Compact Pulsators Observed by Kepler

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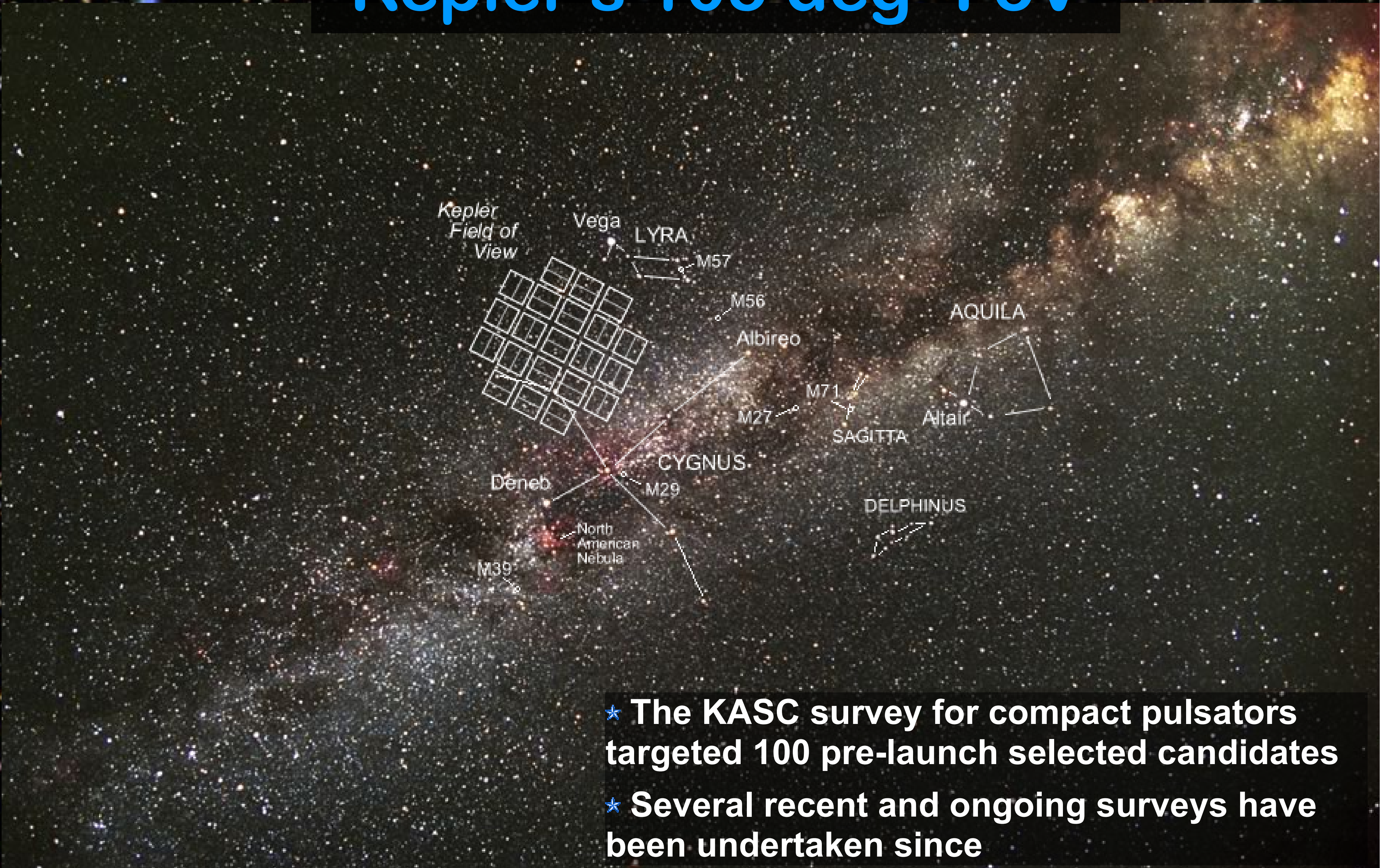
Introduction

- Today I will introduce the KASC survey for compact pulsators in the Kepler field
- Most of these pulsators are hot subdwarf stars – the details of which are tomorrows subject
- Compact variables are characterised by short period variations that requires short integration cycles to resolve
- The two observing modes of Kepler are Short Cadence and Long Cadence; only SC is useful for most compact pulsators!

The Kepler Spacecraft

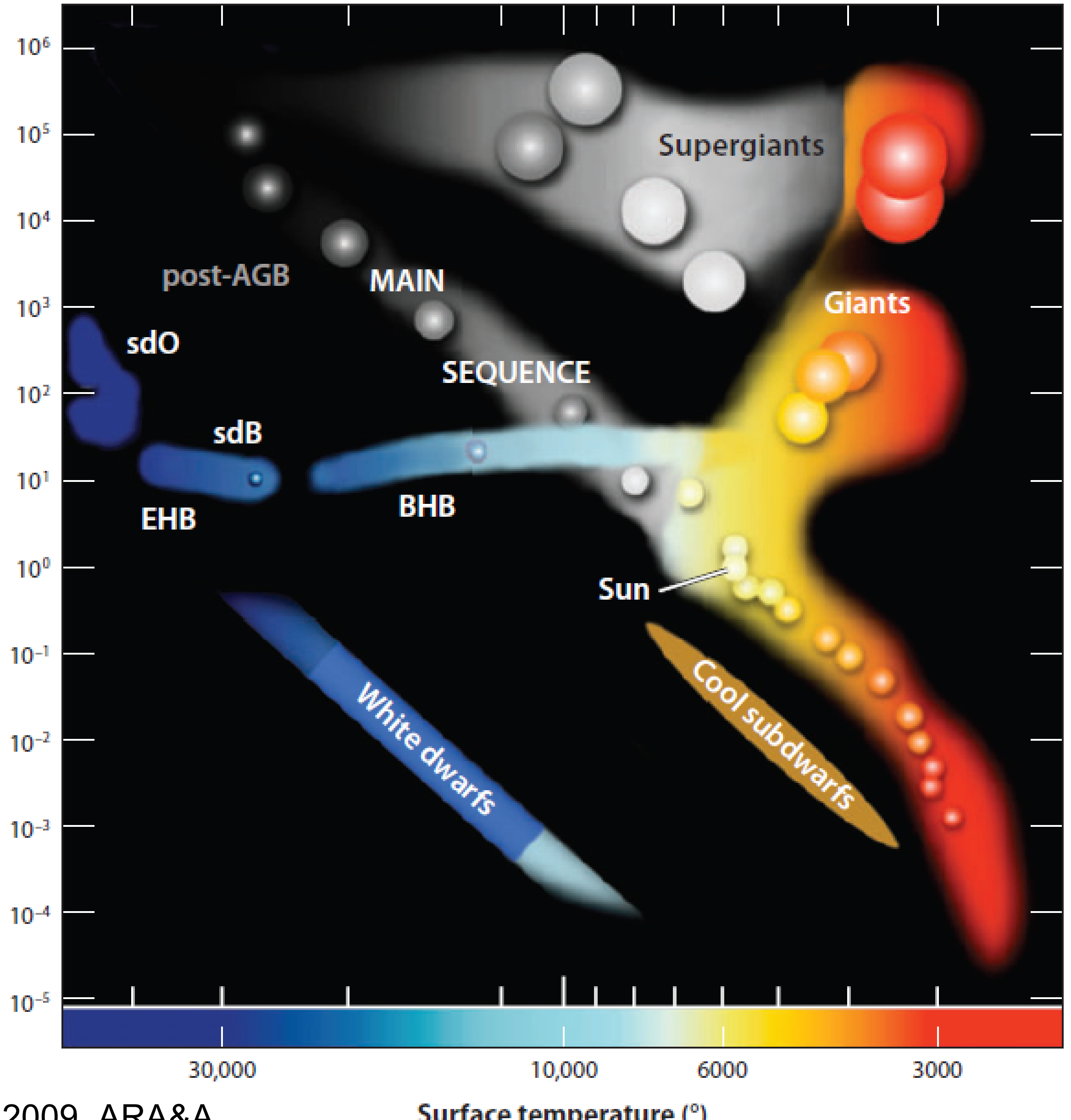
- **Spacecraft in Earth-trailing orbit, launched 7 March, 2009**
- **Schmidt telescope:**
  - 0.95m aperture, 1.4m primary
  - FoV: 105 deg^2, ~4" per pixel
  - 430 – 890 nm passband
  - Fixed field in the Cygnus-Lyra region
- **Detectors:**
  - 42CCDs w/2200x1024 pixels
  - Dynamic range: 9^{th} to 16^{th} mag.
  - Integration time is 6.02s, 0.52s readout
  - **Short cadence:** sum of 9 frames: 59s
  - **Long cadence:** sum of 270: 29.5m
- **Telemetry:**
  - Earth downlink every month
    only data for selected targets are transmitted
- Mission length; originally 3.5 years, now extended to 7.5 years (through 2016)

Kepler's 105 deg^2 FoV



- The KASC survey for compact pulsators targeted 100 pre-launch selected candidates
- Several recent and ongoing surveys have been undertaken since

What's a compact pulsator?



