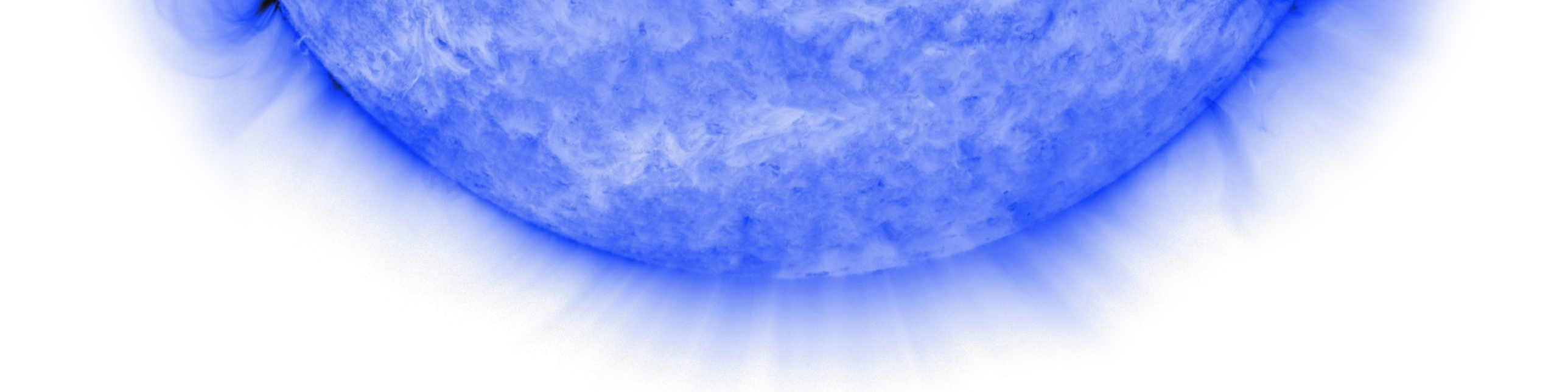


# The internal rotation profile of a gravity mode B star pulsator in the *Kepler* field

## The ups and downs in the forward modelling of 19 quasi-equally spaced rotationally-split dipole modes


Péter I. Pápics | KU Leuven (Belgium)

E. Moravveji, C. Aerts,
A. Tkachenko, S. A. Triana,
S. Bloemen, J. Southworth


CoRoT 3 - KASC 7 Toulouse
08/07/2014

KU LEUVEN

# Introduction

## GOALS

Calibrate stellar structure and evolution models

Cornerstones in stellar astrophysics

GX chemical enrichment, age of Universe, stellar life cycles, planetary system formation, stellar cluster dynamics, etc.

## MASSIVE STARS

Convective core + radiative envelope (on MS)

Important internal **mixing processes**

**Core overshooting**

**Internal differential rotation**

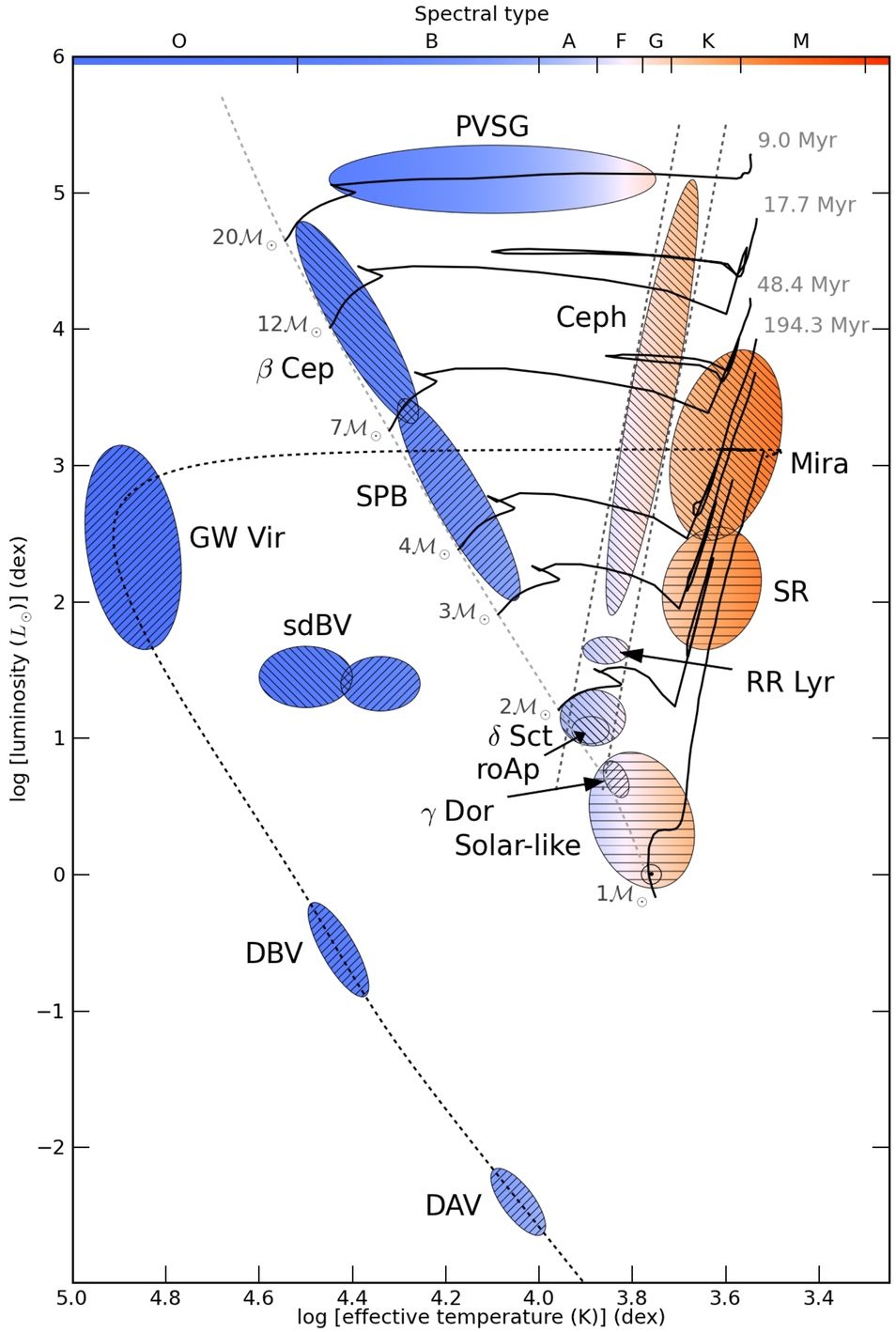
etc.

Many **uncertainties**! -> Effecting the **lifetime**!

Only **12 stars with $\alpha_{ov}$** and **3 with ~Ω(*r*)** so far

Dependence on *magnetic field*? *Mass*?

Contribution to *angular momentum transport*?

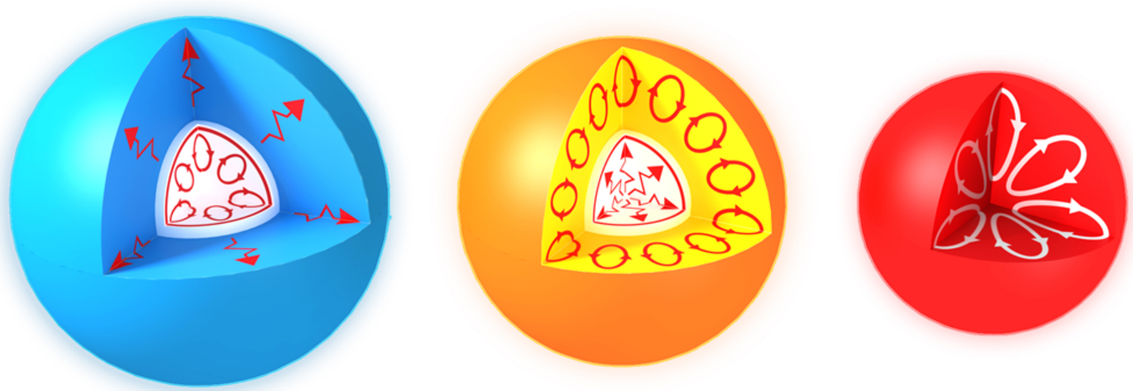



## SPB (SLOWLY PULSATING B STARS)

$M \approx 2.5 - 8\ M_{Sun}$, 11 000 – 22 000 K

High-order gravity modes (P ≈ 0.5 – 3 day)

