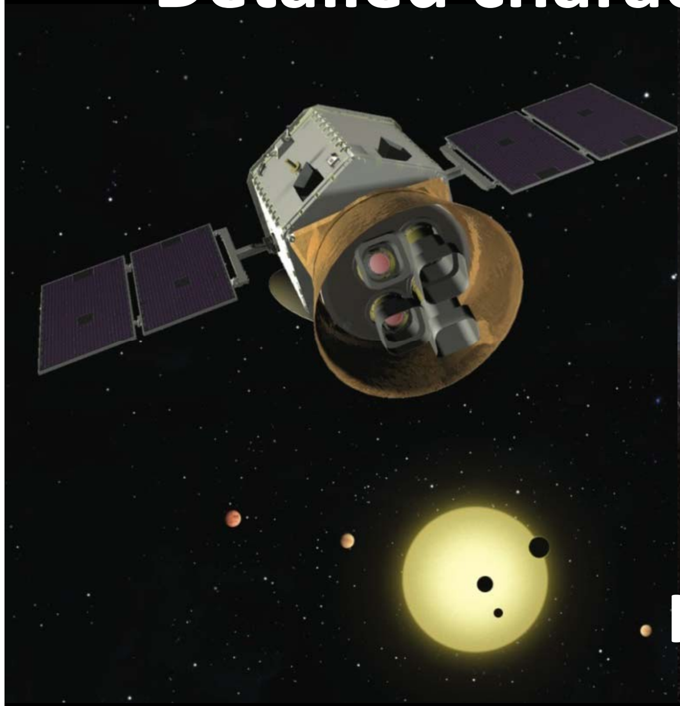
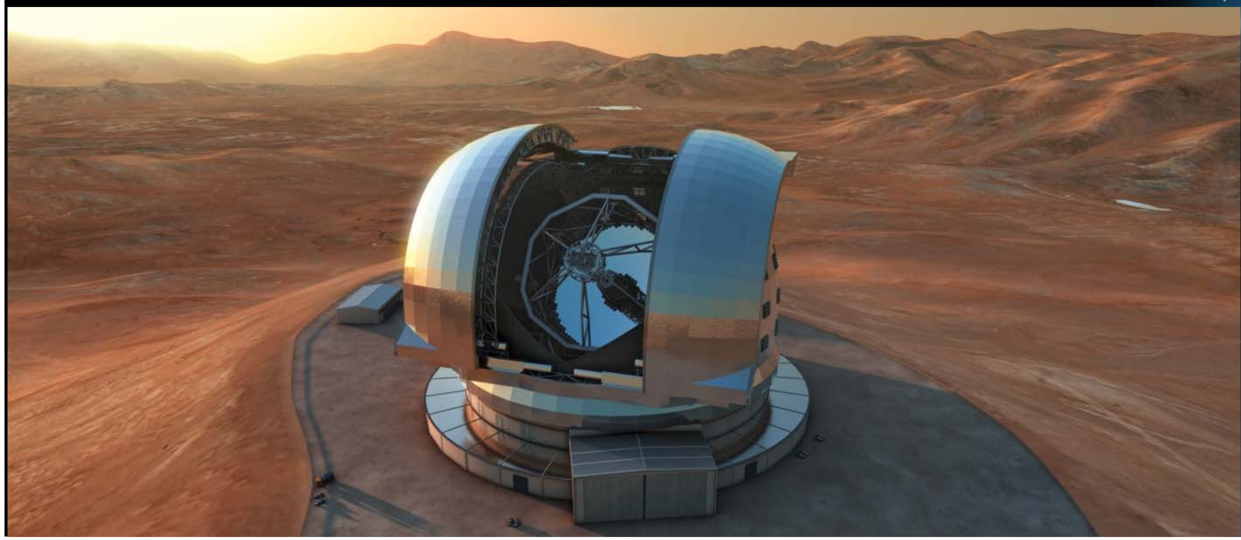
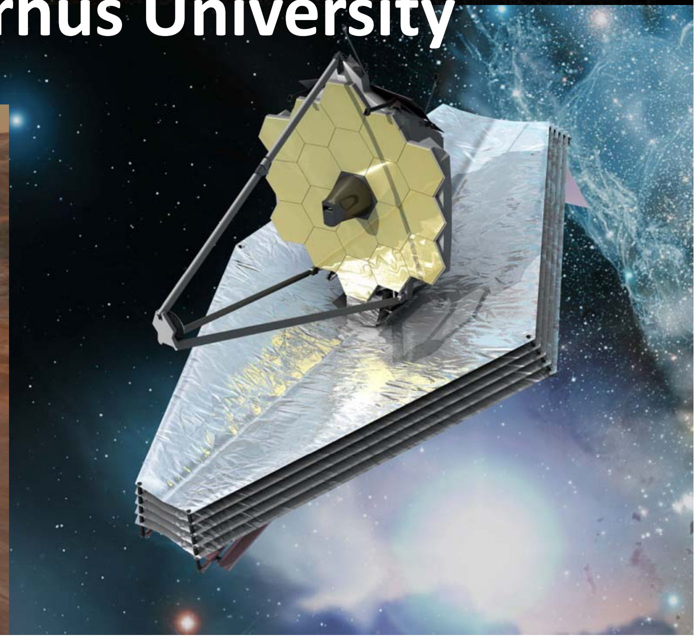
Detailed characterization of stars with planets



Hans Kjeldsen, Aarhus University





Detailed characterization of stars with planets

- Characterizing exoplanets and their atmospheres requires in most cases detailed knowledge of the host star.
- Several techniques are available for measurement of global stellar properties and some of those offer possibilities to characterize the host stars at a very detailed level.
- I will in this talk especially focus on the use of asteroseismology to measure global properties

Asteroseismology

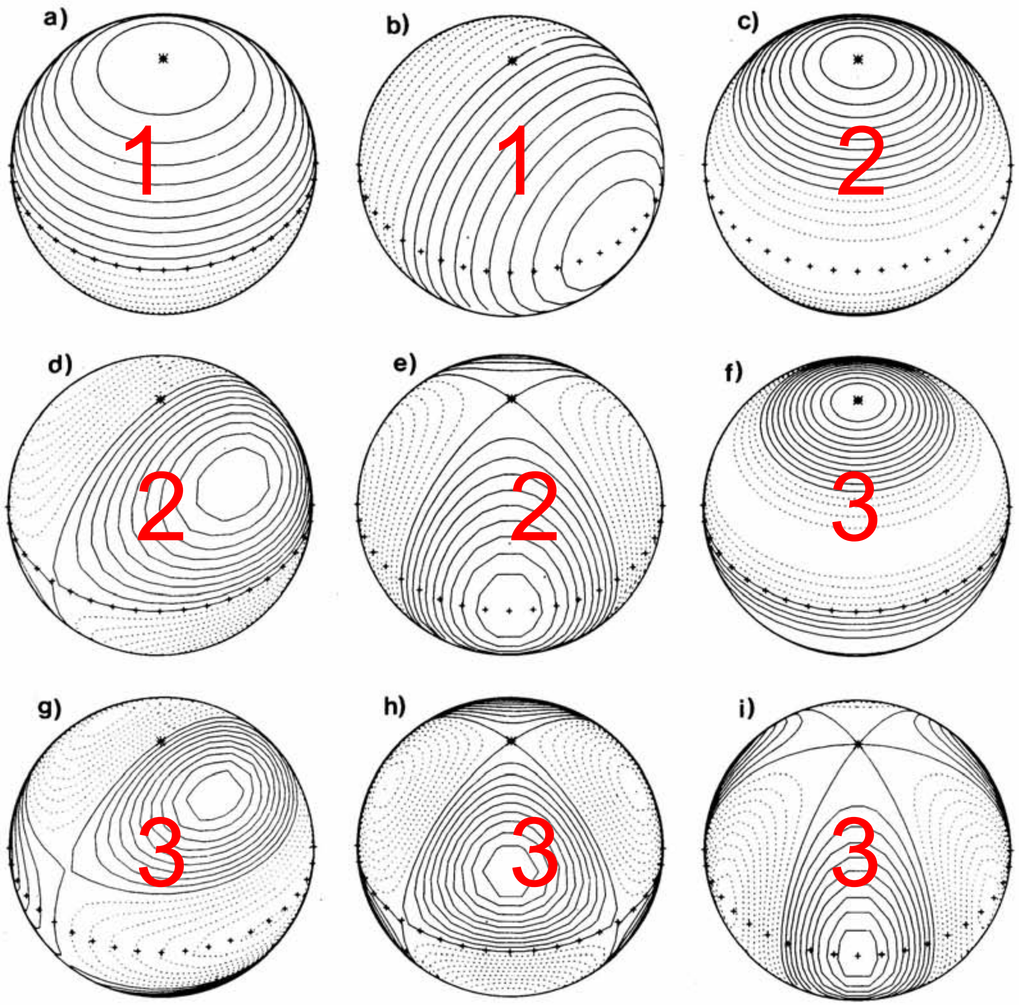
- Mean **density** – better than 1%
- **Mass** (more accurate if we also have [Fe/H] and Teff) – better than 5-8%
- **Radius** from Mass and density – better than 2-3%
- **Surface gravity** from Radius and density – better than 3%
- **Age** / Evolutionary stage – better than 10% of turn-off age
- Rotation period, inclination axis, differential rotation

Observational Asteroseismology: Observables

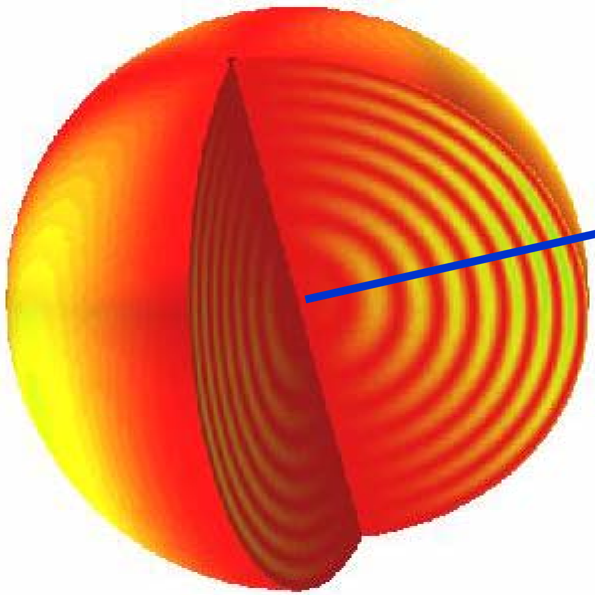
- Oscillation frequencies and frequency differences/ratios/splittings
- Oscillation mode identification (degree, order and mode type; *g*/*p*/*f*, *mixed*)
- Oscillation mode properties (amplitude, amplitude ratios, phase, phase differences, life time, …)
- Changes (short term and long term) in mode parameters (frequencies, amplitudes, …)