Heber 2009, ARA&A

- Evolved stars that reside below the main sequence
- Mainly sdB pulsators, but also sdO and white dwarfs

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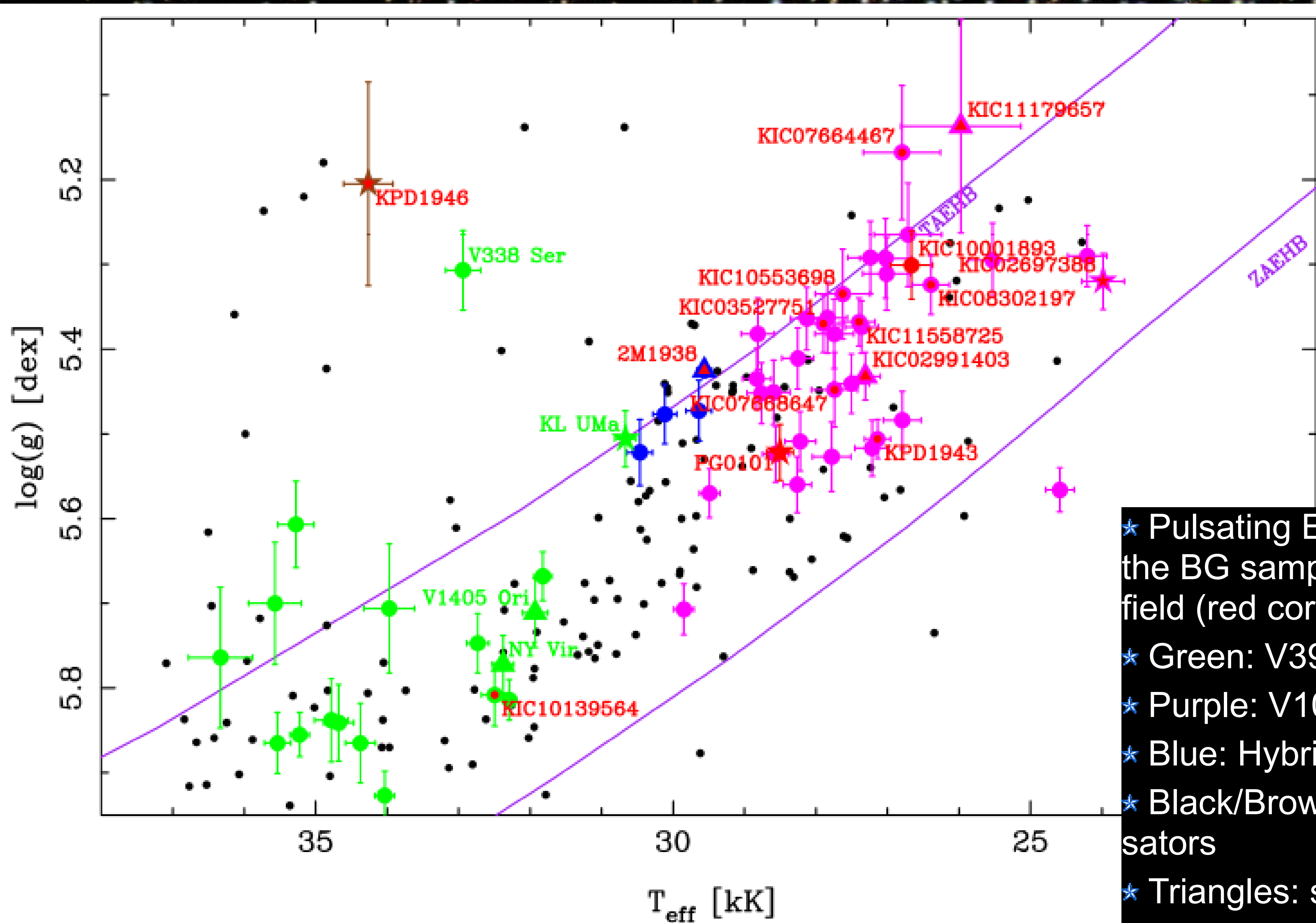
The KASC Compact Pulsator Survey checked 110 candidates

- **Pulsating hot subdwarf stars**
  - V361 Hya (p-mode) 2
  - V1093 Her (g-mode) 11
  - V1093 Her sdB+dM 2
  - Hybrid eclipsing sdB+dM 1
- **Cataclysmic variables**
  - Nova-like 2
  - AM Cvn 1
- **Non-pulsating compact binaries**
  - Eclipsing sdB+WD 1
  - Beaming sdB+WD 2
  - Non-eclipsing sdO/B+dM 2
  - sdO/B+F/G/K w/var. comp's 10
- **Pulsating white dwarf stars**
  - ZZ Ceti pulsators (DAVs) 1
  - V777 Her pulsators (DBVs) 1

See Østensen et al. 2010, 2011 for the full list of compact pulsators and binaries, and example light-curves

The Kepler sample of sdBVs



- Pulsating EHB stars in the BG sample and Kepler field (red core)
- Green: V391 Hya stars
- Purple: V1093 Her stars
- Blue: Hybrid DW Lyns
- Black/Brown: Non-pulsators
- Triangles: sdB+dM
- Stars: sdB+WD
- Bullets: single/unknown

From a survey of compact pulsators in the Kepler field: Østensen, Silvotti, Charpinet et al. (2010, MNRAS 409, 1470; 2011, MNRAS 414, 2860)

The Kepler sample of sdBVs

www.ster.kuleuven.be/~roy/wg11/

Index	KeplerID	Short name	Name	Class	RA	Dec	mag	Quarter	Most recent dedicated paper
Pippin	2697388	J19091+3756	J19091+3756	sdBV	19:09:07.1	+37:56:14	15.391	Q56789ABC	Charpinet et al. (2011)
Merry	2991403	J19272+3808	J19272+3808	sdBV+dM	19:27:15.9	+38:08:08	17.136	Q56789ABC	Pablo et al. (2012, MNRAS 422, 1343)
Frodo	2991276	J19271+3810	J19271+3810	sdBV-t	19:27:09.1	+38:10:26	17.423	Q.6789AB.	-
Samwise	3527751	J19036+3836	J19036+3836	sdBV	19:03:37.0	+38:36:13	14.859	Q56789ABC	-
Rosie	5807616	J19454+4105	KPD1943+4058	sdBV	19:45:25.5	+41:05:34	15.019	Q56789ABC	Charpinet et al. (2011, Nature 480, 496)
Will	7664467	J18561+4319	J18561+4319	sdBV	18:56:07.1	+43:19:19	16.45	Q56789AB.	-
Primula	7668647	J19051+4318	FBS1903+432	sdBV	19:05:06.2	+43:18:31	15.402	Q.6789ABC	-
Paladin	8302197	J19310+4413	J19310+4413	sdBV	19:31:03.4	+44:13:26	16.43	Q56789AB.	-
Tobold	9472174	J19385+4603	2M1938+4603	sdBV+dM	19:38:32.6	+46:03:59	12.264	Q56789ABC	-
Otho	10001893	J19095+4659	J19095+4659	sdBV	19:09:33.5	+46:59:04	15.846	Q.6789ABC	-
Saradoc	10139564	J19249+4707	J19249+4707	sdBV	19:24:58.2	+47:07:54	16.13	Q56789ABC	Baran et al. (arXiv:1206.3841)
Hamfast	10553698	J19531+4743	J19531+4743	sdBV+WD	19:53:08.4	+47:43:00	15.134	Q...89A.C	-
Bilbo	10670103	J19346+4758	J19346+4758	sdBV	19:34:39.9	+47:58:12	16.53	Q56789ABC	-
Rorimac	11179657	J19023+4850	J19023+4850	sdBV+dM	19:02:21.9	+48:50:52	17.065	Q567.9AB.	Pablo et al. (2012, MNRAS 422, 1343)
Mungo	11558725	J19265+4930	J19265+4930	sdBV+WD	19:26:34.1	+49:30:30	14.95	Q.6789ABC	Telting et al. (2012, A&A 544, A1)

