Seismic analysis of red giants on the Asymptotic Giant Branch

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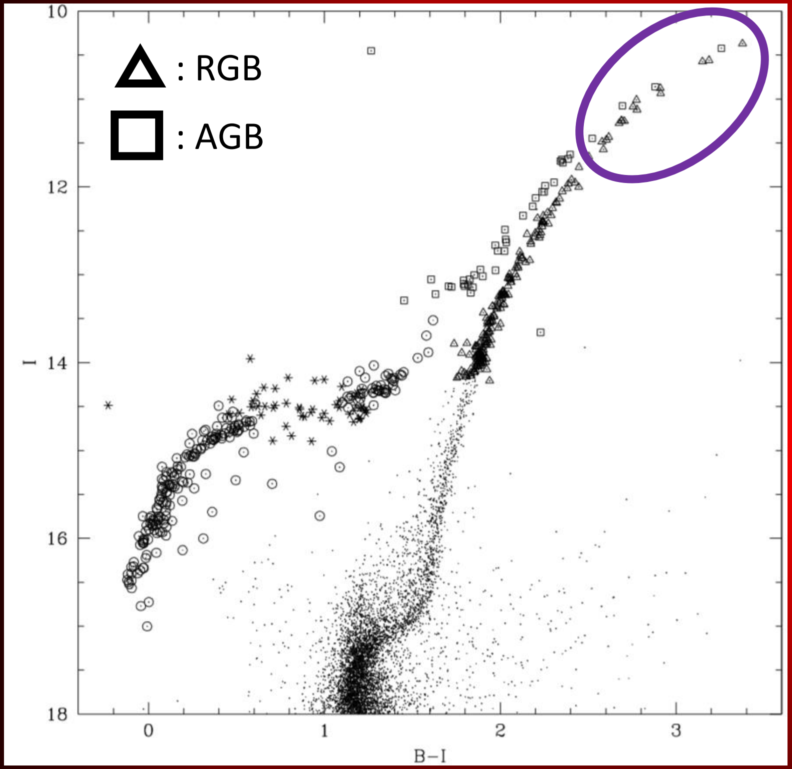
I – Context and Scientific concerns

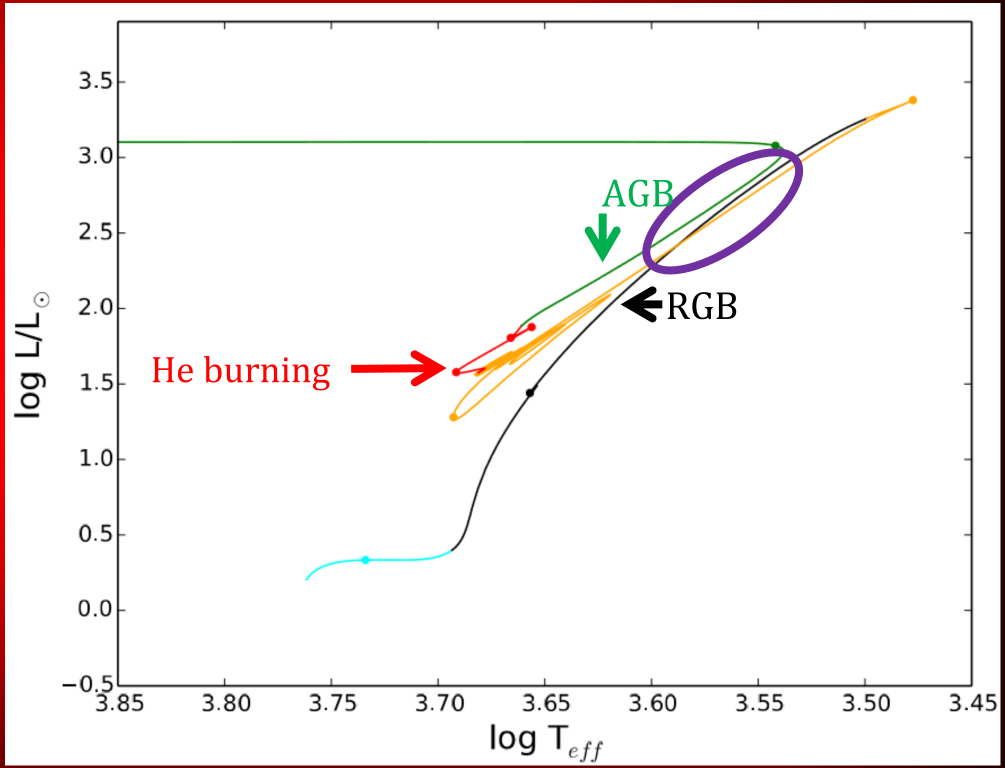
Stellar evolution

RGB: Red Giant Branch
AGB: Asymptotic Giant Branch

- Disentangle evolved AGB stars from evolved RGB stars?



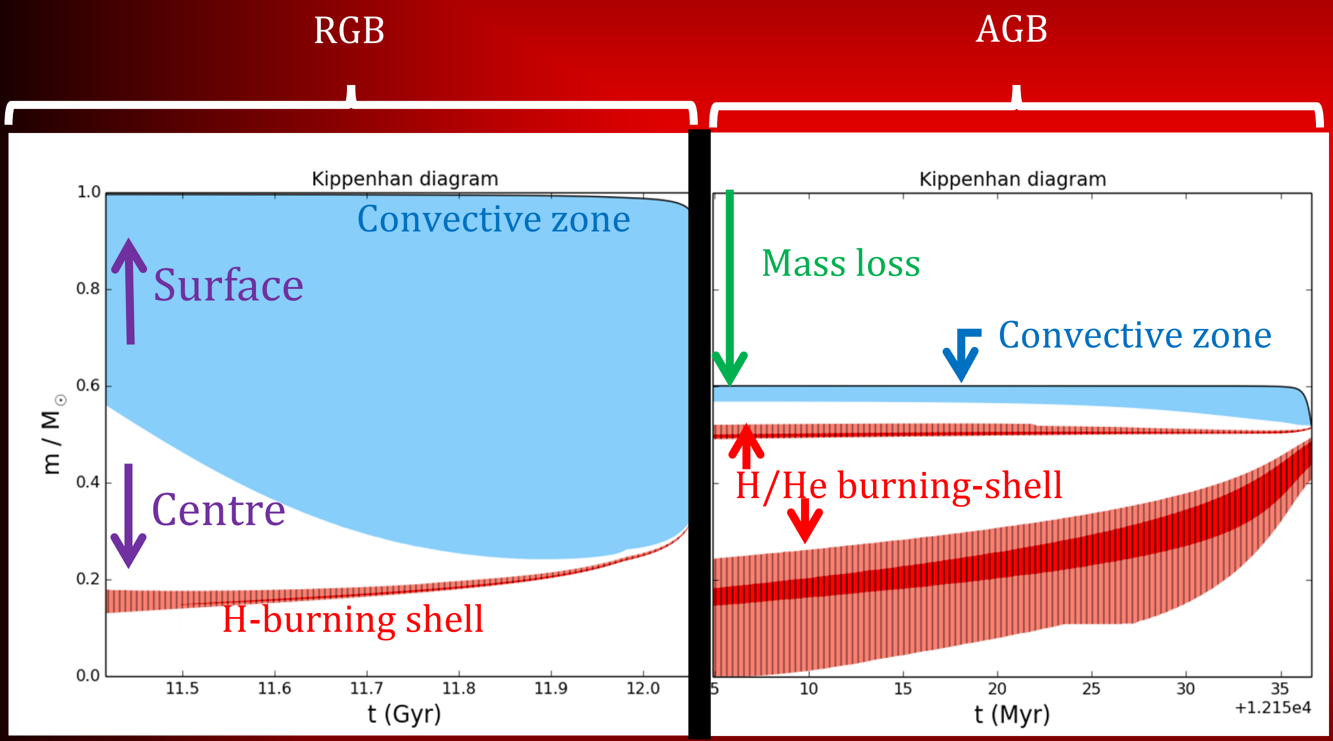
Color-magnitude diagram including stars in the globular cluster M5, Canada-France-Hawaii Telescope (CFHT)
Credit: Sandquist, E. & Bolte, M. 2004



HR diagram ($1M_\odot$) locating the Red Giant and the Asymptotic Giant Branches
Credit: C. Gehan

Stellar evolution

- Yet, structural differences between RGB stars and AGB stars



Internal structure evolution for RGB and AGB stars

Credit: C. Gehan

- How to efficiently disentangle AGB stars from RGB stars ?

Aim of this presentation:

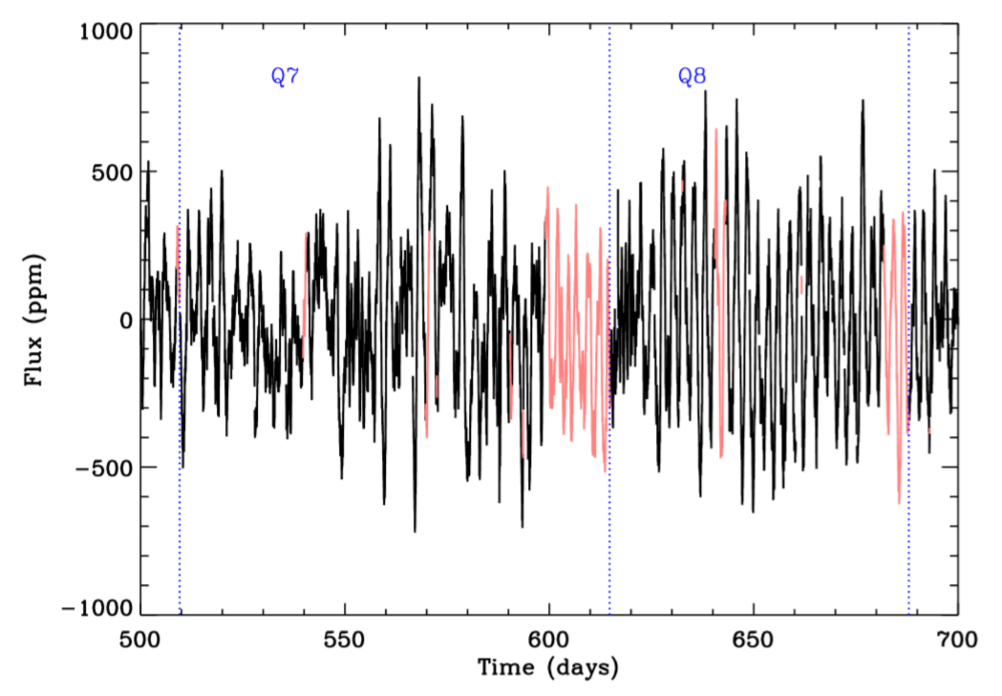
- Characterise evolved stars through their seismic signature in the oscillation spectrum
- Bring constraints on the internal structure with asteroseismology

