



KU LEUVEN



Peak Bagging of red giant stars observed by Kepler:

First results with a new method based on Bayesian Nested Sampling

Enrico Corsaro

Instituut voor Sterrenkunde

enrico.corsaro@ster.kuleuven.be



Outlook

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

Solar-like Oscillations

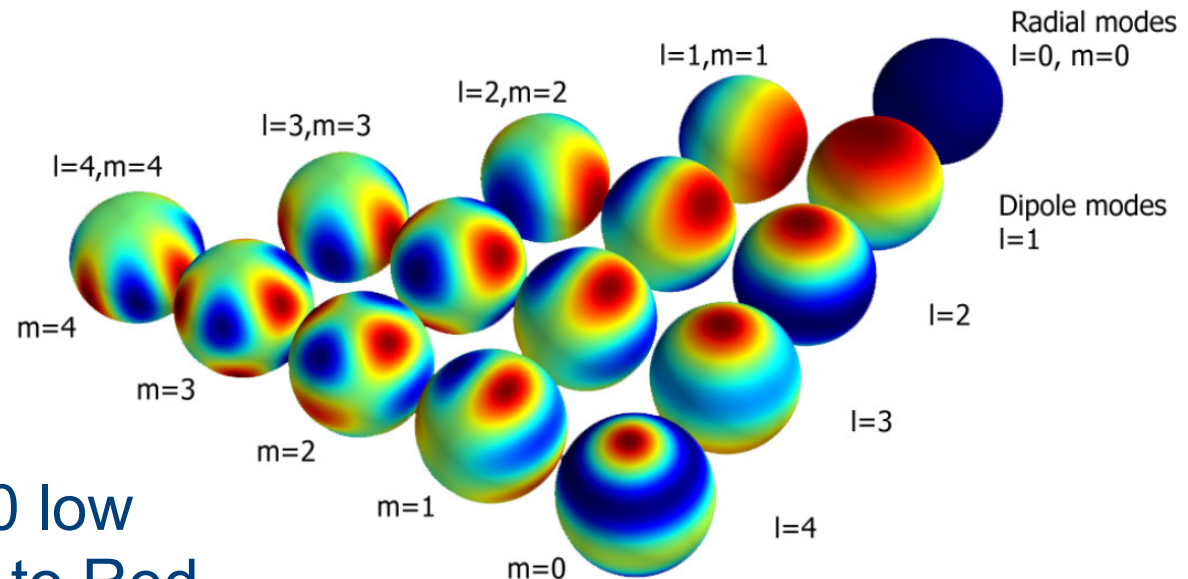
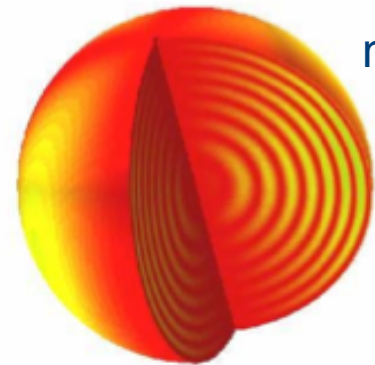
- Introduction
- The sample
- The new method
- First results

Acoustic waves in outer convective envelope (p modes)

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

Tiny brightness variations

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

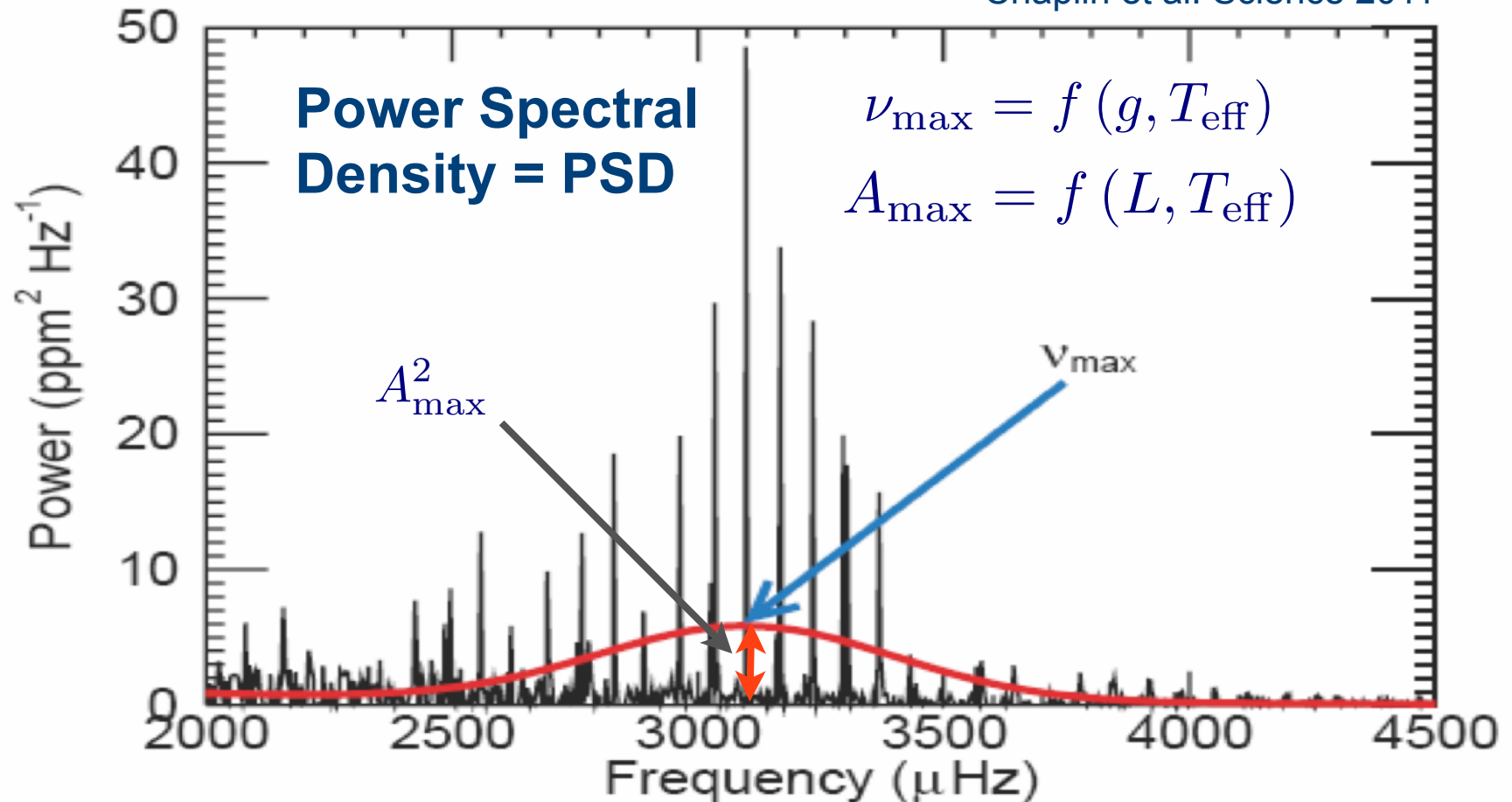


Beck & Kallinger S&W 2013

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

Solar-like Oscillations

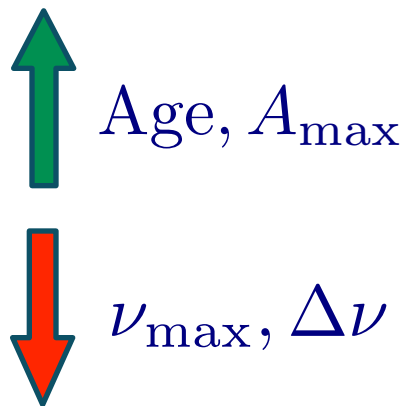
Chaplin et al. Science 2011



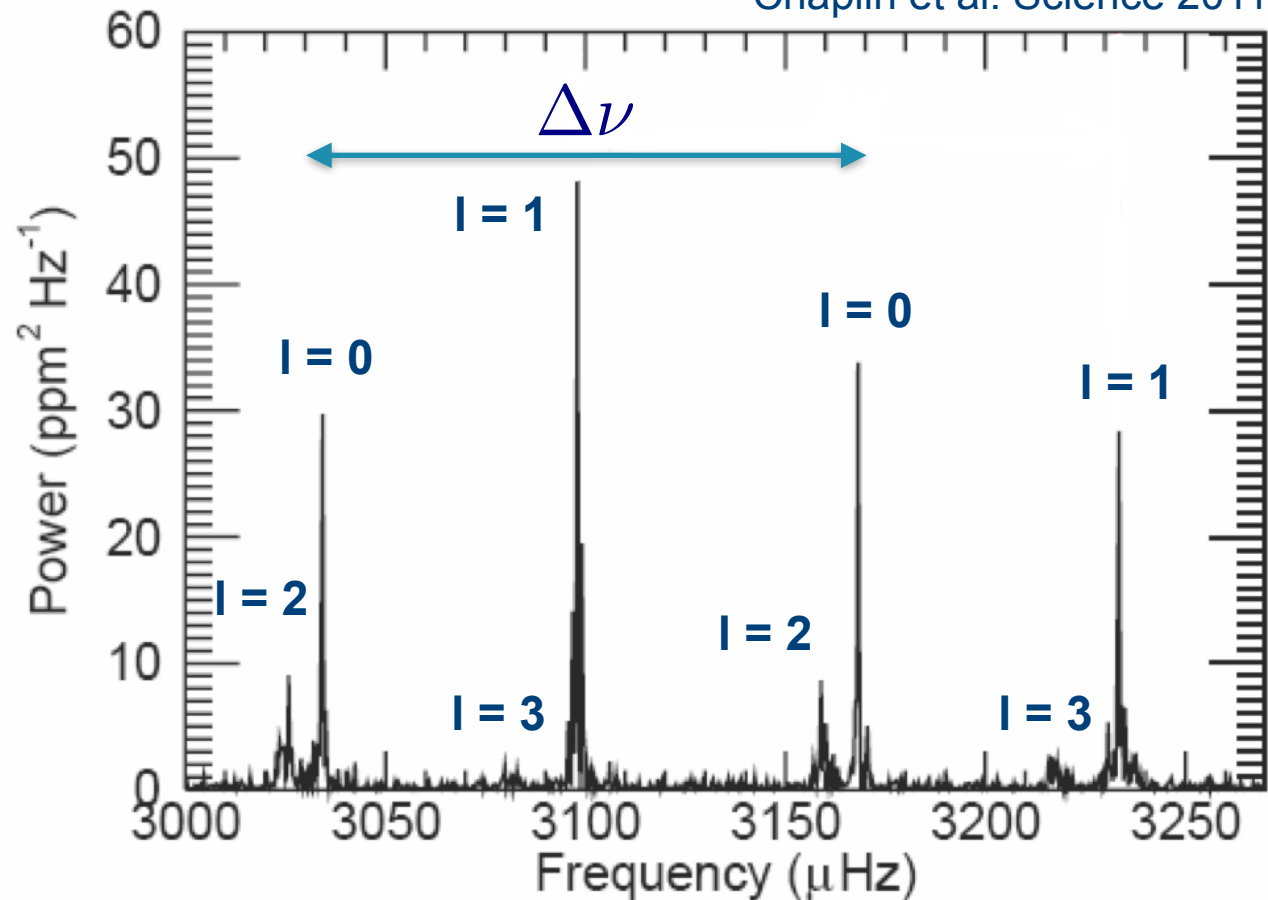
- Introduction
- The sample
- The new method
- First results