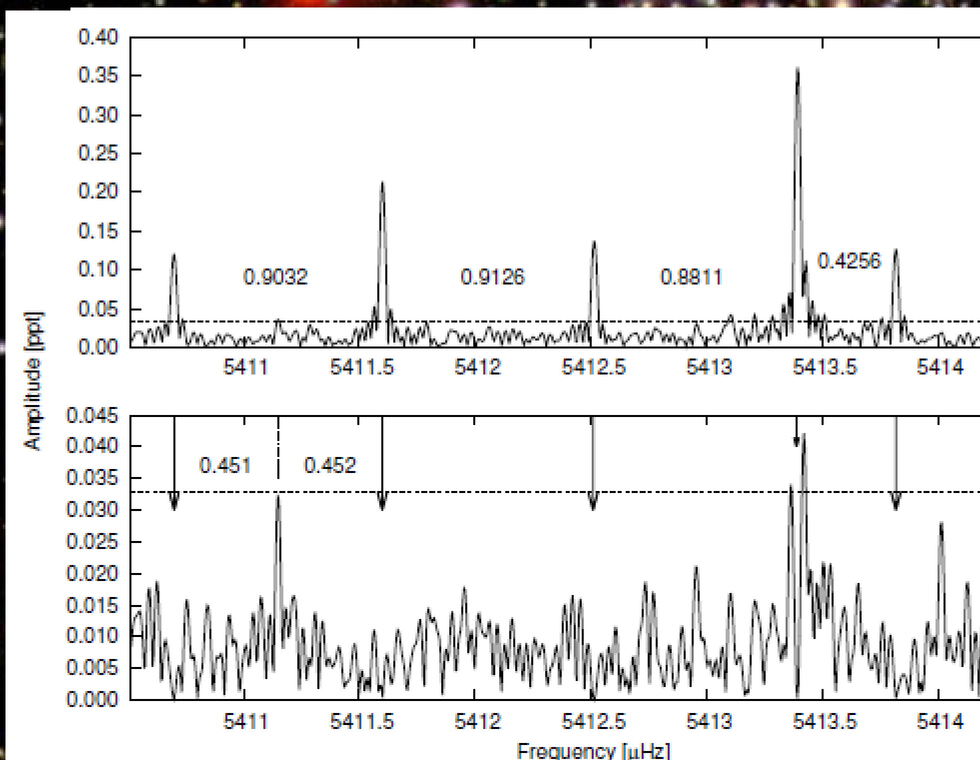
KIC 10139564 = Saradoc

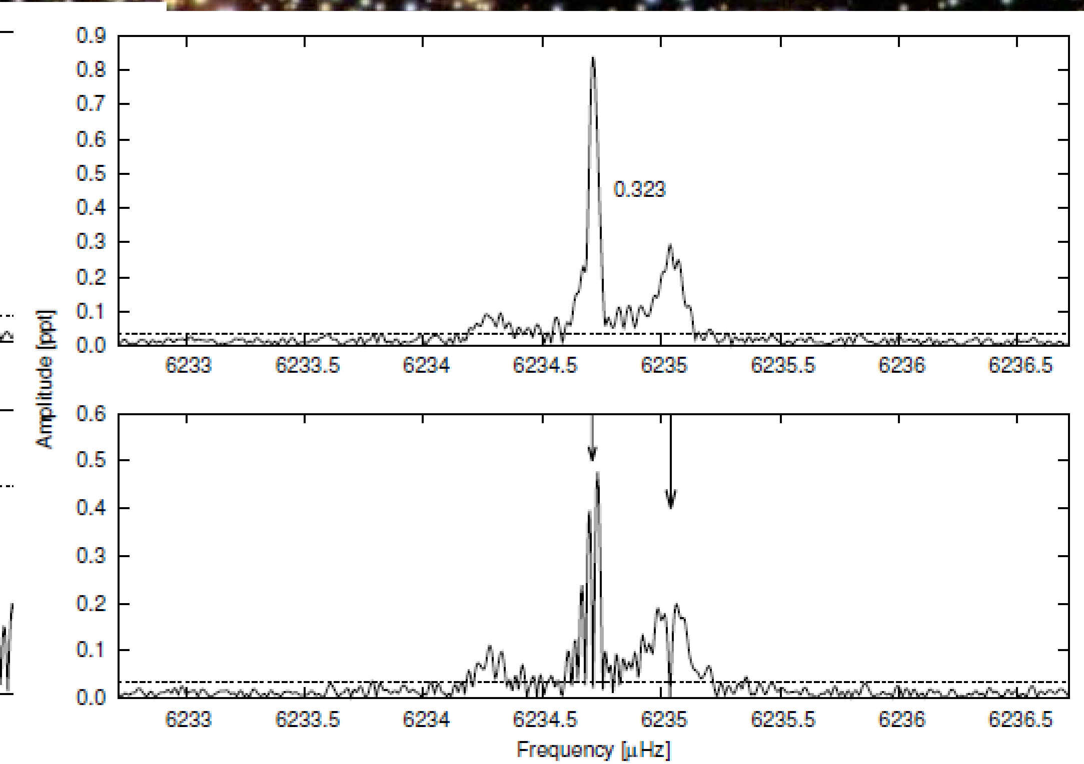
- The only clear short-period sdBV in the Kepler field
- Extensive Kepler short-cadence monitoring has revealed some extraordinary complex pulsation patterns
- Models are currently far from adequate to explain the complex frequency spectrum
- Aseroseismic mode-ID is therefore currently limited to exploring frequency separations and multiplet structures
- It is clear that Saradoc (and all the other sdB pulsators that are not in extremely short period binary orbits) are slow rotators (period on the order of a month or more)

KIC 10139564 = Saradoc

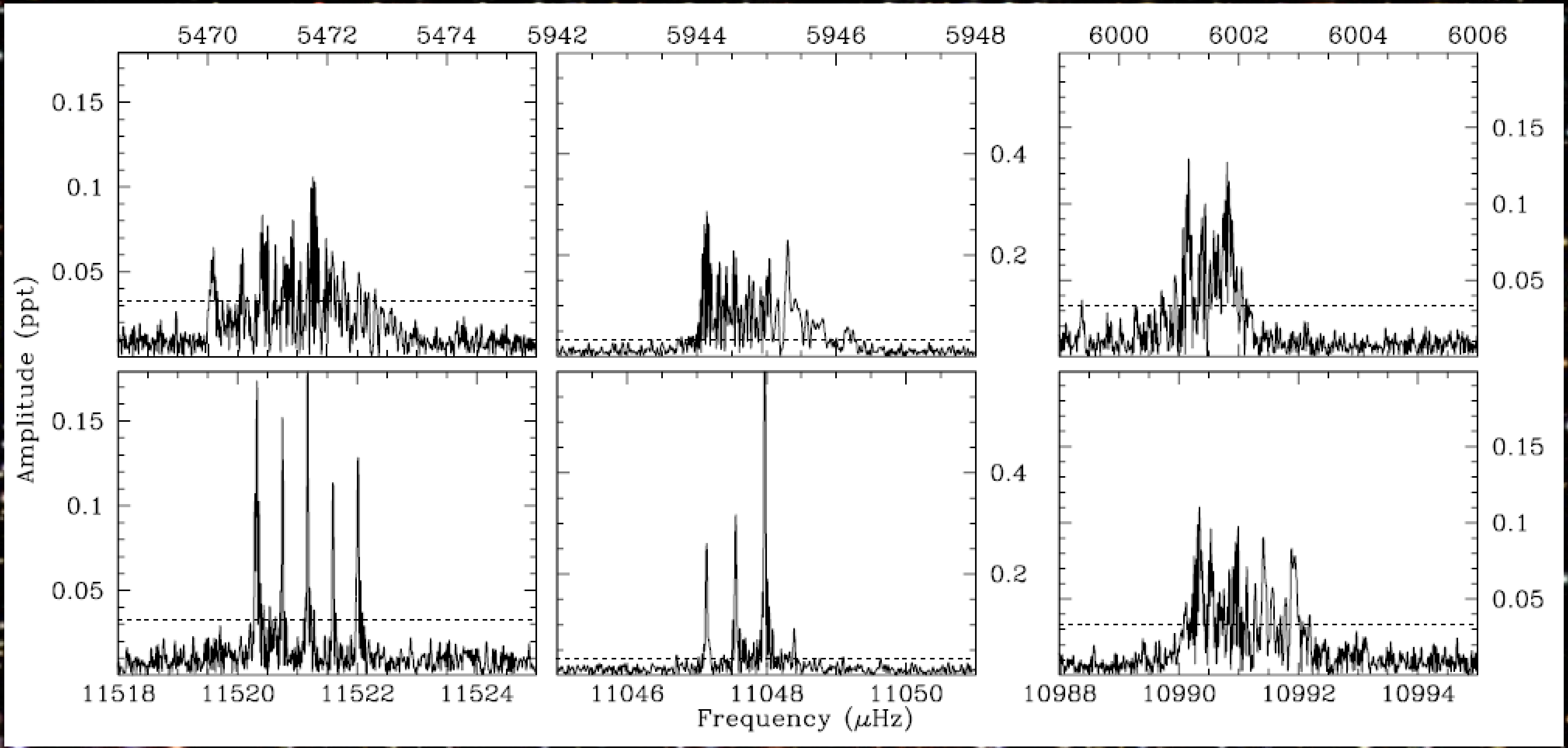
A pulsation zoo in the hot subdwarf B star KIC 10139564 observed by *Kepler*★

A. S. Baran[1,2]†, M. D. Reed[1], D. Stello[3], R.H. Østensen[4], J.H. Telting[5], E. Pakštienė[6], S. J. O'Toole[7], R. Silvotti[8], P. Degroote[4,9], S. Bloemen[4,9], H. Hu[9,10], V. Van Grootel[9,11], B.D. Clarke[12], J. Van Cleve[12], S.E. Thompson[12] S.D. Kawaler[9,13]





KIC 10139564 = Saradoc



- Pulsation peaks beyond the Nyquist limit; the shortest period pulsations detected by Kepler

Long-period sdB pulsators

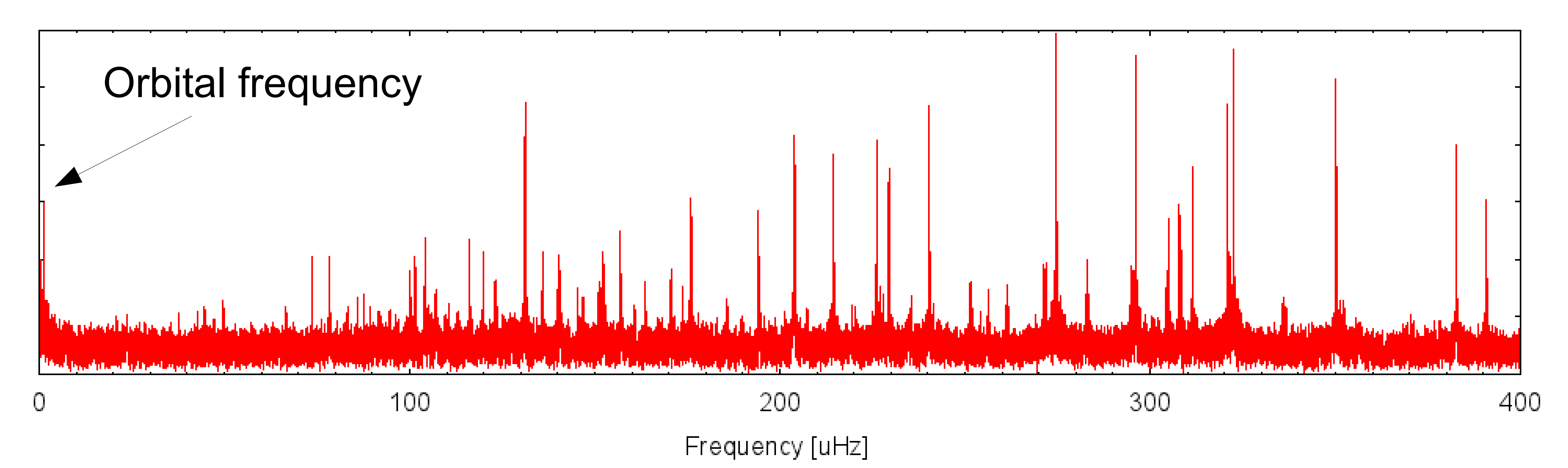
- It has been demonstrated that all the V1093 Her pulsators found in the Kepler field show regular l=1 and l=2 period spacing sequences

- These sequences follow asymptotic theory more closely than atmospheric models predict, which implies that the envelopes are more homogenous than the standard models have presumed (more diffusion or convection processes are required).

