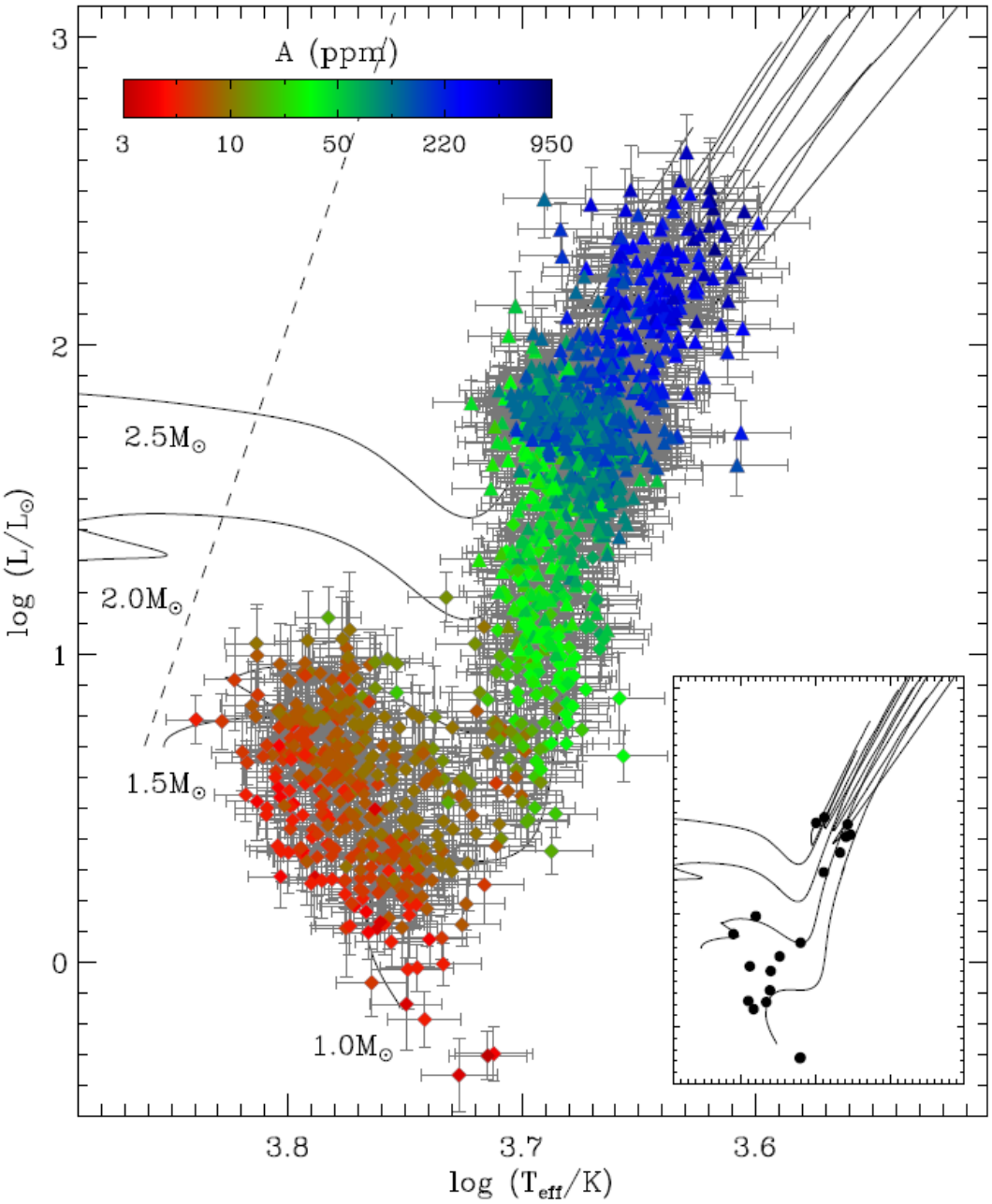
Oscillations in red giants

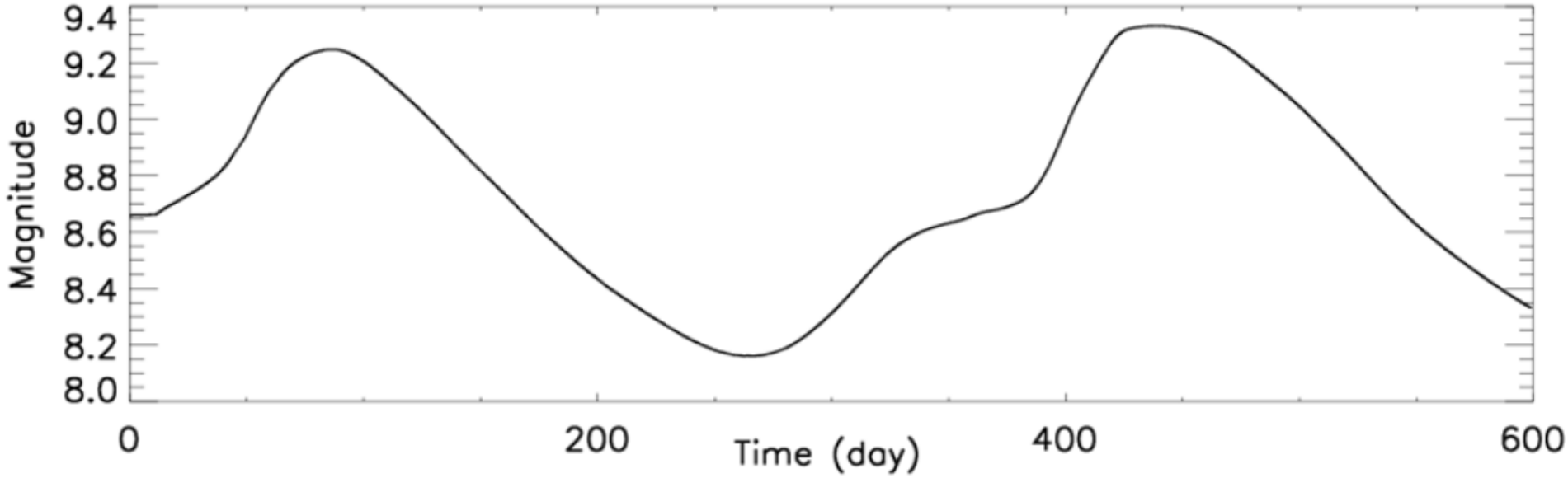
Tim Bedding
(SIfA, Univ. Sydney)

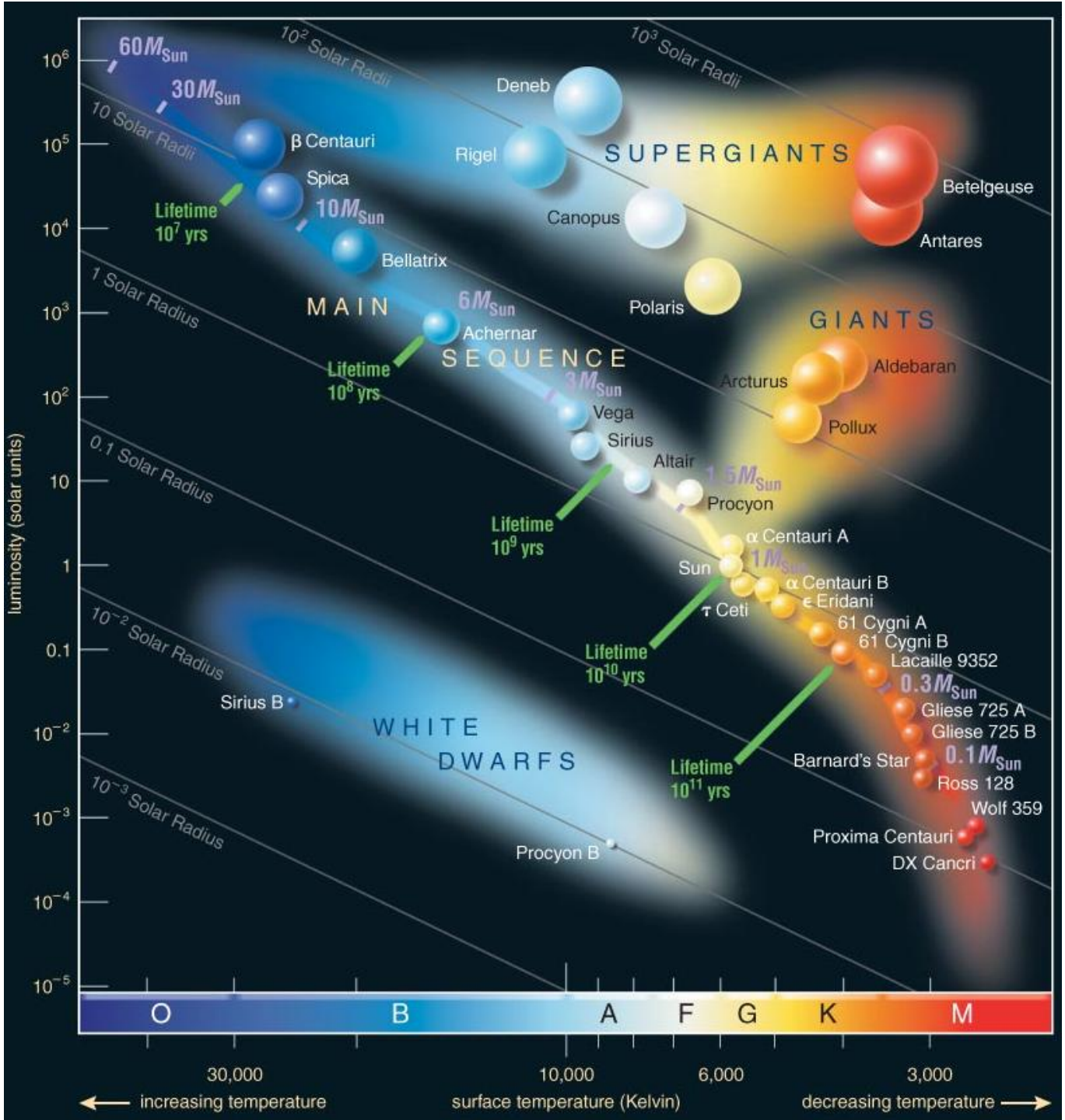


Question: When was the first detection of oscillations in a red giant?

Answer: 1596

A Mira with *Kepler*

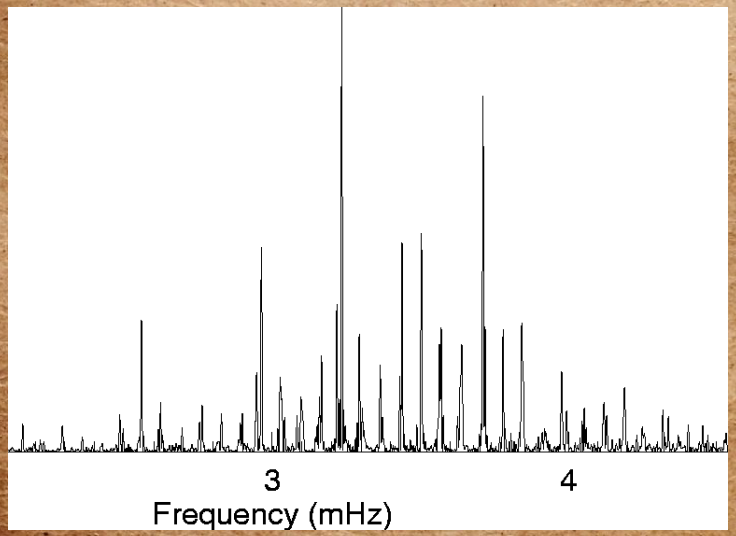



luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$60M_{Sun}$
$30M_{Sun}$
$10M_{Sun}$
$6M_{Sun}$
$3M_{Sun}$
$1.5M_{Sun}$
$1M_{Sun}$
$0.3M_{Sun}$
$0.1M_{Sun}$
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
Deneb
Rigel
SUPERGIANTS
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
MAIN
SEQUENCE
Achernar
GIANTS
Aldebaran
Arcturus
Pollux
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
ϵ Eridani
τ Ceti
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
WHITE
DWARFS
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

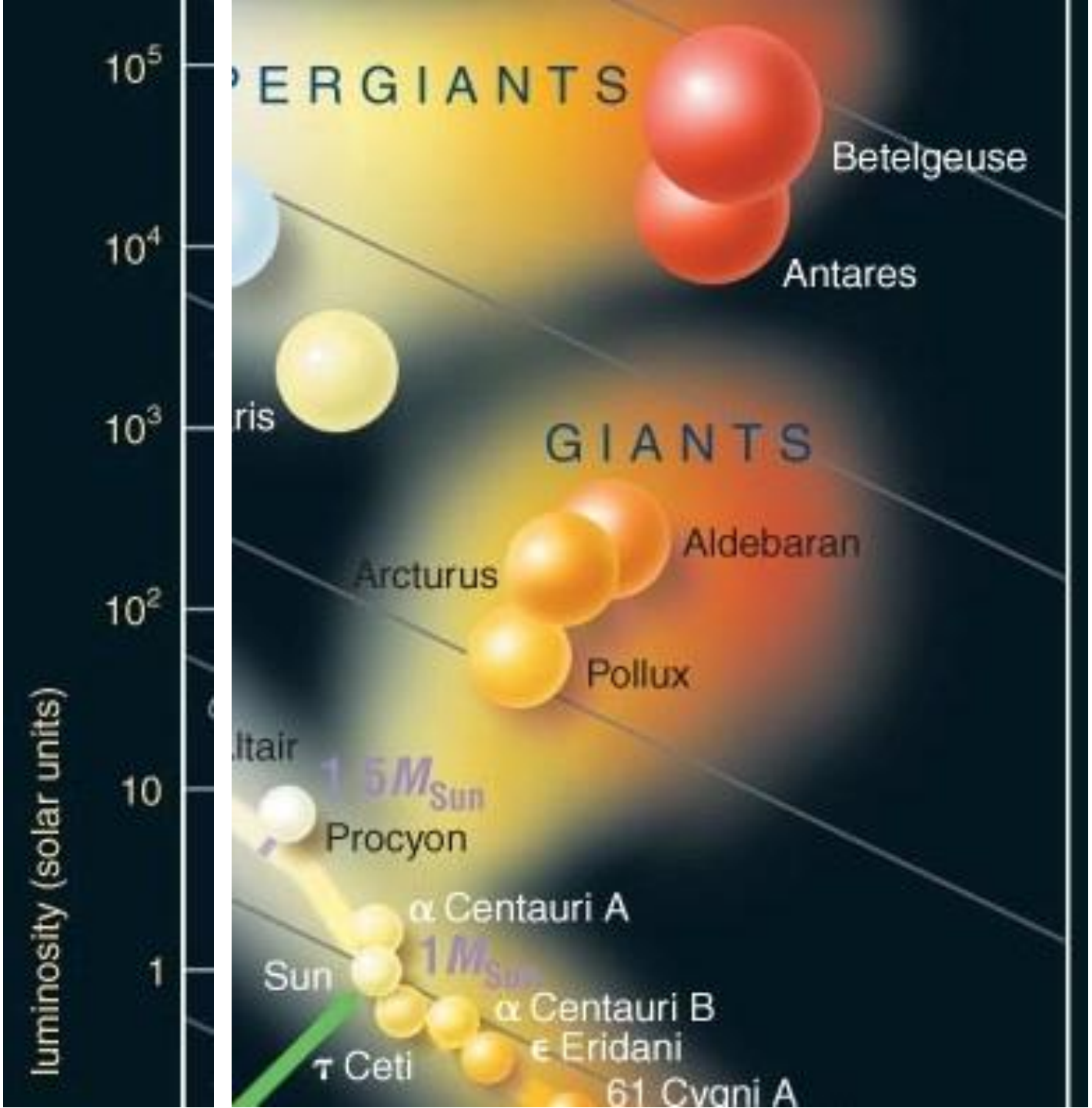
WANTED

DEAD OR ALIVE

Big red version of this:



REWARD $ 1,000,000


luminosity (solar units)
10^5
10^4
10^3
10^2
10
1
ERGIANTS
Betelgeuse
Antares
ris
GIANTS
Aldebaran
Arcturus
Pollux
ltair
1.5M_{Sun}
Procyon
α Centauri A
1M_{Sun}
Sun
α Centauri B
ϵ Eridani
τ Ceti
61 Cygni A

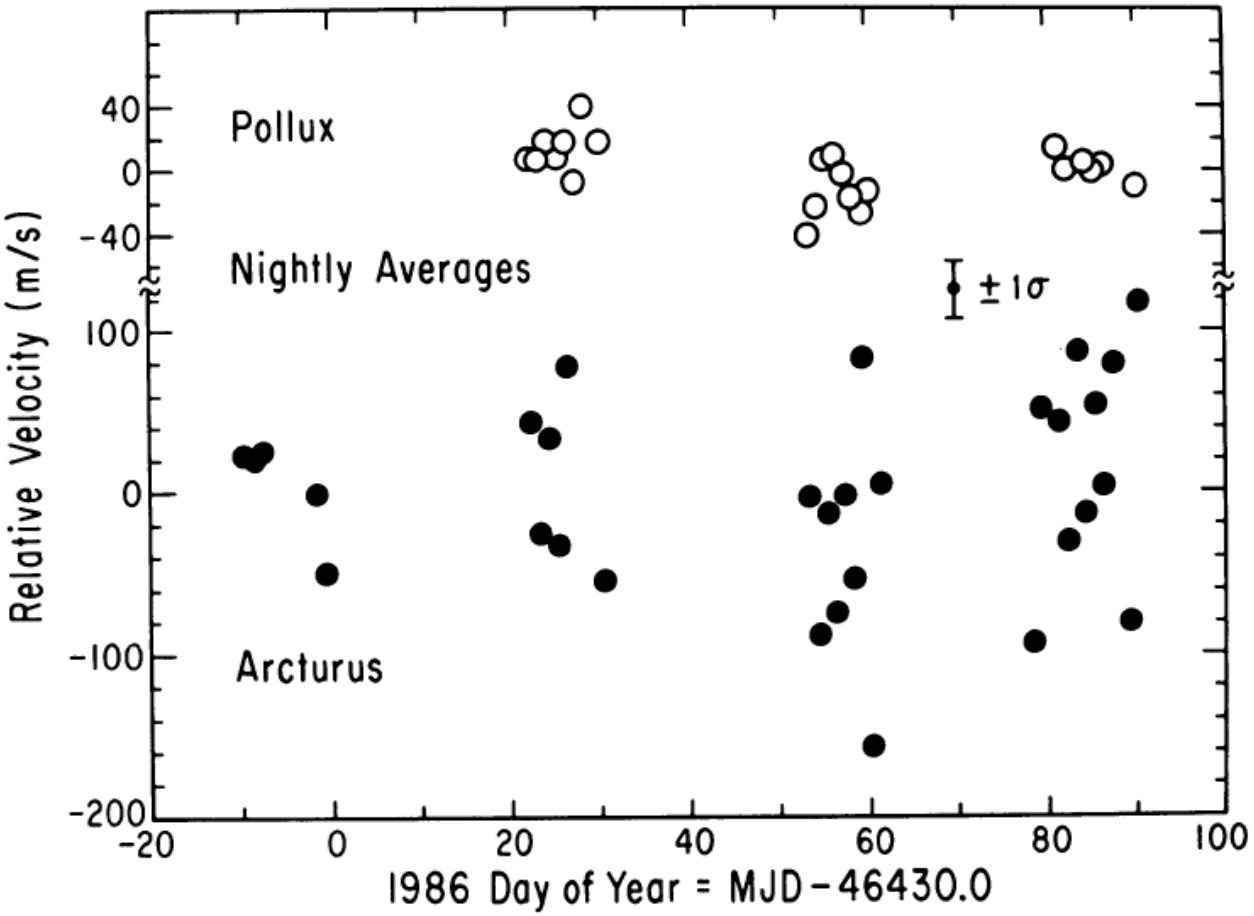
THE ASTROPHYSICAL JOURNAL, 317:L79–L84, 1987 June 15

EVIDENCE FOR PERIODIC RADIAL VELOCITY VARIATIONS IN ARCTURUS

P. H. SMITH, R. S. MCMILLAN, AND W. J. MERLINE
Lunar and Planetary Laboratory, University of Arizona
Received 1986 July 1; accepted 1987 April 13

ABSTRACT

We report evidence for periodic radial velocity variations in Arcturus; the most likely period and amplitude for these variations are 1.842 ± 0.005 days and 160 ± 10 m s^{-1}, respectively. Observations of Pollux taken on many of the same nights show no significant power on time scales between 2 days and 2 months; the nightly



THE ASTROPHYSICAL JOURNAL, 464:L157–L160, 1996 June 20

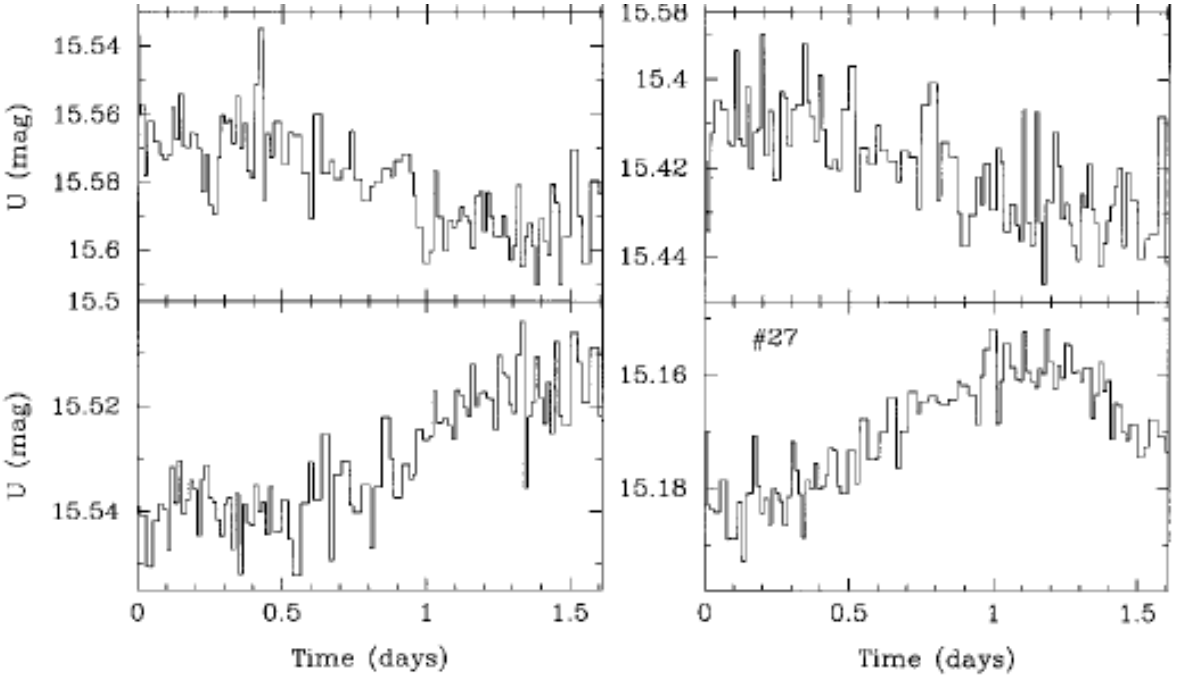
K GIANTS IN 47 TUCANAE: DETECTION OF A NEW CLASS OF VARIABLE STARS[1]

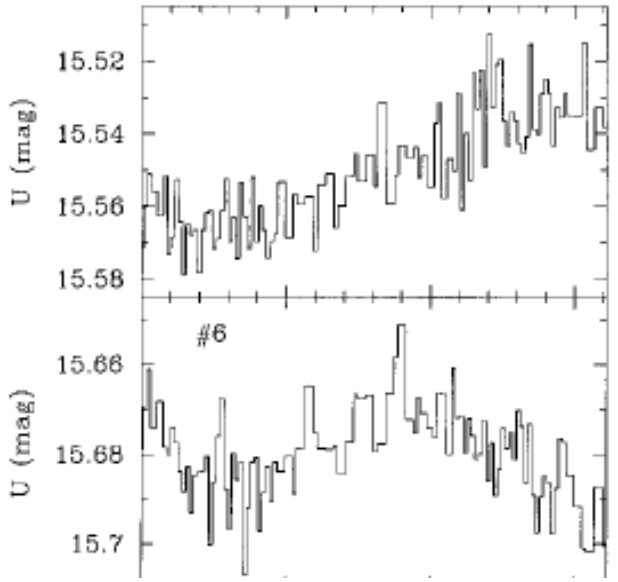
PETER D. EDMONDS AND RONALD L. GILLILAND
Space Telescope Science Institute,[2] 3700 San Martin Drive, Baltimore, MD, 21218

Received 1996 March 7; accepted 1996 April 3

ABSTRACT

We report the discovery of variability among K giants in the globular cluster 47 Tucanae, using a time series of *U* exposures with the *Hubble Space Telescope*. The variables lie along a narrow band in the color-magnitude diagram, joining the faint end of the asymptotic giant branch to the red giant branch. The variations, if coherent, mostly have periods between ~2 and ~4 days, consistent with low-overtone radial pulsation or nonradial pulsation, and *V* amplitudes in the range 5–15 mmag, which explains their nondetection so far in clusters. One of the variables may have a period of 1.1 days and a *V* amplitude of 5.3 mmag. These stars define a new class of variable stars and probably contain variable field K giants such as α Boo as members. An understanding of their variations may have significant ramifications for theories of stellar structure and stellar evolution.