Solar-like Oscillations

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

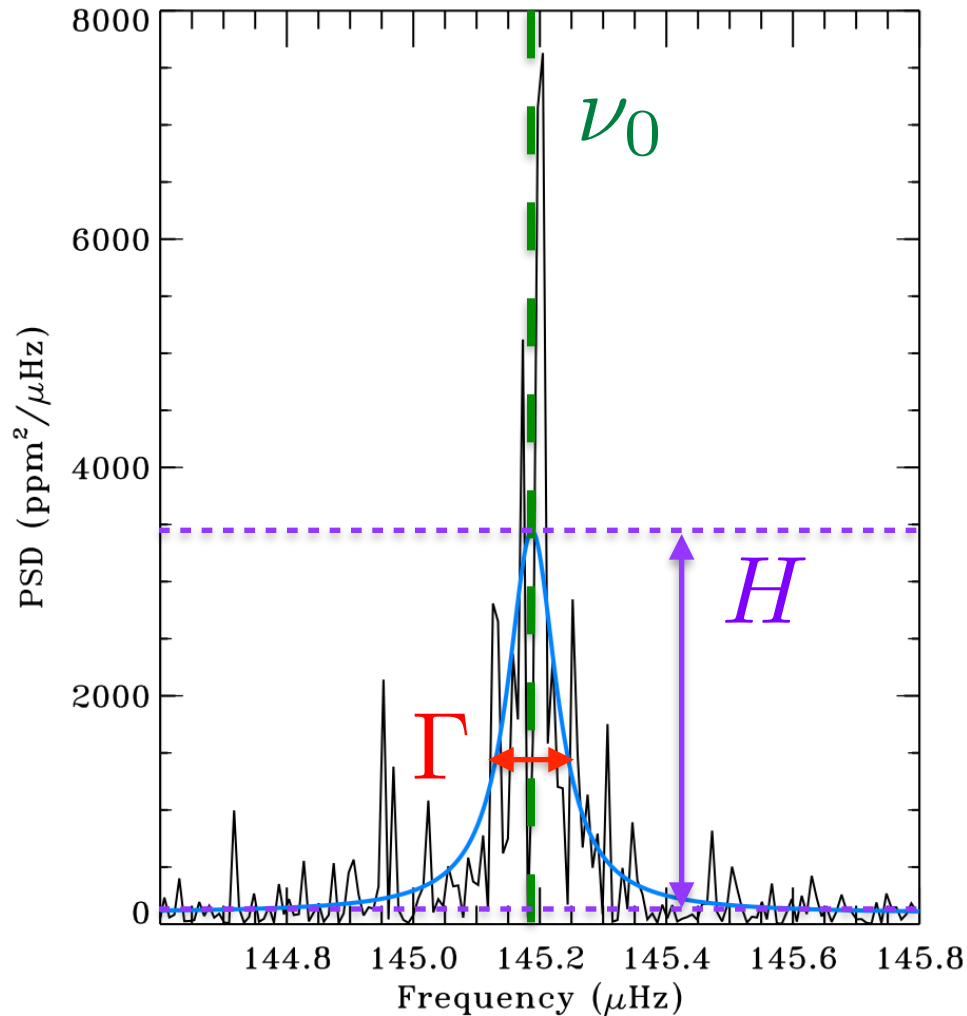


Chaplin et al. Science 2011



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

Solar-like Oscillations



Damped oscillation



Lorentzian profile

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

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

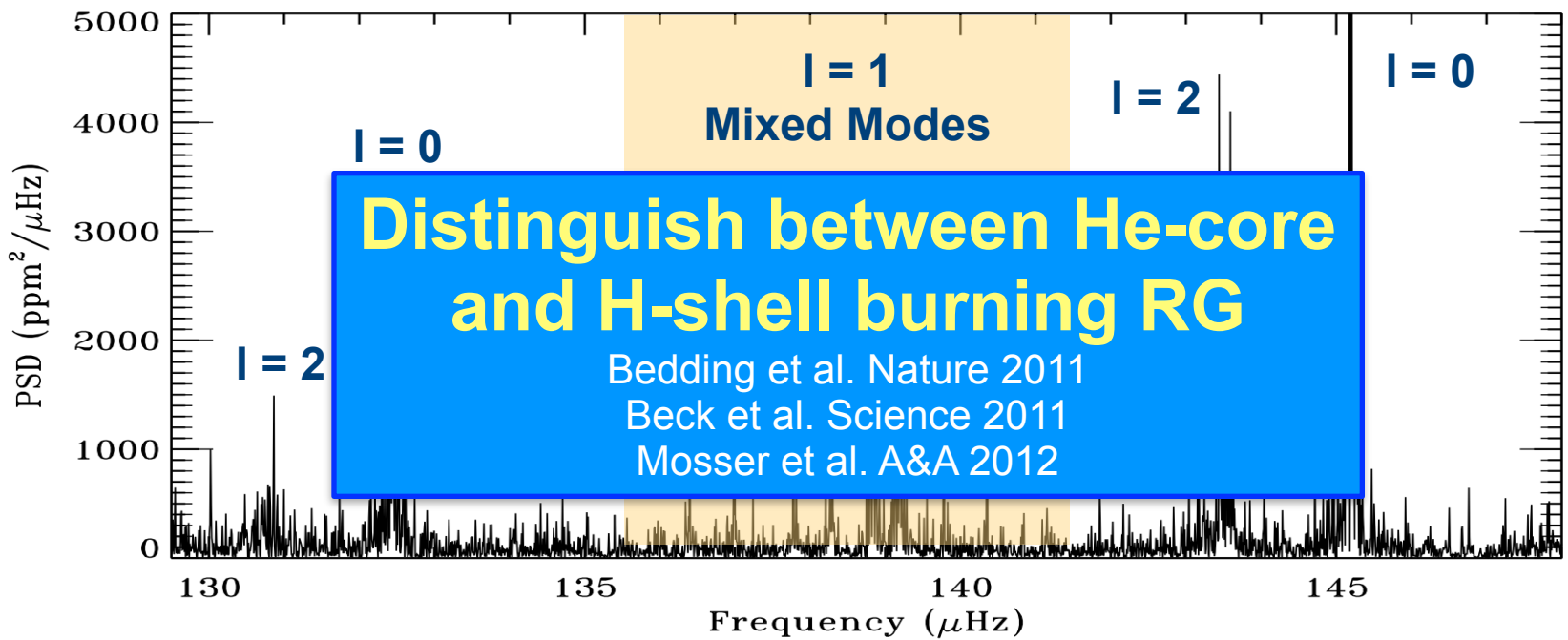
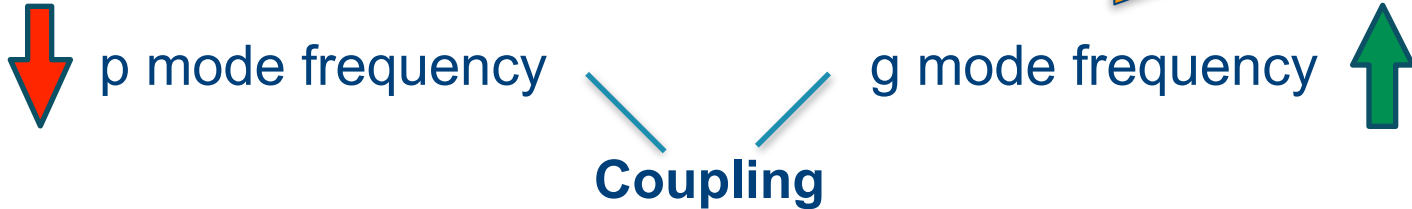
$$A^2 = \pi H \Gamma$$

