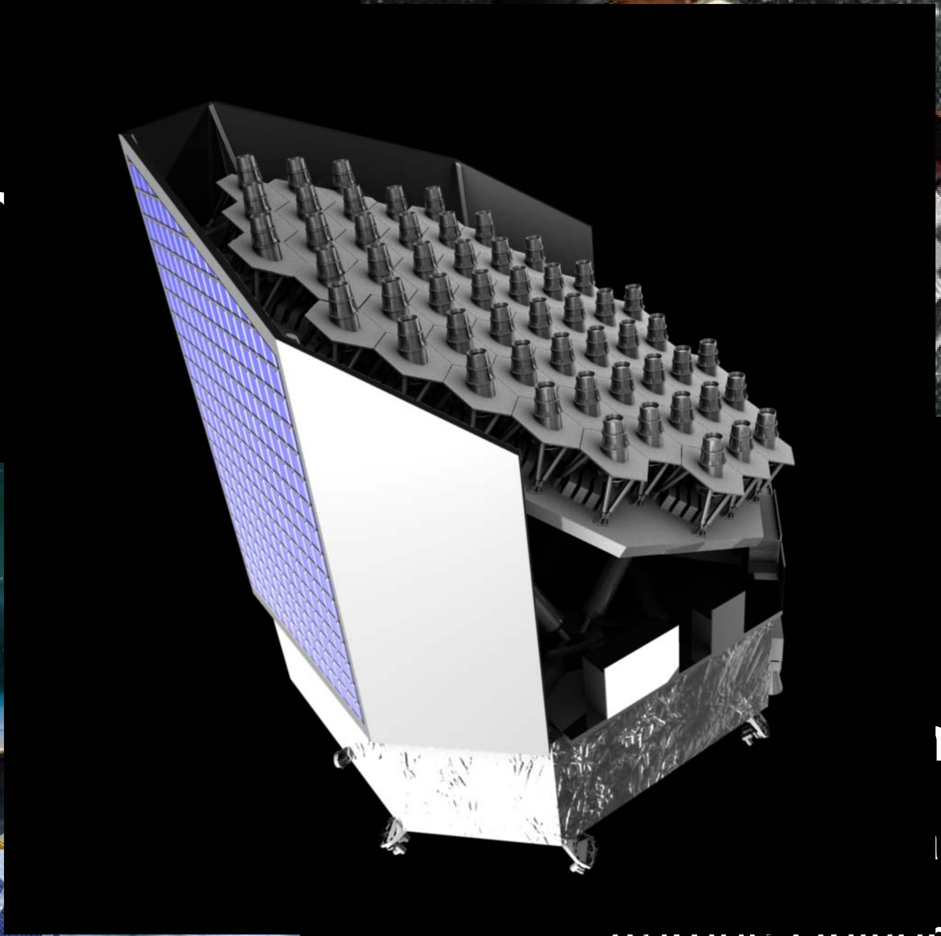
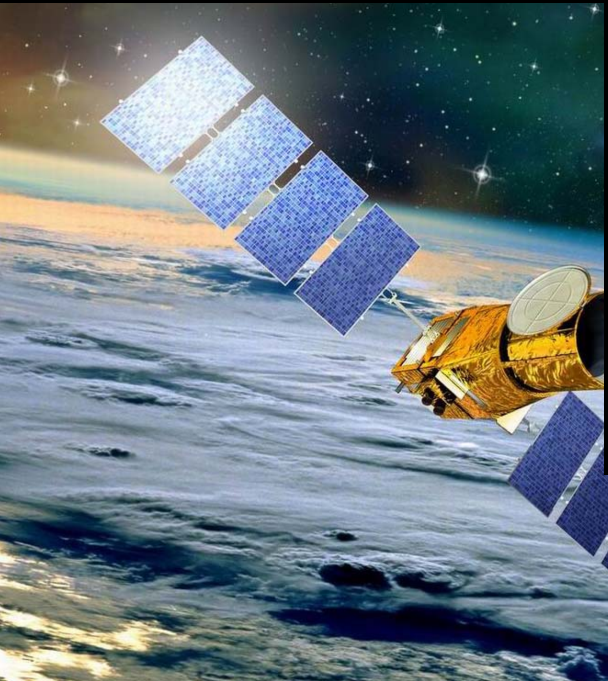
Stellar evolution and asteroseisr





n-Dalsgaard

nd Astronomy

Aarhus University

Stellar evolution, exoplanets and asteroseismology

- Strong observational synergy
  - Very similar observational requirements:
  - very sensitive photometry
  - very long observations
- Strong scientific synergy
  - Characterize central stars in planetary systems
  - Investigate stellar internal properties to improve the above

Stellar evolution, exoplanets and asteroseismology

A marriage made in heaven

Status of space asteroseismology

- WIRE set the direction
- MOST is very successful for relatively large-amplitude pulsators
- CoROT is producing very substantial results, but not in general for exo-planet hosts
- Kepler has shown the power of asteroseismology for a few exo-planet hosts
- **PLATO will utilize that power for thousands of stars**

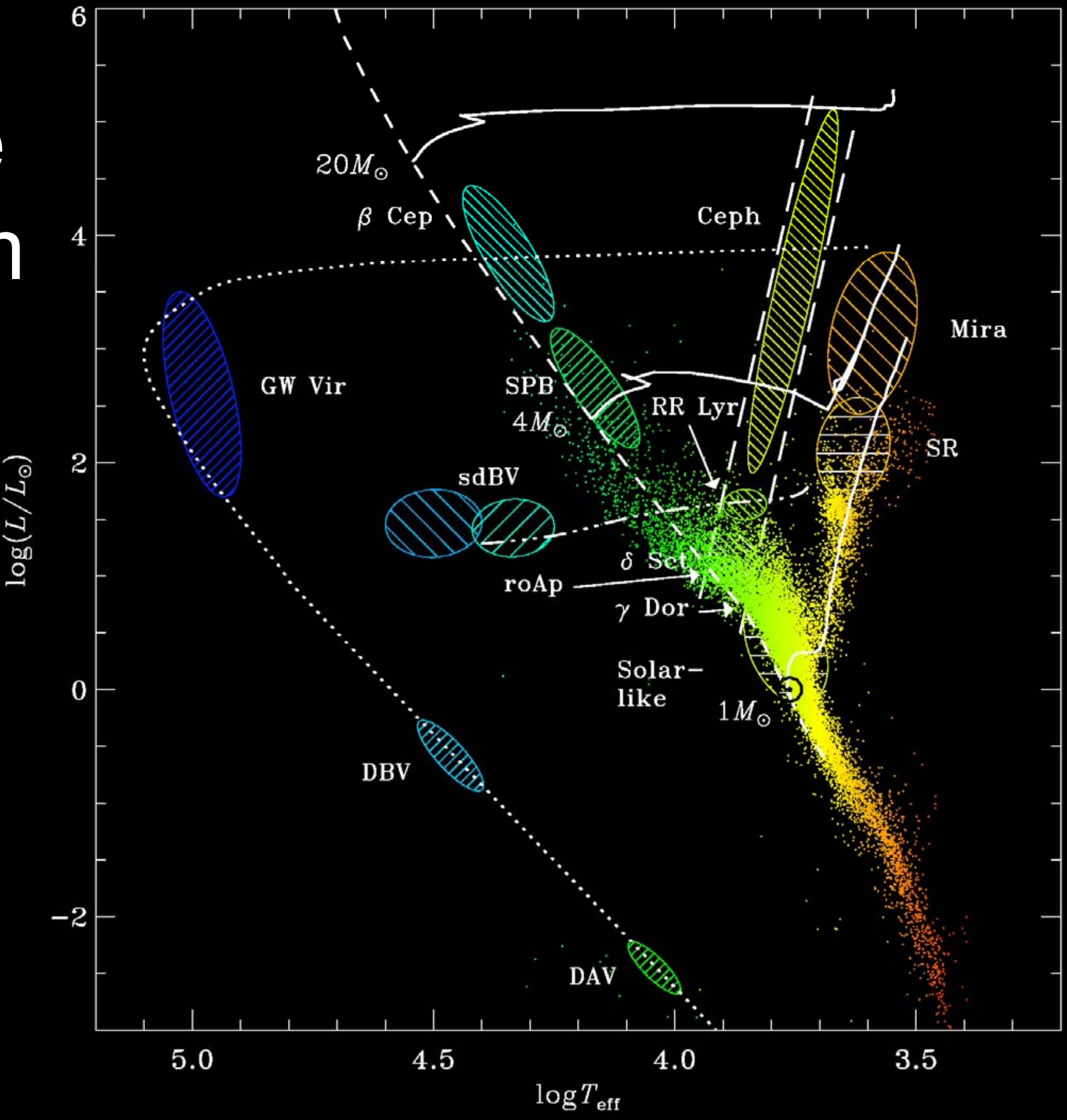
Problems in stellar modelling

- Properties of convective cores
  - Strong effect on age determination
- Effects of rotation
  - Mixing processes
  - Evolution of rotation
  - Modelling of rapidly rotating stars
- Near-surface problems
  - Convection (energy transport and turbulent pressure)
  - Effects on oscillation frequencies

Ways forward

- Improved modelling
- Classical observations
- **Asteroseismic observations**

Pulsating stars in the HR diagram



Kepler

Launched March 2009

Goals of Kepler asteroseismology

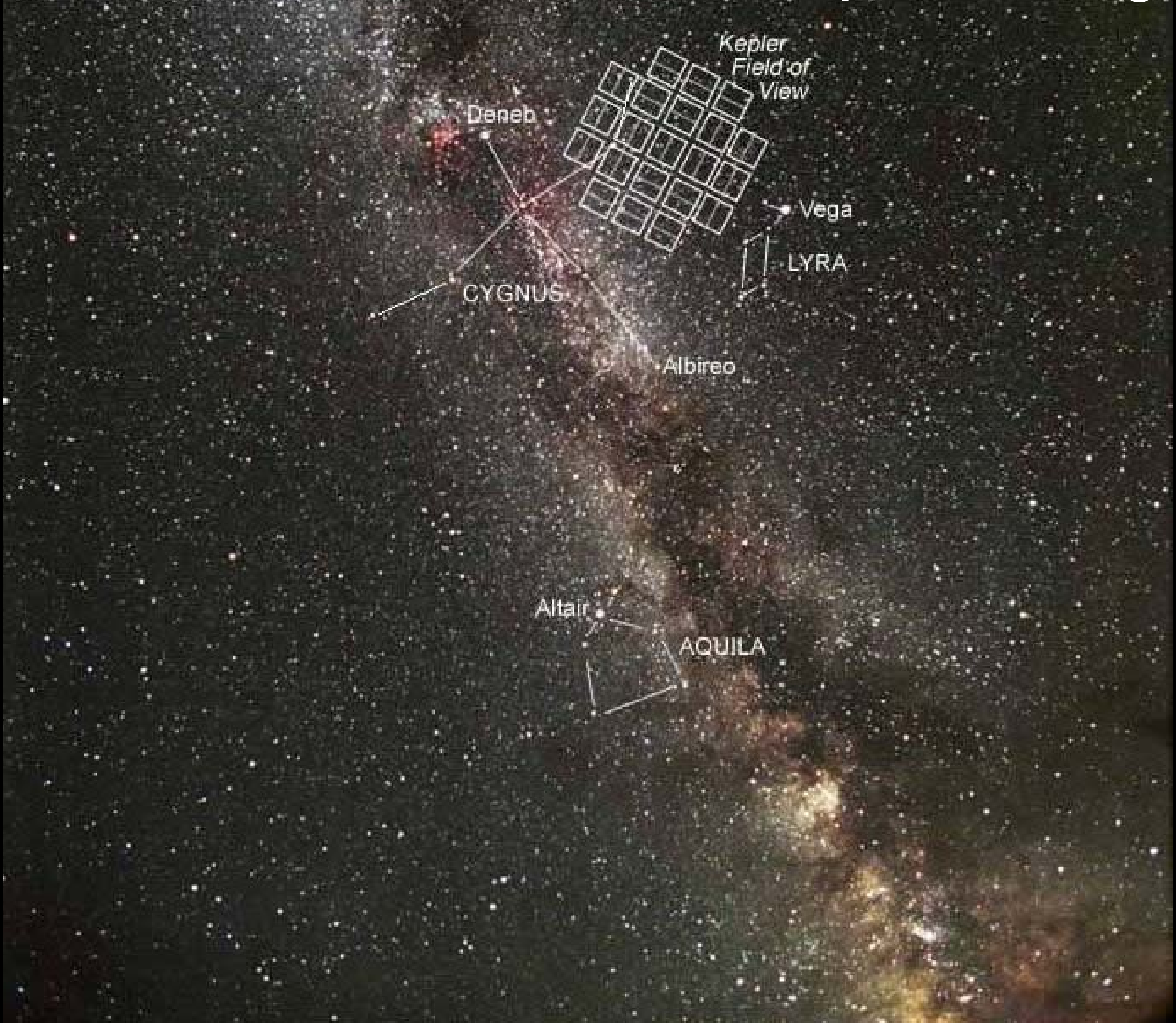
- to provide support for the studies of extrasolar planetary systems by characterizing the central stars of the systems
- to perform in-depth asteroseismic investigations of a large number of stars, predominantly but not exclusively those showing solar-like oscillations.

Goals of ~~Kepler~~ asteroseismology

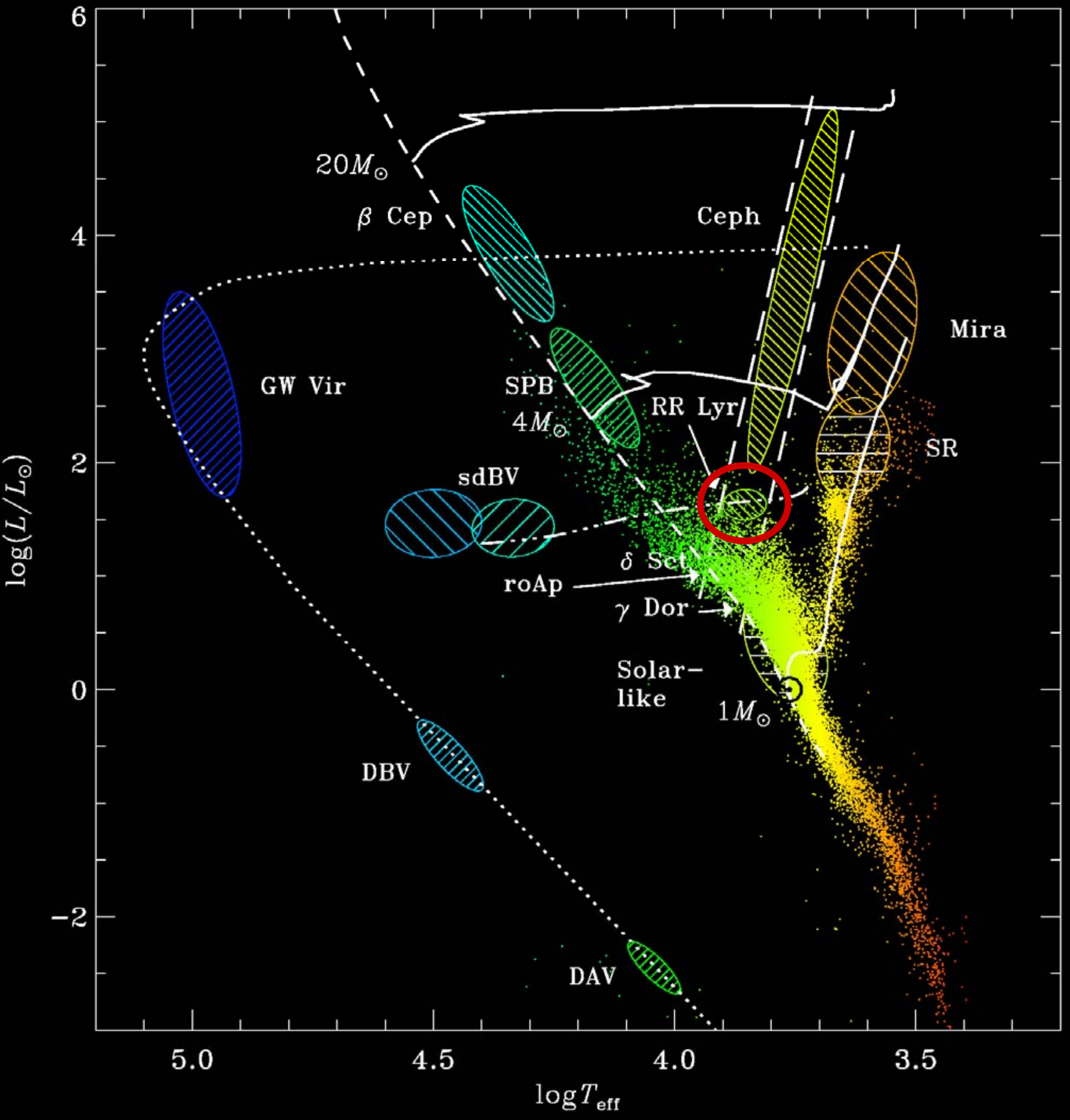
PLATO

- 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.

Kepler Field of View: 110 square degrees



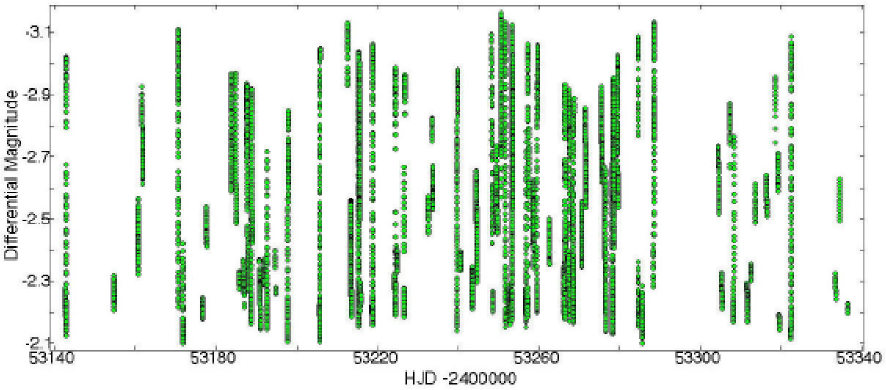
RR Lyrae stars



Blazhko effect in RR Lyrae

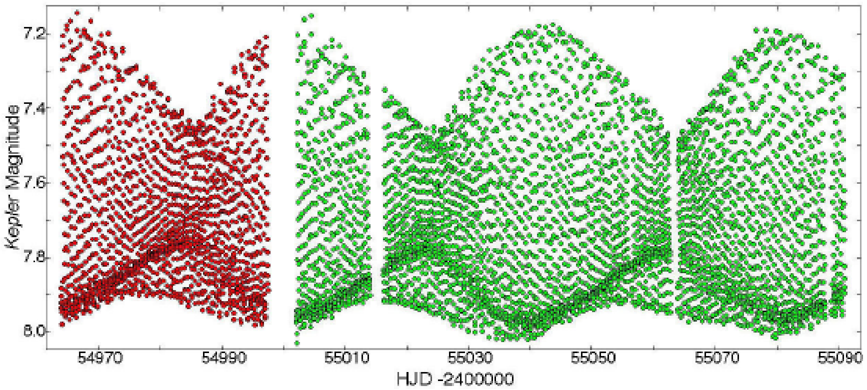
Oscillation period: 0.57 d

Modulation period: 39 d



RR Lyr ground-based data (2004)

Days

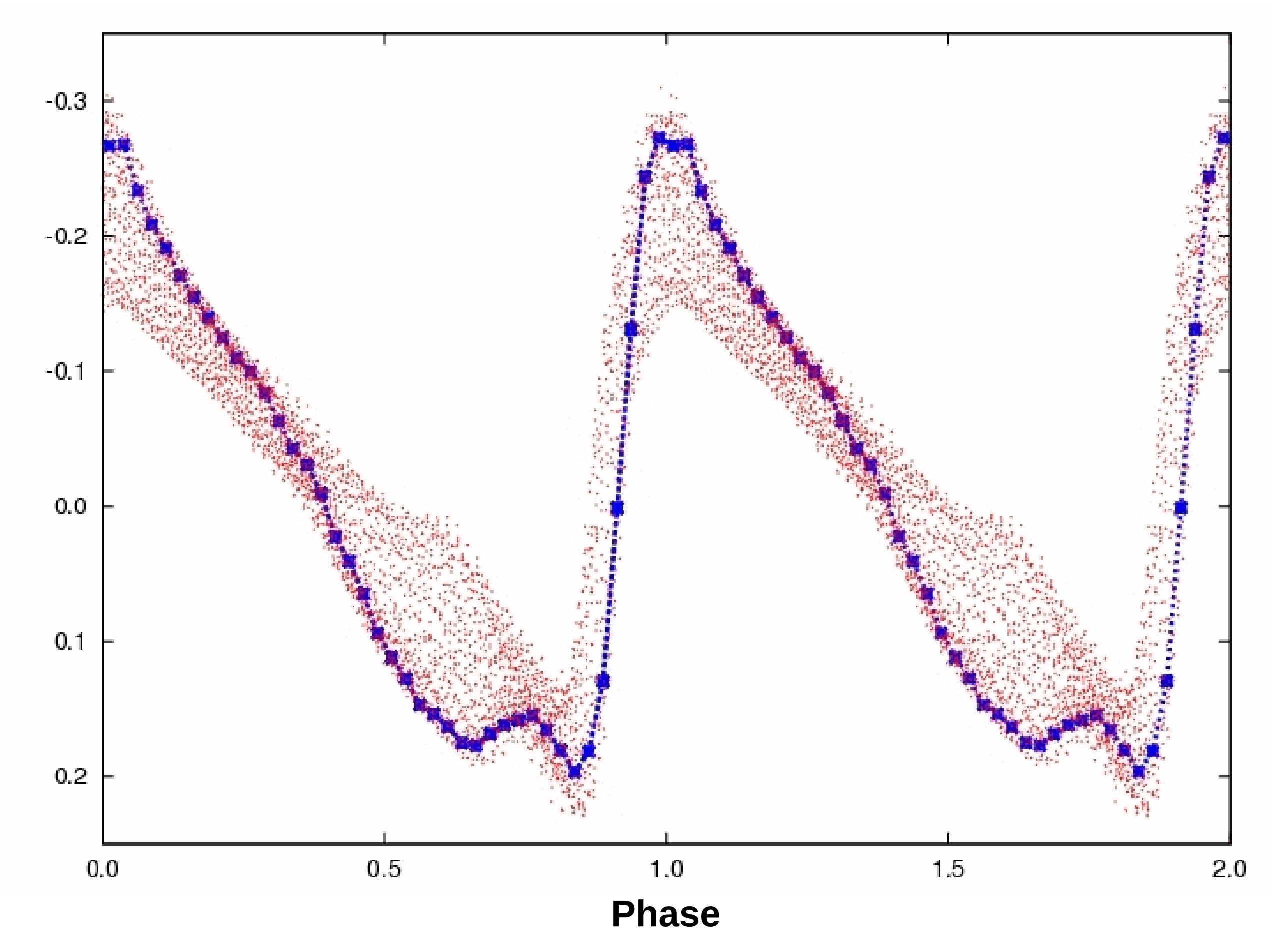


RR Lyr *Kepler* Q1+Q2 data (2009)