ℓ=

0
Radial



Mode degree: ℓ



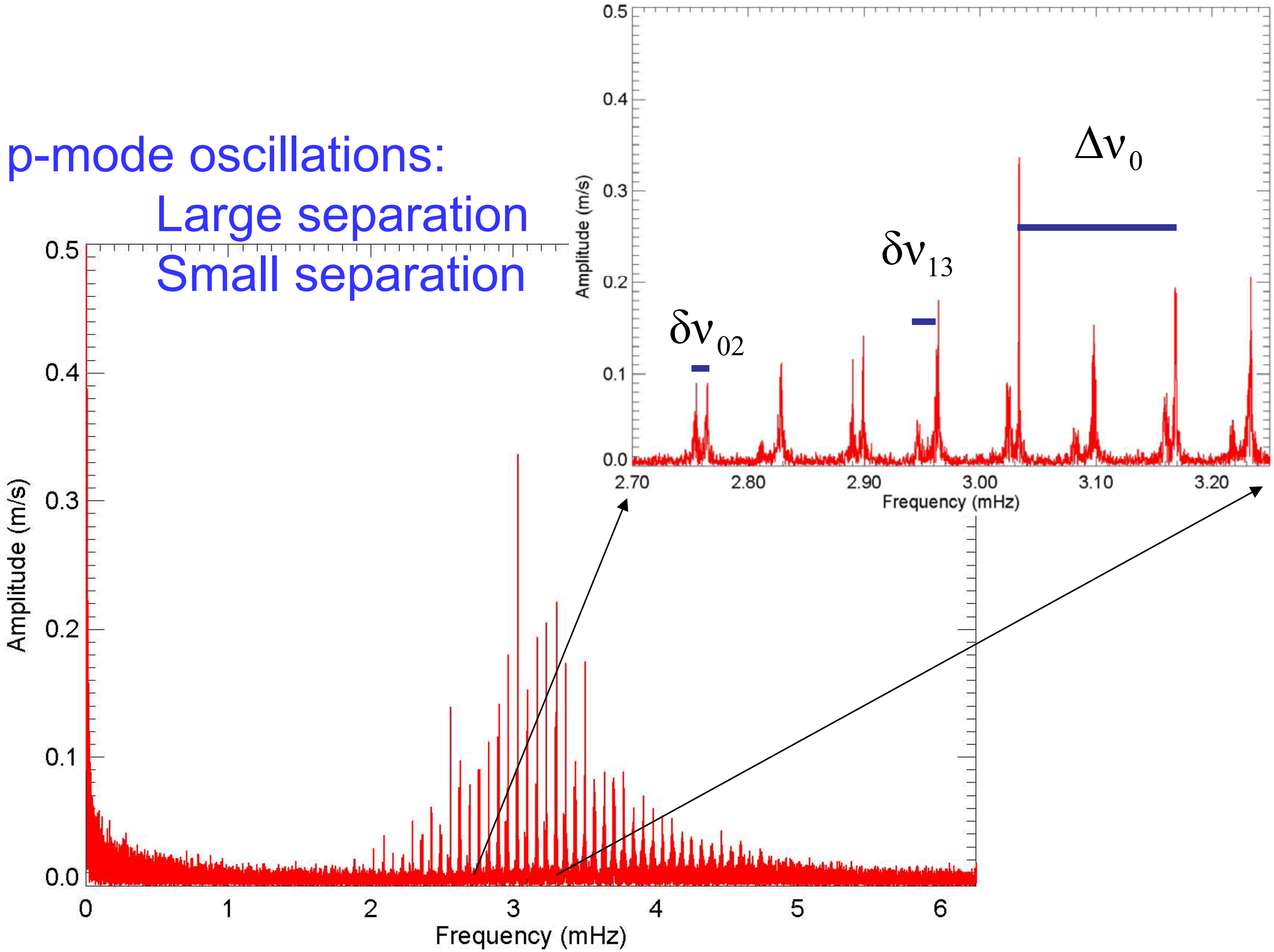
Radial order: n

n = 17

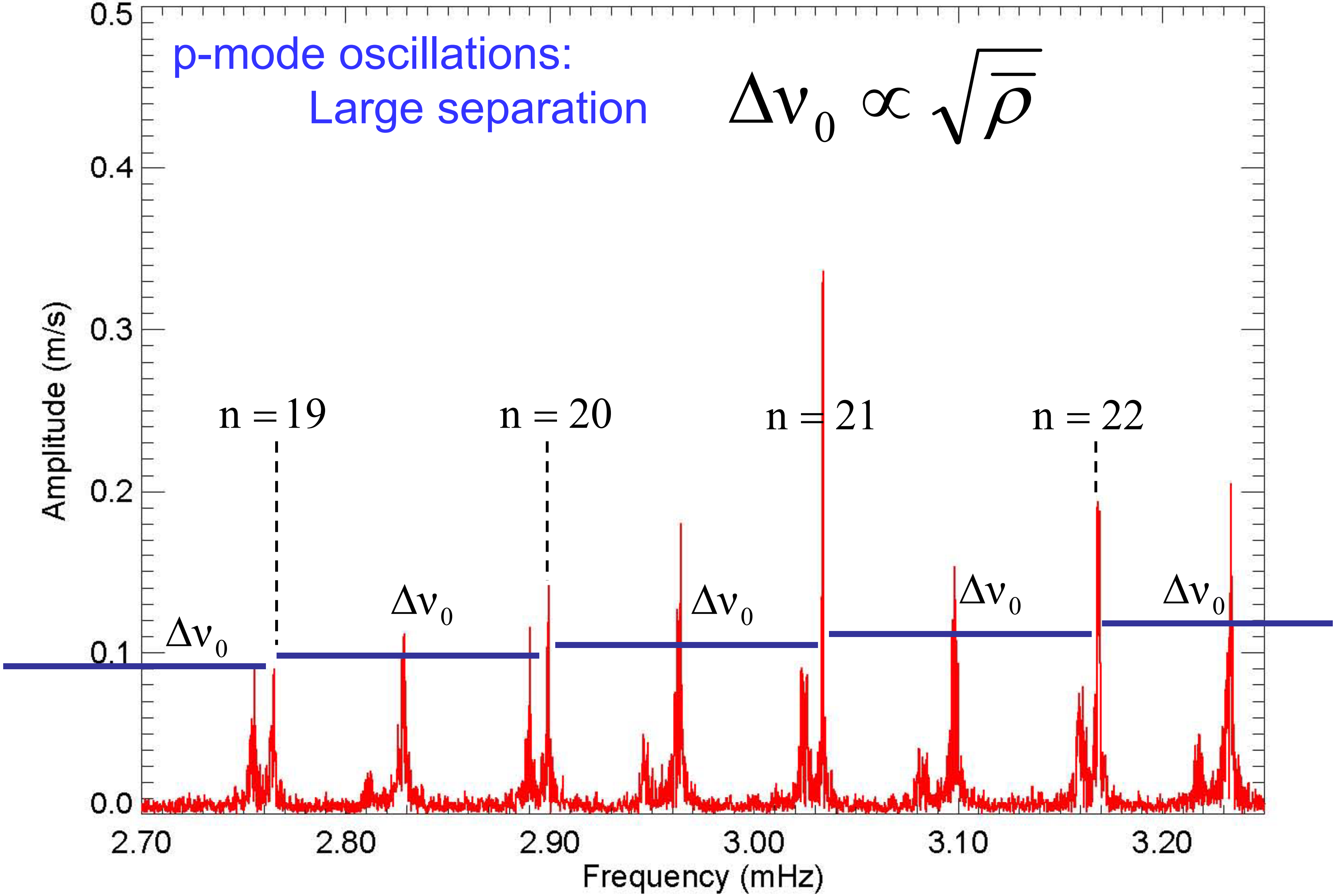
p-mode oscillations:

Large separation

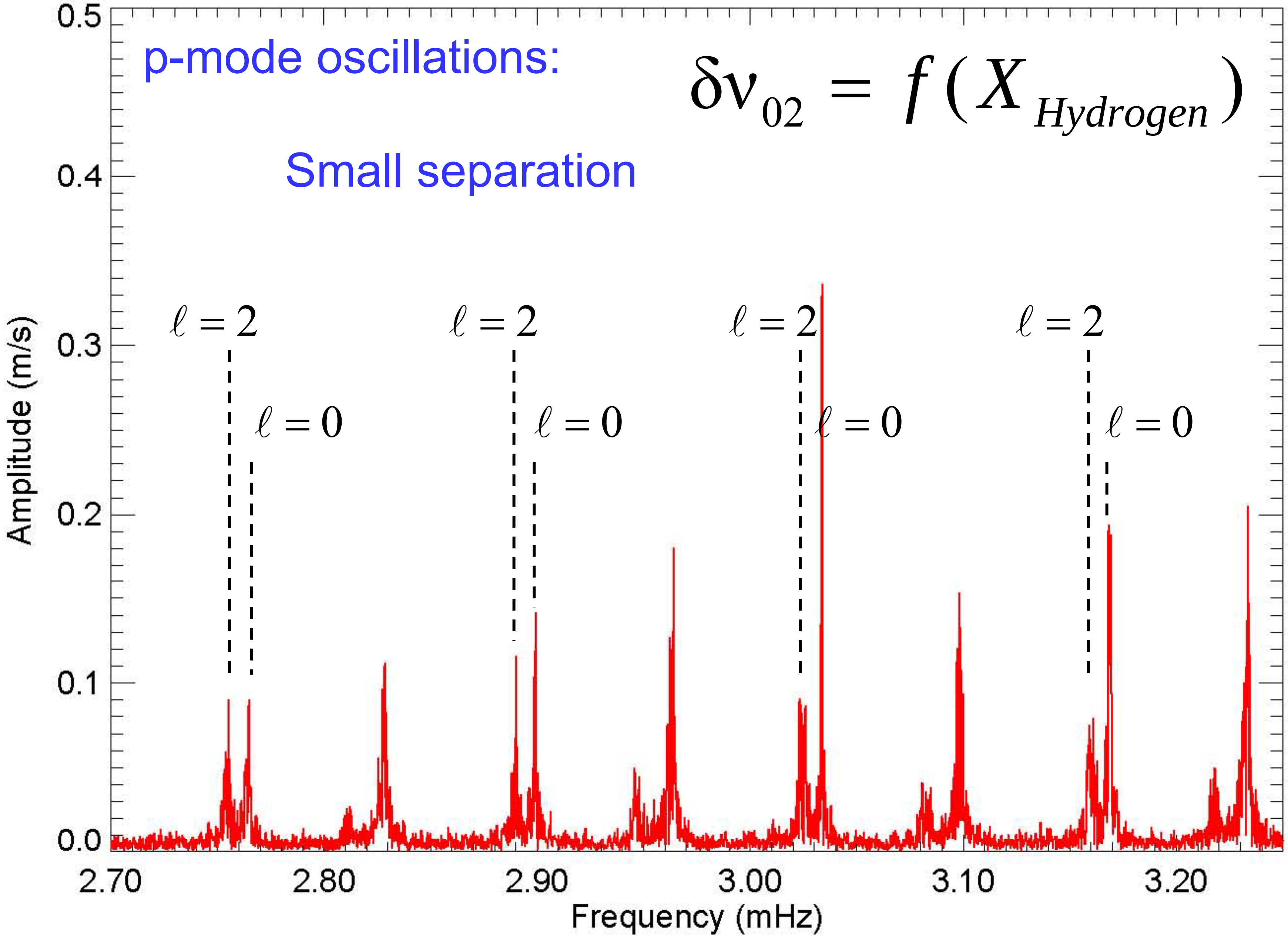
Small separation



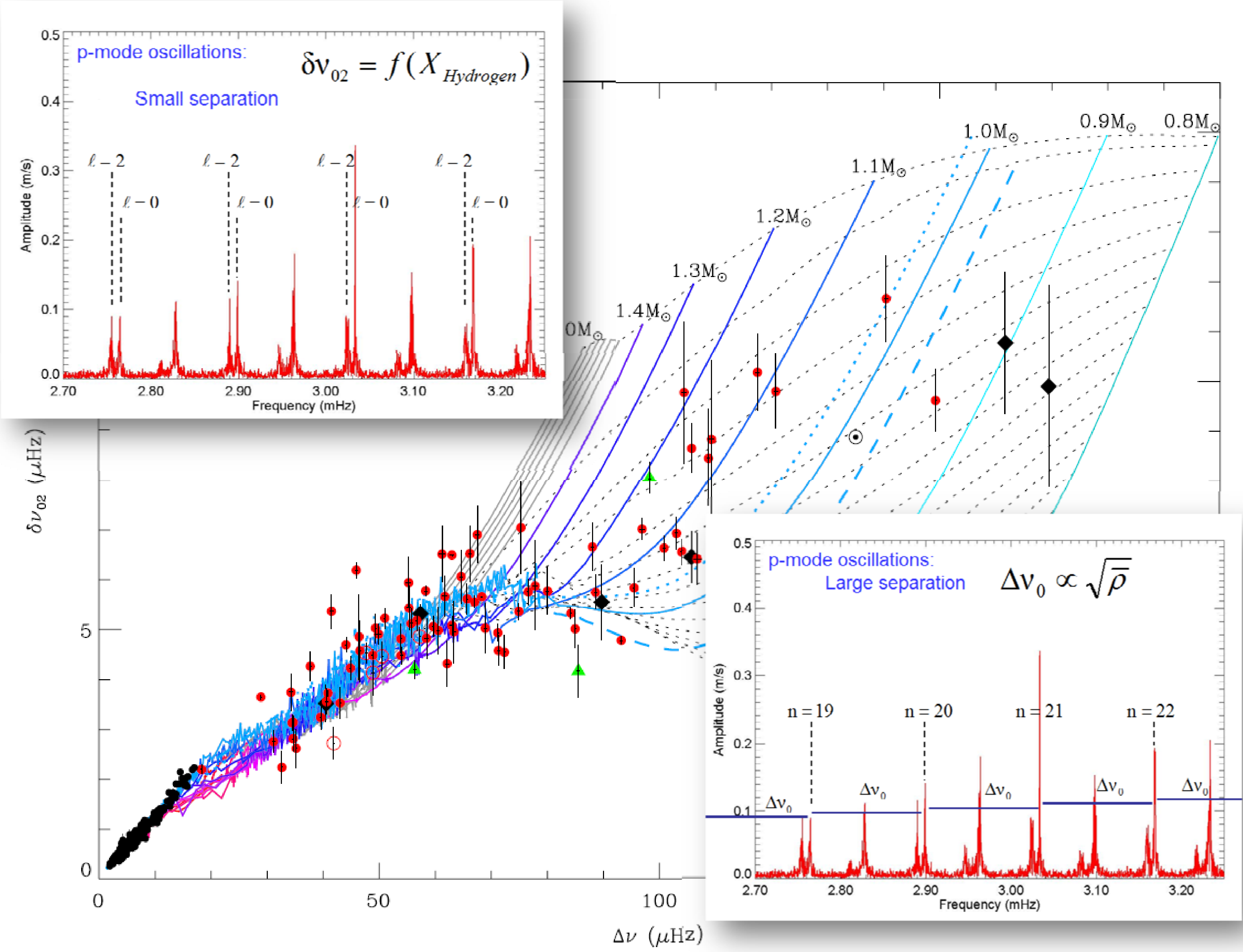
Power Spectrum of a time series



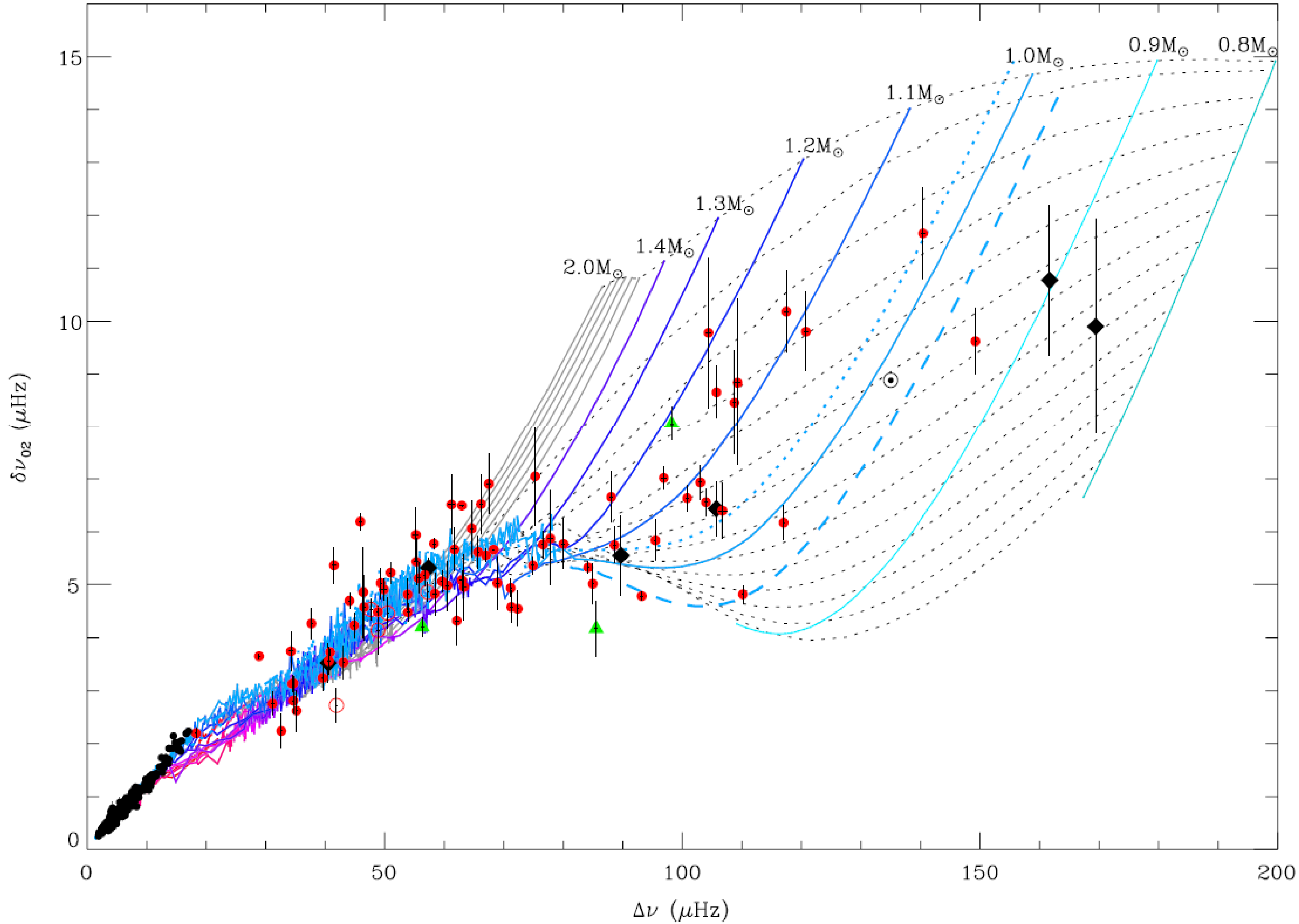
p-mode oscillations:
Large separation
$\Delta\nu_0 \propto \sqrt{\bar{\rho}}$
n = 19
n = 20
n = 21
n = 22
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
Amplitude (m/s)
0.5
0.4
0.3
0.2
0.1
0.0
2.70
2.80
2.90
3.00
3.10
3.20
Frequency (mHz)



p-mode oscillations:
$\delta\nu_{02} = f(X_{Hydrogen})$
Small separation
$\ell = 2$
$\ell = 0$
$\ell = 2$
$\ell = 0$
$\ell = 2$
$\ell = 0$
$\ell = 2$
$\ell = 0$
Amplitude (m/s)
0.5
0.4
0.3
0.2
0.1
0.0
2.70
2.80
2.90
3.00
3.10
3.20
Frequency (mHz)

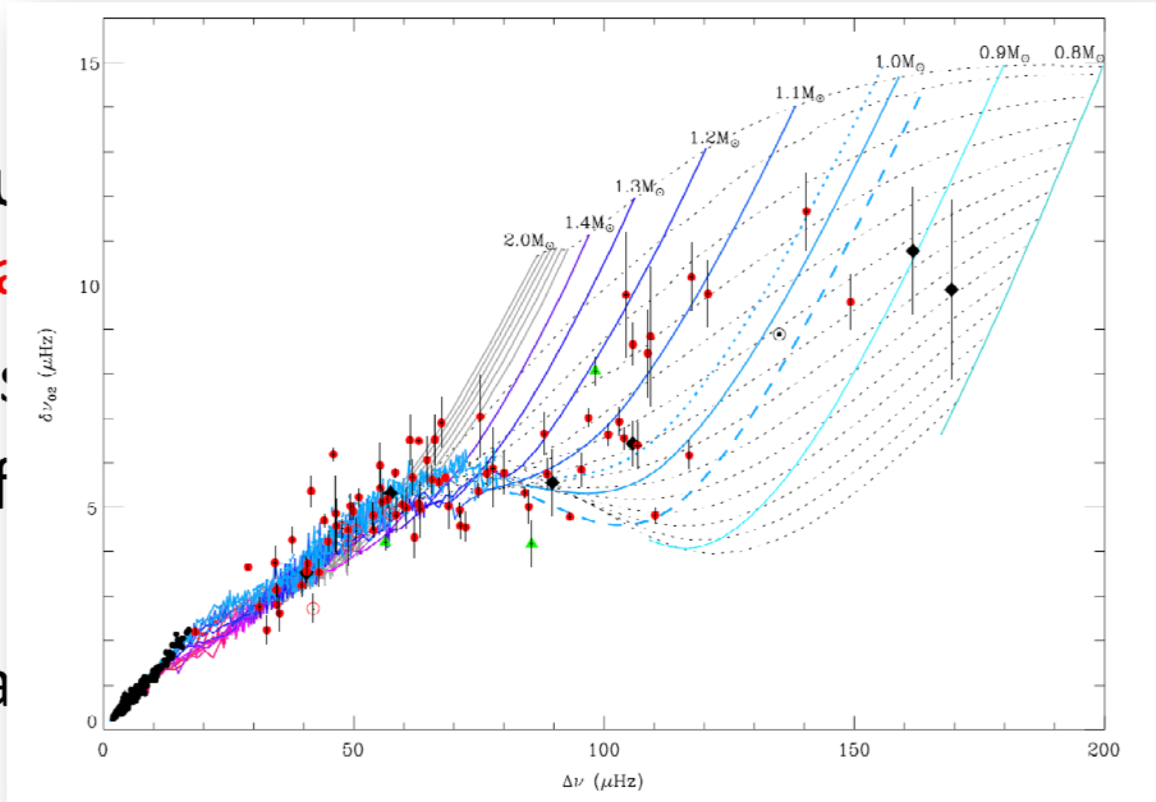

p-mode oscillations:
Small separation
$\delta\nu_{02} = f(X_{Hydrogen})$
ℓ = 2
ℓ = 0
Amplitude (m/s)
Frequency (mHz)
1.4M⊙
1.3M⊙
1.2M⊙
1.1M⊙
1.0M⊙
0.9M⊙
0.8M⊙
δν02 (μHz)
Δν (μHz)
p-mode oscillations:
Large separation
$\Delta\nu_0 \propto \sqrt{\bar{\rho}}$
n = 19
n = 20
n = 21
n = 22
Δν0