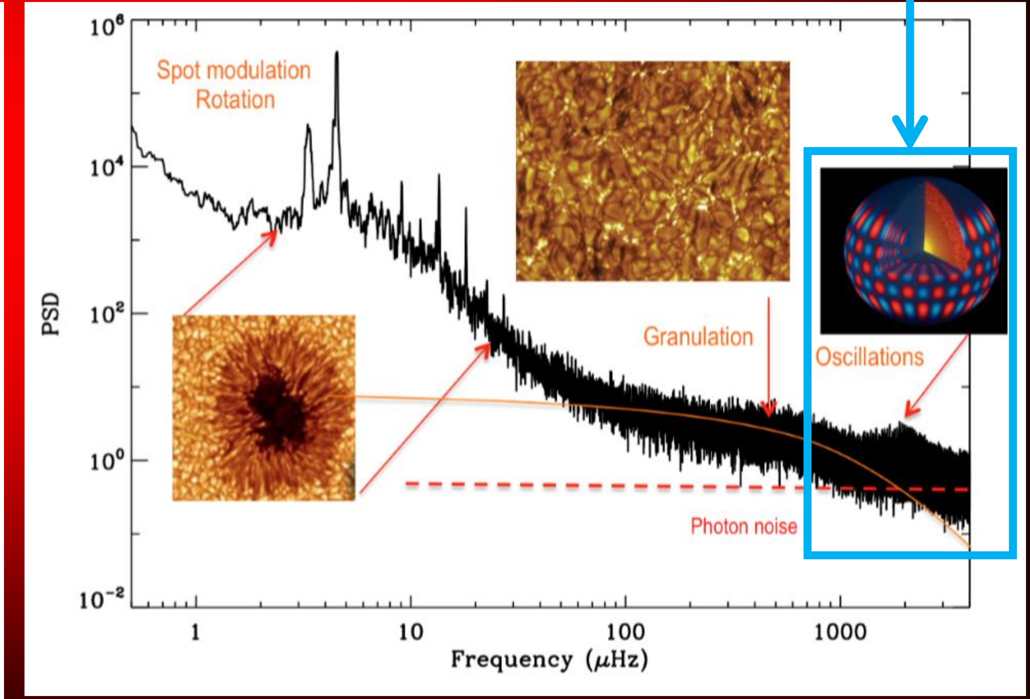
Pressure mode identification

- Constructive interferences give rise to the pressure-mode oscillation spectrum

Fourier transform

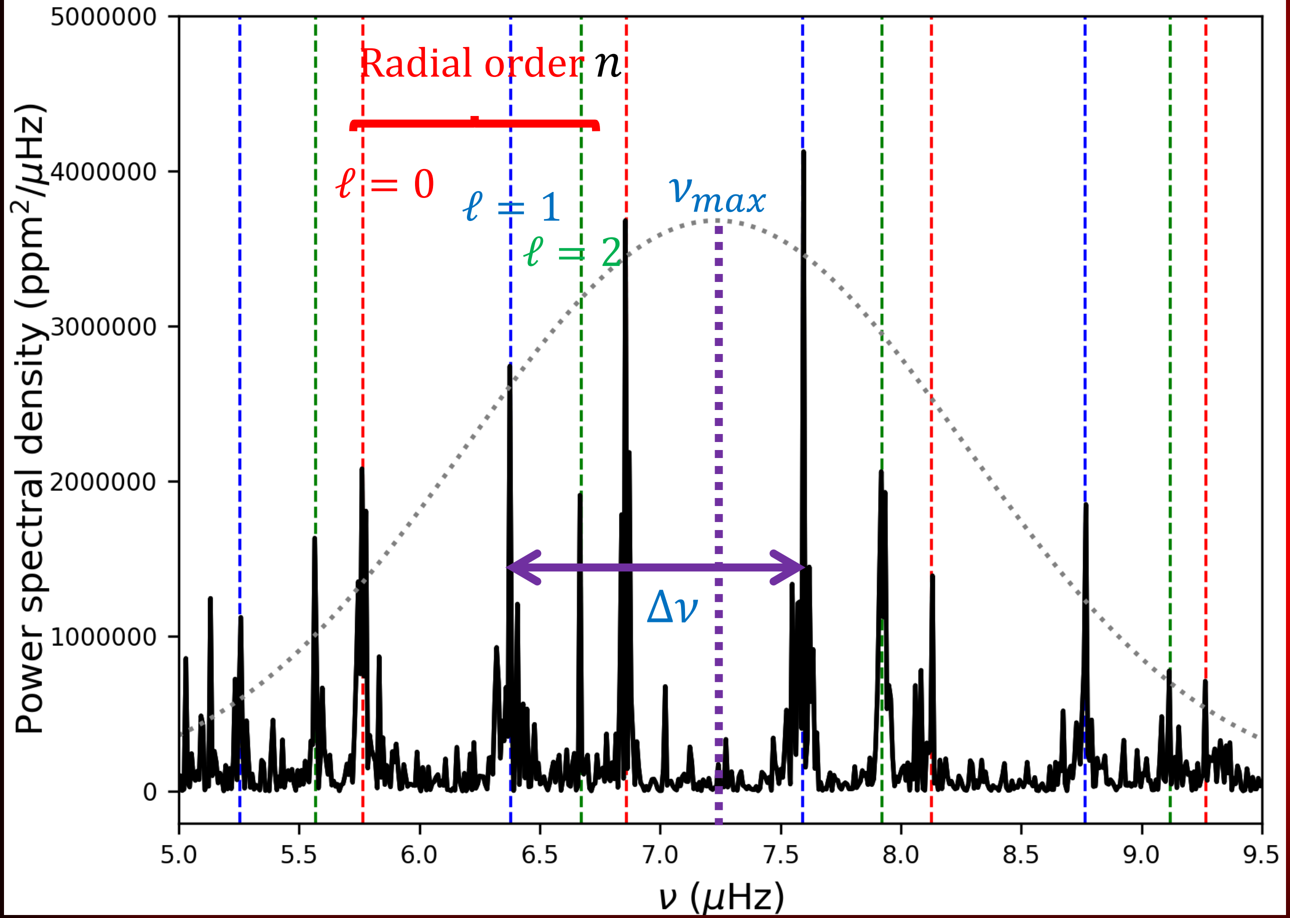
Light curve → Power spectrum





Kepler F star KIC 3733735, *Credit: Garcia R. A. 2015*

Pressure mode identification



KIC 1719297, $\Delta\nu = 1.21\ \mu$Hz

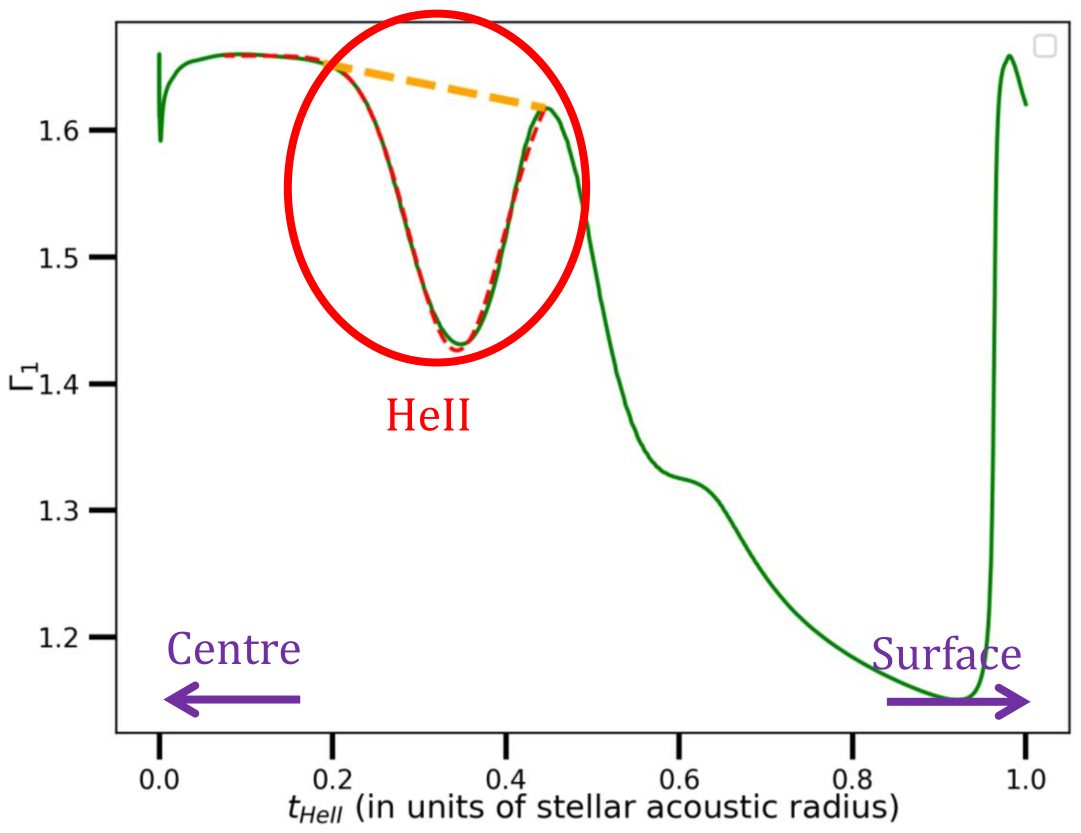
- Modes characterised by a radial order n, and a degree ℓ
- p-mode frequencies for red giants (Mosser et al. 2011a)

$$\boxed{\nu_{n,\ell}^{\mathrm{UP}} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu}$$

ε : acoustic offset
$d_{0\ell}$: small separation
$\Delta\nu$: large separation
α : curvature

II – Characterising the second helium ionisation zone (HeII)

How to probe HeII?



$\Gamma_1 = f(\text{acoustic radius})$, highlighting the second helium ionisation zone (HeII)

$$\Gamma_1 = \left(\frac{\mathrm{d}\ln P}{\mathrm{d}\ln \rho}\right)_s$$

- Sharp variation of Γ_1 over a short distance with respect to the wavelength of the oscillations

- Introduce a modulation in the p-mode pattern:

$$\nu_{n,\ell}^{UP} \rightarrow \nu_{n,\ell}^{UP} + \delta\nu_{n,\ell}$$

caused by HeII

How to probe HeII?

(1) $\nu^{\mathrm{UP}}_{n,\ell} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu$

- Glitch: Modulation in the mode frequencies caused by HeII

Measured in the oscillation spectrum

$$\begin{cases} \Delta\nu_{glitch}(n,\ell) = \nu_{n+1,\ell} - \nu_{n,\ell} \\ \Delta\nu_{noglitch}(n) = \nu^{UP}_{n+1,\ell} - \nu^{UP}_{n,\ell} \end{cases}$$

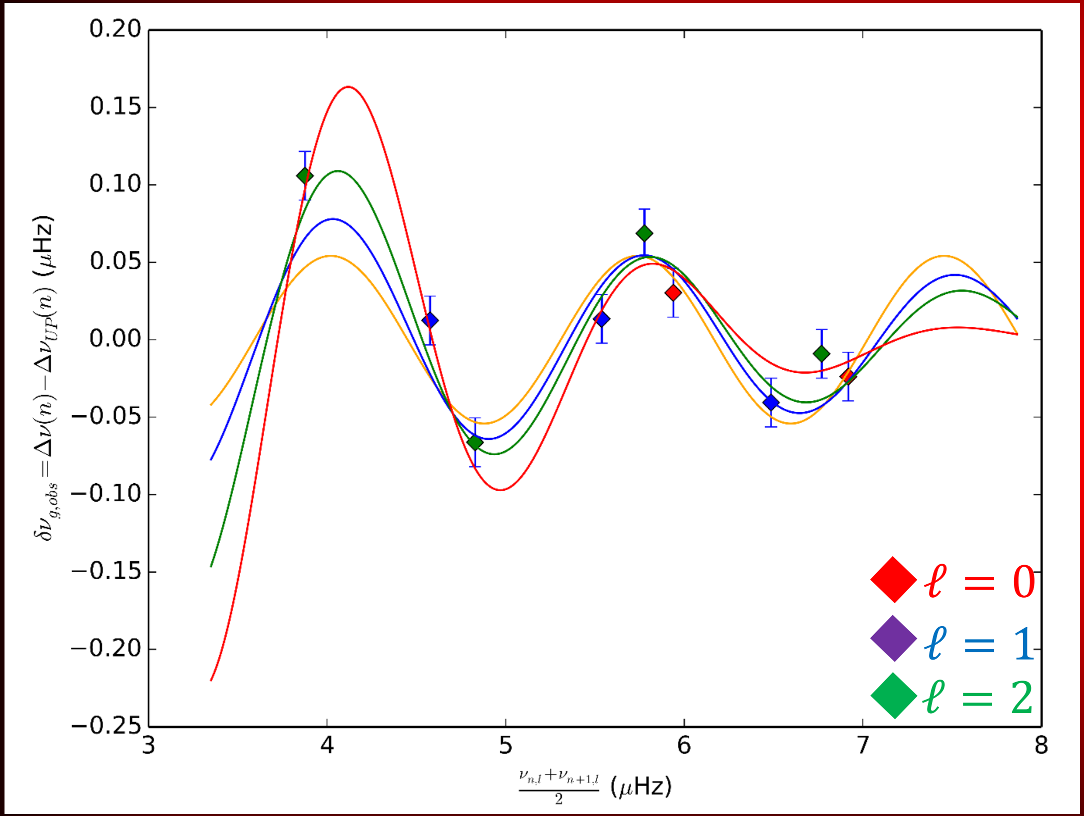
Inferred from (1), *without glitch*

- $\boxed{\delta_{g,obs} = \Delta\nu_{glitch}(n,\ell) - \Delta\nu_{noglitch}(n)}$

