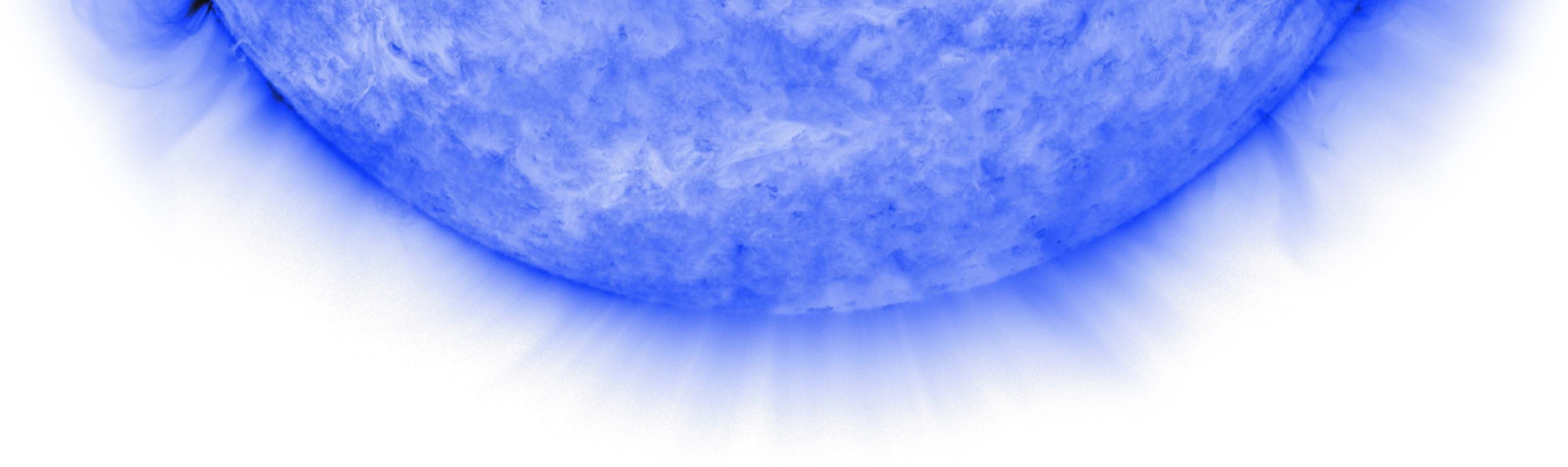


Rotation and mixing in SPB stars

Where are we now?

Péter I. Pápics | KU Leuven (Belgium)

Understanding the roles of rotation, pulsation and chemical peculiarities in the upper main sequence

Lake District (UK) - September 14, 2016

KU LEUVEN

fwo Research Foundation Flanders
Opening new horizons

Introduction

GOAL

Calibrate stellar structure and evolution models

Cornerstones in numerous fields of stellar astrophysics

BITS & PIECES

B-star

'Massive' stars

MS: convective core + radiative envelope

Mixing processes influencing stellar lifetime

Asteroseismology

SPB stars (2.5 - 8 M_{Sun}, 11 000 - 22 000 K)

High order *g* modes (0.5 - 3 d, kappa mechanism)

Characteristic **period spacing**

Many uncertainties:

Rotation

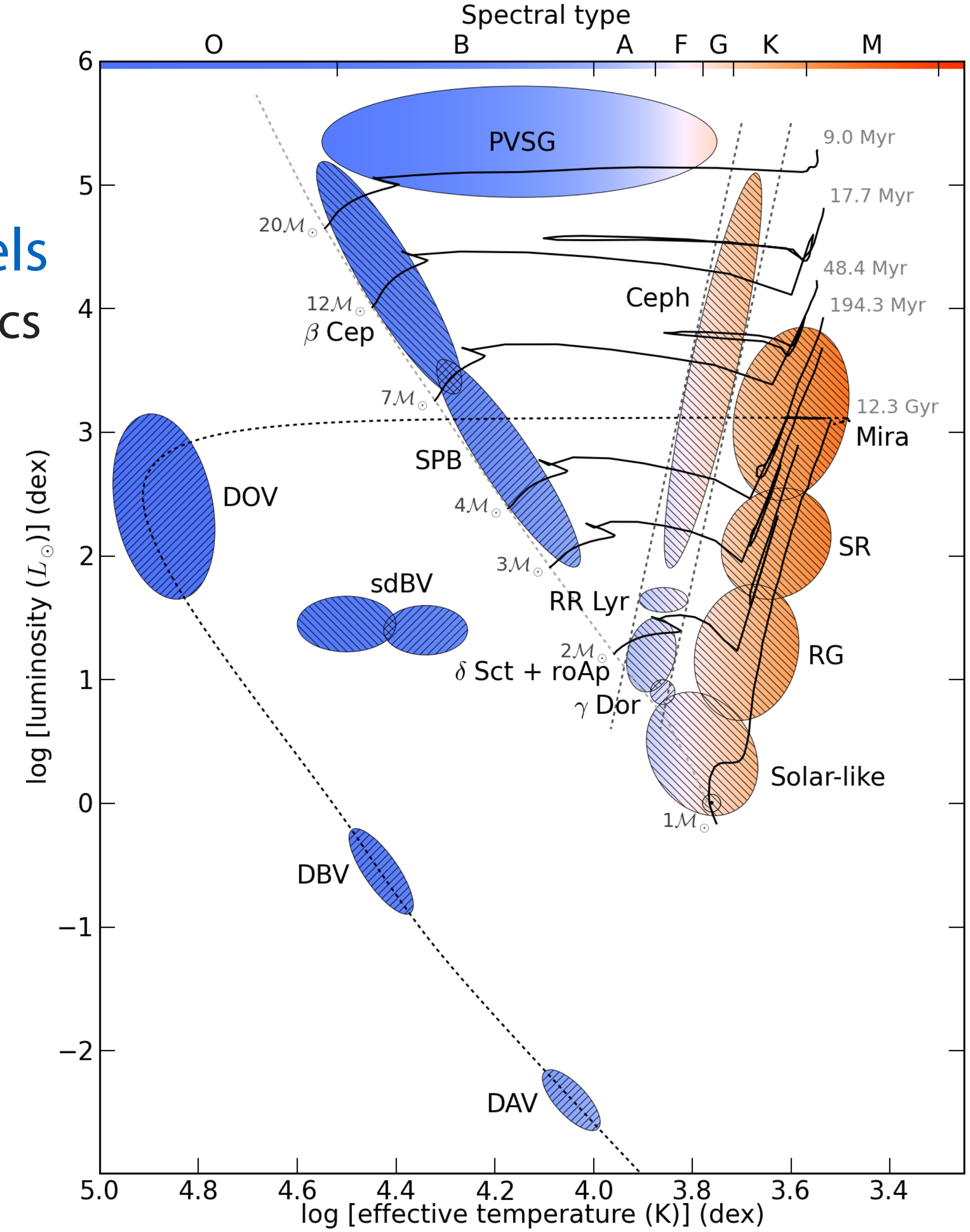
Internal rotation **~Ω(*r*)** for <5 stars

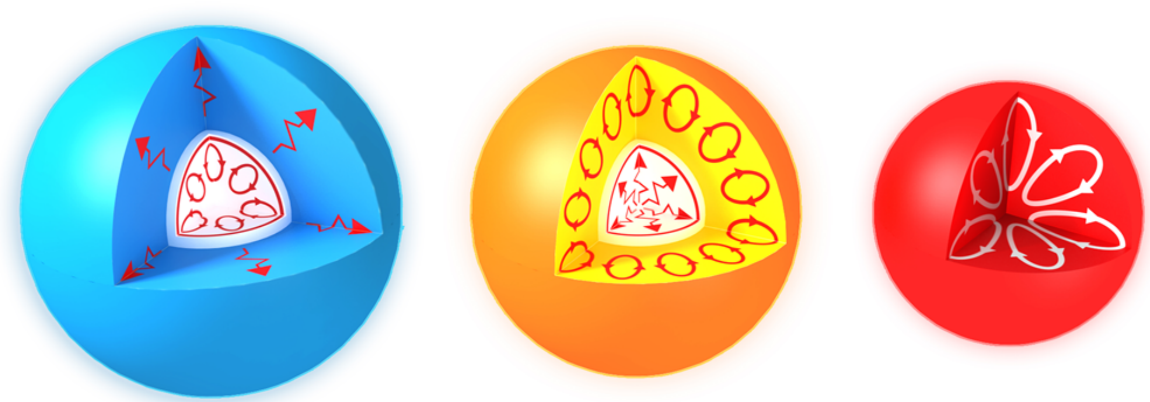
Convection & **O**vershooting & **D**iffusive mixing

Overshooting value α_{ov} for <20 stars

Excitation

Predictions work more-or-less, not perfect in details





Introduction

SEISMIC MODELLING | OVERVIEW

Forward modelling: from observations to physical constraints

Observations

- Ground-based
  - *multicolour photometry*
  - *high-resolution spectroscopy*
- Space-based
  - *uninterrupted photometry*
  - *no colour information*

Data analysis

Fundamental parameters

- T_{eff}, log g, Z, …
  - *SED fitting, spectral synthesis*

Observed pulsation modes

- List of significant frequencies
  - *frequency analysis techniques*
- Quantum numbers (ℓ,m)
  - *photometric amplitude ratios*
  - *line profile variations*

Inside the error box

Model parameters

M, X_{C}, Z, α_{ov}, …

**First approach: assuming a fully mixed core overshoot region*

Stellar evolution code (MESA)

Stellar models

- For specified input physics
  - *physical conditions in the star*

Pulsation code (GYRE)

Theoretical pulsation modes

- List of frequencies with (n,ℓ,m)

Comparison (χ^2)

Constraints

Fundamental parameters / Shortcomings in included physics / Unknown stellar properties (e.g., magnetic field)

The Seismic Fingerprint

PERIOD SPACING

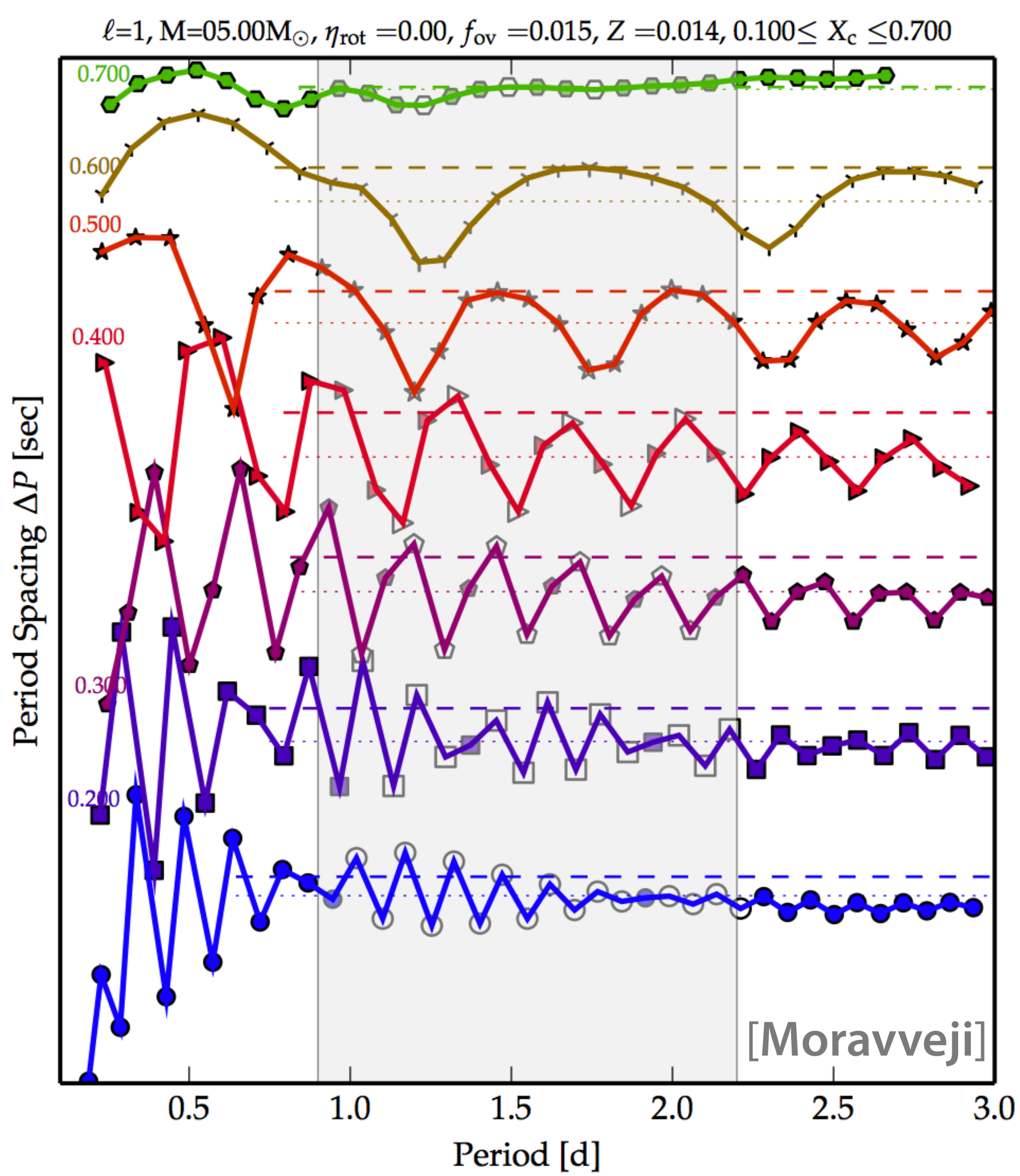
Average spacing

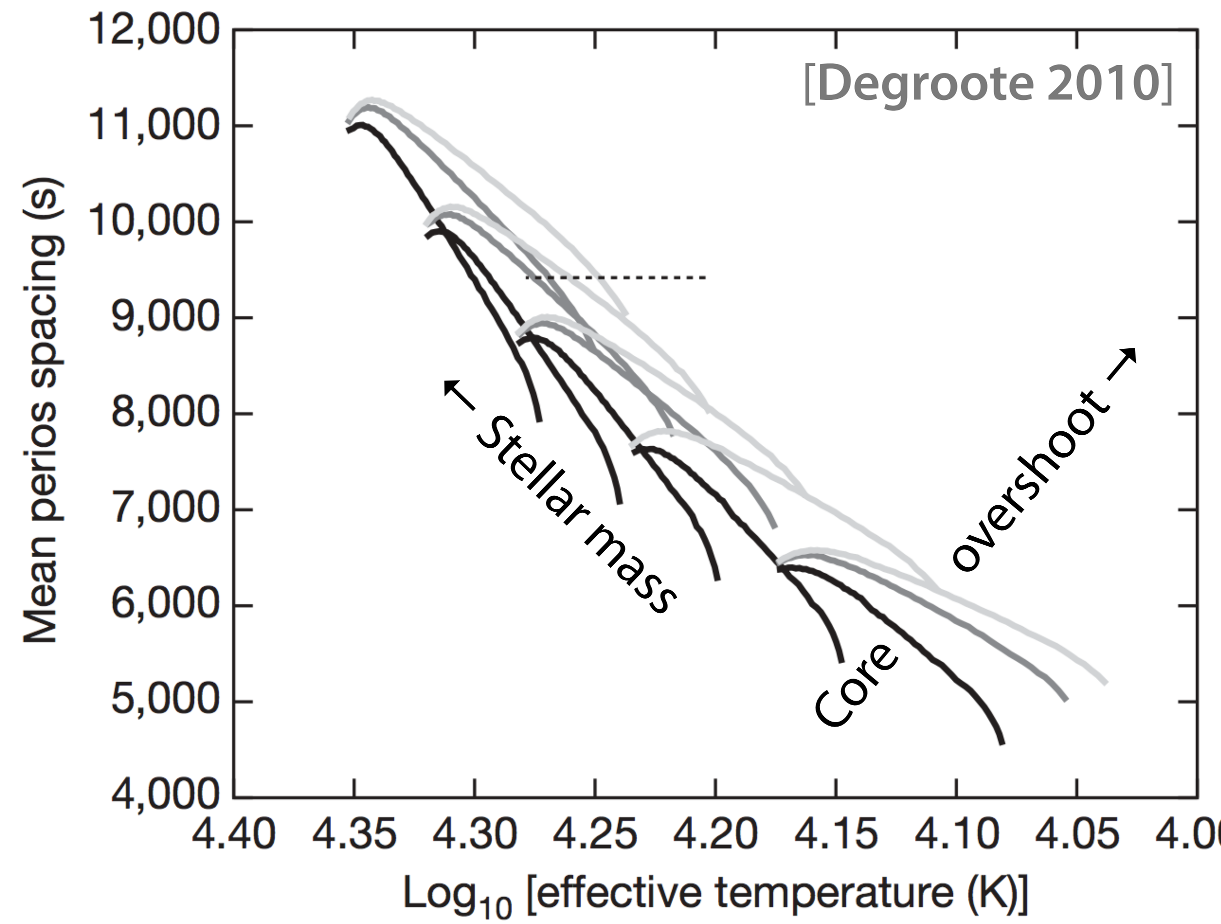
[**Tassoul 1980**]

