Solar-like oscillators

Information in the frequency power spectrum

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Guy R. Davies +

Kepler

CoRoT

PER ARDUA AD ALTA

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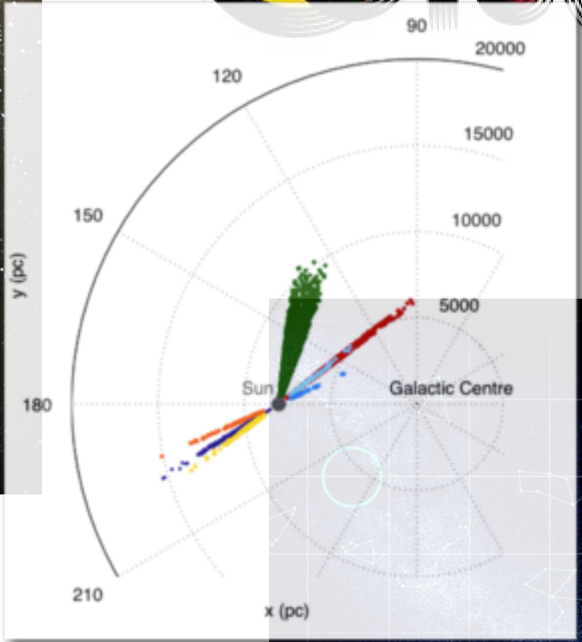

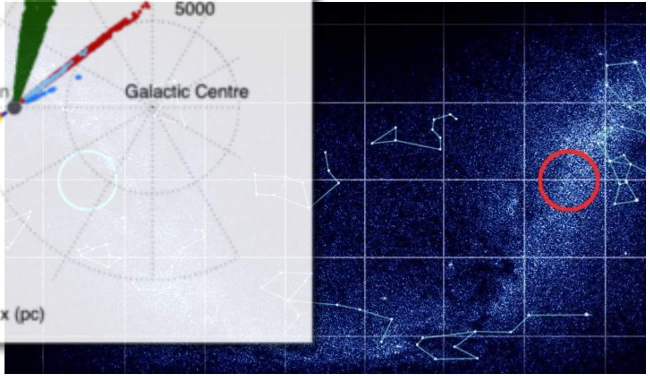

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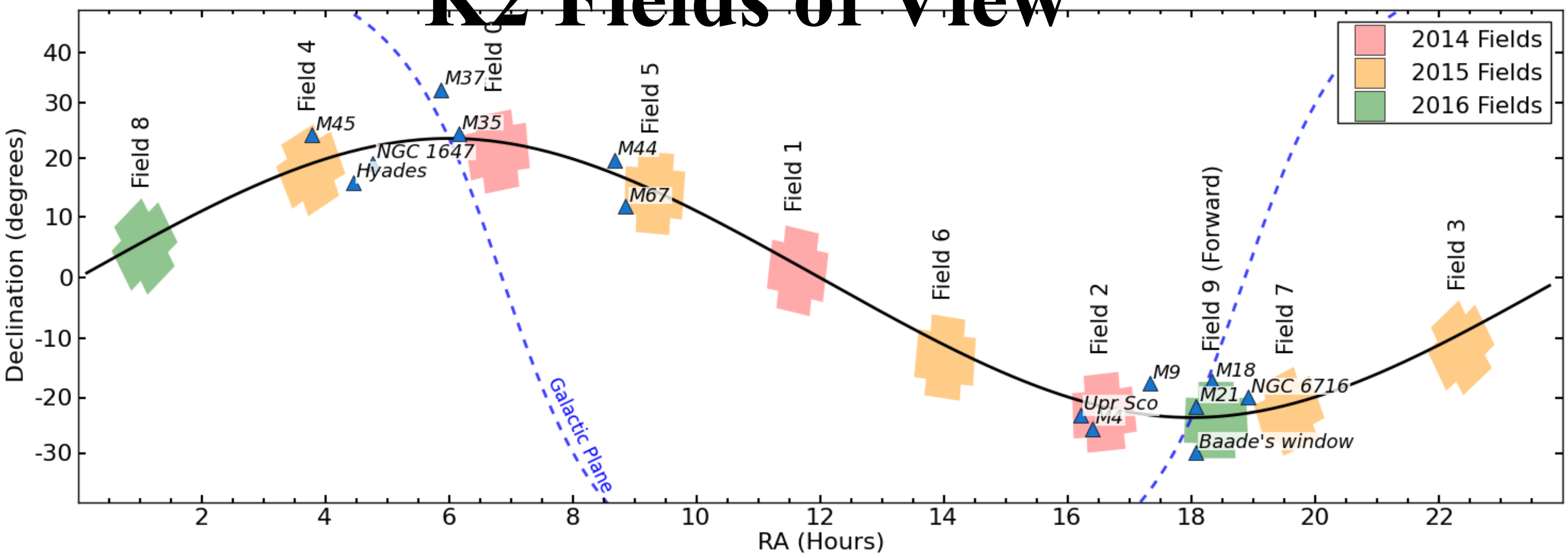
K2 Fields of View



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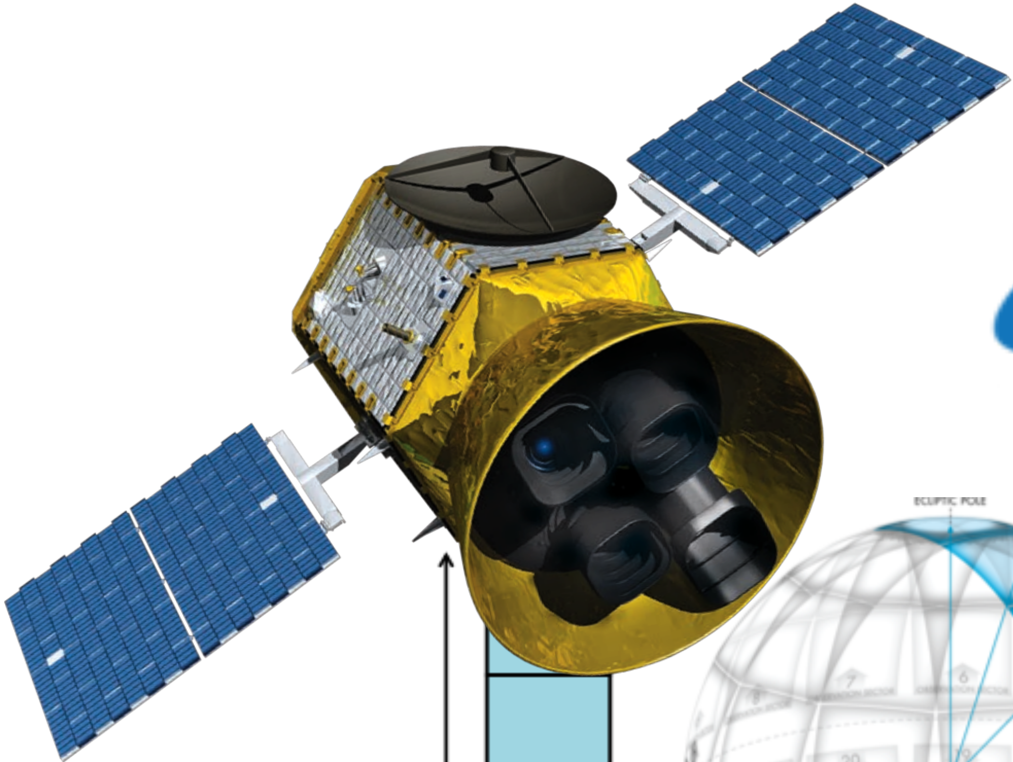

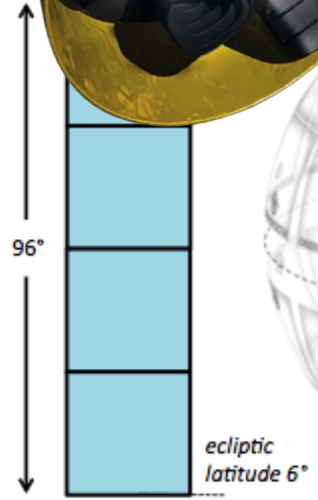

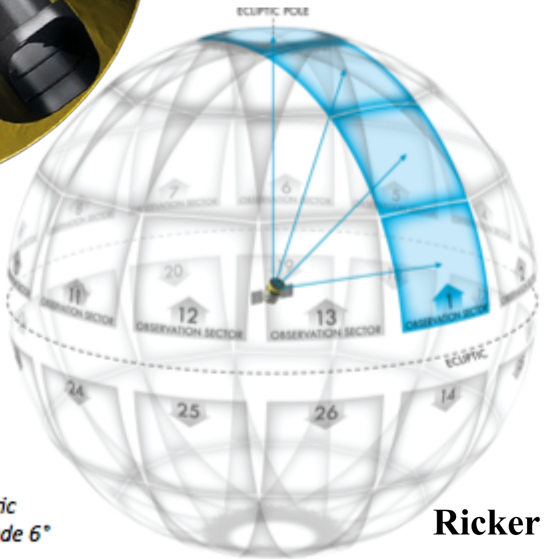

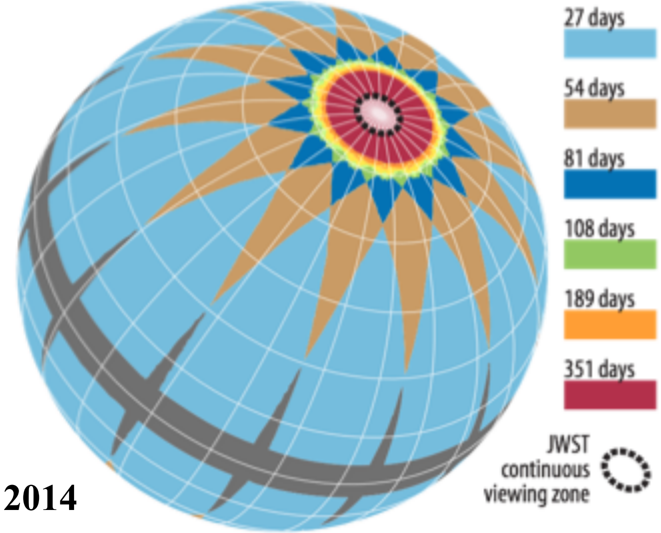

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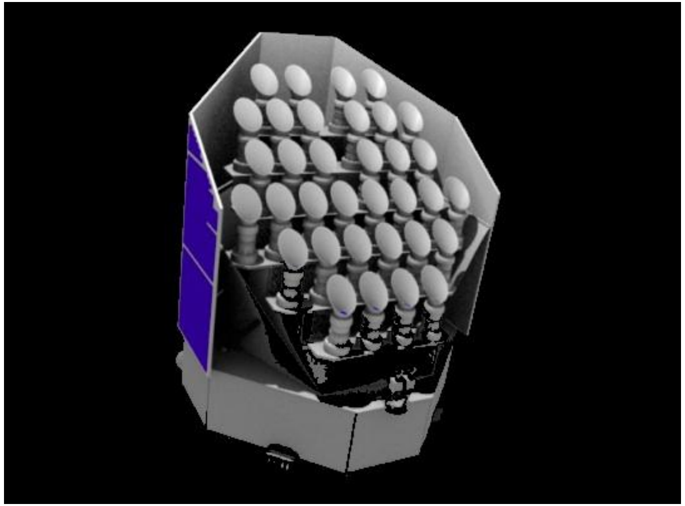

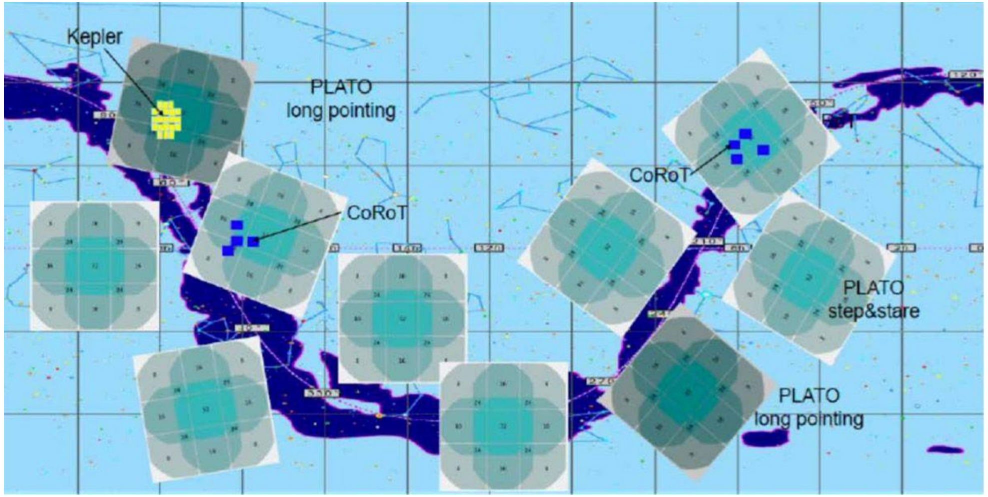

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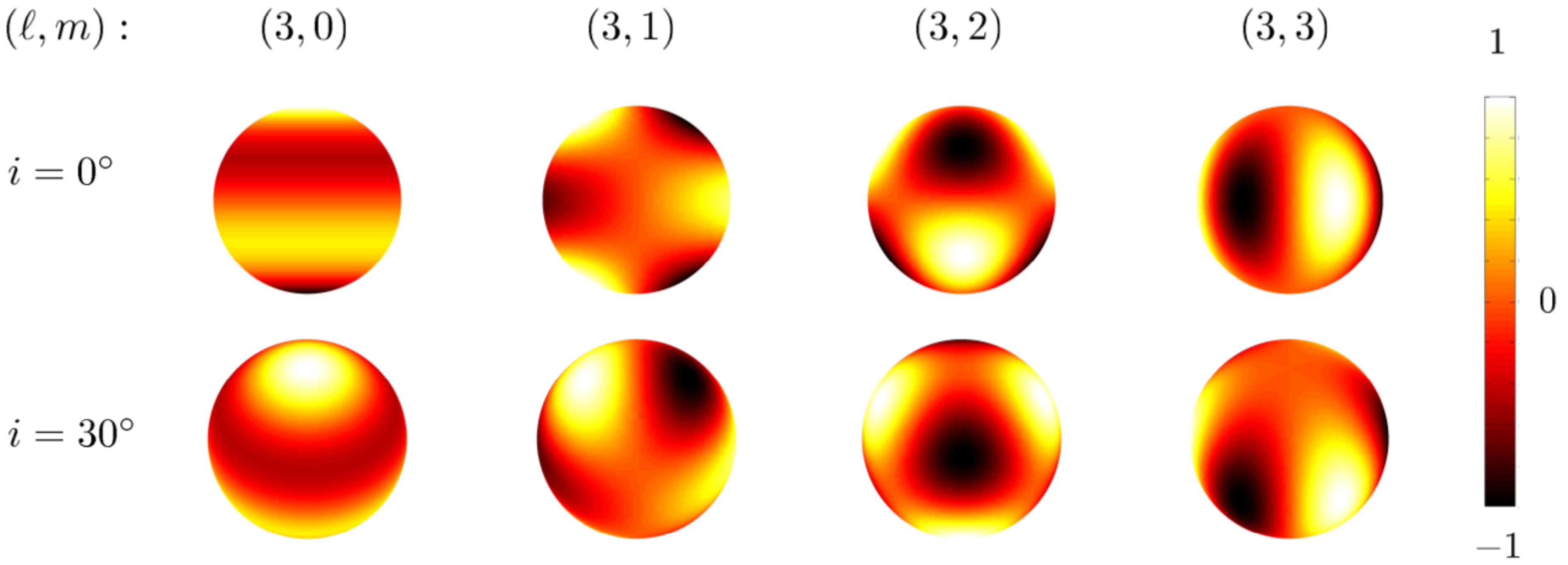
Oscillations produce variations in intensity



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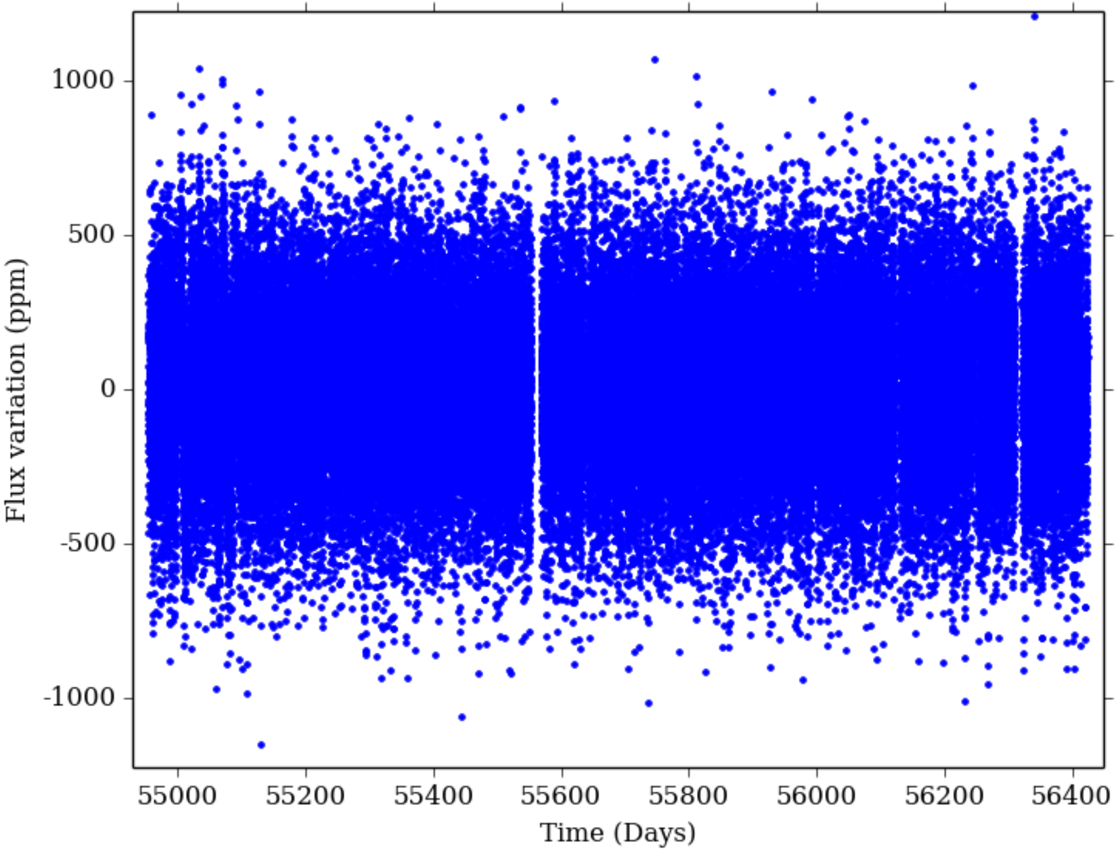
Time domain astronomy



