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The World of Clusters
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KATHOLIEKE UNIVERSITEIT LEUVEN

Asteroseismology of the Open Clusters NGC 6791, NGC 6811, and NGC 6819 from 19 months of Kepler photometry

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Collaborators:
Kepler Asteroseismic Science Consortium Members

Outline

- Highlights in OCs NGC 6791, 6811 & 6819
  Mass and Age, T_{eff} and Metallicity, Mass loss, Rotation, Membership study

- What we expect from Red Giants
  RGB Oscillations
  Asteroseismic parameters and their relation to stars' fundamental properties

- Ensemble results from 19 months photometry
  ε and C-D diagrams, Ensemble échelle diagrams, Linewidths, Period spacings of mixed dipole modes

Section 1

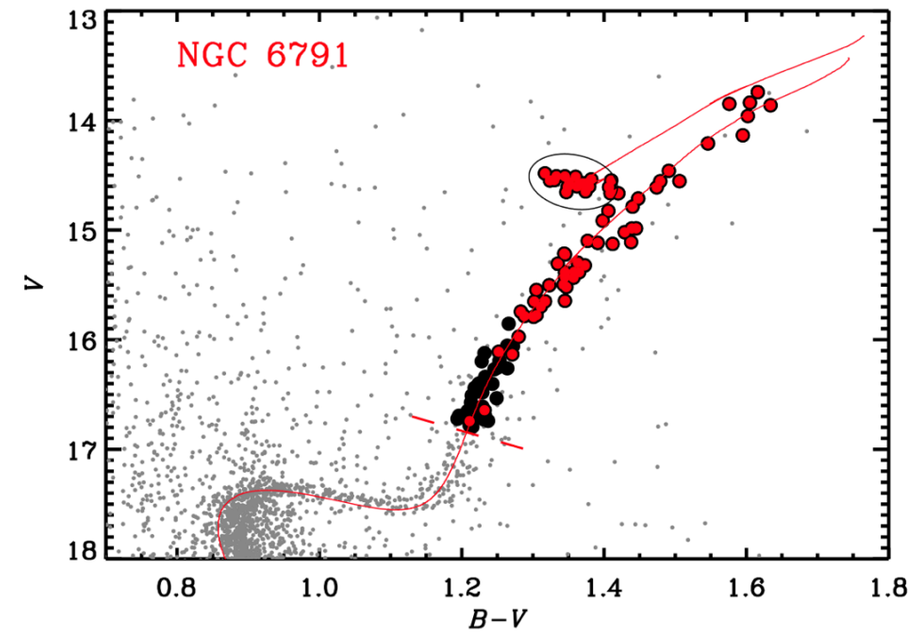
Highlights in Open Clusters

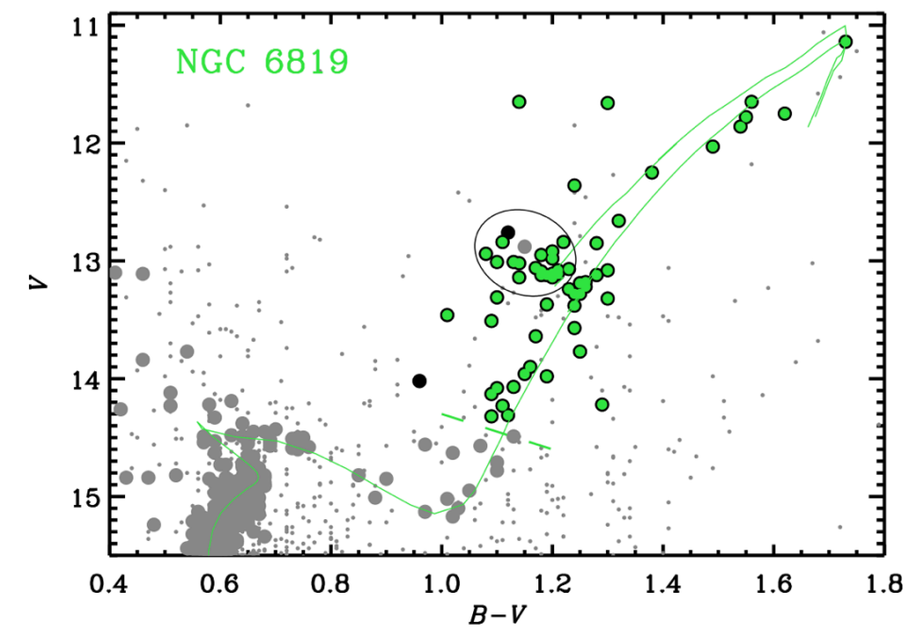
OCs General Properties

Mass & Age

- **Brogaard, K., et al., 2012, A&A, 543, 106**
  with eclipsing binaries
  NGC 6791 extremely old
  Average mass of RGB stars:
  $M_{RGB} = 1.15 \pm 0.02\ M_{\odot}$
  Age: ~ 8.3 Gyr

- **Basu, S., et al. 2011, ApJ, 729, 10**
  with asteroseismic grid fitting
  NGC 6819 middle aged
  Average mass of RGB stars:
  $M_{RGB} = 1.68 \pm 0.03\ M_{\odot}$
  Age: between 2 and 2.4 Gyr





Adapted from Stello et al. 2011b

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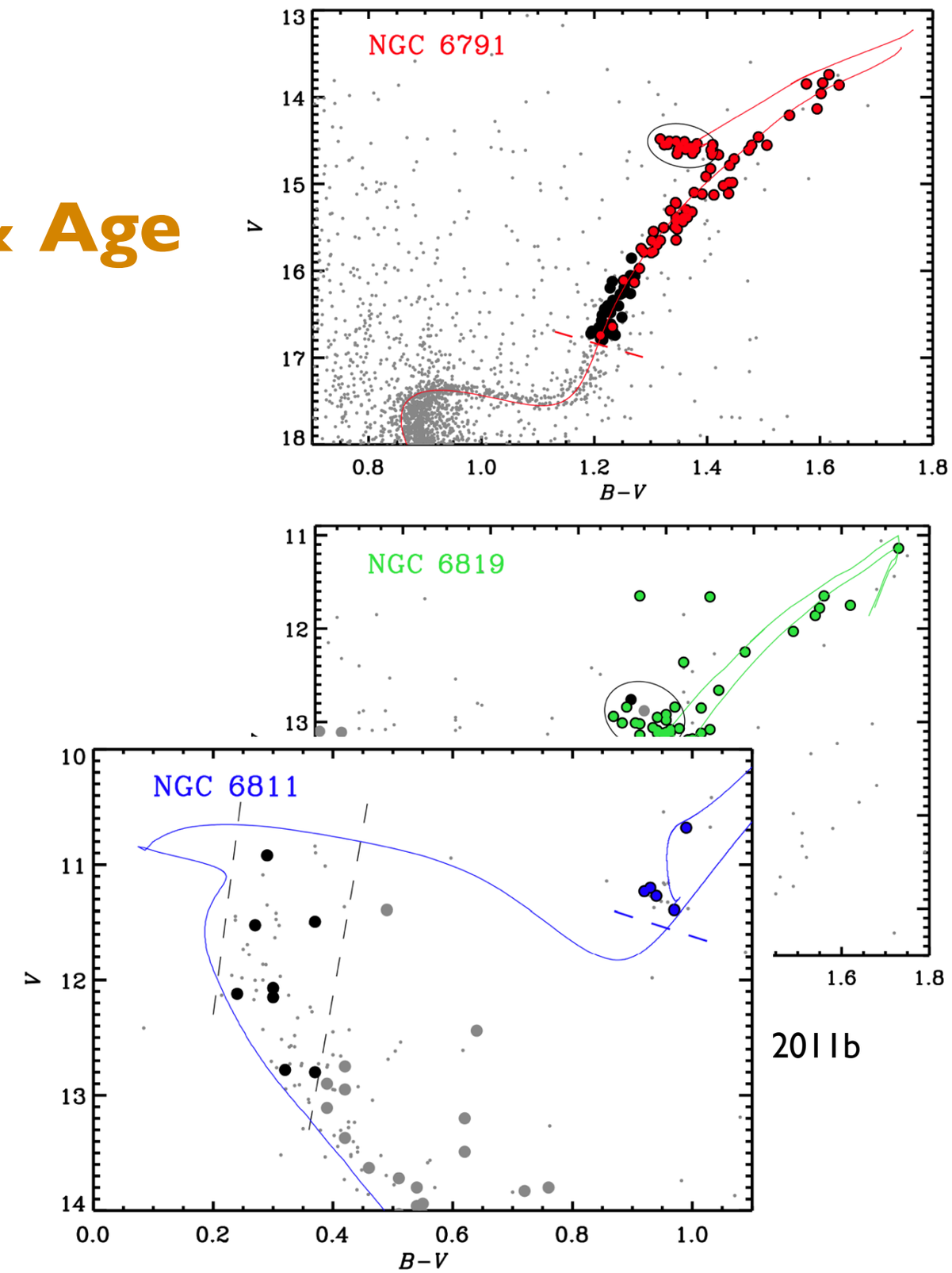
  NGC 6819 middle aged
  Average mass of RGB stars:
  $M_{RGB} = 1.68 \pm 0.03\ M_\odot$
  Age: between 2 and 2.4 Gyr

- **NGC 6811** young, only red clump (RC) stars
  Stello, D., et al. 2011, ApJ, 739, 13
  Average mass of RC stars:
  $M_{RC} = 2.35\ M_\odot$
  Glushkova, E. V. et al, AstL, 25, 86
  Age = 0.7 ± 0.1 Gyr



2011b

OCs General Properties

Metallicity

Brogaard, K., et al., 2011, A&A, 525, 2

- **NGC 6791** metal rich
  [Fe / H] = 0.29 ± 0.03 (random) ± 0.07 (systematic)

Bragaglia, A., et al., 2001, AJ, 121, 327

- **NGC 6819** solar metallicity
  [Fe / H] = 0.09 ± 0.03

Bruntt et al. 2012
Molenda-Zakowicz et al. 2013

- **NGC 6811** ~ solar metallicity

Mass loss

Miglio, A., et al. 2012, MNRAS, 419, 2077

- Direct estimates of mass loss rates for NGC 6791 and NGC 6819
- **NGC 6791** significant mass loss
  $\Delta M = 0.09 \pm 0.03$ (random) ± 0.04 (systematic) $M_\odot$
- **NGC 6819** no mass loss
  $\Delta M = -0.03 \pm 0.04\ M_\odot$

Rotation

Meibom, S., et al., 2011, ApJ, 733, 9

- Study of stellar rotation in **NGC 6811**
  Periods ~ 11 days in early K-type

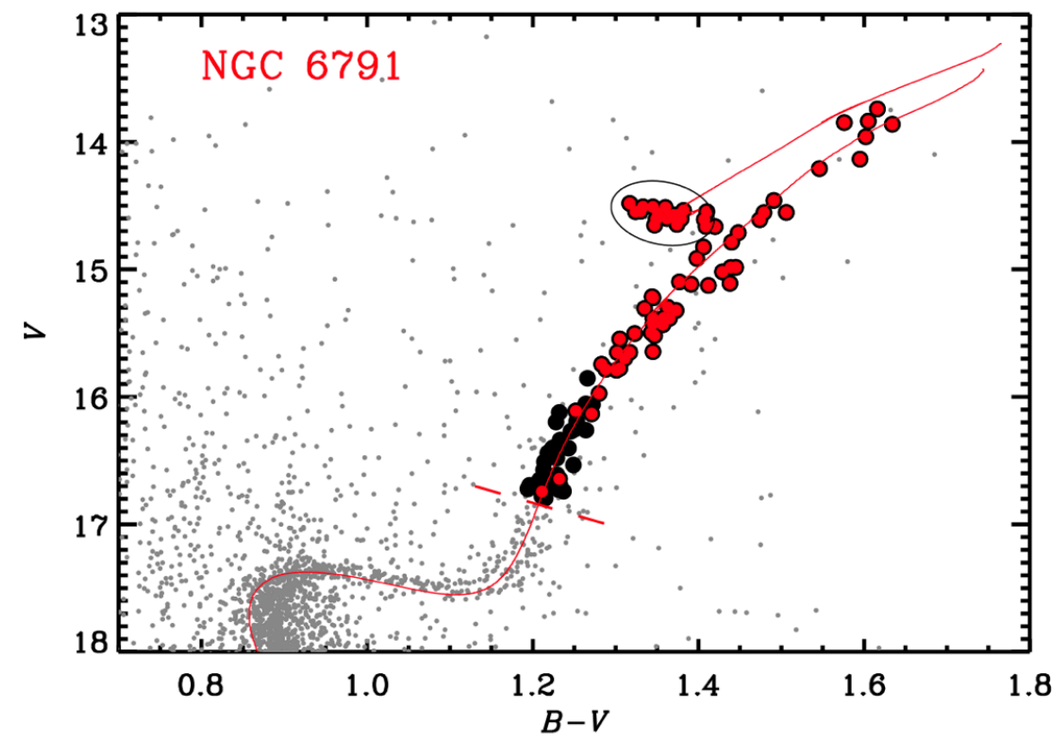
Membership study

Stello, D., et al. 2011, ApJ, 739, 13

- Membership study of the Red Giants from color-magnitude diagrams (CMD)
- Identification of targets with evidence of RGB oscillations

Stello, D., et al. 2011, ApJ, 737, 10

- Amplitude estimates for oscillations in the three OCs



Adapted from Stello et al. 2011b

Our sample of 115 Red Giants observed by Kepler

60 RGs for **NGC 6791** (RGB and RC)
5 RGs for **NGC 6811** (only RC)
50 RGs for **NGC 6819** (RGB and RC)

Section 2

What we expect from Red Giants

...see also Josefina's talk

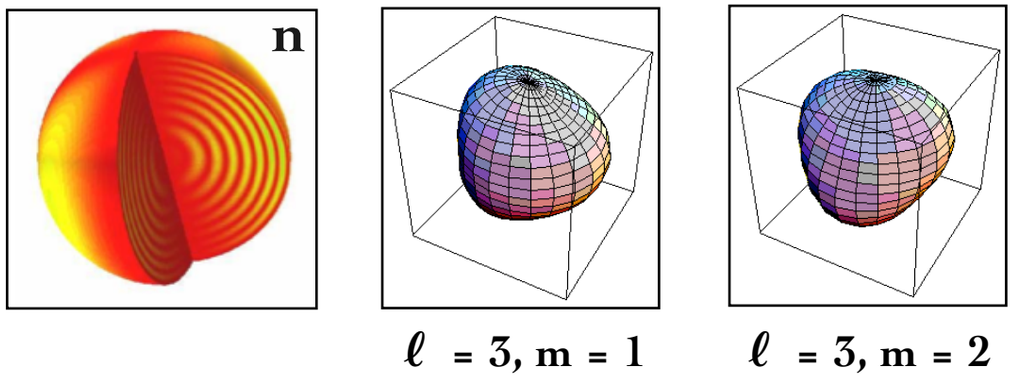
RGB Oscillations

Pressure modes (p modes)

(Solar-like Oscillations)

Vandakurov 1968; Tassoul 1980; Gough 1986

$$\nu_{\mathrm{n},\ell} = \Delta\nu(n + \ell/2 + \epsilon) - \delta\nu_{0,\ell}$$



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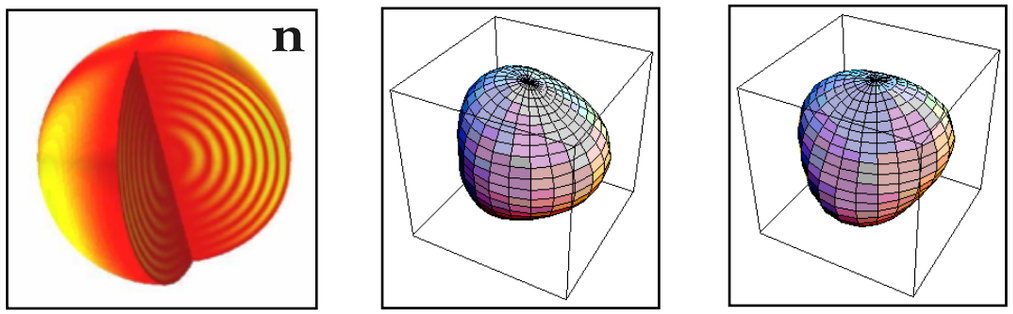
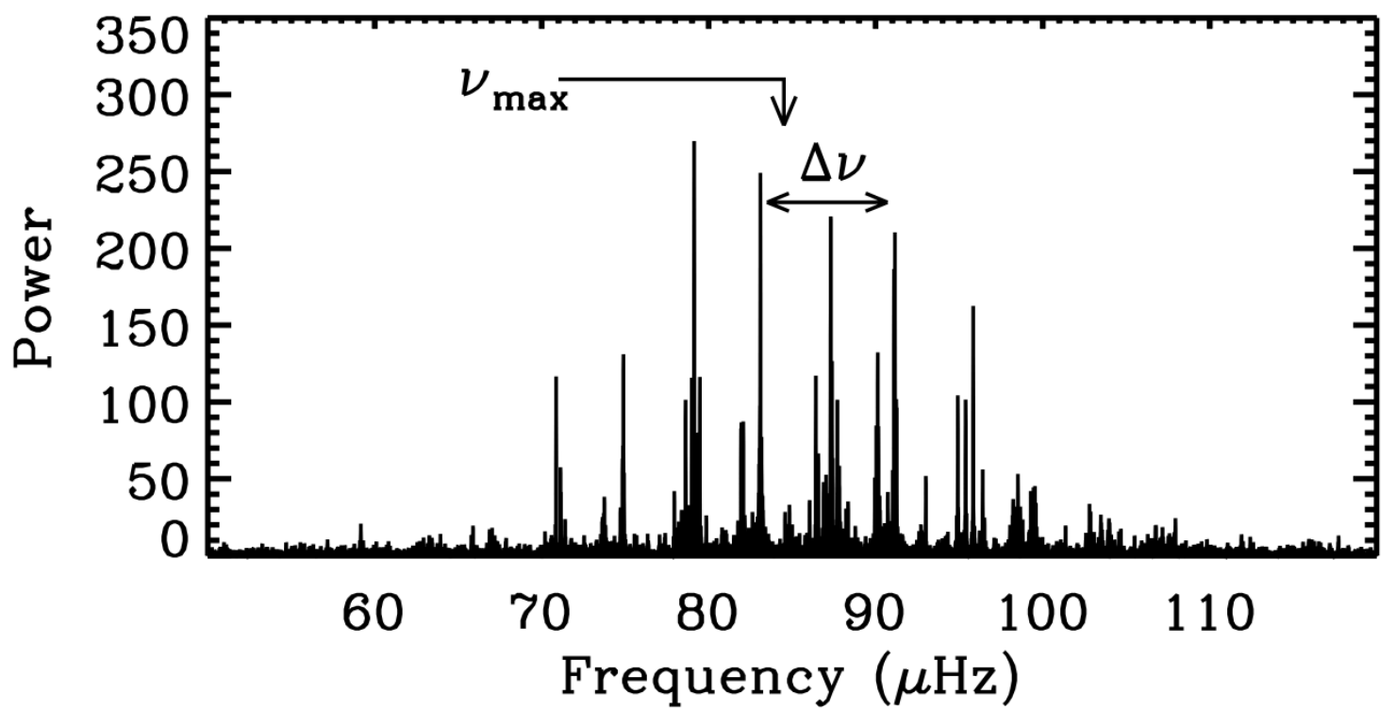


ℓ = 3, m = 1 ℓ = 3, m = 2

Adapted from Stello et al. 2013



$$\Delta\nu \propto \sqrt{\bar{\rho}}$$

$$\nu_{\mathrm{max}} \propto g/T_{\mathrm{eff}}$$

as the star evolves

Pressure modes (p modes)

(Solar-like Oscillations)

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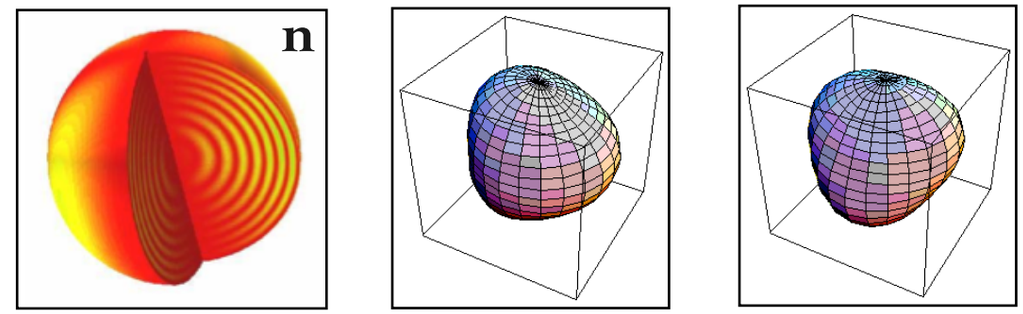

