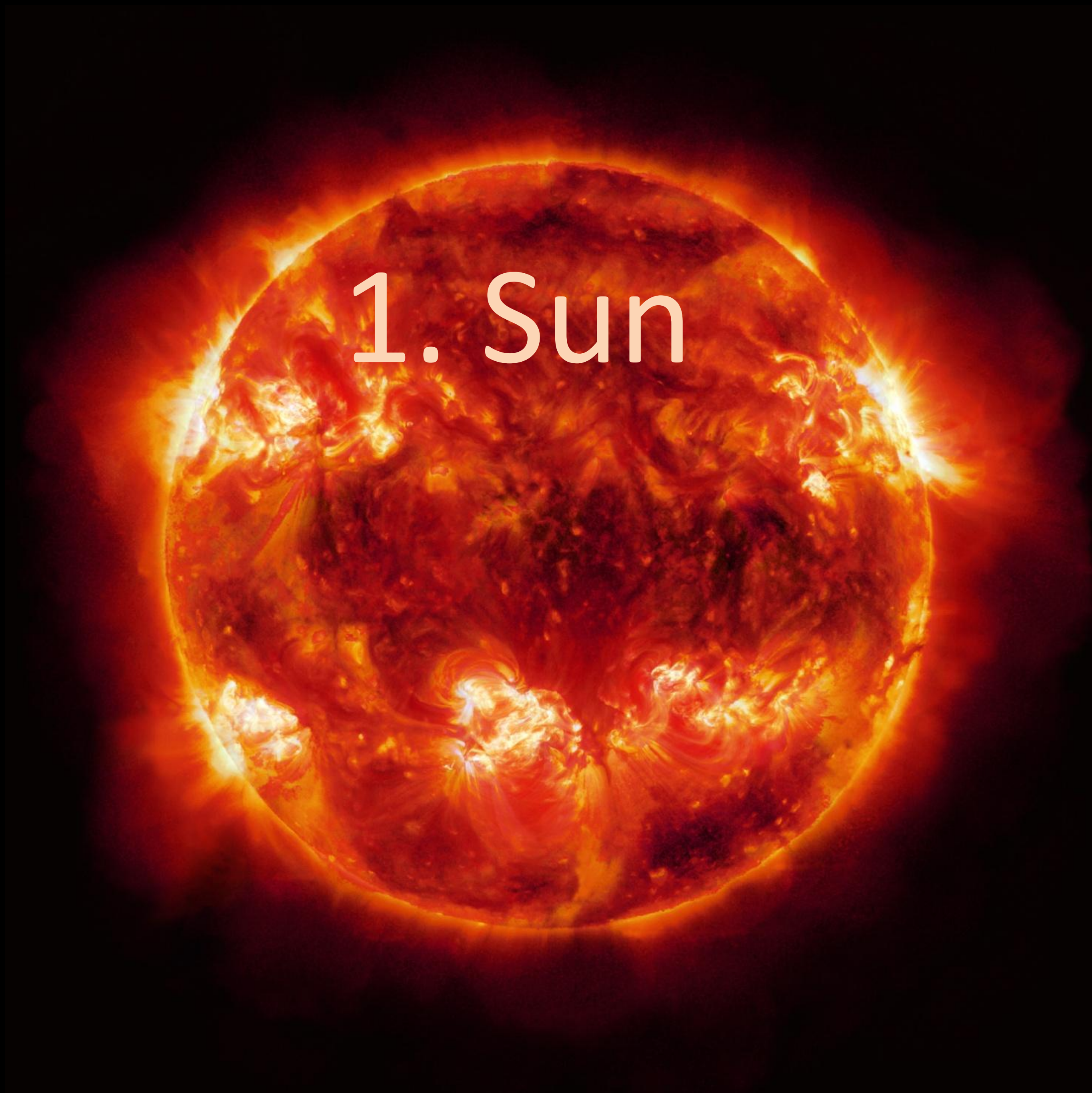
Part 2

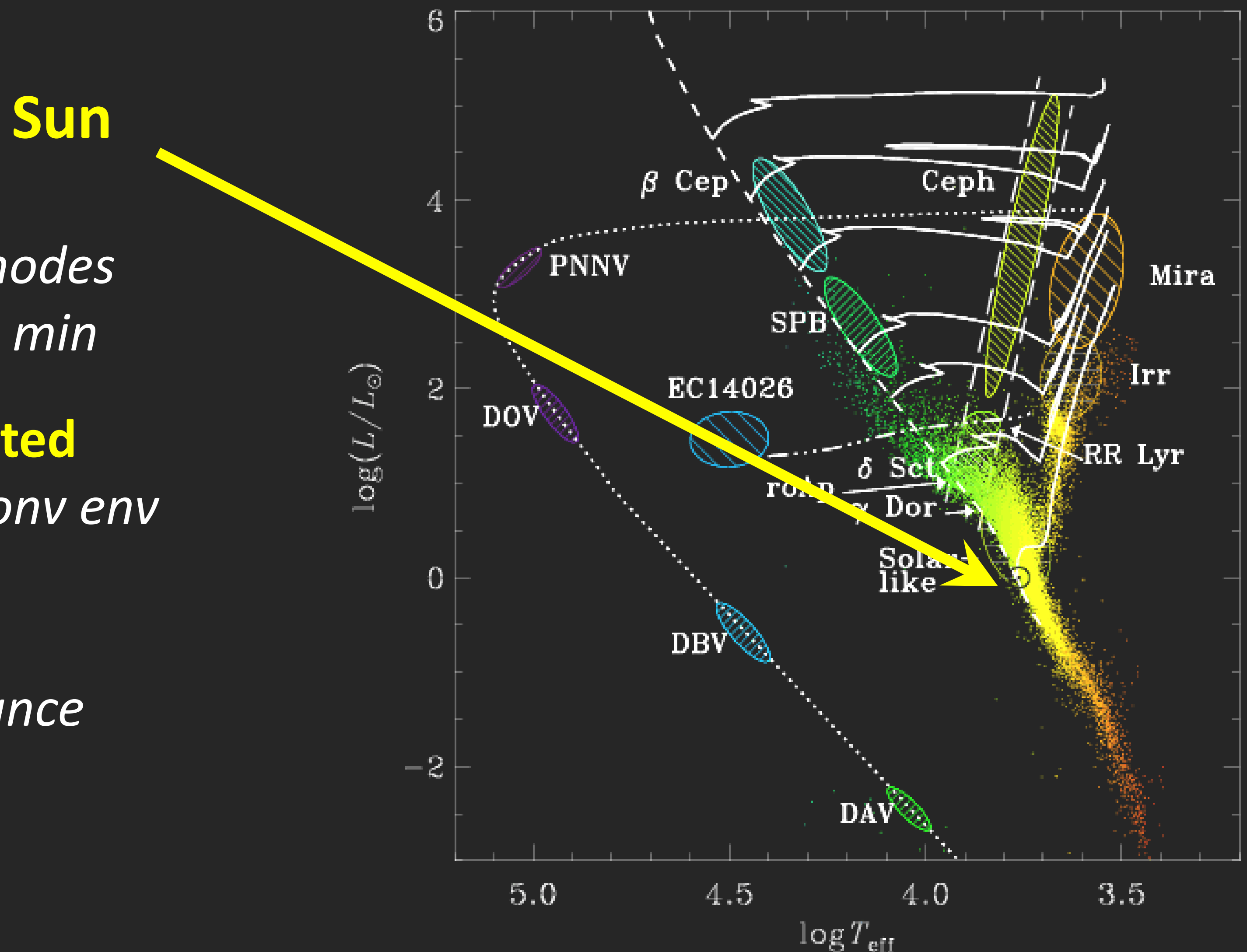

1. Sun

Stochastic excitation mechanism

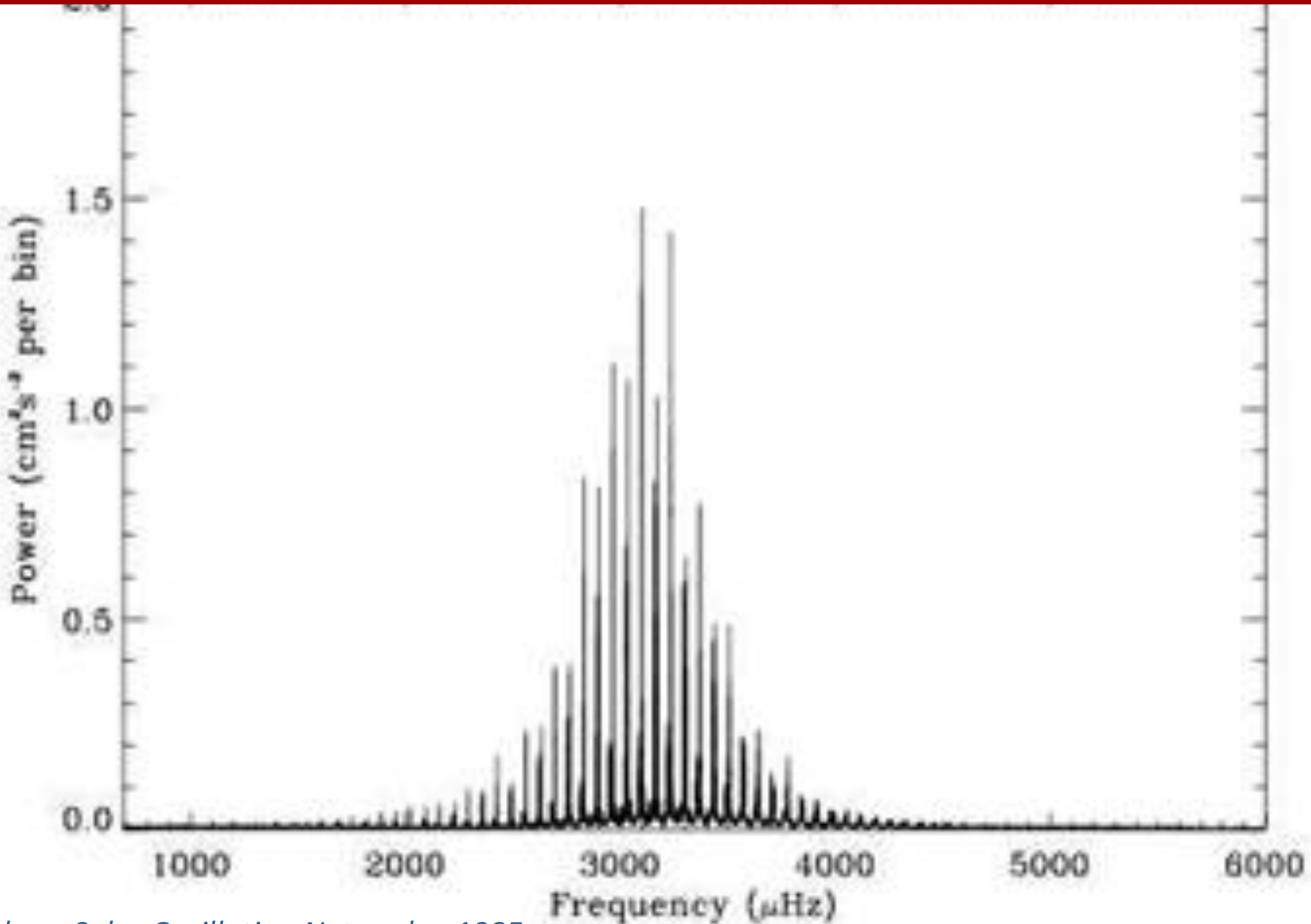
- *pressure modes*
  periods : 5 min

Physics tested

- *depth of conv env*
- *diffusion*
- *rotation*
- *He abundance*

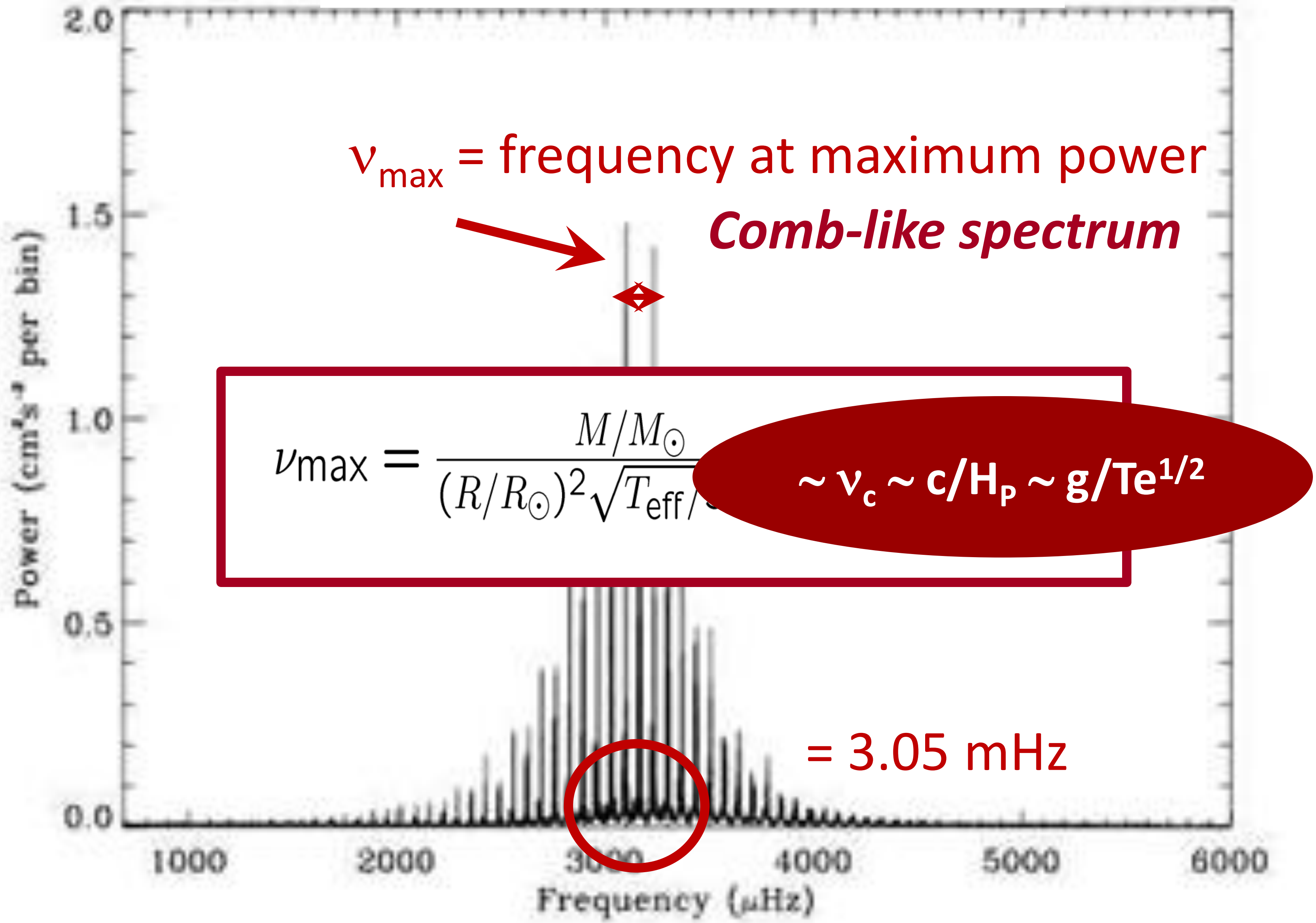


Stochastically excitated high order p-modes



Birmingham Solar Oscillation Network – 1985
Australia – South Africa – Chile – California - Teneriffe

Bison solar power spectrum



Brown et al. 1991   Kjeldsen & Bedding 1995

high order modes → asymptotic behaviour

$$\nu_{n\ell} = \Delta\nu_0 \left(n + \frac{\ell}{2} + \varepsilon\right) + \delta\nu$$

large separation

(n,ℓ) ↔ (n-1,ℓ)

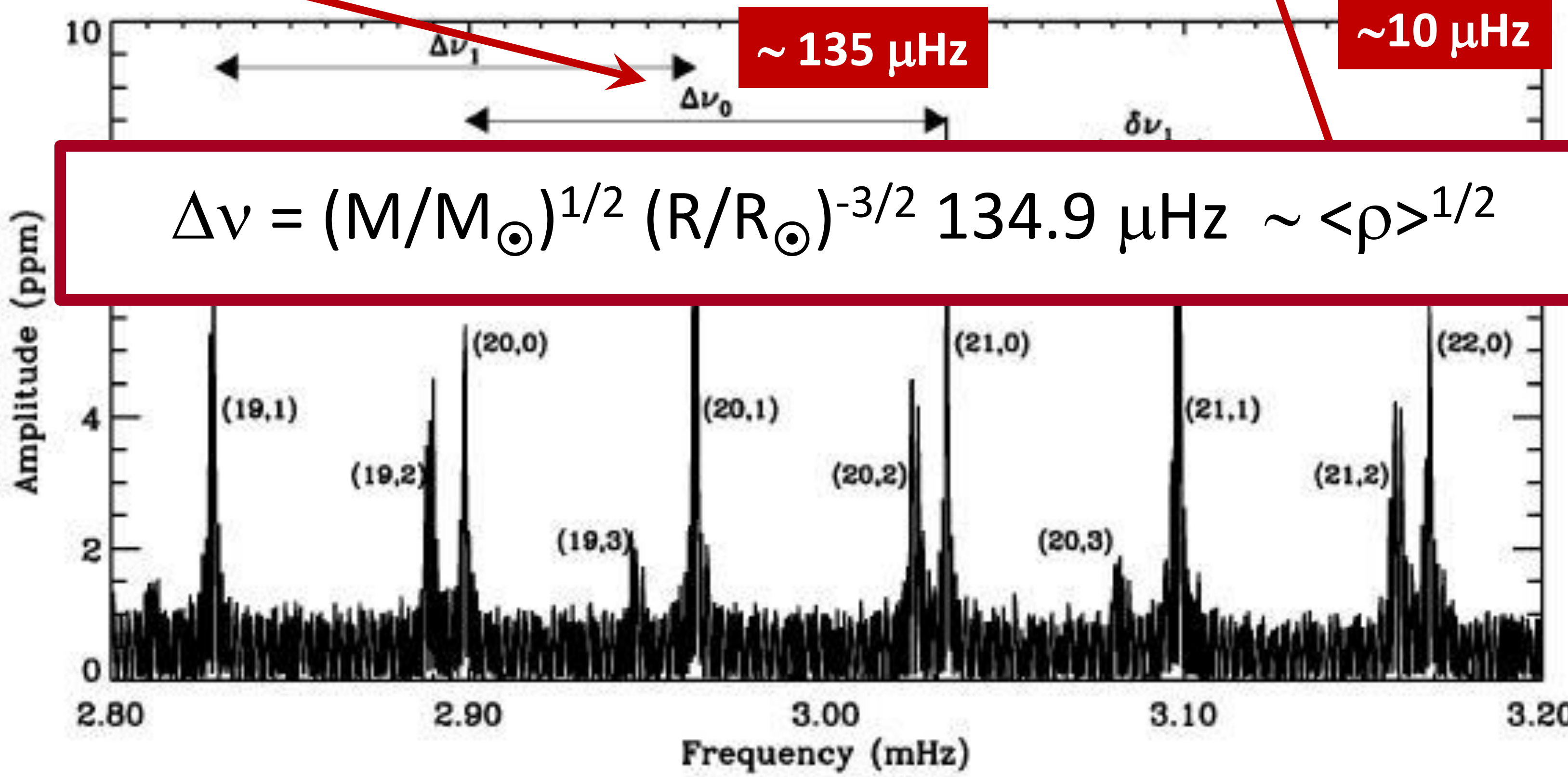
~ 135 μHz

small separation

(n,ℓ) ↔ (n-1,ℓ+2)

~10 μHz

$$\Delta\nu = (M/M_\odot)^{1/2}\,(R/R_\odot)^{-3/2}\;134.9\ \mu\text{Hz} \;\sim\; \langle\rho\rangle^{1/2}$$

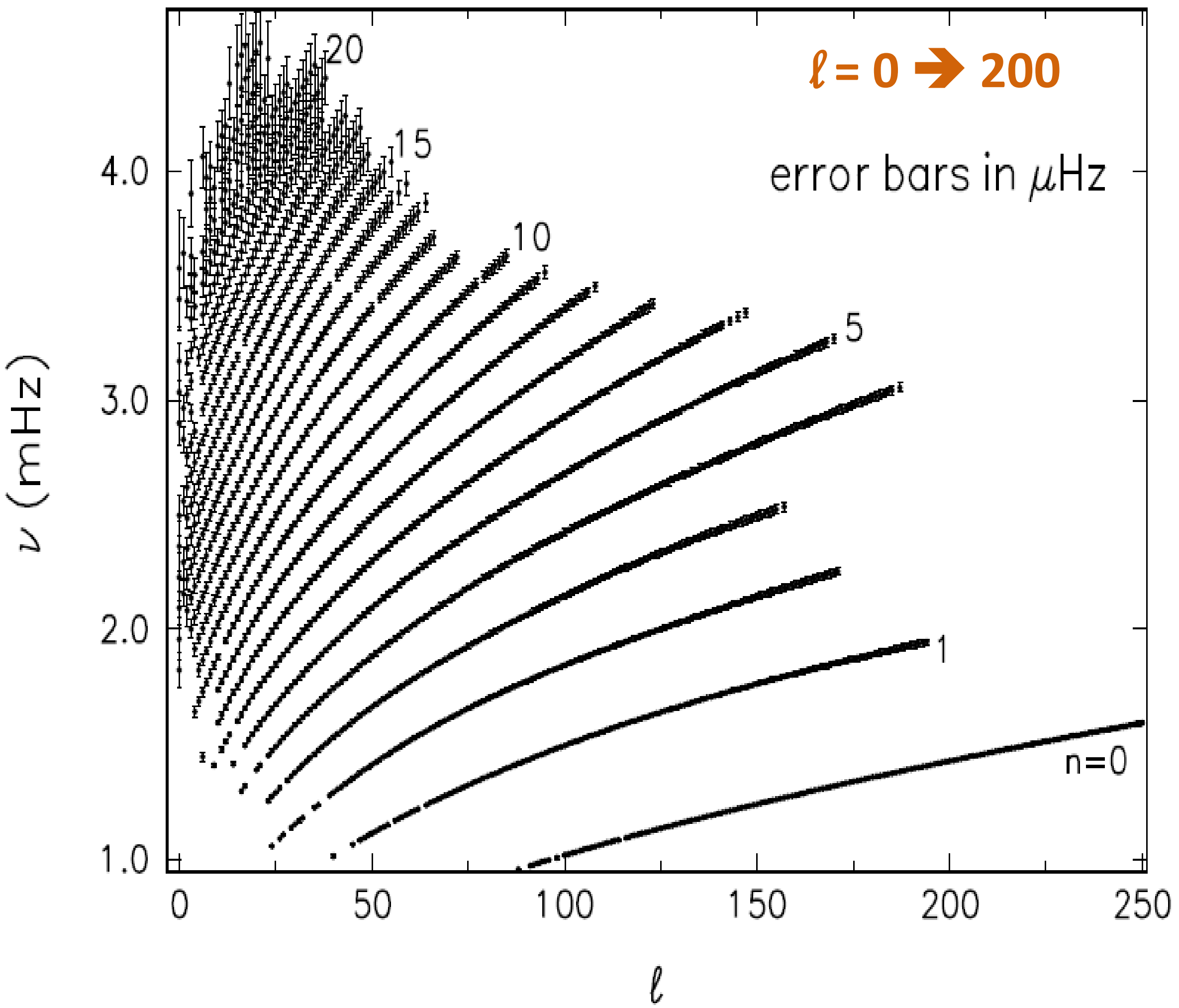


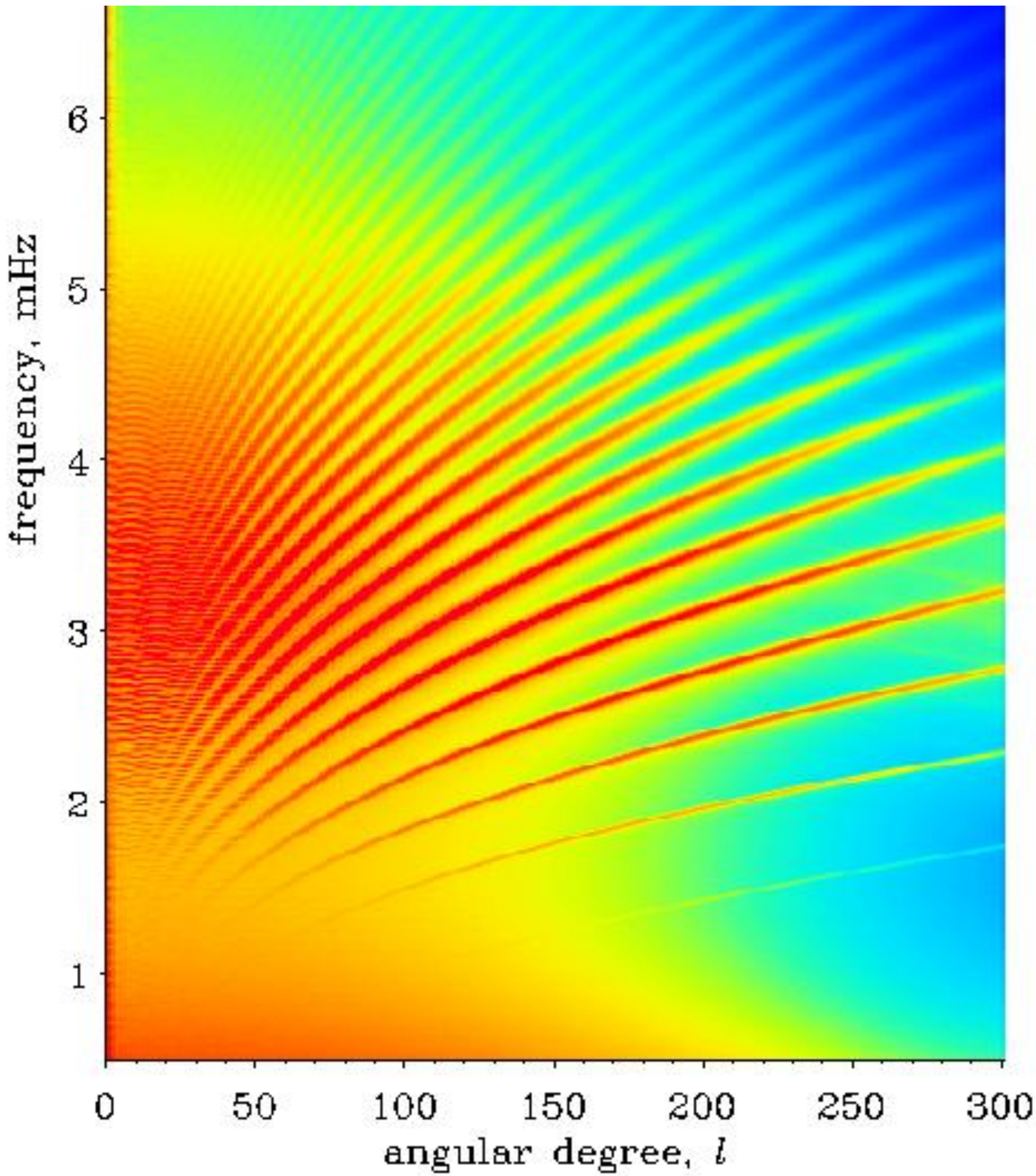
SOHO – Global Oscillation at Low Frequencies

Brown et al. 1991 Kjeldsen & Bedding 1995

Stochastically excitated high order p-modes

thousands of observed pressure modes





http://sohowww.nascom.nasa.gov/gallery/Helioseismology/mdi005.html

Helioseismology

Forward problem : We have a stellar structure

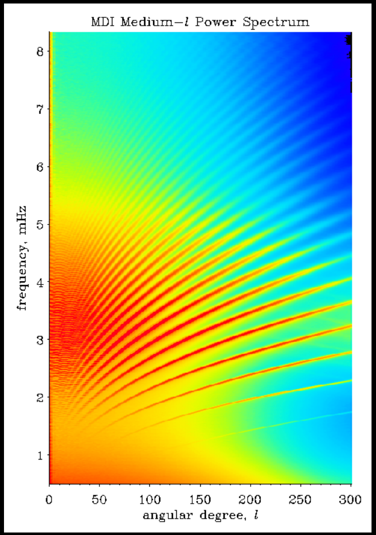
What are its frequencies?

Inverse problem : We have frequencies

What is the stellar structure?