- This permits direct mode identification from the frequency spectra of most modes observed

KIC 11558725 = Mungo

- Telting et al (2012, A&A 544, A1) analysed Q6 – Q10 data and spectroscopy, and found it to be an sdB+WD binary (non-eclipsing) with a 10d orbital period
- They measured the orbit in 3 independent ways
  - Spectroscopic radial velocities; K1 = 58.1 +/- 1.7 km/s
  - Doppler beaming from Kepler light-curve
  - Rømer delay in pulsations



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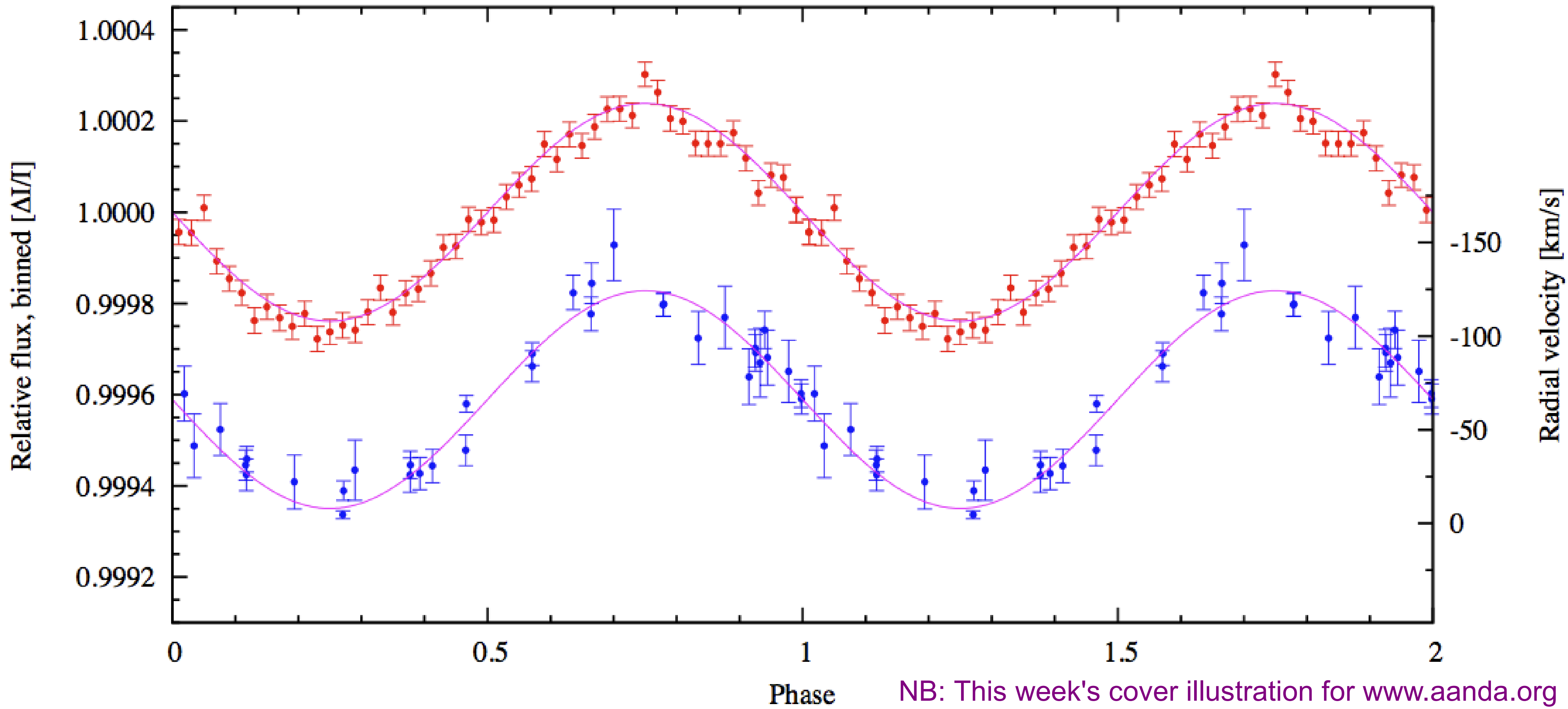
KIC 11558725 = Mungo

- When the Kepler data is folded on the orbital period, a sinosoidal modulation lines up with the spectroscopic RVs



NB: This week's cover illustration for www.aanda.org

KIC 7975824 = KPD 1946+4340

Doppler beaming:

$$F_\lambda = F_{0,\lambda}\left(1 - B\frac{v_r}{c}\right)$$

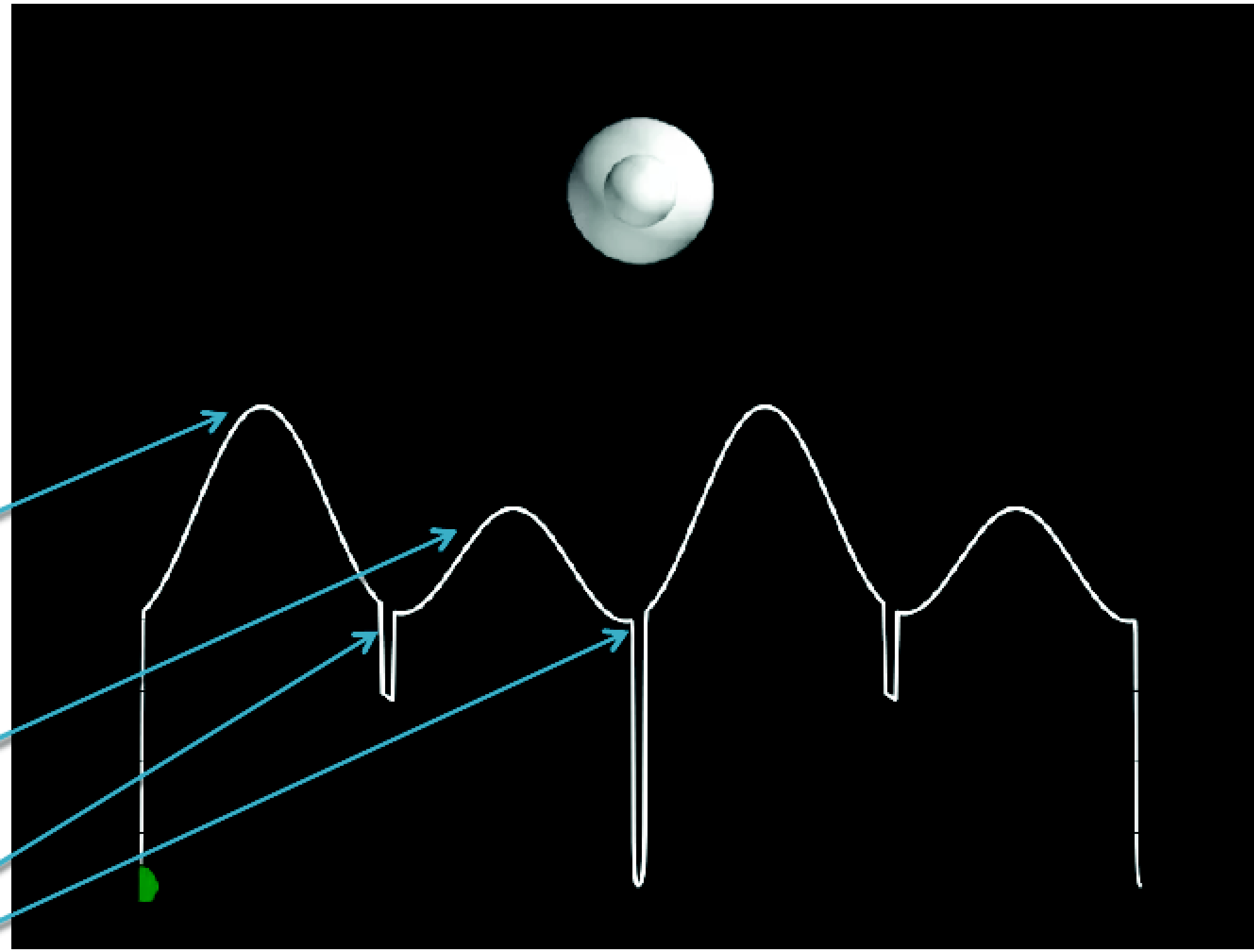
$$\langle B \rangle = \frac{\int \epsilon_\lambda \lambda F_\lambda B \, d\lambda}{\int \epsilon_\lambda \lambda F_\lambda \, d\lambda}$$

$$B = 5 + \mathrm{d}\ln \mathrm{F}_\lambda / \mathrm{d}\ln\lambda$$

Ellipsoidal maximum
+ beaming maximum

Ellipsoidal maximum
+ beaming minimum

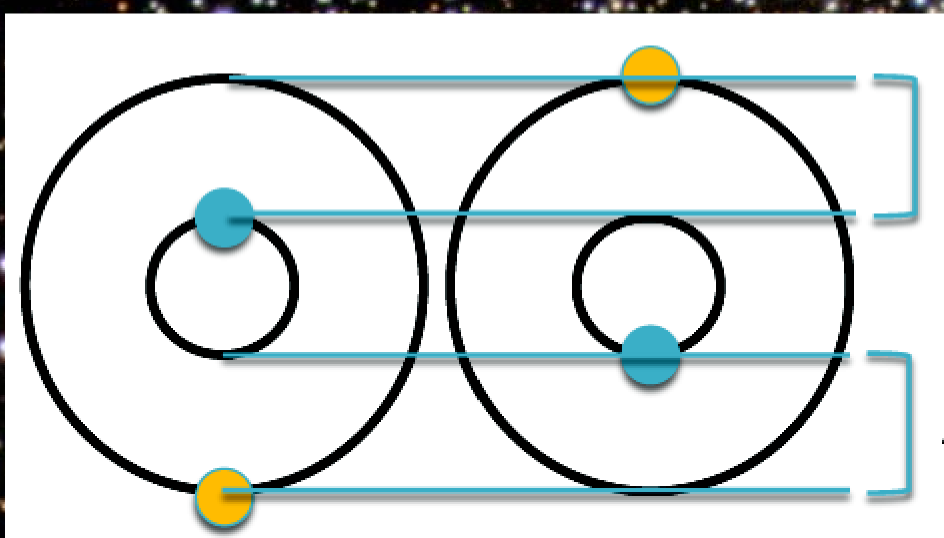
Ellipsoidal minimum
+ no beaming



Ellipsoidal modulation, reflection, eclipses+transits, lensing

KIC 11558725 = Mungo

- The Rømer delay is the difference in light travel time as one star (or planet) orbits another
- In eclipsing binaries it leads to an offset in the times of primary and secondary eclipse
- For a pulsating star like Mungo, the Rømer delay produces phase shifts in the arrival times of the light curves



KIC 11558725 = Mungo

- ‘Rømer delay’ (light travel time) due to size of the orbit

$$\Delta t_R = \frac{a_{sdB} \sin i}{c} = \frac{K}{c}\frac{P_{orb}}{2\pi}\sqrt{1-e^2} ,$$

- Time delay in light of sdB as a function of time

$$T_{delay}(t) = \Delta t_R \cos\left(\frac{2\pi}{P_{orb}}(t - T_{orb})\right)$$

Assuming circular orbit

T_{orb} = sdB closest to the Sun

- Expected signal:

$$\frac{\Delta I(t)}{I} = A_B \sin\left(\frac{2\pi}{P_{orb}}(t - T_{orb})\right)$$ ← Beaming

$$+ \sum_i A_{i,puls} \sin\left(2\pi F_{i,puls}(t - T_{i,puls} + T_{delay}(t))\right)$$ ← Pulsations with Rømer delay

