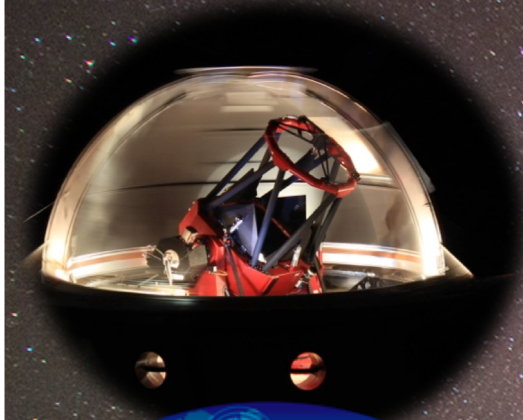


High precision radial velocity monitoring of Arcturus with SONG:

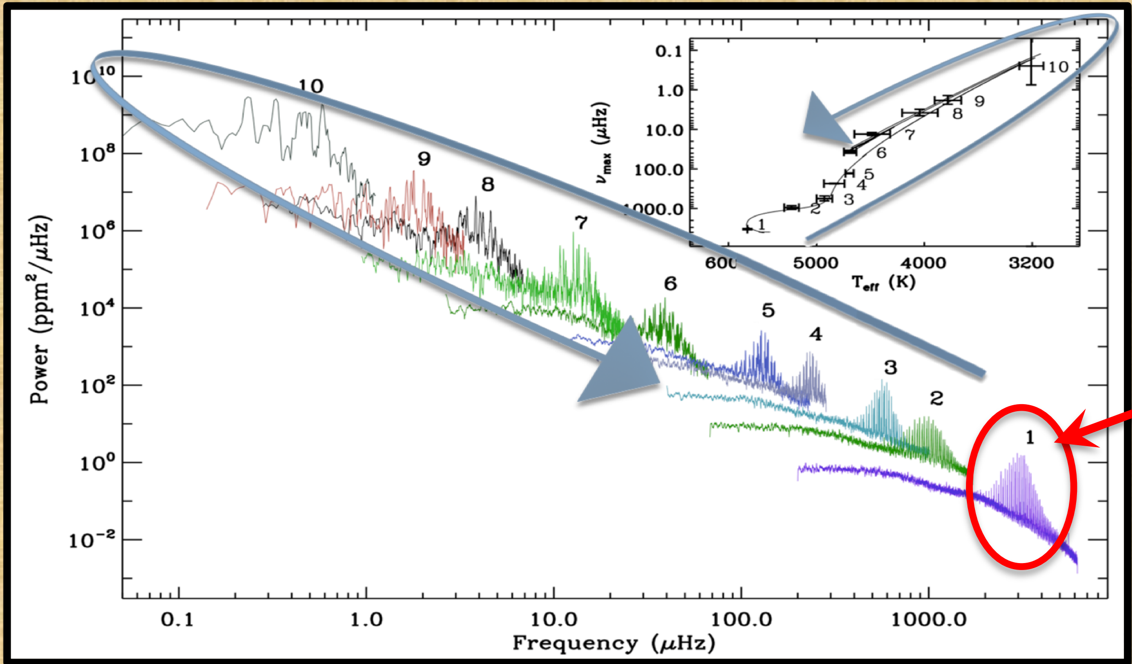
Results of the 2.5-year continuous campaign

Pere L. Pallé, T. Roca Cortés, M.A. Andersen, F. Grundahl, C. Régulo, , H. Kjeldsen, R.A. García, J. F. Pérez Hernández, J.A. Belmonte, P. Beck, S. Mathur and the SONG Team (*)

Mads Fredslund Andersen, Michael Ingemann Andersen, Victoria Antoci, Jørgen Christensen-Dalsgaard, Licai Deng, Søren Frandsen, Frank Grundahl, Rasmus Handberg, Kennet Harpsøe, Markus Hundertmark, Jens Jessen-Hansen, Xiaojun Jiang, Uffe Gråe Jørgensen, Hans Kjeldsen, Niels Michaelsen, Pere Lluís Pallé, Per Kjærgaard Rasmussen, René Tronsgaard Rasmussen, Ditte Slumstrup, Jesper Skottfelt, Anton Norup Sørensen and Eric Weiss.

Motivation (s)....

- **Take advantage of new insights on stellar structure and evolution resulting from current "Space Photometry Revolution" (CoROT, Kepler and K2) and the use of ASTEROSEISMOLOGY inferences**
  - To directly obtain more precise Mass (~ 4%) & Radius (~ 2%) from global seismic parameters and Age (~ 12%) from constrained models
  - Brightest stars ($m_V < 6$) not included (yet ! !)



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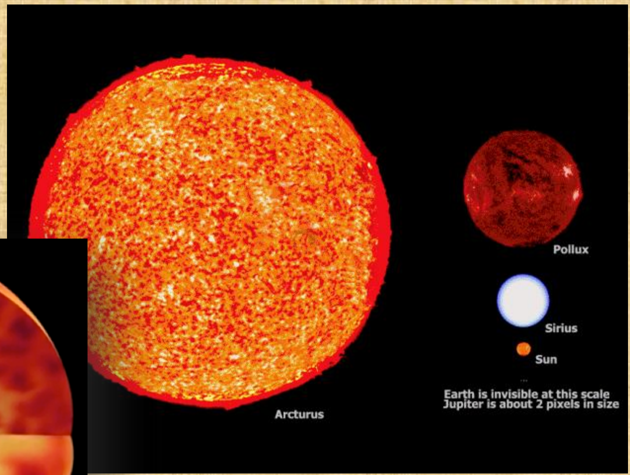
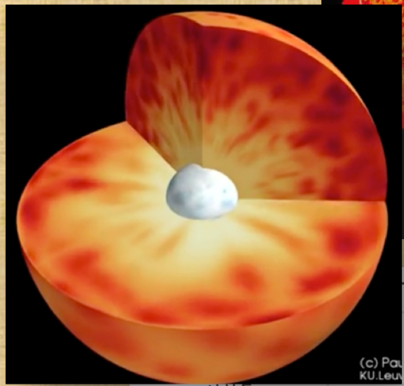
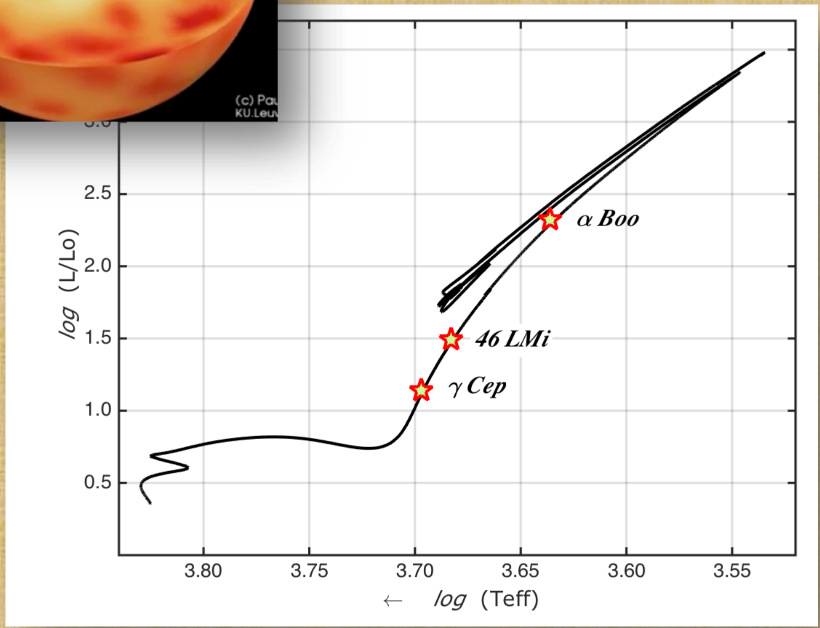
- **Take advantage of new insights on stellar structure and evolution resulting from current "Space Photometry Revolution" (CoROT, Kepler and K2) and the use of ASTEROSEISMOLOGY inferences**
  - To directly obtain more precise Mass (~ 4%) & Radius (~ 2%) from global seismic parameters and Age (~ 12%) from constrained models
- **To confirm our early discovery** (Belmonte et al.,1990) **of the spectrum of normal modes of oscillation of Arcturus and to improve its determination**
  - Making use of a new, AR^3, precise and devoted telescopic infrastructure: The Hertzsprung SONG telescope and its high-resolution I2 echelle spectrograph

Our "protagonist"….