Characteristic **period spacing**

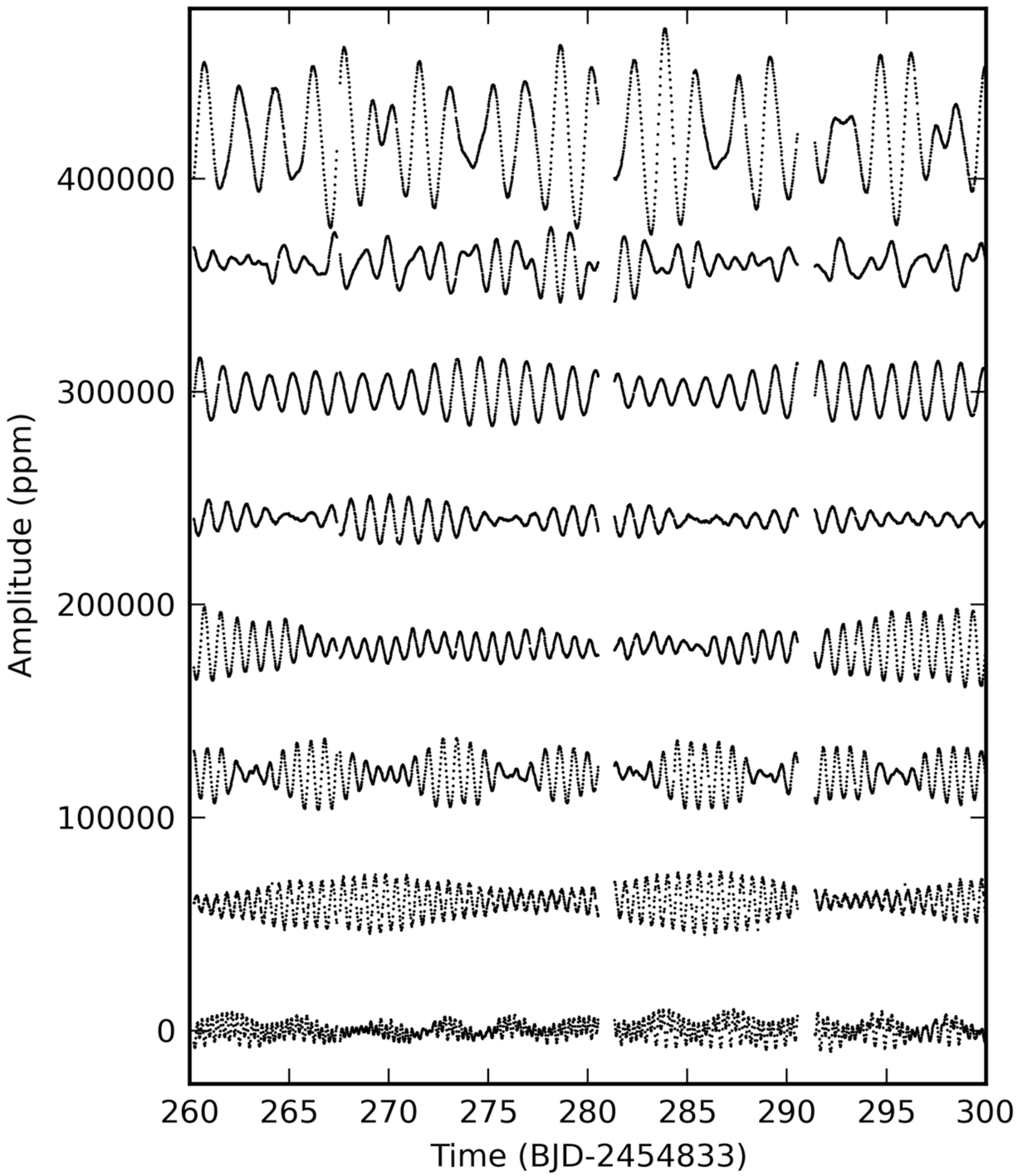


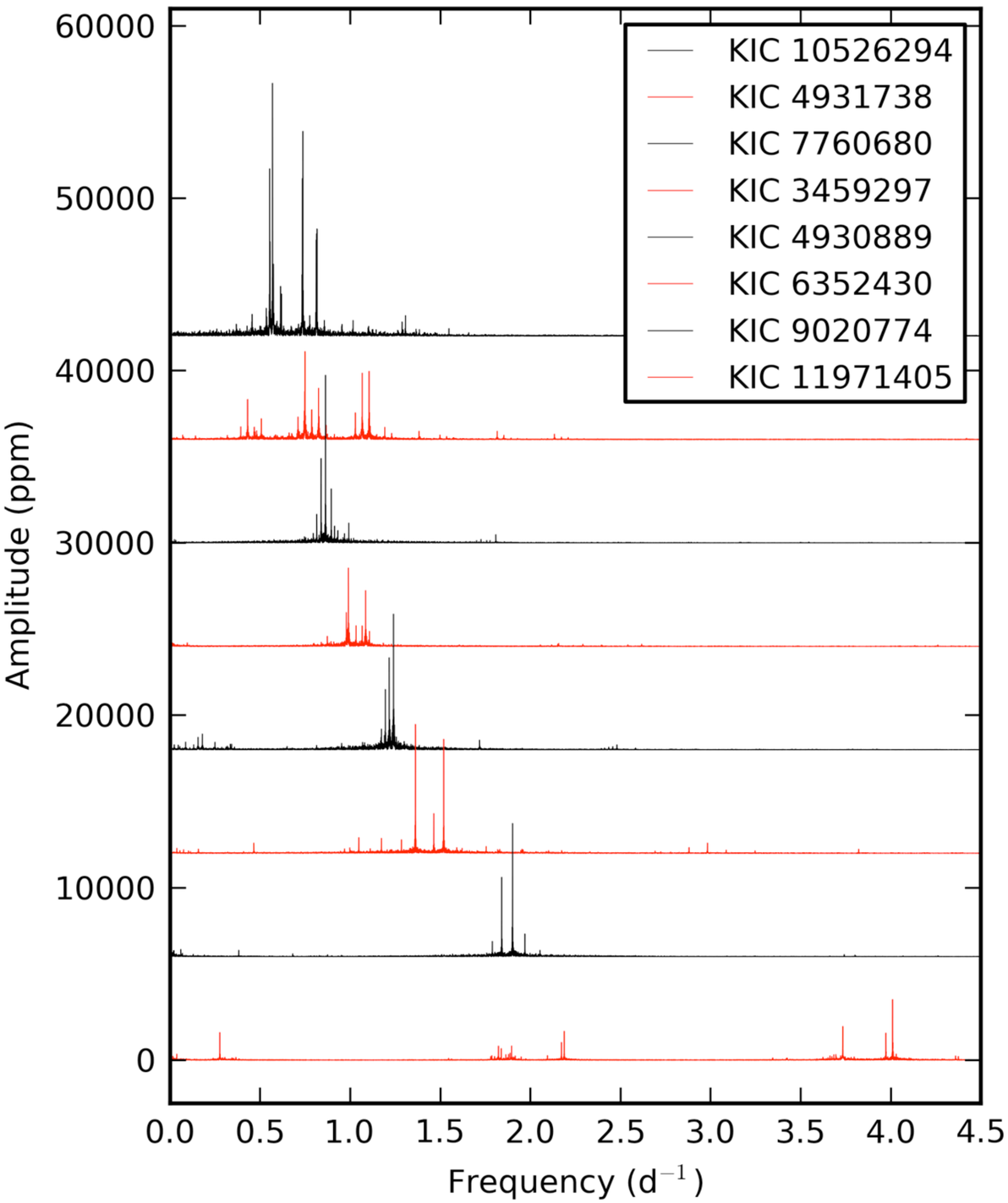
# *Kepler* GO on 8 interesting B-type stars

## TOWARDS A GENERAL PICTURE

Slow & fast rotators, single & binary stars across the instability strips

[**Pápics et al. 2013** & in preparation]

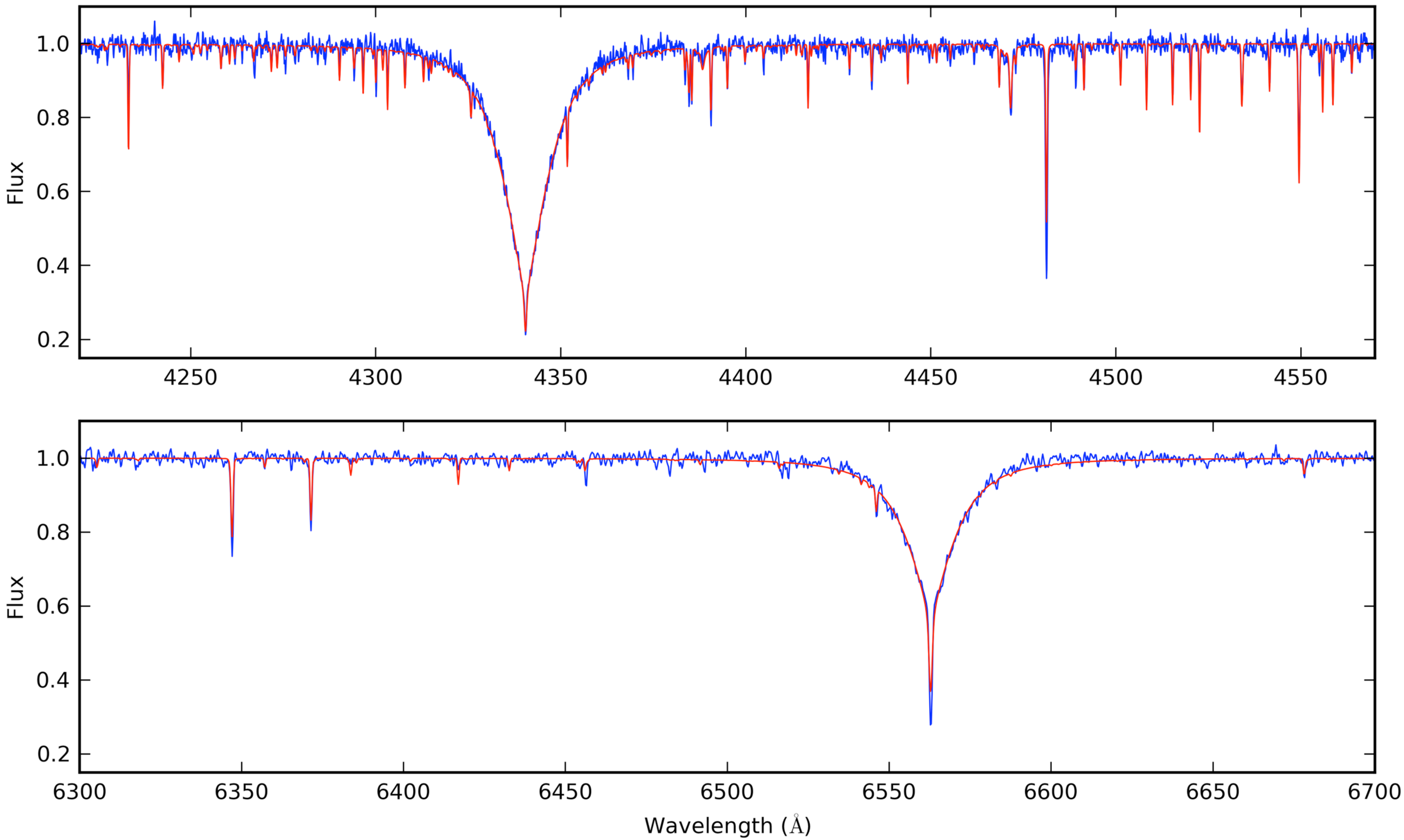


# KIC 10526294

## FUNDAMENTAL PARAMETERS

### ISIS@WHT spectra



# KIC 10526294

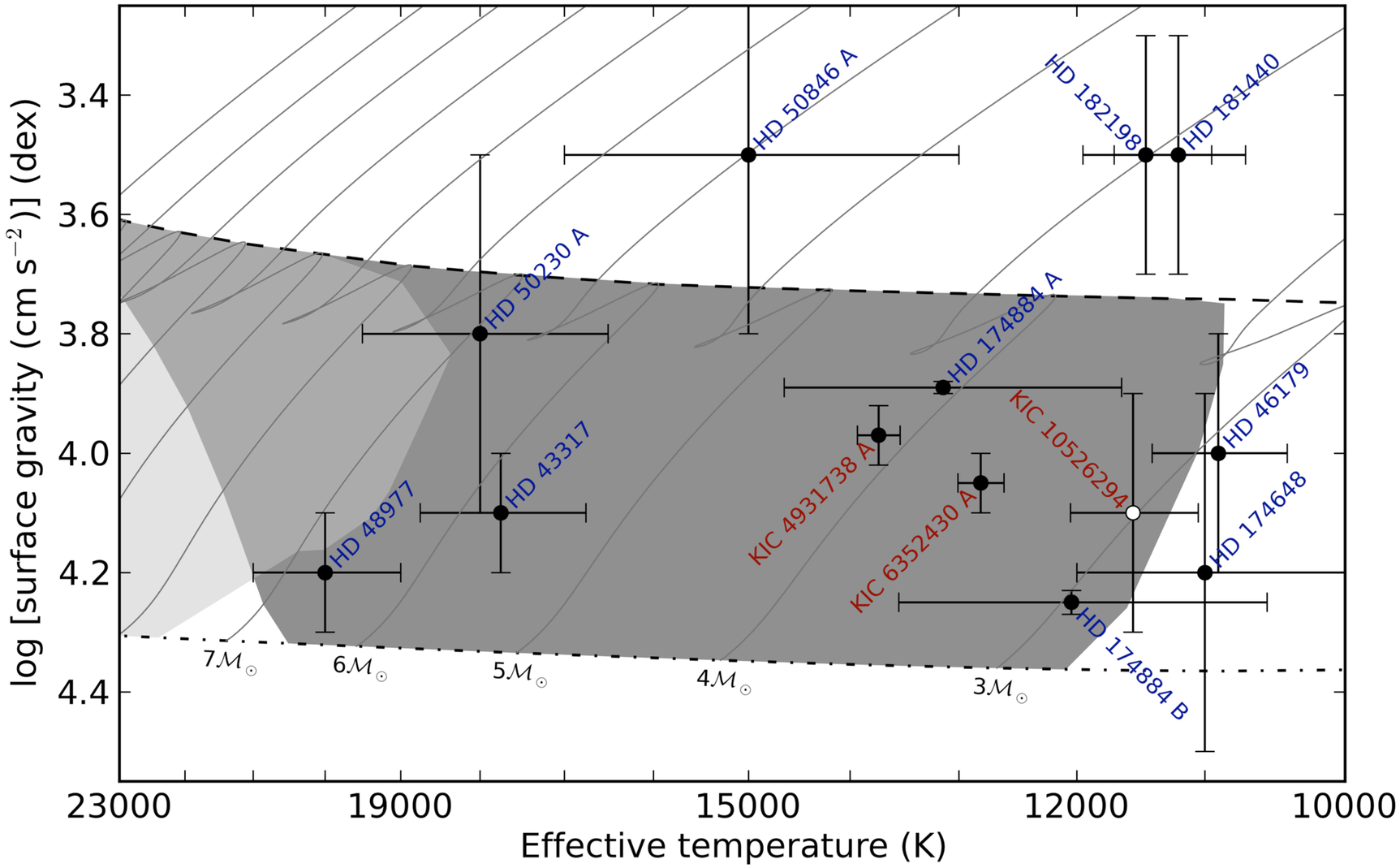
## FUNDAMENTAL PARAMETERS

One of the coolest SPBs

Slow (projected) rotation

No sign of binary component

| Parameter | KIC 10526294 |
|---|---|
| $T_{\rm eff}$ (K) | $11550 \pm 500$ |
| $\log g$ (cgs) | $4.1 \pm 0.2$ |
| $Z$ | $0.016 \pm {}^{0.013}_{0.007}$ |
| Gaussian line broadening (km s$^{-1}$) | $18 \pm 4$ |
| $\xi_{\rm t}$ (km s$^{-1}$) | 2.0 (fixed) |
| Spectral type[a] | B8.3 V |