Days

Kolenberg et al. (2010, in the press)

Blazhko effect in RR Lyrae

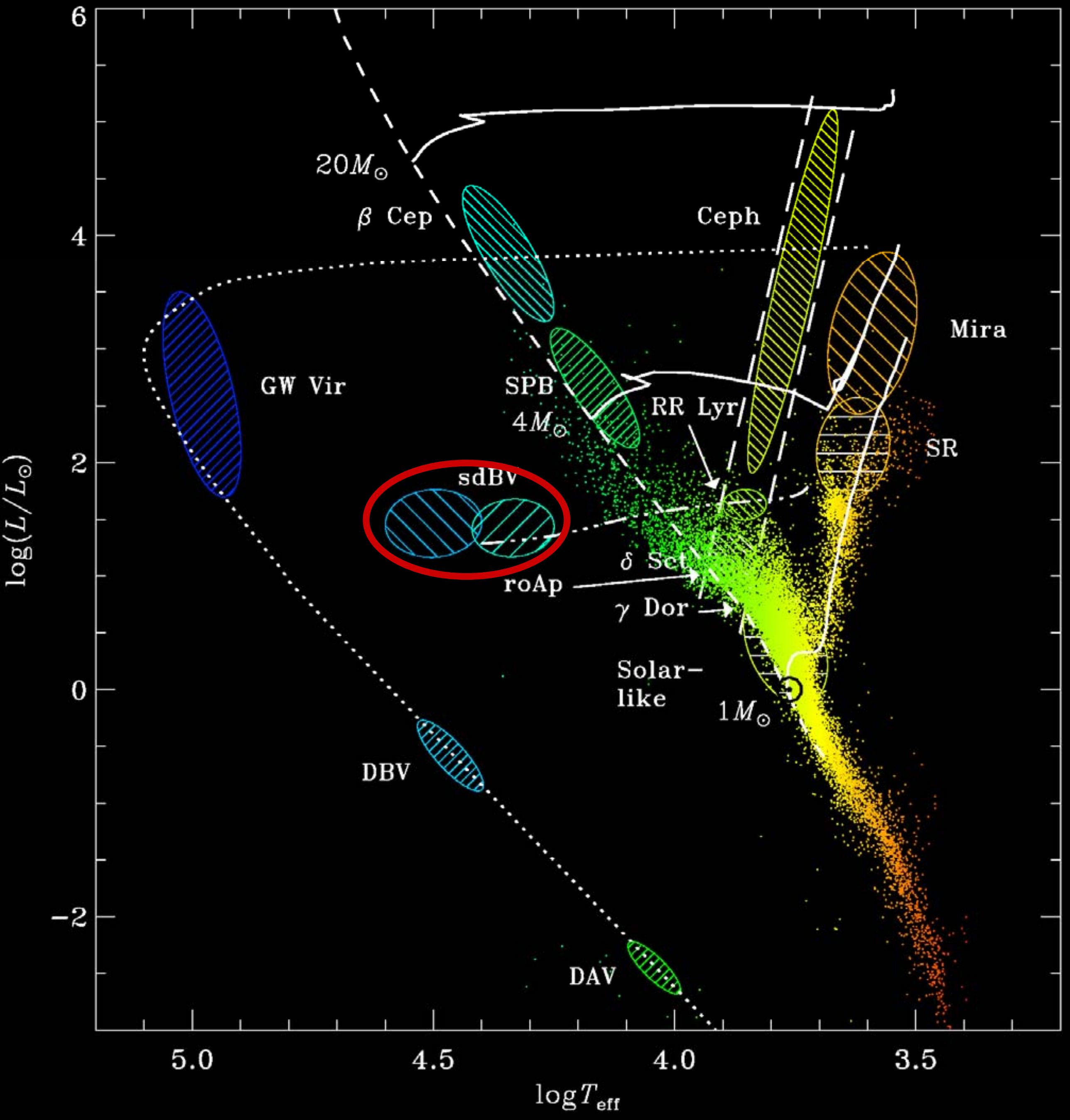


Thanks to R. Szabó

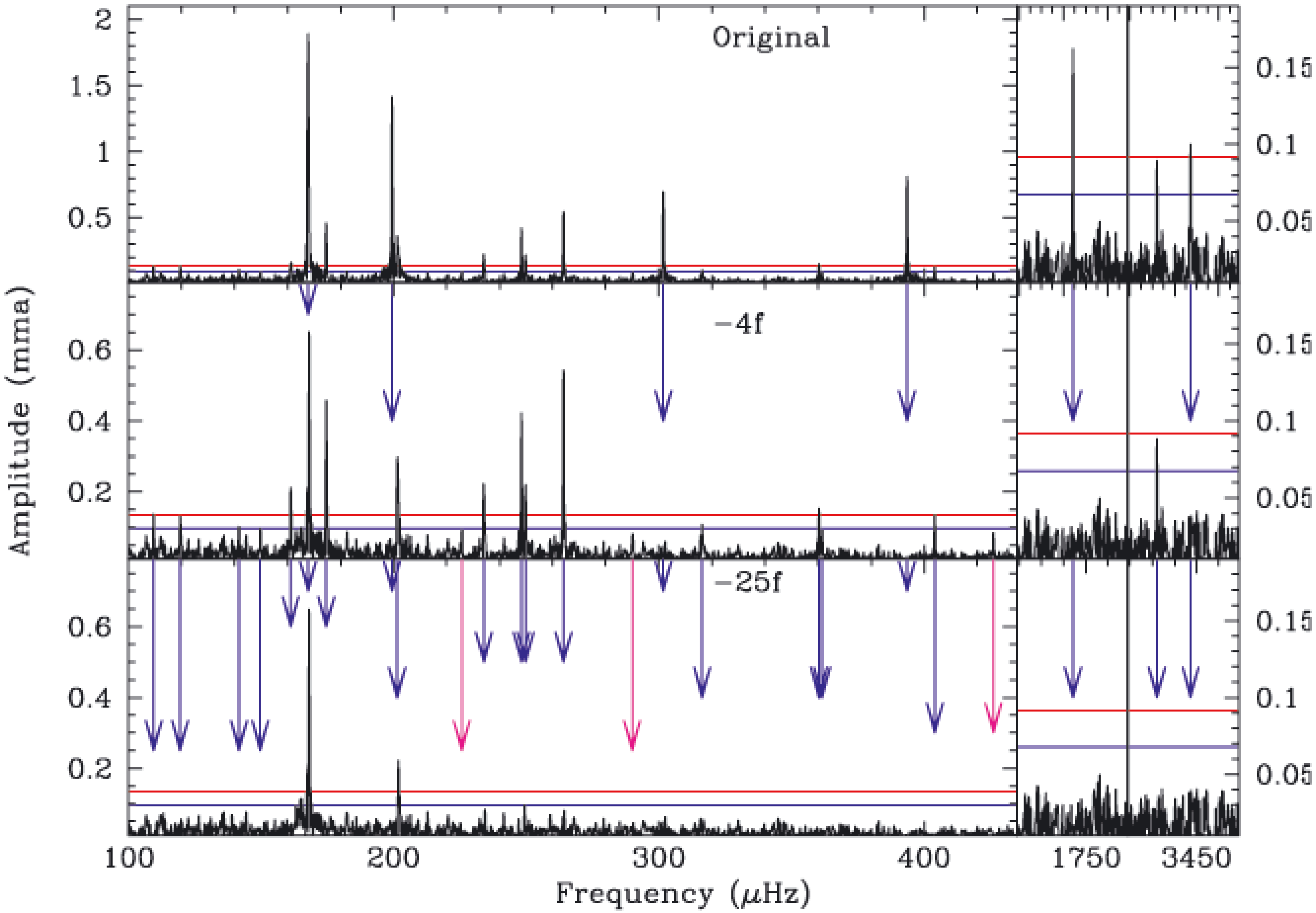
Subdwarf B stars

Core He burning

Extreme mass loss after red-giant phase



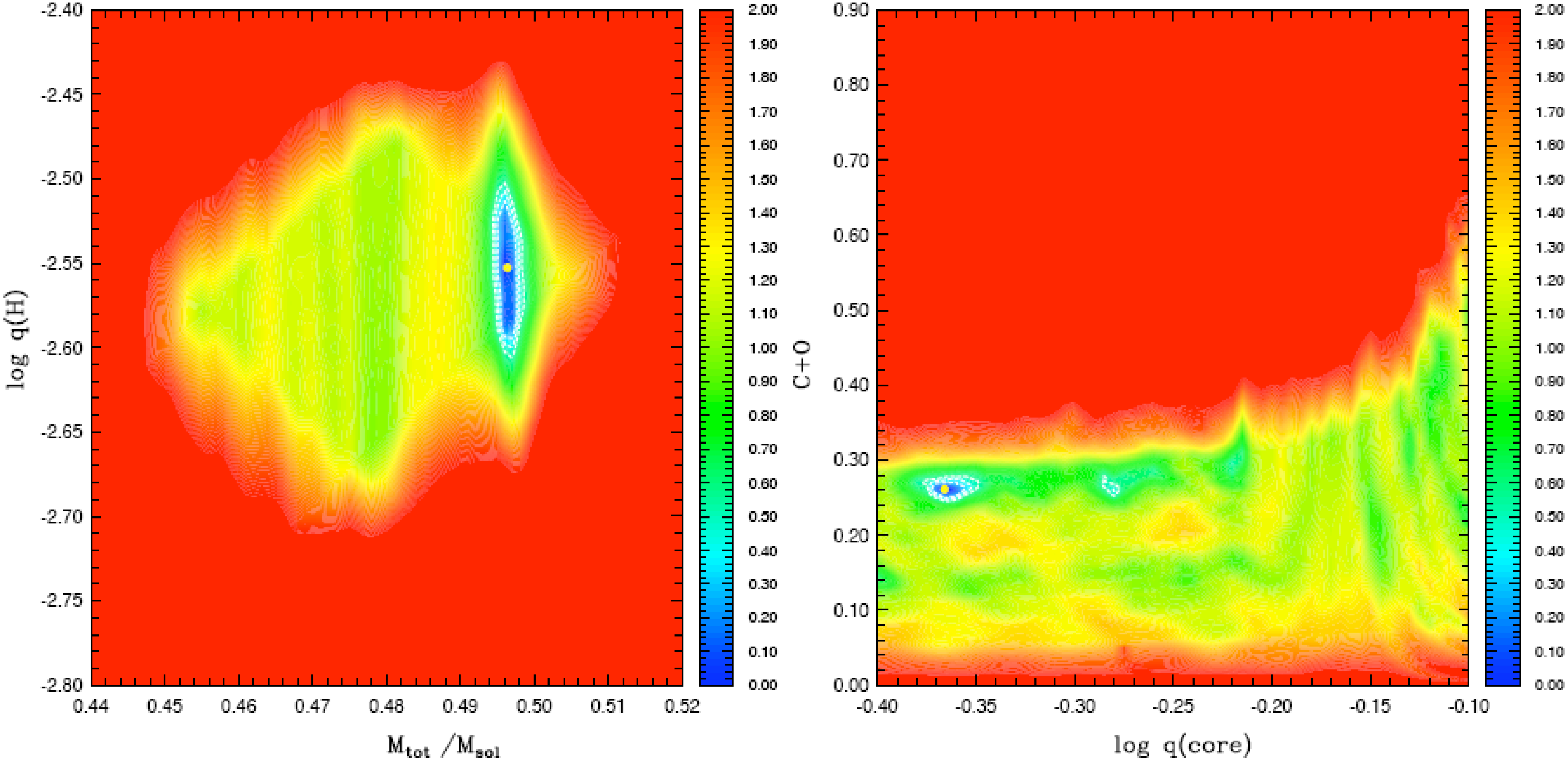
g modes in a subdwarf B star



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

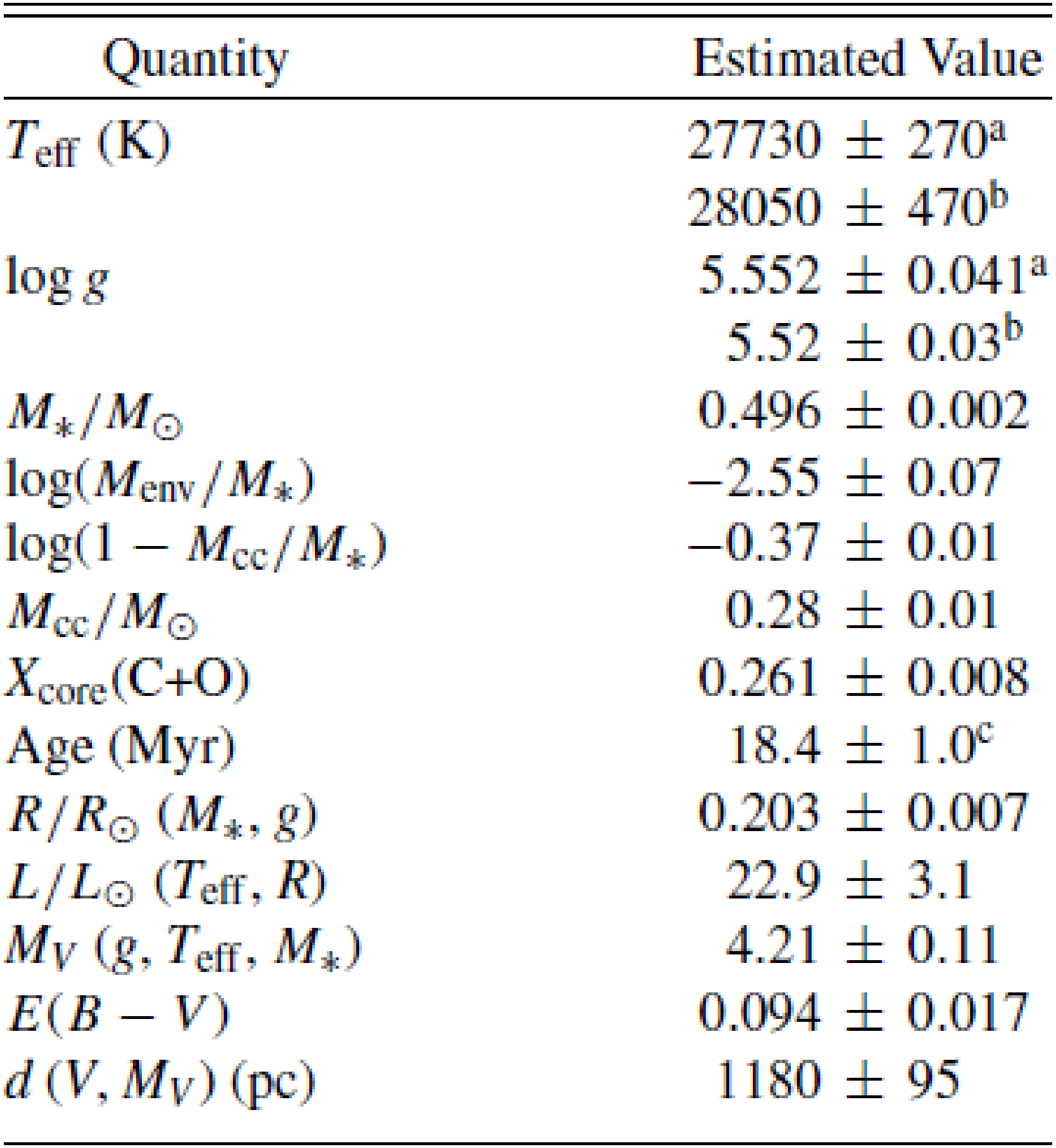
Fit to observed periods

$$\sum(\Pi_i^{\rm obs} - \Pi_i^{\rm mod})^2$$



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

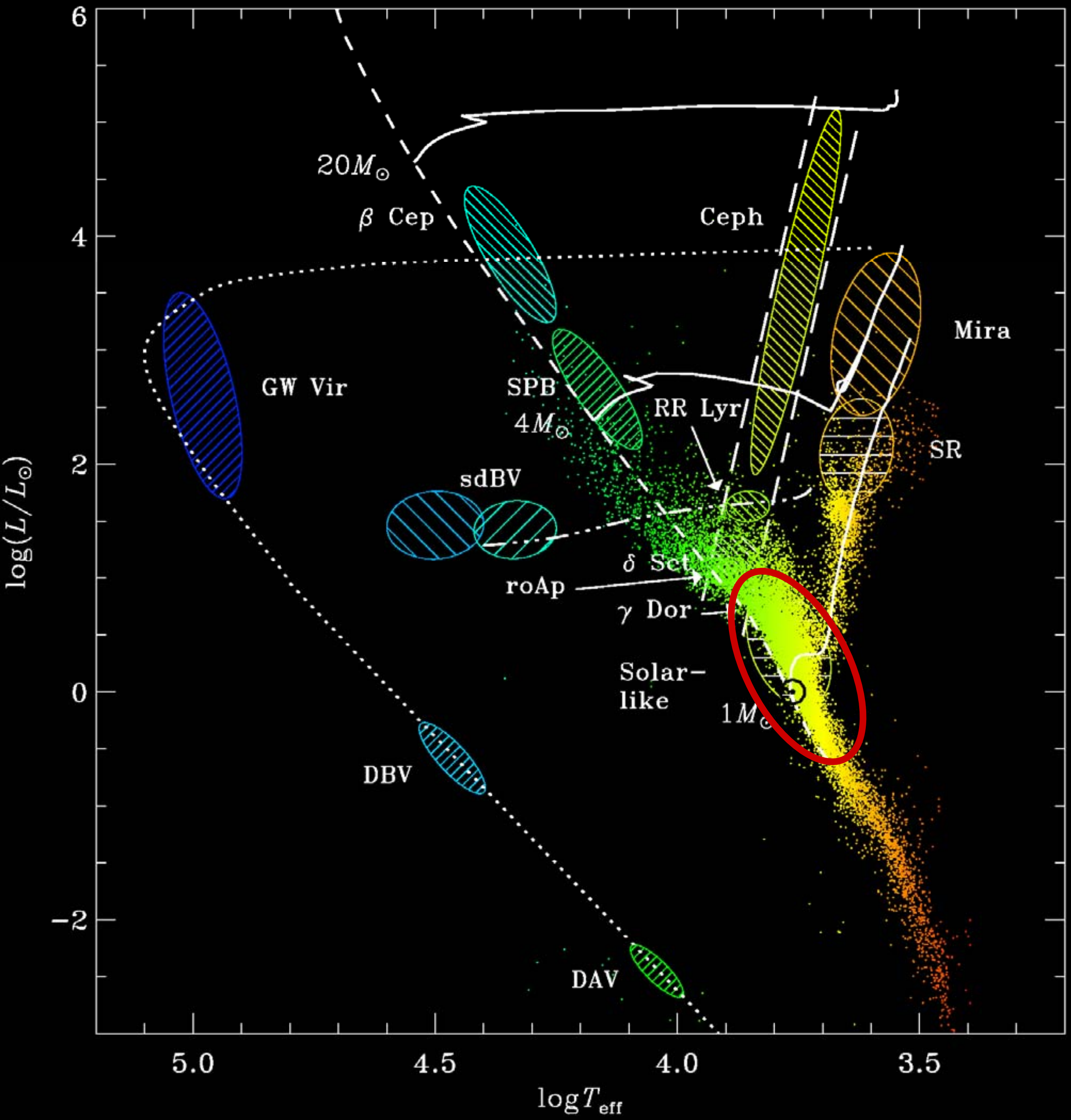
[a] From spectroscopy

[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

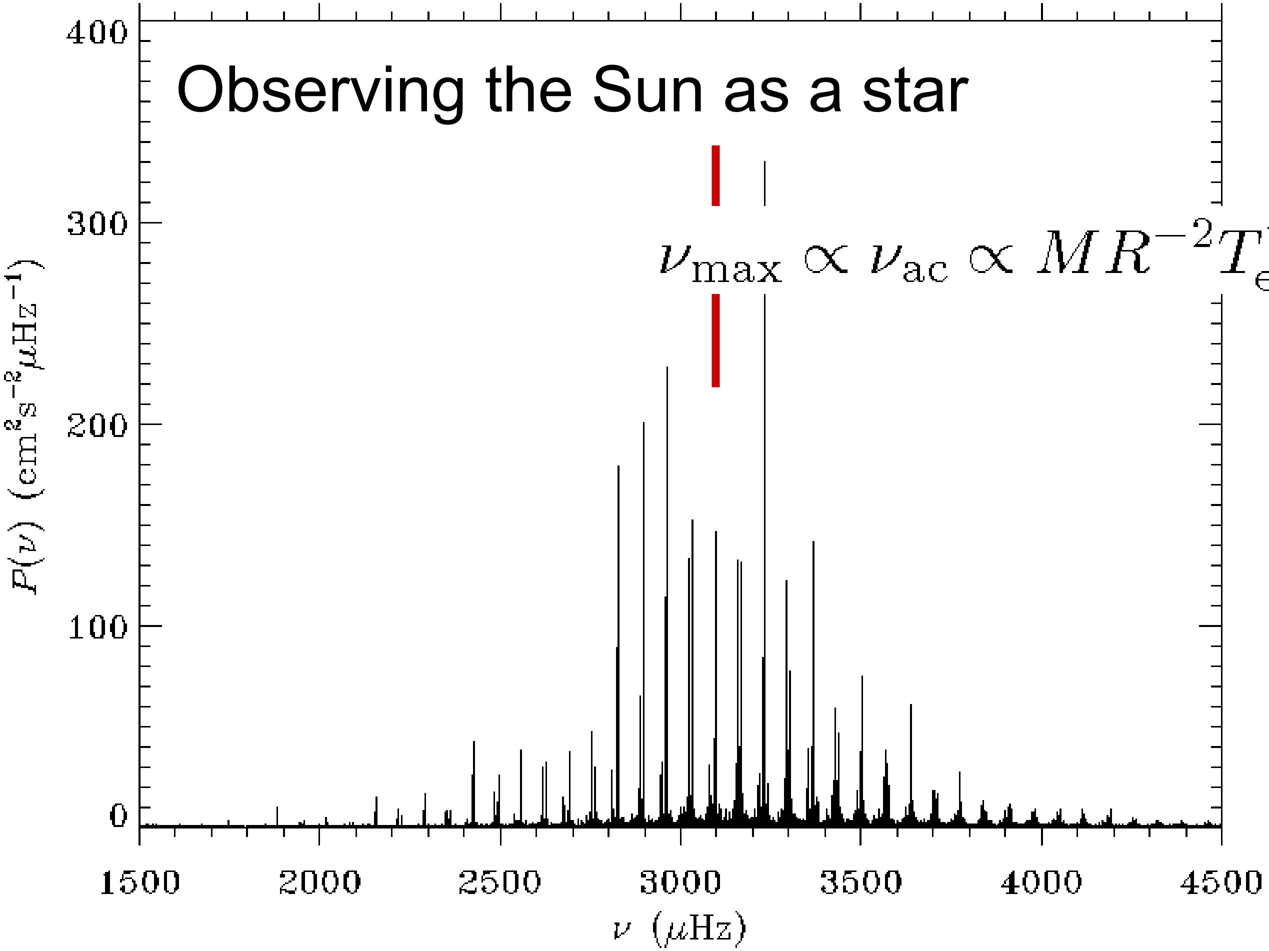
$$\Delta\nu = \left[2 \int_0^R \frac{\mathrm{d}r}{c} \right]^{-1}$$