How to probe HeII?

$$(1)\quad \nu_{n,\ell}^{\mathrm{UP}} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu$$

- Glitch: Modulation in the mode frequencies caused by HeII



Modulation of $\Delta\nu(\mathrm{n})$ in frequency, KIC 9100325, $\Delta\nu = 0.97\ \mu$Hz

Measured in the oscillation spectrum

$$\begin{cases} \Delta\nu_{glitch}(n,\ell) = \nu_{n+1,\ell} - \nu_{n,\ell} \\ \Delta\nu_{noglitch}(n) = \nu_{n+1,\ell}^{UP} - \nu_{n,\ell}^{UP} \end{cases}$$

Inferred from (1), *without glitch*

- $\delta_{g,obs} = \Delta\nu_{glitch}(n,\ell) - \Delta\nu_{noglitch}(n)$

$$\delta_{g,obs}(\nu) = \mathcal{A}\left(\frac{\nu_{\max}}{\nu}\right)^2 \langle\Delta\nu\rangle \cos\left(\frac{2\pi(\nu-\nu_{max})}{\mathcal{G}<\Delta\nu>} + \Phi\right)$$

Amplitude

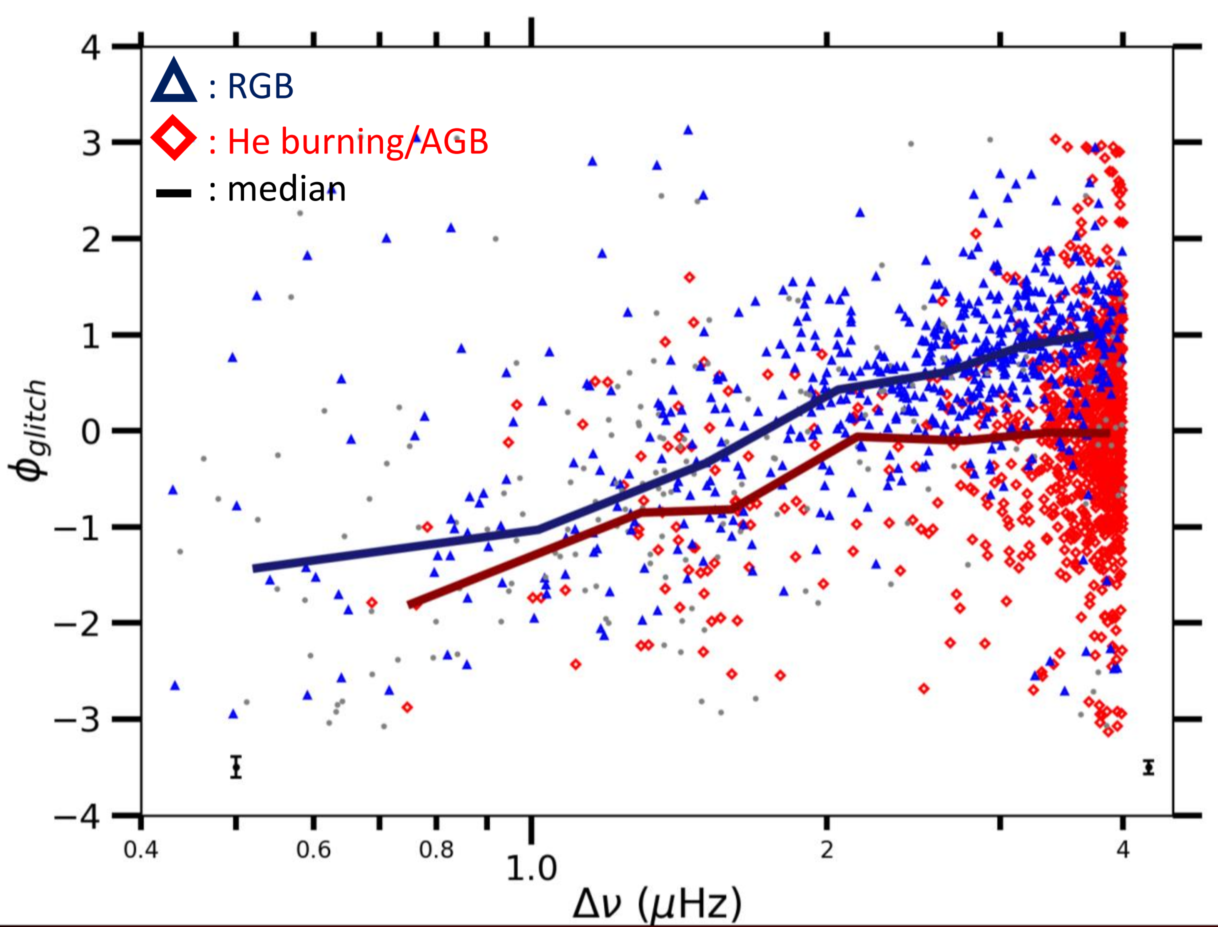
Location

Phase

Credit : *Vrard et al. 2015*

III – Disentangling RGB and AGB stars

Results: Phase Φ

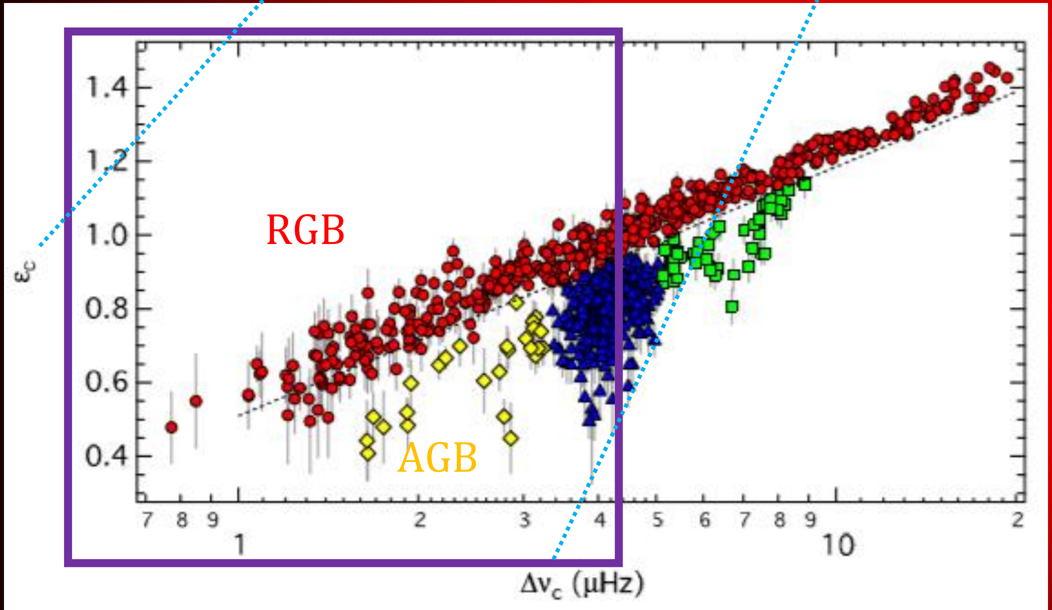


- Globally, $\Phi_{AGB} < \Phi_{RGB}$ at given $\Delta\nu$
  - Reliable distinction between Φ_{AGB} and Φ_{RGB}
  - Effects of stellar evolution

Dréau et al. 2021, submitted & accepted in A&A

Results: Phase Φ

$$\nu_{n,\ell} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu$$



$\epsilon(\Delta\nu)$, local measurement of the large separation $\Delta\nu$

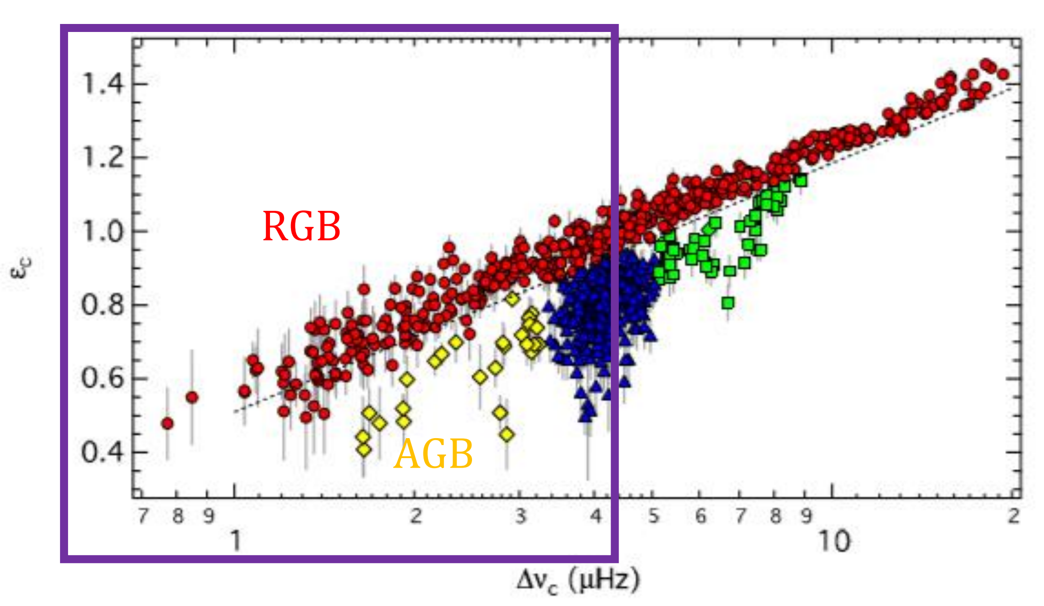
Credit: Kallinger et al. 2012

- Classification method based on the acoustic offset ε, but they did not identify the clear physical basis

Results: Phase Φ

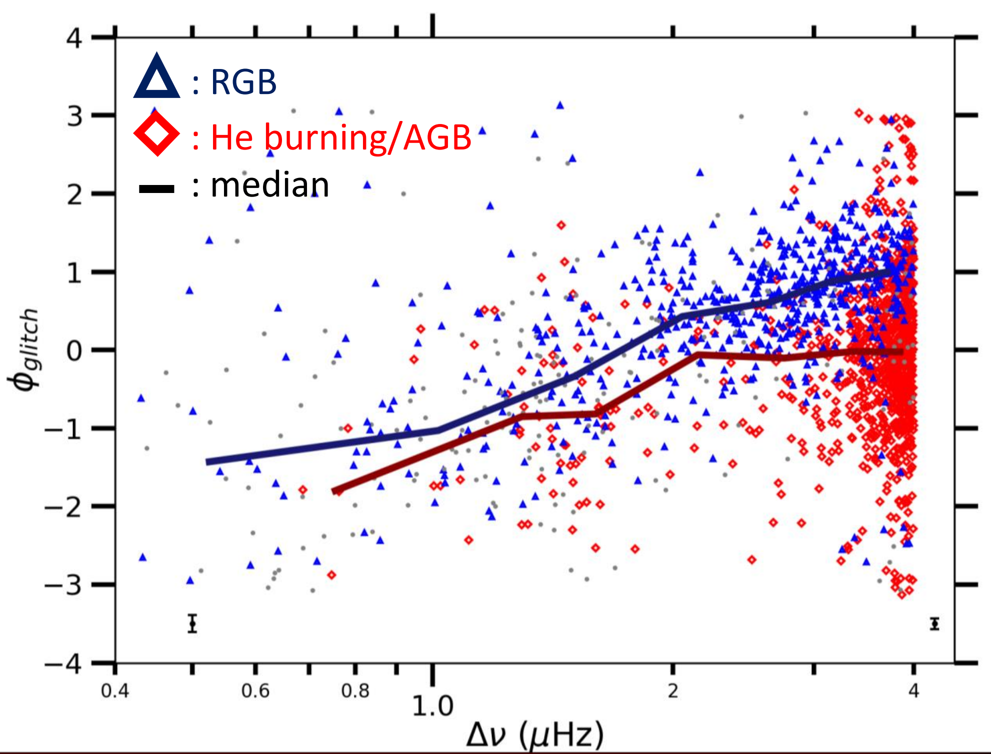
$$\nu_{n,\ell} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu \longrightarrow \boxed{\delta\varepsilon = -(n+\varepsilon)\delta(\log\Delta\nu)}$$

- A local change in ε <=> A local change in $\Delta\nu$ ⟶ Signature of HeII!



