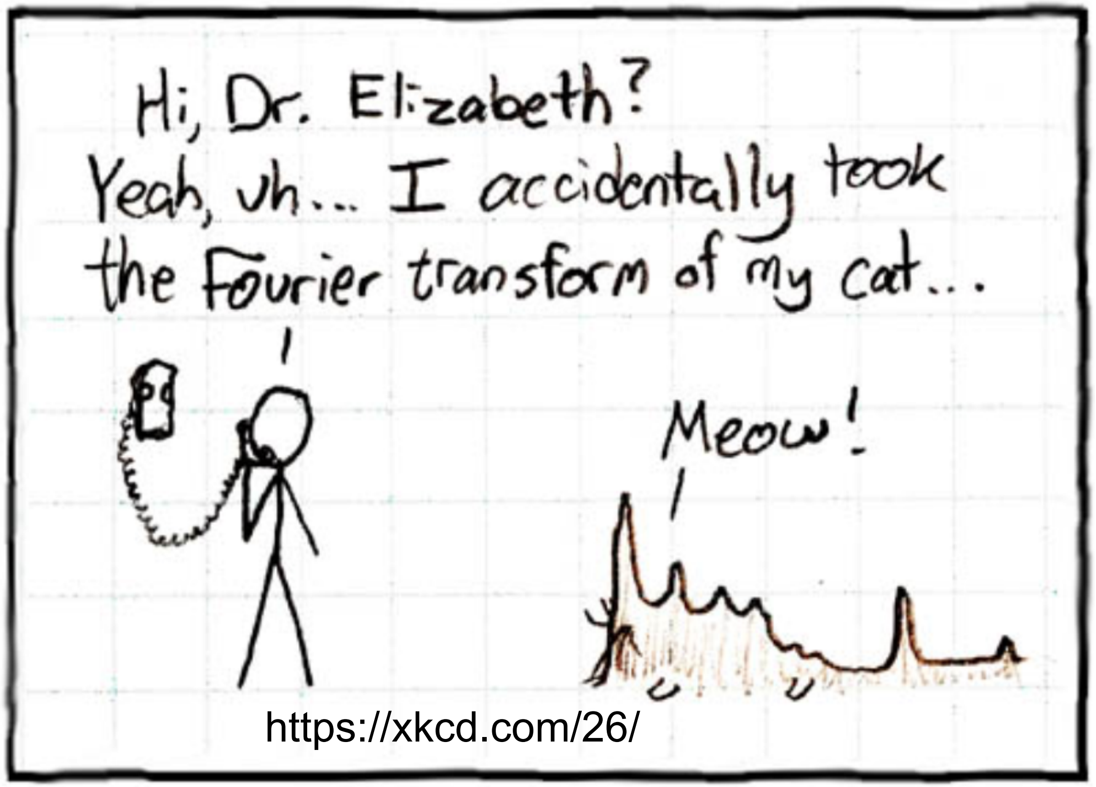
Asteroseismology with SONG

Tim Bedding

THE UNIVERSITY OF SYDNEY

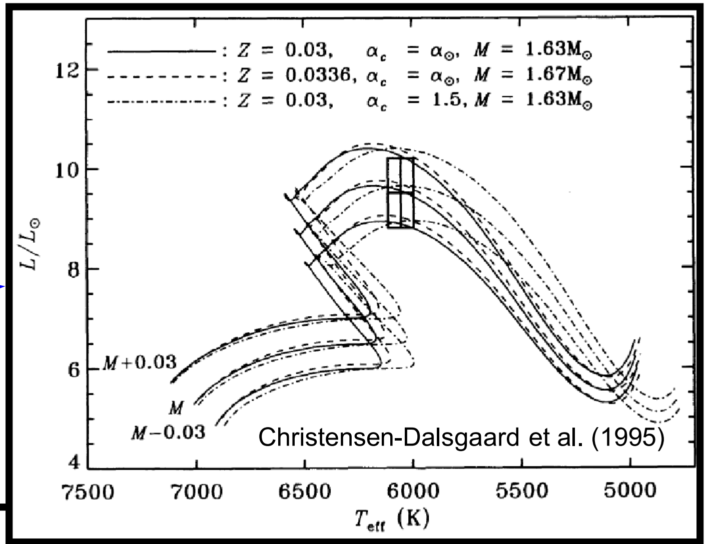
STELLAR ASTROPHYSICS CENTRE



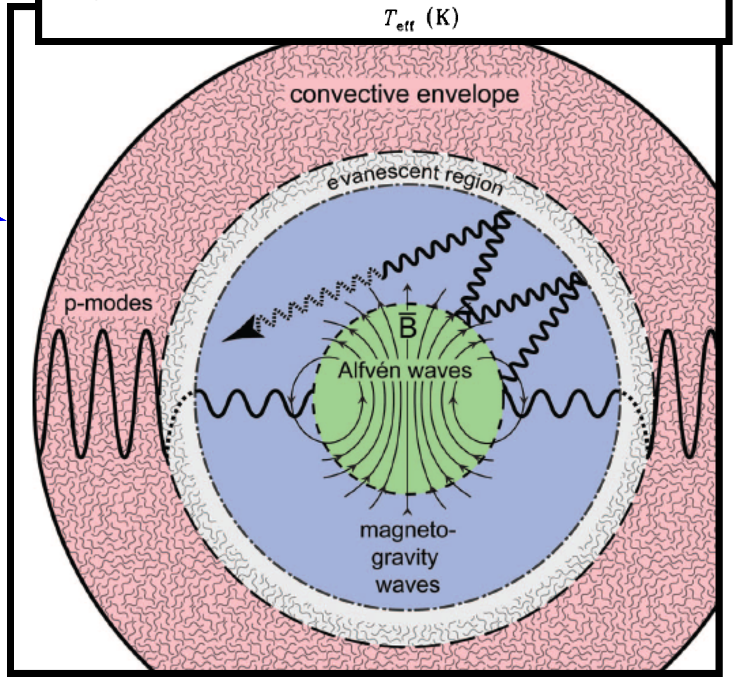
https://xkcd.com/26/

The aims of asteroseismology:

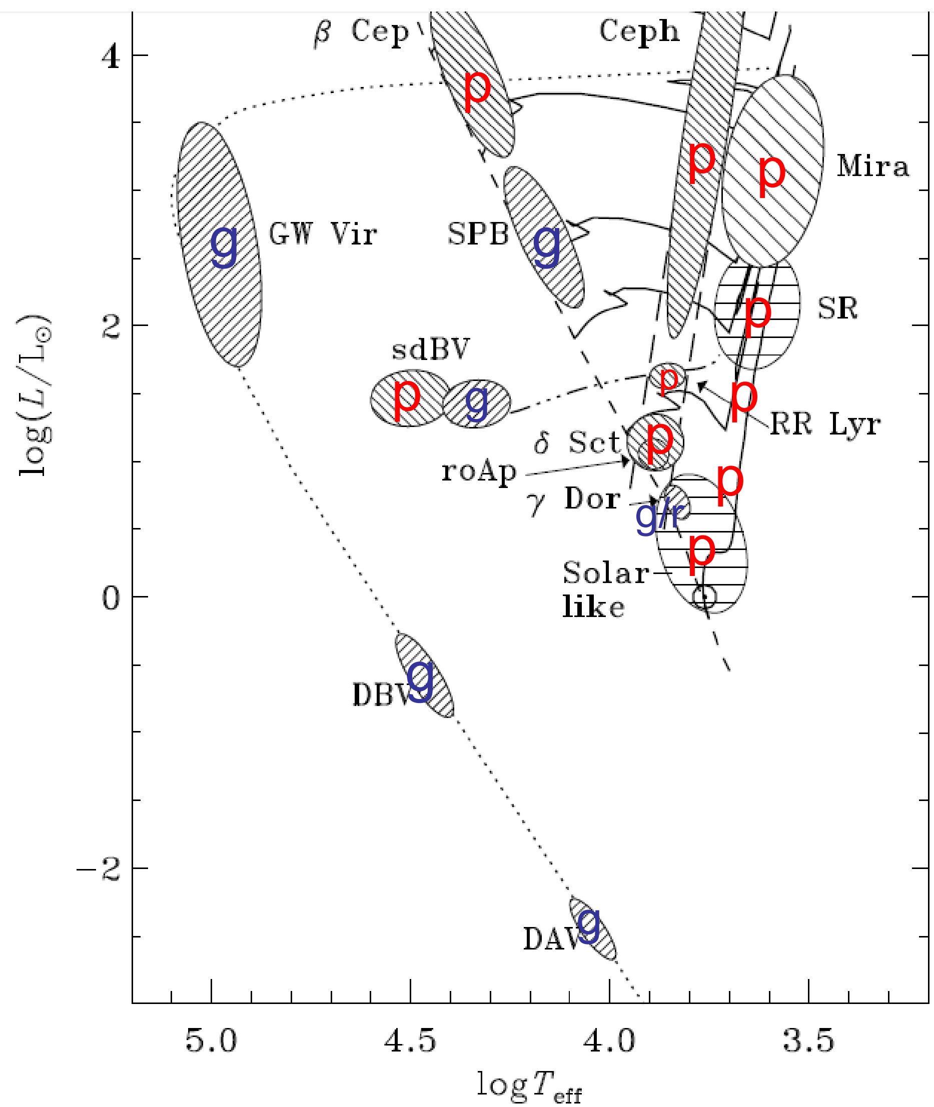
1. Use the oscillations of stars to measure their *properties*: e.g., mass, radius, age, internal rotation (including inclination)



2. Improve our understanding of the *physics* of stars: convection (including surface layers, core overshoot, etc.), angular momentum transport, magnetic fields, etc.



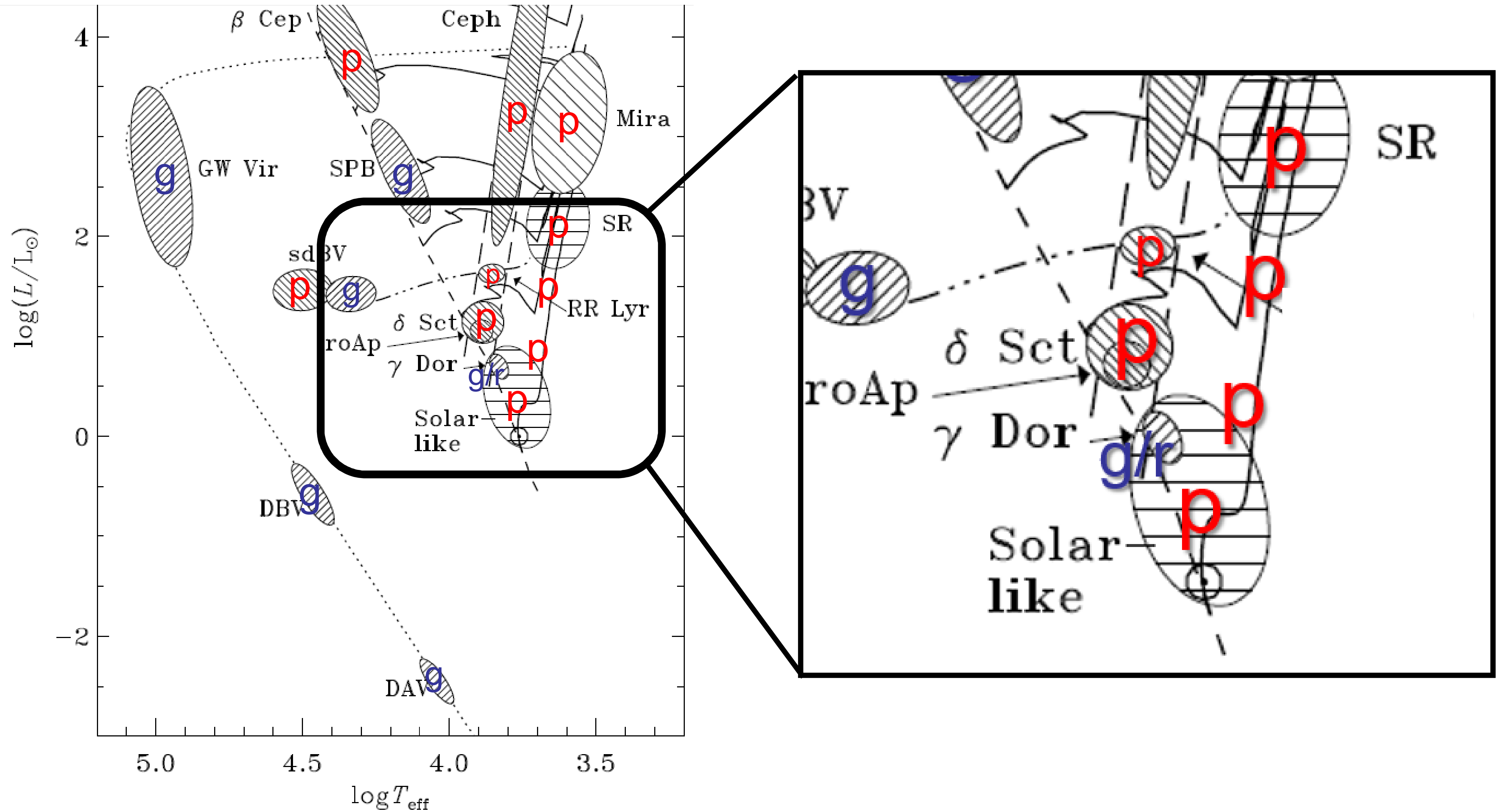
Fuller et al. (2015)



Christensen-Dalsgaard

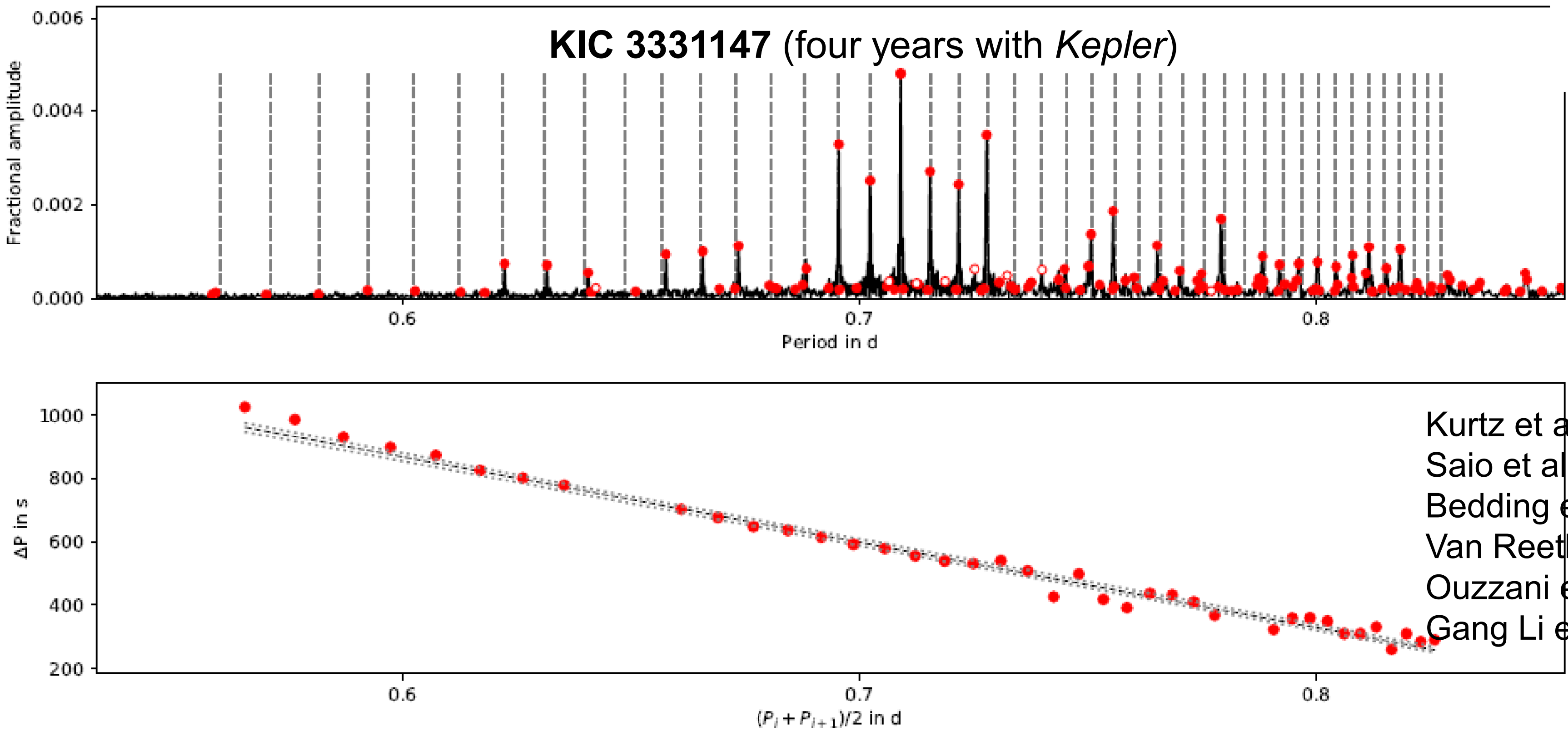
Classical pulsators with SONG

- white dwarfs and sdB stars: too faint
- O and B stars: line-profile variations? (see talk by Sergio Simón-Díaz)
- Cepheids: combine with interferometry?
- RR Lyraes: ?
- roAp stars: ?
- δ Scuti & γ Doradus: *see next slides*
- Miras: shocks?
- semiregulars: long secondary periods?



Christensen-Dalsgaard

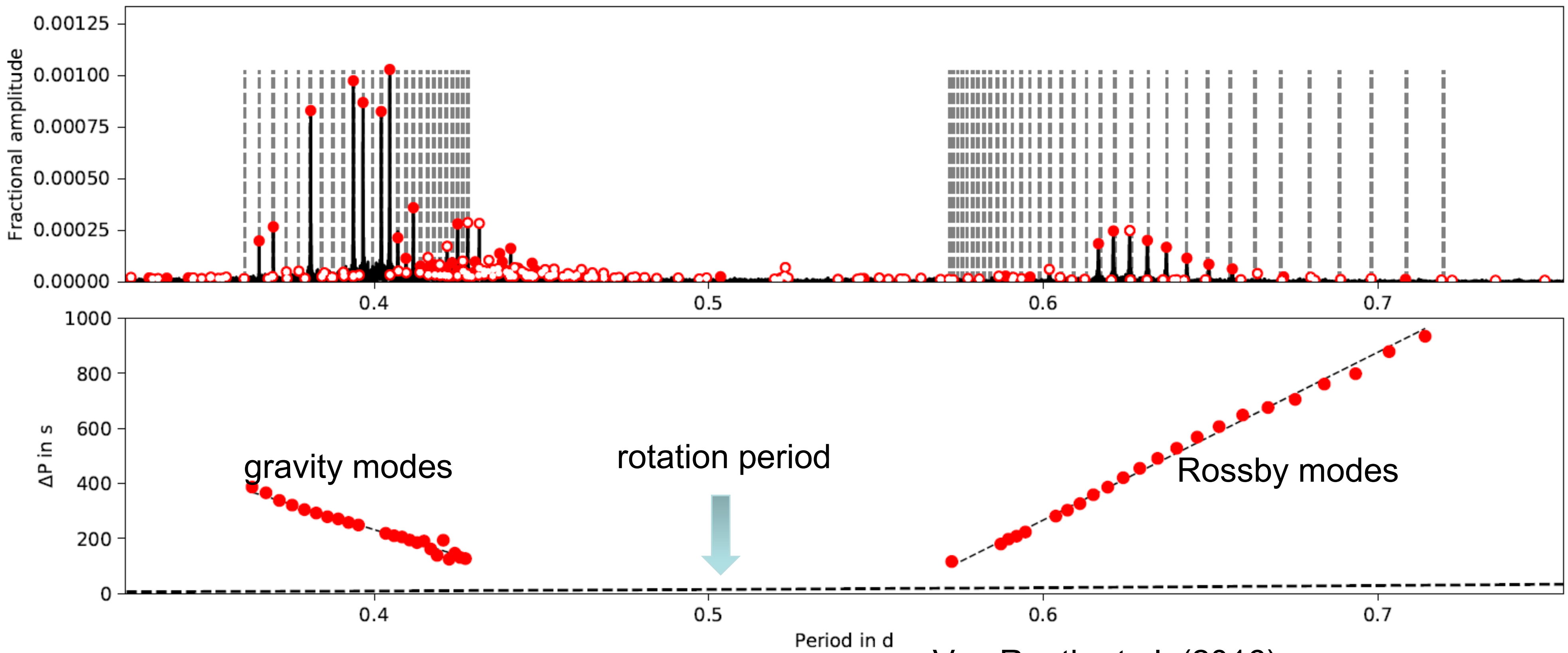
γ Dor stars



Kurtz et al. (2014)
Saio et al. (2015, 2018)
Bedding et al. (2015)
Van Reeth et al. (2015ab, 2016)
Ouzzani et al. (2017, 2018)
Gang Li et al. (submitted & in prep.)

529 stars with clear period-spacing patterns
(more than main-sequence solar-like oscillators!)

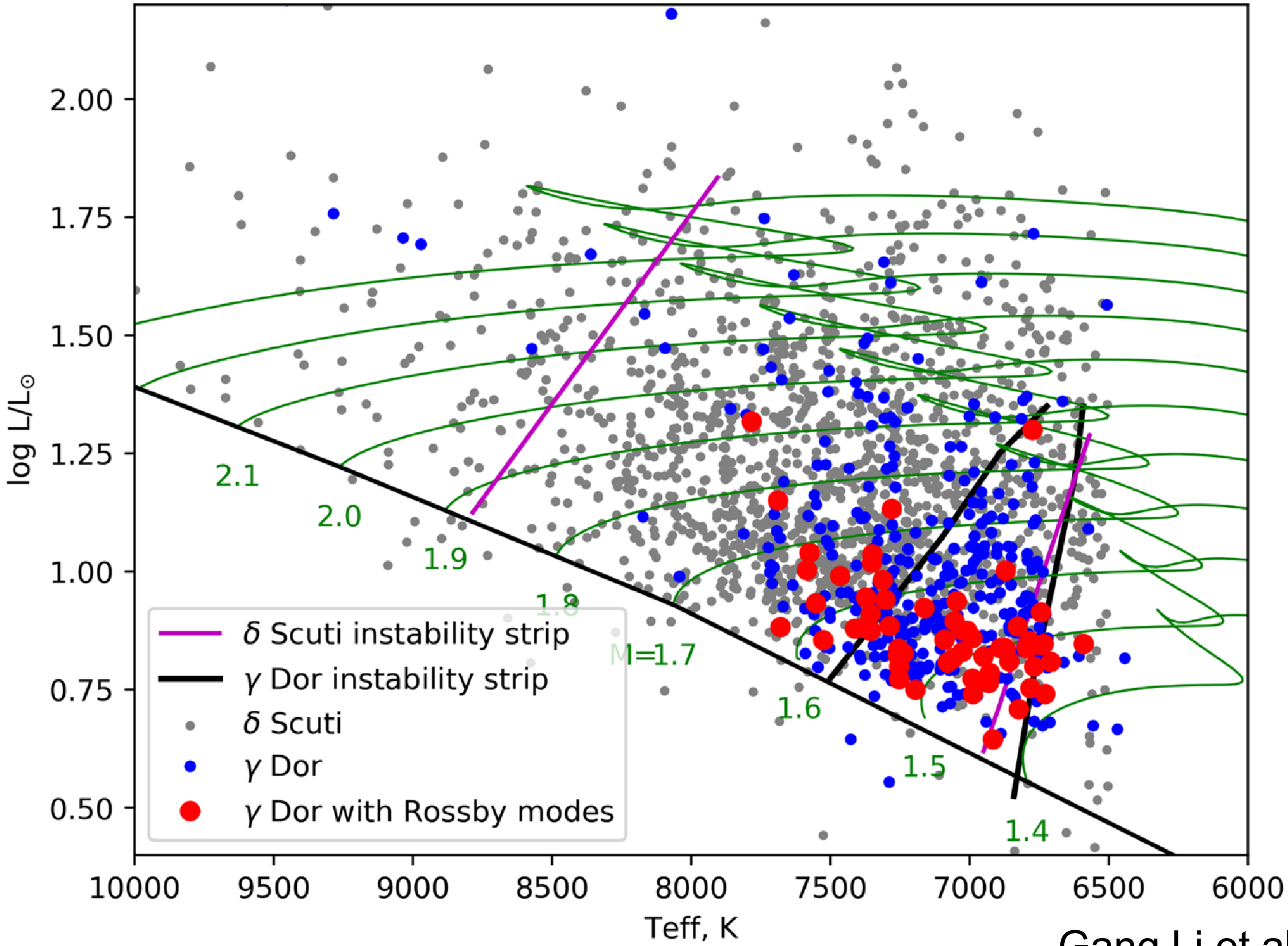
gravity and Rossby modes in γ Dor stars



Van Reeth et al. (2016)
Saio et al. (2018)
Gang Li et al. (submitted & in prep.)

p modes, g modes & r modes

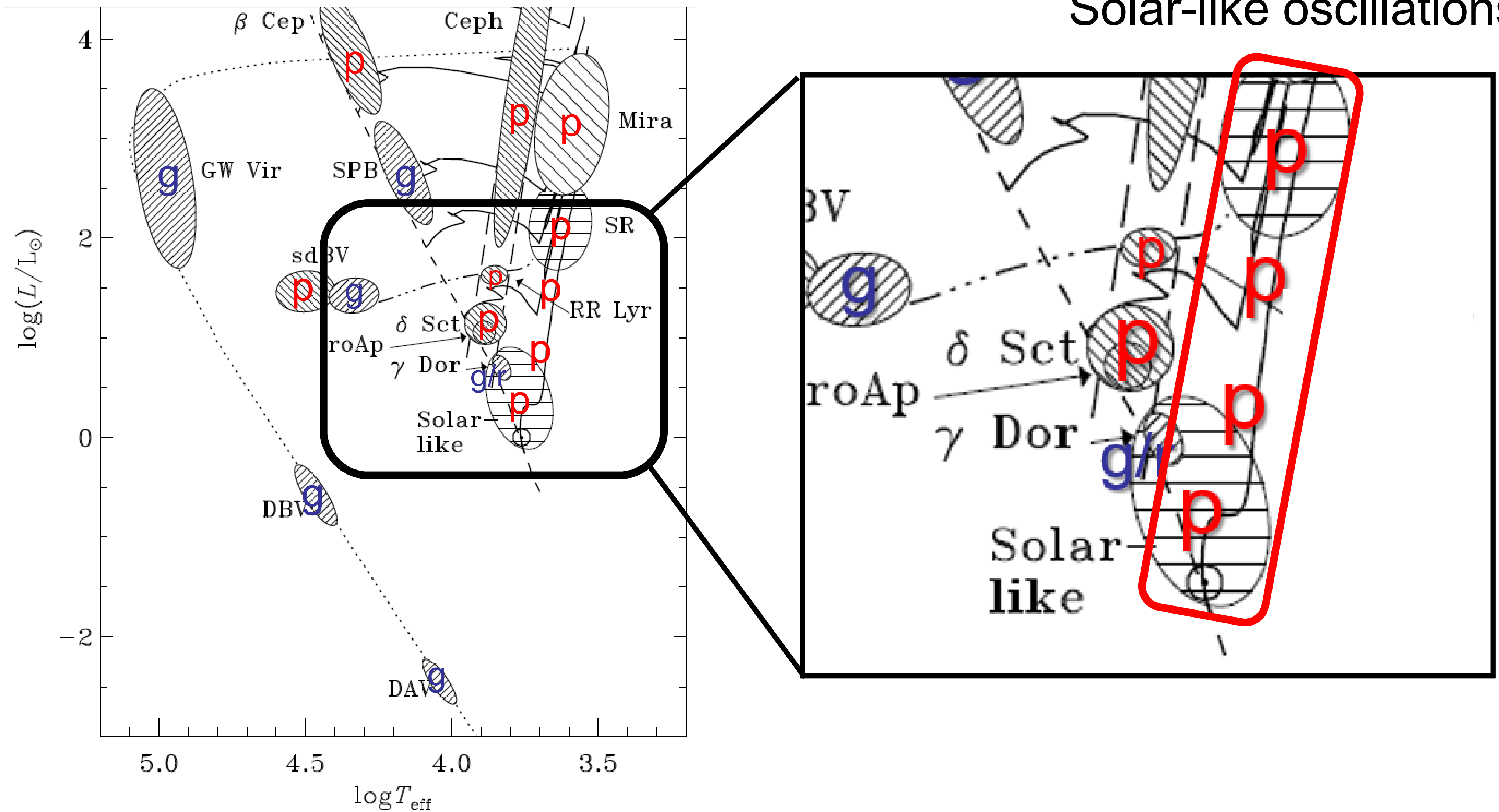
Kepler + Gaia DR2



δ Sct &
γ Dor with
SONG:
maybe?

