UNIVERSITY OF
BIRMINGHAM

BASICS OF ASTEROSEISMOLOGY

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and

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OUTLINE

A Adiabatic perturbations of a static, smooth, spherical star: pressure, gravity, and mixed modes

oscillation spectrum of a 1 M_{sun} star

B seismic observables: going beyond scaling relations

$\Delta\nu$, ΔP

individual mode frequencies

moving away from A: sharp structure variations

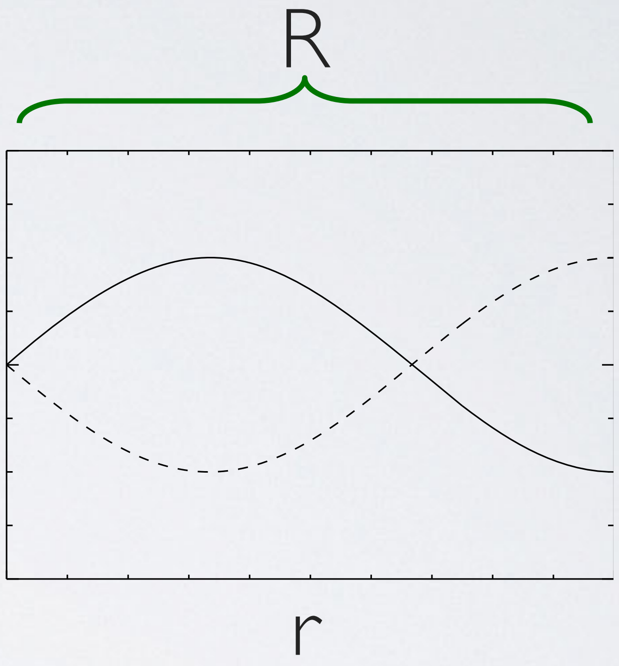
C summary & caveats

ASTEROSEISMOLOGY

analogy to a simple case: oscillations in an organ pipe

1-D acoustic wave equation

$$\frac{d^2 P'}{dr^2} + \frac{\sigma^2}{c^2} P' = 0 \qquad c^2 = \gamma_1 \frac{P}{\rho}$$

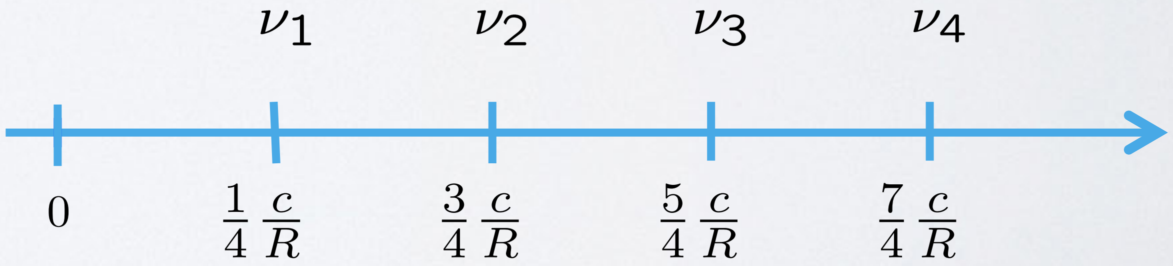


- boundary conditions
- c uniform

$$P'(r,t) = A \sin(\sigma t) \cos(\sigma r / c)$$

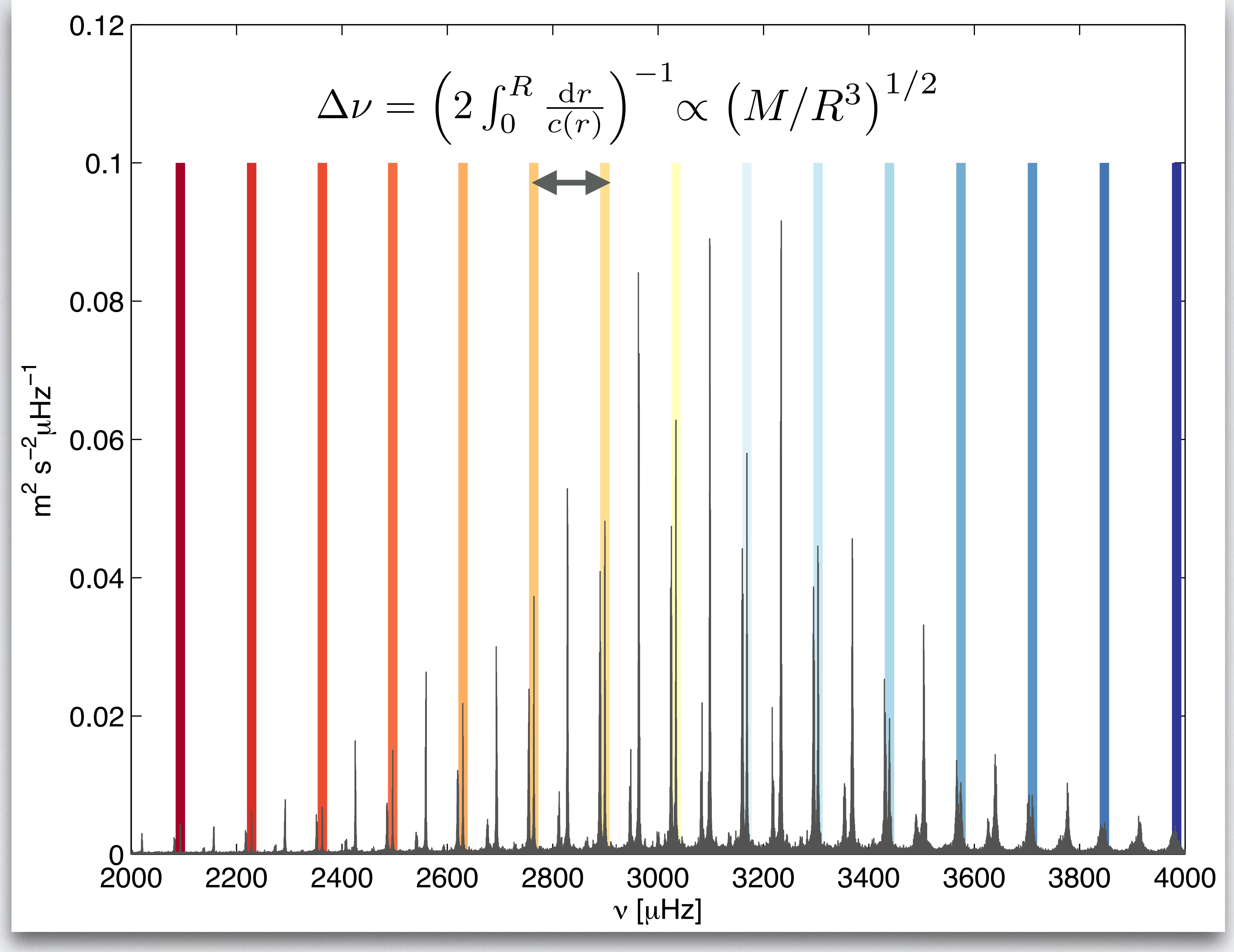
$$\nu = \frac{\sigma}{2\pi} = (n + 1/2) \frac{c}{2R} = (n + 1/2)(2t_{\rm ac})^{-1}$$

Harmonic frequencies



$$\boxed{\Delta\nu = \nu_n - \nu_{n-1} = 1/2 \ \frac{c}{R}}$$

SOLAR FREQUENCY SPECTRUM

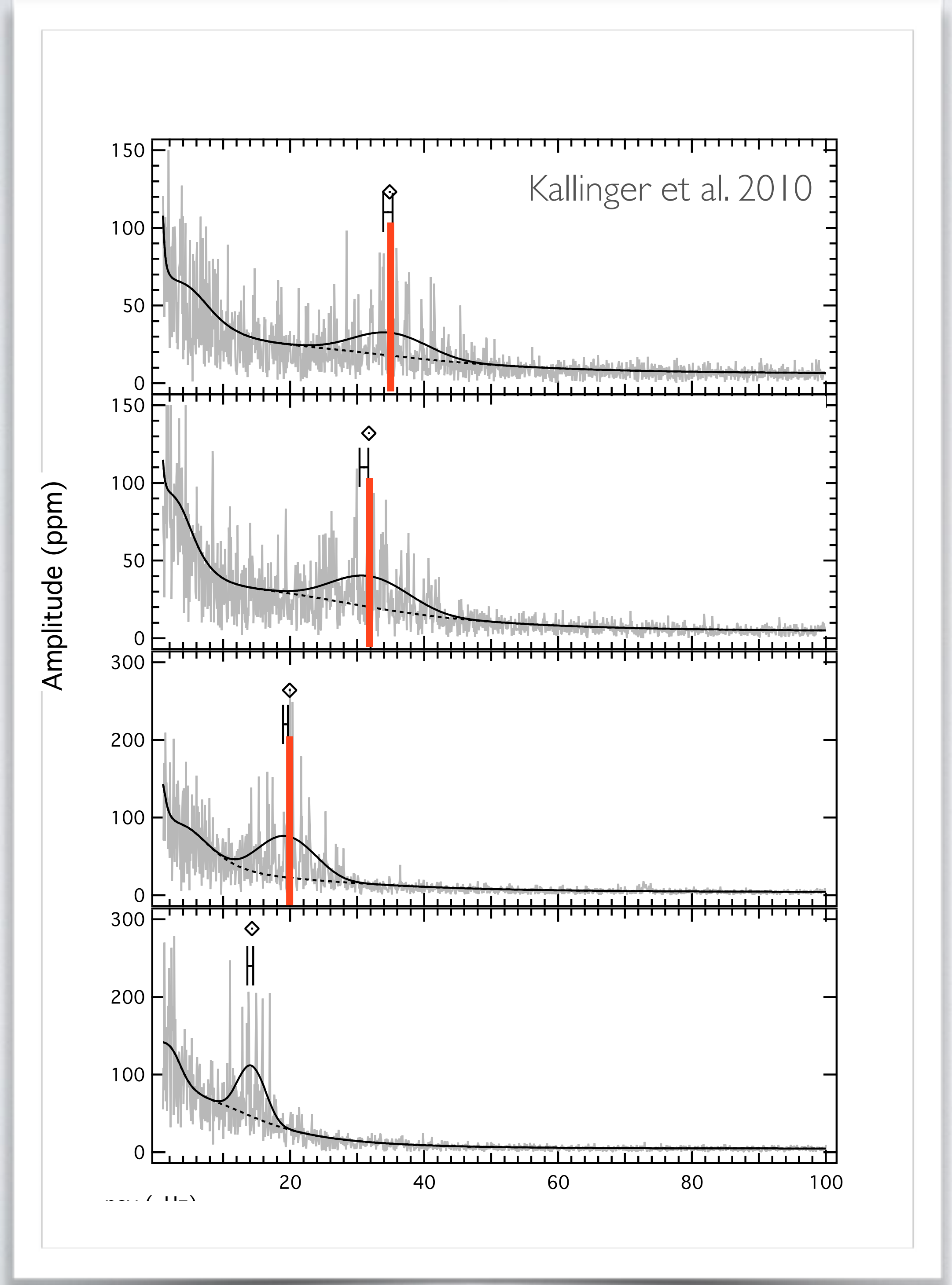


BiSON data

Davies et al. 2014

SOLAR FREQUENCY SPECTRUM

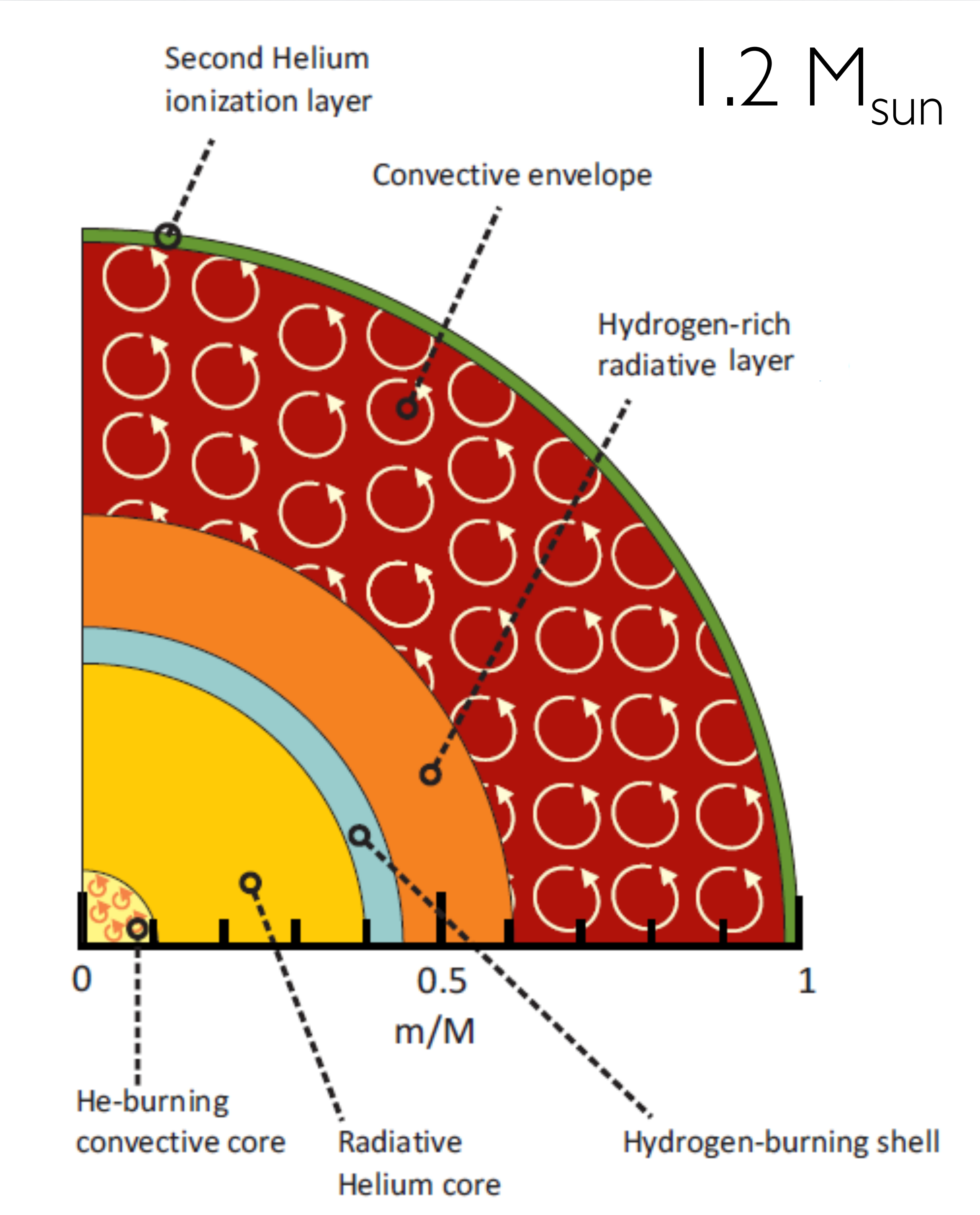
ν_{max}



$$\nu_{\mathrm{max}} \simeq \frac{M/\mathrm{M}_{\odot}}{(R/\mathrm{R}_{\odot})^{2}\sqrt{T_{\mathrm{eff}}/T_{\mathrm{eff},\odot}}}\,\nu_{\mathrm{max},\odot}$$

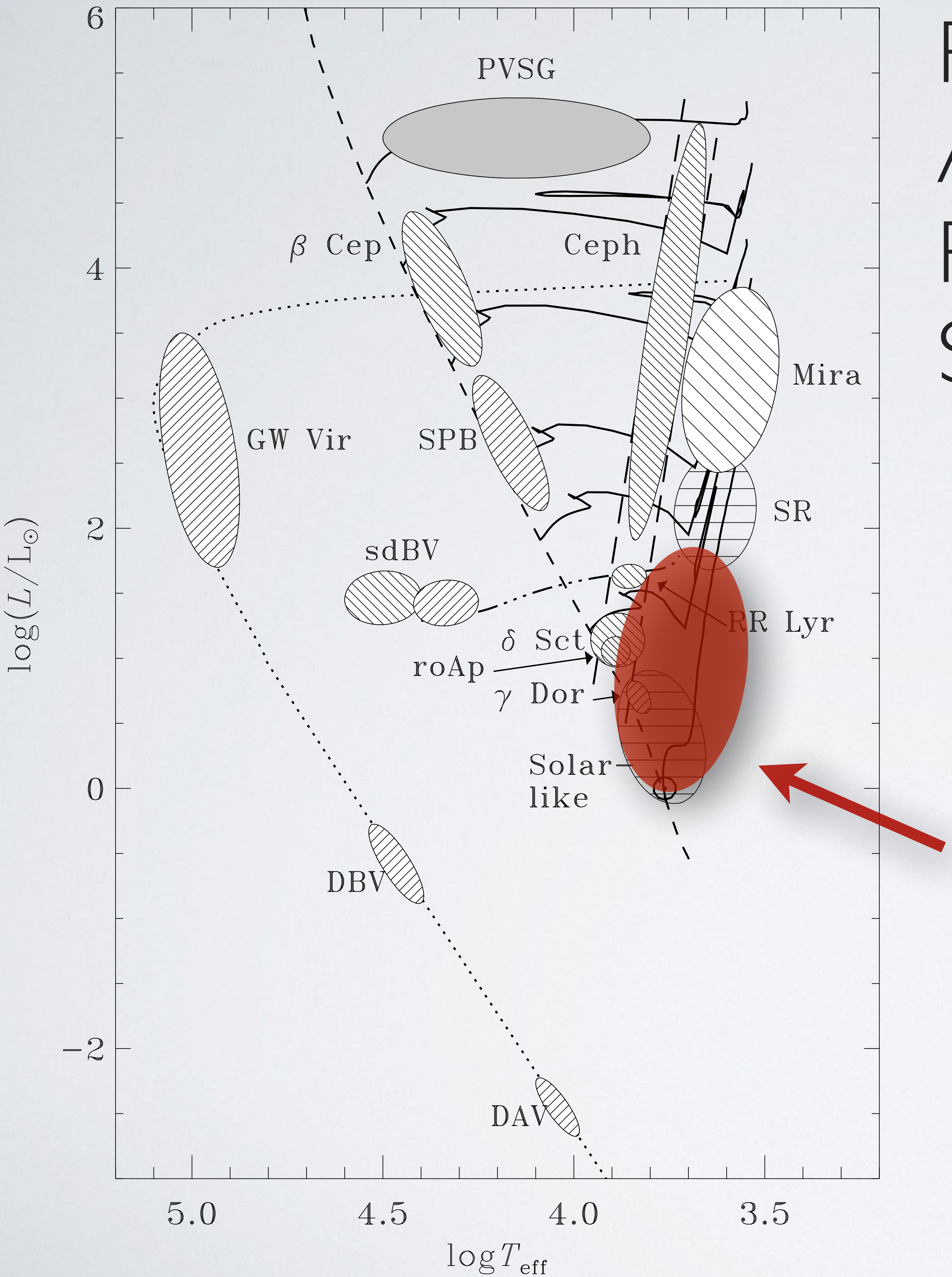
Brown et al. 1991
Kjeldsen&Bedding 1995
Belkacem et al. 2011

ASTEROSEISMOLOGY



⇄ oscillation frequencies

Aerts, Christensen-Dalsgaard & Kurtz 2009



PULSATING STARS AND STELLAR POPULATIONS STUDIES

Solar-Like Oscillating Stars:

Standard Clocks and Rulers for Galactic Studies

Desirable properties:

- intrinsically luminous
- numerous
- photospheric composition proxy of the ISM at time of birth
- pulsation spectrum rich yet simple
- precise distance and age indicators
- span a wide age interval sampling look-back times as long as the age of the Galaxy.

