The Space Photometry Revolution
CoRoT Symp. 3 - KASC 7 July 8, 2014, Toulouse, France

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Peak Bagging of red giant stars observed by Kepler:

First results with a new method based on Bayesian Nested Sampling

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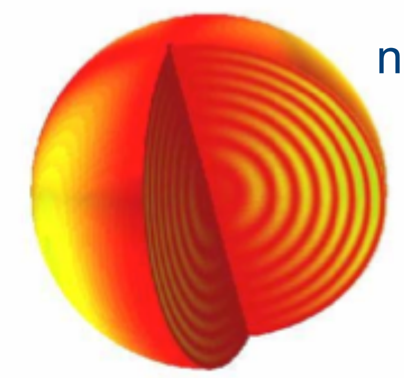
Outlook

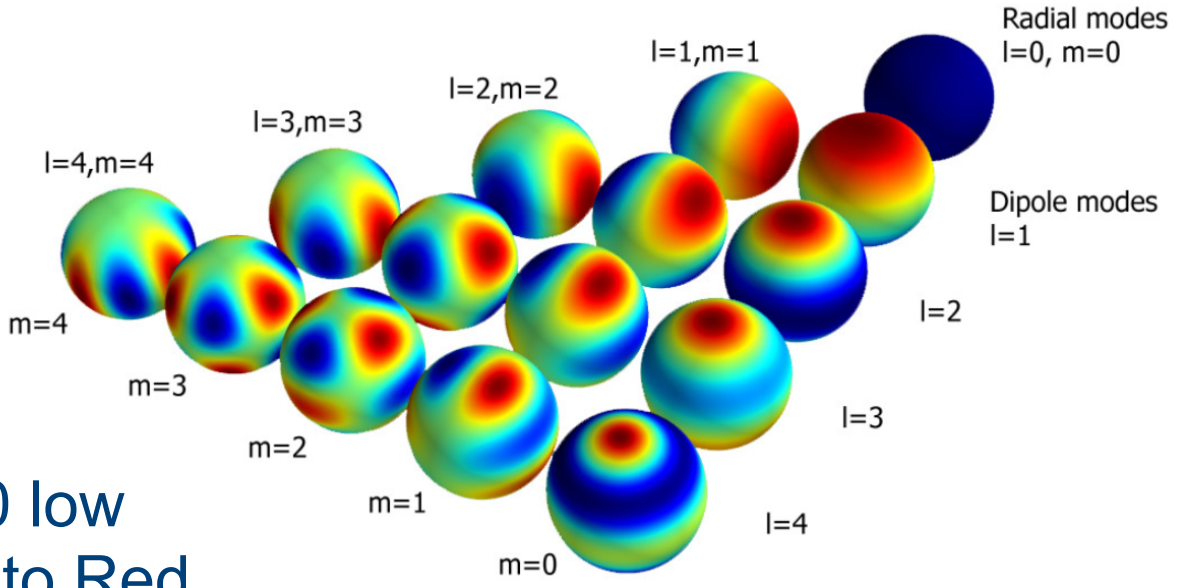
- Introduction
- The sample
- The new method
- First results

Solar-like Oscillations



Acoustic waves in outer convective envelope (p modes)