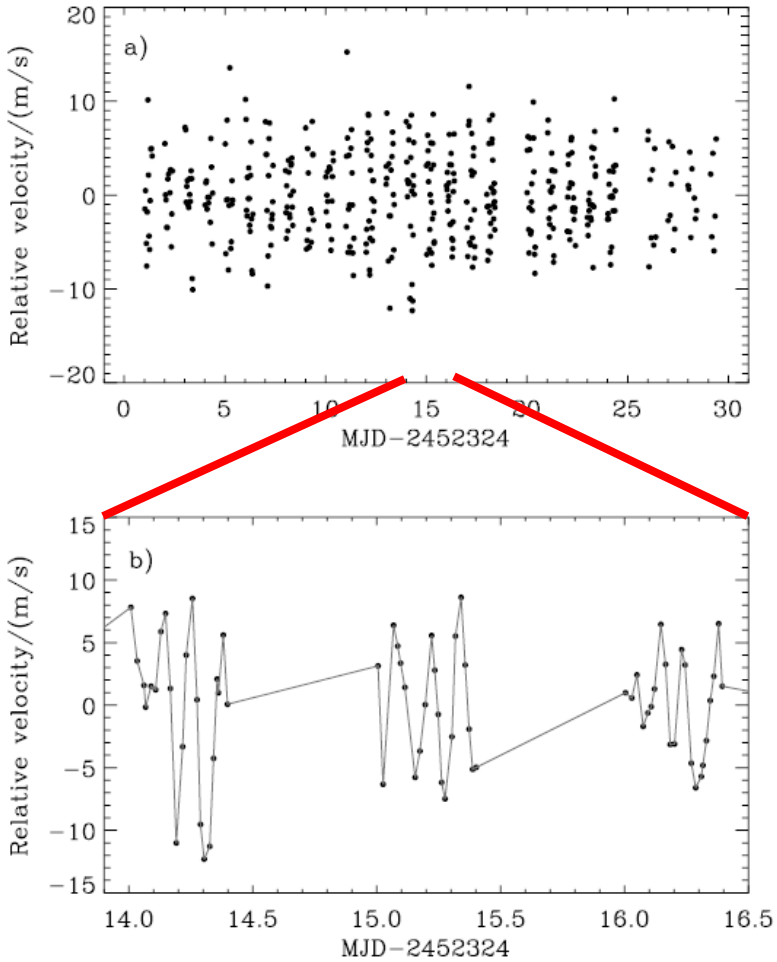




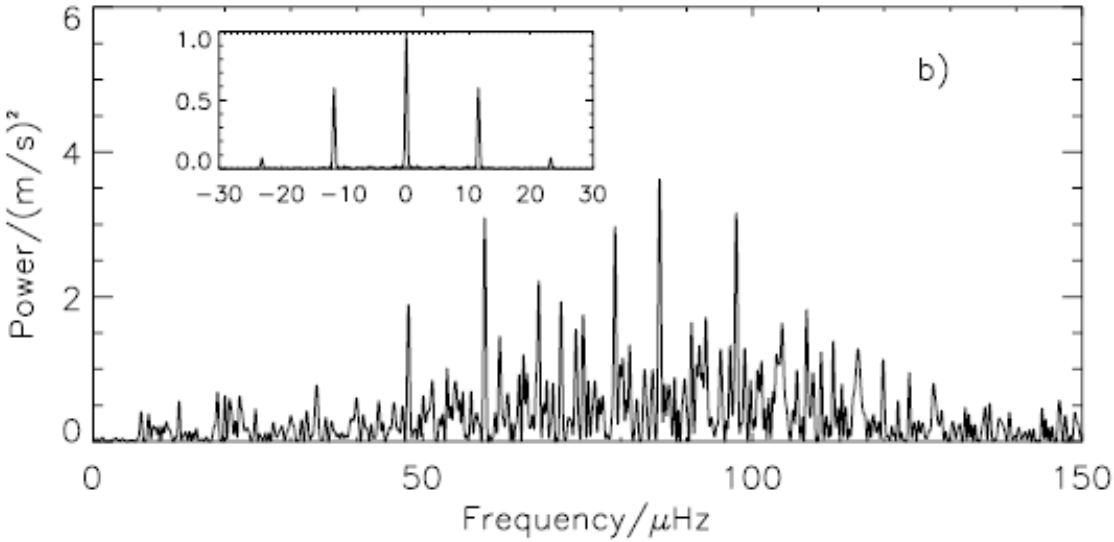
Detection of Solar-like oscillations in the G7 giant star ξ Hya

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)

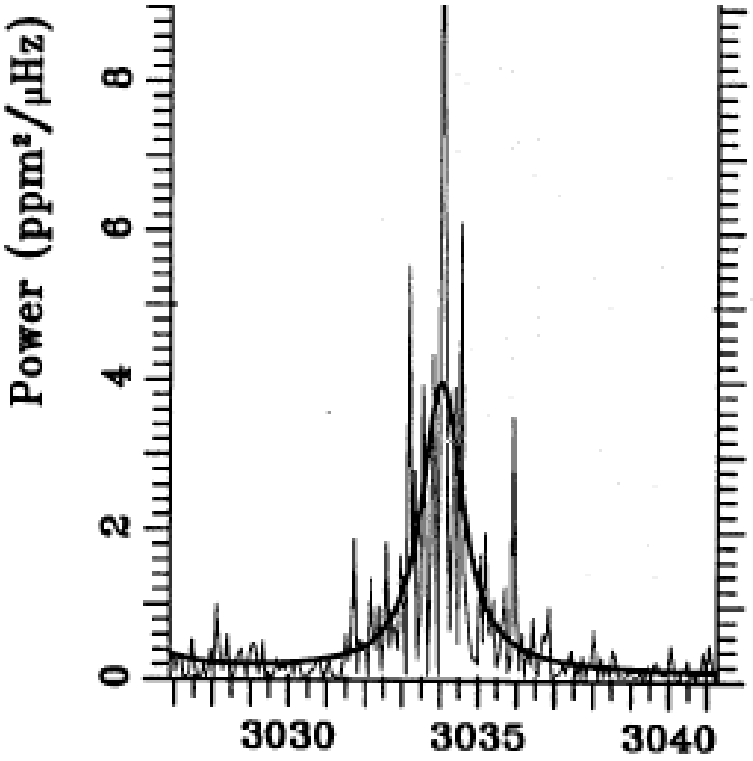


CORALIE at the Swiss 1.2-m Leonhard Euler Telescope at La Silla, Chile



Why is it so messy?

Mode lifetimes (τ=2 to 4 days in the Sun)

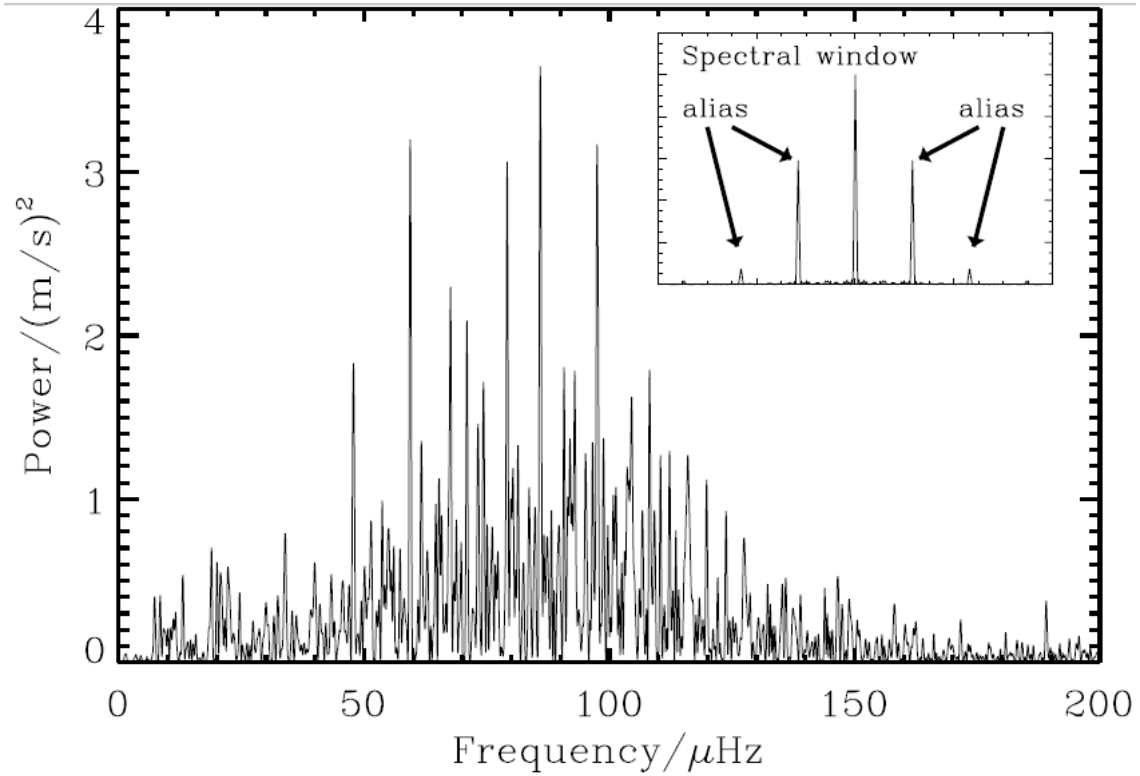


Lorenztian envelope:
FWHM = 1 to 2μHz

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]

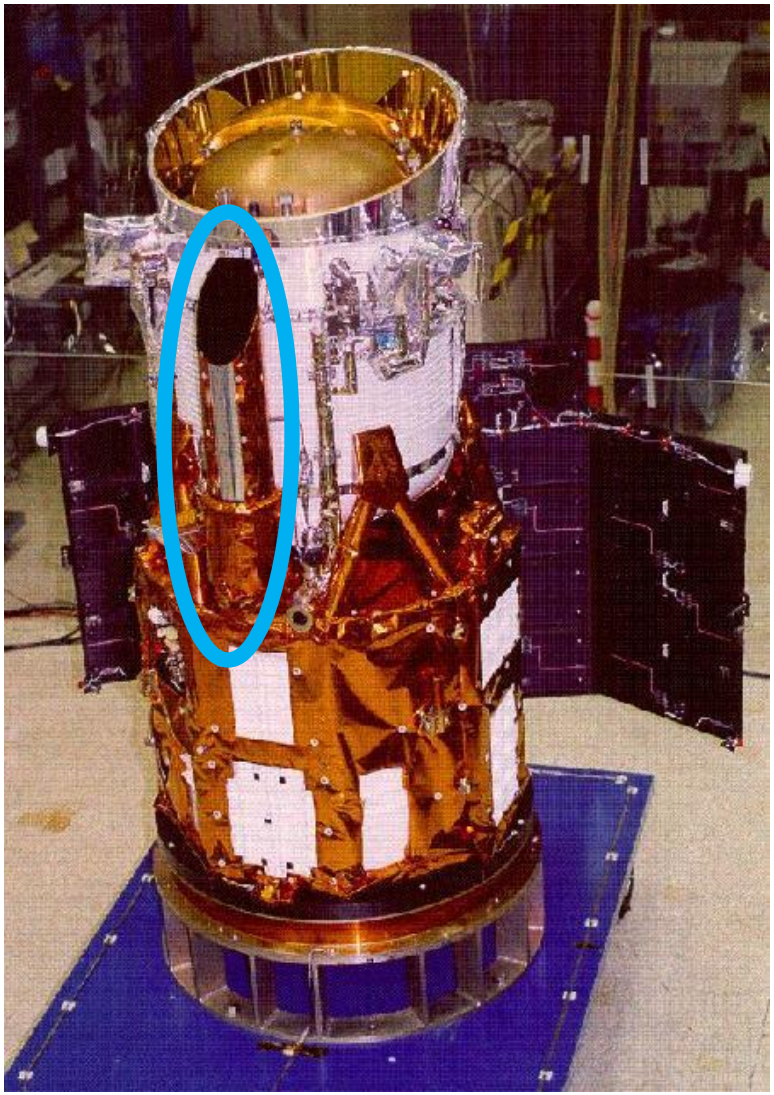
$\tau \sim$ 2–3 days; Stello et al. 2004



$\tau \sim$ 15–20 days; Houdek & Gough 2002

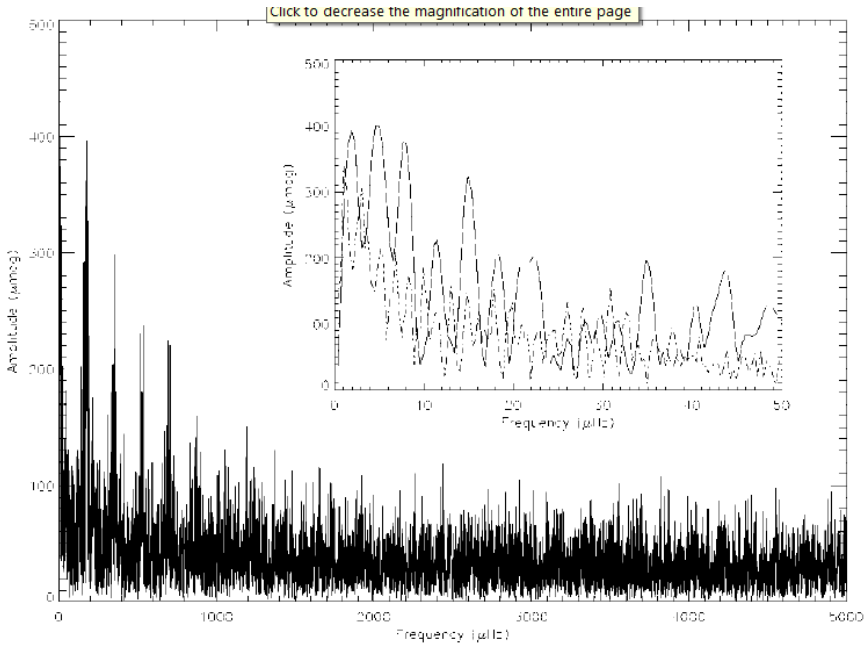
Wide Field Infrared Explorer (WIRE)

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

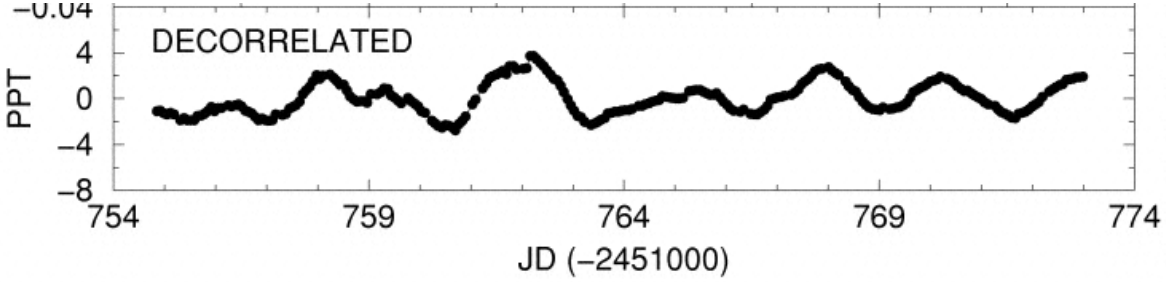


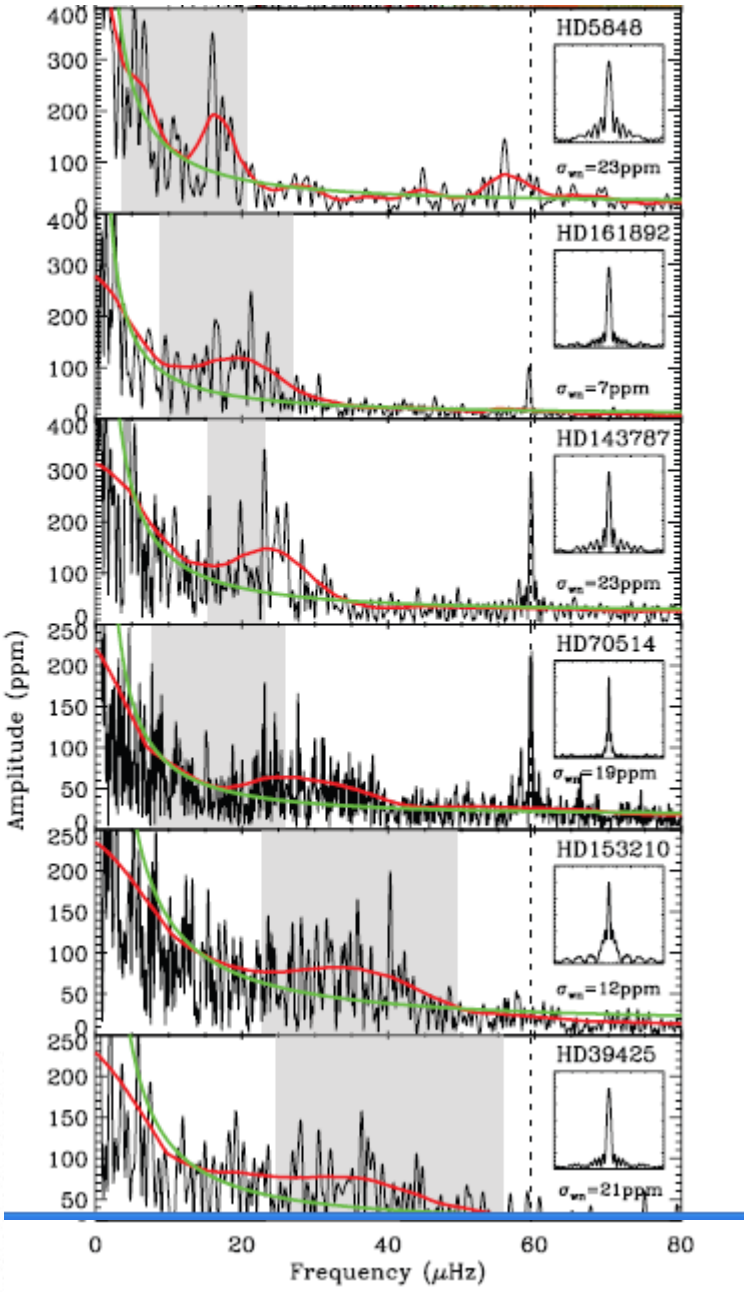
WIRE observations of K giants

α UMa (Buzasi et al. 2003)



Arcturus (Retter et al. 2003)





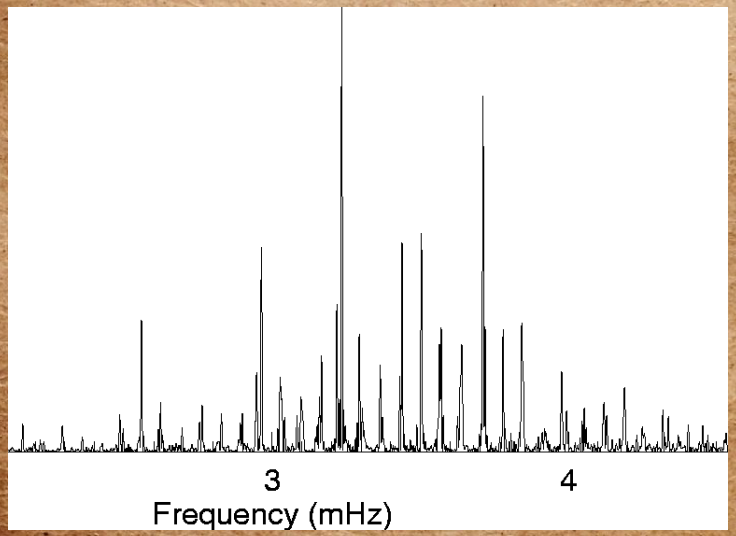
Stello et al. (2008)

STILL

WANTED

DEAD OR ALIVE

Big red version of this:

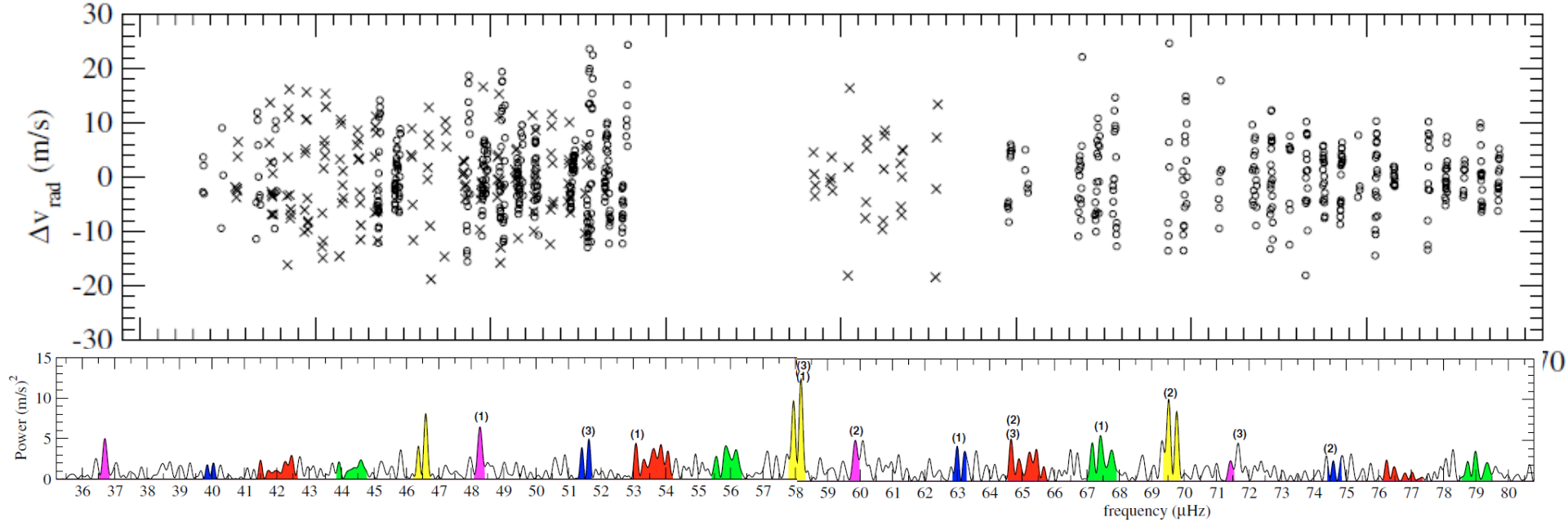


REWARD $ 1,000,000

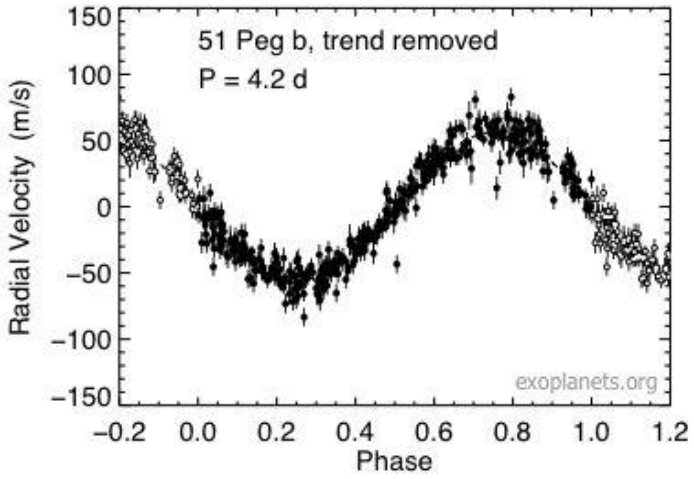
Discovery of solar-like oscillations in the red giant ε Ophiuchi*

