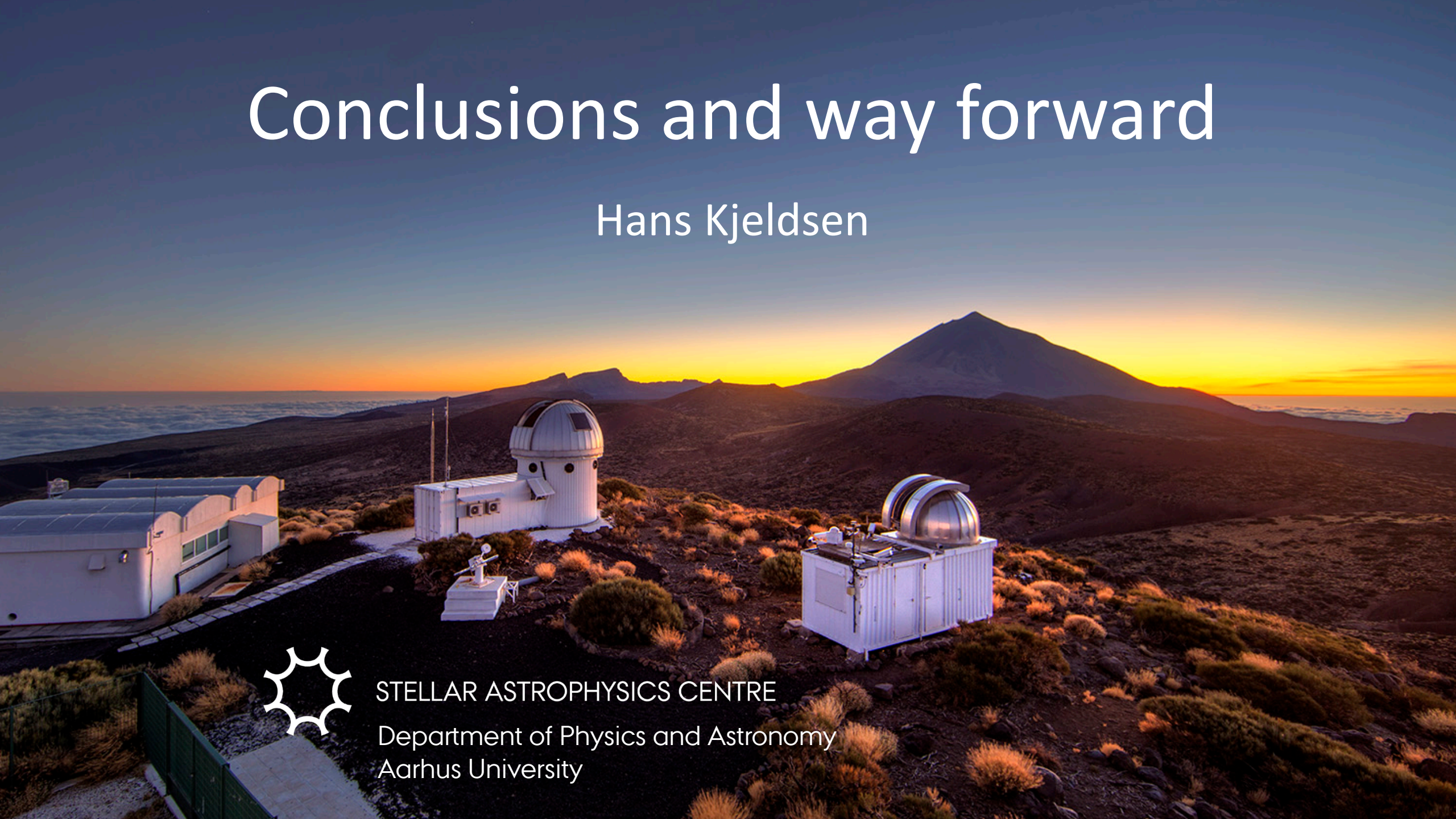
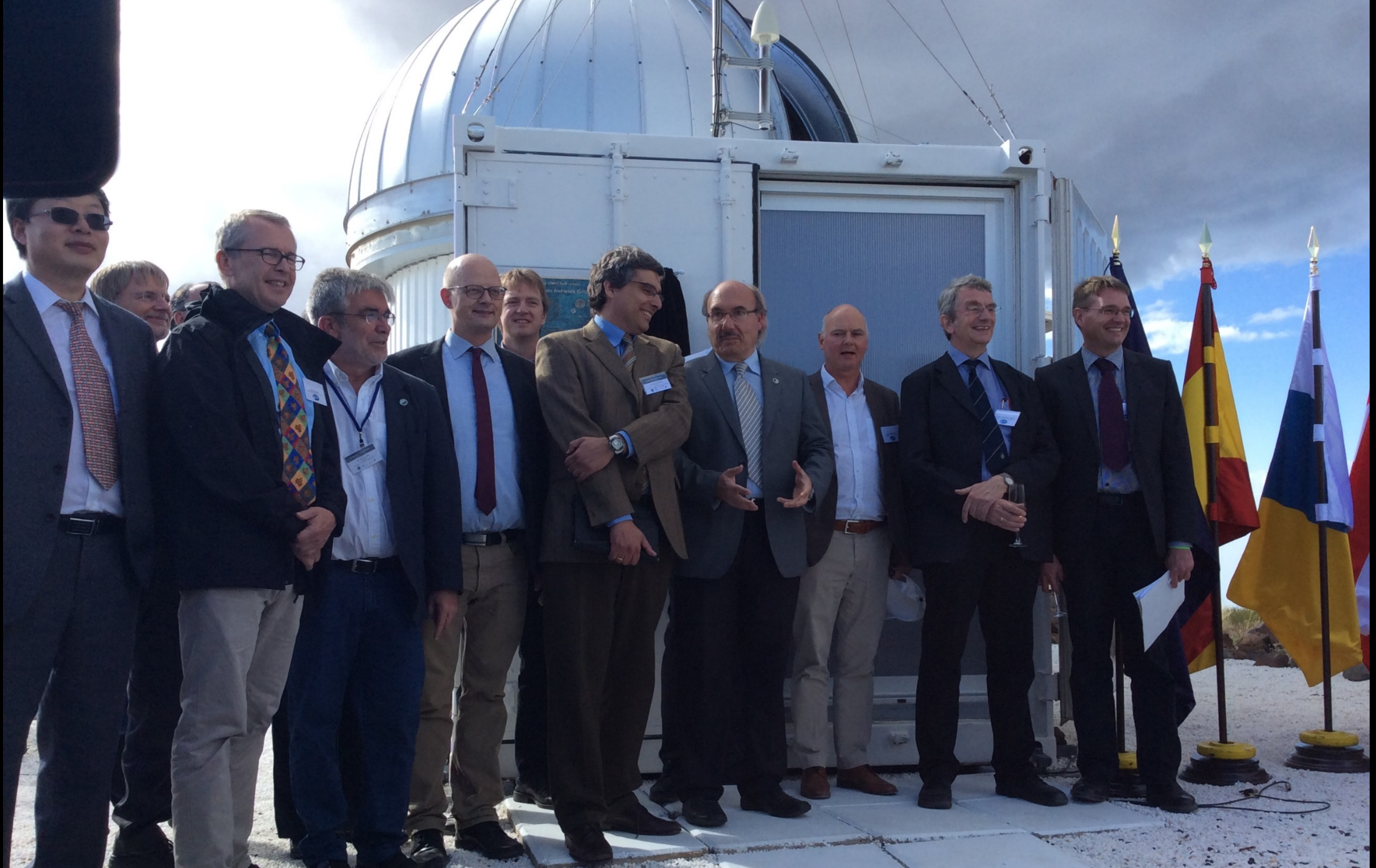
Conclusions and way forward

Hans Kjeldsen

STELLAR ASTROPHYSICS CENTRE
Department of Physics and Astronomy
Aarhus University



25 October 2014

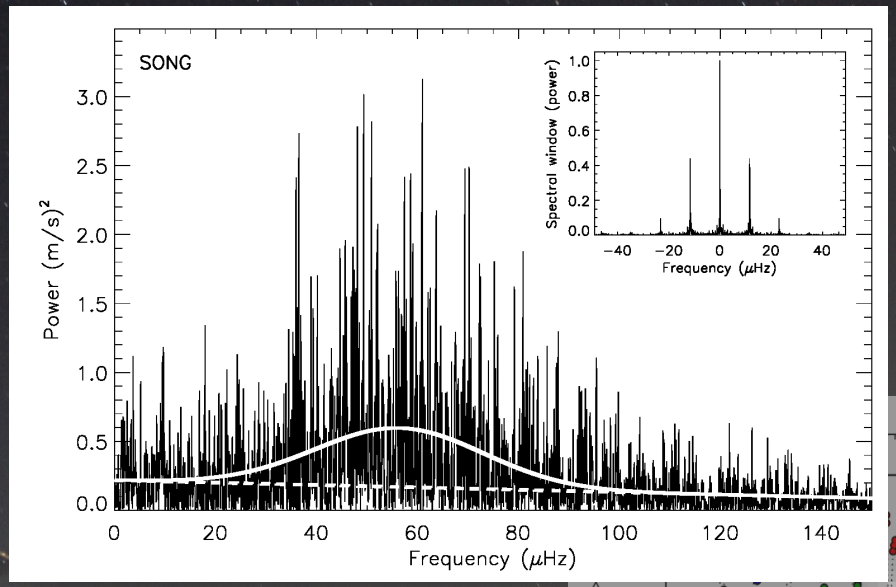


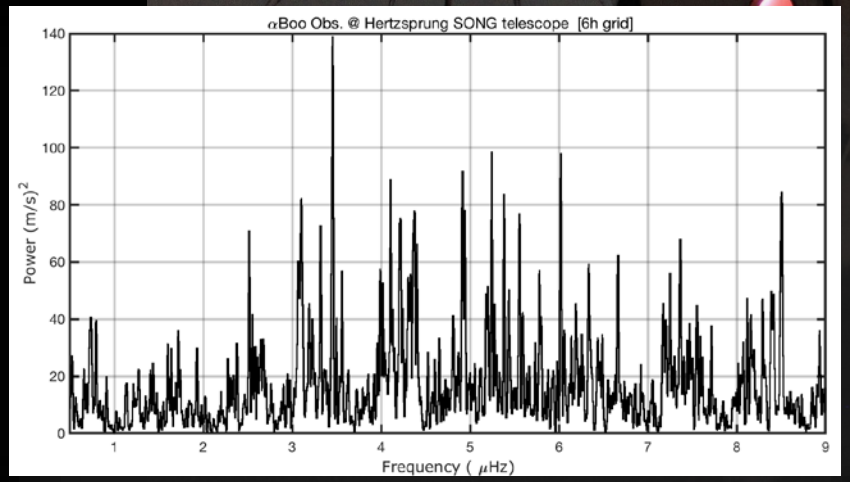
25 October 2014

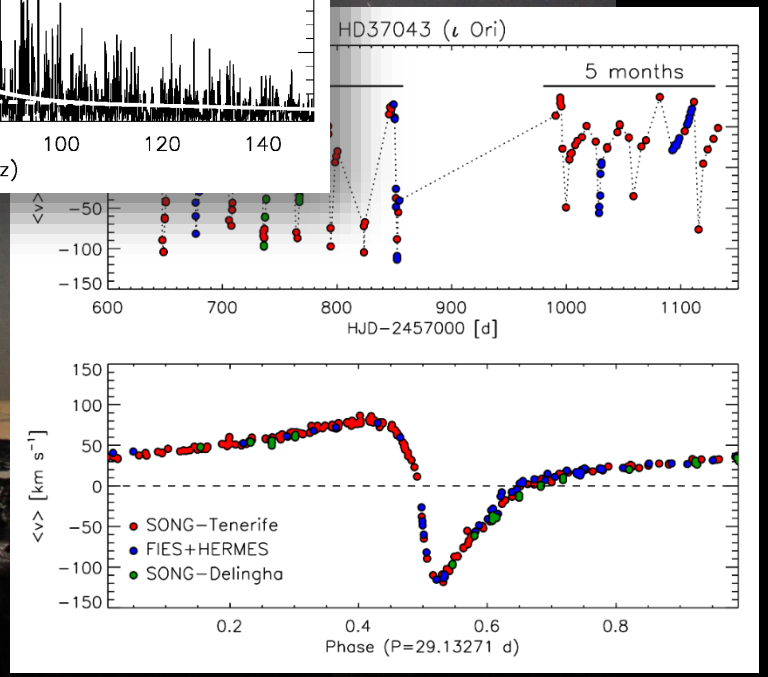
25 October 2014

SONG is fantastic facility for research

SONG is fantastic facility for research

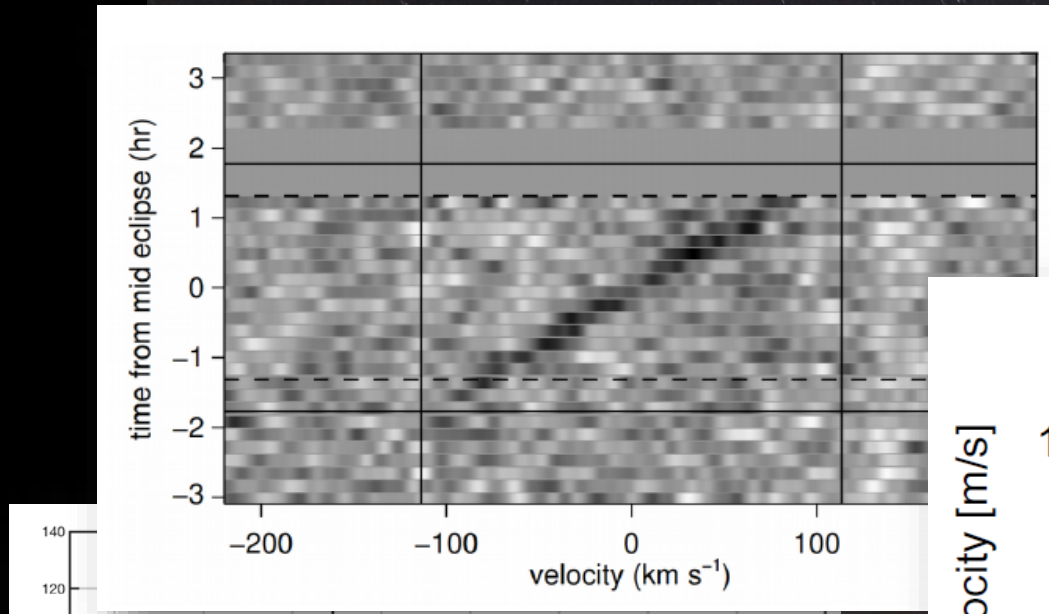


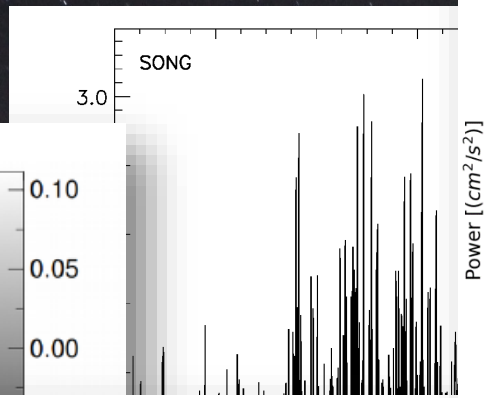


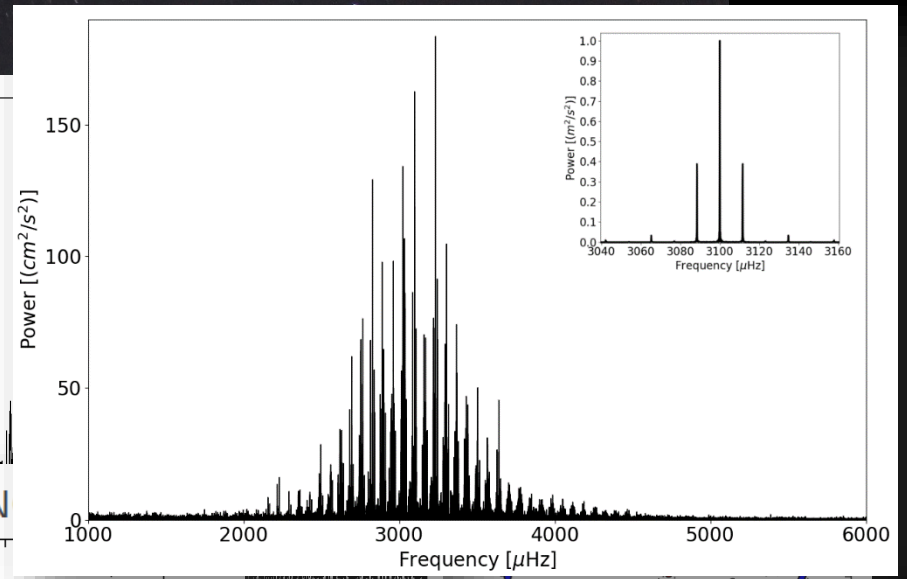


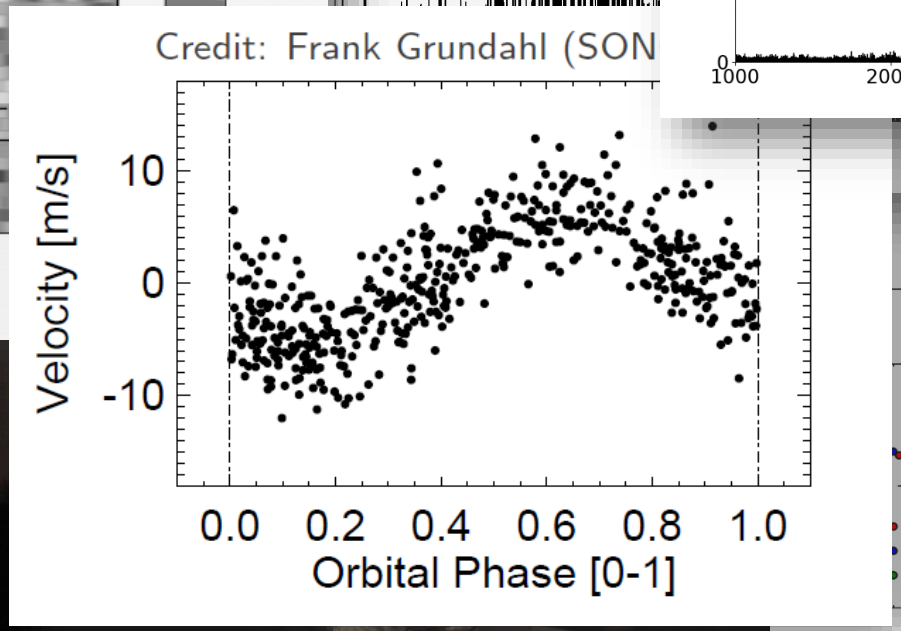
Credit: Mads Fredslund Andersen

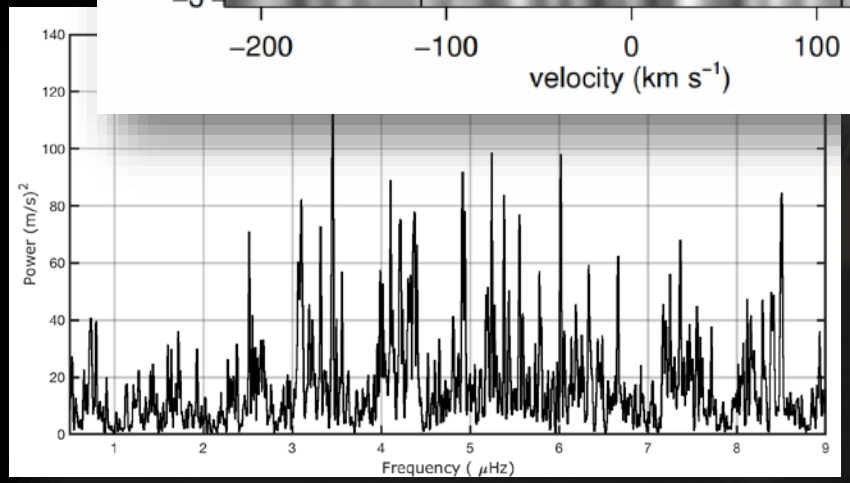
SONG is fantastic facility for research

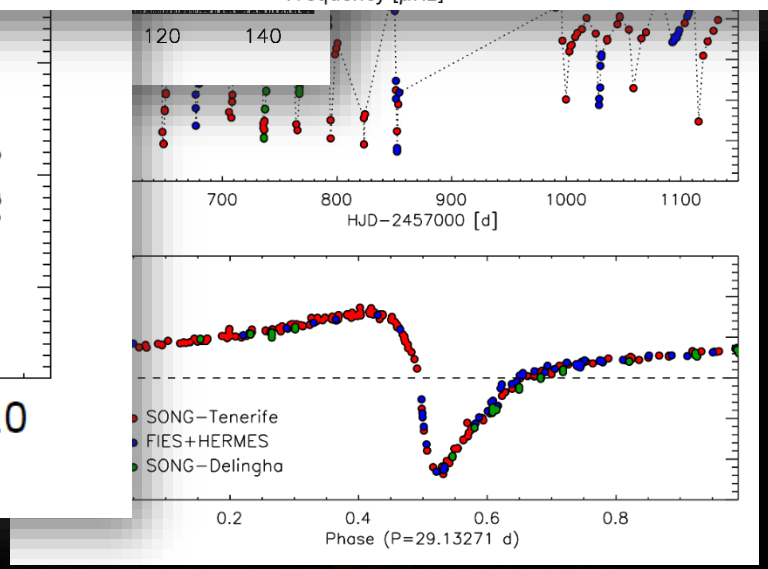












Credit: Mads Fredslund Andersen

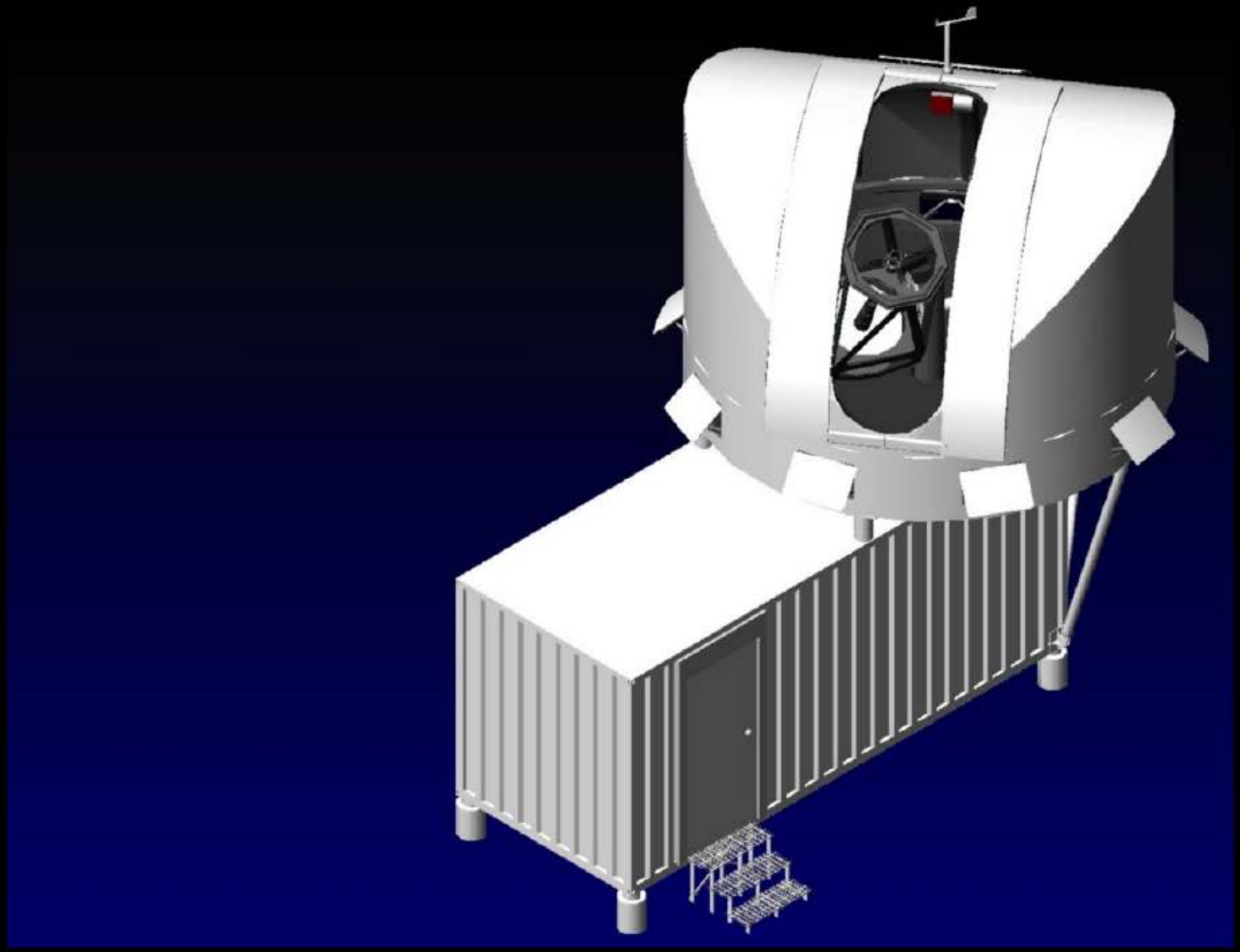
SONG hardware

SONG hardware

- Time domain astronomy
- PI experiment that is seen as “one instrument”
- Main instrument is a spectrograph
- Optimized for Iodine (I_2) and low-cost solutions
- Robotic and a limited staff

Early concept (December 2005)