Inversion of frequencies

Data : *a huge set of observed frequencies :*



$\nu_{obs,i}$ **i = 1, ..., n**

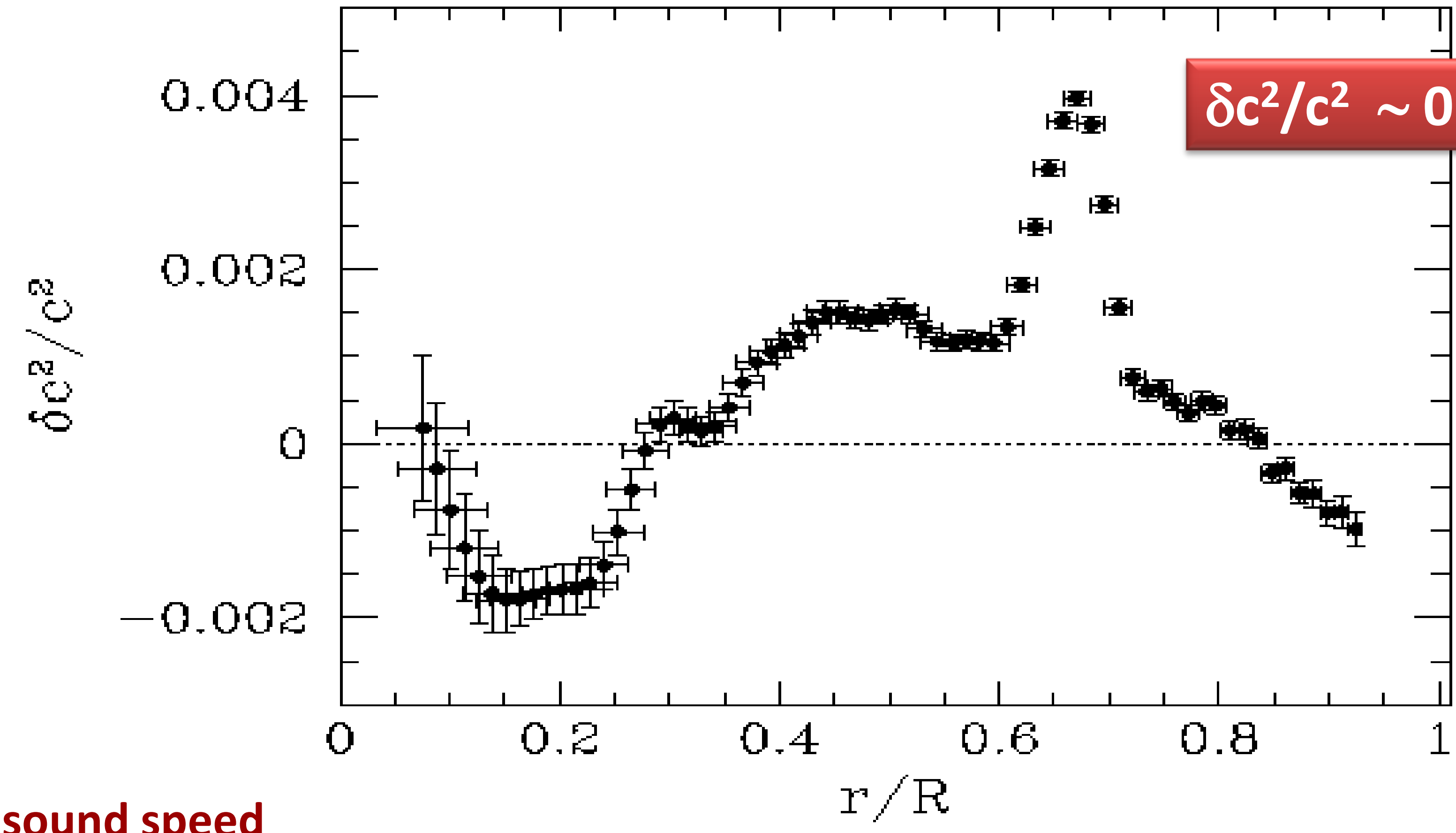
First approximation theoretical model : c_0^2 (r)

Inversion method ➔ ***find δc^2 such that***

$c_0^2(r) + \delta c^2$ fits $\nu_{obs,i}$

Inversion of frequencies

Sun – Standard solar model



$\delta c^2/c^2 \sim 0.4\%$

c : sound speed

Success of helioseismology

Surface helium abundance

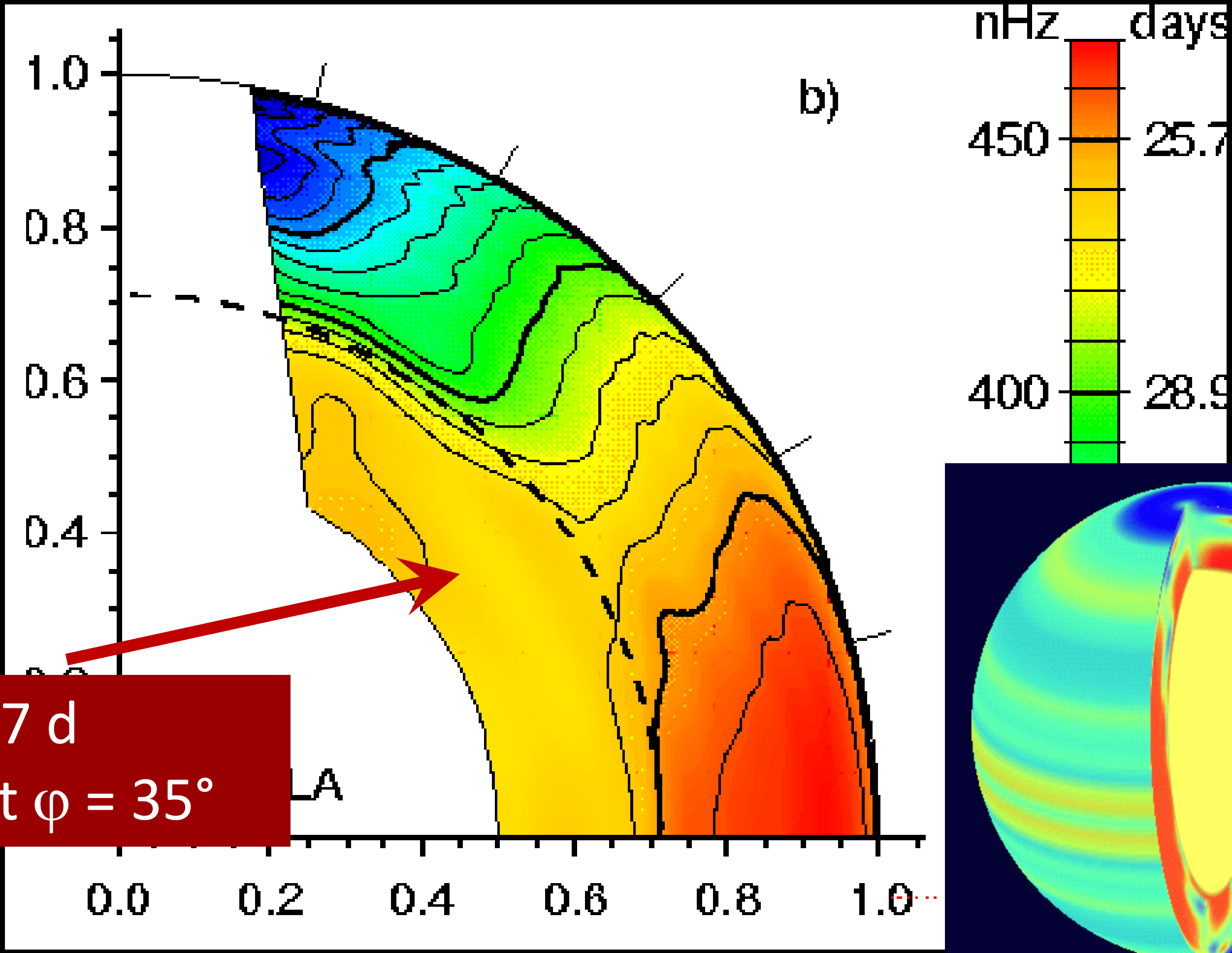
0.248 ± 0.001

diffusion

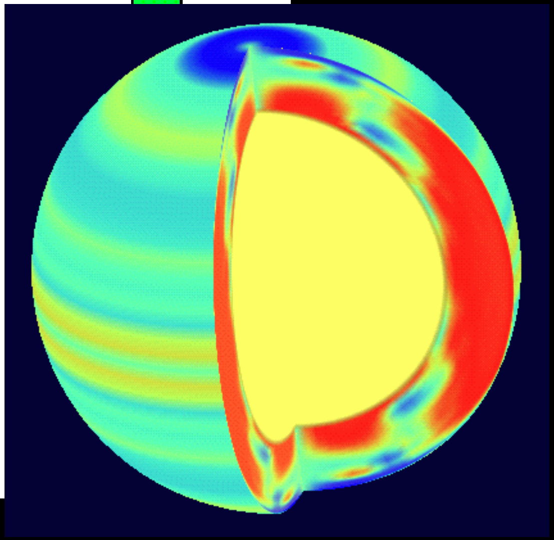
Convective envelope inner boundary

$(0.287 \pm 0.001)\ R_{\odot}$

Solar internal rotation



$P_{rotation}$ ~ 27 d
~ $P_{rotation}$ at φ = 35°



Differential rotation in the convective zone
Solid rotation in the radiative zone

Trouble in paradise

see M. Asplund ‘s 2nd lecture

2. Solar-like stars

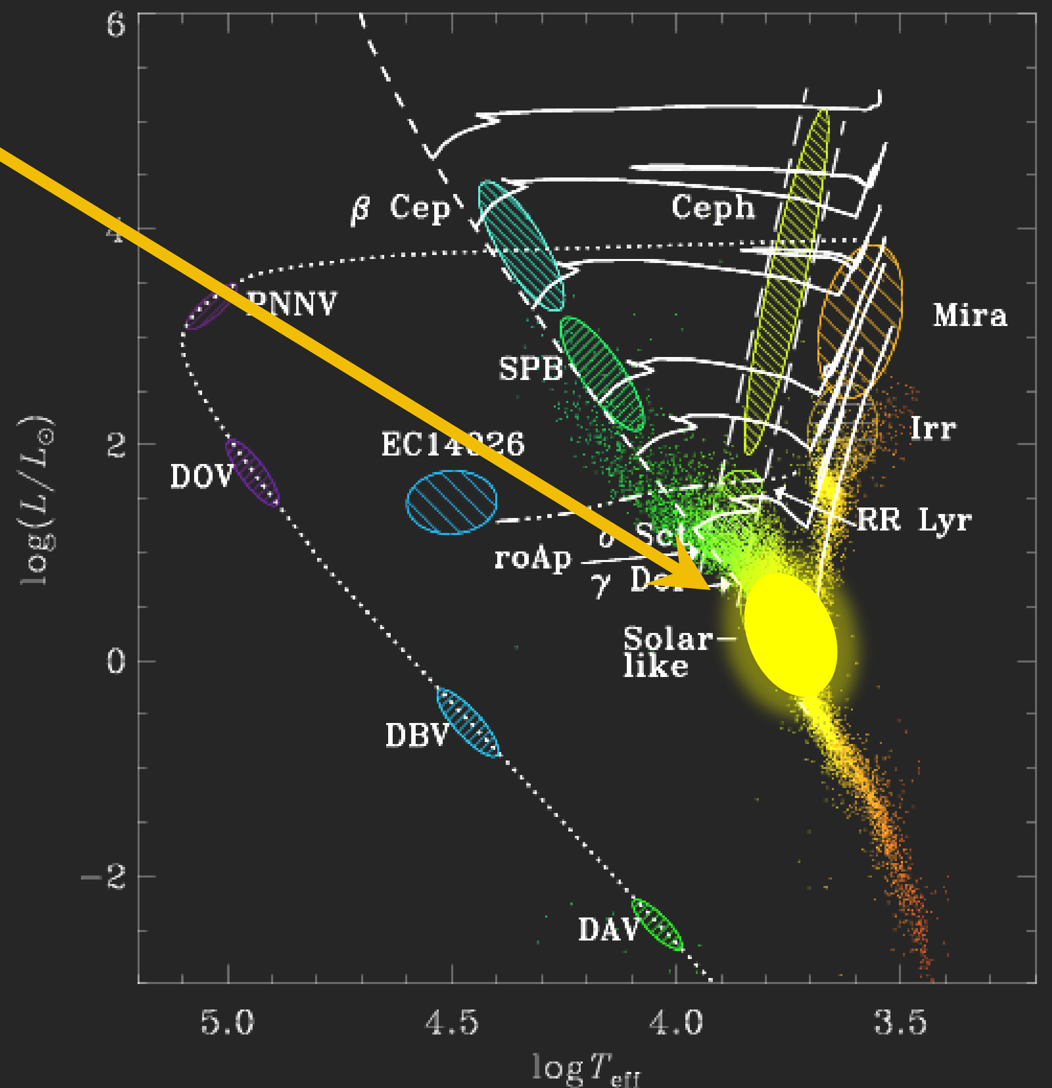
Stochastic excitation mechanism

Solar-type stars

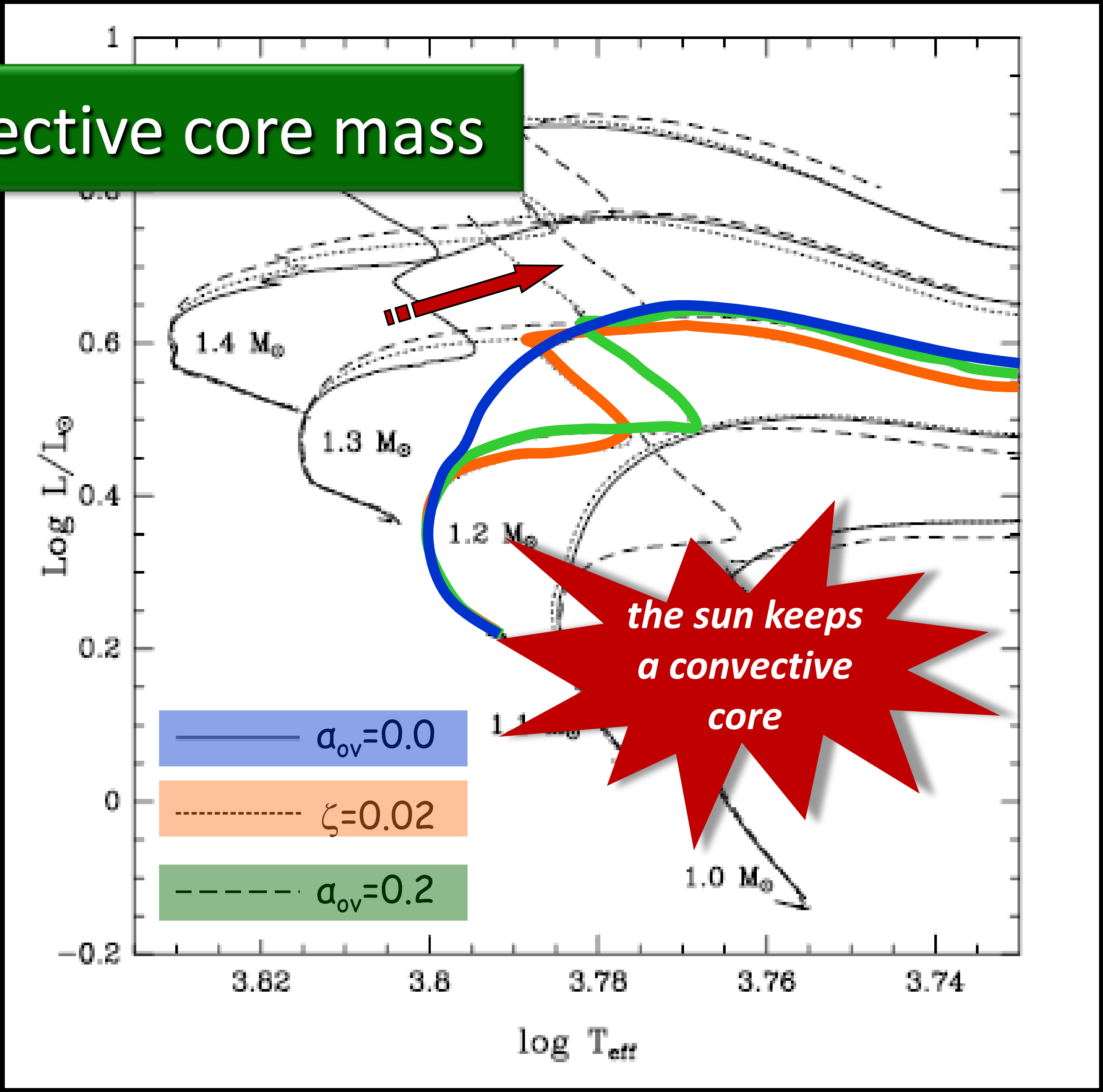
- *MS F-G stars 0.9-1.5 $M_\odot$ rad core/conv env*
- *pressure modes periods : 3 – 8 min*

Physics tested

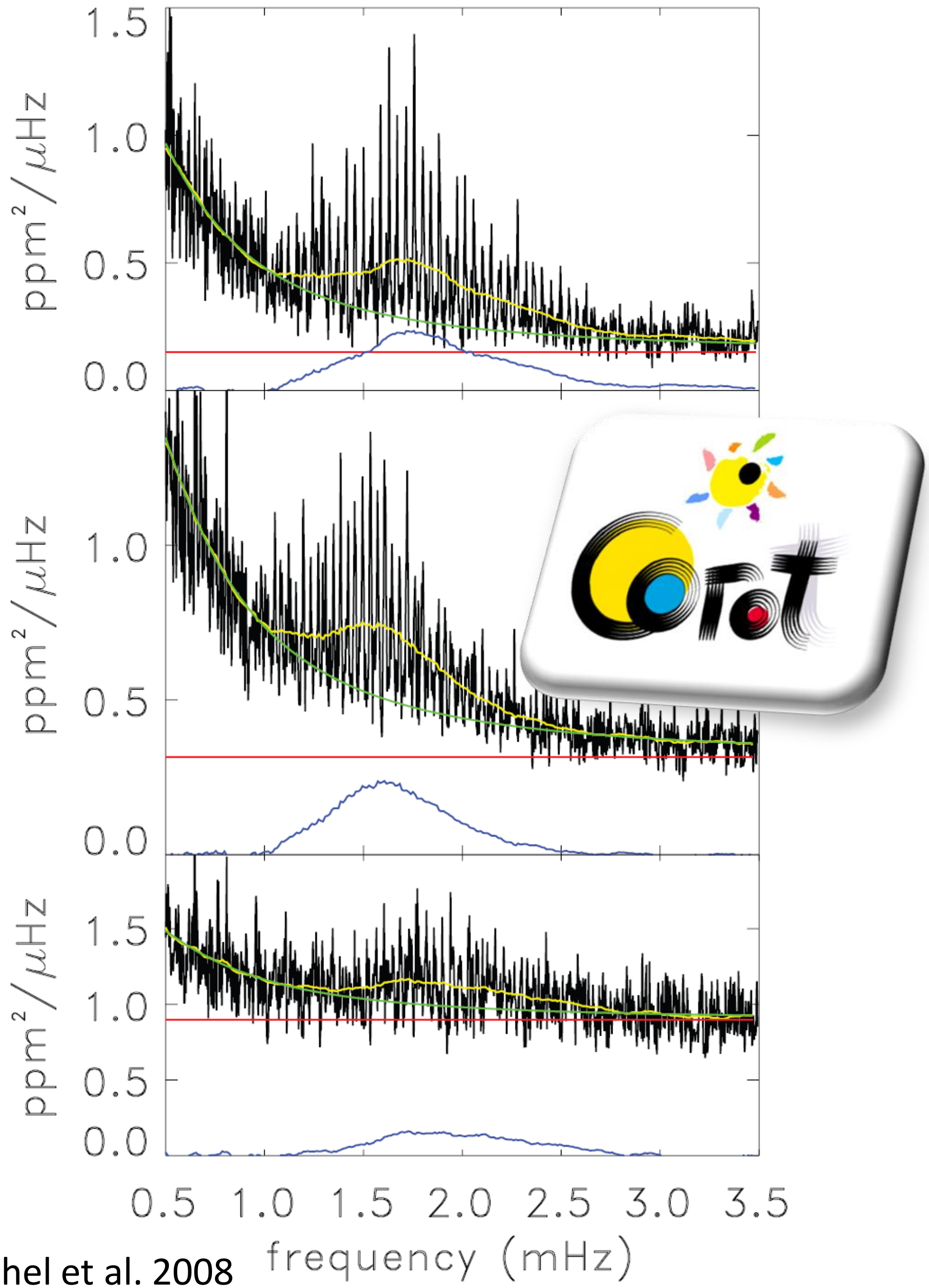
- *convection*
- *overshooting*
- *diffusion*
- *rotation*



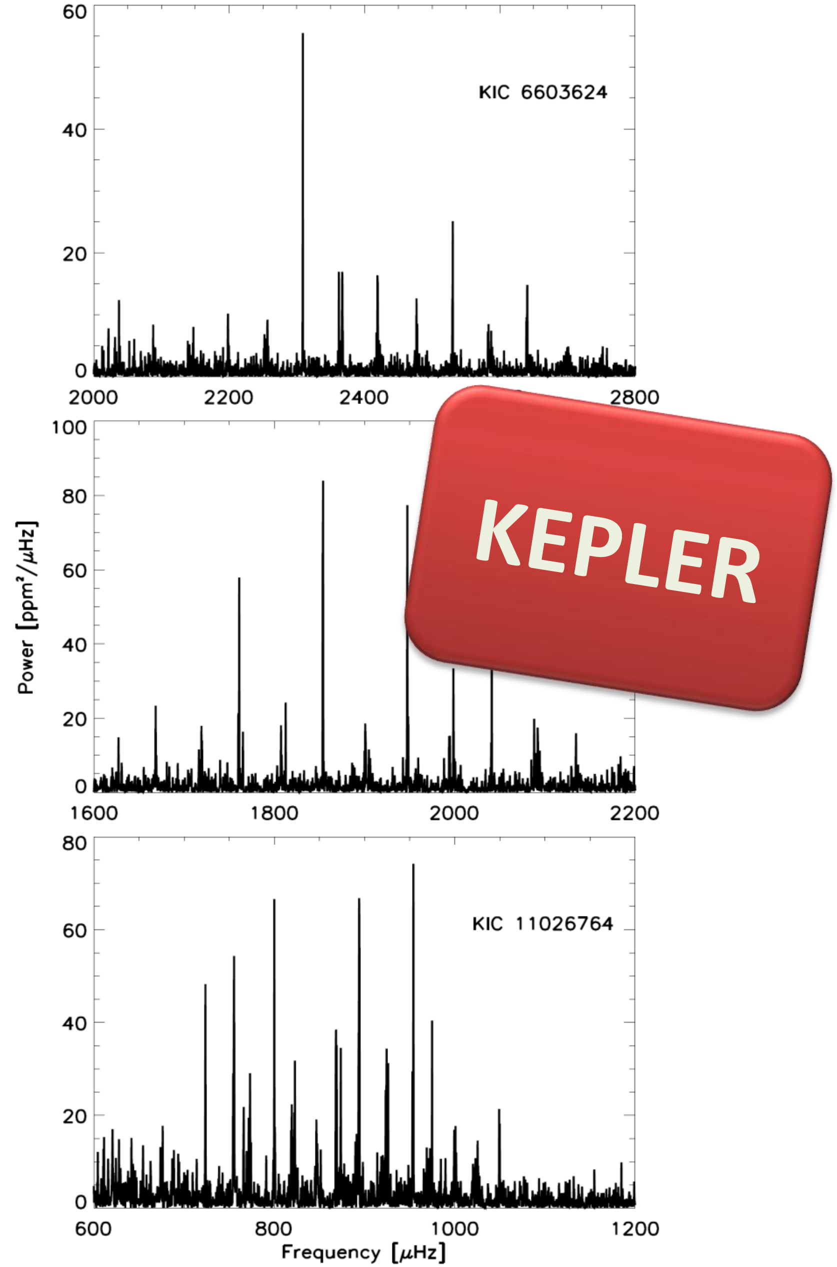
Convective core mass



Ventura, Zeppieri, Mazzitelli & D'Antona 1998

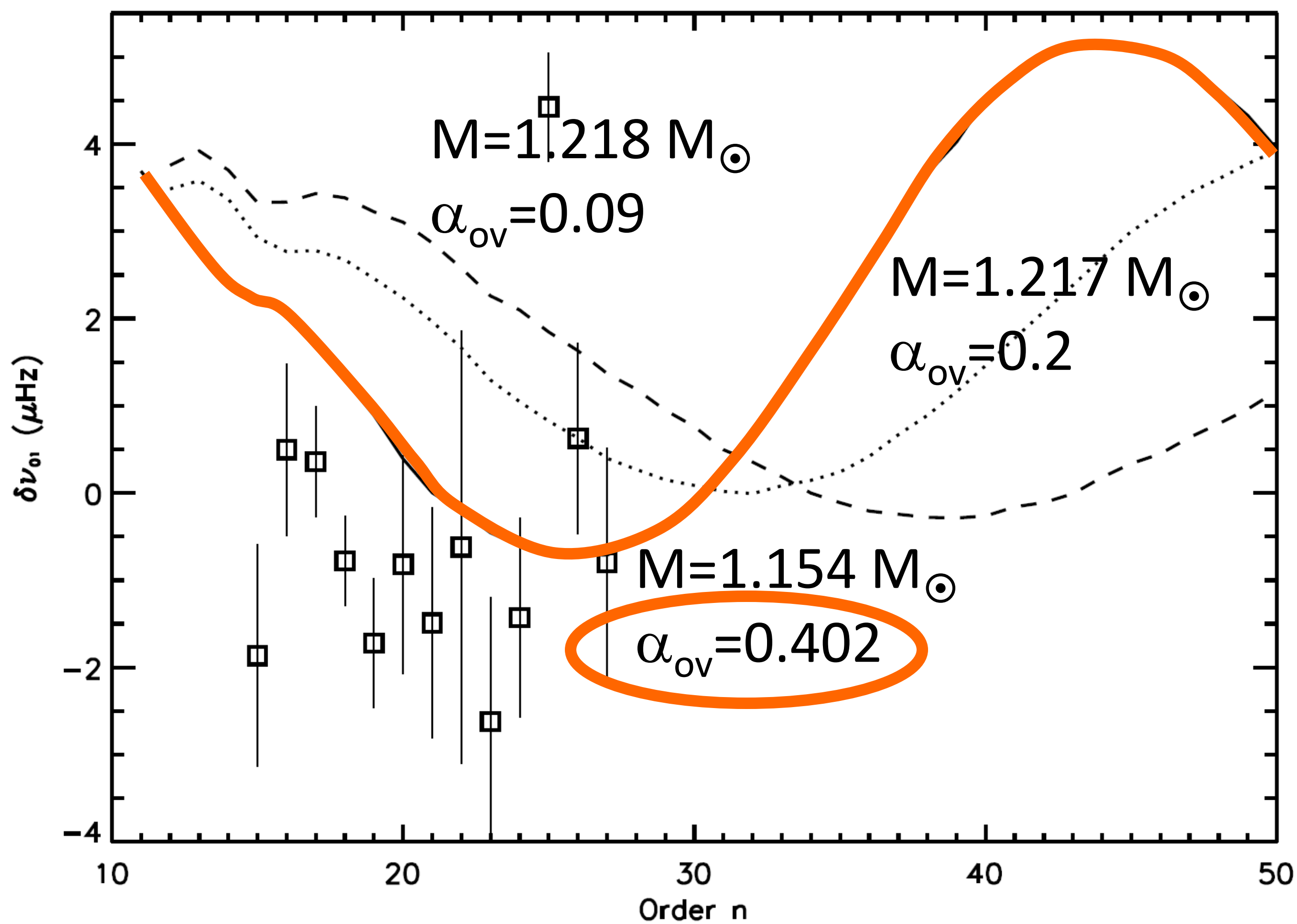


Michel et al. 2008



Chaplin et al. 2010

CoRoT target HD49933



3. Red giant stars

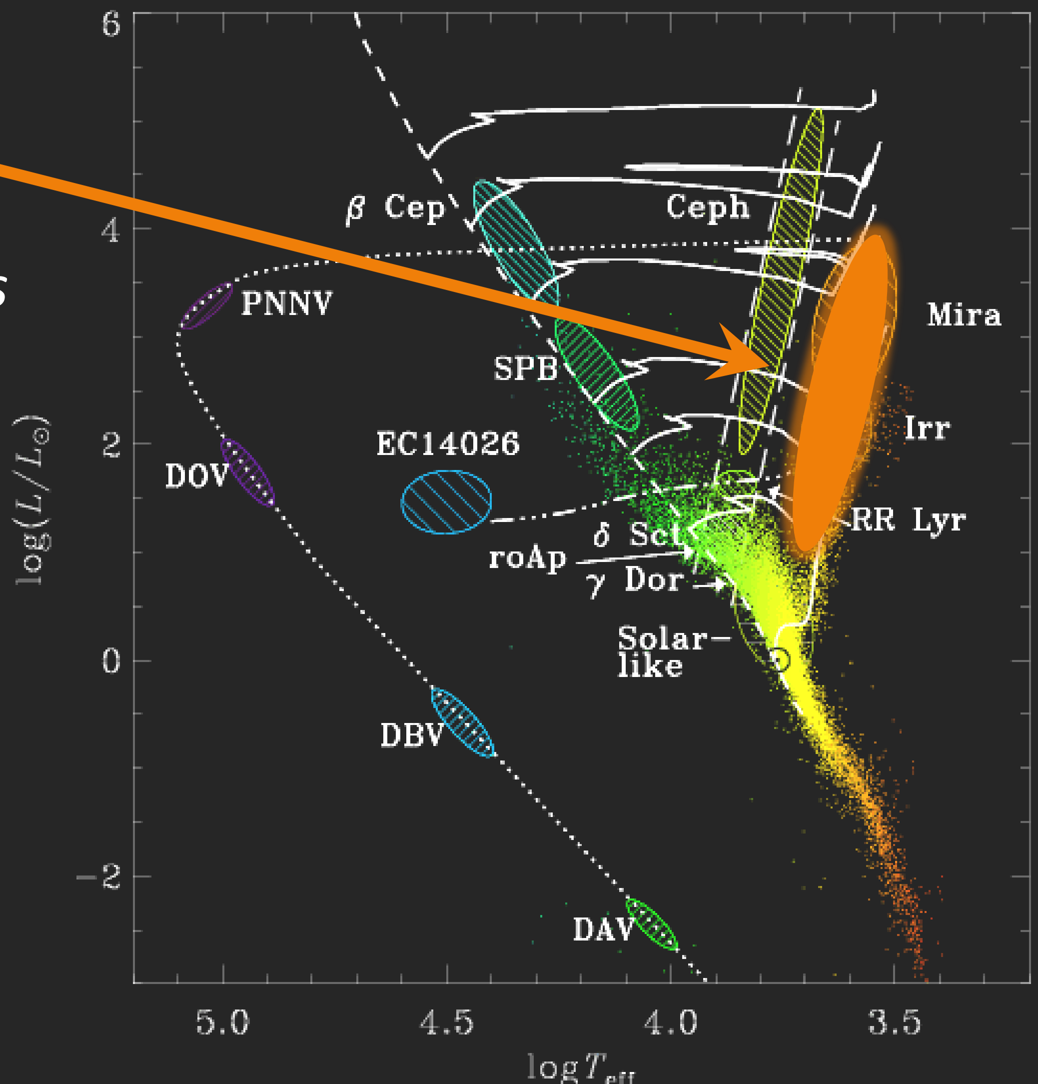
Stochastic excitation mechanism

Red giants

- *high amplitude radial modes*
- *moderate amplitude radial and non-radial modes excited by turbulent motions*

Physics tested

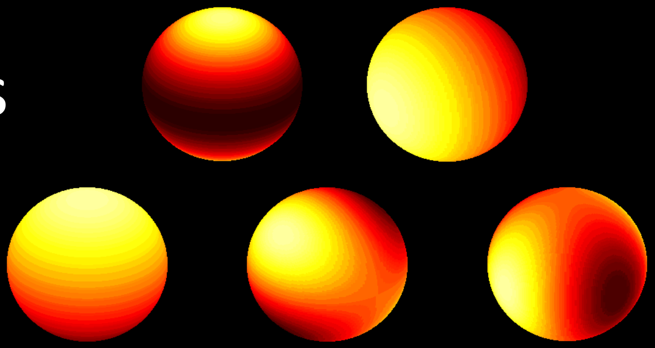
- *evolutionary state*
- *HeII ionization zone*
- *He abundance*
- *stellar population synthesis*