$\epsilon(\Delta\nu)$, local measurement of the large separation $\Delta\nu$

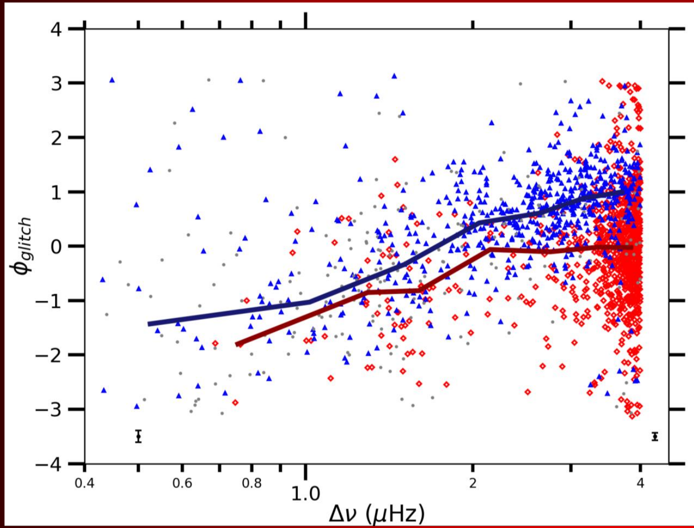
Credit: Kallinger et al. 2012

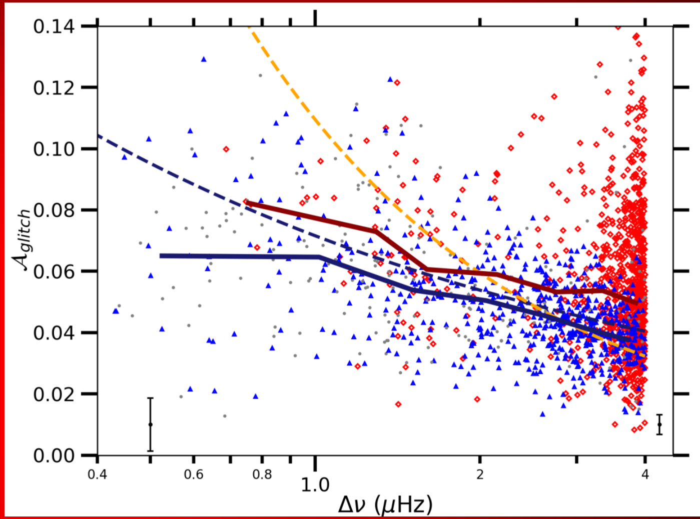


Dréau et al. 2021, submitted & accepted in A&A

What have we learnt?

→ Clear **structure differences** between RGB and AGB stars: HeII





- The classification method based on the acoustic offset ε is in fact based on the signature of HeII
- Different glitch amplitude, correlated with a different variation in Γ_1 and a different temperature at HeII

→ Work in progress: use the seismic parameters to constrain stellar models

Thanks for your attention !

Supplementary materials

Outline

I –Context and scientific concerns

- The necessity to better constrain stellar structure at evolved stages
- Extract signatures of evolution in the oscillation spectrum
- Design a classification method for evolved stars

II – Characterising the second helium ionisation zone (HeII)

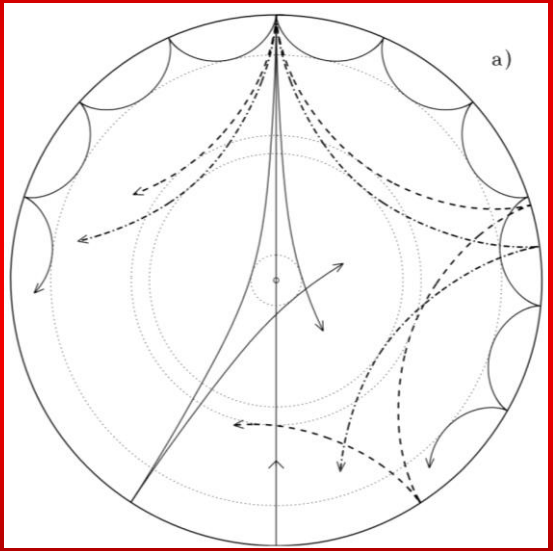
- Modulation induced in the acoustic mode frequencies

III – Disentangling RGB and AGB stars

Asteroseismology

→ Probe stellar interiors with waves that propagate inside stars and which are sensitive to stellar evolution

Pressure waves



Sun-like pulsators

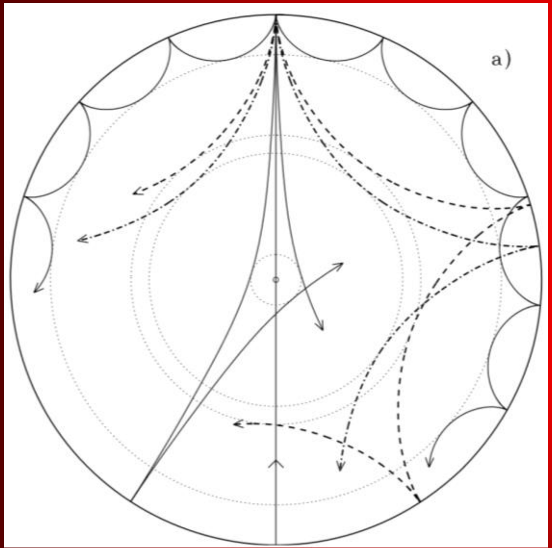
Credit : Cunha et al. 2007

- For evolved giants, main source of information: pressure waves

Asteroseismology

→ Probe stellar interiors with waves that propagate inside stars and which are sensitive to stellar evolution

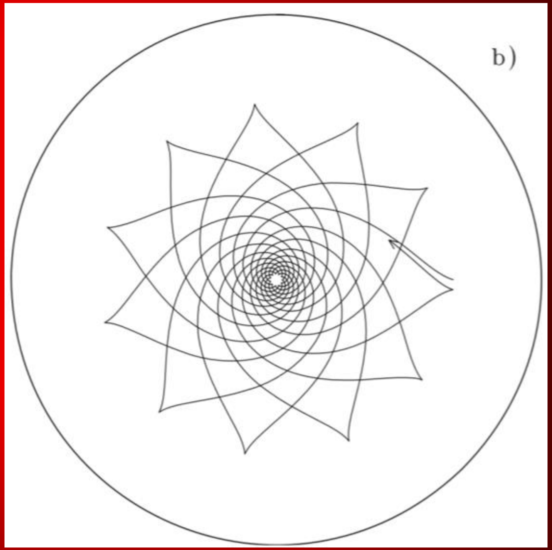
Pressure waves



- Excited by turbulent convection near stellar surface
- Propagate in the whole star

Sun-like pulsators
Credit : Cunha et al. 2007

Gravity waves

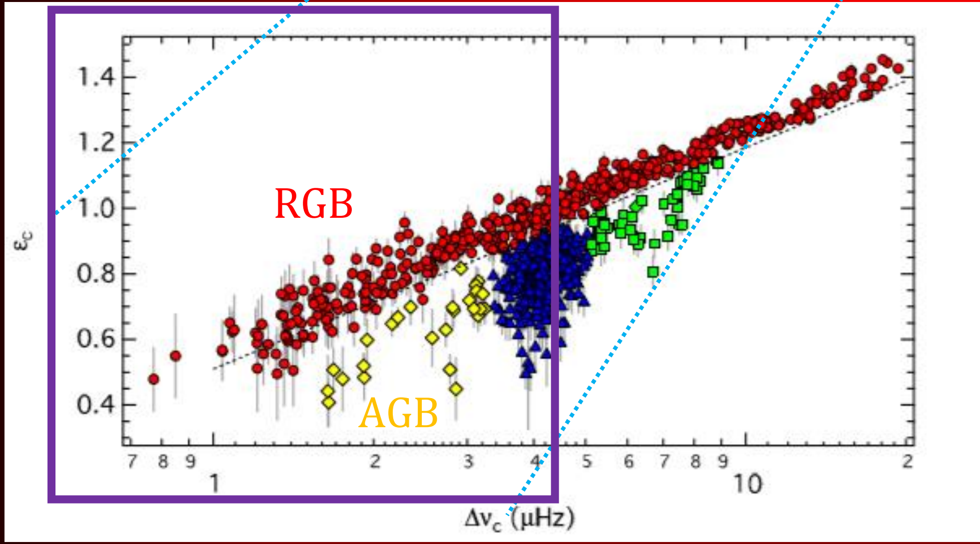


- Excited near the transition of radiative and convective zones
- Propagate in regularly stratified regions: radiative zones