White et al. 2011



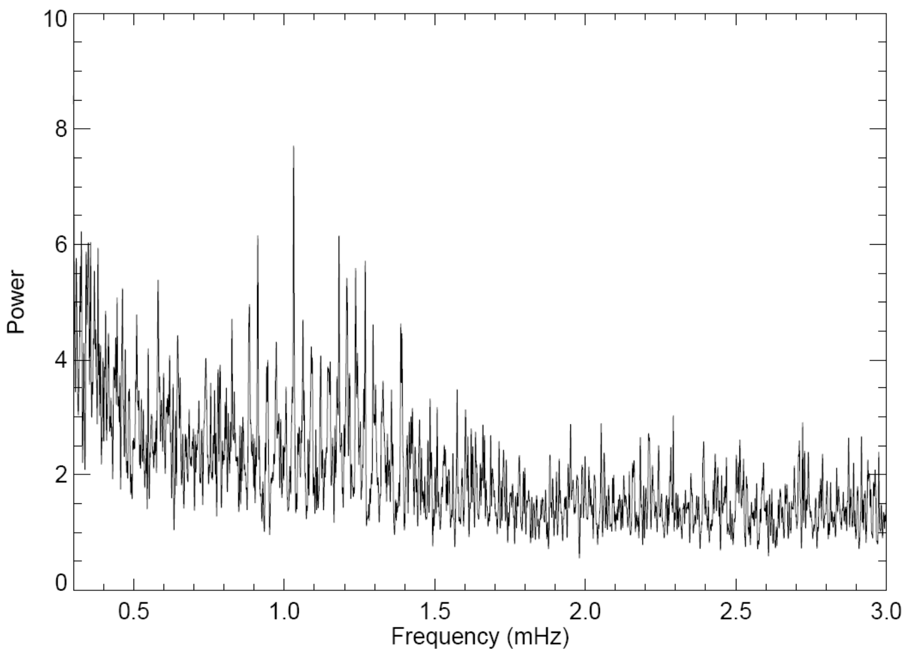
Asteroseismology

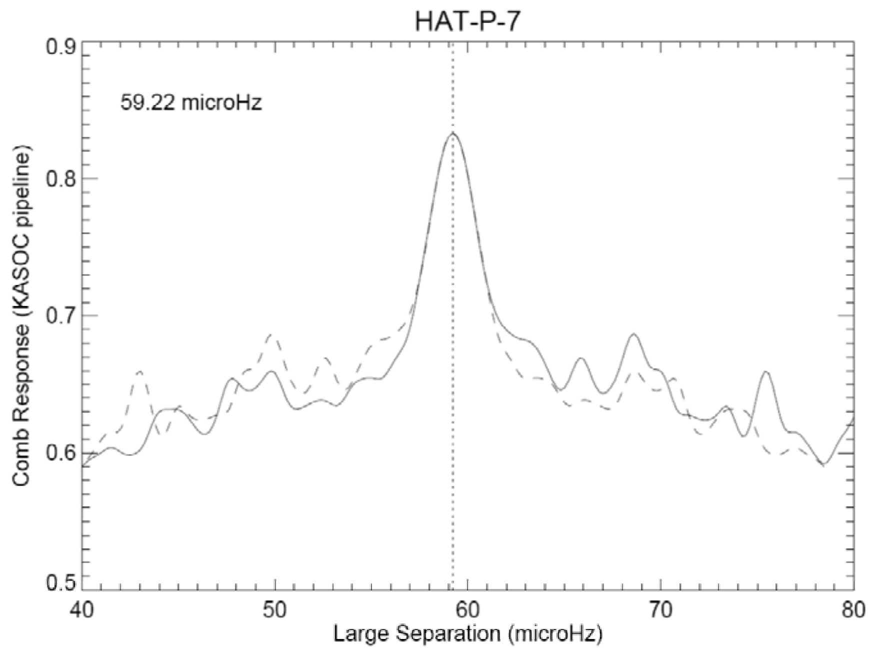
- Mean **density** –
- **Mass** (more accu
  Teff) – better tha
- **Radius** from Ma
- **Surface gravity** f
  than 3%
- **Age** / Evolutiona
  off age
- Rotation period, inclination axis, differential rotation

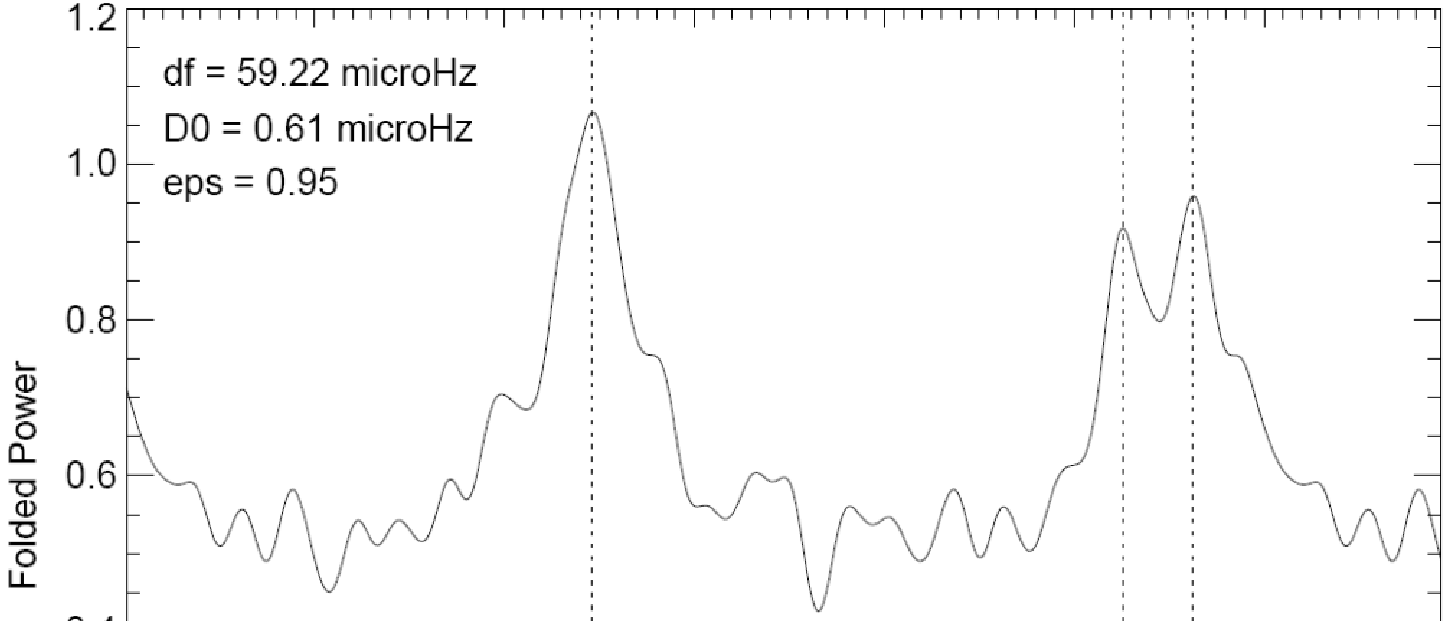


Levels of detection

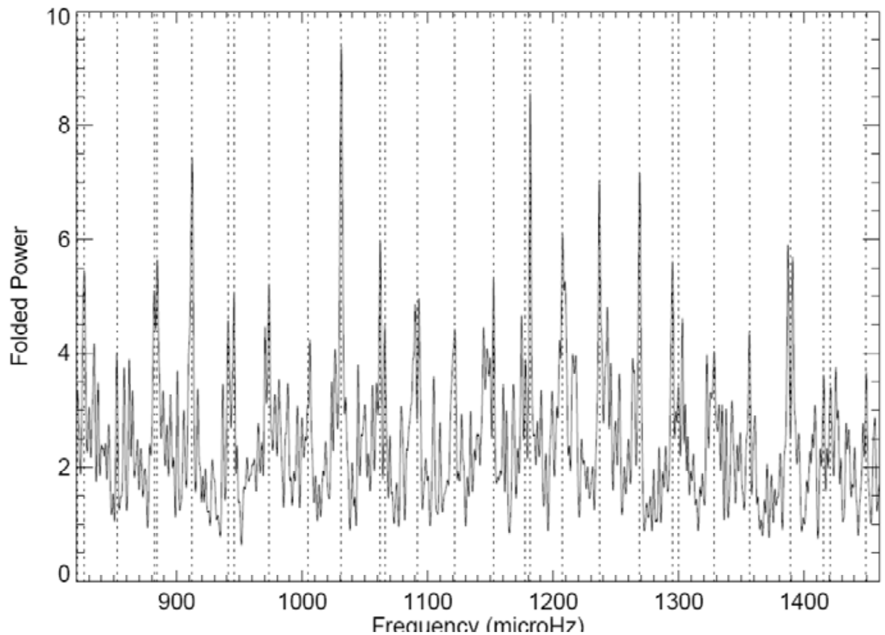
- Excess power (and frequency at max. Power)
- p-mode signature (large separation)







- Detailed p-mode structure (small separation)



Levels of detection

- Excess power (and frequency at max. Power)
- p-mode signature (large separation)
- Detailed p-mode structure (small separation)
- Individual frequencies (Echelle diagram)