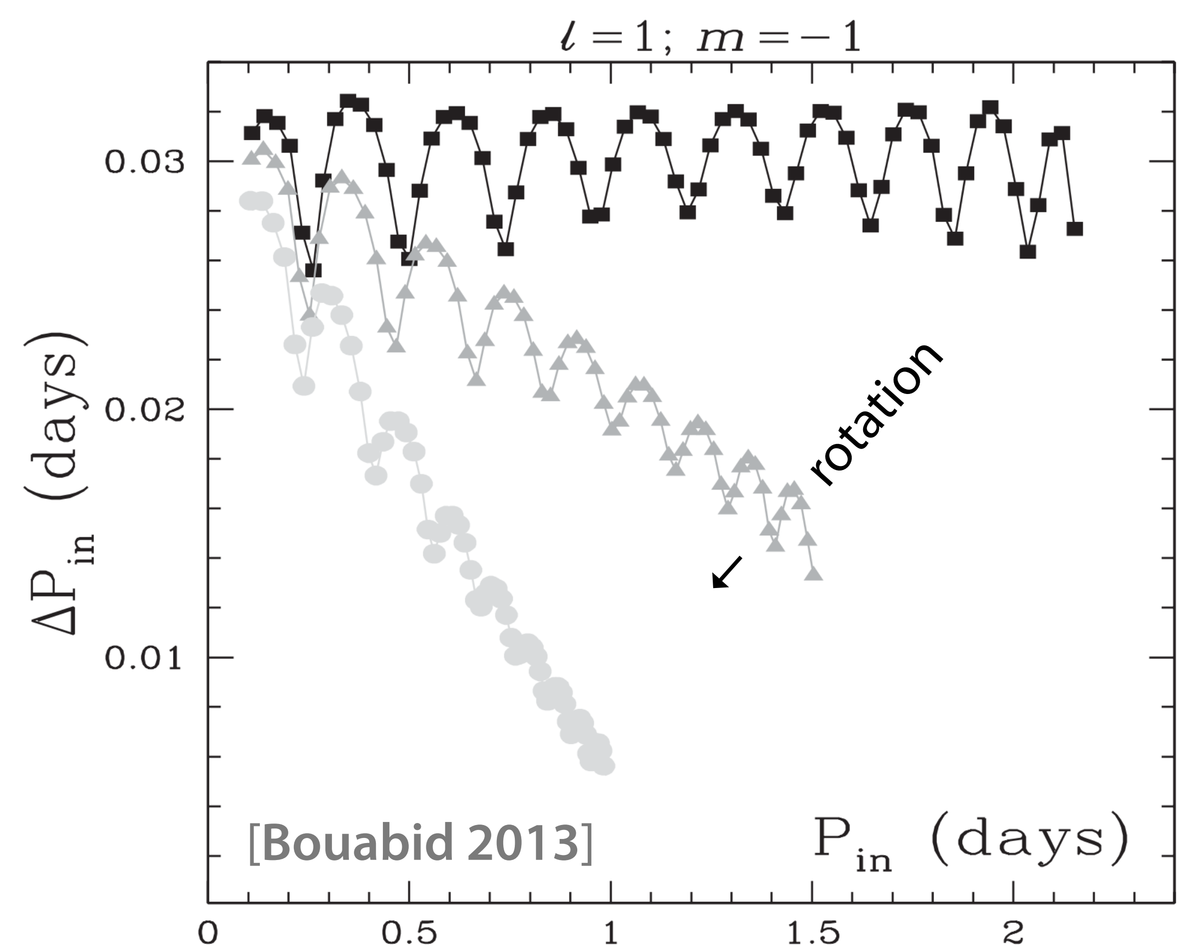
Shape of the period spacing ‘function’

Periodic deviations [**Miglio et al. 2008**]

Tilt [**Bouabid et al. 2013**]







History Lesson

Astron. Astrophys. 246, 453–468 (1991)

ASTRONOMY AND ASTROPHYSICS

Slowly pulsating B stars*

C. Waelkens

Astronomisch Instituut, Katholieke Universiteit Leuven, Celestijnenlaan 200 B, B-3001 Heverlee, Belgium

Received December 20, 1990; accepted February 21, 1991

Abstract. We analyse photometric data, gathered during several years, of seven B-type variable stars that were previously discussed by Waelkens and Rufener (1985). It is found that all these stars are multiperiodic variables with periods of the order of days. For HD 177863, two periods could be identified, for HD 74560 and HD 181558 three periods, for HD 123515 four periods, for HD 74195 five periods, for HD 143309 six periods, and for HD 160124 eight periods.

Acknowledgements. We are grateful to C. Aerts, P. Bartholdi, M. Burnet, K. Degryse, D. Heynderickx, P. Lampens, and K. Van Den Abeele for their contributions to the observations, to N. Cramer and F. Rufener for their contribution to the reductions, to G. Burki and F. Rufener for the generous awarding of observing time for this project, to D.W. Kurtz for useful advice in the naming of these stars. I am also indebted to Mrs. L. Dumortier for the processing of the manuscript with the LaTeX package. Financial support from the Belgian Fund for Collective Research is gratefully acknowledged.

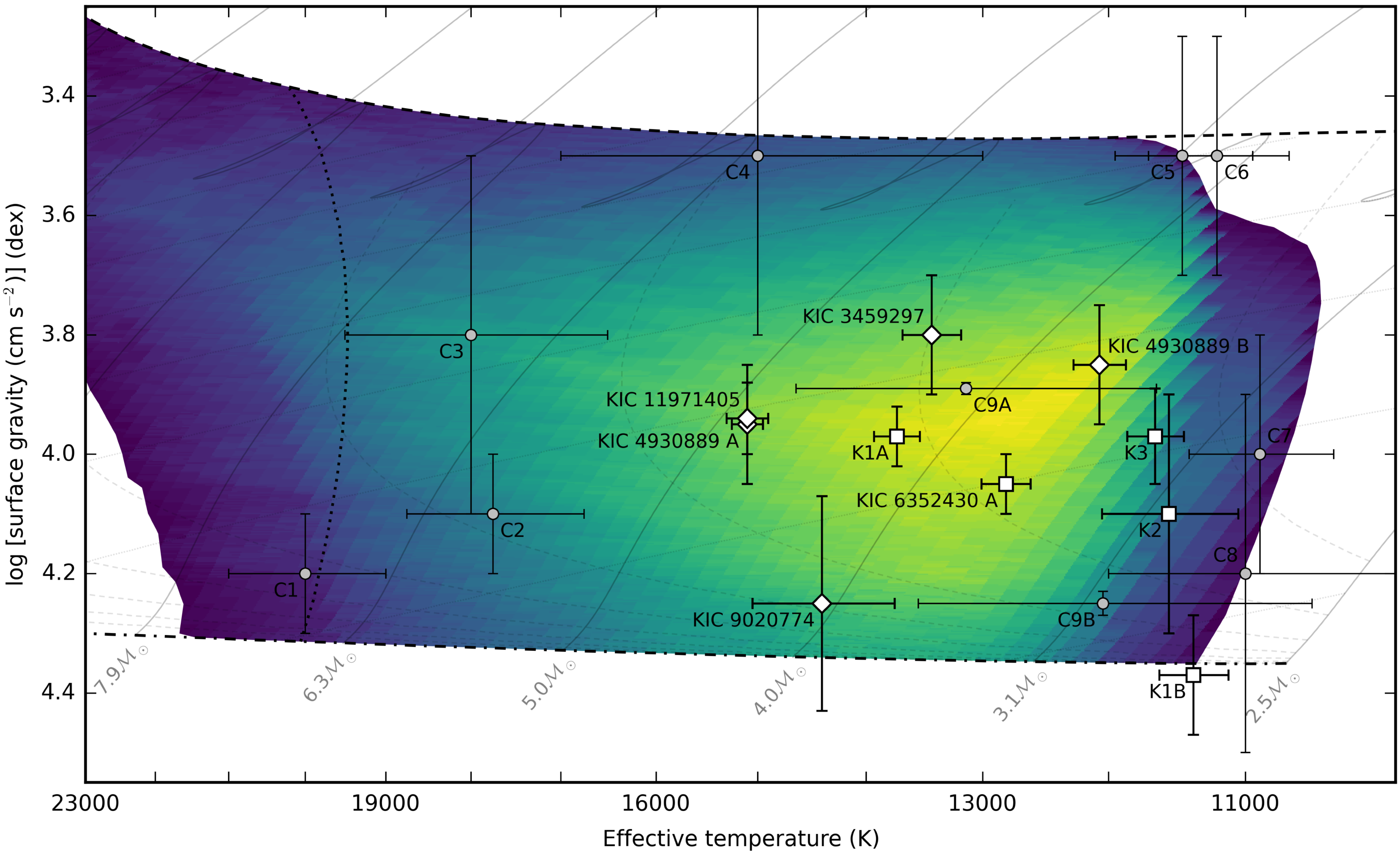
Observations from 1976 to 1988 resulting in **2 to 8 frequencies per star**…
Extremely difficult from the ground…

- 72 SPBs from **Hipparcos** (10x increase in the total number) identified by [**Waelkens et al. 1998**]
- Long-term **follow-up campaigns** driven by Hipparcos discoveries [~**2000s**]
- The first **hybrid β Cep/SPB pulsator** is also found [**Handler 2009**]
- Space-age…

25 Years Later

CoRoT AND *KEPLER*

See also [**Aerts 2015, Moravveji 2016**]

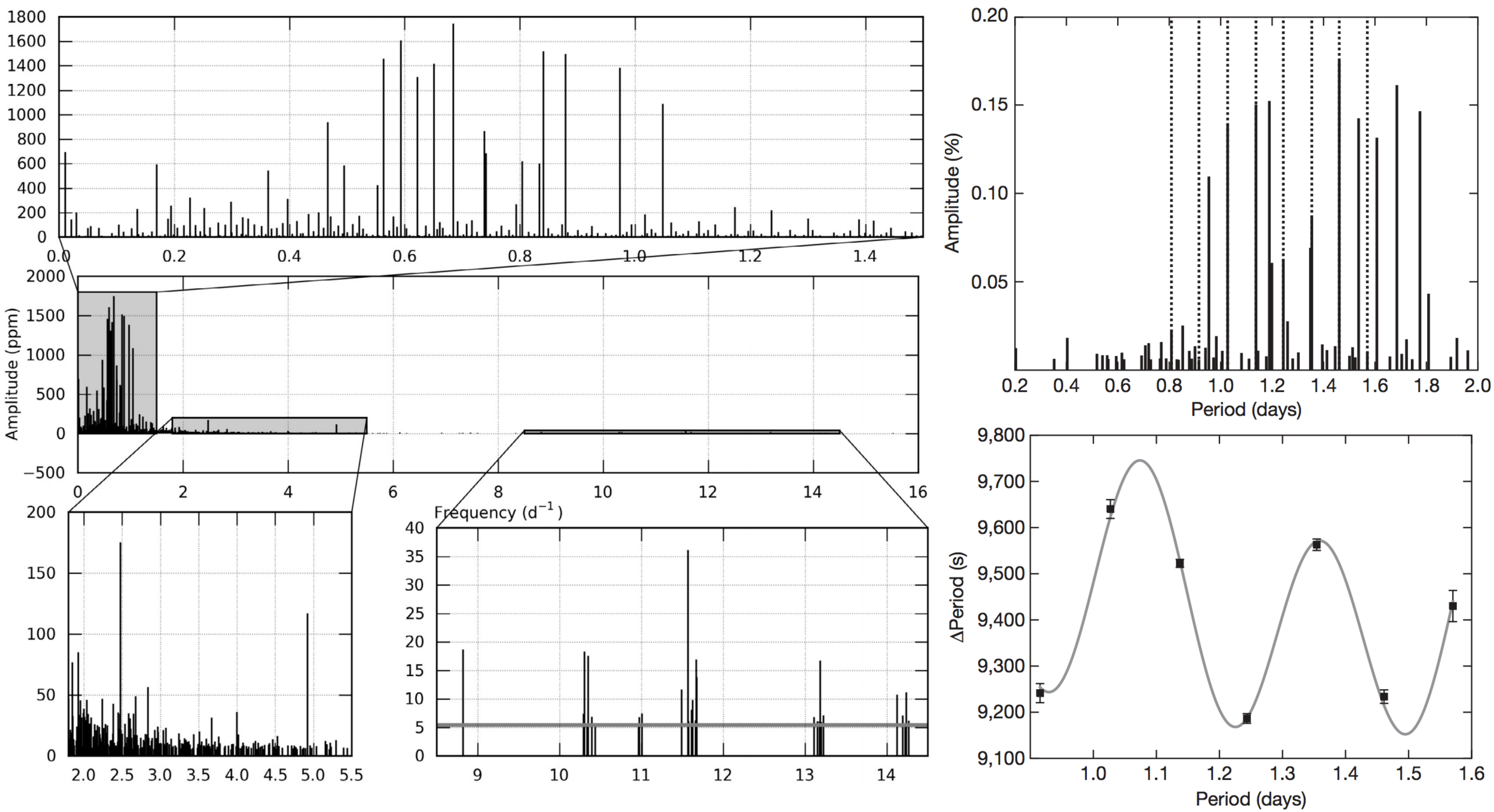


The Start of the Space Revolution with CoRoT

THE FIRST DETECTIONS OF PERIOD SPACINGS

HD 50230 [**Degroote et al. 2010**, Nature]

Hybrid pulsator (*g* and *p* modes), average *g* mode spacing 9418 sec



The Start of the Space Revolution with CoRoT

THE FIRST DETECTIONS OF PERIOD SPACINGS

HD 43317 [Pápics et al. 2012]

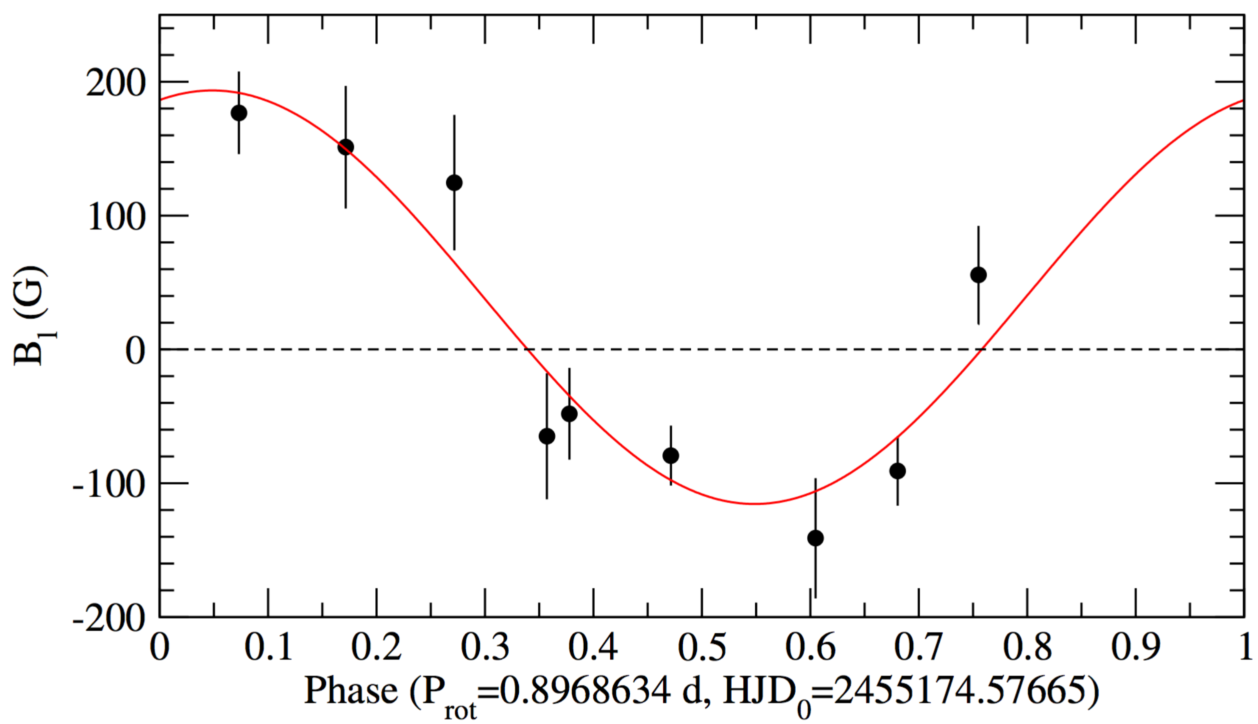
Pulsation + rotation (50% critical)

