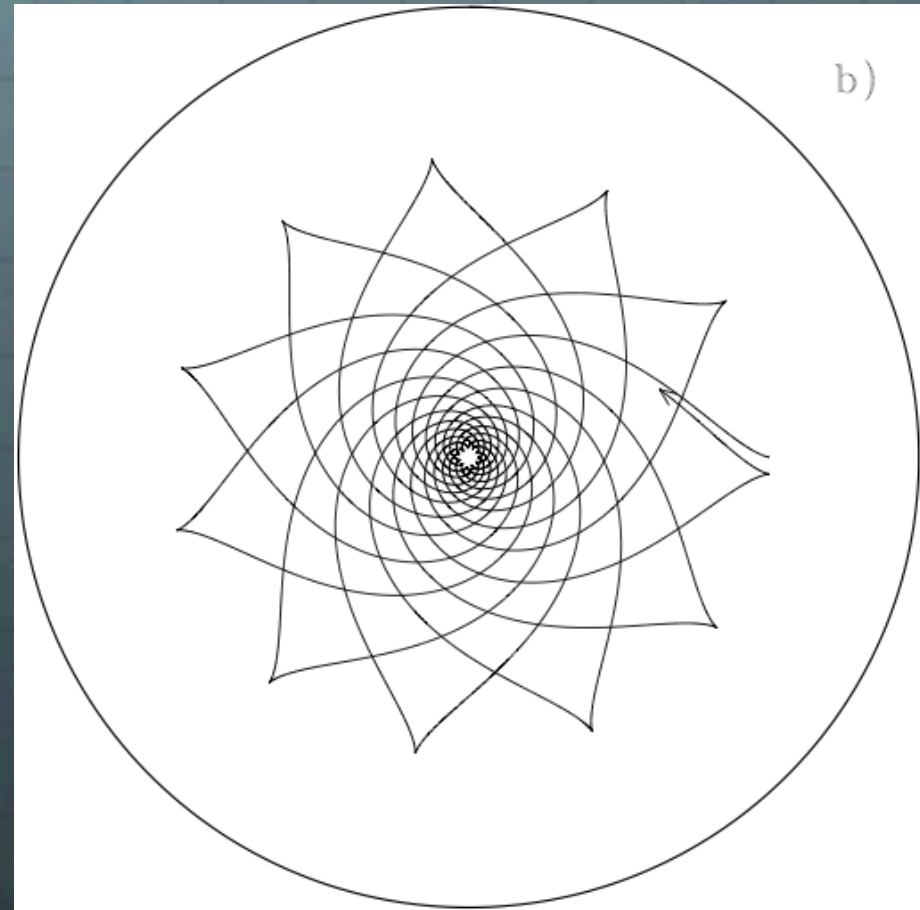
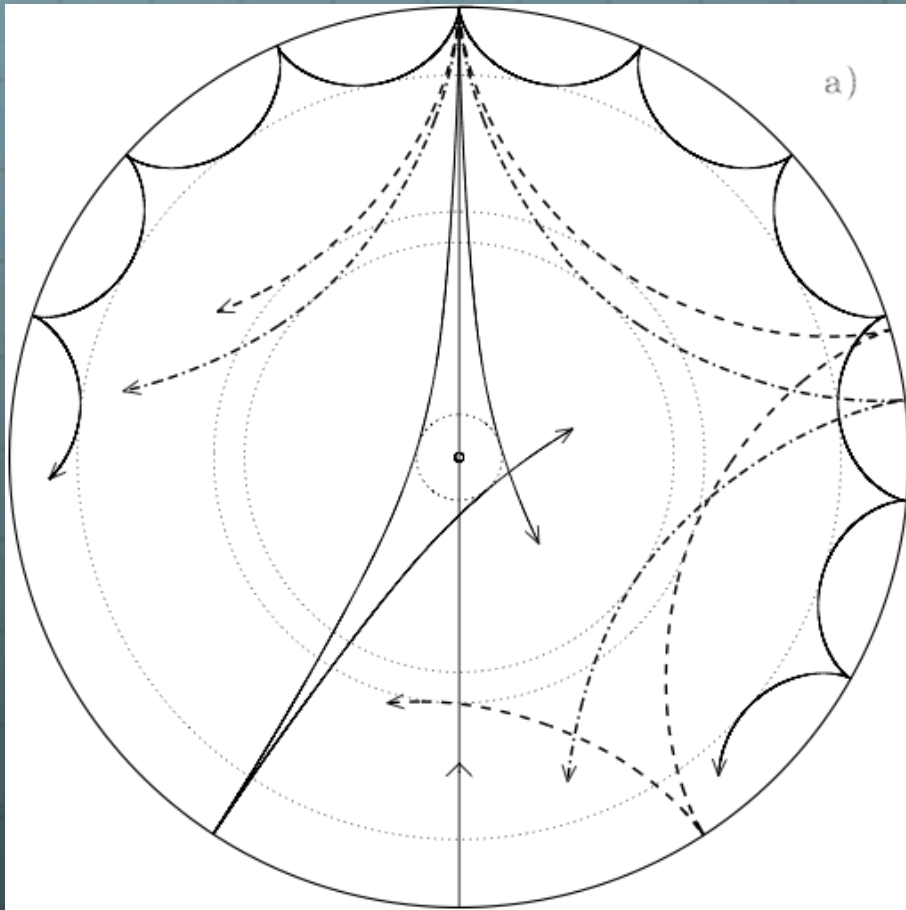
🌍 Sound speed

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

🌍 Turning radius

🌍 Acoustic cavity

p modes and g modes



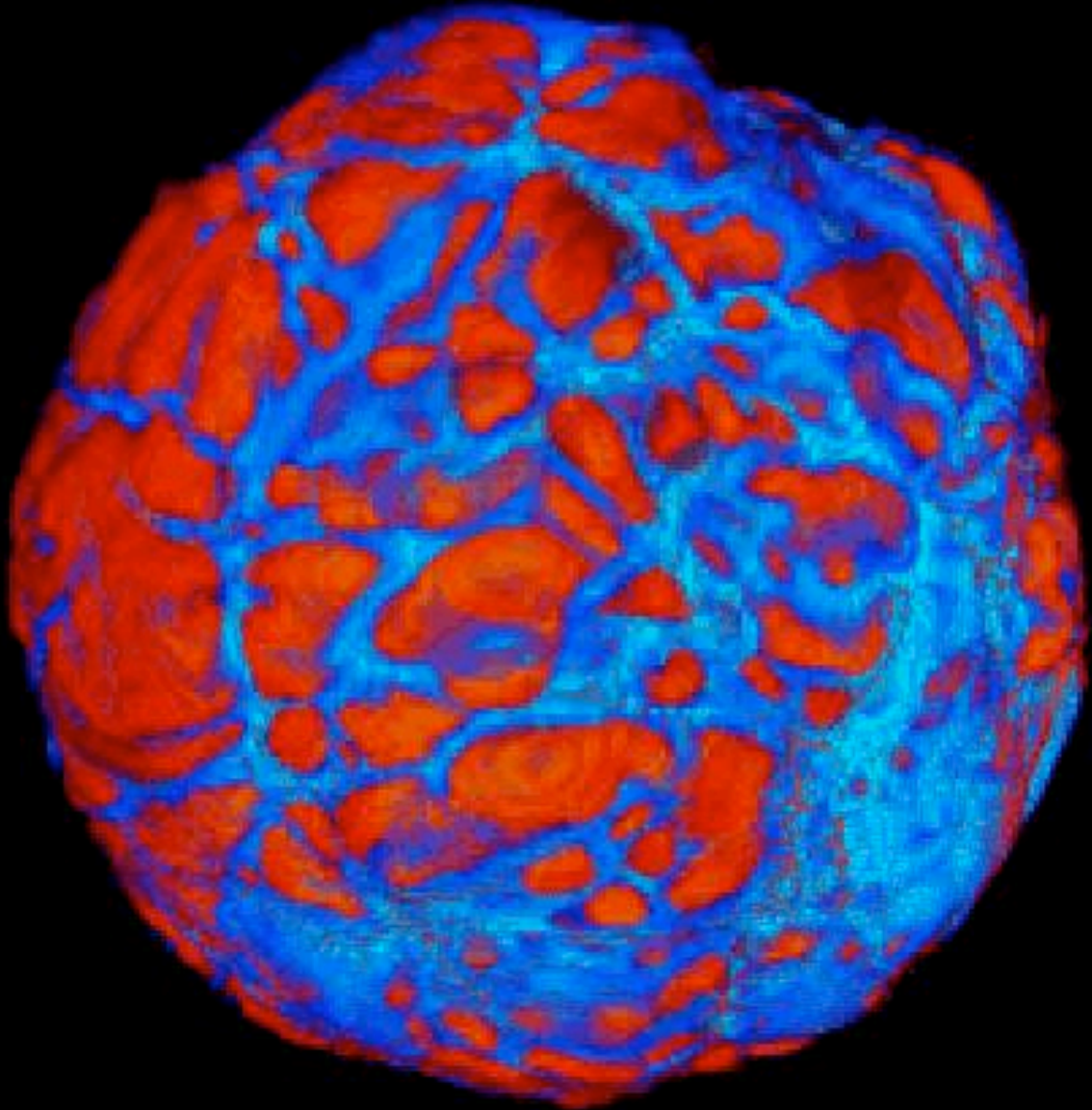
Driving mechanisms

Heat engine mechanism

- 🌐 Gains heat on compression
- 🌐 κ -mechanism (κ = 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

