The Sun as a star

Insights from BiSON, Kepler, and CoRoT

Guy R Davies

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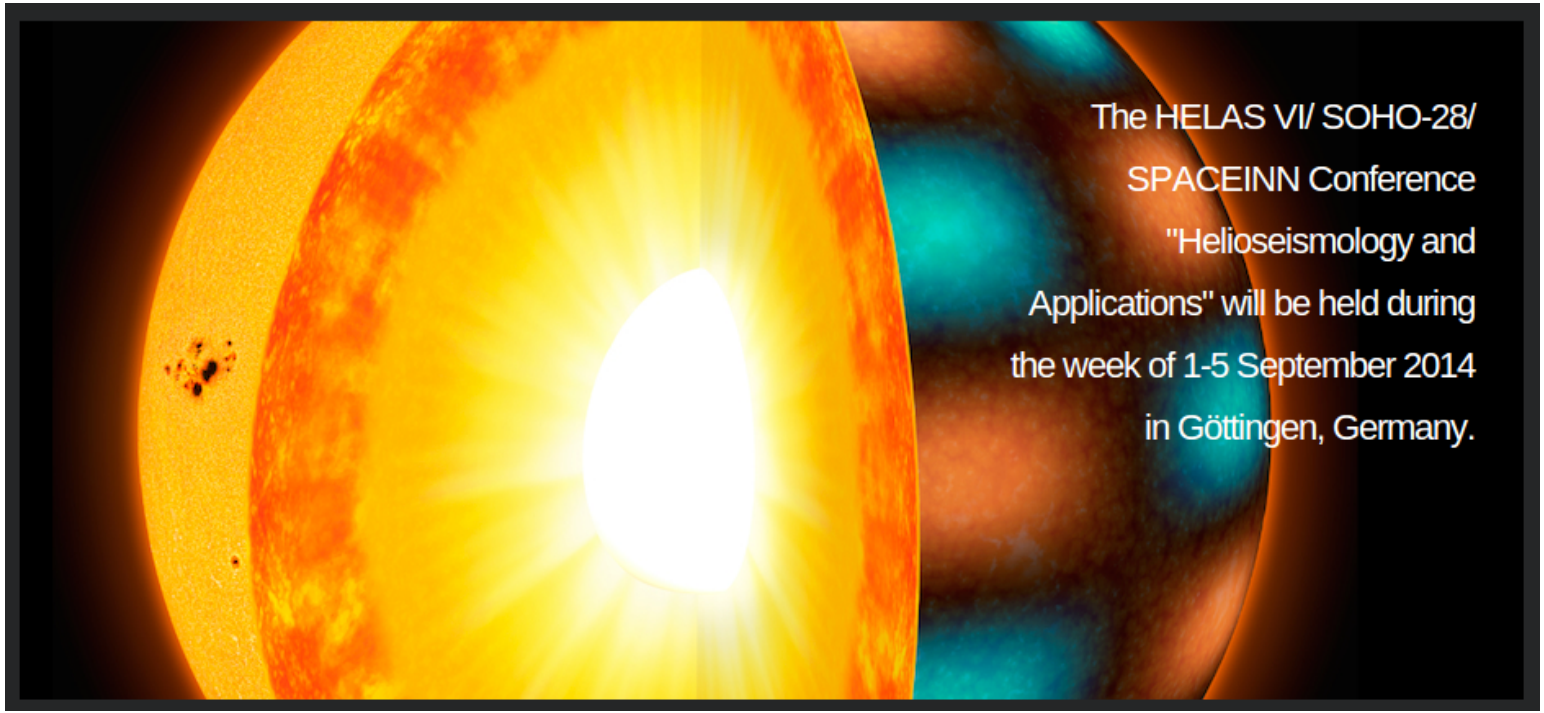
The Sun



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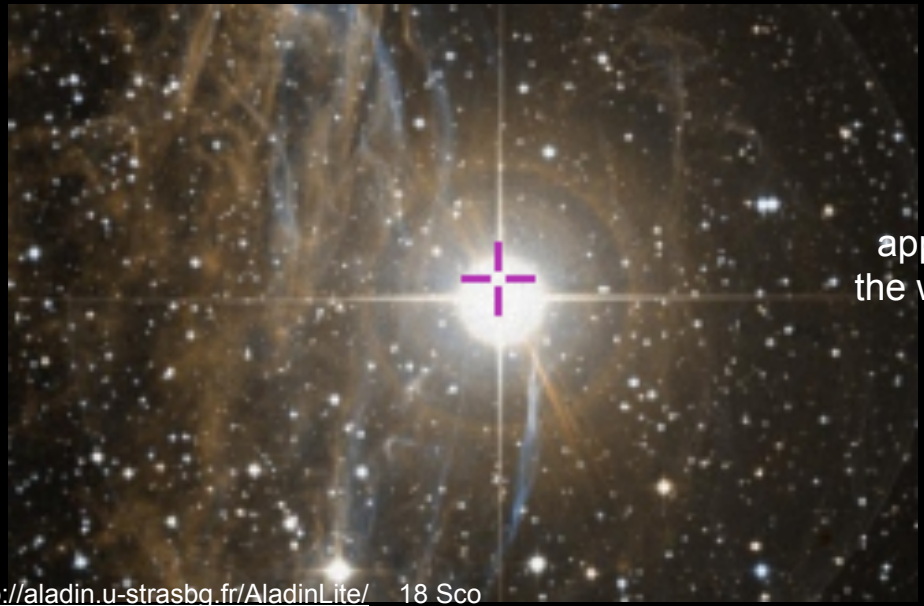
The Sun is one of many stars



http://aladin.u-strasbg.fr/AladinLite/ 18 Sco

The HelasVI / Soho-28 SPACEINN conference "Helioseismology and applications" will be held during the week of 1-5 September 2014 in Gottingen, Germany

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The Sun is a (the) star

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BiSON: Sun as a star

- **Ground based 6 station network**
- **1978 to present**
- **1985 onwards three or more stations**
- **Radial velocity using resonant scattering spectrometers**
- **Calibrated data are freely available!**

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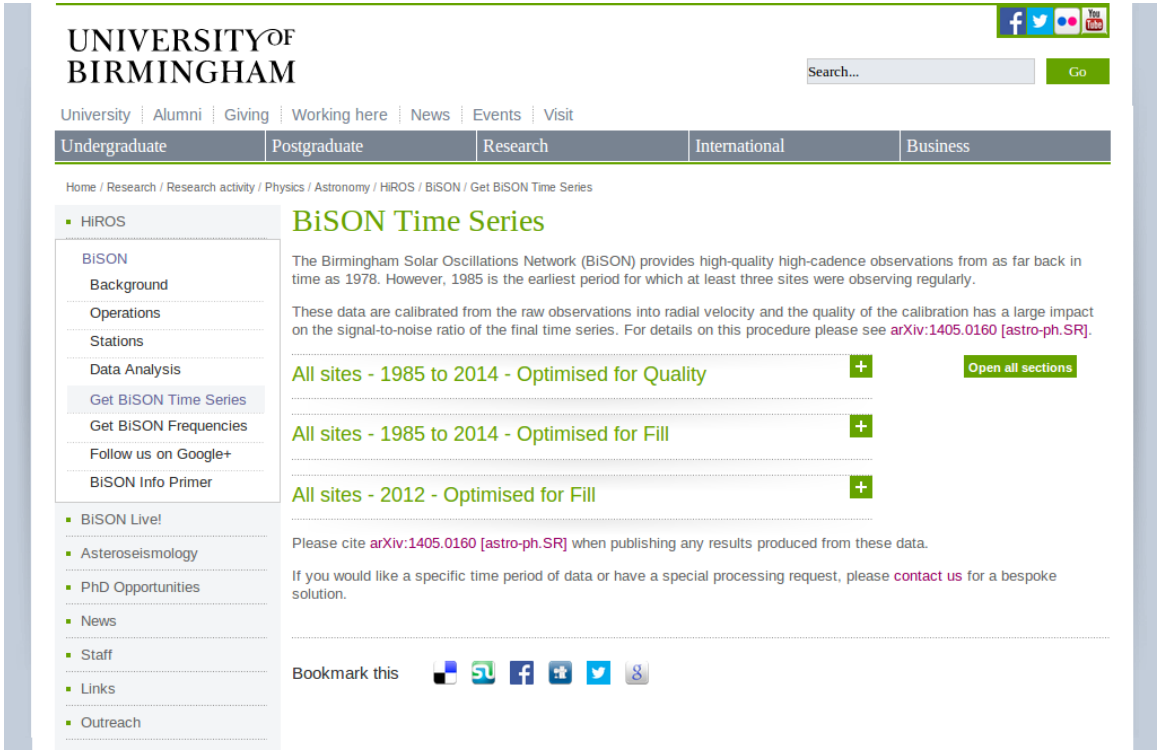
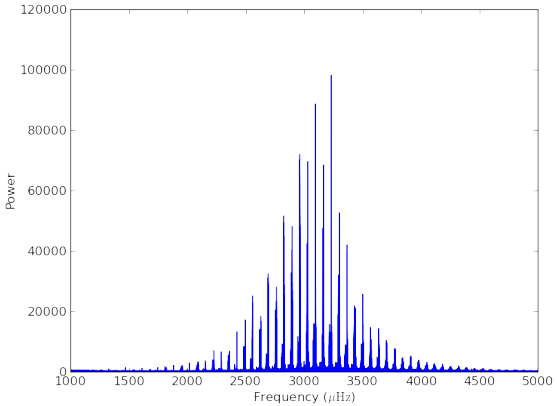
BiSON: Get the data





