Introduction to Asteroseismology

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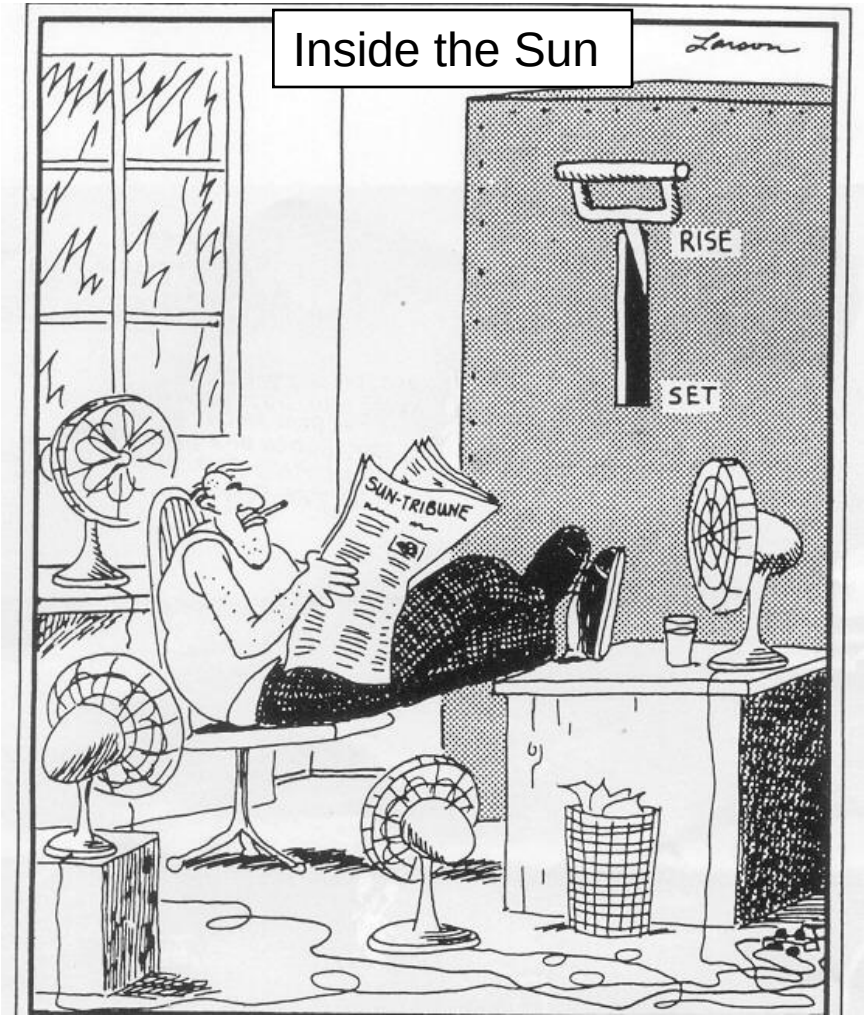
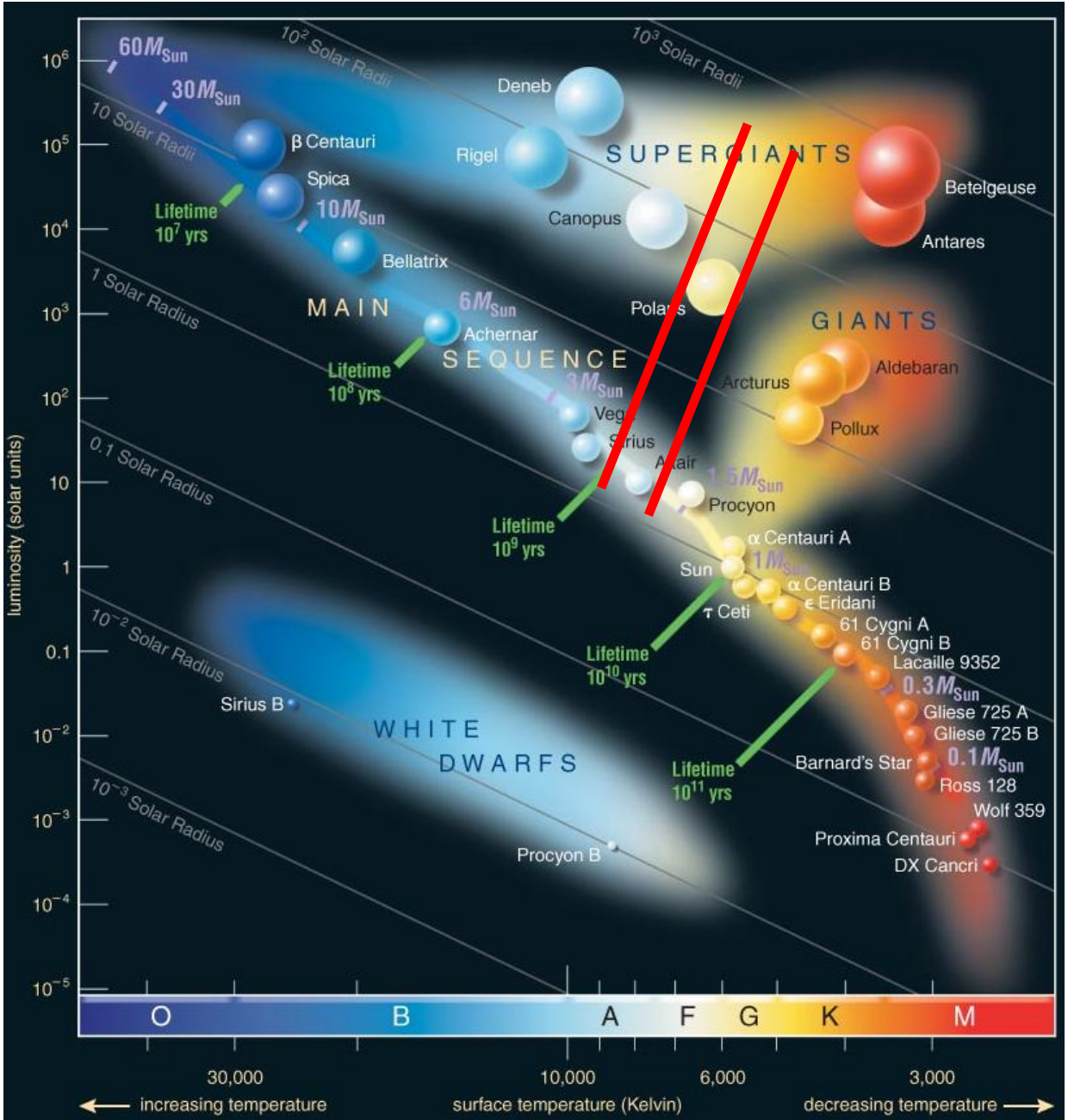


Asteroseismology:

- the study of “starquakes”
- probing stellar interiors using their oscillations

Topics

- What are stellar oscillations?
- Why do stars oscillate?
- How do we observe these oscillations?
- How do we analyse the data?
- What are we learning?

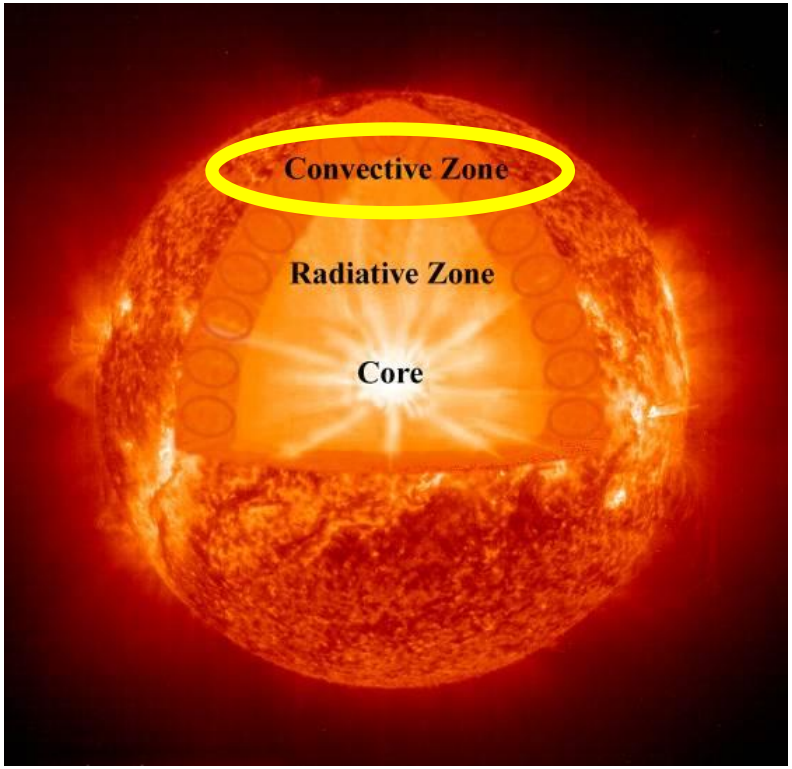


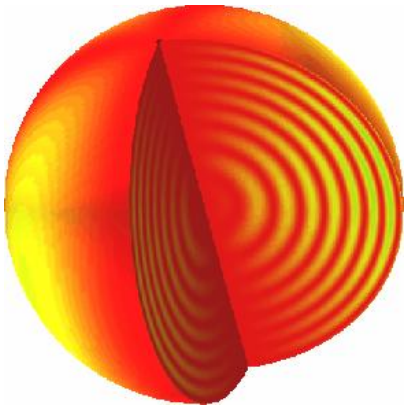
Hertzsprung-Russell diagram

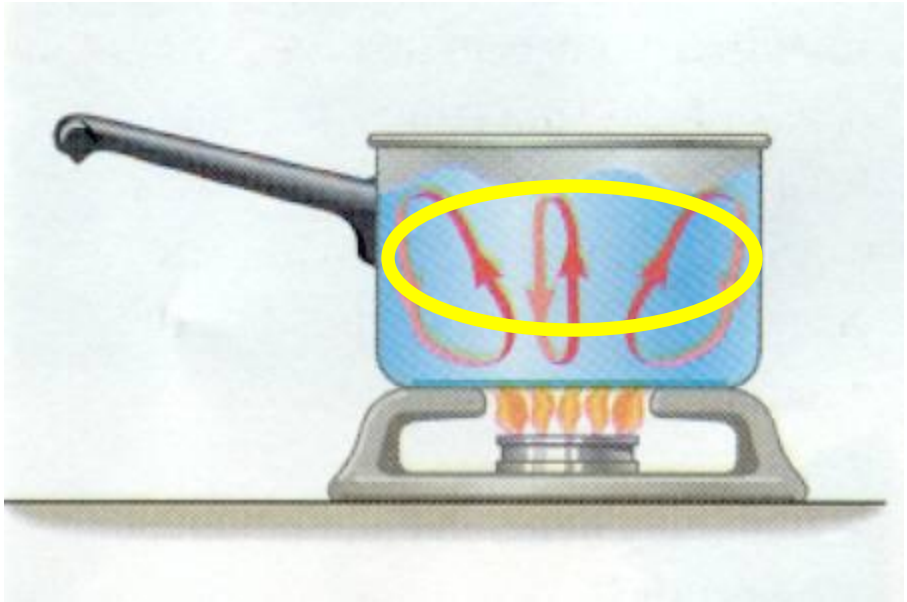
- Many classes of pulsating stars
- we only discuss solar-like oscillations
- “pulsation” vs. “oscillation”? (no difference)

Oscillations in the Sun:

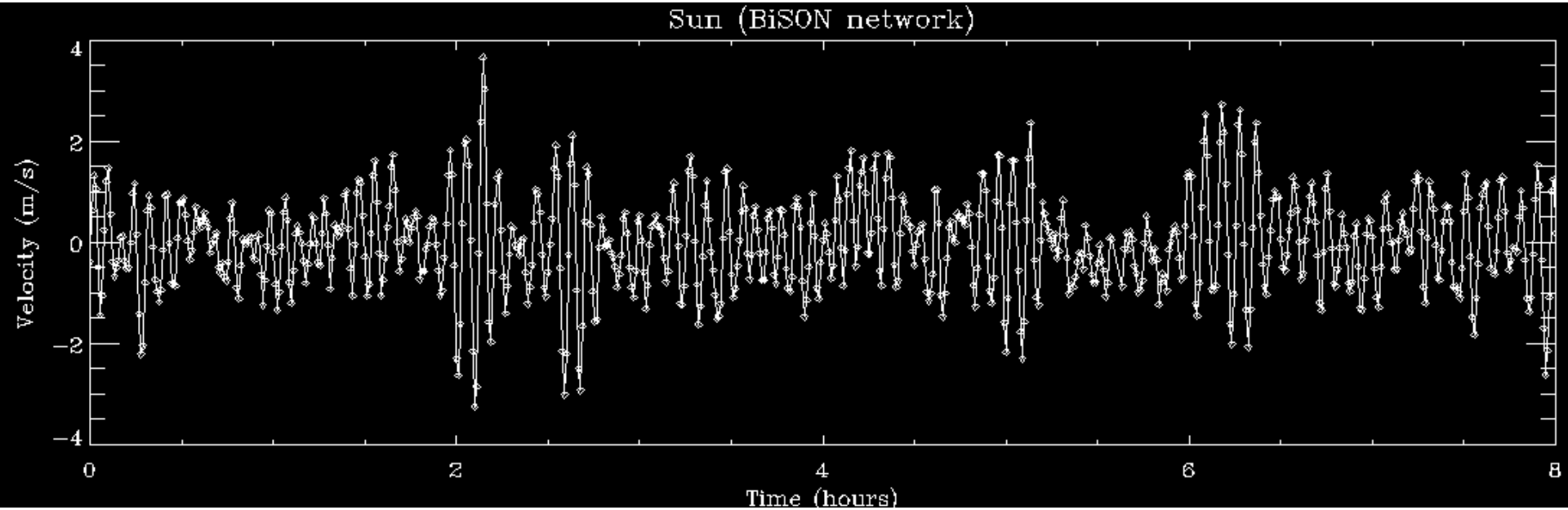
Convection excites the oscillations by shaking the star, creating standing waves





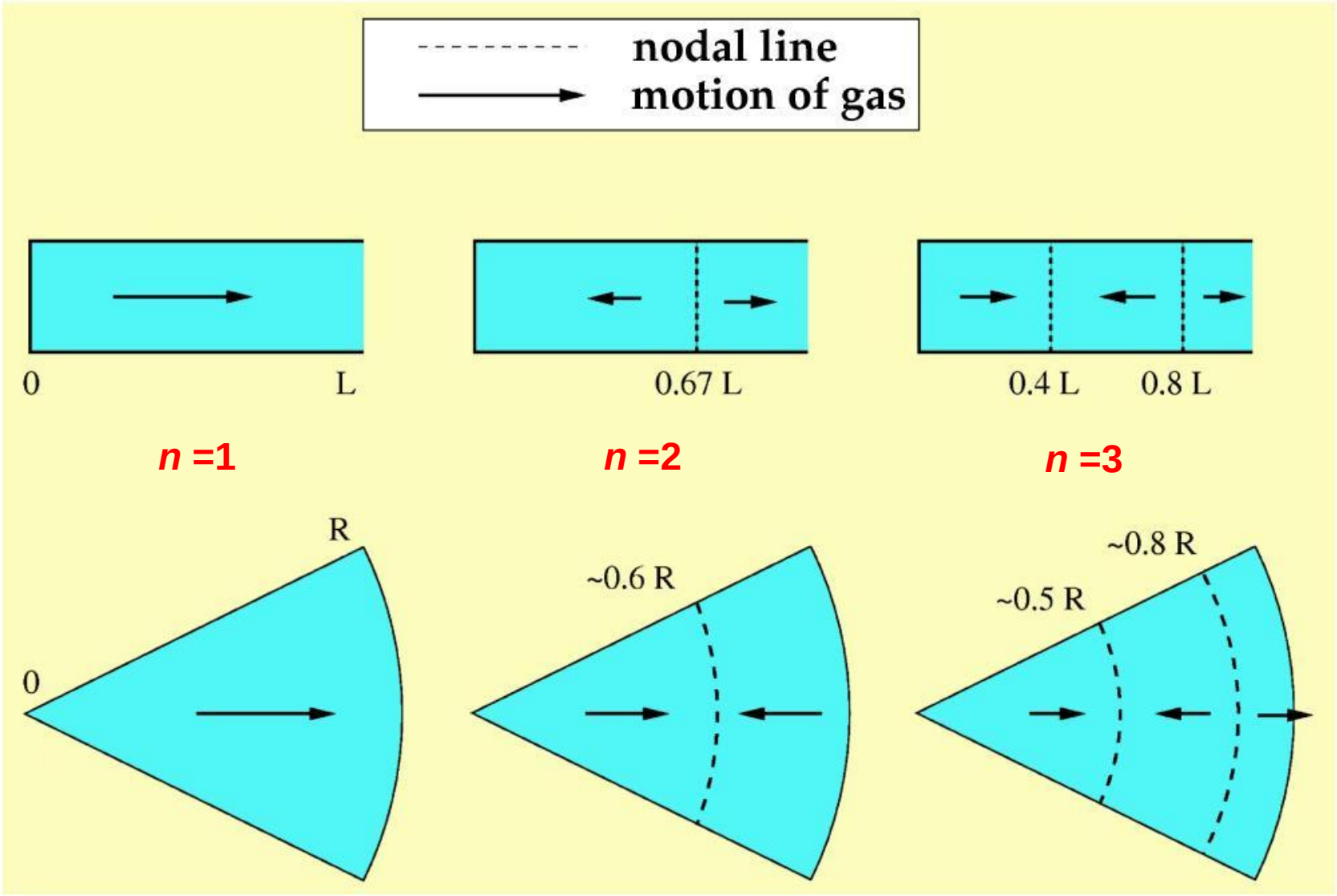


Oscillations in the Sun (Doppler shift)

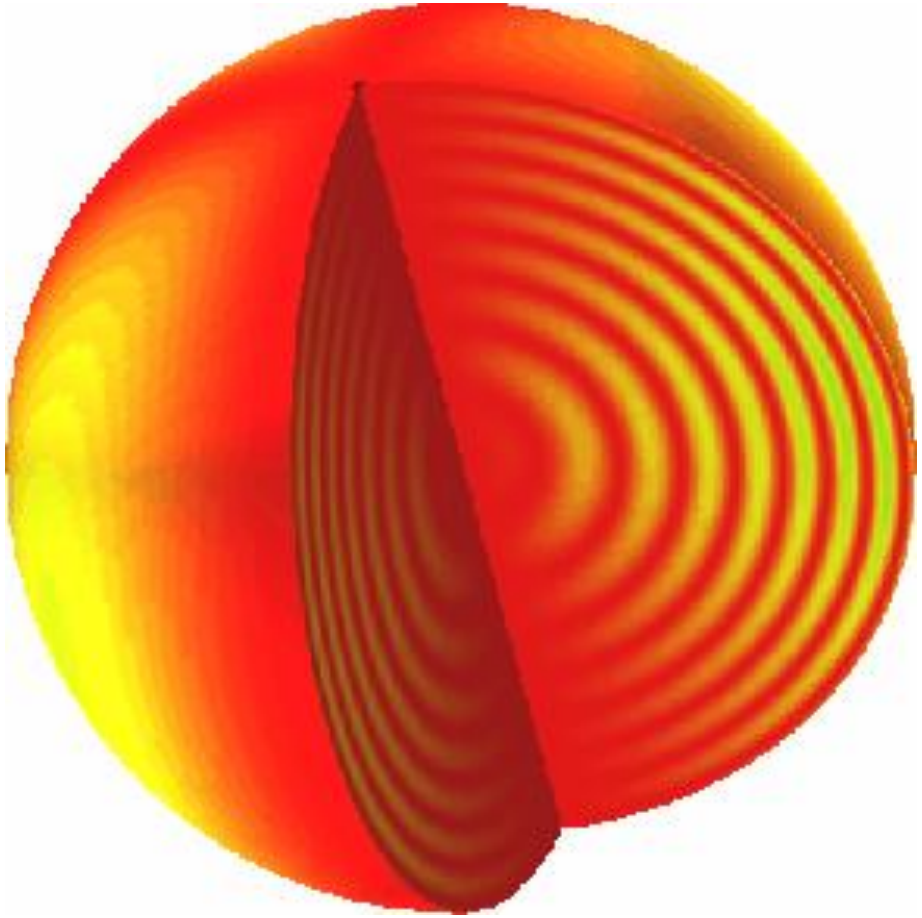


BiSON (Birmingham Solar Oscillations Network)

p-mode oscillations are standing sound waves



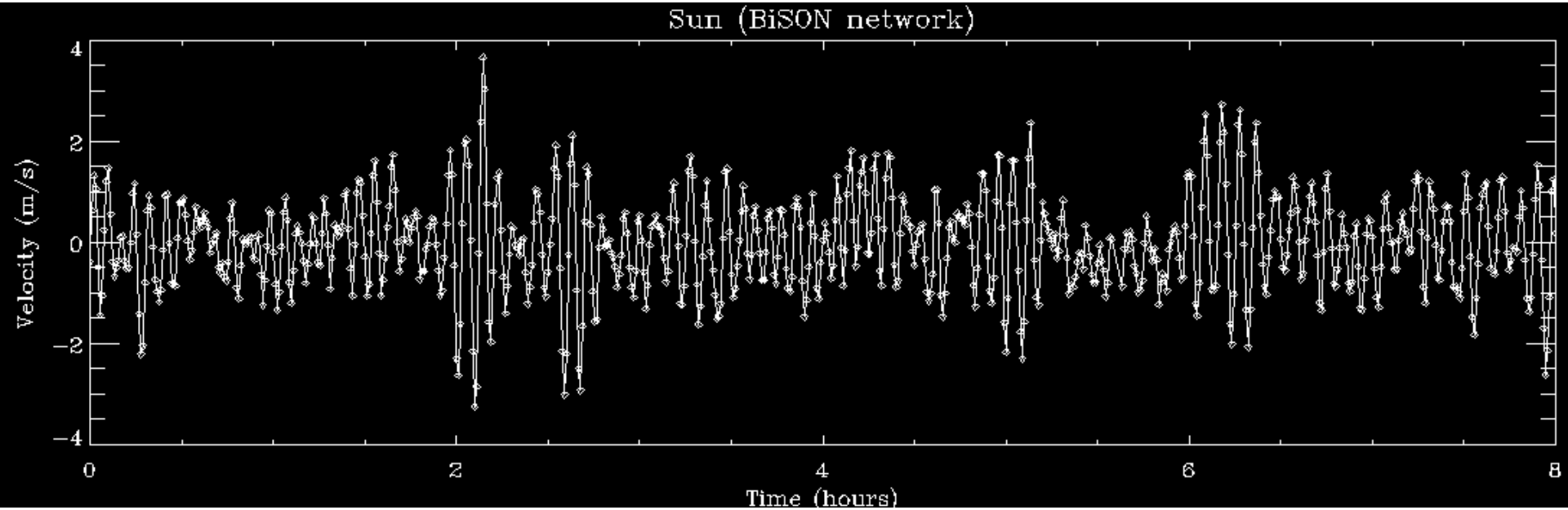
n is called the *radial order* of the overtone



n =18

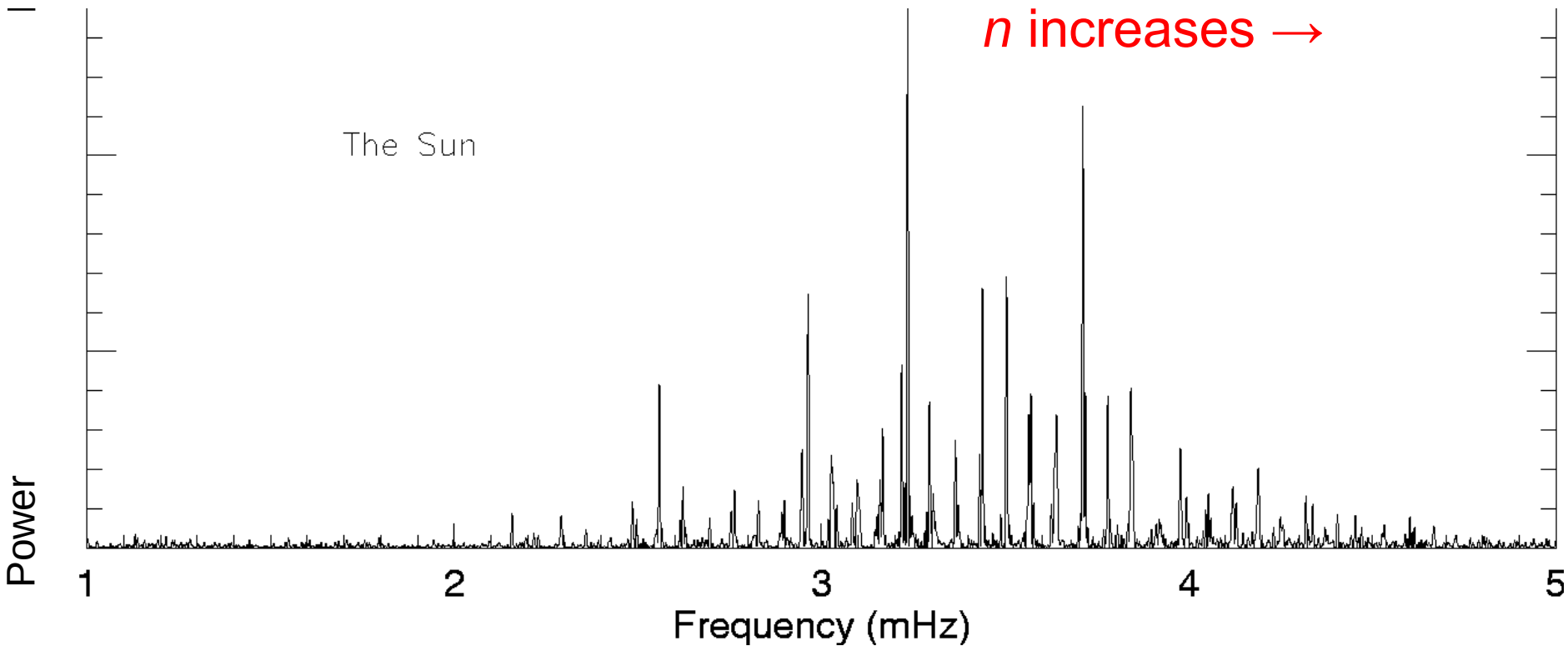
oscillation frequency of each mode depends on mode pattern (e.g., n) and on internal sound speed

Oscillations in the Sun (Doppler shift)



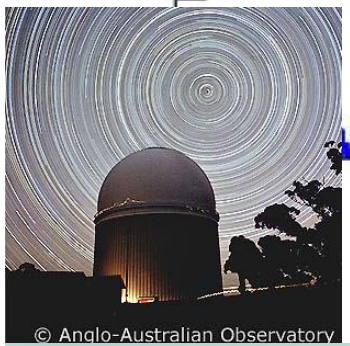
BiSON (Birmingham Solar Oscillations Network)

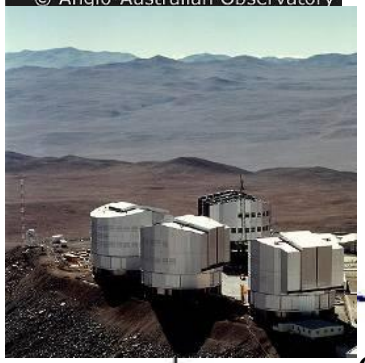
Fourier power spectrum of solar velocities:



p-mode overtones are approximately regularly spaced in frequency

$\Delta\nu$





α Centauri A
(Bedding et al. 2004)

15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

The Sun

n increases →

the Sun

α Centauri B
(Kjeldsen et al. 2005)

17 18 19 20 21 22 23 24 25 26 27 28 29

(4 x Power)

1 2 3 4 5

Frequency (mHz)

A revolution in asteroseismology

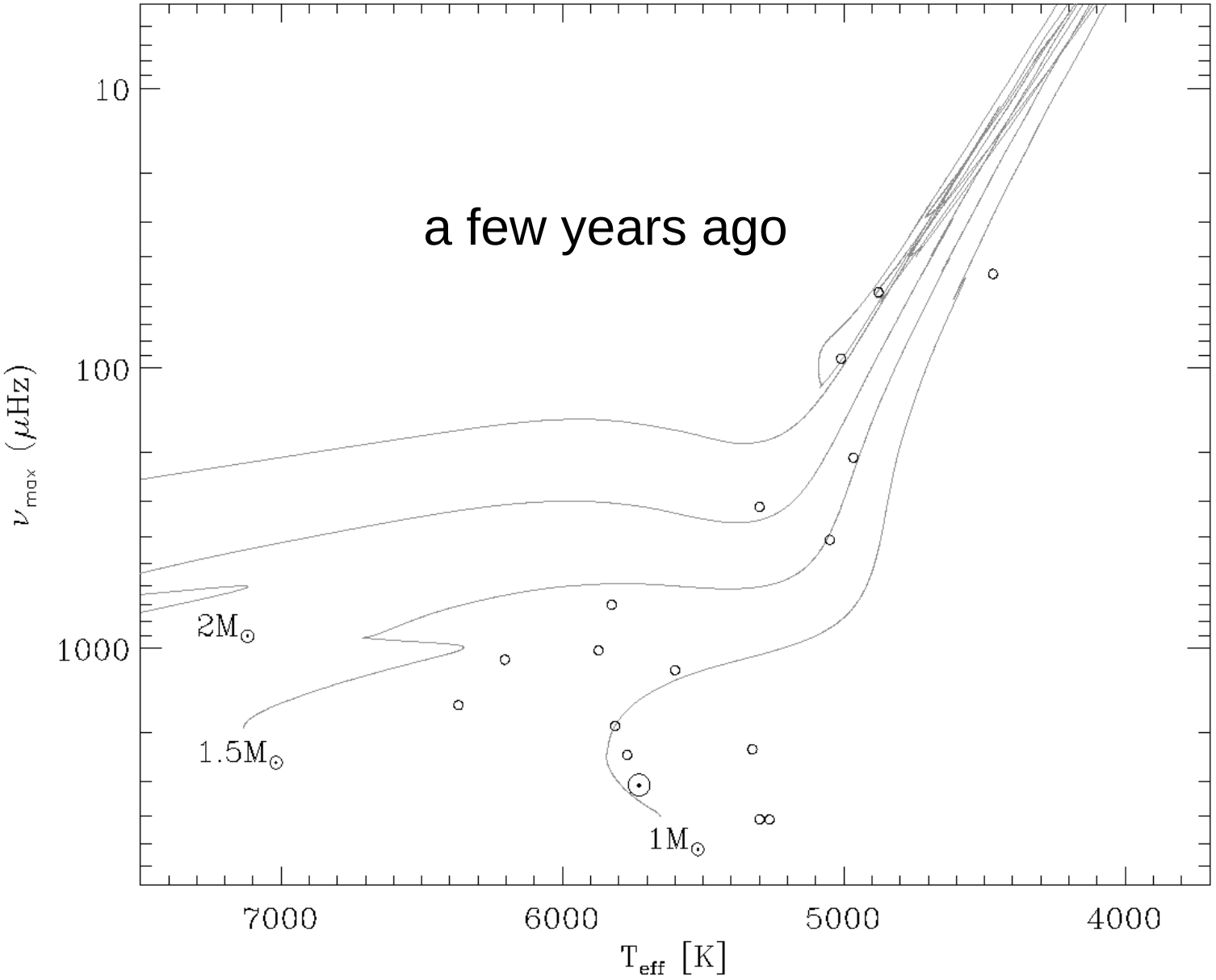


figure by Daniel Huber

CoRoT (27 cm telescope)

Launched: 27 December 2006

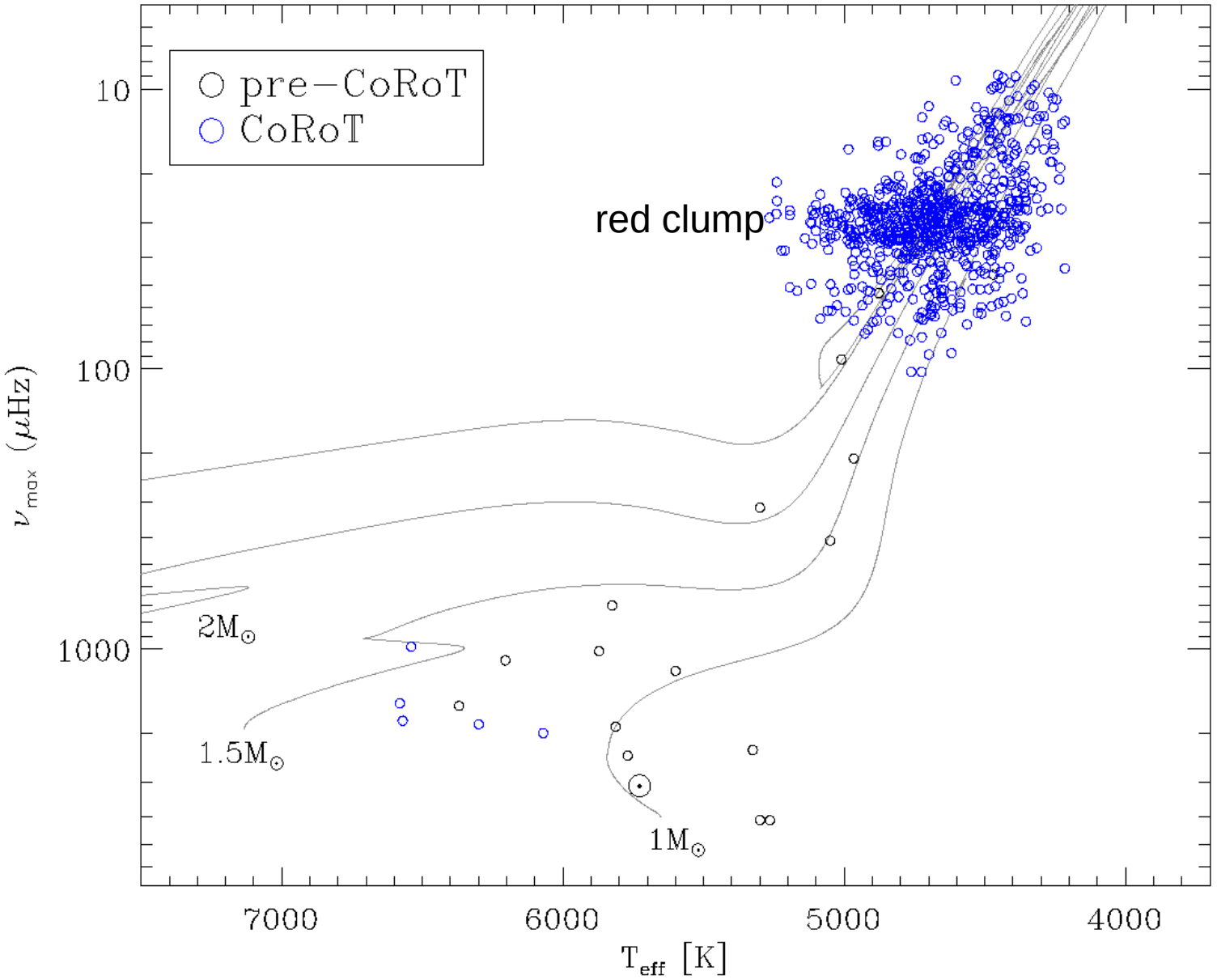
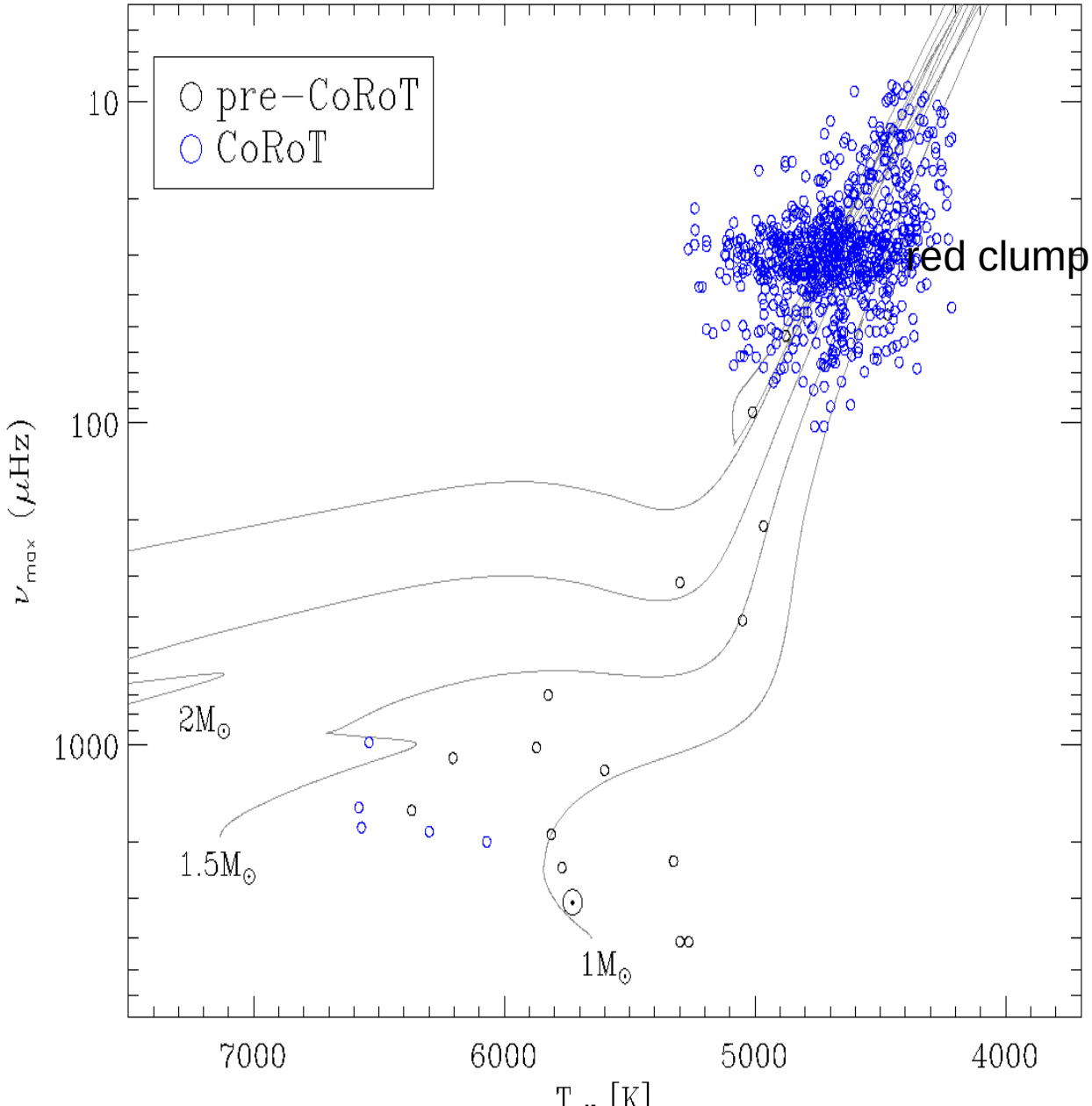