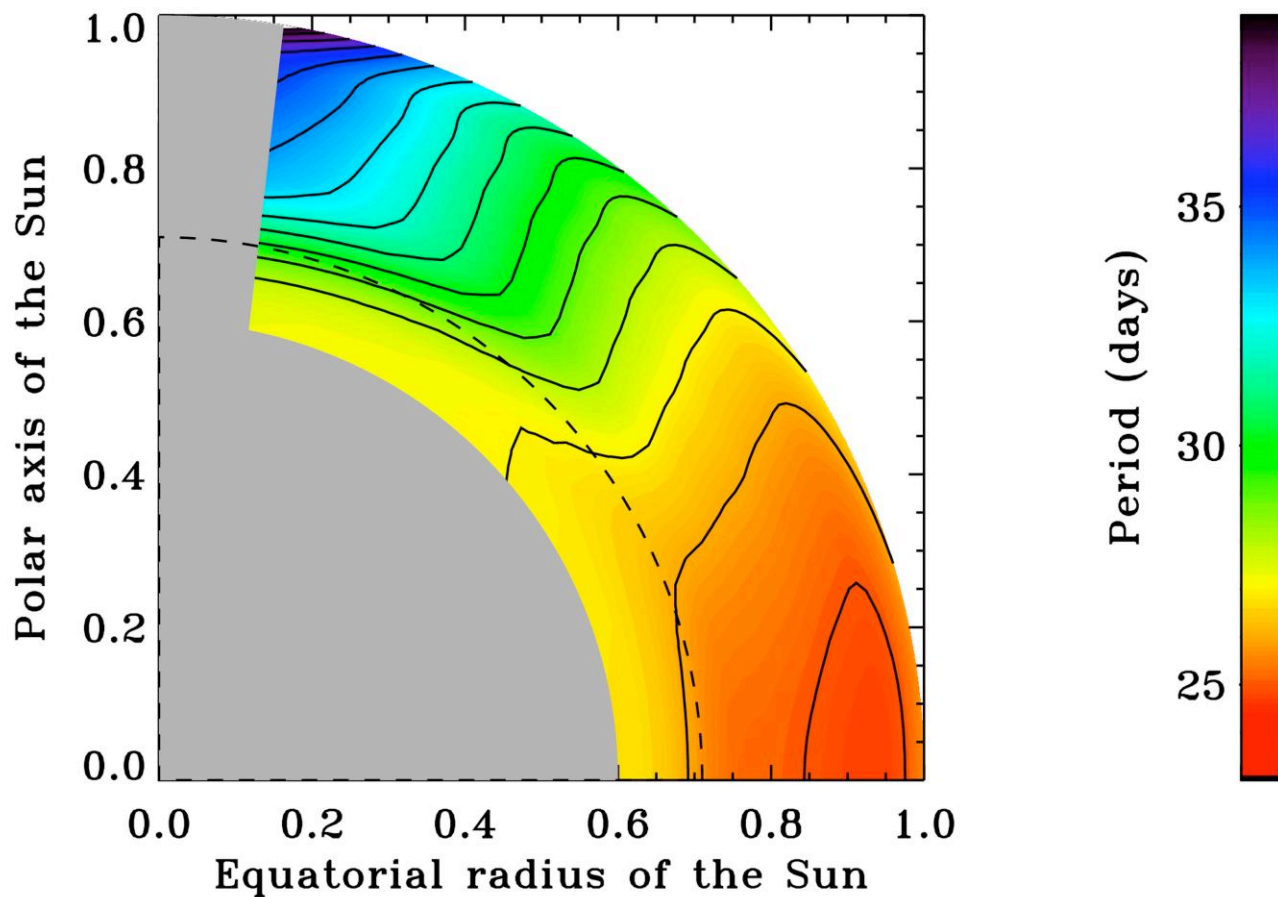
- 🌐 Star resonates with acoustic noise
- 🌐 Solar-like oscillators
- 🌐 Main interest in exoplanet finding



LCSE
University
of
Minnesota

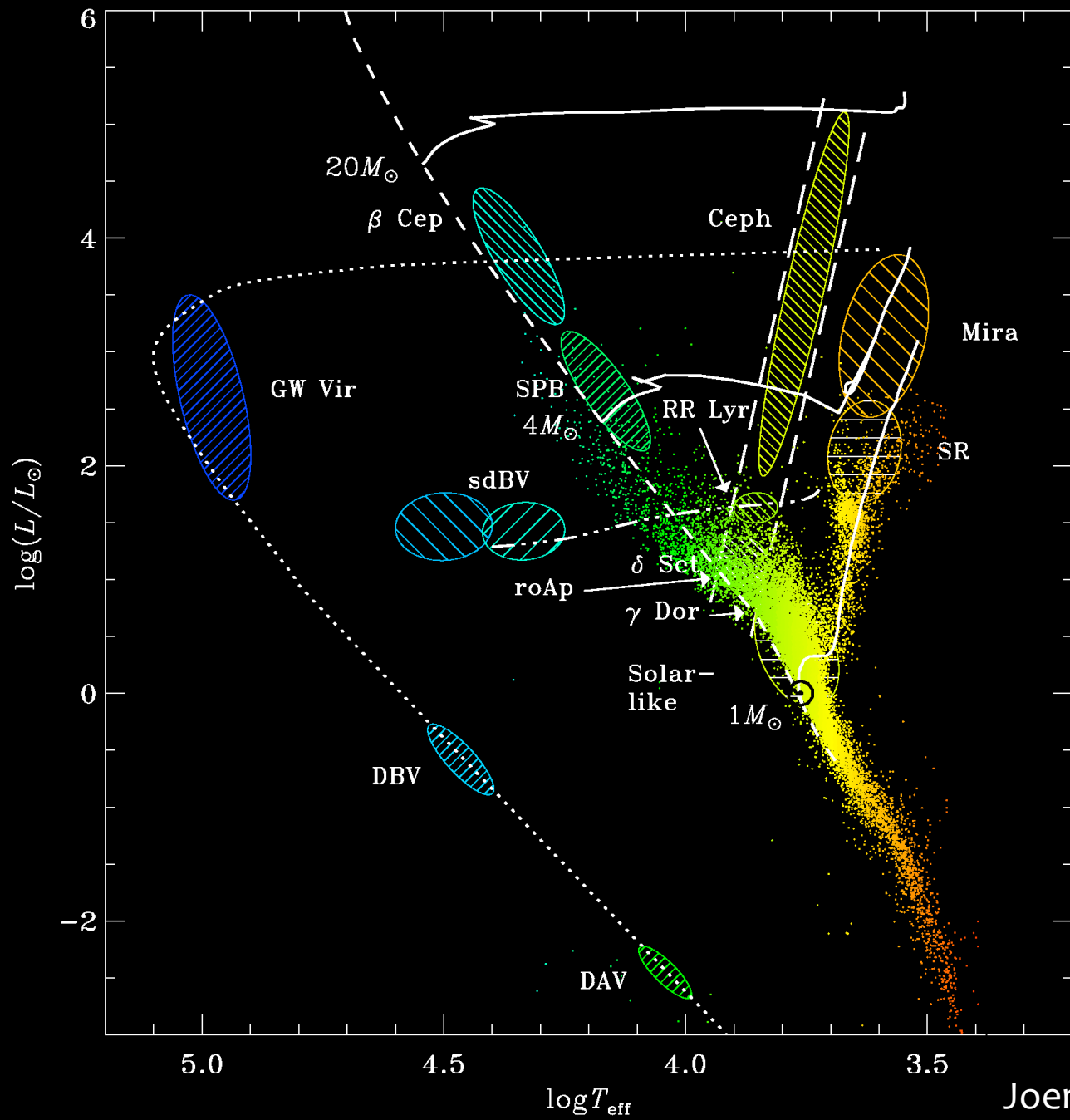
“...the deep interior of the Sun ...is less accessible
...than any other region of the universe.”

Eddington 1926



Helioseismology:
The solar interior
is
accessible now!