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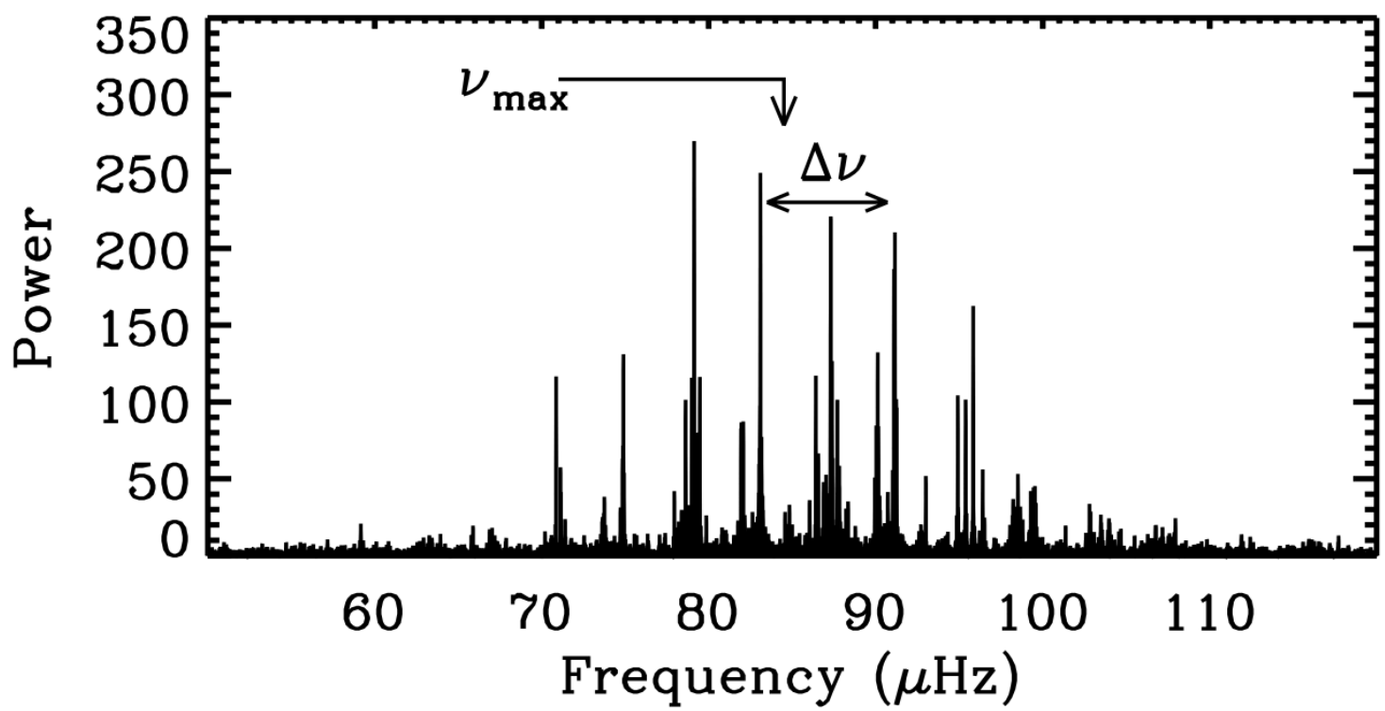

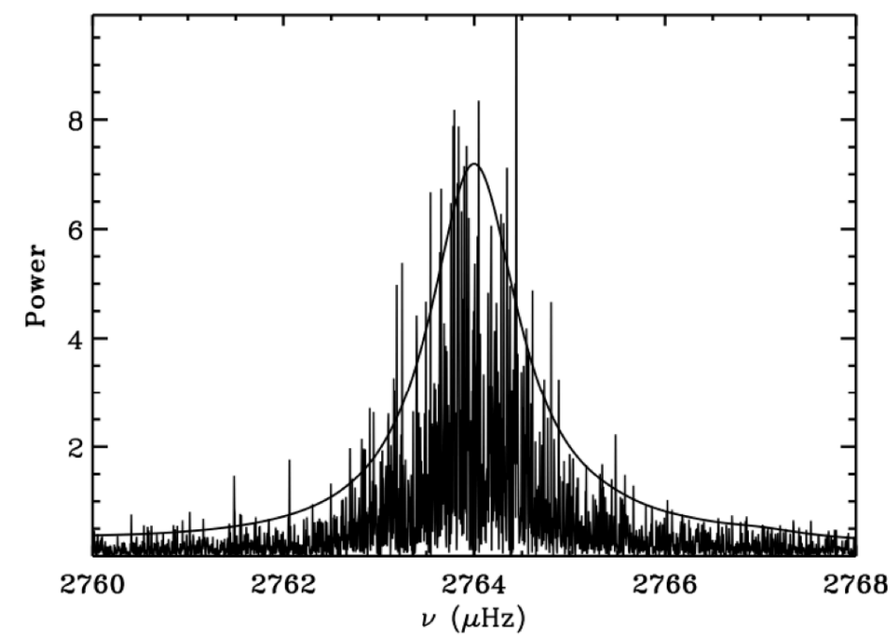

Stochastic excitation and damping

$$\Delta\nu \propto \sqrt{\bar{\rho}}$$

$$\nu_{\mathrm{max}} \propto g/T_{\mathrm{eff}}$$

as the star evolves

Pressure modes (p modes)

(Solar-like Oscillations)

Vandakurov 1968; Tassoul 1980; Gough 1986

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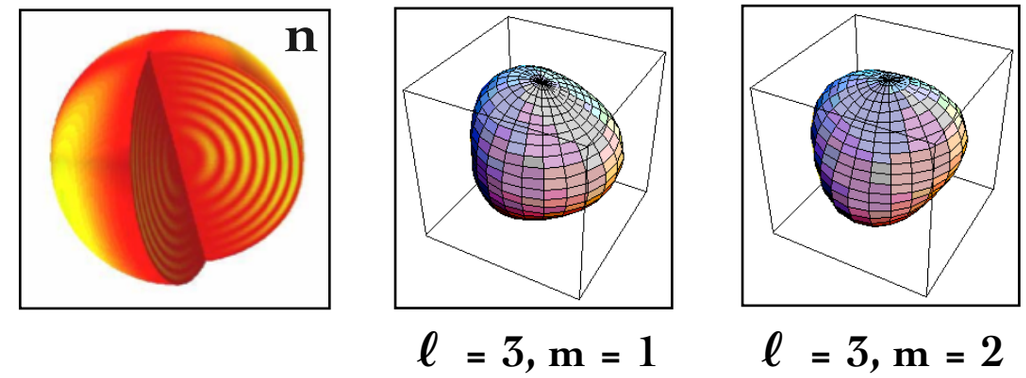
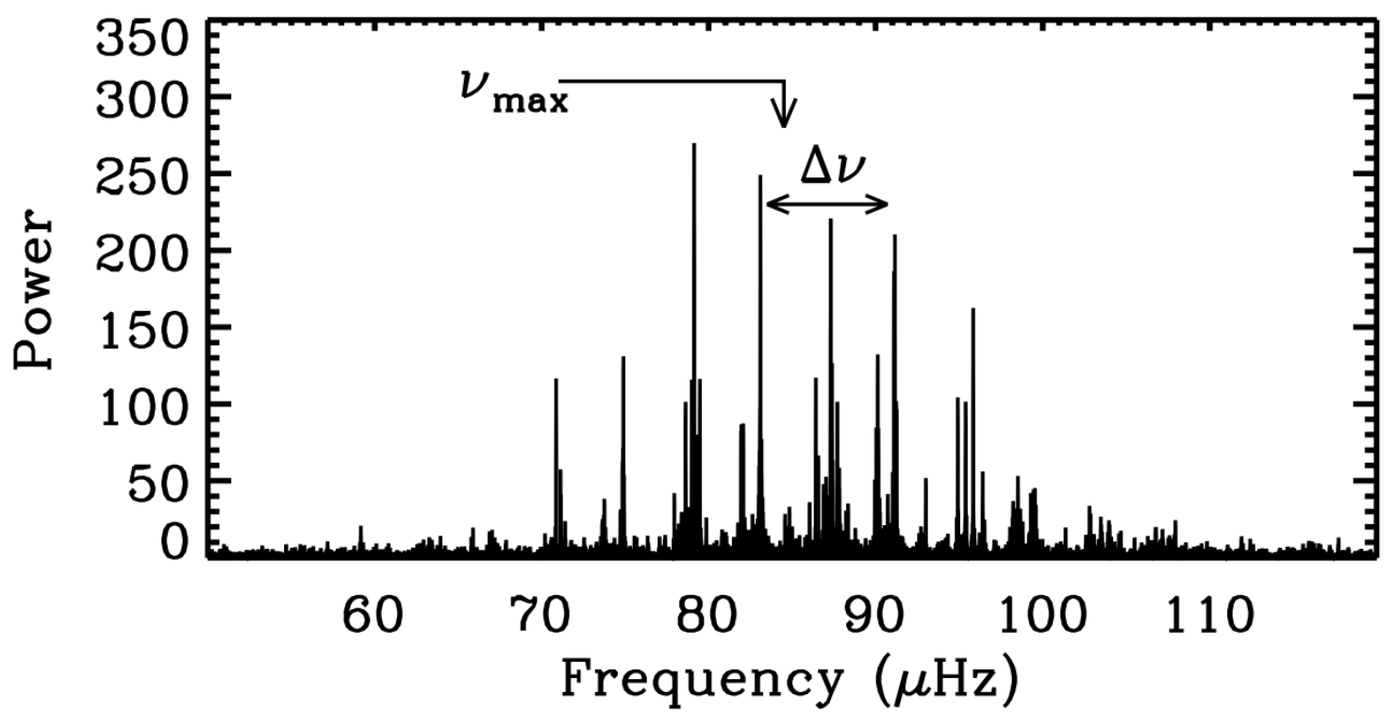


Adapted from Stello et al. 2013



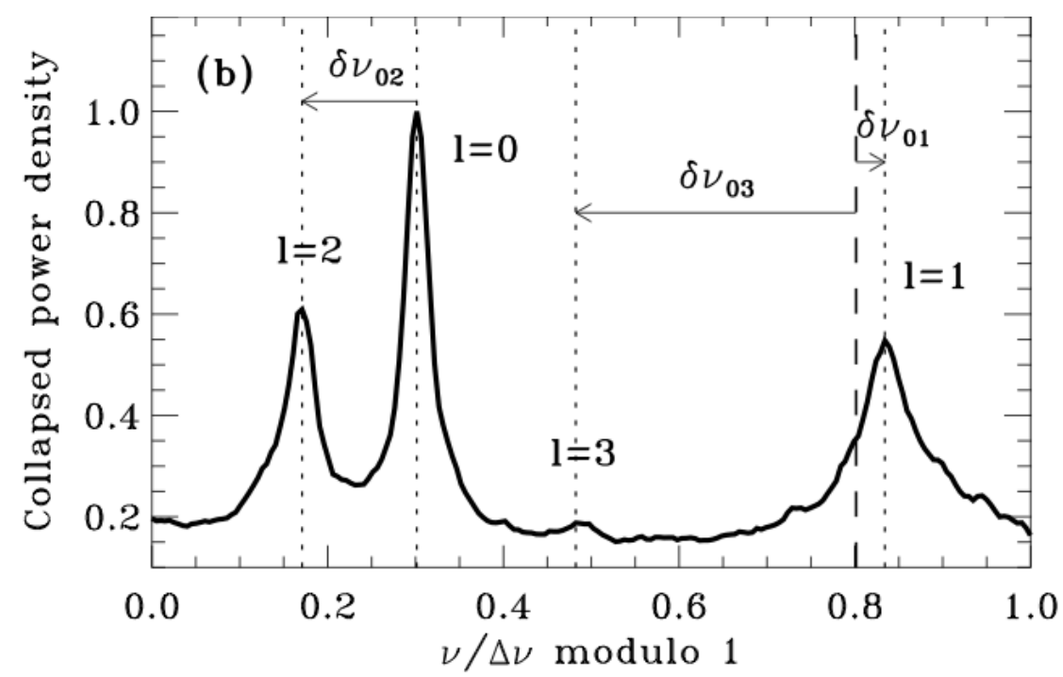
$$\Delta\nu \propto \sqrt{\bar{\rho}}$$

$$\nu_{\max} \propto g/T_{\rm eff}$$

as the star evolves

Small frequency spacings $\delta\nu_{0l}$

Adapted from Corsaro et al. 2012b



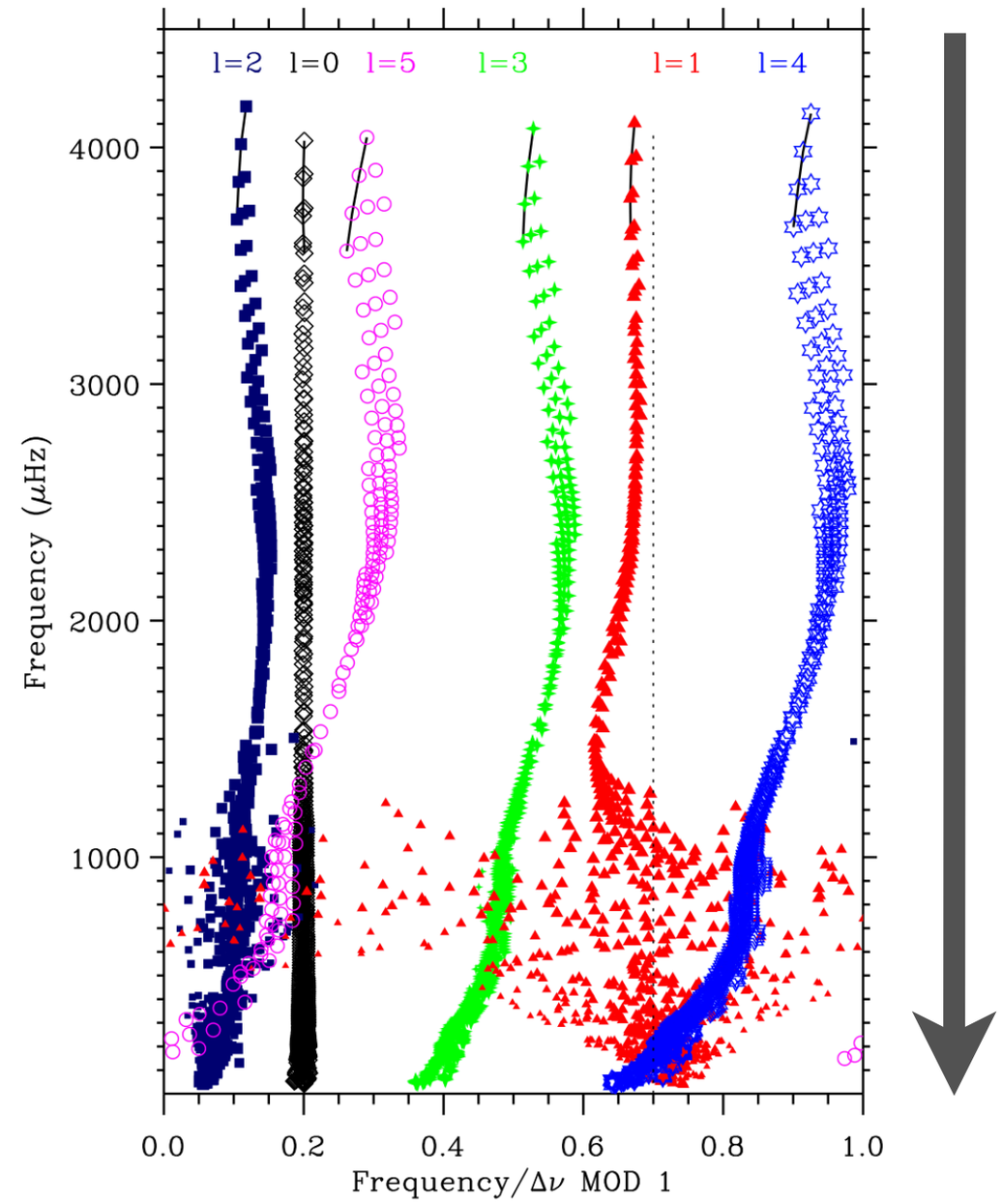
RGB Oscillations

Gravity modes (g modes)

(Radiative cores)

- As the star evolves p modes ⬇ in frequency
- As the star evolves g modes ⬆ in frequency
- From subgiant phase of evolution Mixed modes are generated (mostly dipole modes)

Stello, D. (2012; ASPC 462, 200)



RGB Oscillations

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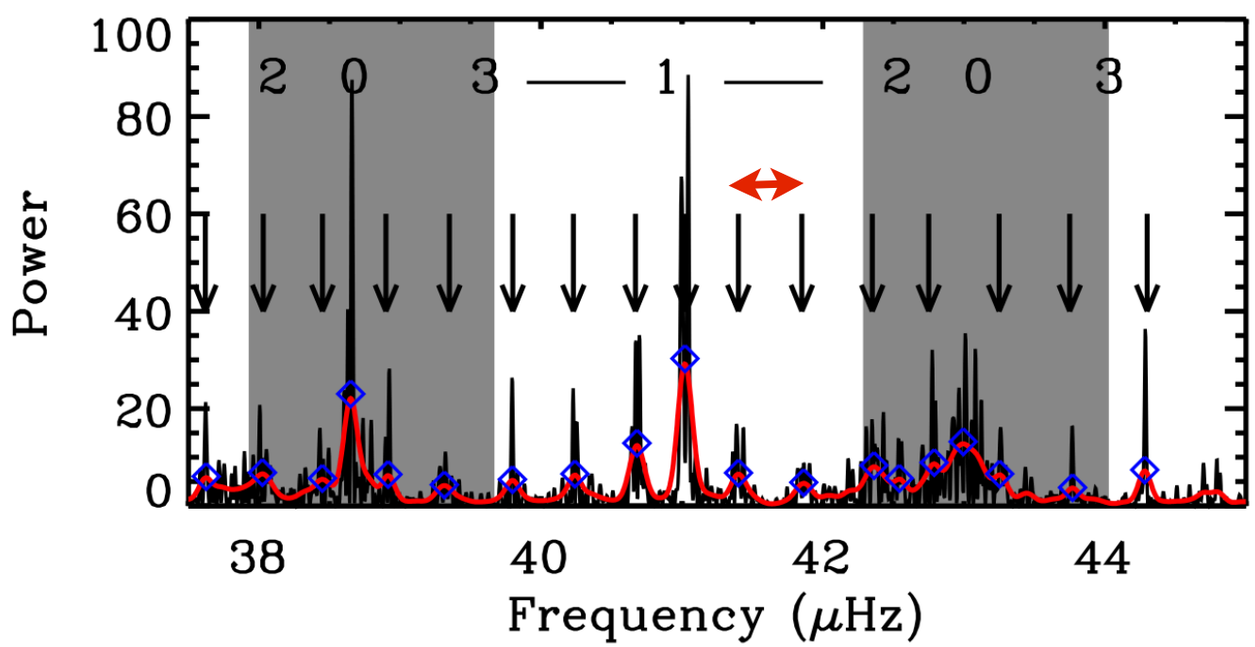
Mixed modes + p modes
= Oscillations in Red Giants



Adapted from Stello et al. 2013

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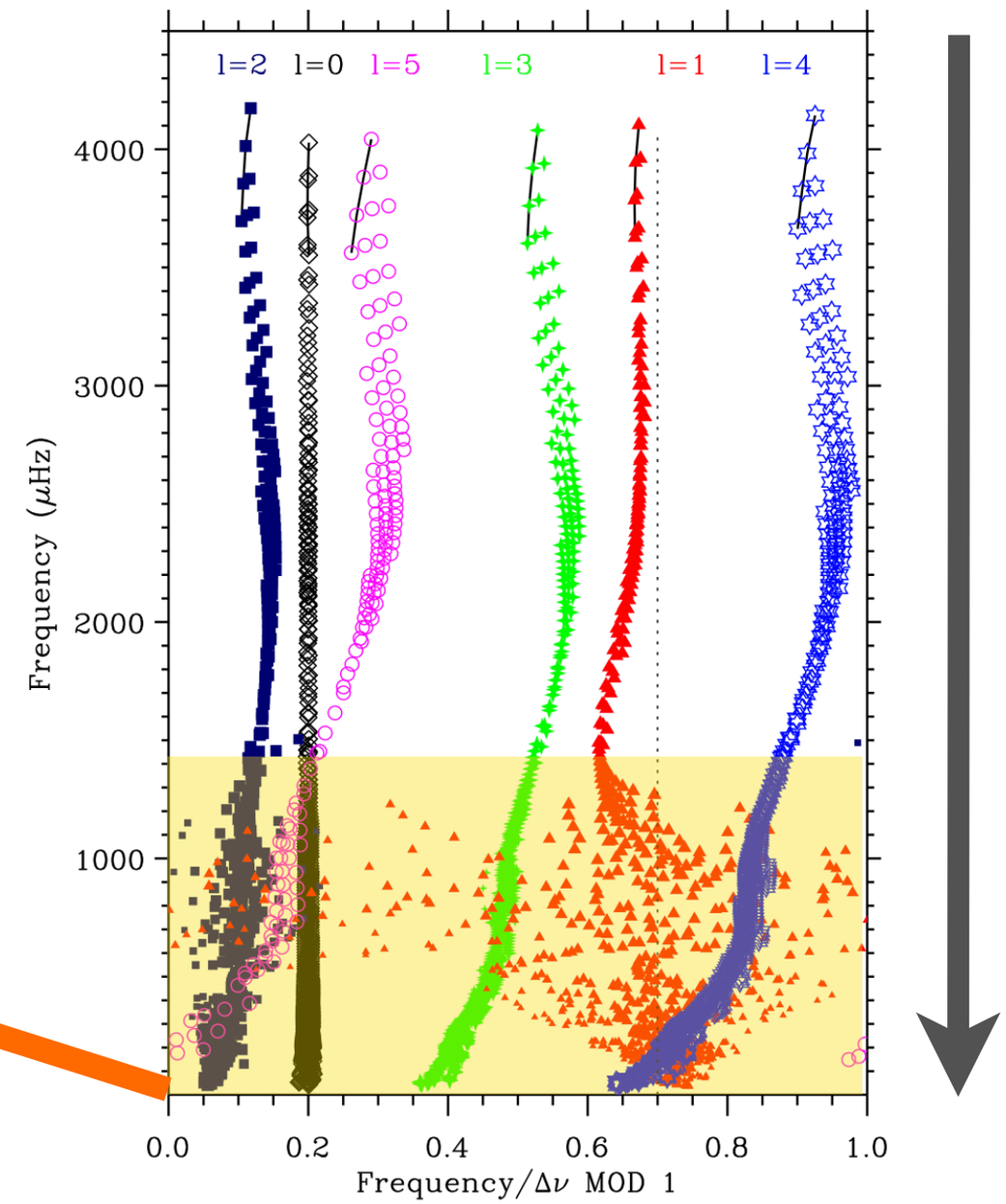