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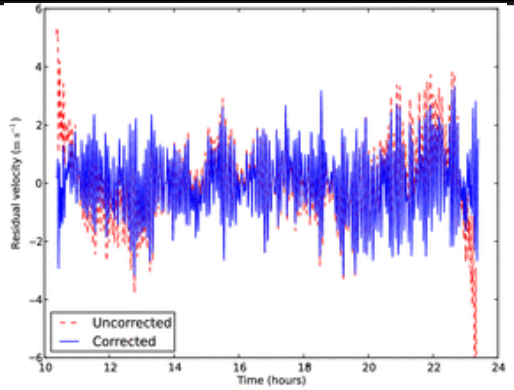
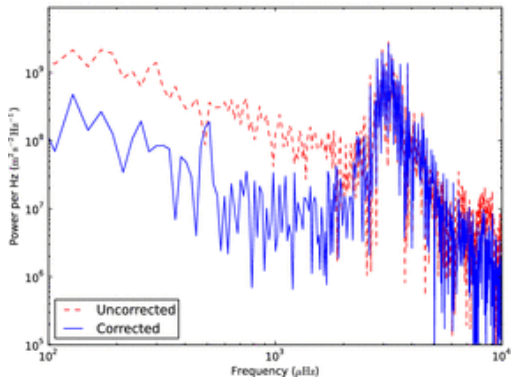
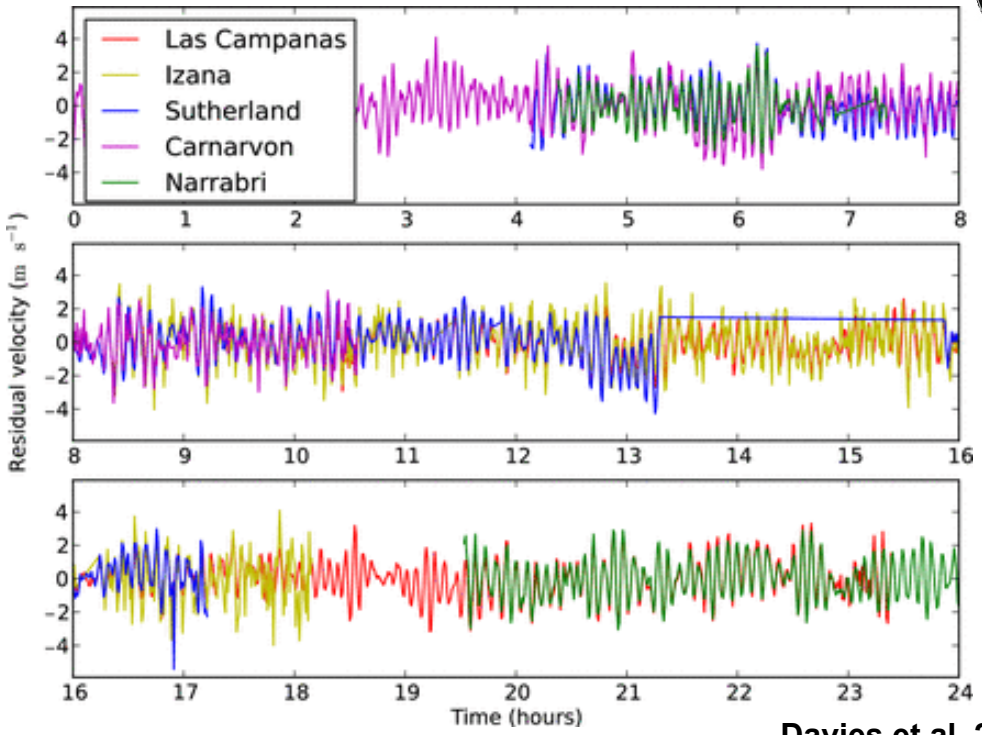
http://bison.ph.bham.ac.uk/index.php?page=bison,timeseries

BiSON: Improved calibration







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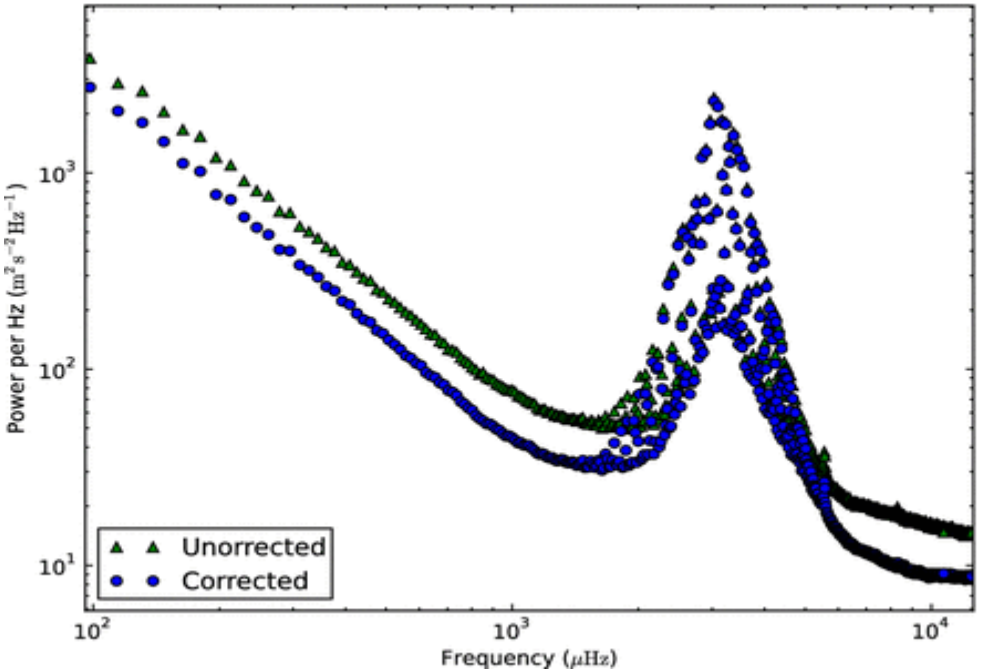
Davies et al. 2014a

BiSON: Improved calibration



- **Applied to 22 years of data and smoothed to help the eye.**
- **Signal-to-noise ratio improvement across a broad range of frequencies.**
- **This is most accessible in the low-frequency region.**

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Davies et al. 2014a

BiSON: Low-frequency p modes

- **Increased SNR leads to new BiSON detections (a couple).**
- **Measured frequencies,**
- **linewidths,**
- **amplitudes,**
- **and rotational splittings.**

n	l	Frequency (μHz)	Ln width (μHz)	Ln height ($m^2\,s^{-2}\,\mu Hz^{-1}$)	Ln amplitude^2 ($m^2\,s^{-2}$)	Splitting (μHz)
6	0	$972.615^{+0.002}_{-0.002}$	$-5.2^{+0.8}_{-0.6}$	$5.8^{+0.9}_{-0.9}$	$1.2^{+0.4}_{-0.4}$	–
7	0	$1117.993^{+0.004}_{-0.004}$	$-4.7^{+0.5}_{-0.4}$	$5.3^{+0.5}_{-0.4}$	$1.0^{+0.4}_{-0.4}$	–
7	1	$1185.604^{+0.003}_{-0.003}$	$-4.7^{+0.6}_{-1.2}$	$5.4^{+1.6}_{-0.5}$	$2.0^{+0.3}_{-0.3}$	$0.402^{+0.003}_{-0.003}$
8	0	$1263.198^{+0.005}_{-0.005}$	$-3.8^{+0.6}_{-1.5}$	$5.3^{+1.8}_{-0.5}$	$2.0^{+0.3}_{-0.3}$	–
8	1	$1329.635^{+0.003}_{-0.003}$	$-3.8^{+0.3}_{-0.2}$	$5.5^{+0.3}_{-0.3}$	$2.8^{+0.2}_{-0.2}$	$0.397^{+0.003}_{-0.003}$
8	2	$1394.689^{+0.005}_{-0.005}$	$-3.5^{+0.3}_{-0.3}$	$4.6^{+0.3}_{-0.3}$	$2.5^{+0.2}_{-0.2}$	$0.405^{+0.002}_{-0.002}$
9	0	$1407.472^{+0.006}_{-0.006}$	$-3.4^{+0.4}_{-0.4}$	$5.3^{+0.4}_{-0.4}$	$2.4^{+0.2}_{-0.2}$	–
9	1	$1472.839^{+0.006}_{-0.006}$	$-2.5^{+0.2}_{-0.2}$	$4.9^{+0.2}_{-0.2}$	$3.5^{+0.1}_{-0.1}$	$0.398^{+0.005}_{-0.005}$
9	2	$1535.853^{+0.005}_{-0.005}$	$-2.6^{+0.2}_{-0.1}$	$5.0^{+0.2}_{-0.2}$	$3.7^{+0.1}_{-0.1}$	$0.407^{+0.003}_{-0.003}$
10	0	$1548.336^{+0.007}_{-0.007}$	$-2.5^{+0.2}_{-0.2}$	$5.4^{+0.2}_{-0.2}$	$3.4^{+0.1}_{-0.1}$	–
9	3	$1591.536^{+0.014}_{-0.014}$	$-2.4^{+0.3}_{-0.3}$	$3.7^{+0.3}_{-0.3}$	$2.77^{+0.2}_{-0.2}$	$0.400^{+0.005}_{-0.005}$
10	1	$1612.724^{+0.006}_{-0.006}$	$-2.2^{+0.2}_{-0.1}$	$5.6^{+0.1}_{-0.2}$	$4.56^{+0.06}_{-0.06}$	$0.404^{+0.005}_{-0.005}$
10	2	$1674.538^{+0.008}_{-0.008}$	$-1.8^{+0.1}_{-0.1}$	$4.9^{+0.1}_{-0.1}$	$4.55^{+0.06}_{-0.06}$	$0.402^{+0.004}_{-0.004}$
11	0	$1686.594^{+0.012}_{-0.012}$	$-1.6^{+0.1}_{-0.1}$	$5.3^{+0.1}_{-0.1}$	$4.18^{+0.08}_{-0.08}$	–
10	3	$1729.088^{+0.022}_{-0.022}$	$-1.4^{+0.2}_{-0.2}$	$3.5^{+0.2}_{-0.2}$	$3.65^{+0.12}_{-0.12}$	–
11	1	$1749.285^{+0.007}_{-0.007}$	$-1.7^{+0.1}_{-0.1}$	$5.8^{+0.1}_{-0.1}$	$5.26^{+0.05}_{-0.05}$	$0.407^{+0.008}_{-0.008}$
11	2	$1810.308^{+0.009}_{-0.009}$	$-1.3^{+0.1}_{-0.1}$	$5.2^{+0.1}_{-0.1}$	$5.28^{+0.04}_{-0.04}$	$0.403^{+0.004}_{-0.004}$
12	0	$1822.202^{+0.012}_{-0.012}$	$-1.2^{+0.1}_{-0.1}$	$5.8^{+0.1}_{-0.1}$	$5.04^{+0.05}_{-0.05}$	–
11	3	$1865.280^{+0.016}_{-0.016}$	$-1.0^{+0.1}_{-0.1}$	$4.2^{+0.1}_{-0.1}$	$4.66^{+0.06}_{-0.06}$	$0.395^{+0.005}_{-0.005}$
12	1	$1885.089^{+0.009}_{-0.009}$	$-1.1^{+<0.1}_{-<0.1}$	$6.0^{+<0.1}_{-<0.1}$	$6.03^{+0.03}_{-0.03}$	$0.403^{+0.008}_{-0.008}$
12	2	$1945.824^{+0.013}_{-0.013}$	$-0.8^{+<0.1}_{-<0.1}$	$5.4^{+<0.1}_{-<0.1}$	$5.99^{+0.03}_{-0.03}$	$0.392^{+0.006}_{-0.006}$
13	0	$1957.452^{+0.012}_{-0.012}$	$-0.9^{+<0.1}_{-<0.1}$	$6.1^{+0.1}_{-0.1}$	$5.66^{+0.04}_{-0.04}$	–