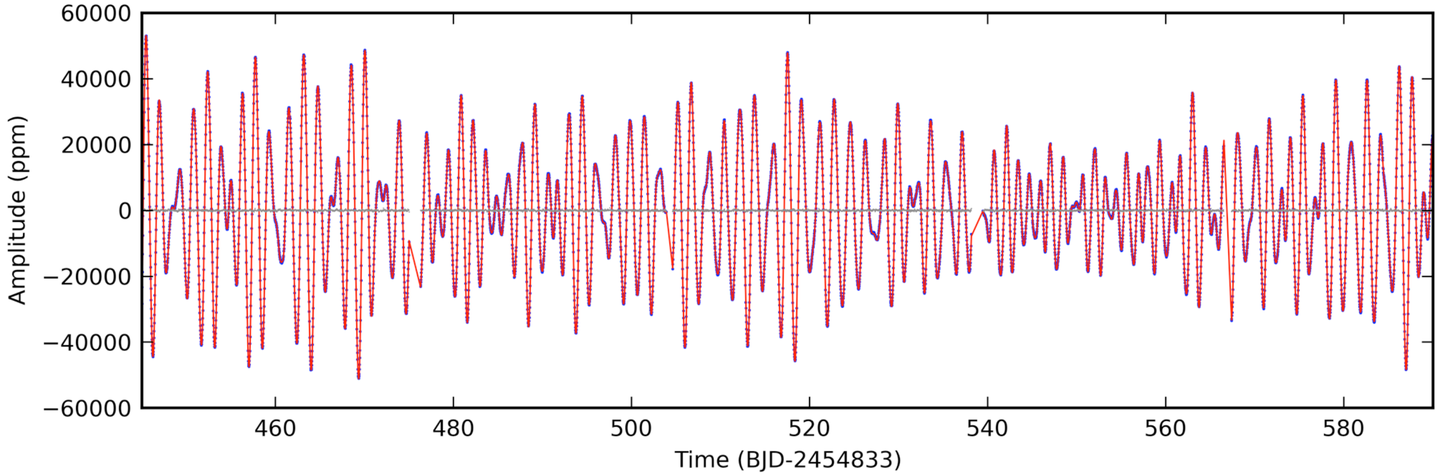


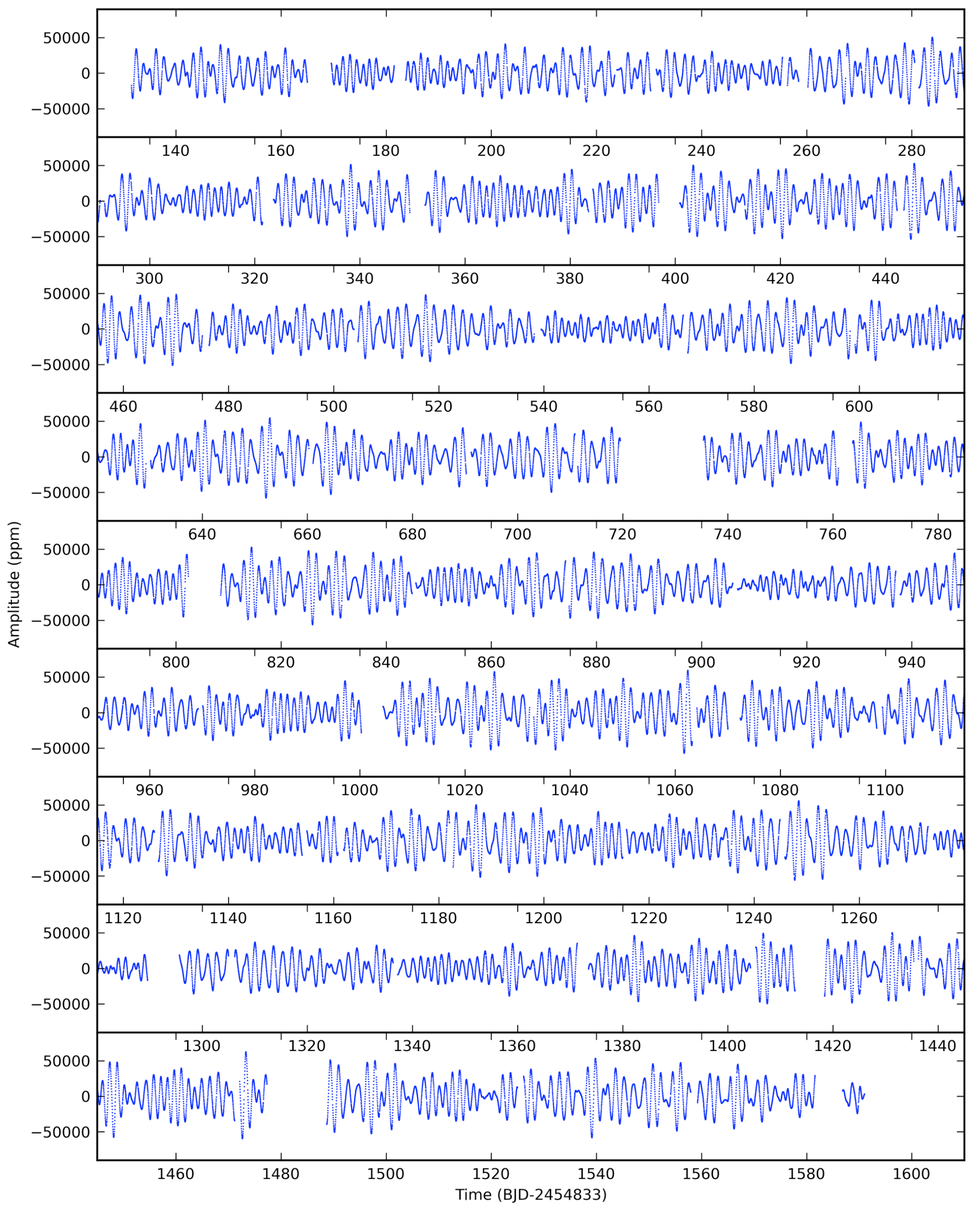
# KIC 10526294

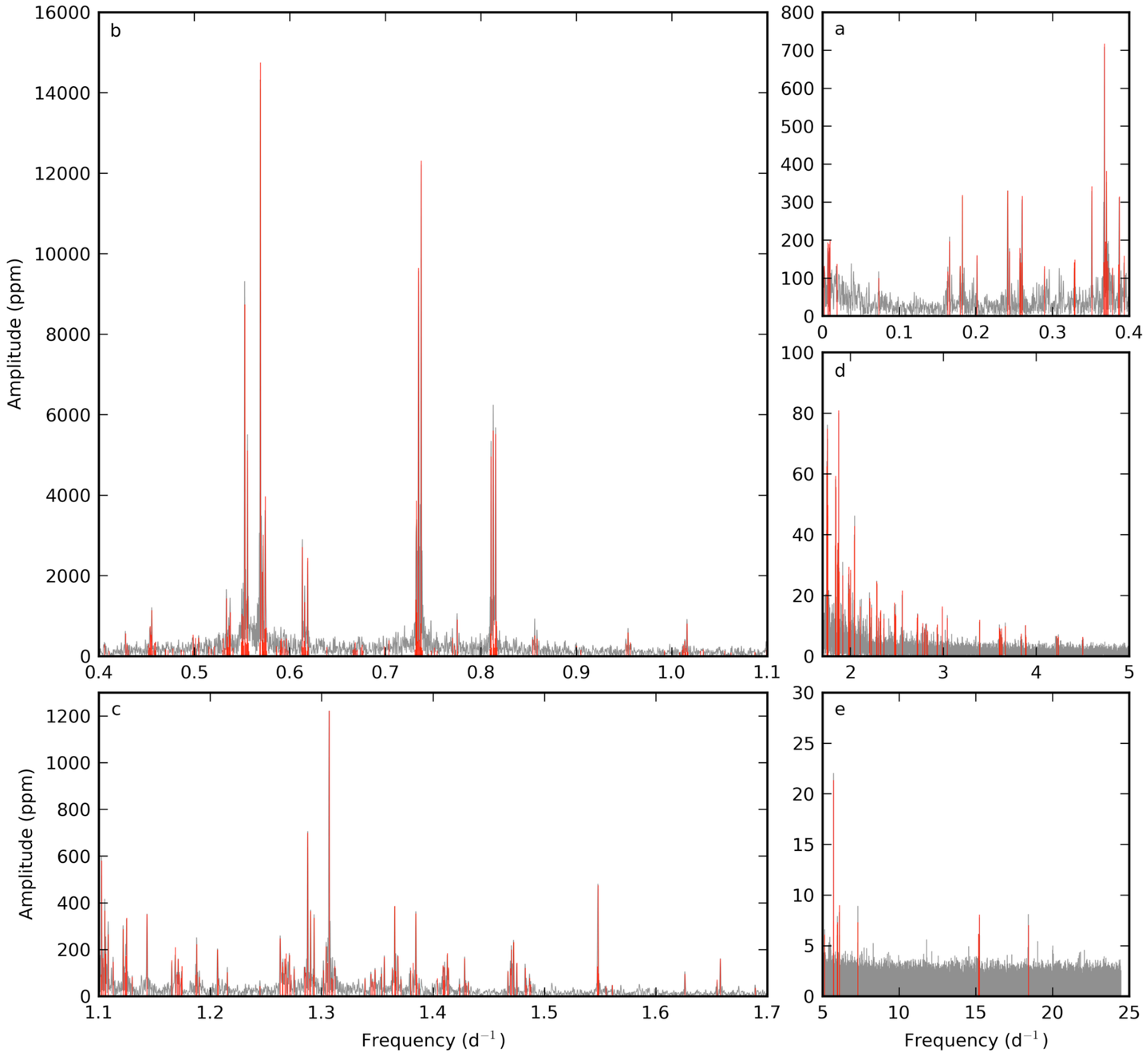
## KEPLER PHOTOMETRY

Q1-Q17 LC (4 years, 91% cover.)