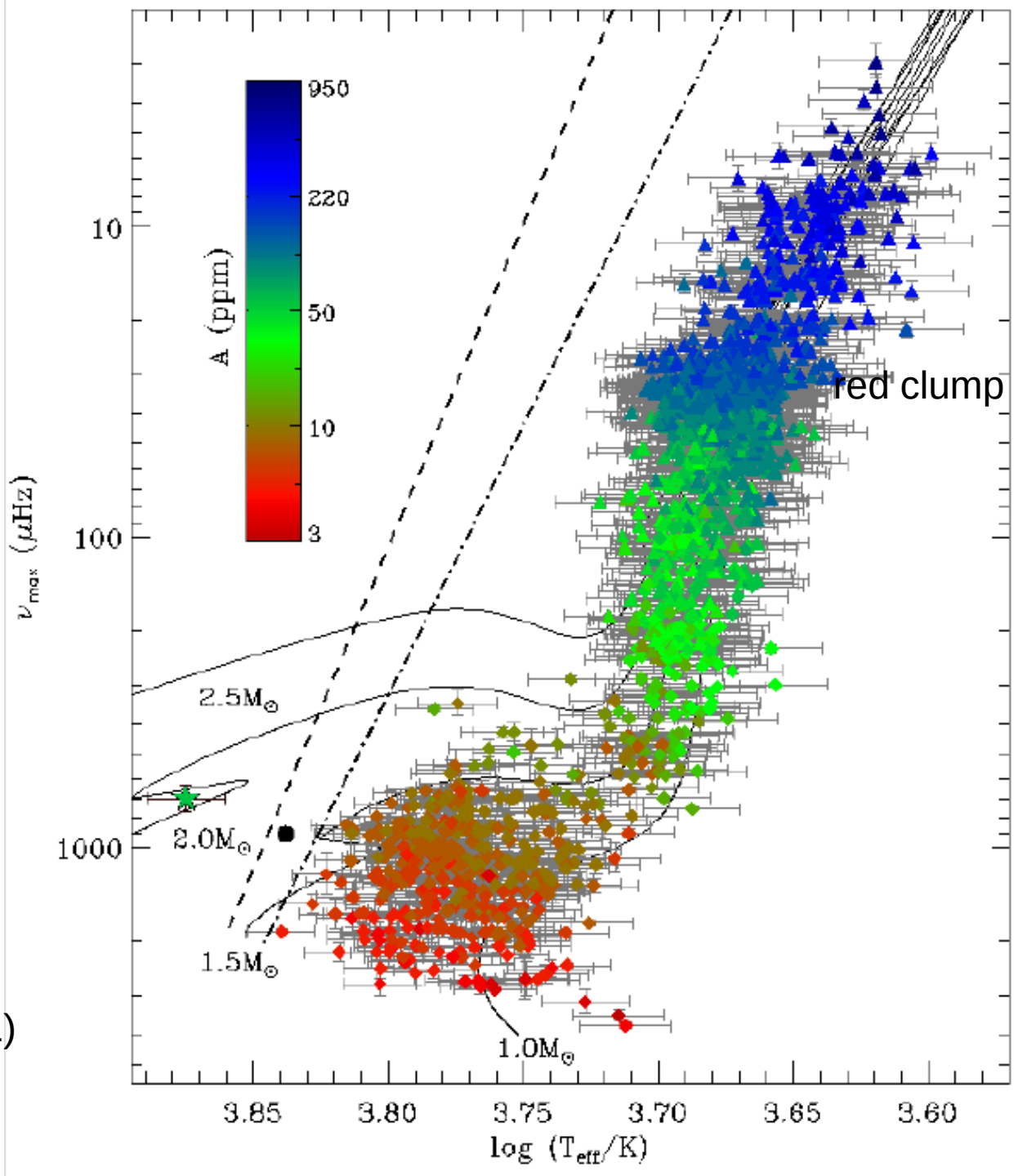
figure by Daniel Huber

Kepler

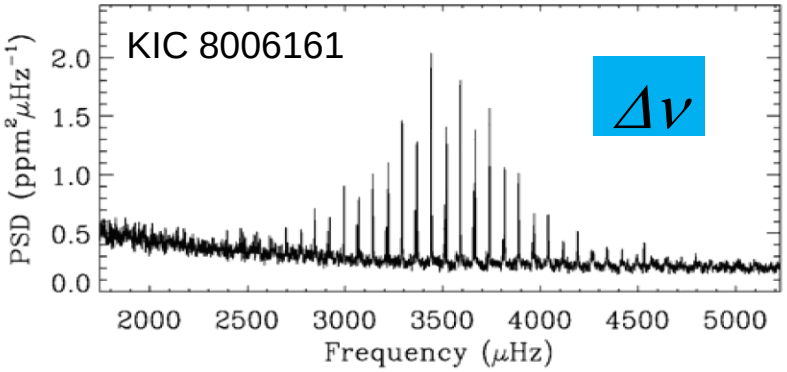
95cm Schmidt telescope;. Observations commenced: 1 May 2009

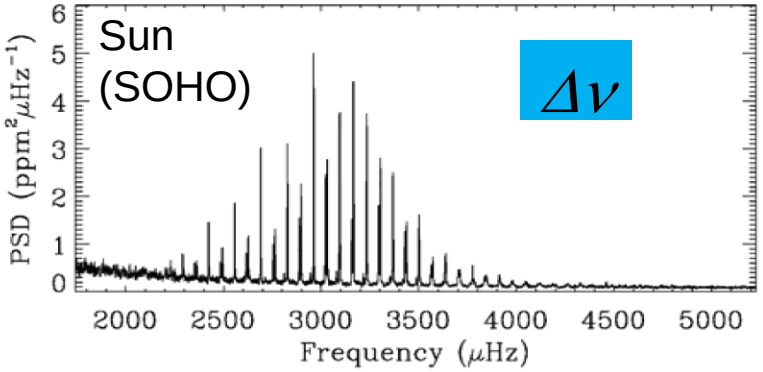

pre-CoRoT
CoRoT
red clump
10
100
1000
ν_{max} (μHz)
2M$_\odot$
1.5M$_\odot$
1M$_\odot$
7000
6000
5000
4000
T$_{eff}$ [K]

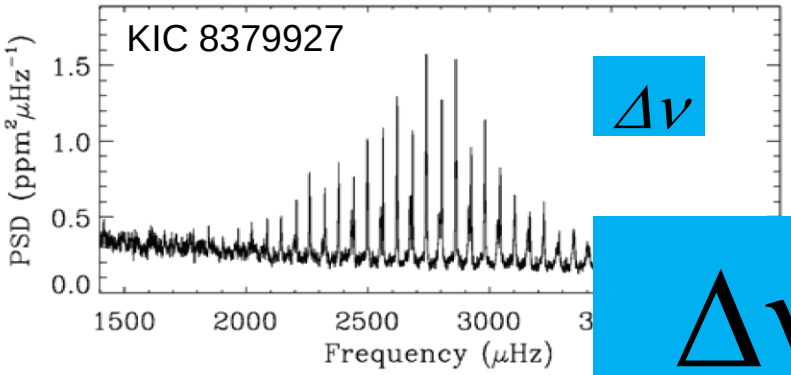
Kepler

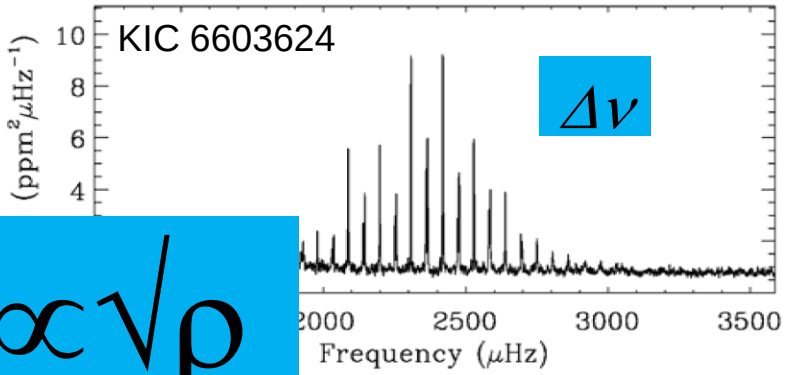


Huber et al. (2011)

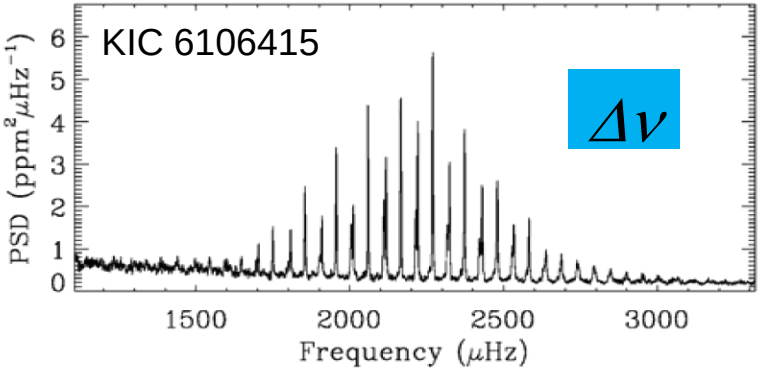


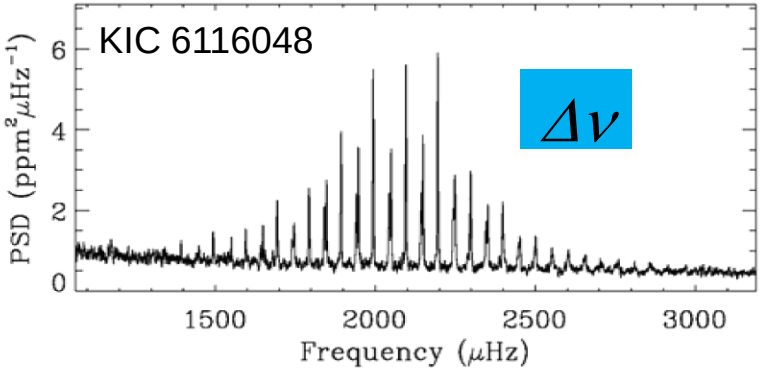


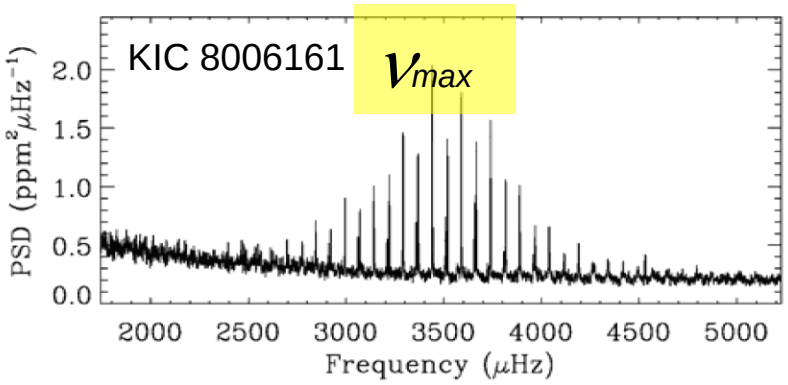


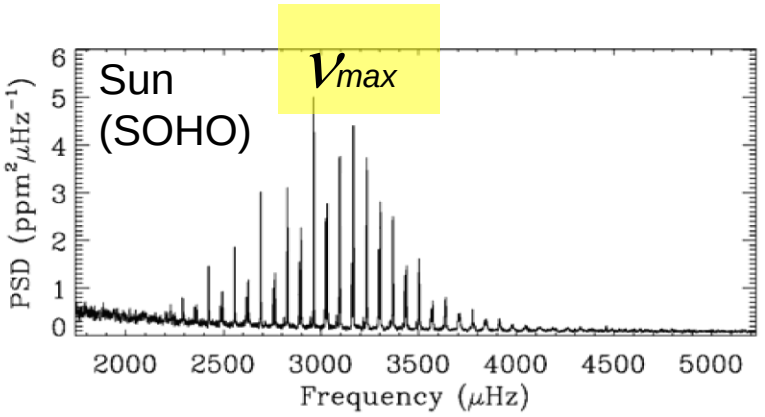


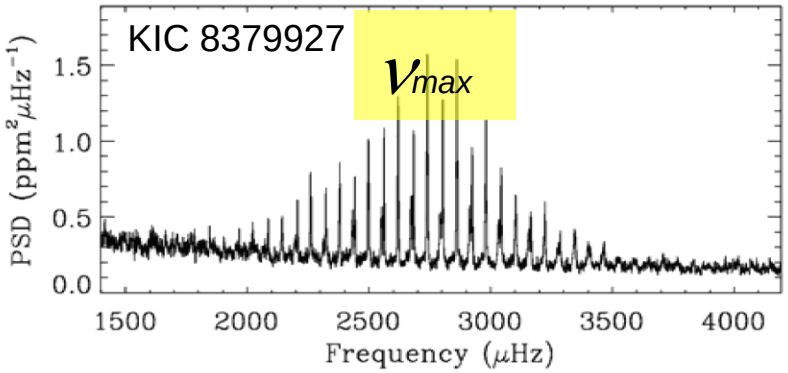
$$\Delta\nu \propto \sqrt{\rho}$$

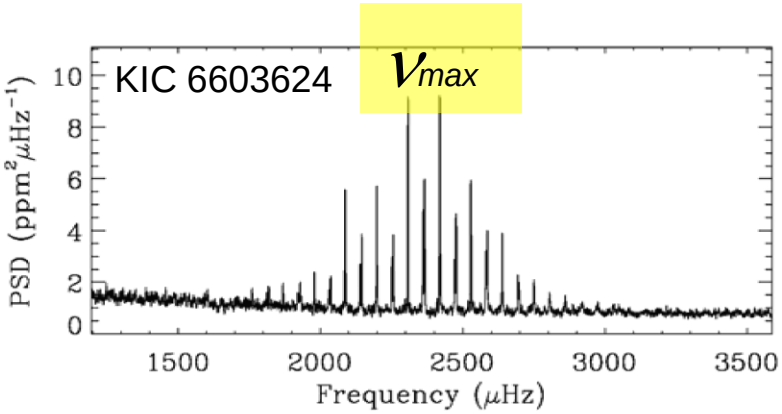


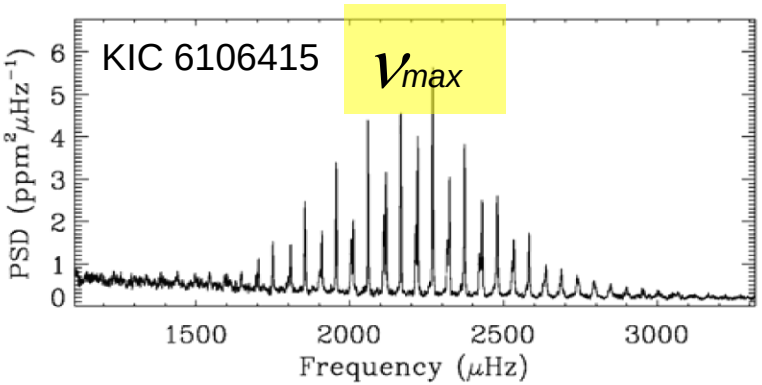


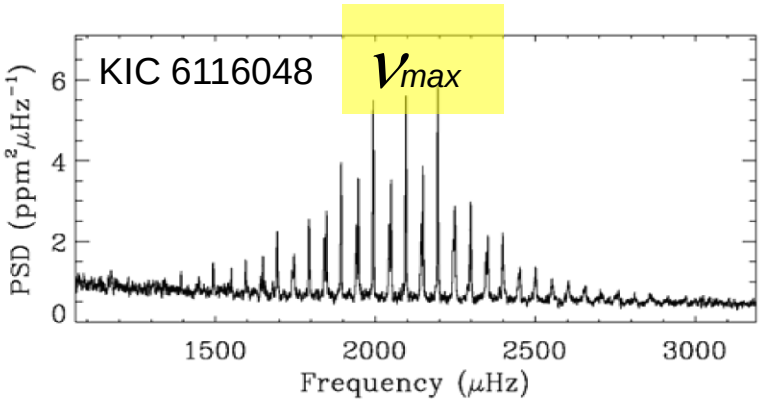

KIC 8006161
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)


Sun
(SOHO)
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)

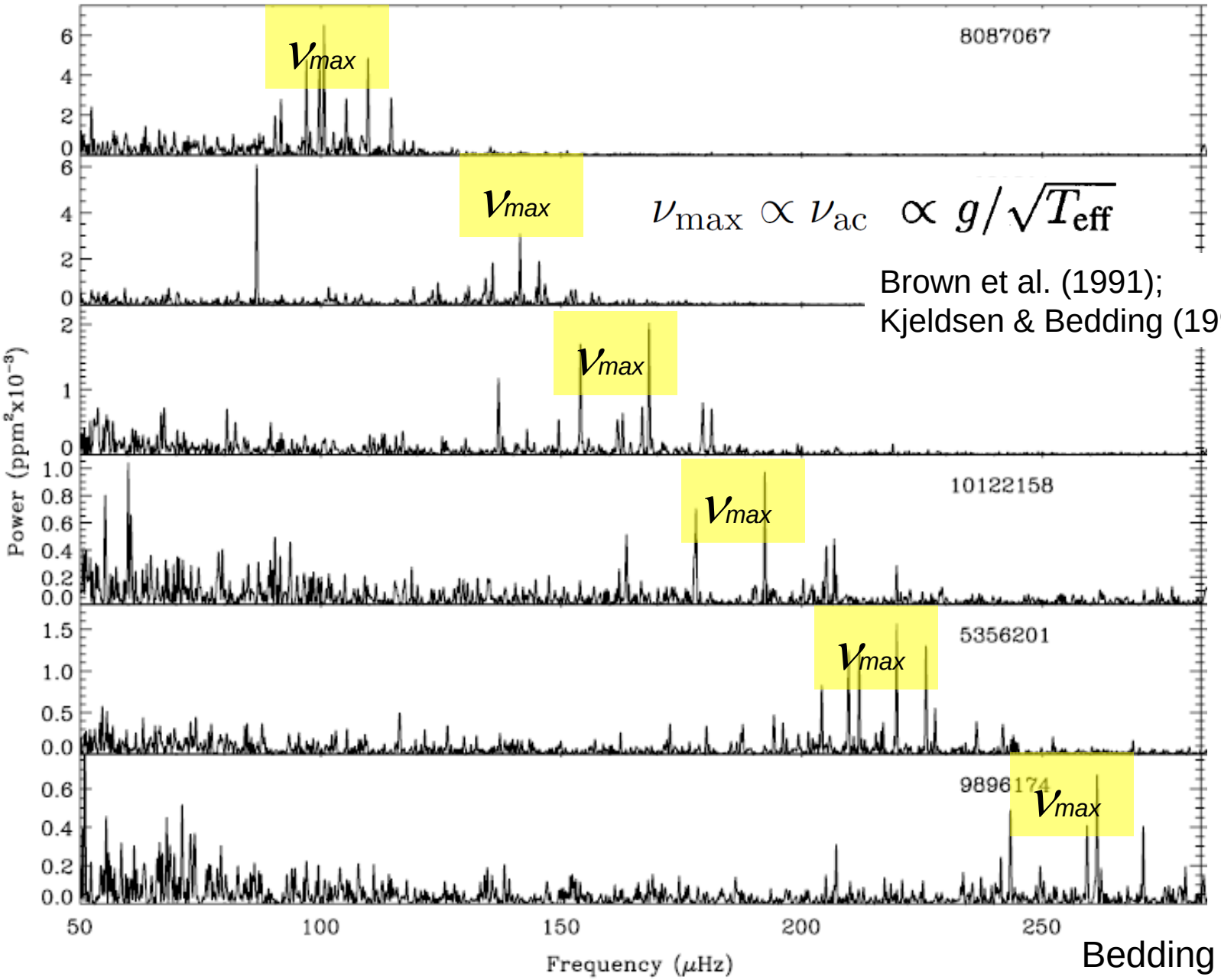

KIC 8379927
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)


KIC 6603624
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)


KIC 6106415
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)


KIC 6116048
ν_{max}
PSD (ppm^2 μHz^{-1})
Frequency (μHz)

Red giants with Kepler (first 30 days)



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

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

Bedding et al. 2010

Scaling relations:

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

Solve to get mass and radius:

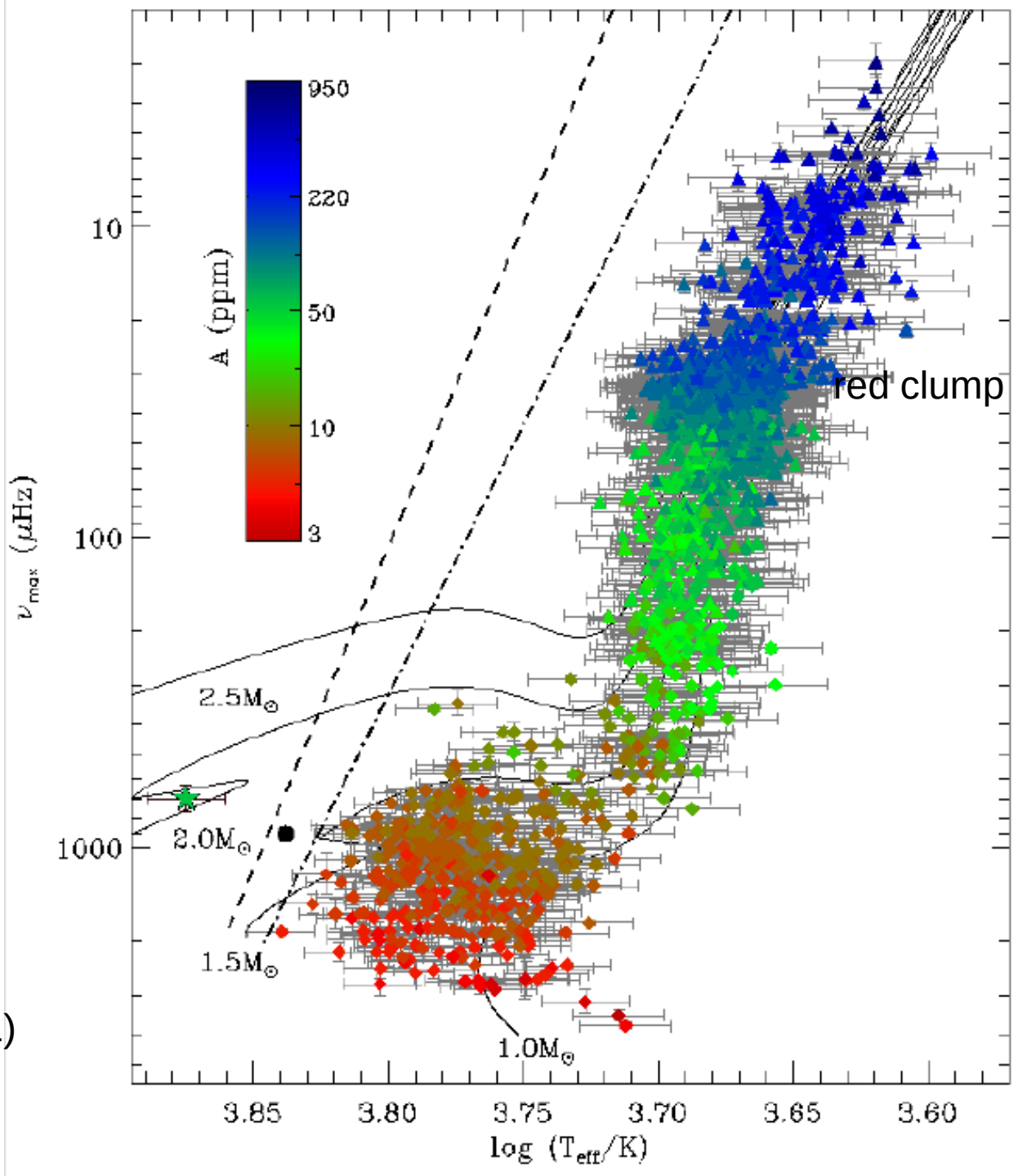
$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

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

(and luminosity)

Detailed modelling of individual frequencies gives much more, including ages

Kepler



Huber et al. (2011)

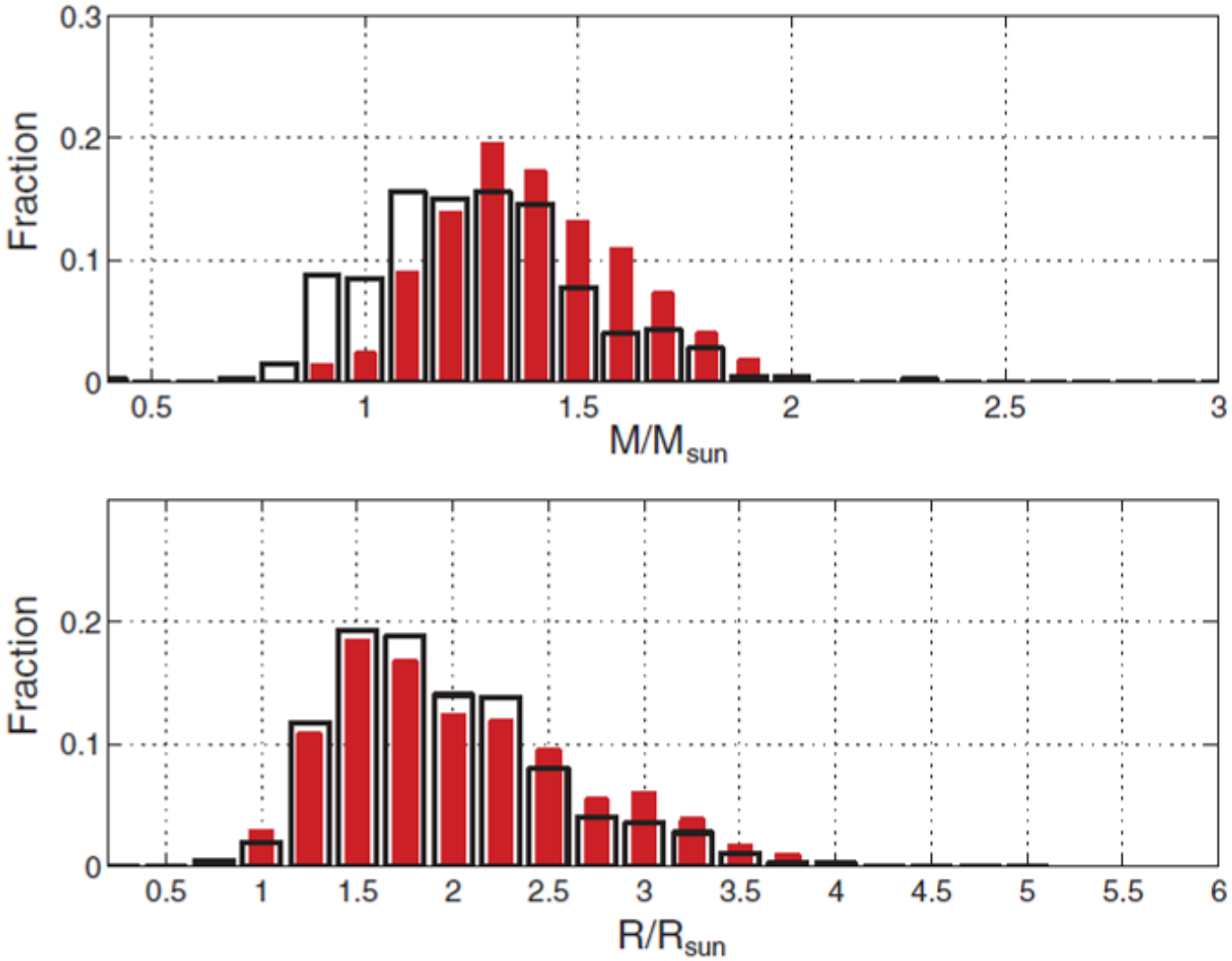
Ensemble Asteroseismology of Solar-Type Stars with the NASA Kepler Mission

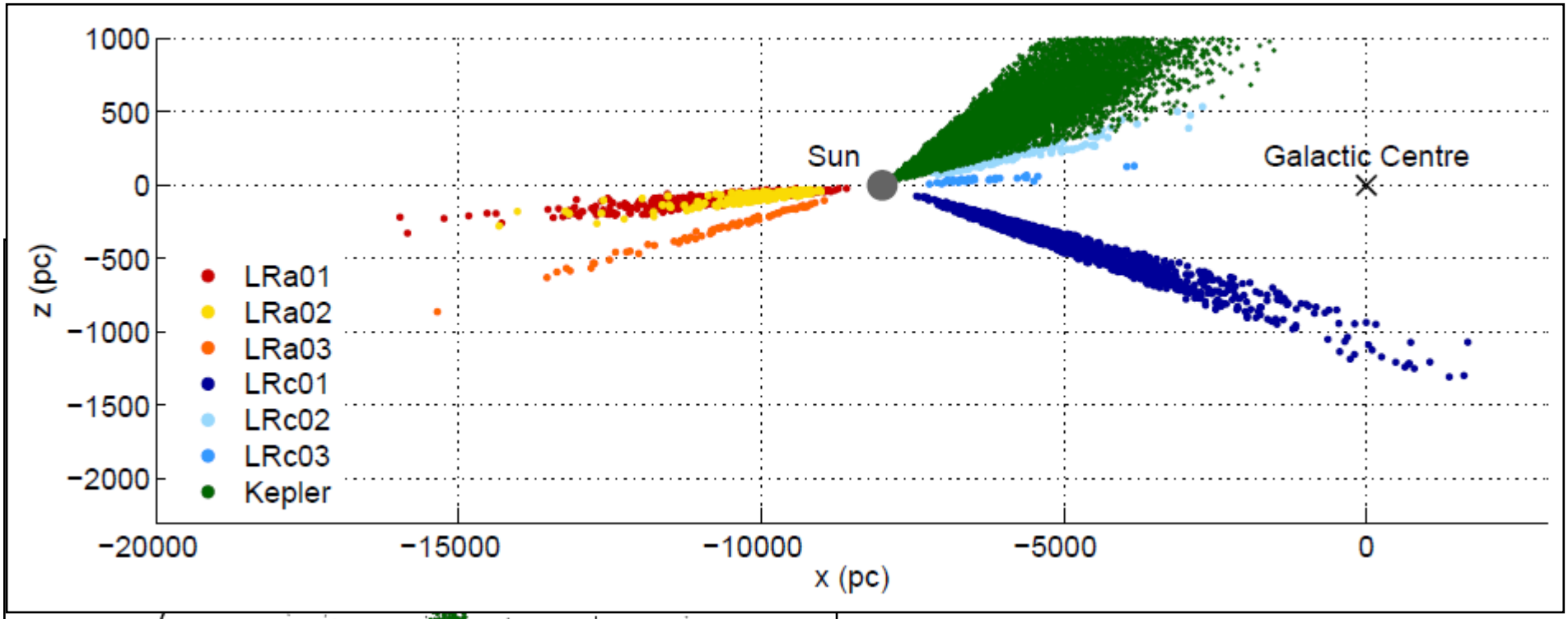
W. J. Chaplin,[1]* H. Kjeldsen,[2] J. Christensen-Dalsgaard,[2] S. Basu,[3] A. Miglio,[1,4] T. Appourchaux,[5] T. R. Bedding,[6] Y. Elsworth,[1] R. A. García,[7] R. L. Gilliland,[8] L. Girardi,[9] G. Houdek,[10] C. Karoff,[2] S. D. Kawaler,[11] T. S. Metcalfe,[12] J. Molenda-Żakowicz,[13] M. J. P. F. G. Monteiro,[14]

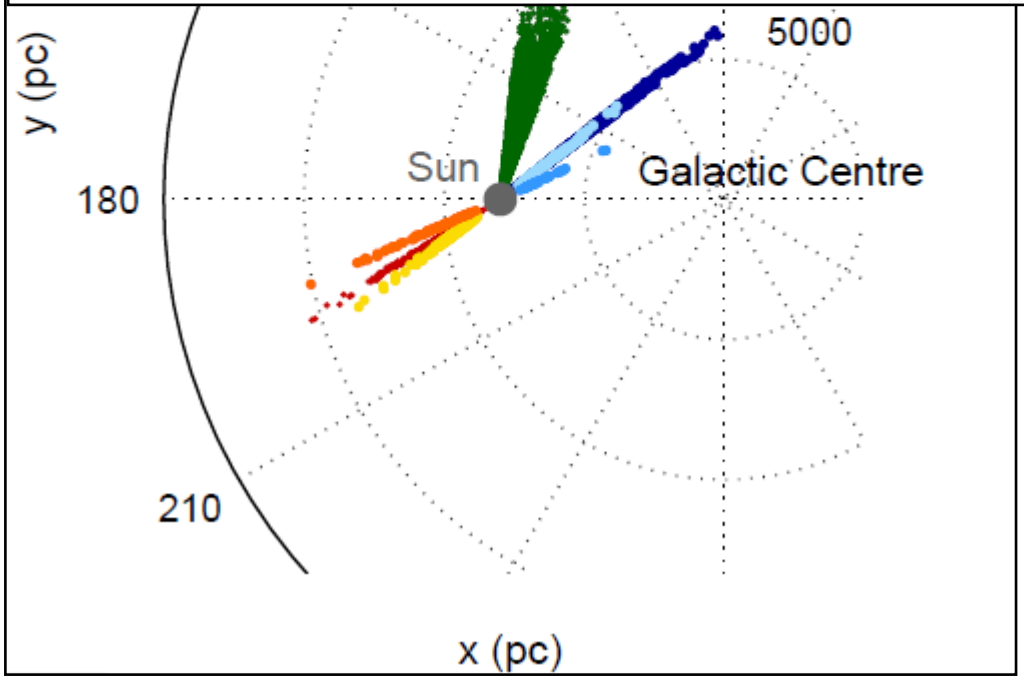
Chaplin et al. (2011, *Science*)

- survey of 2000 stars for 1 month each
- detections in 500 stars

Fig. 3. Black lines show histograms of the observed distribution of masses (**top**) and radii (**bottom**) of the Kepler ensemble (*27*). In red, the predicted distributions from population synthesis modeling, after correction for the effects of detection bias (*27*). The population modeling was performed by using the TRILEGAL code (*34*, *35*).