Davies et al. 2014b

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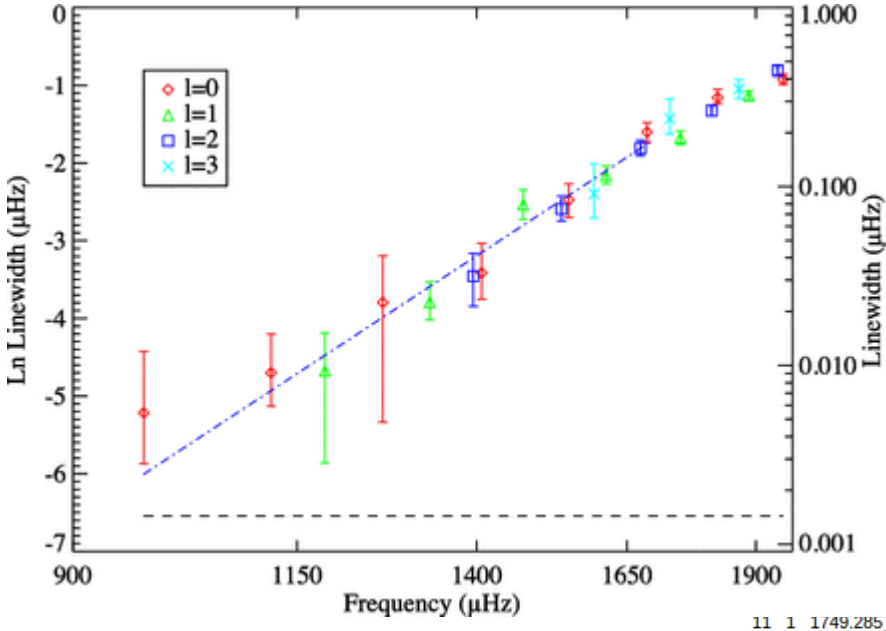
BiSON: Low-frequency p modes



			y	Ln width (μHz)	Ln height ($m^2\,s^{-2}\,\mu Hz^{-1}$)	Ln amplitude^2 ($m^2\,s^{-2}$)	Splitting (μHz)
			$^{+0.002}_{-0.002}$	$-5.2^{+0.8}_{-0.6}$	$5.8^{+0.9}_{-0.9}$	$1.2^{+0.4}_{-0.4}$	–
			$^{+0.004}_{-0.004}$	$-4.7^{+0.5}_{-0.4}$	$5.3^{+0.5}_{-0.4}$	$1.0^{+0.4}_{-0.4}$	–
			$^{+0.003}_{-0.003}$	$-4.7^{+0.6}_{-1.2}$	$5.4^{+1.6}_{-0.5}$	$2.0^{+0.3}_{-0.3}$	$0.402^{+0.003}_{-0.003}$
			$^{+0.005}_{-0.005}$	$-3.8^{+0.6}_{-1.5}$	$5.3^{+1.8}_{-0.5}$	$2.0^{+0.3}_{-0.3}$	–
			$^{+0.003}_{-0.003}$	$-3.8^{+0.3}_{-0.2}$	$5.5^{+0.3}_{-0.3}$	$2.8^{+0.2}_{-0.2}$	$0.397^{+0.003}_{-0.003}$
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			$^{+0.006}_{-0.006}$	$-3.4^{+0.4}_{-0.4}$	$5.3^{+0.4}_{-0.4}$	$2.4^{+0.2}_{-0.2}$	–
			$^{+0.006}_{-0.006}$	$-2.5^{+0.2}_{-0.2}$	$4.9^{+0.2}_{-0.2}$	$3.5^{+0.1}_{-0.1}$	$0.398^{+0.005}_{-0.005}$
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			$^{+0.007}_{-0.007}$	$-2.5^{+0.2}_{-0.2}$	$5.4^{+0.2}_{-0.2}$	$3.4^{+0.1}_{-0.1}$	–
			$^{+0.014}_{-0.014}$	$-2.4^{+0.3}_{-0.3}$	$3.7^{+0.3}_{-0.3}$	$2.77^{+0.2}_{-0.2}$	$0.400^{+0.005}_{-0.005}$
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			$^{+0.012}_{-0.012}$	$-1.6^{+0.1}_{-0.1}$	$5.3^{+0.1}_{-0.1}$	$4.18^{+0.08}_{-0.08}$	–
			$^{+0.022}_{-0.022}$	$-1.4^{+0.2}_{-0.2}$	$3.5^{+0.2}_{-0.2}$	$3.65^{+0.12}_{-0.12}$	–
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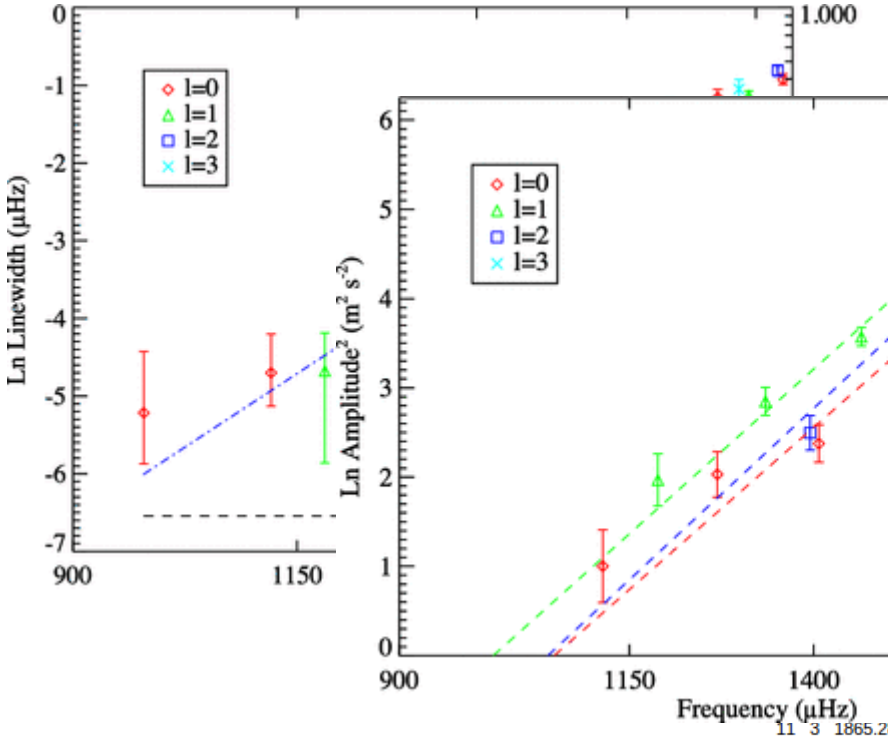
BiSON: Low-frequency p modes



