CoRoT3 / KASC7 – Toulouse – 07/2014

Calibrating core overshooting in low-mass stars with *Kepler* data

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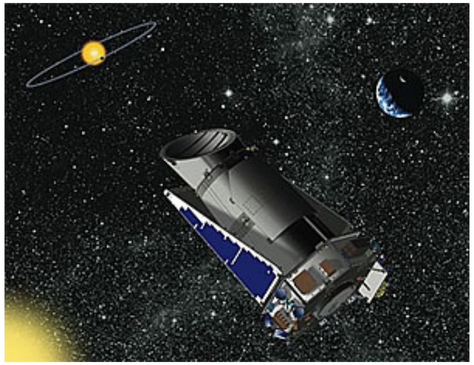
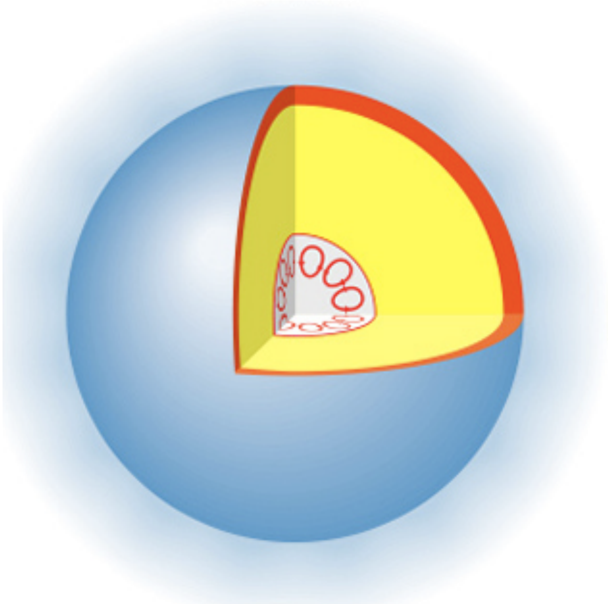


Extension of convective cores

- Several physical processes could extend the size of convective cores : *overshooting, semi-convection, rotational mixing…*

  ⇒ large uncertainties on **stellar ages**



- Implementation in 1D stellar models
  - instantaneous mixing: simple extension of the mixed core over

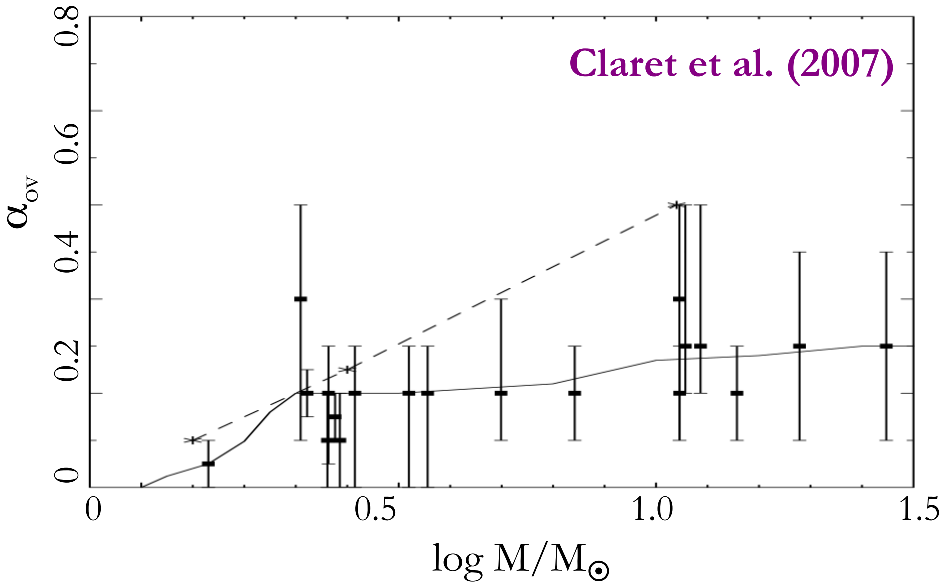
    $$d_{\mathrm{ov}} = \alpha_{\mathrm{ov}} \min(H_P, R_{\mathrm{c}})$$

  - diffusive mixing
  - turbulent convection models

Existing constraints on core overshooting

- Color-Magnitude diagrams of clusters
  - Main Sequence lifetime extended with overshooting

- Eclipsing binaries



⇒ need for **extended cores** with $\alpha_{ov} \sim 0.2$

⇒ an **increase of α_{ov} with stellar mass**?

- Seismology
  - Evidence for an extended core in several MS stars

    (**Deheuvels et al. 2010**, **Degroote et al. 2010**, **Neiner et al. 2012**, **Silva-Aguirre et al. 2013**, **Goupil et al. 2013**)

How seismology can probe the core size

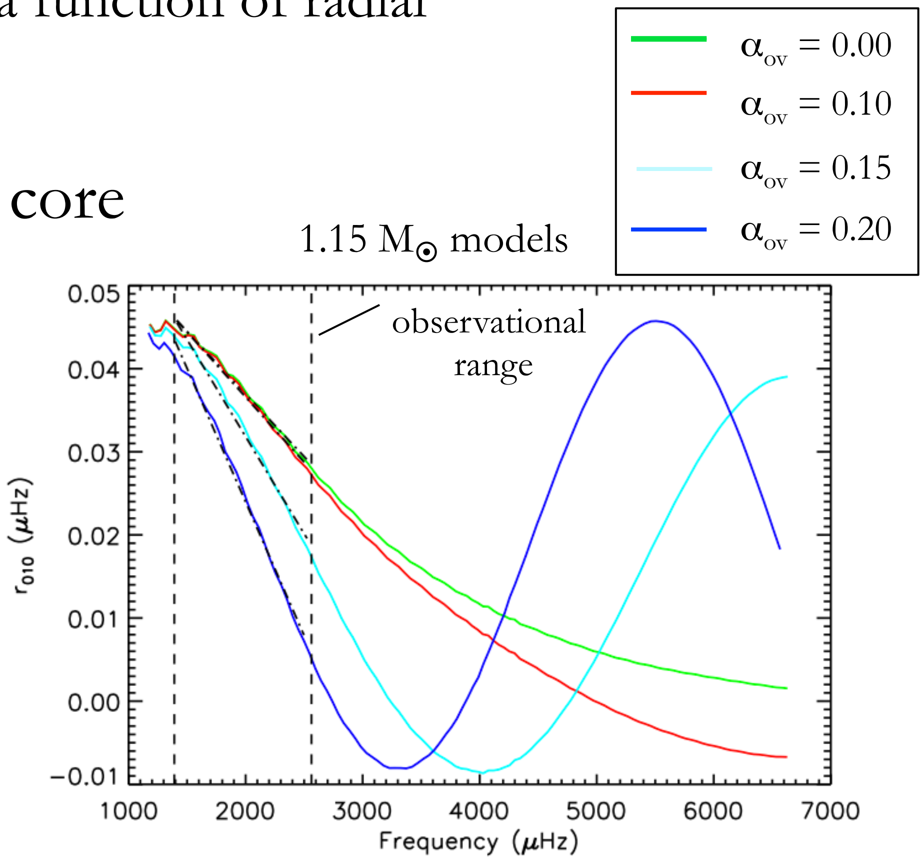
- The core boundary induces an acoustic glitch
  - ⇒ mode frequencies "oscillate" as a function of radial order (**Gough 1990**)