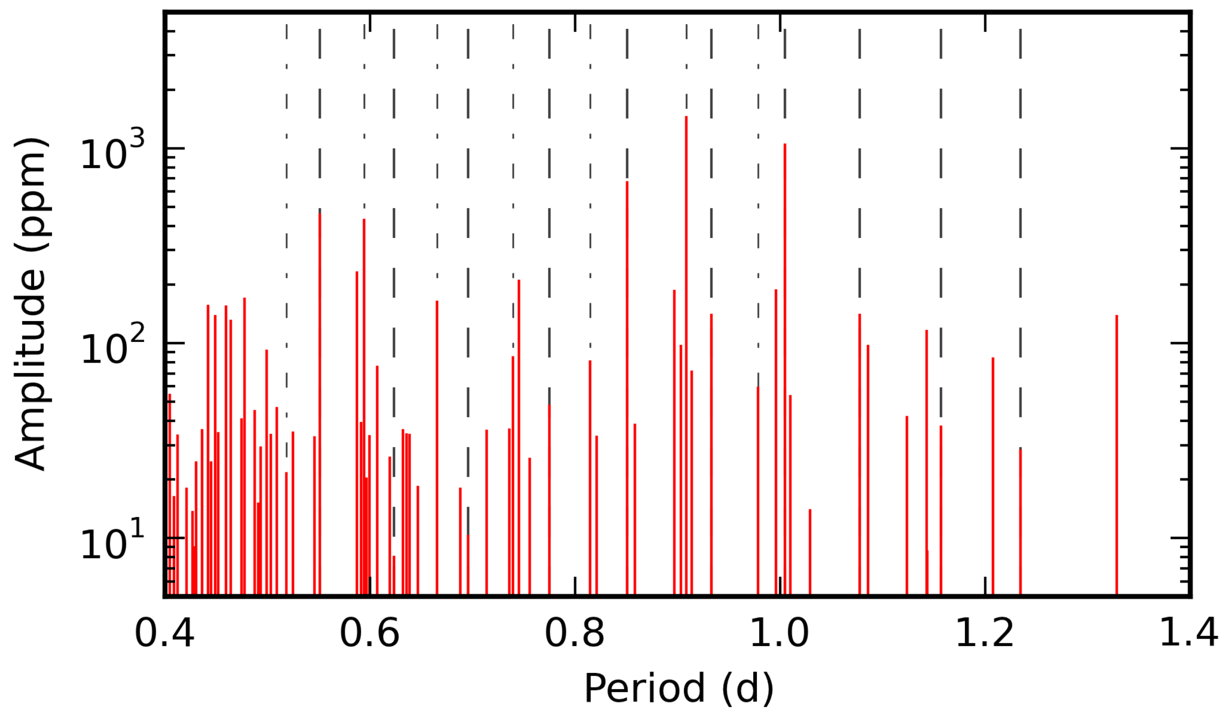
Gravito-inertial modes

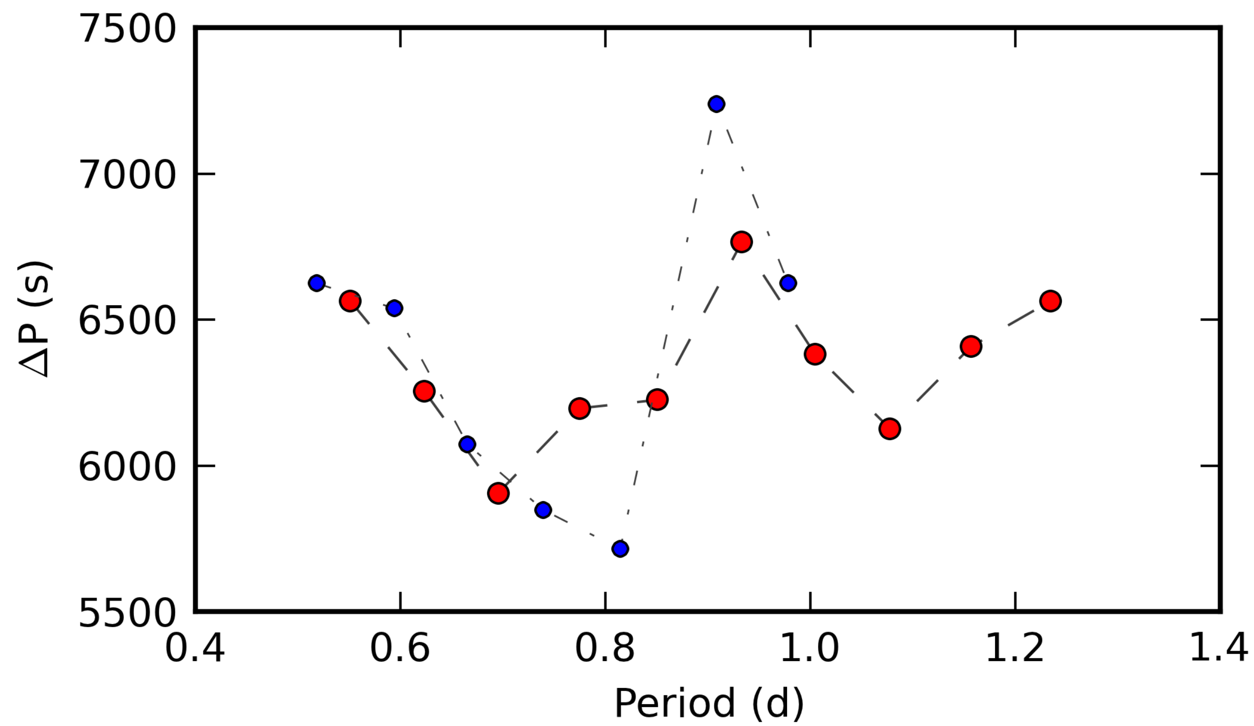
Spacings: 6339 & 6380 sec (zonal & retrograde)

Rotation P confirmed with **spectropolarimetry**

Magnetic star [**Briquet et al. 2013**]







Extending the Timebase with *Kepler*

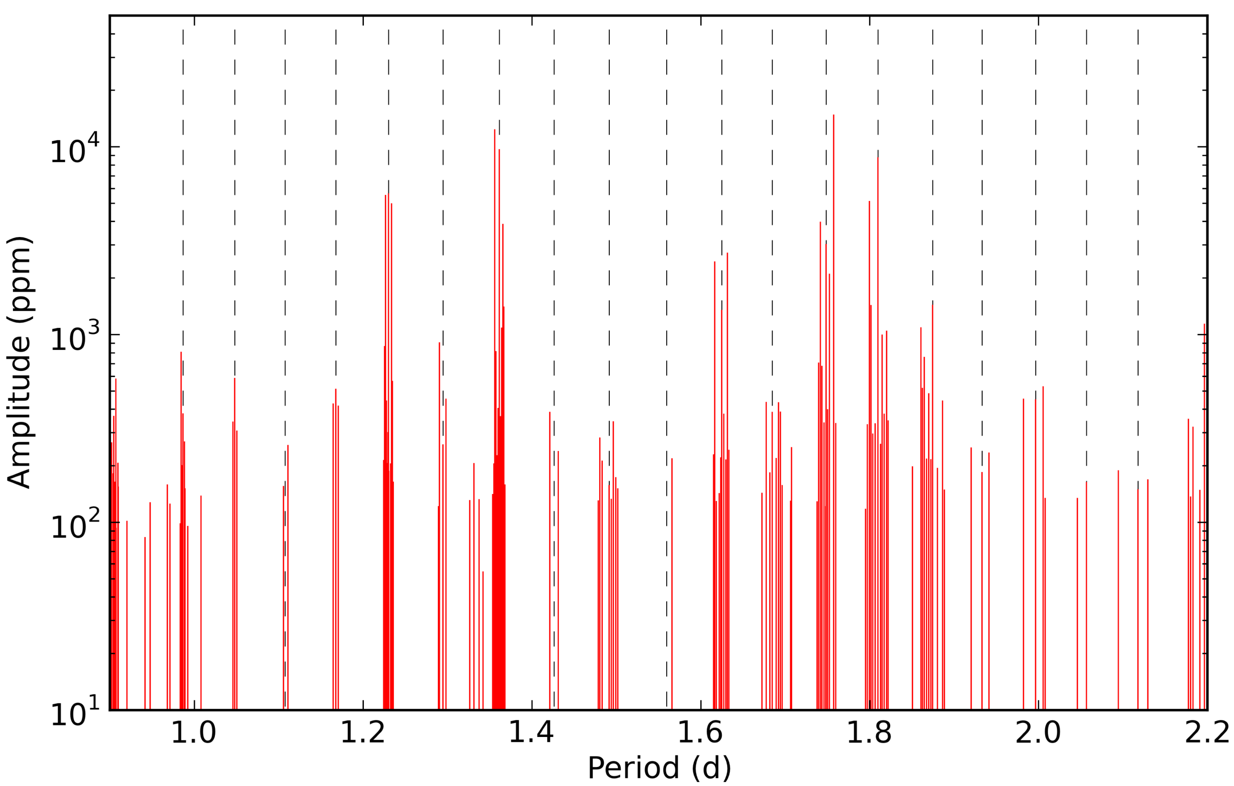
THE ROSETTA STONE OF SLOWLY ROTATING SPB STARS

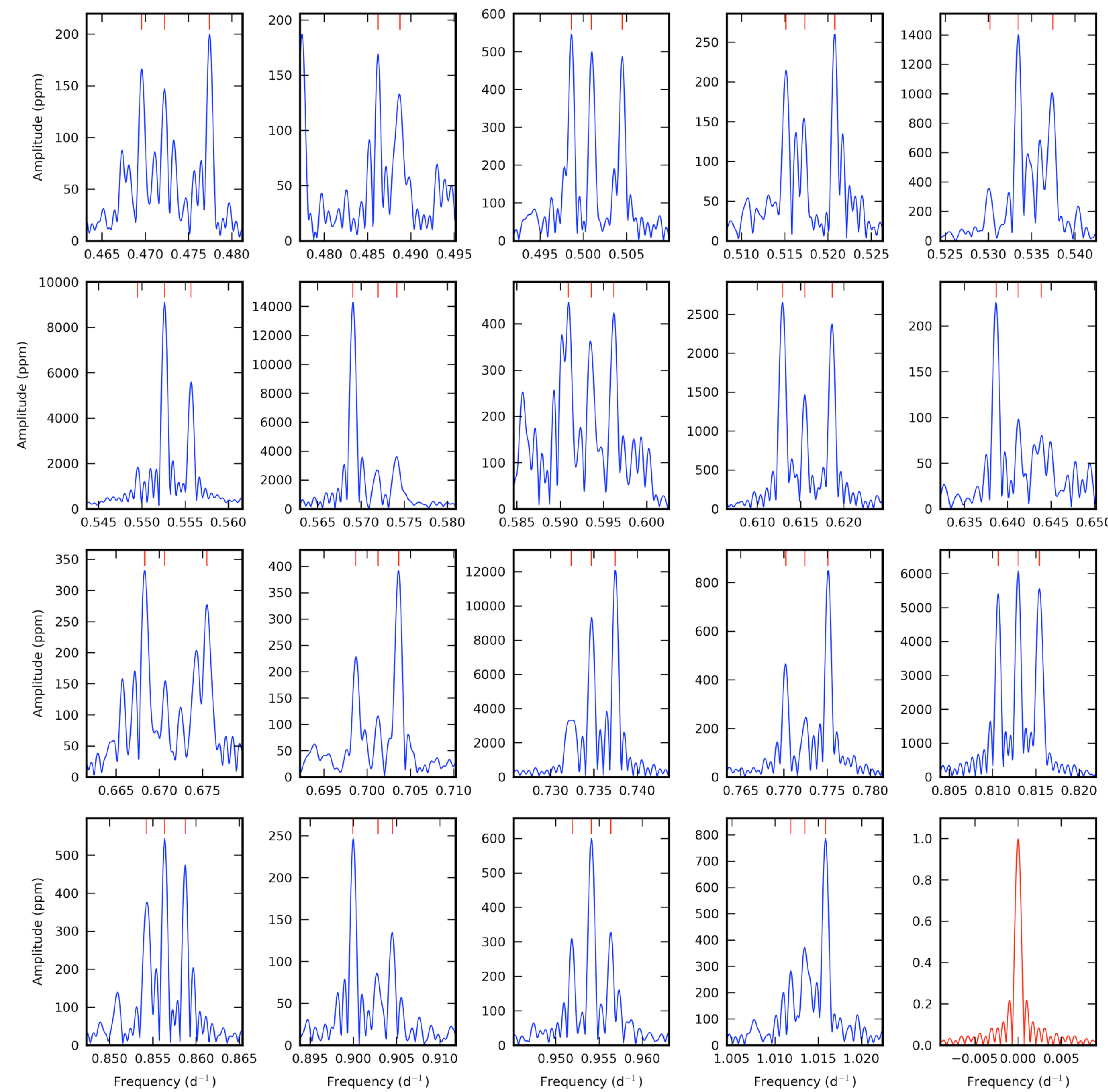
KIC 10526294 [**Pápics et al. 2014**, Moravveji et al. 2015, Triana et al. 2015]

The first actual **seismic modelling** of an SPB star

19 rotationally split gravity modes with nearly equal period spacing (5428 sec)

- Observed trend in splittings -> non-rigid internal rotation profile
- Extremely slow rotator, ***v* sin *i* ≤ 7 km s^{-1}**





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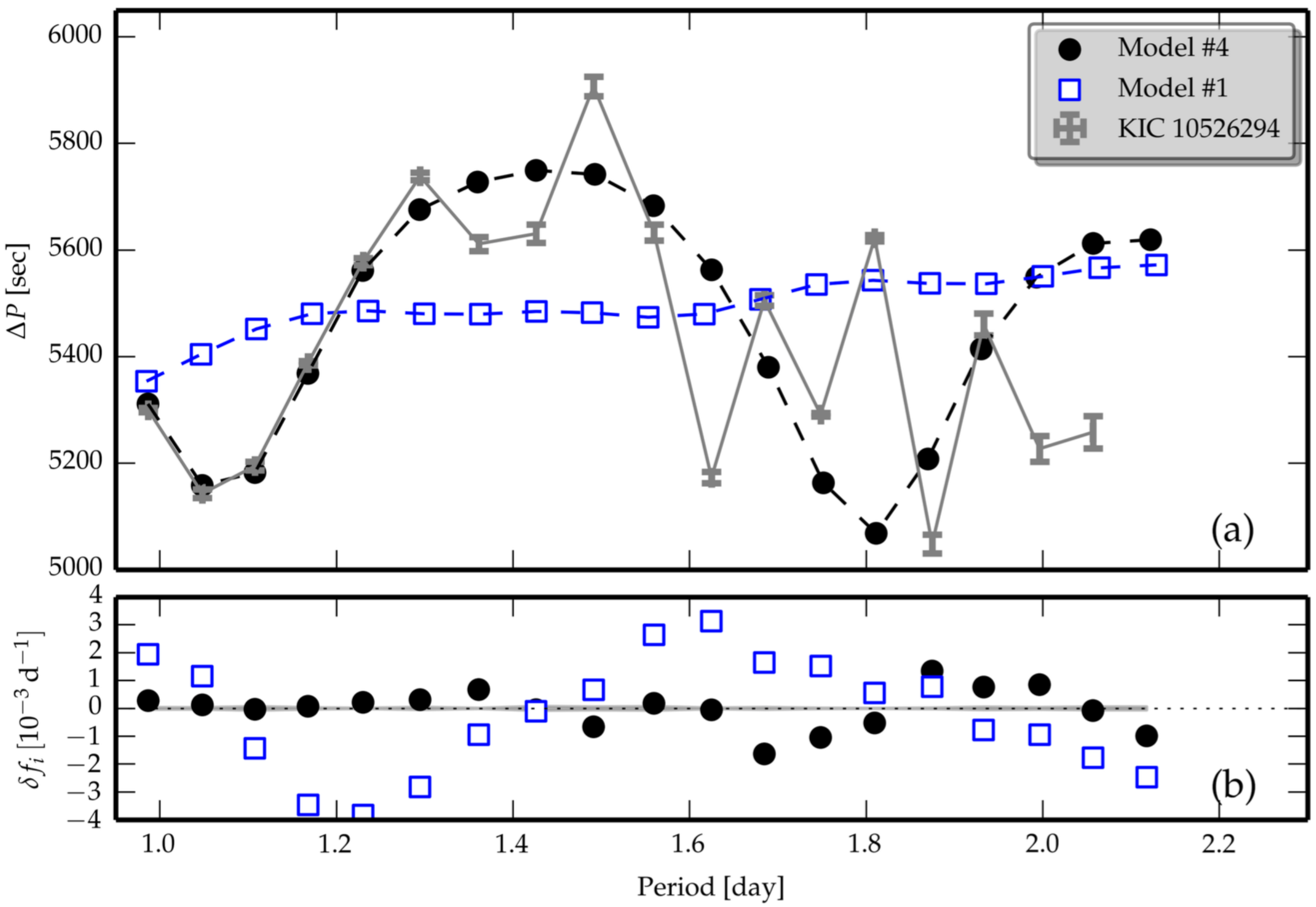
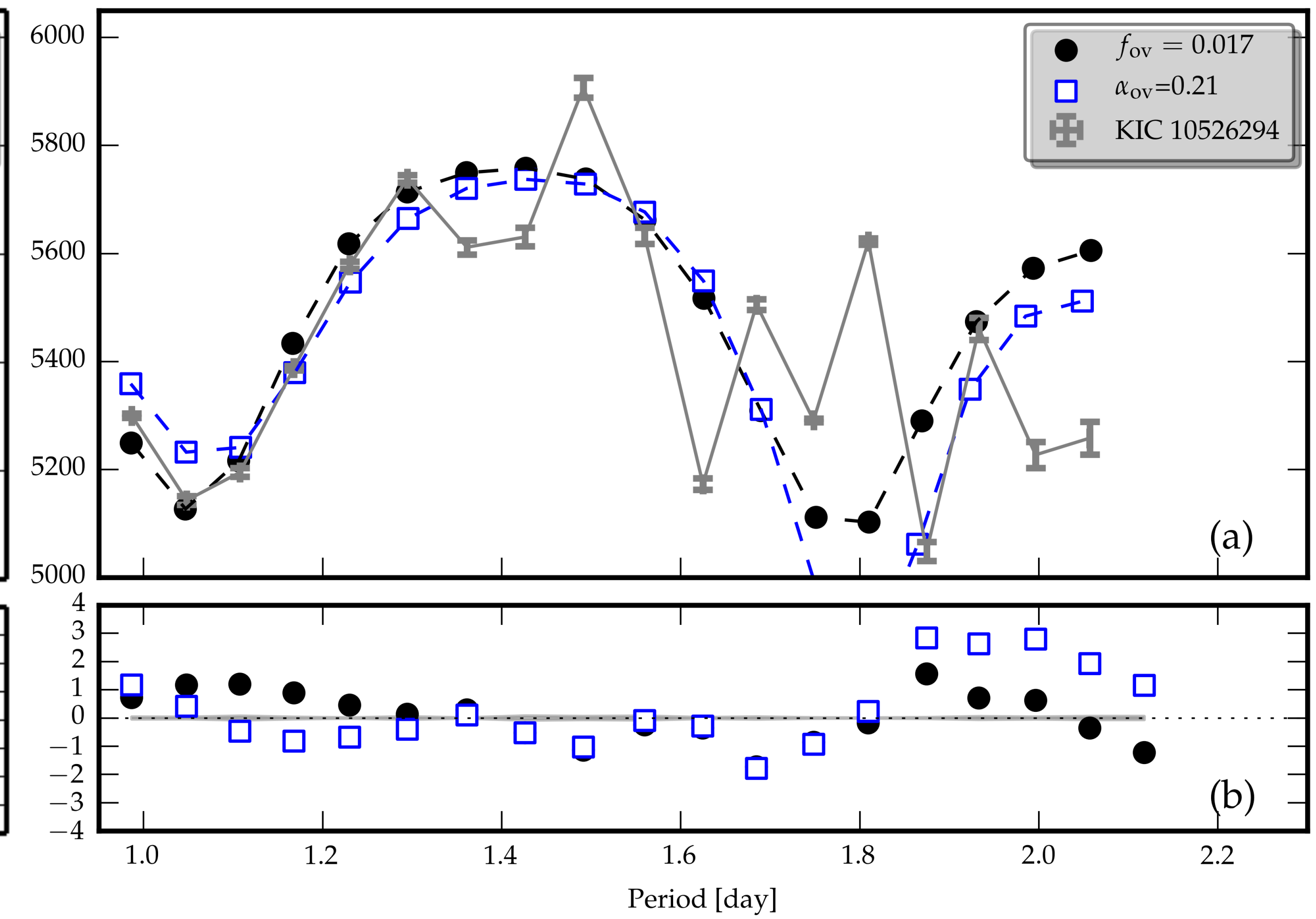
The first actual **seismic modelling** of an SPB star

