Asteroseismology in the era of Kepler

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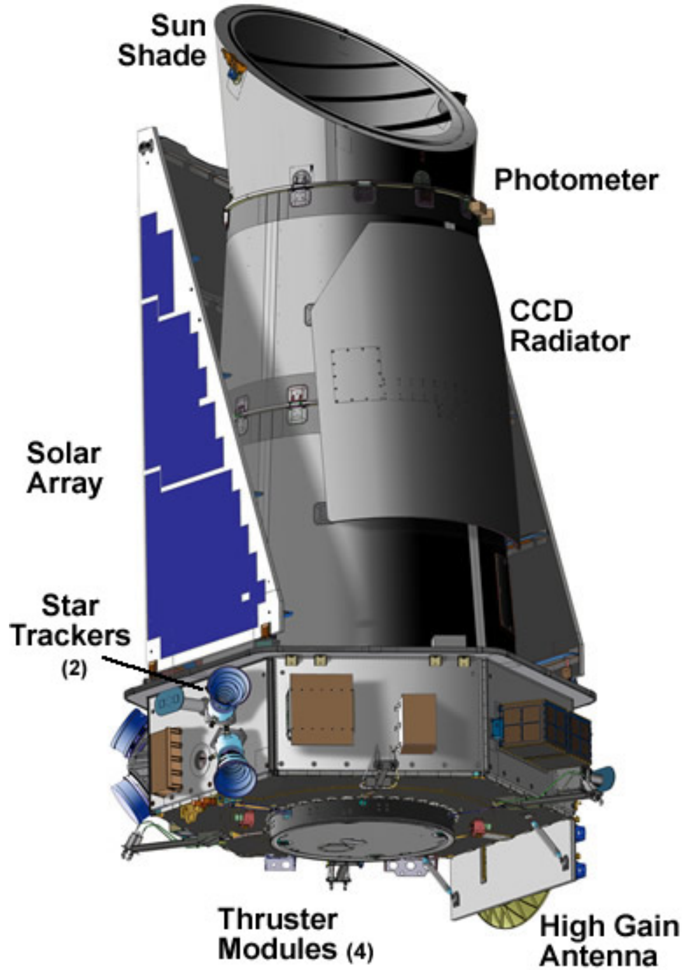
Space helio- and asteroseismology

Notable successes

Kepler

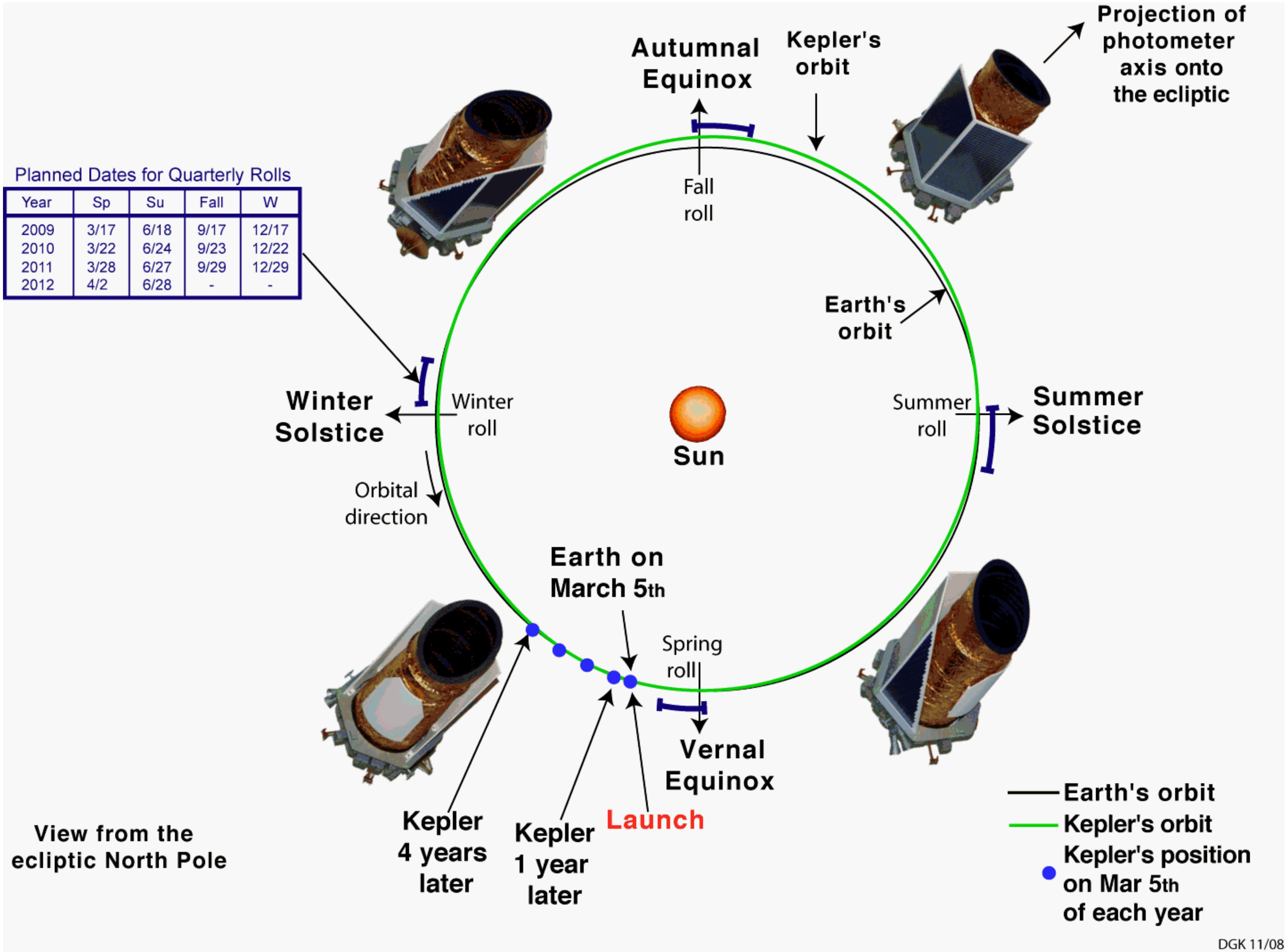
Goals of Kepler asteroseismology

- to provide support for the studies of extrasolar planetary systems by characterizing the central stars of the systems
- to perform in-depth asteroseismic investigations of a large number of stars, predominantly but not exclusively those showing solar-like oscillations.


Sun Shade
Photometer
CCD Radiator
Solar Array
Star Trackers (2)
Thruster Modules (4)
High Gain Antenna

Kepler launch

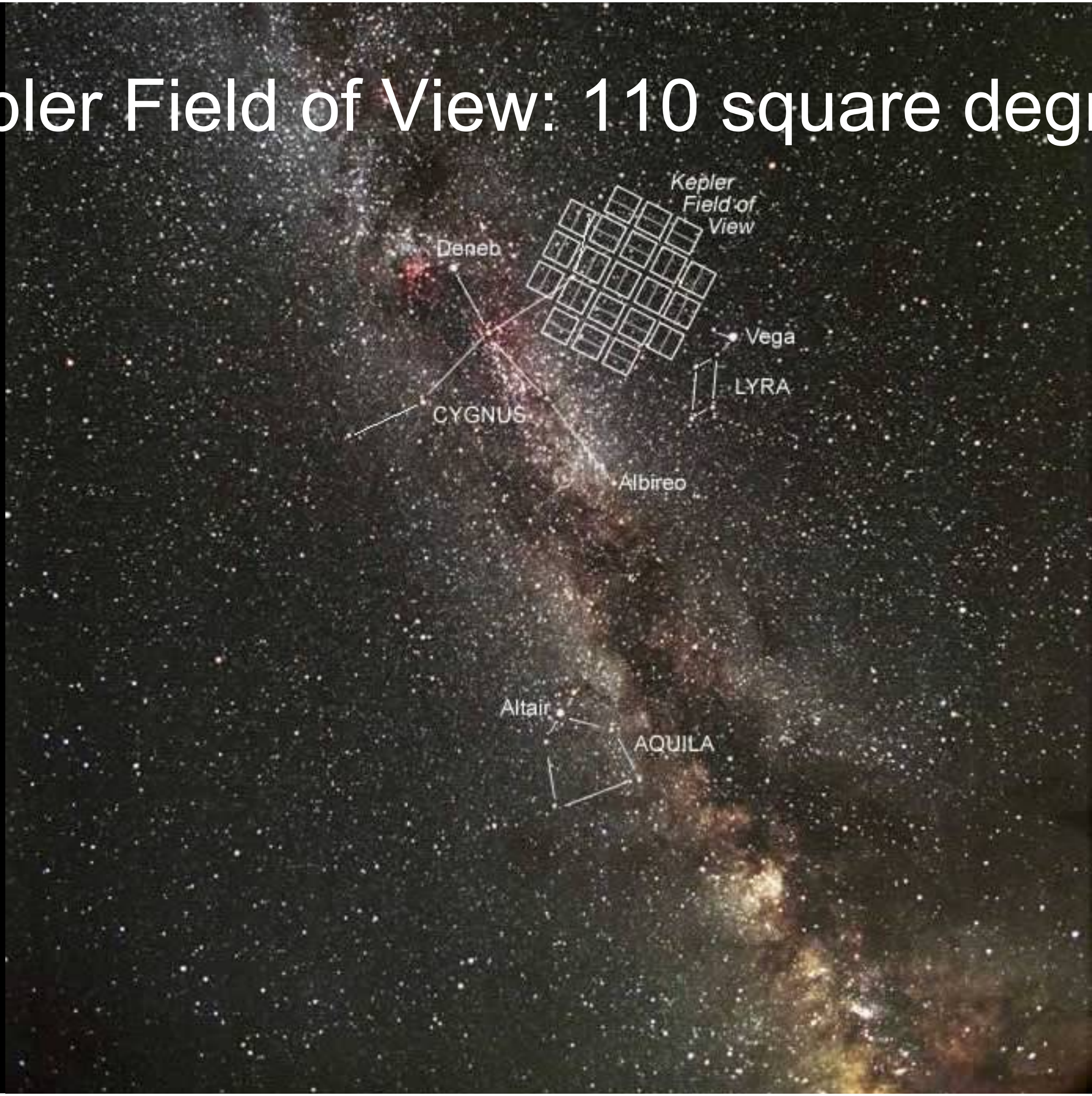
7 March 2009



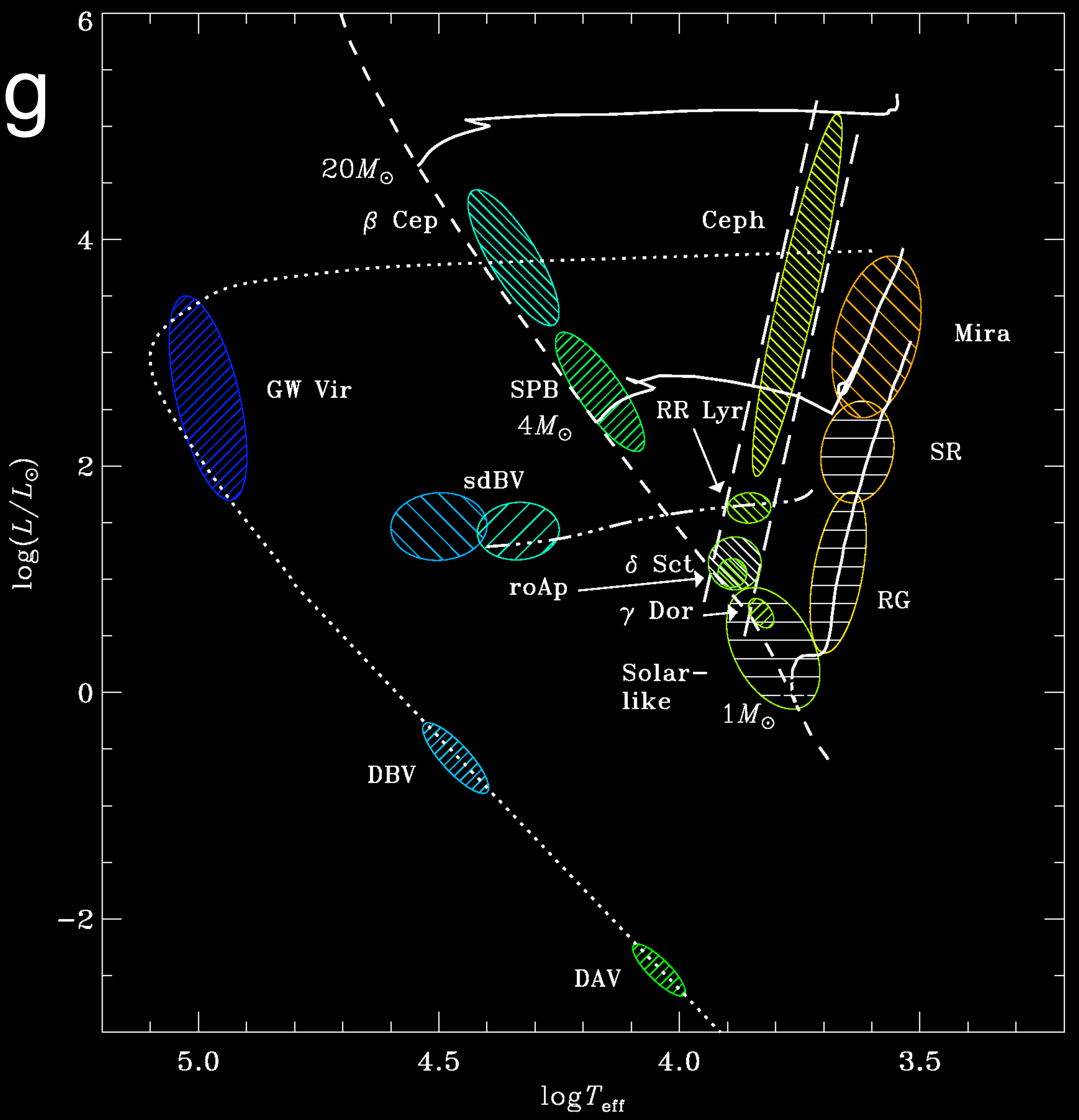
Planned Dates for Quarterly Rolls

Year	Sp	Su	Fall	W
2009	3/17	6/18	9/17	12/17
2010	3/22	6/24	9/23	12/22
2011	3/28	6/27	9/29	12/29
2012	4/2	6/28	-	-