Typical *g* mode SPB spectrum



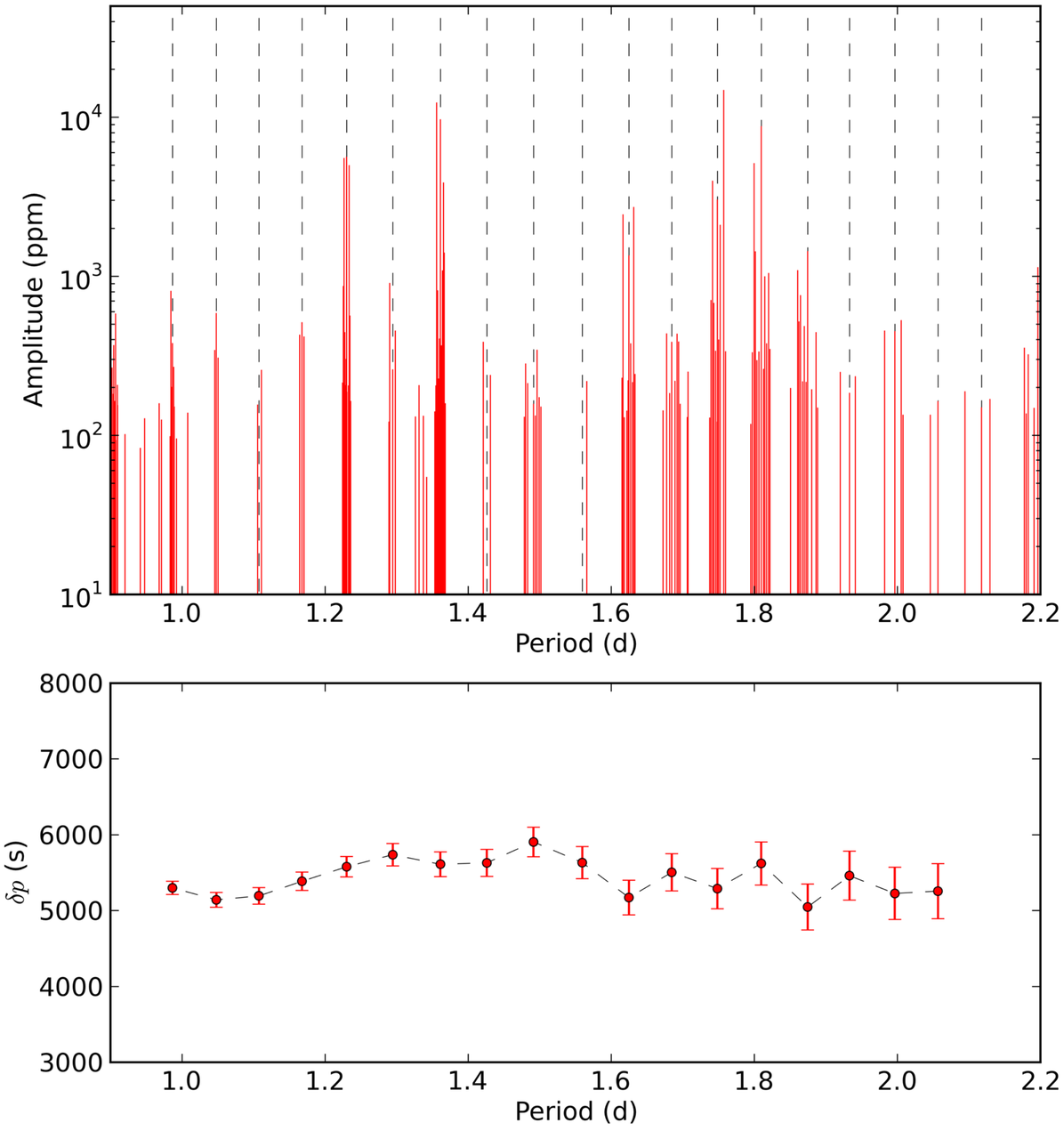



# KIC 10526294

## PERIOD SPACING & ROTATIONAL SPLITTING

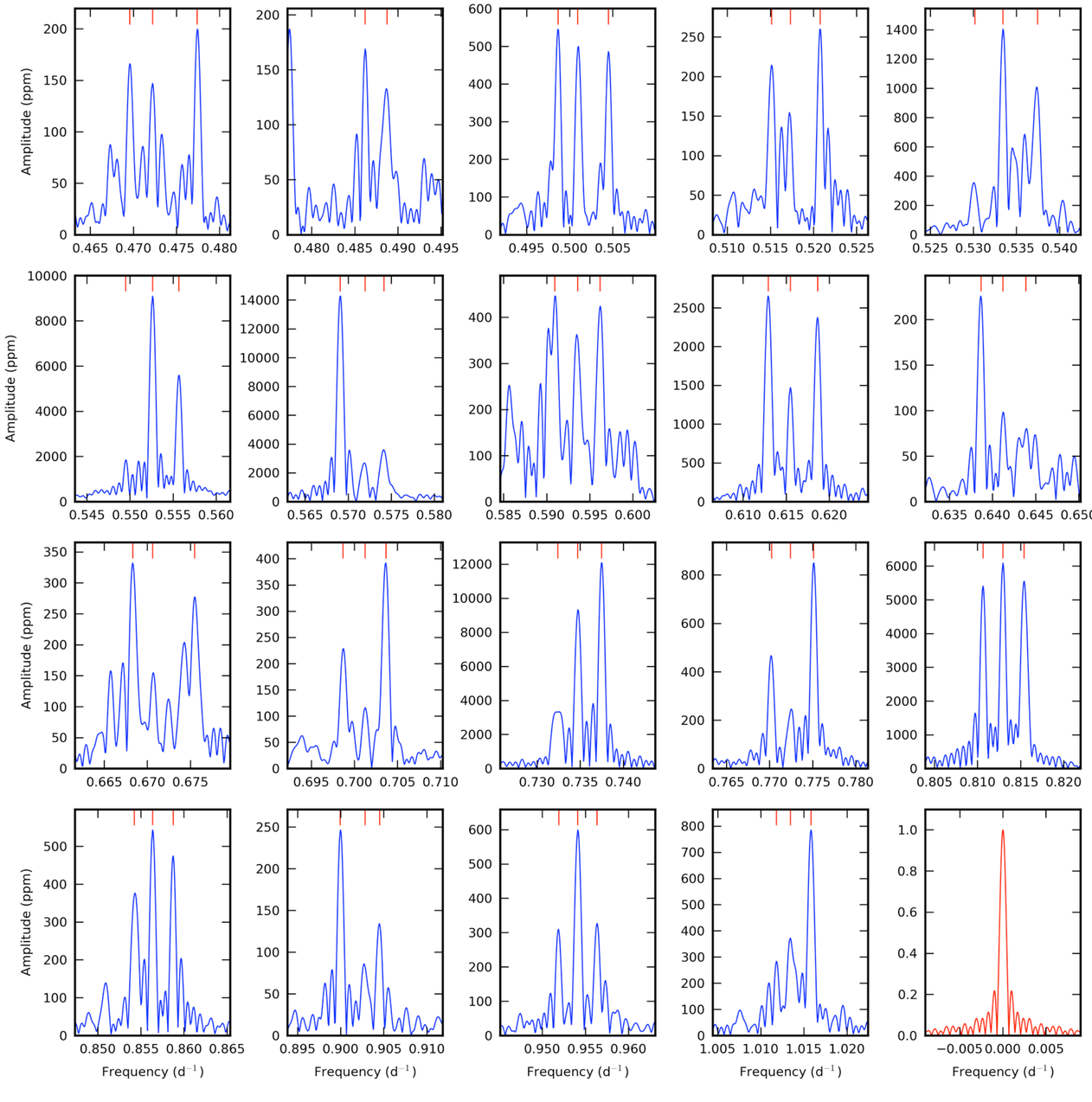
19 rotationally split g modes with nearly equal period spacing

Observed trend in splittings -> non-rigid internal rotation profile









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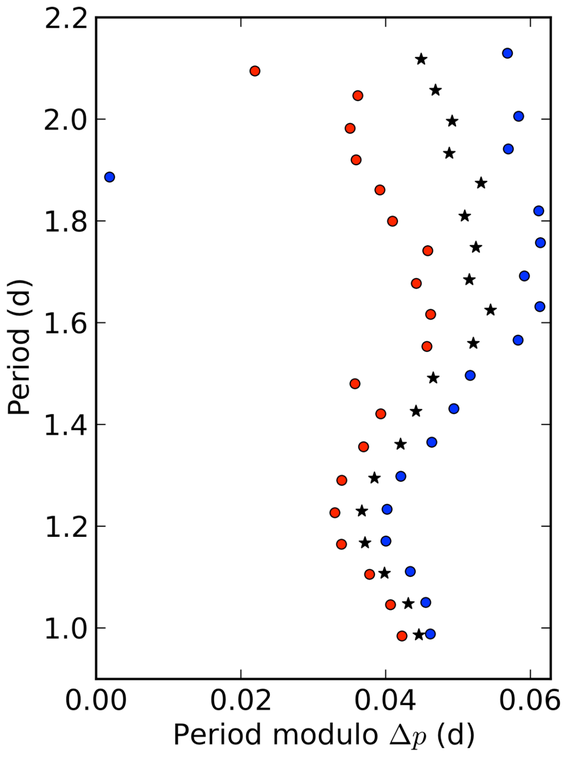