- Extra **diffusive mixing** (**log D_{mix} = 1.75-2.00**) improves the fit by a factor of ~11
- **Exponentially decaying prescription of overshoot** is the preferred over step-function (**f_{ov} = 0.017-0.018** and $10f_{\text{ov}} \approx \alpha_{\text{ov}}$, factor ~4 improvement).
- Constraints on M(Z), R, and age (best model at **3.25 M_{Sun}, X_c = 0.627**)
- Very high frequency precision: deviation from model < 0.3%





Extending the Timebase with *Kepler*

THE ROSETTA STONE OF SLOWLY ROTATING SPB STARS

KIC 10526294 [Pápics et al. 2014, Moravveji et al. 2015, **Triana et al. 2015**]

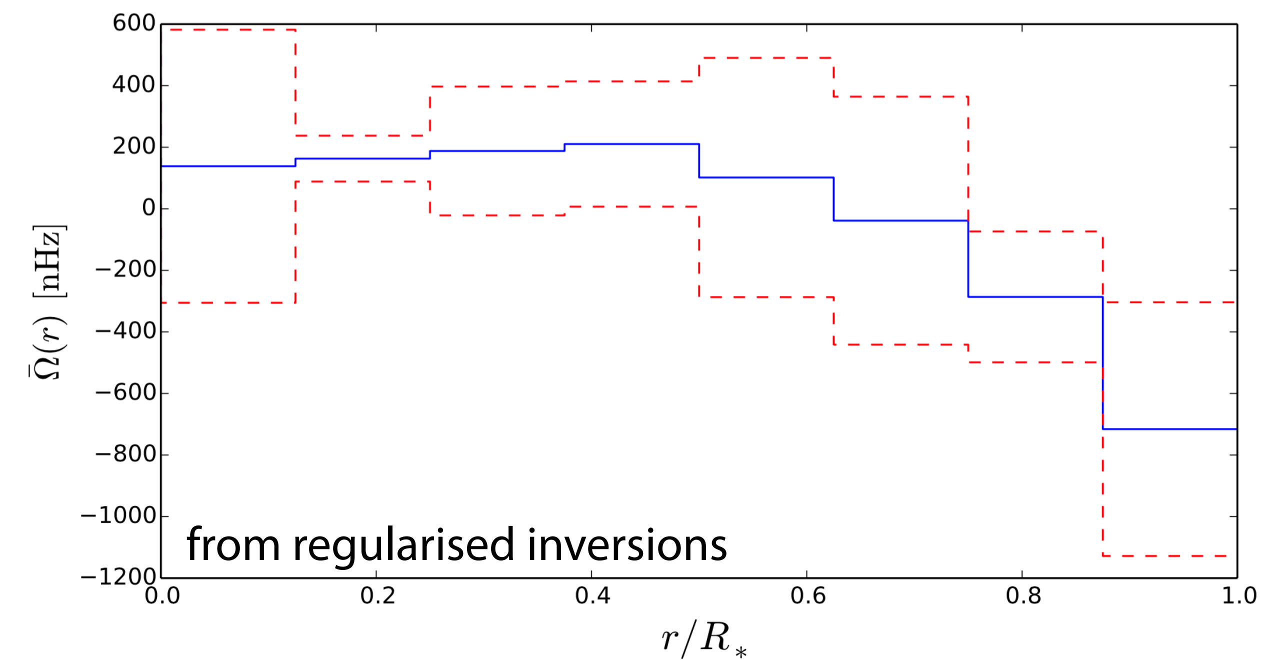
Inversion of the 19 rotationally split dipole modes using kernels from the best seismic model.
Different inversion methods, error sets, and profile function assumptions explored.

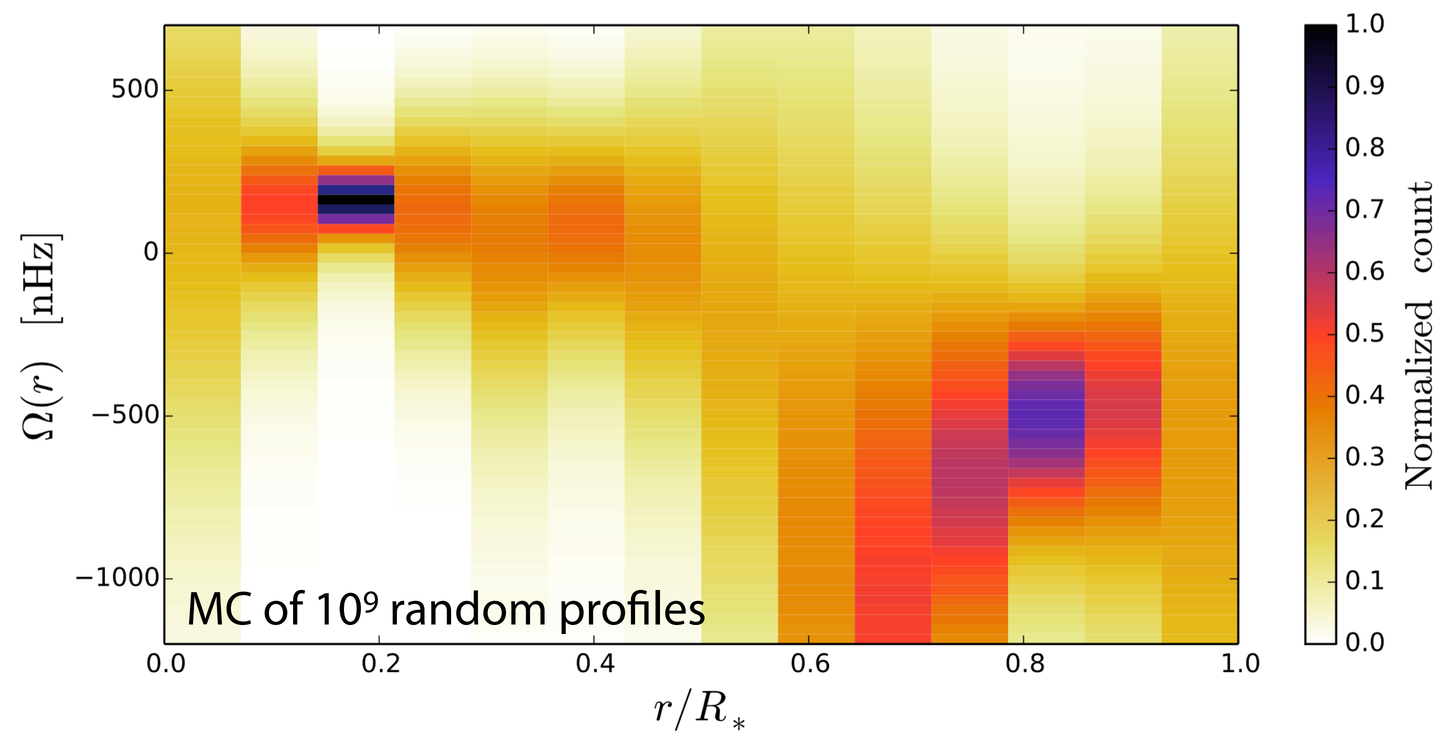
The rotation rate near the core-envelope boundary is well constrained: 163±89 nHz

Envelope rotation is less constrained:
- **solid body rotation at 2σ** level
- **counter rotation at 1σ** level (IGW)

Depth averaged rotation period: 186 days

Earlier results for A-F stars:
- slightly slower core than envelope
  [**Kurtz et al. 2014**]
  [**Schmid et al. 2015**]
  [**Murphy et al. 2016**]
- slightly faster core than envelope
  [**Saio et al. 2015**]
  [**Schmid et al. 2015**]





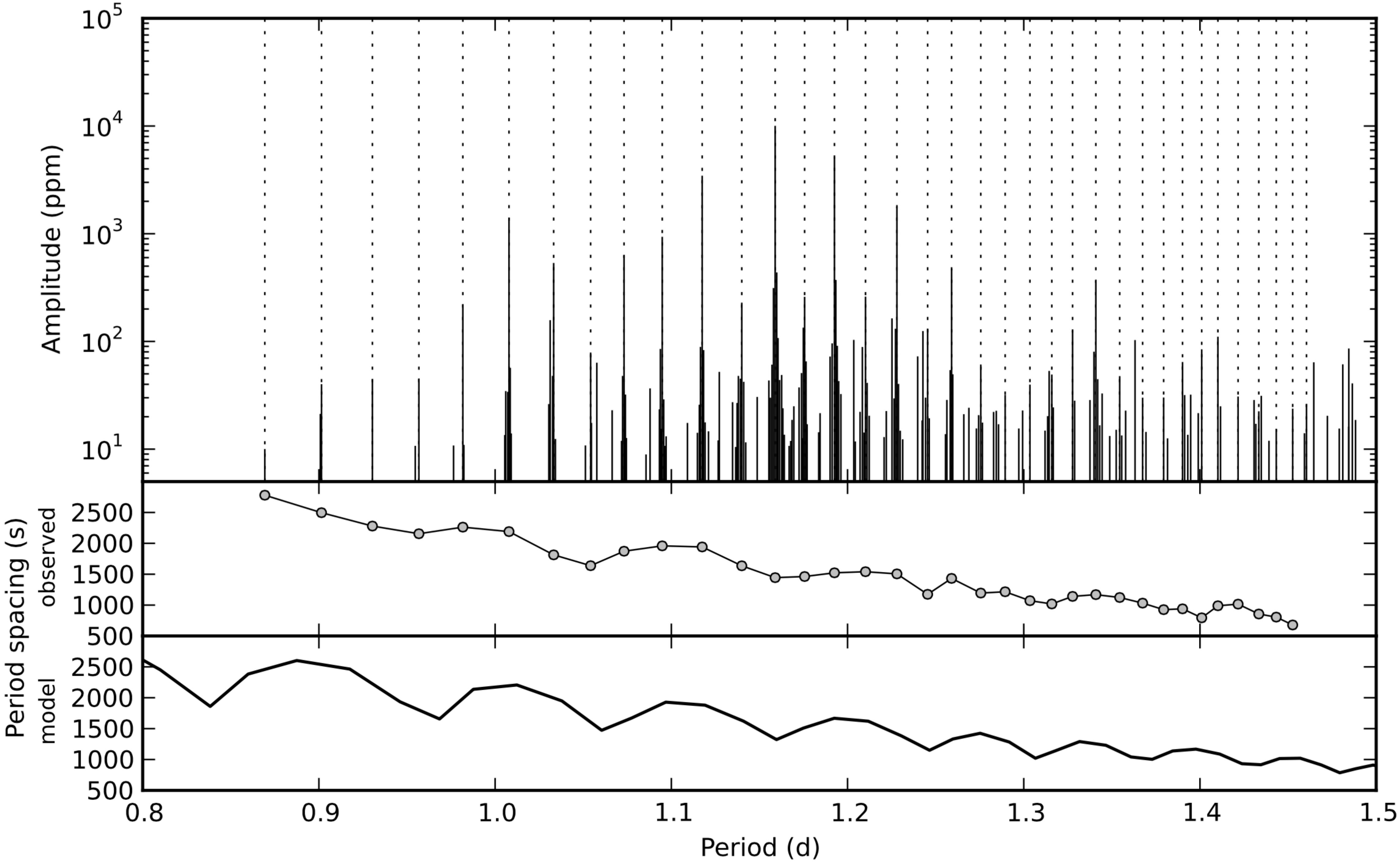
Turning on the Rotation

THE FIRST TILTED PERIOD SERIES

KIC 7760680 [**Pápics et al. 2015**, **Moravveji et al. 2016**]

A faster rotator copy of KIC 10526294 ($v \sin i \sim 62$ km s^{-1})

36 gravity modes ($\ell=1$, $m=1$), period series tilted by **rotation**: $f'=f_0+m\beta_{n\ell}\Omega$