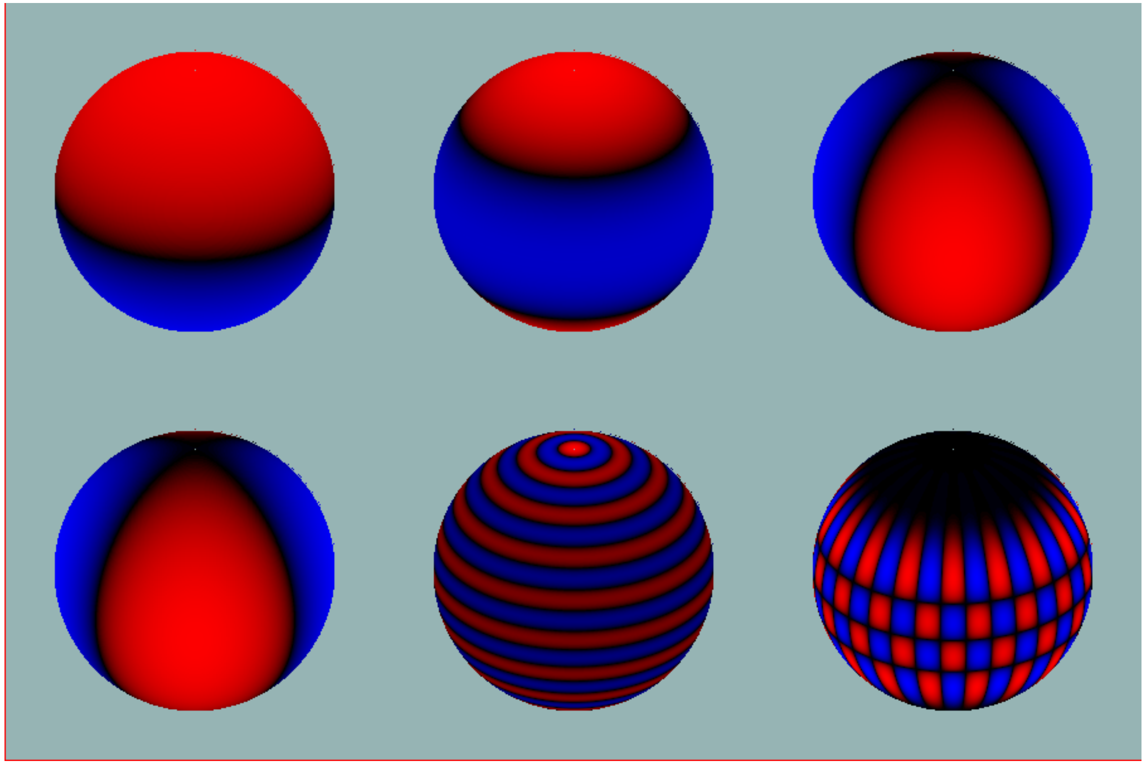
Kepler Field of View: 110 square degrees



The playing field



Basic properties of oscillations



Behave like spherical harmonics

$Y_l^m(\theta, \phi) e^{-i\omega t} \sim P_l^m(\cos\theta)\cos(m\phi - \omega t)$

$k_{\mathrm{h}} = 2\pi/\lambda = \sqrt{l(l+1)}/R$

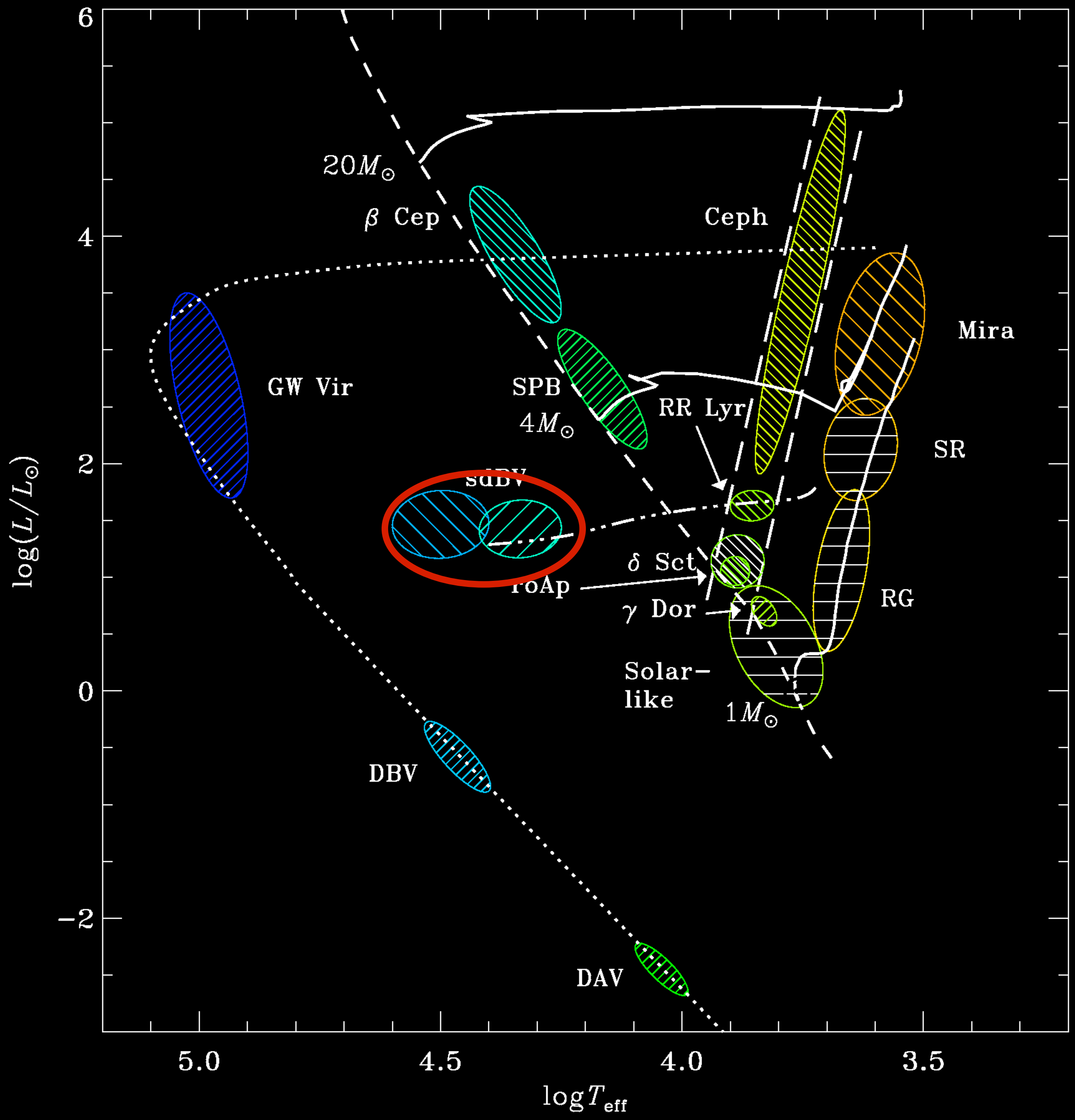
Types of stellar oscillations

- Acoustic modes (p modes)
  - Standing sound waves
  - Relatively high frequency
  - Depend mainly on sound speed
  - Extend to centre of star, at low degree
- g modes
  - Standing internal gravity waves
  - Relatively low frequency
  - Depend mainly on the buoyancy frequency, strongly sensitive to composition profile

Subdwarf B stars

Core He burning

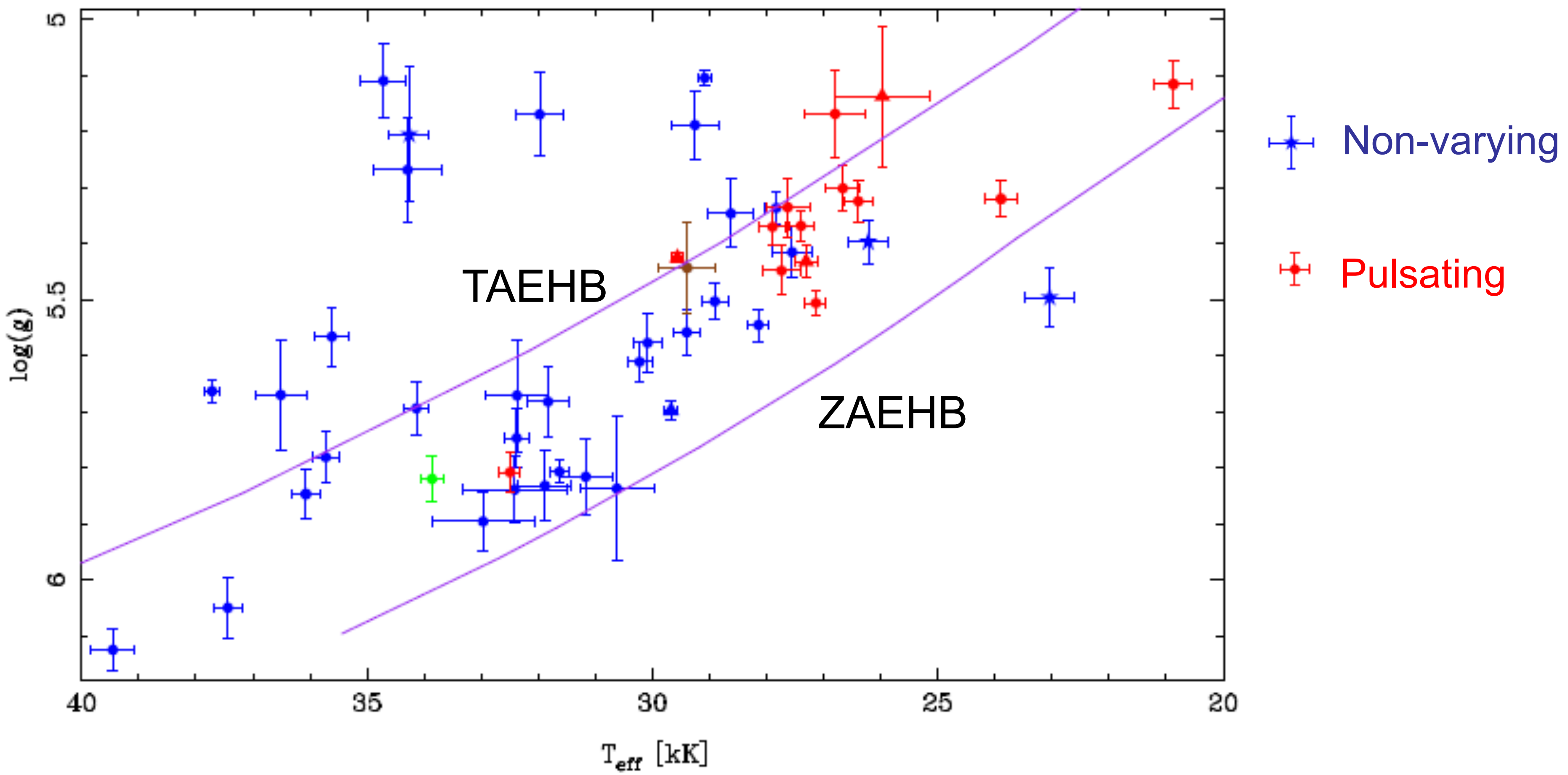
Extreme mass loss after red-giant phase



Subdwarf B stars

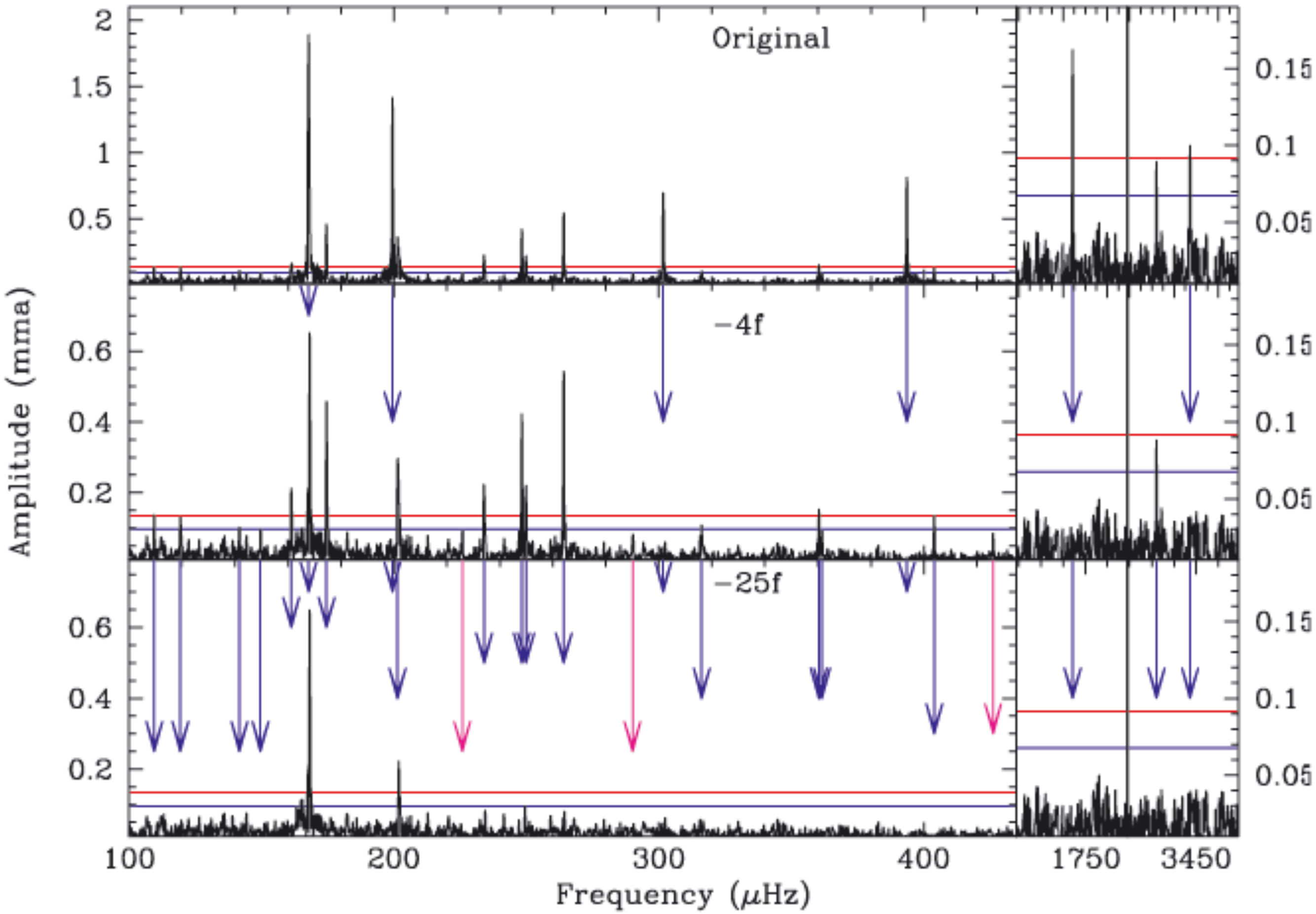
- Extreme horizontal branch stars, very thin envelope
- Core helium burning
- Two types of pulsating sdB stars:
  - Short-period (V362 Hya stars): 100 – 600 s
  - Long-period (V1093 Her stars): 1 – 2 h
- 14 found with Kepler, almost all long period

