Challenges for fitting observations of PLATO subgiant stars

PLATO STESCI Workshop – Milazzo – 05/2018

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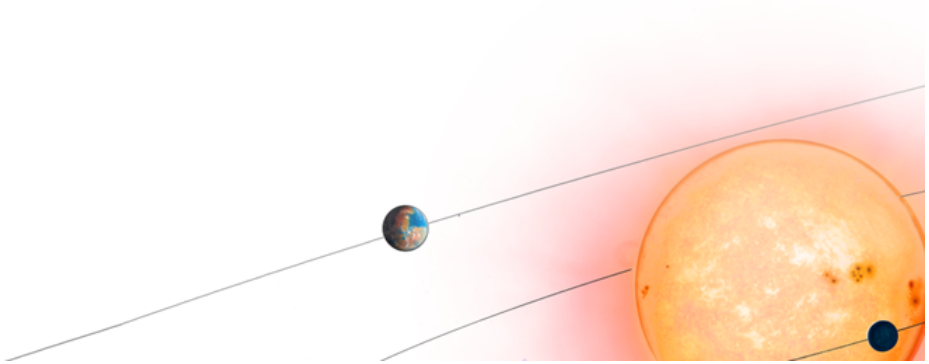
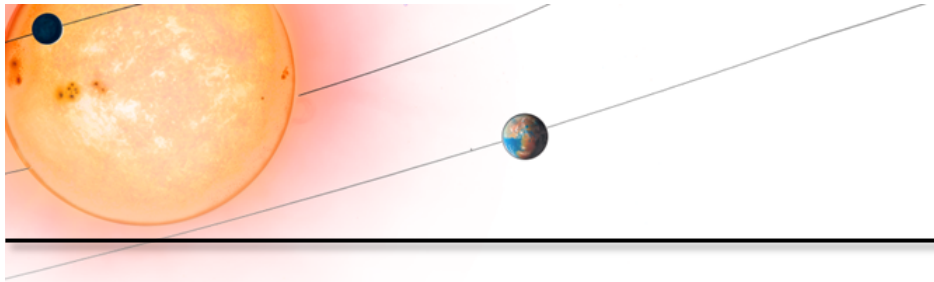


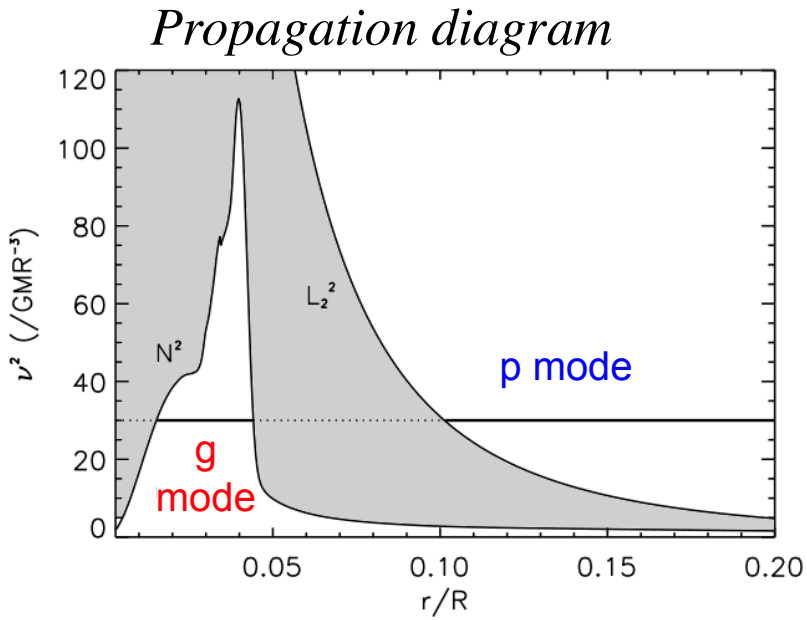


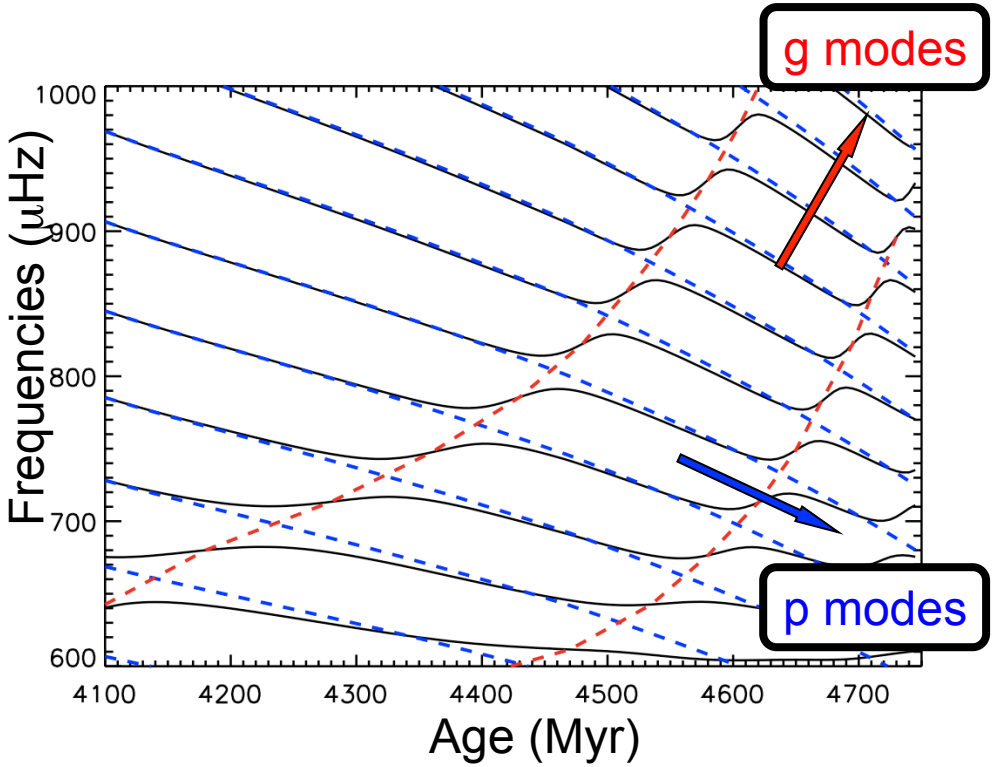
Outline

- What can mixed modes tell us about stellar cores?
- Current modeling techniques and performances
- Challenges for stellar modeling

Mixed modes

- For evolved stars (past main-sequence turnoff), the Brunt-Väisälä frequency becomes huge (central density ρ_c ↗↗)

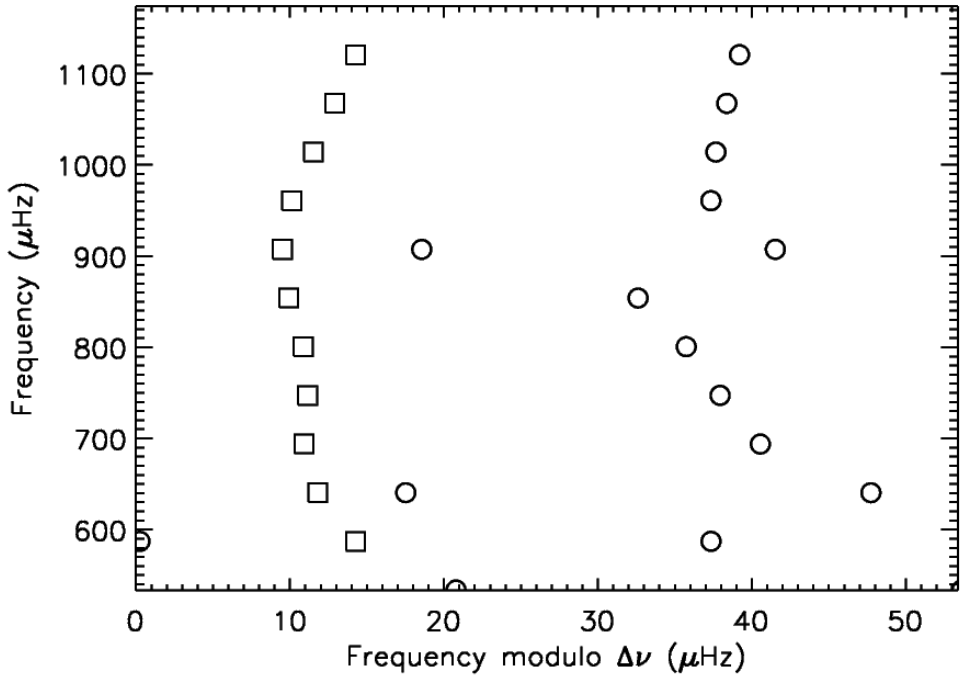




- Interest of mixed modes :
  1. They are sensitive to the core structure
  2. Their amplitudes are much larger then those of pure g modes

Oscillation spectra of subgiants

- Variations in the oscillation spectrum during the subgiant phase
  - Example for a 1.3-$M_\odot$ model



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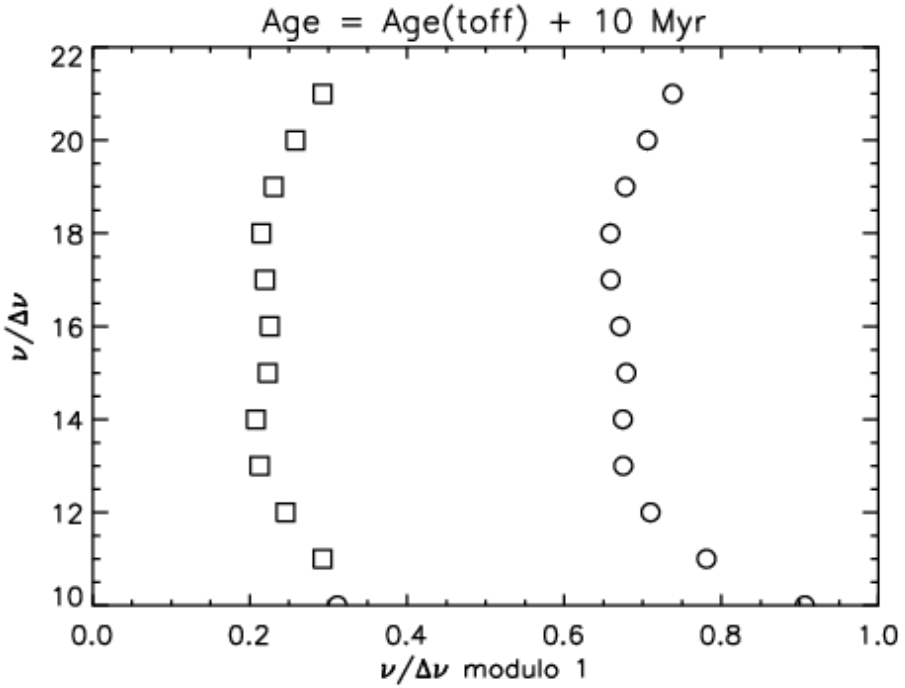