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

Large frequency separation:

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

odes



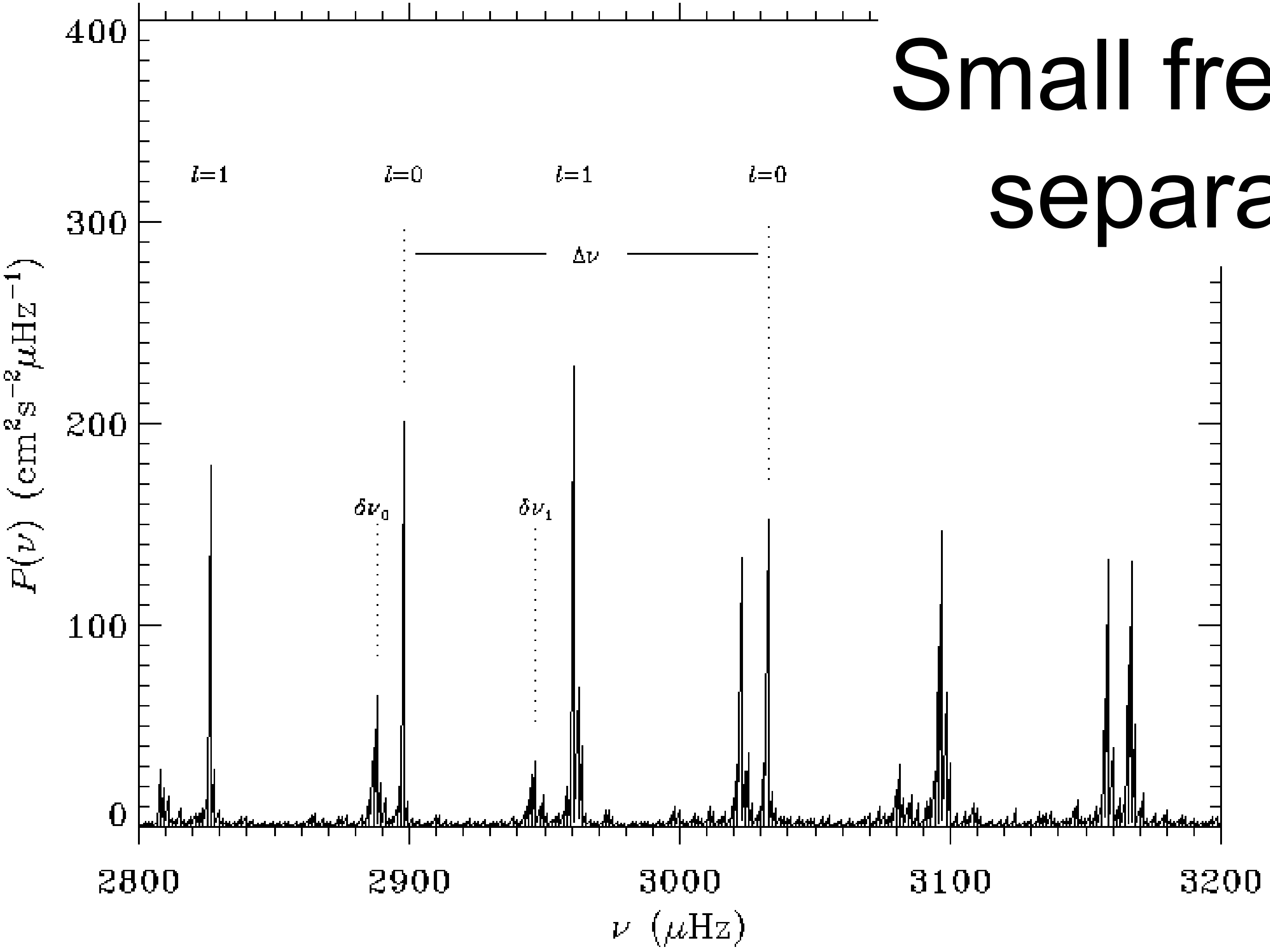
Observing the Sun as a star

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

Large frequency separation:

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

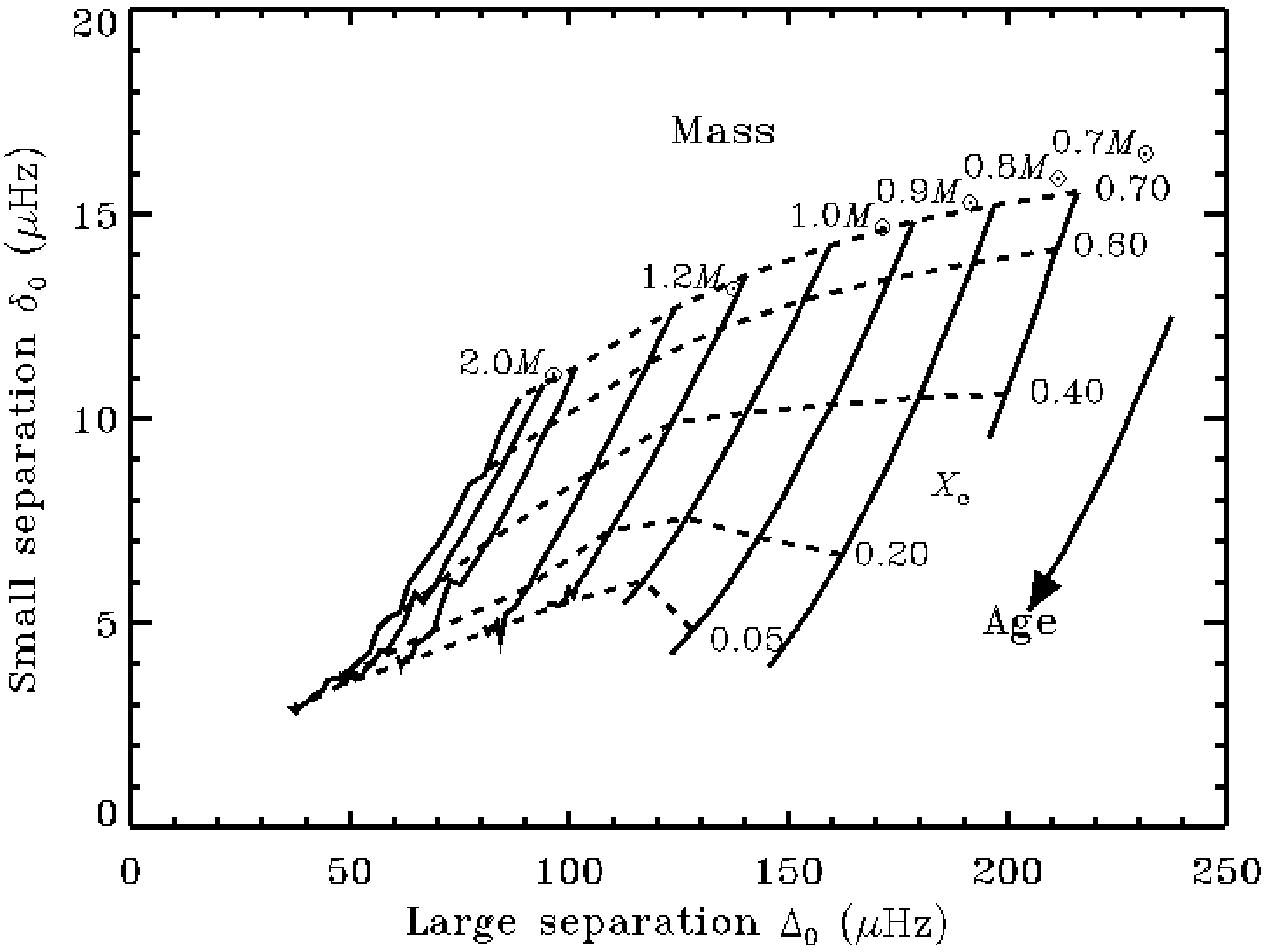
Small frequency separations



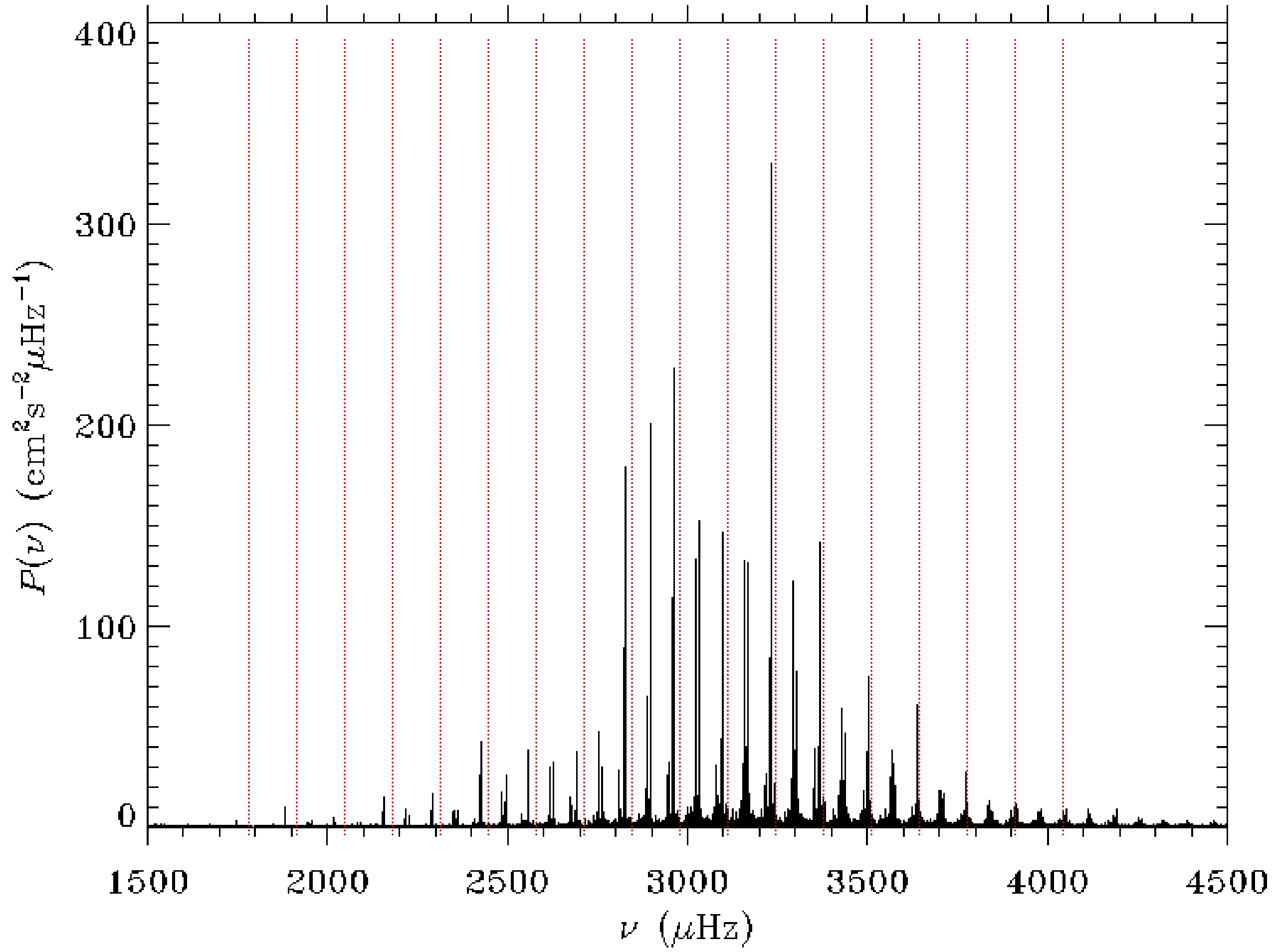
Frequency separations:

$$\delta\nu_{nl} = \nu_{nl} - \nu_{n-1\,l+2} \simeq -(4l+6)\frac{\Delta\nu}{4\pi^2\nu_{nl}}\int_0^R \frac{\mathrm{d}c}{\mathrm{d}r}\frac{\mathrm{d}r}{r}$$

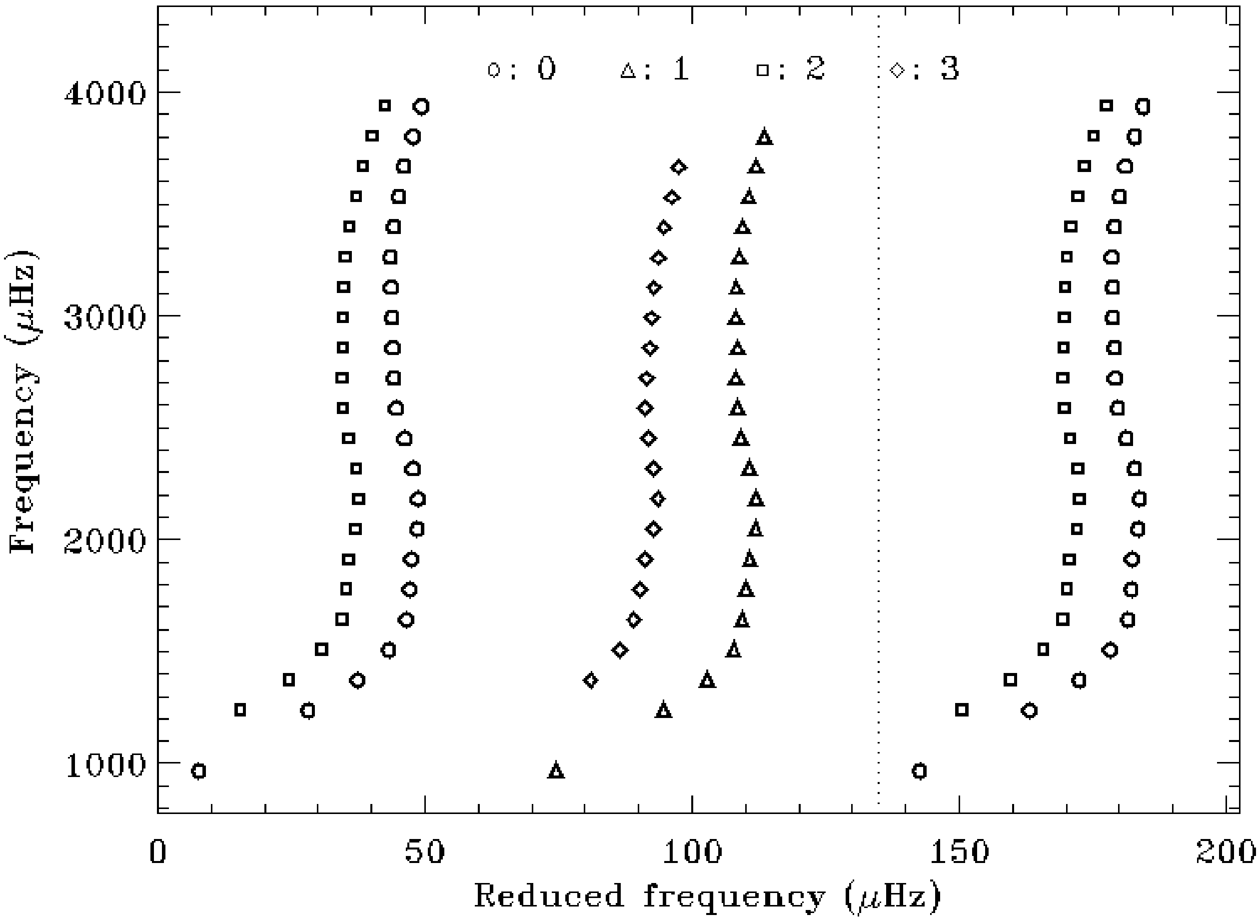
Asteroseismic HR diagram

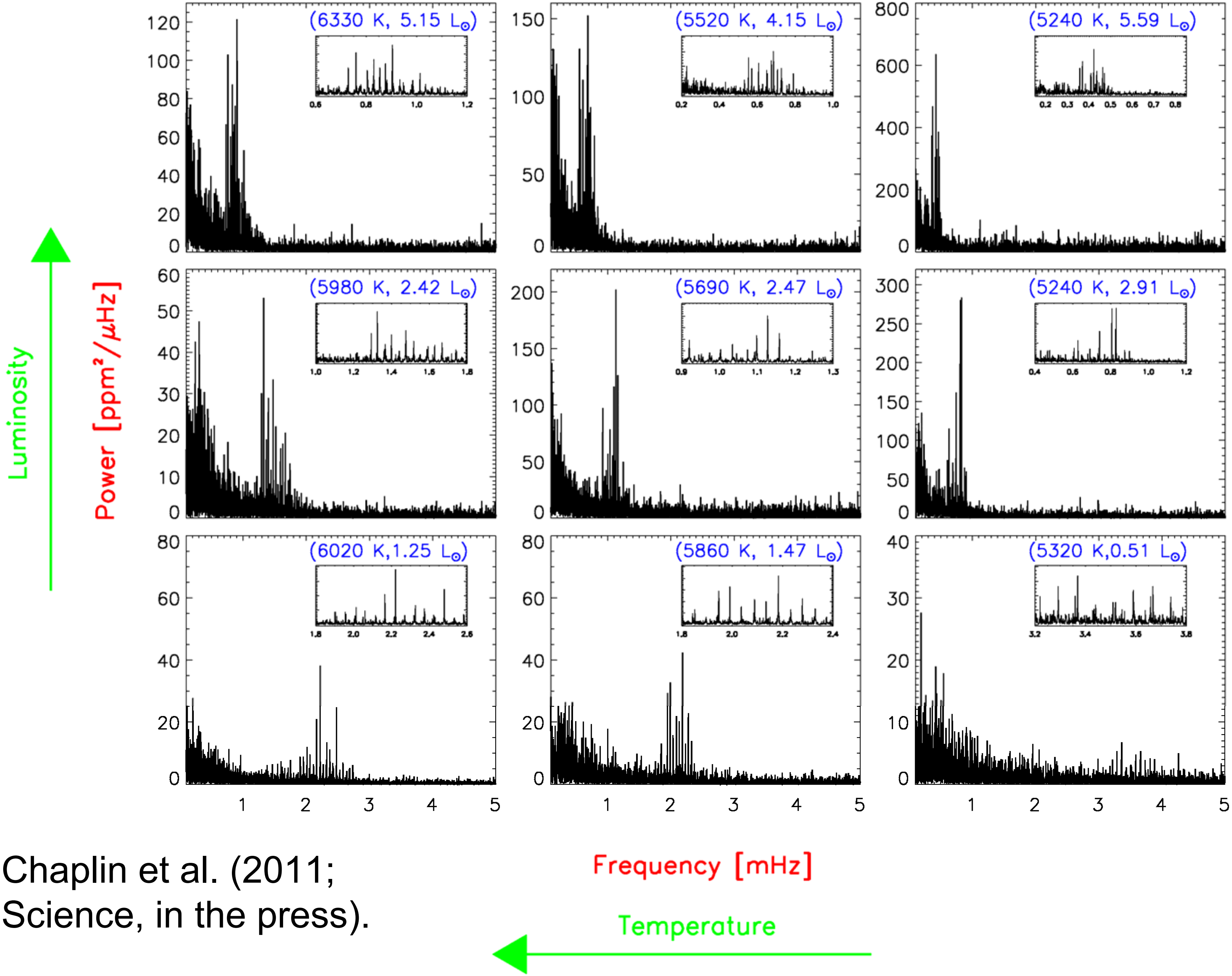


Echelle diagram



Echelle diagram



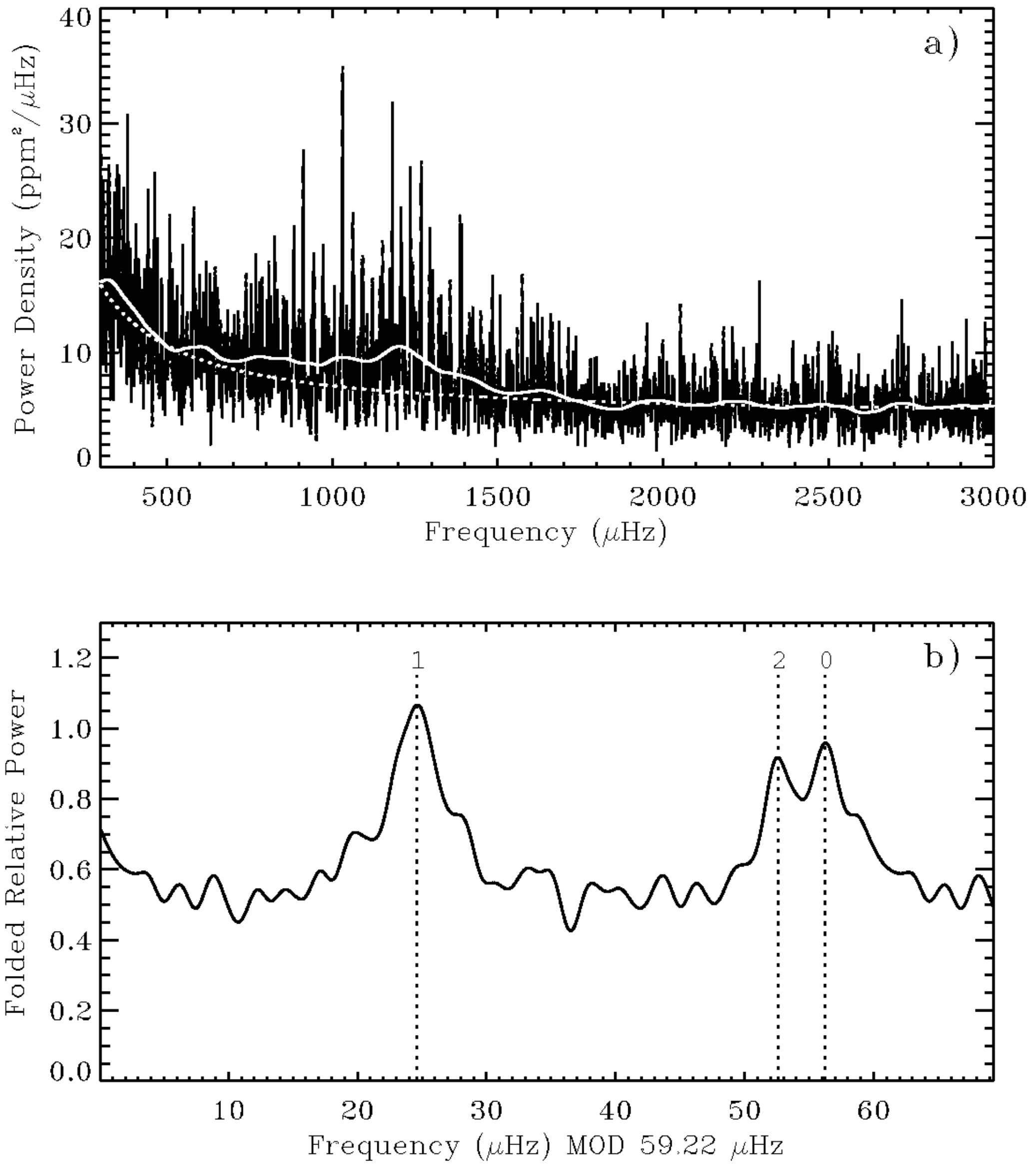


Chaplin et al. (2011; Science, in the press).

