Asteroseismology

Data analysis and diagnostics

Why do stars oscillate?

- convective outer layers in which stochastic excitation of oscillations takes place
- some outer layers act as a heat engine: partial ionisation zones absorb and accumulate energy generated in the stellar interior (opacity mechanism)
- forced oscillations may occur due to tidal effects in close binaries

Heat engine: opacity (κ) mechanism

How could the opacity increase with compression?
Kramers law:

$$\kappa \propto \frac{\rho}{T^{3.5}}$$

compression: ρ, T increase, opacity decrease
special circumstances:

partial ionization zones

Heat engine: opacity (κ) mechanism

hot star T_{eff} = 7500 K:
He II ionization zone close to the surface ⇒ density to low to drive pulsations
⇒ *blue edge* instability strip

cool star T_{eff} = 5500 K:
He II ionization zone deep enough to drive pulsations, BUT pulsations damped in outer layers due to convection
⇒ *red edge* instability strip

Convective blocking

Convection timescales too slow to respond to pulsations

→ Effective blocking by convection of the luminosity perturbation at the base of the convective zone, leading to heating in phase with compression

→ Heat-engine

Stochastic 'solar-like' oscillations

acoustic energy present in the outer convection zone such that the star resonates in some of its natural oscillation frequencies, i.e., some of the stochastic noise is transferred to energy of global oscillations

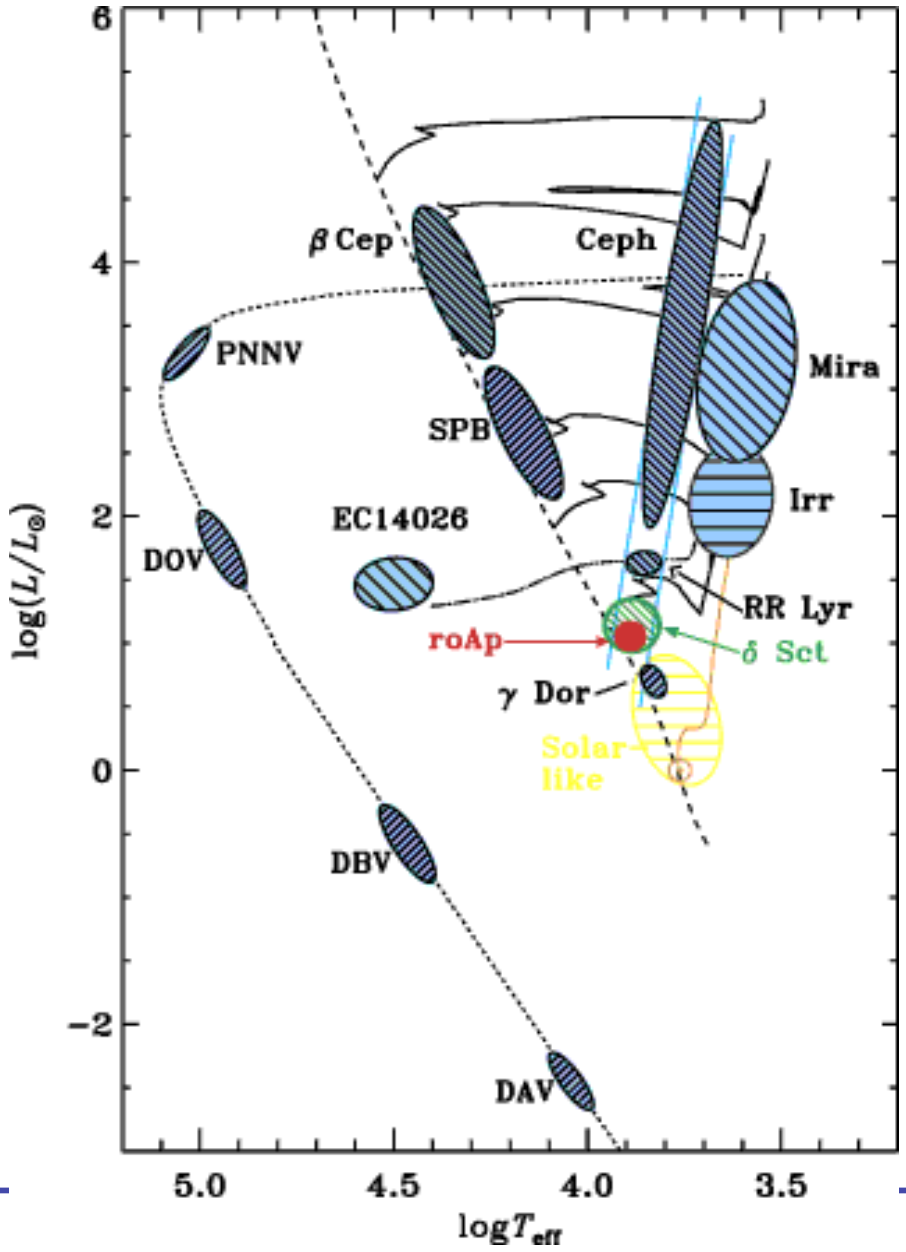
$\Rightarrow$ thought to be present in all stars with turbulent outer layers, i.e., the Sun, red giants

Tidal excitation

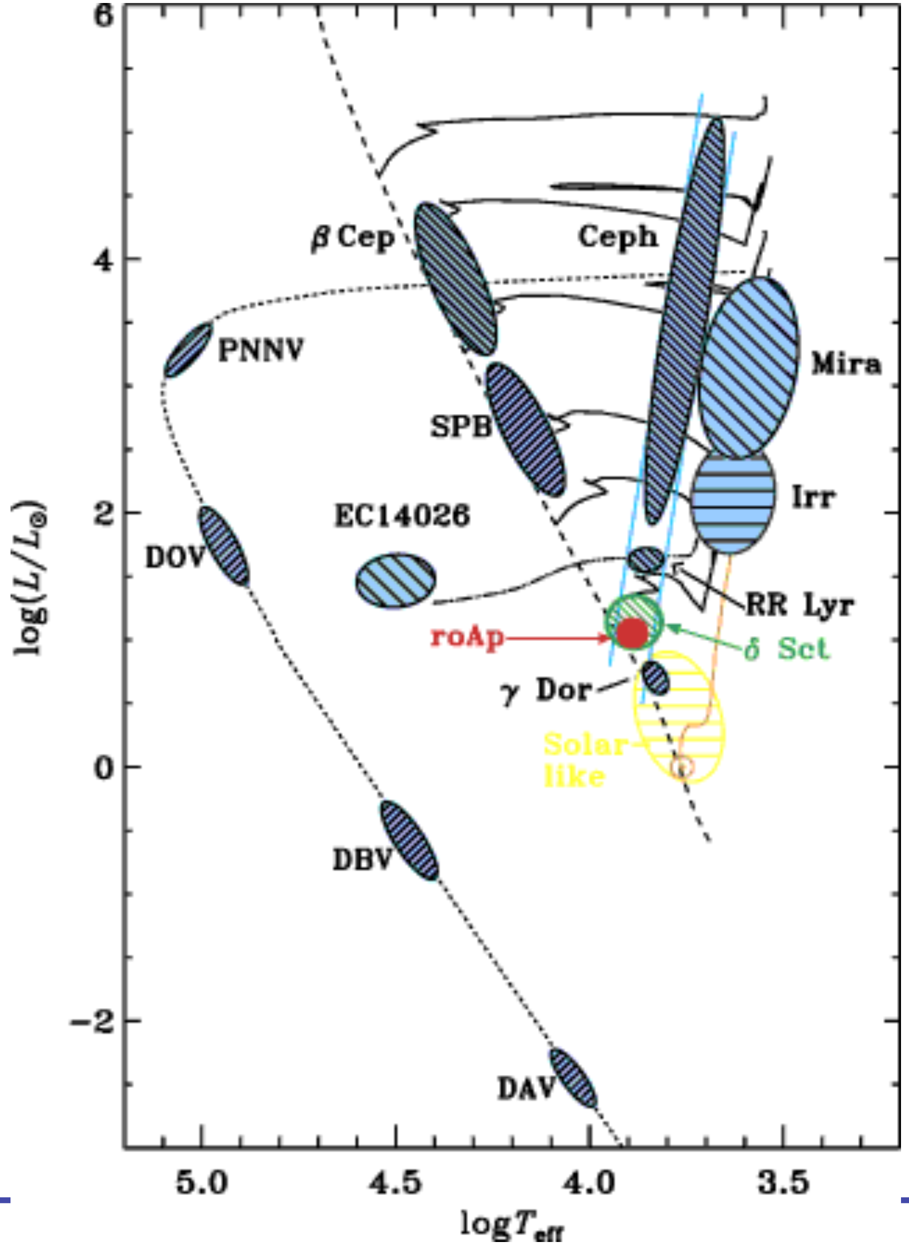
Resonant excitation of free oscillation modes by the tidal action of a companion can in principle be an effective way to trigger oscillations in binary components.

Suitable resonances depend on the properties of the oscillation modes of the star, the period and eccentricity of the orbit and on the component mass and radius.

Which stars oscillate?



Oscillating stars: solar-like oscillations



Excitation mechanism:
Stochastic excitation in convective outer regions

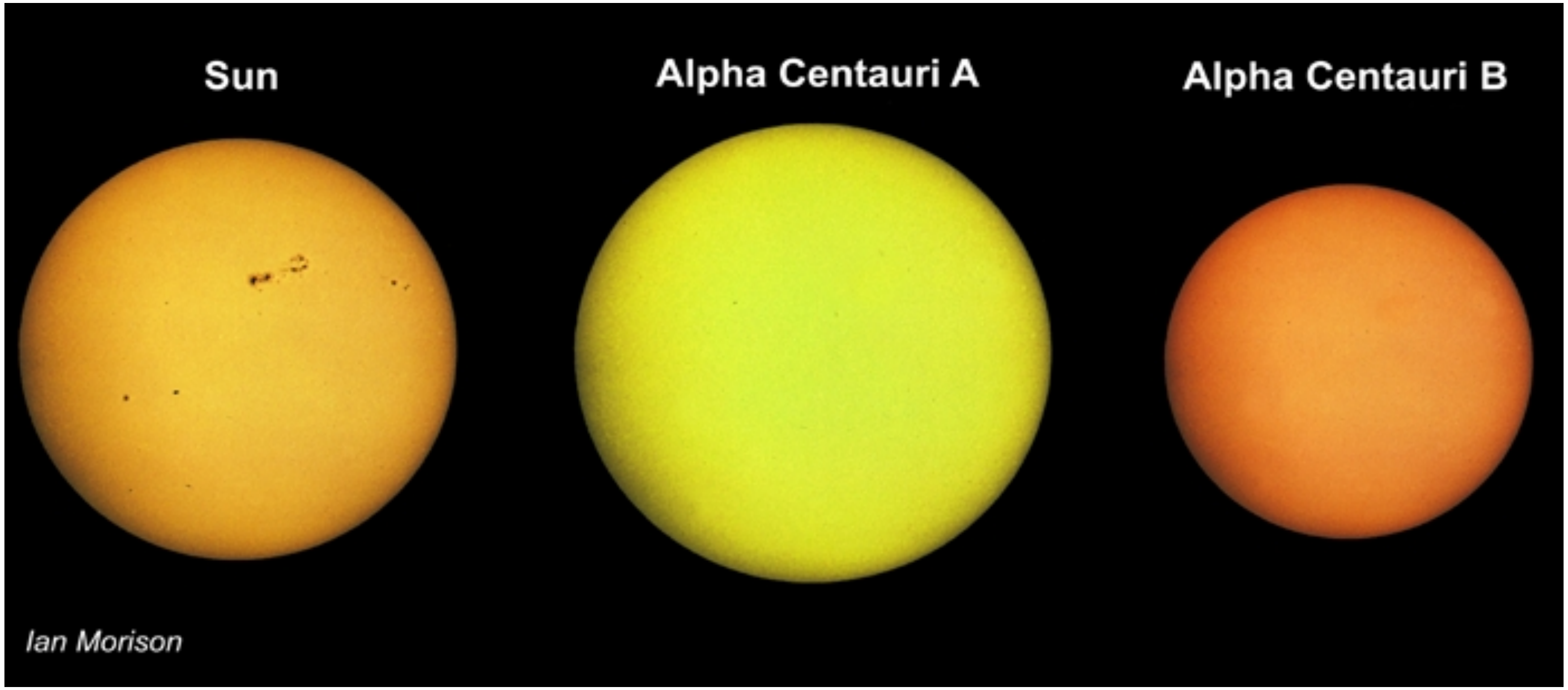
Restoring force: pressure

Typical periods: minutes - days

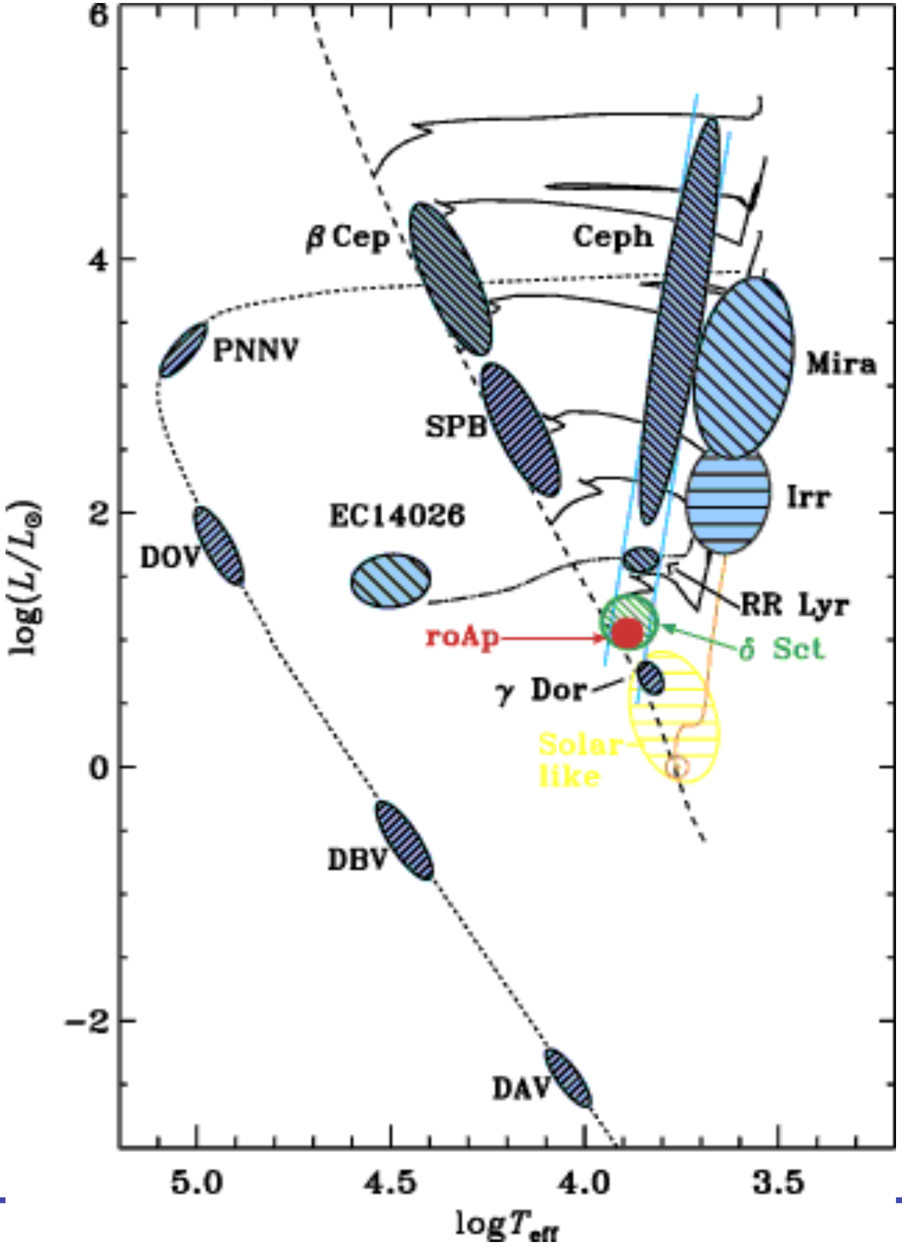
Evolutionary phase: MS, SG, RG

Mass range: low - intermediate

Solar-like stars



Oscillating stars: γ Doradus stars



Excitation mechanism: ? convective blocking of the radiative energy transport due to long convective turn-over times in the stellar envelope

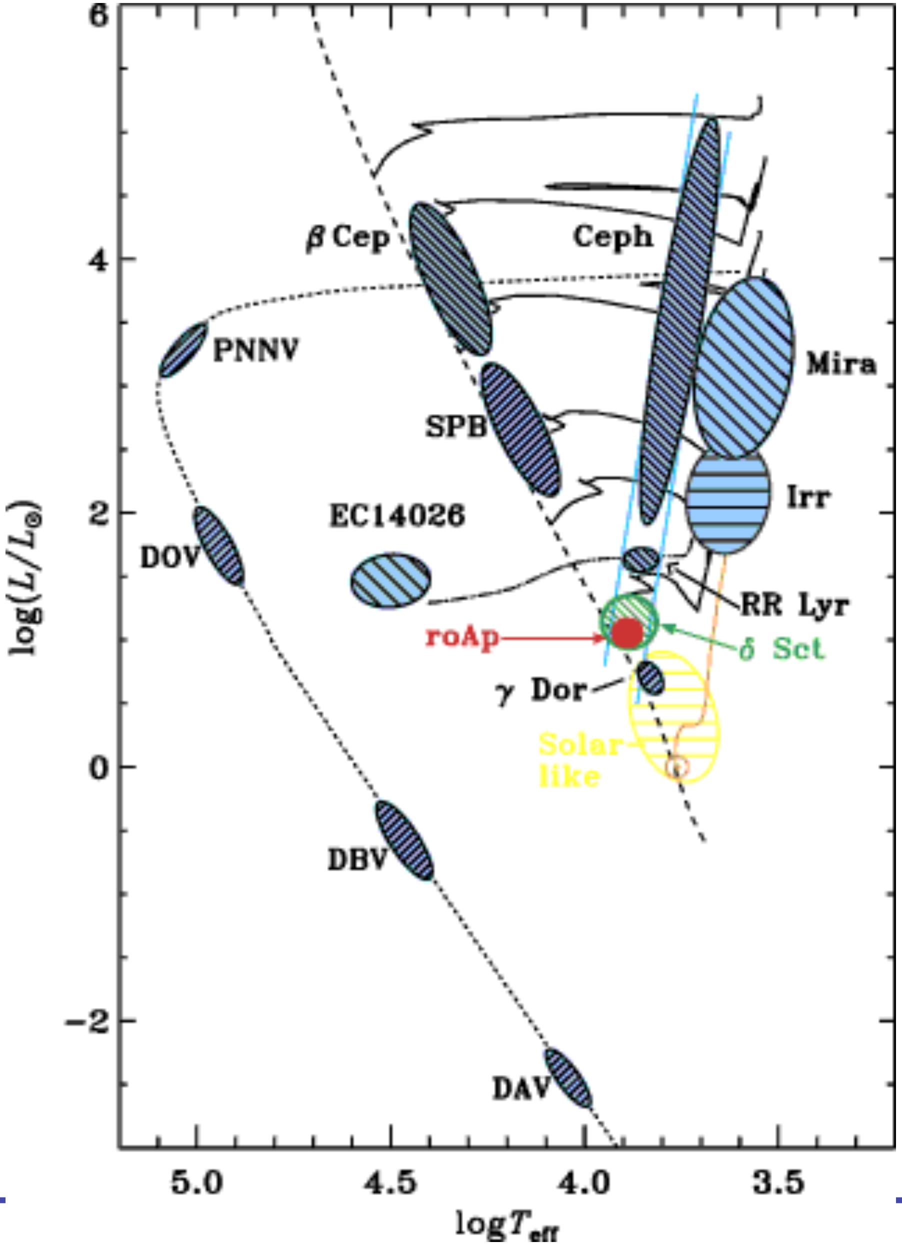
Restoring force: gravity

Typical periods: 0.5 - 3 days

Evolutionary phase: MS

Mass range: 1.5-1.8 M_{Sun}

Oscillating stars: δ Scuti stars



Excitation mechanism:
κ - mechanism (He II)

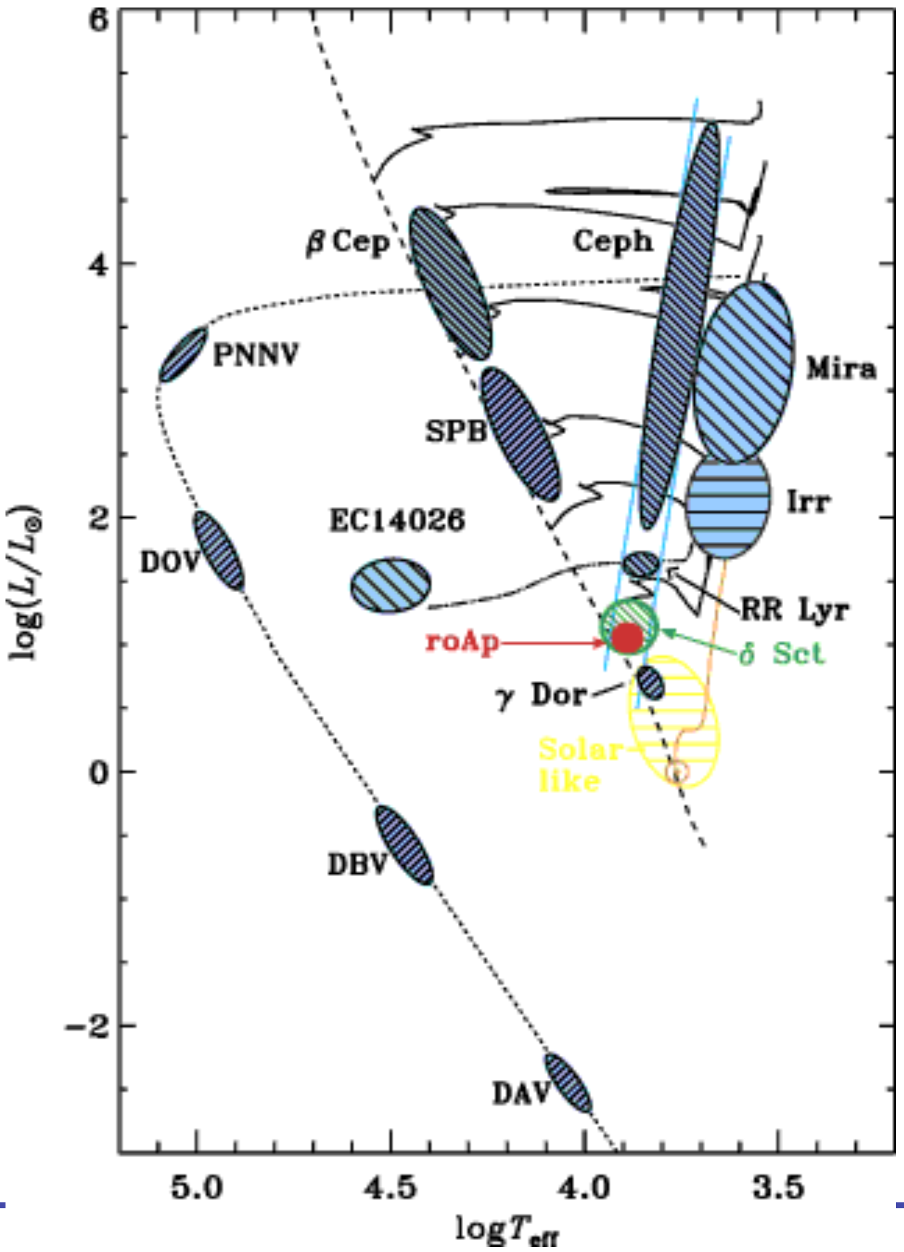
Restoring force: pressure

Typical periods: 0.02 - 0.25 days

Evolutionary phase: MS, SG

Mass range: 1.5-2.5 M_{Sun}

Oscillating stars: rapidly oscillating Ap stars



Excitation mechanism:
κ mechanism

Restoring force: pressure

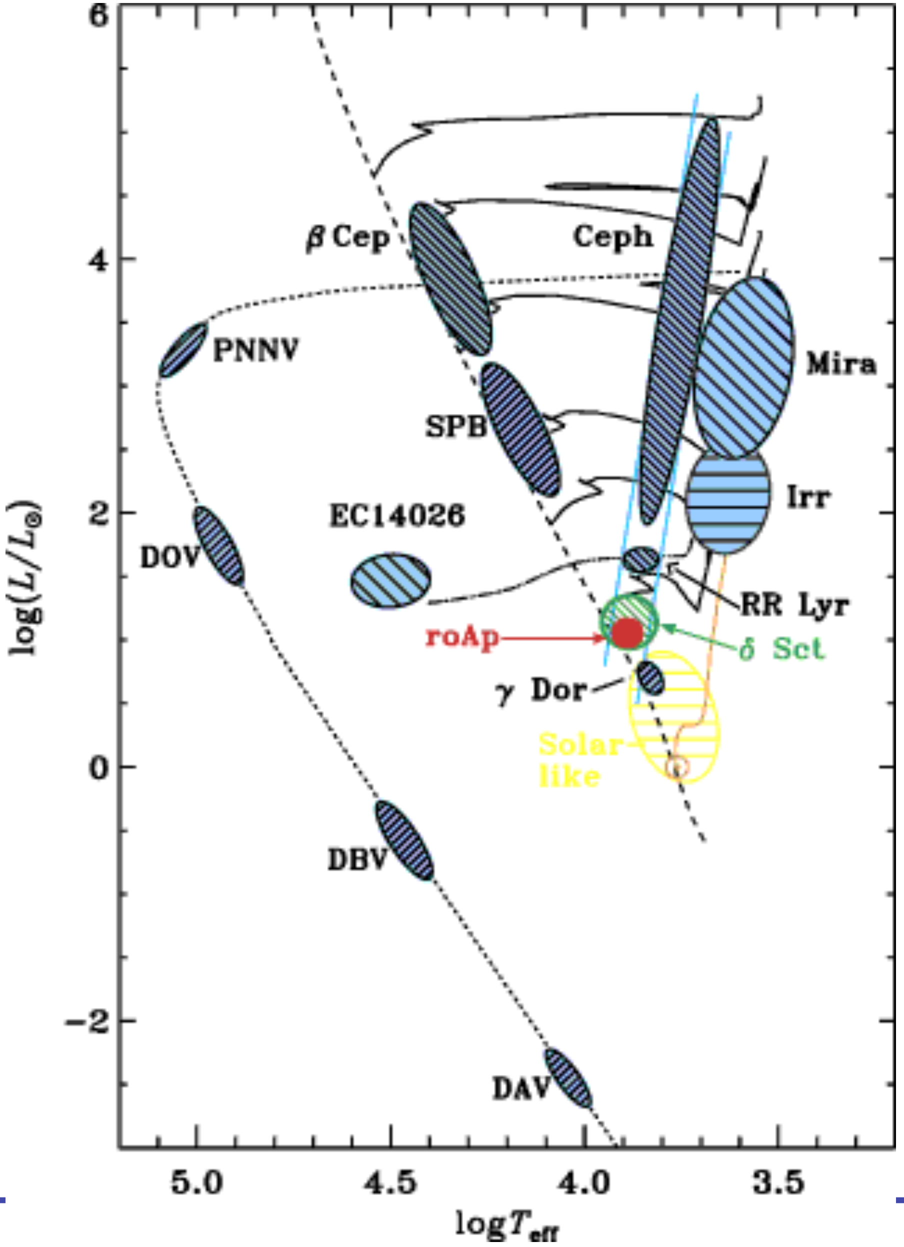
Typical periods: 5-20 mins

Evolutionary phase: MS

Mass range: 1.5-2.0 M_{Sun}

Highly magnetic stars

Oscillating stars: slowly pulsating B stars



Excitation mechanism:
κ mechanism (Fe)

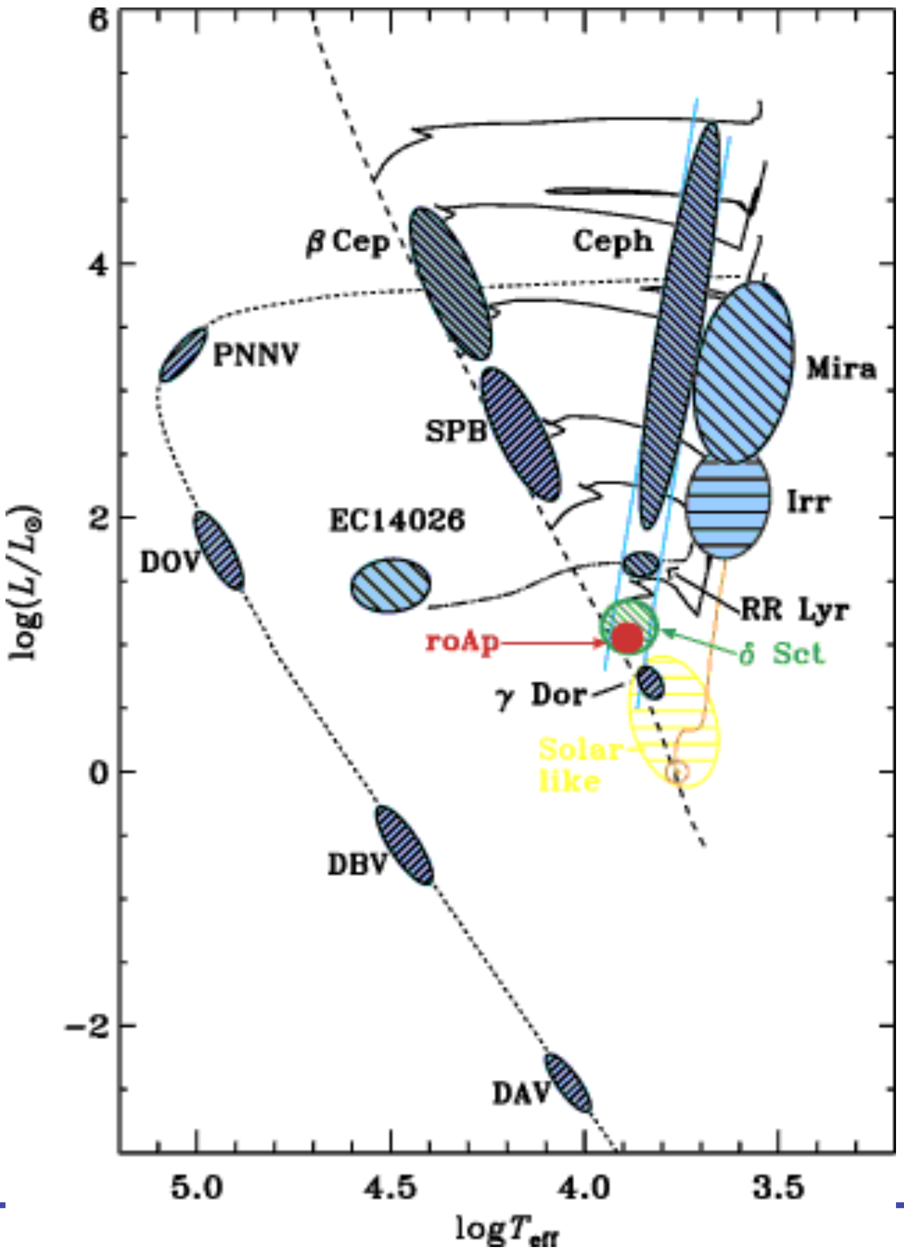
Restoring force: gravity

Typical periods: 1-3 days

Evolutionary phase: MS

Mass range: 2-7 M_{Sun}

Oscillating stars: β Cep stars



Excitation mechanism:
κ mechanism (Fe)