courtesy of
Rachel Howe

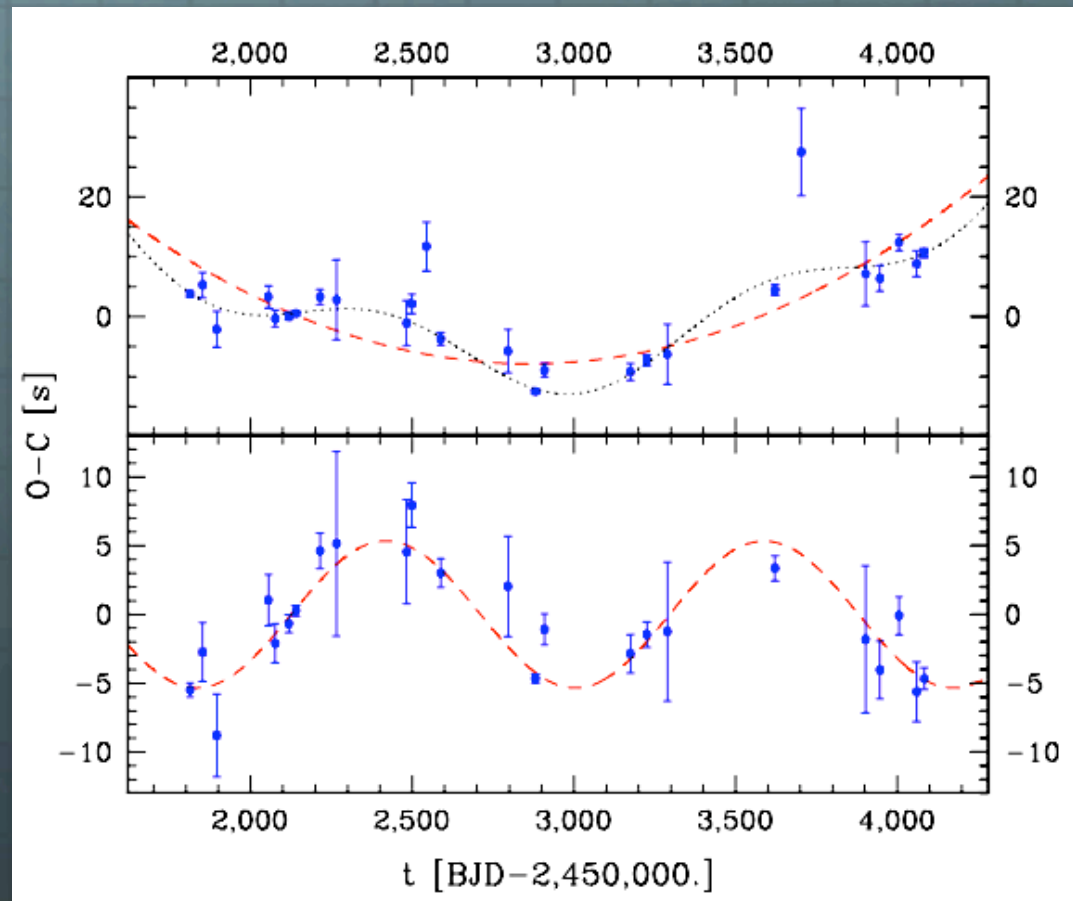


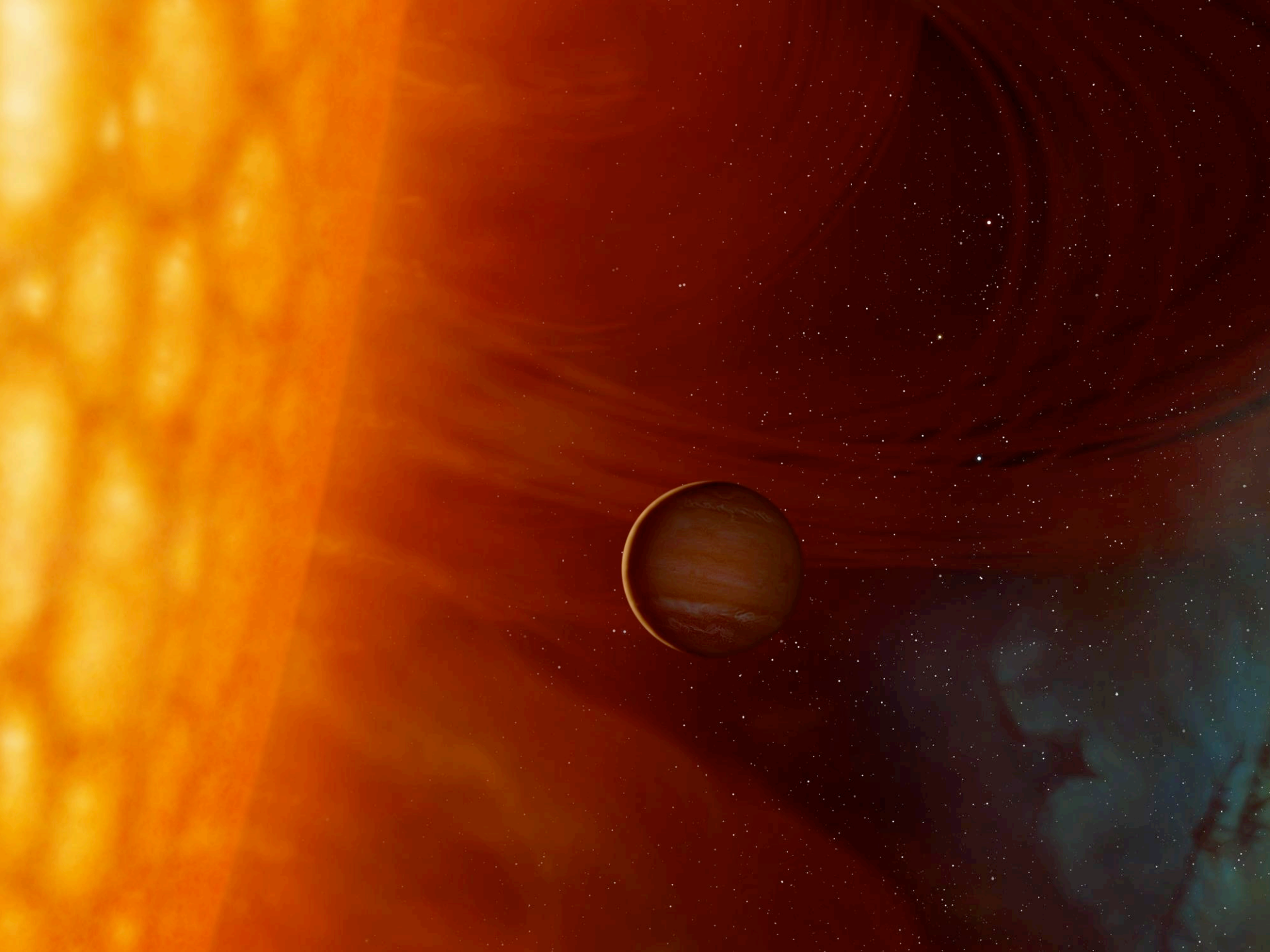
courtesy of
Joergen Christensen-Dalsgaard

Planet-finding: the timing method

- 🌍 V391 Peg
- 🌍 sdBV star
- 🌍 Excellent clock
- 🌍 7 years with WET

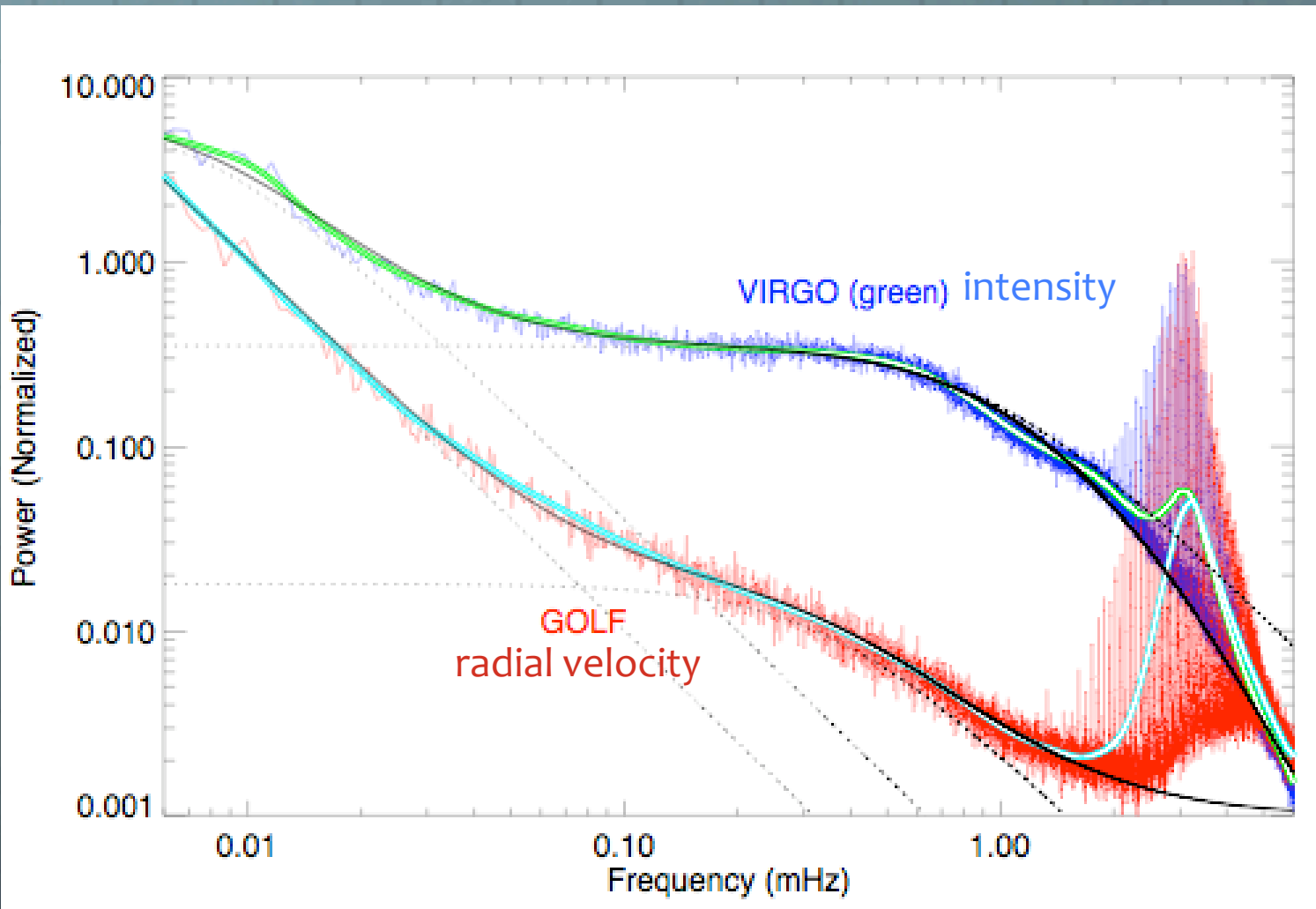
- 🌍 V391b Peg
- 🌍 $3 M_j$
- 🌍 $a = 1.7$ au
- 🌍 $a = 1$ au
- in red giant stage





The era of Kepler:

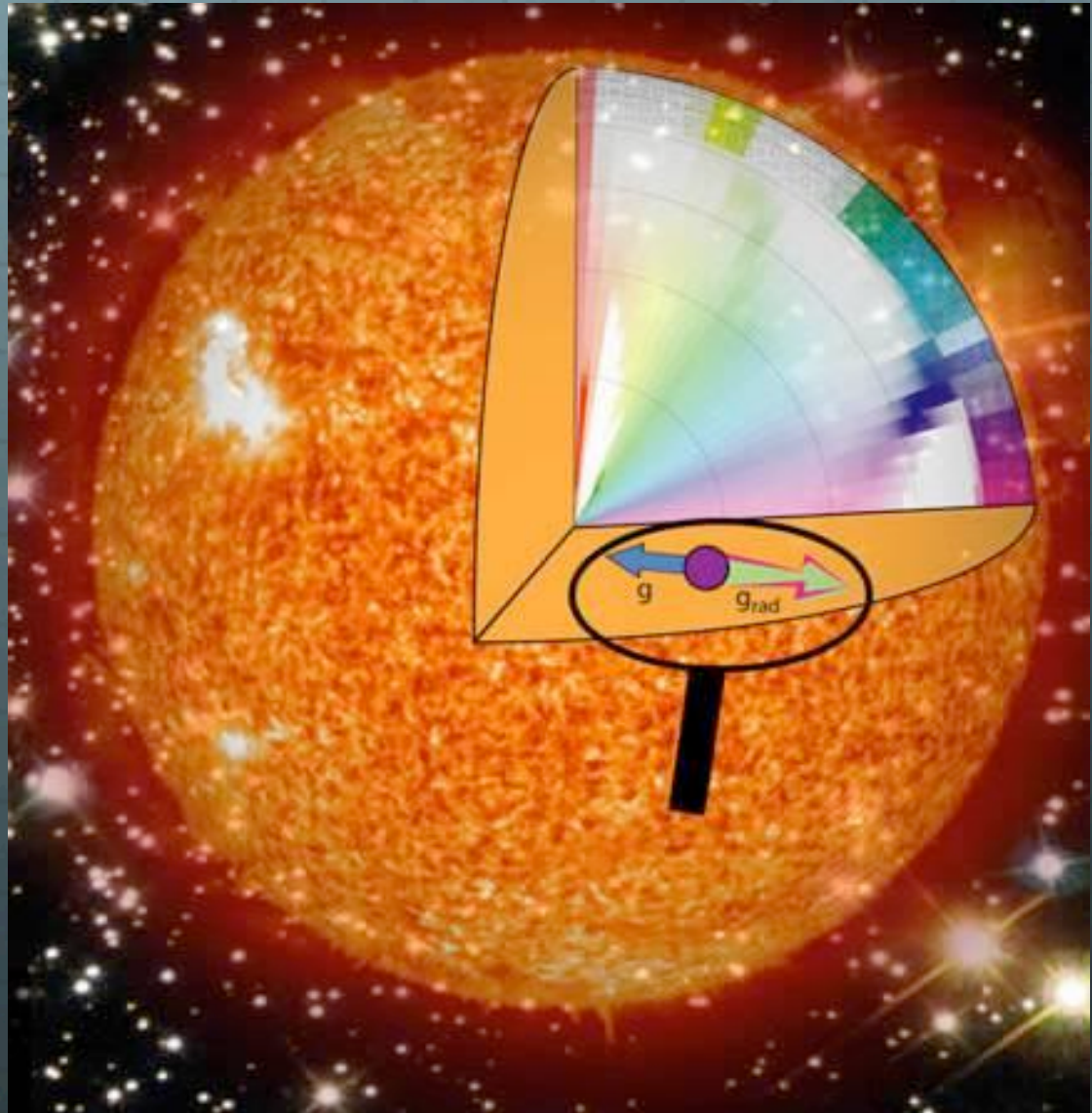
Why do asteroseismology from the ground?