- **It is basically "*our future Sun*"**
- αBoo: and "evolved Reg Giant".
- Studied for more than a century (Lord, 1904)
- Part of the "Arcturus stream":
  - Not in the plane of the Milky Way. An ancient dwarf galaxy?
- V= -0.5 mag, K 2 III
- L ~170 $L_\odot$, M=1.08 ± 0.06$M_\odot$, R=25.4 ± 0.2$R_\odot$
- Teff= 4286 ± 30 K
- *log*(g) =1.66 ± 0.05
- [Fe/H]= -0.52 ± 0.04
- Age : 7.1 ± 1.4 Gy
- Vrot ~2.4 Km/s
- Interferometry: well resolved
- Hipparcos reanalysed Catalogue:
  - Flagged as "unreliable"
- Stellar standard:
  - IR spectroscopic/Photometric and IAU-RV standard
- Binary/multiple system?







Reference Observations..

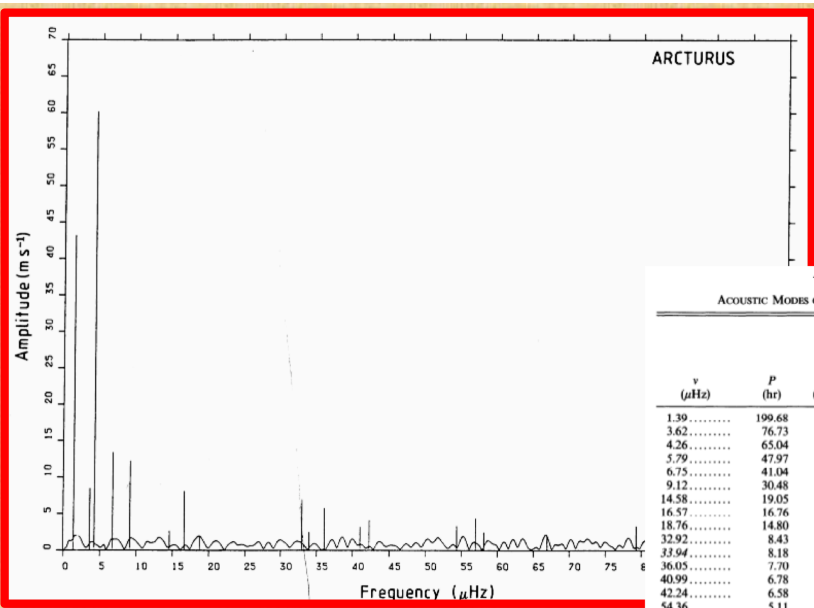
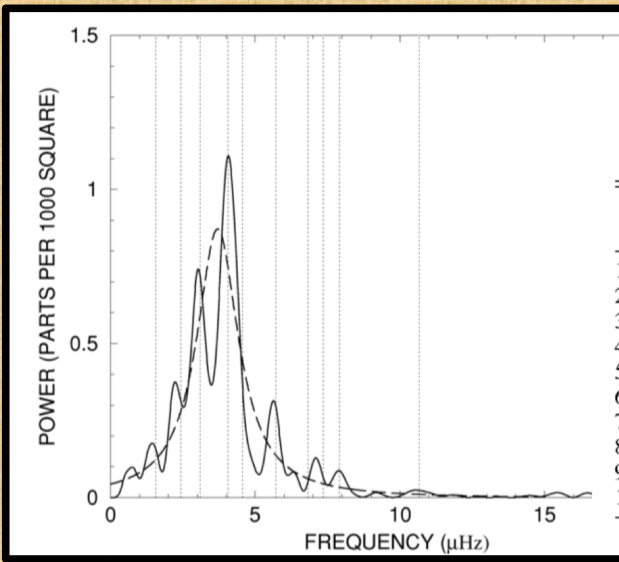


TABLE 4

ACOUSTIC MODES OF OSCILLATION OF α BOOTIS

ν (μHz)	P (hr)	A (ms^{-1})	$\Delta\nu_0$ 2.3 ± 0.2 μHz n	l	5.0 ± 0.3 μHz n	l
1.39	199.68	43.20	0	0	0	0
3.62	76.73	8.56	0	1	...	...
4.26	65.04	60.24	1	1	0	1
5.79	47.97	3.09	2	0	...	...
6.75	41.04	13.47	2	1	1	0
9.12	30.48	12.32	3	1	1	1
14.58	19.05	2.72	5	1	2	1
16.57	16.76	8.18	6	1	3	0
18.76	14.80	2.04	7	1	3	1
32.92	8.43	7.05	13	1	7	0
33.94	8.18	2.54	14	0	...	...
36.05	7.70	5.79	15	0	7	1
40.99	6.78	3.27	17	1	8	1
42.24	6.58	4.21	18	0	9	0
54.36	5.11	3.41	23	1	11	0
56.94	4.87	4.45	24	1	11	1
58.10	4.78	2.49	25	0	...	...
[illegible]	4.15	2.18	28	1	13	1
[illegible]	3.50	3.37	33	1	16	0

Belmonte et al., 1990.
Stellar MOF (Δv) at WHT 1988.
10 consecutive full nights (1/ T ~ 1 μHz)
Individual ℓ=0,1 eigenmodes
Max Amplitude Amplitude ~ 60 m/s
ν_max ~ 4.3 μHz (~2.7 days)
Δν= 2.3 μHz or 5.0 μHz
Intrinsic large variation ~ 200 m/s



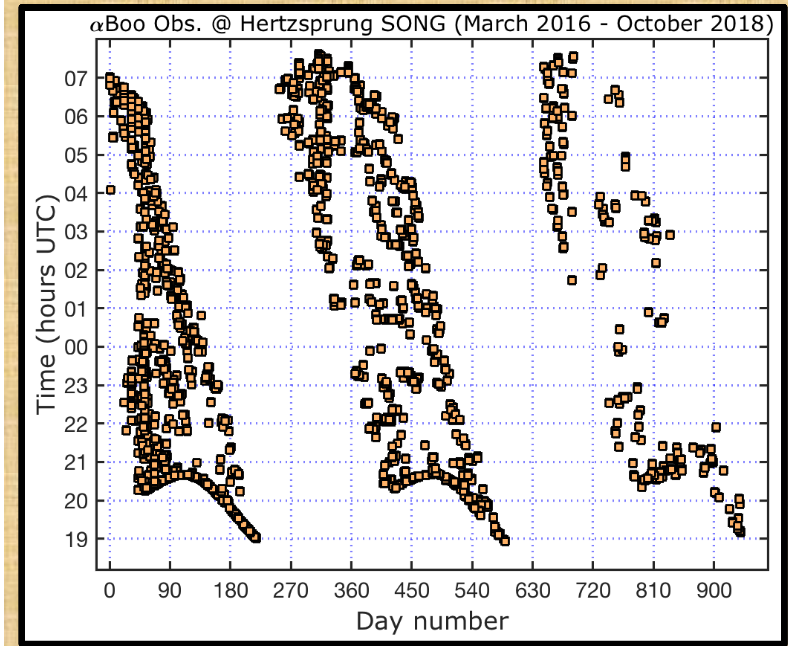
THE HIGHEST PEAKS IN THE AMPLITUDE SPECTRUM