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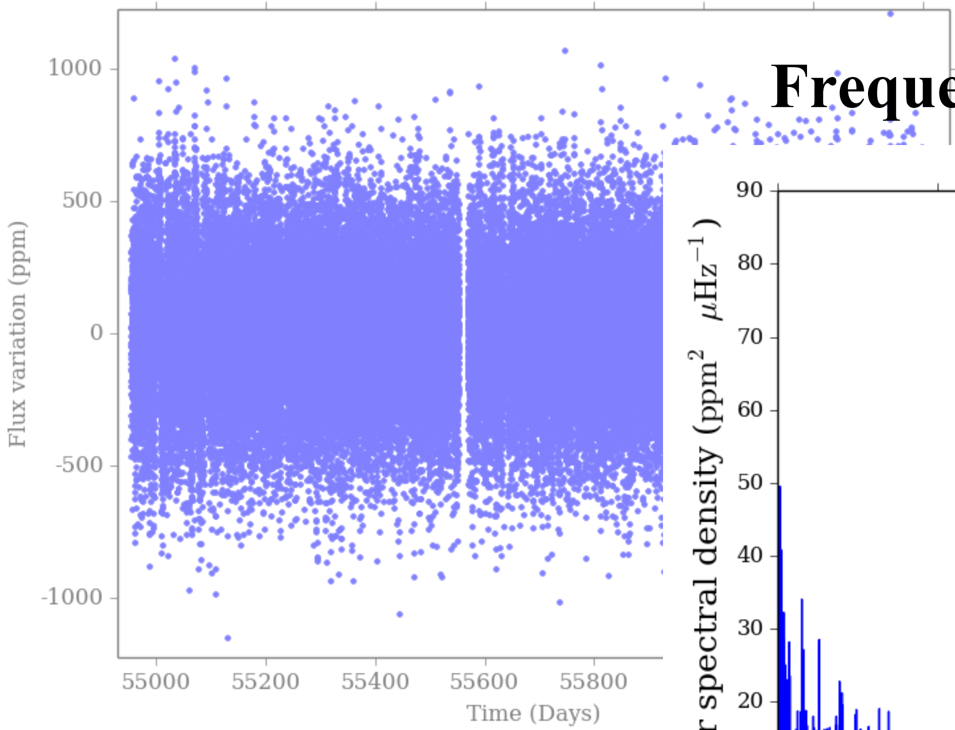
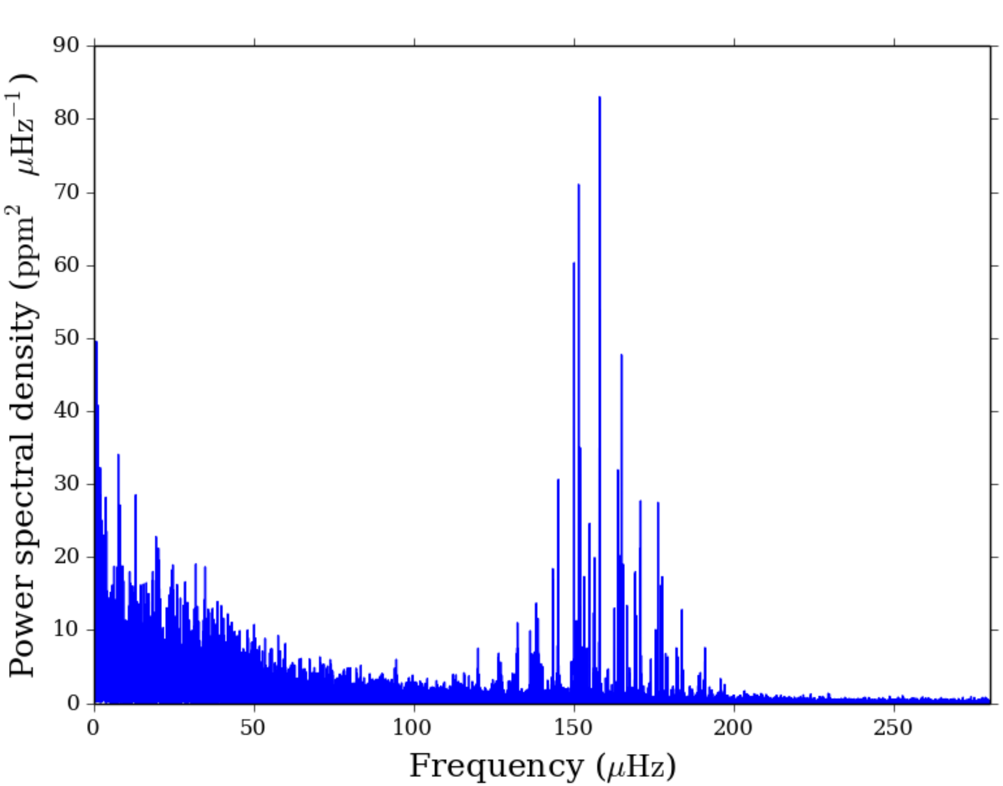
Frequency domain astronomy!





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Sun-like stars

Solar type	Solar analog	Solar twin
K2 through to F8	5200 to 6300 K	5720 to 5830 K
Main sequence	Main sequence and no close companion	MS, 3.5 to 5.6 Gyr, and no stellar companion
Any metallicity	Solar +- 0.3 dex	Solar +- 0.05 dex
A lot of stars	>30 within 50 ly e.g., Alpha Cen A (& B)	A handful e.g., 18 Sco

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Solar-like oscillators

Evolved Sun-like stars	Solar type	Solar analog	Solar twin	The Sun
Cooler	K2 through to F8	5200 to 6300 K	5720 to 5830 K	5777 K
Sub giant Red giant	Main sequence	Main sequence	MS, 3.5 to 5.6 Gyr	4.5 Gyr
Any	Any metallicity	Solar +- 0.3 dex	Solar +- 0.05 dex	Solar
Many many detectable	A lot	>30 within 50 ly e.g., Alpha Cen A (& B)	A handful e.g., 18 Sco	Just the one!

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Asteroseismology of Solar-Type and Red-Giant Stars

Annual Review of Astronomy and Astrophysics
Vol. 51: 353-392 (Volume publication date August 2013)
First published online as a Review in Advance on June 26, 2013
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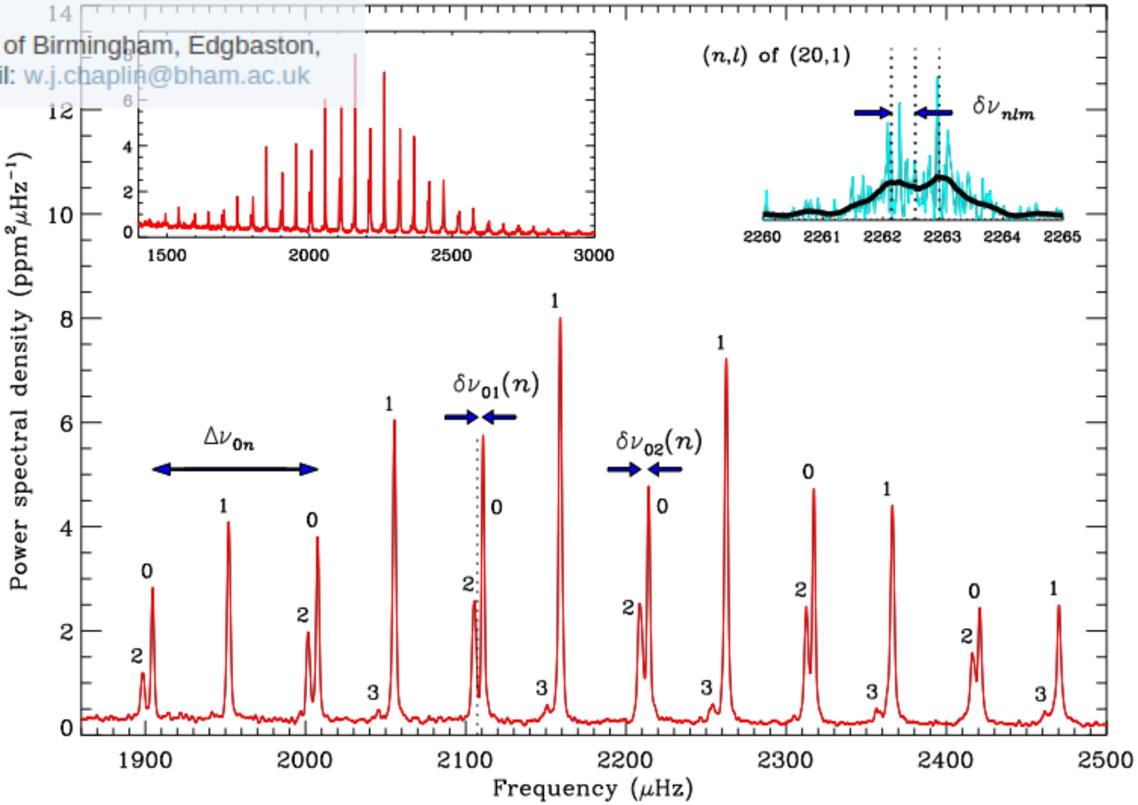
School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom; email: w.j.chaplin@bham.ac.uk



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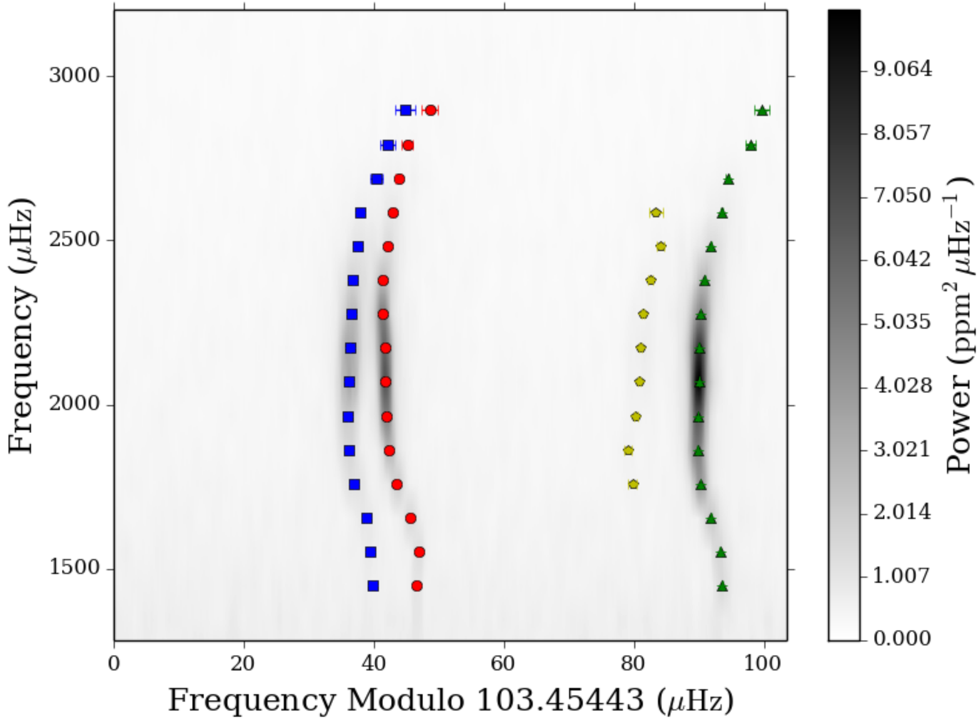
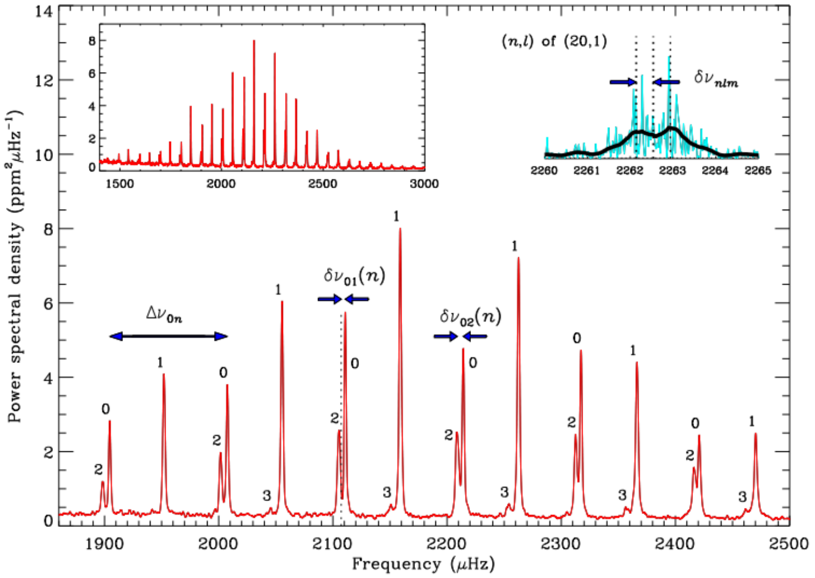
Sun-like MS stars - echelle diagram