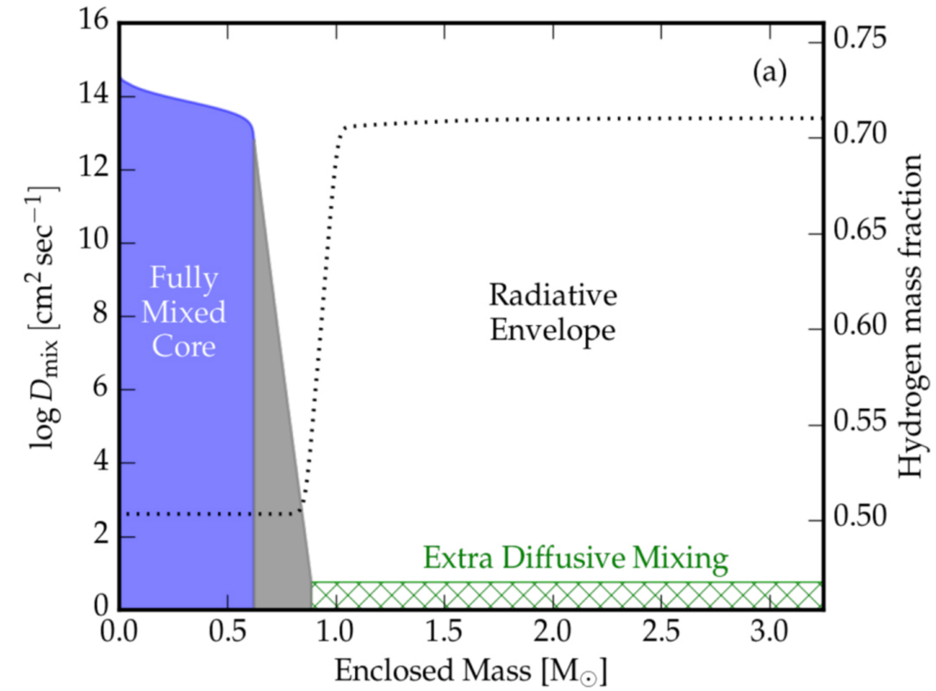
Turning on the Rotation

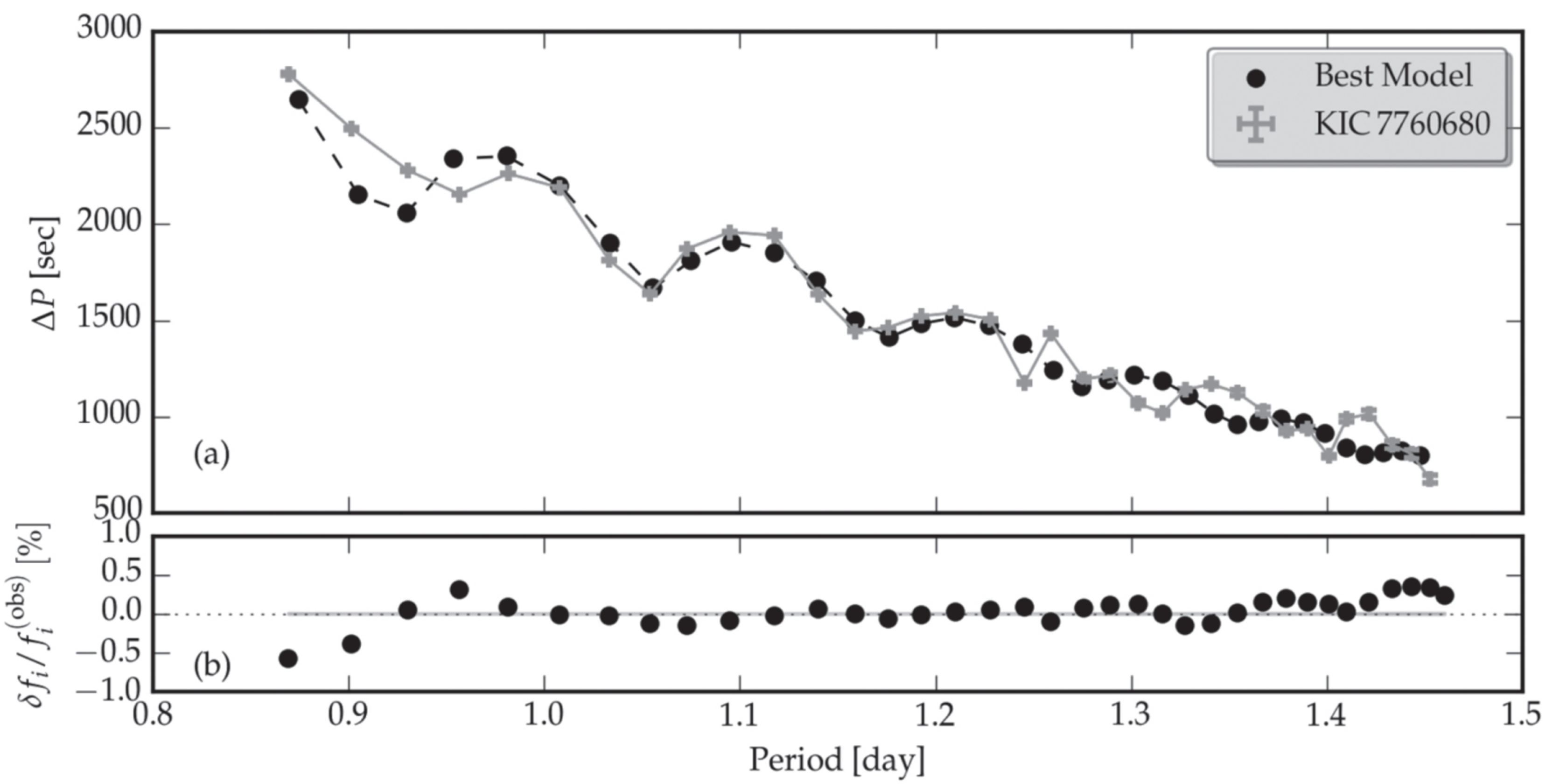
THE FIRST TILTED PERIOD SERIES

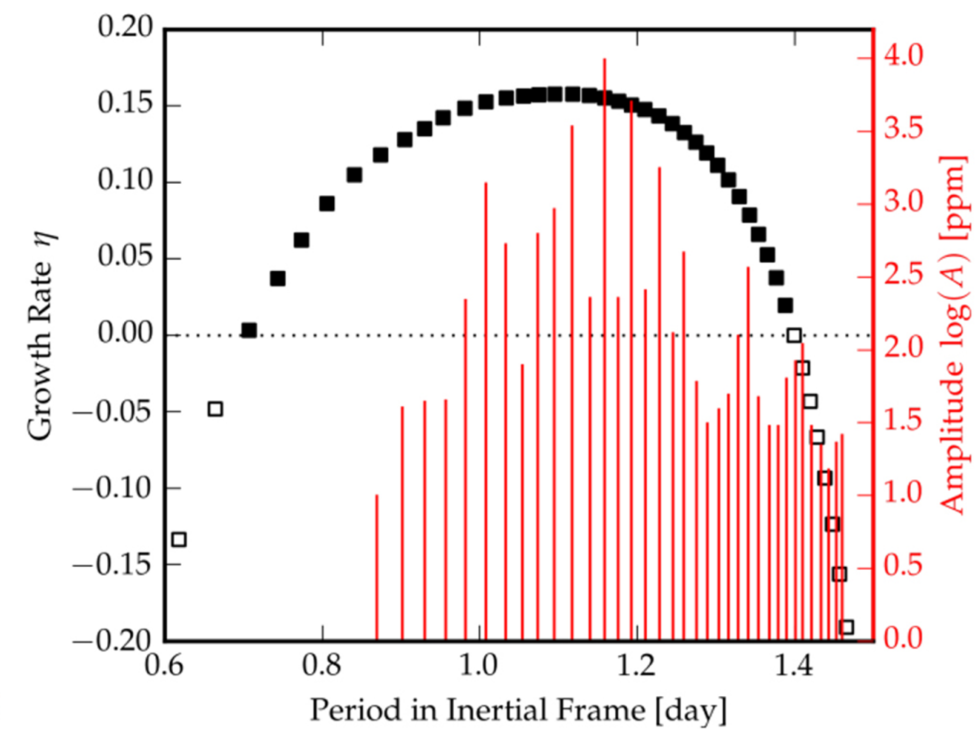
KIC 7760680 [Pápics et al. 2015, Moravveji et al. 2016]

Forward modelling results

- **3.25 M_{Sun}**
- **f_{rot} = 0.4805 d^{-1}** (26% critical, $i \approx 80°$)
- **f_{ov} = 0.024 ± 0.001**
- **logD_{ext} = 0.75 ± 0.25**
- **X_c = 0.503**
- Very high frequency precision: deviation from model < 0.5%







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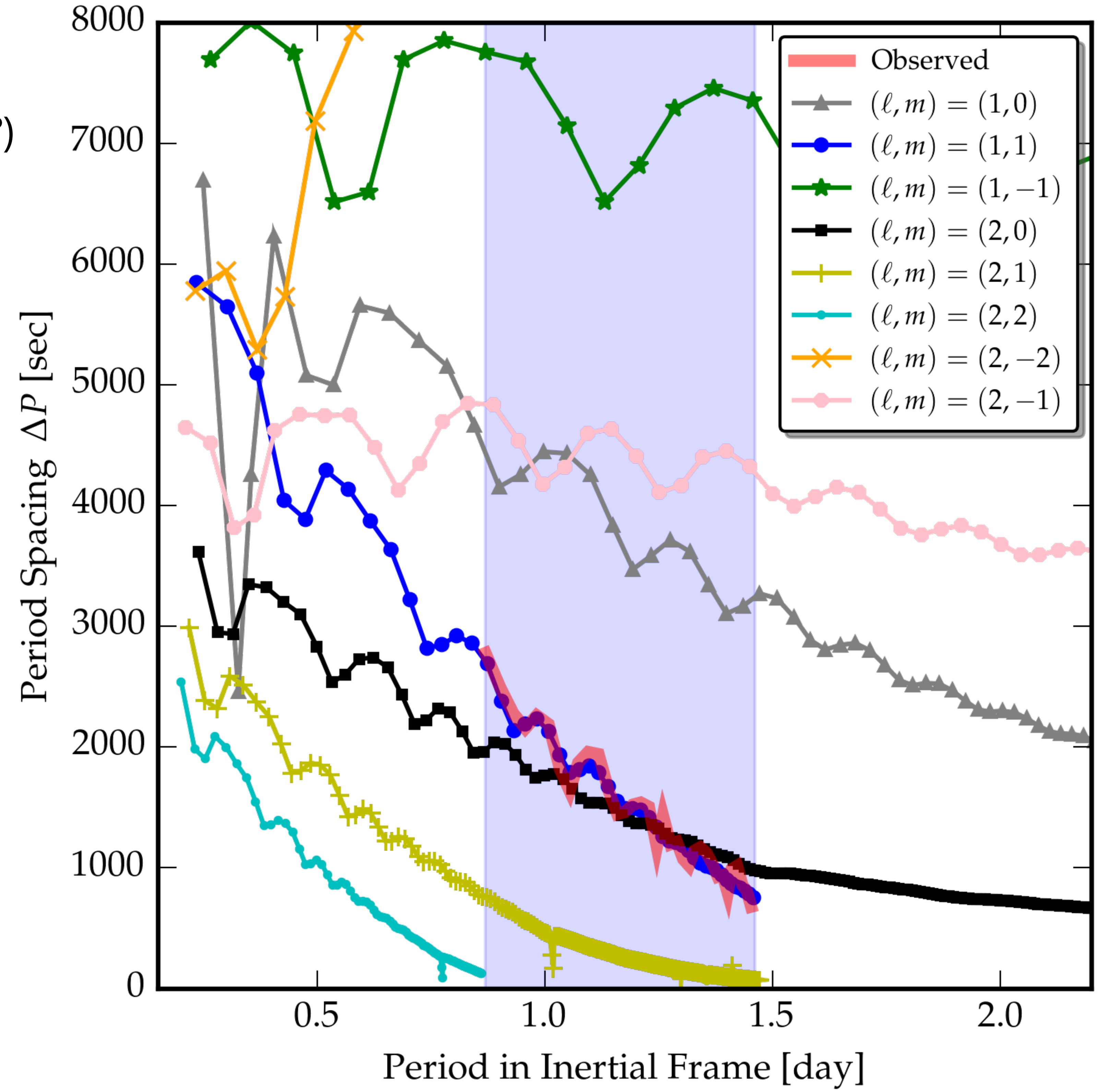
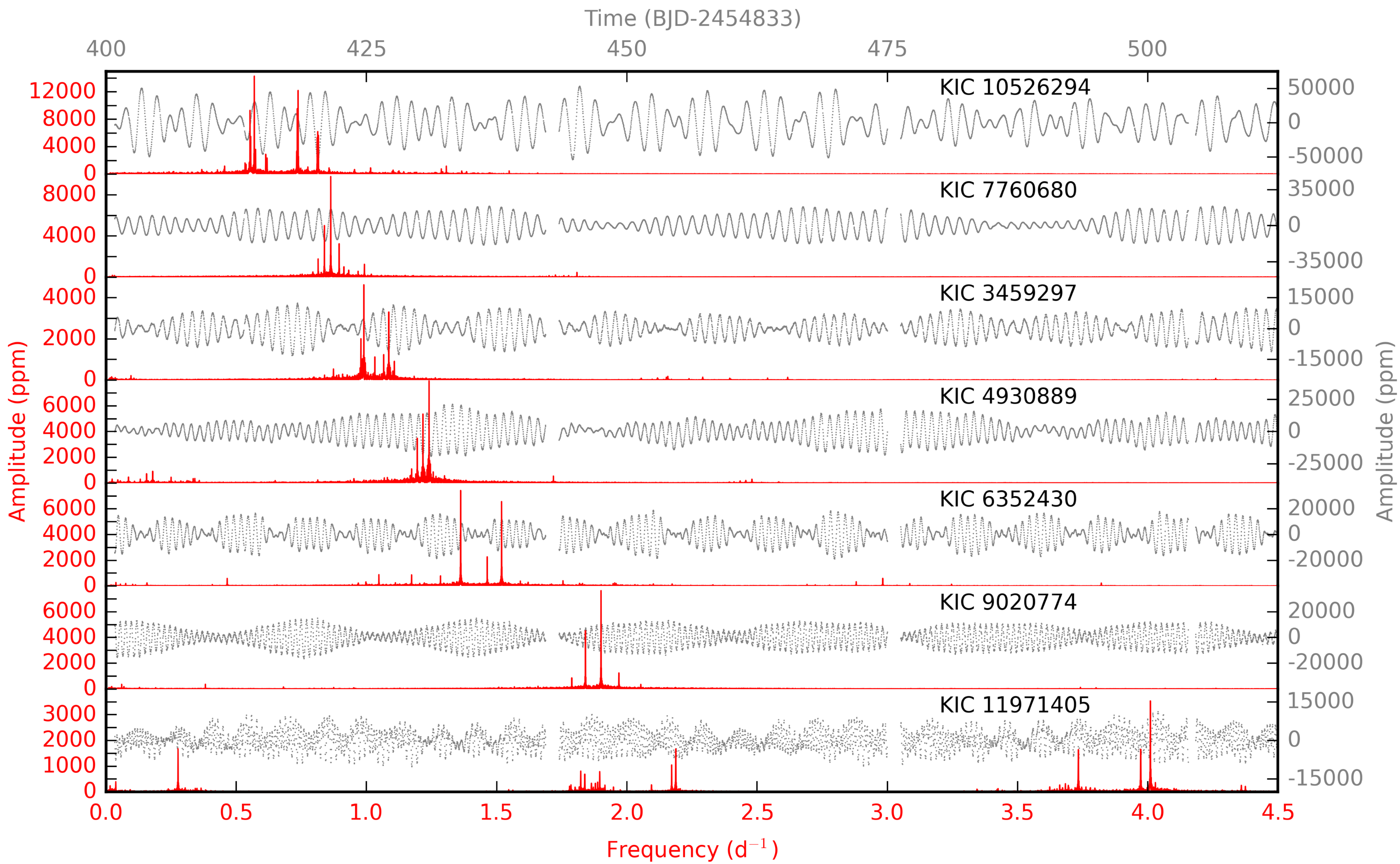


Exploring the *Kepler*-sample

PERIOD SERIES EVERYWHERE

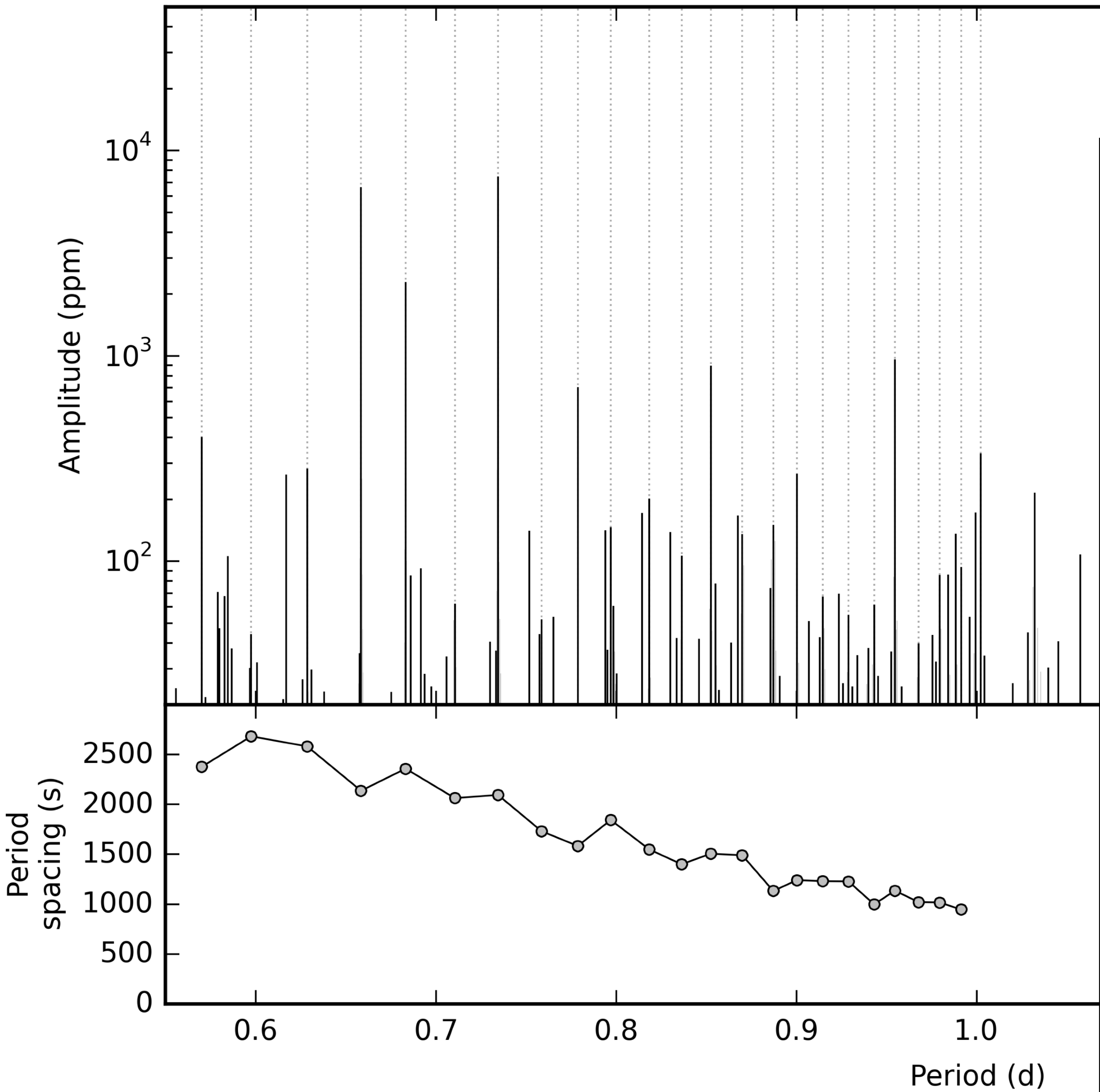
5 new detections at higher rotation rates [**Pápics et al. soon™**]