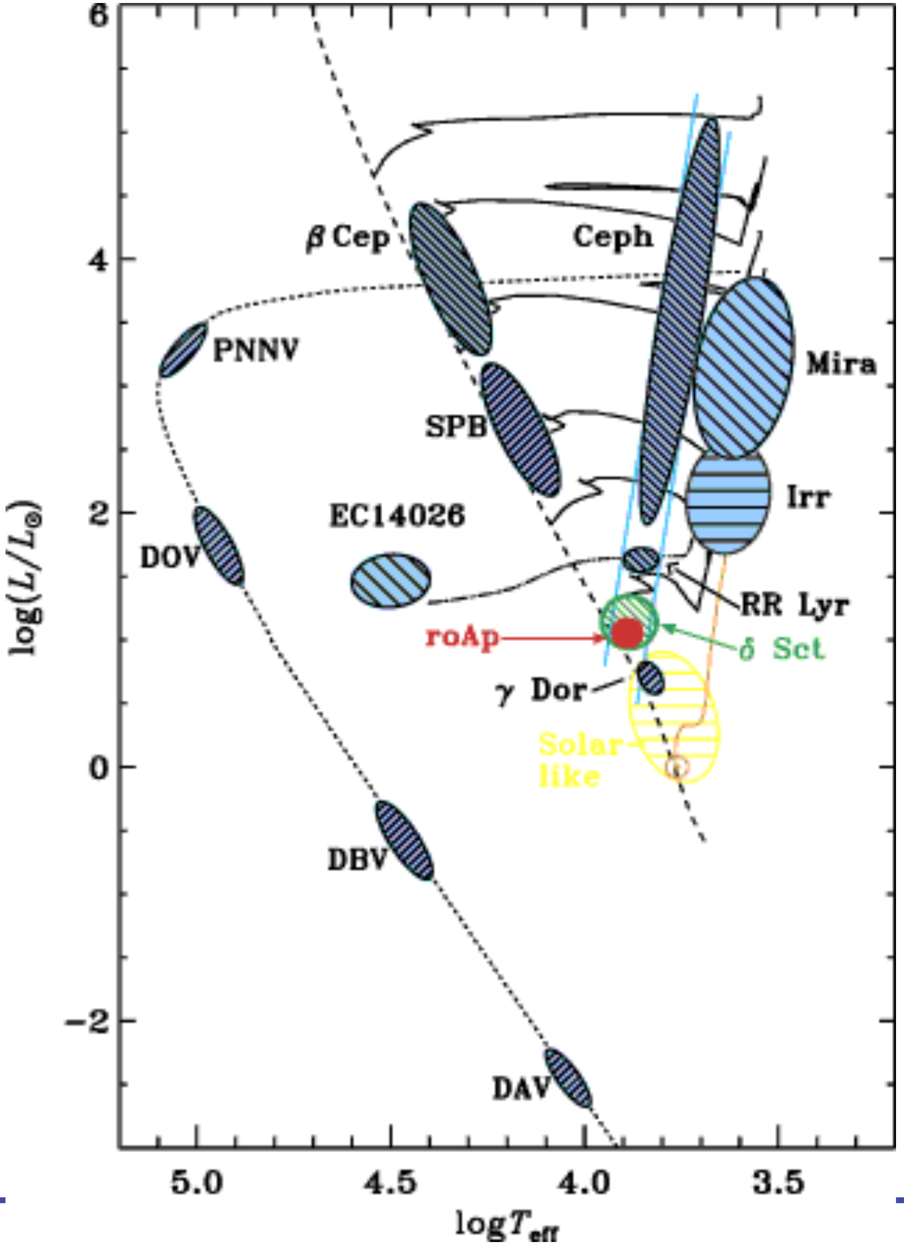
Restoring force: pressure

Typical periods: 2-8 hours

Evolutionary phase: MS,G

Mass range: 8-18 M_{Sun}

Oscillating stars: RR Lyrae stars



Excitation mechanism:
κ mechanism (He II)

Restoring force: pressure

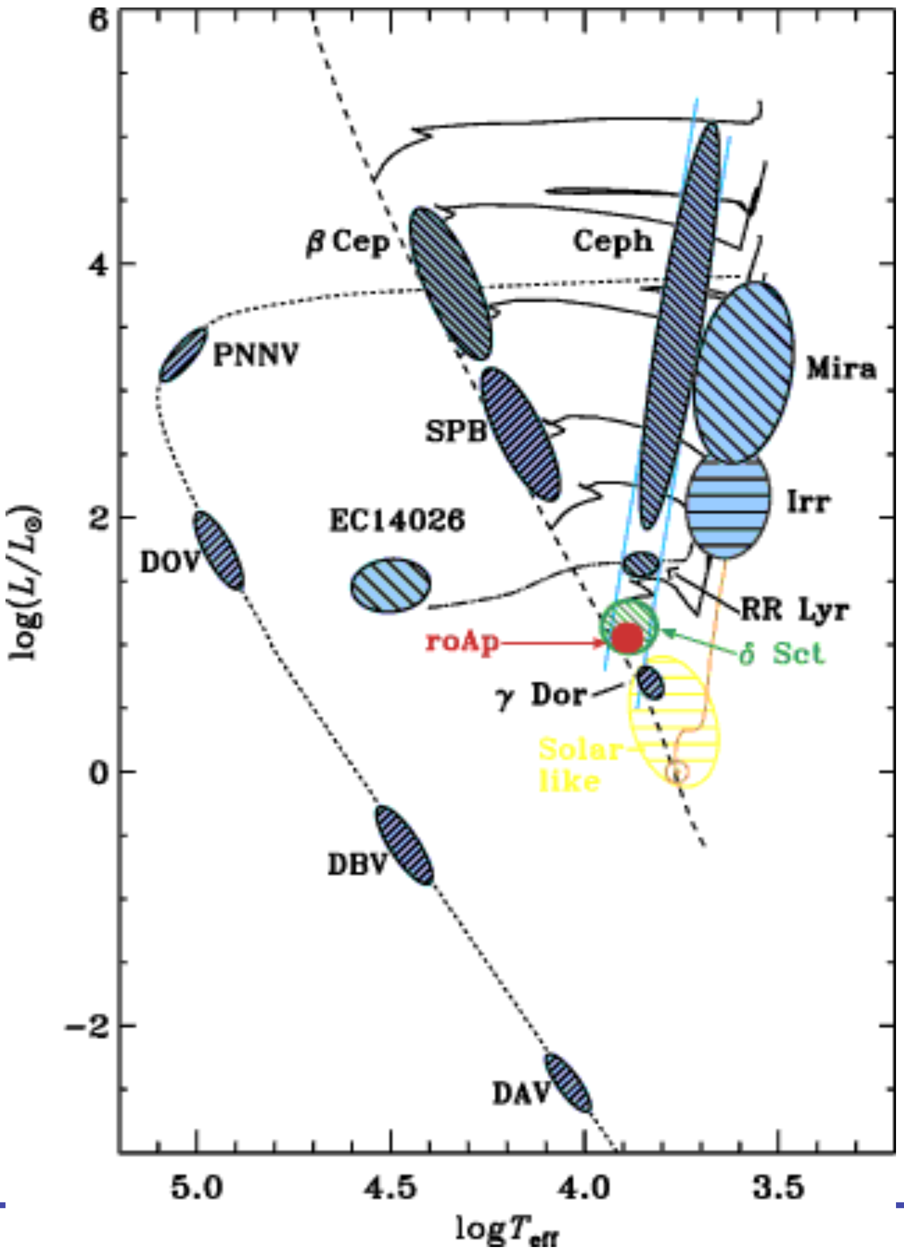
Typical periods: 0.3-0.5 days

Evolutionary phase: G

Mass range: 0.6-0.8 M_{Sun}

Blazhko effect

Oscillating stars: Cepheids



Excitation mechanism:
κ mechanism (He II)

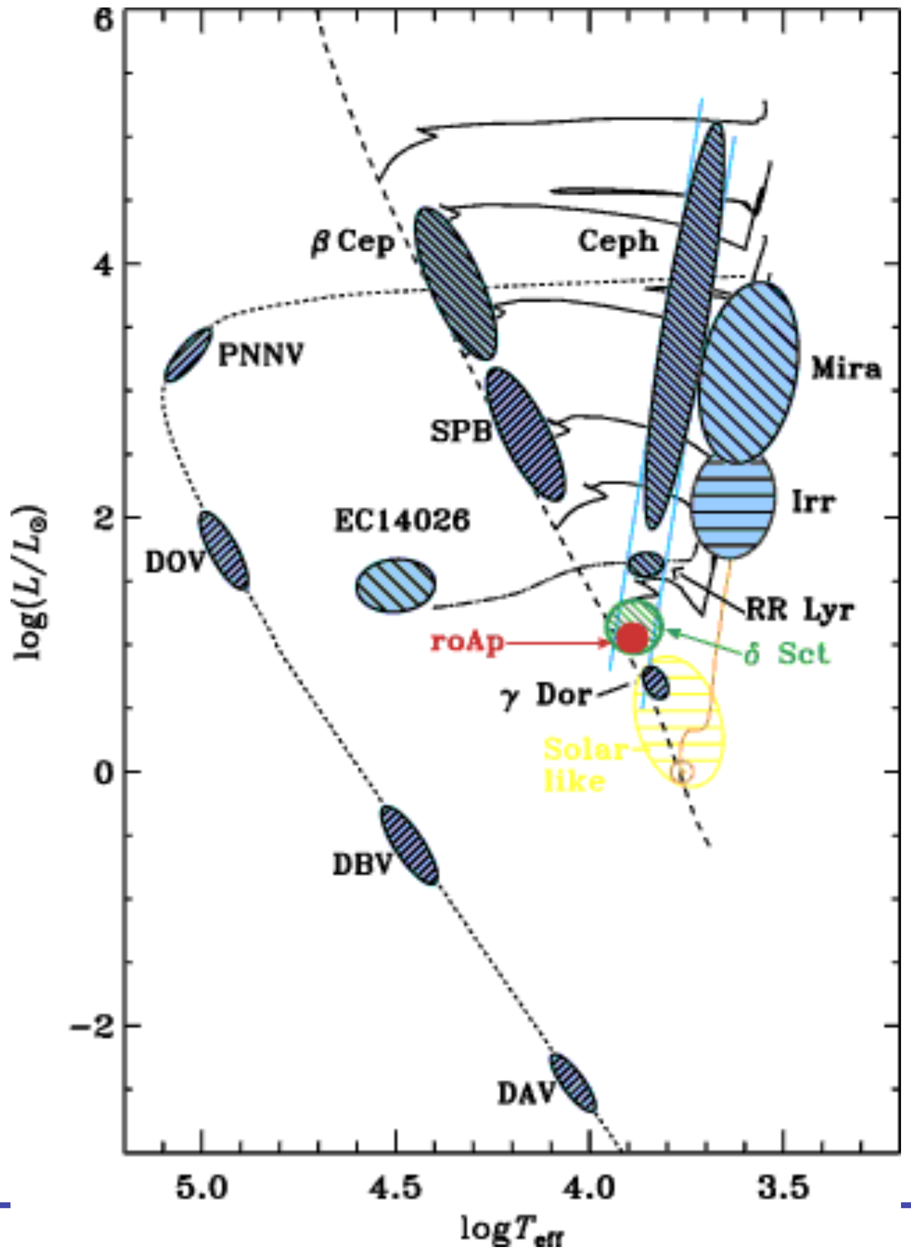
Restoring force: pressure

Typical periods: 1-50 days

Evolutionary phase: SG

Mass range: 4-20 M_{Sun}

Oscillating stars: Mira



Excitation mechanism:
κ mechanism (H I and He II)

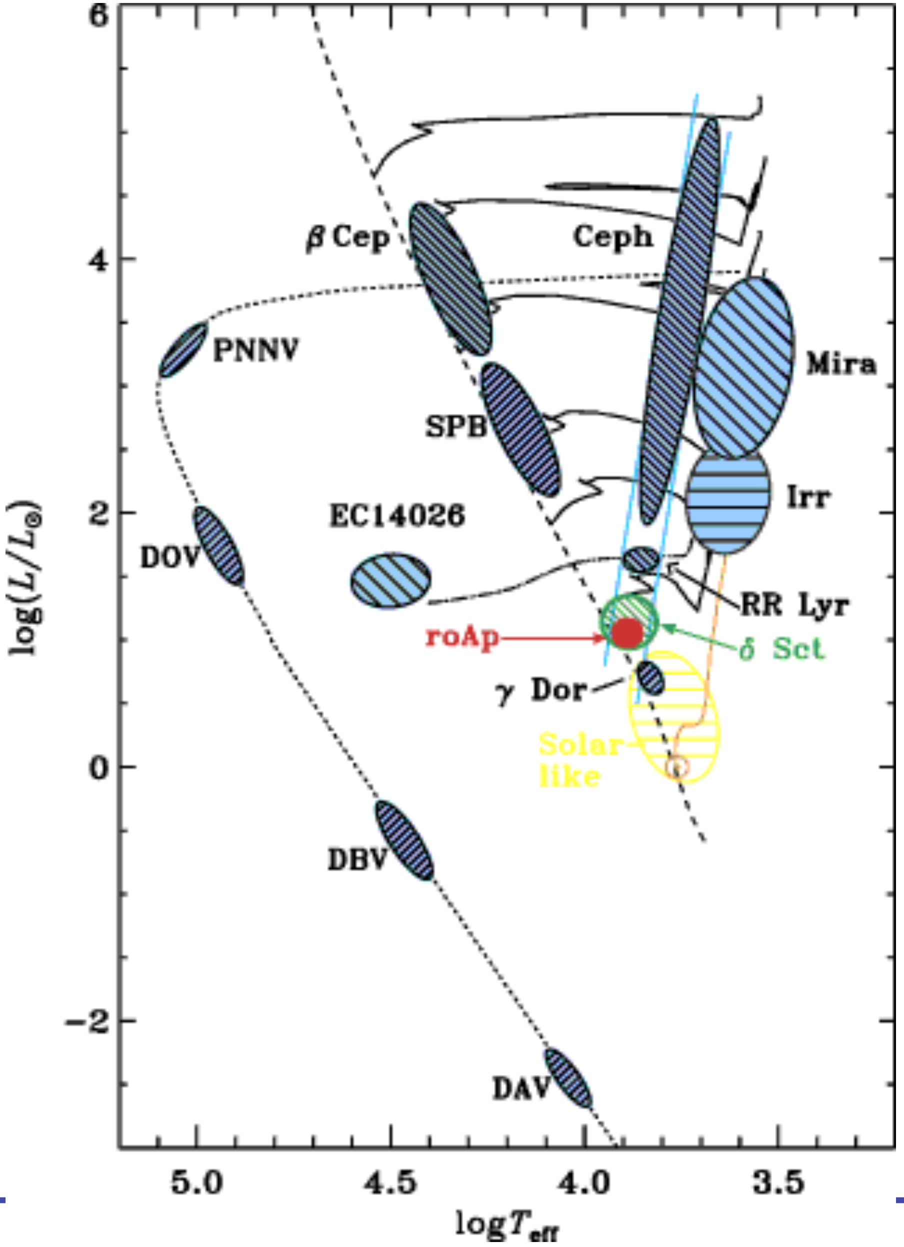
Restoring force: pressure

Typical periods: > 80 days

Evolutionary phase: G, SG

Mass range: low - intermediate

Oscillating stars: Semi-regular variables



Excitation mechanism: Stochastic excitation in convective outer region

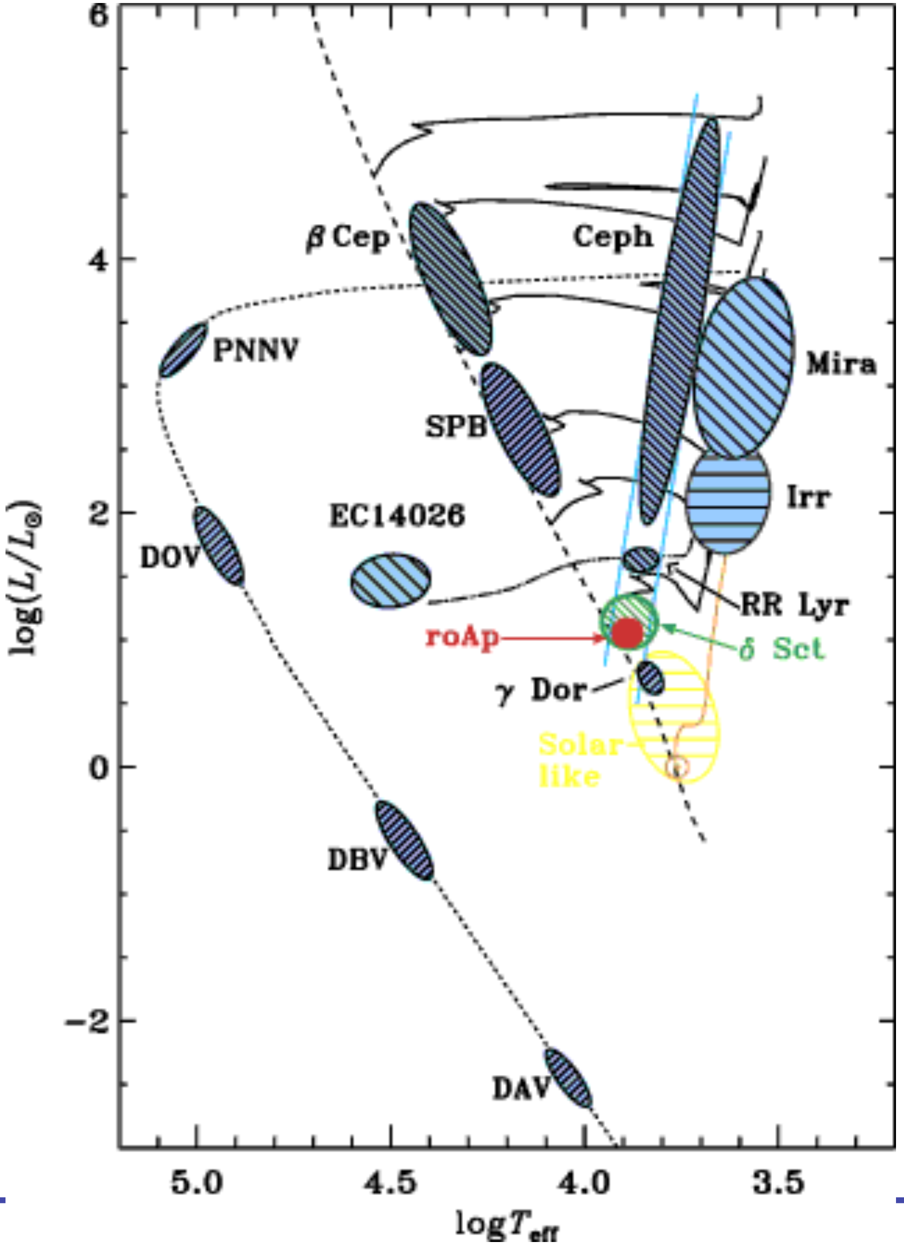
Restoring force: pressure

Typical periods: > 80 days

Evolutionary phase: G, SG

Mass range: low - intermediate

Oscillating stars: subdwarf B stars (EC14026)



Excitation mechanism:
κ mechanism (Fe II)

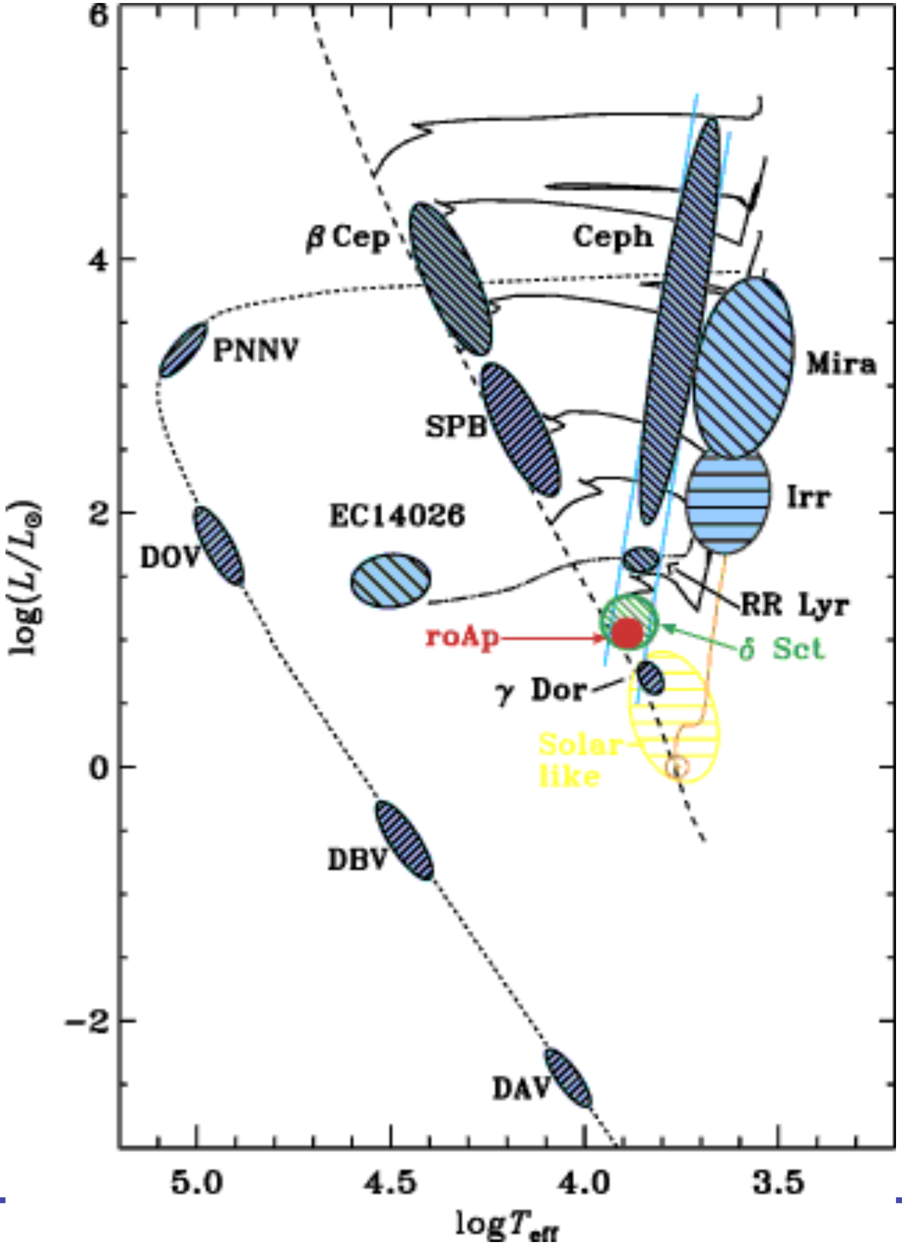
Restoring force: pressure

Typical periods: 80 - 600 s

Evolutionary phase: SD

Mass range: < 0.5 M_{Sun}

Oscillating stars: subdwarf B stars (Betsy)



Excitation mechanism: κ mechanism (Fe II)

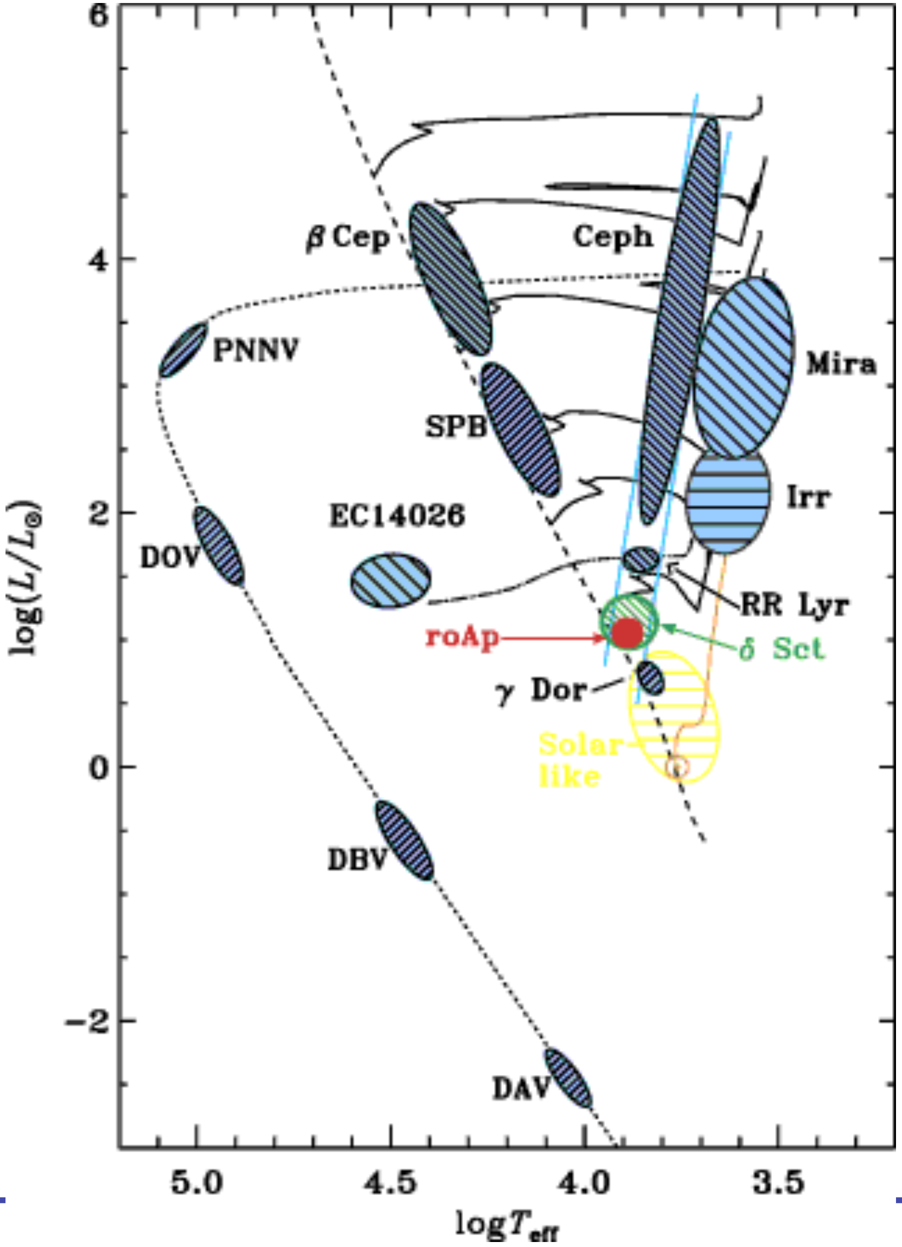
Restoring force: gravity

Typical periods: 1 hour

Evolutionary phase: SD

Mass range: < 0.5 M_{Sun}

Oscillating stars: white dwarfs



Excitation mechanism:

κ mechanism (DO C/O & DB He II)

convection (DA)