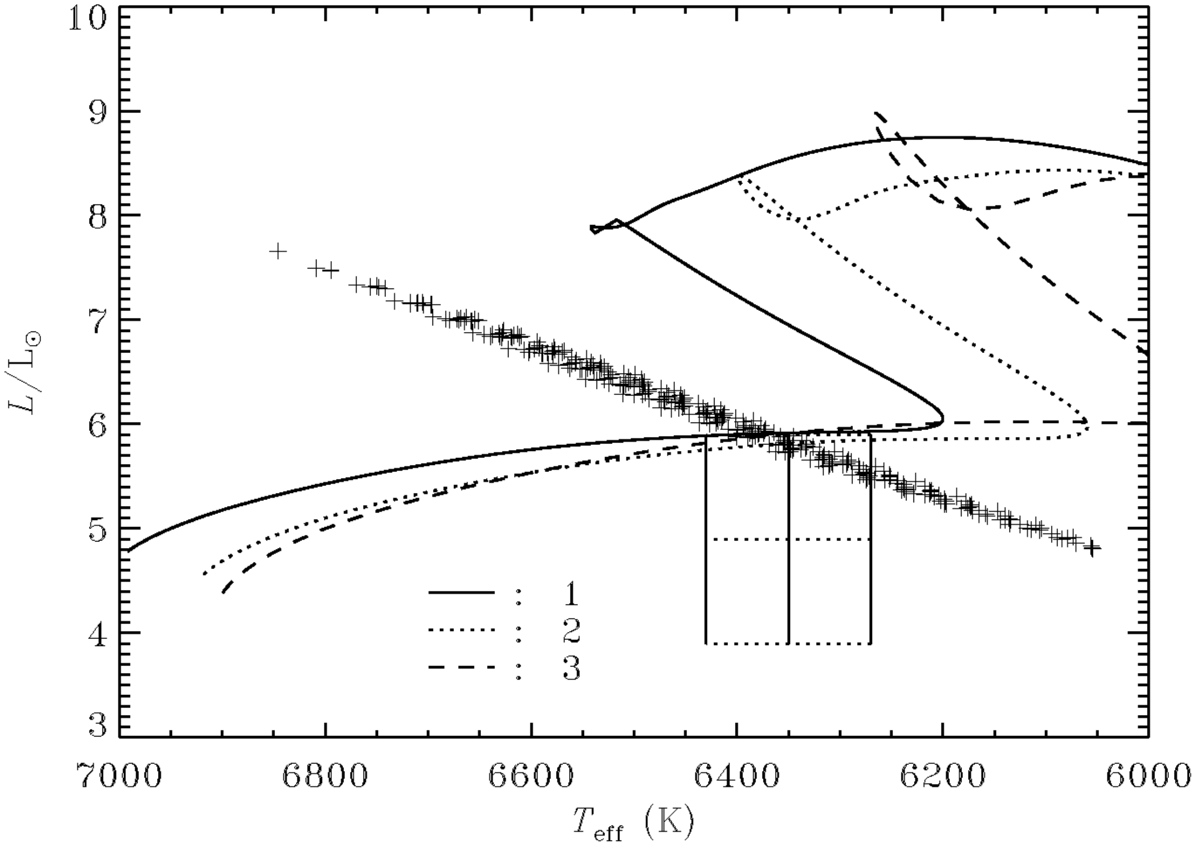
Asteroseismology for exo-planet hosts

- Determine mass, radius (with some dependence on stellar models)
- Constrain age
- Constrain rotation period and possibly orientation of rotation axis

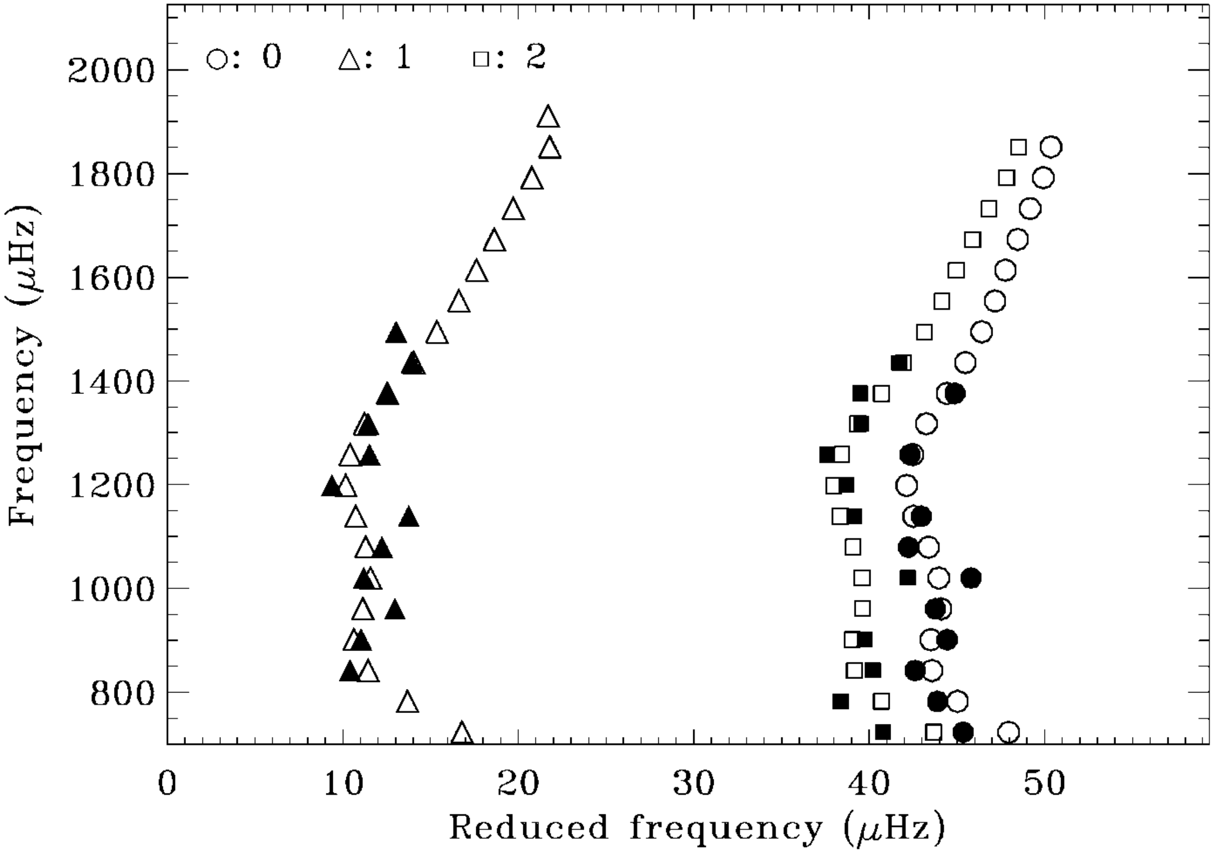
HAT-P-7 spectrum



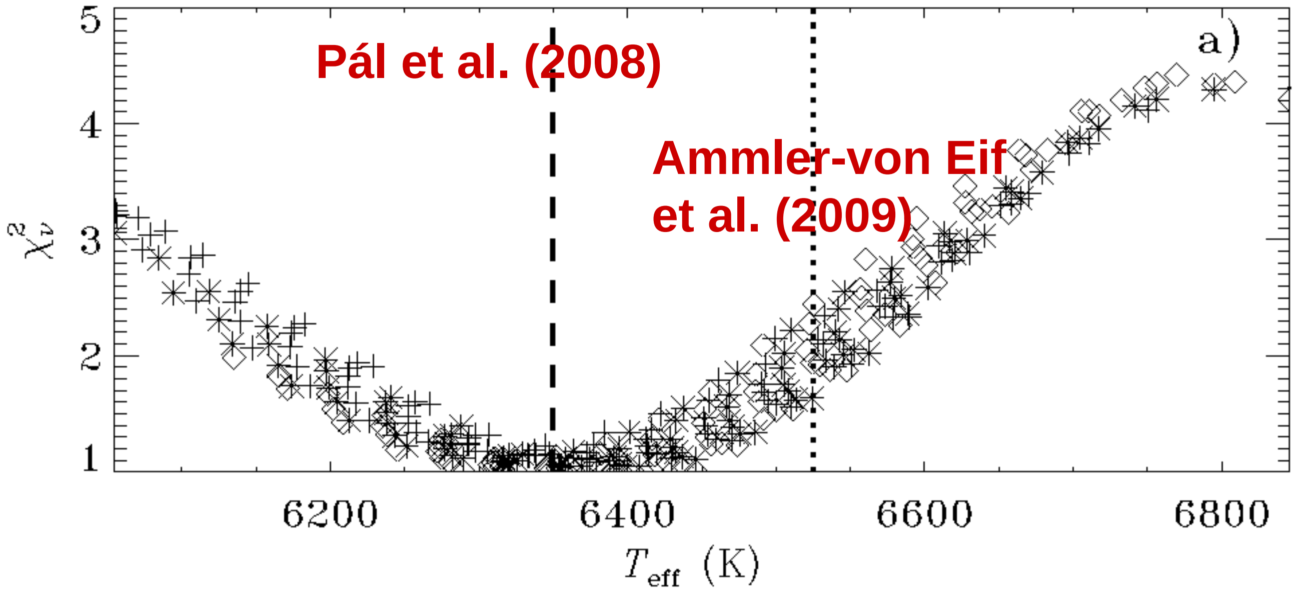
Evolution models



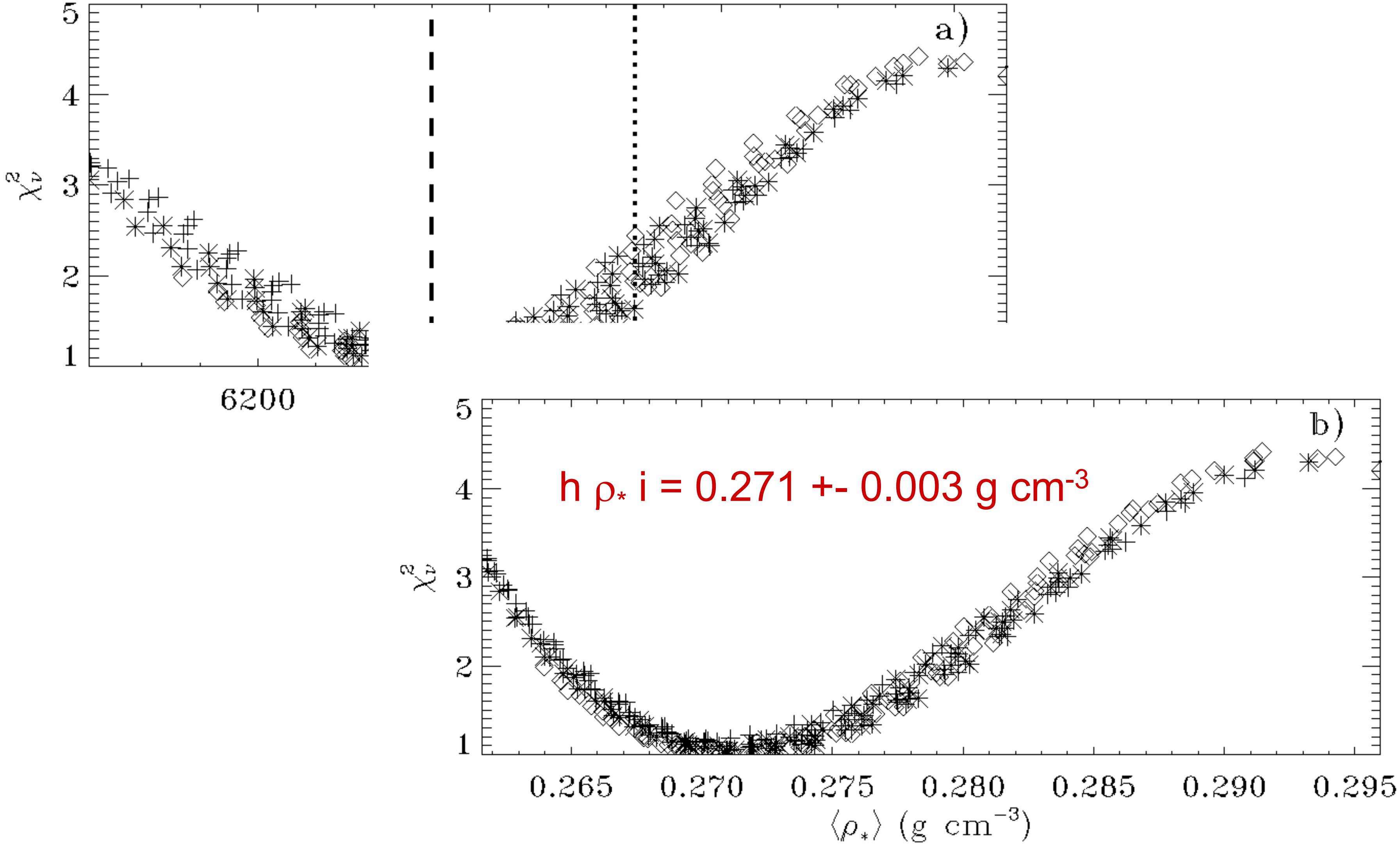
Match of model and observations



Least-squares fits

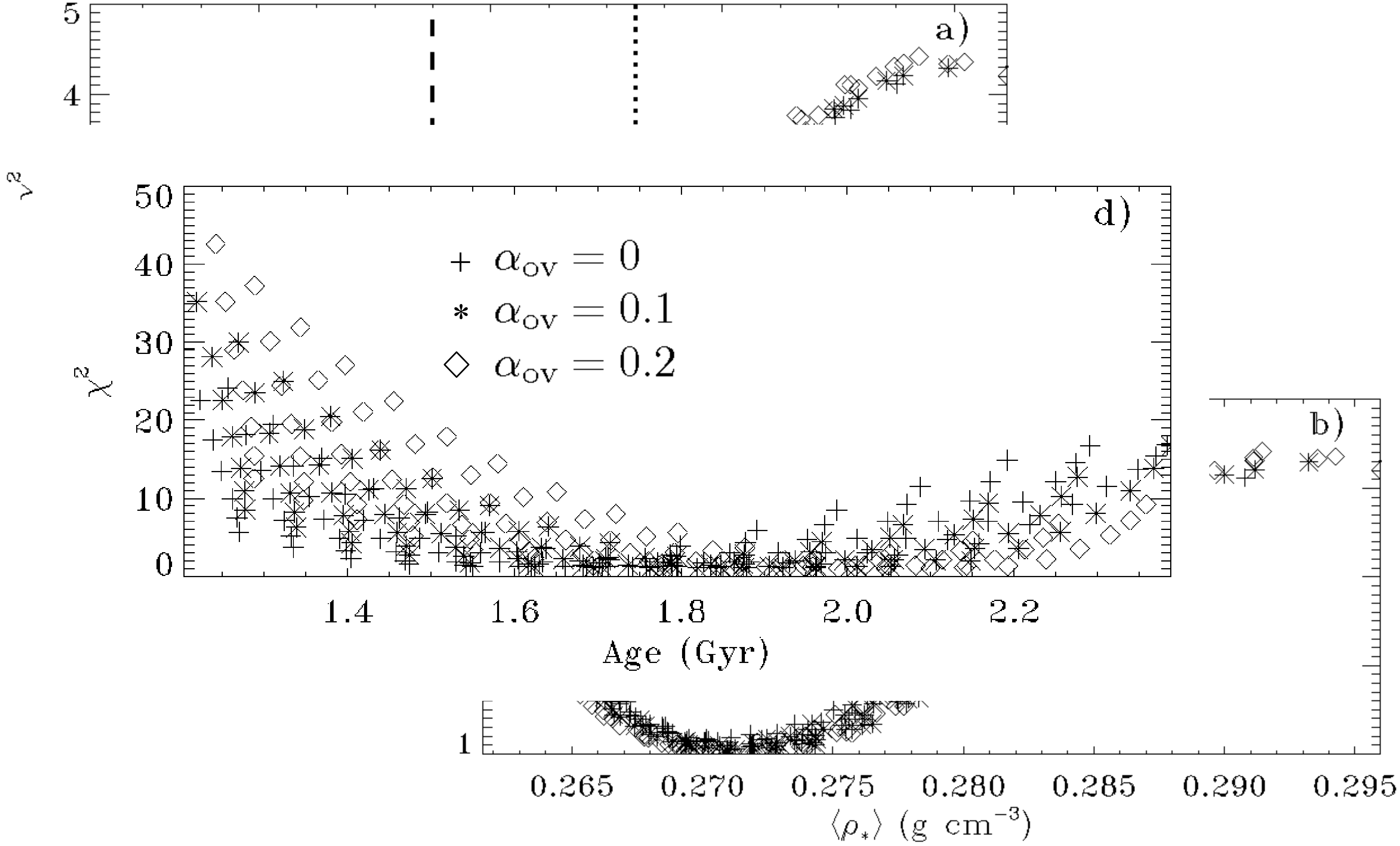


Least-squares fits



h ρ_* i = 0.271 +- 0.003 g cm^{-3}

Least-squares fits



Summary of results

$M = 1.520 \pm 0.036 M_\odot$

$R = 1.991 \pm 0.018 R_\odot$

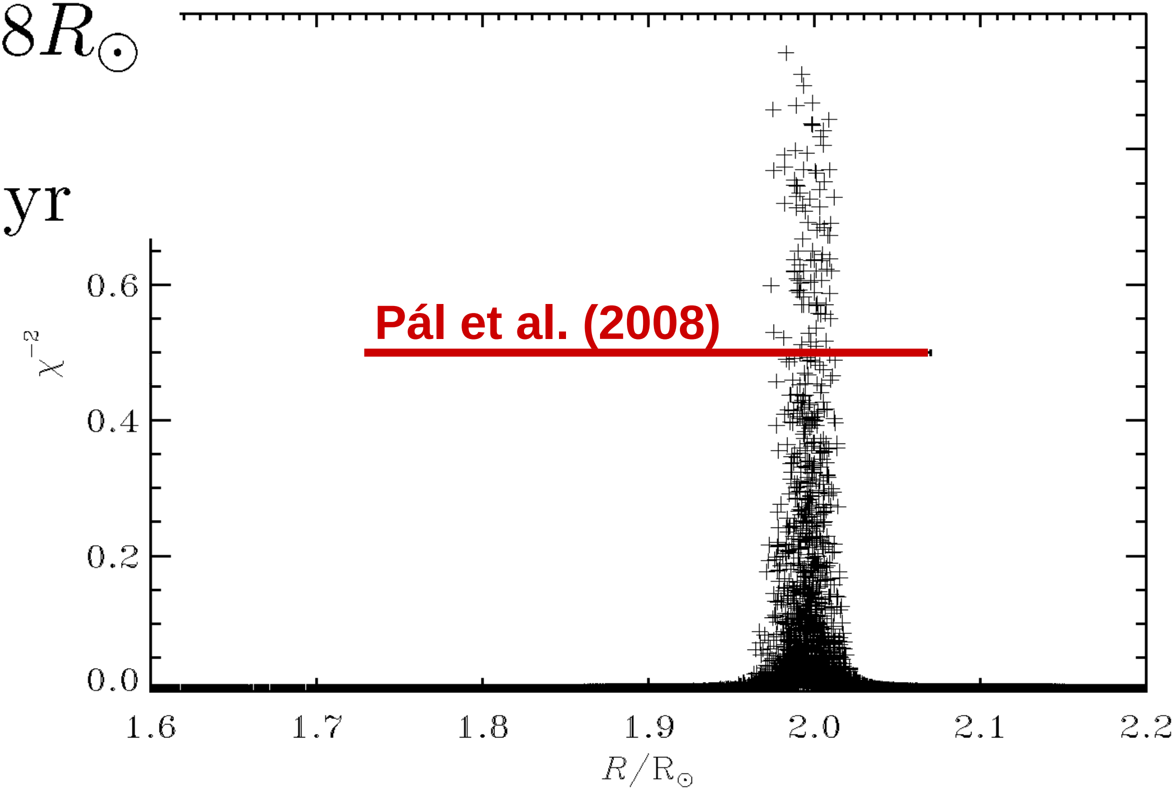
$\text{Age:} \quad 1.9 \pm 0.3\,\text{Gyr}$