			Ln width (μHz)	Ln height ($m^2\,s^{-2}\,\mu Hz^{-1}$)	Ln amplitude² ($m^2\,s^{-2}$)	Splitting (μHz)
					$1.2^{+0.4}_{-0.4}$	–
					$1.0^{+0.4}_{-0.4}$	–
					$2.0^{+0.3}_{-0.3}$	$0.402^{+0.003}_{-0.003}$
					$2.0^{+0.3}_{-0.3}$	–
					$2.8^{+0.2}_{-0.2}$	$0.397^{+0.003}_{-0.003}$
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					$2.4^{+0.2}_{-0.2}$	–
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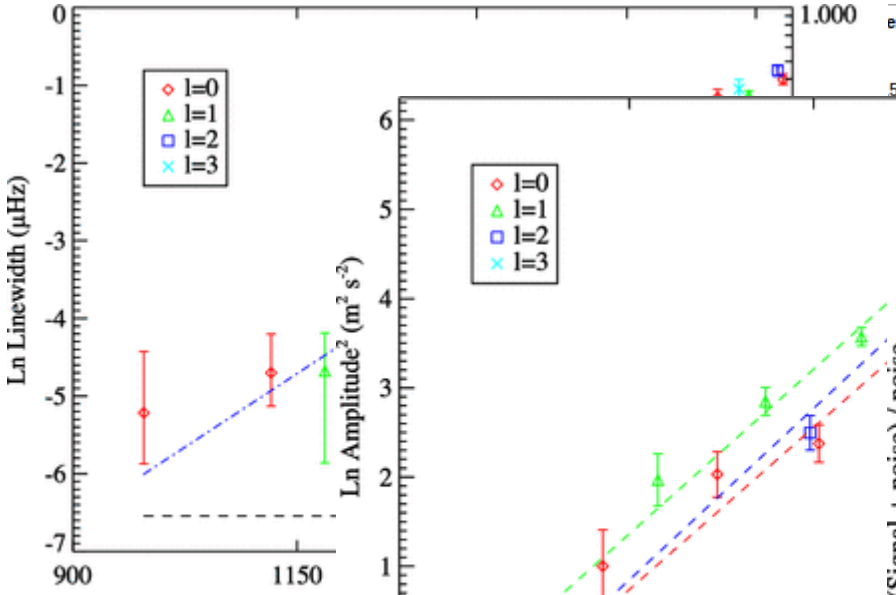
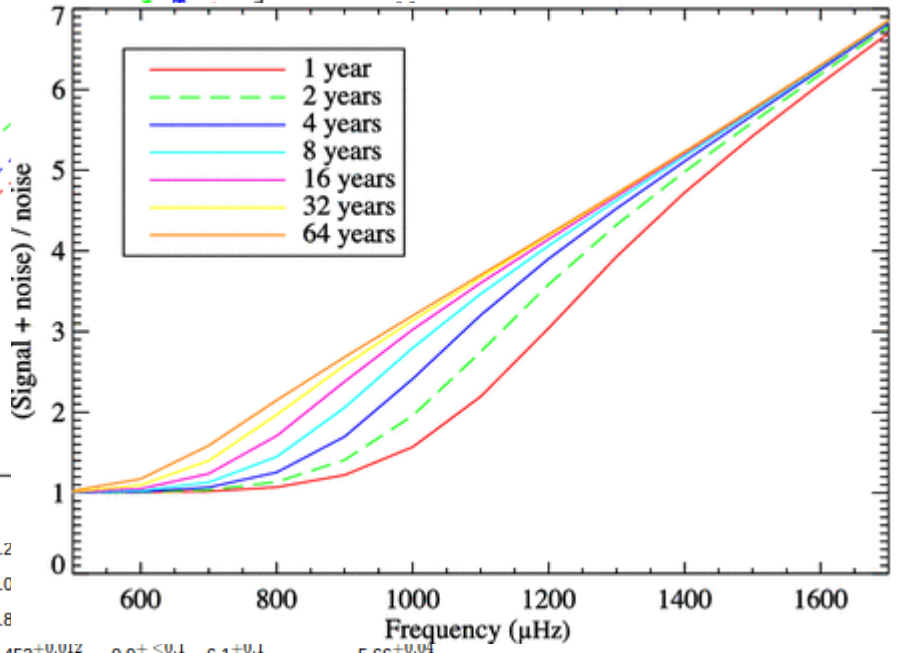
BiSON: Low-frequency p modes



ency	Ln width (μHz)	Ln height ($m^2 s^{-2} \mu Hz^{-1}$)	Ln amplitude² ($m^2 s^{-2}$)	Splitting (μHz)
$5^{+0.002}_{-0.005}$	$-5.2^{+0.8}_{-0.6}$	$5.8^{+0.9}_{-0.6}$	$1.2^{+0.4}_{-0.4}$	–
			$1.0^{+0.4}_{-0.4}$	–
			$2.0^{+0.3}_{-0.3}$	$0.402^{+0.003}_{-0.003}$
11 3 1865.2				
12 1 1885.0				
12 2 1945.8				
13 0 1957.452$^{+0.012}_{-0.012}$	$-0.9^{+<0.1}_{-<0.1}$	$6.1^{+0.1}_{-0.1}$	$5.66^{+0.04}_{-0.04}$	–



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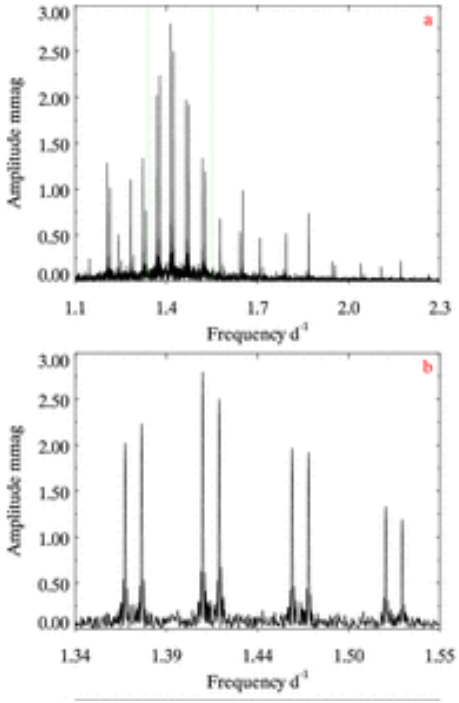
Kepler: Searching for g modes



Asteroseismic measurement of surface-to-core rotation in a main-sequence A star, KIC 11145123

“Easy” to detect g modes.

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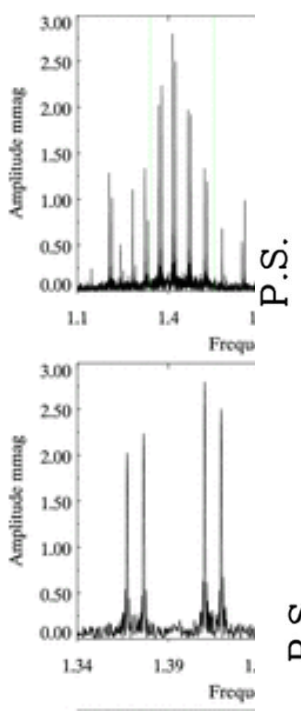
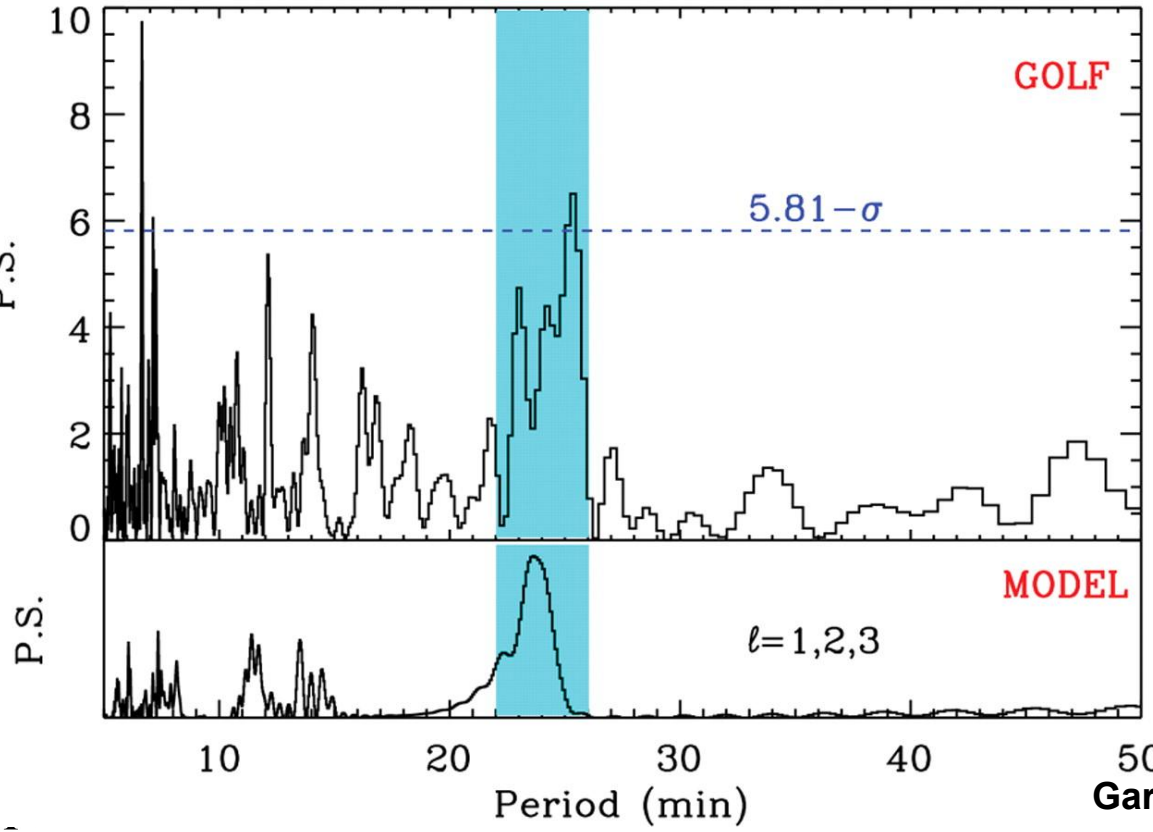
Kurtz et al. 2014