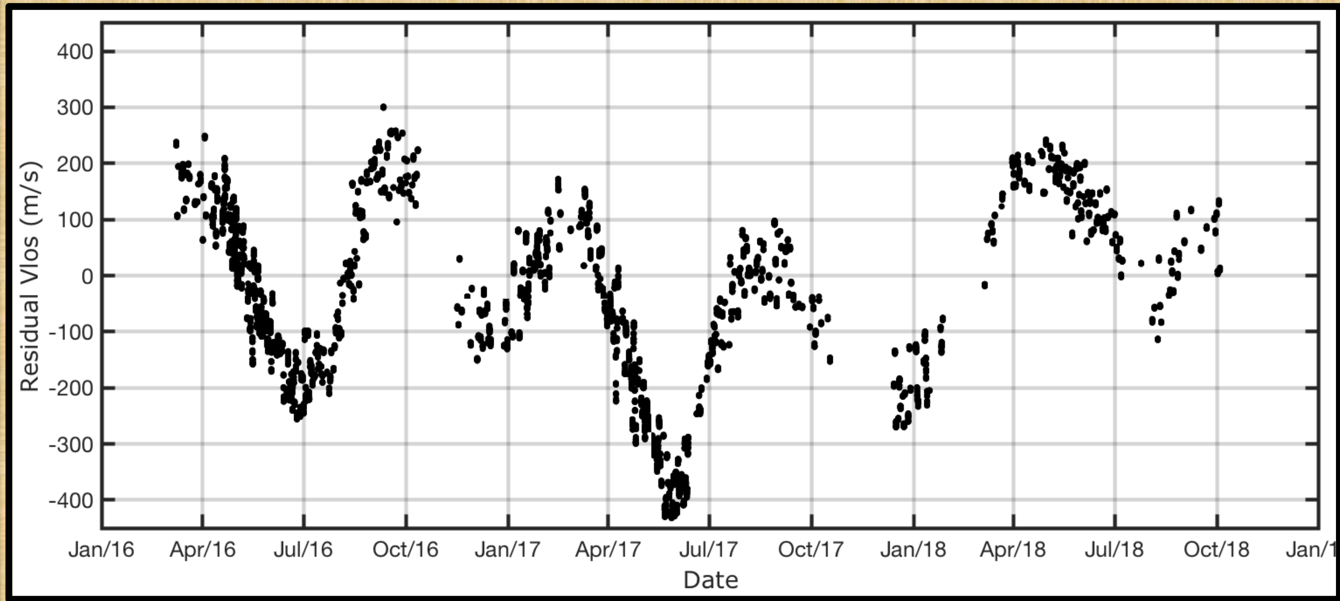
Peak	Frequency (μHz)	Semiamplitude (ppt)
1	4.07	1.39
2	3.09	0.98
3	2.44	0.78
4	5.71	0.56
5	1.56	0.47
6	4.57	0.36
7	7.91	0.31
8	7.35	0.26
9	10.66	0.20
10	6.81	0.14

Deuter et al, 2003
Space photometry (ΔI) with WIRE StarTracker
19 continuous days in 2000 (1/ T ~ 0.6 μHz
Individual modes ℓ=0 eigenmodes
Max Amplitude ~ 10^{-3} ppm
ν_max ~ 4.1 μHz
Δν= 0.82 μHz

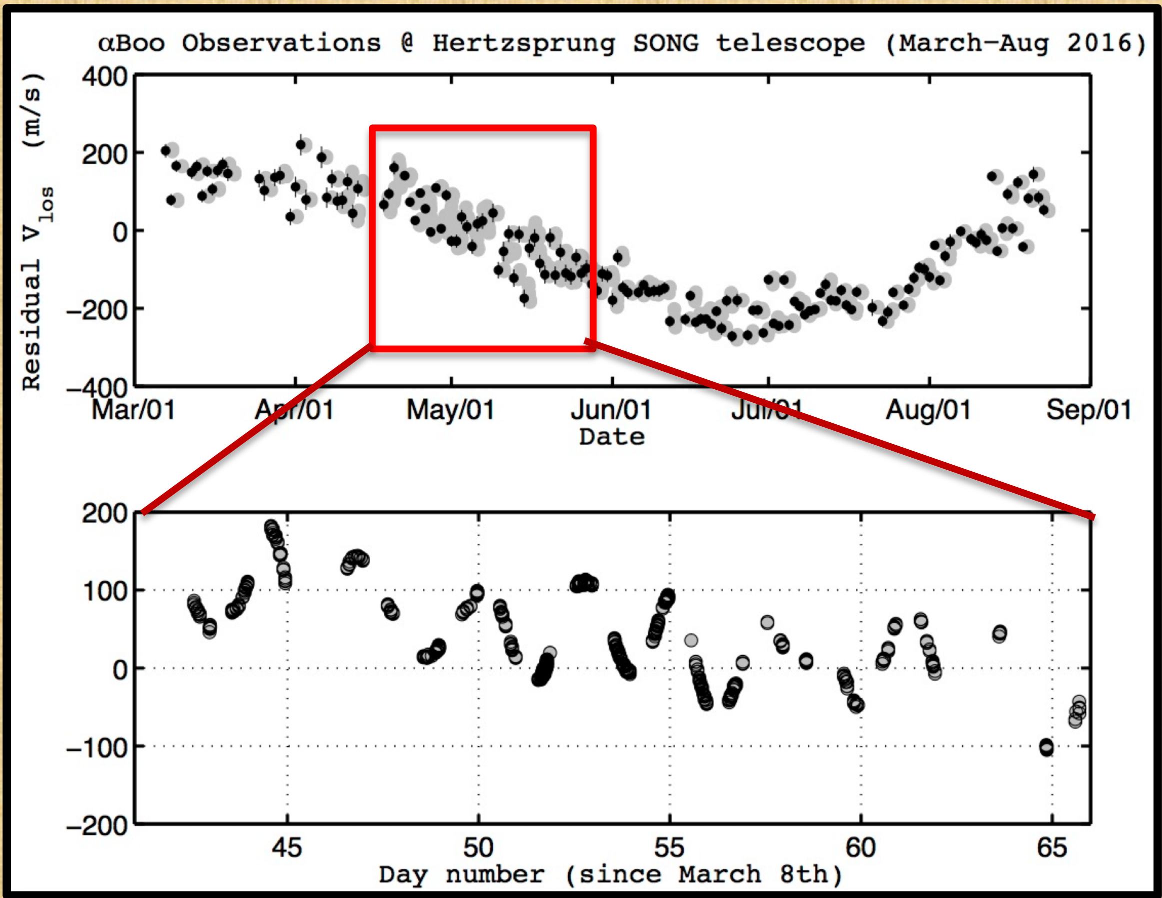
Arcturus Observations with Hertzsprung SONG @ Obs. Teide

- Almost circumpolar from OT (10.7 months/year with altitude >12 deg)
- Nightly observed (few "visits" /night) from **March 2016- October 2018**
- A total of 9613 spectra on 524 days (out of 940.. 56%)
- Extracted RV using I2 technique [Butler(1996), Grundahl et al., 2017)].
- Mean uncertainty per point (20 s) of about 2.1 m/s
- By-side products: equally space time series (30-min/1-6 h) and mean daily RVs





Results for the first analysed subset (160 days)....