Summary of results

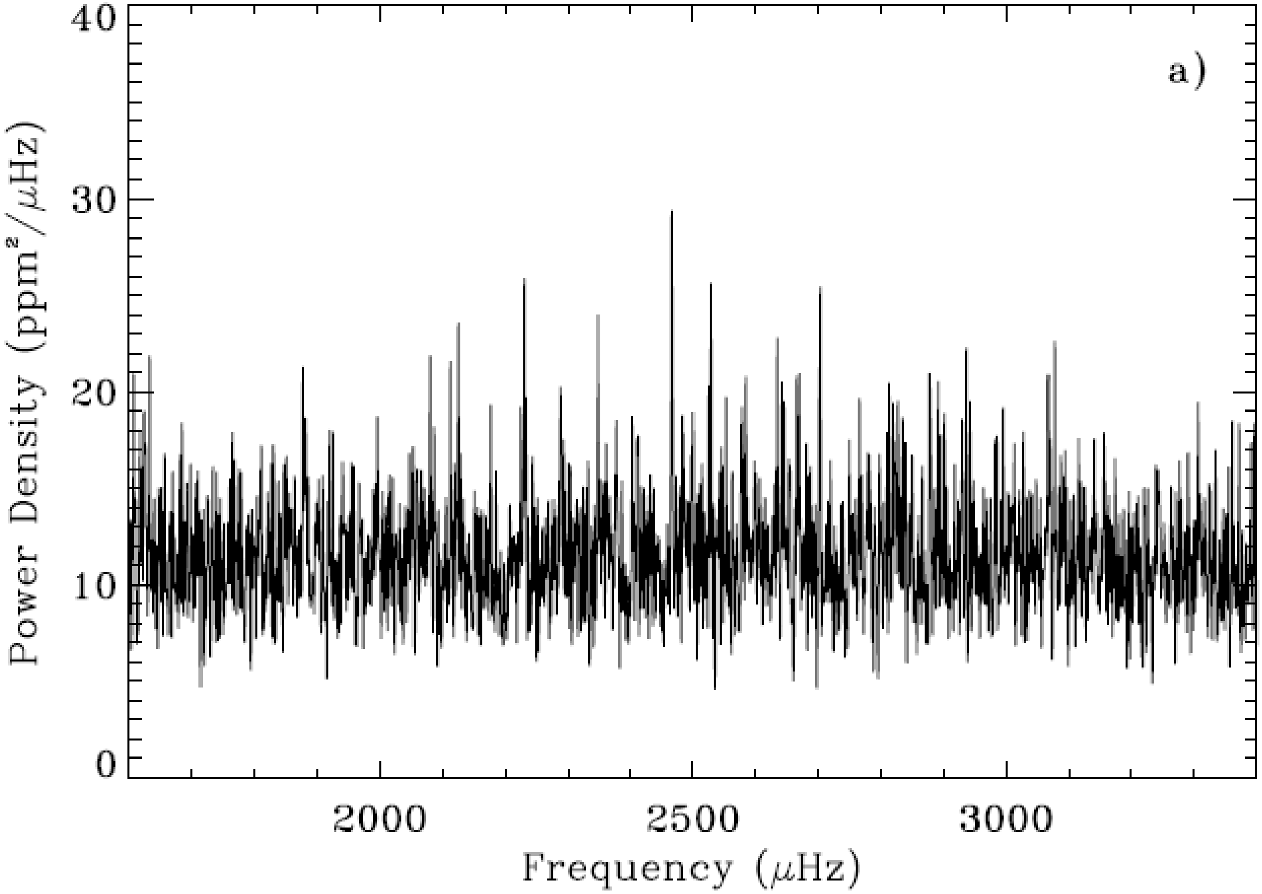
$$M = 1.520 \pm 0.036 M_\odot$$

$$R = 1.991 \pm 0.018 R_\odot$$

$$\text{Age:}\quad 1.9 \pm 0.3\,\text{Gyr}$$



Asteroseismology for Kepler 10b



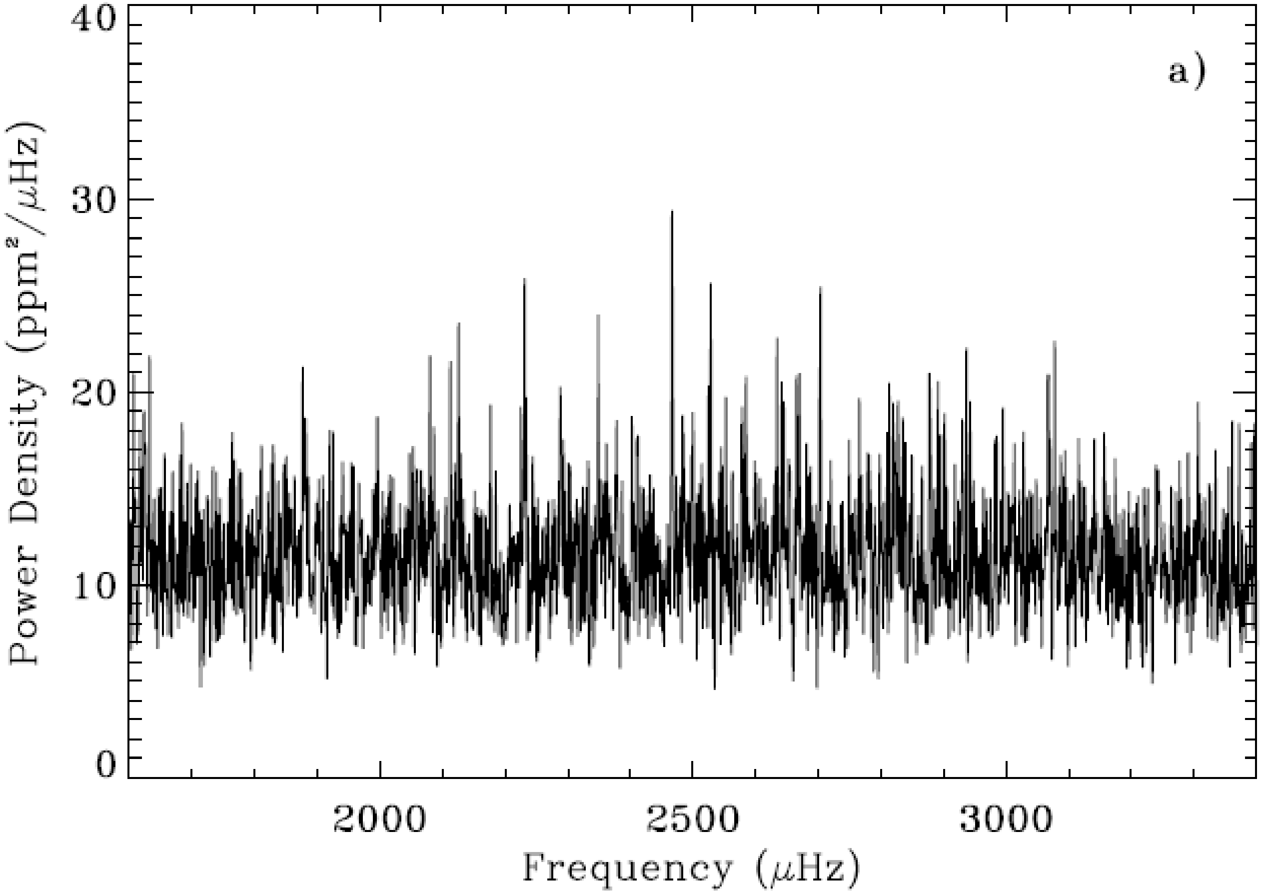
Asteroseismology for Kepler 10b

Star:

Mass:
0.90§ 0.06 M–

Radius:
1.06 §0.02 R–

Alge:
12 §5 Gyr



Kepler 10b, Kepler's first rocky planet

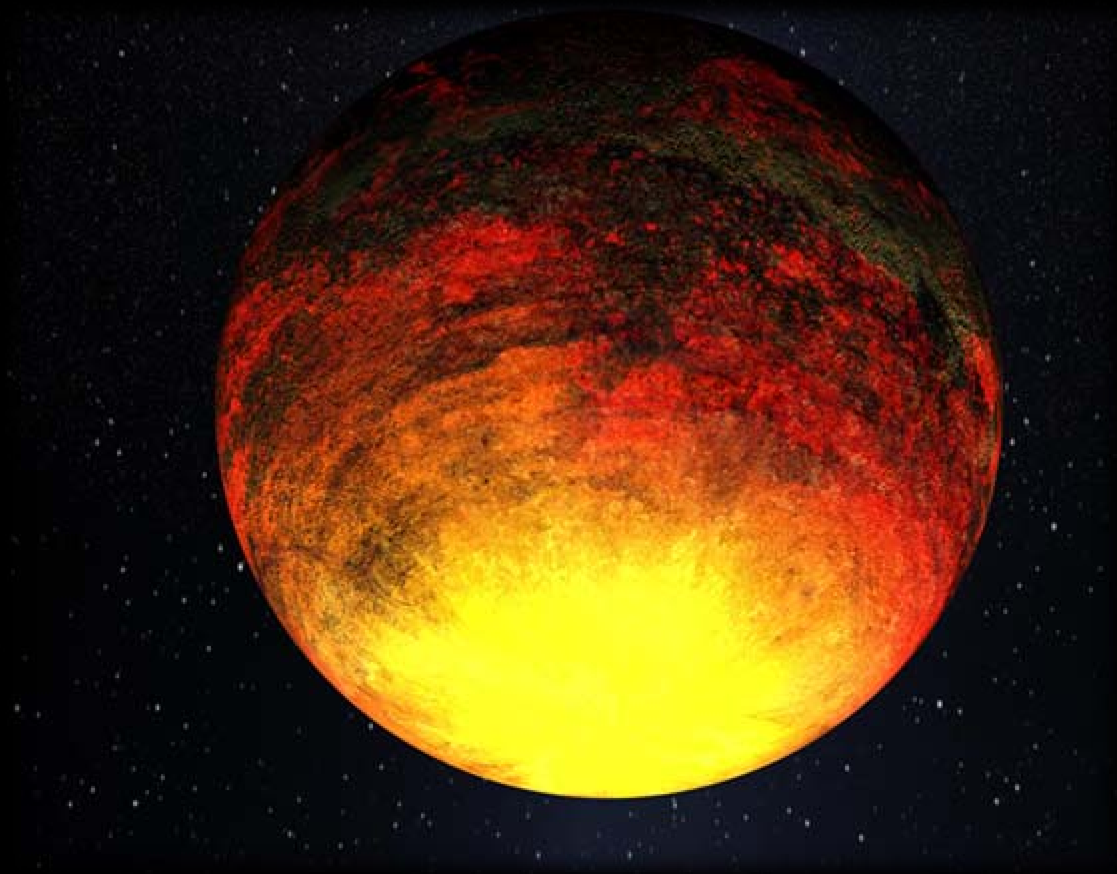
Planet:
Orbital period: 0.84 d

Radius:
1.42 +- 0.03 $R_{\copyright}$

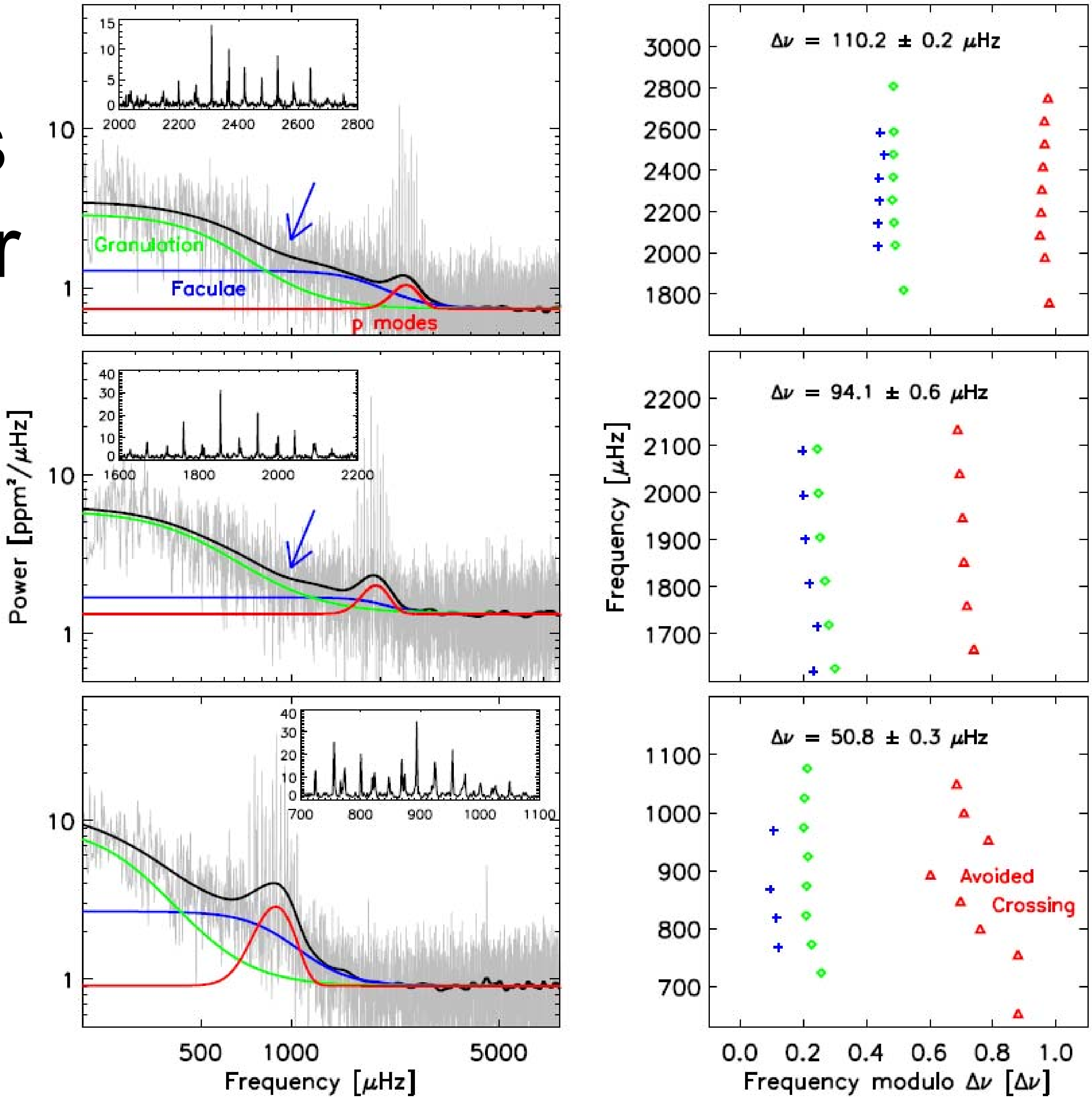
Mass:
4.6 +- 1.2 $M_{\copyright}$

Mean density:
8.8 +- 2.5 g/cm^3

Mean surface
temperature: 1800 K

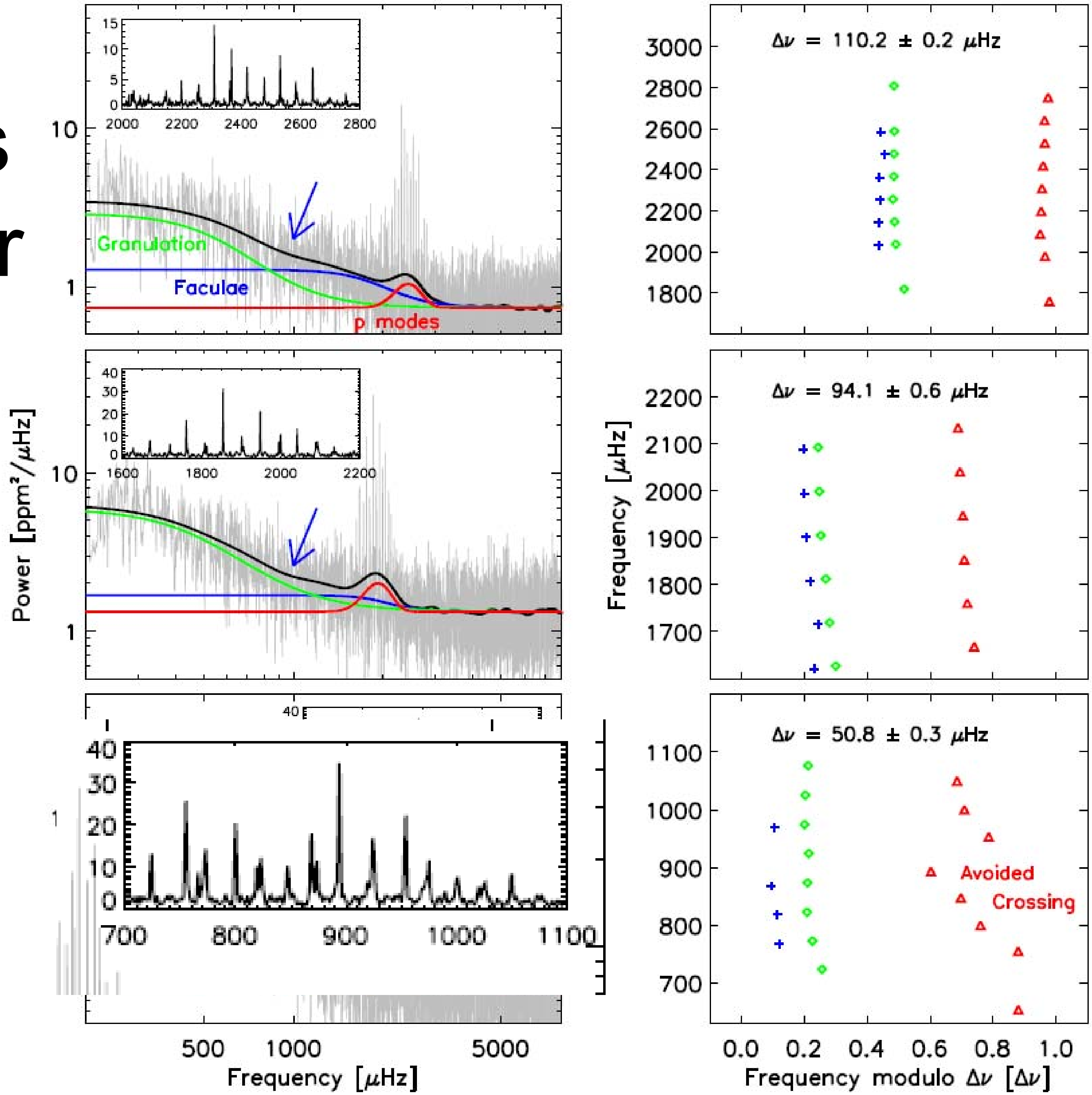


Solarlike oscillations from Kepler



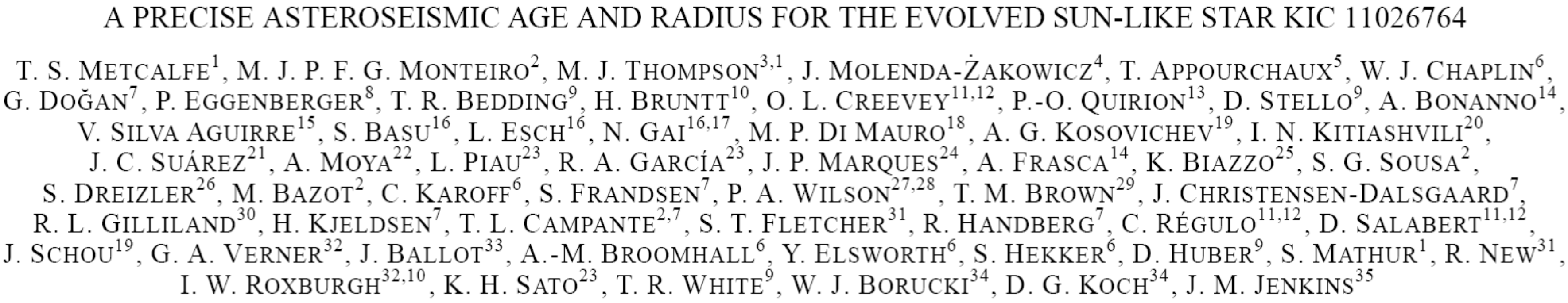
Chaplin et al (2010; ApJ 713, 169)

Solarlike oscillations from Kepler



Chaplin et al (2010; ApJ 713, 169)

The evolved solar-type star KIC 11026764 (Gemma)



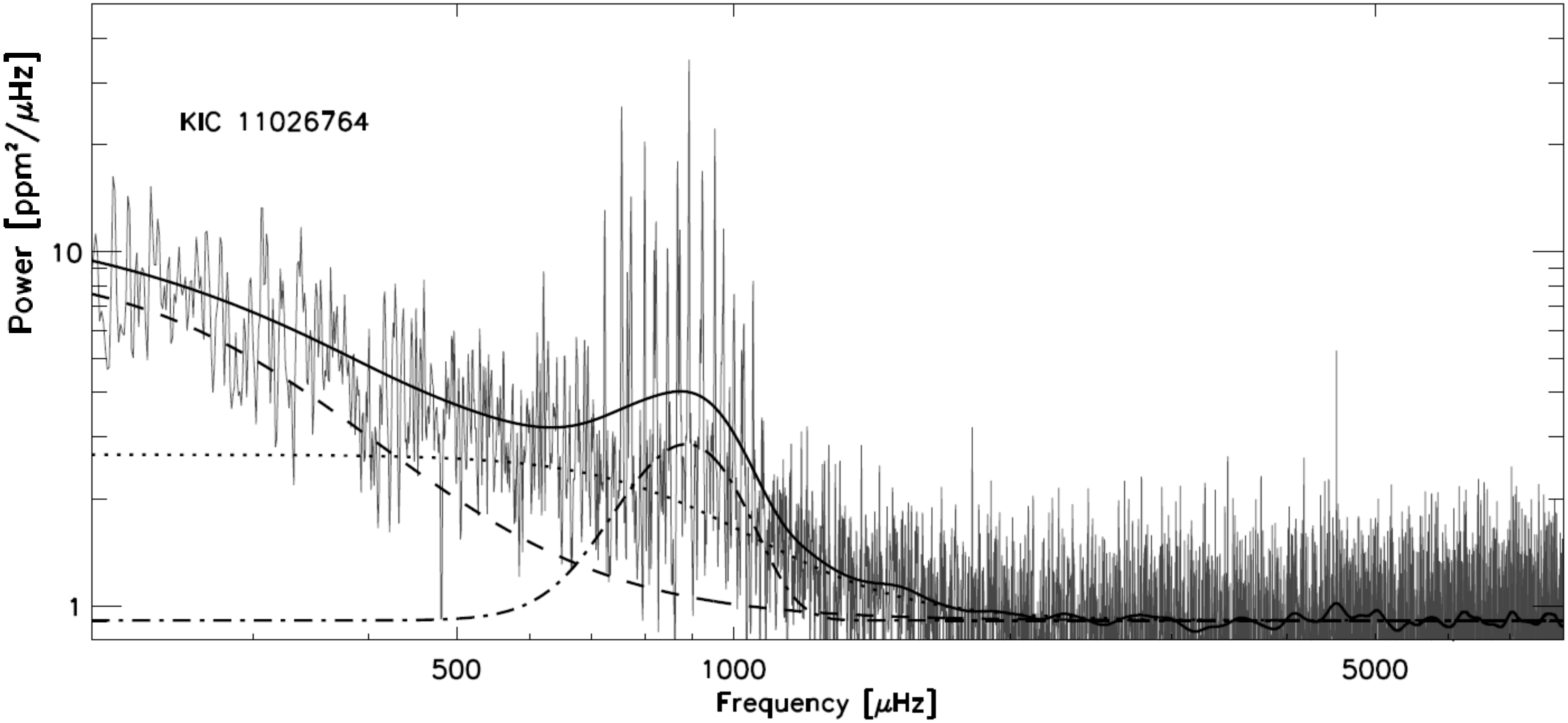
A PRECISE ASTEROSEISMIC AGE AND RADIUS FOR THE EVOLVED SUN-LIKE STAR KIC 11026764