$$\nu_{\mathrm{n,l,m}}$$

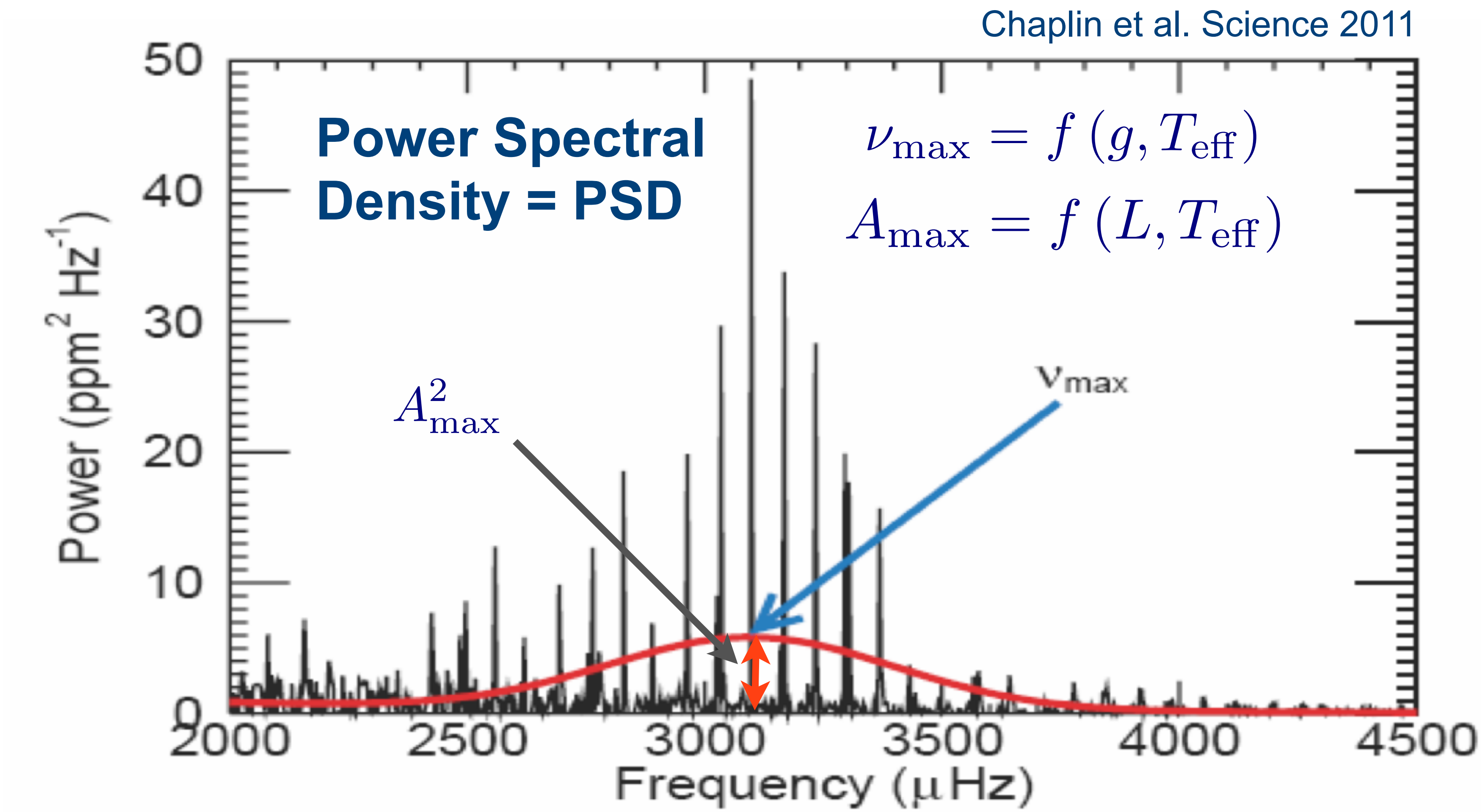


Tiny brightness variations

Observed in > 15000 low mass stars from MS to Red Giants

Beck & Kallinger S&W 2013

Solar-like Oscillations

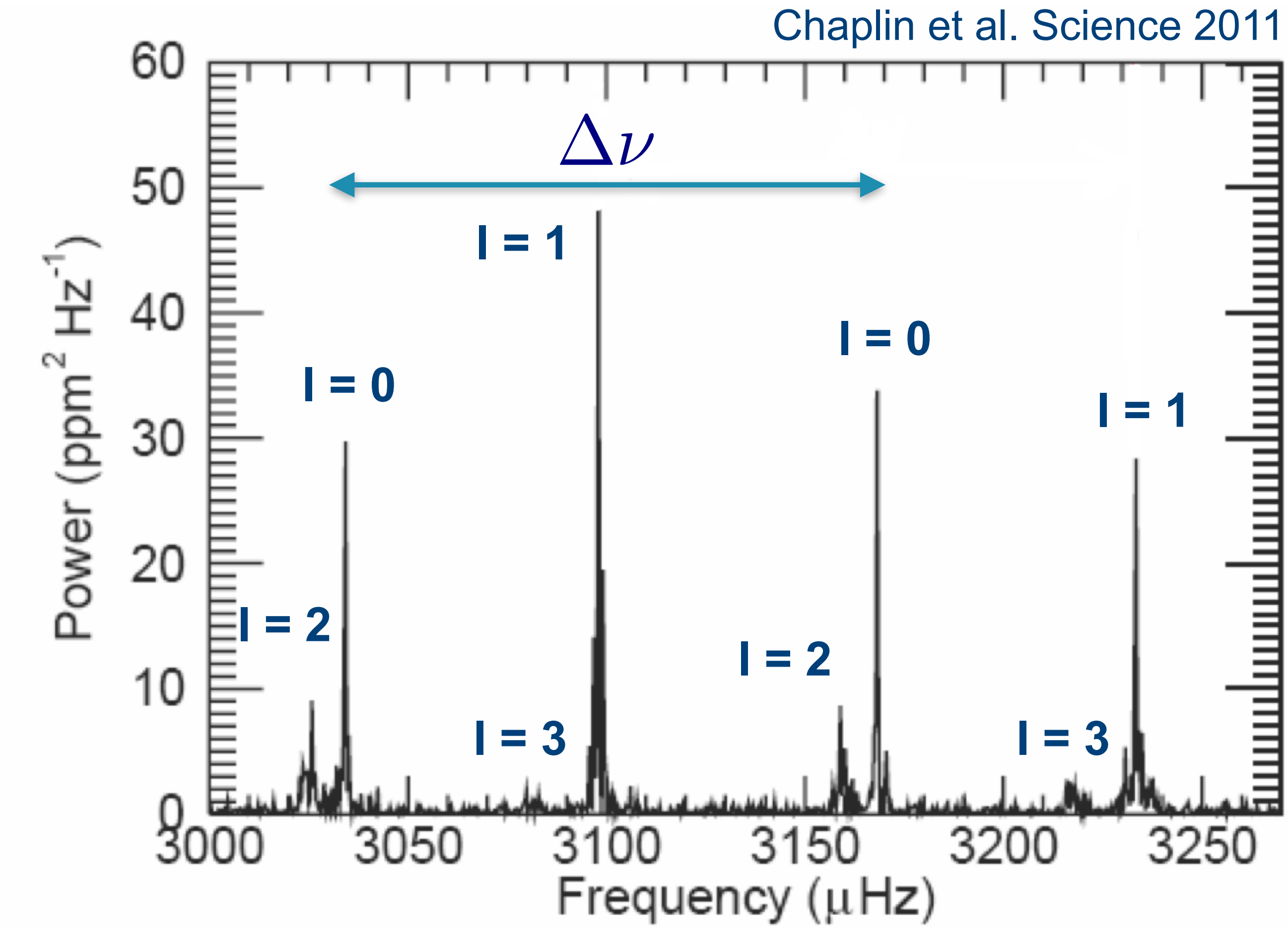


Solar-like Oscillations

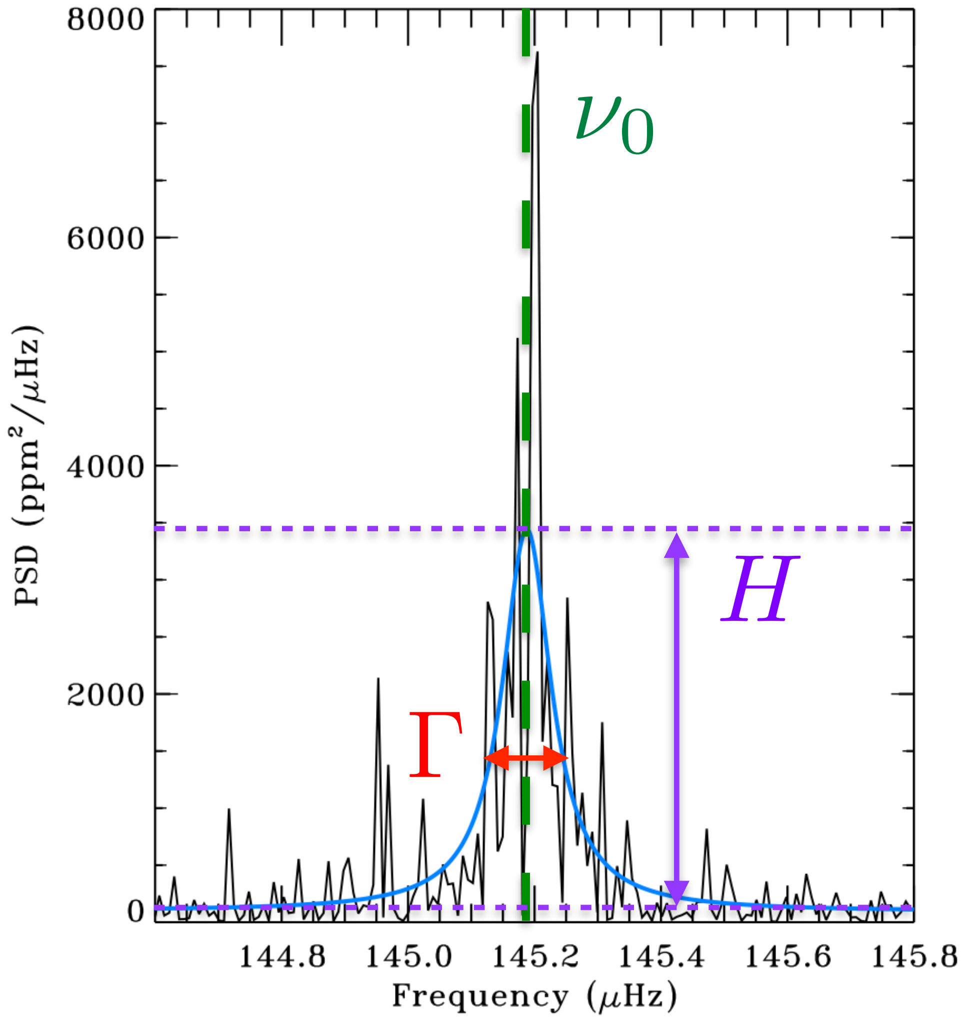
$$\Delta\nu = f\left(\bar{\rho}\right)$$

$\text{Age}, A_{\max}$

$\nu_{\max}, \Delta\nu$



Solar-like Oscillations



Damped oscillation

Lorentzian profile

$$T_{\mathrm{obs}} \gg \tau$$

$$\Gamma \propto \tau^{-1}$$

$$A^2 = \pi H \Gamma$$

$$\boxed{\nu_0, \Gamma, A}$$

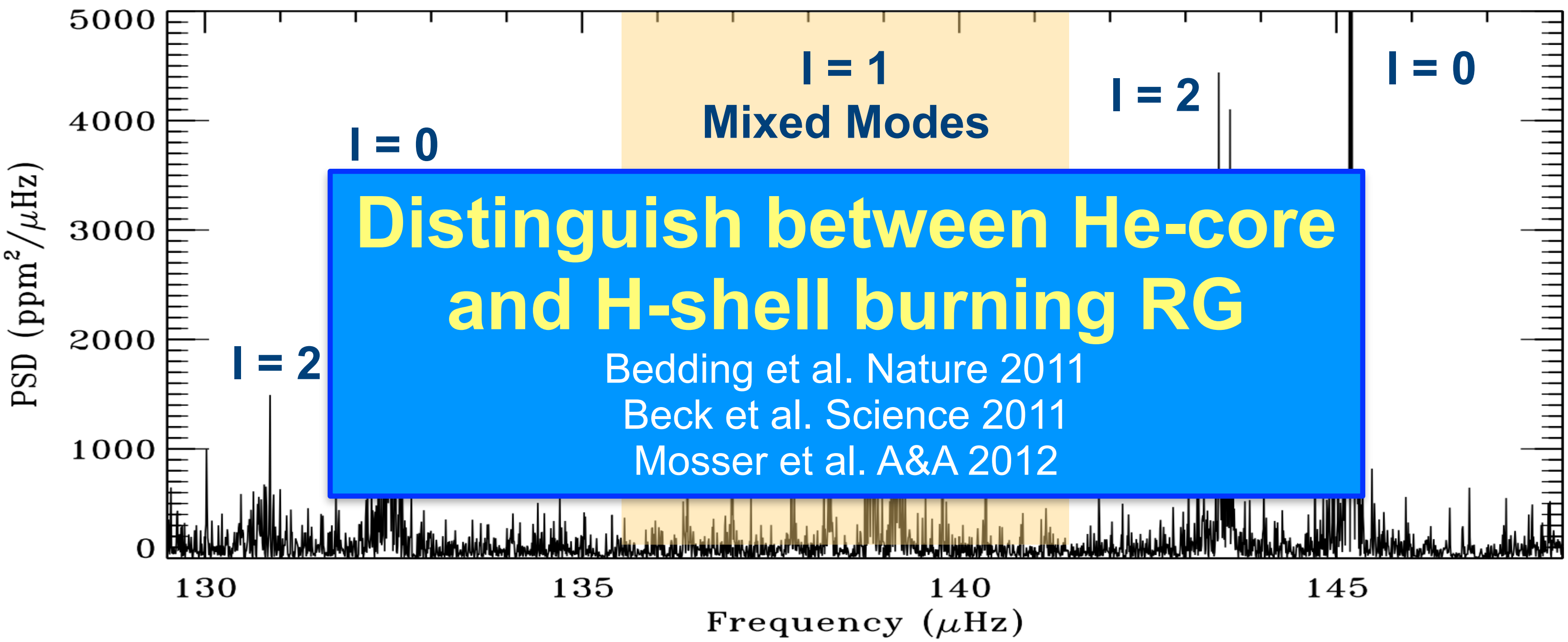
Oscillations in Red Giants

Star evolves from MS to RGB phase

p mode frequency

g mode frequency

Coupling



Distinguish between He-core and H-shell burning RG

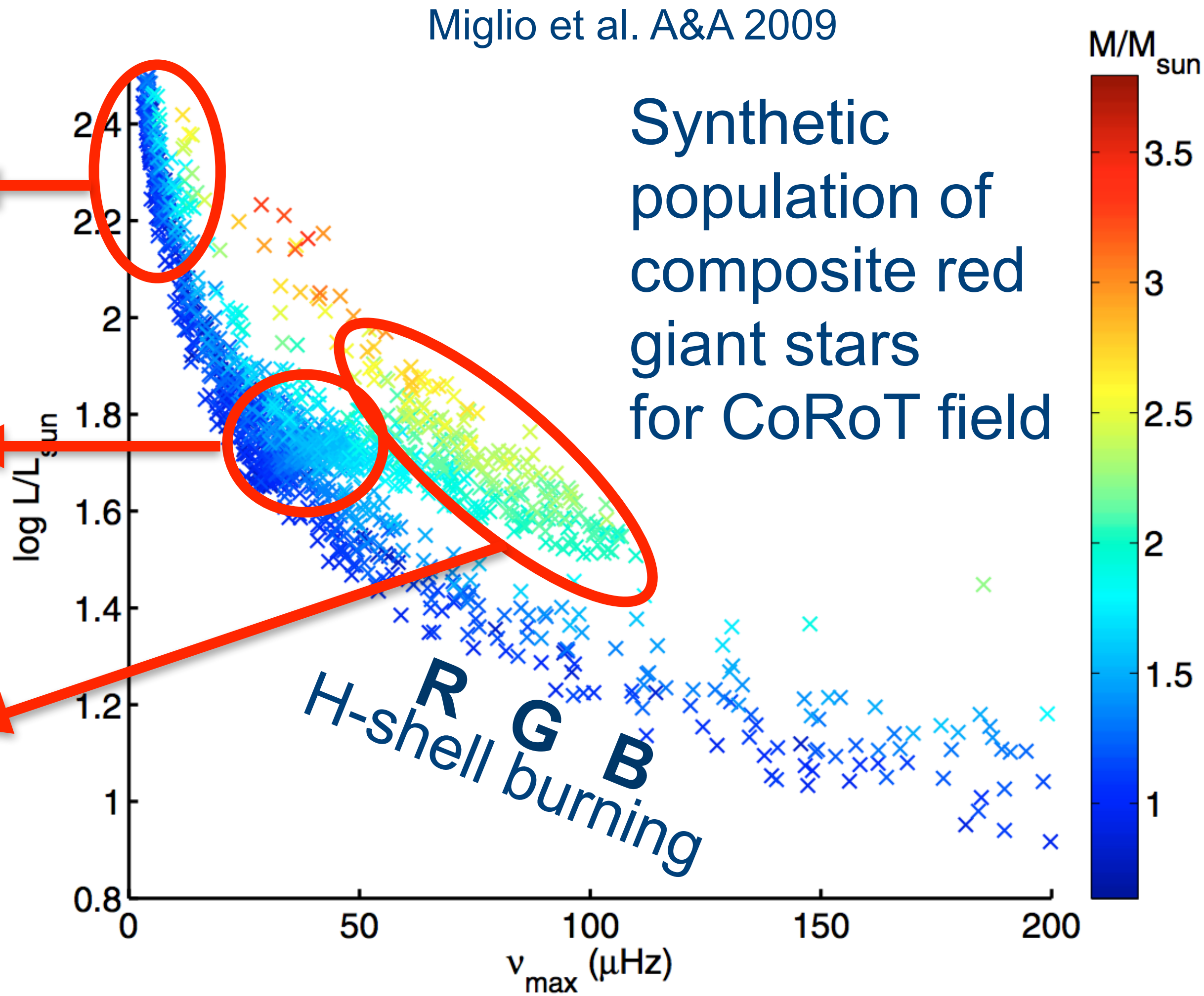
Bedding et al. Nature 2011
Beck et al. Science 2011
Mosser et al. A&A 2012