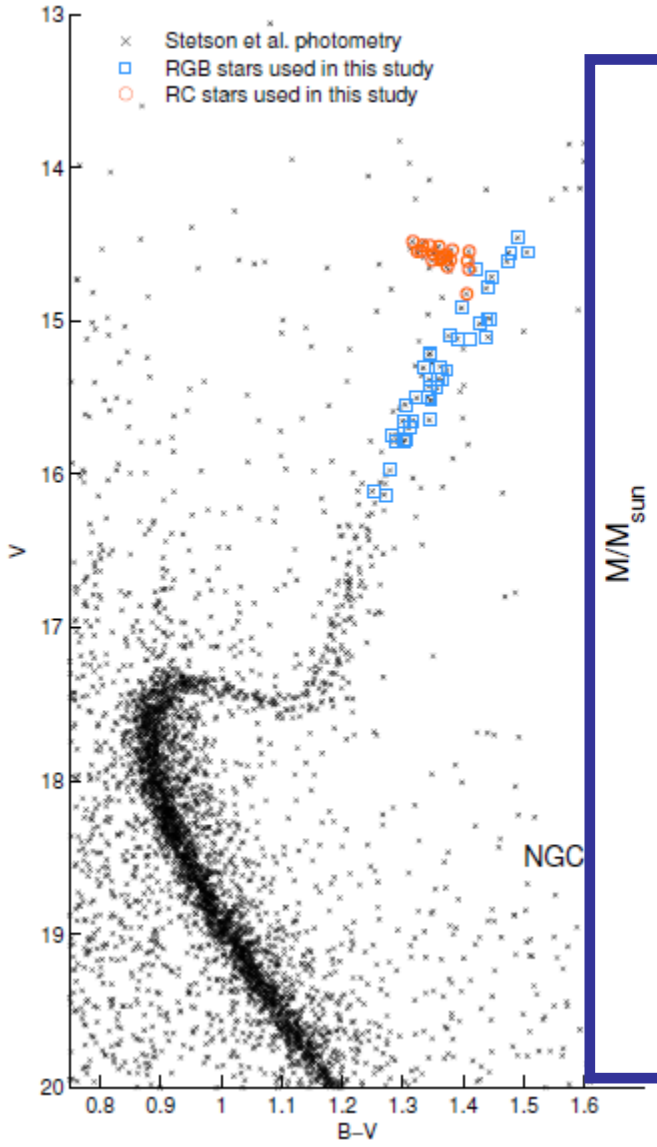




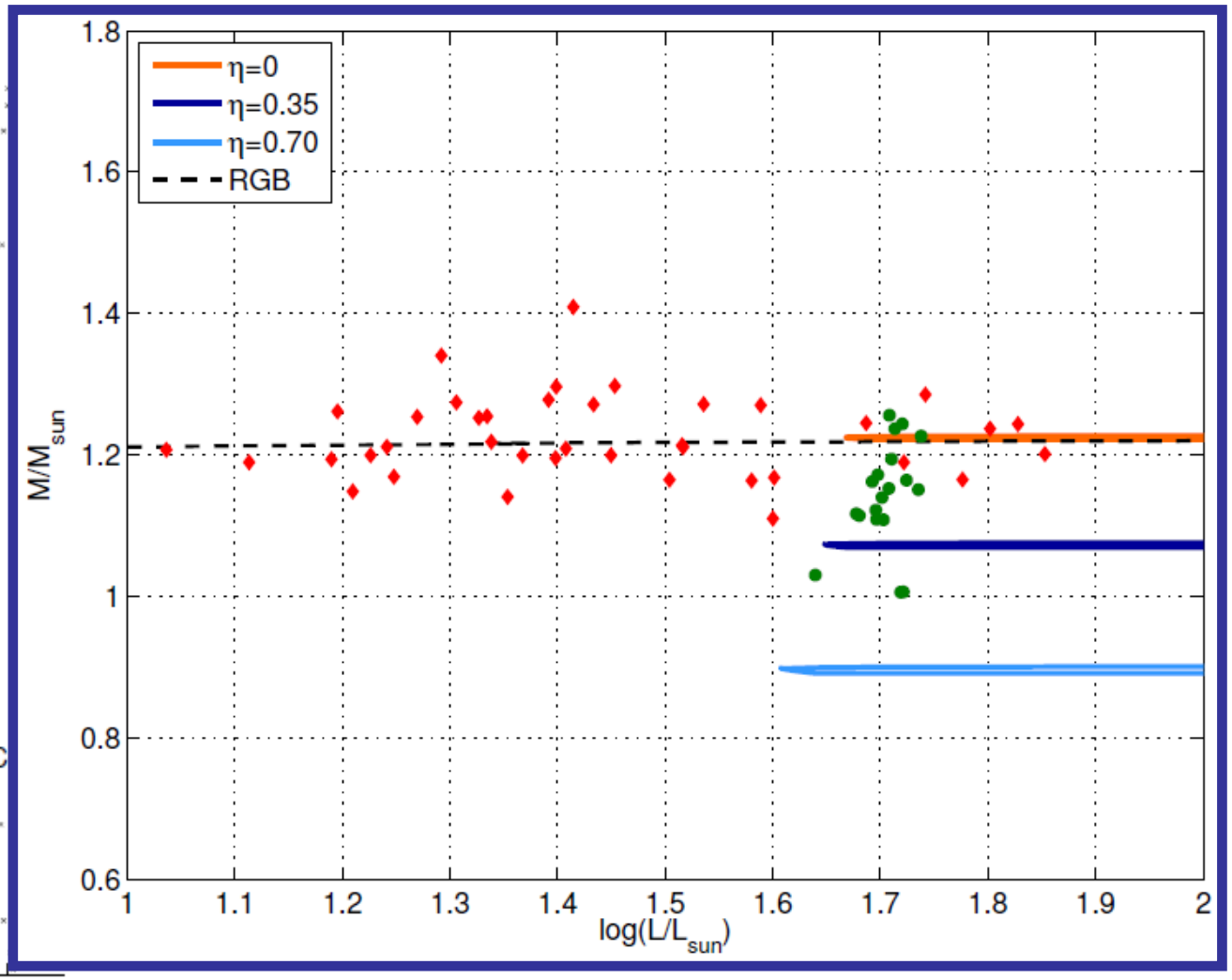
Population studies

(Miglio et al. 2011)

Open clusters mass loss



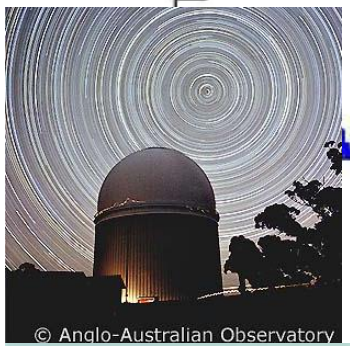
Stello et al. (2011)

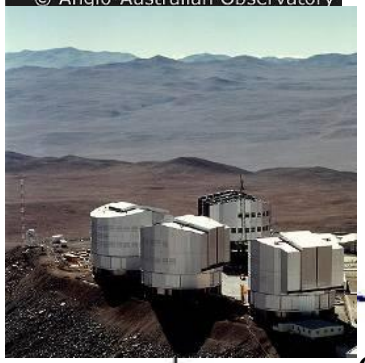


Miglio et al. (2011)

What else can we do?

A closer look at the frequency spectra...





α Centauri A
(Bedding et al. 2004)

15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31

The Sun

n increases →

the Sun

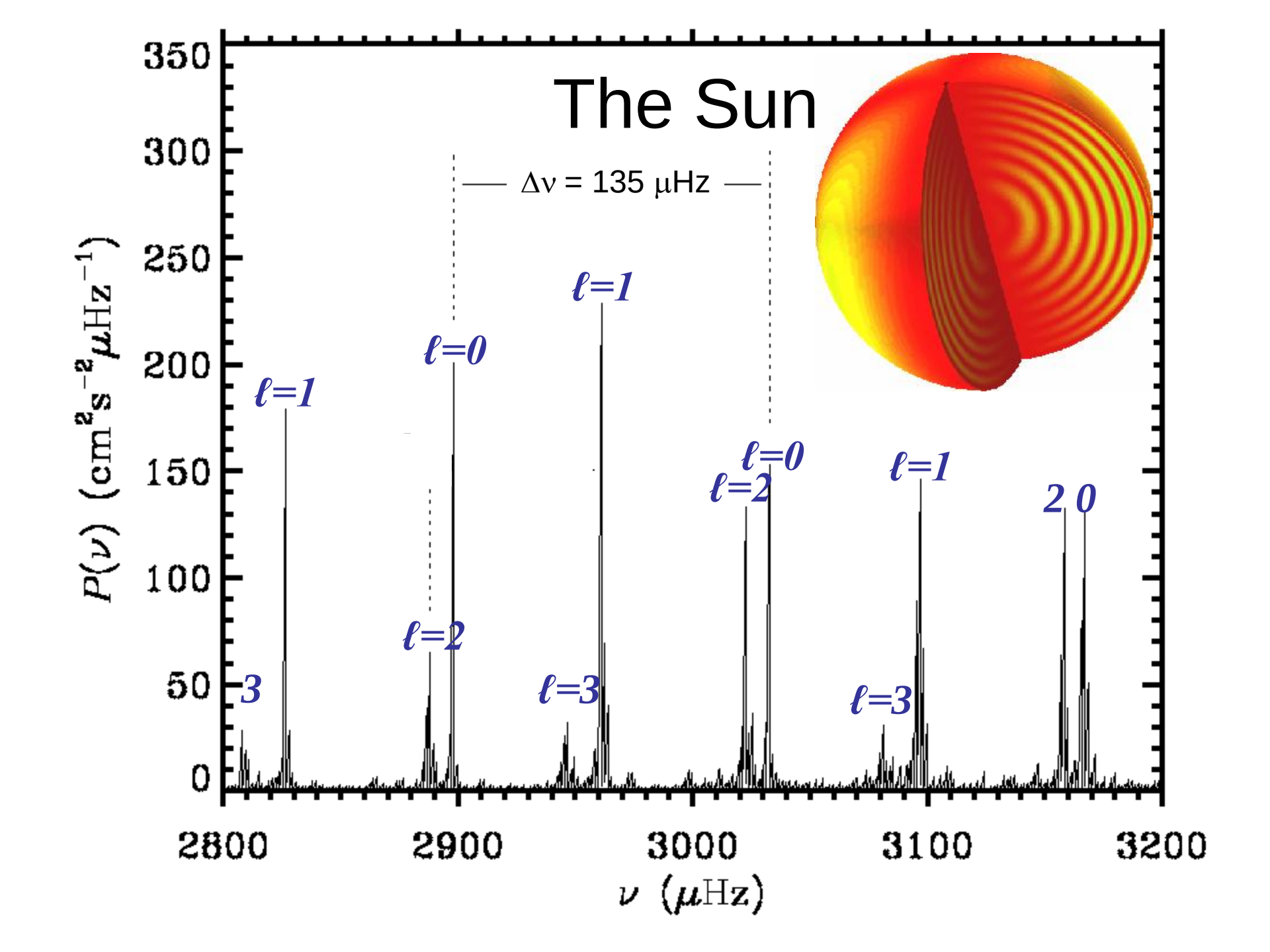
α Centauri B
(Kjeldsen et al. 2005)

17 18 19 20 21 22 23 24 25 26 27 28 29

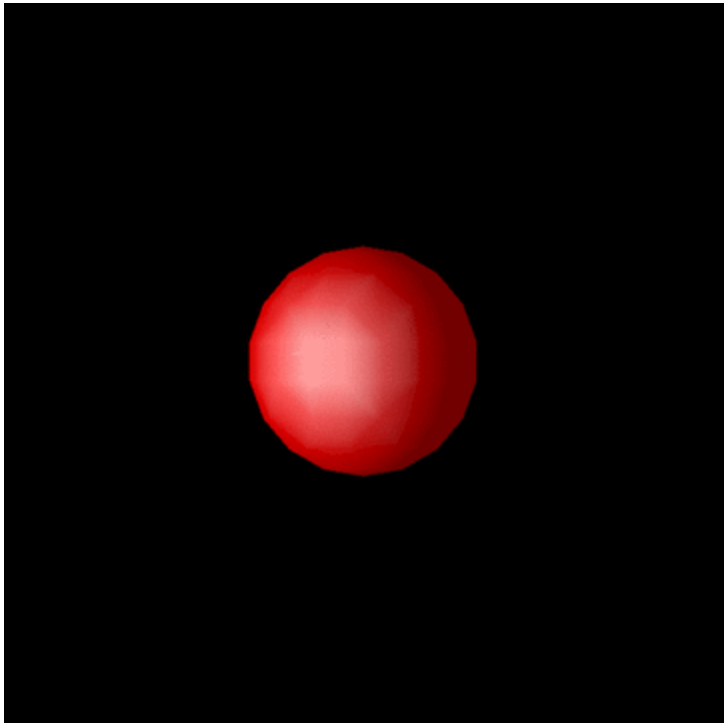
(4 x Power)

1 2 3 4 5

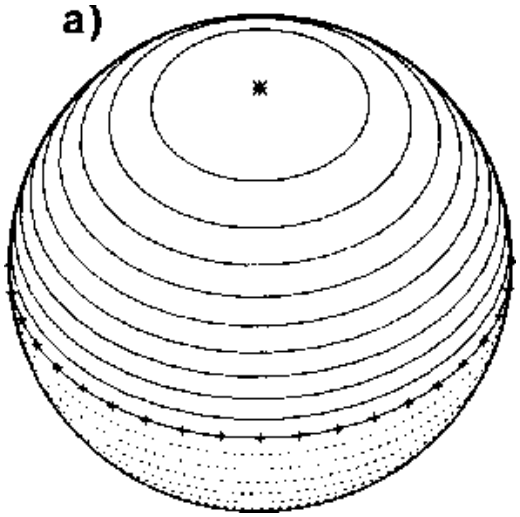
Frequency (mHz)


The Sun
Δν = 135 μHz
ℓ=1
ℓ=0
ℓ=1
ℓ=0
ℓ=2
ℓ=1
2 0
ℓ=2
3
ℓ=3
ℓ=3
350
300
250
200
150
100
50
0
2800
2900
3000
3100
3200
$P(\nu)$ $(\mathrm{cm^2 s^{-2} \mu Hz^{-1}})$
ν $(\mu\mathrm{Hz})$

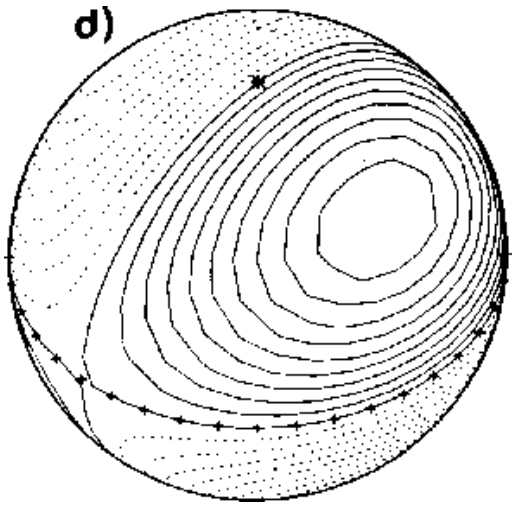
ℓ =0 (radial modes)



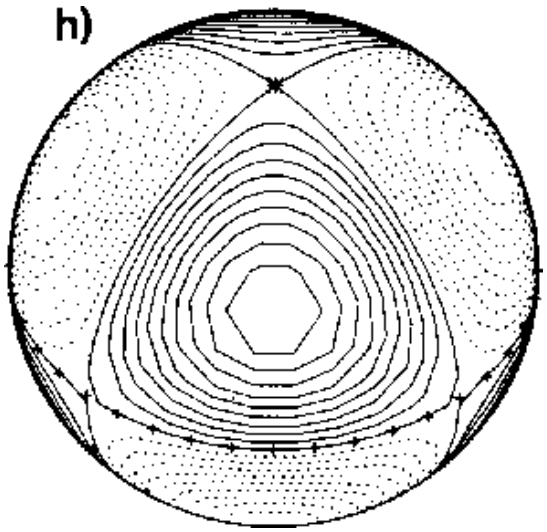
ℓ =1,2,3,... (non-radial modes)



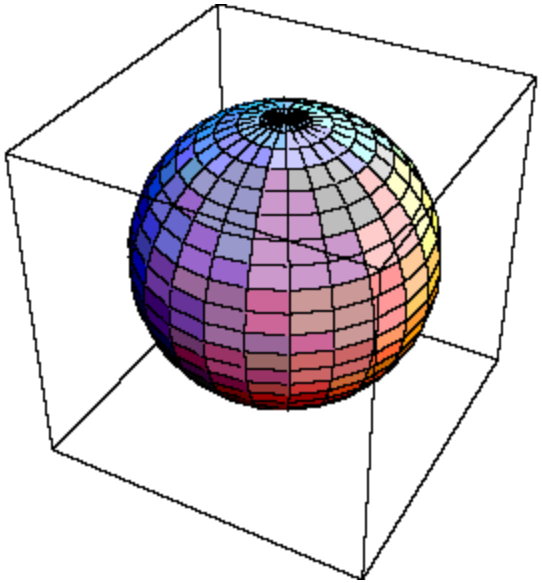
ℓ=1

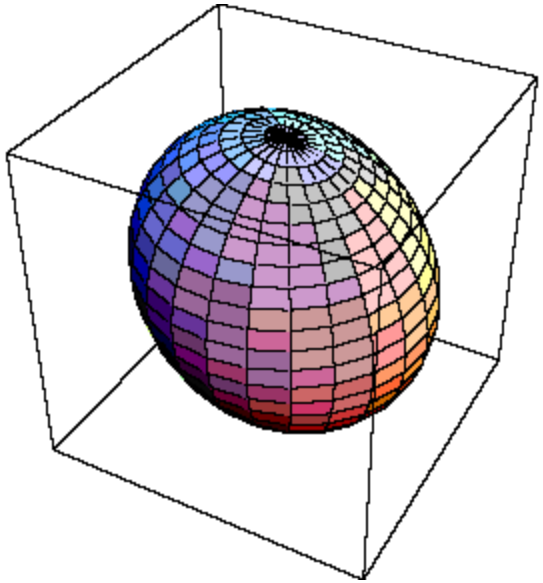


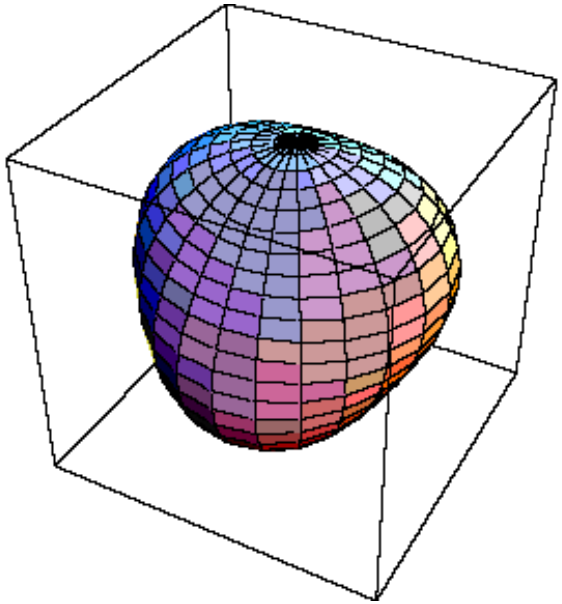
ℓ= 2



ℓ= 3

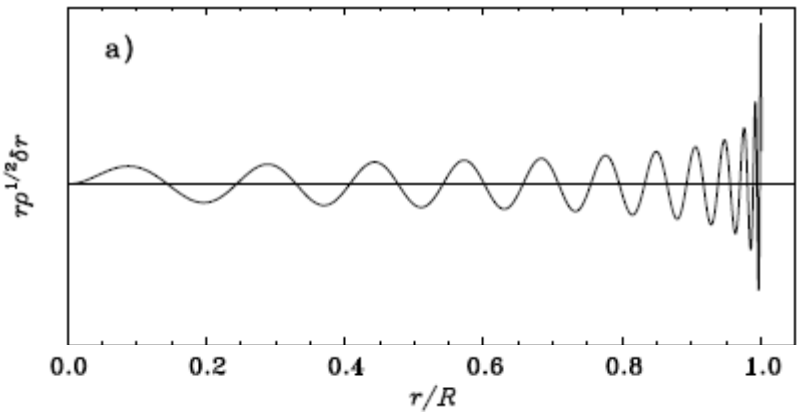


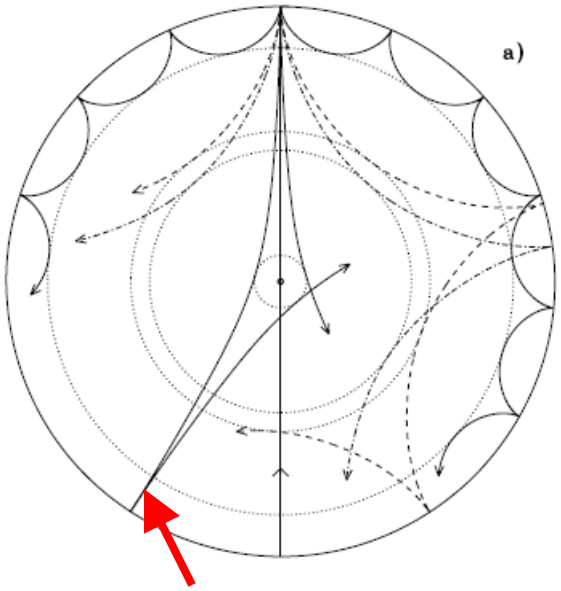




p modes

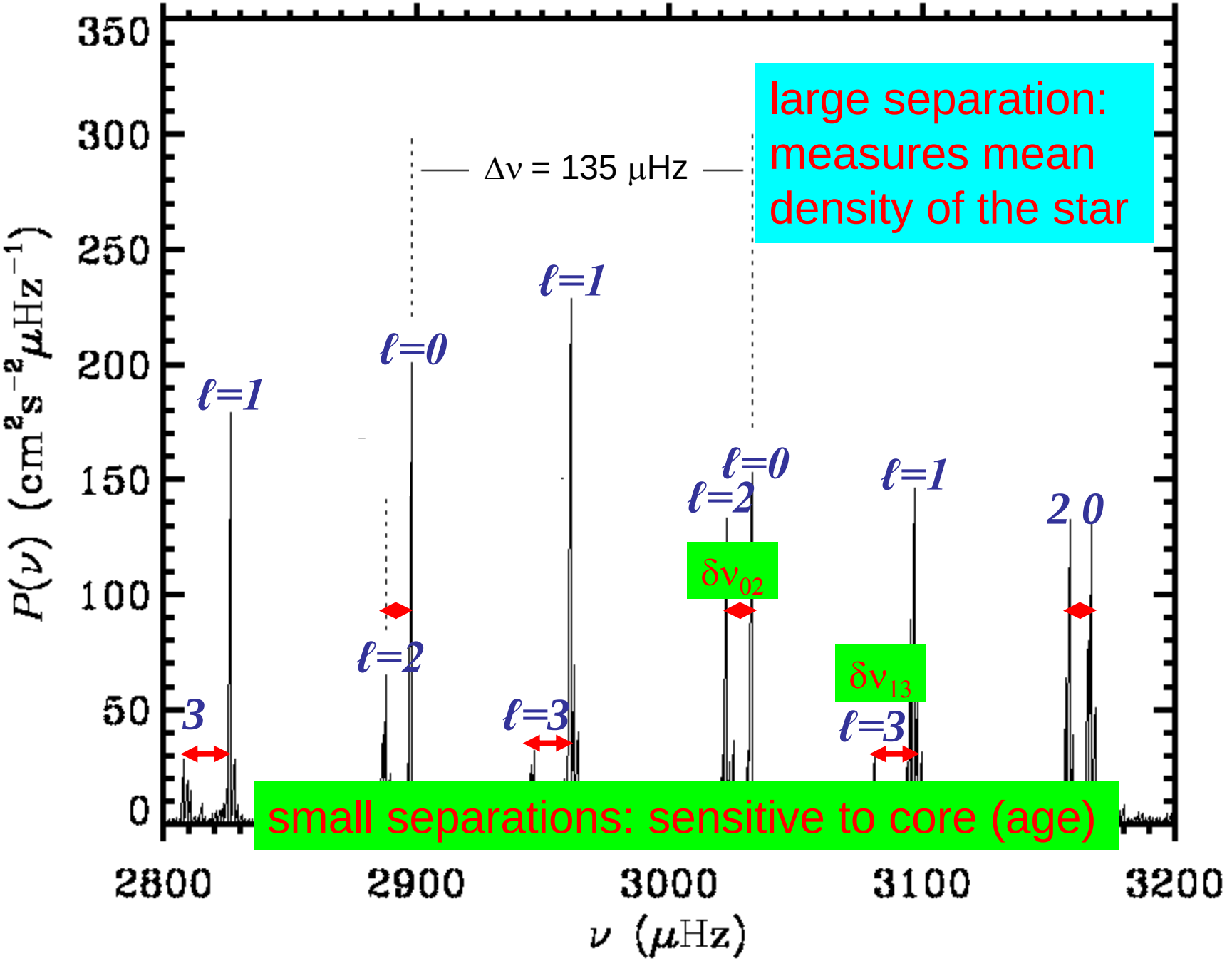
p mode with l = 0



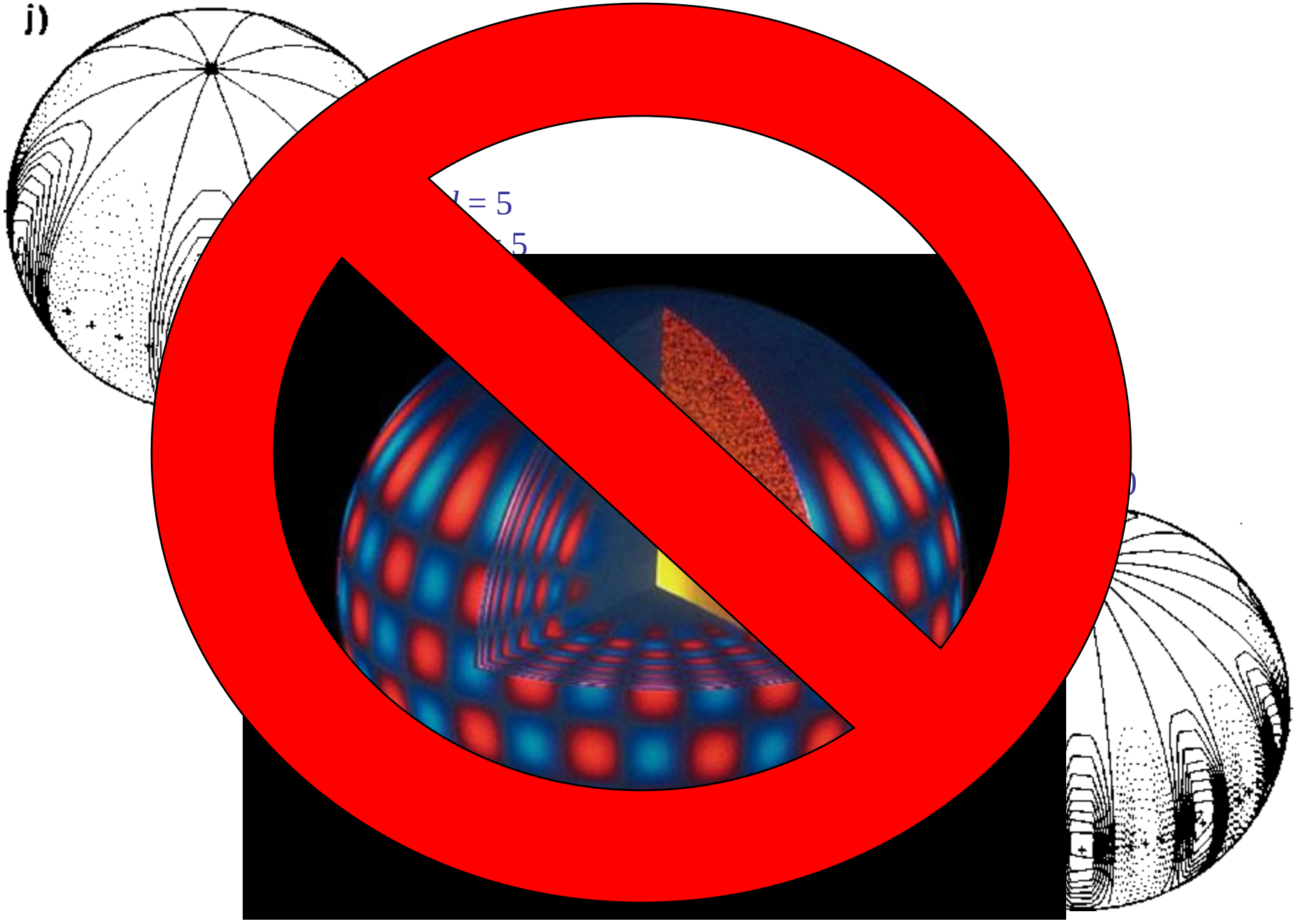


p mode with l = 2

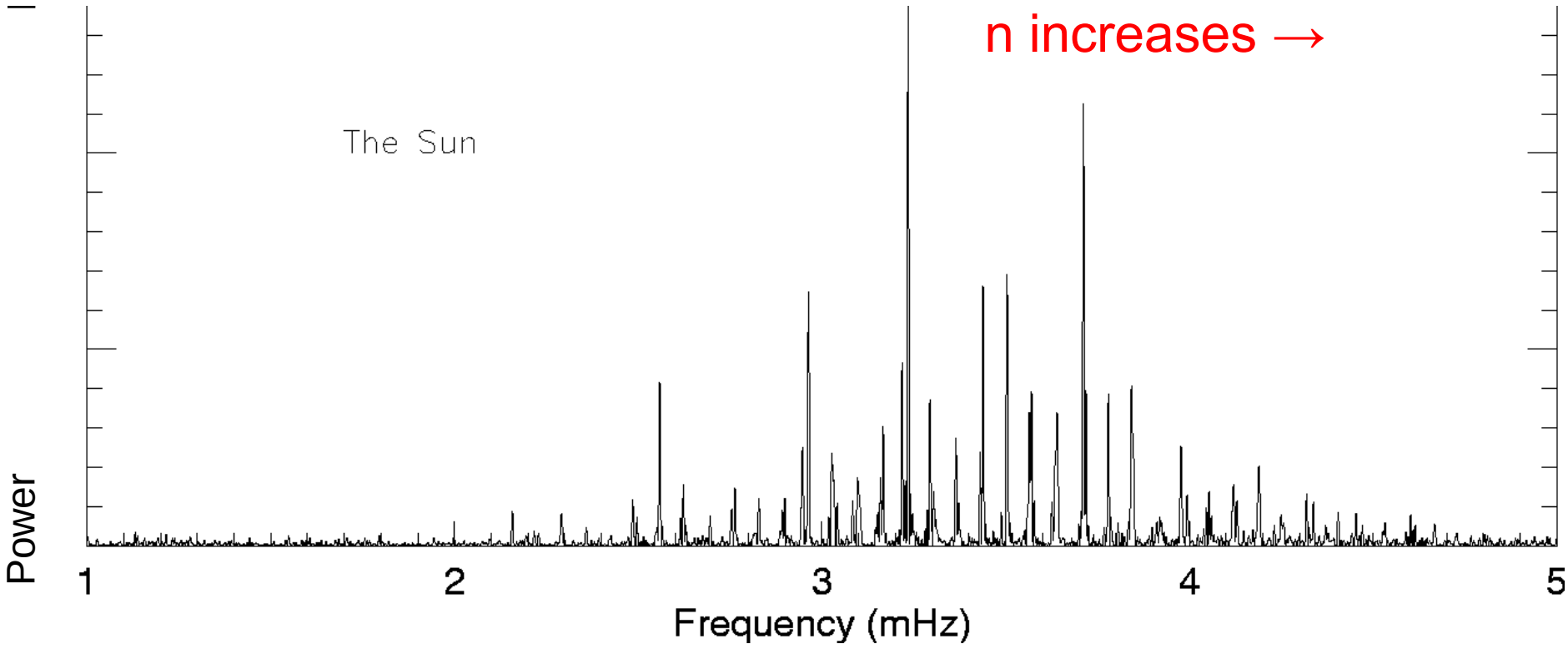
Christensen-Dalsgaard et al. (lecture notes) and Aerts et al. (2010, “Asteroseismology”)

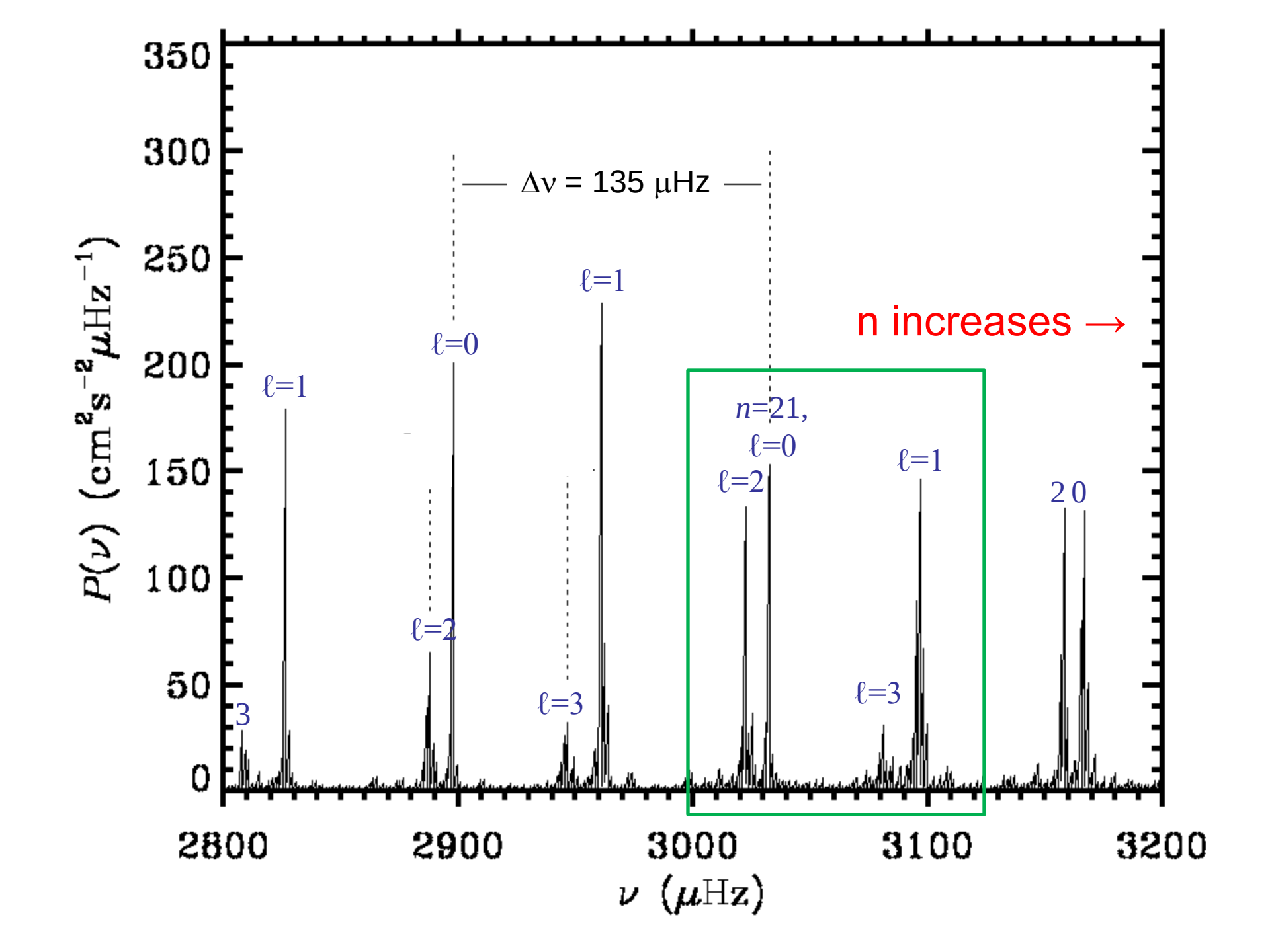

large separation: measures mean density of the star
Δν = 135 μHz
ℓ=1
ℓ=0
ℓ=1
ℓ=0
ℓ=2
ℓ=1
2 0
δν02
ℓ=2
δν13
3
ℓ=3
ℓ=3
small separations: sensitive to core (age)
P(ν) (cm²s⁻²μHz⁻¹)
ν (μHz)
350
300
250
200
150
100
50
0
2800
2900
3000
3100
3200

j)

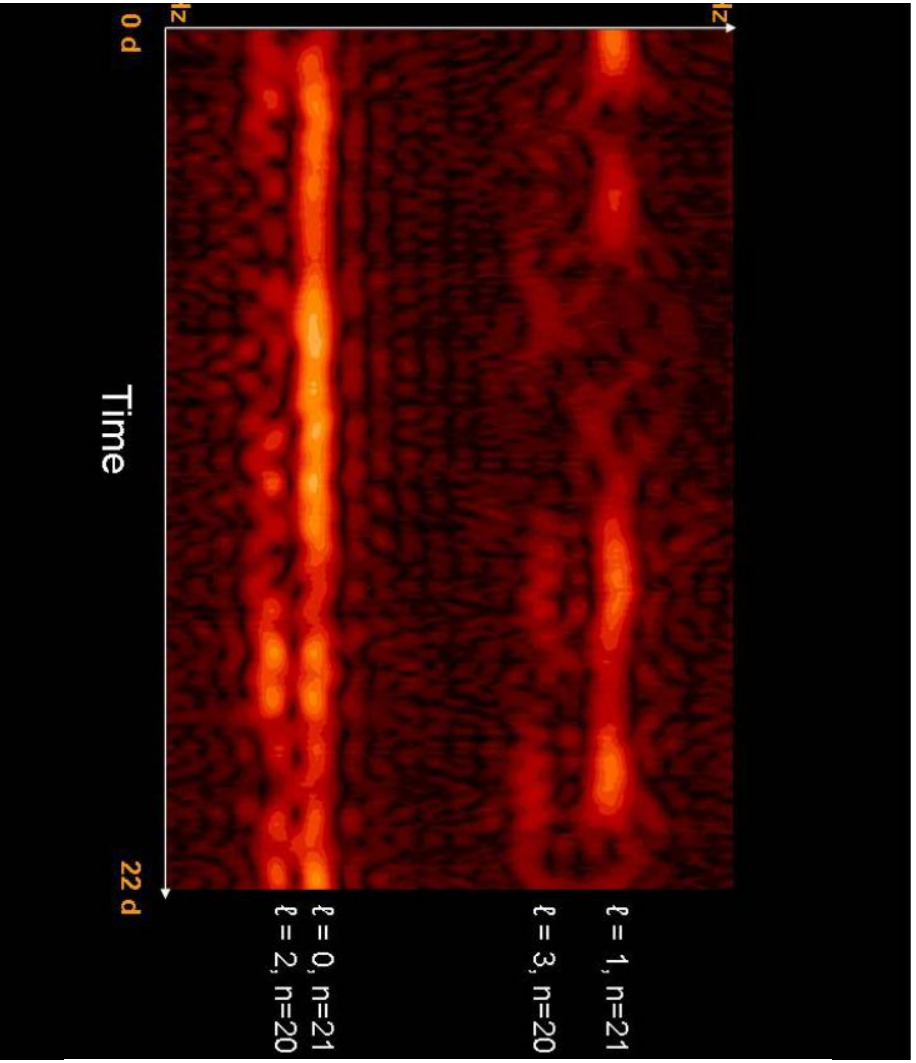


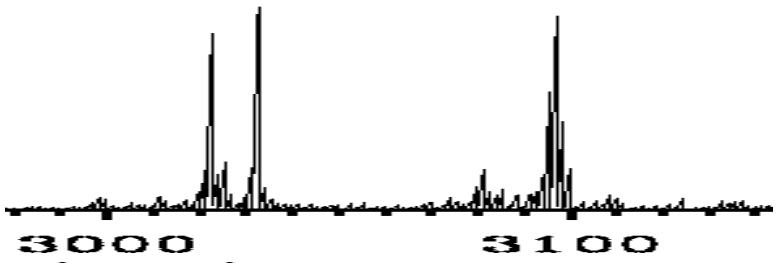
Fourier power spectrum of solar velocities:




Δν = 135 μHz
n increases →
ℓ=1
ℓ=0
ℓ=1
ℓ=1
n=21,
ℓ=0
ℓ=2
ℓ=2
ℓ=3
ℓ=3
3
2 0
350
300
250
200
150
100
50
0
2800
2900
3000
3100
3200
P(ν) (cm²s⁻²μHz⁻¹)
ν (μHz)

http://owww.phys.au.dk/~hans/tidsserie/Lecture_04.pdf

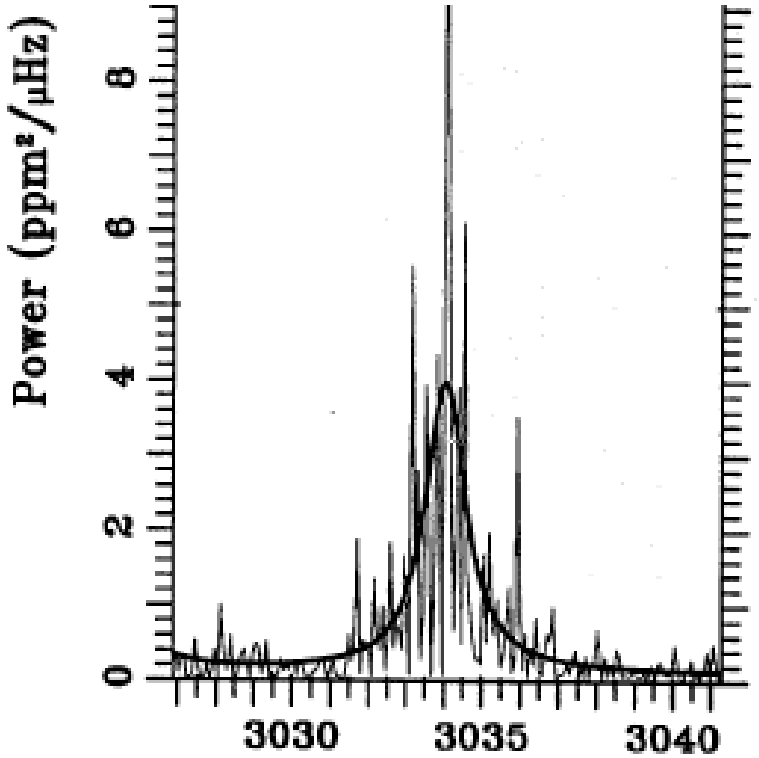




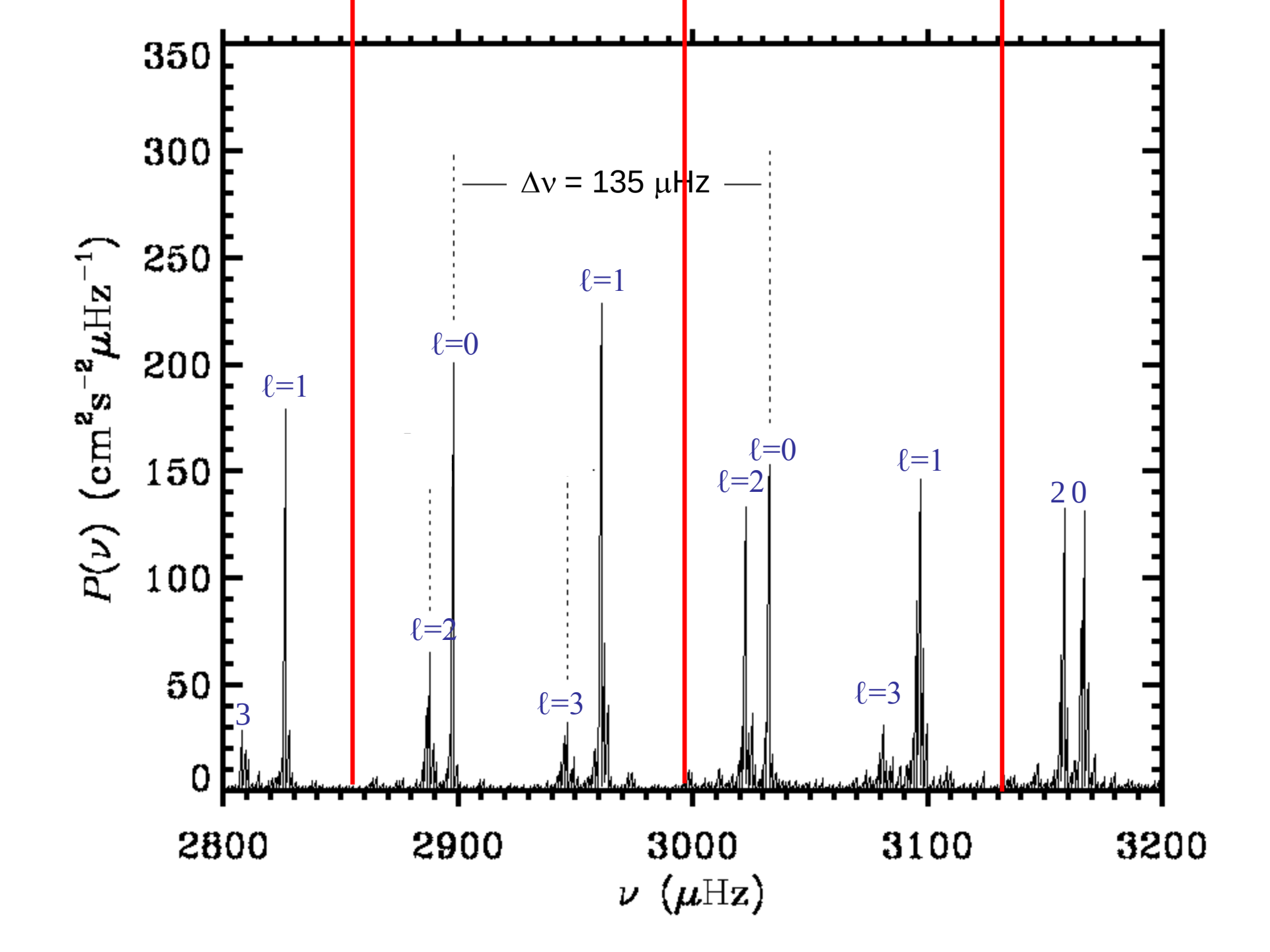
Modes in Sun have lifetimes of τ=2 to 4 days.

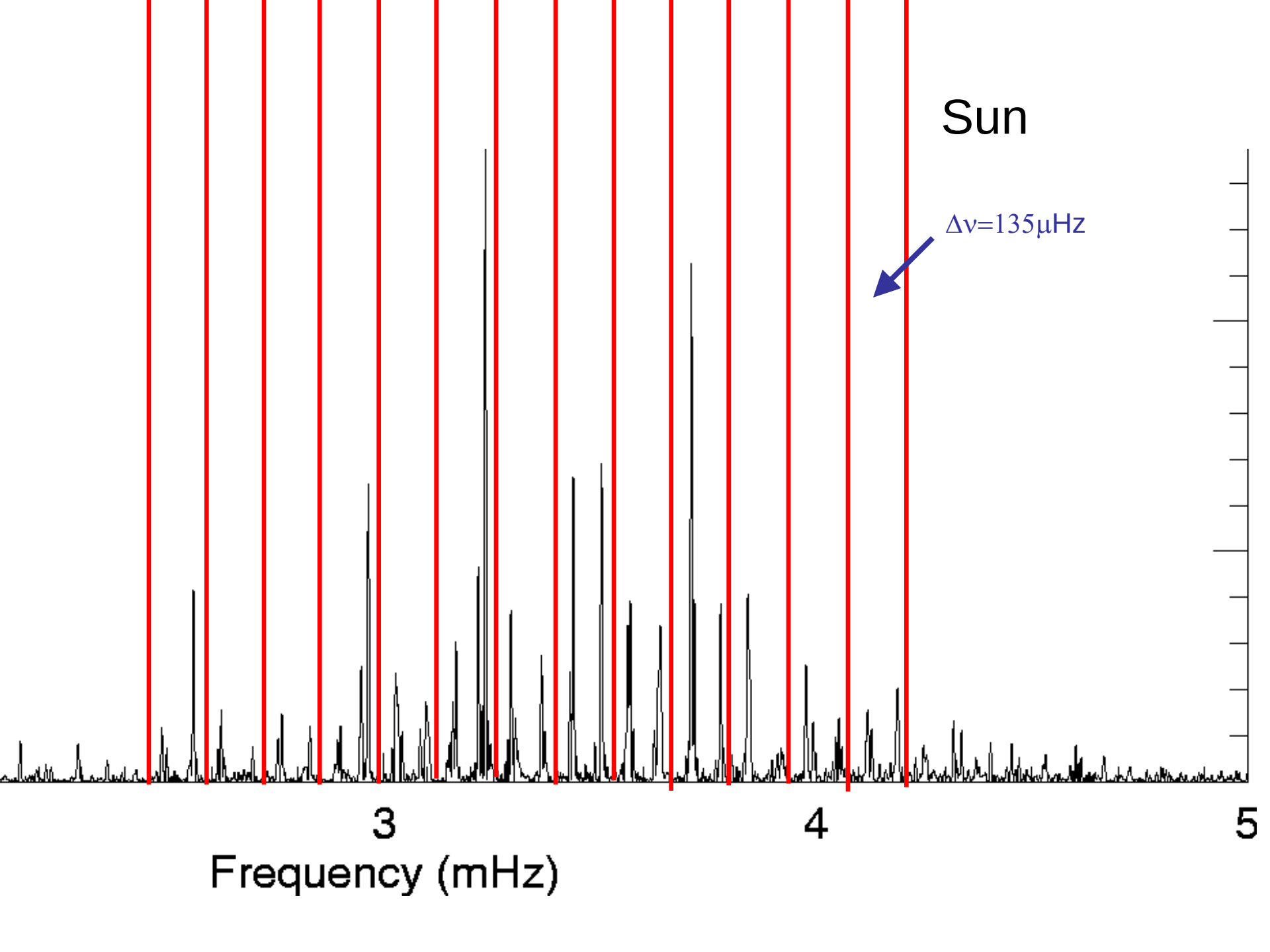
Lorenztian envelope:

$\Gamma=\pi/\tau$

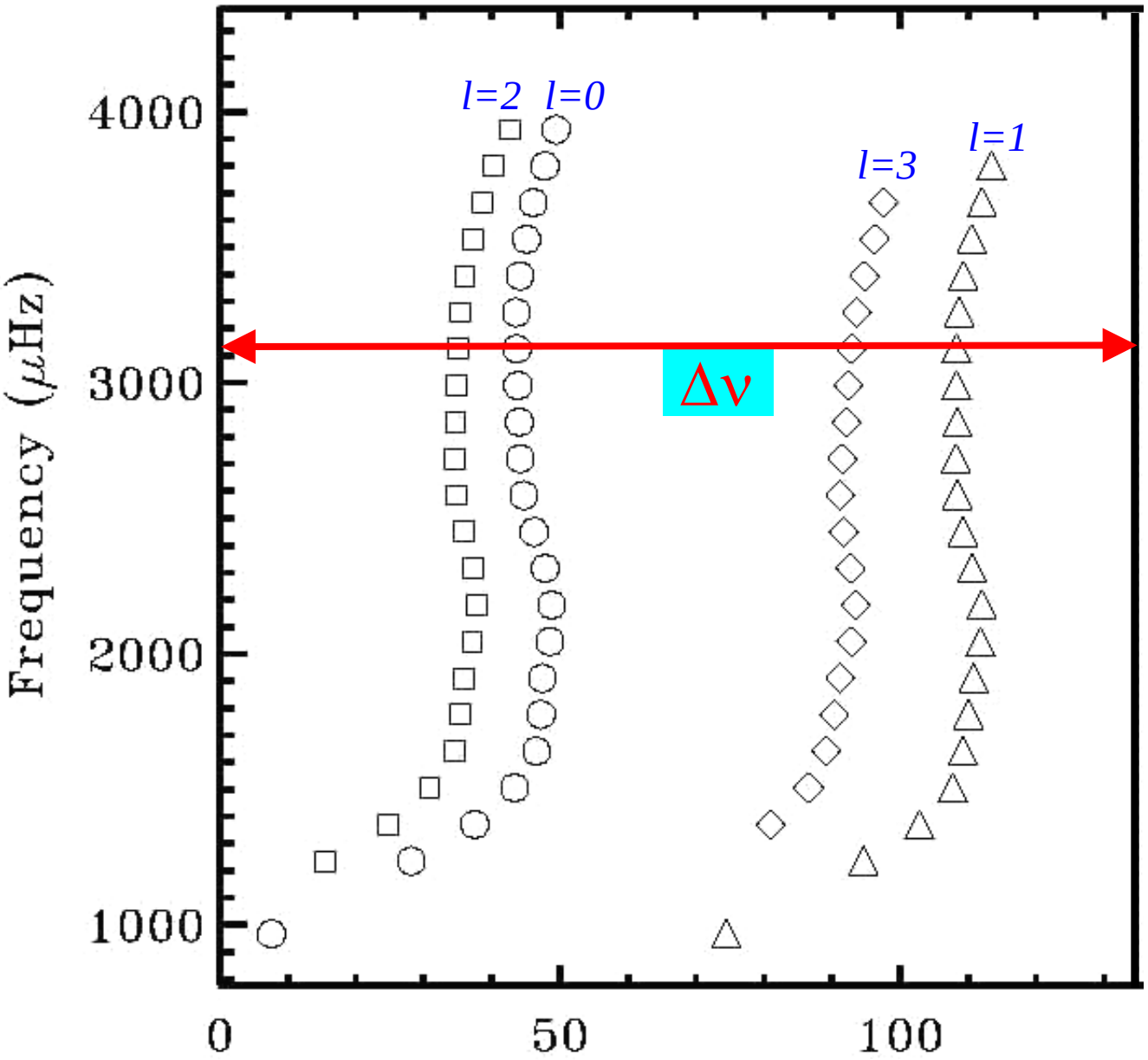


The Fabulous Échelle Diagram


Δν = 135 μHz
ℓ=1
ℓ=0
ℓ=1
ℓ=2
ℓ=0
ℓ=1
2 0
ℓ=2
ℓ=3
ℓ=3
3
$P(\nu)$ $(\mathrm{cm^2 s^{-2} \mu Hz^{-1}})$
ν $(\mu\mathrm{Hz})$
0
50
100
150
200
250
300
350
2800
2900
3000
3100
3200

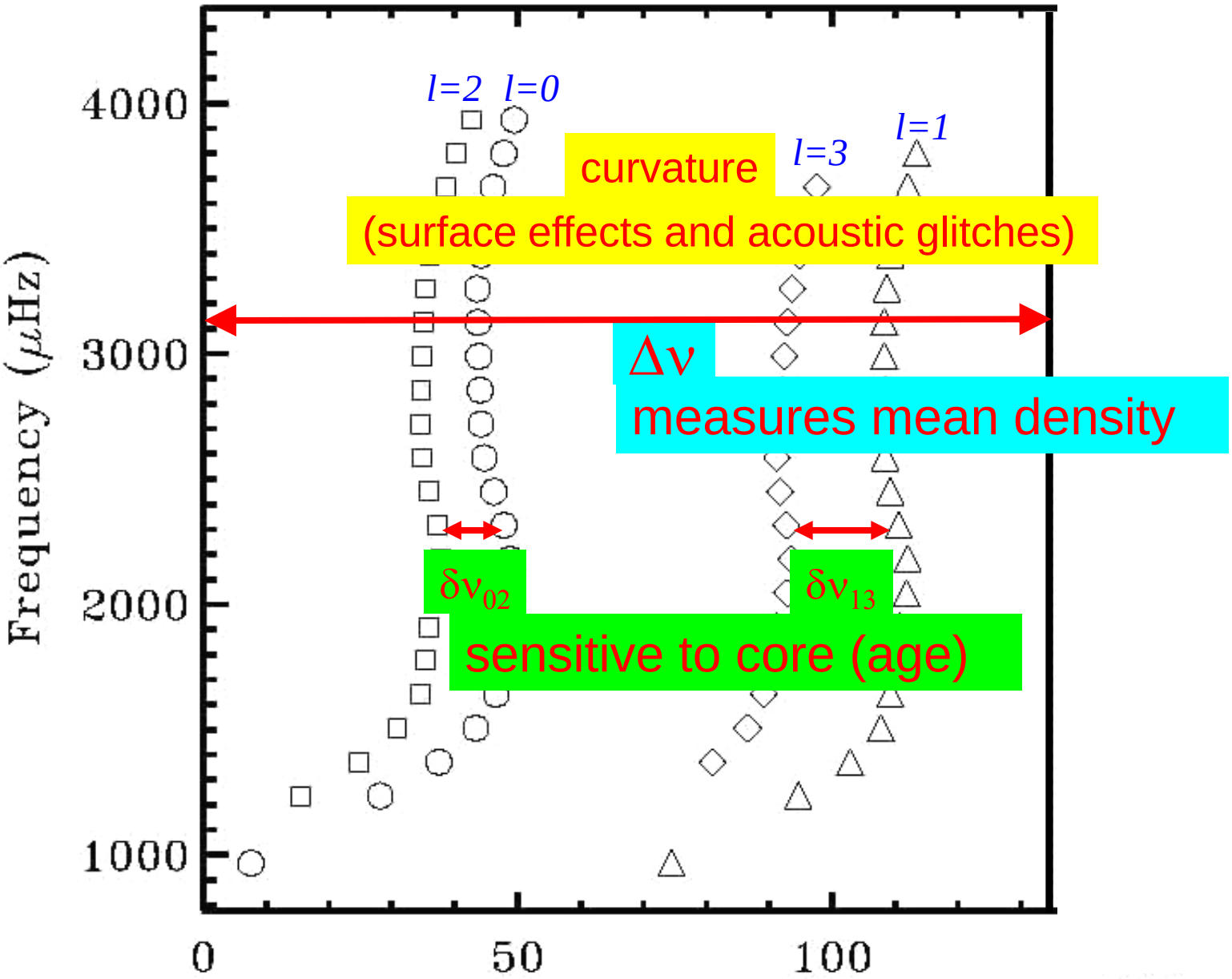

Sun
Δν=135μHz
3
4
5
Frequency (mHz)

The Sun: échelle diagram



BISON freq.

The Sun: échelle diagram



BISON freq.

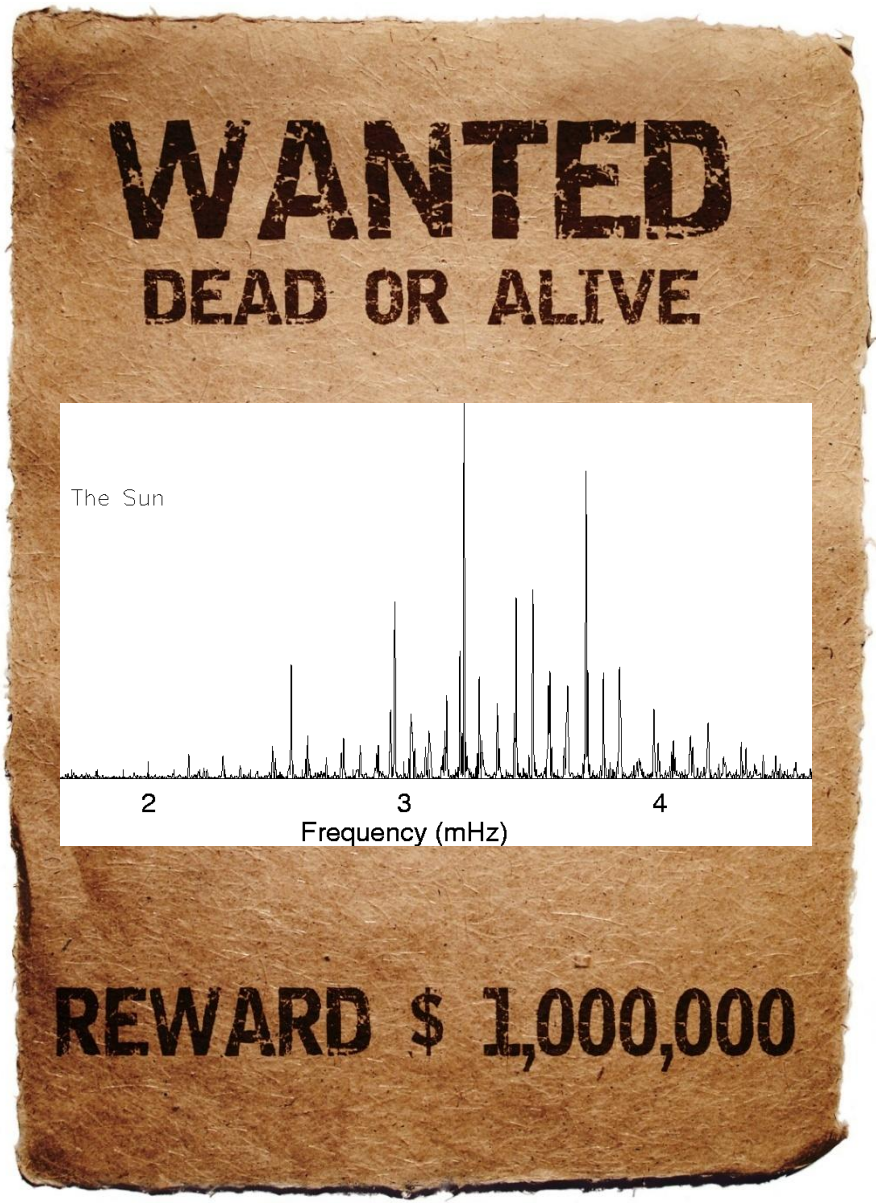
Exercise 1: make an echelle diagram with these 14 frequencies

2140
2147
2198
2252
2257
2308
2362
2367
2419
2478
2530
2583
2587
2640

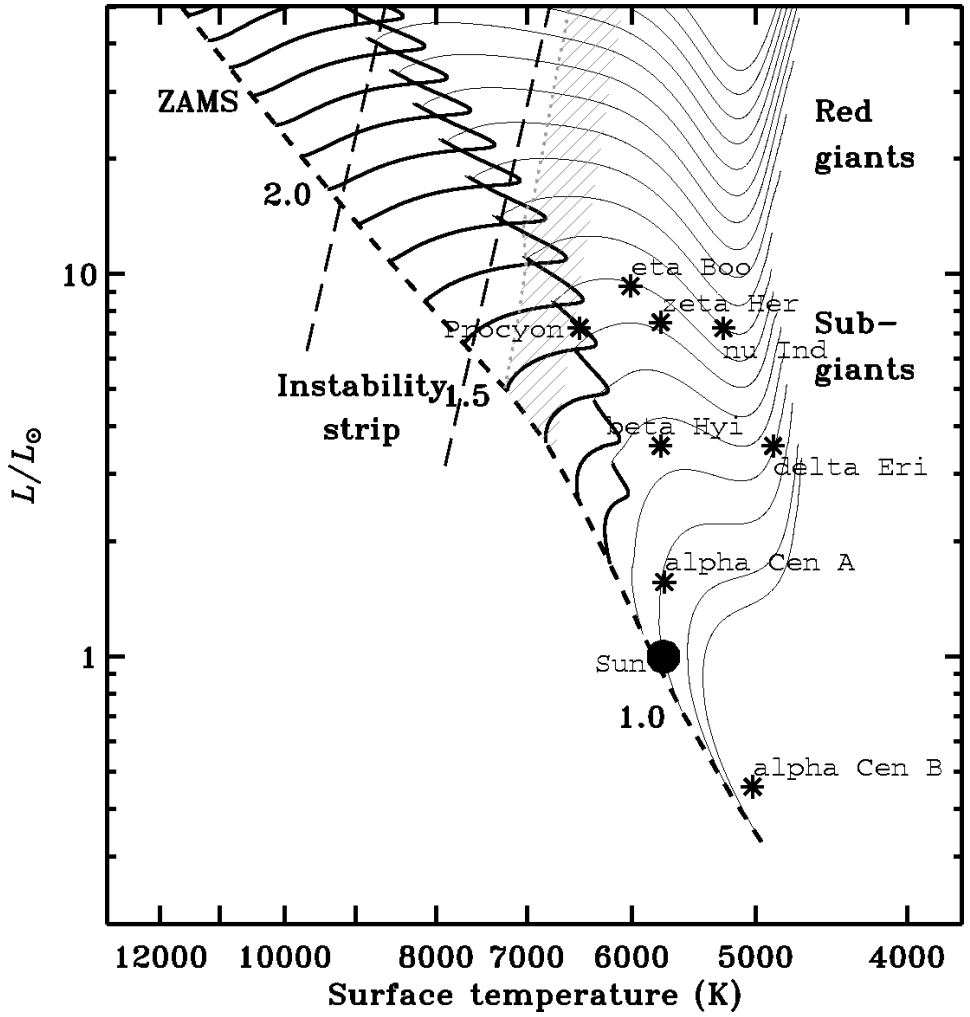
- plot (frequency) versus (frequency mod $\Delta\nu$)
- find the best $\Delta\nu$ (hint start with about 120μHz)
- what happens if you change $\Delta\nu$ slightly?

So that is what we are looking for in other stars.

Now for an overview of observational results (some highlights)



Observations of solar-like oscillations: some highlights



Lots of effort in the 1980s, but ...

Asteroseismology of solar-like stars has so far produced disappointing results.

(written in 1993)

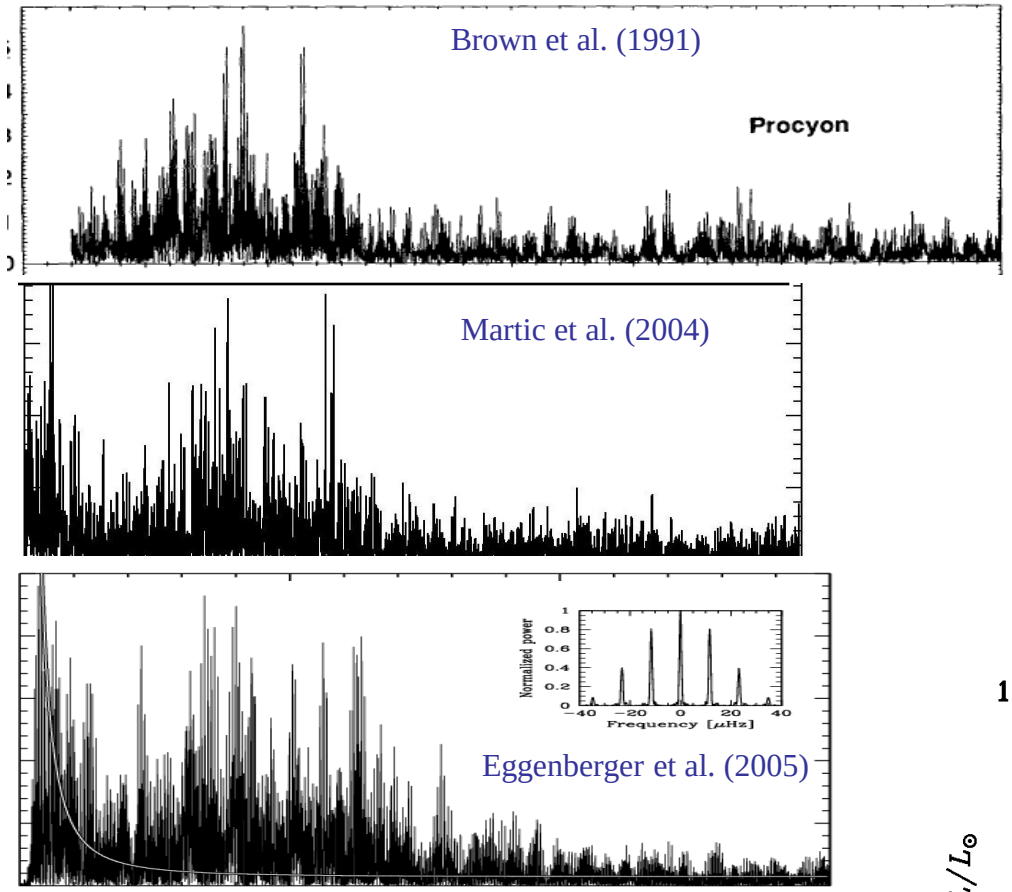
Kjeldsen & Bedding (1995)

1993: Stars with claimed detections

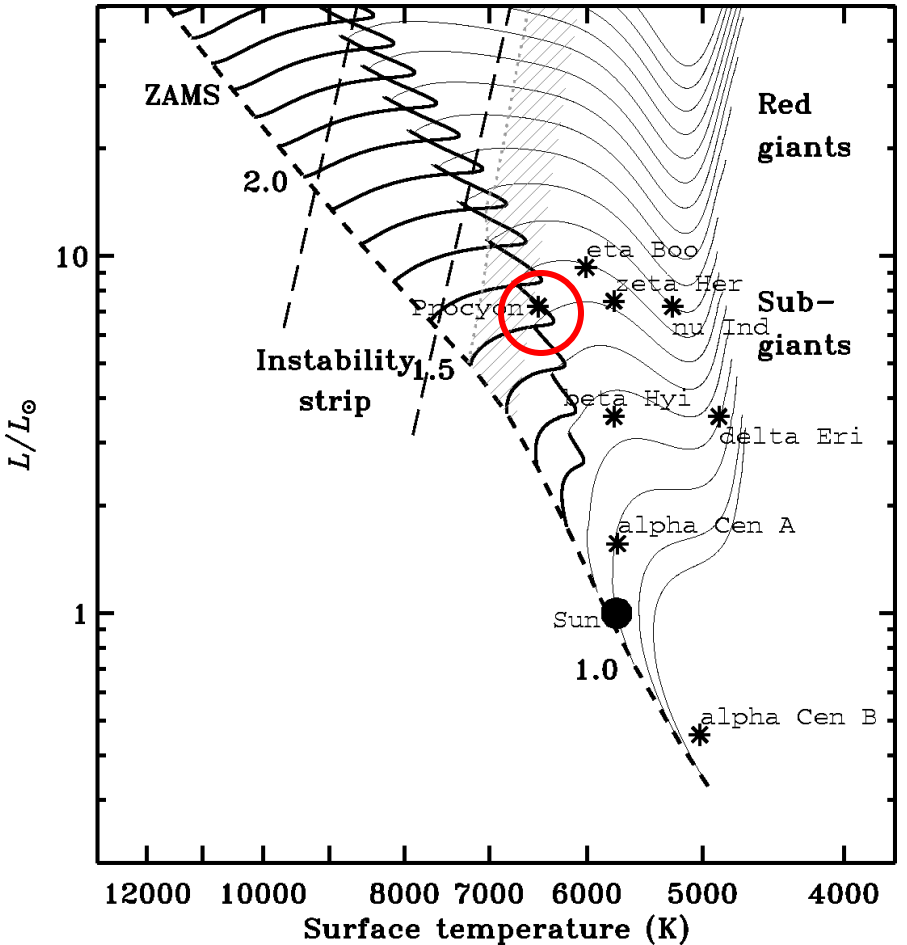
- ε Eridani (K2 V; Noyes et al. 1984)
- Procyon (F5 IV; Gelly et al. 1986; Brown et al. 1991; Bedford et al. 1993)
- α Cen A (G2 V; Gelly et al. 1986; Pottasch et al. 1992)
- Arcturus (K2 III; Belmonte et al. 1990)
- HD 155543 (F2 V; Belmonte et al. 1990b)

1993: Stars with confirmed detections

Velocity observations of Procyon (F5 IV)

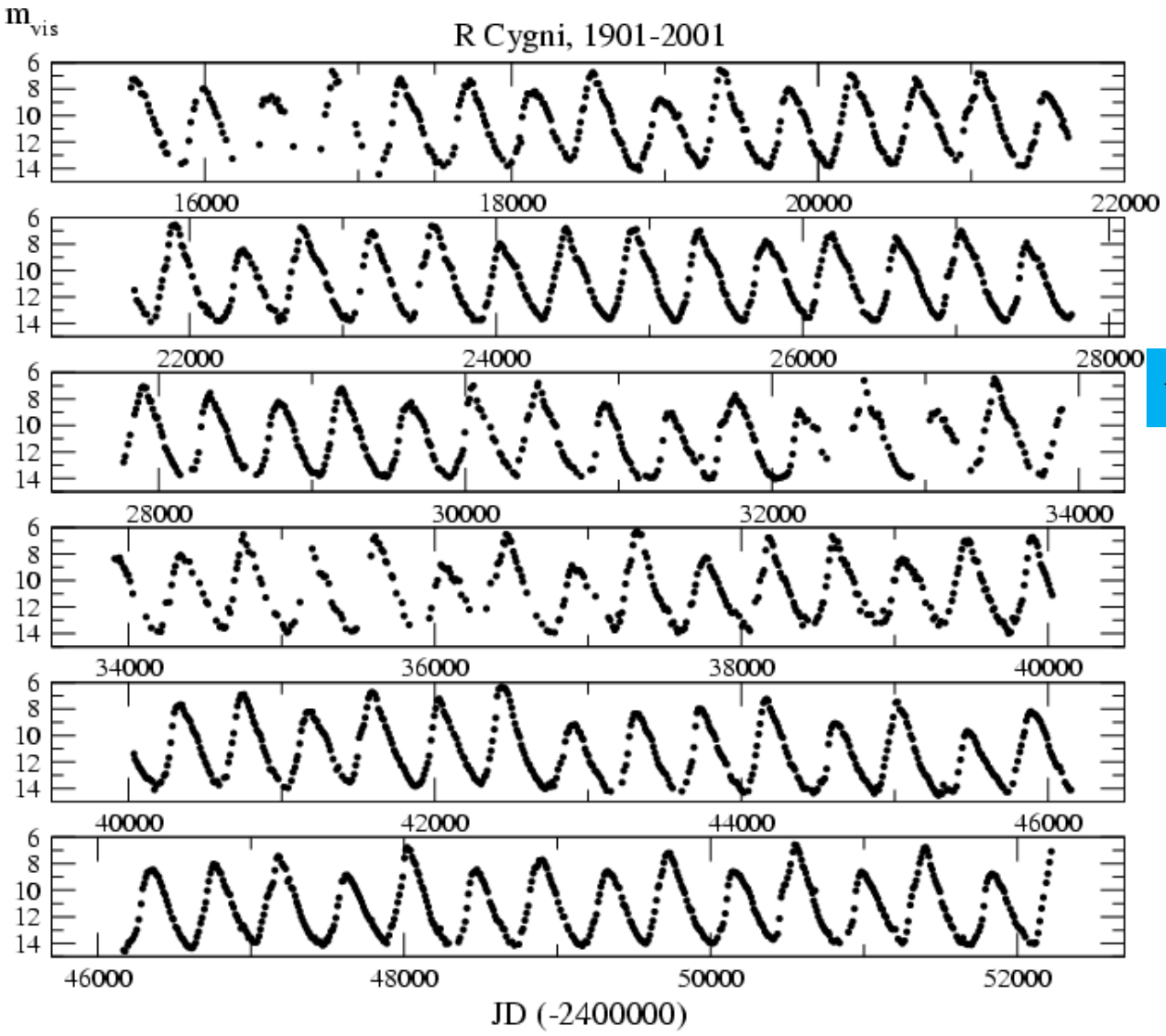


$\Delta\nu \approx 55\mu$Hz but no agreement on individual frequencies



Method 1: changes in velocity using the Doppler effect

Method 2: changes in luminosity (photometry)



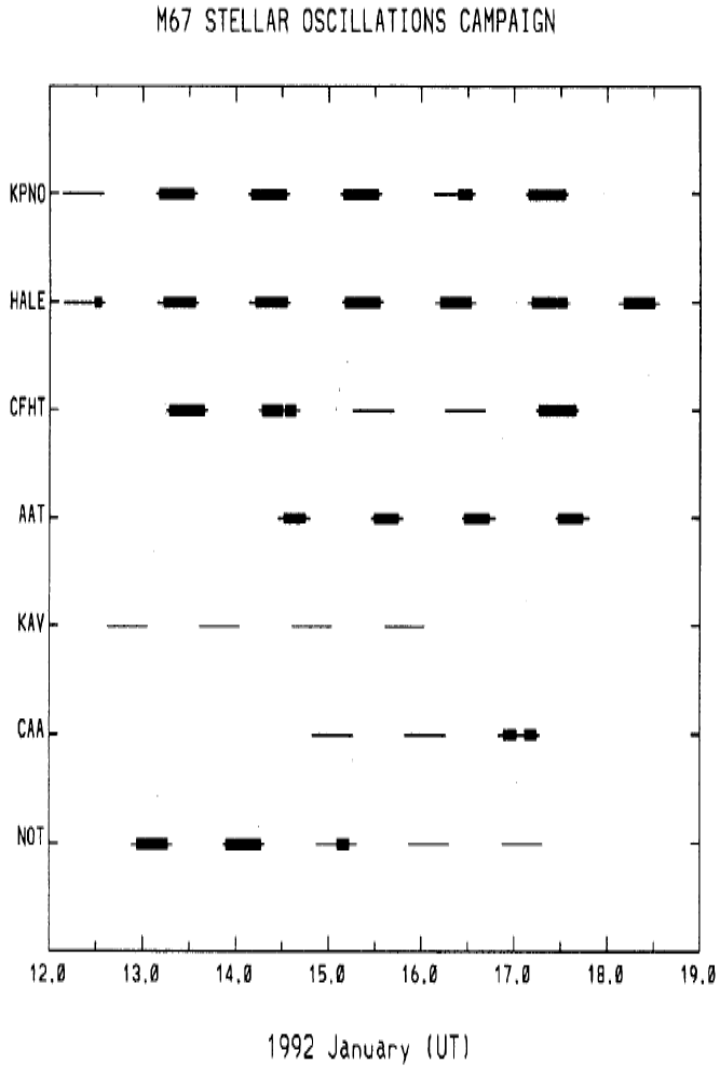
why does luminosity change?