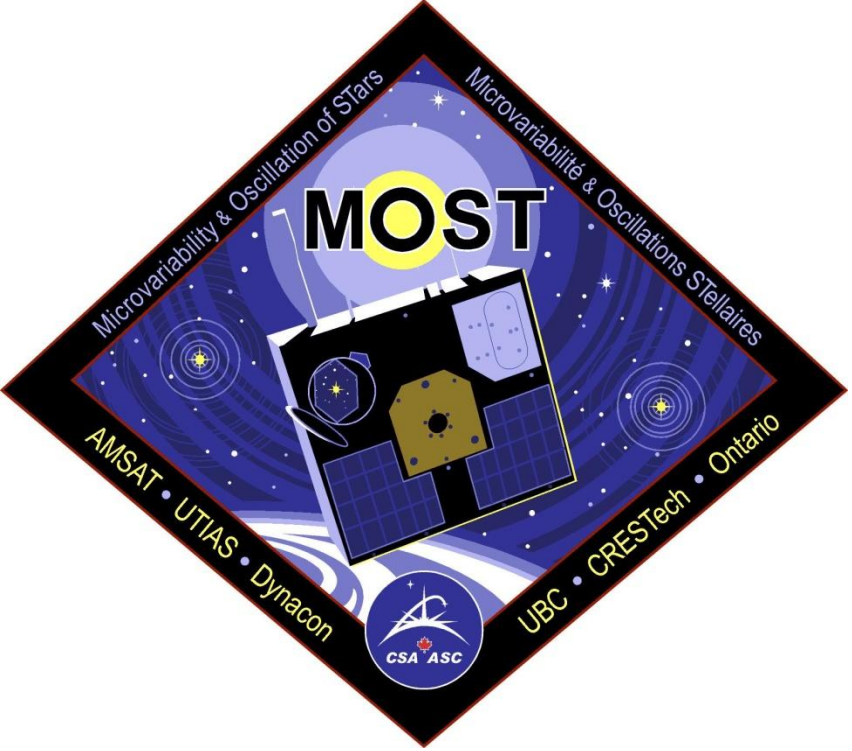
J. De Ridder[1], C. Barban[1], F. Carrier[2], A. Mazumdar[1], P. Eggenberger[2],
C. Aerts[1], S. Deruyter[3], and J. Vanautgaerden[1]

(2006)

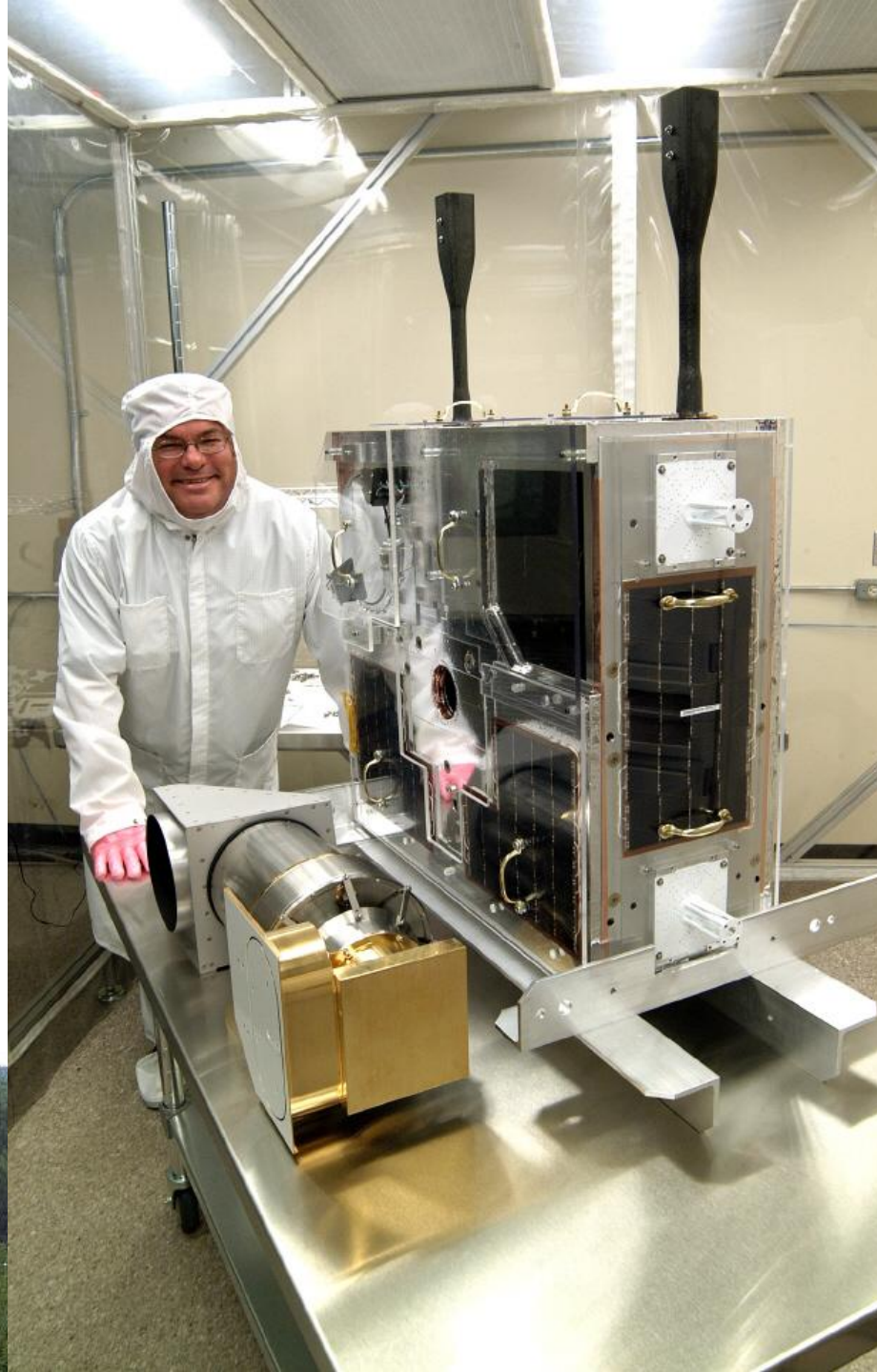


CORALIE and ELODIE



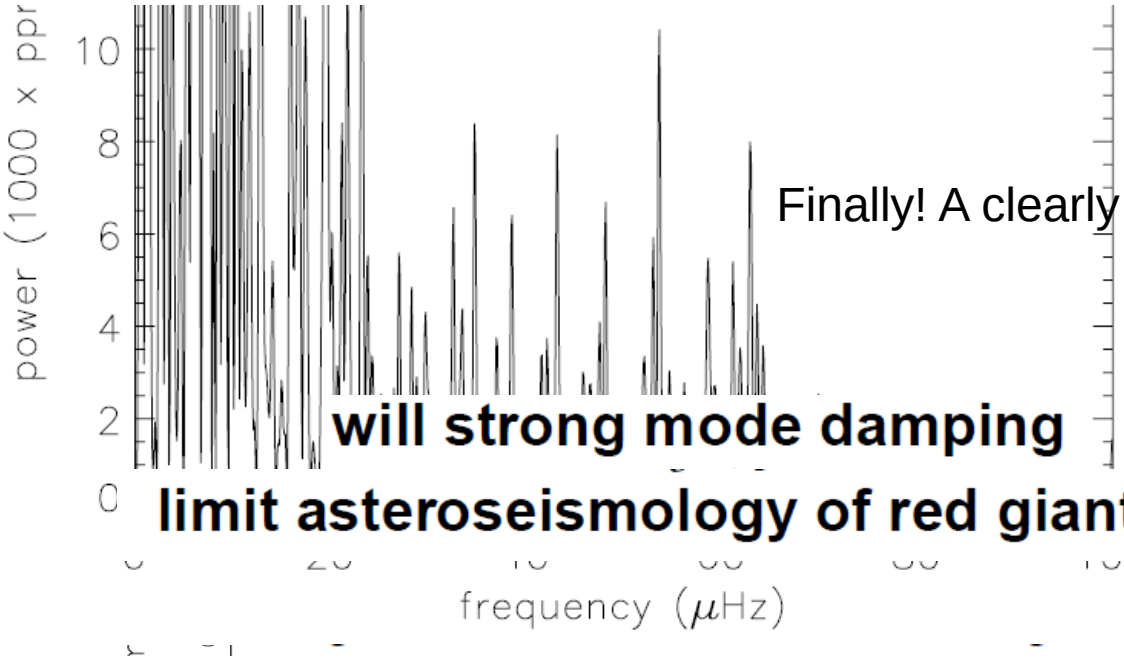


Launched June 30, 2003 (15 cm)



Detection of solar-like oscillations in the red giant star ϵ Ophiuchi by MOST spacebased photometry*

C. Barban[1,2], J. M. Matthews[3], J. De Ridder[2], F. Baudin[4], R. Kuschnig[3], A. Mazumdar[5,2], R. Samadi[1], D. B. Guenther[6], A. F. J. Moffat[7], S. M. Rucinski[8], D. Sasselov[9], G. A. H. Walker[3], and W. W. Weiss[11]

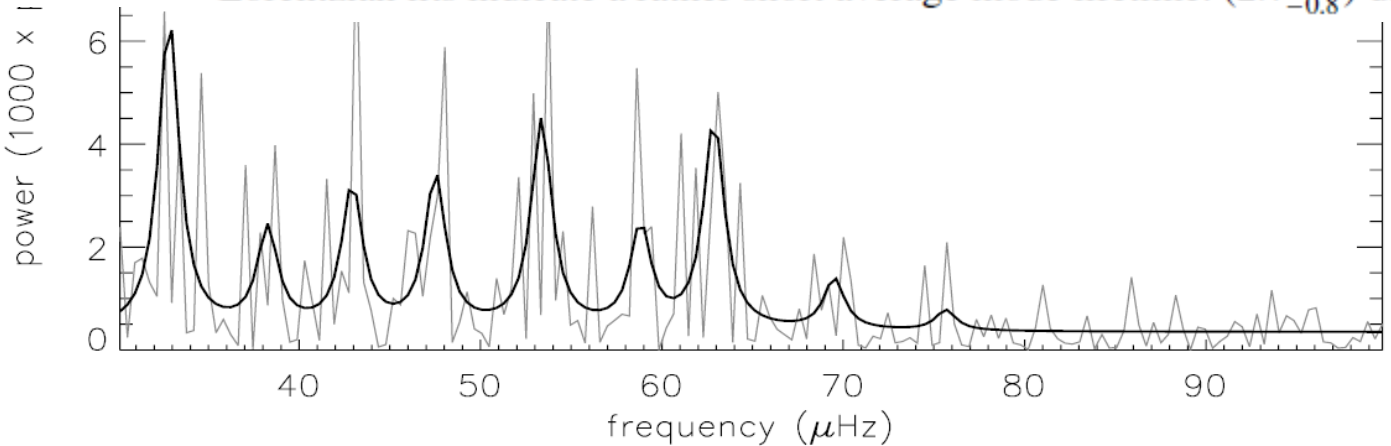


Barban et al. (2007)

Finally! A clearly regular series of peaks

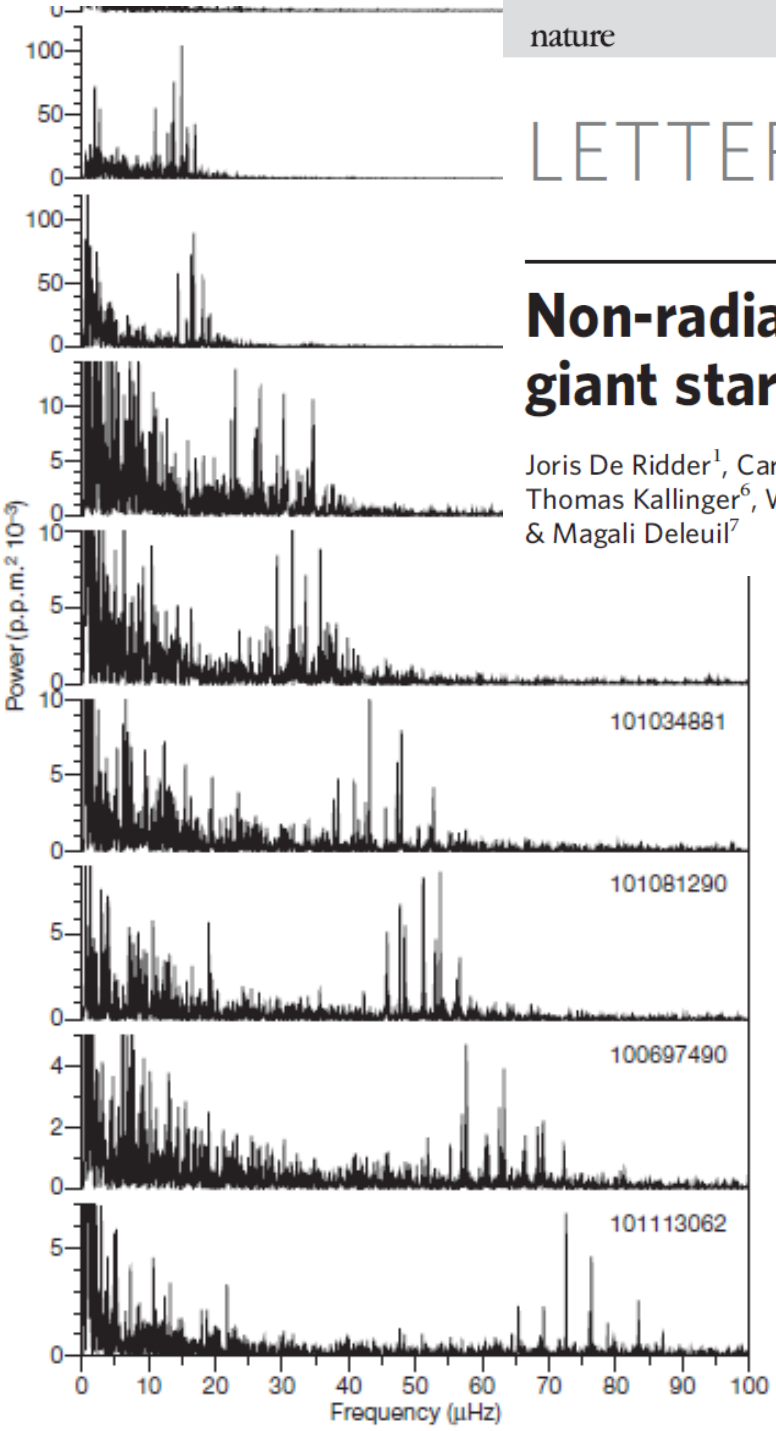
will strong mode damping limit asteroseismology of red giant stars?

The line widths and Lorentzian fits indicate a rather short average mode lifetime: $(2.7^{+0.6}_{-0.8})$ days.



CoRoT (27 cm)

Launched: 27 December 2006



nature

LETTERS

Non-radial o giant stars

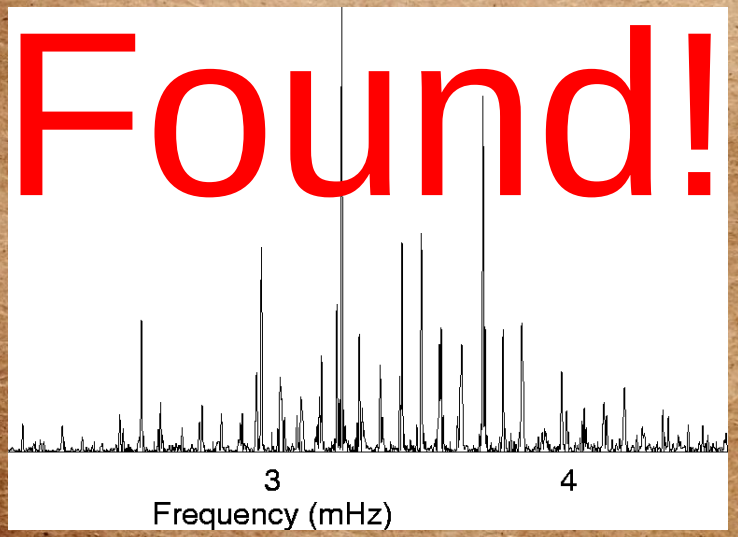
Joris De Ridder[1], Caroline I Thomas Kallinger[6], Werne & Magali Deleuil[7]

WANTED

DEAD OR ALIVE

Big red version of this:

Found!



REWARD $ 1,000,000

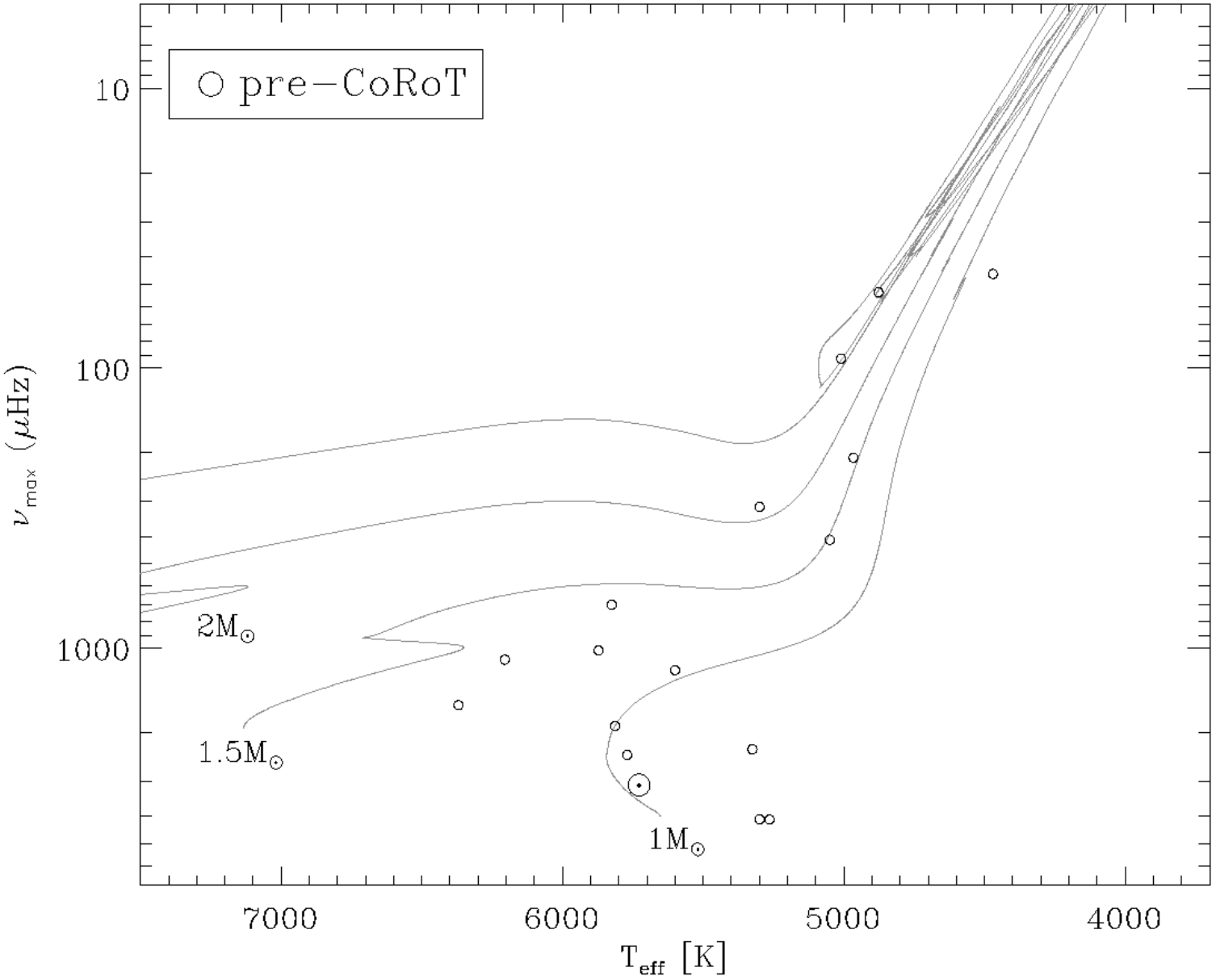


figure by Daniel Huber

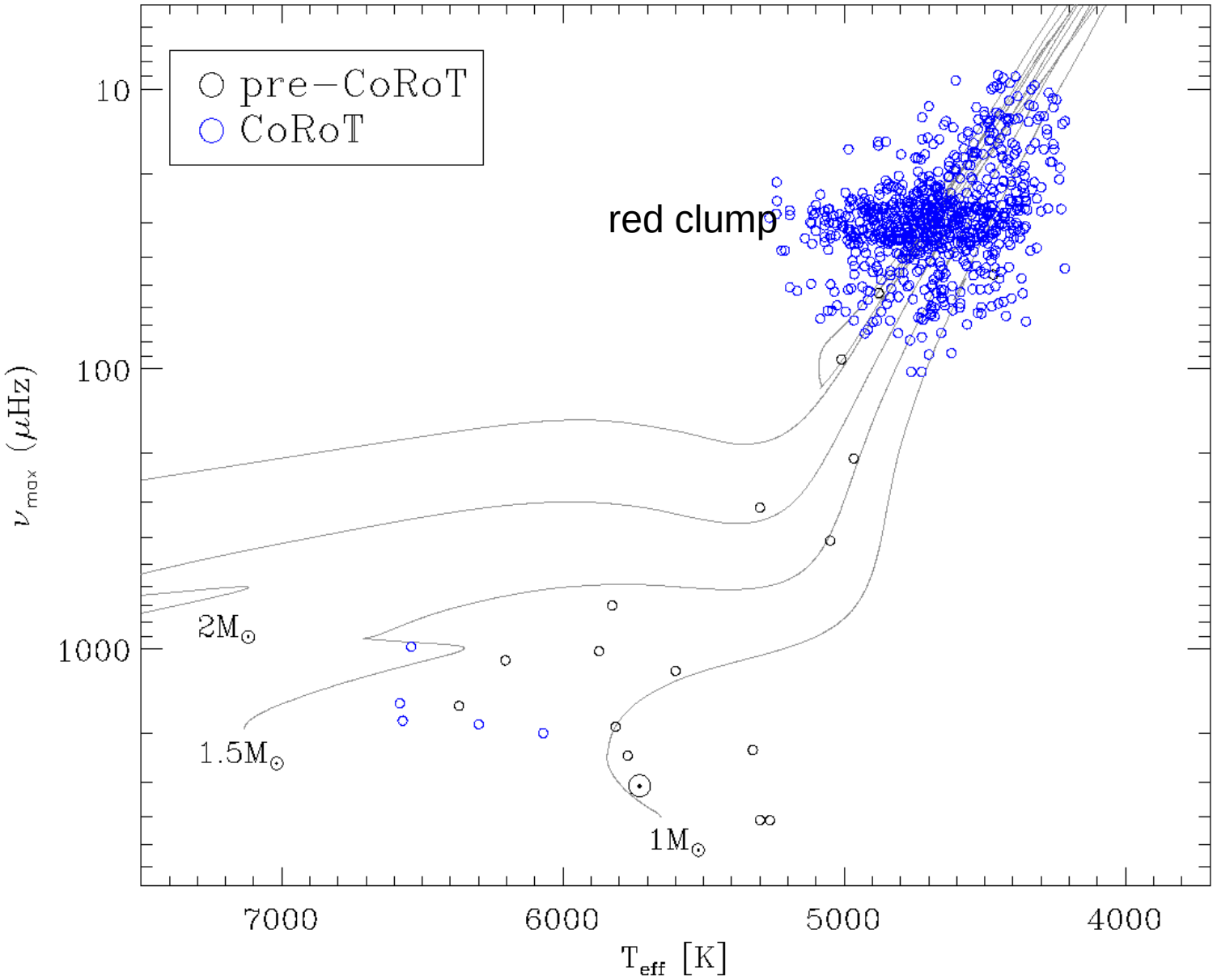


figure by Daniel Huber

The birth of ensemble asteroseismology

Characteristics of solar-like oscillations in red giants observed in the CoRoT exoplanet field⋆,⋆⋆