White et al. 2012

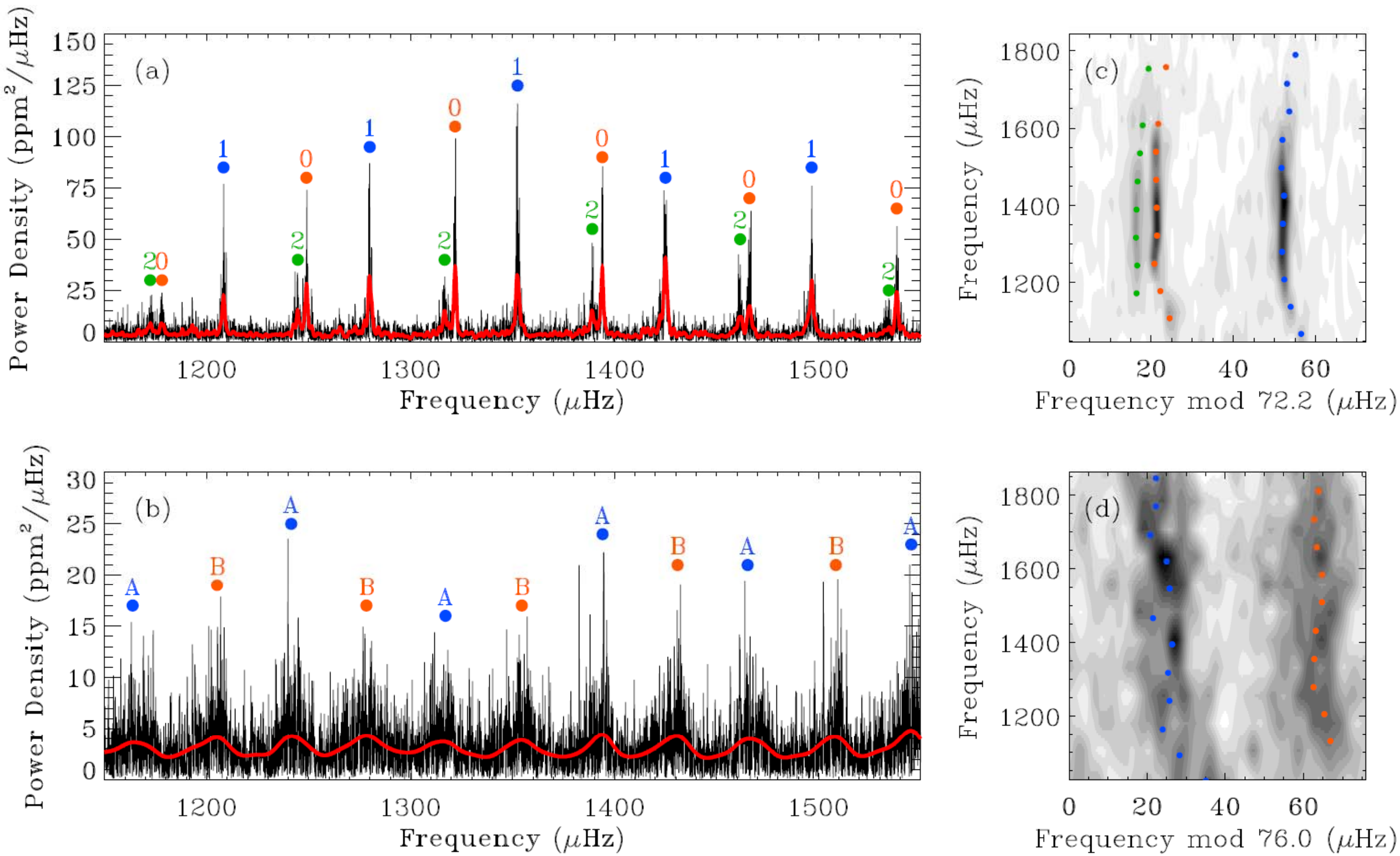
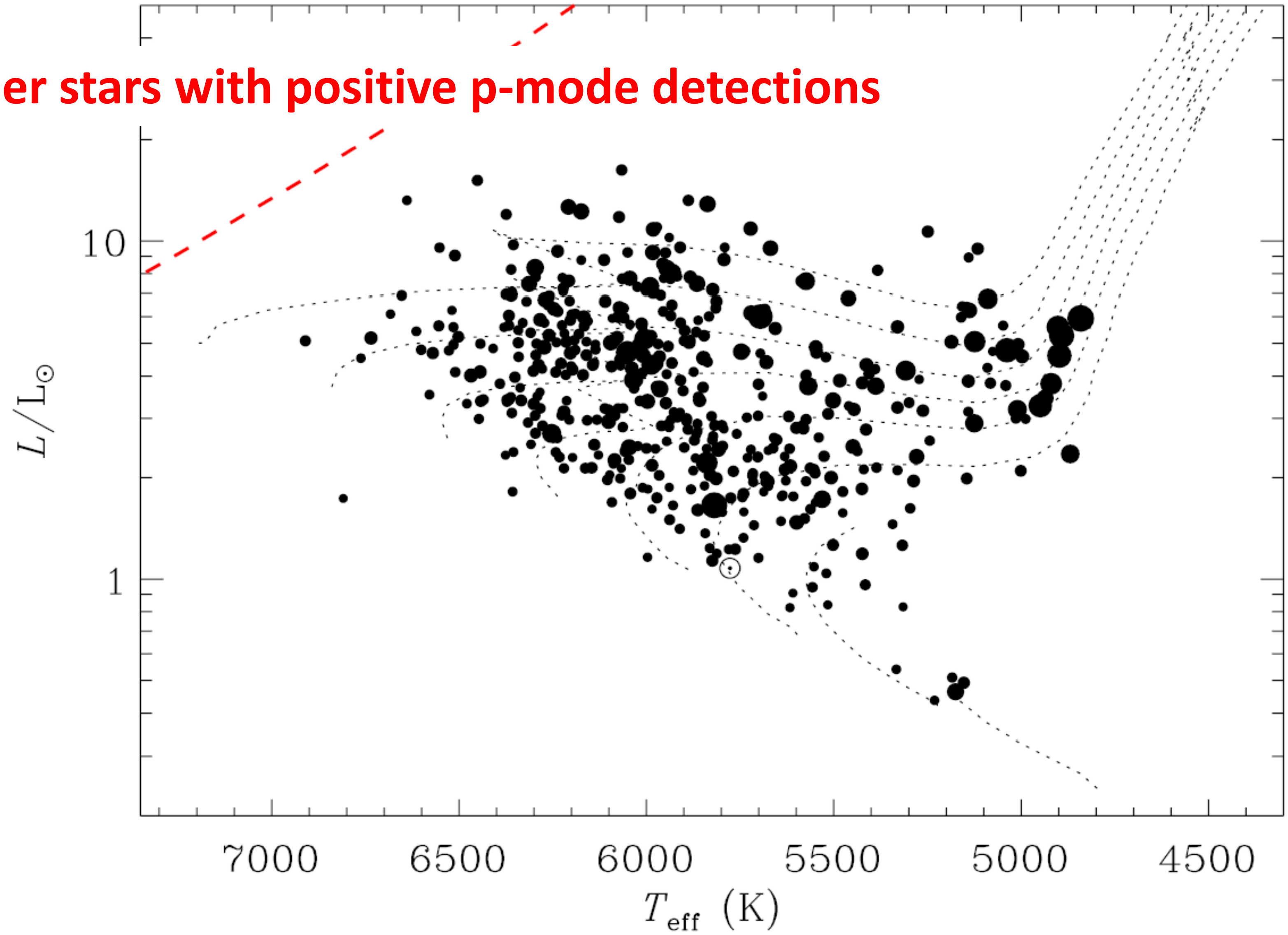


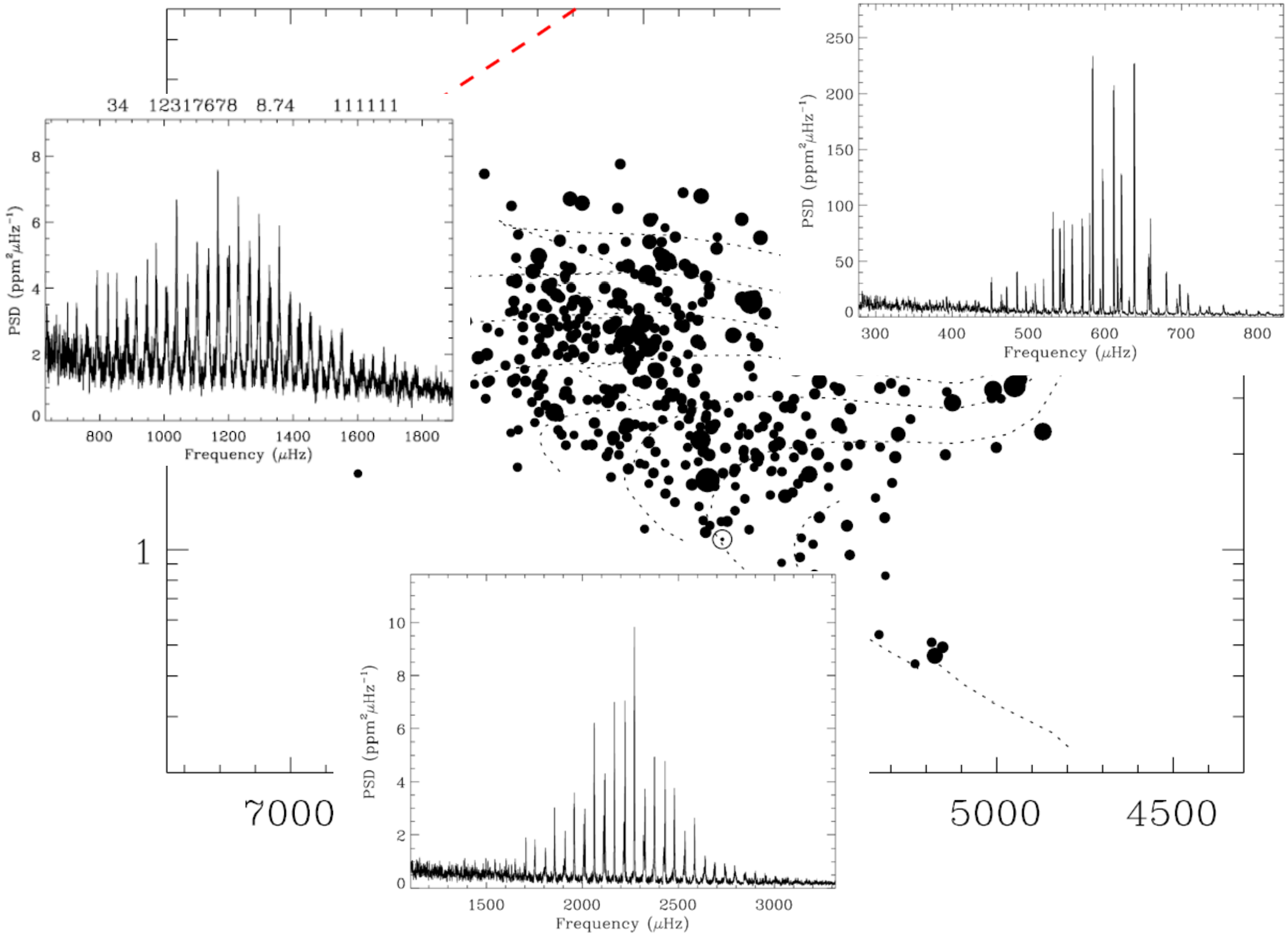
FIG. 1.— Power spectra of (a) a G star, KIC 6933899, and (b) an F star, KIC 2837475, with their corresponding échelle diagrams (c) and (d), respectively. The red curves show the power spectra after smoothing. Mode identification of the G star is trivial, with modes of $l = 0$ (orange), 1 (blue) and 2 (green) labelled. For the F star it is not clear whether the peaks labelled 'A' (blue) or 'B' (orange) correspond to the $l = 1$ or $l = 0, 2$ modes.

