Asteroseismology Across the HR diagram

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Plan

The zoo of pulsating stars in the HR diagram

Asteroseismology for planet-hosting stars characterization

Asteroseismology for probing the interior of stars

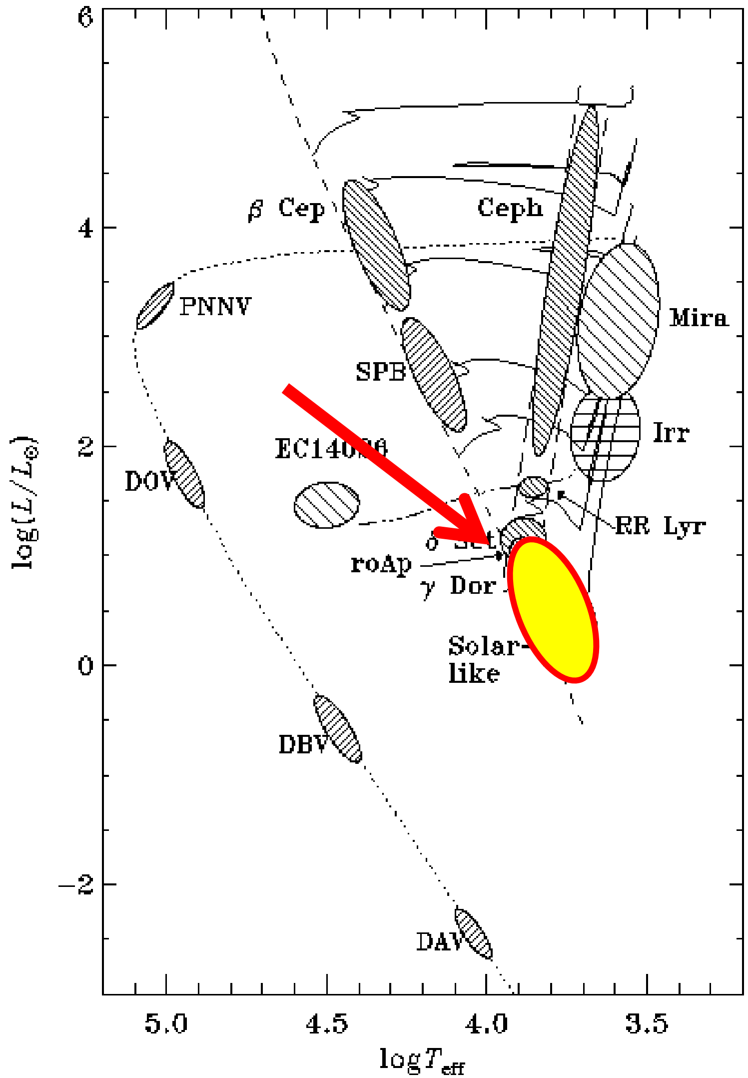
Asteroseismology for the study of our Galaxy