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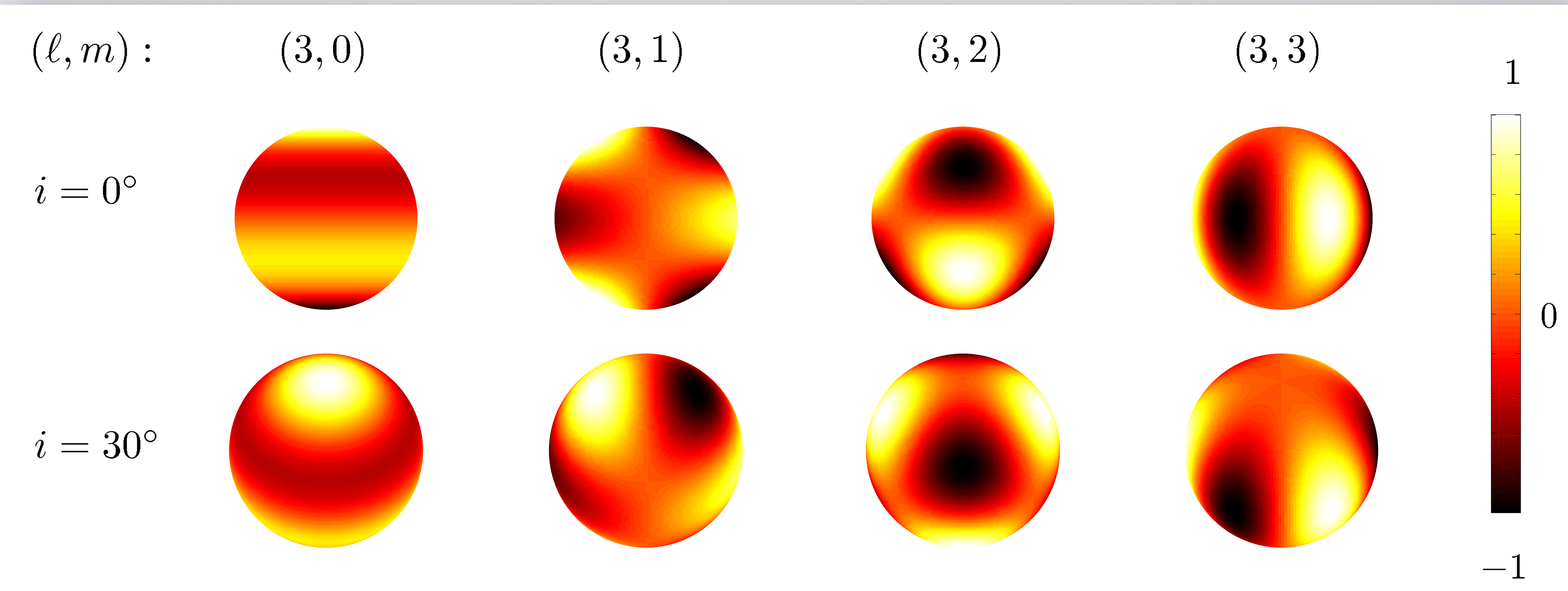
ASTEROSEISMOLOGY

no rotation:

$$\xi \propto \xi_{n\ell}(r)\, Y_\ell^m(\theta,\phi)e^{-i2\pi\nu_{n\ell}\,t}$$

l: number of nodal lines



ASTEROSEISMOLOGY

oscillation modes in stars: 2 main families

pressure modes

- acoustic waves → largely determined by sound speed

$$c^2 = \Gamma_1 \frac{P}{\rho} \qquad \Gamma_1 = \left(\frac{\partial \ln p}{\partial \ln \rho}\right)_{\mathrm{ad}}$$

- high frequencies

gravity modes

- restoring force: buoyancy
- largely determined by $N^2 = g\left(\frac{1}{\Gamma_1 p}\frac{\mathrm{d}p}{\mathrm{d}r} - \frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r}\right)$
- low frequencies
- propagate in radiative regions
- sensitive to near-core conditions

BASIC PROPERTIES OF OSCILLATION MODES

first order asymptotic approximation
e.g. Vandakurov, 1967, Tassoul ApJS 43 1980

main hyp: eigenfunction vary much more rapidly than equilibrium structure

p-mode frequencies

$$\nu_{nl} \simeq \left(n + \tfrac{l}{2} + \tfrac{1}{4} + \alpha\right) \Delta\nu \qquad \Delta\nu = \left(2 \int_0^R \tfrac{\mathrm{d}r}{c(r)}\right)^{-1} \propto \left(M/R^3\right)^{1/2}$$

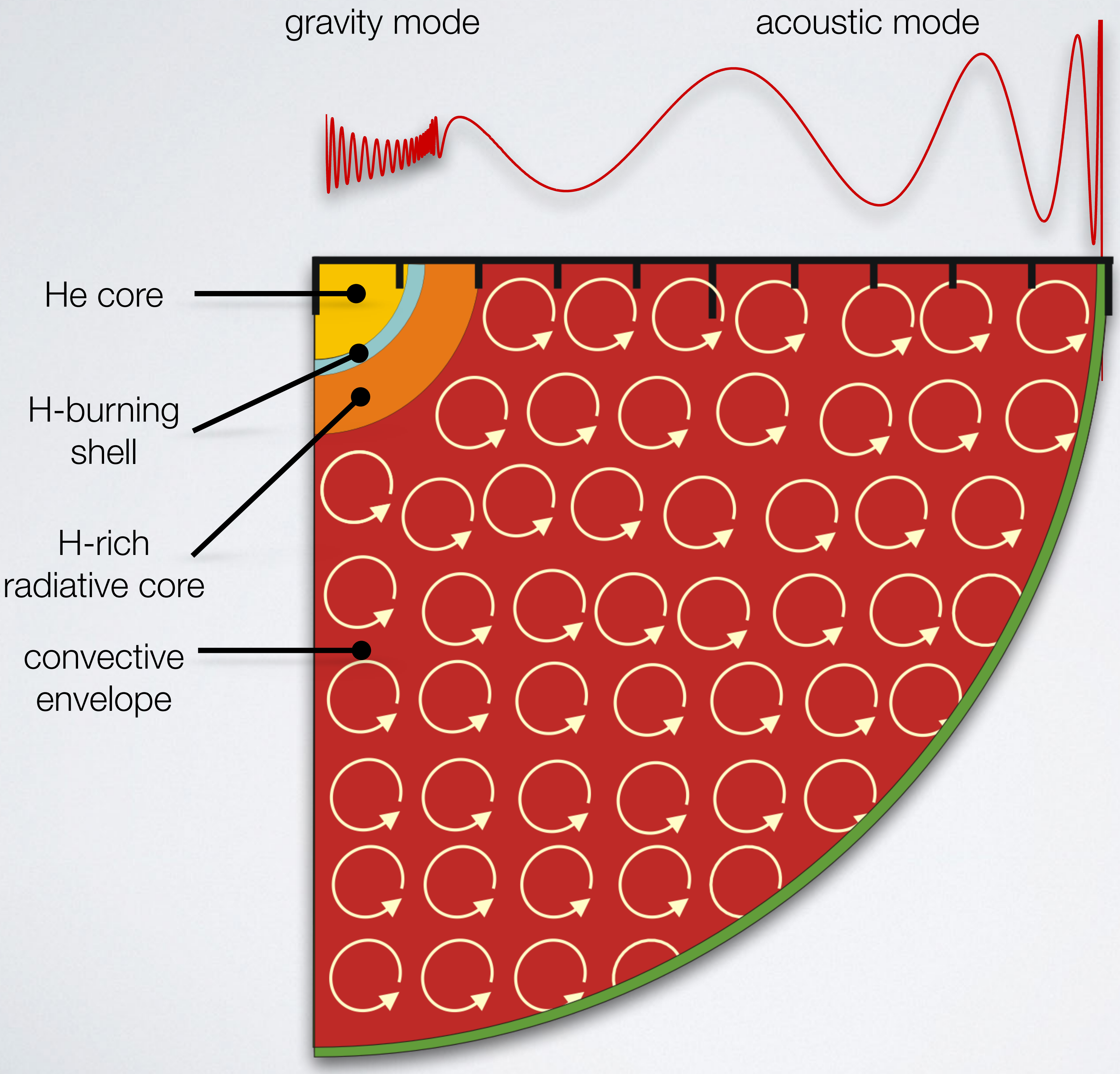
constant frequency spacing

g-mode periods

$$P_{nl} \simeq \Delta P_l \left(n + \epsilon\right) \qquad \Delta P = \frac{2\pi^2}{\sqrt{l(l+1)}} \left(\int_{r_1}^{r_2} N \frac{\mathrm{d}r}{r}\right)^{-1}$$

constant period spacing

non-radial modes in red-giant stars



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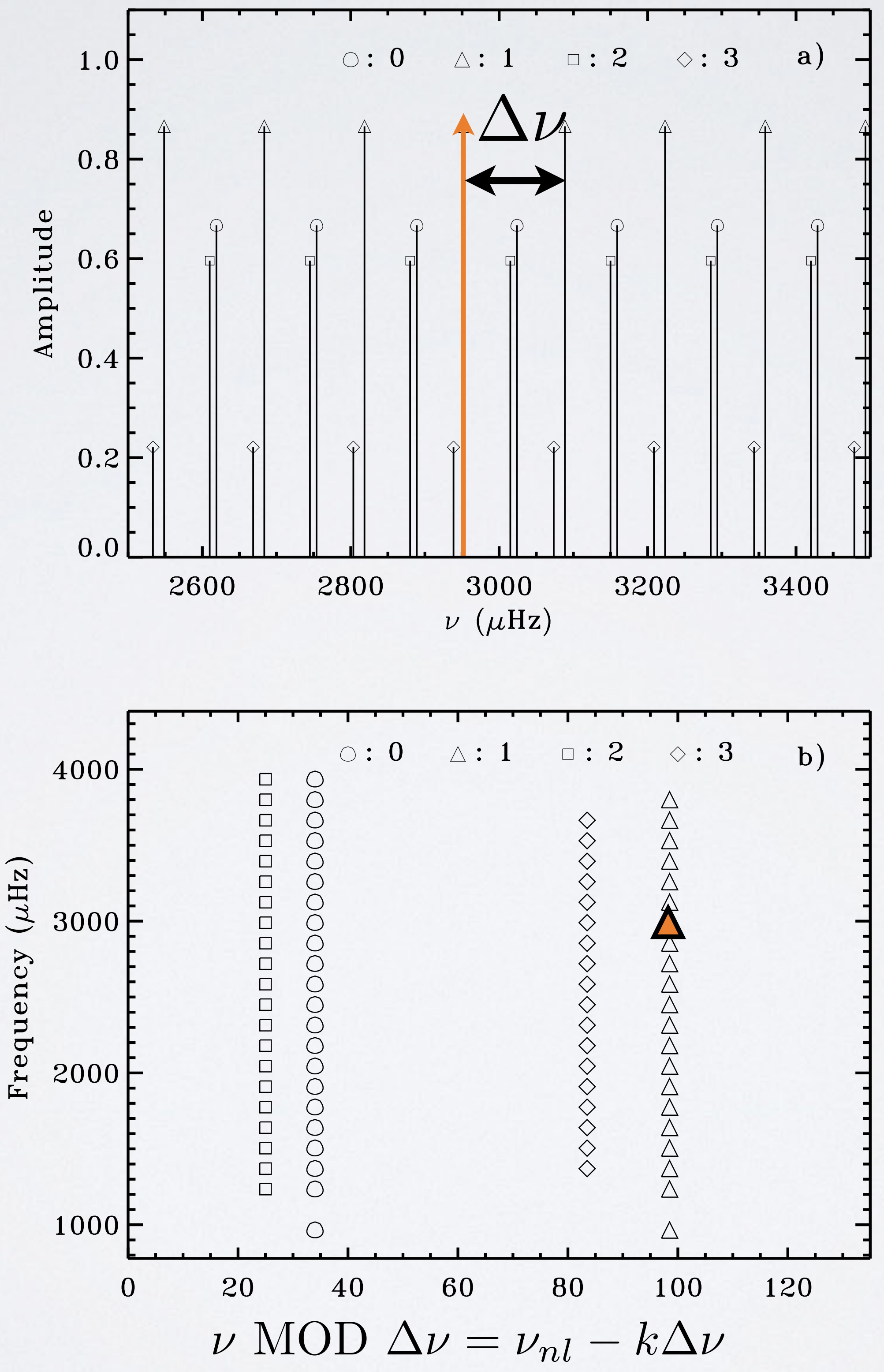
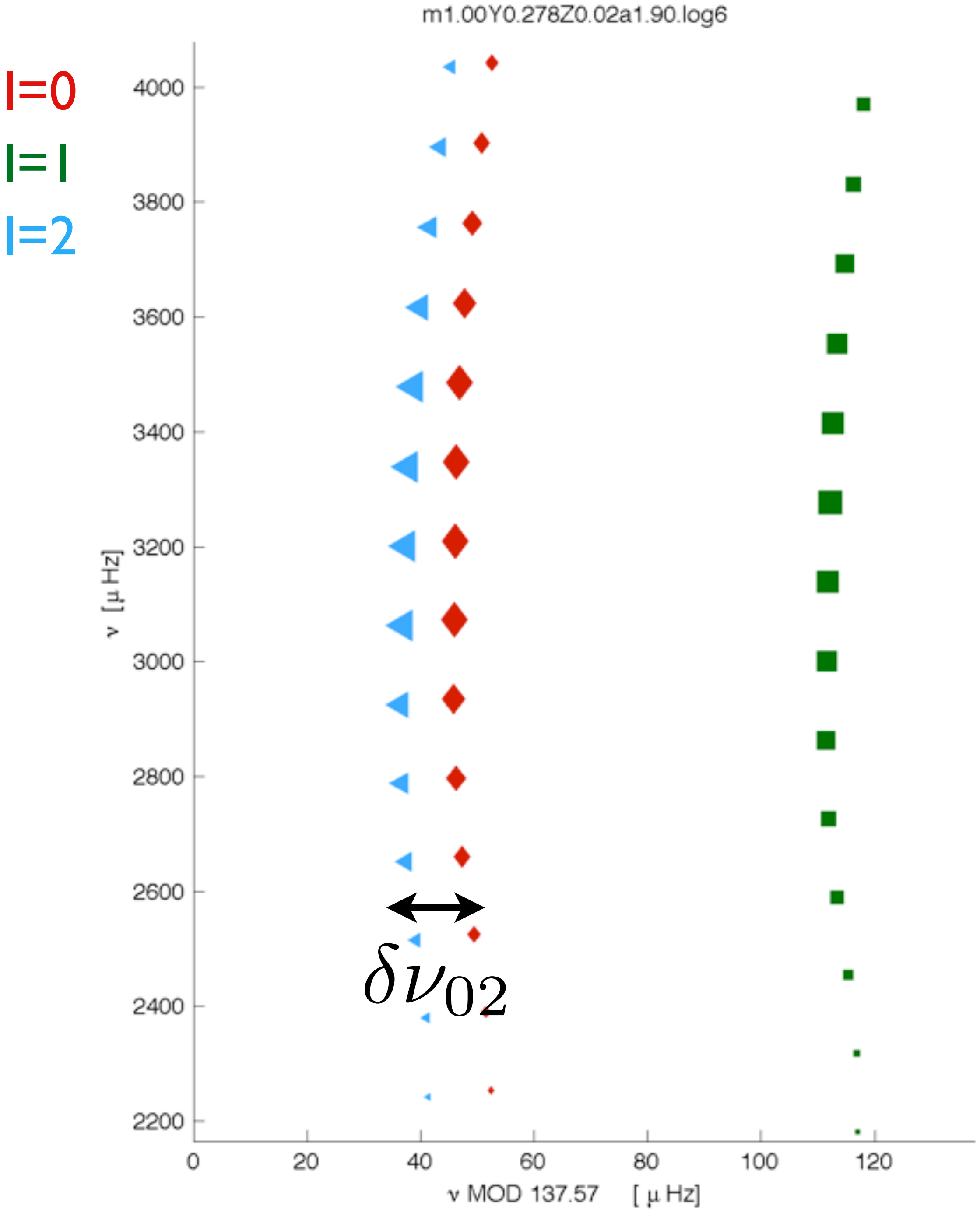
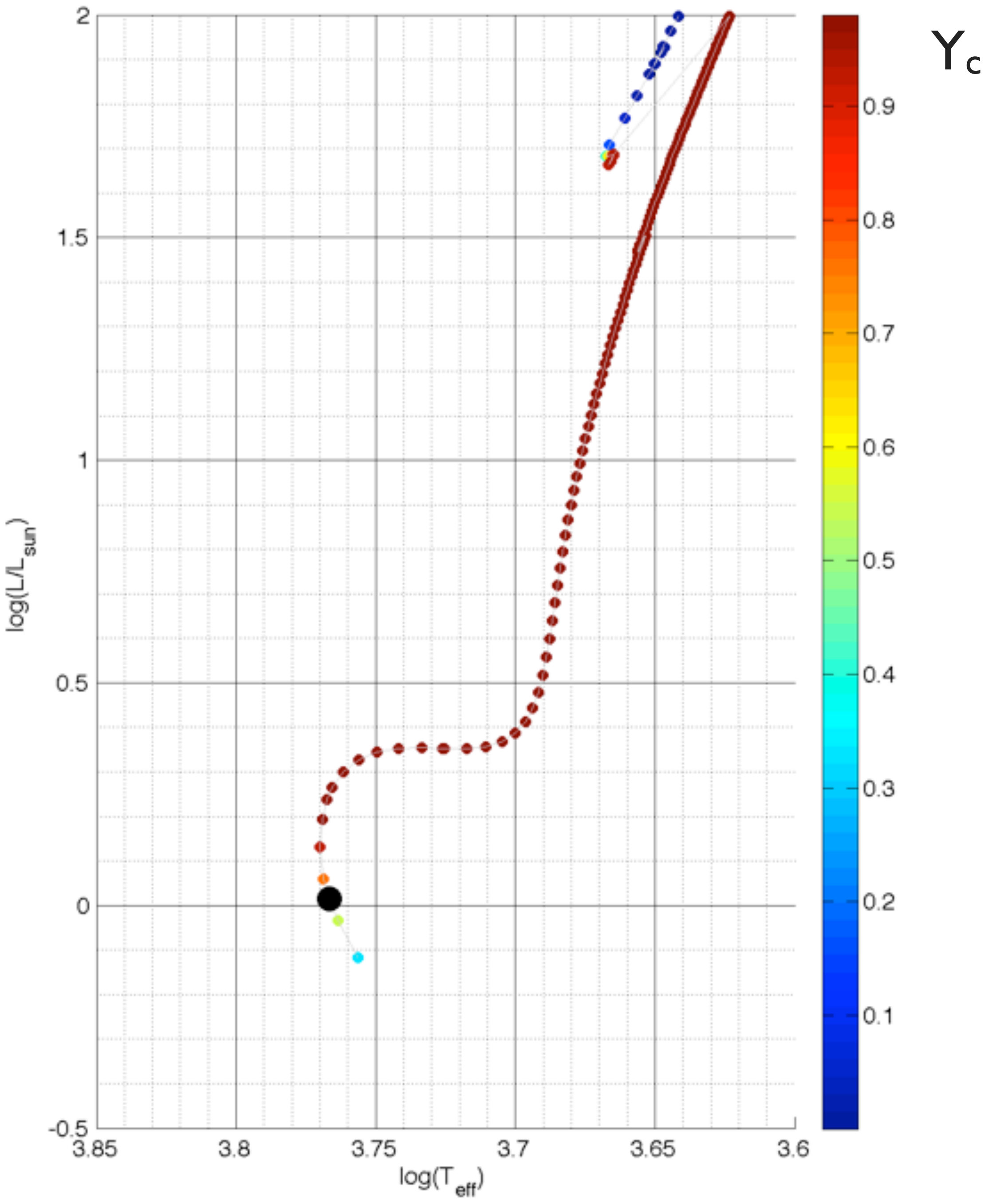
Echelle diagrams