T. S. Metcalfe[1], M. J. P. F. G. Monteiro[2], M. J. Thompson[3,1], J. Molenda-Żakowicz[4], T. Appourchaux[5], W. J. Chaplin[6], G. Doğan[7], P. Eggenberger[8], T. R. Bedding[9], H. Bruntt[10], O. L. Creevey[11,12], P.-O. Quirion[13], D. Stello[9], A. Bonanno[14], V. Silva Aguirre[15], S. Basu[16], L. Esch[16], N. Gai[16,17], M. P. Di Mauro[18], A. G. Kosovichev[19], I. N. Kitiashvili[20], J. C. Suárez[21], A. Moya[22], L. Piau[23], R. A. García[23], J. P. Marques[24], A. Frasca[14], K. Biazzo[25], S. G. Sousa[2], S. Dreizler[26], M. Bazot[2], C. Karoff[6], S. Frandsen[7], P. A. Wilson[27,28], T. M. Brown[29], J. Christensen-Dalsgaard[7], R. L. Gilliland[30], H. Kjeldsen[7], T. L. Campante[2,7], S. T. Fletcher[31], R. Handberg[7], C. Régulo[11,12], D. Salabert[11,12], J. Schou[19], G. A. Verner[32], J. Ballot[33], A.-M. Broomhall[6], Y. Elsworth[6], S. Hekker[6], D. Huber[9], S. Mathur[1], R. New[31], I. W. Roxburgh[32,10], K. H. Sato[23], T. R. White[9], W. J. Borucki[34], D. G. Koch[34], J. M. Jenkins[35]

(2010; ApJ 723, 1583)

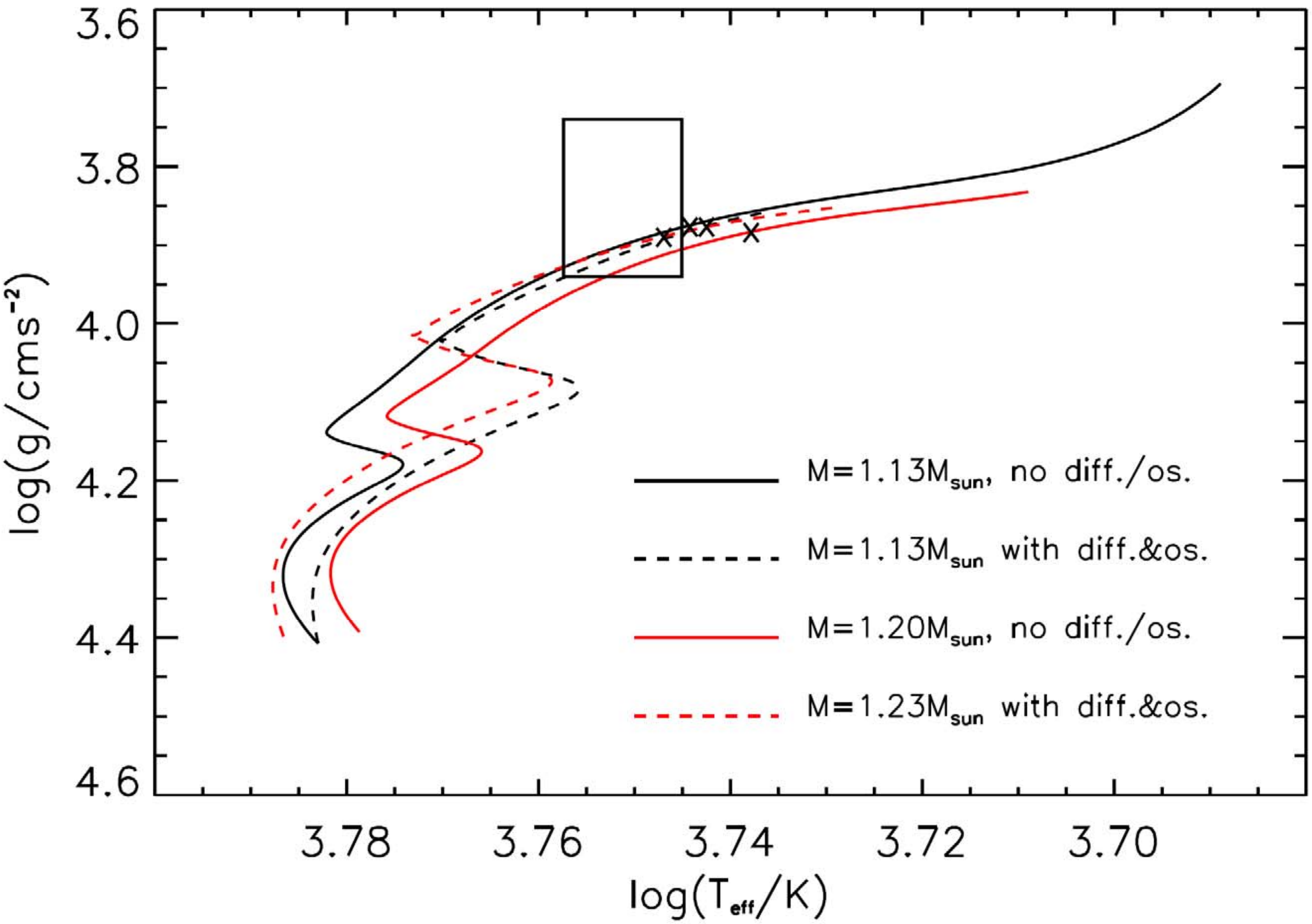
With thanks to Gülnur Doğan, Aarhus University, and Michael Thompson, Univ. of Sheffield / HAO, NCAR

Power spectrum

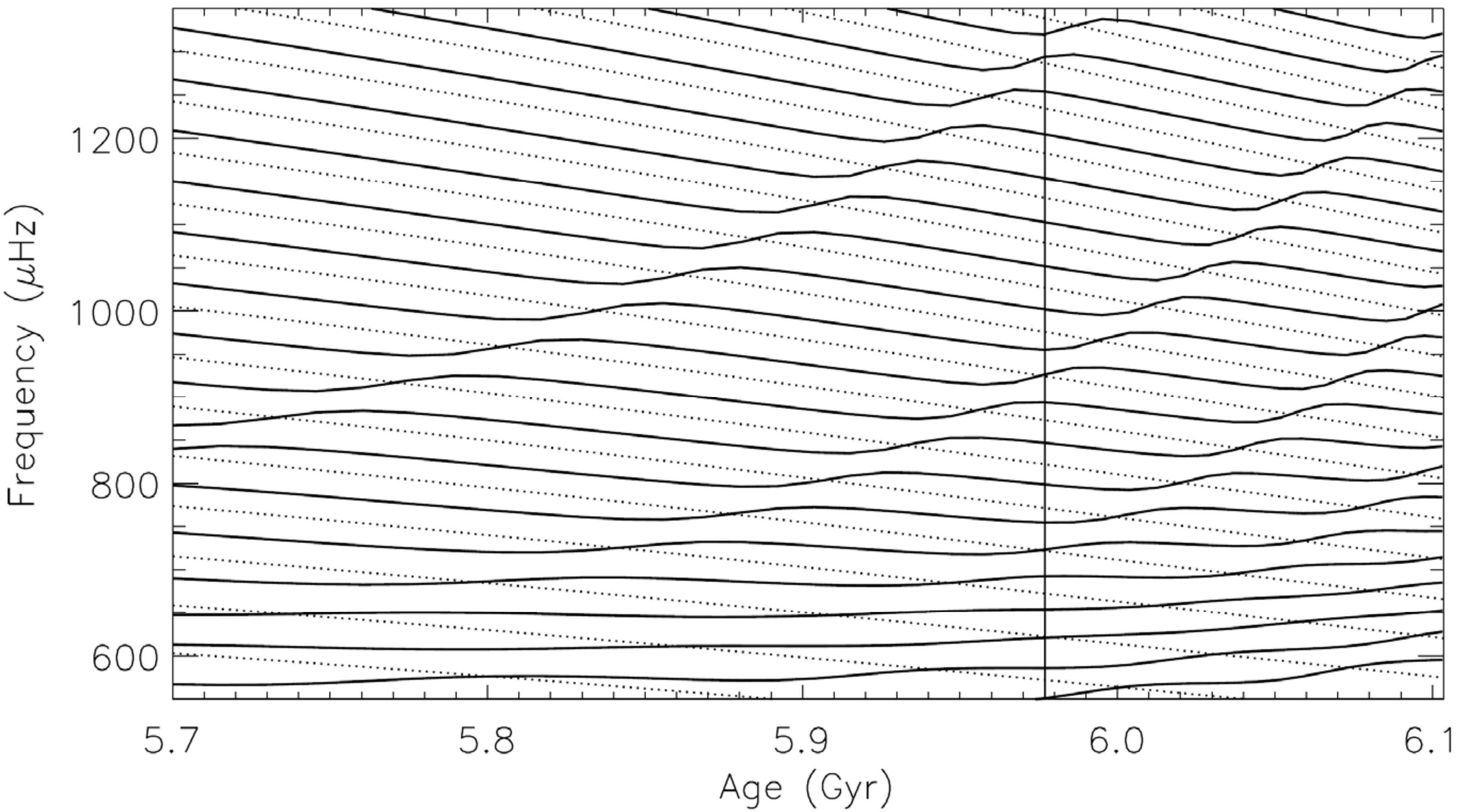


Chaplin et al. (2010, ApJ 713, L169)

Evolution in global properties

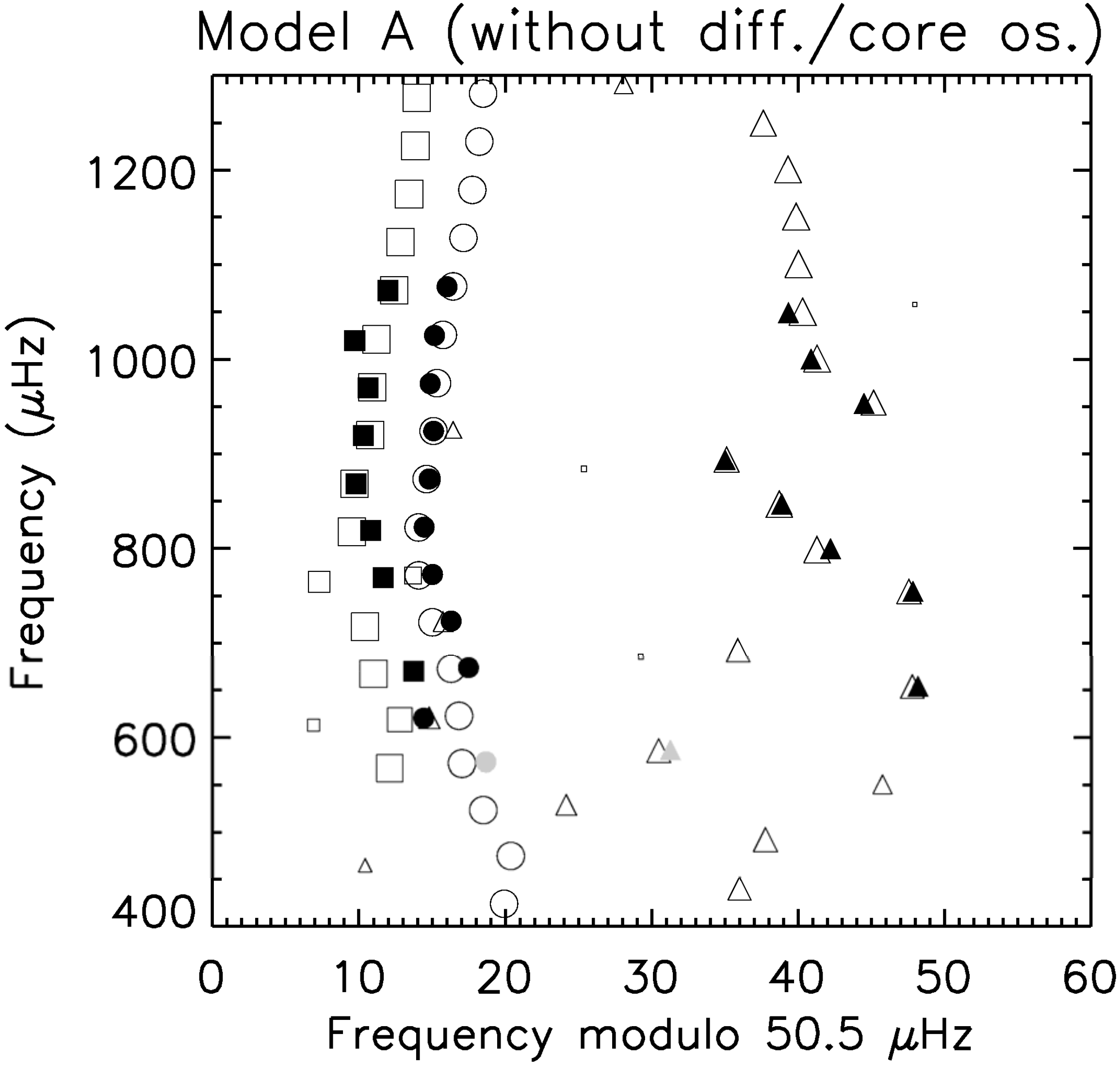


Mixed modes



Metcalfe et al. 2010

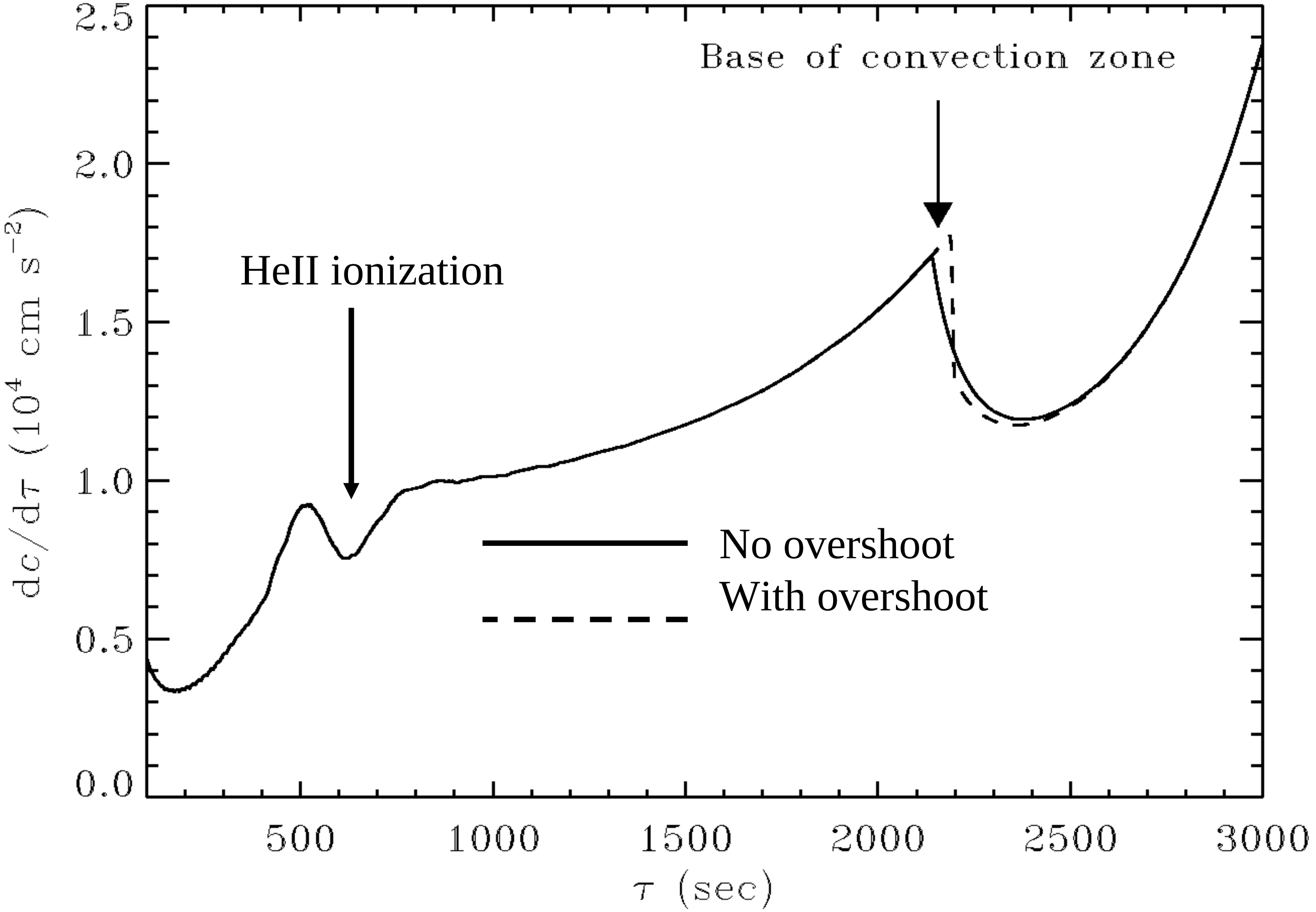
Echelle diagram



Things to come

(or already coming)

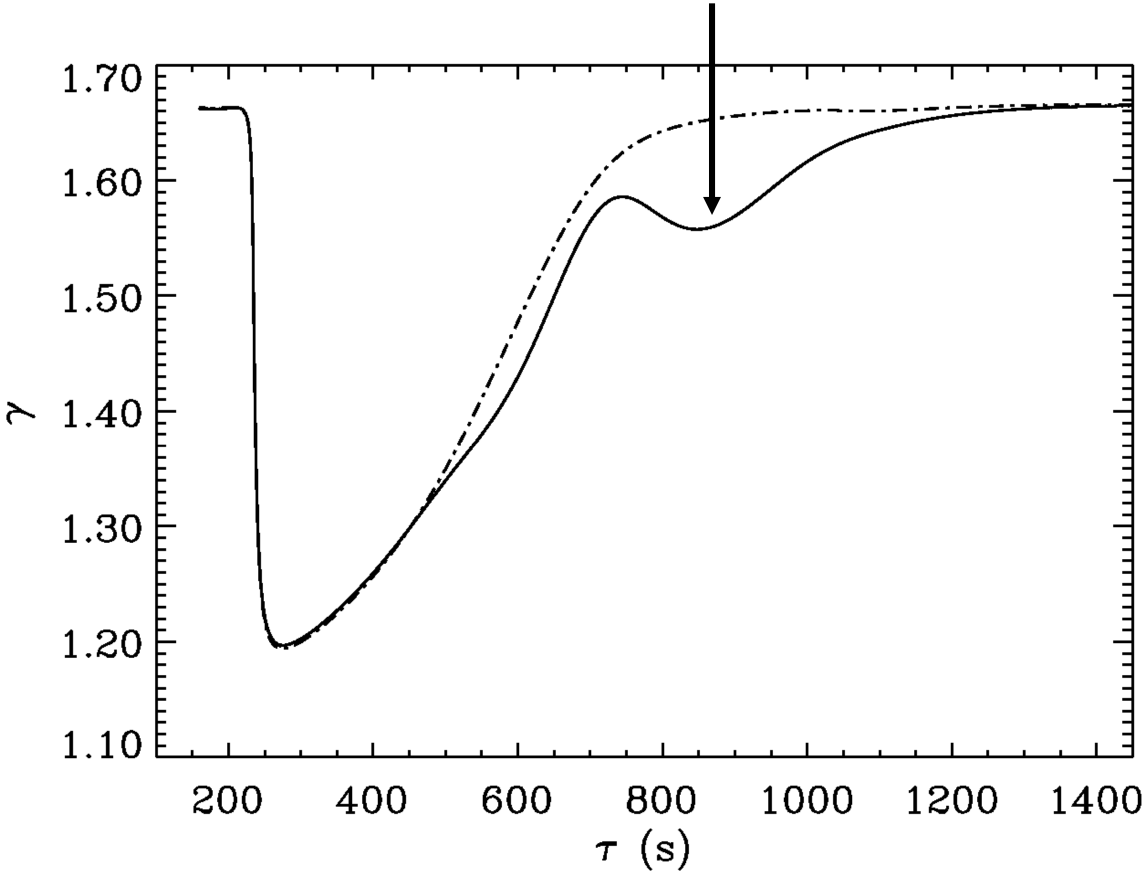
Sharp features in stellar models



$$\tau = \int_r^R \mathrm{d}r/c$$

Γ_1 and ionization

HeII ionization



$$\tau = \int_r^R \mathrm{d}r/c$$

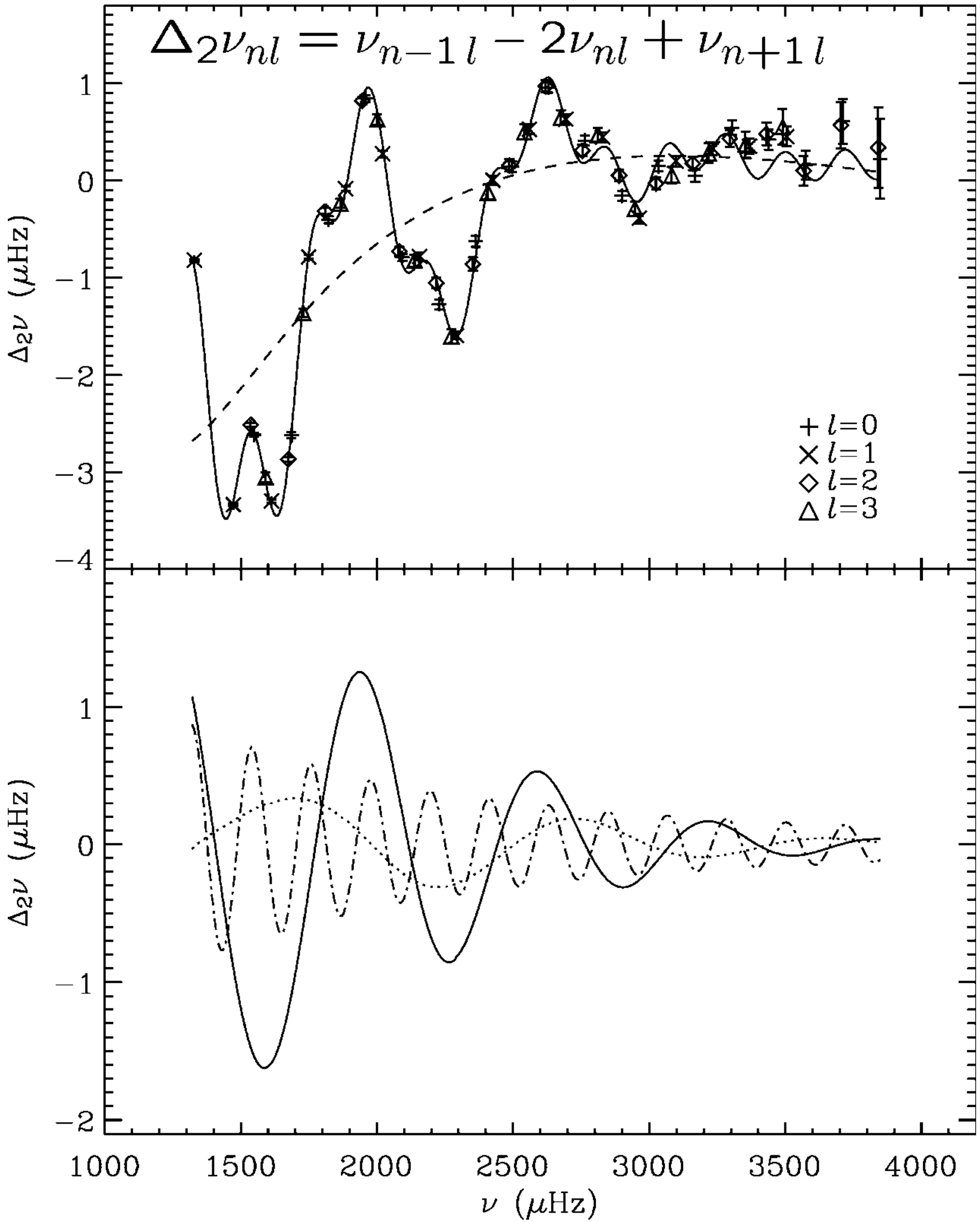
Frequency perturbation caused by glitch

Compare with model where glitch has been smoothed:

$$\pm! = A(!) \sin(2! ¿_g + Á)$$

where $¿_g$ is acoustical depth of glitch.