The zoo of pulsating stars in the HR diagram

Solar-like stars

Rich structured spectra of p-modes propagating in their envelope

Very successful probing by asteroseismology

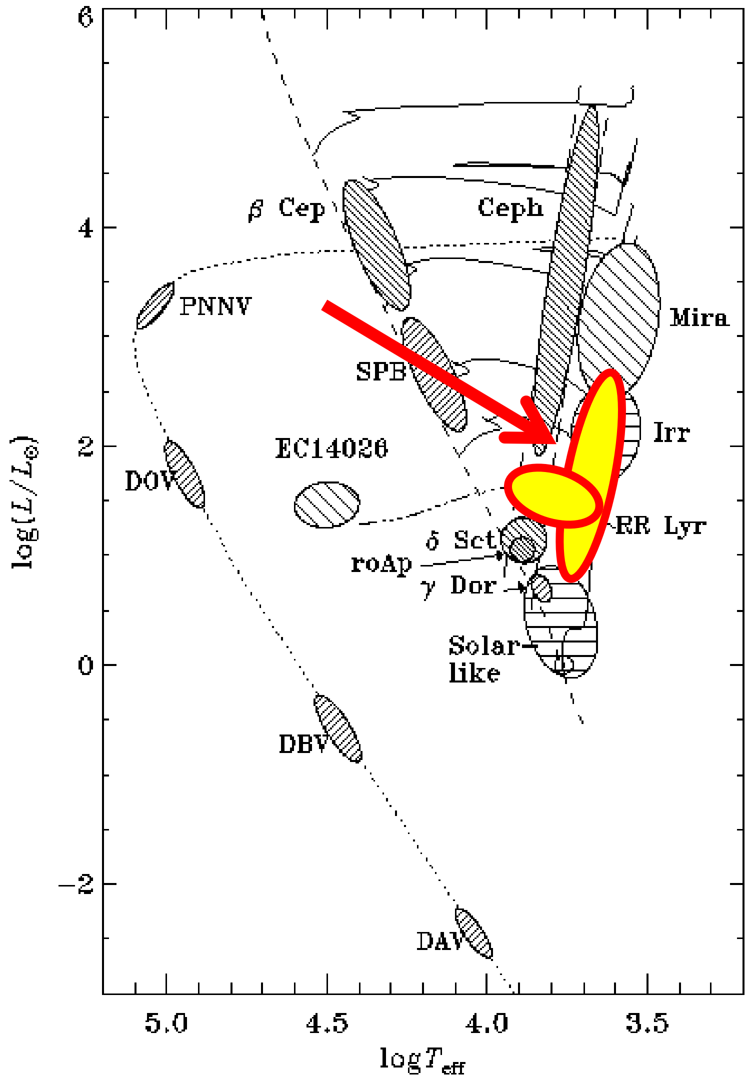


The zoo of pulsating stars in the HR diagram

Red giants
solar-like oscillations

Rich structured spectra
of p-modes and mixed modes probing
both the core and the envelope

Very successful probing
by asteroseismology



The zoo of pulsating stars in the HR diagram

Intermediate mass stars

δ Scuti
γ Doradus
roAp

Massive stars

β Cephei
Slowly Pulsating B

Rich oscillation spectra of p-, g- and mixed modes, but complex structure

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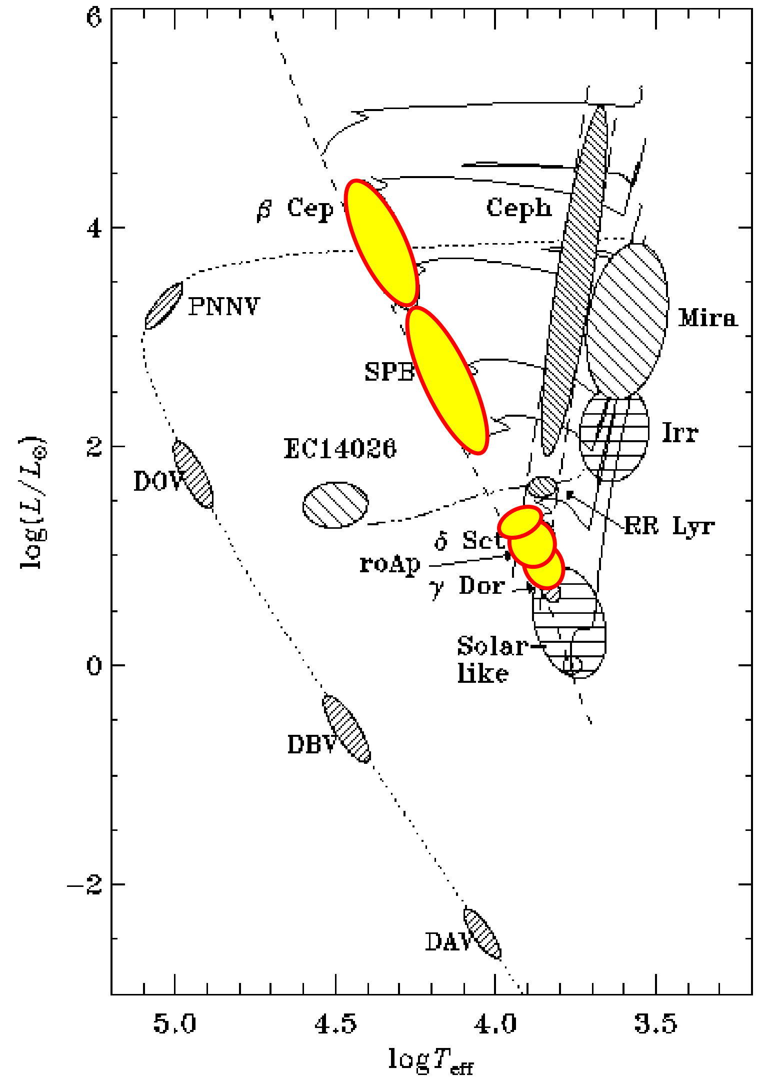
High potential but difficult to interpret