Aerts, Christensen-Dalsgaard & Kurtz 2009



spectra of 1 M_{sun} models form ZAMS to core-He burning



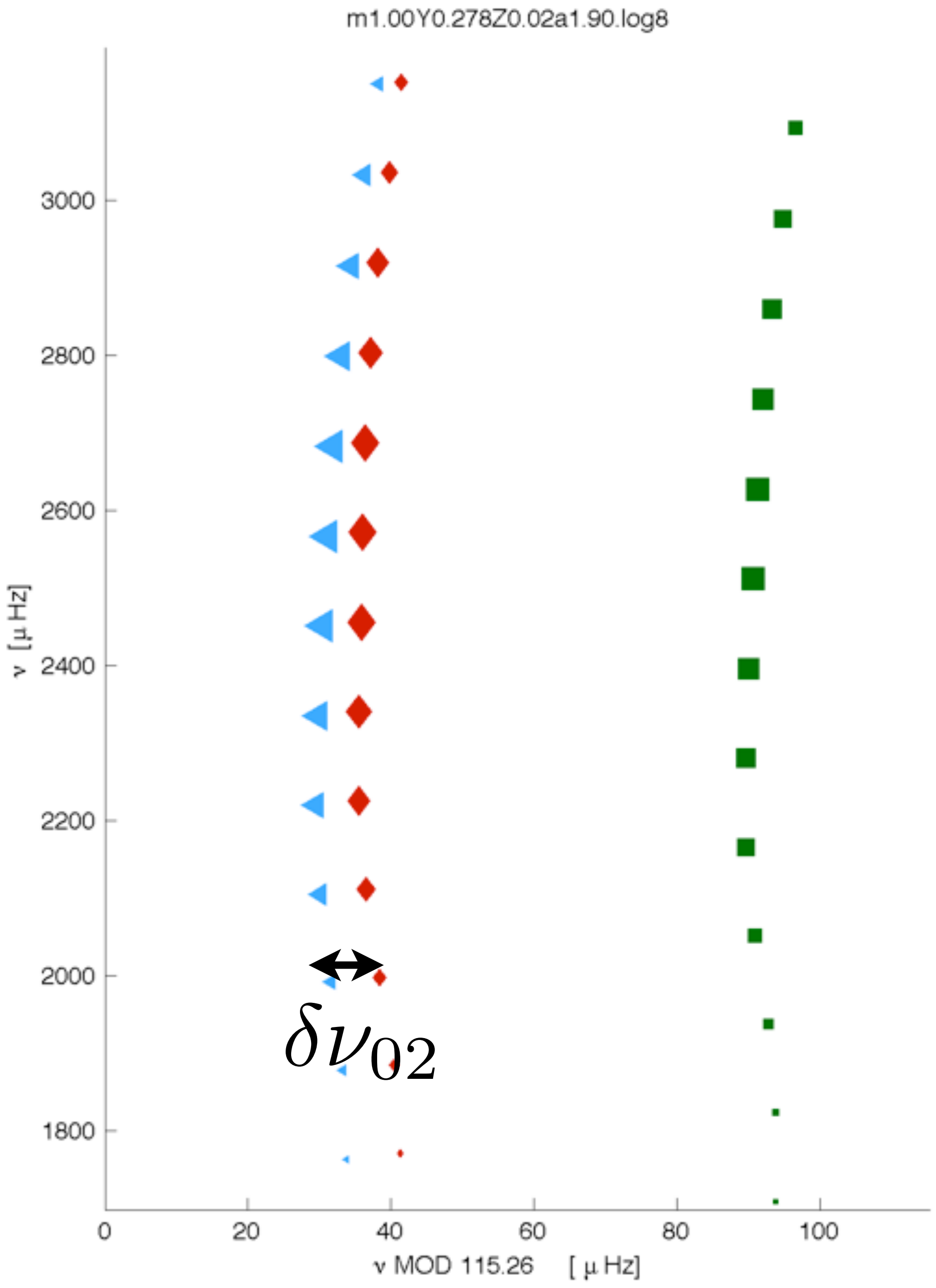


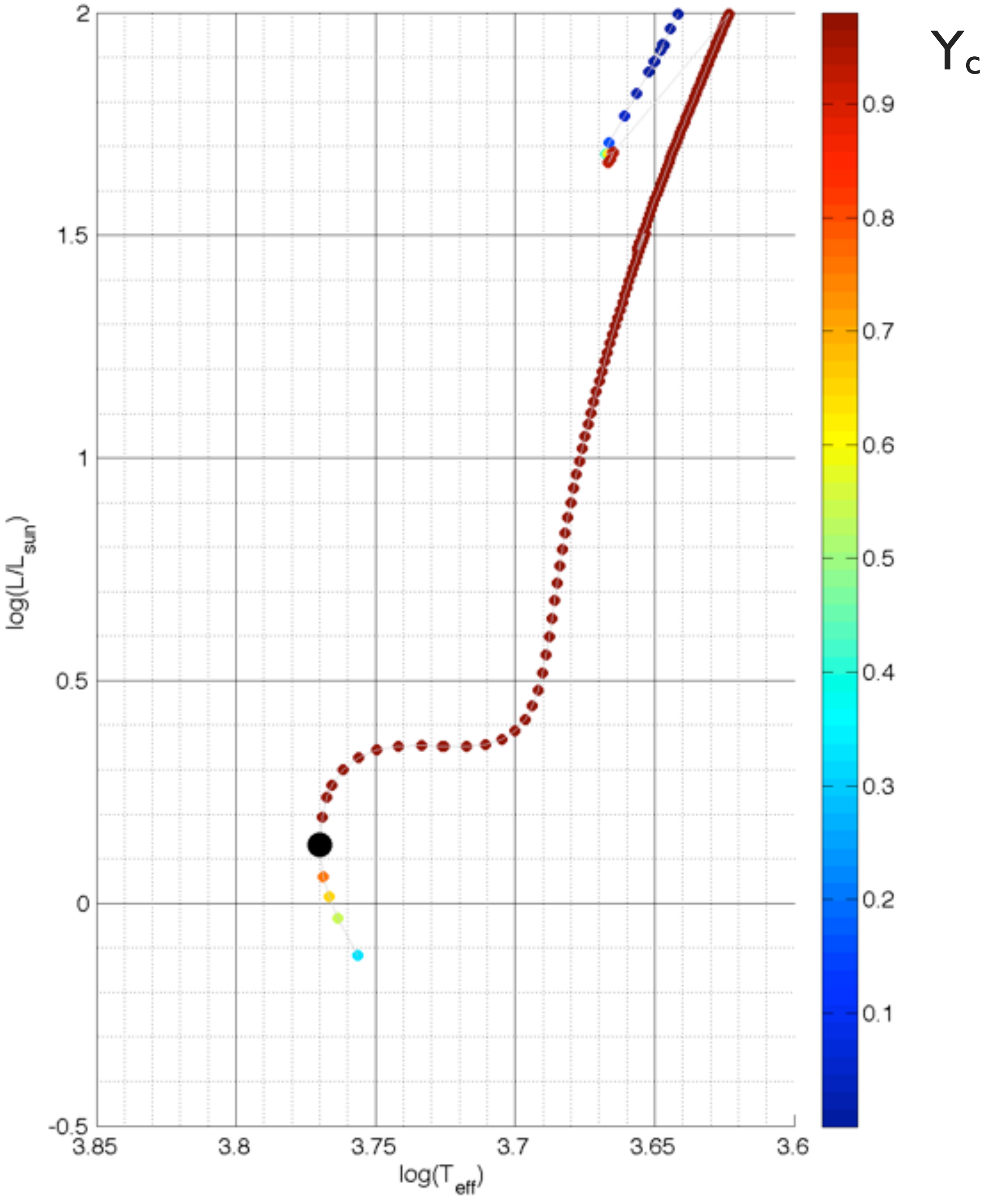
spectra of 1 M_{sun} models form ZAMS to core-He burning

l=0

l=1

l=2





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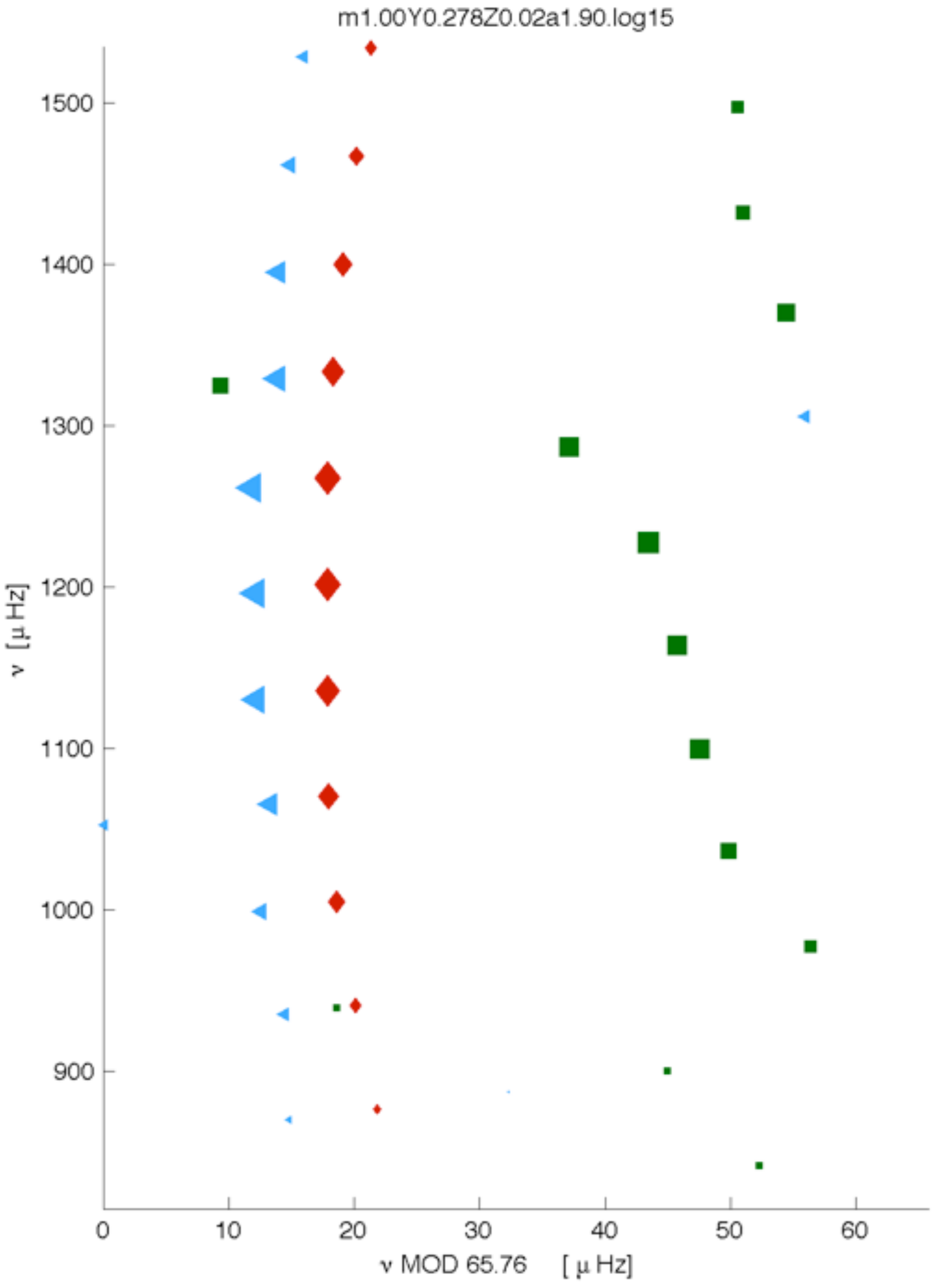

