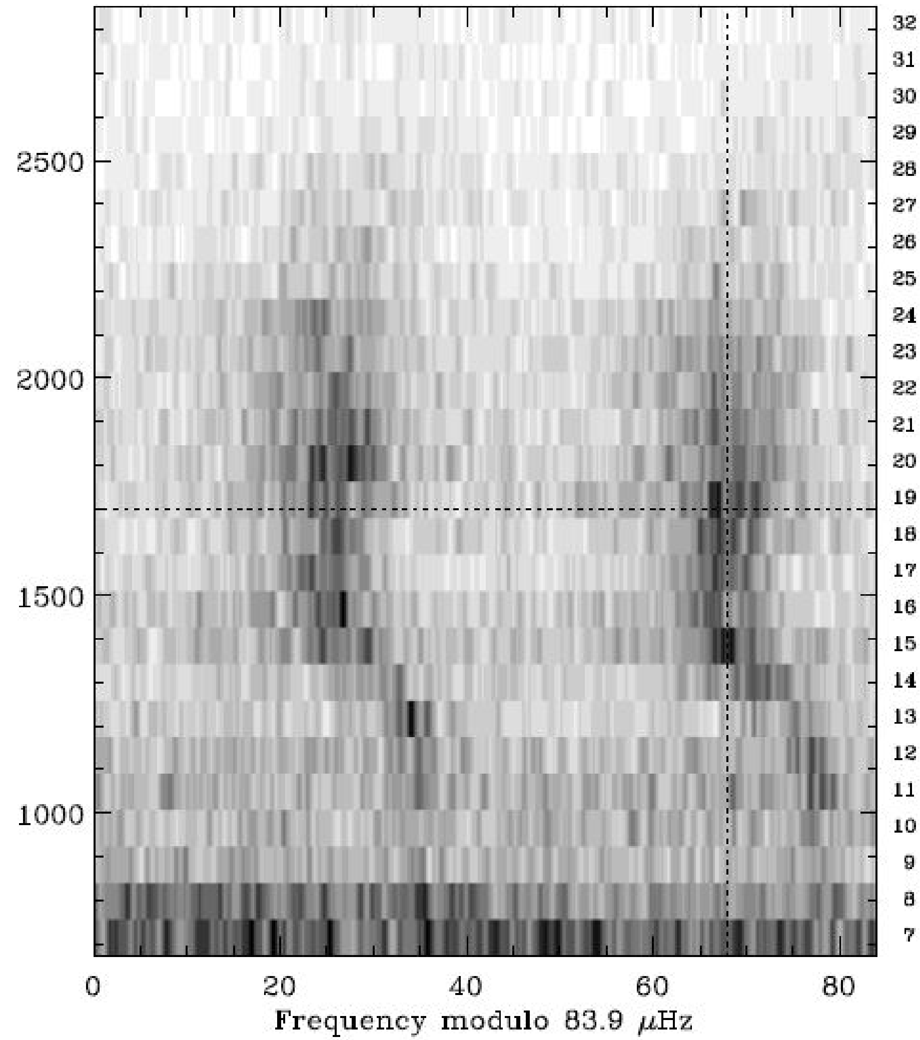
STELLAR ASTROPHYSICS CENTRE

THE UNIVERSITY OF SYDNEY

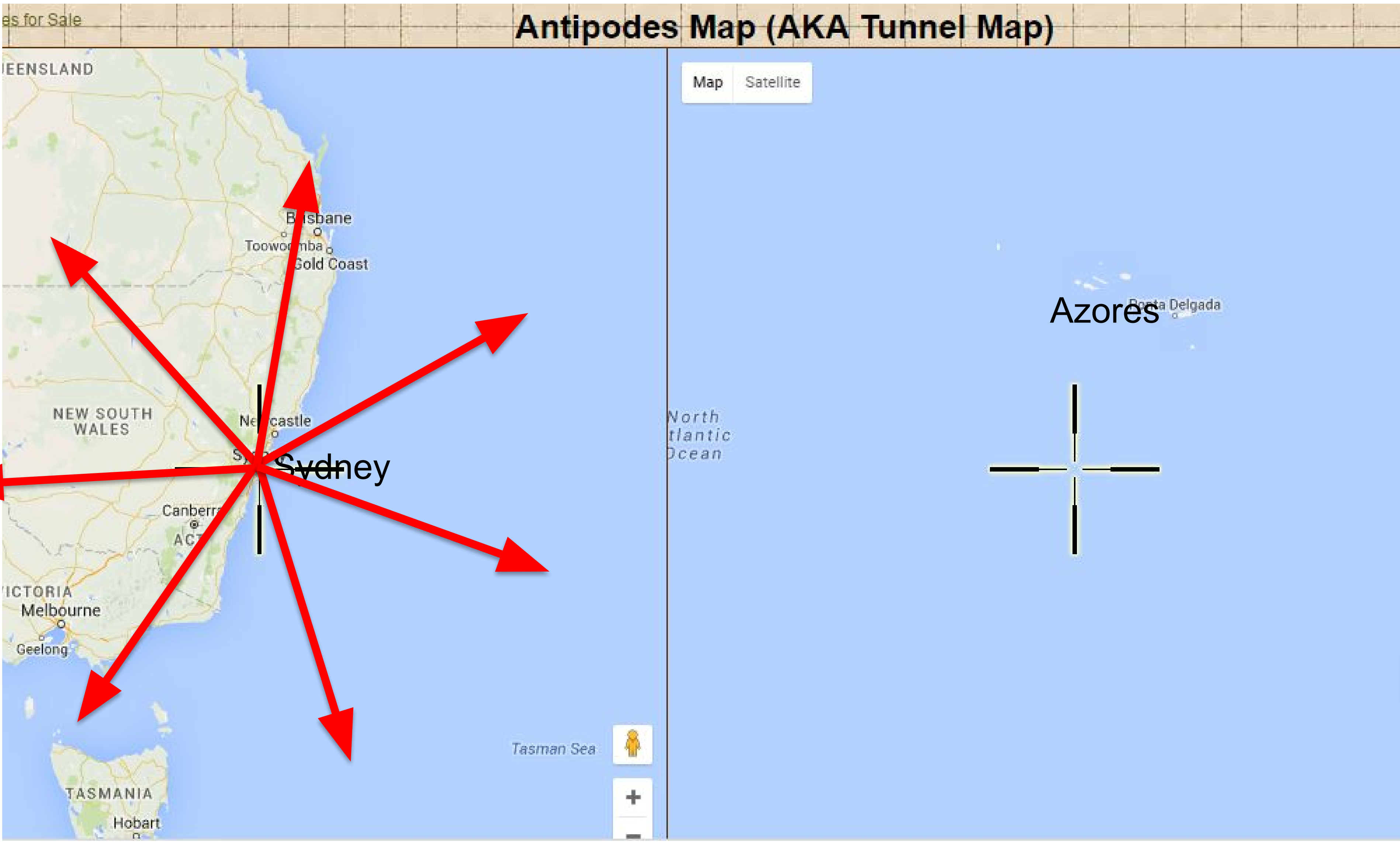
Can we do asteroseismology on F stars?

Tim Bedding
(University of Sydney)

with Warrick Ball, Doug Compton, Joyce Guzik, Daniel Huber, Mikkel Lund, Simon Murphy, Durlabh Pande, Aleksa Sarai, Dennis Stello, Tim White

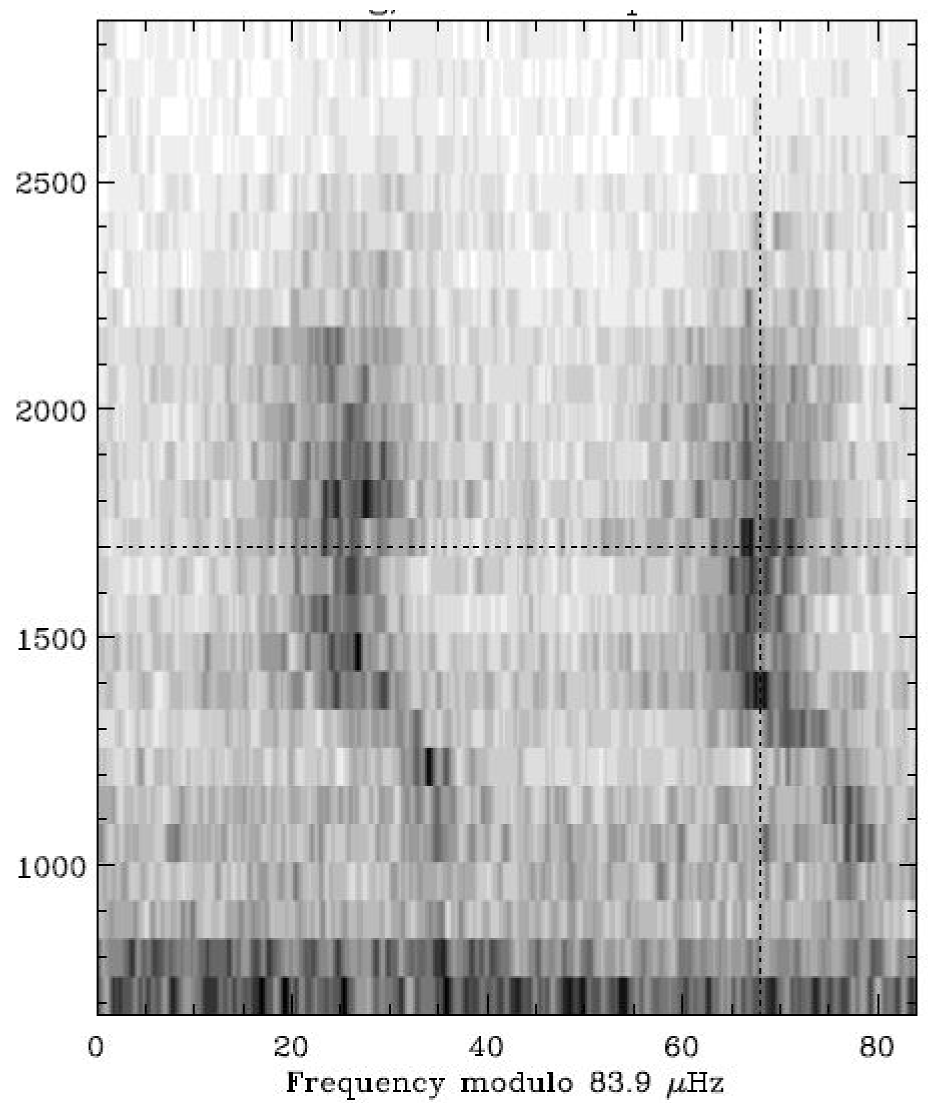


Finding chart:



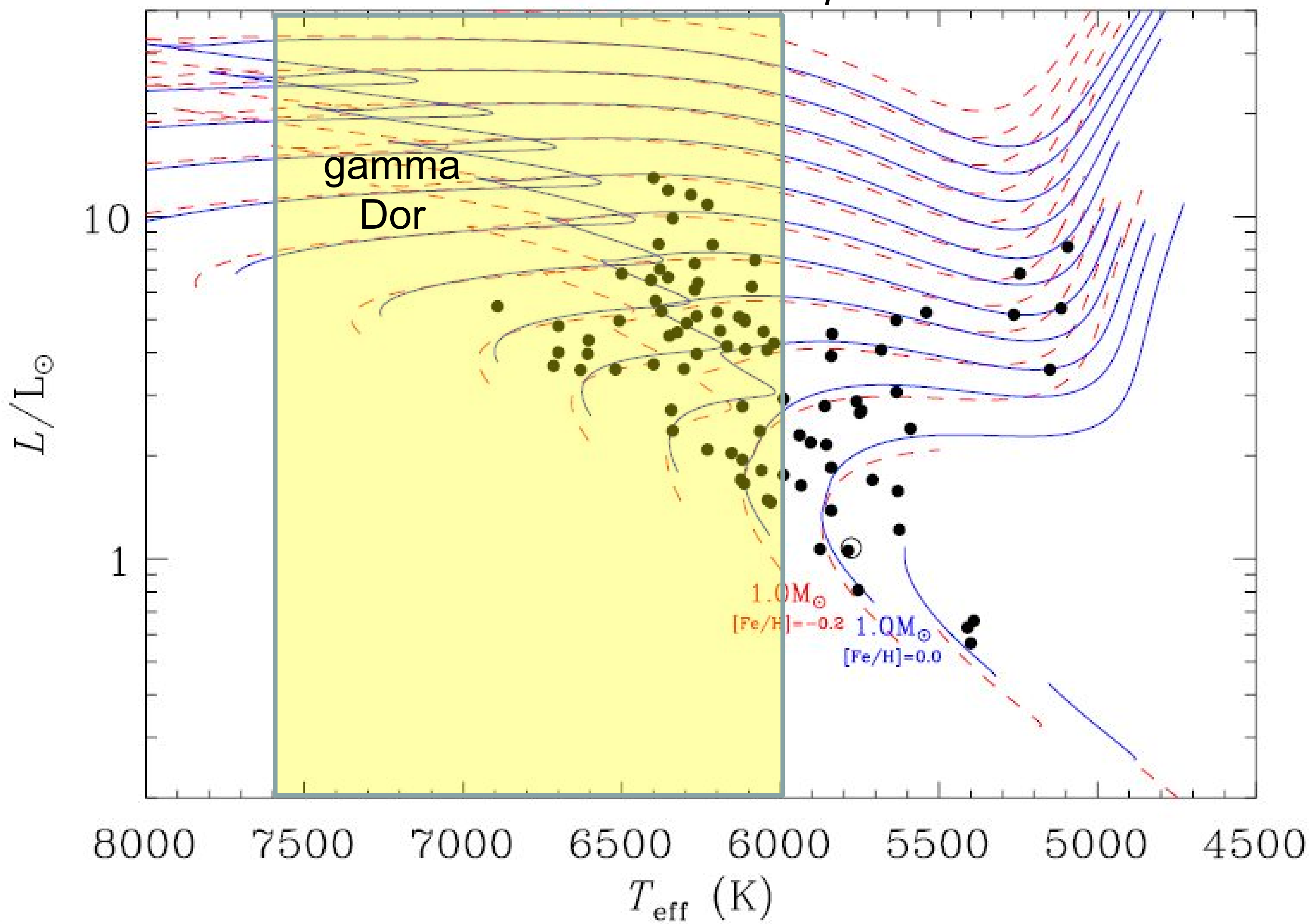
Can we do asteroseismology on F stars?

yes!



CHAPLIN ET AL. (2014)

Solar-like oscillations from *Kepler* short cadence



Why do we care about F stars?

Why do we care about F stars?

- intermediate mass, convective cores, rotation
- (they include the gamma Dor stars)
- lots of solar-like oscillators in the *Kepler* data

Solving the Bloody F-star problem in Asteroseismology

Douglas Compton[1]; Tim Bedding[1]; Dennis Stello[1]; Warrick Ball[2]
[1]School of Physics, University of Sydney, [2]Institute for Astrophysics, University of Goettingen

Magnetic activity of F stars observed by *Kepler*★

S. Mathur[1,2], R. A. García[1], J. Ballot[3,4], T. Ceillier[1], D. Salabert[1,5], T. S. Metcalfe[2,6], C. Régulo[7,8], A. Jiménez[7,8], and S. Bloemen[9,10]

A nice G star

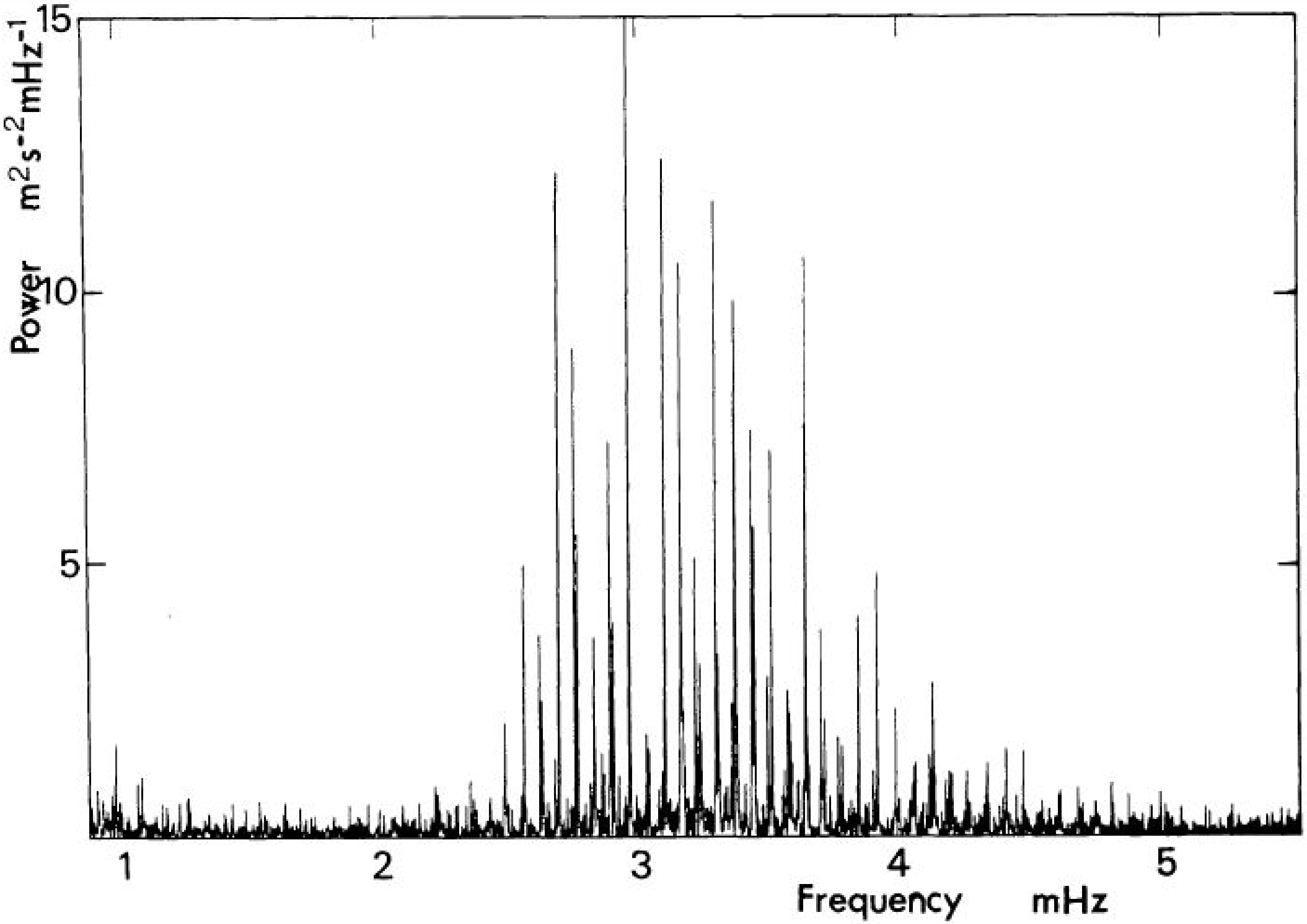


Fig. 1. Power spectrum of the South Pole data, which consists of the full-disk Doppler shift measurements recorded during the first week of January, 1980. The sample analyzed here has a duration of about 6 days, including three gaps of 2 to 3 hr. The frequency resolution is $\Delta\nu = 1.97\ \mu\text{Hz}$.

Grec et al. (1983)

the échelle diagram:

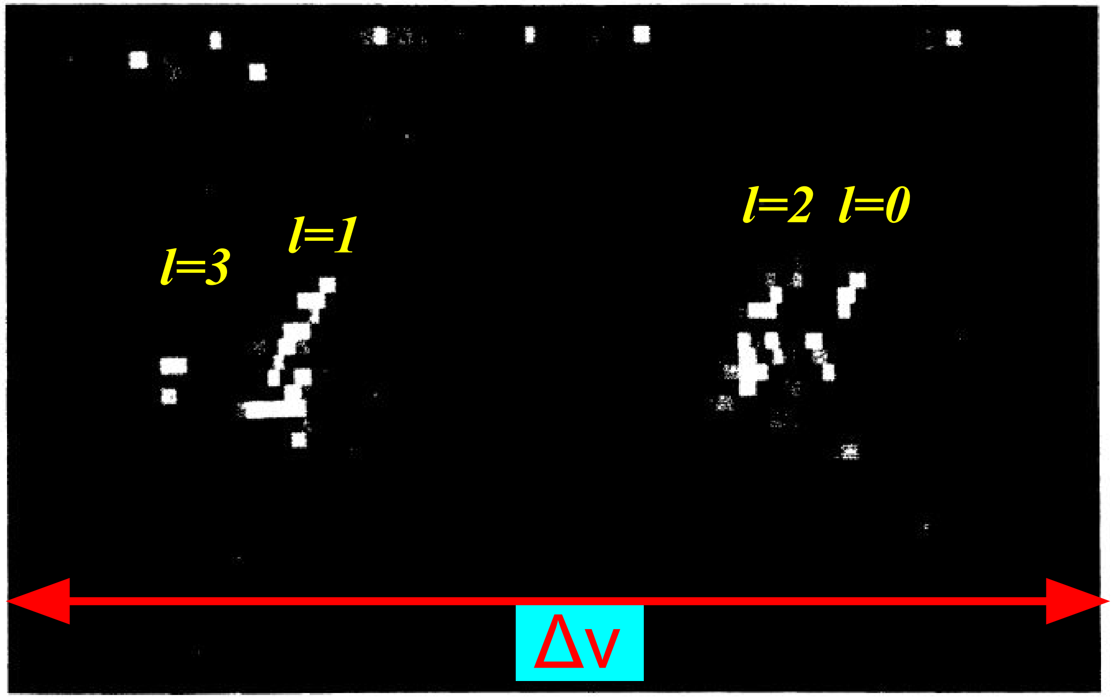
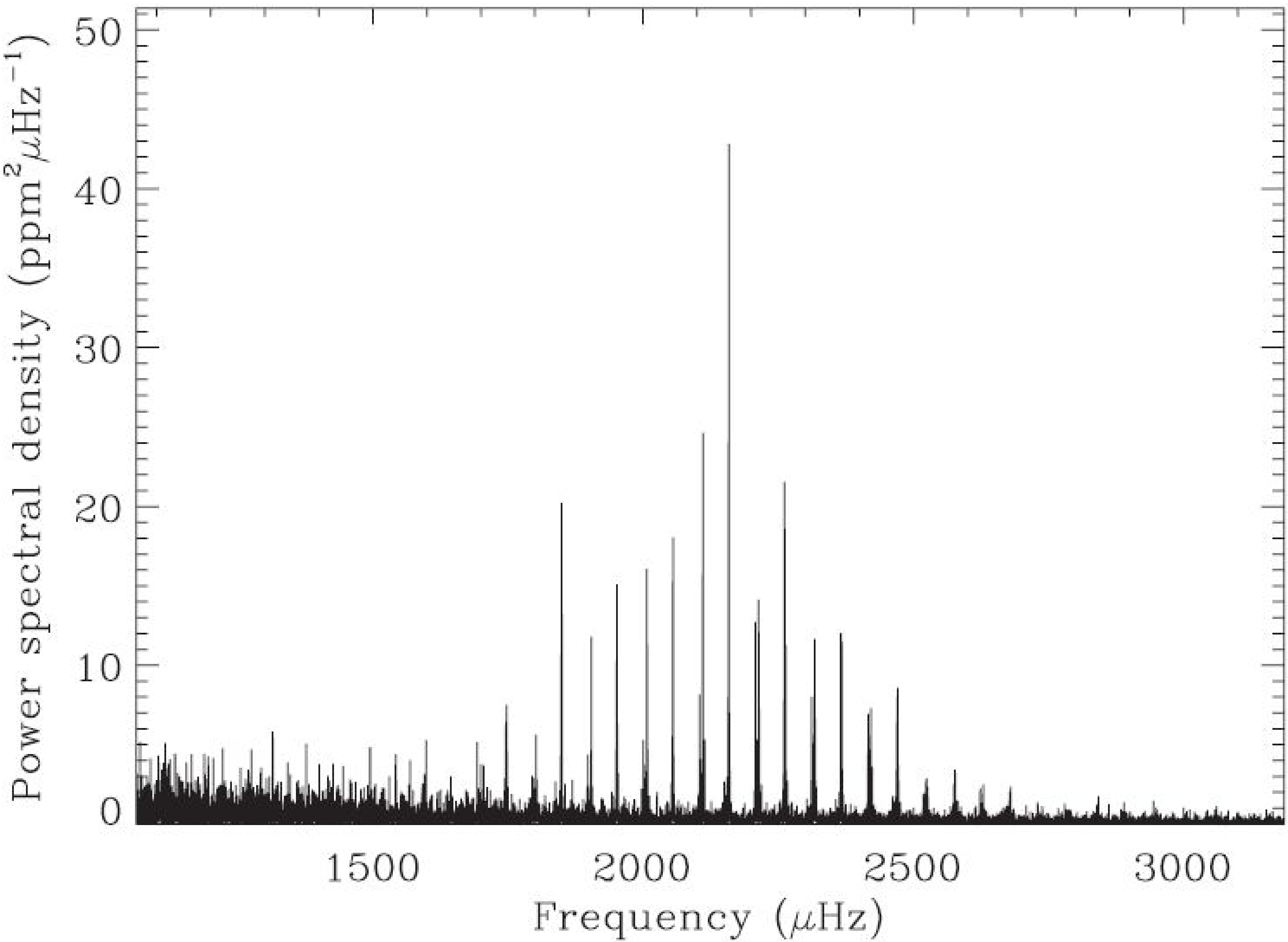
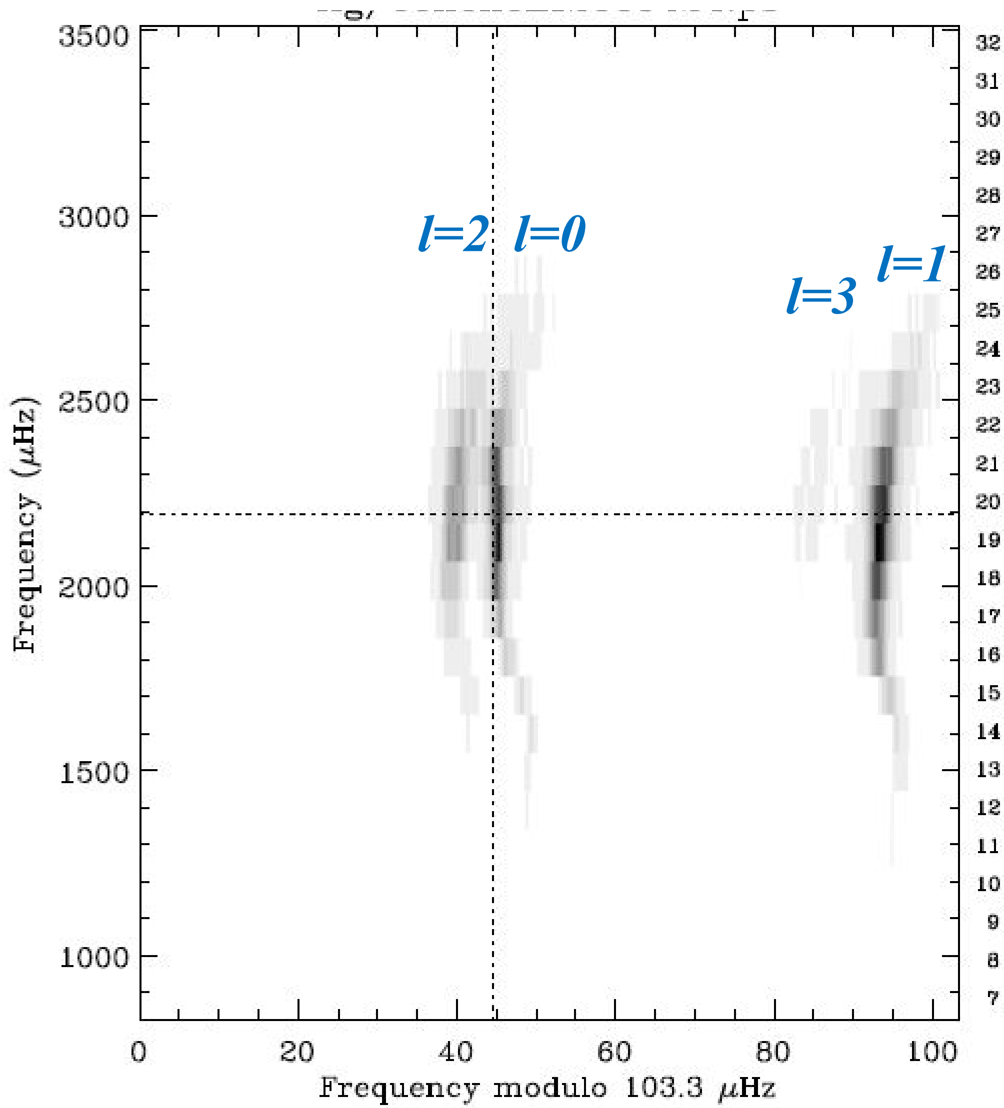