Low-mass Low-luminosity Red Giants

High-luminosity RGB

He-burning (Red Clump)

He-burning (2^{nd} Red Clump)

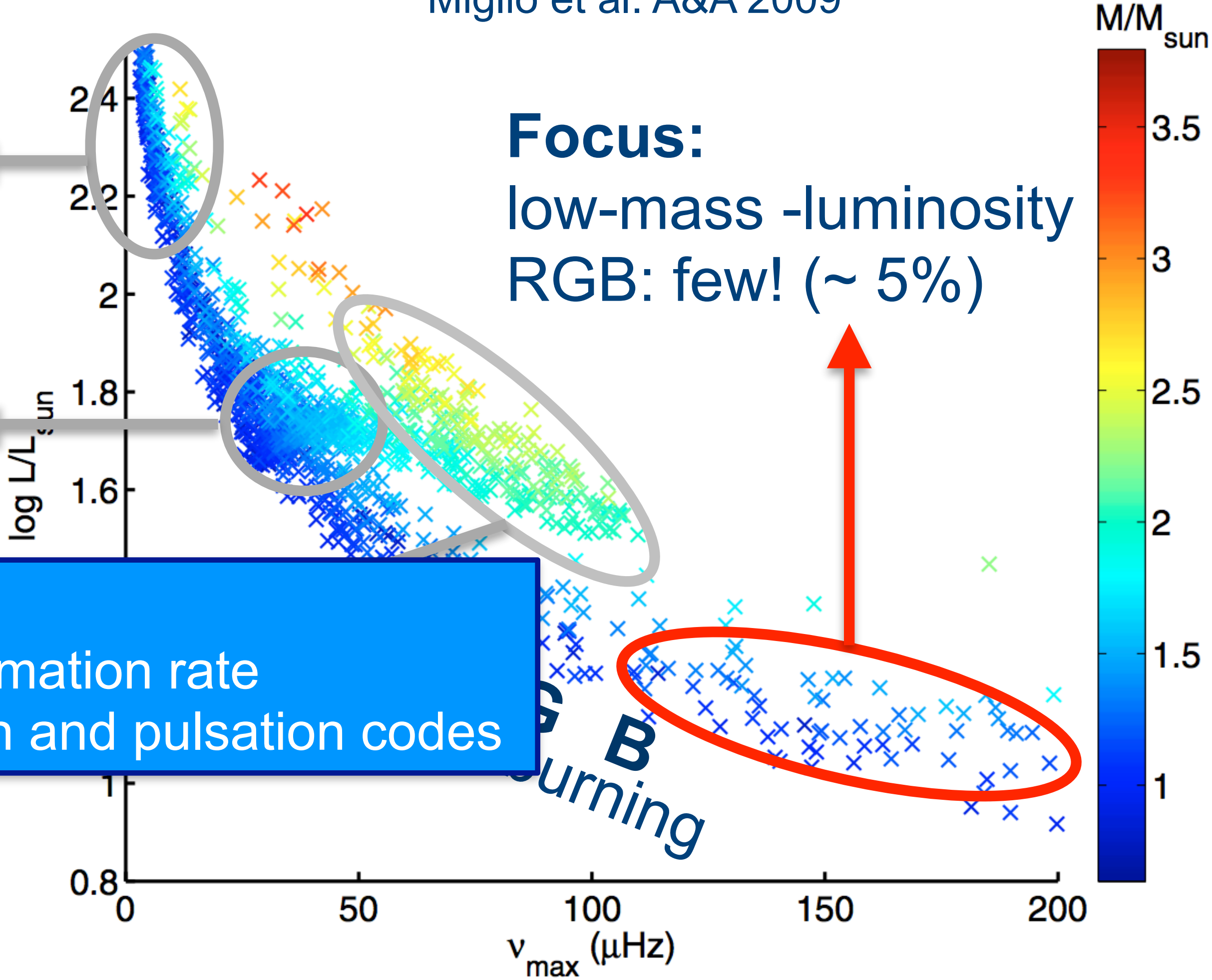


Low-mass Low-luminosity Red Giants

Miglio et al. A&A 2009

Tip of the RGB
$\nu_{\max} \gtrsim 110\,\mu\mathrm{Hz}$

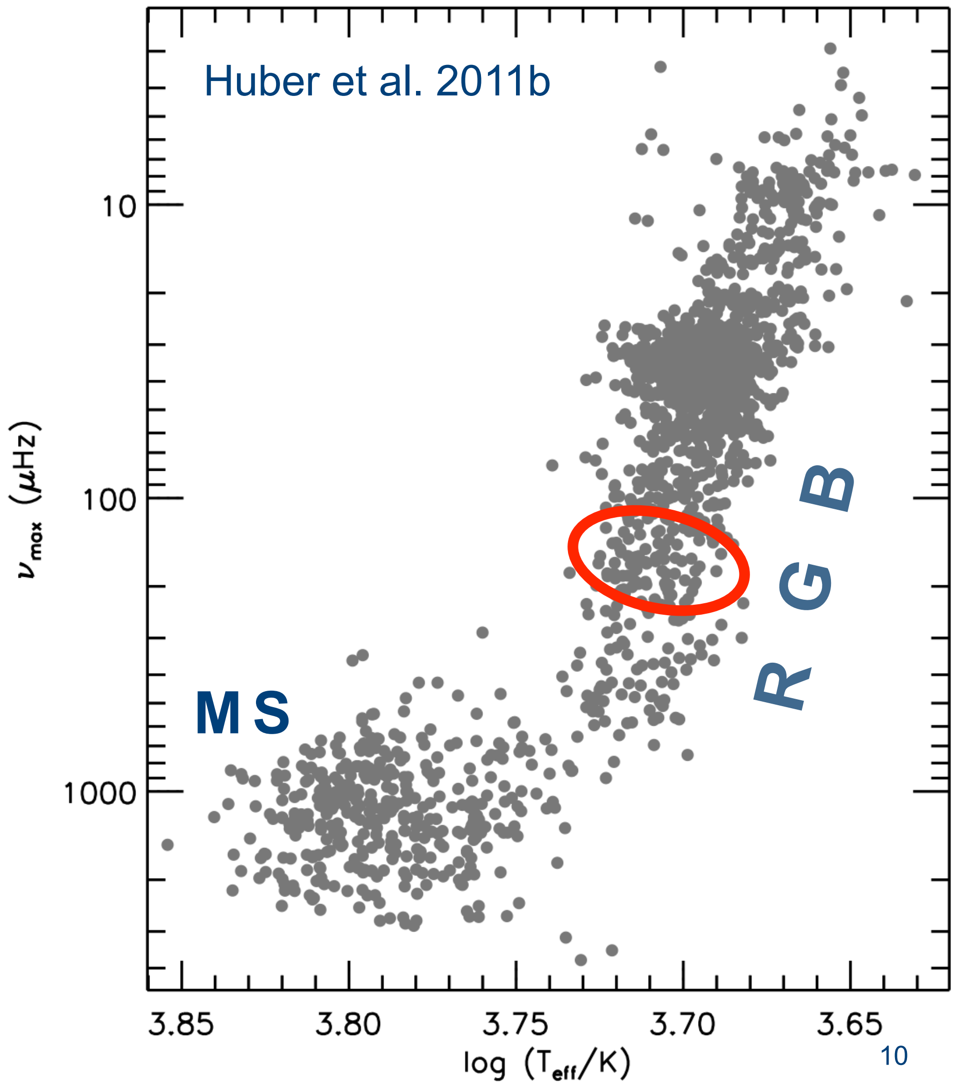
He-burning
(Red Clump)



Focus:
low-mass -luminosity
RGB: few! (~ 5%)

Important to:
- constrain stellar formation rate
- test stellar evolution and pulsation codes