Oscillatory signals



Fit

He I

He II

BCZ

BiSON frequencies.
Houdek & Gough (2007; MNRAS 375, 861)

Effects of rotation

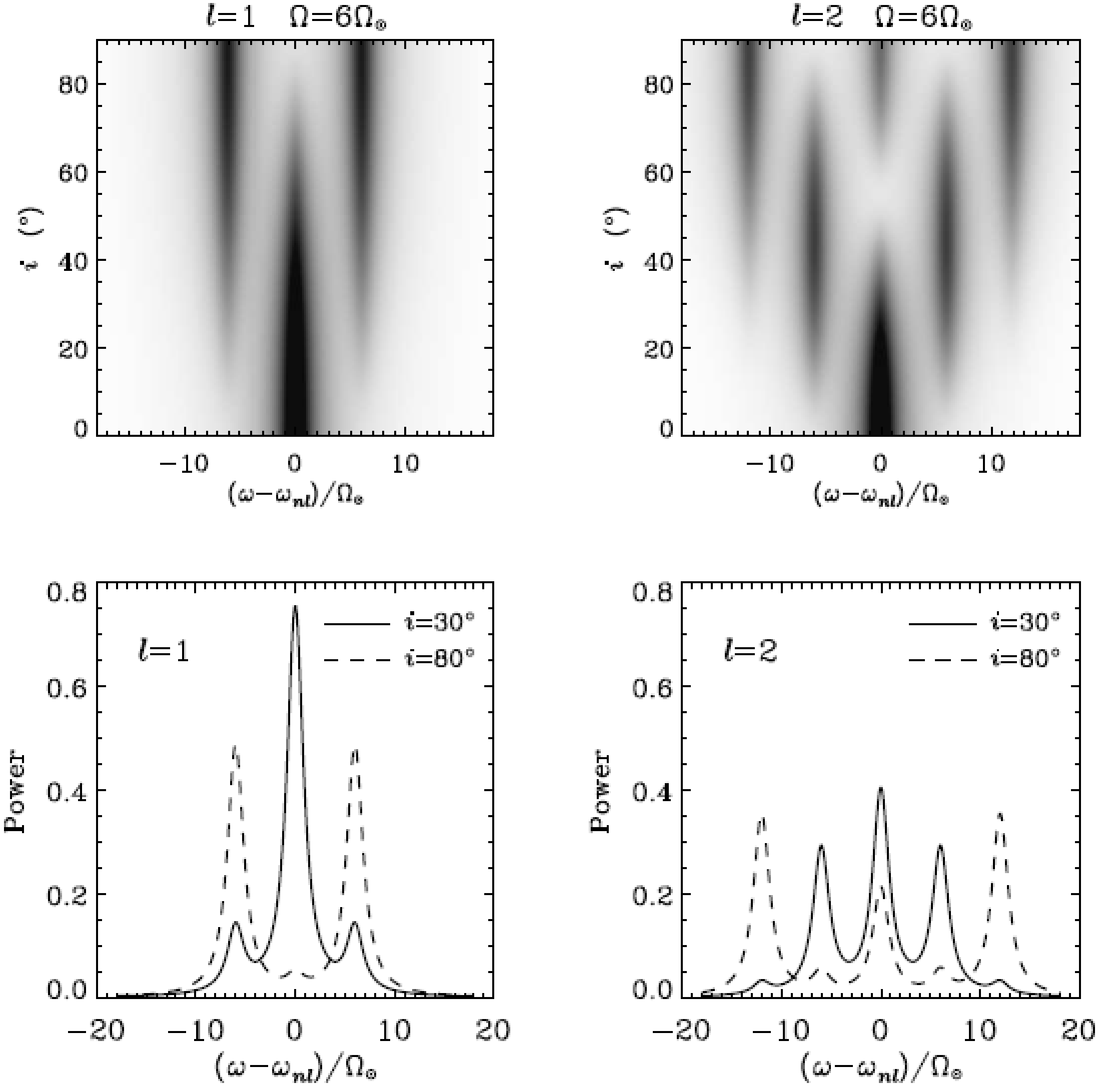
$$\delta\omega_{nlm} = m \int_0^R \int_0^\pi K_{nlm}(r,\theta)\Omega(r,\theta) r \mathrm{d}r \mathrm{d}\theta \ ,$$

For p modes, except very low degree:

$$\delta\omega_{nlm} \simeq m \frac{\int_V \rho |\boldsymbol{\delta r}|^2 \Omega \mathrm{d}V}{\int_V \rho |\boldsymbol{\delta r}|^2 \mathrm{d}V} = m\langle\Omega\rangle$$

Geometry of rotation

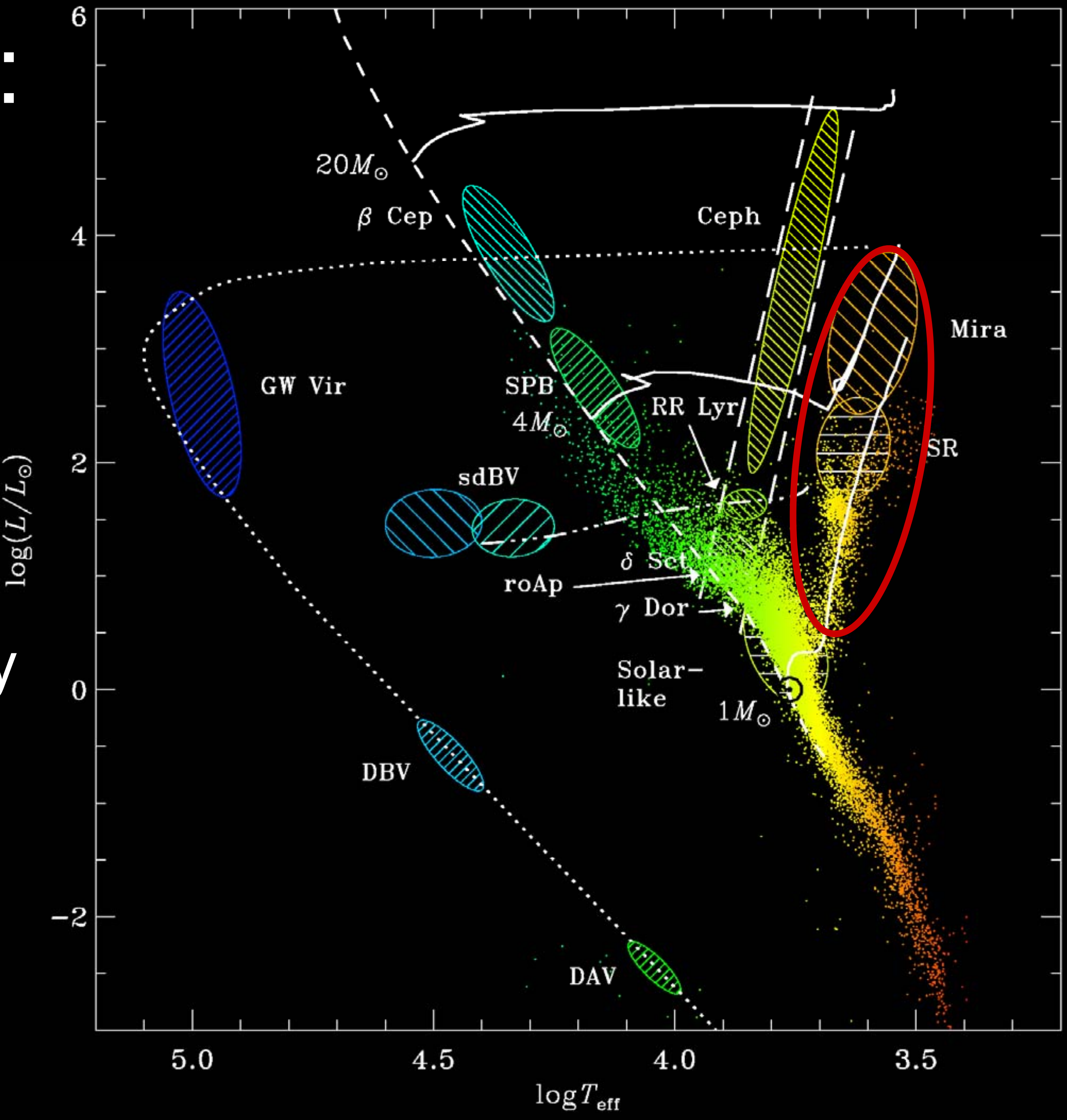
Assume same average amplitude



Gizon & Solanki (2003)

Red giants:

high points of space asteroseismology



A prediction

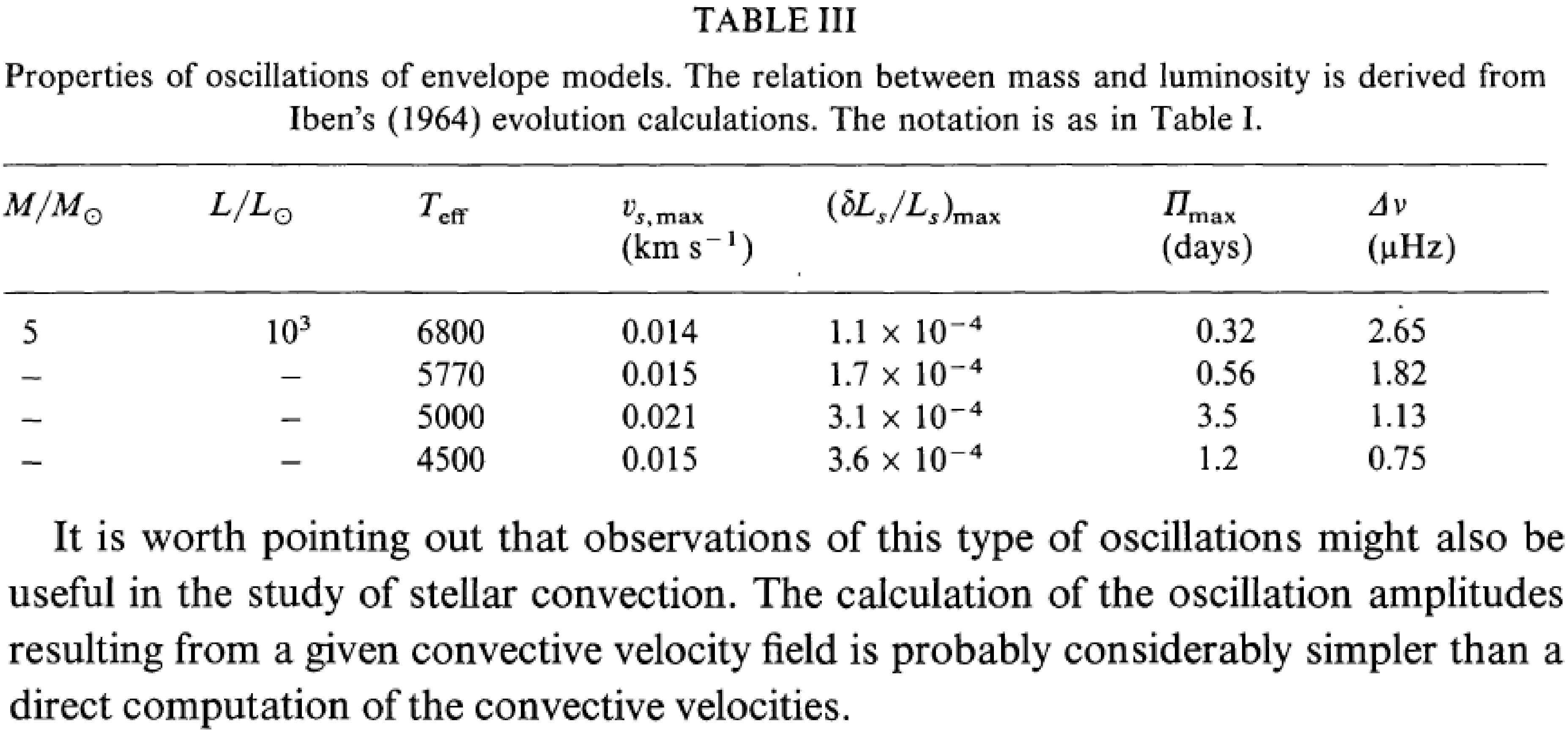


TABLE III

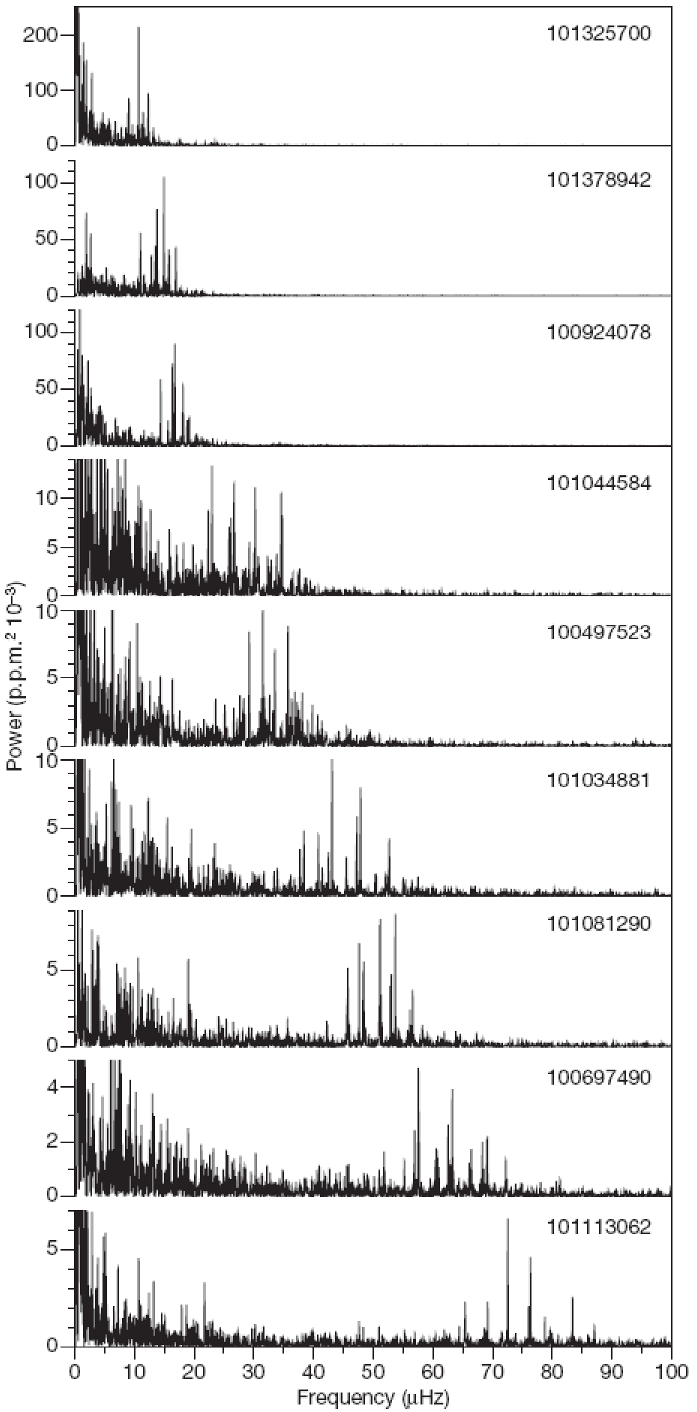
Properties of oscillations of envelope models. The relation between mass and luminosity is derived from Iben's (1964) evolution calculations. The notation is as in Table I.

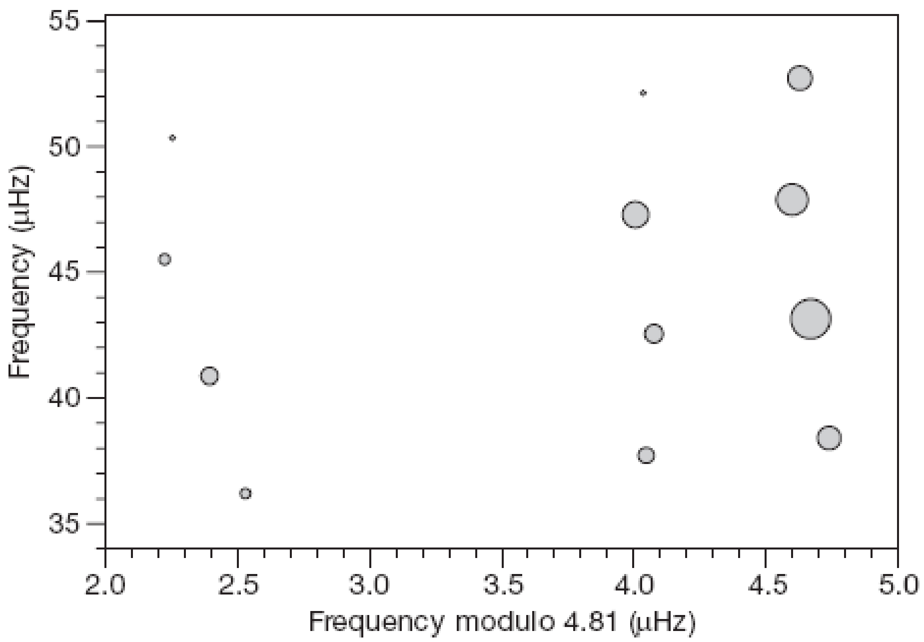
$M/M_\odot$	$L/L_\odot$	$T_{\rm eff}$	$v_{s,\max}$ (km s^{-1})	$(\delta L_s/L_s)_{\max}$	$\Pi_{\max}$ (days)	$\Delta\nu$ (μHz)
5	10^3	6800	0.014	1.1×10^{-4}	0.32	2.65
–	–	5770	0.015	1.7×10^{-4}	0.56	1.82
–	–	5000	0.021	3.1×10^{-4}	3.5	1.13
–	–	4500	0.015	3.6×10^{-4}	1.2	0.75

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)