Fig. 2. Same as Figure 1, but the spectrum is now cut into slices of 136 μHz each. Each slice is displayed under the previous one on a video screen. The two lines on the right are the modes of even degrees ($l = 0$ is at the extreme right). The curvature of the four lines displays the departure from equidistance of the four sequence of radial harmonics. This curvature, which is expected from theory, even in the asymptotic approximation, makes possible the identification of each peak with its radial order, leaving room for almost no ambiguity. The first line displayed at the top of the picture starts at the frequency $\nu = 295.7$ μHz.

another nice G star (16 Cyg A)



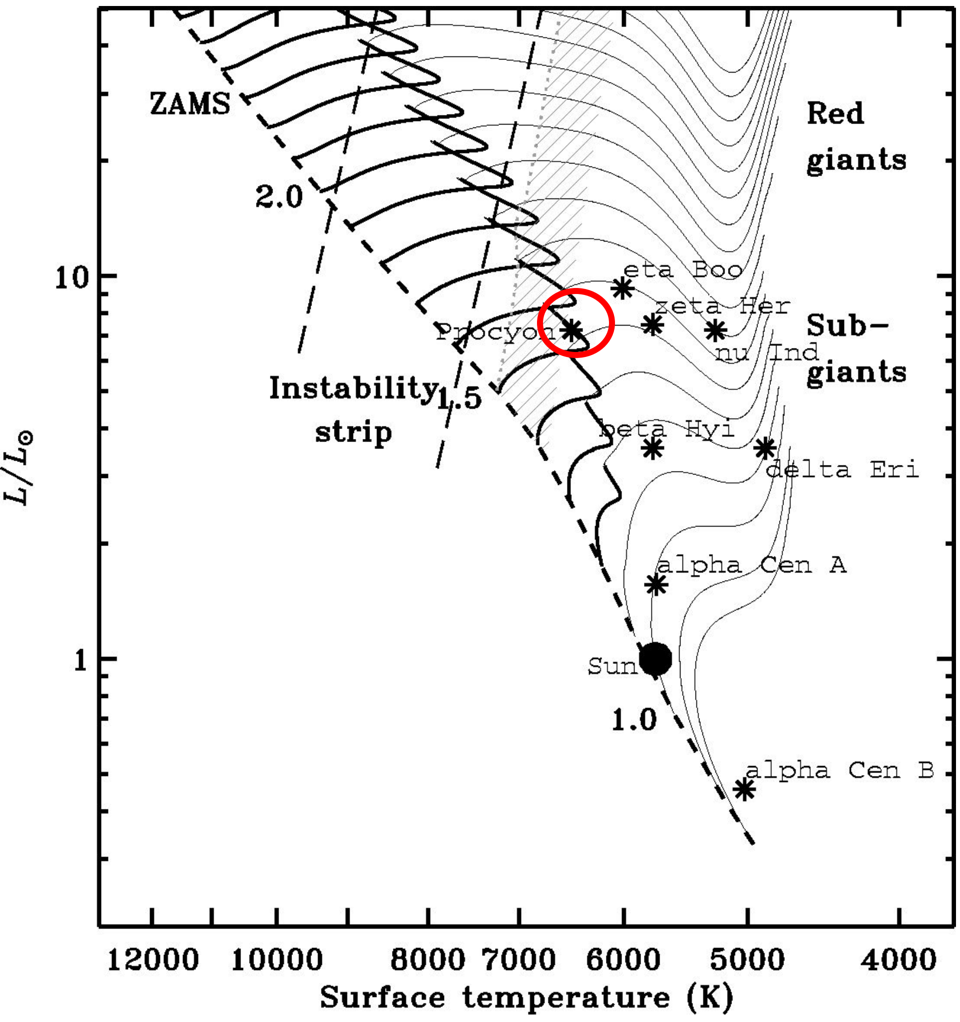
Metcalfe et al. (2012)



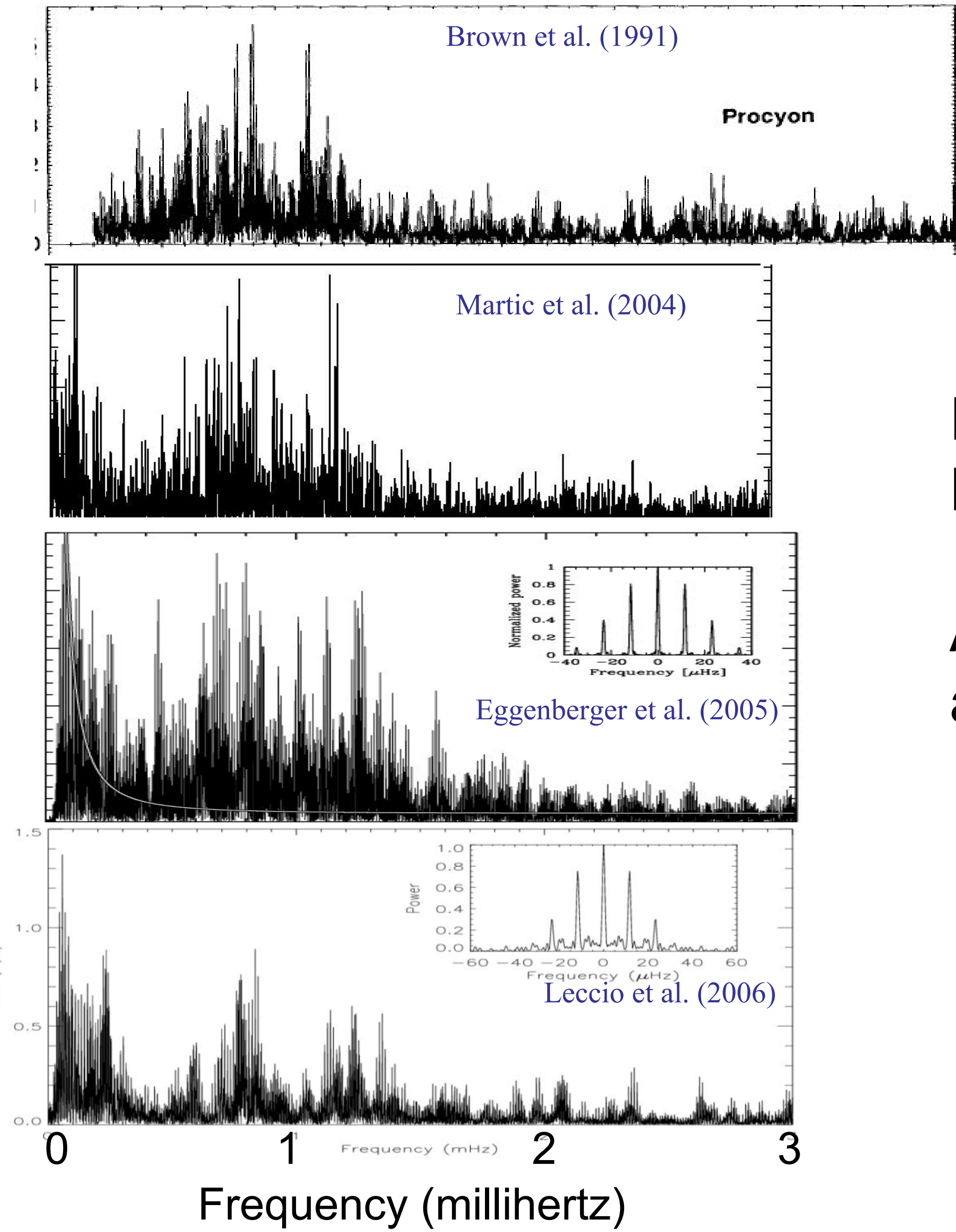
l=2
l=0
l=3
l=1
3500
3000
2500
2000
1500
1000
Frequency (μHz)
0
20
40
60
80
100
Frequency modulo 103.3 μHz
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7

13 orders

Procyon A



- angular diameter = 5.40±0.03 mas (1%; VLTI)
- parallax = 285.9 ± 0.9 mas (0.5%; Hipparcos)
- radius = 2.04±0.02 (1%)
- mass = 1.46±0.03 (2%; binary orbit)



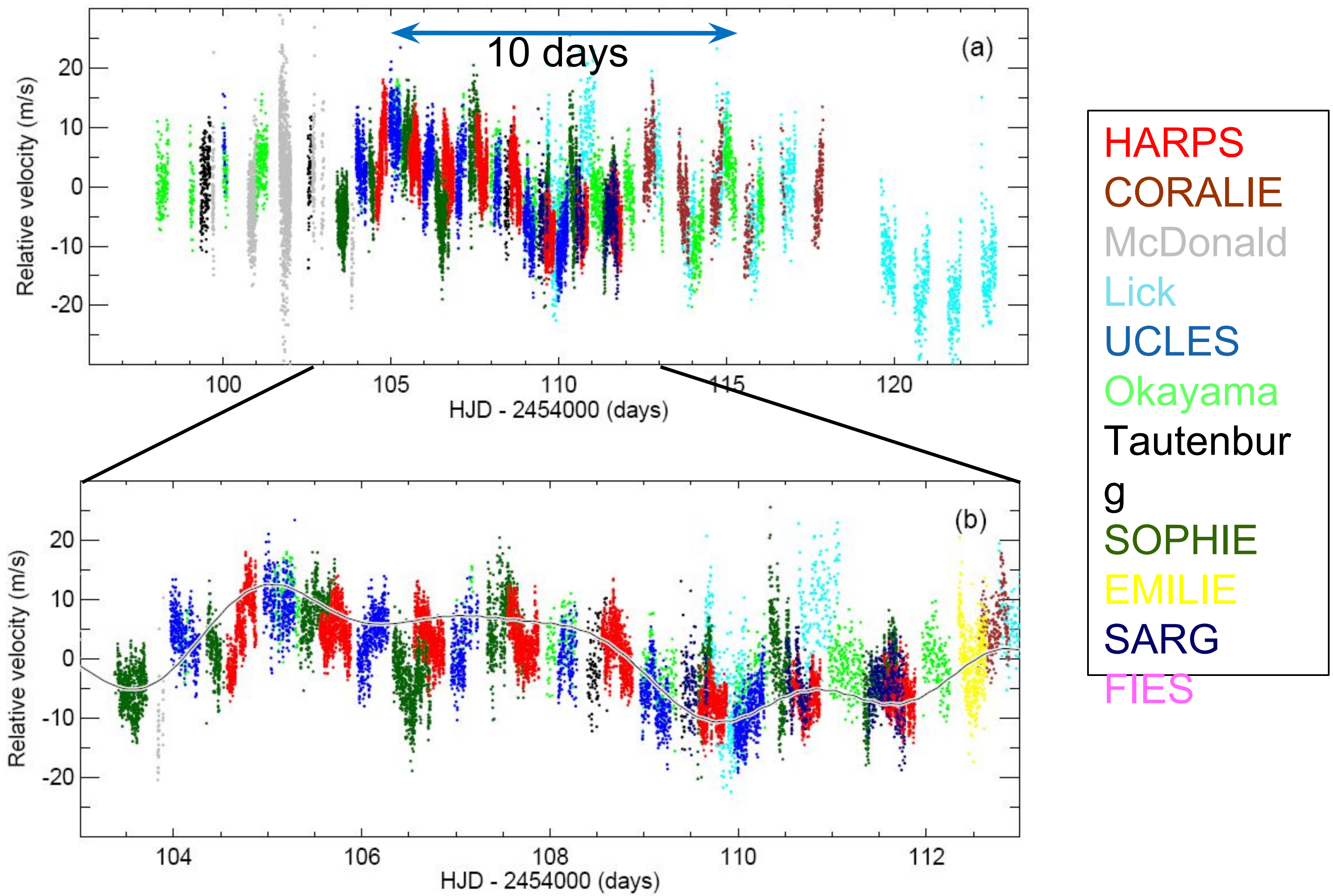
Procyon velocity observations

Fourier power spectra of Doppler measurements.

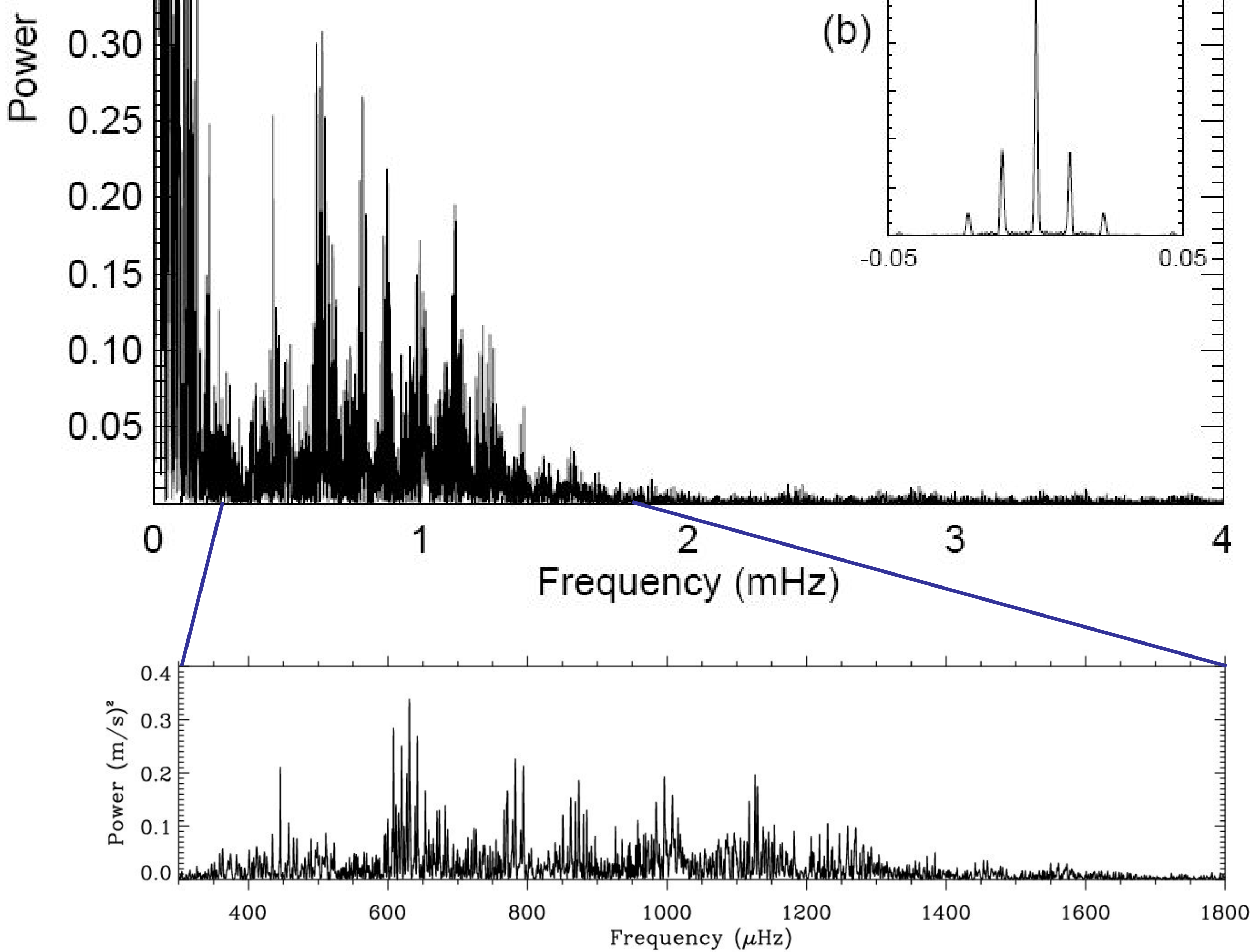
All have power centred at about 1 mHz (15-20 minutes)

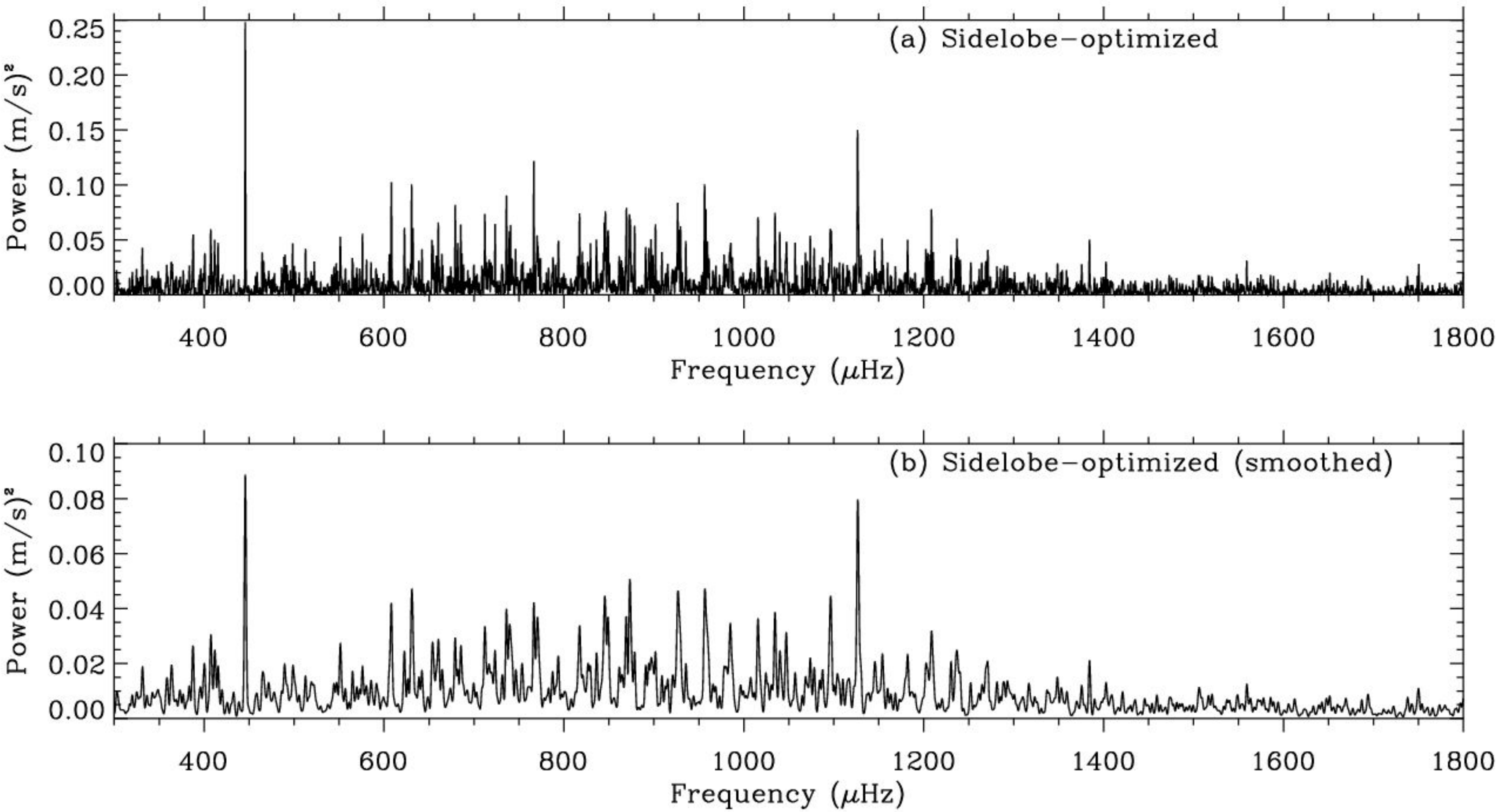
$\Delta\nu \approx 55\mu Hz$

2007 Procyon Campaign: 11 telescopes at 8 observatories over 25 days



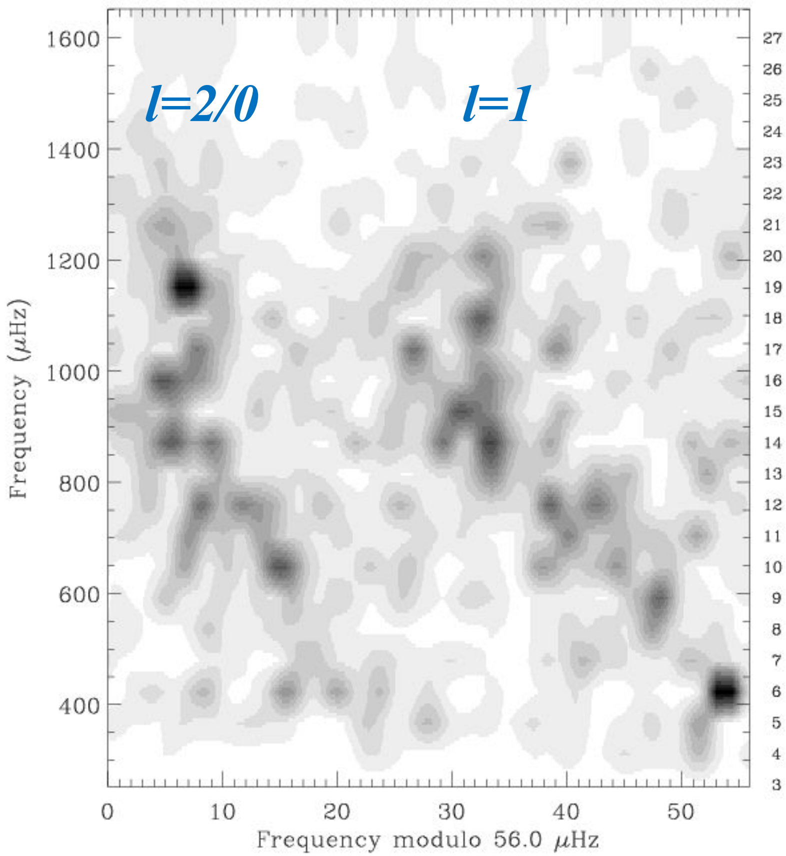
Arentoft et al. (2008), Bedding et al. (2009)