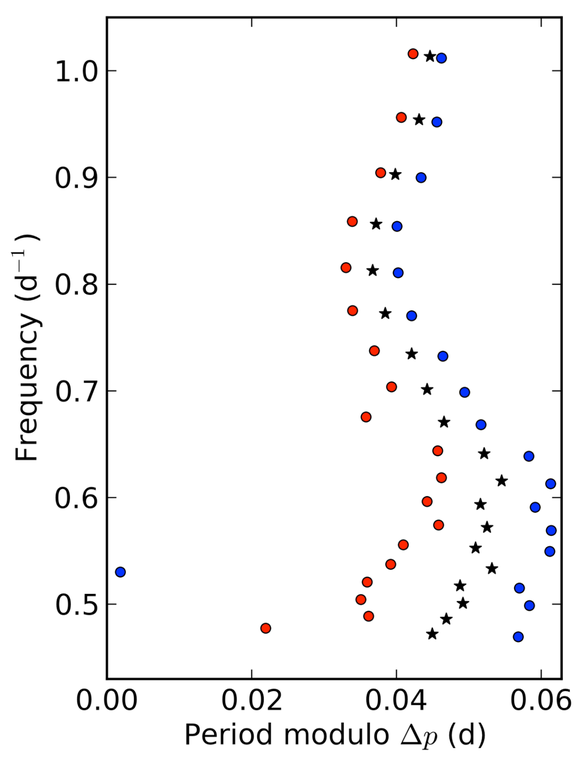


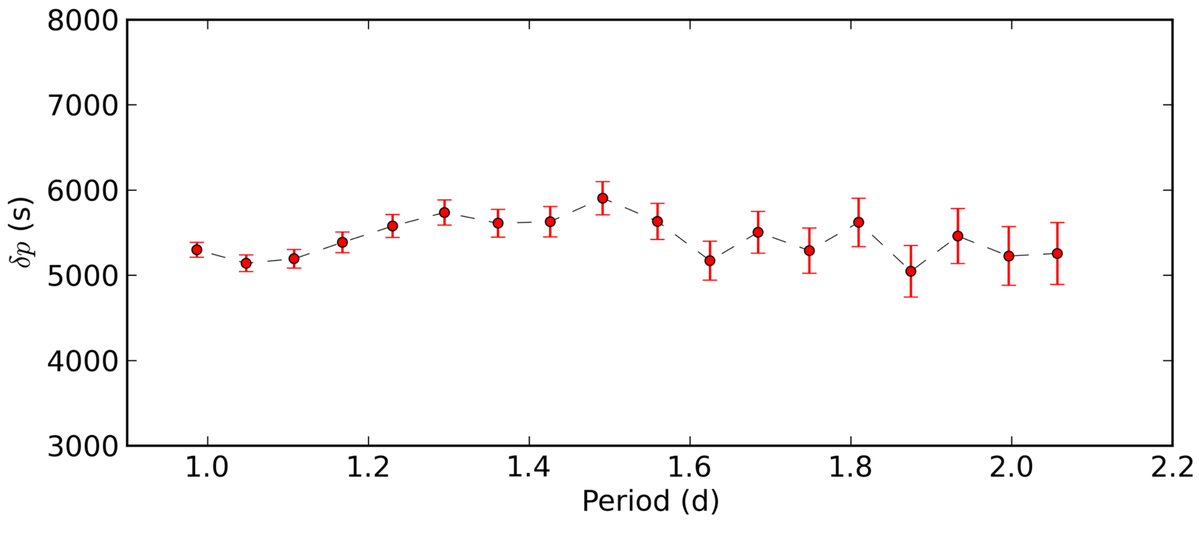


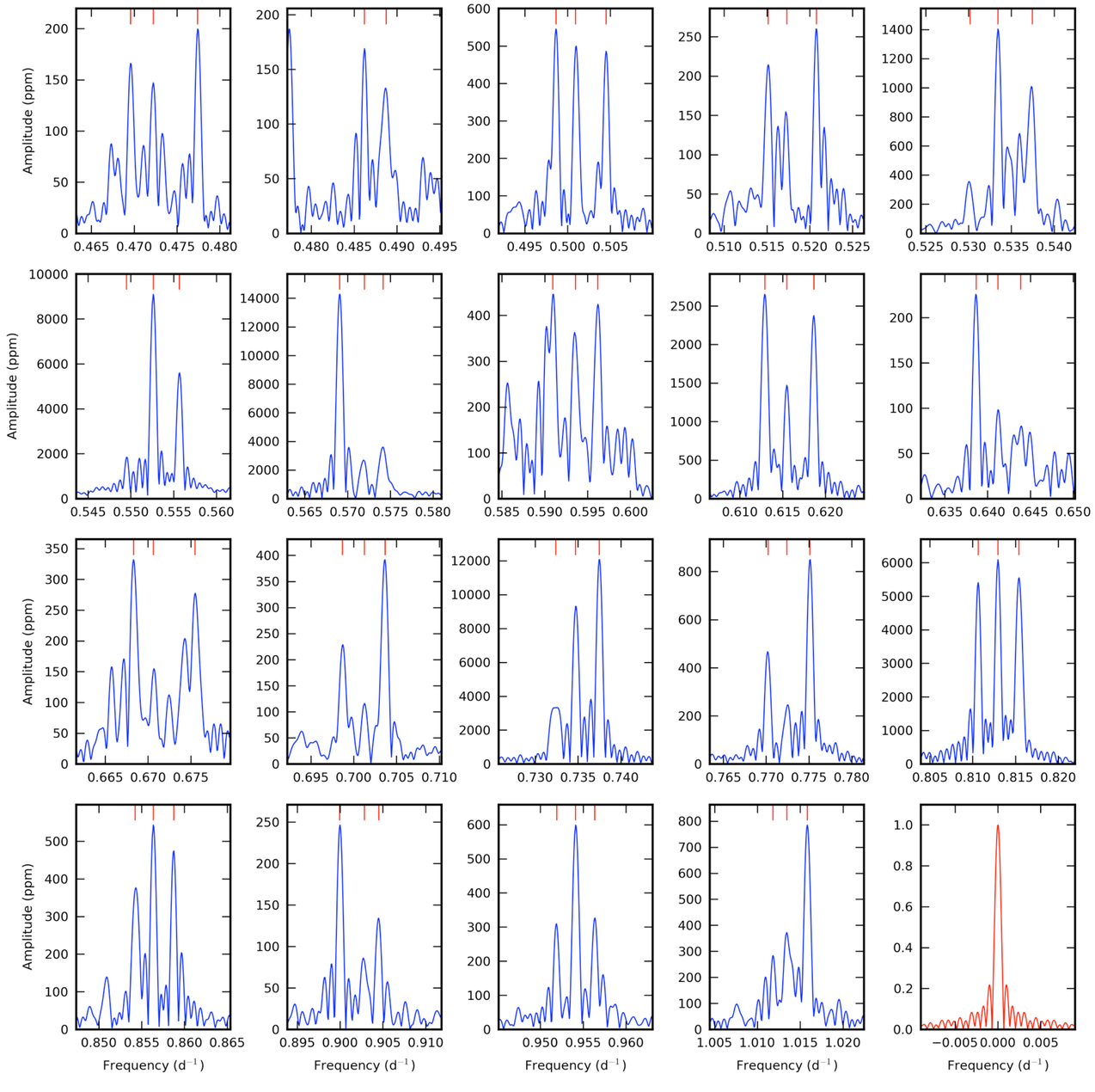

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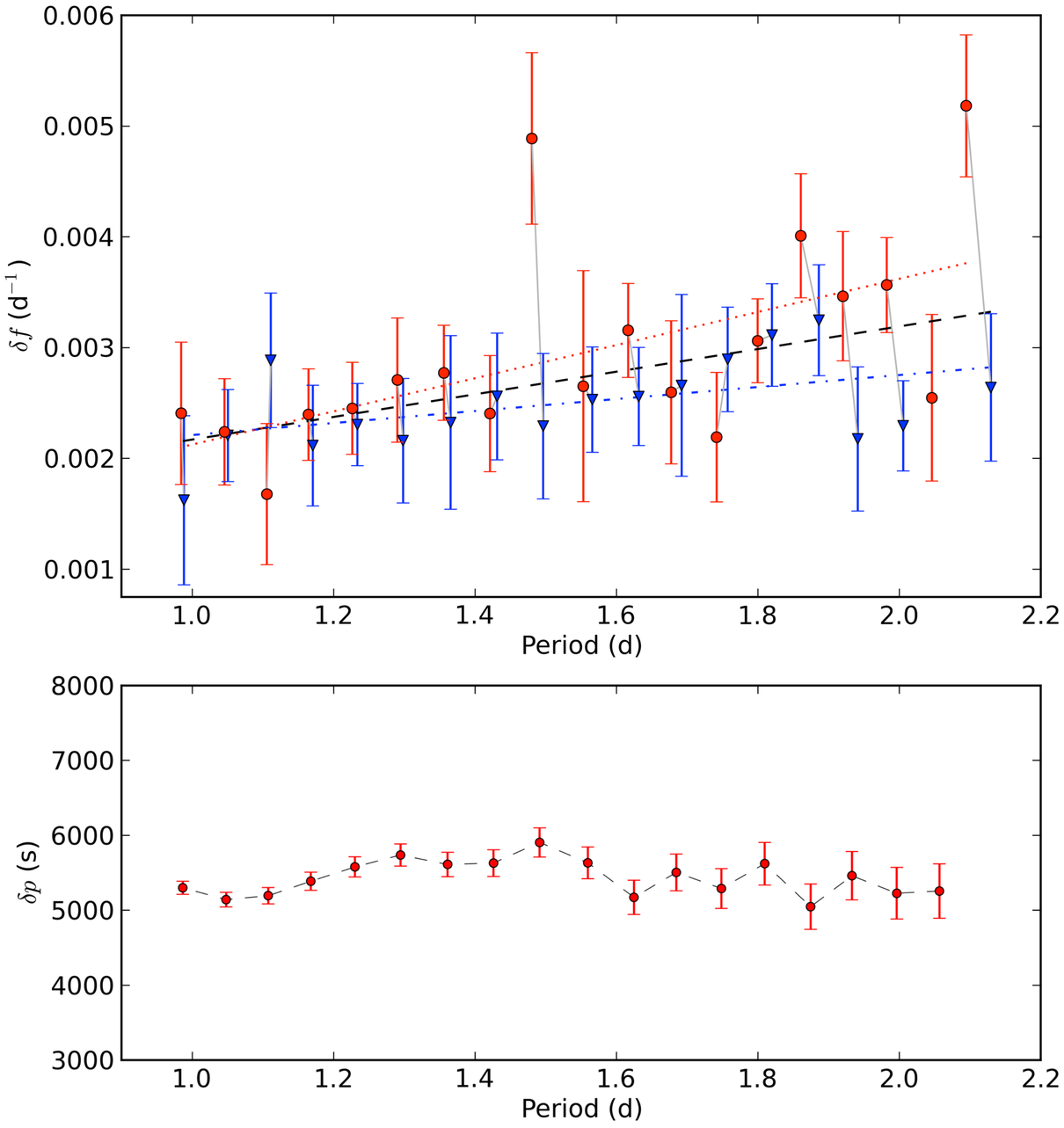
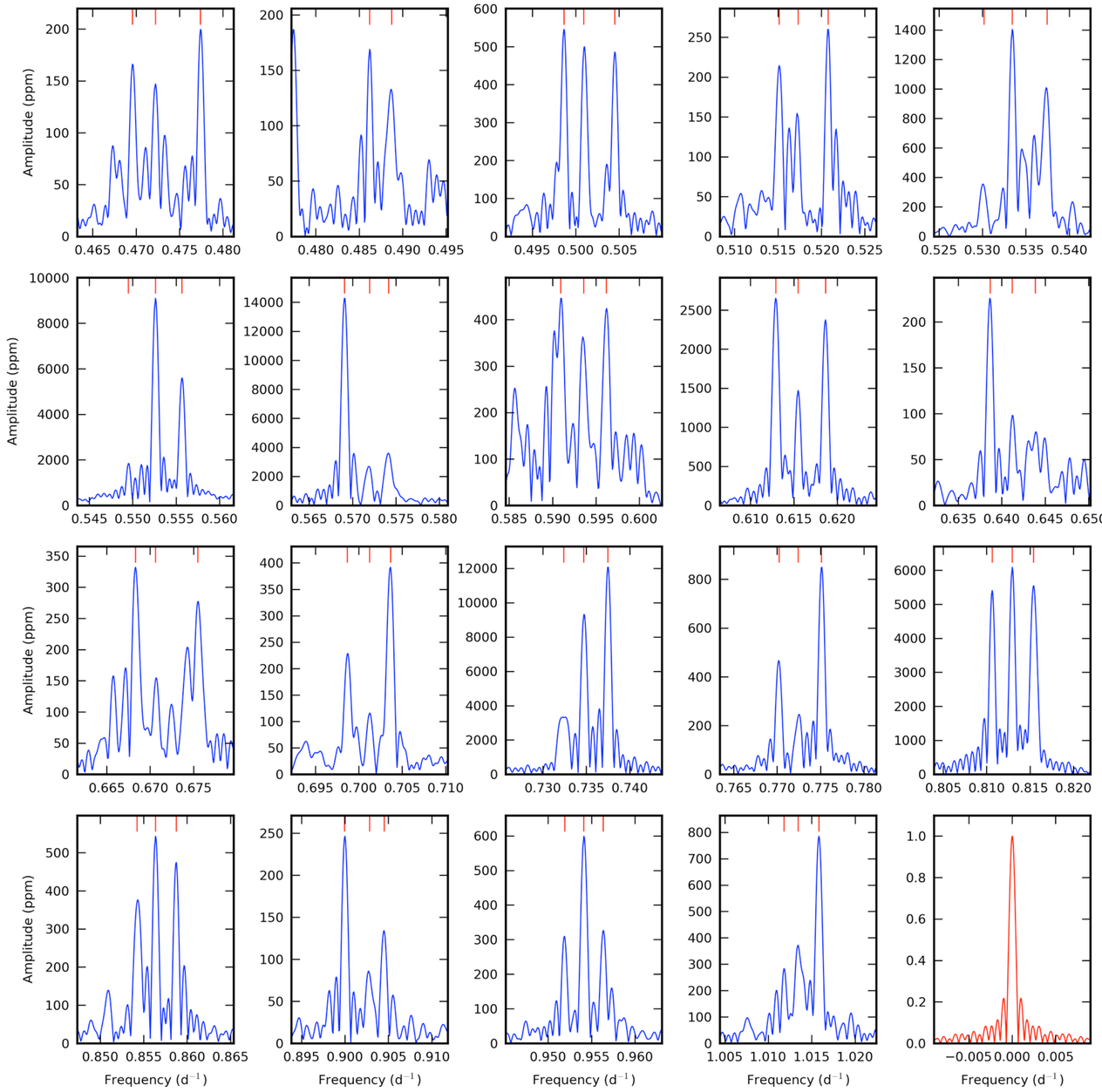


# KIC 10526294

## 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**
- $T_{\rm eff}$, log $g$, $Z$
  - *from SED fitting, spectral synthesis*

**Observed pulsation modes**
- List of significant frequencies
  - *from frequency analysis techniques*
- Mode ID: Quantum numbers ($l$,$m$)
  - *from photometric amplitude ratios*
  - *from line profile variations*