Sample selection



Global properties for 1600 stars observed by *Kepler*

$$\nu_{\rm max}, \Delta\nu, A_{\rm max}$$

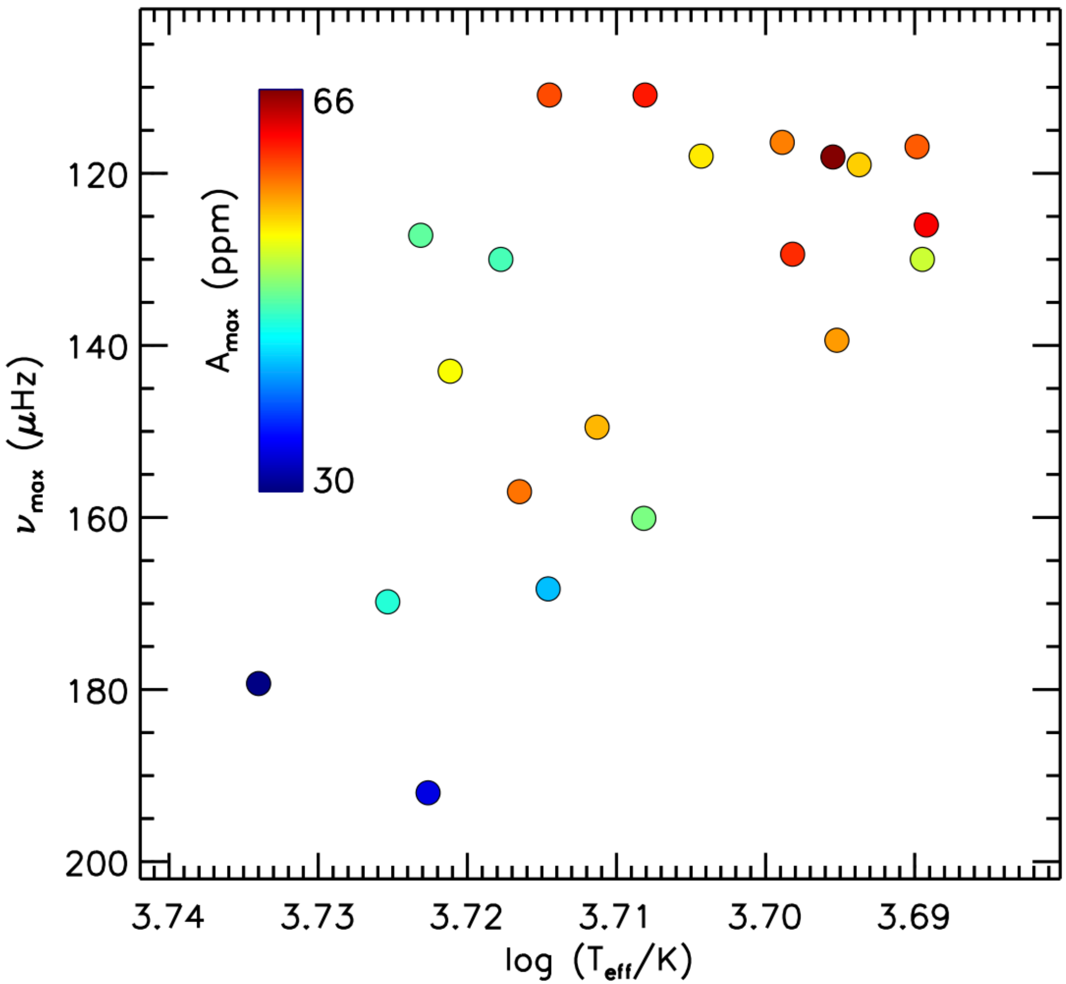
Global study of mixed modes available: confirmed **RGB stars**

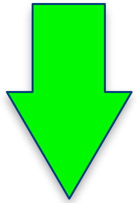
Mosser et al. A&A 2012

$$\nu_{\rm max} \in [110, 200]\ \mu\text{Hz}$$

highest SNR

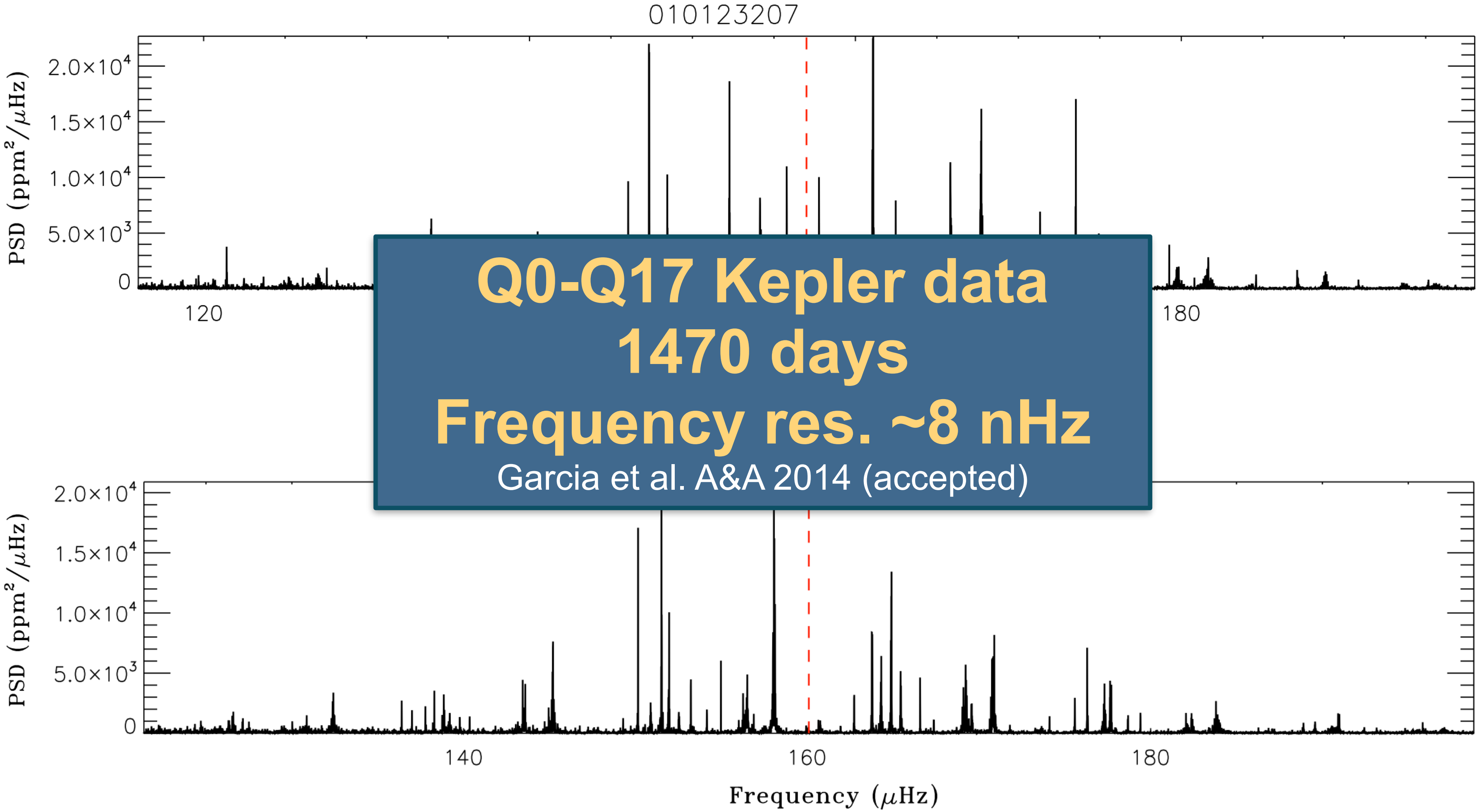
Sample selection





21 low-mass low-luminosity RGB stars

Example of PSD



Q0-Q17 Kepler data
1470 days
Frequency res. ~8 nHz
Garcia et al. A&A 2014 (accepted)

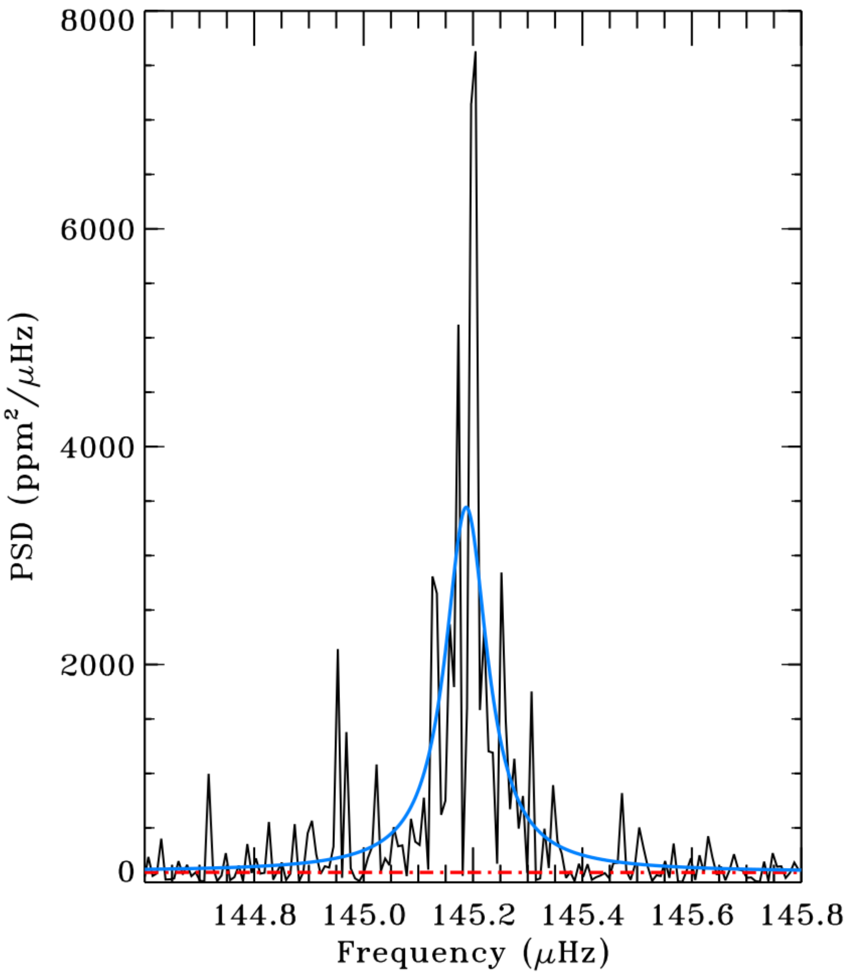
Peak Bagging Analysis

1. Estimation of background signal in the PSD

2. Physical characterization of each oscillation mode

$$\nu_0, \Gamma, A$$

3. Mode identification ***(n,l,m)***



Peak Bagging Analysis

- **AIM:**
  Efficient Peak Bagging analysis of the 21 RGB and detailed study of their asteroseismic properties

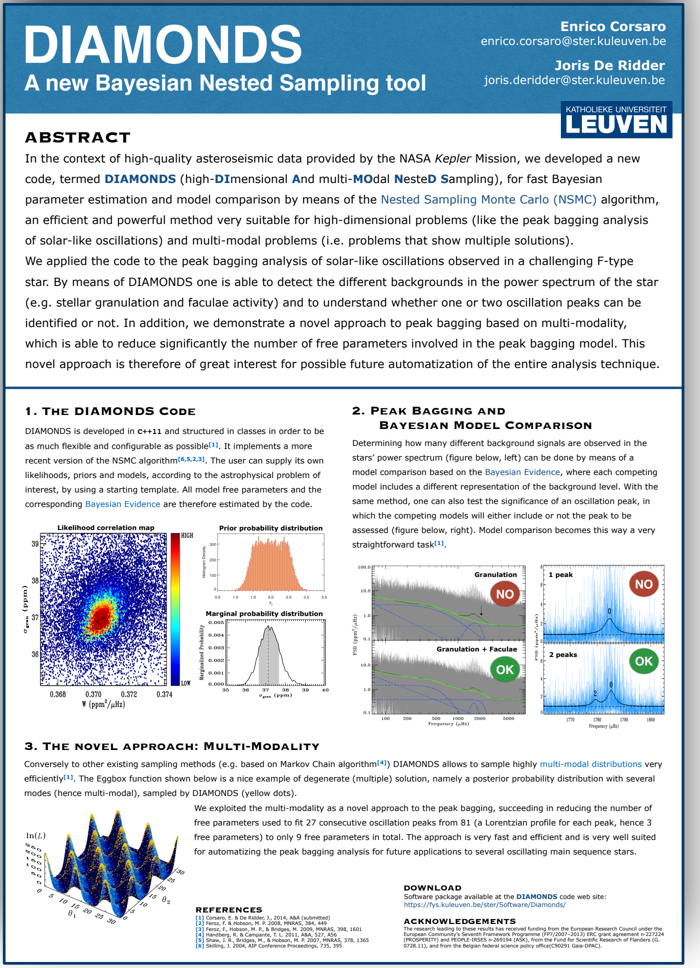
  Corsaro E., De Ridder J., Garcia R. A. (in prep.)