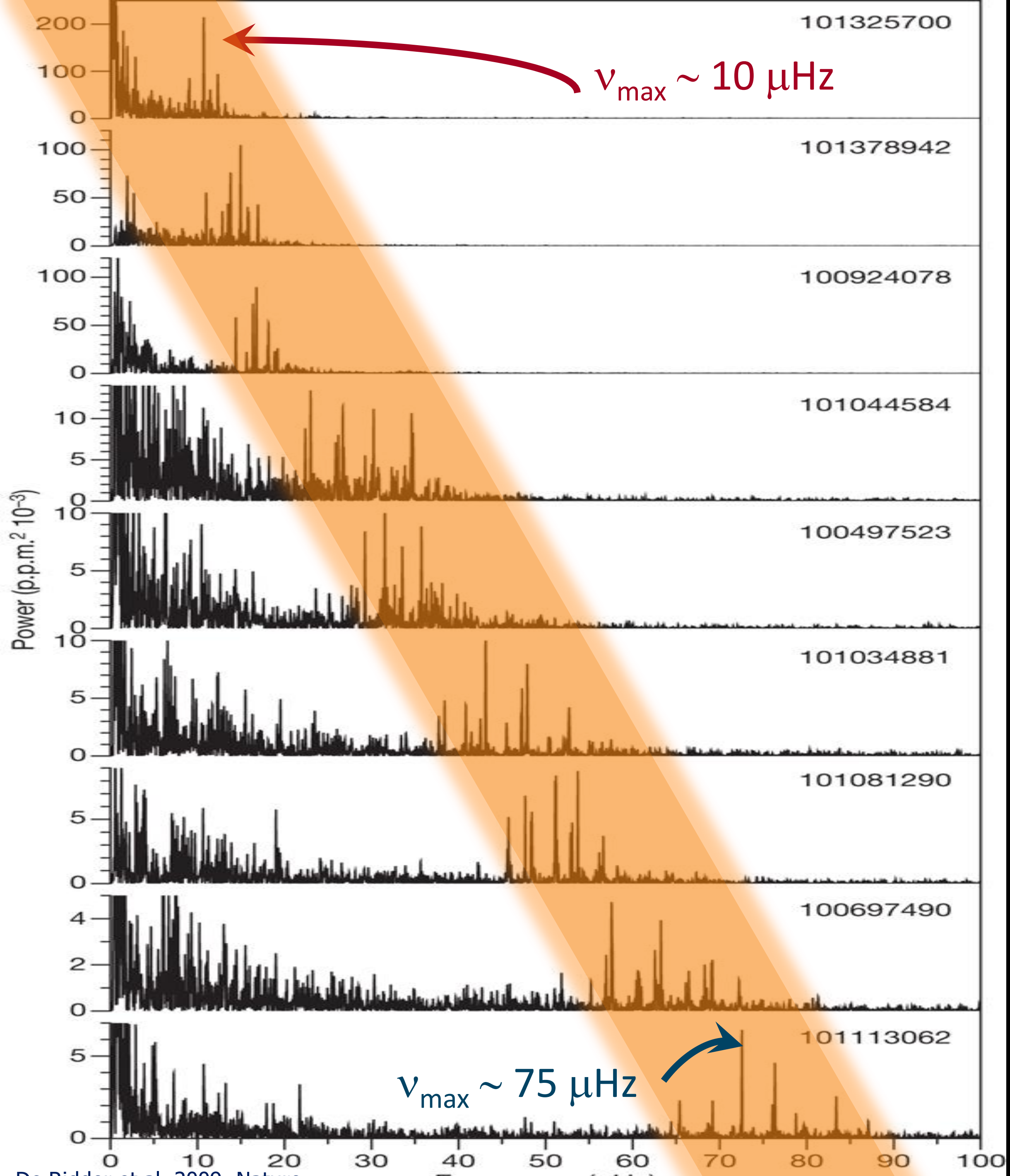


CoRoT discovers a whole orchestra of red giants

- Radial and non radial modes

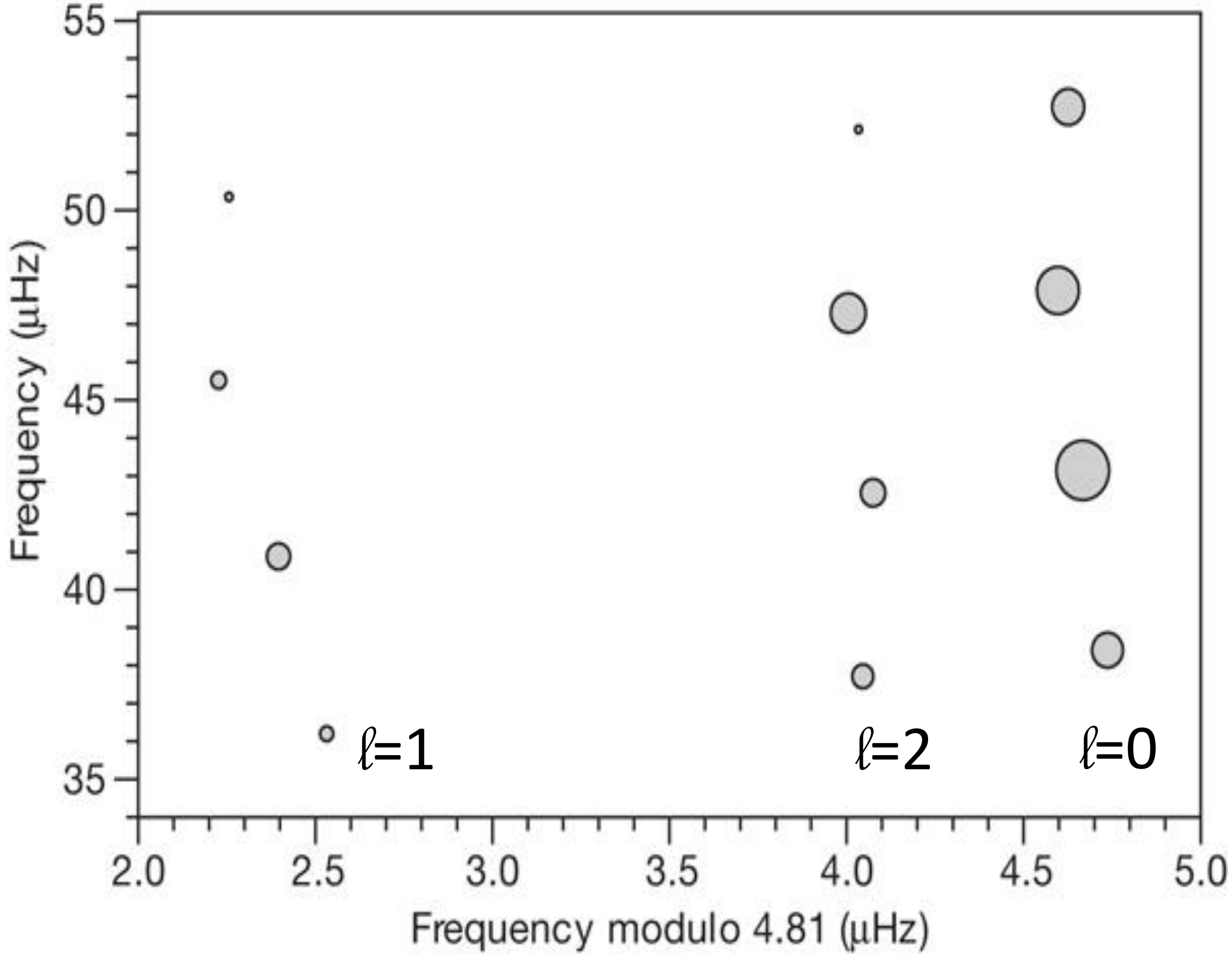
De Ridder et al. 2009, Nature 459, 398





De Ridder et al. 2009, Nature

CoRoT-101034881

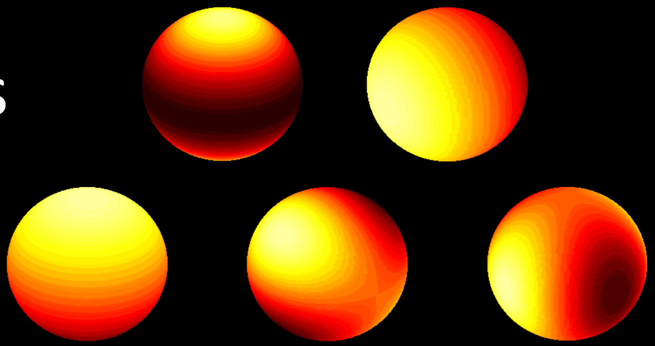


De Ridder et al. 2009, Nature

CoRoT discovers a whole orchestra of red giants

- Radial and non radial modes

De Ridder et al. 2009, Nature 459, 398



- Solar-like oscillations in ~ 1400 red giants in LRc01 exofield

Hekker et al. 2009 A&A, 506, 465
Mosser et al. 2010 A&A, 517, 22

Seismology of stellar populations

Seismo Field

- few (~ 10) well constrained bright targets

Detailed seismology of chosen targets

Exo Field

- Seismic constraints for hundreds of pulsating stars (11 < m_v <15)

Seismology of populations of stars!

A

Determination of global parameters

- Study stellar populations
- Distance estimation

CoRoT red giants: synthetic population

Population Synthesis software:

TRILEGAL (TRIdimensional modeL of thE GALaxy, Girardi et al. 2005)

The ingredients:

- Stellar Models
- Initial Mass Function
- Stellar Formation Rate
- Age-Metallity Relation
- Morphology galaxy

Red giant population NOW

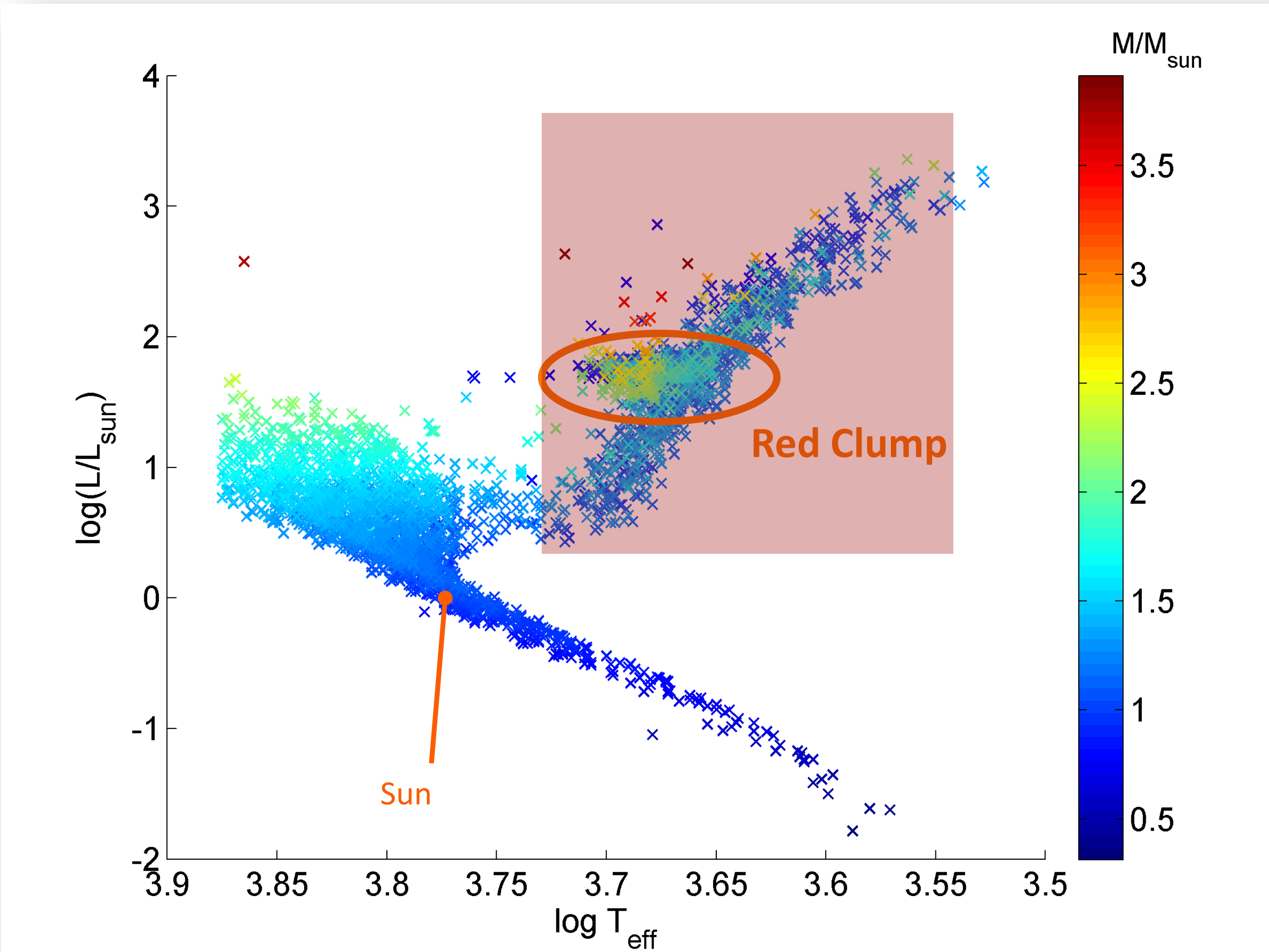
Predictions on seismic properties of the observed population of red giants

$$\nu_{\rm max} = \frac{M/M_\odot}{(R/R_\odot)^2\sqrt{T_{\rm eff}/5777K}}\,3.05\ {\rm mHz}$$

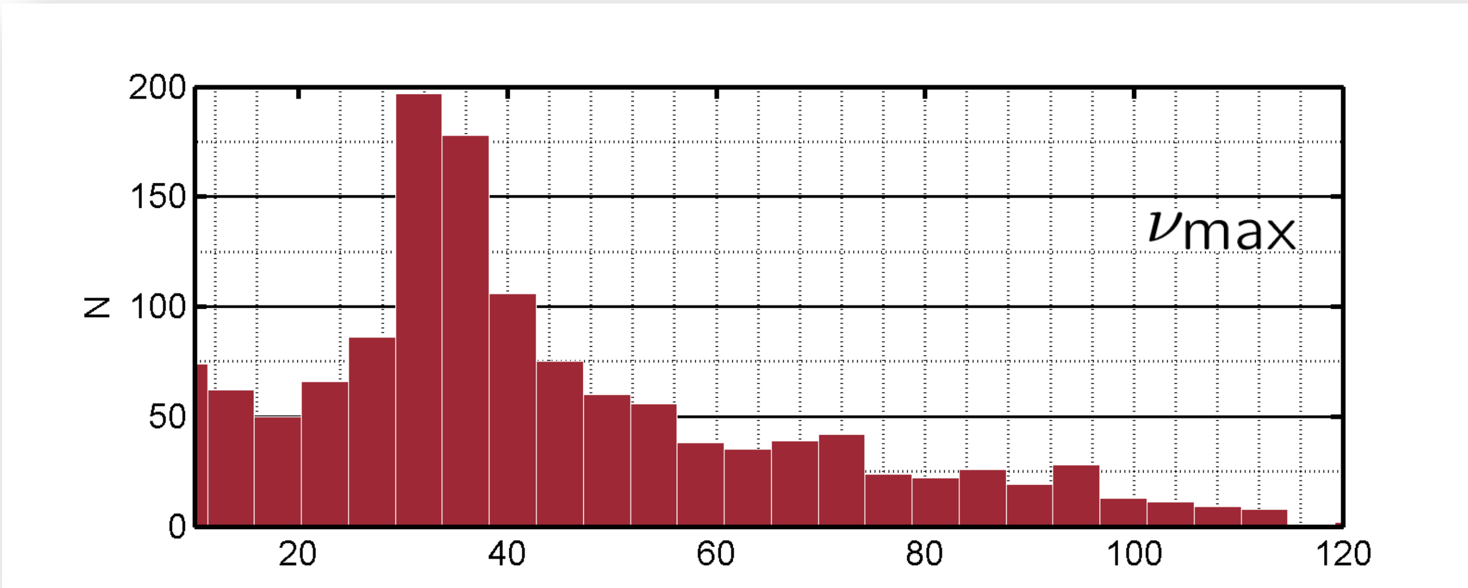
$$\Delta\nu = \sqrt{\frac{M/M_\odot}{(R/R_\odot)^3}}\,134.9\mu{\rm Hz}$$

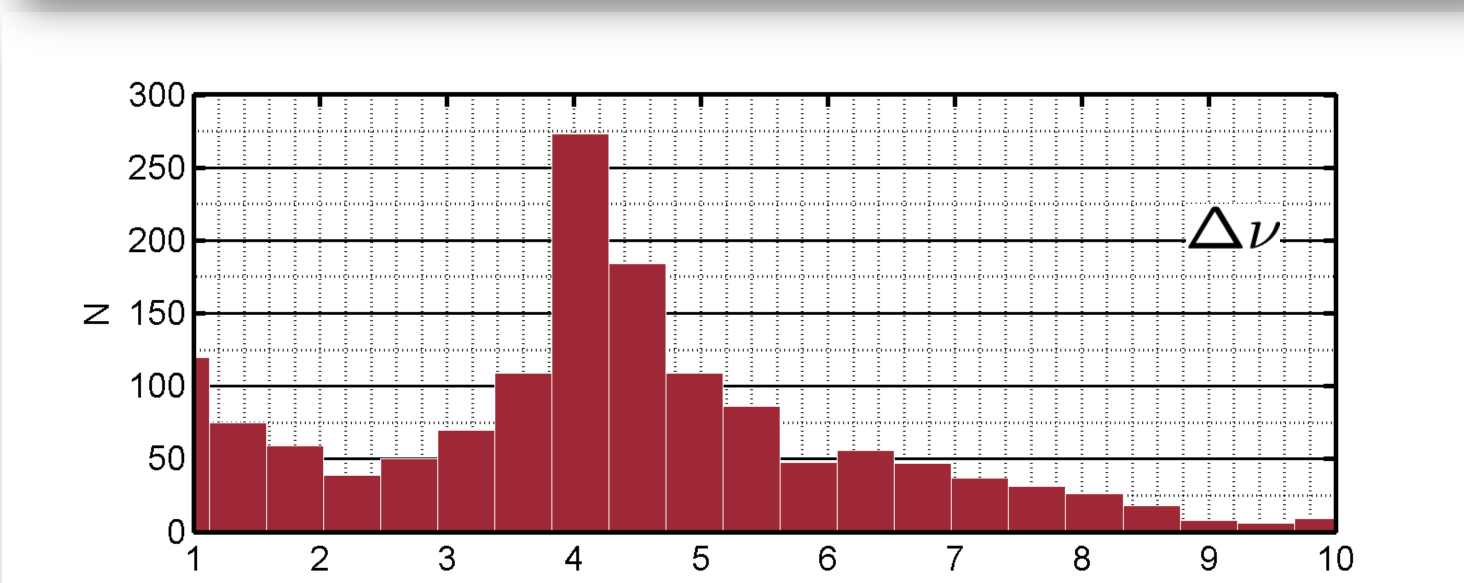
Brown et al. 1991 , Kjeldsen & Bedding 1995

Red giants: population study

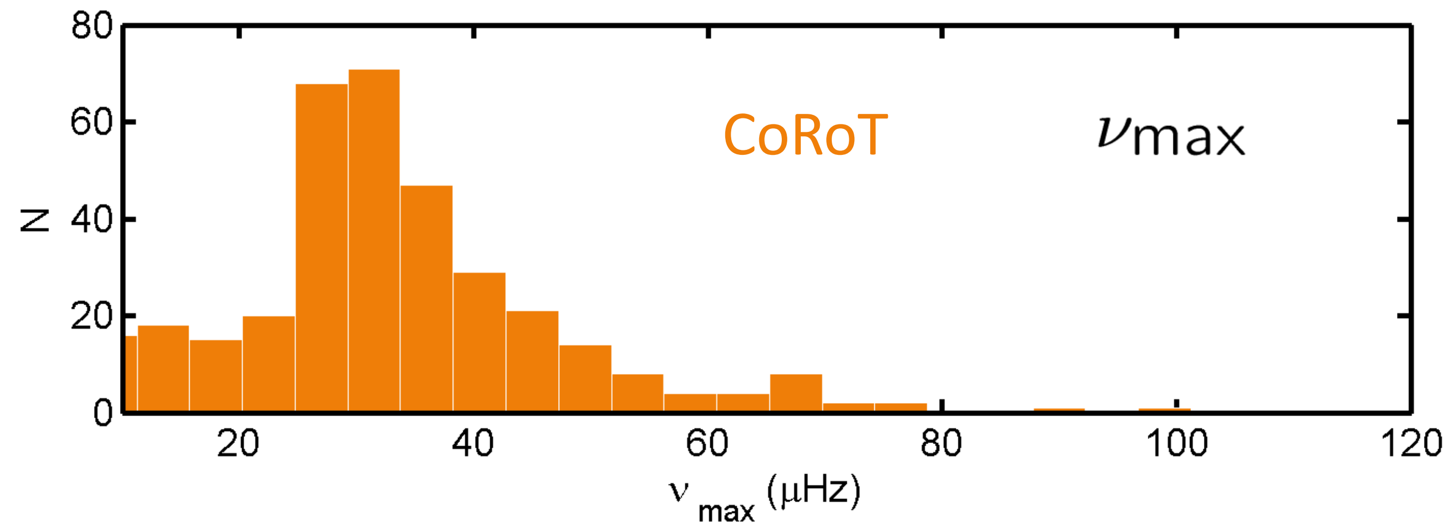


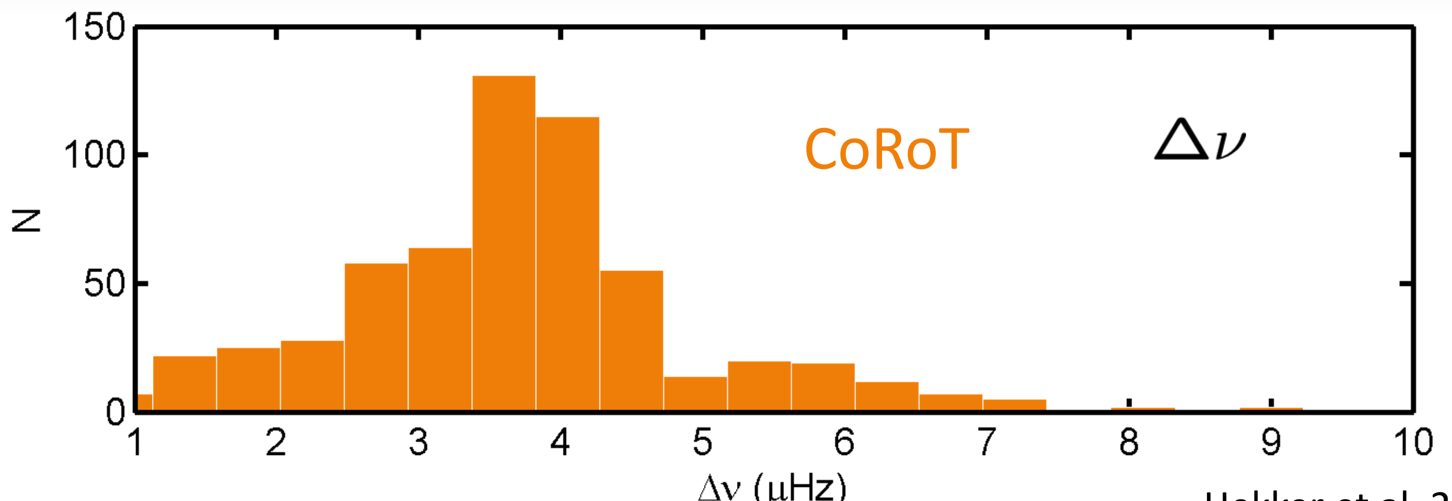
Red giant population NOW: ν_{max} and $\Delta\nu$





CoRoT red giants: ν_{max} and $\Delta\nu$

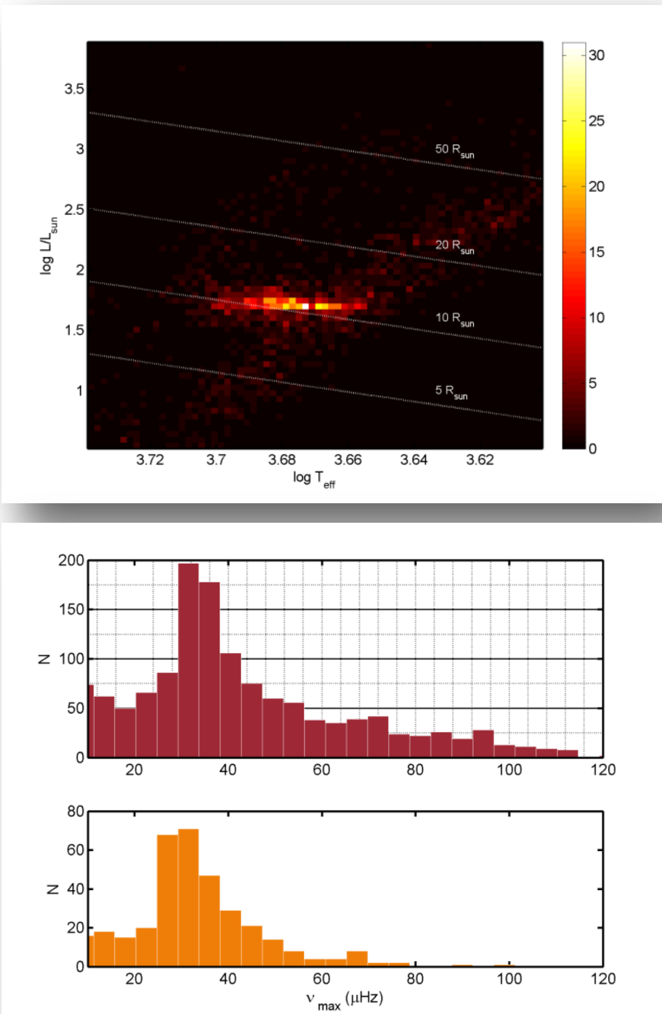




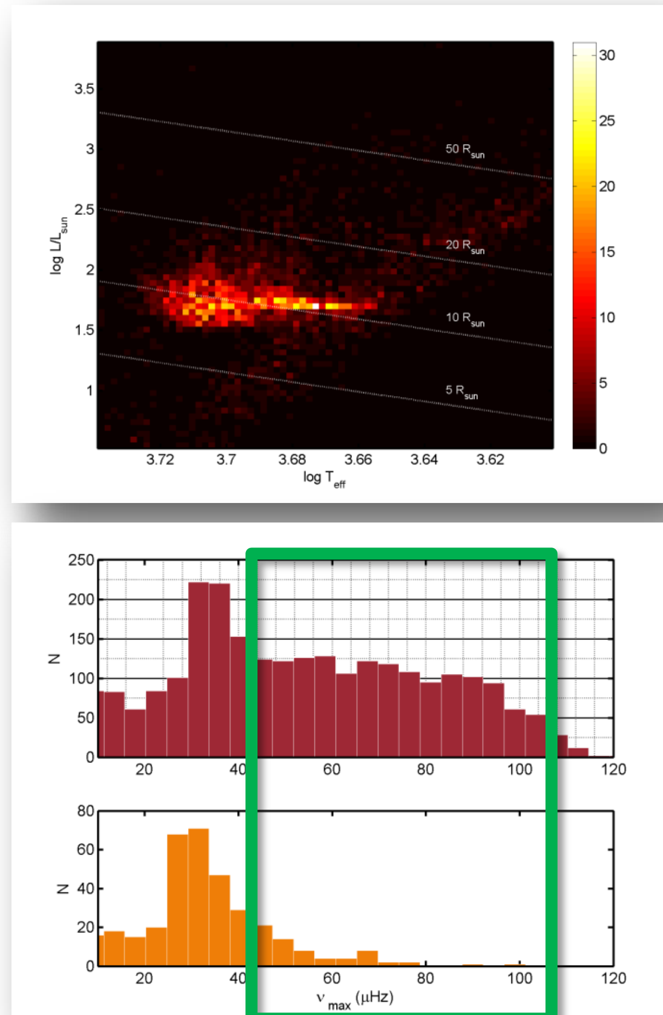
Hekker et al. 2009

Red giants: population study

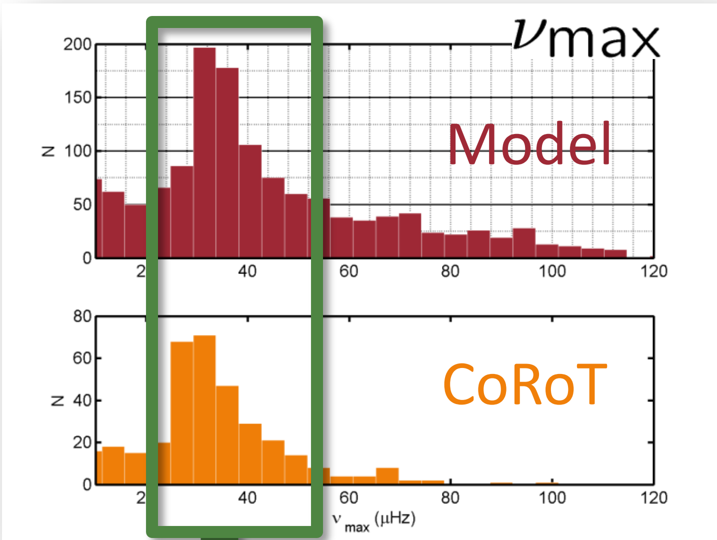
Constant Star Formation Rate

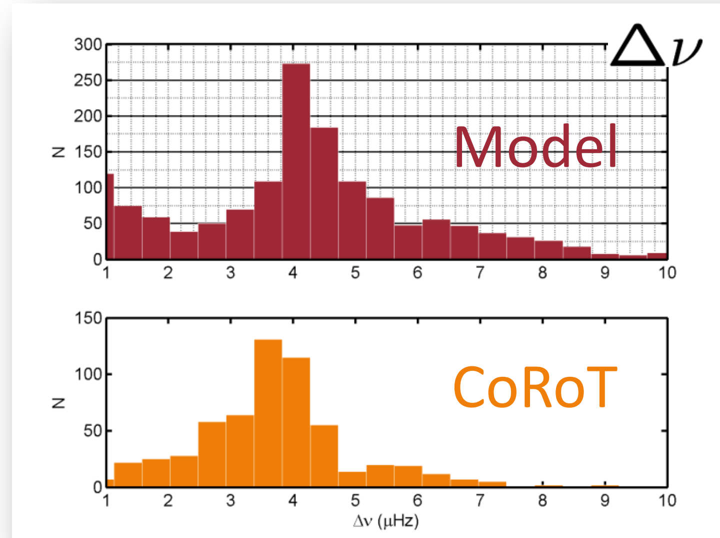


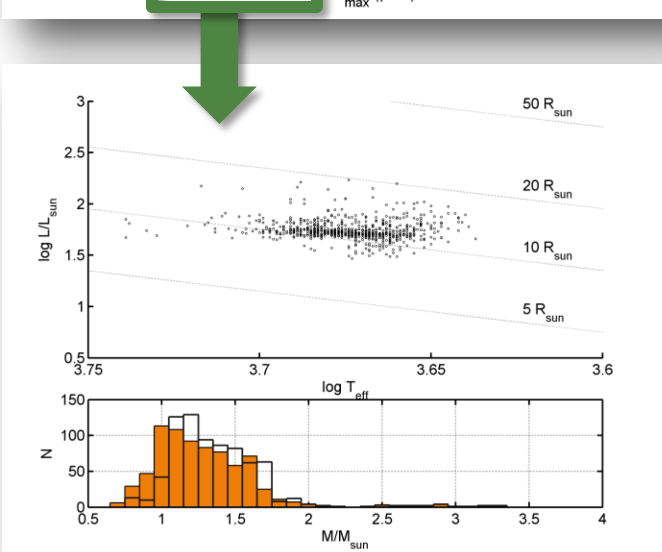
Recent burst 0-1 Gyr (e.g Rocha-Pinto et al. 2000)



CoRoT red giants: population study







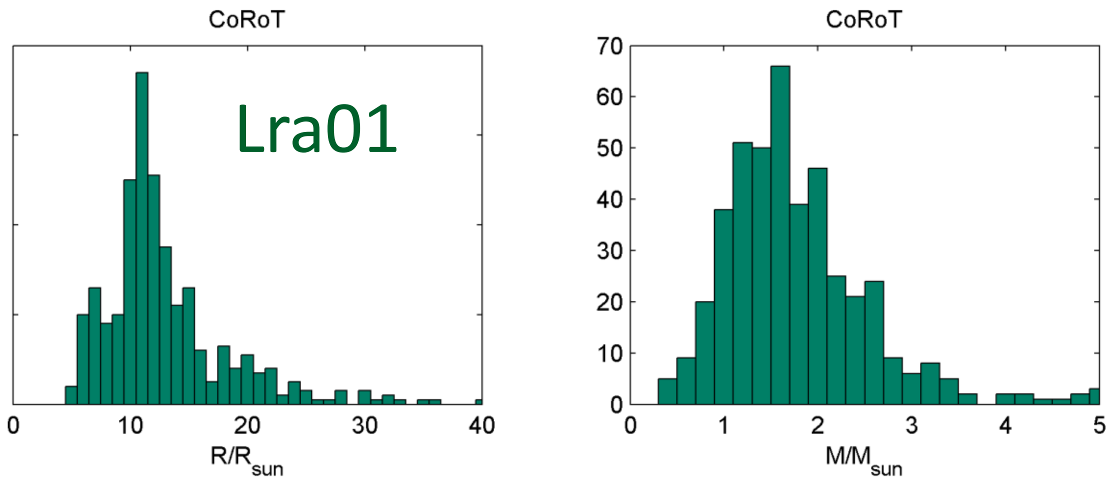
We can identify Red Clump stars from their ν_{max} and $\Delta\nu$

Miglio et al. 2009 A&A 503, L21

CoRoT Lra01

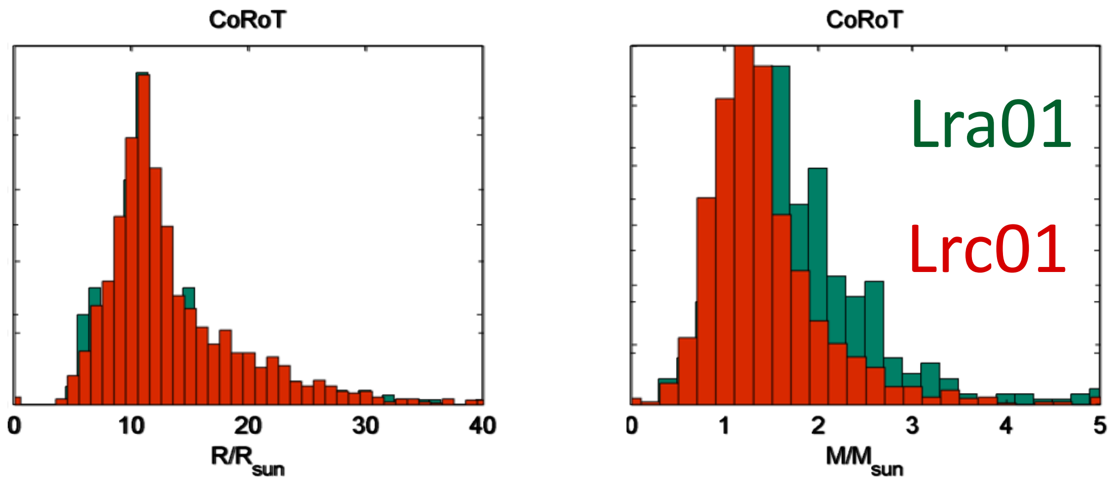
(l,b)=(212,-2)