An early sketch for the design

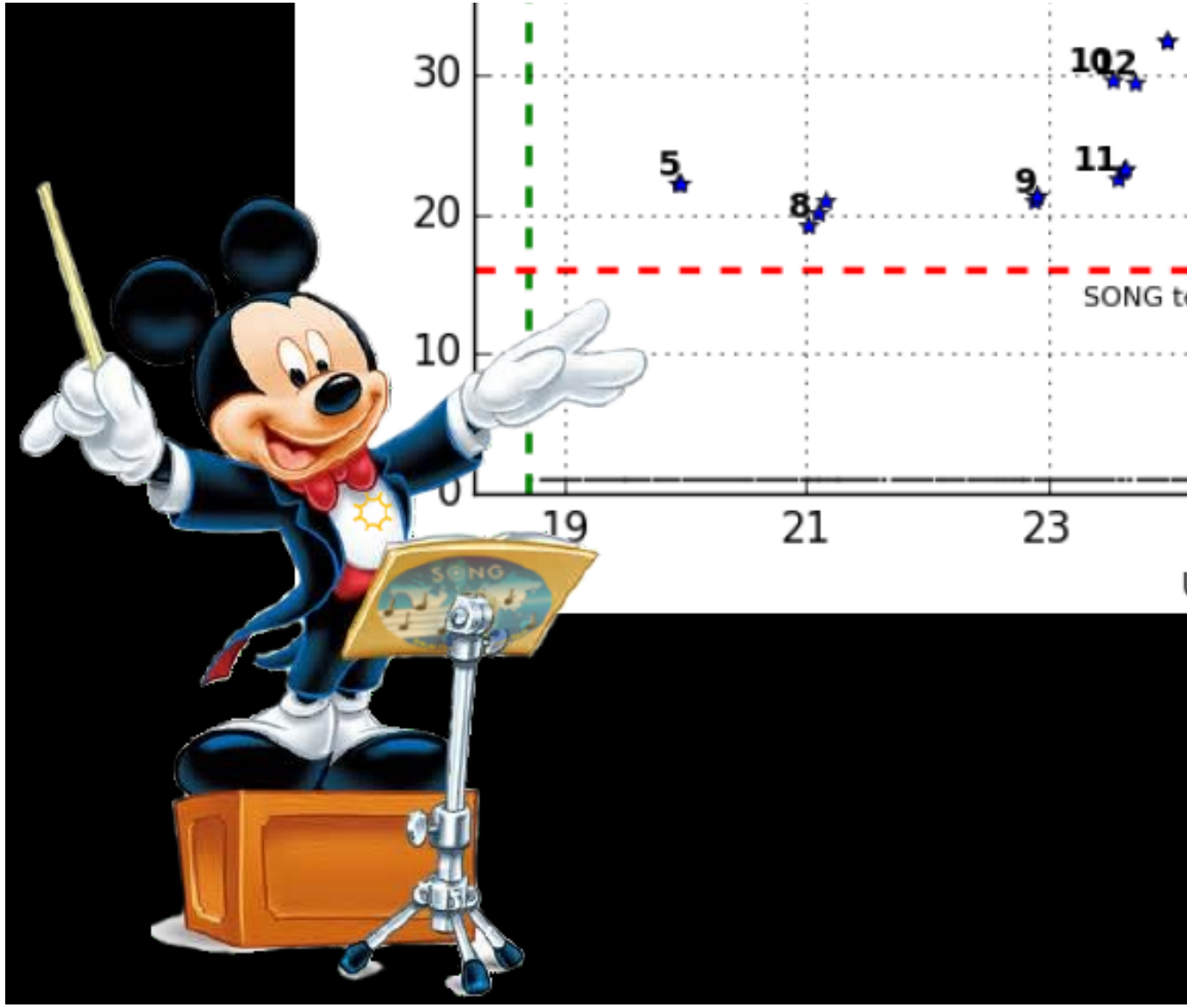


SONG is unique

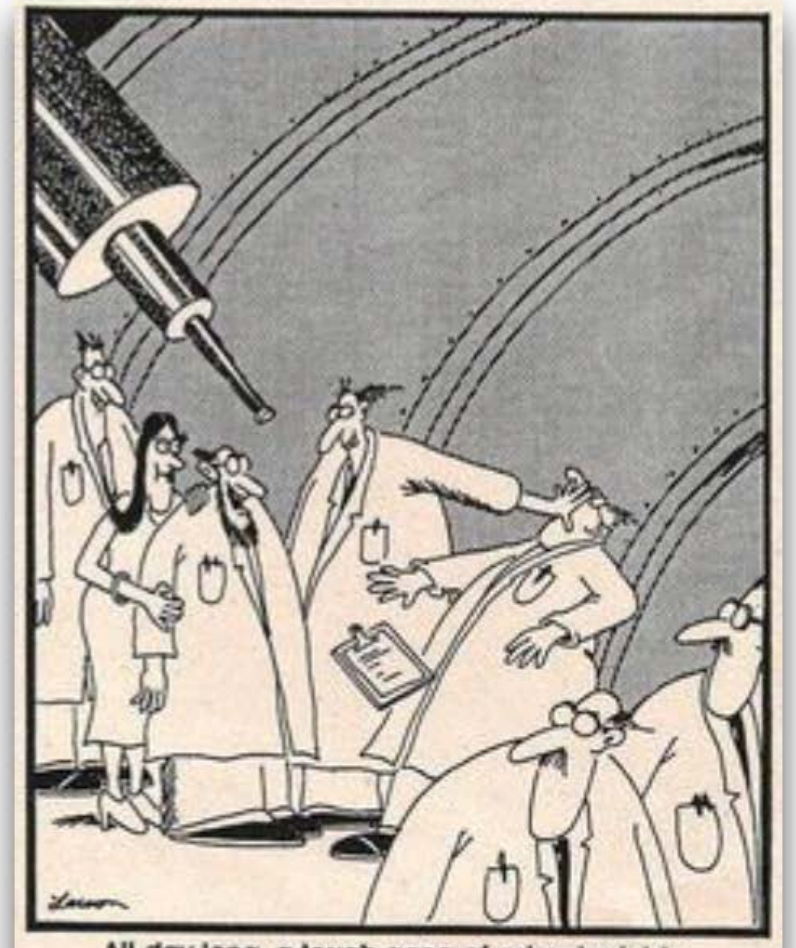
- It works very well! … with a very high duty cycle
- Robotic facility – key scheduling/flexible scheduling – using internal science priorities
- Fast Track activities - ToO
- Pipeline – Iodine (I_2 velocities)
- We can take scientific risks and do additional experiments (e.g. like the solar-SONG)

SONG operations

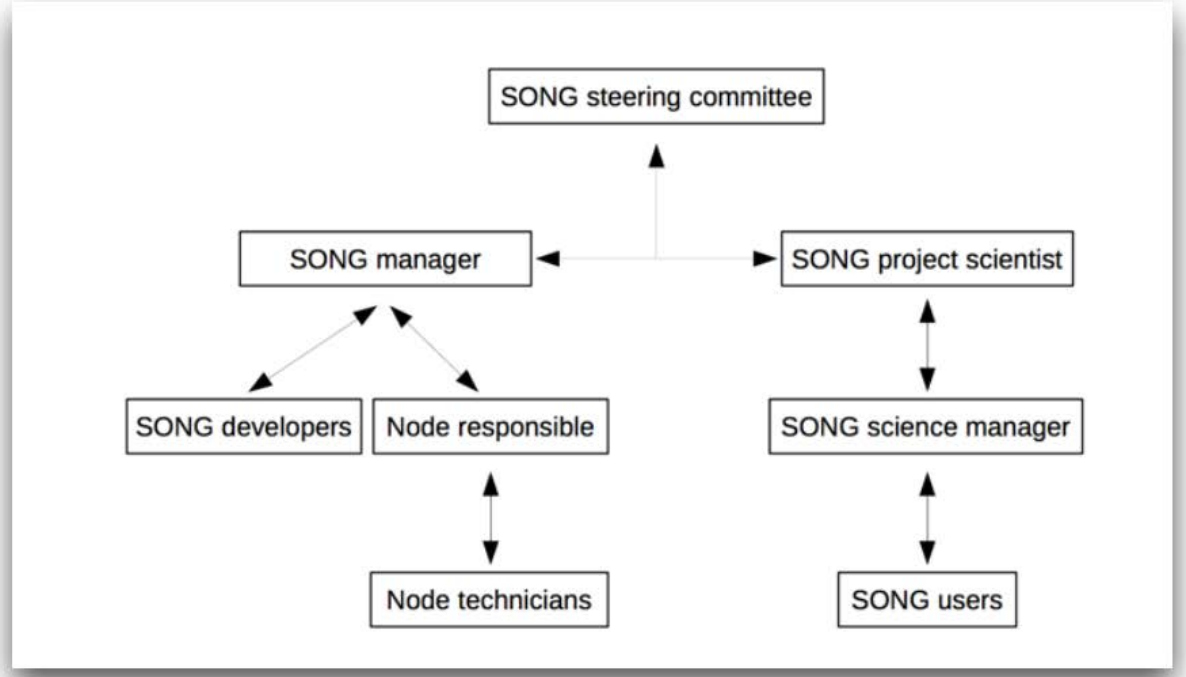
- Policies
- Conductor
- SODA



Why do we need policies?



Network Structure



Nau. Twilight begins

Observations plot for the night: 2017-11-12

Nau. Twilight ends

Altitude

UTC Hours

SONG telescope lower limit

Moon

Used time

Lenght of night:
12:19:12

Integration time:
09:37:04

Read out time:
00:05:00

Targets:

1: HIP 116727
2: HD 190603
3: HD 207198
4: HD 2905
5: HD 30614
6: HD 188015
7: HD 191201
8: 77 Tau
9: HD 37128
10: HD 203030
11: HD 38771
12: HD 37041
13: HD 17505
14: HD 10780
15: HD 37022
16: HD 54662
17: HD 109358
18: HD 33564
19: VV Ori
20: HIP 38253
21: HD 137759
22: VV CrV
23: HIP 31592
24: HIP 36616

soda.phys.au.dk

SONG Data Search

Object

Object name: mu Her

Projects

Stellar properties

Temporal constraints

Data types

Instrument

Telescope:

Site:

SONG Spectrograph:

Iodine: Iodine cell2

Slit:

Files

Search

Deselect all

Choose table columns

Show Query

		File name	Data Type	File size	Object name	Obs. Start	V Mag	Project
☑		s1_2017-08-30T21-15-20_ext	1D extracted spectrum	4.0 MB	mu Her	57995.8856504	3.42	P05-16
☑		s1_2017-08-30T21-13-14_ext	1D extracted spectrum	4.0 MB	mu Her	57995.8841978	3.42	P05-16
☑		s1_2017-08-30T21-11-08_ext	1D extracted spectrum	4.0 MB	mu Her	57995.8827423	3.42	P05-16
☑		s1_2017-08-29T21-15-35_ext	1D extracted spectrum	4.0 MB	mu Her	57994.8858326	3.42	P05-16
☑		s1_2017-08-29T21-13-31_ext	1D extracted spectrum	4.0 MB	mu Her	57994.884389	3.42	P05-16
☑		s1_2017-08-29T21-11-26_ext	1D extracted spectrum	4.0 MB	mu Her	57994.8829434	3.42	P05-16
☑		s1_2017-08-28T21-15-34_ext	1D extracted spectrum	4.0 MB	mu Her	57993.8858109	3.42	P05-16
☑		s1_2017-08-28T21-13-28_ext	1D extracted spectrum	4.0 MB	mu Her	57993.8843617	3.42	P05-16
☑		s1_2017-08-25T02-21-12_ext	1D extracted spectrum	4.0 MB	mu Her	57990.0980658	3.42	P05-16

AARHUS UNIVERSITY STELLAR ASTROPHYSICS CENTRE

SONG DATA ARCHIVE

Serves SONG data to the community.

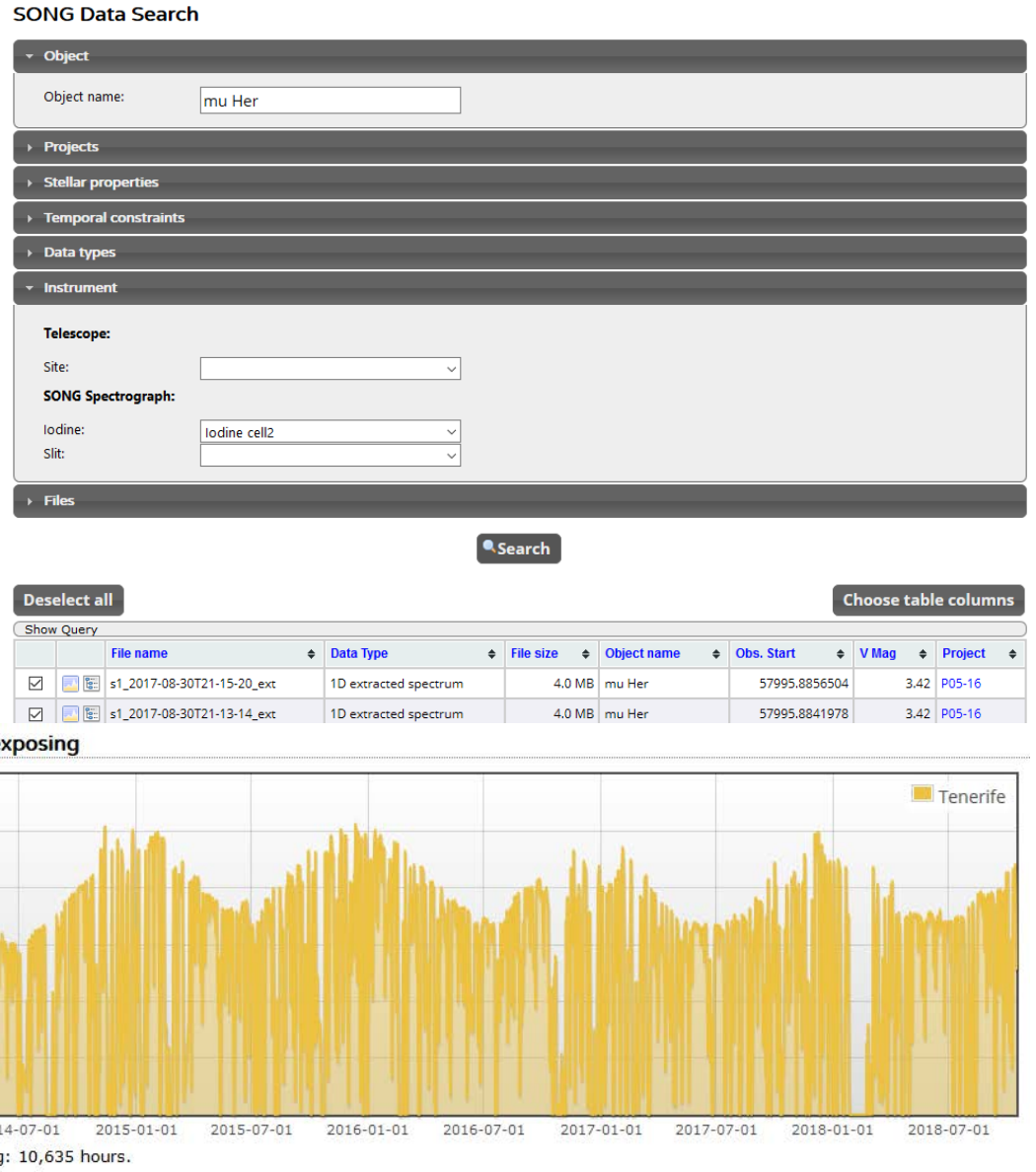
Documentation on data products.

Allows users to define observations (Phase 2).

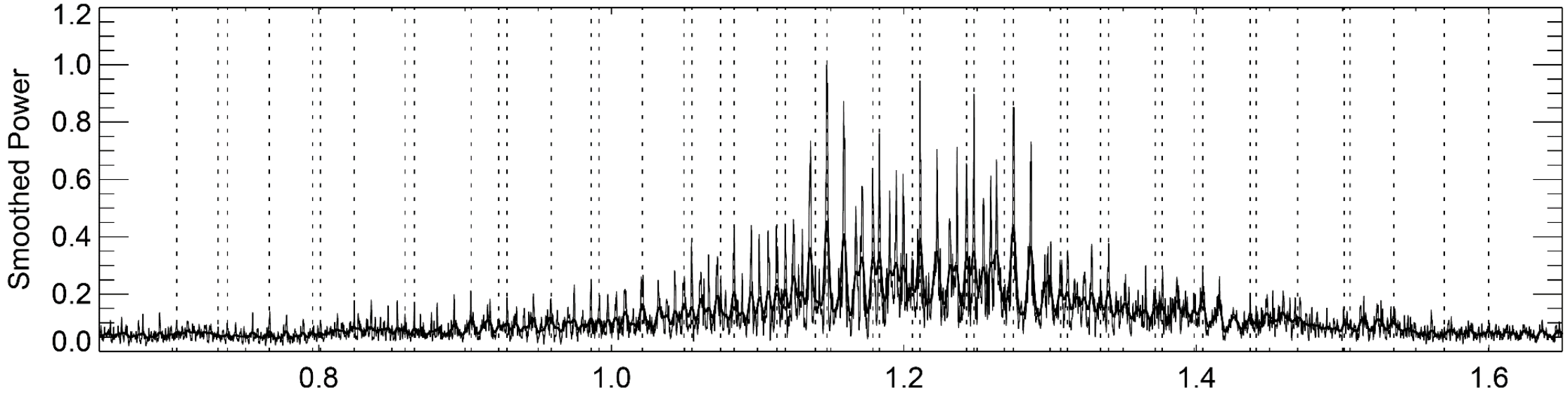
Facilitates the SONG Publication Review.

Live statistics of SONG observations.

... and more to come...



The science from SONG is amazing

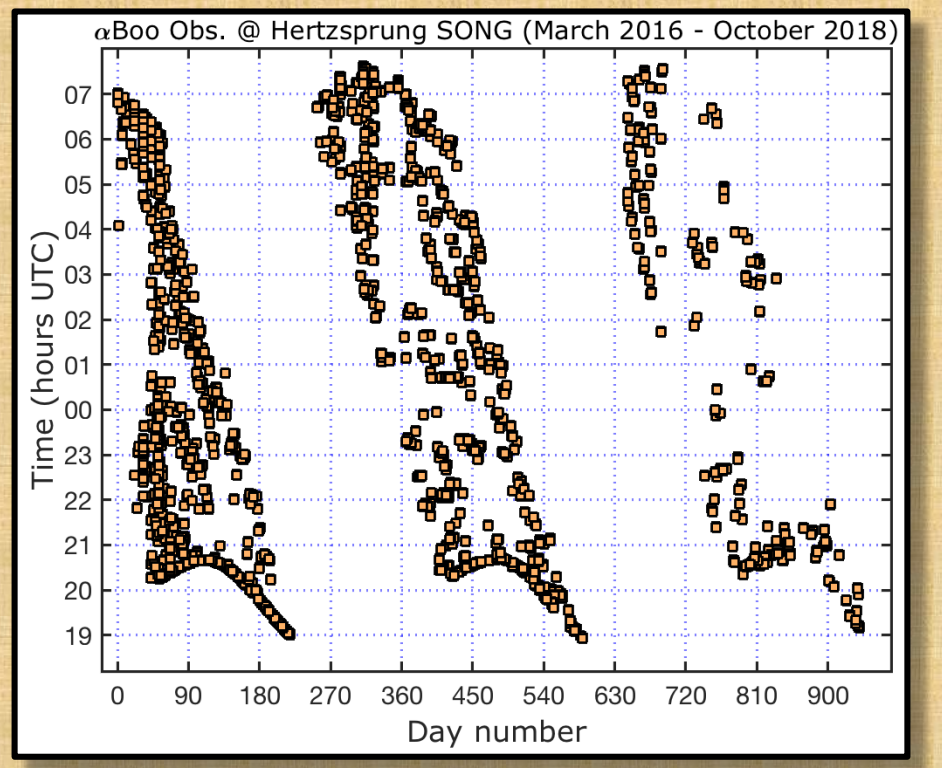


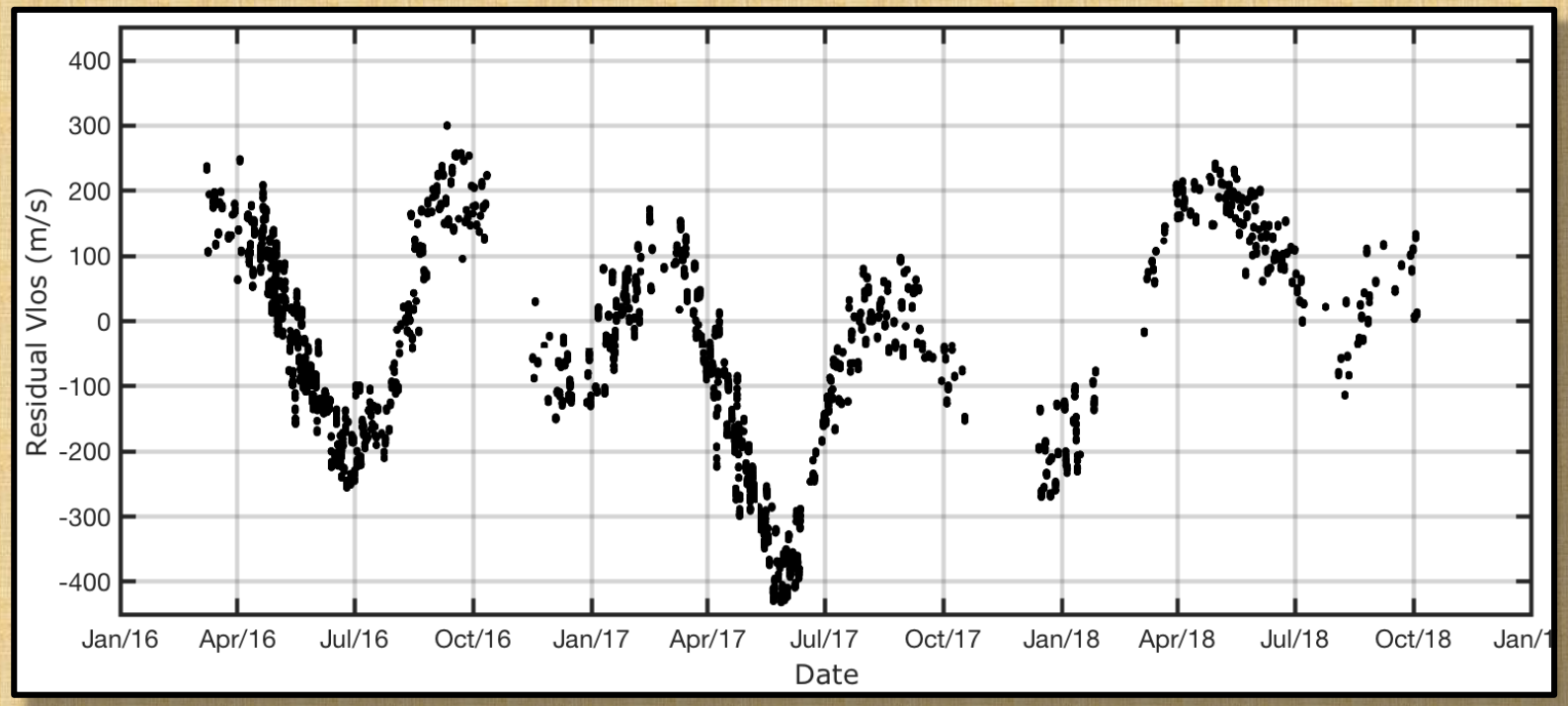
μ Herculis

- Velocities and not ”only” Photometry

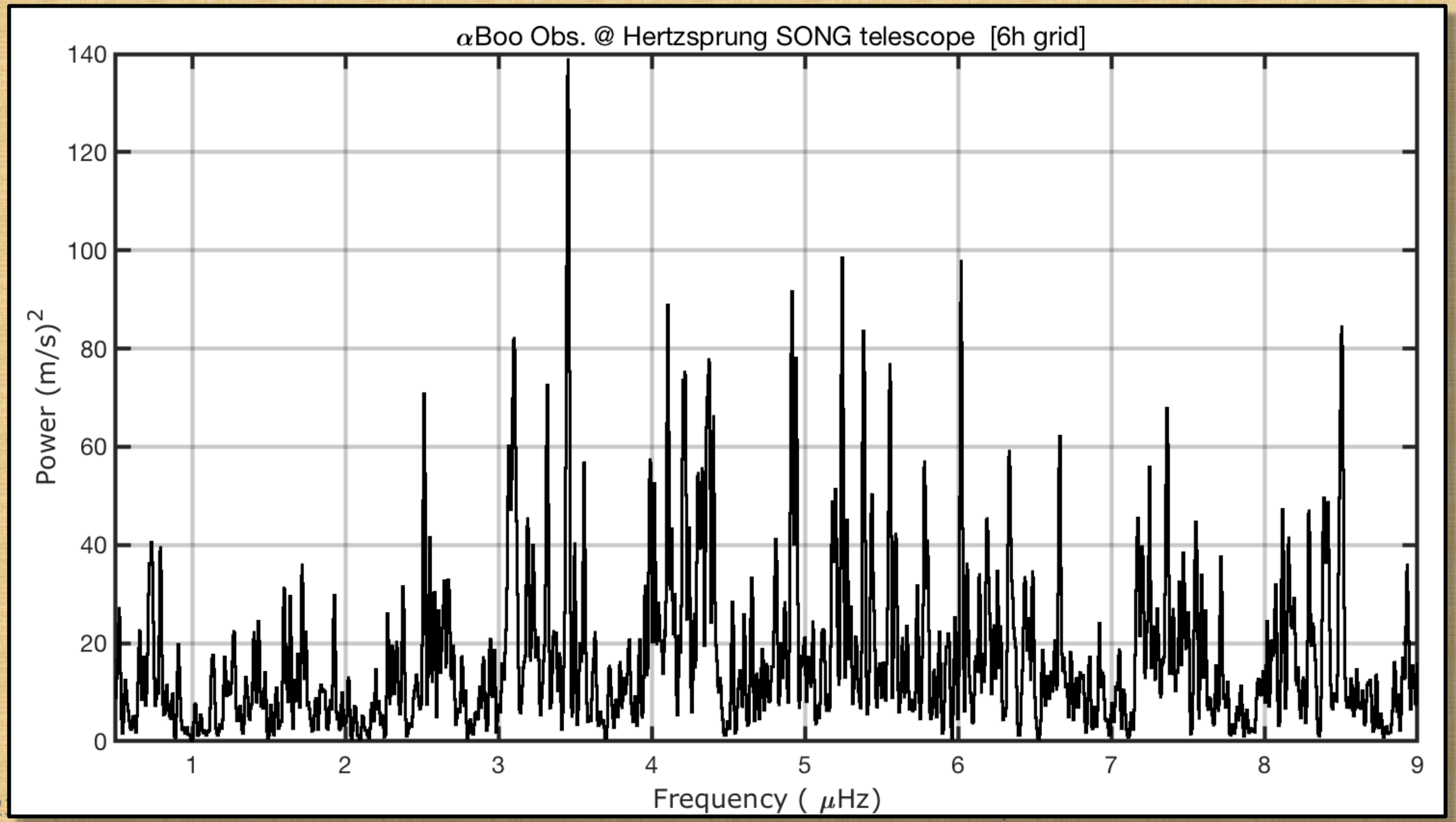
Arcturus Observations with Hertzsprung SONG @ Obs. Teide

- 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





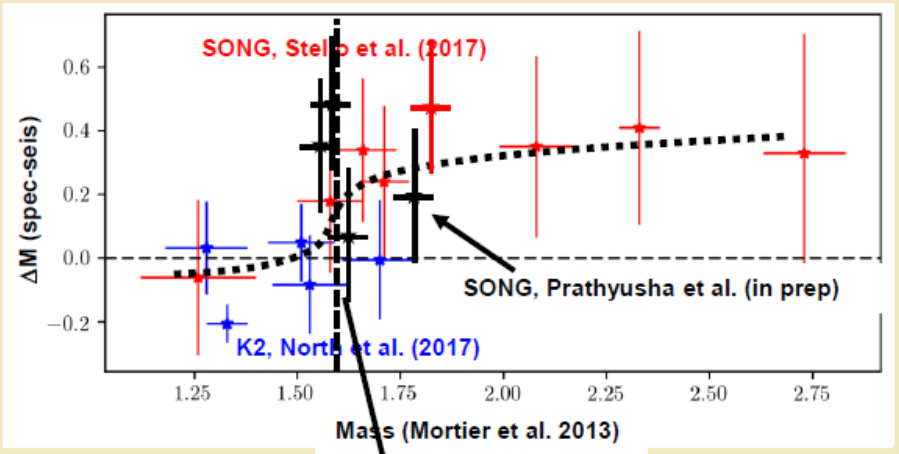
Arcturus Observations with Hertzsprung SONG @ Obs. Teide



My kitchen floor

More SONG data: 2018 season

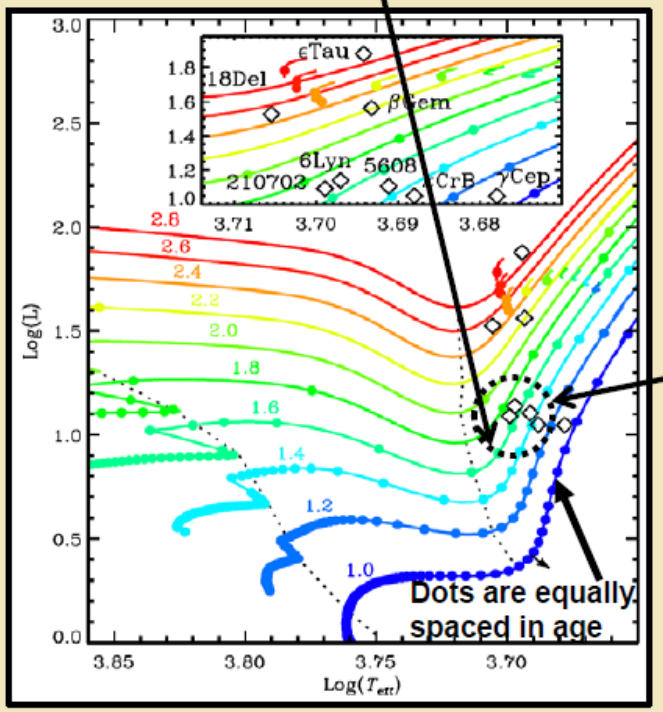
Plot credit: Thomas North



M_{spec} larger

M_{seis} larger

Sai Prathyusha:
Prathyusha et al. (in prep.)