Golf: Searching for g modes





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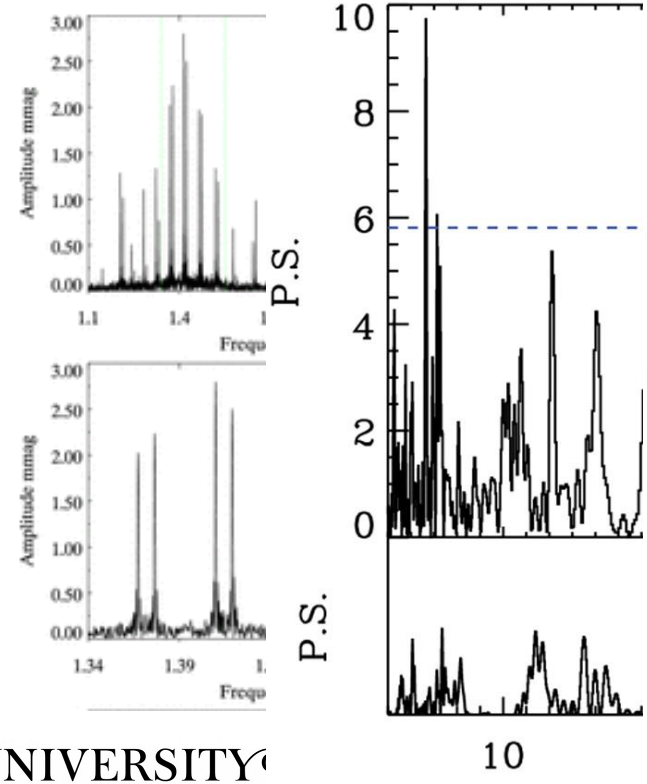
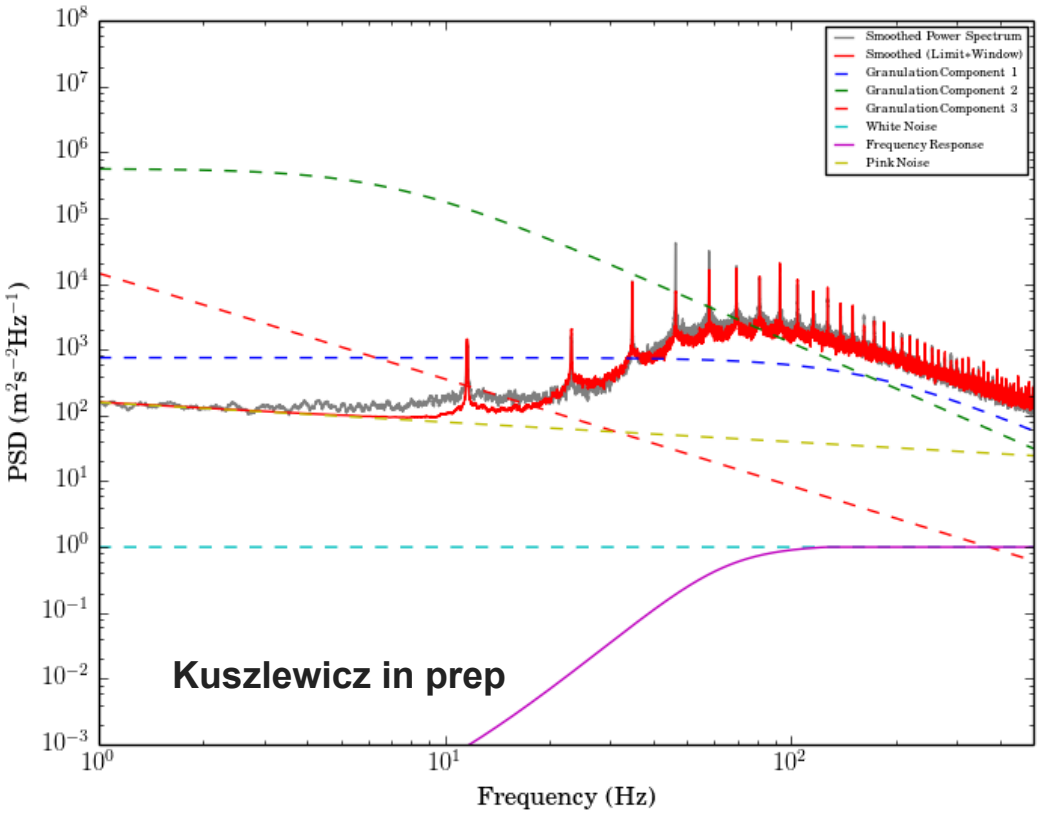
Garcia et al. 2007

BiSON: Searching for g modes





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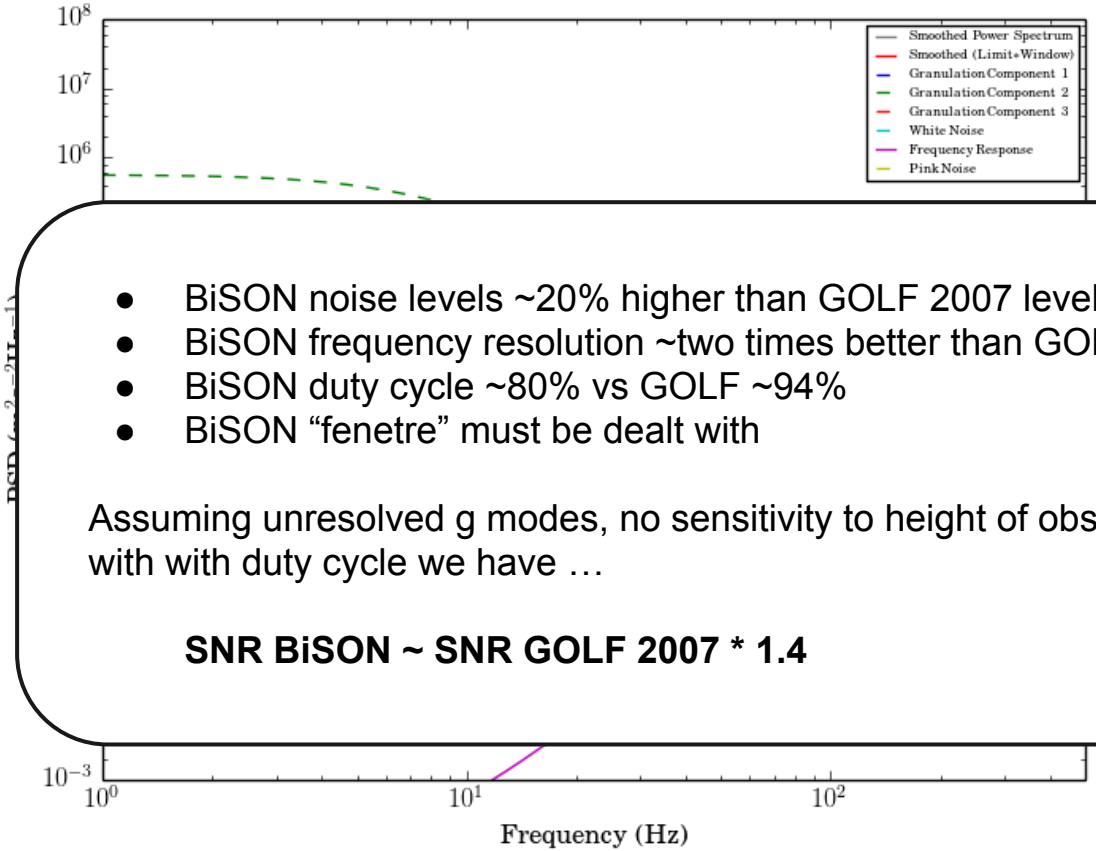
BiSON: Searching for g modes

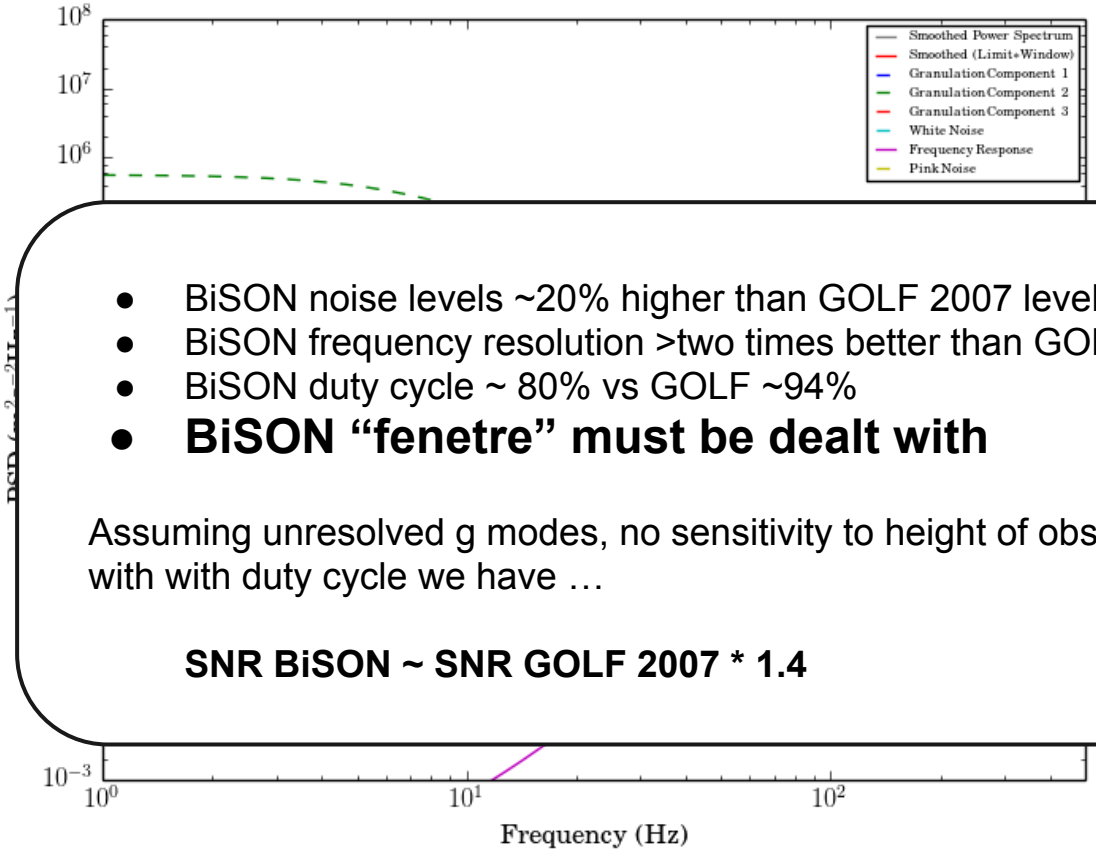


- BiSON noise levels ~20% higher than GOLF 2007 levels
- BiSON frequency resolution ~two times better than GOLF 2007
- BiSON duty cycle ~80% vs GOLF ~94%
- BiSON “fenetre” must be dealt with