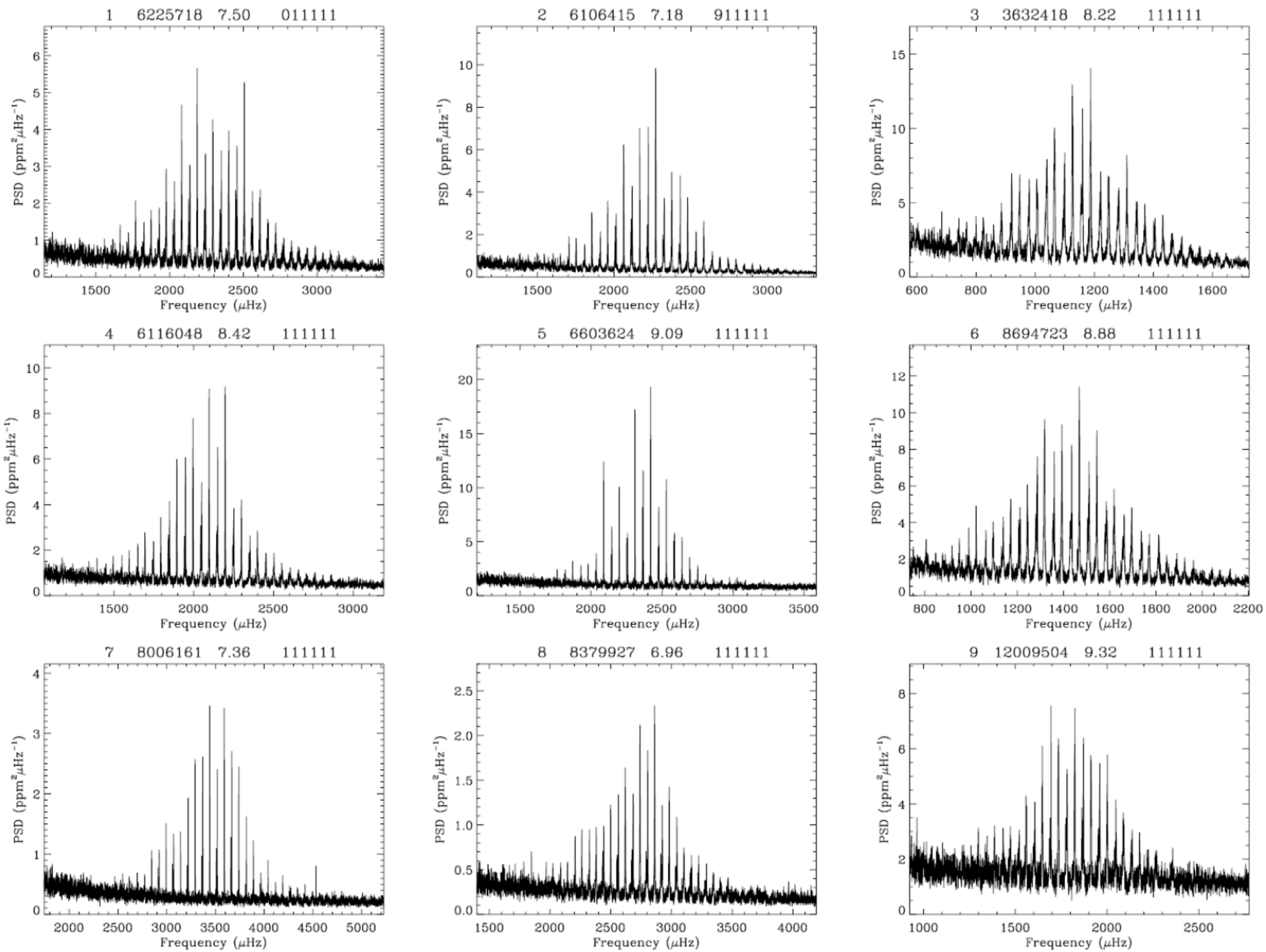
Chaplin et al. 2011

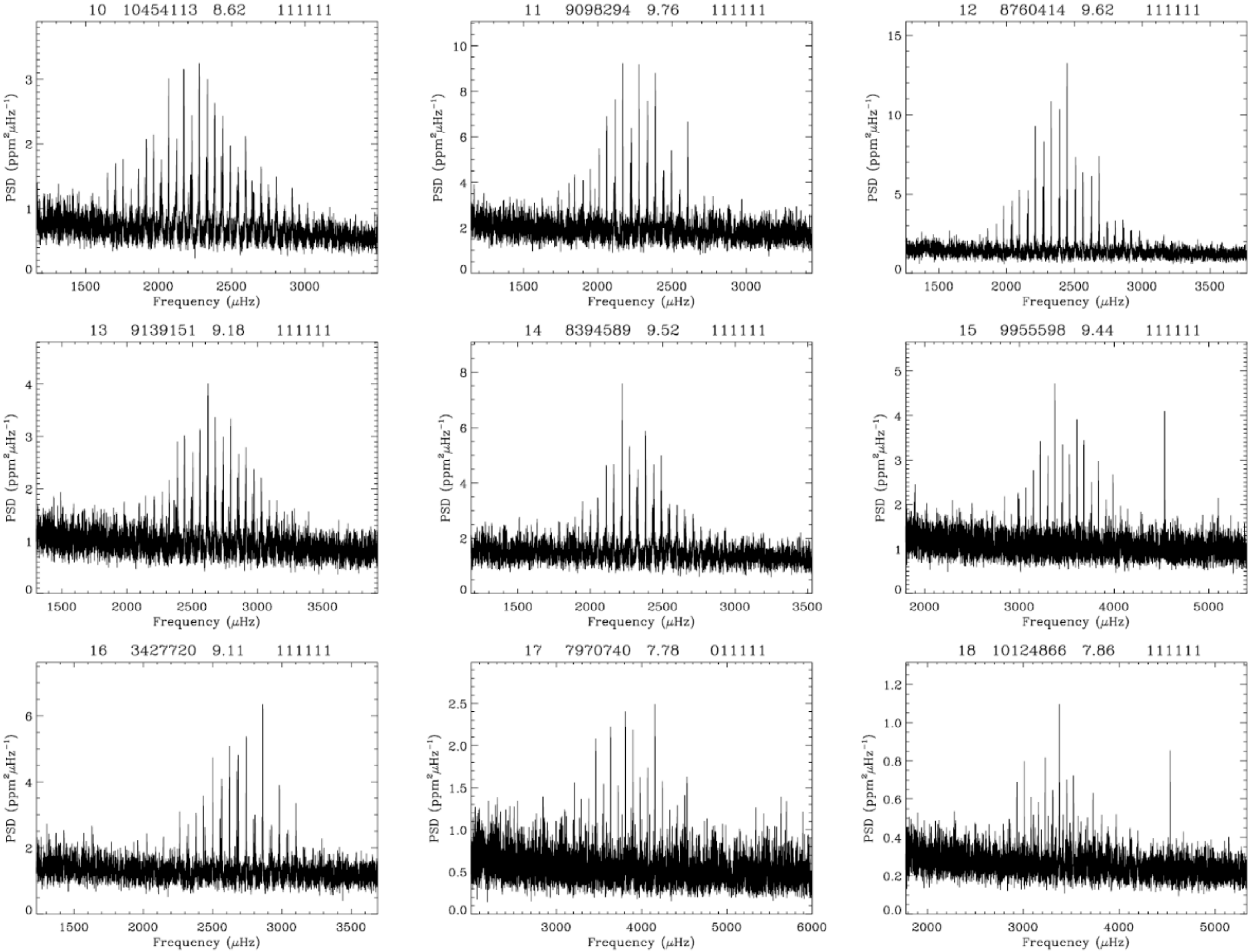
Kepler stars with positive p-mode detections

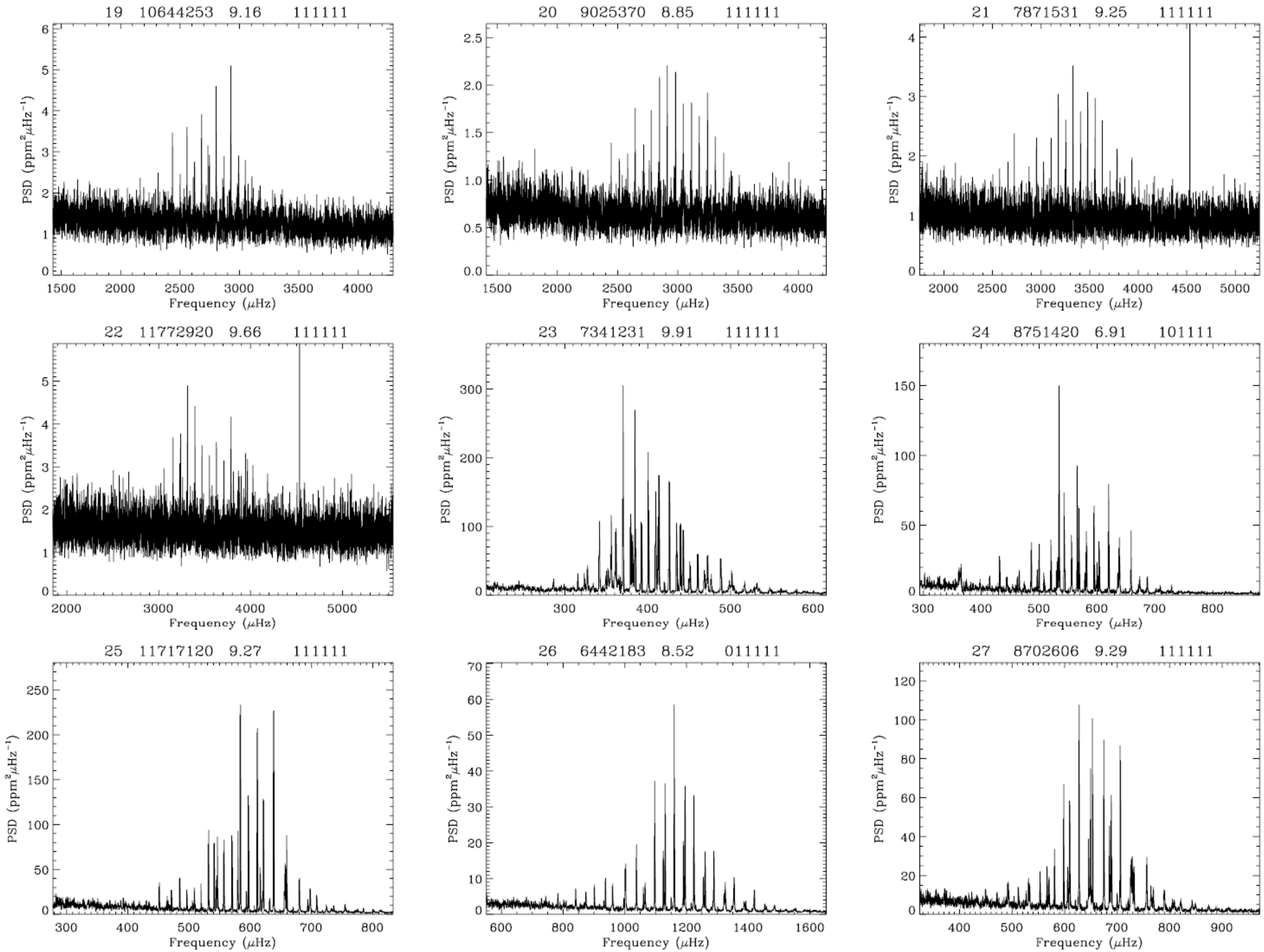


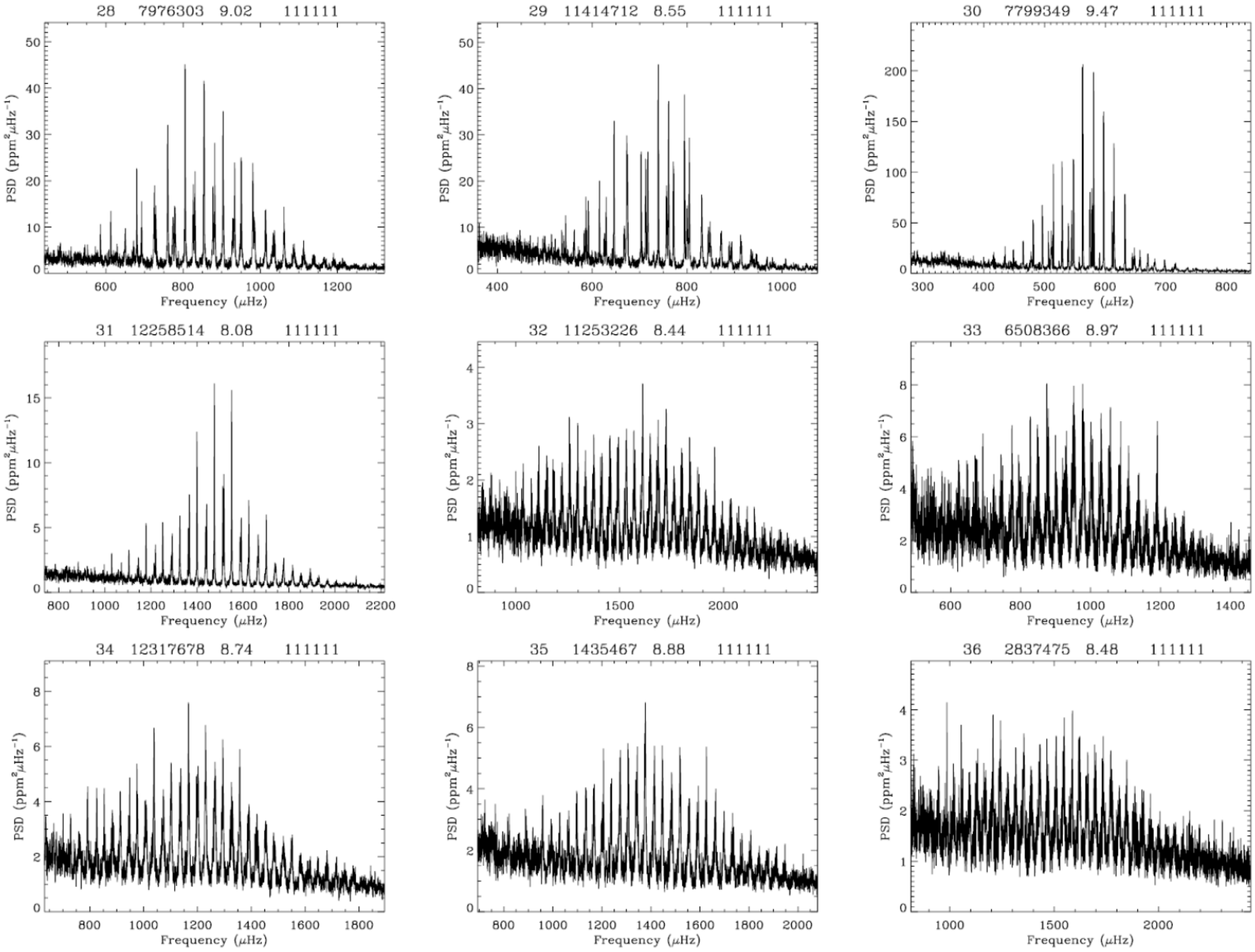
Chaplin et al. 2011




1 6225718 7.50 011111
2 6106415 7.18 911111
3 3632418 8.22 111111
4 6116048 8.42 111111
5 6603624 9.09 111111
6 8694723 8.88 111111
7 8006161 7.36 111111
8 8379927 6.96 111111
9 12009504 9.32 111111
PSD (ppm$^2\mu$Hz^{-1})
Frequency (μHz)