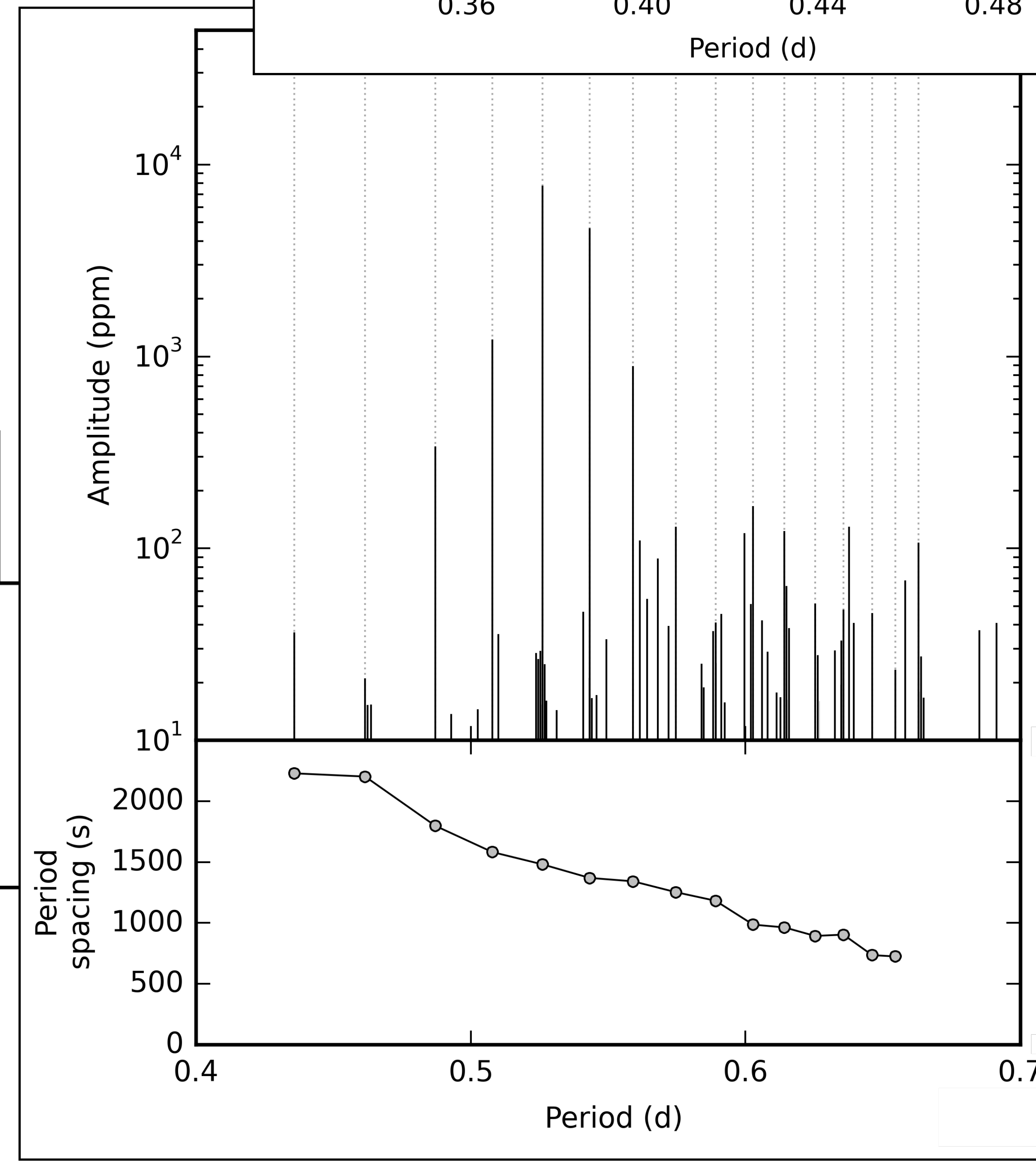


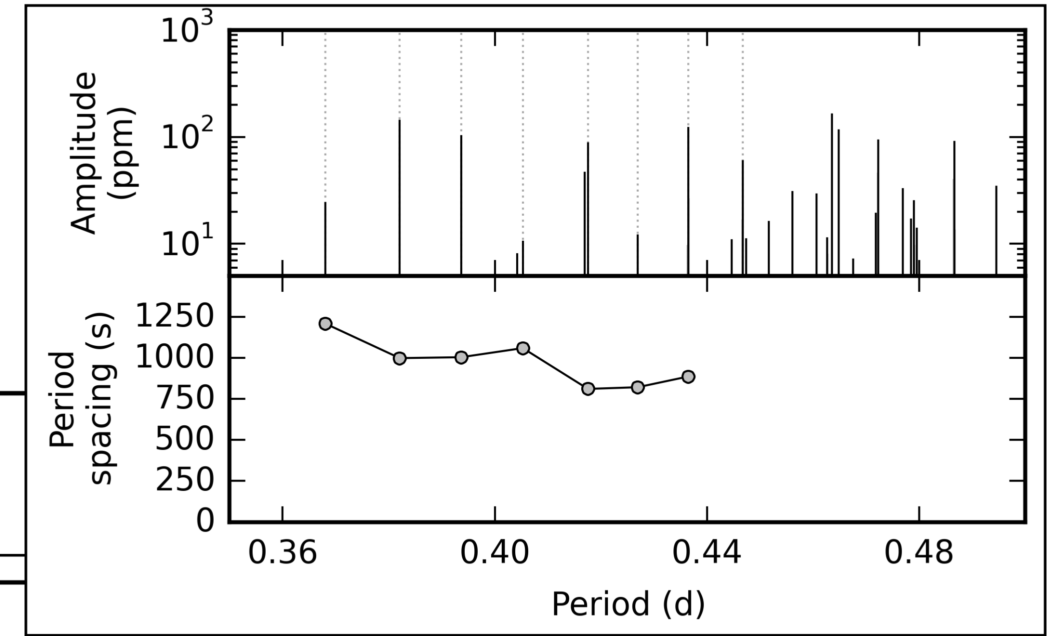
Exploring the *Kepler*-sample

PERIOD SERIES EVERYWHERE

[Pápics et al. soon™]



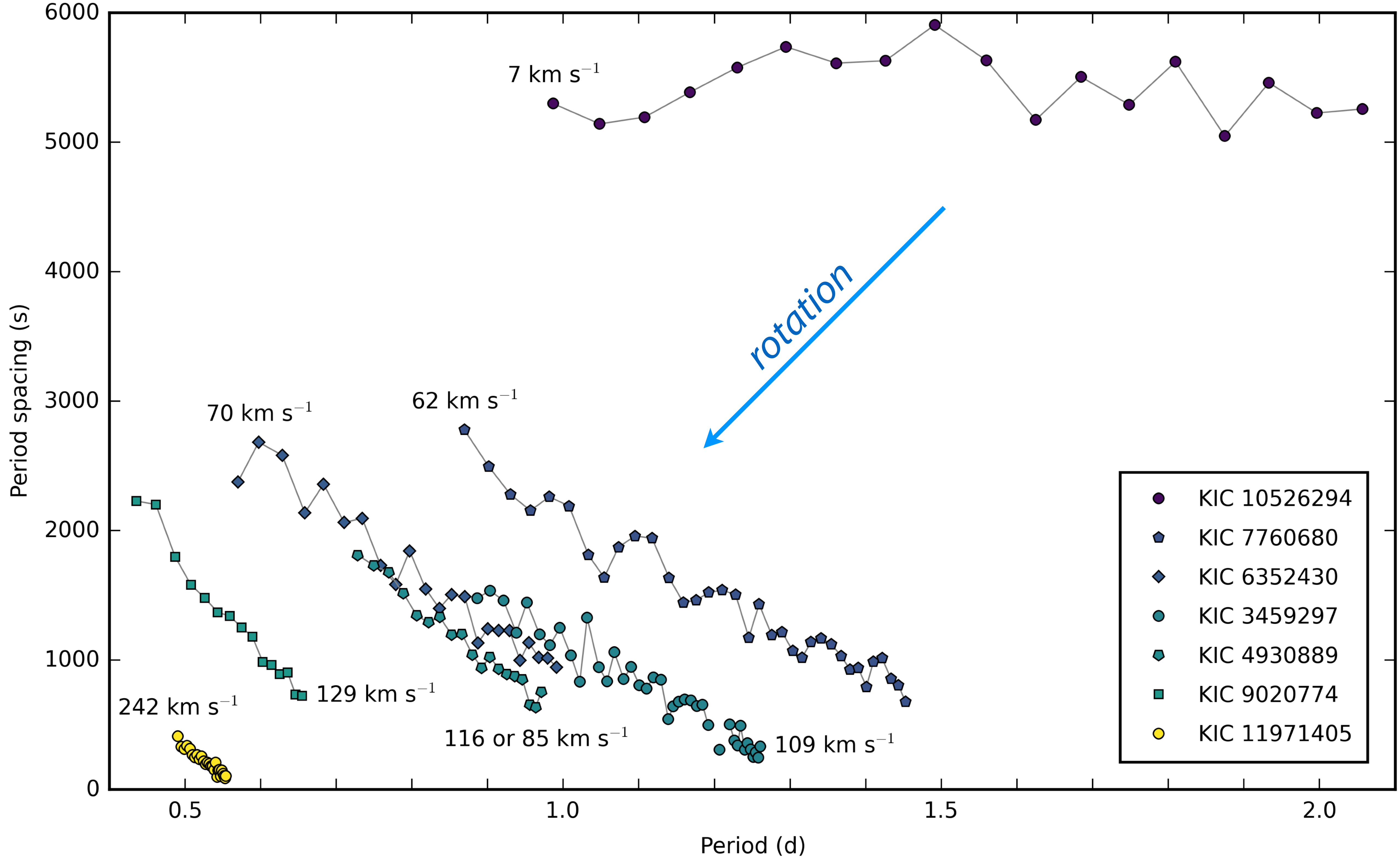




Exploring the *Kepler*-sample

PERIOD SERIES EVERYWHERE

Up to 7 *Kepler* SPB stars with period series [**Pápics et al. soon™**] (ℓ=1, m=1) shown

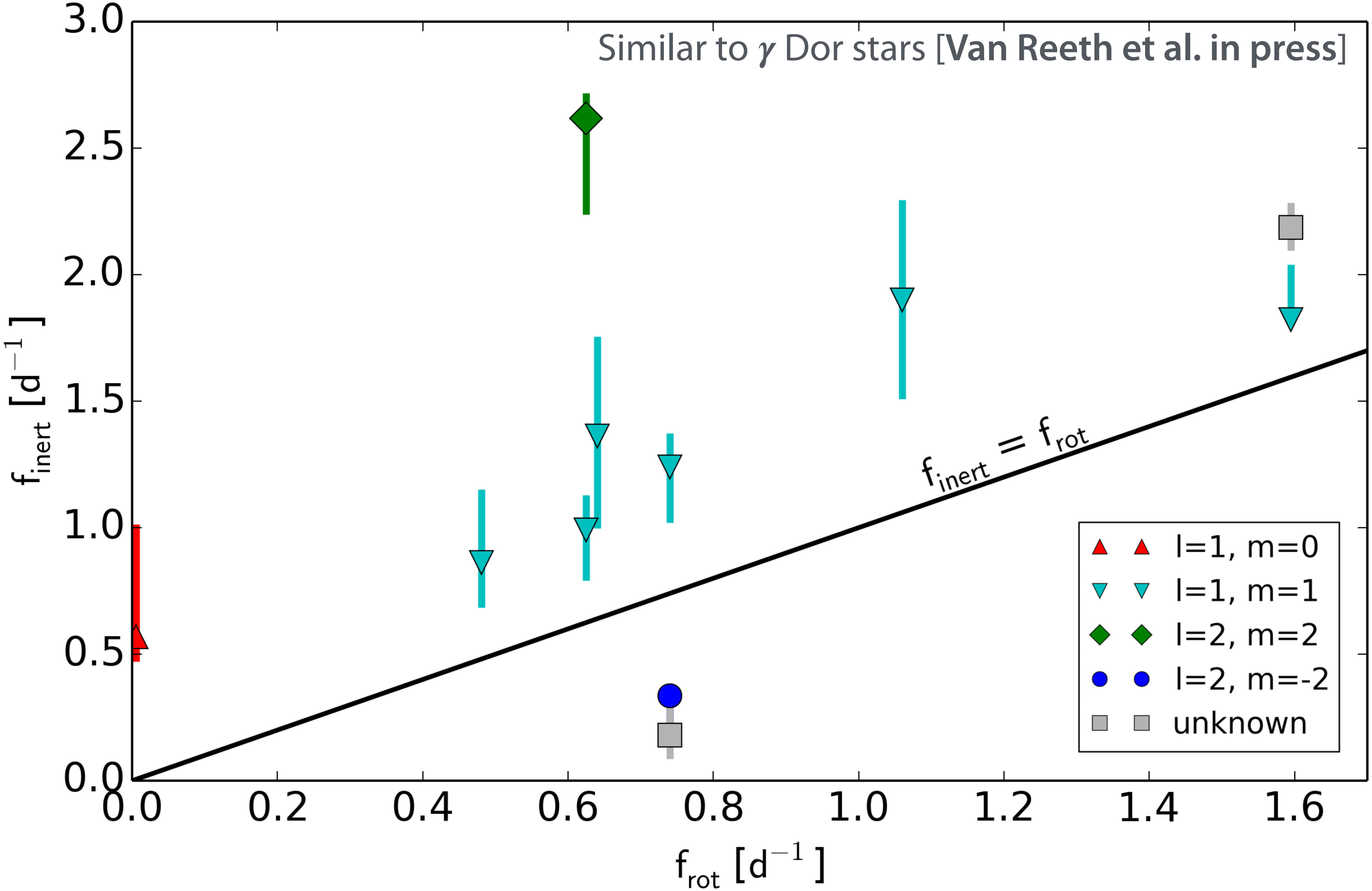


Exploring the *Kepler*-sample

PERIOD SERIES EVERYWHERE

Rotation rates and mode ID from pattern-fitting [**Pápics et al. soon™**]

Mostly prograde dipole modes - agreement with [**Townsend 2003**]

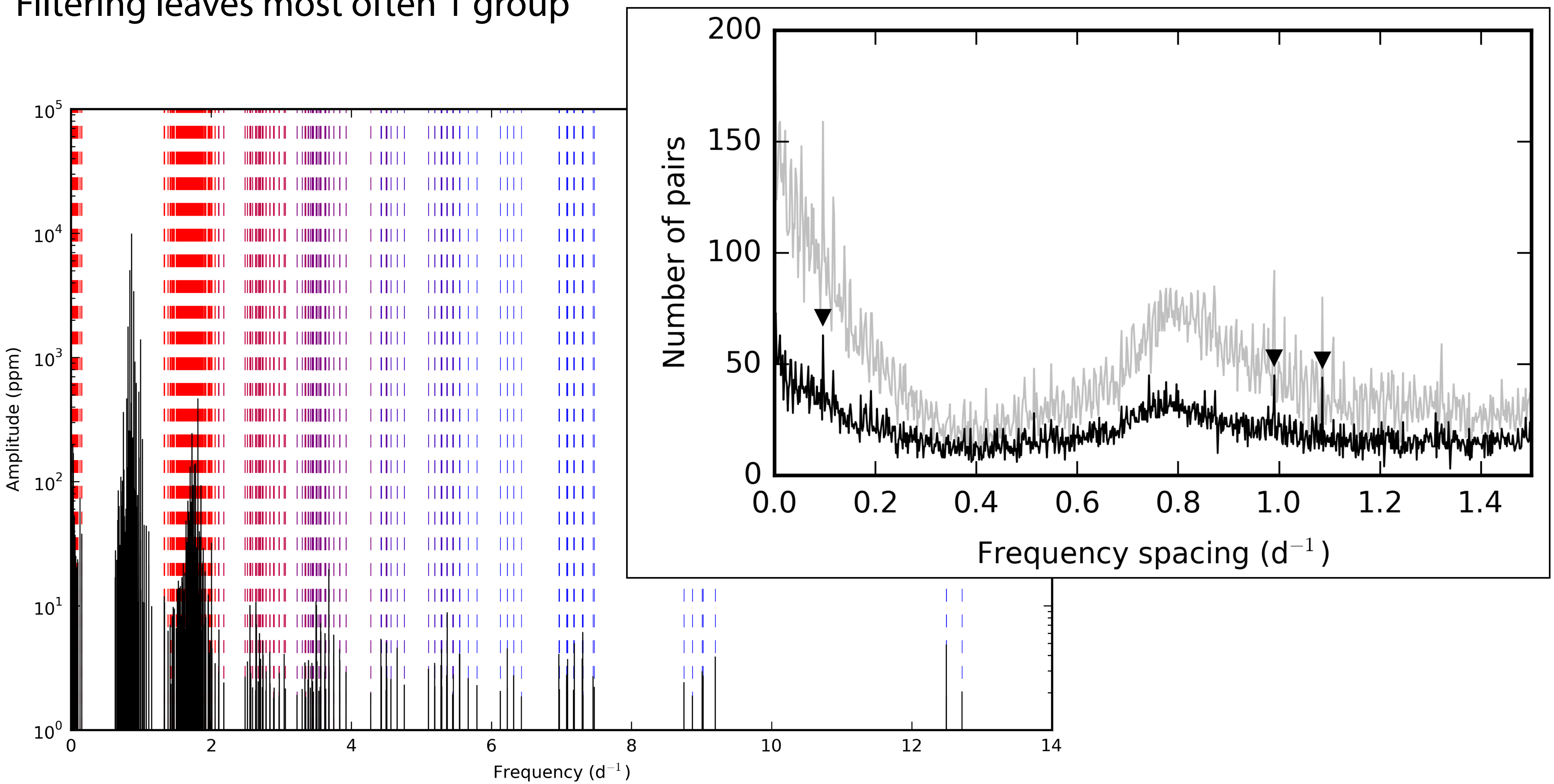


Exploring the *Kepler*-sample

COMBINATION FREQUENCIES

Frequency groups: linear combinations [**Pápics 2012, Kurtz et al. 2015**]