- **CHALLENGE:**

1. Several oscillation modes per star (40-90)
   Dimensions for the fit very high (> 100) and very slow computation
   How to make multi-parameter fits efficient?
   Relevant especially for fitting several stars!
2. **Frequency peak is real or noise? How to understand?**
   Many times ambiguous detections!

Peak Bagging Analysis

- **SOLUTION:**
  Bayesian Nested Sampling (NS)
  Very suited for high-dimensional

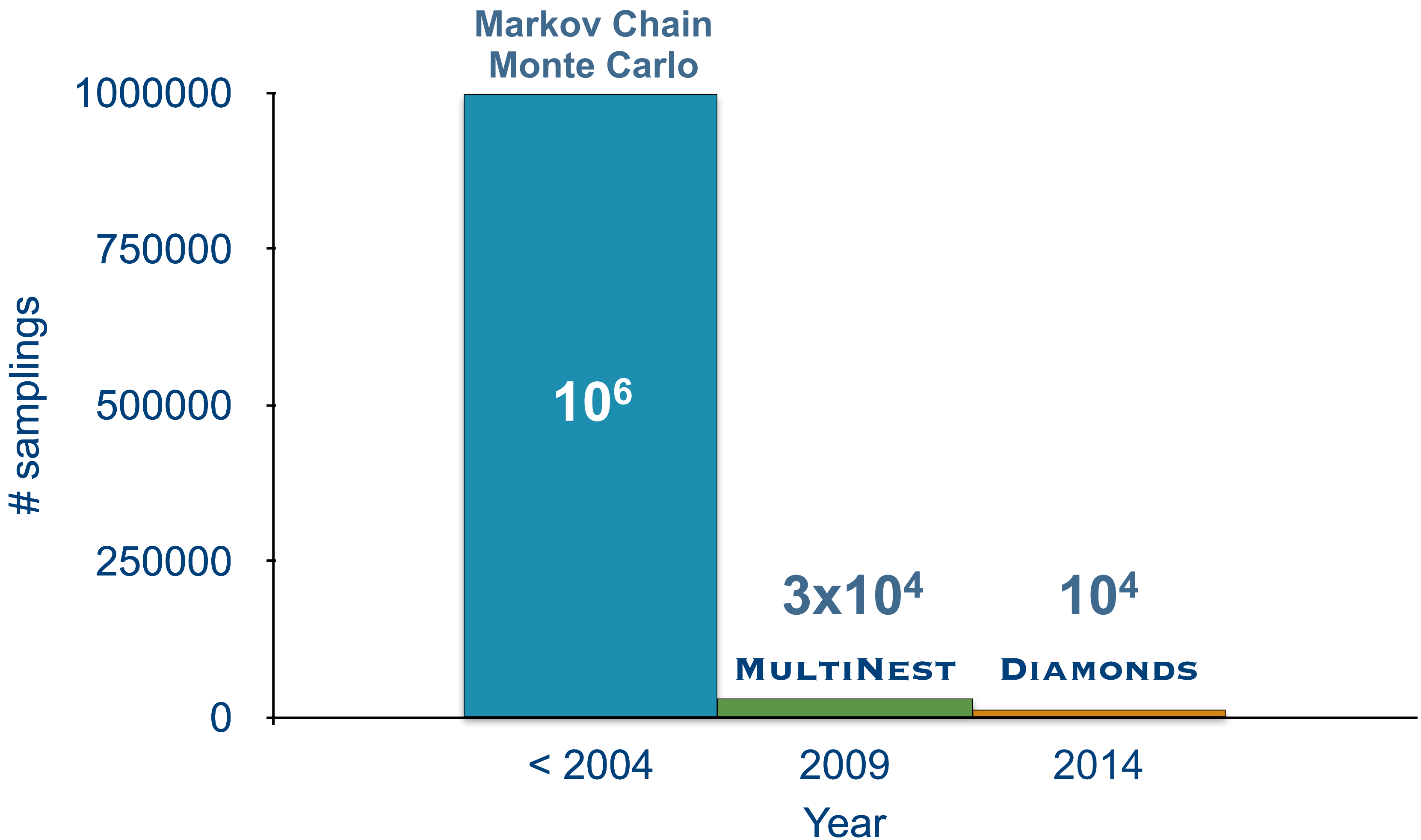


- Existing codes implementing NS

See poster #41 for more details and download link.

2. **DIAMONDS** (C++11)
   Corsaro E. & De Ridder J., A&A (submitted)

Sampling numerical methods



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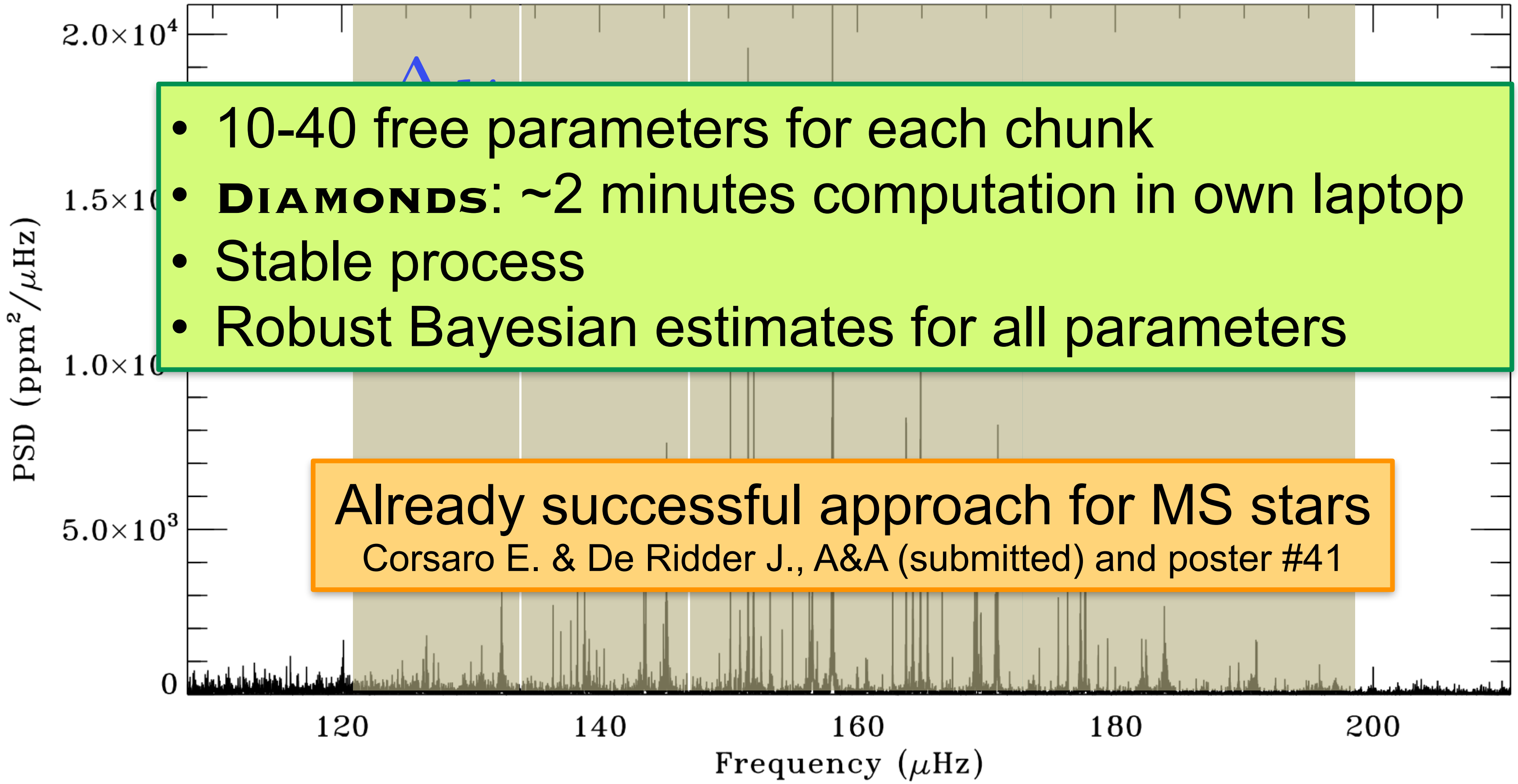
Efficiency of the computation
Chunks of PSD



- 10-40 free parameters for each chunk
- **DIAMONDS**: ~2 minutes computation in own laptop
- Stable process
- Robust Bayesian estimates for all parameters

Already successful approach for MS stars
Corsaro E. & De Ridder J., A&A (submitted) and poster #41