$$\nu_0, \Gamma, A$$

Oscillations in Red Giants

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

Star evolves from MS to RGB phase



Low-mass Low-luminosity Red Giants

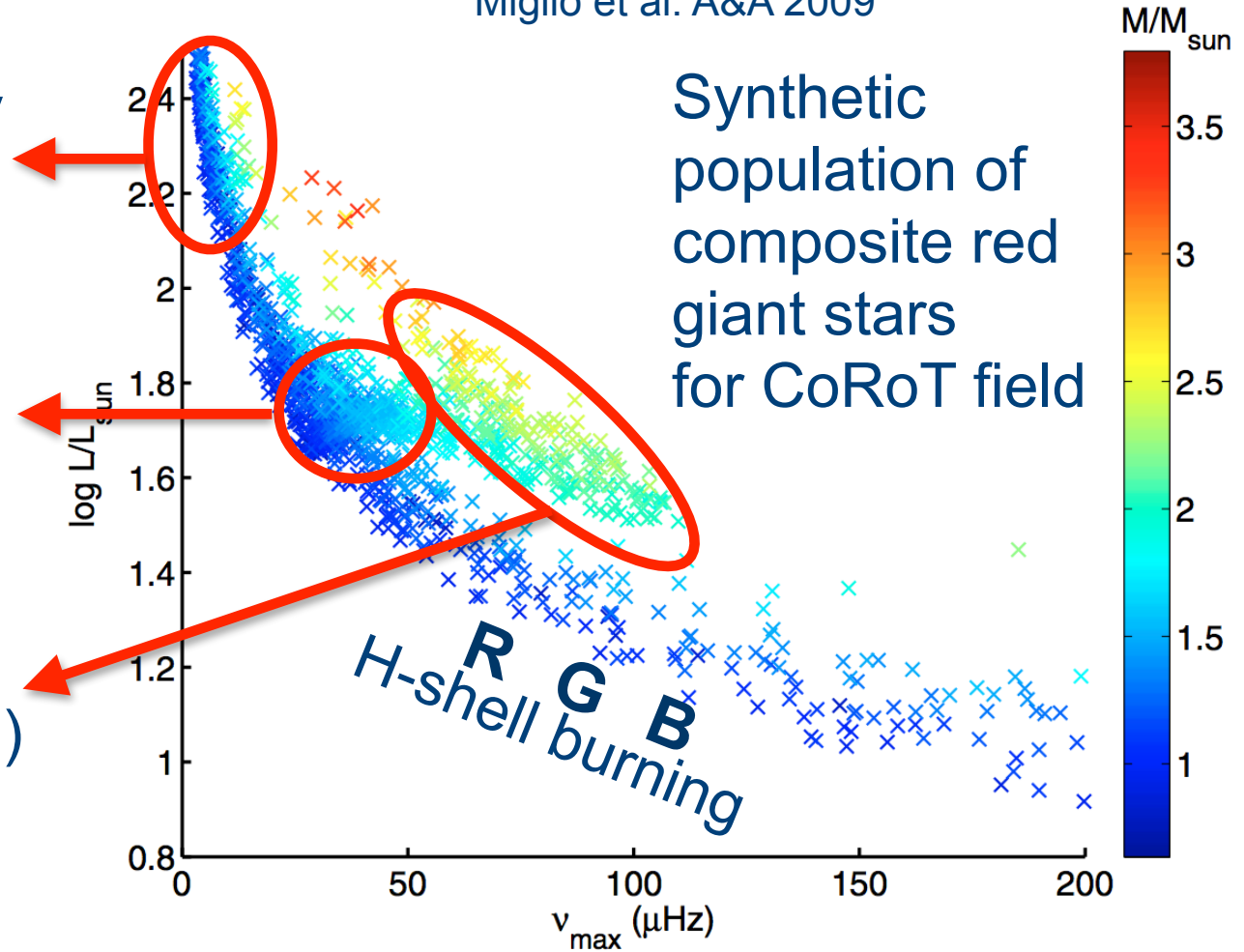
- Introduction
- The sample
- The new method
- First results

Miglio et al. A&A 2009

High-luminosity RGB

He-burning (Red Clump)

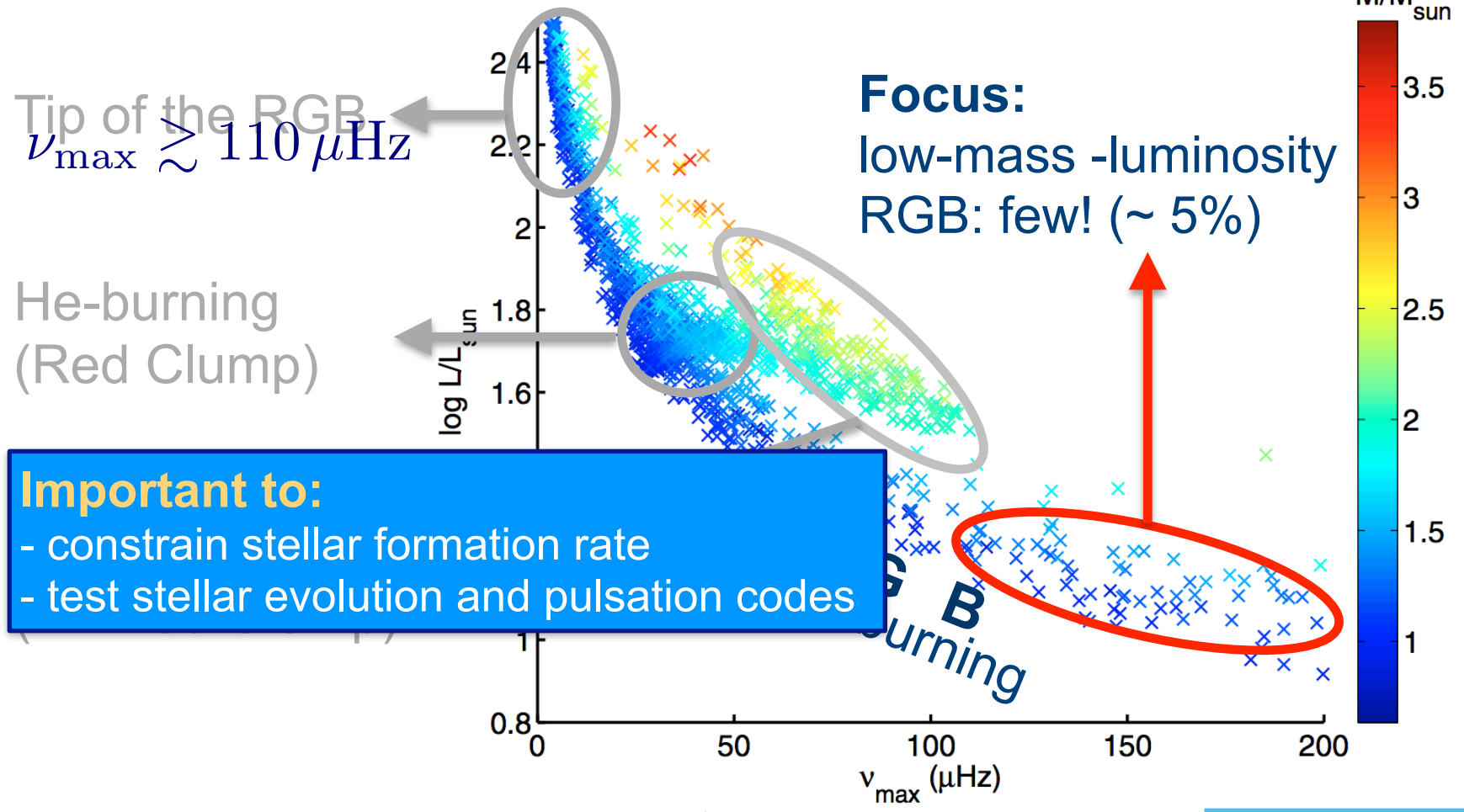
He-burning (2nd Red Clump)



Low-mass Low-luminosity Red Giants

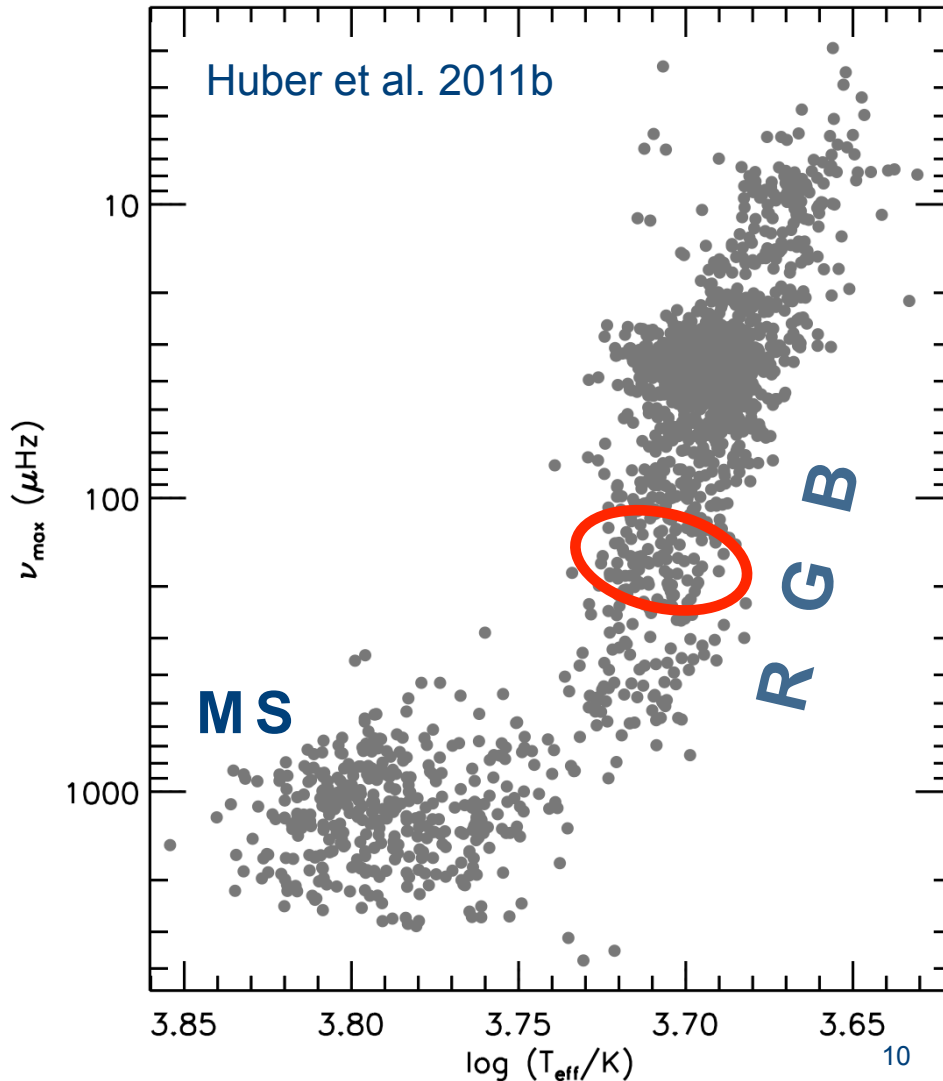
- Introduction
- The sample
- The new method
- First results