Kepler survey



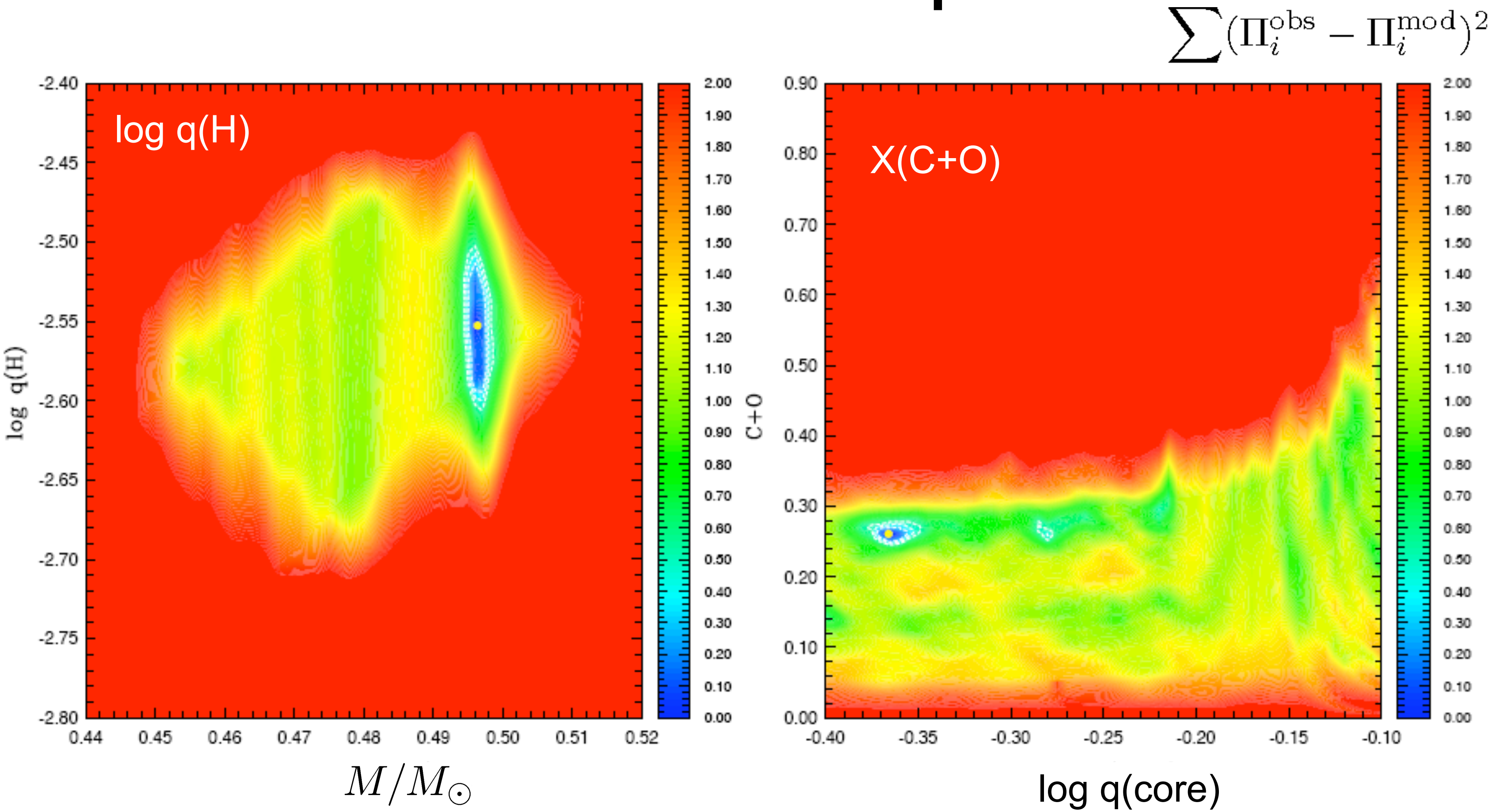
Østensen et al. (2011; MNRAS, in the press)

g modes in a subdwarf B star



Reed et al. (2010; MNRAS 409, 1496)

Fit to observed periods



Van Grootel et al. (2010; ApJ 718, L97)

Stellar parameters

Quantity	Estimated Value
$T_{\rm eff}$ (K)	27730 ± 270[a]
	28050 ± 470[b]
$\log g$	5.552 ± 0.041[a]
	5.52 ± 0.03[b]
$M_*/M_\odot$	0.496 ± 0.002
$\log(M_{\rm env}/M_*)$	-2.55 ± 0.07
$\log(1 - M_{\rm cc}/M_*)$	-0.37 ± 0.01
$M_{\rm cc}/M_\odot$	0.28 ± 0.01
$X_{\rm core}$(C+O)	0.261 ± 0.008
Age (Myr)	18.4 ± 1.0[c]
$R/R_\odot$ (M_*, g)	0.203 ± 0.007
$L/L_\odot$ ($T_{\rm eff}$, R)	22.9 ± 3.1
M_V (g, $T_{\rm eff}$, M_*)	4.21 ± 0.11
$E(B - V)$	0.094 ± 0.017
d (V, M_V) (pc)	1180 ± 95

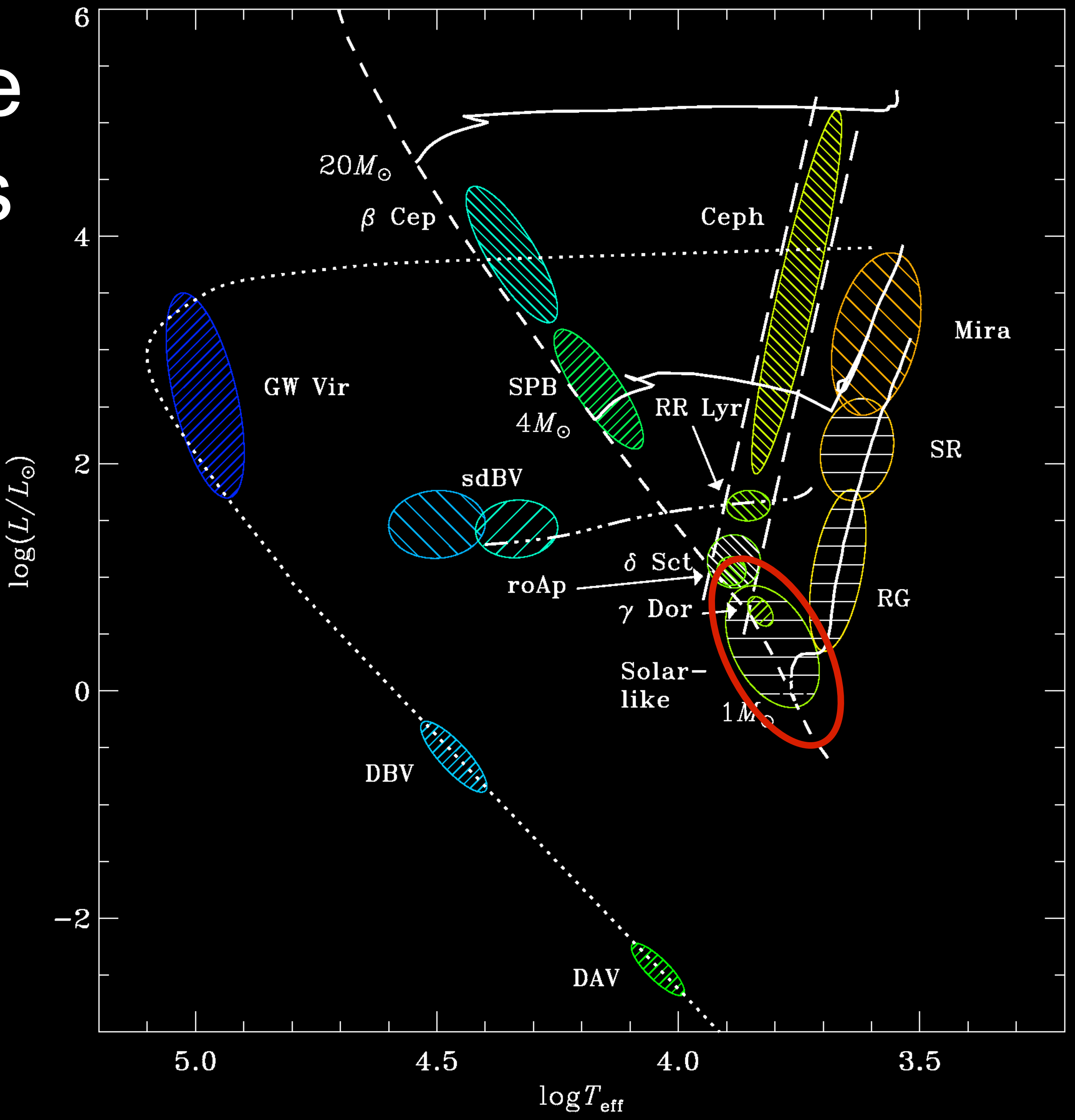
[a]From spectroscopy

[b]From asteroseismology

[c]Since Zero-Age EHB

Van Grootel et al. (2010; ApJ 718, L97)

Solar-like MS stars



Asymptotics of p modes

$$\nu_{nl} \sim \Delta\nu \left(n + \frac{l}{2} + \alpha \right) + \epsilon_{nl}$$

where

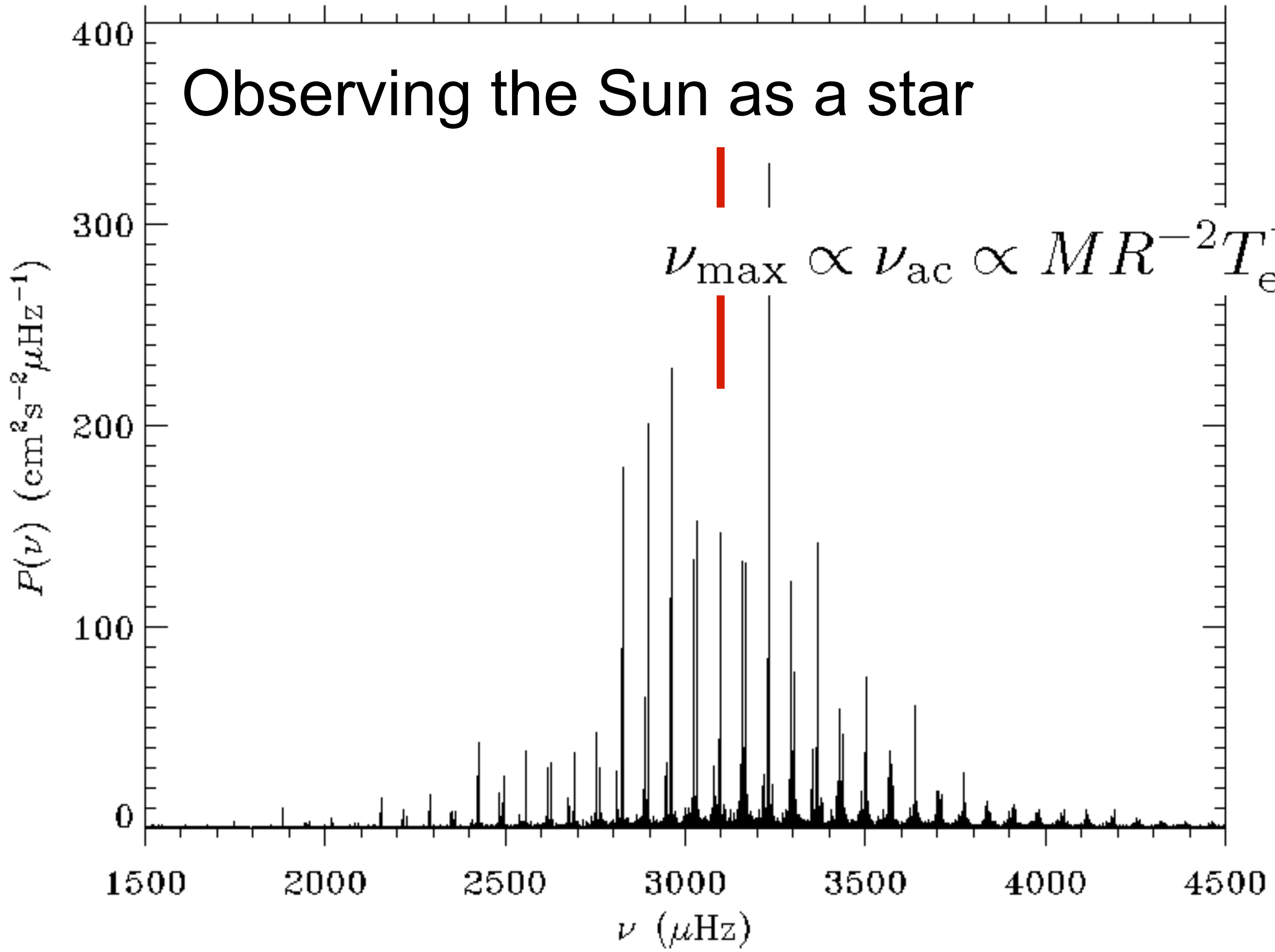
$$\Delta\nu = \left[2 \int_0^R \frac{\mathrm{d}r}{c} \right]^{-1}$$

$\alpha = \alpha(\nu)$ depends on surface properties.

Large frequency separation:

$$\Delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l} \simeq \Delta\nu$$

odes



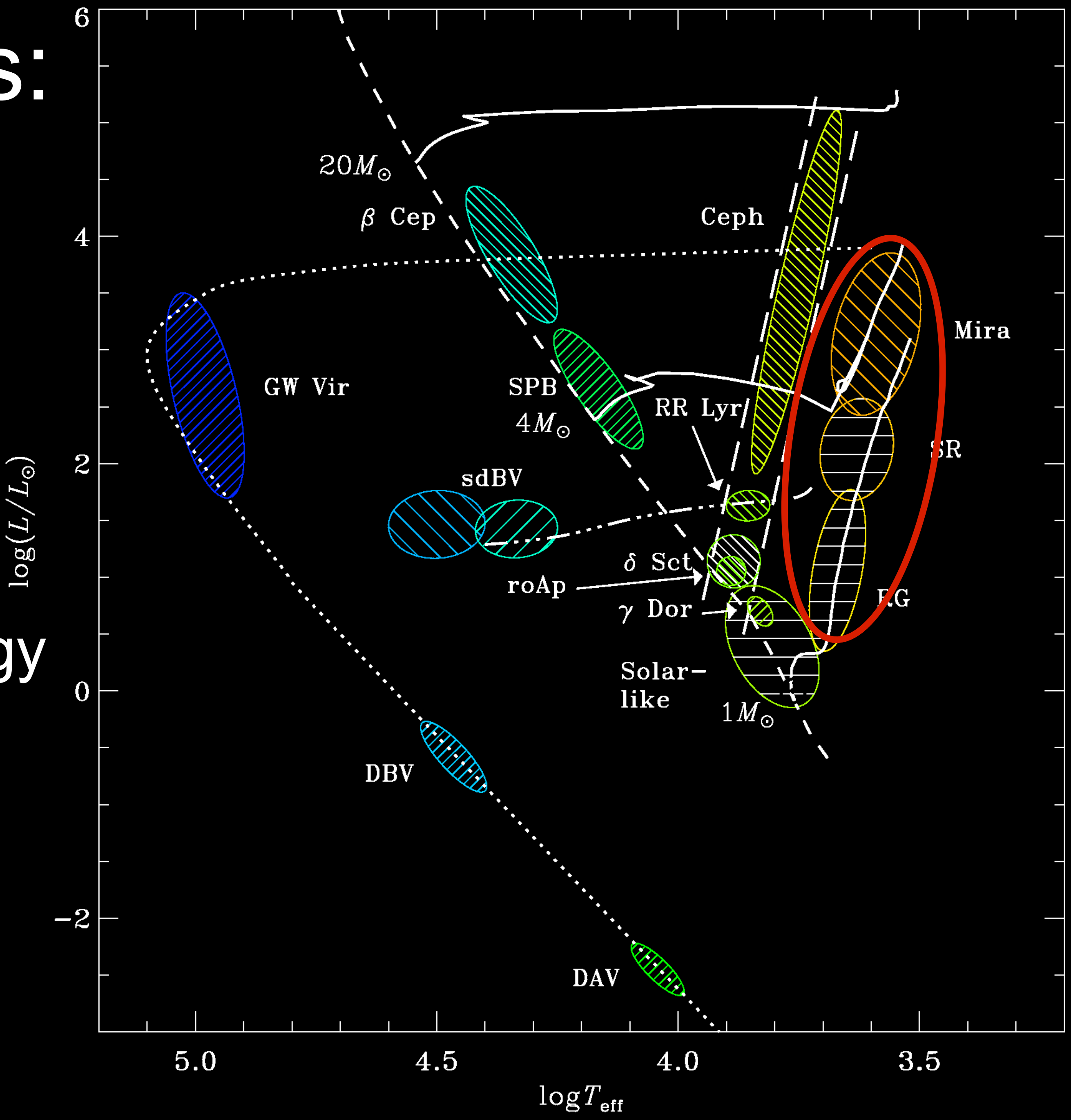
$$\nu_{\rm max} \propto \nu_{\rm ac} \propto M R^{-2} T_{\rm eff}^{-1/2}$$