Assuming unresolved g modes, no sensitivity to height of observation, and power leakage linear with with duty cycle we have …

SNR BiSON ~ SNR GOLF 2007 * 1.4

BiSON: Searching for g modes



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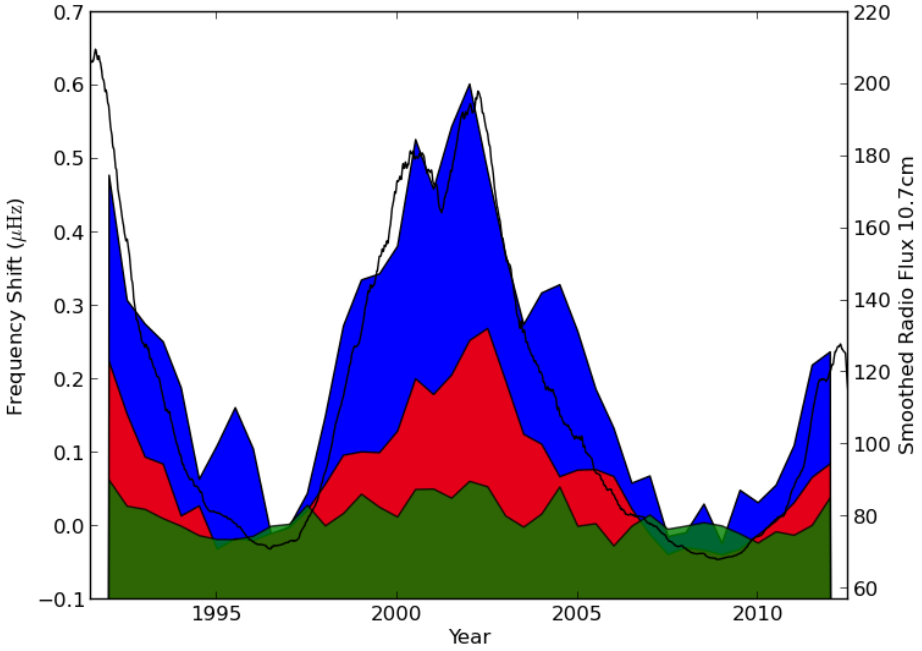
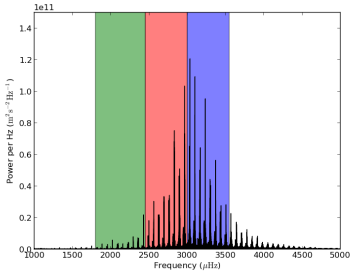
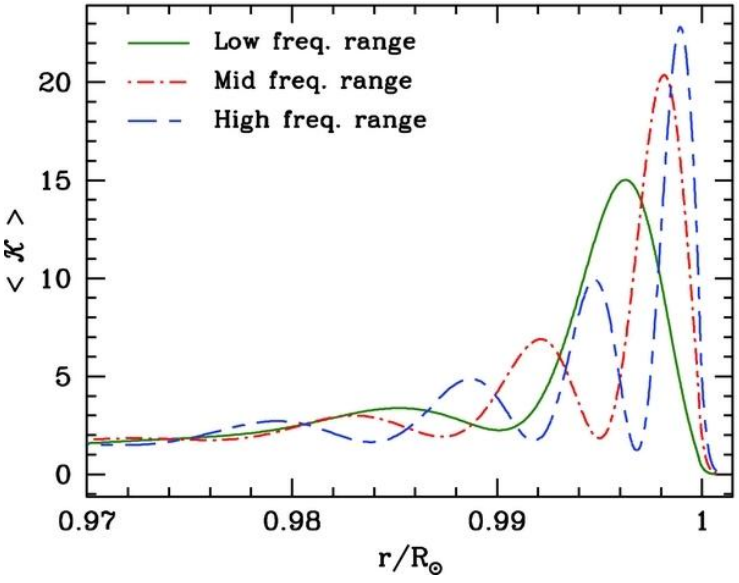
BiSON: Solar cycle







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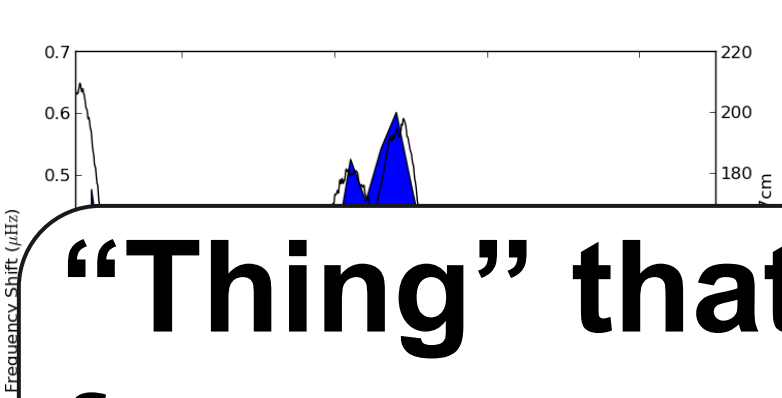
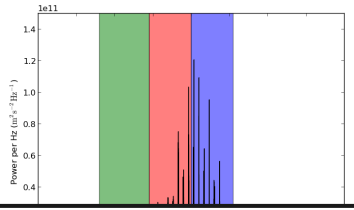
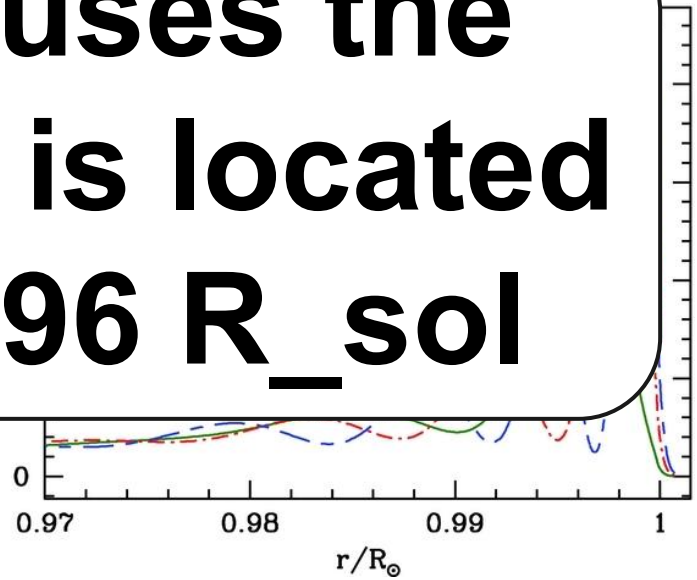
BiSON: Solar cycle





"Thing" that causes the frequency shift is located at a depth > 0.996 R_sol



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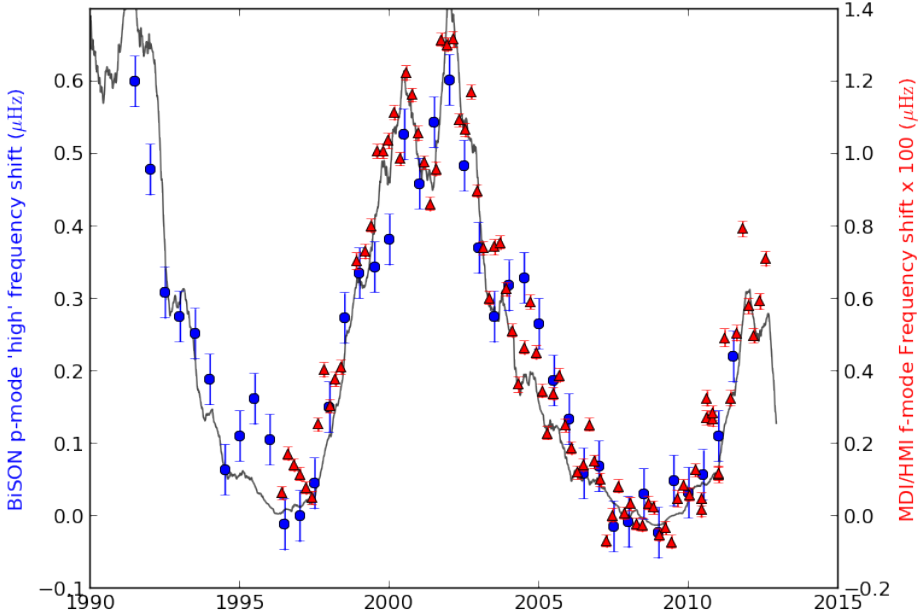
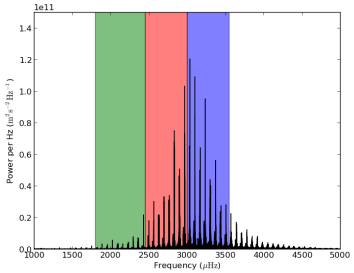
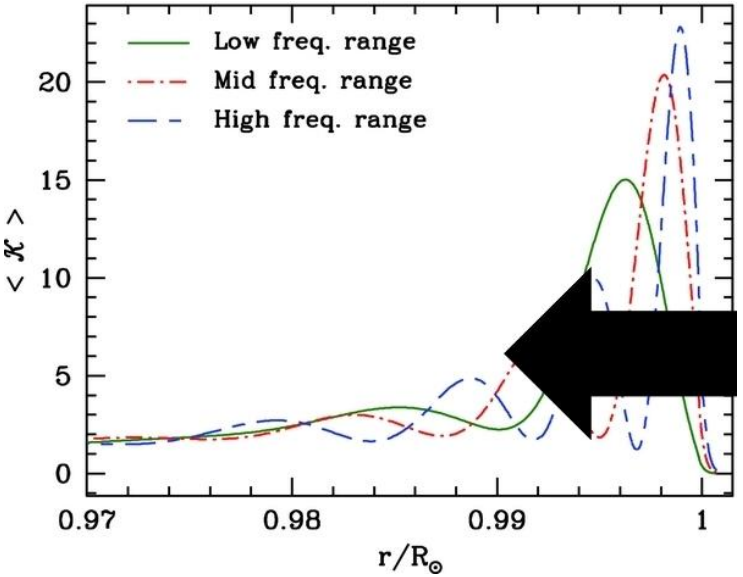
Basu et al. 2012