Power
0.30
0.25
0.20
0.15
0.10
0.05
(b)
-0.05
0.05
0
1
2
3
4
Frequency (mHz)
Power (m/s)²
0.4
0.3
0.2
0.1
0.0
400
600
800
1000
1200
1400
1600
1800
Frequency (μHz)



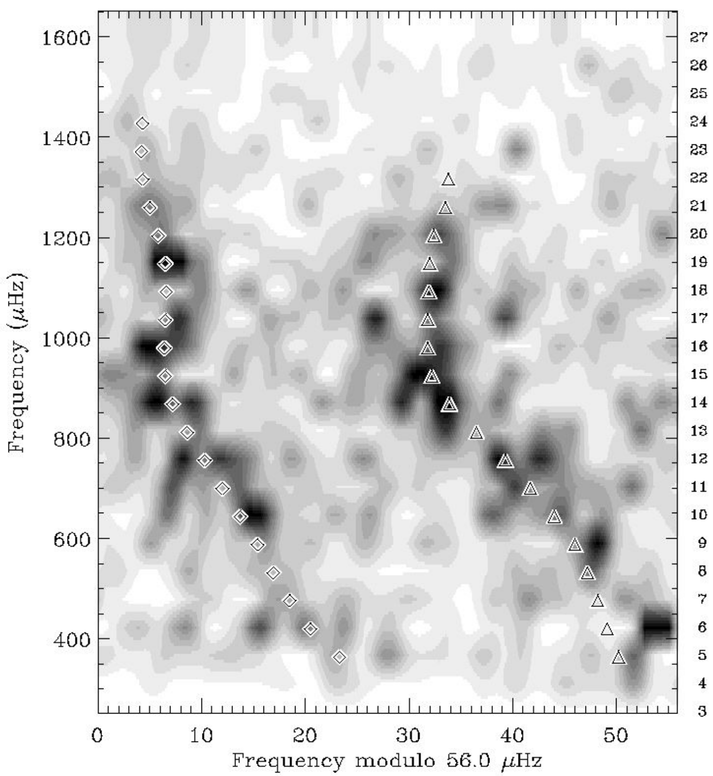
0.25
0.20
0.15
0.10
0.05
0.00
Power (m/s)²
(a) Sidelobe-optimized
400
600
800
1000
1200
1400
1600
1800
Frequency (μHz)
0.10
0.08
0.06
0.04
0.02
0.00
Power (m/s)²
(b) Sidelobe-optimized (smoothed)
400
600
800
1000
1200
1400
1600
1800
Frequency (μHz)

Which ridge is which?

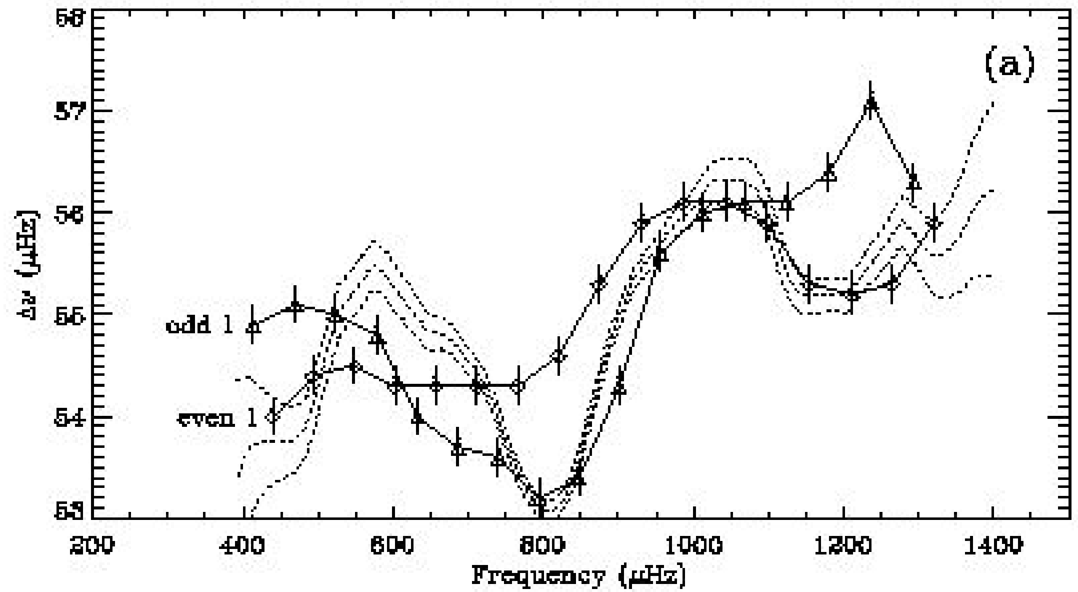


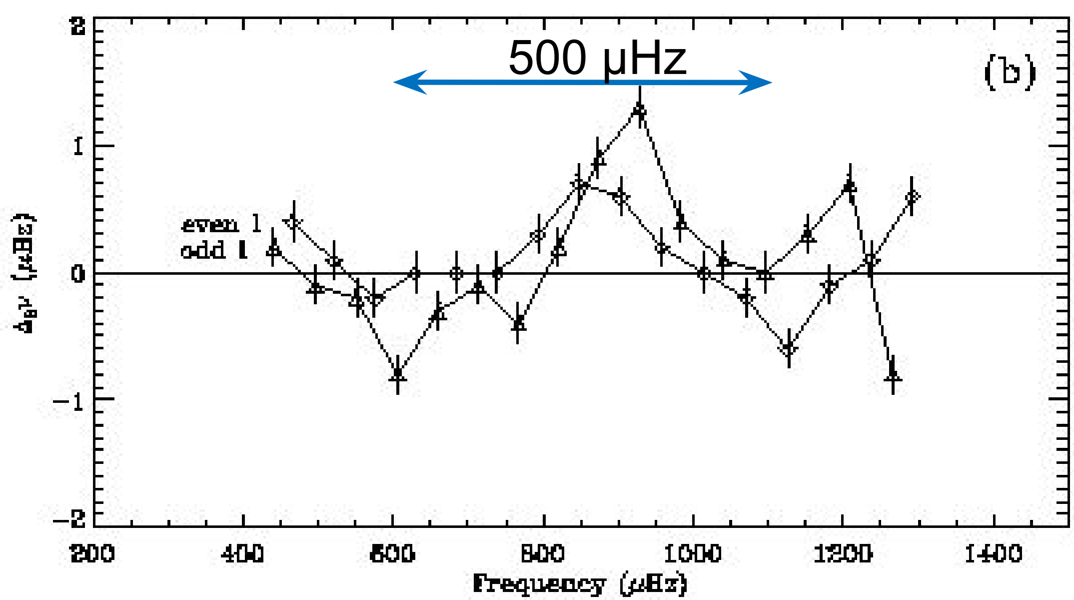
Asteroseismology using ridge spacings

(20 orders)



acoustic glitch at τ=1000s
(He ionization zone)





A&A 488, 705–714 (2008)
DOI: 10.1051/0004-6361:200810297
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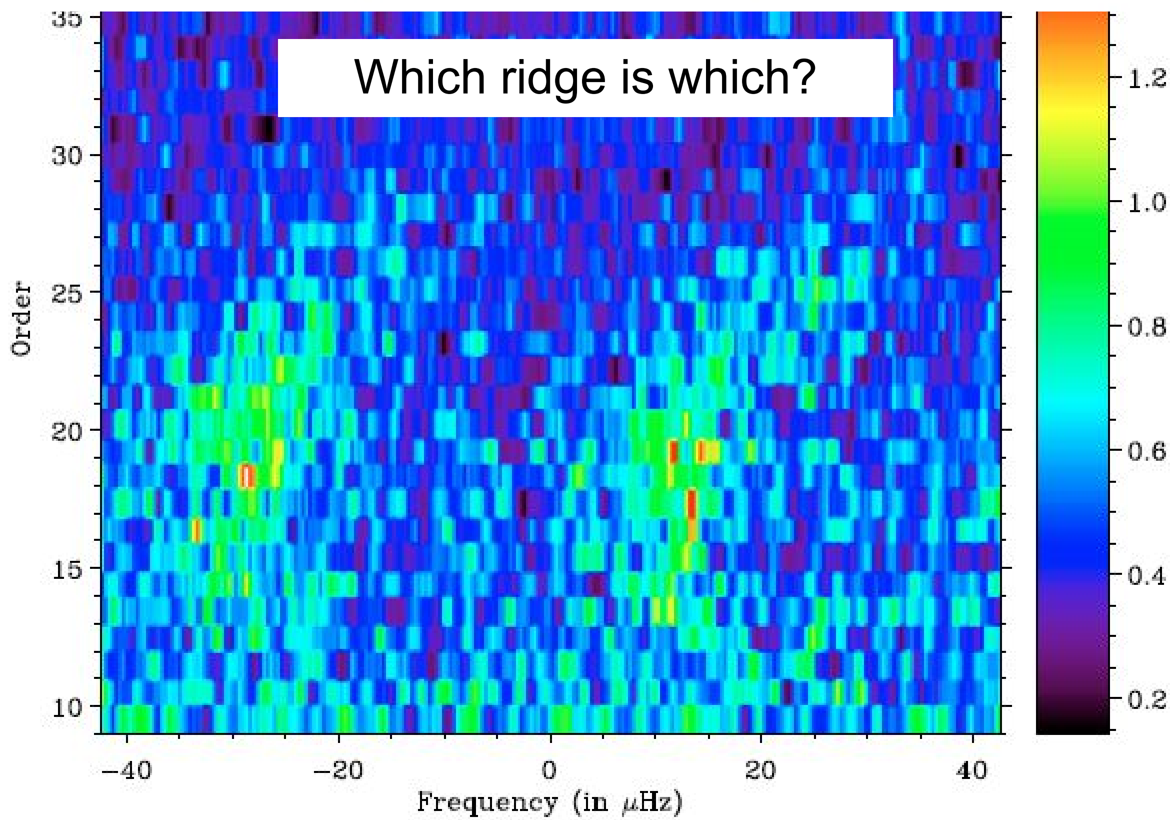
Astronomy & Astrophysics

CoRoT sounds the stars: p-mode parameters of Sun-like oscillations on HD 49933★

T. Appourchaux[1], E. Michel[2], M. Auvergne[2], A. Baglin[2], T. Toutain[3], F. Baudin[1], O. Benomar[1], W. J. Chaplin[3], S. Deheuvels[2], R. Samadi[2], G. A. Verner[4], P. Boumier[1], R. A. García[5], B. Mosser[2], J.-C. Hulot[1], J. Ballot[6], C. Barban[2], Y. Elsworth[3], S. J. Jiménez-Reyes[8], H. Kjeldsen[7], C. Régulo[8], and I. W. Roxburgh[4,2]



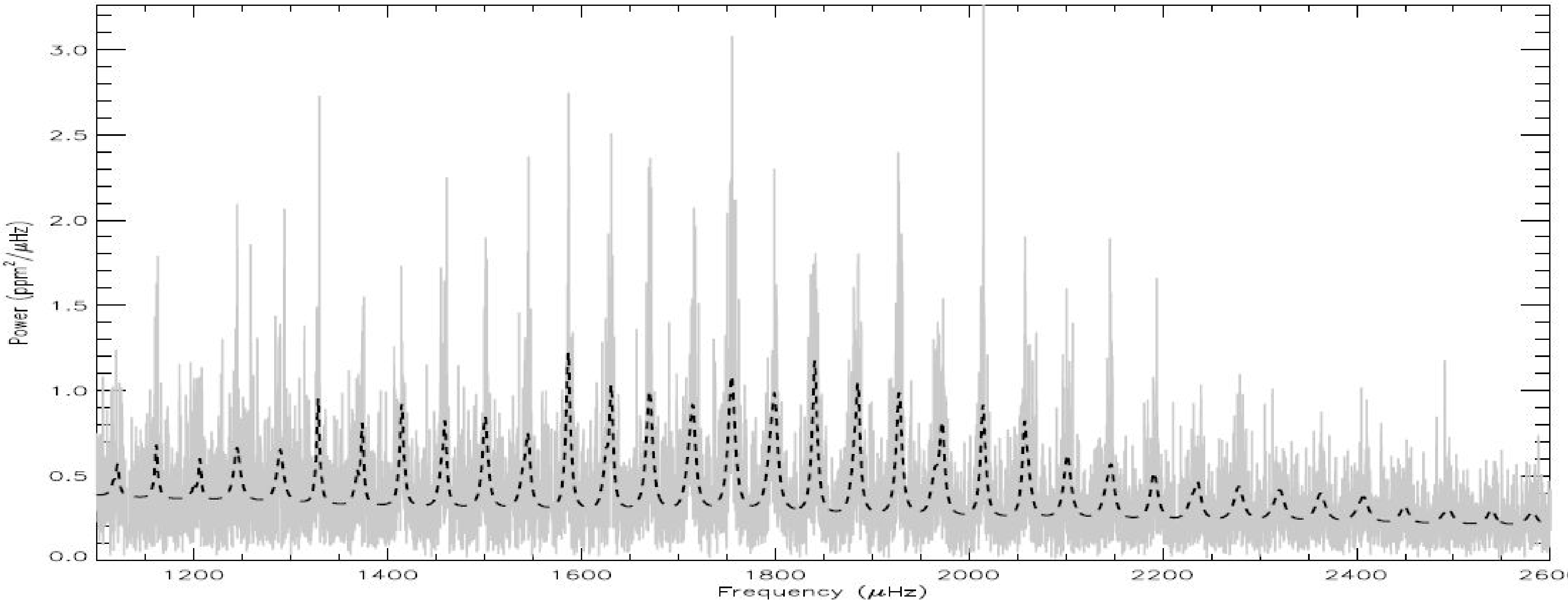


Fig. 1. Mean power spectrum using 3 time series of 60 days (solid grey line), and the fitted model (dashed line).

On posterior probability and significance level: application to the power spectrum of HD 49 933 observed by CoRoT★

T. Appourchaux[1], R. Samadi[2], and M.-A. Dupret[2,3]

Mode width fitting with a simple Bayesian approach

Application to CoRoT targets HD 181420 and HD 49933★

P. Gaulme, T. Appourchaux, and P. Boumier

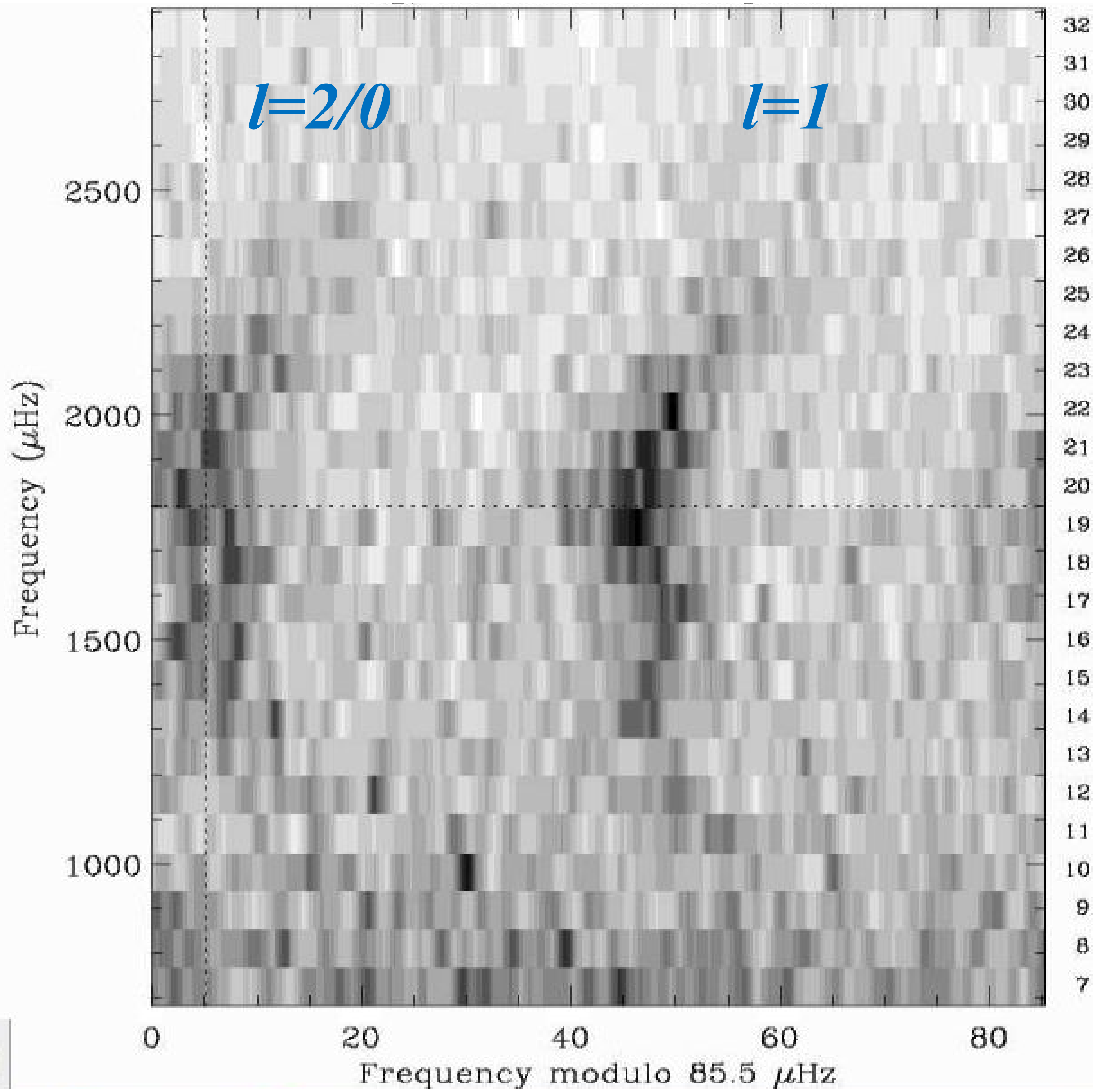
The solar-like oscillations of HD 49933: a Bayesian approach★,★★

O. Benomar, T. Appourchaux, and F. Baudin

A fresh look at the seismic spectrum of HD49933: analysis of 180 days of CoRoT photometry★,★★

O. Benomar[1], F. Baudin[1], T. L. Campante[2,3], W. J. Chaplin[4], R. A. García[5], P. Gaulme[1], T. Toutain[6], G. A. Verner[7], T. Appourchaux[1], J. Ballot[8], C. Barban[9], Y. Elsworth[4], S. Mathur[10], B. Mosser[9], C. Régulo[11,12], I. W. Roxburgh[7], M. Auvergne[9], A. Baglin[9], C. Catala[9], E. Michel[9], and R. Samadi[9]

HD 49933 (CoRoT)



The CoRoT target HD 49933*

II. Comparison of theoretical mode amplitudes with observations

R. Samadi[1], H.-G. Ludwig[2], K. Belkacem[1,3], M. J. Goupil[1], O. Benomar[4], B. Mosser[1], M.-A. Dupret[1,3], F. Baudin[4], T. Appourchaux[4], and E. Michel[1]

The nature of p-modes and granulation in HD 49933 observed by CoRoT*

T. Kallinger[1,2], M. Gruberbauer[1,3], D. B. Guenther[3], L. Fossati[1], and W. W. Weiss[1]

Seismic detection of acoustic sharp features in the CoRoT target HD 49933

A. Mazumdar[1], E. Michel[2], H. M. Antia[3], and S. Deheuvels[2,4]

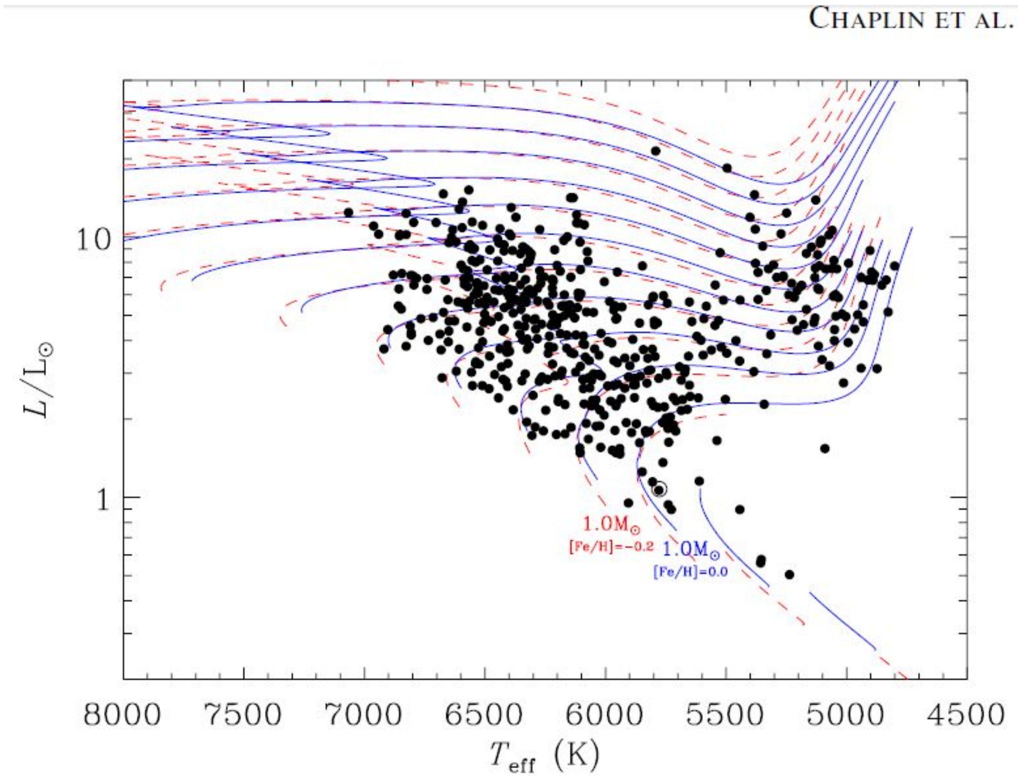
ASTEROSEISMIC ANALYSIS OF THE *CoRoT* TARGET HD 49933

Zhie Liu[1], Wuming Yang[1,2], Shaolan Bi[1], Zhijia Tian[1], Kang Liu[1], Zhishuai Ge[1], Jie Yu[1], Tanda Li[3], Xiaoyan Tan[2], Xin He[1], Yaqian Wu[1], and P. Chintarungruangchai[1]

Surface layer independent model fitting by phase matching: theory and application to HD 49933 and HD 177153 (aka Perky)

Ian W. Roxburgh

Lots of ambiguous F stars How can we decide?