Large frequency separation:

$$\Delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l} \simeq \Delta\nu \propto \langle\rho\rangle^{1/2} \propto (M/R^3)^{1/2}$$

Red giants:

high points of space asteroseismology



A prediction

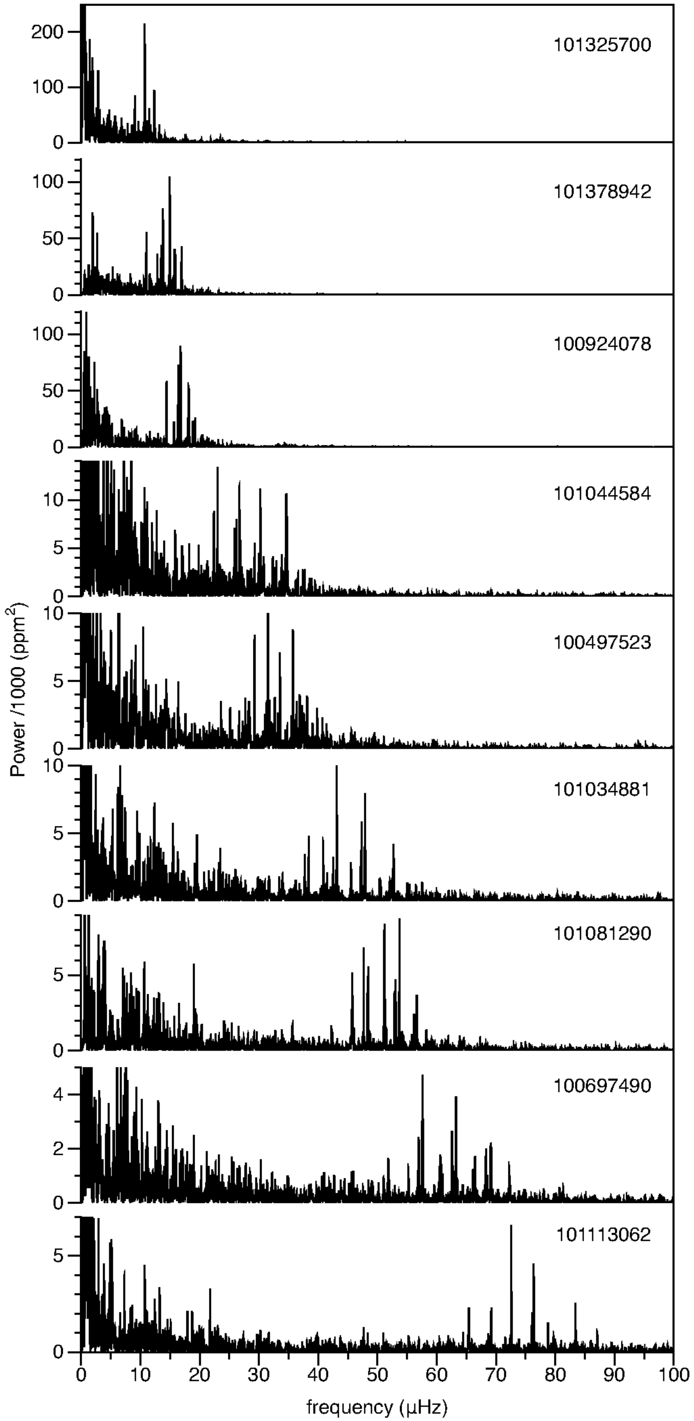
TABLE III

Properties of oscillations of envelope models. The relation between mass and luminosity is derived from Iben's (1964) evolution calculations. The notation is as in Table I.

$M/M_\odot$	$L/L_\odot$	T_{eff}	$v_{s,\max}$ (km s^{-1})	$(\delta L_s/L_s)_{\max}$	$\Pi_{\max}$ (days)	$\Delta\nu$ (μHz)
5	10^3	6800	0.014	1.1×10^{-4}	0.32	2.65
–	–	5770	0.015	1.7×10^{-4}	0.56	1.82
–	–	5000	0.021	3.1×10^{-4}	3.5	1.13
–	–	4500	0.015	3.6×10^{-4}	1.2	0.75

It is worth pointing out that observations of this type of oscillations might also be useful in the study of stellar convection. The calculation of the oscillation amplitudes resulting from a given convective velocity field is probably considerably simpler than a direct computation of the convective velocities.

Christensen-Dalsgaard & Frandsen (1983; Proc. 66th IAU Colloq., eds Gough & Toomre, Solar Phys. 82, 469)

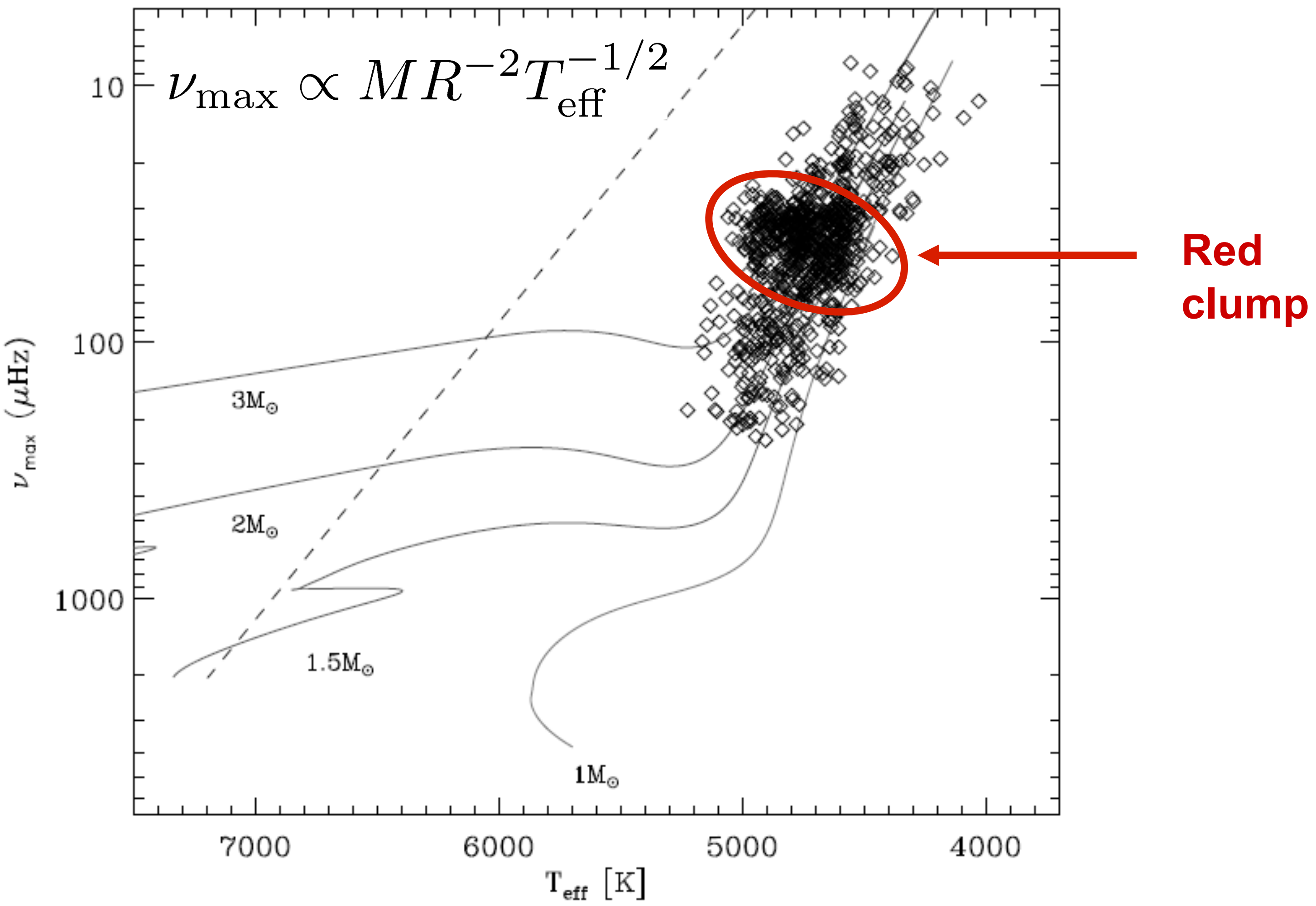


Nonradial oscillations in red giants

$$\nu_{\max} \propto M R^{-2} T_{\text{eff}}^{-1/2}$$

De Ridder et al. (2009; Nature 459, 398)
CoRoT observations

A HR diagram in terms of ν_{max}



Huber et al. (2010)

Diagnostics of stellar global properties

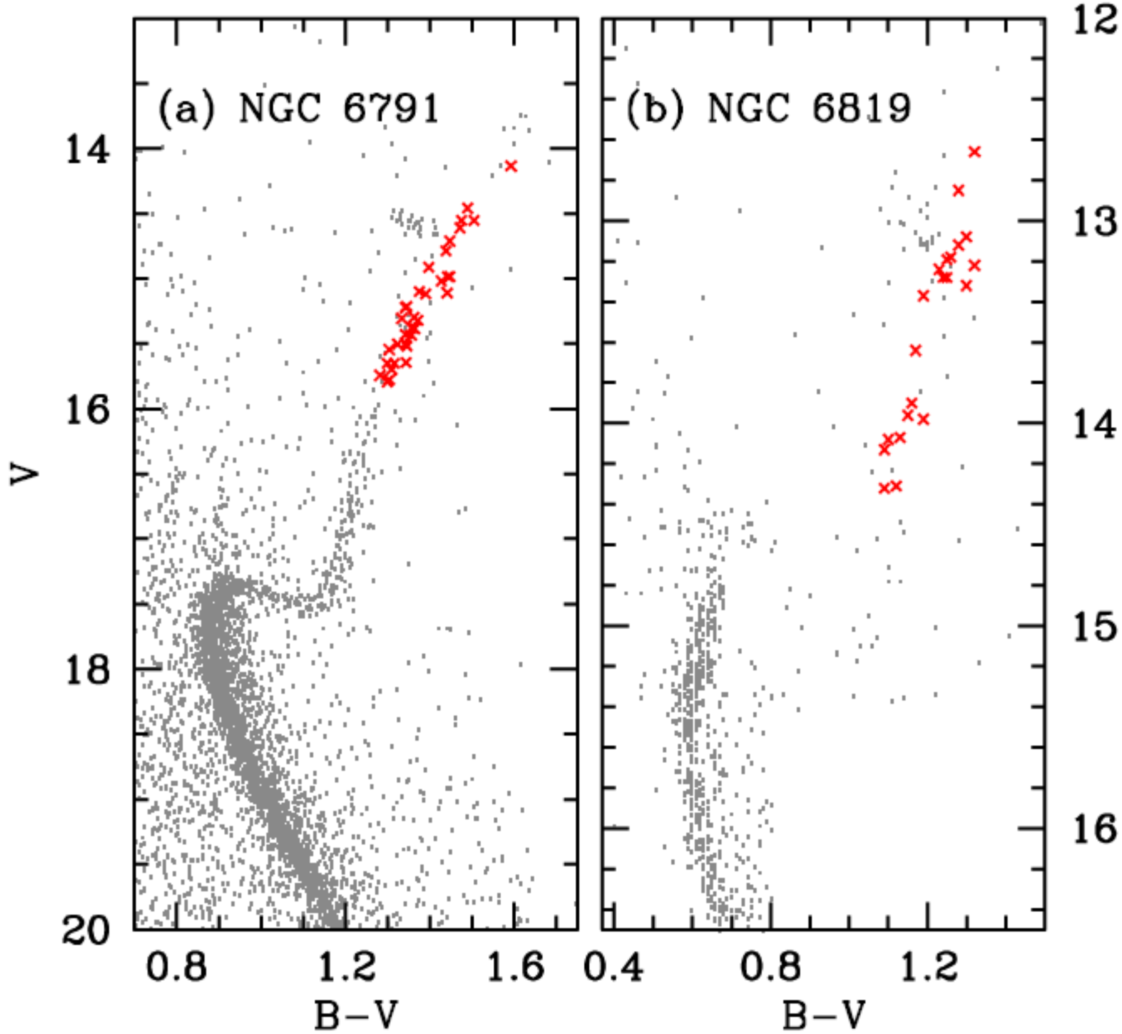
- From

$$\Delta\nu_{nl} \propto (M/R^3)^{1/2}$$

$$\nu_{\max} \propto MR^{-2}T_{\text{eff}}^{-1/2}$$

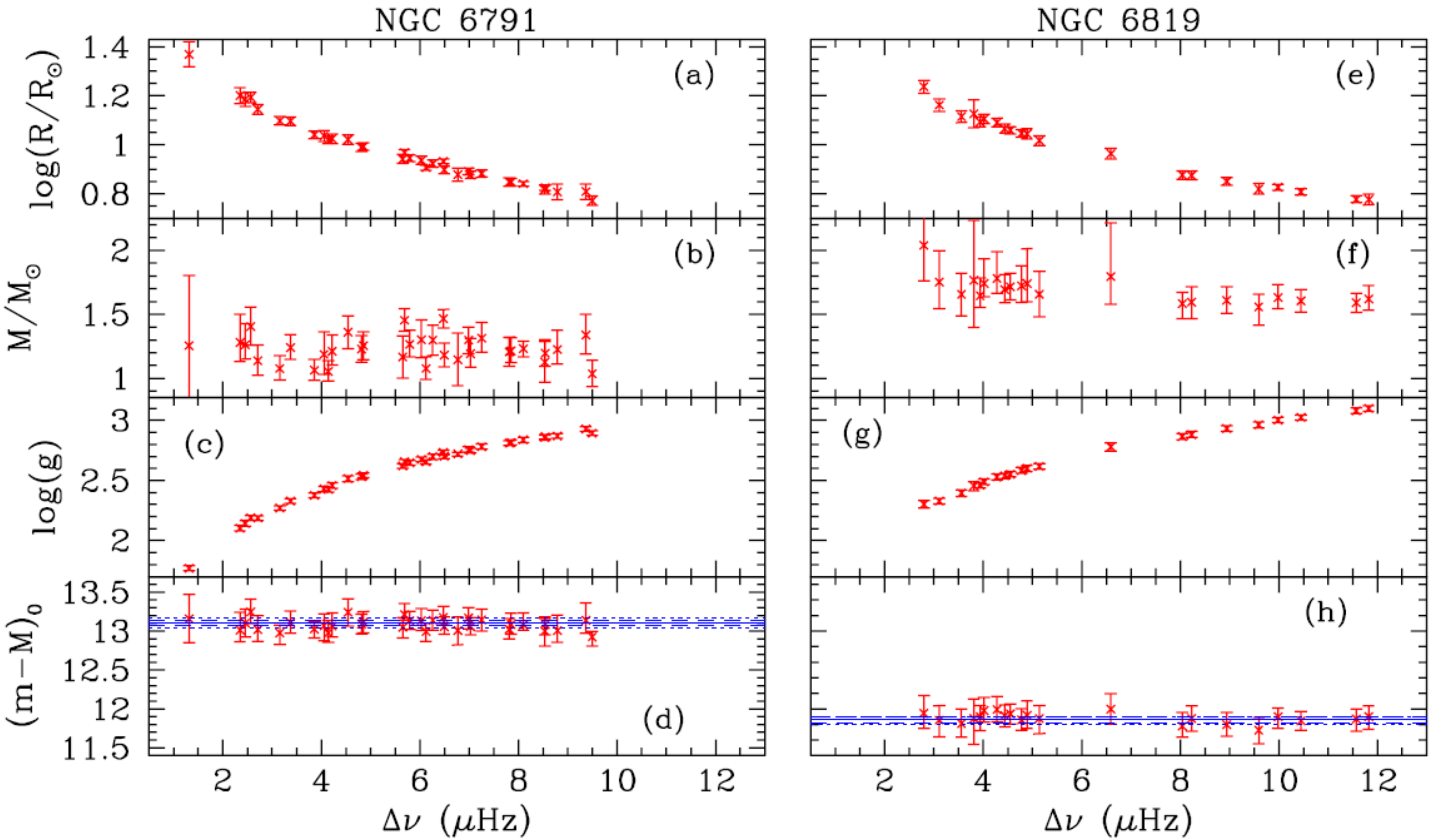
- and observed T_{eff} determine
- **M and R**
- With modelling, determine in addition
- **age**