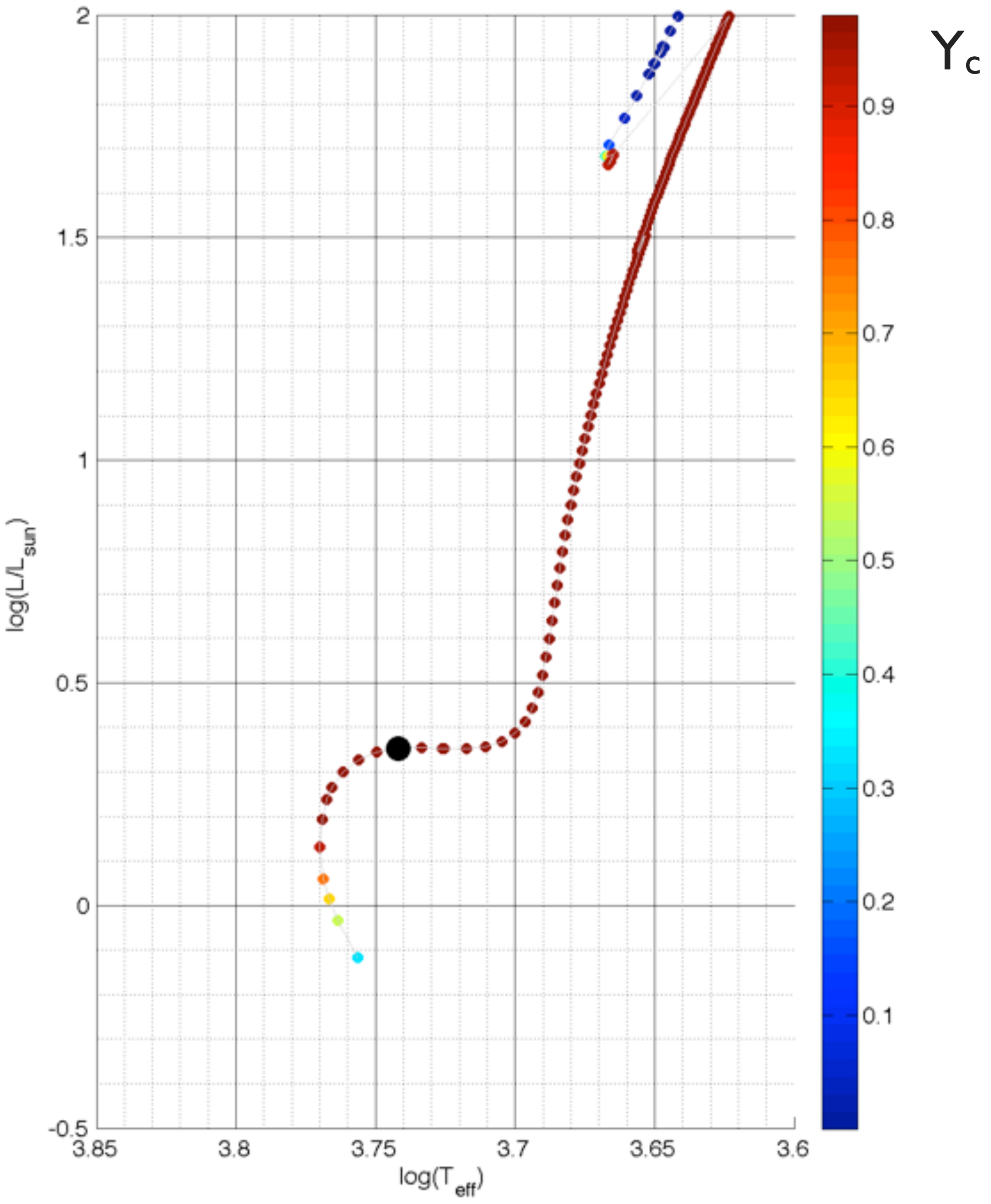

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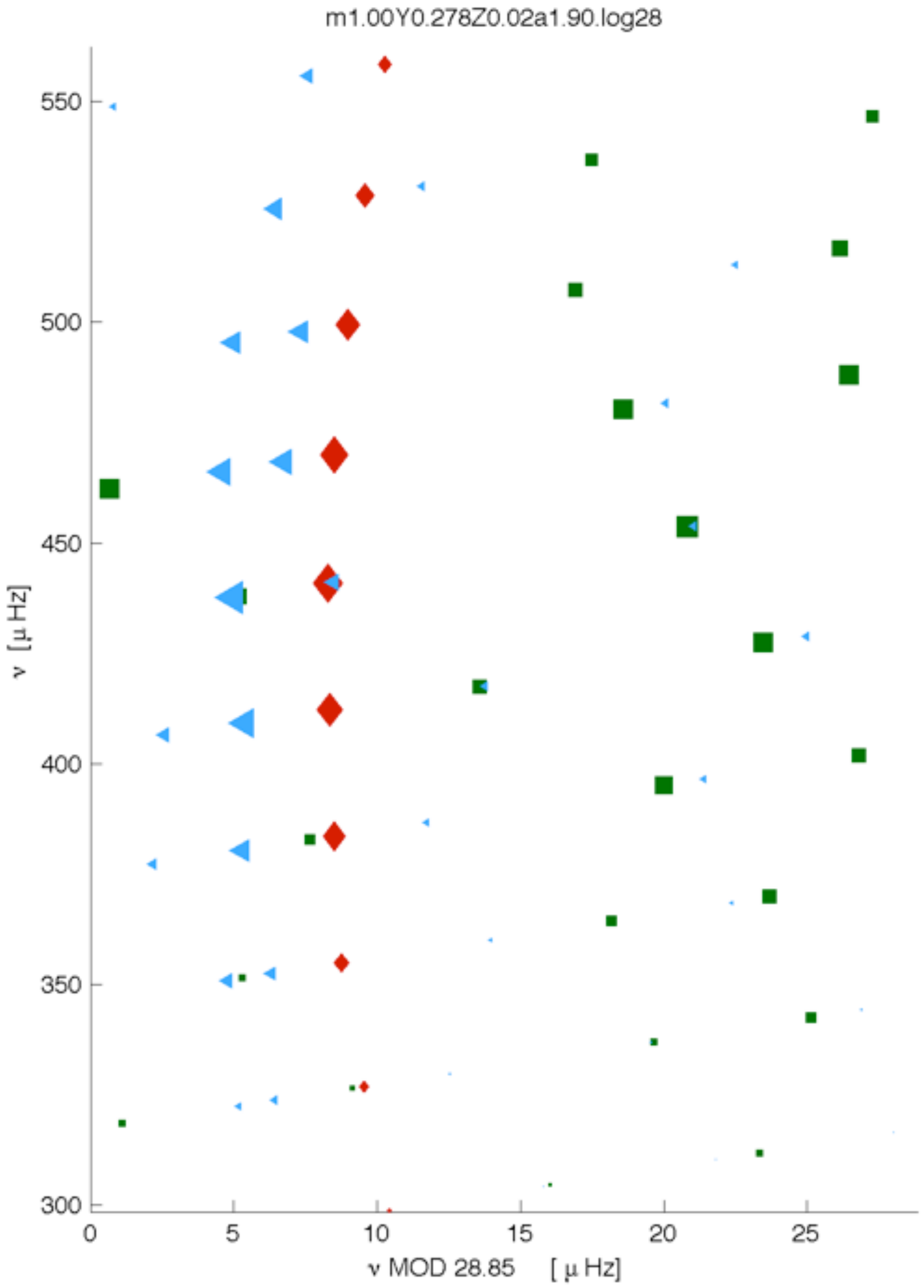

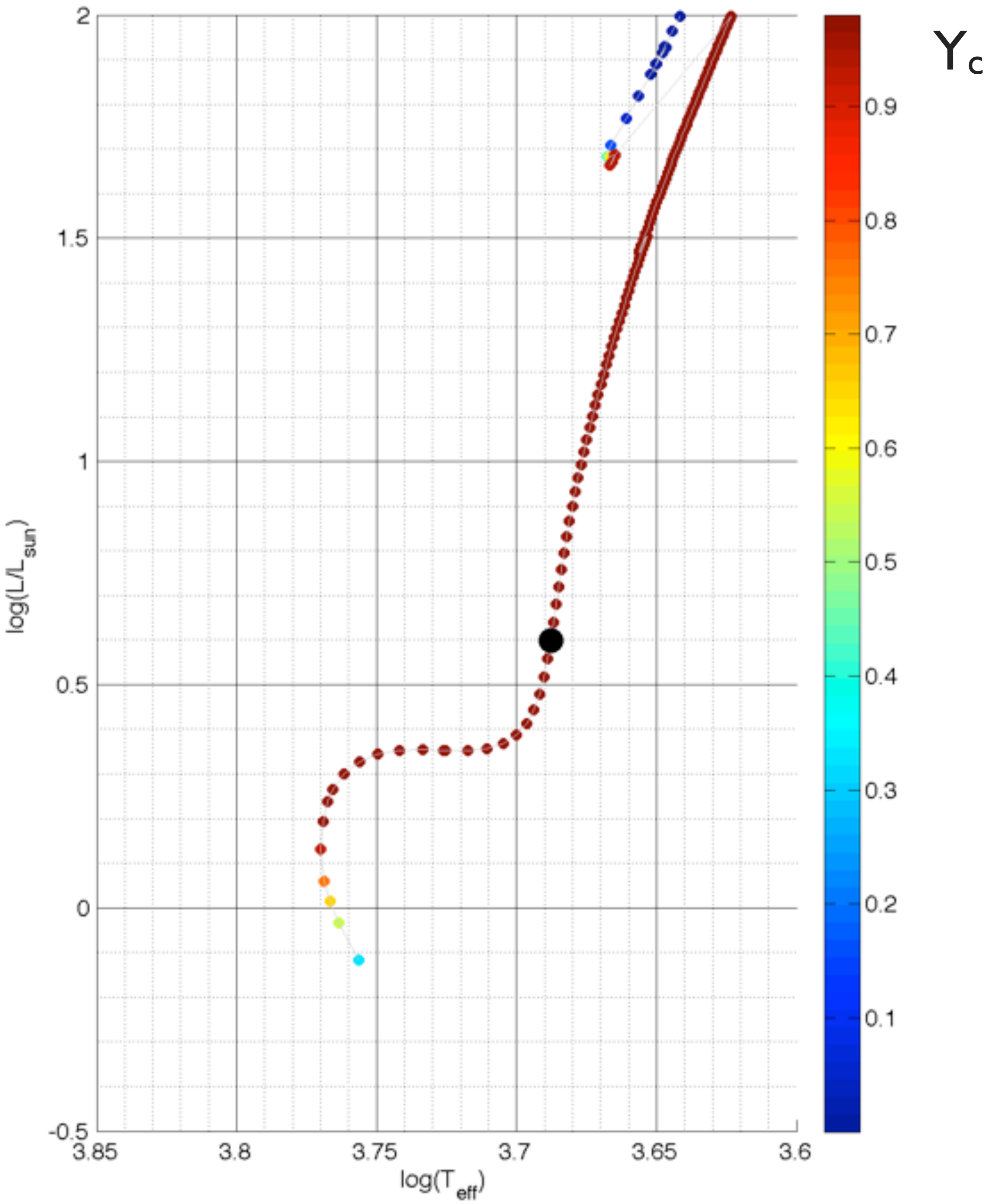

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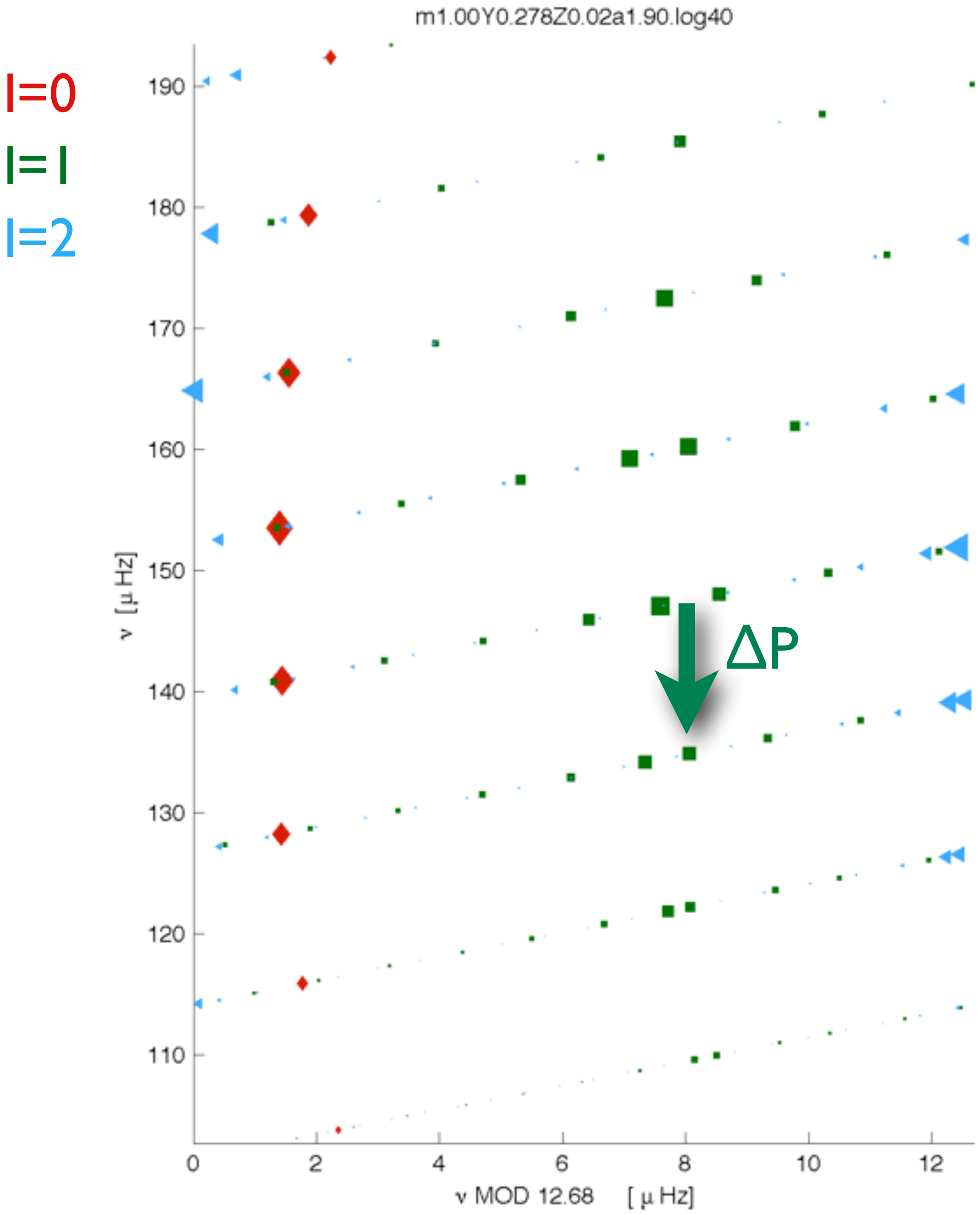
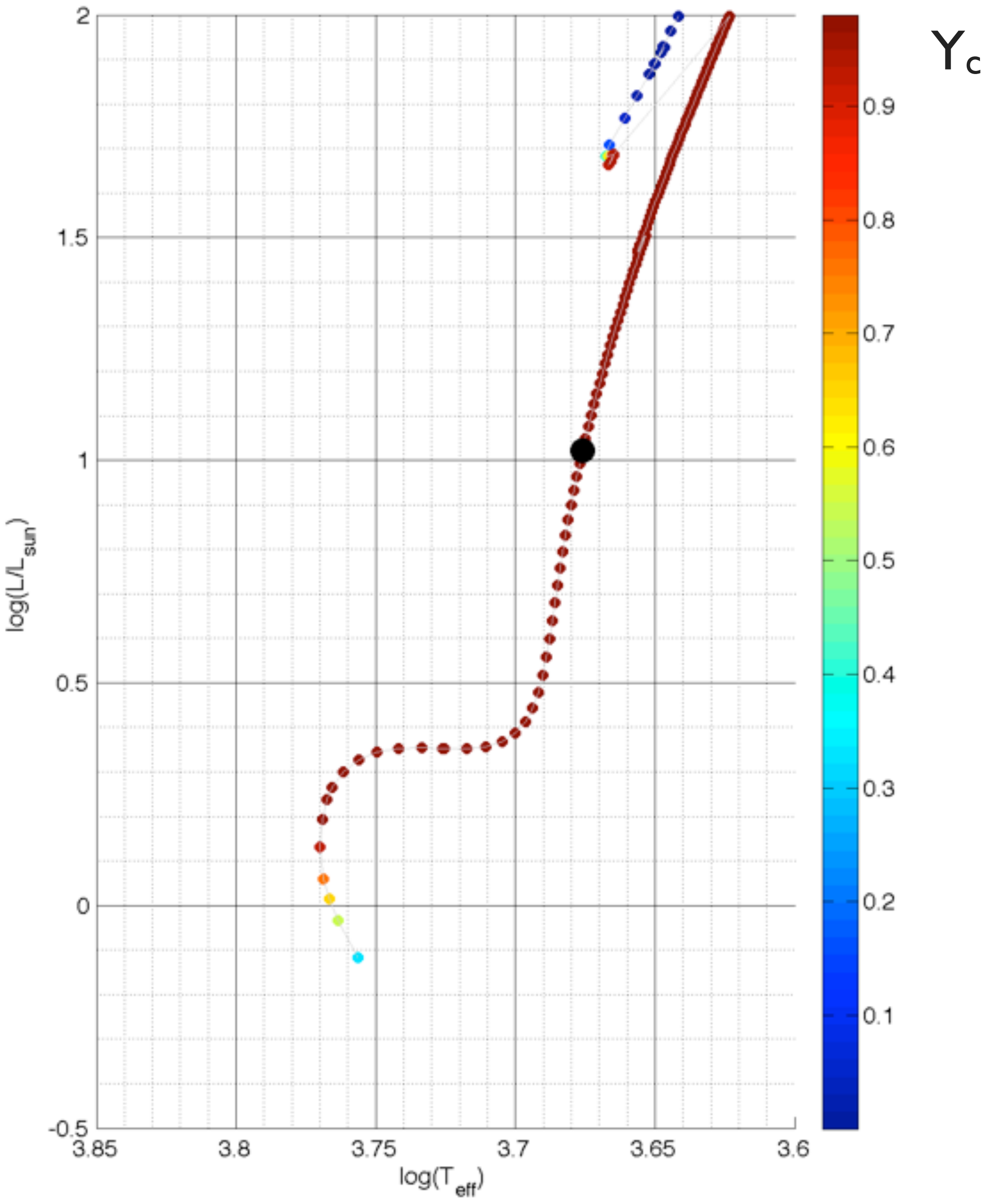
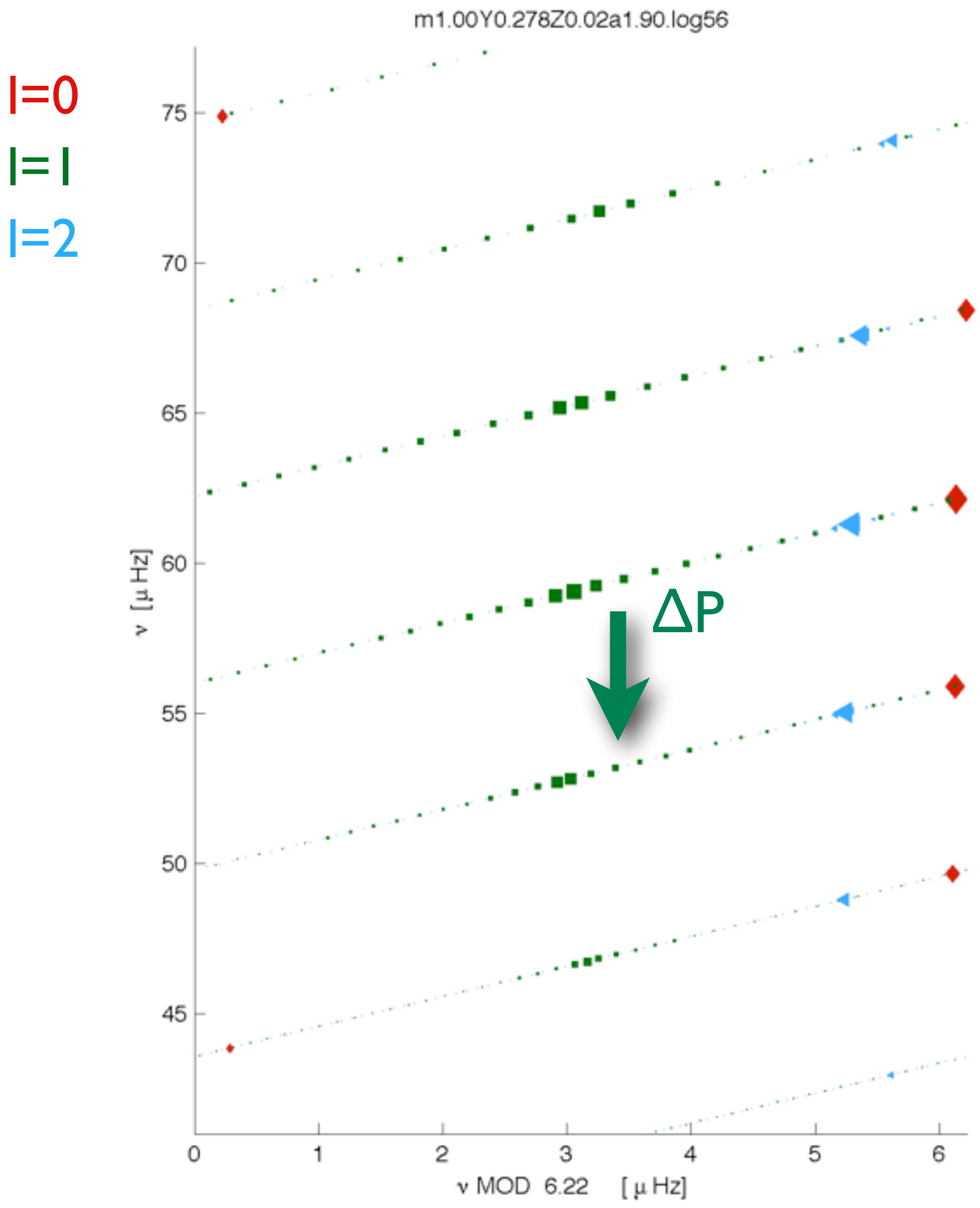
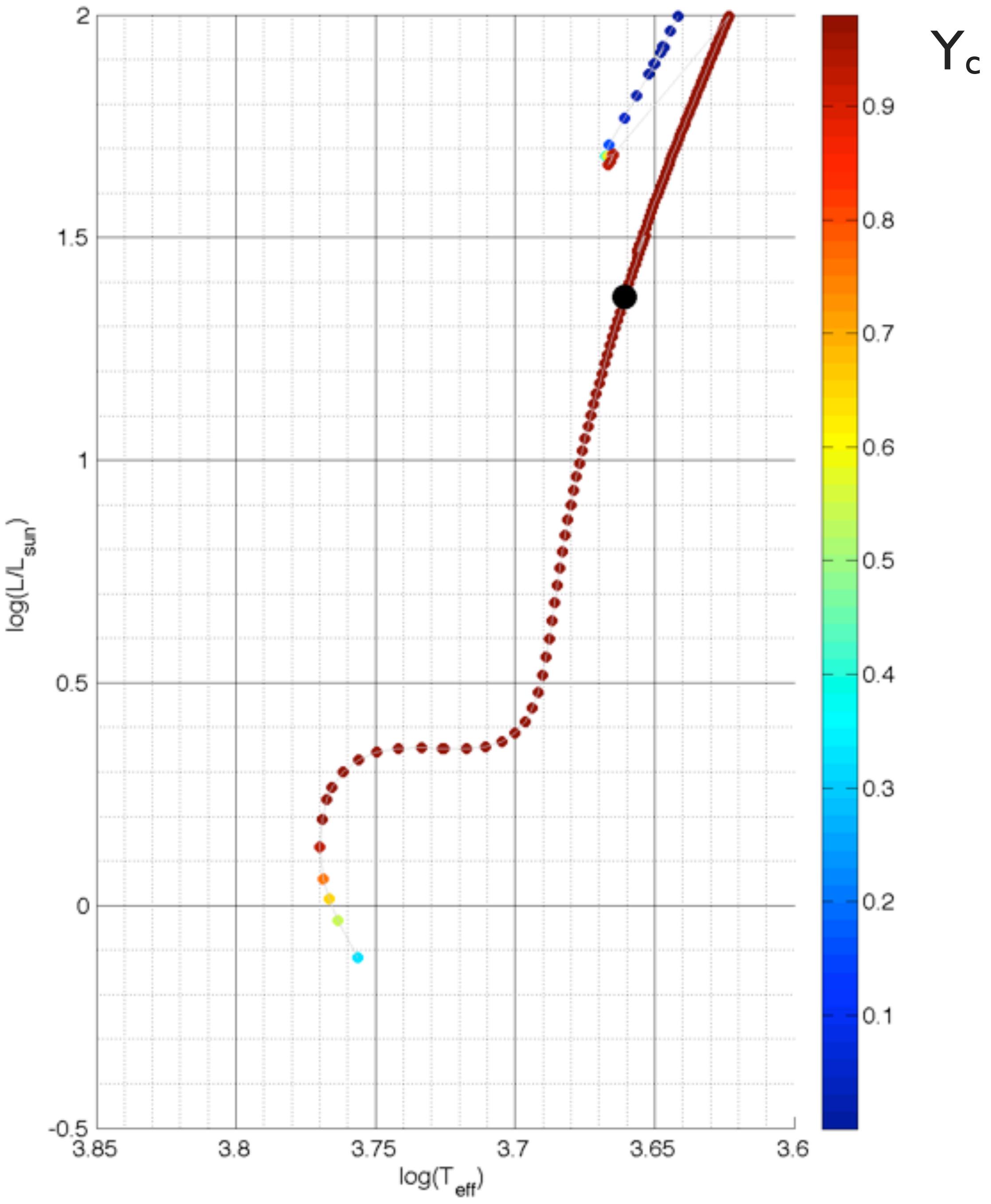