Distinction RGB/AGB stars

- Method to disentangle RGB and AGB stars based on ε

$$\nu_{n,\ell}^{UP} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu$$

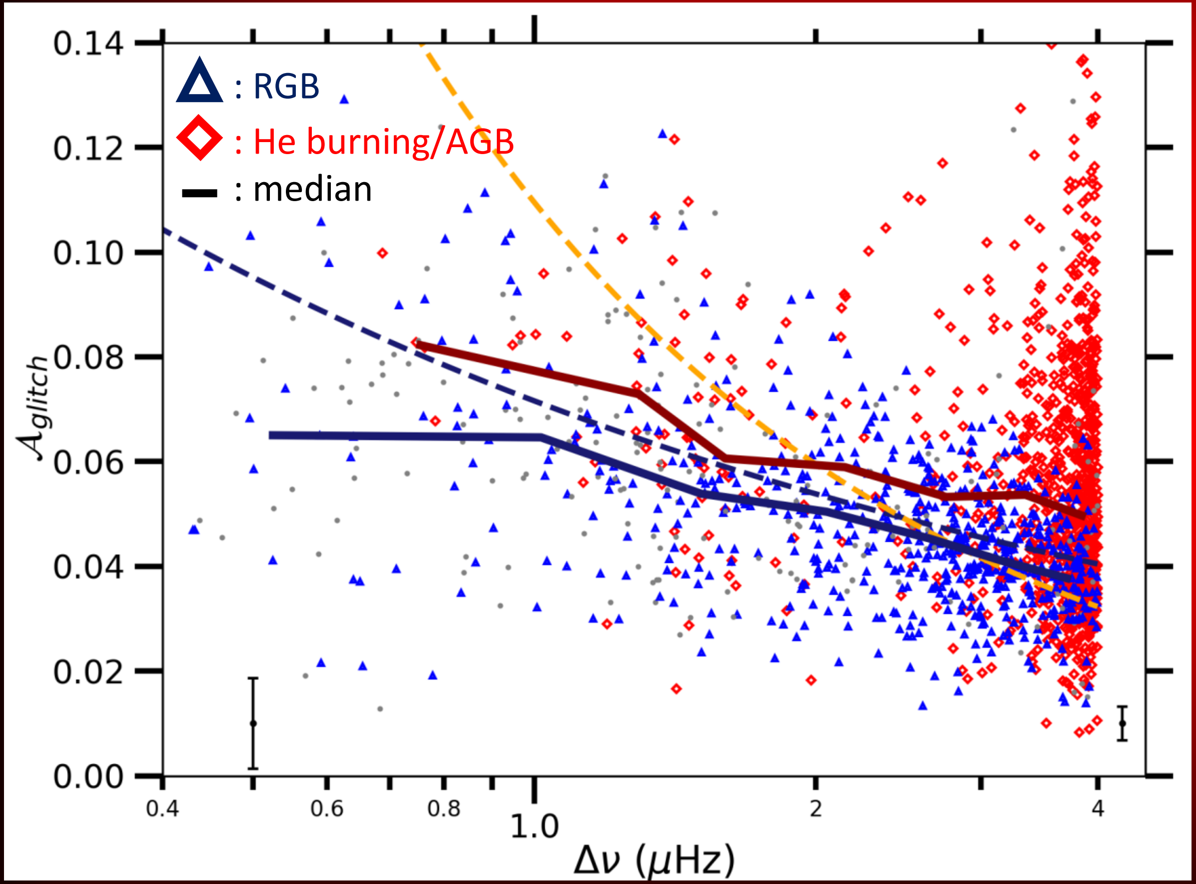


$\epsilon(\Delta\nu)$, local measurement of the large separation $\Delta\nu$
Credit: Kallinger et al. 2012

Aim of this presentation:

- Characterise evolved stars through their seismic signature in the oscillation spectrum
- Design a physical method to disentangle RGB stars from AGB stars
- Understand the results of *Kallinger et al. 2012*

Results: Amplitude $\mathcal{A}$



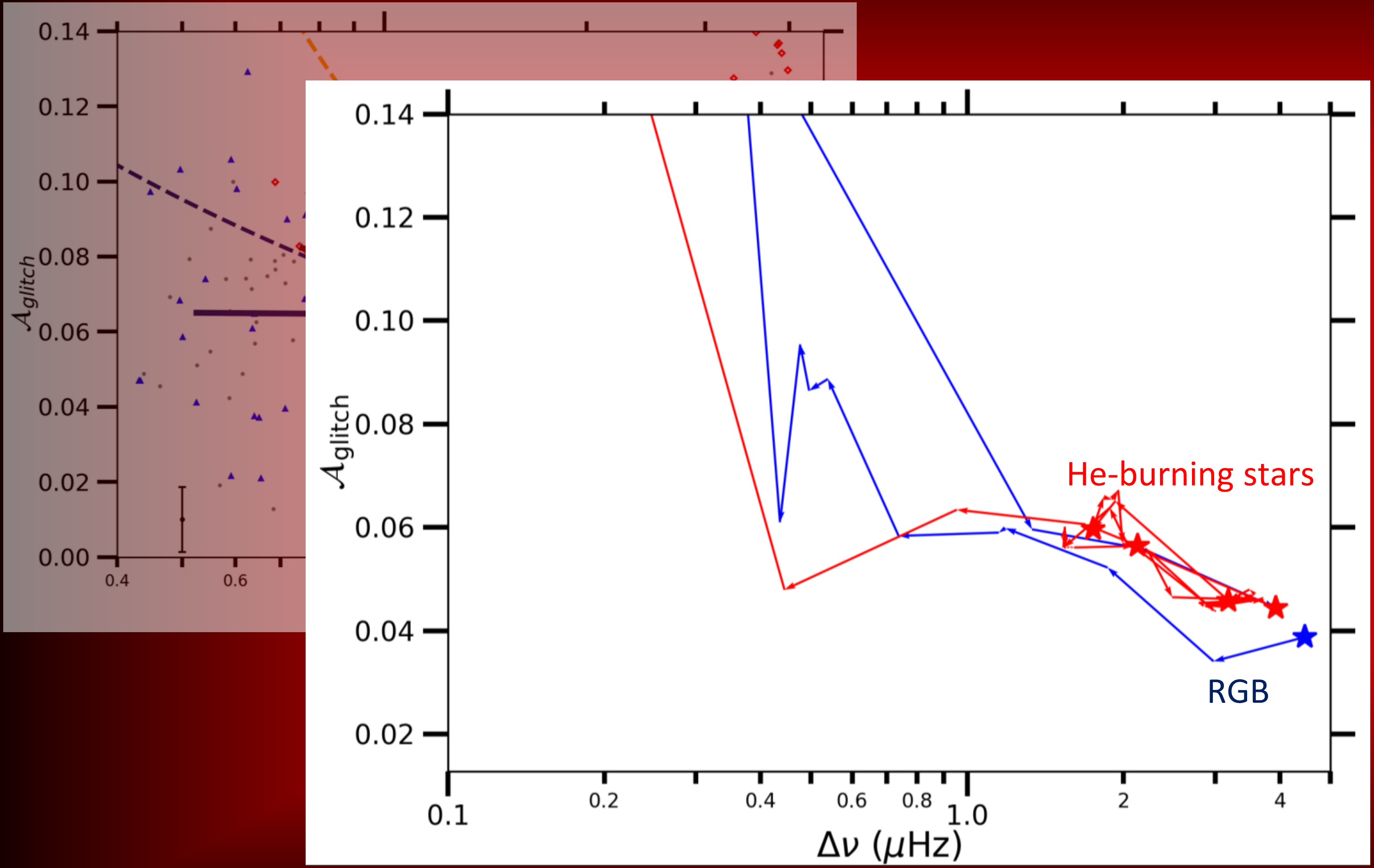
- Globally, $\mathcal{A}_{AGB} > \mathcal{A}_{RGB}$ at given $\Delta\nu$
- Dashed line:

$$\boxed{\mathcal{A}_{\mathrm{RGB}} = (0.072 \pm 0.003)\Delta\nu^{-0.411 \pm 0.006}}$$

- Scattering of $\mathcal{A}_{AGB}$
  - ➢ High magnitude stars

Dréau et al. 2021, submitted & accepted in A&A

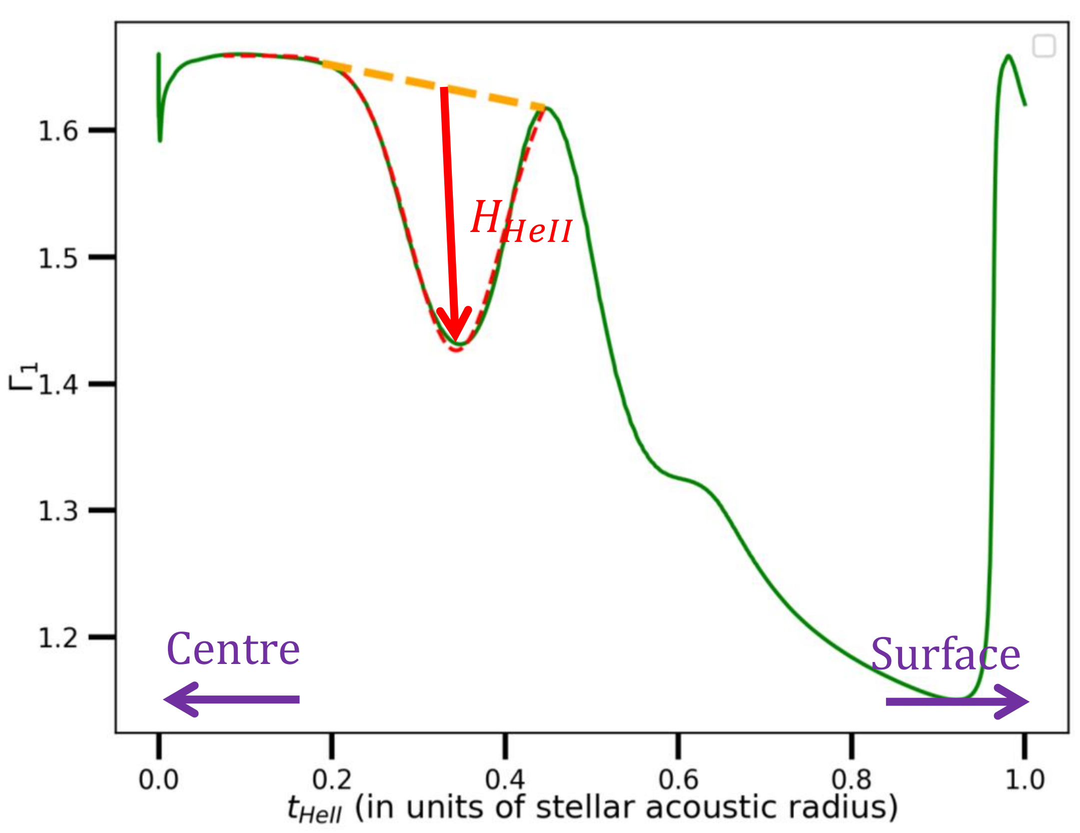
Why $\mathcal{A}_{RGB} < \mathcal{A}_{AGB}$?



- At first glance, models agree with observations: $\mathcal{A}_{AGB} > \mathcal{A}_{RGB}$
- Work in progress

$\mathcal{A}_{glitch} = f(\Delta\nu)$, an initial mass $1M_{\odot}$ star computed with *MESA*