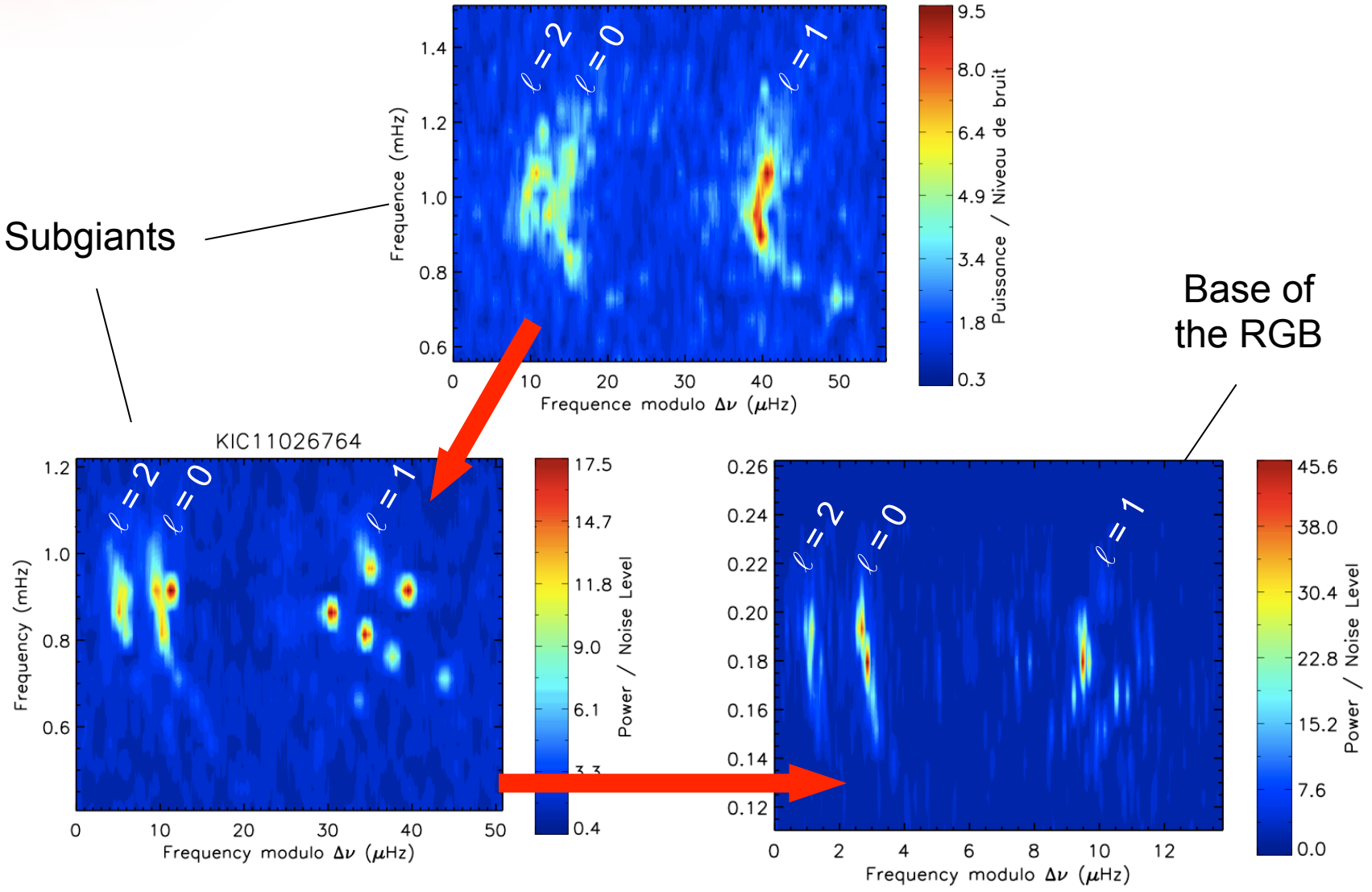
1st avoided crossing

2nd avoided crossing

3rd avoided crossing

4th avoided crossing

Oscillation spectra of subgiants



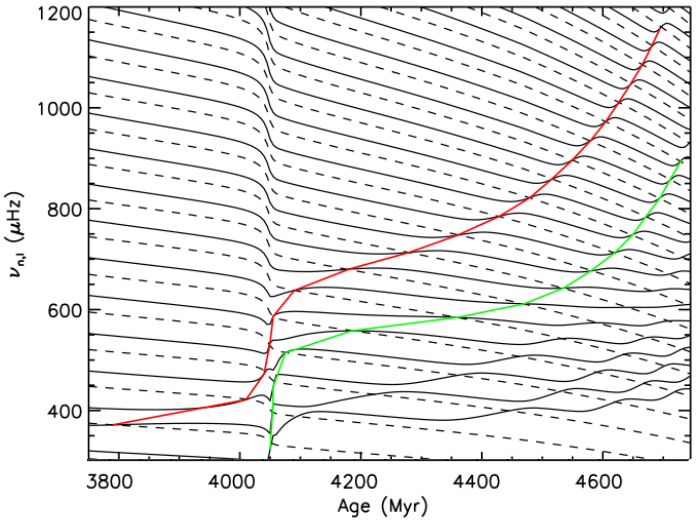
Interest of mixed modes

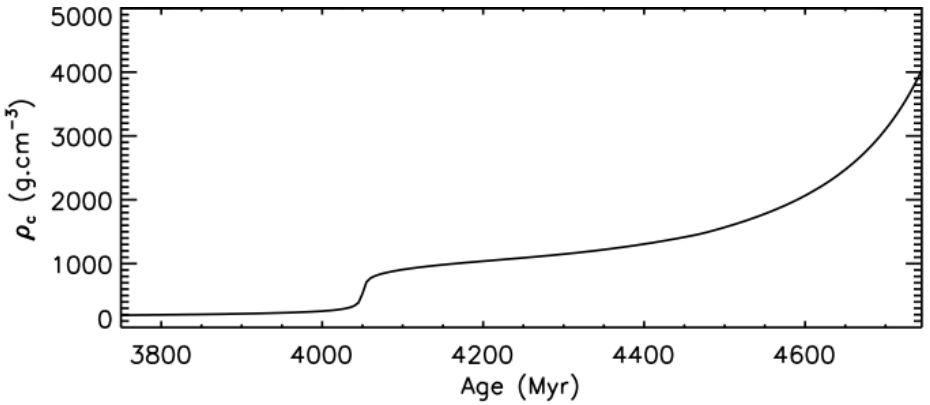
- G-modes sensitive to the Brunt-Väisälä profile in the core

$$\omega_{\rm g} \sim \int_{r_{\rm i}}^{r_{\rm o}} \frac{N}{r}\,{\rm d}r$$

- Variations in the frequency of g modes tightly related to the variations in ρ_c

  ⇒ Strong constraints on the **age** (for given input physics)

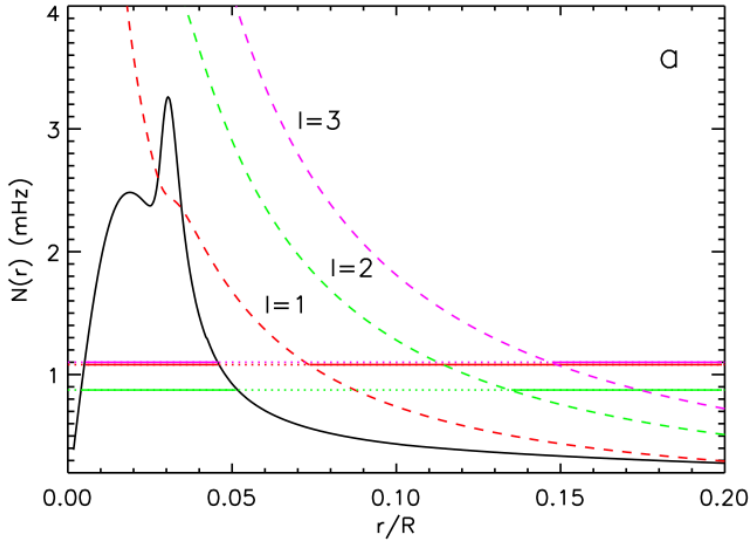




Interest of mixed modes

- G-modes sensitive to the structure of the evanescent zone between the p-mode and g-mode cavities
- JWKB approximation: coupling between p-mode and g-mode cavities given by

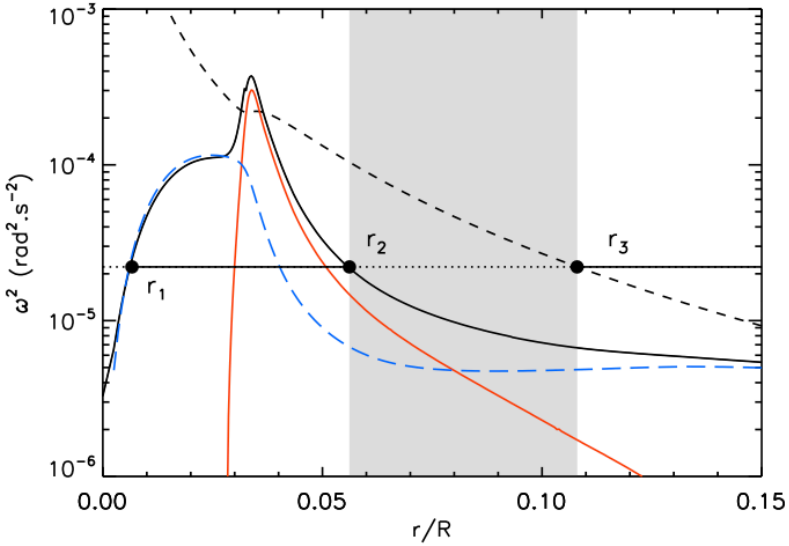
$$q \approx \frac{1}{4}\exp\left(-2\int_{\mathrm{ZE}} \kappa \,\mathrm{d}r\right) \qquad \text{with} \qquad \kappa^2 \approx \frac{\omega^2}{c^2}\left(\frac{S_l^2}{\omega^2}-1\right)\left(1-\frac{N^2}{\omega^2}\right)$$



- Coupling decreases for increasing degree ℓ

Interest of mixed modes

- What is mode coupling $q \approx \frac{1}{4}\exp\left(-2\int_{\mathrm{ZE}} \kappa \, \mathrm{d}r\right)$ sensitive to?



$$N^2 = \frac{g}{H_P}\left(\nabla_{\mathrm{ad}} - \nabla\right) + \frac{g}{H_P}\nabla_\mu$$

- Evanescent zone essentially sensitive to ∇_μ

⇒ Sensitivity to **mixing processes**

- Good news to test stellar physics!
- Not so good news to measure masses, radii, ages, which thus depend on the modeling of mixing processes

+ Sensitivity to stellar **mass**

Oscillation spectra of subgiants

- Detection of mixed modes during the subgiant phase depends on the presence of a convective core during the main-sequence