- Mostly low order (simple)
- Almost always stronger parents
- Dominant peaks produce more combinations
- Filtering leaves most often 1 group



Exploring the *Kepler*-sample

WONDERS OF A WEAK Be SPB

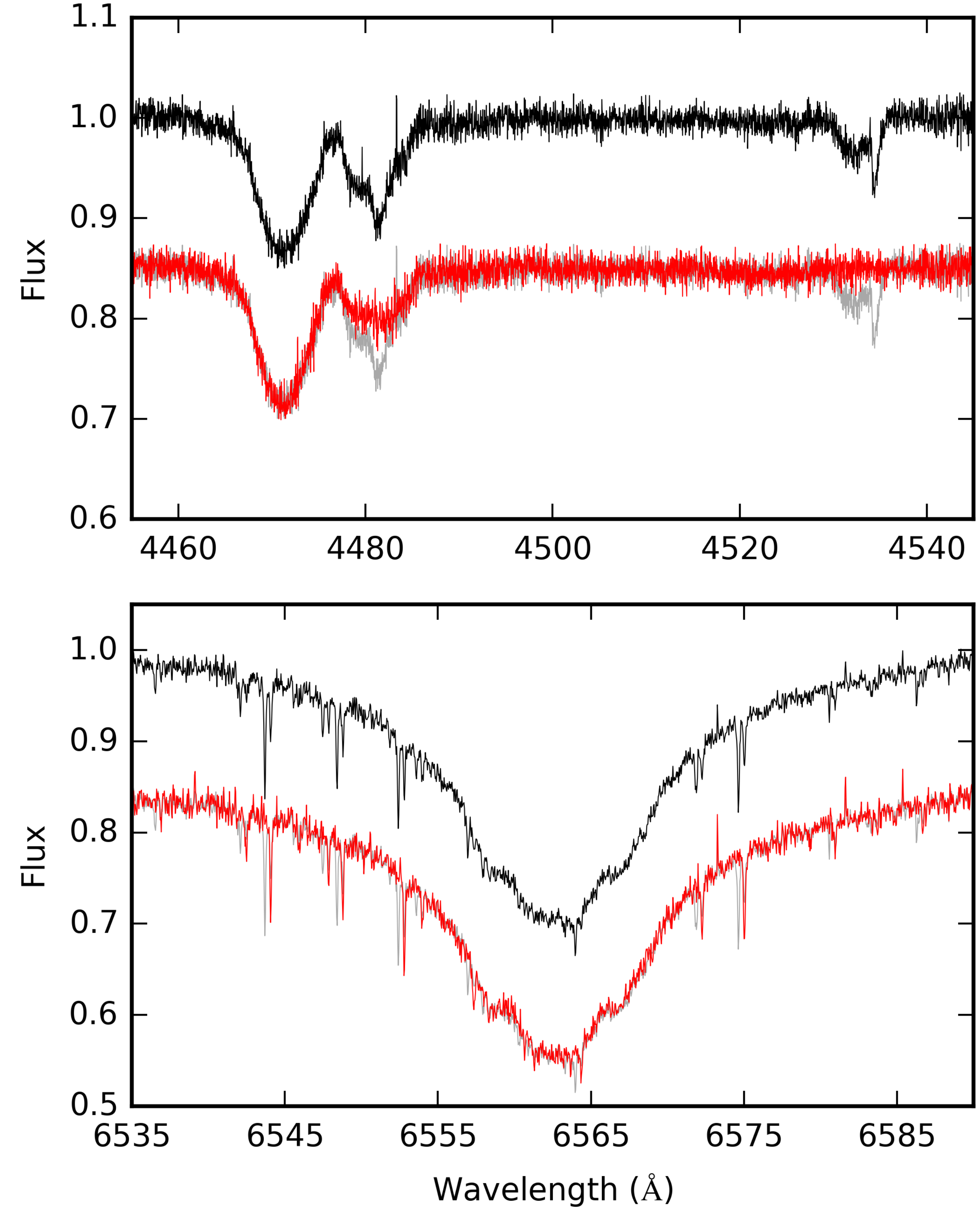
KIC 11971405 [Pápics et al. soon™]

Outbursts found by [**Kurtz et al. 2015**]

Studied also by [**Rivinius et al. in press**]

We have spectra! (2010 and 2015)

Parameter	KIC 11971405
$T_{\rm eff}$ (K)	15100 ± 200
$\log g$ (cgs)	3.94 ± 0.06
$[M/H]$	−0.15 ± 0.14
$v \sin i$ (km s^{-1})	242 ± 14
ξ_t (km s^{-1})	2 (fixed)
Spectral type	B5 IV-Ve
α_{2000}	$19^h42^m48\overset{s}{.}842$
δ_{2000}	$+50°21'39\overset{''}{.}85$
Kepler mag.	9.315

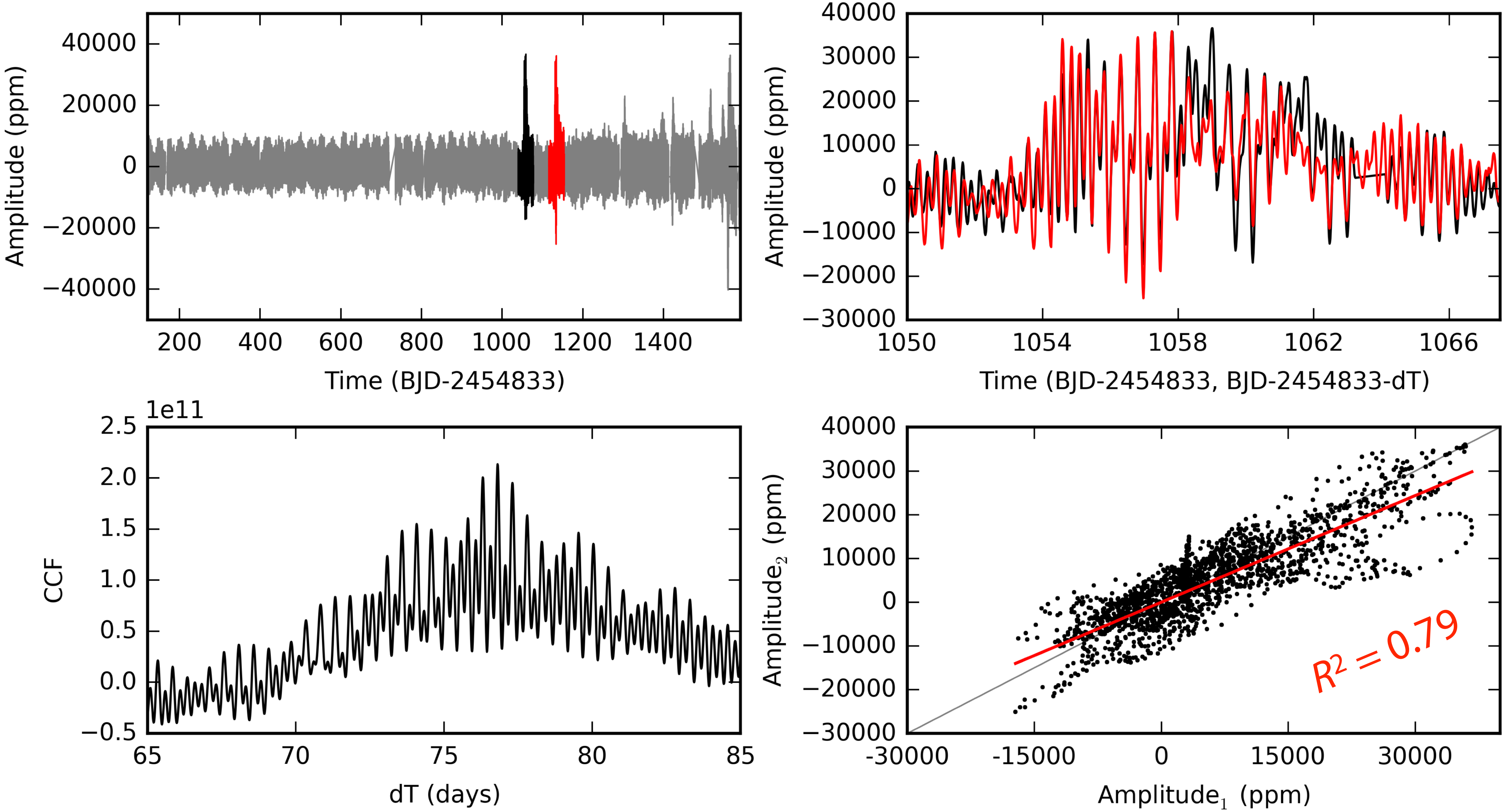


Exploring the *Kepler*-sample

WONDERS OF A WEAK Be SPB

KIC 11971405 [Pápics et al. soon™]

Correlation between the two strong outbursts

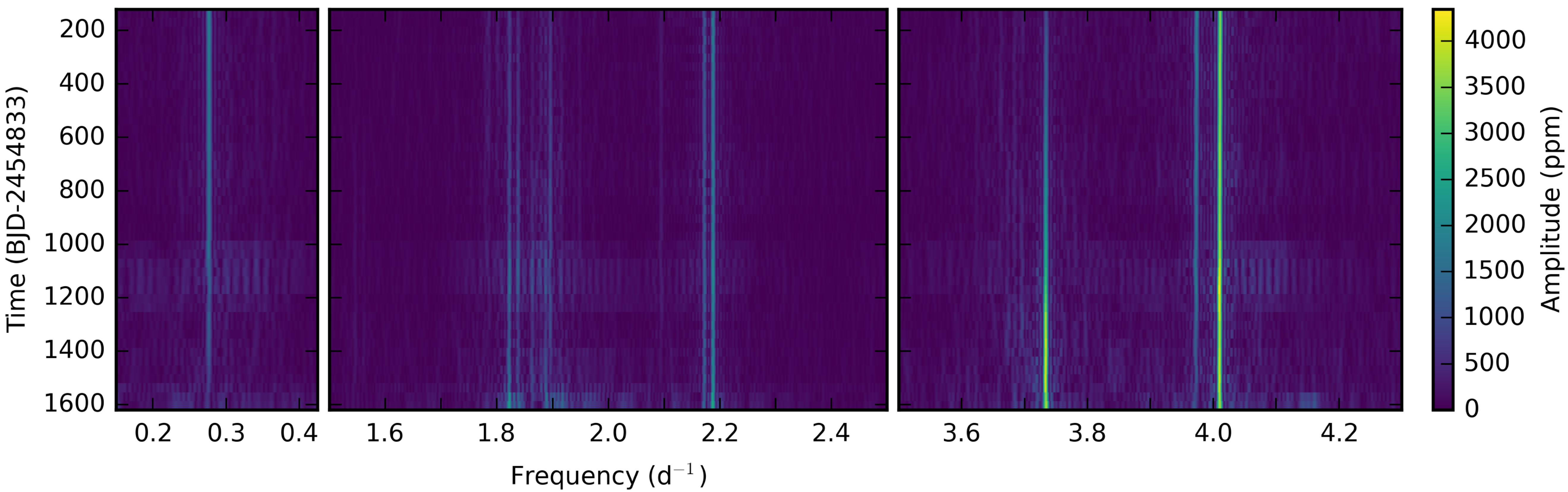


Exploring the *Kepler*-sample

WONDERS OF A WEAK Be SPB

KIC 11971405 [Pápics et al. soon™]

Long-term frequency and amplitude changes



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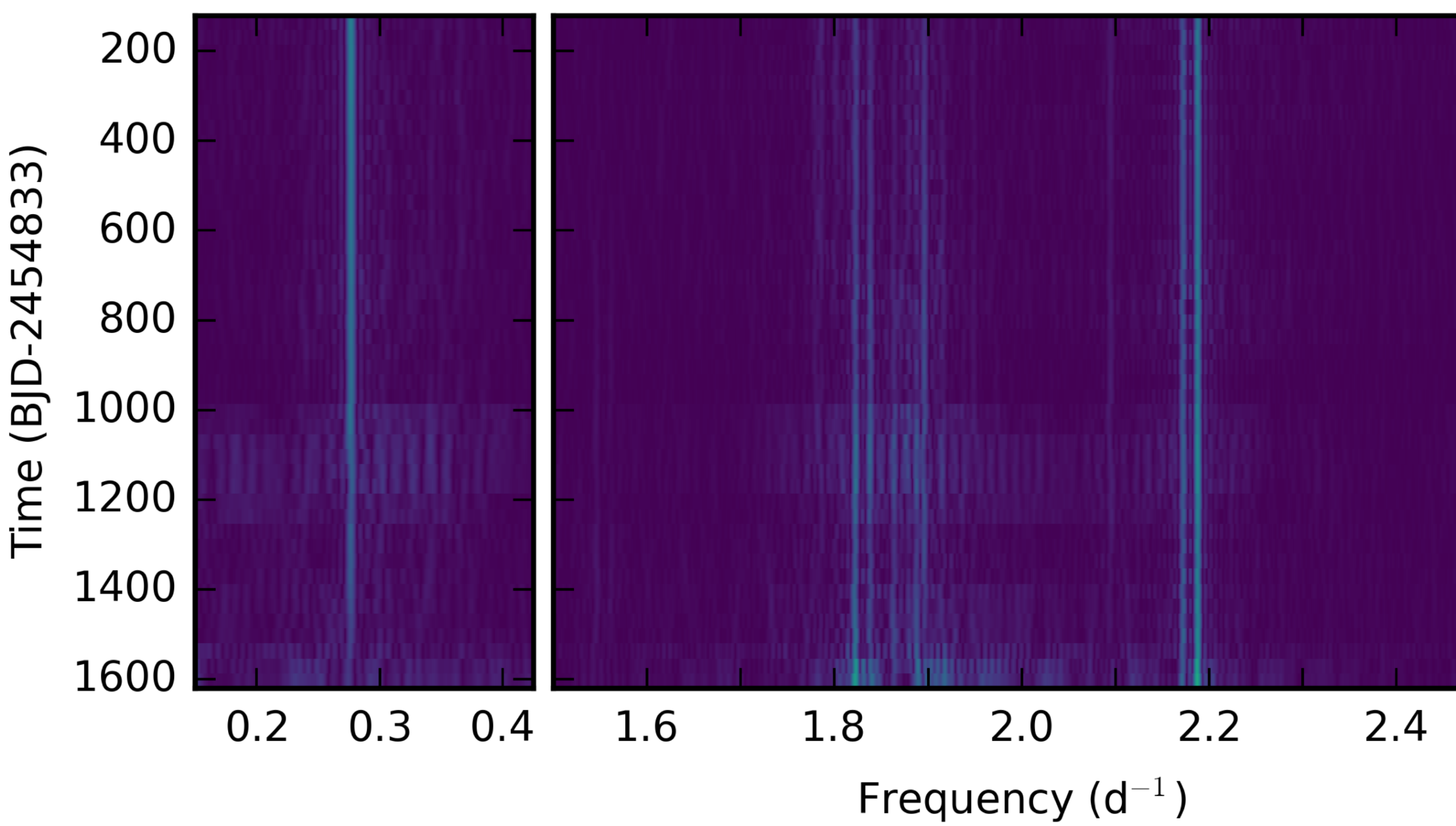