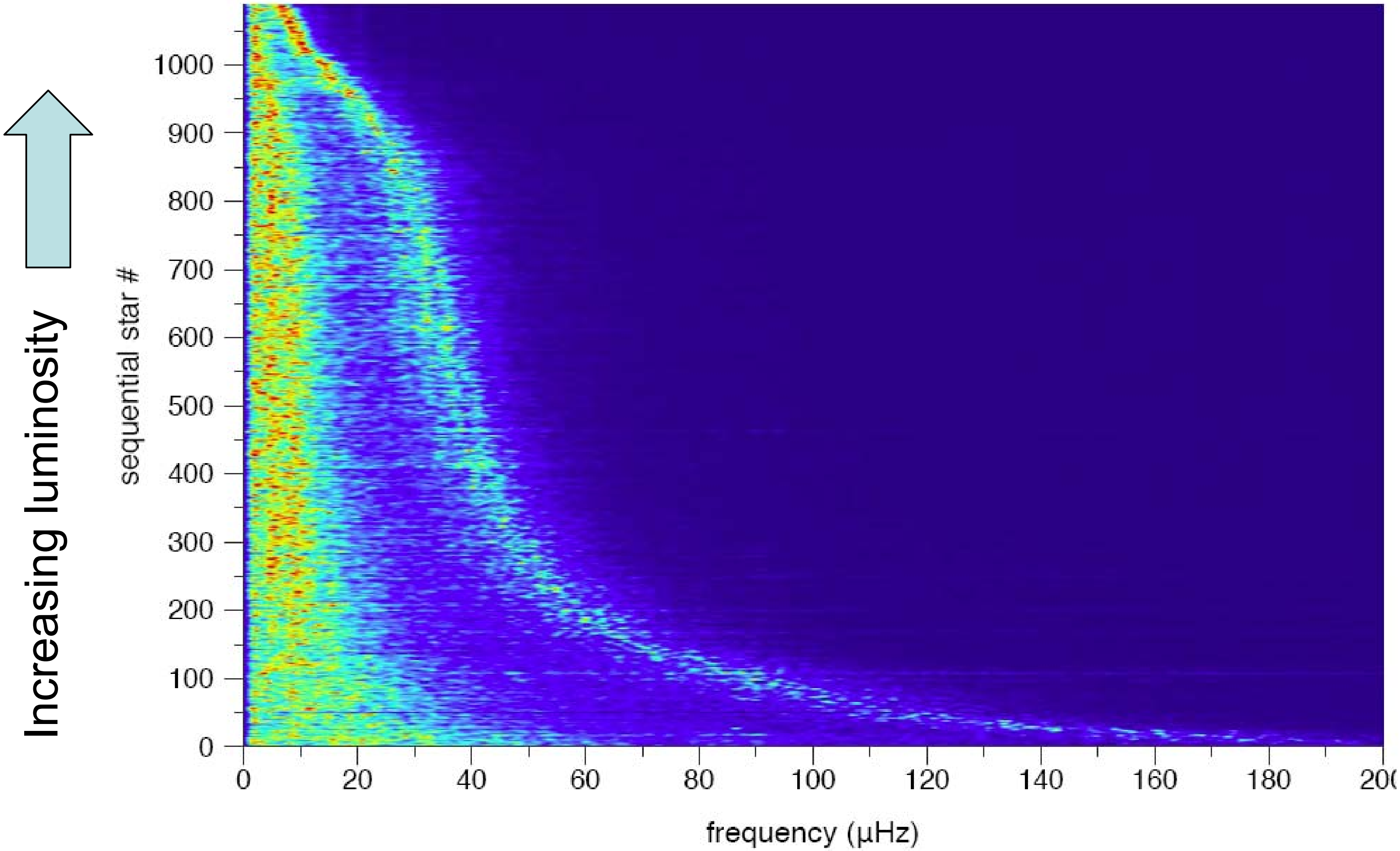
Nonradial oscillations in red giants





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

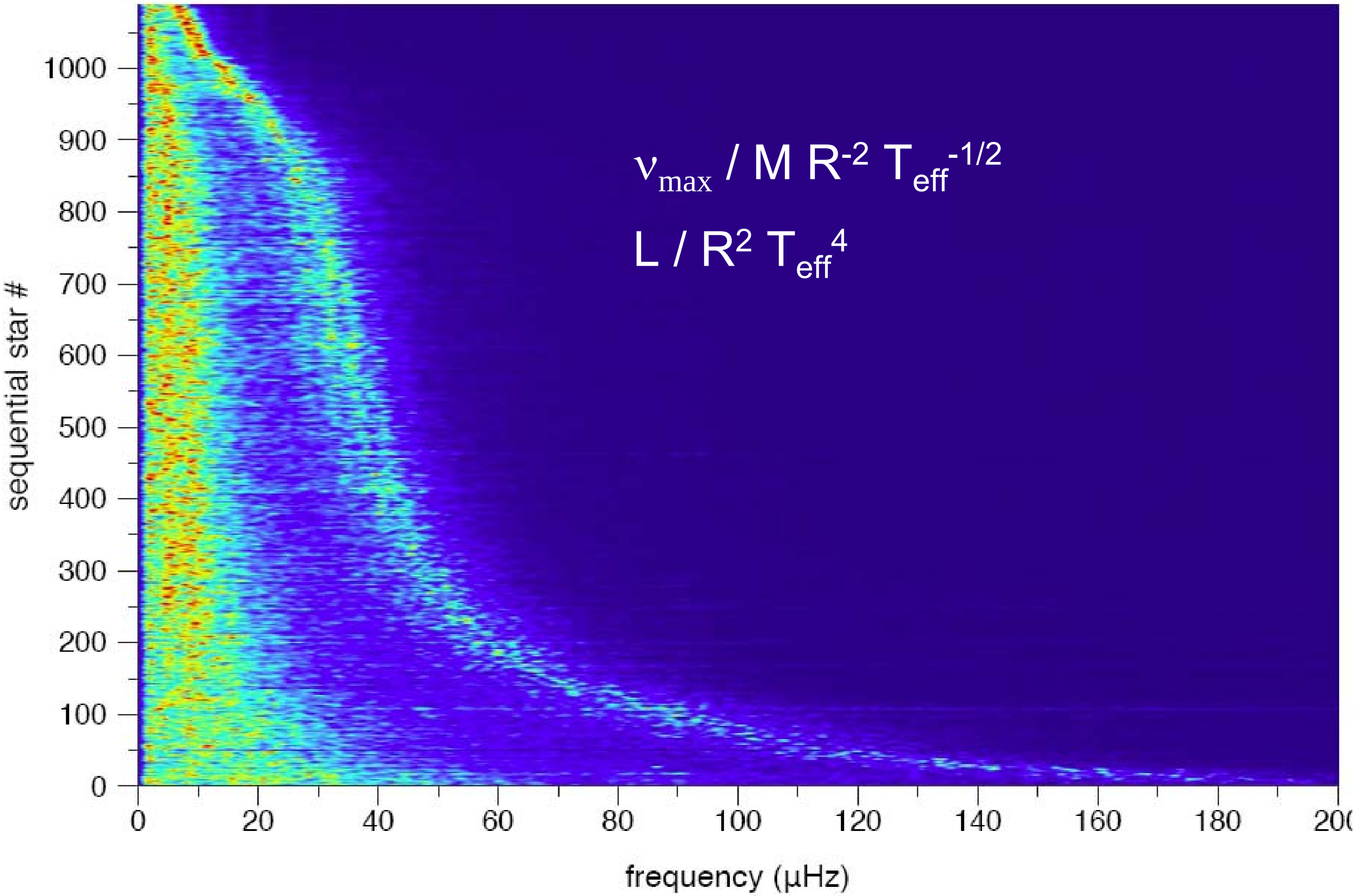
Red giants, stacked power spectra



Gilliland et al. (2010; PASP 122, 131)

Red giants, stacked power spectra

Increasing luminosity

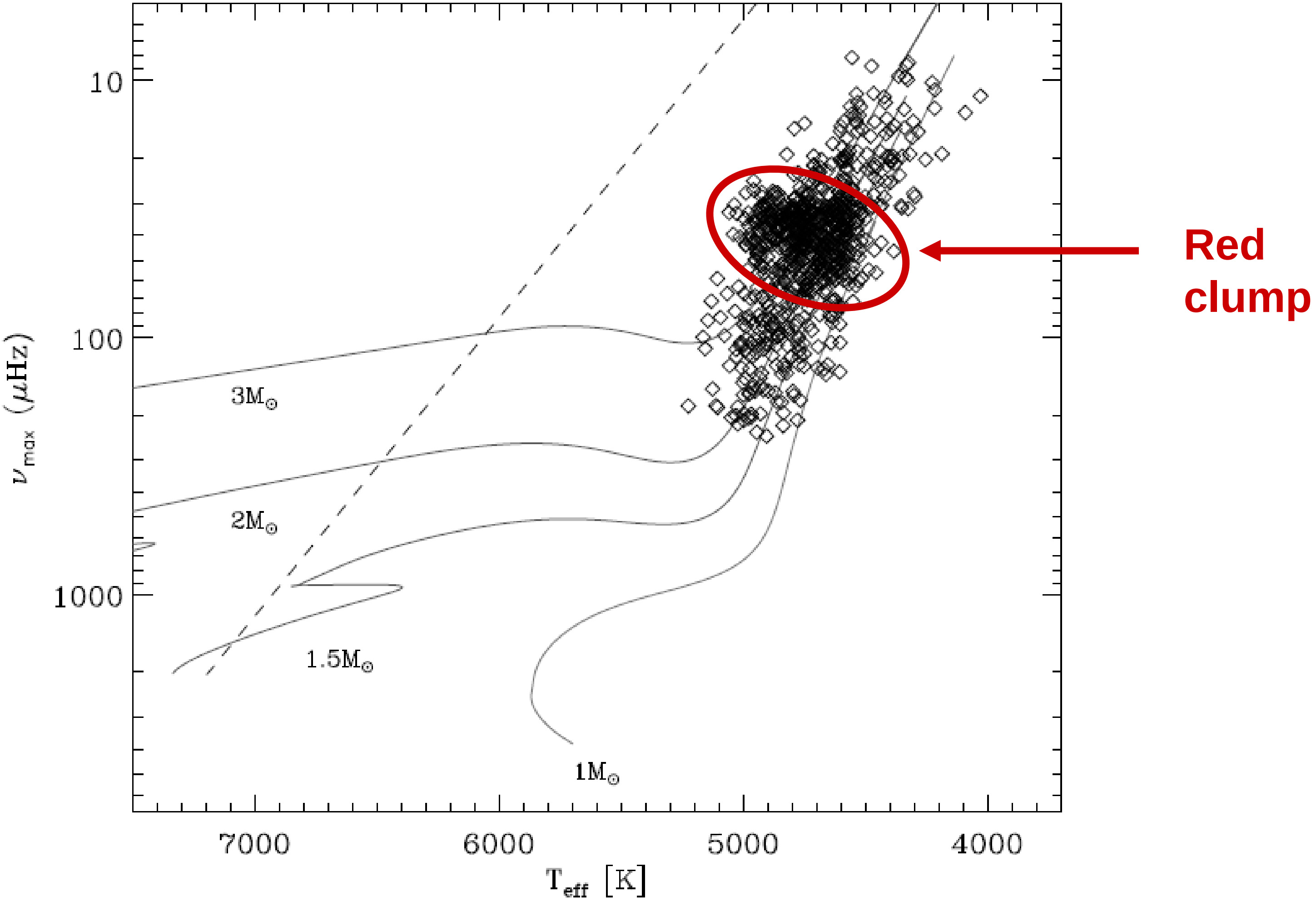


ν_{max} / M R^{-2} $T_{eff}^{-1/2}$

L / R^2 T_{eff}^4

Gilliland et al. (2010; PASP 122, 131)

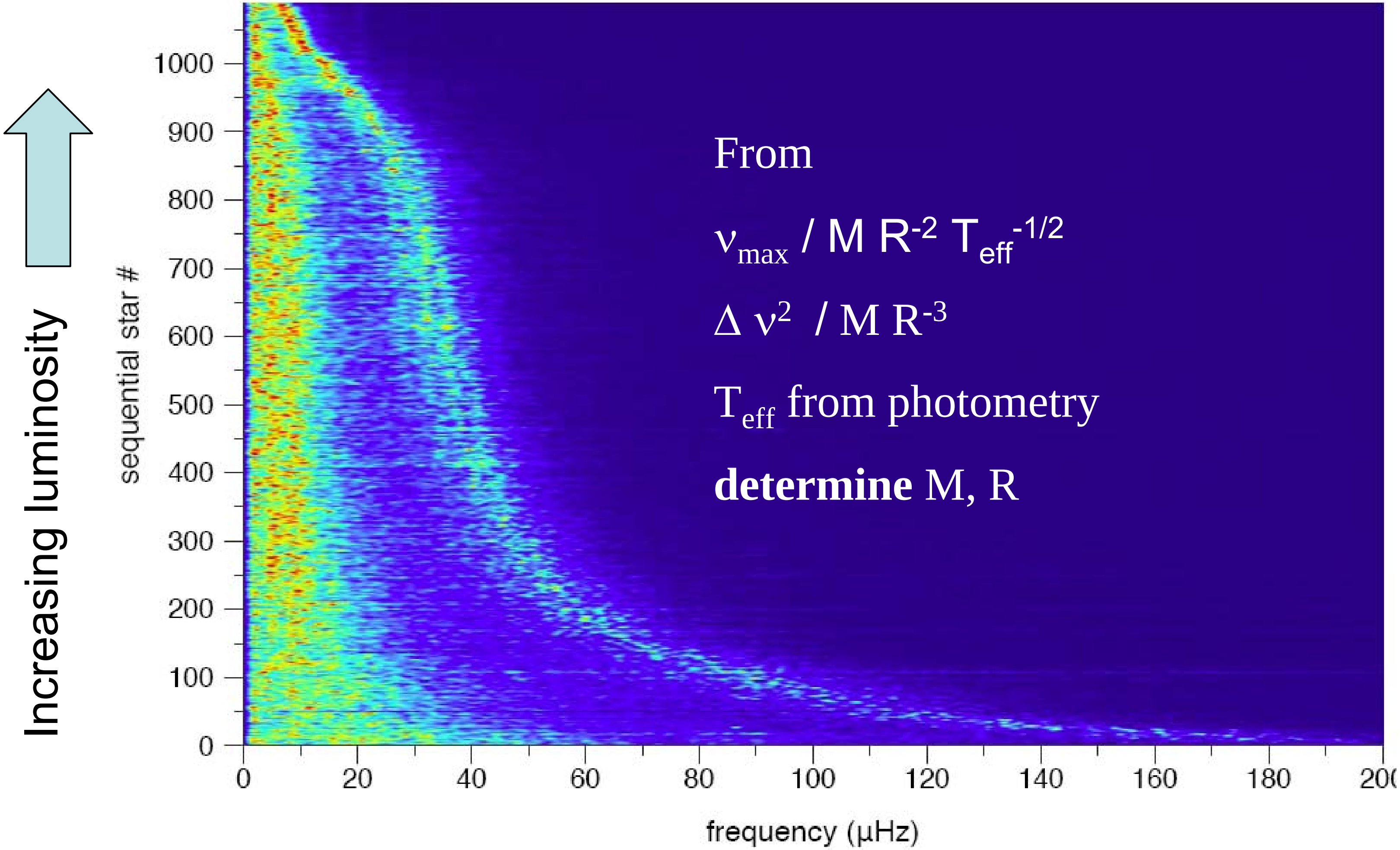
A HR diagram in terms of ν_{max}



Red clump

Huber et al. (2010)

Red giants, stacked power spectra



From

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

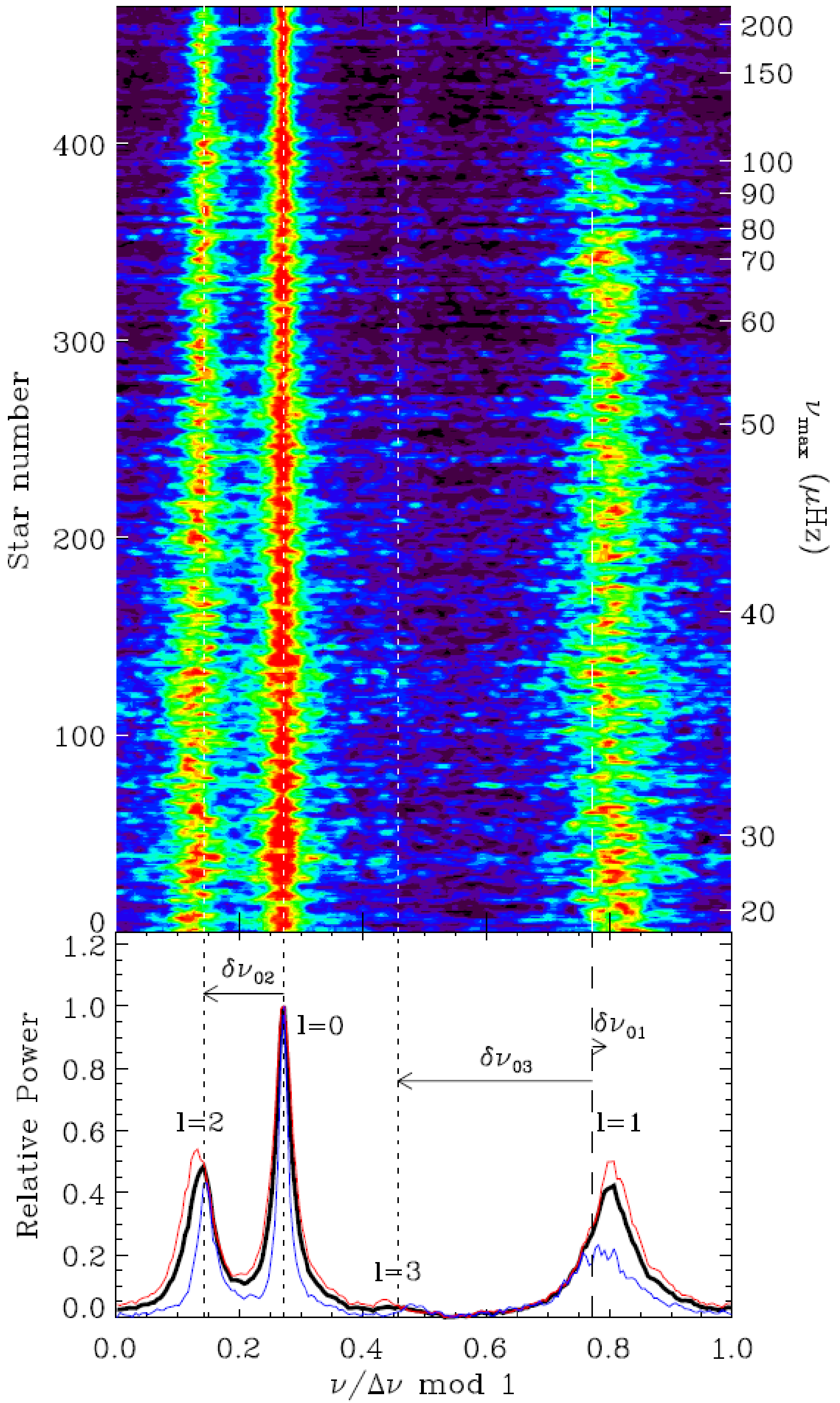
$\Delta \nu^2 / M R^{-3}$

T_{eff} from photometry

determine M, R

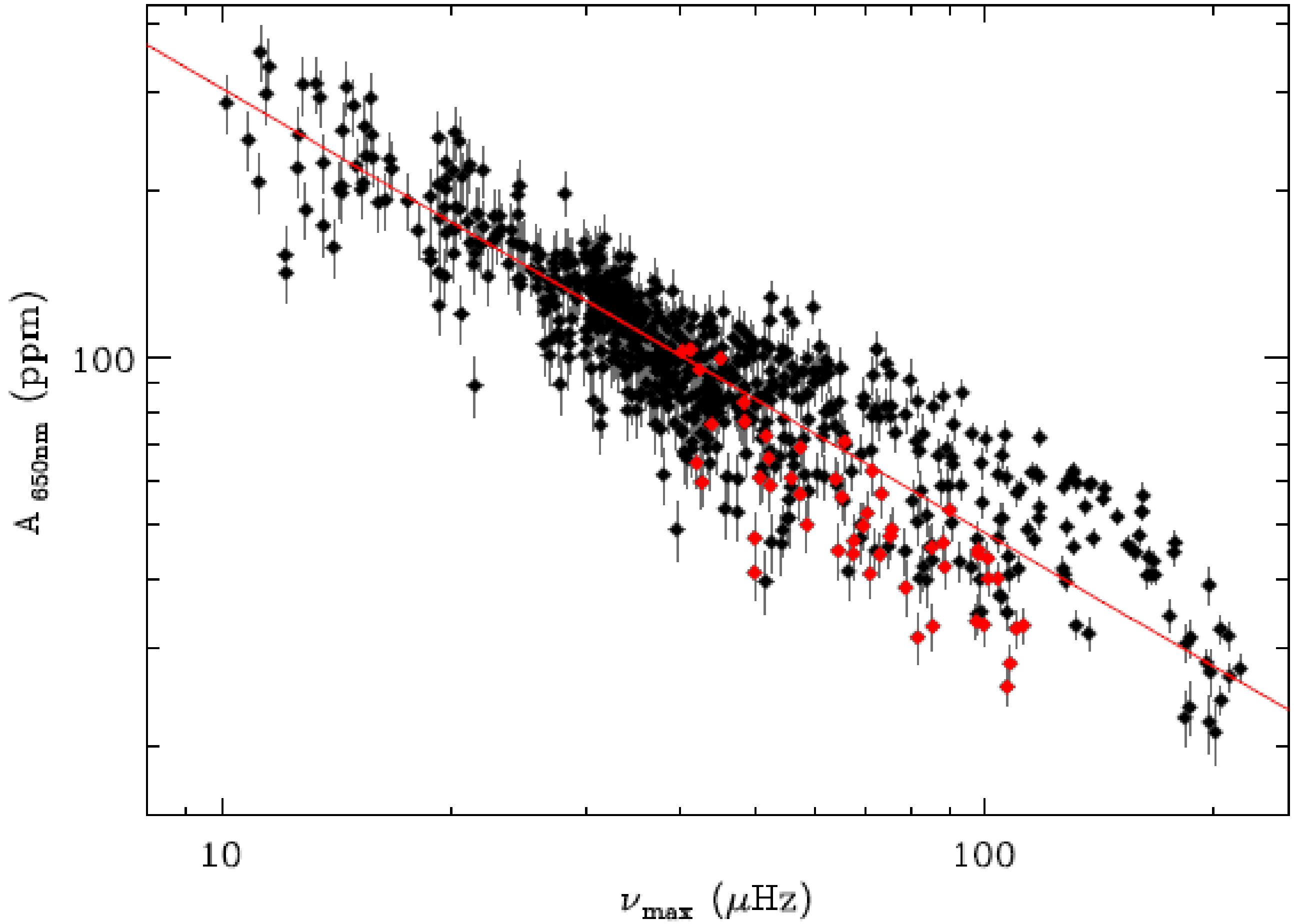
Gilliland et al. (2010; PASP 122, 131)

Combined scaled échelle diagram

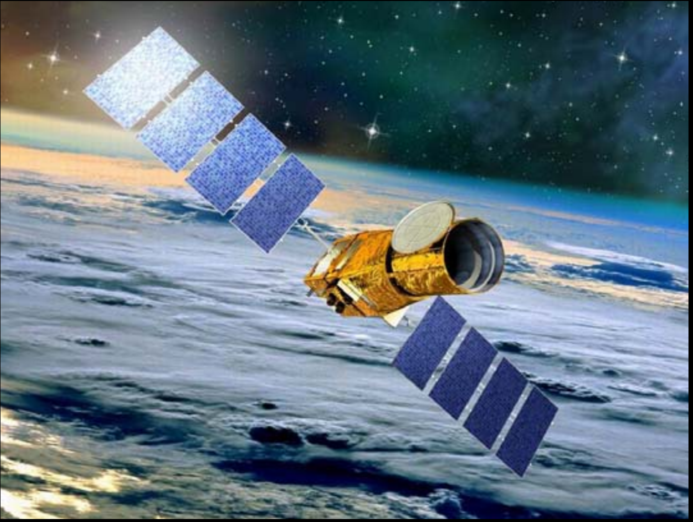


Huber et al. (2010)

Amplitude



Huber et al. (2010)



CoROT, Kepler, PLATO, ….

The fun is just starting!