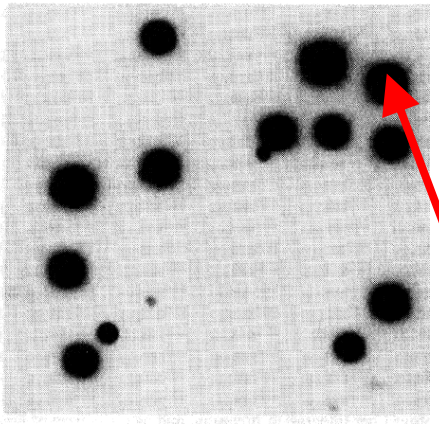
answer: surface temperature changes

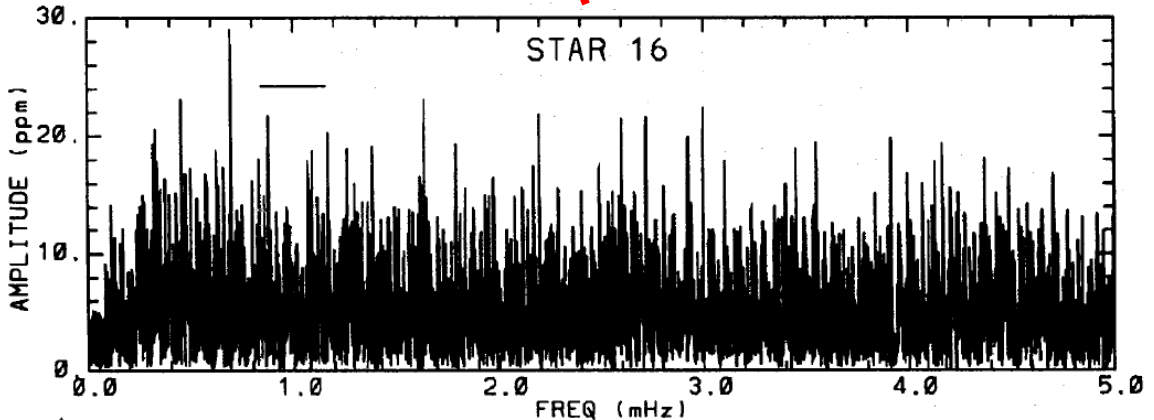
THE ASTRONOMICAL JOURNAL VOLUME 106, NUMBER 6 DECEMBER 1993

A SEARCH FOR SOLAR-LIKE OSCILLATIONS IN THE STARS OF M67 WITH CCD ENSEMBLE PHOTOMETRY ON A NETWORK OF 4 m TELESCOPES

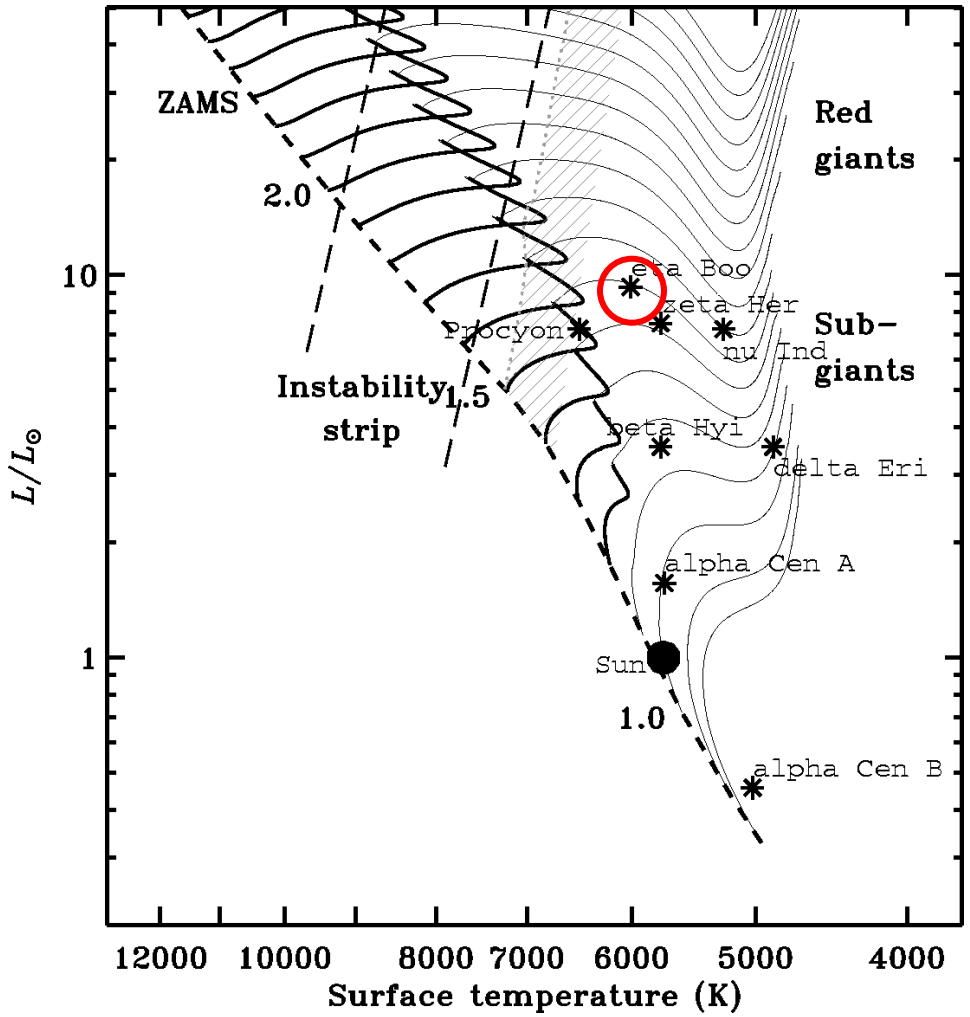
Gilliland et al. (1993)





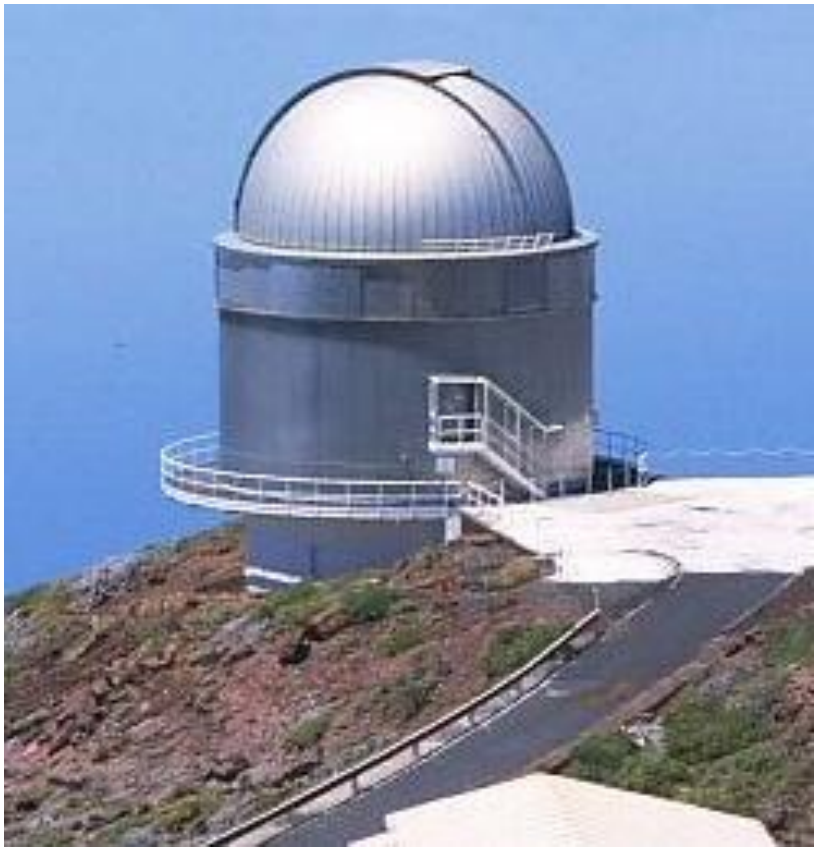


1994: η Boo G0 IV (subgiant)



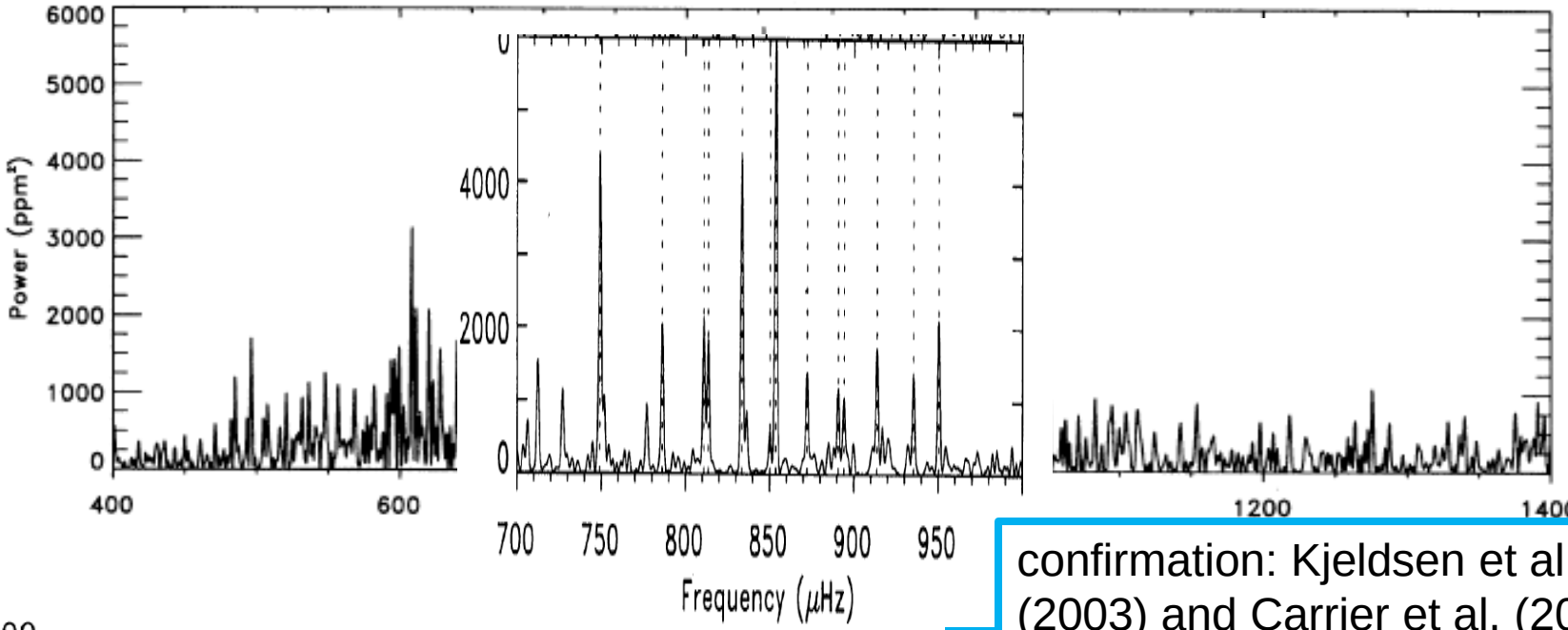
Method 3: variations in equivalent widths of temperature-sensitive lines

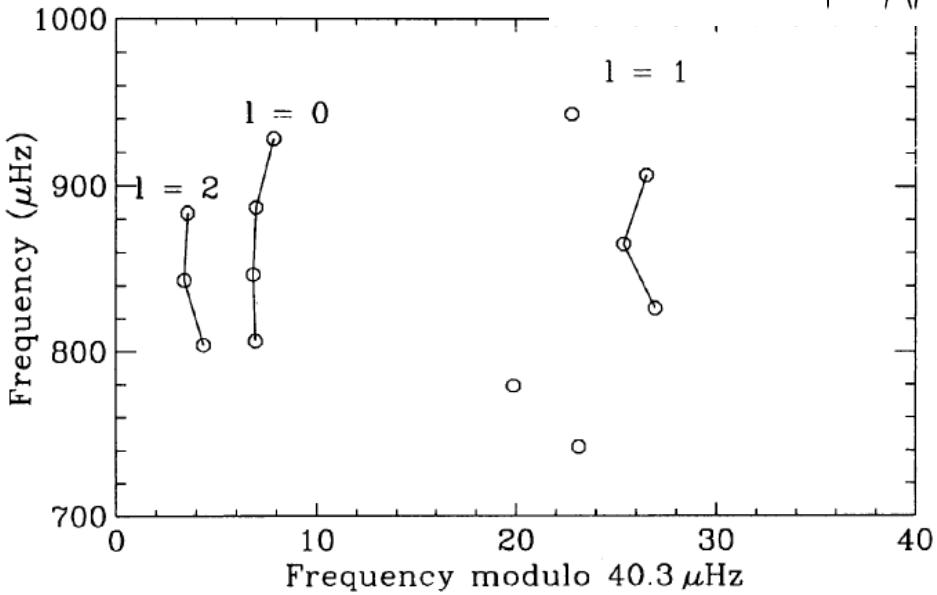
Hans Kjeldsen



Nordic Optical Telescope,
La Palma

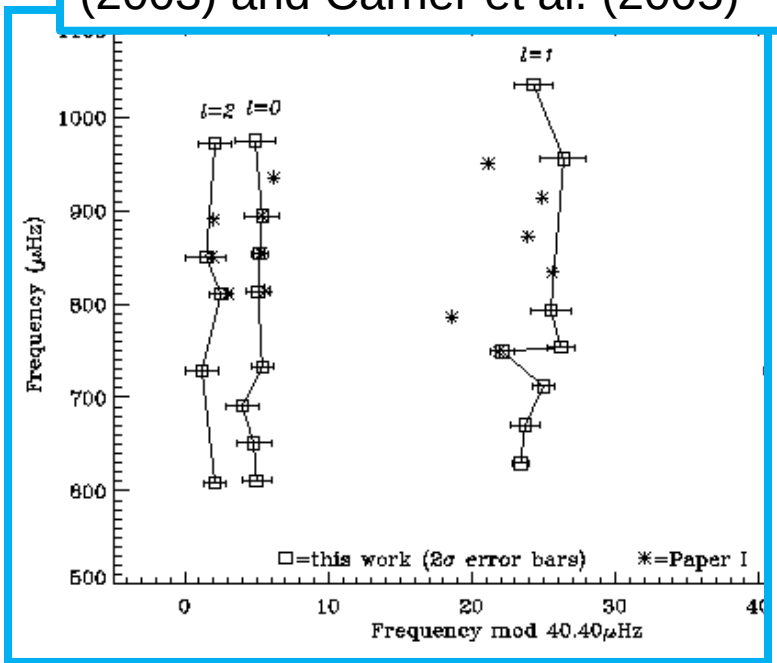
η Boo: G0 subgiant



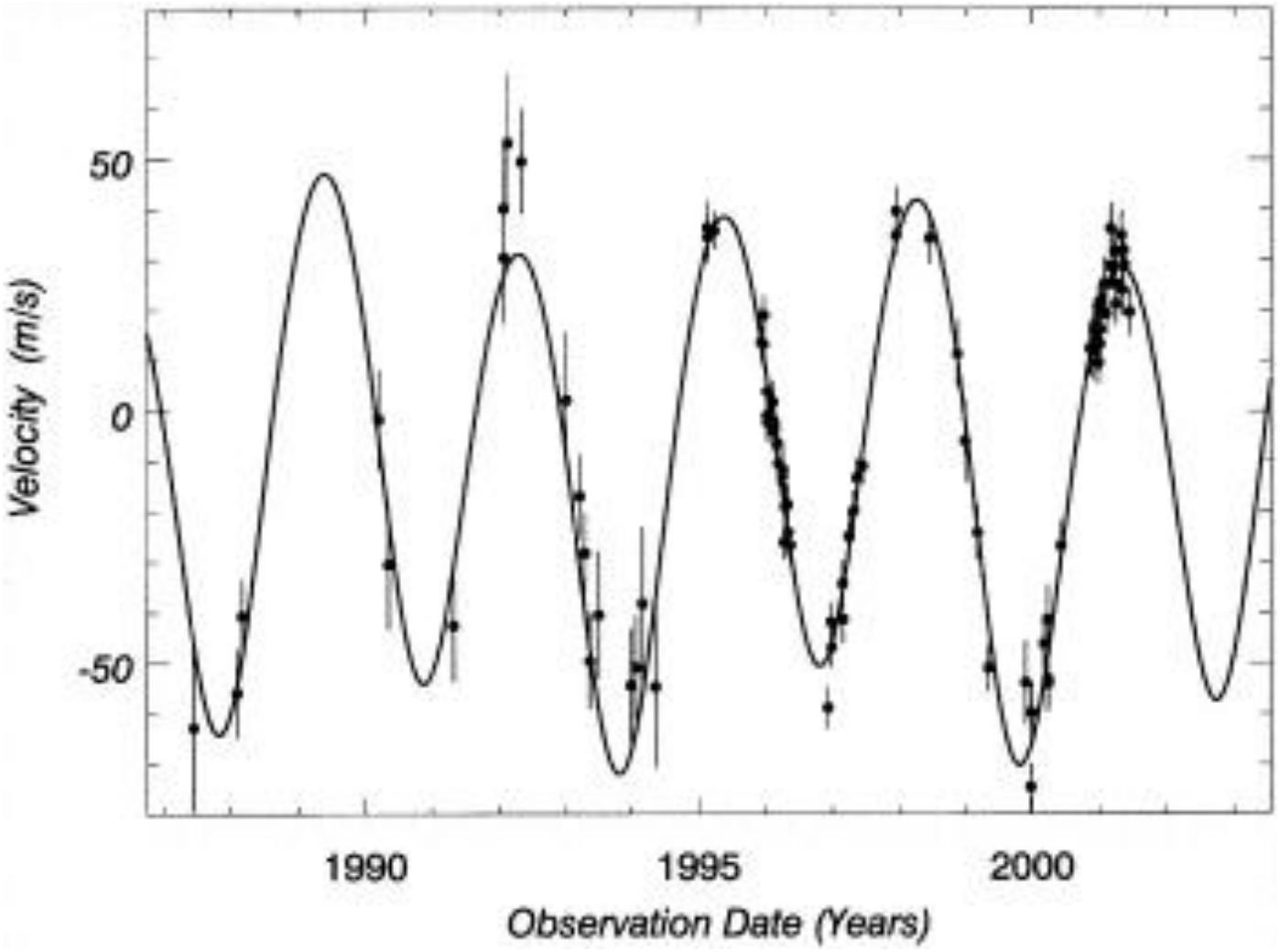


Kjeldsen et al. (1995)

confirmation: Kjeldsen et al. (2003) and Carrier et al. (2005)

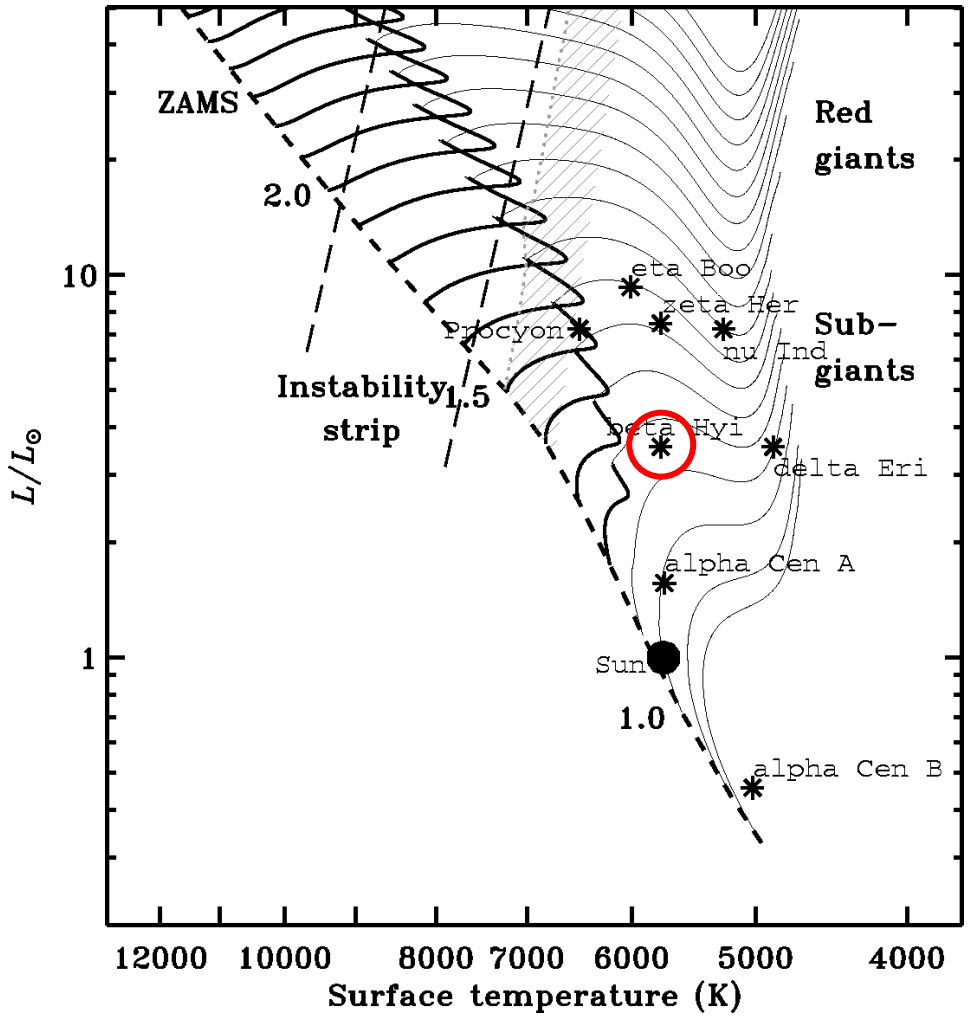


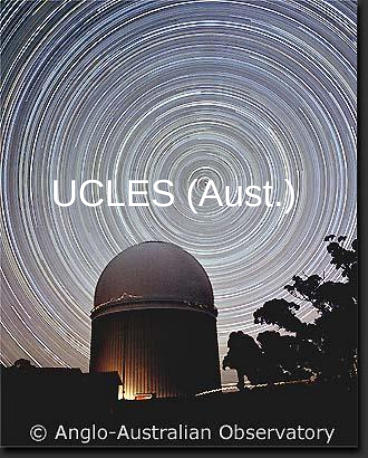
Back to Method 1: what is this?

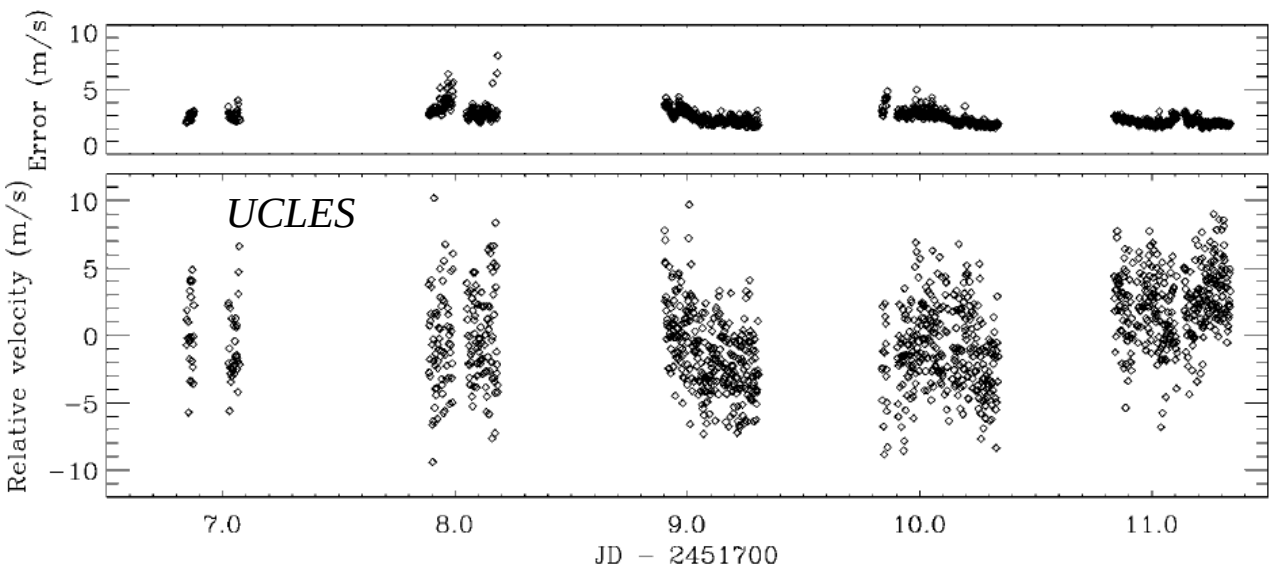


Planets around the star 47 Ursa Majoris

2000: β Hyi G2 IV (subgiant, future Sun)

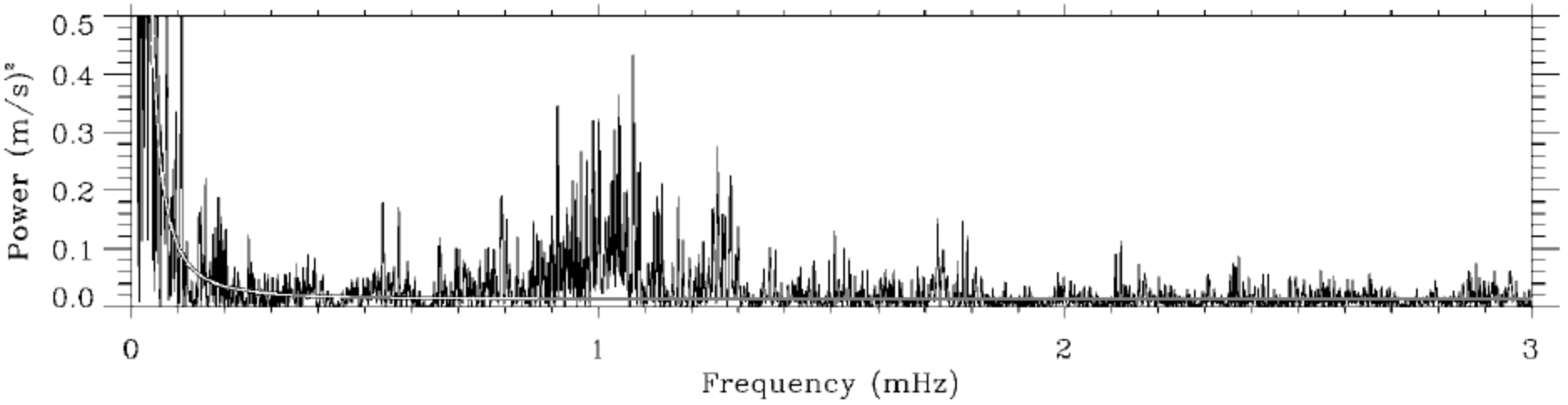






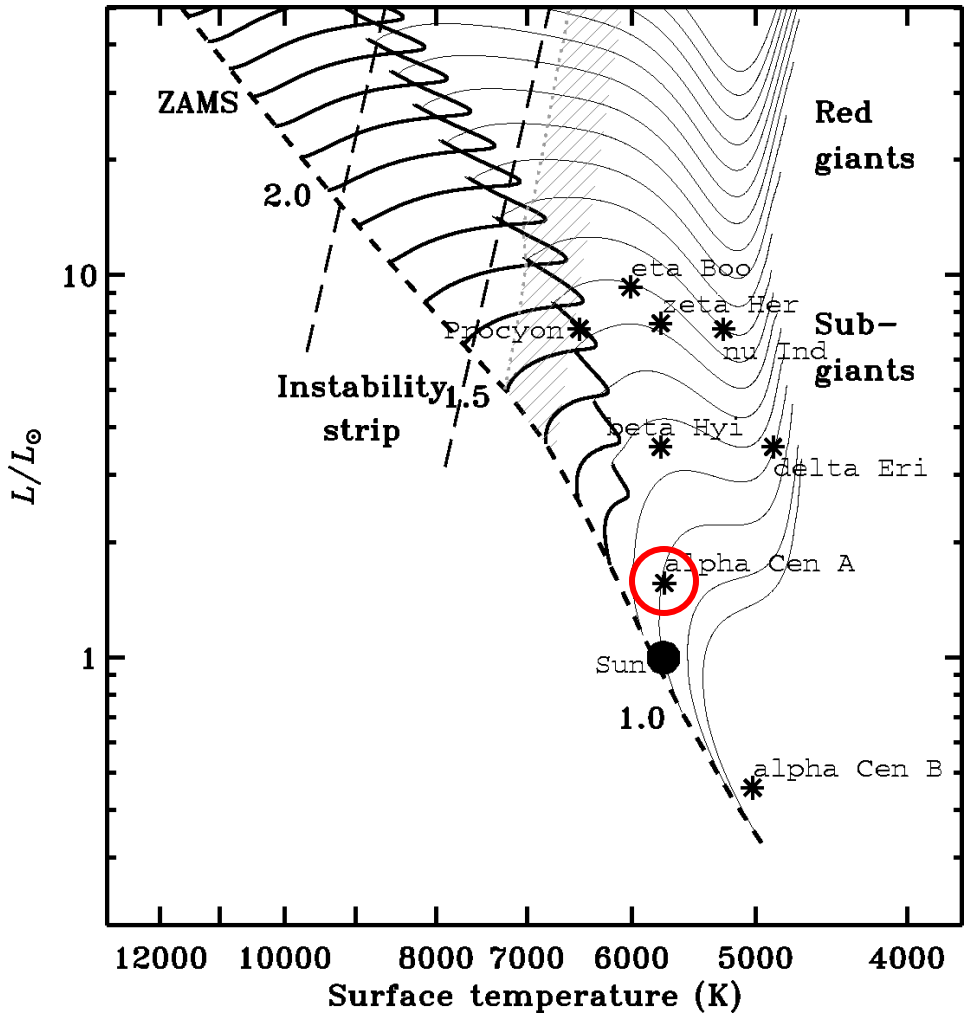
UCLES at the 3.9m
AAT, Australia

velocities (iodine cell)

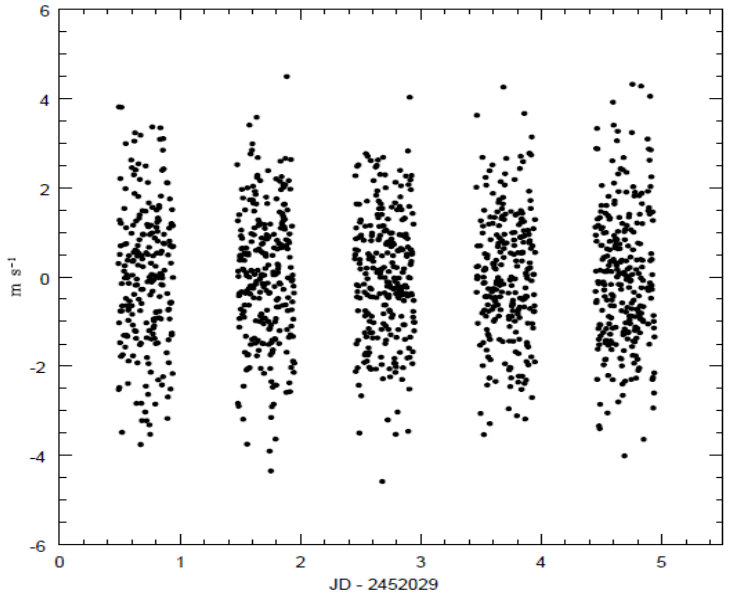


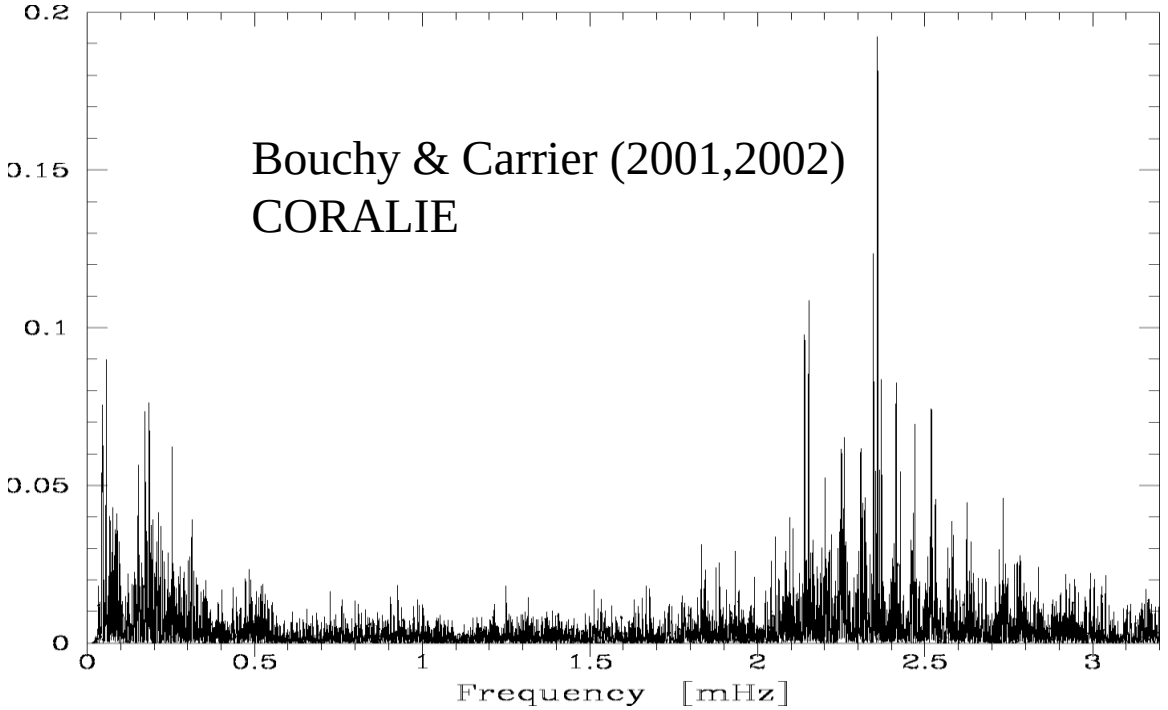
Bedding et al. (2001) and Carrier et al. (2001)

2001: α Cen A (G2 V)

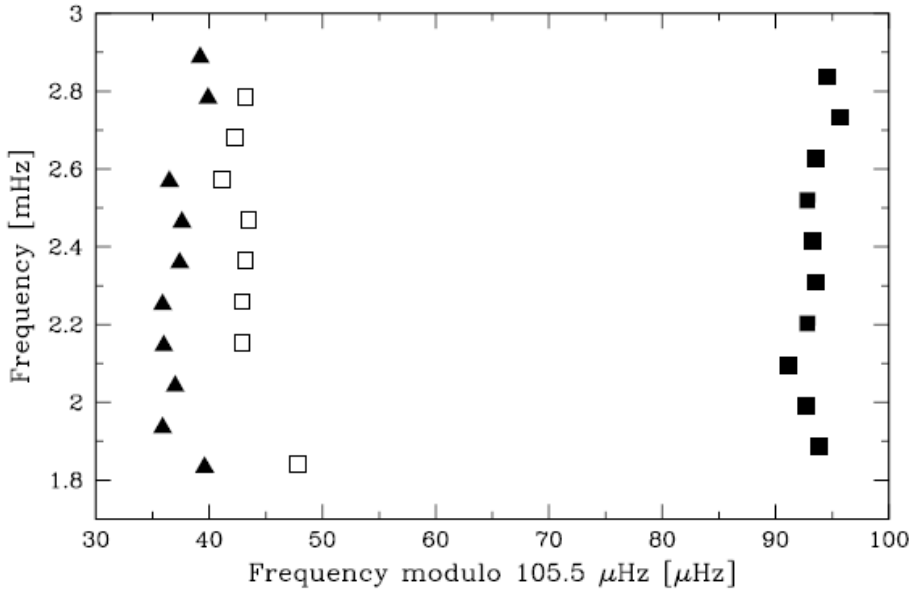


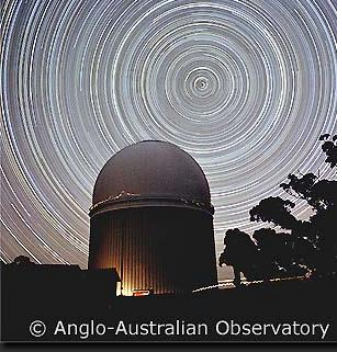
α Cen A

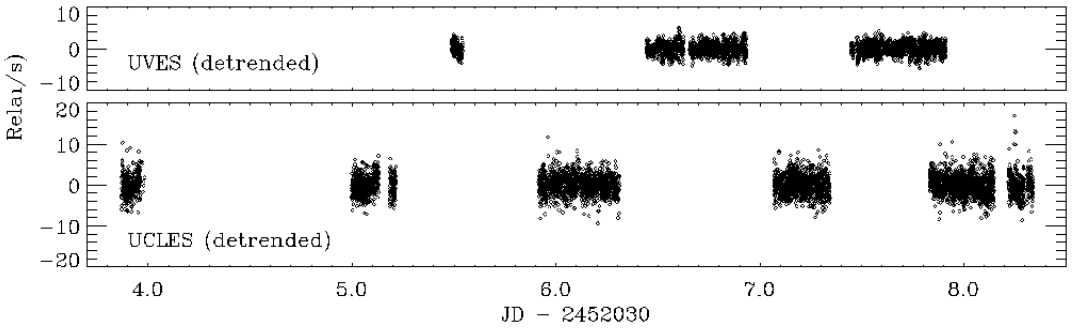


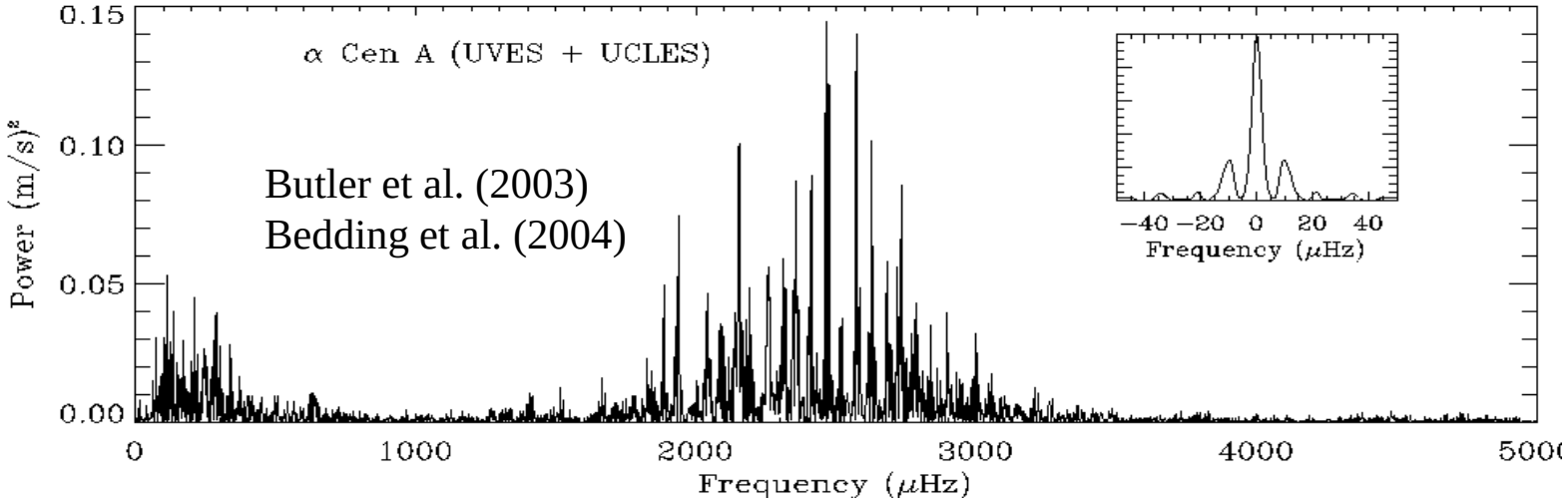


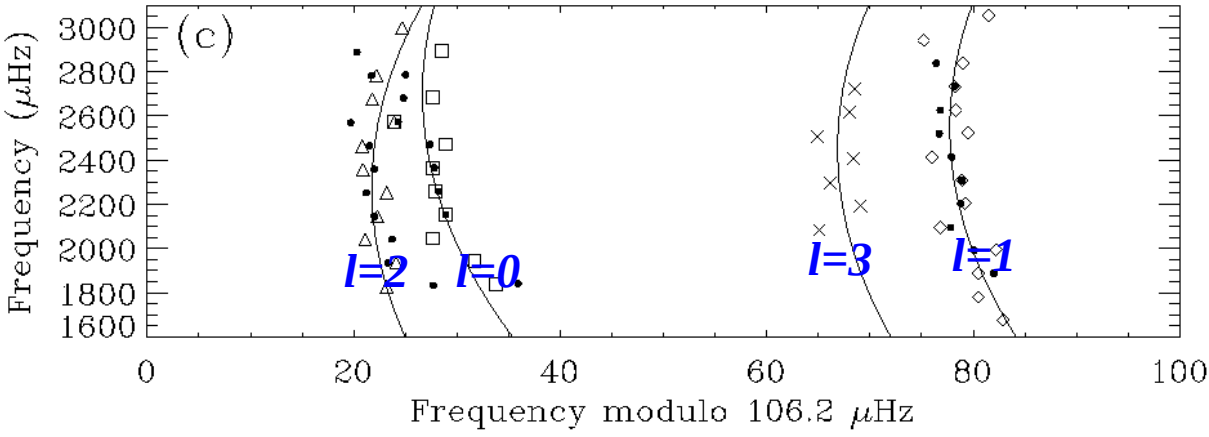
CORALIE at the Swiss 1.2-m Leonhard Euler Telescope at La Silla, Chile