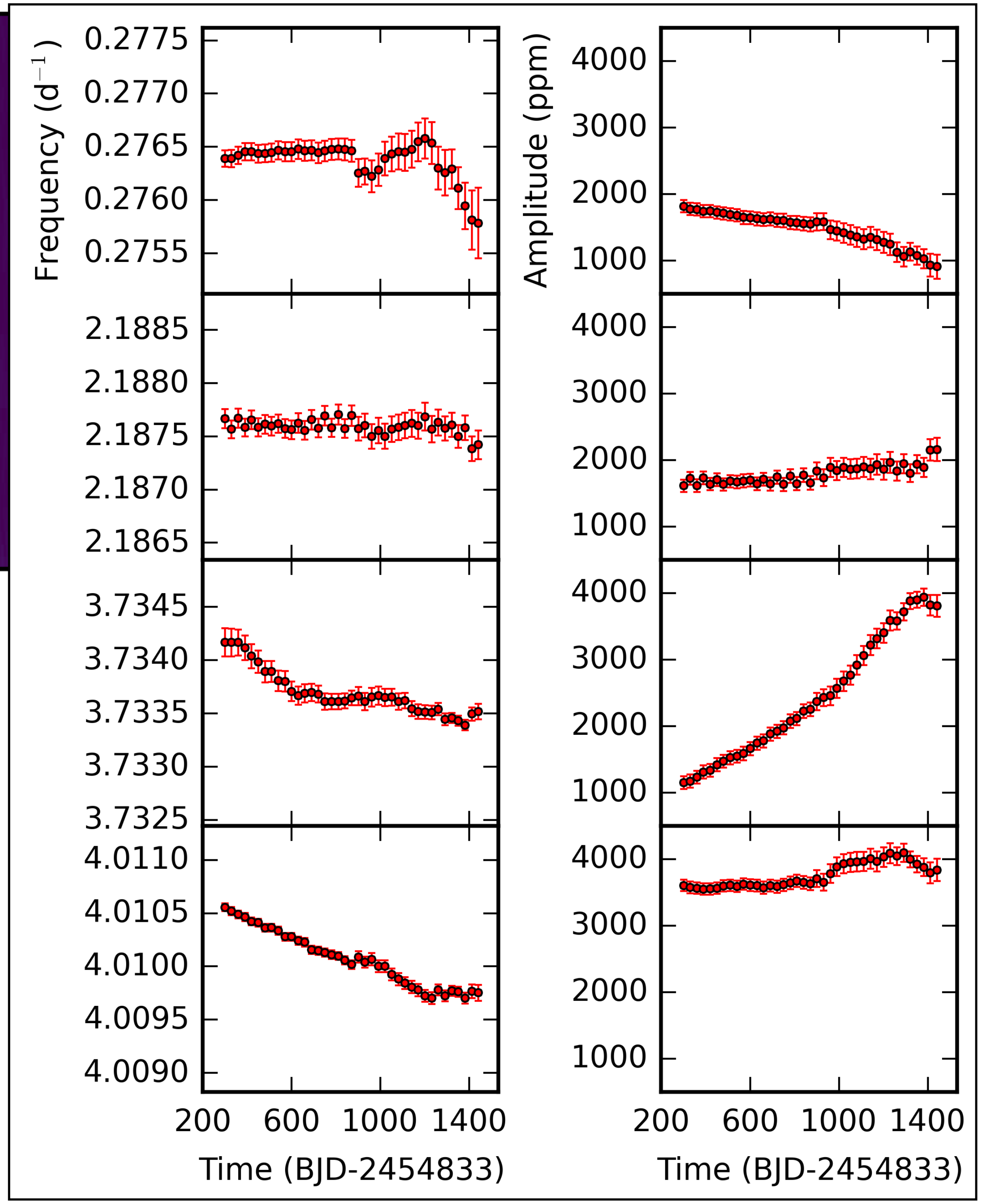

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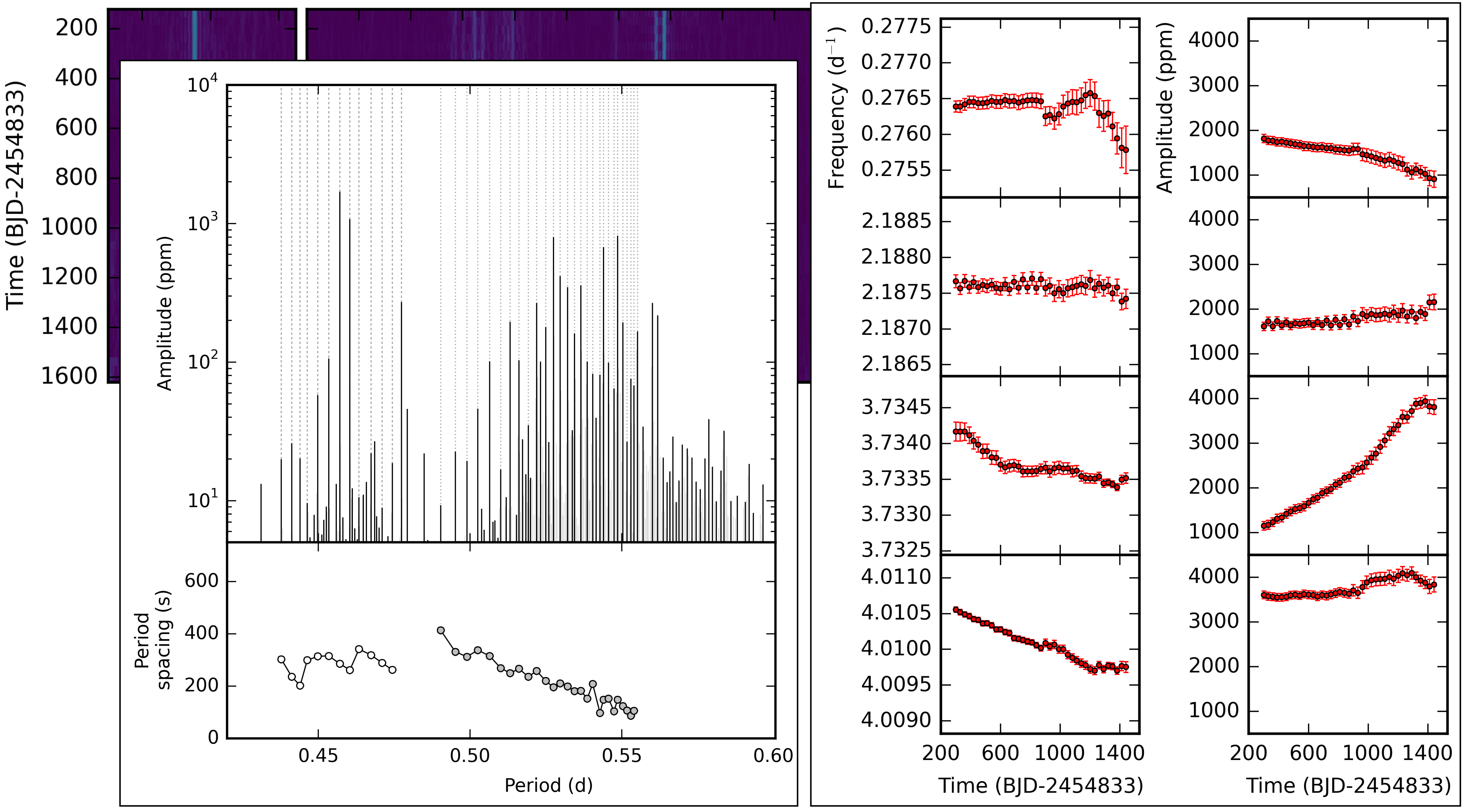


Exploring the *Kepler*-sample

WONDERS OF A WEAK Be SPB

KIC 11971405 [Pápics et al. soon™]

Long-term frequency and amplitude changes

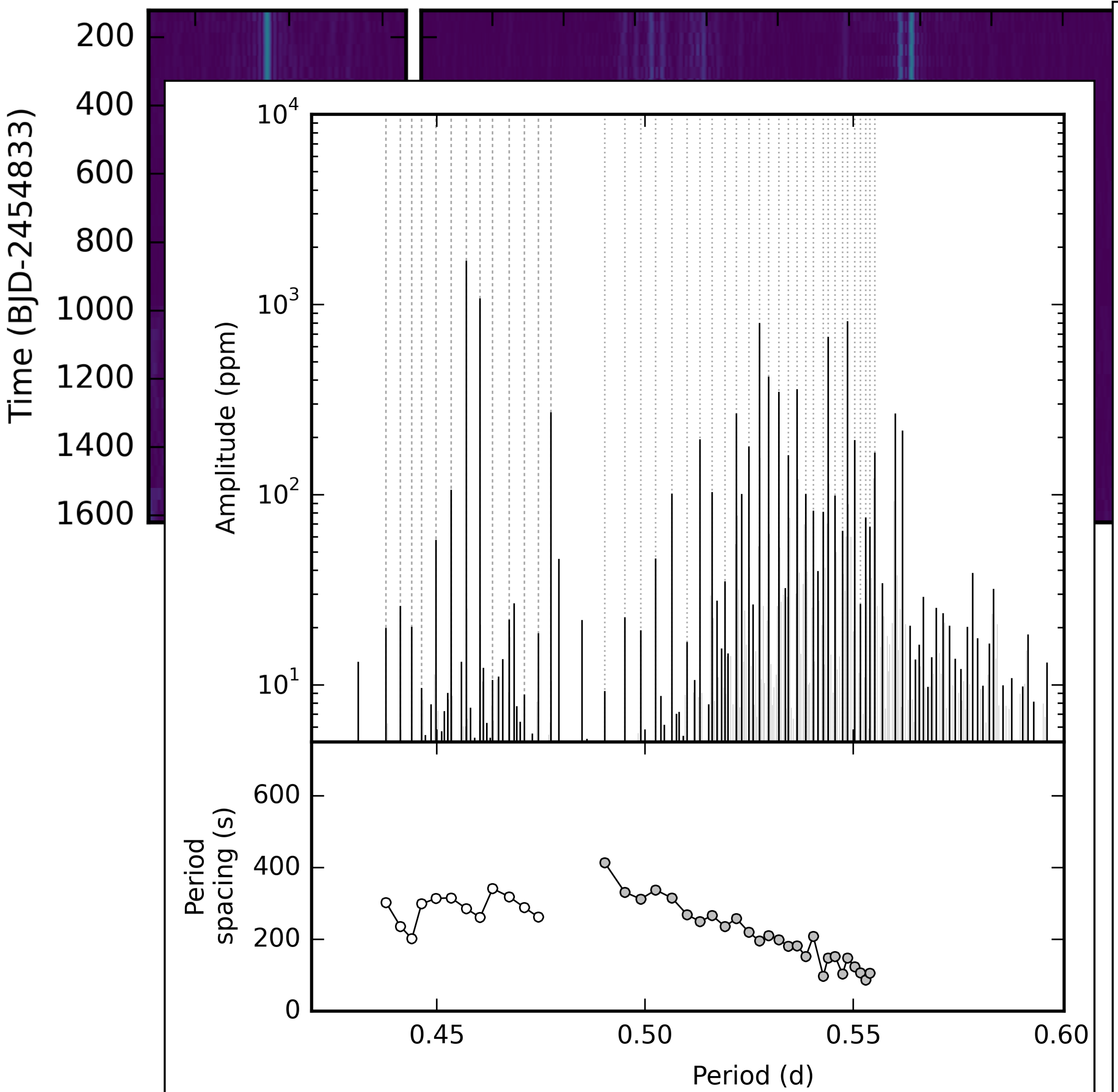
$f_{\mathrm{comb0}} = 4.01030\ \mathrm{d}^{-1}$

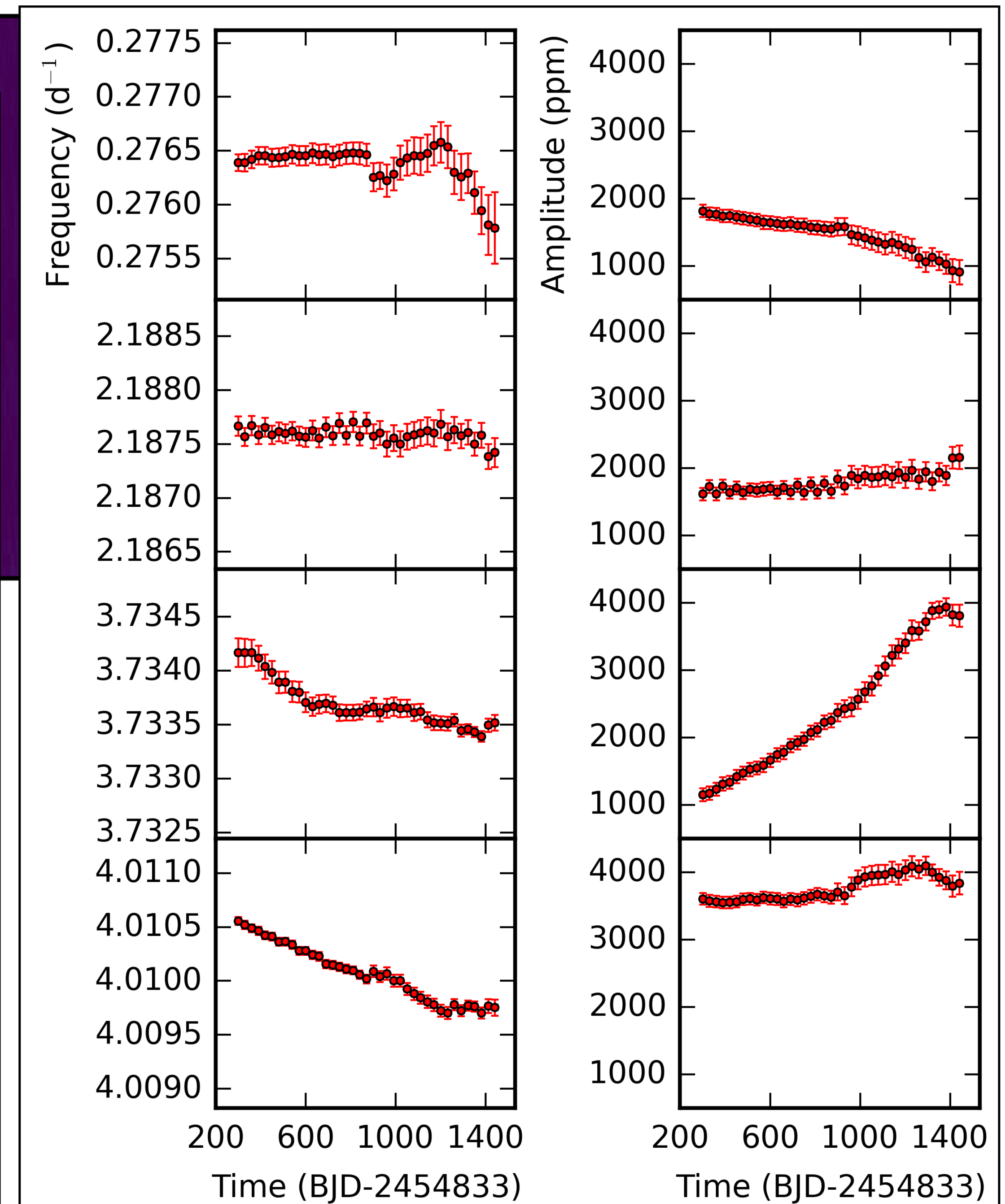
$f_{\mathrm{comb1}} = 1.82267 + 2.18761\ \mathrm{d}^{-1}$

$f_{\mathrm{comb2}} = 1.83831 + 2.17192\ \mathrm{d}^{-1}$

$|\, f_{\mathrm{comb1}} - f_{\mathrm{comb2}} \,| = 0.00004\ \mathrm{d}^{-1}$

Beating of unresolved combination frequencies

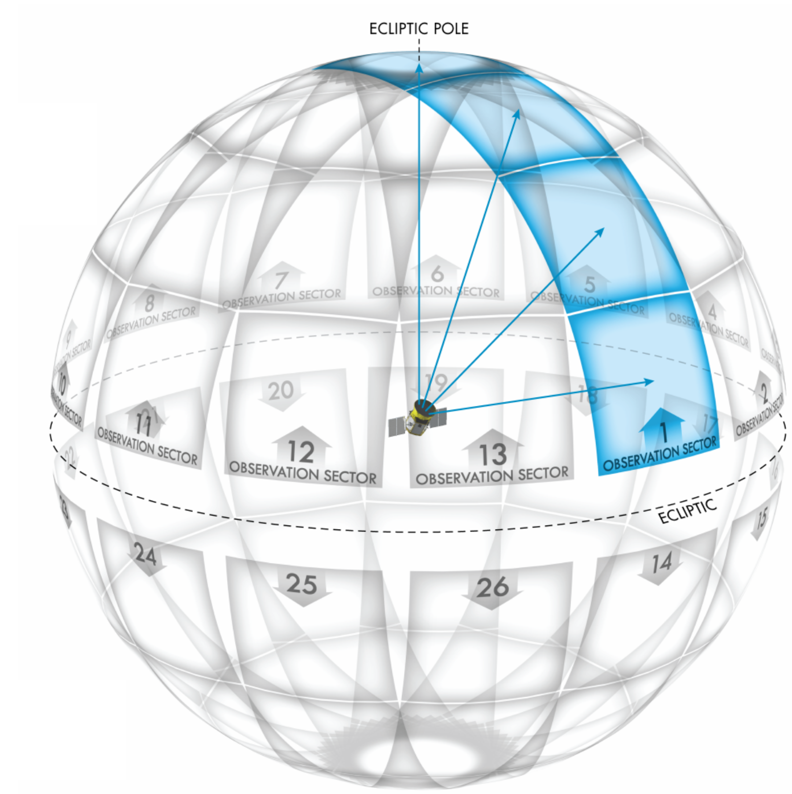




Nota Bene

CONCLUSIONS

- Seismic analysis of SPB stars is still manual work
- Up to 9 known SPB stars with period spacings
- Two fully modelled stars - thanks period spacings!
- Precise constraints on internal mixing parameters
- Five new stars to be done by new PhD students
- We need to extend our sample (*Kepler*, TESS CVZs)
- Improve models (e.g., inclusion of IGWs)



Asteroseismic studies of SPB stars can provide information on the mixing processes inside massive stars on the main sequence.

THANK YOU!

KU LEUVEN

fwo Research Foundation Flanders
Opening new horizons