Restoring force: gravity

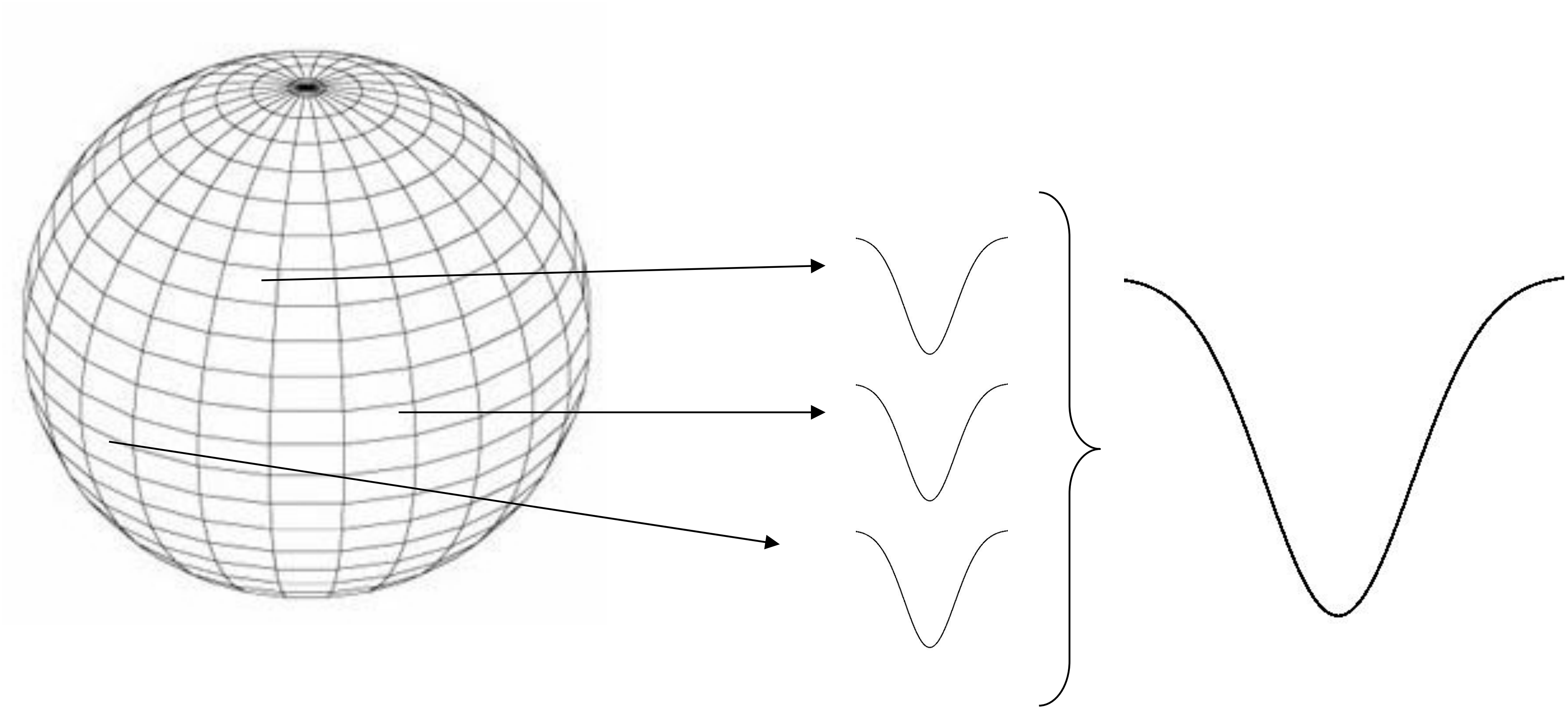
Typical periods: few minutes

Evolutionary phase: SD

Mass range: ~ 0.6 M_{Sun}

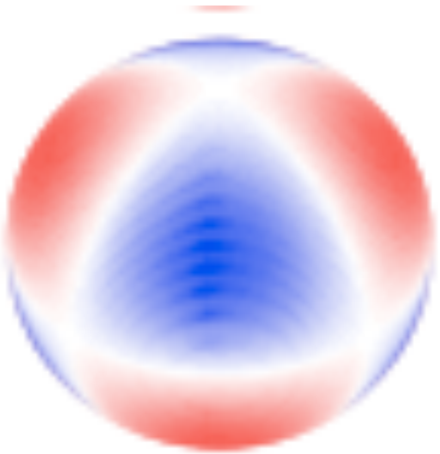
Doppler measurements

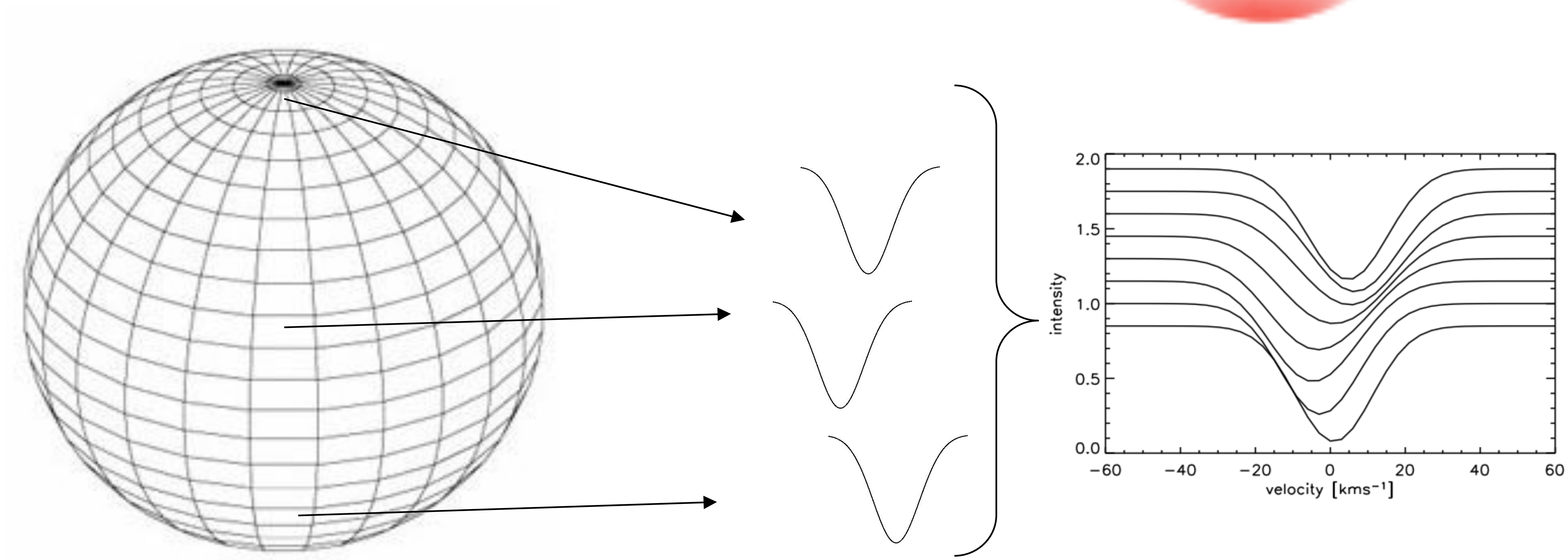
Mechanism: Doppler shift



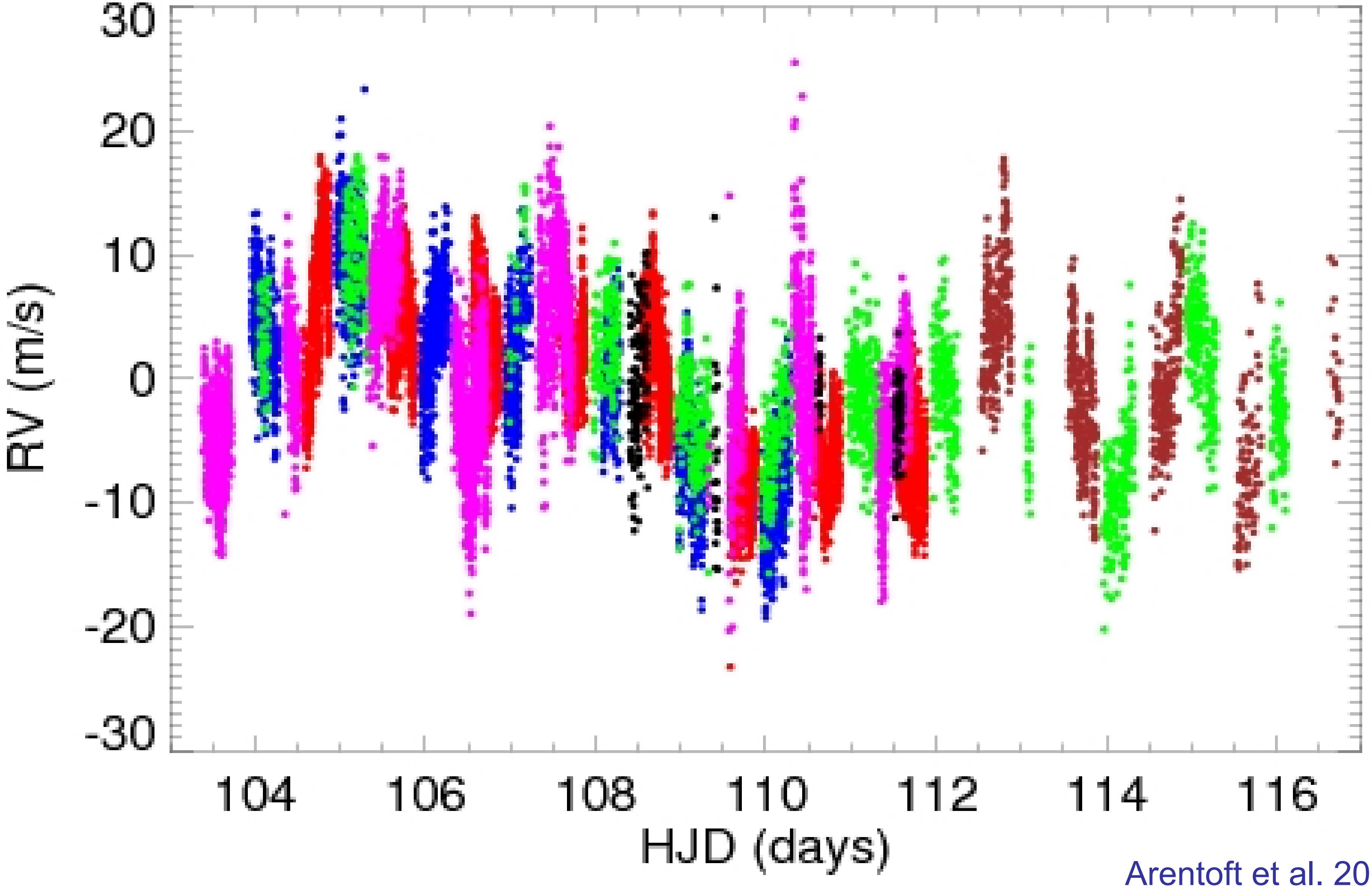
Mechanism: pulsation

$P_{\text{rotatie}} << P_{\text{pulsation}}$



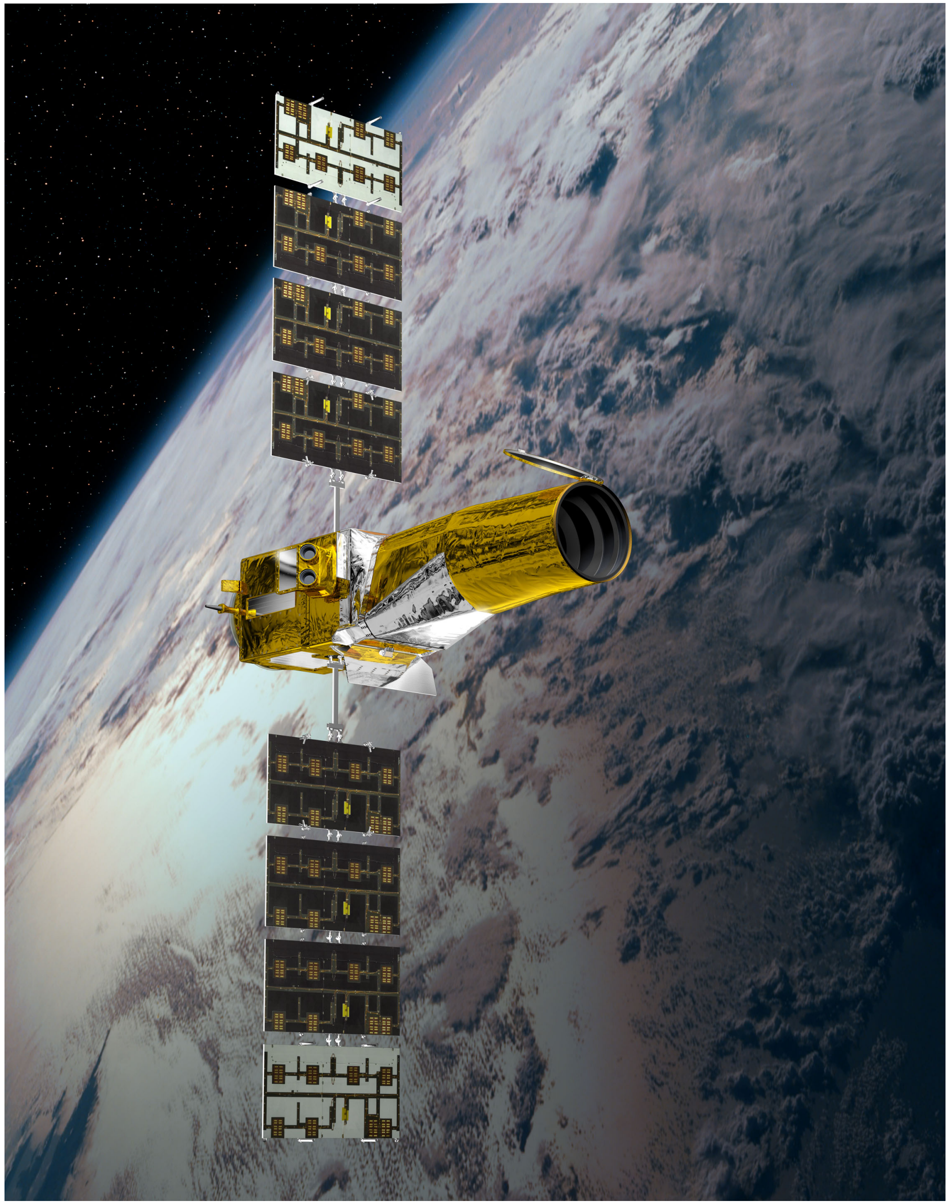


Spectroscopy: multi-site campaign



Arentoft et al. 2008

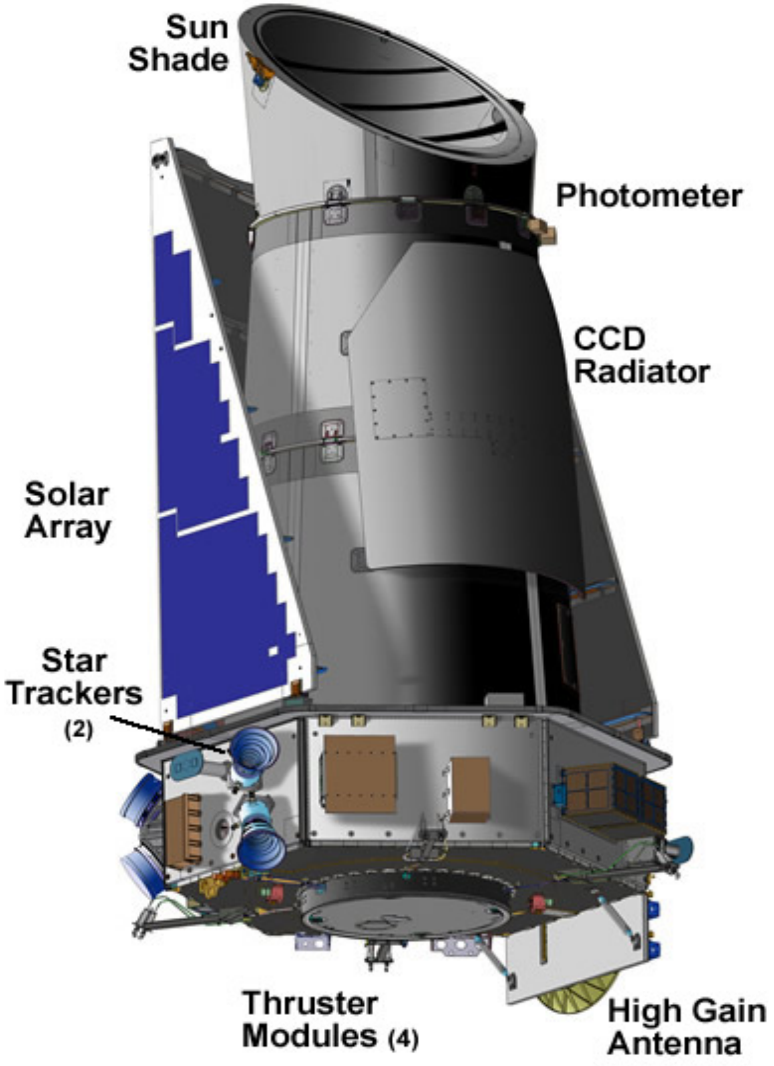
Photometry: CoRoT



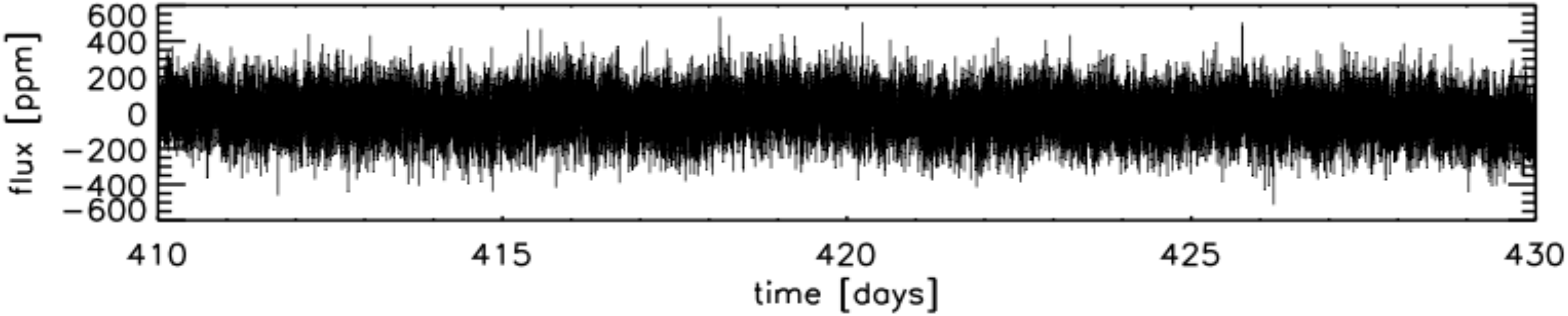
- launched December 26, 2006
- 27 cm telescope
- 2 observing modes:
  - seismology: a few 6-9 mag stars, 30 s integration time
  - exo-planets: 200000 11-16 mag stars, 512 / 32 s integration time
- ~150 days observation runs
- centre and anti-centre fields of view

Photometry: NASA/Kepler

- launched March 6, 2009
- 0.95 m telescope
- 105 square degree FOV direction Cygnus-Lyra
- 2 observing modes:
  - long-cadence, 29.4 minute integration time ~ 150 000 stars
  - short-cadence, 58.8 sec integration time 512 stars



Time series



Important “timescales”

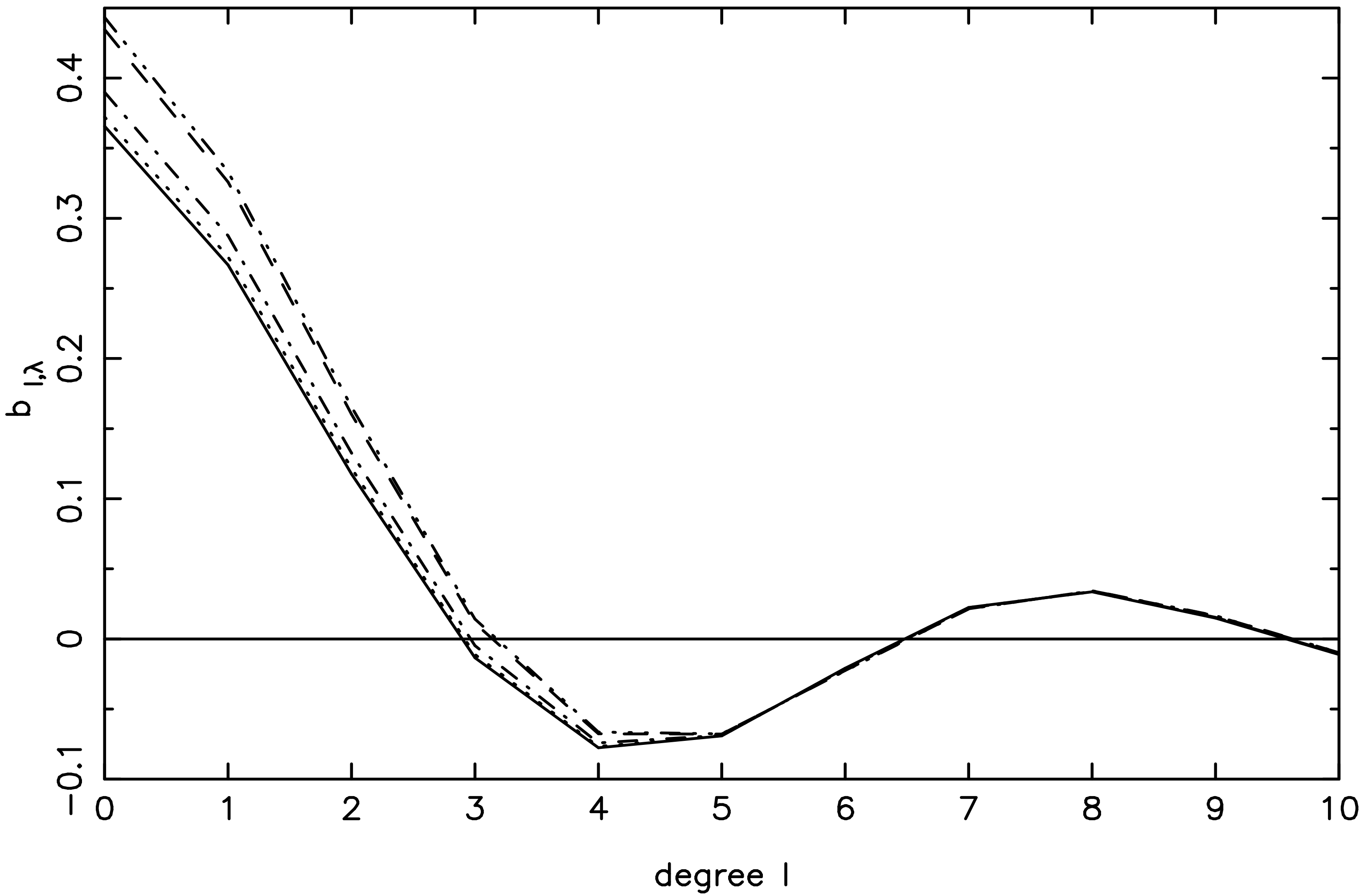
- Frequency resolution in the Fourier power power spectrum is reciprocal of total timespan T of timeseries:

$$\delta\nu = \frac{1}{T}$$

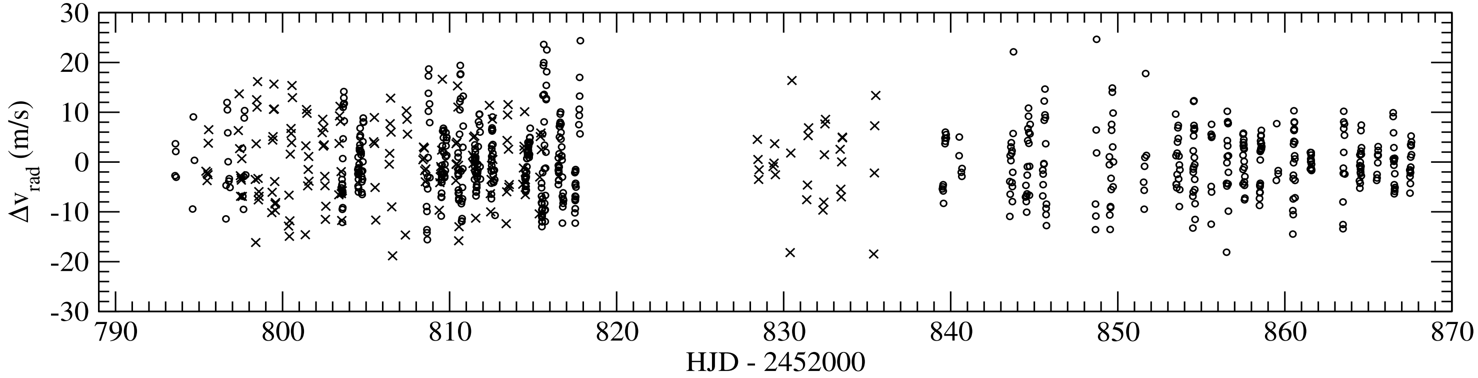
- Nyquist frequency: highest frequency at which one can reliably obtain results depends on the time sampling δt:

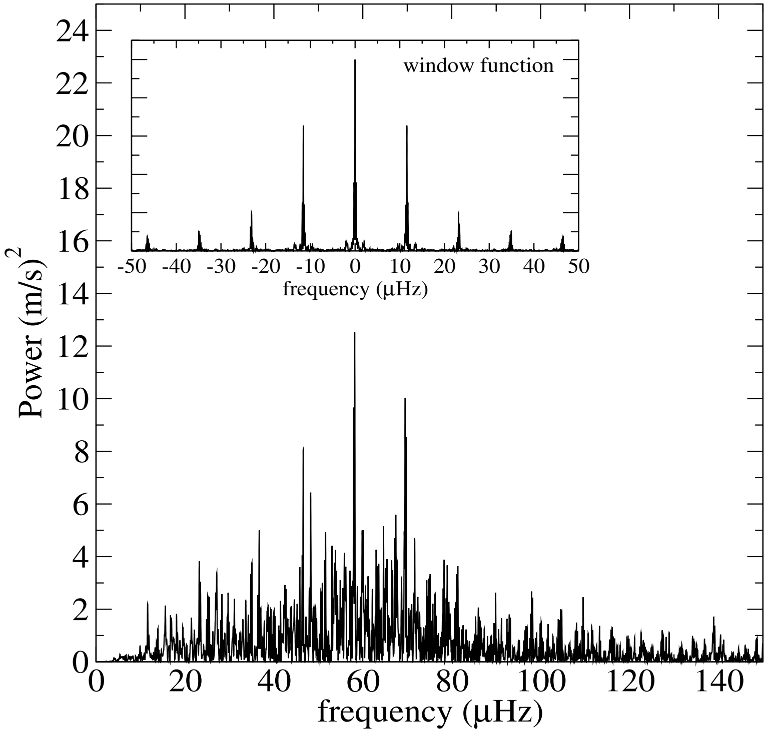
$$\nu_{Nyq} = \frac{1}{2\delta t}$$

Cancellation effects



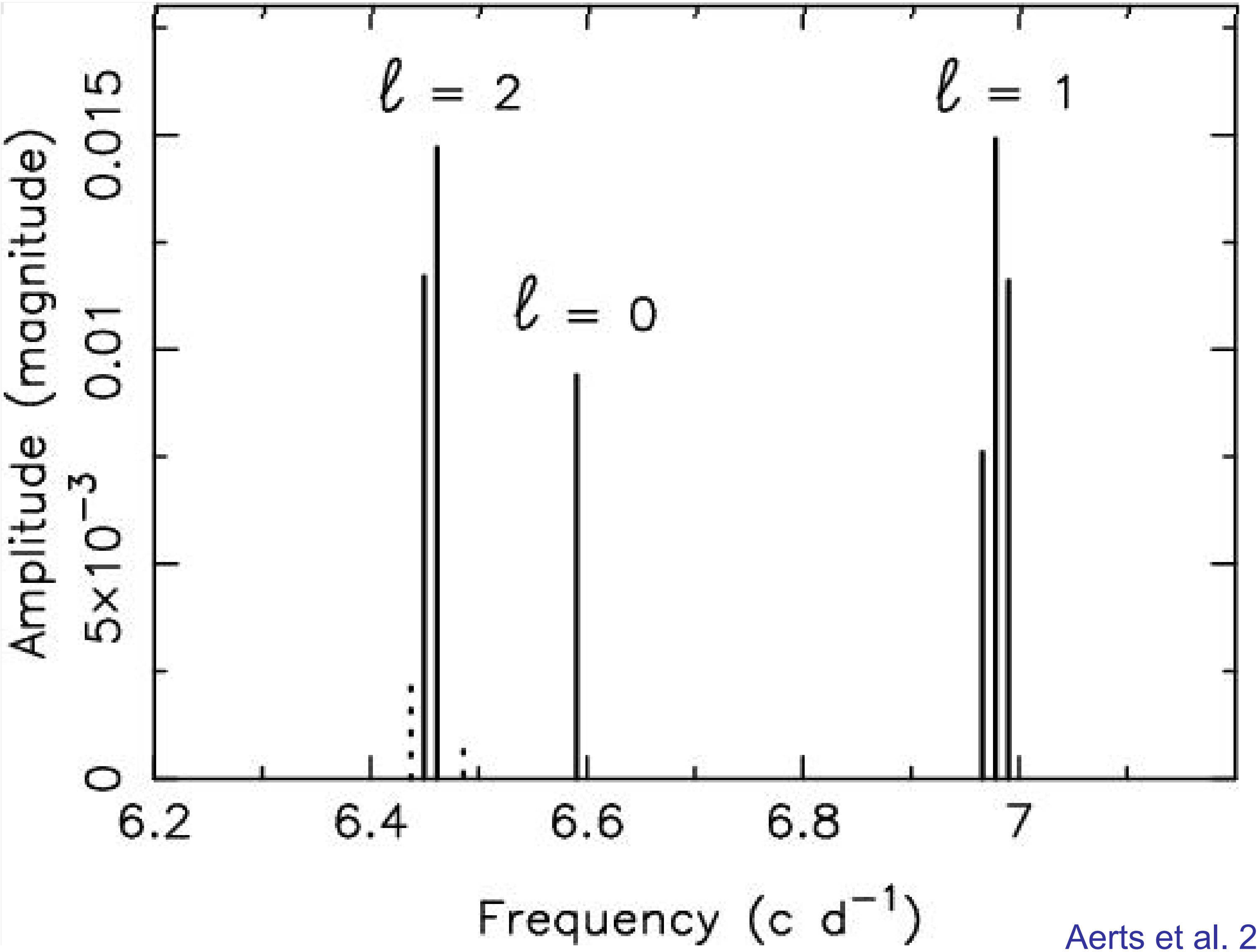
Window function





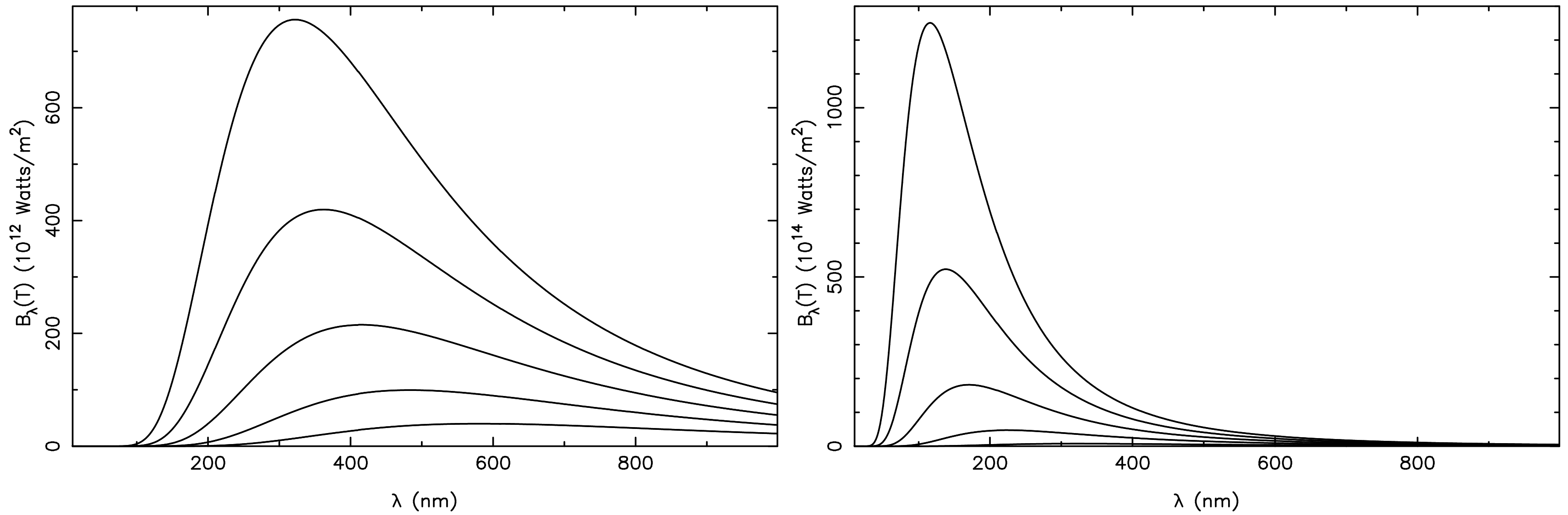
De Ridder et al. 2006

Classical oscillators



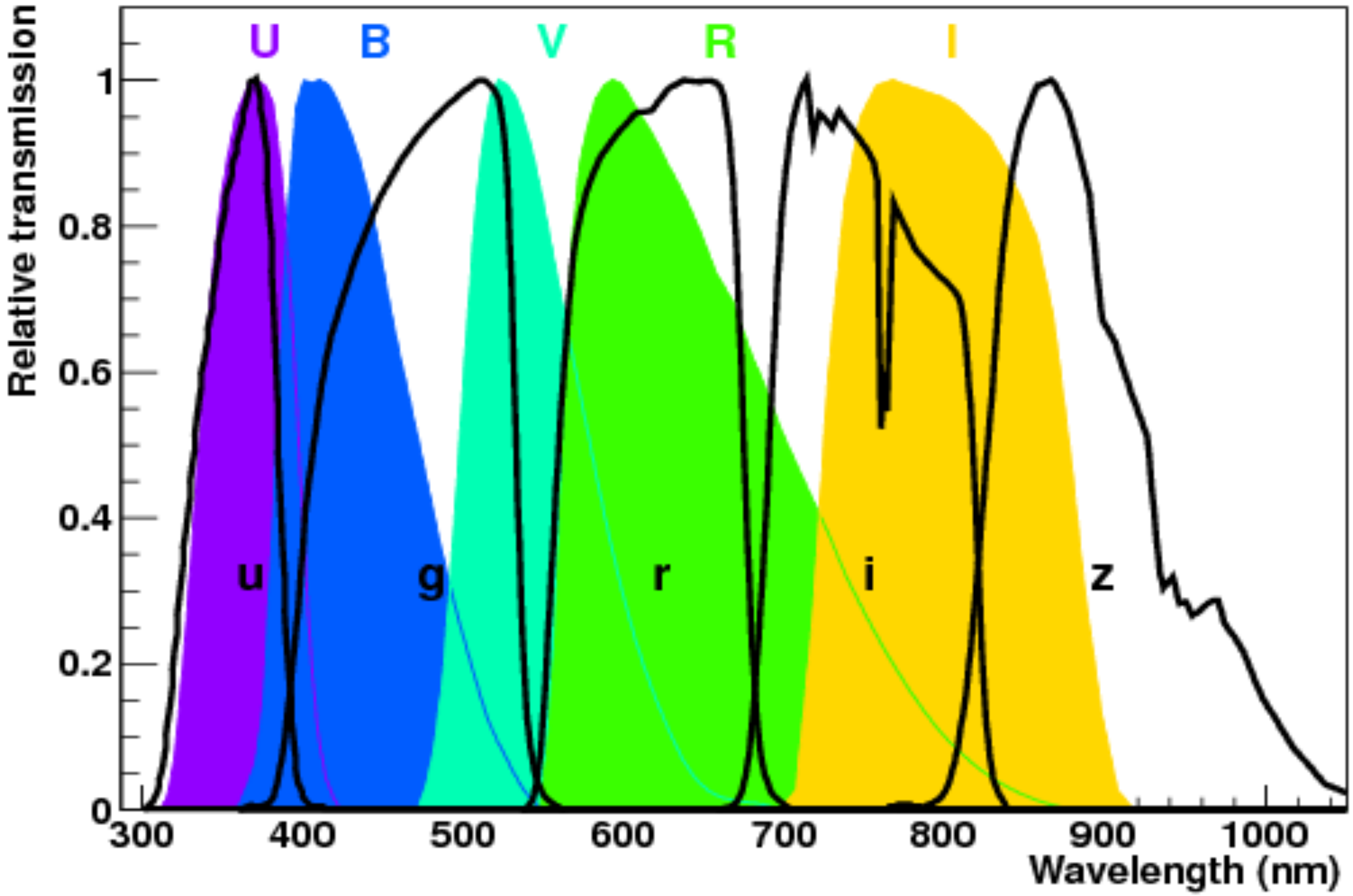
Aerts et al. 2003

Mode identification in classical pulsators

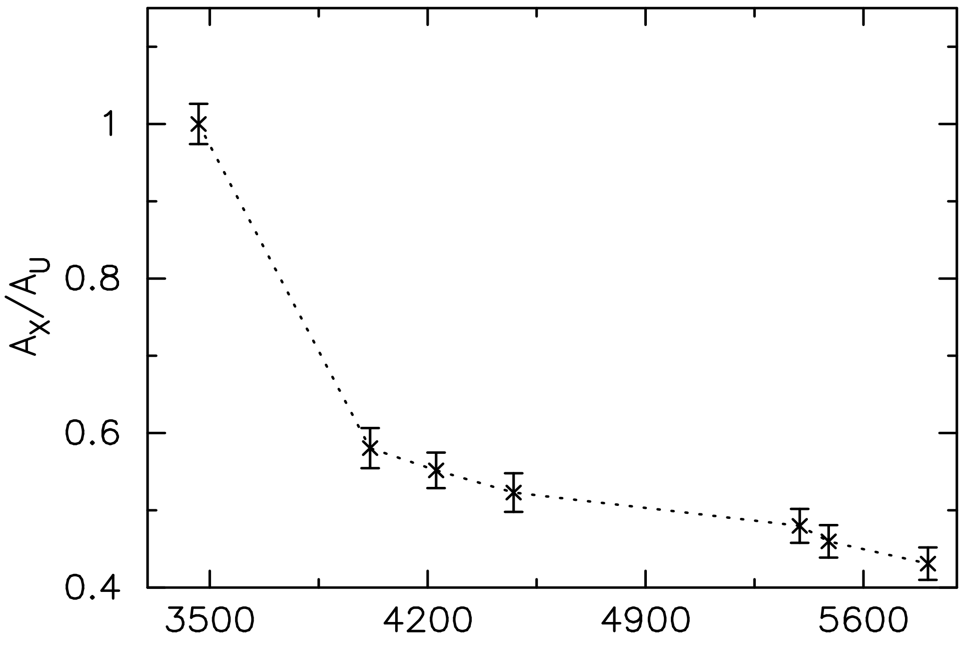


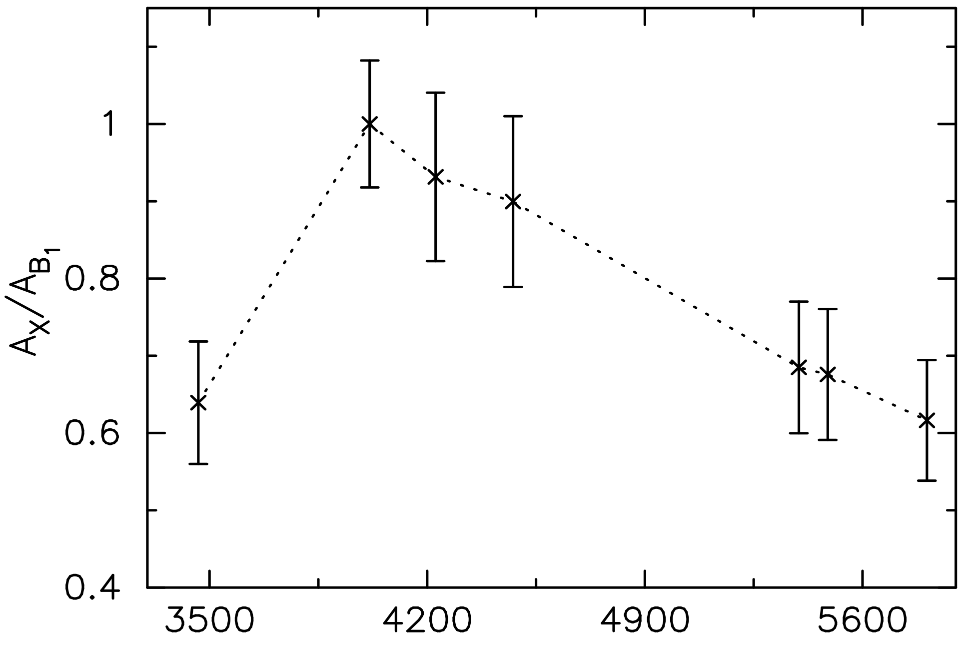
Due to shape of Black Body Radiation:
pulsation amplitude will always be larger in blue than in red

Photometric bands

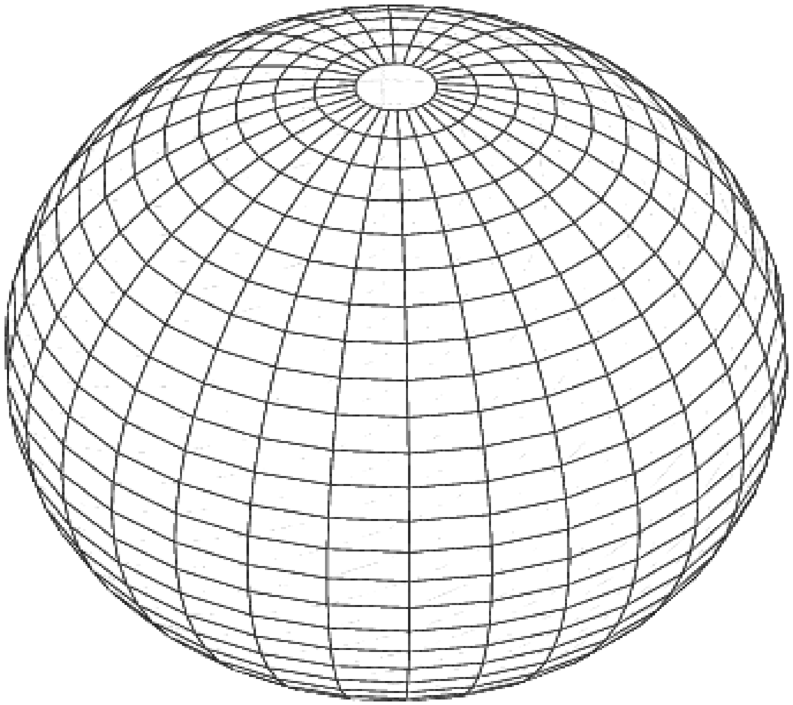


Mode identification in classical pulsators





Mode identification through line profile variations



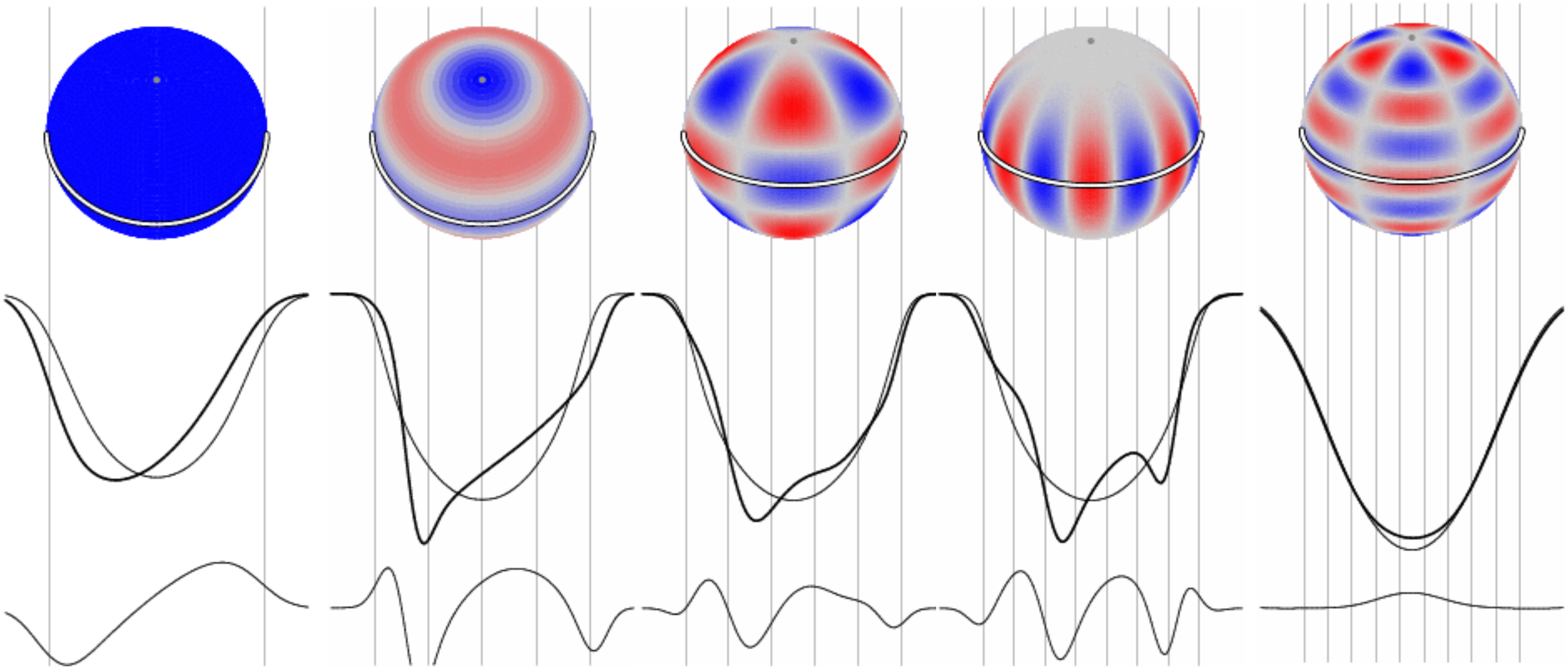
Divide stellar surface into large number of segment, typically > 5000