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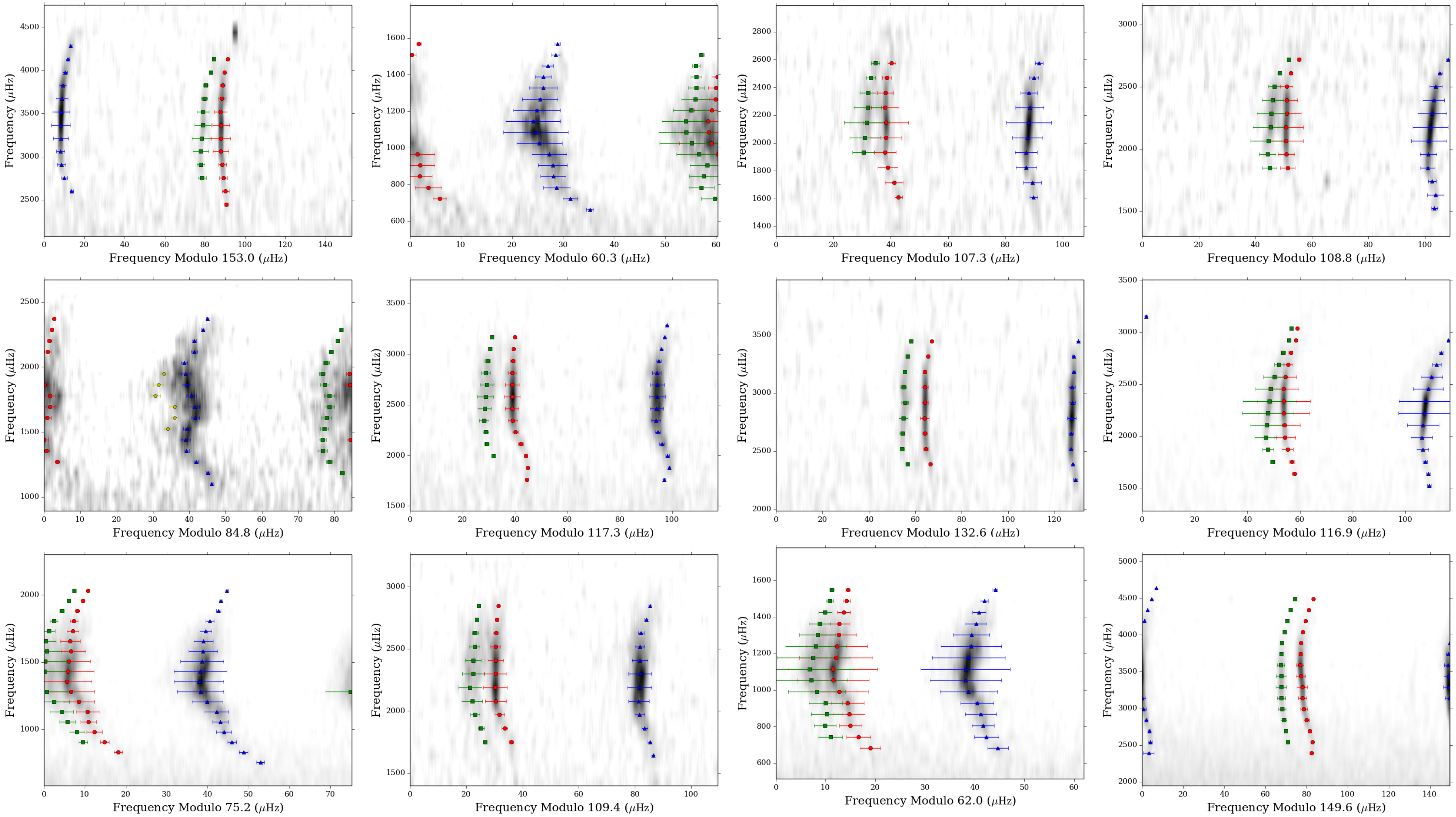
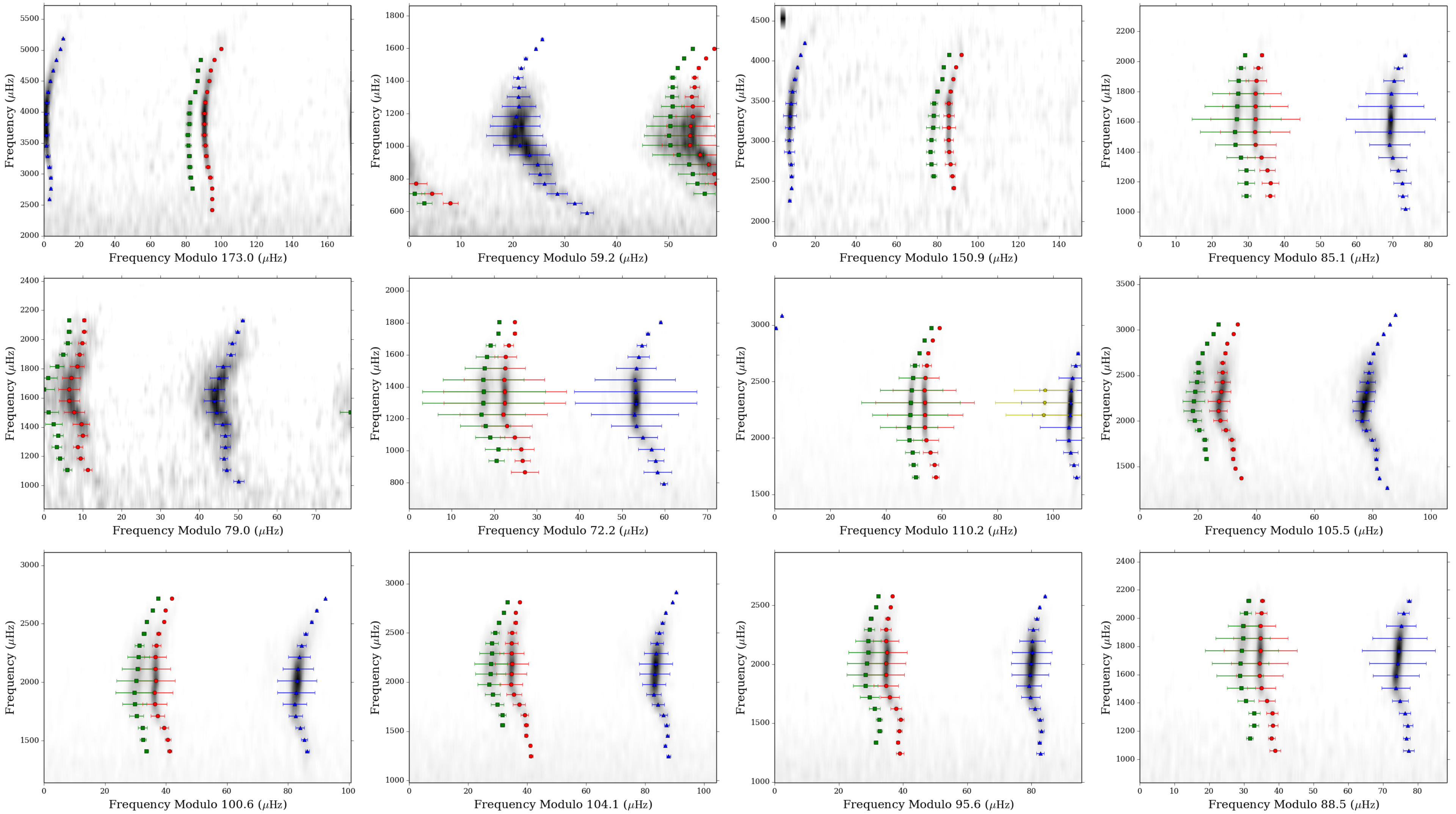
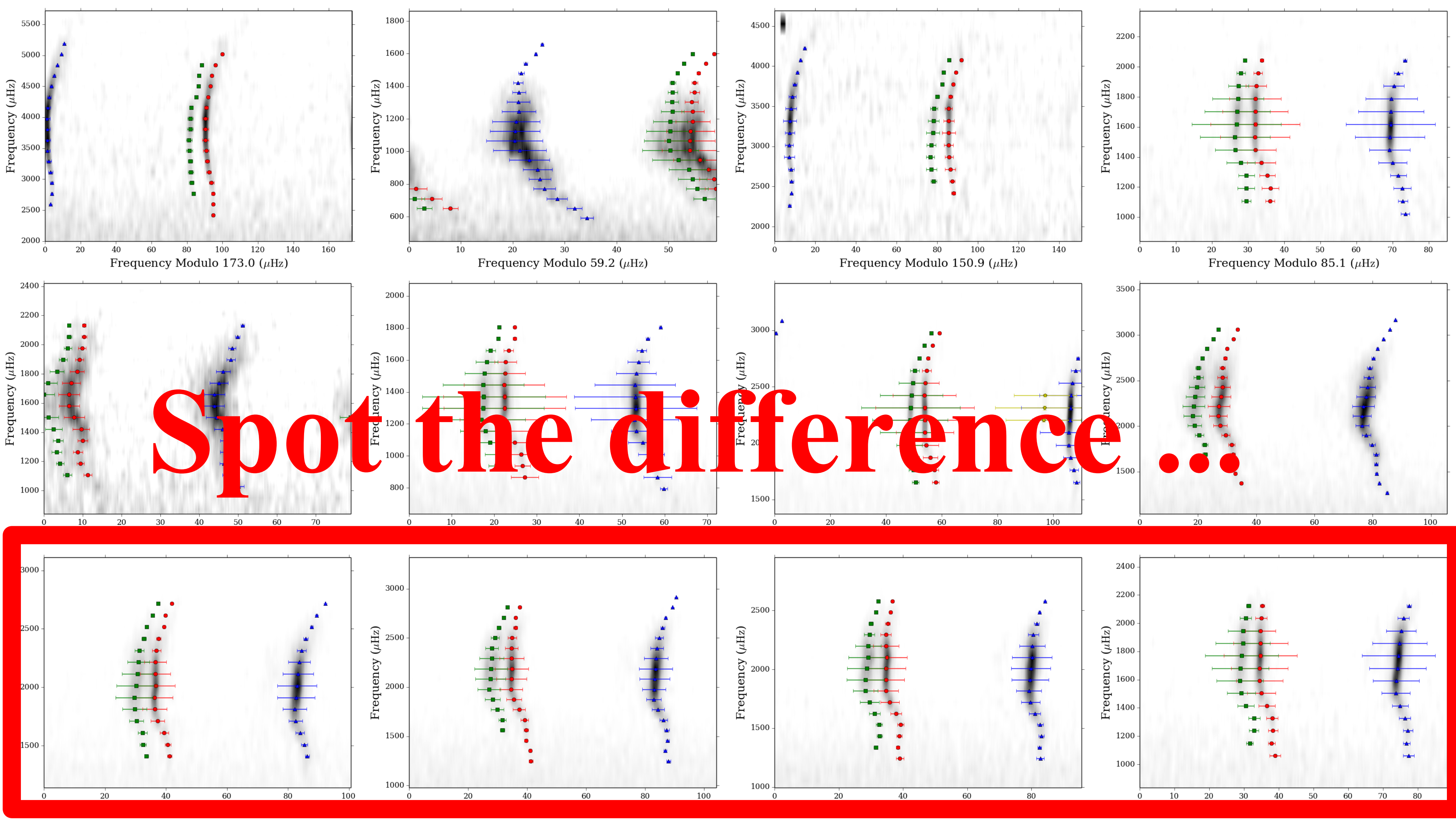
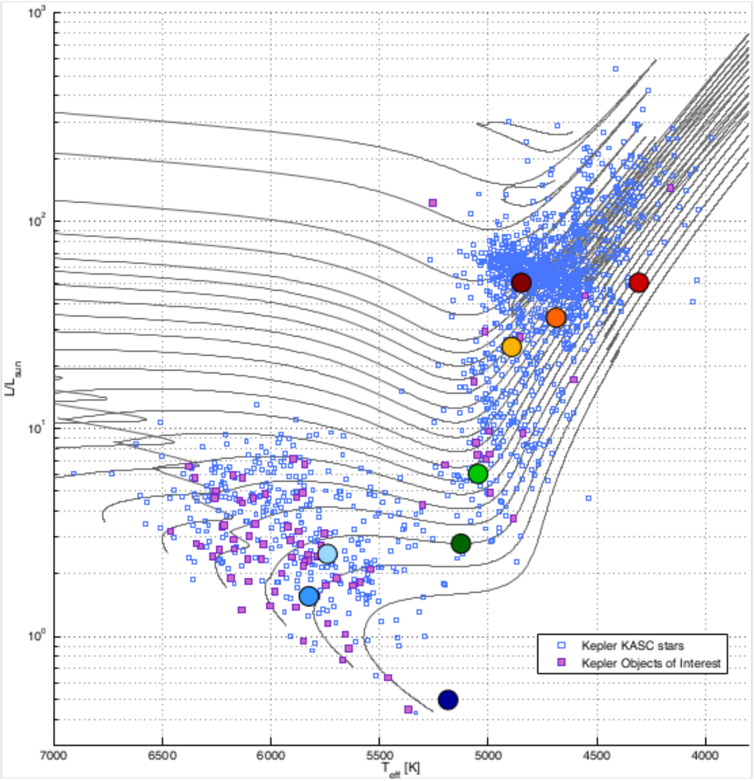


Frequency (μHz)
Frequency Modulo 153.0 (μHz)
Frequency Modulo 60.3 (μHz)
Frequency Modulo 107.3 (μHz)
Frequency Modulo 108.8 (μHz)
Frequency Modulo 84.8 (μHz)
Frequency Modulo 117.3 (μHz)
Frequency Modulo 132.6 (μHz)
Frequency Modulo 116.9 (μHz)
Frequency Modulo 75.2 (μHz)
Frequency Modulo 109.4 (μHz)
Frequency Modulo 62.0 (μHz)
Frequency Modulo 149.6 (μHz)



Frequency (μHz)
Frequency Modulo 173.0 (μHz)
Frequency Modulo 59.2 (μHz)
Frequency Modulo 150.9 (μHz)
Frequency Modulo 85.1 (μHz)
Frequency Modulo 79.0 (μHz)
Frequency Modulo 72.2 (μHz)
Frequency Modulo 110.2 (μHz)
Frequency Modulo 105.5 (μHz)
Frequency Modulo 100.6 (μHz)
Frequency Modulo 104.1 (μHz)
Frequency Modulo 95.6 (μHz)
Frequency Modulo 88.5 (μHz)


Spot the difference ...
Frequency (μHz)
Frequency Modulo 173.0 (μHz)
Frequency Modulo 59.2 (μHz)
Frequency Modulo 150.9 (μHz)
Frequency Modulo 85.1 (μHz)



Chaplin & Miglio, ARAA, 2013

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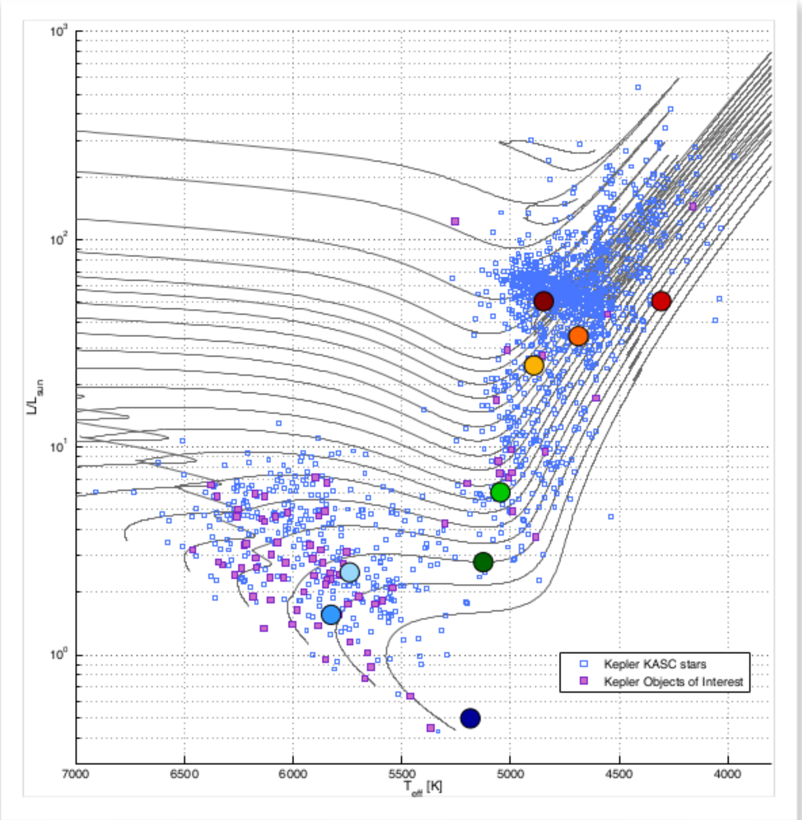

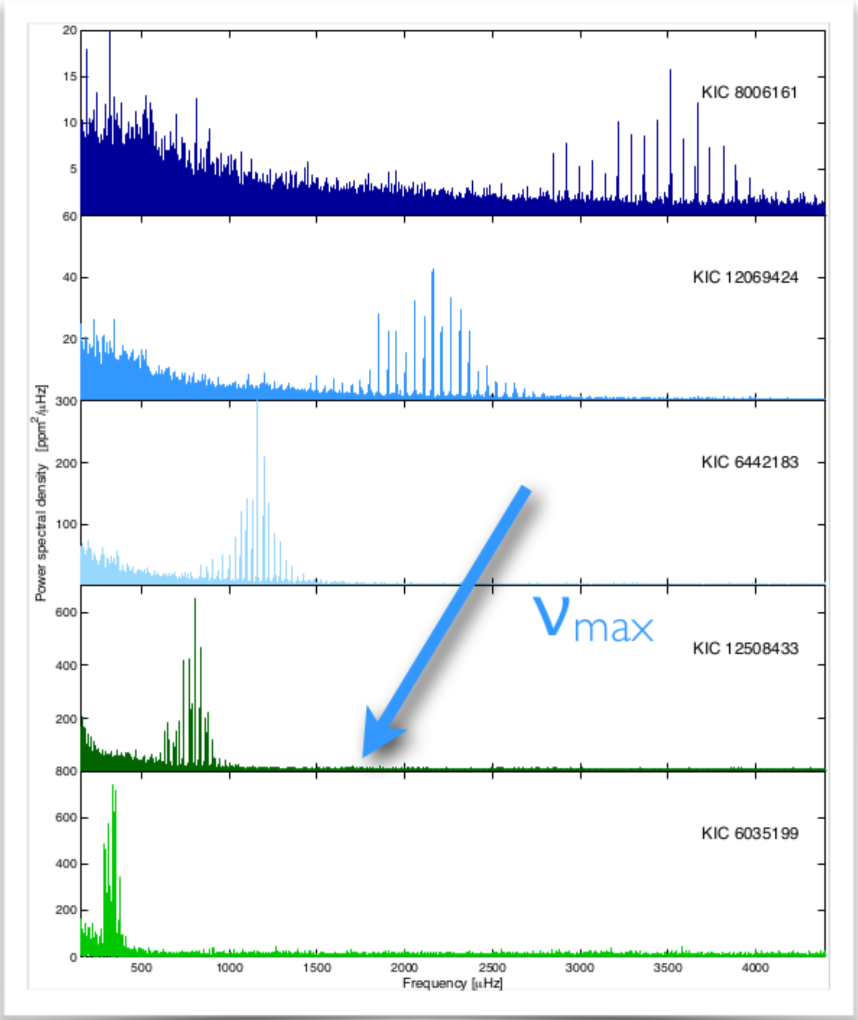

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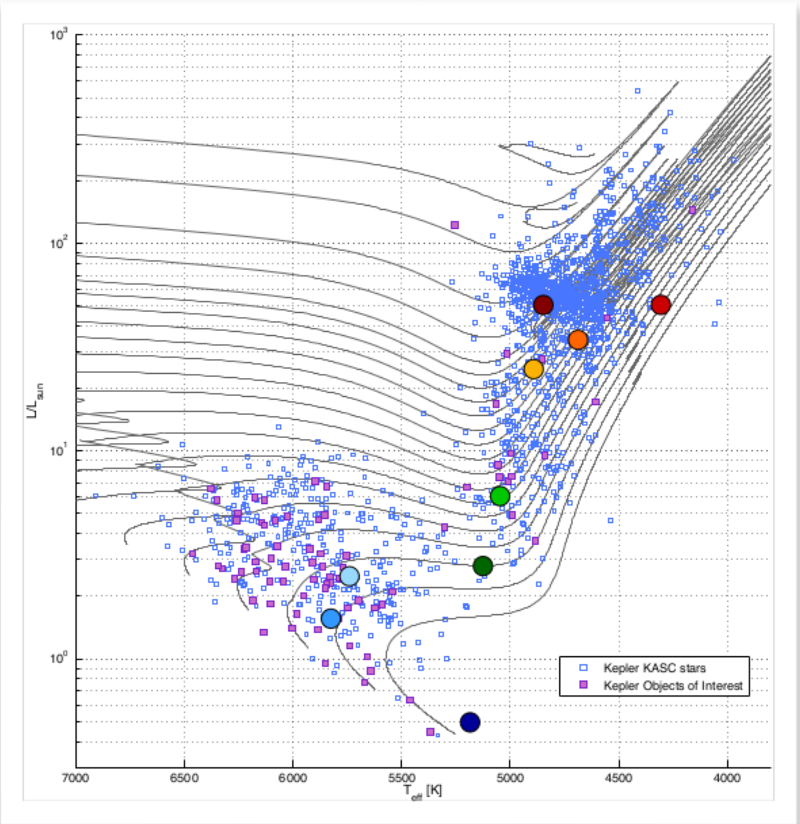