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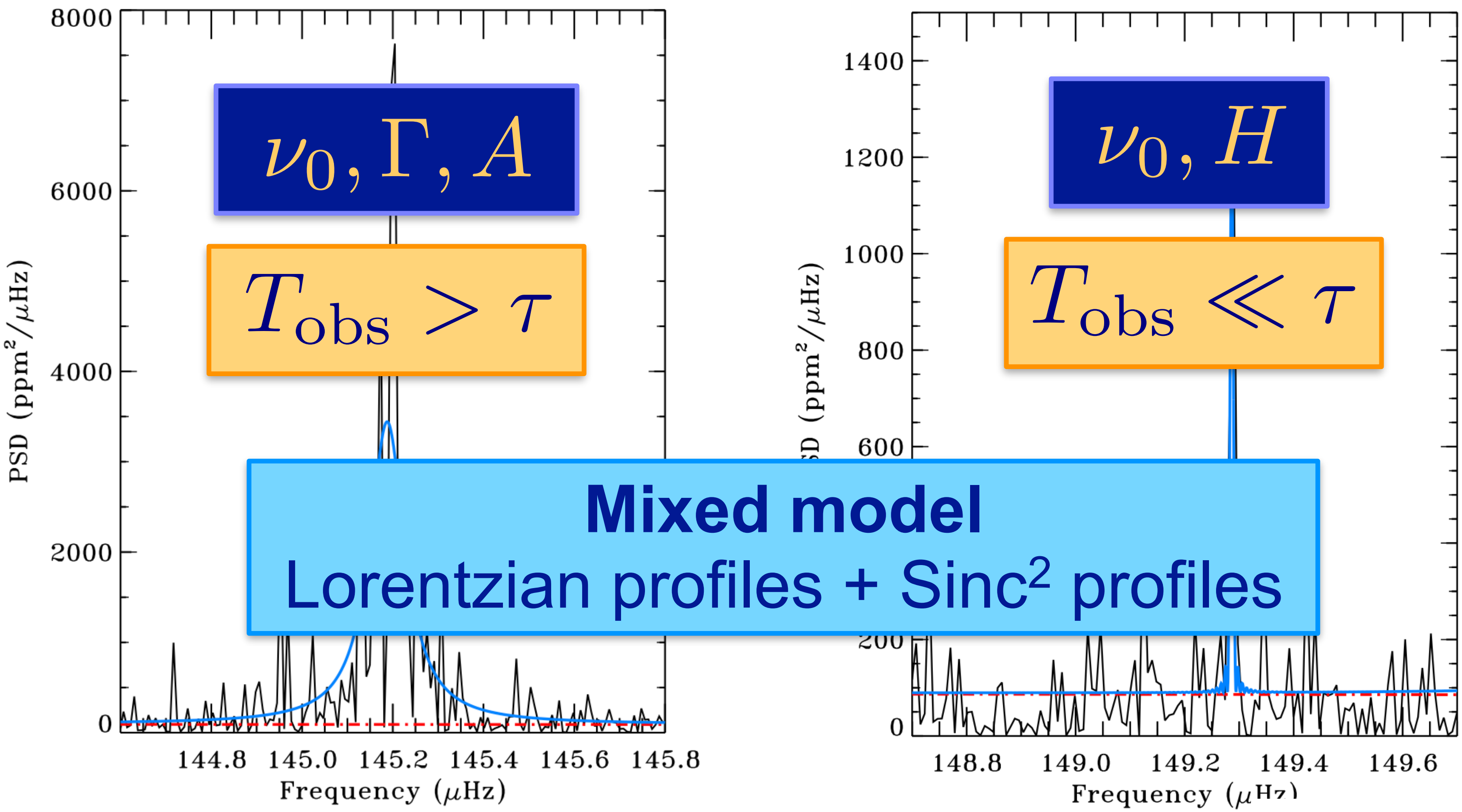
Efficiency of the computation
Peak Bagging Model



ν_0, Γ, A

$T_{\mathrm{obs}} > \tau$

ν_0, H

$T_{\mathrm{obs}} \ll \tau$

Mixed model

Lorentzian profiles + Sinc^2 profiles

Peak Significance Criterion
Bayesian Model Comparison

Bayesian Statistics offers valuable solution to model comparison problem: **Bayesian Evidence** $\mathcal{E}$

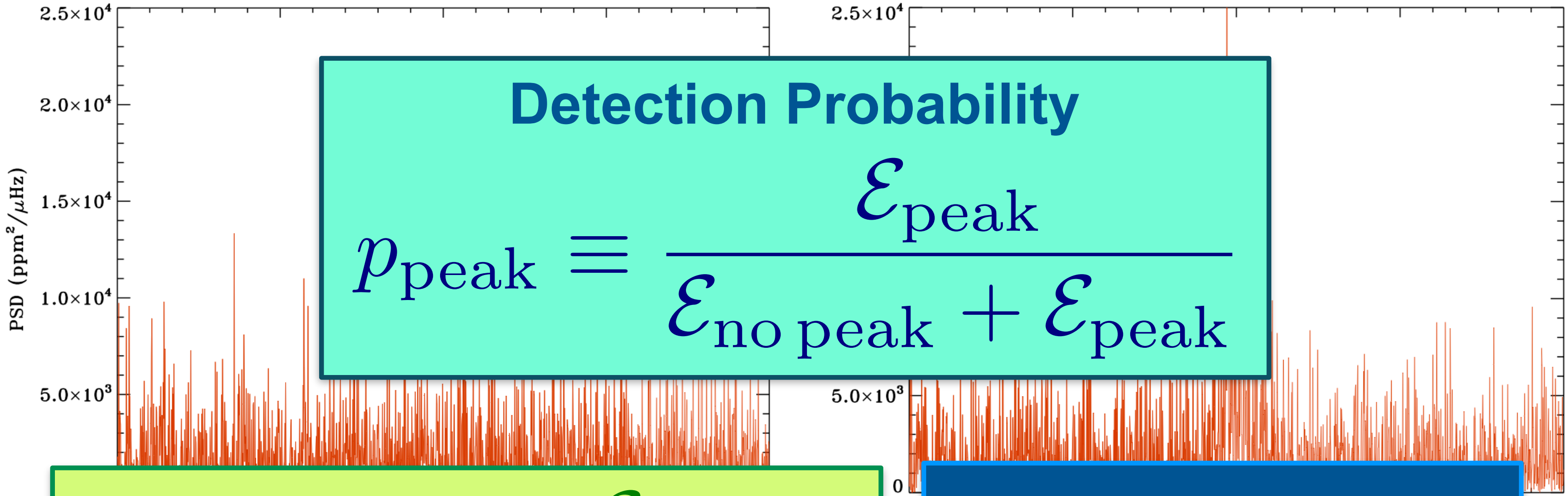
$\mathcal{E}$ ↑ Fit quality ↑ # free parameters ↓

WEIGHT: simple models are preferred

Difficult to obtain with MCMC (very expensive computation). In DIAMONDS (as NS codes) is direct output! → **Model comparison is immediate**

Peak Significance Criterion
Simulation test

900 Simulations **100 Simulations**



Detection Probability

$$p_{\rm peak} \equiv \frac{\mathcal{E}_{\rm peak}}{\mathcal{E}_{\rm no\,peak} + \mathcal{E}_{\rm peak}}$$

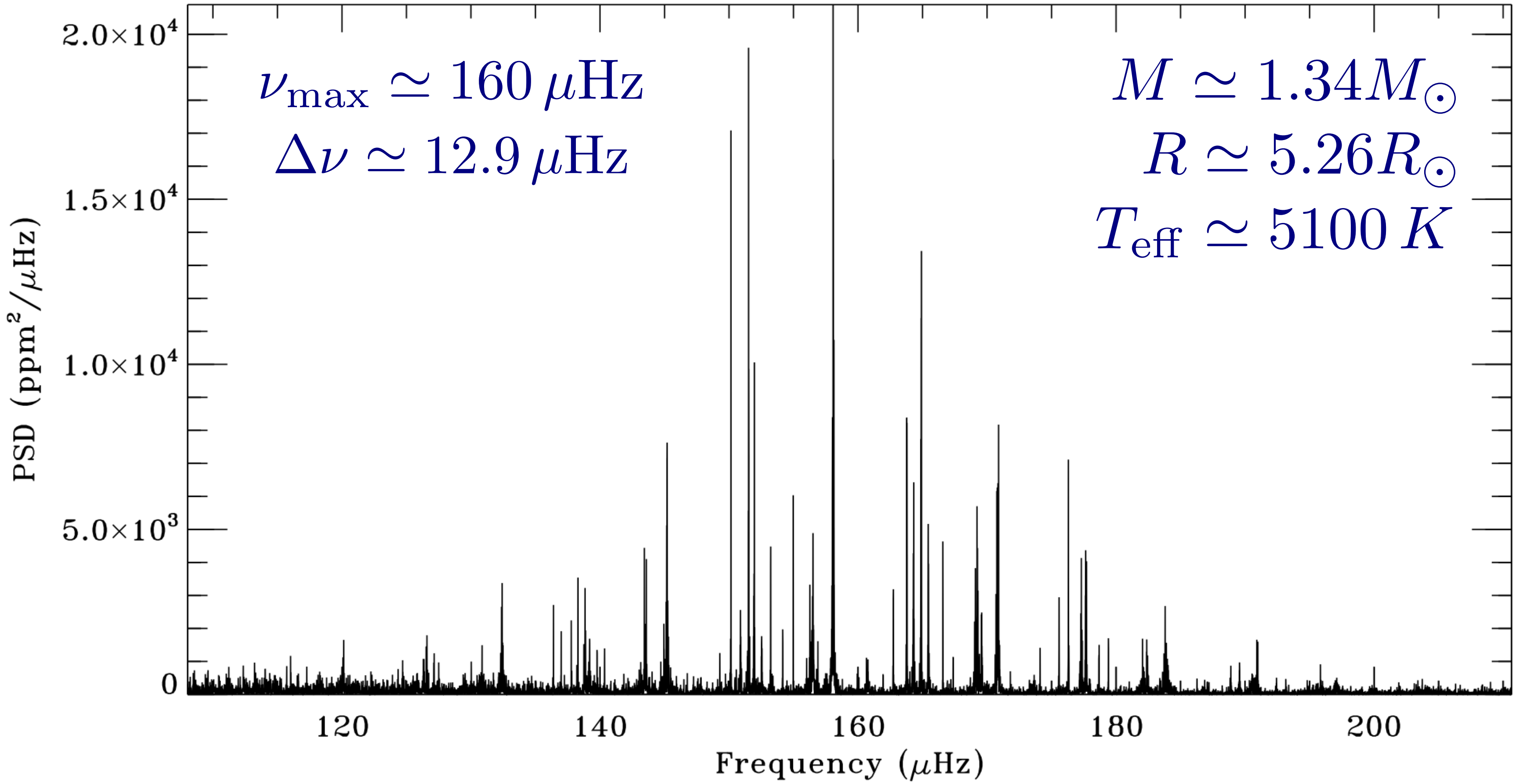
1000 Models → $\mathcal{E}_{\rm no\,peak}$