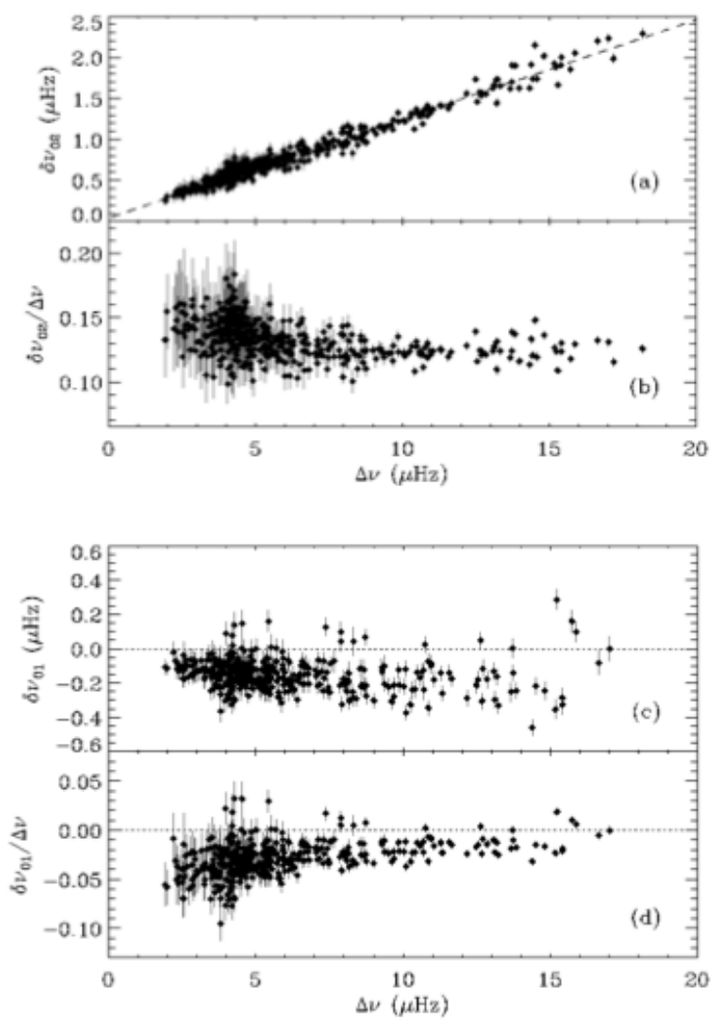
Period spacing ΔP
Sensitive to core structure and composition

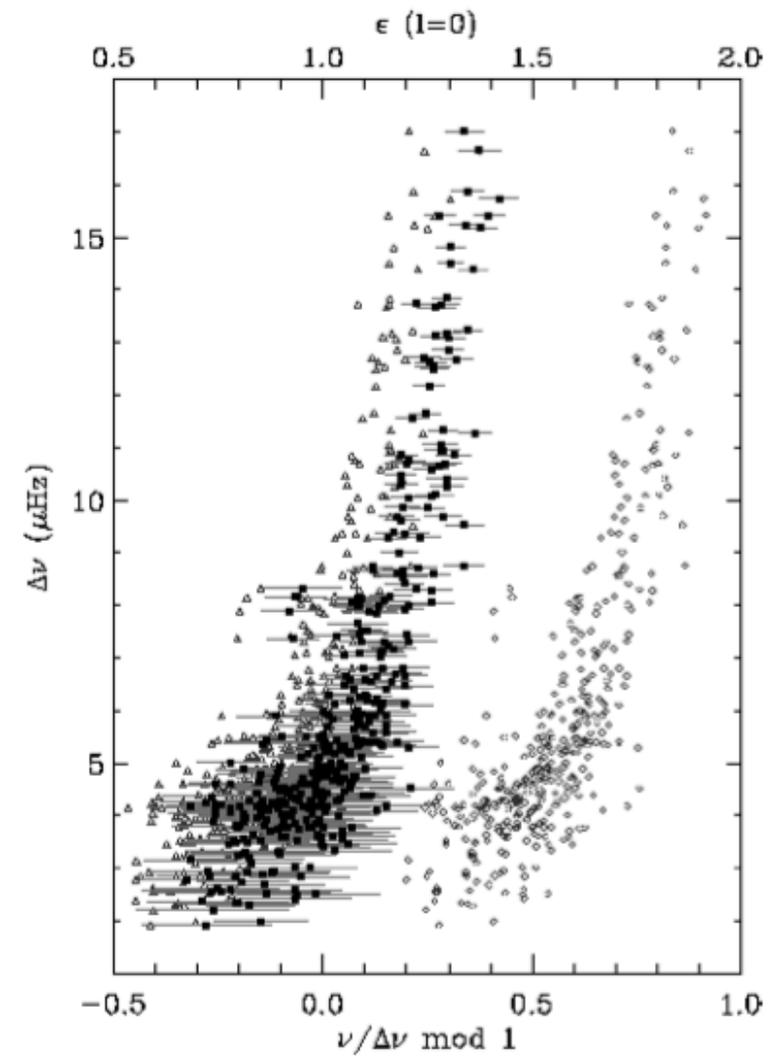
Asymptotic parameters

Huber, D., et al., 2010, ApJ, 723, 1607

- From ensemble analysis (hundreds of RGs) observed with Kepler we have:
  - Tight correlation between $\delta\nu_{02}$, $\delta\nu_{01}$ and $\Delta\nu$
  - ε is a function of fundamental stellar parameters (Mass, Radius)

Mosser, B., et al., 2011, A&A, 525, L9
Kallinger, T., et al., 2012, A&A, 541, 51
Montalbán, J., et al., 2010, ApJ, 721, 182



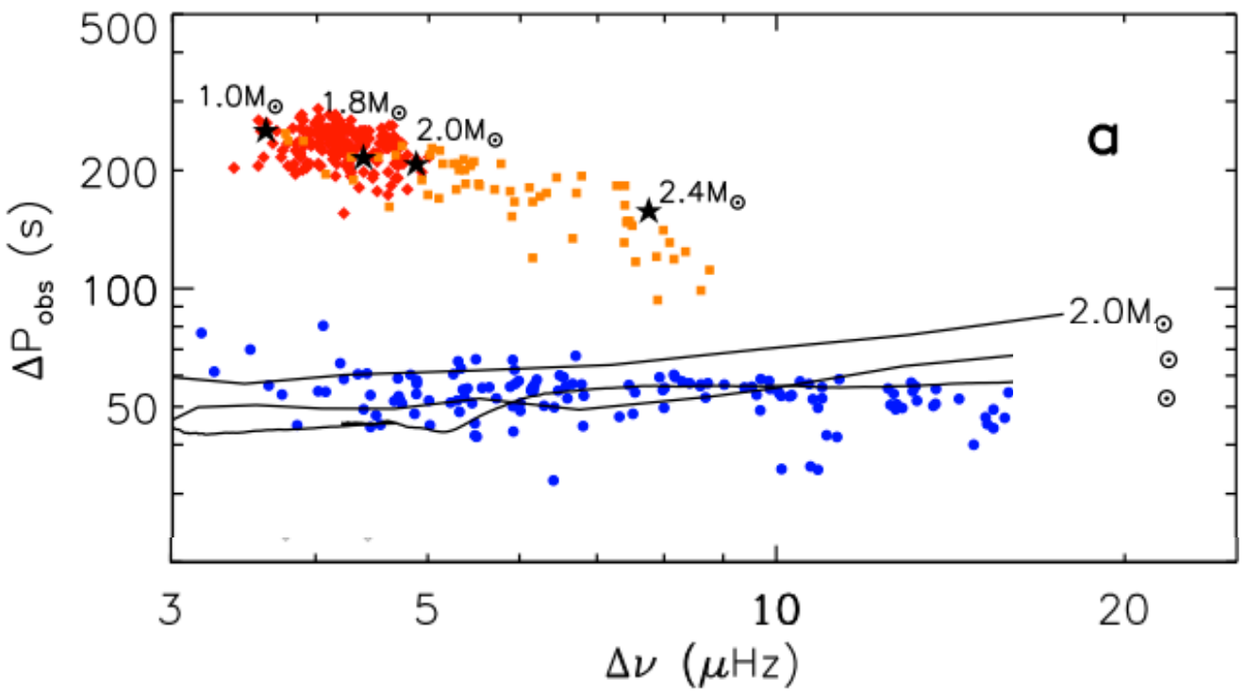


Adapted from Huber et al. 2010

Period Spacings

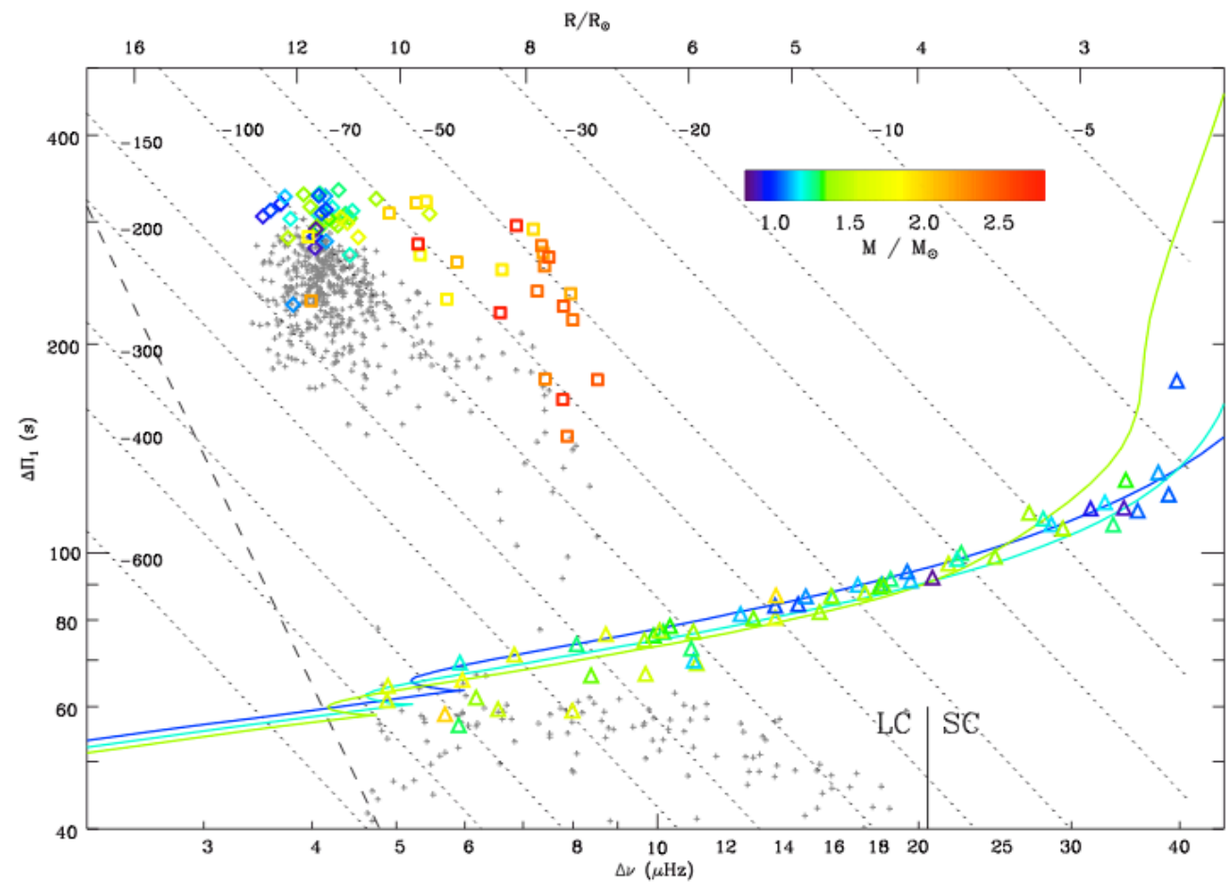
Bedding, T., R., et al., 2011, Nature, 471, 608

- ΔP as a way to distinguish between **He-core** and **H-shell** burning RGs



Adapted from Bedding et al. 2011

Mosser, B., et al., 2012, A&A, 540, 143



Adapted from Mosser et al. 2012

Really powerful tool for contraining the evolutionary stage of Red Giants

Section 3

Ensemble results from 19 months photometry

Why Cluster RGs?

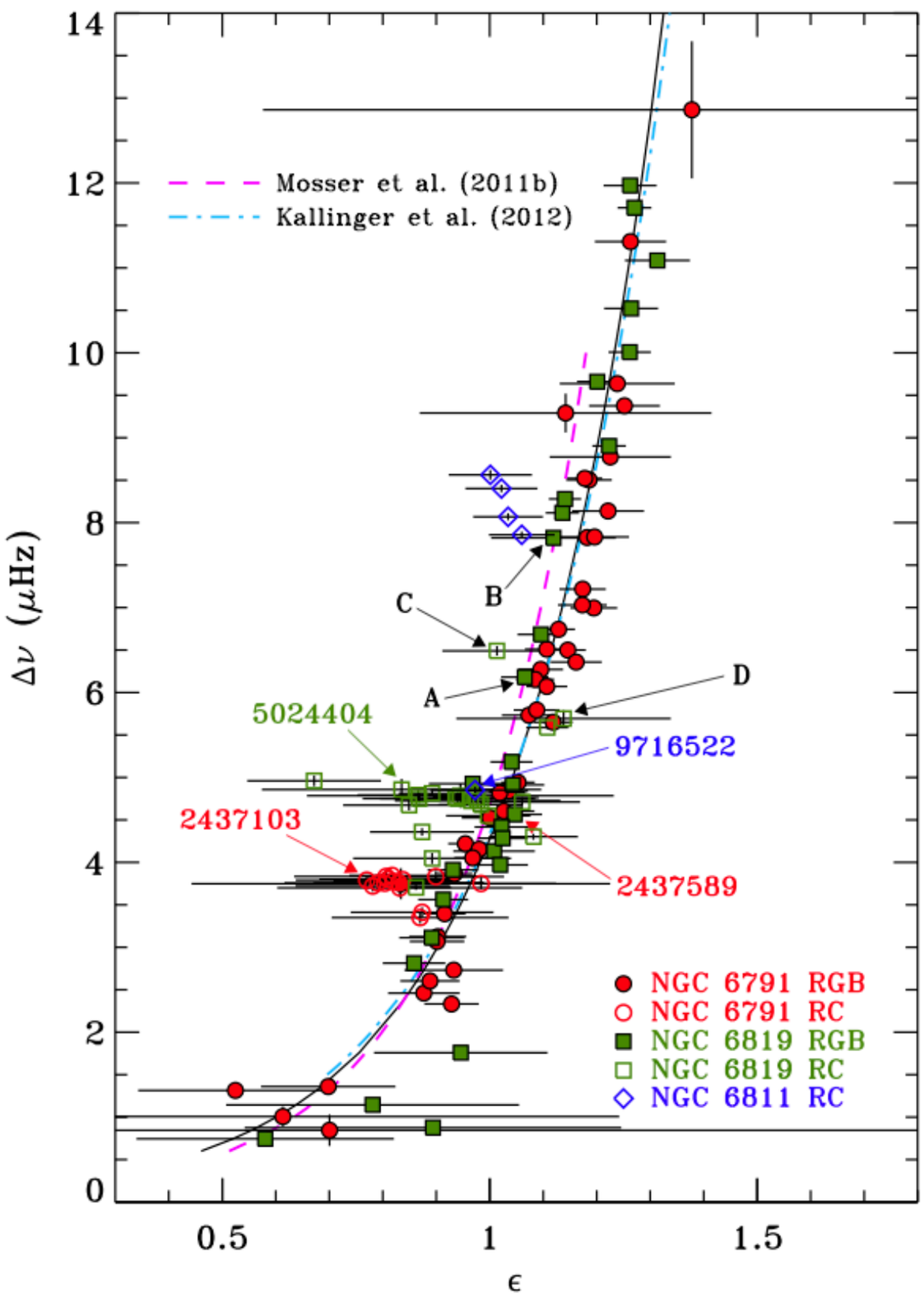
- **Exploiting the common properties of cluster stars**
- Ensemble analysis of asymptotic parameters (AARG code)
- Period spacings analysis
- 19 months of continuous photometry observations with Kepler

(1) More stringent results on asymptotic quantities

(2) Deeper comprehension of the physics behind

(3) Possibility for detailed modeling of the stars

ε diagrams



Adapted from Corsaro et al. 2012

- Verified log-relation by **Mosser et al. 2011**

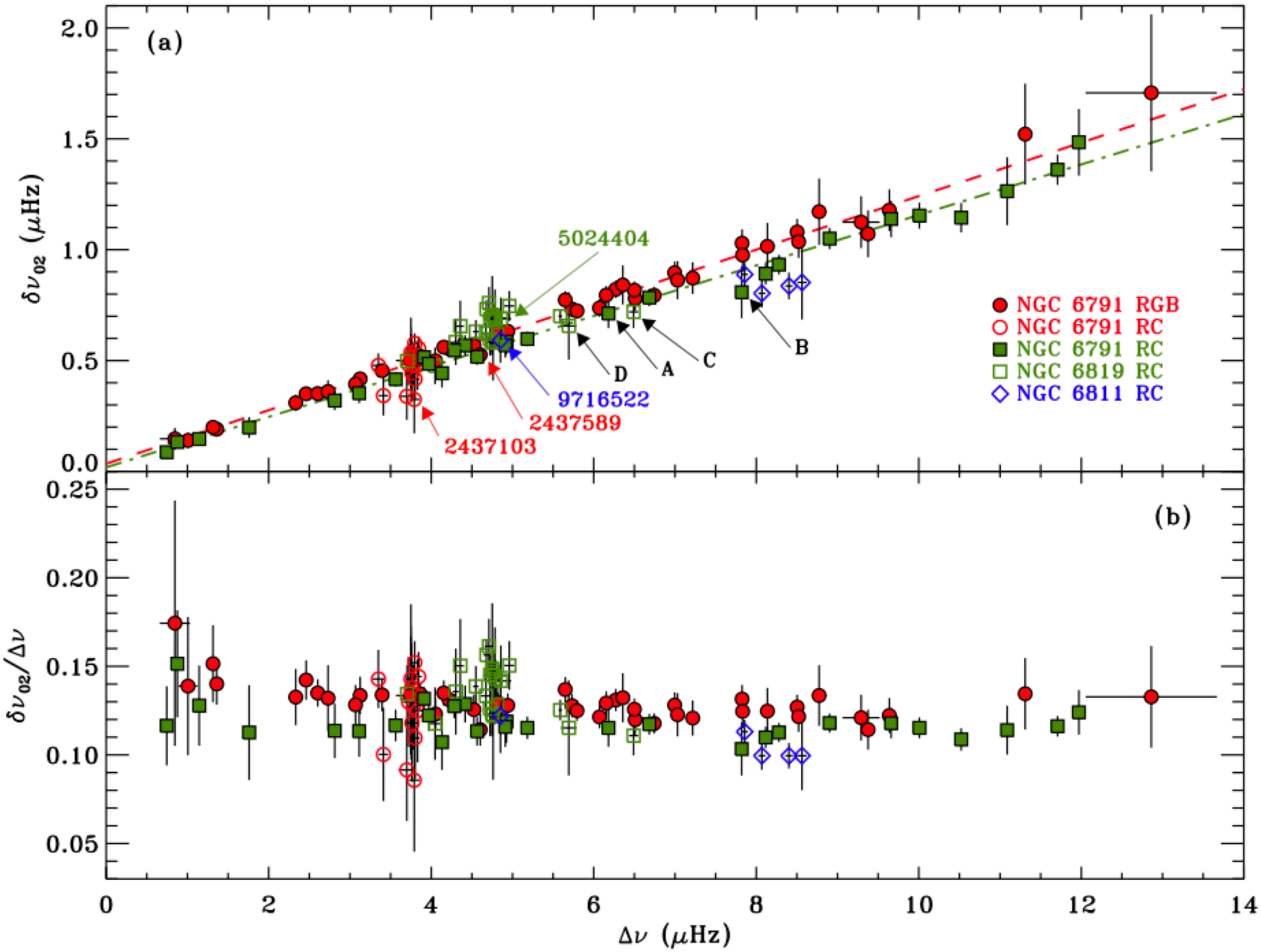
$$\epsilon = (0.601 \pm 0.025) + (0.632 \pm 0.032) \log \Delta\nu$$

- Very good agreement with the results by
  Kallinger et al. 2012 (Kepler)
  Mosser et al. 2011b (CoRoT) on field RGs