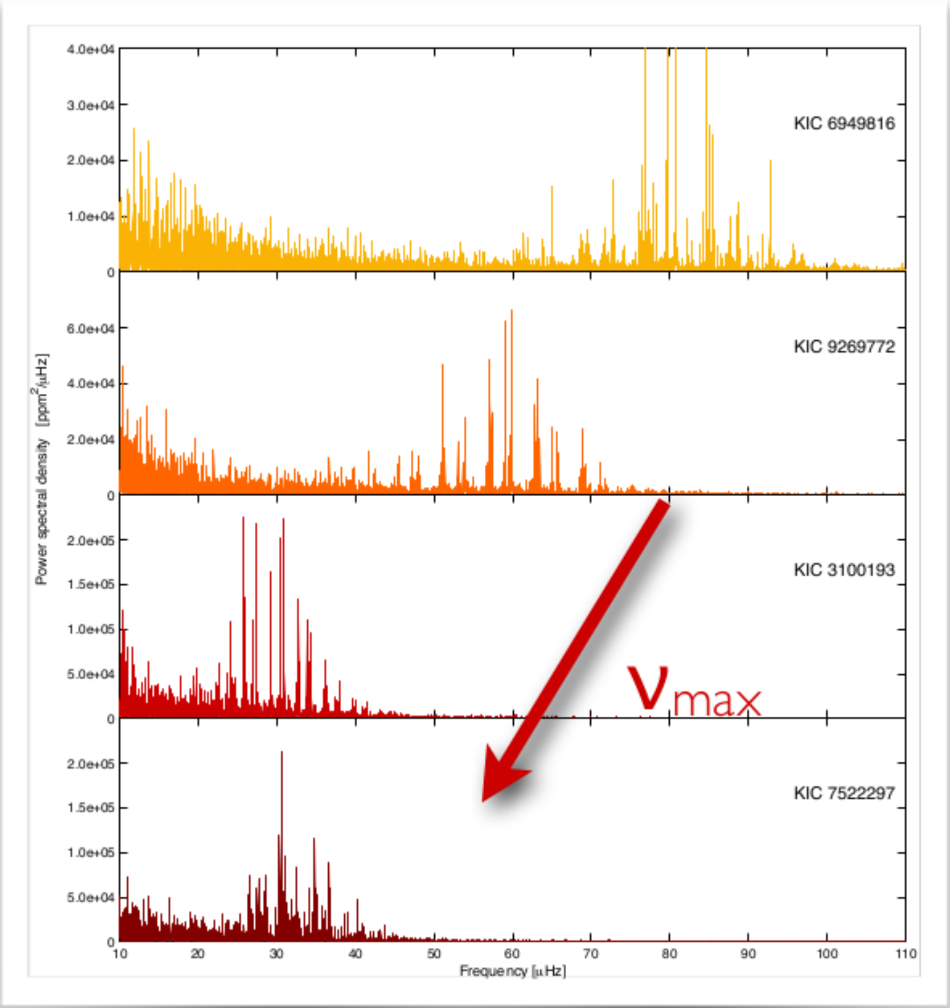

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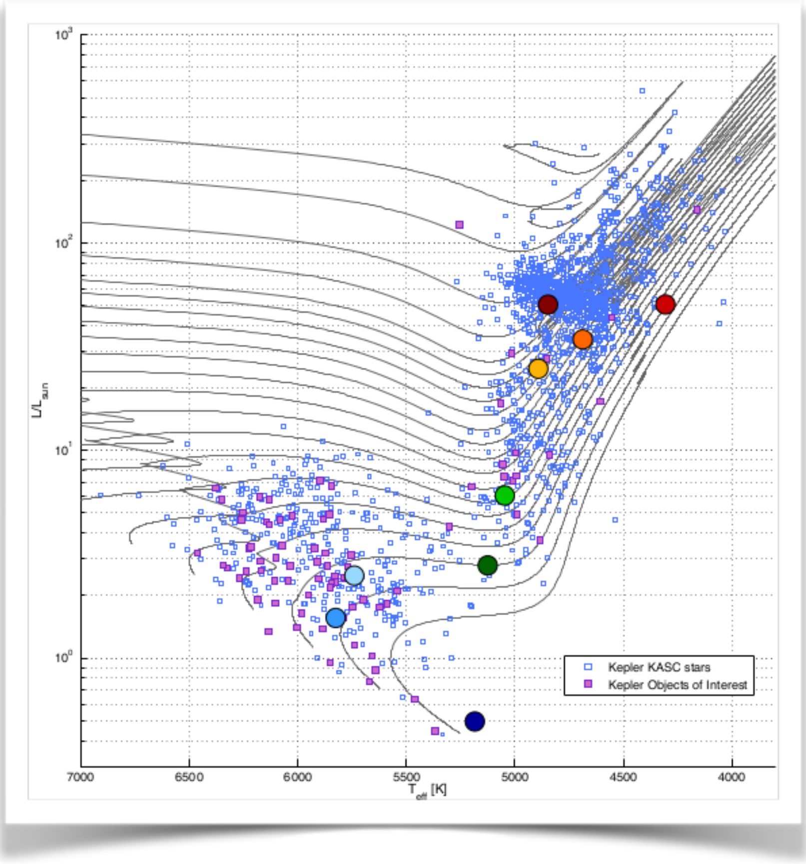

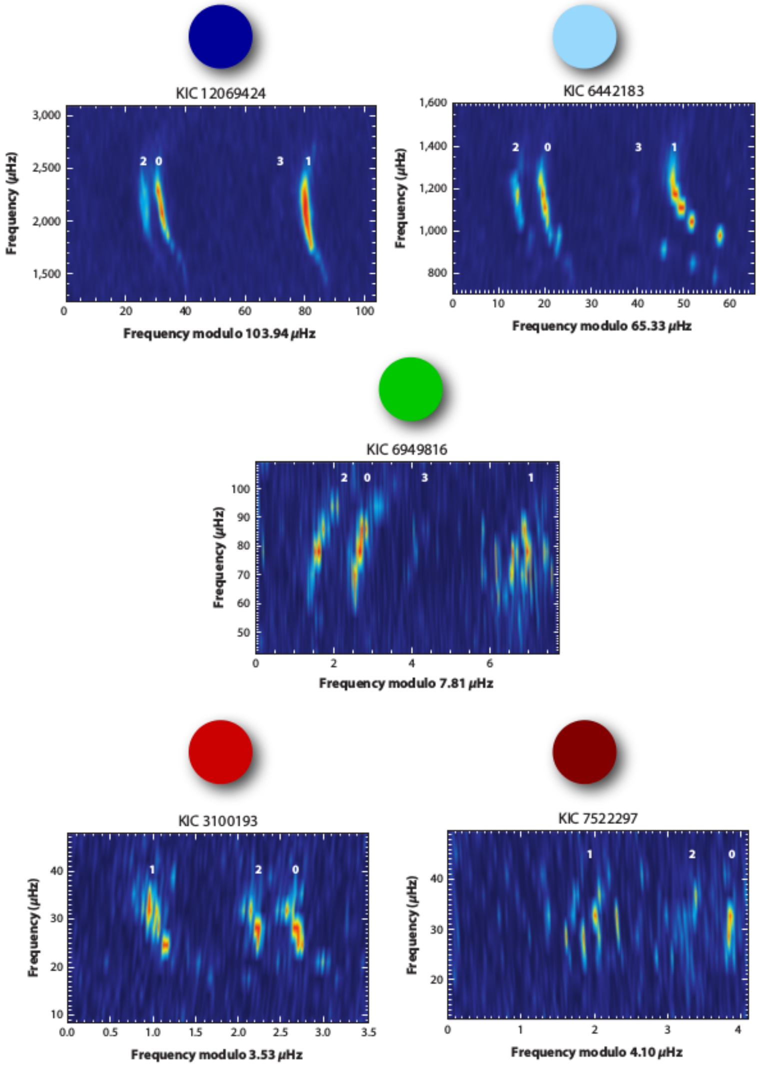

Chaplin & Miglio, ARAA, 2013

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Observations and constraint

Evolved Sun-like stars	**Solar type**	**Solar analog**	**Solar twin**	**The Sun**
Cooler	K2 through to F8	5200 to 6300 K	5720 to 5830 K	5777 K
Sub giant Red giant	Main sequence	Main sequence	MS, 3.5 to 5.6 Gyr	4.5 Gyr
Any	Any metallicity	Solar +- 0.3 dex	Solar +- 0.05 dex	Solar
Many many detectable	A lot	>30 within 50 ly e.g., Alpha Cen A (& B)	A handful e.g., 18 Sco	Just the one!

Progress

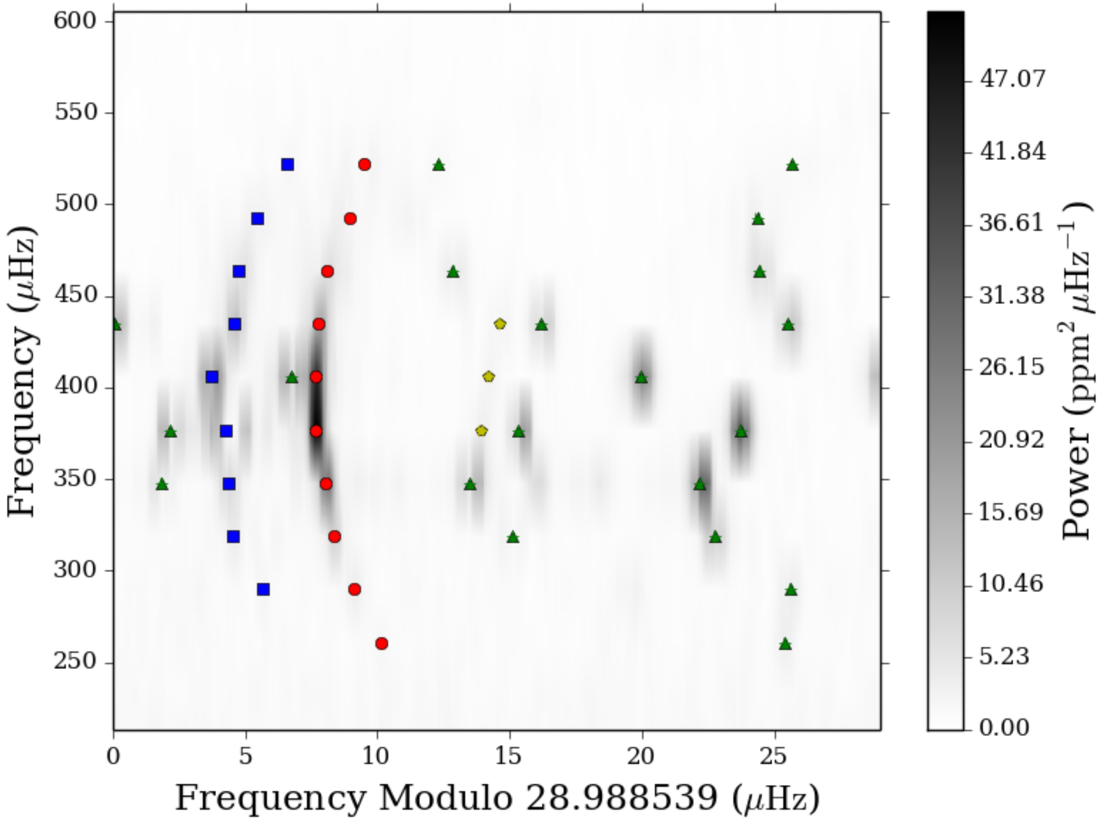
Observations and constraint

Observable	Solar type red giant	Solar type subgiant	Solar type main sequence	The Sun
Average frequency spacings + numax	✓	✓	✓	✓
Period spacing				
Rotation				
Individual frequencies				

Sun-like evolved stars

KIC 7341231 - "Otto"

Mixed modes of oscillation



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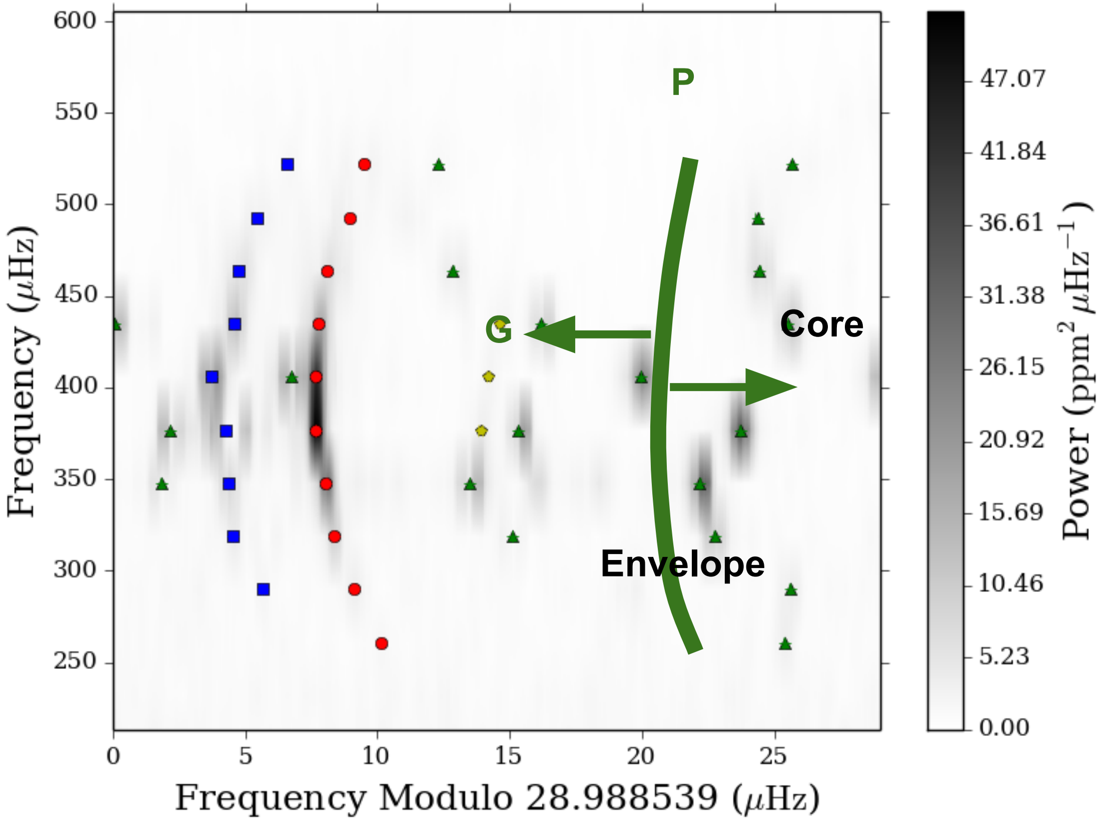
Sun-like evolved stars

KIC 7341231 - "Otto"

Mixed modes of oscillation



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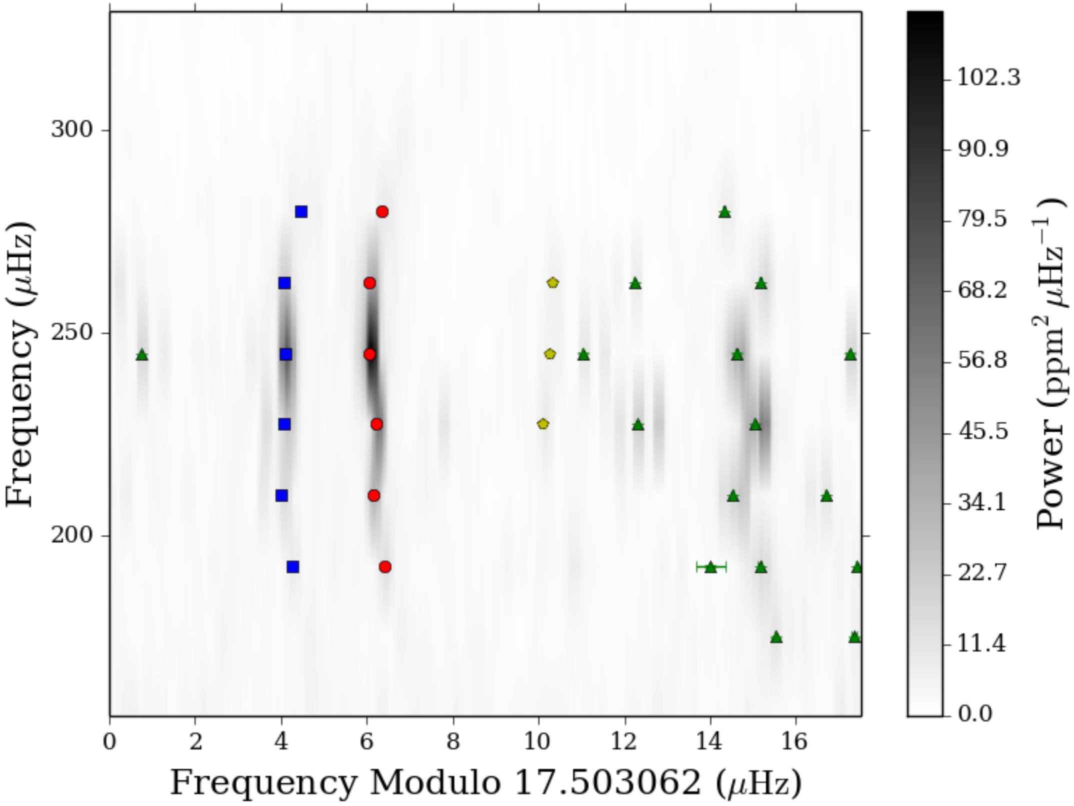
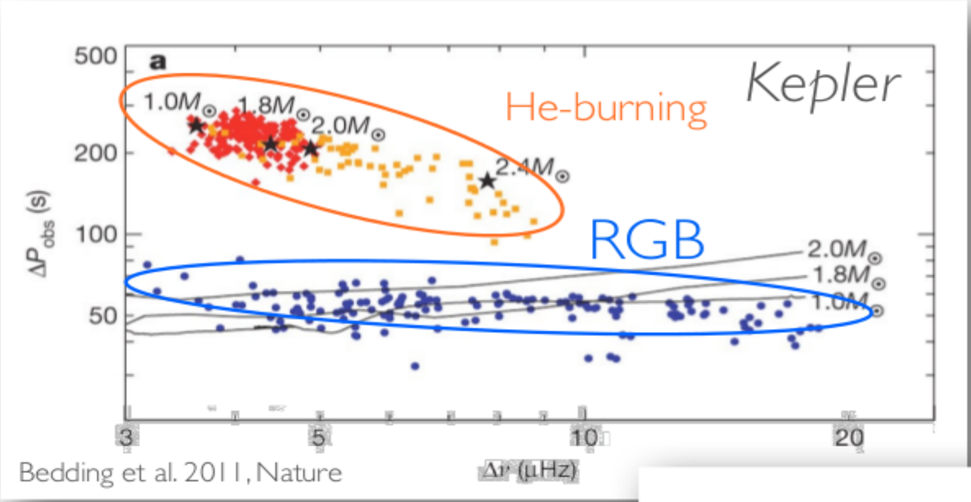
Sun-like red giant branch