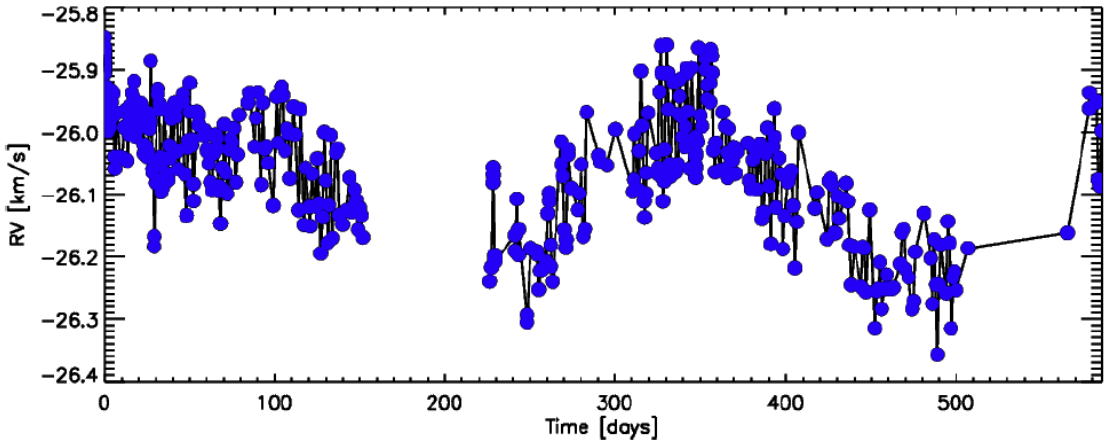


New targets for 2018:

	Spec.	Interferometry
• 24 Sex	5069K	4908K
• HD 167042	5028K	5013K
• (HD 180314)		
• HD 192699		
• HD 200964		

HD 122563 : 290pc, MLT=1.55, logg=1.4

F. Thévenin



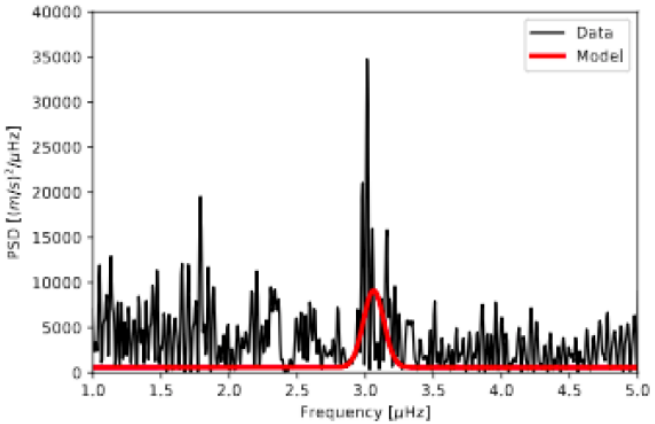


Fig. 2. Power spectral density and background model fit with DIAMONDS to determine ν_{max}. The red line shows the total fit, including the oscillation power excess. See Sect. 2.1.2.

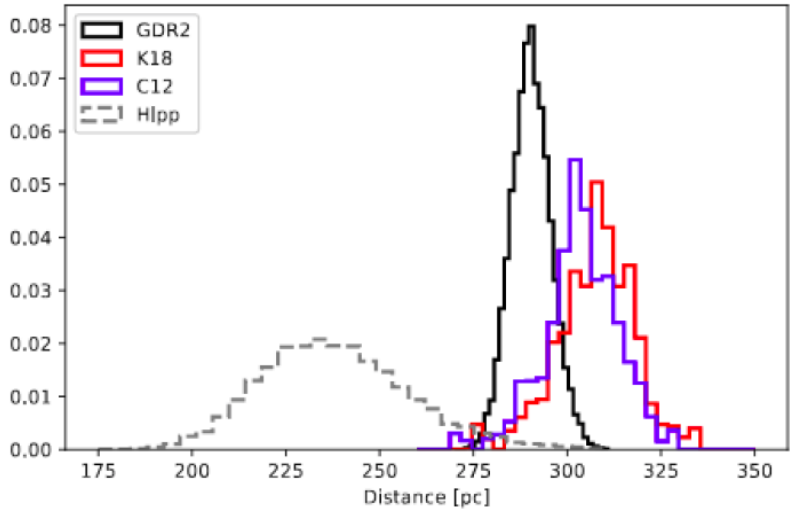
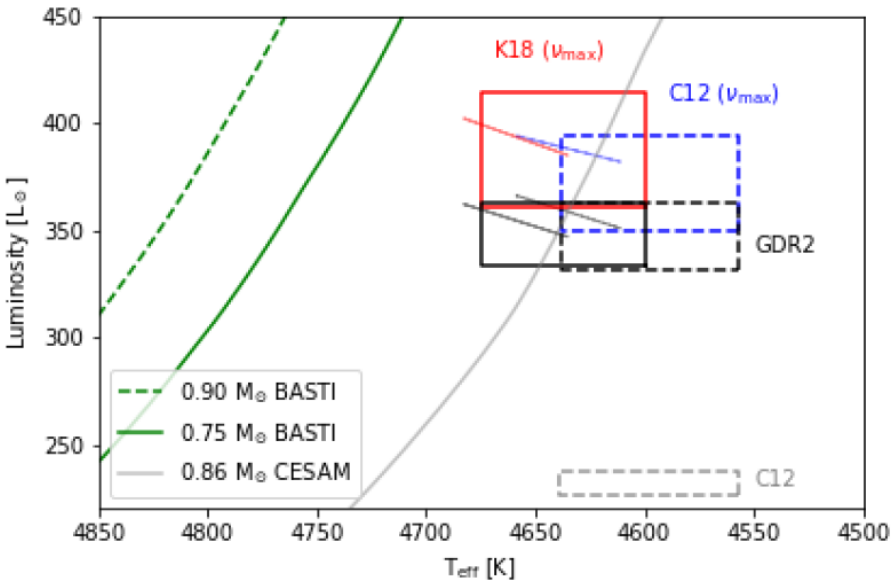
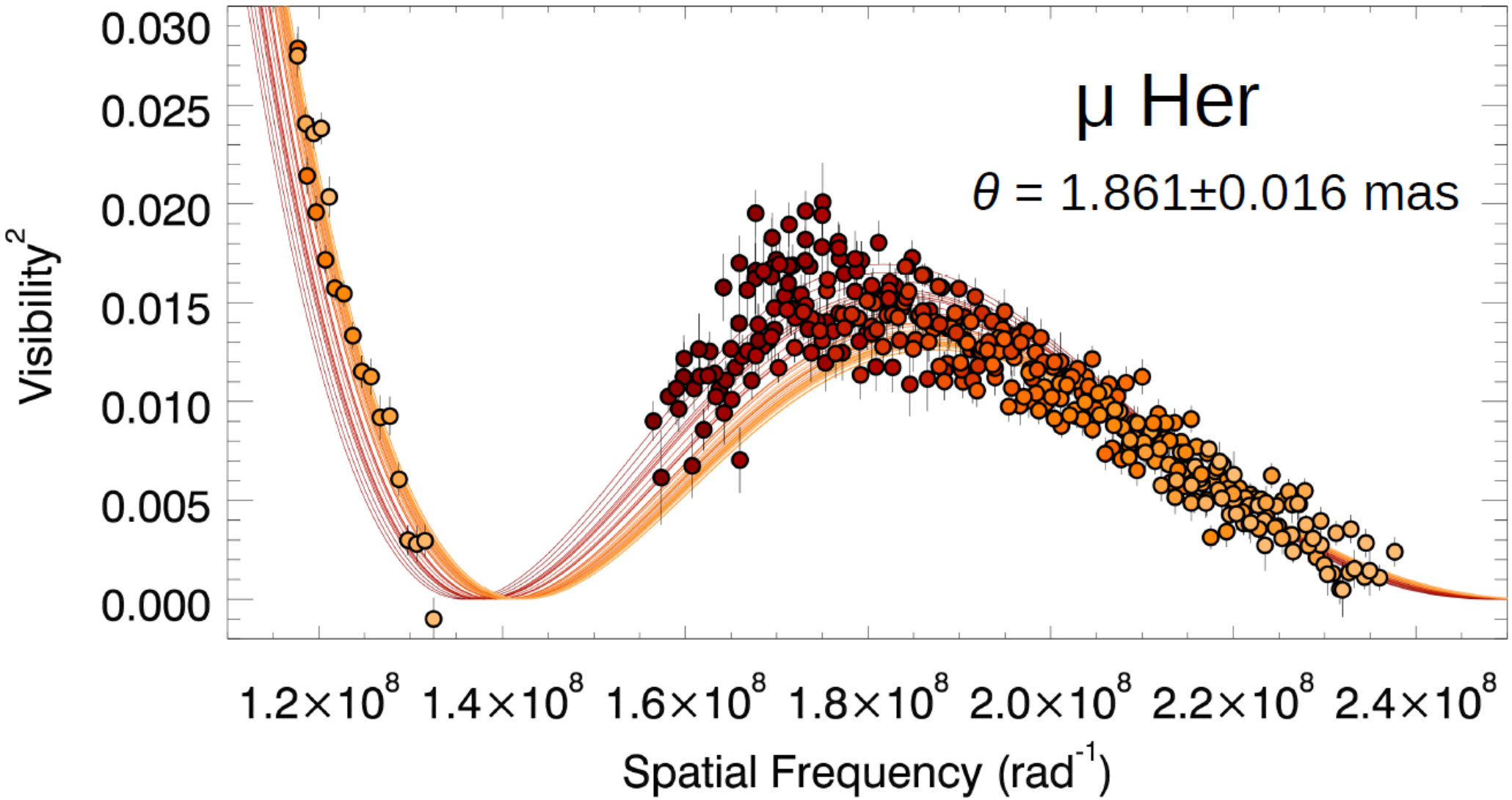
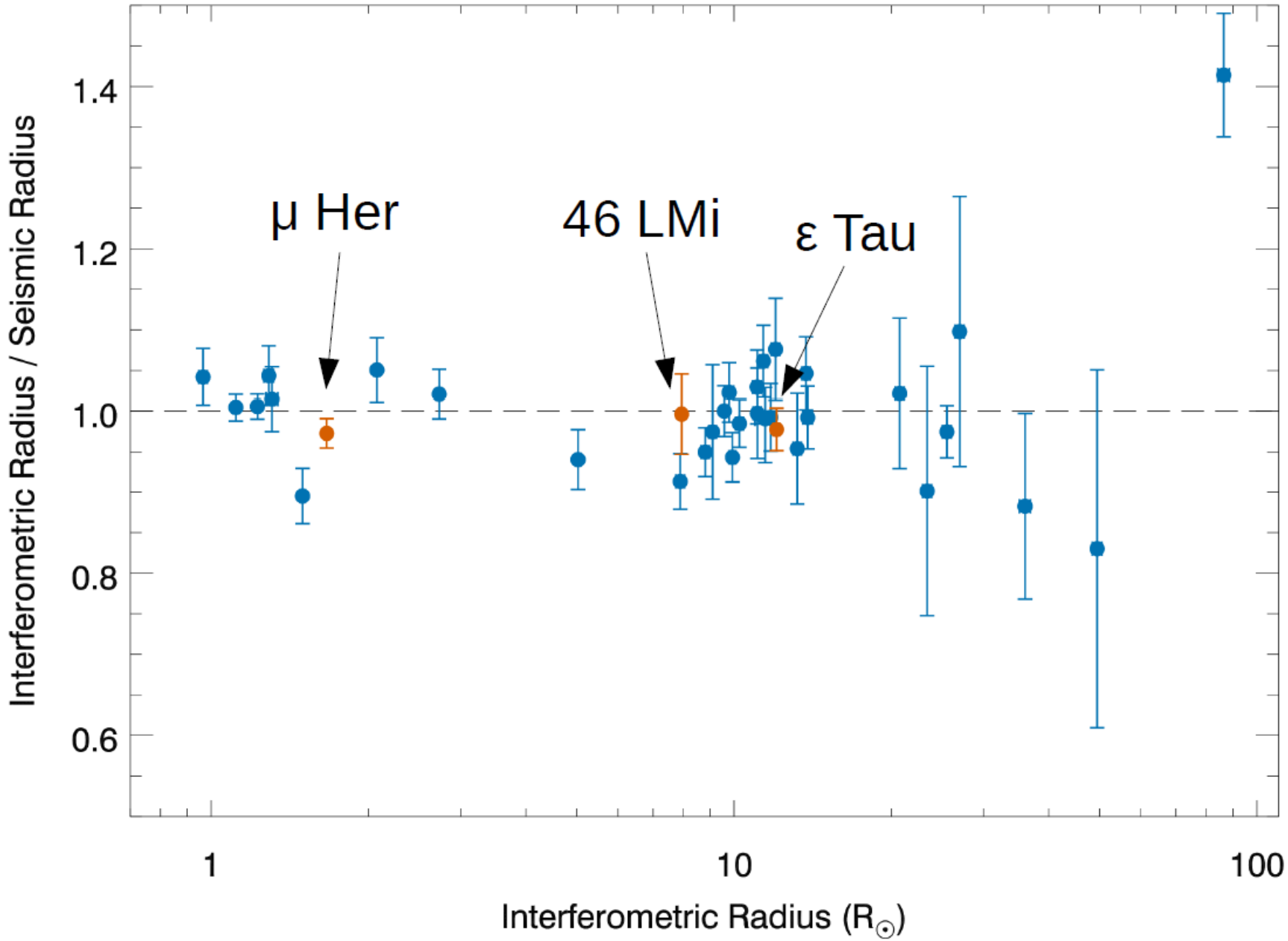
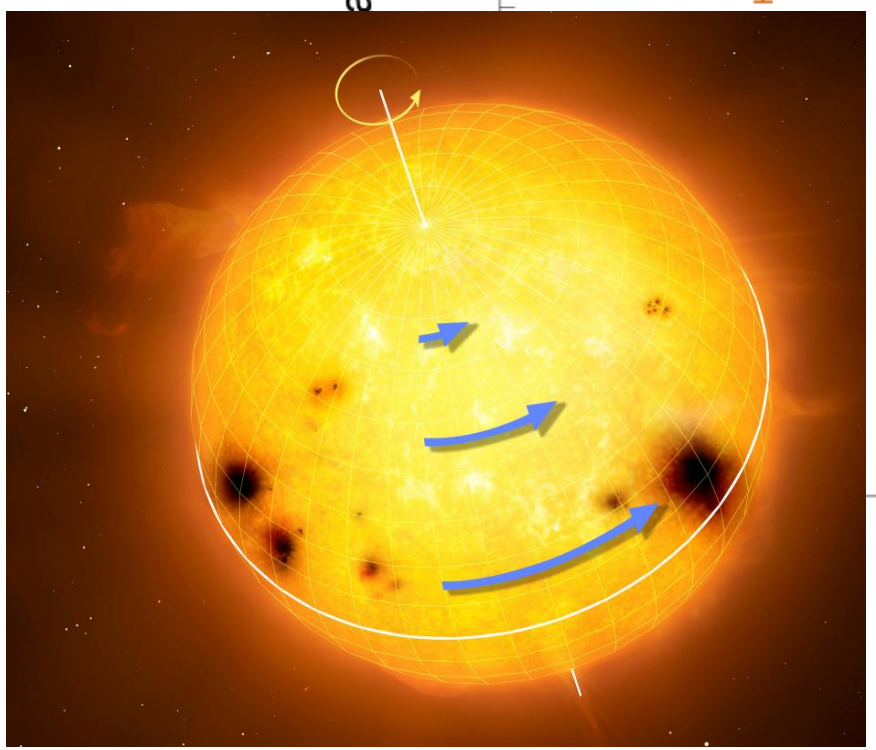


Fig. 3. Distances to HD 122563 derived using parallaxes (black and grey) and asteroseismic inferences (red and blue)

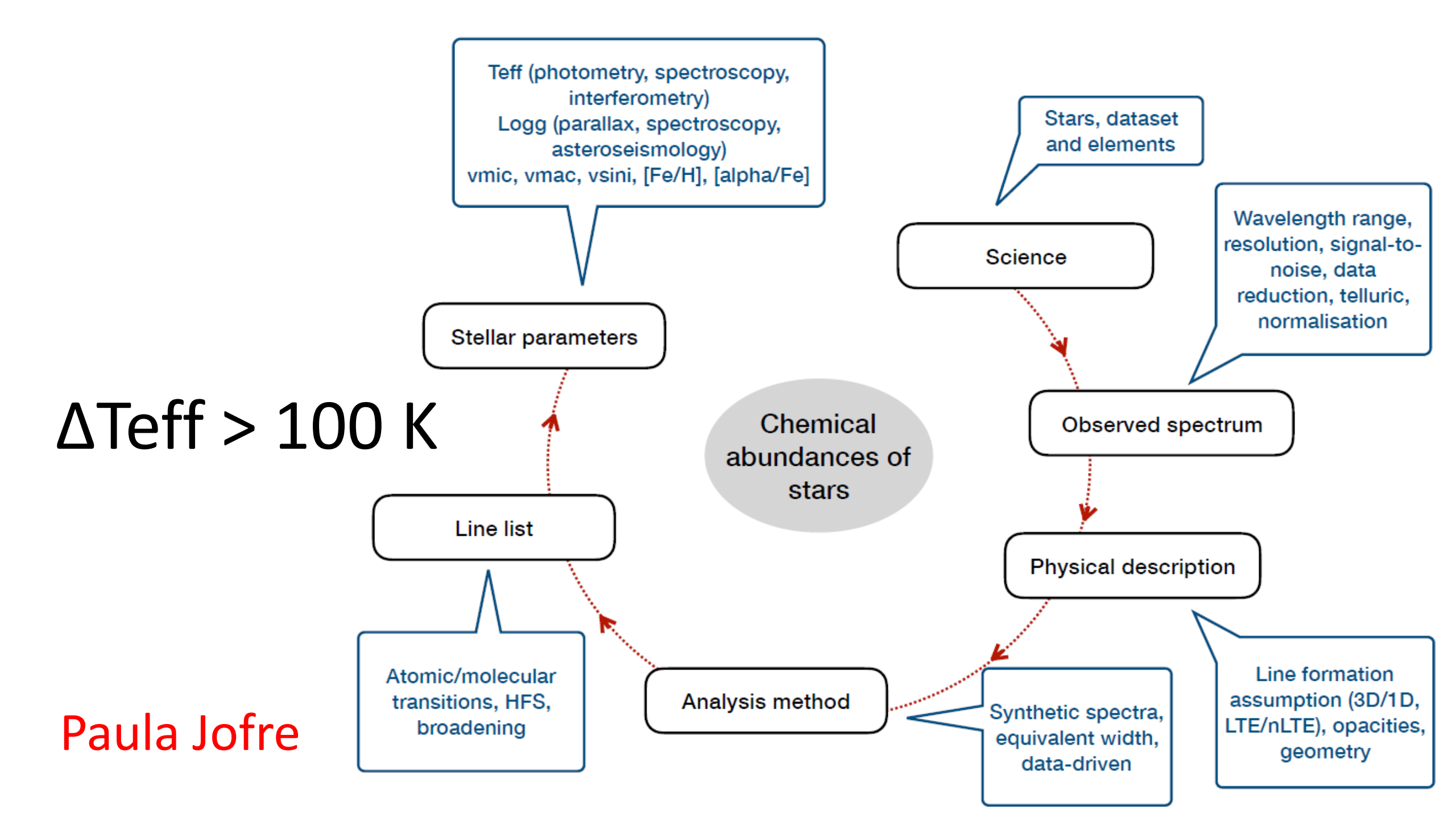



μ Her
θ = 1.861±0.016 mas
Visibility²
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1.2×10⁸
1.4×10⁸
1.6×10⁸
1.8×10⁸
2.0×10⁸
2.2×10⁸
2.4×10⁸
Spatial Frequency (rad⁻¹)


μ Her
46 LMi
ε Tau
1.4
1.2
1.0
0.8
0.6
1
10
100
Interferometric Radius / Seismic Radius
Interferometric Radius (R⊙)

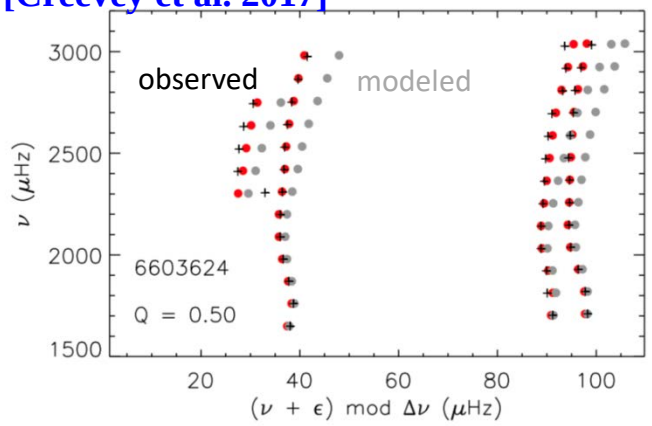


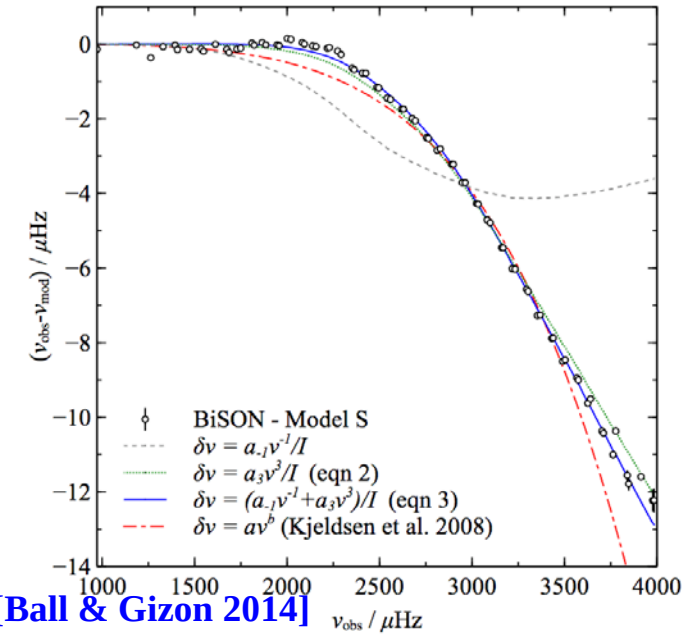
1.4
1.2
1.0
adius / Seismic Radius
μ Her
46 LMi
ε Tau
10
100
Interferometric Radius (R⊙)


ΔTeff > 100 K
Paula Jofre
Teff (photometry, spectroscopy, interferometry)
Logg (parallax, spectroscopy, asteroseismology)
vmic, vmac, vsini, [Fe/H], [alpha/Fe]
Stellar parameters
Line list
Atomic/molecular transitions, HFS, broadening
Analysis method
Synthetic spectra, equivalent width, data-driven
Physical description
Line formation assumption (3D/1D, LTE/nLTE), opacities, geometry
Observed spectrum
Wavelength range, resolution, signal-to-noise, data reduction, telluric, normalisation
Science
Stars, dataset and elements
Chemical abundances of stars

Savita Mathur: Surface effects

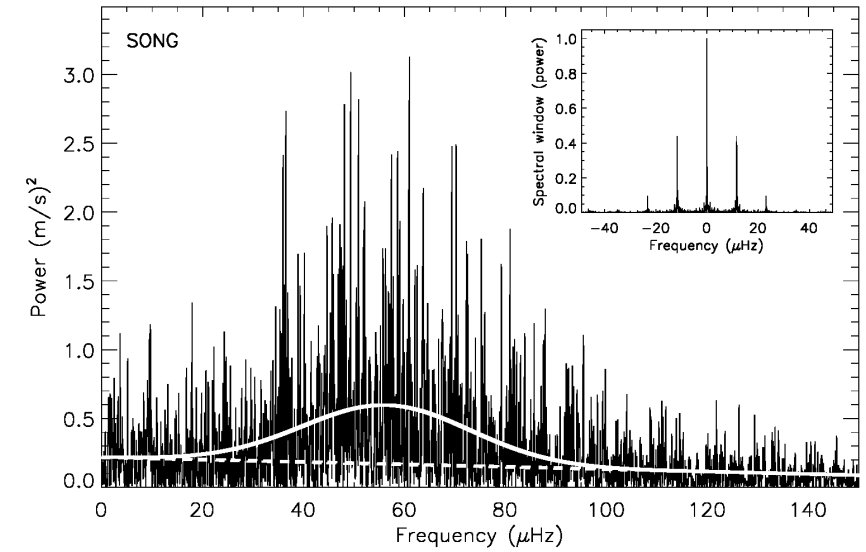
[Creevey et al. 2017]

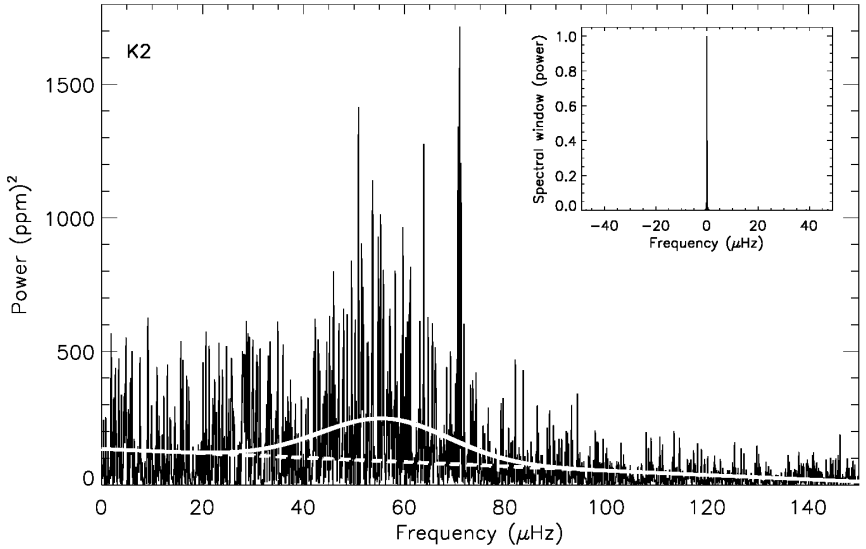


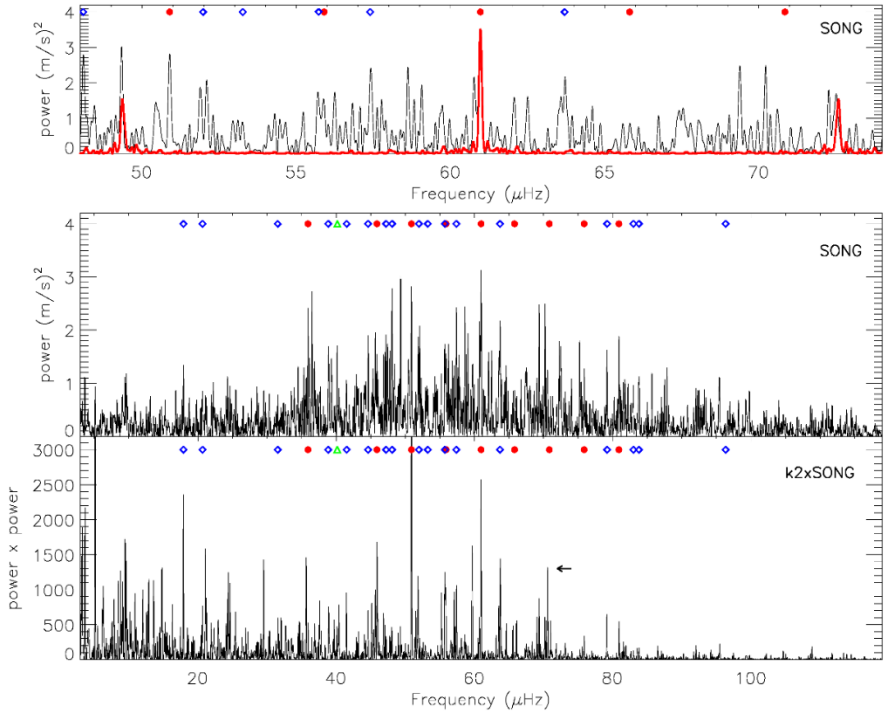


[Ball & Gizon 2014]

- Systematic difference between observed p-mode frequencies and modeled ones
  - Due to the surface layers that are not properly modeled
- Different ways to overcome it:
  - Surface term following the formula of **Kjeldsen et al. (2008)** or **Ball & Gizon (2014)**
  - Use frequency ratios insensitive of the surface effects
  - Use 3D simulations prescriptions by matching with 1D models **[Trampedach et al., 2017]**
- Recent work by **Basu & Kinnane (2018)** (use of BG14, frequency ratios, epsilon differences):
  - different corrections of the surface effects lead to robust estimates of M, R, age







Frequency analysis based on SONG data supported by the better spectral window of K2

Fresh model results from Victor Silva Aguirre (Aarhus),
Fitting asteroseismic parameters + existing photometry
with BASTA models:

Distance: 44.287 pc *(cluster distance ~ 47 pc)*

Radius: 12.16 R_{sun} *(interferometry: 12.06 +/- 0.16 R_{sun})*

Age: $600^{+100}_{-50}\ Myr$ *(cluster age ~ 650 Myr)*

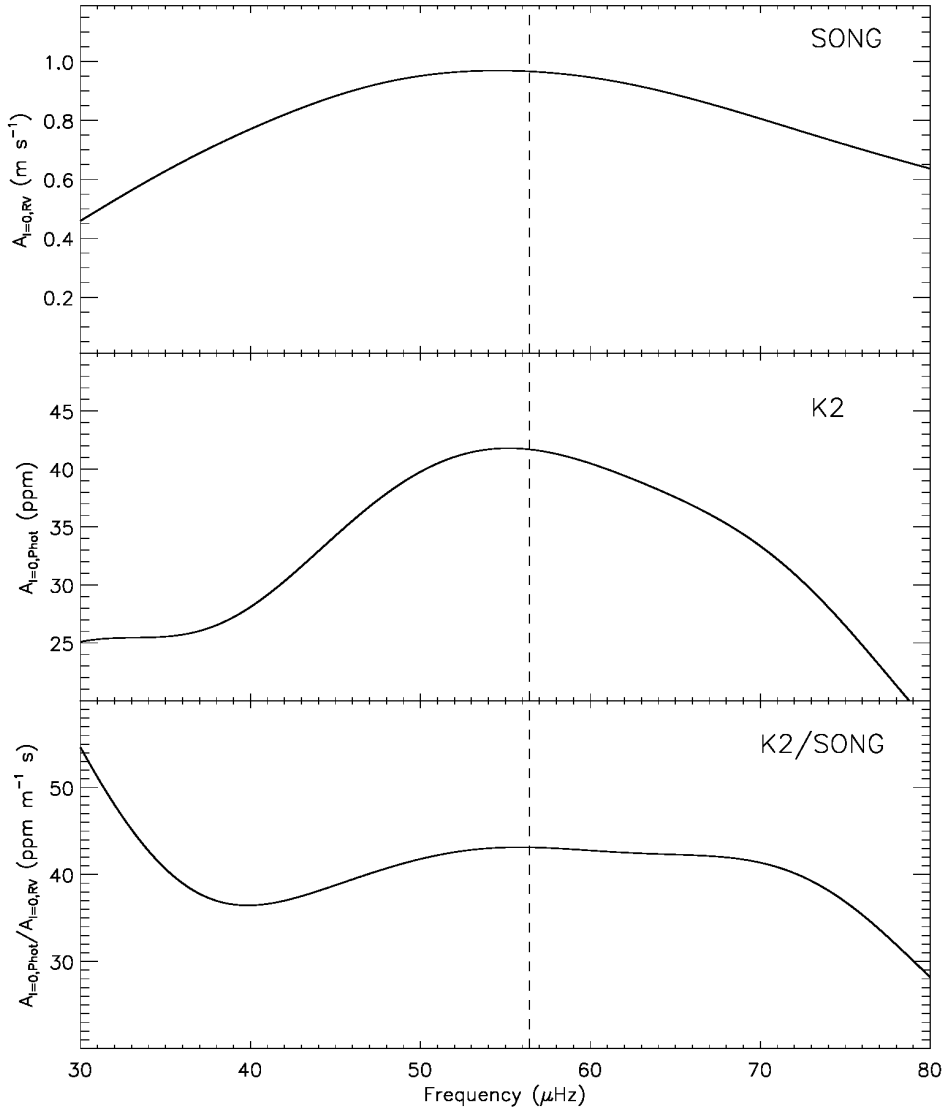
Evolutionary stage: Most likely RGB

Amplitude ratio between photometry and spectroscopy:

Amplitude per radial mode
(Kjeldsen et al. 2008)

Amplitude ratio as a function of frequency;
Procyon (Huber et al. 2011), Sun

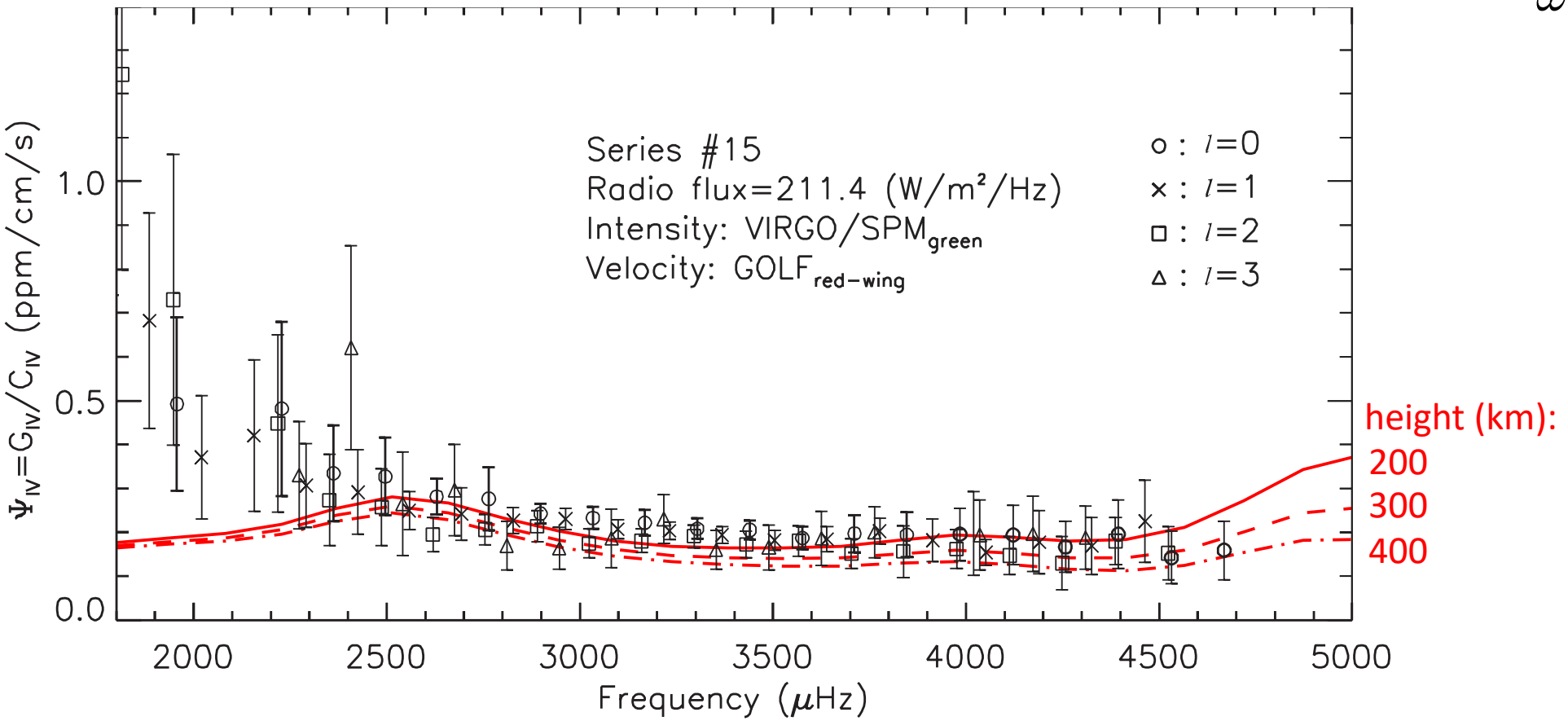
Note: SONG and K2 data non-simultaneous…



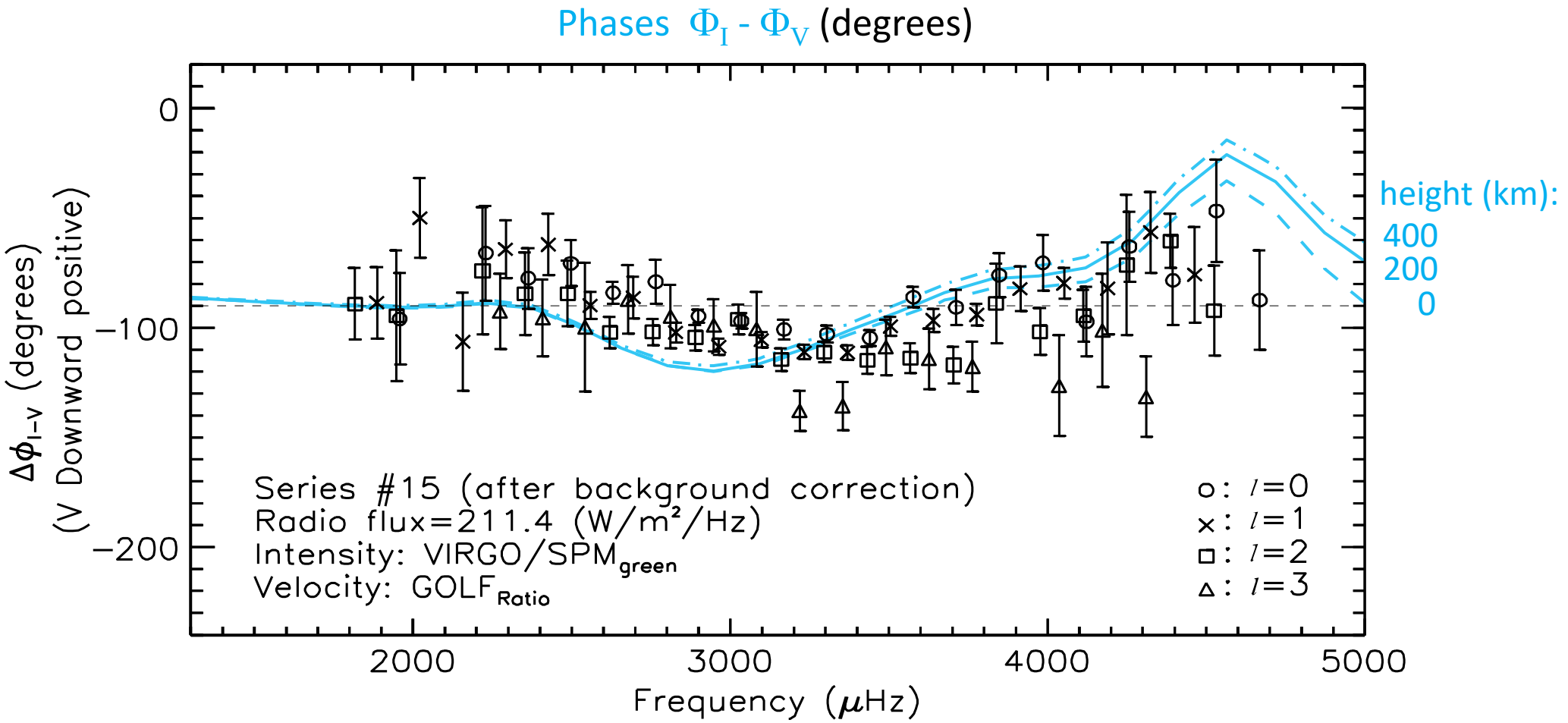
Sun: Virgo and GOLF (data: Jimenez et al 2002)

Amplitude ratios $\Delta L/\Delta V$ (ppm cm^{-1} s)

$$\Delta L/\Delta V =: \frac{\delta L/L}{\omega_r r\ \delta r/r}$$

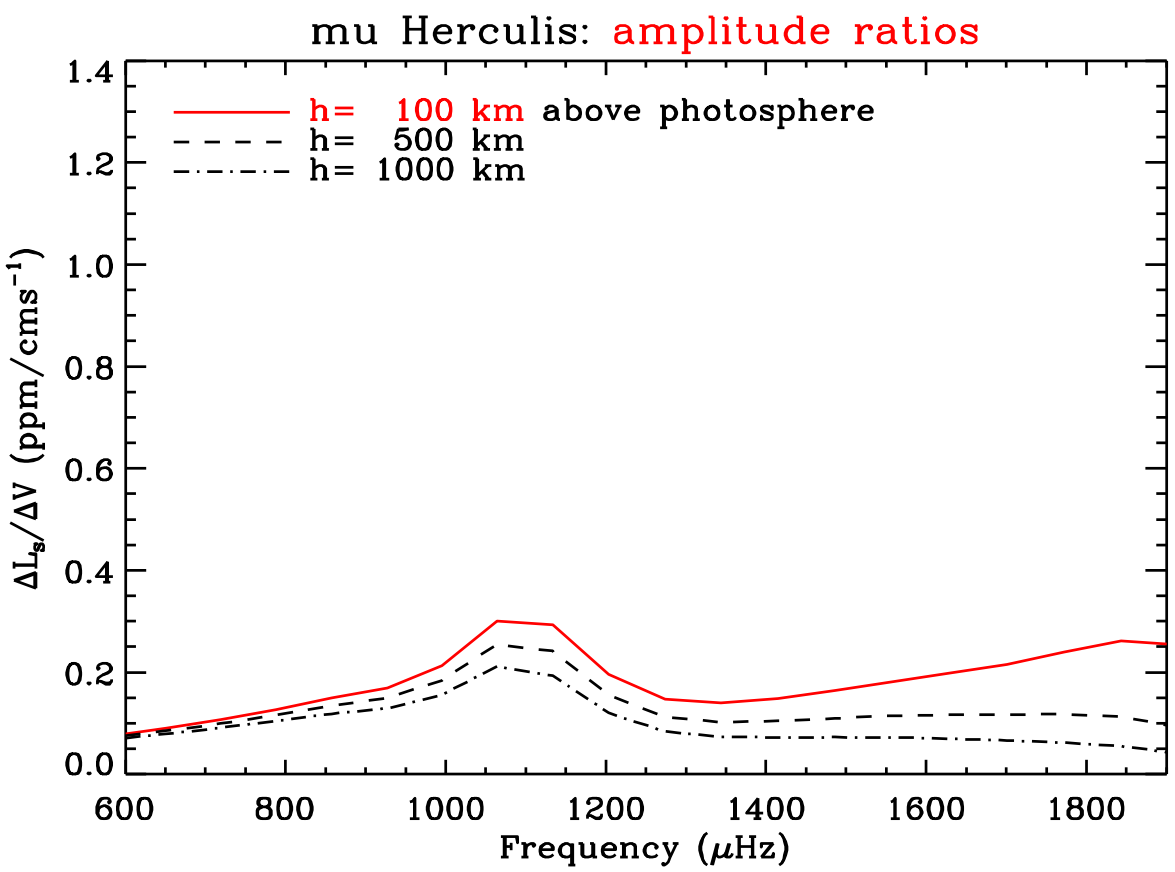


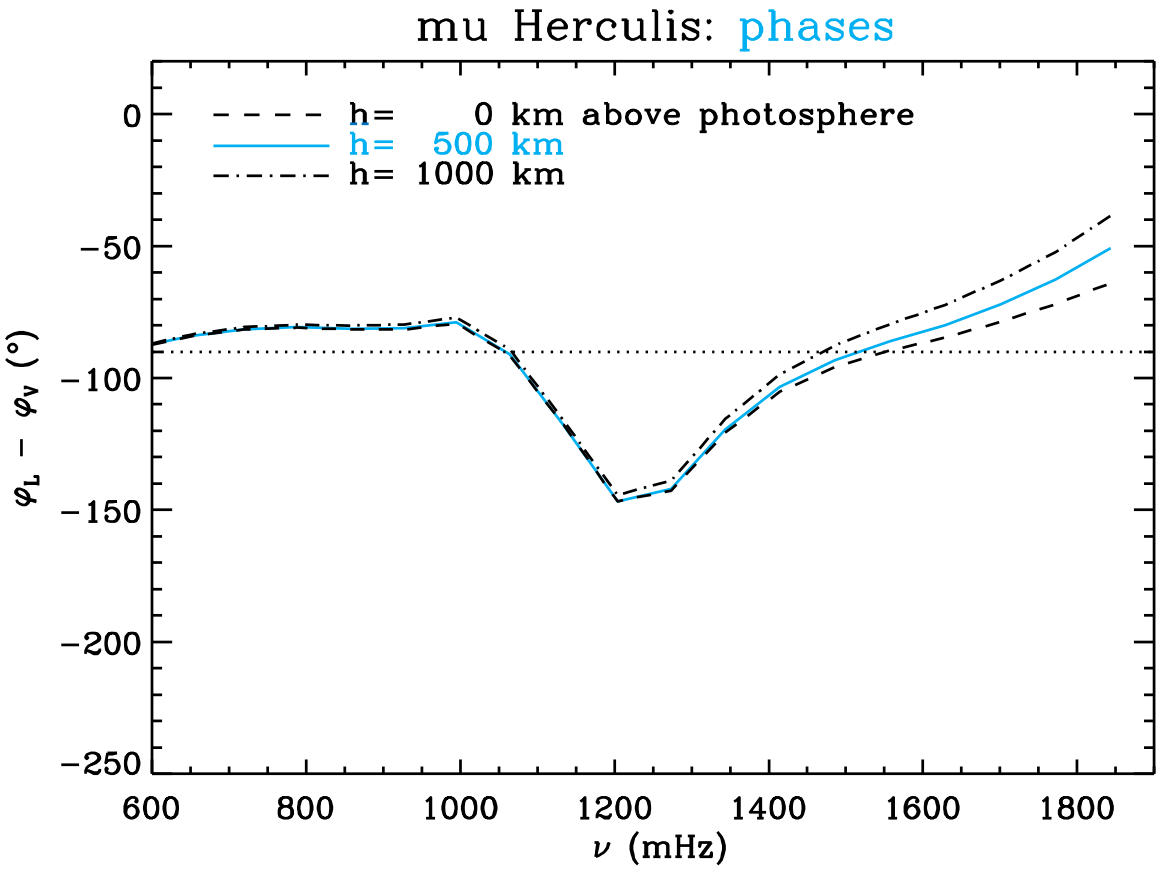
Sun: Virgo and GOLF (data: Jimenez et al 2002)



Sub giants

μ Herculis: T_{eff} = 5649 K ; log g = 4.029





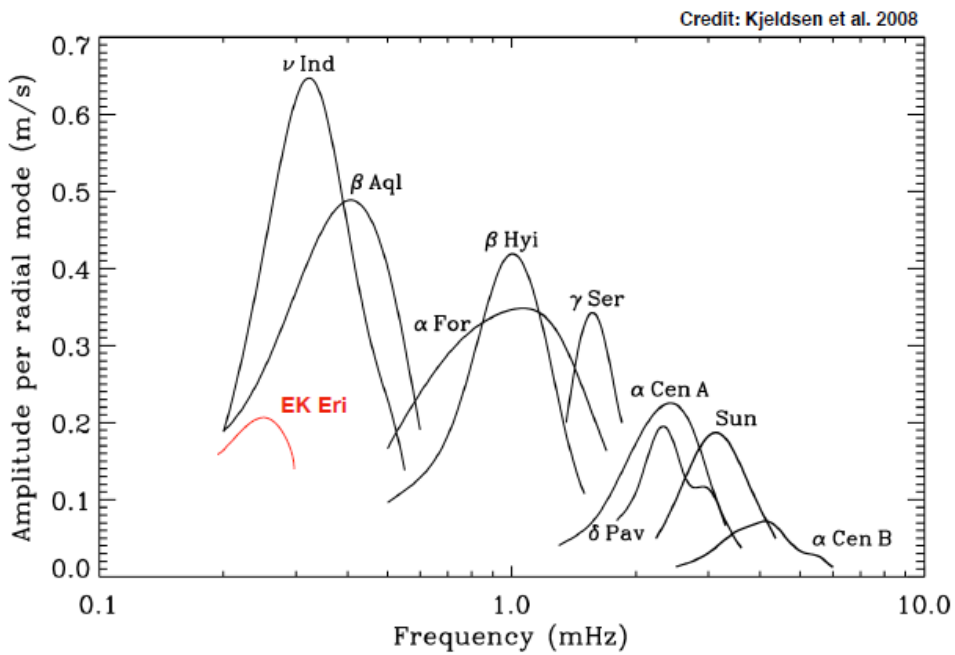
Kjeldsen & Bedding 1995

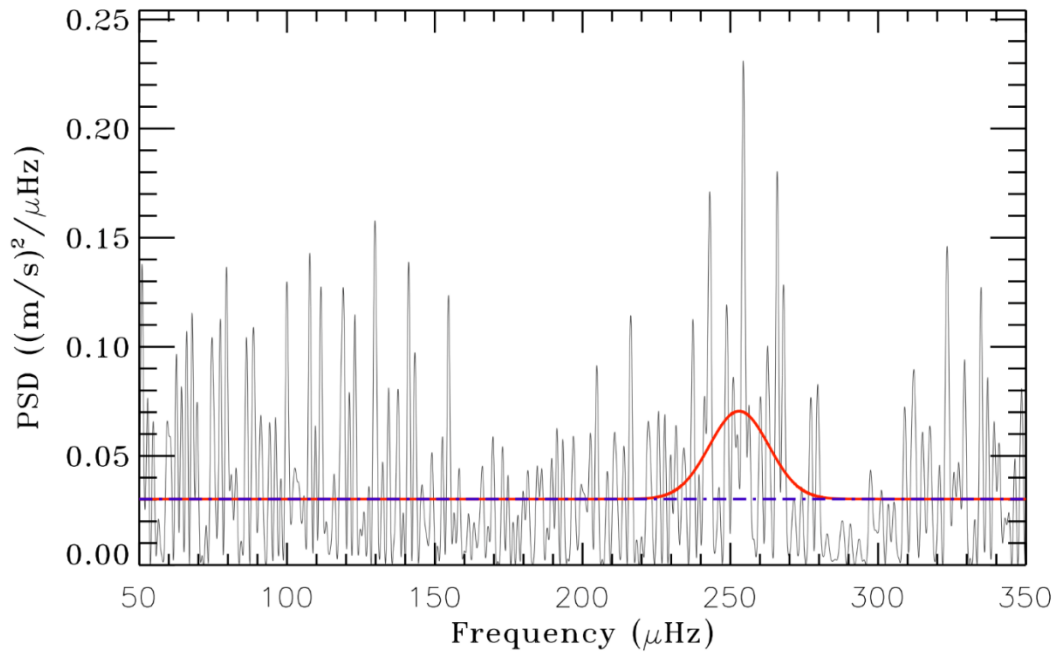
Oscillation amplitude

Strong suppression by magnetic field (almost factor 10) !

$$A_{\max,\ell=0} = 0.22\,\mathrm{m/s}$$

$$A_{\max} \propto \left(\frac{L/L_\odot}{M/M_\odot}\right)$$

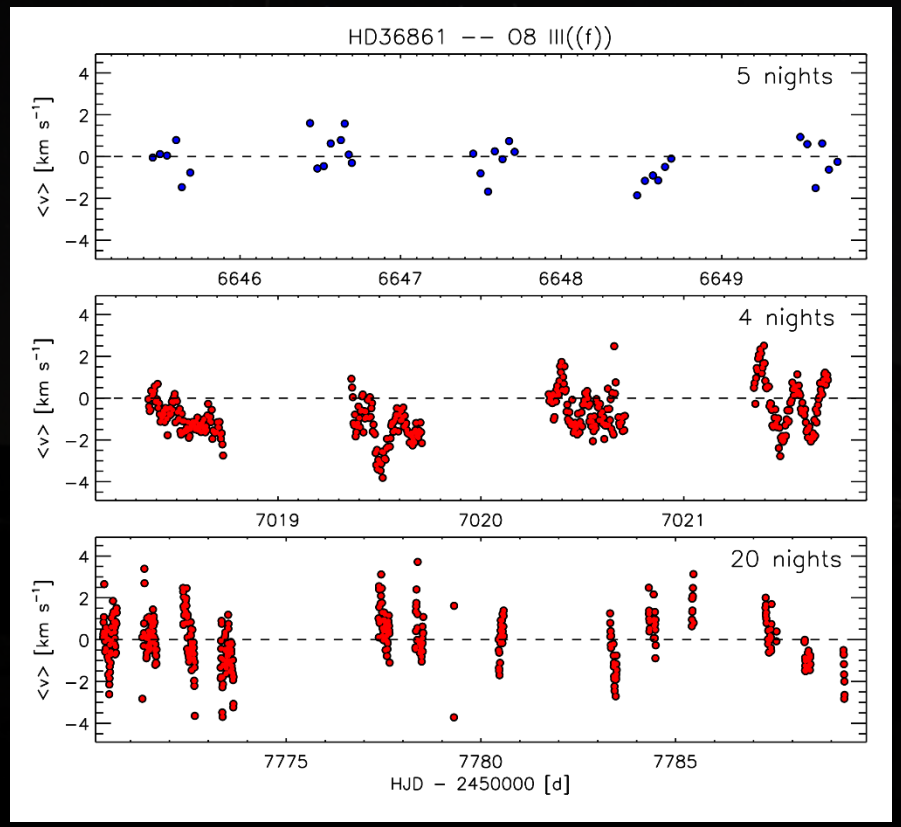




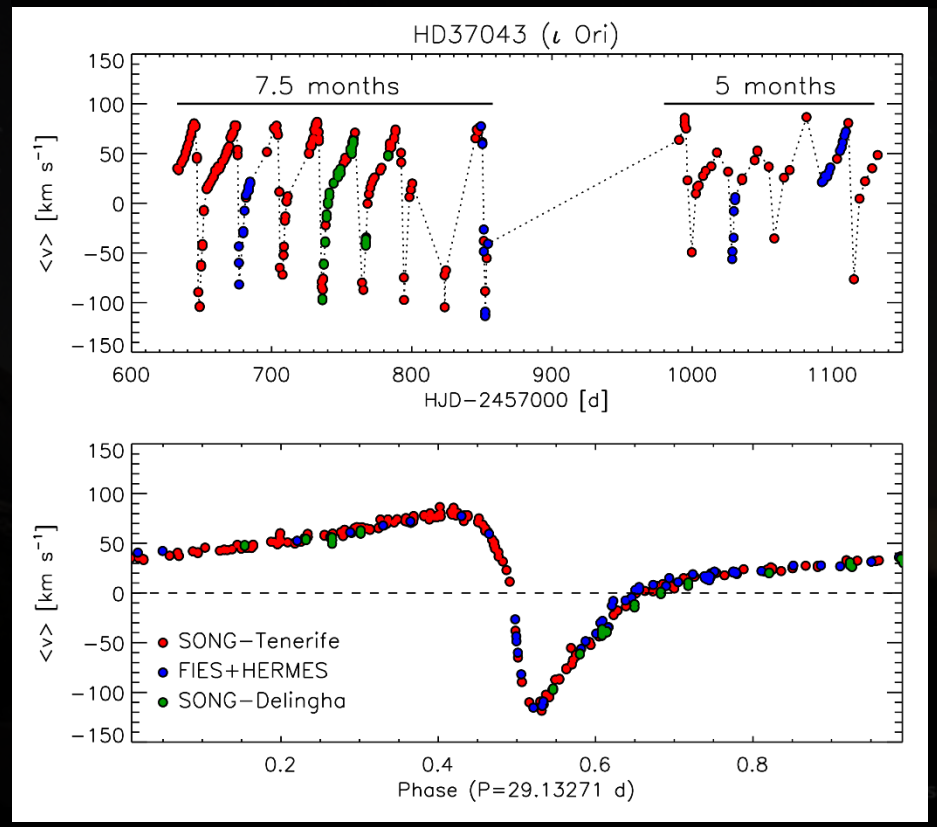
During the last 4 years, SONG has been proven to be a key facility to

Provide empirical information about spectroscopic variability phenomena in O stars and B Supergiants as any other facility in the world can do