$\nu_{max} + \Delta\nu + Te$ → **M, R**



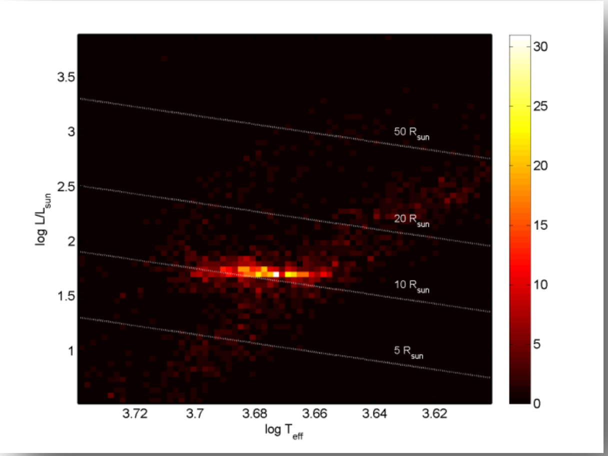
CoRoT Lra01 vs. Lrc01

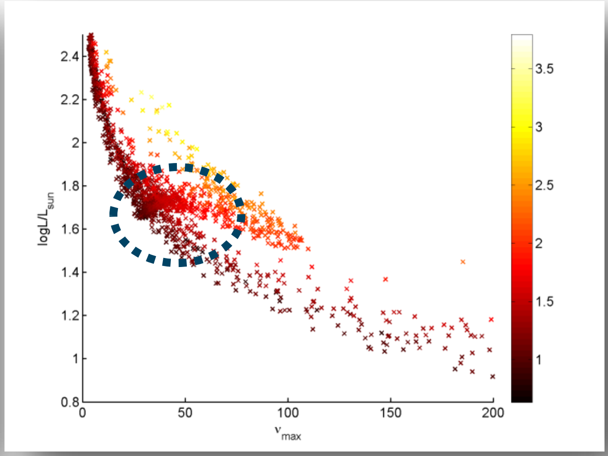
(l,b)=(212,-2) (l,b)=(37,-7)

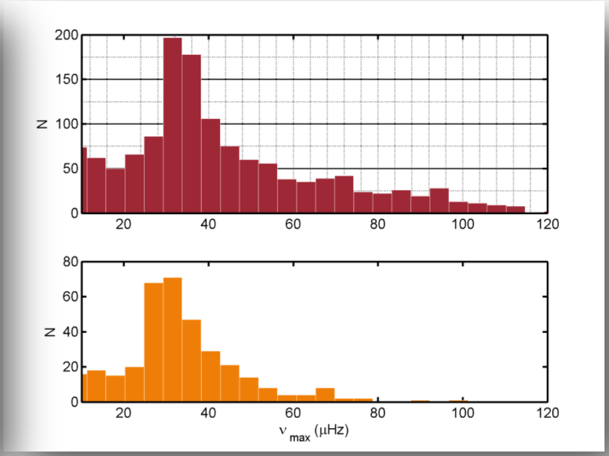


Mosser et a. 2010, Miglio et al. 2010

Red Clump Stars: Distance Indicators







ν_{max} ~ 25 – 40 μHz : Red Clump Stars

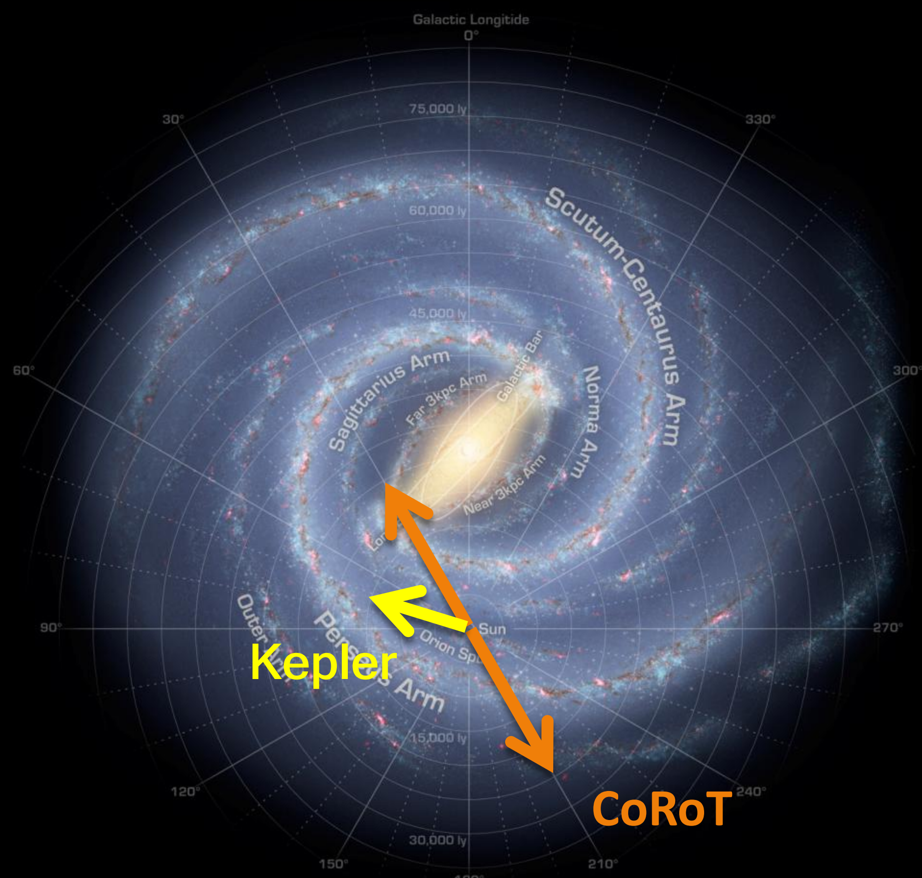
L_{RC} ~ constant →

asteroseismic distance indicator

CoRoT and KEPLER

- CoRoT:
  - $l \sim 35°$ or $l \sim 215°$
  - slightly different b
- Kepler
  - $l \sim 75°, \; 7° \leq b \leq 20°$

- **Structure of the galaxy**
- **Metallicity distribution**
  - **radially**
  - **in depth**



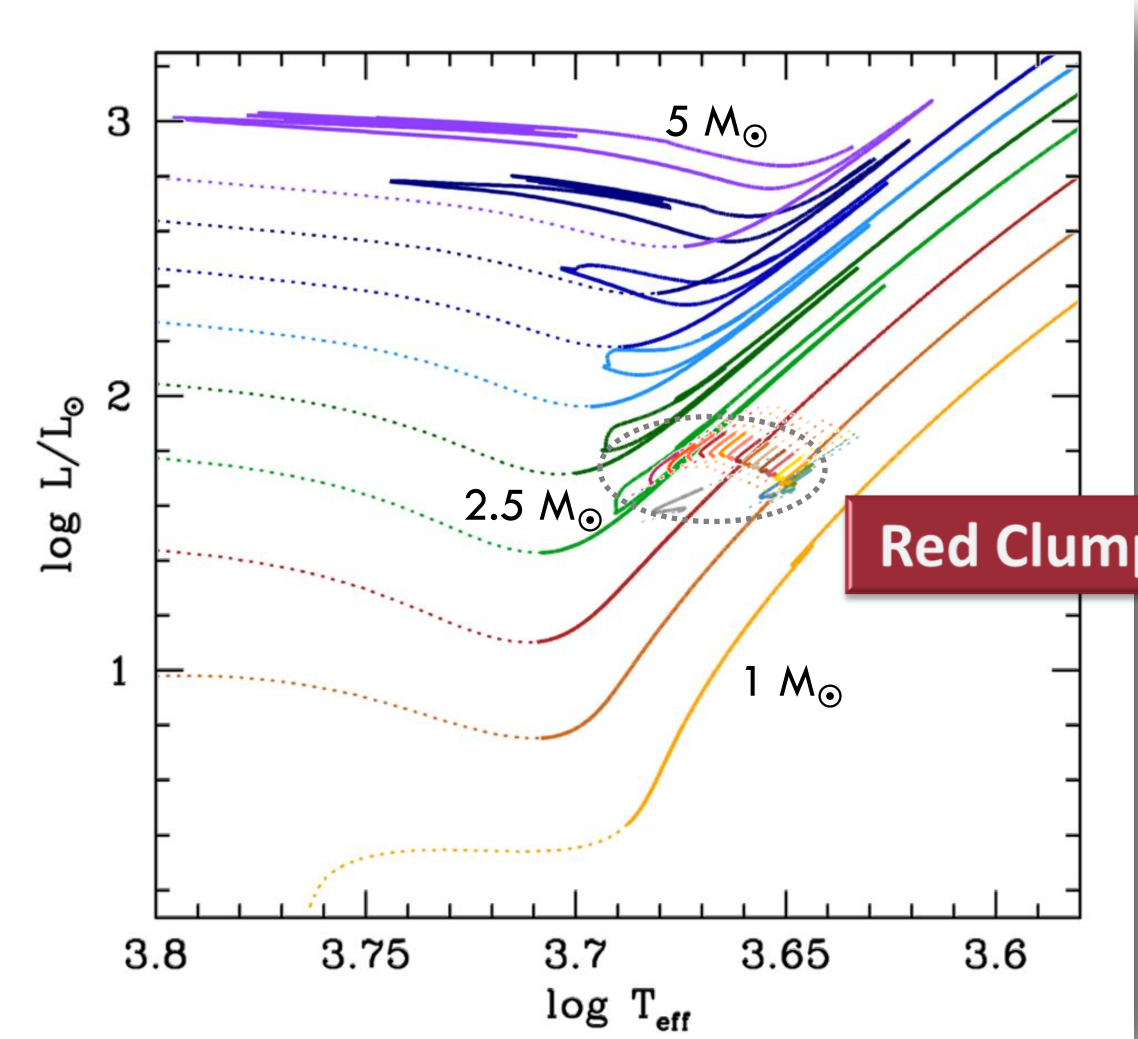
Artist's concept view of the MW - Image credit: NASA/JPL-Caltech

B

Probe the internal structure of giants

- Interpretation of patterns in the acoustic spectrum
- Detection of acoustic glitches

Red giants: evolutionary models



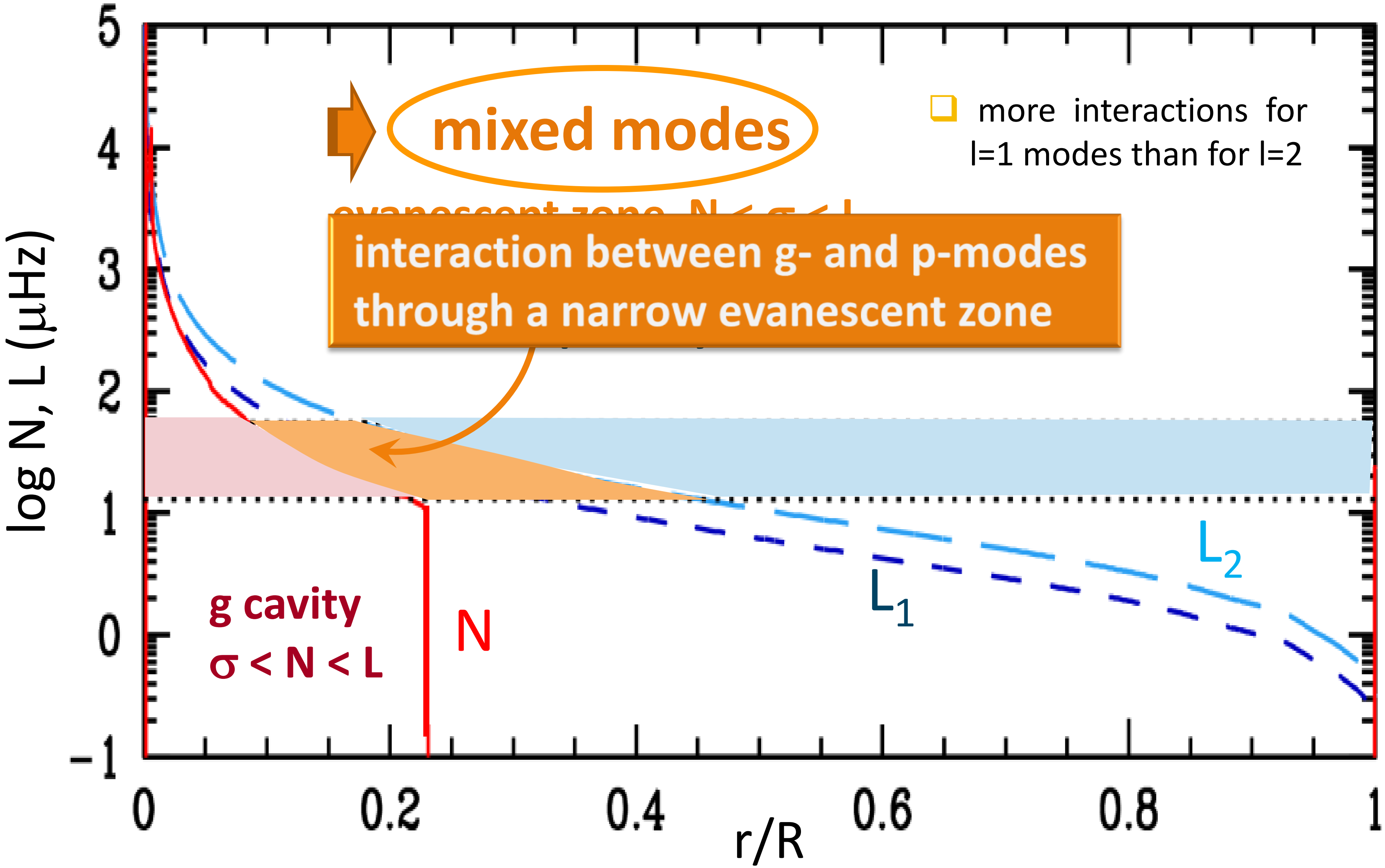
- $M=1.0\text{-}5.0\ M_\odot$
- $Z_0=0.006, 0.01, 0.02, 0.03$
- $Y_0=0.278, 0.250$
- $\alpha_{MLT}=1.6, 1.9$, FST

Red Clump stars

- $M=0.6 – 2.3\ M_\odot$
- $Z_0= 0.02$
- $Y_0=0.300, 0.250$
- $\alpha_{MLT}=1.9$

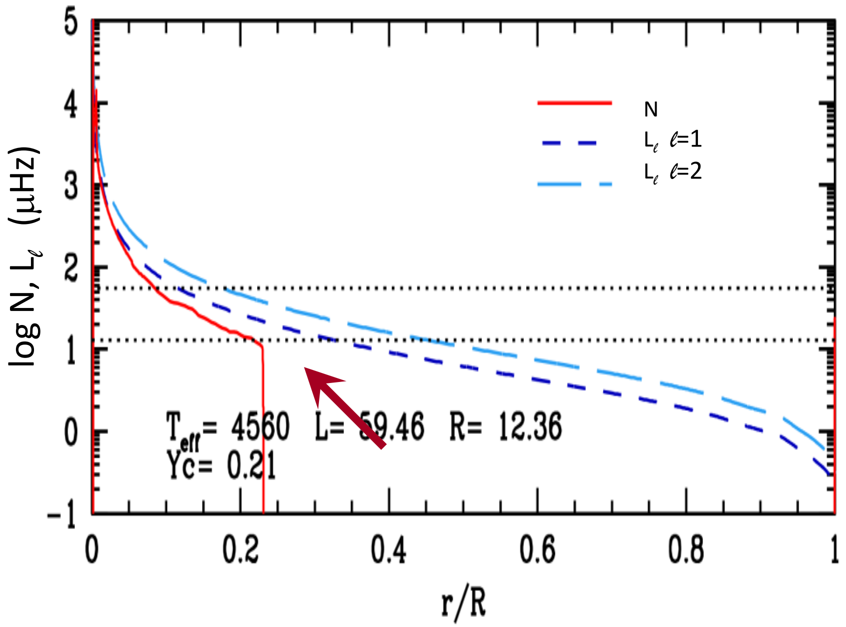
Montalban et al. 2010, AN

Red giants: propagation diagram

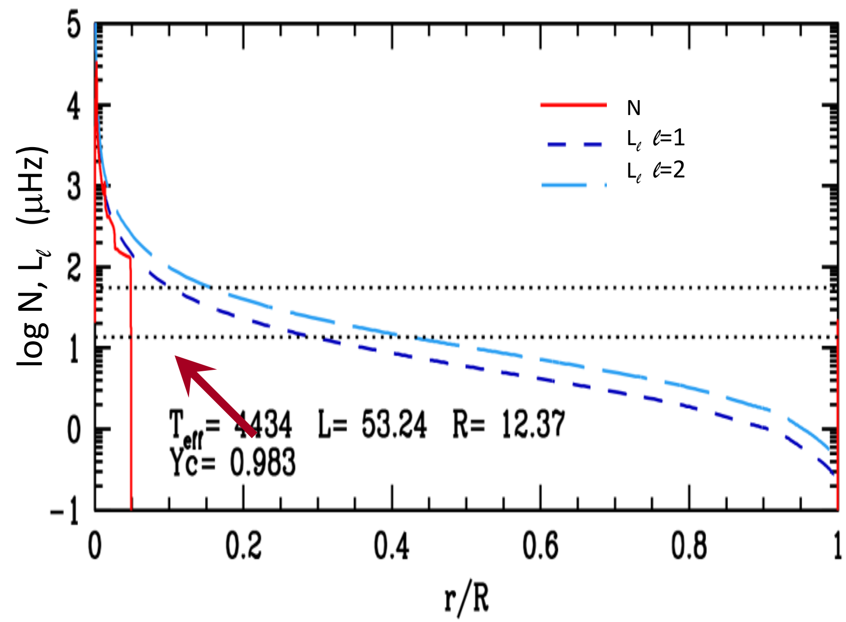


Structural differences

1.5M$_\odot$: core He burning

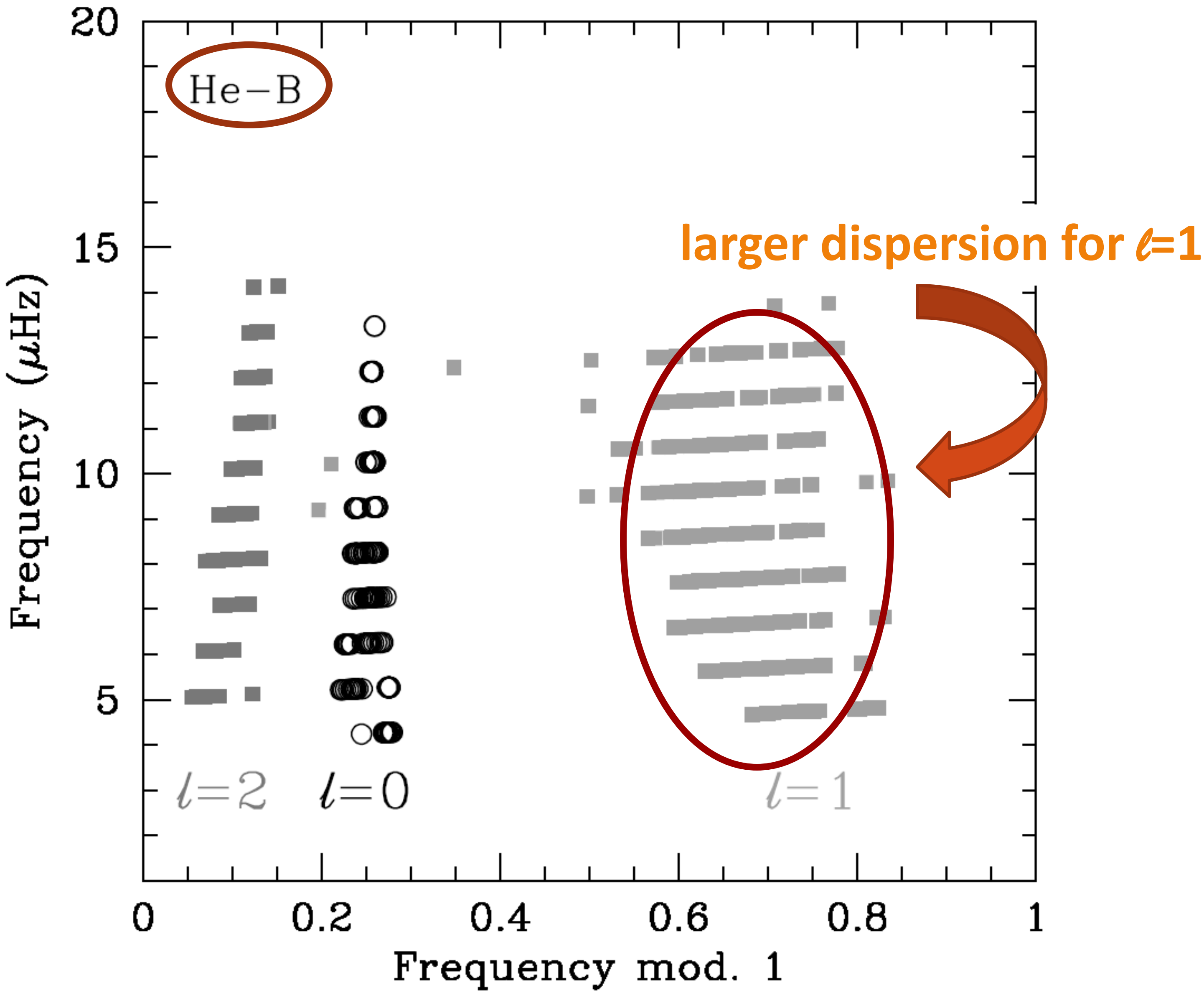


1.5M$_\odot$: ascending Red Giant Branch



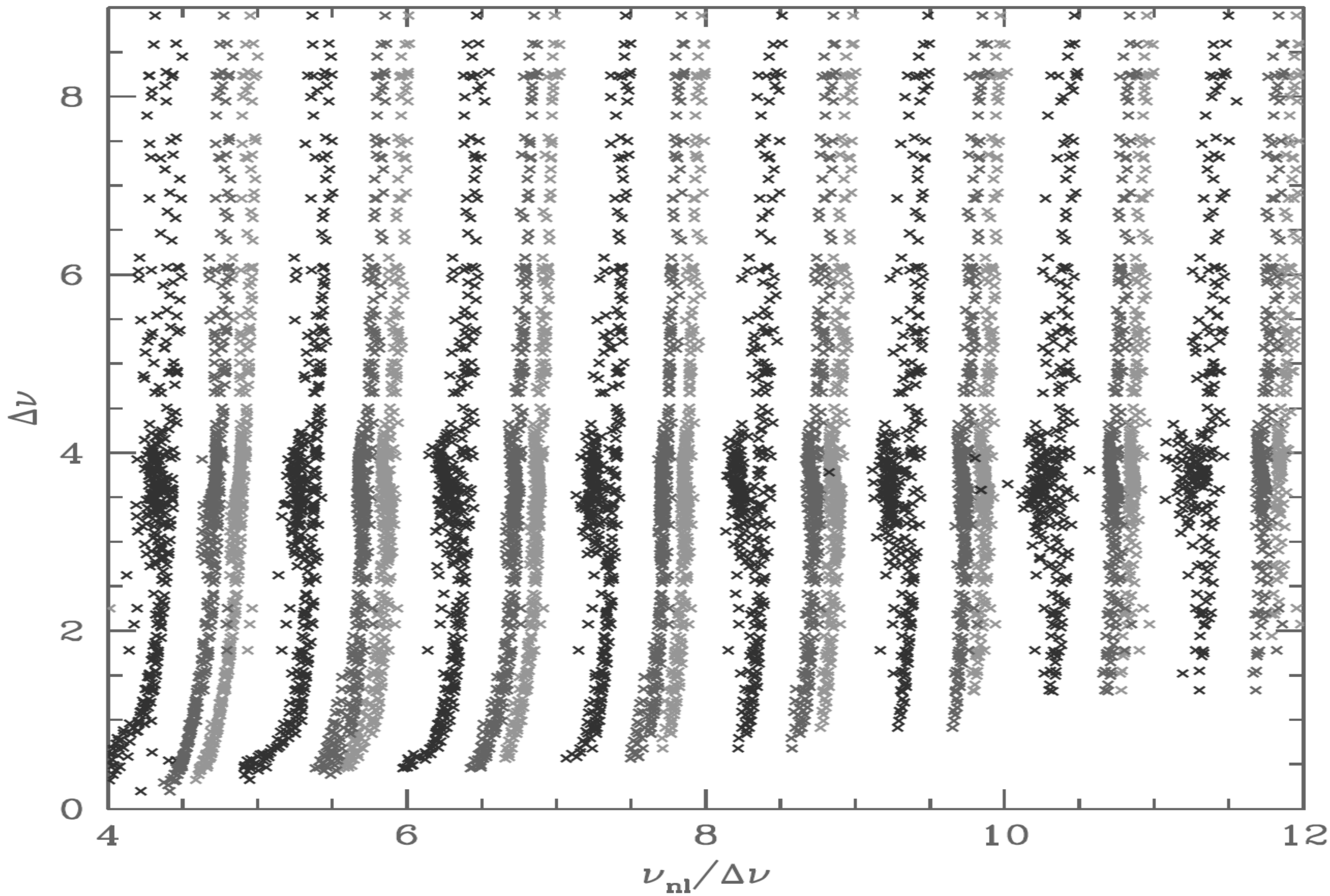
the evanescent zone is much smaller in He burning models than in ascending ones
→ more interaction between p and g modes