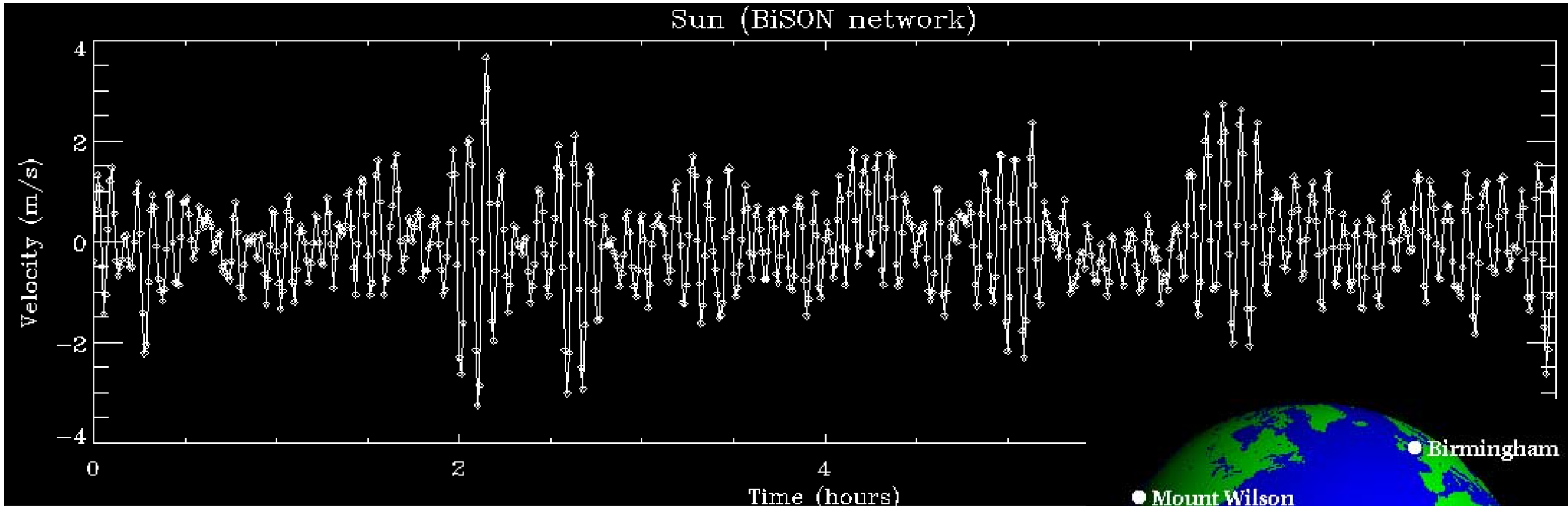
Gang Li et al. (in prep.)
Murphy et al. (in prep.)

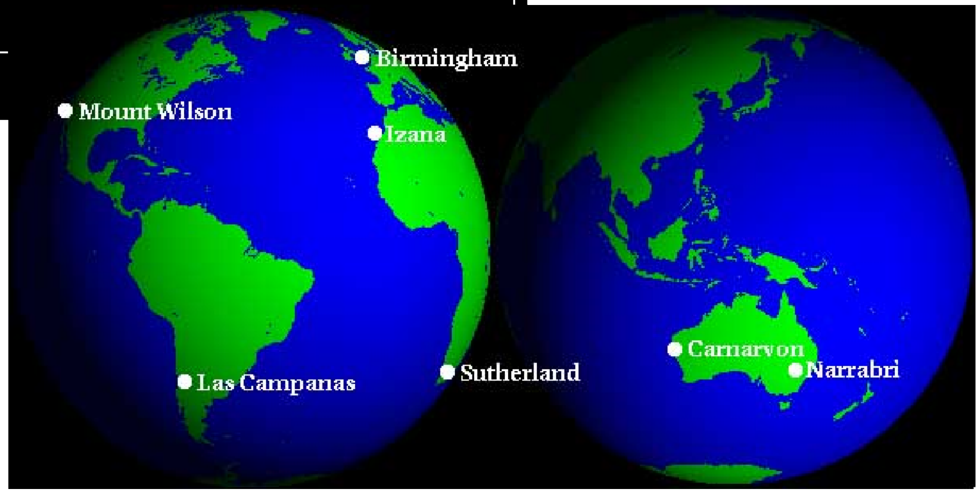
Solar-like oscillations



Christensen-Dalsgaard

Oscillations in the Sun (Doppler shift)

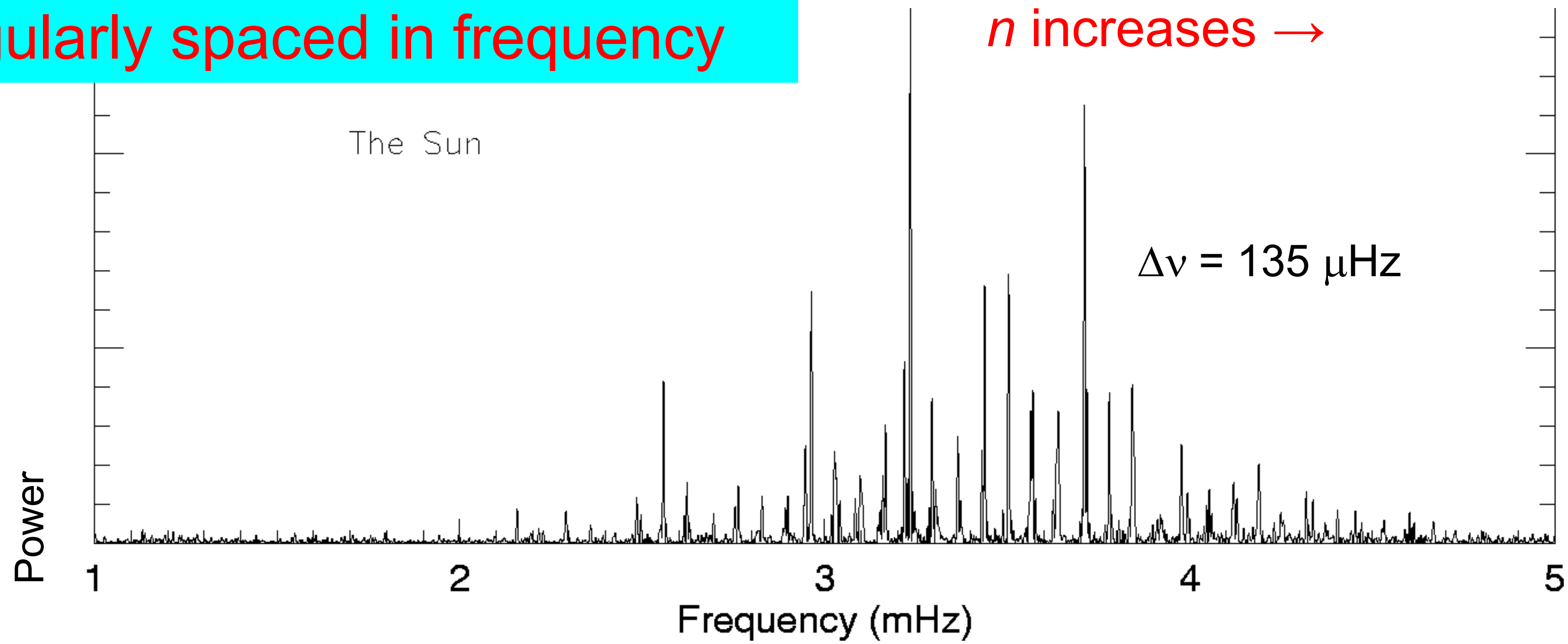




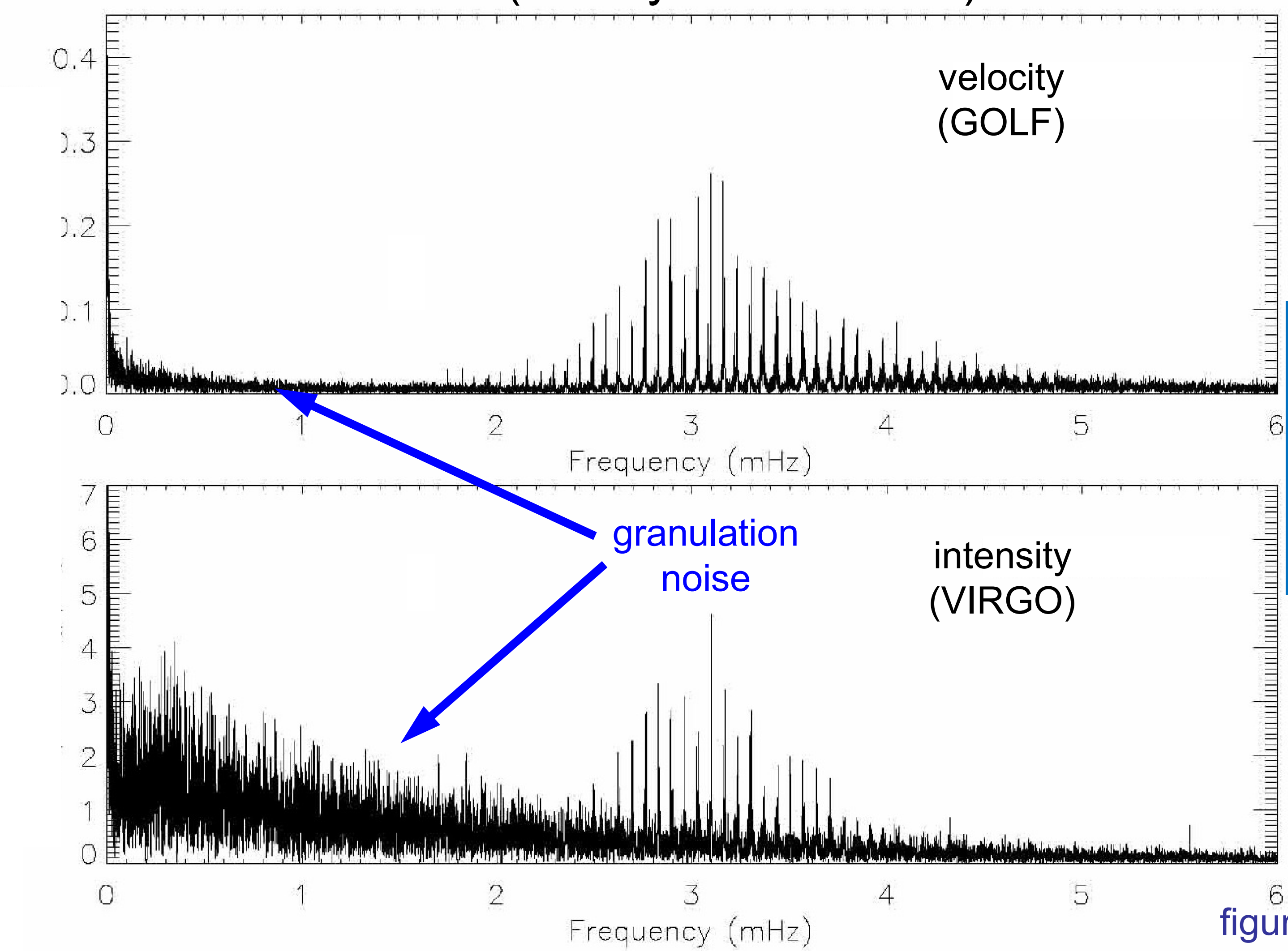
BiSON (Birmingham Solar Oscillations Network)

Fourier power spectrum of solar velocities (BiSON)

p-mode overtones approximately regularly spaced in frequency



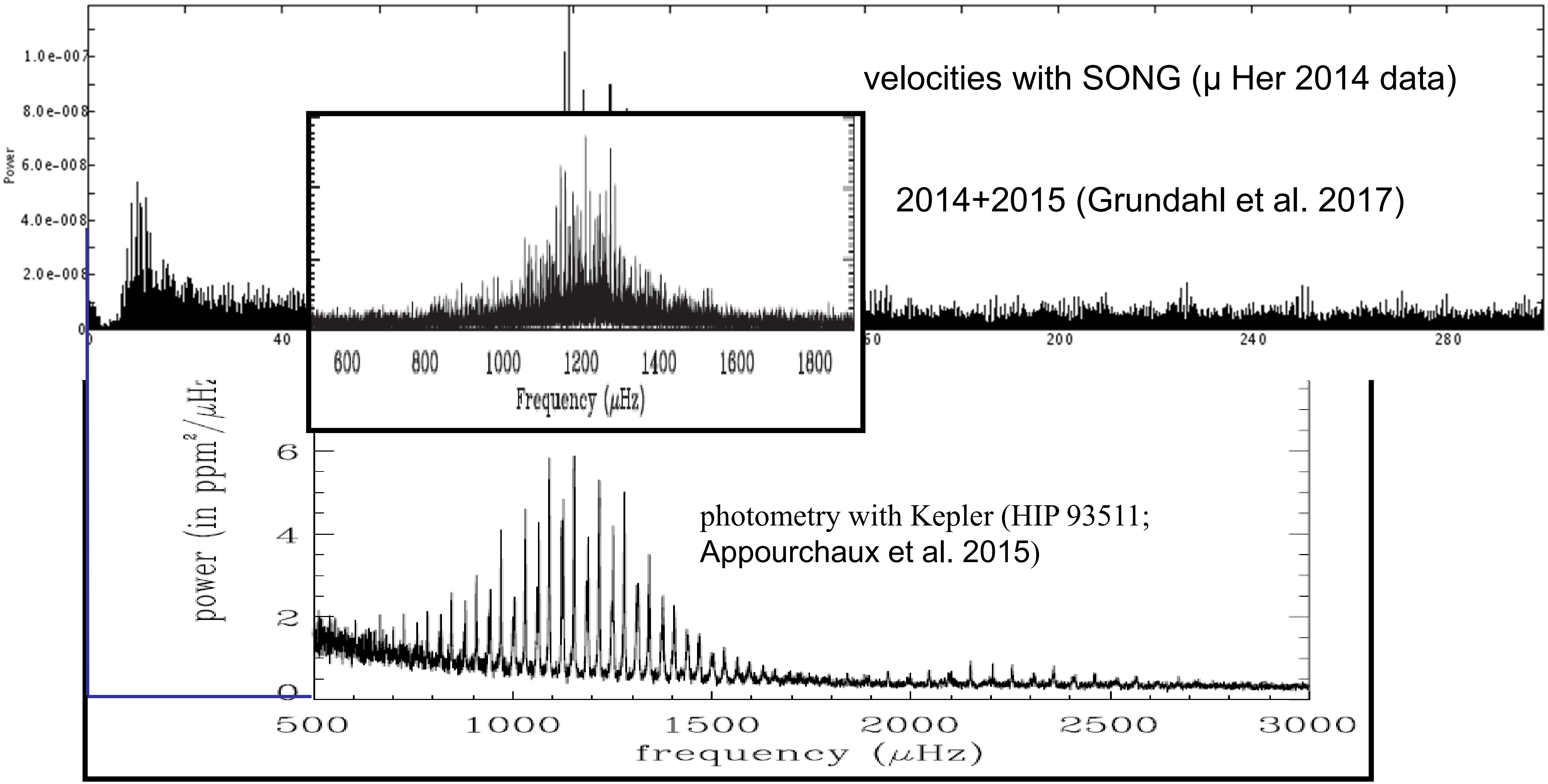
Sun (20 days with SOHO)



Contrast between oscillations and granulation background is *much* higher in velocity than photometry

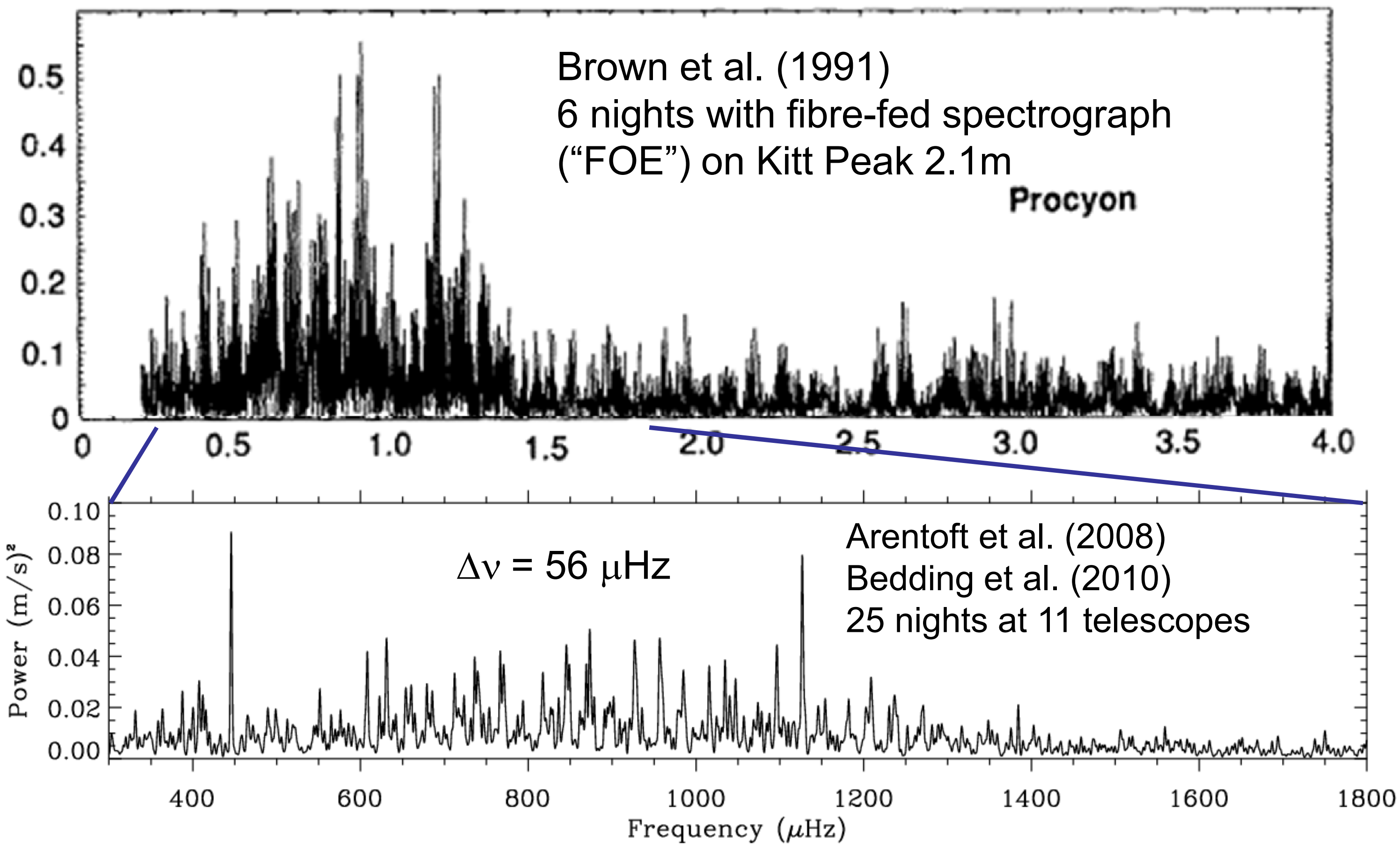
(e.g., Kjeldsen & Bedding 2011)

figures by Hans Kjeldsen

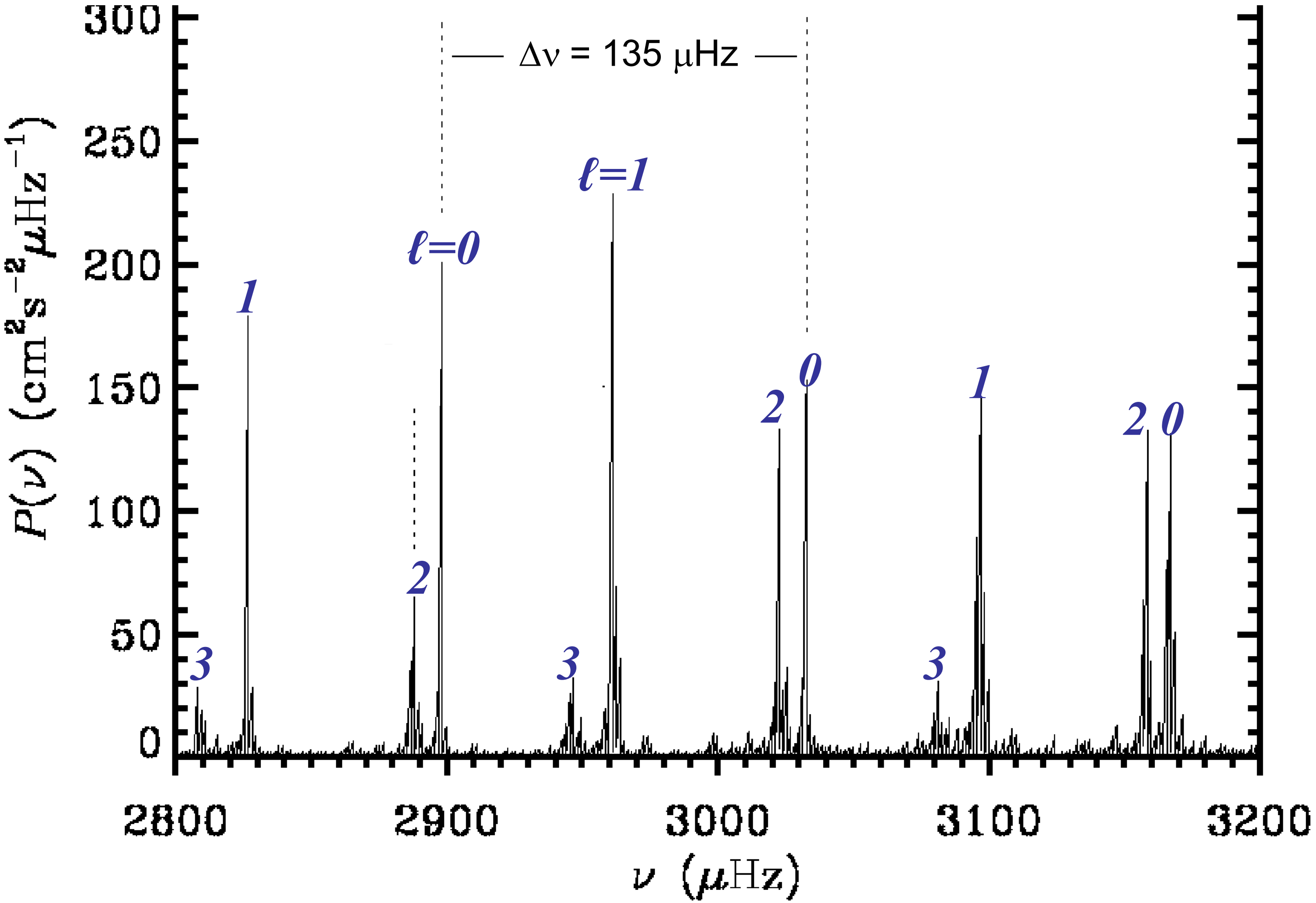

velocities with SONG (μ Her 2014 data)
2014+2015 (Grundahl et al. 2017)
photometry with Kepler (HIP 93511;
Appourchaux et al. 2015)
Power
Frequency (μHz)
power (in ppm²/μHz
frequency (μHz)

Some history (and lessons learned)