Compute for each segment: pulsation and rotation velocity, intensity

Project onto the line-of-sight

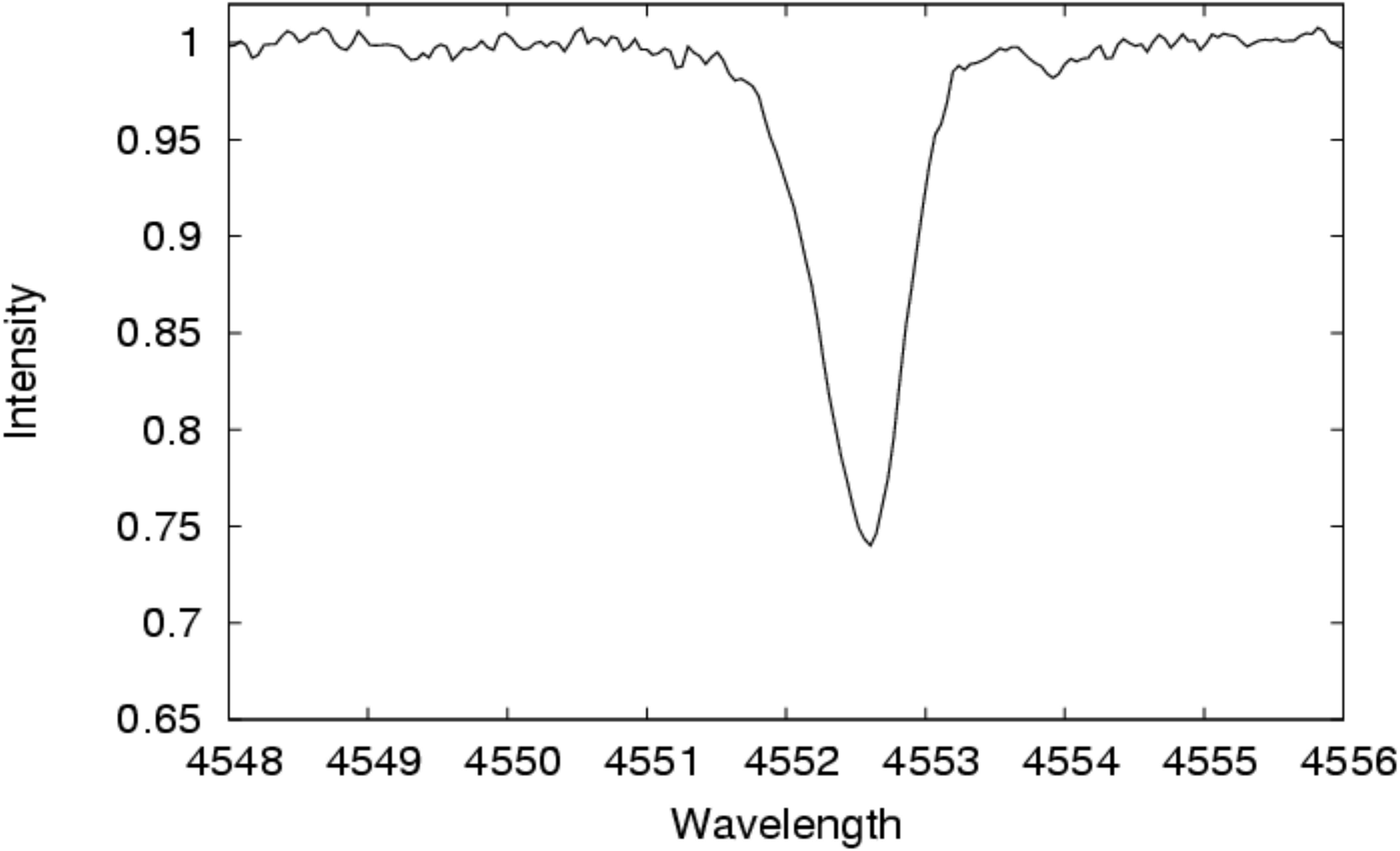
Add up all contributions

Mode identification through line profile variations



12 Lacertae 1

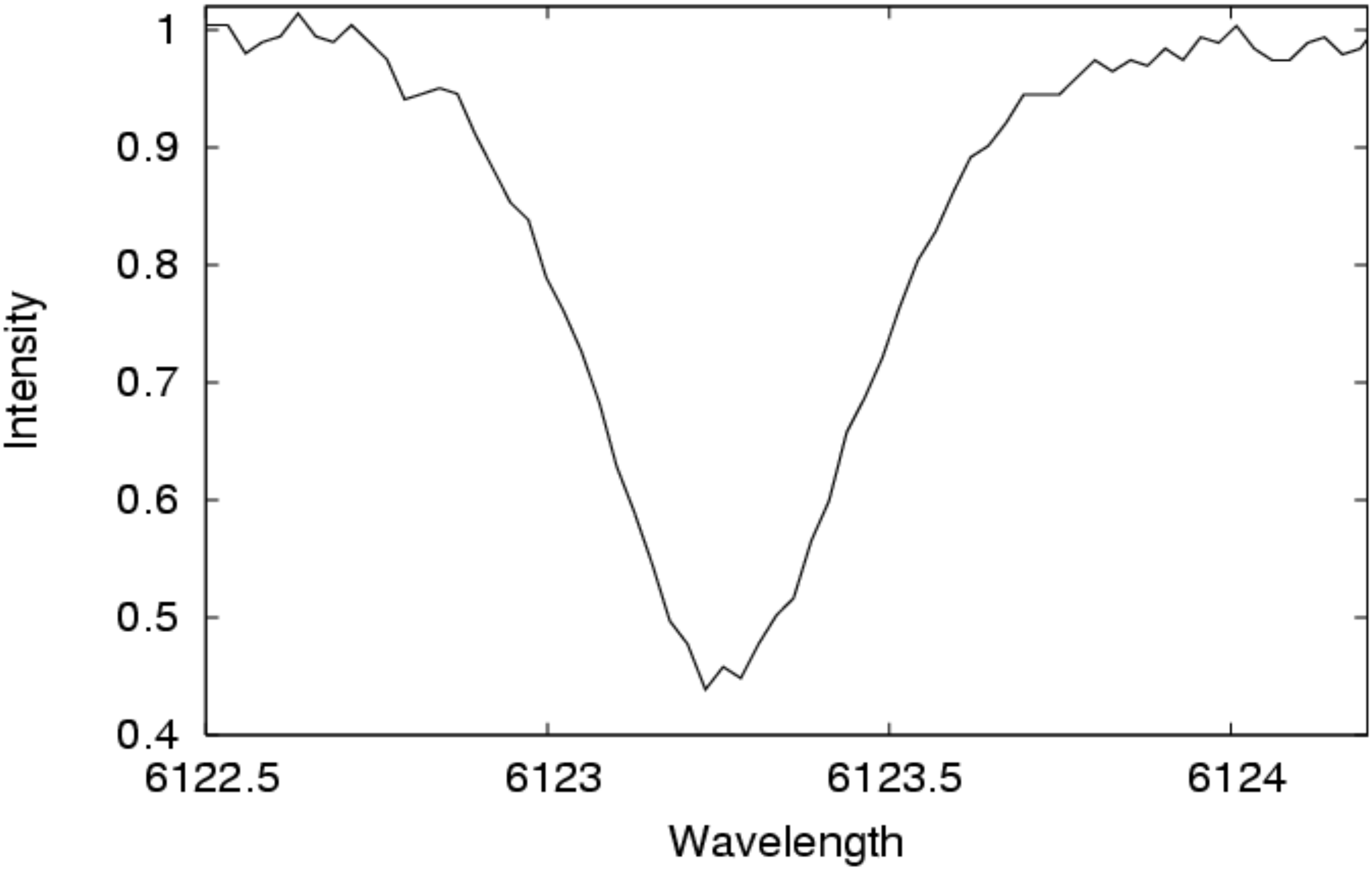
β Cephei



Mathias et al. 2004

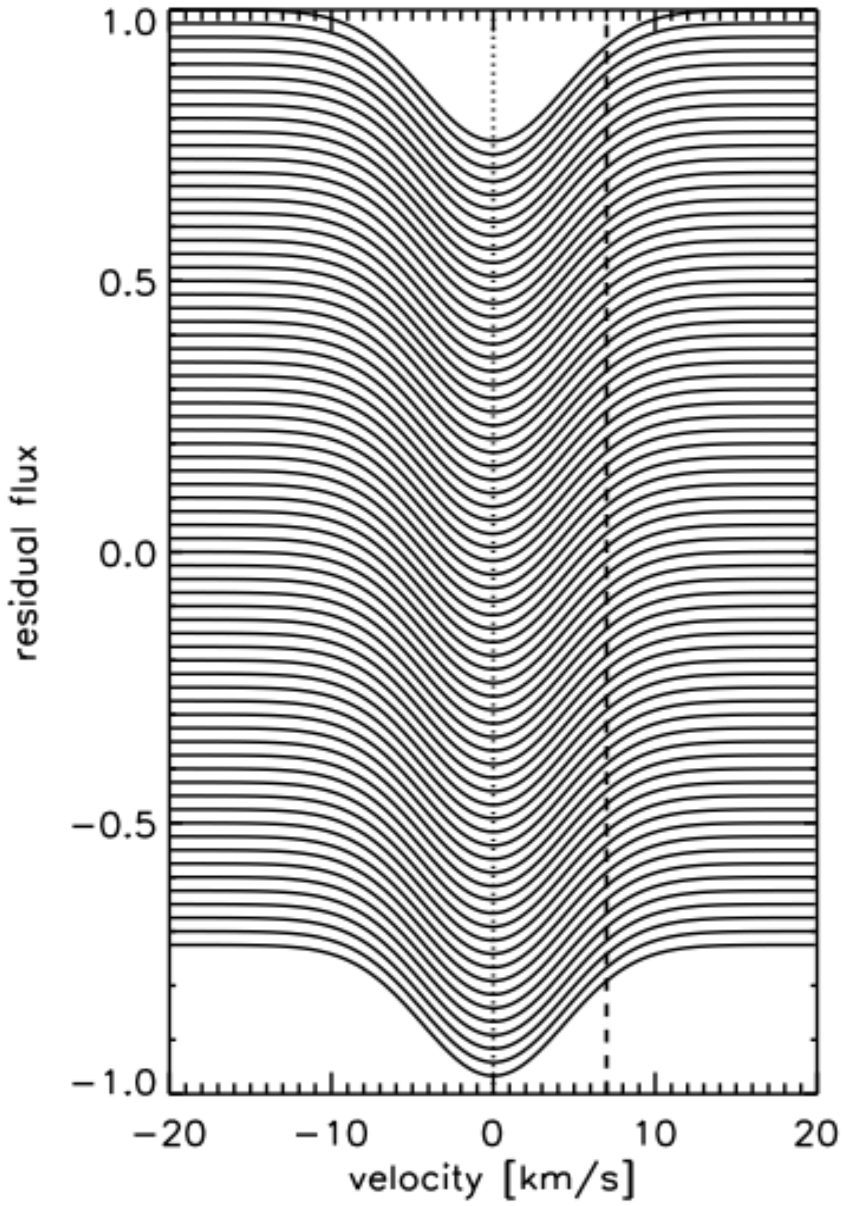
δ Scuti

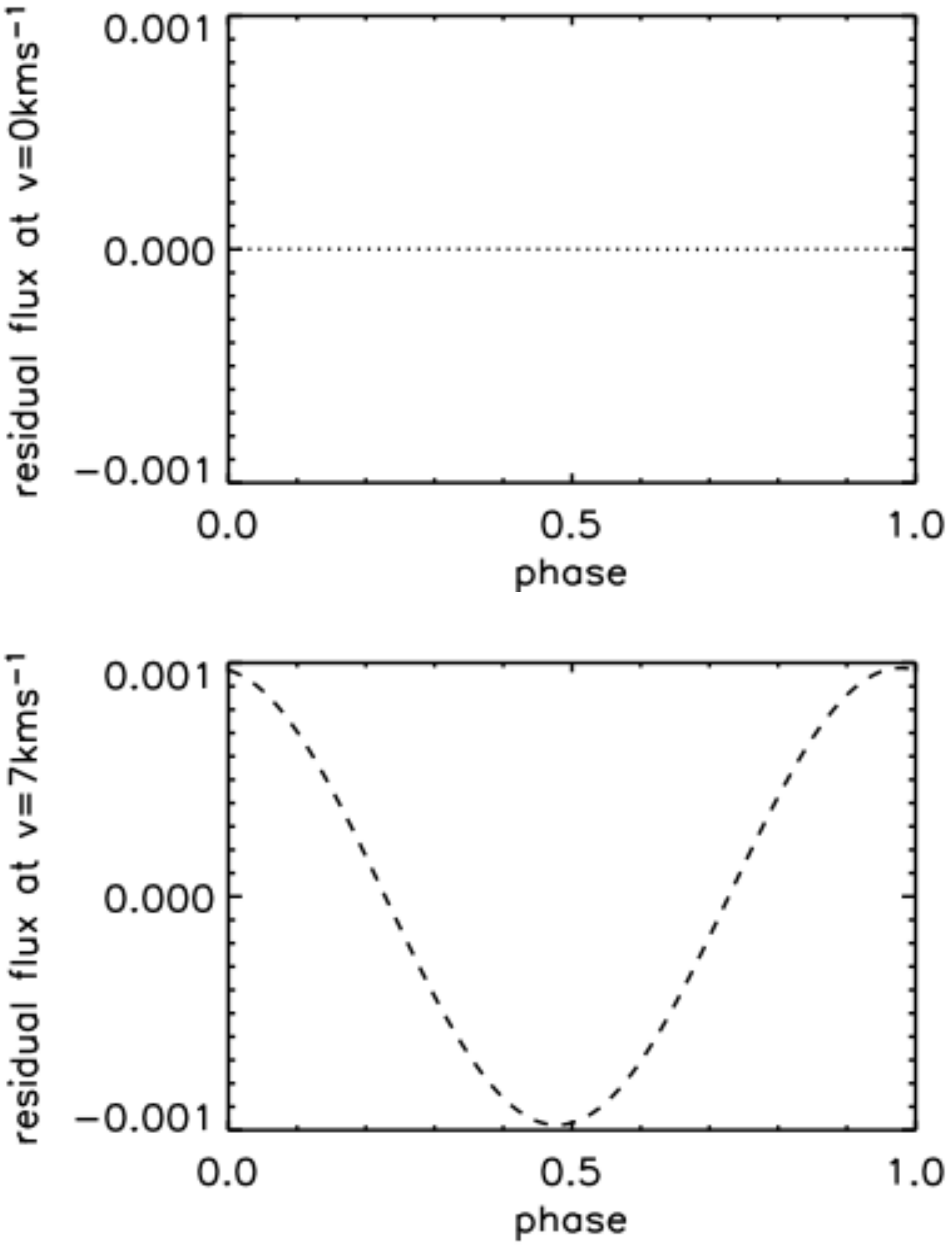
Rho Puppis 1



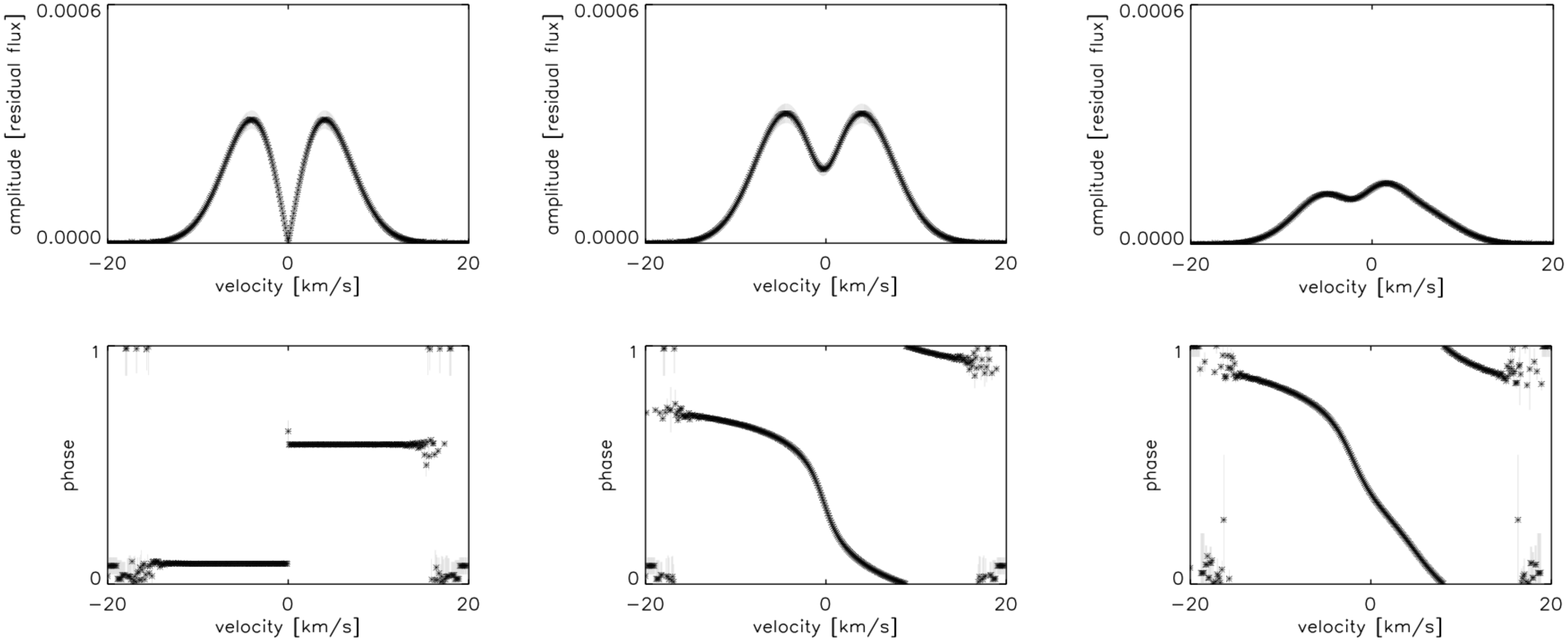
Mathias et al. 1997

line shape fits



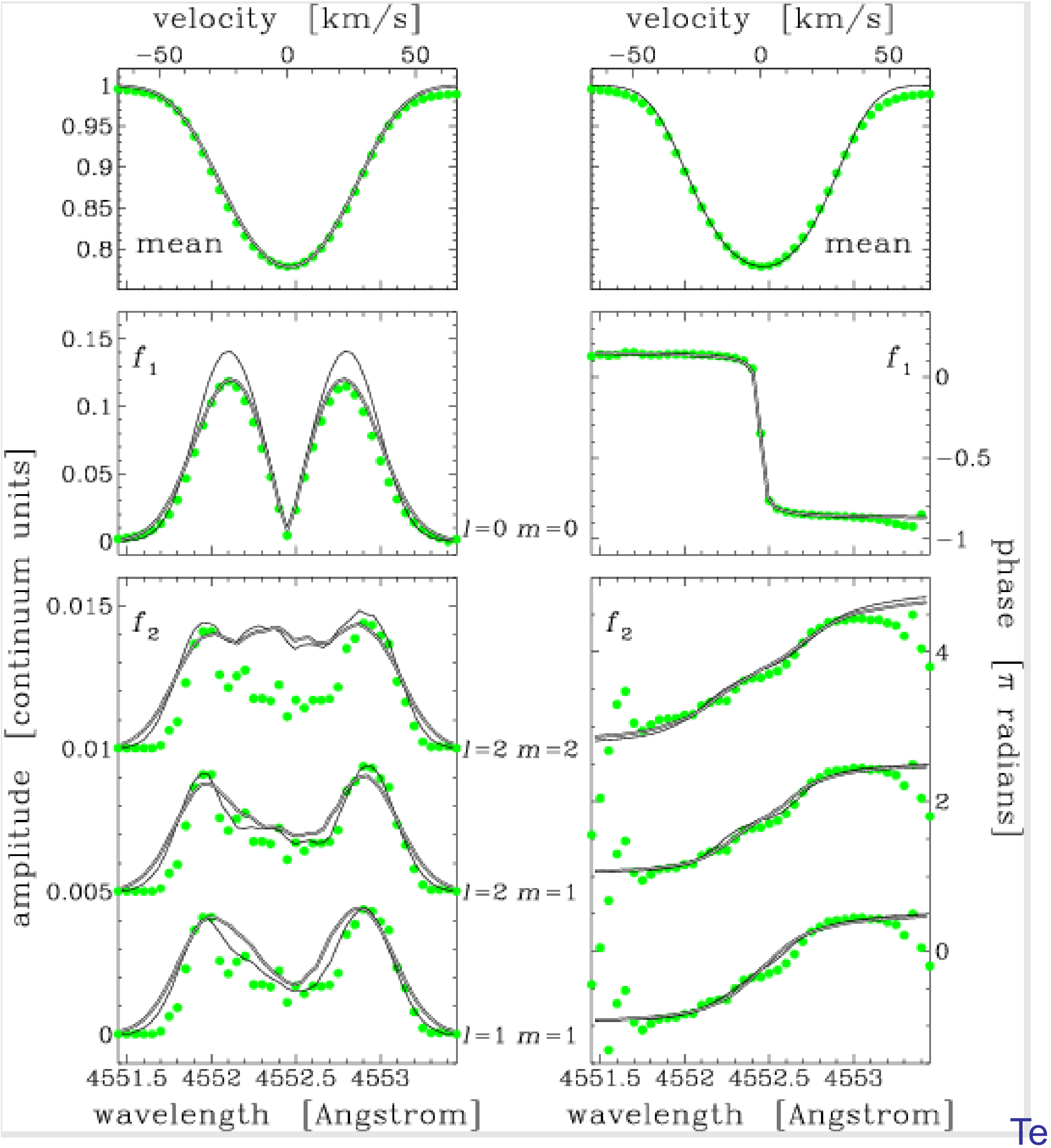


Amplitudes and phases across the line profile



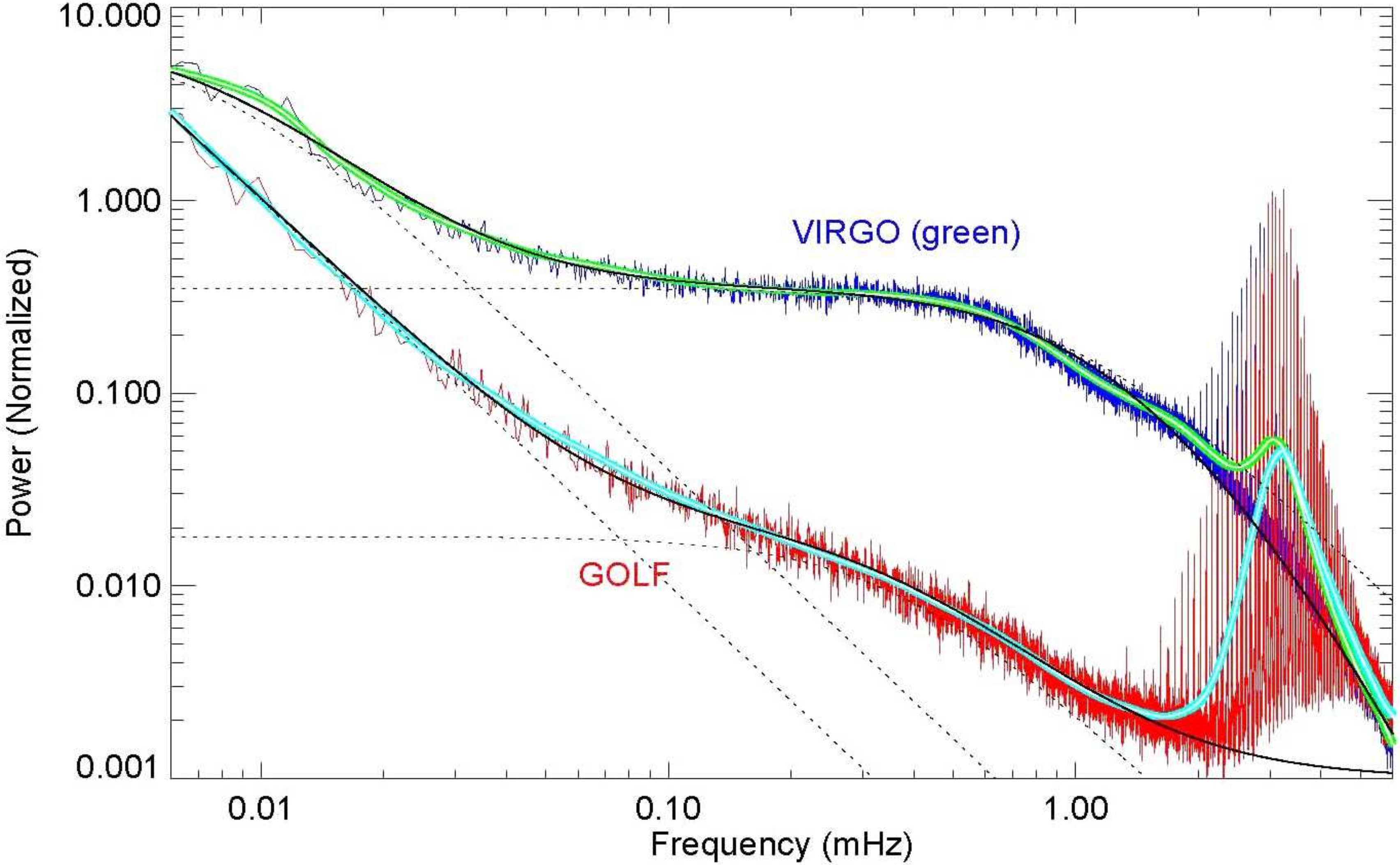
l=2,m=0 l=2,m=1 l=2,m=2

Hekker et al. 2006



Telting et al. 1997

Solar observations



Grundahl et al. 2007

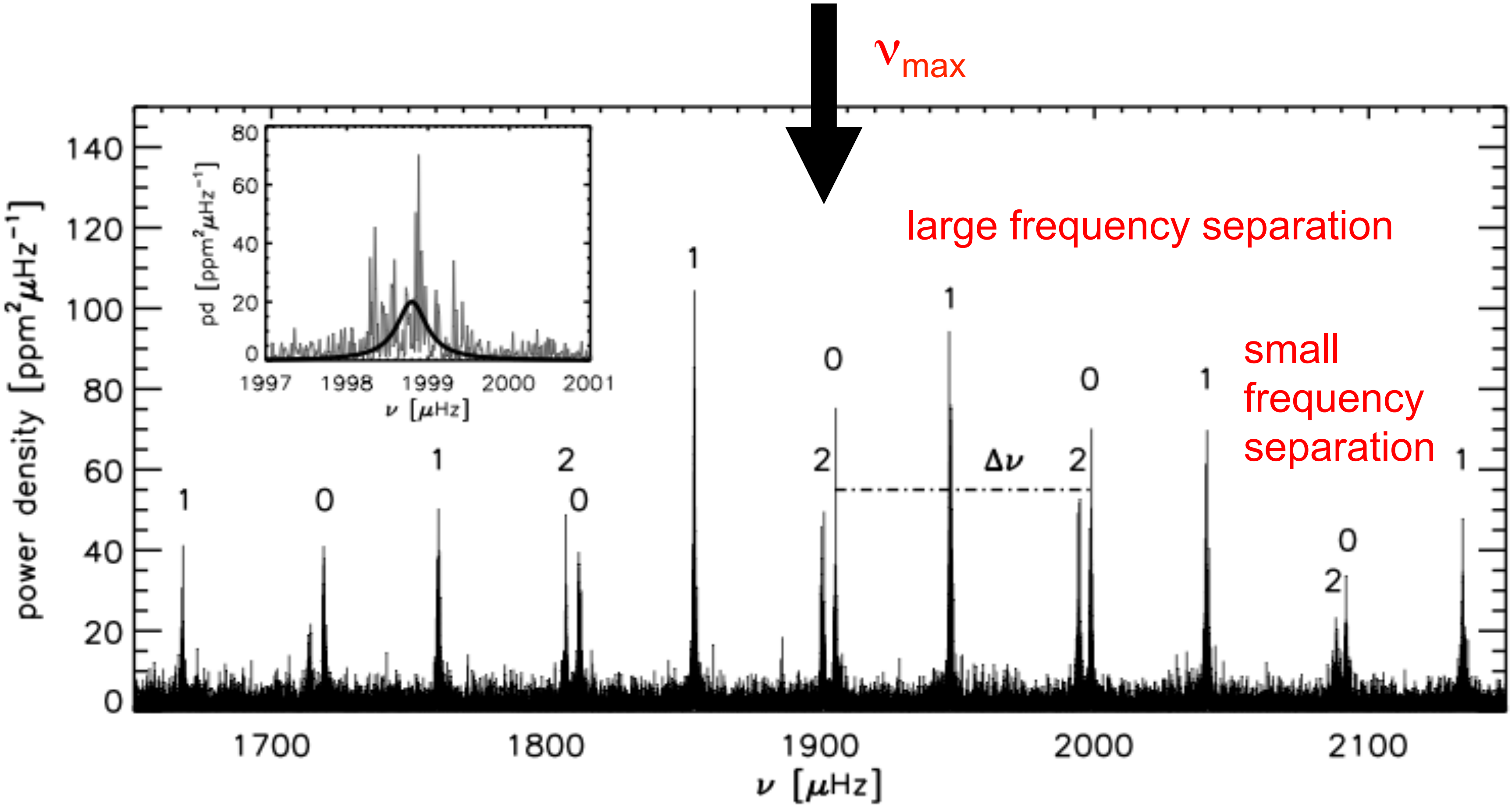
Asymptotic approximation: high-order p modes

$$\nu_{nl} \cong \Delta\nu\left(n + \frac{l}{2} + \varepsilon\right)$$

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}$$

$$\Delta\nu \propto \sqrt{\frac{M}{R^3}} \propto \sqrt{\bar{\rho}}$$

Solar-like oscillations



ν_{max}

large frequency separation

small frequency separation

Scaling relations

$$\nu_{\max} \propto \nu_{\rm ac} \propto \frac{g}{\sqrt{T_{\rm eff}}} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

$$\Delta\nu \equiv \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1} \propto \sqrt{\bar{\rho}} \propto \sqrt{\frac{M}{R^3}}$$

not model dependent

not depending on chemical composition

mass (~10%); radius (~7%); surface gravity (~3%)

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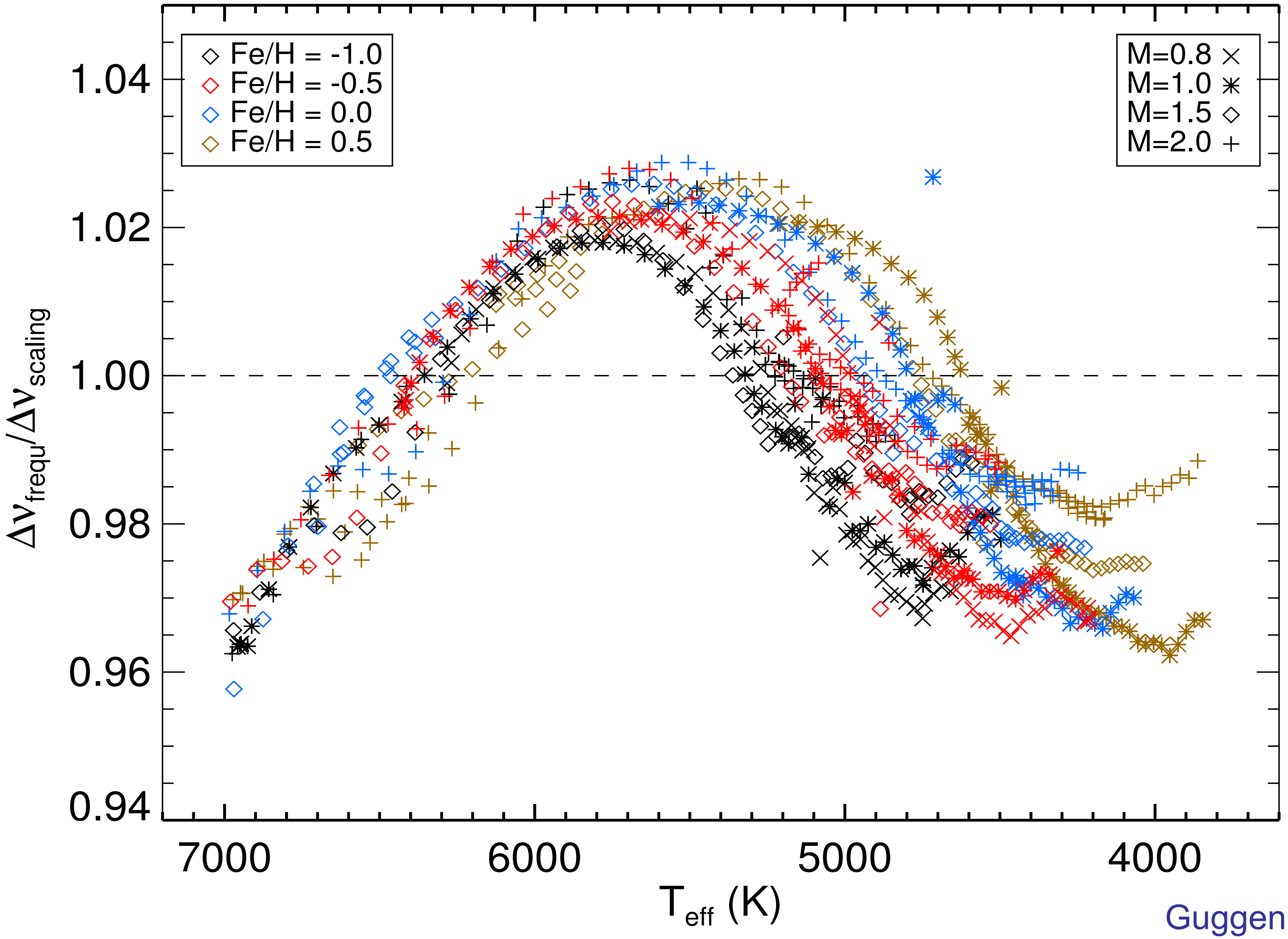
not model dependent

not depending on chemical composition

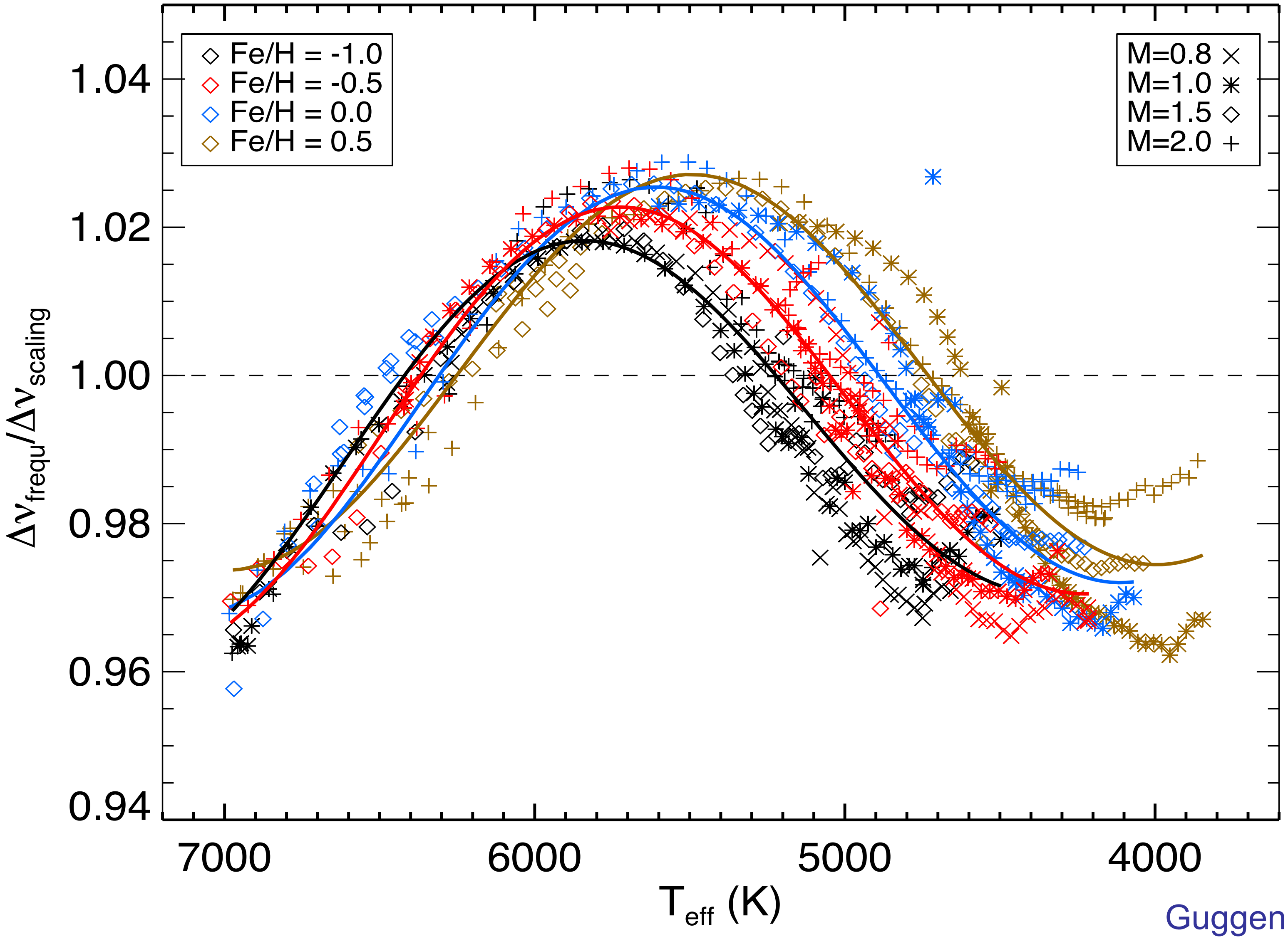
mass (~10%); radius (~7%); surface gravity (~3%)

Reference of scaling relation



Guggenberger et al. 2016

Reference of scaling relation



Guggenberger et al. 2016

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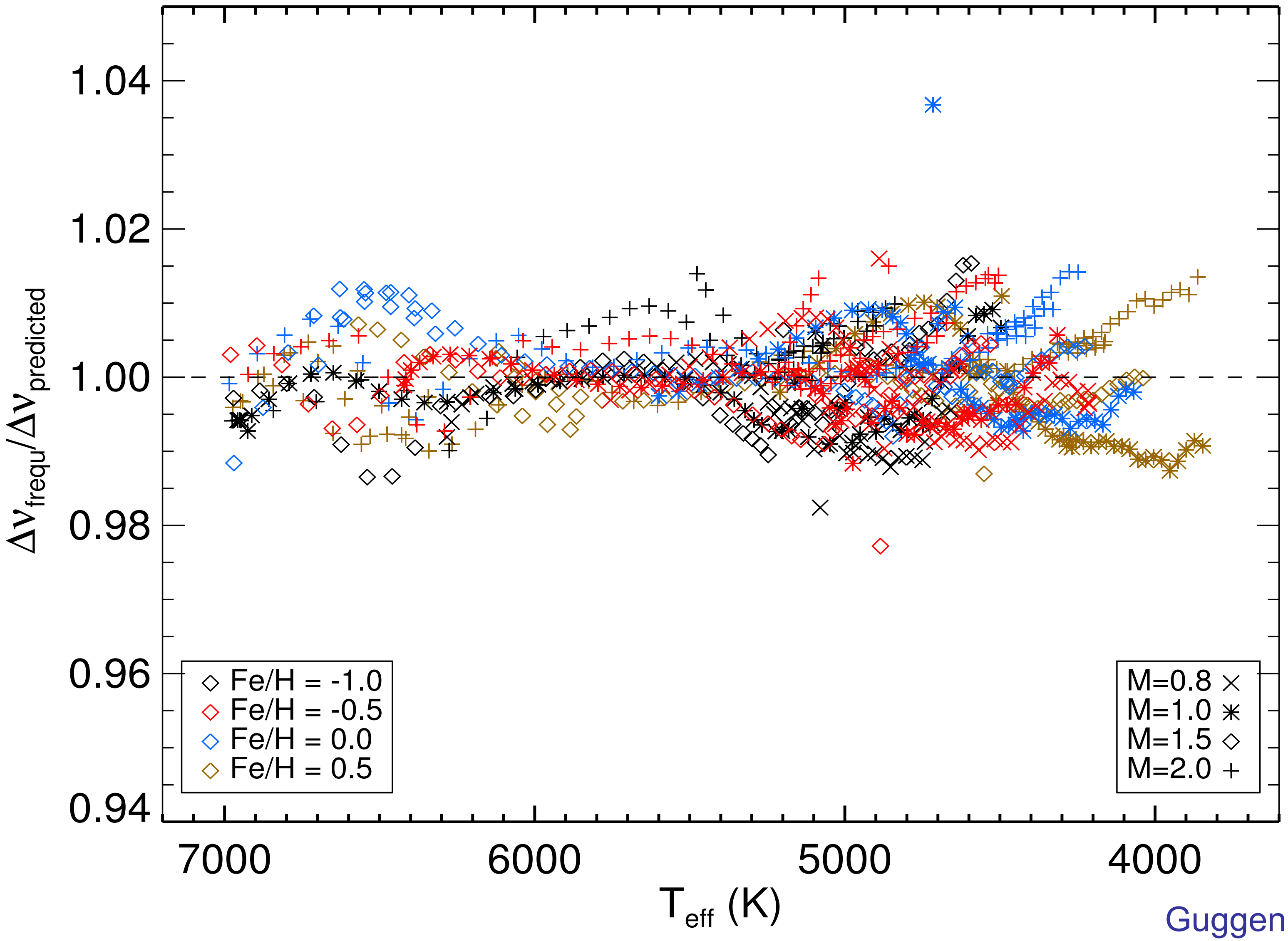
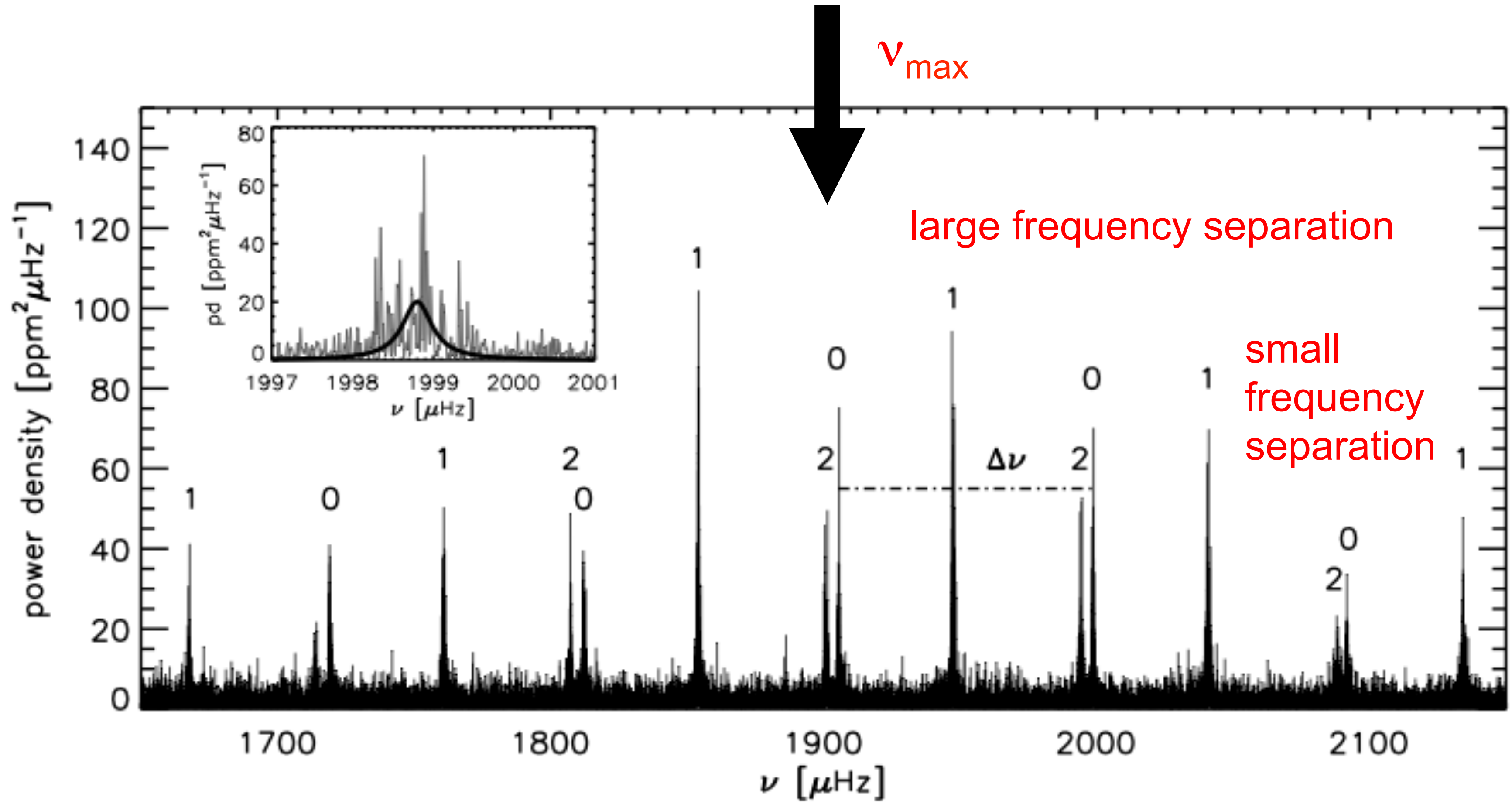