- Seismic indexes sensitive to the core
  - – r_{010} ratios (**Roxburgh & Vorontsov 2003**)

$$r_{01} = \frac{dd_{01}(n)}{\Delta\nu_1(n)}$$

$$r_{10} = \frac{dd_{10}(n)}{\Delta\nu_0(n+1)}$$

period	$\longleftrightarrow$	depth of glitch
amplitude	$\longleftrightarrow$	intensity of glitch

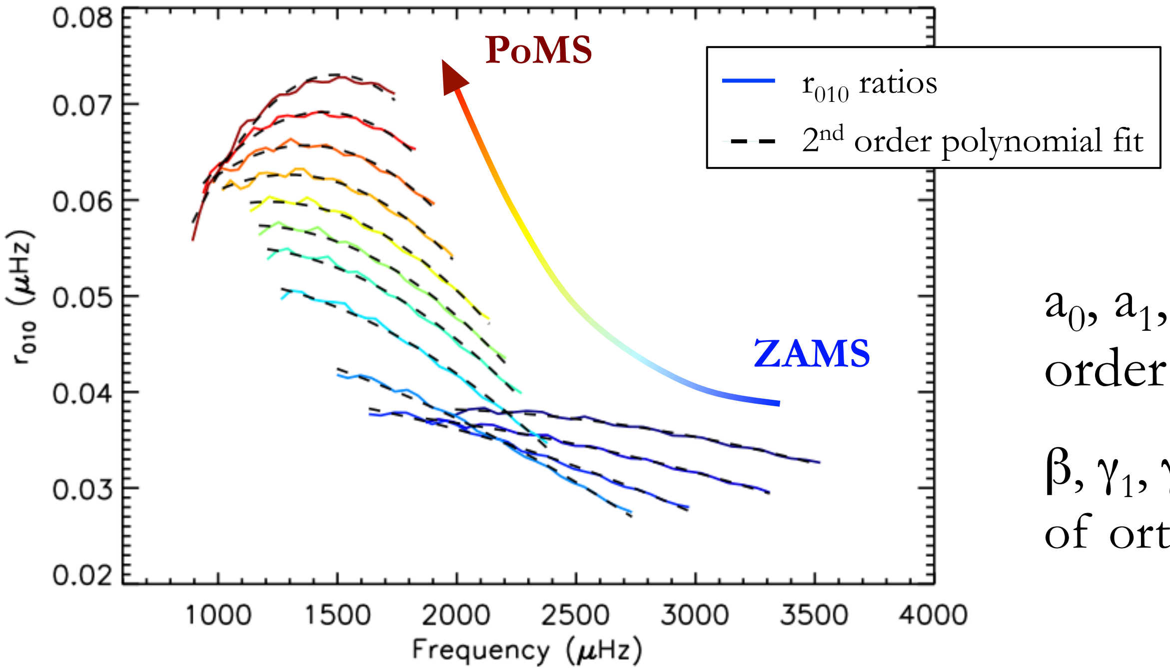


see also **Silva Aguirre et al. (2013)**, **Cunha & Brandaõ et al. (2011), Brandaõ & Cunha al. (2014)**

How seismology can probe the core size

- 2^{nd} order polynomial fit to the r_{010} ratios

$$P(\nu) = a_0 + a_1(\nu - \beta) + a_2(\nu - \gamma_1)(\nu - \gamma_2)$$



a_0, a_1, a_2: coefficients of the 2^{nd} order polynomial fit

β, γ_1, γ_2: determined to have a basis of orthogonal polynomials

- Use of the **mean value a_0** and **mean slope a_1** of r_{010} ratios to constrain the core size

(**Popielski & Dziembowski 2005**, **Deheuvels et al. 2010**, **Silva Aguirre et al. 2011**)