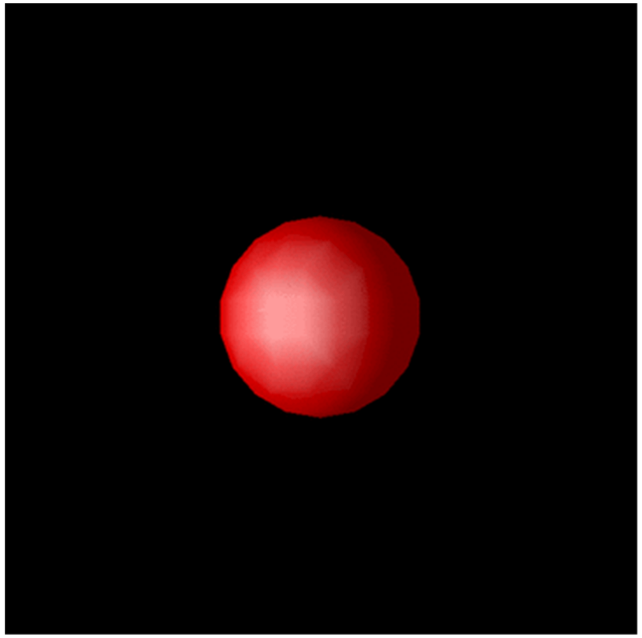
Radial velocity measurements of Procyon (F5V)

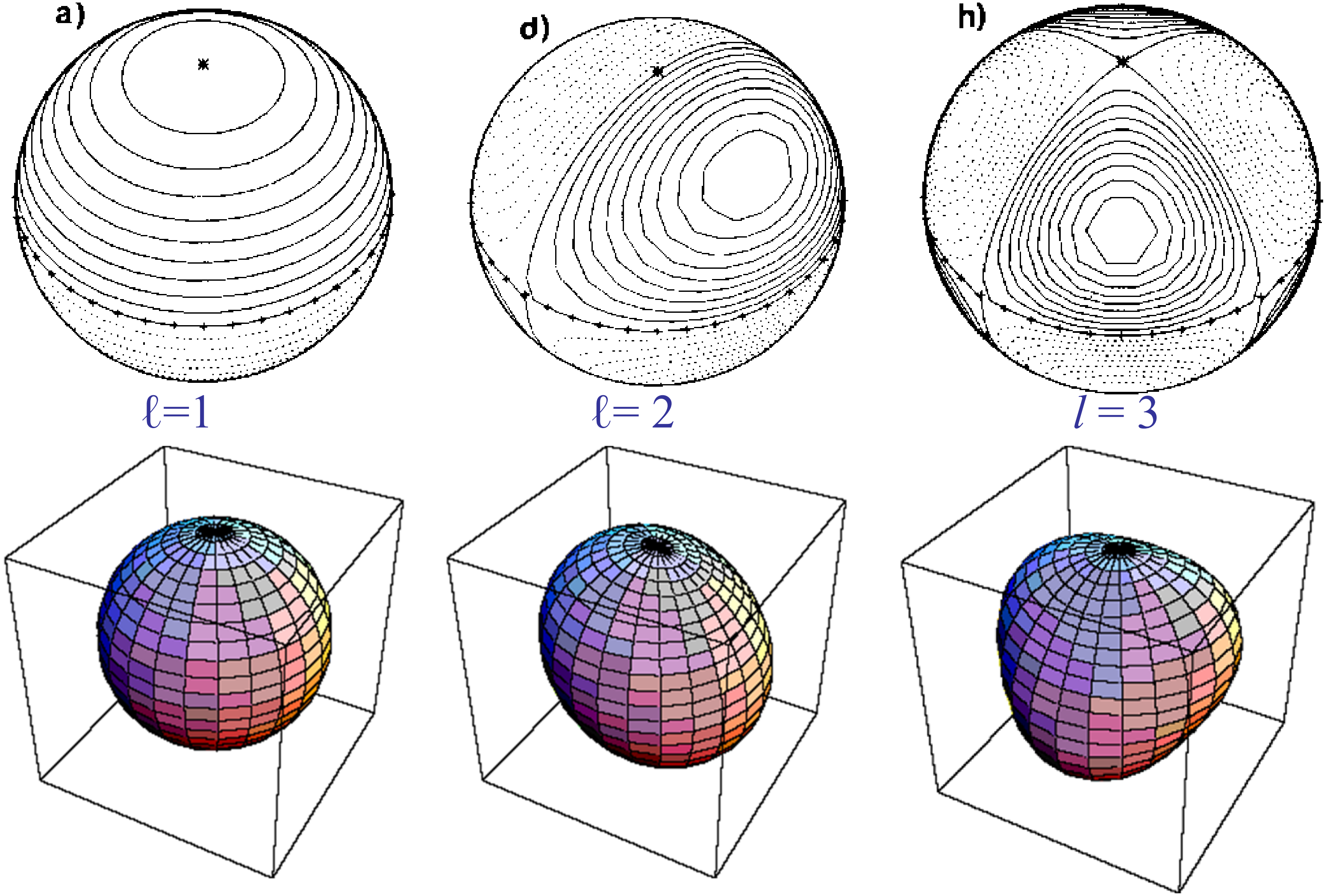


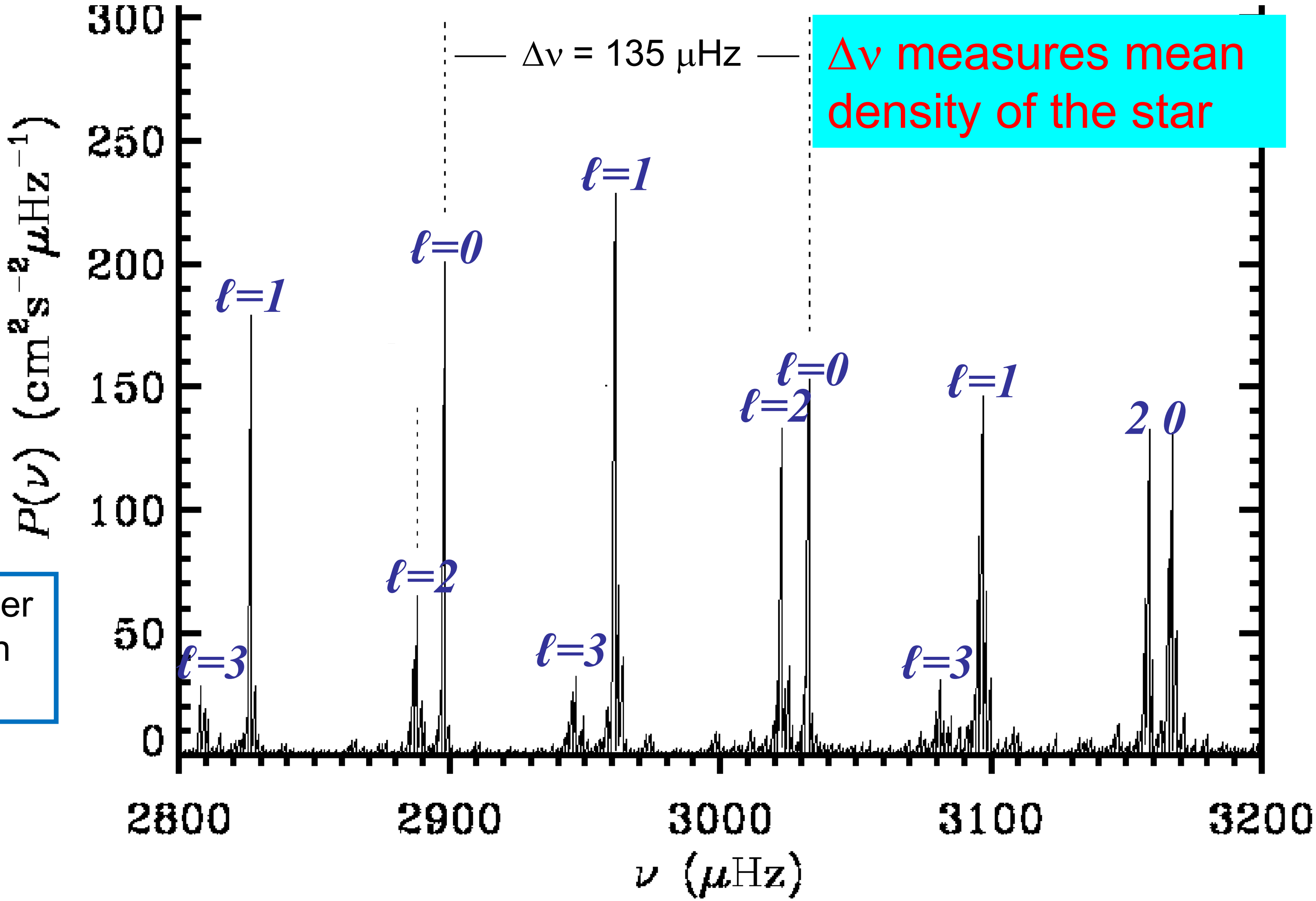
Closer look at the solar power spectrum



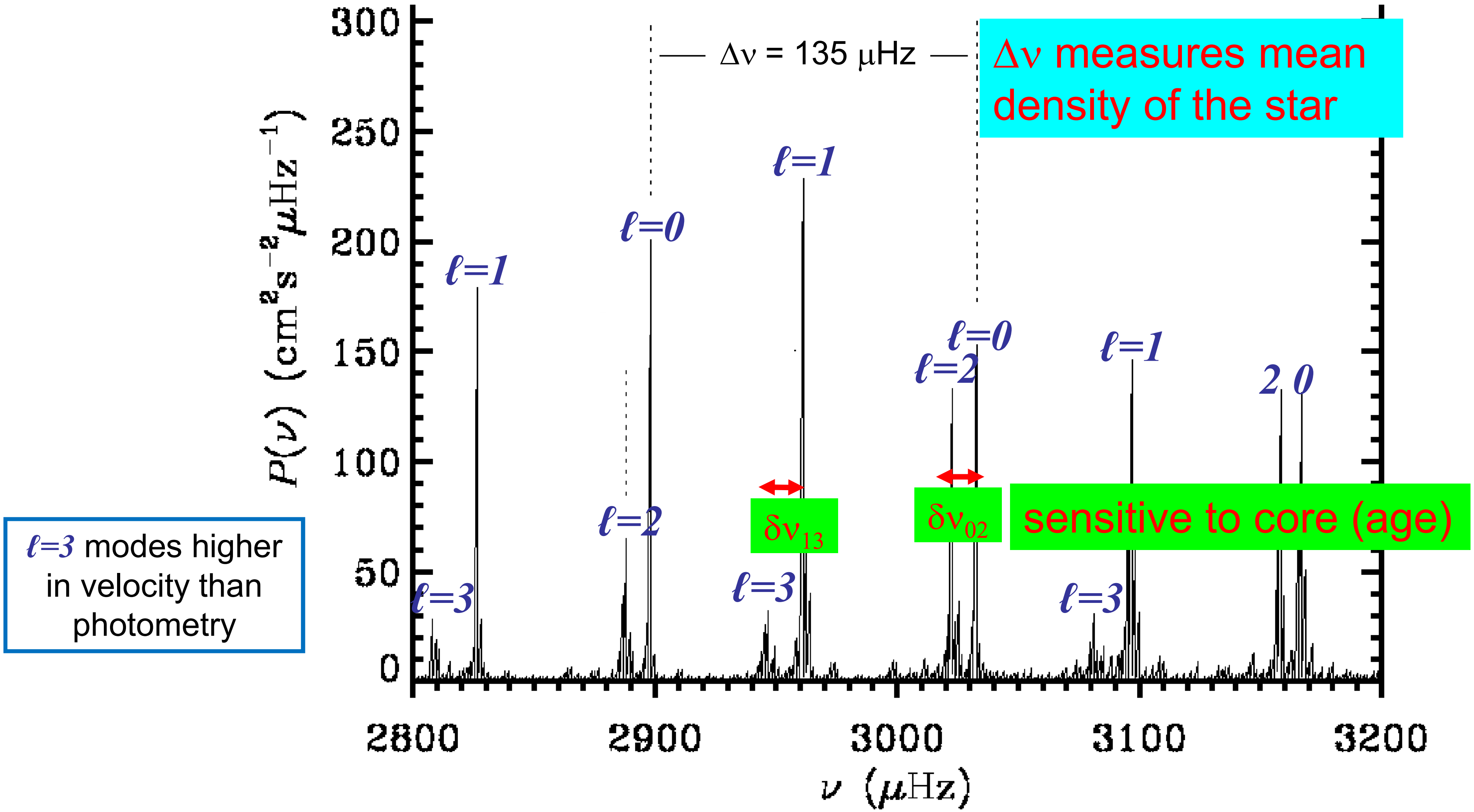
$\ell = 0$ (radial modes)





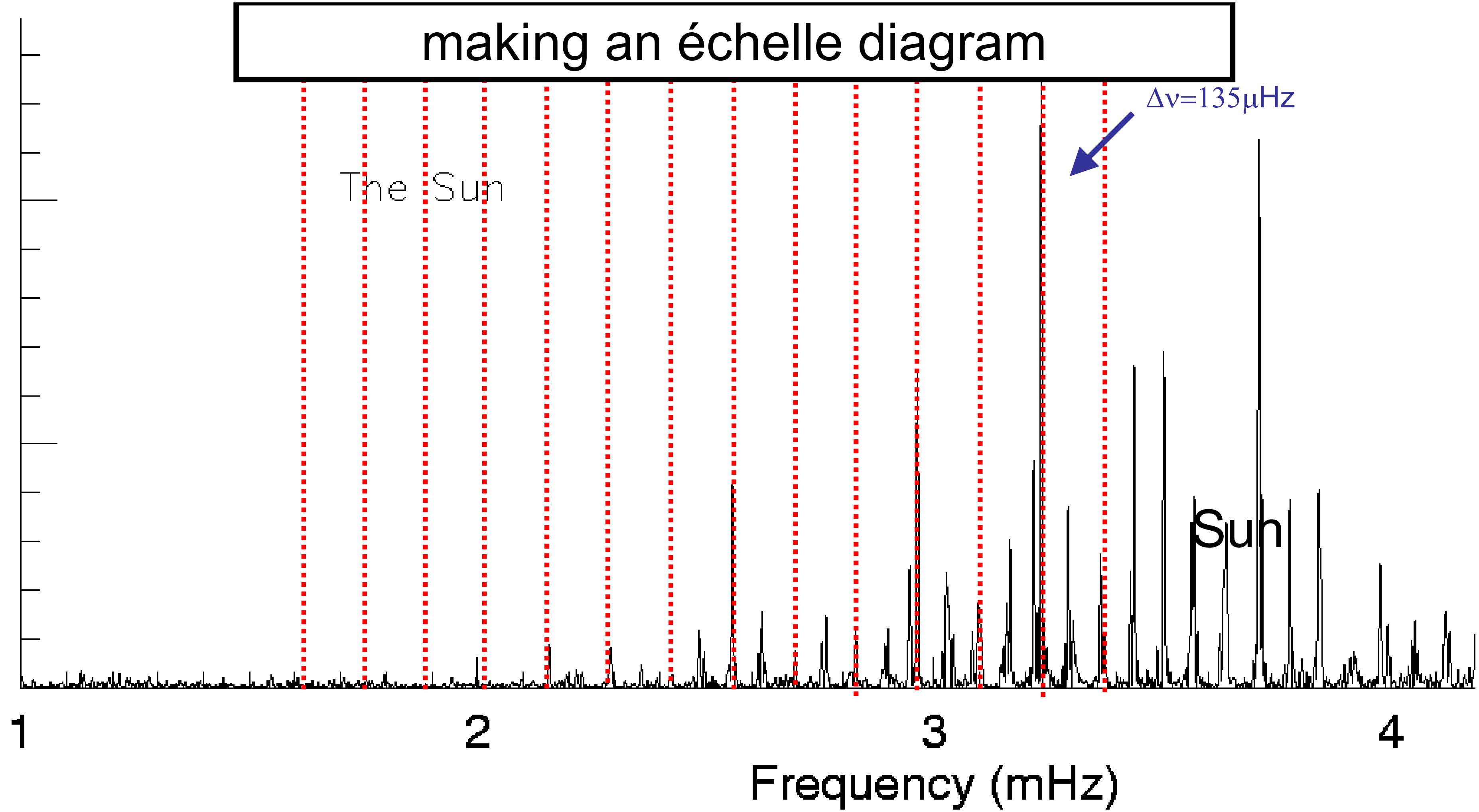


ℓ=3 modes higher in velocity than photometry

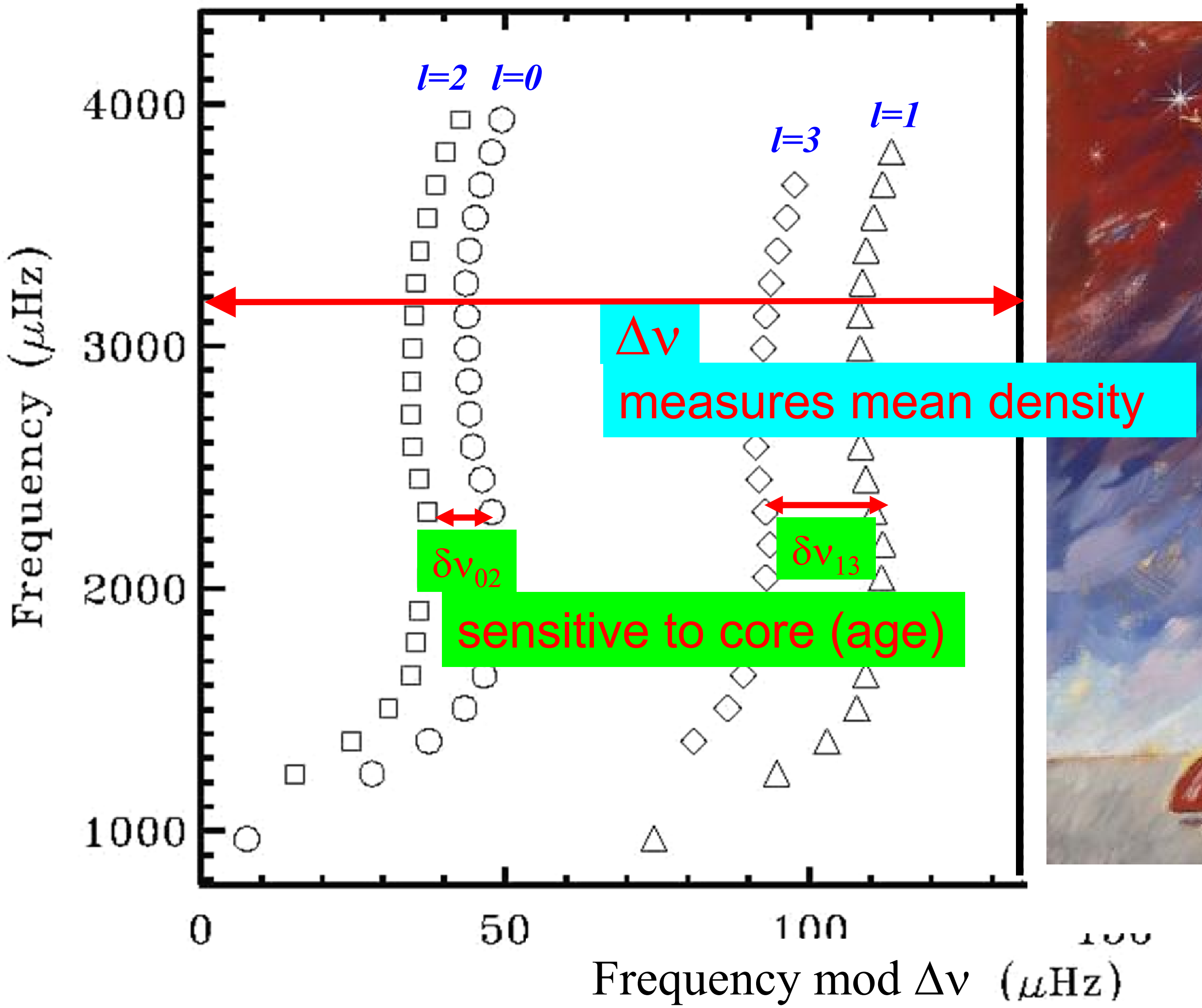


Δν = 135 μHz
Δν measures mean density of the star
ℓ=1
ℓ=0
ℓ=2
ℓ=3
2 0
δν13
δν02
sensitive to core (age)
ℓ=3 modes higher in velocity than photometry
P(ν) (cm²s⁻²μHz⁻¹)
ν (μHz)

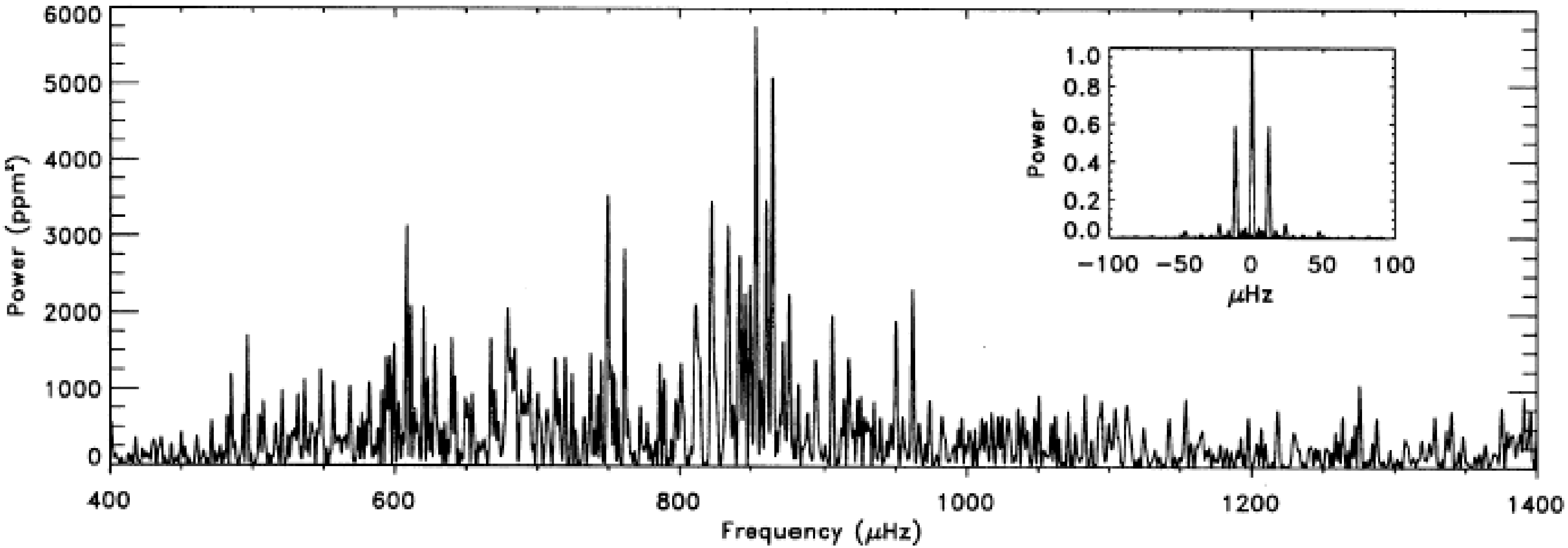
making an échelle diagram



The échelle diagram:

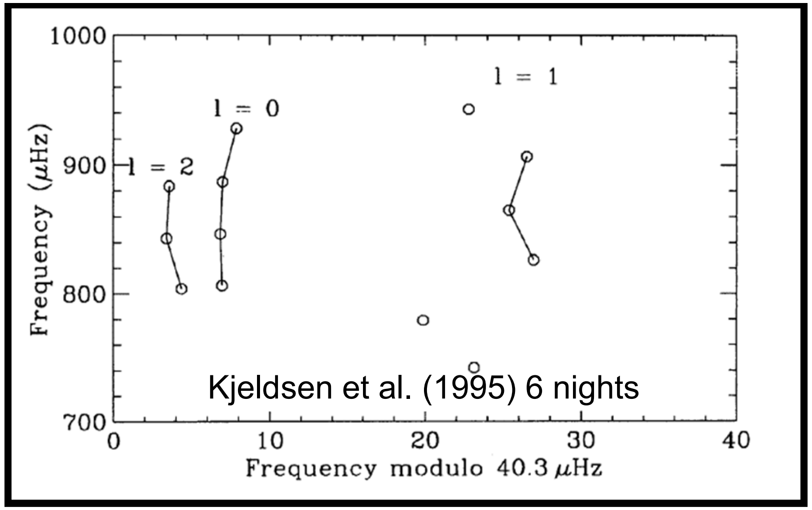


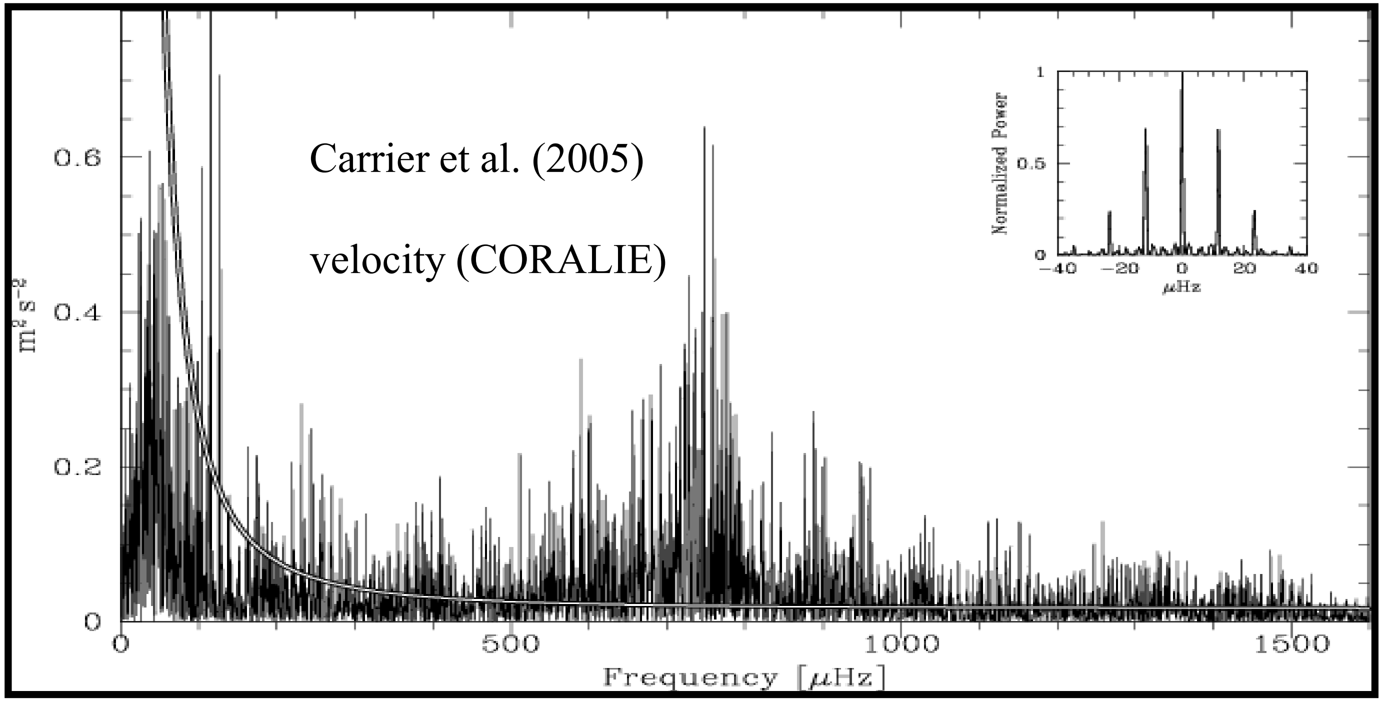
Equivalent-width measurements with NOT of η Boo (G0 IV)

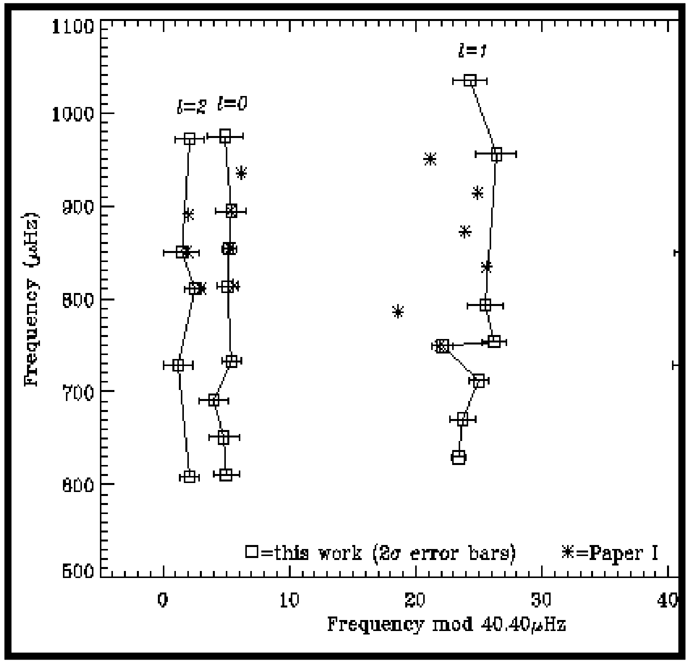


Equivalent-width with SONG could be useful for fast rotators?