courtesy of
Hans Kjeldsen

Atomic diffusion

- Radiative levitation
- Gravitational settling
- Solar model
- White dwarf structure
- Pulsation driving
- Stellar cluster ages



The roAp stars

PERIODIC TABLE Atomic Properties of the Elements

NIST

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Group 1 IA		PERIODIC TABLE Atomic Properties of the Elements										National Institute of Standards and Technology Technology Administration, U.S. Department of Commerce					Group 18 VIIIA																		
1 H Hydrogen 1.00794 1s 13.5984												Physics Laboratory physics.nist.gov					Standard Reference Data Group www.nist.gov/srd		2 He Helium 4.002602 1s ² 24.5874																
2 Li Lithium 6.941 1s ² 2s 5.3917		3 Be Beryllium 9.012182 1s ² 2s ² 9.3227												13 B Boron 10.811 1s ² 2s ² 2p 8.2980		14 C Carbon 12.0107 1s ² 2s ² 2p ² 11.2603		15 N Nitrogen 14.0067 1s ² 2s ² 2p ³ 14.5341		16 O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.6181		17 F Fluorine 18.9984032 1s ² 2s ² 2p ⁵ 17.4228		18 Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645											
3 Na Sodium 22.989770 [Ne]3s 5.1391		4 Mg Magnesium 24.3050 [Ne]3s ² 7.6462												13 Al Aluminum 26.981538 [Ne]3s ² 3p 9.9955		14 Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517		15 P Phosphorus 30.973761 [Ne]3s ² 3p ³ 10.4867		16 S Sulfur 32.065 [Ne]3s ² 3p ⁴ 10.3600		17 Cl Chlorine 35.453 [Ne]3s ² 3p ⁵ 12.9676		18 Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596											
4 K Potassium 39.0983 [Ar]4s 4.3407		5 Ca Calcium 40.078 [Ar]4s 6.1132		6 Sc Scandium 44.955910 [Ar]3d ¹ 4s 6.5615		7 Ti Titanium 47.867 [Ar]3d ² 4s 6.8281		8 V Vanadium 50.9415 [Ar]3d ³ 4s 6.7665		9 Cr Chromium 51.9961 [Ar]3d ⁵ 4s 6.7665		10 Mn Manganese 54.938049 [Ar]3d ⁵ 4s 7.4340		11 Fe Iron 55.845 [Ar]3d ⁶ 4s 7.8810		12 Co Cobalt 58.933200 [Ar]3d ⁷ 4s 7.8810		13 Ni Nickel 58.6934 [Ar]3d ⁸ 4s 7.7264		14 Cu Copper 63.546 [Ar]3d ¹⁰ 4s 7.7264		15 Zn Zinc 65.409 [Ar]3d ¹⁰ 4s 7.7264		16 Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ¹ 4p 5.9933		17 Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994		18 As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886		19 Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524		20 Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138		21 Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996	
5 Rb Rubidium 85.4678 [Kr]5s 4.1771		6 Sr Strontium 87.62 [Kr]5s 5.6949		7 Y Yttrium 88.90585 [Kr]4d ¹ 5s 6.2173		8 Zr Zirconium 91.224 [Kr]4d ² 5s 6.6339		9 Nb Niobium 92.90638 [Kr]4d ⁴ 5s 6.7589		10 Mo Molybdenum 95.94 [Kr]4d ⁵ 5s 7.0924		11 Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.28		12 Ru Ruthenium 101.07 [Kr]4d ⁷ 5s 7.3605		13 Rh Rhodium 102.90550 [Kr]4d ⁸ 5s 7.4589		14 Pd Palladium 106.42 [Kr]4d ¹⁰ 8.3369		15 Ag Silver 107.8682 [Kr]4d ¹⁰ 5s 7.5762		16 Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s 8.9938		17 In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p 5.7864		18 Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439		19 Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 8.6094		20 Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0096		21 I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513		22 Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298	
6 Cs Cesium 132.90545 [Xe]6s 3.8939		7 Ba Barium 137.327 [Xe]6s 5.2117		8 Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251		9 Ta Tantalum 180.9479 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496		10 W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640		11 Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335		12 Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382		13 Ir Iridium 192.217 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9670		14 Pt Platinum 195.078 [Xe]4f ¹⁴ 5d ⁹ 6s ¹ 8.9588		15 Au Gold 196.96655 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹ 9.2255		16 Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375		17 Tl Thallium 204.3833 [Hg]6p 6.1082		18 Pb Lead 207.2 [Hg]6p ² 7.4167		19 Bi Bismuth 208.98038 [Hg]6p ³ 7.2855		20 Po Polonium (209) [Hg]6p ⁴ 8.414		21 At Astatine (210) [Hg]6p ⁵		22 Rn Radon (222) [Hg]6p ⁶ 10.7485			
7 Fr Francium (223) [Rn]7s 4.0727		8 Ra Radium (226) [Rn]7s ² 5.2784		9 Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ² 6.0 ?		10 Db Dubnium (262) [Rn]5f ¹⁴ 6d ³ 7s ²		11 Sg Seaborgium (266) [Rn]5f ¹⁴ 6d ⁴ 7s ²		12 Bh Bohrium (264) [Rn]5f ¹⁴ 6d ⁵ 7s ²		13 Hs Hassium (277) [Rn]5f ¹⁴ 6d ⁶ 7s ²		14 Mt Meitnerium (268) [Rn]5f ¹⁴ 6d ⁷ 7s ²		15 Uun Ununilium (281)		16 Uuu Unununium (272)		17 Uuuu Ununquadium (285)		18 Uuq Ununquadium (289)		19 Uuh Ununhexium (292)											

Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s ⁻¹	(exact)
Planck constant	<i>h</i>	6.6261 × 10 ⁻³⁴ J s	(<i>h</i> = <i>h</i> /2π)
elementary charge	<i>e</i>	1.6022 × 10 ⁻¹⁹ C	
electron mass	<i>m_e</i>	9.1094 × 10 ⁻³¹ kg	
	<i>m_ec²</i>	0.5110 MeV	
proton mass	<i>m_p</i>	1.6726 × 10 ⁻²⁷ kg	
fine-structure constant	<i>α</i>	1/137.036	
Rydberg constant	<i>R_∞</i>	10 973 732 m ⁻¹	
	<i>R_∞c</i>	3.289 842 × 10 ¹⁵ Hz	
	<i>R_∞hc</i>	13.6057 eV	
Boltzmann constant	<i>k</i>	1.3807 × 10 ⁻²³ J K ⁻¹	

- Solids
- Liquids
- Gases
- Artificially Prepared

Atomic Number: 58
Ground-state Level: 1G₄
Symbol: **Ce**
Name: Cerium
Atomic Weight: 140.116
Ground-state Configuration: [Xe]4f¹5d⁰6s²
Ionization Energy (eV): 5.5387

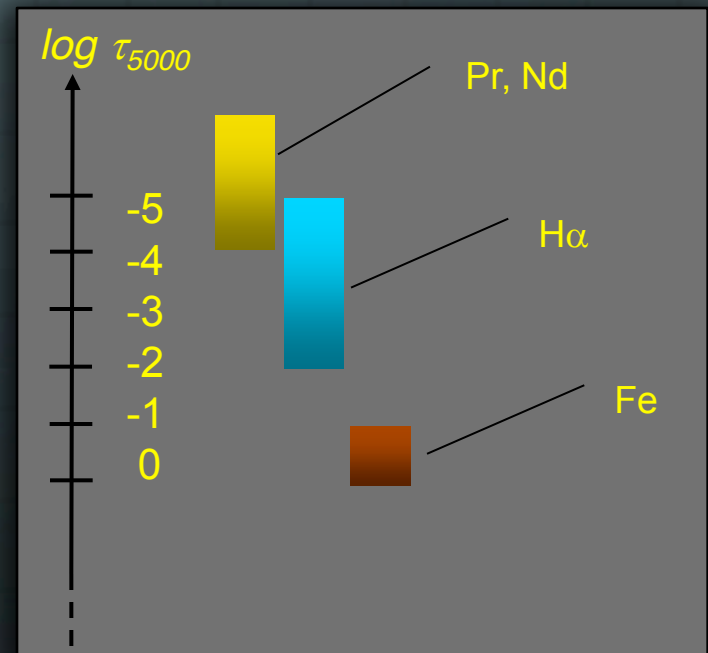
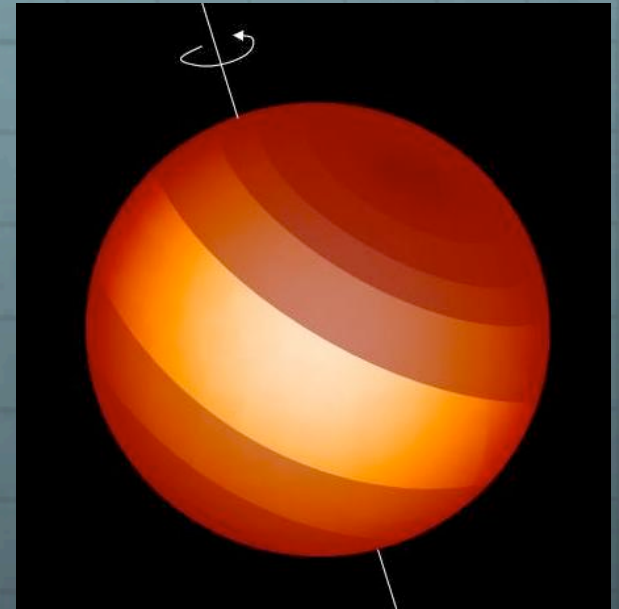
Lanthanides		57 La Lanthanum 138.9055 [Xe]5d ¹ 6s ² 5.5769	58 Ce Cerium 140.116 [Xe]4f ¹ 5d ⁰ 6s ² 5.5387	59 Pr Praseodymium 140.90785 [Xe]4f ³ 6s ² 5.473	60 Nd Neodymium 144.24 [Xe]4f ⁴ 6s ² 5.5250	61 Pm Promethium (145) [Xe]4f ⁵ 6s ² 5.582	62 Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	63 Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	64 Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1499	65 Tb Terbium 158.92534 [Xe]4f ⁹ 6s ² 5.8838	66 Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9389	67 Ho Holmium 164.93032 [Xe]4f ¹¹ 6s ² 6.2015	68 Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	69 Tm Thulium 168.93421 [Xe]4f ¹³ 6s ² 6.1843	70 Yb Ytterbium 173.04 [Xe]4f ¹⁴ 6s ² 6.2542	71 Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259
Actinides		89 Ac Actinium (227) [Rn]6d ¹ 7s ² 5.17	90 Th Thorium 232.0381 [Rn]6d ² 7s ² 6.3067	91 Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ² 5.89	92 U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	93 Np Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2657	94 Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0260	95 Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738	96 Cm Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9914	97 Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1979	98 Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	99 Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.42	100 Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50	101 Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	102 No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	103 Lr Lawrencium (262) [Rn]5f ¹⁴ 7s ² 7p ¹ 4.9 ?