Guggenberger et al. 2016

Solar-like oscillations



ν_{max}

large frequency separation

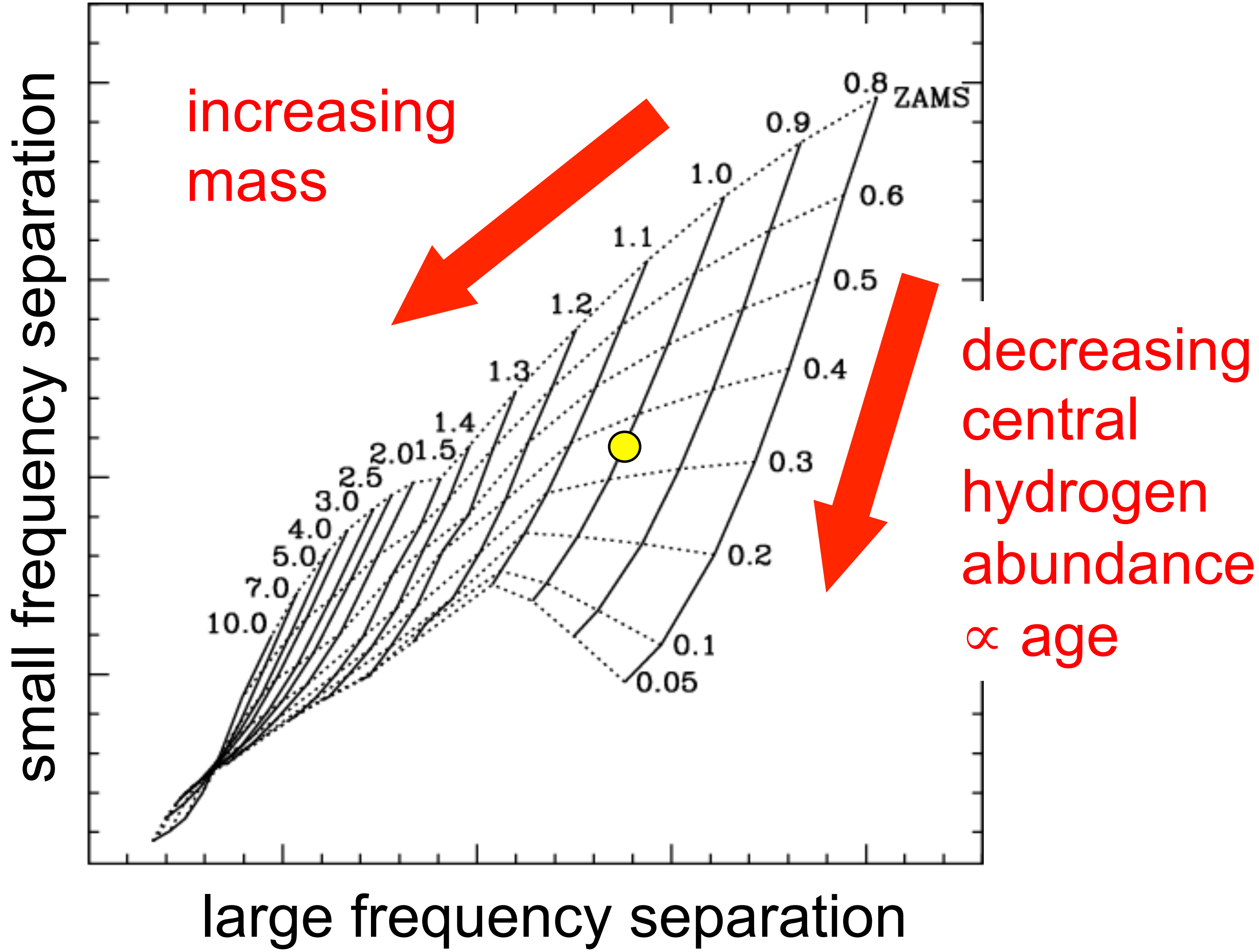
small frequency separation

Hekker & Mazumdar 2014

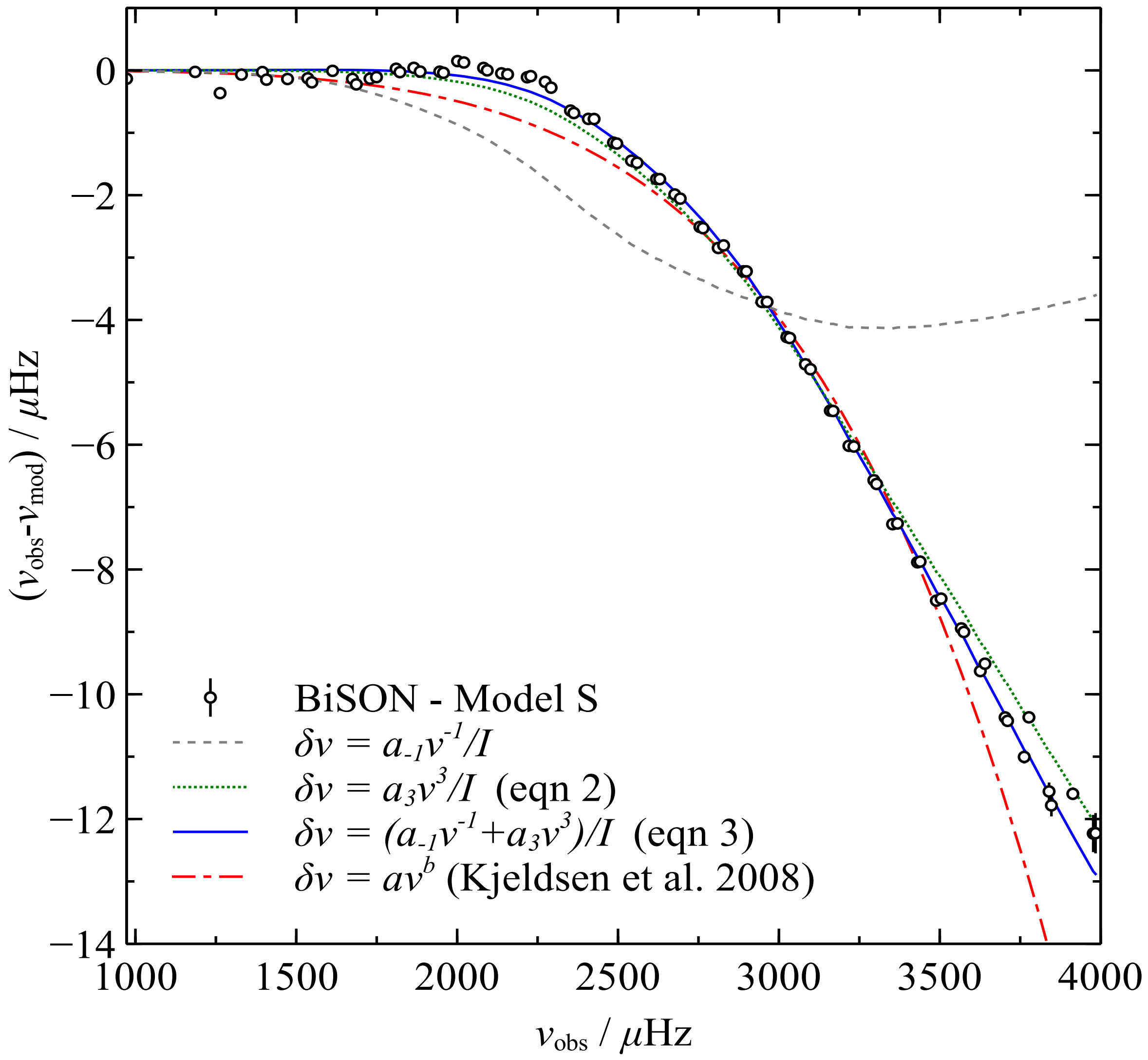
Asymptotic approximation: high-order p modes

$$\nu_{nl} \cong \Delta\nu\left(n + \frac{l}{2} + \varepsilon\right) + l(l+1)\frac{\Delta\nu}{4\pi^2\nu_{nl}}\int_0^R \frac{dc}{dr}\frac{dr}{c}$$

C-D Diagram

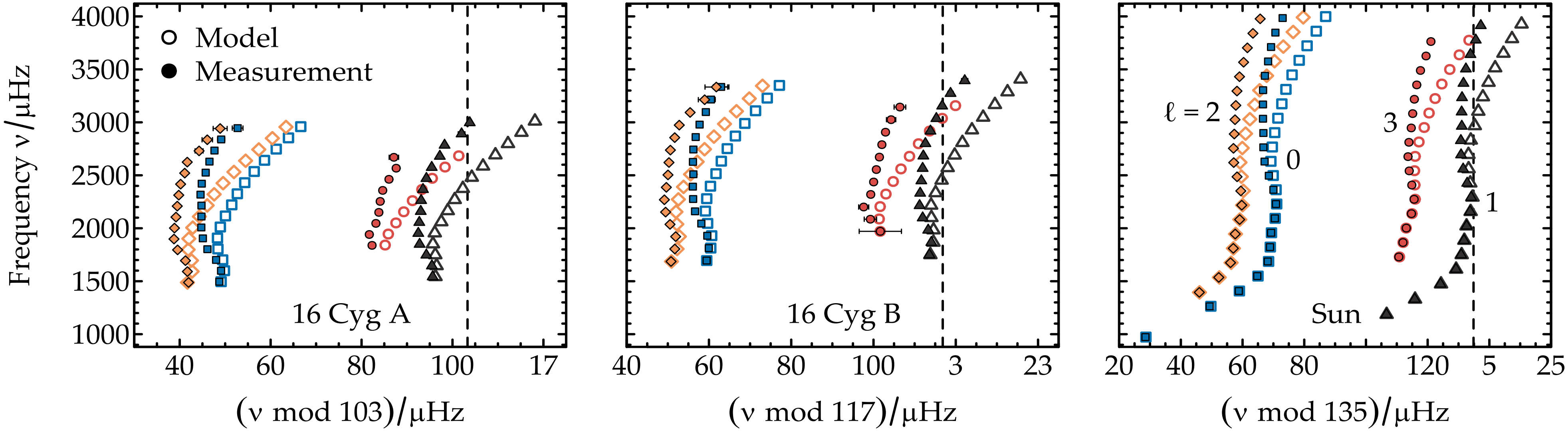

increasing mass
decreasing central hydrogen abundance ∝ age
small frequency separation
large frequency separation
0.8
ZAMS
0.9
1.0
1.1
1.2
1.3
1.4
1.5
2.0
2.5
3.0
4.0
5.0
7.0
10.0
0.6
0.5
0.4
0.3
0.2
0.1
0.05

Individual frequencies: surface term



Ball et al. 2014

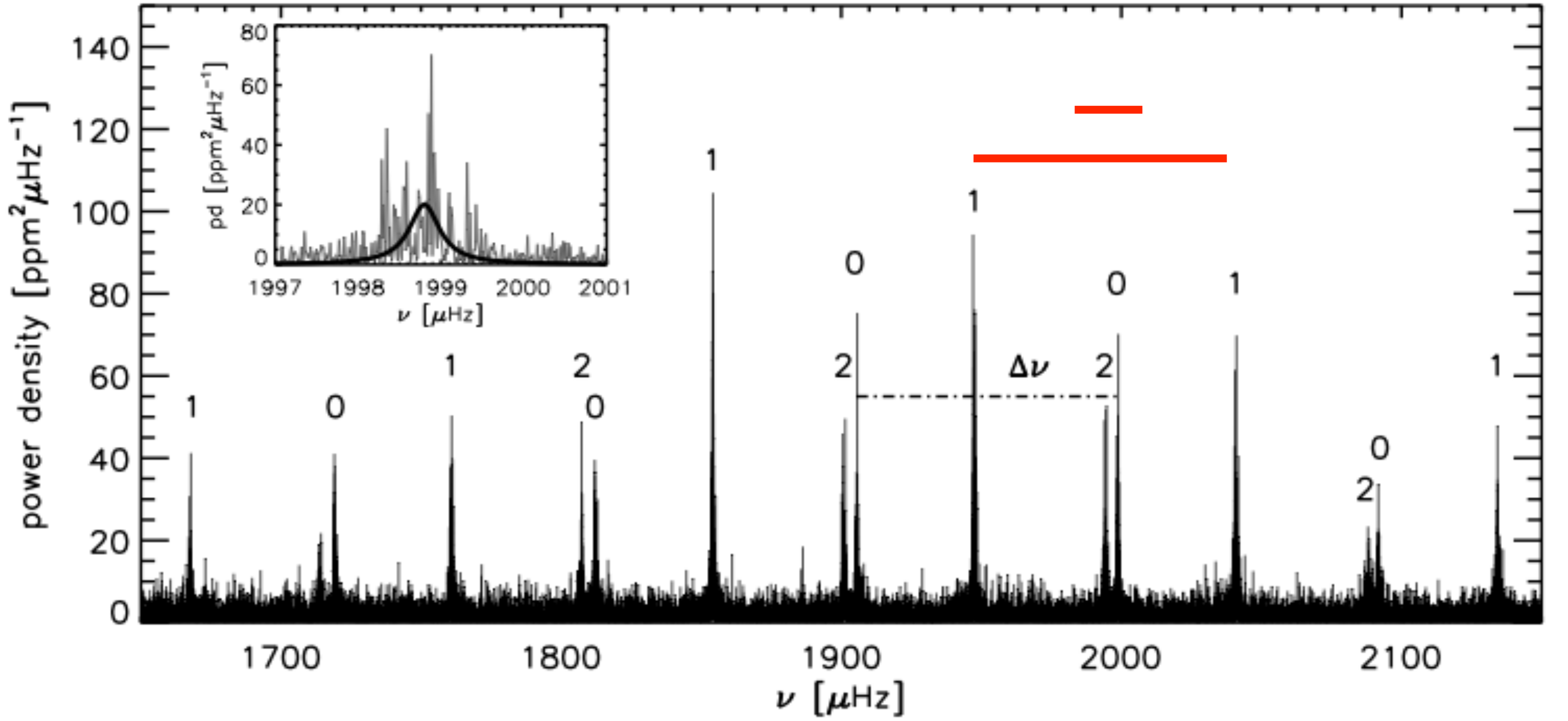
Individual frequencies: surface term



Bellinger et al. submitted

Frequency ratios

$$r_{02} = \frac{\nu_{n\ 0} - \nu_{n-1\ 2}}{\nu_{n\ 1} - \nu_{n-1\ 1}}$$



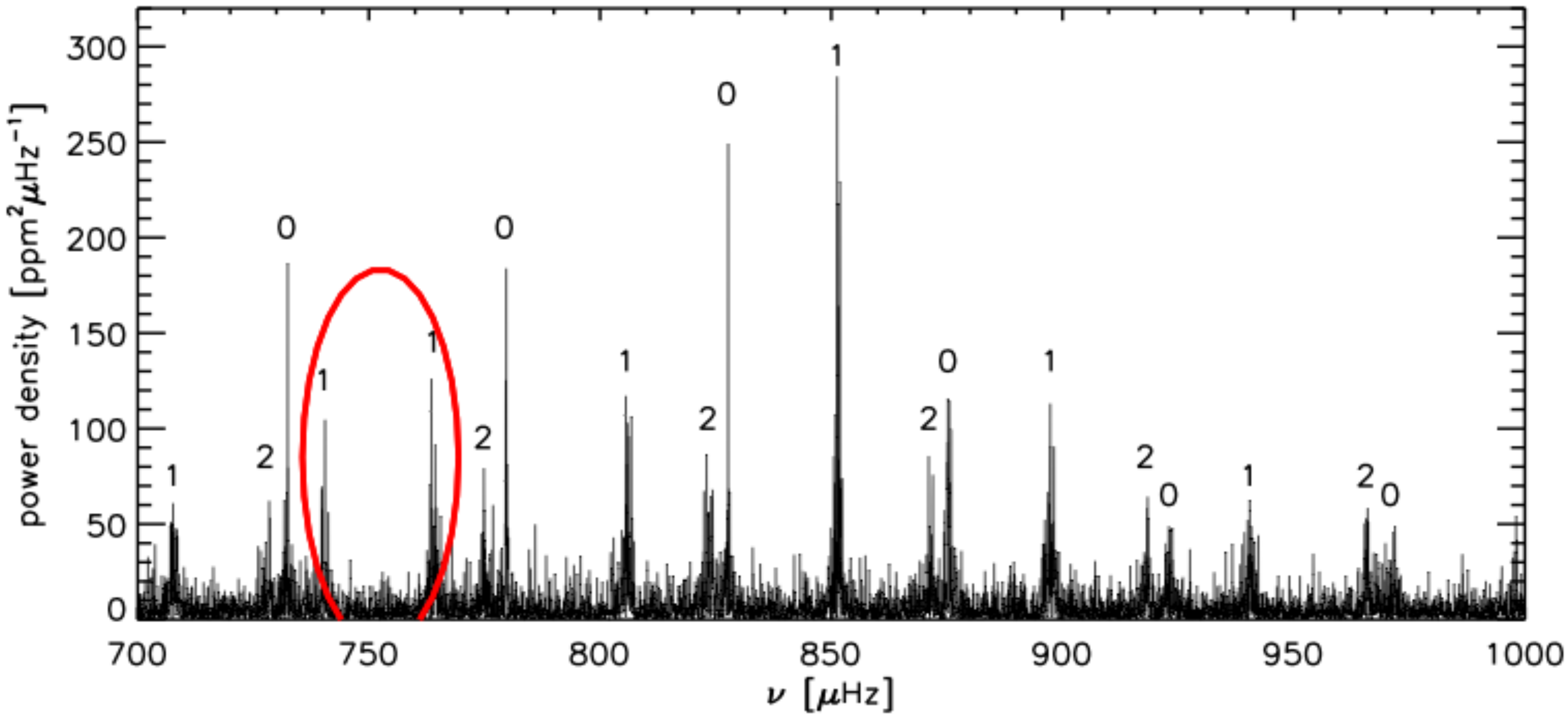
Asymptotic approximation: high-order g modes

$$\Pi_{nl} \cong \frac{\Delta\Pi}{\sqrt{l(l+1)}}\left(n + \frac{l}{2} + \varepsilon\right)$$

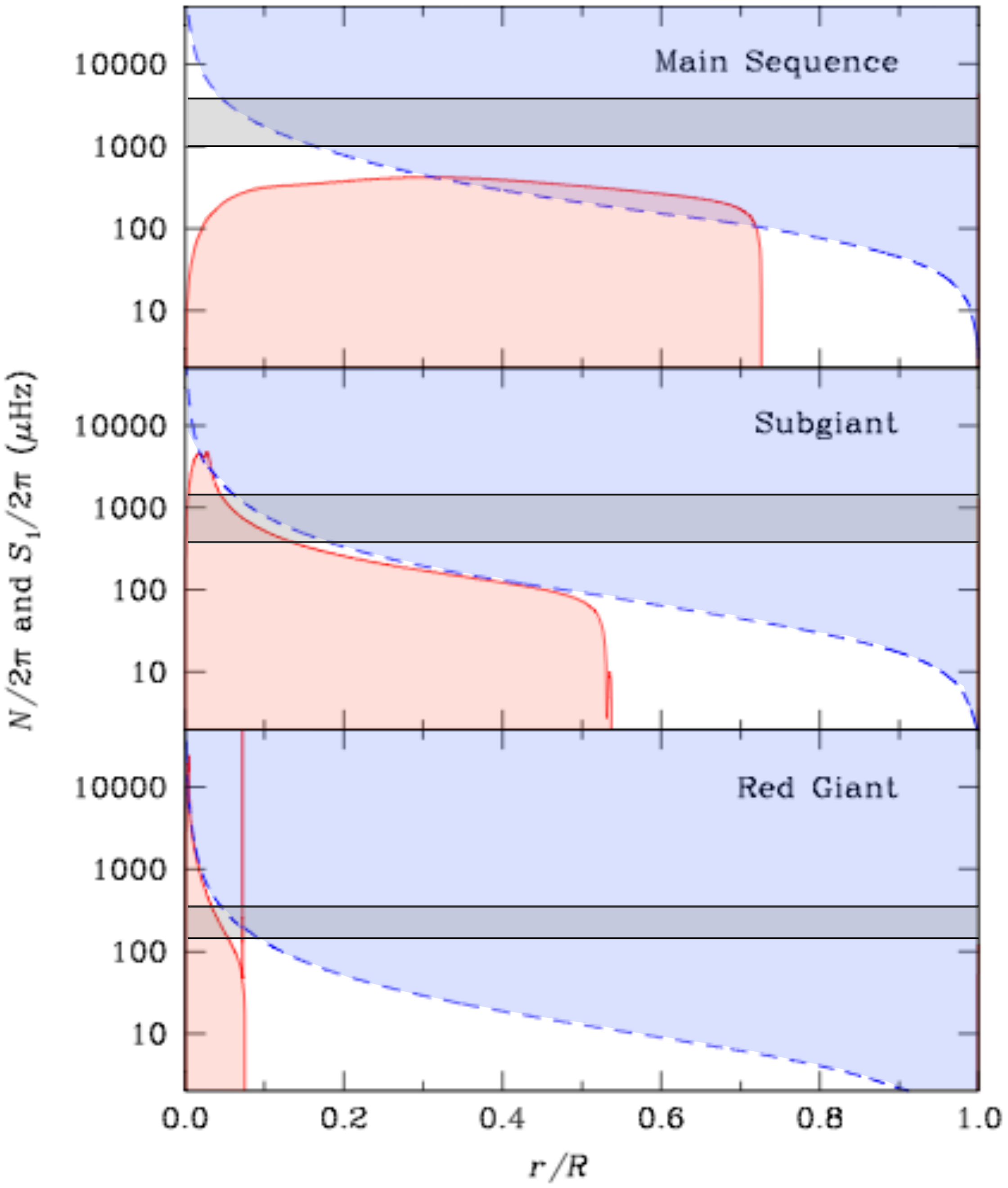
$$\Delta\Pi = (2\pi)^2\left(\int_0^R \frac{N(r)}{r}\,dr\right)^{-1}$$

$$N^2 \equiv \frac{Gm}{r^2}\left(\frac{1}{\Gamma_1}\frac{d\ln P}{dr} - \frac{d\ln P}{dr}\right)$$