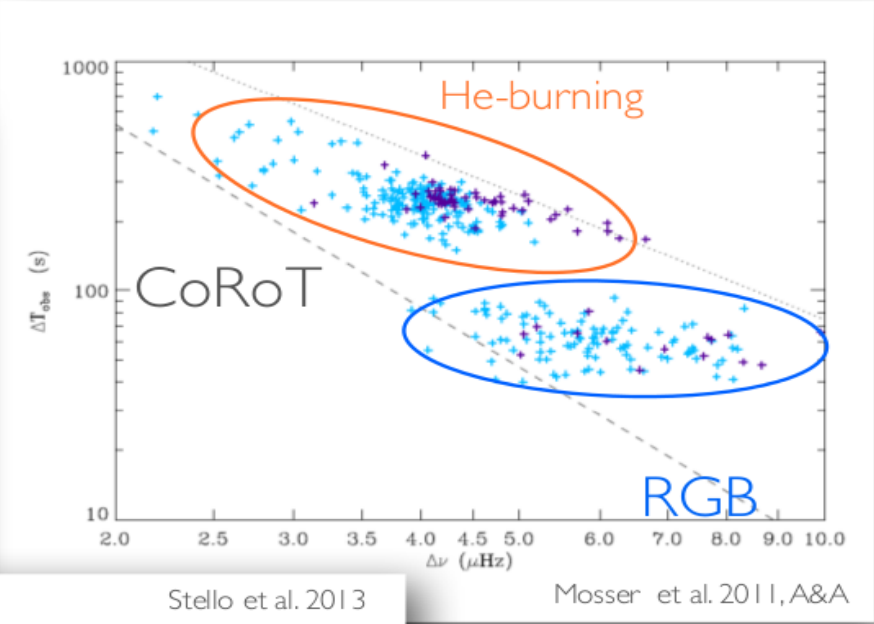
Kepler-56

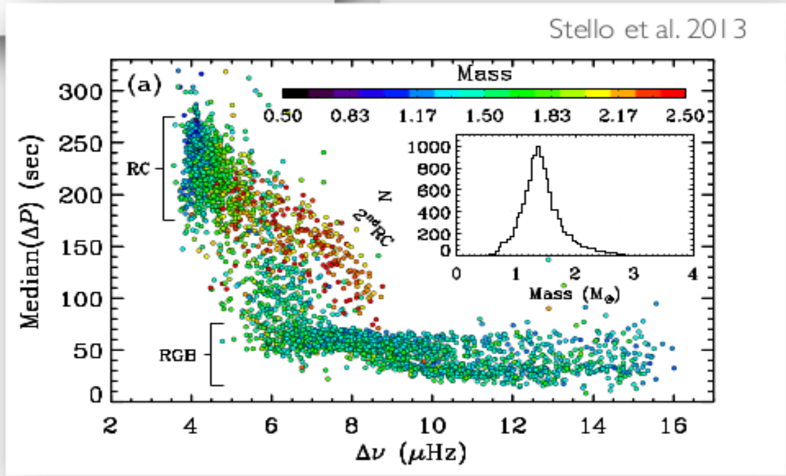
RGB star with mixed modes



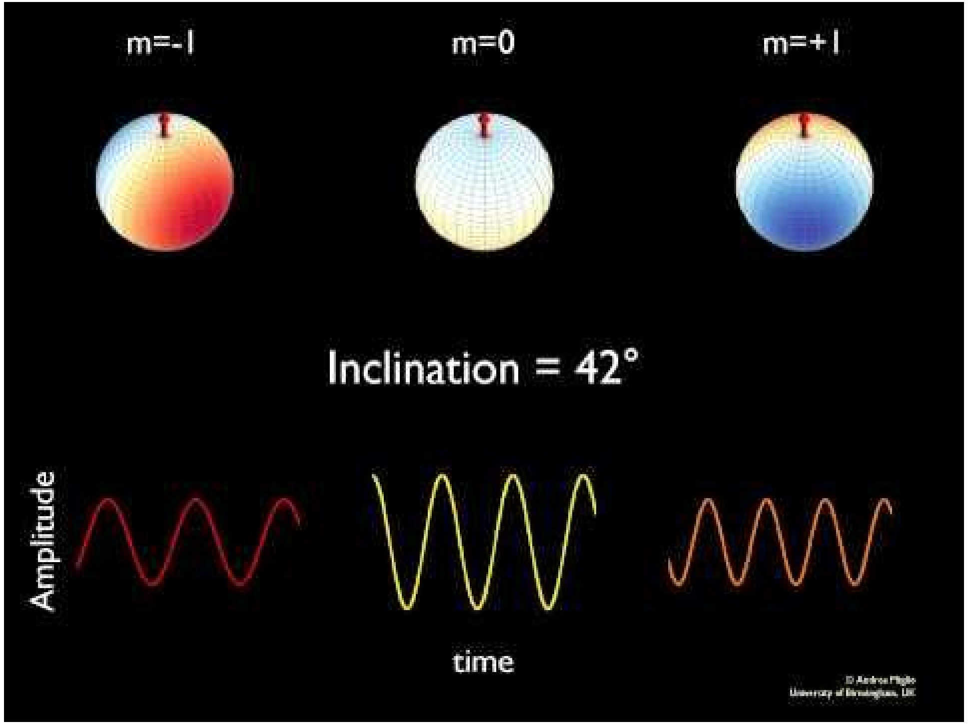
Observations with Kepler and CoRoT:







Rotation



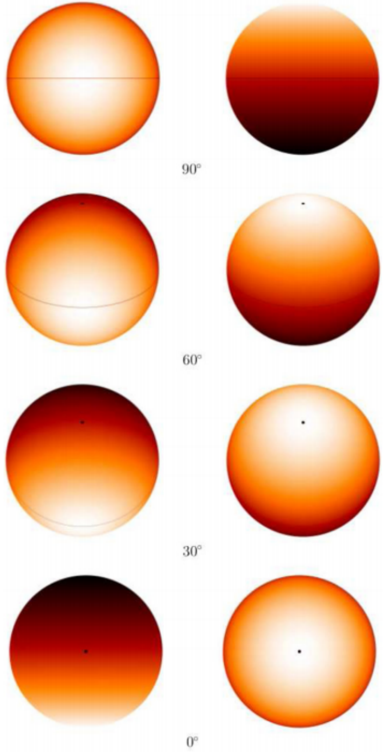


Figure 6. Intensity perturbations for $l = 1$ mode components, at a phase corresponding to extreme displacement of the oscillations. Plotted are patterns for $m = 1$ (left-hand column) and $m = 0$ (right-hand column) modes viewed at different angles, $i_s = 90°$ (top row), $60°$ (second row), $30°$ (third row), and $0°$ (bottom row). The filled circles mark the pole of the rotation axis and the lines the stellar equator.

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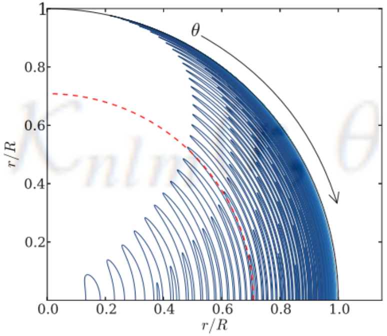
Internal rotation

$$\delta\nu_{nlm} = \int_0^{\pi}\int_0^{R} \mathcal{K}_{nlm}(r,\theta)\mathcal{N}(r,\theta) r\,dr\,d\theta .$$

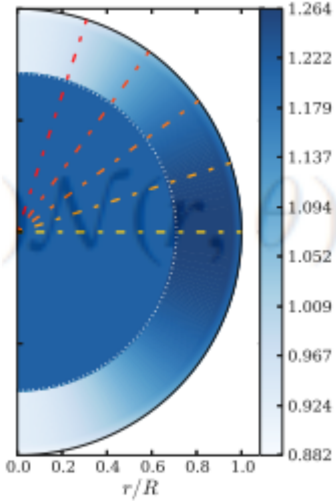
Internal rotation

$$\delta\nu_{nlm} = \int_0^{\pi}\int_0^{R} K_{nlm}(r,\theta)\,\Omega(r,\theta)\, r\,dr\,d\theta.$$

Frequency splitting



Kernel



Rotation profile

Lund+ 2014

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Internal rotation - 1D

$$\delta \nu_{n,l} = (2\pi)^{-1} \int_0^R K_{n,l}(r)\Omega(r)\, dr.$$

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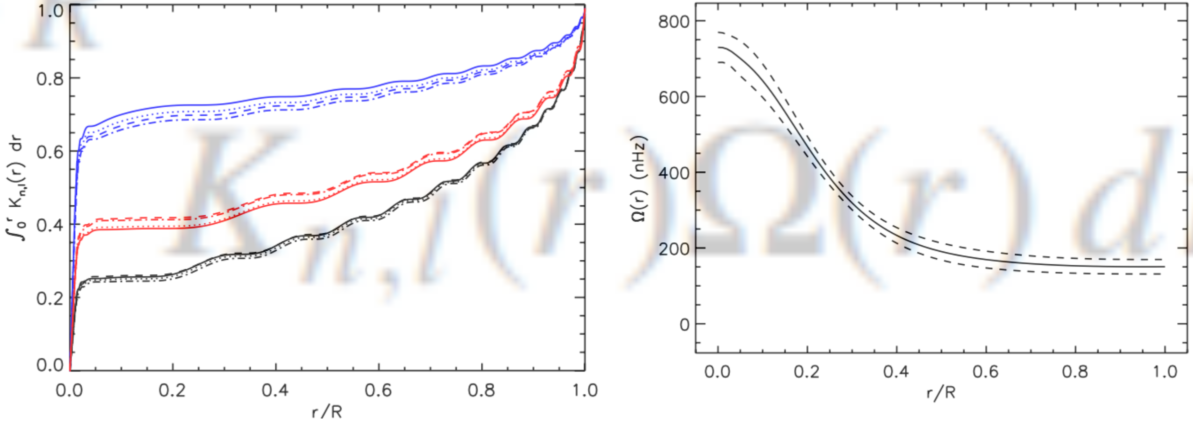
Internal rotation - 1D

$$\int_0^R K_{n,l}(r)\,\Omega(r)\,dr.$$



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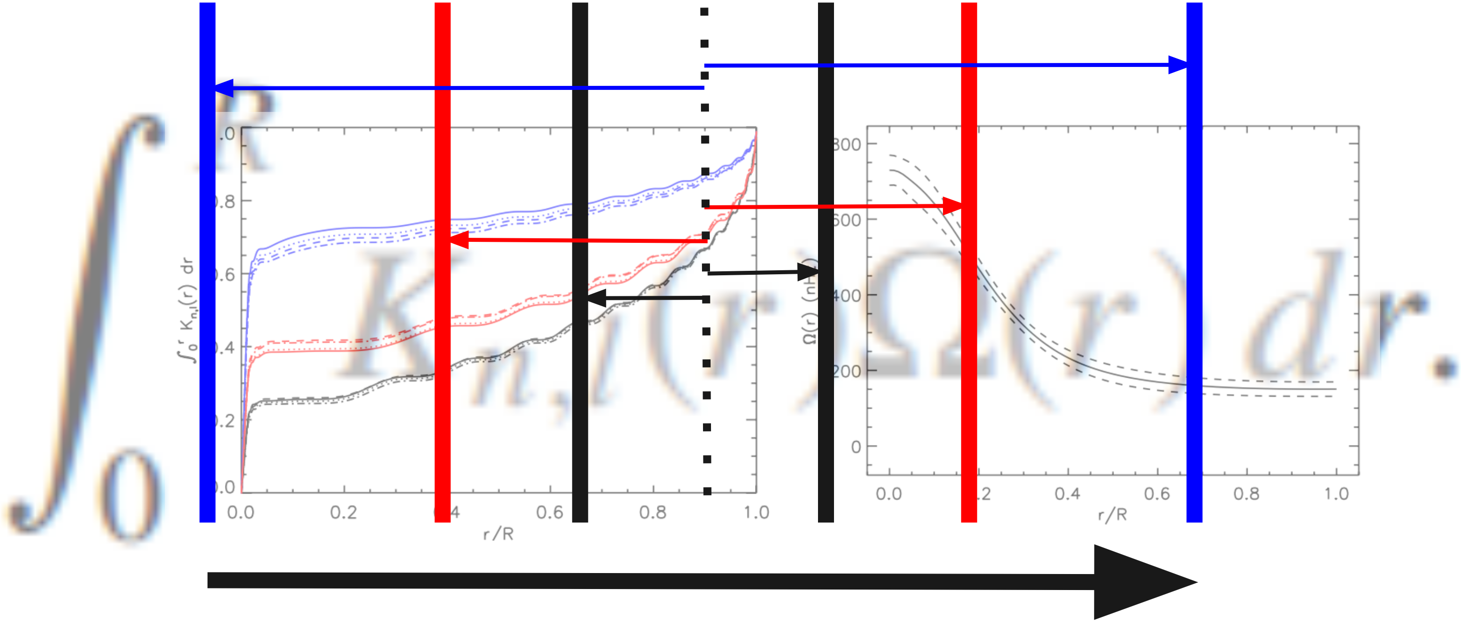
Deheuvels+ 2012

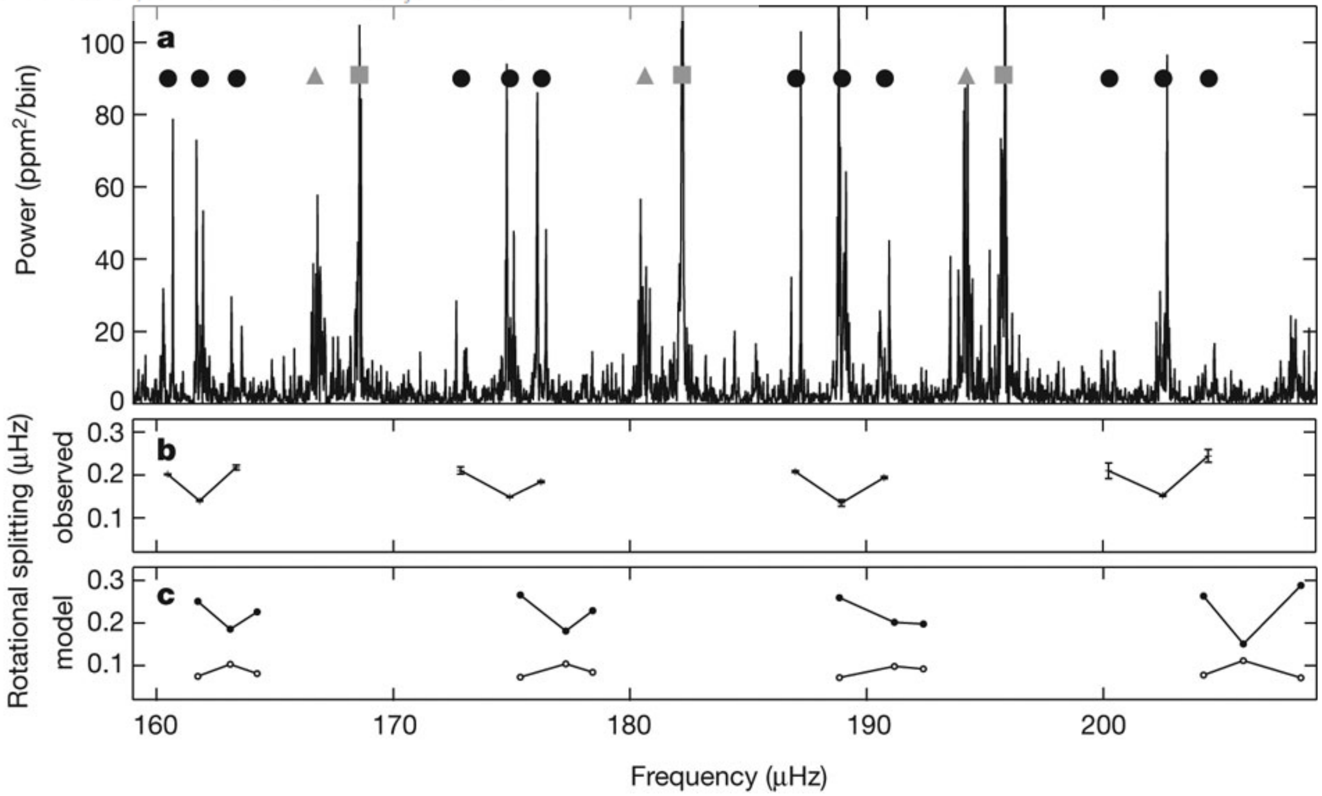
Rotation - 1D



Frequency

Fast core rotation in red-giant stars as revealed by gravity-dominated mixed modes

Paul G. Beck[1], Josefina Montalban[2], Thomas Kallinger[1,3], Joris De Ridder[1], Conny Aerts[1,4], Rafael A. García[5], Saskia Hekker[6,7], Marc-Antoine Dupret[2], Benoit Mosser[8], Patrick Eggenberger[9], Dennis Stello[10], Yvonne Elsworth[7], Søren Frandsen[11], Fabien Carrier[1], Michel Hillen[1], Michael Gruberbauer[12], Jørgen Christensen-Dalsgaard[11], Andrea Miglio[7], Marica Valentini[2], Timothy R. Bedding[10], Hans Kjeldsen[11], Forrest R. Girouard[13], Jennifer R. Hall[13] & Khadeejah A. Ibrahim[13]