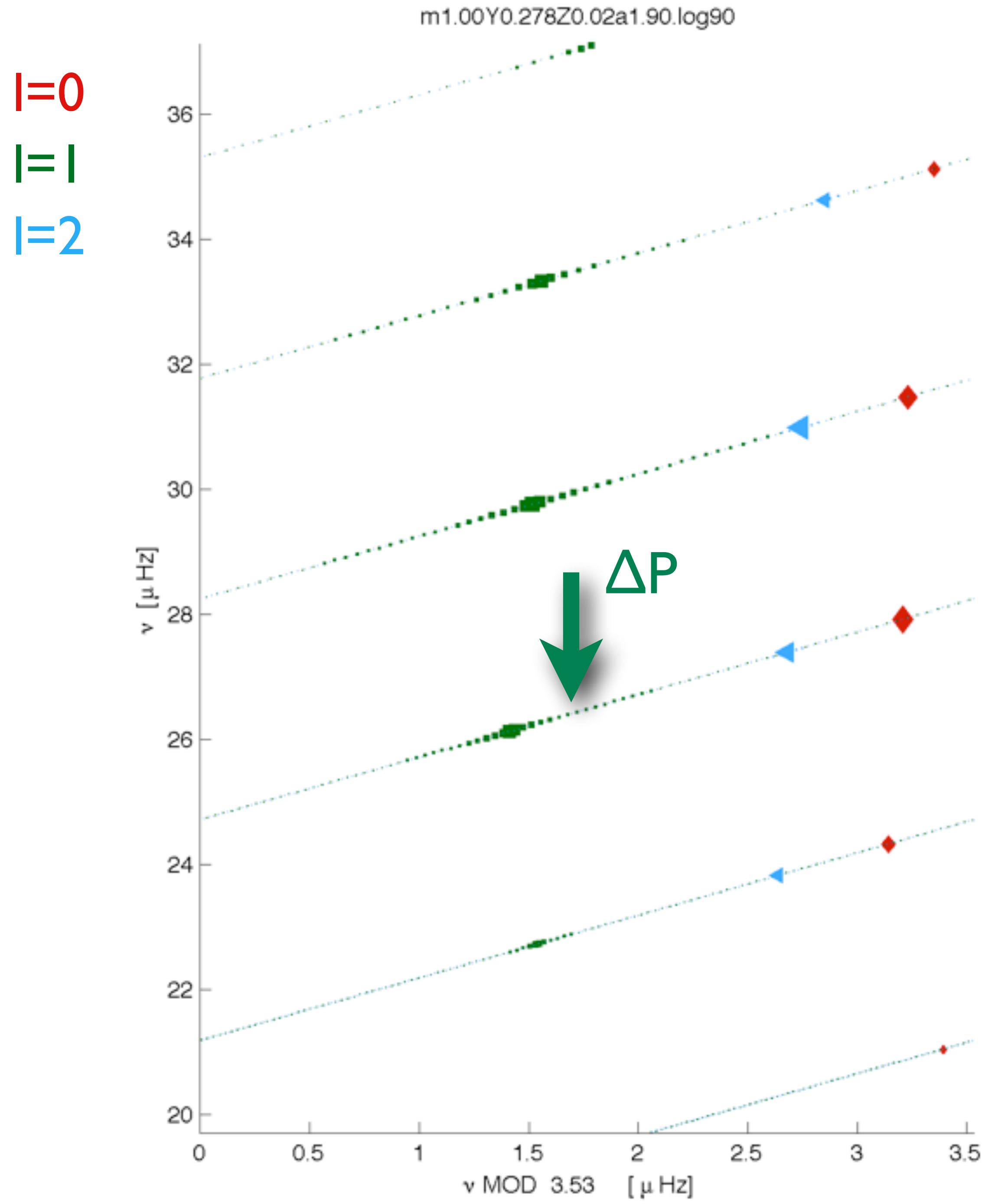


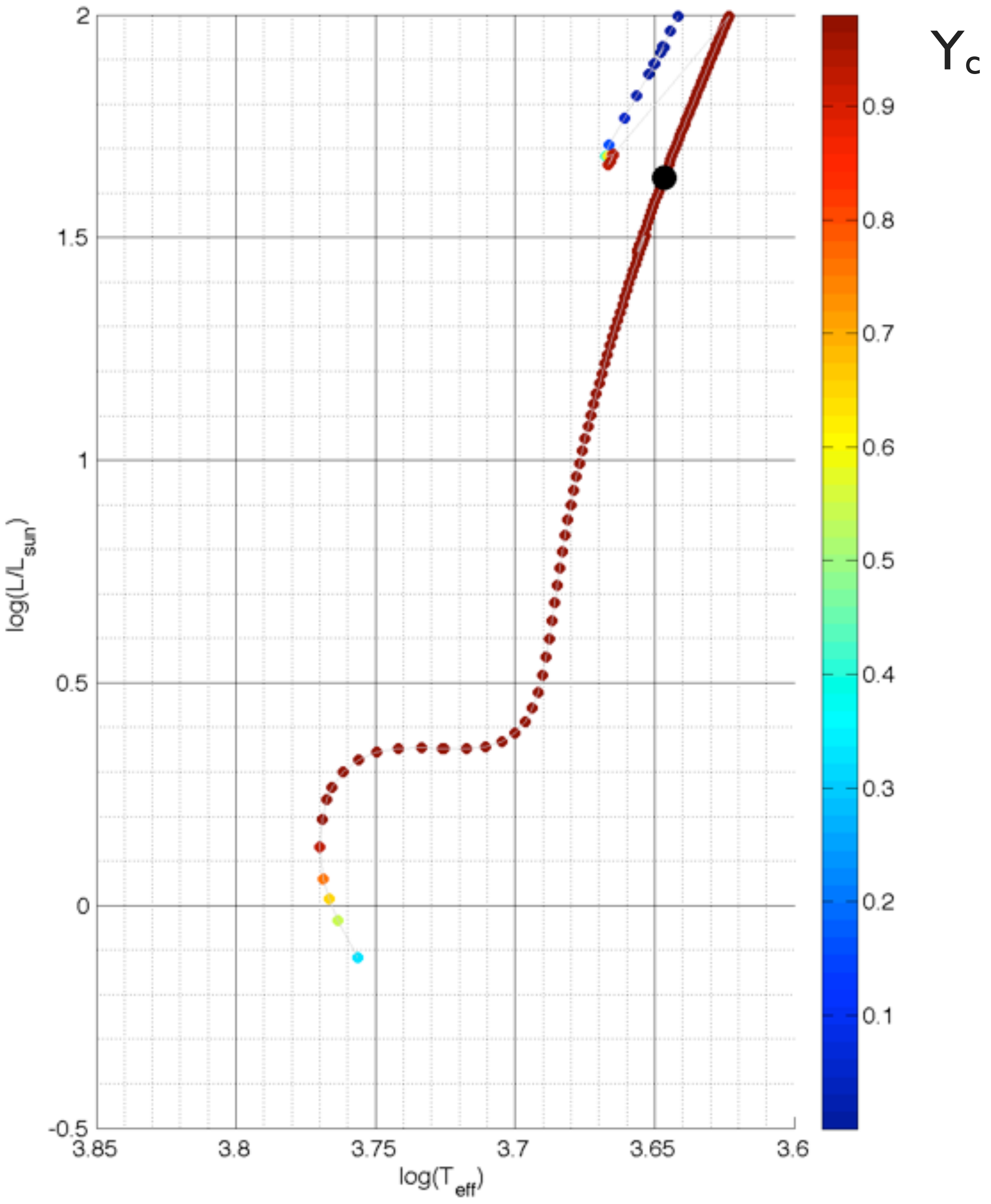
spectra of 1 M_{sun} models form ZAMS to core-He burning