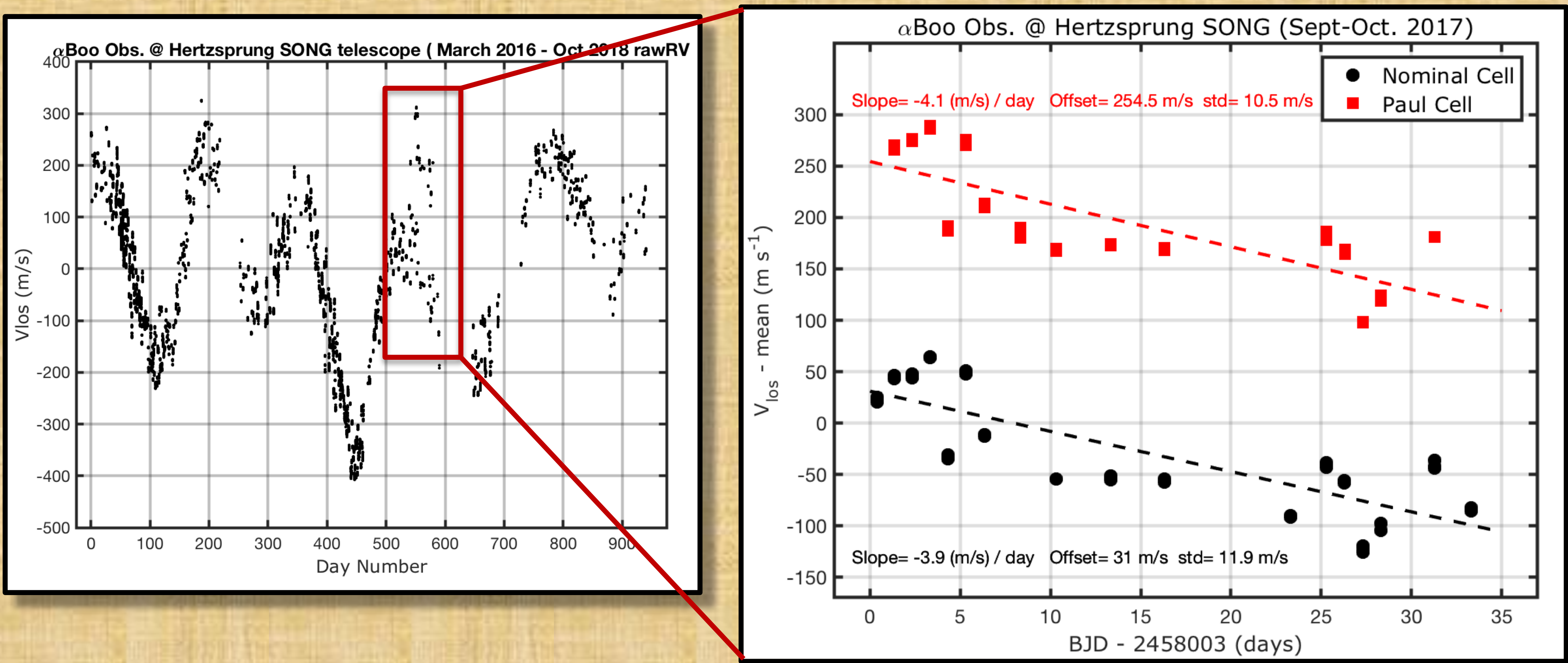


- Oscillatory signal (2.2 days) nicely seen !!!!
- The "never observed before" smooth long period variation:
  - Barycentric correction
  - Effect of the I2 Cell
  - Pipeline effect
  - Instrumental - Atmospheric

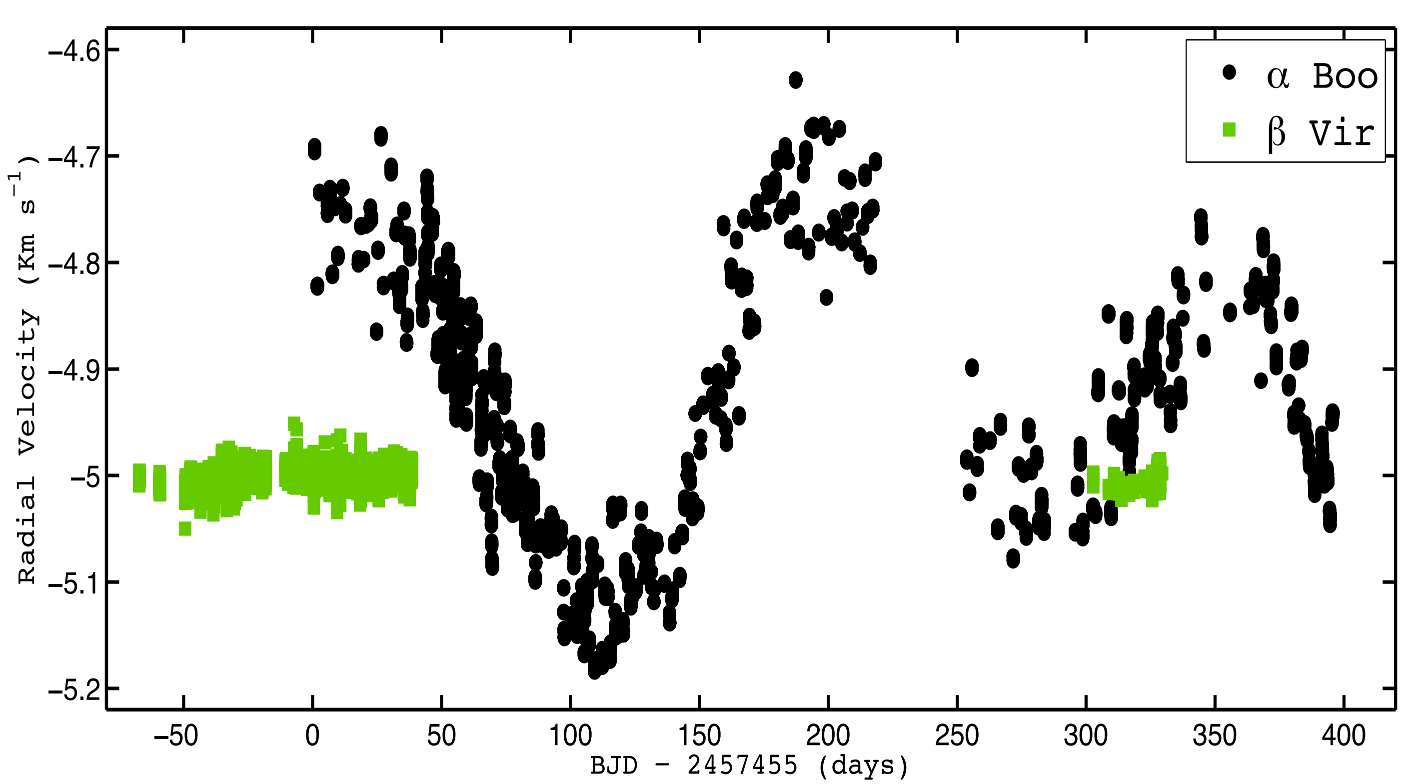
Alternatively::

- Signature of a companion ??
- Rotationally modulated magnetic activity signal ???

A possible I2 cell effect….