Kjeldsen et al. (1995)
6 nights

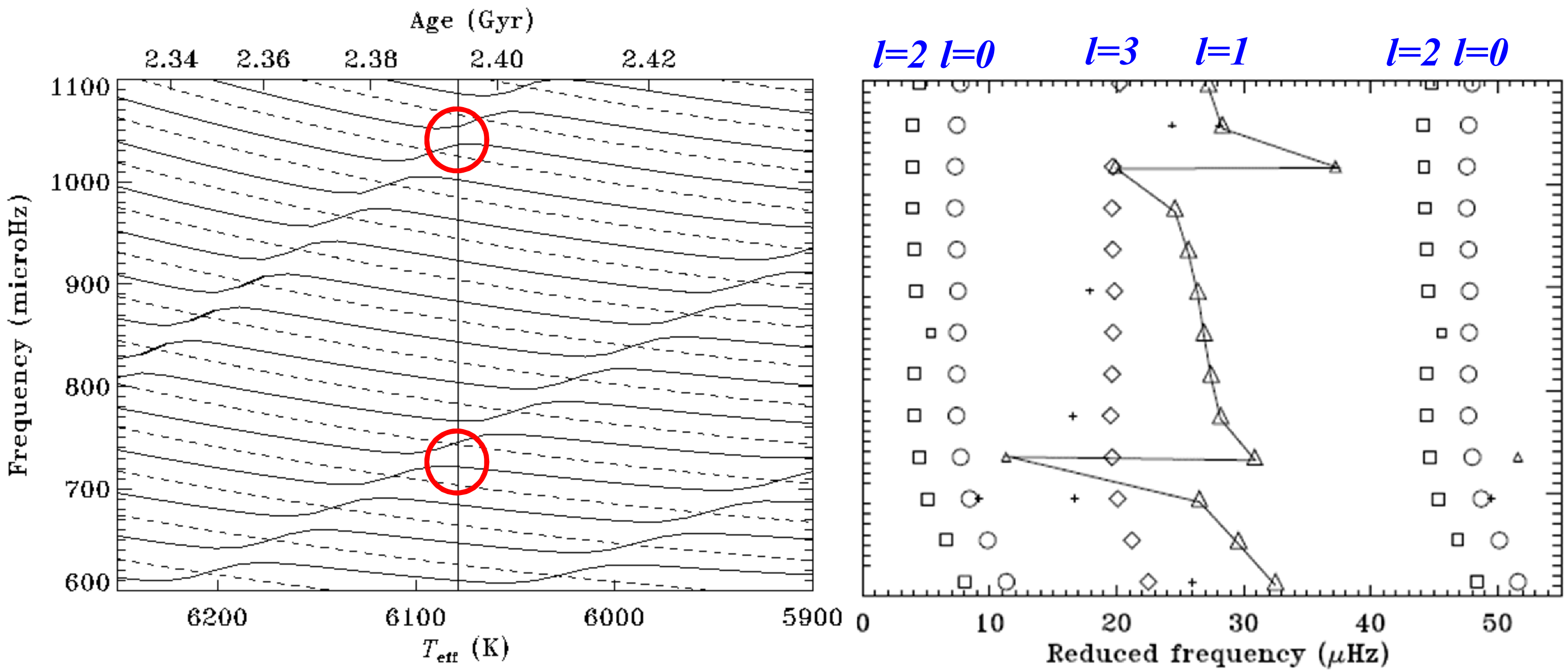






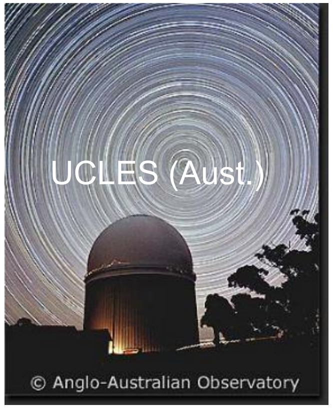
Kjeldsen et al. 2003
(four sets of data)

Mixed modes, mode bumping and avoided crossings

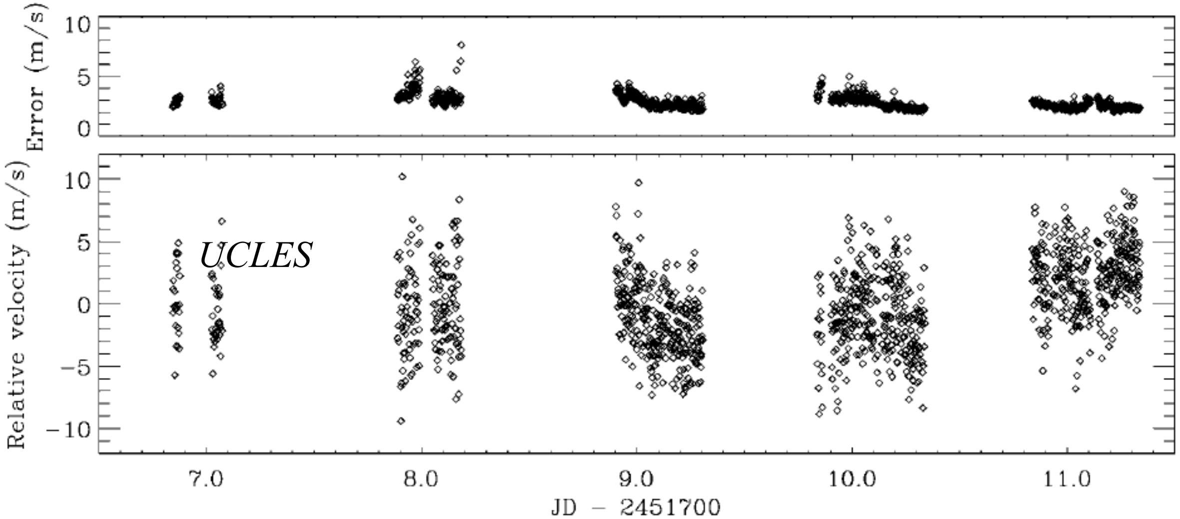


Models for eta Boo; Christensen-Dalsgaard et al. (1995)

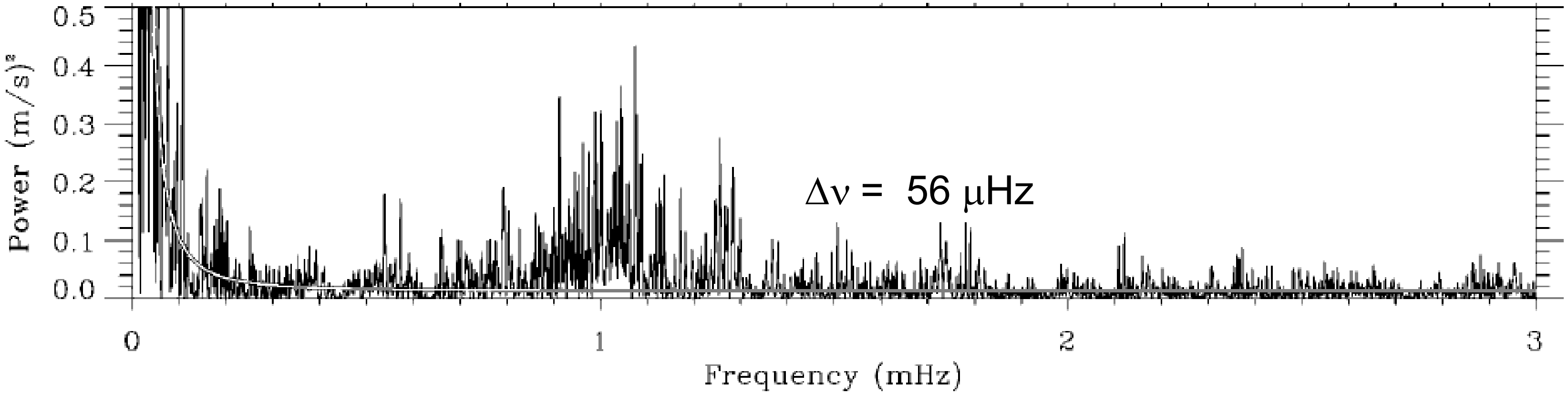
β Hyi (G2 IV)



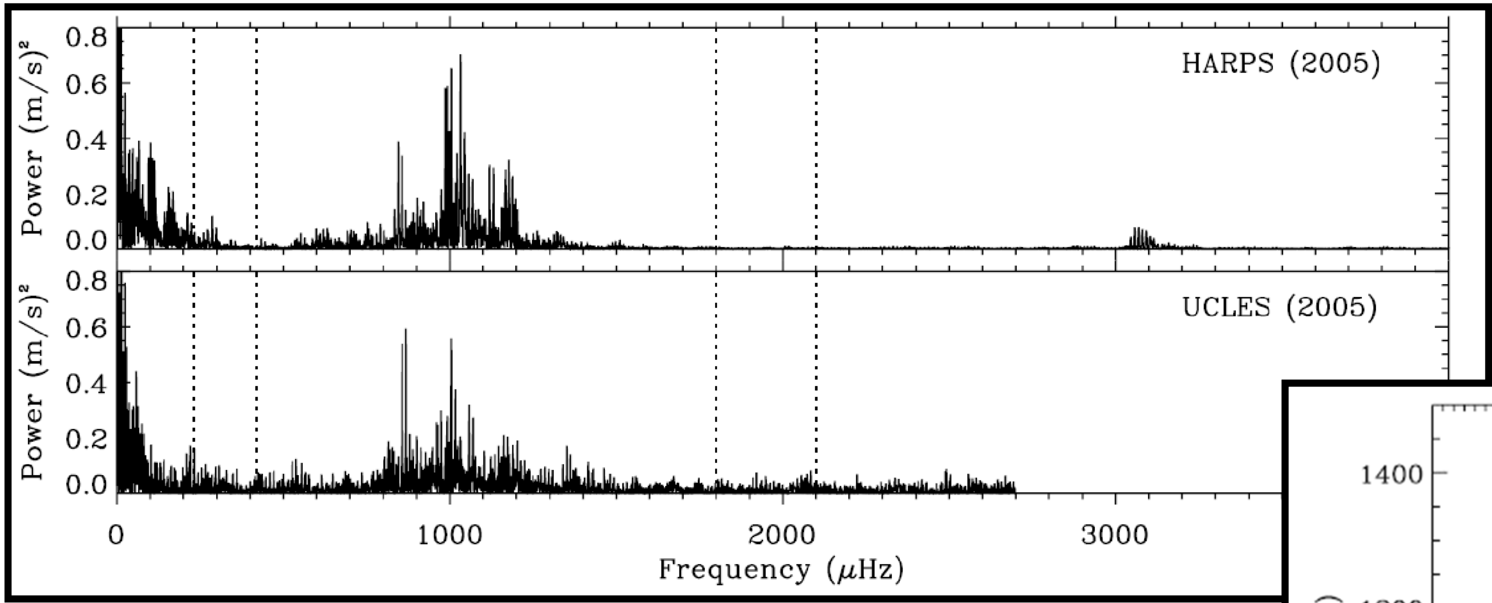
UCLES at the 3.9m AAT, Australia

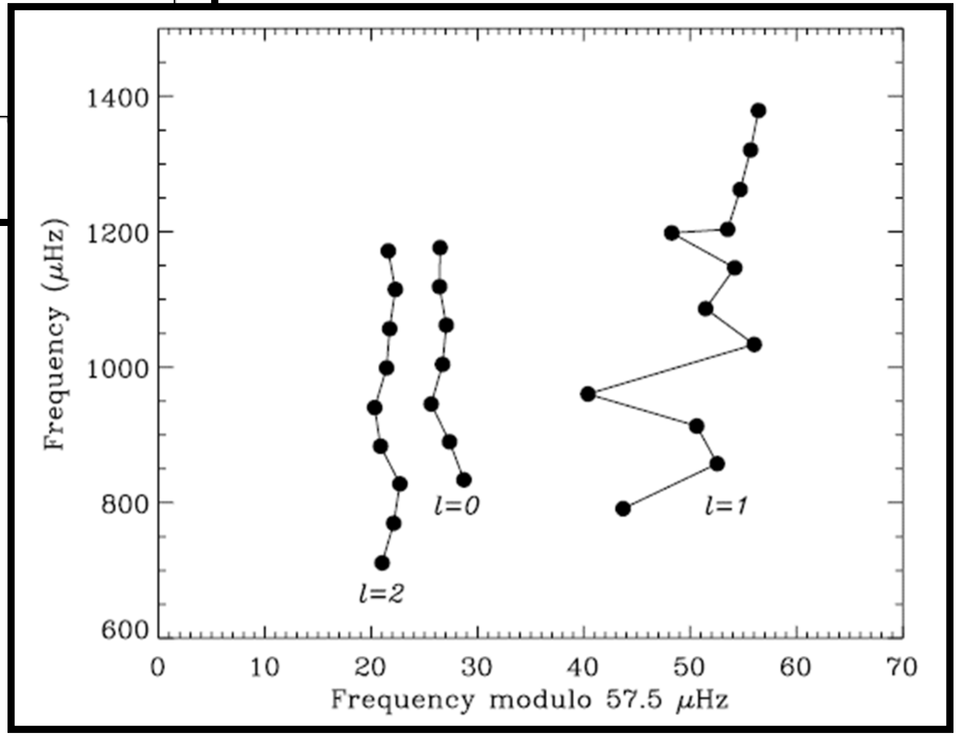


velocities (iodine cell)



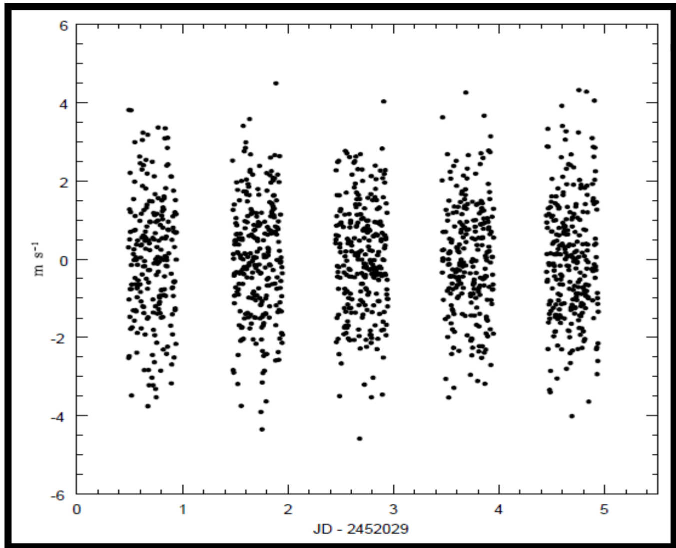
Bedding et al. (2001) and also CORALIE: Carrier et al. (2001)

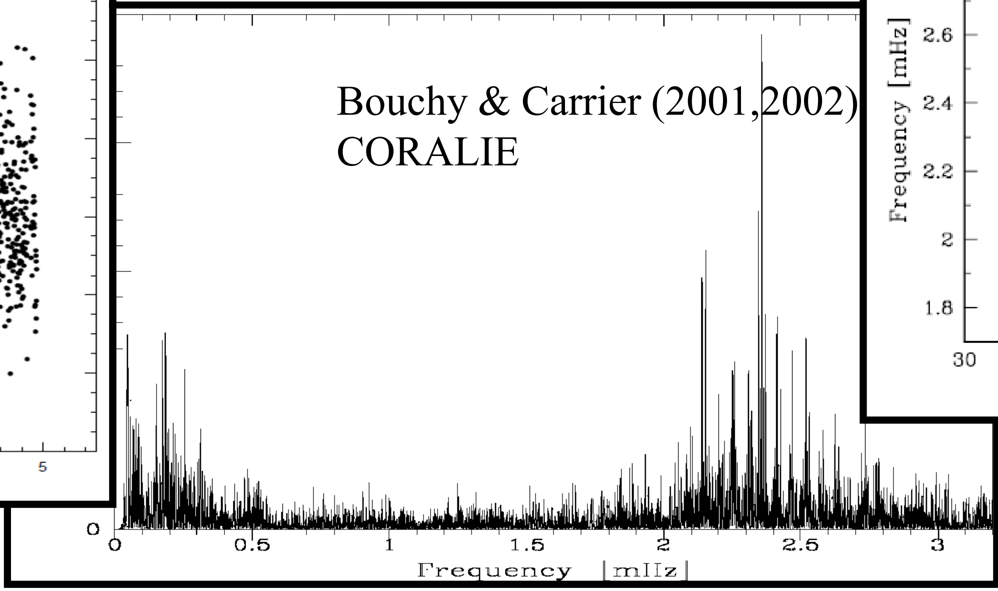


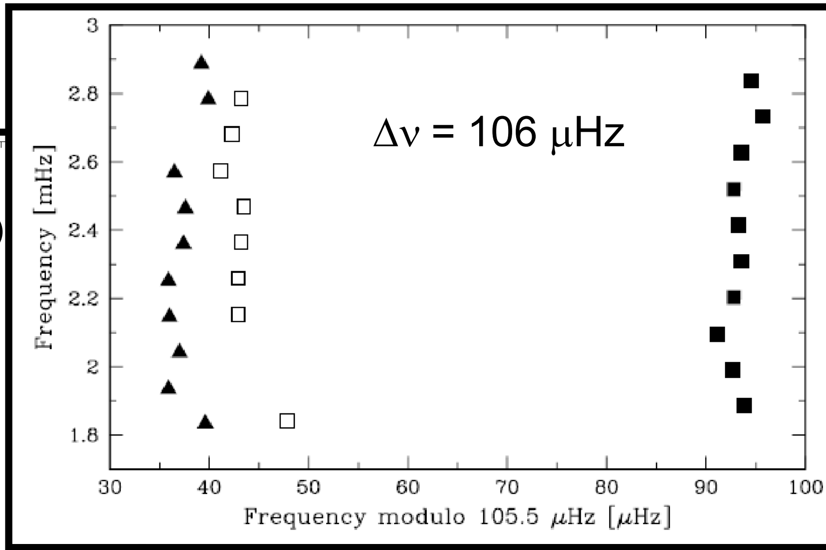


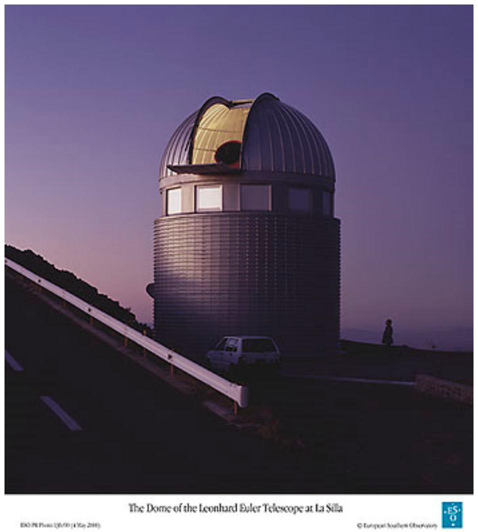
Bedding et al. (2007)
8 nights on two telescopes
(AAT/UCLES with iodine and ESO 3.6m/HARPS)

α Cen A (G2V)

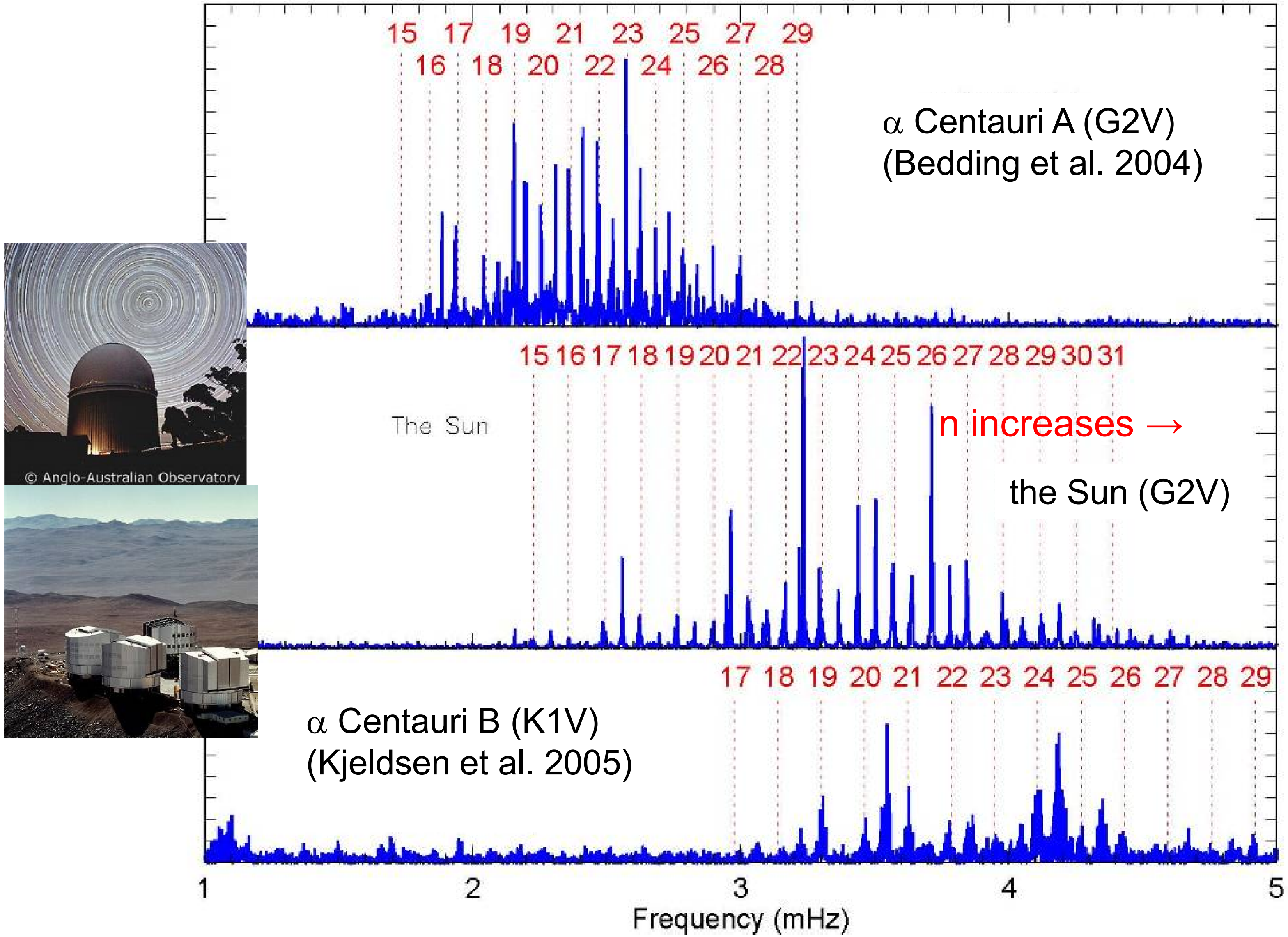








CORALIE at the Swiss 1.2-m Leonhard Euler Telescope at La Silla, Chile


α Centauri A (G2V)
(Bedding et al. 2004)
15 17 19 21 23 25 27 29
16 18 20 22 24 26 28
The Sun
15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
n increases →
the Sun (G2V)
α Centauri B (K1V)
(Kjeldsen et al. 2005)
17 18 19 20 21 22 23 24 25 26 27 28 29
© Anglo-Australian Observatory
1
2
3
4
5
Frequency (mHz)