*Inside the error box*

**Model parameters**
- $M$, $X_{\rm C}$, $Z$, $\alpha_{\rm ov}$

↓ ***Stellar evolution code (MESA)***

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

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

↓ ***Pulsation code (GYRE)***

***Comparison ($\chi^2$)*** ↔ ↓

**Theoretical pulsation modes**
- List of frequencies with ($n$,$l$,$m$)

**Constraints**

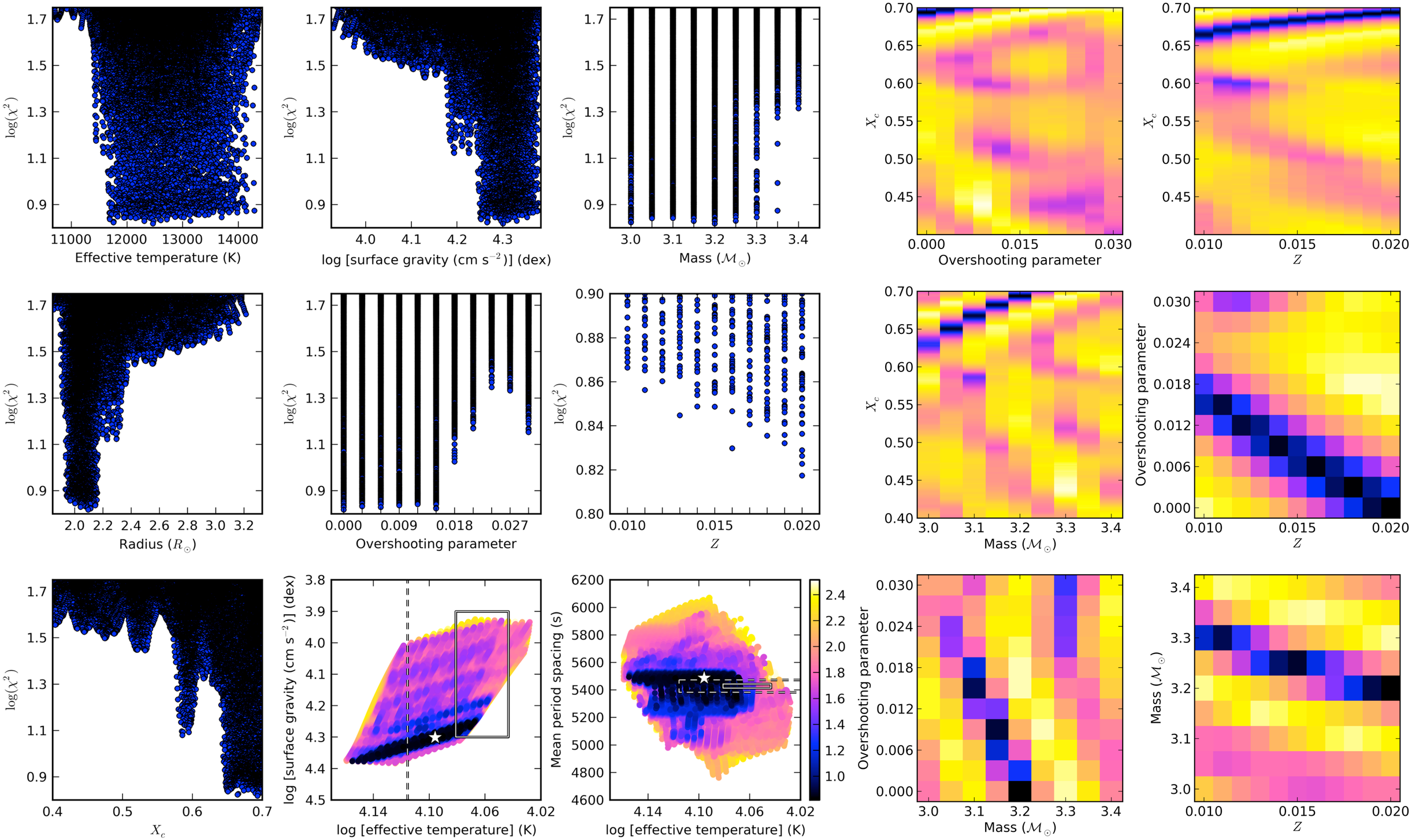
Fundamental parameters / Shortcomings in included physics / Unknown stellar properties (e.g., magnetic field)

# KIC 10526294

## SEISMIC MODELLING | PROCESS

4D parameter space - strong correlations

| Parameter | min. | max. | $\delta$ |
|---|---|---|---|
| Mass ($\mathcal{M}_\odot$) | 3.00 | 3.40 | 0.05 |
| Core overshoot value | 0.000 | 0.030 | 0.003 |
| Initial metallicity | 0.010 | 0.020 | 0.001 |
| Central hydrogen fraction | 0.400 | 0.700 | 0.001 |



# KIC 10526294

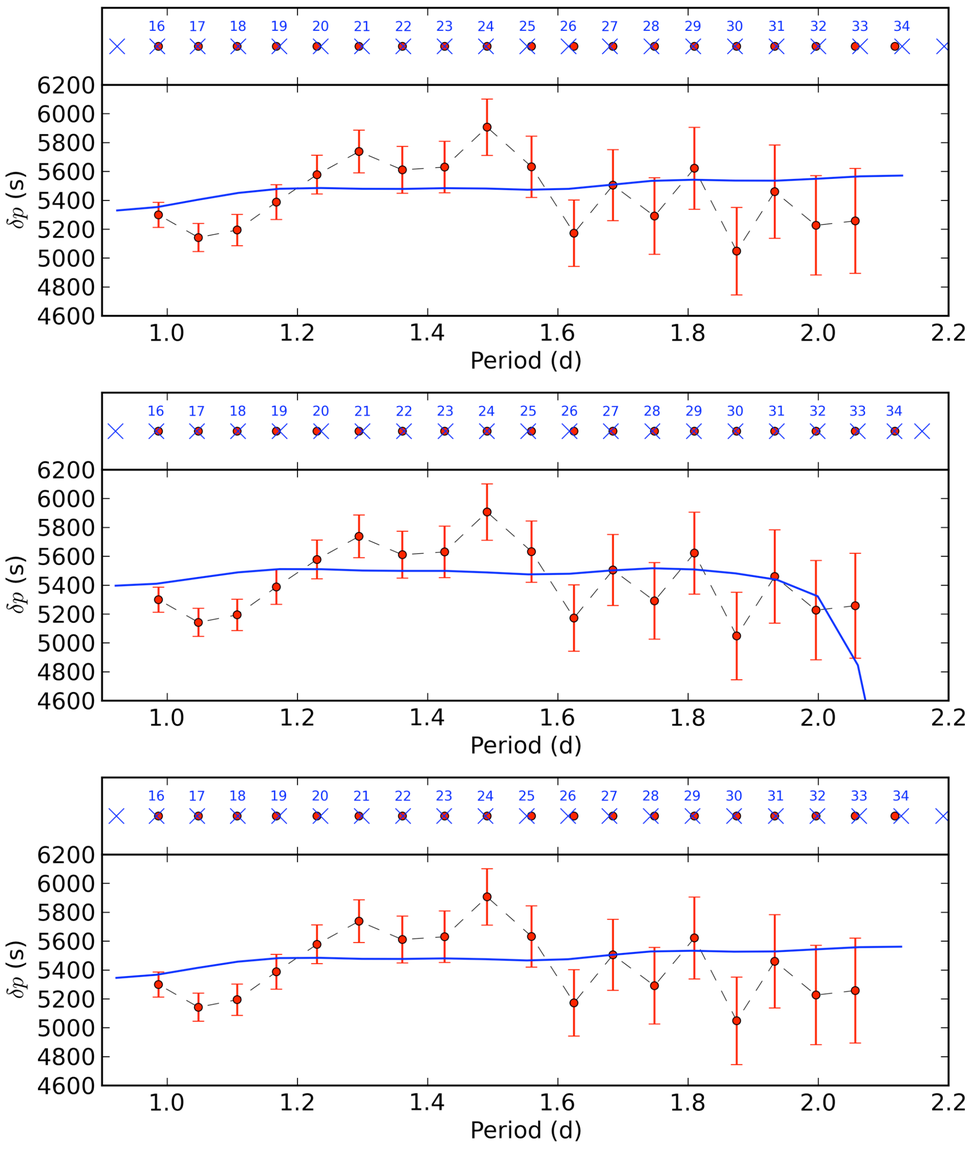
## SEISMIC MODELLING | RESULTS

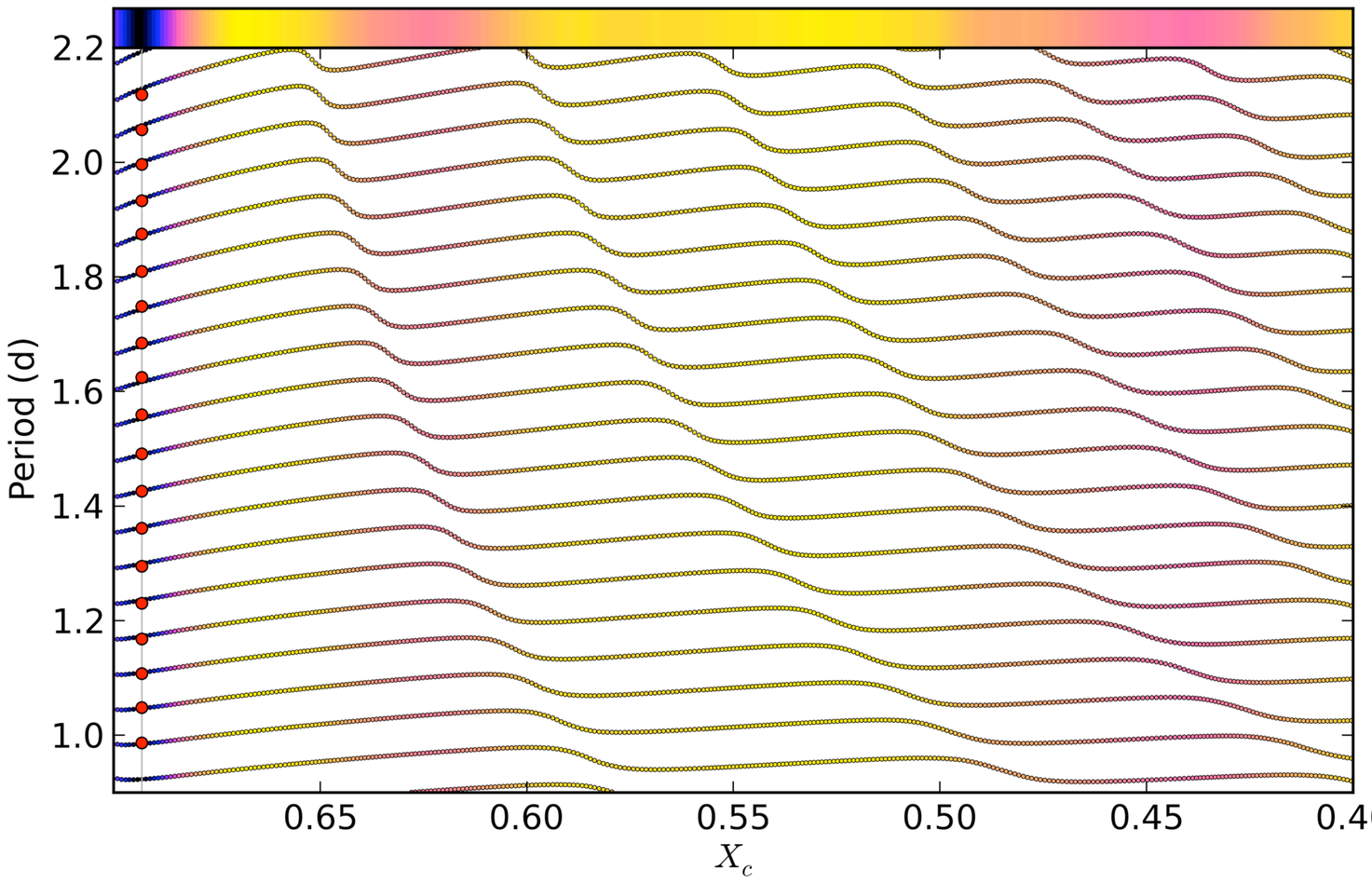
Young star: $X_c > 0.64$

Overshooting: $\alpha_{ov} \leq 0.15$

Rotation period: ~188 days

| Model | $T_{\rm eff}$ | $\log g$ | Mass | Radius | Core overshoot ($f_{ov}$) | $Z$ | $X_c$ | Age | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | K | dex | $M_\odot$ | $R_\odot$ | | mass fraction | | Myr | |
| 1 | 12 470 | 4.30 | 3.20 | 2.10 | 0.000 | 0.020 | 0.693 | 12.0 | 6.567 |
| 2 | 11 760 | 4.27 | 3.00 | 2.11 | 0.015 | 0.020 | 0.665 | 45.1 | 6.649 |
| 3 | 12 310 | 4.30 | 3.15 | 2.09 | 0.006 | 0.020 | 0.690 | 15.8 | 6.744 |
| 4 | 13 140 | 4.33 | 3.25 | 2.04 | 0.000 | 0.016 | 0.696 | 10.5 | 6.757 |
| 5 | 12 610 | 4.31 | 3.20 | 2.07 | 0.003 | 0.019 | 0.695 | 11.2 | 6.793 |