10 10454113 8.62 111111
11 9098294 9.76 111111
12 8760414 9.62 111111
13 9139151 9.18 111111
14 8394589 9.52 111111
15 9955598 9.44 111111
16 3427720 9.11 111111
17 7970740 7.78 011111
18 10124866 7.86 111111
PSD (ppm$^2\mu$Hz^{-1})
Frequency (μHz)


19 10644253 9.16 111111
20 9025370 8.85 111111
21 7871531 9.25 111111
22 11772920 9.66 111111
23 7341231 9.91 111111
24 8751420 6.91 101111
25 11717120 9.27 111111
26 6442183 8.52 011111
27 8702606 9.29 111111
PSD (ppm$^2\mu$Hz^{-1})
Frequency (μHz)


28 7976303 9.02 111111
29 11414712 8.55 111111
30 7799349 9.47 111111
31 12258514 8.08 111111
32 11253226 8.44 111111
33 6508366 8.97 111111
34 12317678 8.74 111111
35 1435467 8.88 111111
36 2837475 8.48 111111
PSD (ppm$^2\mu$Hz^{-1})
Frequency (μHz)

Asteroseismology

- Mean **density** – better than 1%
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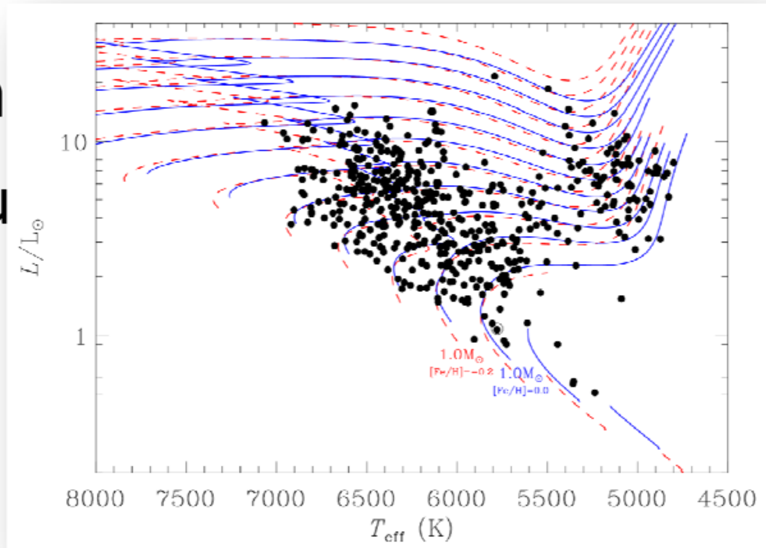
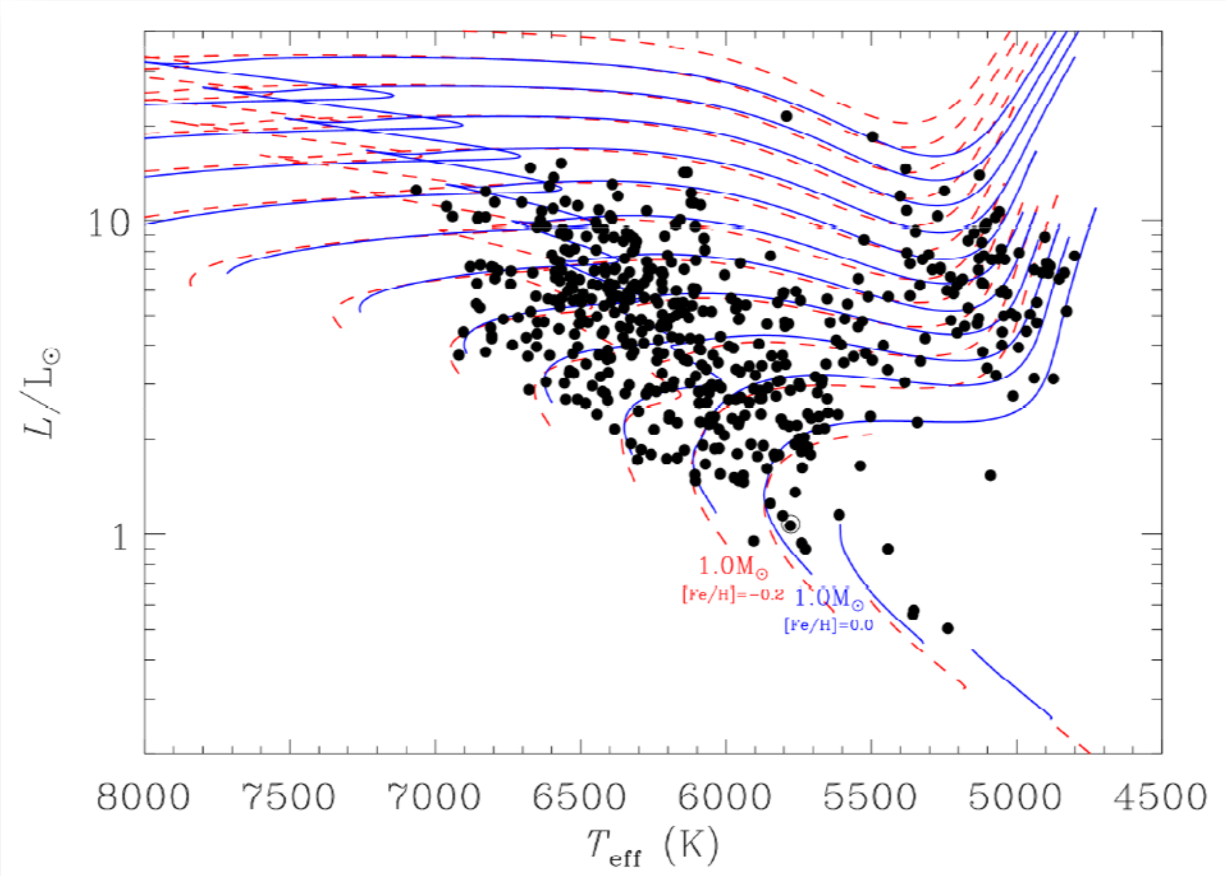
- **Radius** from Mass and den
- **Surface gravity** from Radiu than 3%
- **Age** / Evolutionary stage – off age

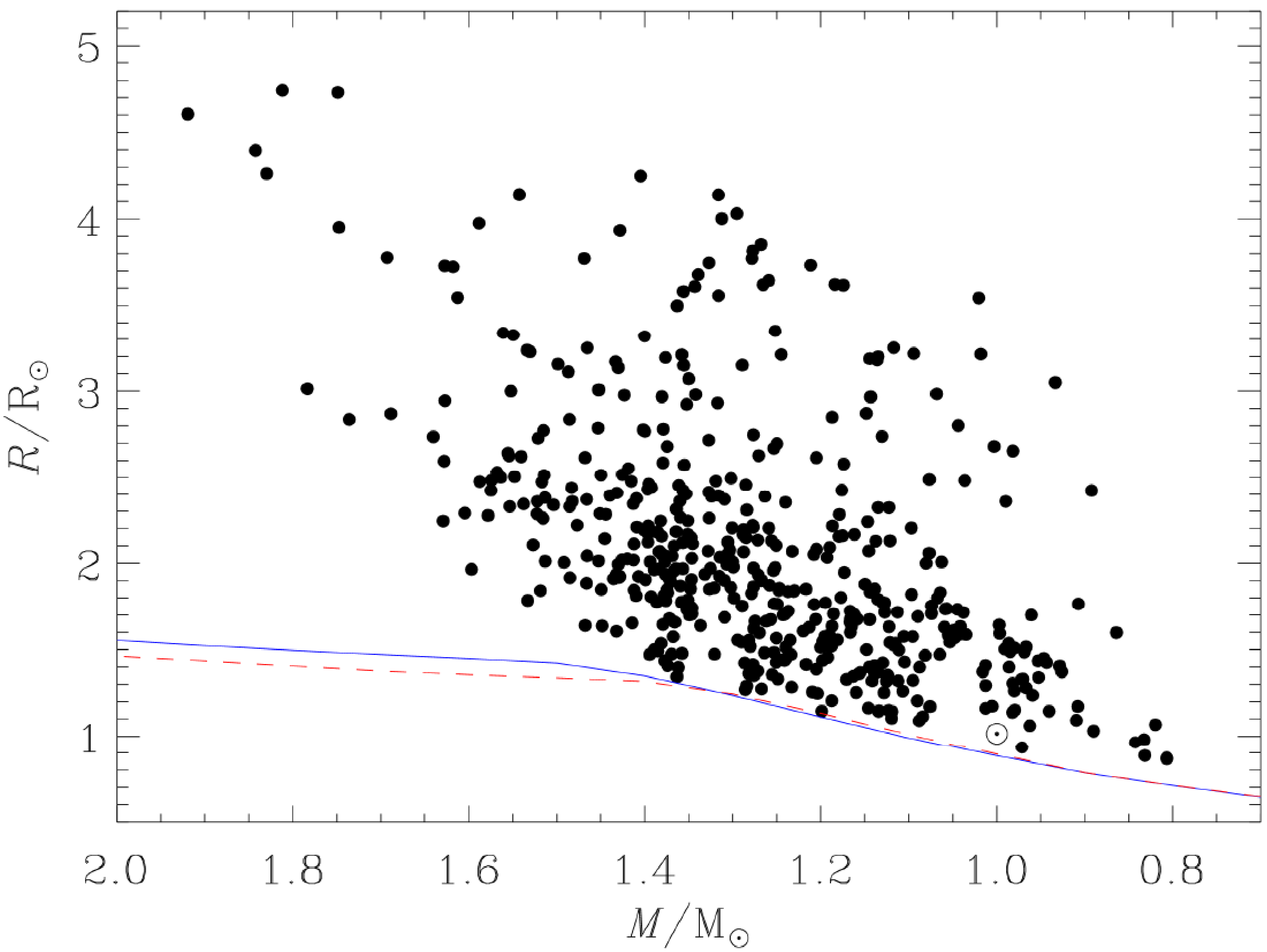


- Rotation period, inclination axis, differential rotation

Asteroseismic fundamental properties of solar-type stars observed by the NASA *Kepler* Mission

W. J. Chaplin[1,2], S. Basu[3], D. Huber[4,5], A Serenelli[6], L. Casagrande[7], V. Silva Aguirre[2], W. H. Ball[8,9], O. L. Creevey[10,11], L. Gizon[9,8], R. Handberg[1,2], C. Karoff[2], R. Lutz[8,9], J. P. Marques[8,9], A. Miglio[1,2], D. Stello[12,2], M. D. Suran[13], D. Pricopi[13], T. S. Metcalfe[14,2], M. J. P. F. G. Monteiro[15], J. Molenda-Żakowicz[16], T. Appourchaux[11], J. Christensen-Dalsgaard[2], Y. Elsworth[1,2], R. A. García[17], G. Houdek[2], H. Kjeldsen[2], A. Bonanno[18], T. L. Campante[1,2], E. Corsaro[19,18], P. Gaulme[20], S. Hekker[21,9], S. Mathur[14,22], B. Mosser[23], C. Régulo[24,25], D. Salabert[26]