Miglio et al. A&A 2009



Sample selection

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



Global properties for
1600 stars observed
by *Kepler*

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

Global study of mixed
modes available:

confirmed **RGB stars**

Mosser et al. A&A 2012

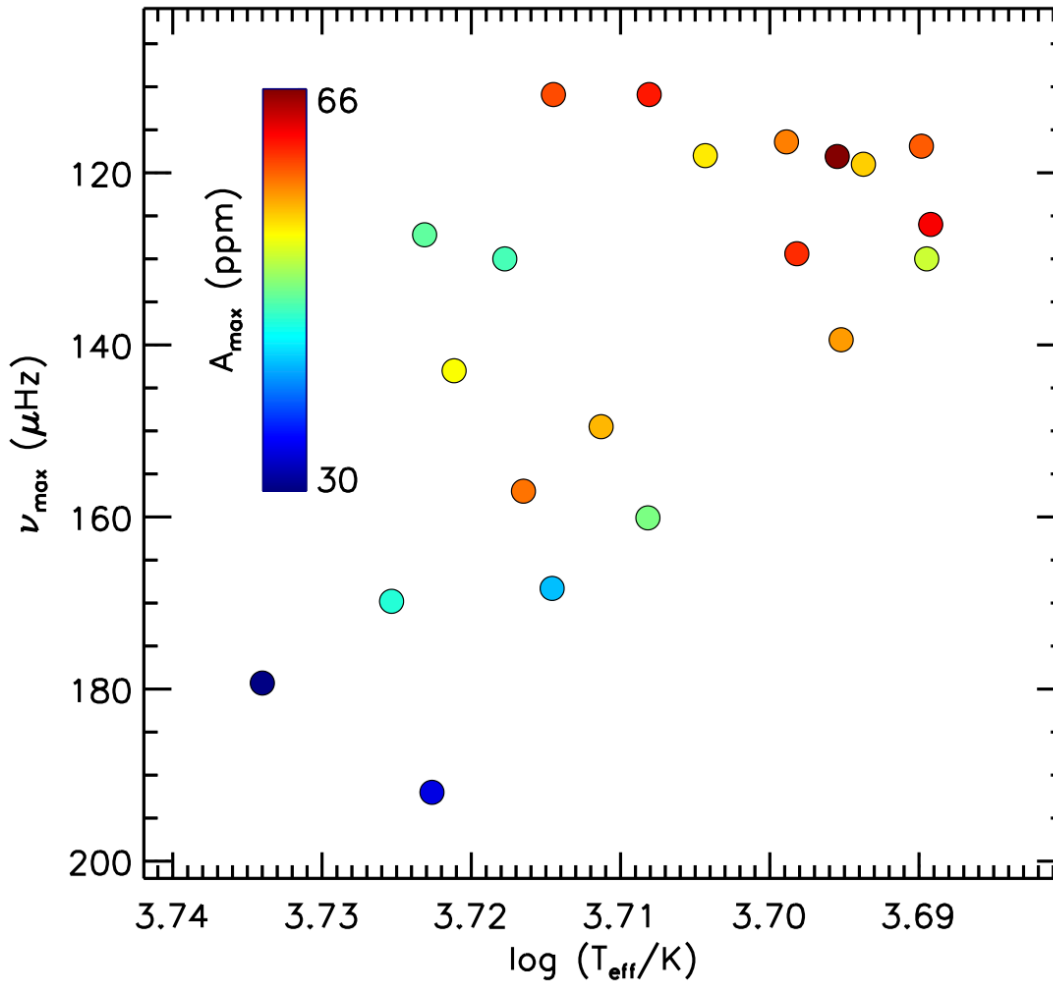
$$\nu_{\max} \in [110, 200] \mu\text{Hz}$$

highest SNR

KU LEUVEN

Sample selection

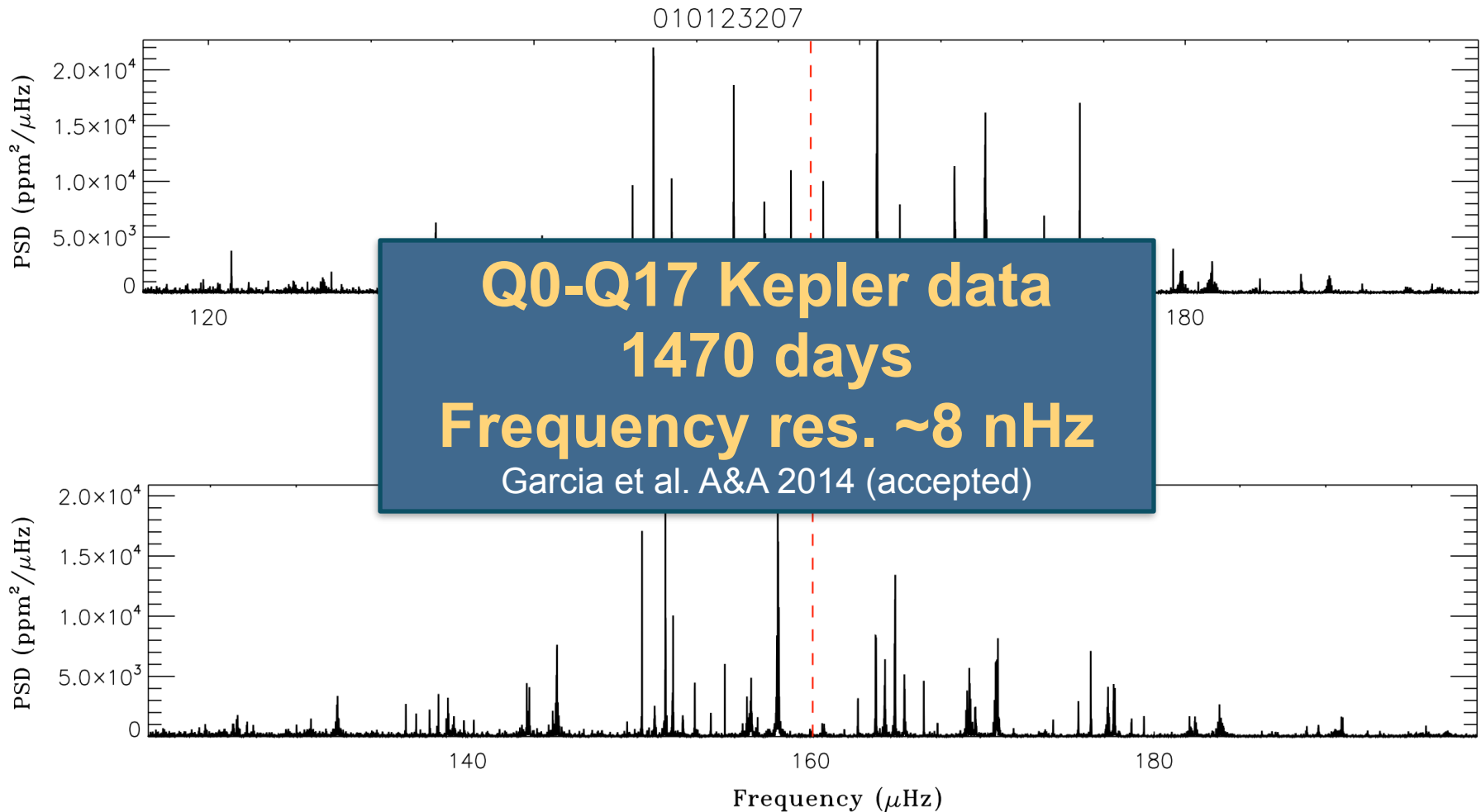
- Introduction
- **The sample**
- The new method
- First results



21 low-mass low-luminosity RGB stars

Example of PSD

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

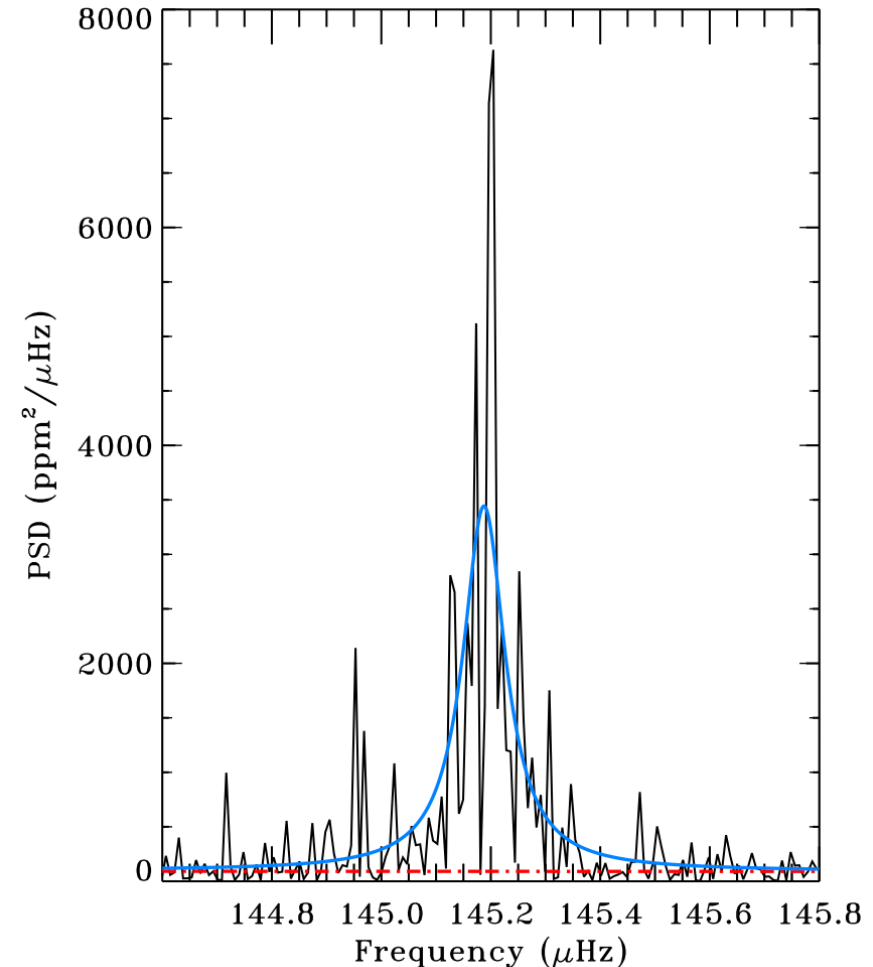


Peak Bagging Analysis

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

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

- **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)

DIAMONDS

A new Bayesian Nested Sampling tool

Enrico Corsaro
enrico.corsaro@ster.kuleuven.be

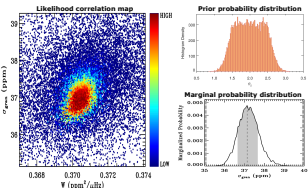
Joris De Ridder
joris.deridder@ster.kuleuven.be

ABSTRACT

In the context of high-quality asteroseismic data provided by the NASA *Kepler* Mission, we developed a new code, termed **DIAMONDS** (high-Dimensional And multi-Modal Nested Sampling), for fast Bayesian parameter estimation and model comparison by means of the *Nested Sampling Monte Carlo* (NSMC) algorithm, an efficient and powerful method very suitable for high-dimensional problems (like the peak bagging analysis of solar-like oscillations) and multi-modal problems (i.e. problems that show multiple solutions). We applied the code to the peak bagging analysis of solar-like oscillations observed in a challenging F-type star. By means of DIAMONDS one is able to detect the different backgrounds in the power spectrum of the star (e.g. stellar granulation and faculae activity) and to understand whether one or two oscillation peaks can be identified or not. In addition, we demonstrate a novel approach to peak bagging based on multi-modality, which is able to reduce significantly the number of free parameters involved in the peak bagging model. This novel approach is therefore of great interest for possible future automatization of the entire analysis technique.