  – For 1 $M_\odot$-star (radiative core on the MS), apparition of 1st avoided crossing in the observed frequency range $\Delta\tau$ = 2.2 Gyr after end of the main sequence

  $\Rightarrow$ $\Delta\tau/\tau_{MS}$ = 24%

  – For 1.3 $M_\odot$-star (convective core on the MS), apparition of 1st avoided crossing in the observed frequency range $\Delta\tau$ = 20 Myr after end of the main sequence

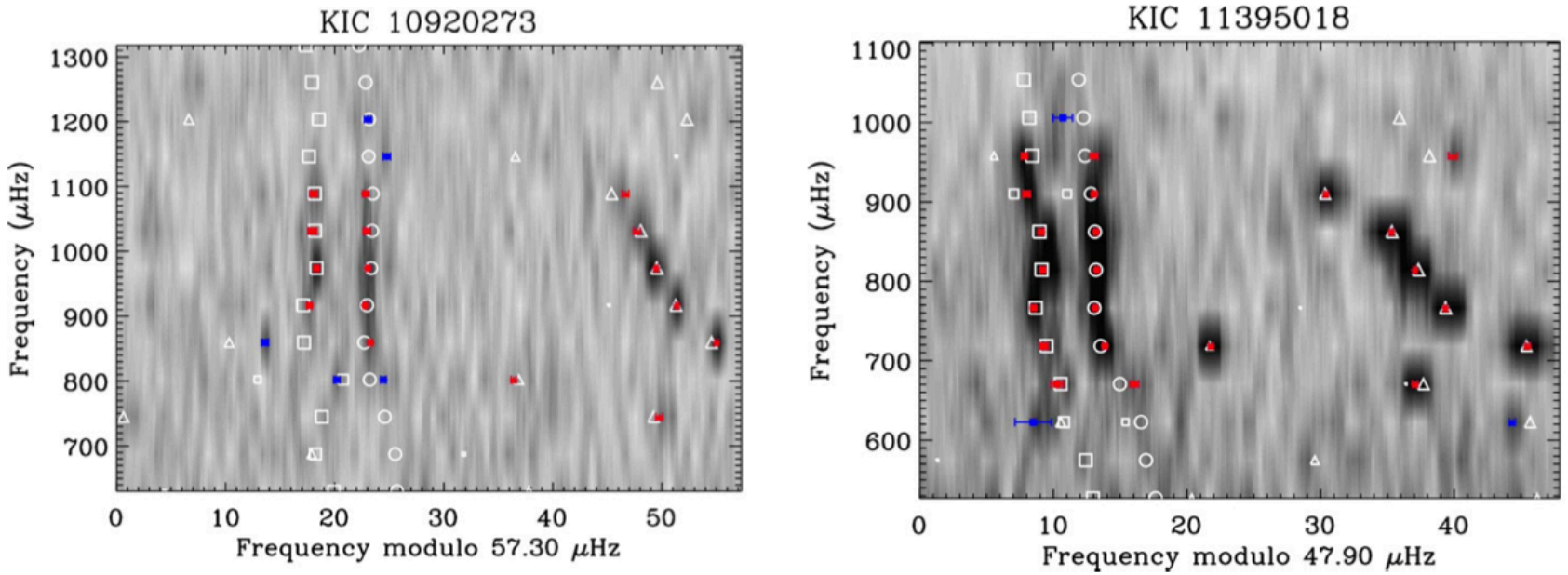
  $\Rightarrow$ $\Delta\tau/\tau_{MS}$ = 0.5%

Modeling techniques

- Grid-based modeling (**Brandão et al. 2011**, **Dogan et al 2013, Stockholm et al. in prep.**)
  - Usually involve computation of several sub-grids with refined mesh in the regions of minimal χ^2 values
- AMP (Asteroseismic Modeling Portal, **Metcalfe et al. 2009, Dogan et al. 2013, Metcalfe et al. 2014**):
  - Parallel genetic algorithm for a first global search
  - Levenberg-Marquardt algorithm + Single-Value Decomposition for a local search
- Levenberg-Marquardt algorithm (**Deheuvels & Michel 2011**)
  - Adapted to treat subgiants with mixed modes
- Downhill simplex method (**Ball et al. 2017**)
  - First search within a coarse grid before applying simplex method

Performances

- Example 1: Seismic modeling of two Kepler subgiants **(Doğan et al. 2013)**



Performances

- Example 1: Seismic modeling of two Kepler subgiants **(Doğan et al. 2013)**

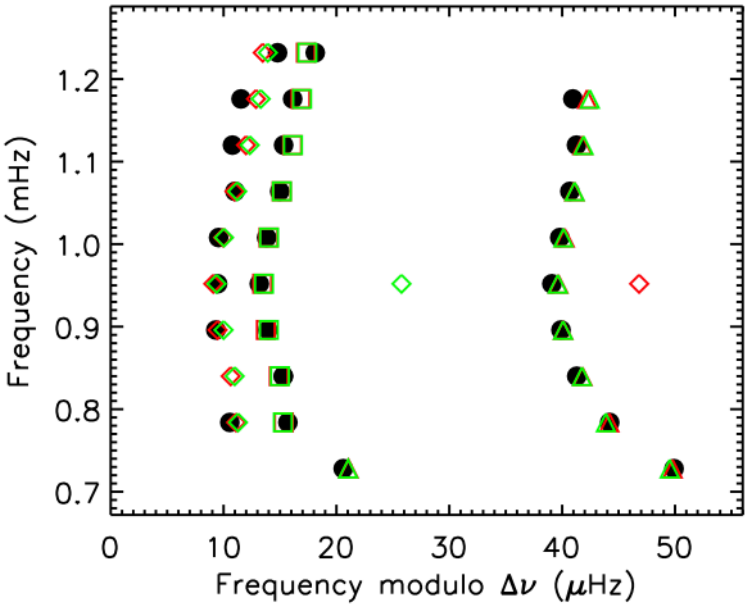
Table 5
Fitted Parameters for KIC 11395018

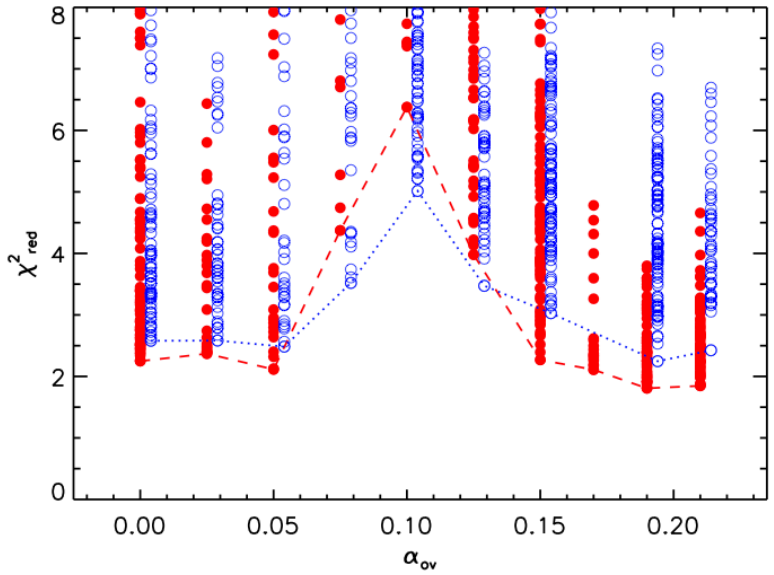
Model	$M/M_\odot$	$(Z/X)_i$	Y_i	α	t (Gyr)	$L/L_\odot$	$R/R_\odot$	$T_{\rm eff}$ (K)	log g	[Fe/H]	X_c	$\chi^2_{\rm seis}$	$\chi^2_{\rm atm}$
BA1 (AMP)	1.23	0.034	0.301	1.94	4.46	4.40	2.158	5697	3.860	0.144	0.0	8.07	0.49
BA2 (AMP)	1.32	0.028	0.241	1.94	4.84	4.53	2.210	5671	3.869	0.049	0.0	8.51	0.69
BA3 (AMP)[a]	1.26	0.034	0.294	2.02	4.28	4.64	2.175	5749	3.863	0.140	0.0	7.36	0.55
BB1 (ASTEC1)	1.235	0.033	0.282	1.80	5.05	4.04	2.156	5573	3.861	0.114	0.0	17.03	1.02
BB2 (ASTEC1)[a]	1.22	0.040	0.310	1.80	4.65	4.11	2.154	5605	3.858	0.213	0.0	17.08	1.02
BC1 (ASTEC2)	1.25	0.034	0.297	1.81	4.29	4.42	2.265	5615	3.820	0.116	0.0	47.34	0.90
BC2 (ASTEC2)[b]	1.32	0.043	0.270	1.81	4.89	4.06	2.211	5515	3.870	0.243	0.0	17.65	2.01
BD (CESAM)	1.29	0.030	0.260	0.64[c]	4.50	4.89	2.190	5806	3.866	0.026	0.0	4.04	1.19
BE (Geneva)	1.32	0.033	0.275	1.80	4.30	5.18	2.207	5867	3.871	0.120	0.0	115.69	1.37
Weighted mean	1.27	0.033	0.276		4.57	4.54	2.184	5706	3.863	0.103			
Standard deviation	(0.04)	(0.004)	(0.022)		(0.23)	(0.30)	(0.024)	(92)	(0.008)	(0.070)			
Creevey et al. (2012)	1.37 ± 0.11				3.9 ± 1.4 4.5 ± 0.5[d]	4.2 ± 1.1	2.23 ± 0.04		3.88 ± 0.02 3.86 ± 0.03[e]				

- Large values of $\chi^2_{\rm red}$ for best-fit models (even with 8 mths of data)
  - Caused by problems in stellar models ? Or pb in the fitting procedure…
- Large disparities in the reduced χ^2 of the best-fit models for different modeling techniques!