λ Ori: A massive β-Cep type pulsating star



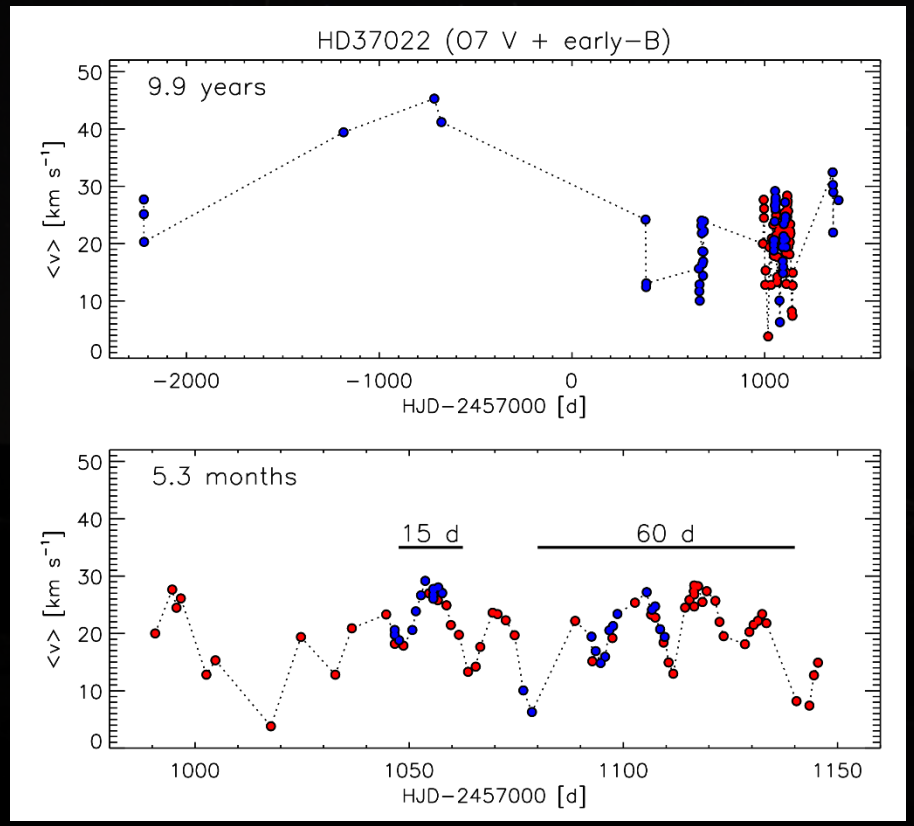
ι Ori: A massive eccentric binary



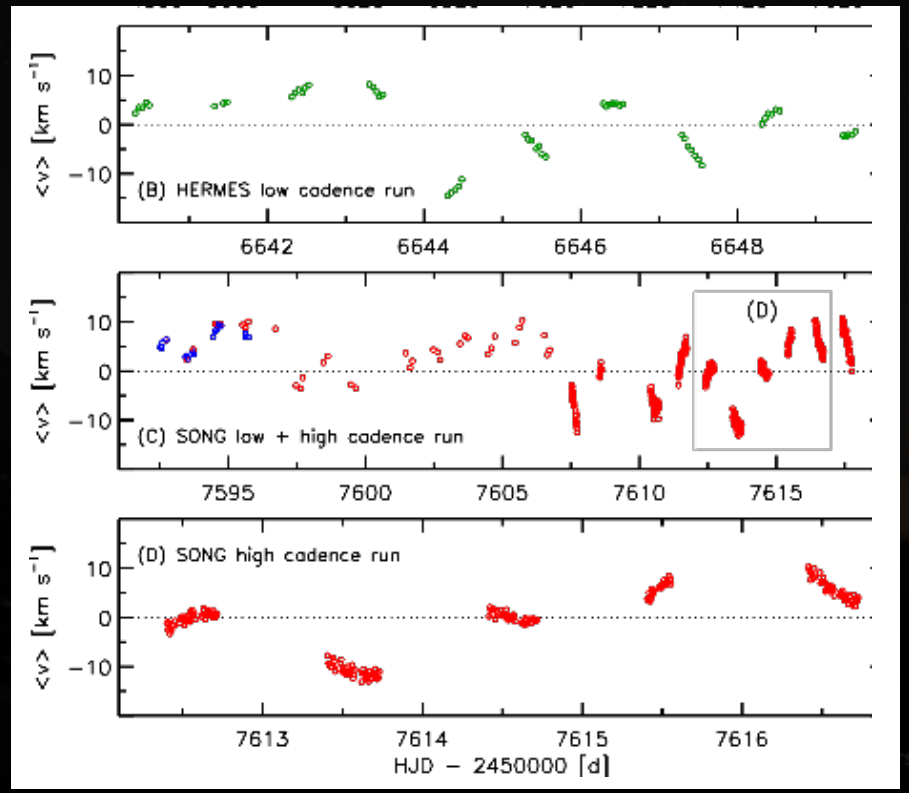
During the last 4 years, SONG has been proven to be a key facility to

Provide empirical information about spectroscopic variability phenomena in O stars and B Supergiants as any other facility in the world can do

θ^1 Ori C: A massive magnetic star

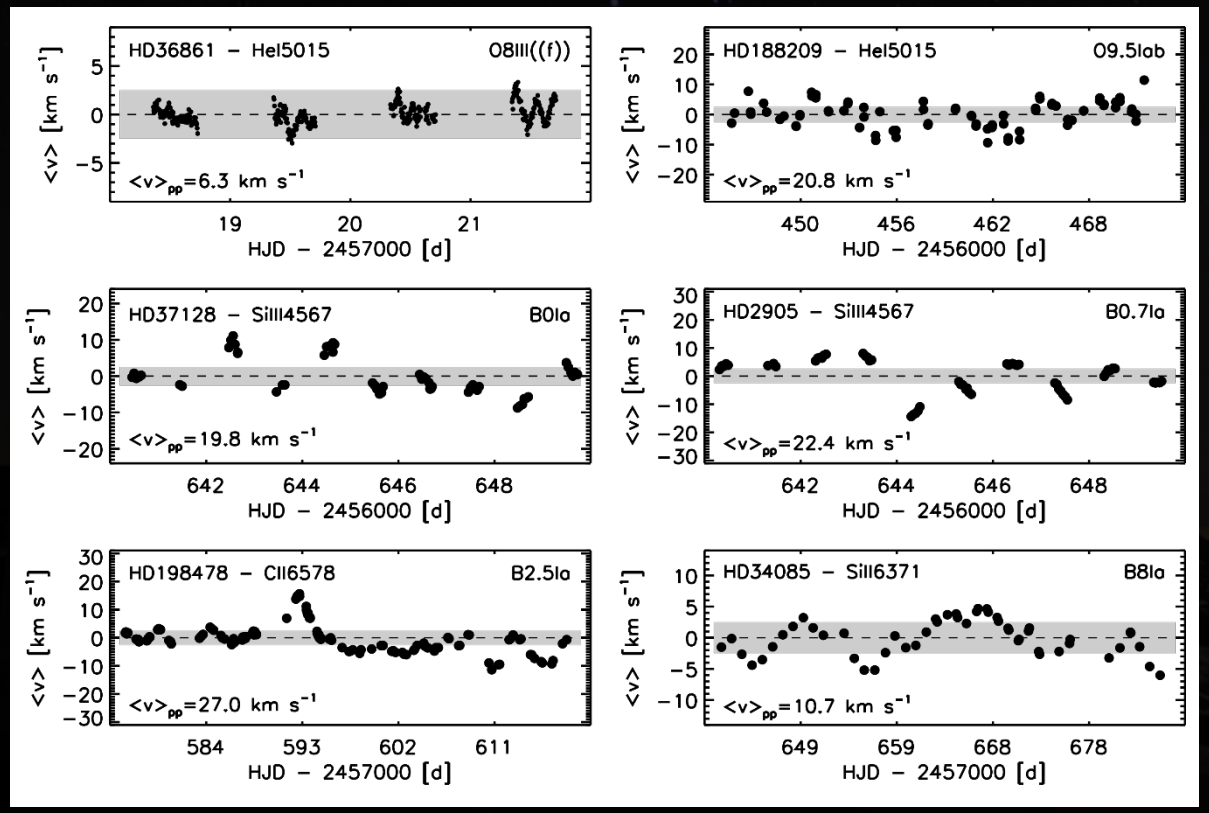


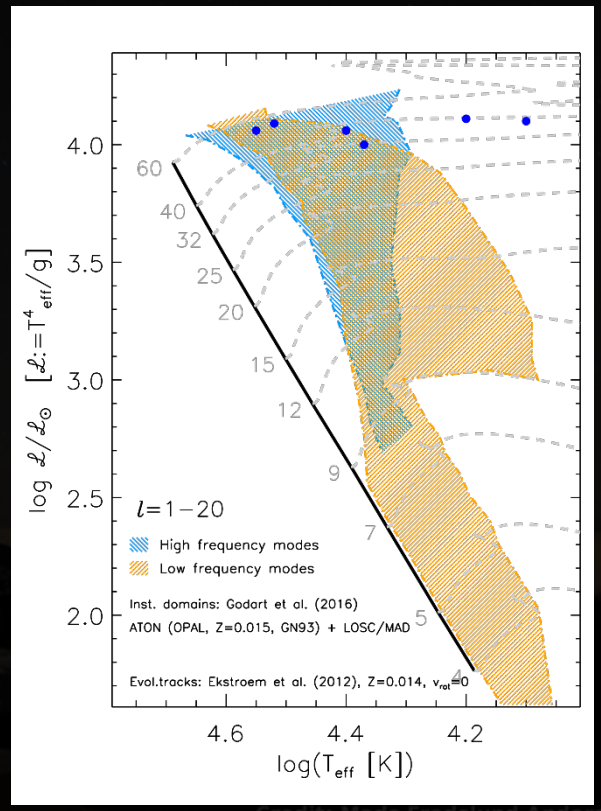
κ Cas: A prototypical exmple of photospheric variability in O and early-B Sgs



During the last 4 years, SONG has been proven to be a key facility to

Step forward in our understanding of the pulsational properties (i.e. internal structure) of massive stars along their evolution





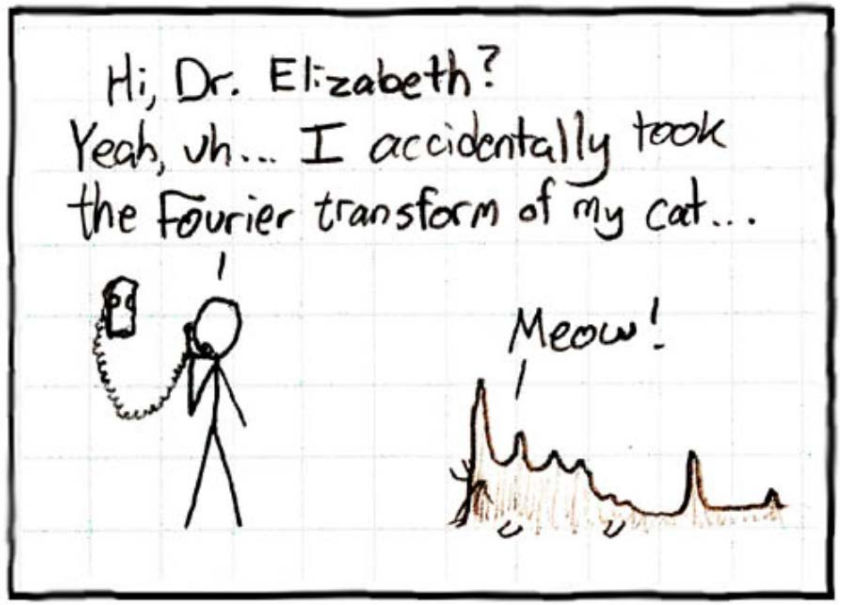
Credit: Mads Fredslund Andersen

Asteroseismology with SONG – Tim Bedding

1. velocity is very good for solar-like oscillations
2. robotic operation and flexible scheduling – great!
3. full sky coverage (eventually)
4. good spectral window for selected targets (eventually)
5. simultaneous with *TESS* – lots of oppoprtunities
6. continue to choose targets carefully, diversify science, remember weights and spectral window!

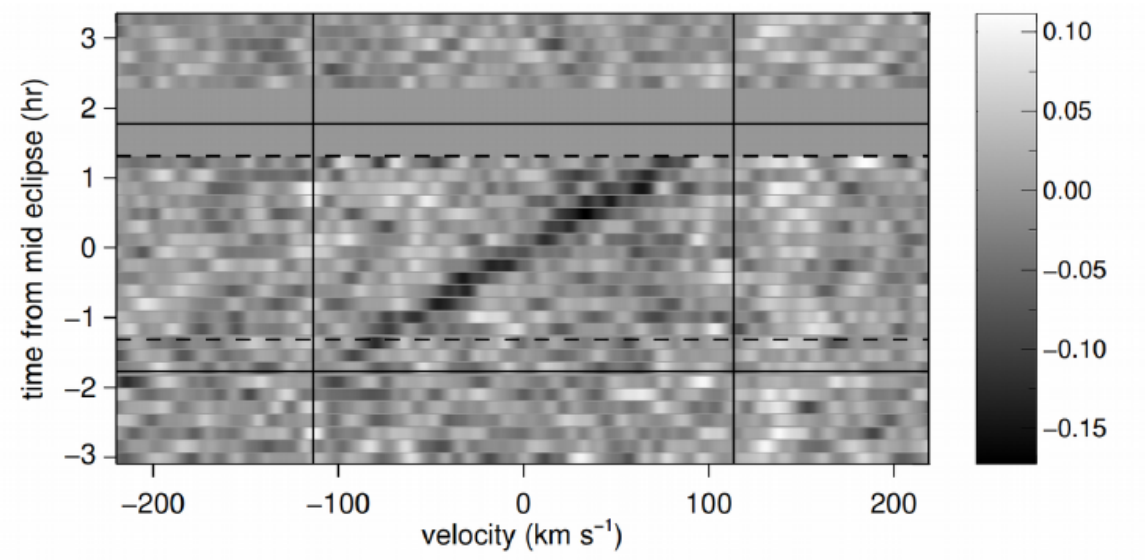
$\nu_{\rm max} \propto g/\sqrt{T_{\rm eff}}$

$\Delta\nu \propto \sqrt{\rho}$

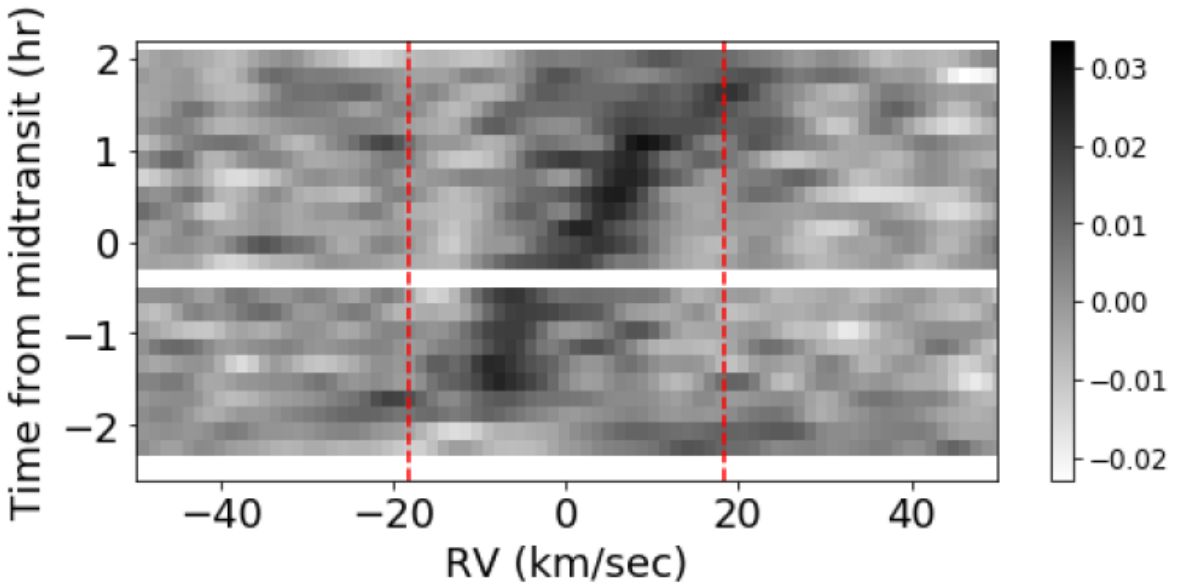


SONG & MASCARA

- Confirmation of planets: spectroscopic transit follow-up with SONG.
- Detection: Two (soon three) hot Jupiters orbiting bright stars.
- MASCARA-3: sufficient precision for *both* RV follow-up and spectroscopic transit follow-up with SONG.
- Very promising for SONG follow-up of TESS targets.

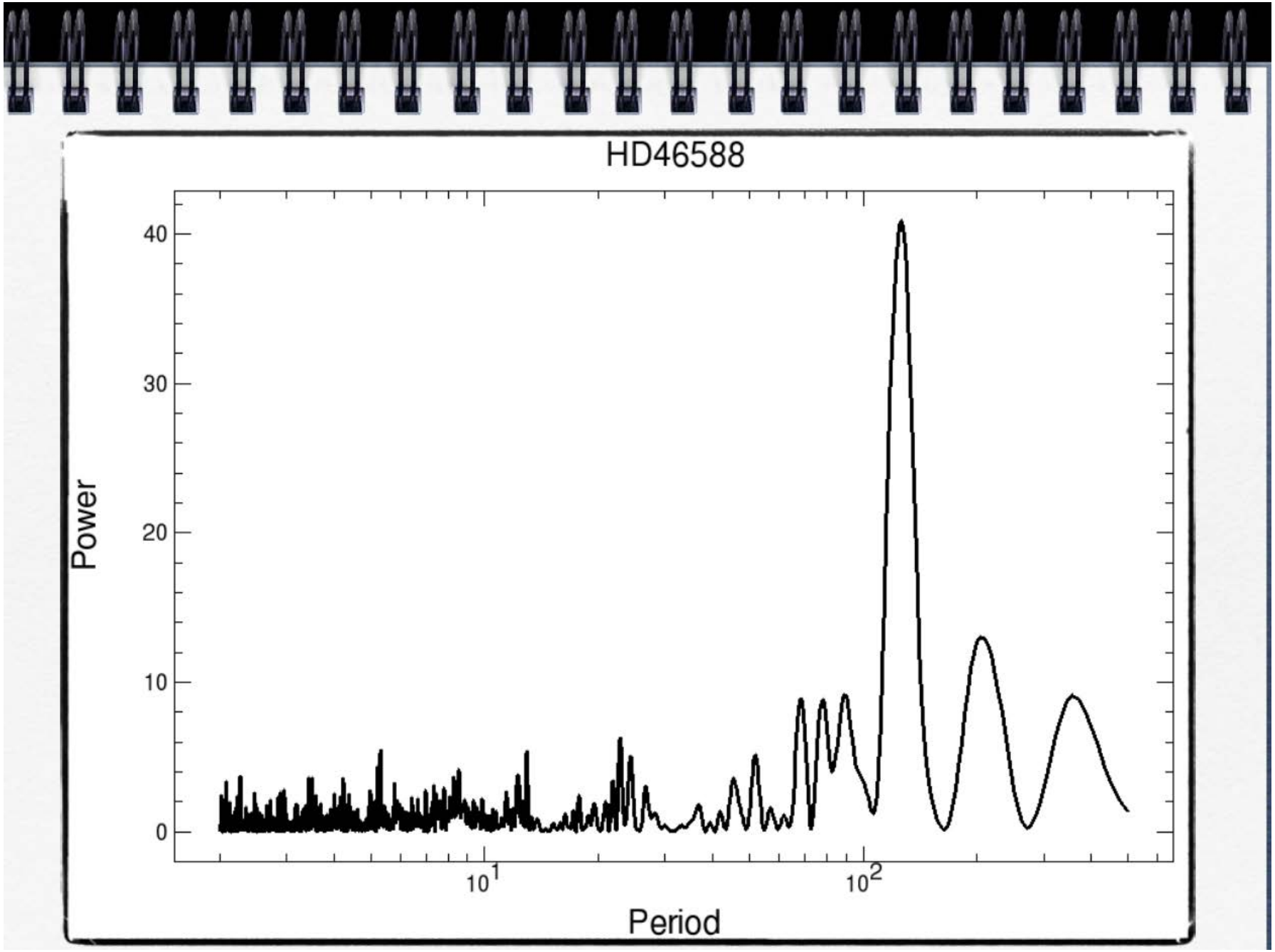


Talens et al. 2018 (MASCARA-2b)

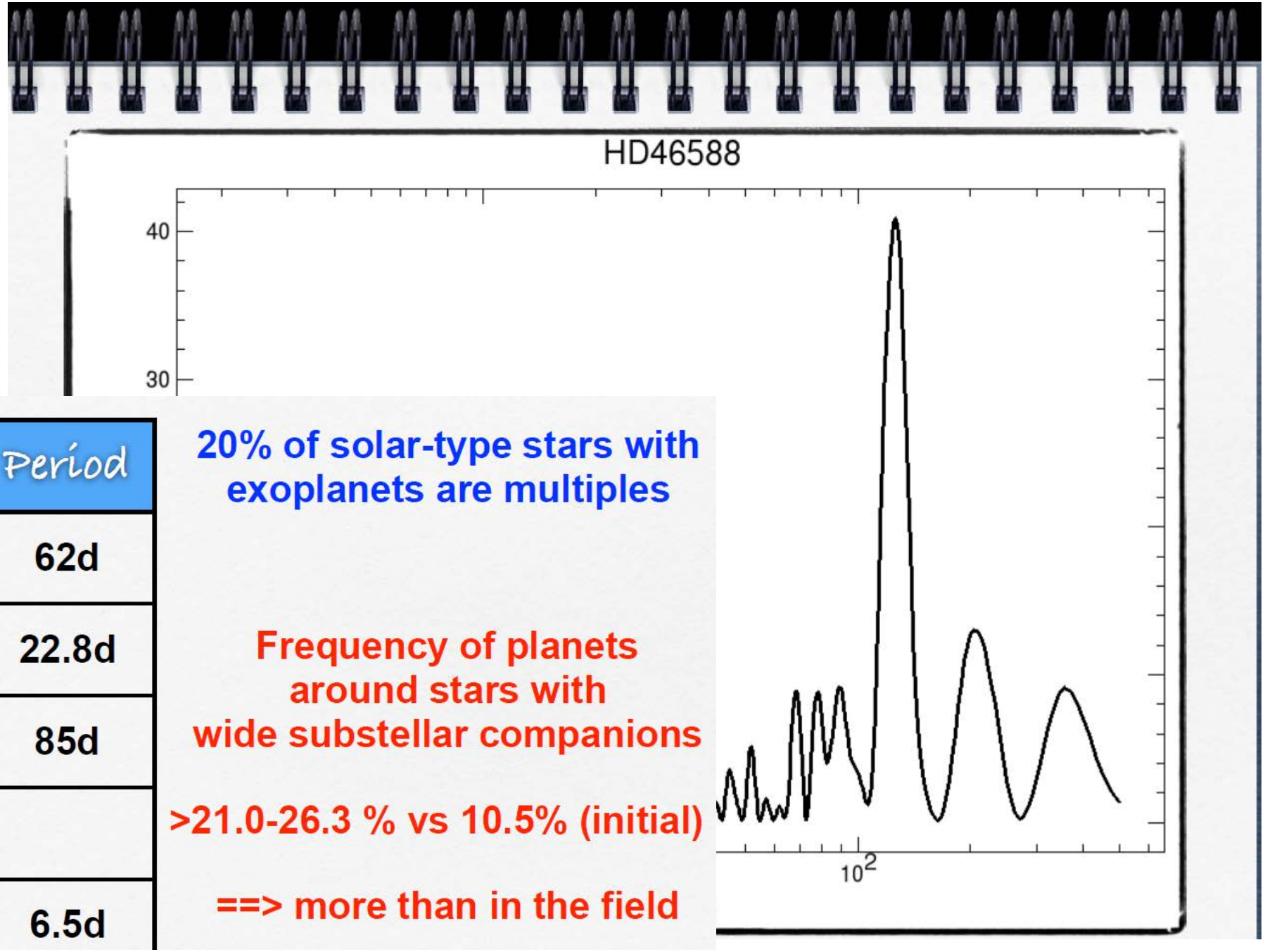


Hjorth et al. in prep (MASCARA-3b)

Nicolas Lodieu



Nicolas Lodieu



Name	Planet(s)	Period
HD3651	V	62d
HD46588	V	22.8d
GJ504	V	85d
HN Peg	X	
HD203030	?	6.5d

20% of solar-type stars with exoplanets are multiples

Frequency of planets around stars with wide substellar companions

>21.0-26.3 % vs 10.5% (initial)

==> more than in the field

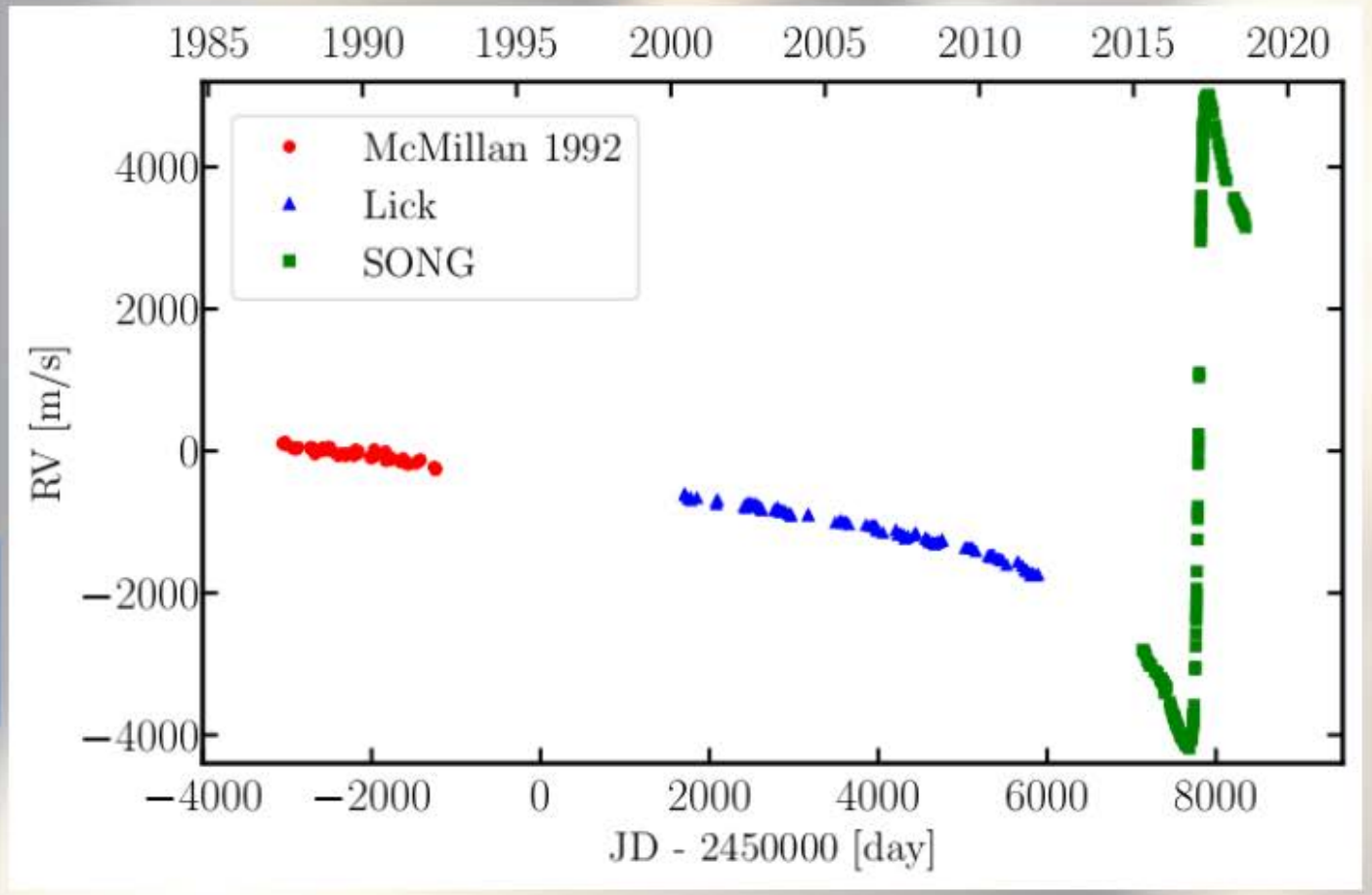
Planets around K/G giants

Paul Heeren
Exoplanet group
LSW - Heidelberg

If confirmed:

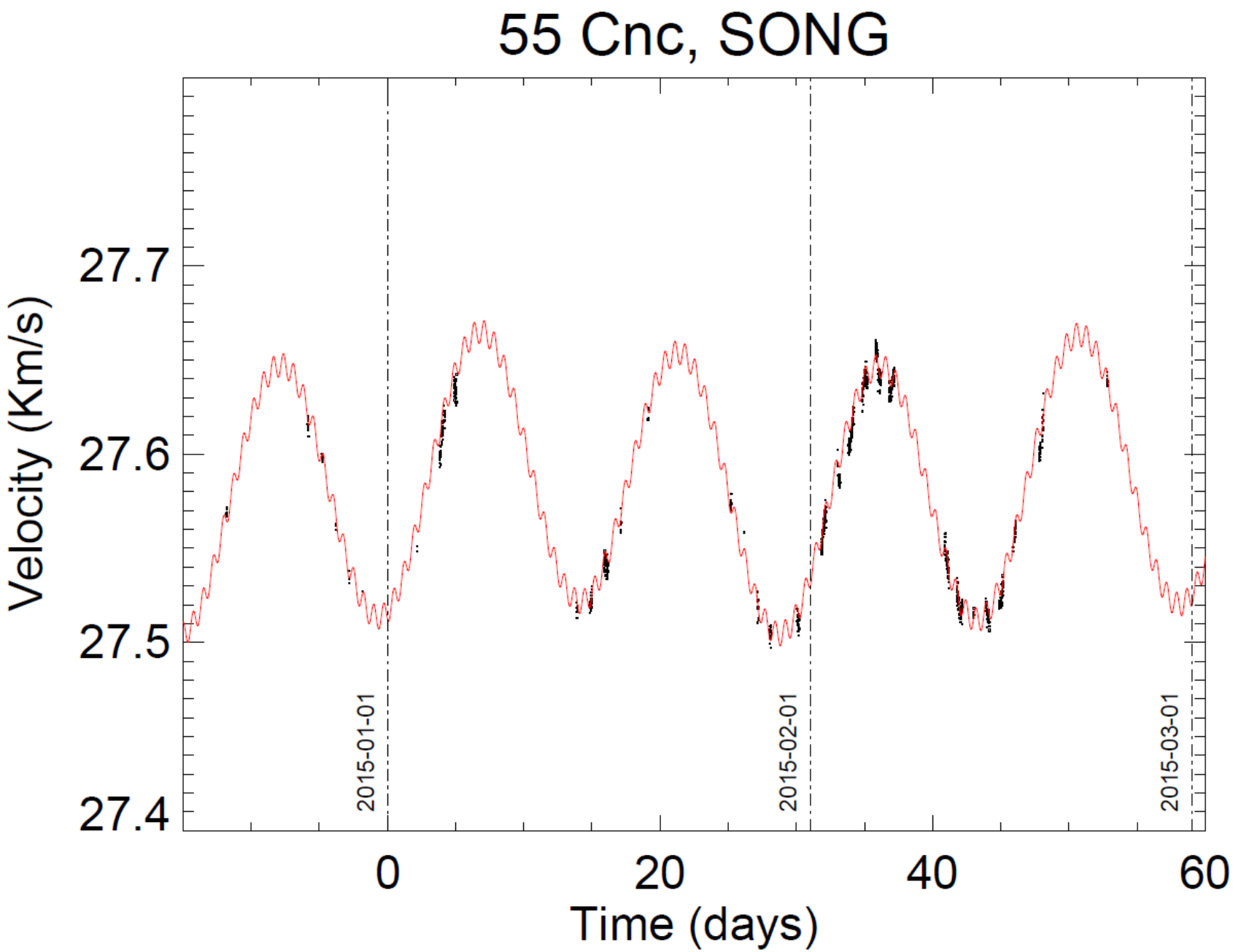
Some of the closest binaries known to date to host planets (or other interesting stuff like oscillations/heartbeats etc.?)