The zoo of pulsating stars in the HR diagram

Subdwarf B stars (sdB)

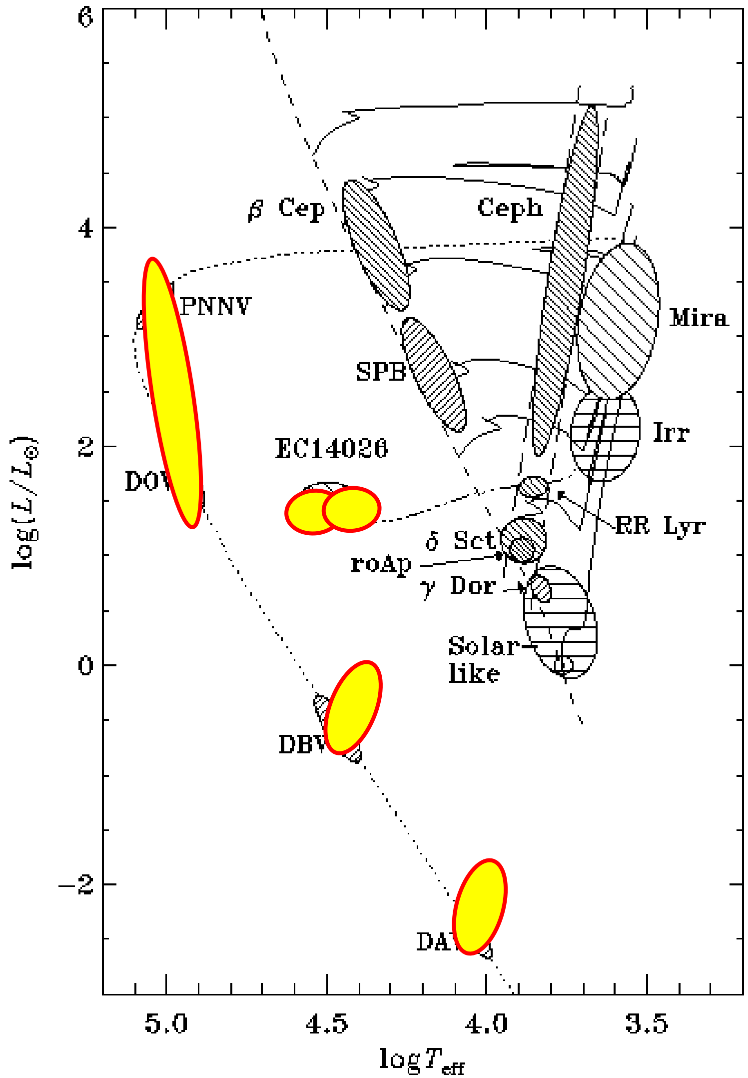
EC 14026 (p-modes)
PG 1716 (g-modes) } Hybrids