S. Hekker[1,2,3], T. Kallinger[4,8], F. Baudin[5], J. De Ridder[2], C. Barban[6], F. Carrier[2], A. P. Hatzes[7], W. W. Weiss[4], and A. Baglin[6]

Oscillating red giants in the CoRoT exofield: asteroseismic mass and radius determination⋆

T. Kallinger[1,2], W. W. Weiss[1], C. Barban[3], F. Baudin[3], C. Cameron[4], F. Carrier[5], J. De Ridder[5], M.-J. Goupil[3], M. Gruberbauer[4,1], A. Hatzes[6], S. Hekker[7,8,5], R. Samadi[3], and M. Deleuil[9]

Probing populations of red giants in the galactic disk with CoRoT⋆

A. Miglio[1,⋆⋆], J. Montalbán[1], F. Baudin[2], P. Eggenberger[1,3], A. Noels[1], S. Hekker[4,5,6], J. De Ridder[5], W. Weiss[7], and A. Baglin[8]

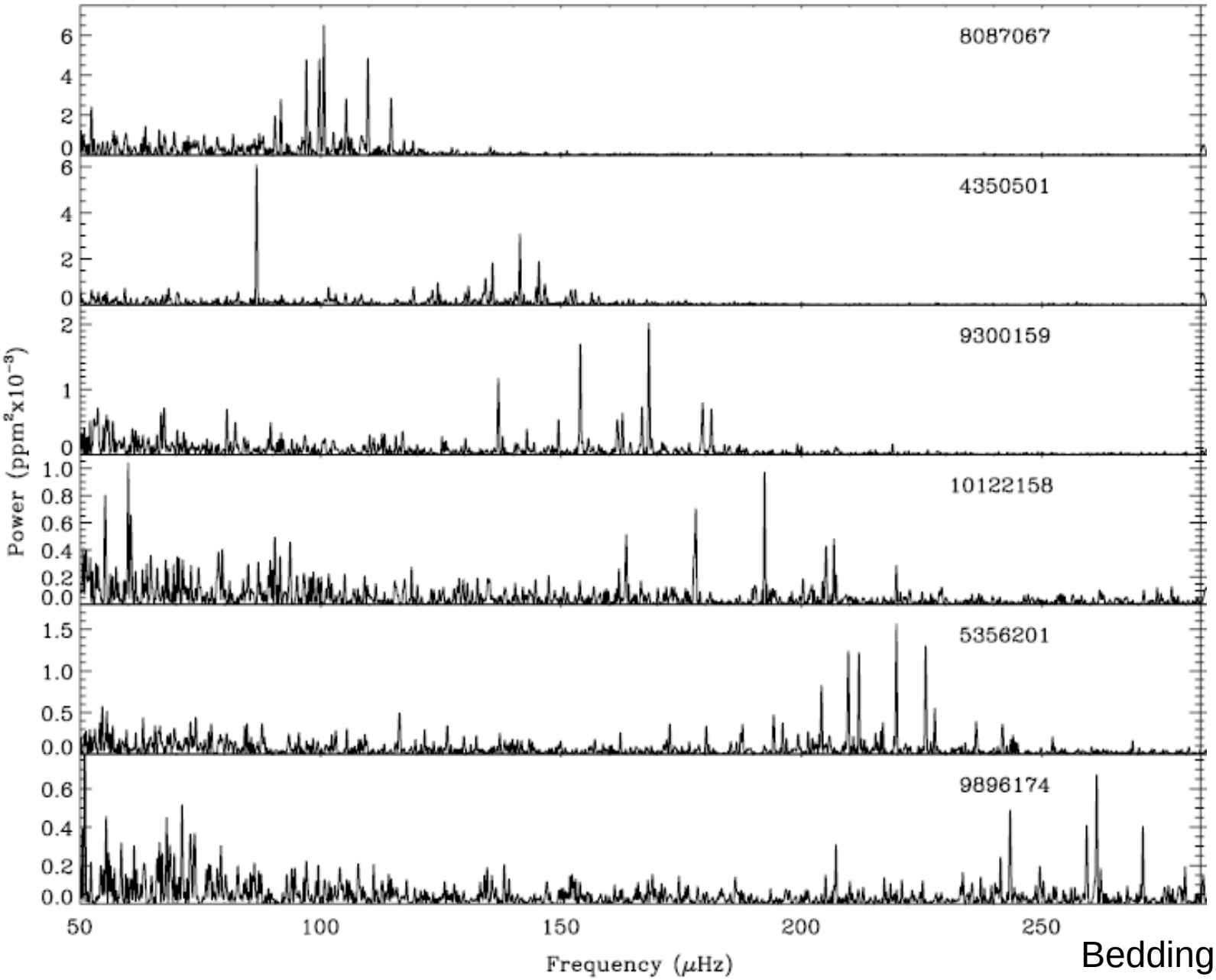
Red-giant seismic properties analyzed with CoRoT⋆

B. Mosser[1], K. Belkacem[2,1], M.-J. Goupil[1], A. Miglio[2,⋆⋆], T. Morel[2], C. Barban[1], F. Baudin[3], S. Hekker[4,5], R. Samadi[1], J. De Ridder[5], W. Weiss[6], M. Auvergne[1], and A. Baglin[1]

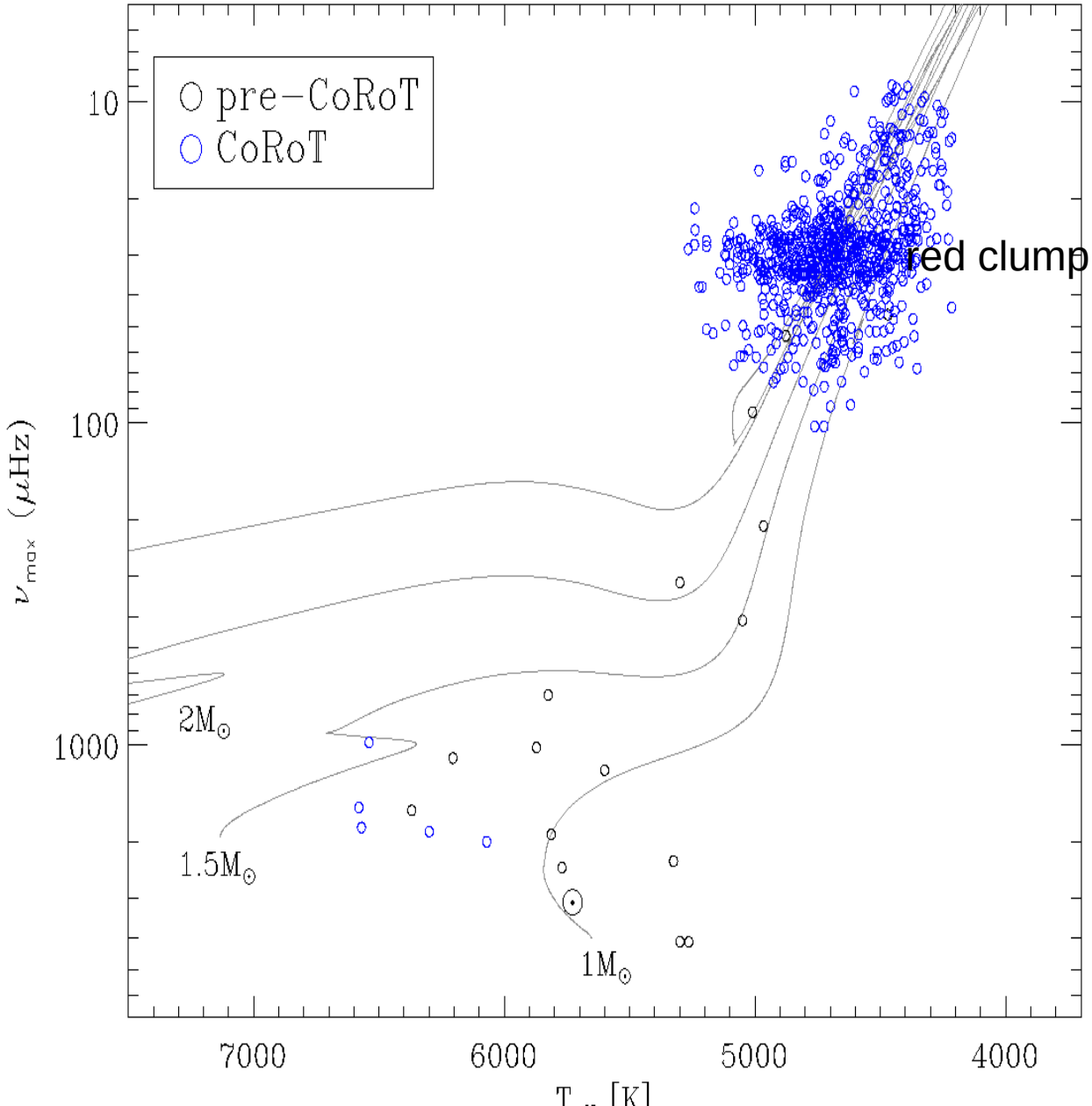
Kepler

95cm Schmidt telescope; Launched: 6 March 2009. Observations commenced: 1 May 2009

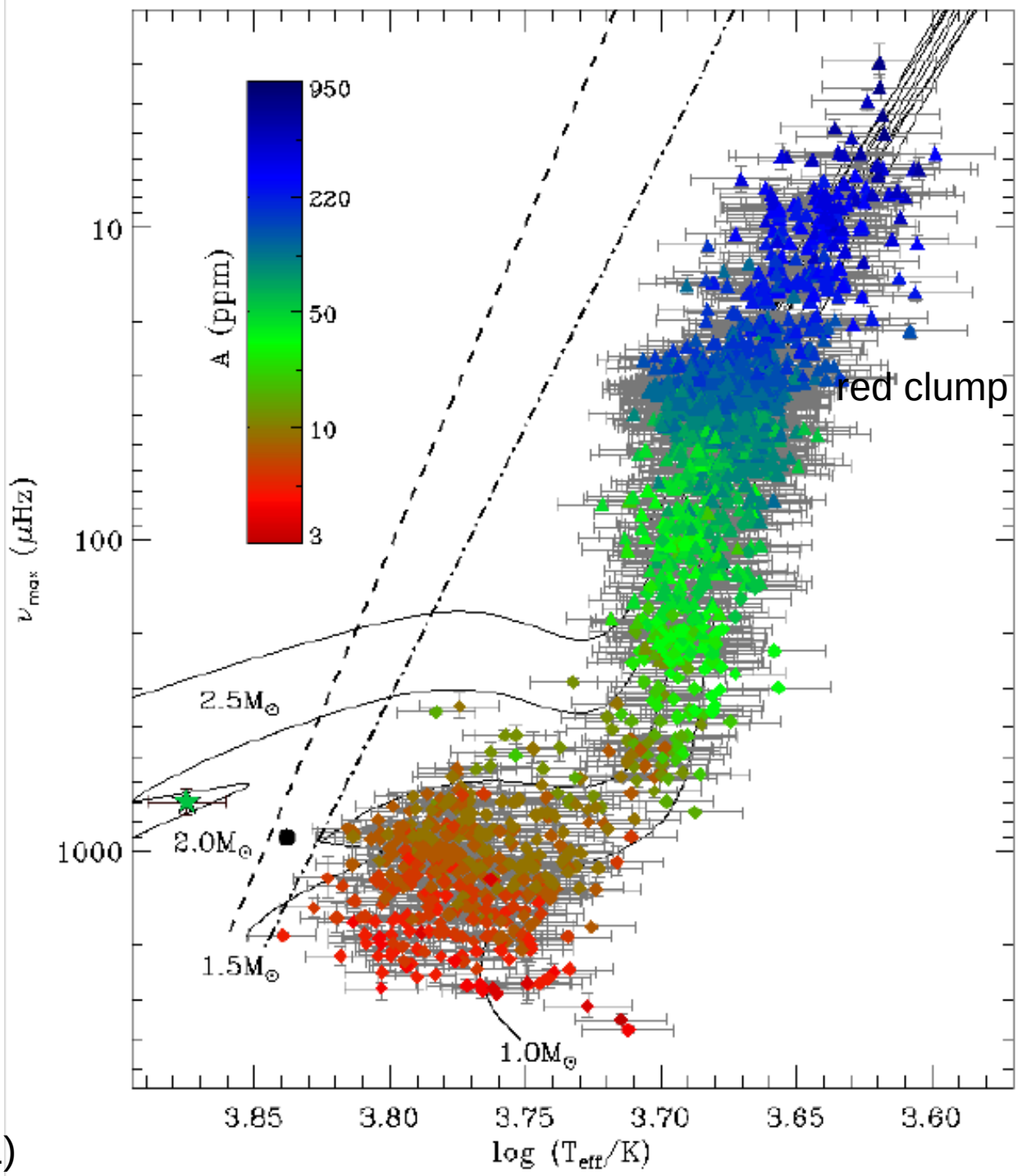
Red giants with Kepler (first 30 days)



Bedding et al. 2010


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)

Scientific results: What can we do with all these stars?

Modelling individual stars

Non-radial oscillations in the red giant HR 7349 measured by CoRoT⋆

F. Carrier[1], J. De Ridder[1], F. Baudin[2], C. Barban[3], A. P. Hatzes[4], S. Hekker[5,6,1], T. Kallinger[7,8], A. Miglio[9], J. Montalbán[9], T. Morel[9], W. W. Weiss[7], M. Auvergne[3], A. Baglin[3], C. Catala[3], E. Michel[3], and R. Samadi[3]

Evidence for a sharp structure variation inside a red-giant star

A. Miglio[1,⋆], J. Montalbán[1], F. Carrier[2], J. De Ridder[2], B. Mosser[3], P. Eggenberger[4], R. Scuflaire[1], P. Ventura[5], F. D'Antona[5], A. Noels[1], and A. Baglin[3]

Modelling *Kepler* observations of solar-like oscillations in the red-giant star HD 186355

C. Jiang,[1] B. W. Jiang,[1] J. Christensen-Dalsgaard,[2] T. R. Bedding,[3] D. Stello,[3] D. Huber,[3] S. Frandsen,[2] H. Kjeldsen,[2] C. Karoff,[2] B. Mosser,[4] P. Demarque,[5] M. N. Fanelli,[6] K. Kinemuchi,[6] F. Mullally[7]

Solar-like oscillations from the depths of the red-giant star KIC 4351319 observed with *Kepler*

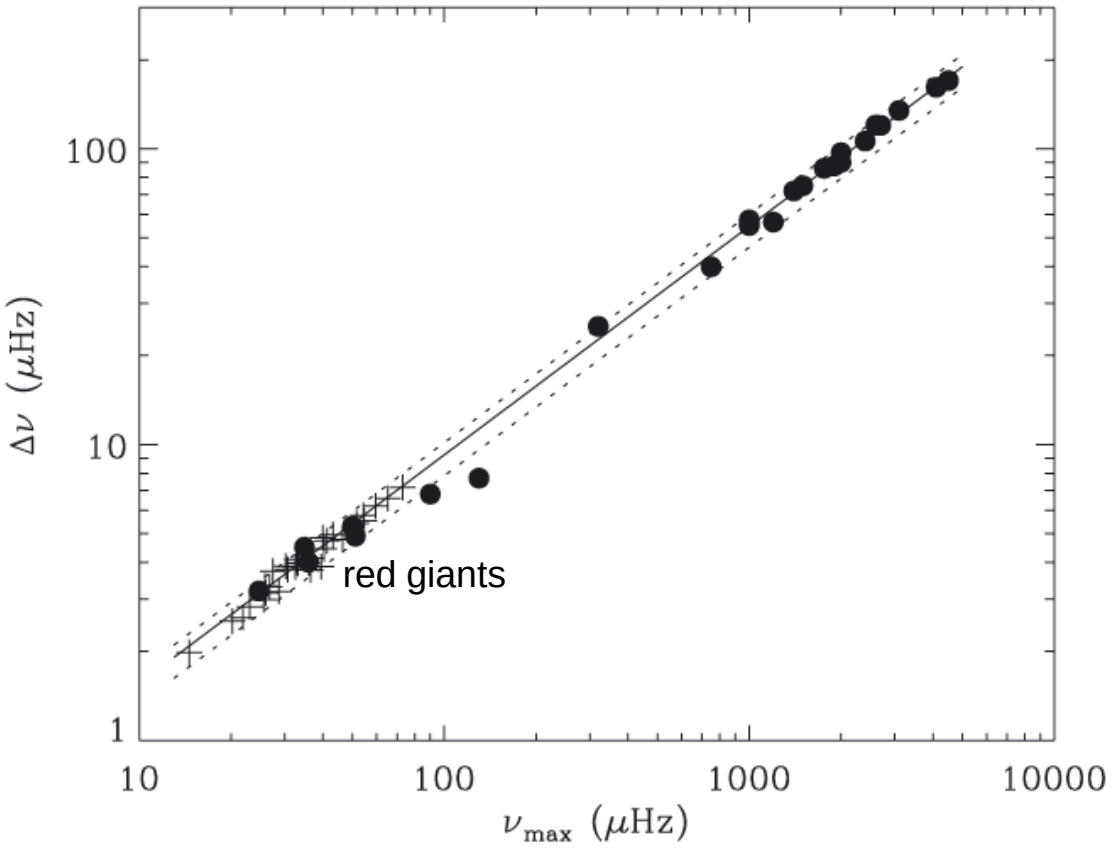
M. P. Di Mauro,[1⋆] D. Cardini,[1] G. Catanzaro,[2] R. Ventura,[2] C. Barban,[3] T. R. Bedding,[4] J. Christensen-Dalsgaard,[5] J. De Ridder,[6] S. Hekker,[7,8] D. Huber,[4] T. Kallinger,[9,10] A. Miglio,[7,11] J. Montalban,[11] B. Mosser,[3] D. Stello,[4] K. Uytterhoeven,[12,13] K. Kinemuchi,[14] H. Kjeldsen,[5] F. Mullally[15] and M. Still[14]

Ensemble asteroseismology:

$\Delta\nu$ versus ν_{max}

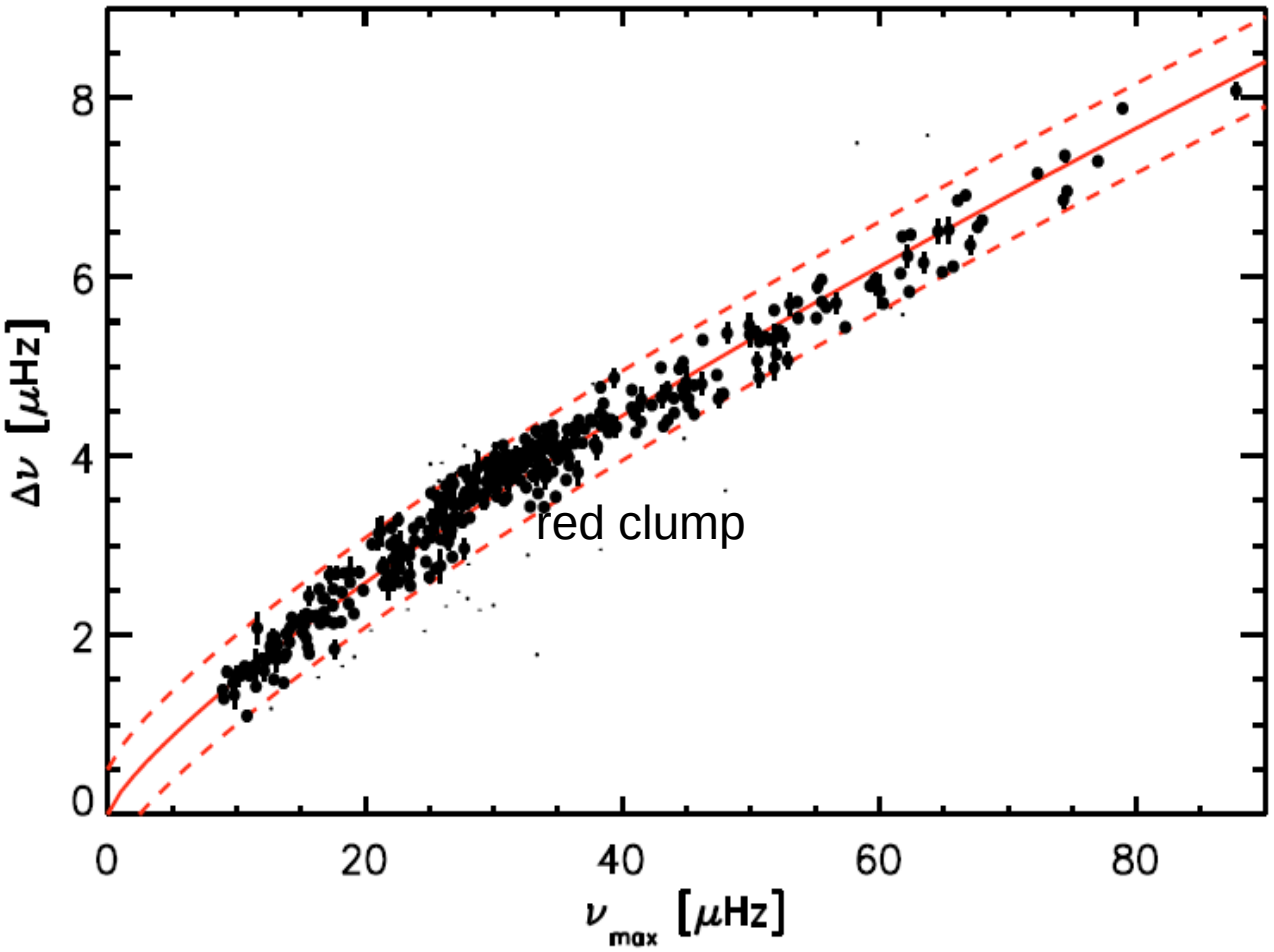
Table 1. Published measurements of $\Delta\nu$ and ν_{max}.