BiSON: Solar cycle + f mode







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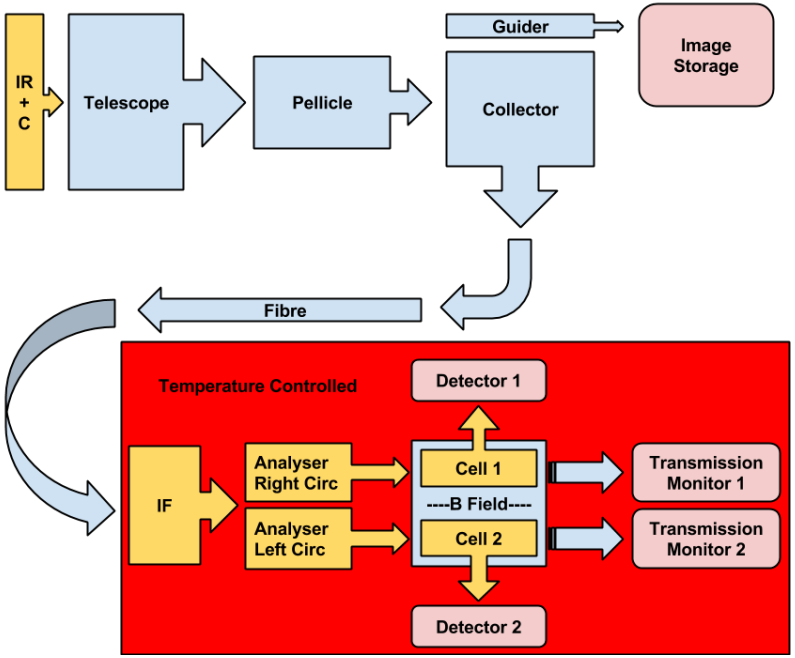
Davies et al. in prep

BiSON: The mini future



BiSON Mini

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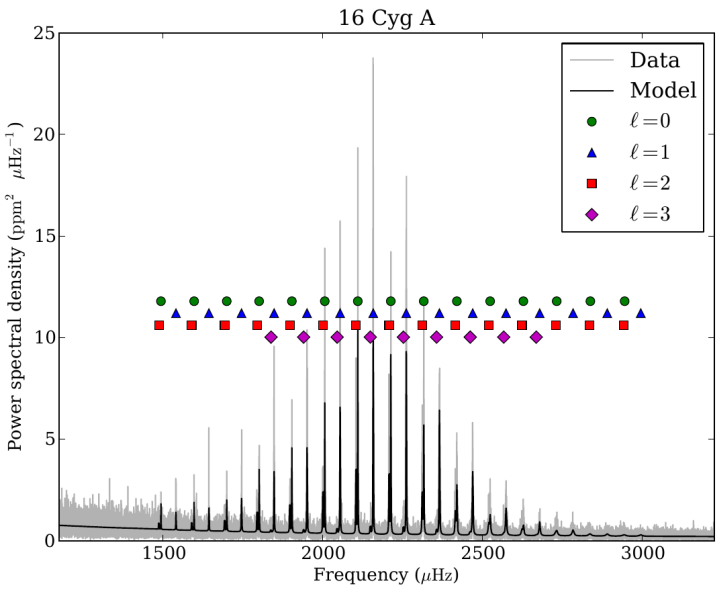
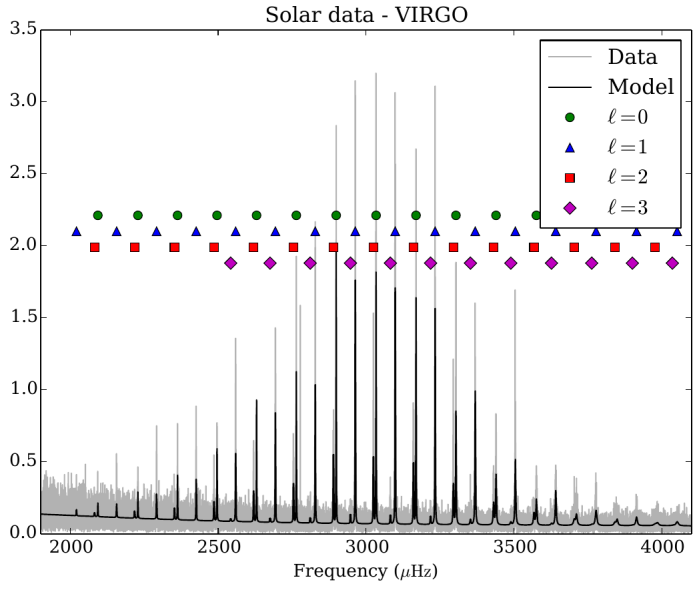
The stars as a Sun

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 metalicity	Solar +- 0.3 dex	Solar +- 0.05 dex
About 10% of stars	>30 within 50 ly e.g., Alpha Cen A (& B)	A handful e.g., 18 Sco

Kepler: Solar analog





	16 Cyg A	16 Cyg B	16 Cyg Bb
Age (Gyr)	6.8 ± 0.4^{a}	6.8 ± 0.4^{a}	6.8 ± 0.4
Mass	1.11 ± 0.02^{a} $M_{\odot}$	1.07 ± 0.02^{a} $M_{\odot}$	2.38 ± 0.04^{c} M_{Jup}
Radius	1.243 ± 0.008^{a} $R_{\odot}$	1.127 ± 0.007^{a} $R_{\odot}$	-
$B-V$	$0.64^{b} \pm 0.01$	$0.66^{b} \pm 0.01$	n/a
Orbital Period	$> 13000^{c}$ yr	$> 13000^{c}$ yr	798.5 ± 1.0^{c} days
Eccentricity	0.54 to 1^{d}	0.54 to 1^{d}	0.689 ± 0.011^{c}
Orbital Inclination (°)	100 to 160^{d}	100 to 160^{d}	$45/135^{c}$

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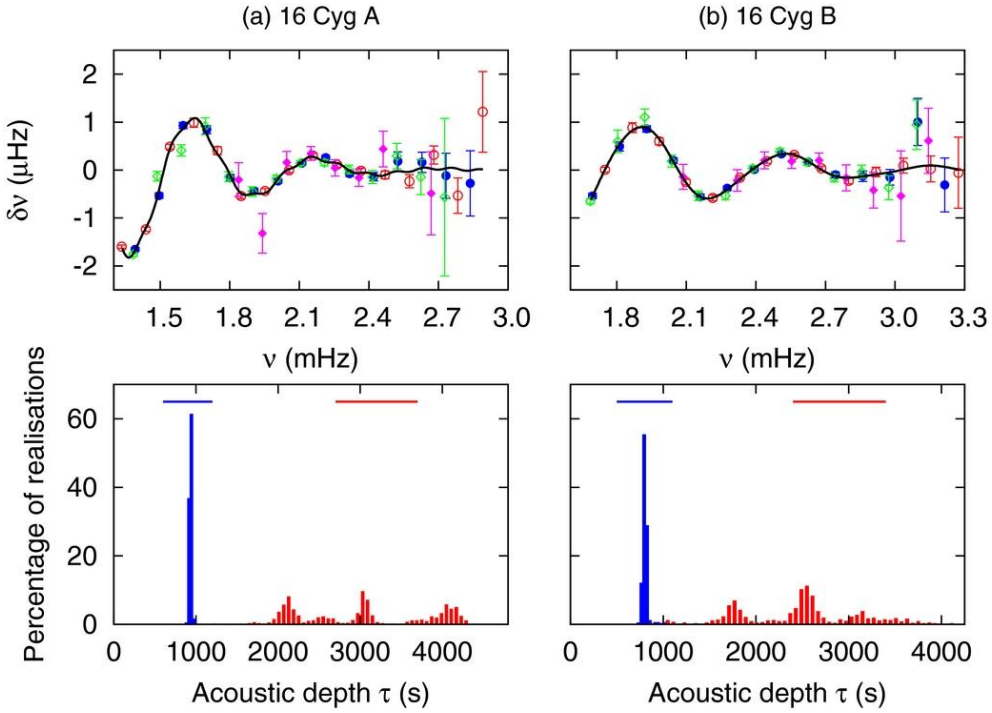
Kepler: 16 Cyg He II



Helium abundance

	MESA		YREC
Method	GS98	AGSS09	GS98
	16 Cyg A		
A	0.238 ± 0.009	0.243 ± 0.009	0.231 ± 0.009
B	0.239 ± 0.021	0.242 ± 0.023	0.236 ± 0.016
C	0.250 ± 0.009	0.251 ± 0.009	0.249 ± 0.009
	16 Cyg B		
A	0.263 ± 0.012	0.266 ± 0.012	0.257 ± 0.009
B	0.218 ± 0.013	0.228 ± 0.011	0.219 ± 0.009
C	0.251 ± 0.010	0.254 ± 0.010	0.255 ± 0.009