spectra of 1 M$_{sun}$ models form ZAMS to core-He burning





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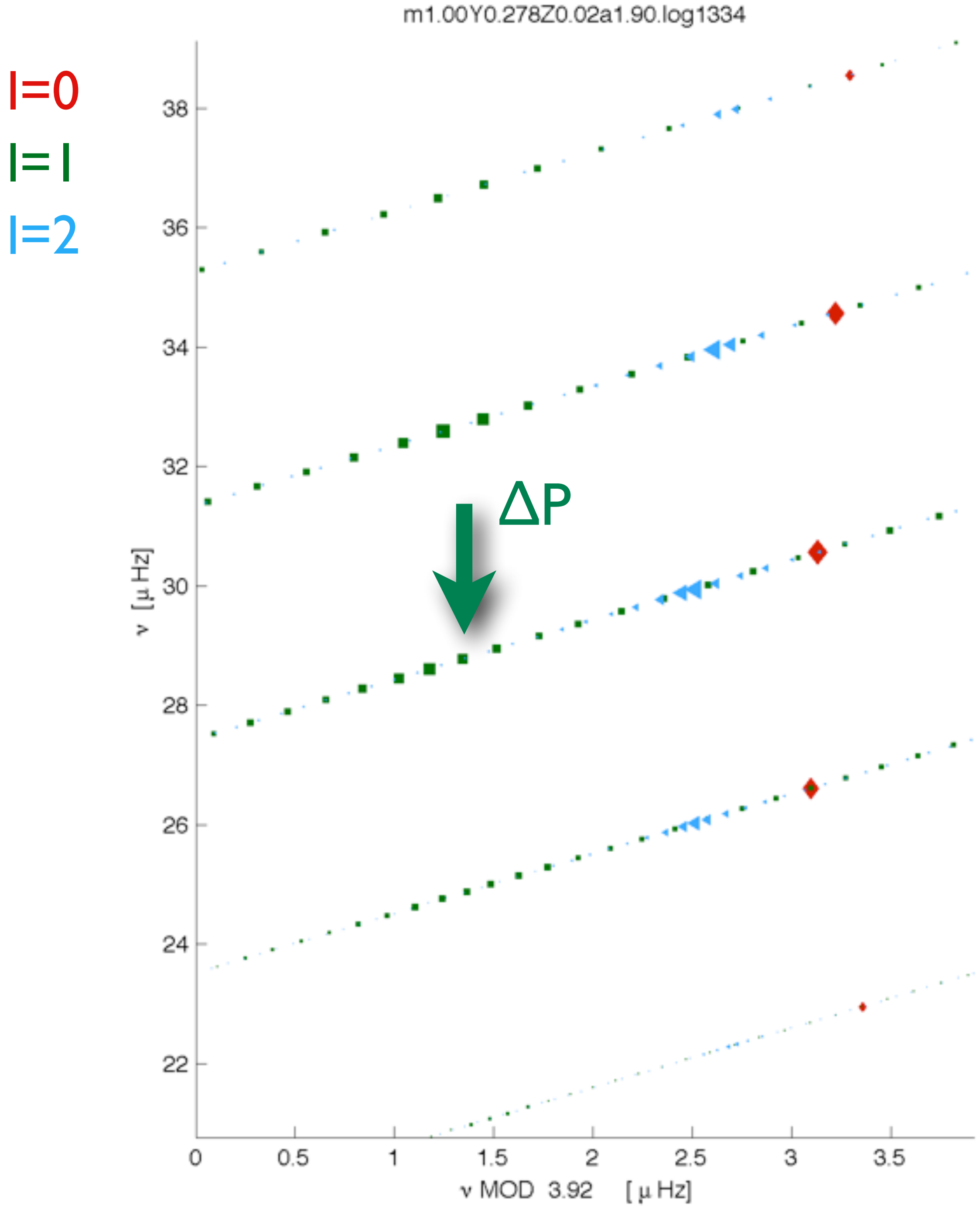
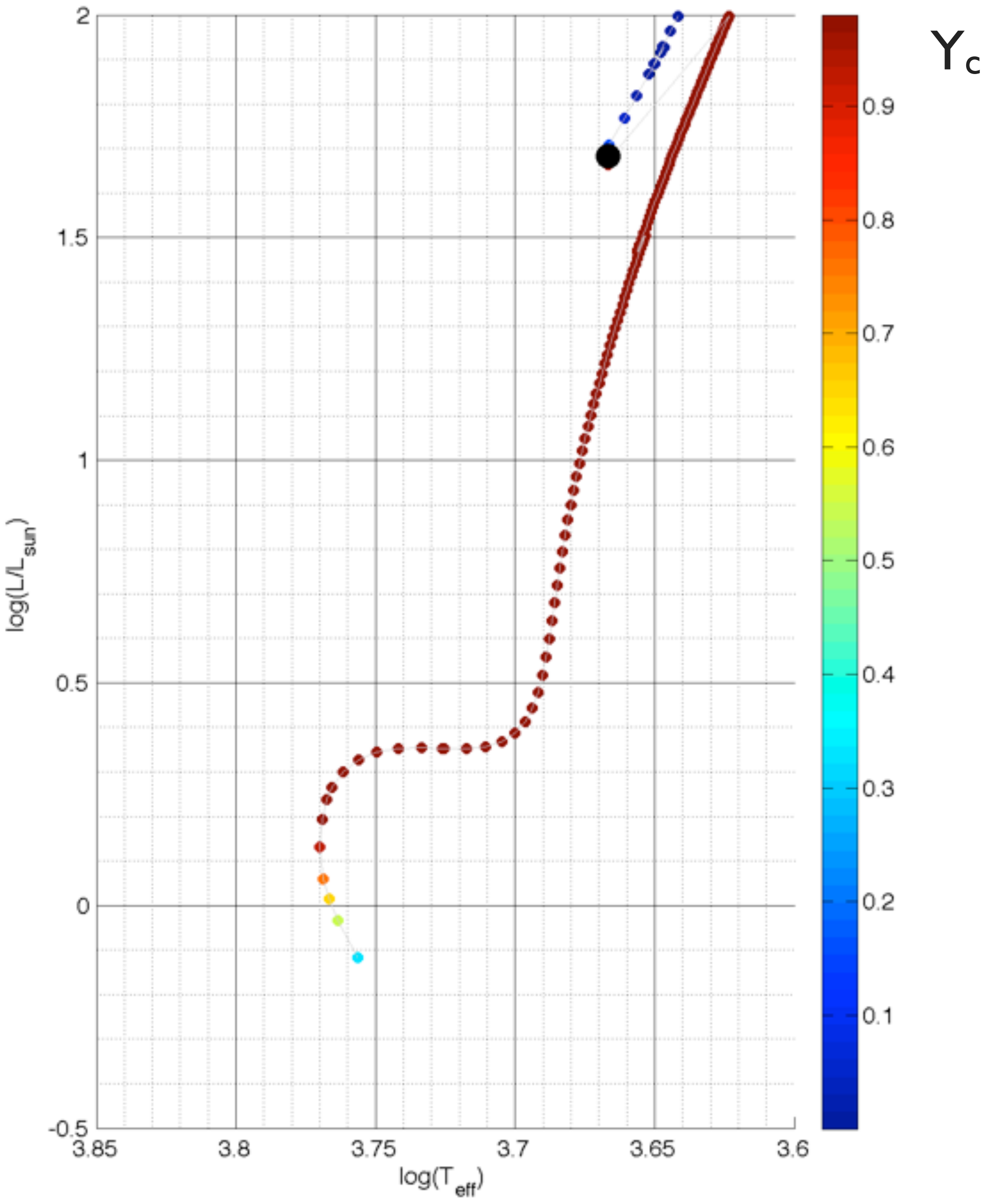
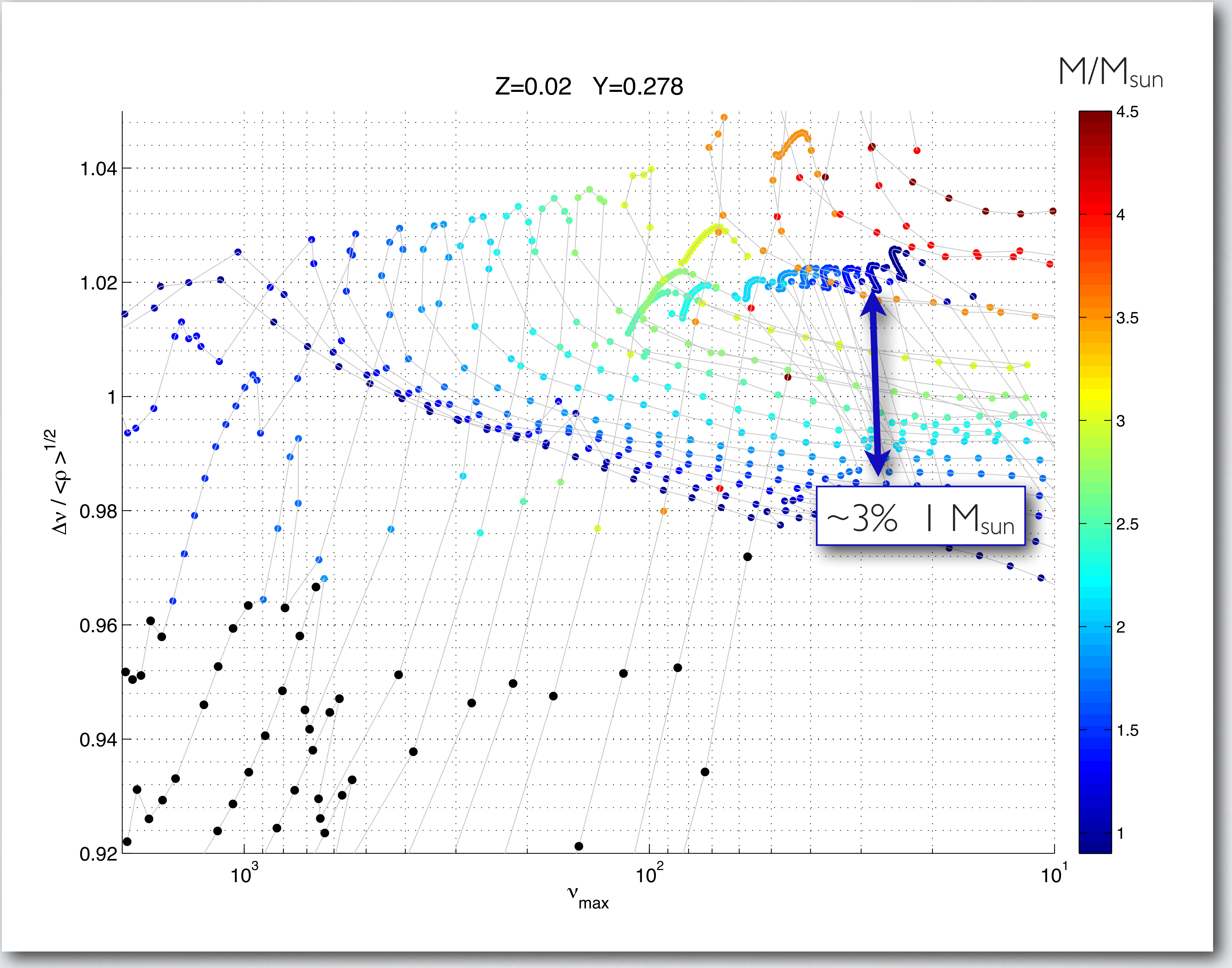




Ensemble seismology

- combine $\Delta\nu$, $\nu_{\max}$, $T_{\rm eff}$ → mass, radius
- impose that a solution $(\nu_{\max}, \Delta\nu, [{\rm Fe/H}], T_{\rm eff})$ belongs to an evolutionary track
- consider model-computed $\Delta\nu$
- consider period spacing, small frequency separations
- model individual frequencies

$\Delta\nu$ SCALING

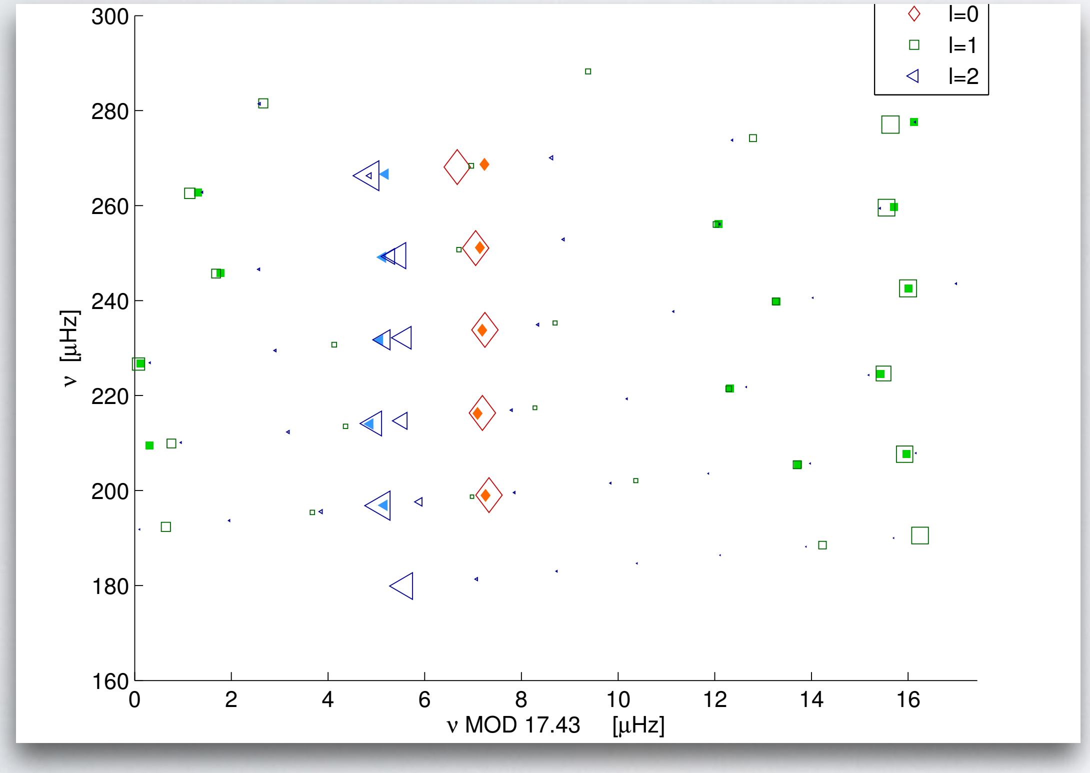


main-sequence and RGB: see e.g. Stello et al. 2009, White et al. 2011

INDIVIDUAL RADIAL-MODE FREQUENCIES

e.g. Kepler 56 Huber et al. 2013

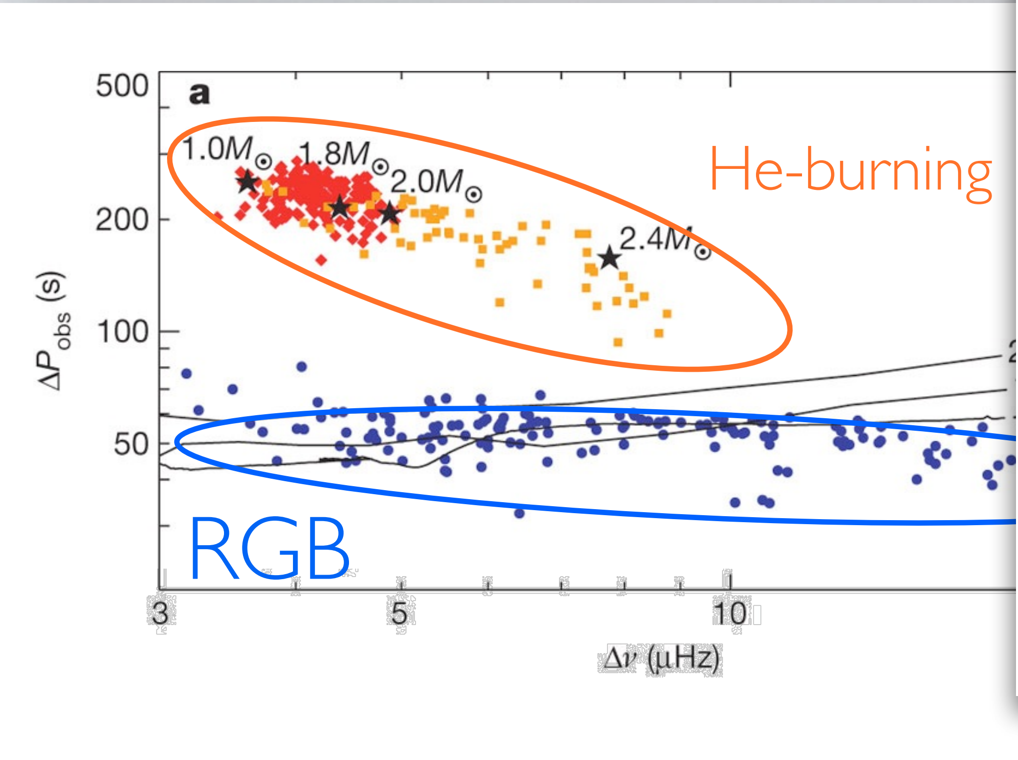
- scaling / grid-based approach: $\langle\rho\rangle = 0.0234 \pm 0.0003 \text{ g cm}^{-3}$
- radial modes frequencies: $\langle\rho\rangle = 0.0246 \pm 0.0002 \text{ g cm}^{-3}$