Star	$\Delta\nu$ (μHz)	ν_{max} (μHz)	Source
τ Cet	170	4500	Teixeira et al. (2009)
α Cen B	161.4	4100	Kjeldsen et al. (2008)
Sun	134.8	3100	Kjeldsen et al. (2008)
ι Hor	120	2700	Vauclair et al. (2008)
γ Pav	120.3	2600	Mosser et al. (2008)
α Cen A	106.2	2400	Kjeldsen et al. (2008)
HD 175726	97	2000	Mosser et al. (2009)
μ Ara	90	2000	Bouchy et al. (2005)
HD 181906	87.5	1900	Garcia et al. (2009)
HD 49933	85.9	1760	Appourchaux et al. (2008)
HD 181420	75	1500	Barban et al. (2009)
β Vir	72	1400	Carrier et al. (2005b)
μ Her	56.5	1200	Bonanno et al. (2008)
β Hyi	57.5	1000	Kjeldsen et al. (2008)
Procyon	55	1000	Arentoft et al. (2008)
η Boo	39.9	750	Carrier, Eggenberger & Bouchy
ν Ind	25.1	320	Kjeldsen et al. (2008)
η Ser	7.7	130	Barban et al. (2004)
ξ Hya	6.8	90	Frandsen et al. (2002)
β Vol	4.9	51	Unpublished *WIRE* data
ϵ Oph	5.3	50	Barban et al. (2007)
ξ Dra	4.0	36	Unpublished *WIRE* data
κ Oph	4.5	35	Unpublished *WIRE* data
HR3280	3.2	25	Unpublished *WIRE* data
31 *CoRoT* giants	2–7	15–73	Kallinger et al. (2009)



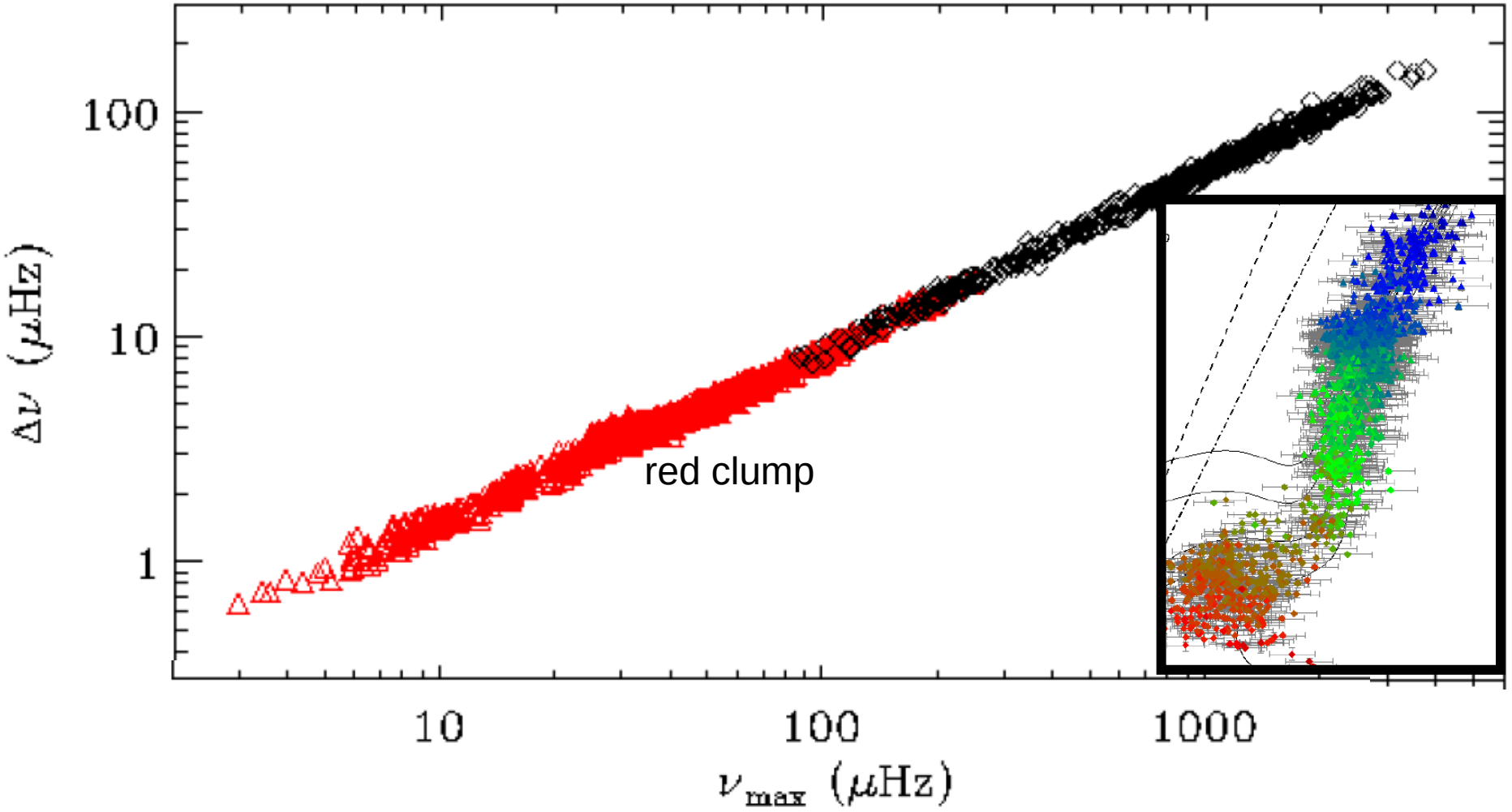
Stello et al. (2009)

Red giants with CoRoT



Hekker et al. (2009)

Kepler

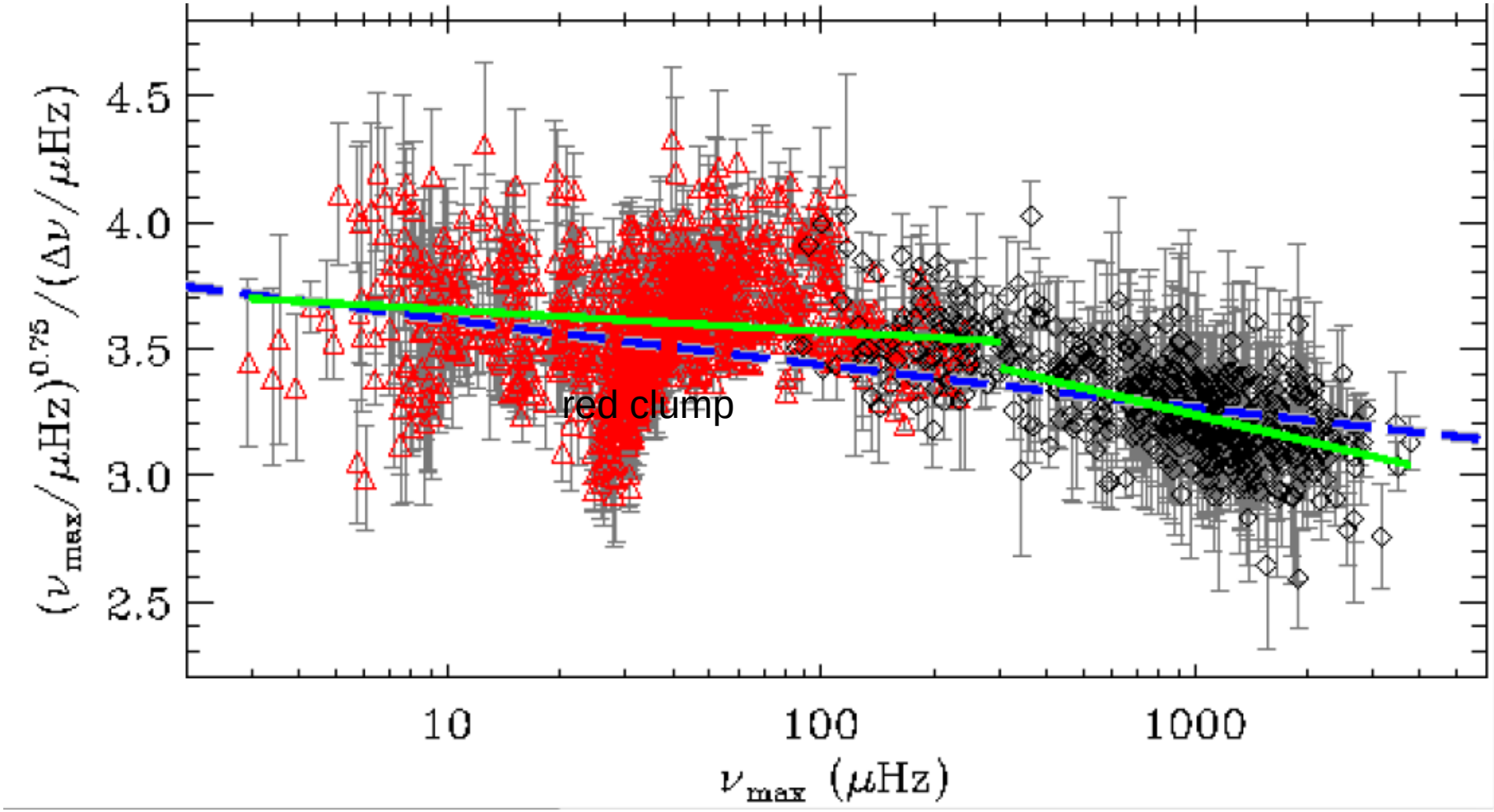


Huber et al. (2011)

Scaling relations:

$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2}$$

$$\nu_{\rm max} \propto \nu_{\rm ac} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$



Huber et al. (2011)

Scaling relations:

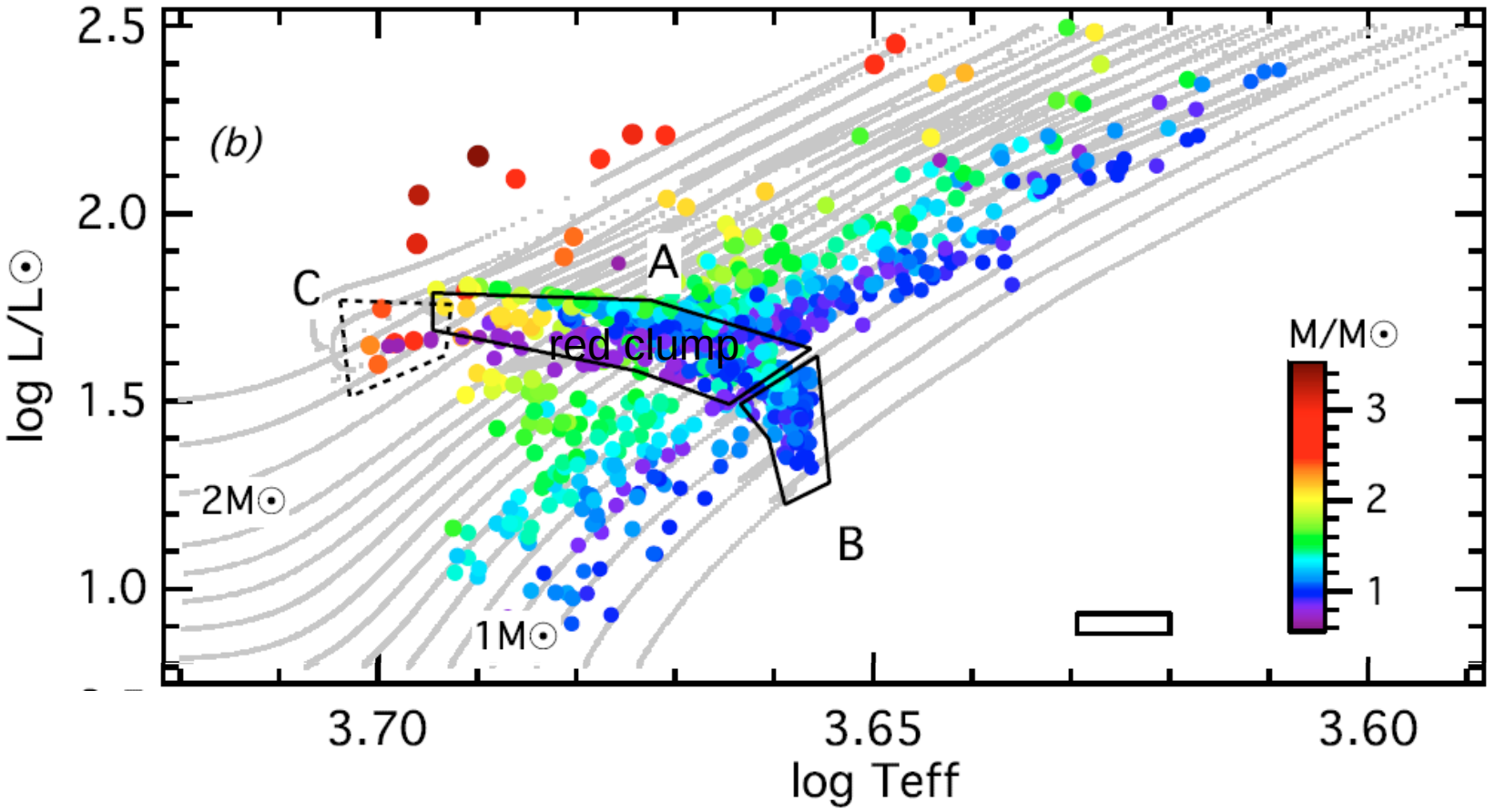
$$\Delta\nu \propto \left(\frac{M}{R^3}\right)^{1/2} \qquad \nu_{\rm max} \propto \nu_{\rm ac} \propto \frac{M}{R^2\sqrt{T_{\rm eff}}}$$

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)

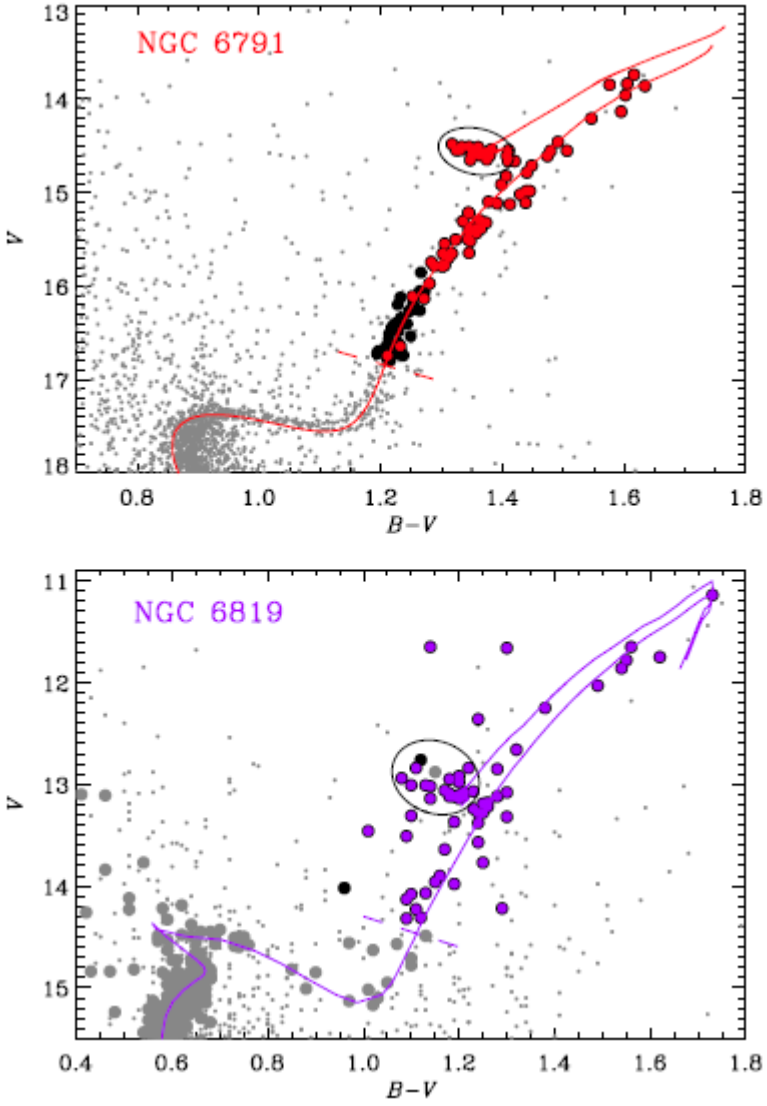


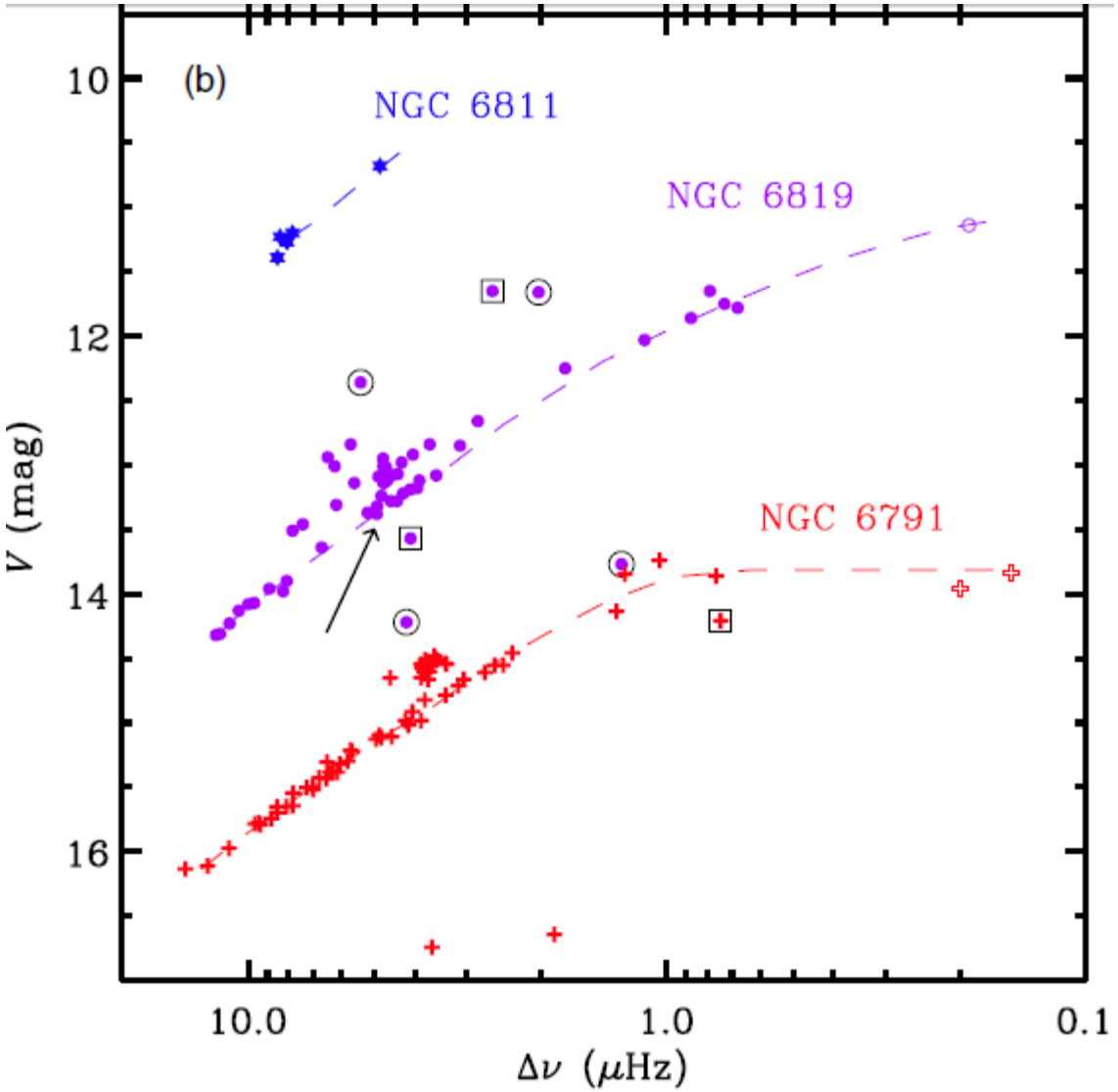
Kallinger et al. (2010) - Kepler

So we can get *M*, *R* and *L* for all stars

What else can we do?

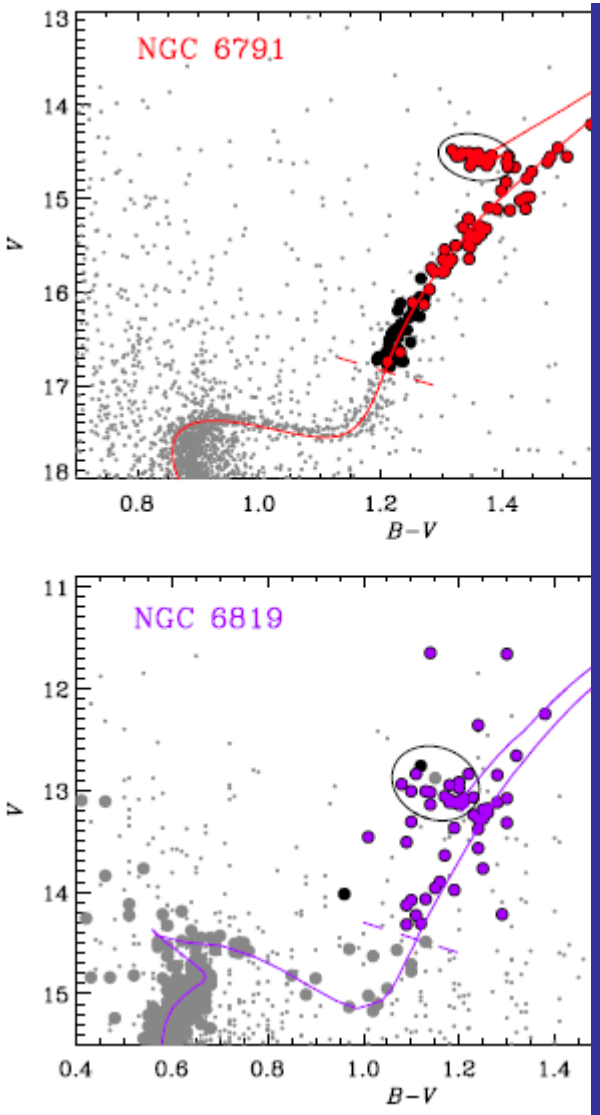
Open clusters membership

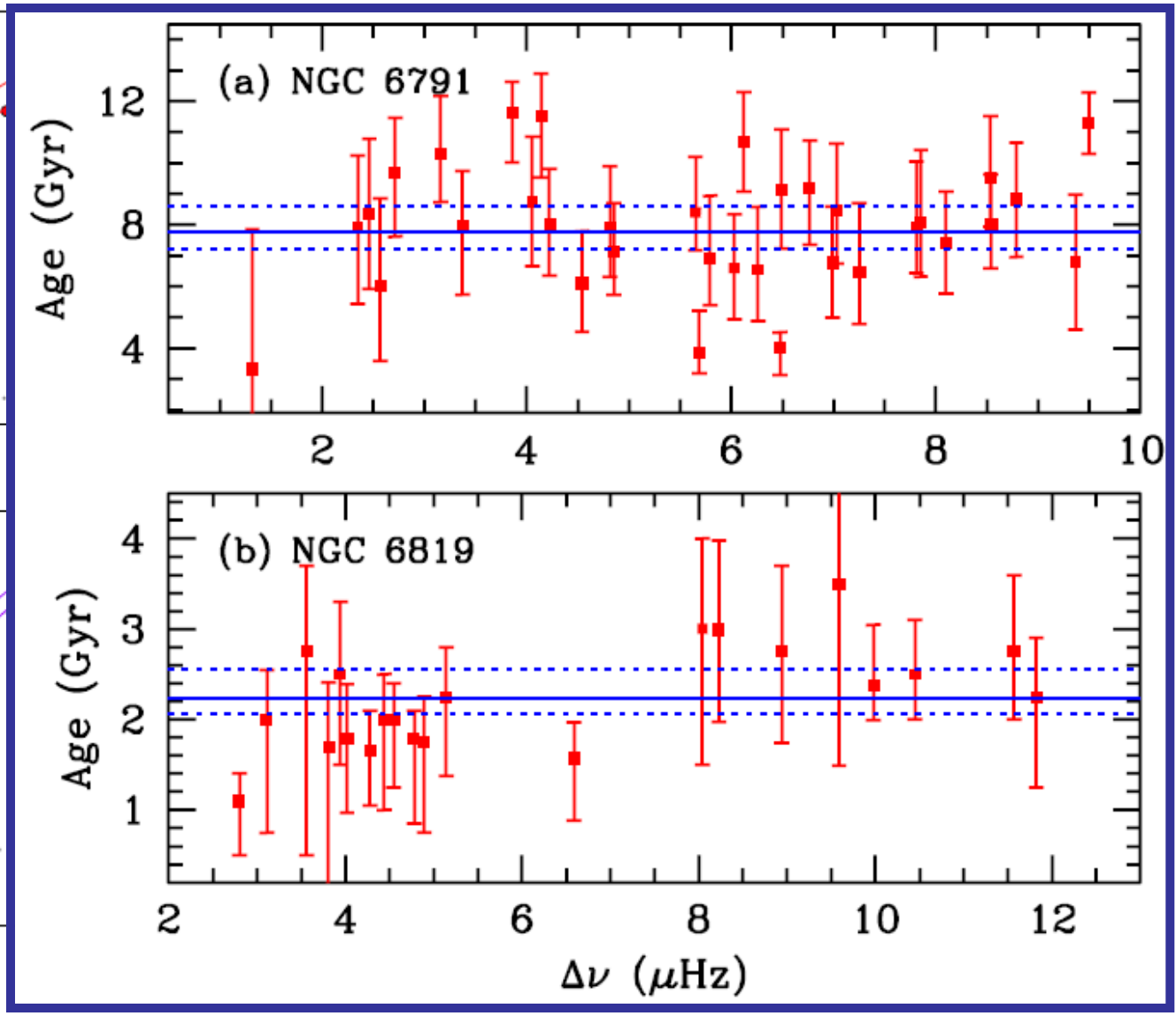




Stello et al. (2011)