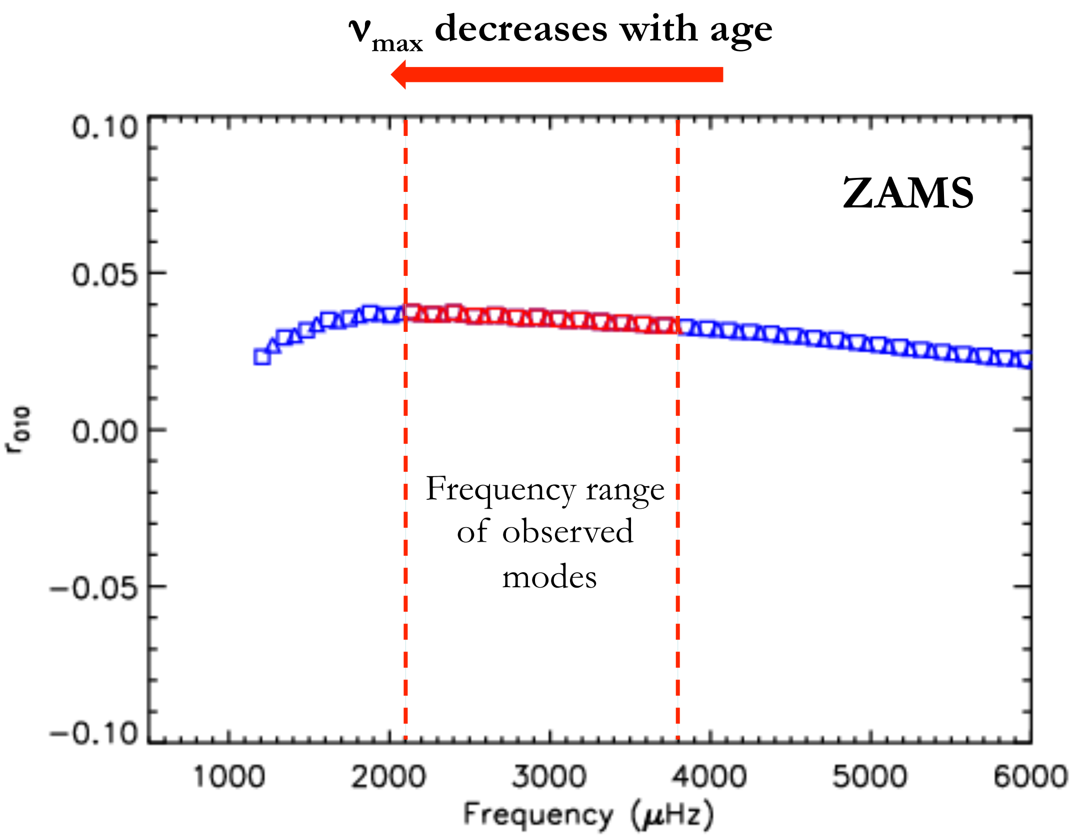
Testing the seismic diagnostic

- Grid of models: evolution code CESAM2k + oscillation code LOSC (with varying mass, age, metallicity, helium abundance, **core overshooting)**
- 3 goals:

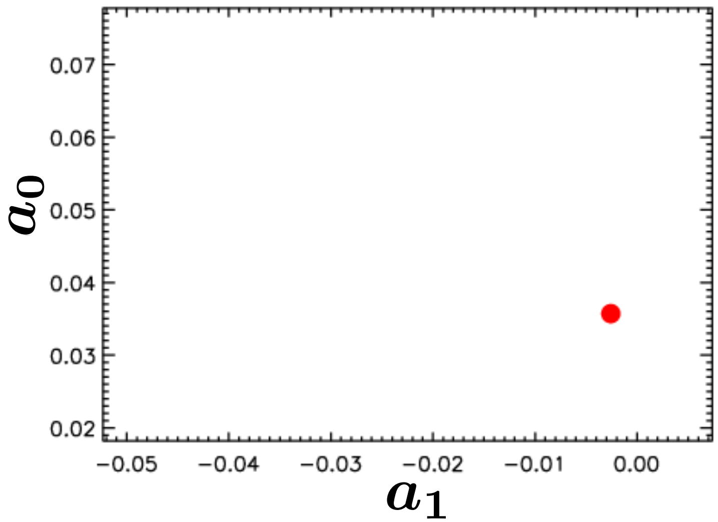
1. Validate the diagnostic
2. Determine a list of criteria to select the best Kepler targets
3. Interpret these data by confronting them to the grid of models and obtain constraints on α_{ov} if possible

Evolution of r_{010} ratios in time

- Evolution of r_{010} ratios with age:



$1.2\text{-}M_{\odot}$ models

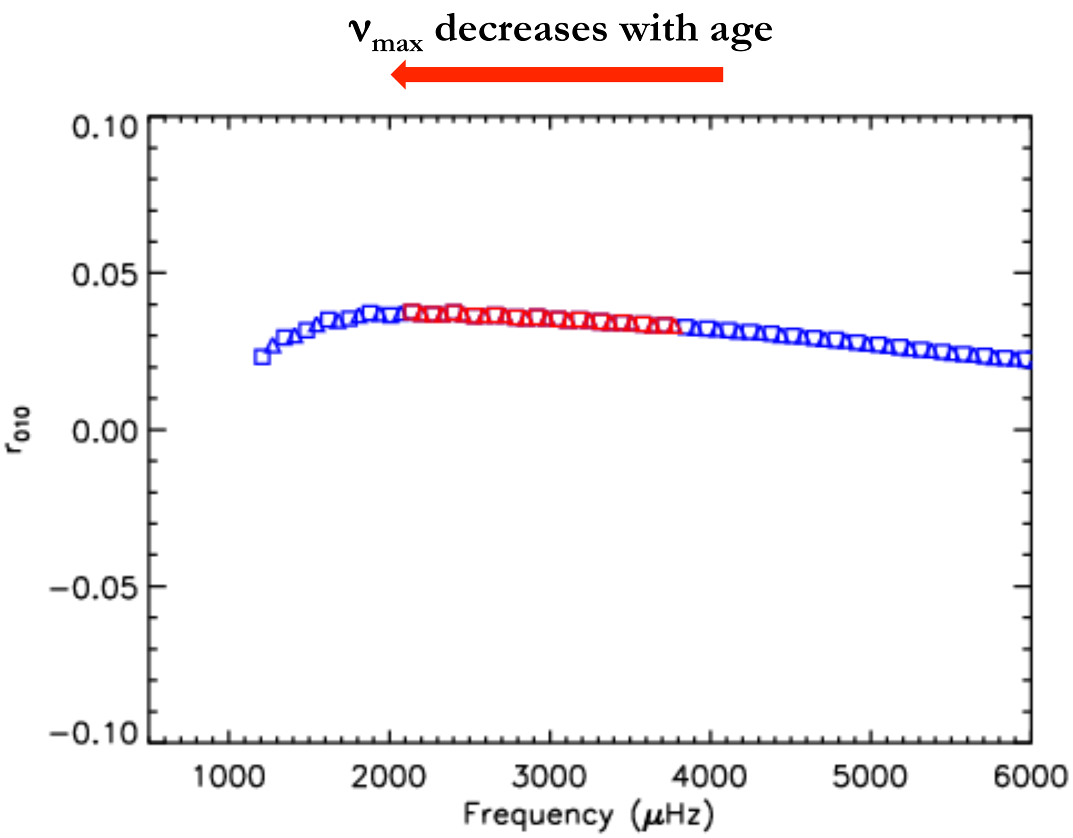


a_0 = mean value

a_1 = mean slope

Evolution of r_{010} ratios in time

- Evolution of r_{010} ratios with age:



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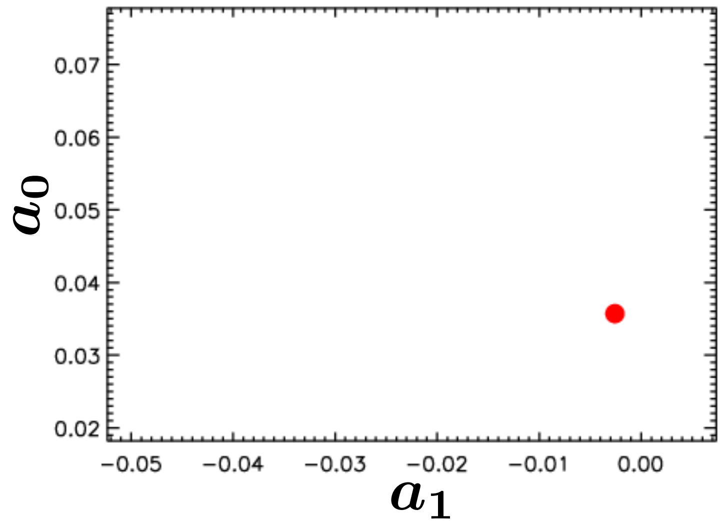
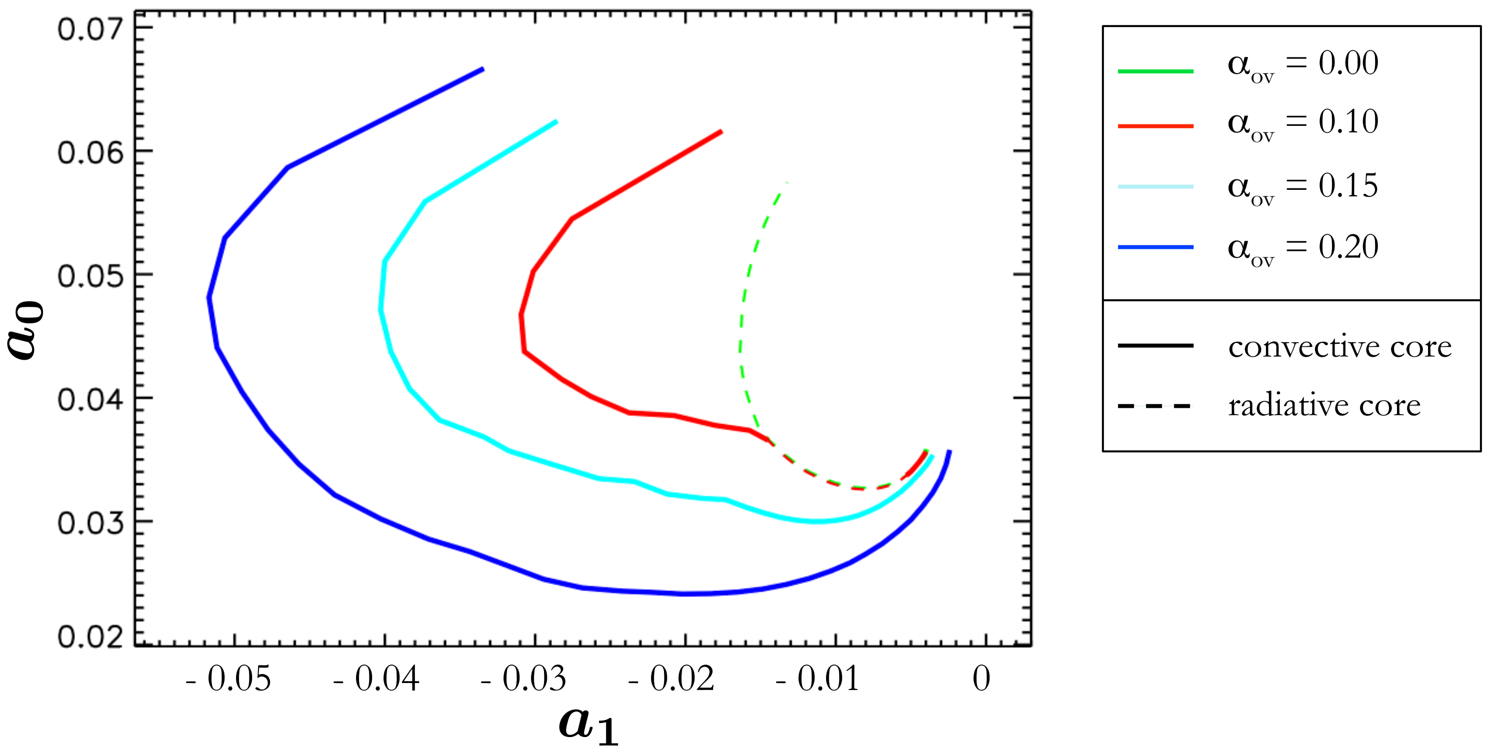