“the ε method”

THE ASTROPHYSICAL JOURNAL LETTERS, 751:L36 (7pp), 2012 June 1 doi:10.1088/2041-8205/751/2/L
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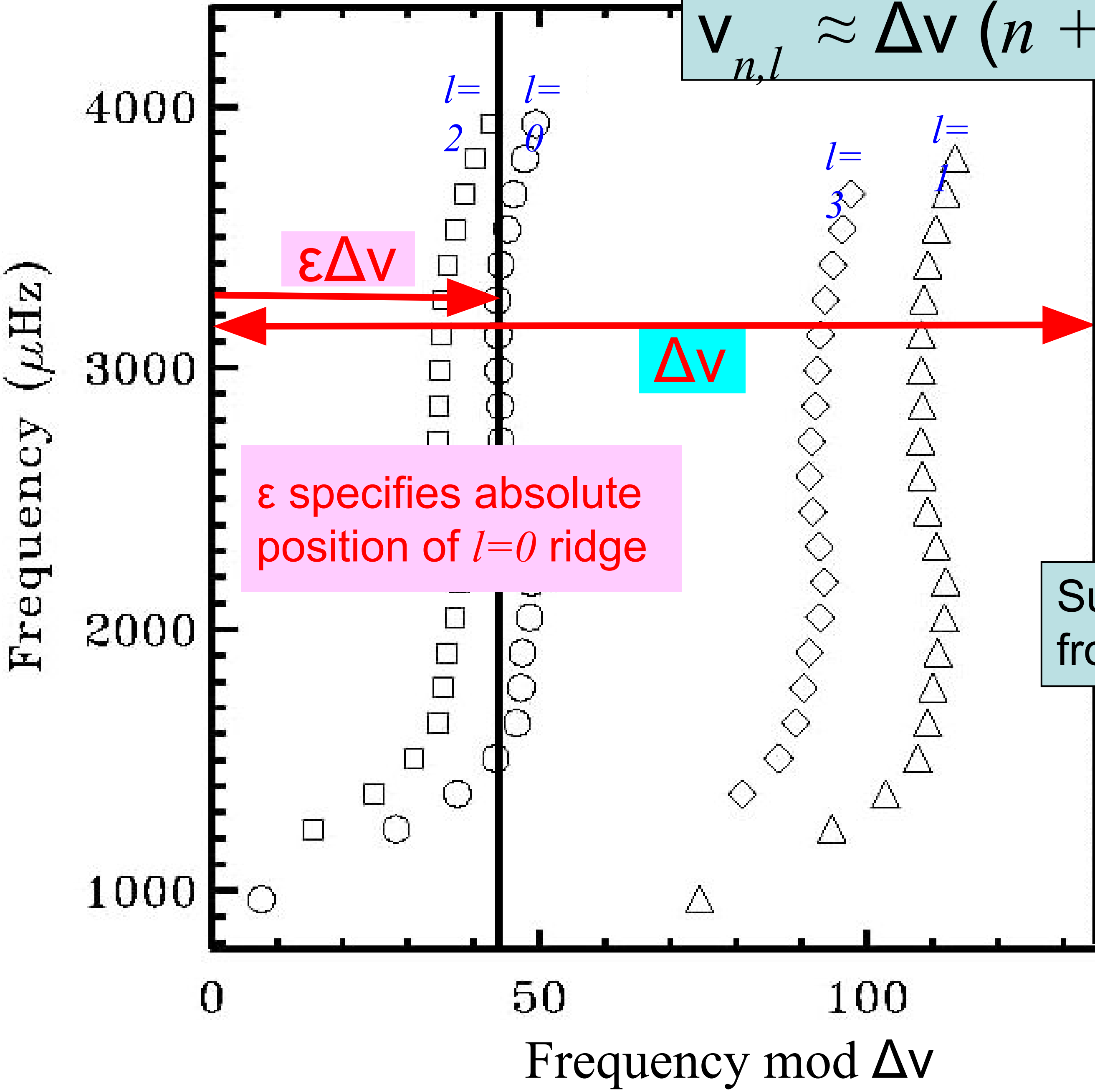
SOLVING THE MODE IDENTIFICATION PROBLEM IN ASTEROSEISMOLOGY OF F STARS OBSERVED WITH *KEPLER*

TIMOTHY R. WHITE[1,2], TIMOTHY R. BEDDING[1], MICHAEL GRUBERBAUER[3], OTHMAN BENOMAR[1], DENNIS STELLO[1], THIERRY APPOURCHAUX[4], WILLIAM J. CHAPLIN[5], JØRGEN CHRISTENSEN-DALSGAARD[6], YVONNE P. ELSWORTH[5], RAFAEL A. GARCÍA[7], SASKIA HEKKER[5,8], DANIEL HUBER[1,9], HANS KJELDSEN[6], BENOÎT MOSSER[10], KAREN KINEMUCHI[11], FERGAL MULLALLY[12], AND MARTIN STILL[11]

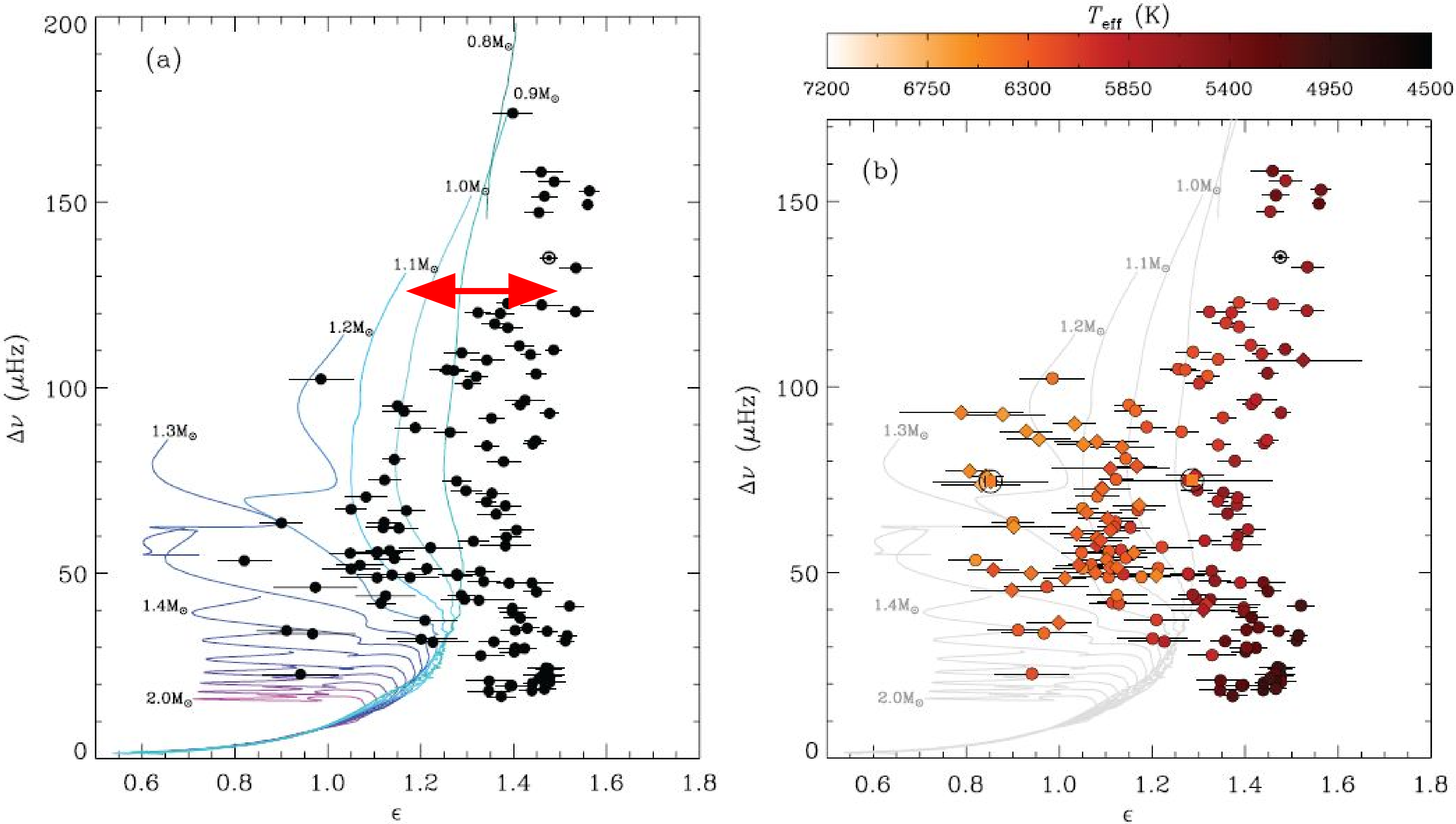
$$\nu_{n,l} \approx \Delta\nu\,(n + \tfrac{1}{2}l + \varepsilon) - \delta\nu_{0l}$$



Sun has ε=1.3 (we know *n* from models!)

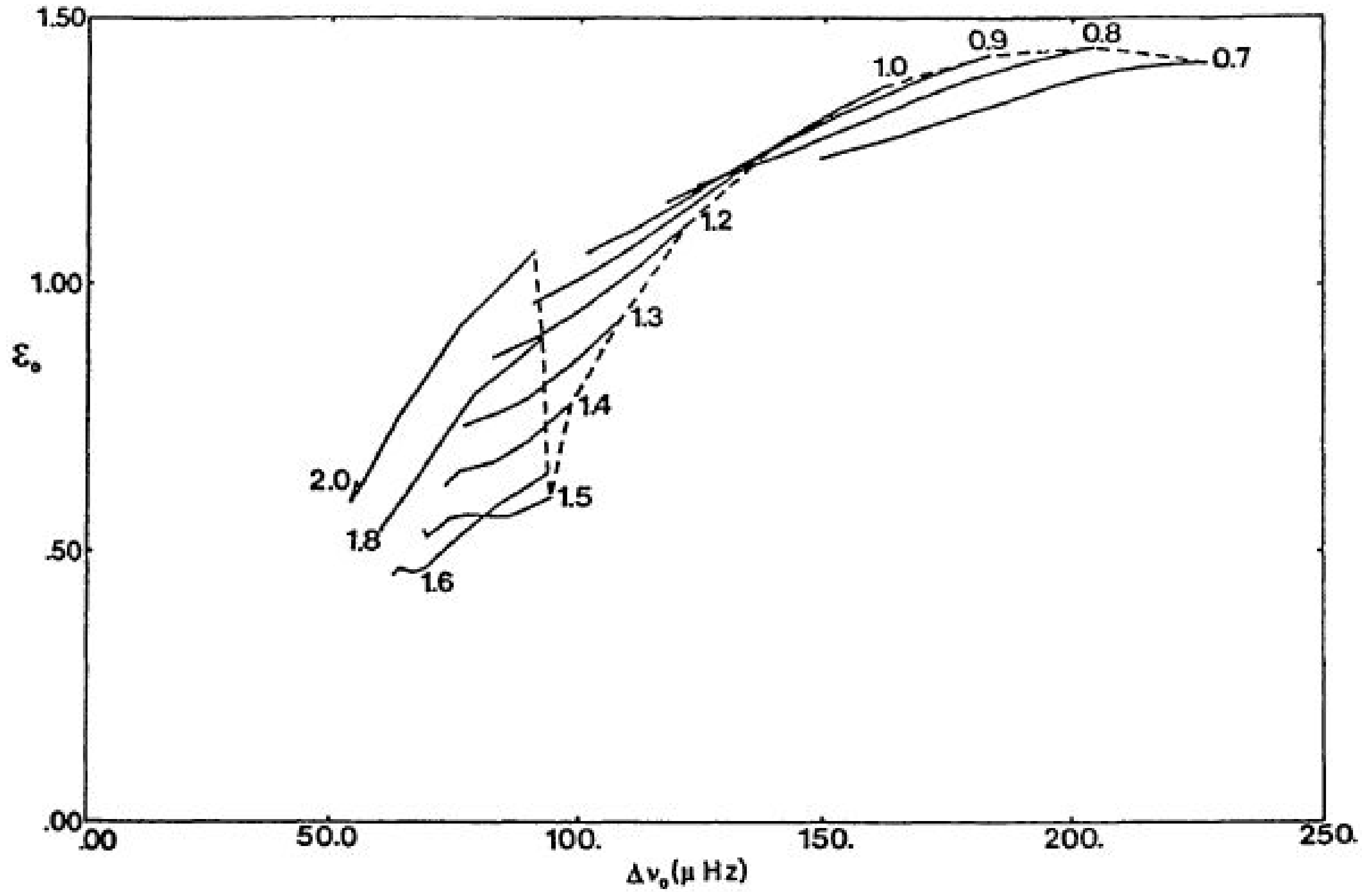
Echelle diagrams for 109 unambiguous stars from full mission (includes subgiants and SC RGB)

[insert PDF (p. 82)]

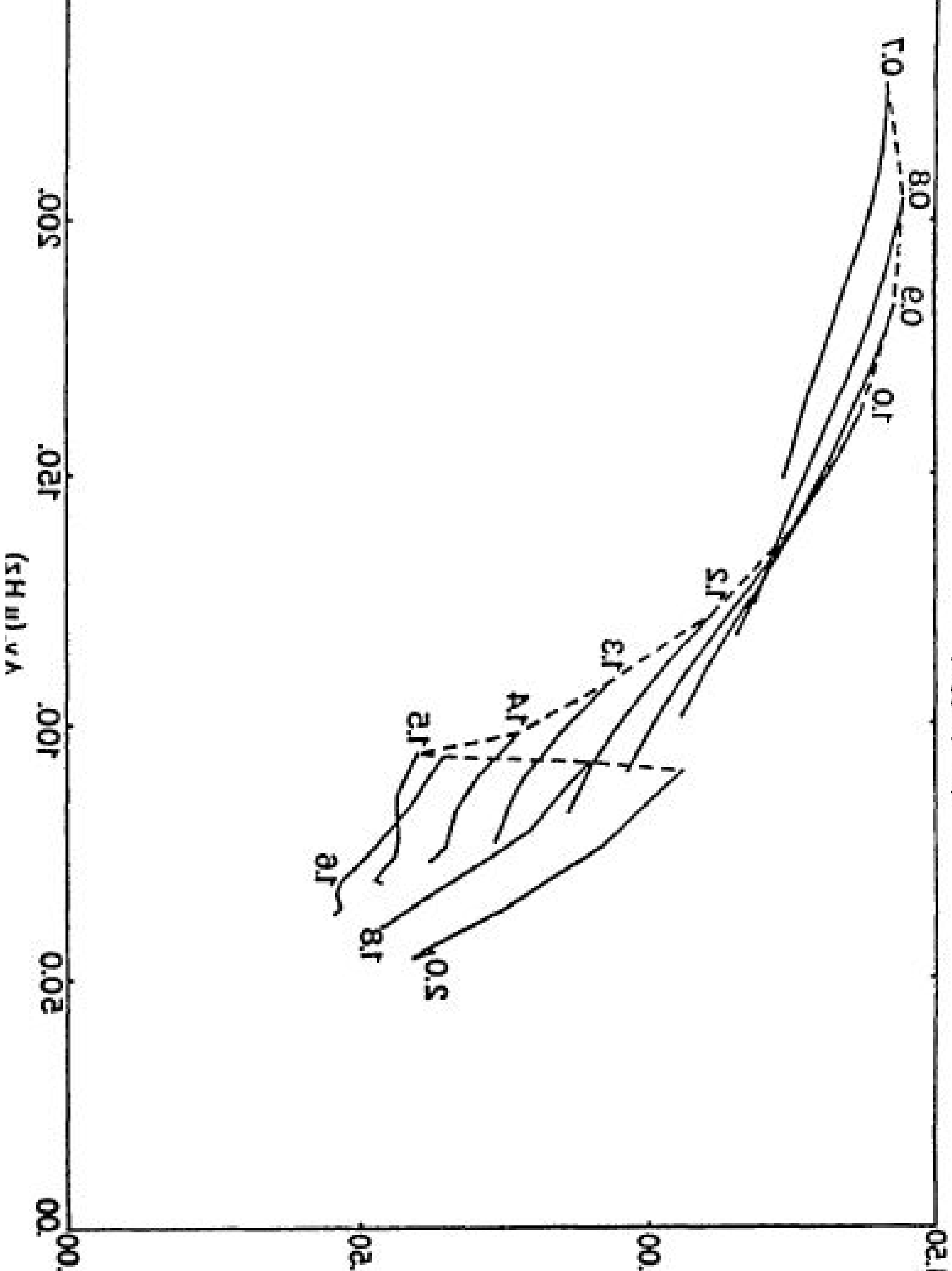


White et al. (2012)

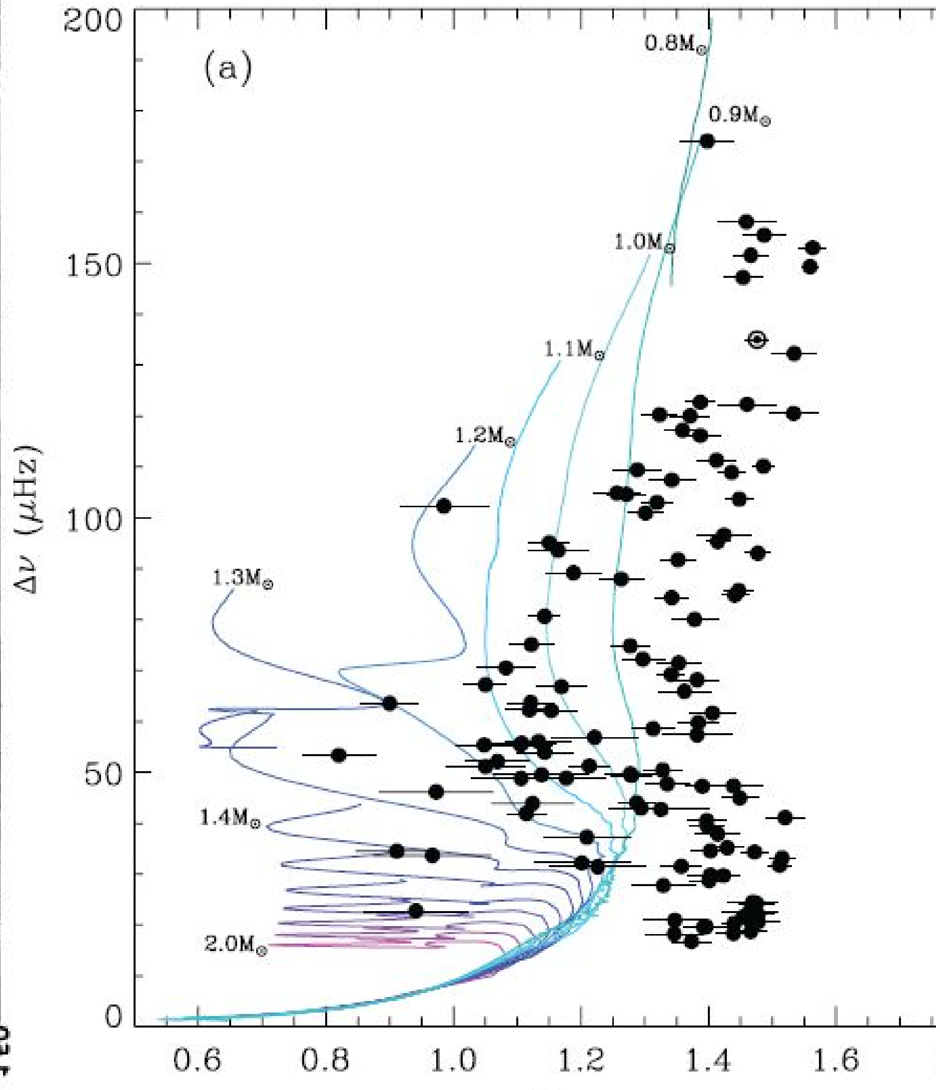
A HERTZSPRUNG-RUSSELL DIAGRAM FOR STELLAR OSCILLATIONS



Christensen-Dalsgaard et al. (1988)

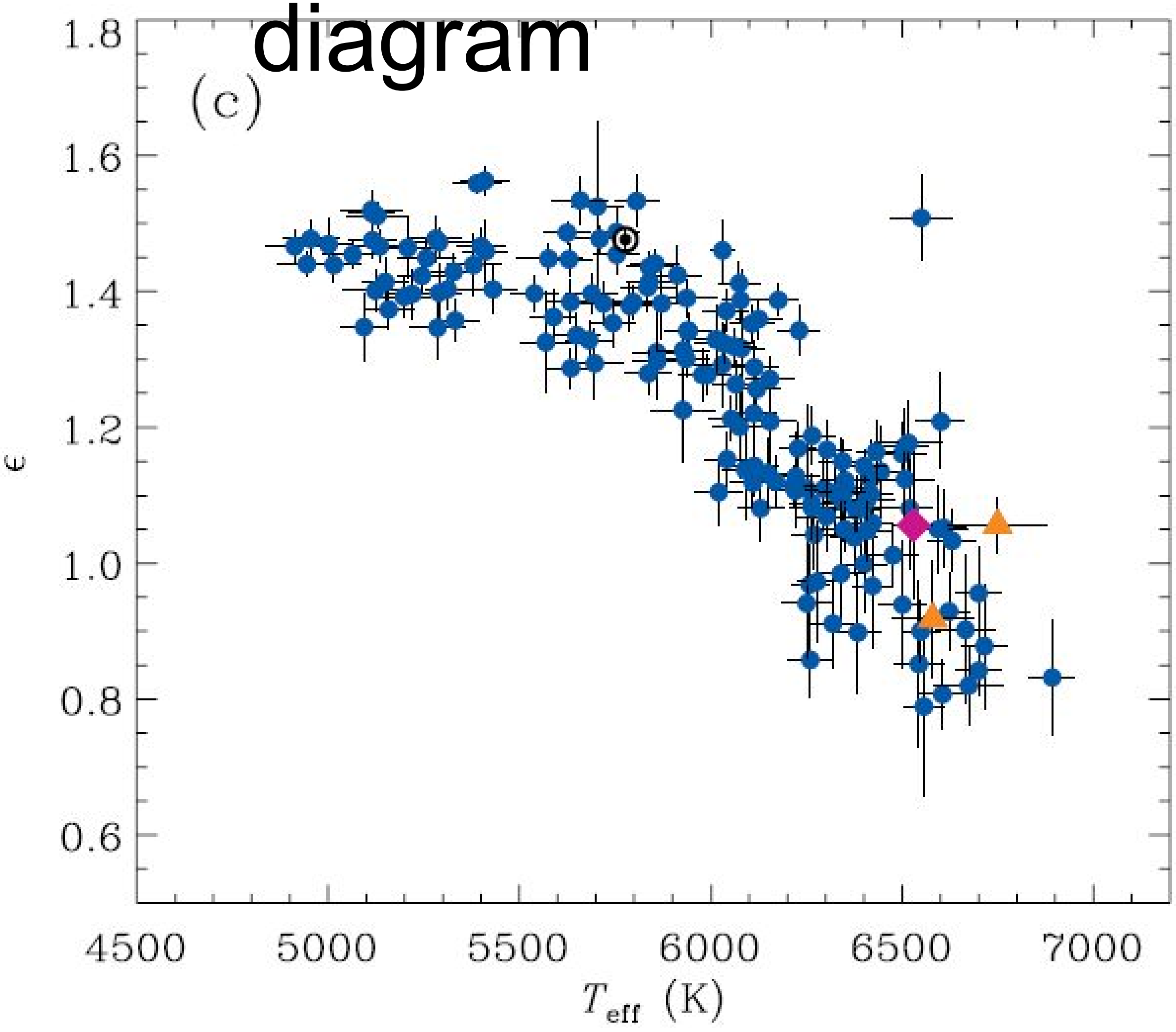


Christensen-Dalsgaard et al. (1988)