Discarding a non-stellar origin…

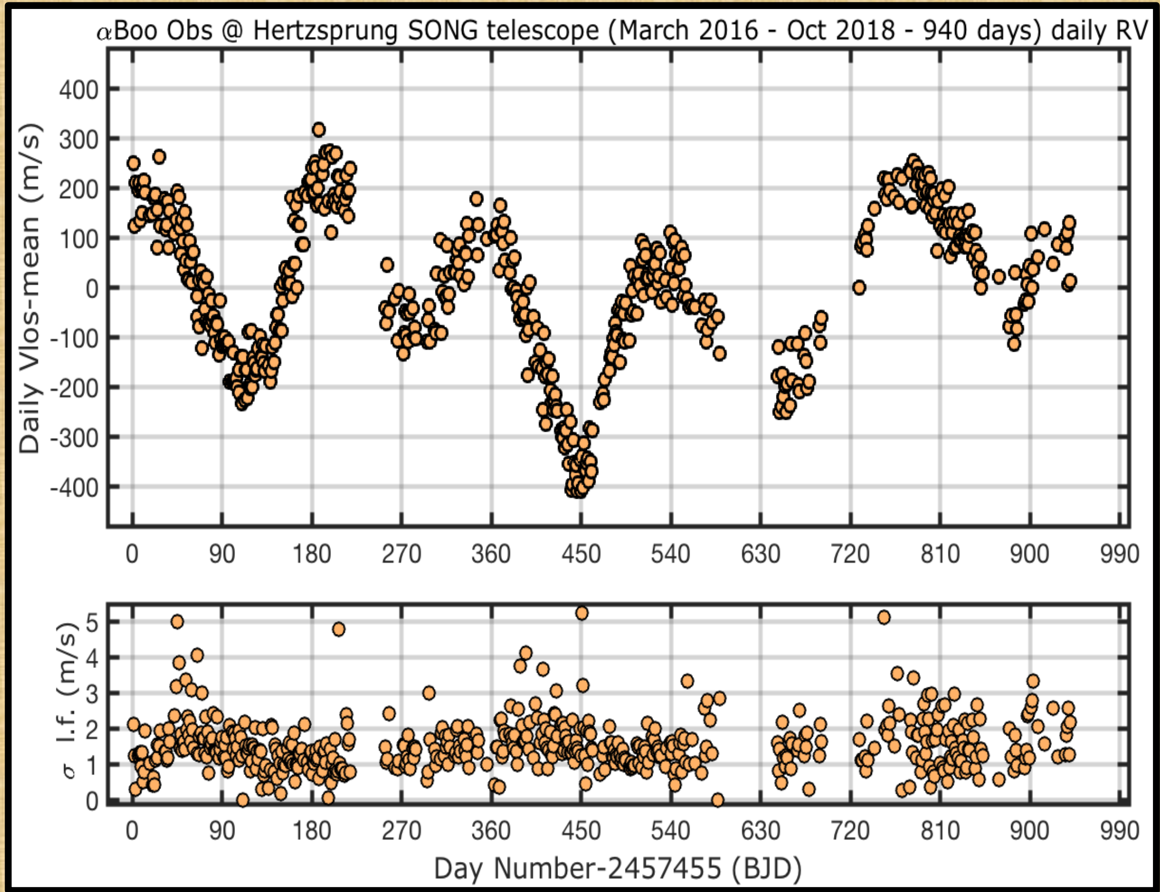


- Alternative codes: Debra Fisher, Paul Butler. OK
- Verifying calculation Barycentric correction OK

And….

- Simultaneous observations of βVir:
  - same sky, instrument and pipeline. OK

Stellar origin...



- Gray & Brown(2006): spectroscopic data span of 23 years found a ~ 2-year modulation of **~ 10 m/s**
  - Shorter periods due to multiple active longitudes modulation (3 ??)
- Hatzes & Cochran(1993): spectroscopic 4.5 years data found a 213-day periodicity with **~ 500 m/s amplitude**.

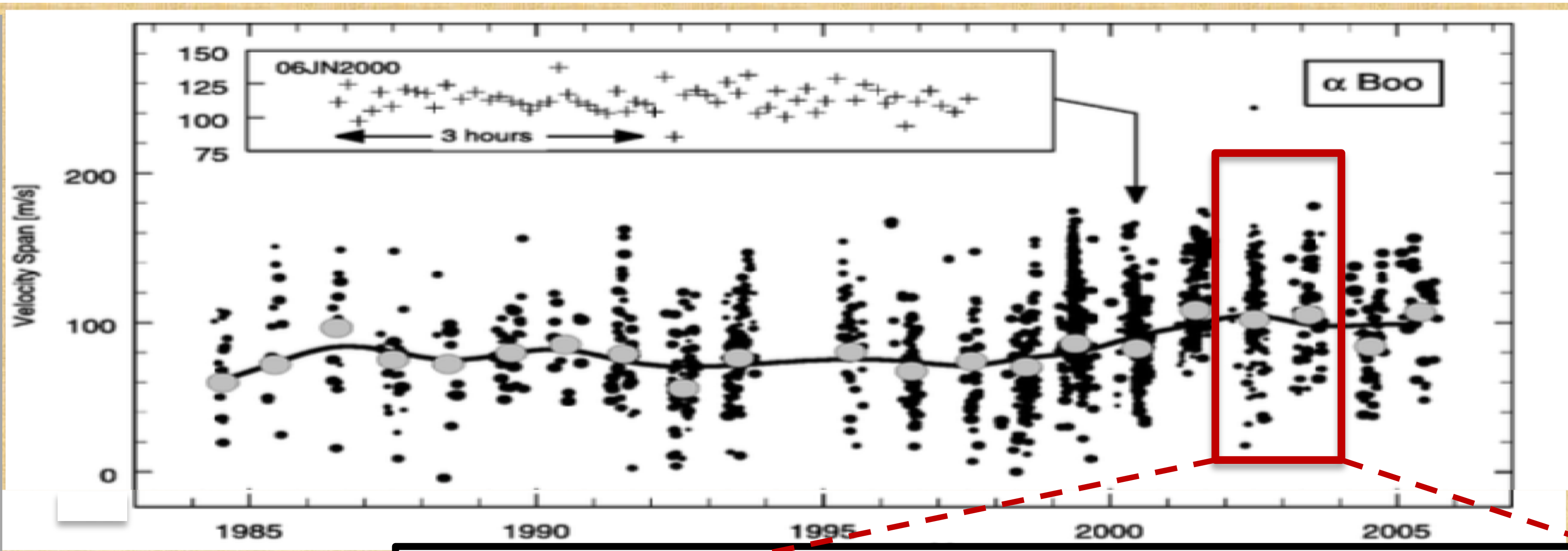
- **Our signal:**
- ~ 176-day periodicity with 185-200 m/s amplitude
- ~~Negative slope of ~ 100 (m/s) / year~~

Possible causes of these large (huge) discrepancies:

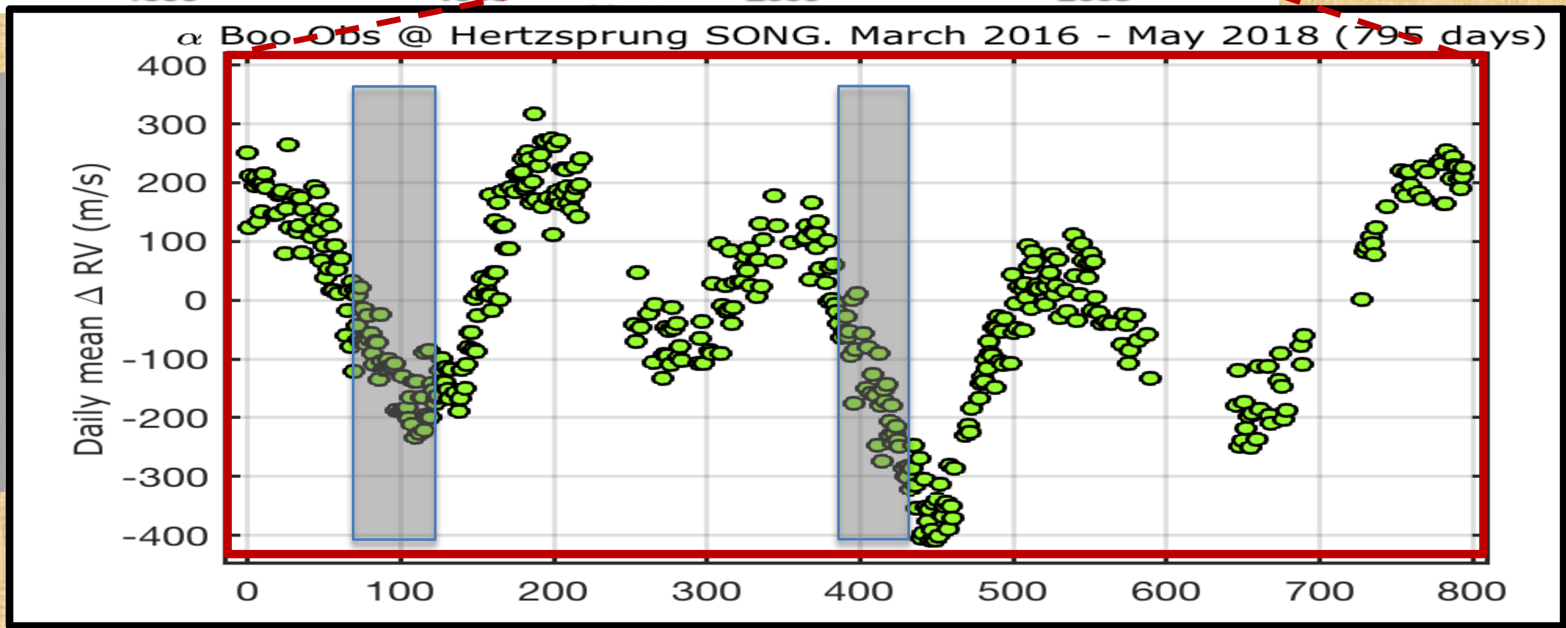
1. Sampling & selection effect ?
2. A long period (> 20-year) stellar magnetic cycle ?
3. ....