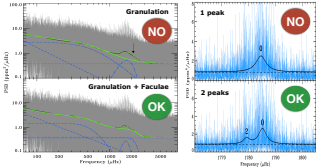
1. THE DIAMONDS CODE

DIAMONDS is developed in C++11 and structured in classes in order to be as much flexible and configurable as possible^[1]. It implements a more recent version of the NSMC algorithm^[6,4,2,3]. The user can supply its own likelihoods, priors and models, according to the astrophysical problem of interest, by using a starting template. All model free parameters and the corresponding Bayesian Evidence are therefore estimated by the code.



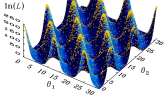
2. PEAK BAGGING AND BAYESIAN MODEL COMPARISON

Determining how many different background signals are observed in the stars' power spectrum (figure below, left) can be done by means of a model comparison based on the Bayesian Evidence, where each competing model includes a different representation of the background level. With the same method, one can also test the significance of an oscillation peak, in which the competing models will either include or not the peak to be assessed (figure below, right). Model comparison becomes this way a very straightforward task^[1].



3. THE NOVEL APPROACH: MULTI-MODALITY

Conversely to other existing sampling methods (e.g. based on Markov Chain algorithm^[4]) DIAMONDS allows to sample highly multi-modal distributions very efficiently^[1]. The Eggbox function shown below is a nice example of degenerate (multiple) solution, namely a posterior probability distribution with several modes (hence multi-modal), sampled by DIAMONDS (yellow dots).



We exploited the multi-modality as a novel approach to the peak bagging, succeeding in reducing the number of free parameters used to fit 27 consecutive oscillation peaks from 81 (a Lorentzian profile for each peak, hence 3 free parameters) to only 9 free parameters in total. The approach is very fast and efficient and is very well suited for automatizing the peak bagging analysis for future applications to several oscillating main sequence stars.

REFERENCES

[1] Corsaro E. & De Ridder J., 2014, A&A (submitted)

[2] De Ridder J., Corsaro E., 2013, MNRAS, 426, 2662

[3] De Ridder J., Corsaro E., 2013, MNRAS, 426, 2662

[4] Gelman, A., Su, J., Pittau, M. G., 2007, MNRAS, 376, 1295

[5] Gelman, A., Su, J., Pittau, M. G., 2007, MNRAS, 376, 1295

ACKNOWLEDGMENTS

The collaboration to these results has involved funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement 022214 (200702197) and ERC-LSO (2010-2014) (LSO) from the Fund for Scientific Research of the Flemish Region (F.R.S.-FNRS) and from the Belgian National Research Foundation (N.R.F.).

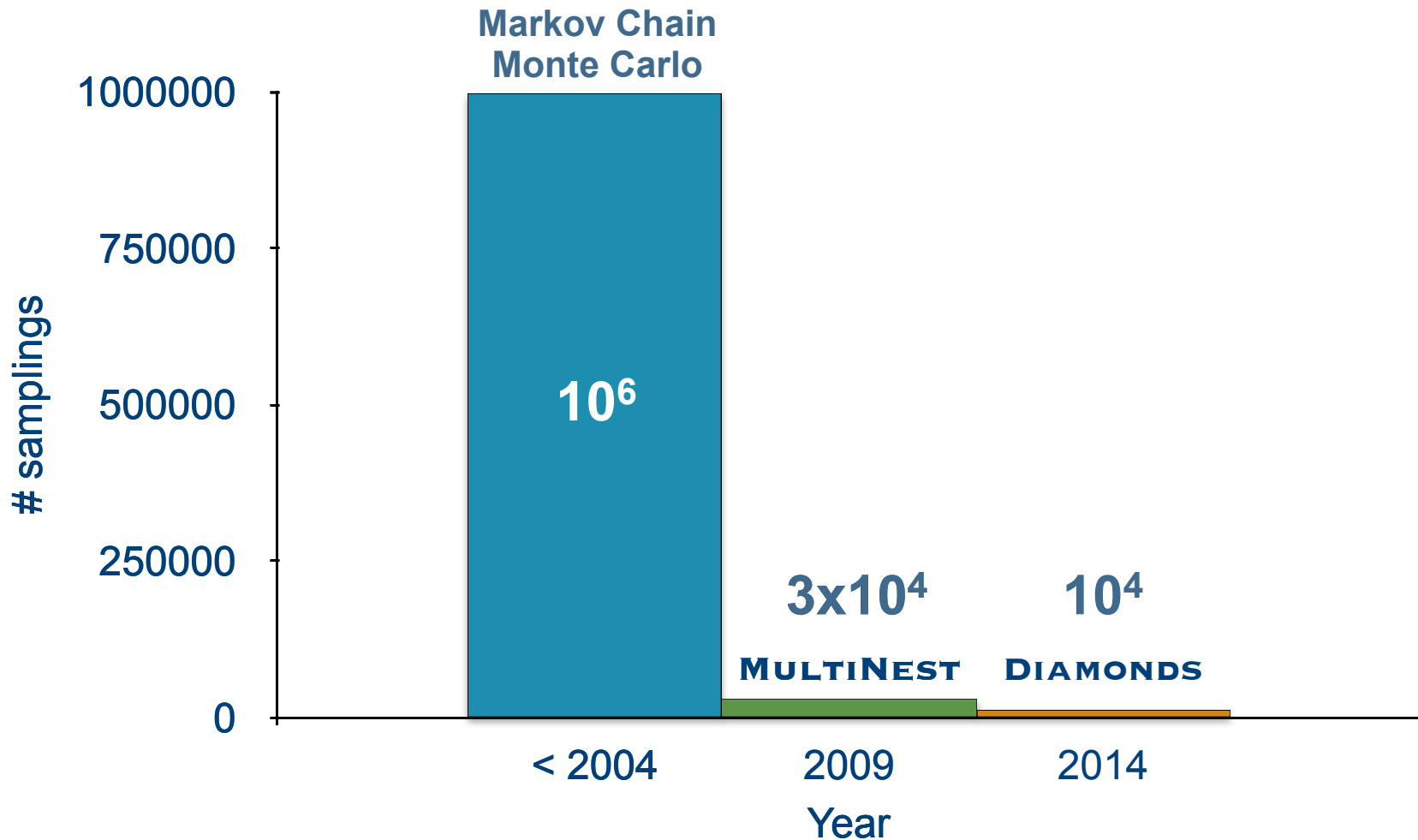
DOWNLOAD

Software package available at the DIAMONDS code web site:
<https://my.kuleuven.be/~software/diamonds/>