Montalban et al. 2010, AN



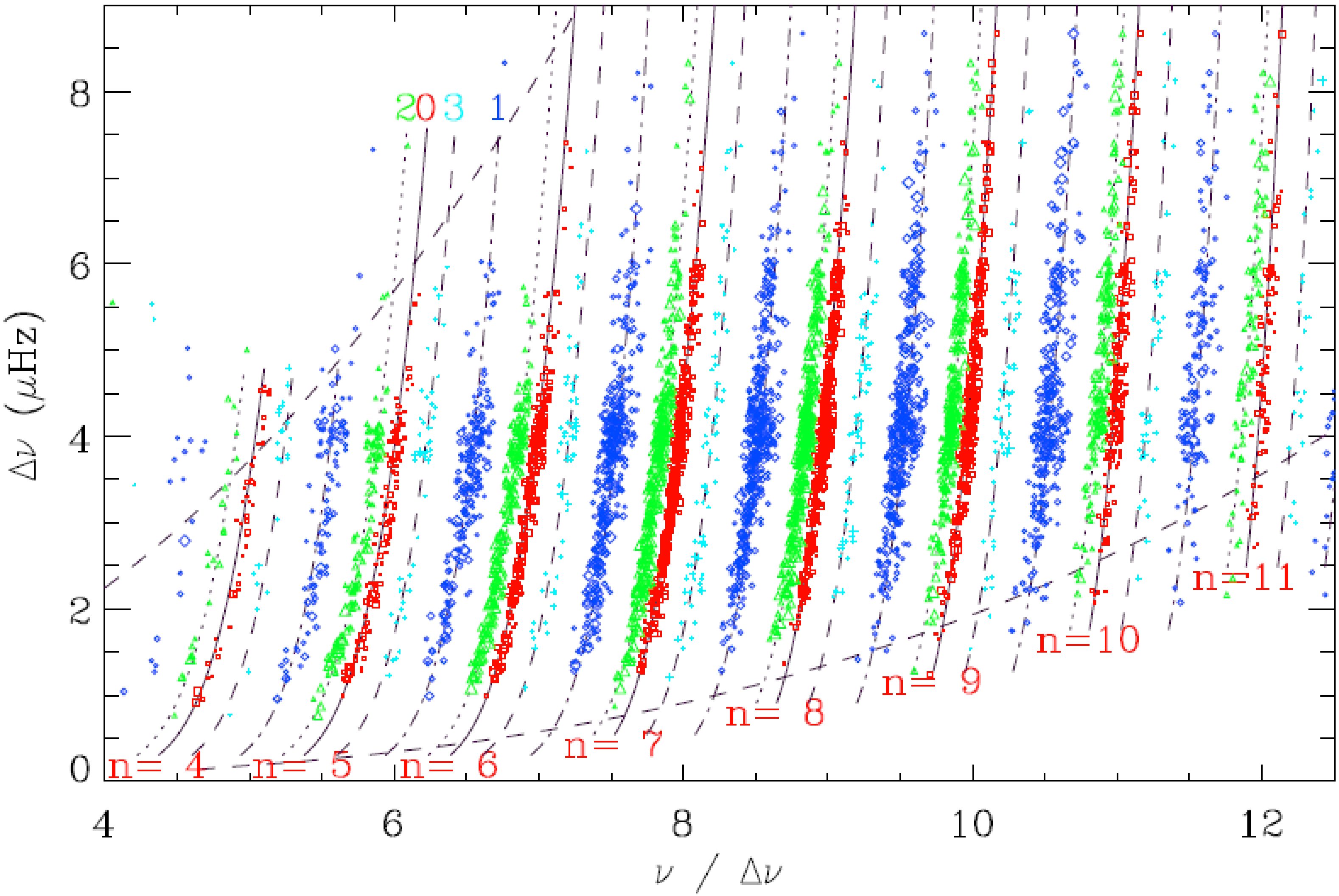
Montalban et al. 2010, AN

CoRoT exofield LRc01 : theoretical pattern



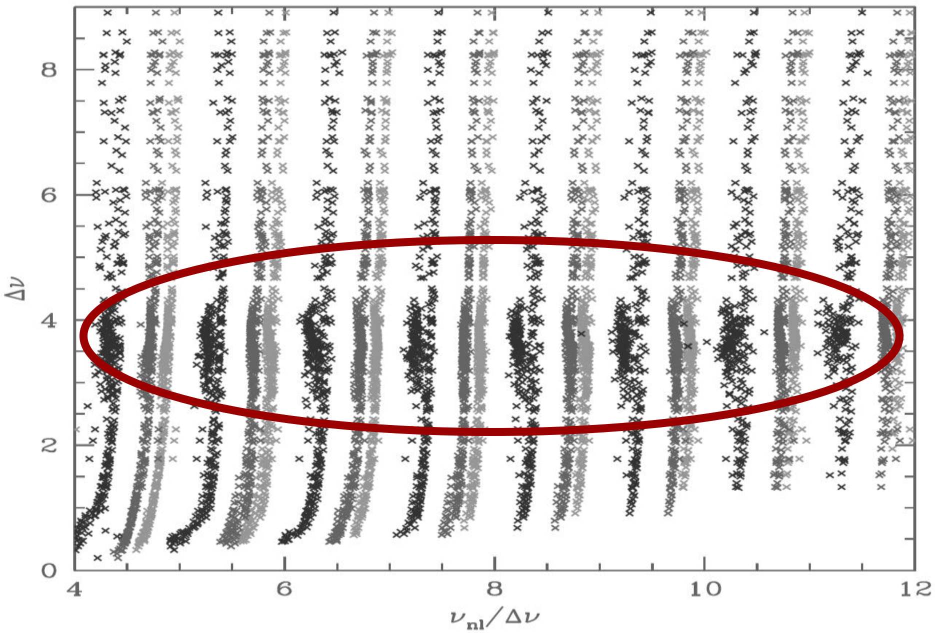
Montalban et al. 2010, ApJL

CoRoT exofield LRc01 : observations

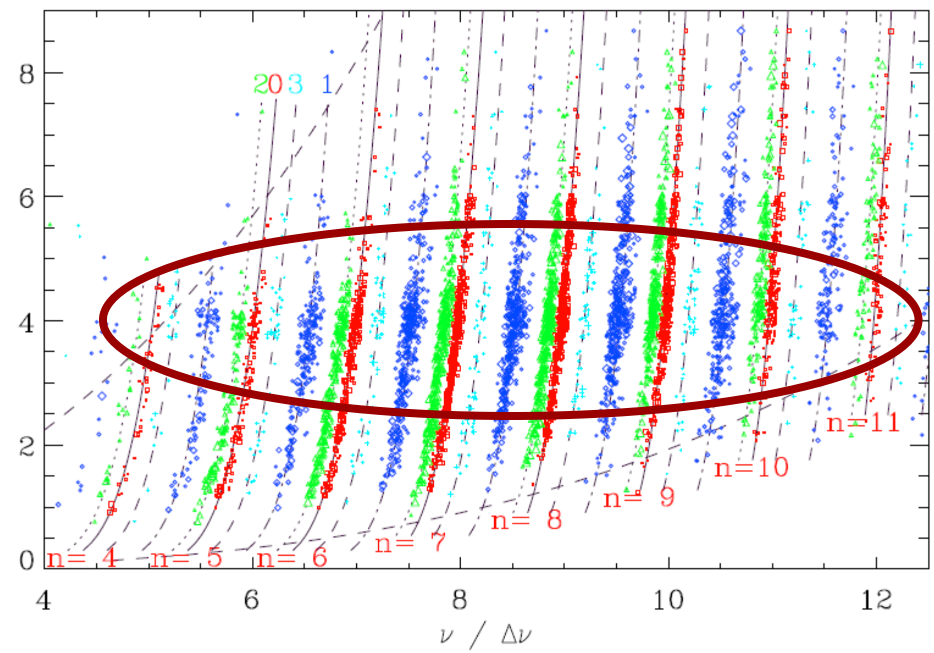


Mosser et al. 2010

theory versus observations

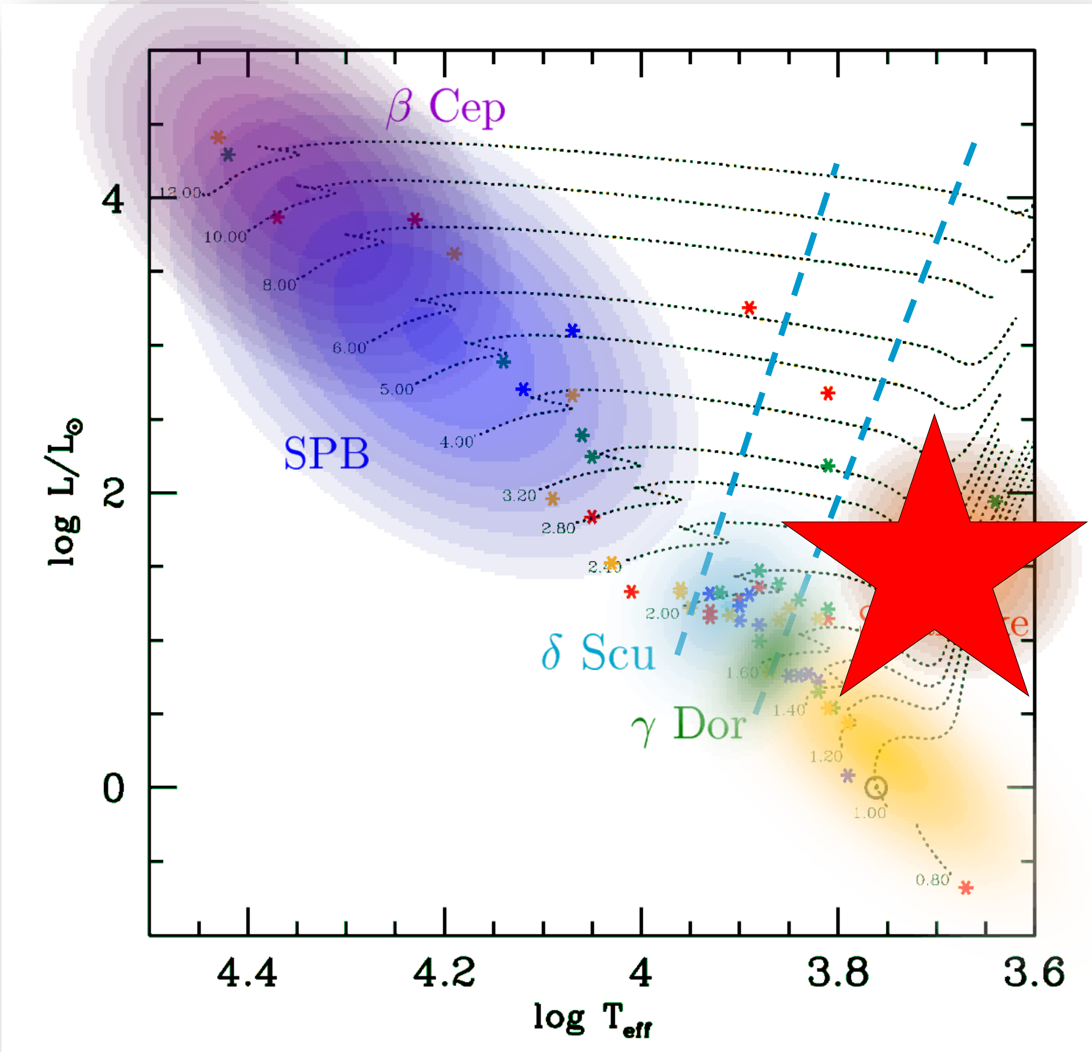


Montalban et al. 2010, ApJL



Mosser et al. 2010

Red giants: acoustic glitches



CoRoT target HR7349

V=5.8

π= 9.64 ± 0.34

L=69 ± 7 $L_\odot$

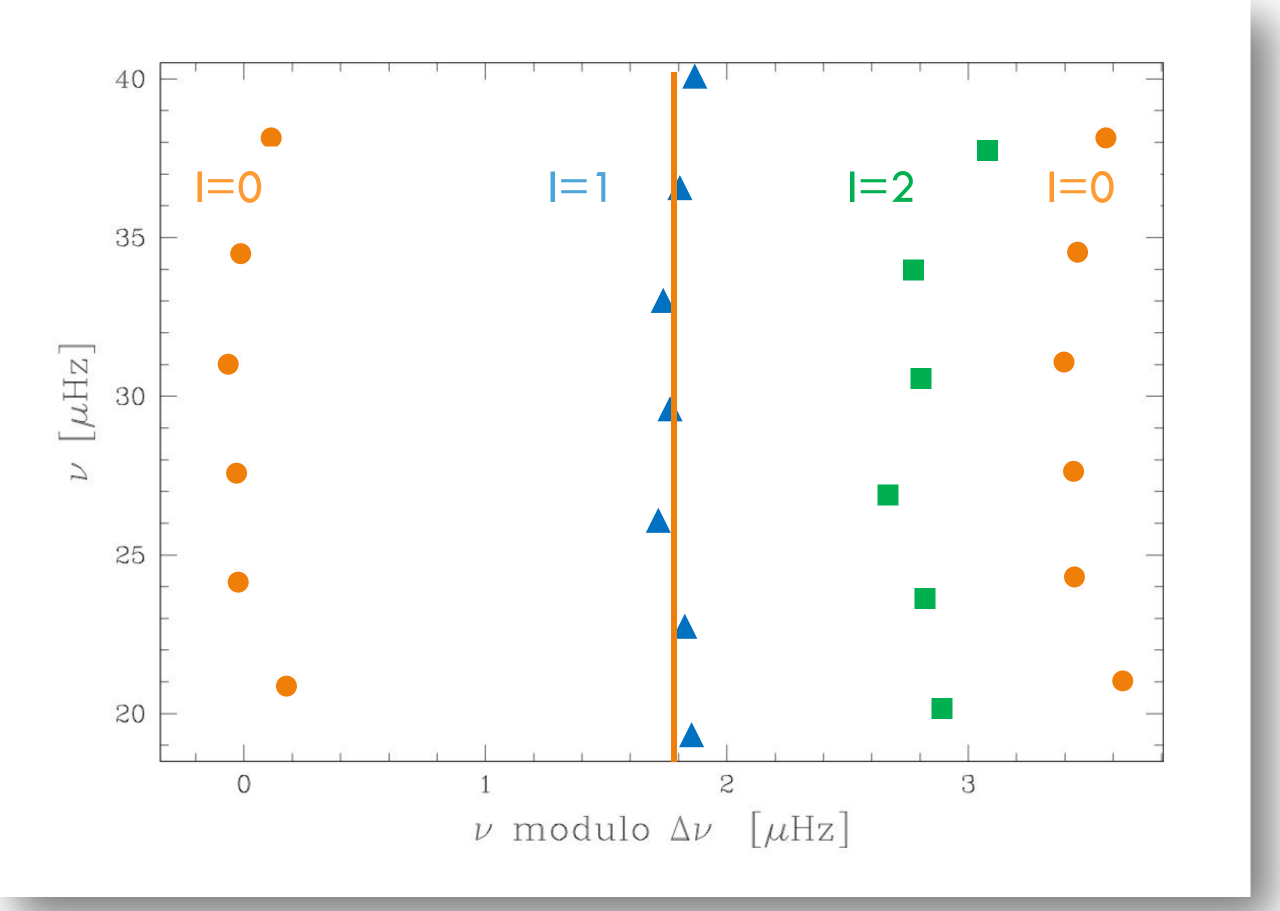
T_{eff}=4700 ± 100 K

[Fe/H]=-0.1 ± 0.1

HR 7349: CoRoT observations

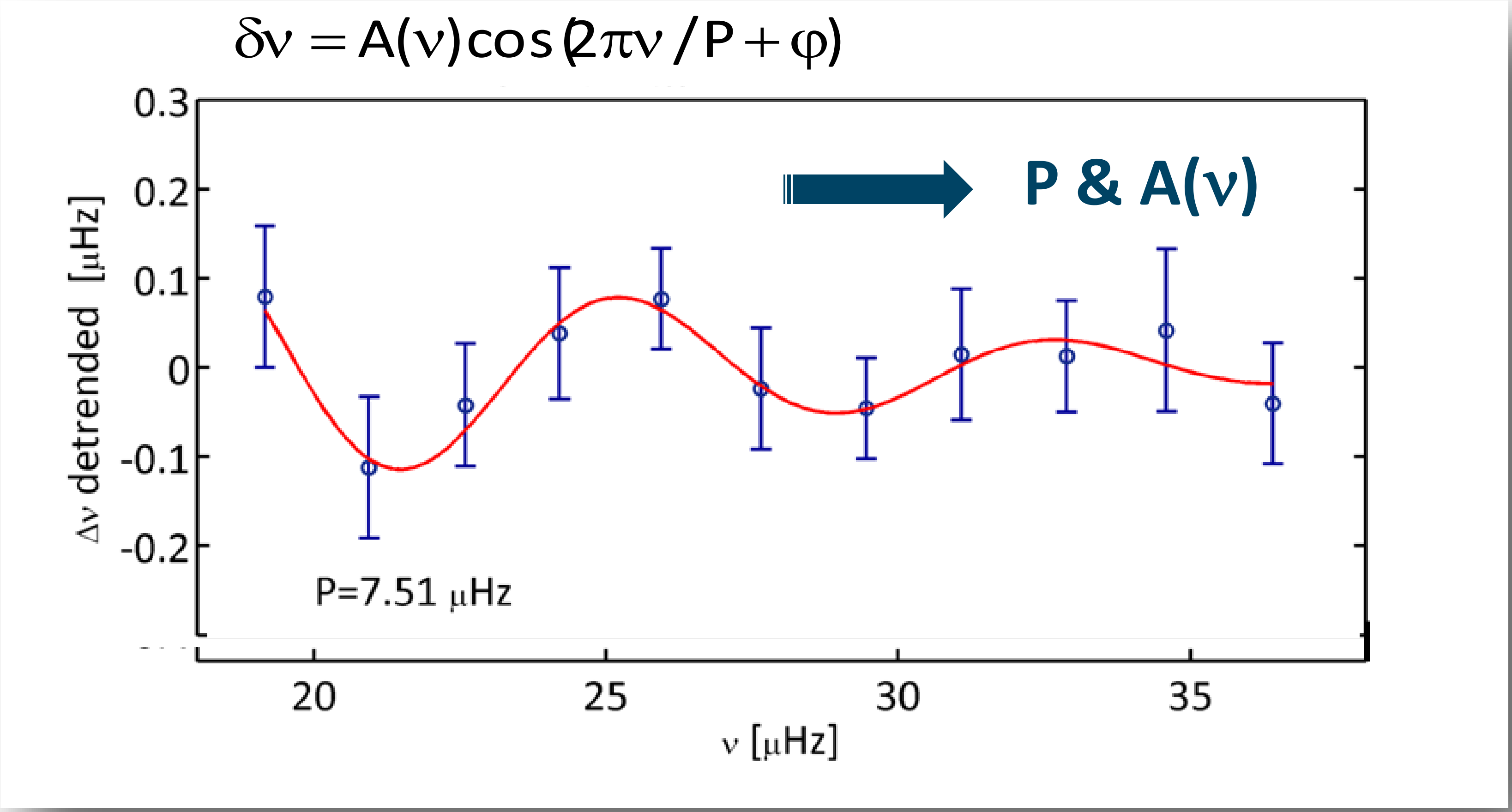
CoRoT target
seismo-field
long run

19 modes
detected
18-40 μHz



Carrier et al. 2010 A&A

Periodic component in ν



Miglio et al. 2010

Periodic component in ν

- Clear signature of an acoustic glitch in the star

$$\delta\nu = A(\nu)\cos(4\pi t_* \nu + \varphi)$$

$$t_* = \int_{r_*}^{R} dr/c$$

$$\tau_* = \tau_0 - t_* = 1/(2\Delta\nu) - t_*$$

acoustic depth

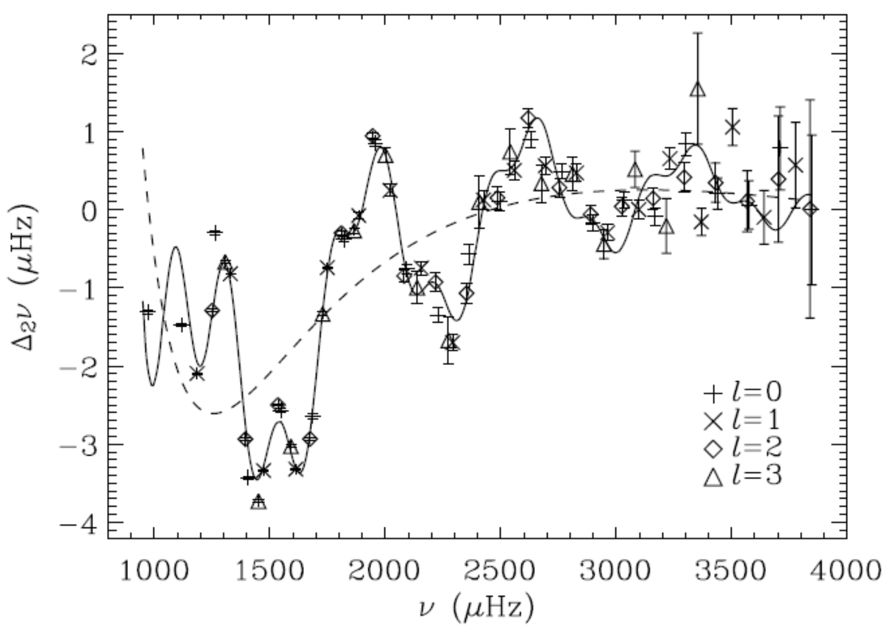
acoustic radius

Period ⟷ **acoustic depth (*)**

Gough 1990

Acoustic glitches

- The solar case



Houdek & Gough, 2007 Ballot et al. 2004

6 years GOLF observations

Acoustic radius of

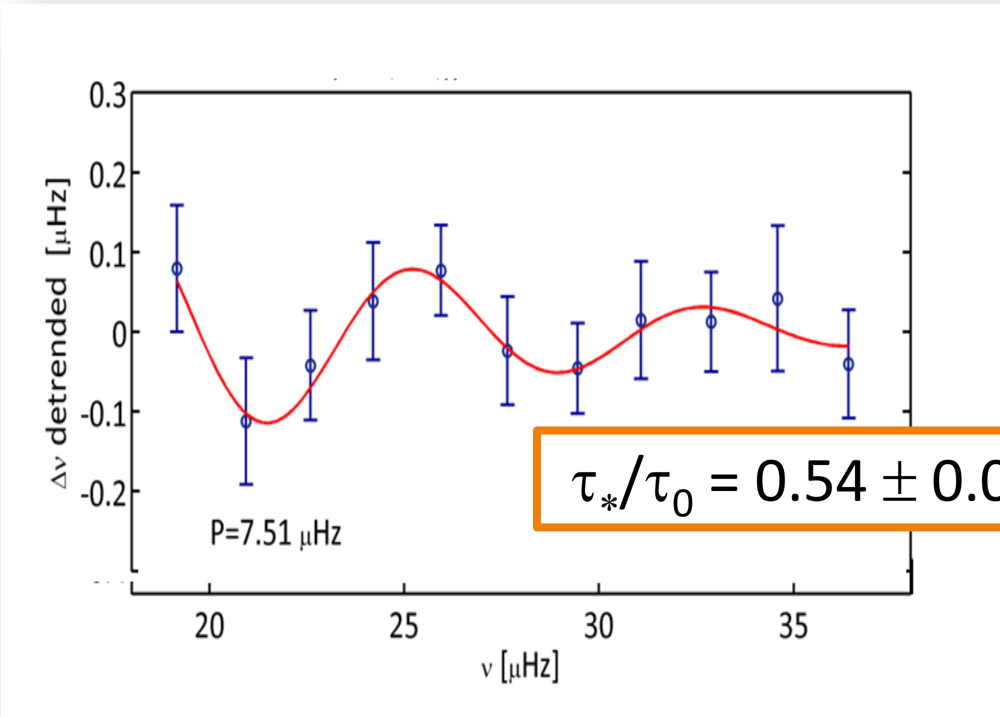
- base of the CZ
- HeII ionization zone

Possible for other stars?

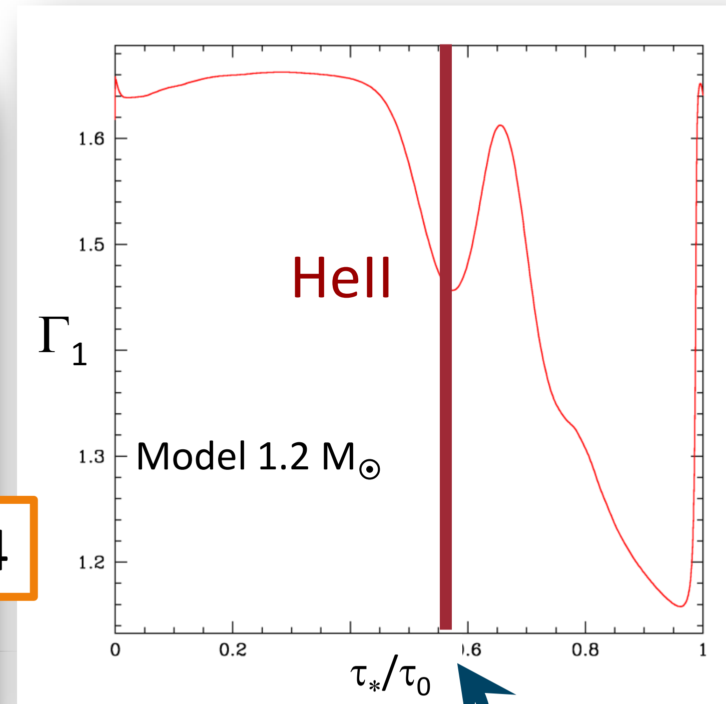
Perez Hernandez & Christensen-Dalsgaard 1998
Roxburgh&Vorontsov, 1998
Monteiro et al. 1998, 2000
Mazumdar&Antia 2001
Ballot et al. 2004
Basu et al. 2004
Verner et al. 2006
Houdek & Gough 2007
Mazumdar & Michel 2010

Acoustic glitches

$$c^2 = \Gamma_1 \frac{P}{\rho}$$



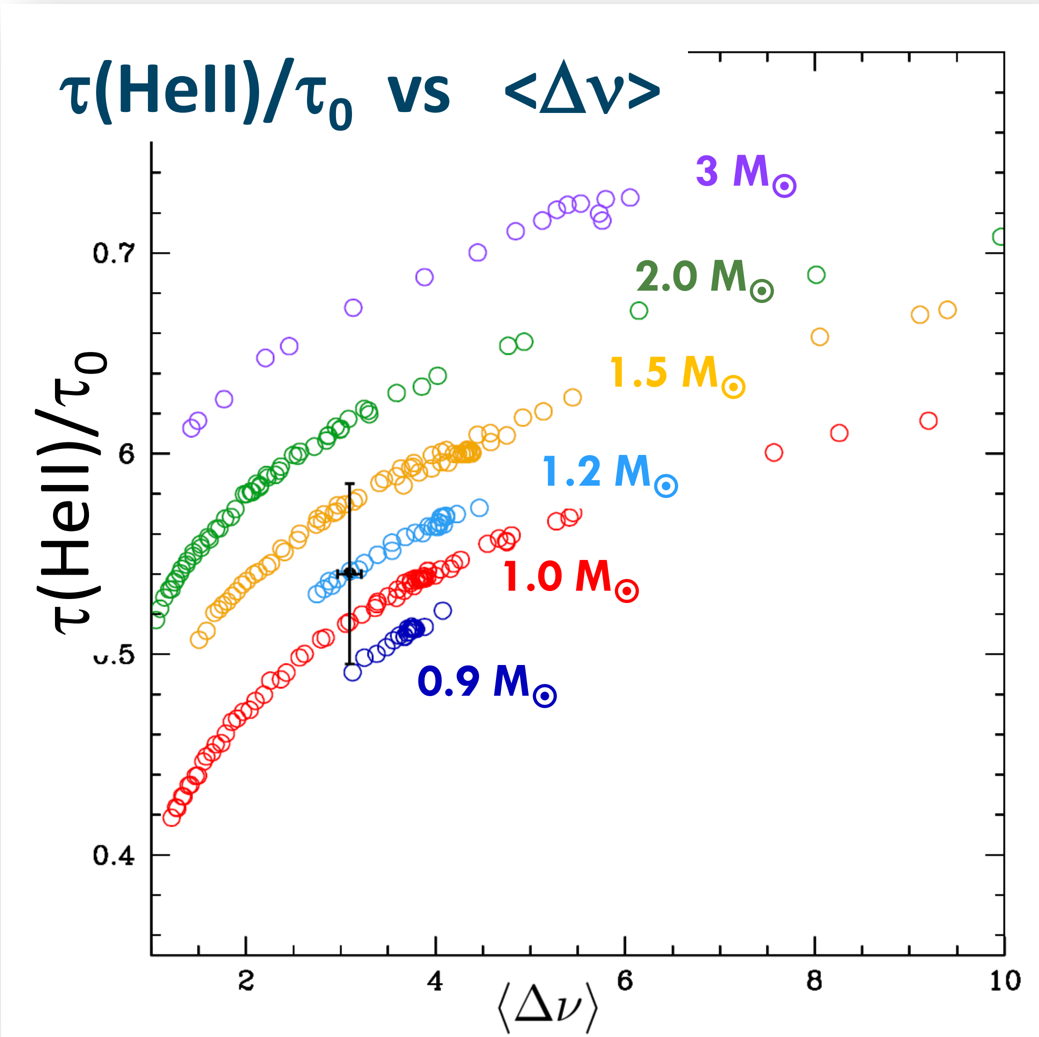
$\tau_*/\tau_0 = 0.54 \pm 0.04$



$\tau_*/\tau_0 = 0.54$

Miglio et al. 2010

Acoustic glitches



1. $\tau(\mathrm{HeII})/\tau_0$

$<\Delta\nu>$

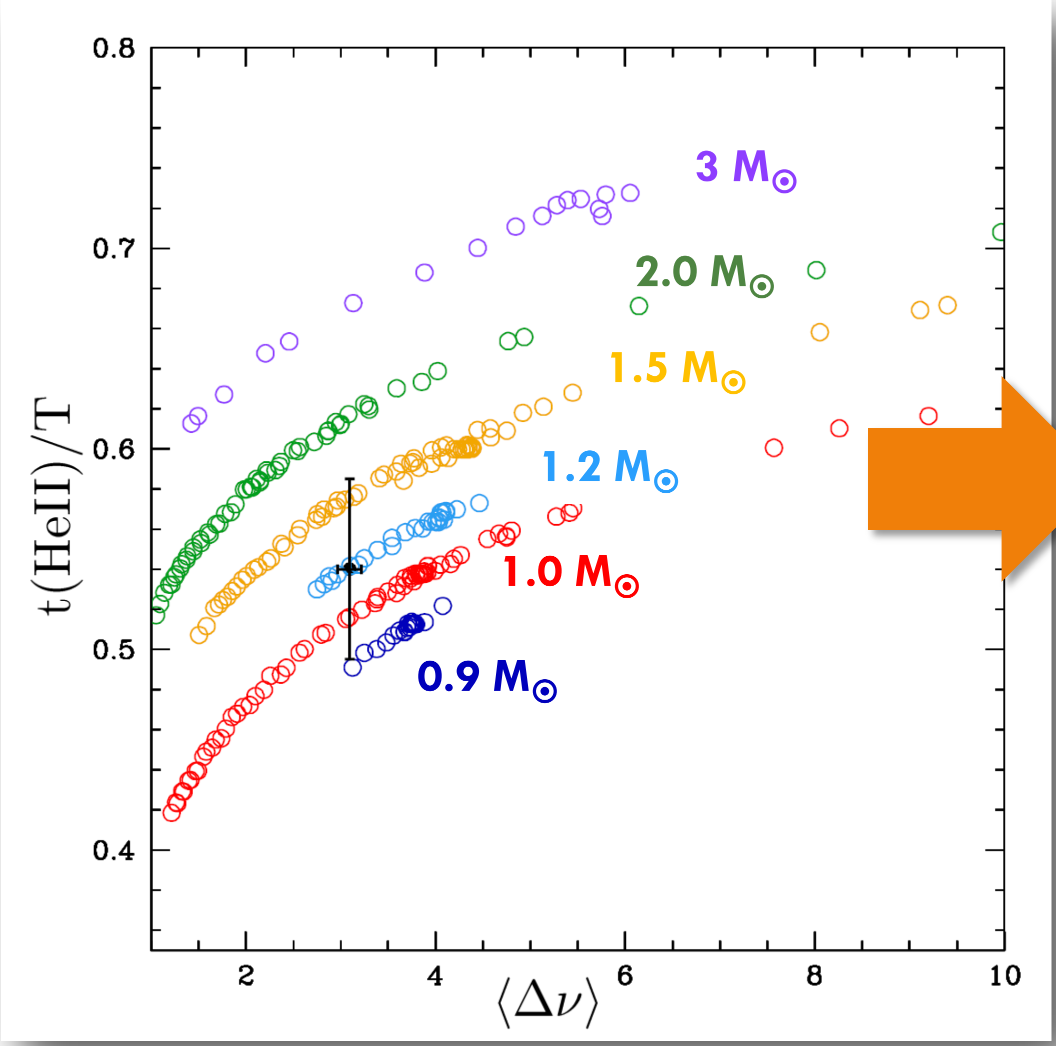
M

2. M

$<\Delta\nu>$

R

Acoustic glitches



M = 1.2 ± 0.3 M⊙

R = 12.2 ± 1.3 R⊙

Parallax (→ L) and Te

R = 12.3 ± 1.2 R⊙

M ???

4. SPB stars

κ-mechanism in the « iron » bump

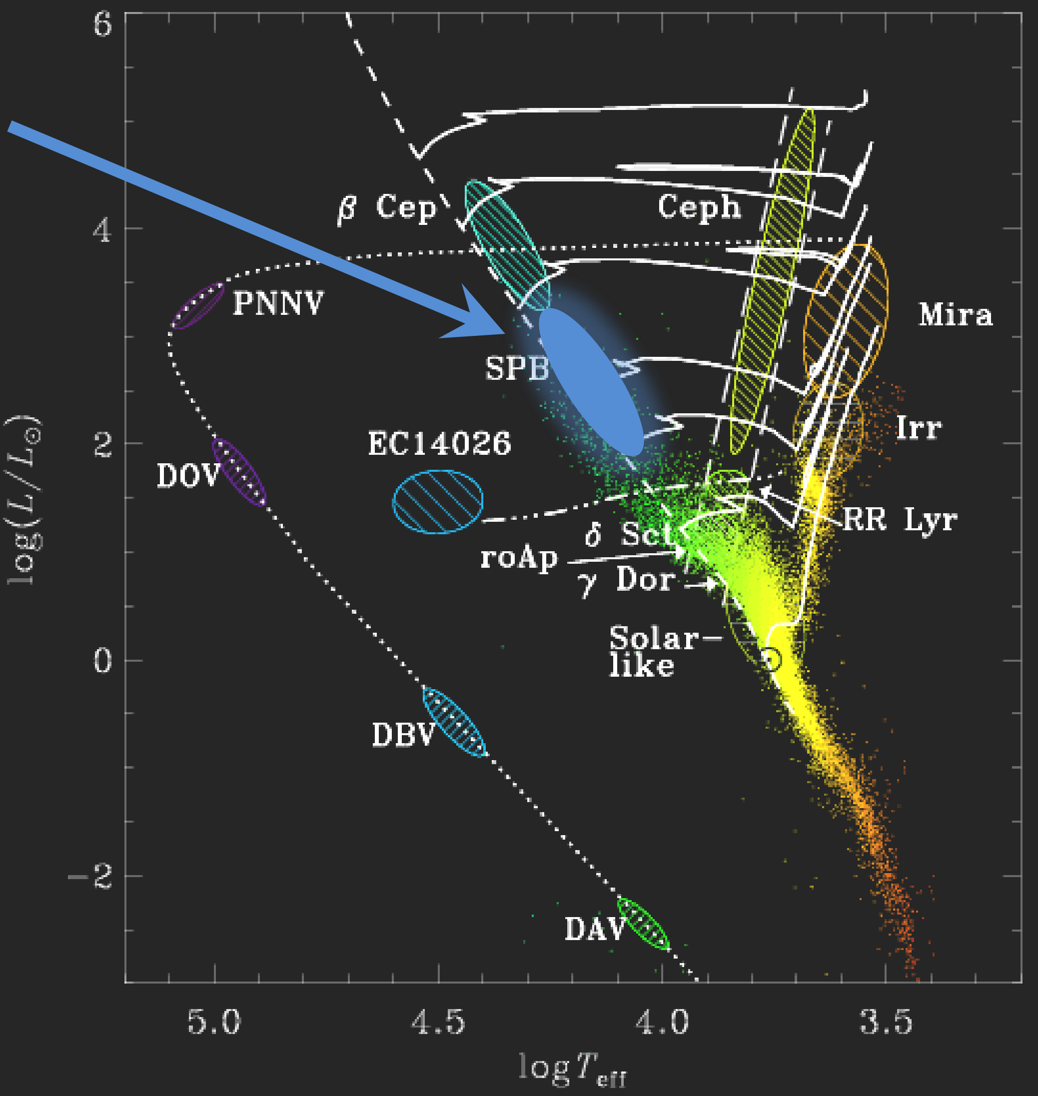
Slowly Pulsating B

- *MS B stars 3-9 $M_\odot$*
  conv core/rad env

- *gravity modes*
  periods : 1 – 4 d

Physics tested

- *overshooting*
- *diffusion*
- *rotation*
- *H profile*



Period spacing in high order g-modes

A sharp feature in the Brunt-Väisälä frequency shows up as a sinusoidal component in the g-mode period spacing

The period is related to the location of the sharp feature

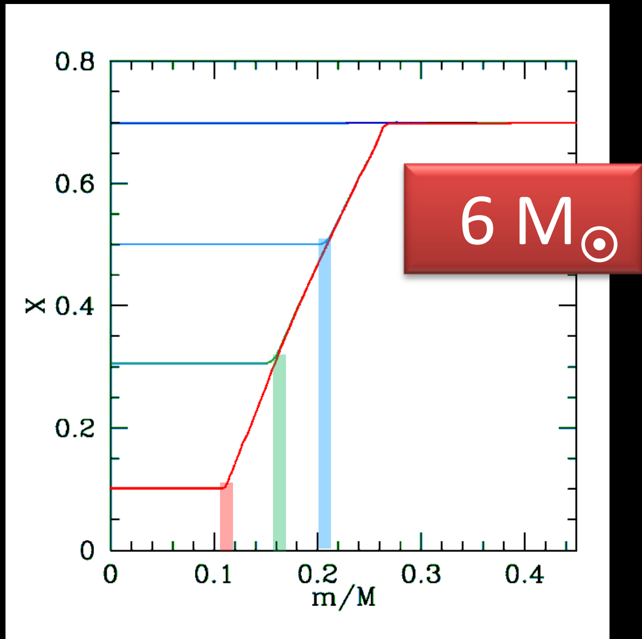
The period ↘ if the extent of the μ-gradient $[x_0, x_\mu]$ ↗

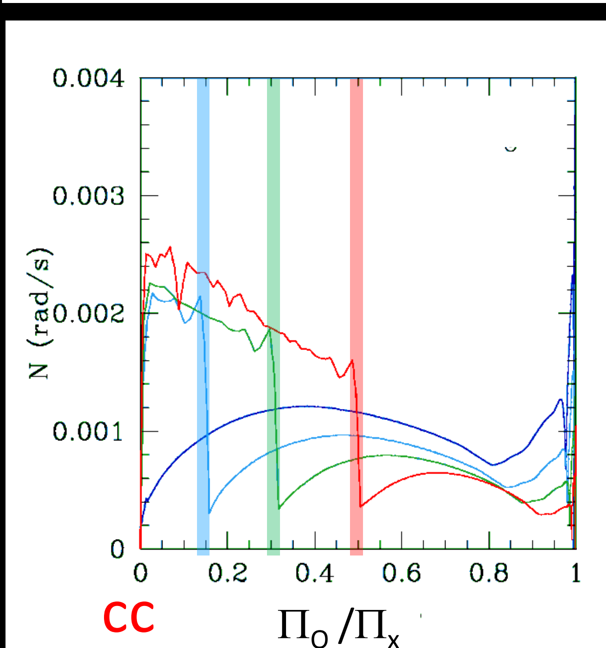
chemical composition discontinuities in WD