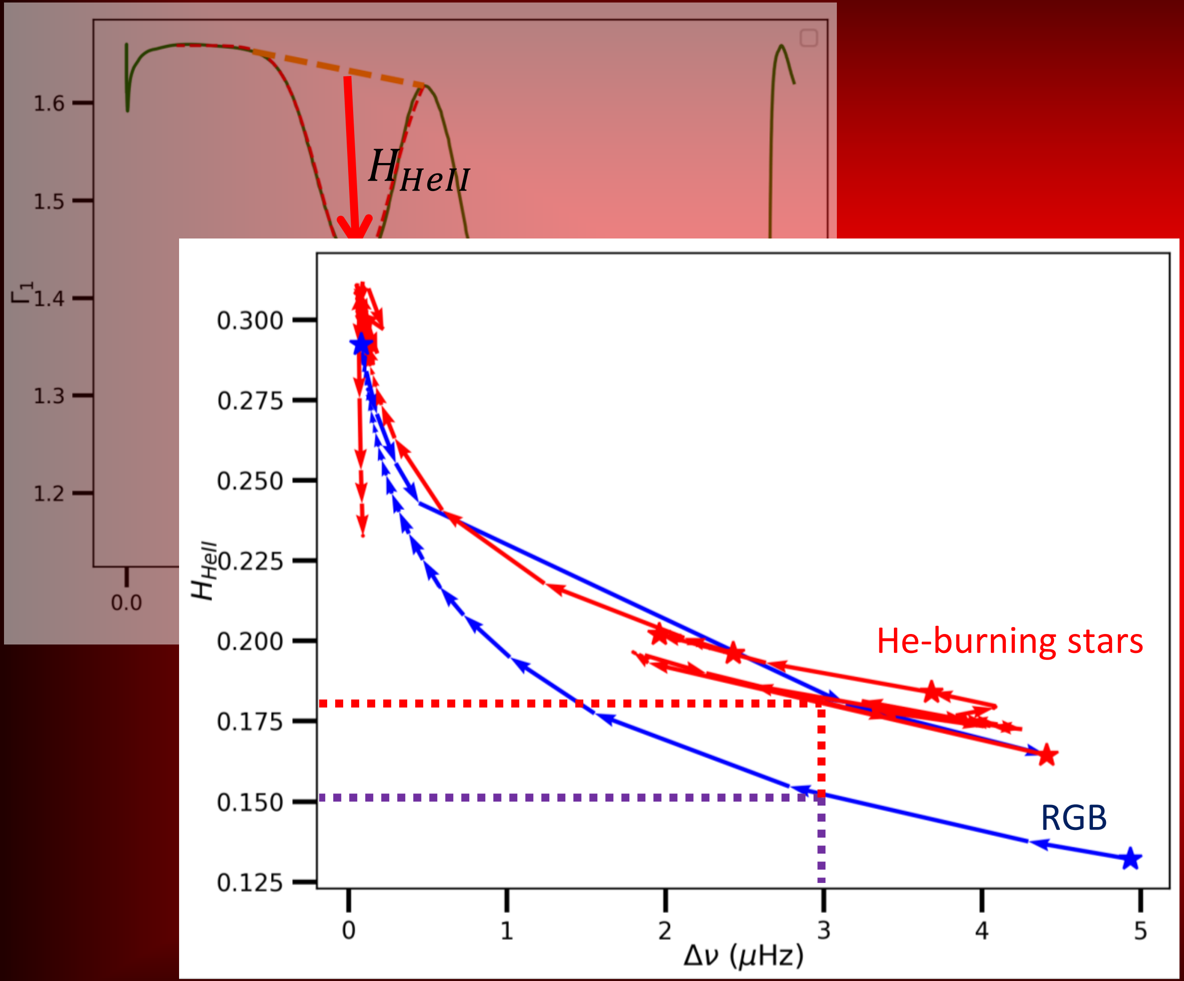
Why $\mathcal{A}_{RGB} < \mathcal{A}_{AGB}$?



$\Gamma_1 = f(\text{acoustic radius})$, for a $1M_{\odot}$ red giant

- Intuitively, we can think the depth of the dip of Γ_1, noted H_{HeII}, plays a role
- We expect **large $\mathcal{A}$ for large H_{HeII}** (to be quantitatively confirmed)

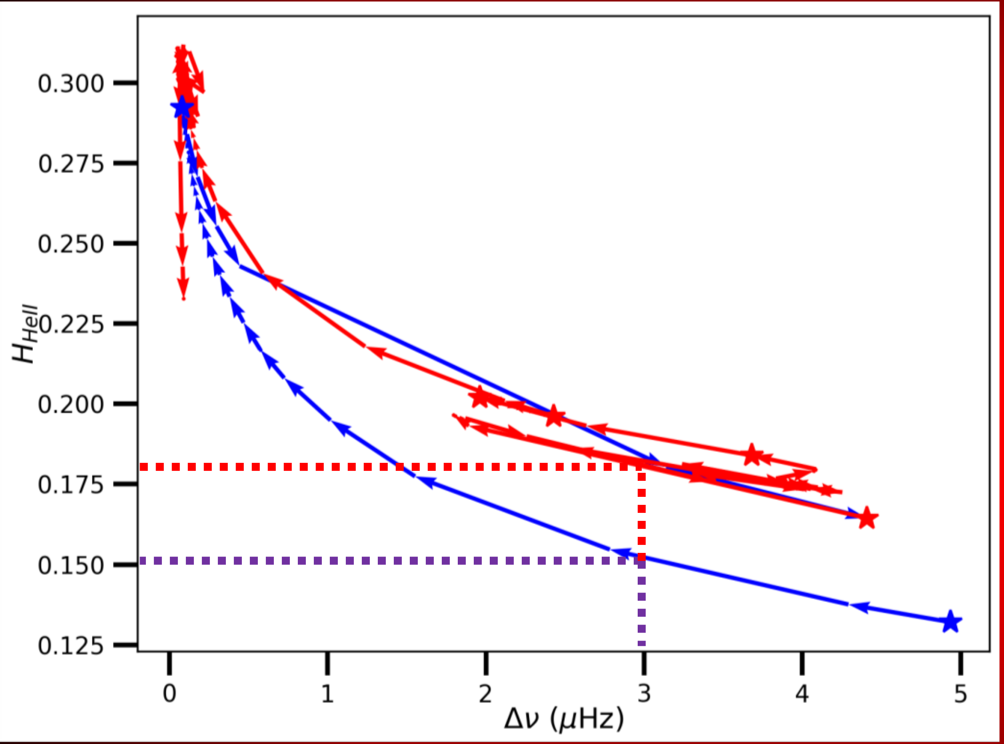
Why $\mathcal{A}_{RGB} < \mathcal{A}_{AGB}$?

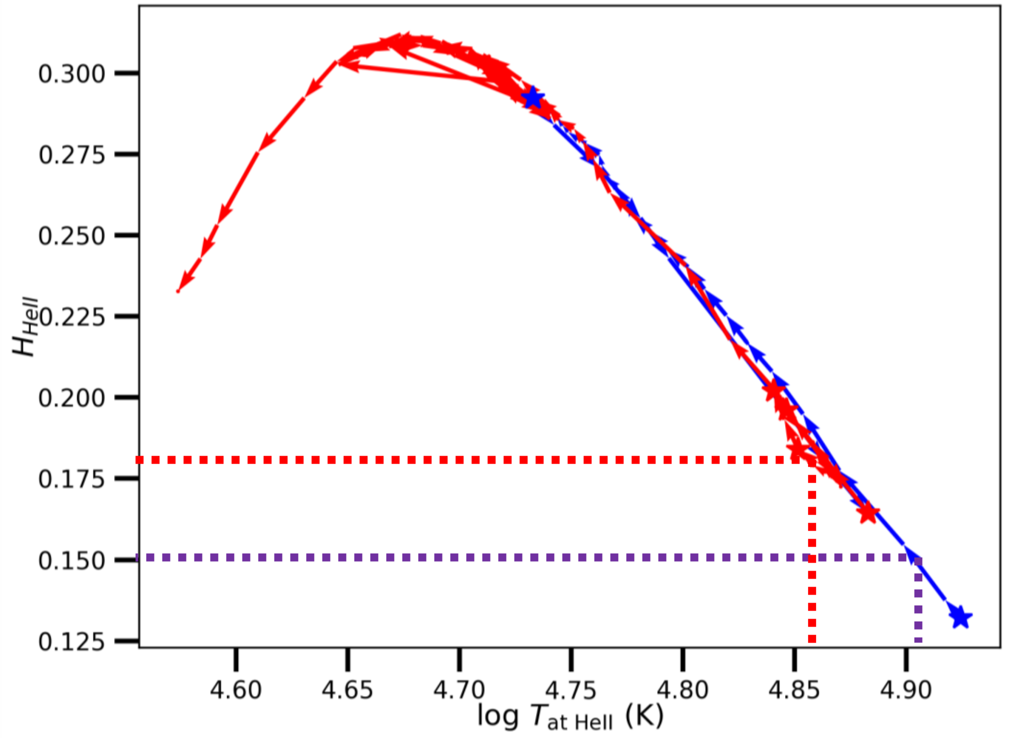


- At fixed $\Delta\nu$, $H_{HeII,AGB} > H_{HeII,RGB}$
- At first glance, models agree with observations: $\mathcal{A}_{AGB} > \mathcal{A}_{RGB}$

$\mathrm{H_{HeII}} = f(\Delta\nu)$, an initial mass $1M_\odot$ star computed with *MESA*

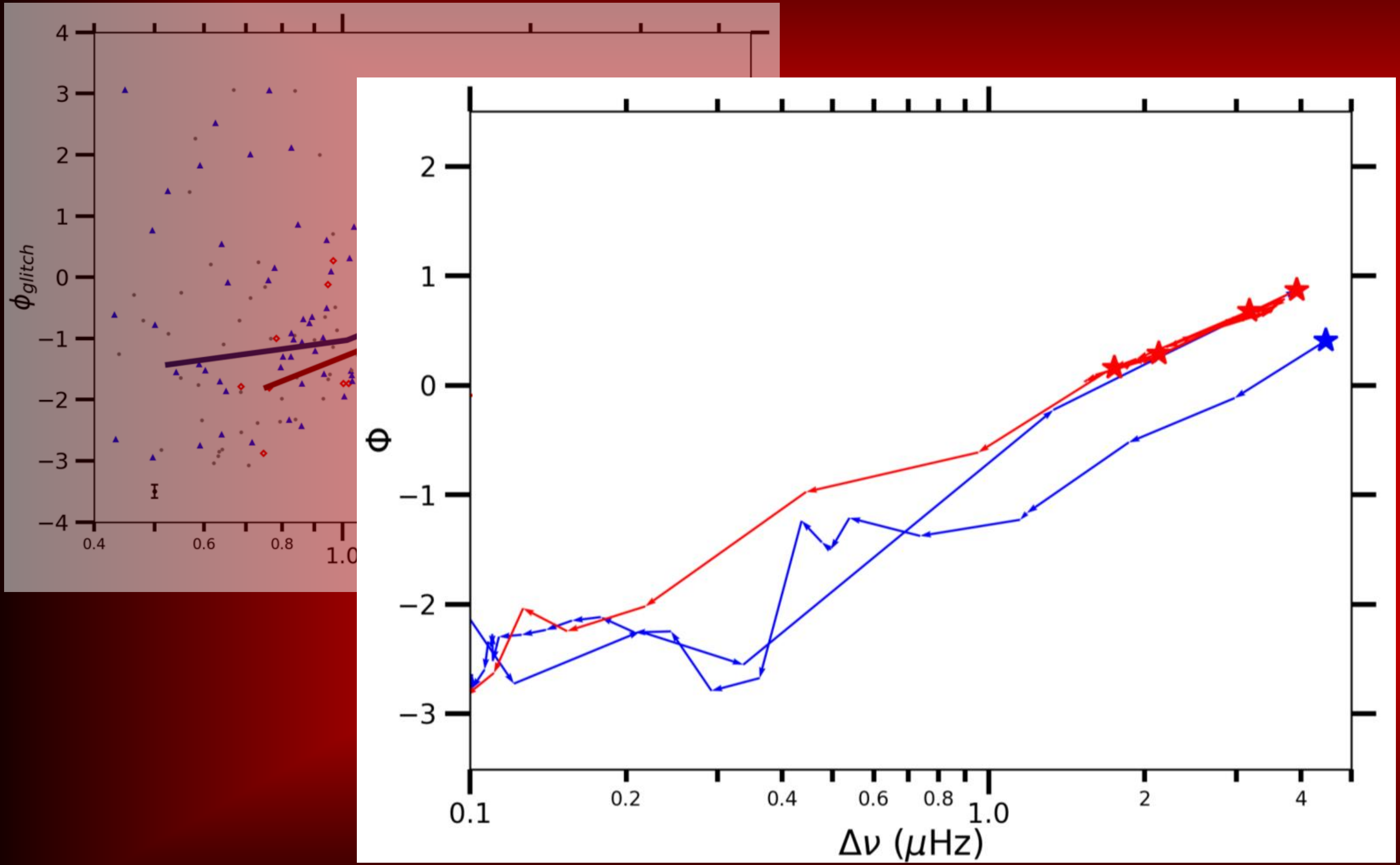
Why $\mathcal{A}_{RGB} < \mathcal{A}_{AGB}$?