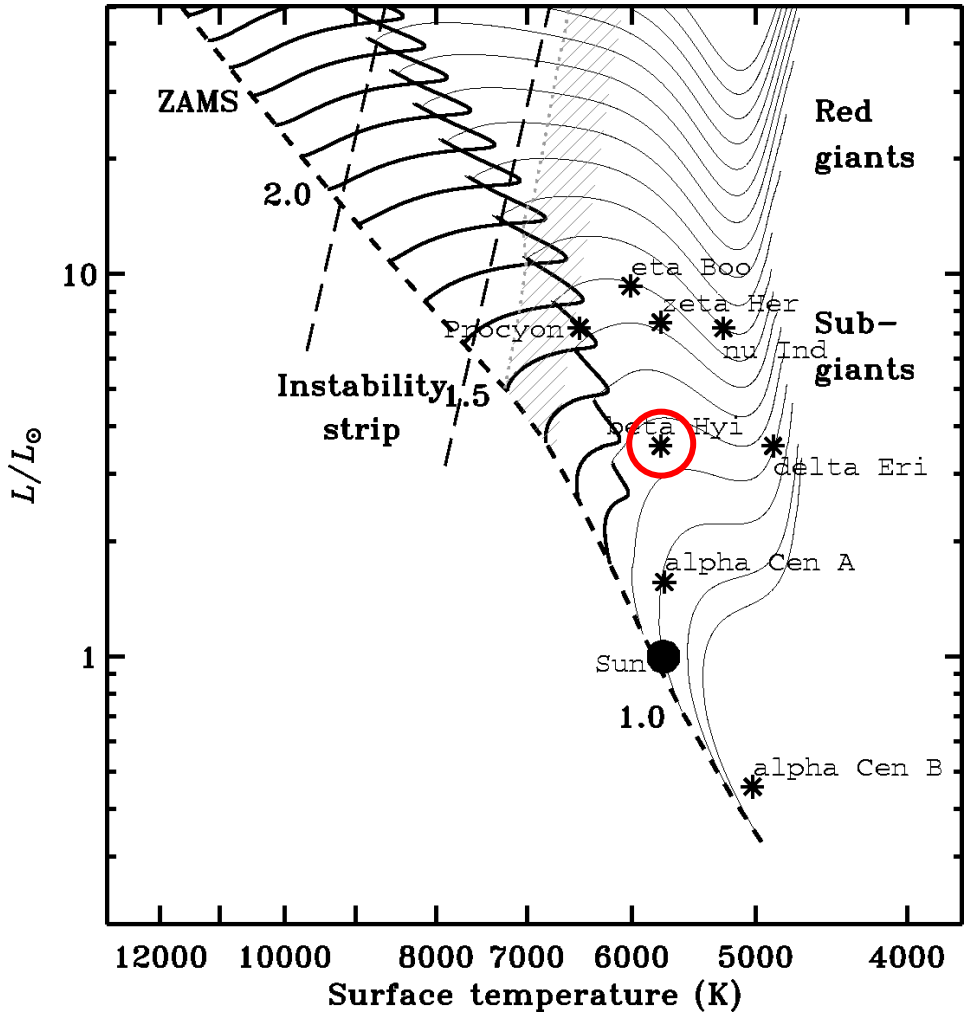

© Anglo-Australian Observatory


UVES (detrended)
UCLES (detrended)
Rela/s)
JD − 2452030


α Cen A (UVES + UCLES)
Butler et al. (2003)
Bedding et al. (2004)
Power (m/s)²
Frequency (μHz)

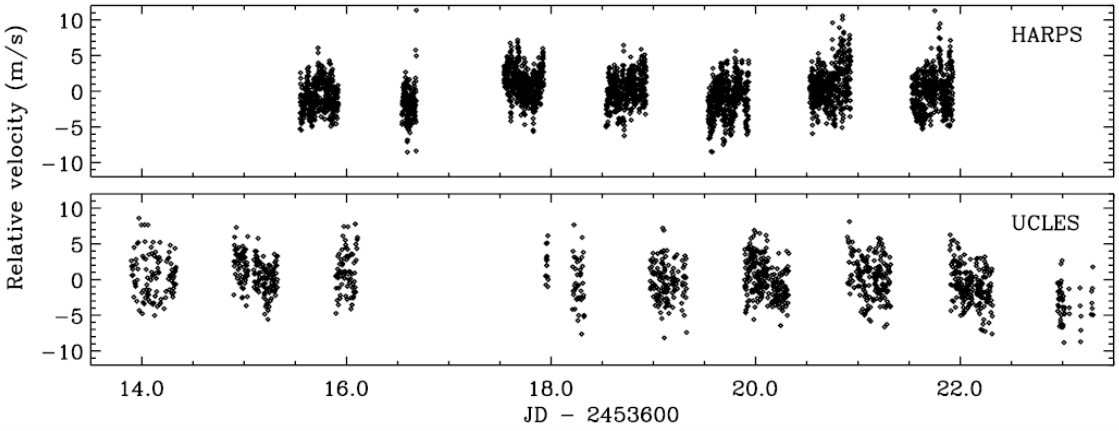

(c)
l=2
l=0
l=3
l=1
Frequency (μHz)
Frequency modulo 106.2 μHz

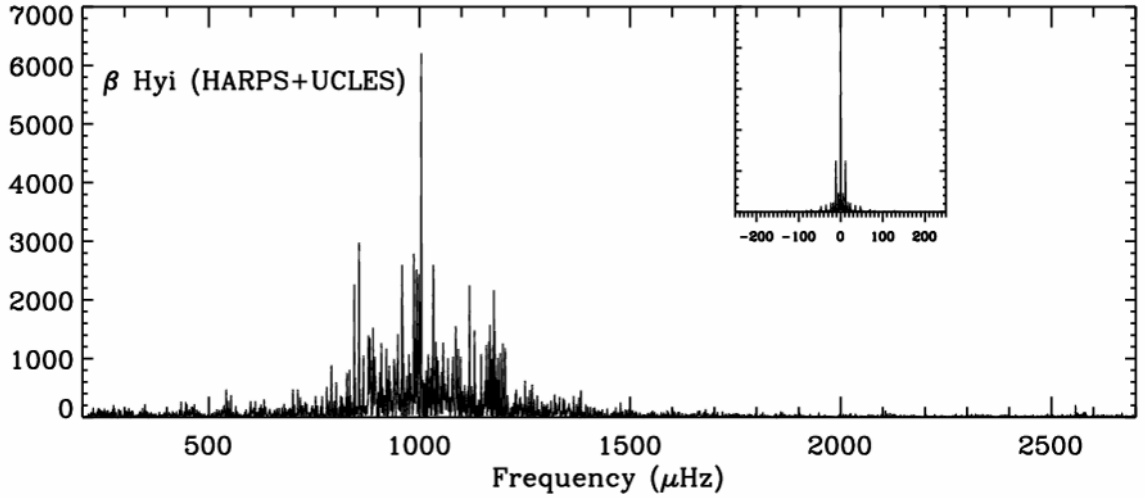
2007 Back to the future: β Hyi G2 IV (subgiant, future Sun)

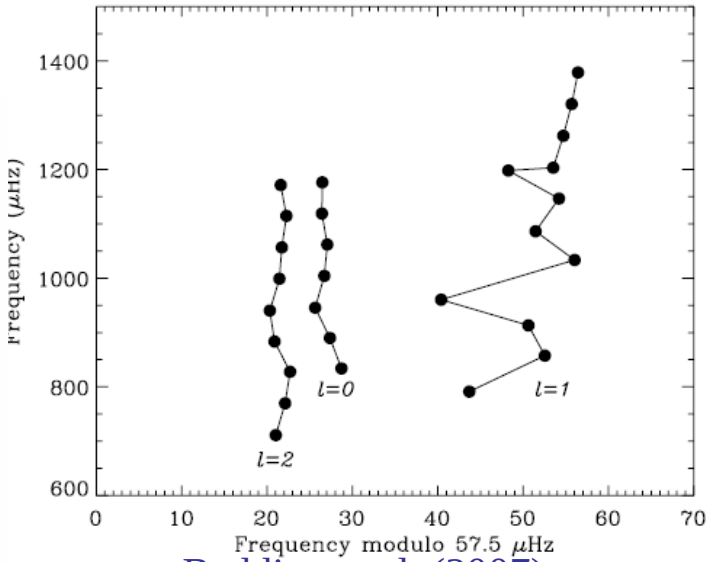


SOLAR-LIKE OSCILLATIONS IN THE G2 SUBGIANT β HYDRI FROM DUAL-SITE OBSERVATIONS

Timothy R. Bedding,[1] Hans Kjeldsen,[2] Torben Arentoft,[2] Francois Bouchy,[3,4] Jacob Brandbyge,[2]
Brendon J. Brewer,[1] R. Paul Butler,[5] Jørgen Christensen-Dalsgaard,[2] Thomas Dall,[6]
Søren Frandsen,[2] Christoffer Karoff,[2] László L. Kiss,[1] Mario J. P. F. G. Monteiro,[7]
Frank P. Pijpers,[8] Teresa C. Teixeira,[7] C. G. Tinney,[9] Ivan K. Baldry,[9,10]
Fabien Carrier,[3,11] and Simon J. O'Toole[1,9]







Bedding et al. (2007)

2008: The Procyon campaign

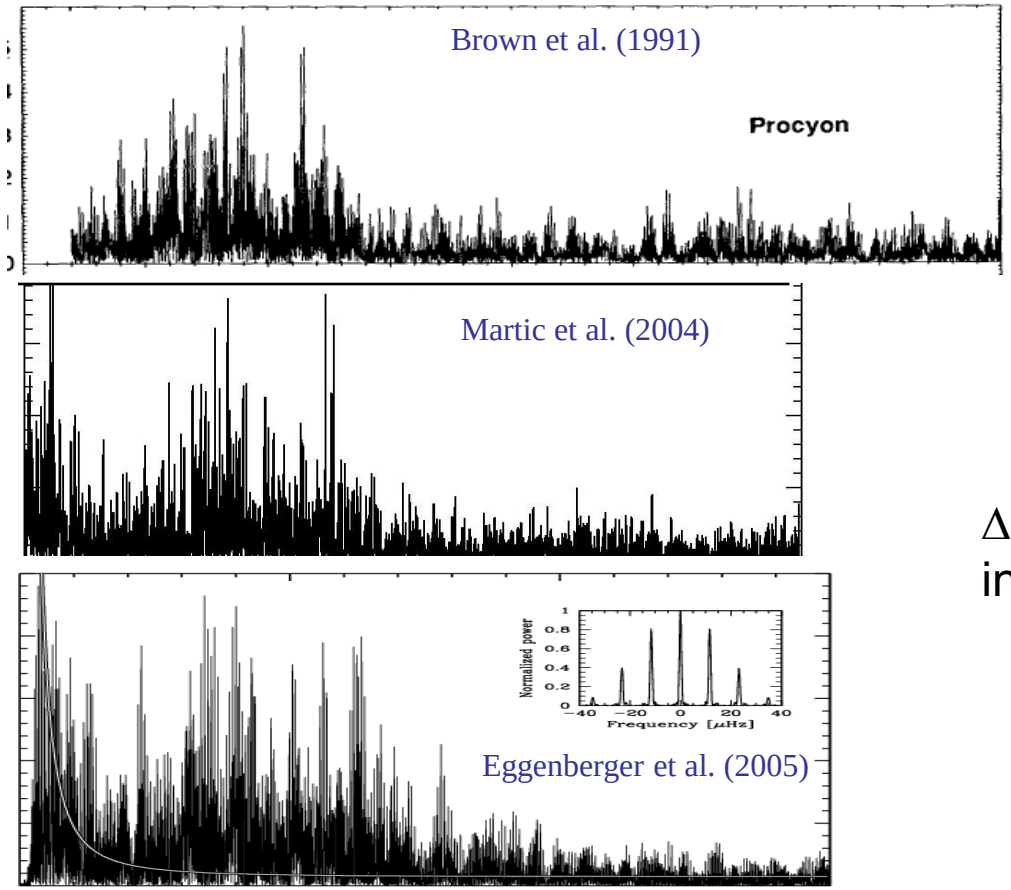
A MULTISITE CAMPAIGN TO MEASURE SOLAR-LIKE OSCILLATIONS IN PROCYON. I. OBSERVATIONS, DATA REDUCTION, AND SLOW VARIATIONS

Torben Arentoft,[1] Hans Kjeldsen,[1] Timothy R. Bedding,[2] Michaël Bazot,[1,3] Jørgen Christensen-Dalsgaard,[1] Thomas H. Dall,[4] Christoffer Karoff,[1] Fabien Carrier,[5] Patrick Eggenberger,[6] Danuta Sosnowska,[7] Robert A. Wittenmyer,[8] Michael Endl,[8] Travis S. Metcalfe,[9] Saskia Hekker,[10,11] Sabine Reffert,[12] R. Paul Butler,[13] Hans Bruntt,[2] László L. Kiss,[2] Simon J. O'Toole,[14] Eiji Kambe,[15] Hiroyasu Ando,[16] Hideyuki Izumiura,[15] Bun'ei Sato,[17] Michael Hartmann,[18] Artie Hatzes,[18] Francois Bouchy,[19] Benoit Mosser,[20] Thierry Appourchaux,[21] Caroline Barban,[20] Gabrielle Berthomieu,[22] Rafael A. Garcia,[23] Eric Michel,[20] Janine Provost,[22] Sylvaine Turck-Chièze,[23] Milena Martić,[24] Jean-Claude Lebrun,[24] Jerome Schmitt,[25] Jean-Loup Bertaux,[24] Alfio Bonanno,[26] Serena Benatti,[27] Riccardo U. Claudi,[27] Rosario Cosentino,[26] Silvio Leccia,[28] Søren Frandsen,[1] Karsten Brogaard,[1] Lars Glowienka,[1] Frank Grundahl,[1] and Eric Stempels[29]

A MULTI-SITE CAMPAIGN TO MEASURE SOLAR-LIKE OSCILLATIONS IN PROCYON. II. MODE FREQUENCIES

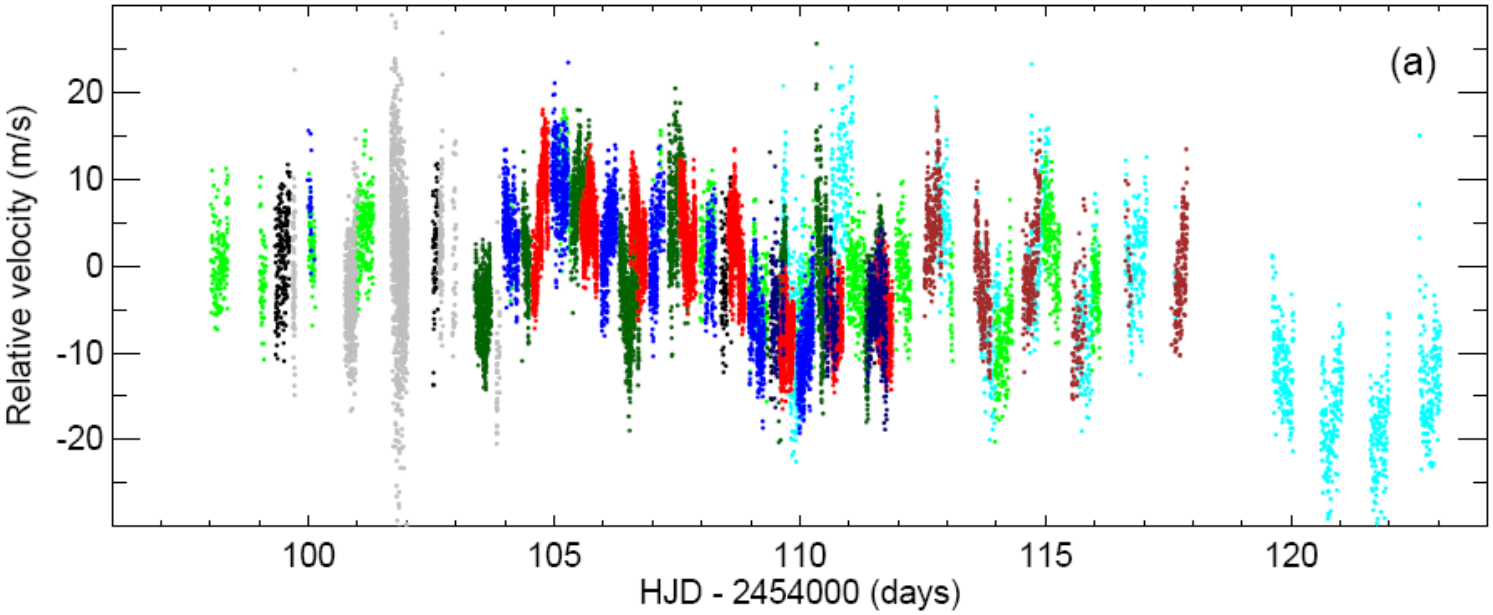
Timothy R. Bedding[1], Hans Kjeldsen[2], Tiago L. Campante[2,3], Thierry Appourchaux[4], Alfio Bonanno[5], William J. Chaplin[6], Rafael A. Garcia[7], Milena Martić[8], Benoit Mosser[9], R. Paul Butler[10], Hans Bruntt[1,11], László L. Kiss[1,12], Simon J. O'Toole[13], Eiji Kambe[14], Hiroyasu Ando[15], Hideyuki Izumiura[14], Bun'ei Sato[16], Michael Hartmann[17], Artie Hatzes[17], Caroline Barban[11], Gabrielle Berthomieu[18], Eric Michel[11], Janine Provost[18], Sylvaine Turck-Chièze[7], Jean-Claude Lebrun[8], Jerome Schmitt[19], Jean-Loup Bertaux[8], Serena Benatti[20], Riccardo U. Claudi[21], Rosario Cosentino[5], Silvio Leccia[22], Søren Frandsen[2], Karsten Brogaard[2], Lars Glowienka[2], Frank Grundahl[2], Eric Stempels[23], Torben Arentoft[2], Michaël Bazot[2], Jørgen Christensen-Dalsgaard[2], Thomas H. Dall[24], Christoffer Karoff[2], Jens Lundgreen-Nielsen[2], Fabien Carrier[25], Patrick Eggenberger[26], Danuta Sosnowska[27], Robert A. Wittenmyer[28,29], Michael Endl[28], Travis S. Metcalfe[30], Saskia Hekker[6,31], and Sabine Reffert[32]

Velocity observations of Procyon (F5 IV)

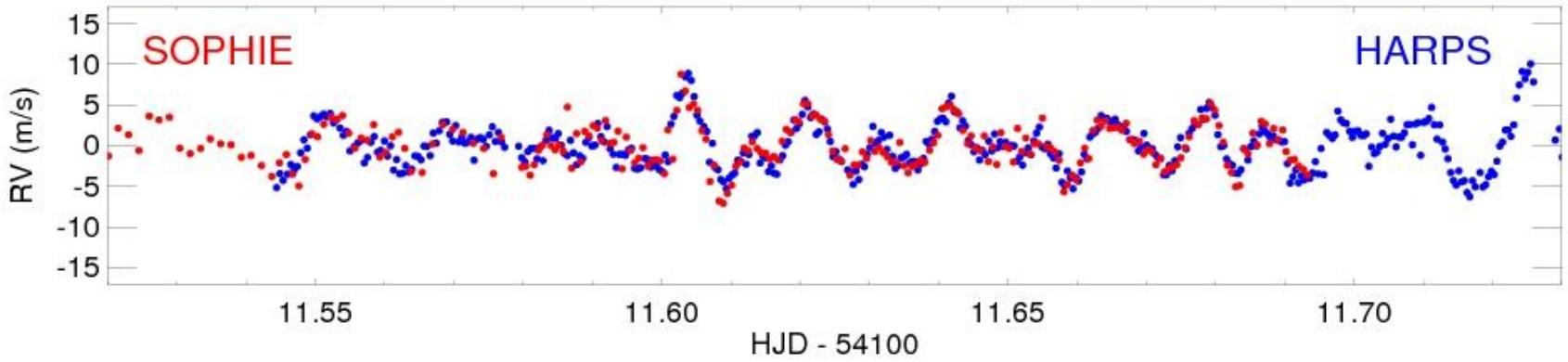


$\Delta\nu \approx 55\mu$Hz but no agreement on individual frequencies

2008: Velocities of Procyon with a network of 11 telescopes at 8 observatories over 25 days

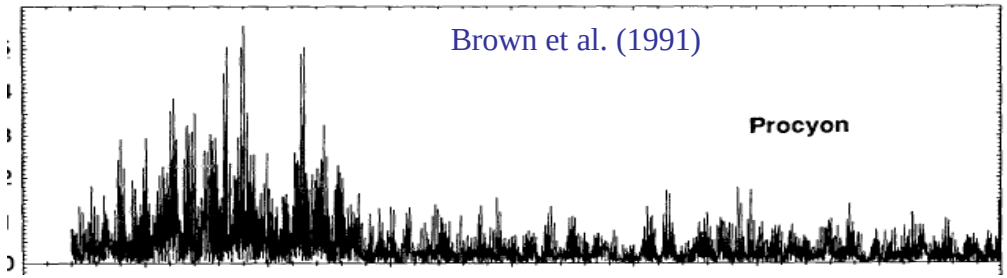


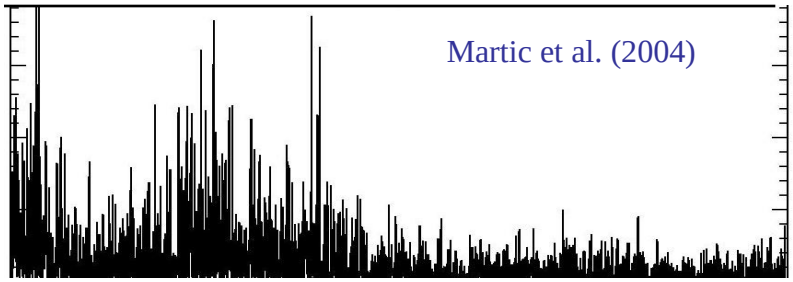
HARPS
CORALIE
McDonald
Lick
UCLES
Okayama
Tautenburg
SOPHIE
EMILIE
SARG
FIES

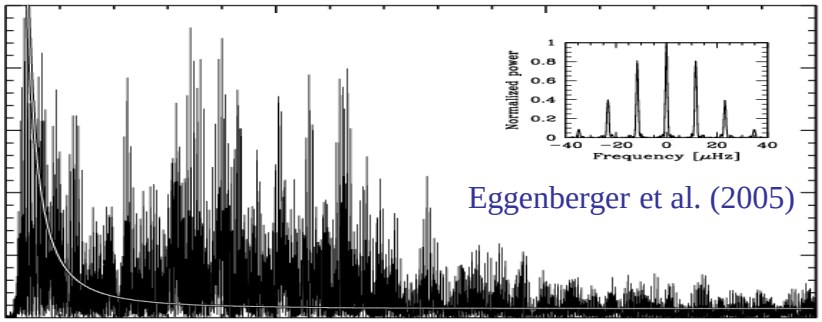


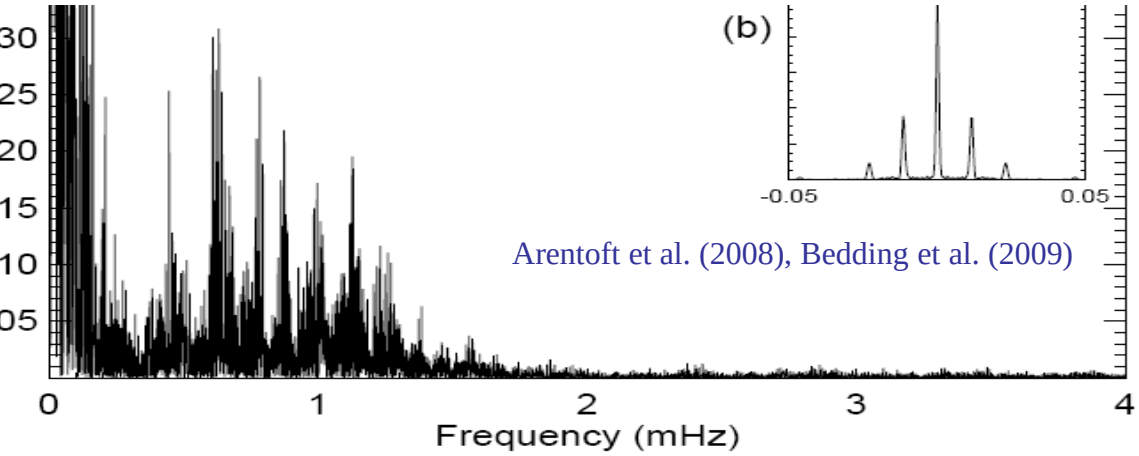
Arentoft et al. (2008), Bedding et al. (2009)

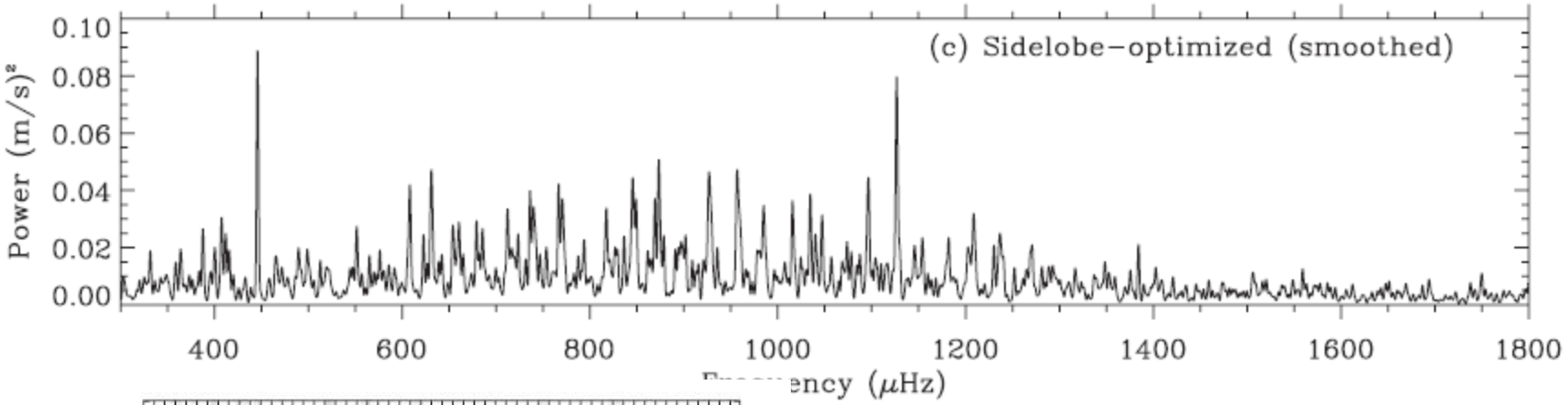
Velocity observations of Procyon (F5 IV)

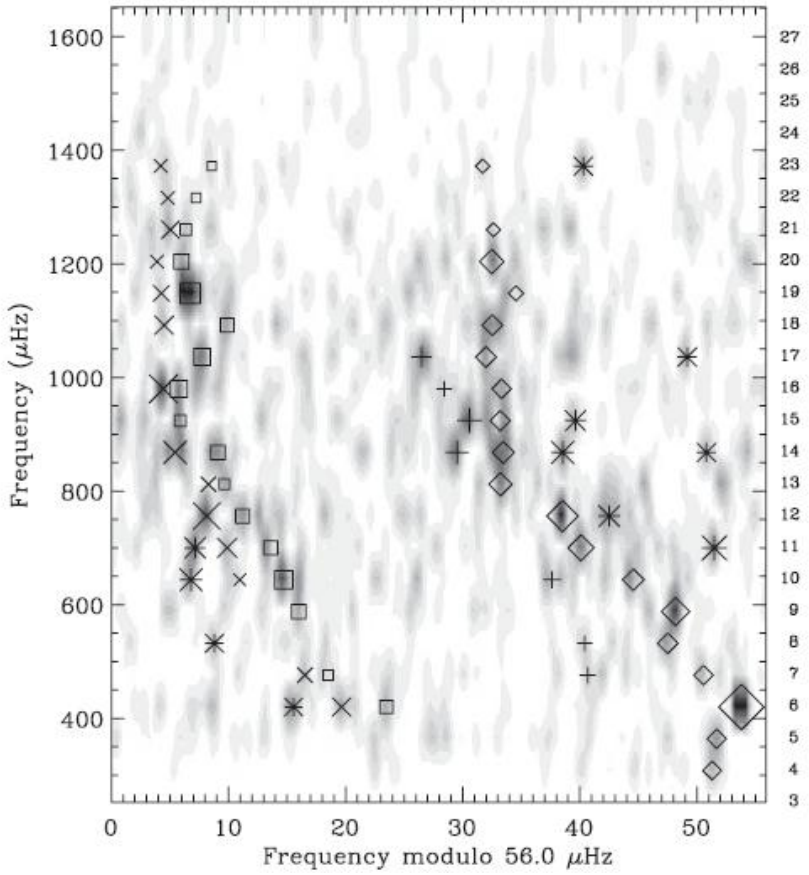










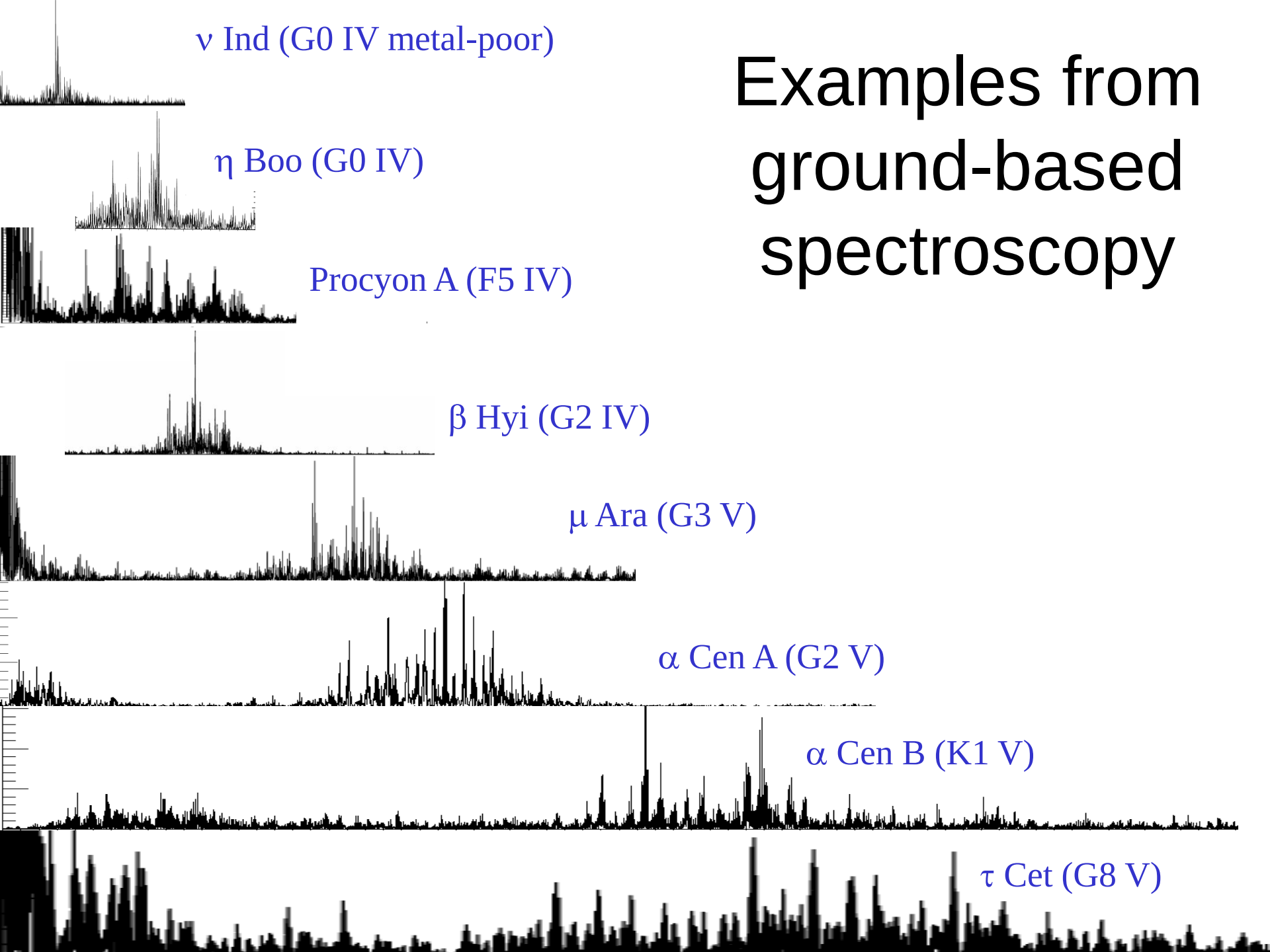


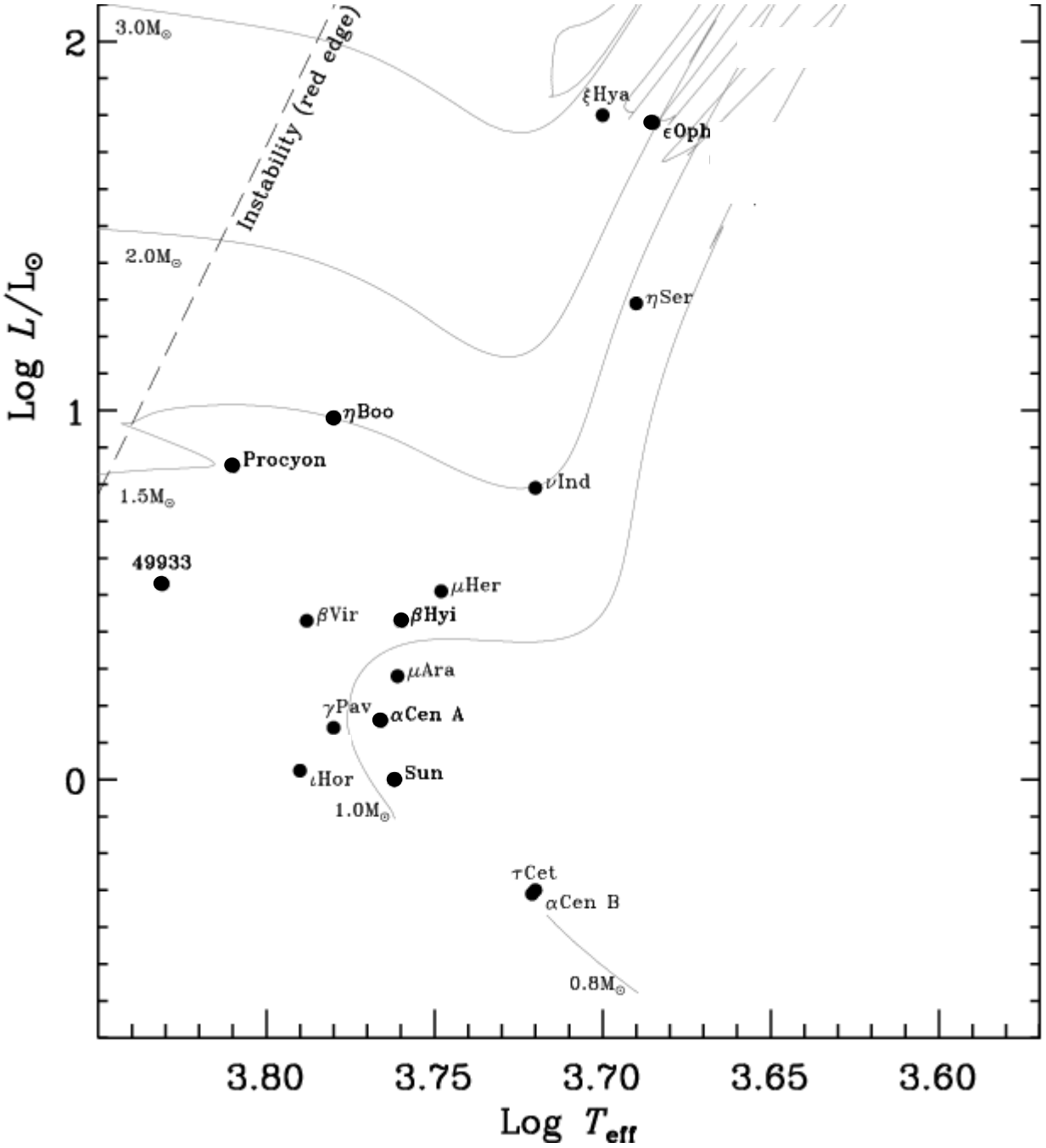
broad modes (short lifetimes)