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## SEISMIC MODELLING | RESULTS

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| Model | $T_{\rm eff}$ K | log $g$ dex | Mass $M_\odot$ | Radius $R_\odot$ | Core overshoot ($f_{ov}$) | $Z$ mass fraction | $X_c$ mass fraction | Age Myr | $\chi^2$ |
|---|---|---|---|---|---|---|---|---|---|
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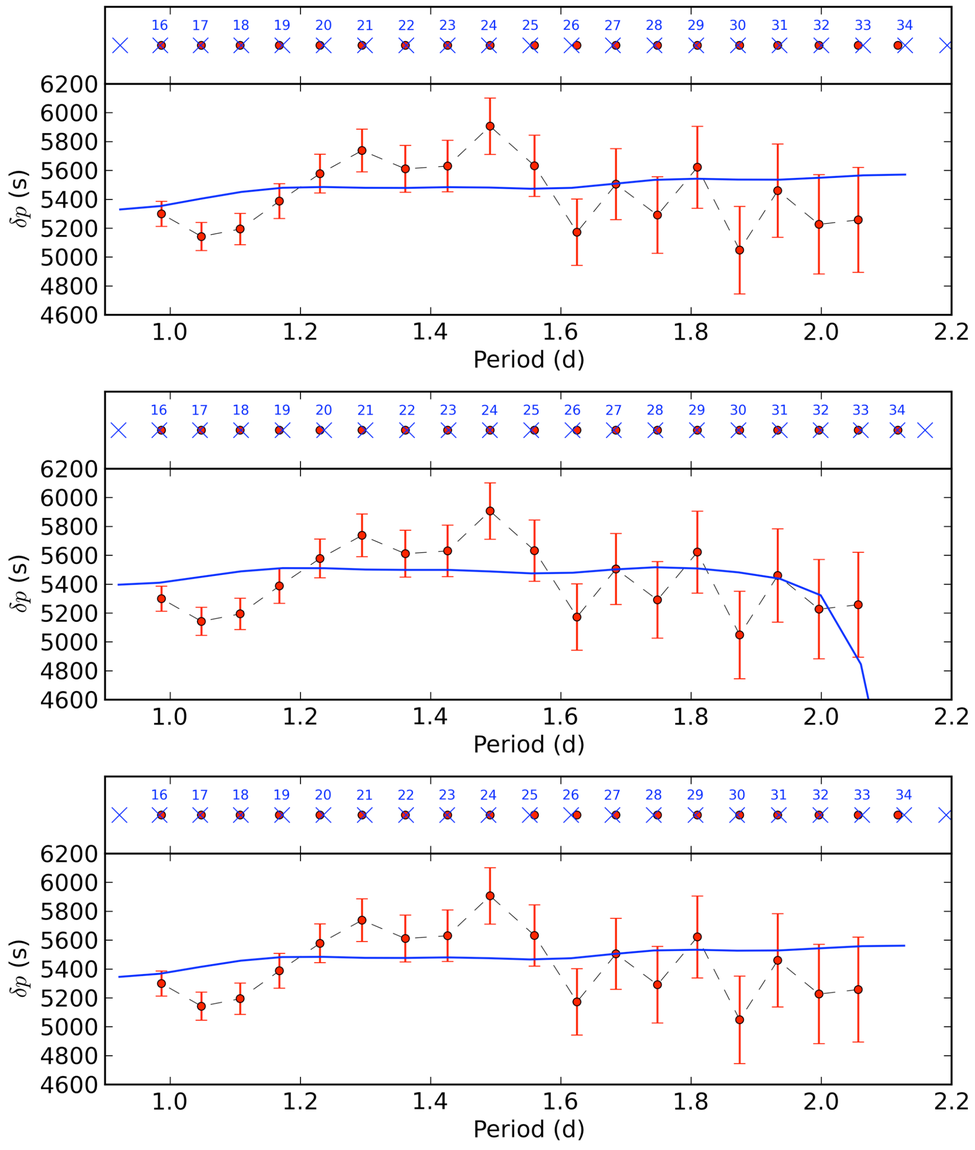
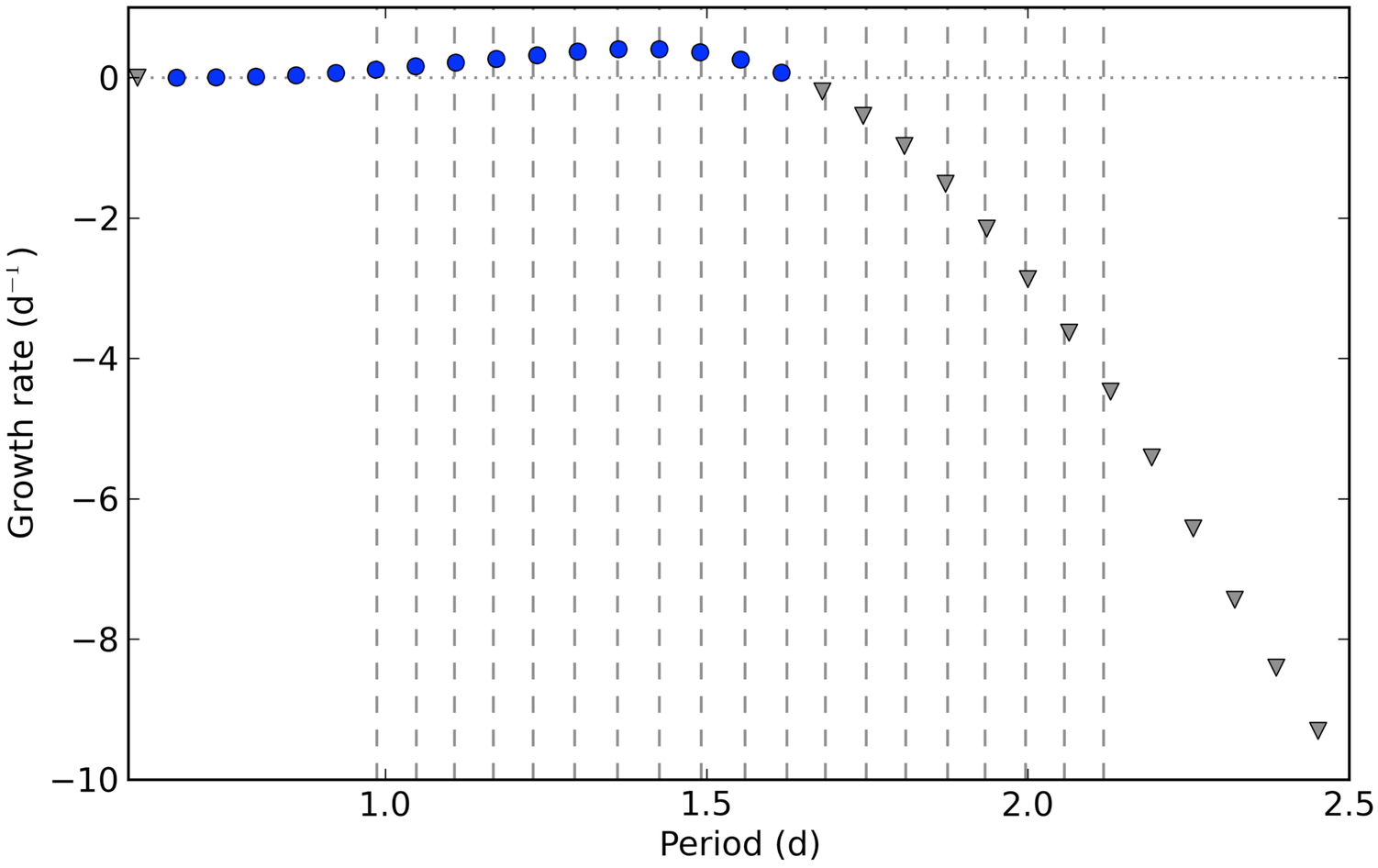


# KIC 10526294

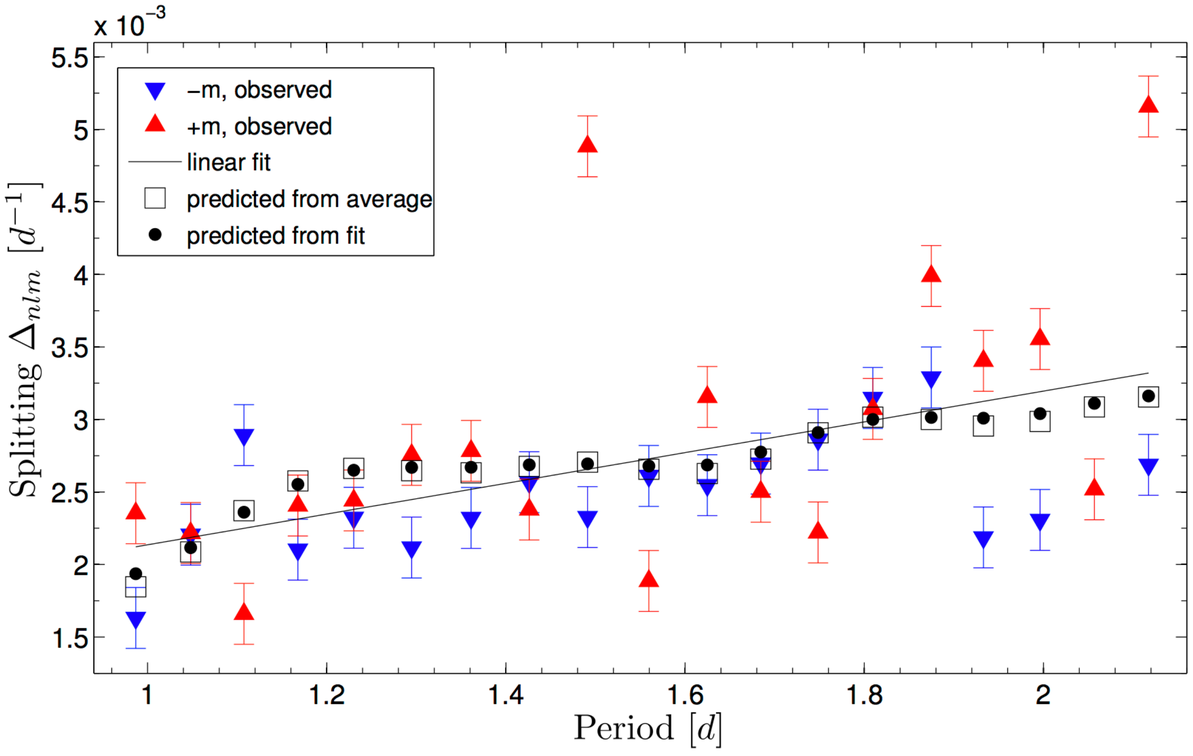
## DERIVATION OF THE INTERNAL ROTATION PROFILE