- Power-law relation provides another reliable law

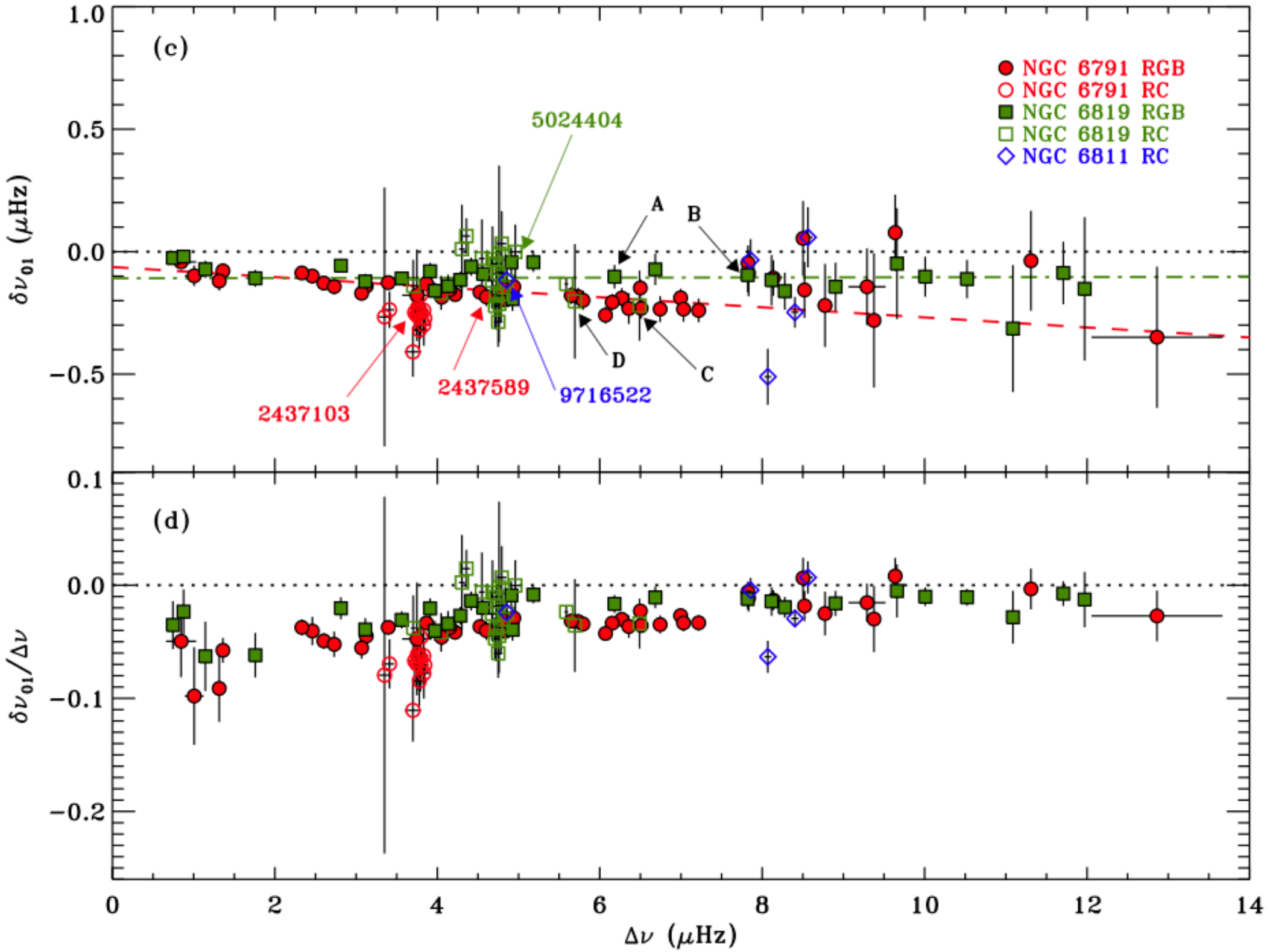
$$\epsilon = (0.681 \pm 0.017)\Delta\nu^{0.261 \pm 0.014}$$

C-D diagrams for $\delta\nu_{02}$



Adapted from Corsaro et al. 2012

C-D diagrams for $\delta\nu_{01}$



Adapted from Corsaro et al. 2012

C-D diagrams

- Evidence for **mass dependence**. We correlate the slope **b** of the linear fit in the C-D diagram to mass:

$$b_{02} = (0.138 \pm 0.012) + (-0.014 \pm 0.008)\left(\frac{M_{\rm RGB}}{M_\odot}\right)$$ $\delta\nu_{02}$ ↓ M ↑

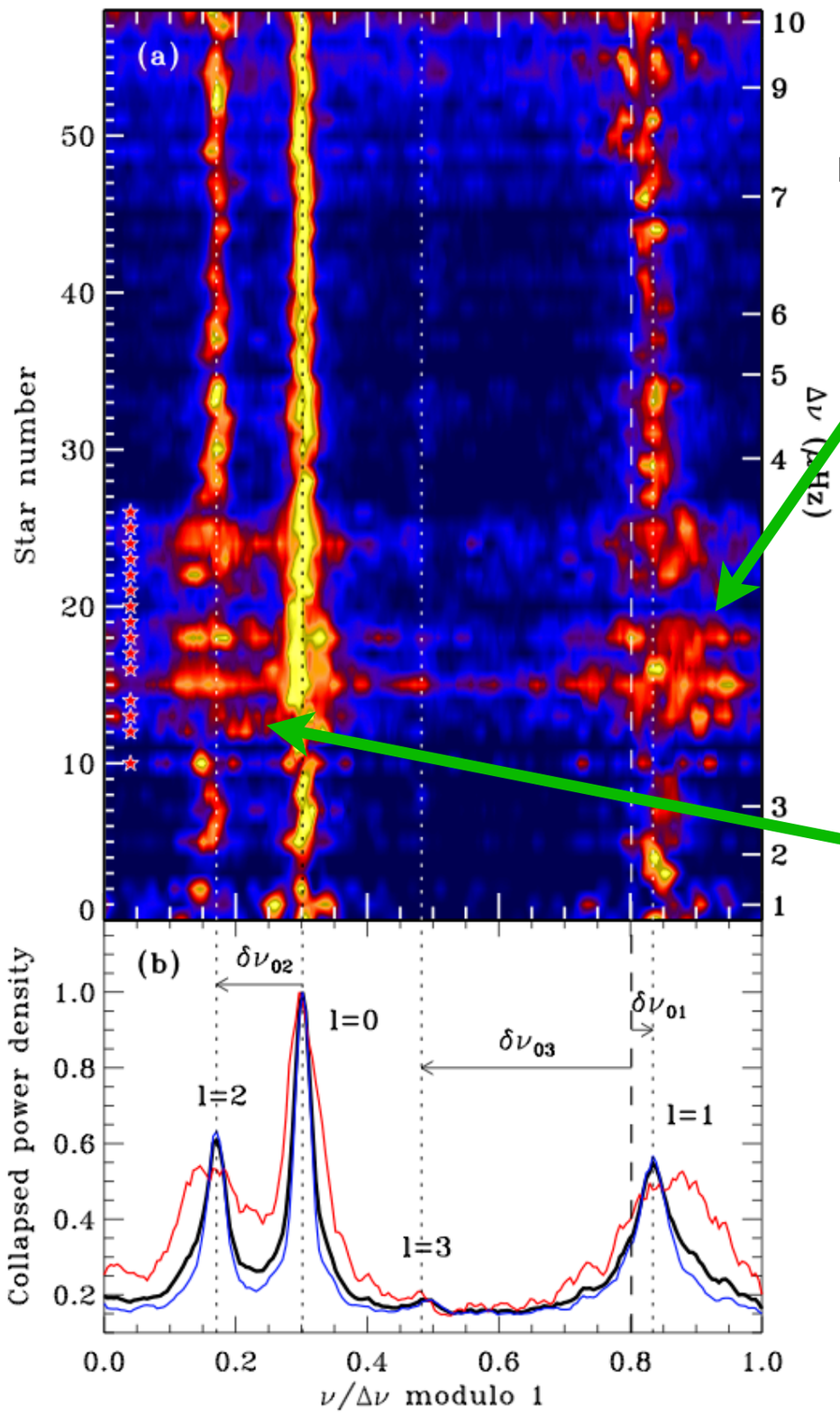
$$b_{01} = (-0.073 \pm 0.012) + (0.044 \pm 0.008)\left(\frac{M_{\rm RGB}}{M_\odot}\right)$$ $\delta\nu_{01}$ ↑ M ↑

↓

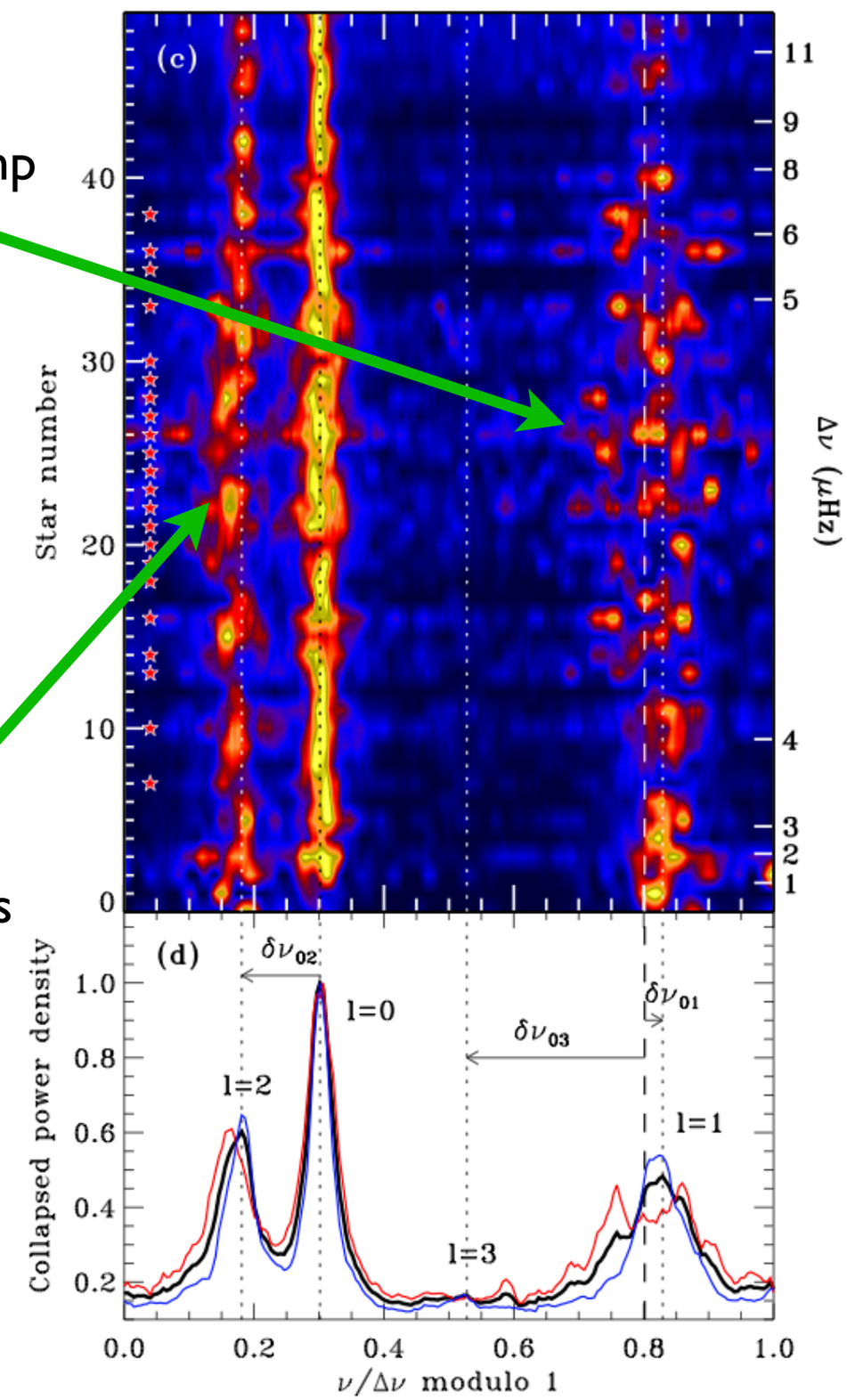
- Qualitatively agreement with theoretical results by Montalban et al. 2011

Ensemble échelle diagrams

NGC 6791



NGC 6819



Mixed dipole modes more pronounced in Clump stars

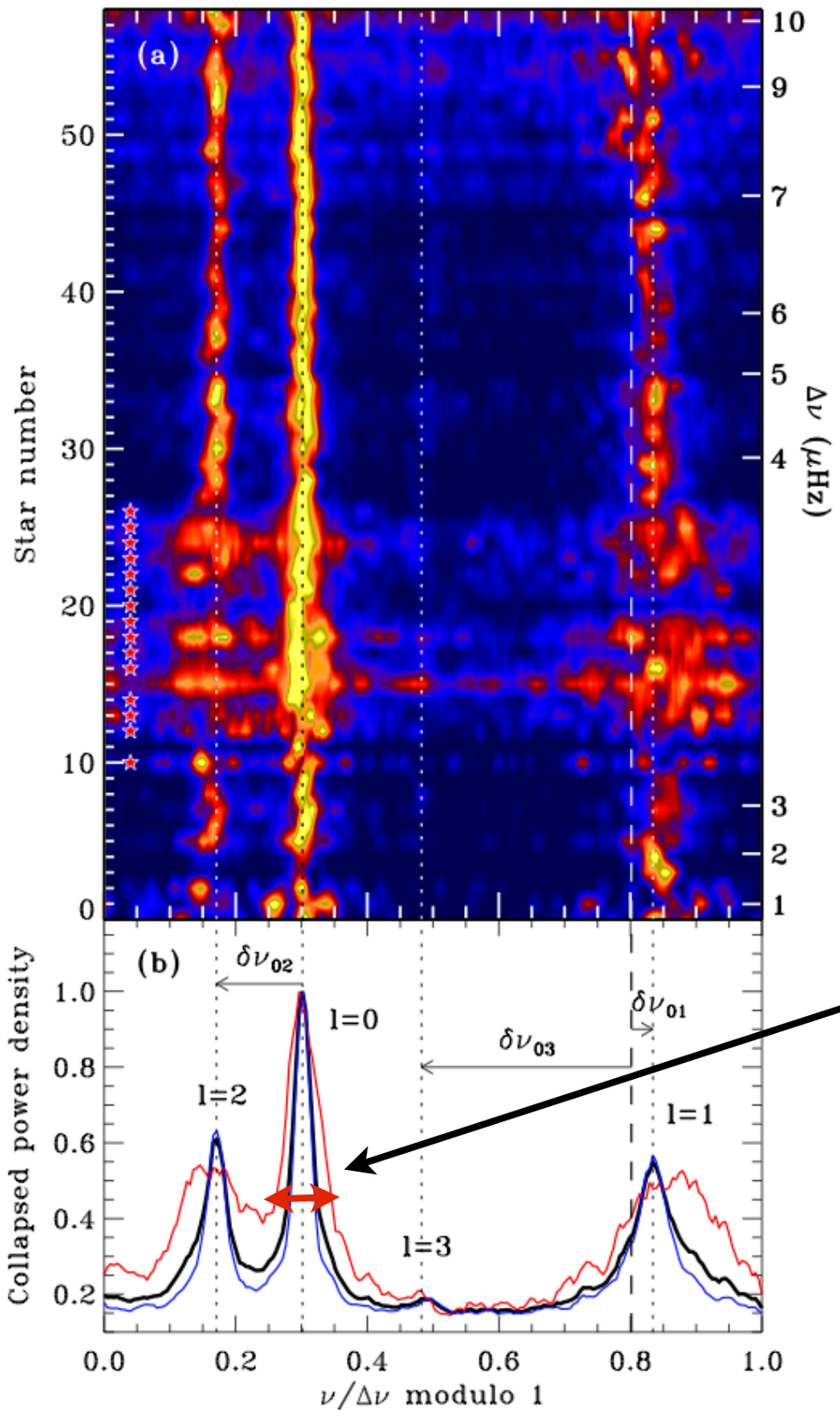
Broadening of l = 2 ridges for RC stars - Mixed quadrupole modes

Adapted from Corsaro et al. 2012

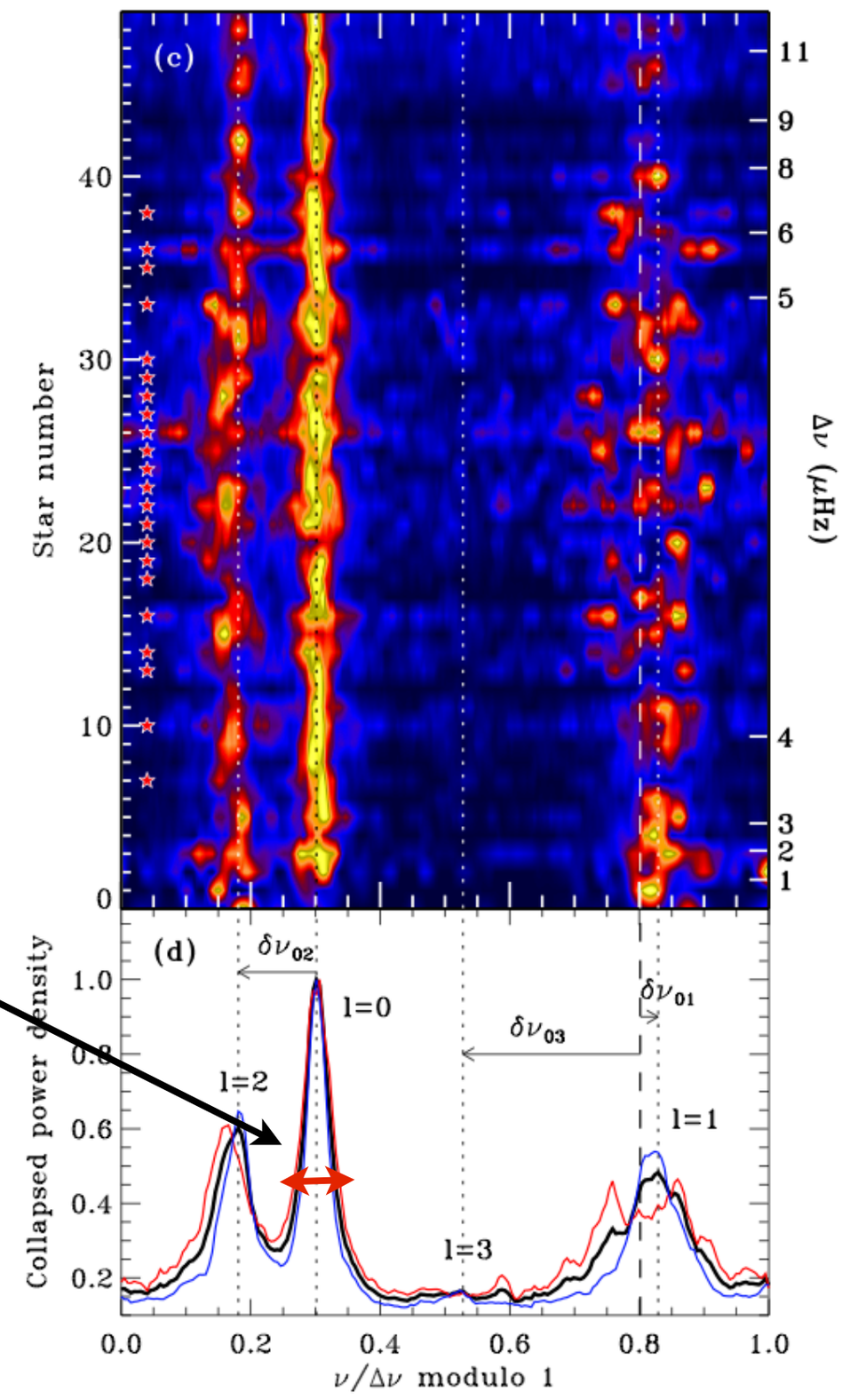
Corsaro, E. *et al.* 2012, ApJ, 757, 190