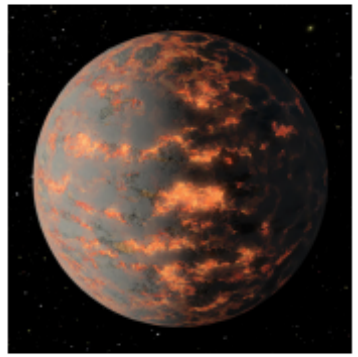
Test stone for planet formation theories



Extended survey durations needed

SONG helps us to constrain orbital parameters

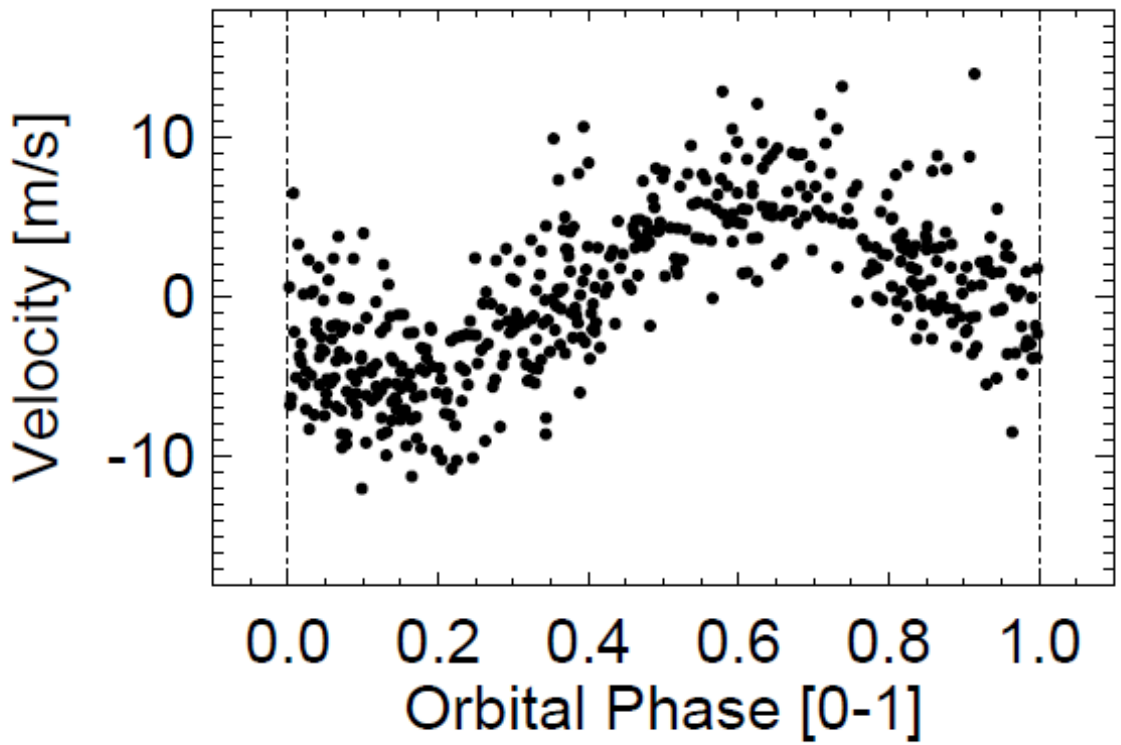

55 Cnc, SONG
Velocity (Km/s)
27.7
27.6
27.5
27.4
2015-01-01
2015-02-01
2015-03-01
0
20
40
60
Time (days)



Credit: NASA

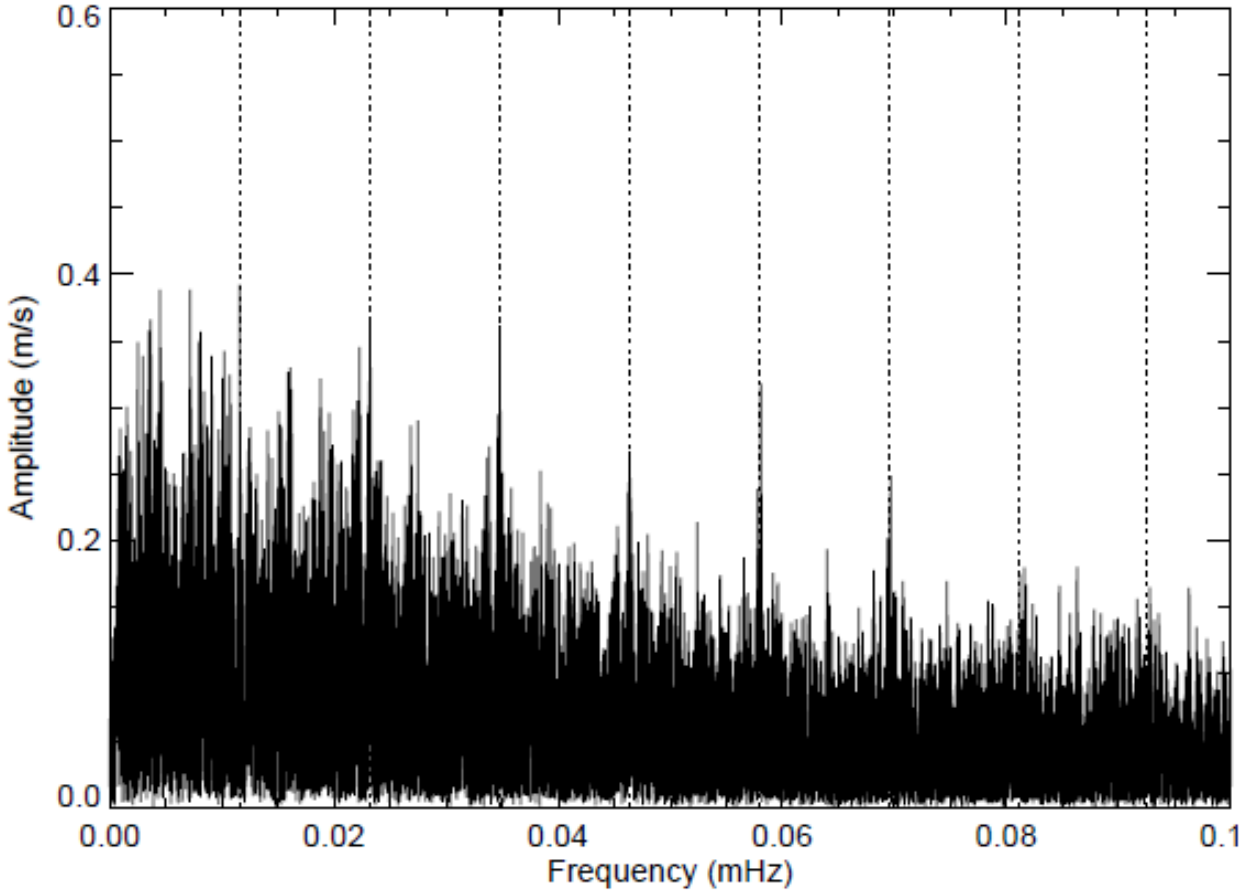
- Solar-like star.
- $P = 0.74$ days,
  $M_{\rm p} = 8.0\ {\rm M}_{\oplus}$,
  $R_{\rm p} = 1.9\ {\rm R}_{\oplus}$
  Bourrier et al. (2018).
- Figure: ~ 10 nights over two months with SONG.

Credit: Frank Grundahl (SONG)



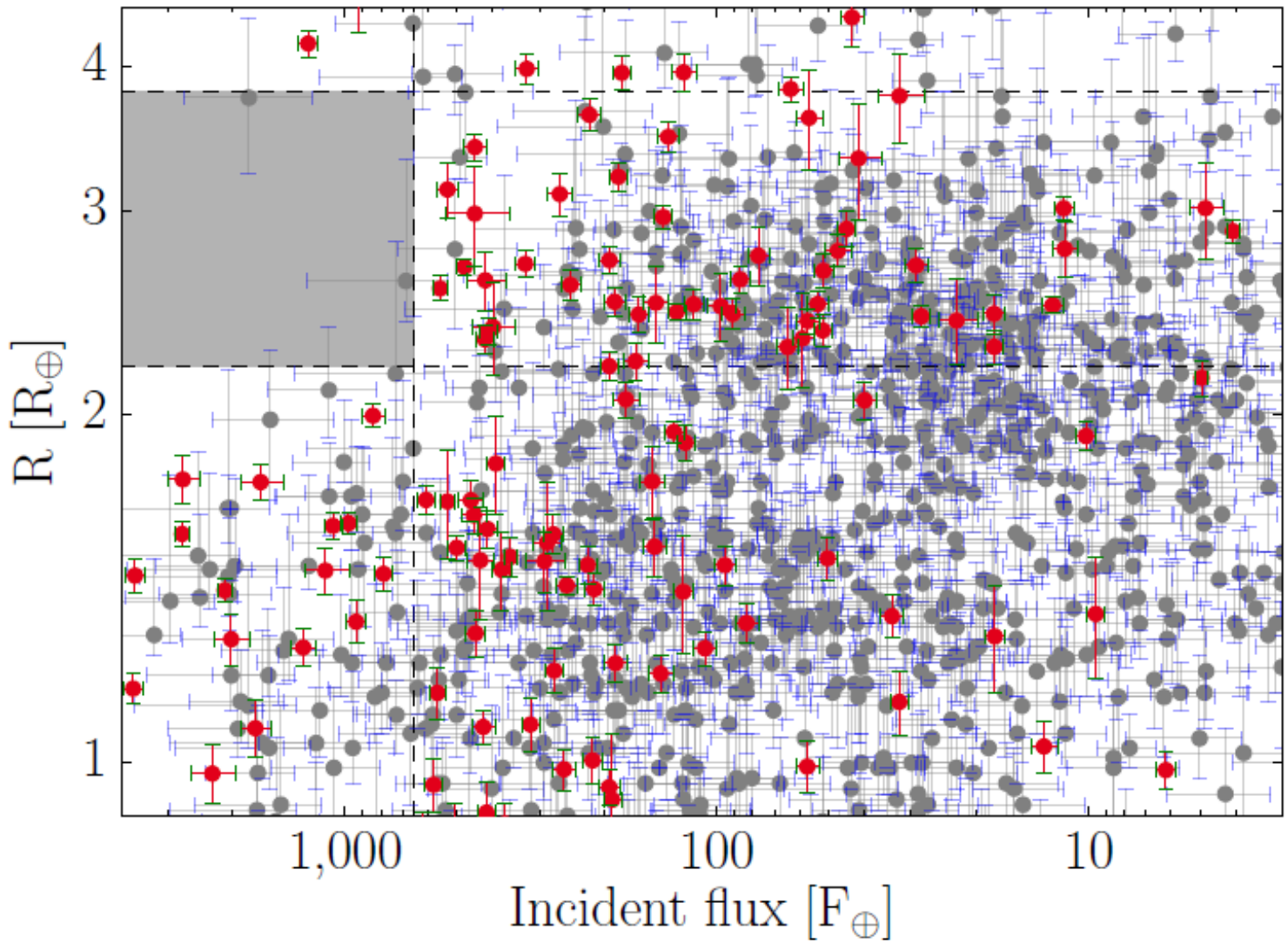
- SONG focuses on larger semiamplitudes (order $1\ \mathrm{m/s}$).
- $M_* = 1\ \mathrm{M}_\odot$ and $P = 2\ \mathrm{days} = 0.006\ \mu\mathrm{Hz}$.
- Upper-limit: $0.4\ \mathrm{m/s}$.

$\Rightarrow\ (m_\mathrm{p} \sin i)_\mathrm{min} \approx 0.8\ \mathrm{M}_\oplus$.

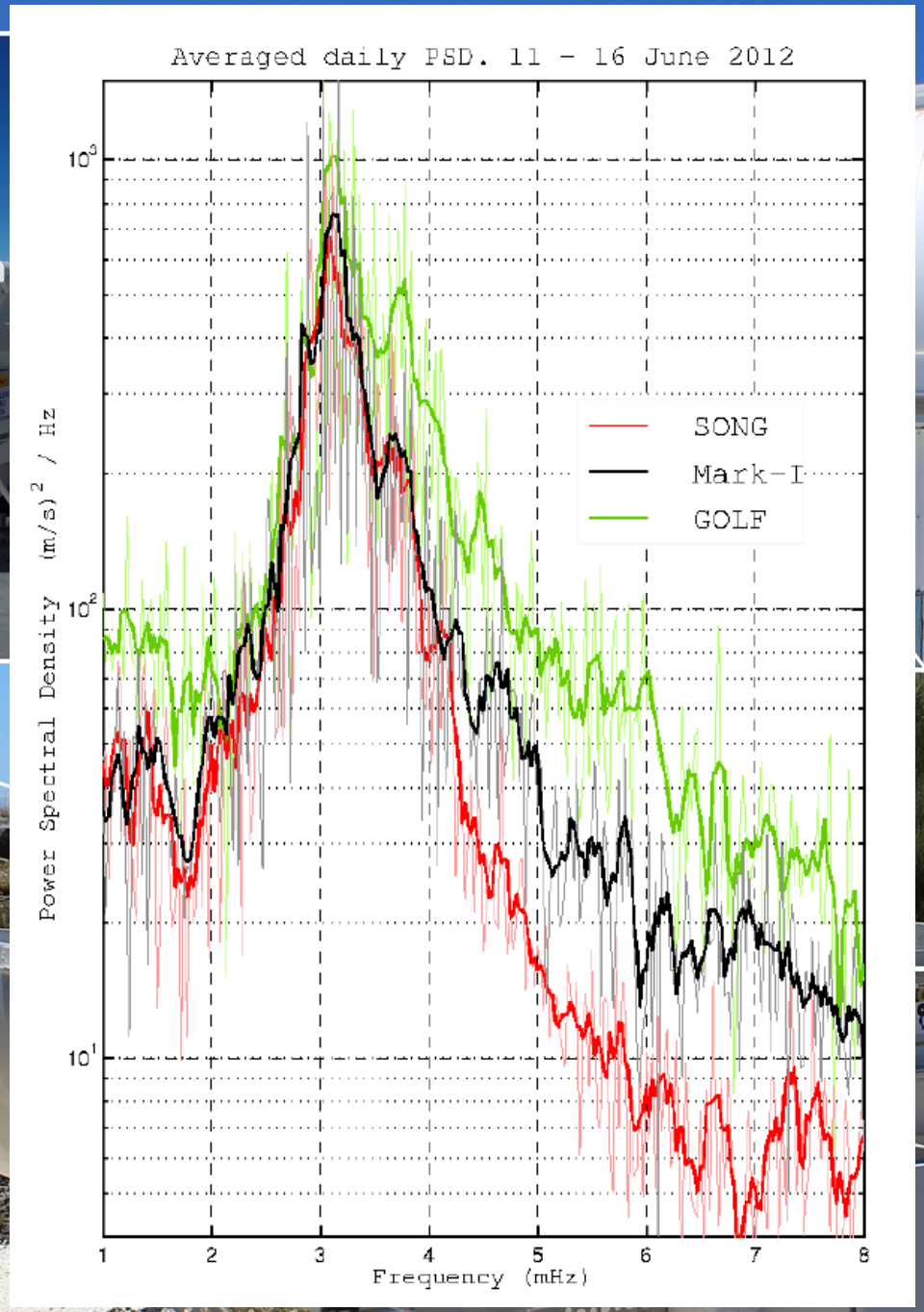


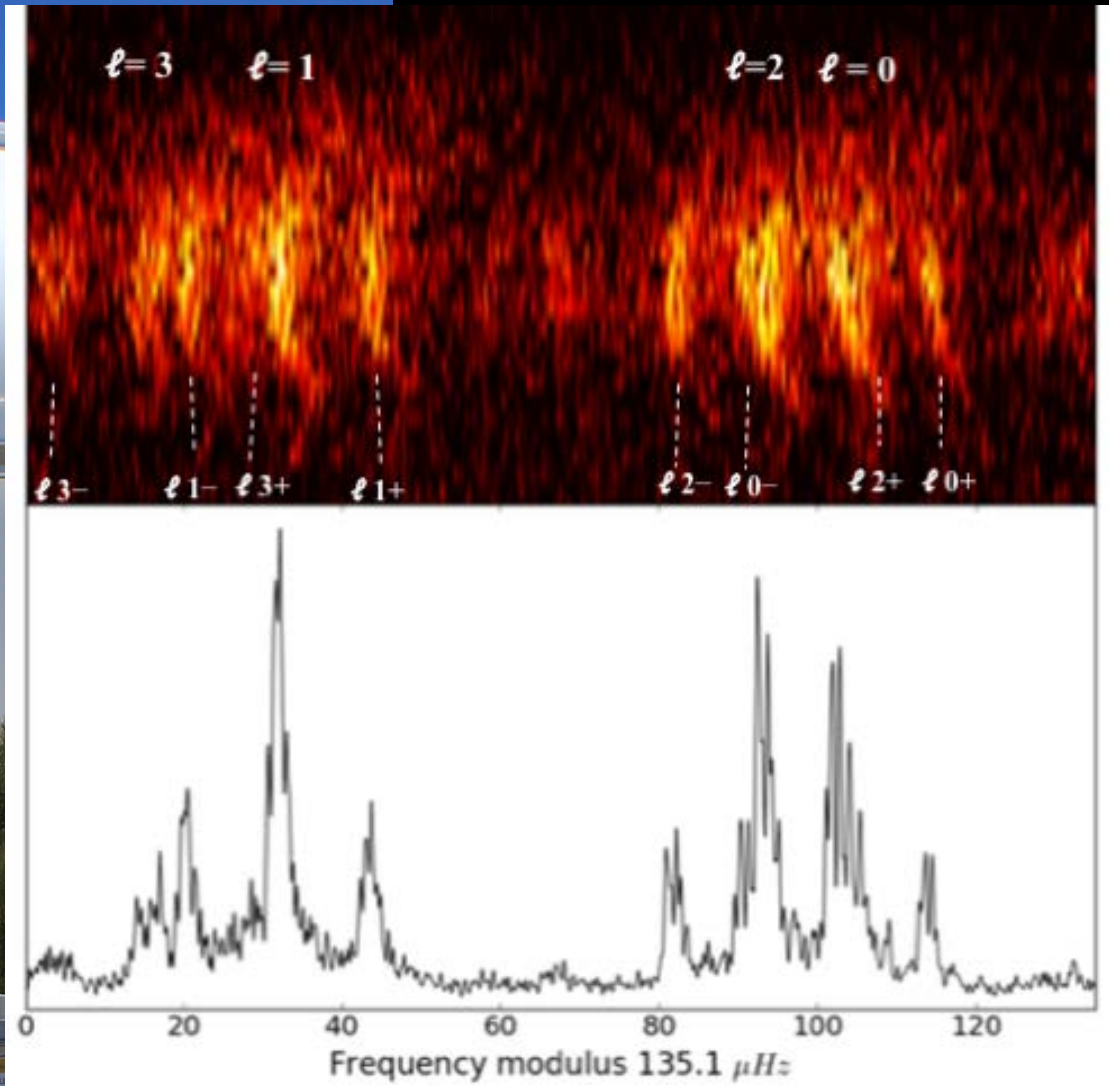
- SONG focuses on larger semiamplitudes (order 1 $\mathrm{m/s}$).
- $M_* = 1\ \mathrm{M}_\odot$ and $P = 2\ \mathrm{days} = 0.006\ \mu\mathrm{Hz}$.
- Upper-limit: 0.4 $\mathrm{m/s}$.

$\Rightarrow\ (m_\mathrm{p} \sin i)_\mathrm{min} \approx 0.8\ \mathrm{M}_\oplus$.

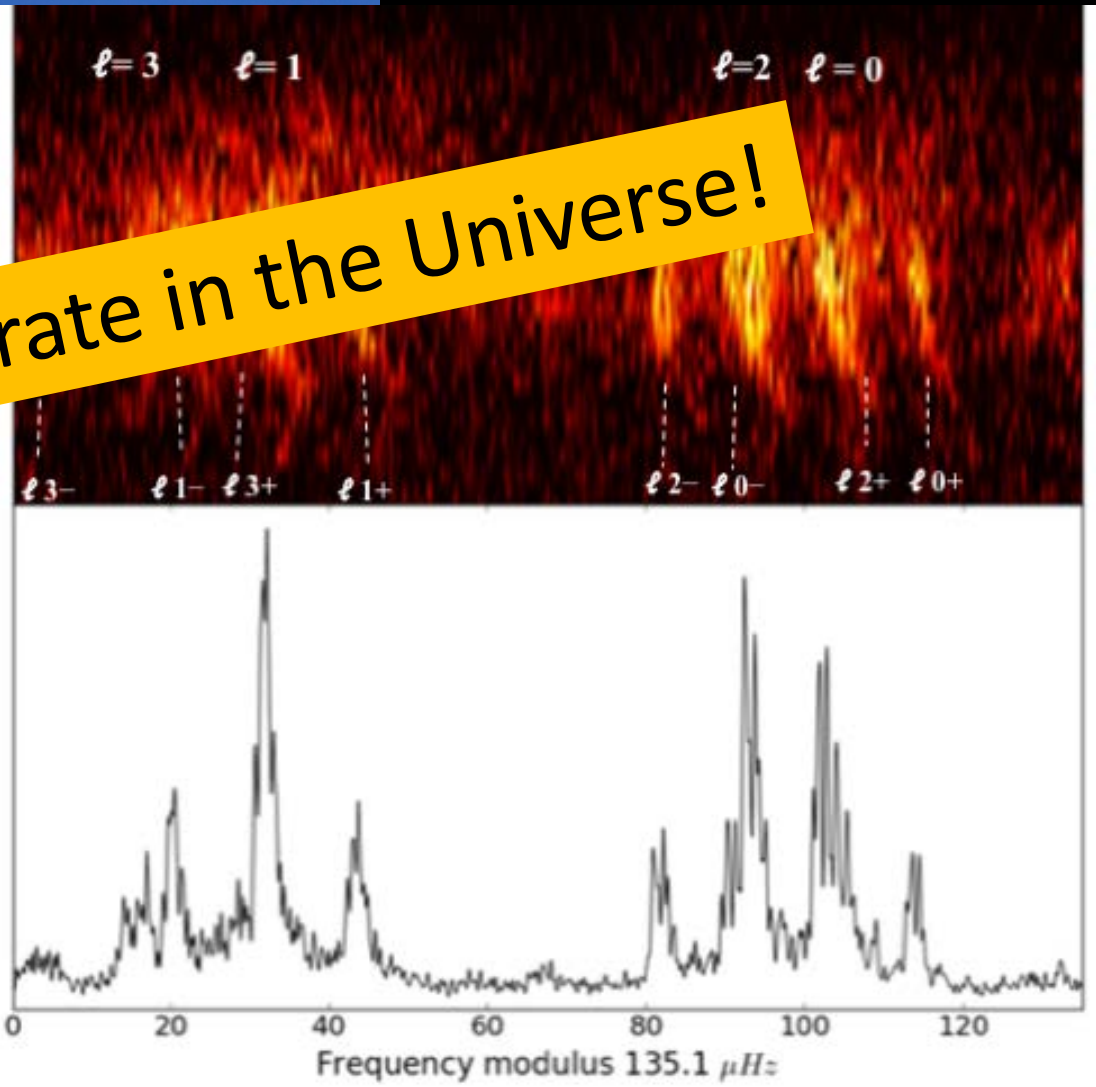


Solar-SONG:
400 µm telescope


Averaged daily PSD. 11 - 16 June 2012
Power Spectral Density (m/s)^2 / Hz
10^3
10^2
10^1
SONG
Mark-I
GOLF
1
2
3
4
5
6
7
8
Frequency (mHz)


ℓ= 3
ℓ= 1
ℓ=2
ℓ = 0
ℓ3−
ℓ1−
ℓ3+
ℓ1+
ℓ2−
ℓ0−
ℓ2+
ℓ0+
0
20
40
60
80
100
120
Frequency modulus 135.1 μHz

The most accurate in the Universe!