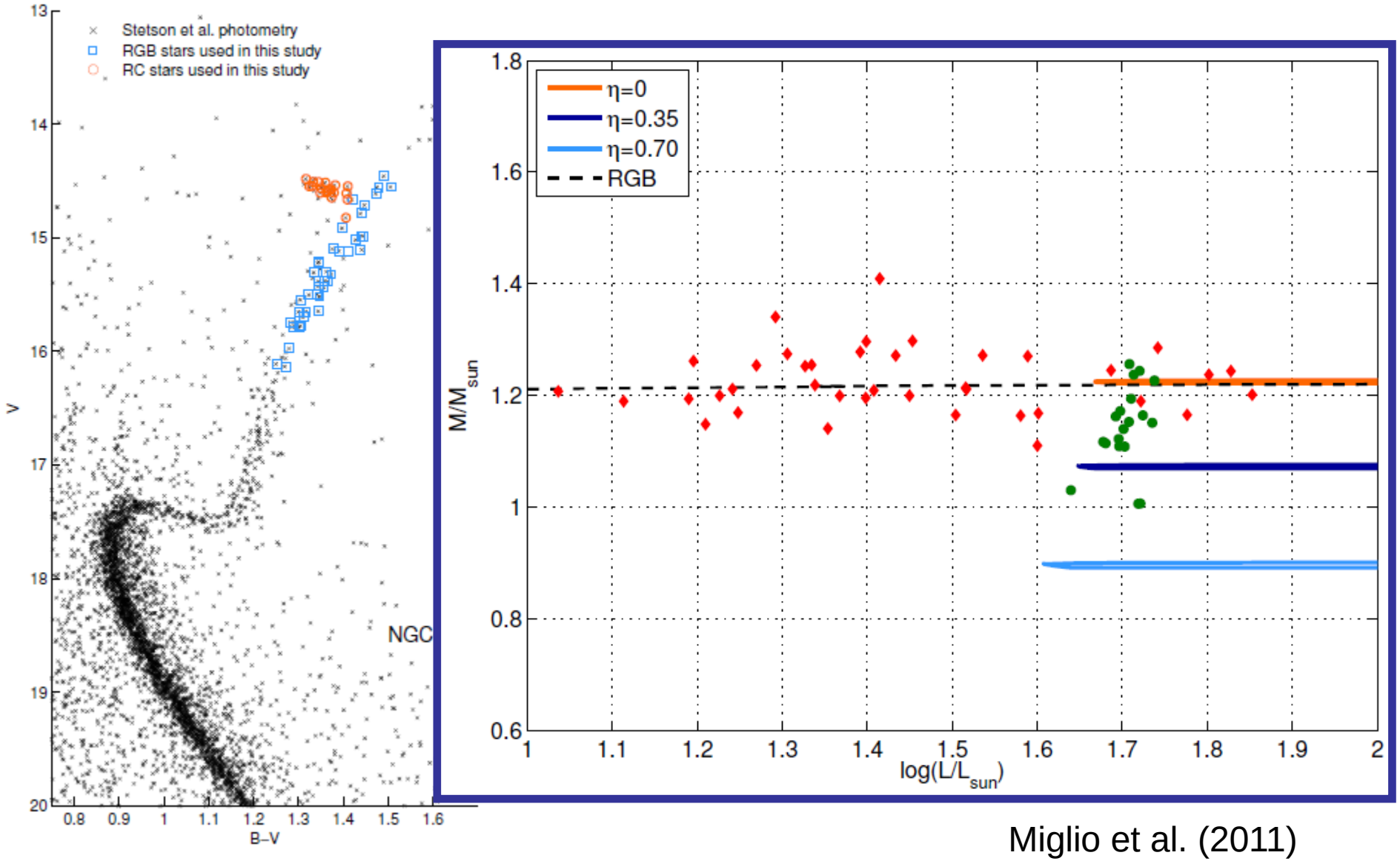
Open clusters ages





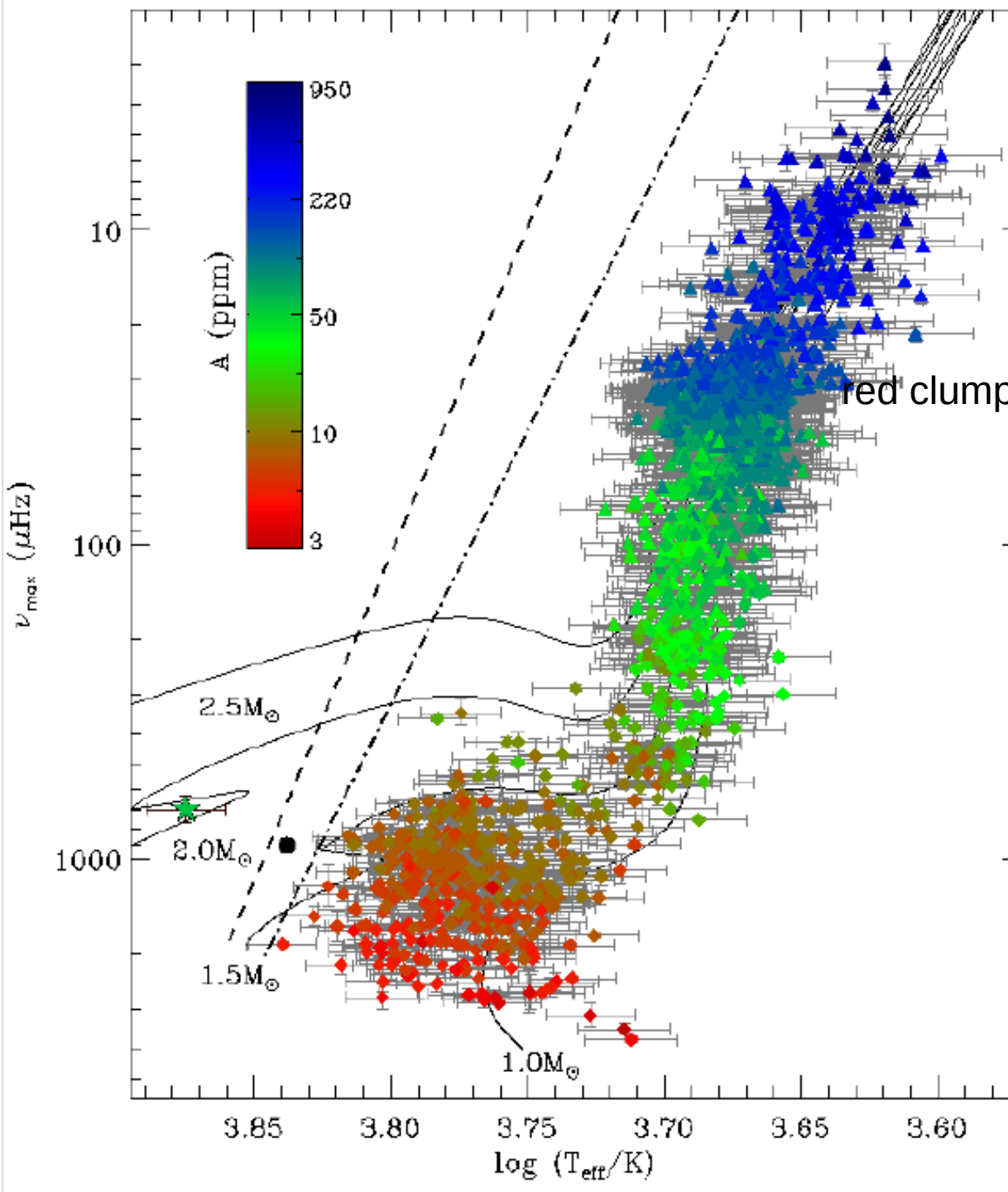
Basu et al. (2011)

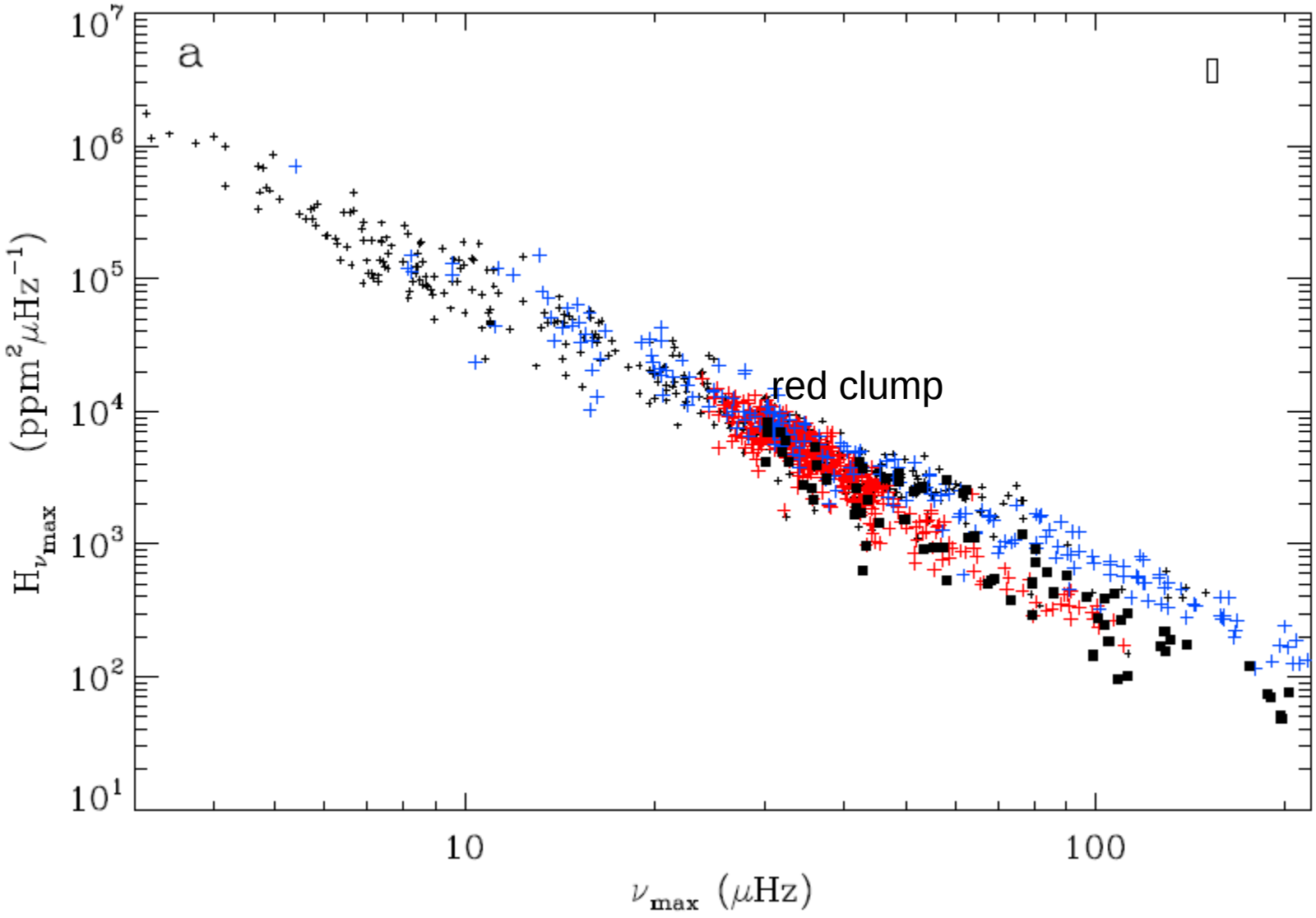
Open clusters mass loss



Miglio et al. (2011)

Amplitudes


950
220
50
10
3
A (ppm)
10
100
1000
ν_{max} (μHz)
2.5M$_\odot$
2.0M$_\odot$
1.5M$_\odot$
1.0M$_\odot$
red clump
3.85
3.80
3.75
3.70
3.65
3.60
log (T$_{eff}$/K)



Mosser et al. (2011) - Kepler

Amplitudes :

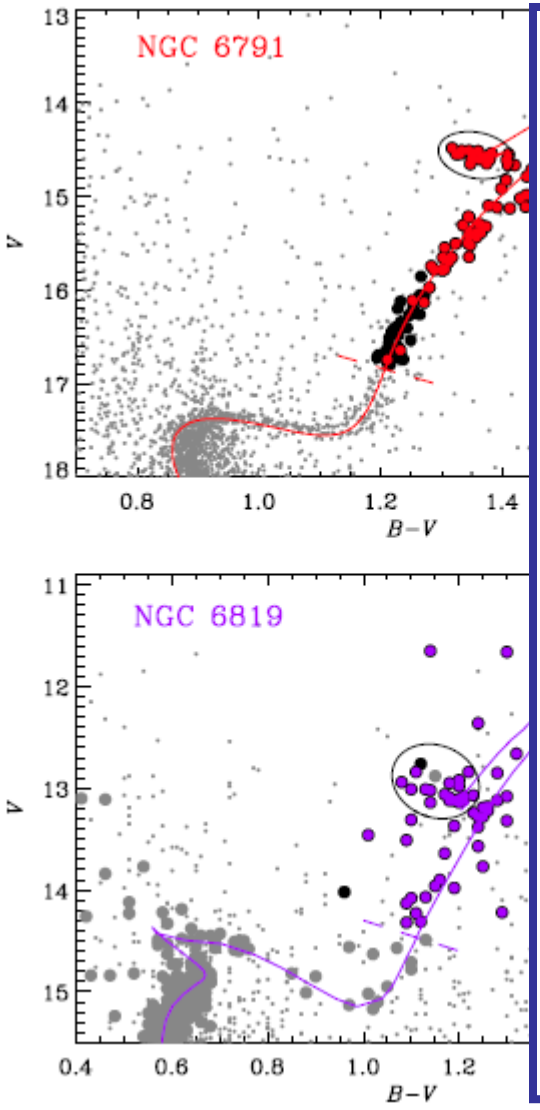
Kjeldsen & Bedding (1995):

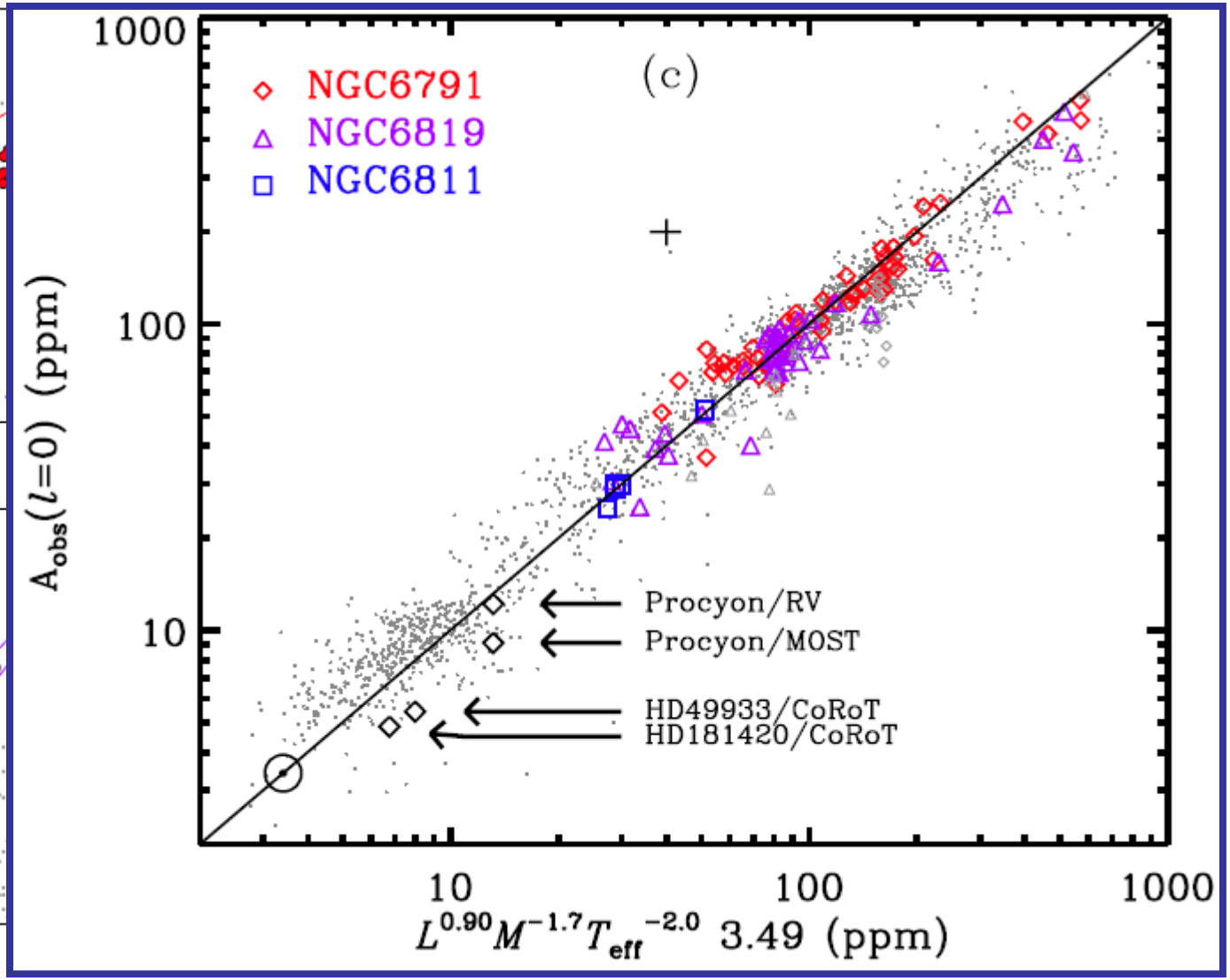
$$A_\lambda \propto L/\left(MT_{\rm eff}^2\right)$$

Stello et al. (2011) – Kepler open clusters

$$A_\lambda \propto L^{0.90}/\left(M^{1.7}T_{\rm eff}^2\right)$$

Open clusters amplitudes



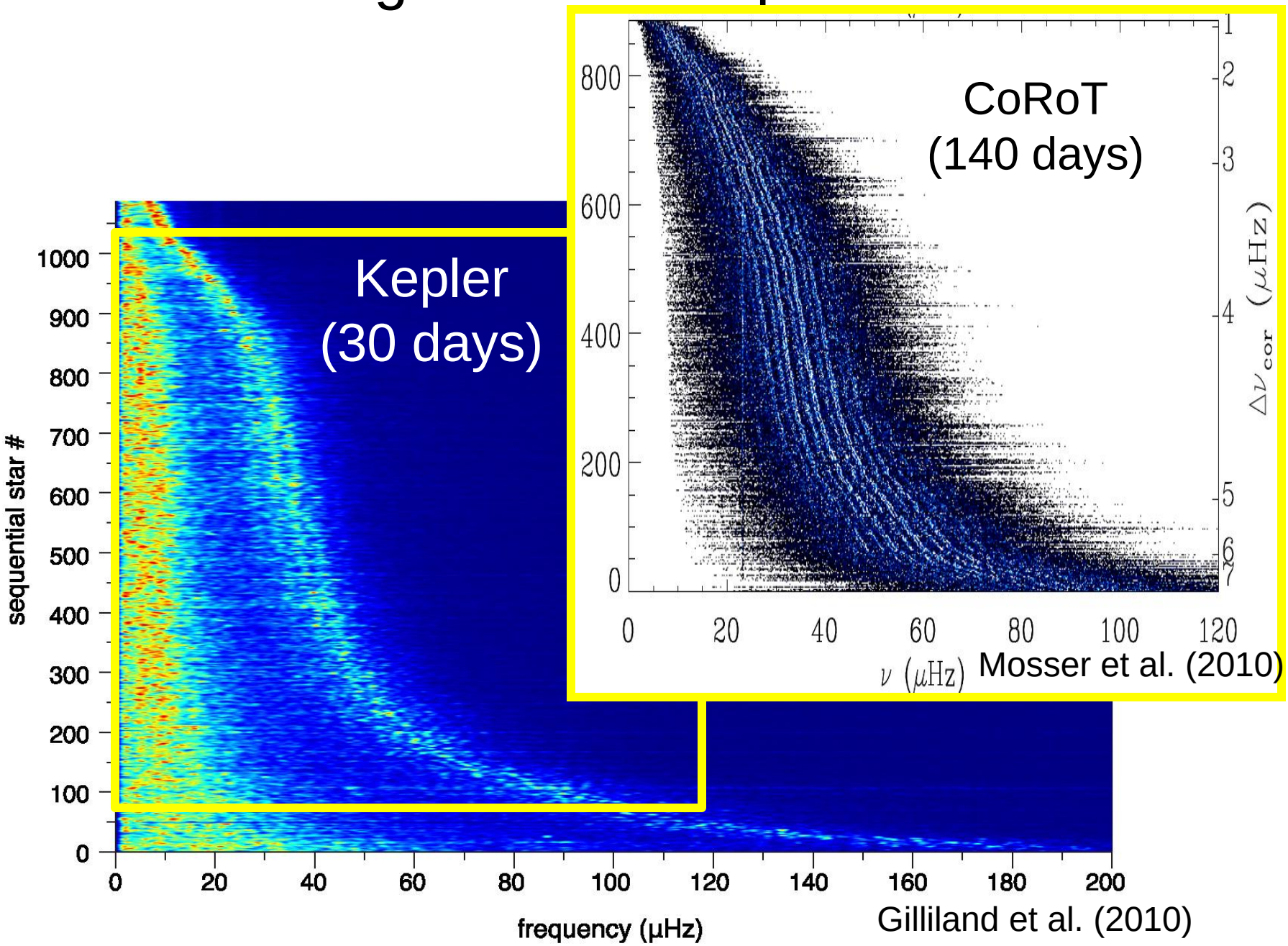


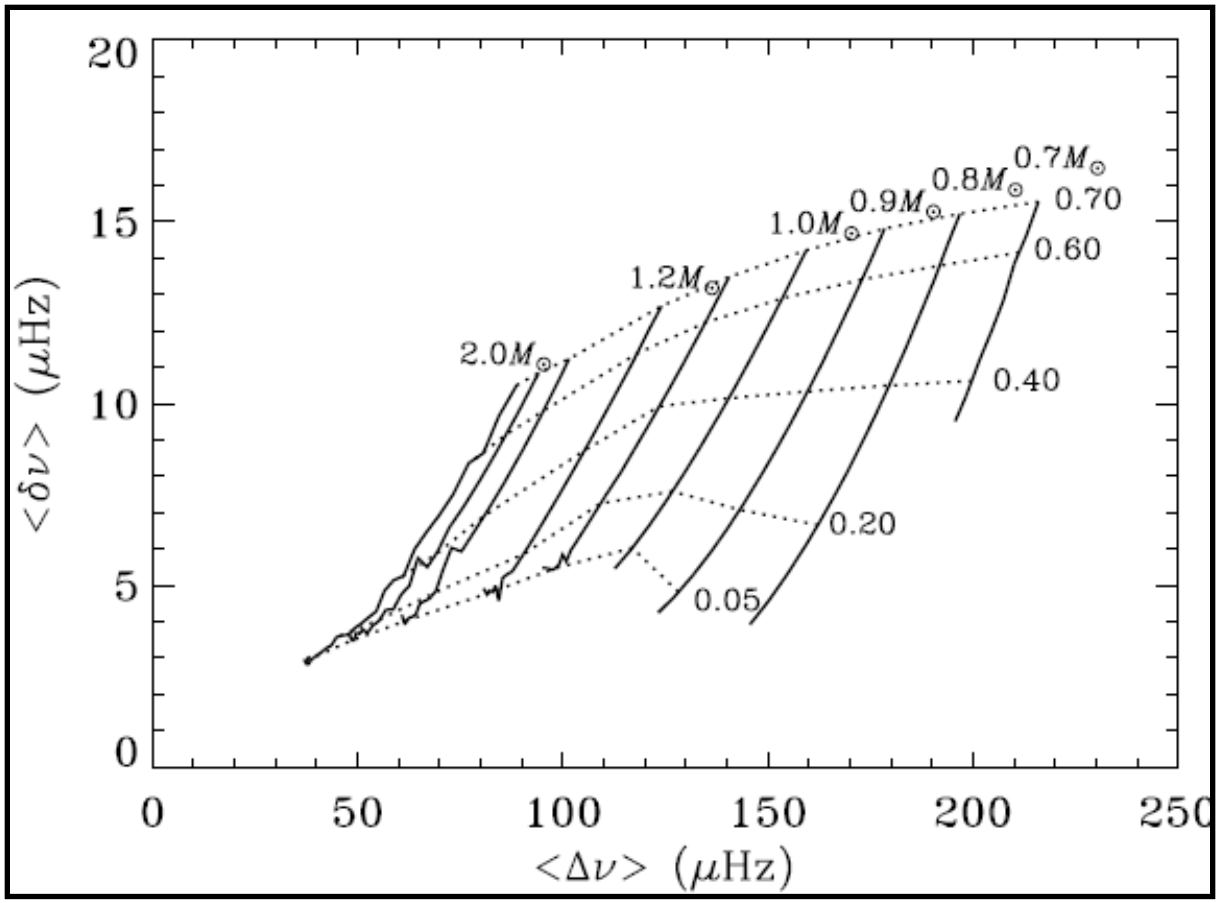
Stello et al. (2011)

What else can we do?