Ensemble échelle diagrams

NGC 6791



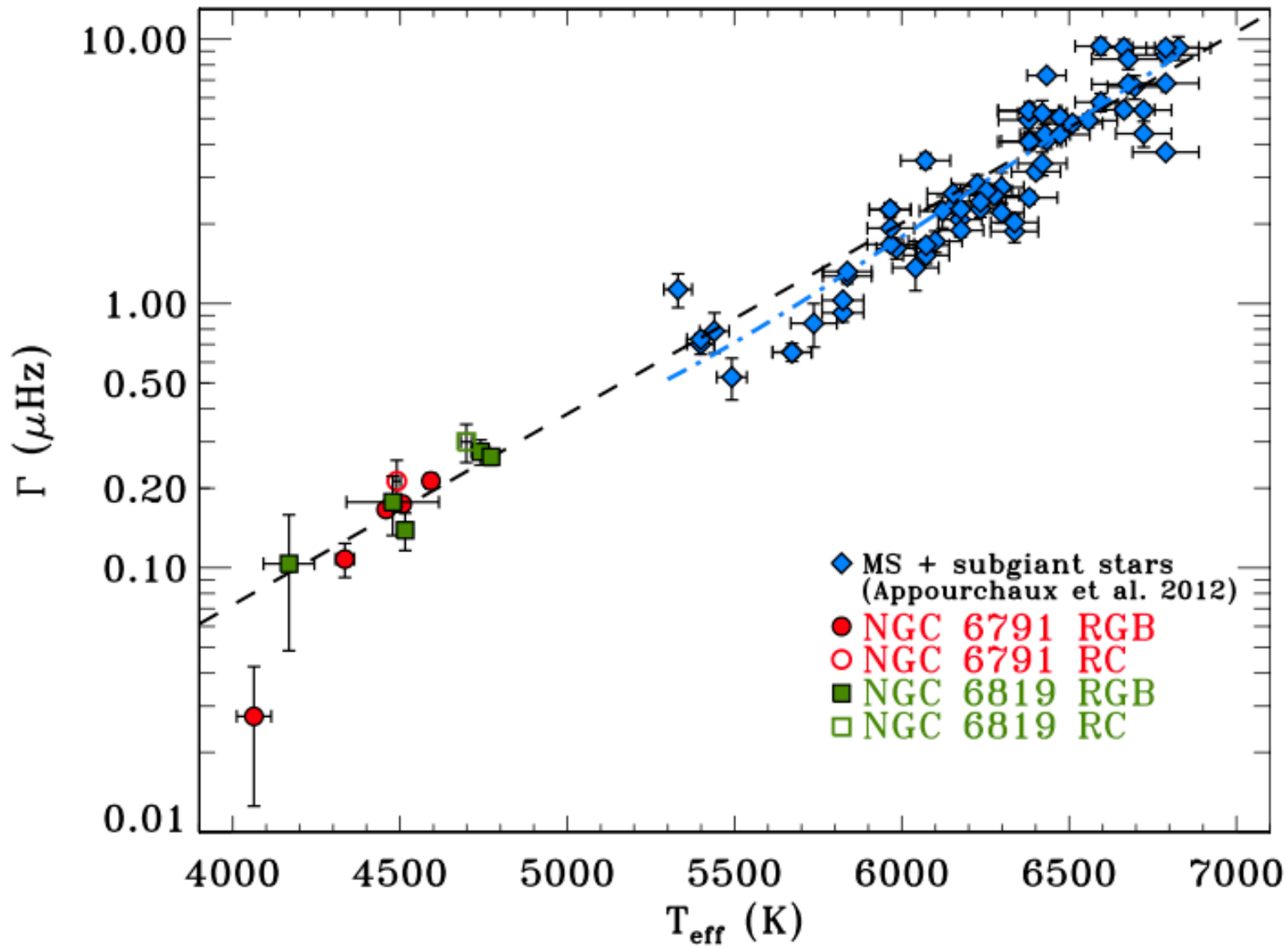
NGC 6819



Linewidths are related to damping of the modes

Adapted from Corsaro et al. 2012

Linewidths and T_{eff}



Adapted from Corsaro et al. 2012

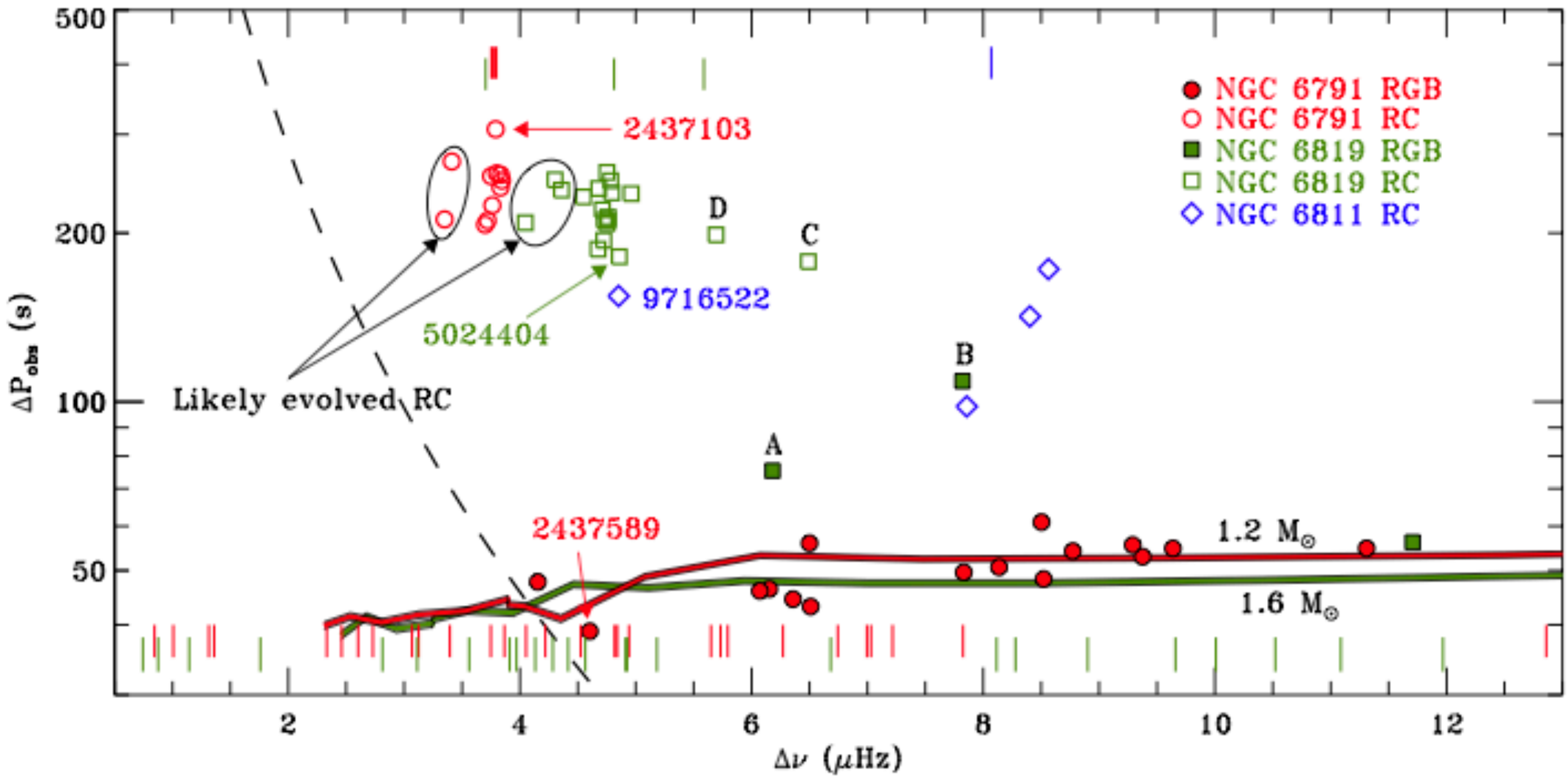
Hekker, S., et al., 2011, A&A, 530, 100

- Temperature estimates for the three clusters from (V - K) color
- Exponential correlation between linewidths and T_{eff} (even for cooler stars) - **One law only from MS to RG stars**

$$\Gamma = \Gamma_0 \exp\left(\frac{T_{\rm eff} - 5777\,K}{T_0}\right)\ \mu\mathrm{Hz}$$

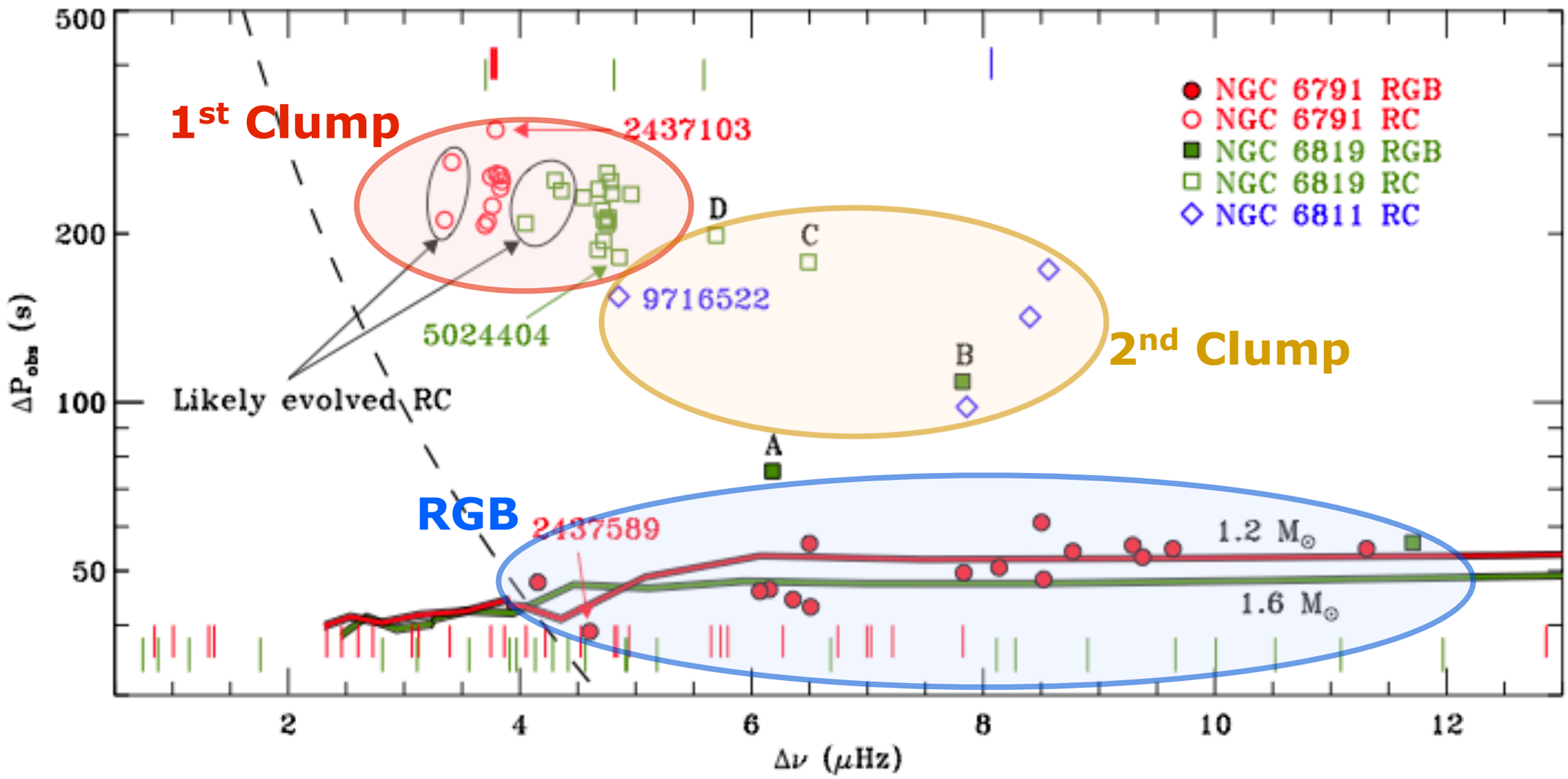
$$\Gamma_0 = 1.39 \pm 0.10\,\mu\mathrm{Hz}$$
$$T_0 = 601 \pm 3\,\mathrm{K}$$

ΔP_{obs}-$\Delta\nu$ diagram



Adapted from Corsaro et al. 2012

ΔP_{obs}-$\Delta\nu$ diagram

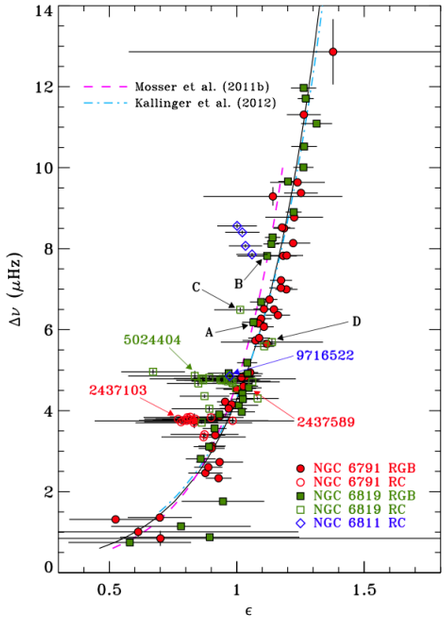


Adapted from Corsaro et al. 2012

- 53 RGs, where ΔP_{obs} could be measured
- **RGB stars** show agreement with theoretical predictions by **White, T., et al. 2012, ApJ, 419, 2077**
- Some of them are standing outside the expected regions: discussion of **14 special cases** **(AGB stars, Binaries, Blue Stragglers, Evolved Clump stars)**

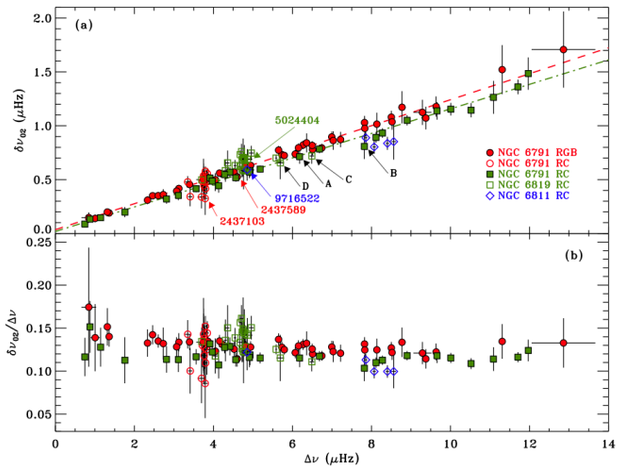
Conclusions

- **Log-relation ε-mean density of the stars confirmed and improved** also for cluster RGs and new power law relation tested



- First evidence for **mass dependence of small spacings $\delta\nu_{02}$ and $\delta\nu_{01}$** in cluster RGs (in qualitative agreement with predictions)

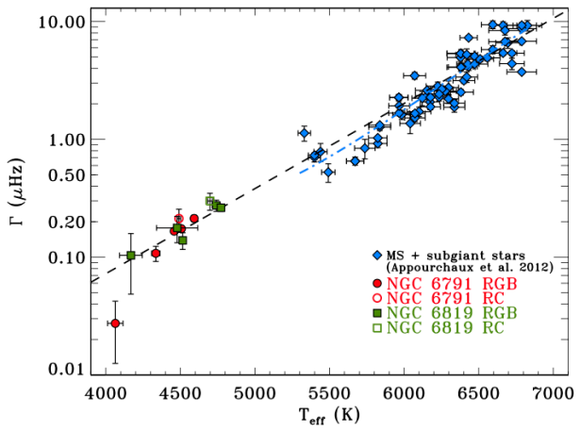
- **Different behaviour of RC stars in C-D diagrams** relative to their RGB counterparts (theoretical models for post He-flash phase are required)



Corsaro, E. *et al.* 2012, ApJ, 757, 190

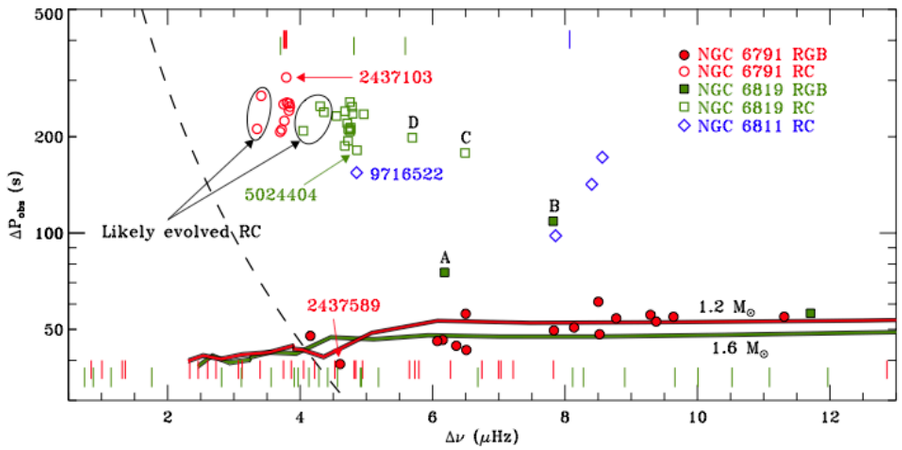
Conclusions

- **New exponential law for linewidths** as a function of temperature



- **53 Red Giants** could be classified in their evolutionary stage

- Period spacing analysis revealed **14 stars** to be **at a different stage of evolution** than anticipated from the CMD - **Very interesting for modeling!**



- **6 evolved RC stars** to be modeled theoretically

Corsaro, E. *et al.* 2012, ApJ, 757, 190

Acknowledgements

Thank you for your attention!

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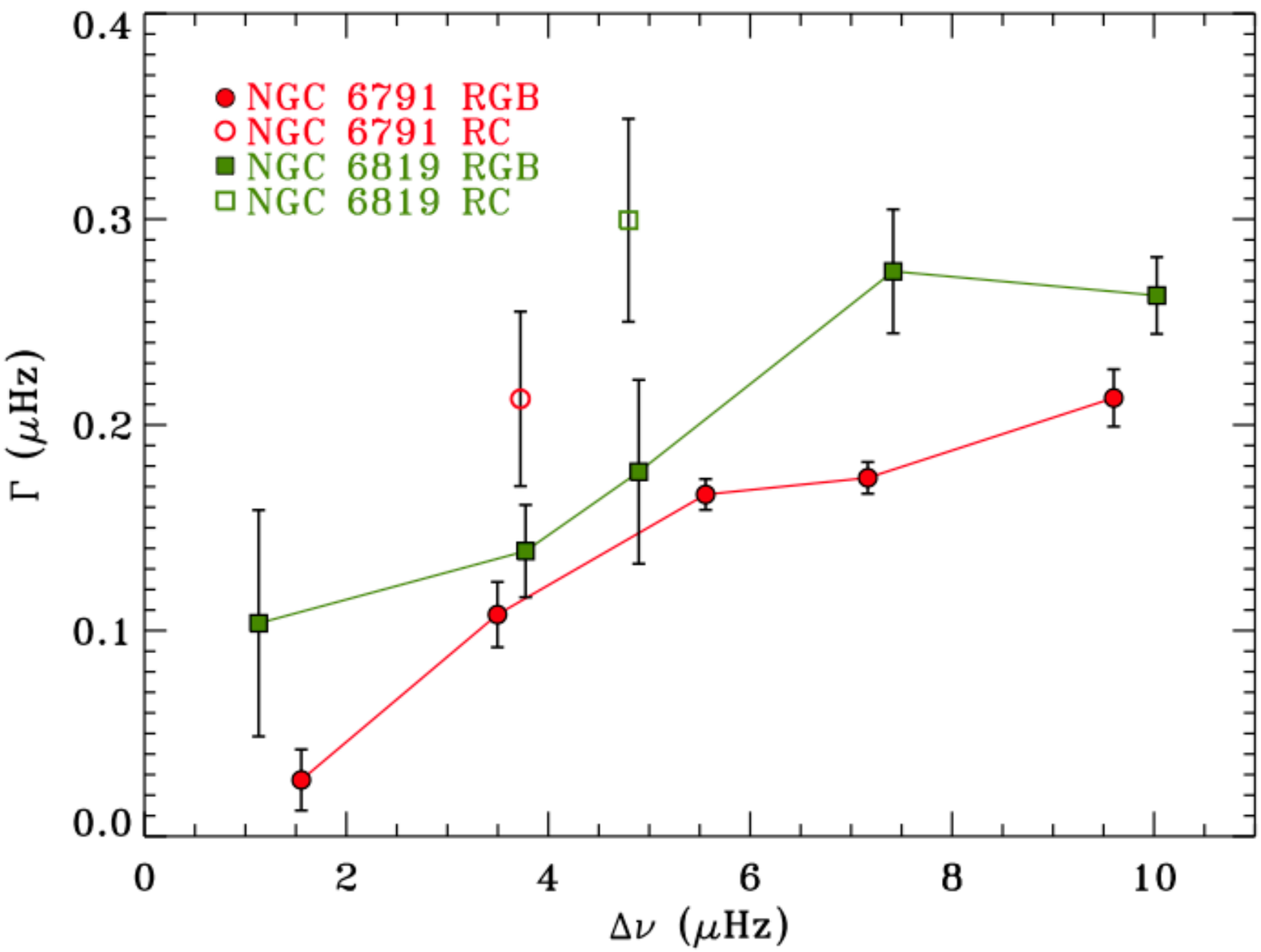
Linewidths



Adapted from Corsaro et al. 2012

- Evidence for a systematic difference in temperature of the two clusters
- Linewidths increase with temperature
  (in agreement with Huber et al. 2010 and Kallinger et al. 2012)
- RC stars have larger linewidths because of higher temperatures

Interesting targets list

Outliers ΔP_{obs}

KIC ID	NGC	Notes[a]	ν_{max} (μHz)	$\Delta\nu$ (μHz)	ϵ	$\delta\nu_{02}$ (μHz)	$\delta\nu_{01}$ (μHz)	ΔP_{obs} (s)
5112361	6819	(A) Outlier	67.4 ± 1.4	6.181 ± 0.025	1.066 ± 0.044	0.712 ± 0.066	-0.102 ± 0.048	75
4937770	6819	(B) Outlier	93.8 ± 2.4	7.821 ± 0.076	1.119 ± 0.117	0.808 ± 0.117	-0.096 ± 0.070	109
5024414	6819	(C) Outlier	77.1 ± 1.5	6.490 ± 0.056	1.013 ± 0.103	0.720 ± 0.072	-0.220 ± 0.143	178
5024476	6819	(D) Outlier	67.0 ± 1.7	5.693 ± 0.097	1.138 ± 0.201	0.656 ± 0.152	-0.203 ± 0.234	199

Adapted from Corsaro et al. 2012

Other interesting cases

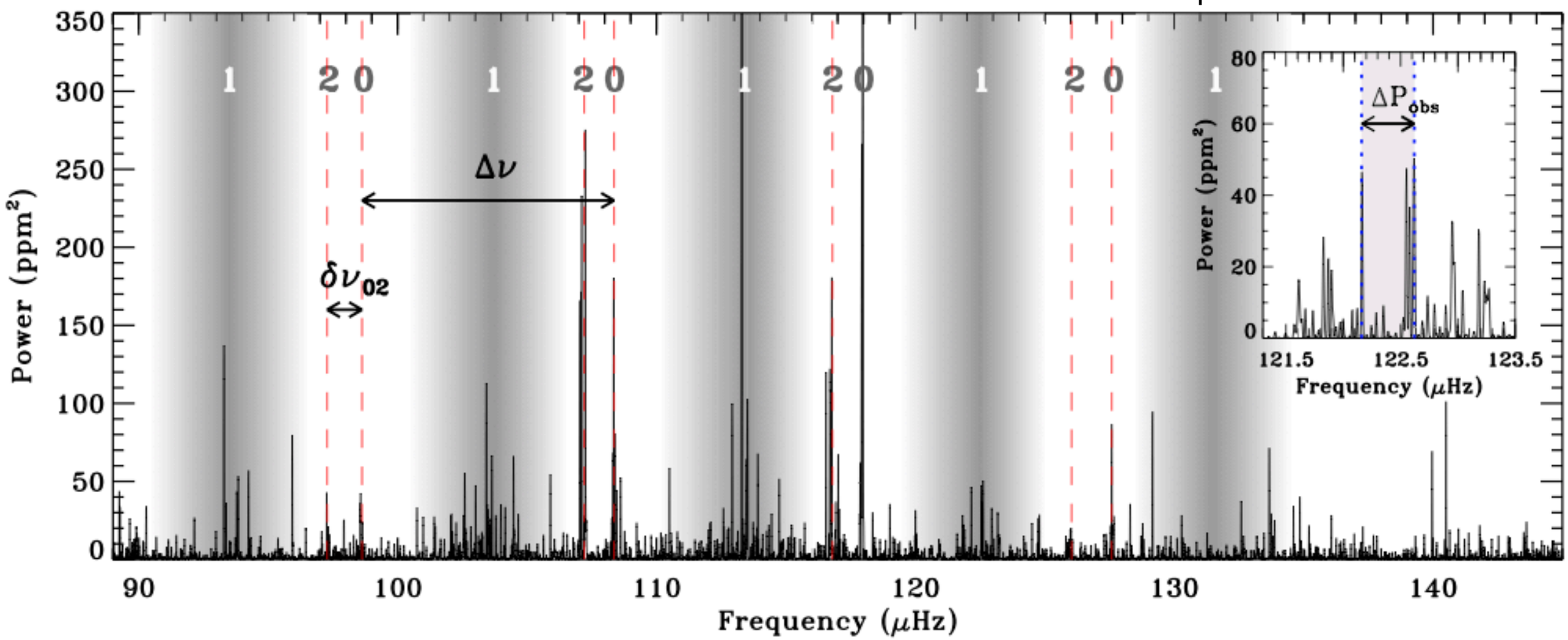
KIC ID	NGC	Notes[a]	ν_{max} (μHz)	$\Delta\nu$ (μHz)	ϵ	$\delta\nu_{02}$ (μHz)	$\delta\nu_{01}$ (μHz)	ΔP_{obs} (s)
2437103	6791	Misclassified CMD	29.7 ± 1.7	3.791 ± 0.064	0.770 ± 0.132	0.325 ± 0.153	-0.242 ± 0.114	306
2437589	6791	Misclassified CMD	46.5 ± 1.5	4.603 ± 0.026	1.026 ± 0.057	0.526 ± 0.042	-0.184 ± 0.038	39
5024404	6819	Misclassified CMD	48.8 ± 0.7	4.857 ± 0.126	0.835 ± 0.261	0.689 ± 0.095	-0.122 ± 0.072	182
9716522	6811	AGB	54.9 ± 1.0	4.852 ± 0.036	0.973 ± 0.084	0.592 ± 0.102	-0.116 ± 0.099	154
2436417	6791	Likely evolved RC	26.7 ± 0.8	3.412 ± 0.058	0.874 ± 0.133	0.342 ± 0.090	-0.237 ± 0.074	268
2437804	6791	Likely evolved RC	26.5 ± 1.6	3.350 ± 0.070	0.870 ± 0.165	0.478 ± 0.054	-0.266 ± 0.529	212
5024601	6819	Likely evolved RC	31.8 ± 1.7	3.704 ± 0.028	0.862 ± 0.065	0.498 ± 0.061	-0.140 ± 0.107	-
5112401	6819	Likely evolved RC	38.2 ± 0.7	4.047 ± 0.068	0.892 ± 0.158	0.476 ± 0.082	-0.169 ± 0.069	209
5112950	6819	Likely evolved RC	42.8 ± 1.3	4.302 ± 0.036	1.082 ± 0.083	0.584 ± 0.104	0.010 ± 0.181	249
5112974	6819	Likely evolved RC	41.7 ± 0.7	4.358 ± 0.045	0.874 ± 0.099	0.655 ± 0.115	0.064 ± 0.073	239