Detections of solar-like oscillations: 2008

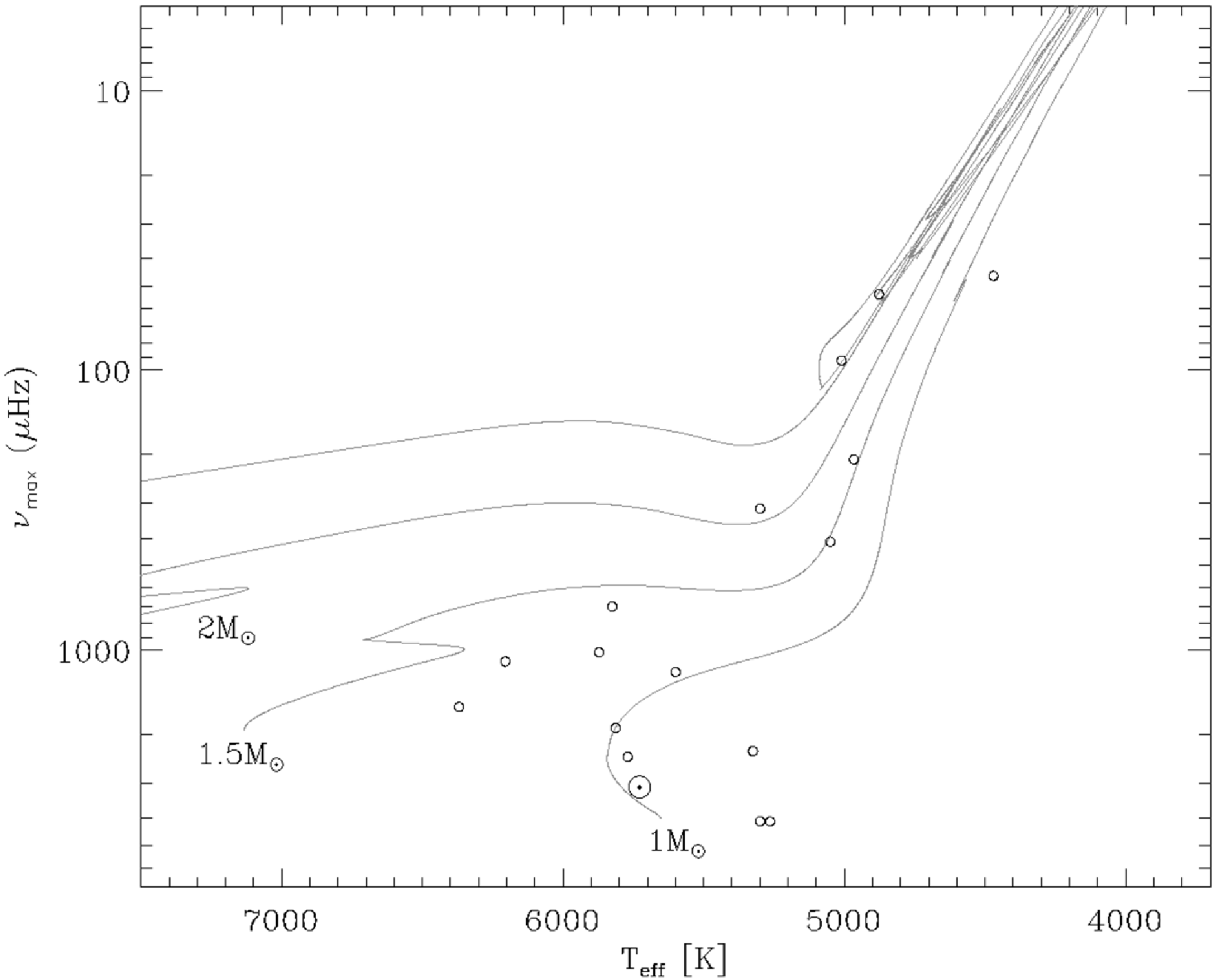
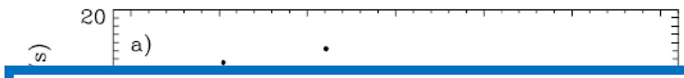


figure by Daniel Huber

Detection of Solar-like oscillations in the G7 giant star ξ Hya

S. Frandsen[1], F. Carrier[2], C. Aerts[3], D. Stello[1], T. Maas[3], M. Burnet[2], H. Bruntt[1], T. C. Teixeira[4,1], J. R. de Medeiros[5], F. Bouchy[2], H. Kjeldsen[1,6], F. Pijpers[1,6], and J. Christensen-Dalsgaard[1,6]

Frandsen et al. (2002)

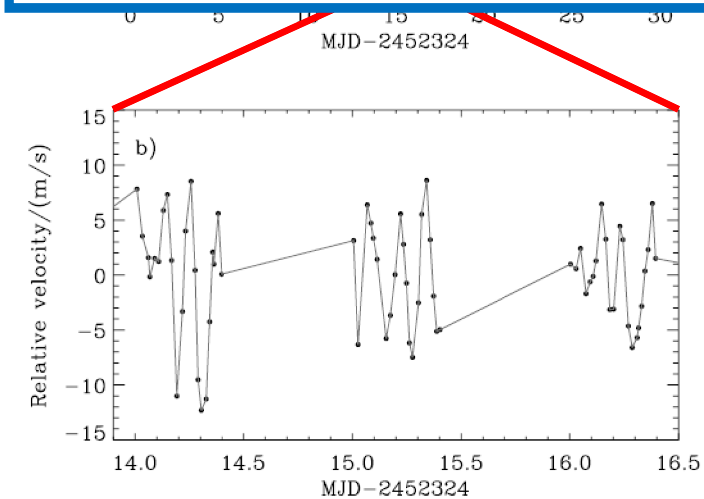


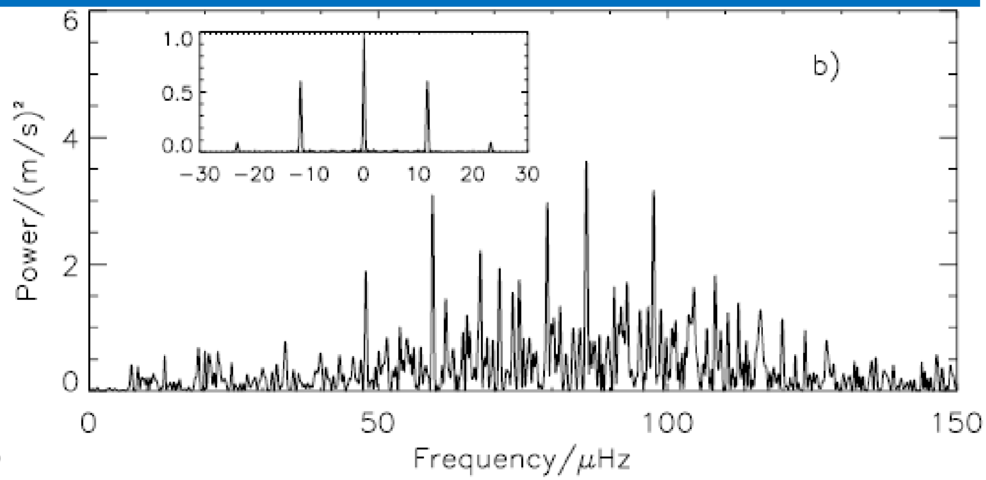
CORALIE at the Swiss 1.2-m

Oscillation mode lifetimes in ξ Hydrae: will strong mode damping limit asteroseismology of red giant stars?★

D. Stello[1,2,3], H. Kjeldsen[1], T. R. Bedding[2], and D. Buzasi[3]

(2006)

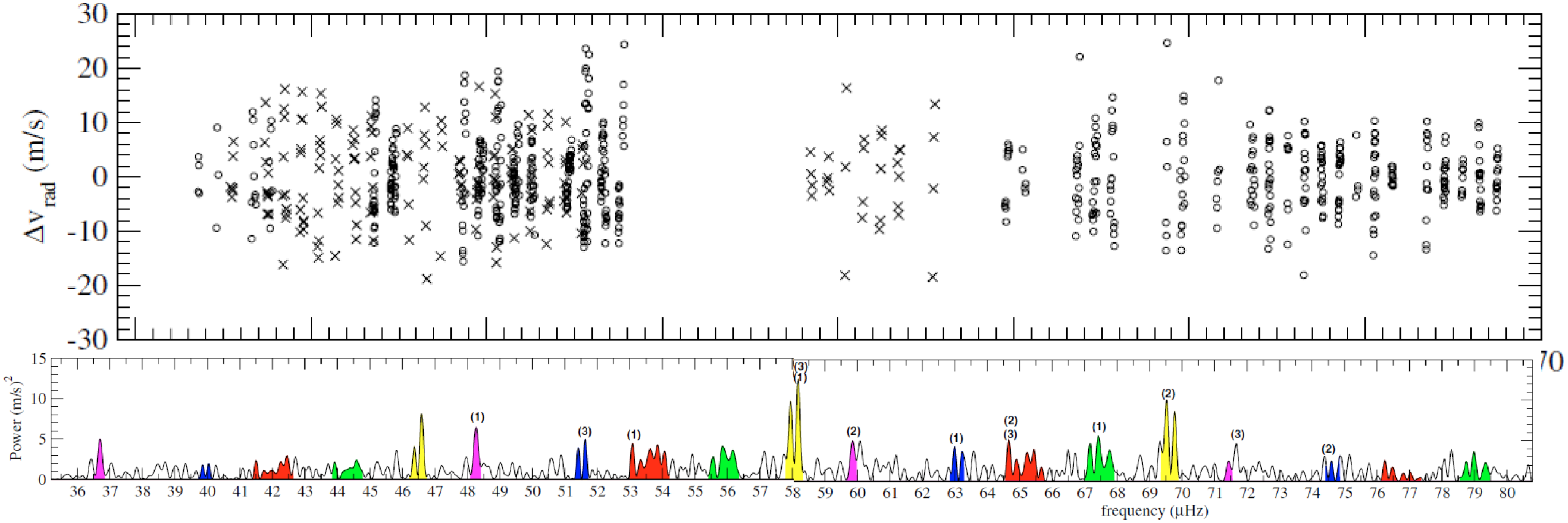




Discovery of solar-like oscillations in the red giant ε Ophiuchi*

J. De Ridder[1], C. Barban[1], F. Carrier[2], A. Mazumdar[1], P. Eggenberger[2],
C. Aerts[1], S. Deruyter[3], and J. Vanautgaerden[1]

(2006)



CORALIE and ELODIE

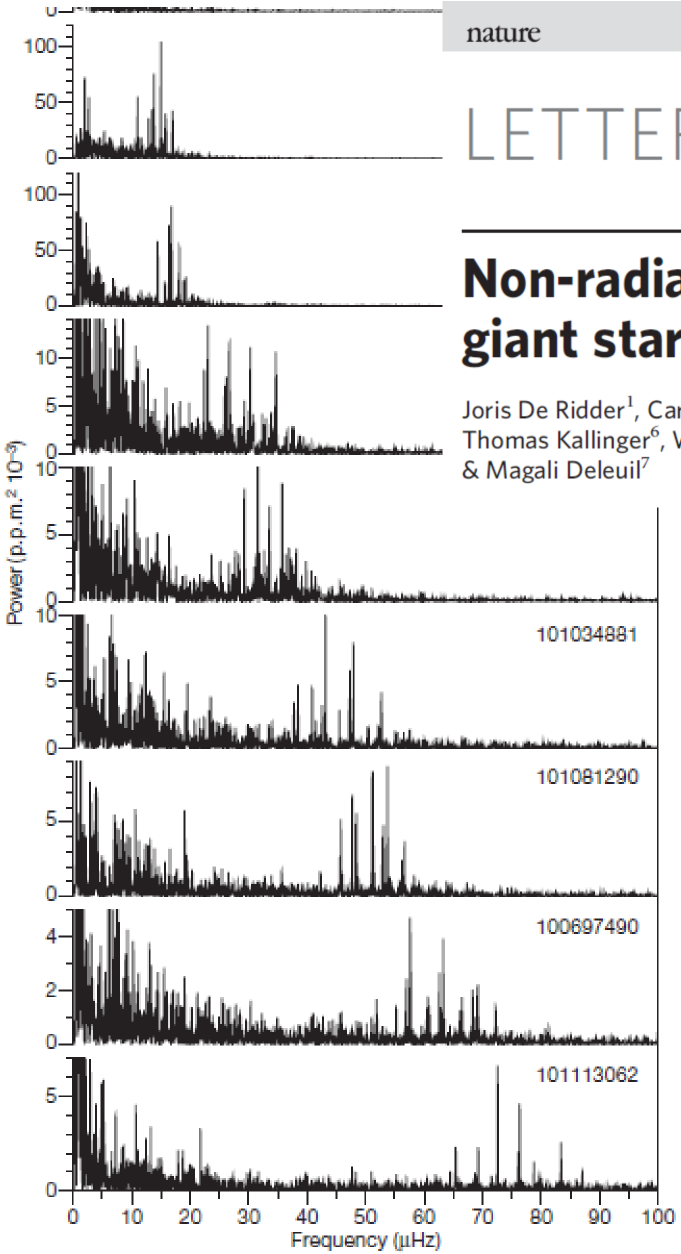
nature | Vol 459 | 21 May 2009 | doi:10.1038/nature08022

LETTERS

Red giants with CoRoT
(De Ridder et al. 2009)
150 days

Non-radial oscillation modes with long lifetimes in giant stars

Joris De Ridder[1], Caroline Barban[2], Frédéric Baudin[3], Fabie
Thomas Kallinger[6], Werner W. Weiss[6], Annie Baglin[2], Mic
& Magali Deleuil[7]



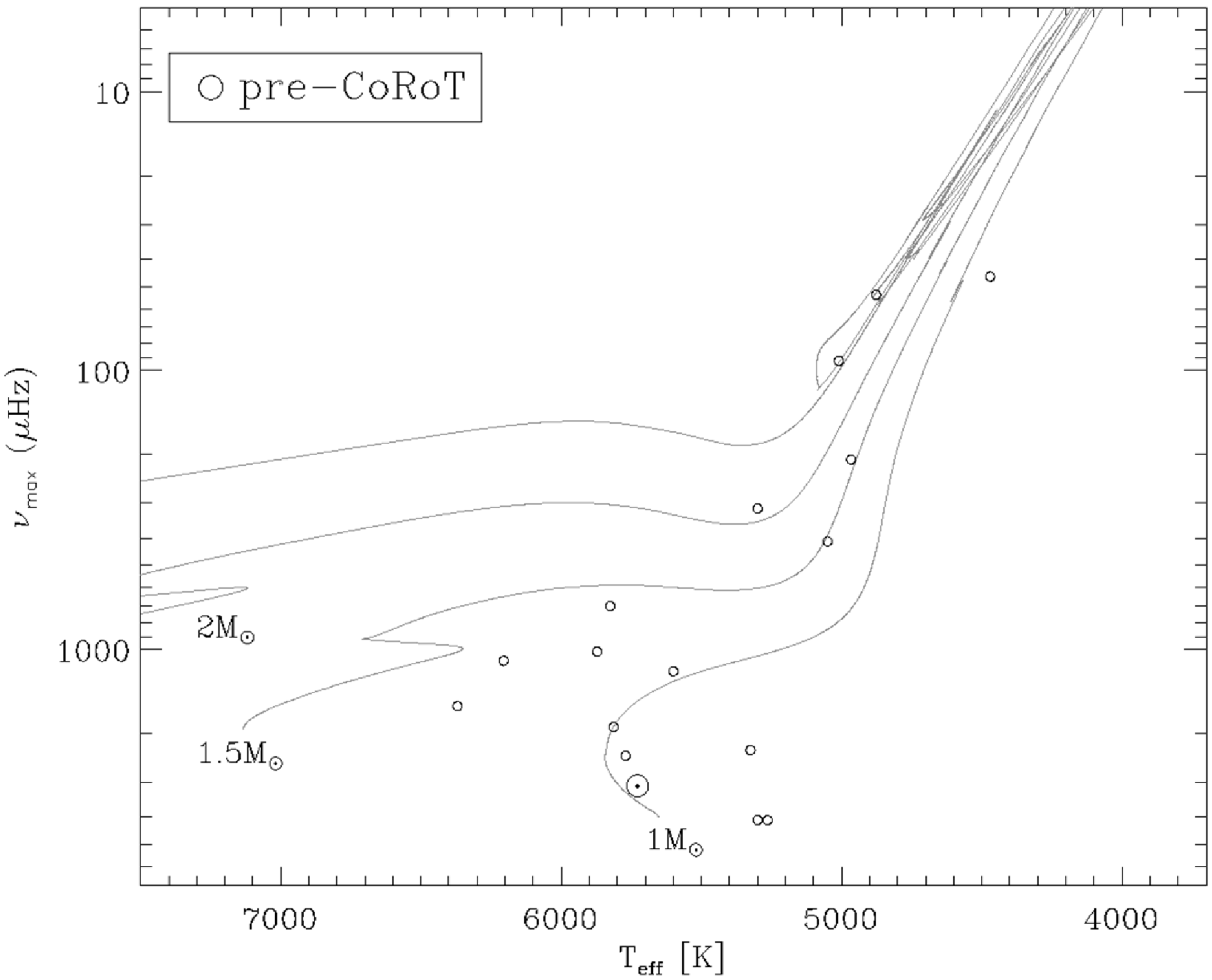


figure by Daniel Huber

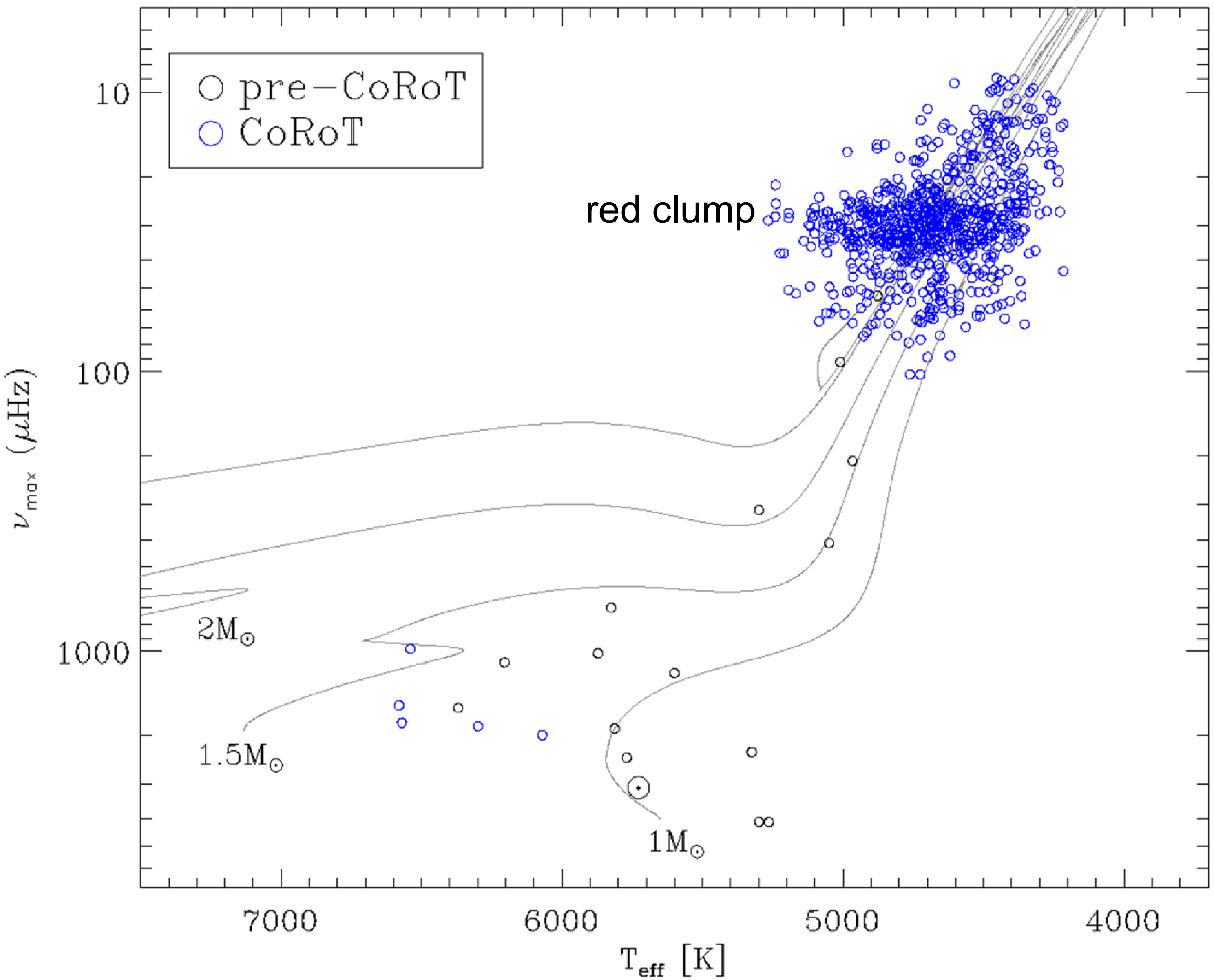
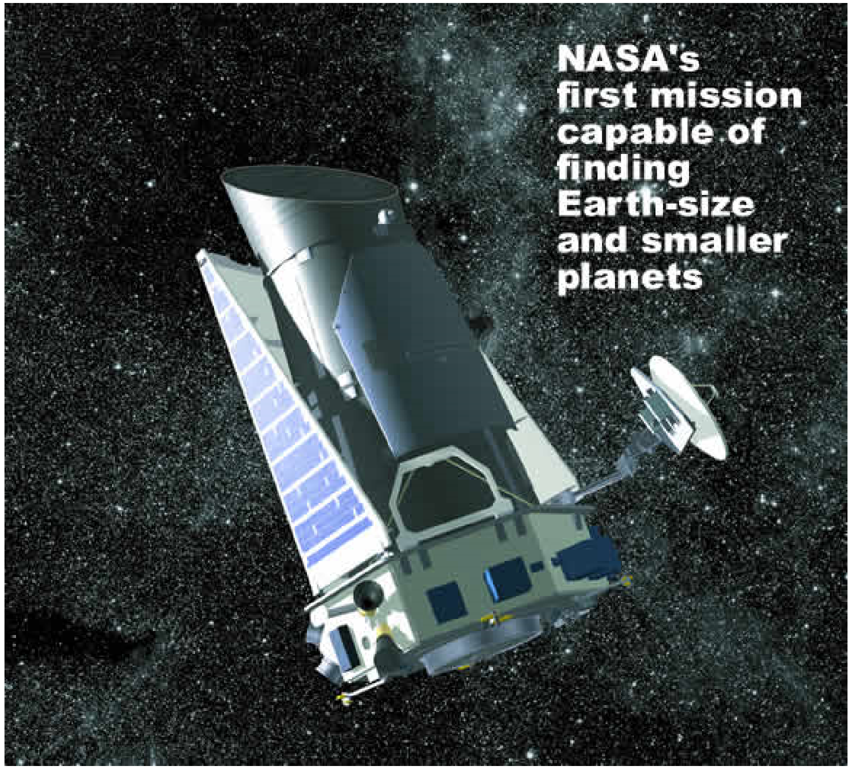
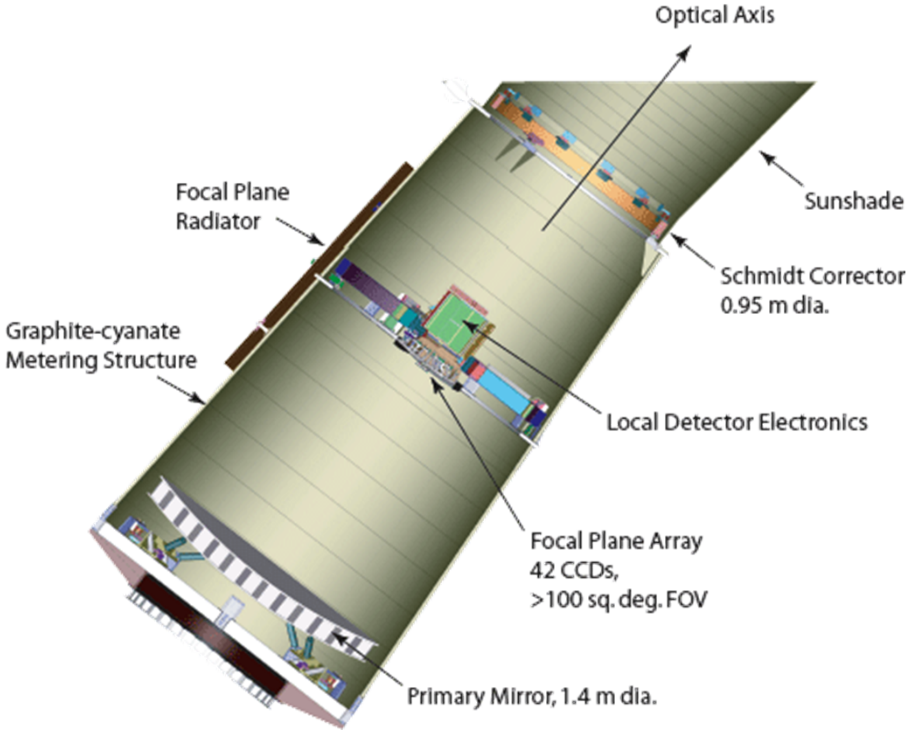