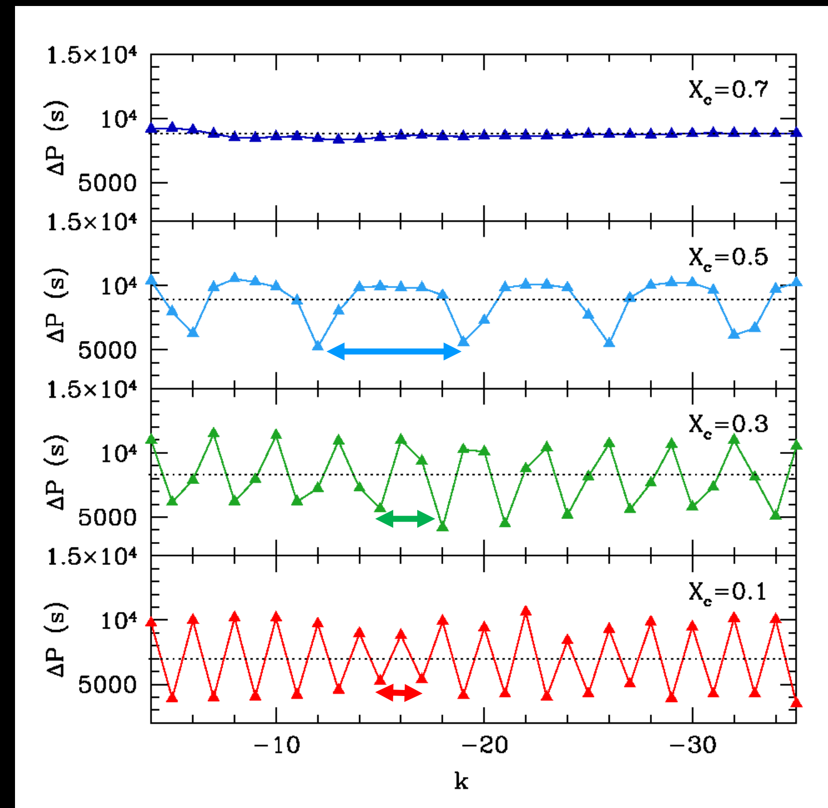
Montgomery et al. 2003

Miglio, Montalban, Noels & Eggenberger 2008
Gough 1993; Brassard et al. 1992; Berthomieu & Provost 1988; Dziembowski et al. 1993

SPB





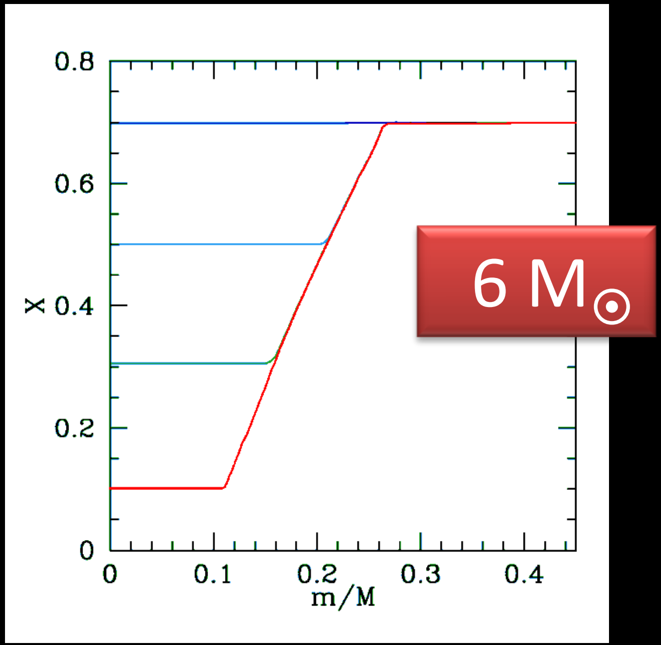


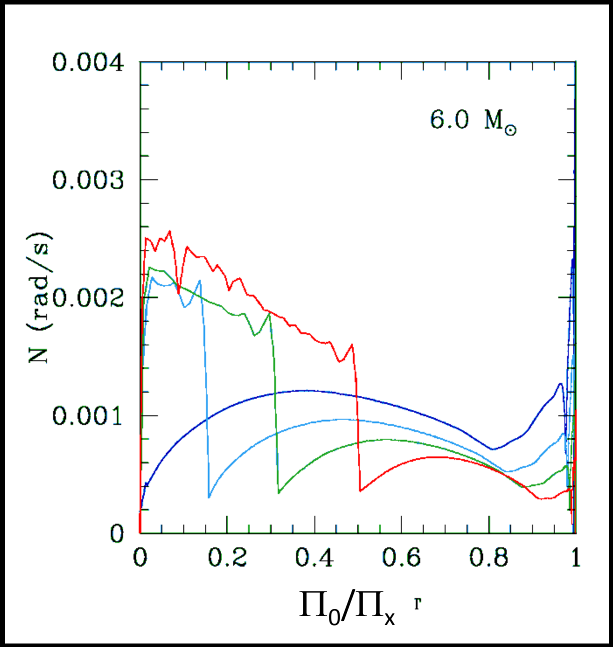
Miglio, Montalban, Noels & Eggenberger 2008

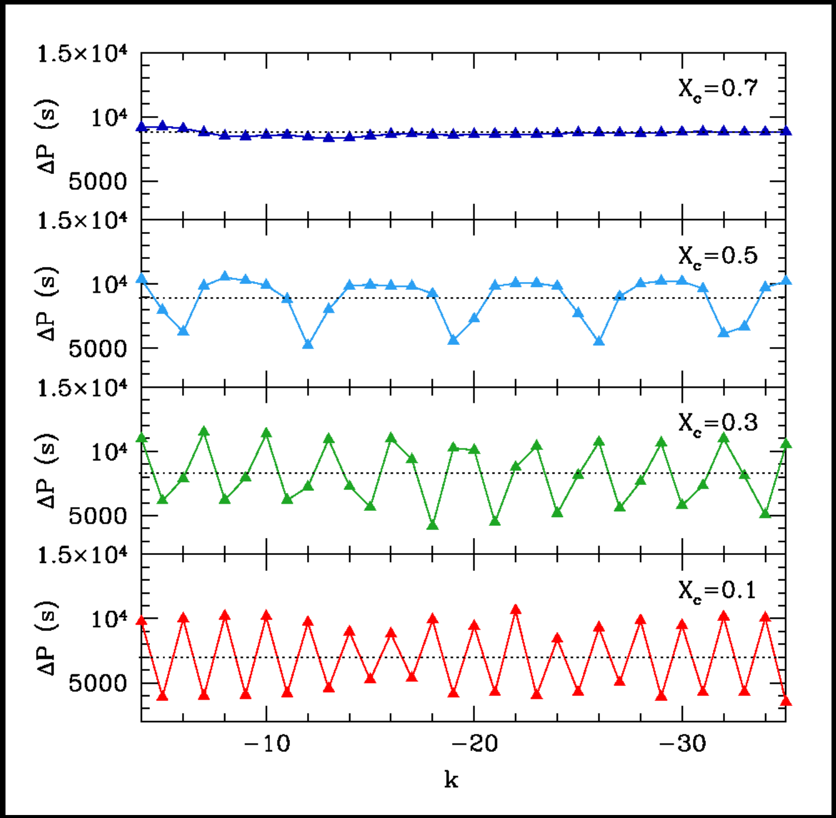
Is the extra mixing due to

- instantaneous overshooting
- diffusive overshooting
- rotational mixing ?

With a smoother sharp feature, the amplitude of the oscillation in period spacing is modulated by a factor $1/P_k$



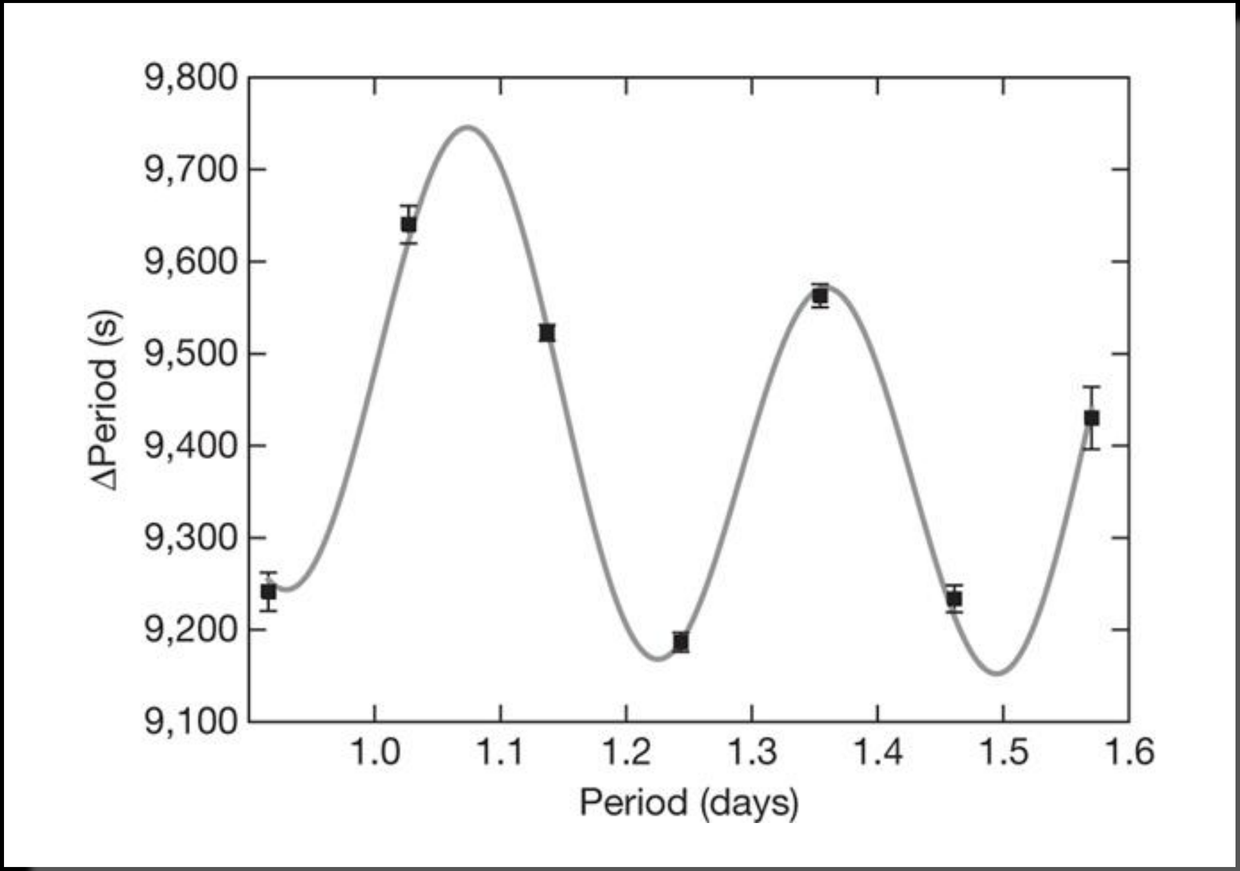




Miglio, Montalban, Noels & Eggenberger 2008

CoRoT target HD50230

First detection of an oscillatory component in the g-mode period spacing of an SPB star

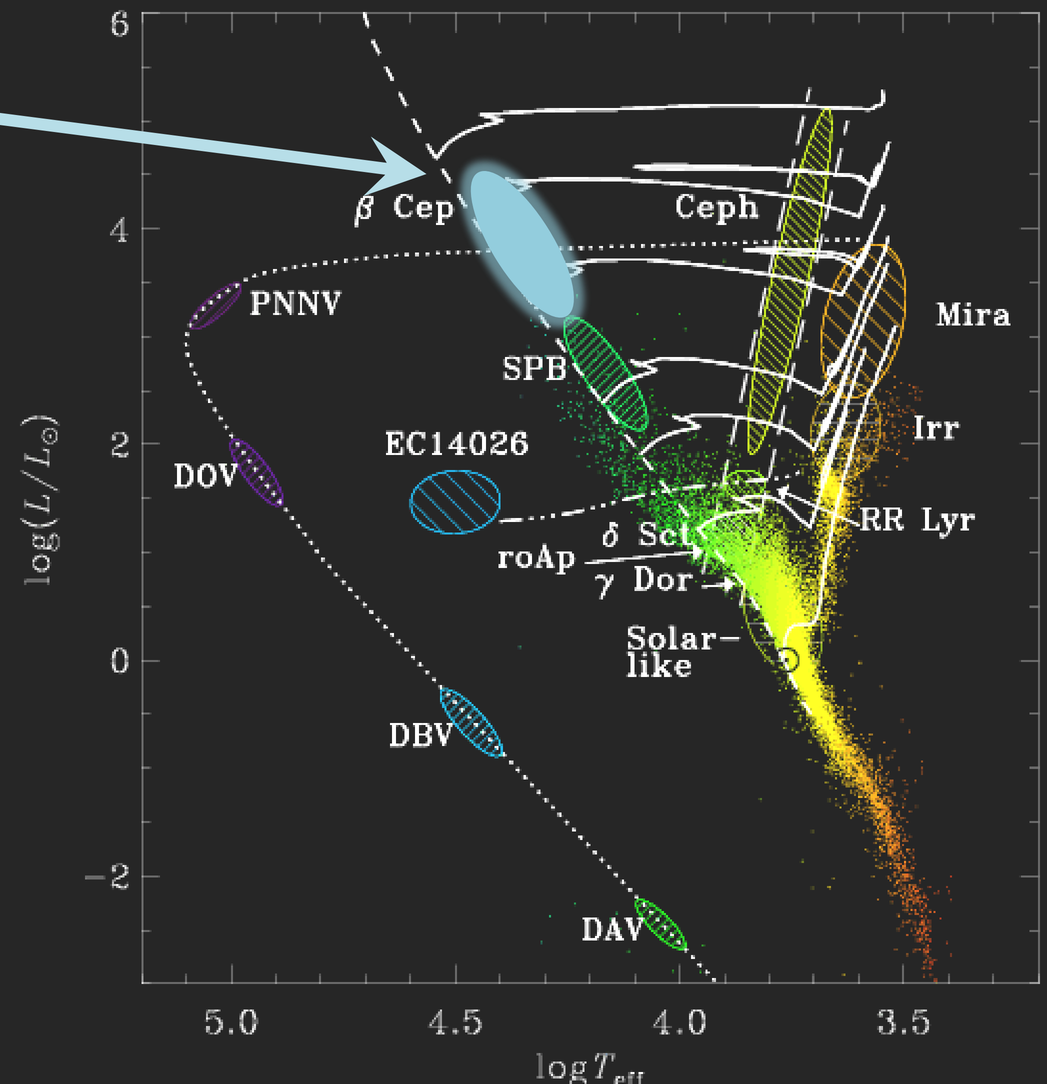


De Groote et al. 2009, Nature

5. β Cephei stars

κ-mechanism and stochastic excitation

β Cephei stars



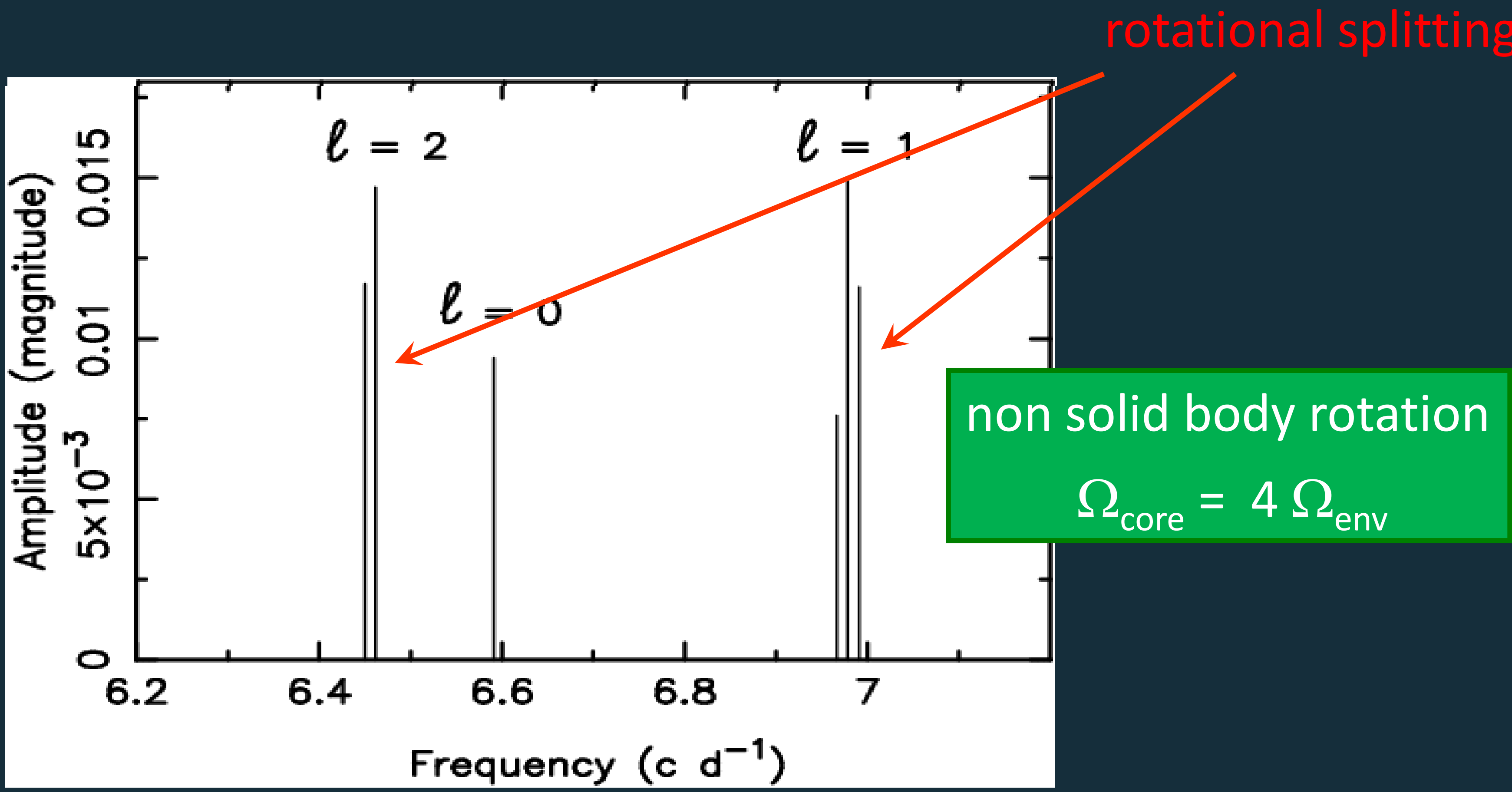
- *MS B stars 7-20 $M_\odot$ conv core/rad env*
- *mixed p-g modes periods : 3 – 8 h*

Physics tested

- *overshooting*
- *diffusion*
- *rotation*

Success

HD 129929 = V836 Cen
20 yr observations



non solid body rotation

$\Omega_{core} = 4\,\Omega_{env}$

Aerts et al. 2003, Science

Problems in our Galaxy

- Theoretical models are unable to excite high frequency modes
- Seismic fitting requires very large overshooting parameter

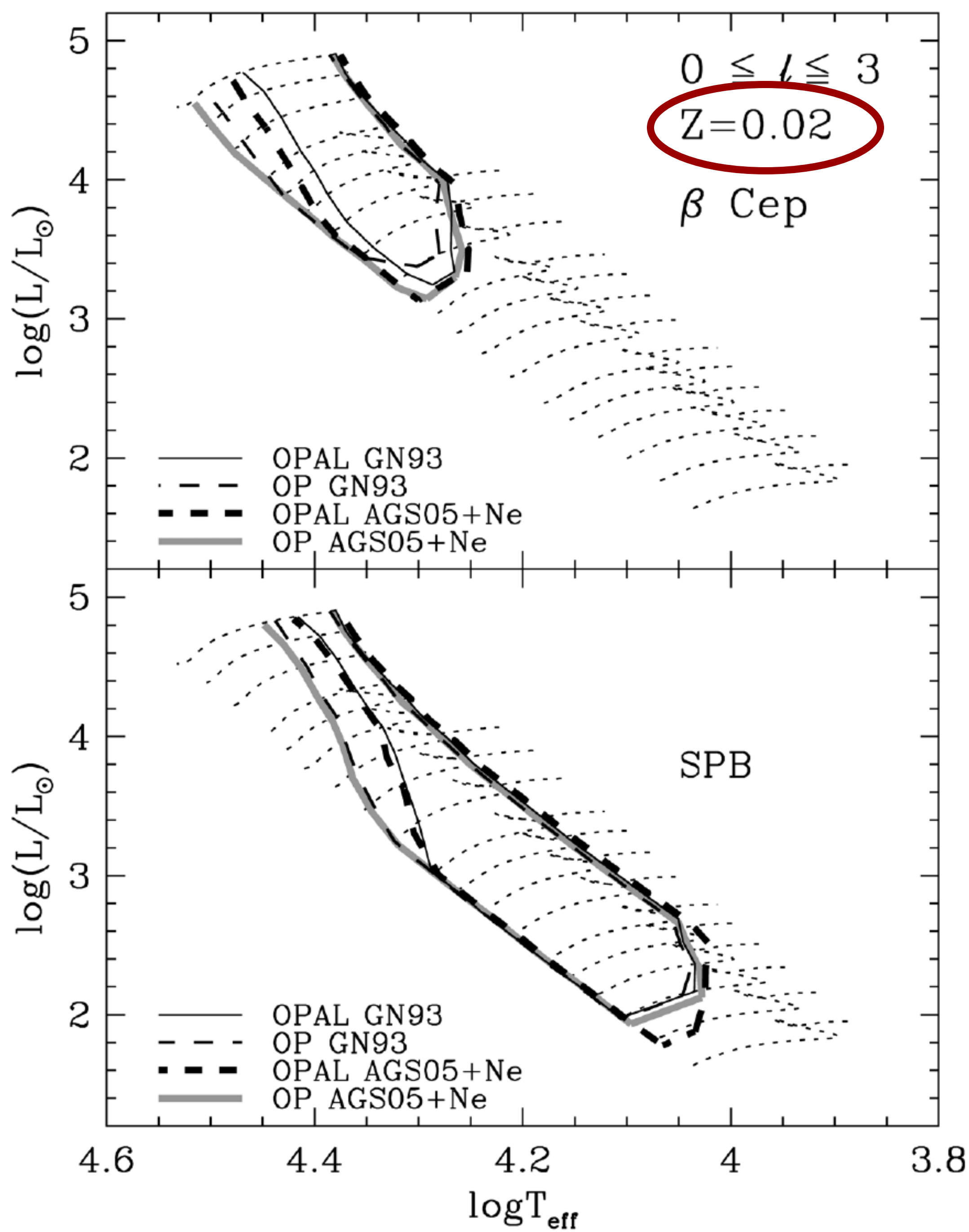
ν Eri → Handler et al. 2004, Aerts et al. 2004, De Ridder et al. 2004, Jerzykiewicz et al. 2005, Pamyatnykh et al. 2004

12 Lac → Handler et al. 2006, Desmet et al. 2007, Desmet et al. 2009, Ausseloos et al. 2005

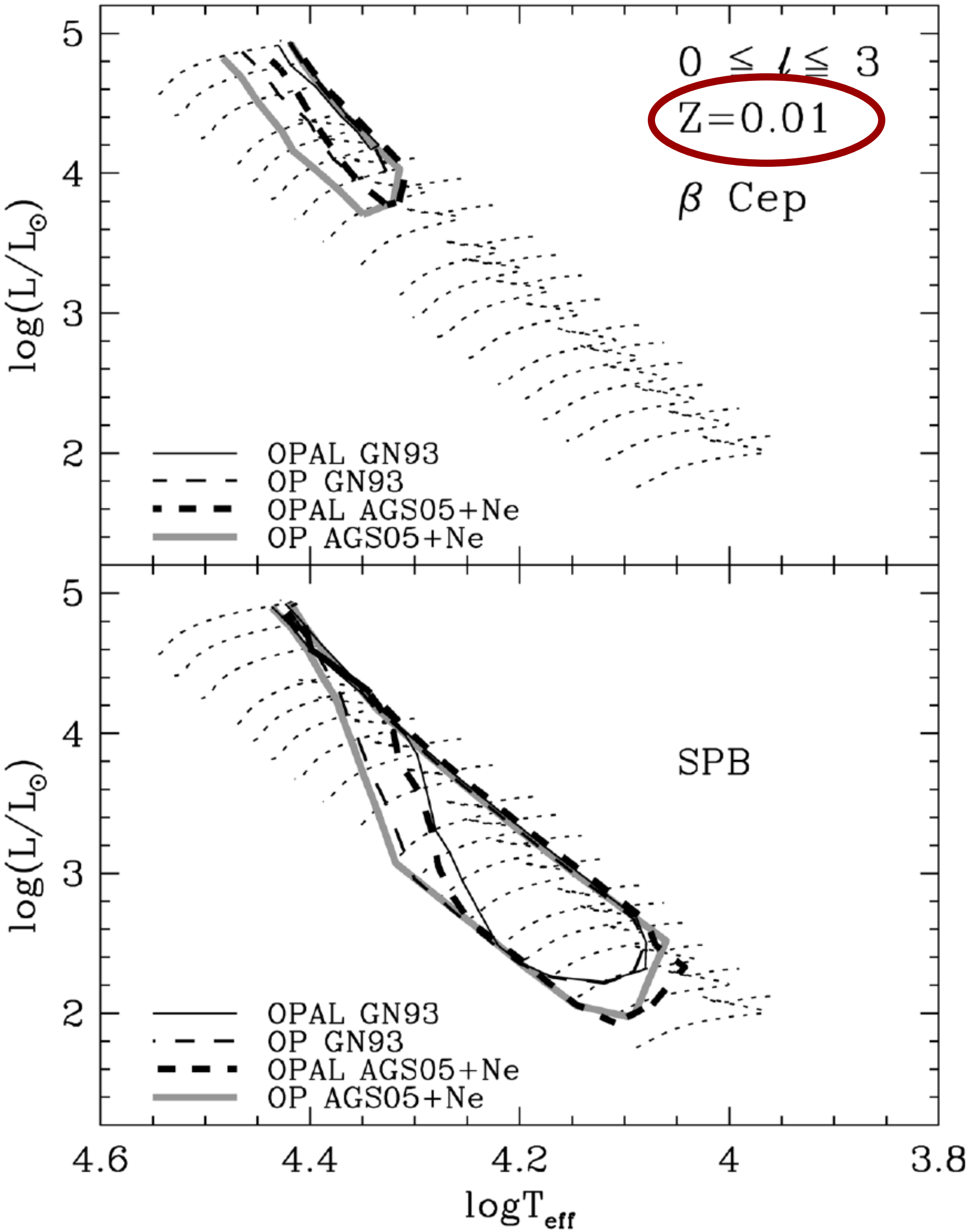
θ Oph → Handler et al. 2005, Briquet et al. 2005, Briquet et al. 2007, Daszkiewicz & Walczak 2009