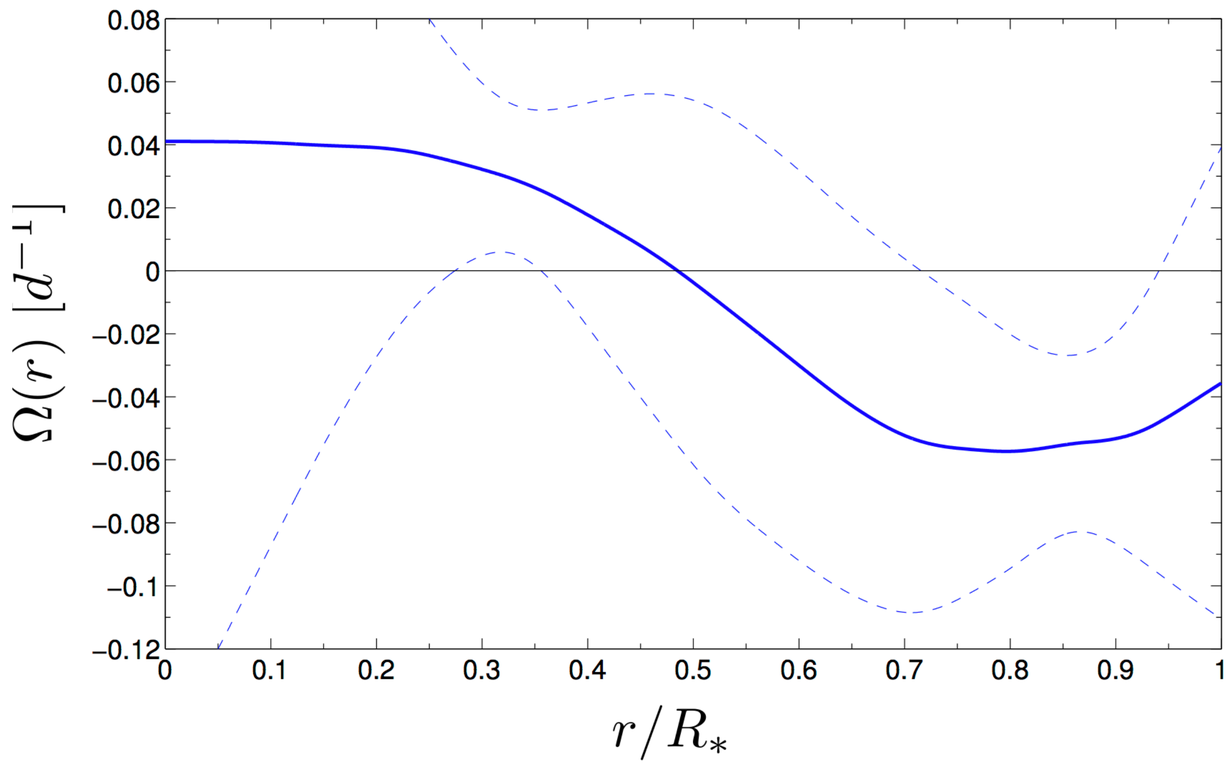
Inversion of the 19 rotationally split dipole modes [**Triana et al.** submitted]

Starting from kernels of the 5 best forward models by regularised least-squares

Counter-rotation in the stellar envelope with $\Omega_{core} / \Omega_{surface} = -0.53$

Result independent of the model (1-5), radial grid resolution, and of the smoothing parameter




Angular momentum distribution consistent with recent numerical simulations

Internal gravity waves (IGW) can transport angular momentum leading to a slowly rotating core and a counter-rotating outer radiative envelope.

IGWs can also explain KIC 11145123 [Kurtz et al. 2014]

# Future

## IMPROVED INPUT PHYSICS

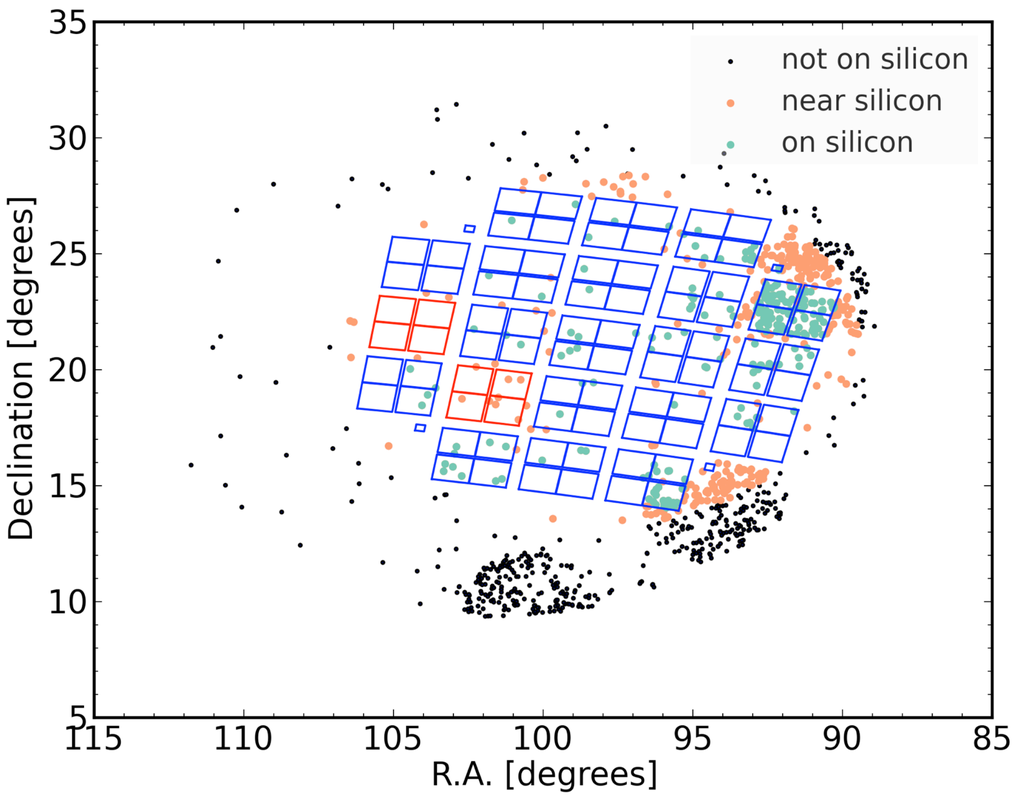
Extra mixing [**Moravveji et al.** in preparation]

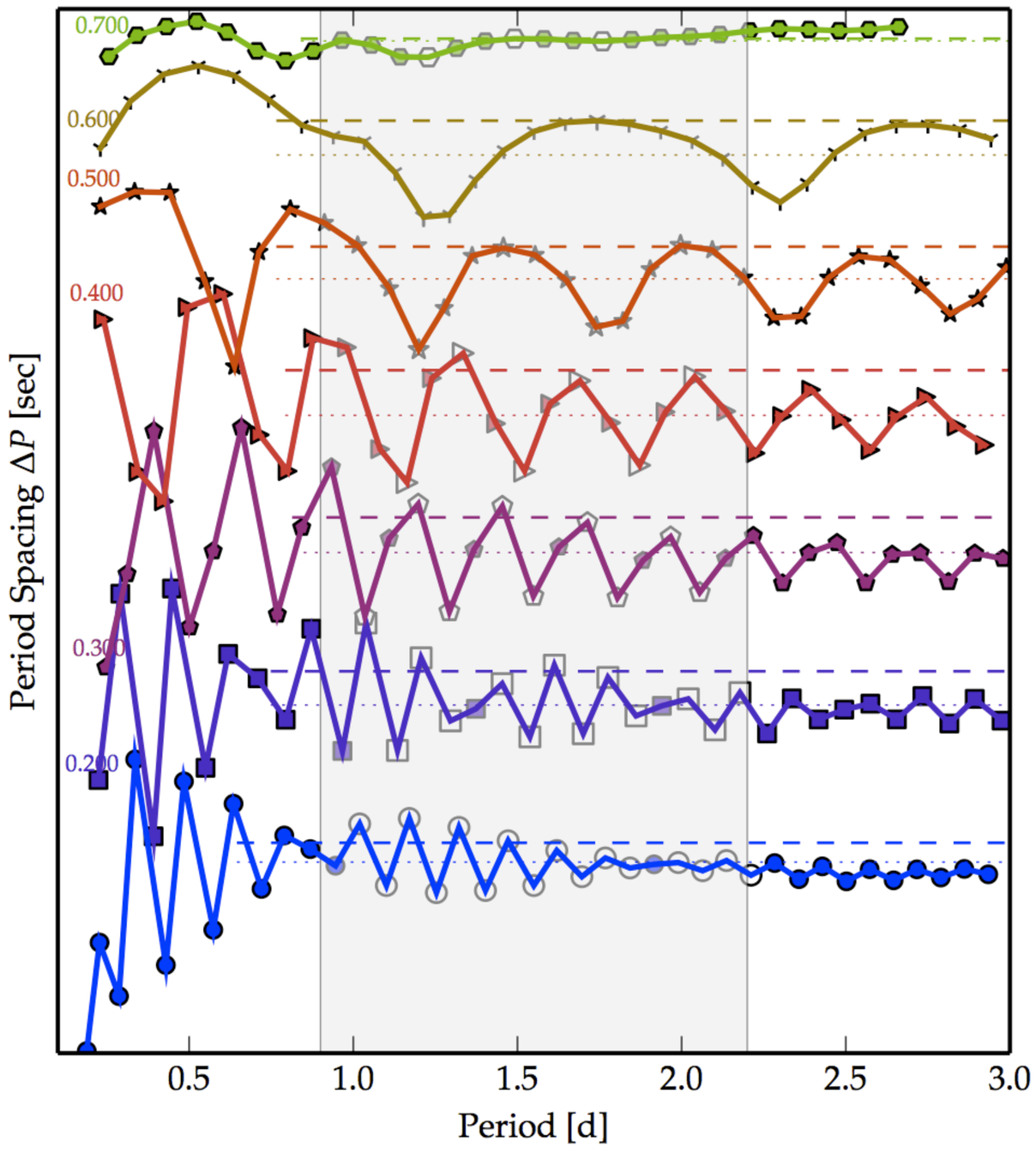
Magnetic fields, rotation, excitation issues, etc.

## B STARS WITH K2

200 (candidate) B-type pulsators in Field 0

- Limited frequency resolution
- Supporting ground-based spectroscopy
- **Aim:** find period series -> physical parameters
- Precision dependent on position in the HRD
  - Massive, slightly evolved ($X_c$ 0.6-0.2) stars are the best



# KIC 10526294

## CONCLUSIONS [Pápics et al. 2014, in press for A&A]

- A new slowly pulsating B-type star near the cool edge of the SPB instability strip
- Fundamental parameters from follow-up spectroscopy
- Series of 19 dipole modes nearly equally spaced in period
- Each of the dipole modes shows very narrow rotationally split components
- The amount of splitting is systematically higher towards longer periods, which already points towards a non-rigid internal rotation profile
- From forward modelling we constrain the central hydrogen fraction $X_c > 0.64$
- The core overshooting parameter is constrained to be $\alpha_{ov} \leq 0.15$
- This is the third detection of a series of quasi-equally spaced gravity modes in a main sequence B-type star [Degroote et al. 2010 & Pápics et al. 2012]
- This is the first actual seismic modelling of an SPB star
- From a frequency inversion $\Omega_{core} / \Omega_{surface} = -0.53$ (counter-rotation in envelope)