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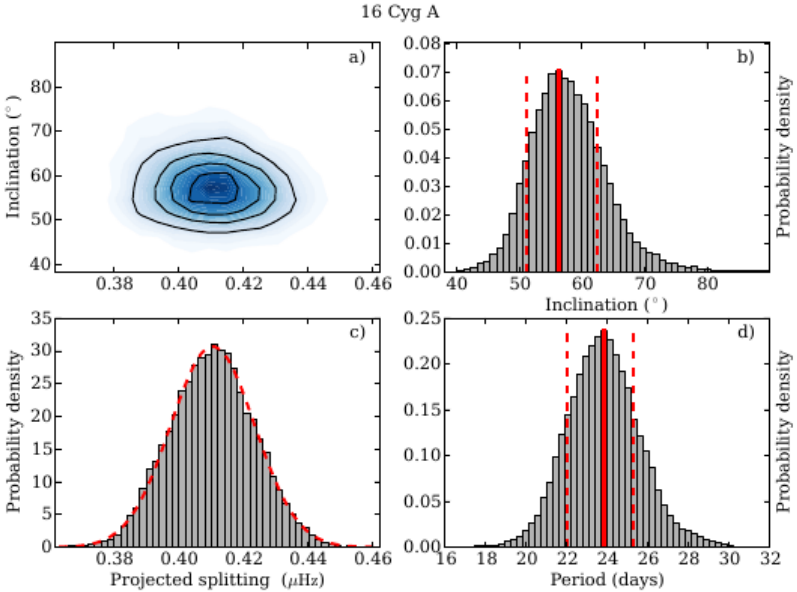
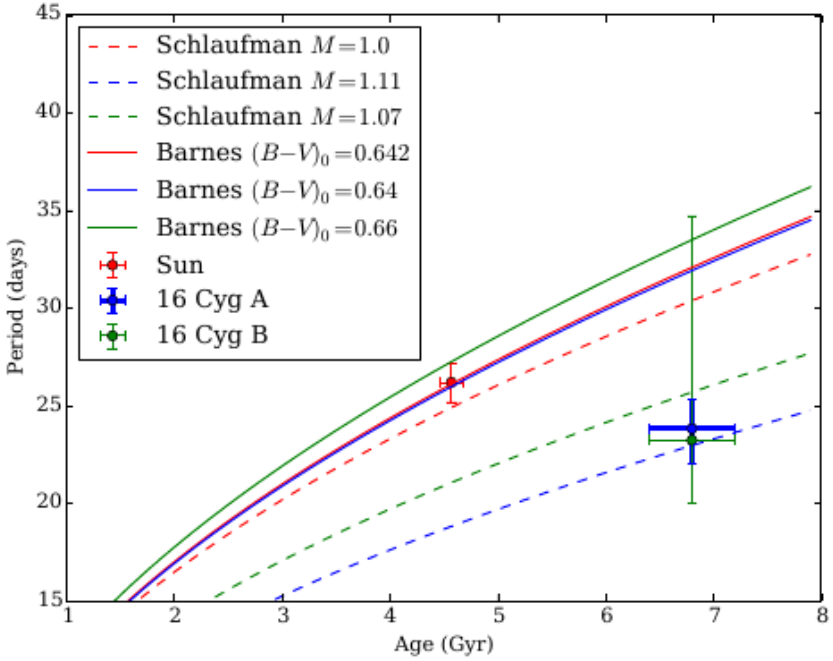
Verma et al. 2014

Kepler: 16 Cyg Rotation



Davies et al. 2014c



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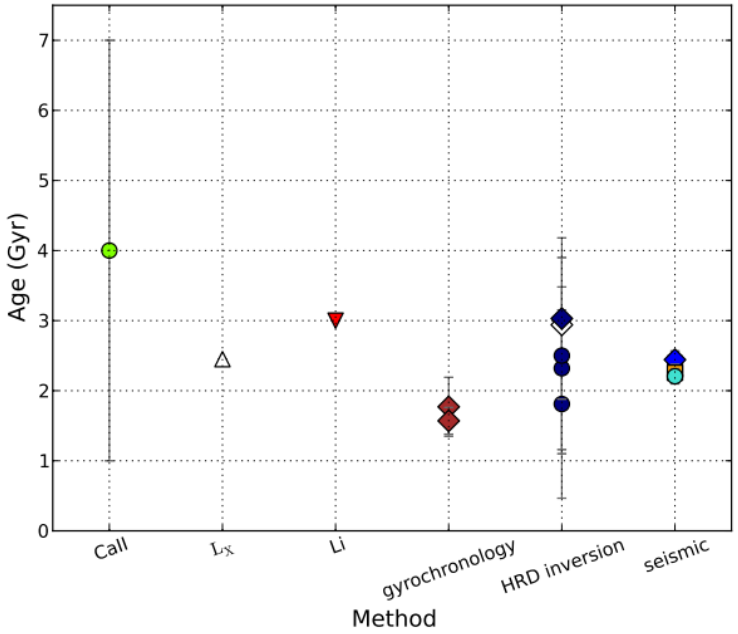
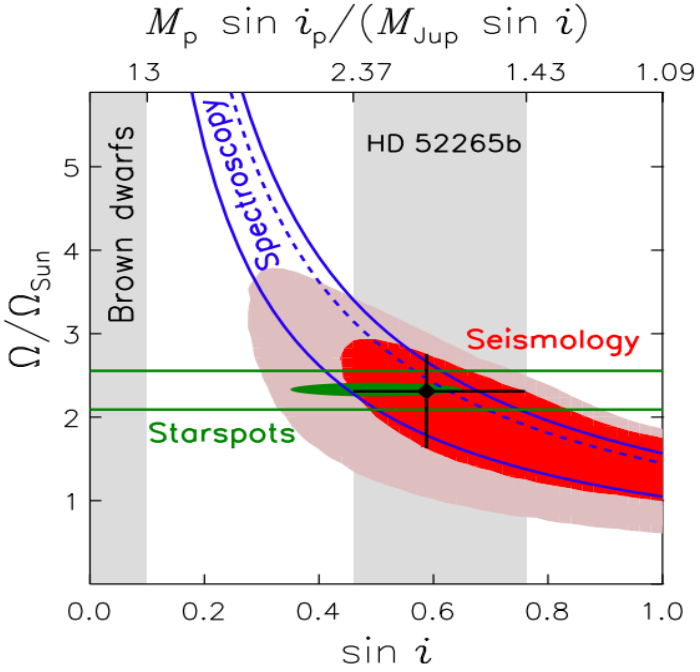
CoRoT: HD 52265



Lebreton & Goupil 2014

Gizon et al. 2013



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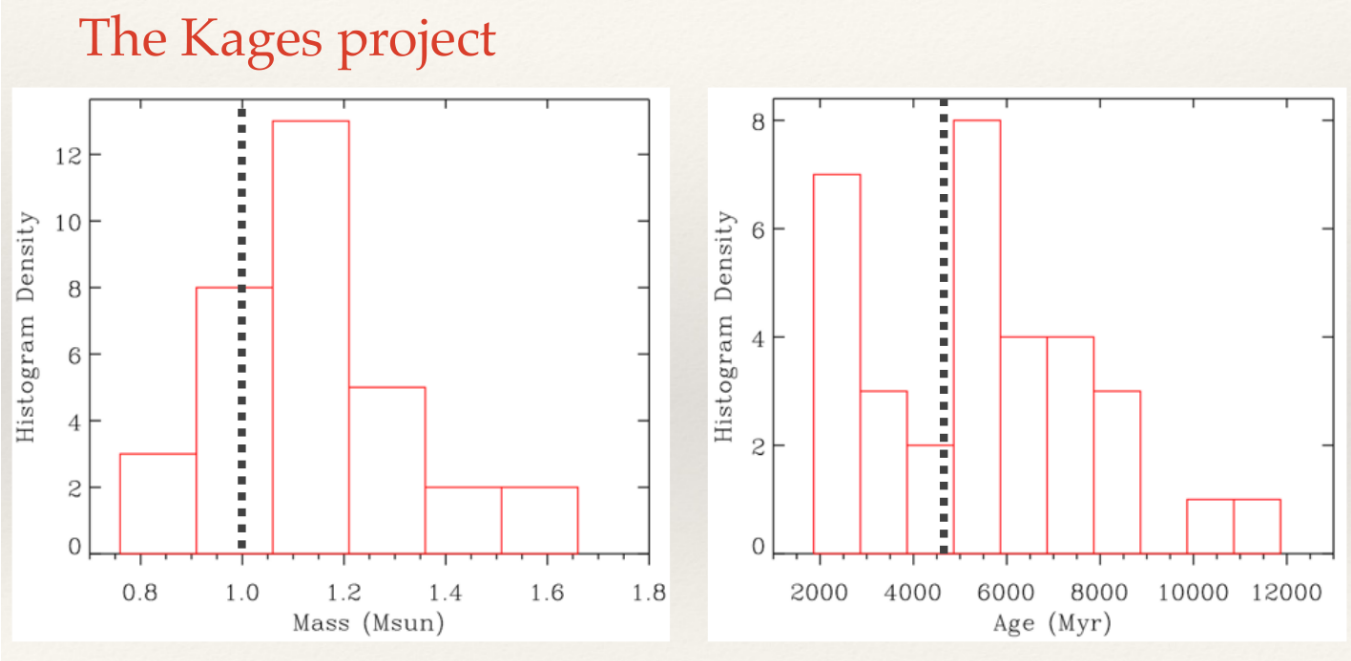
Kepler: 33 Solar type KOI's



Davies et al. 2014d
Silva Aguirre 2014

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Conclusions

- **Plenty still to learn about the Sun**
- **Lots still to learn about Sun-like stars**
- **...**