¹Based upon ¹²C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

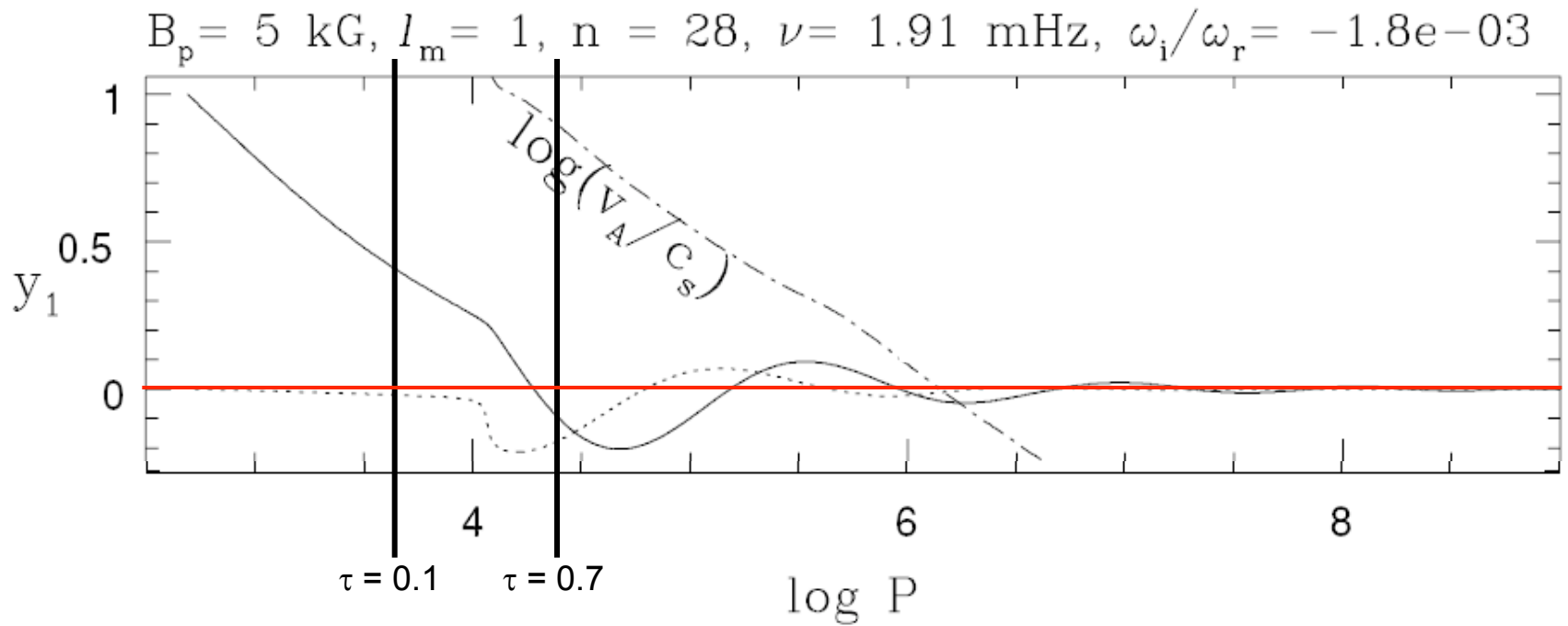
The roAp stars

- 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

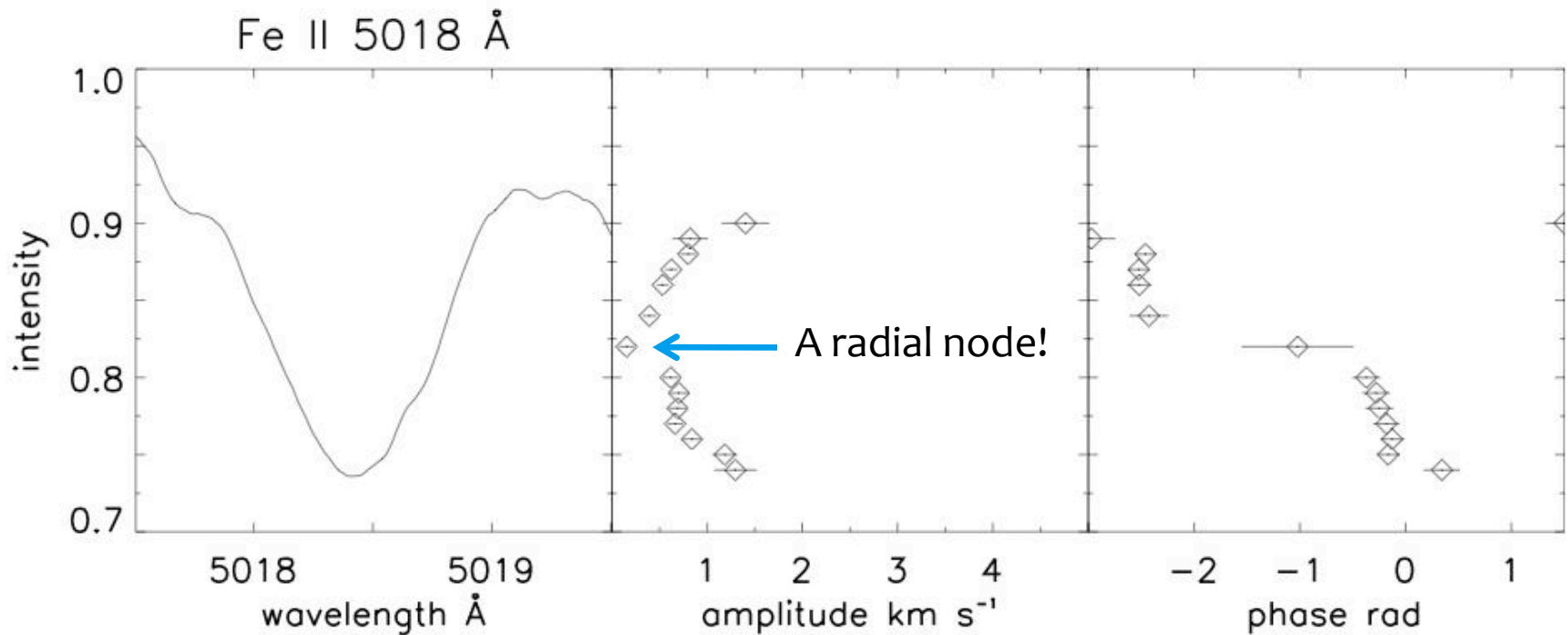




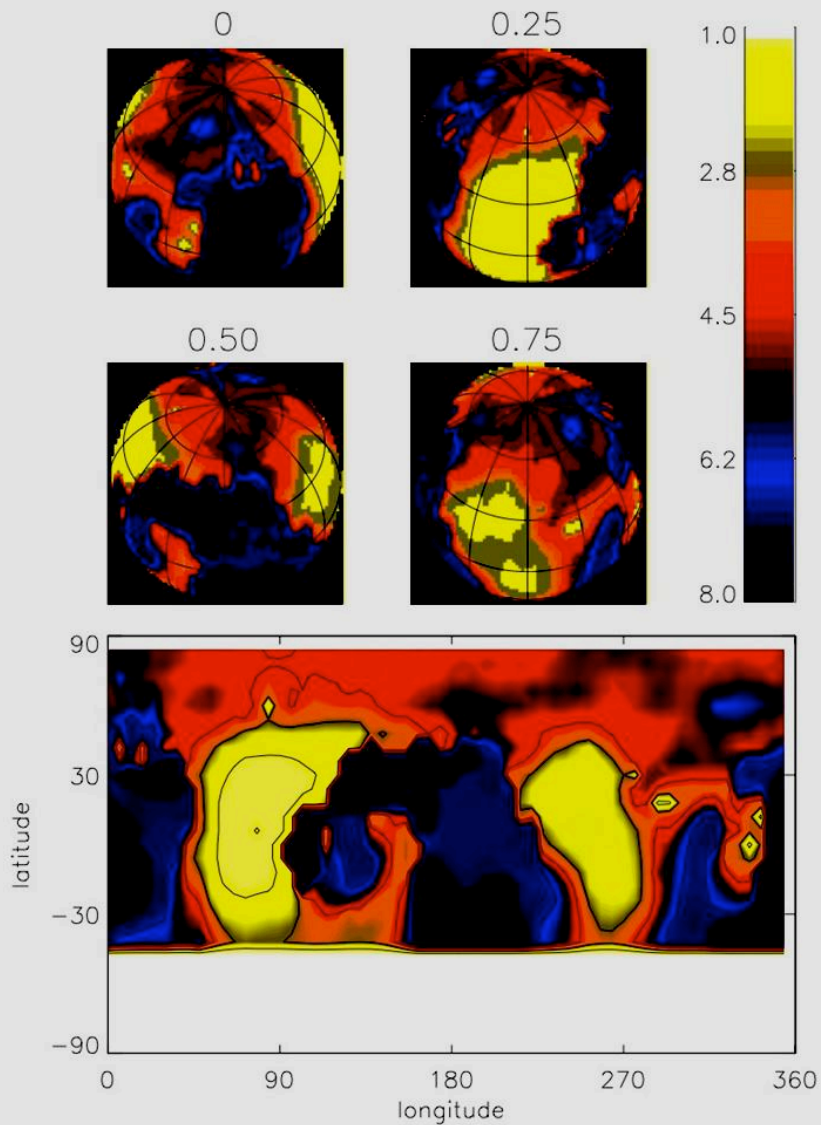
Theoretical expectation