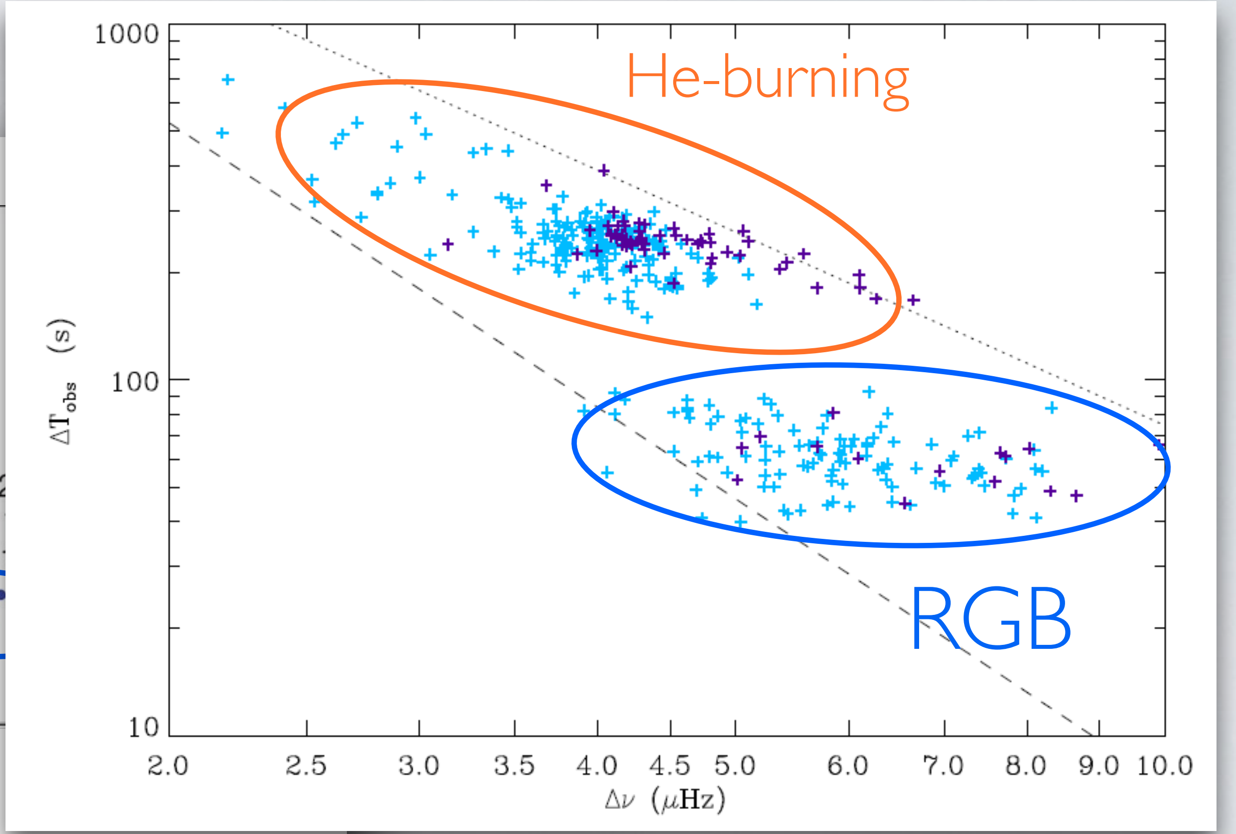
5% offset in the mean density

PERIOD SPACING

Evolutionary state

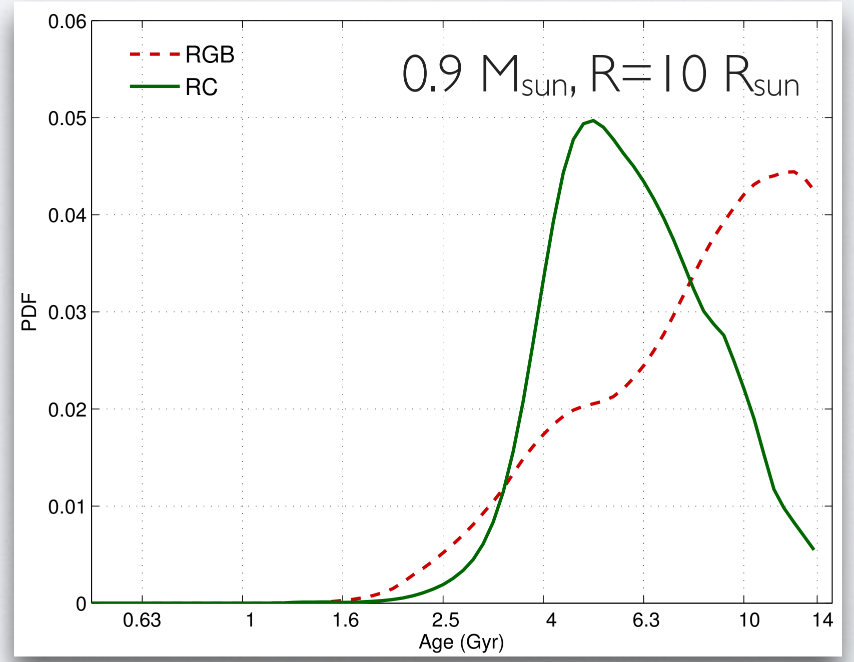


Bedding et al. 2011, Nature



Mosser et al. 2011, A&A

crucial to get robust age estimates



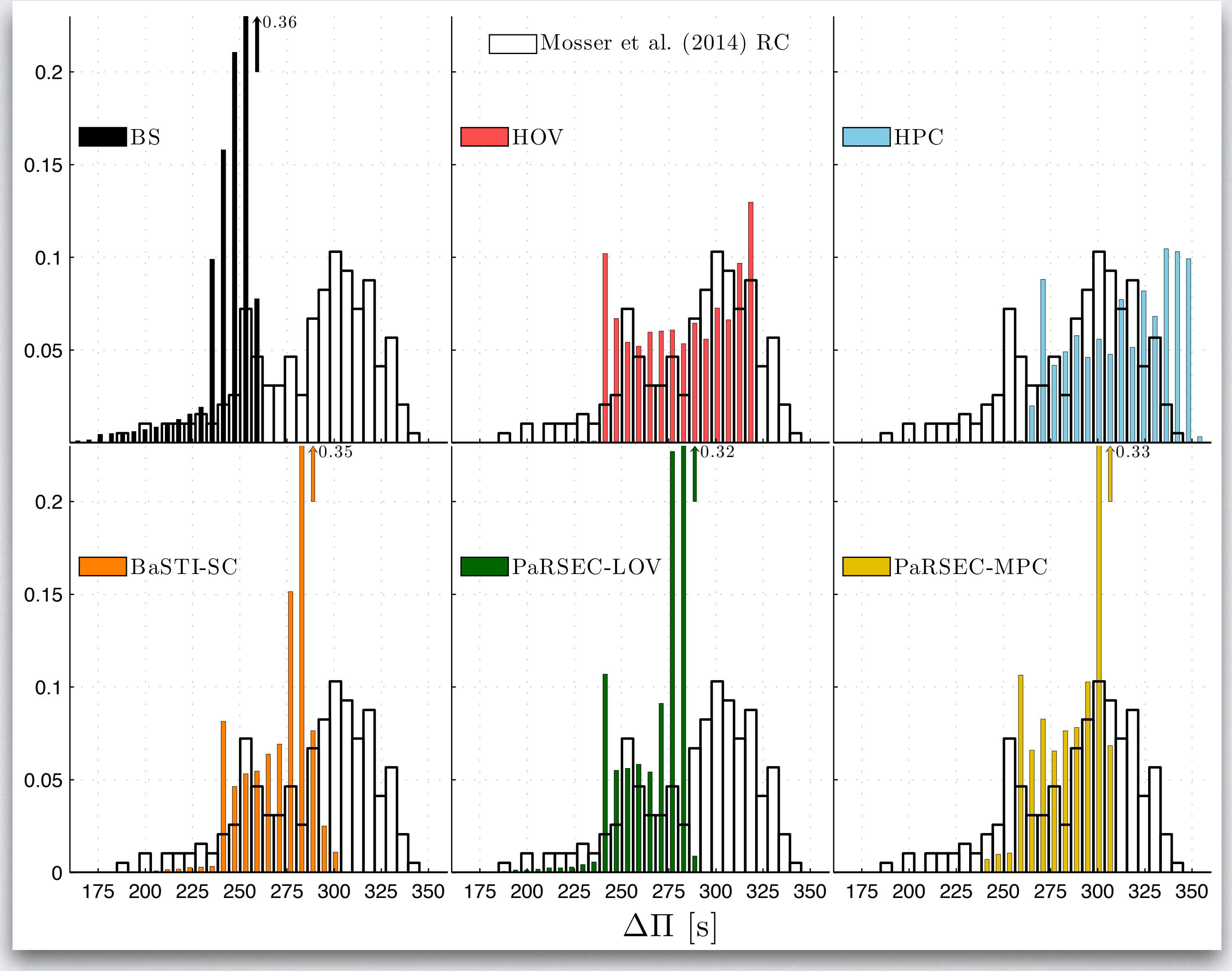
Miglio et al. 2015

PERIOD SPACING

testing models of RC stars

Montalban et al, 2013

improve accuracy of model predictions



Bossini et al, submitted

ASYMPTOTIC APPROXIMATION

deviations from simple asymptotic patterns

$$\Delta\nu = \left(2\int_0^R \frac{\mathrm{d}r}{c(r)}\right)^{-1} \qquad \Delta P = \frac{2\pi^2}{\sqrt{l(l+1)}}\left(\int_{r_1}^{r_2} N\frac{\mathrm{d}r}{r}\right)^{-1}$$

diagnostics of regions of sharp-structure variation in the star

SIGNATURES OF SHARP-STRUCTURE VARIATIONS

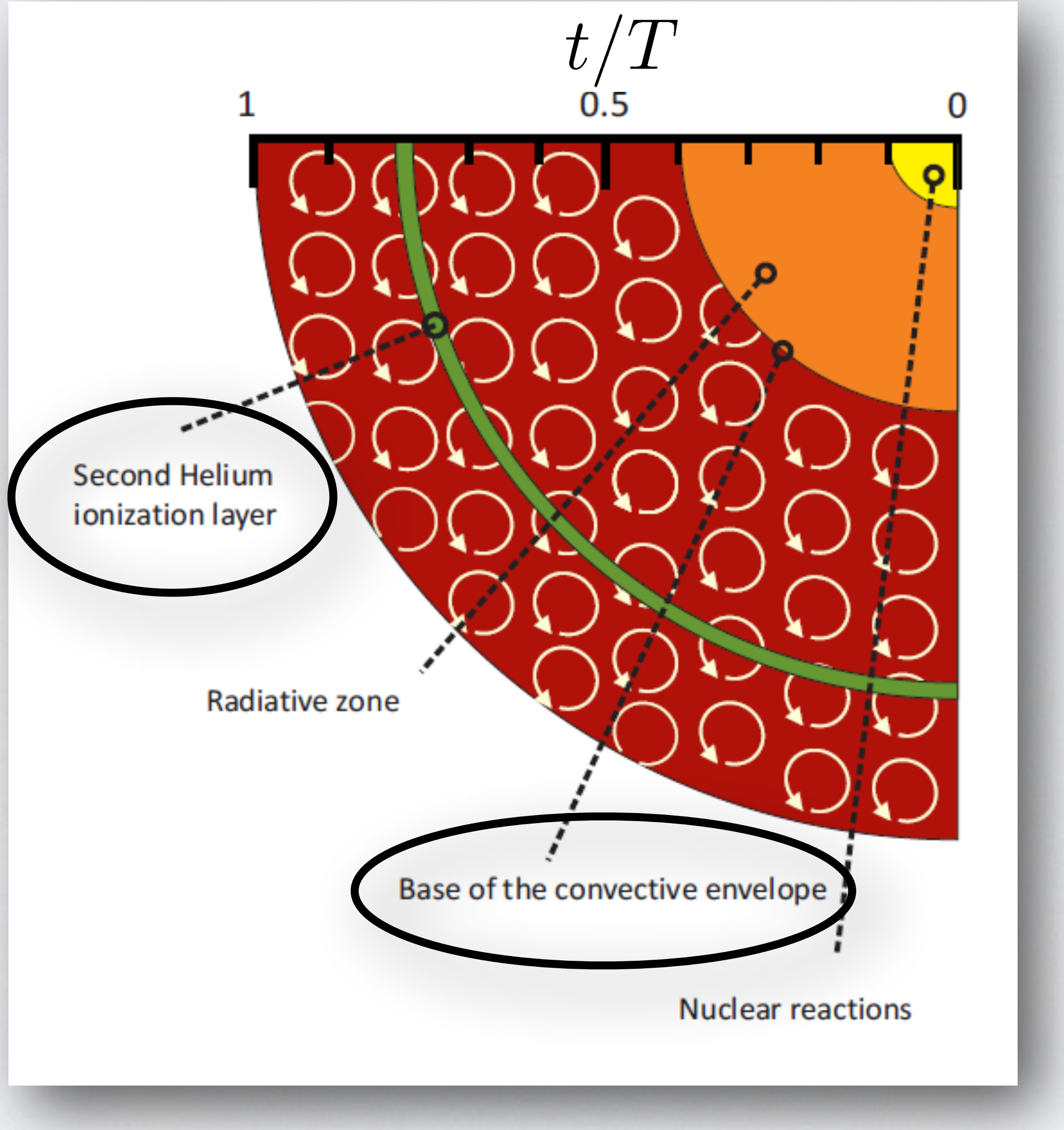
quasi-discontinuity in the distribution of an equilibrium variable inside the star → oscillatory components in the frequencies of oscillation

e.g. acoustic glitches in the Sun

sharp variations of Γ_1 due to helium ionisation

↓

envelope Helium abundance



transition from convective to radiative transport at the base of the convective envelope

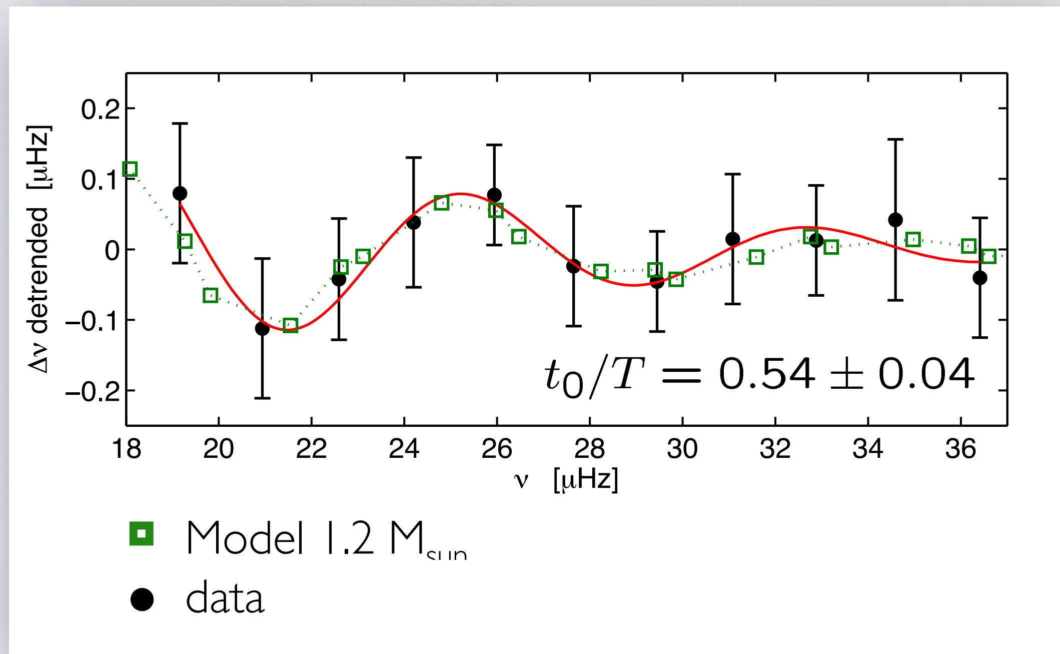
↓

depth of the convective envelope

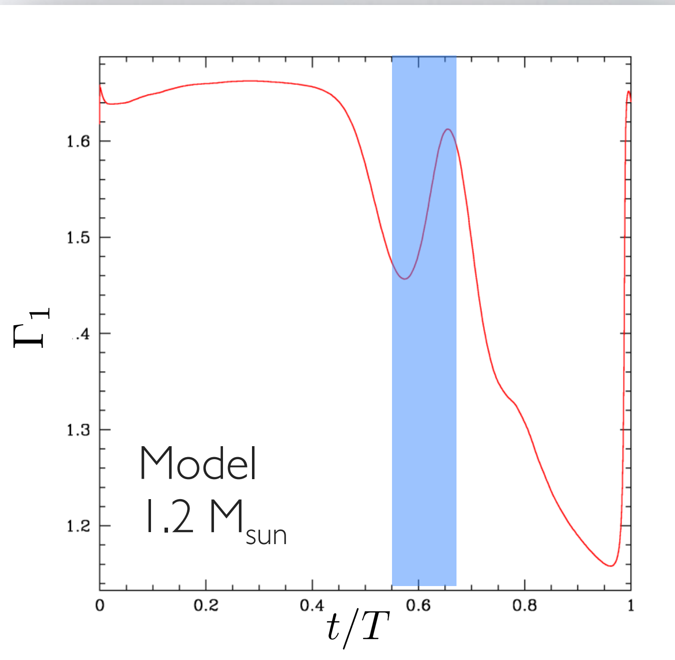
ACOUSTIC GLITCHES IN STARS

- BCZ and HeII in Sun-like stars e.g. Mazumdar et al. 2014
- Signature of convective cores e.g. Silva Aguirre et al. 2013
- HeII ionisation region in a red giant Miglio et al. 2010

HeII ionisation zone in a red giant: CoRoT data



Miglio et al. 2010



where

$$t(r) = \int_0^r \frac{dr'}{c}$$

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

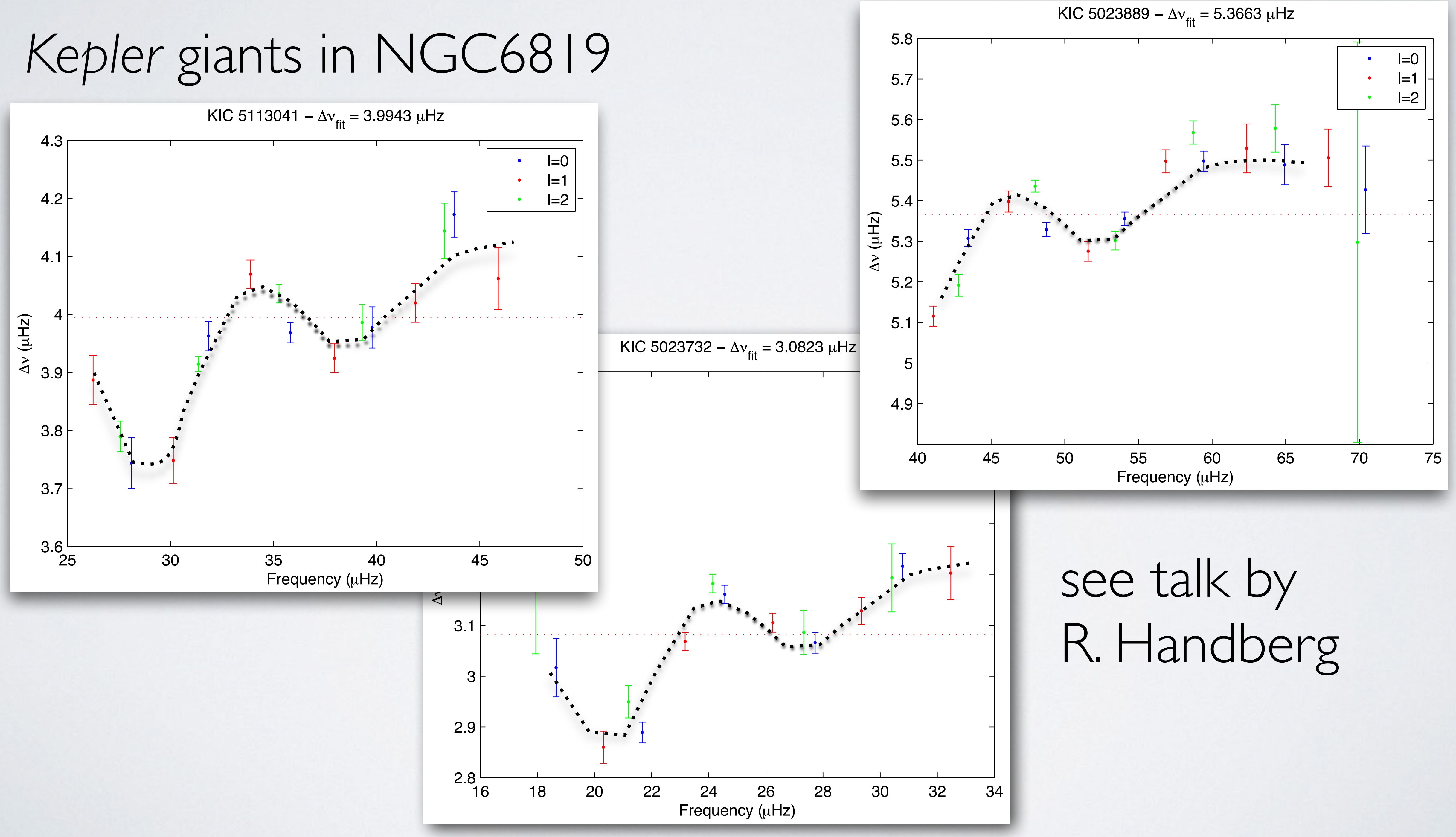
$$\Gamma_1 = \left(\frac{\partial \ln P}{\partial \ln \rho}\right)_{ad}$$