Rich oscillation spectra of p- and g-modes, successful asteroseismology

White dwarfs

GW Virginis
DBV
DAV

Rich oscillation spectra of g-modes, successful asteroseismology and high potential for cosmochronology



Asteroseismology for planet-hosting stars characterization

Characterization of the hosting star

Spectro-photometric measurements + atmosphere models
→ Teff, log g, L, **radius**, chemical composition

} See talk of T. Morel

+ stellar structure models → **Mass, age**

+ interferometry → More precise **radius**

+ Oscillation frequencies → More precise **mean density, radius, mass, age, …**

Characterization of its planets

Stellar masses and radii → **Masses and radii of the planets**

Age of the star = **Age of the planetary system**

Stellar surface composition → **Initial chemical composition of the system**

Asteroseismology for planet-hosting stars characterization

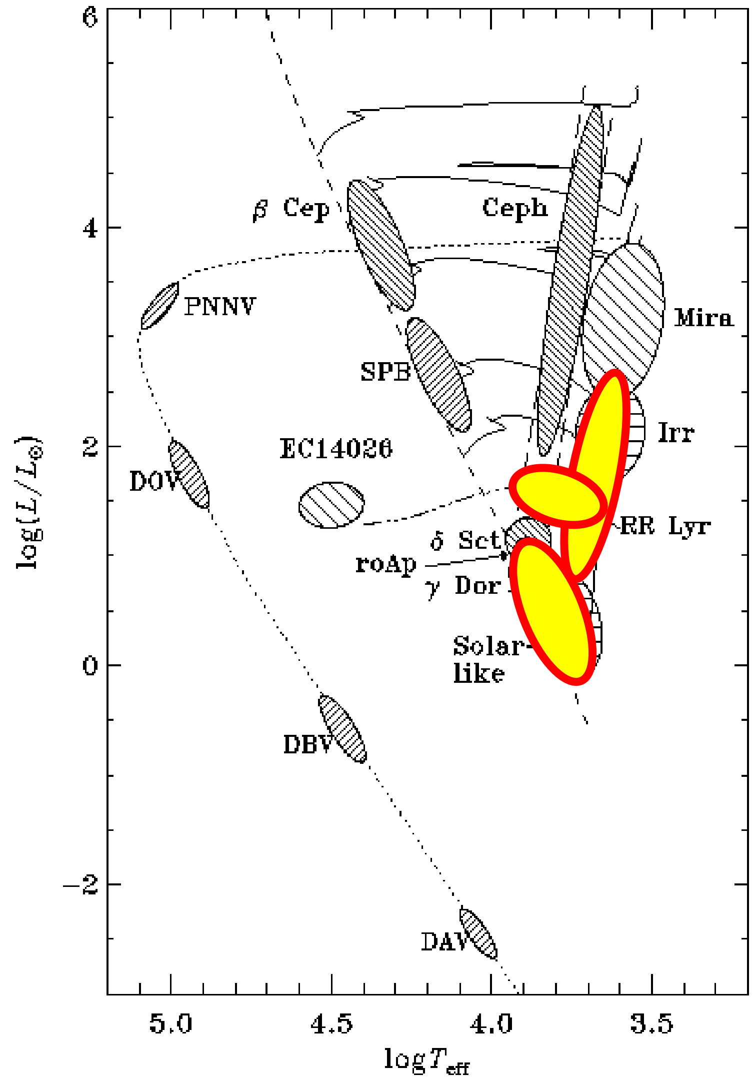
Solar-like stars and red giants

Rich structured spectra of p-modes probing the envelope

Oscillations spectra of homologous stars scale as:

$$\nu_{n,l} \propto \left(\int dr/c\right)^{-1} \propto \sqrt{M/R^3}$$

Mean density is measured with very high precision by asteroseismology



PLATO 2.0 Science Workshop
ESTEC, Noordwijk, 29-31 July 2013

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

Rich structured spectra of p-modes probing the envelope

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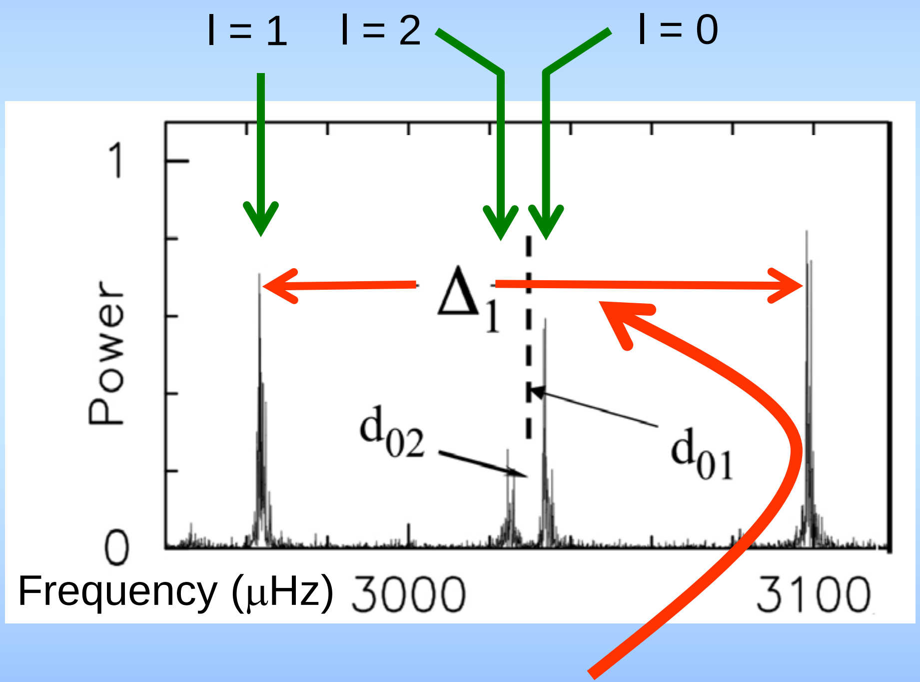
Mean density is measured with very high precision by asteroseismology

Structured spectra

Easy mode identification



Excellent seismic indicator of the mean density: the **large separation** :

$$\Delta_{n,\ell} = \nu_{n,\ell} - \nu_{n-1,\ell} \simeq \left(2 \int_0^R \frac{dr}{c} \right)^{-1} \propto \sqrt{\frac{GM}{R^3}}$$

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

Another useful seismic indicator: the frequency at maximum power ν_{max}

Empirical law (Brown et al., Kjeldsen & Bedding): $\nu_{max} \propto \nu_{cut} \propto g/T_{eff}^{1/2}$

Combining the $\Delta\nu$ and ν_{max} scaling laws:

$$\frac{R}{R_\odot} = \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}$$

$$\frac{M}{M_\odot} = \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3/2}$$

$\Delta\nu$, ν_{max}, T_{eff} → **R, M**

Main limitation:
stars are not homologous → More precise but still approximate measurements of masses and radii

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

$$\frac{R}{R_\odot} = \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}$$

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Simulations: The Sun as a star observed by TESS and PLATO

TABLE 2 – Déterminations de $\Delta\nu$ et $\nu_{\max}$ pour les différentes simulations

Mission	Cible	Durée	magnitude	$M/M_\odot$	$\delta(M/M_\odot)$	$\delta M/M$	$R/R_\odot$	$\delta(R/R_\odot)$	$\delta R/R$
TESS	Sun	1 mois	5	1.105	0.248	22.4%	1.020	0.051	5 %
	Sun	1 mois	9	1.240	0.533	43 %	1.089	0.201	18.5 %
Plato	Sun	2 ans	8.2	1.170	0.186	15.9%	1.044	0.026	2.5 %
		2 ans	9	1.120	0.180	16.1%	1.030	0.027	2.6 %
		2 ans	10	1.181	0.237	20.0%	1.049	0.042	4.0 %
		2 ans	11	1.552	0.546	35.2%	1.143	0.142	12.4 %

Goupil, Baudin et al. 2013

Results for Plato simulated data (2 years) for a 9 mag star
are similar to Tess ones (1 month) for a 5 mag star.