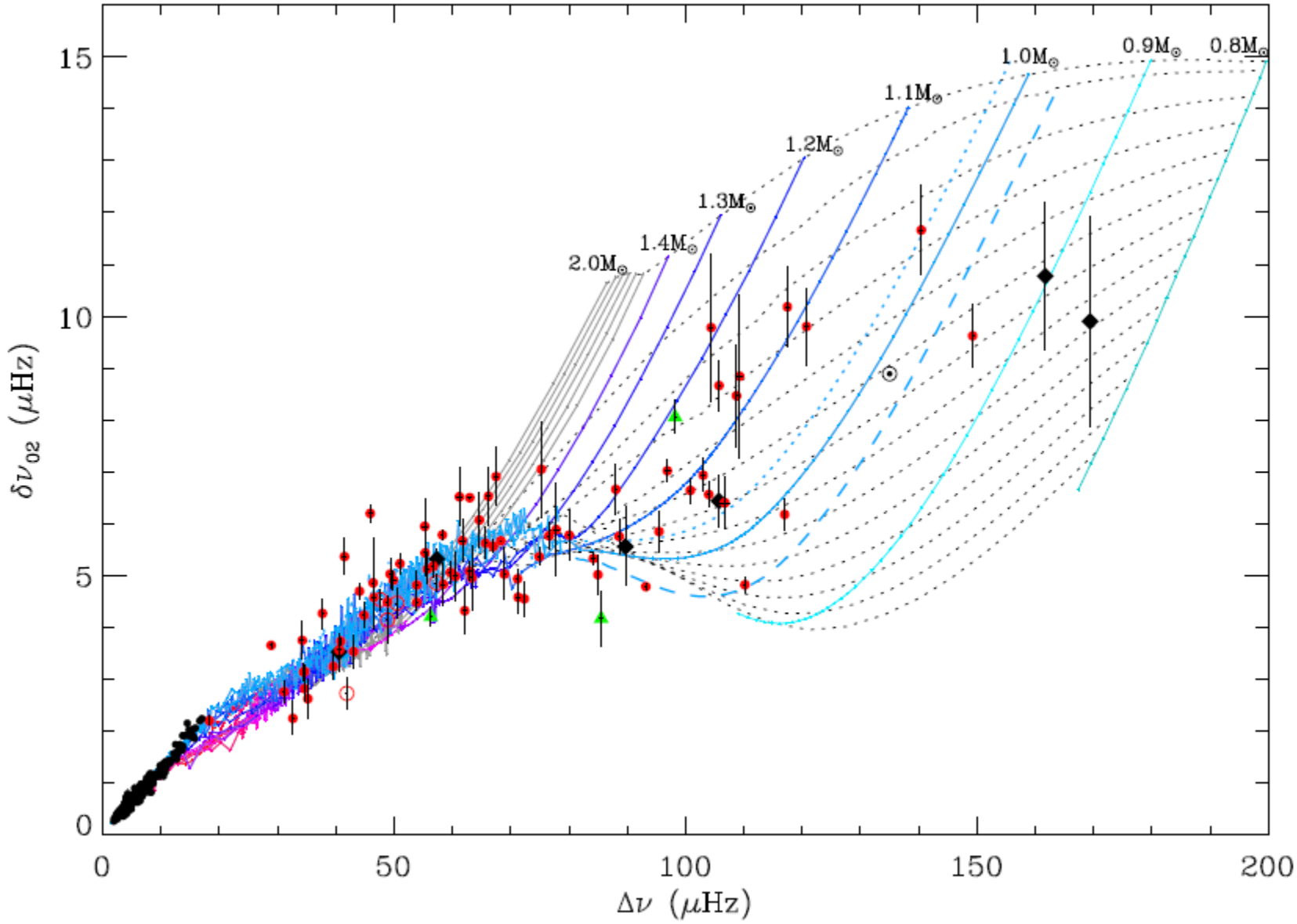
A closer look at the frequency spectra...

Red giants with Kepler & CoRoT

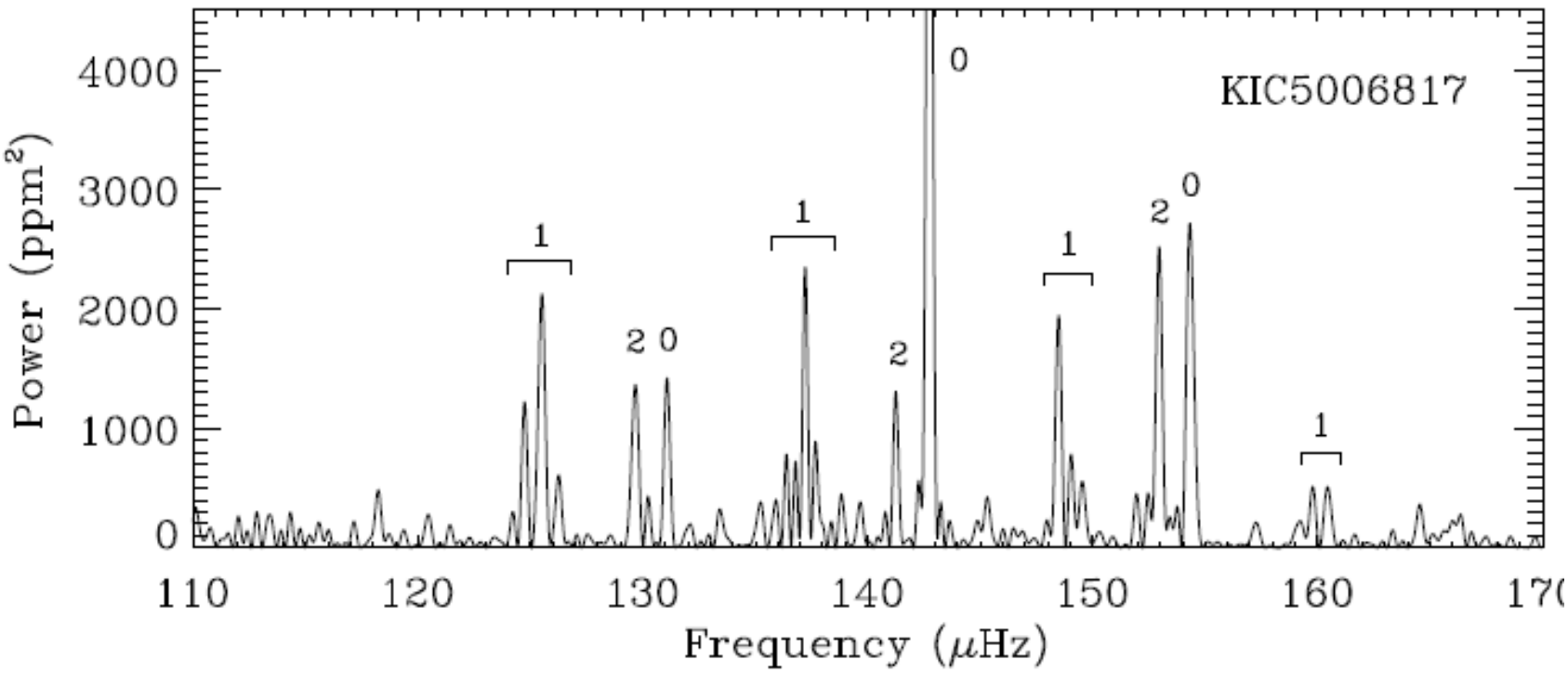




Christensen-Dalsgaard (1988,1993)

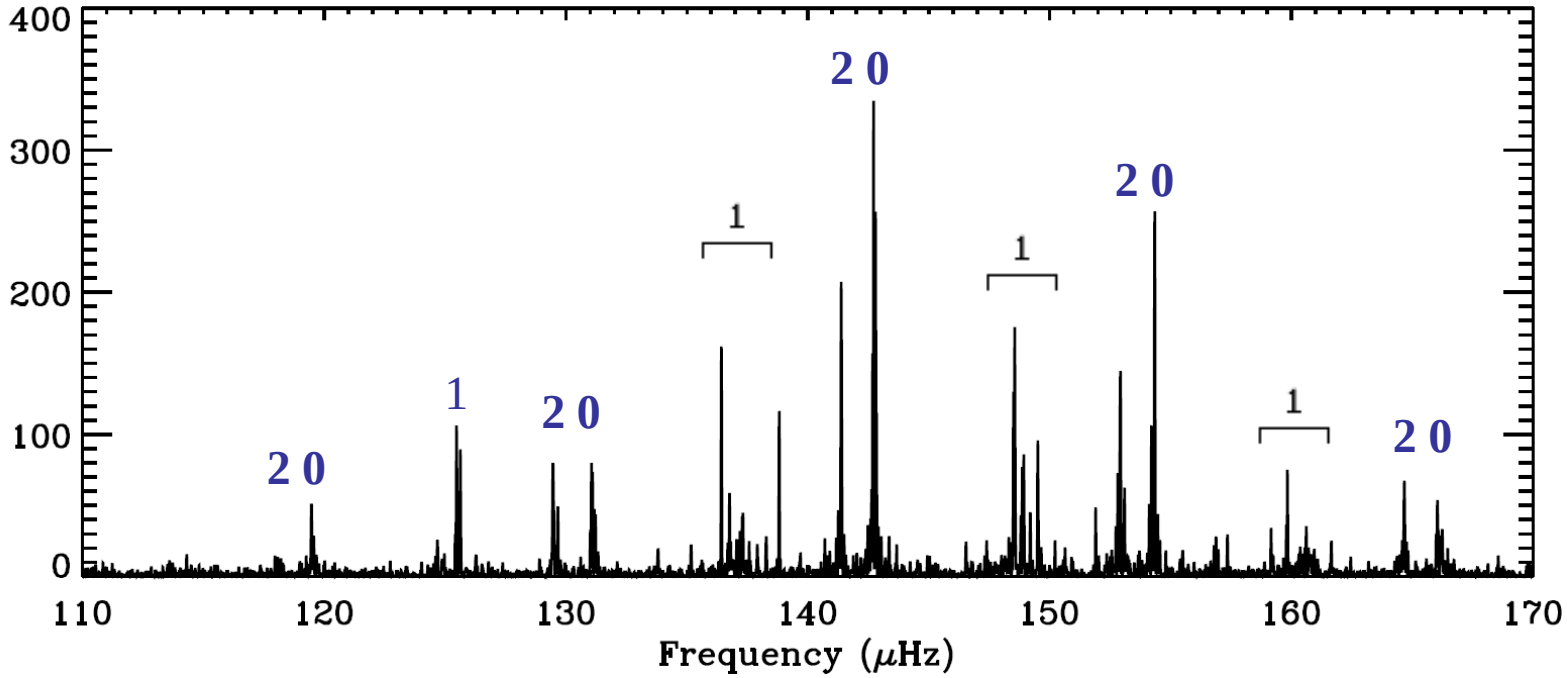


White et al. (2011)



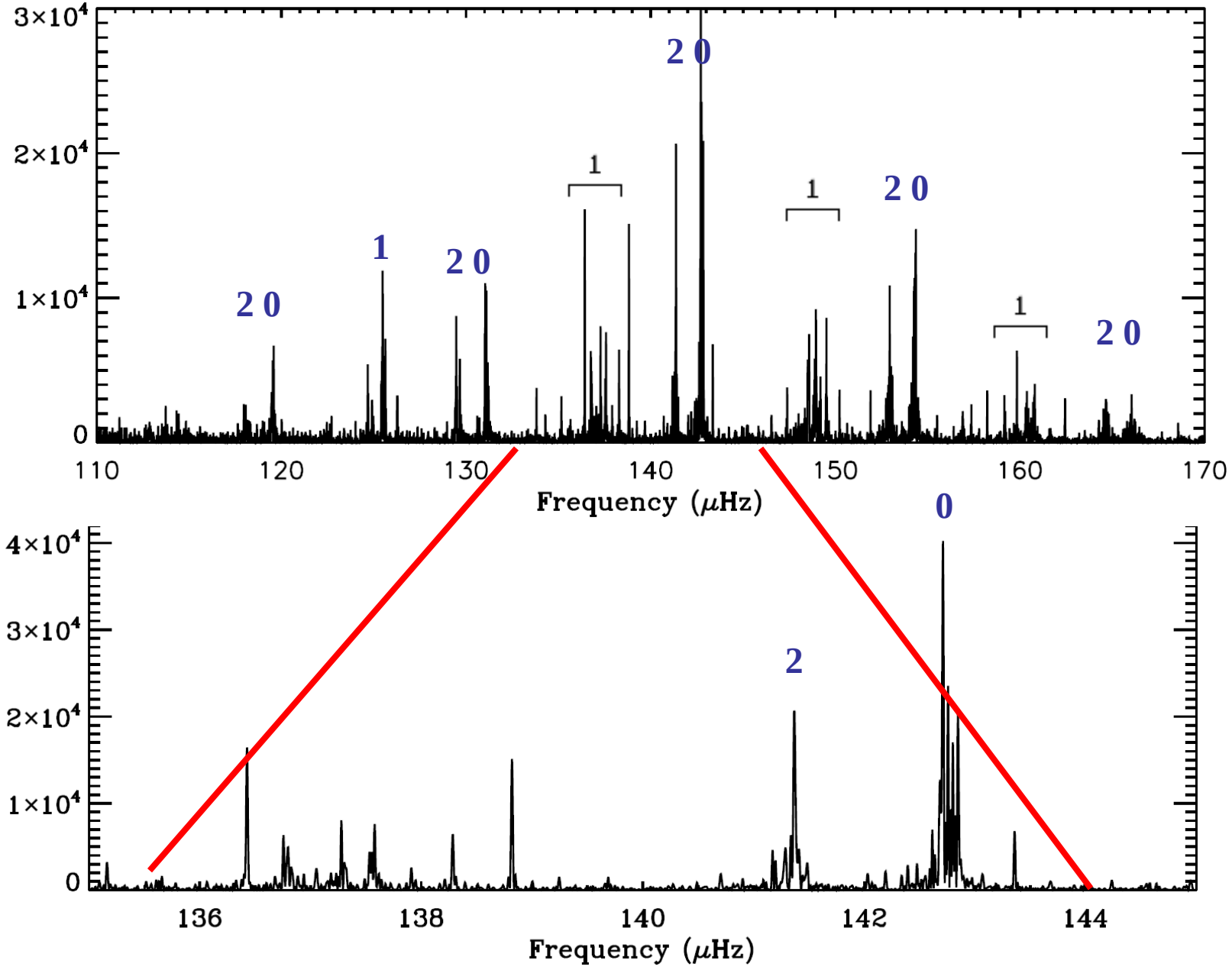
Kepler red giant (1 month)

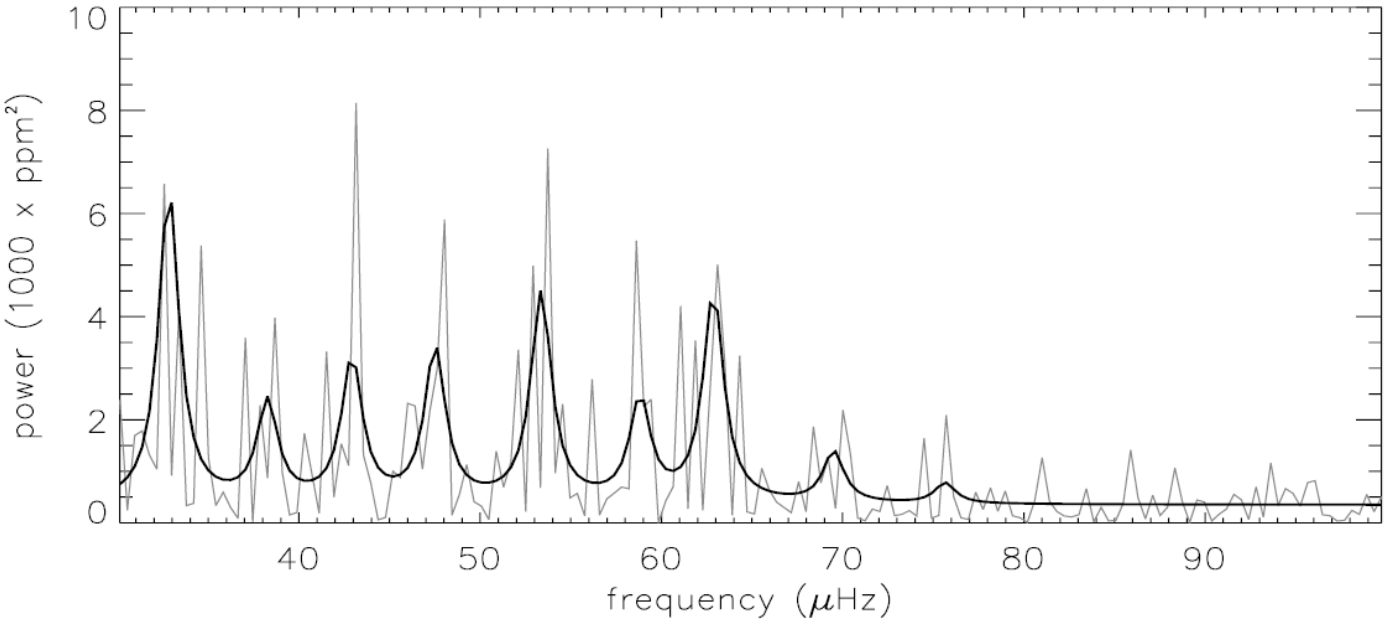
Bedding et al. (2010)



same red giant (10 months)

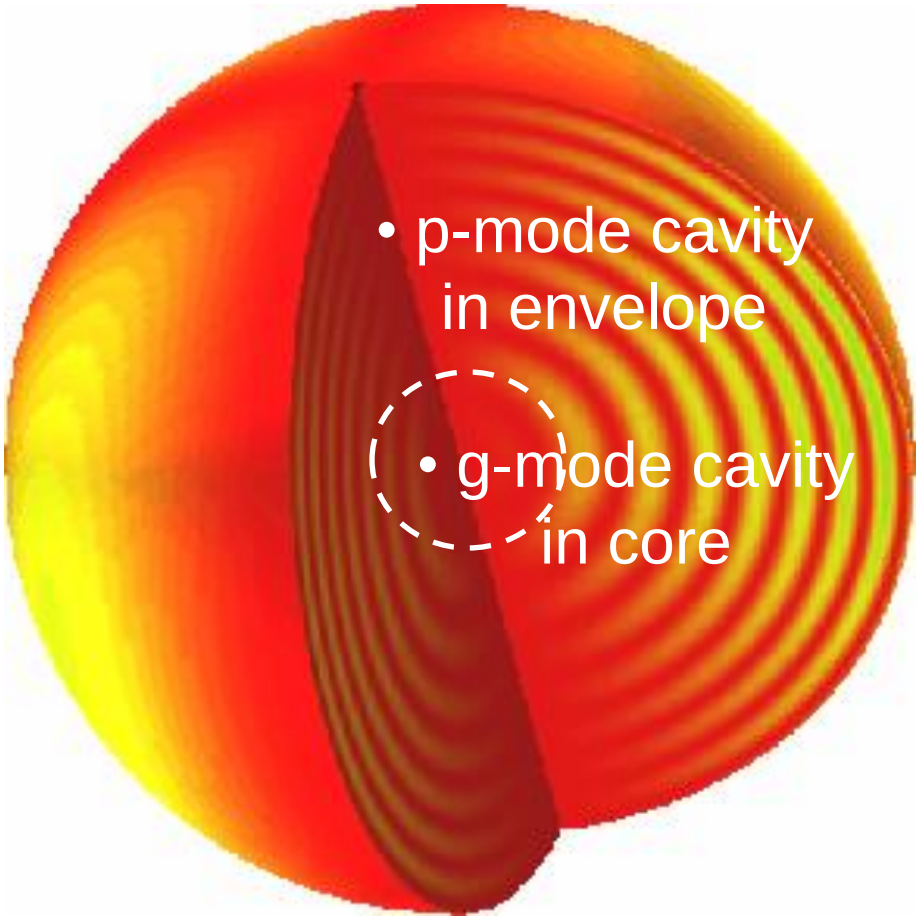
same red giant (19 months)