Resolving the third dimension – HD99563



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

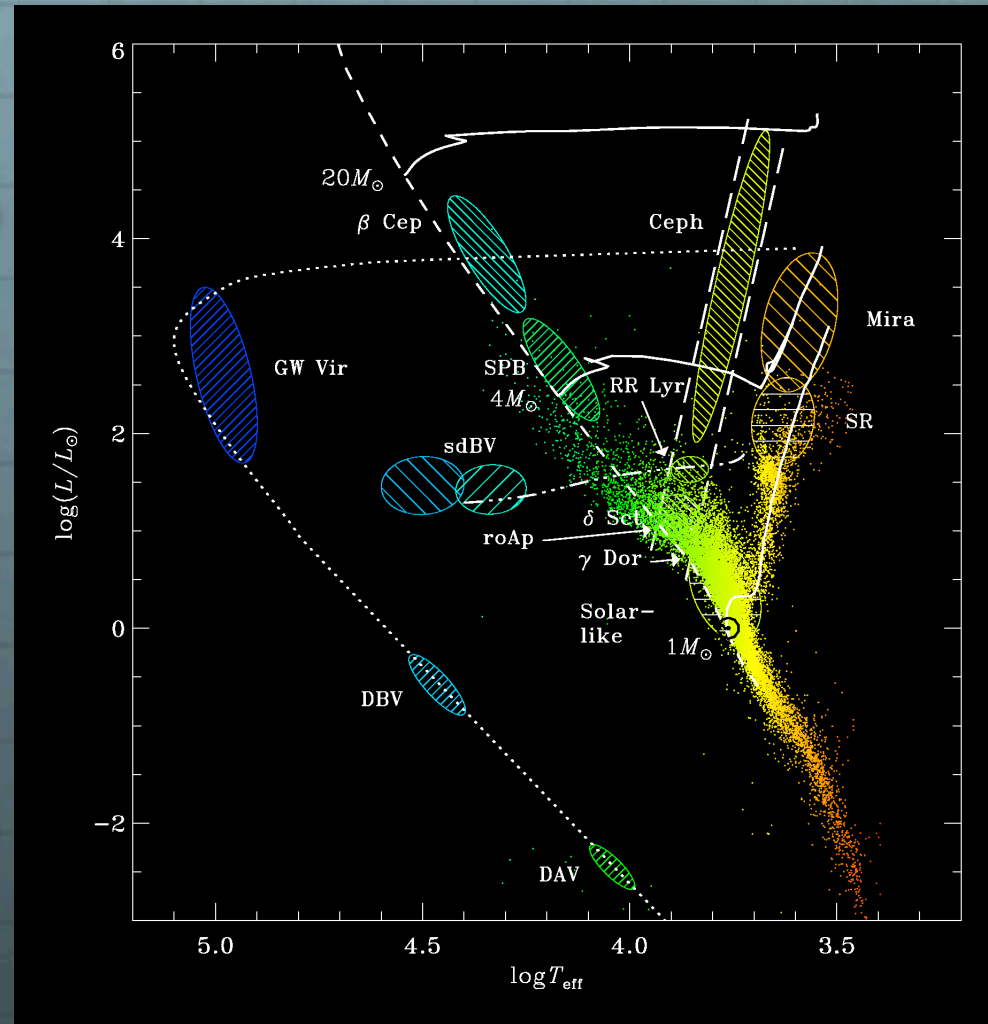
BPM 37093

DAV

$M = 1.09 M_{\odot}$

$T_{\text{eff}} = 11730 \text{ K}$

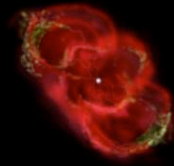
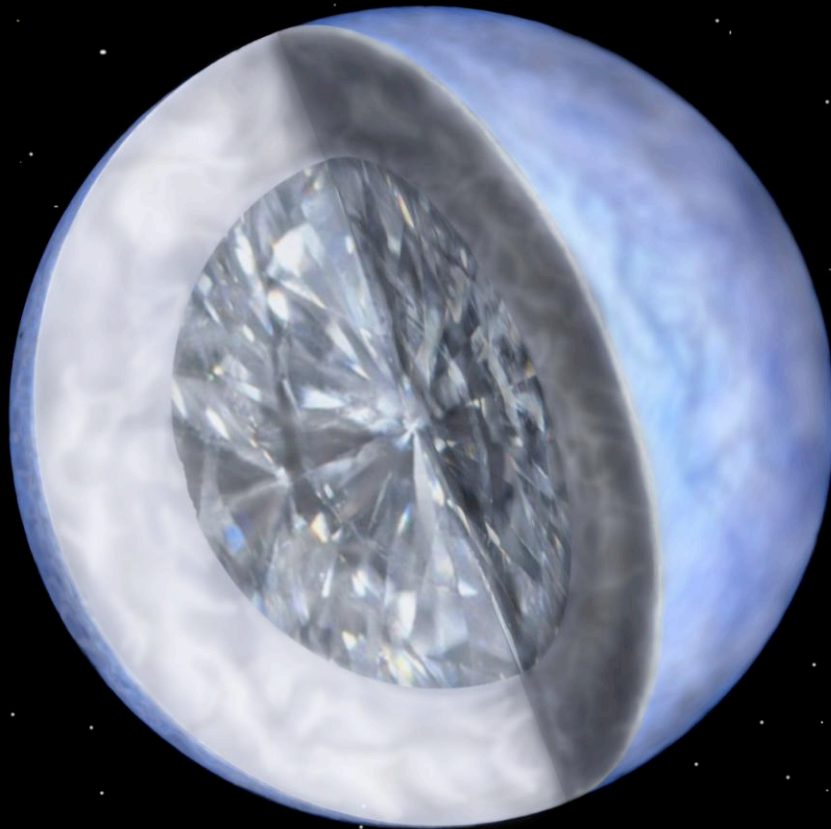
Partially crystallized
C-O core