figure by Daniel Huber

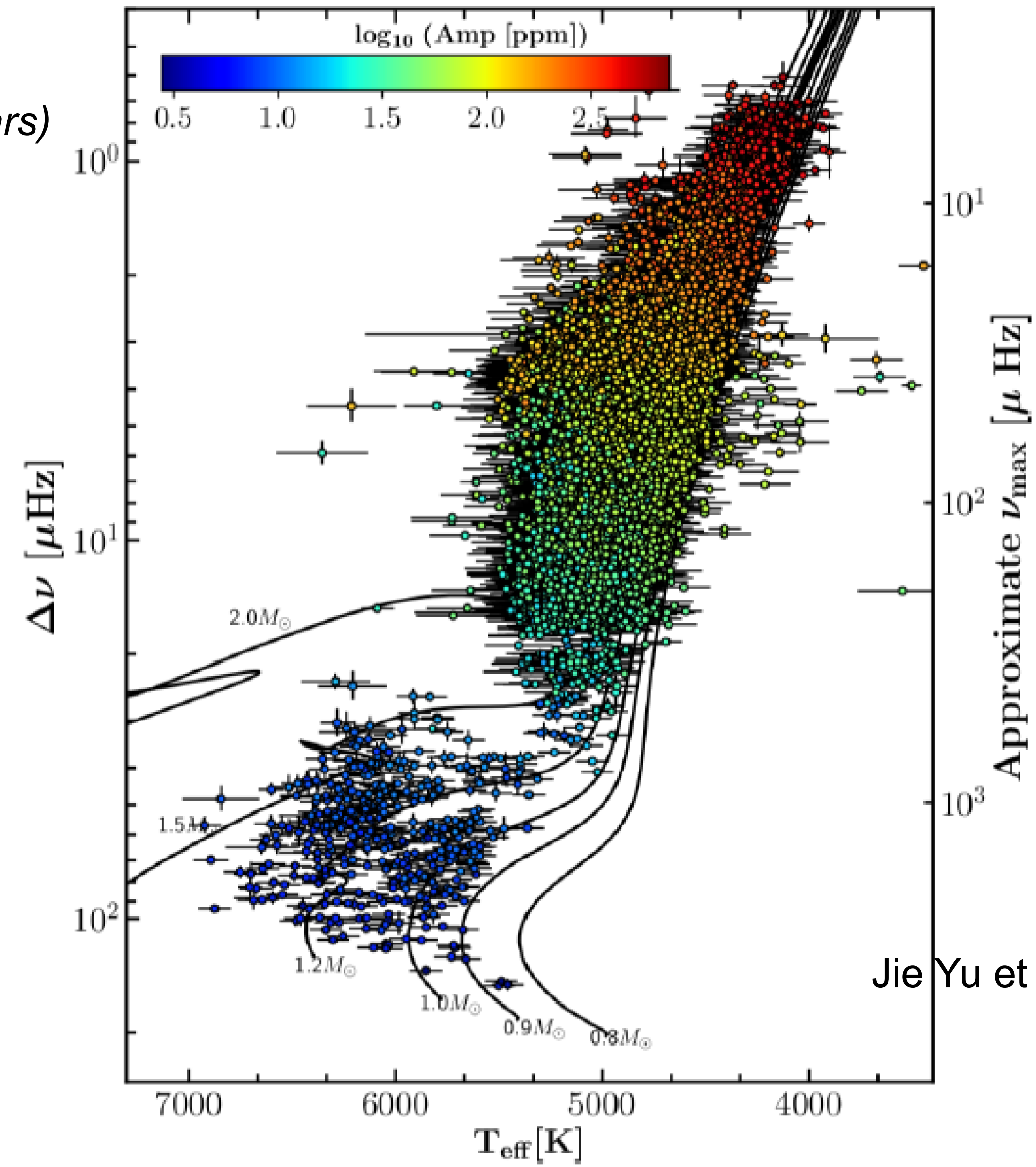
NASA *Kepler* Mission



Launched 6 March 2009



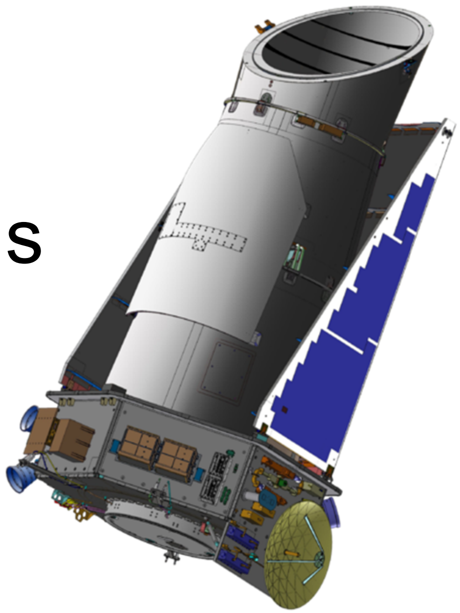
after 4 years of *Kepler (16,000 stars)*

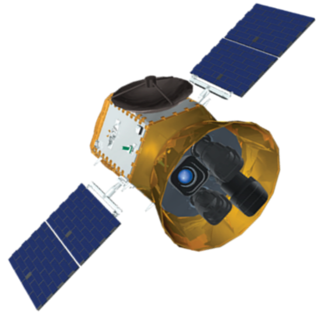


Jie Yu et al. (2017, 2018ab)

How can SONG compete/contribute?

versus





Predicting radial-velocity jitter induced by stellar oscillations based on *Kepler* data

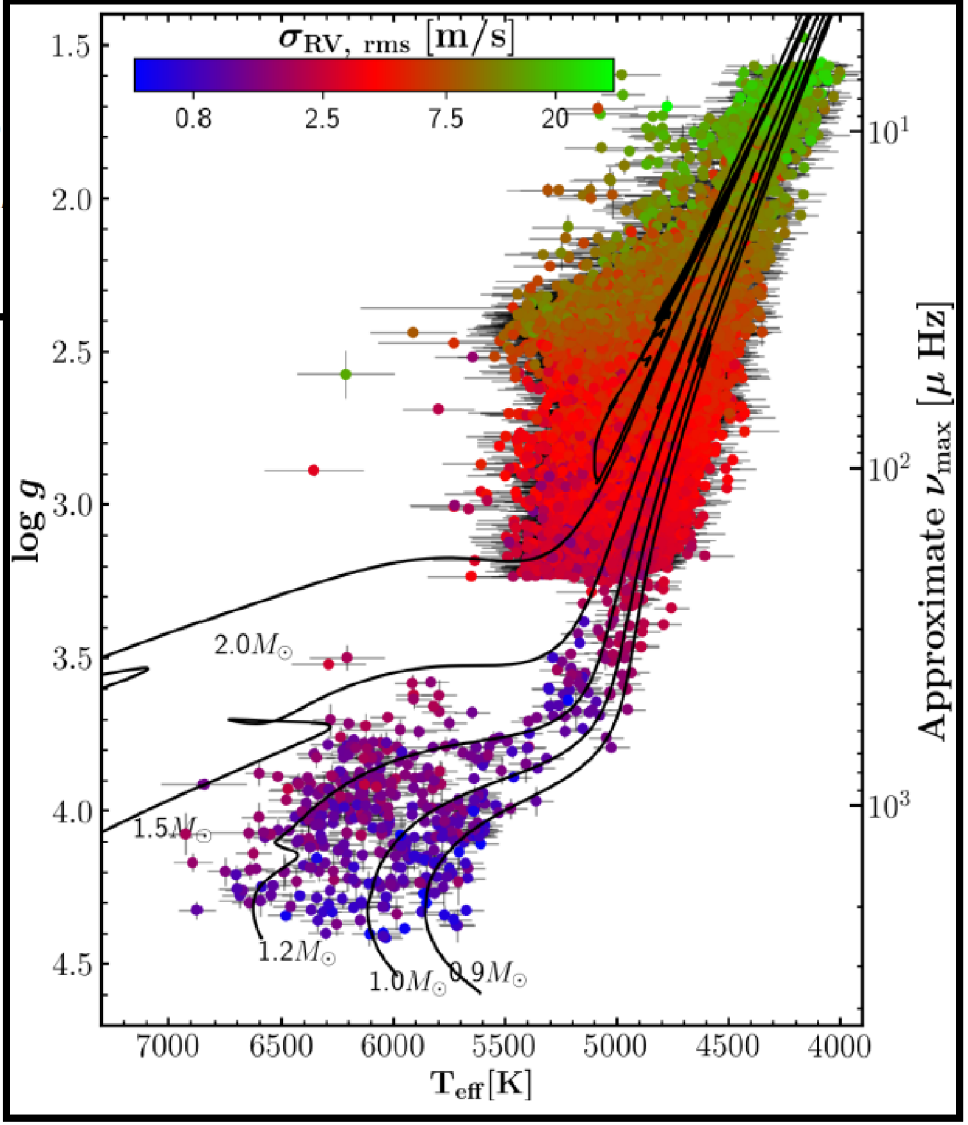
Jie Yu,[1,2★] Daniel Huber,[1,2,3,4] Timothy R. Bedding[1,2] and Dennis Stello

[1] *Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia*
[2] *Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK 8000 Aarhus C,*
[3] *Institute for Astronomy, University of Hawai'i, 2680 Wood-lawn Drive, Honolulu, HI 96822, USA*
[4] *SETI Institute, 189 Bernardo Avenue, Mountain View, CA 94043, USA*
[5] *School of Physics, University of New South Wales, NSW 2052, Australia*

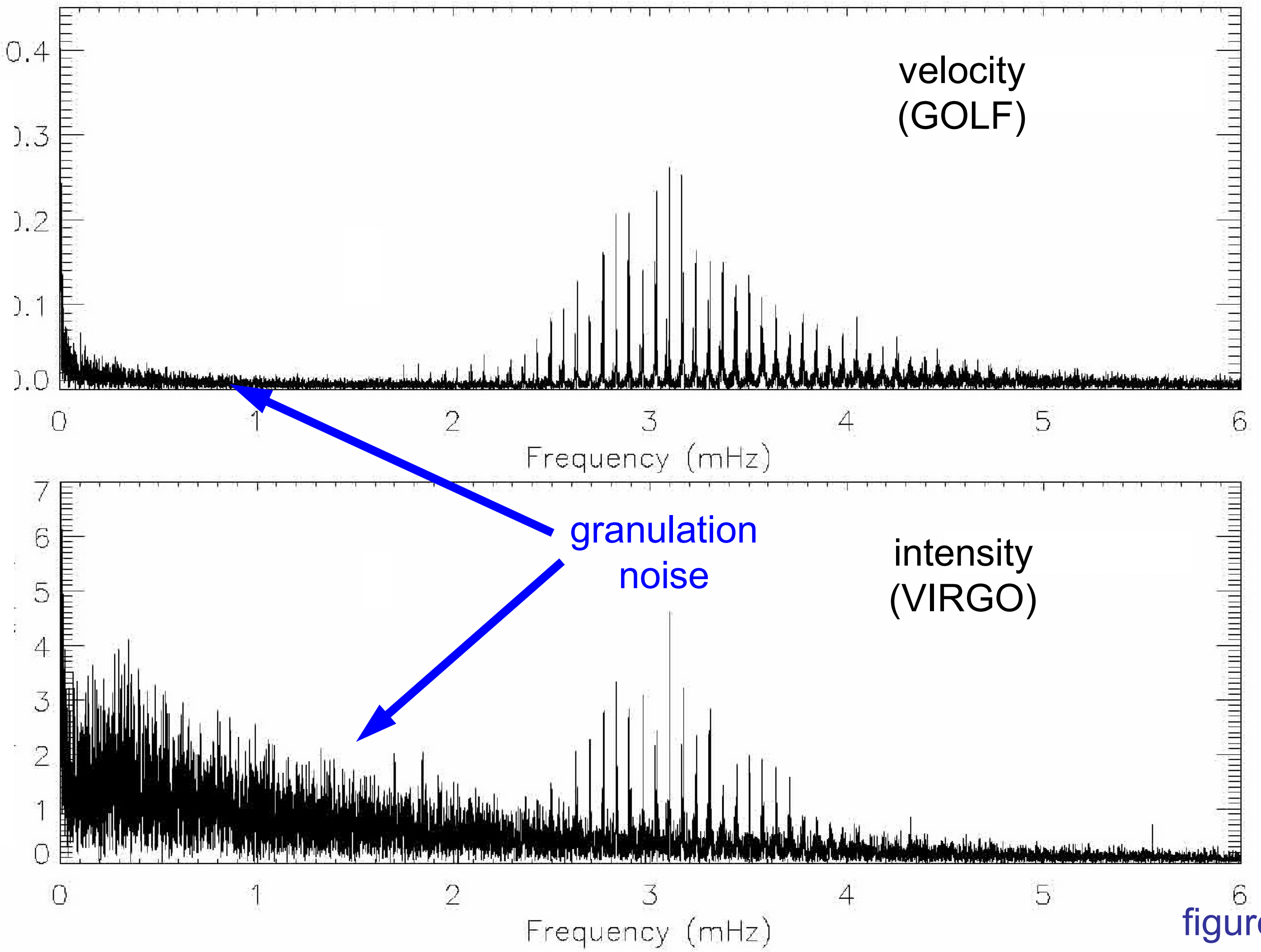
From the photometric oscillation amplitude A_λ, we were able to obtain the RV amplitude $\upsilon_{\rm osc}$ via the relation given by Kjeldsen & Bedding (1995):

$$\upsilon_{\rm osc} = ({\rm A}_\lambda/20.1{\rm ppm})\,(\lambda/550\ {\rm nm})\,(T_{\rm eff}/5777\ {\rm K})^2\ [{\rm m\ s}^{-1}], \qquad (2)$$

where $T_{\rm eff}$ is the effective temperature, and $\lambda = 600$ nm was taken as a representative wavelength for the broad bandpass of the *Kepler* telescope.



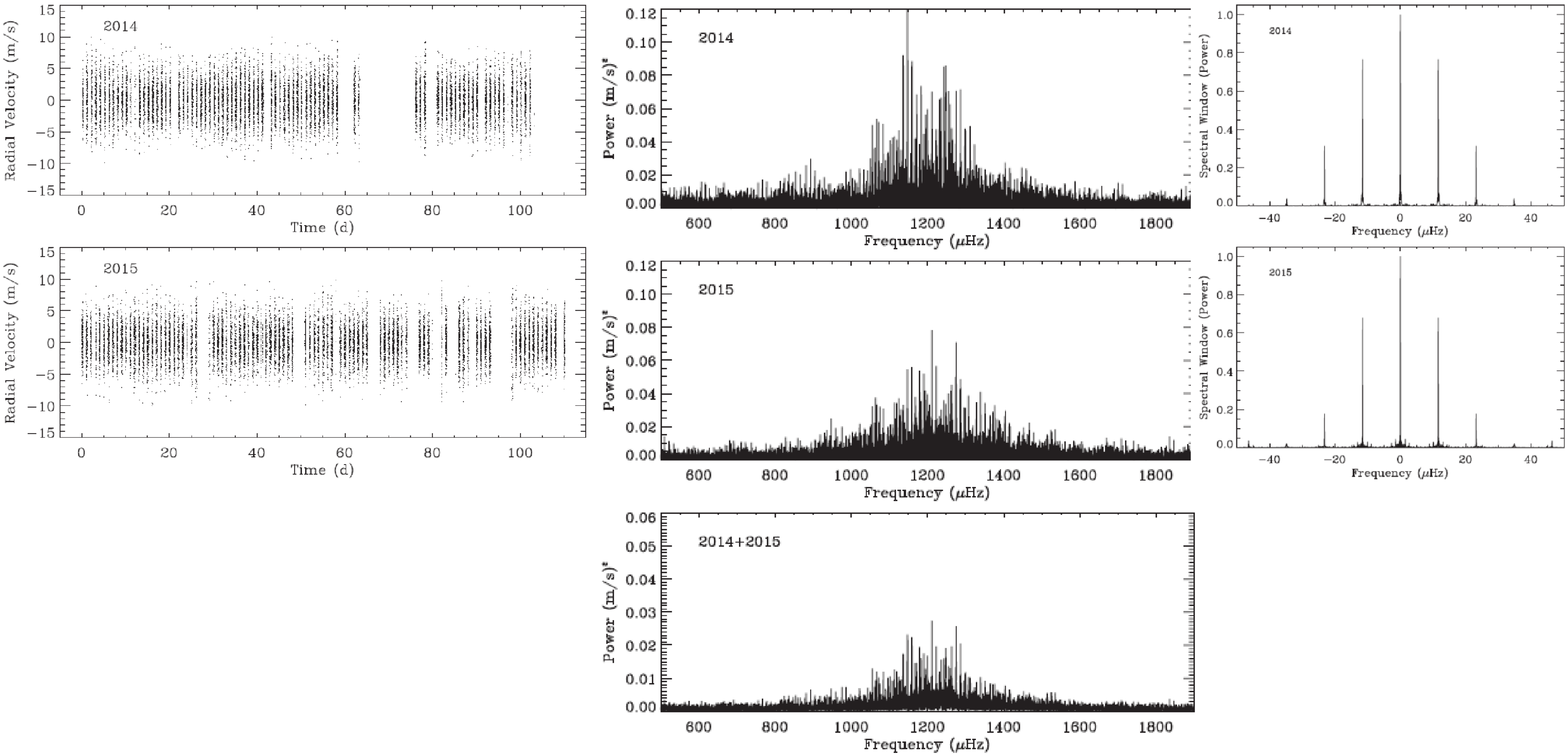
Sun (20 days with SOHO)



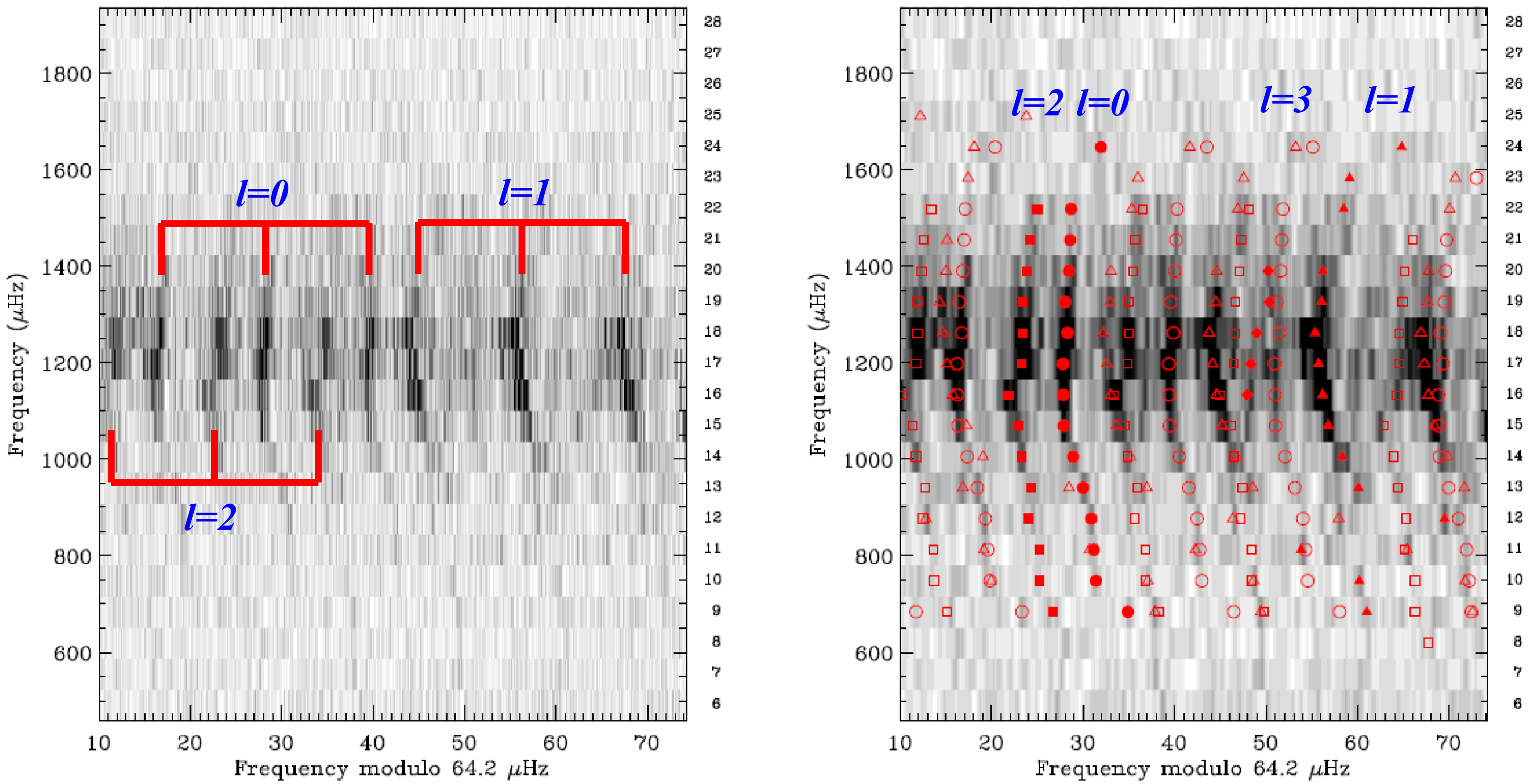
figures by Hans Kjeldsen

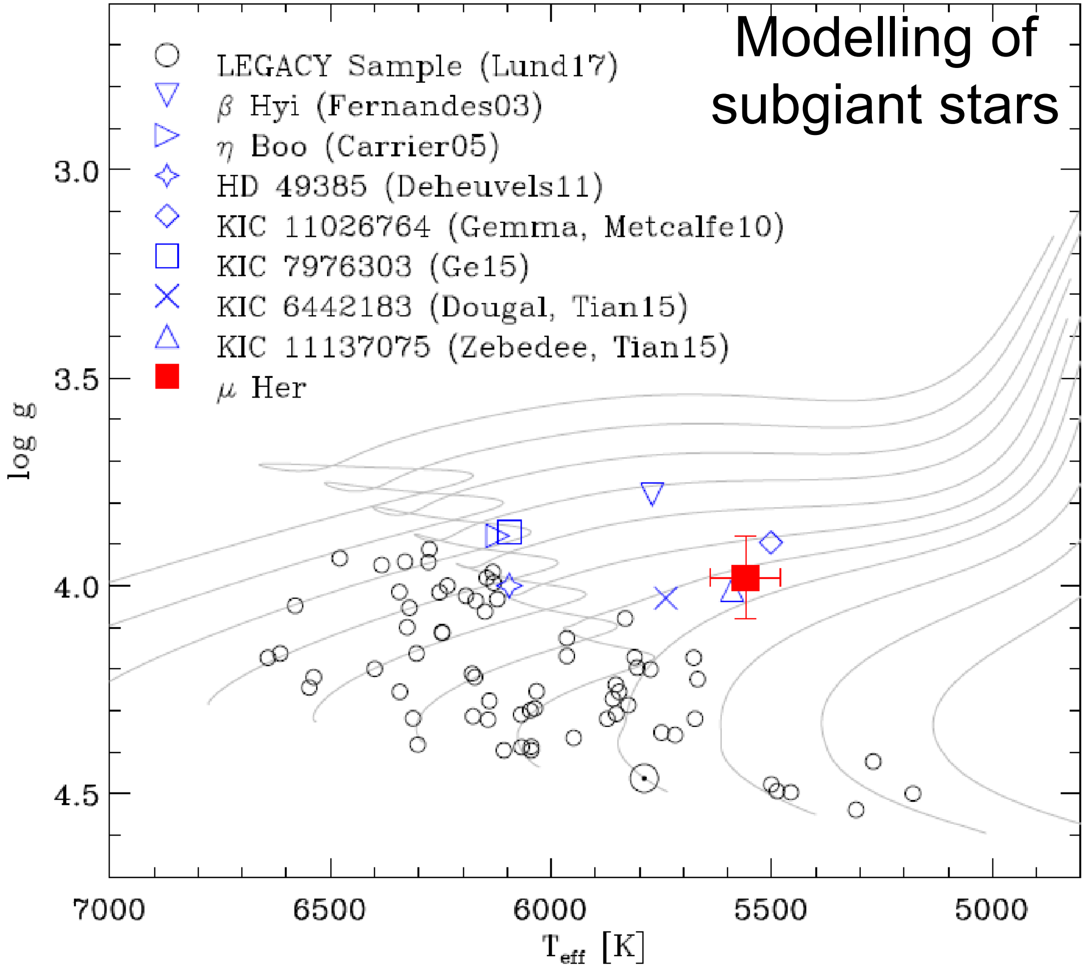
First Results from the Hertzsprung SONG Telescope: Asteroseismology of the G5 Subgiant Star μ Herculis*

F. Grundahl[1], M. Fredslund Andersen[1], J. Christensen-Dalsgaard[1], V. Antoci[1], H. Kjeldsen[1], R. Handberg[1], G. Houdek[1], T. R. Bedding[1,2], P. L. Pallé[3,4], J. Jessen-Hansen[1], V. Silva Aguirre[1], T. R. White[1], S. Frandsen[1], S. Albrecht[1], M. I. Andersen[5], T. Arentoft[1], K. Brogaard[1], W. J. Chaplin[1,6], K. Harpsøe[7], U. G. Jørgensen[7], I. Karovicova[8], C. Karoff[1,9], P. Kjærgaard Rasmussen[5], M. N. Lund[1,6], M. Sloth Lundkvist[1,10], J. Skottfelt[7,11], A. Norup Sørensen[5], R. Tronsgaard[1], and E. Weiss[1]


2014
2015
2014+2015
Radial Velocity (m/s)
Time (d)
Power (m/s)²
Frequency (μHz)
Spectral Window (Power)

μ Her is an ideal target for single-site observations!
$\Delta\nu/2$ = 2.8 c/d
(see also Arentoft et al. 2014)