“bloody F star”

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

Examples from ground-based spectroscopy





Ground-based velocity

(stars with reliable $\Delta\nu$)

figure by Dennis Stello

The next step from the ground: a network dedicated to asteroseismology

First node in Tenerife

VELUX®

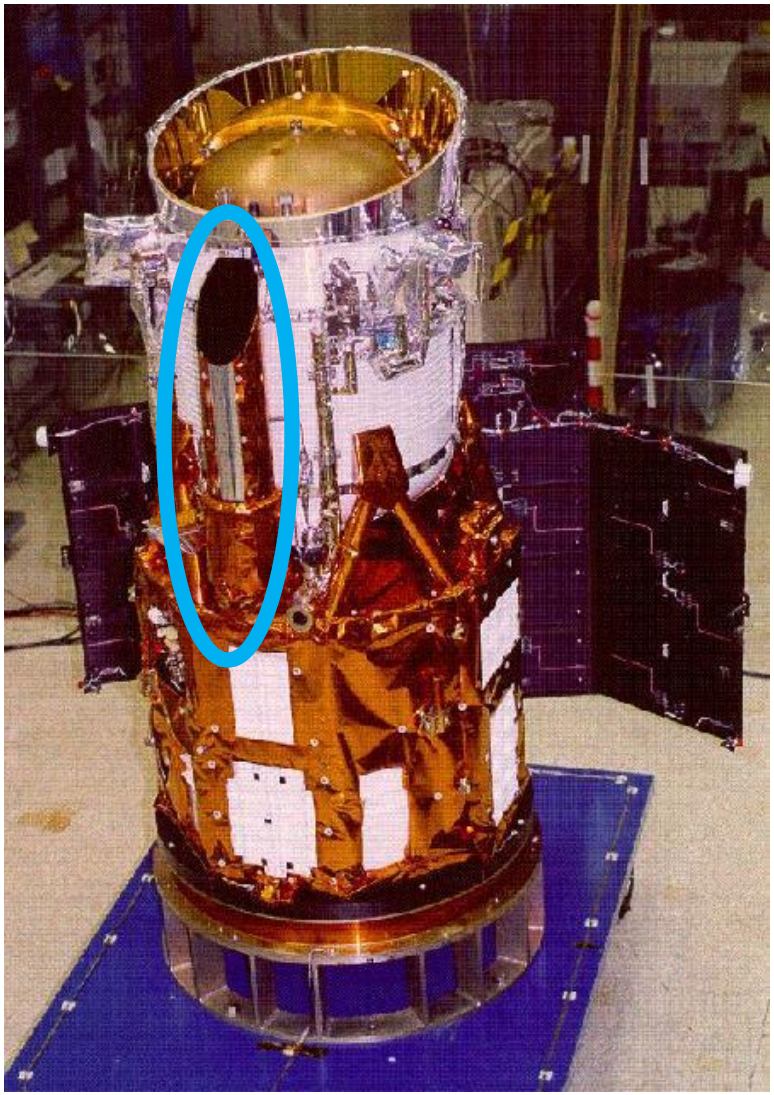
Carlsberg®

Solar-like oscillations from space

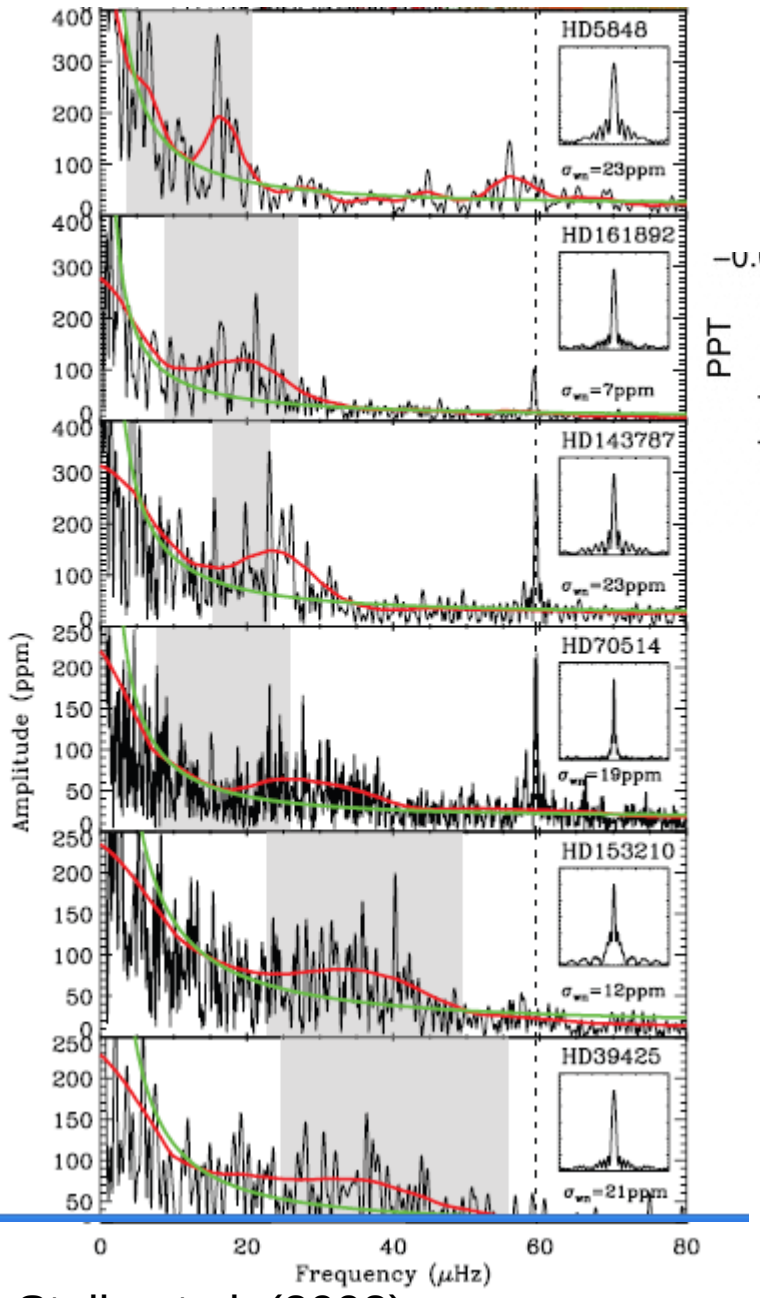
- *WIRE* (NASA): 5cm
- *MOST* (Canada): 15cm
- *COROT* (France/ESA): 27cm
- *Kepler* (NASA): 95cm

Wide Field Infrared Explorer (WIRE)

- launched on 5 March 1999
- primary mission failed
- asteroseismology using the 5cm star camera (Derek Buzasi)

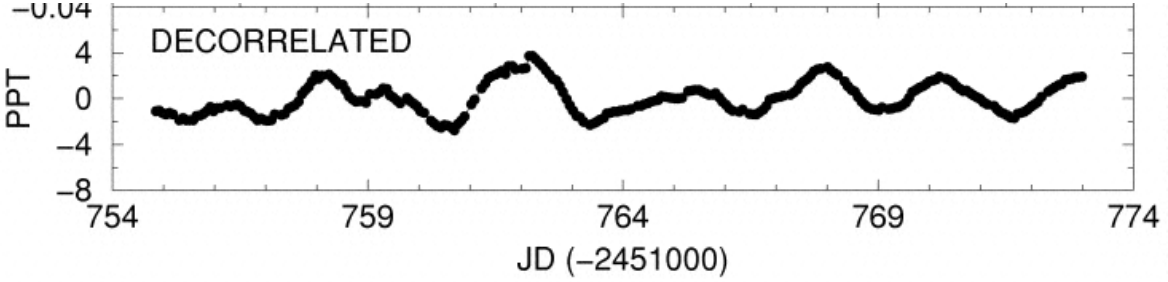


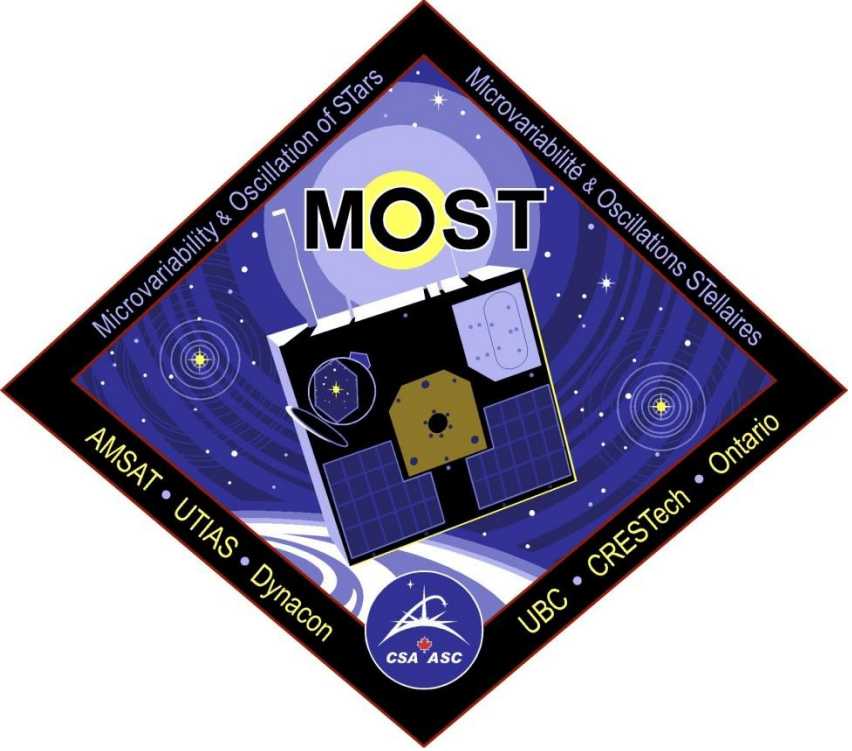
WIRE photometry of red giants



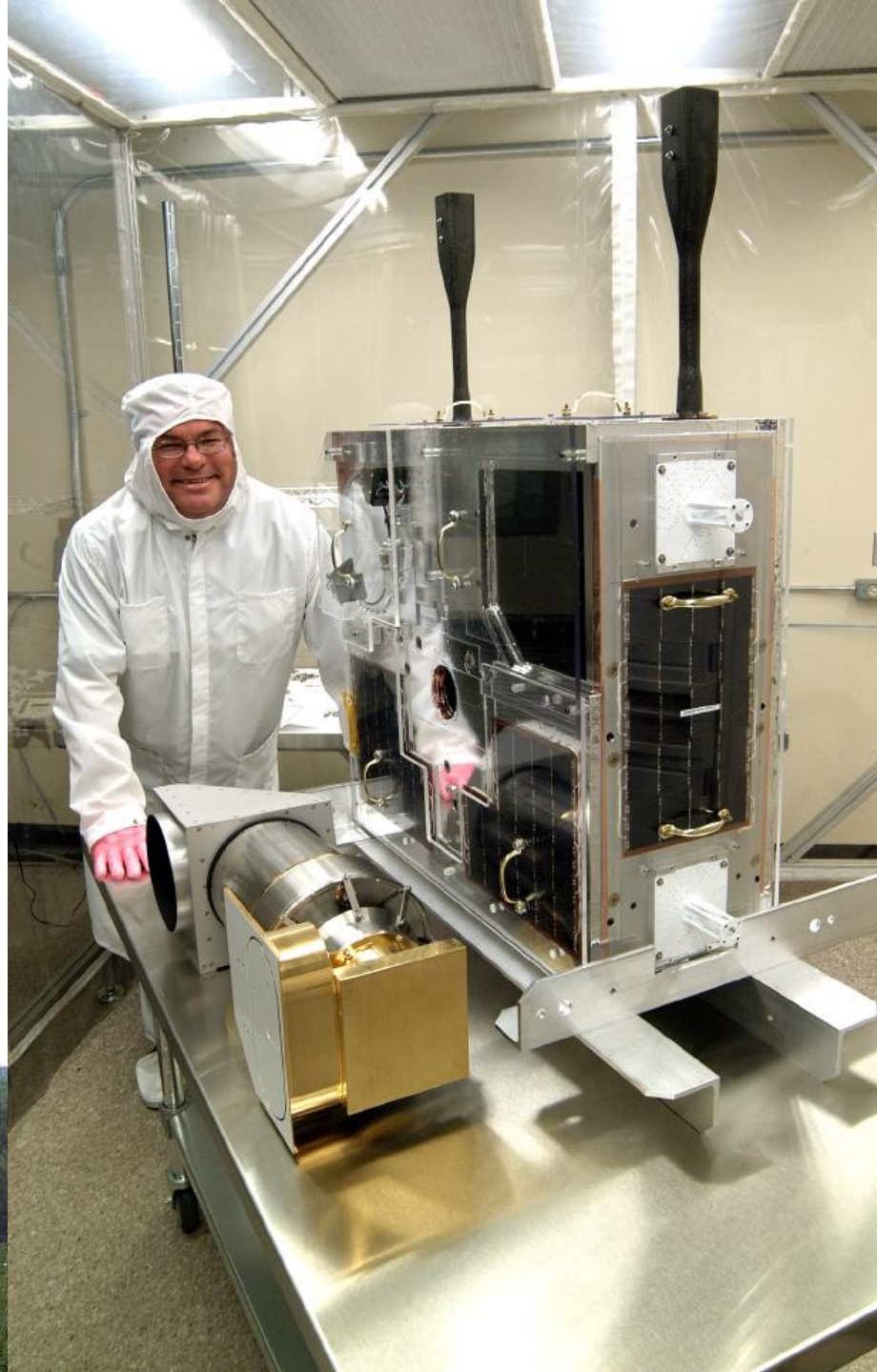
Stello et al. (2008)

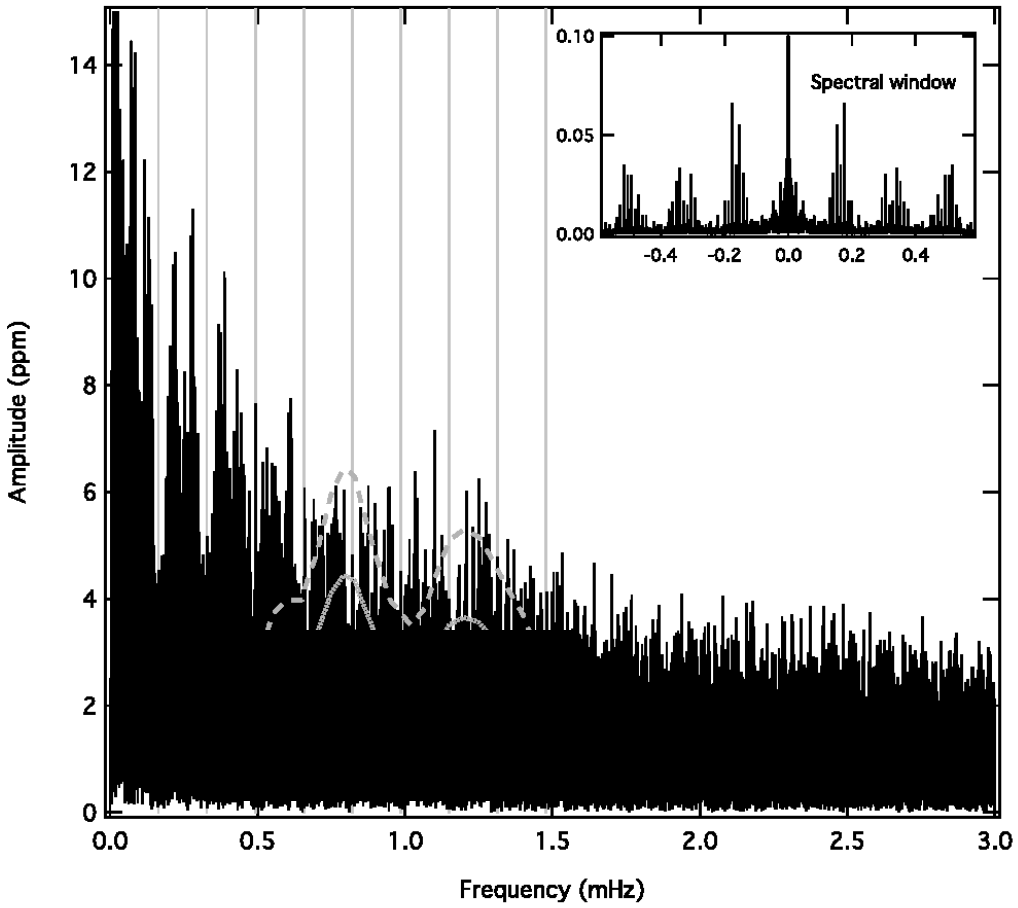
Arcturus (Retter et al. 2003)





Launched June 30, 2003 (15 cm)



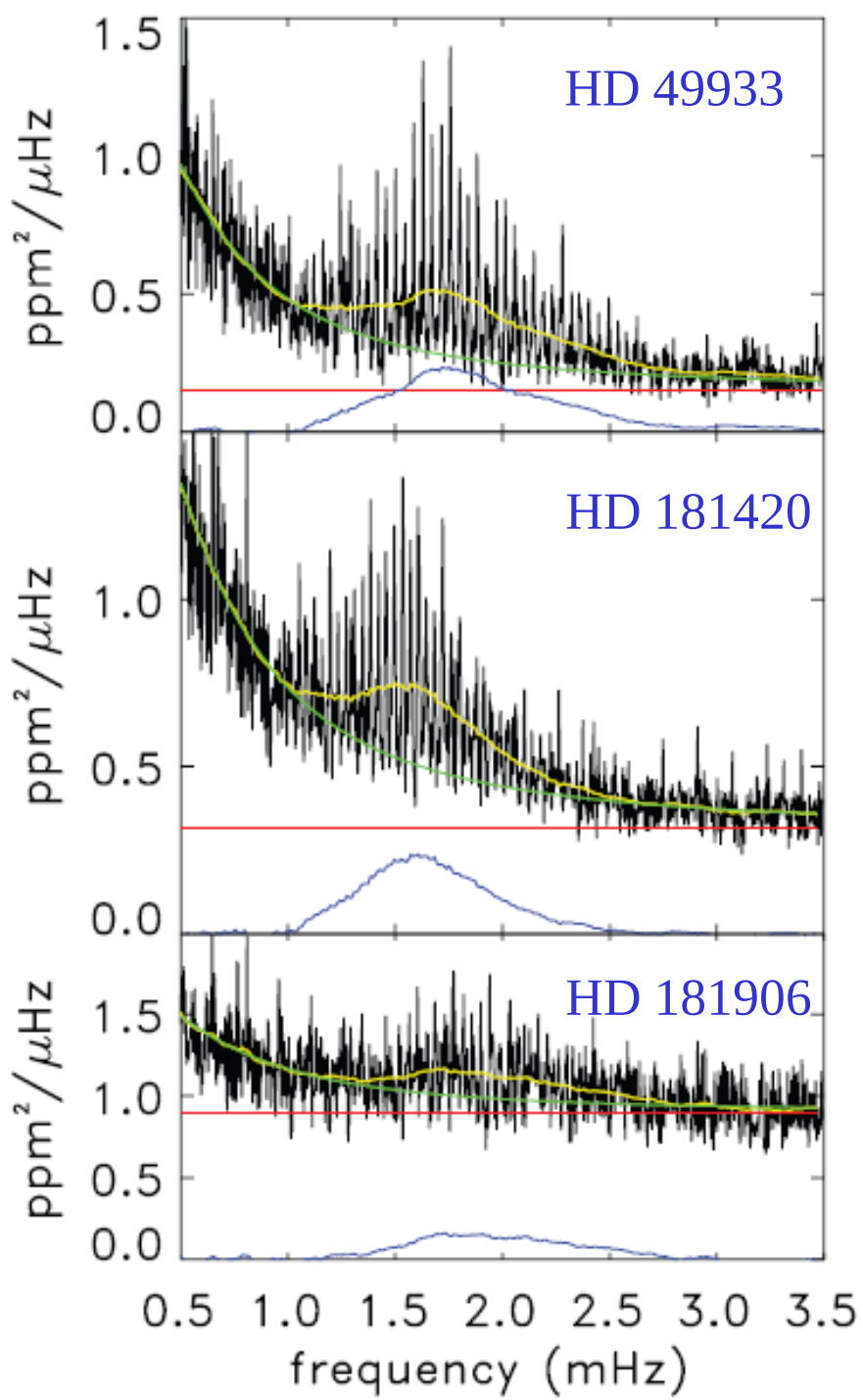


more data on Procyon with MOST: Guenther et al. (2008)

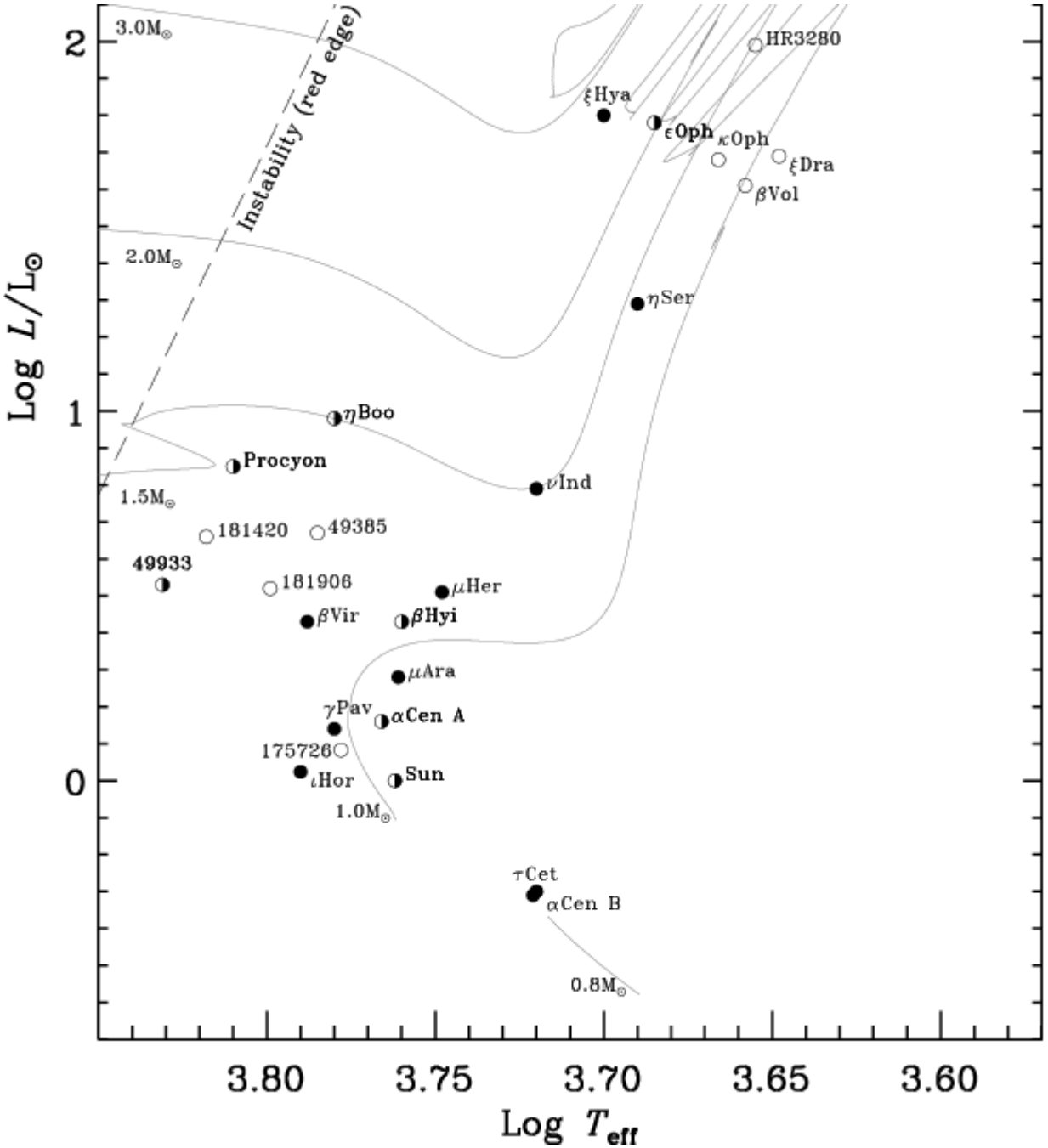
see also Huber et al. (2011)

CoRoT (27 cm)

Launched: 27 December 2006



F stars with CoRoT
(Michel et al. 2008)



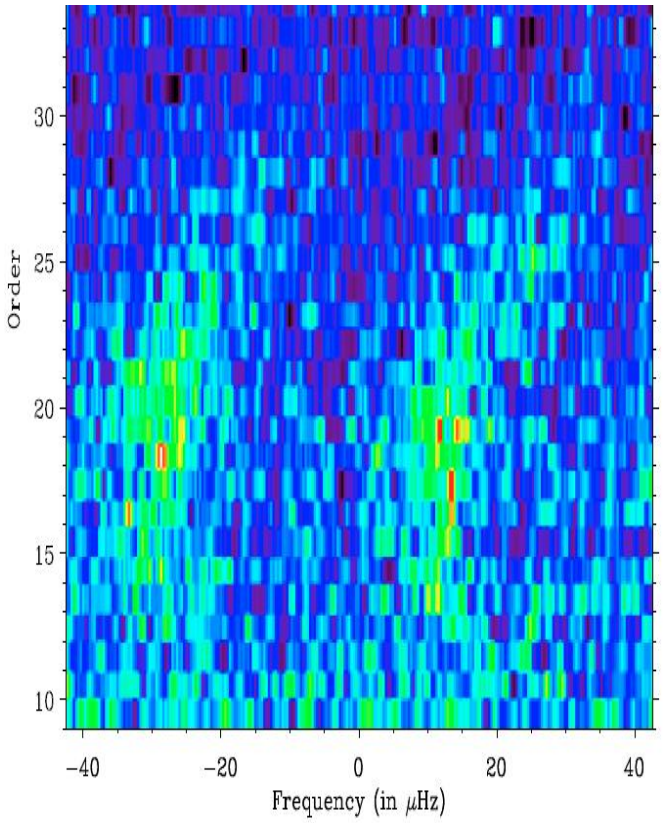
pre-Kepler

Stars with reliable $\Delta\nu$

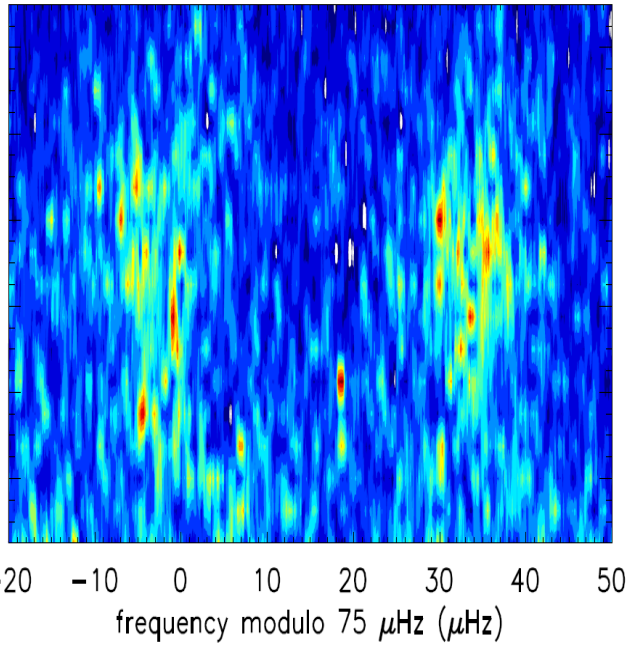
●=spectroscopy
○=photometry

figure by Dennis Stello

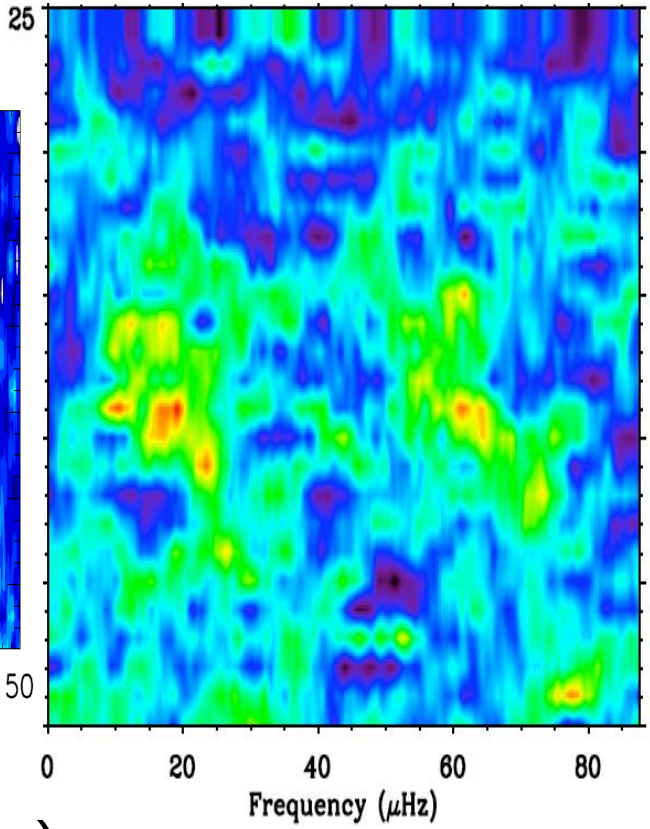
HD 49933
Appourchaux et al. (2008),
Benomar et al. (2009), etc.



HD 181420
Barban et al. (2009)

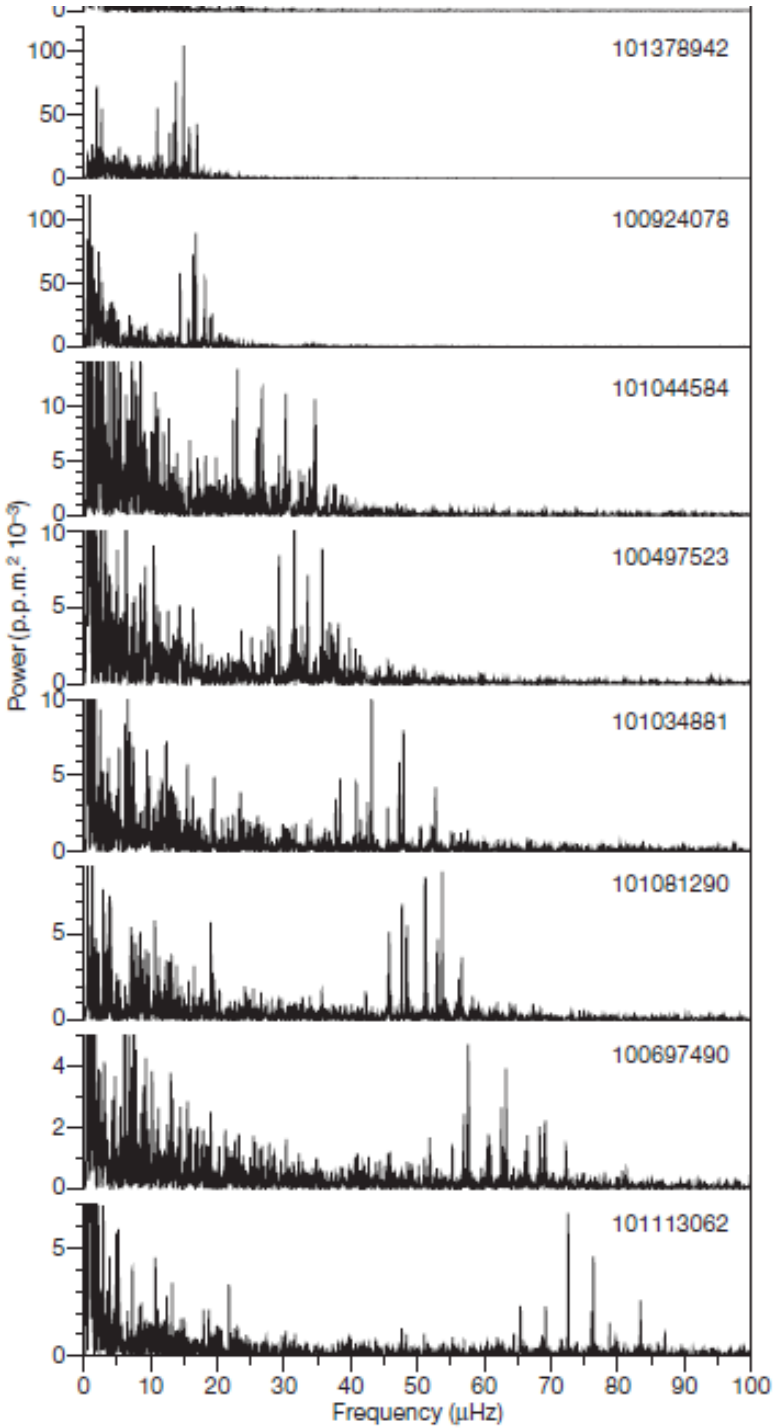


HD 181906
Garcia et al. (2009)



broad modes (short lifetimes)

more bloody F stars



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

beautiful!