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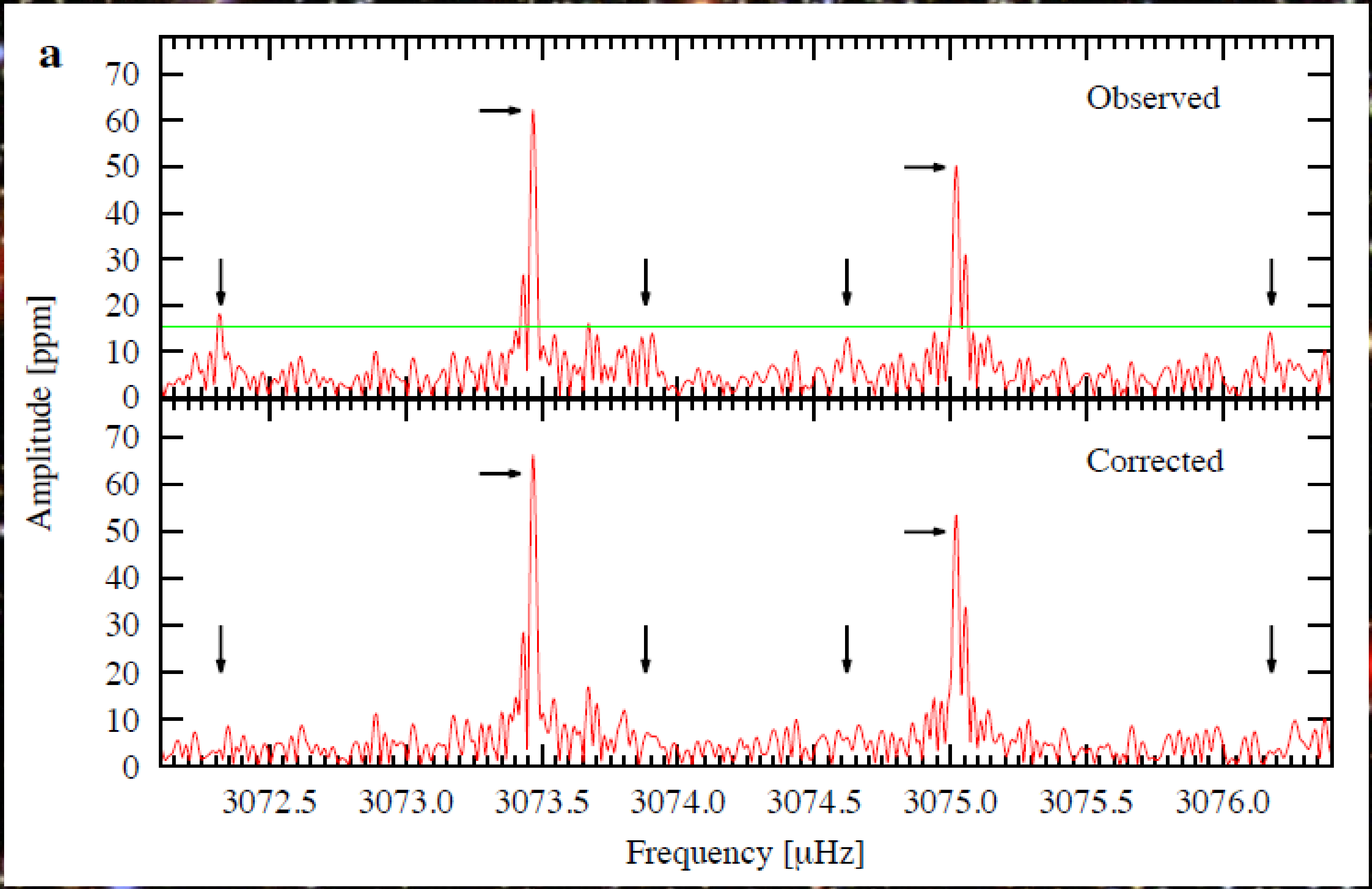
KIC 11558725 = Mungo

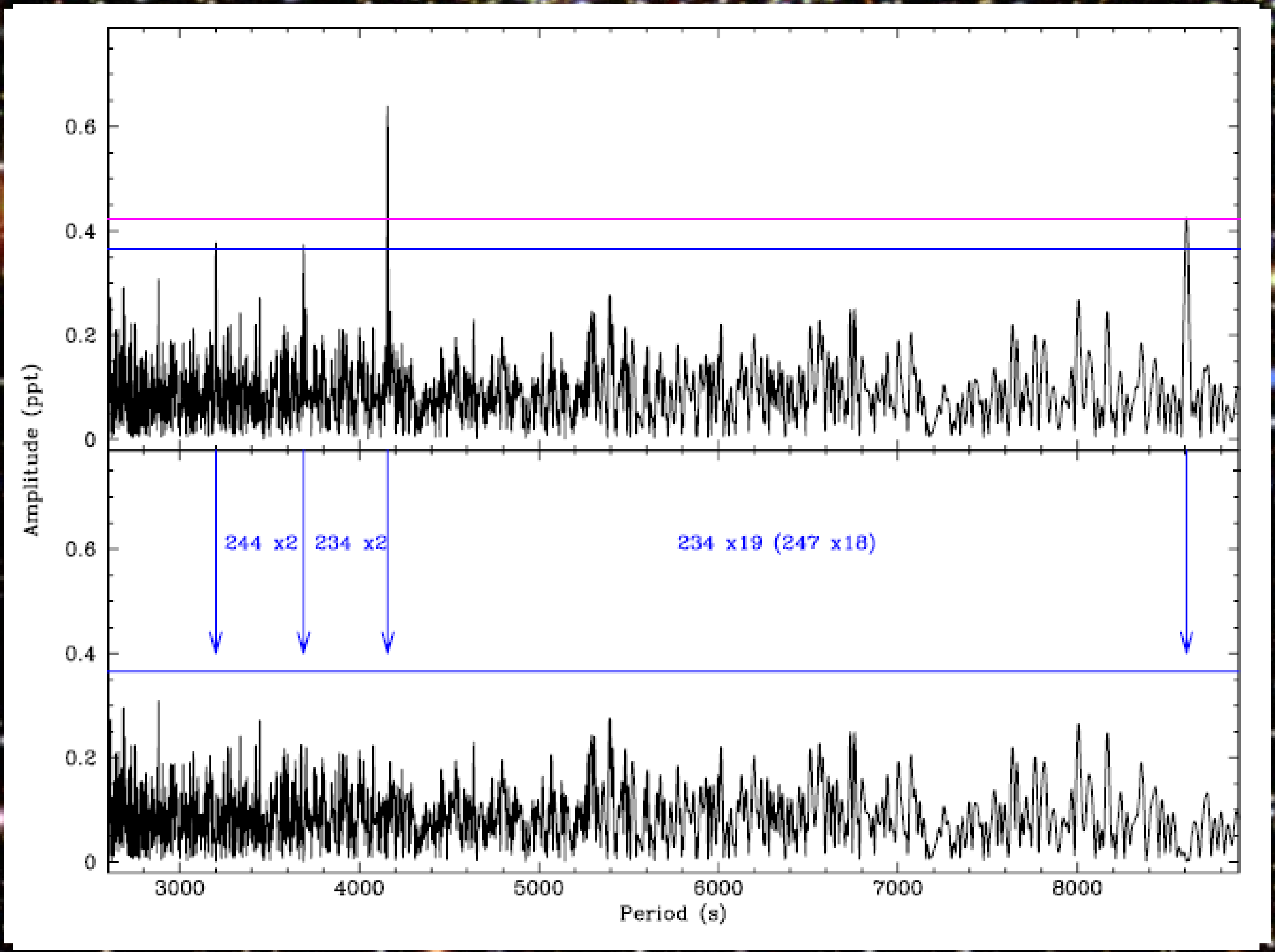


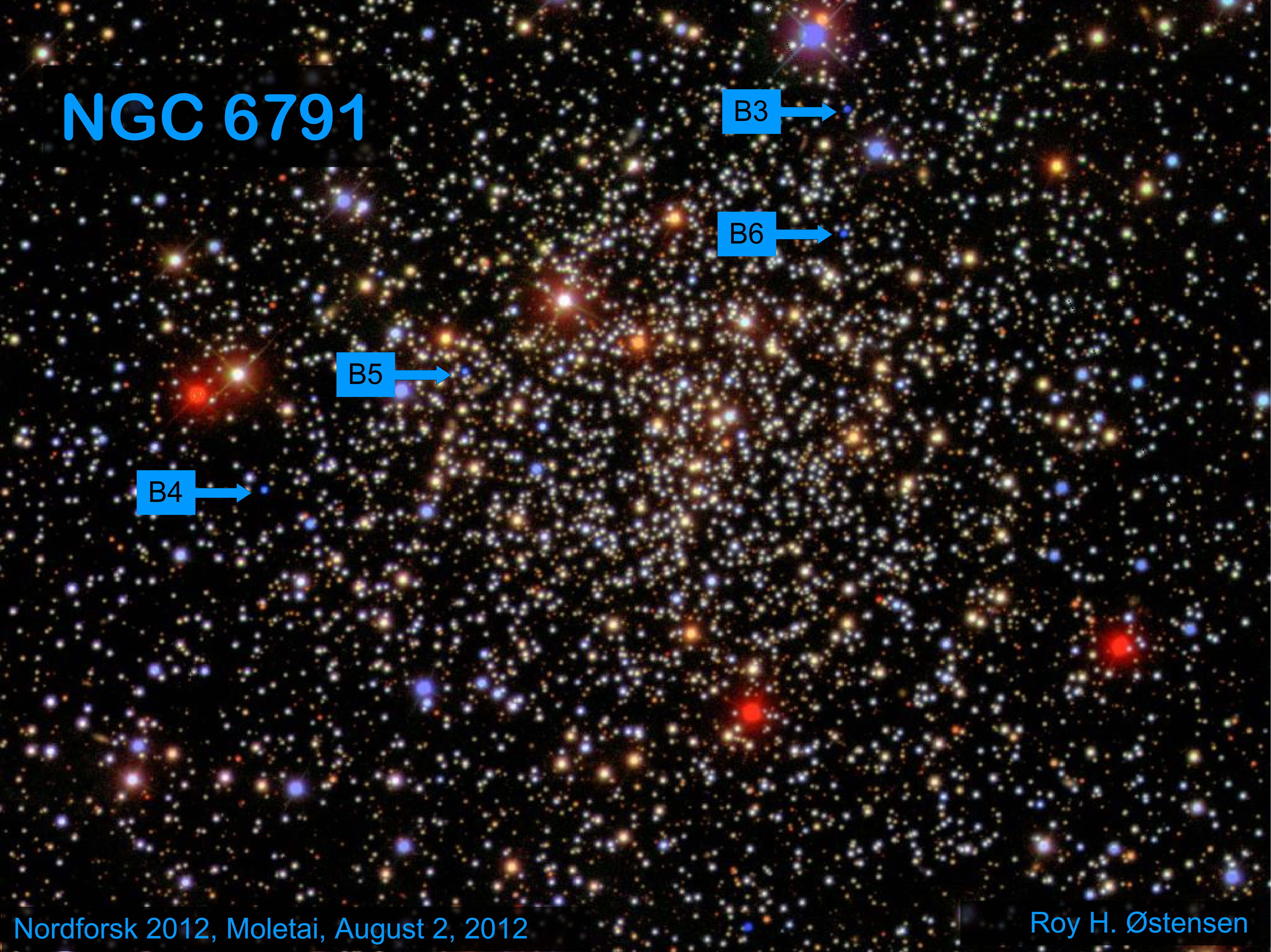
Long-period sdB pulsators
Latest news:

Two new pulsating sdB stars was detected in the cluster NGC 6791 from Q11 1-month DDT-time runs.