Adapted from Corsaro et al. 2012

Power Spectra

- **KIC 2436593** RGB star belonging to NGC 6791
  ν_{max} = 111.64 μHz
  $\Delta\nu$ = 9.64 μHz
  ε = 1.238
  $\delta\nu_{02}$ = 1.178 μHz
  $\delta\nu_{01}$ = 0.078 μHz
  ΔP_{obs} = 54.7 s

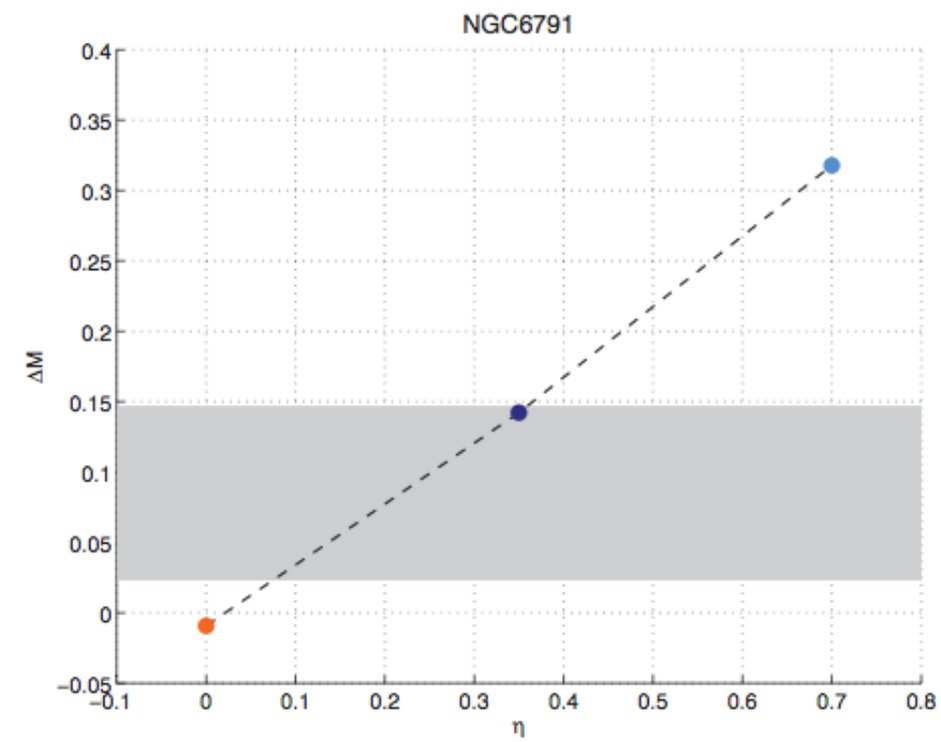
Adapted from Corsaro et al. 2012

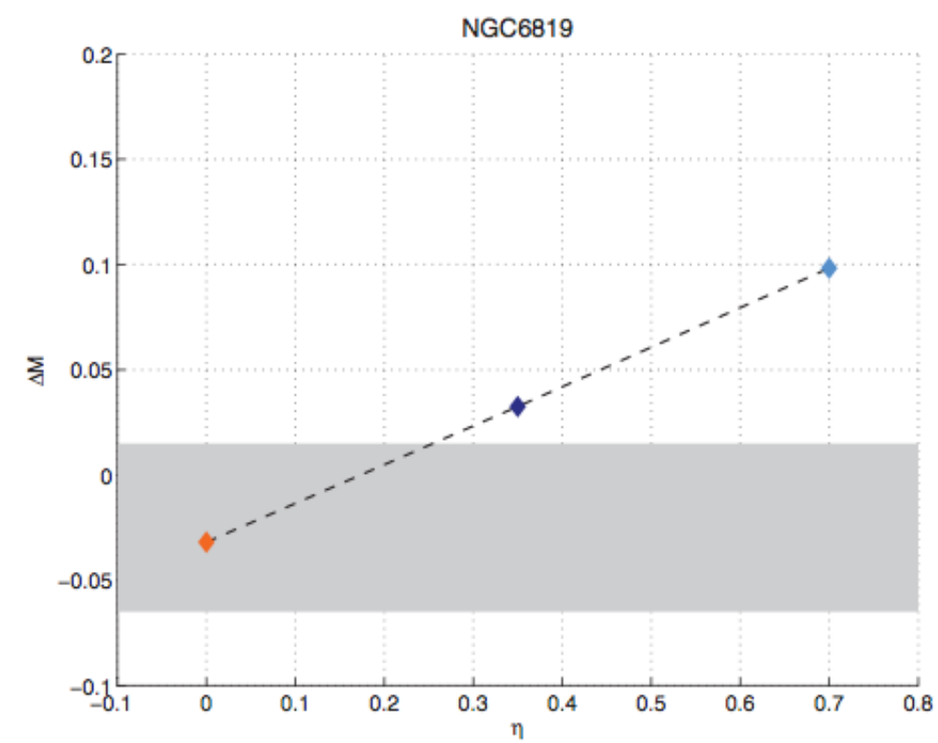


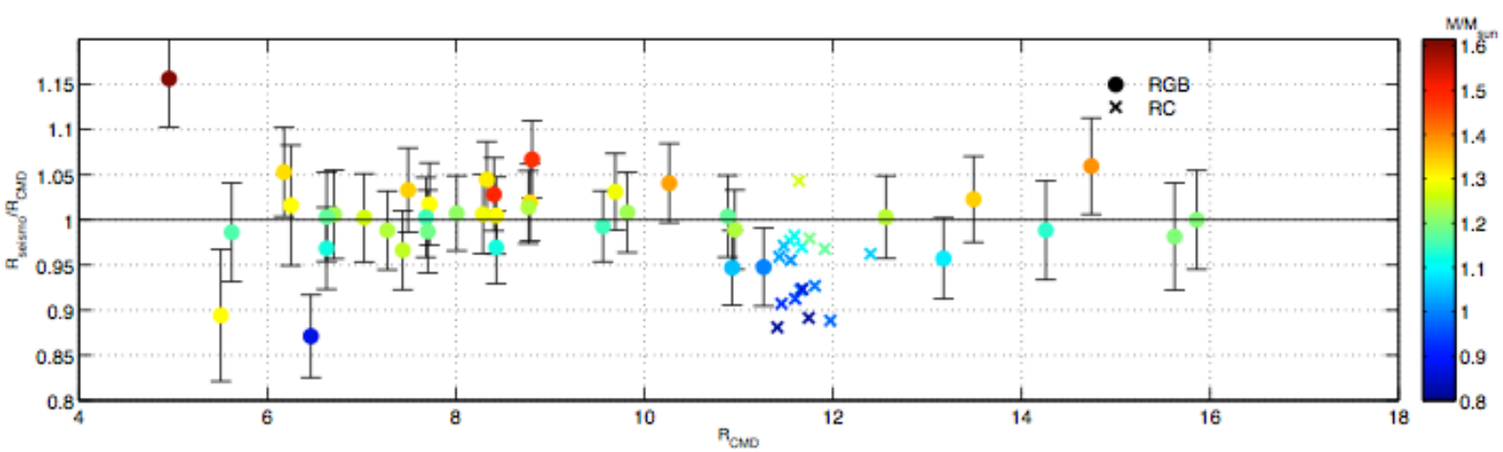
Mass loss

Miglio, A., et al. 2012, MNRAS, 419, 2077

- Direct estimates of mass loss rates for NGC 6791 and NGC 6819
- Mass correction to the Δν scaling relation for clump stars
- **NGC 6791** significant mass loss
  $\Delta M = 0.09 \pm 0.03$ (random) ± 0.04 (systematic) $M_\odot$
  M_{RC} (corrected) = $1.15 \pm 0.03\ M_\odot$ (2.7 % corr.)
- **NGC 6819** no mass loss
  $\Delta M = -0.03 \pm 0.04\ M_\odot$
  M_{RC} (corrected) = $1.65 \pm 0.04\ M_\odot$ (1.9 % corr)







Adapted from Miglio et al. 2012

Adapted from Miglio et al. 2012

Section 4

Discussion of interesting targets

Interesting targets list

Outliers ΔP_{obs}

KIC ID	NGC	Notes[a]	ν_{max} (μHz)	$\Delta\nu$ (μHz)	ϵ	$\delta\nu_{02}$ (μHz)	$\delta\nu_{01}$ (μHz)	ΔP_{obs} (s)
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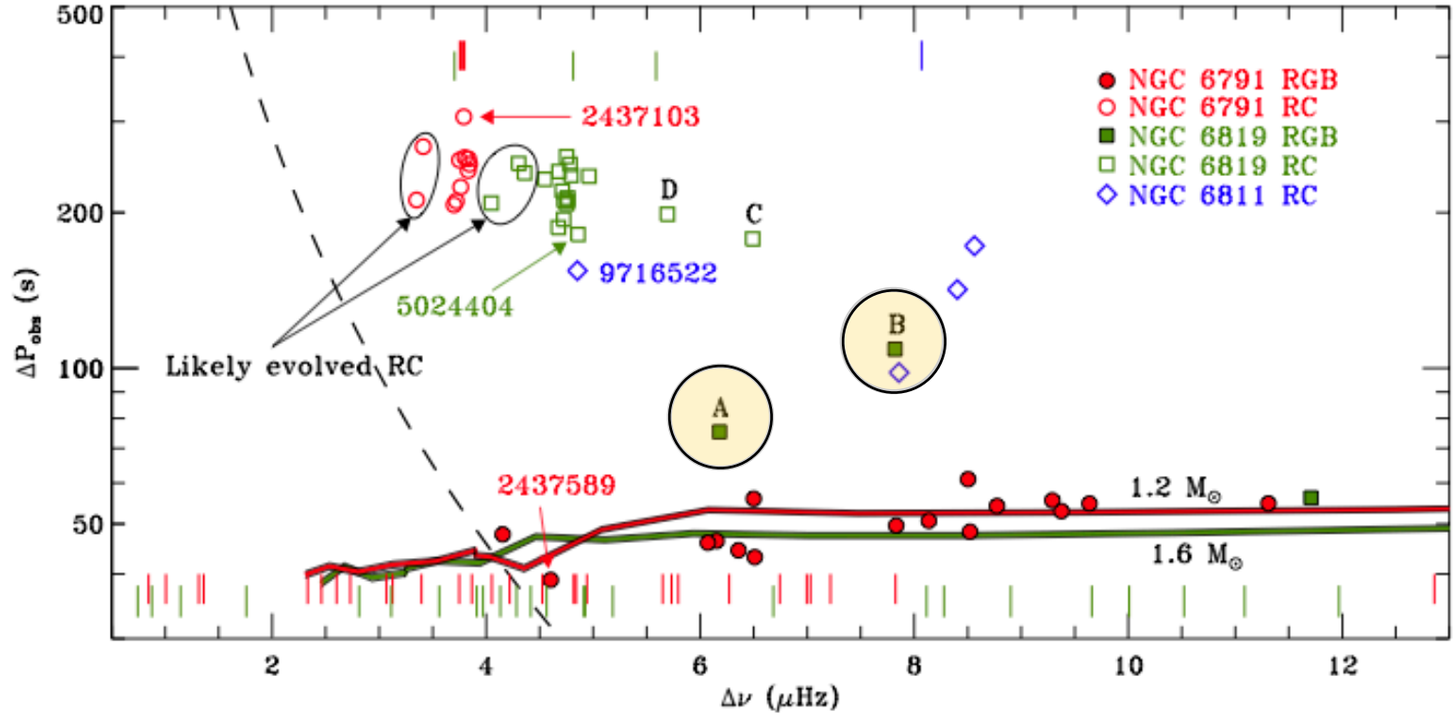
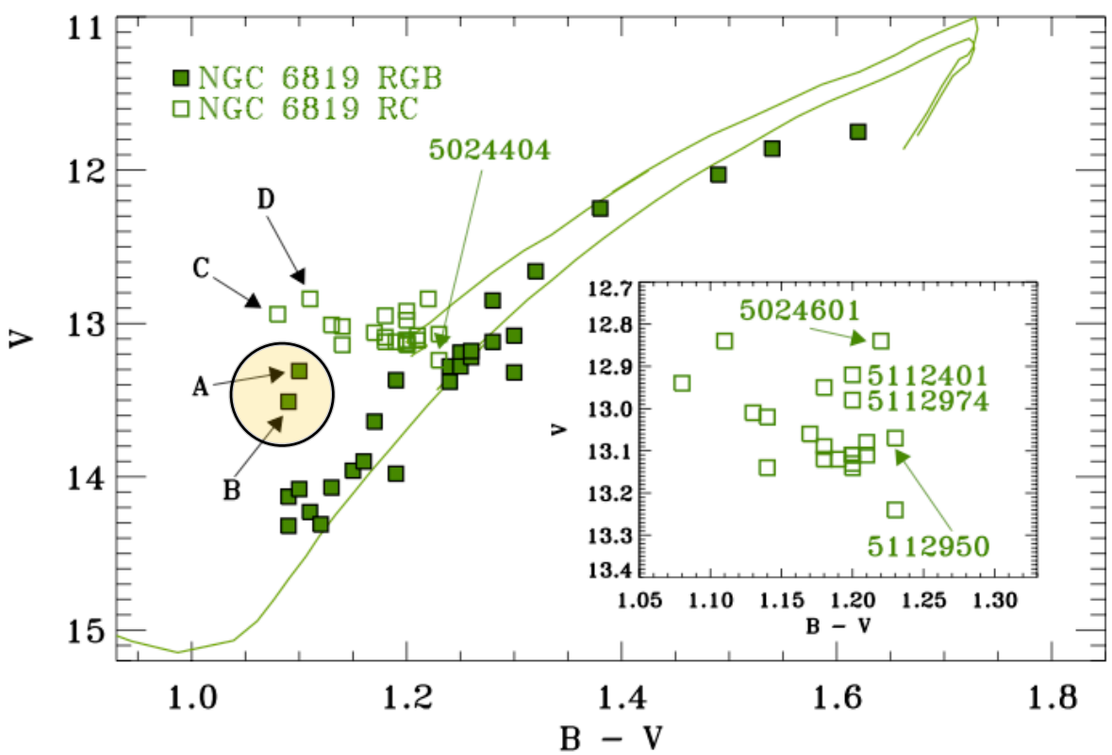
Adapted from Corsaro et al. 2012

Outliers ΔP_{obs}

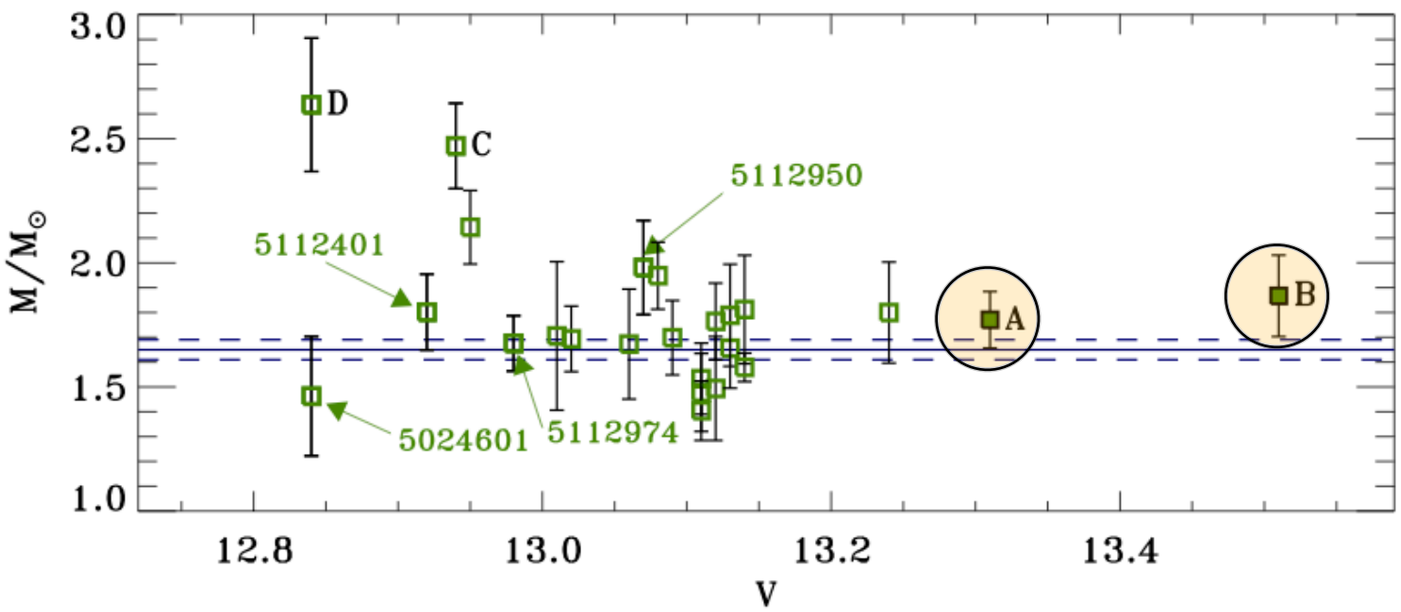
- **A**, **B**, **C**, **D** unexpected position in the ΔP_{obs}-$\Delta\nu$ diagram
- **A**, **B** are likely to be **binary stars**, with one component RGB and another faint less-evolved component (suggested by their lower B-V color)