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

With rich oscillation spectra, asteroseismology can do much better.

Direct approach :

Free parameters : Mass, age, hélium, chemical transitions, mixing-length, extra-mixing, …

Local or global **minimization** → Search of stellar model best reproducing observations (frequencies, Teff, L, g, …)

See talks of M. Bazot, V. Van Grootel, W. Chaplin, H. Kjeldsen

Results: Precise measurements of **Mass**, **radius**, **age**, helium content, mixing-length, extra-mixing, …

But results are model dependent …

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

Measurements of **ages** are model dependent

Changing prescriptions on extra-mixing, micro- and macroscopic transport processes of chemicals modifies the quantity of burned hydrogen and thus the duration of the main sequence phase.

Degeneracies in the parameter space

-The **mean density** is much better constrained than **masses** and **radii** individually.

- **Helium – mass** degeneracy (can sometimes be lifted)

With present precisions on the observed frequencies + photospheric parameters :

Ages to 10-20% accuracy
Masses to 2-4% accuracy
Radii to 1-2% accuracy

Goupil et al. 2013

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

Future prospects for improving even more the accuracies

Seismic inversion

Begins to be possible with long time series obtained in the space missions era

Variational principle → Probe of internal sound speed, rotation, … profiles

Extremely successful for the Sun (helioseismology)

→ Global characteristics (mean density, …) with very high precision and accuracy (~ 0.5%, Reese et al. 2012)

Much less model dependent ! See talk of D. Reese

Asteroseismology for planet-hosting stars characterization

Solar-like stars and red giants

Future prospects for improving even more the accuracies

Better correcting near-surface inaccuracies (surface effects)

Empirical approach (Kjeldsen et al. 2008)

Simple frequency correction approach calibrated on the Sun

→ To be extended to stars "very" different from the Sun: subgiants, red giants, F stars, …

Physical approach

- Inaccuracies in the treatment of convection → Using 3D LES simulations
- Inaccuracies in mode physics → Non-adiabatic computations with Time-Dependent Convection

Asteroseismology for probing the interior of stars

Solar-like stars and red giants

p-modes frequencies mainly depend on

- the sound speed : $c^2 = \frac{\Gamma_1 P}{\rho} \propto \frac{\Gamma_1 T}{\mu}$
- the rotation profile : $\Omega(r, \theta)$

→ Convection and opacities throughout T

→ Transport processes of chemicals and angular momentum throughout Γ_1, μ, Ω

Seismic indicators :

Large separation, mean density : $\Delta_{n,\ell} = \nu_{n,\ell} - \nu_{n-1,\ell} \propto \sqrt{\frac{GM}{R^3}}$

Small separation, age : $\delta_{n,\ell} = \nu_{n-1,\ell+2} - \nu_{n,\ell}$

Scaled small separation : $r_{02,n} = \delta_{n,0}/\Delta_{n,1}$ → Poorly affected by surface effects

Small spacing : $\delta_{01,n} = \nu_{n,0} - 2\nu_{n,1} + \nu_{n+1,0}$

Second order difference : $\delta_{2,n,\ell} = \nu_{n+1,\ell} - 2\nu_{n,\ell} + \nu_{n-1,\ell}$

→ - Helium content in the envelope
- Base of the convective envelope

Asteroseismology for probing the interior of stars

Mixed modes in subgiants and red giants

As a star evolves, its core contracts and its envelope expands

➡ Formation of two mode cavities, one in the core and the other in the envelope

➡ Presence of **mixed modes** probing the core:

Buoyancy frequency

$$N^2 = -g \left(\frac{1}{\Gamma_1} \frac{\mathrm{d}\ln P}{\mathrm{d}r} - \frac{\mathrm{d}\ln \rho}{\mathrm{d}r} \right)$$