amplitude of the component correlated with Y

ACOUSTIC GLITCHES IN GIANTS

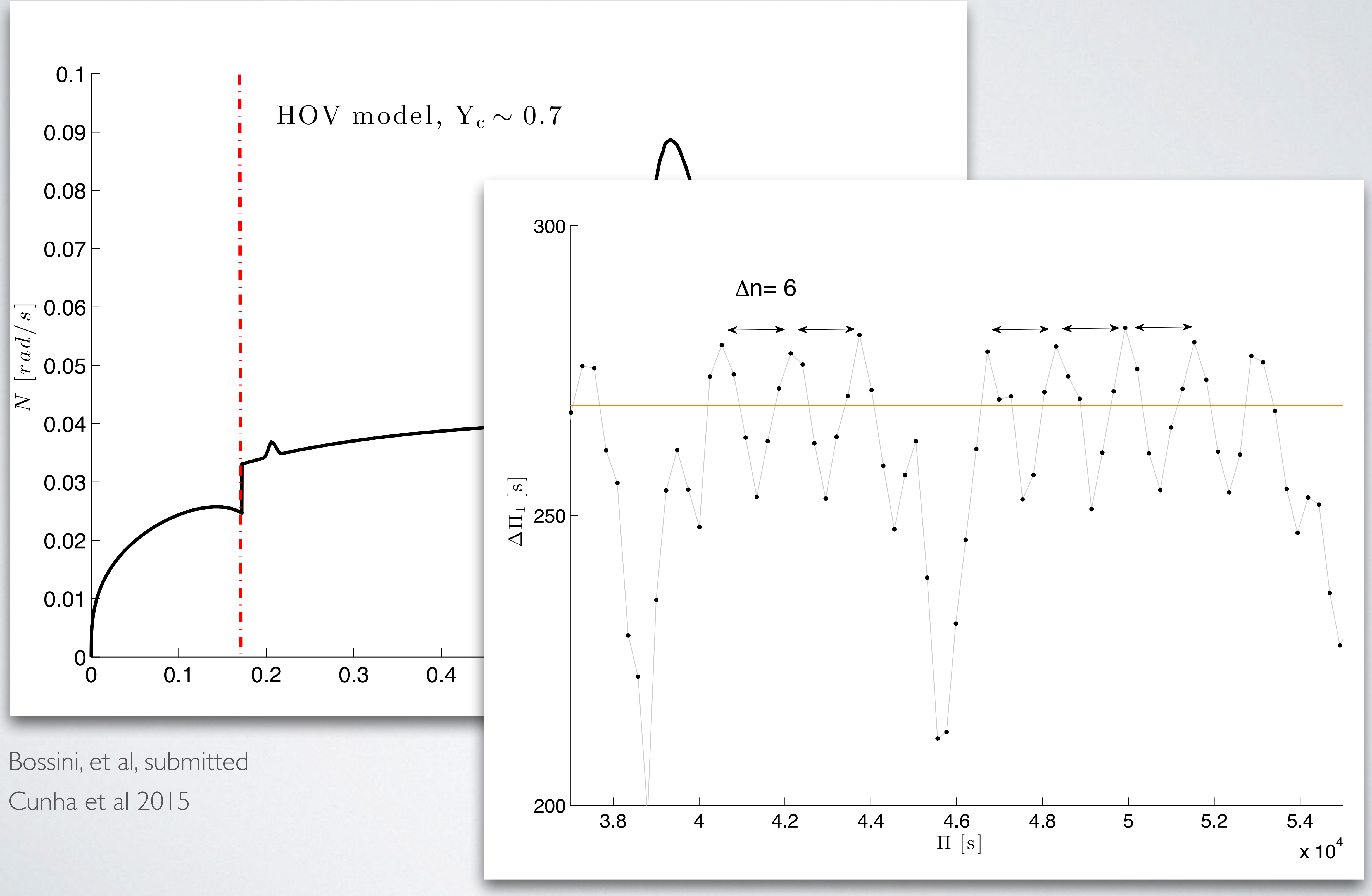
Kepler Broomhall et al. 2014 Corsaro et al. 2015 Vrard et al. 2015

Kepler giants in NGC6819



see talk by
R. Handberg

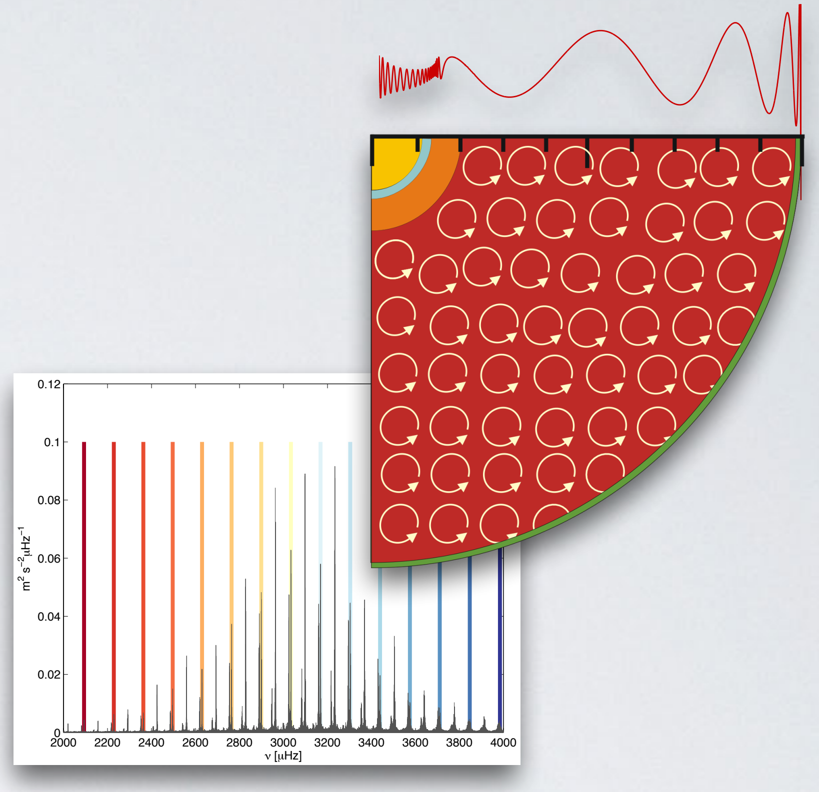
BUOYANCY GLITCHES IN GIANTS



Bossini, et al, submitted

Cunha et al 2015

SUMMARY



- gentle introduction to asteroseismology

- scaling relations : "entry level seismology"

➡ individual radial-mode frequencies

period spacing in RGB and RC

seismic signatures of glitches in the stellar structure

SUMMARY

- why? aiming for precision astrophysics

seismic observables depend on the internal structure,
hence on our (limited) knowledge of stellar physics

✔ tension models against asteroseismic constraints
(e.g. rotation / mixing)

⚠ M, R, Age depend on our understanding of stellar physics.

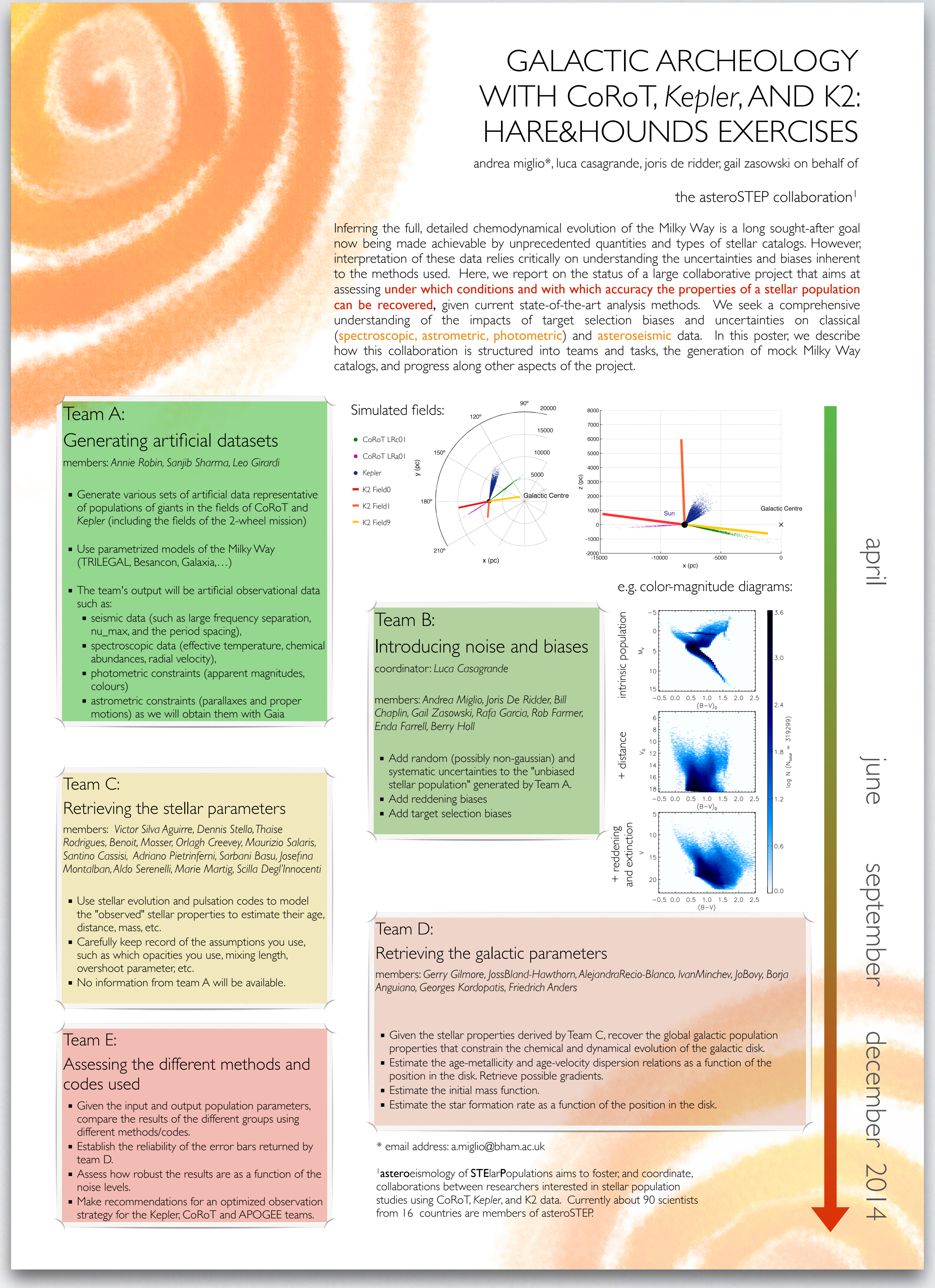
precise age and mass: easy → significant step forward

but … what about accuracy? what are your needs?

asteroSTEP:

Hare&hounds exercises

status and next steps:
Thu @ 14:00



GALACTIC ARCHEOLOGY WITH CoRoT, *Kepler*, AND K2: HARE&HOUNDS EXERCISES

andrea miglio*, luca casagrande, joris de ridder, gail zasowski on behalf of

the asteroSTEP collaboration[1]

Inferring the full, detailed chemodynamical evolution of the Milky Way is a long sought-after goal now being made achievable by unprecedented quantities and types of stellar catalogs. However, interpretation of these data relies critically on understanding the uncertainties and biases inherent to the methods used. Here, we report on the status of a large collaborative project that aims at assessing **under which conditions and with which accuracy the properties of a stellar population can be recovered**, given current state-of-the-art analysis methods. We seek a comprehensive understanding of the impacts of target selection biases and uncertainties on classical (spectroscopic, astrometric, photometric) and asteroseismic data. In this poster, we describe how this collaboration is structured into teams and tasks, the generation of mock Milky Way catalogs, and progress along other aspects of the project.

Team A:
Generating artificial datasets

members: *Annie Robin, Sanjib Sharma, Leo Girardi*

- Generate various sets of artificial data representative of populations of giants in the fields of CoRoT and *Kepler* (including the fields of the 2-wheel mission)
- Use parametrized models of the Milky Way (TRILEGAL, Besancon, Galaxia,…)
- The team's output will be artificial observational data such as:
  - seismic data (such as large frequency separation, nu_max, and the period spacing),
  - spectroscopic data (effective temperature, chemical abundances, radial velocity),
  - photometric constraints (apparent magnitudes, colours)
  - astrometric constraints (parallaxes and proper motions) as we will obtain them with Gaia

Simulated fields:

e.g. color-magnitude diagrams:

Team B:
Introducing noise and biases

coordinator: *Luca Casagrande*

members: *Andrea Miglio, Joris De Ridder, Bill Chaplin, Gail Zasowski, Rafa Garcia, Rob Farmer, Enda Farrell, Berry Holl*

- Add random (possibly non-gaussian) and systematic uncertainties to the "unbiased stellar population" generated by Team A.
- Add reddening biases
- Add target selection biases

Team C:
Retrieving the stellar parameters

members: *Victor Silva Aguirre, Dennis Stello, Thaise Rodrigues, Benoit, Mosser, Orlagh Creevey, Maurizio Salaris, Santino Cassisi, Adriano Pietrinferni, Sarbani Basu, Josefina Montalban, Aldo Serenelli, Marie Martig, Scilla Degl'Innocenti*

- Use stellar evolution and pulsation codes to model the "observed" stellar properties to estimate their age, distance, mass, etc.
- Carefully keep record of the assumptions you use, such as which opacities you use, mixing length, overshoot parameter, etc.
- No information from team A will be available.

Team D:
Retrieving the galactic parameters

members: *Gerry Gilmore, JossBland-Hawthorn, AlejandraRecio-Blanco, IvanMinchev, JoBovy, Borja Anguiano, Georges Kordopatis, Friedrich Anders*

- Given the stellar properties derived by Team C, recover the global galactic population properties that constrain the chemical and dynamical evolution of the galactic disk.
- Estimate the age-metallicity and age-velocity dispersion relations as a function of the position in the disk. Retrieve possible gradients.
- Estimate the initial mass function.
- Estimate the star formation rate as a function of the position in the disk.

Team E:
Assessing the different methods and codes used

- Given the input and output population parameters, compare the results of the different groups using different methods/codes.
- Establish the reliability of the error bars returned by team D.
- Assess how robust the results are as a function of the noise levels.
- Make recommendations for an optimized observation strategy for the Kepler, CoRoT and APOGEE teams.

april

june

september

december 2014

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* email address: a.miglio@bham.ac.uk

[1] **astero**eismology of **STE**lar**P**opulations aims to foster, and coordinate, collaborations between researchers interested in stellar population studies using CoRoT, *Kepler*, and K2 data. Currently about 90 scientists from 16 countries are members of asteroSTEP.

GALACTIC ARCHEOLOGY WITH CoRoT, *Kepler*, AND K2: HARE&HOUNDS EXERCISES

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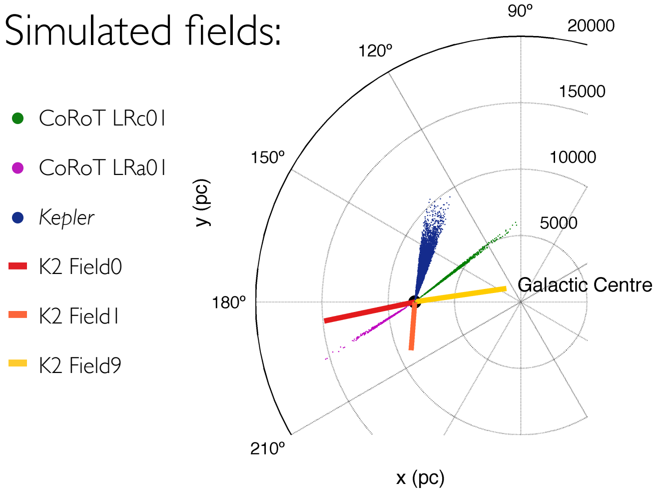
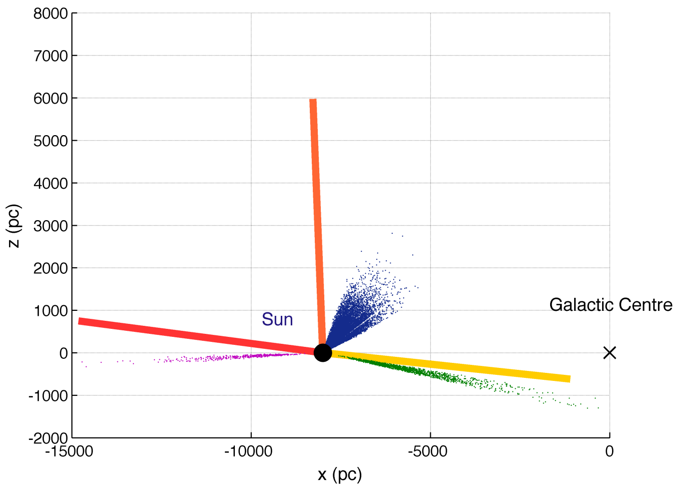
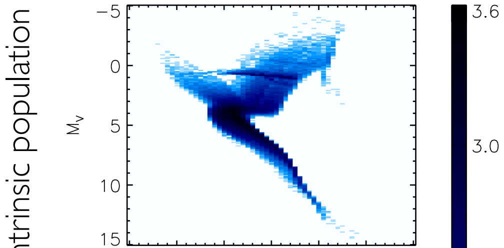
Simulated fields:





e.g. color-magnitude diagrams:



Team B:
Introducing noise and biases

coordinator: *Luca Casagrande*

april