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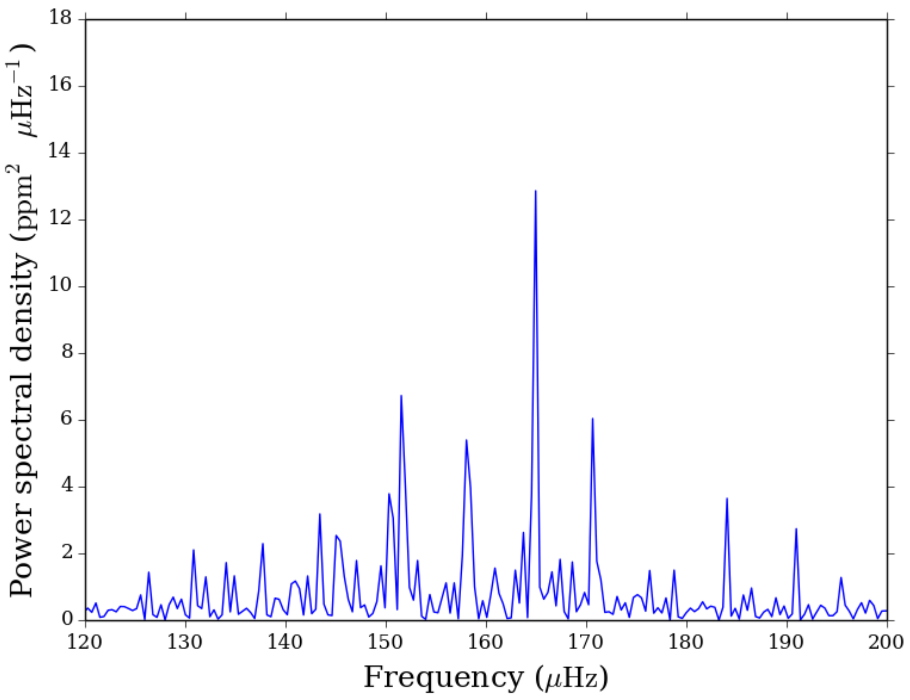
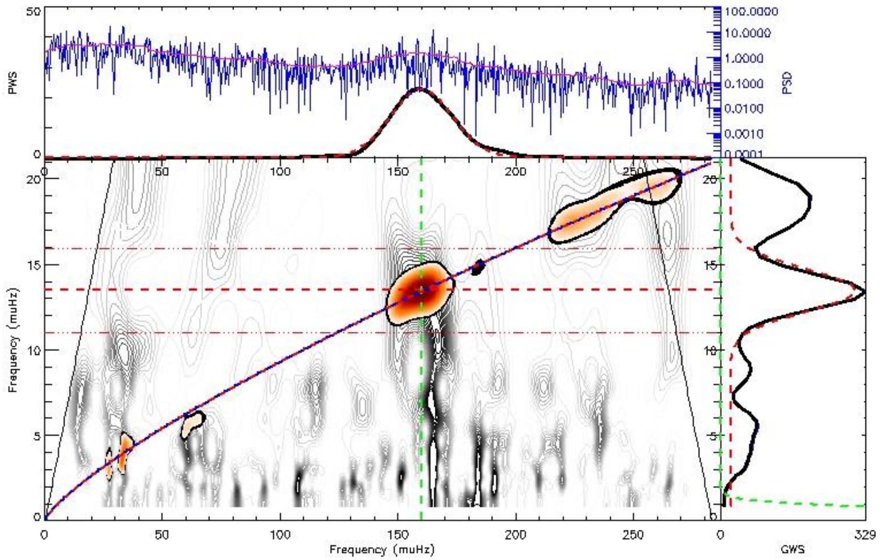
What happens when you only have 27 days of data? (e.g. TESS)



dnu = 13 +- 1 muHz
numax = 160 muHz
period spacing = ?
rotation = ?
Individual frequencies - for l=0



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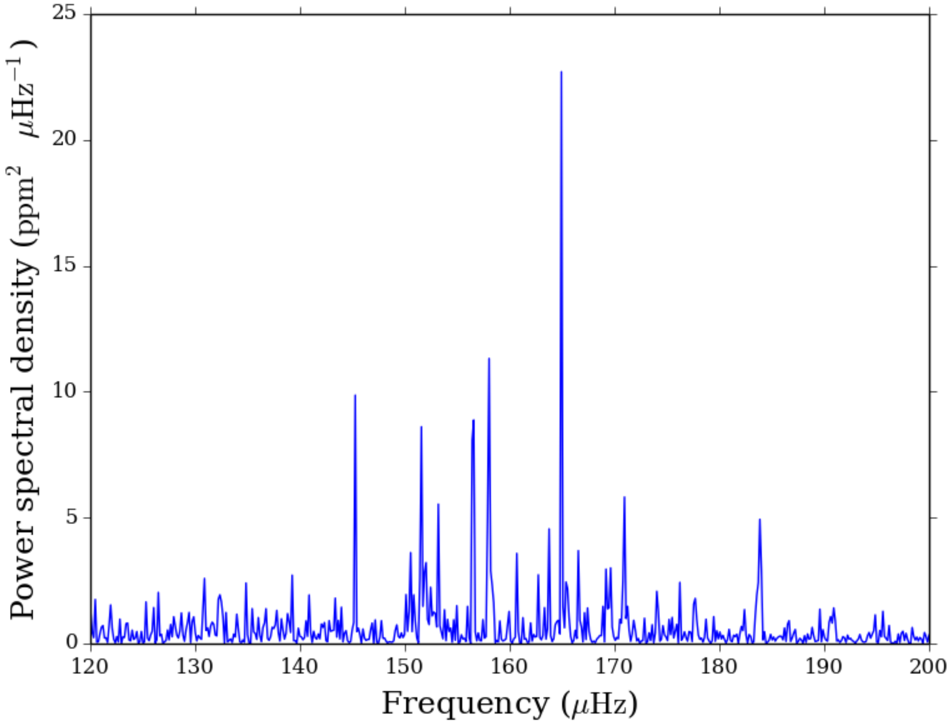
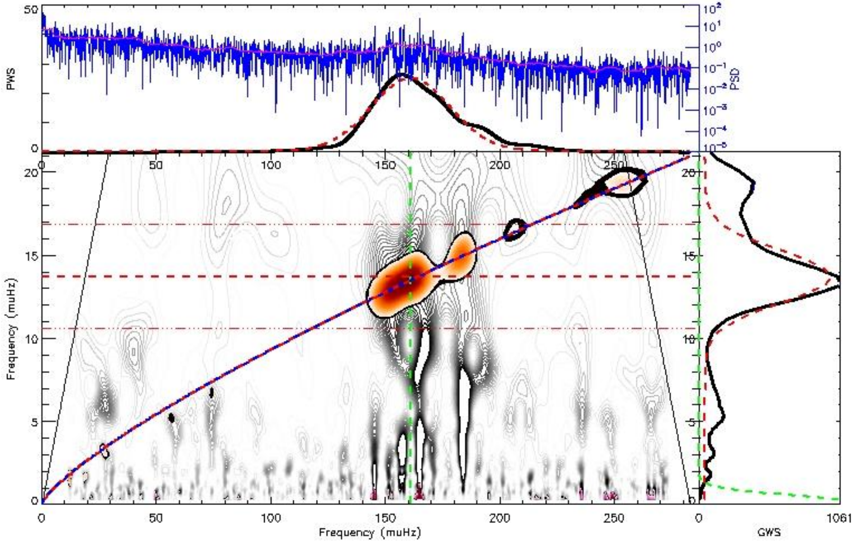
What happens when you only have 70 days of data? (e.g. K2)



dnu = 13.3 +- 0.7 muHz
numax = 161.2 muHz
period spacing = ?
rotation = ?
Individual frequencies - for l=0,2



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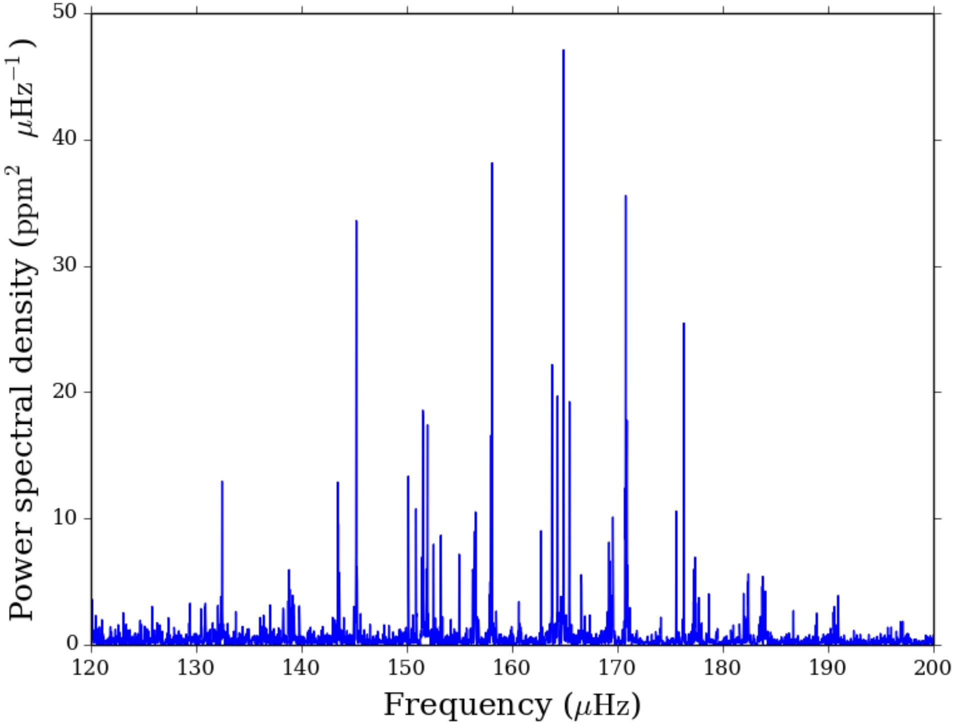
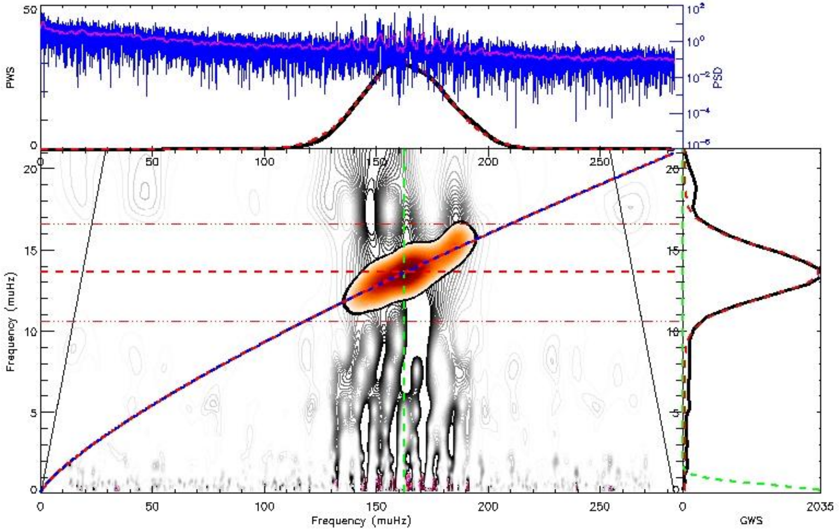
What happens when you only have 351 days of data? (e.g. Best TESS)



dnu = 12.9 +- 0.2 muHz
numax = 162.6 muHz
period spacing = 80.45 +- 0.04 s
rotation <Omega Core> = 0.43 +- 0.03 muHz
Individual frequencies - for l=0,2,1,(3)



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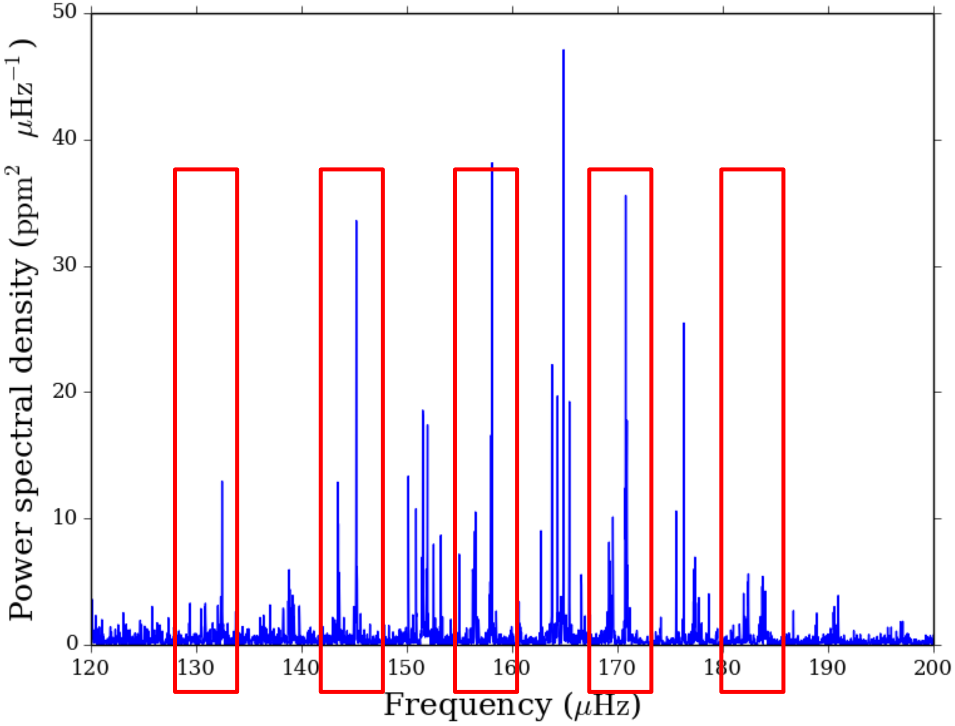
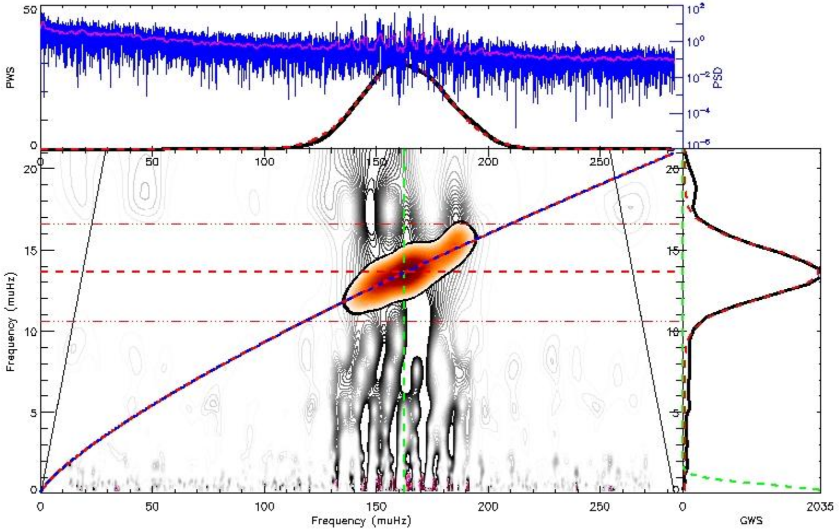
What happens when you only have 351 days of data? (e.g. Best TESS)



dnu = 12.9 +- 0.2 muHz
numax = 162.6 muHz
period spacing = 80.45 +- 0.04 s
rotation <Omega Core> = 0.43 +- 0.03 muHz
Individual frequencies - for l=0,2,1,(3)



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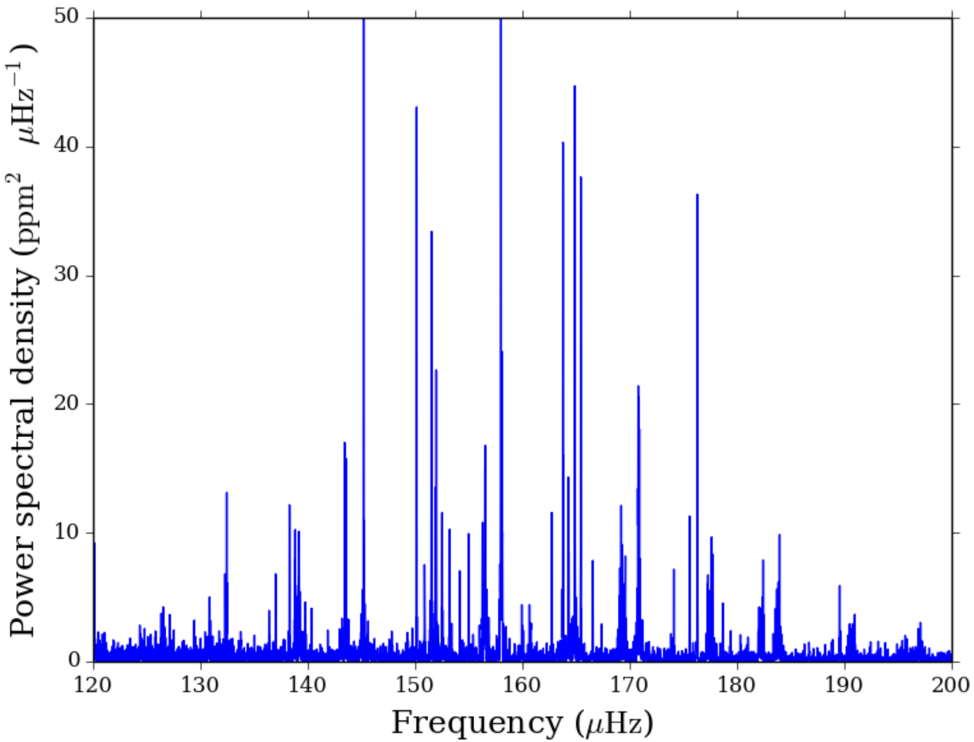
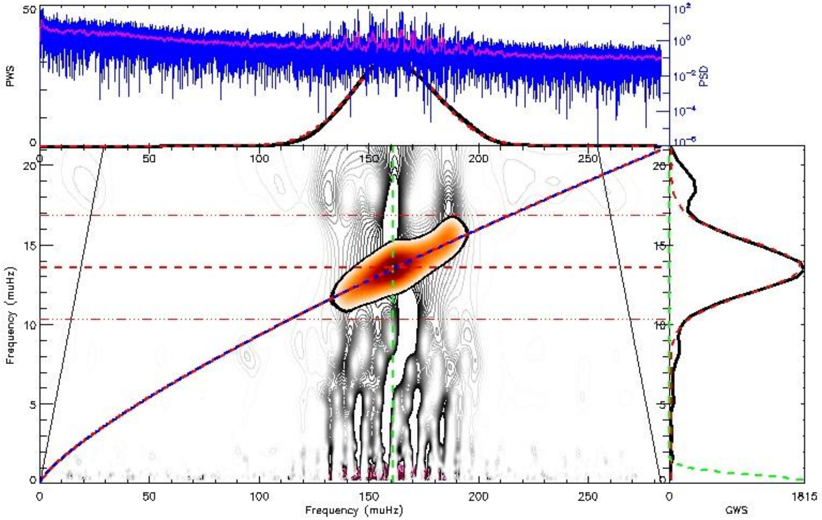
l = 2,0 modes