Sampling numerical methods

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



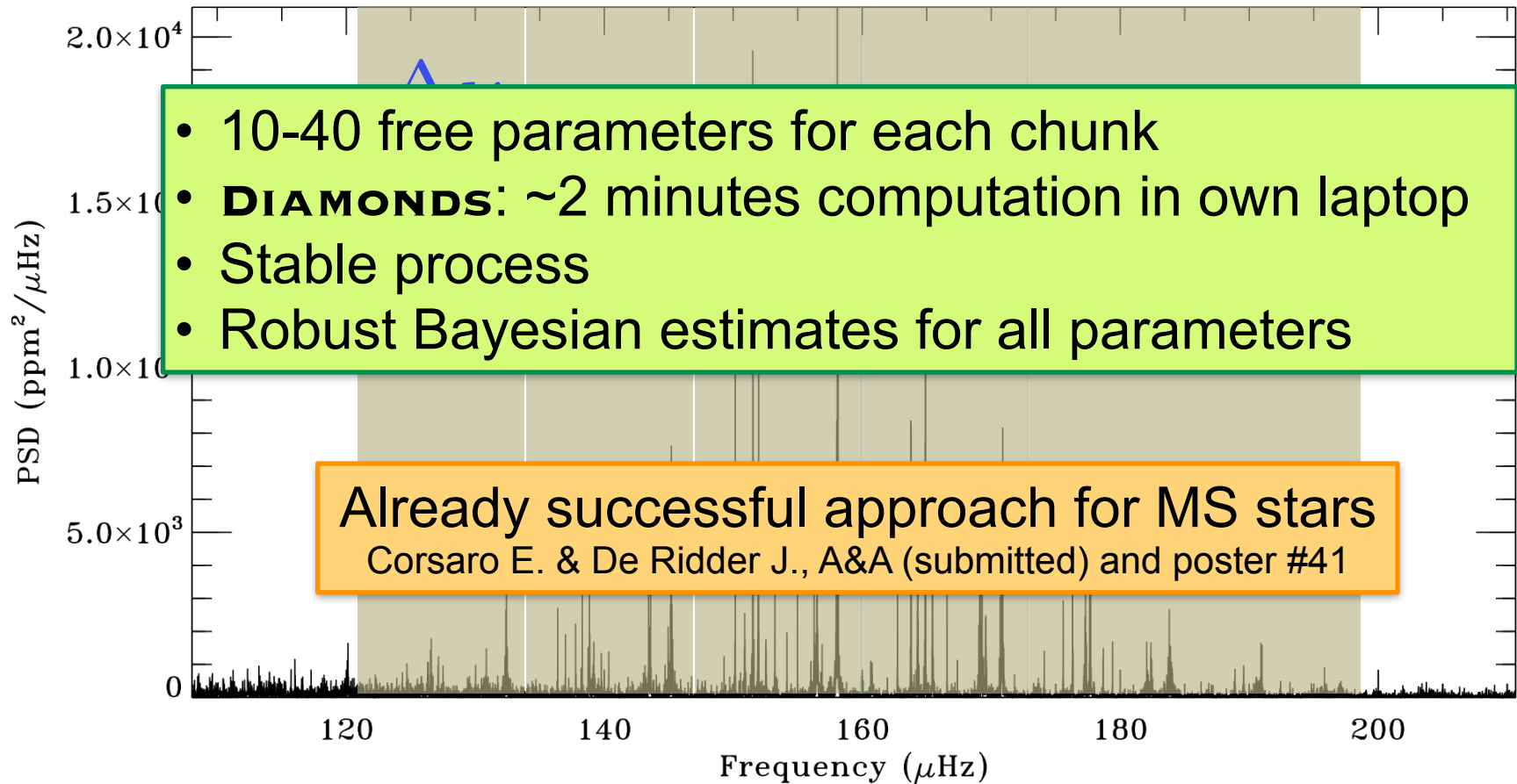
16

KU LEUVEN

Efficiency of the computation

Chunks of PSD

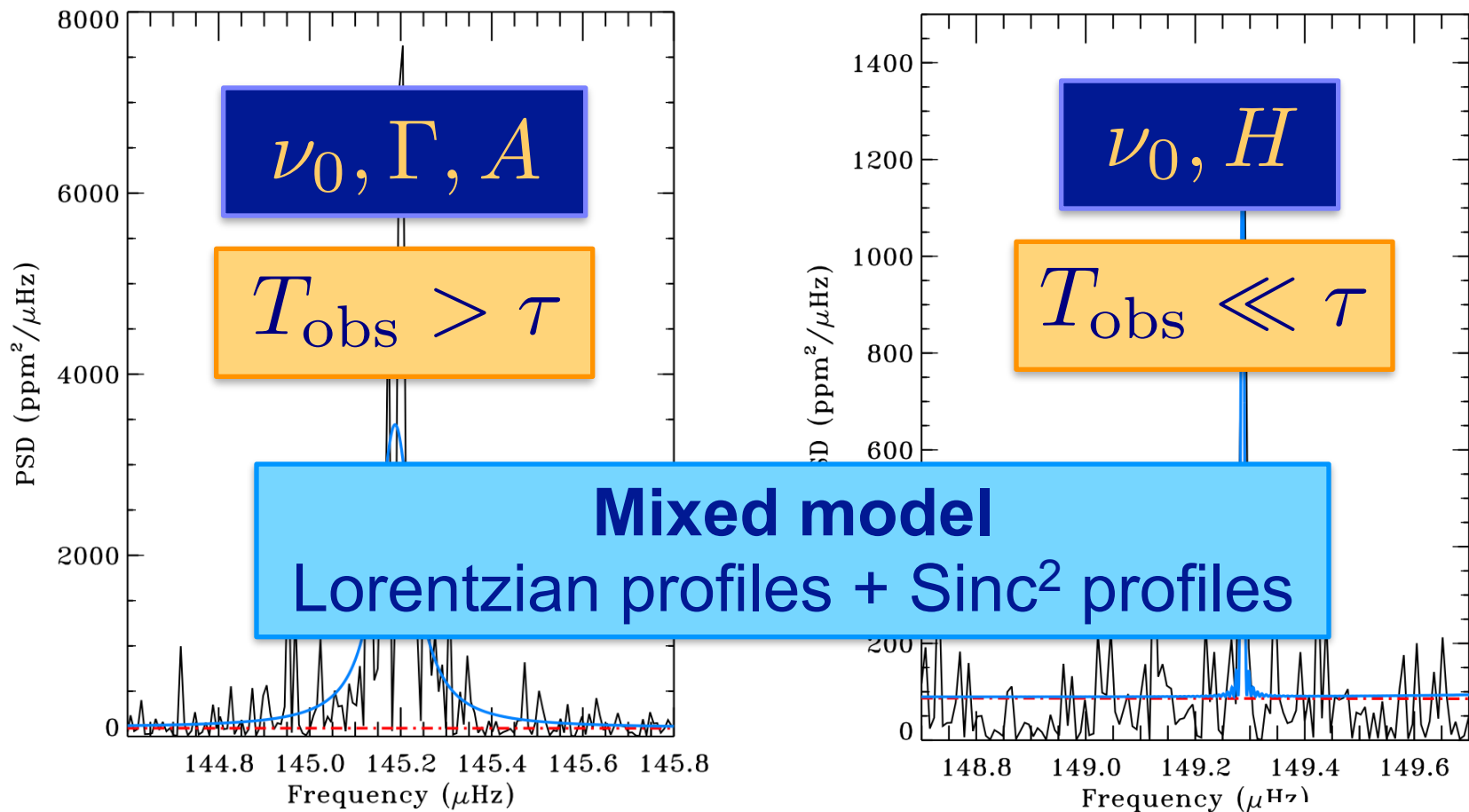
- Introduction
- The sample
- **The new method**
- First results



Efficiency of the computation

Peak Bagging Model

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

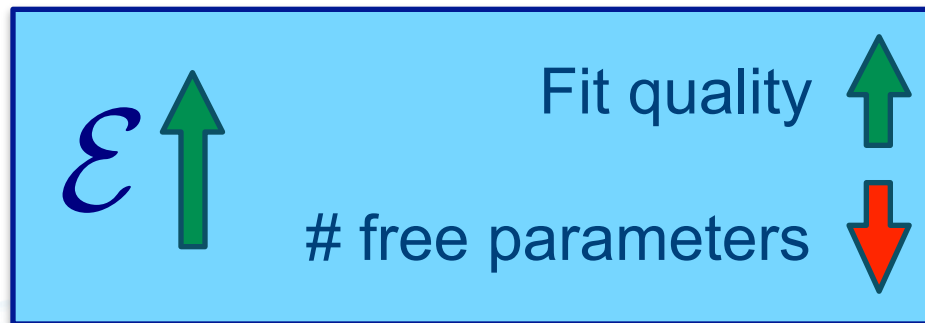


- Introduction
- The sample
- **The new method**
- First results

Peak Significance Criterion

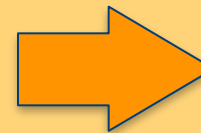
Bayesian Model Comparison

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



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

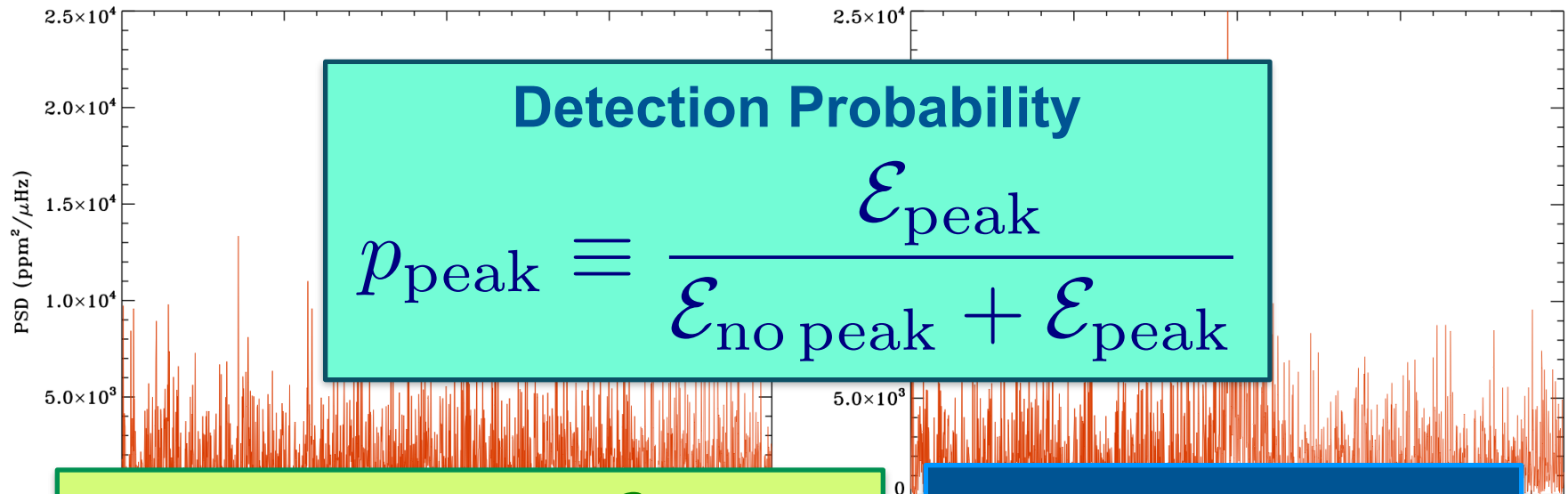
- Introduction
- The sample
- **The new method**
- First results

Peak Significance Criterion

Simulation test

900 Simulations

100 Simulations



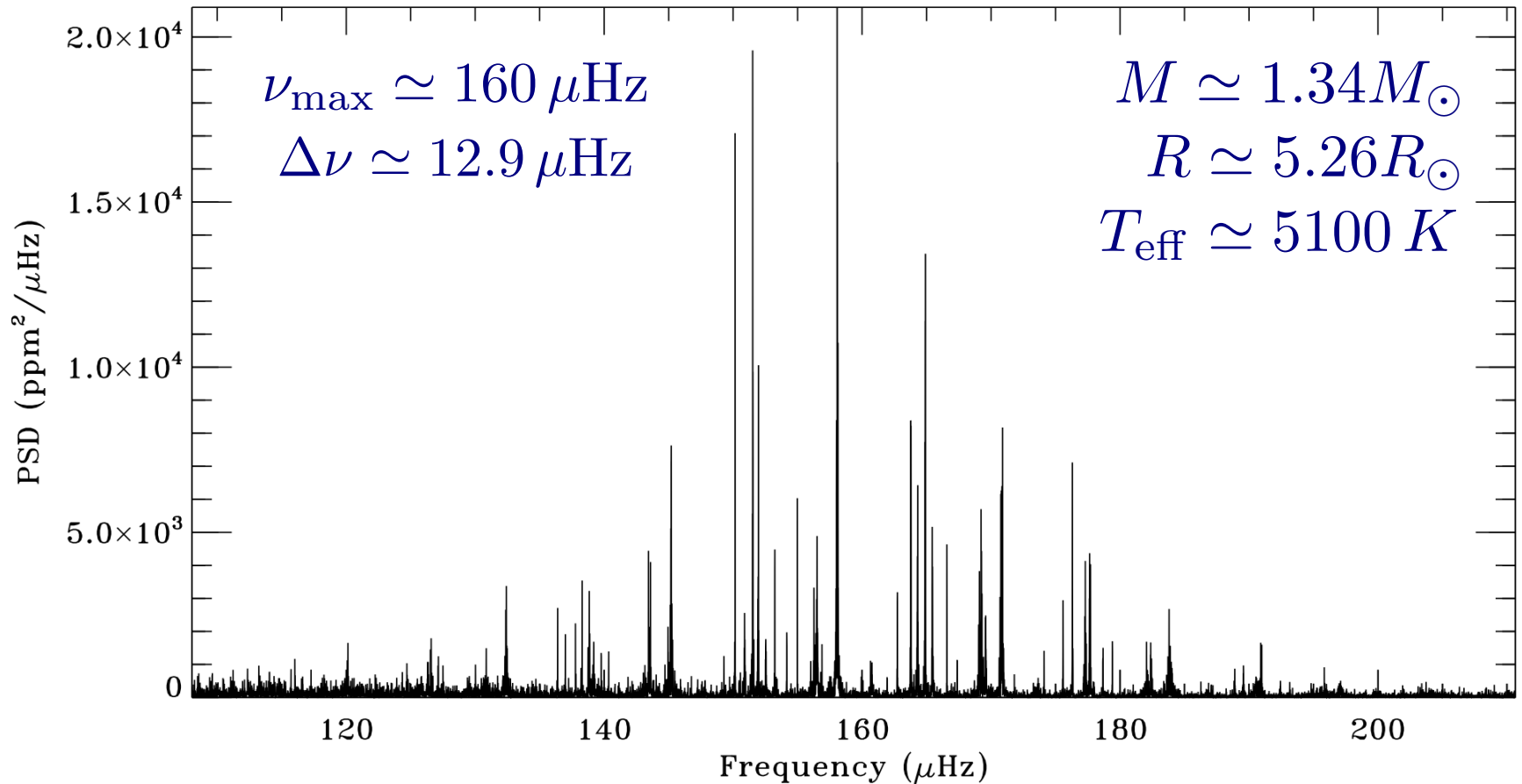
1000 Models → $\mathcal{E}_{\text{no peak}}$
1000 Models → $\mathcal{E}_{\text{peak}}$

$p_{\text{peak}} \gtrsim 99\%$
All peaks found!