Kepler open clusters



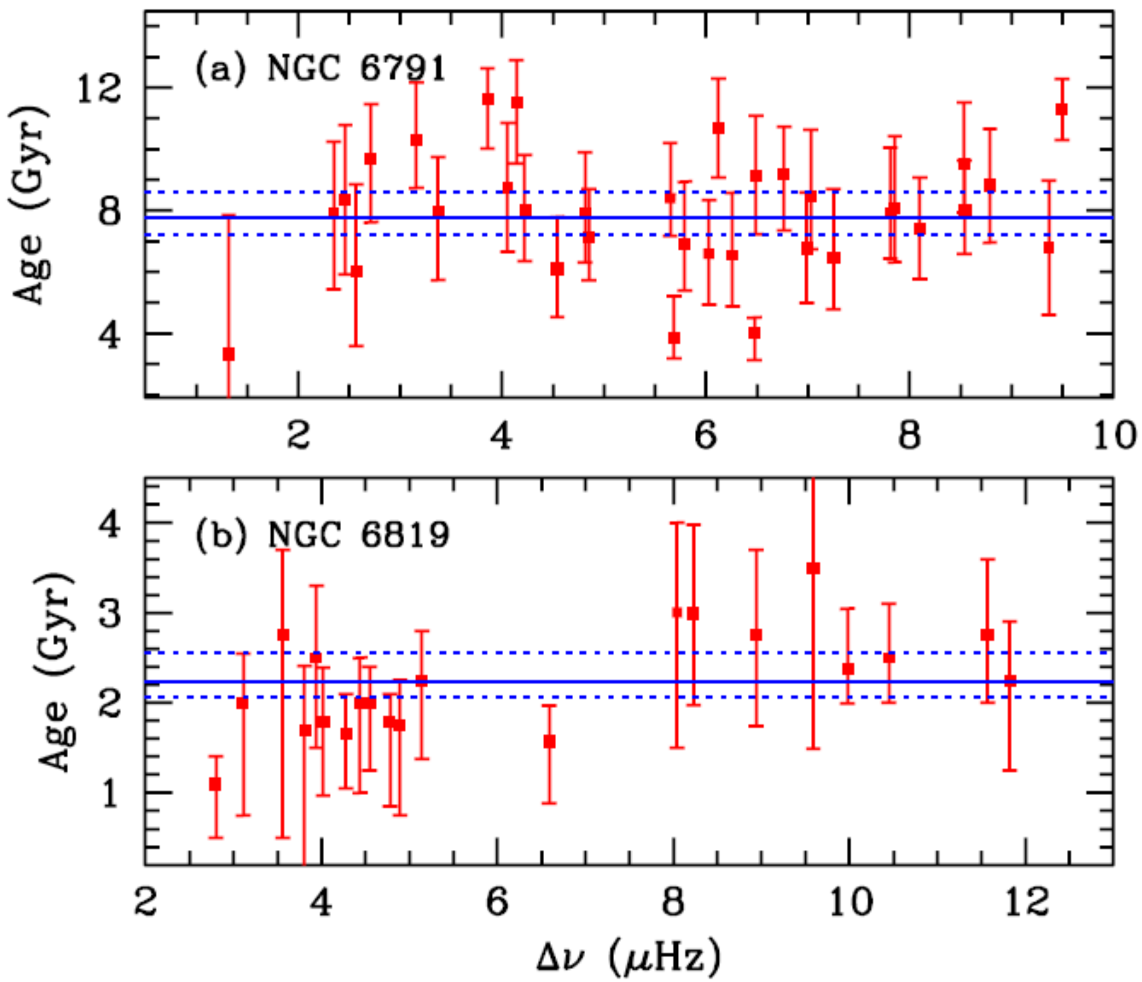
Basu et al. (2011; ApJ 729, L10)

Kepler open clusters



Basu et al. (2011; ApJ 729, L10)

Kepler open clusters



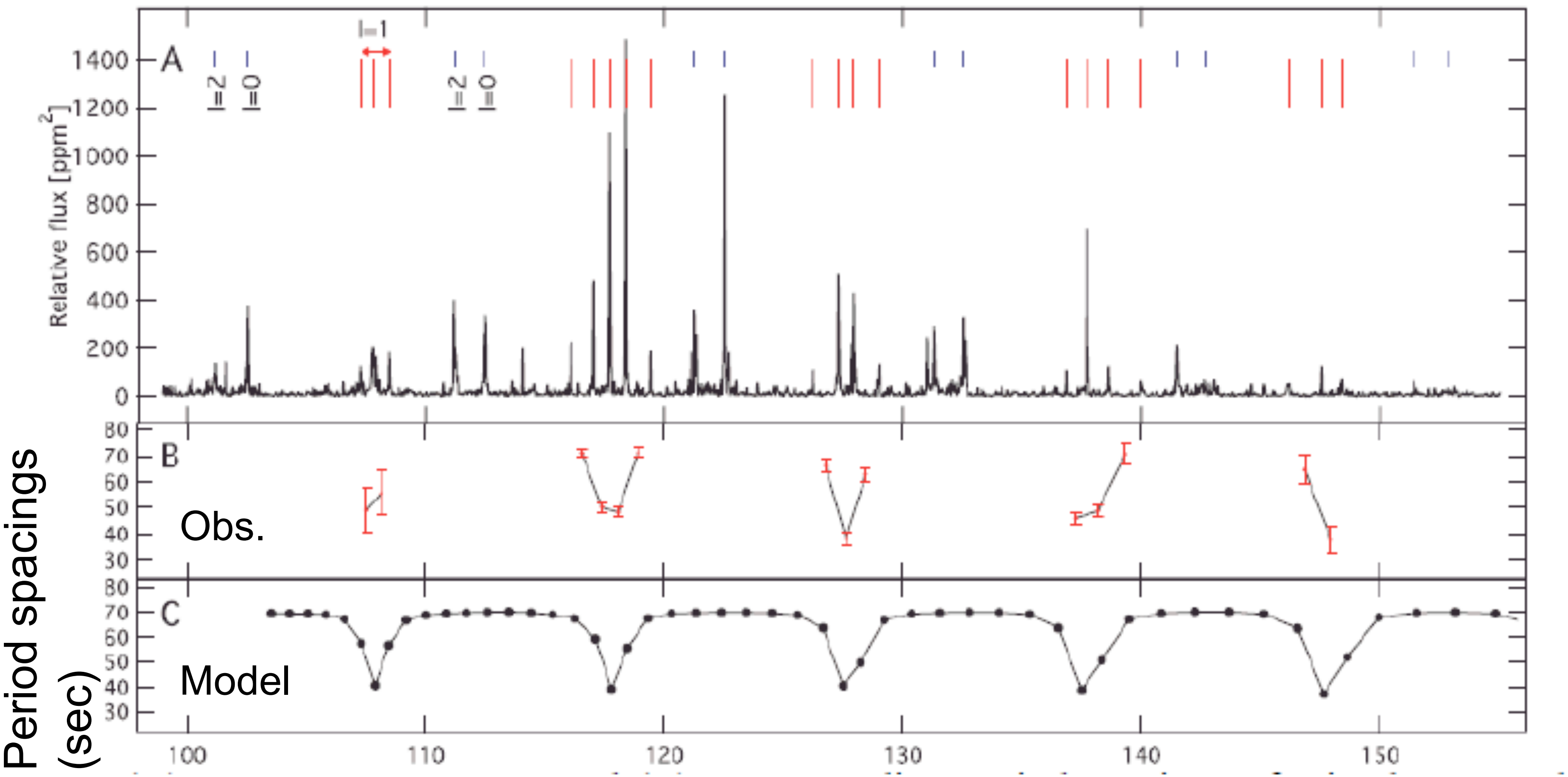
Basu et al. (2011; ApJ 729, L10)

Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star

P. G. Beck,[1*] T. R. Bedding,[2] B. Mosser,[3] D. Stello,[2] R. A. García,[4] T. Kallinger,[5] S. Hekker,[6,7] Y. Elsworth,[6] S. Frandsen,[7] F. Carrier,[1] J. De Ridder,[1] C. Aerts,[1,9] T. R. White,[2] D. Huber,[2] M.-A. Dupret,[10] J. Montalbán,[10] A. Miglio,[10] A. Noels,[10] W. J. Chaplin,[6] H. Kjeldsen,[8] J. Christensen-Dalsgaard,[8] R. L. Gilliland,[11] T. M. Brown,[12] S. D. Kawaler,[13] S. Mathur,[14] J. M. Jenkins[15]

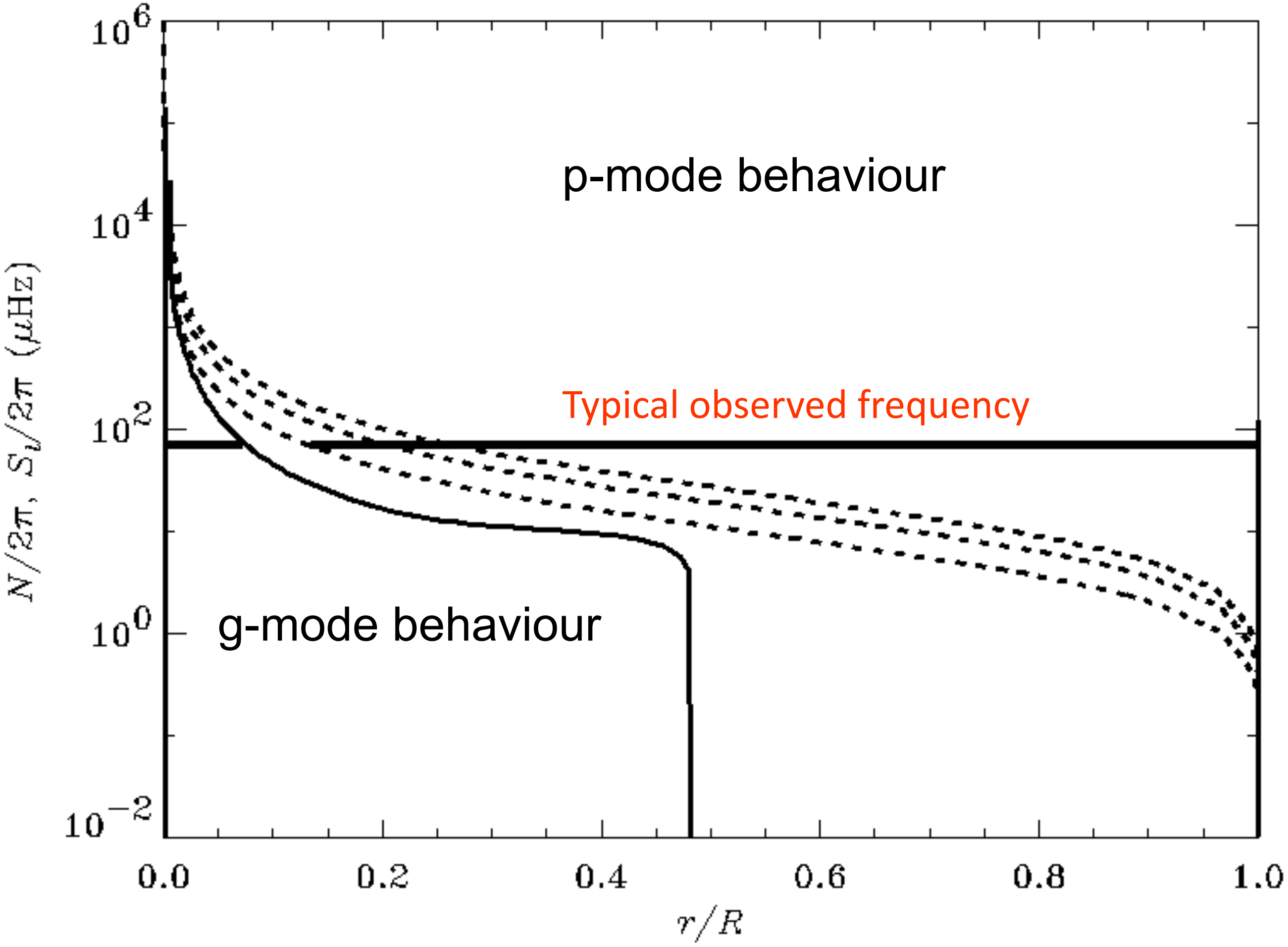
Beck et al.
Science (2011; 332, 205)

Kepler observations



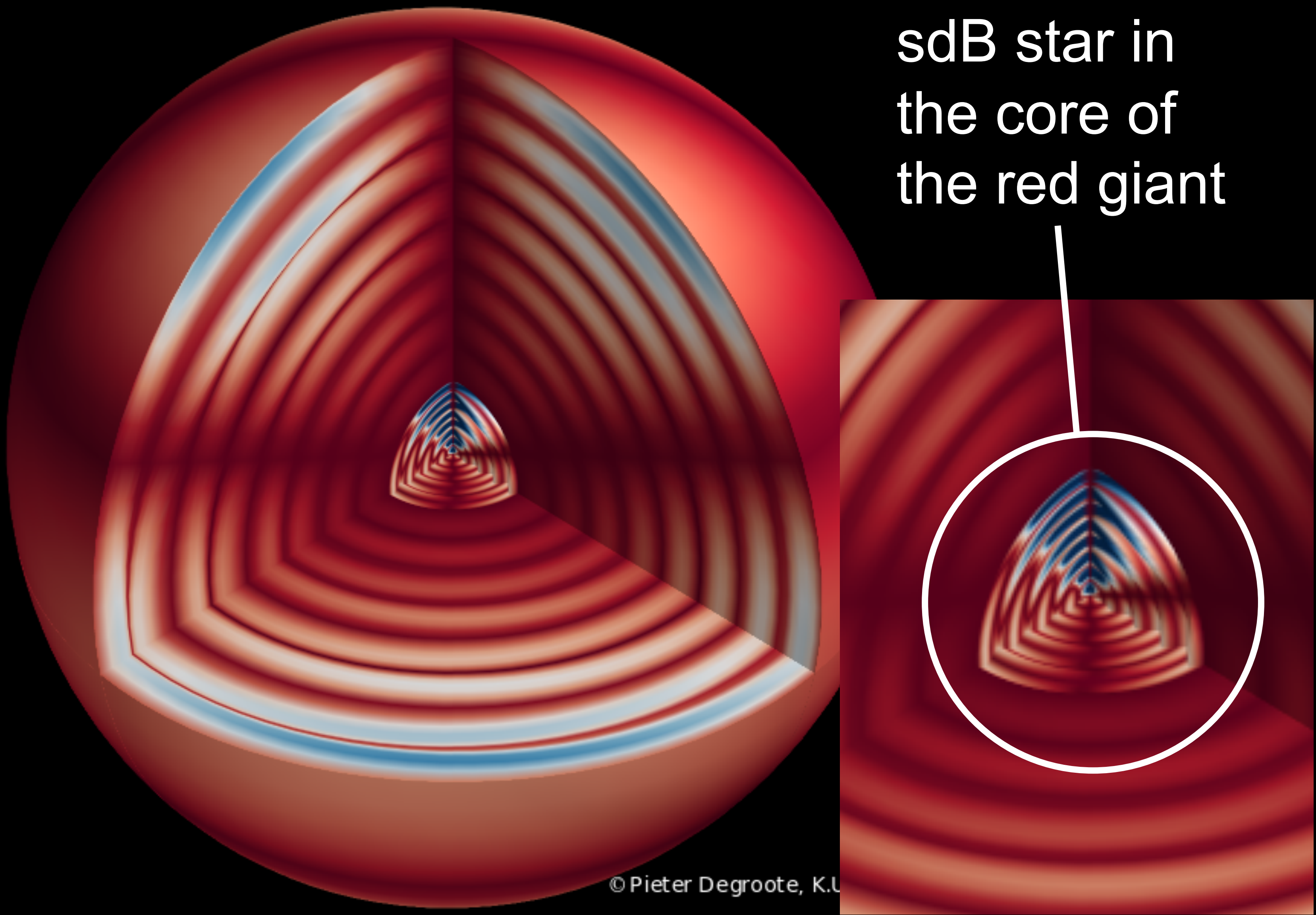
Beck et al. (2011; Science 332, 205)