Metcalf, 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

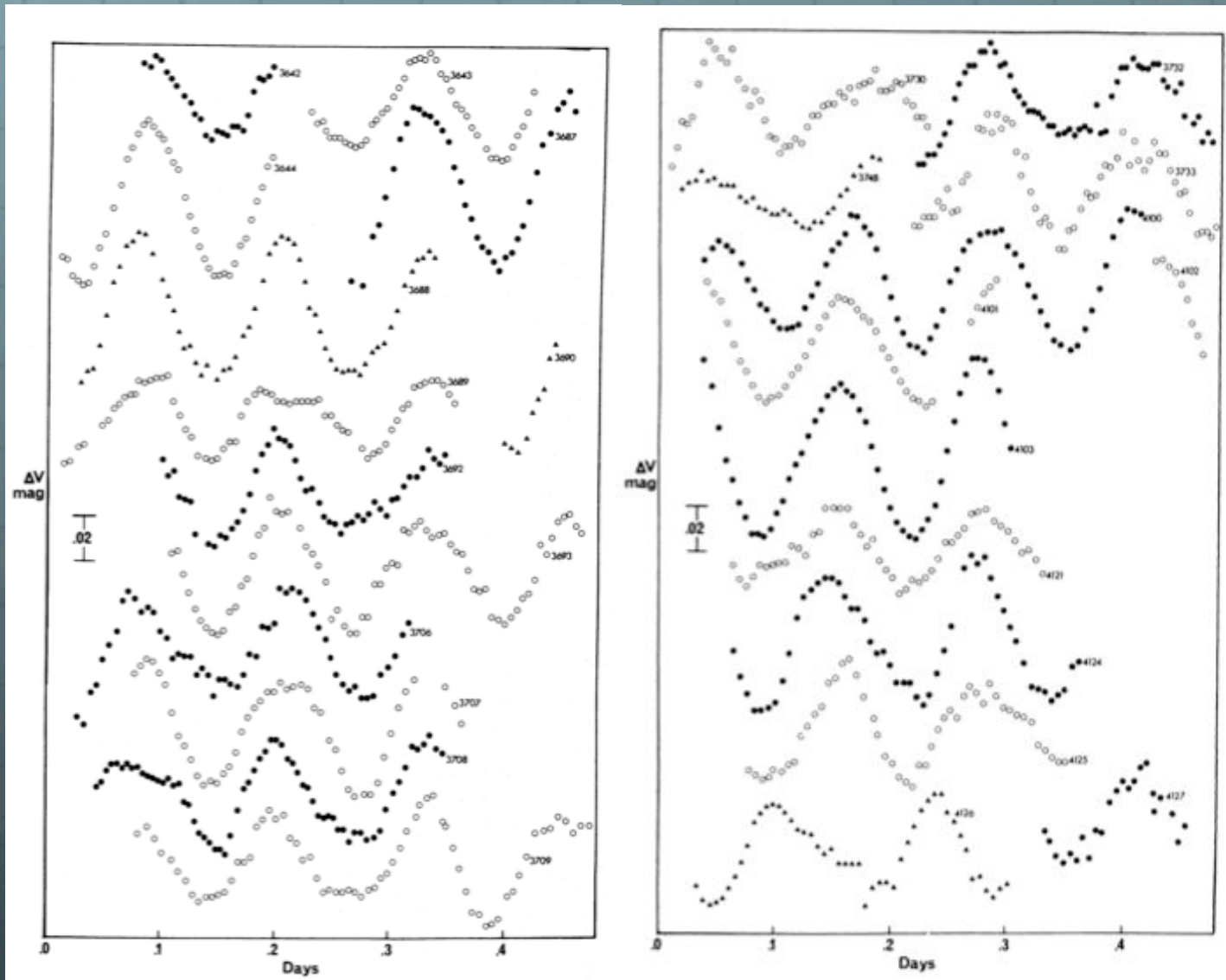


Kepler

A Search for Terrestrial Planets



The μ mag revolution



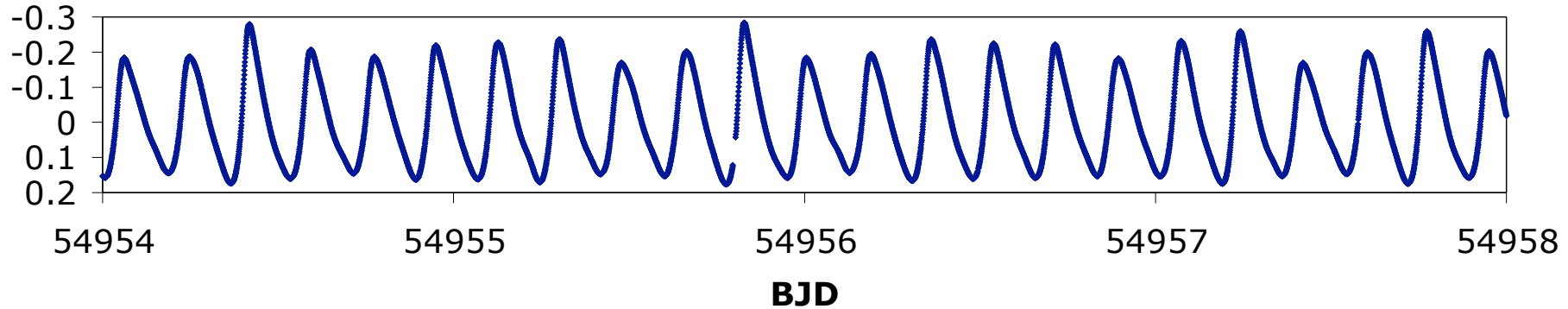
HD188136
 δ Sct star

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 Tychoenic 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
-  Gravitational lensing

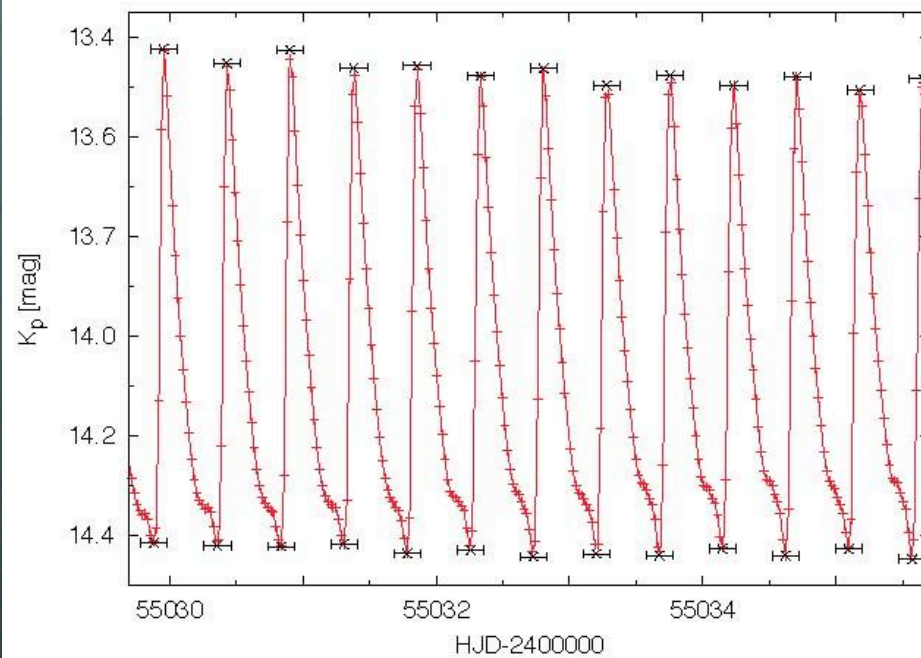
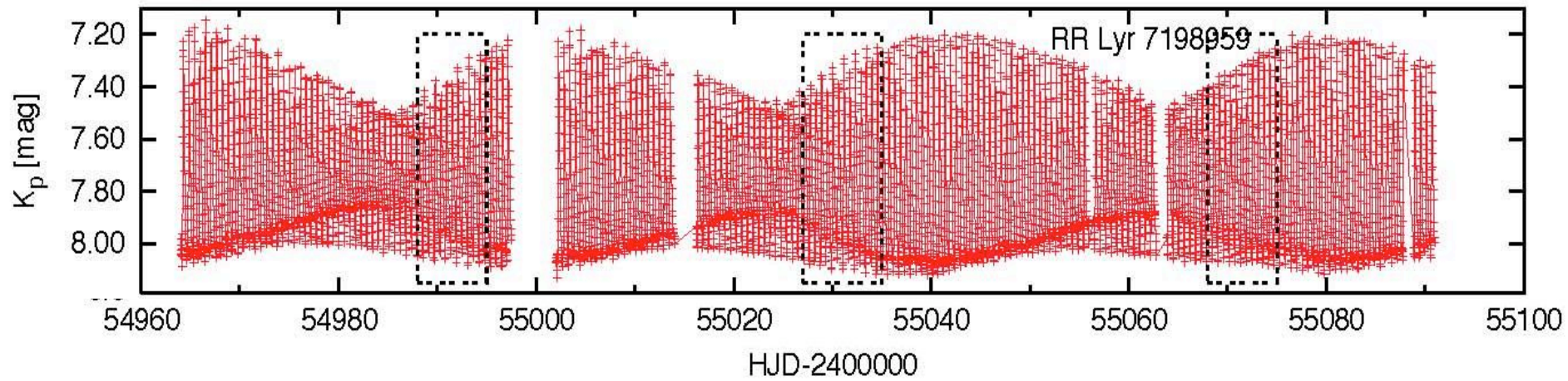
Bloemen and the Kepler team,
2010, MNRAS, in press

KIC 8677585

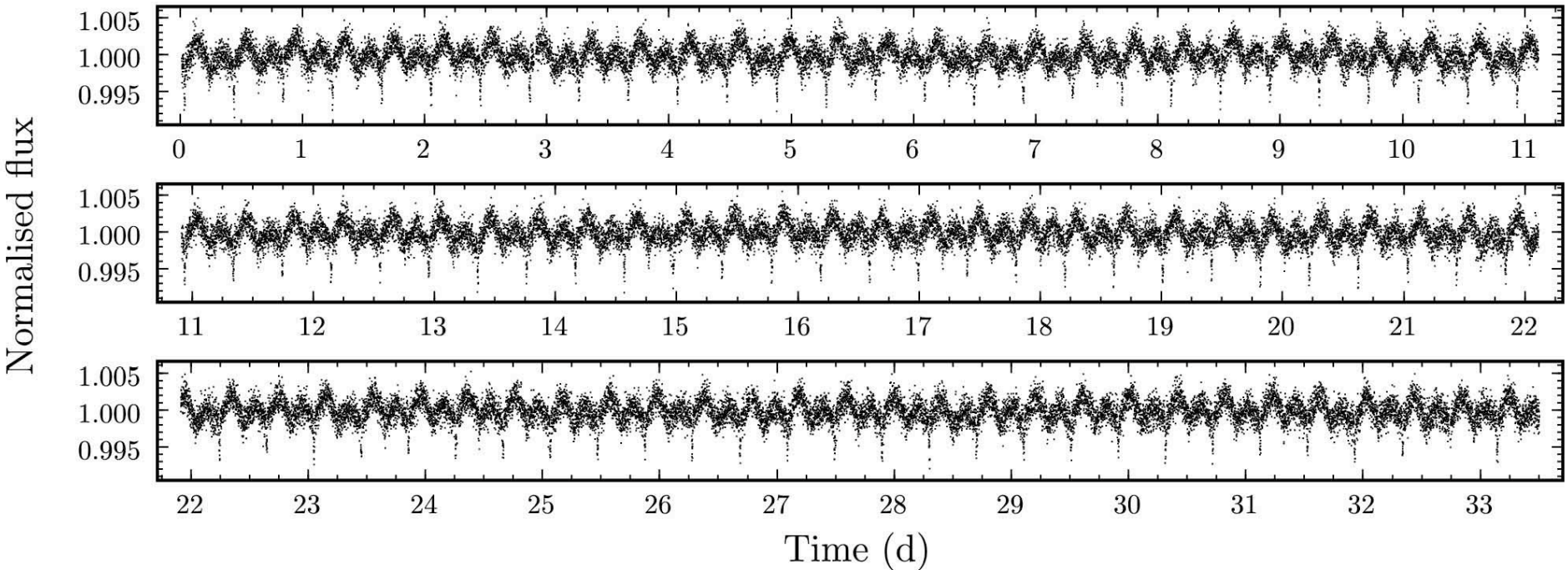
-  roAp star
-  Unpredicted, unprecedented g mode