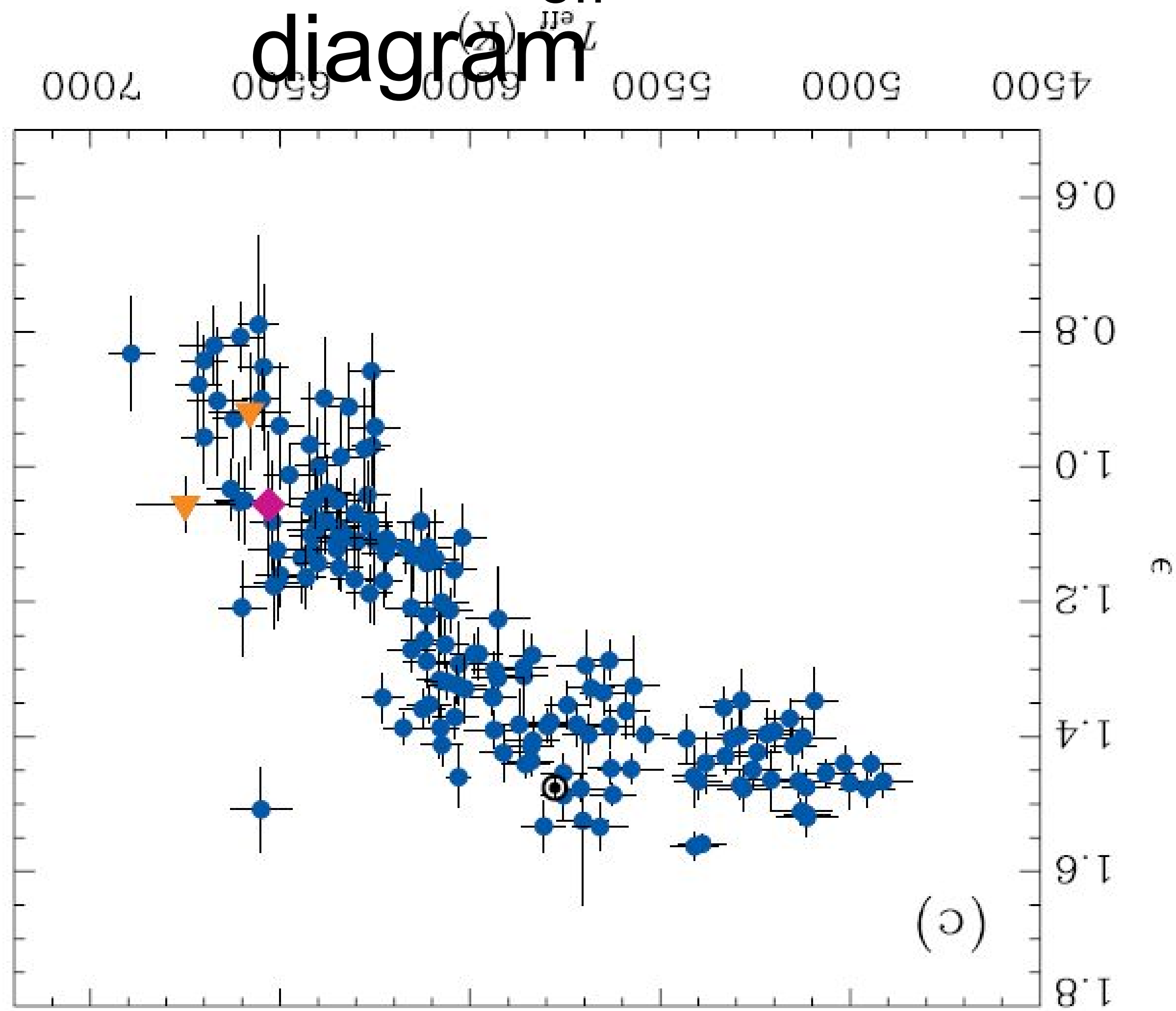


White et al. (2012)

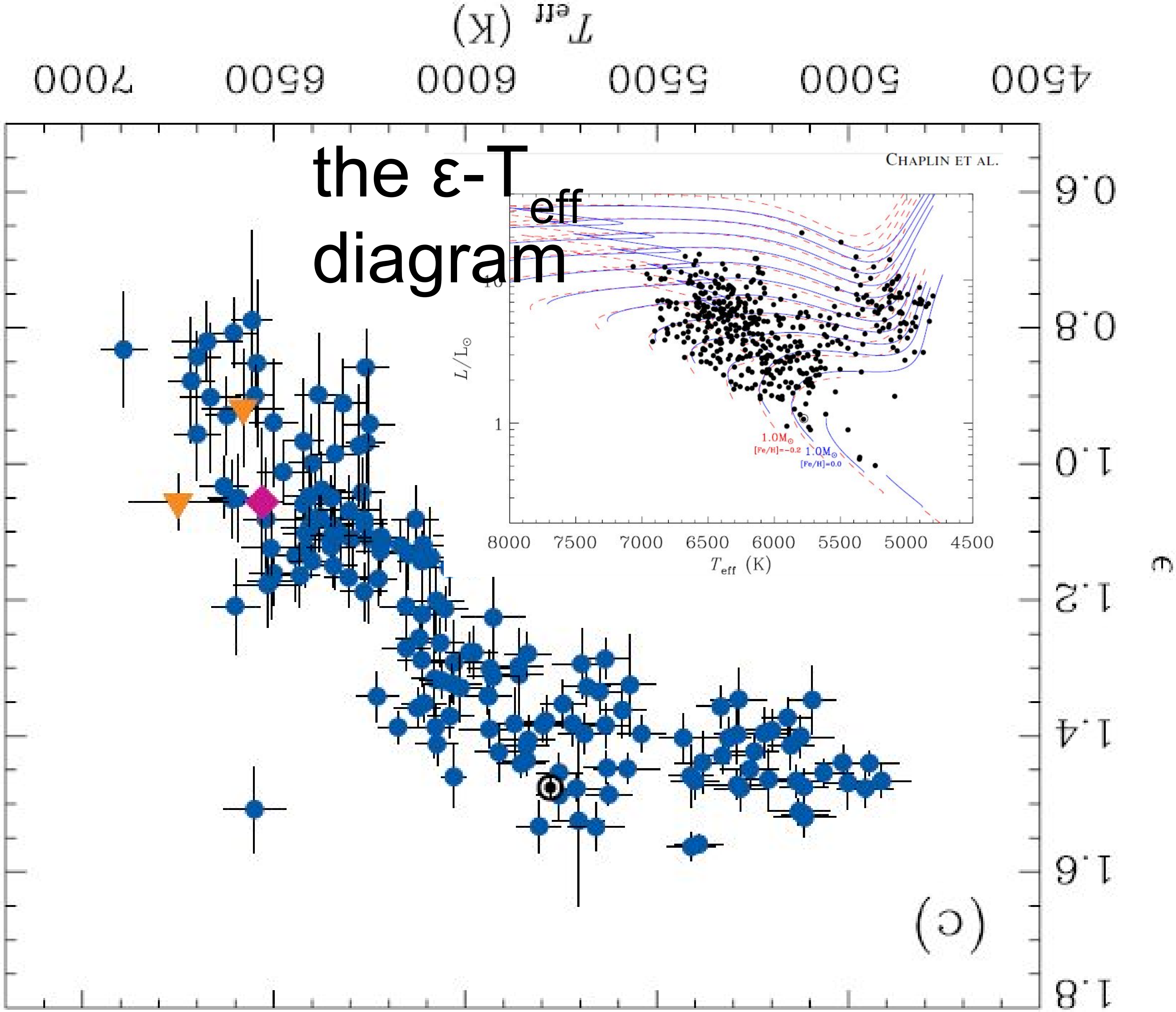
the ε-T_{eff} diagram

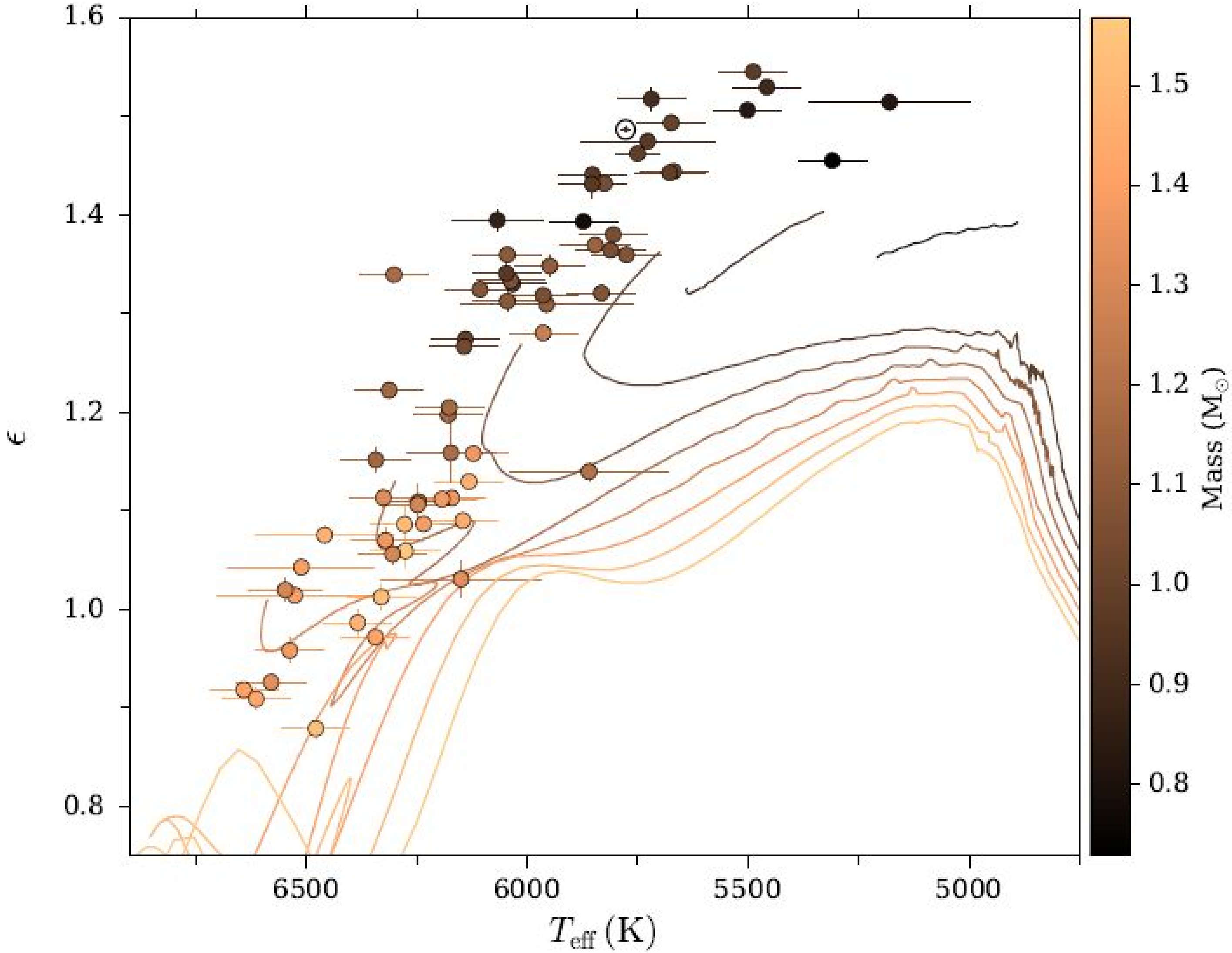


the ε-T_{eff} diagram



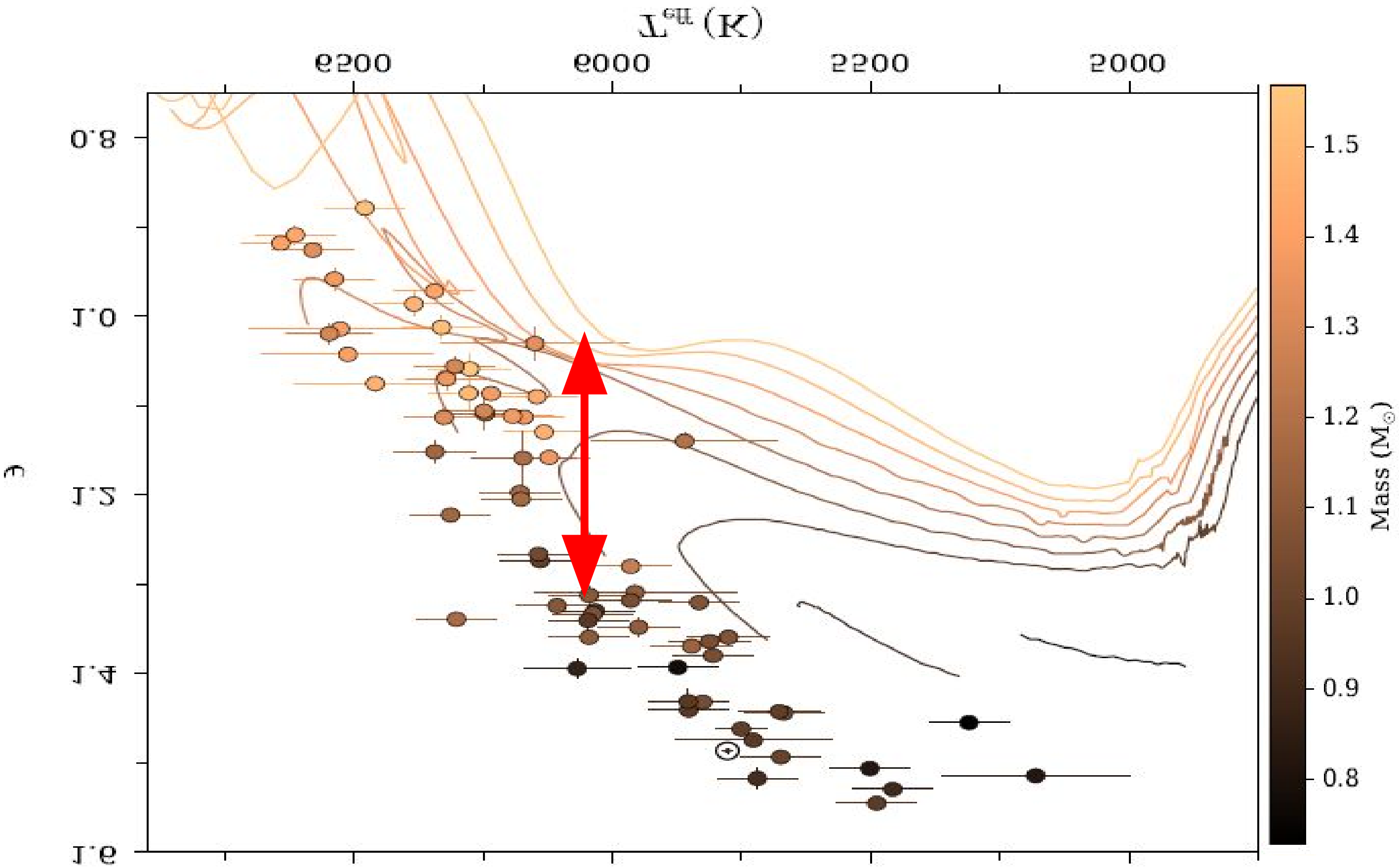
the ε-T_{eff} diagram





Kepler Legacy sample – 66 main-sequence stars (Lund et al., in prep.)

the Legacy ε-T_{eff} diagram

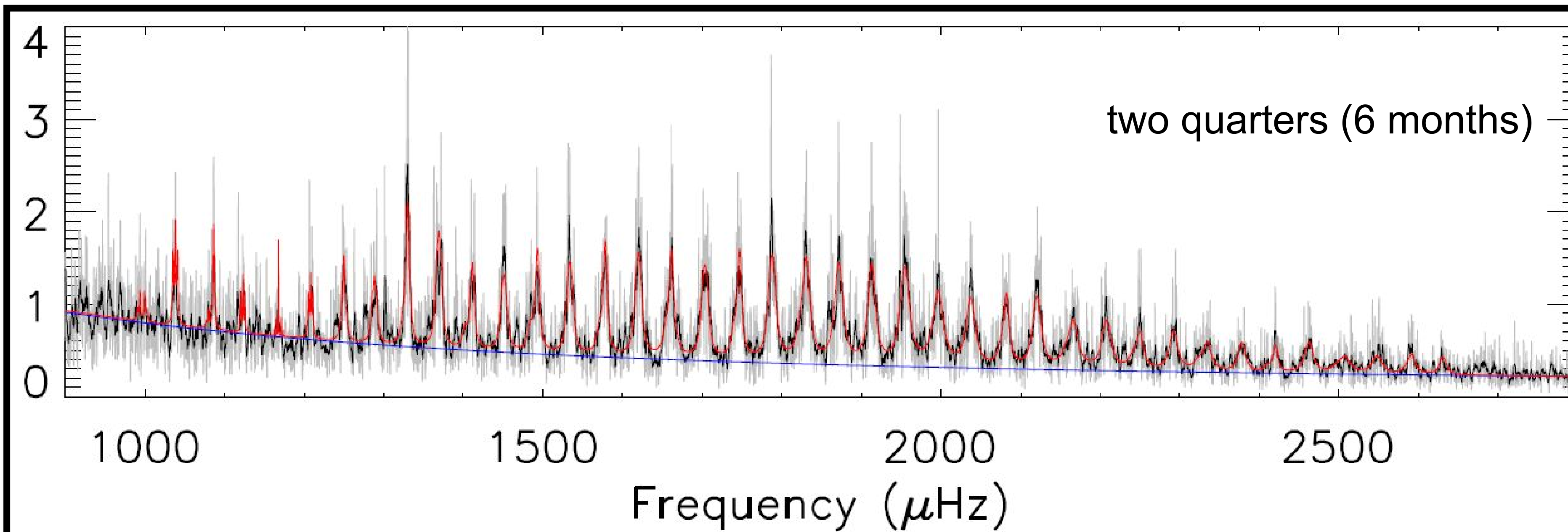


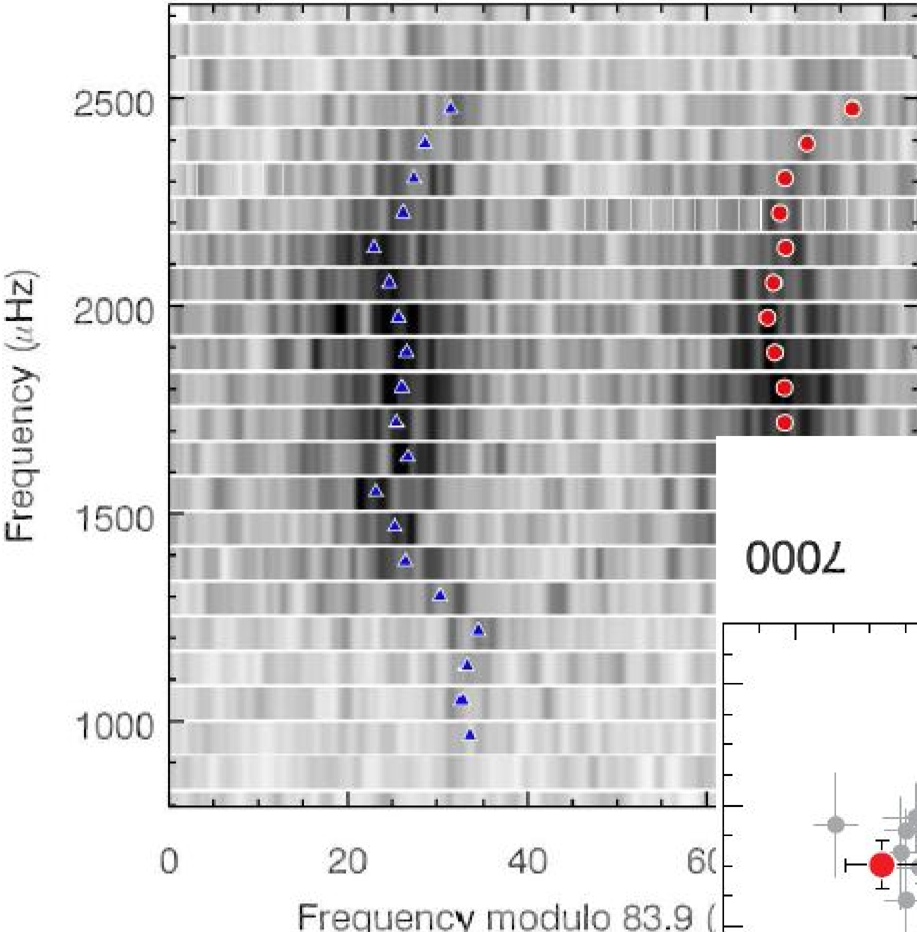
Kepler Legacy sample – 66 well-observed main-sequence stars (Lund et al., in prep.)

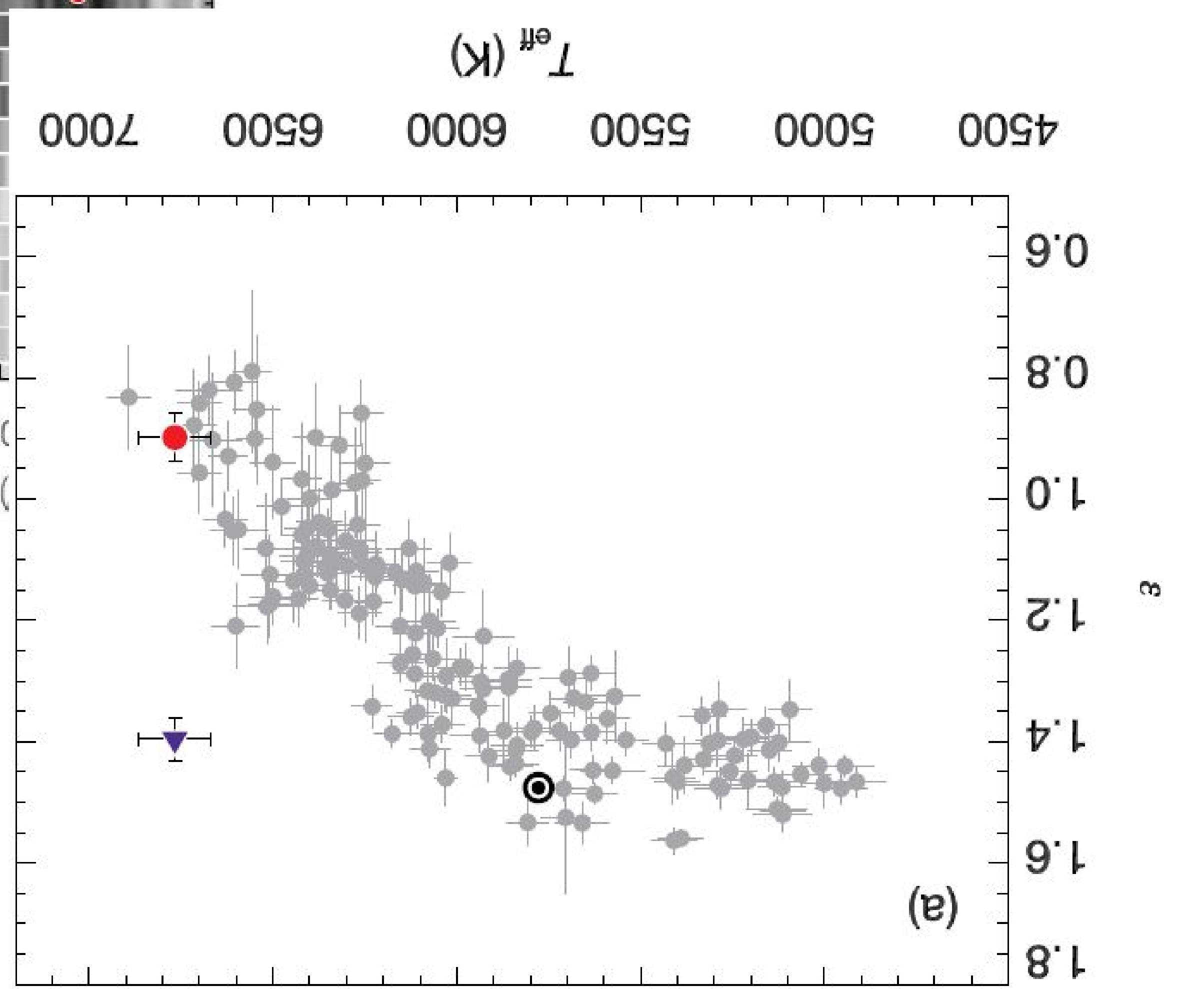
Application to θ Cyg (V=4.5; F3V)

DETECTION OF SOLAR-LIKE OSCILLATIONS, OBSERVATIONAL CONSTRAINTS, AND STELLAR MODELS FOR θ CYG, THE BRIGHTEST STAR OBSERVED BY THE *KEPLER* MISSION

J. A. Guzik[1], G. Houdek[2], W. J. Chaplin[3,2], B. Smalley[4], D. W. Kurtz[5], R.L. Gilliland[6], F. Mullally[7], J.F. Rowe[7], S. T. Bryson[8], M. D. Still[8,9], V. Antoci[2], T. Appourchaux[10], S. Basu[11], T. R. Bedding[12,2], O. Benomar[12,13], R. A. Garcia[14], D. Huber[12,2], H. Kjeldsen[2], D. W. Latham[15], T.S. Metcalfe[16], P. I. Pápics[17], T. R. White[12,18,2], C. Aerts[17,19], J. Ballot[34], T. S. Boyajian[11], M. Briquet[20], H. Bruntt[2,21], L. A. Buchhave[22,23], T. L. Campante[3,2], G. Catanzaro[24], J. Christensen-Dalsgaard[2], G. R. Davies[3,2,14], G. Doğan[2,26,27], D. Dragomir[28], A. P. Doyle[25,4],Y. Elsworth[3,2], A. Frasca[24], P. Gaulme[29, 30], M. Gruberbauer[31], R. Handberg[2], S. Hekker[32,2], C. Karoff[2,26], H. Lehmann[33], P. Mathias[34,35], S. Mathur[16], A. Miglio[3,2], J. Molenda-Żakowicz[36], B. Mosser[37], S. J. Murphy[12,2], C. Régulo[38,39], V. Ripepi[40], D. Salabert[14], S. G. Sousa[41], D. Stello[12,2], K. Uytterhoeven[38,39]







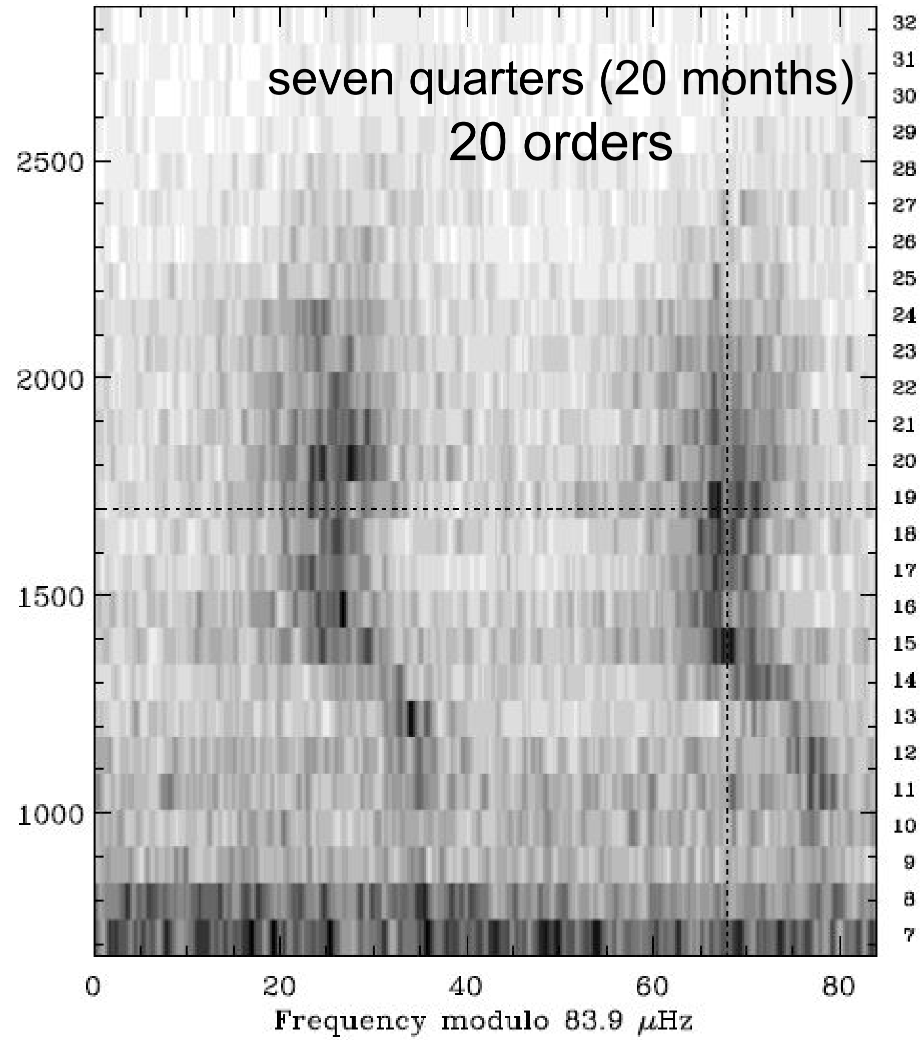
spread causes
problems when
ridges are not clear

Can we do asteroseismology on F stars?