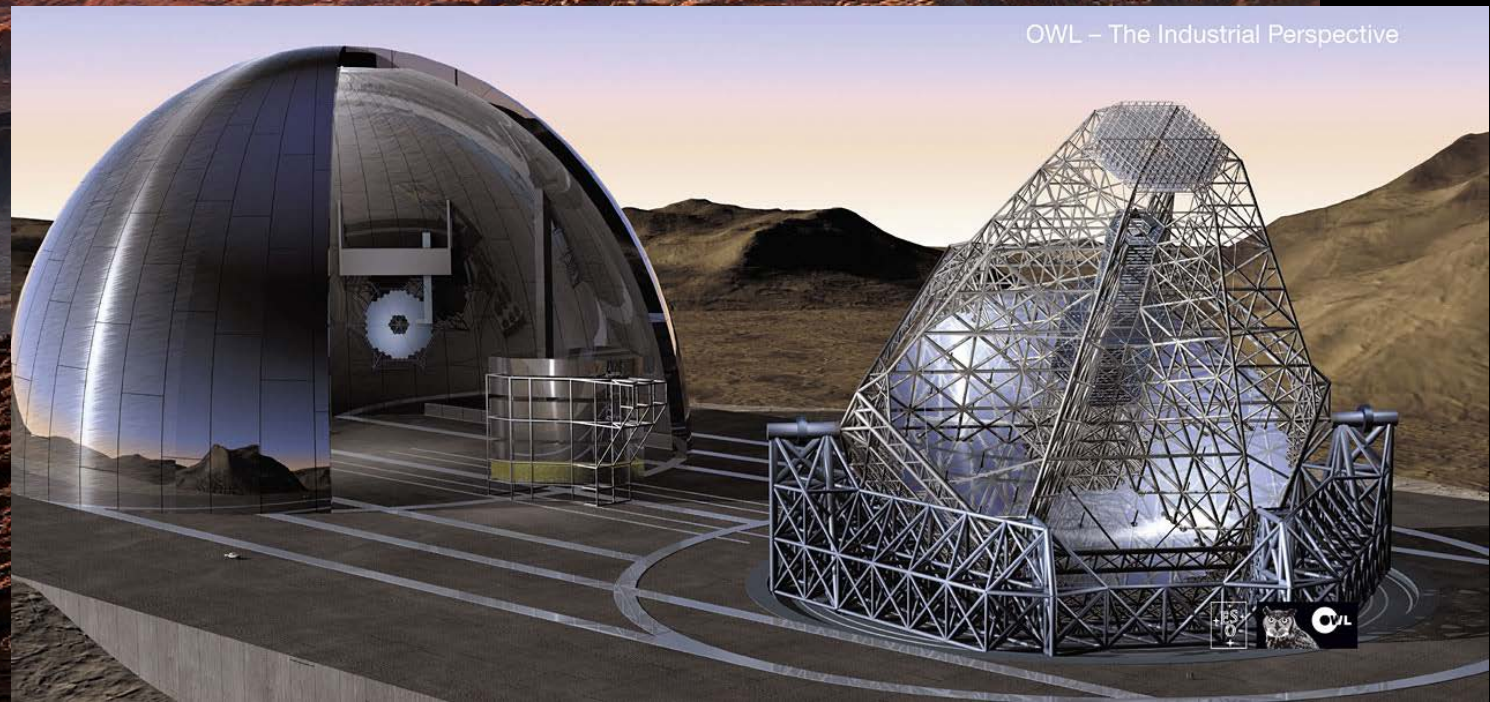
Solar-SONG:
400 µm telescope


Proxima b

Proxima b

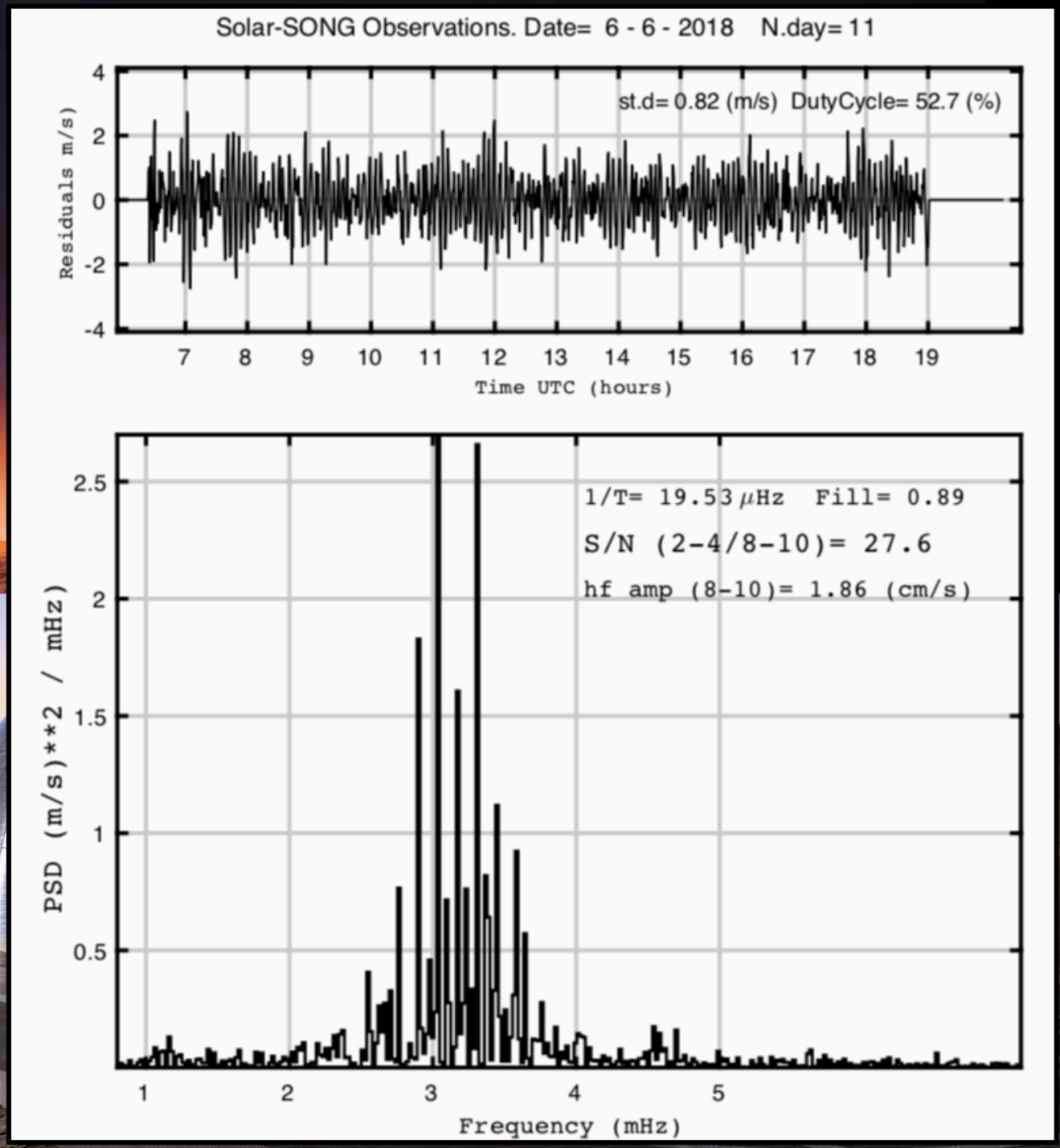
Solar-SONG:
400 µm telescope

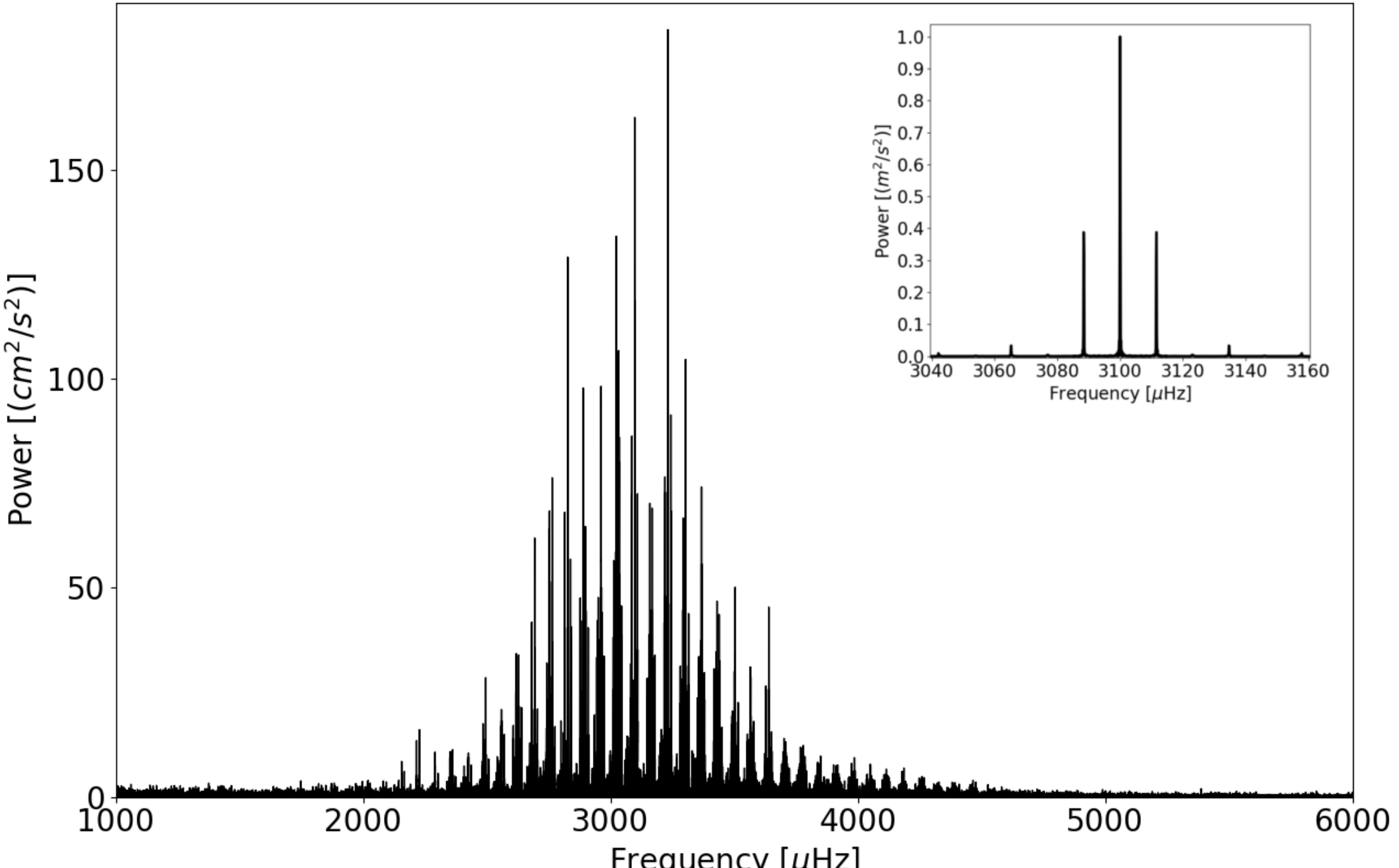
Solar-Proxima b:
140 m telescope

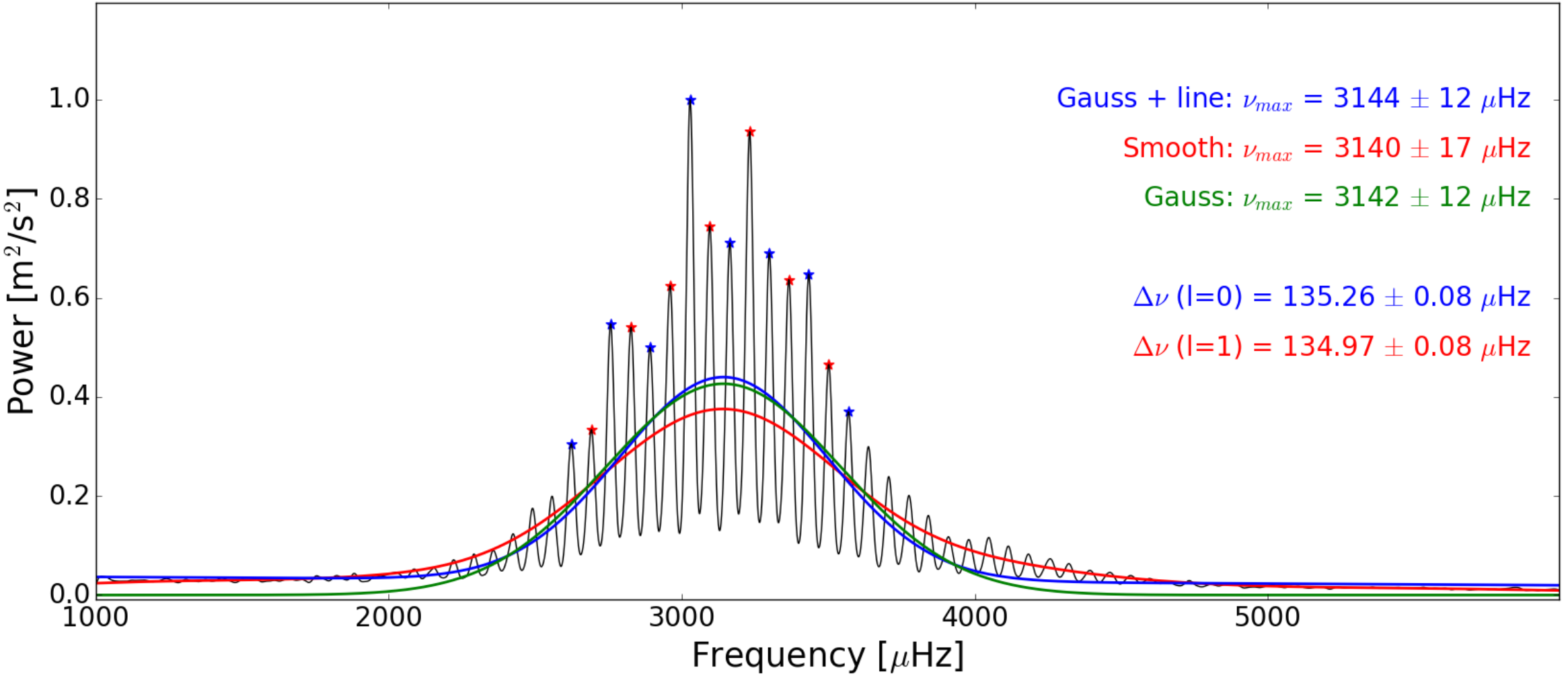


Solar-SONG:
400 µm telescope

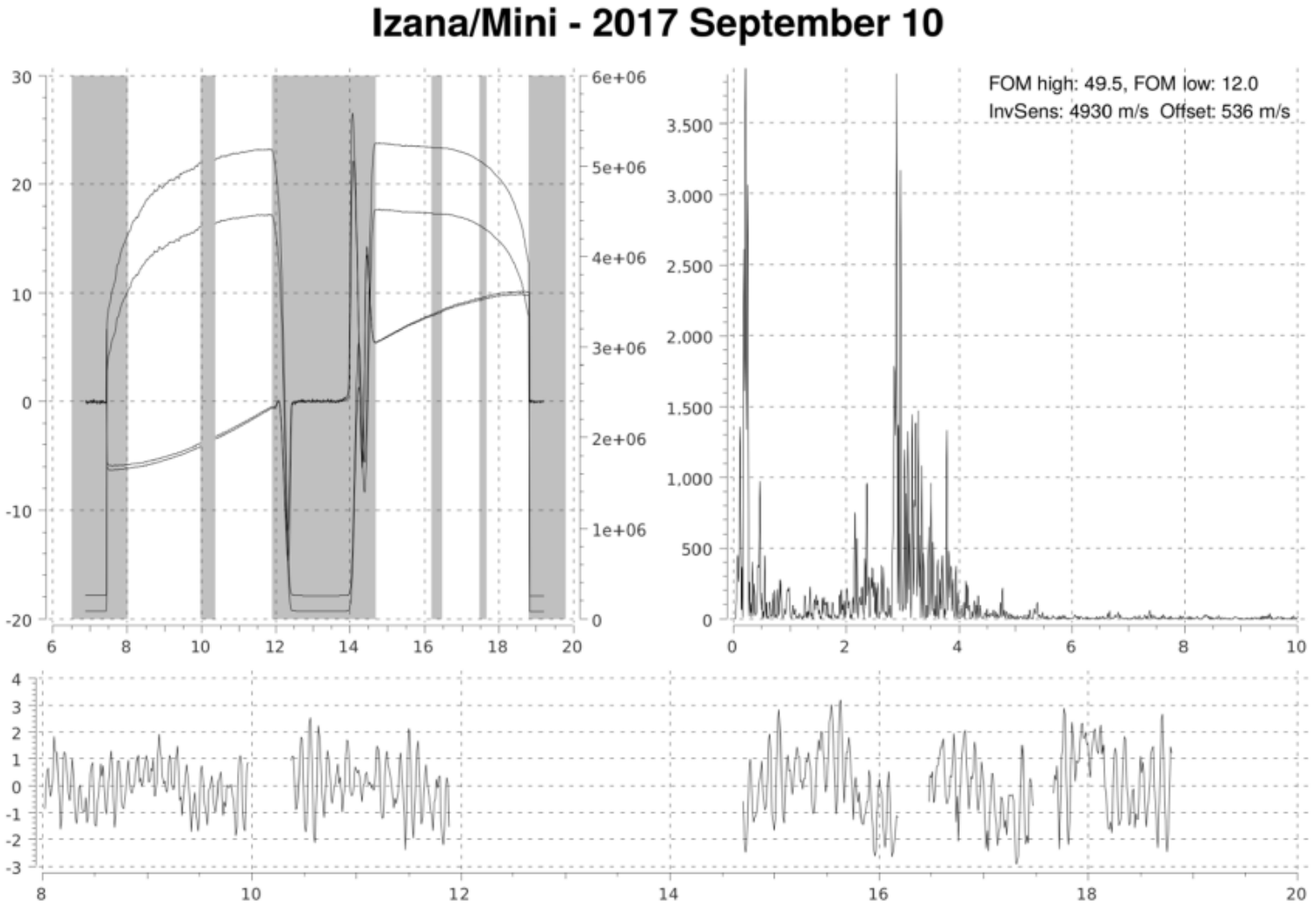
Solar-Proxima b:
140 m telescope




Power [(cm^2/s^2)]
Frequency [μHz]
0
50
100
150
1000
2000
3000
4000
5000
6000
Power [(m^2/s^2)]
Frequency [μHz]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
3040
3060
3080
3100
3120
3140
3160


Gauss + line: ν_{max} = 3144 ± 12 μHz
Smooth: ν_{max} = 3140 ± 17 μHz
Gauss: ν_{max} = 3142 ± 12 μHz
$\Delta\nu$ (l=0) = 135.26 ± 0.08 μHz
$\Delta\nu$ (l=1) = 134.97 ± 0.08 μHz
Power [m^2/s^2]
Frequency [μHz]
0.0
0.2
0.4
0.6
0.8
1.0
1000
2000
3000
4000
5000

BiSON-Izana - Use light from coelostat plus fibre to feed new mini spectrometer. Very good quality.



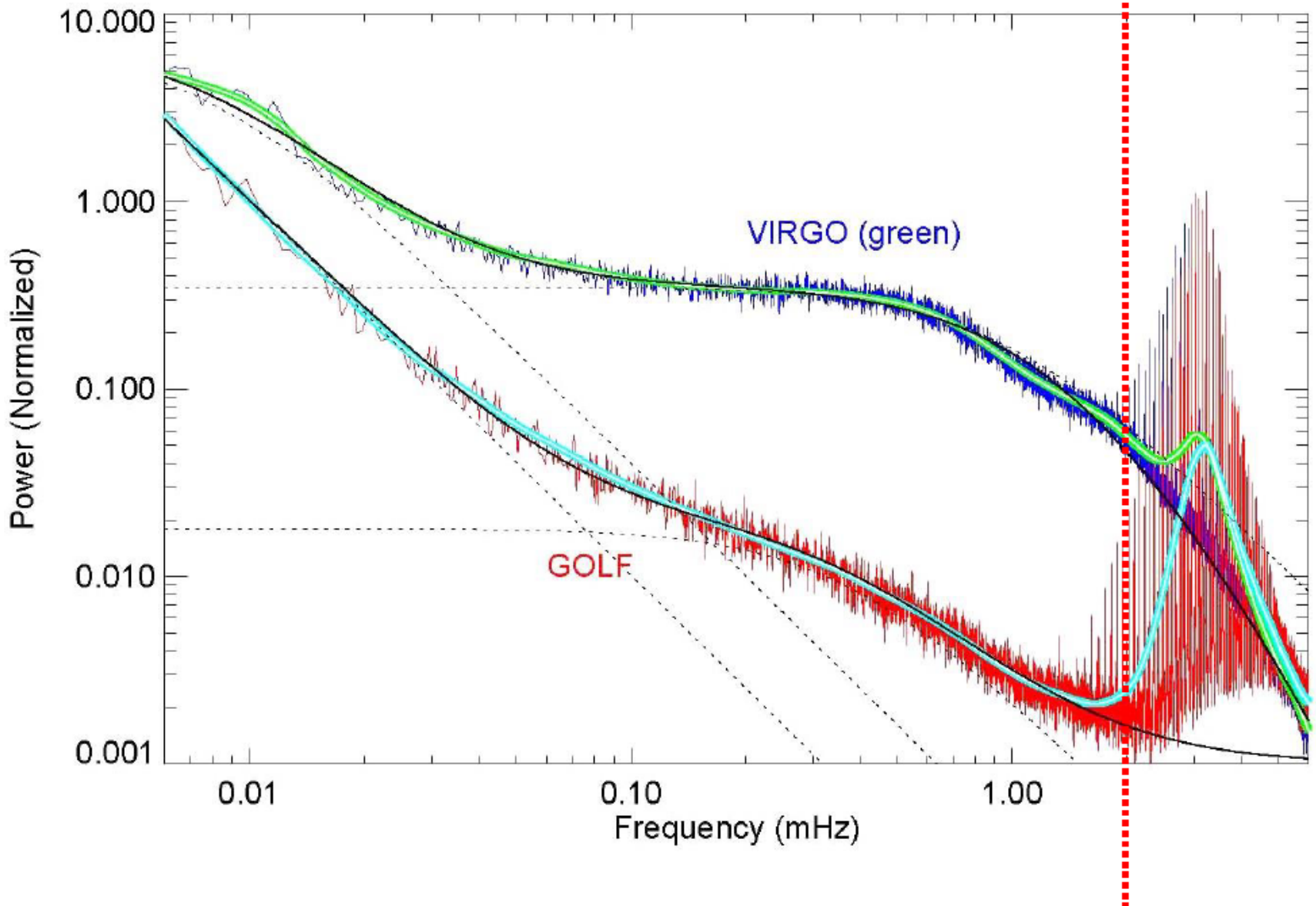
Outreach and Recruitment

Upper secondary School visits

The SONG synergies

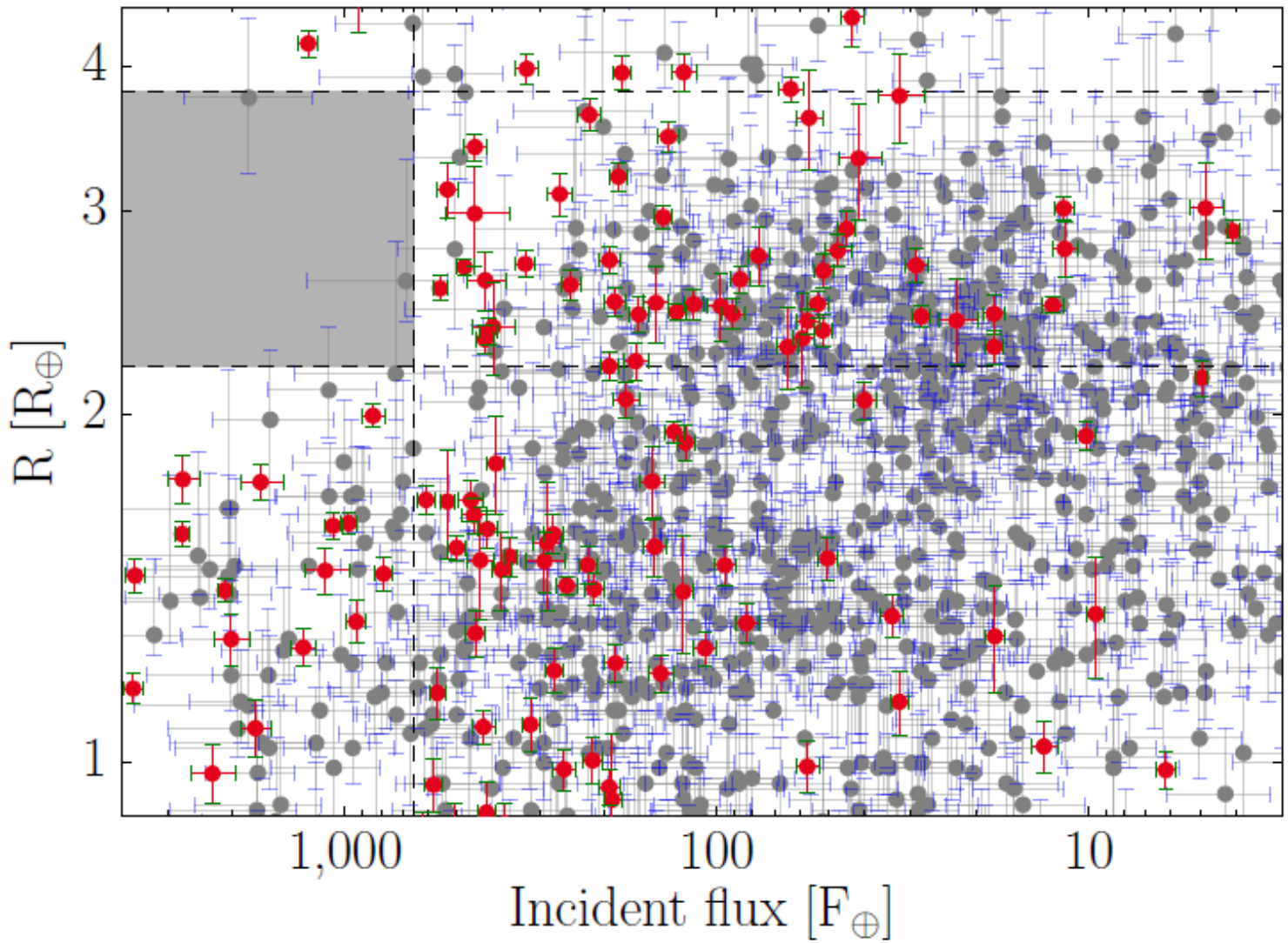
- TESS (Kepler, PLATO, CHEOPS)
- BRITE
- Other telescopes (NOT, TNG, ESO, AAT, Gemini, Keck…

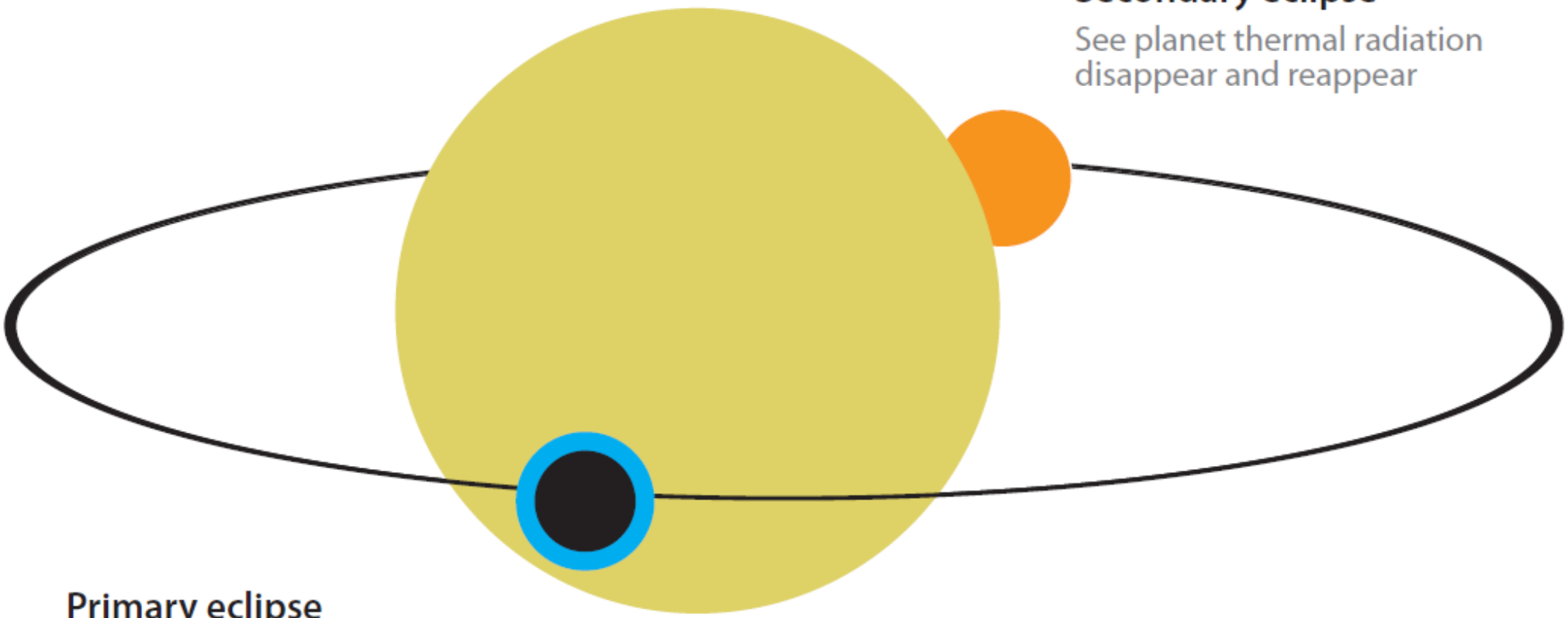
Stellar noise vs. oscillations



- SONG focuses on larger semiamplitudes (order 1 $\mathrm{m/s}$).
- $M_* = 1\ \mathrm{M}_\odot$ and $P = 2\ \mathrm{days} = 0.006\ \mu\mathrm{Hz}$.
- Upper-limit: 0.4 $\mathrm{m/s}$.

$\Rightarrow\ (m_\mathrm{p} \sin i)_\mathrm{min} \approx 0.8\ \mathrm{M}_\oplus$.