- They are KIC 2569576 = B3 & KIC 2437937 = B5
- These two come in addition to the sdBV+dM binary pulsator already known
(KIC 2438324 = B4, Pablo et al. 2011, ApJ 740, 47)
- One short-period pulsator candidate was also investigated (B6), but is not a pulsator

Long-period sdB pulsators
Latest news:




NGC 6791
B3
B6
B5
B4
Nordforsk 2012, Moletai, August 2, 2012
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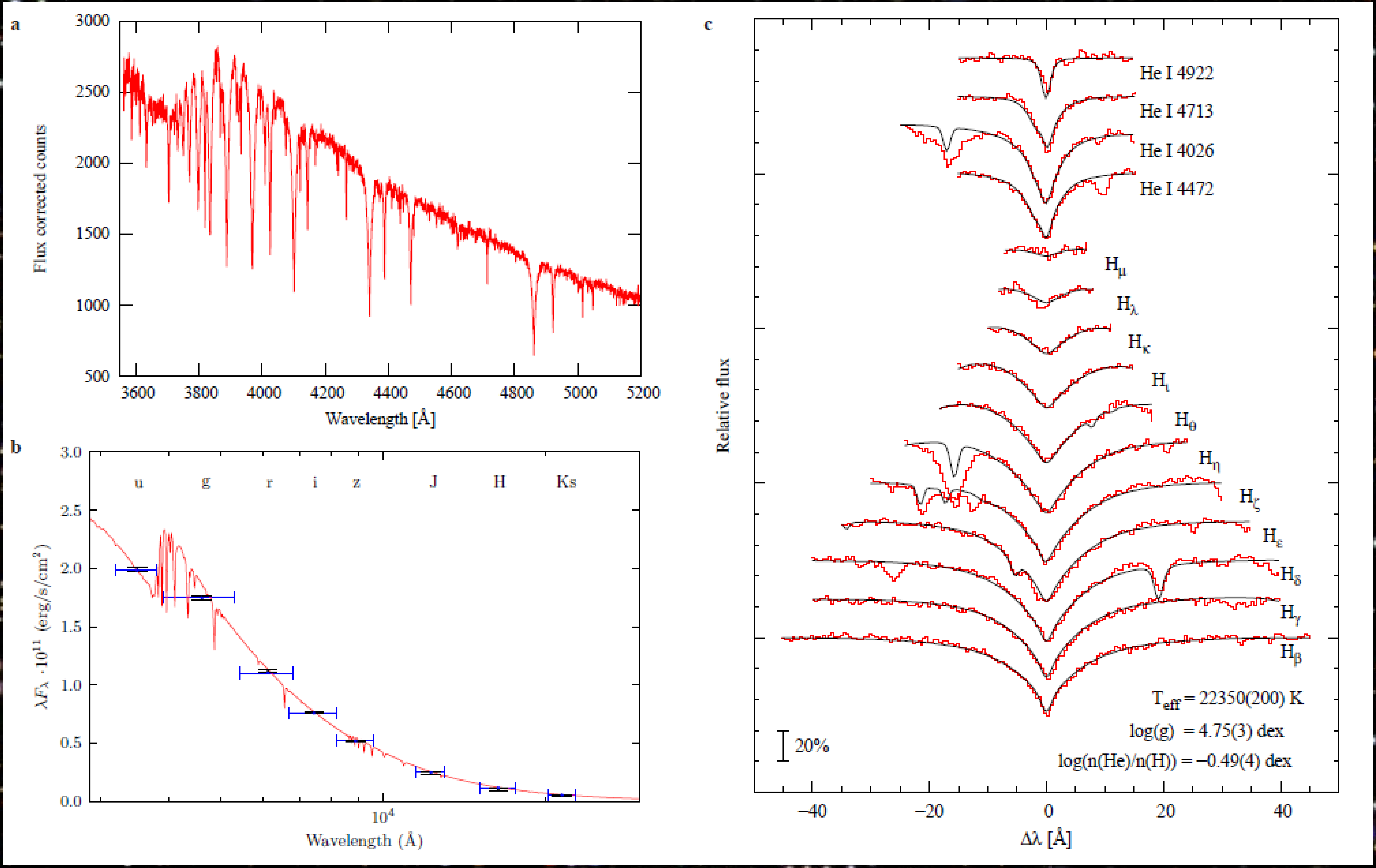
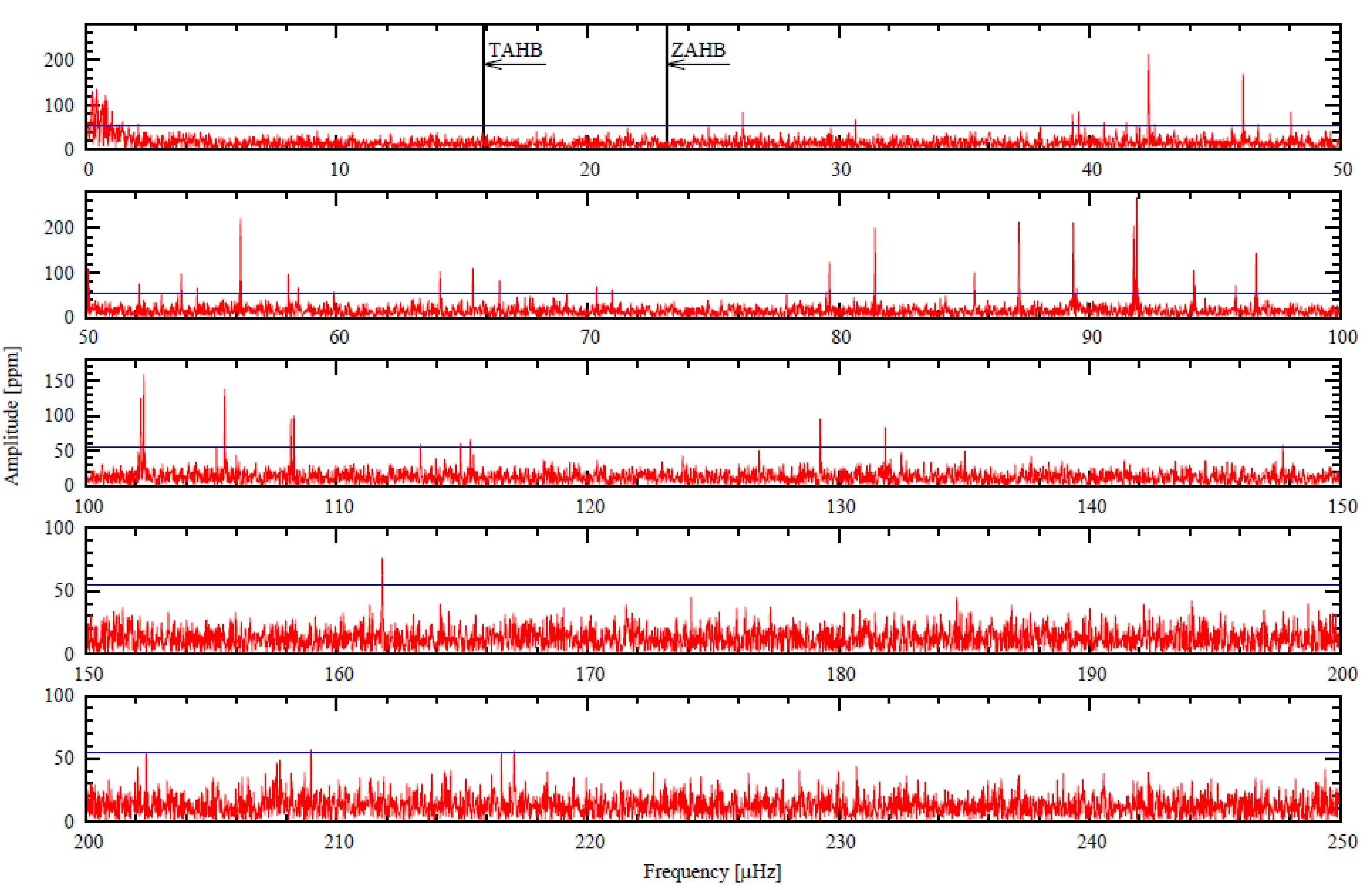
KIC 1718290 = Largo

- Østensen et al (2012, ApJL 753, 17) analysed public long cadence data of KIC 1718290, and found that it shows a similar period spacing structure as the V1093 Her pulsators
- It is different from normal sdB stars in several ways
  - It's surface gravity is less than 5, i.e. it is not a classic EHB star
  - It is rather helium rich, where as normal sdB stars are helium depleted (typicallly by a factor 10 to 100 wrt solar abundance)