Eigenfield Obs. Canada

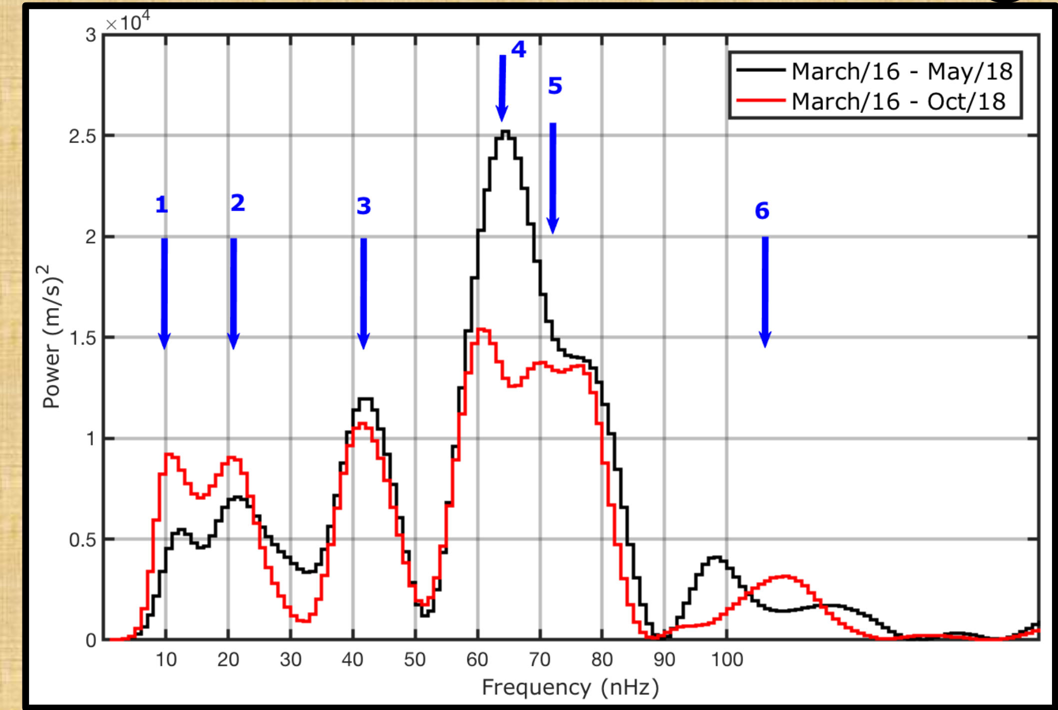
Gray & Brown, 2006



SONG. Obs Teide



Stellar magnetic related….



- Multiperiodic signal
- Similarities with the well know Solar Activity signals:
  - Rotationally modulated magnetic signal of 13-day (sunspots , *plages*, ….)
  - Active longitudes?

Series#13: 794 days 1/T=14.6 nHz

	freq (nHz)	T (days)	width T (+/-)	Amp (m/s)
#1	12.4			
#2	21.6			
#3	41.8	277	48	109
#4	64.9	178	20	158
#5	76.2	152	15	118
#6	98.6	117	8	63

Series #14 940 days 1/T= 12.3 nHz

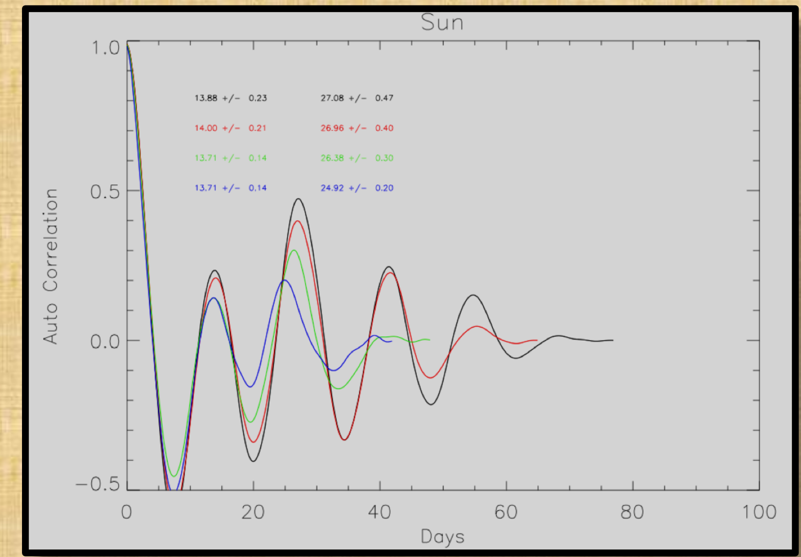
	freq (nHz)	T (days)	width T (+/-)	Amp (m/s)
#1	11.1			
#2	20.3			
#3	41.5	279	42	103
#4	61.1	190	19	124
#5	73.5	158	13	117
#6	109.5	106	6	55

The quasi-periodic features induced by stellar magnetic features are extremely relevant in the context of exoplanet detection and their characterization

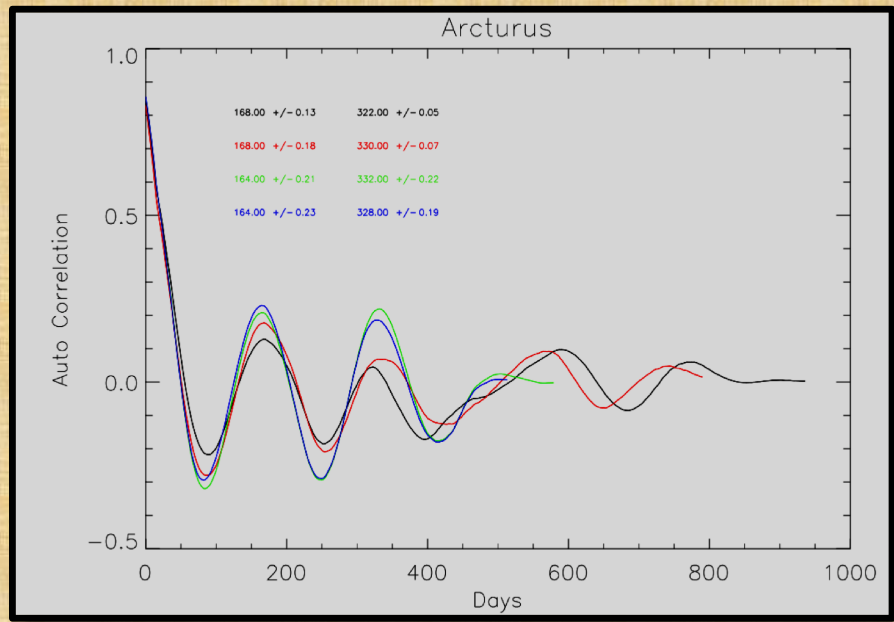
[P_{rot} - P_{mod}]..trying to disentangle

McQuillan et al. (2013): Improved technique (ACF) to distinguish between modulation and rotation signals.