- Some evidence that $H_{HeII,AGB} > H_{HeII,RGB}$ linked to a difference of temperature at HeII, noted T_{atHeII}
- Clear **correlation** between H_{HeII} and $T_{at\ HeII}$

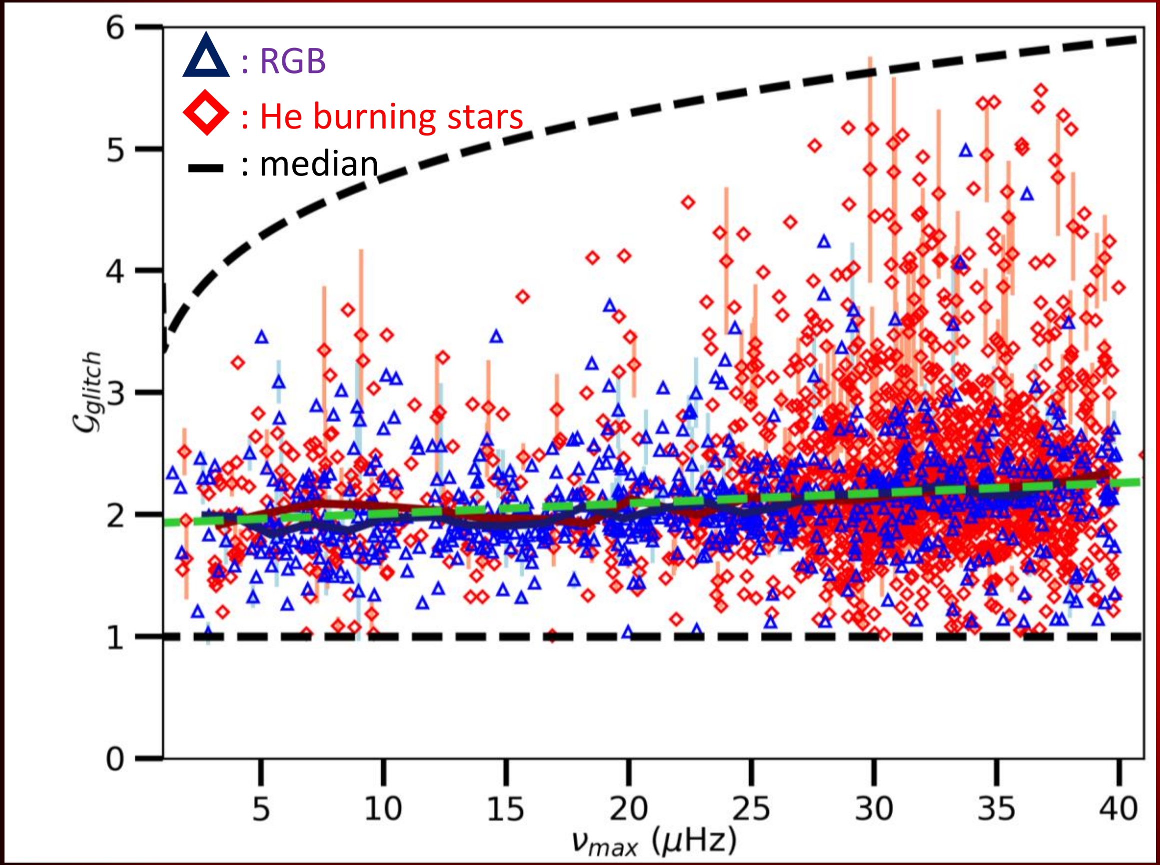
Results: Phase Φ



$\Phi_{glitch} = f\,(\Delta\nu)$, an initial mass $1M_{\odot}$ star computed with *MESA*

- Stellar models: $\Phi_{AGB} > \Phi_{RGB}$ in disagreement with observations
- We need to implement more realistic microphysics and macrophysics
- Work in progress

Results: Period $\mathcal{G}$



- $\mathcal{G}$ decreases towards low ν_{max}
- Globally, $\mathcal{G}_{AGB} \approx \mathcal{G}_{RGB}$ at given ν_{max}
- Dashed line:

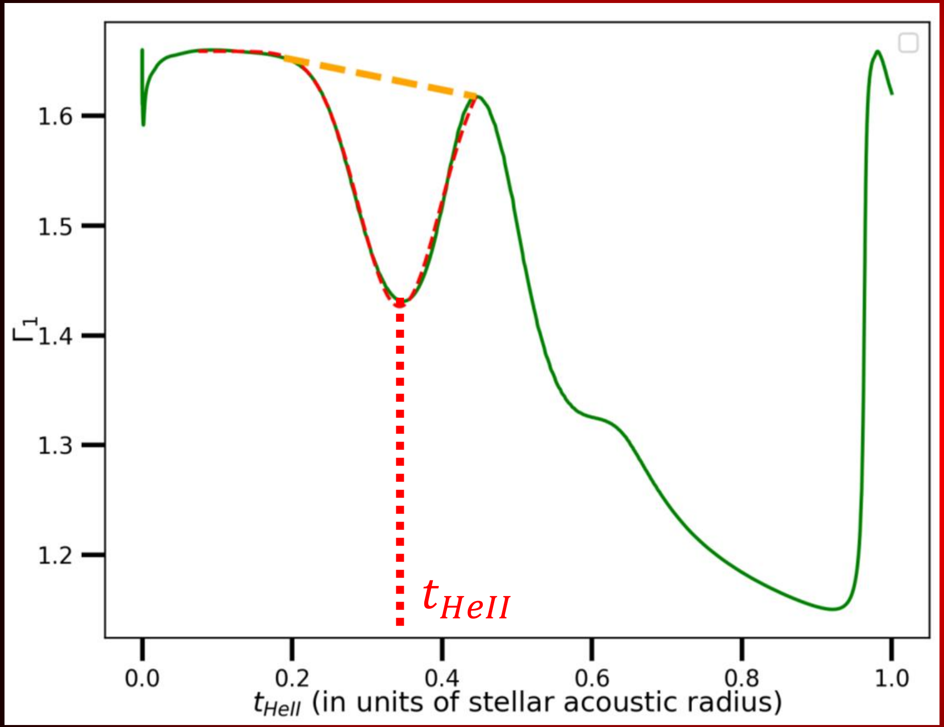
$$\boxed{\mathcal{G}_{RGB} = (1.922 \pm 0.041) + (0.009 \pm 0.002)\nu_{max}}$$

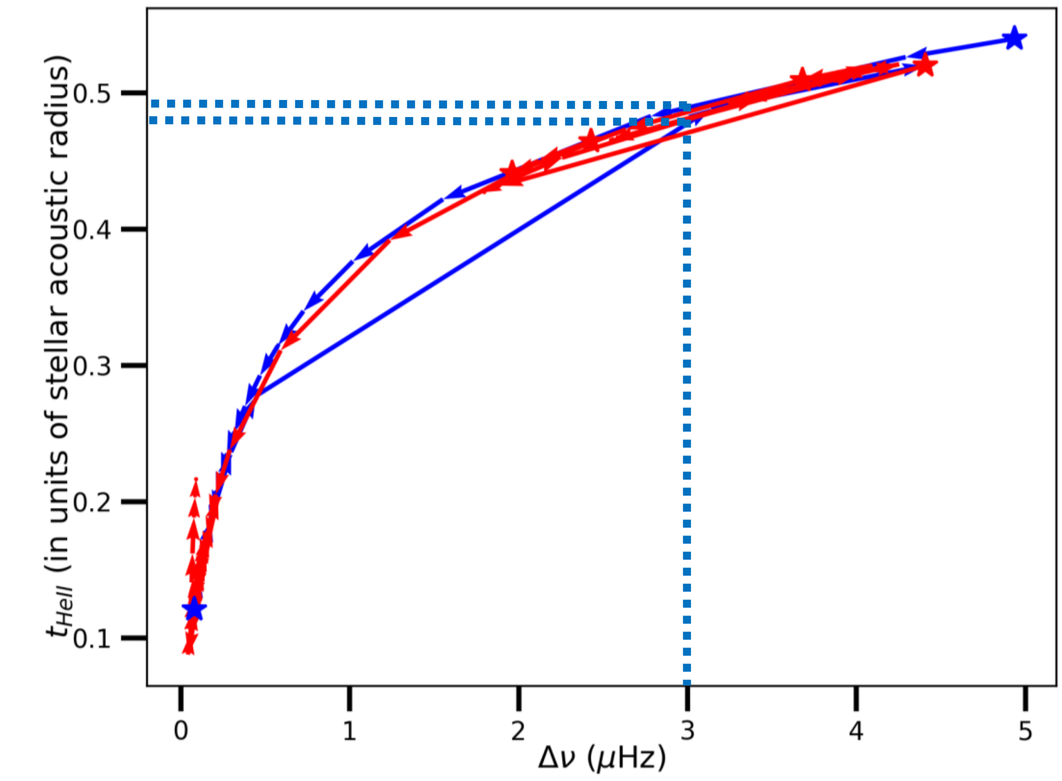
- $\mathcal{G}_{AGB}$ more scattered than $\mathcal{G}_{RGB}$
  - ➢ $\mathcal{G}_{AGB}$ may be overestimated because of mixed modes

Results: Period $\mathcal{G}$

- Reminder: $\mathcal{G}$ is directly linked to the location of HeII, noted t_{HeII}:

$$t_{HeII} = 1 - \frac{1}{\mathcal{G}}$$



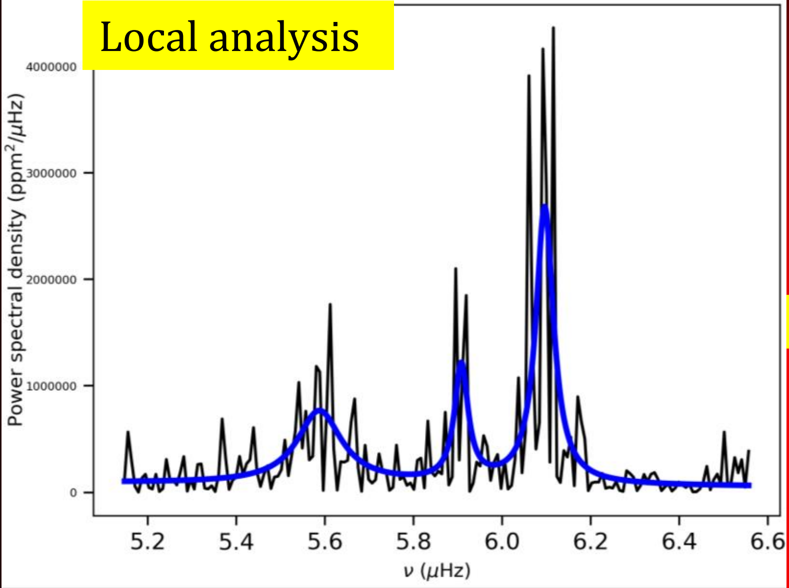


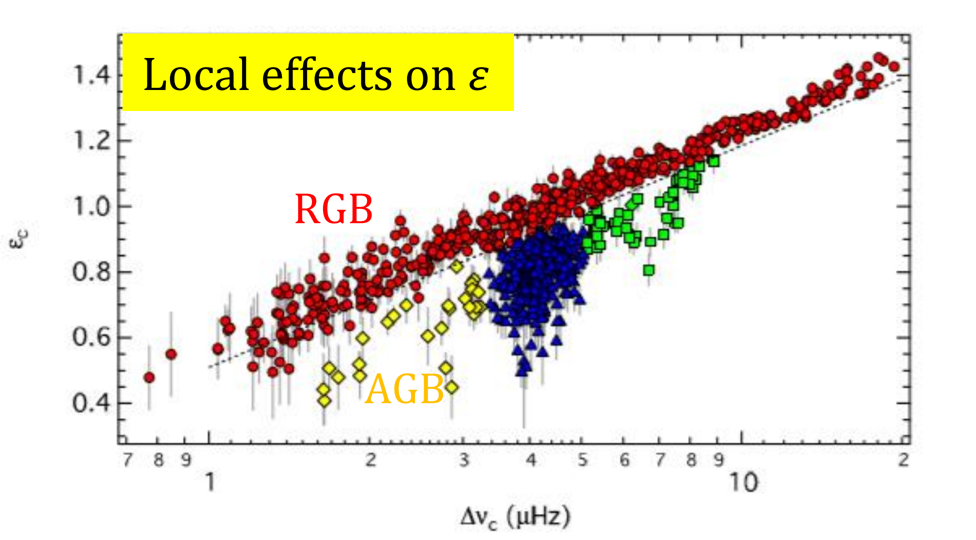
$\mathrm{t_{HeII}} = f(\Delta\nu)$, an initial mass $1M_{\odot}$ star computed with *MESA*