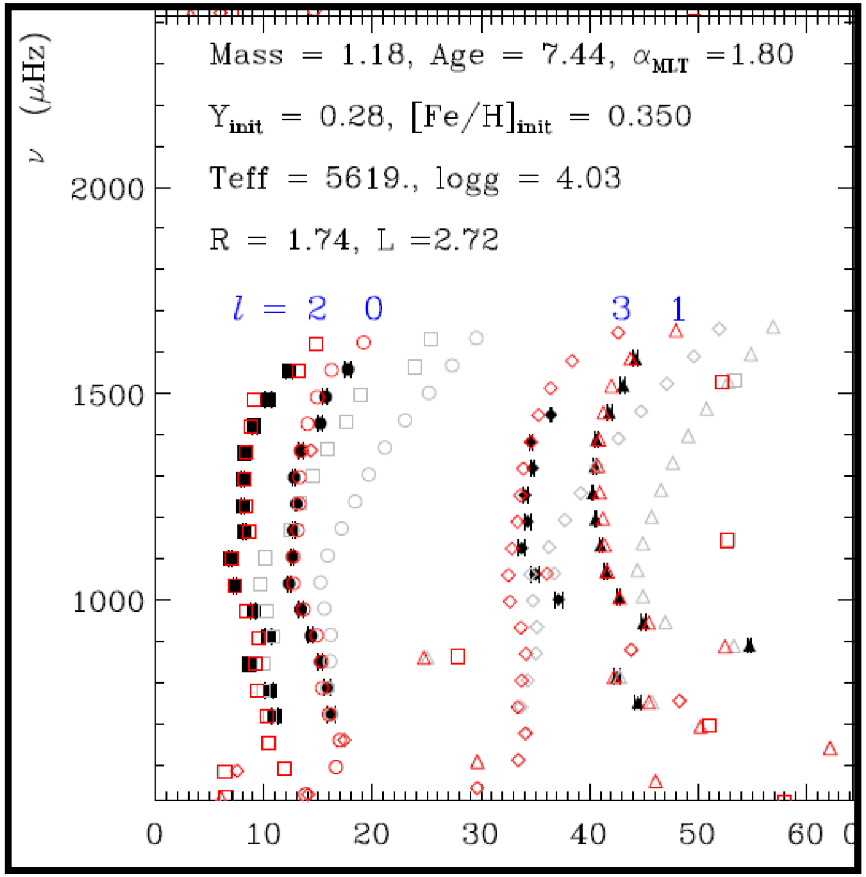


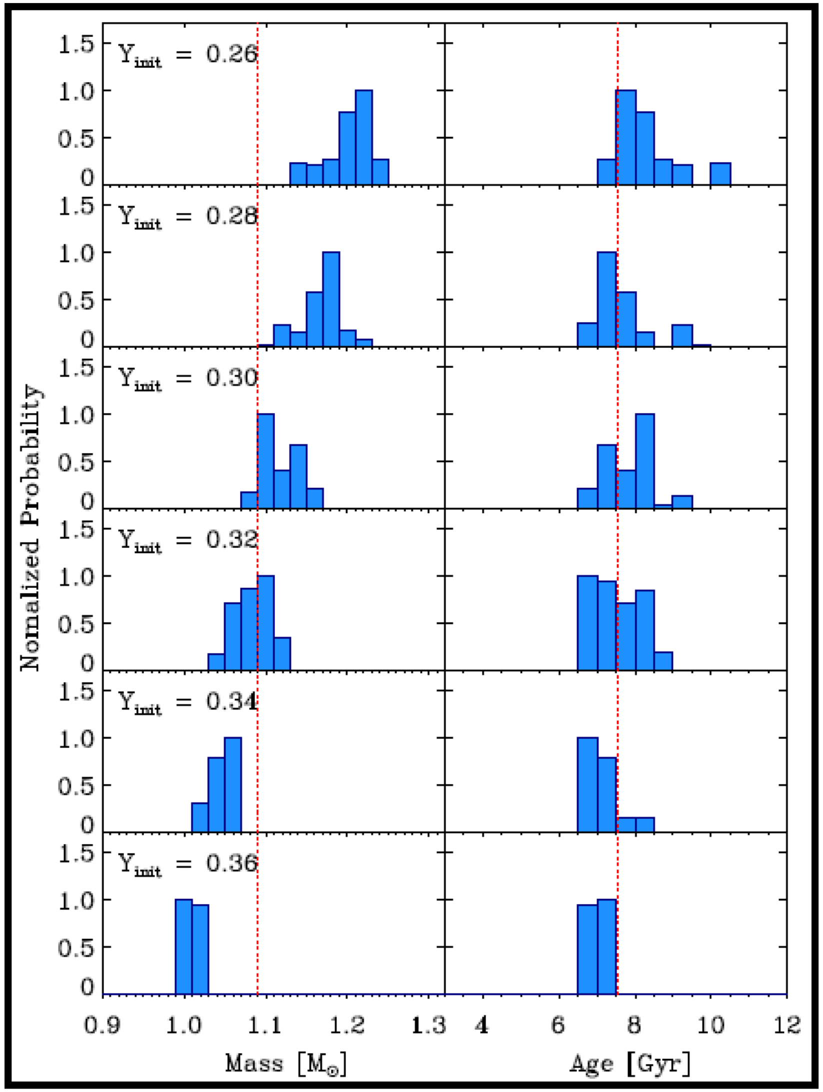


Tanda Li et al. (submitted)

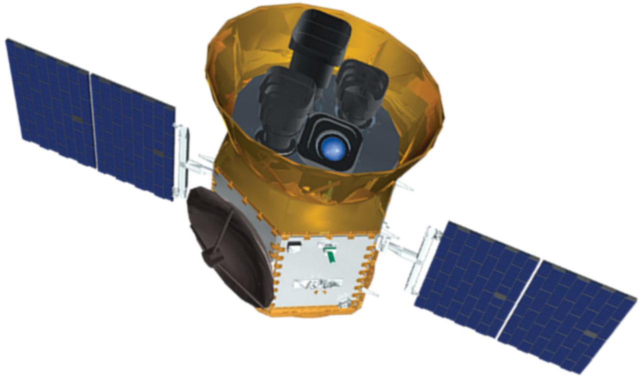
Asteroseismic modelling of the subgiant μ Herculis using SONG data: lifting the degeneracy between age and model input parameters

Tanda Li[1,2,3★], Timothy R. Bedding[1,2] , Hans Kjeldsen[2], Dennis Stello[4,2],
Jørgen Christensen-Dalsgaard[2]
[1]*Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia*
[2]*Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark*
[3]*Key Laboratory of Solar Activity, National Astronomical Observatories, Chinese Academy of Science, Beijing 100012, China*
[4]*School of Physics, University of New South Wales, Australia*


Mass = 1.18, Age = 7.44, α_{MLT} =1.80
Y_{init} = 0.28, $[Fe/H]_{init}$ = 0.350
Teff = 5619., logg = 4.03
R = 1.74, L =2.72
l = 2 0 3 1
ν (μHz)
2000
1500
1000
0 10 20 30 40 50 60


Y_{init} = 0.26
Y_{init} = 0.28
Y_{init} = 0.30
Y_{init} = 0.32
Y_{init} = 0.34
Y_{init} = 0.36
Nomalized Probability
1.5 1.0 0.5 0
0.9 1.0 1.1 1.2 1.3
Mass $[M_{\odot}]$
4 6 8 10 12
Age [Gyr]

Simultaneous observations with TESS



The Astrophysical Journal, 731:94 (9pp), 2011 April 20 doi:10.1088/0004-637X/731/2/94

SOLAR-LIKE OSCILLATIONS AND ACTIVITY IN PROCYON: A COMPARISON OF THE 2007 *MOST** AND GROUND-BASED RADIAL VELOCITY CAMPAIGNS

Daniel Huber[1], Timothy R. Bedding[1], Torben Arentoft[2], Michael Gruberbauer[3], David B. Guenther[3], Günter Houdek[4], Thomas Kallinger[4,5], Hans Kjeldsen[2], Jaymie M. Matthews[5], Dennis Stello[1], and Werner W. Weiss[4]
[1] Sydney Institute for Astro
[2] Danish AsteroSeismology
[3] Institute for Computational
[5] Department of Physics a

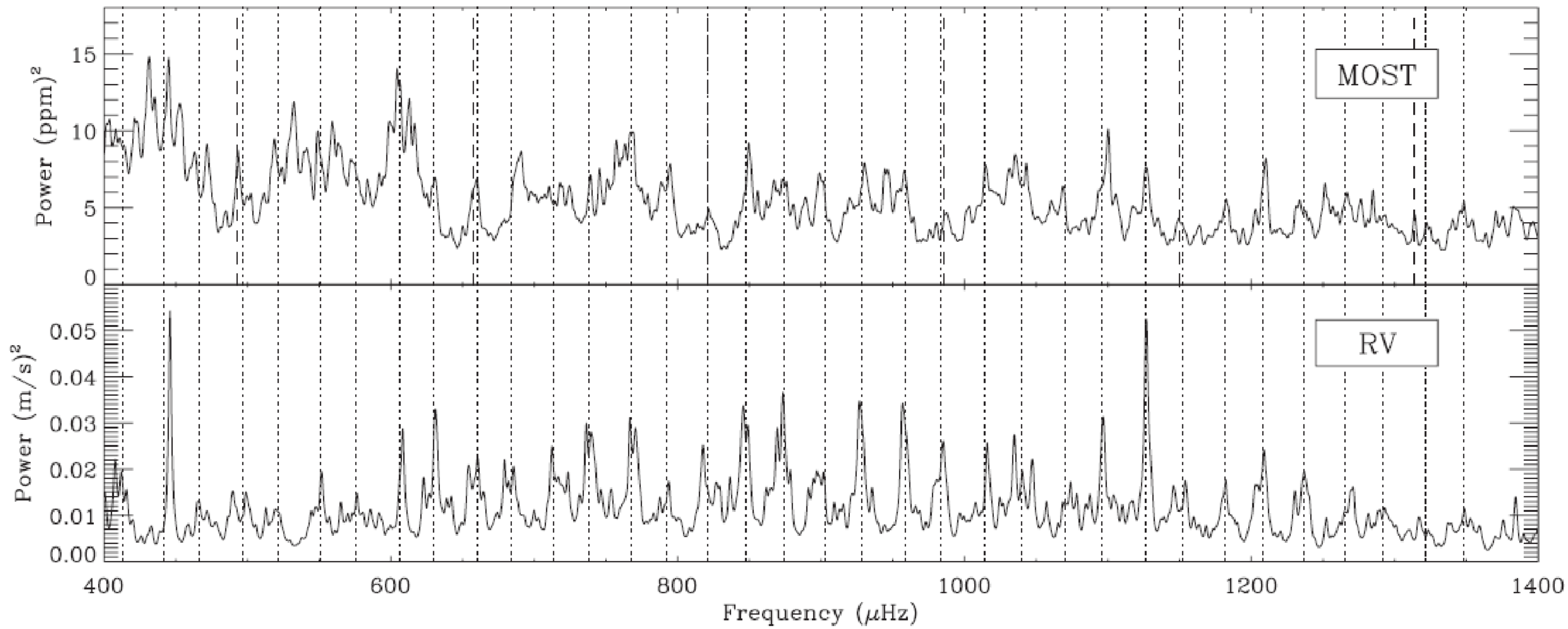


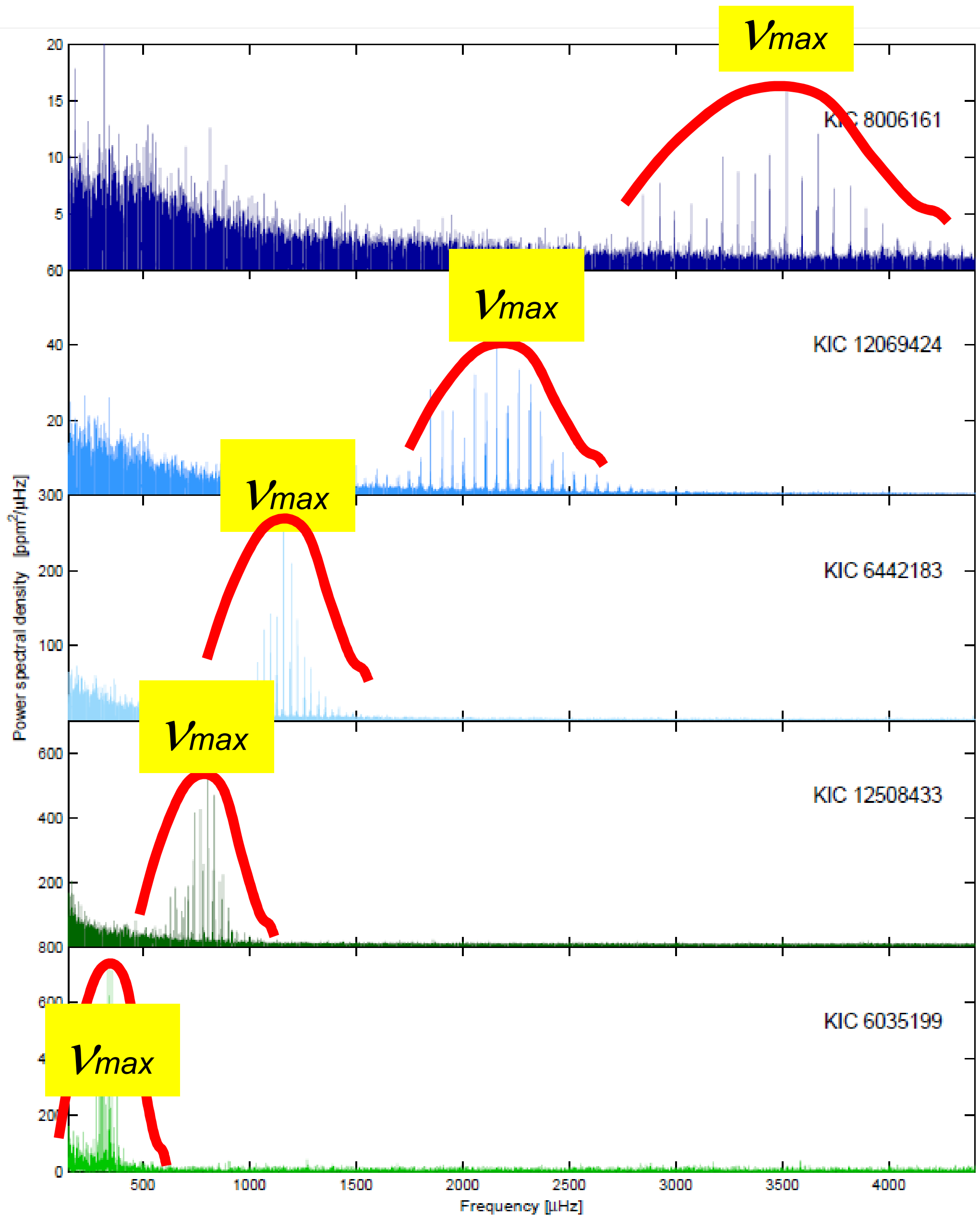
Figure 4. Power spectra of Procyon from *MOST* photometry (upper panel) and the radial velocity campaign (lower panel), smoothed with a Lorentzian with a width of 2.5 μHz (corresponding to a mode lifetime of 1.5 days). Dotted lines mark the odd and even ridge centroids identified in the velocity data. Dashed lines show the harmonics of the *MOST* orbital frequency.

see talks by Dan Huber
& Günter Houdek

Checking the scaling relations for red giants

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

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



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

Brown et al. (1991);
Kjeldsen & Bedding (1995)

Chaplin & Miglio (2013)

Scaling relations:

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2} \qquad \nu_{\max} \propto \nu_{\rm ac} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

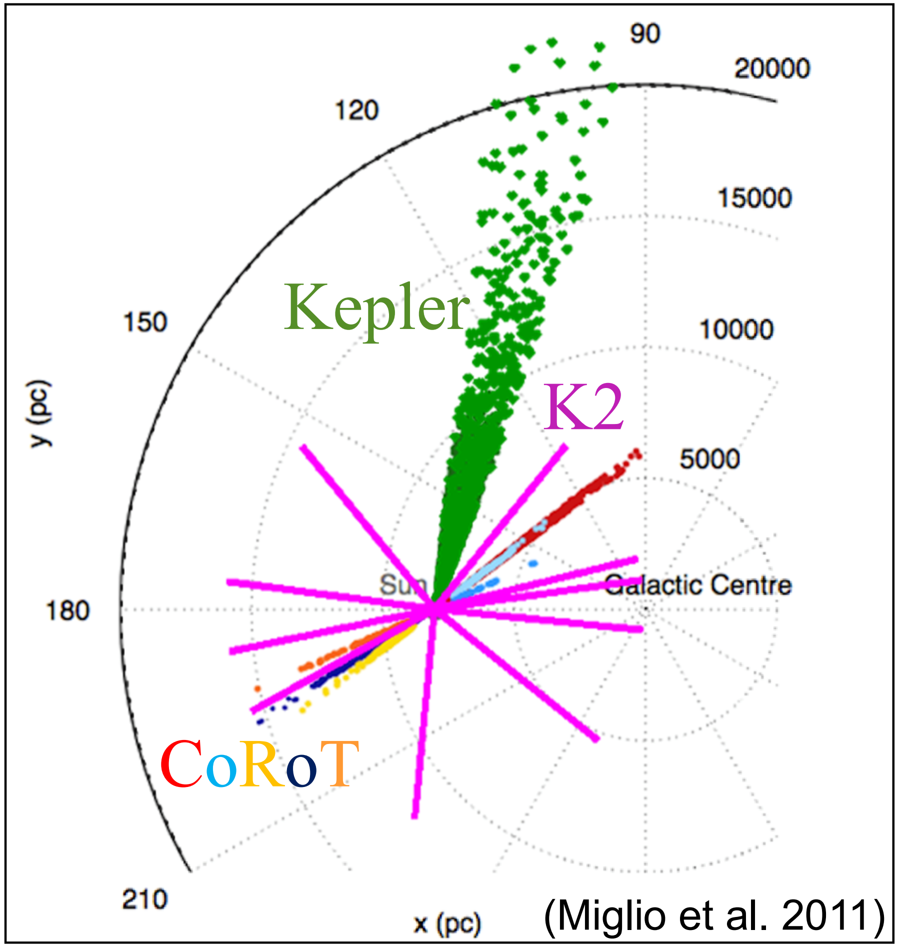
Solve to get mass and radius:

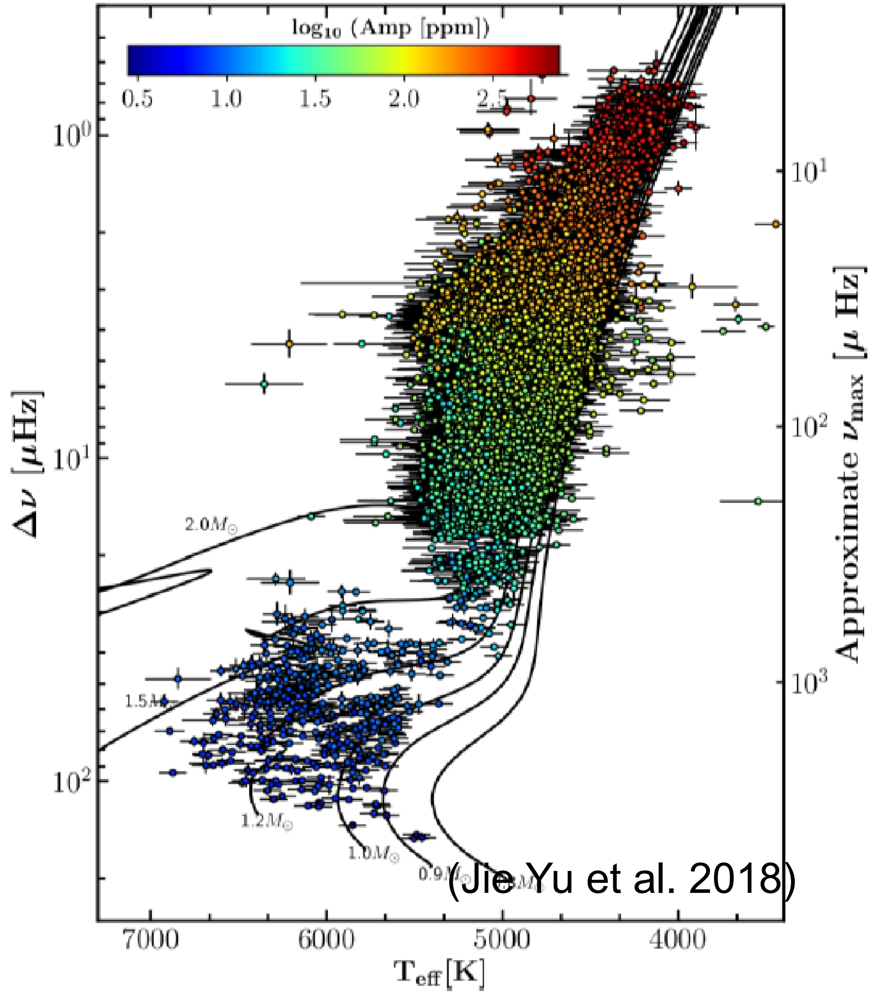
$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$\frac{R}{R_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

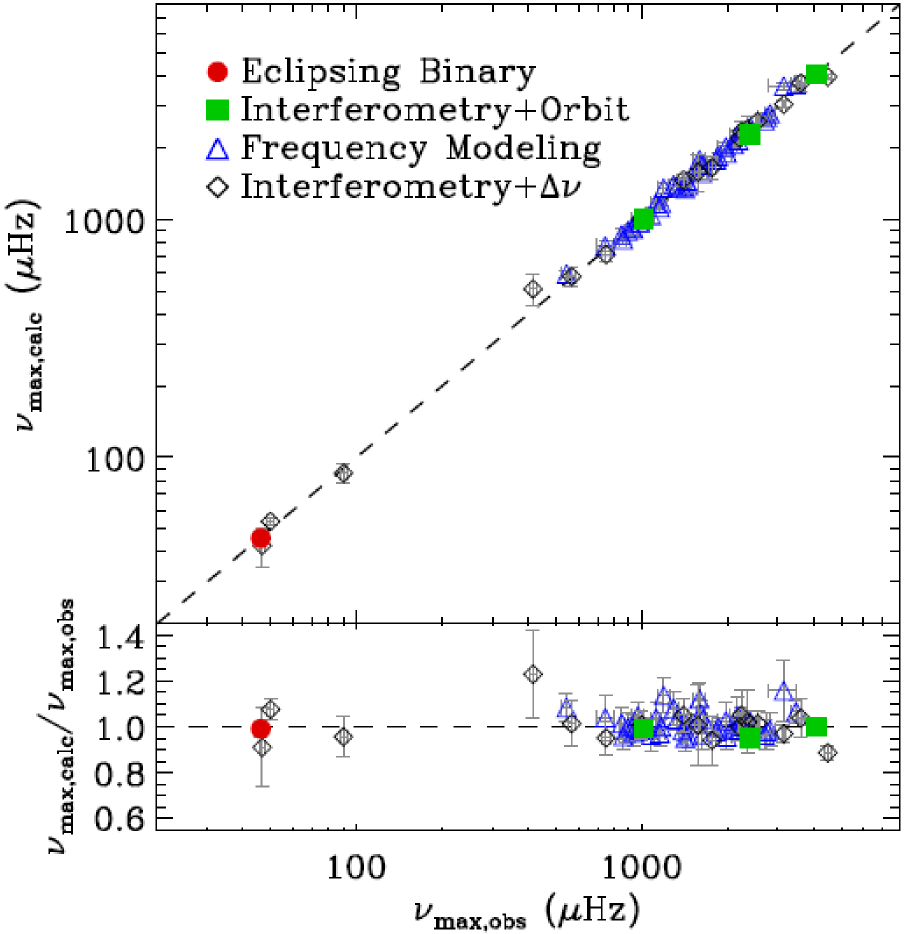
(and luminosity)

Population studies (Galactic archaeology)





How far can we trust the scaling relations?