- Behaviour of highest peaks of the ACF as a function of data length: the associated rotation signal enhanced against its harmonic.
- Well proven also with the Sun (22-years data from GOLF/SoHO): highest AC peak for 27d (rotation) than for 13d (transit time of activity features)

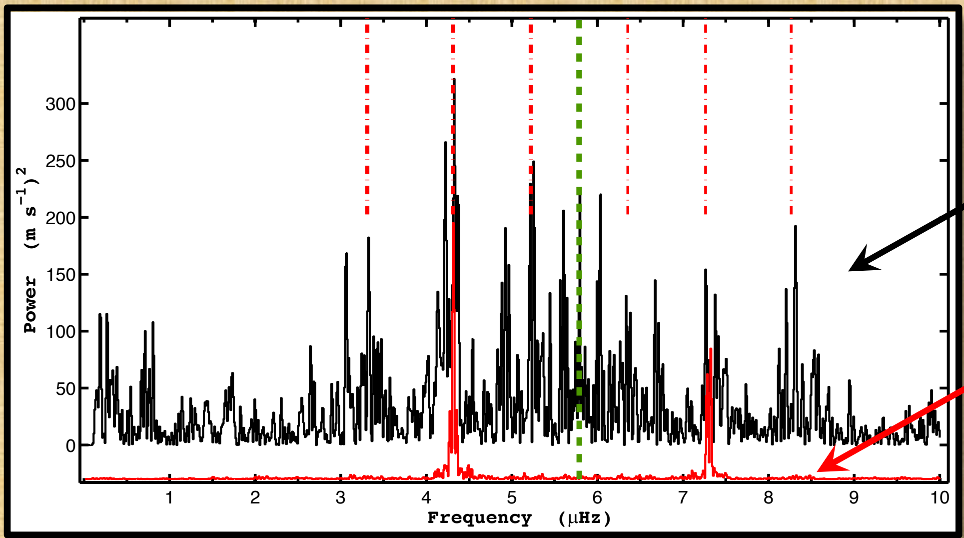


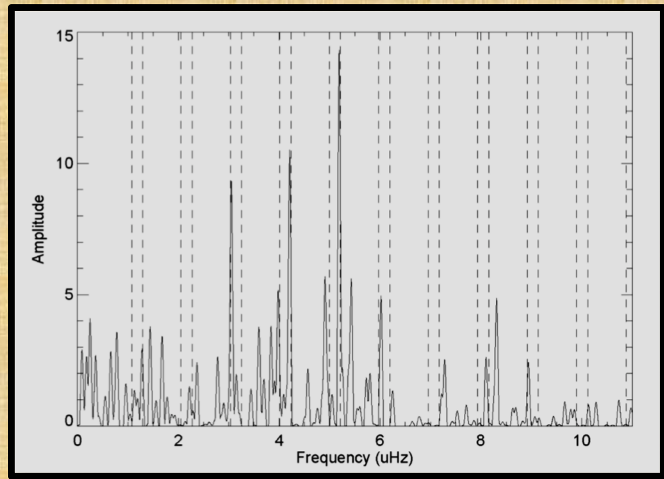
Not conclusive..

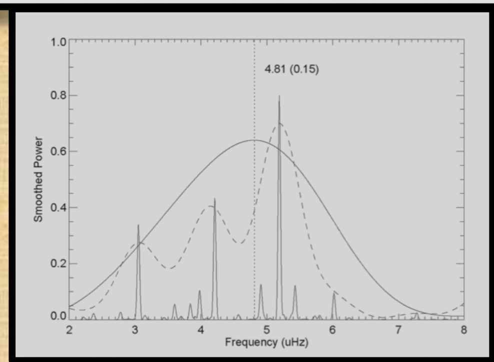


The spectrum of the oscillation modes....

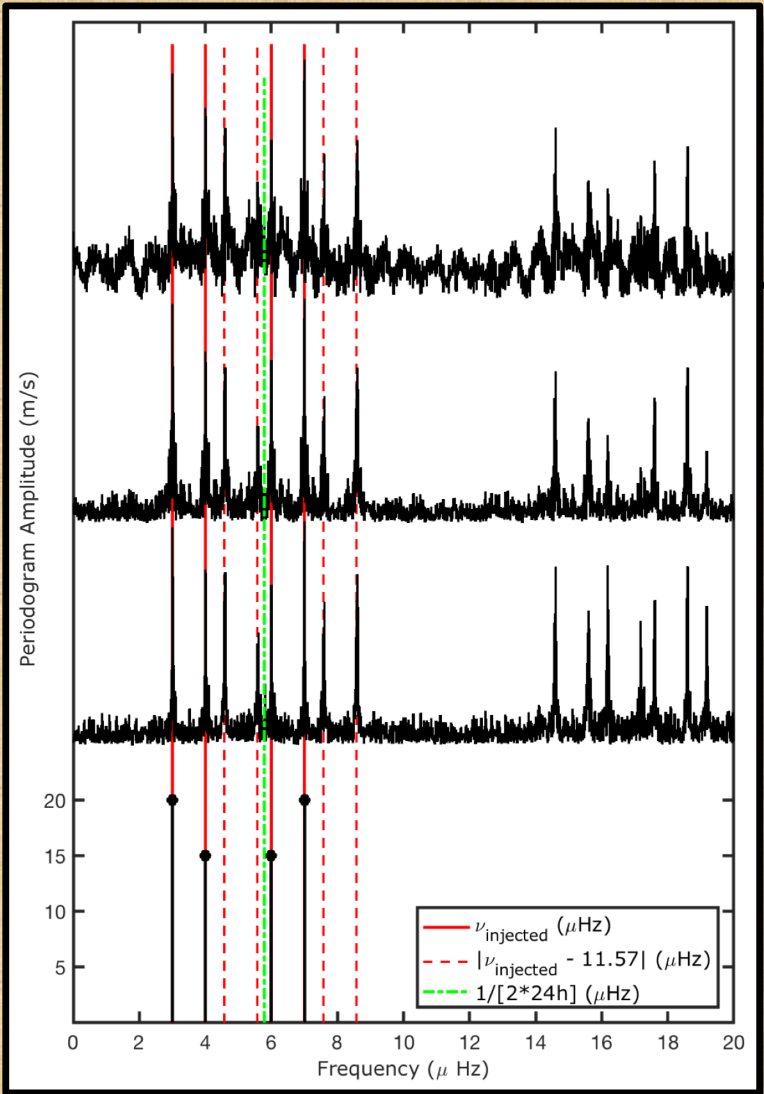
- Unlike the rich spectrum of modes for the solar case, for this evolved RG, just a few overtones (n) of low-degree modes ($\ell < 3$) are expected
- Large oscillatory signal (~15 m/s per single mode) but low duty cycle (large spurious side-lobes







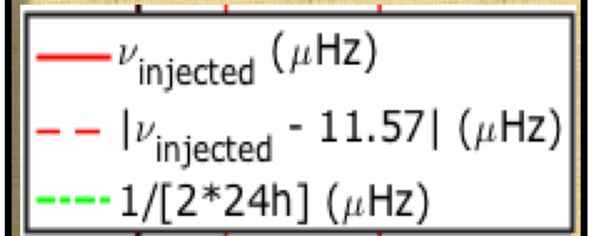
- Extensive processes/techniques to reconstruct the spectrum (correct for SW) and to determine the two global parameters: ($\Delta\nu$, ν_{max})