a_0 = mean value

a_1 = mean slope

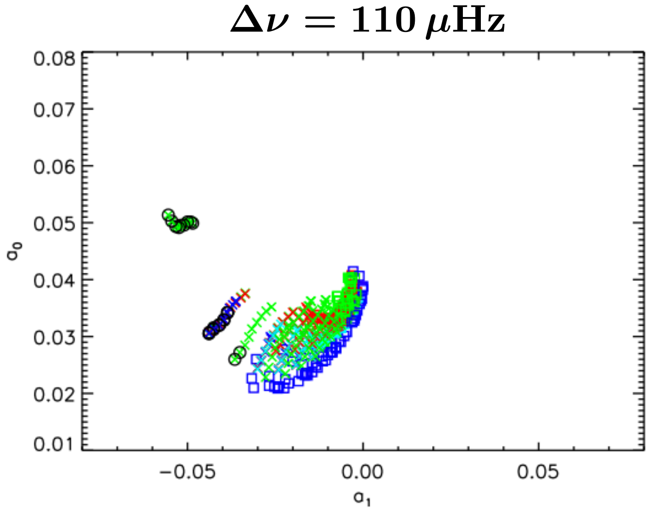
Effects of core overshooting

- Effect of core overshooting on the evolutionary tracks in the (a_1, a_0) plane

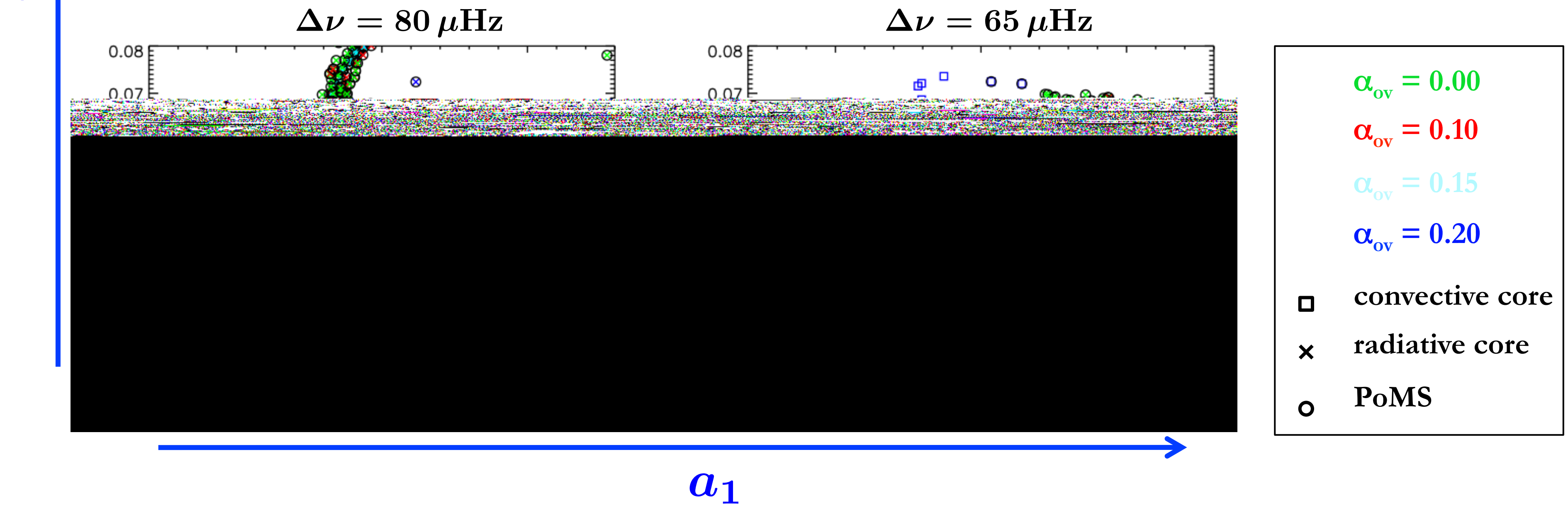


⇒ Effects of other parameters?

Grid of models at fixed Δν



- For stars evolved enough, we can determine:
  - **Evolutionary status** (MS or PoMS)
  - Existence of a **convective core**
  - **Size of the core** if it exists



Selection of *Kepler* targets

- Choice of optimal targets to probe the core size:
  - evolved enough so a $\nabla\mu$ has had time to build up
  - not too evolved so that ℓ=1 modes are not yet mixed

$$\Rightarrow \quad 60\,\mu\text{Hz} \lesssim \Delta\nu \lesssim 110\,\mu\text{Hz}$$

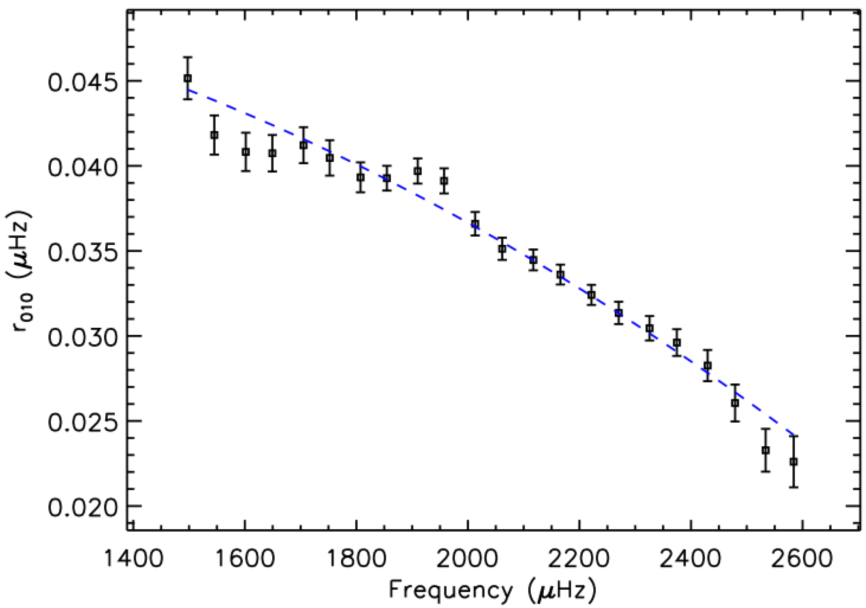
- Need for a good frequency resolution (at least 10 *Kepler* quarters)