1000 Models → $\mathcal{E}_{\rm peak}$

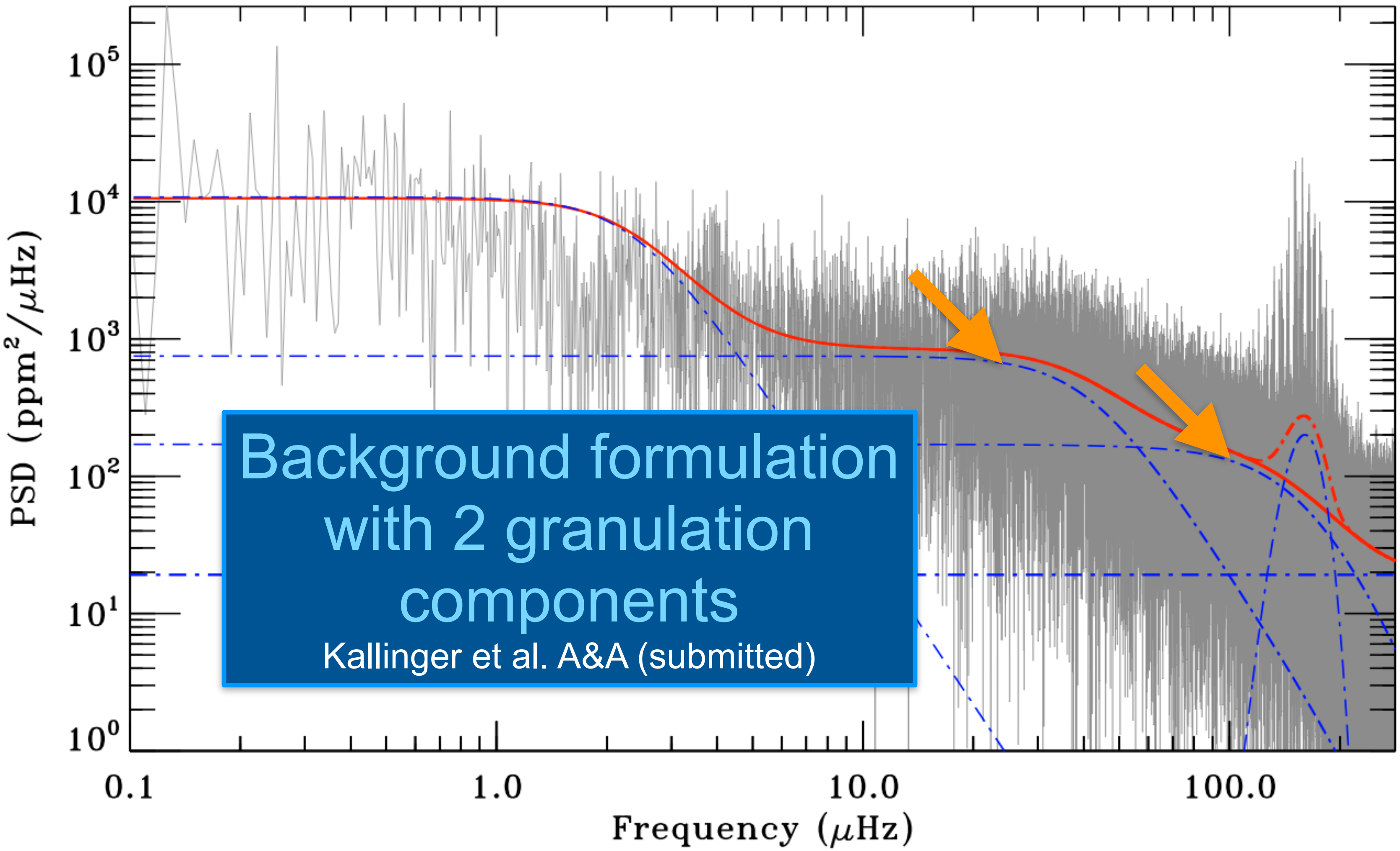
$$p_{\rm peak} \gtrsim 99\,\%$$

All peaks found!

Application
KIC 12008916

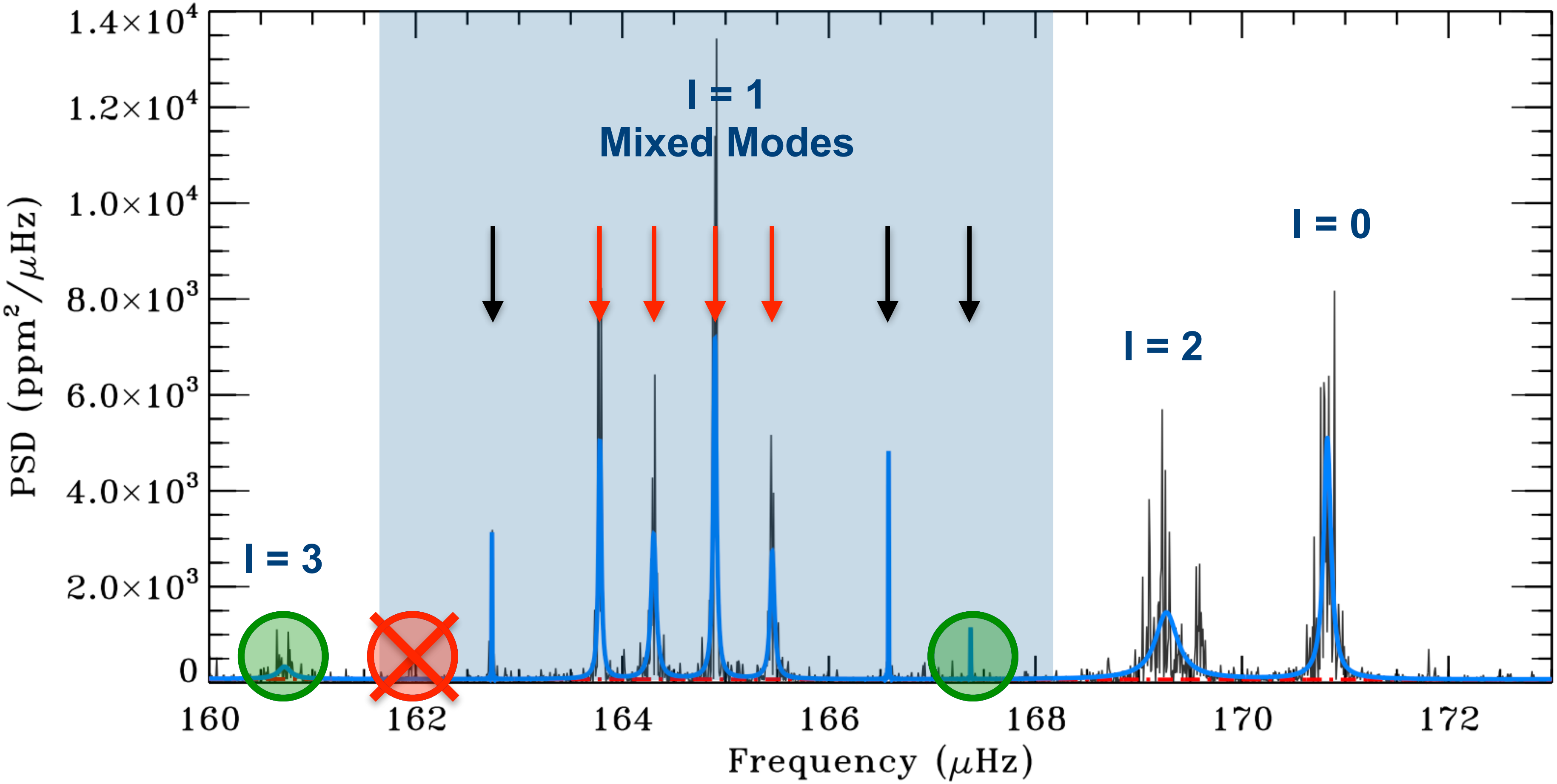


Background

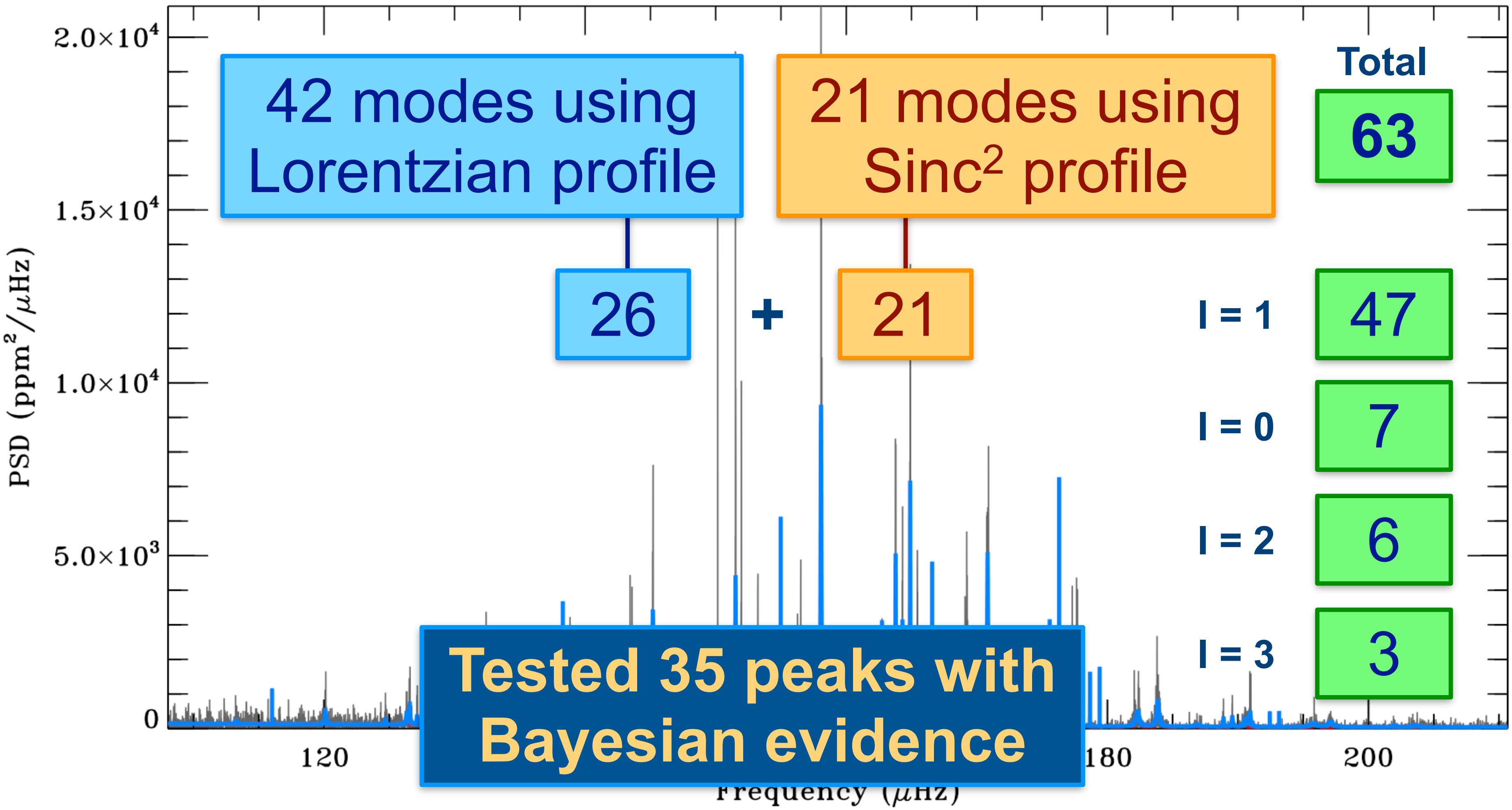


Background formulation with 2 granulation components
Kallinger et al. A&A (submitted)
PSD (ppm²/μHz)
Frequency (μHz)
0.1
1.0
10.0
100.0
10⁰
10¹
10²
10³
10⁴
10⁵