- Models agree with observations:

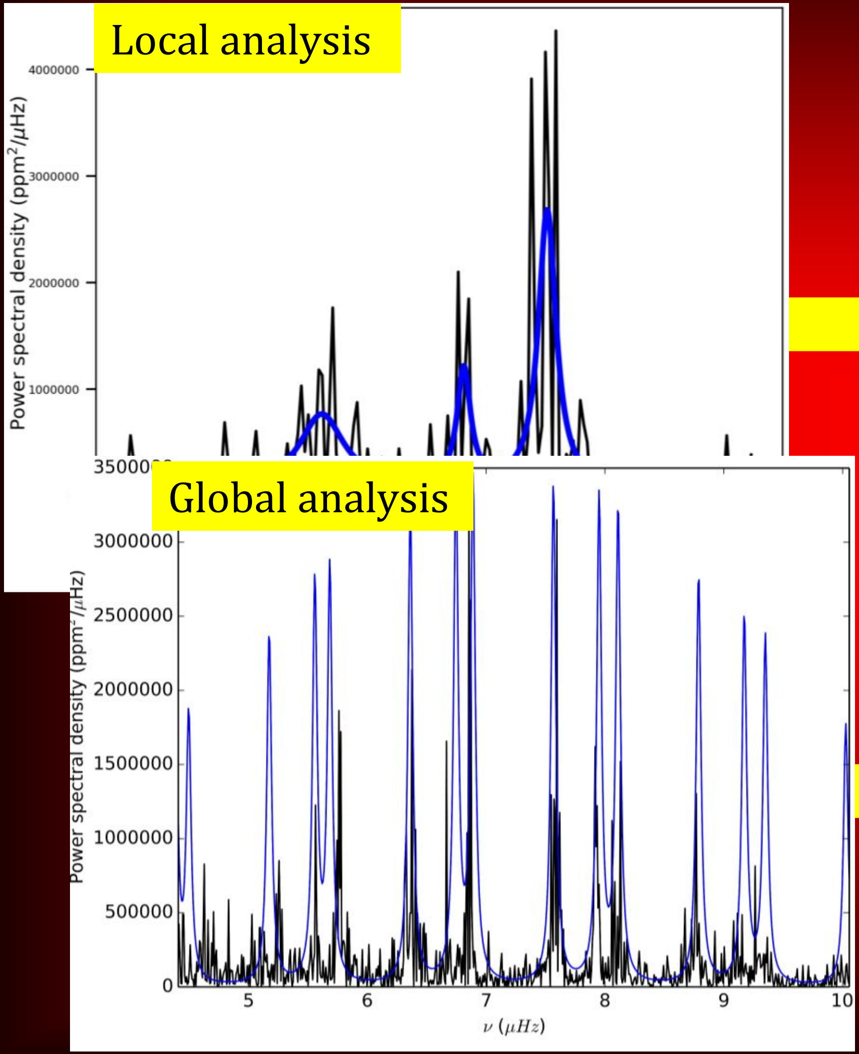
$$t_{HeII,AGB} \approx t_{HeII,RGB}$$

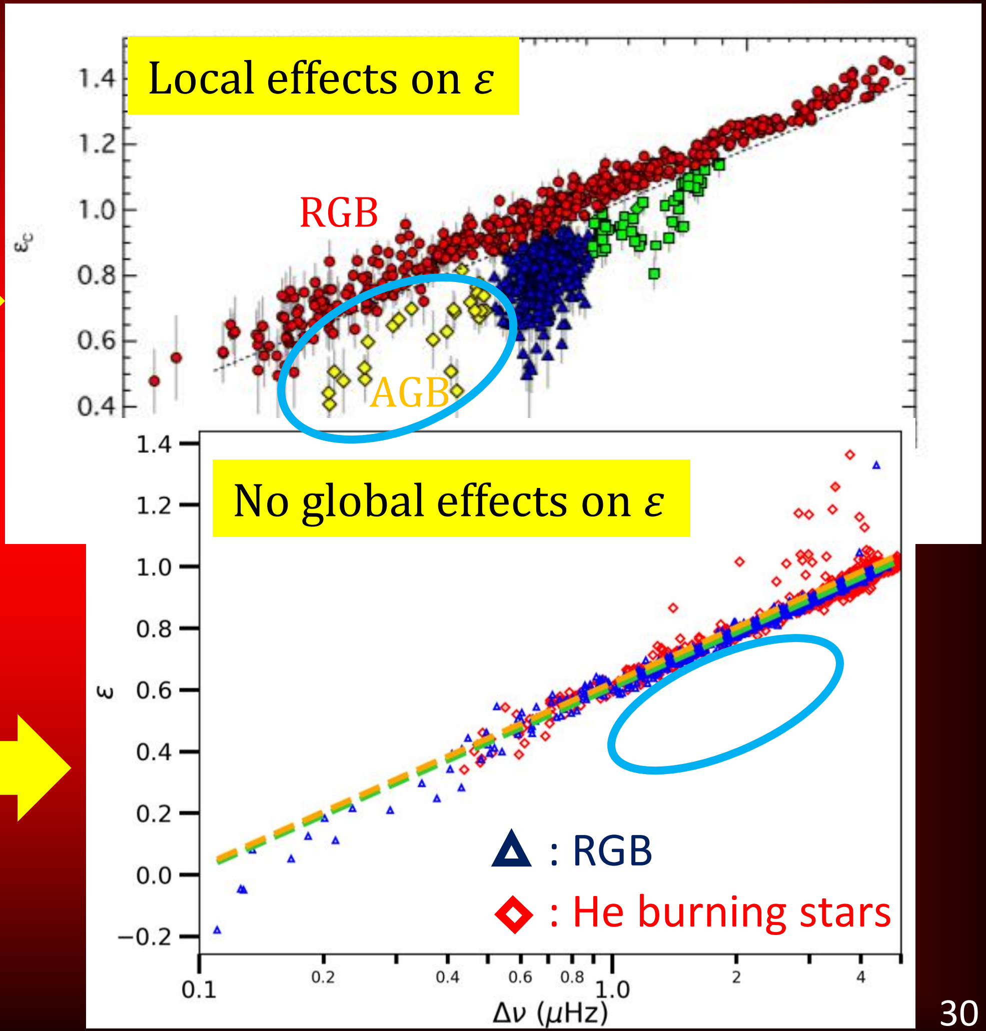
Why Φ_{AGB} different from Φ_{RGB}?





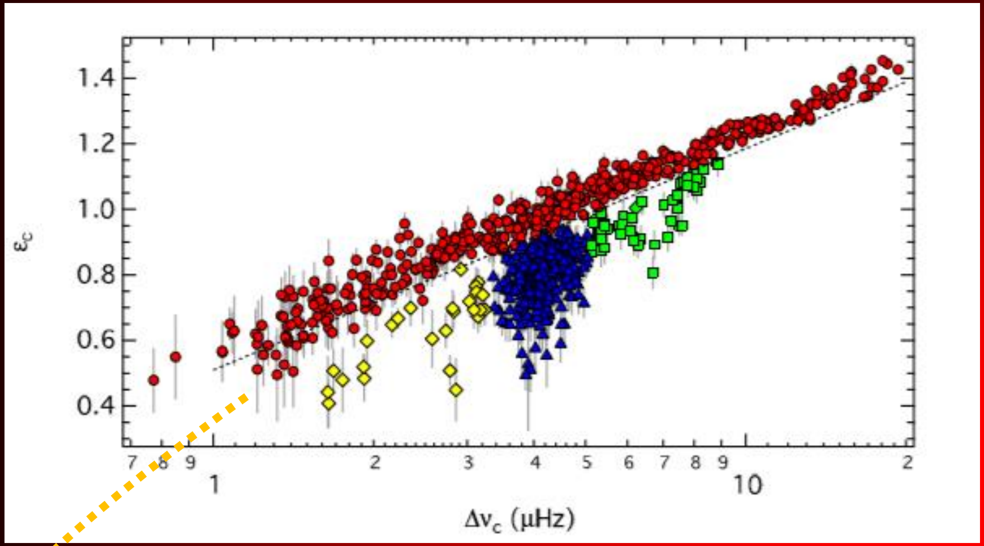
Why Φ_{AGB} different from Φ_{RGB}?

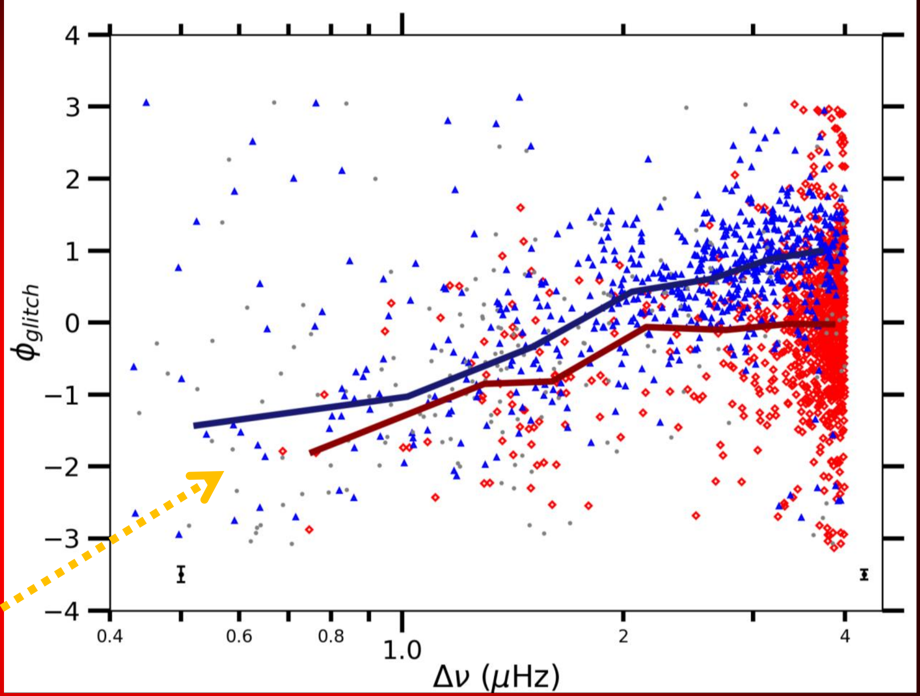




Local effects: glitches

$$(1)\ \nu_{n,\ell}^{\mathrm{UP}} = \left(n + \frac{\ell}{2} + \varepsilon + d_{0\ell} + \frac{\alpha}{2}(n - n_{max})^2\right)\Delta\nu$$





- By computing the derivative of (1):

$$\boxed{\delta\varepsilon = -(n+\varepsilon)\delta(\log \Delta\nu)}$$

- A local change in ε <=> A local change in $\Delta\nu$ → Signature of HeII!

$$||$$

$$\mathcal{A}\left(\frac{\nu_{\max}}{\nu}\right)^2 < \Delta\nu > \cos\left(\frac{2\pi(\nu - \nu_{max})}{\mathcal{G}<\Delta\nu>} + \Phi\right)$$