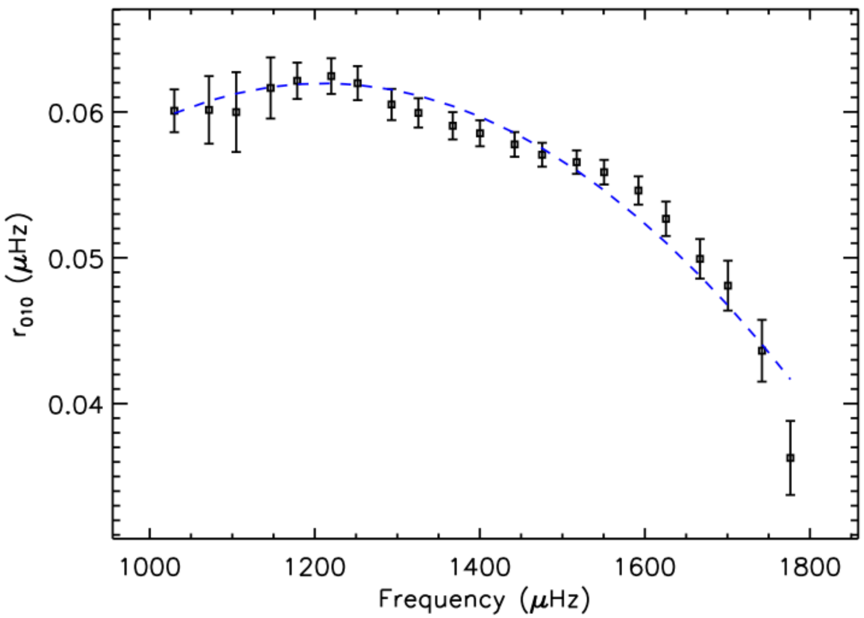
$\Rightarrow$ 24 *Kepler* targets chosen among **Chaplin et al. (2014)**

Extraction of mode frequencies

- Extraction of $\ell=0$ and $\ell=1$ mode frequencies using **maximum likelihood estimation** (MLE)
  - Only high-SNR modes retained

- r_{010} ratios for 2 of the selected targets:



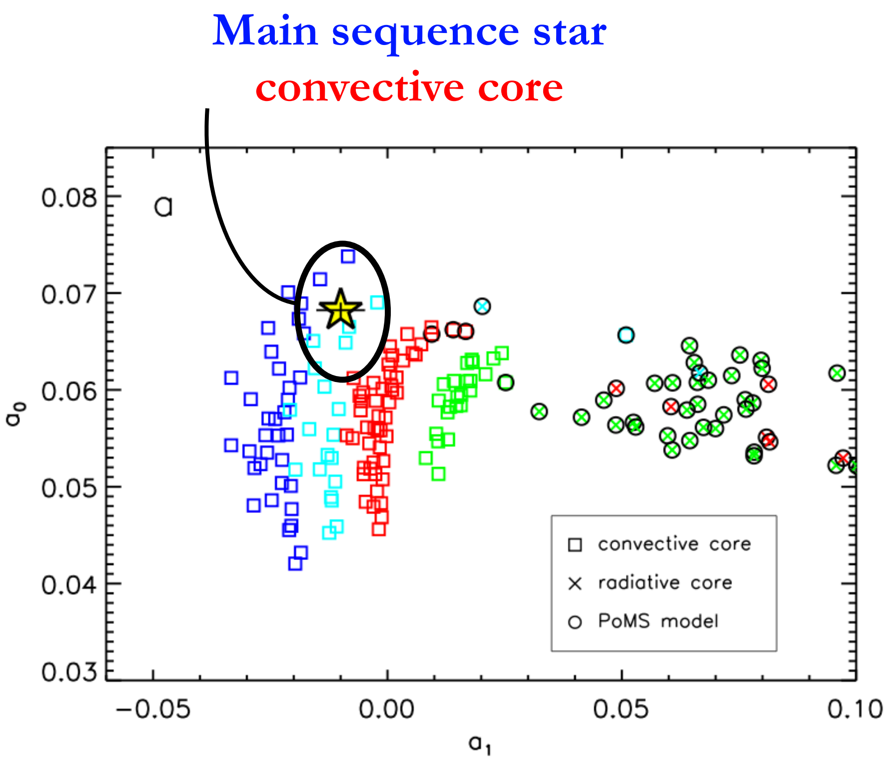


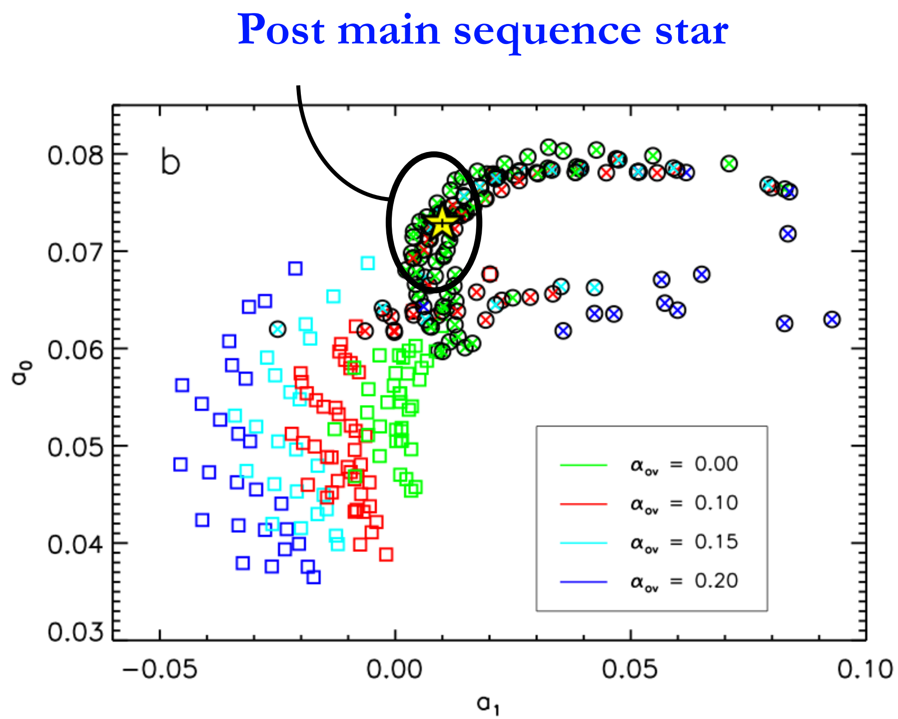
Confronting observations to the grid of models

- **Evolutionary status** disentangled for 22 stars:

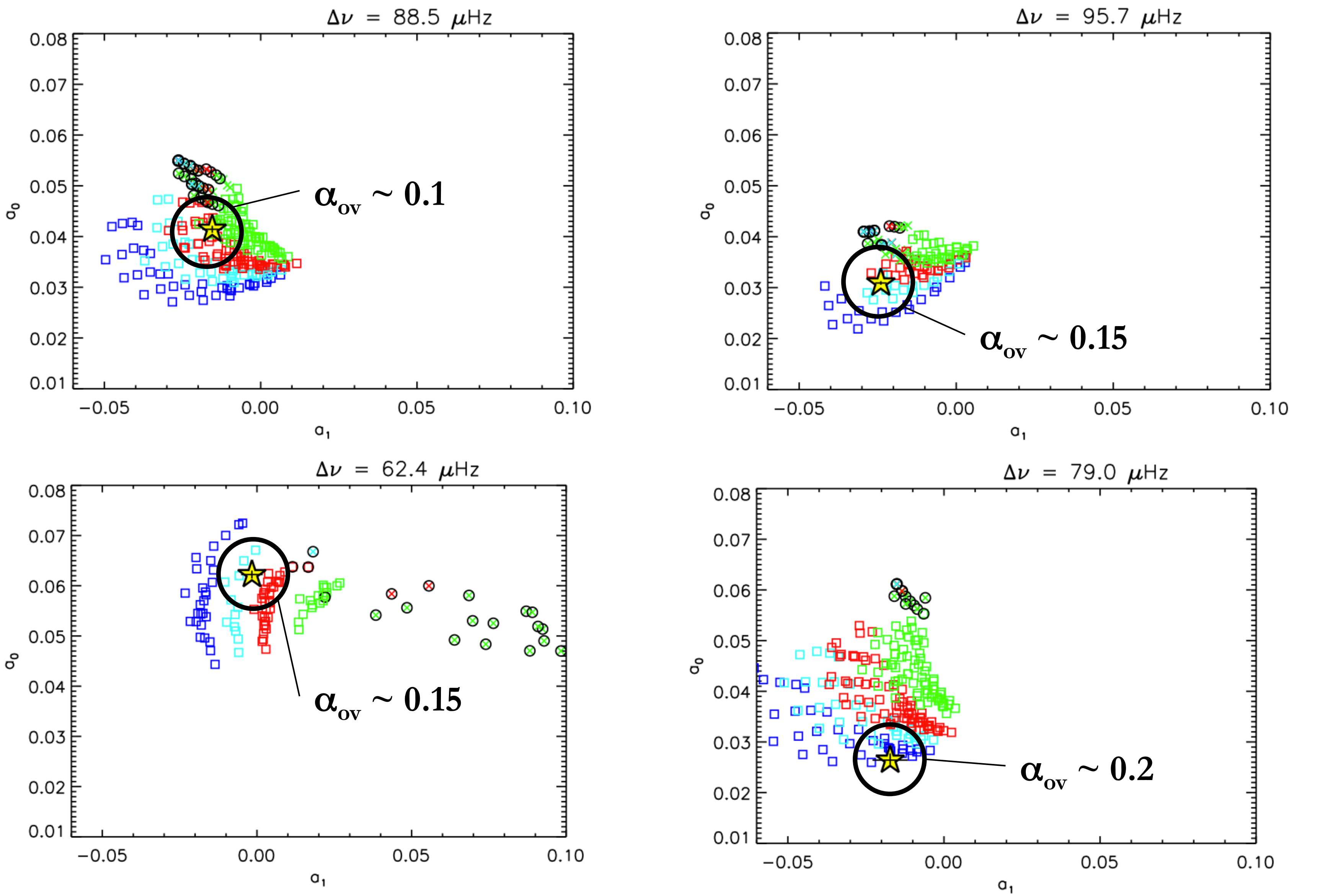
  12 MS stars / 10 PoMS stars / 2 uncertain

- Among MS stars, **convective core** detected for 8 stars





Constraints on the size of the convective core



Results

- **Evolutionary status** disentangled for 22 stars (12 MS / 10 PoMS)
- Among MS stars, **convective core** detected for 8 stars
- Stars that have a convective core draw a ***very consistent picture of core overshooting***
  - *all the targets* require an extension of the core beyond the Schwarzschild limit ($\boldsymbol{\alpha_{ov} > 0}$)
  - *none of the targets* are consistent with an extension beyond 0.2 H_p ($\boldsymbol{\alpha_{ov} < 0.2}$)
  - Only the most massive target (1.37 $M_\odot$) consistent with $\alpha_{ov} \sim 0.2$

$\Rightarrow$ ***Dependence of core overshooting on stellar mass?***

Core overshooting vs stellar mass

- Optimization runs using the **Levenberg-Marquardt** algorithm (**Miglio & Montalban 05**)
  - Optimal grid models used as a starting point
  - Grids of models enable to avoid secondary minima
  - Yields more precise estimate of α_{ov}

- Constraints:
  - *Classical:* T_{eff}, $(Z/X)_{surf}$, $\log g_{seism}$
  - *Seismic:* lowest-order radial modes, a_0, a_1, a_2
- Free parameters:
  - Mass, age, Y_i, $(Z/X)_i$, α_{ov}