Performances

- Example 2: Seismic modeling of a CoRoT subgiant **(Deheuvels & Michel 2011)**

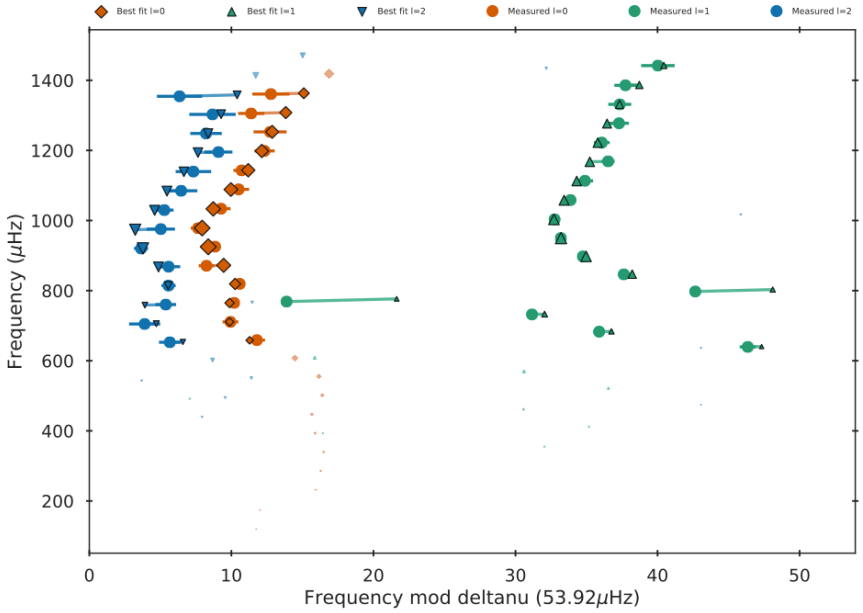




- Good statistical agreement with data ("only" 5 months of data)
- Two possible solutions, with either a small ($d_{ov} < 0.05\ H_P$) or a large ($d_{ov} \sim 0.20\ H_P$) amount of core overshooting during the MS

Performances

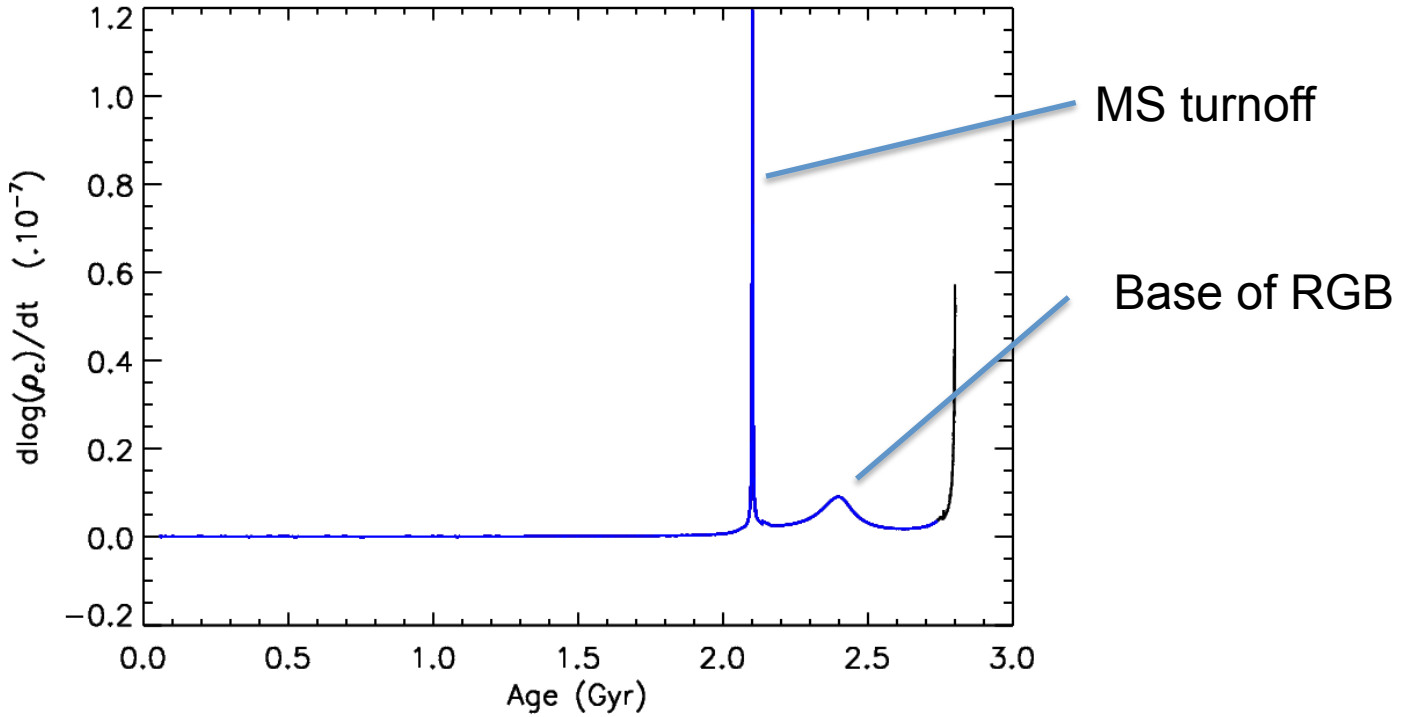
- Example 3: Seismic modeling of a bright Kepler subgiant with BASTA **(Stockholm et al. in prep)**



- Grid details: $\Delta M = 0.01$ M, $\Delta(Z/X) = 0.03$ dex

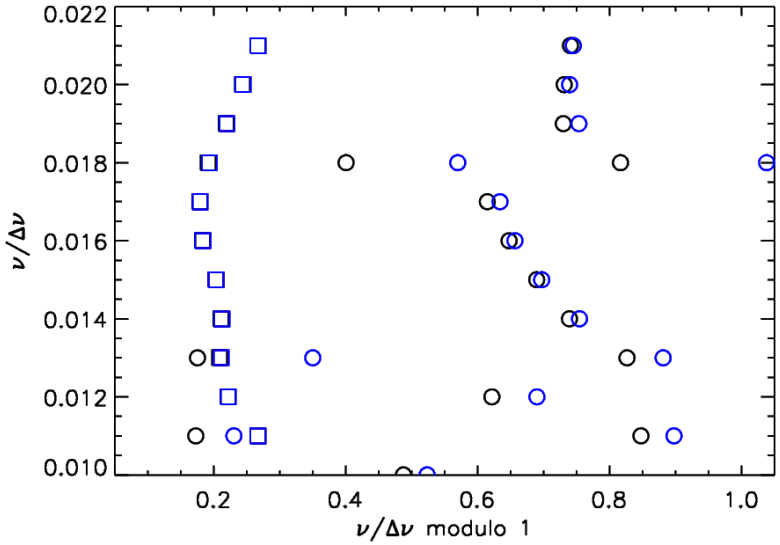
Sensitivity of mixed modes to stellar age

- Variations in the frequencies of g modes tightly related to those of ρ_c



Sensitivity of mixed modes to stellar age

- Variations in the normalized frequencies after Δt = 10 Myr

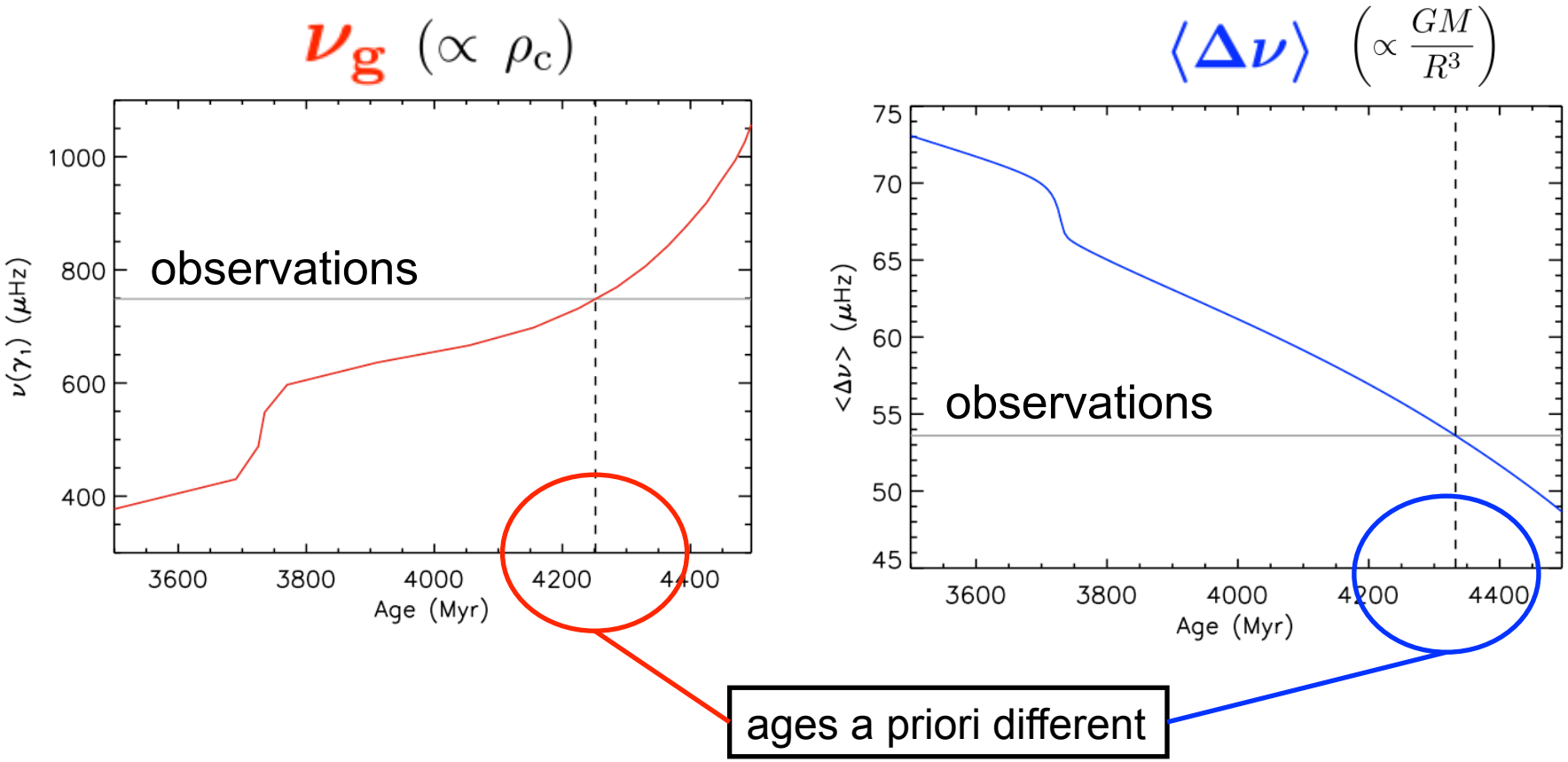


- Typically $\dot{\nu}_{\mathrm{g}} \sim 1\,\mu\mathrm{Hz.Myr}^{-1}$ => requires grid-step ~ 1 Myr
- The rate of variations in the frequencies of mixes modes also changes rapidly: for p-dominated modes, $\dot{\nu}_{\mathrm{mix}} < 0$ while for g-dominated modes, $\dot{\nu}_{\mathrm{mix}} > 0$