Adapted from Corsaro et al. 2012



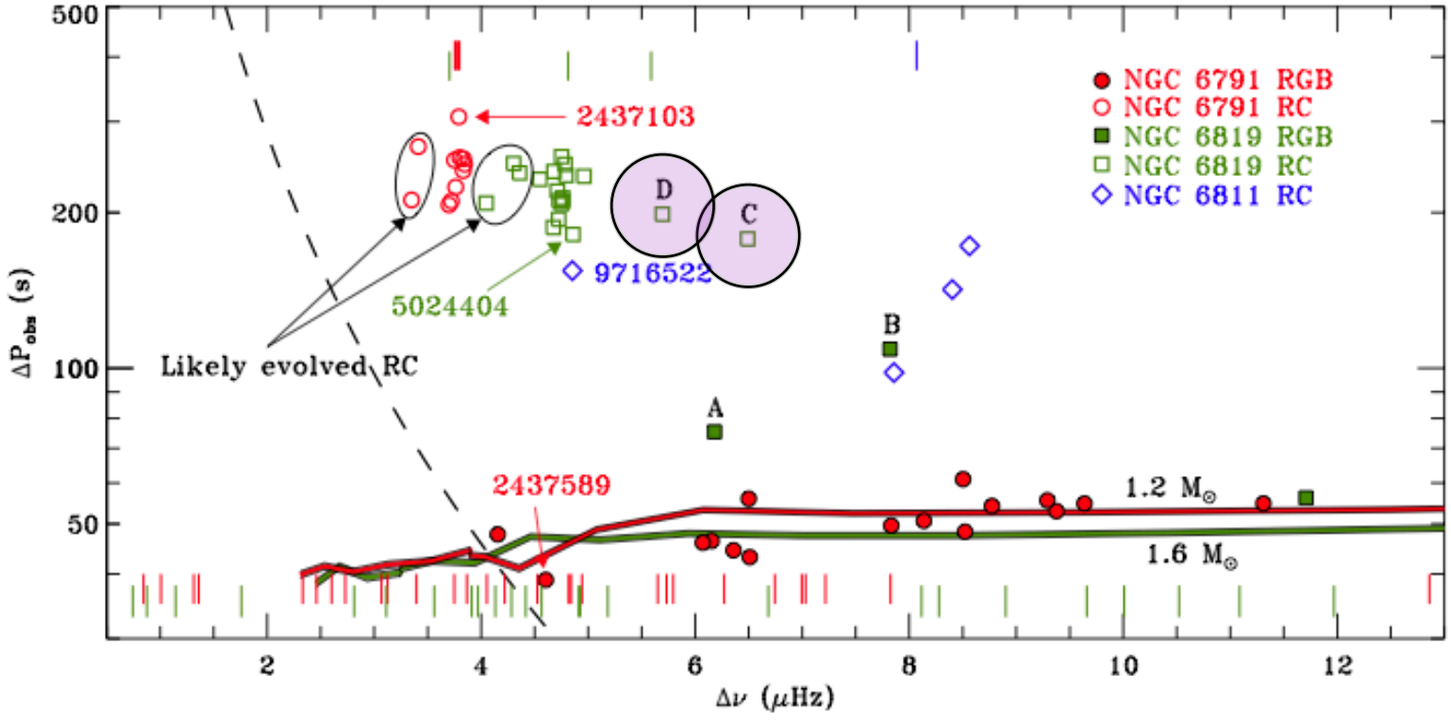
Adapted from Corsaro et al. 2012



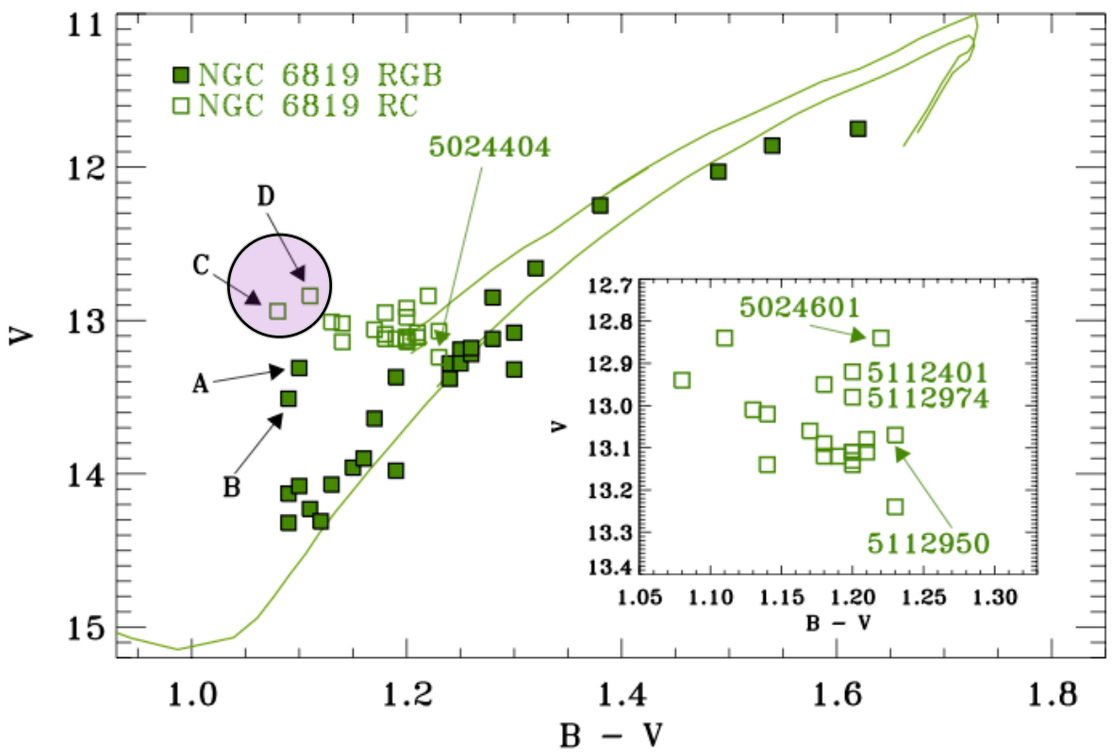
Adapted from Corsaro et al. 2012

Outliers ΔP_{obs}

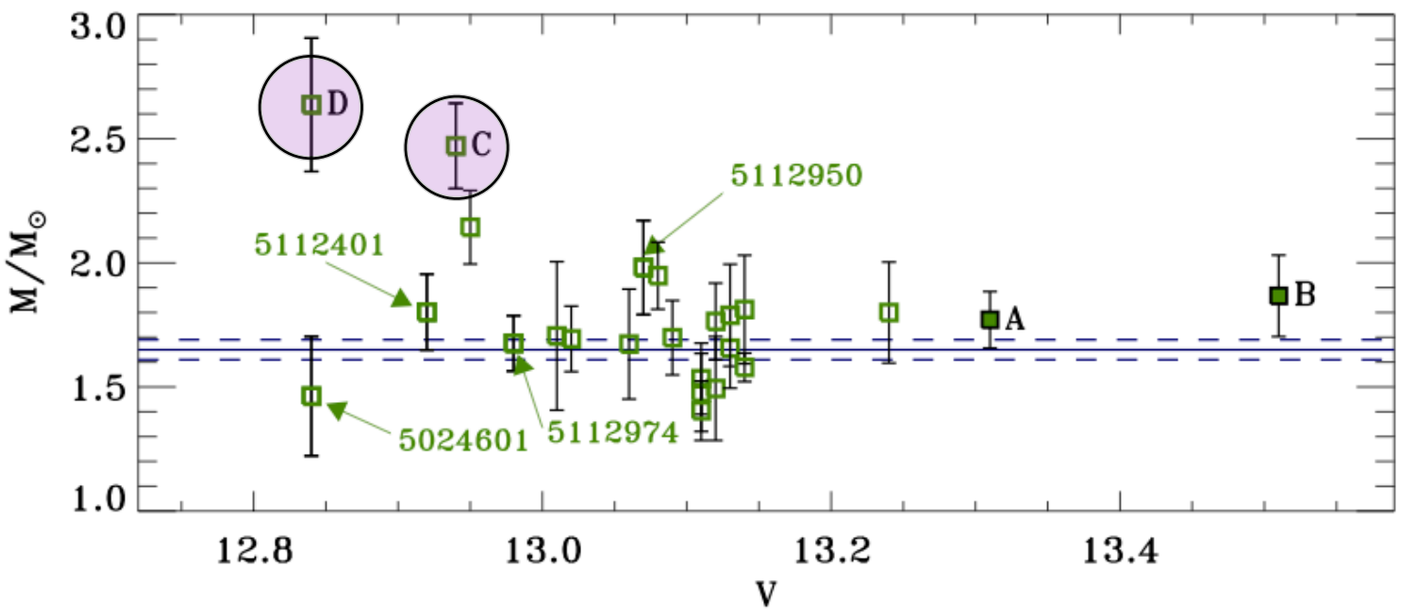
- A, B, C, D unexpected position in the ΔP_{obs}-$\Delta\nu$ diagram
- **C, D** have a high mass estimate and are likely to be **evolved blue straggler** stars (BSS) as suggested by **Rosvick, J. M., & Vandenberg, D. A. 1998, AJ, 115, 1516**



Adapted from Corsaro et al. 2012



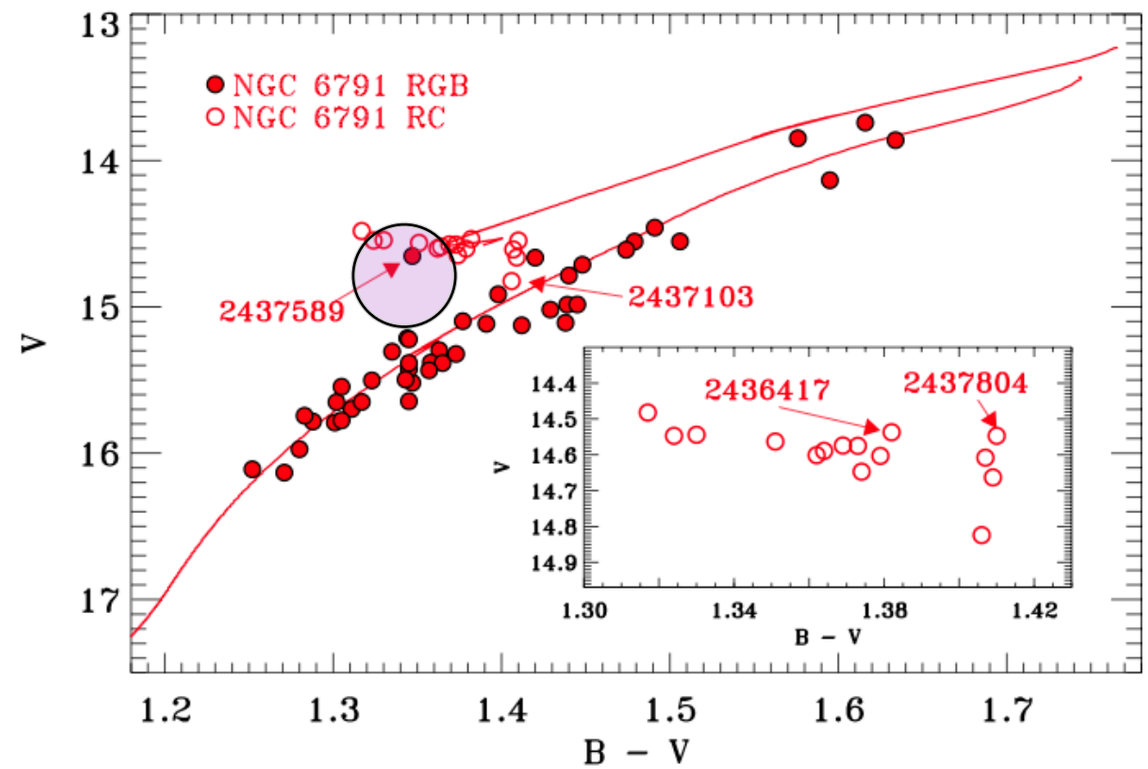
Adapted from Corsaro et al. 2012



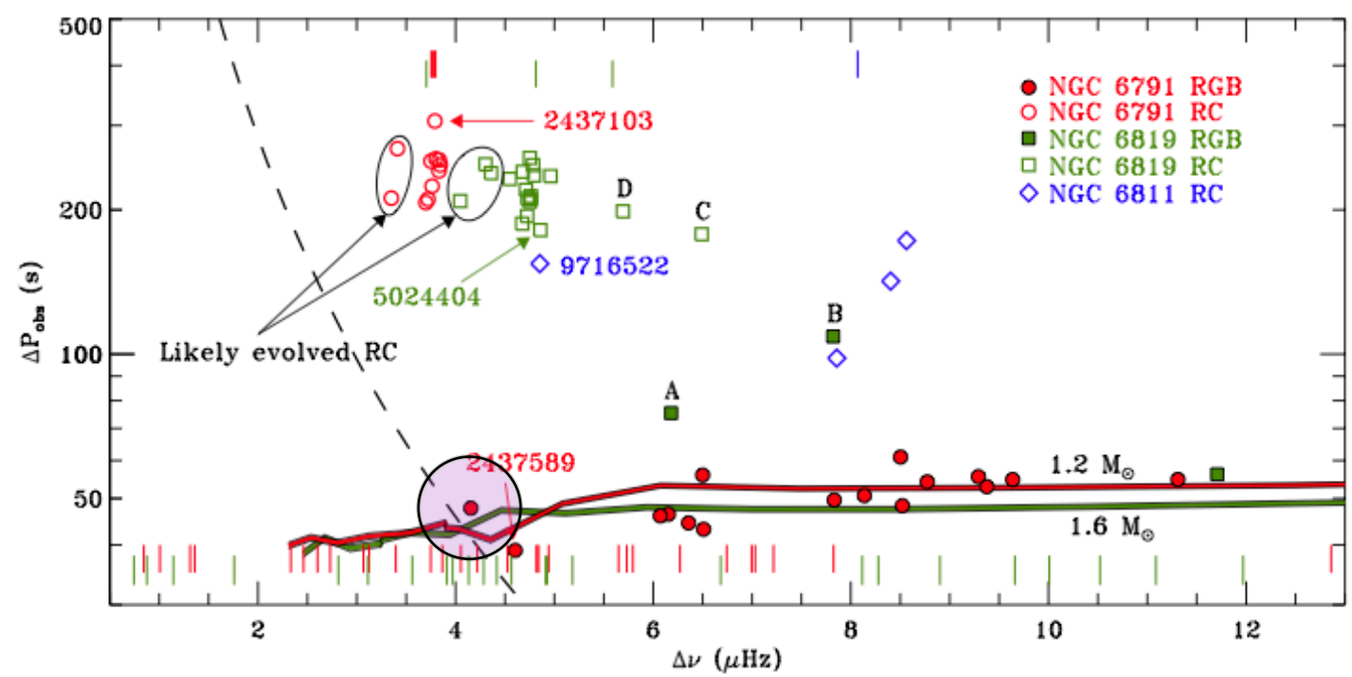
Adapted from Corsaro et al. 2012

Other interesting cases

- **KIC 2437589** misclassified from CMD
  Higher mass than other RGB (1.7 $M_\odot$)
  Suggestion by Brogaard et al. 2012 for **BSS** in the RGB phase



Adapted from Corsaro et al. 2012



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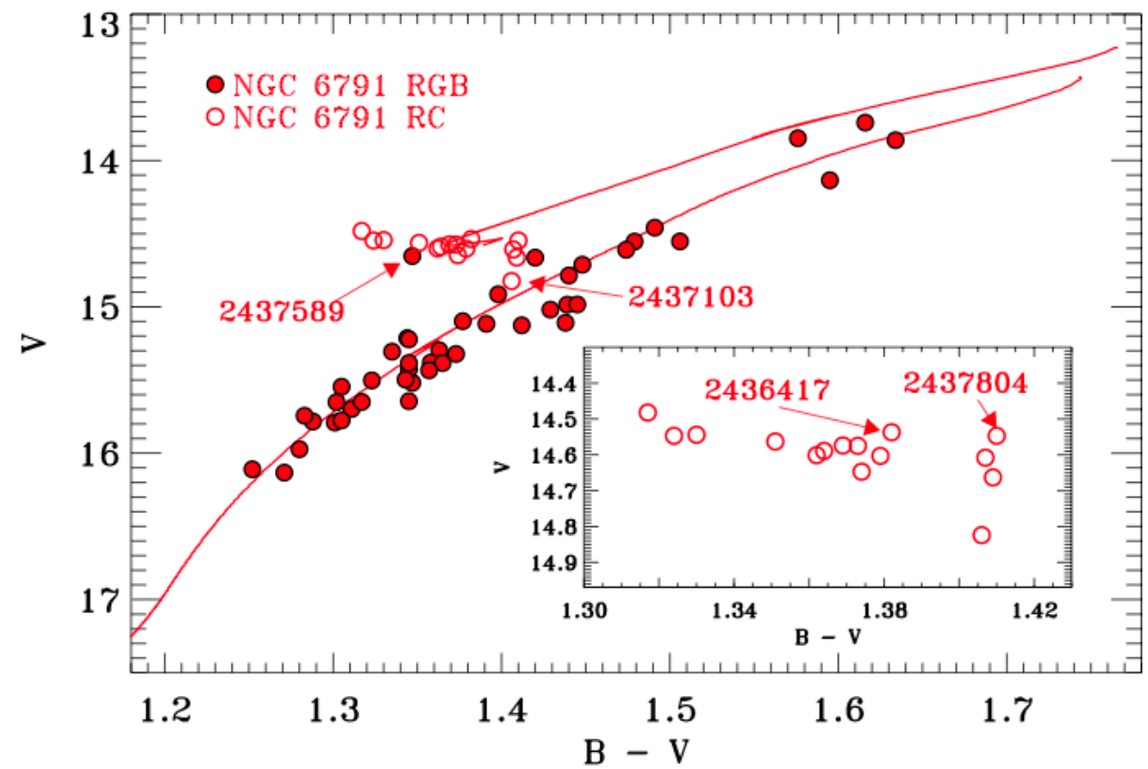
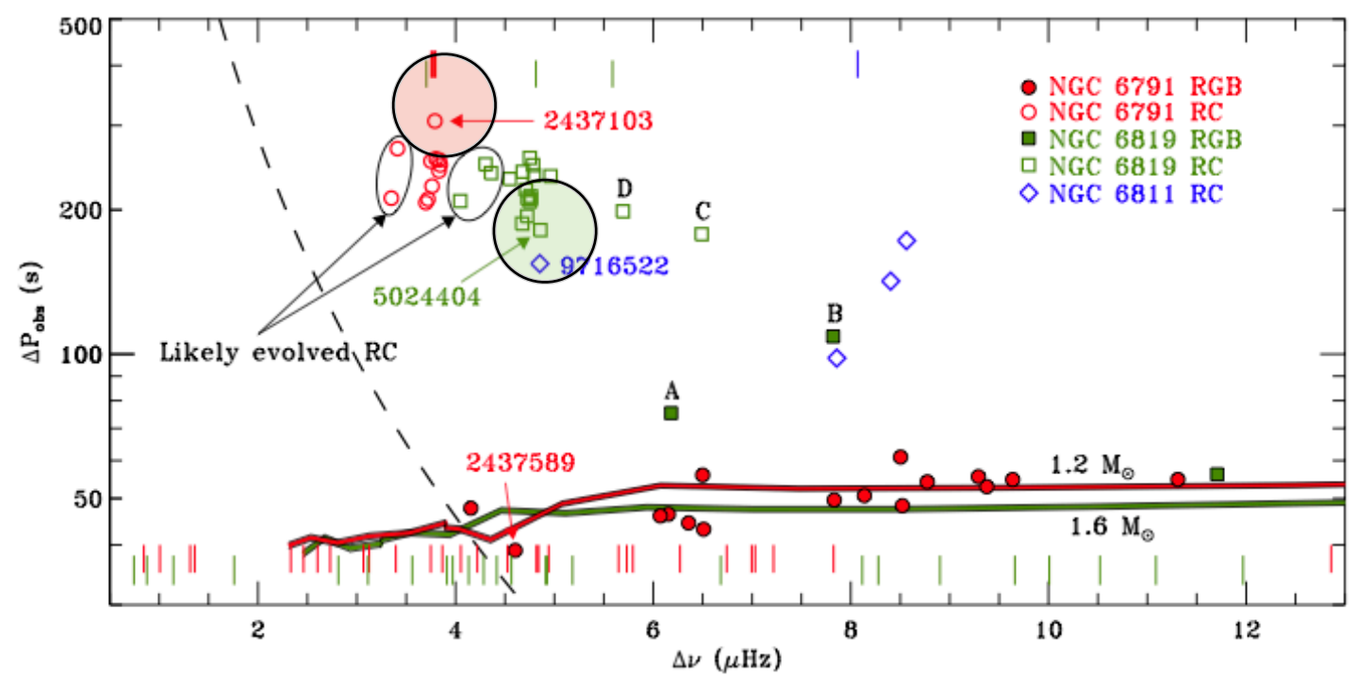
- **KIC 2437103** (ΔP_{obs} = 306 s) and **KIC 5024404** (ΔP_{obs} = 182 s) **misclassified** from CMD. Both **RC** stars