Peak Bagging Results



Peak Bagging Results



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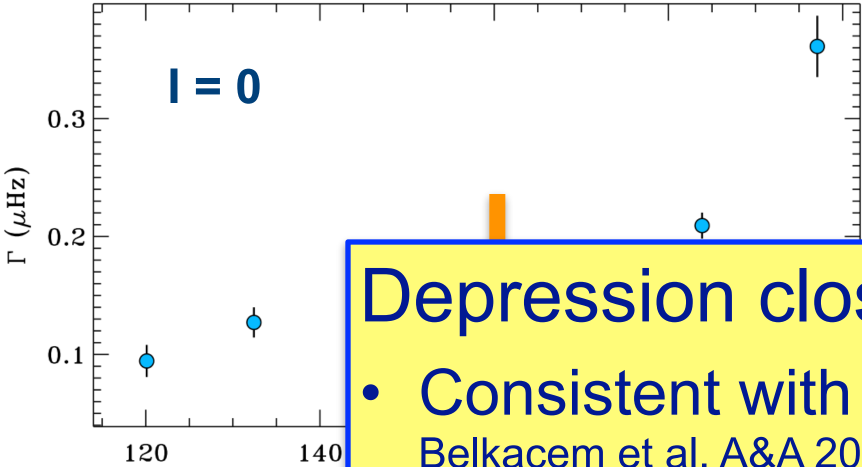
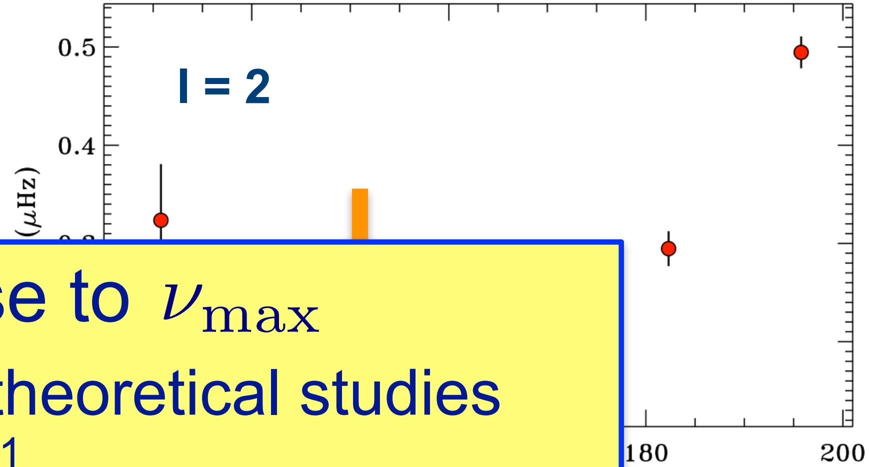
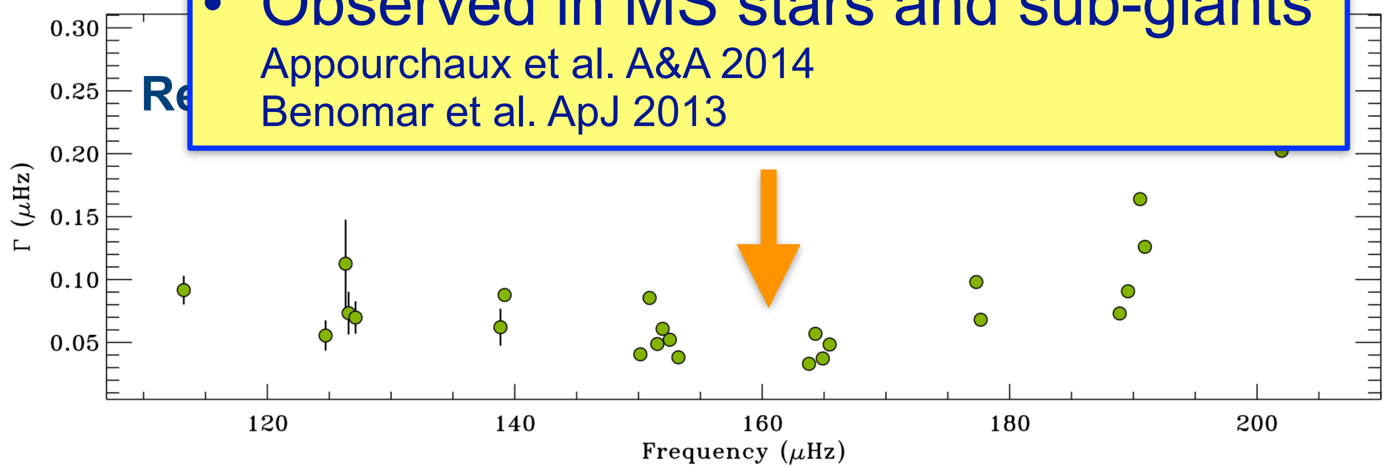
Linewidth depression



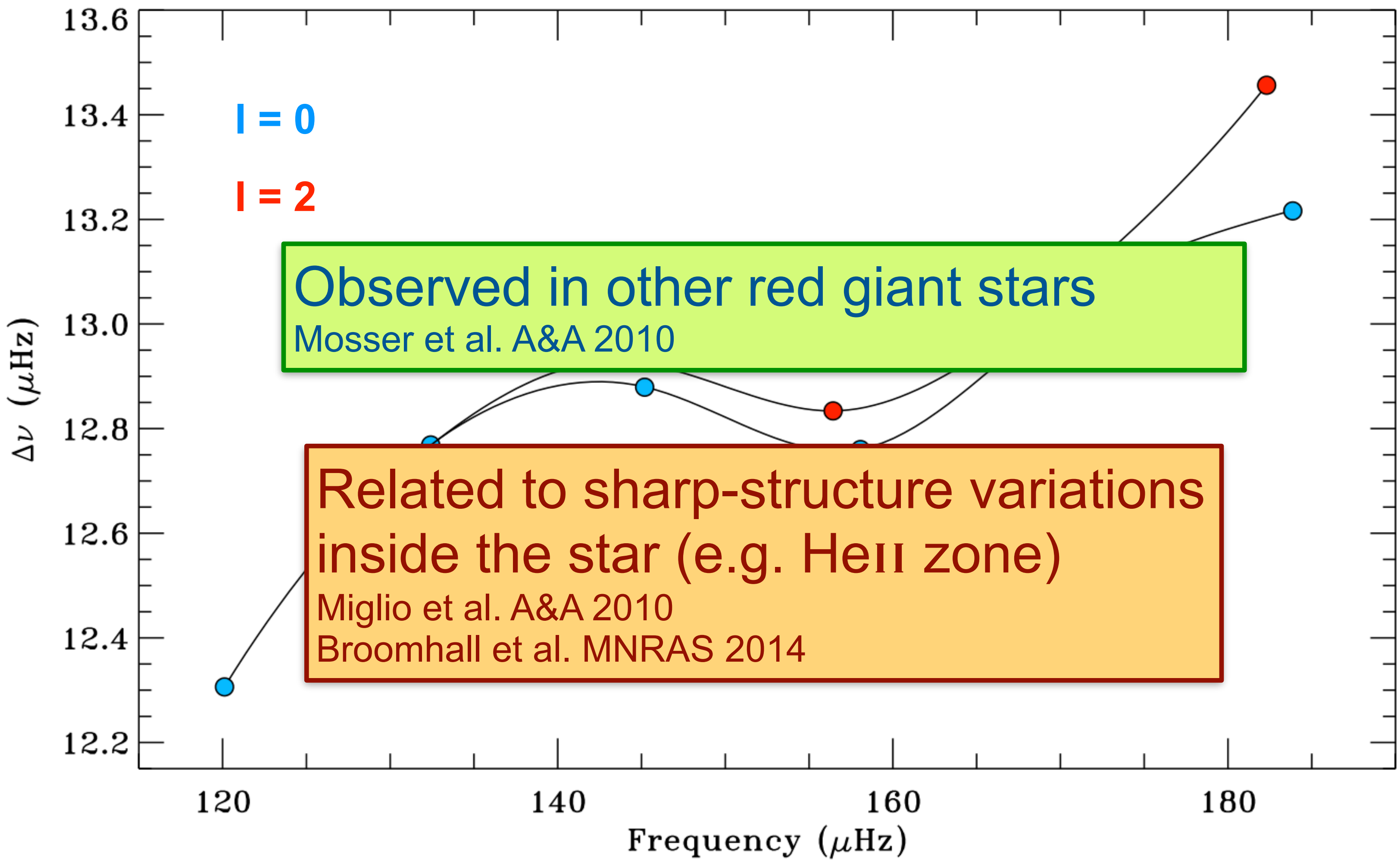




Depression close to ν_{max}

- Consistent with theoretical studies
  Belkacem et al. A&A 2011
- Observed in MS stars and sub-giants
  Appourchaux et al. A&A 2014
  Benomar et al. ApJ 2013

Acoustic glitches



Conclusions

- **Low-luminosity -mass RGB** stars are **few (~5%)**: study is important for testing star formation rates, stellar structure and evolution codes.
- With **T > 4 years** observations, **peak bagging analysis** is **necessary** (global analyses cannot go much further)
- Peak bagging of RGB stars with **Diamonds** very efficient **and** with optimal **peak significance criterion**
- Towards automated (at least partially) peak bagging analysis for several Red Giants (work in progress)
  Already feasible for MS stars (even challenging F-type)! (see poster **#41**)

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