Mode trapping

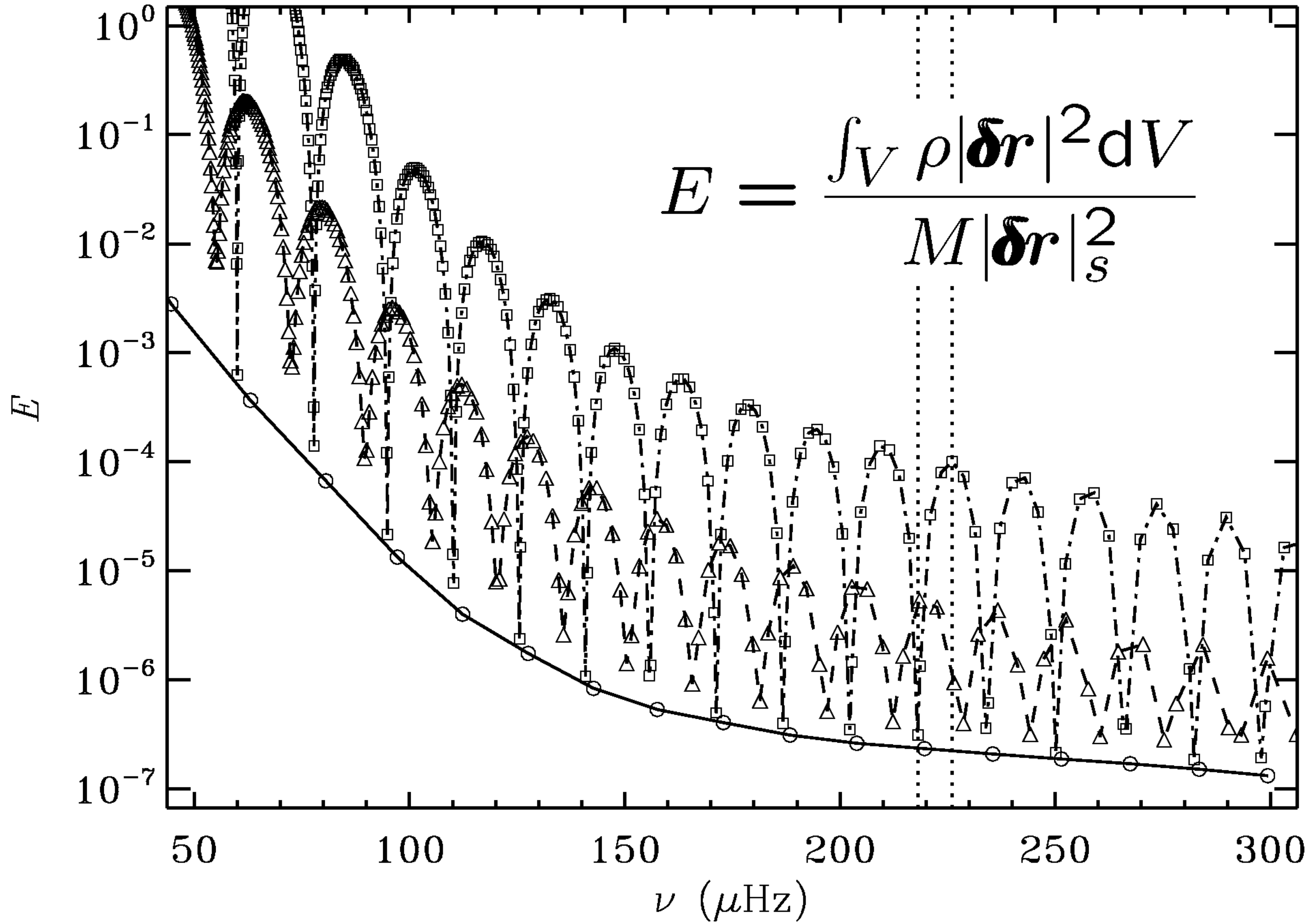


Two types of modes in one star

An sdB star in the core of a red giant



Mode inertia

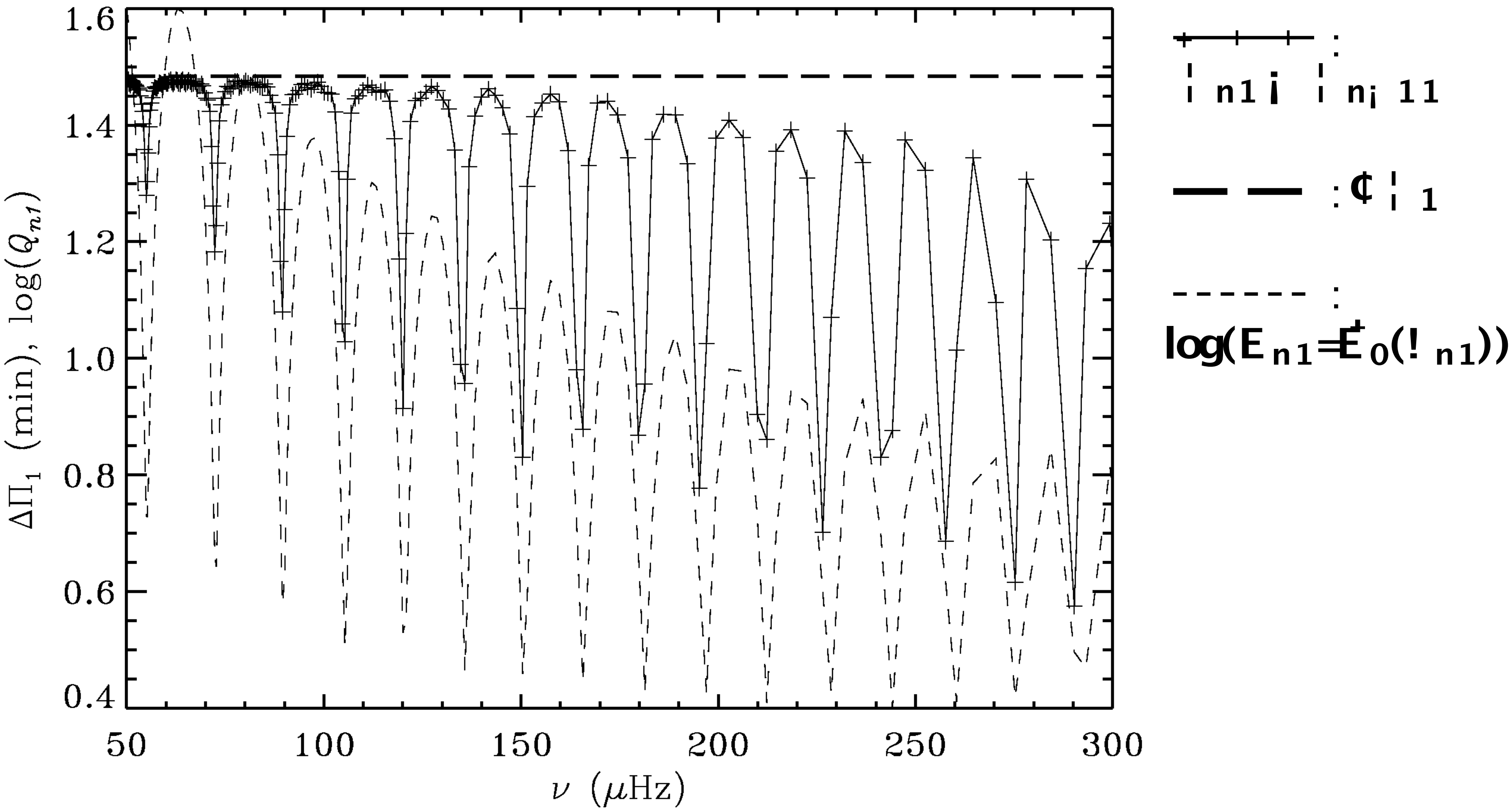


g-mode period spacings

$$P_n = \frac{\Pi_0}{L}(n + \epsilon) \ , \qquad L = \sqrt{l(l+1)}$$

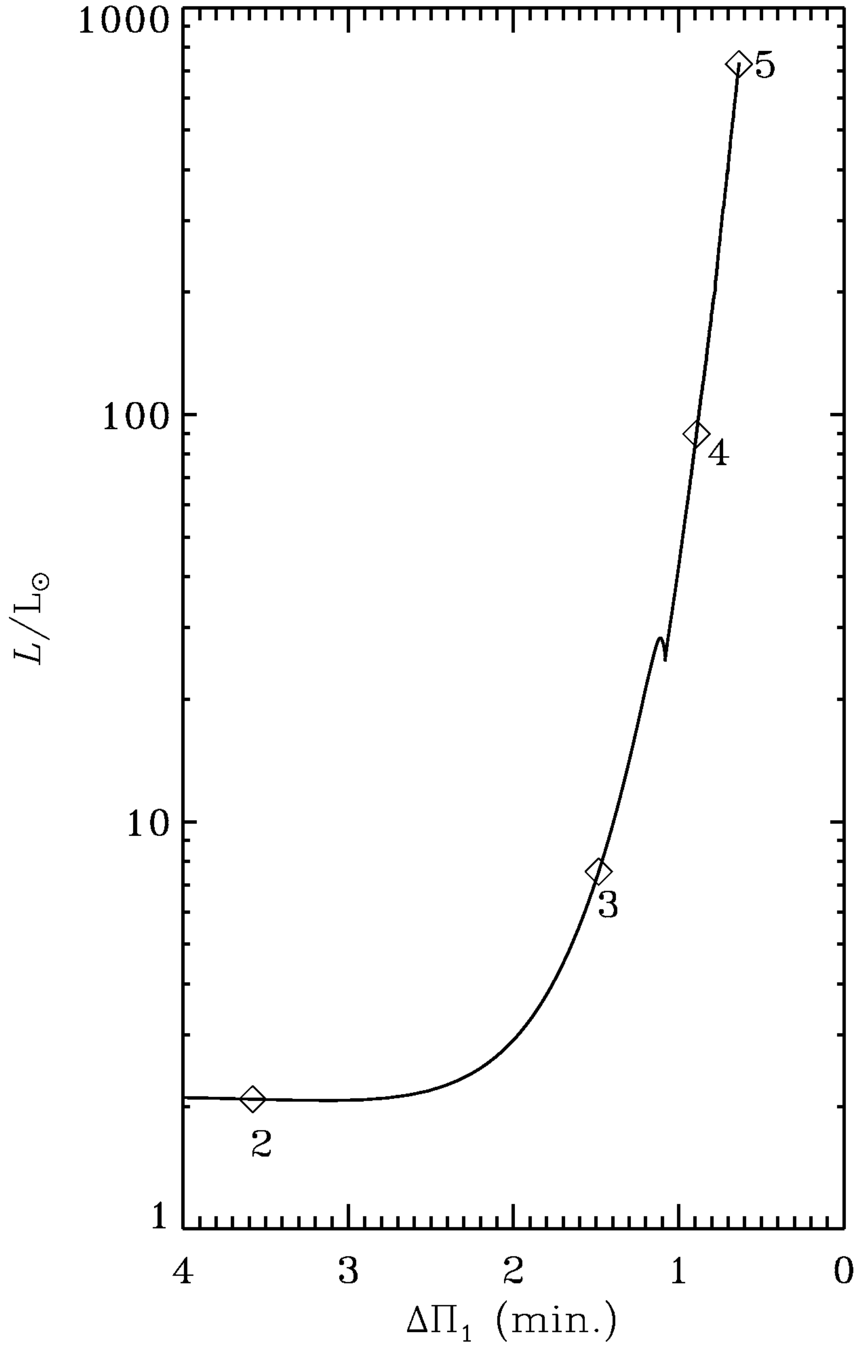
$$\Pi_0 = 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r} \right)^{-1}$$

1 M–, 8 L–



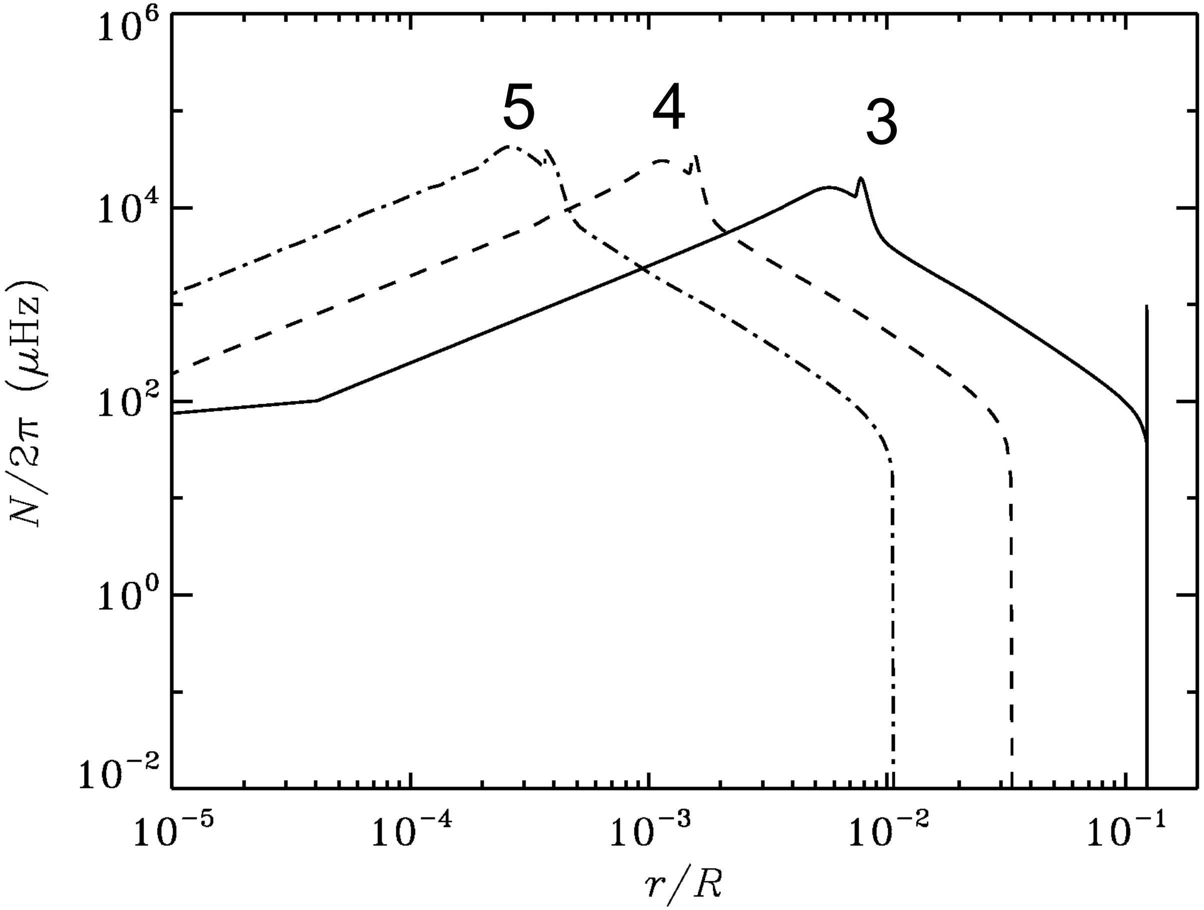
$\Delta\Pi_1$ (min), $\log(Q_{n1})$
ν (μHz)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
50
100
150
200
250
300
log(E n1=E 0(! n1))