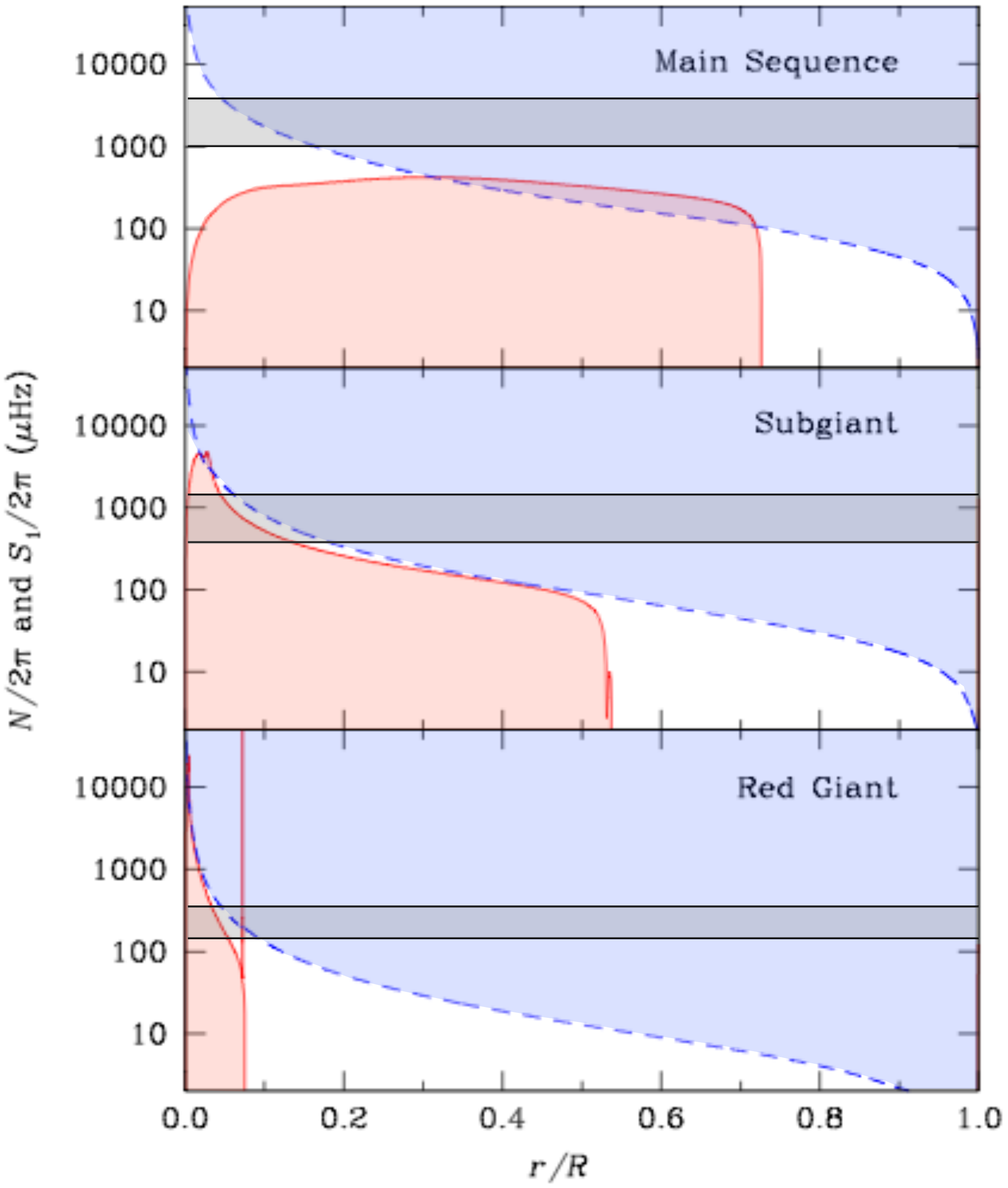
Subgiant



Hekker & Mazumdar 2014



Hekker & Mazumdar 2014

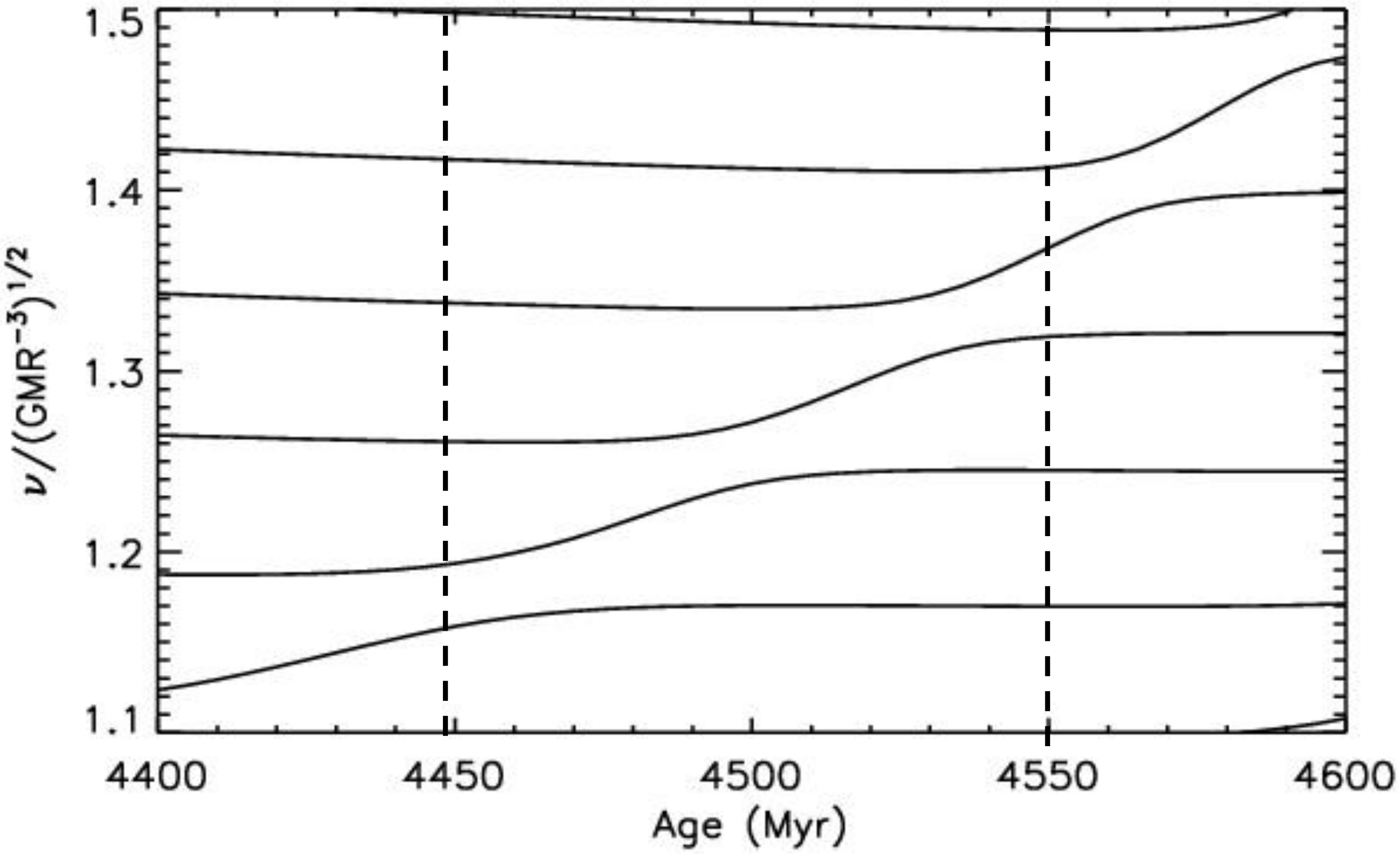


-Brunt-Väisälä frequency
buoyancy cavity

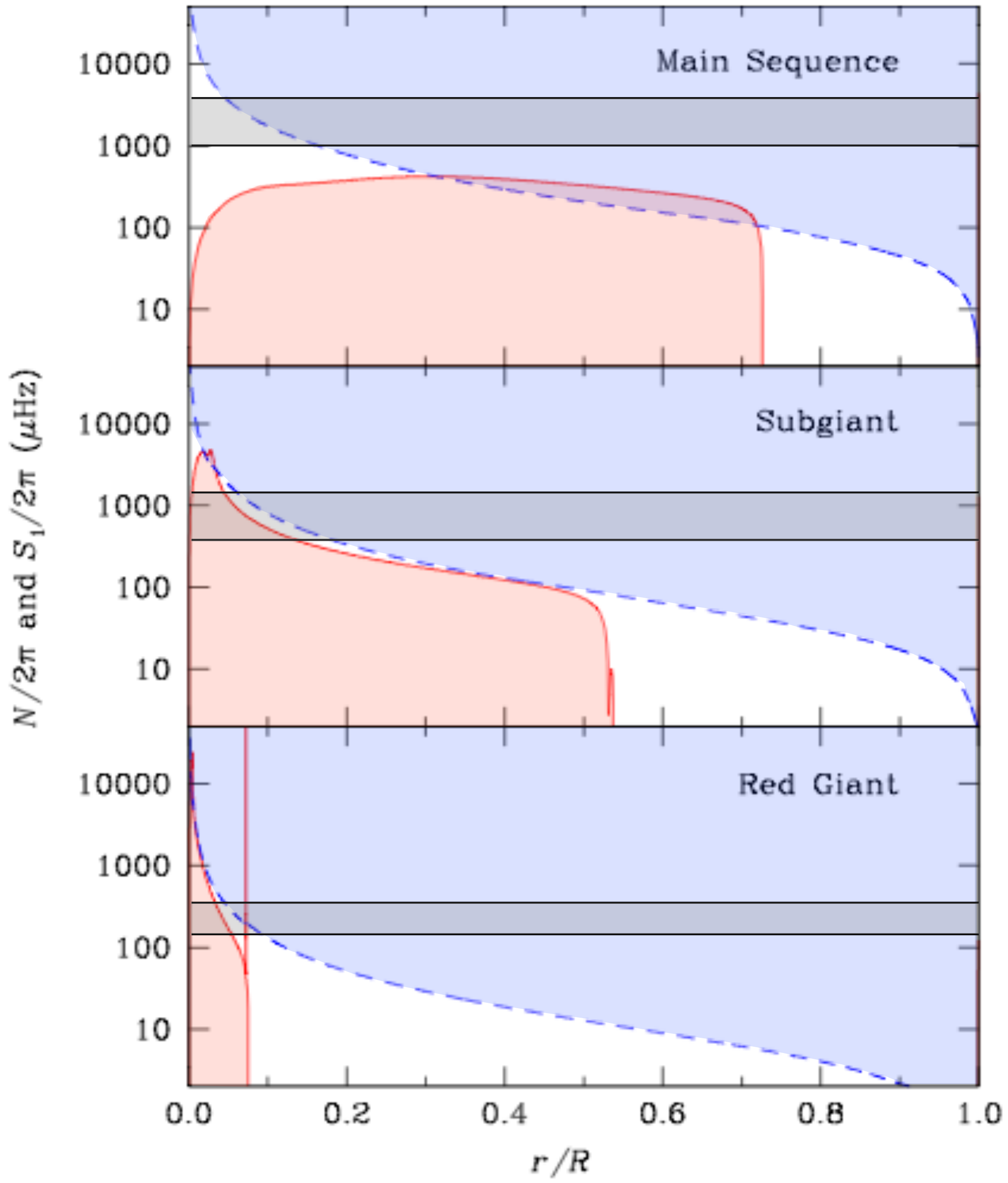
- Lamb frequency
acoustic cavity

Hekker & Mazumdar 2014

Evolution



Deheuvels & Michel 2011

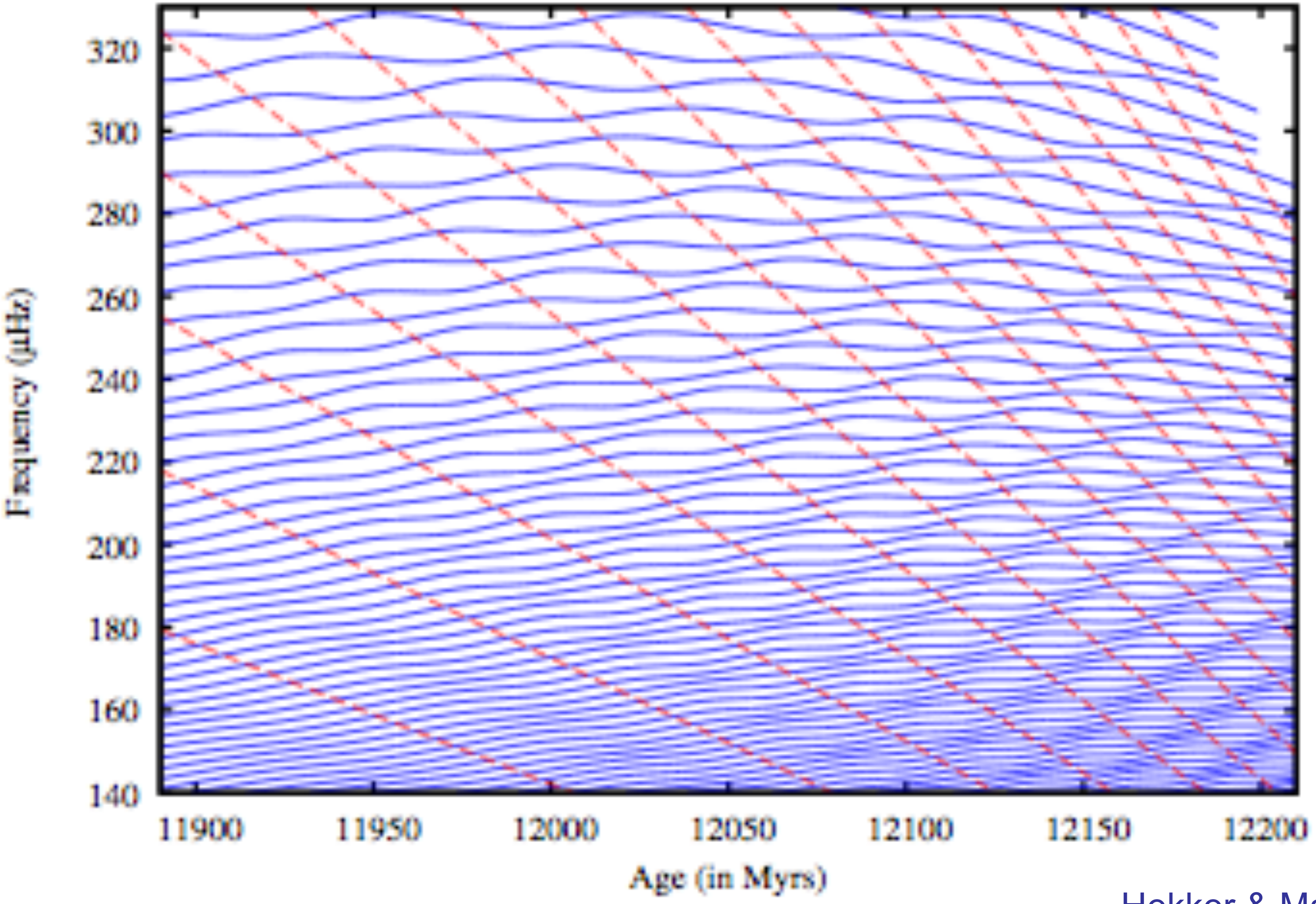


-Brunt-Väisälä frequency
buoyancy cavity

- Lamb frequency
acoustic cavity

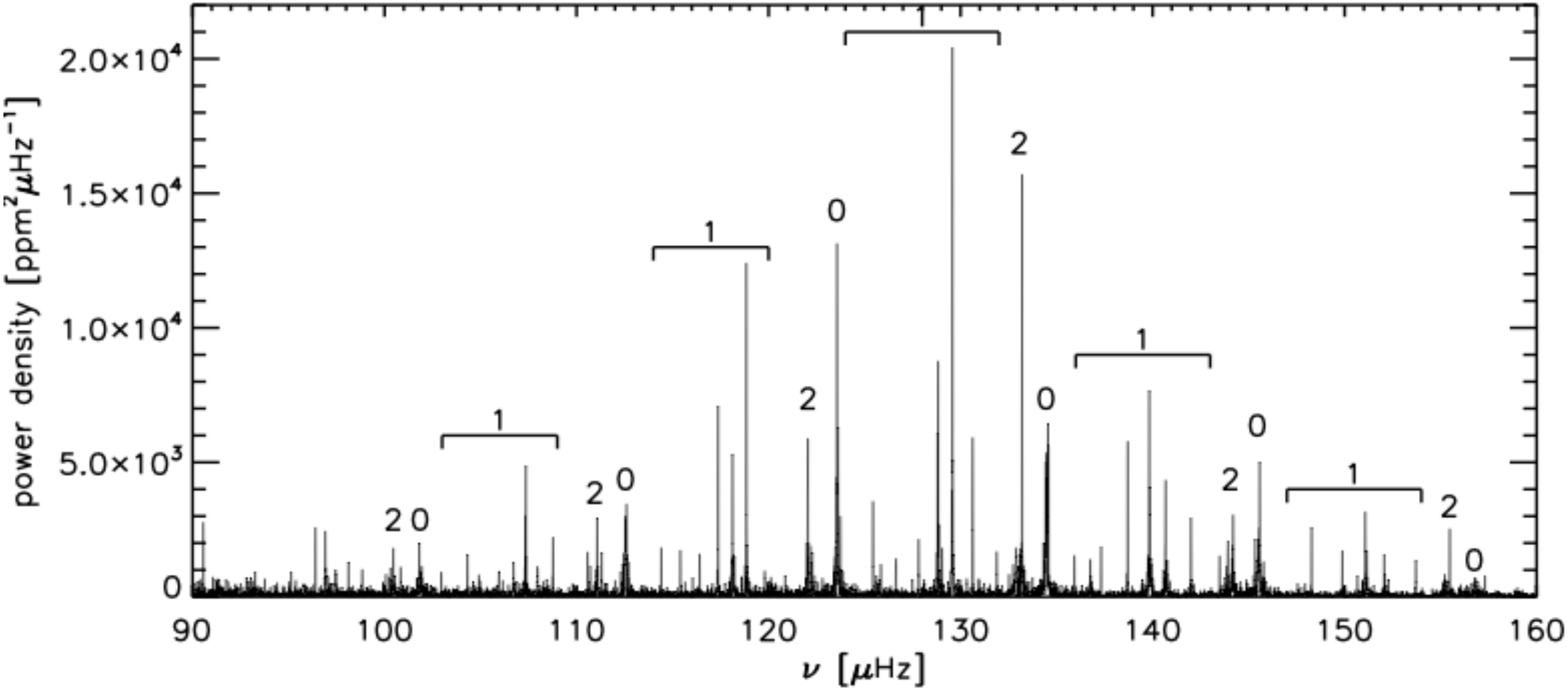
Hekker & Mazumdar 2014

Evolution



Hekker & Mazumdar 2014

Red giant



Hekker & Mazumdar 2014

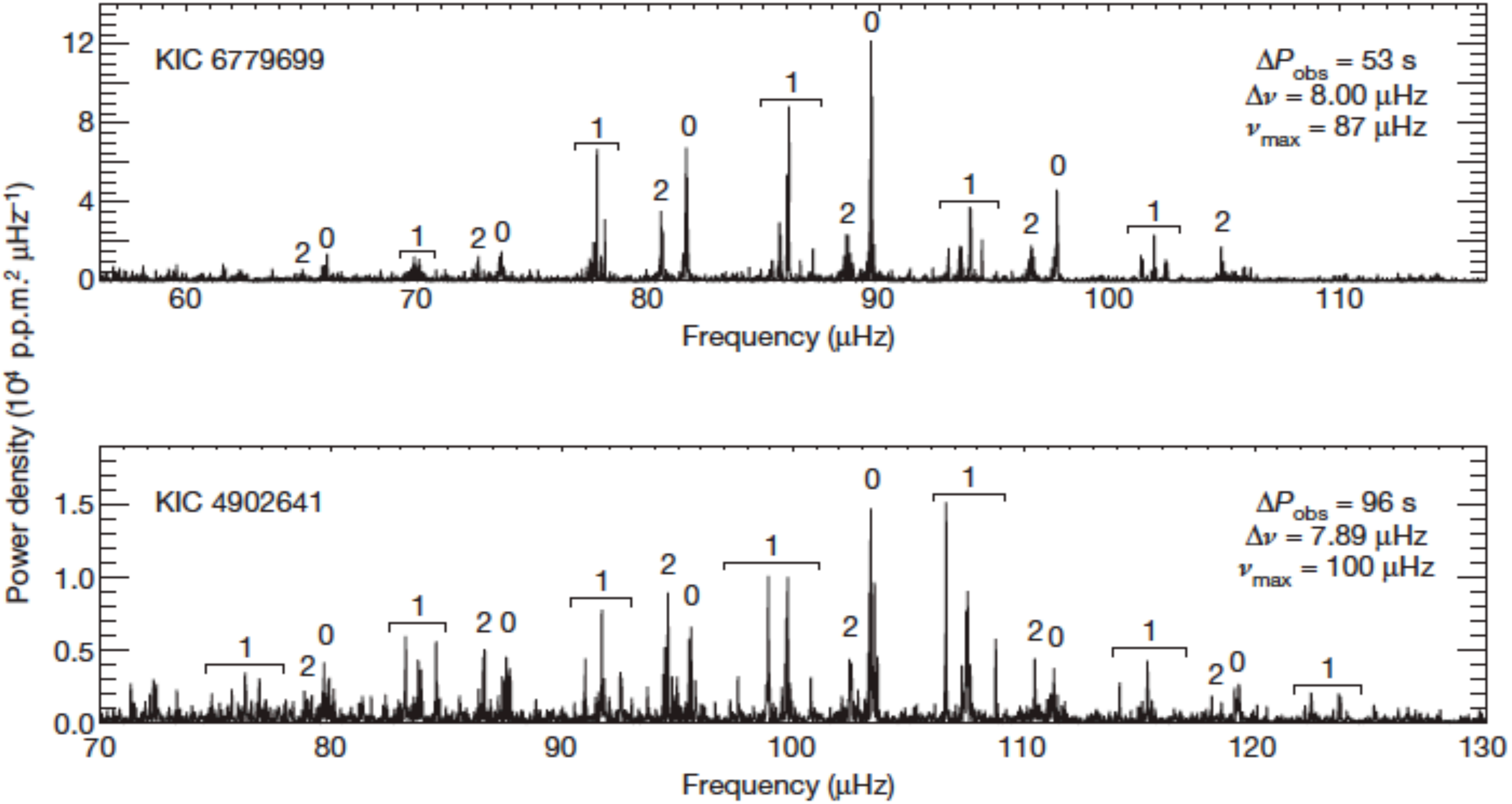
Asymptotic approximation: high-order g modes

$$\Pi_{nl} \cong \frac{\Delta\Pi}{\sqrt{l(l+1)}}\left(n+\frac{l}{2}+\varepsilon\right)$$

$$\Delta\Pi = (2\pi)^2\left(\int_0^R \frac{N(r)}{r}\,dr\right)^{-1}$$

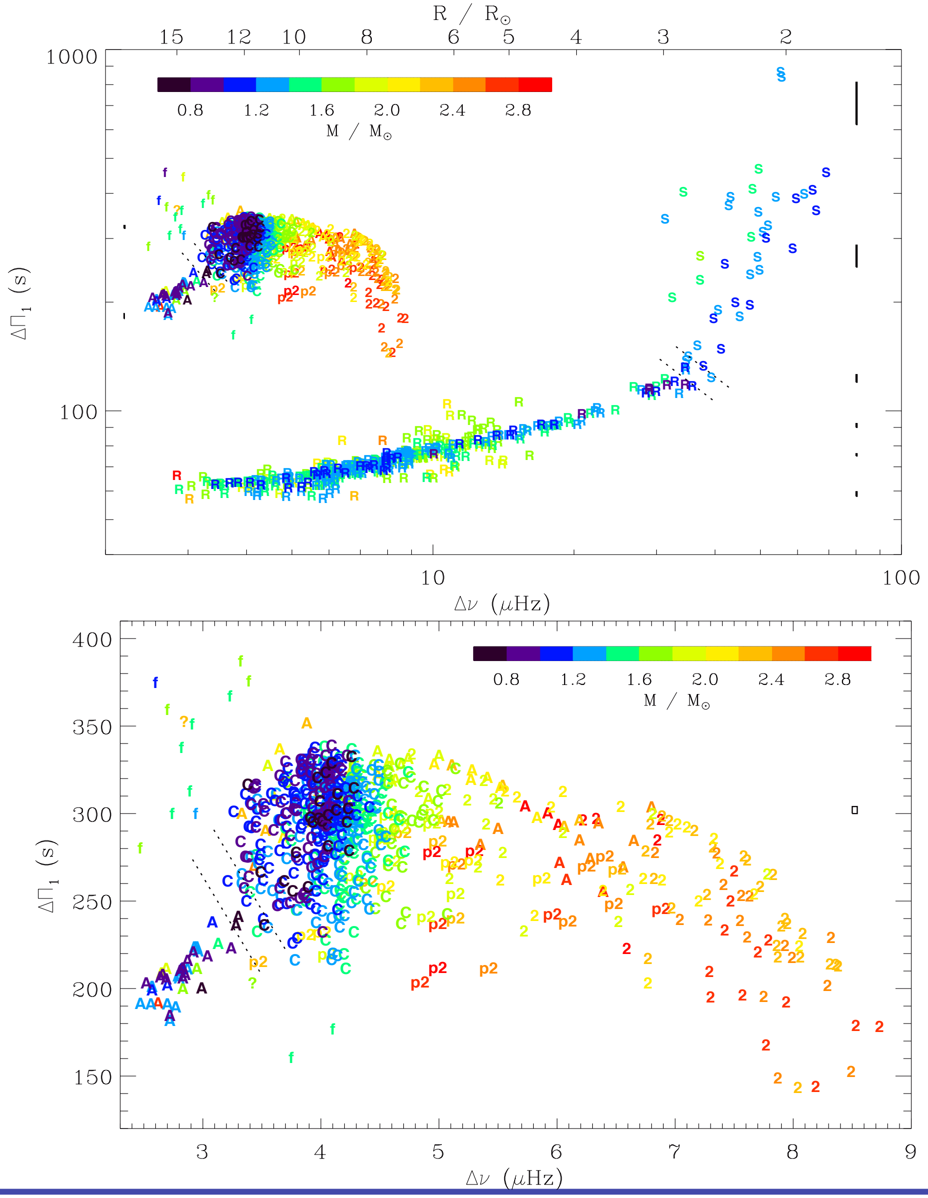
$$N^2 \equiv \frac{Gm}{r^2}\left(\frac{1}{\Gamma_1}\frac{d\ln P}{dr}-\frac{d\ln P}{dr}\right)$$