Sensitivity of mixed modes to stellar age

g-mode frequencies

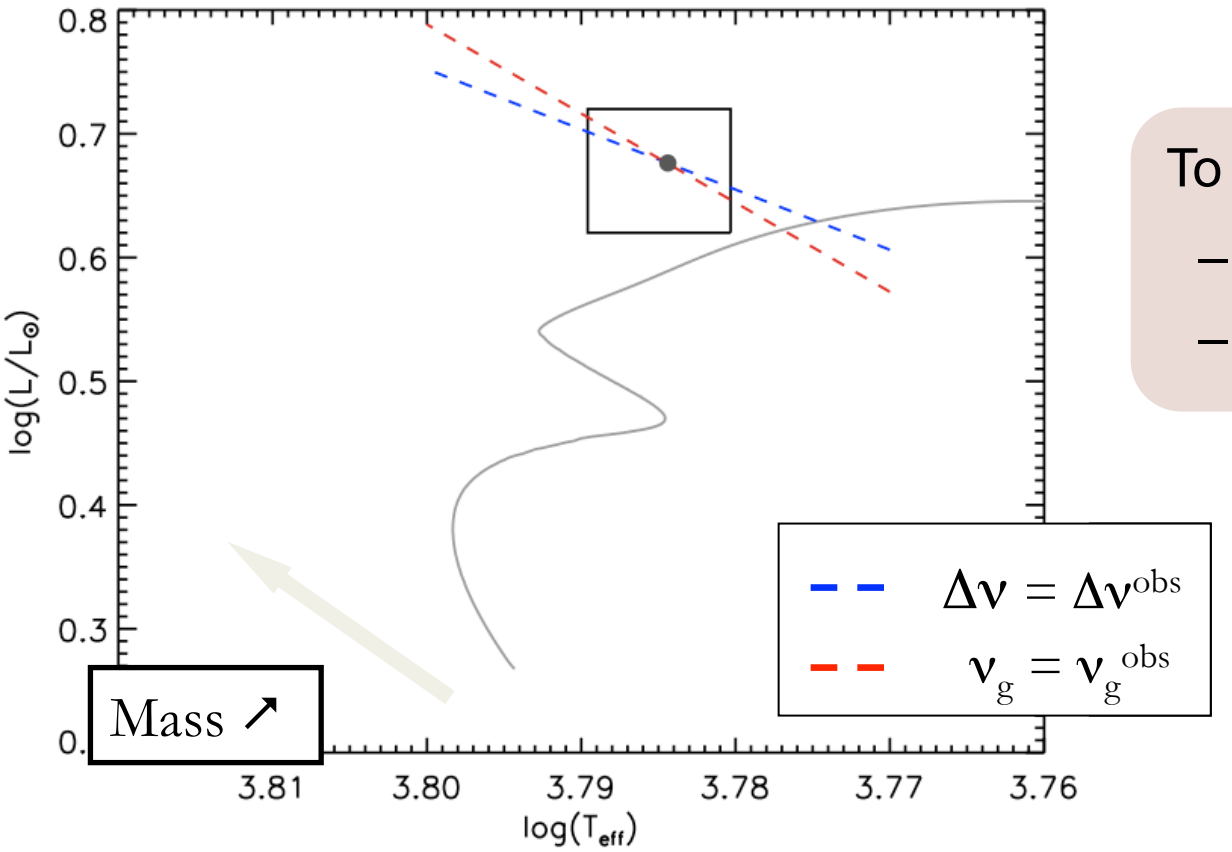
large separation



Which are the models that fit both conditions simultaneously?

Sensitivity of mixed modes to stellar mass

- We showed that for a given physics, the knowledge of $\Delta\nu$ and ν_g imposes one and one only mass **(Deheuvels & Michel 2011)**



To verify both conditions

- one mass only ($\tilde{M}$)
- one age only ($\tilde{\tau}$)

Sensitivity of mixed modes to stellar mass

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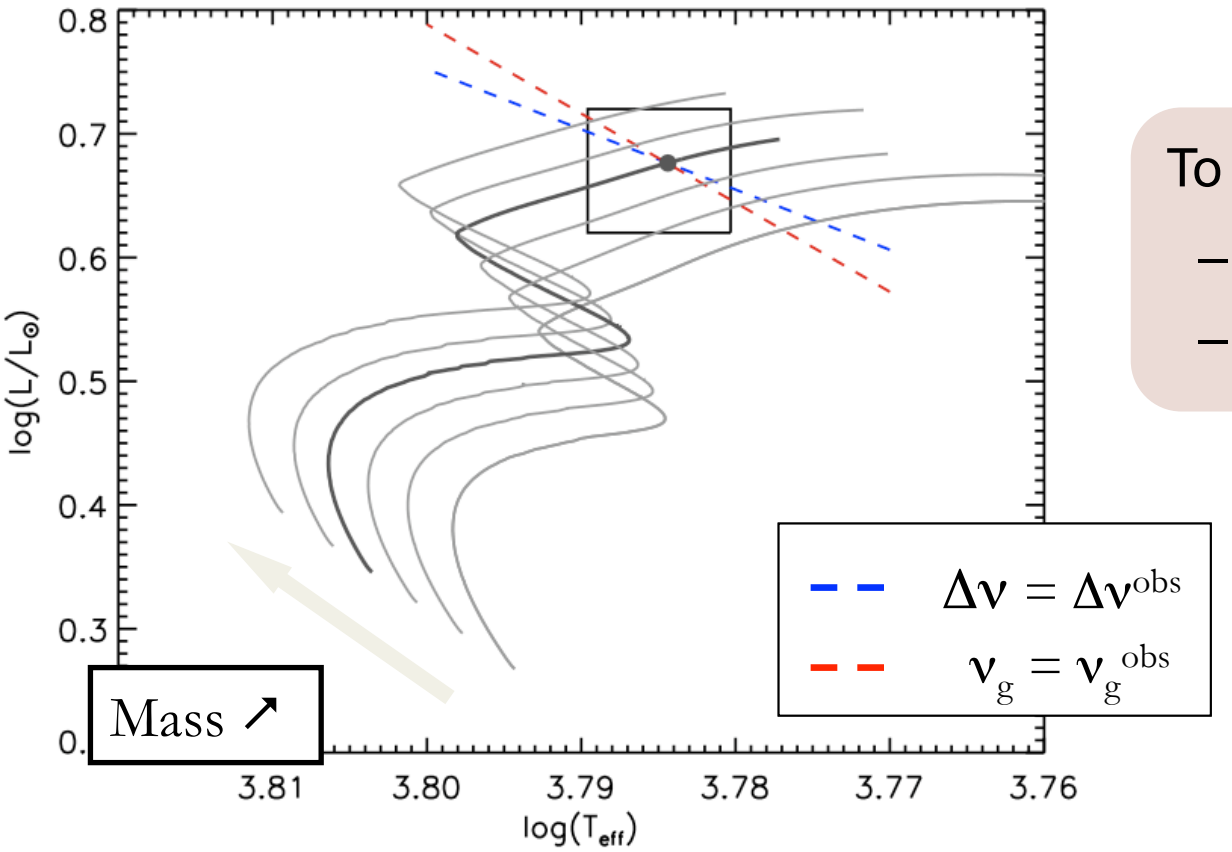
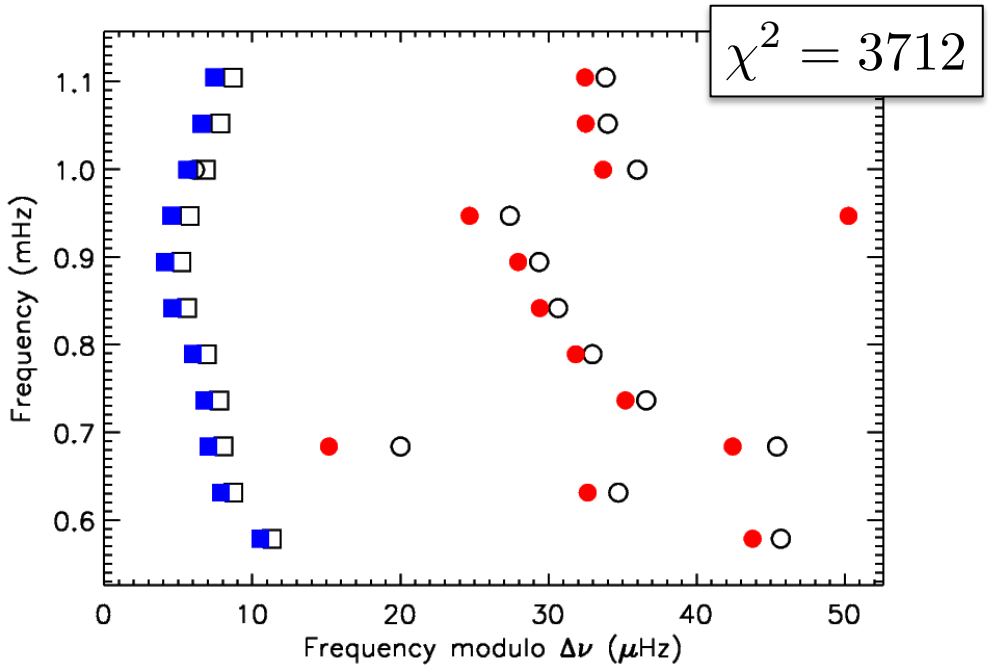


To verify both conditions

- one mass only ($\tilde{M}$)
- one age only ($\tilde{\tau}$)

Sensitivity of mixed modes to stellar mass

- Question: *What grid-mesh is required for the stellar mass to model subgiants?*
- Grid with time step of 1 Myr, step of $\Delta M = 0.01\ M_\odot$ in mass ($M = 1.29, 1.30, 1.31\ M_\odot$), fixed input physics
- Reference model: $M = 1.295\ M_\odot$, Age = 4200 Myr, same physics as grid



$$\chi^2 = \sum \frac{(\nu_i^{\rm mod} - \nu_i^{\rm ref})^2}{\sigma_i^2}$$

- We assume $\sigma_\nu = 0.2 \mu{\rm Hz}$
- With a perfect model, we expect

$$E(\chi^2) = n_{\rm freq} = 24$$

Sensitivity of mixed modes to stellar mass

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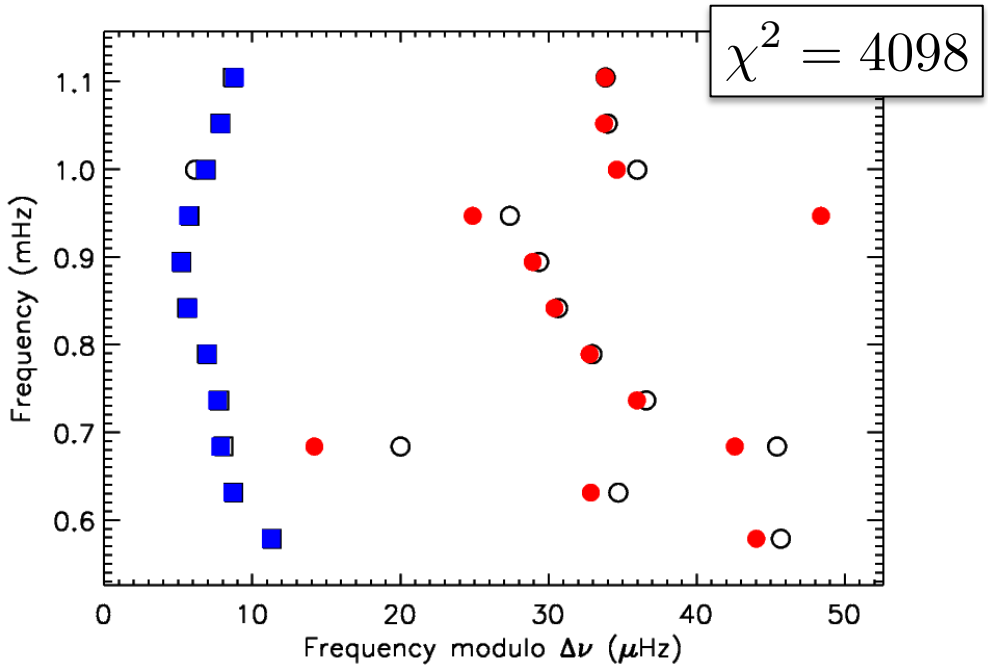