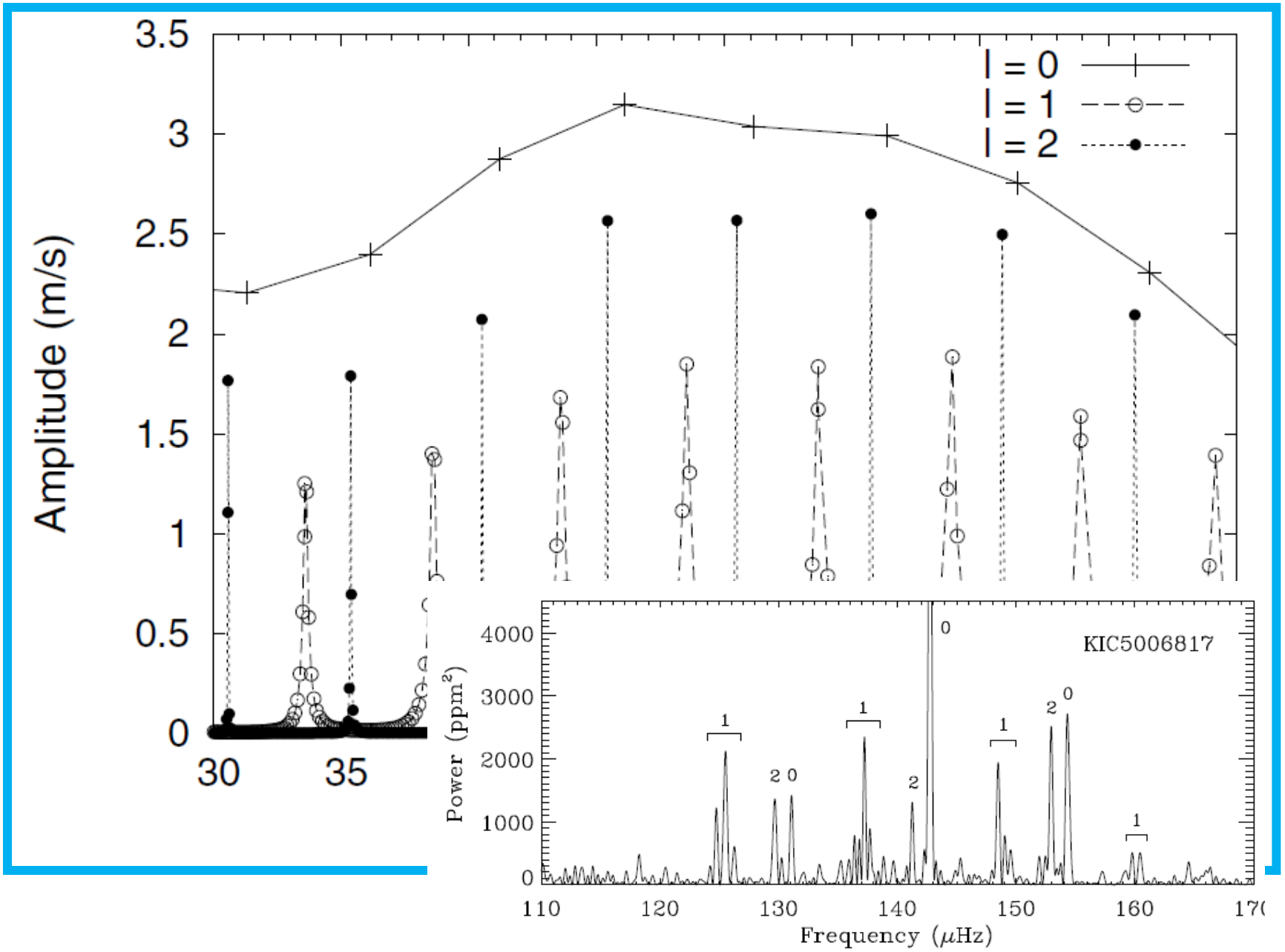




Barban et al. (2007)

Mixed modes arise from coupling between p and g modes with the same *l*

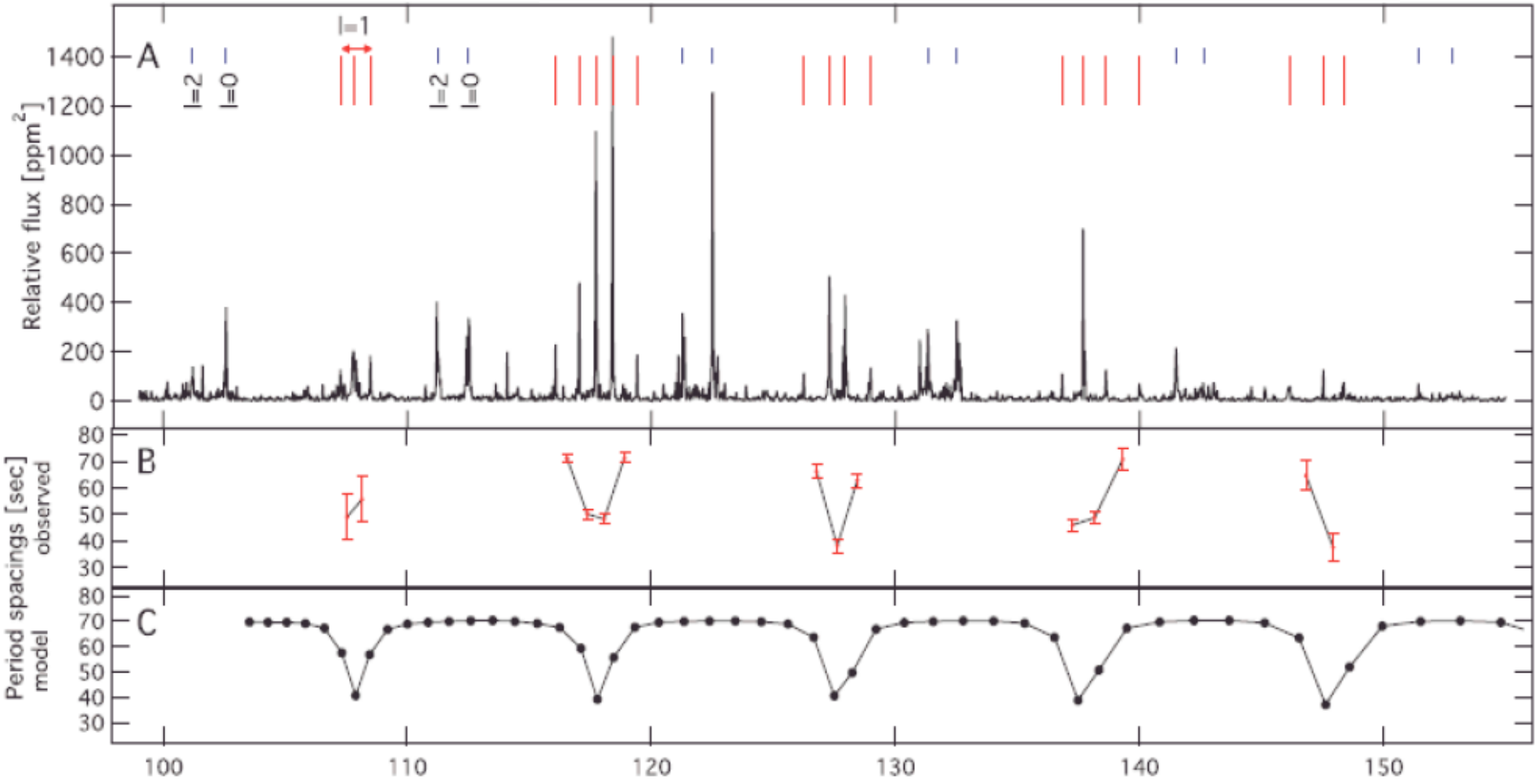




Dupret et al. (2009)
see also Christensen-Dalsgaard (2004)

Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star

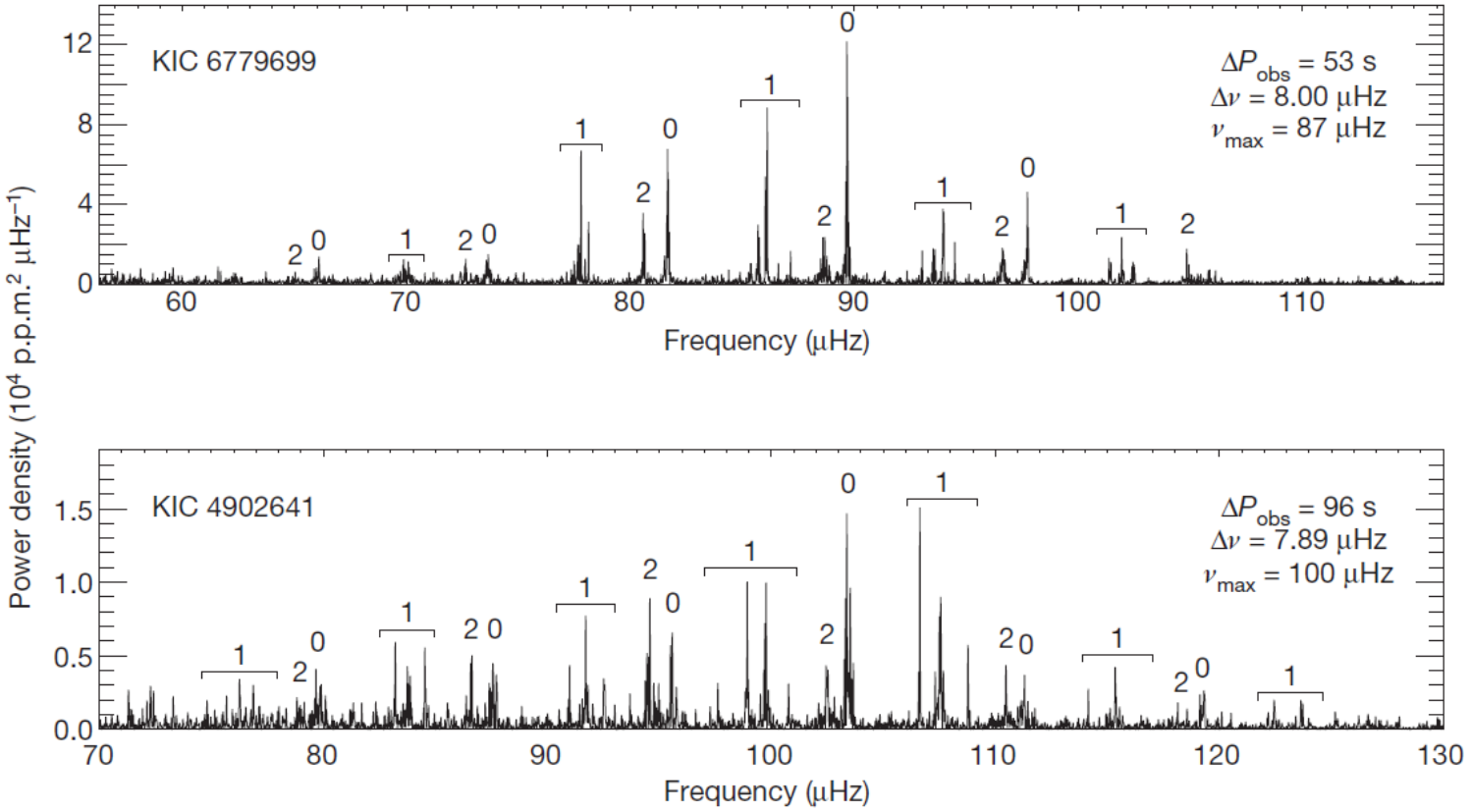
P. G. Beck,[1]* T. R. Bedding,[2] B. Mosser,[3] R. A. Garcia,[4] T. Kallinger,[5] S. Hekker,[6], Y. Elsworth,[6] S. Frandsen,[7] D. Stello,[2] F. Carrier,[1] J. De Ridder,[1] C. Aerts,[1,8] T. R. White,[2] D. Huber,[2] M.-A. Dupret,[9] J. Montalbán,[9] A. Miglio,[9] A. Noels,[9] W. J. Chaplin,[6] H. Kjeldsen,[7] J. Christensen-Dalsgaard,[7] R. L. Gilliland,[10] T. M. Brown,[11] S. D. Kawaler,[12] S. Mathur,[13] J. M. Jenkins,[14],

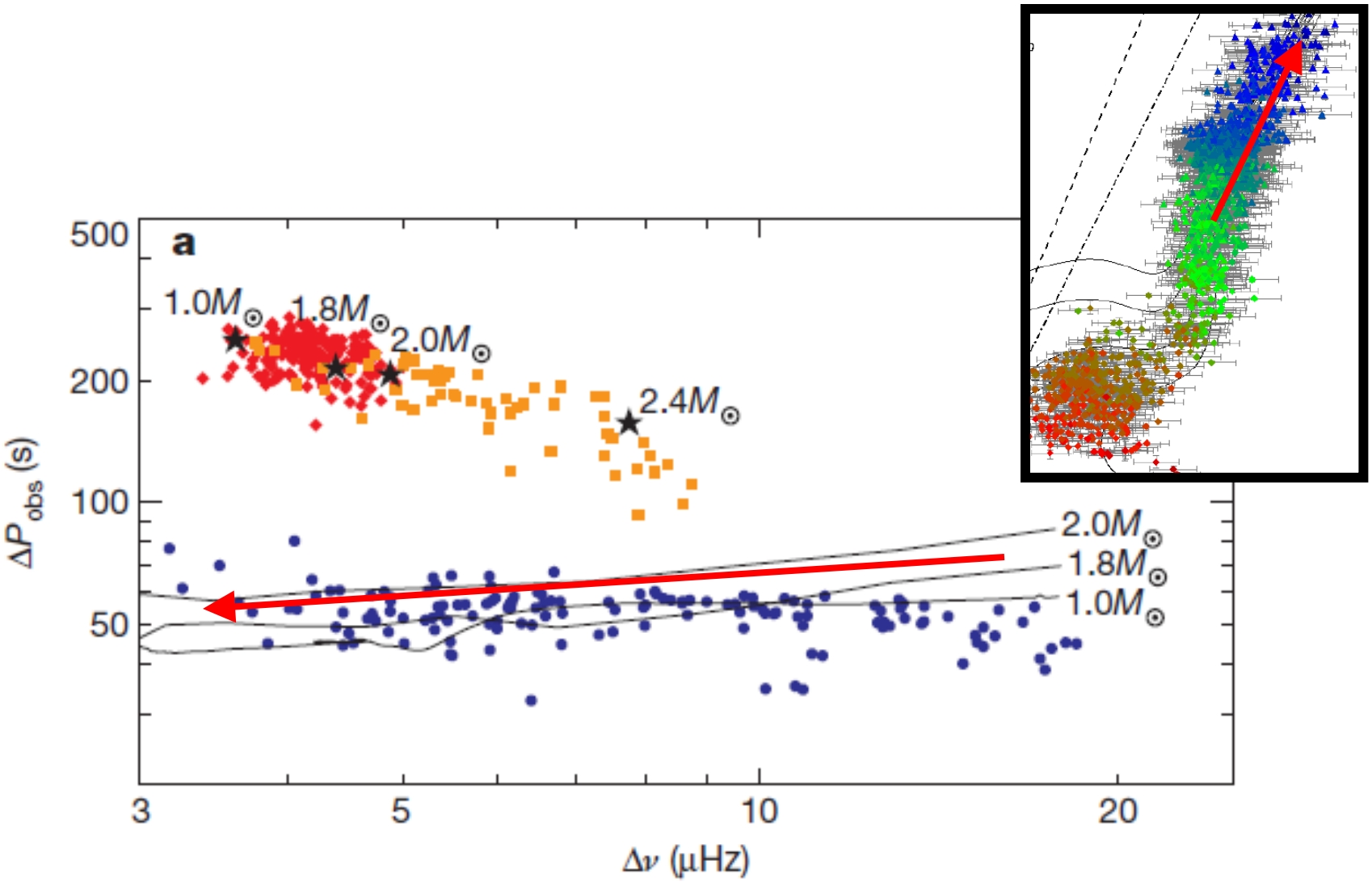


LETTER

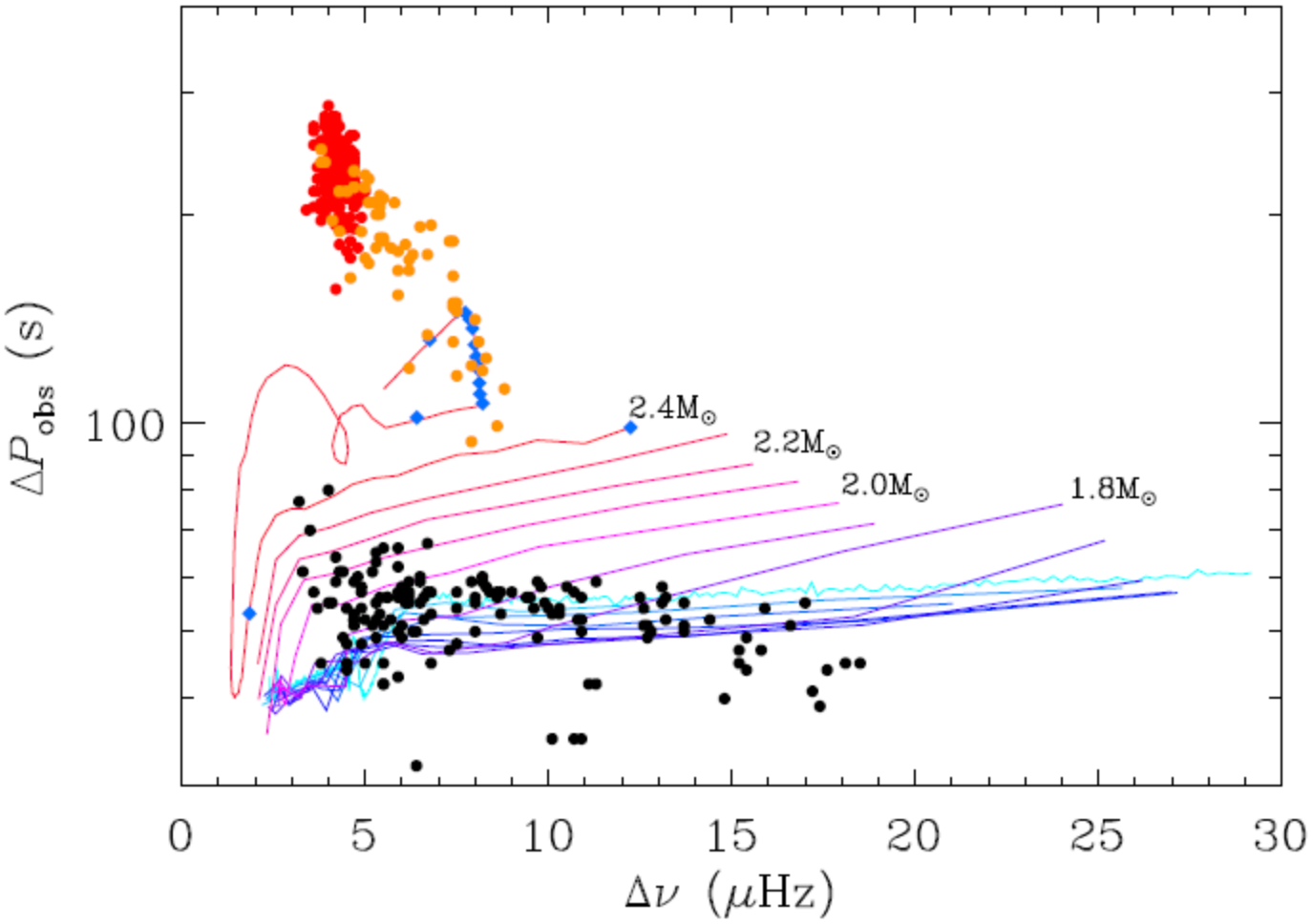
Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

Timothy R. Bedding[1], Benoit Mosser[2], Daniel Huber[1], Josefina Montalbán[3], Paul Beck[4], Jørgen Christensen-Dalsgaard[5], Yvonne P. Elsworth[6], Rafael A. García[7], Andrea Miglio[3,6], Dennis Stello[1], Timothy R. White[1], Joris De Ridder[4], Saskia Hekker[6,8], Conny Aerts[4,9], Caroline Barban[2], Kevin Belkacem[10], Anne-Marie Broomhall[6], Timothy M. Brown[11], Derek L. Buzasi[12], Fabien Carrier[4], William J. Chaplin[6], Maria Pia Di Mauro[13], Marc-Antoine Dupret[3], Søren Frandsen[5], Ronald L. Gilliland[14], Marie-Jo Goupil[2], Jon M. Jenkins[15], Thomas Kallinger[16], Steven Kawaler[17], Hans Kjeldsen[5], Savita Mathur[18], Arlette Noels[3], Victor Silva Aguirre[19] & Paolo Ventura[20]





Bedding et al. (2011); see also Mosser et al. (2011) for CoRoT results



T. White et al. (submitted to ApJ)

LETTER

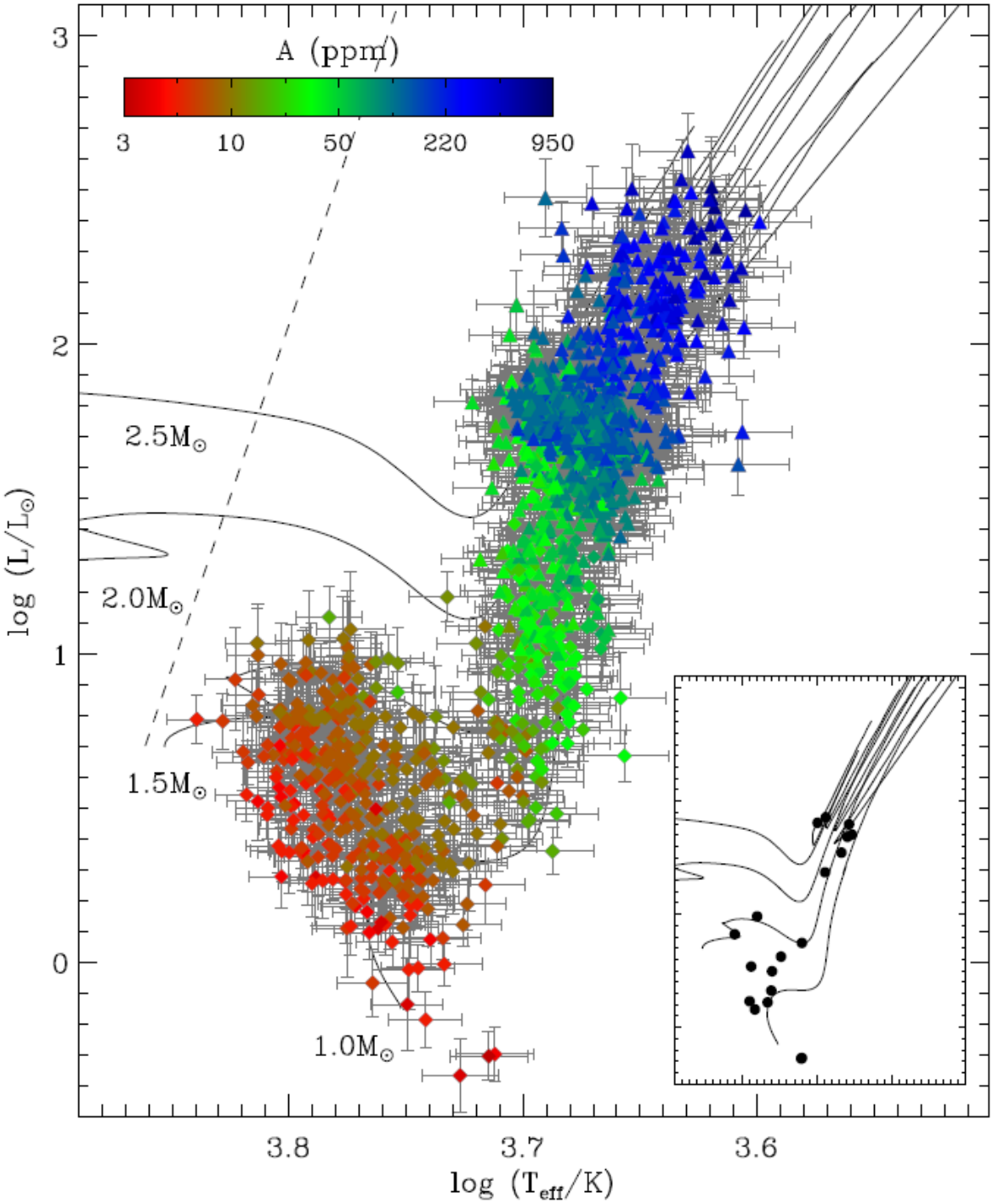
doi:10.1038/nature10612

Fast core rotation in red-giant stars as revealed by gravity-dominated mixed modes

Paul G. Beck[1], Josefina Montalban[2], Thomas Kallinger[1,3], Joris De Ridder[1], Conny Aerts[1,4], Rafael A. García[5], Saskia Hekker[6,7], Marc-Antoine Dupret[2], Benoit Mosser[8], Patrick Eggenberger[9], Dennis Stello[10], Yvonne Elsworth[7], Søren Frandsen[11], Fabien Carrier[1], Michel Hillen[1], Michael Gruberbauer[12], Jørgen Christensen-Dalsgaard[11], Andrea Miglio[7], Marica Valentini[2], Timothy R. Bedding[10], Hans Kjeldsen[11], Forrest R. Girouard[13], Jennifer R. Hall[13] & Khadeejah A. Ibrahim[13]

in press
(under embargo!)

Thank you


A (ppm)
3
10
50
220
950
2.5M⊙
2.0M⊙
1.5M⊙
1.0M⊙
log (L/L⊙)
log (T_eff/K)
3.8
3.7
3.6
3
2
1
0