SPB and β Cephei instability strips

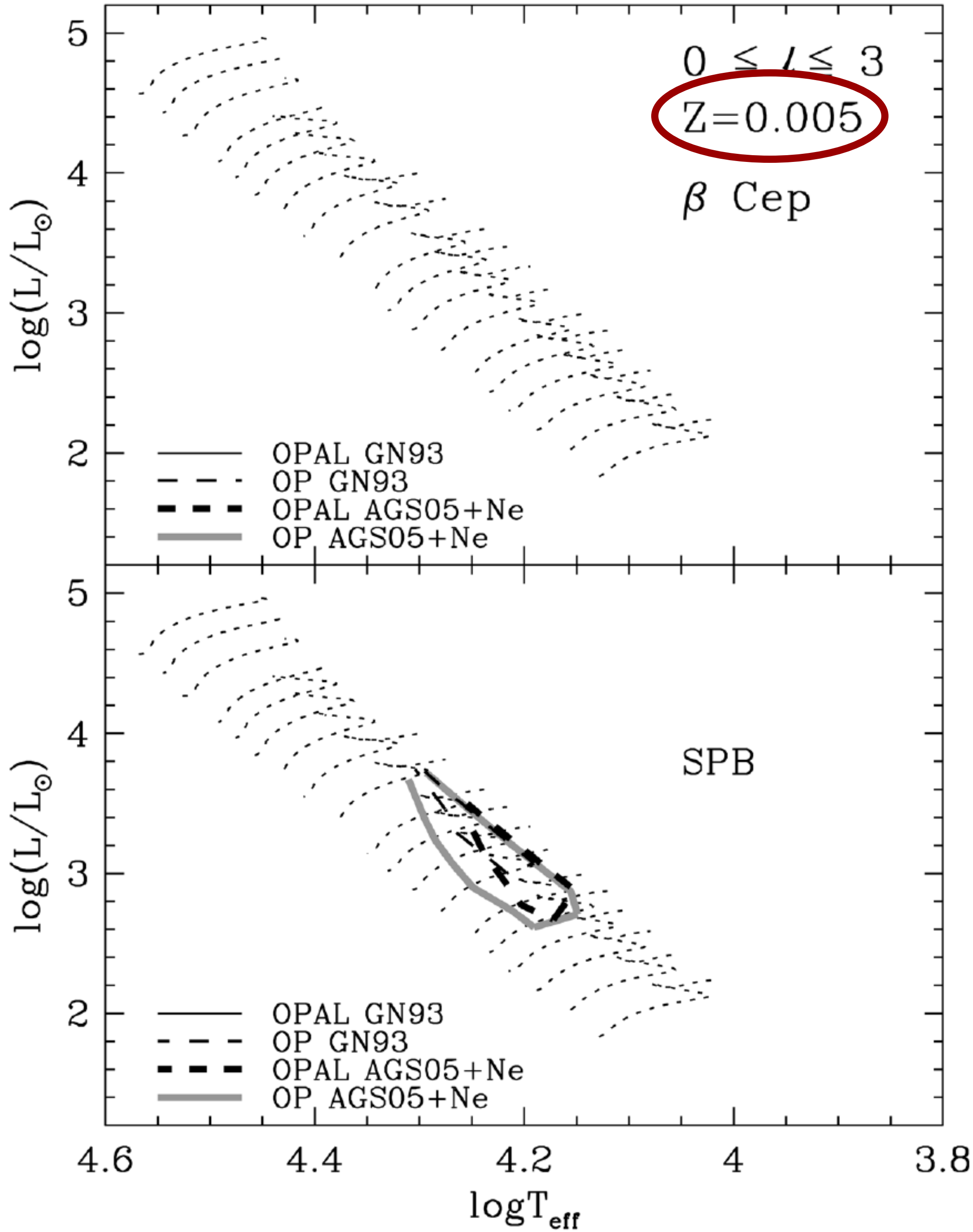
Strong influence of the metallicity



Miglio et al. 2007

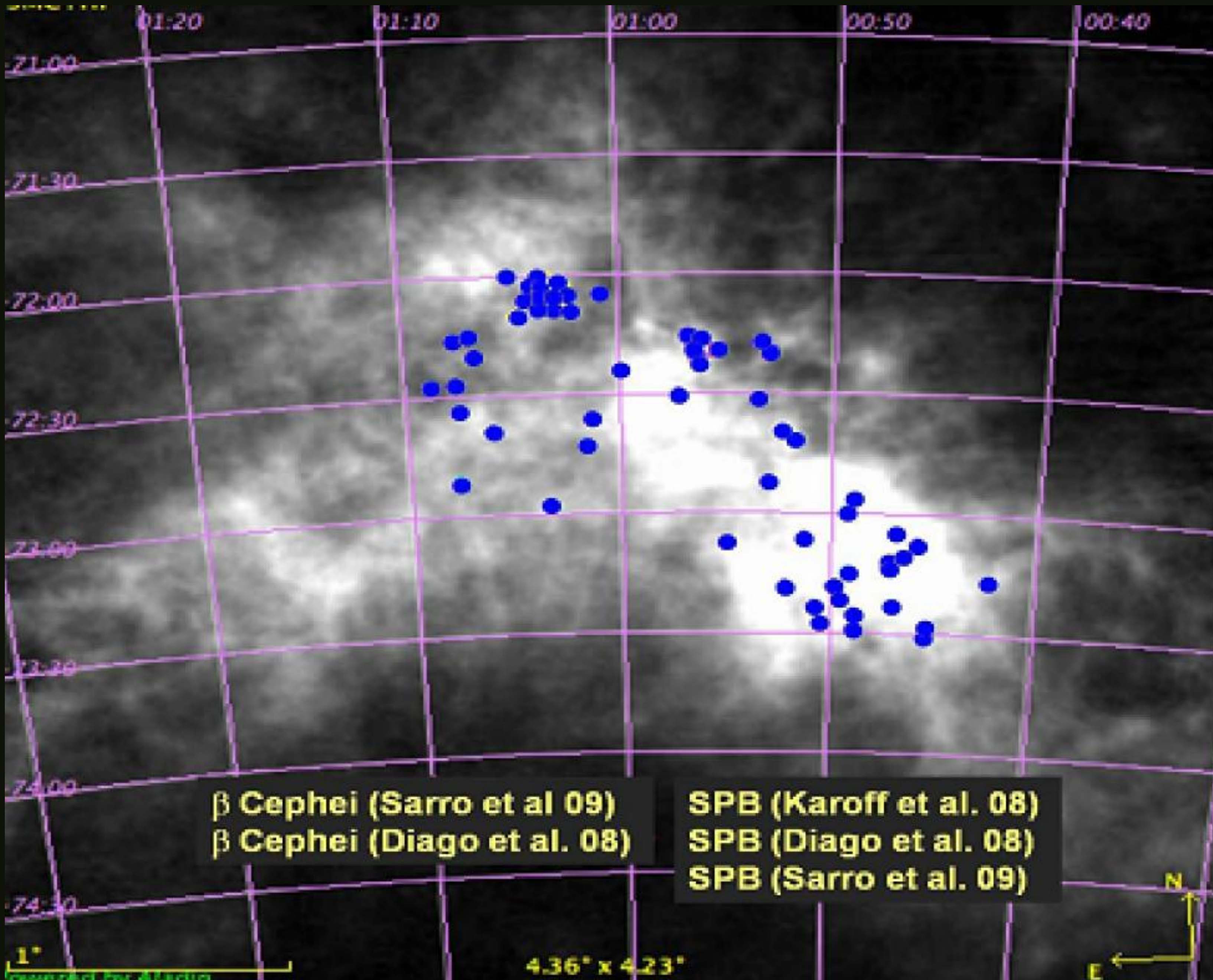


Miglio et al. 2007



Miglio et al. 2007

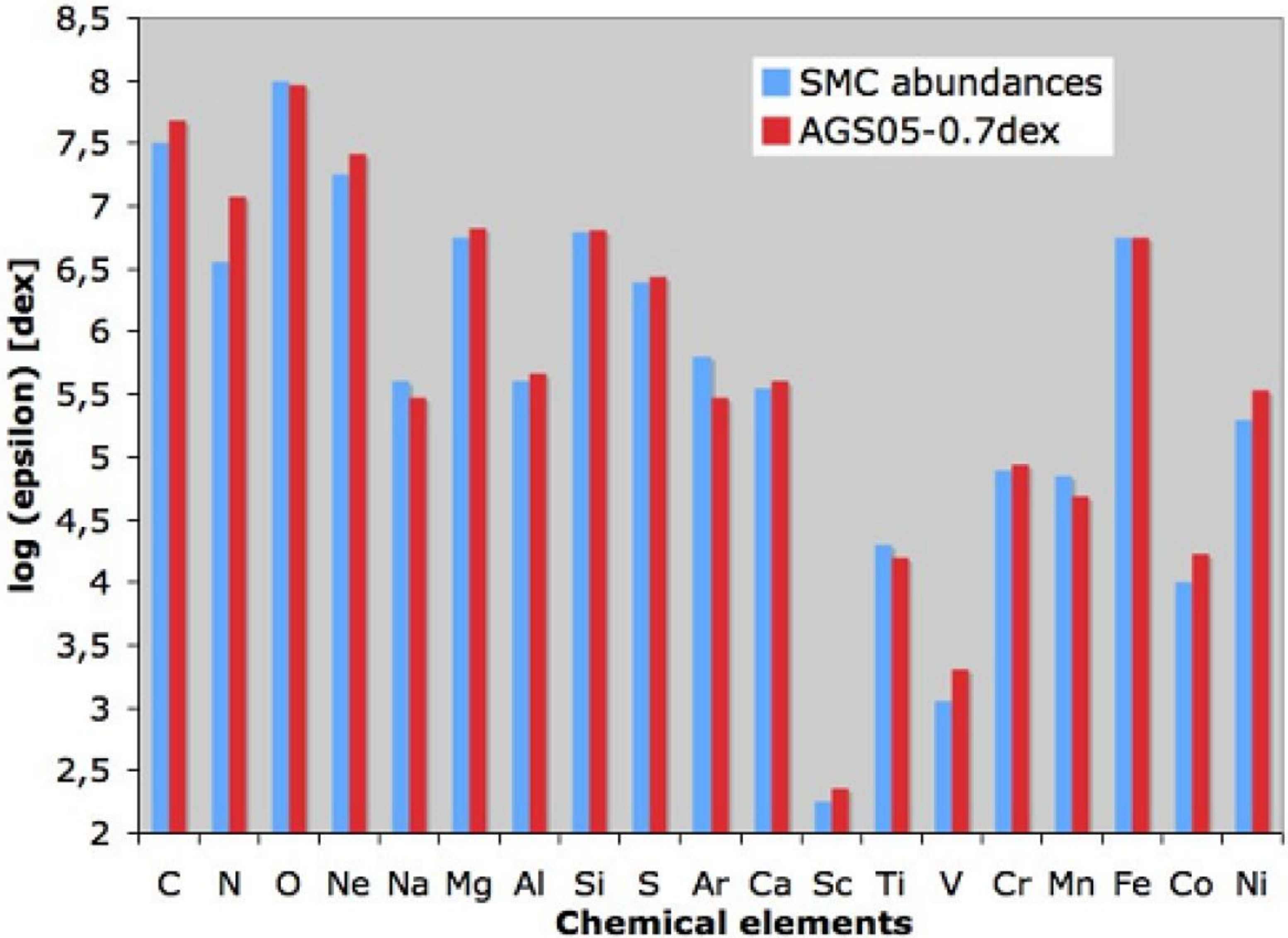
However, candidates SPB and β Cephei in the SMC - Z$\sim$ 0.0024



01:20
01:10
01:00
00:50
00:40
-71:00
-71:30
-72:00
-72:30
-74:00
β Cephei (Sarro et al 09)
β Cephei (Diago et al. 08)
SPB (Karoff et al. 08)
SPB (Diago et al. 08)
SPB (Sarro et al. 09)
N
E
1°
4.36° x 4.23°
owered by Aladin

Possible solutions

- High metallicity in SMC β Cep stars
- Accumulation of iron in the opacity bump at $2.\ 10^5$ K
- Physics: underestimation of the opacity


SMC abundances
AGS05-0.7dex
log (epsilon) [dex]
8,5
8
7,5
7
6,5
6
5,5
5
4,5
4
3,5
3
2,5
2
C N O Ne Na Mg Al Si S Ar Ca Sc Ti V Cr Mn Fe Co Ni
Chemical elements

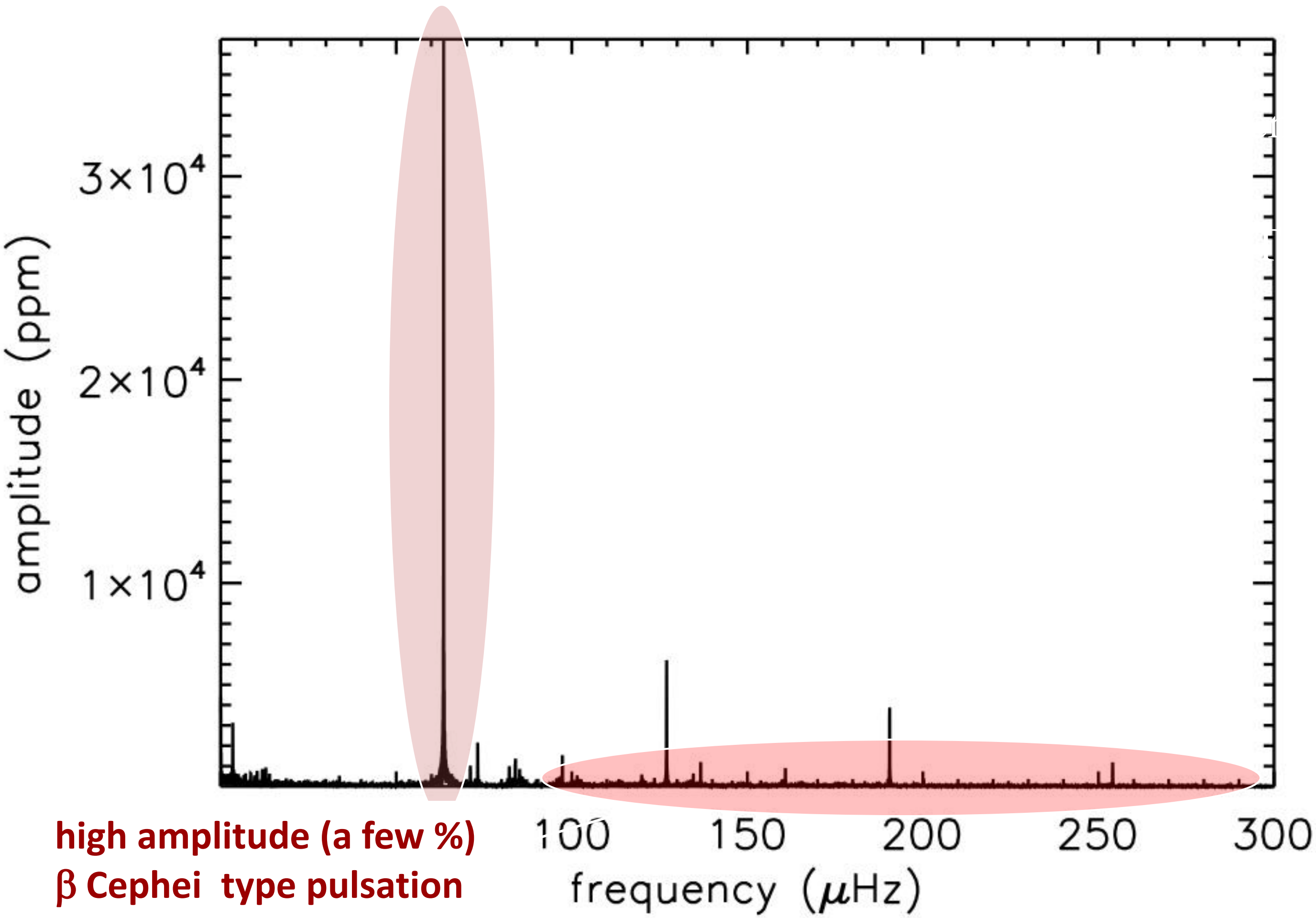
Morel, 2009

Another success

β Cephei HD 180642

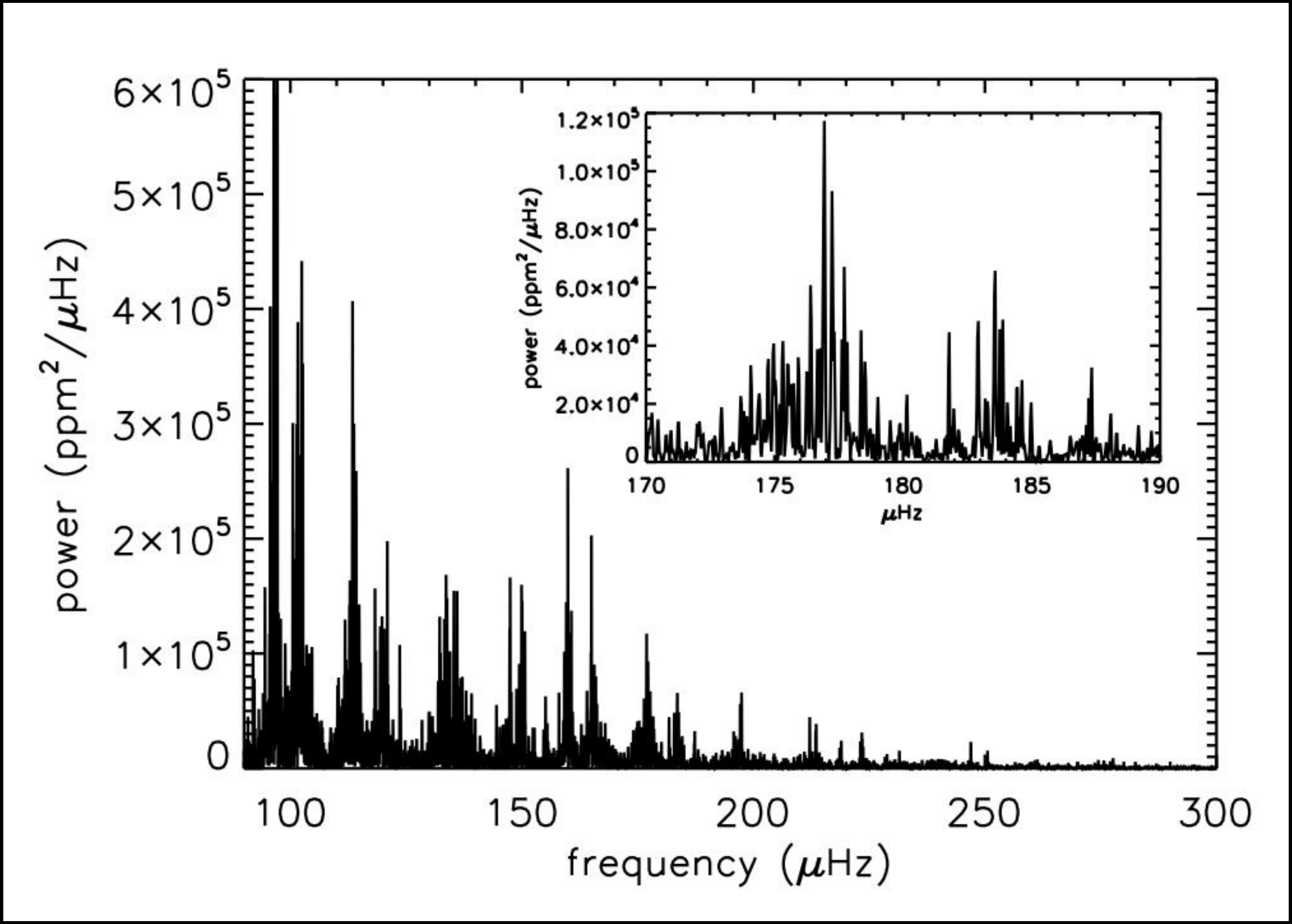
La Chimère d'Arezzo, bronze étrusque

a chimera …



amplitude (ppm)
3×10⁴
2×10⁴
1×10⁴
100
150
200
250
300
frequency (μHz)
high amplitude (a few %)
β Cephei type pulsation

Solar-like oscillations $\nu \sim$ 100-300 μHz



Belkacem et al. 2009, Science

6. B supergiants

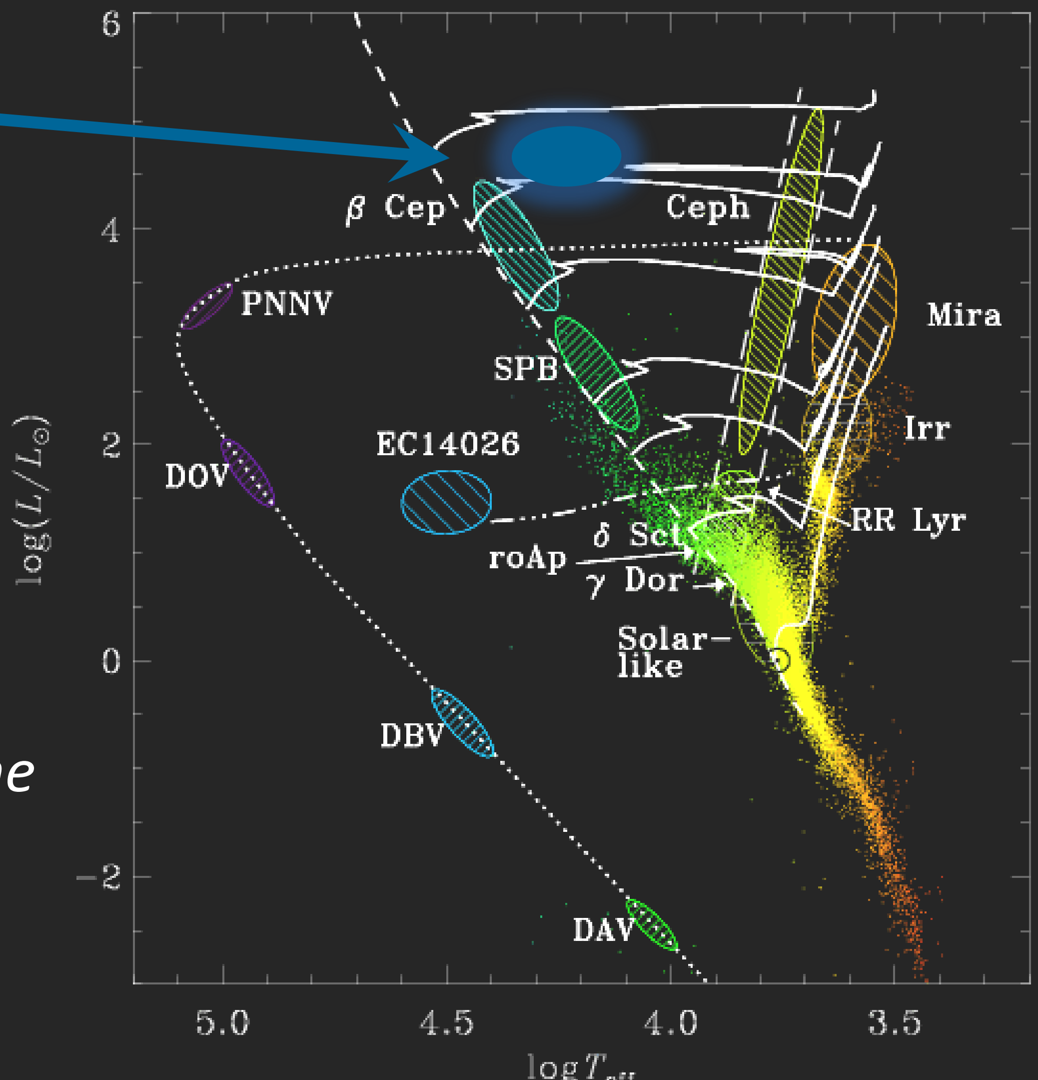
κ-mechanism in the « iron » bump

B supergiants

- *post MS massive stars*
- *p and g modes*

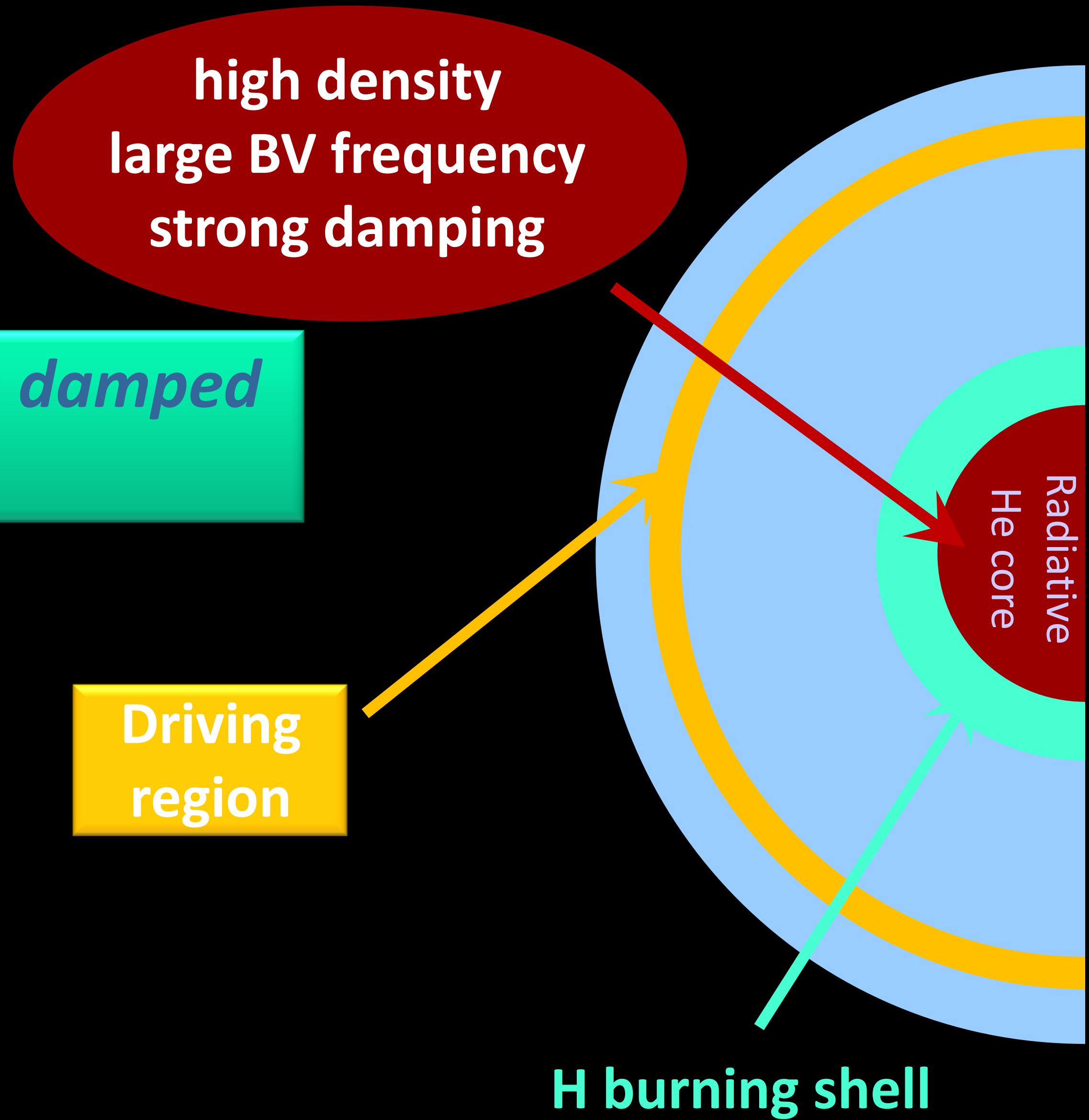
Physics tested

- *intermediate convection zone*
- *mass loss*
- *overshooting*



Supergiant internal structure

most g-modes are damped in a post MS star



- κ-mechanism

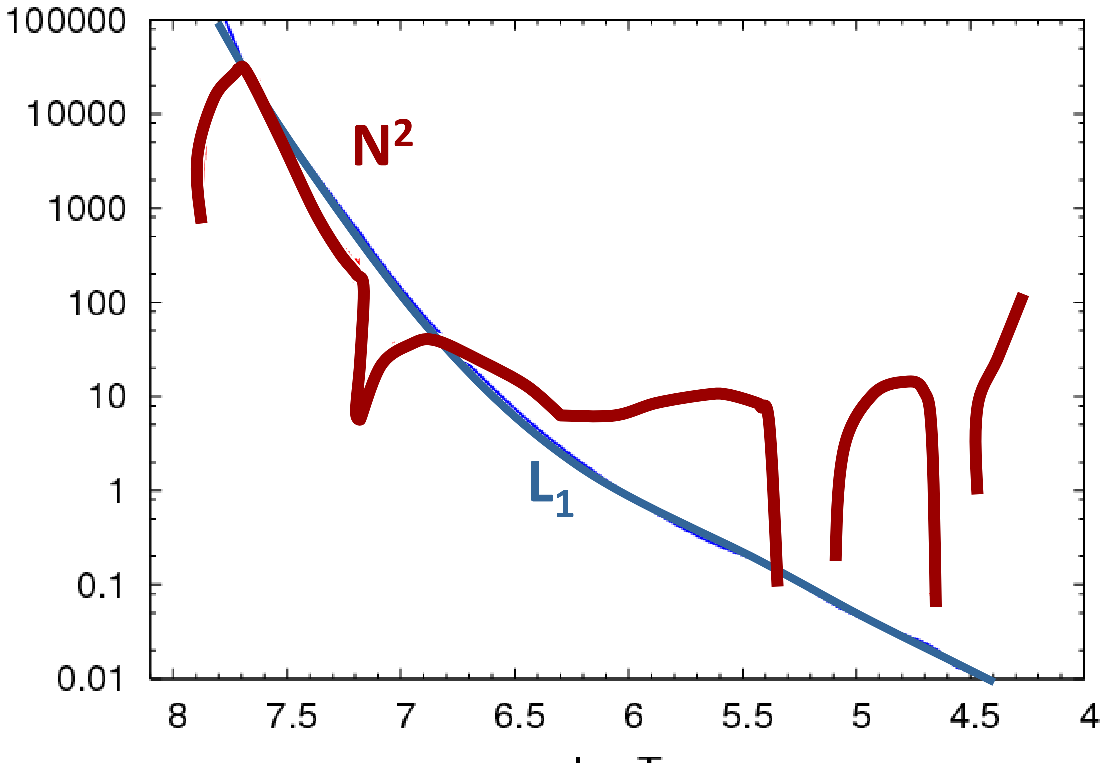
Saio et al. 2006

Radiative damping

After core H-burning, ρ becomes very large in the contracting He core

→ N^2 (÷ρ) >>>

→ $k(r) \simeq \sqrt{\ell(\ell+1)}\, N/(\sigma r)$ >>>

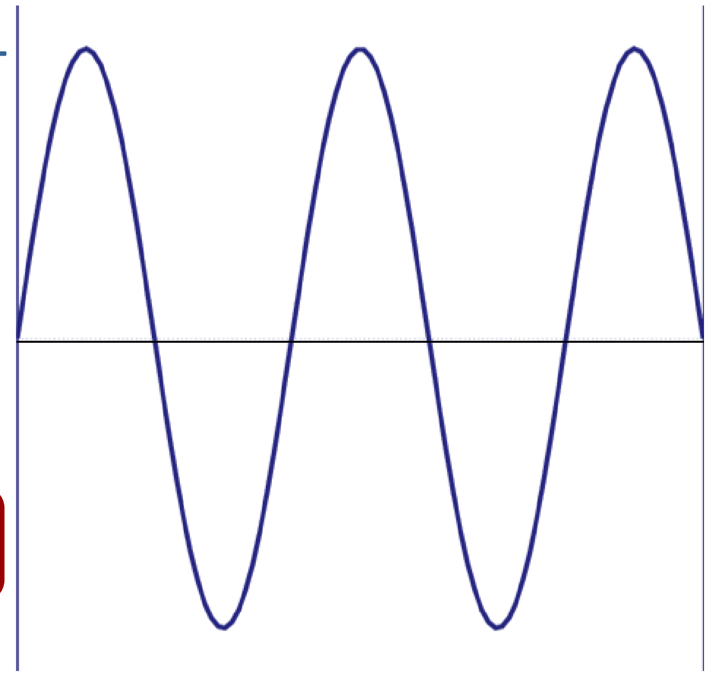


→ k >> → large number of spatial oscillations in the core

Radiative damping

- k >> → large number of spatial oscillations in the core
- k >> → large variations of the temperature gradient

$\delta T/T = A \sin(kr+\varphi)$



most g-modes are damped in a post MS star

$\delta L/L = Ak \cos(kr+\varphi)\, dr/d\ln T$

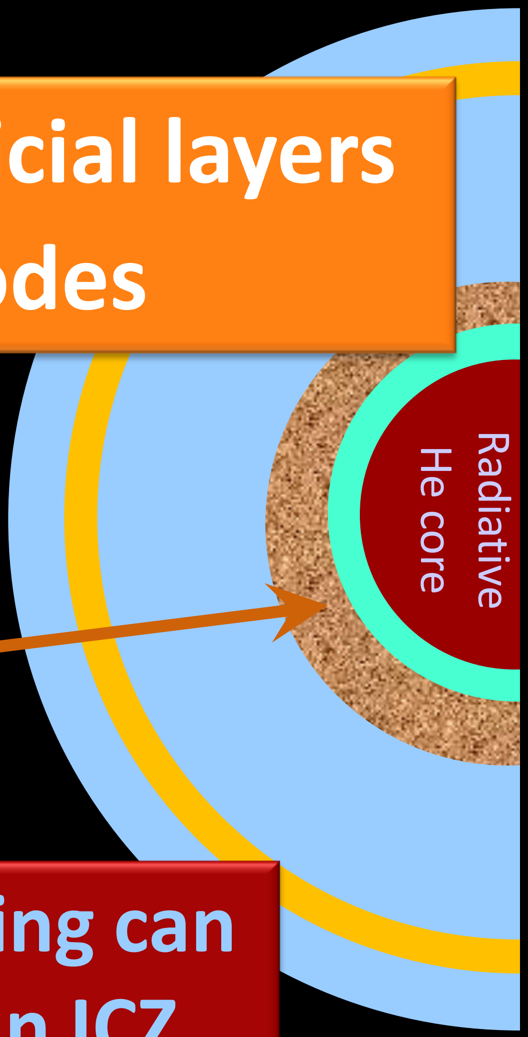
$d\delta L/dm = - L\, Ak^2 \sin(kr+\varphi)\, dr/d\ln T$

$$\frac{dW}{dr} = -\frac{1}{2}\frac{\delta T}{T}\frac{d\delta L}{dr} \approx \frac{1}{2} A^2 k^2 \sin^2(kr+\varphi) L \frac{dr}{d\ln T} < 0$$

→ ***strong damping***

Supergiant internal structure

The κ-mechanism in the superficial layers is sufficient to excite some g-modes



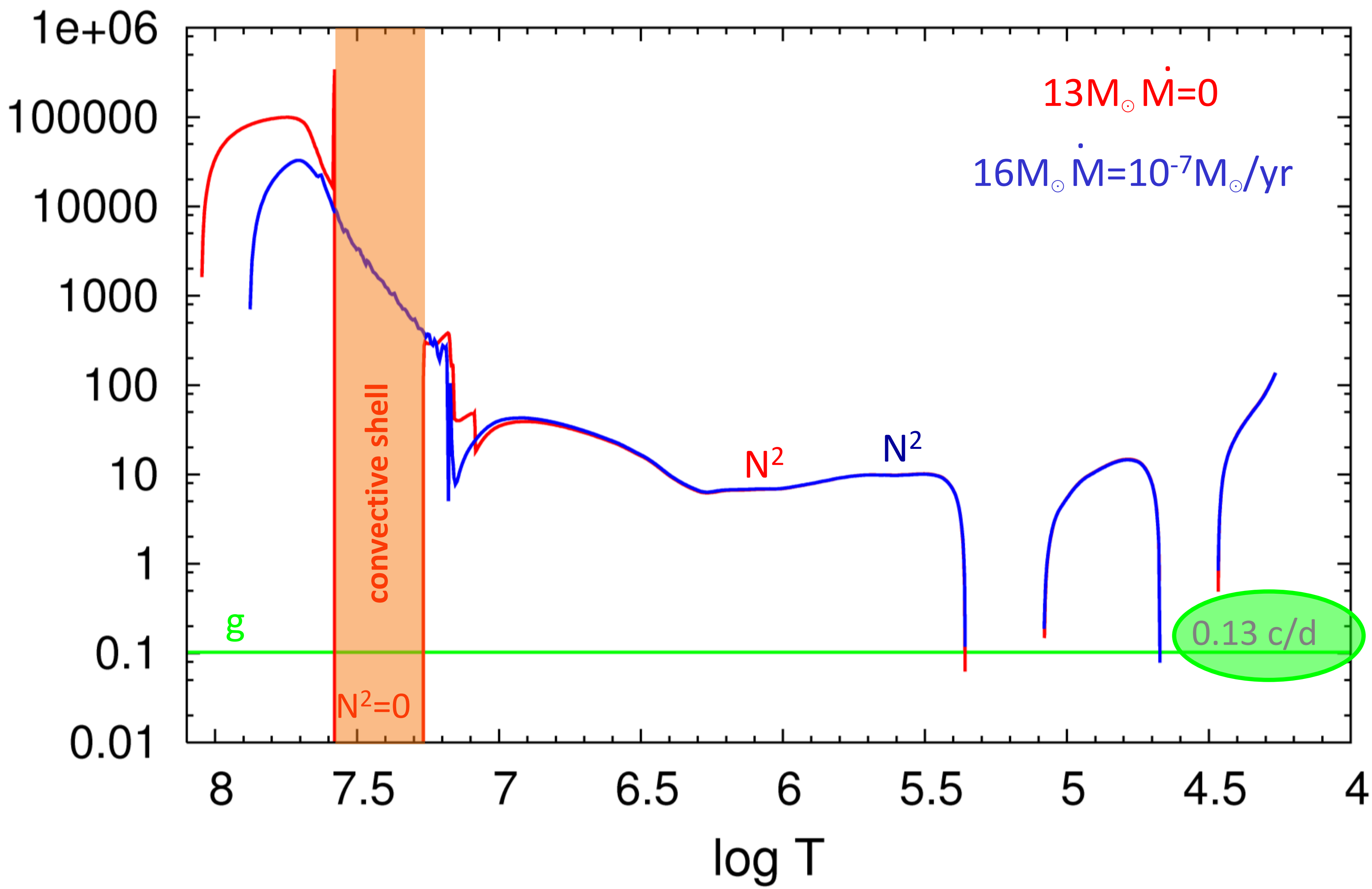
But…

An intermediate convective zone (ICZ) can prevent some g-modes from entering the radiative core