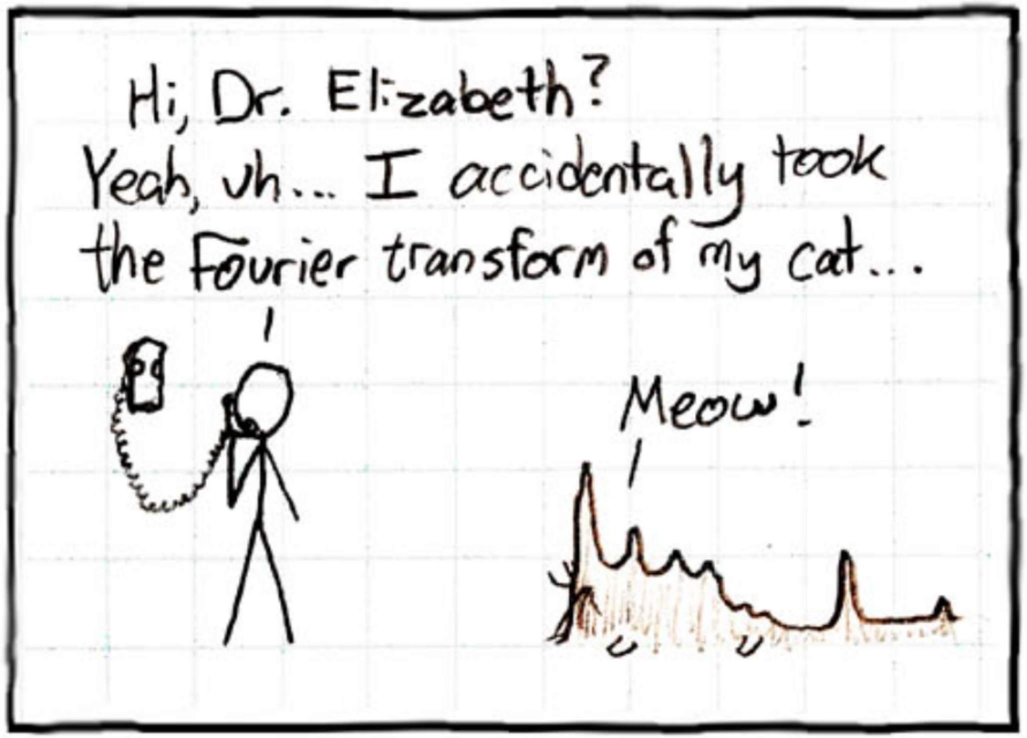


Huber (2014)

see talks by Dennis Stello, Søren Frandsen, Dan Huber, Tim White, …

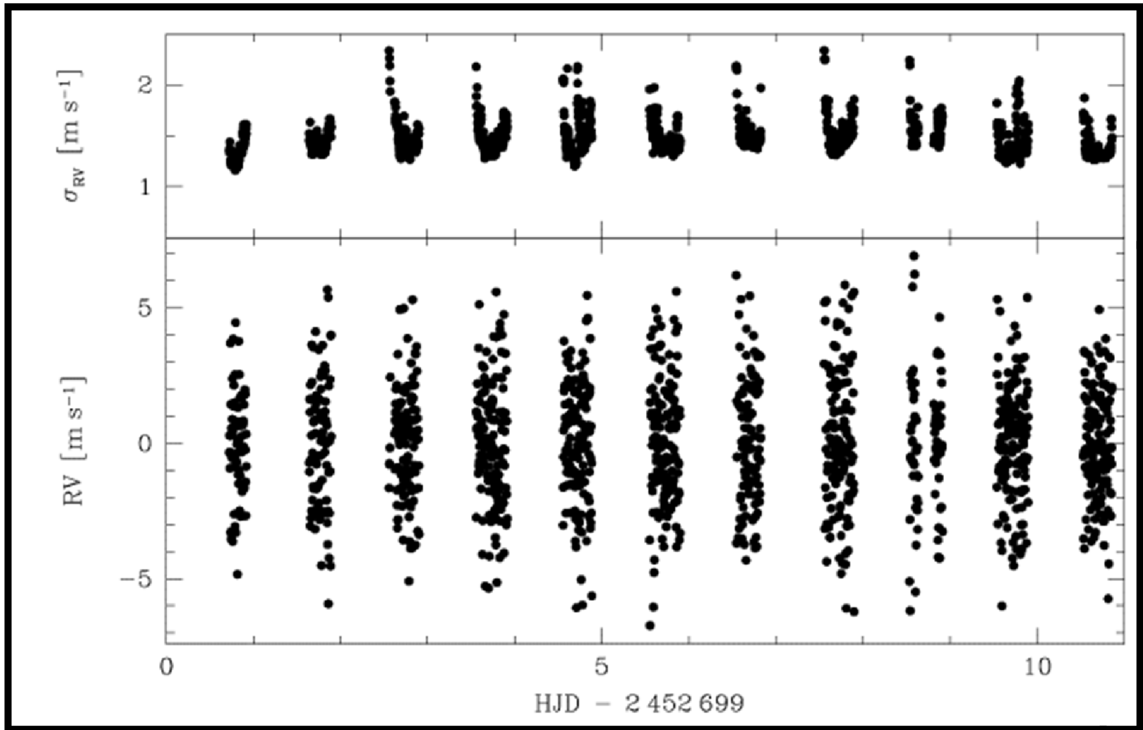
Weighting data

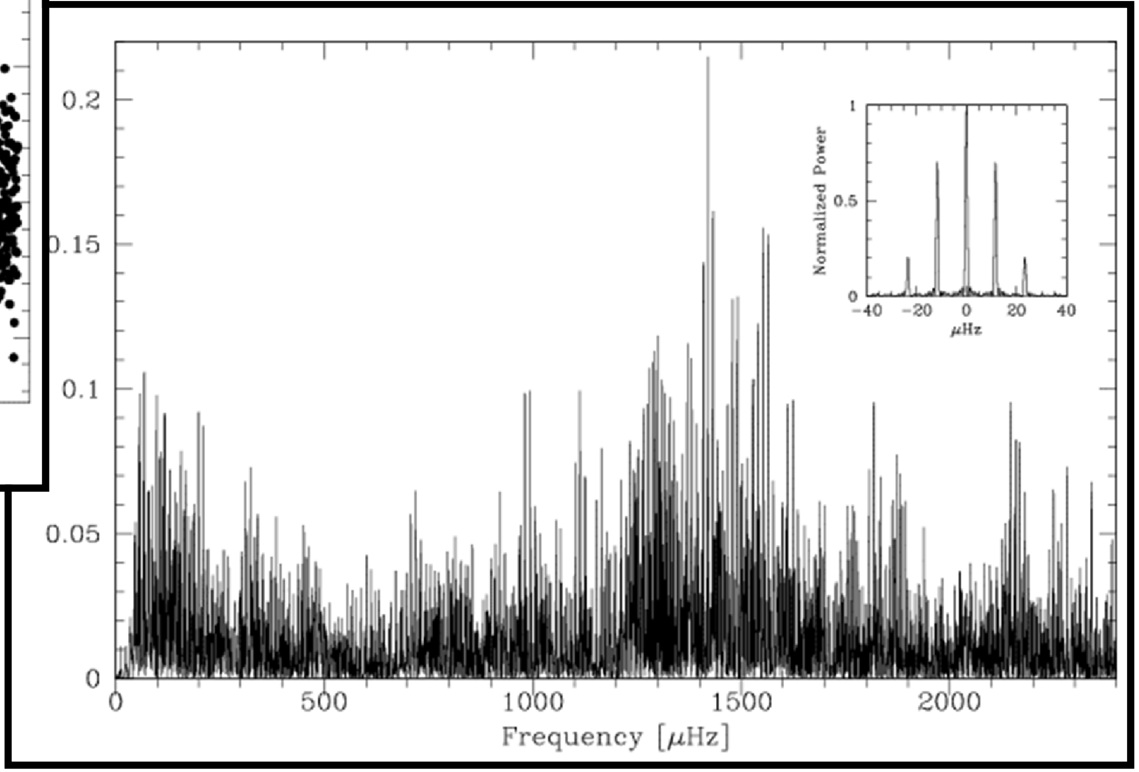
some data are more equal than others!



Single-site: β Vir (F9 V)

Carrier et al. (2005): CORALIE





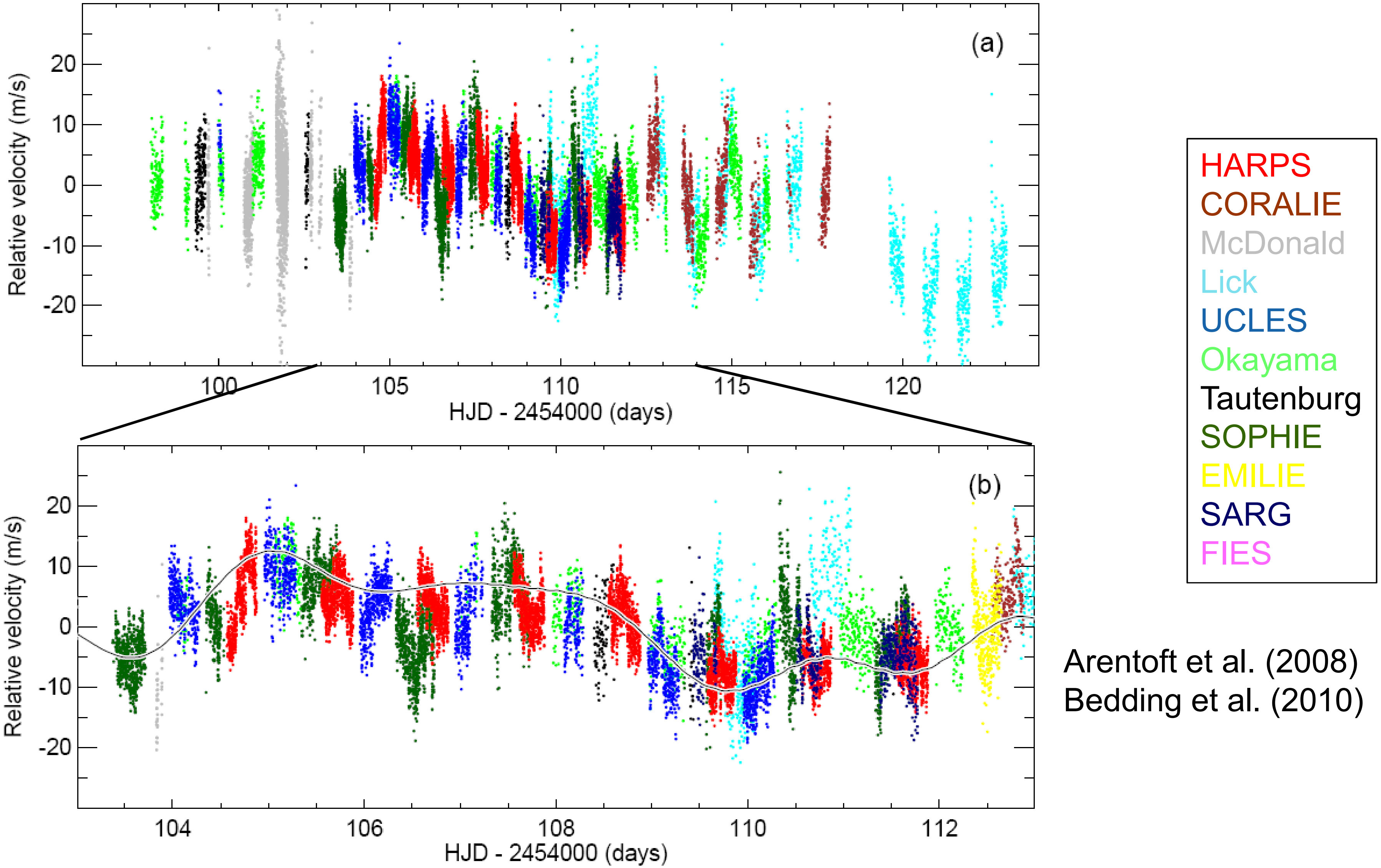
weighting (use 1/variance) reduces the noise in the Fourier spectrum.

Q: What is the down side?

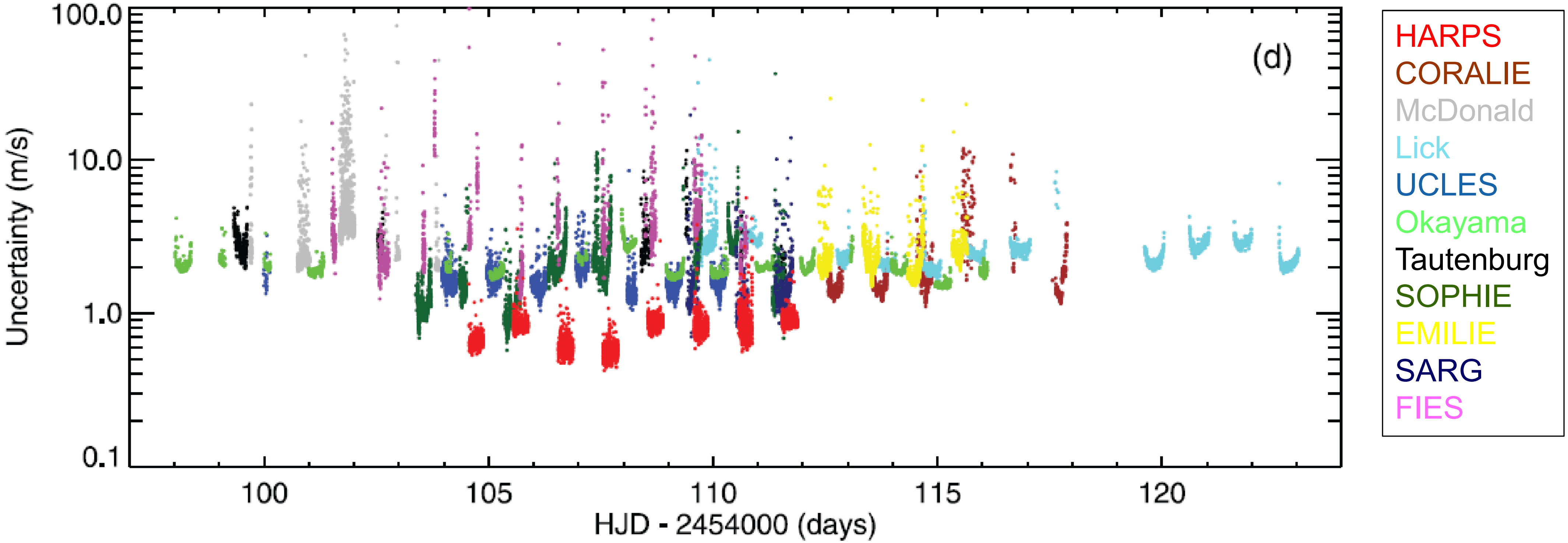
A: higher sidelobes in spectral window

Multi-site: Procyon (F5 IV)

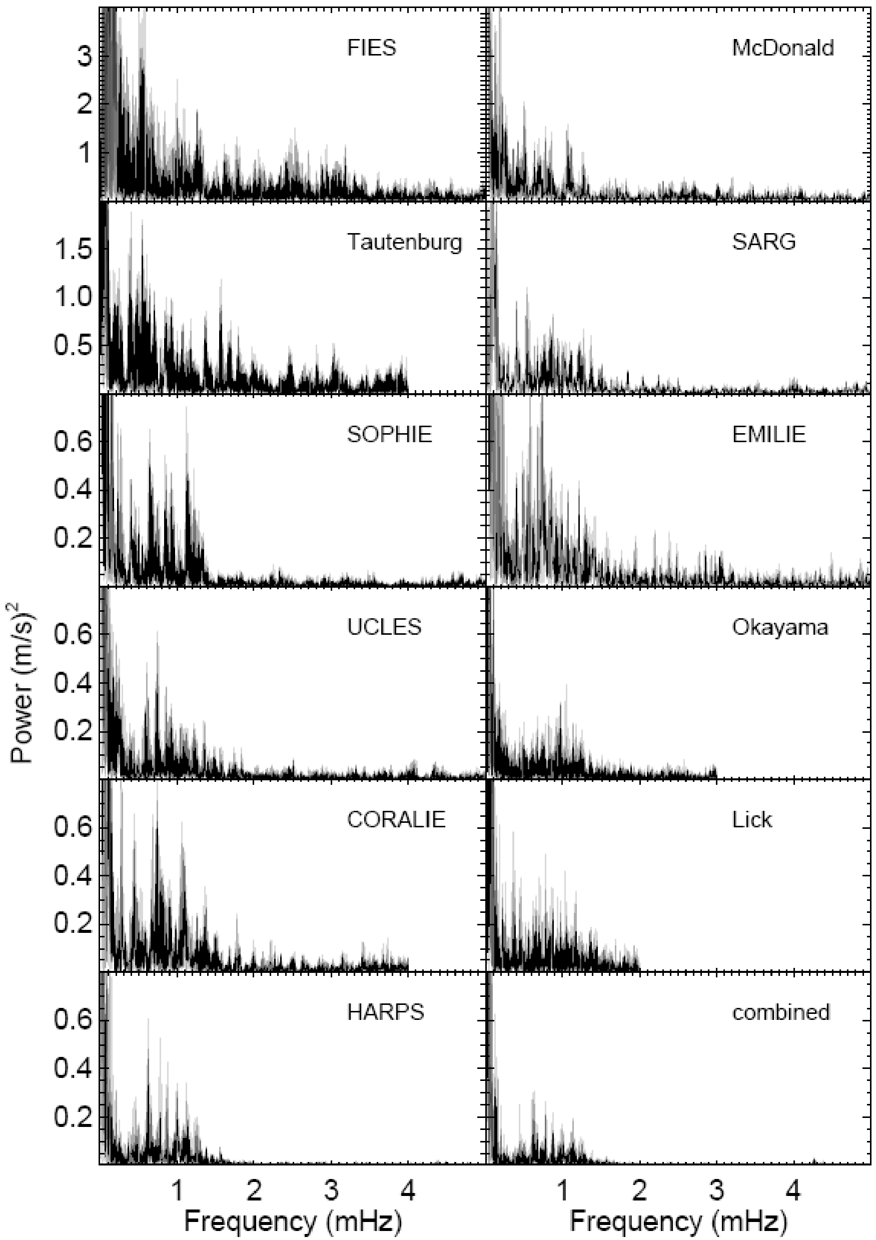
11 telescopes at
8 observatories
over 25 days



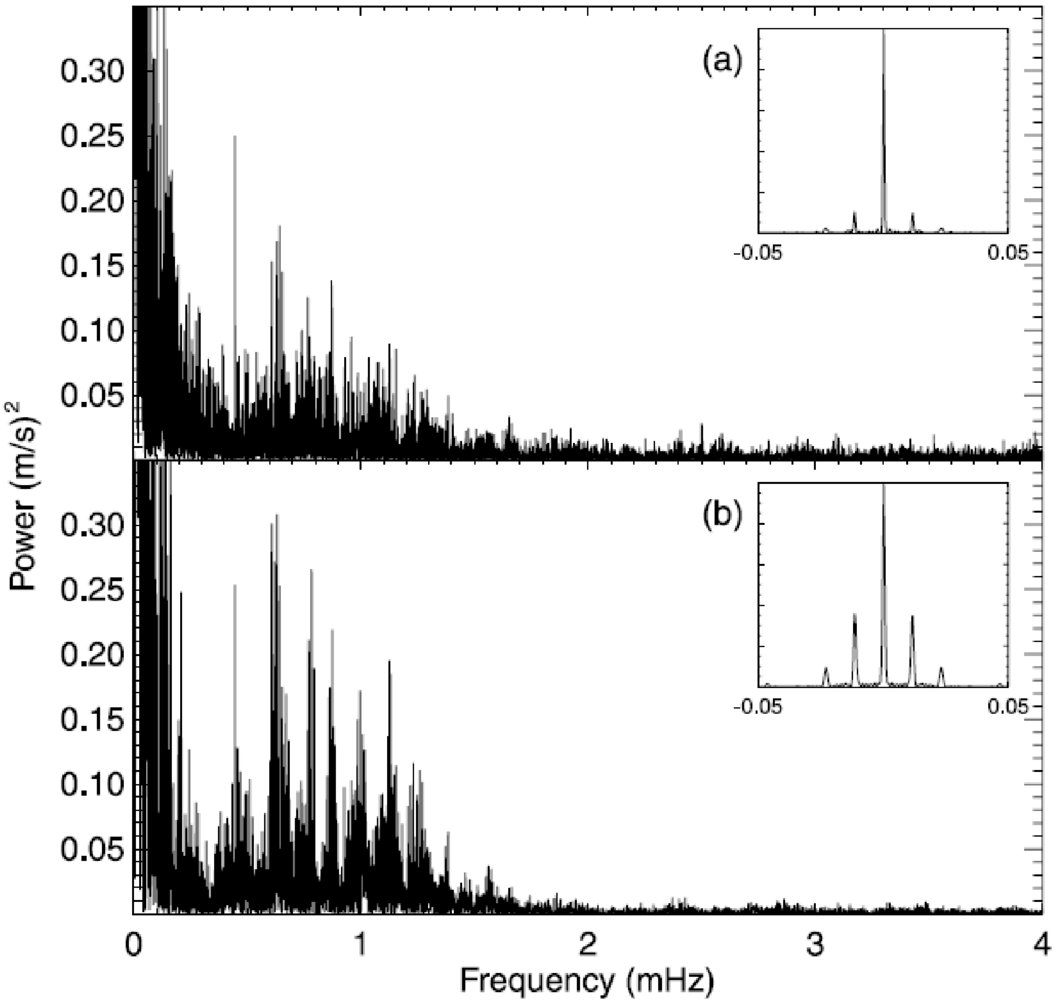
Arentoft et al. (2008)
Bedding et al. (2010)



Arentoft et al. (2008), Bedding et al. (2010)



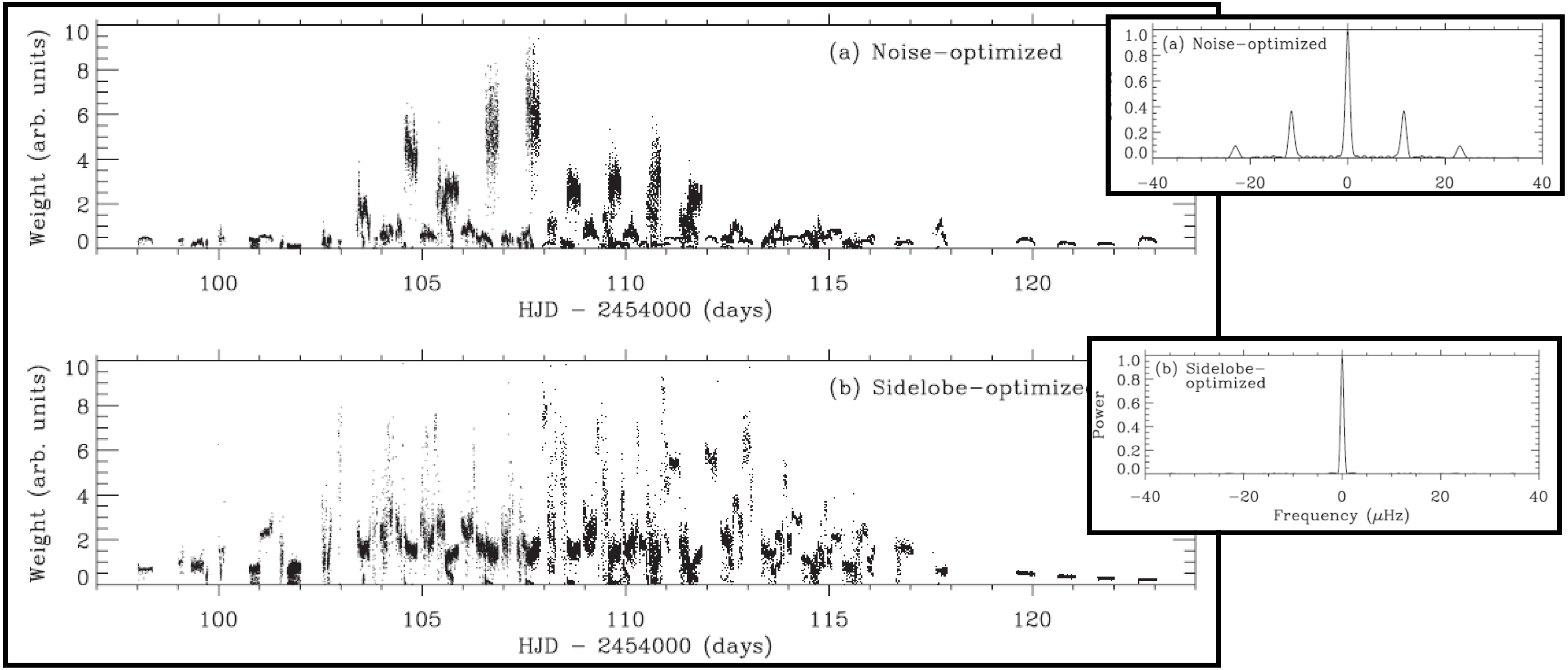
Arentoft et al. (2008),
Bedding et al. (2010)



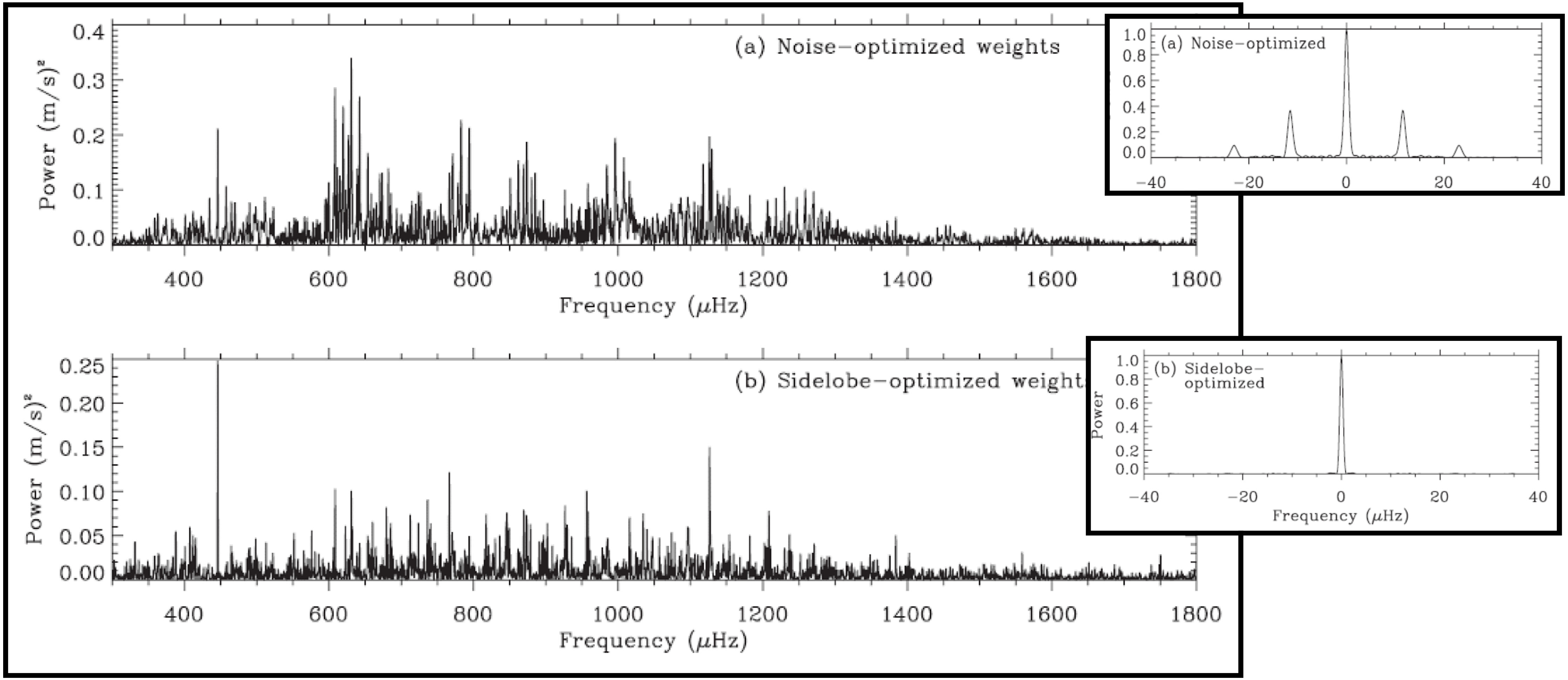
no weights

noise-optimised weights

Arentoft et al. (2008), Bedding et al. (2010)



Arentoft et al. (2008), Bedding et al. (2010)



Arentoft et al. (2008), Bedding et al. (2010)

On the importance of using weights:

- use weights for single-site data
- use weights for combining multi-site data
- adjust weights to reduce *noise* and *sidelobes* in Fourier spectrum (trade-off)

Summary

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