↳
- Density contrast ➡ Age
- Core chemical composition ➡ Transport of chemicals
- Core rotation ➡ Transport of angular momentum

Subgiants:

- Precise seismic measurements of ages
- Seismic probing of the μ-gradient region
- Seismic probing of internal rotation

➡ See papers of Deheuvels et al. 2010-2012

Asteroseismology for probing the interior of stars

Mixed modes in subgiants and red giants

Red giants:

- The period spacing of mixed modes, a powerful seismic indicator:
  - Clear distinction between H-shell and He-core burning red giants:
    Bedding et al. (Kepler, Nature, 2011), Mosser et al. (CoRoT, A&A, 2011)
  - Indicator of the Helium core mass during the He-burning phase
    Montalbán et al. (2013)

- Detection of rotational multiplets

  The core of red giants is rotating much more slowly than expected:

  Beck et al. (2011), Eggenberger et al. (2012), Mosser et al. (2012)

  Which physical process leads to such an important core-envelope angular momentum transfer ?

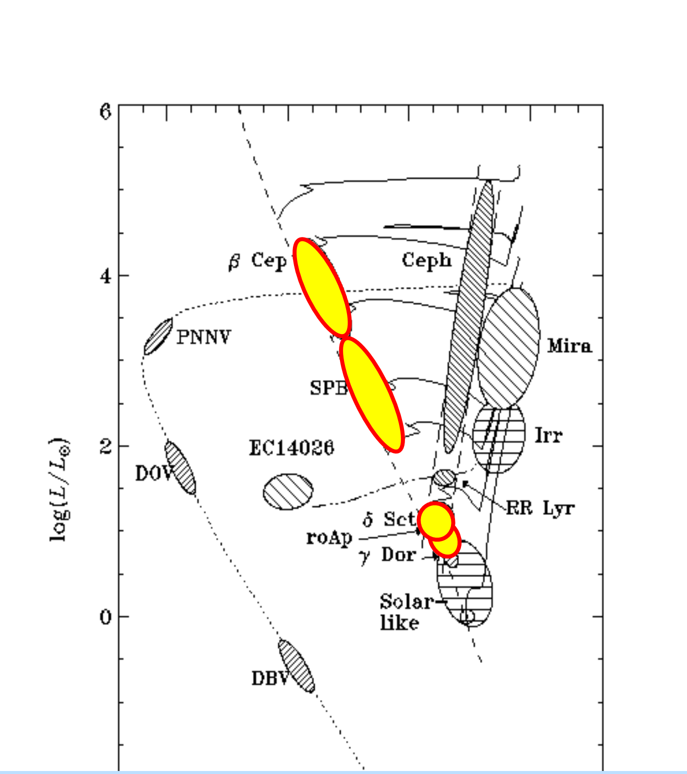
Asteroseismology for probing the interior of stars

Intermediate mass stars

δ Scuti : low-order p-modes
γ Doradus : high-order g-modes
} Hybrids

Massive stars

β Cephei : low-order p-modes
Slowly Pulsating B : g-modes
} Hybrids



Oscillation spectra holding information on both their core and envelope (hybrids)

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High potential but difficult to interpret because :

- **Mode identification** only possible for the dominant modes observed in multi-color photometry or spectroscopy

- **Rotation** is often fast ➡ Complicates the spectra
  ➡ Structure models still in their infancy
  ➡ Oscillation codes are time-consuming