Application

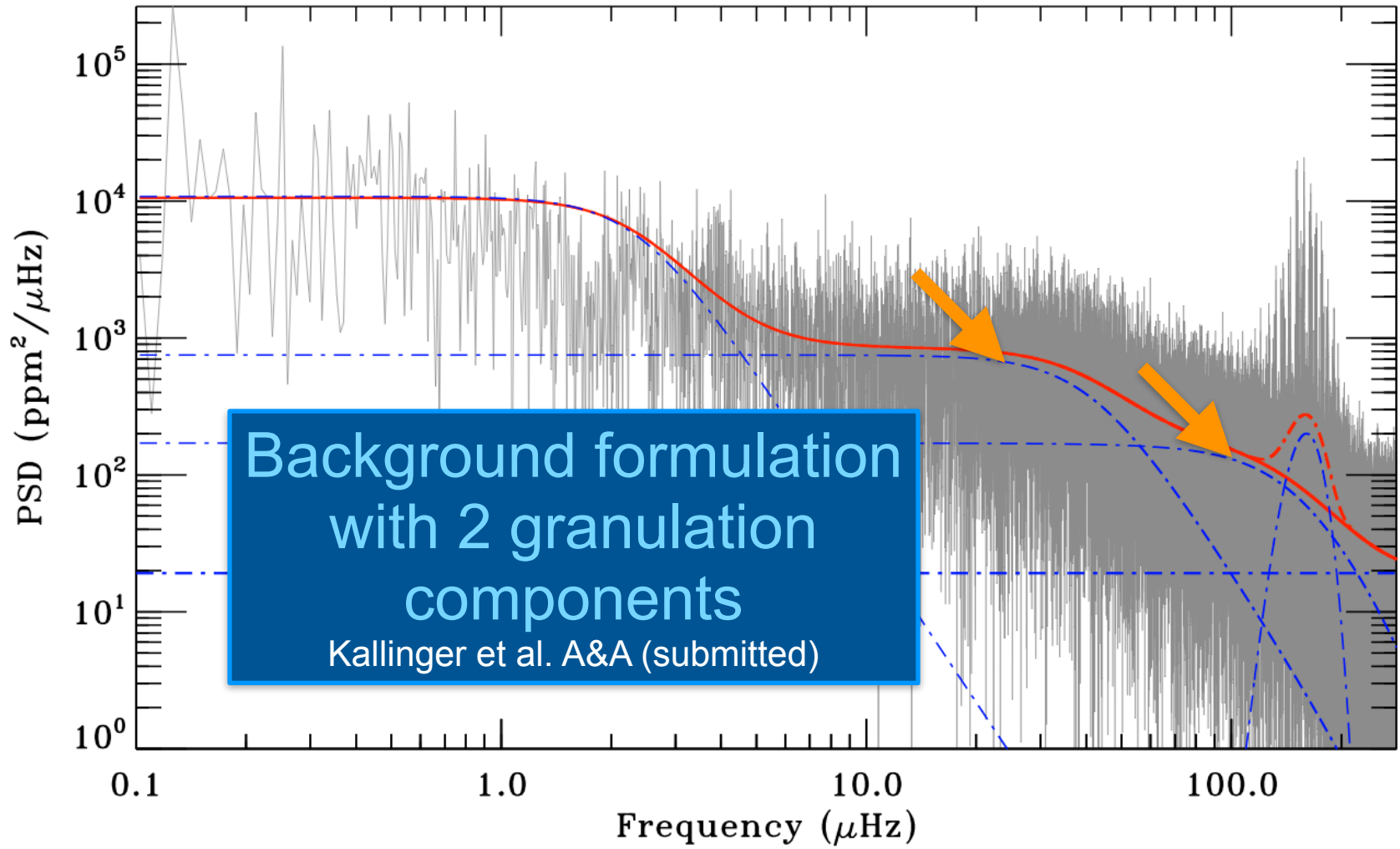
KIC 12008916

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



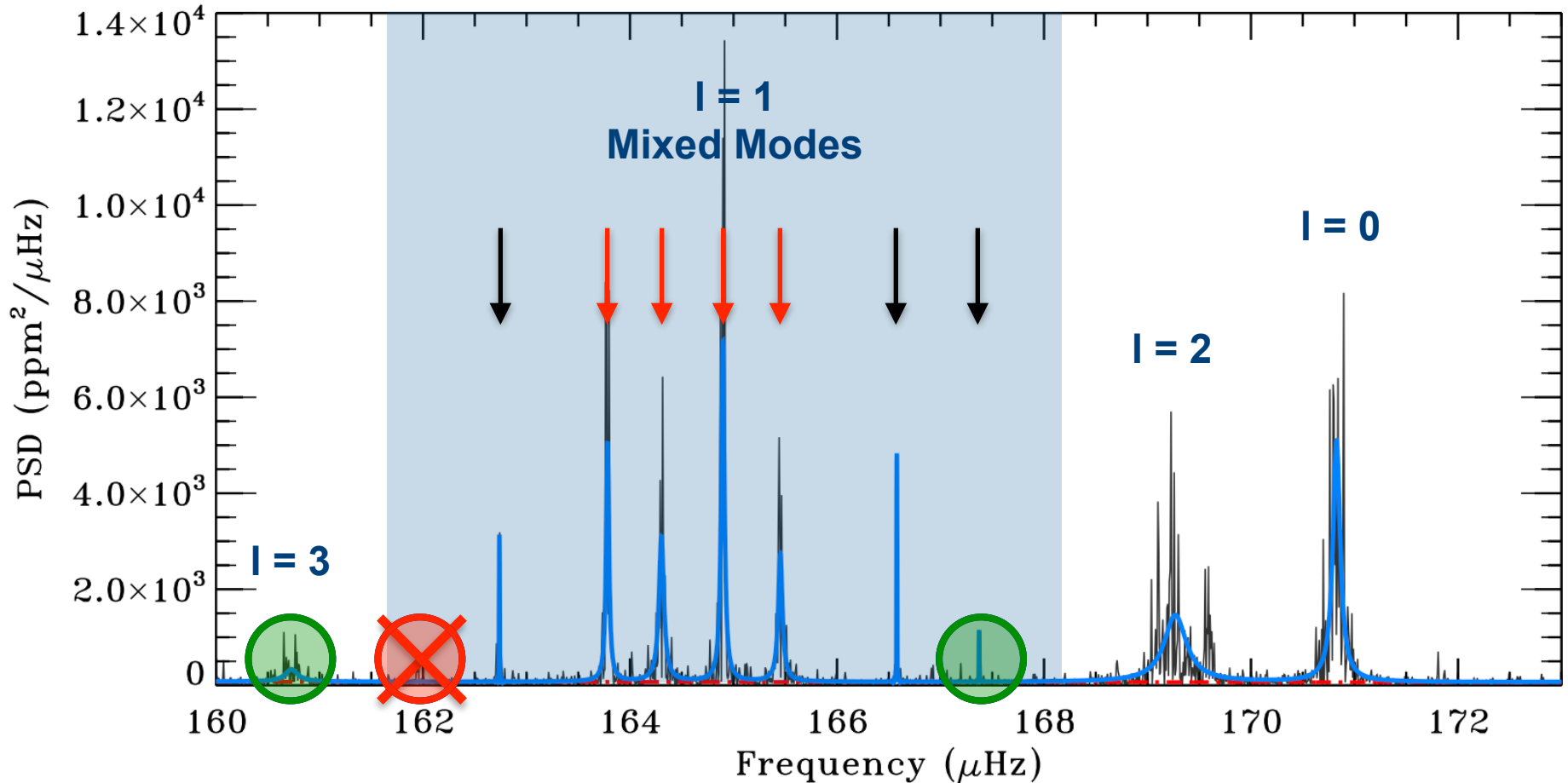
Background

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



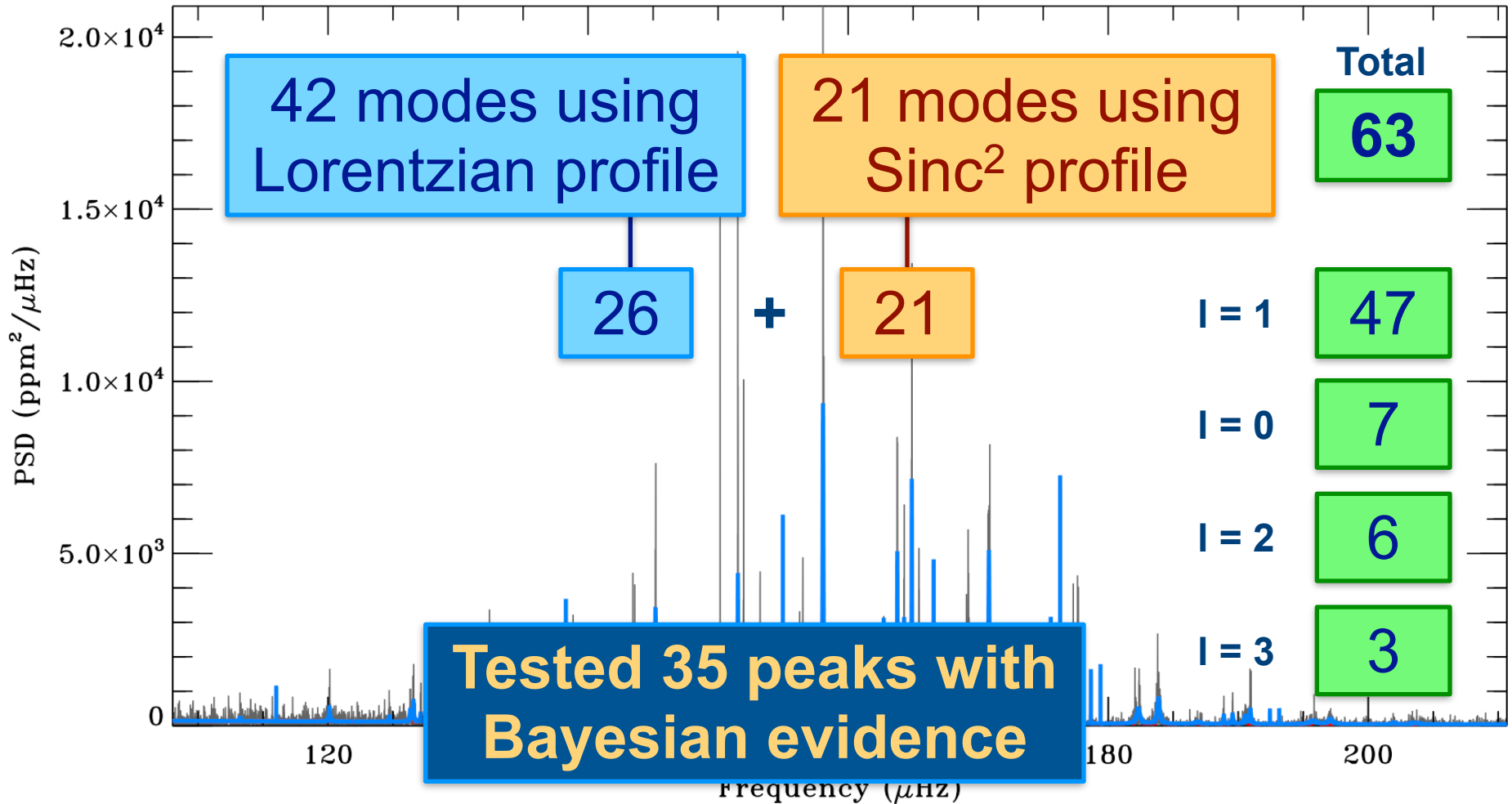
- Introduction
- The sample
- The new method
- **First results**

Peak Bagging Results

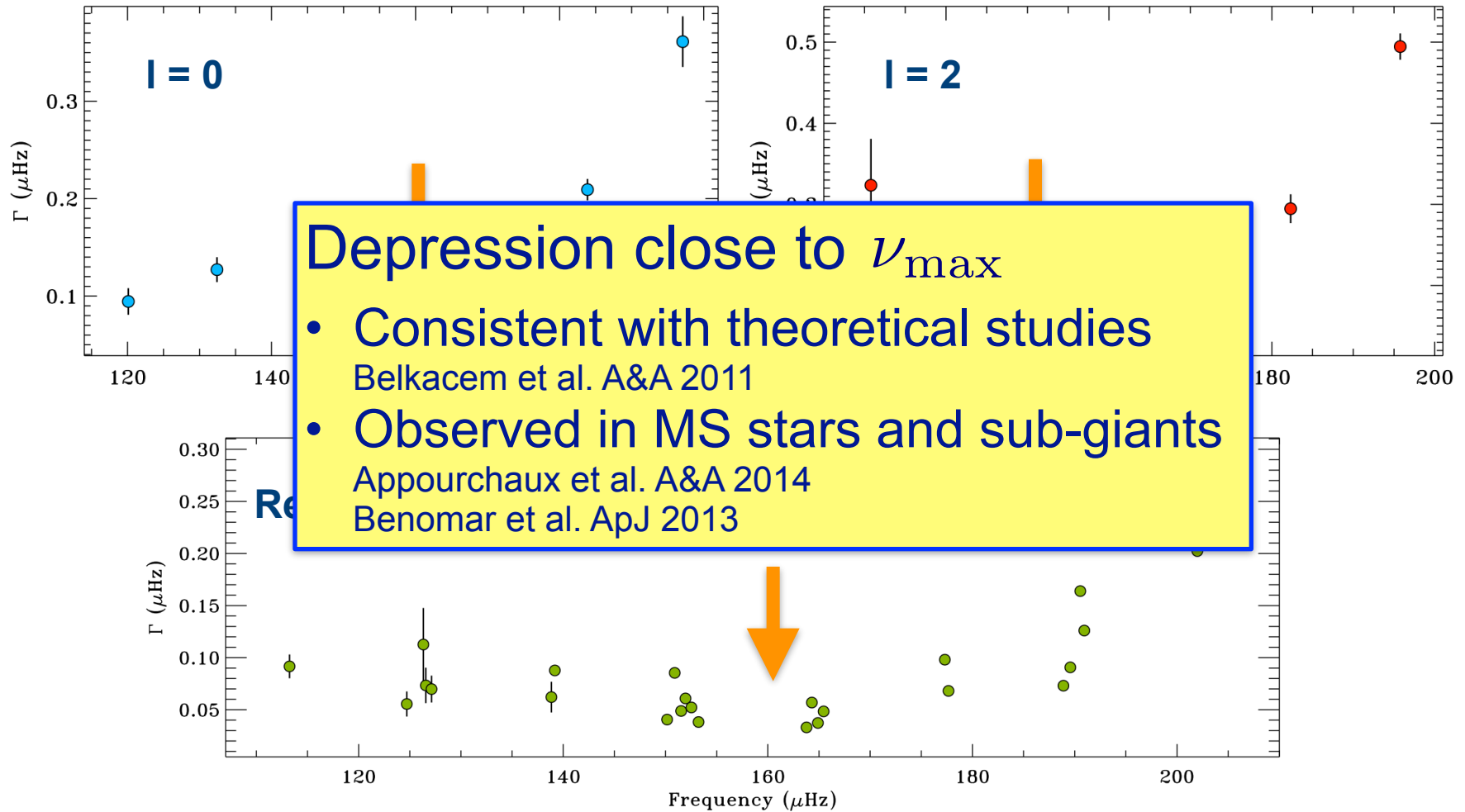


- Introduction
- The sample
- The new method
- **First results**

Peak Bagging Results