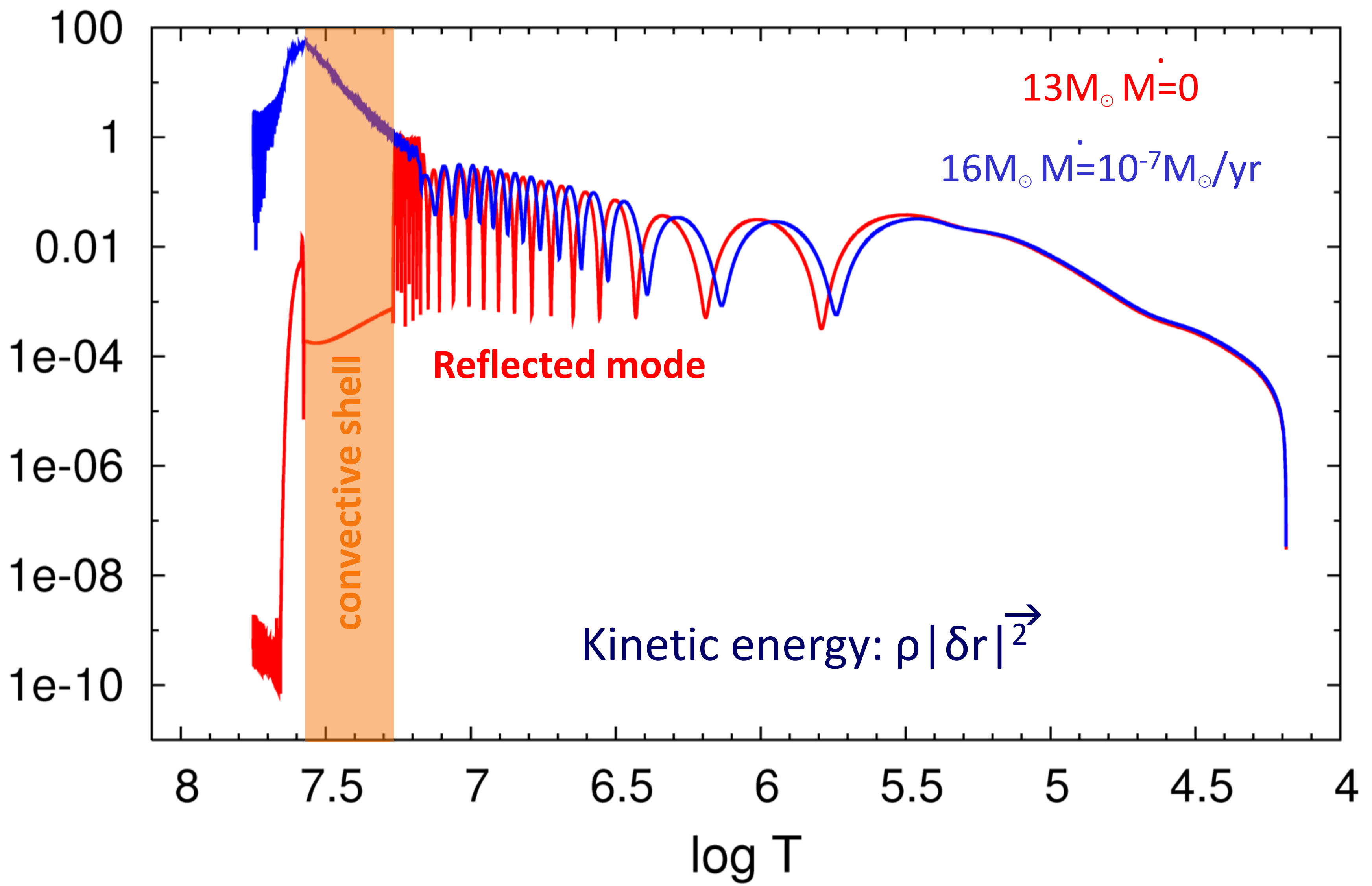
Mass loss and/or overshooting can prevent the appearance of an ICZ

Saio et al. 2006

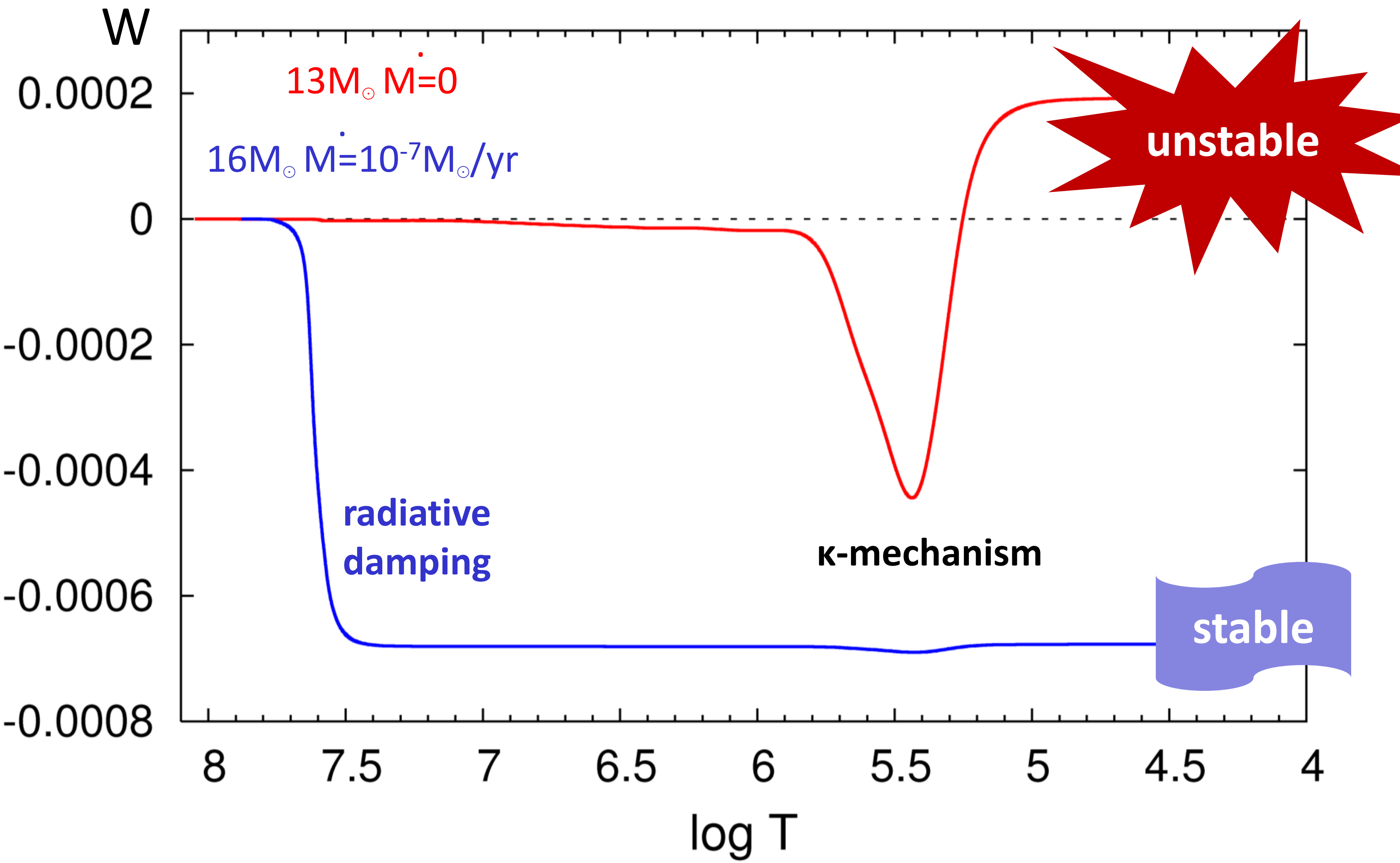
see G. Meynet 's lectures



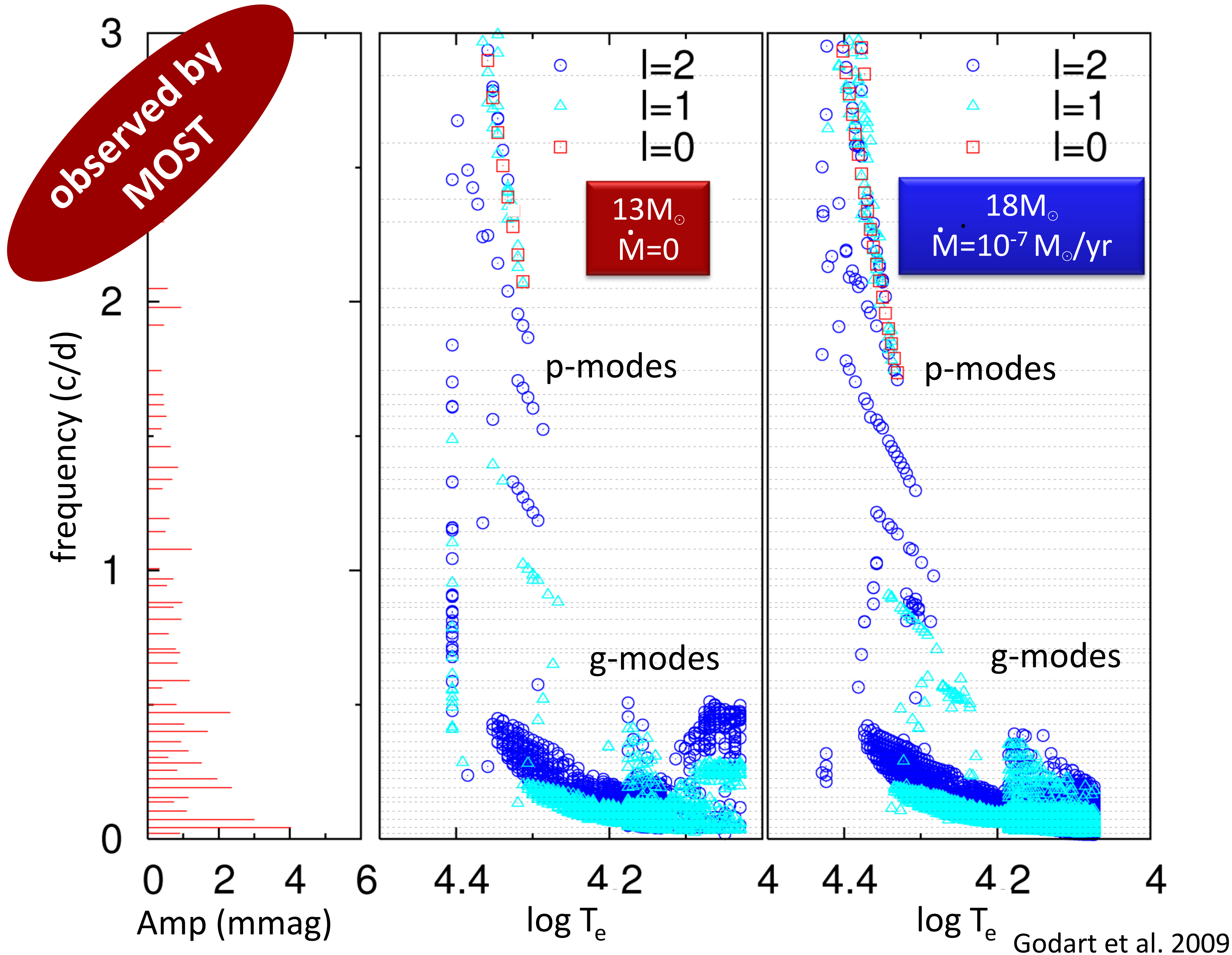
Godart et al. 2009



Godart et al. 2009



Godart et al. 2009



observed by MOST
frequency (c/d)
Amp (mmag)
log T_e
l=2
l=1
l=0
$13M_\odot$
$\dot{M}=0$
$18M_\odot$
$\dot{M}=10^{-7}\,M_\odot/yr$
p-modes
g-modes
0
1
2
3
0
2
4
6
4.4
4.2
4
Godart et al. 2009

7. O stars

stochastic and strange mode excitation

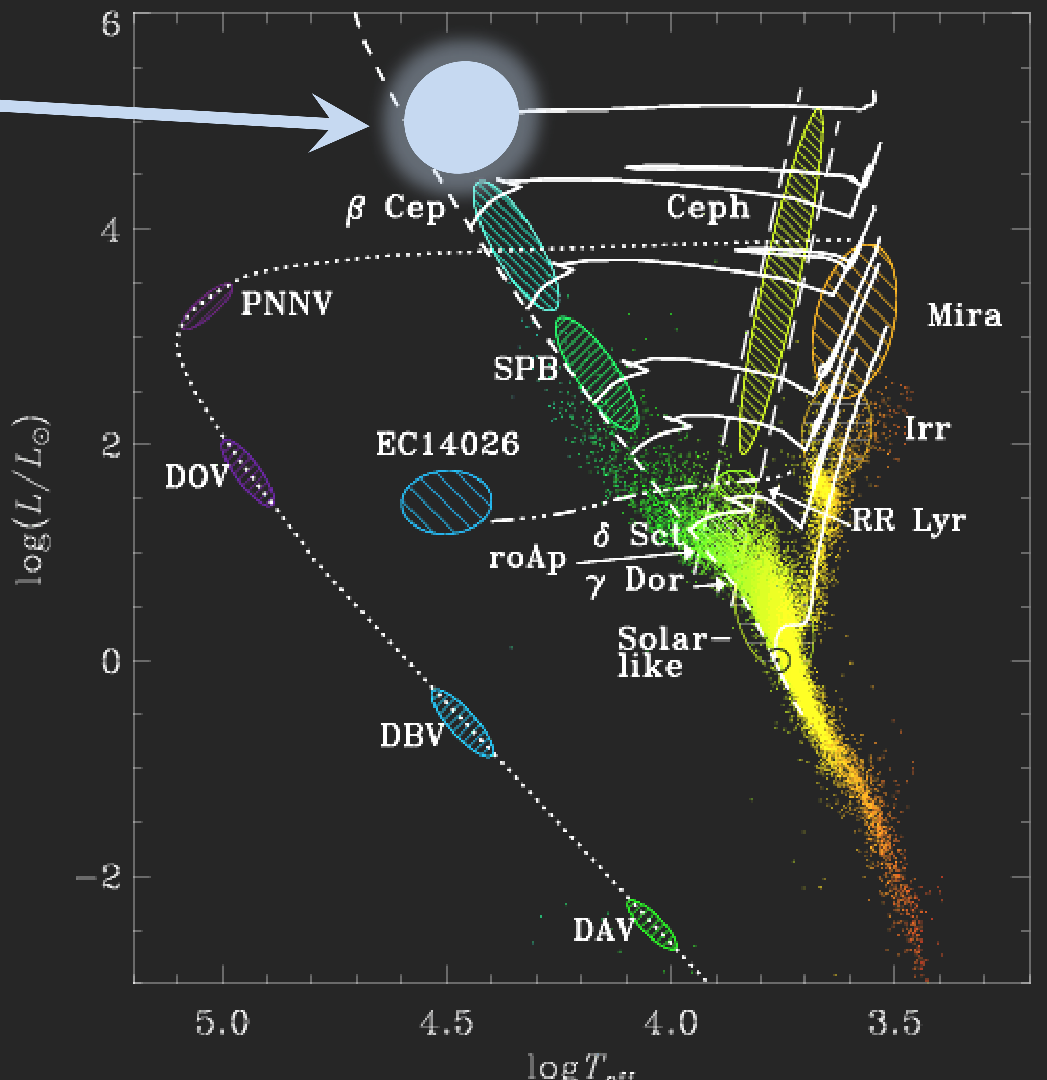
O stars

- *MS and post MS very massive stars*

- *solar like oscillations*
- *strange modes ???*

Physics tested

- *radiation pressure*
- *mass loss*



A CoRoT O star HD 46149

Binary system composed of

- a primary O8.5 V star (Mv= 7.6, vsini = 79km/s)
- a suspected hot B type companion

Mahy et al. 2009

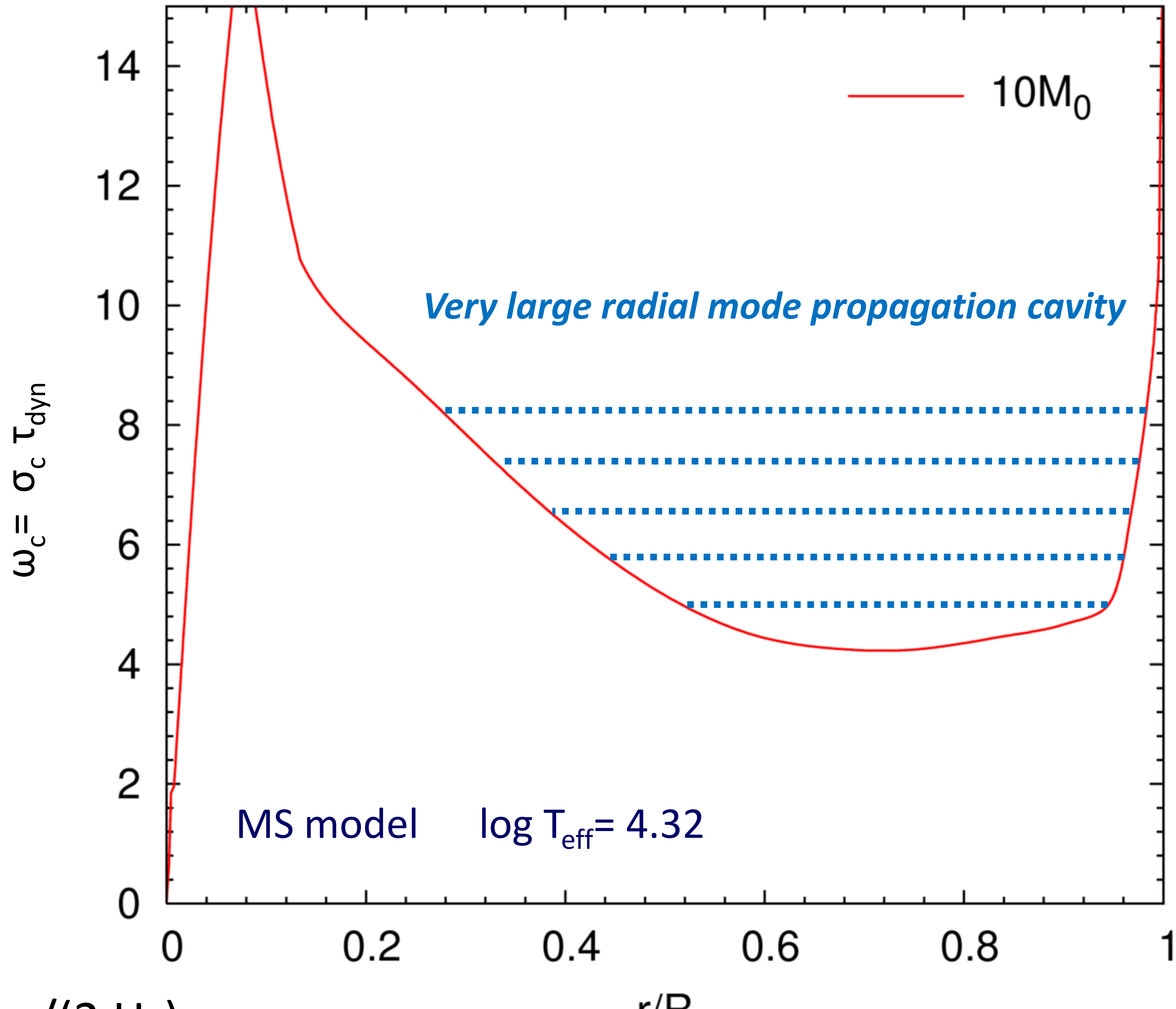
- CoRoT lightcurve : signature of low order p-modes
- **frequency spacing = $\Delta\nu_0/2$**

solar-like oscillations

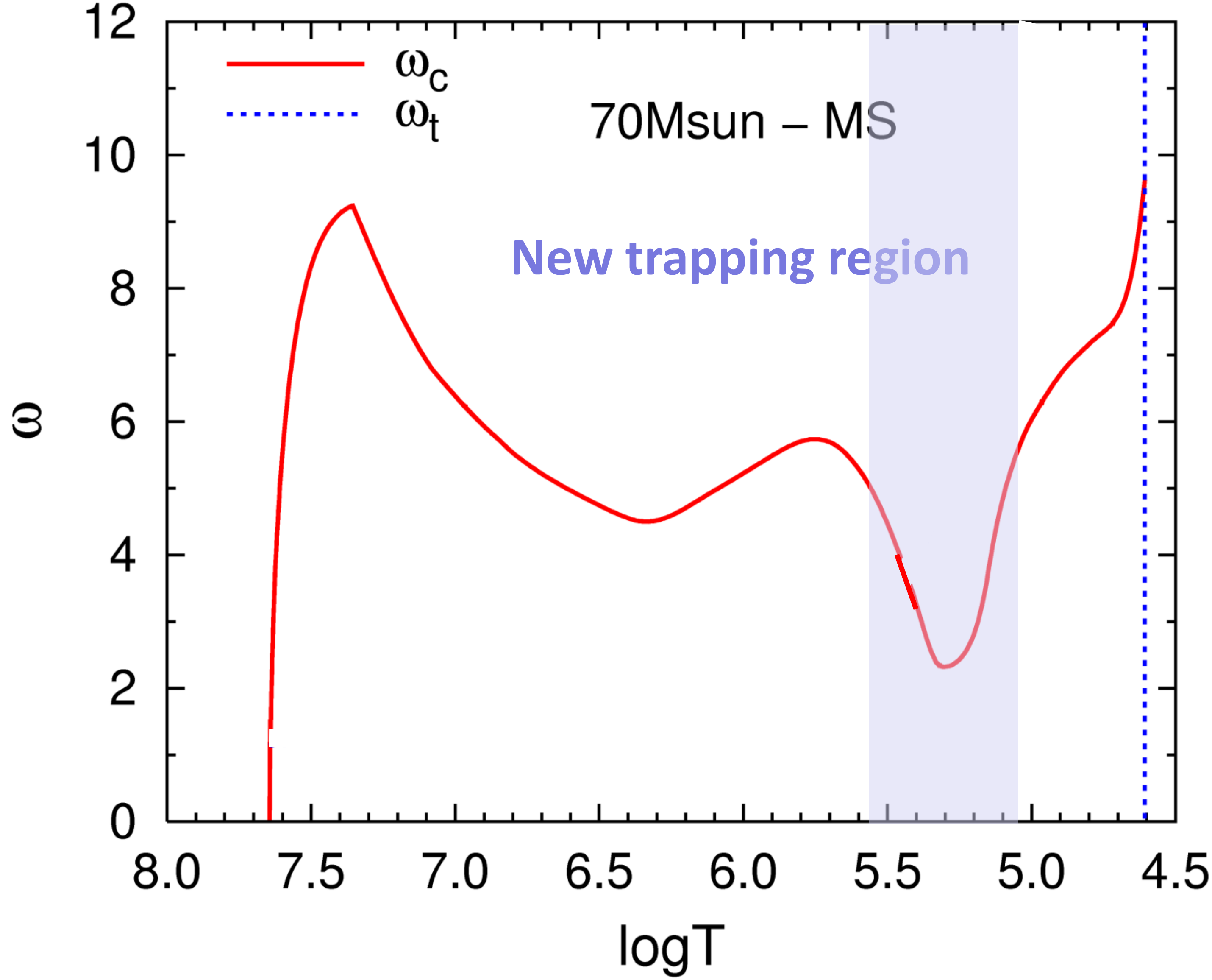
Degroote et al. 2009

Strange modes

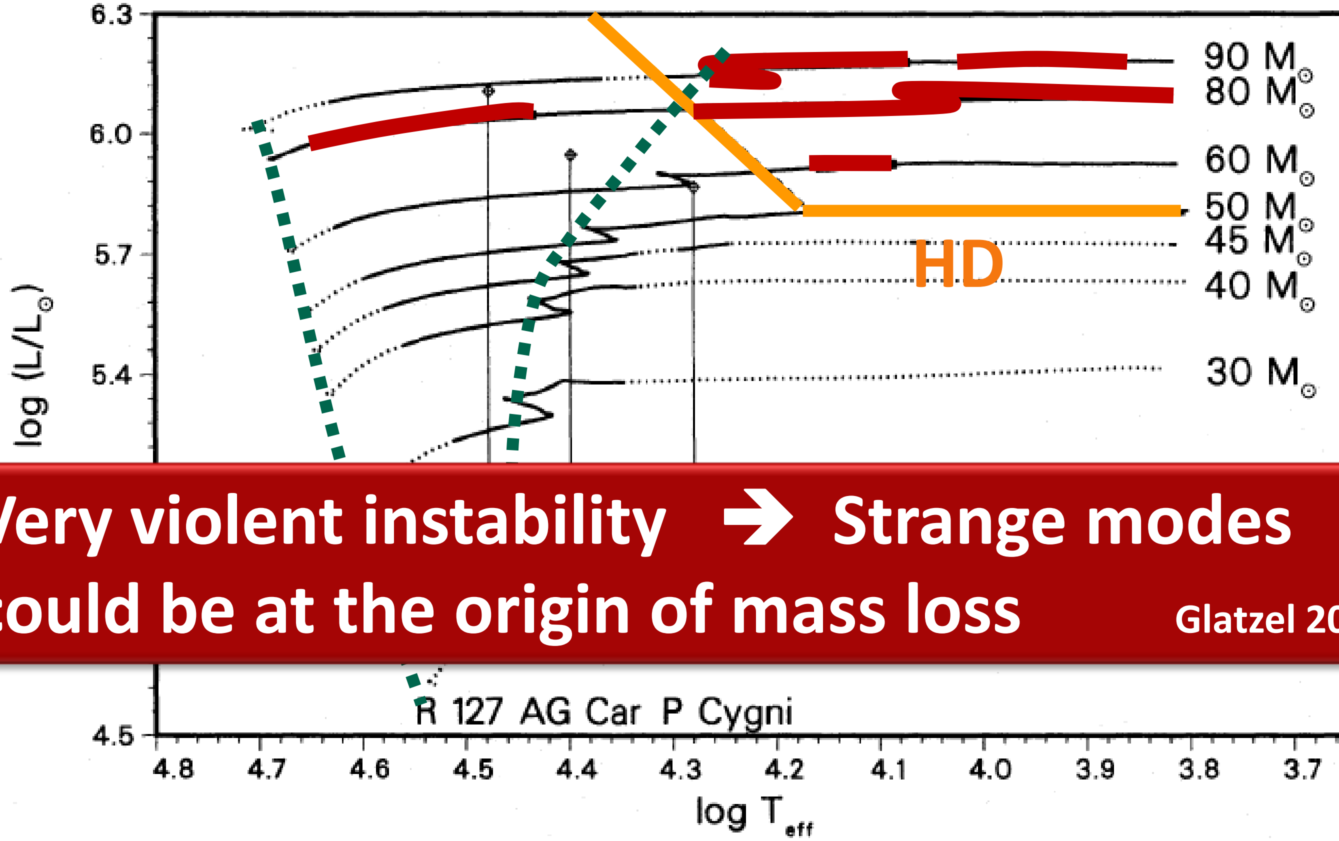
Wood 1976
Shibahashi and Osaki 1981
Glatzel, Kiriakidis 1993
Kiriakidis, et al. 1993
Saio et al. 1998



$\sigma_c \sim c\,/(2\,H_P)$



ω_c
ω_t
70Msun – MS
New trapping region
ω
logT
12
10
8
6
4
2
0
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5



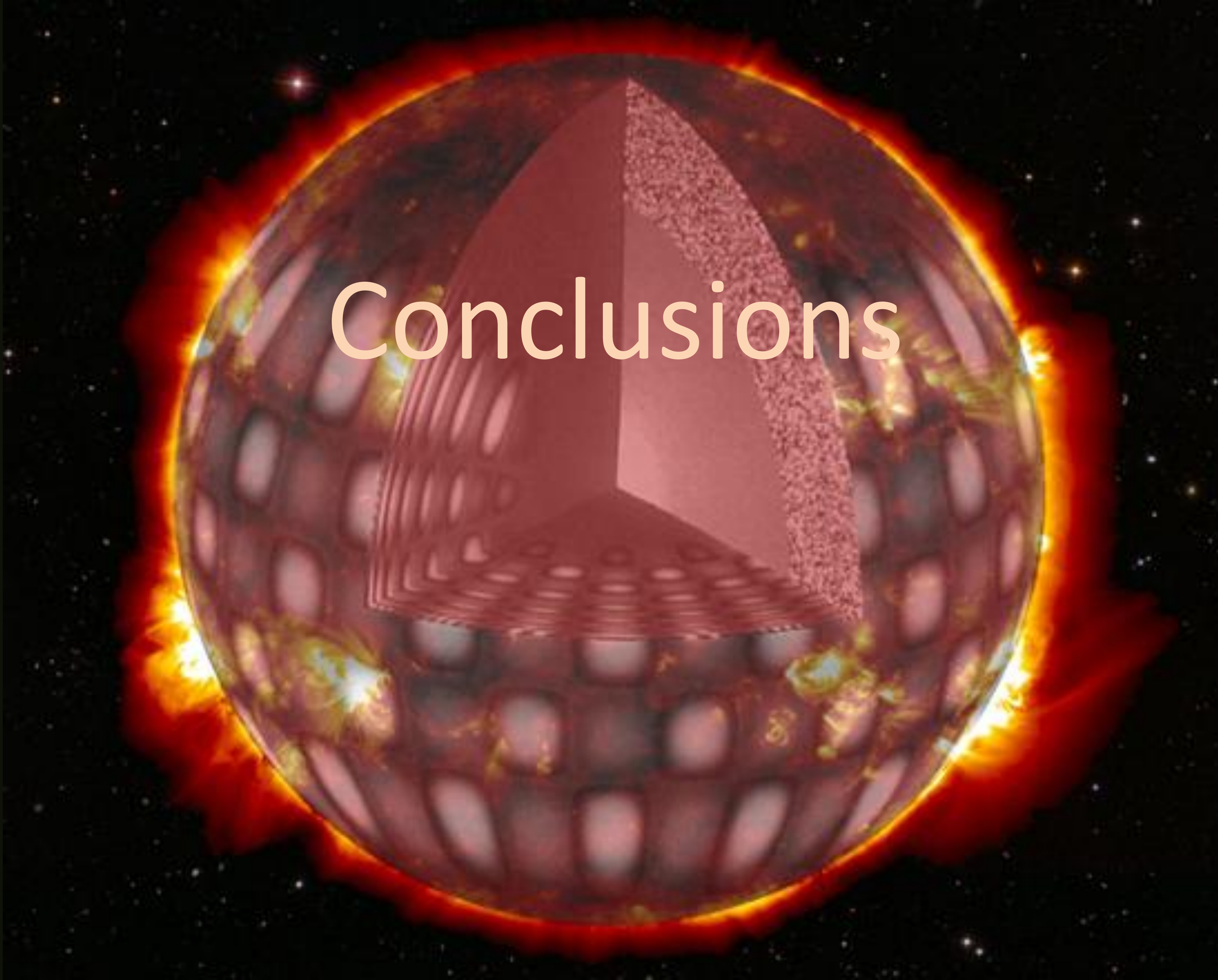
Very violent instability → Strange modes could be at the origin of mass loss Glatzel 2009

CoRoT stars HD50064 : a strange mode candidate

(Aerts et al. 2010)

Kiriakidis, Fricke, Glatzel 1993

Conclusions



- Asteroseismology is indeed a tool to unveil stellar interiors
- Much more to be learned with MOST, CoRoT, KEPLER, PLATO and SONG

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