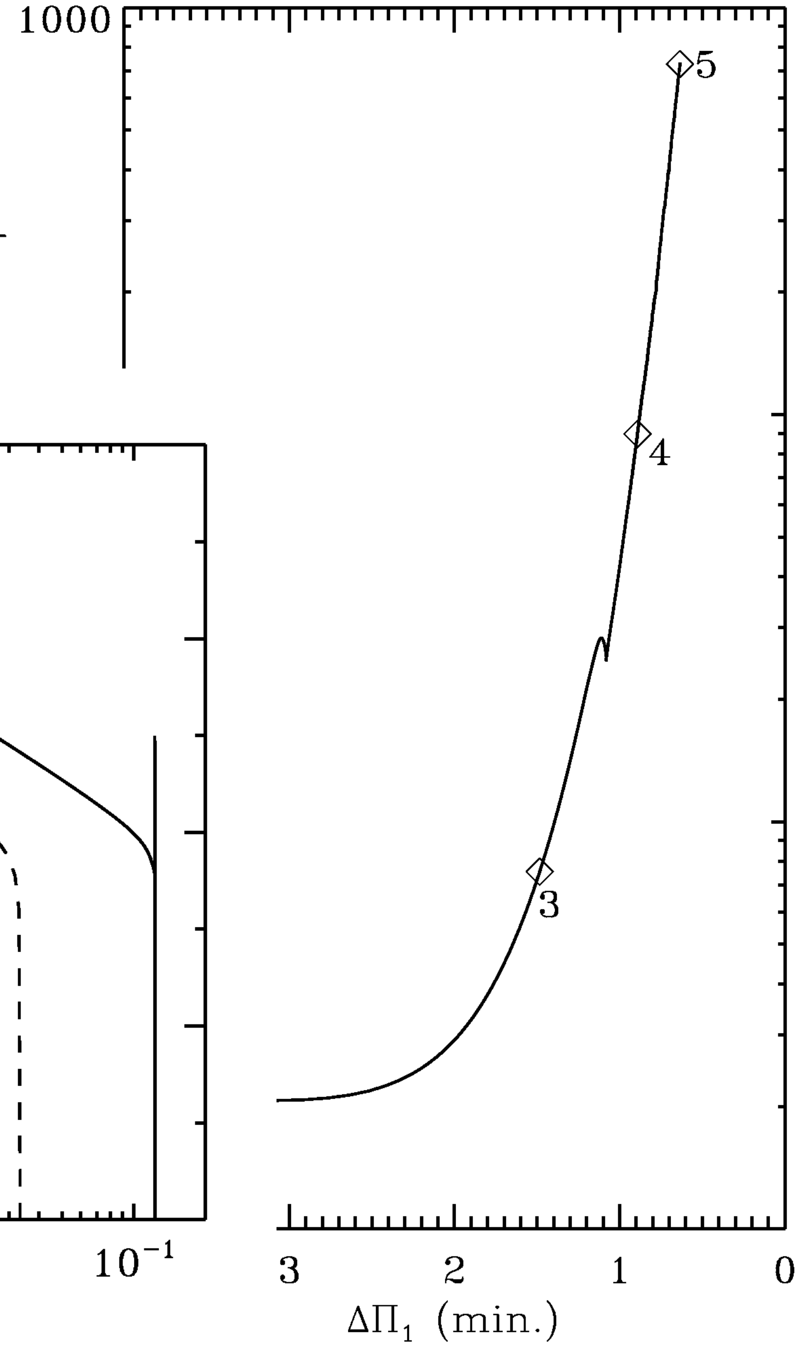
Asymptotic ¢ ¦$_1$ 1 M–



Asymptotic ¢ ¦1

$$\Delta\Pi_1 = \sqrt{2}\pi^2 \left(\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r} \right)^{-1}$$





LETTER

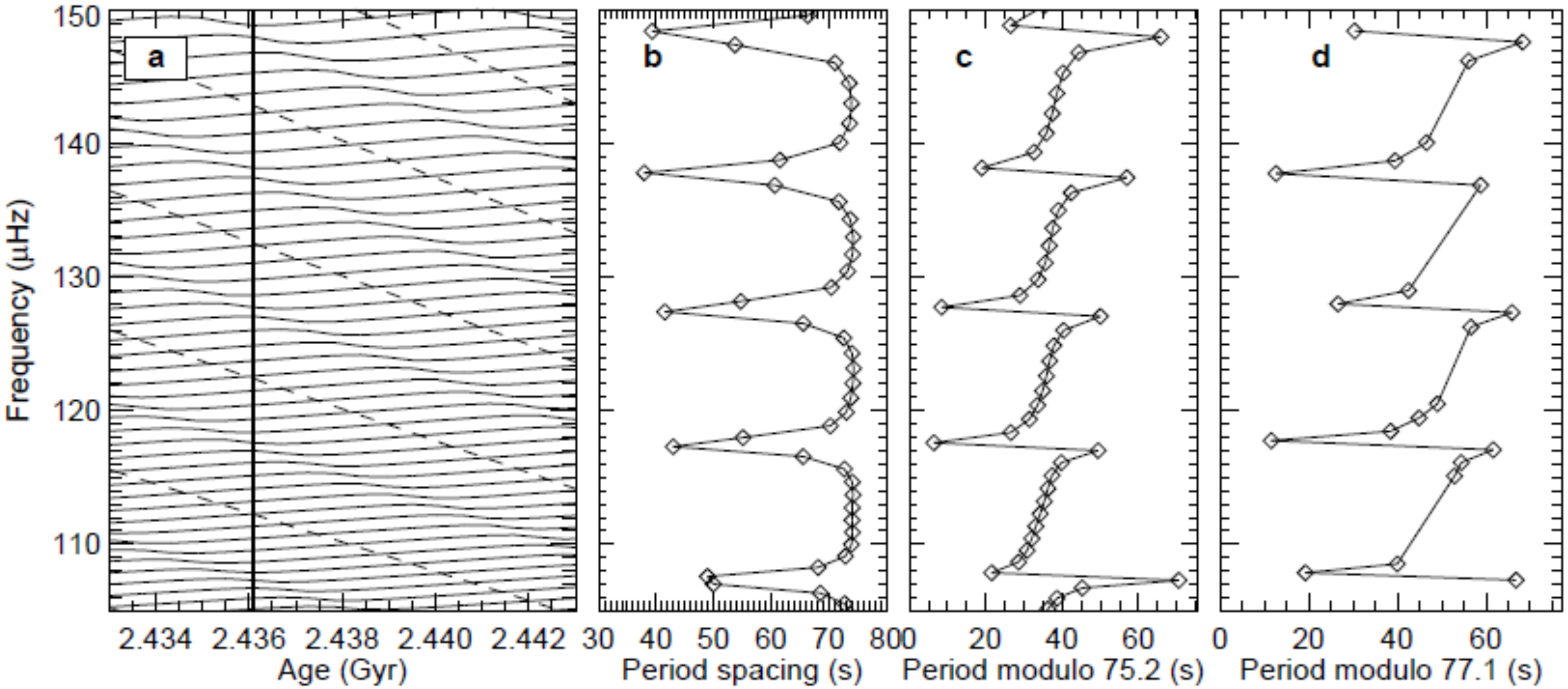
doi:10.1038/nature09935

Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

Timothy R. Bedding[1], Benoit Mosser[2], Daniel Huber[1], Josefina Montalbán[3], Paul Beck[4], Jørgen Christensen-Dalsgaard[5], Yvonne P. Elsworth[6], Rafael A. García[7], Andrea Miglio[3,6], Dennis Stello[1], Timothy R. White[1], Joris De Ridder[4], Saskia Hekker[6,8], Conny Aerts[4,9], Caroline Barban[2], Kevin Belkacem[10], Anne-Marie Broomhall[6], Timothy M. Brown[11], Derek L. Buzasi[12], Fabien Carrier[4], William J. Chaplin[6], Maria Pia Di Mauro[13], Marc-Antoine Dupret[3], Søren Frandsen[5], Ronald L. Gilliland[14], Marie-Jo Goupil[2], Jon M. Jenkins[15], Thomas Kallinger[16], Steven Kawaler[17], Hans Kjeldsen[5], Savita Mathur[18], Arlette Noels[3], Victor Silva Aguirre[19] & Paolo Ventura[20]

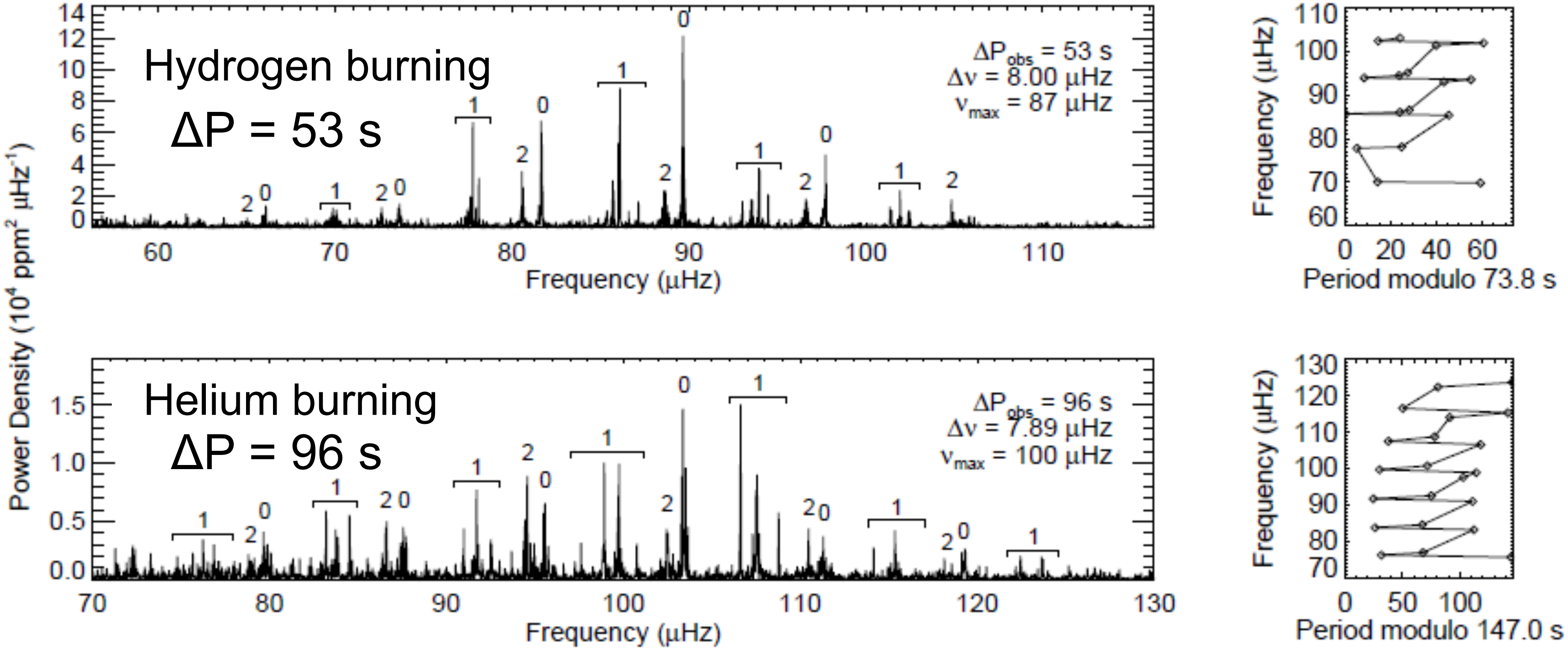
Bedding et al. (Nature, 2011, 471, 608)

Red-giant model



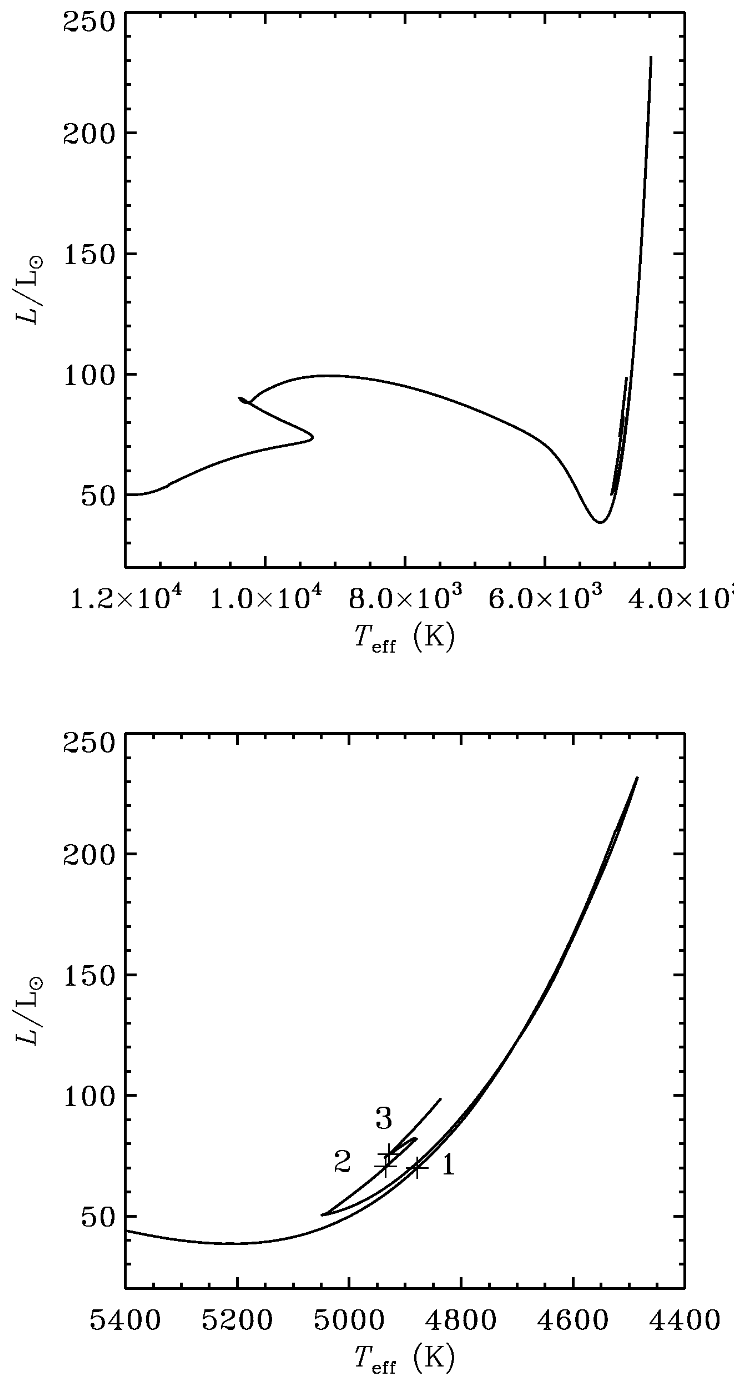
Bedding et al. (Nature, 2011, 471, 608)