Mixed modes



Bedding et al. 2011

Period spacing



S: subgiant

R: red giant branch star

f: helium subflash stage

C: red clump

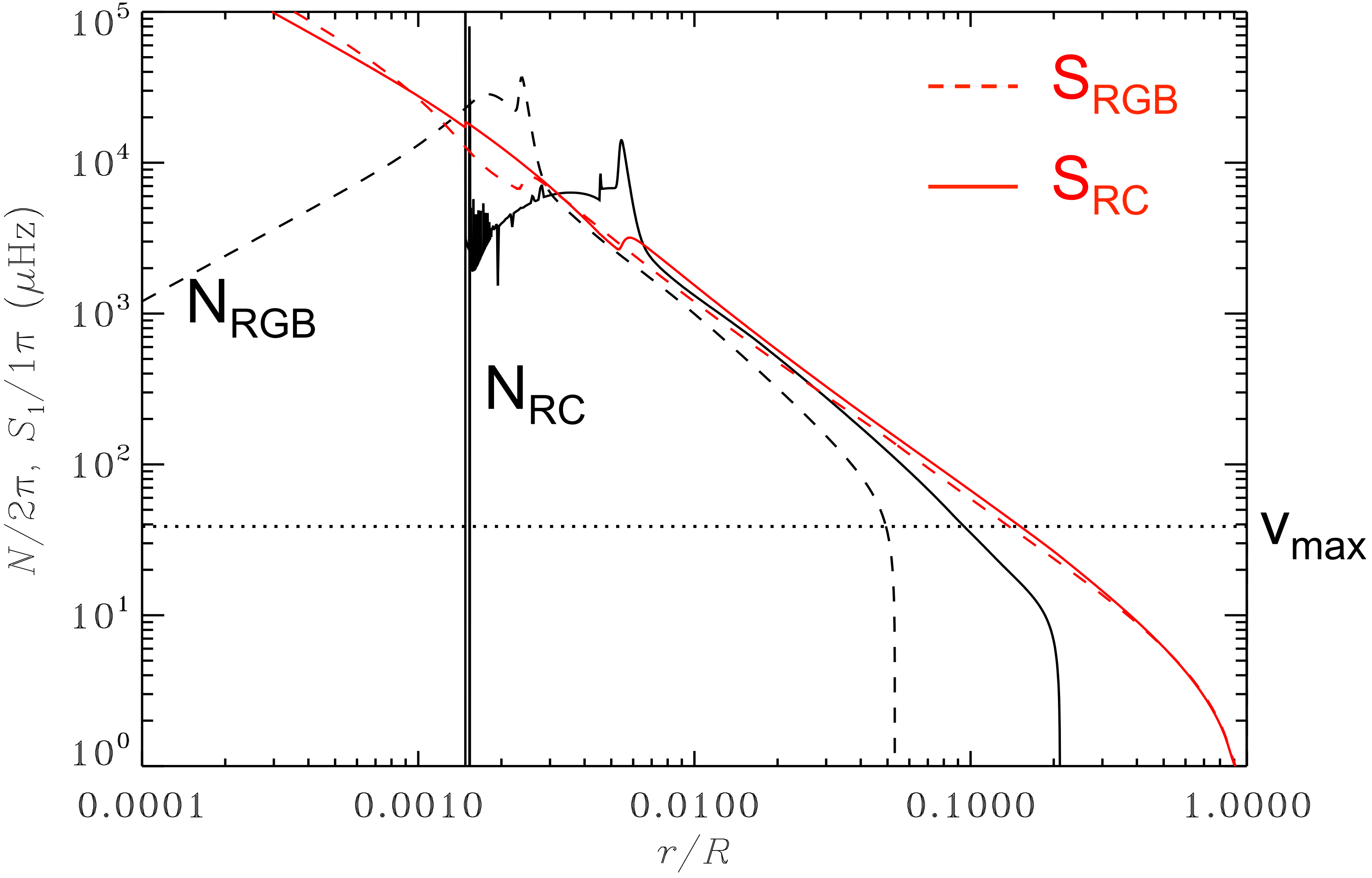
p2: pre secondary clump

2: secondary clump

A: stars leaving the clump moving towards AGB

Mosser et al. 2014

Brunt-Väisälä frequency

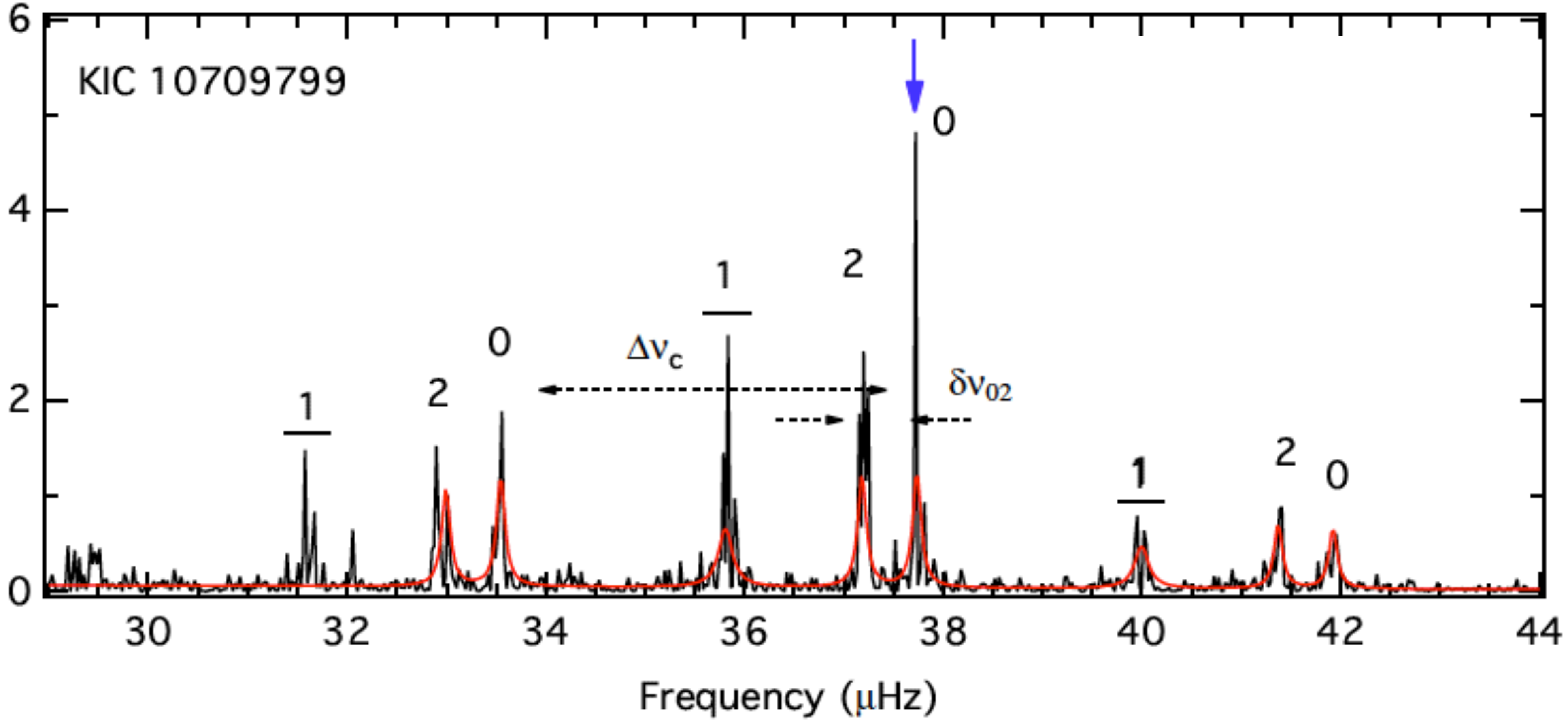


Hekker & Christensen-Dalsgaard 2017

Phase method

$$\nu_{n,0} \approx \Delta\nu_c (n + \varepsilon_c)$$

Kallinger, Hekker et al. 2012

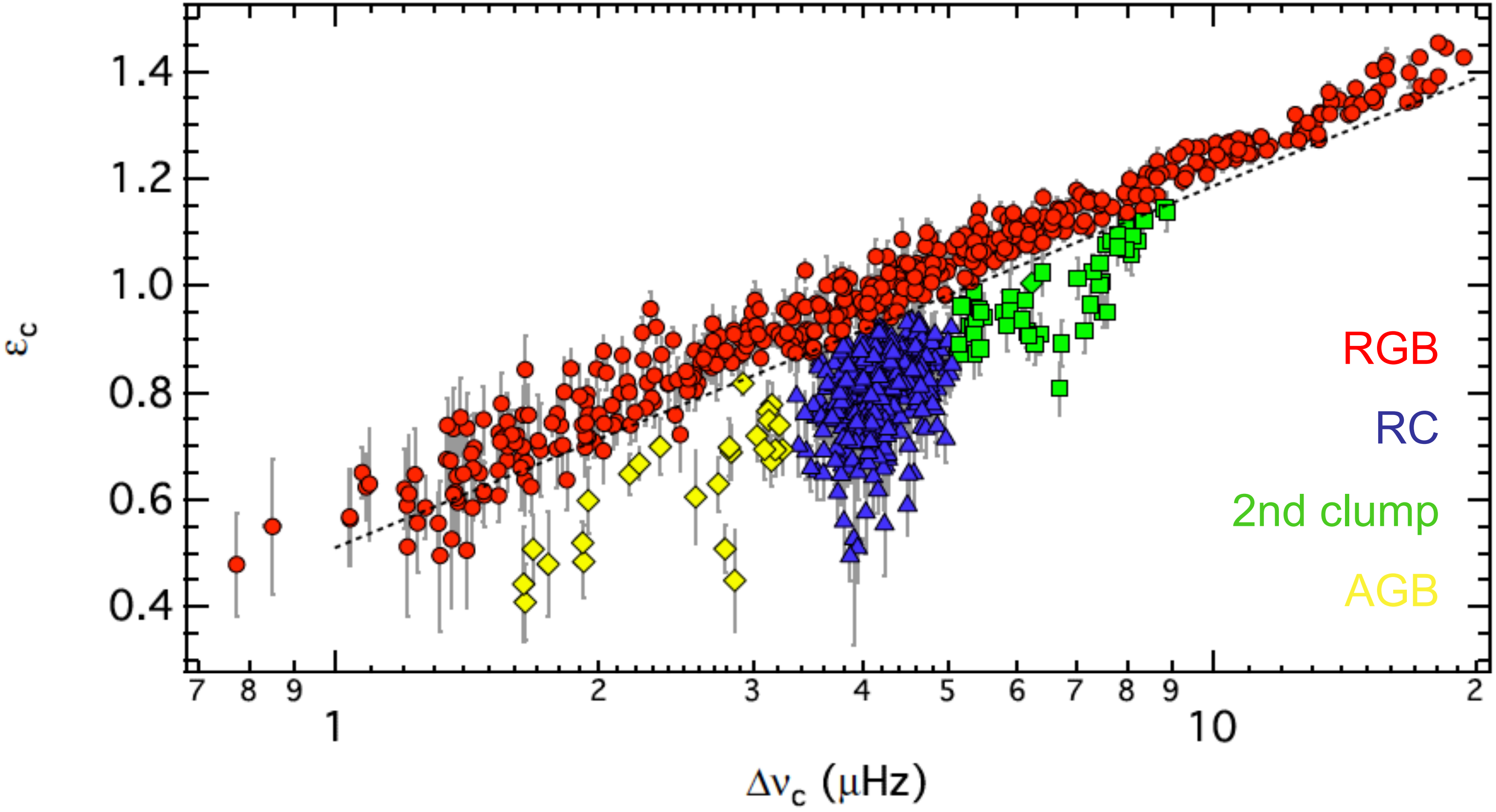


$\nu_{n-1,0}$ $\nu_{n,0}$ $\nu_{n+1,0}$

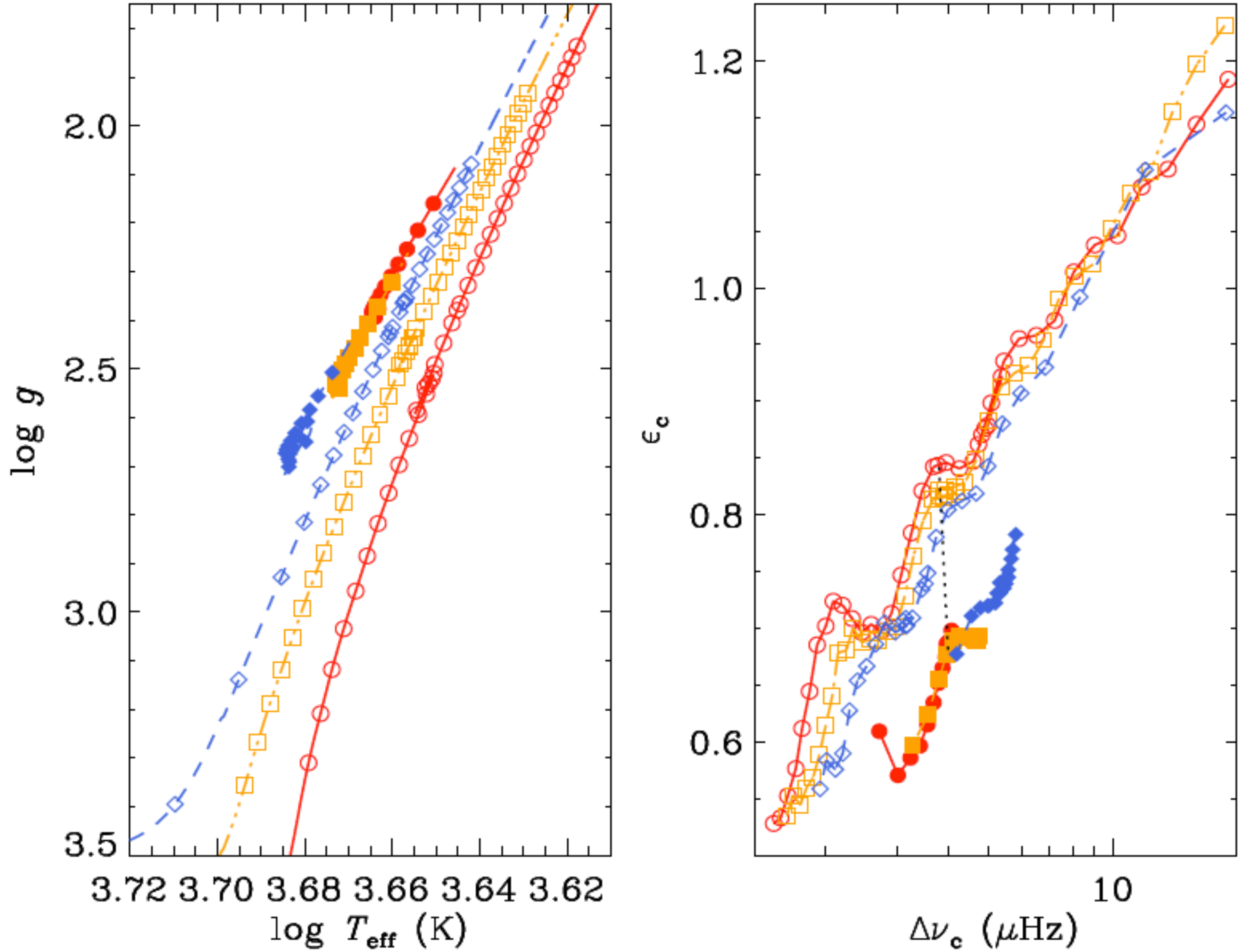
Phase method

$$\nu_{n,0} \approx \Delta\nu_c (n + \varepsilon_c)$$

Kallinger, Hekker et al. 2012



Phase method explained



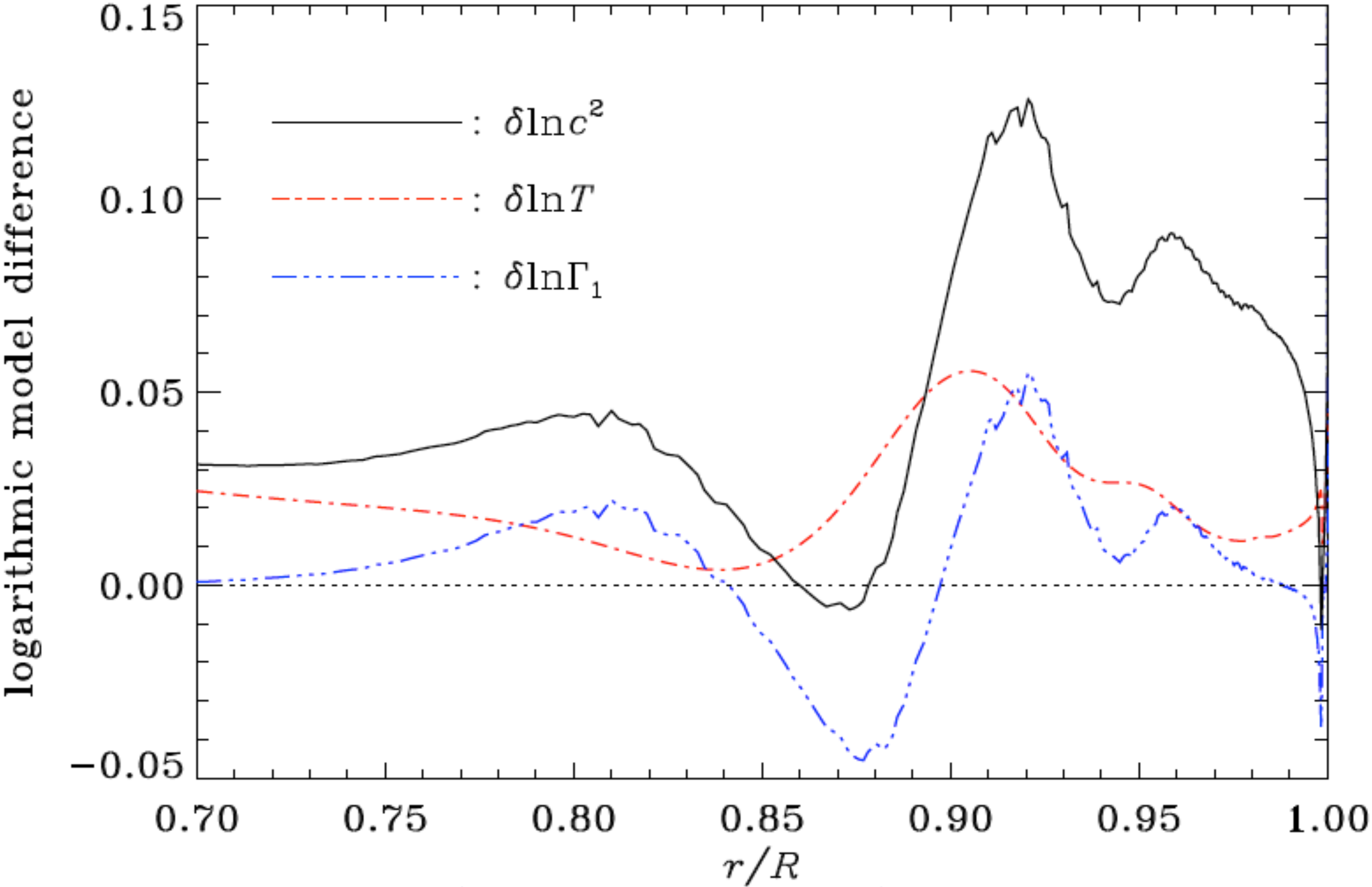
$M = 1\ M_{sun}$

$M = 1.5\ M_{Sun}$

$M = 2\ M_{Sun}$

Christensen-Dalsgaard, Silva Aguirre, Elsworth, Hekker 2014

Phase method explained

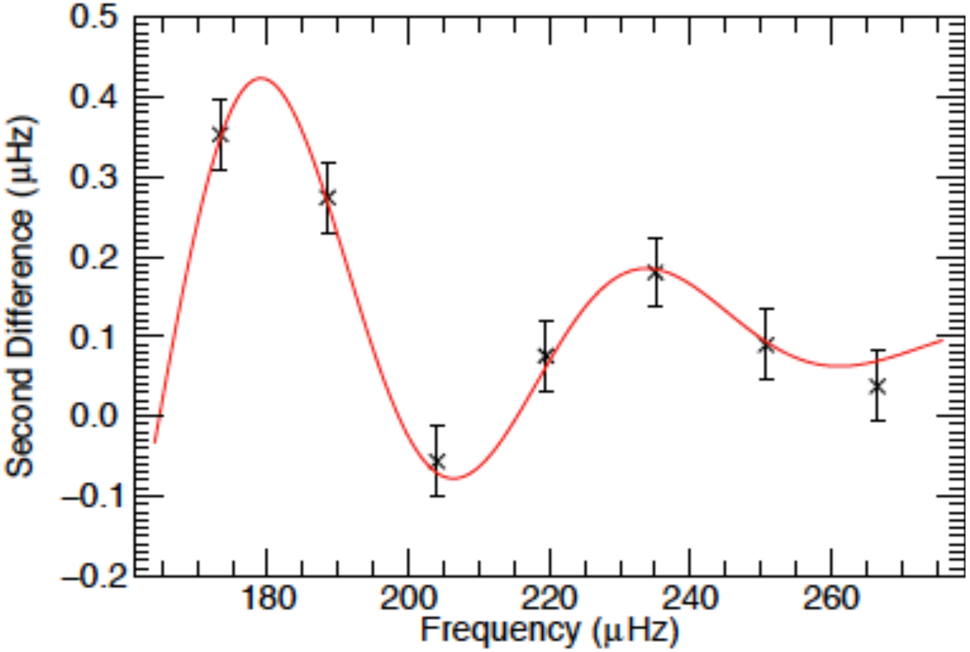


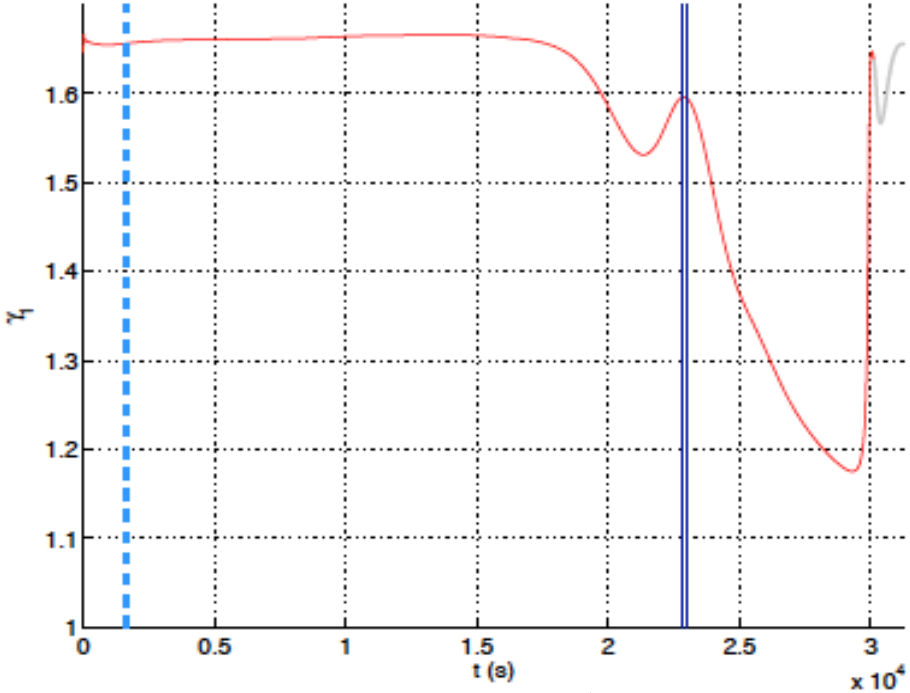
Christensen-Dalsgaard, Silva Aguirre, Elsworth, Hekker 2014

Stellar internal structures

Broomhall et al., 2014

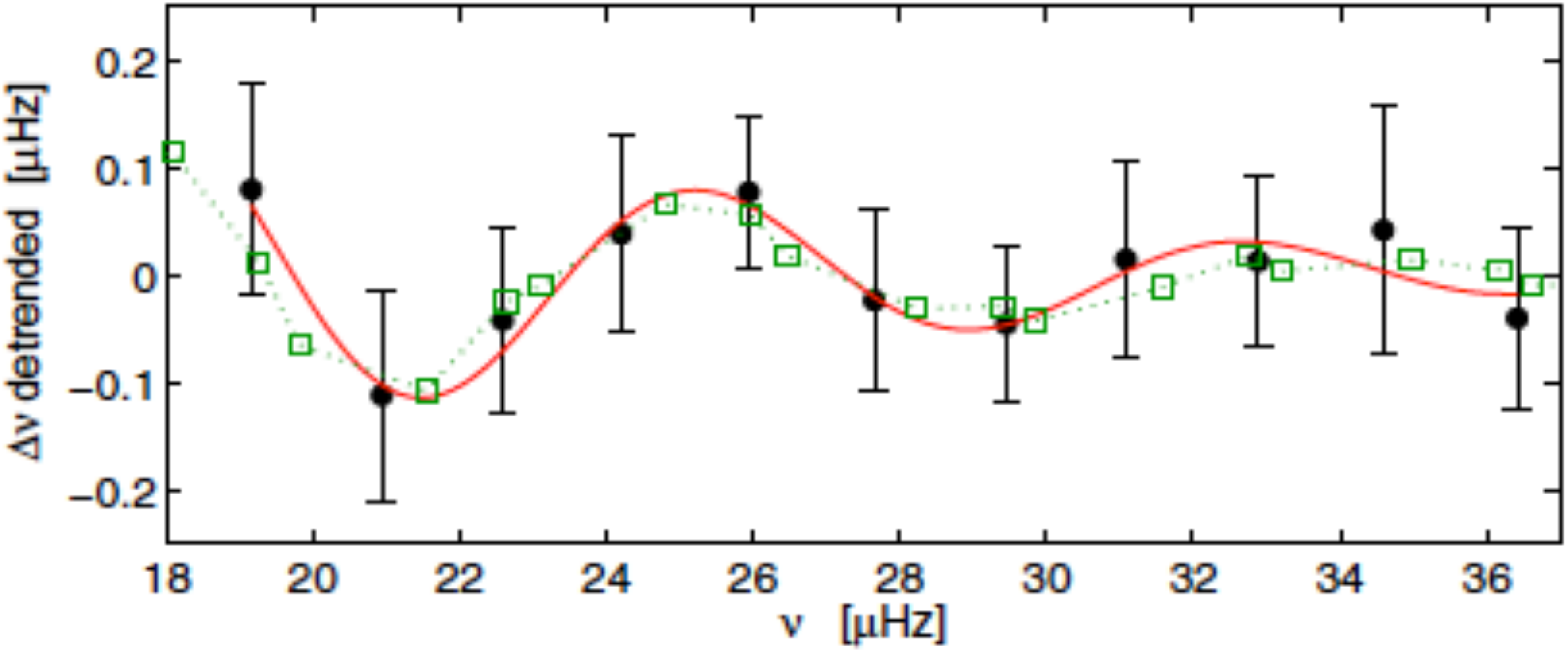
$$\Delta_2 \nu_{n,l} \equiv \nu_{n-1,l} - 2\nu_{n,l} + \nu_{n+1,l}$$





$$\gamma_1 = \left(\frac{d \ln P}{d \ln \rho} \right)_s$$

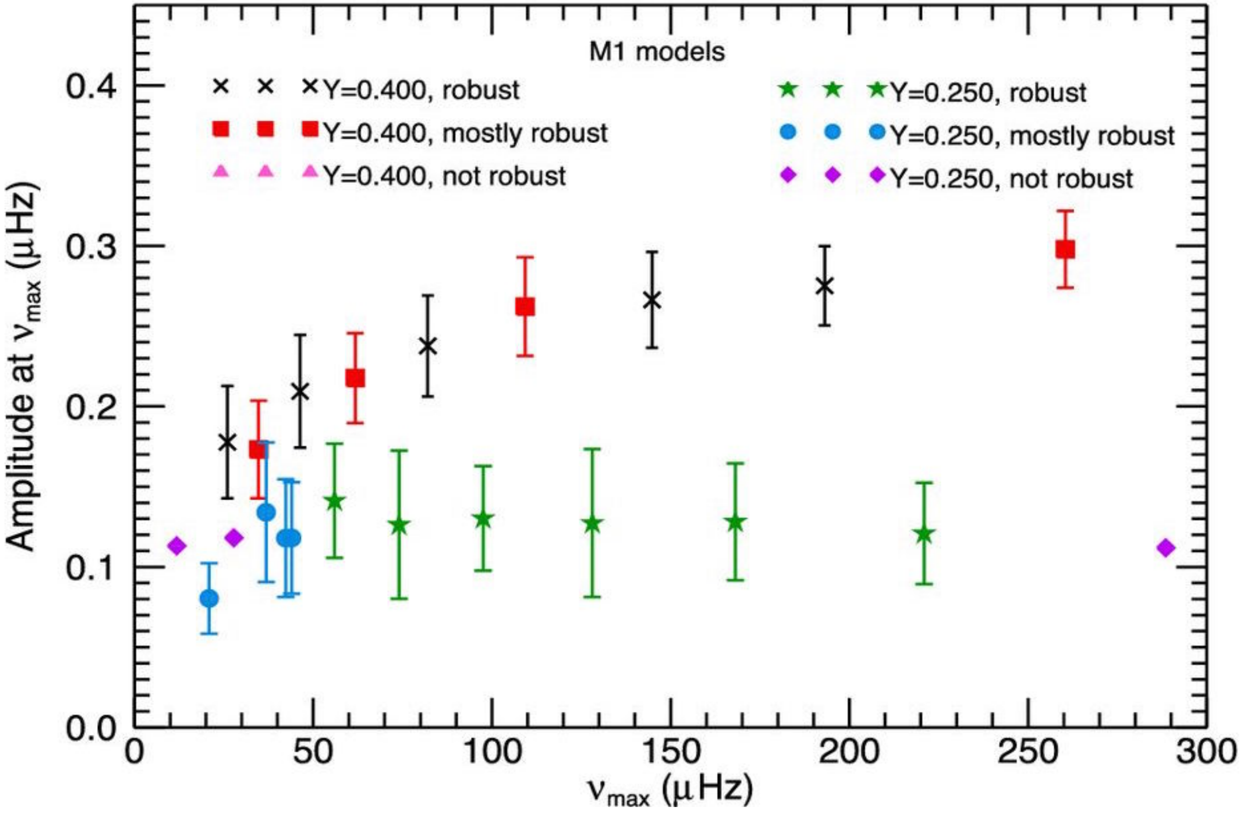
Individual frequencies: acoustic glitches



Miglio et al. 2010

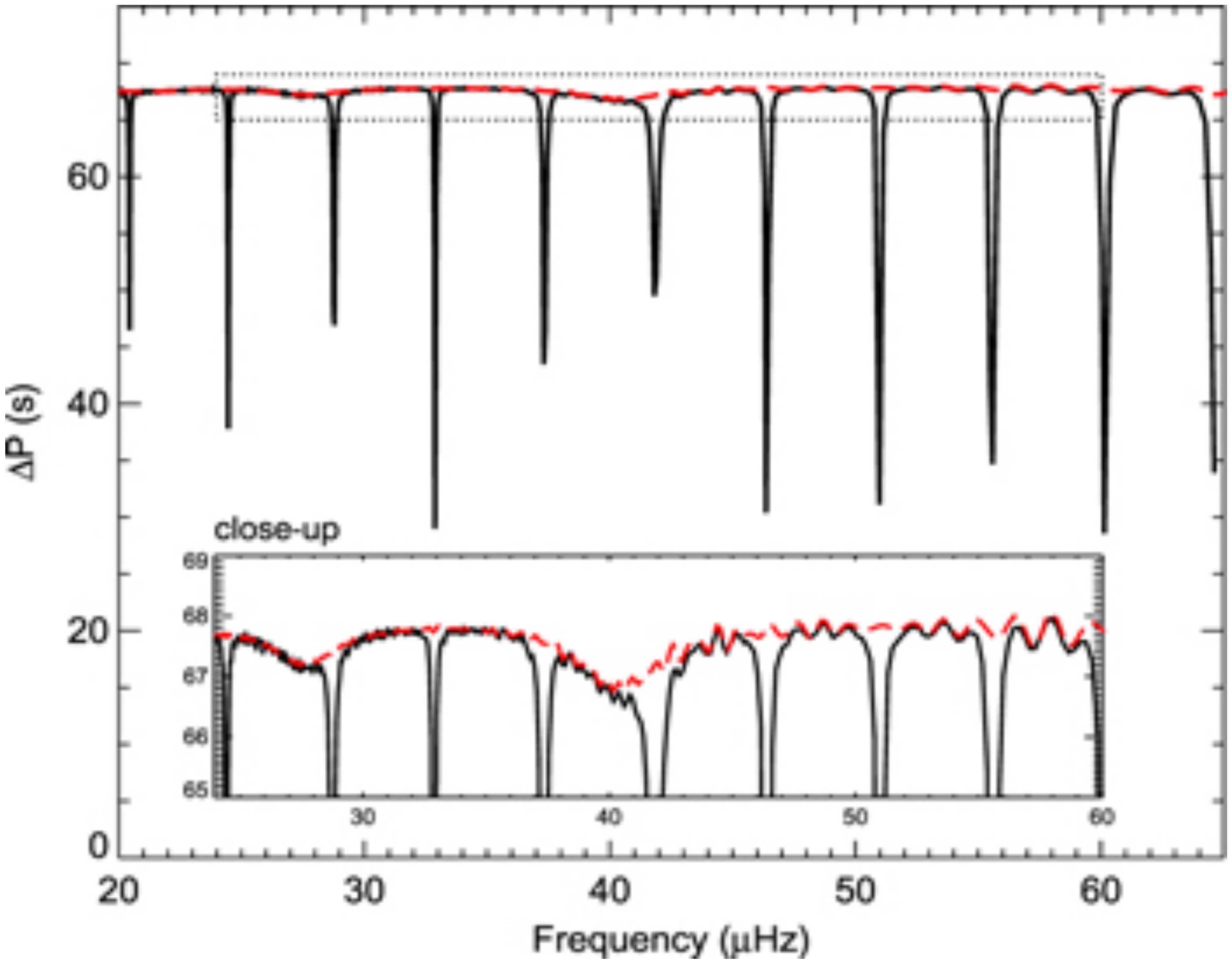
Individual frequencies: acoustic glitches

- (acoustic) radius and strength of He II ionisation zone
- possible indirect measure of He content



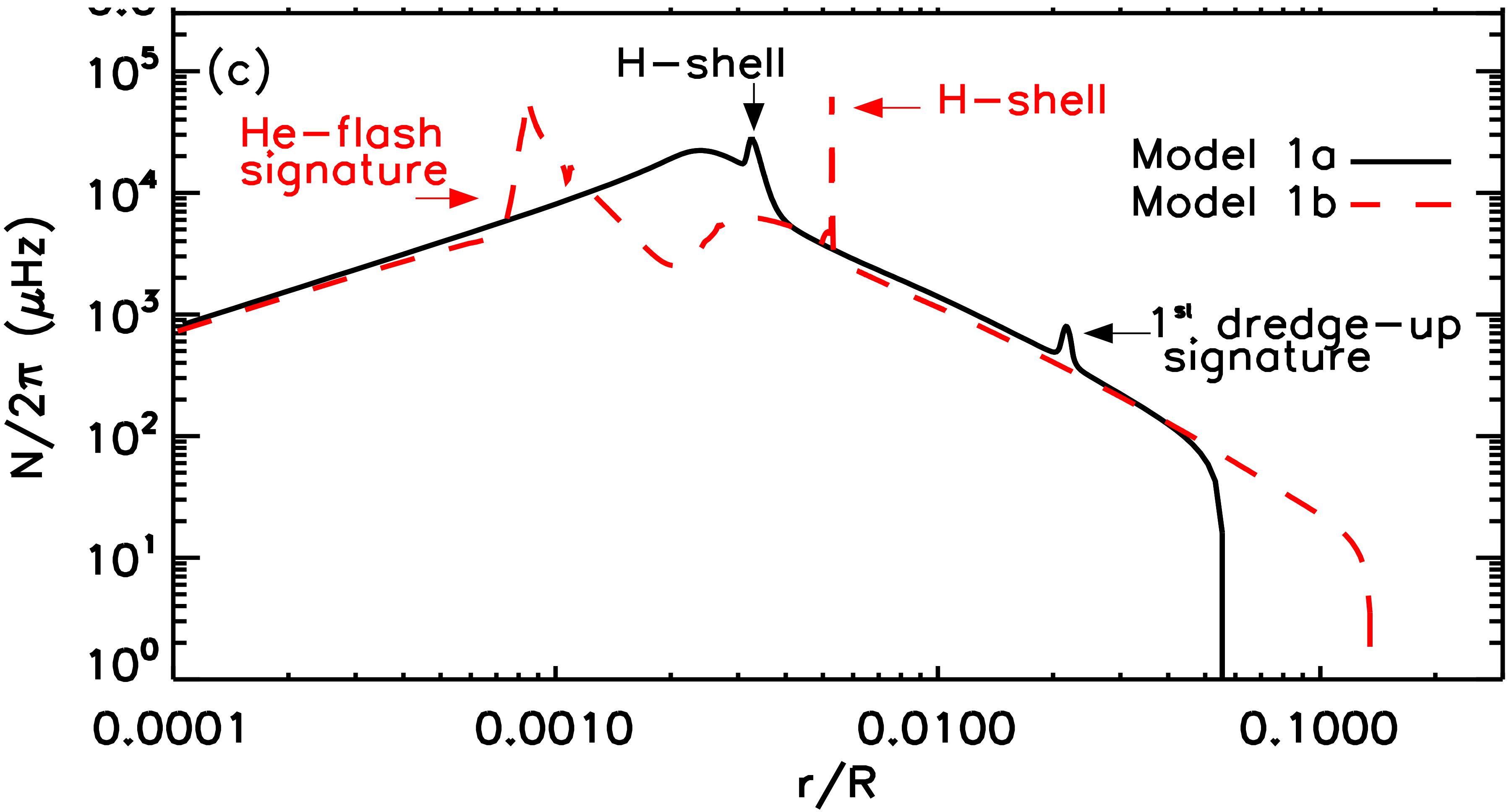
Broomhall et al. 2014

Individual frequencies: buoyancy glitches



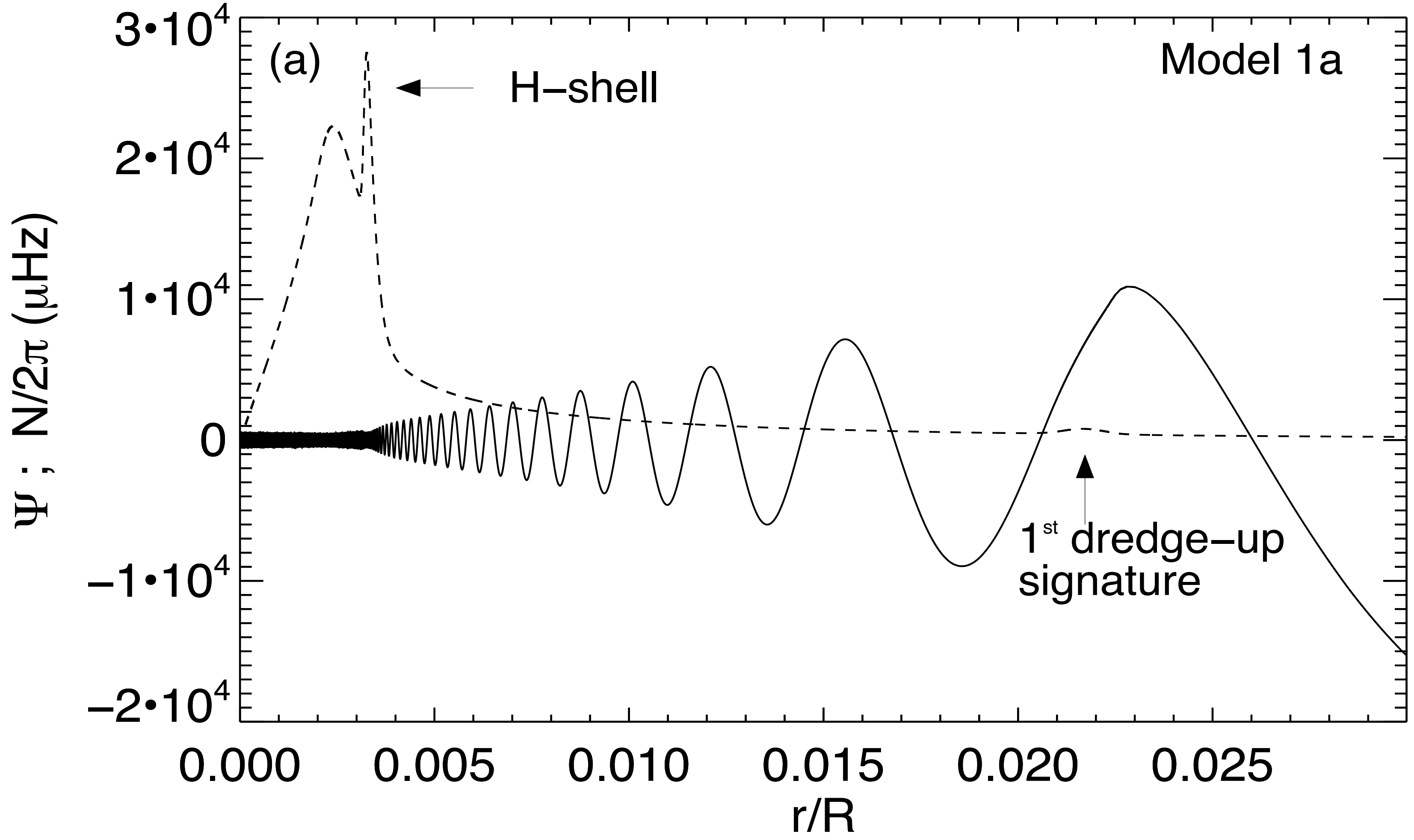
Cunha et al. 2015

Individual frequencies: buoyancy glitches



Cunha et al. 2015

Individual frequencies: buoyancy glitch



Cunha et al. 2015