KIC 1718290 = Largo



KIC 1718290 = Largo



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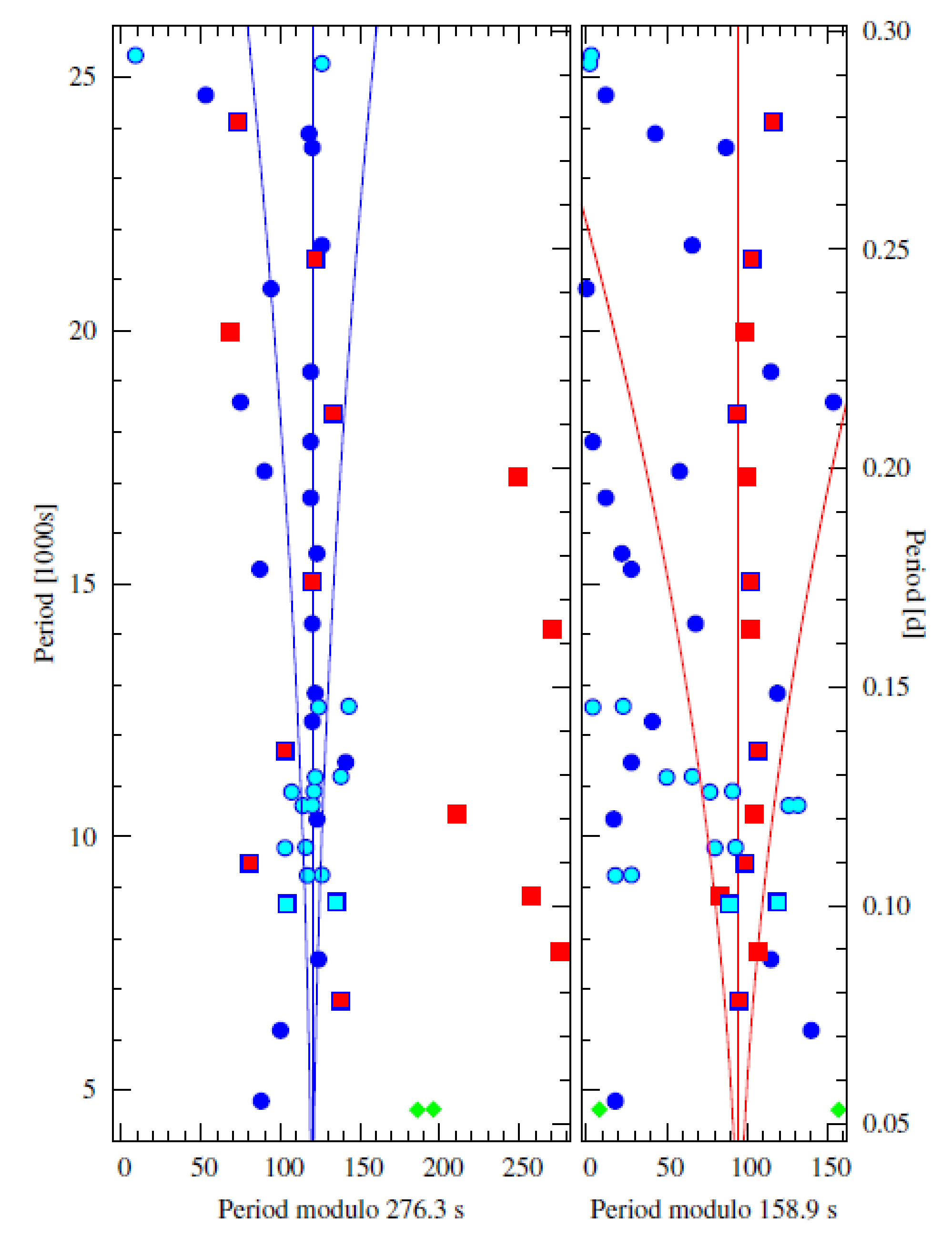
KIC 1718290 = Largo



- An echelle diagram for g-modes is different than for p-modes;
  - Period instead of frequency
  - The separation period is different for different angular degree, *l*
  - So one has to make one diagram for each *l*
  - Largo has a very regular period spacing pattern, where all modes can be identified
  - This implies a thicker envelope with more mixing, than for regular sdB stars
  - Note the rotational splitting diverg-ing due to the inverse relationship with period

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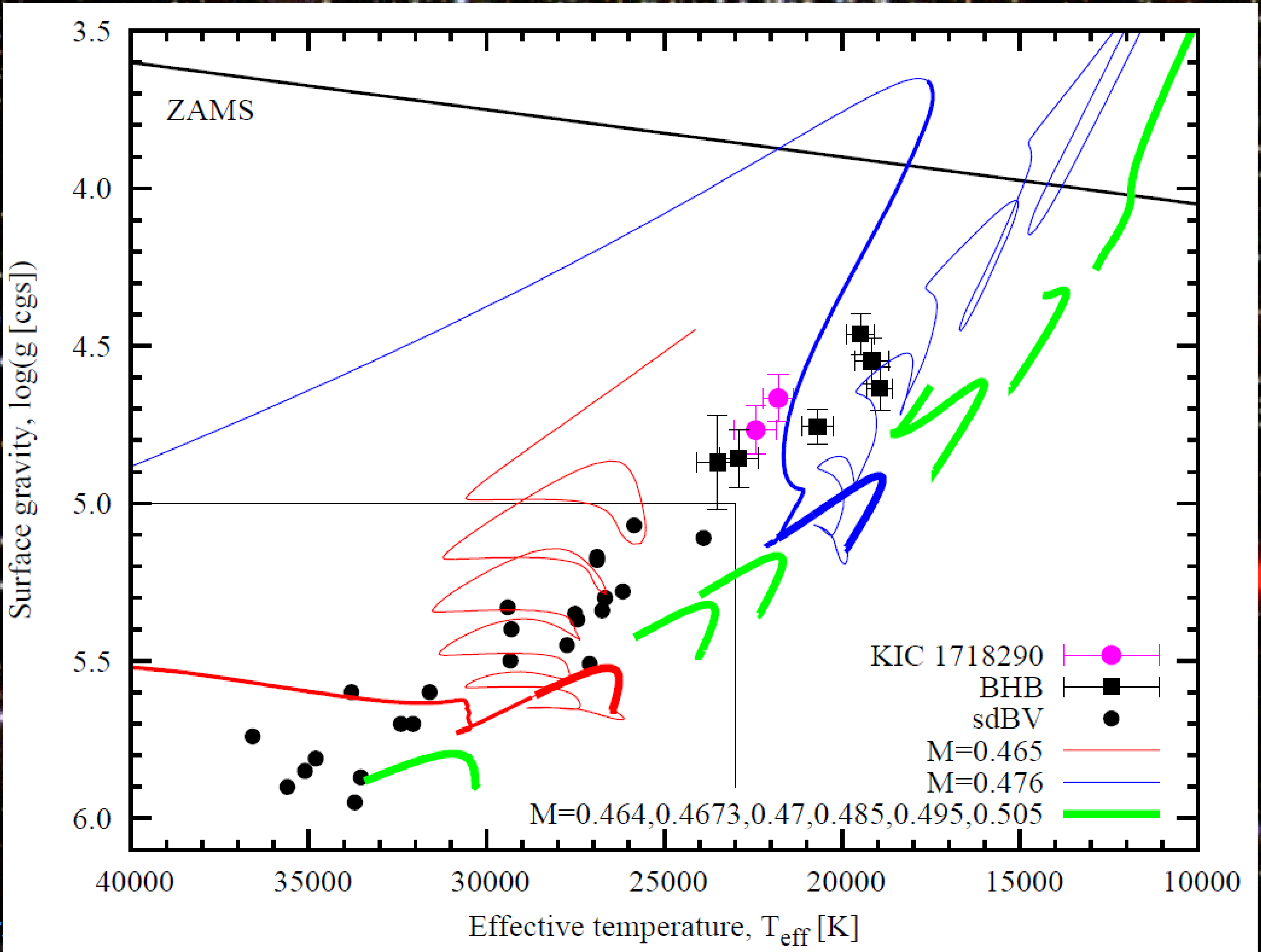
Largo is the first pulsator on the blue HB



Nordfor

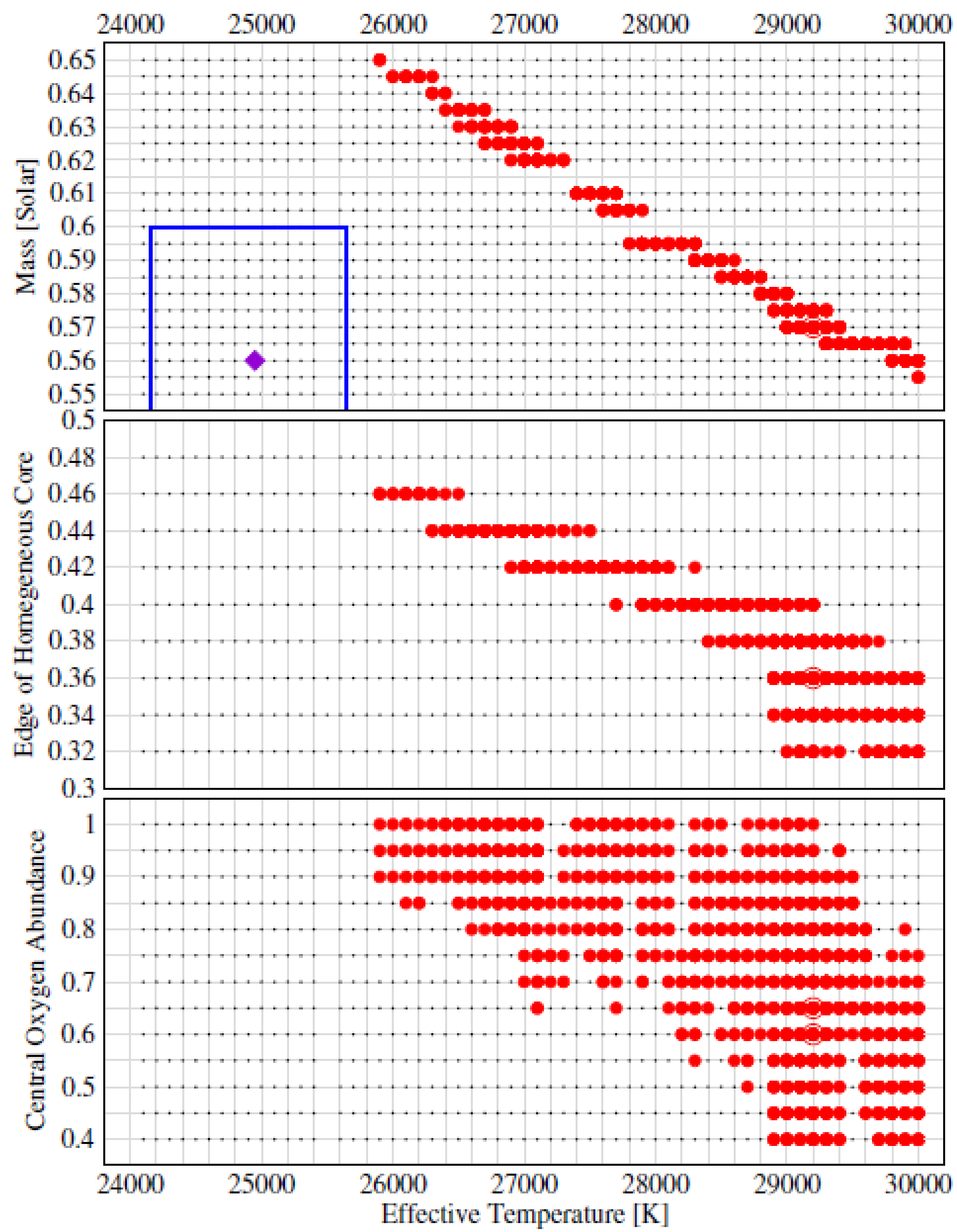
Østensen

KIC 8626021: A V777 Her pulsator (DBV)