What happens when you only have 730 days of data? (e.g. PLATO long)



dnu = 12.97 +- 0.17 muHz
numax = 161.3 muHz
period spacing = 80.45 +- 0.02 s
rotation <Omega Core> = 0.44 +- 0.04 muHz
Individual frequencies - for l=0,2,1,3



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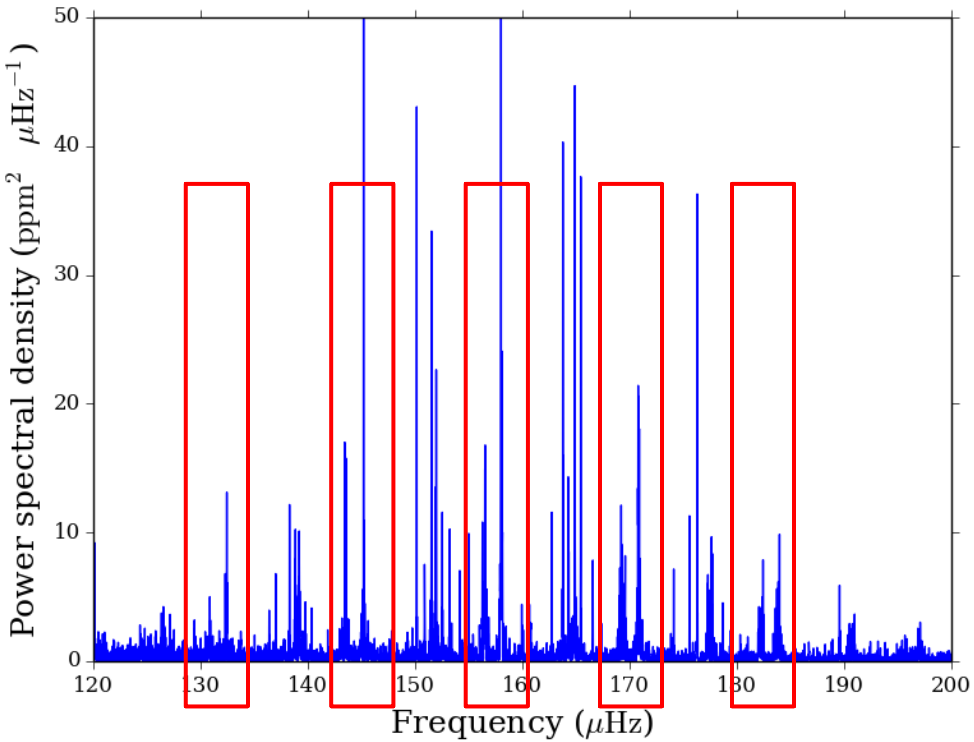
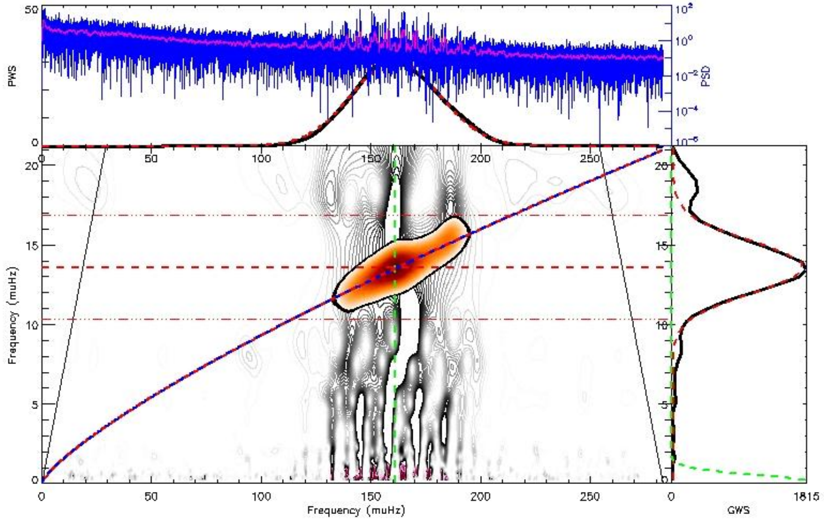
What happens when you only have 730 days of data? (e.g. PLATO long)

dnu = 12.97 +- 0.17 muHz
numax = 161.3 muHz
period spacing = 80.45 +- 0.02 s
rotation <Omega Core> = 0.44 +- 0.04 muHz
Individual frequencies - for l=0,2,1,3





l = 2,0 modes

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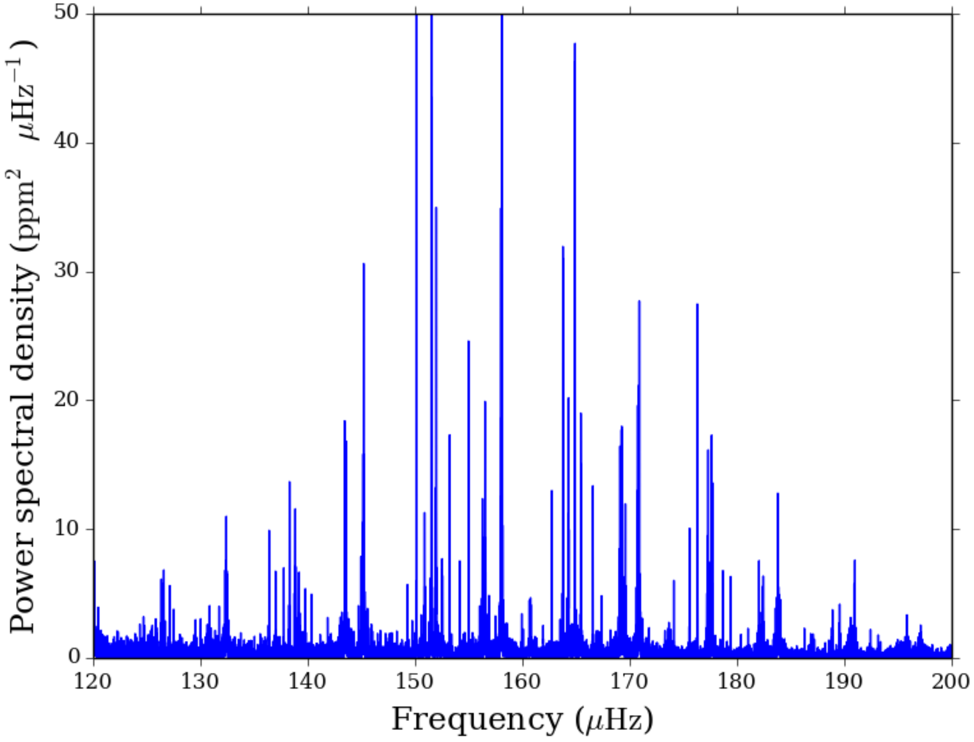
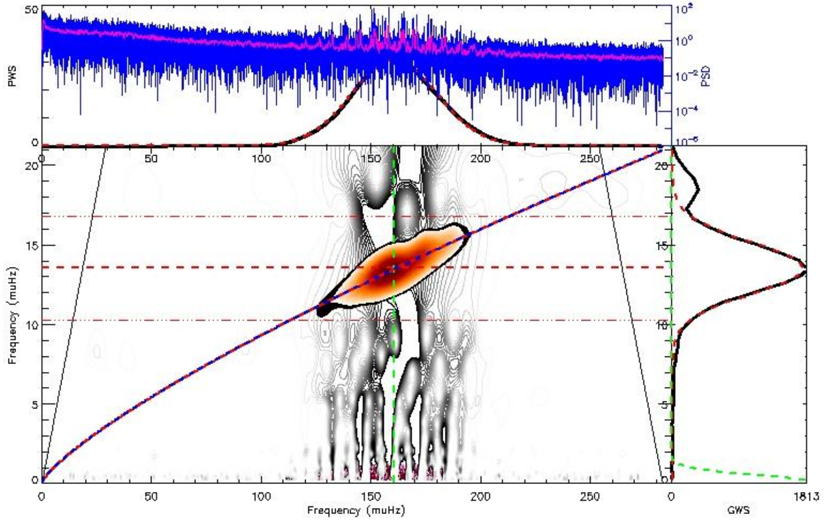
What happens when you *only* have 1335 days of data? (e.g. Best PLATO/Kepler)



dnu = 12.97 +- 0.27 muHz
numax = 160.8 muHz
period spacing = 80.446 +- 0.004 s
rotation <Omega Core>= 0.43 +- 0.01 muHz
Individual frequencies - for l=0,2,1,3



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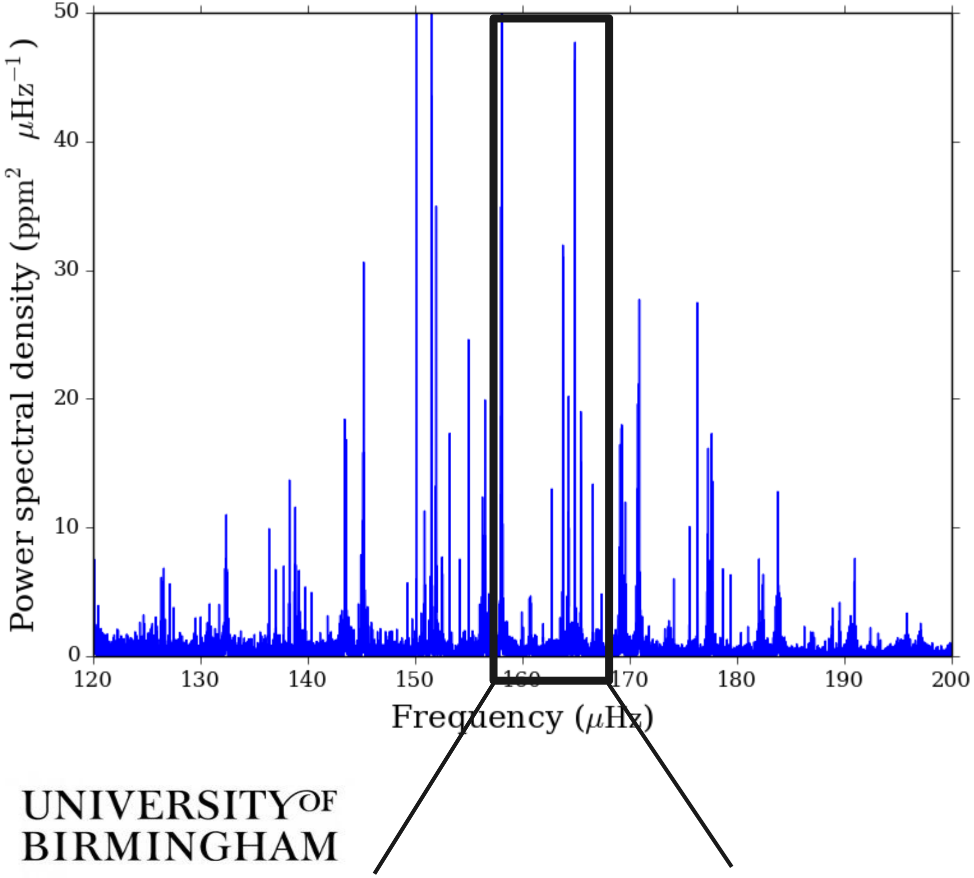
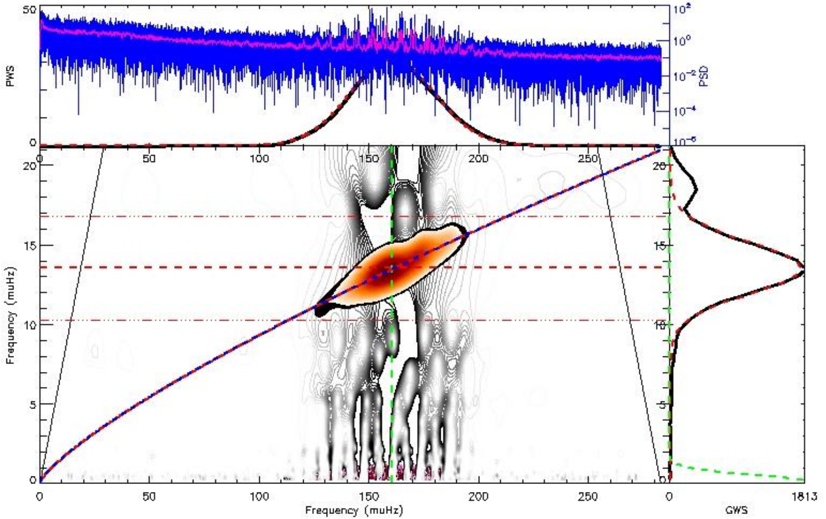
What happens when you *only* have 1335 days of data? (e.g. Best PLATO/Kepler)



dnu = 12.97 +- 0.27 muHz
numax = 160.8 muHz
period spacing = 80.446 +- 0.004 s
rotation <Omega Core>= 0.43 +- 0.01 muHz
Individual frequencies - for l=0,2,1,3