Kepler observations

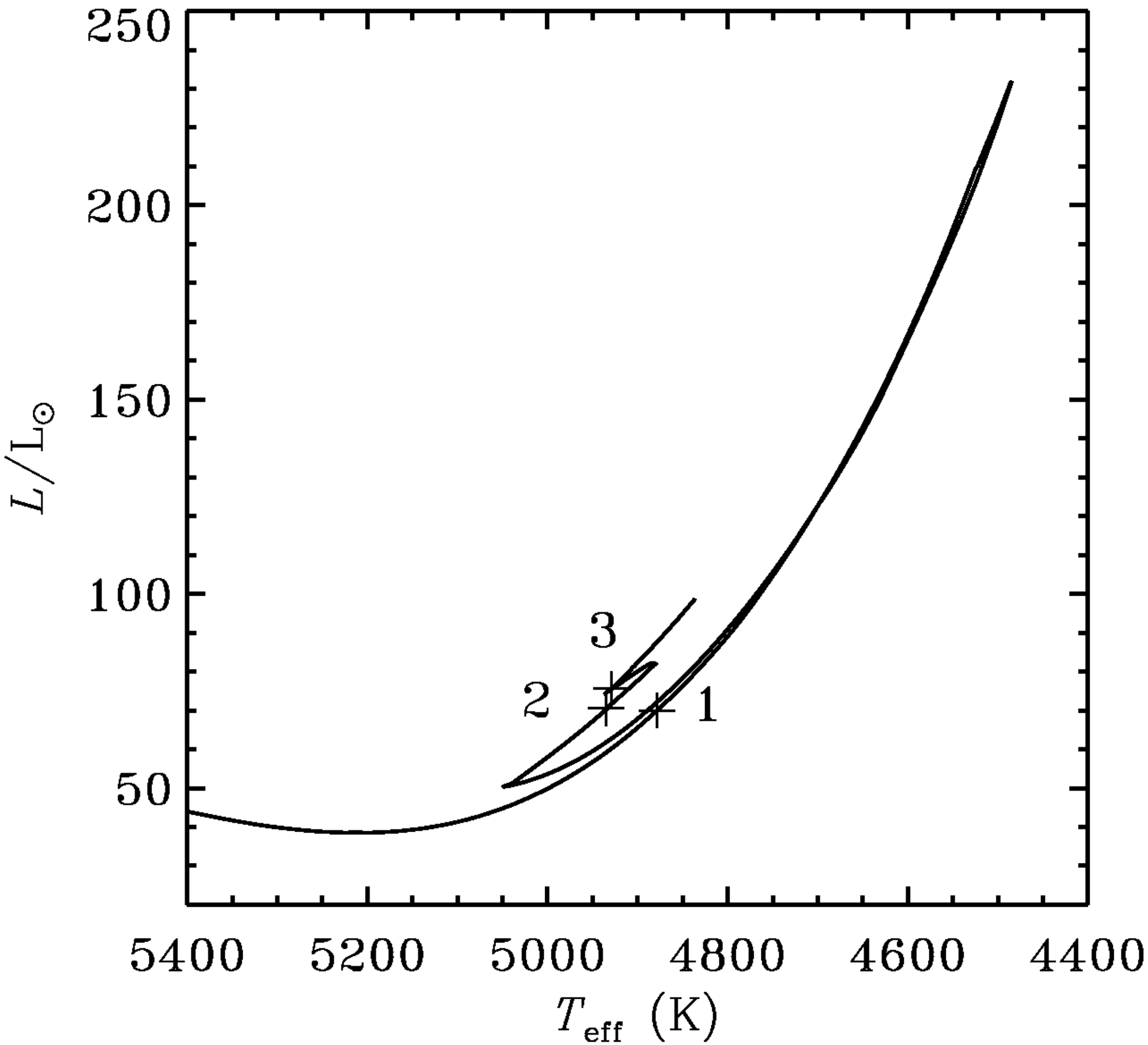


Bedding et al. (Nature, 2011, 471, 608)

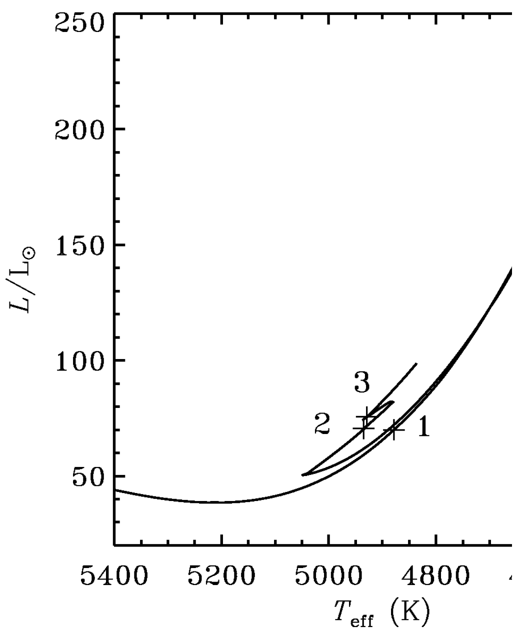
2.5 $M_\odot$ evolution

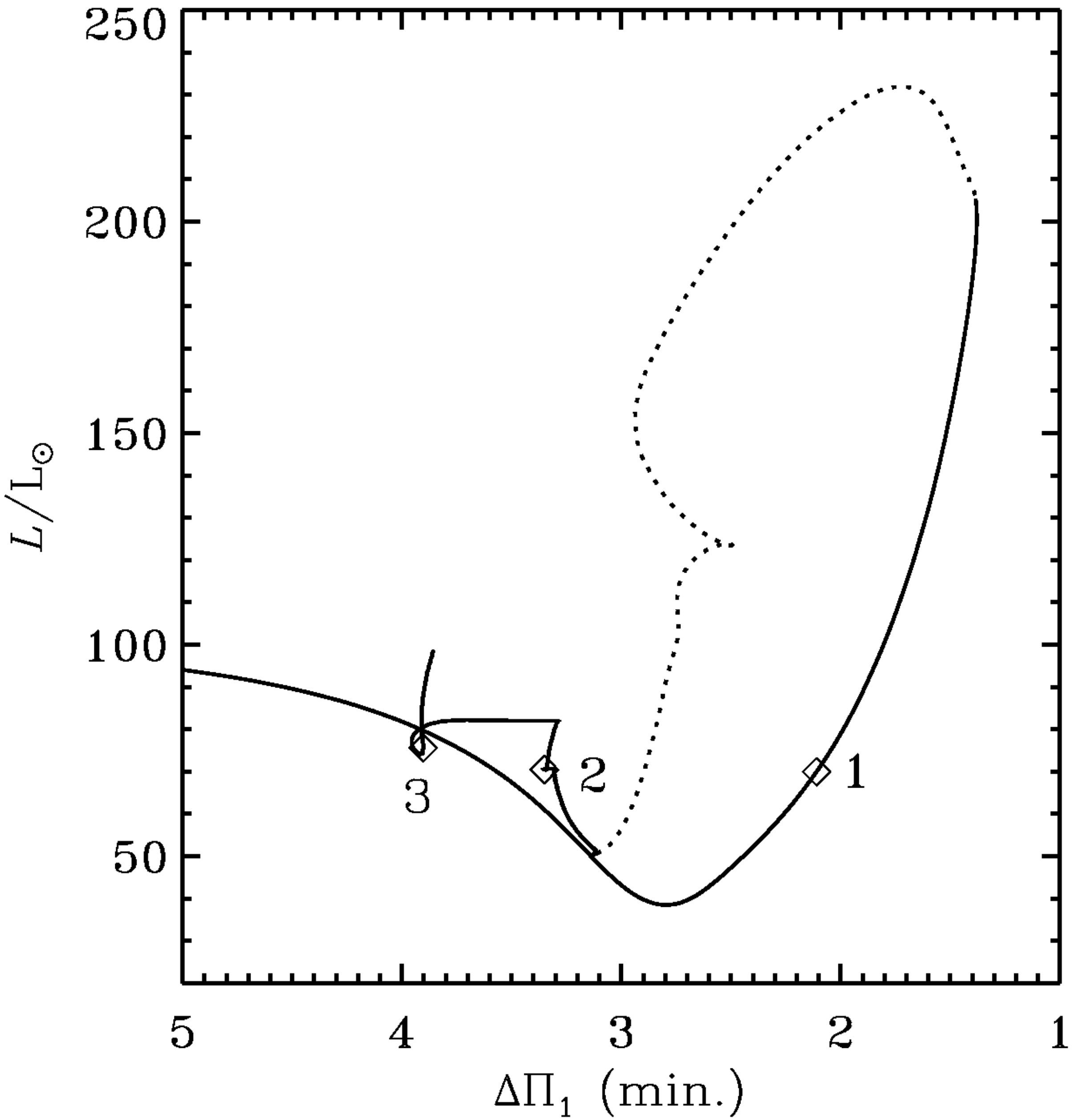


2.5 M⊙ evolution

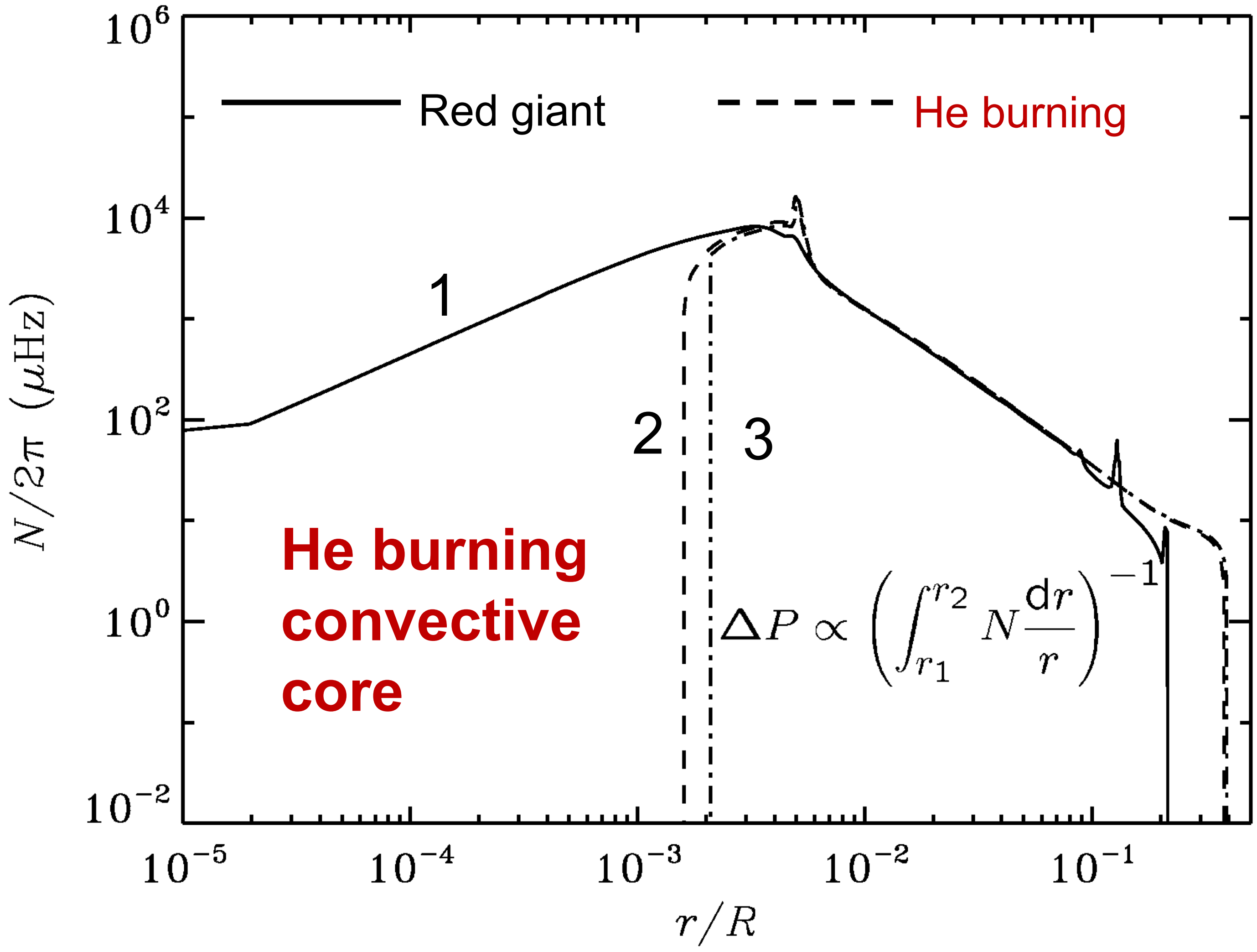


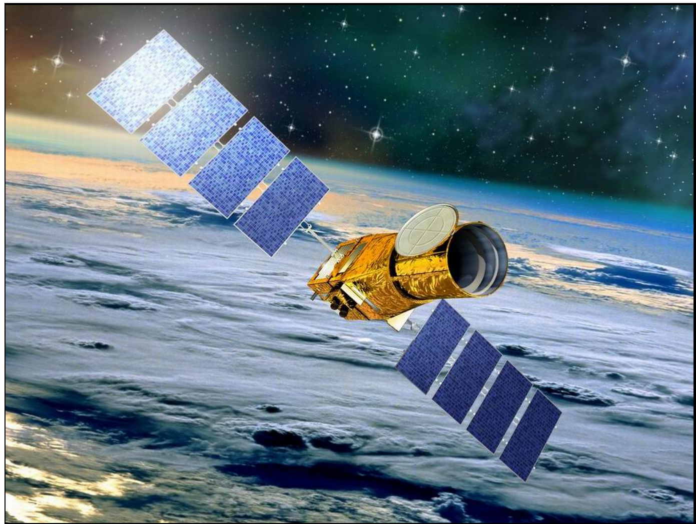
2.5 M– evolution





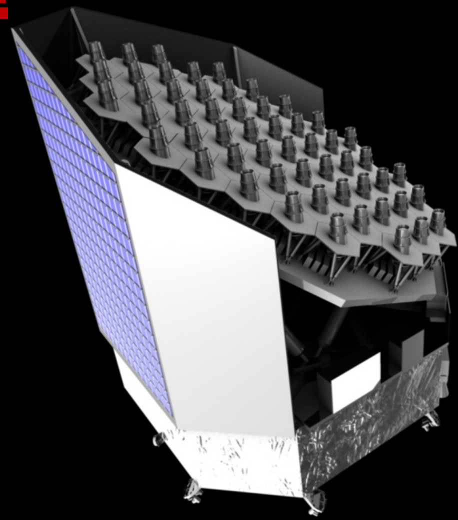
Buoyancy frequencies





CoRoT, Kepler, SONG, PLATO, ….

The fun is just starting!



Douglas at work