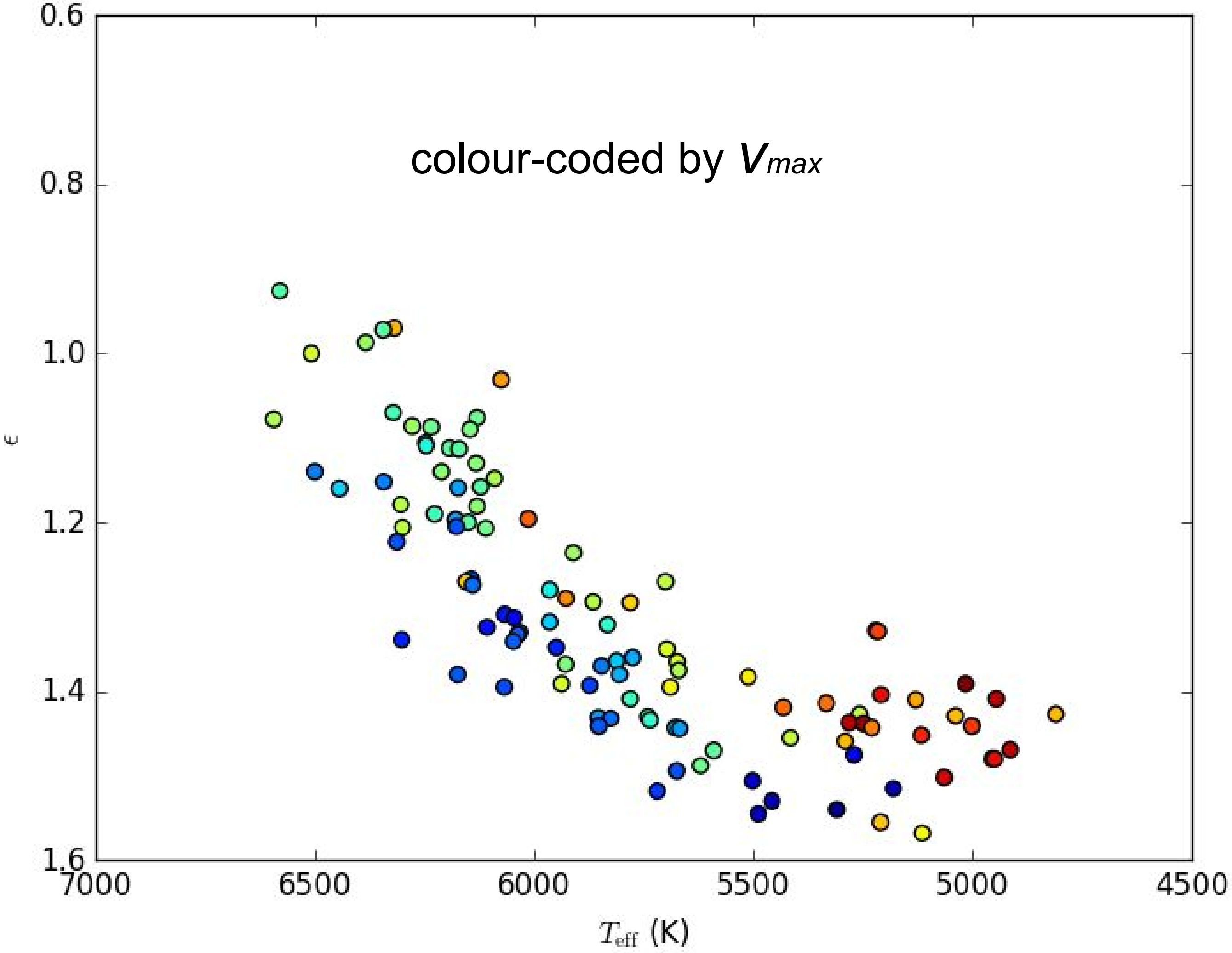
Tim Bedding

(University of Sydney)

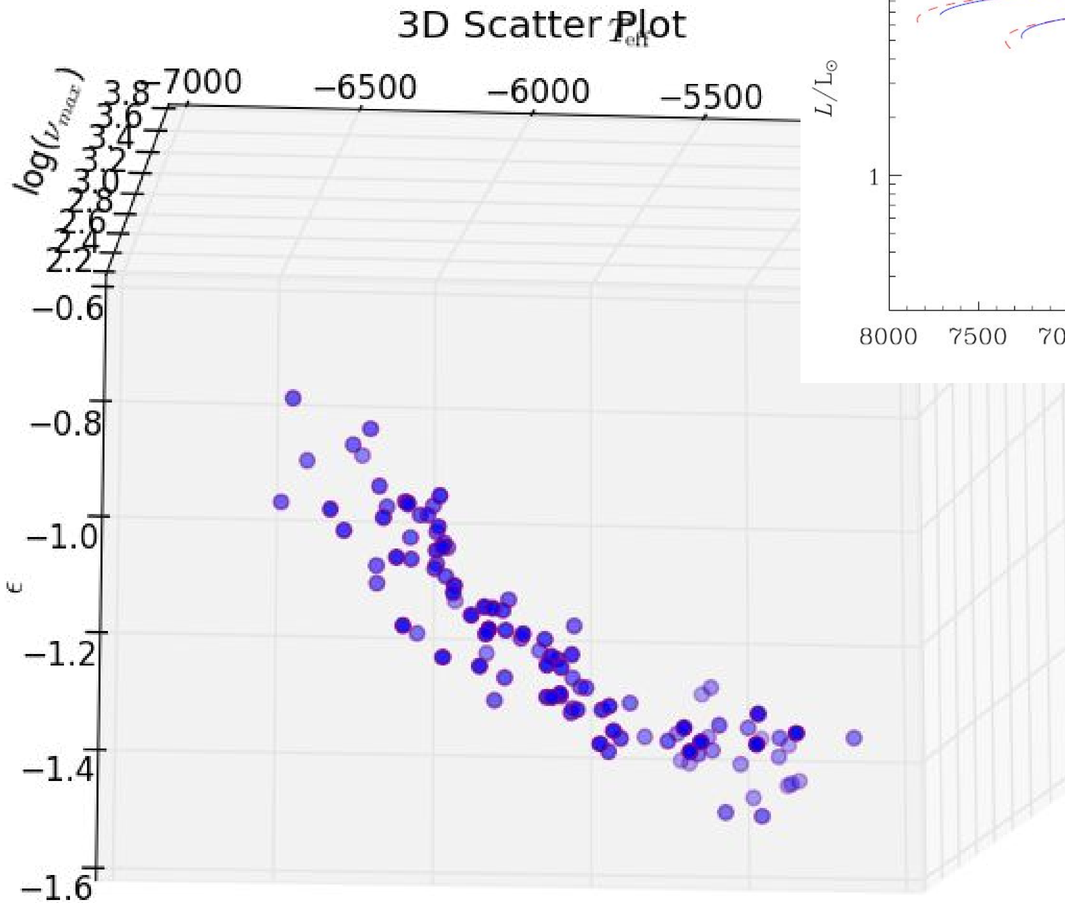
with Warrick Ball, Doug Compton, Joyce Guzik, Daniel Huber, Mikkel Lund, Simon Murphy, Durlabh Pande, Aleksa Sarai, Dennis Stello, Tim White, Vichi Antoci

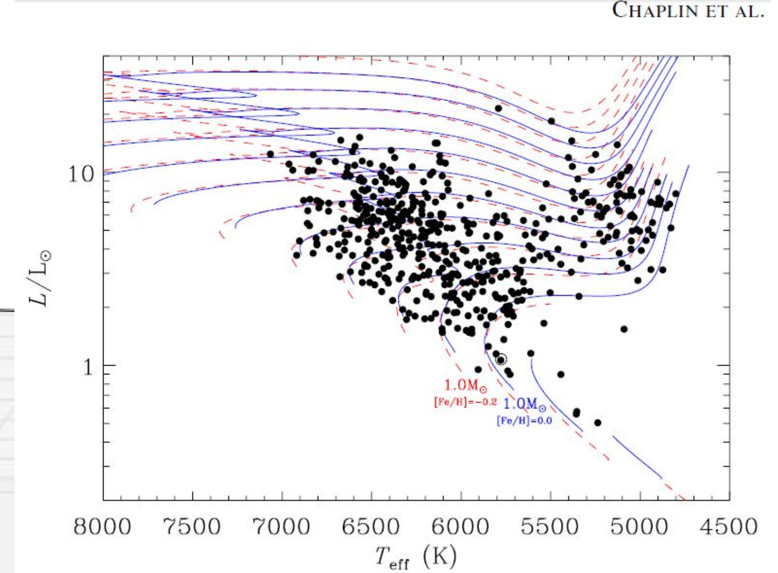


Revised ε-T_{eff} diagram



109 unambiguous stars from full mission (includes subgiants and SC RGB) - see earlier PDF



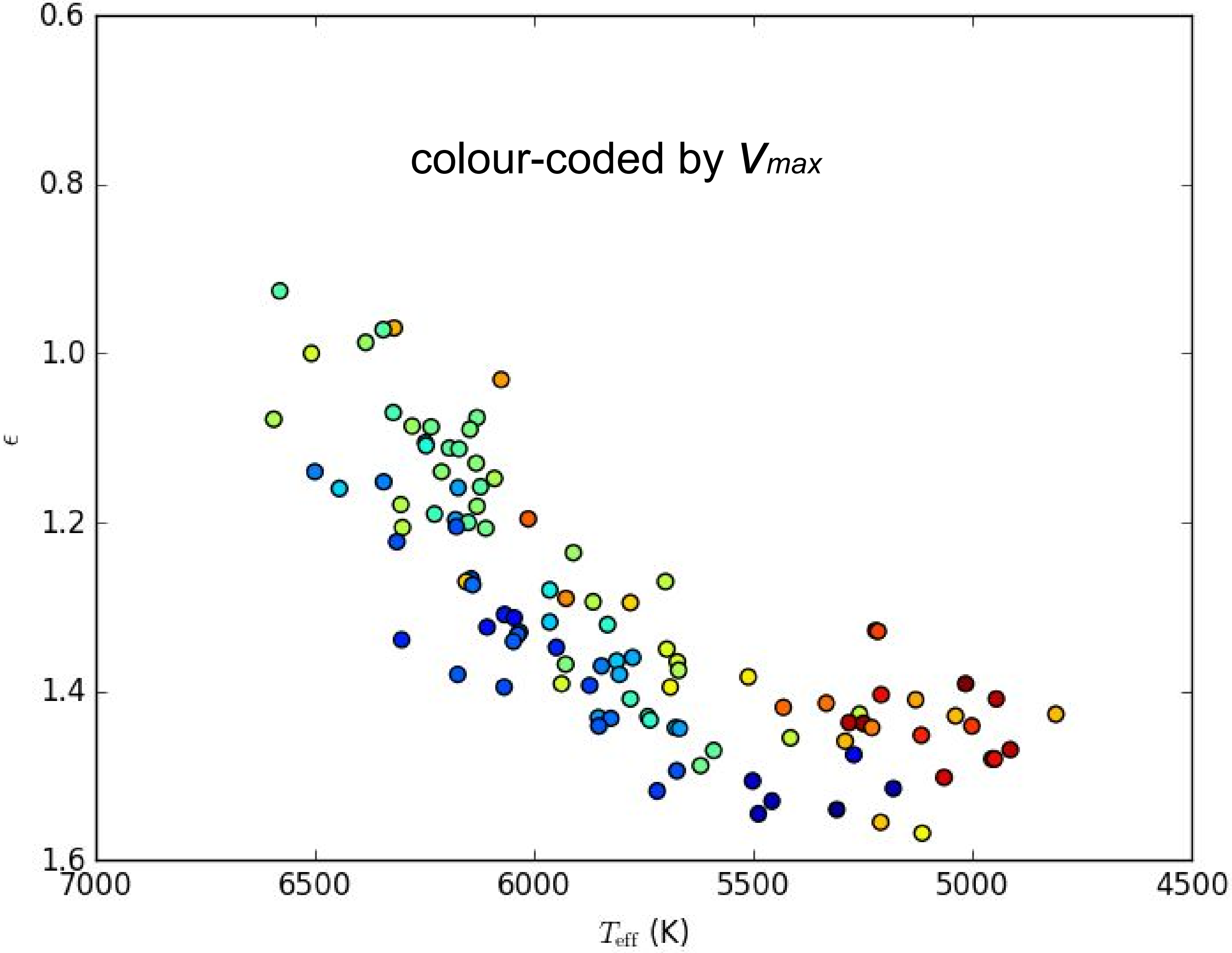


tight correlation of ε with Teff and numax

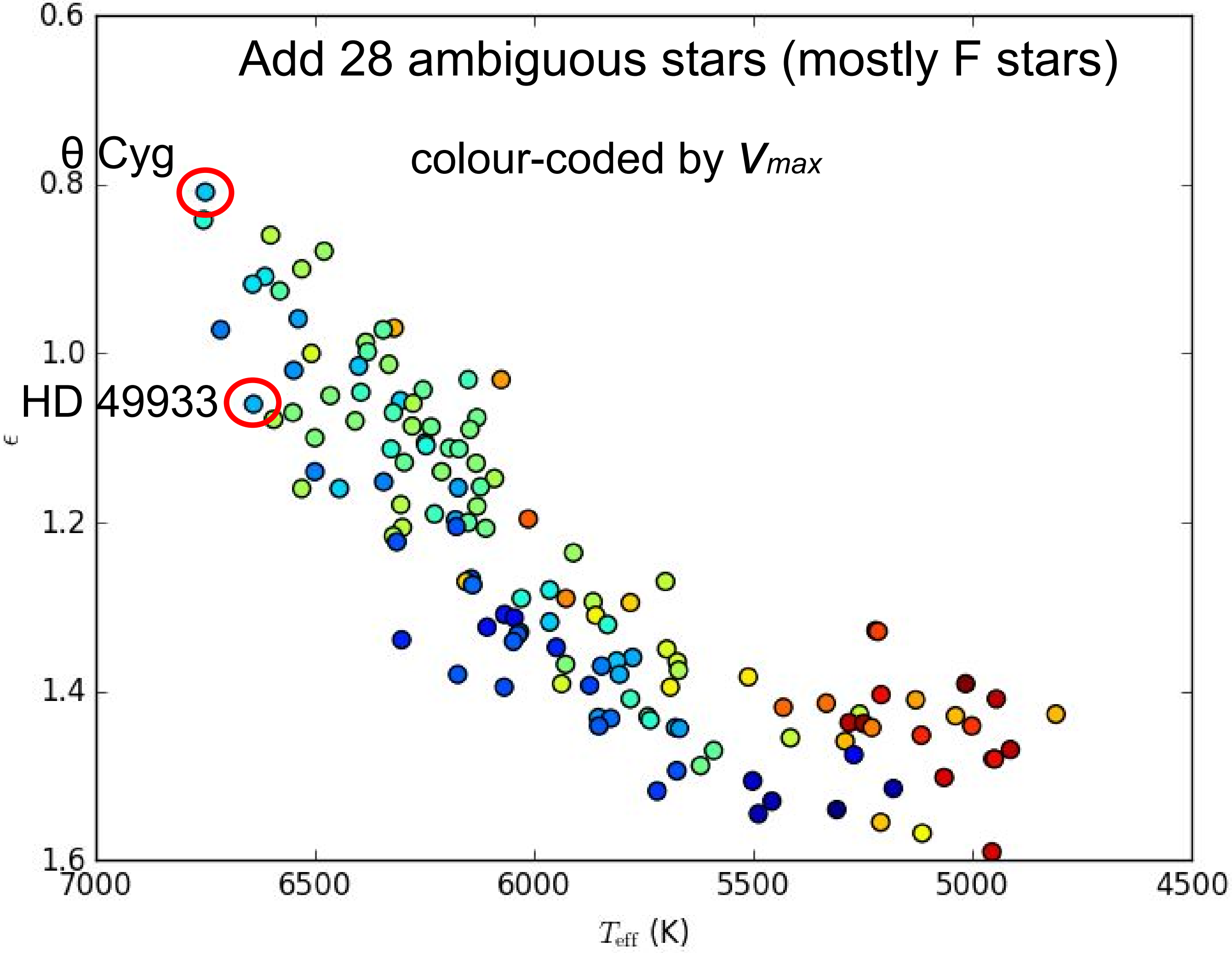
Echelle diagrams for 28 ambiguous stars from full mission (mostly F stars)

[insert PDF]

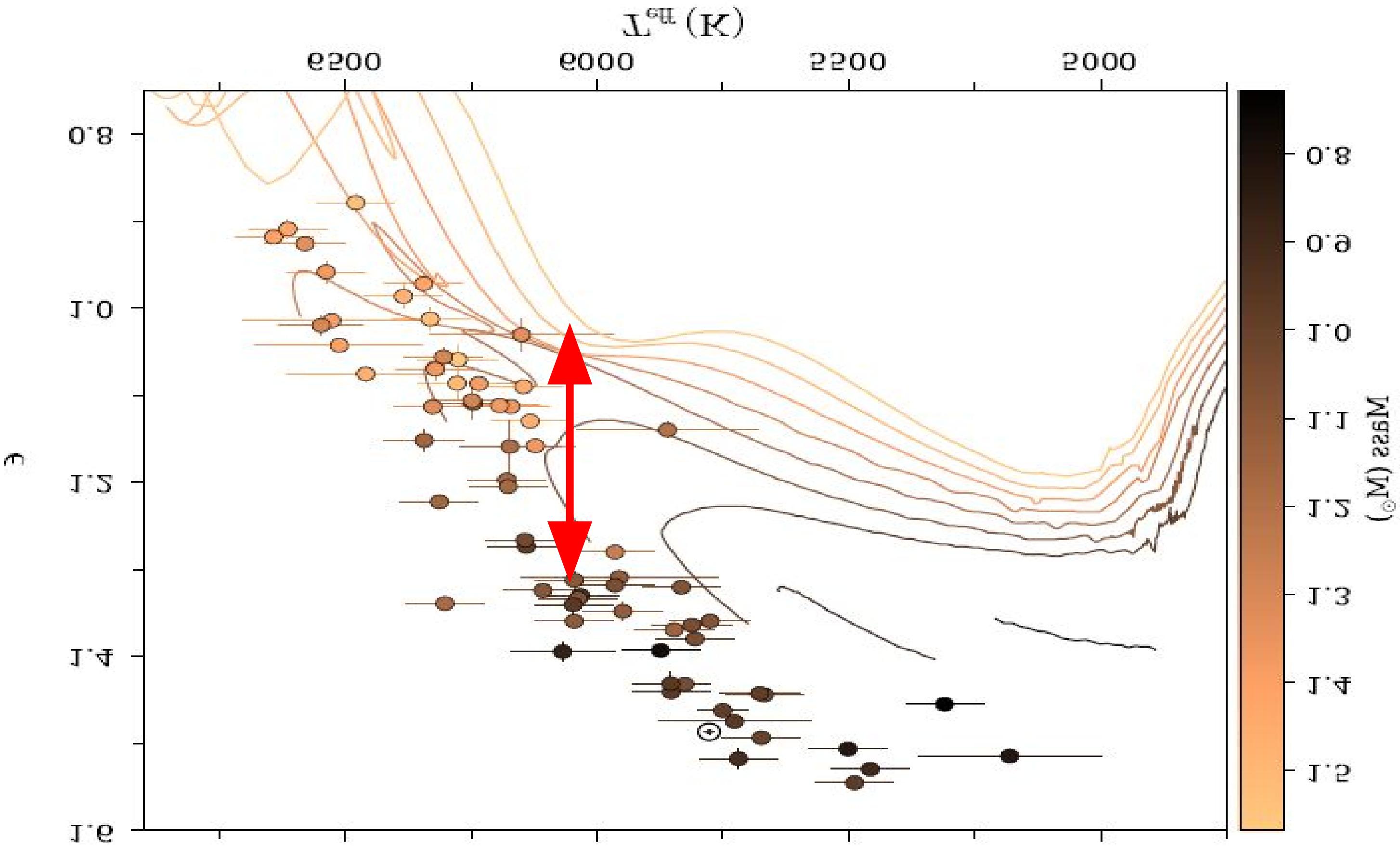
Revised ε-T_{eff} diagram



Revised ε-T_{eff} diagram

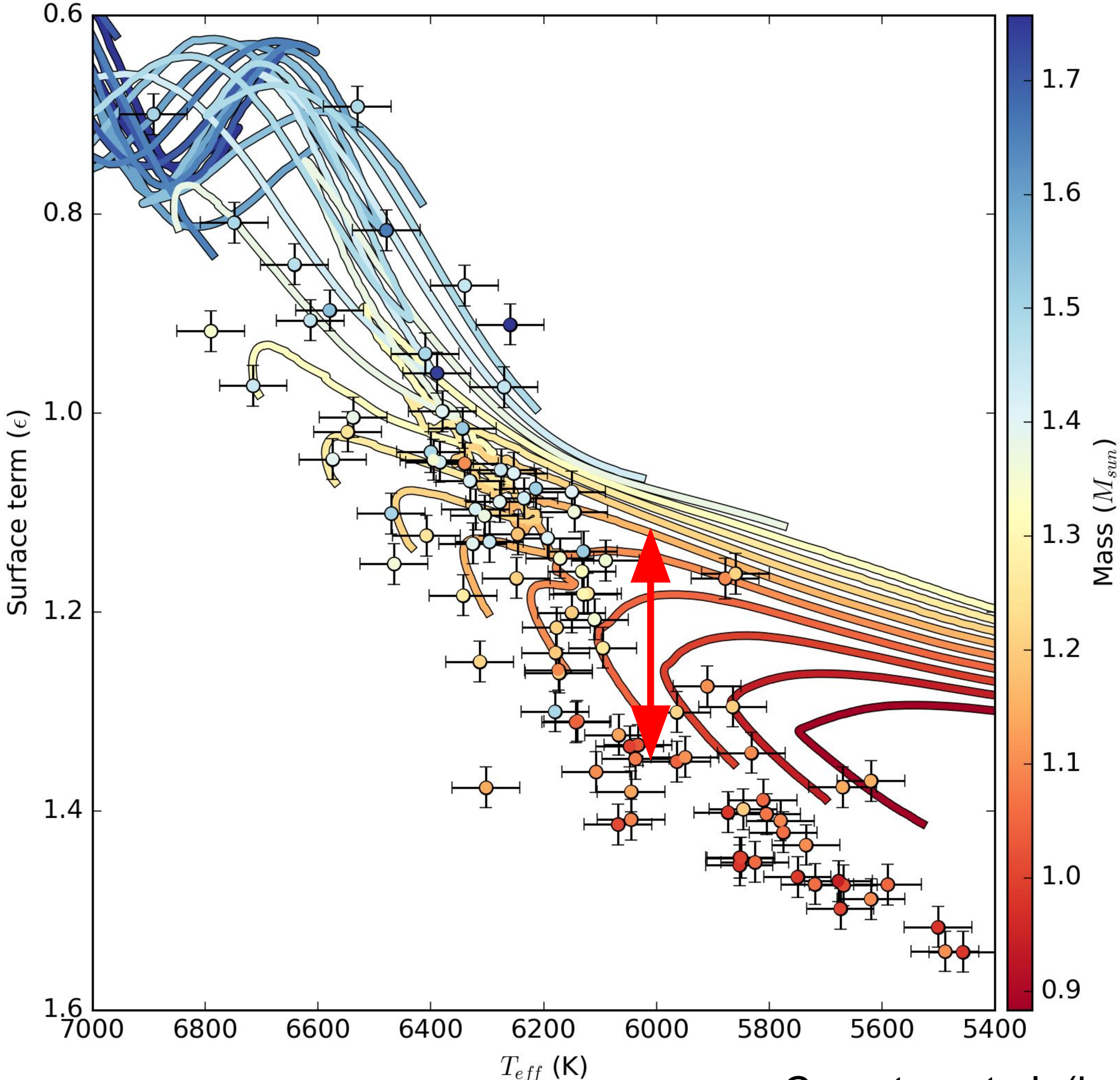


What about the surface term?