Secondary eclipse

See planet thermal radiation disappear and reappear

Primary eclipse

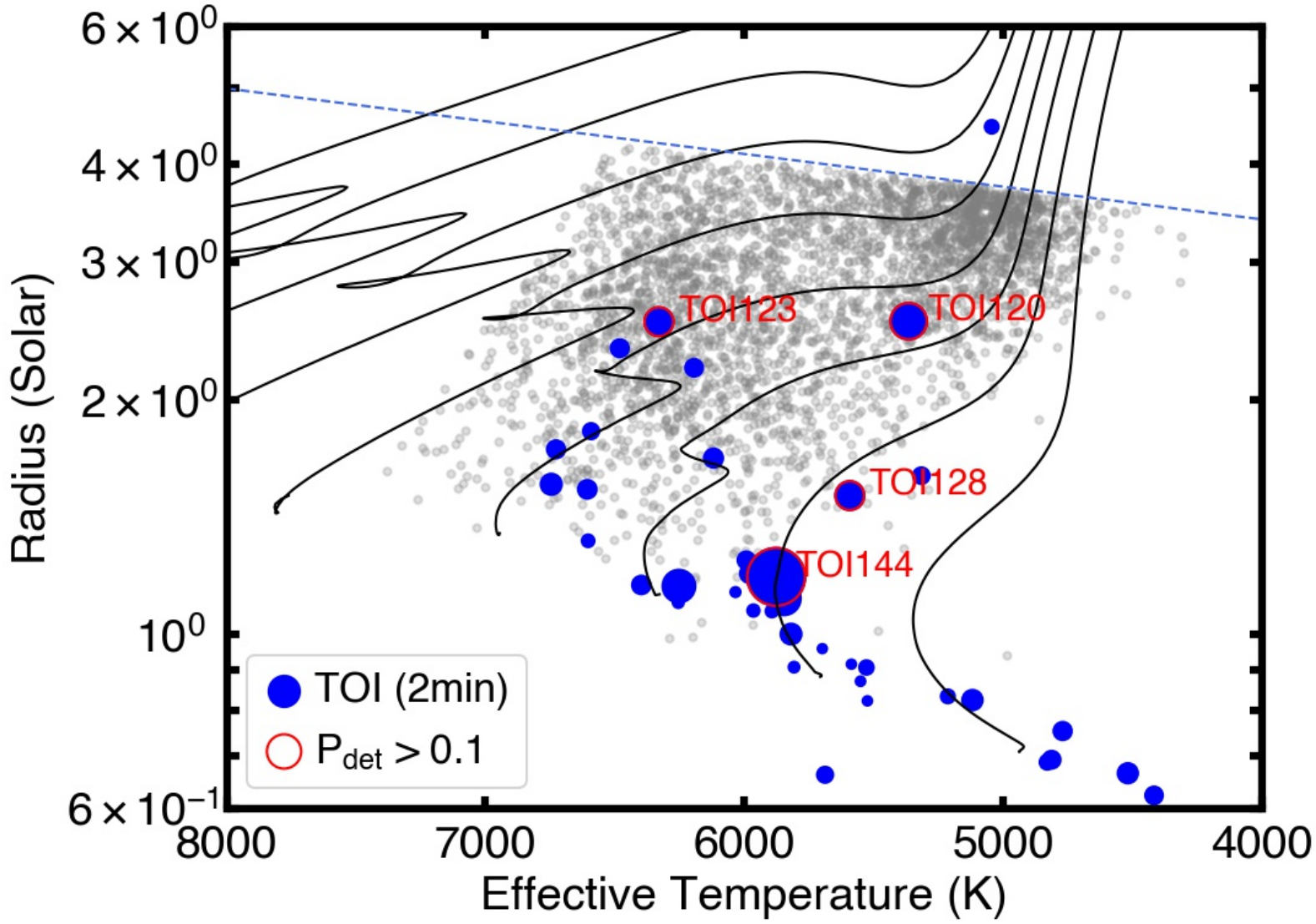
Measure size of planet

See star's radiation transmitted through the planet atmosphere

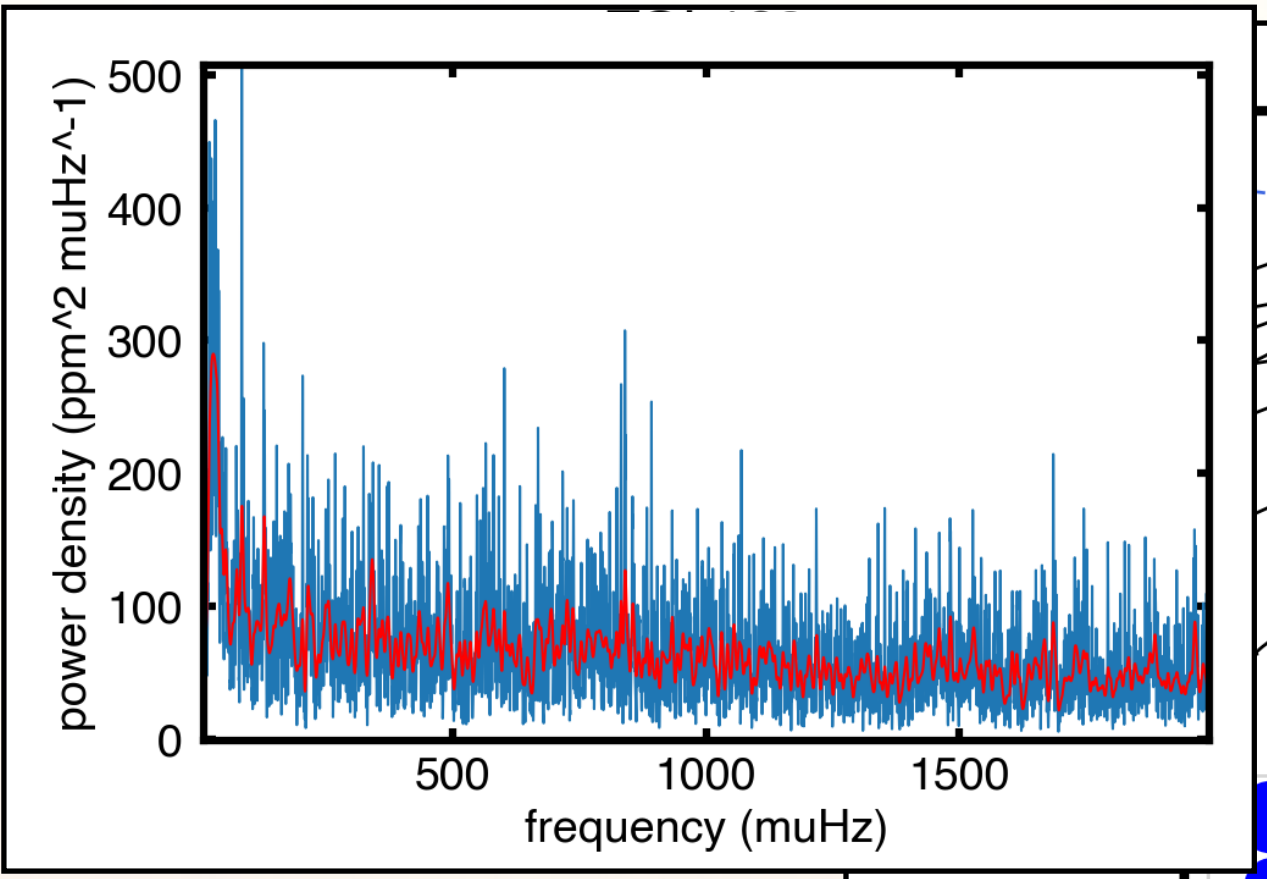
Learn about atmospheric circulation from thermal phase curves

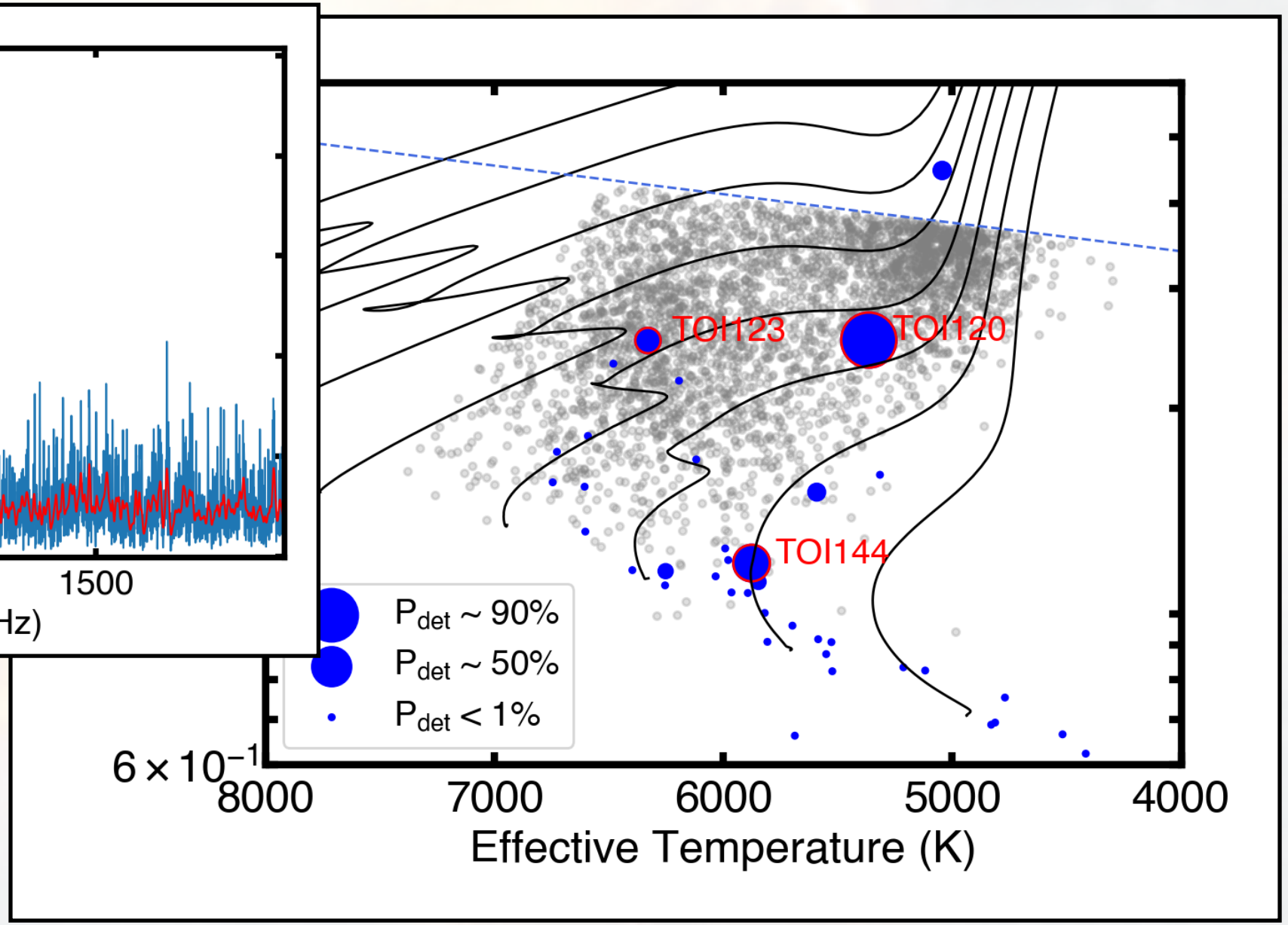
Seager et al. 2014

First Discoveries: TESS Alerts

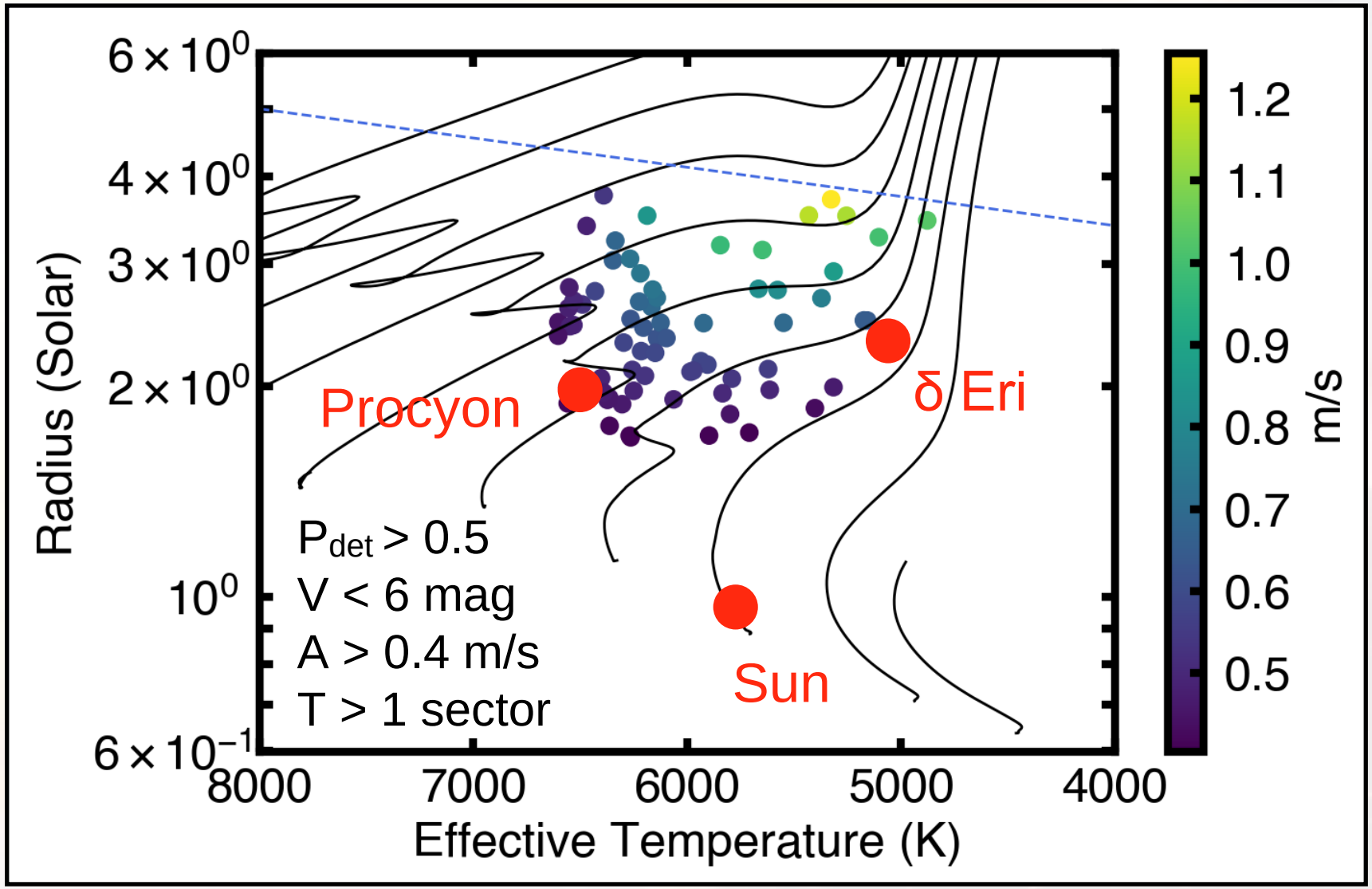


Asteroseismology of TESS Alerts

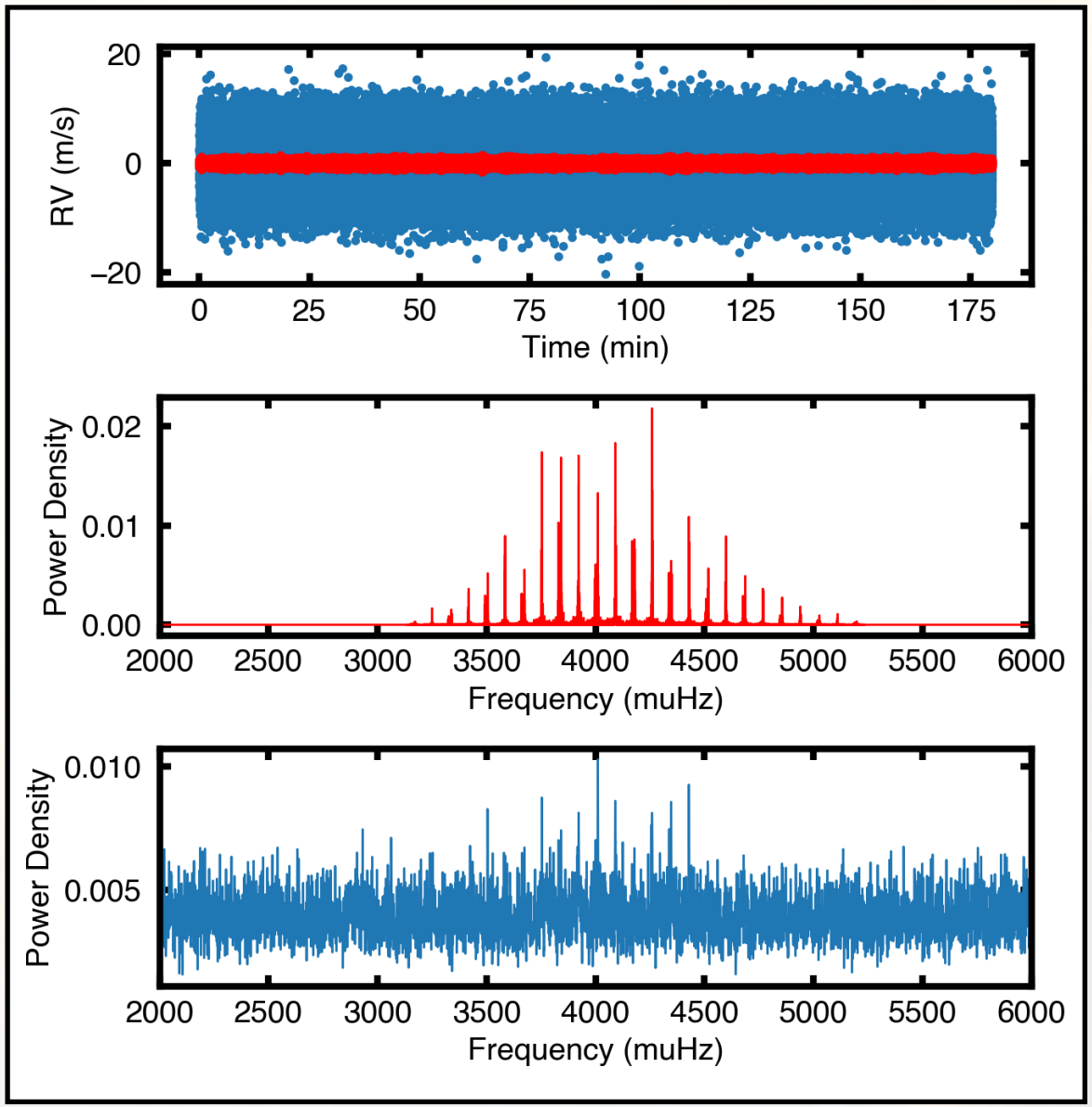




The SONG-TESS Sample



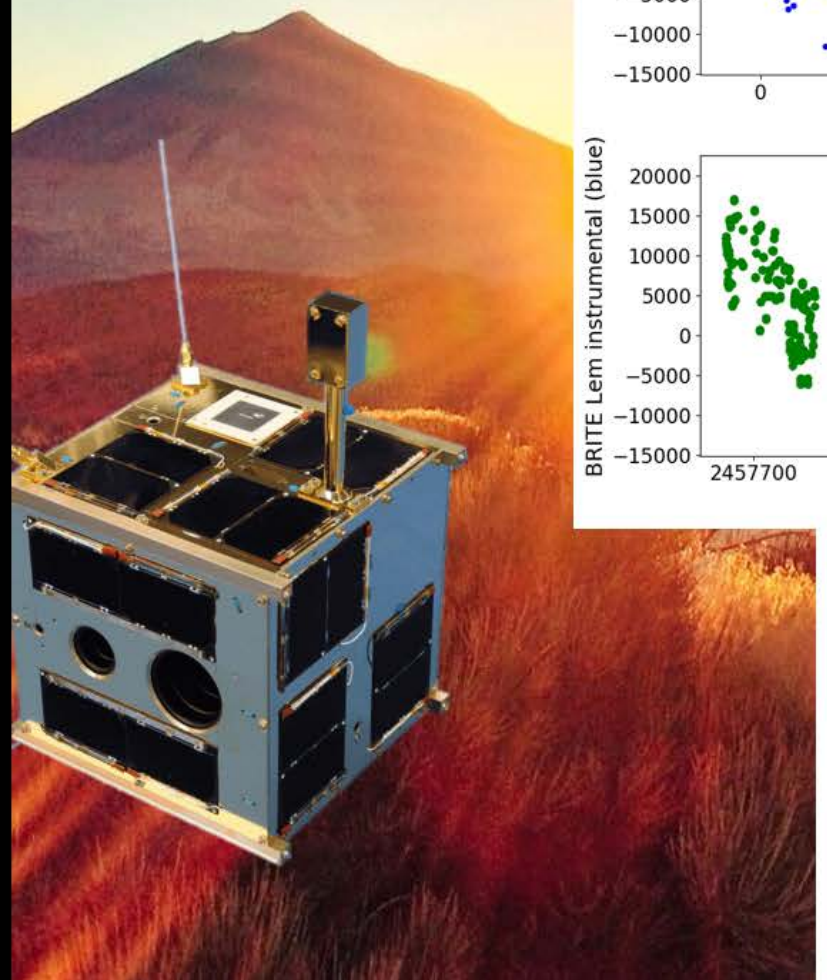
Late G / early K with SONG

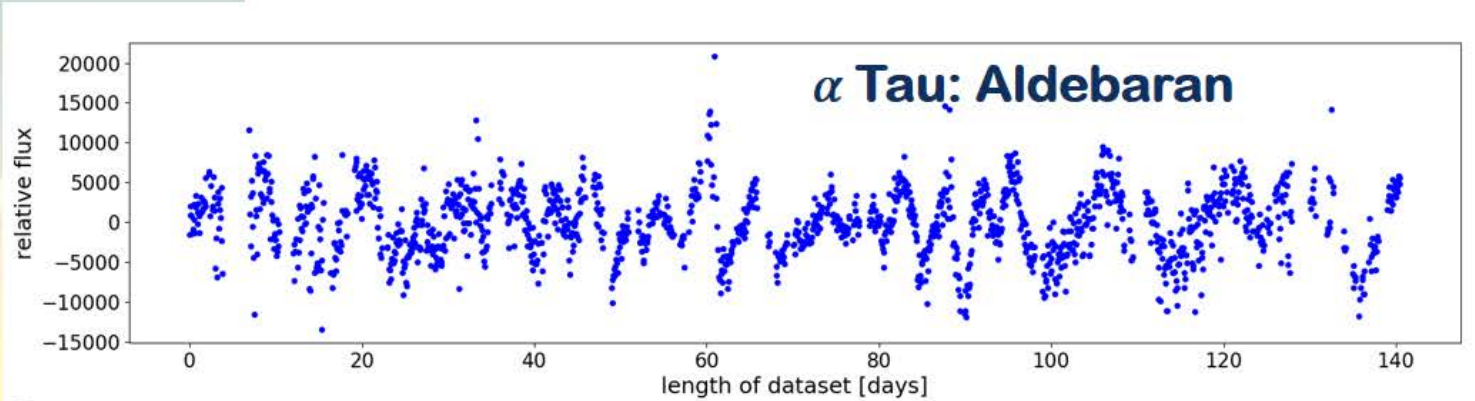


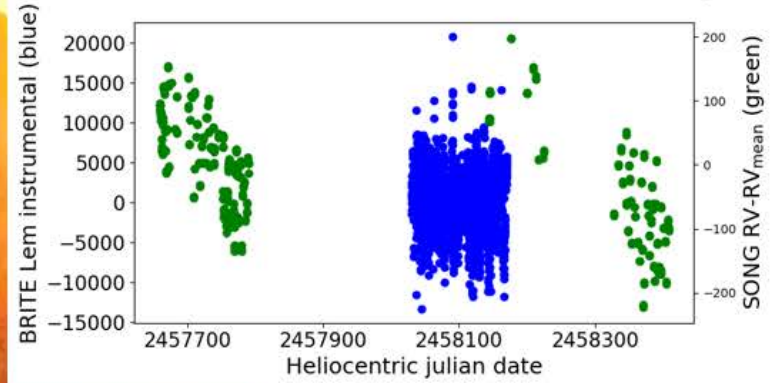
- ~6 month observations with ~80% duty cycle, 1 minute cadence with 4 m/s RV precision (cf σ Dra)
- ~8 cm/s amplitude (similar to α Cen b)
- Observations don't need to be contiguous!

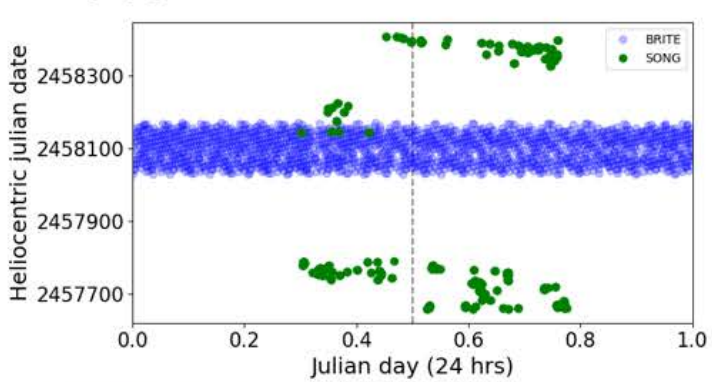
P. Beck

BRITE & SONG



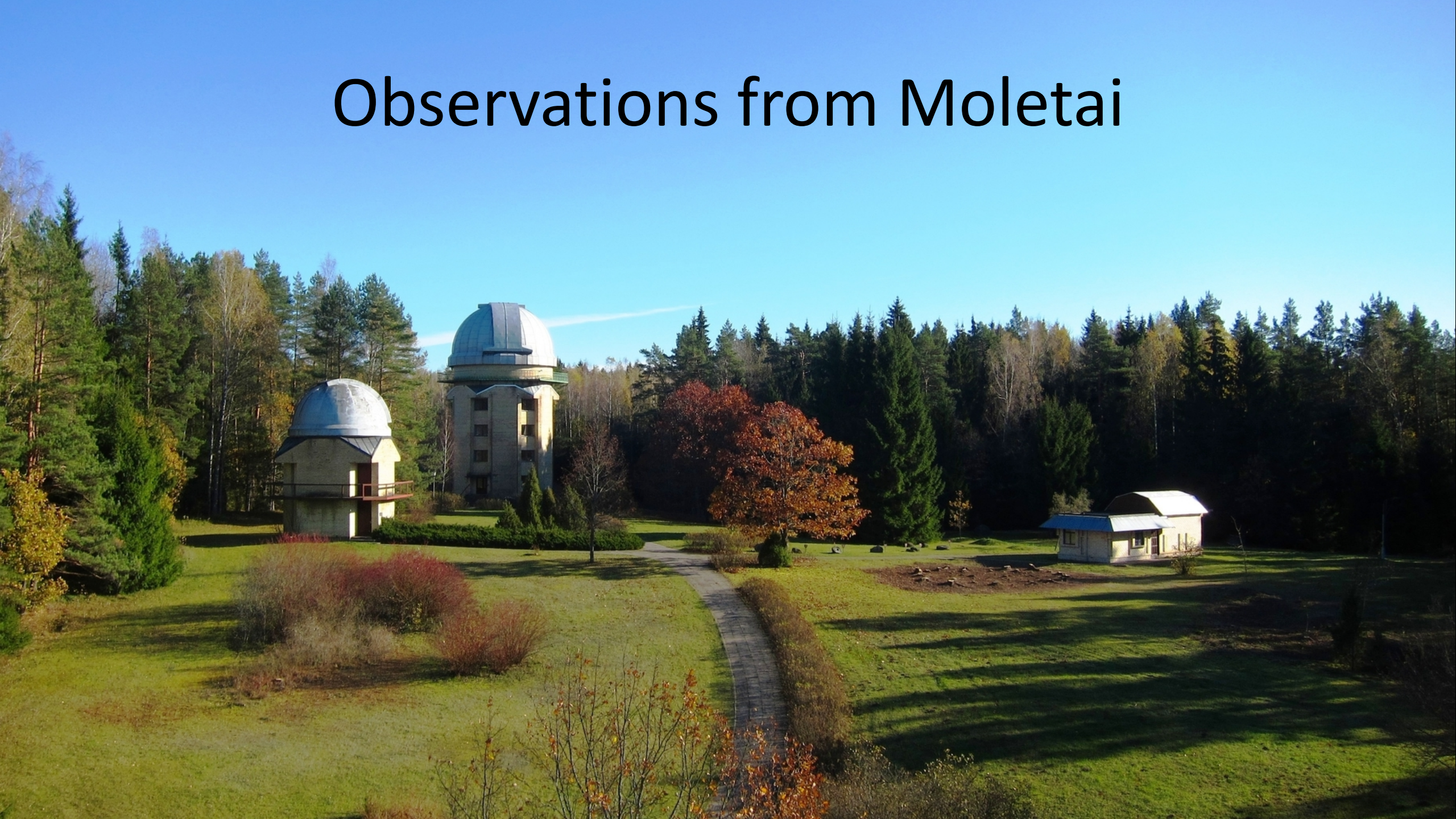






TNG

Observations from Moletai



SONG – collaborations and nodes

- Inviting more researchers (incl. students) from the community to become partners in our collaboration
- Additional nodes

Delingha site

SONG Australia


Let’s all get back to work!