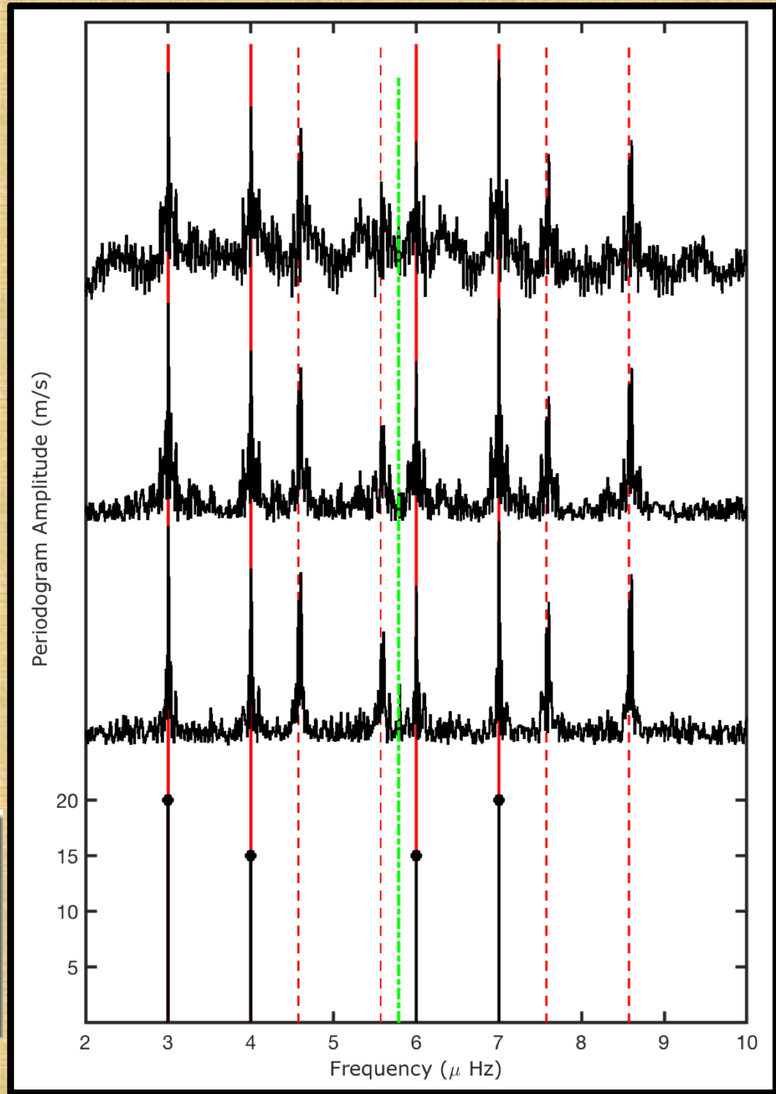


Original

Unif. Grid 30m

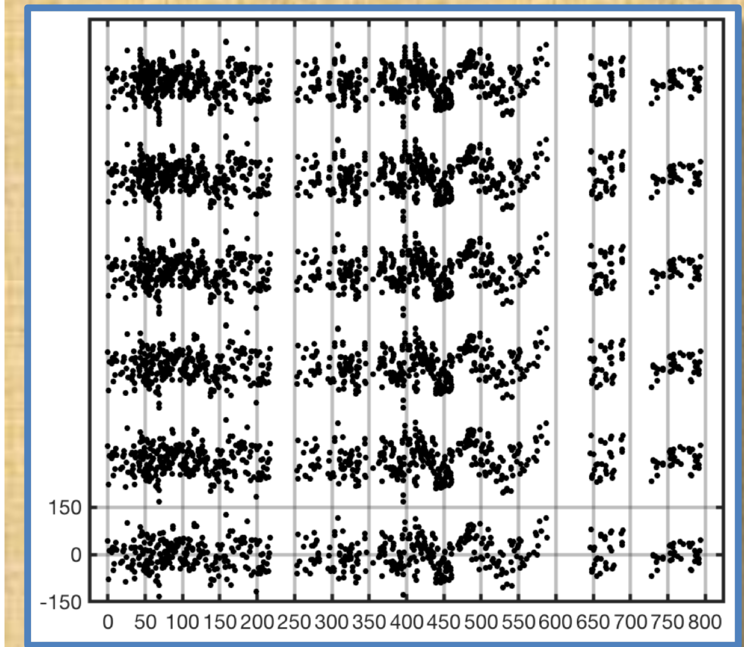
Daily RV

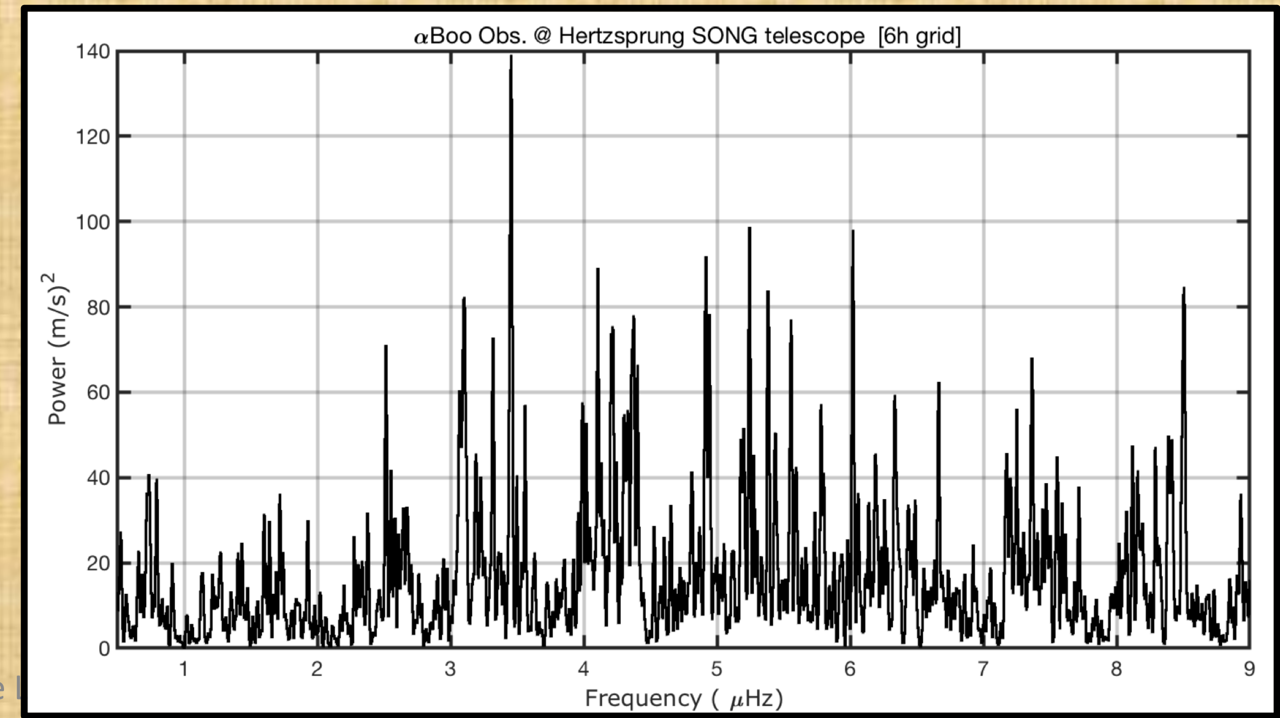




The eigenmodes spectrum….

- Despite the high precision of individual data samples (RV) and large oscillatory signal (~15 m/s per single mode) the spectrum is rather complex because:
  - Poor duty cycle
  - Frequency range of eigenmodes expected to be BELOW 11.57 μHz (1-day) and -even worst- CLOSE to 1/2 (11.57 μHz). Additional "sidelobes" IN the oscillations frequency range
  - Temporal data distribution (density) biased.
  - Additional effects coupling e Spec Window





Summarizing....

- The ***AR³*** SONG concept WORKS ! ! !
- Excellent sensitivity to velocity fluctuations induced by normal oscillation modes, BUT....
  - Need to minimize daily aliases: MORE NODES REQUIRED ! !
- **The brightest star in the Northern hemisphere is not as well known as thought ......**
  - Its character (single/multiple), magnetic activity, precise location on the H-R diagram, ...
- A complete seismic & physical characterization of αBoo well on-track but more extensive work required
- Seismology of Bright Stars, Exoplanets and other time domain programs on-going with SONG
- A unique opportunity for contemporary coordinated observations with TESS (Intensity & Radial Velocity) and will largely benefit from GAIA outcome