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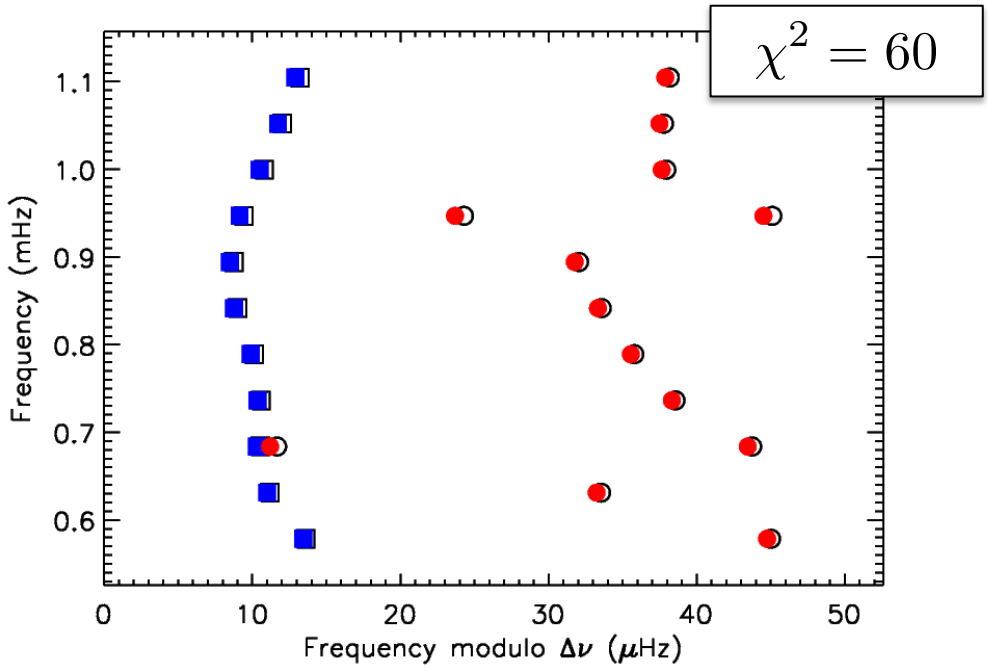
Sensitivity of mixed modes to stellar mass

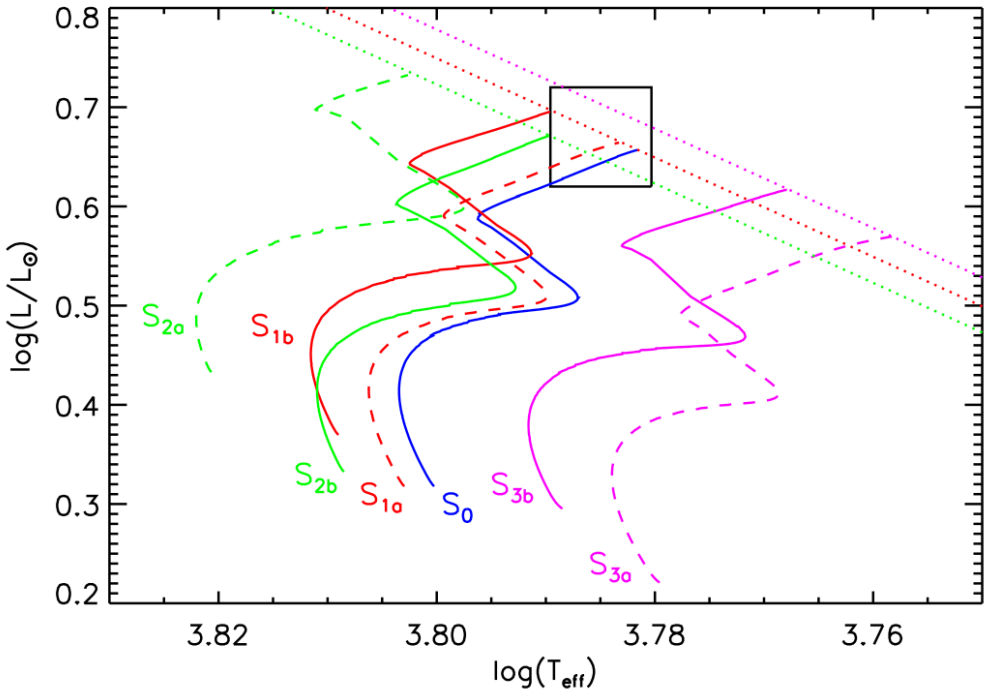
- Question: *What grid-mesh is required for the stellar mass to model subgiants?*
- Grid with time step of 1 Myr, step of $\Delta M = 0.001\ M_\odot$ in mass ($M = 1.299, 1.300, 1.301\ M_\odot$), fixed input physics
- Reference model: $M = 1.2995\ M_\odot$, Age = 4110 Myr, same physics as grid



- With a precision of σ_ν = 0.2 μHz, **a grid mesh $\Delta M < 0.001\ M_\odot$ is required in mass to avoid "missing" models**

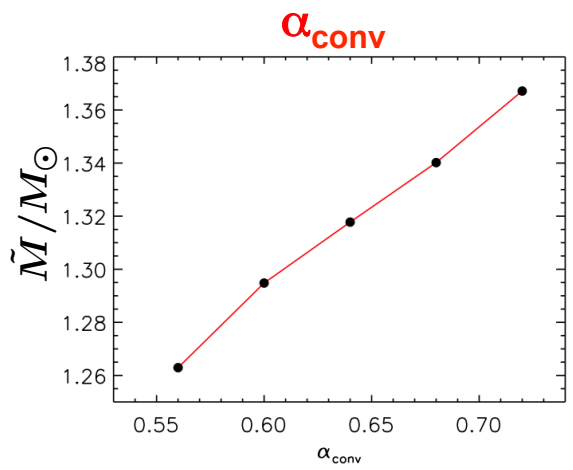
How does $\tilde{M}$ vary with stellar parameters?

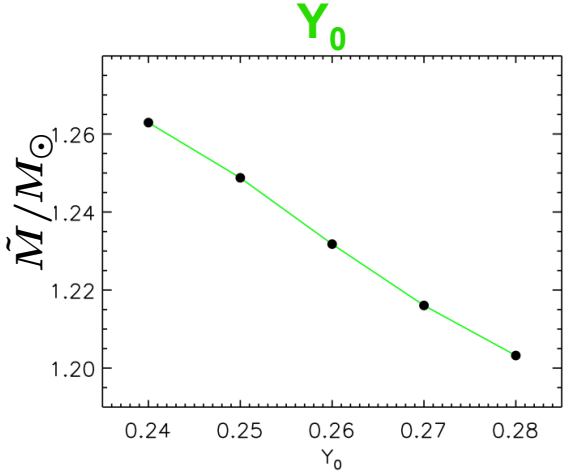
- Idea: using the observed value of $\Delta\nu$ and the frequency of the most g-like mode(s) to pre-select models
- Variations in $\tilde{M}$ for varying **mixing length** parameter α_{conv}, initial **helium** Y_0, and **metallicity** (AGS05 to GN93)

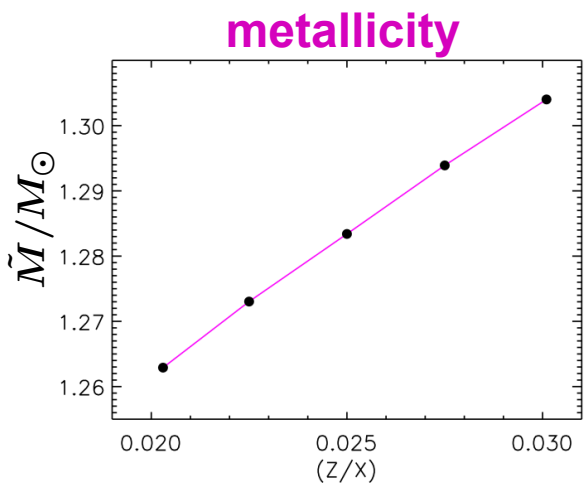


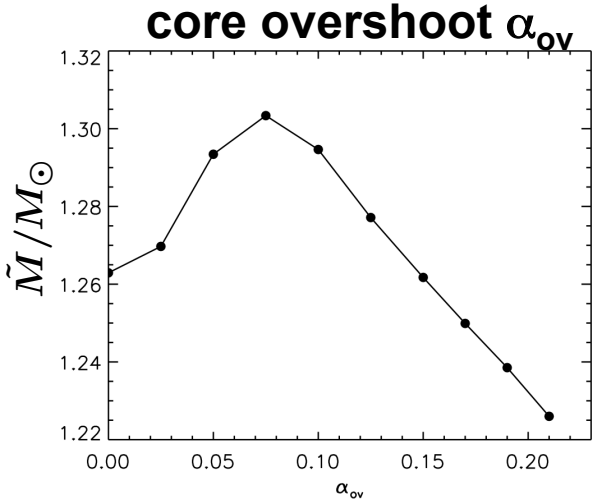
How does $\tilde{M}$ vary with stellar parameters?