Asteroseismology for probing the interior of stars

Intermediate and high mass main sequence stars

Oscillation spectra strongly depend on the buoyancy frequency:

$$N^2 = -g\left(\frac{1}{\Gamma_1}\frac{\mathrm{d}\ln P}{\mathrm{d}r} - \frac{\mathrm{d}\ln\rho}{\mathrm{d}r}\right)$$

$$\simeq \frac{\rho g^2}{P}(\nabla_{\mathrm{ad}} - \nabla + \nabla_\mu)$$

Temperature gradient ➡ Convective zone boundaries, …

Mean molecular weight gradient ➡ chemical composition

Period spacing of g-modes : $\Delta P = P_{k,\ell} - P_{k-1,\ell} \simeq \frac{2\pi^2}{\sqrt{\ell(\ell+1)}}\left(\int_{r_c}^{R}\frac{N}{r}\,\mathrm{d}r\right)^{-1}$

Good indicator of :

- Core hydrogen abundance ➡ Age
- Chemical profile and extra-mixing above the convective core

↳ Macroscopic transport of chemicals:

- Convective penetration
- Shear turbulence
- Meridional circulation, …

Asteroseismology for probing the interior of stars

Intermediate and high mass main sequence stars

Seismic probing of internal rotation (when rotational multiplets are detected)

Some stars have a core rotating about three times faster than the envelope

Others seem to rotate rigidly, why ? → - Magnetic field ? No correlation …
- Angular momentum transport by waves and modes ?

Non-adiabatic asteroseismology

Comparison between the theoretical and observed ranges of excited modes

In massive stars : mode excitation by a κ-mechanism in the Iron opacity bump

↳ **Constraints on opacities** → Evidences of Iron accumulation and/or opacity underestimation (LMC and SMC)

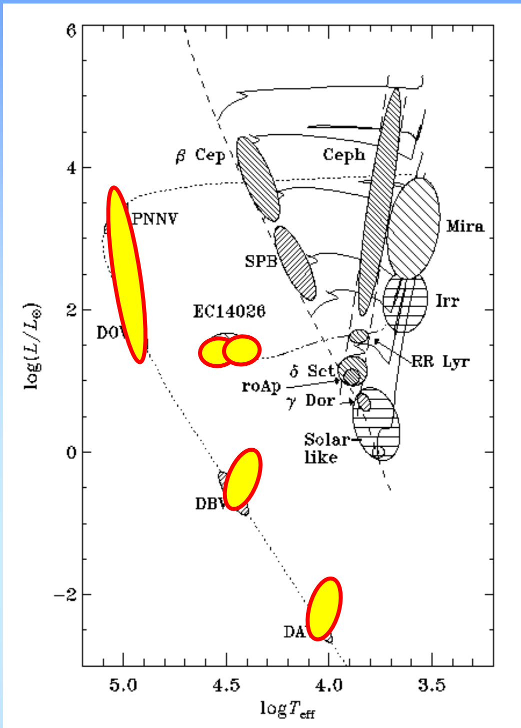
See Salmon et al. (2012)

In intermediate mass stars : mode excitation and damping depend on **convection**

↳ **Constraints on convection treatment**

Asteroseismology for probing the interior of stars

Subdwarf B stars (sdB)



Rich oscillation spectra of p- and g-modes

Successful seismic probing of :

total mass, mass of thin H envelope, radius,

core chemical composition: X_c(C+O) → age

extension of convective core → extra-mixing

See next talk by V. Van Grootel

Non-adiabatic asteroseismology

↳ Strong constraints on transport of chemicals

See works of H. Hu (2008-2011)

White dwarfs

Rich oscillation spectra of g-modes

Successful seismic probing of :

total mass, location of chemical transition zones (H-He, He-CO), …

Asteroseismology for the study of our Galaxy

Red giants

$\Delta\nu$ and ν_{max} , T_{eff} for ~ 10^4 red giants observed by CoRoT, Kepler

Precise measurements of

masses, radii, distances, ages

$$\frac{R}{R_\odot} = \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{1/2}$$

$$\frac{M}{M_\odot} = \left(\frac{\nu_{max}}{\nu_{max,\odot}}\right)^{3}\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{3/2}$$

See wednesday talk of A. Miglio

White dwarfs cosmochronology

Classical and seismic characterization ➡ **ages**

3D view of the evolution of the Milky Way

Thank you