- Østensen et al (2011, ApJL 736, 39) obtained Kepler short cadence DDT time (Q7.2) of the first pulsating WD found in the Kepler field
- The 1-month dataset contained 11 pulsation peaks, of which 9 formed neatly spaced triplets, allowing them to be associated with rotationally split triplets
- The target will hopefully be observed for the remainder of the mission, permitting the most detailed asteroseismic modelling of a WD ever
- Before the end of the Kepler mission, we will hopefully be able to detect the period changes associated with cooling of the WD

Asteroseismology from DBV modeling

THE ASTROPHYSICAL JOURNAL LETTERS, 742:L16 (5pp), 2011 November 20



doi:10.1088/2041-8205/742/1/L16

ELD DBV WHITE DWARF. IT IS A HOT ONE

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11 October 12; published 2011 November 2

TRACT

able 2
and Best-fit Parameters for WD J1929+4447

Grid 2			Best Fit
Minimum	Maximum	Step Size	
24100	30000	100	29200
0.555	0.650	0.05	0.570
	−2.80 (fixed)		−2.80
−6.10	−6.50	0.20	−6.30
0.40	1.00	0.05	0.60, 0.65[a]
0.32	0.48	0.02	0.36

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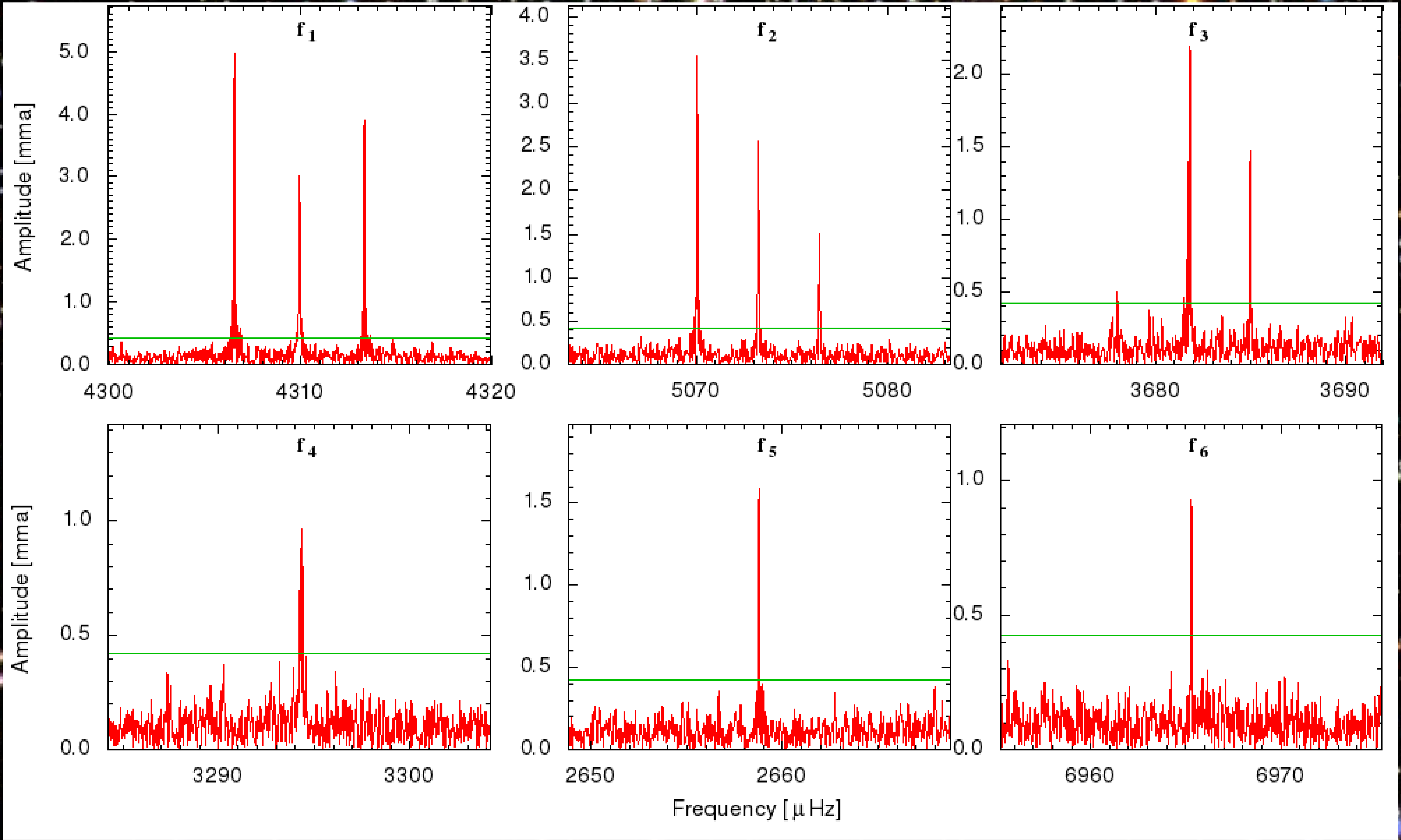
The V777 Her with 6 months of SC data



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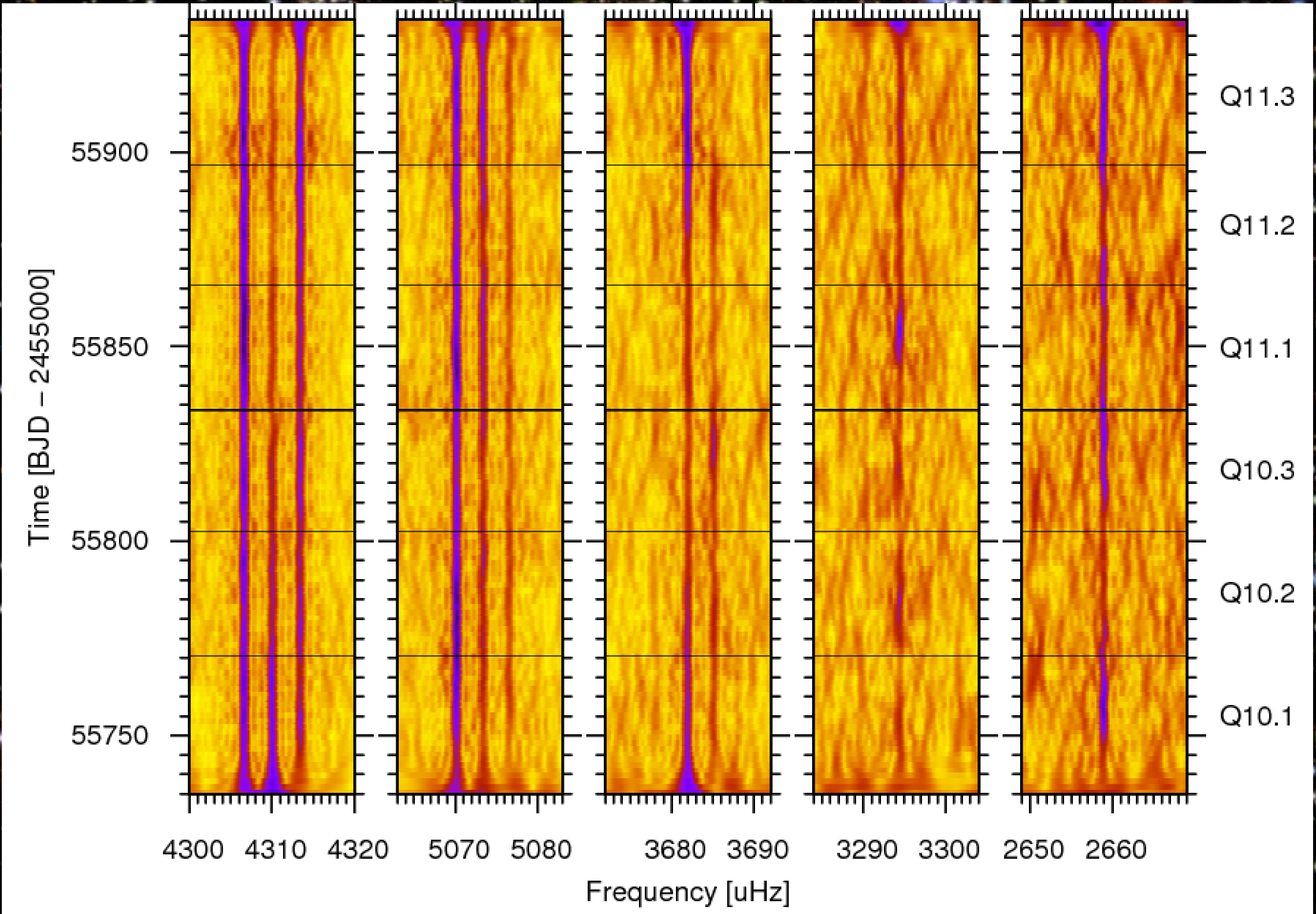

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Things to keep in mind...

- Compact stars are faint and the pulsators are rare, and they are normally not targeted through the Kepler planet search
- Any attempt at detecting compact pulsators must start with some survey data
- Anybody who finds a good pulsator candidate can propose it as a target through the Kepler DDT or GO programs
- Most compact pulsators require short cadence data, which is a limited resource, but white dwarf pulsators are very competitive
- There are still many white dwarf pulsators waiting to be found!