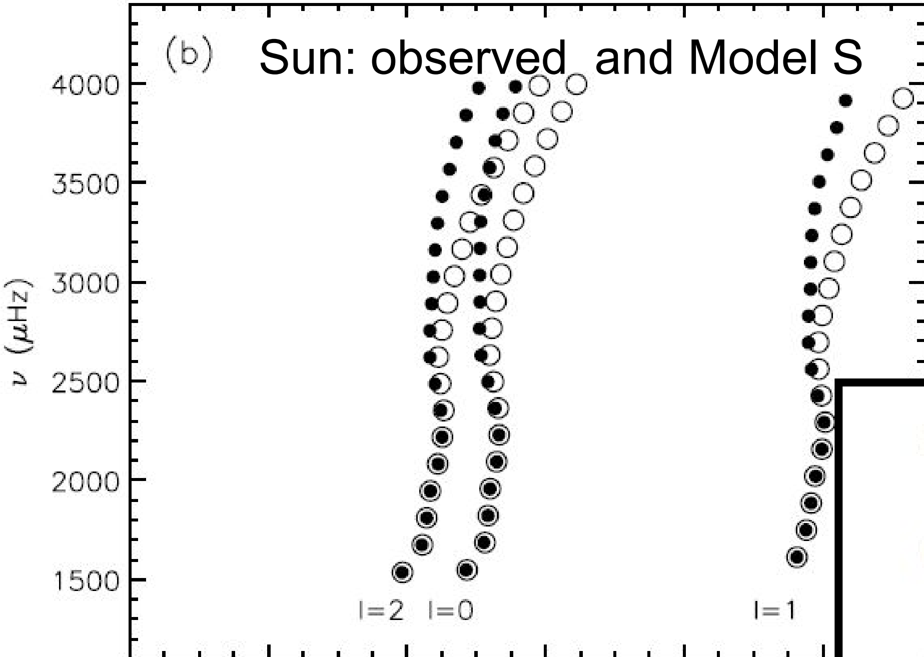


Kepler Legacy sample – 66 main-sequence stars (Lund et al., in prep.)

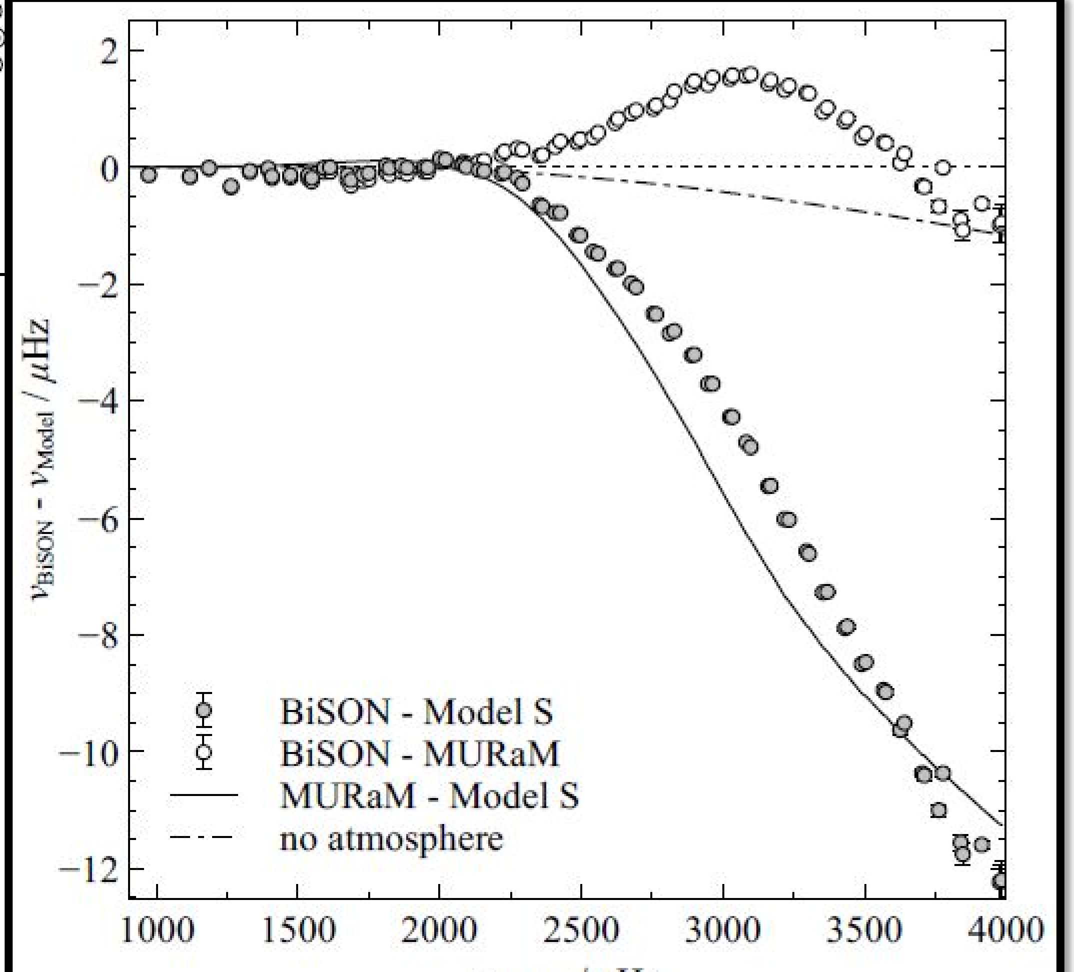
What about the surface term?



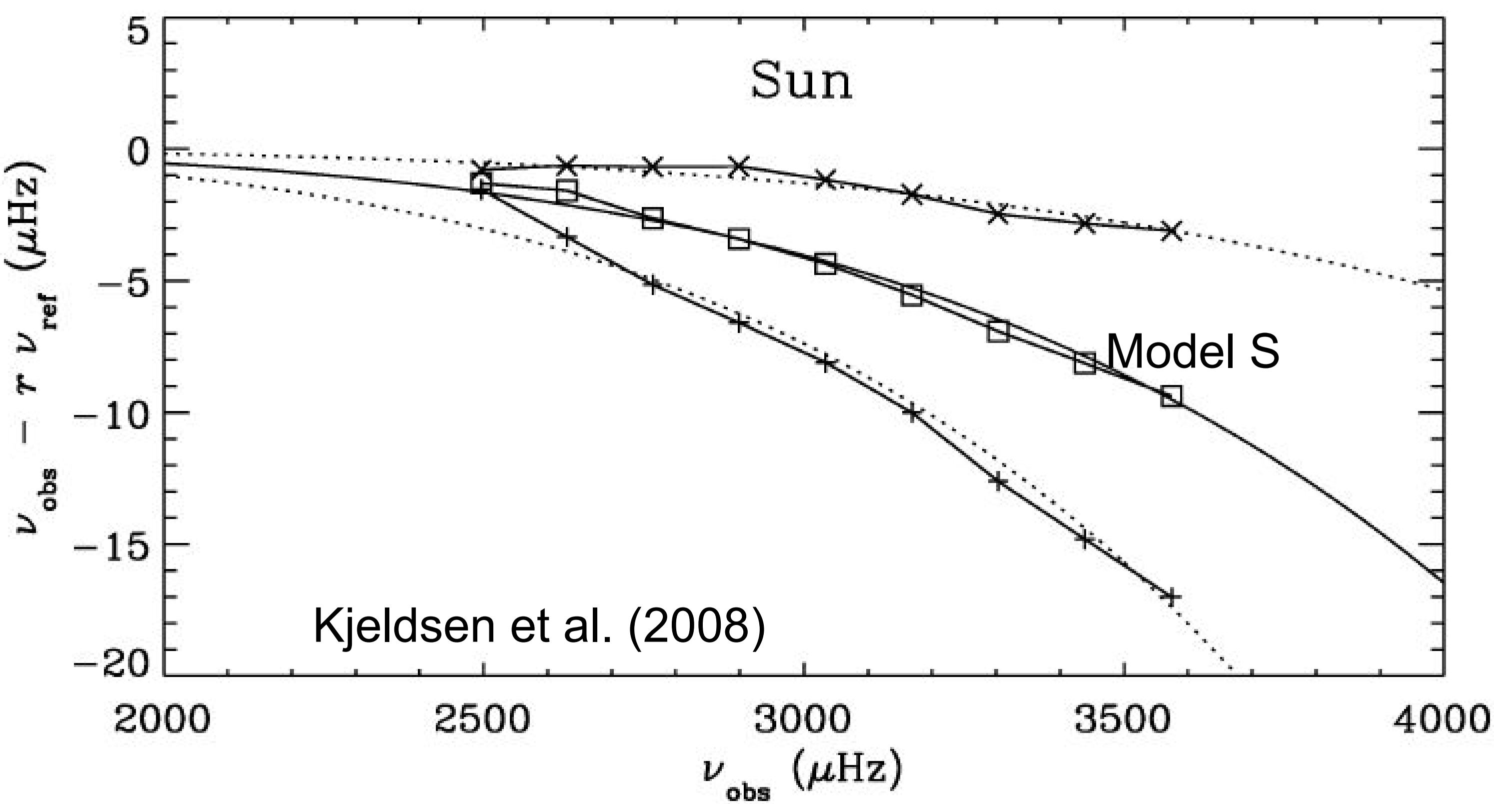
Compton et al. (in prep.)

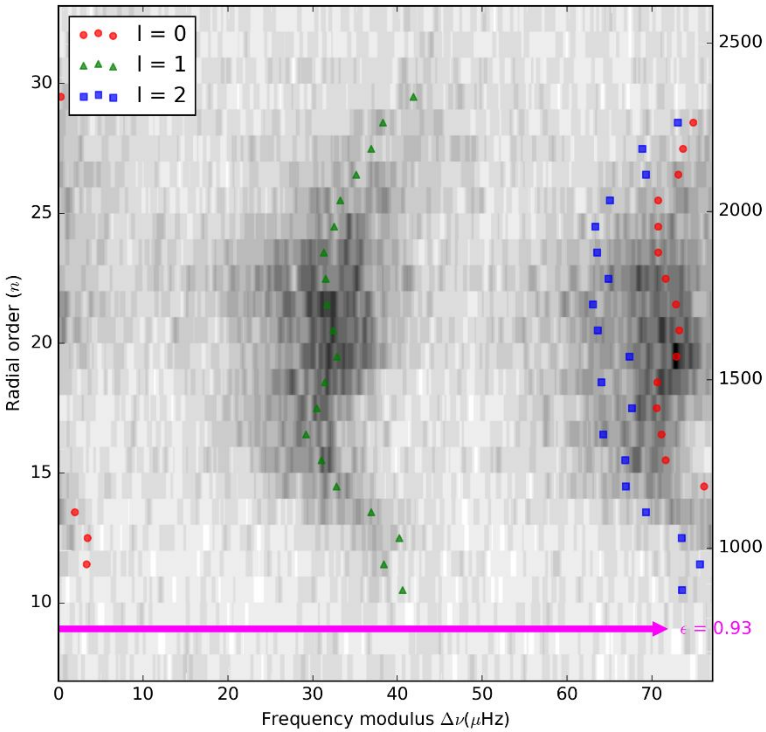


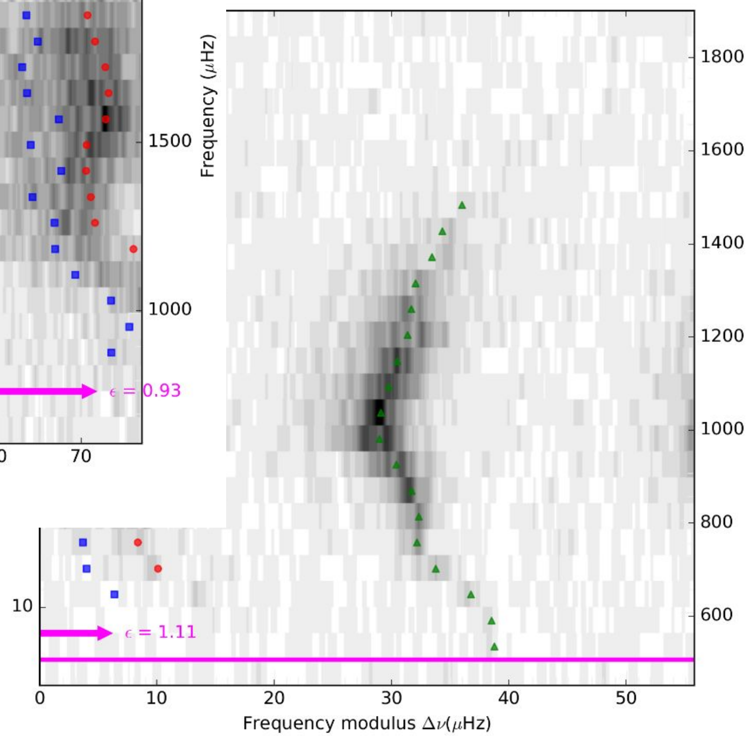
Gilliland et al. (2010)

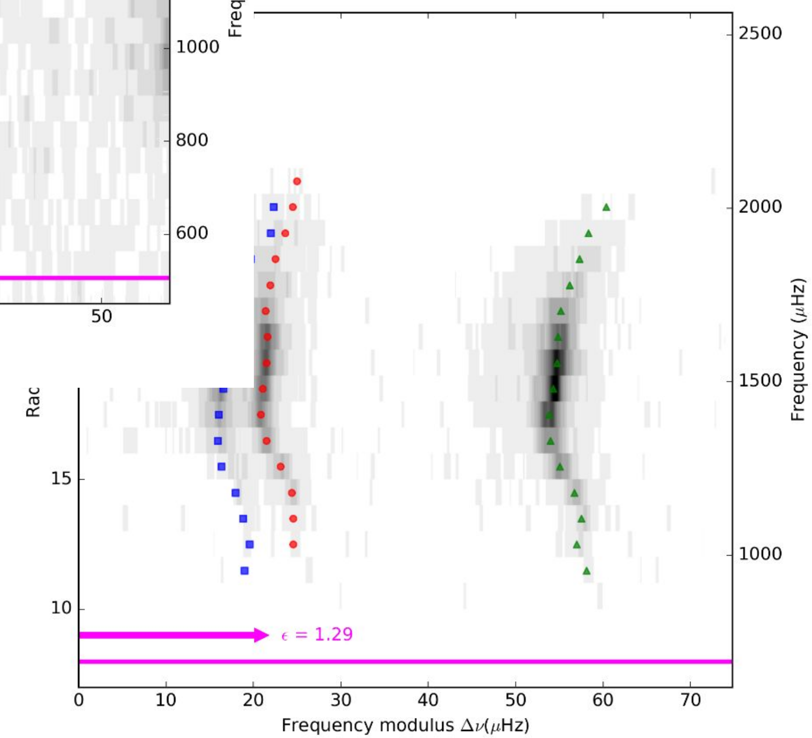


Ball & Gizon (2016)

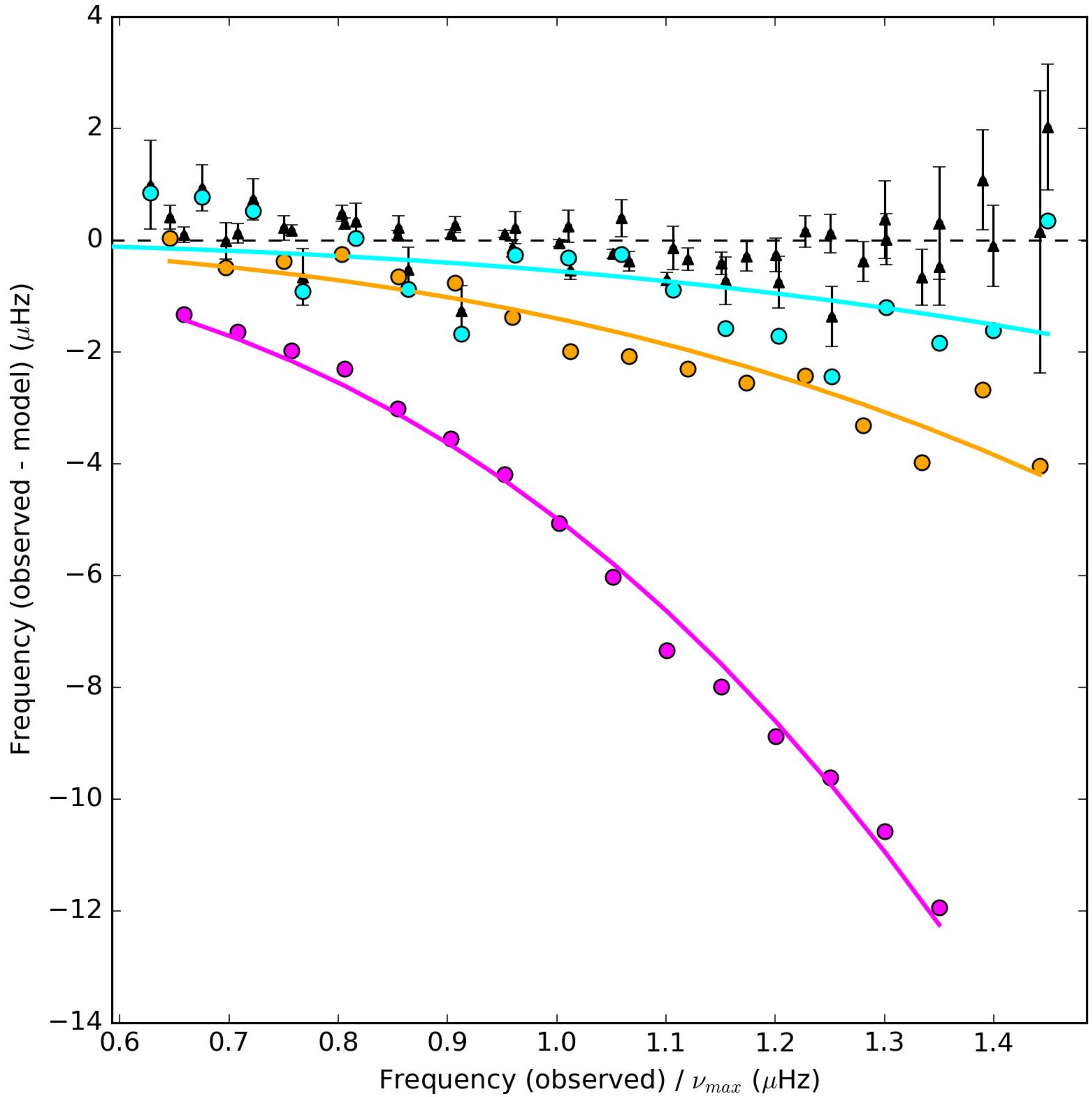

Sun
Model S
Kjeldsen et al. (2008)
$\nu_{obs} - r\,\nu_{ref}$ (μHz)
ν_{obs} (μHz)
5
0
−5
−10
−15
−20
2000
2500
3000
3500
4000



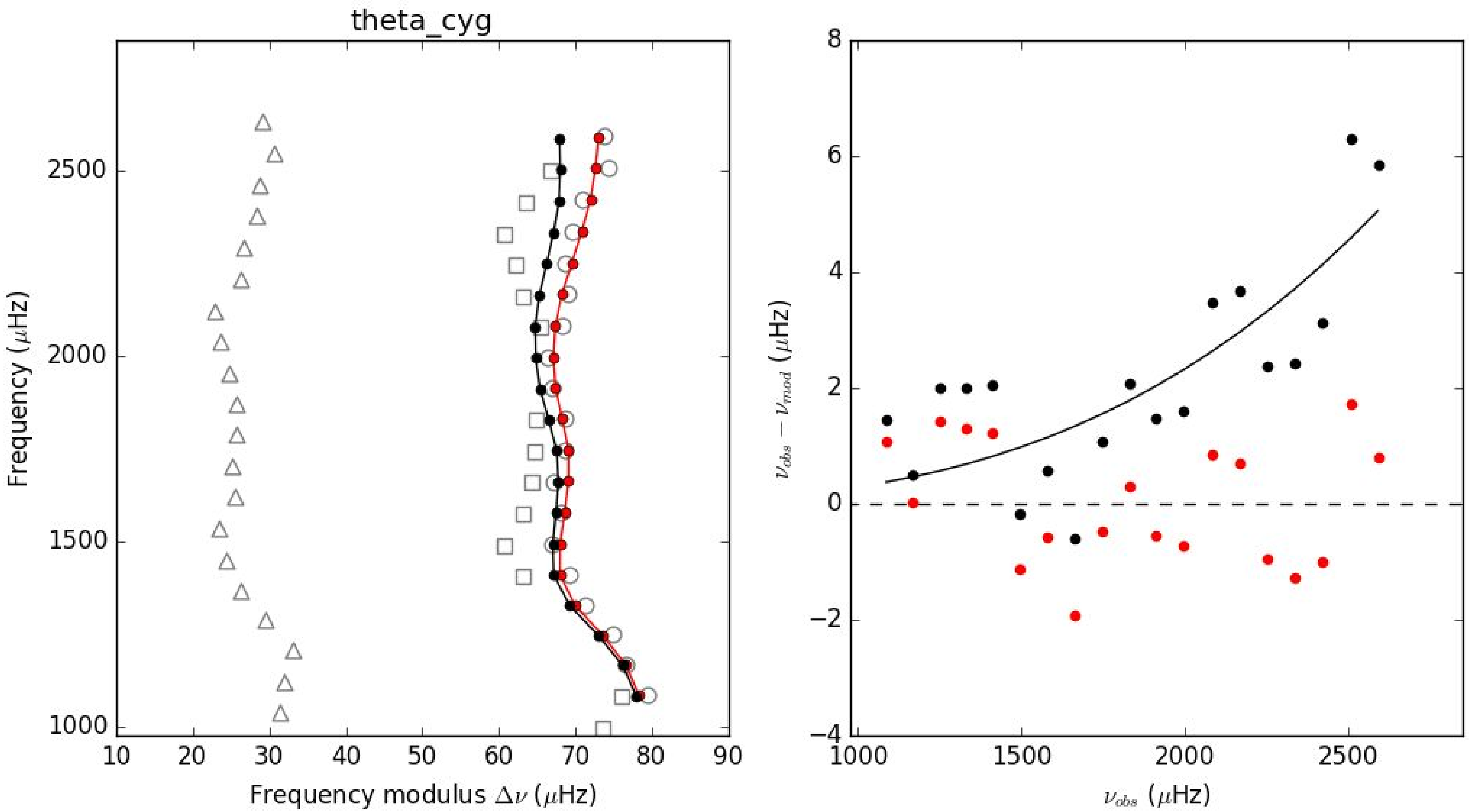




fitting models with MESA
Compton et al. (in prep.)