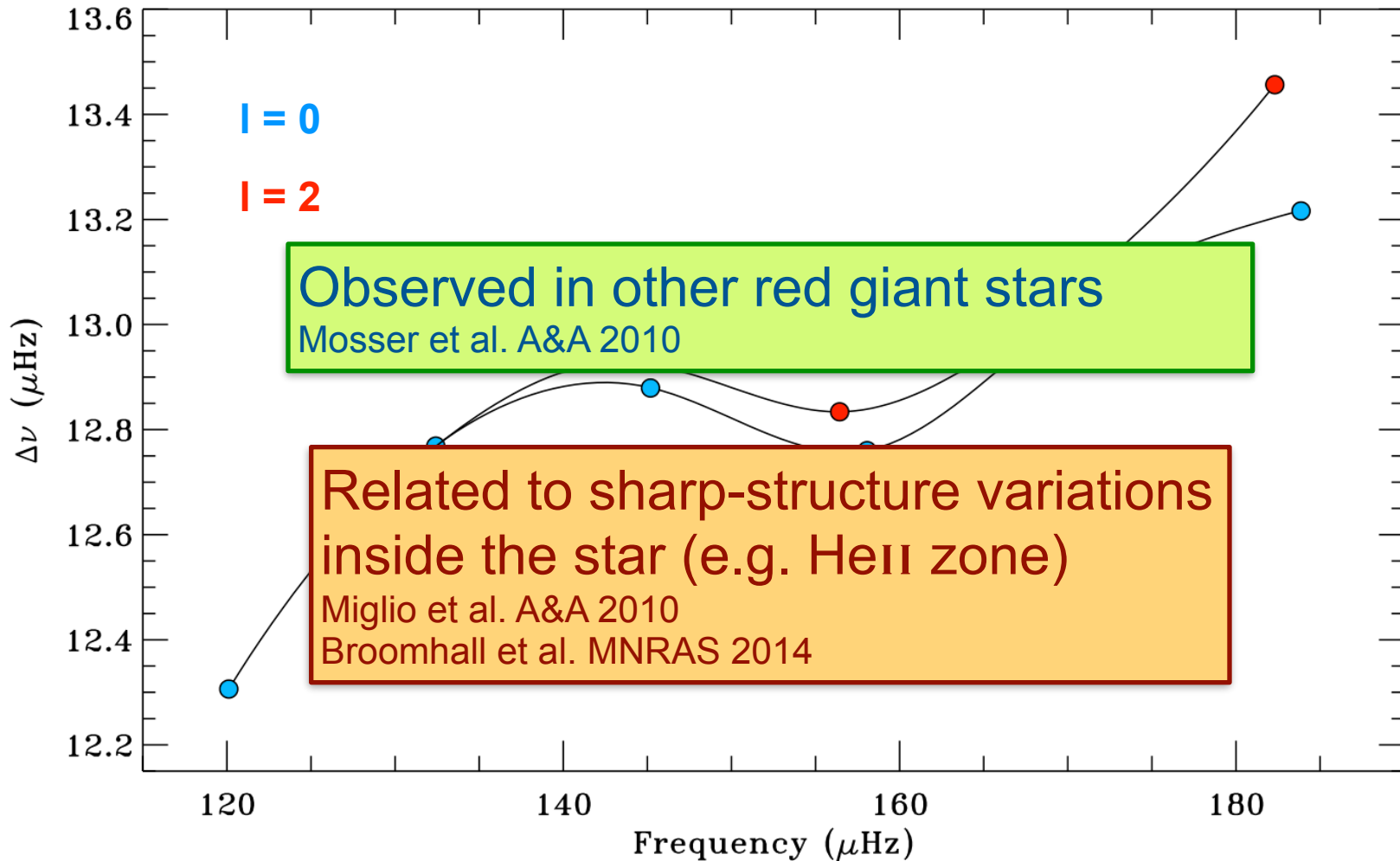


Linewidth depression



25

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)

Acknowledgements

The research leading to these results has received funding from:

- The European Research Council under the European Community's Seventh Framework Programme (FP7/2007--2013)/ERC grant agreement n°227224 (PROSPERITY) and PEOPLE-IRSES n°269194 (ASK)
- The Fund for Scientific Research of Flanders (G.0728.11)
- The Belgian federal science policy office (C90291 Gaia-DPAC)