Balona and the Kepler team,
2010, MNRAS, submitted

RR Lyr



KPD 1946 +4340



🌍 The sdB star is an EHB star

🌍 He star

🌍 Mass probably $0.5 M_{\odot}$

🌍 $P_{\text{orb}} = 0.403739 \text{ d}$

🌍 $V = 14.30; K_p = 14.65$

🌍 White dwarf companion

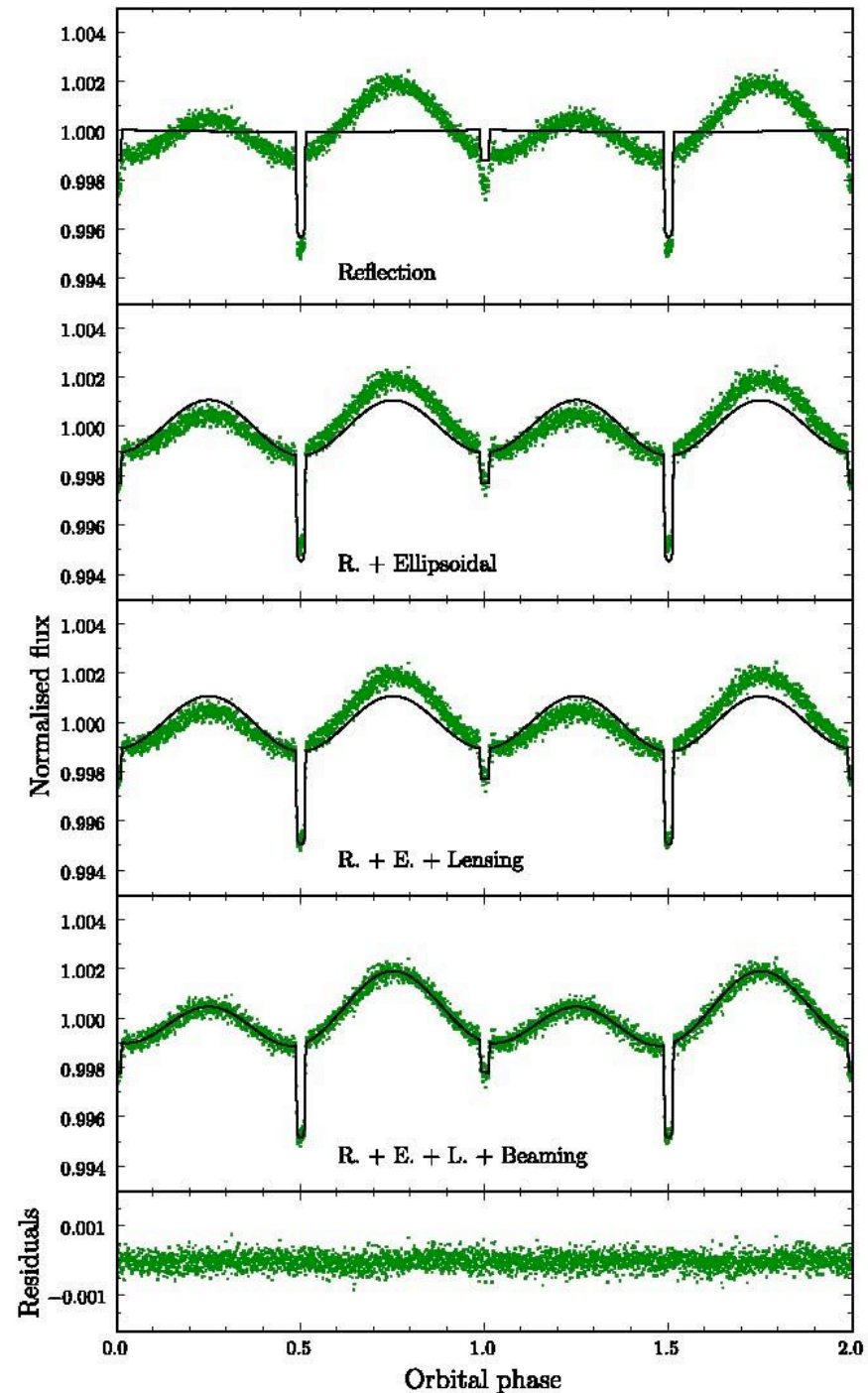
🌍 Eclipsing binary

KPD 1946 +4340

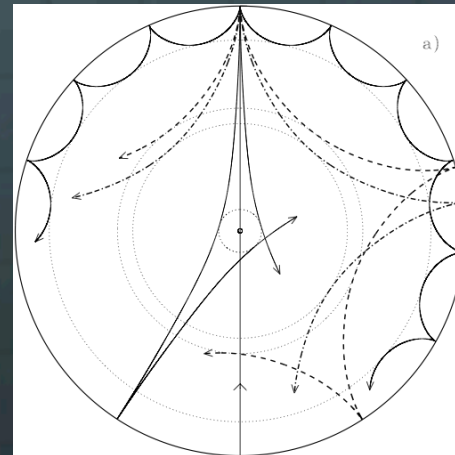
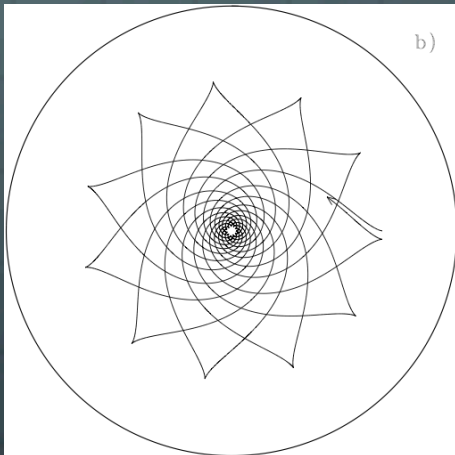
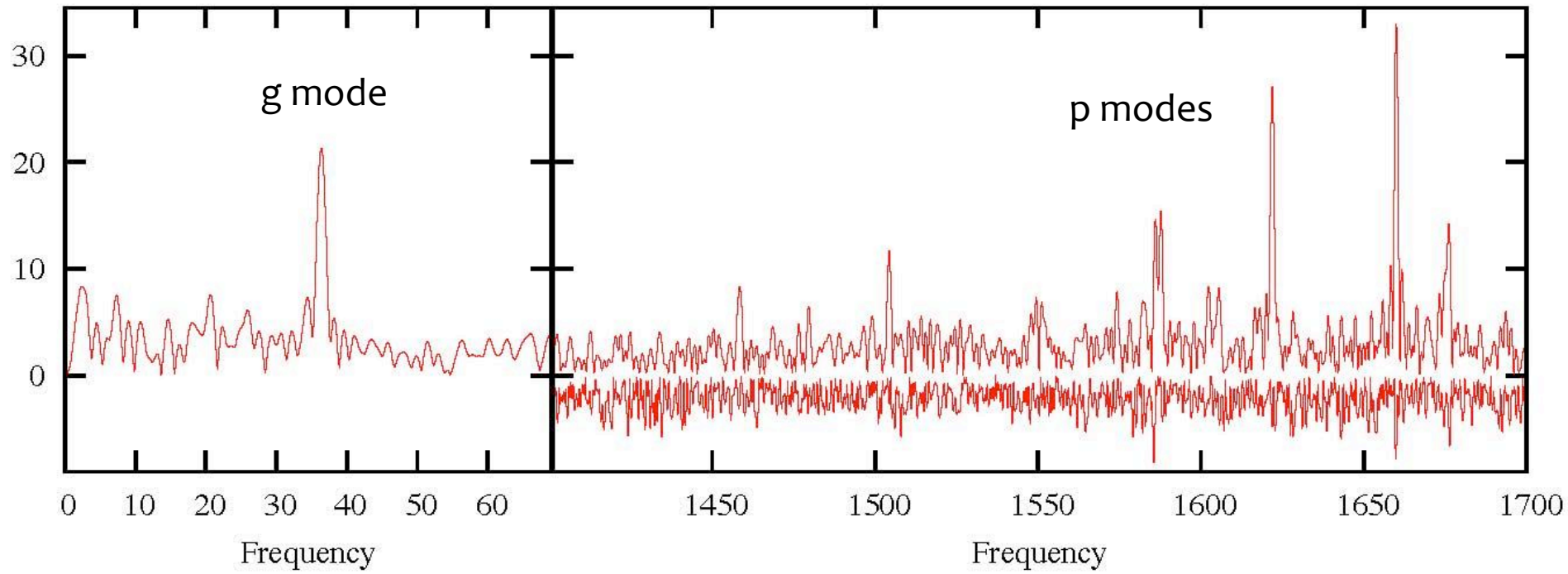
Distortion of the sdB star accounts for some of the ellipsoidal variability, but not all.

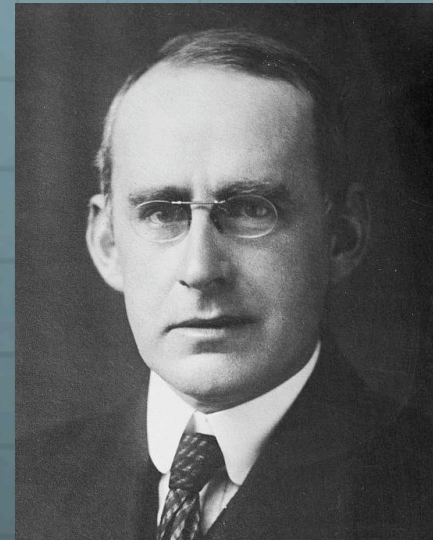
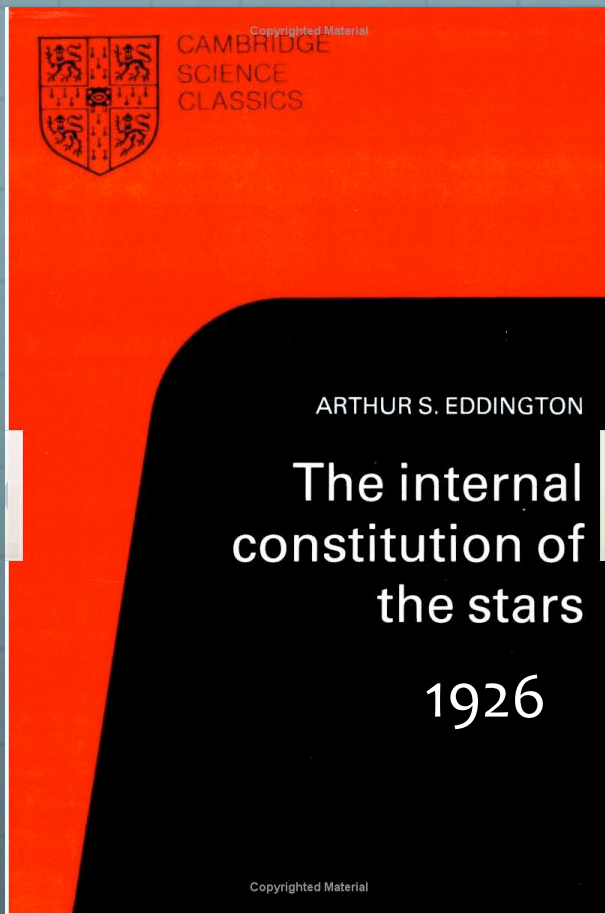
Gravitational lensing reduces the apparent geometrical cross-section of the white dwarf

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



KIC 8677585





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

Asteroseismology:



a new

Keplerian revolution