- Variations in $\tilde{M}$ for varying **mixing length** parameter α_{conv}, initial **helium** Y_0, **metallicity**, and **core overshoot** α_{ov}



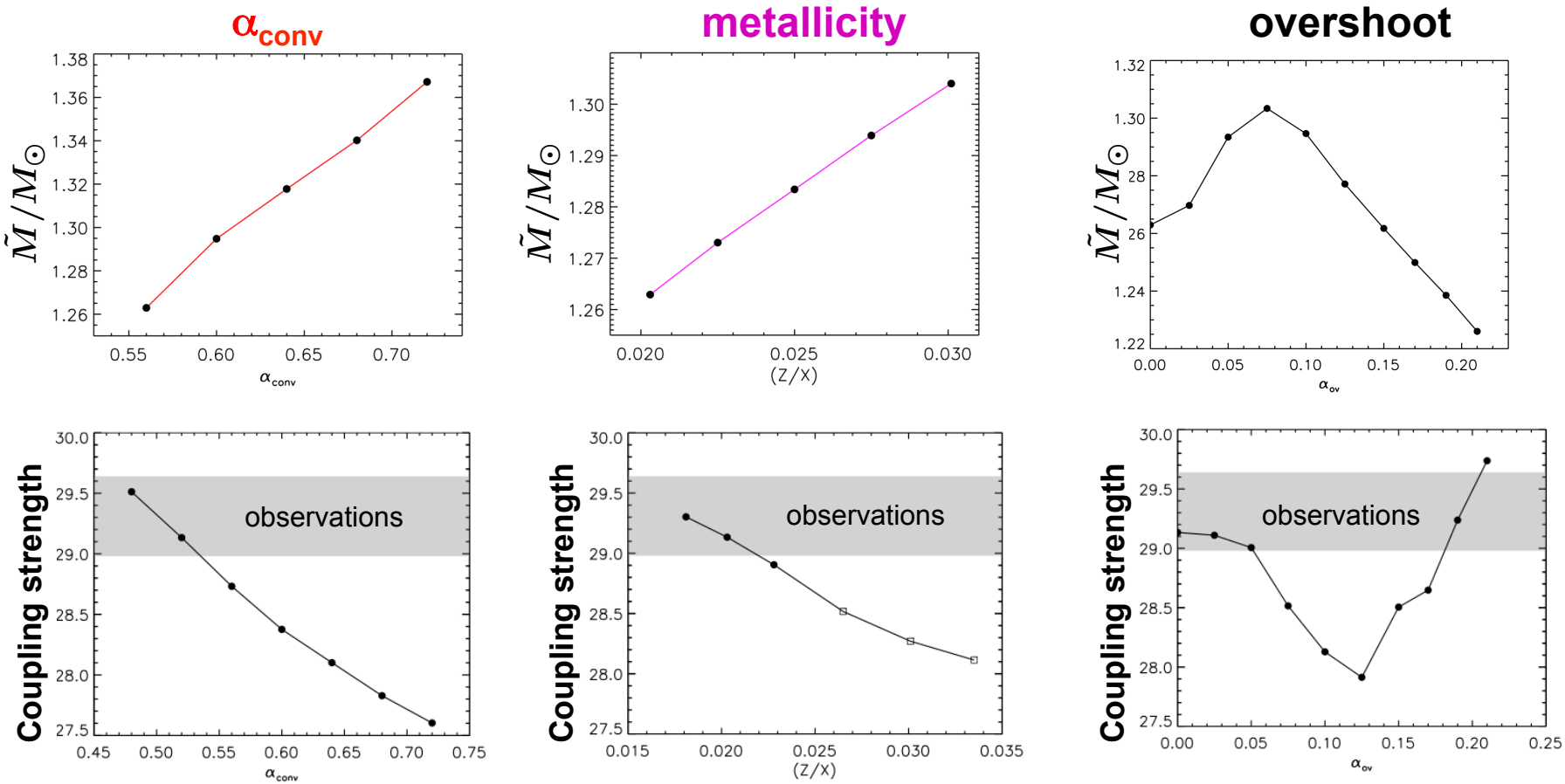






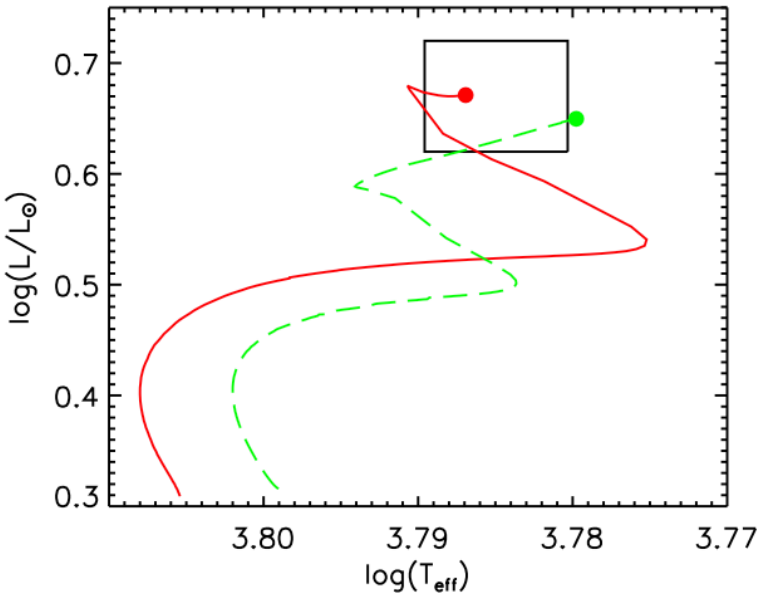
Link between mode coupling and stellar mass

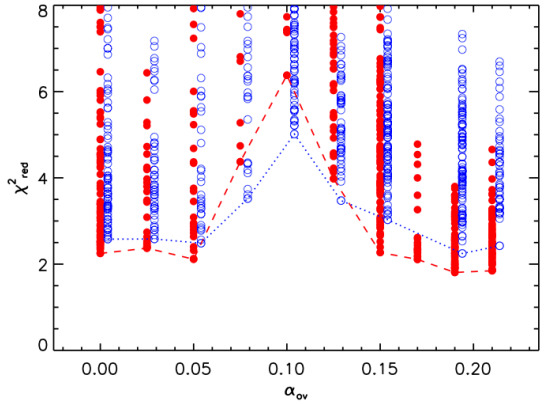
- Seismic modeling of HD49385 (**Deheuvels & Michel 2011**)
  - Tight anti-correlation between mass and coupling strength



Link between mode coupling and stellar mass

- Seismic modeling of HD49385 (**Deheuvels & Michel 2011**)
  - Tight anti-correlation between mass and coupling strength
  - Reason for bimodality of solutions for this target
  - Not specific to this target, expected to occur for stars close to the turnoff





Link between mode coupling and stellar mass

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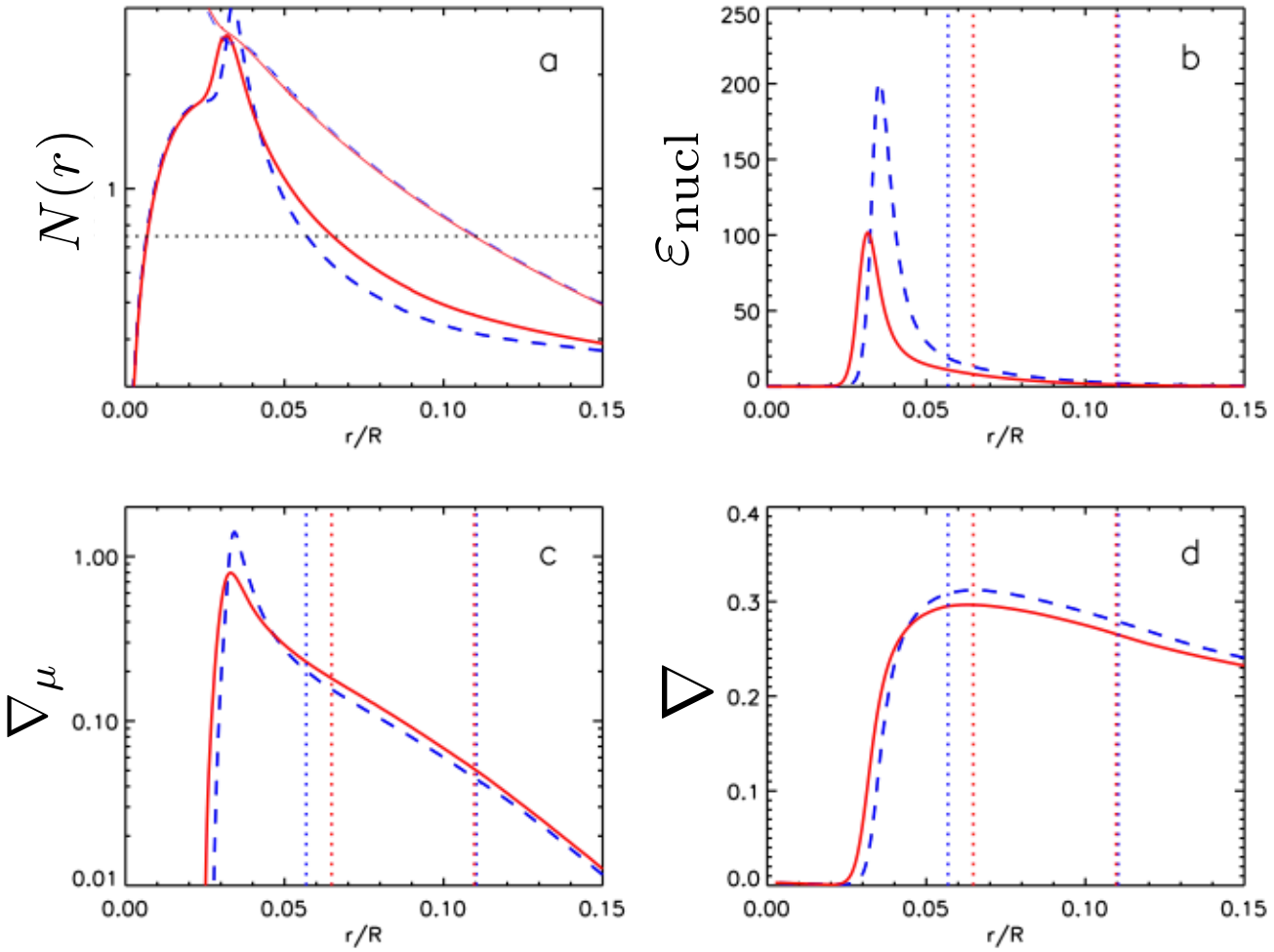
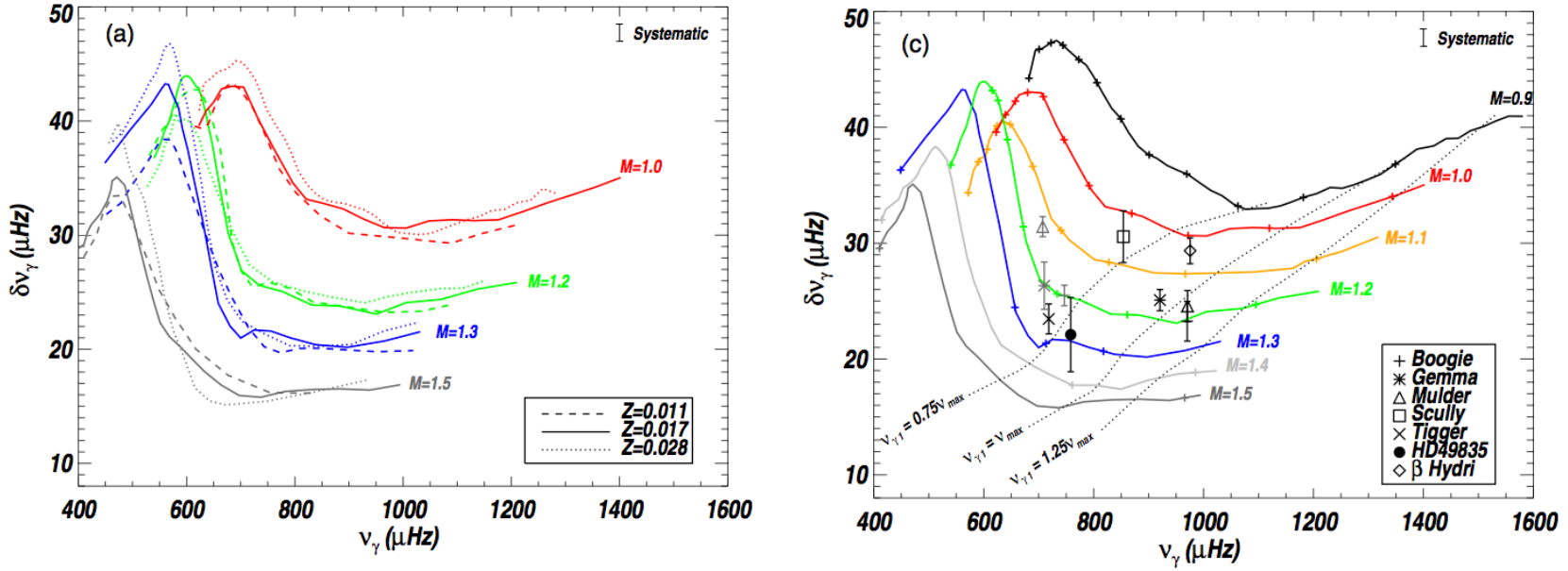