Adapted from Corsaro et al. 2012



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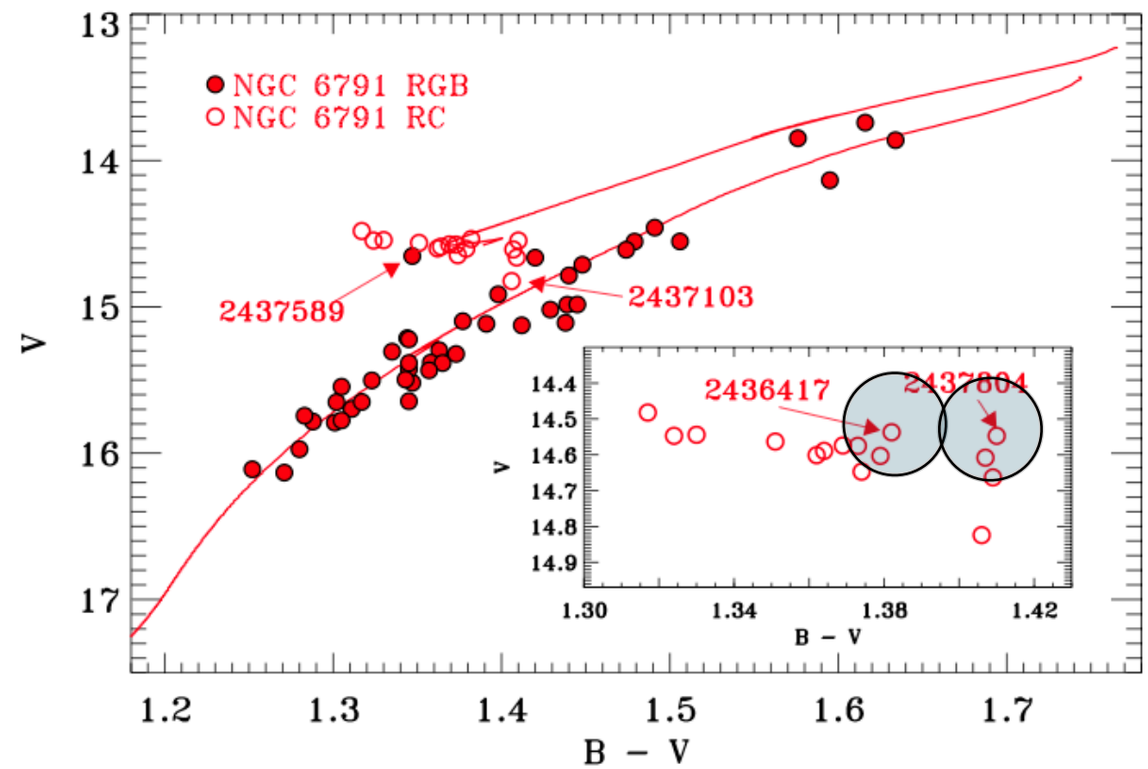
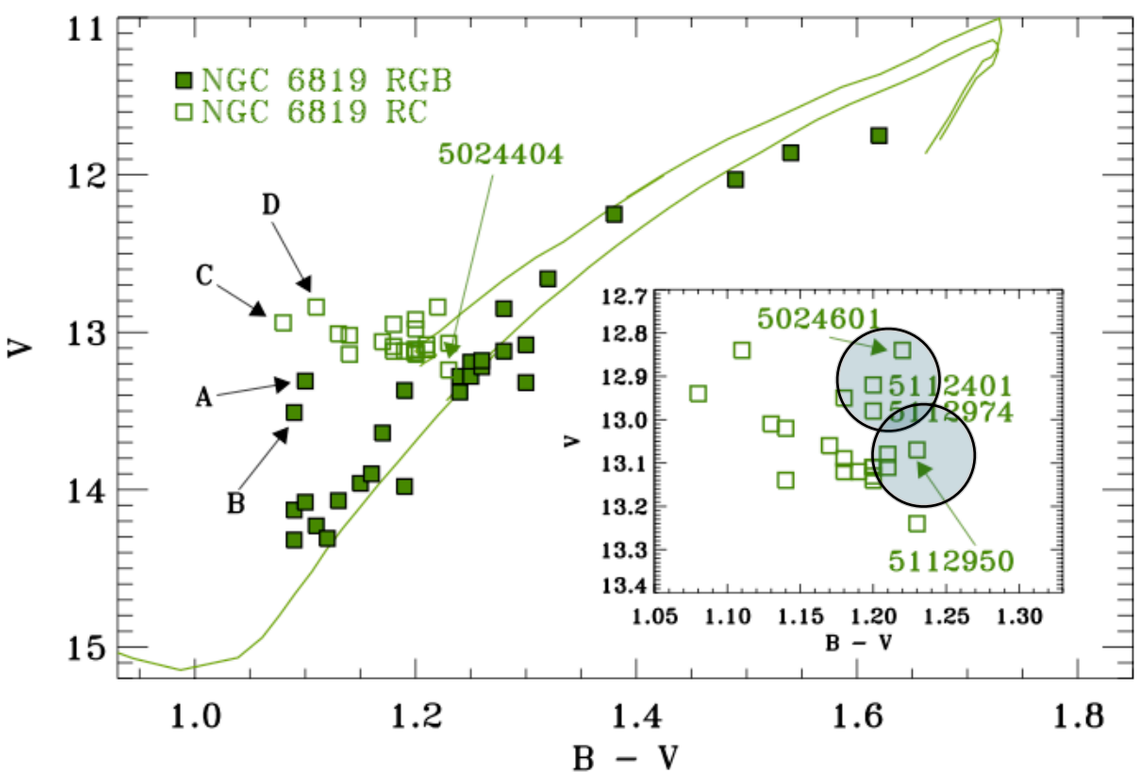
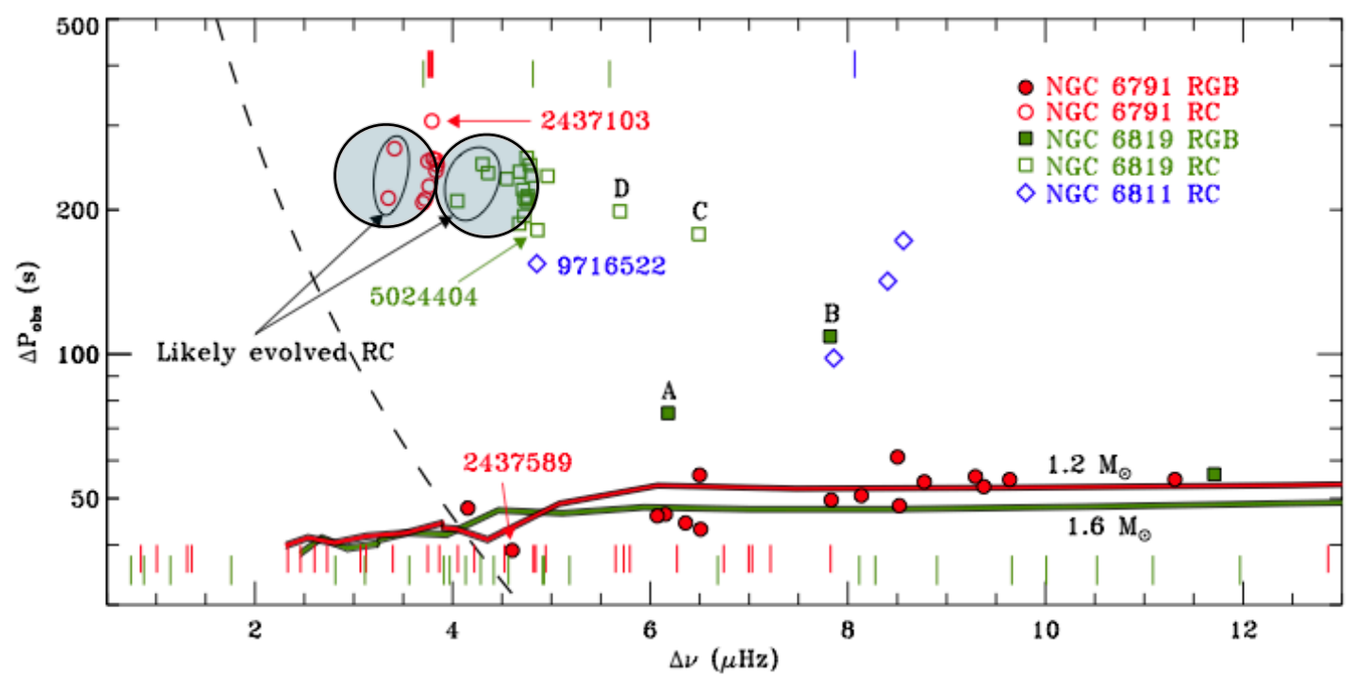
- **6 likely evolved RC stars** - Show masses of RC stars but lower $\Delta\nu$. Hence larger radii



Adapted from Corsaro et al. 2012



Adapted from Corsaro et al. 2012



Adapted from Corsaro et al. 2012

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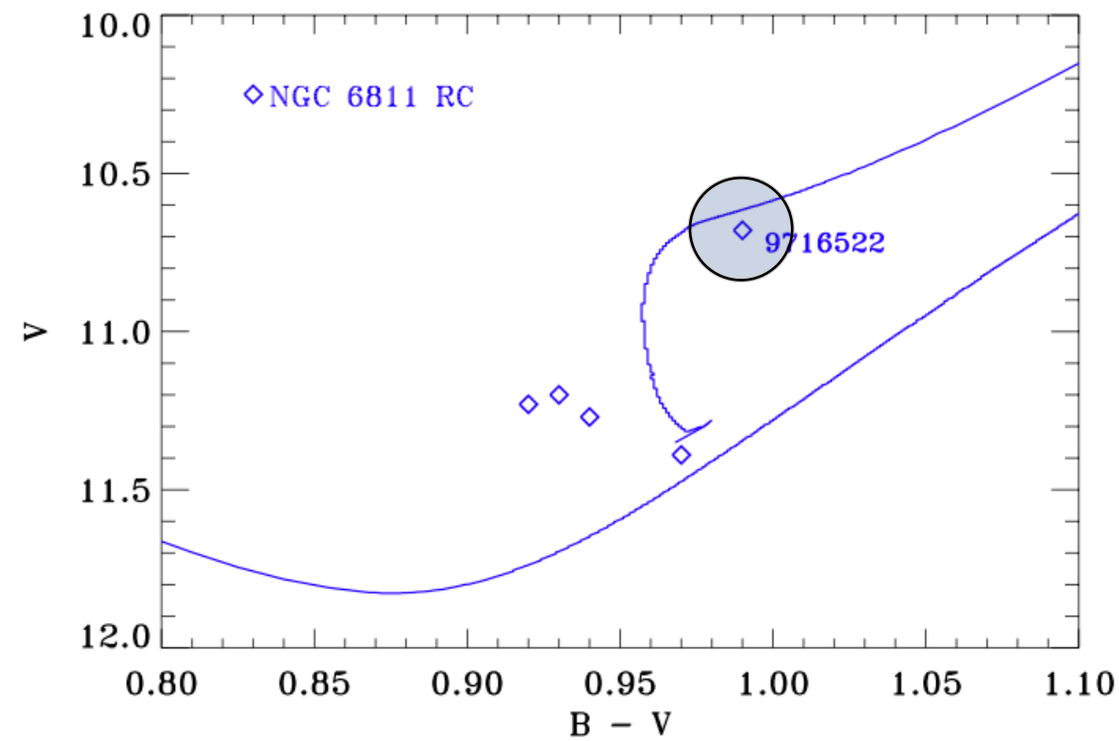
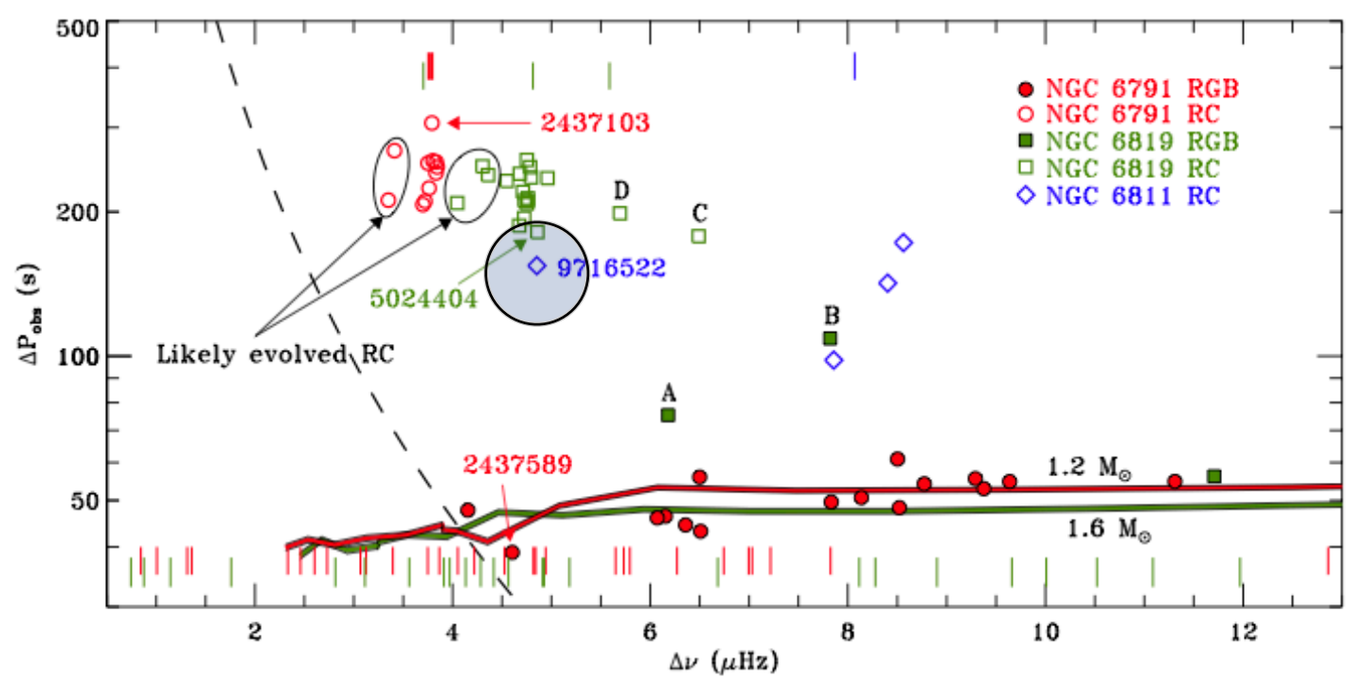
- **6 likely evolved RC stars** - Show masses of RC stars but lower $\Delta\nu$. Hence larger radii

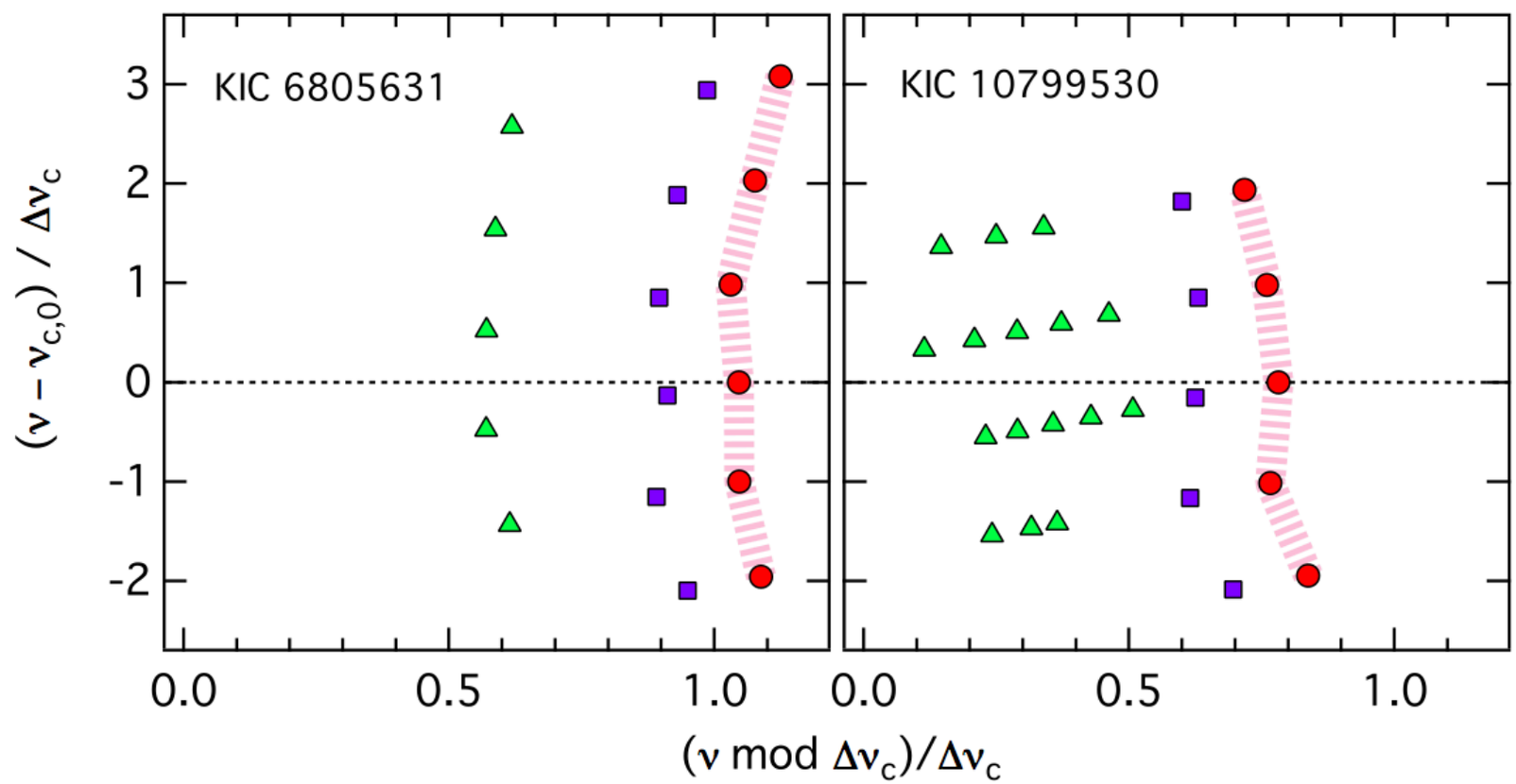
- **KIC 9716522** (ΔP_{obs} = 154 s) is an AGB as suggested by Stello et al. 2011b from CMD



Adapted from Corsaro et al. 2012



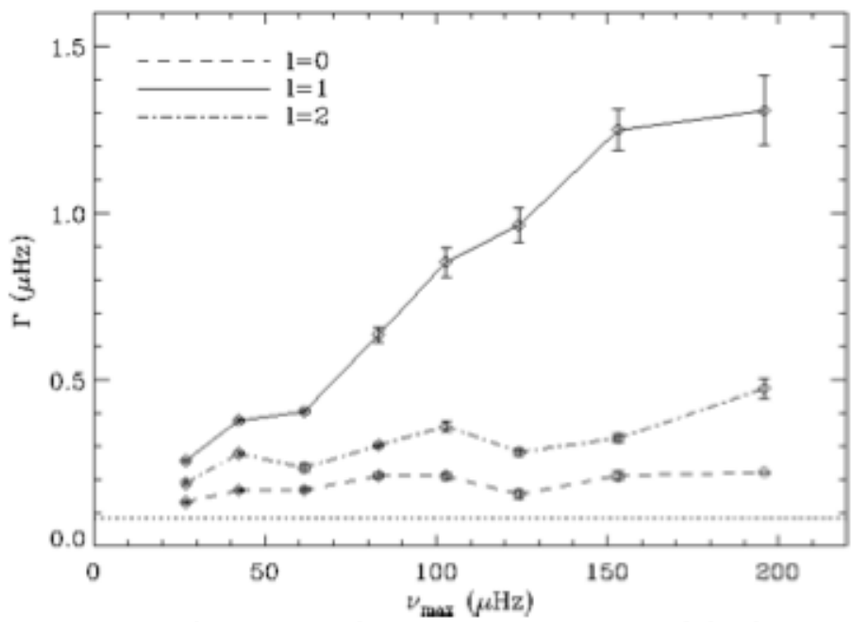
Adapted from Corsaro et al. 2012


KIC 6805631
KIC 10799530
3
2
1
0
-1
-2
0.0
0.5
1.0
0.0
0.5
1.0
$(\nu - \nu_{c,0}) / \Delta\nu_c$
$(\nu \bmod \Delta\nu_c)/\Delta\nu_c$

Linewidths and T_{eff}

Huber, D., et al., 2010, ApJ, 723, 1607

- Linewidths of 800 RGs appear to increase with increasing Δν



Adapted from Huber et al. 2010

Kallinger, T., et al., 2012, A&A, 541, 51

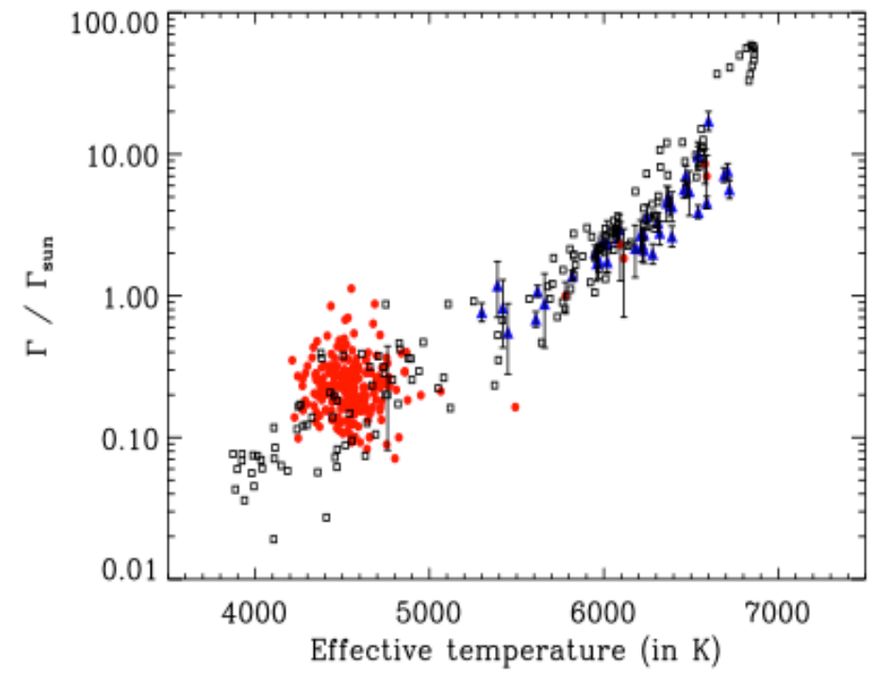
- Linewidths increase with the logarithm of Δν

Baudin, F., et al., 2011, A&A, 529, 84

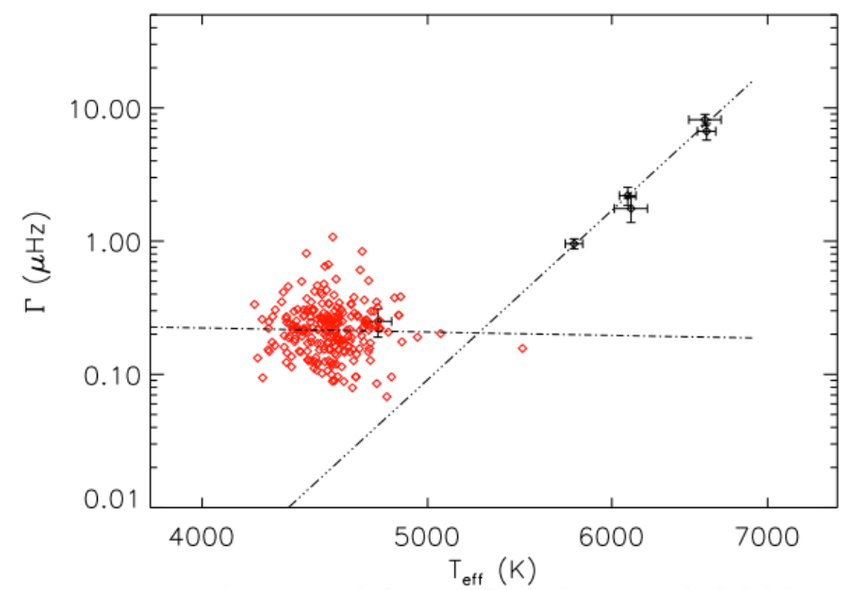
- No evident correlation of linewidths with T_{eff} for RGs observed with CoRoT (5 months)

Belkacem, K., et al., 2012, A&A, 540, 7

- Linewidths correlate well with T_{eff}, both from Kepler and CoRoT



Adapted from Belkacem et al. 2012



Adapted from Baudin et al. 2011