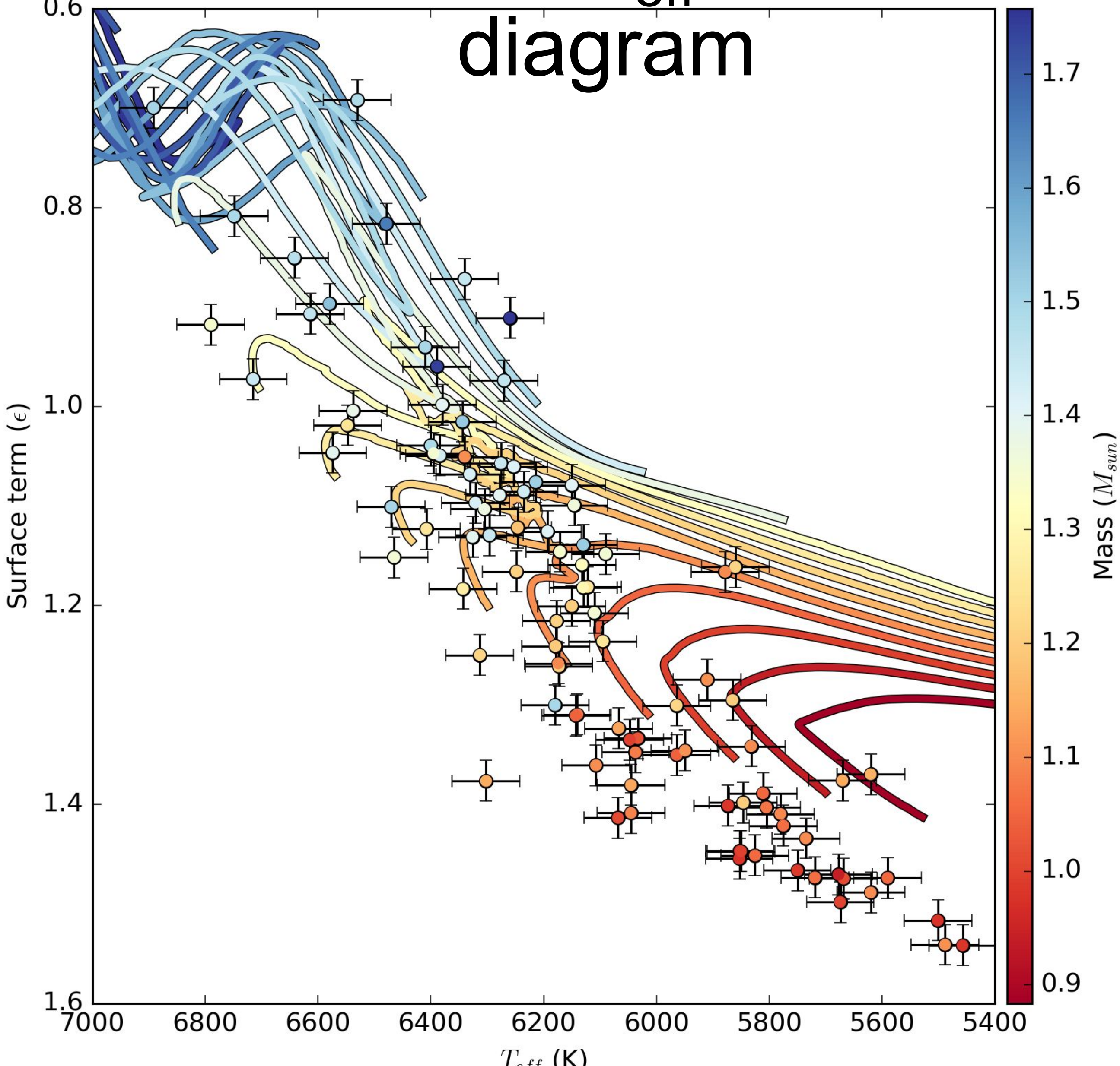


Compton et al. (in prep.)



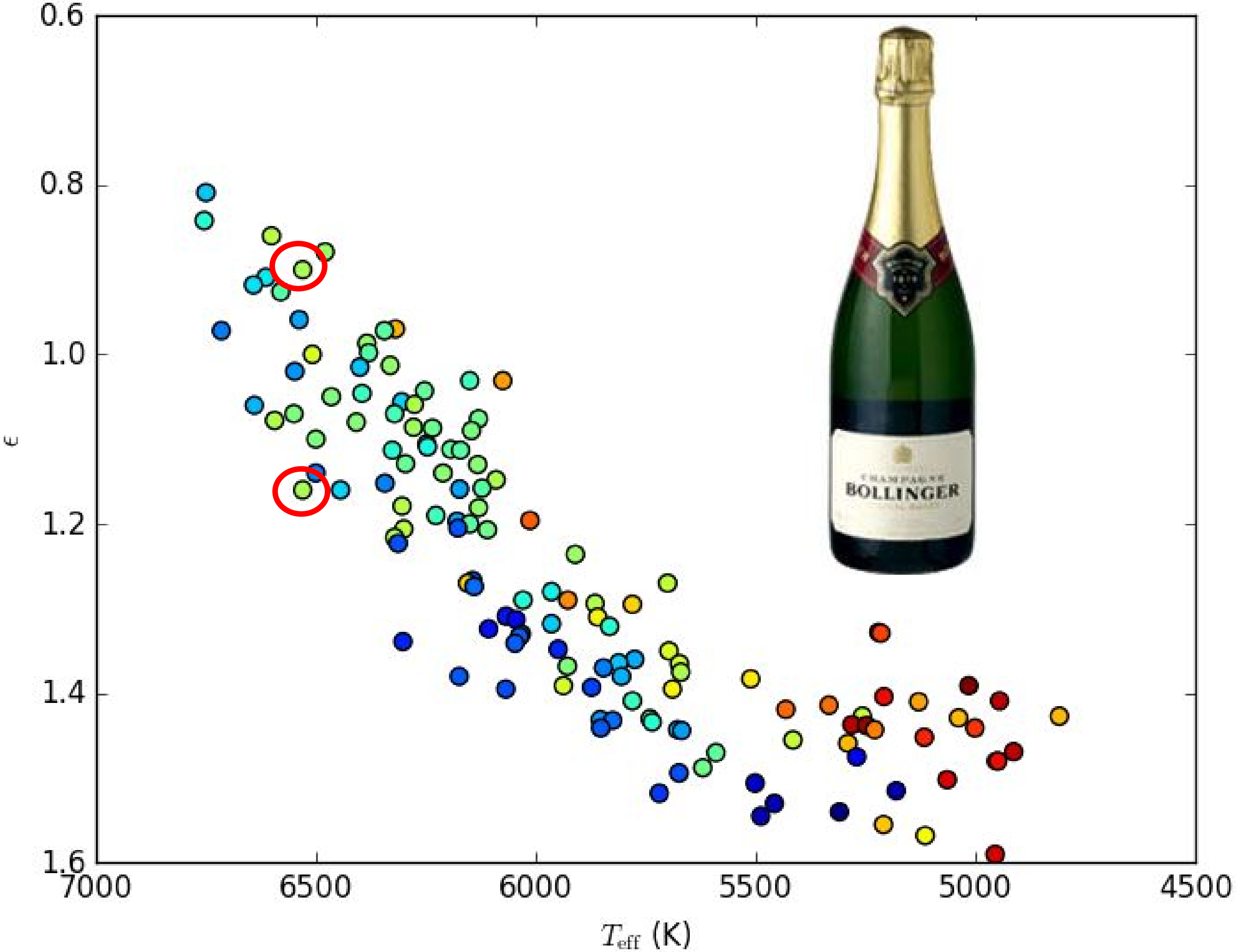
Compton et al. (in prep.)

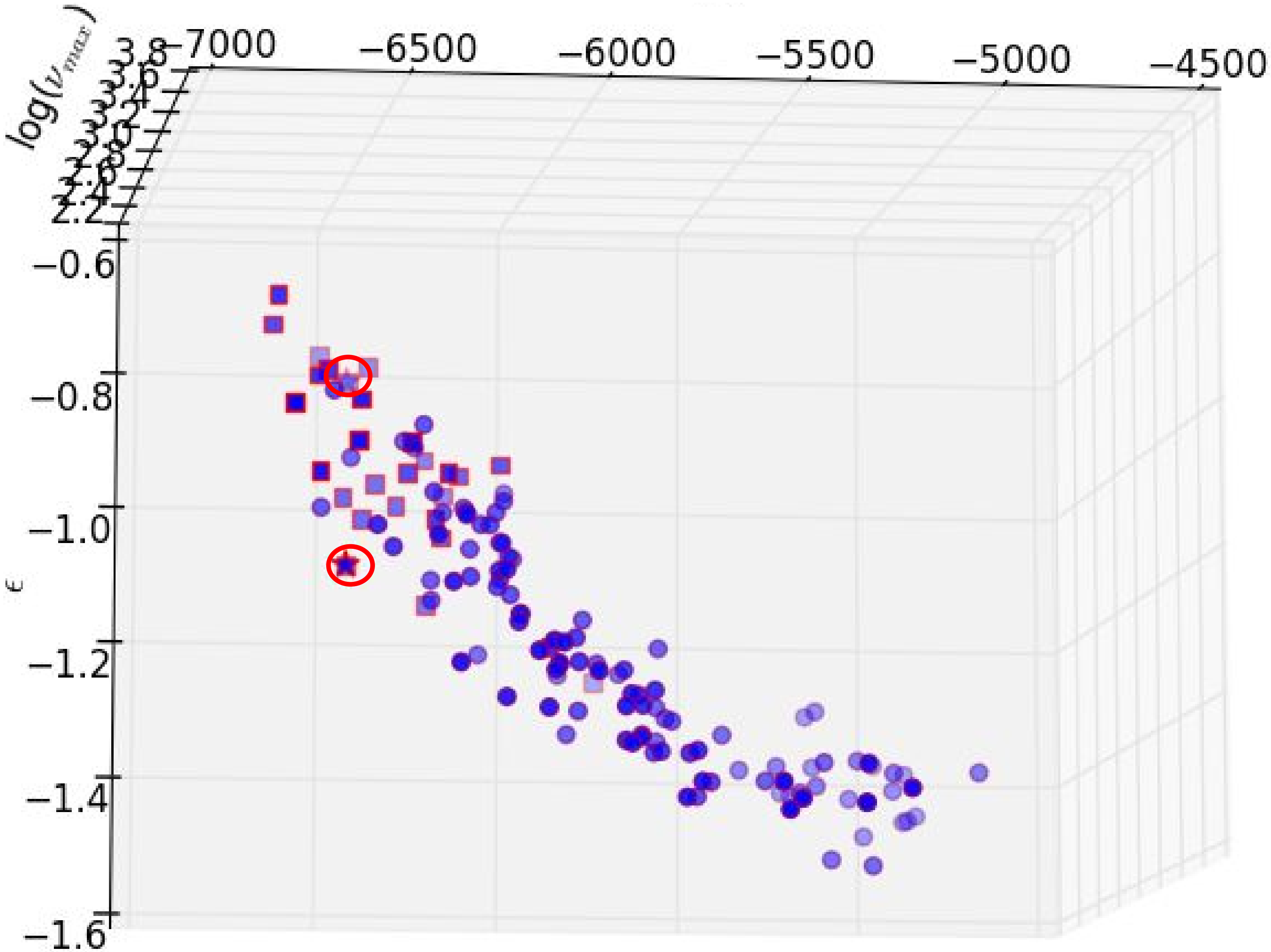
ε-T_{eff} diagram



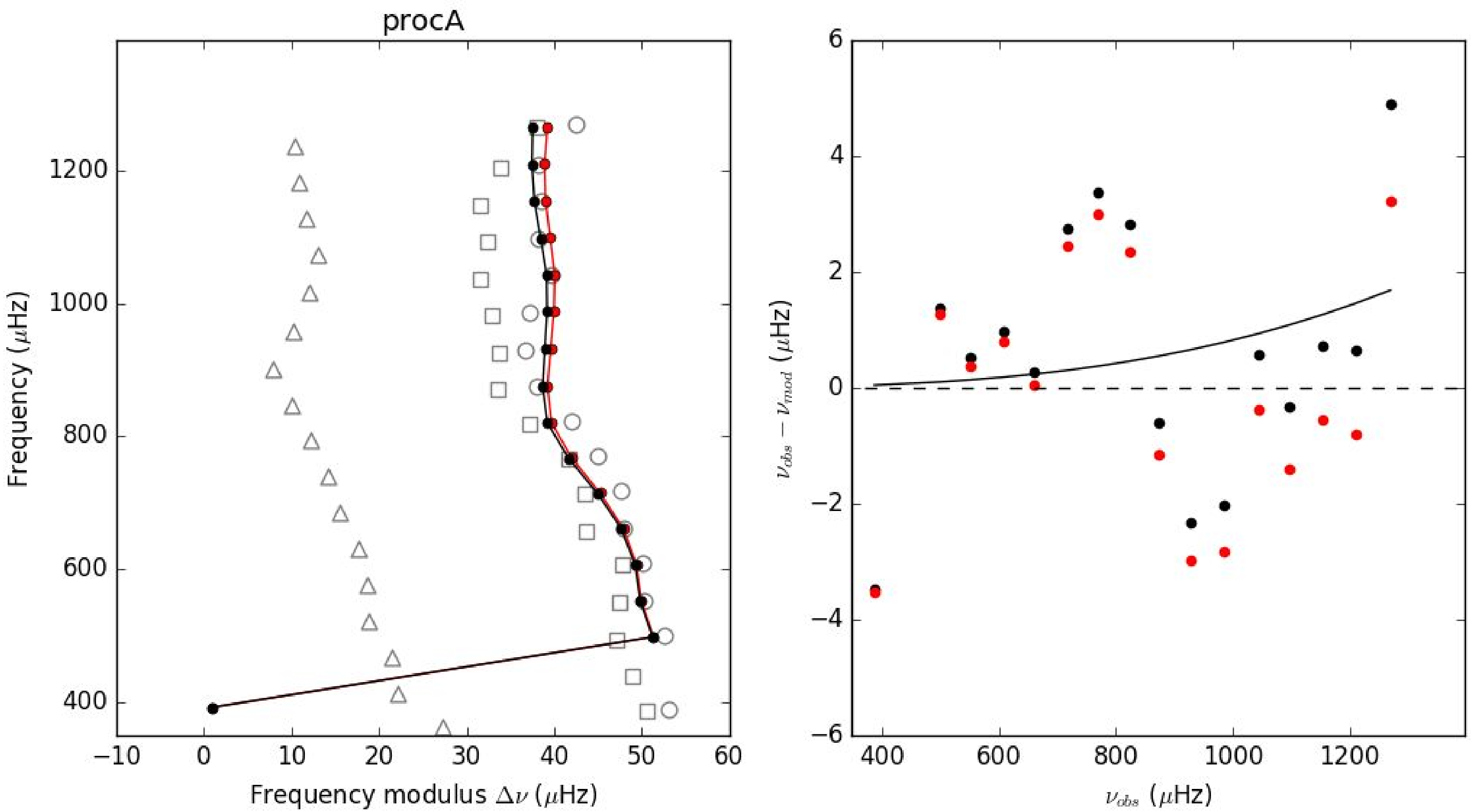
Compton et al. (in prep.)

So what about Procyon?





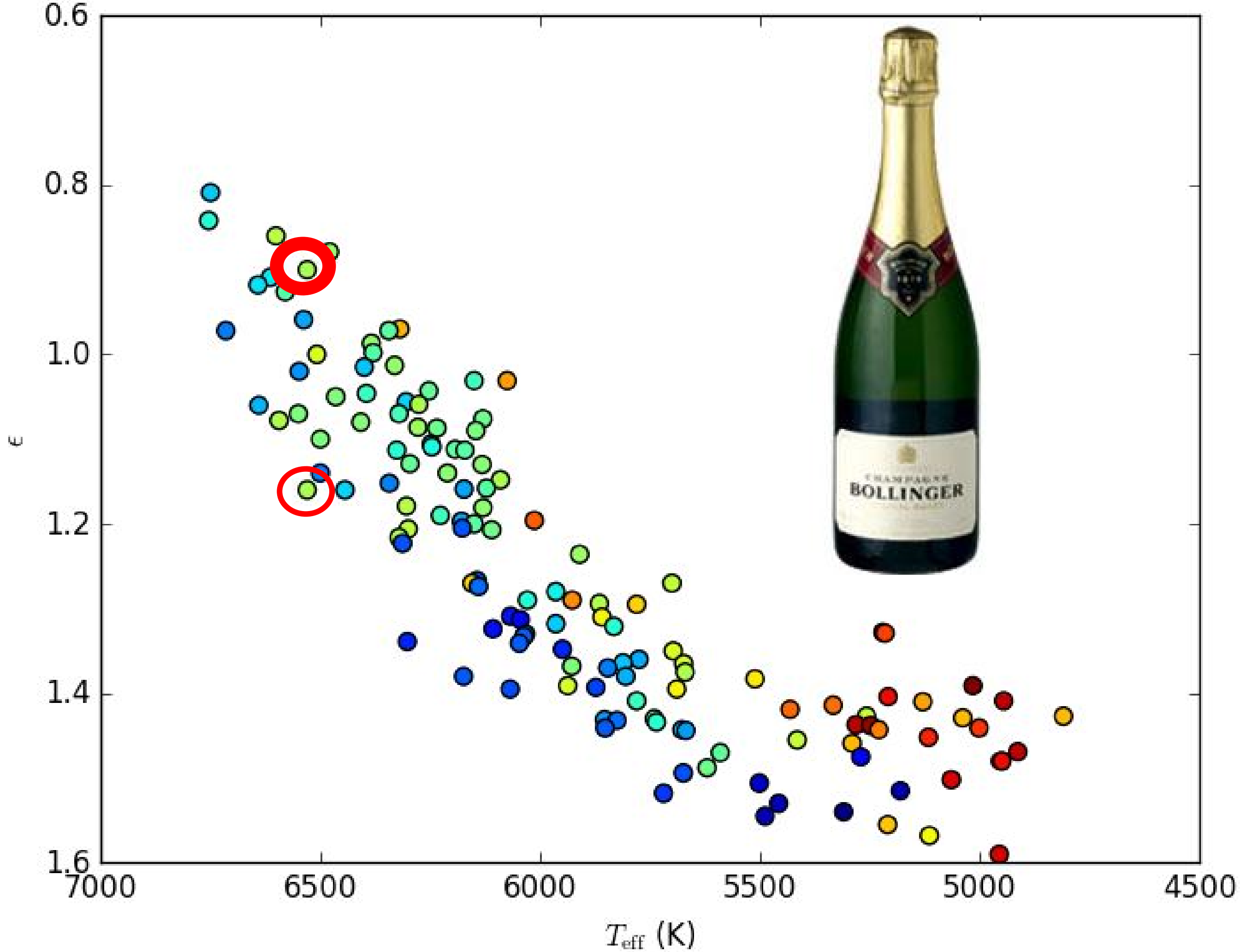
−7000
−6500
−6000
−5500
−5000
−4500
$\log(\nu_{max})$
3.8
3.6
2.2
ϵ
−0.6
−0.8
−1.0
−1.2
−1.4
−1.6



see Bedding et al. (2010)

Compton et al. (in prep.)

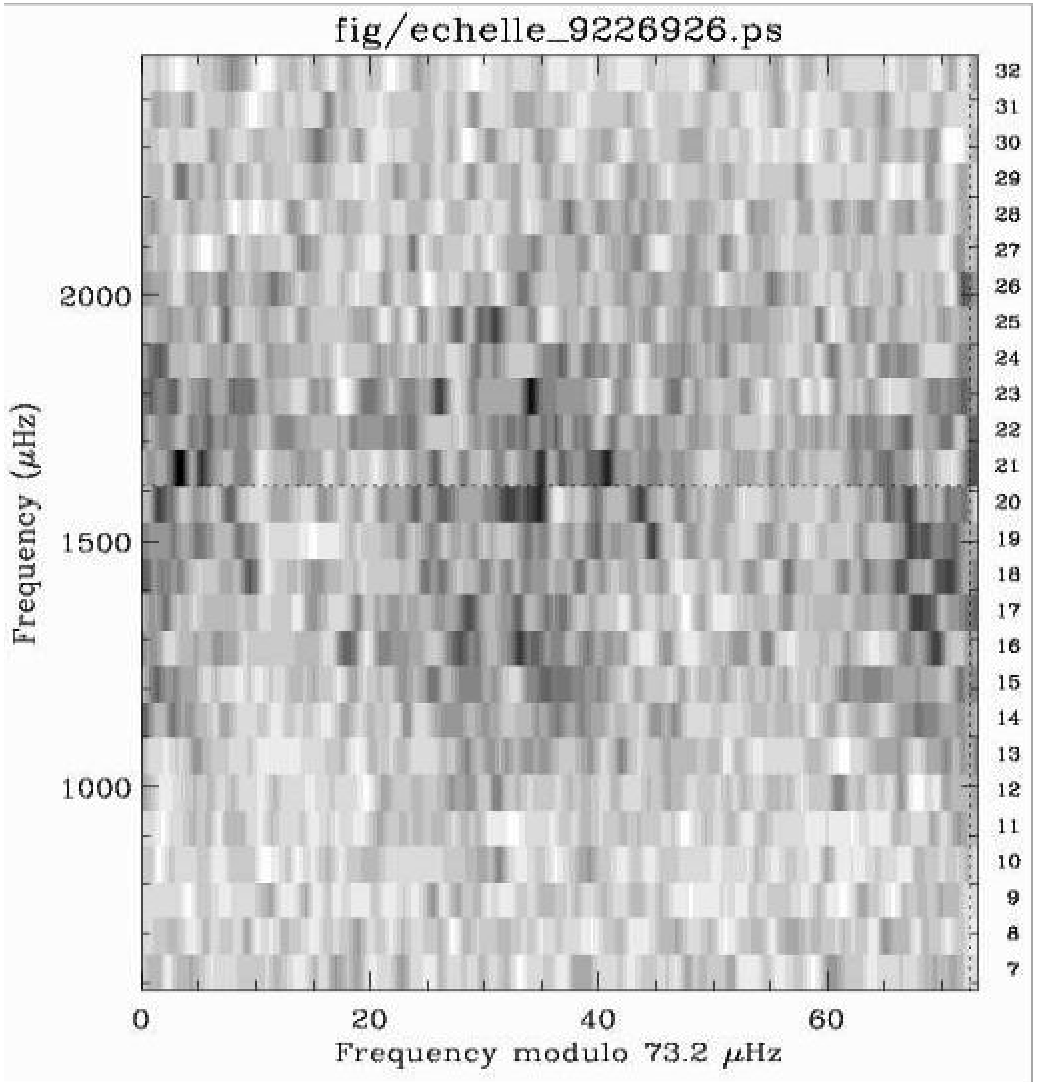
So what about Procyon?



Conclusions

- mode identification is now straightforward if the ridges are clear (i.e., if seismology is possible at all)
- the “surface term” appears to grower smaller as T_{eff} increases
- we *can* do asteroseismology on F stars (especially acoustic glitches over many orders)
- so please join the fun with “Fabulous” F stars!

the hottest F star with solar-like oscillations
Teff = 6892 K (Bruntt et al. 2012)



dow Help

143%

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Stellar model fits and inversions

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Key words stars: evolution – stars: interiors – stars: oscillations – methods: data analysis

The recent asteroseismic data from the CoRoT and *Kepler* missions have provided an entirely new basis fo
stellar properties. This has led to a rapid development in techniques for analysing such data, although it is p
say that we are still far from having the tools required for the full use of the potential of the observations. H
brief overview of some of the issues related to the interpretation of asteroseismic data.