Link between mode coupling and stellar mass

- Anti-correlation btw mass and coupling strength also found by fitting asymptotic expressions to mode frequencies of stellar models (**Benomar et al. 2012**)
  - Proposed as a way of estimating stellar masses

Coupling strength



Correction of near-surface effects

- Issue of the correction of near-surface effects
  - Using frequency ratios such as r_{01} or r_{10} is impractical because of mixed modes
  - 3D simulations of convection are far too computationally demanding for stellar modeling
  - Only empirical corrections are thus available so far (e.g., **Kjeldsen et al. 2008**, **Ball & Gizon 2014**, **Sonoi et al. 2015**)

$$\nu_{n,\ell}^{\mathrm{obs}} - \nu_{n,\ell}^{\mathrm{best}} = a \left(\frac{\nu_{n,\ell}^{\mathrm{obs}}}{\nu_0} \right)^b$$

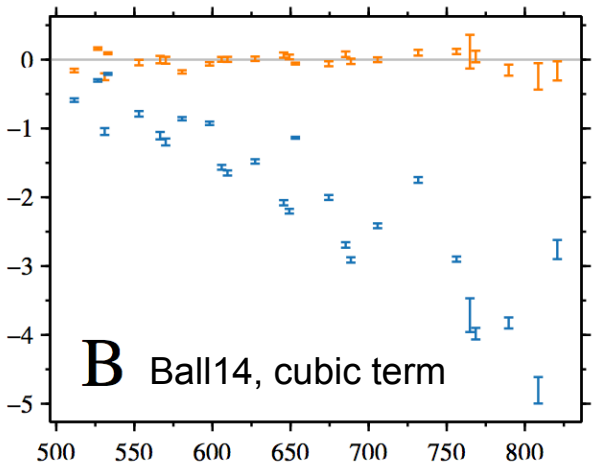
$$\nu_{\mathrm{cor}} - \nu_{\mathrm{mdl}} = \frac{s_0 \nu_{\max}}{Q} \left[1 - \frac{1}{1 + (\nu_{\mathrm{mdl}}/\nu_{\max})^{s_1}} \right]$$

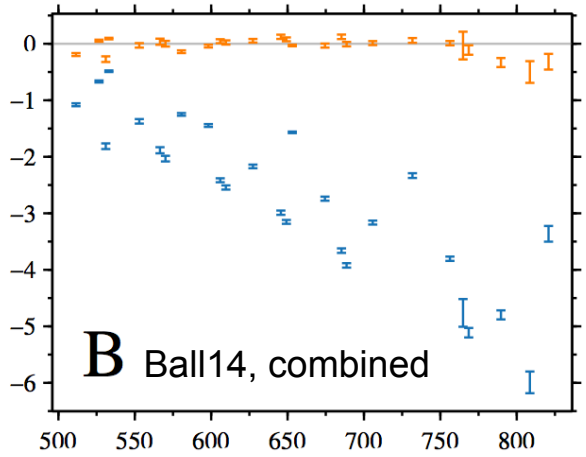
$$\nu_{\mathrm{cor}} - \nu_{\mathrm{mdl}} = a_3 \left(\frac{\nu_{\mathrm{mdl}}}{\nu_{\mathrm{ac}}} \right)^3 / \mathcal{I}$$

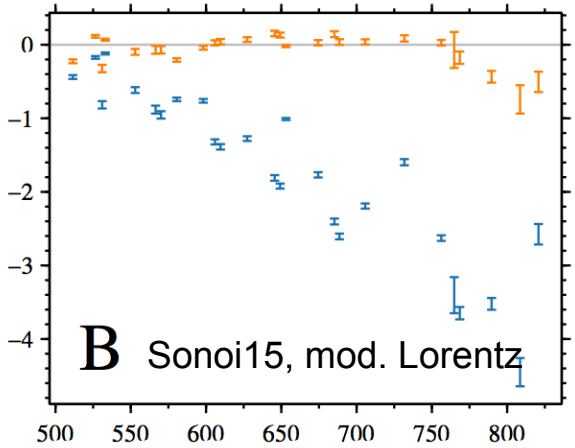
$$\nu_{\mathrm{cor}} - \nu_{\mathrm{mdl}} = \left[a_{-1} \left(\frac{\nu_{\mathrm{mdl}}}{\nu_{\mathrm{ac}}} \right)^{-1} + a_3 \left(\frac{\nu_{\mathrm{mdl}}}{\nu_{\mathrm{ac}}} \right)^3 \right] / \mathcal{I}$$

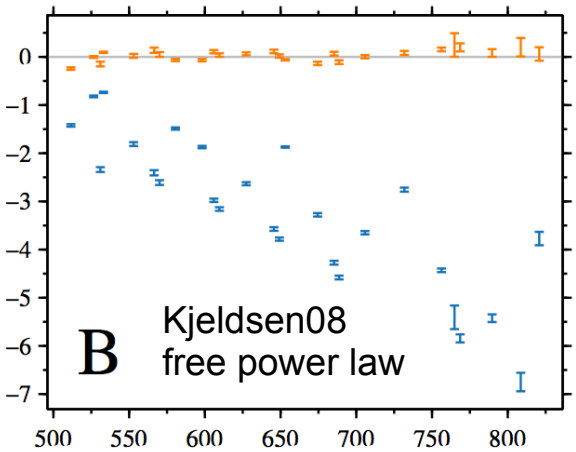
Correction of near-surface effects

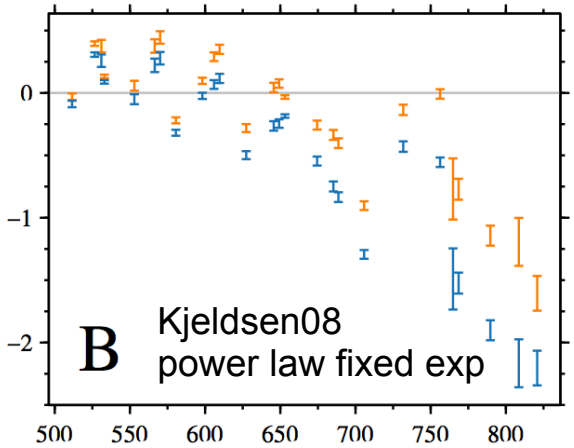
- Issue of the correction of near-surface effects (**Ball et al. 2017**)





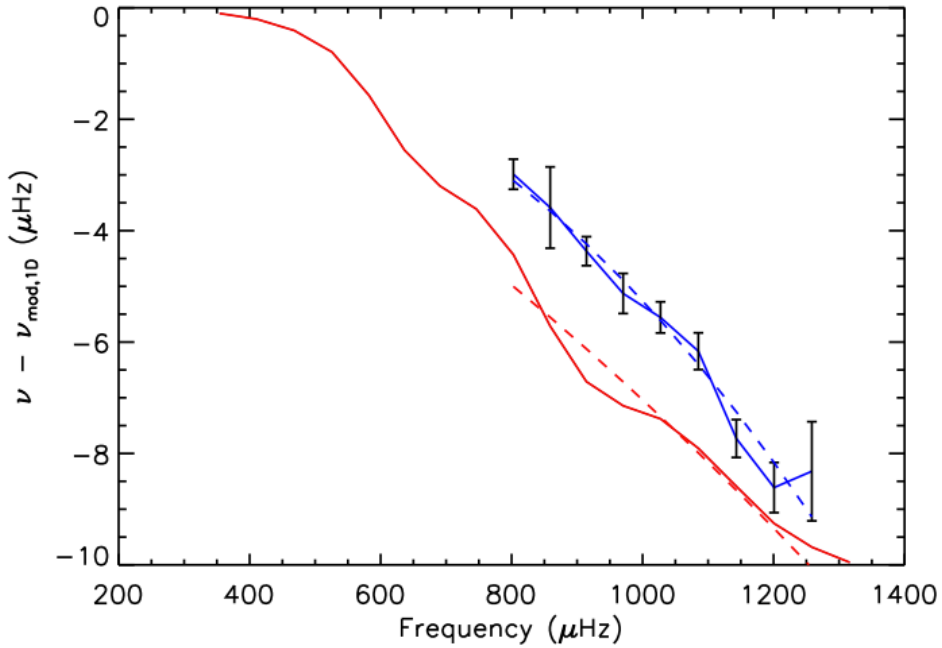




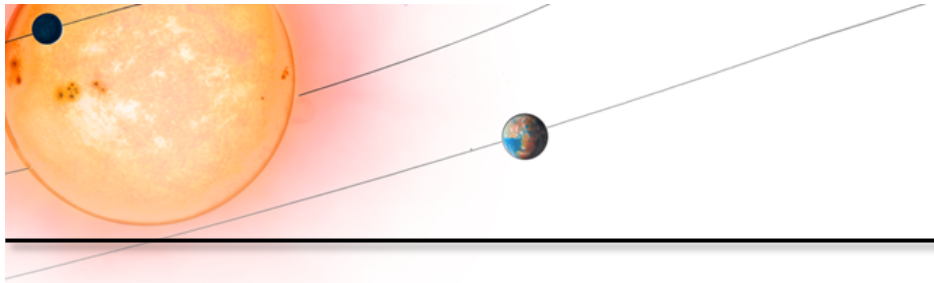


Correction of near-surface effects

- Alternative way: learn from “patched” models
- Example: 3D numerical simulation of the outer layers of CoRoT subgiant HD49385 with ANTARES (by Friedrich Kupka) “patched” to seismic 1D stellar model



	Observed NSE	Predicted NSE (patched models)
a (μHz)	-5.42	-7.18
b	2.40	1.55



Discussion

- Interest of performing interpolations within grids?

- Investigate potential of structural inversions using mixed modes