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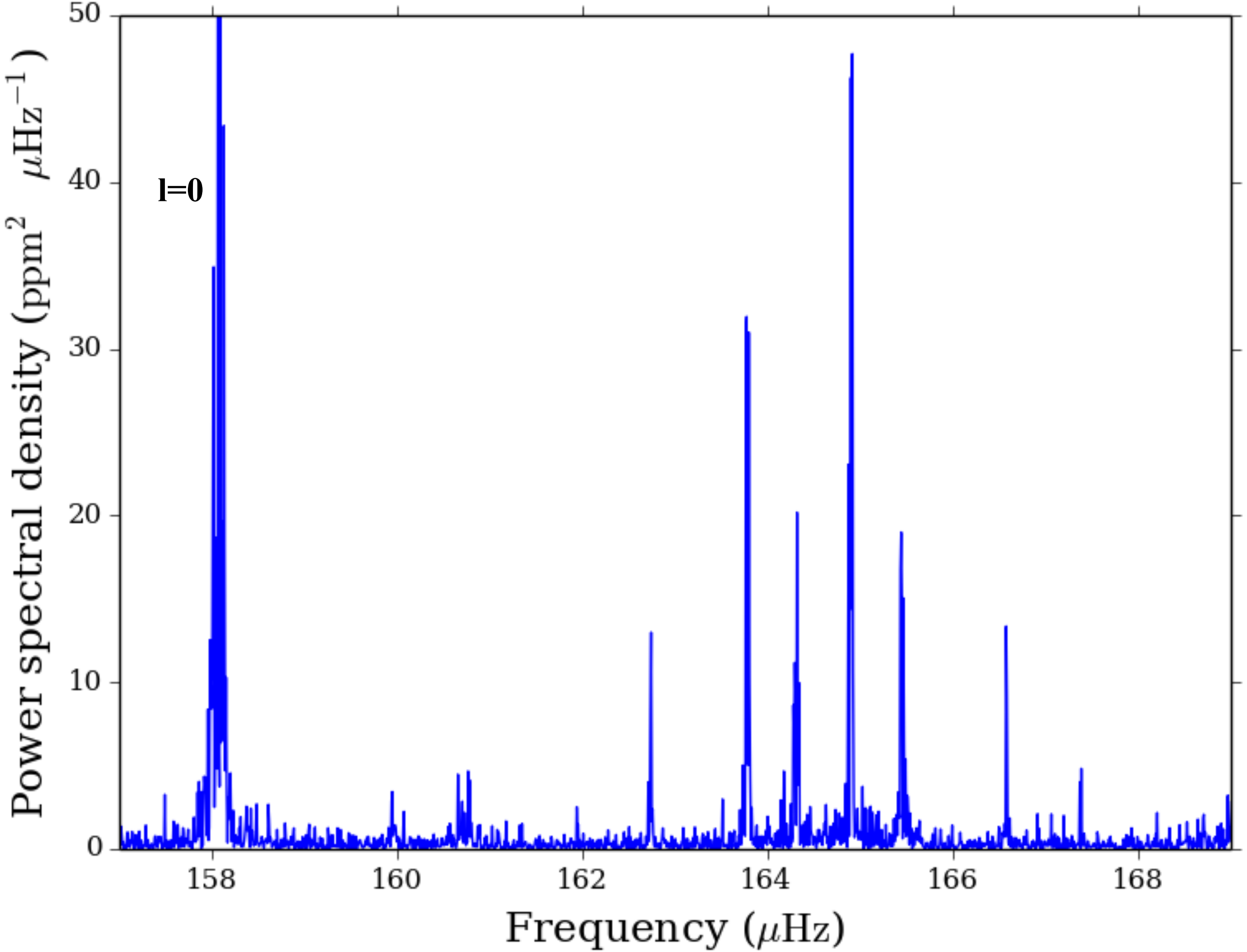
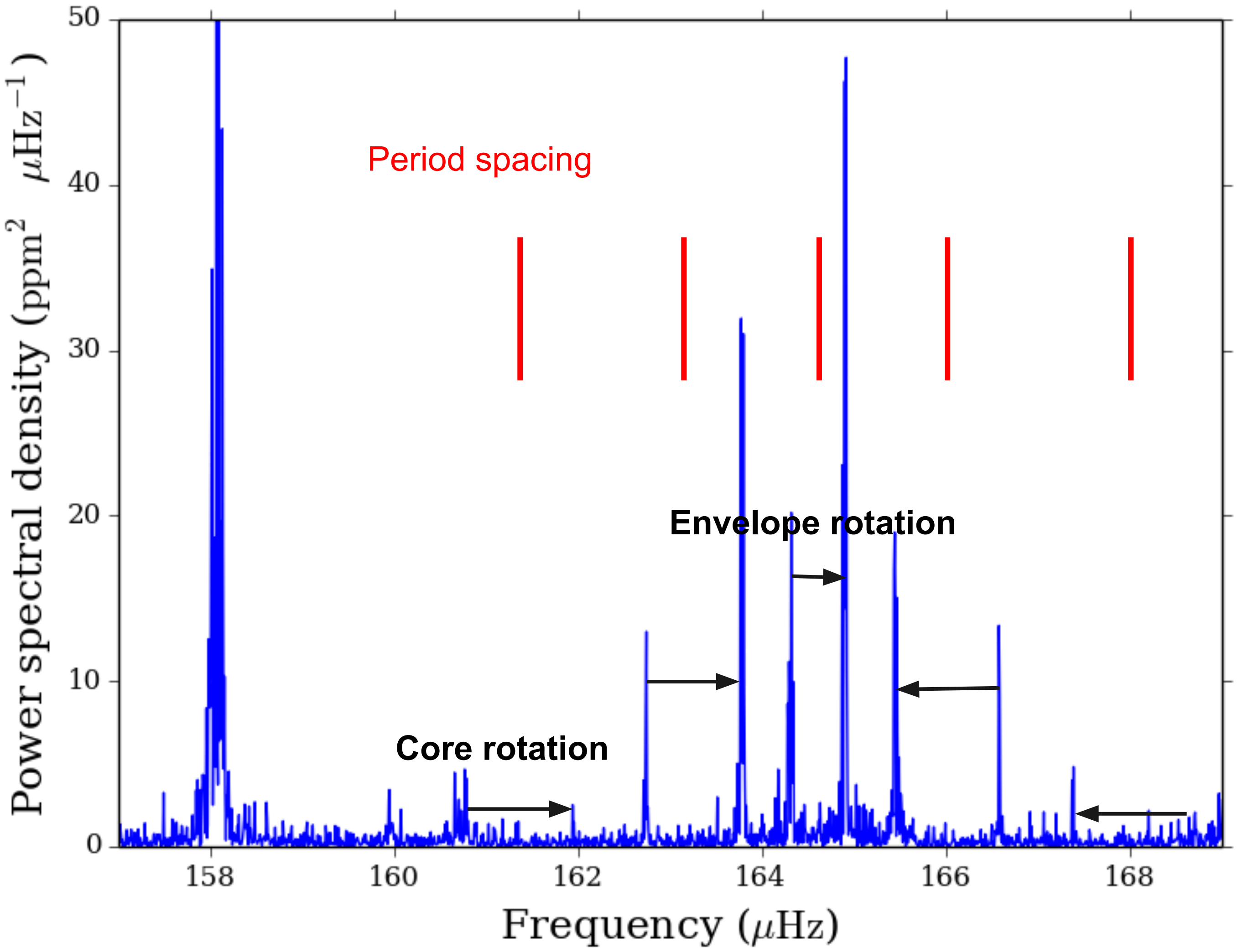

l=0
Power spectral density (ppm^2 μHz^{-1})
Frequency (μHz)
0
10
20
30
40
50
158
160
162
164
166
168



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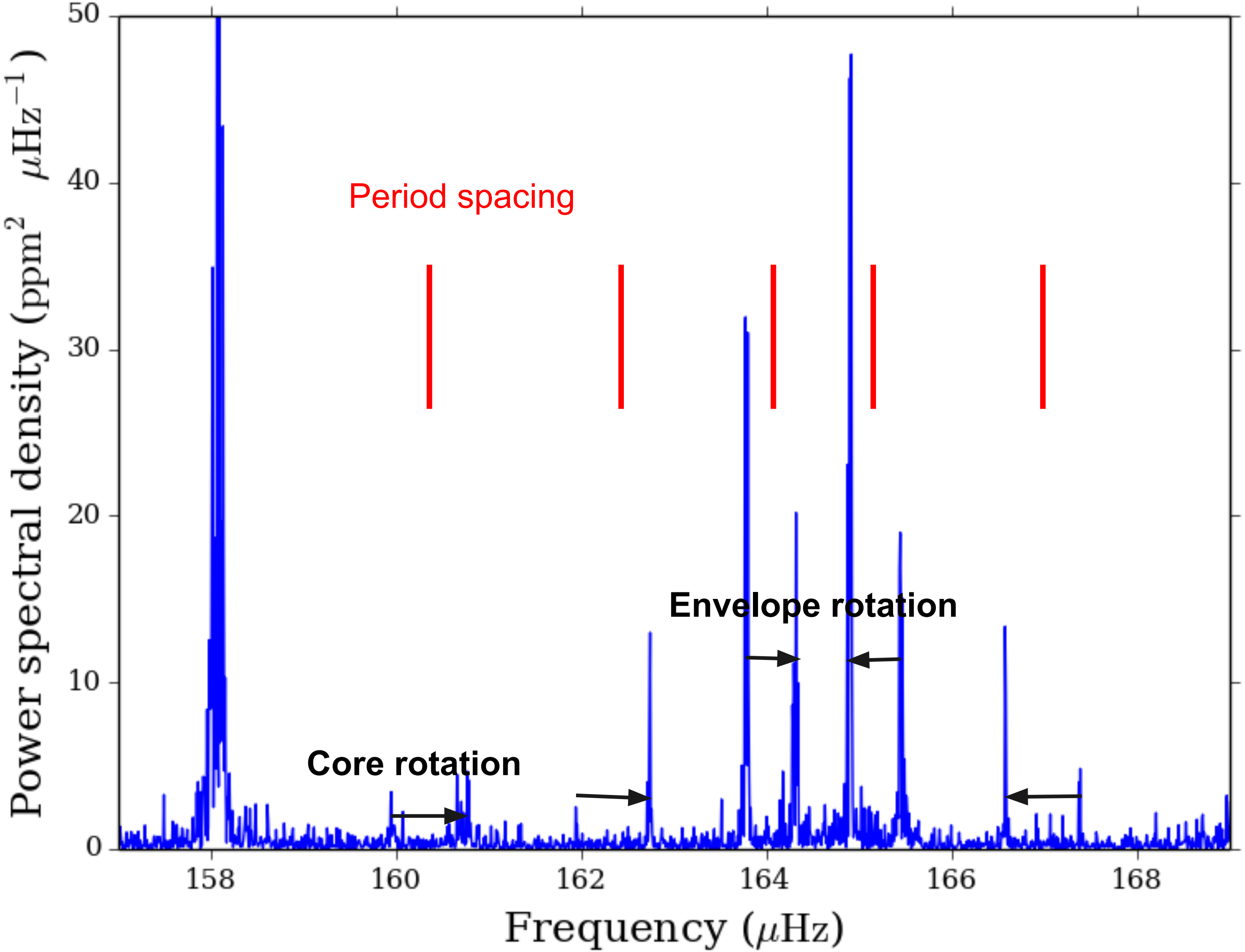

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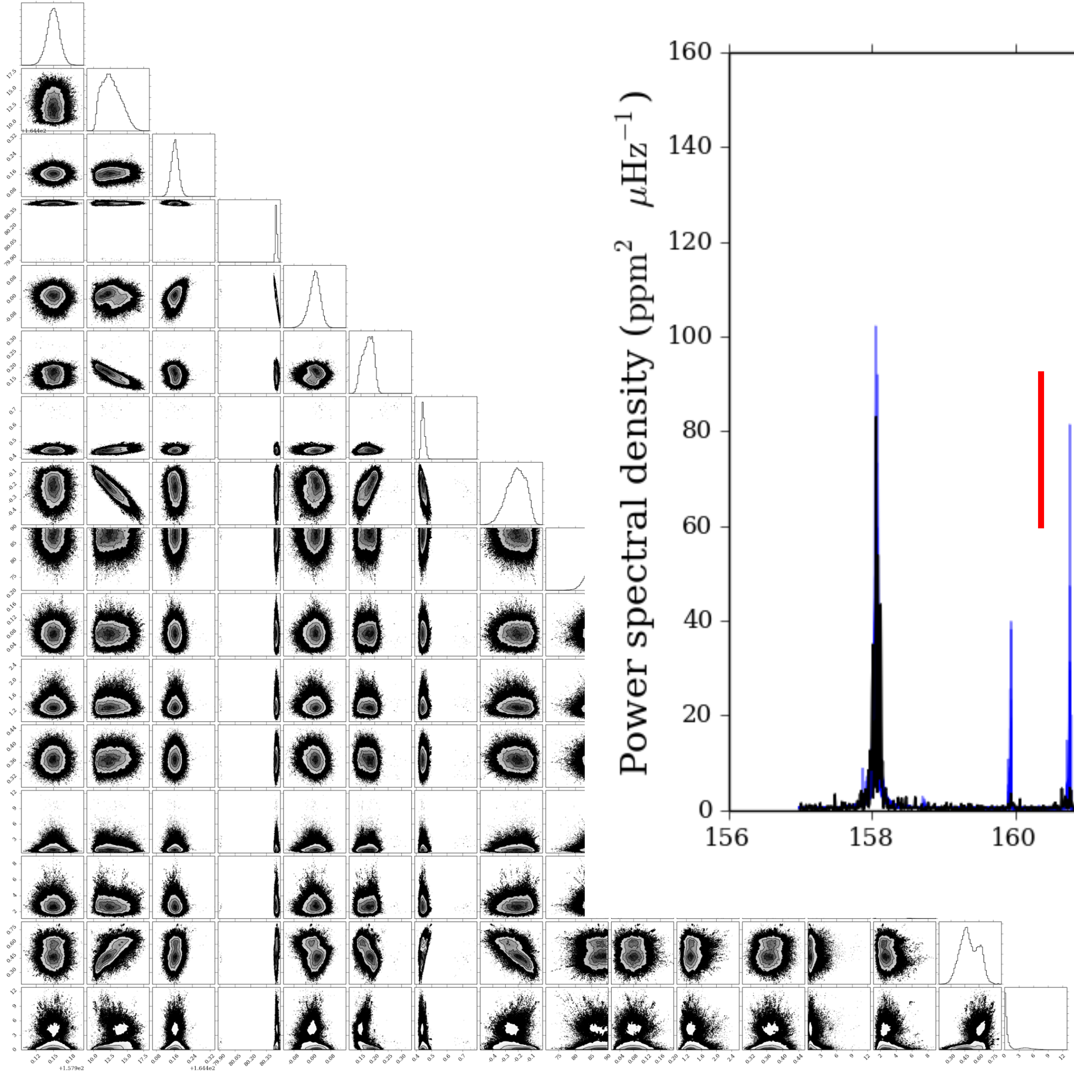

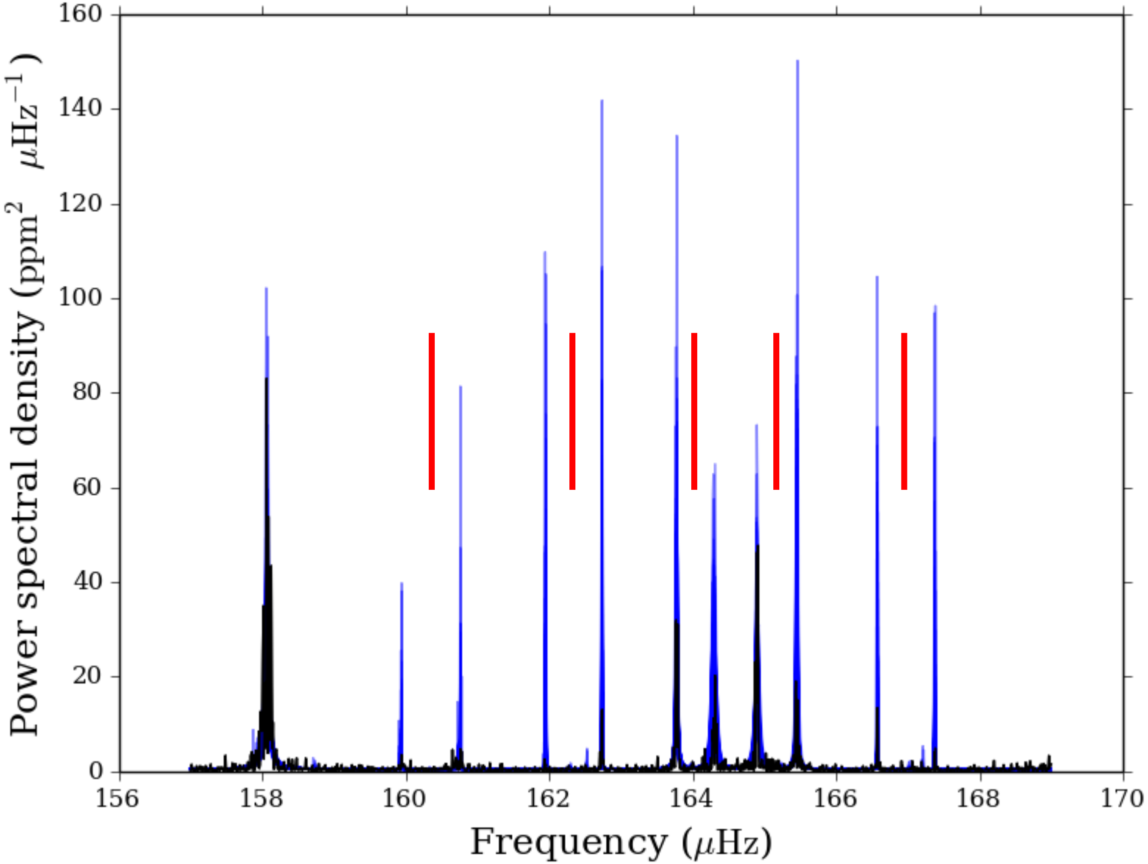

See the next talk for more on period spacing.

Observations and constraint

Observable	Red giant	Solar type subgiant	Solar type main sequence	The Sun
Average frequency spacings + numax	✓	✓	✓	✓
Period spacing	Probably (not all)	Possibly	Difficult	Very difficult
Rotation	Probably (even less than above)	Radial differential rotation - some	Average splitting	Helioseismology - map of interior
Individual frequencies	Yes - Mode ID is/was a problem … Benoit ...	Yes	Yes	Yes

Getting from observables to intrinsic properties you lot care about ...

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Why should we correct reported pulsation frequencies for stellar line-of-sight Doppler velocity shifts?

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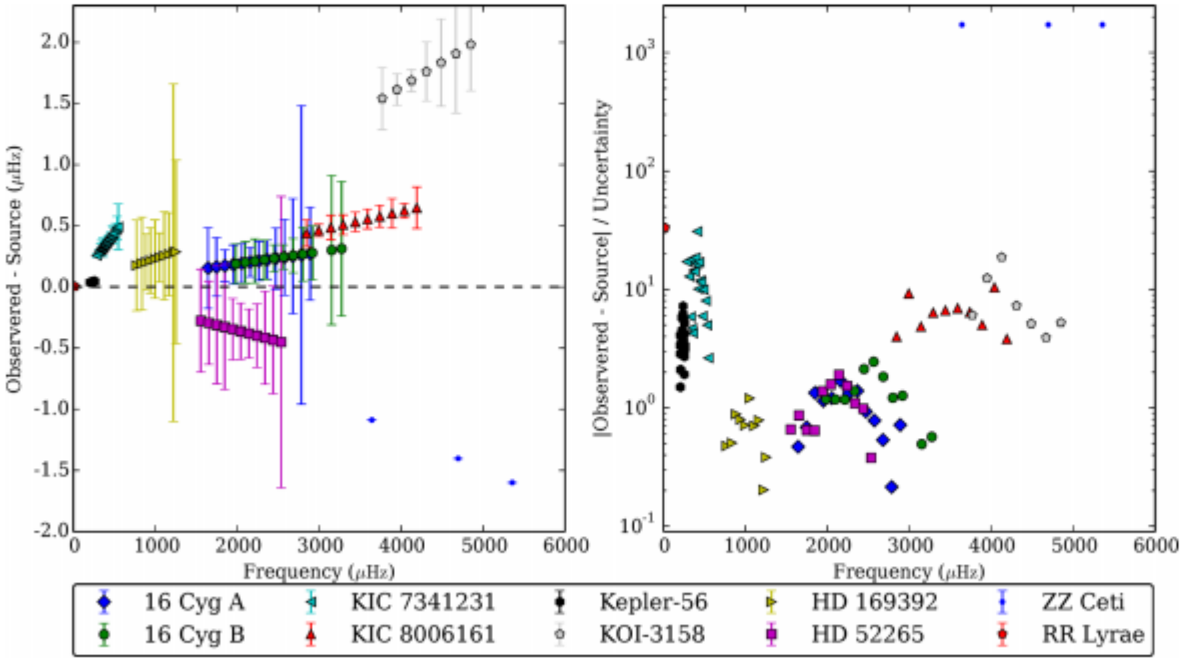

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Figure 2. Differences in published (e.g. Solar system barycentric frame of reference) and Doppler shift corrected (source frame of reference) pulsation frequencies for a selection of stars and modes of oscillation. The left-hand panel gives the differences as a function of frequency while the right-hand panel displays the difference divided by the uncertainty.