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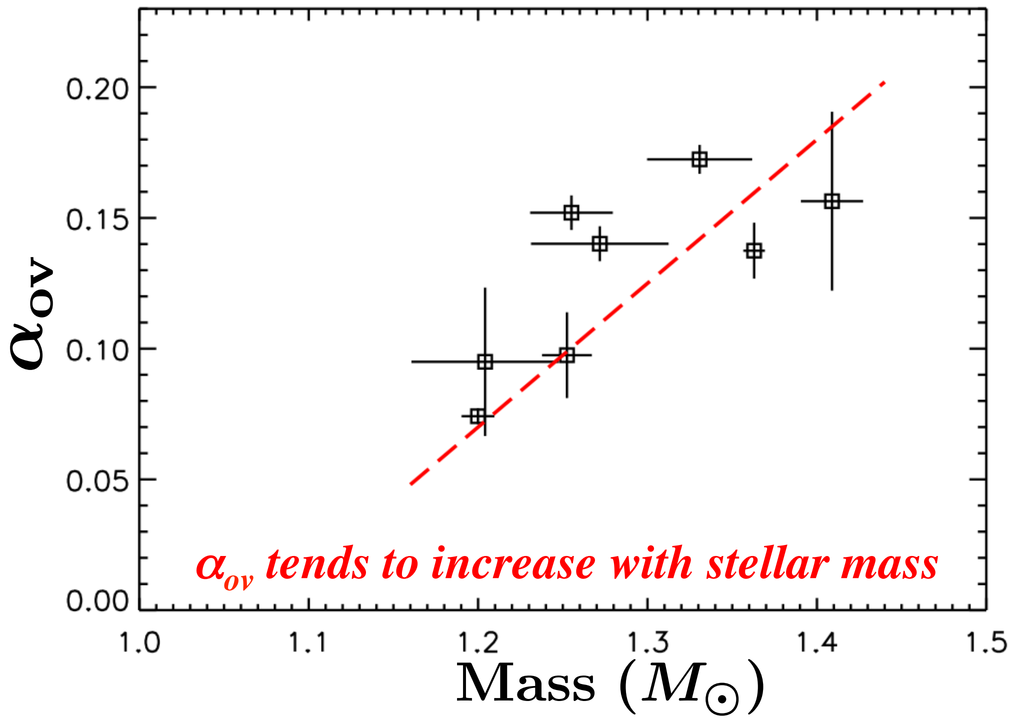
$$\alpha_{\rm ov} = (0.55 \pm 0.06)\, M + (-0.59 \pm 0.07)$$



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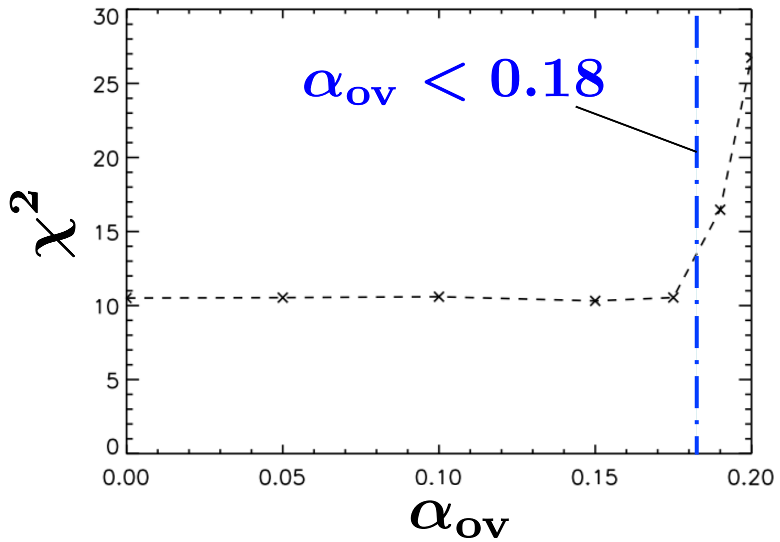
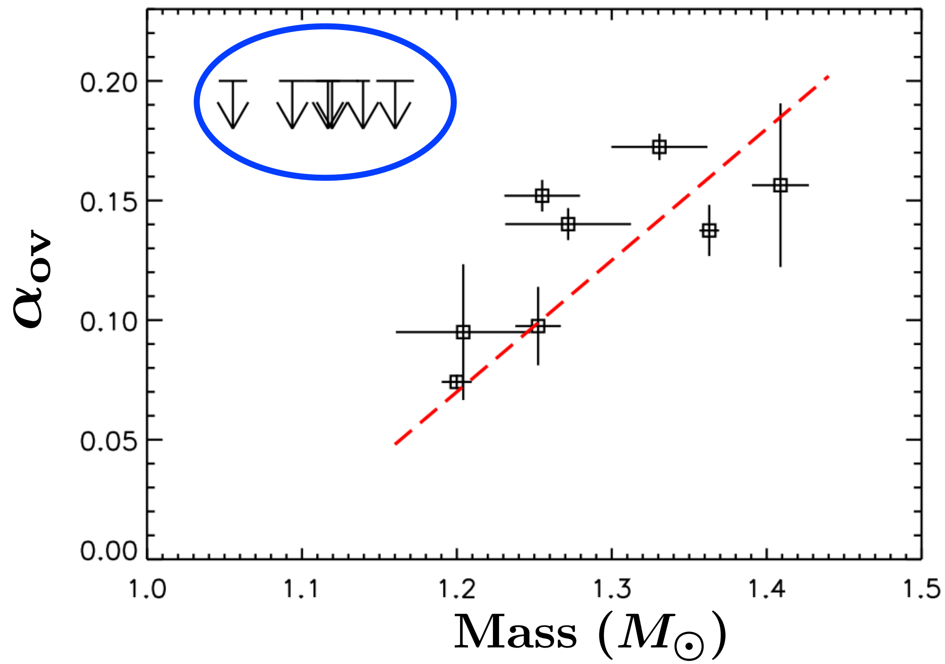
Core overshooting vs stellar mass

- Constraints on core overshooting from **low-mass PoMS stars**

Upper limit to α_{ov} for 6 targets





Conclusion & Perspectives

- The coefficients of a polynomial fit to the r_{010} ratios can be used to
  - Determine the **evolutionary status**
  - Test the **existence of a convective core**
  - Estimate the **extension of the core** if it exists

- Application to 24 Kepler targets ($0.9 < M/M_{\odot} < 1.4$)
  - Constraints on α_{ov} for 14 stars
  - $0 < \alpha_{ov} < 0.2$
  - α_{ov} increases with stellar mass for low-mass stars

Conclusion & Perspectives

- Calibrate extension of convective cores as a function of stellar mass (other parameters?)

$$\alpha_{\mathrm{ov}} = (0.55 \pm 0.06)\, M + (-0.59 \pm 0.07)$$

- Model-dependent results

$\Rightarrow$ need to study in more details the impact of

  - Description of core overshooting (diffusive overshooting with GARSTEC)
  - Different microphysics

- Extend this study to F stars