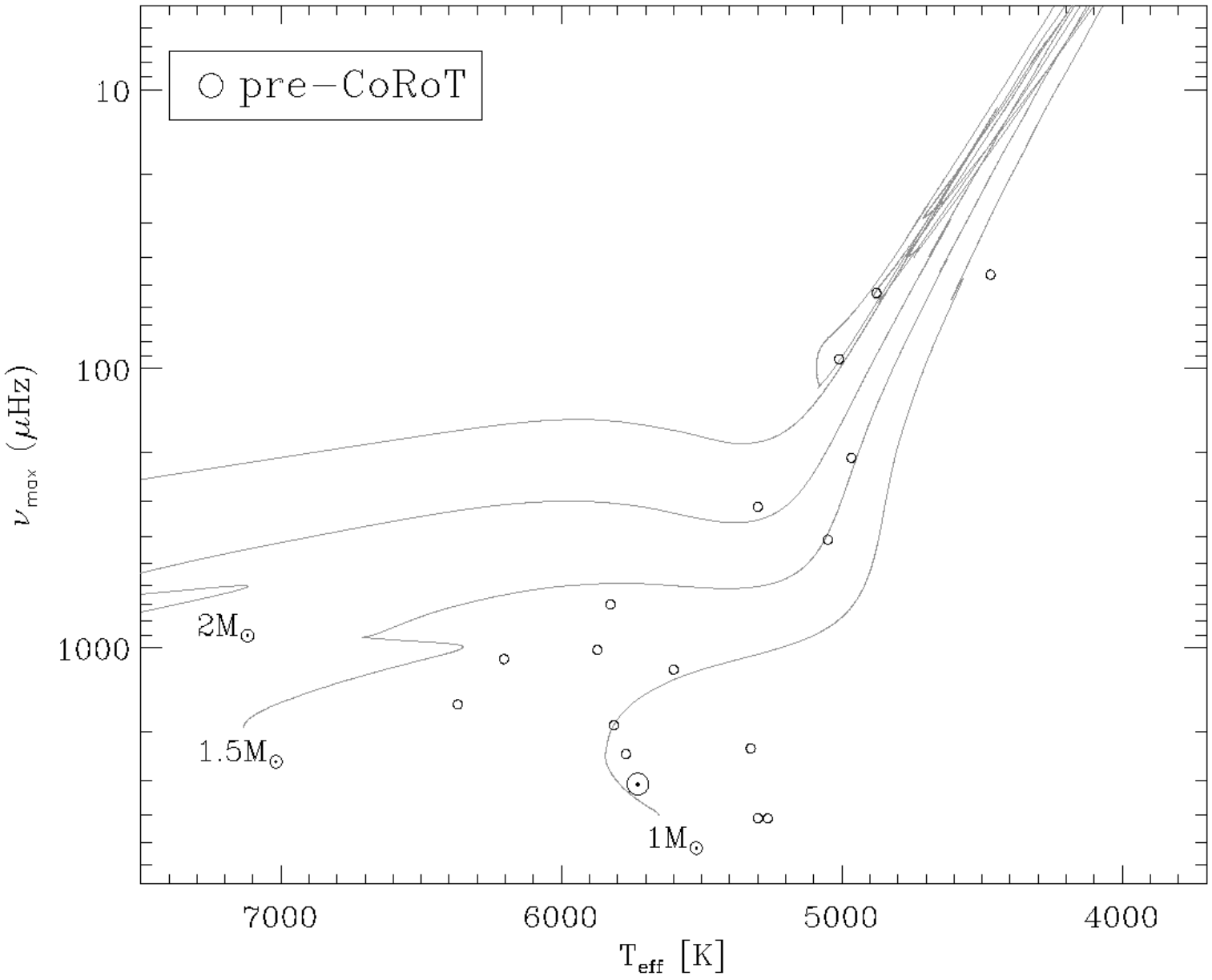


figure by Daniel Huber

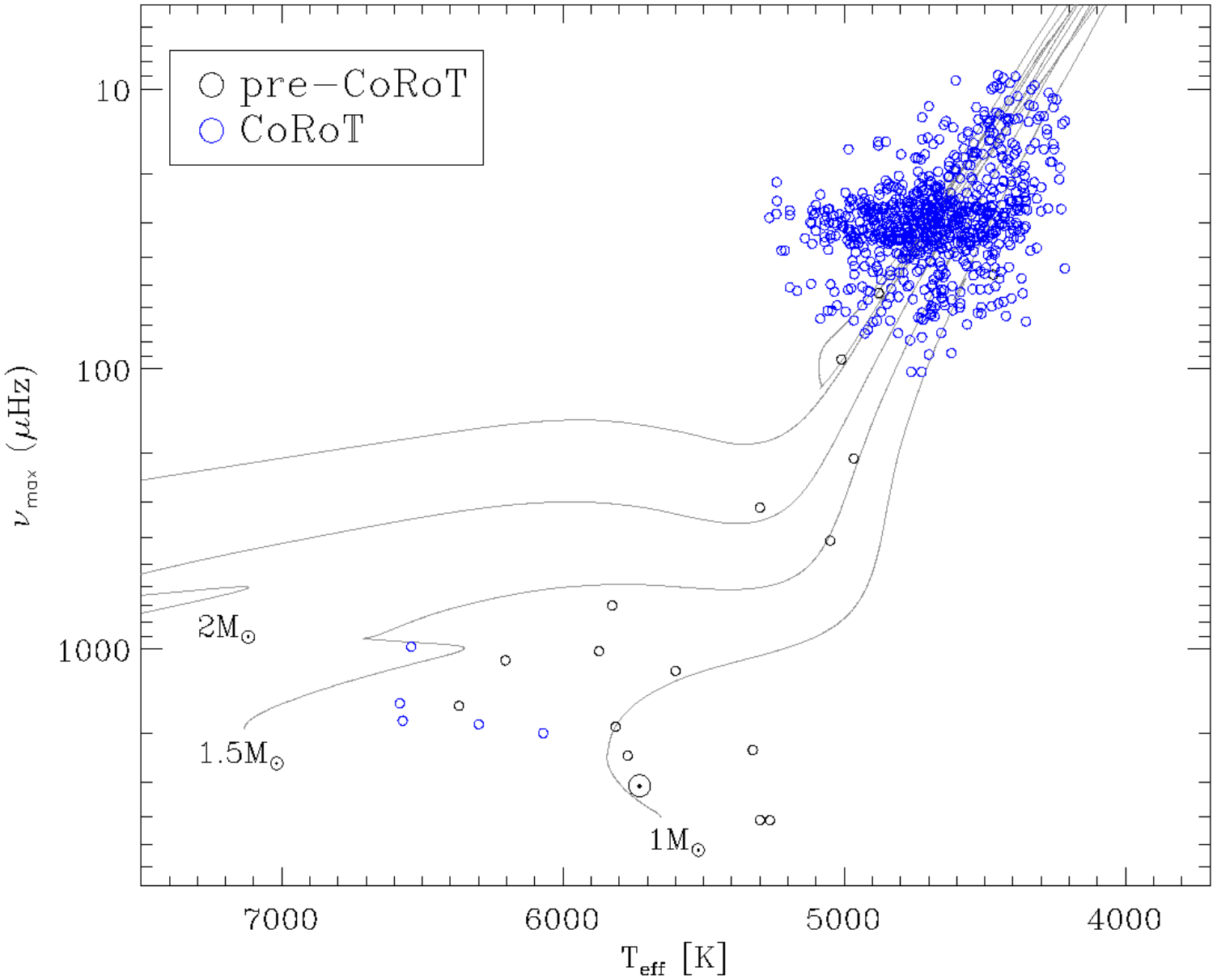
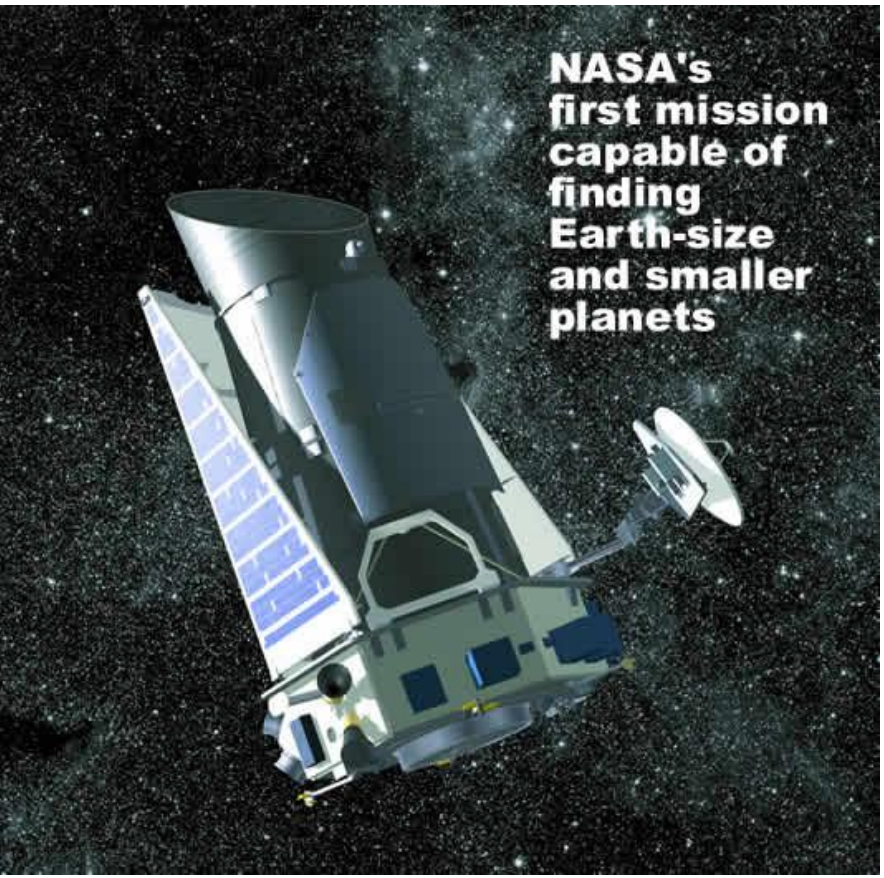
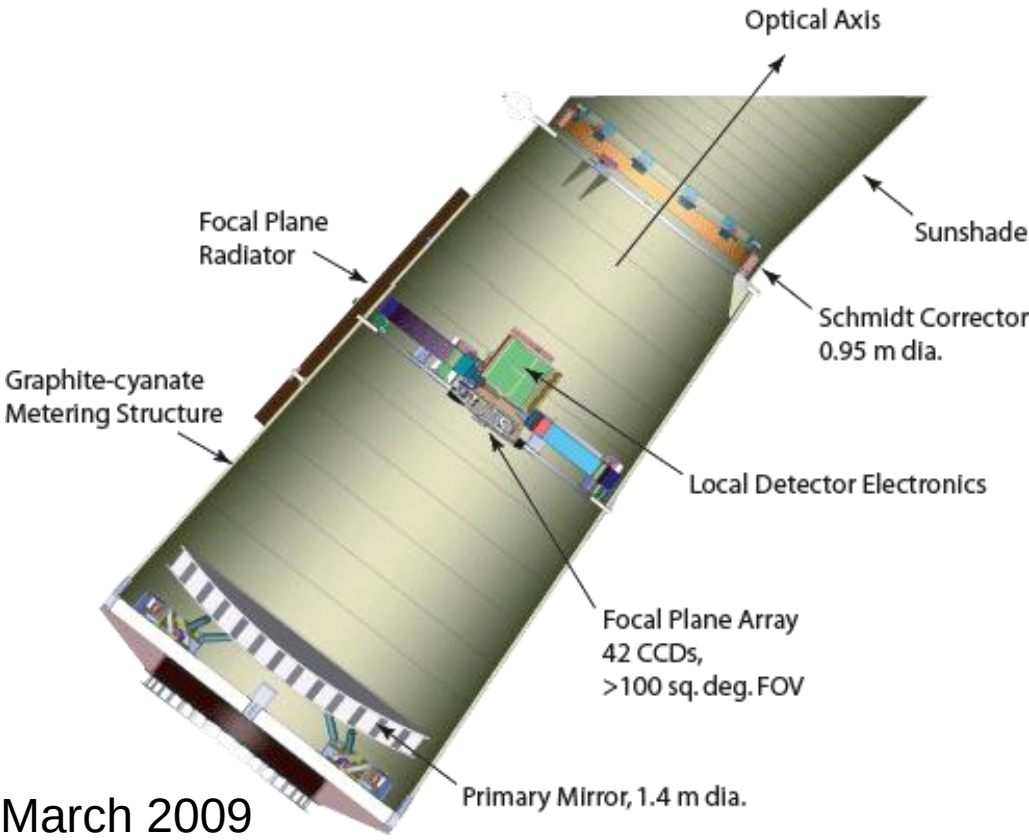


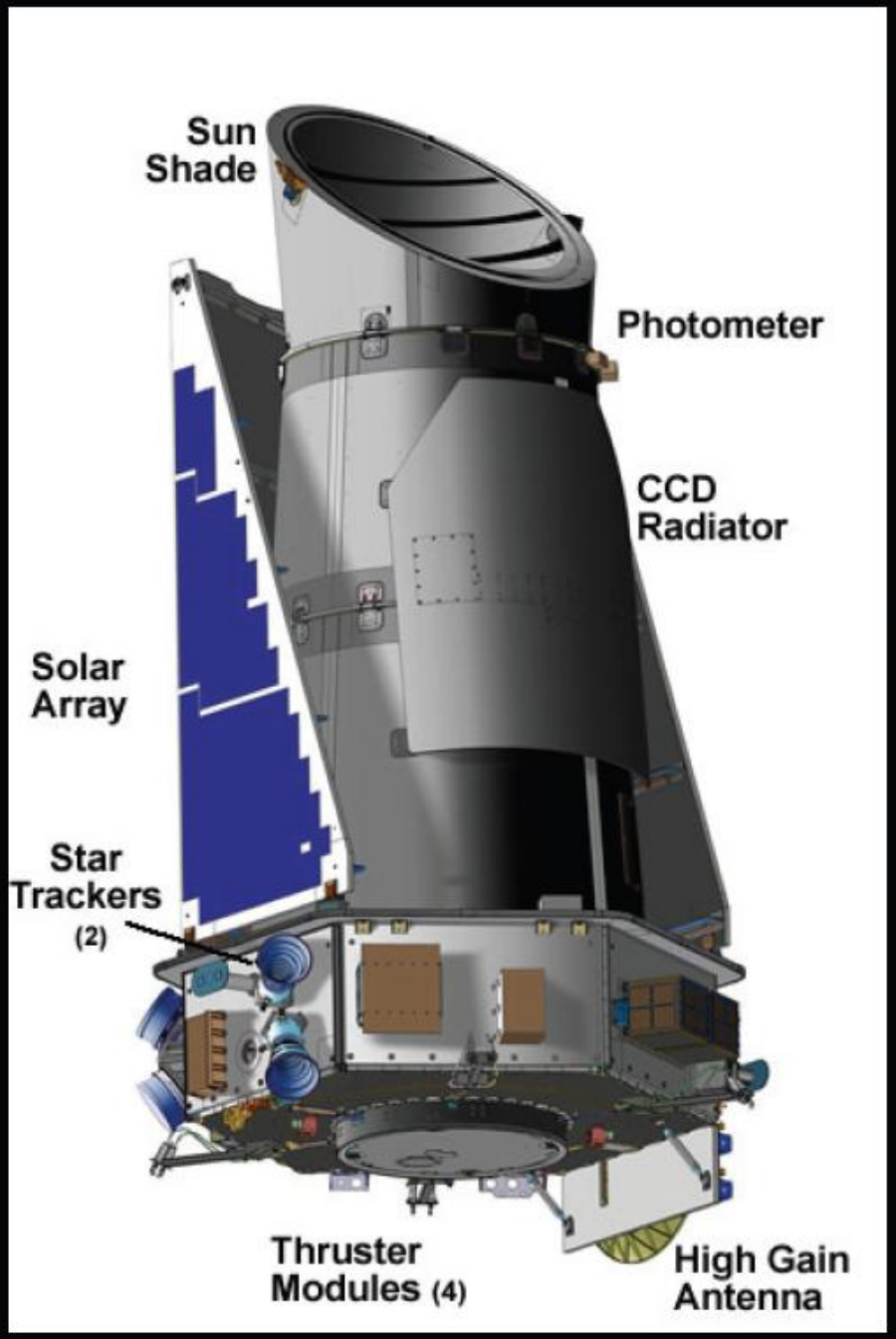
figure by Daniel Huber

Kepler (95 cm)

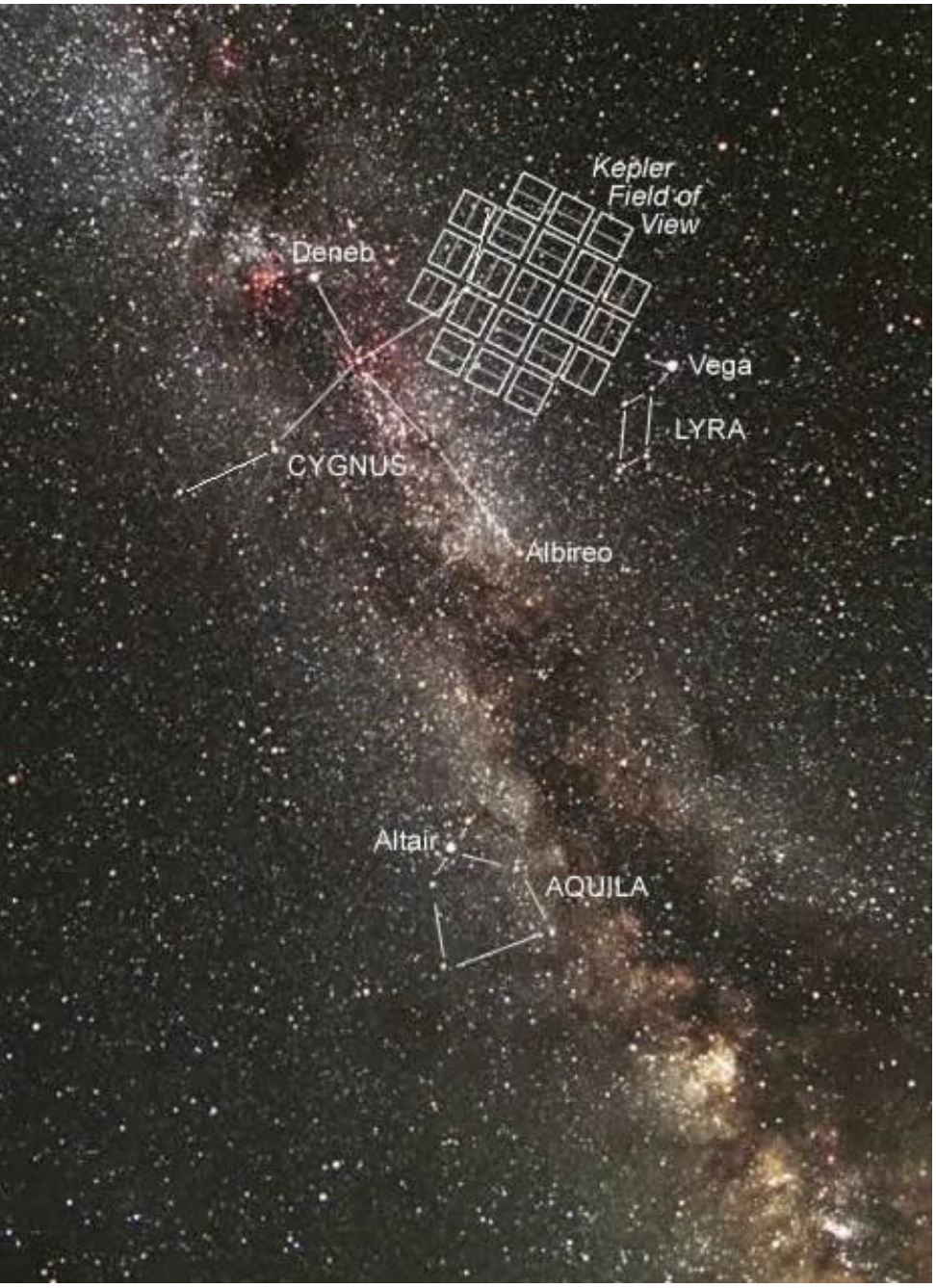


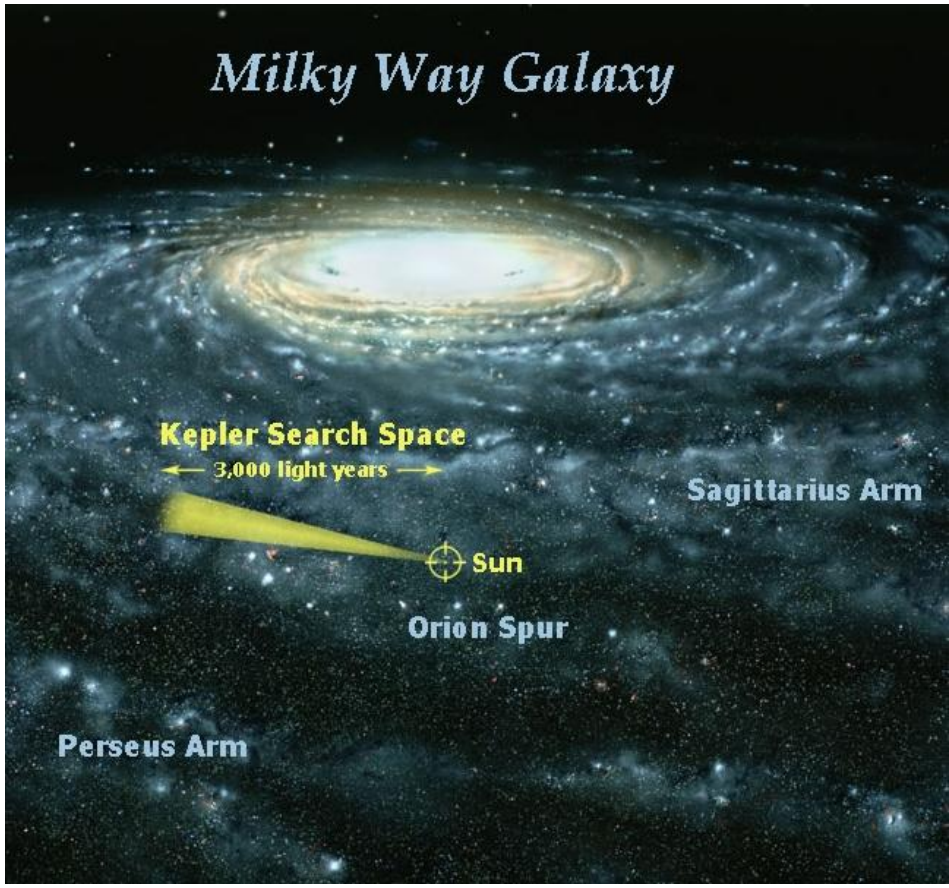


Launched 6 March 2009


Sun Shade
Photometer
CCD Radiator
Solar Array
Star Trackers (2)
Thruster Modules (4)
High Gain Antenna

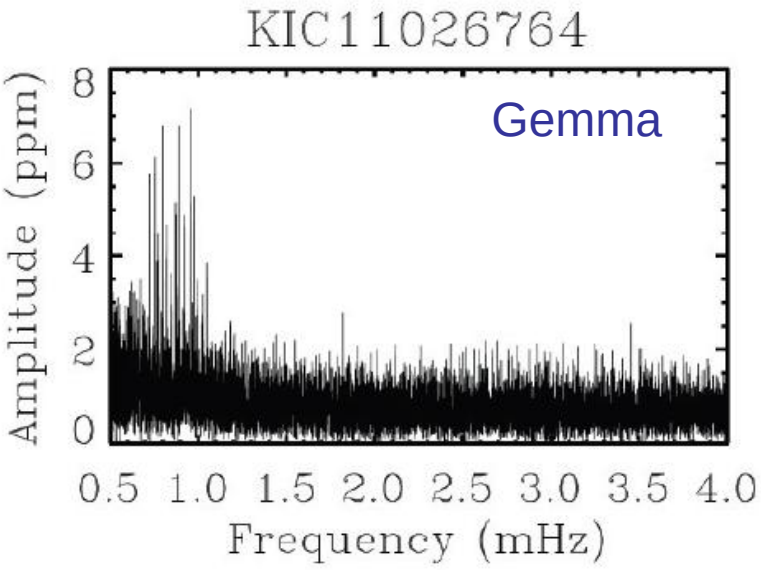
Launched 6 March 2009

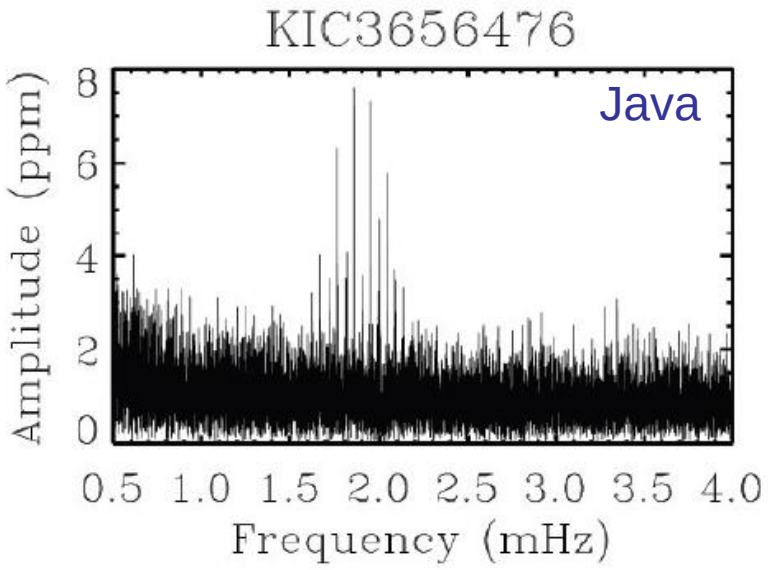


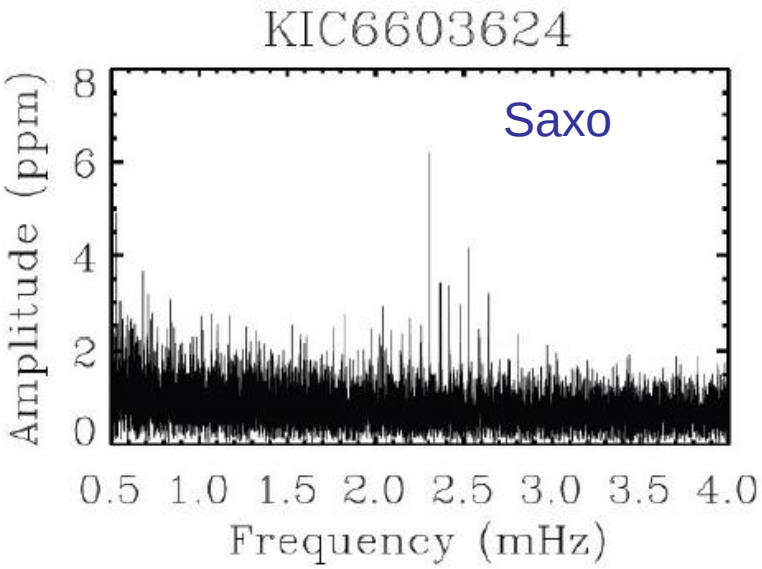


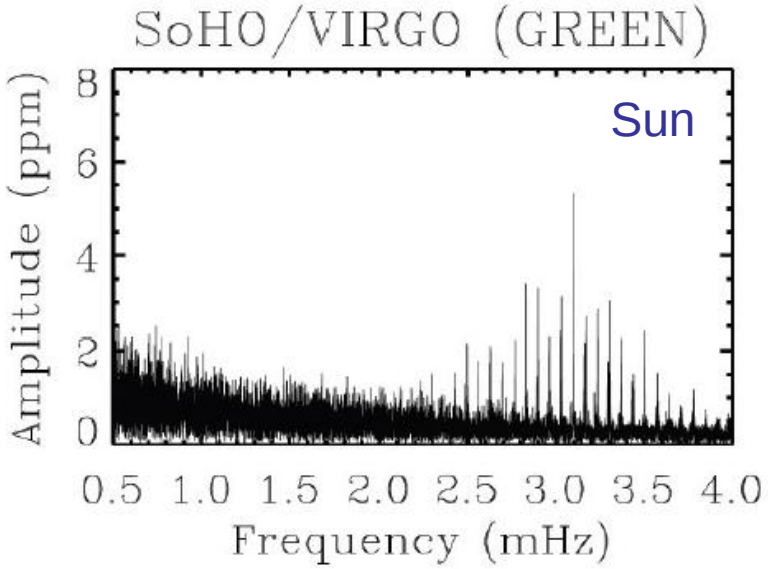
- *not* in low-Earth orbit
- one field for >4 years

Three G-type stars after one month with Kepler



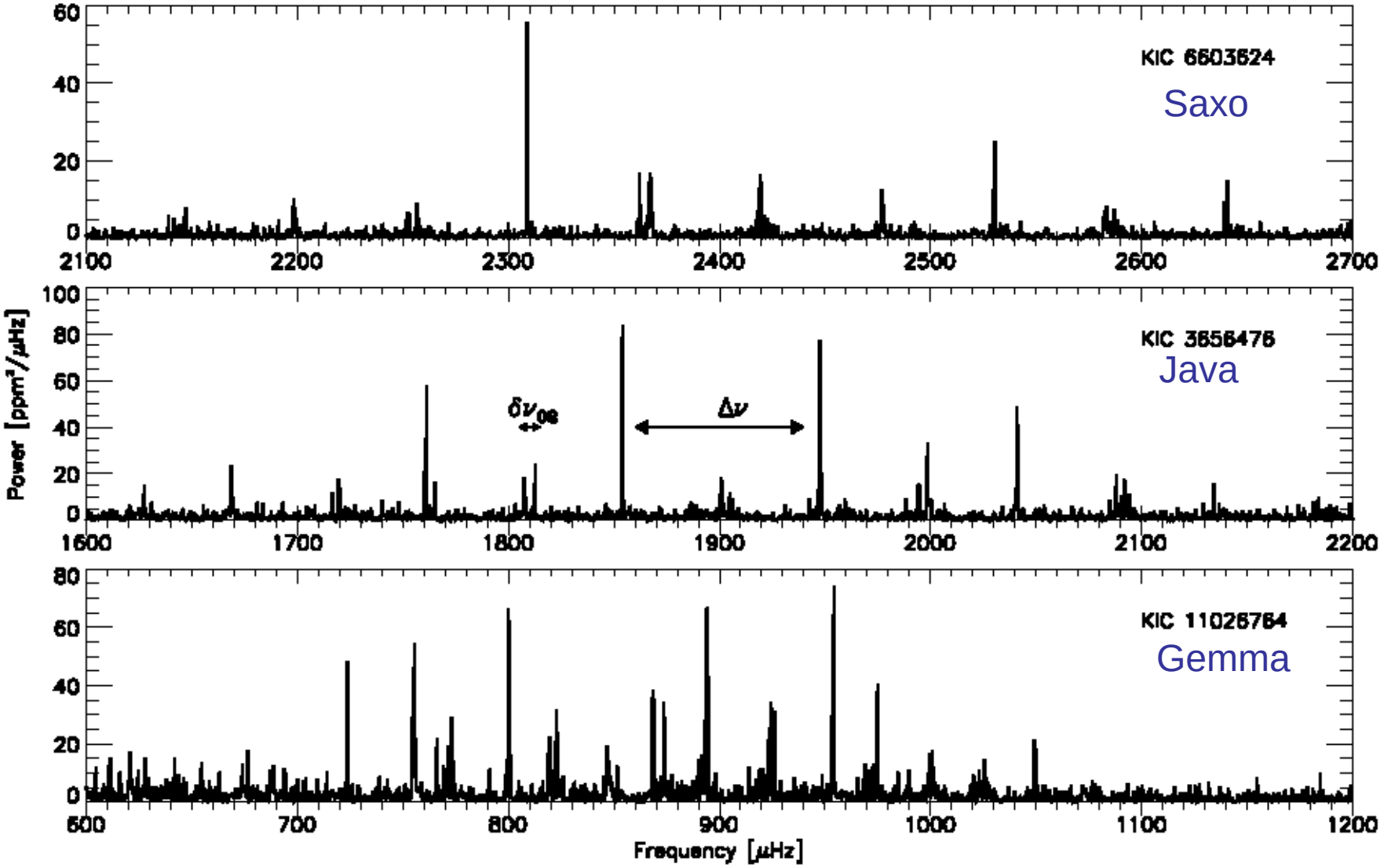


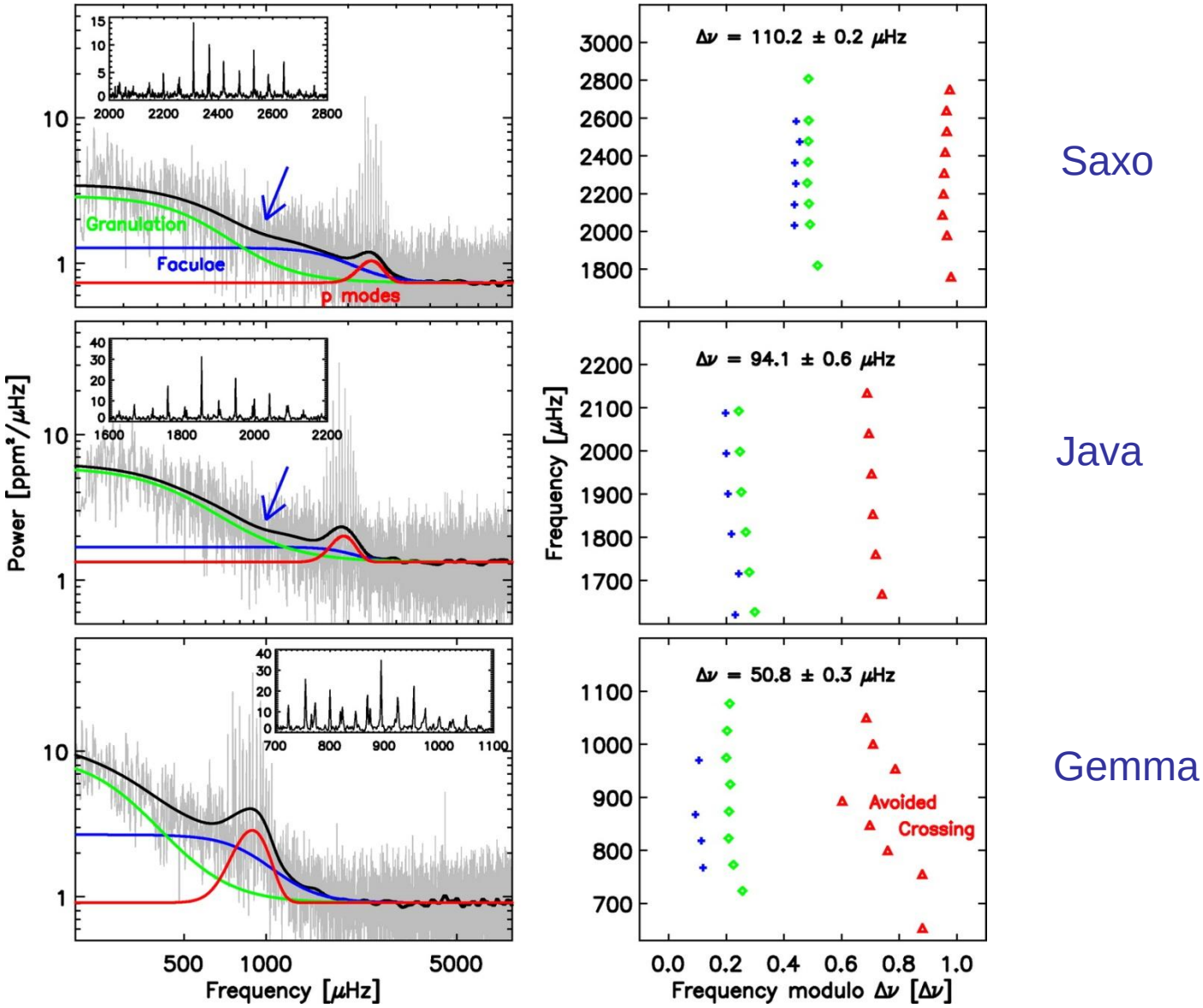




http://owww.phys.au.dk/~hans/tidsserie/Lecture_12.pdf

Three G stars with Kepler (Chaplin et al. 2010)





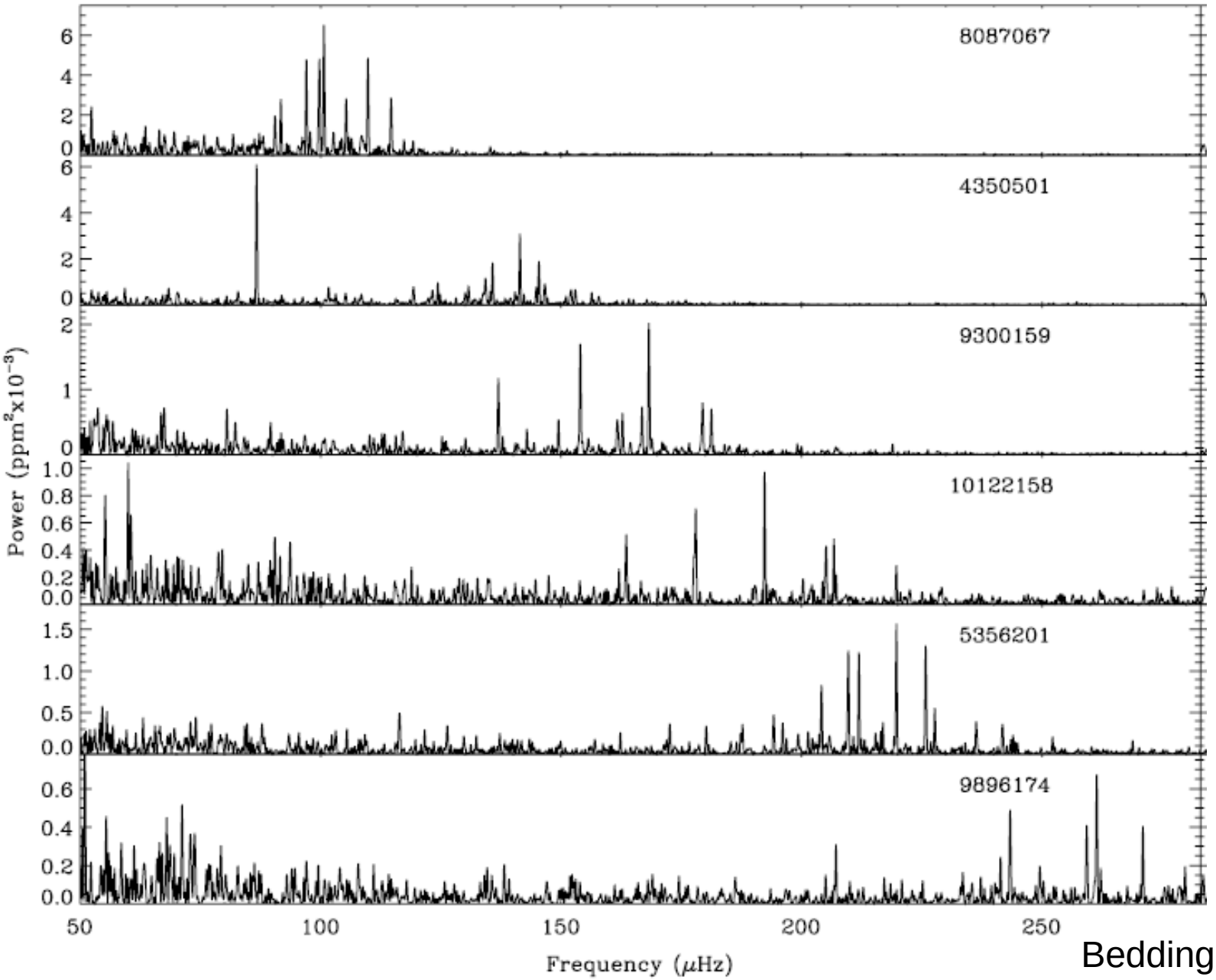
Saxo

Java

Gemma

Gilliland et al. (2010)

Red giants with Kepler (first 30 days)



Bedding et al. 2010

Exercise 1: make an echelle diagram with these 14 frequencies

2140
2147
2198
2252
2257
2308
2362
2367
2419
2478
2530
2583
2587
2640

- plot (frequency) versus (frequency mod $\Delta\nu$)
- find the best $\Delta\nu$ (hint start with about 120μHz)
- what happens if you change $\Delta\nu$ slightly?