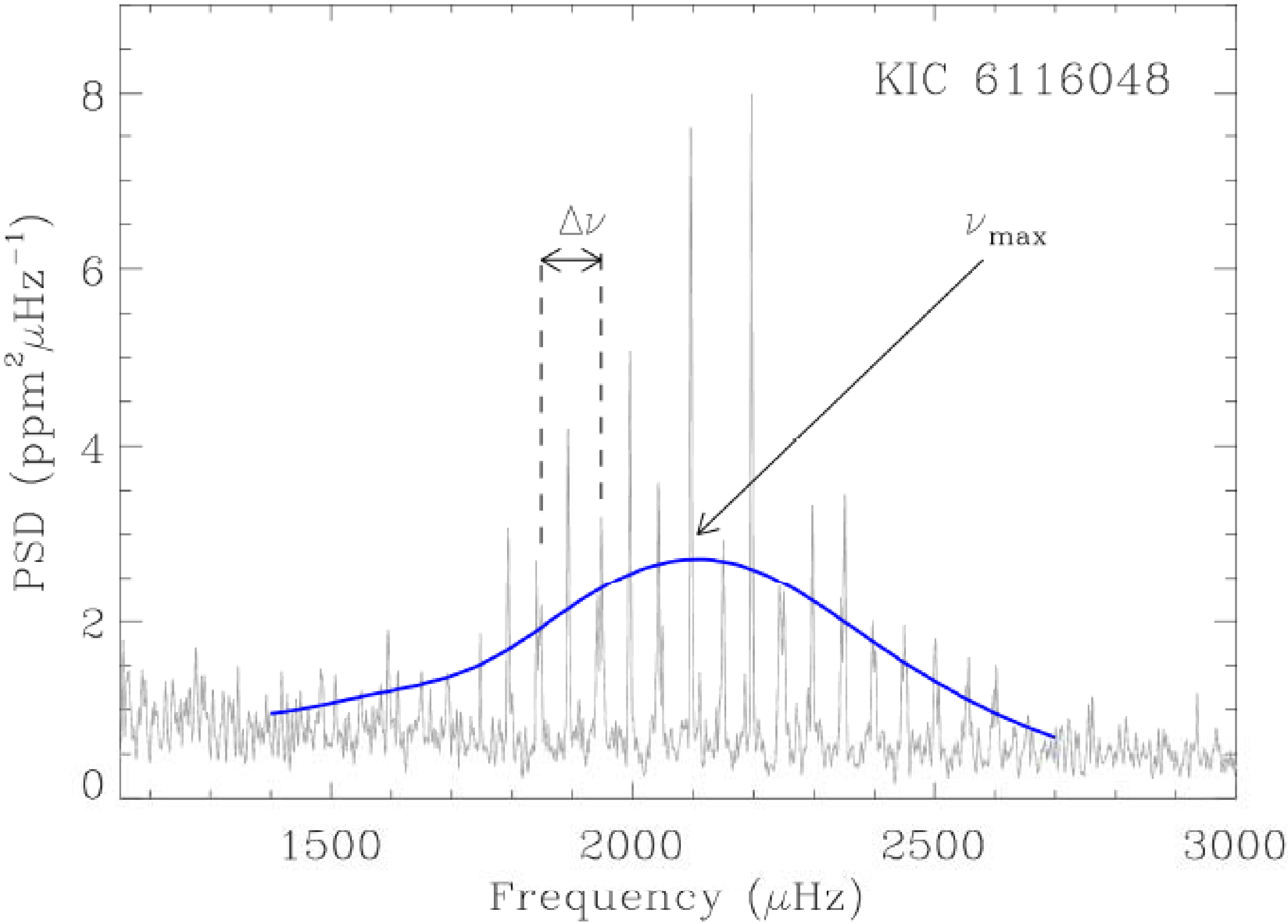


5
4
3
2
1
R/R⊙
2.0
1.8
1.6
1.4
1.2
1.0
0.8
M/M⊙

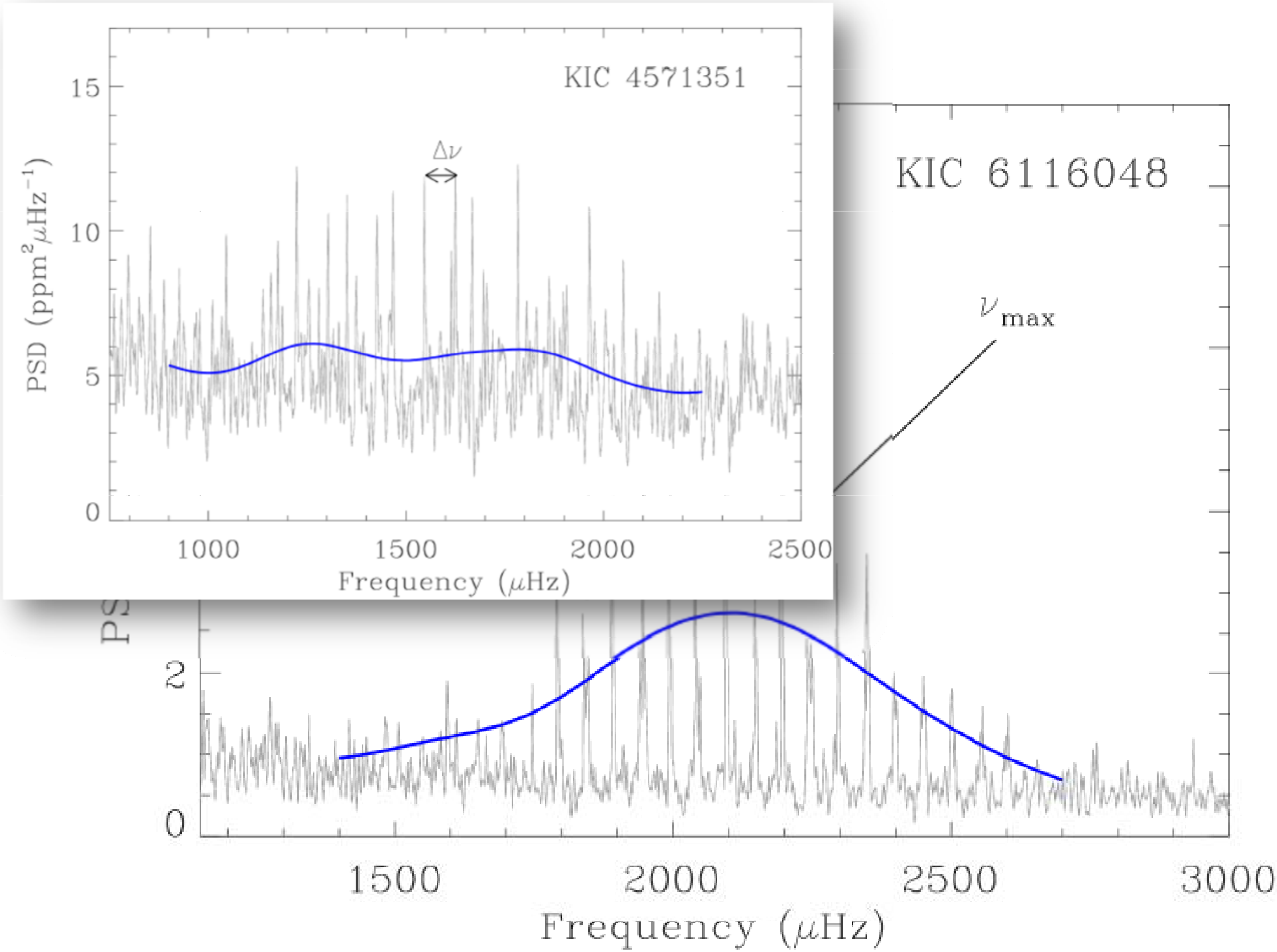
Levels of detection

- Excess power (and frequency at max. Power)
- p-mode signature (large separation)
- Detailed p-mode structure (small separation)
- Individual frequencies (Echelle diagram)

For exoplanets we often have to deal with low-SNR oscillations



From Chaplin et al. 2013



From Chaplin et al. 2013

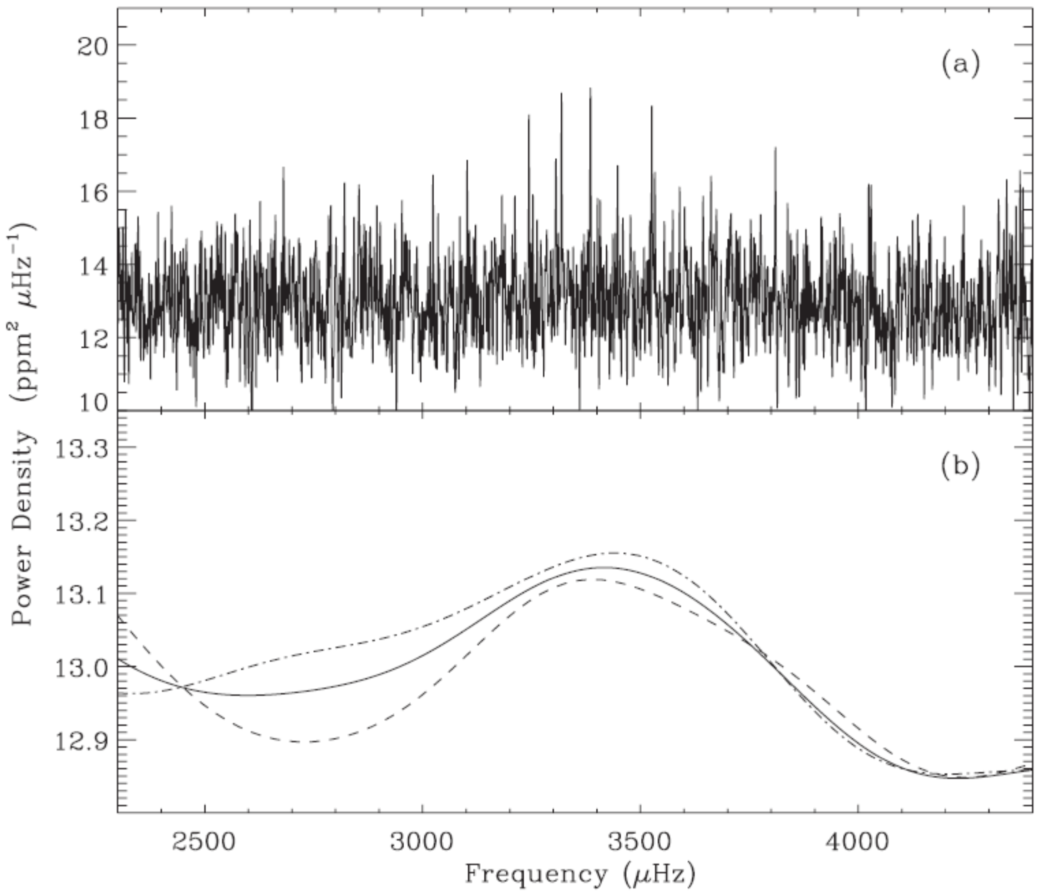
Measurement of Large Separation

- Power of power
- Auto Correlation
- Comb response / Match filter (using the asymptotic relation)

The Astrophysical Journal, 761:53 (10pp), 2012 December 10 doi:10.1088/0004-637X/761/1/53

PHOTOMETRICALLY DERIVED MASSES AND RADII OF THE PLANET AND STAR IN THE TrES-2 SYSTEM

Thomas Barclay[1,2], Daniel Huber[1,11], Jason F. Rowe[1,3], Jonathan J. Fortney[4], Caroline V. Morley[4], Elisa V. Quintana[1,3], Daniel C. Fabrycky[4,12], Geert Barentsen[5], Steven Bloemen[6], Jessie L. Christiansen[1,3], Brice-Olivier Demory[7], Benjamin J. Fulton[8], Jon M. Jenkins[1,3], Fergal Mullally[1,3], Darin Ragozzine[9], Shaun E. Seader[1,3], Avi Shporer[8,10], Peter Tenenbaum[1,3], and Susan E. Thompson[1,3]



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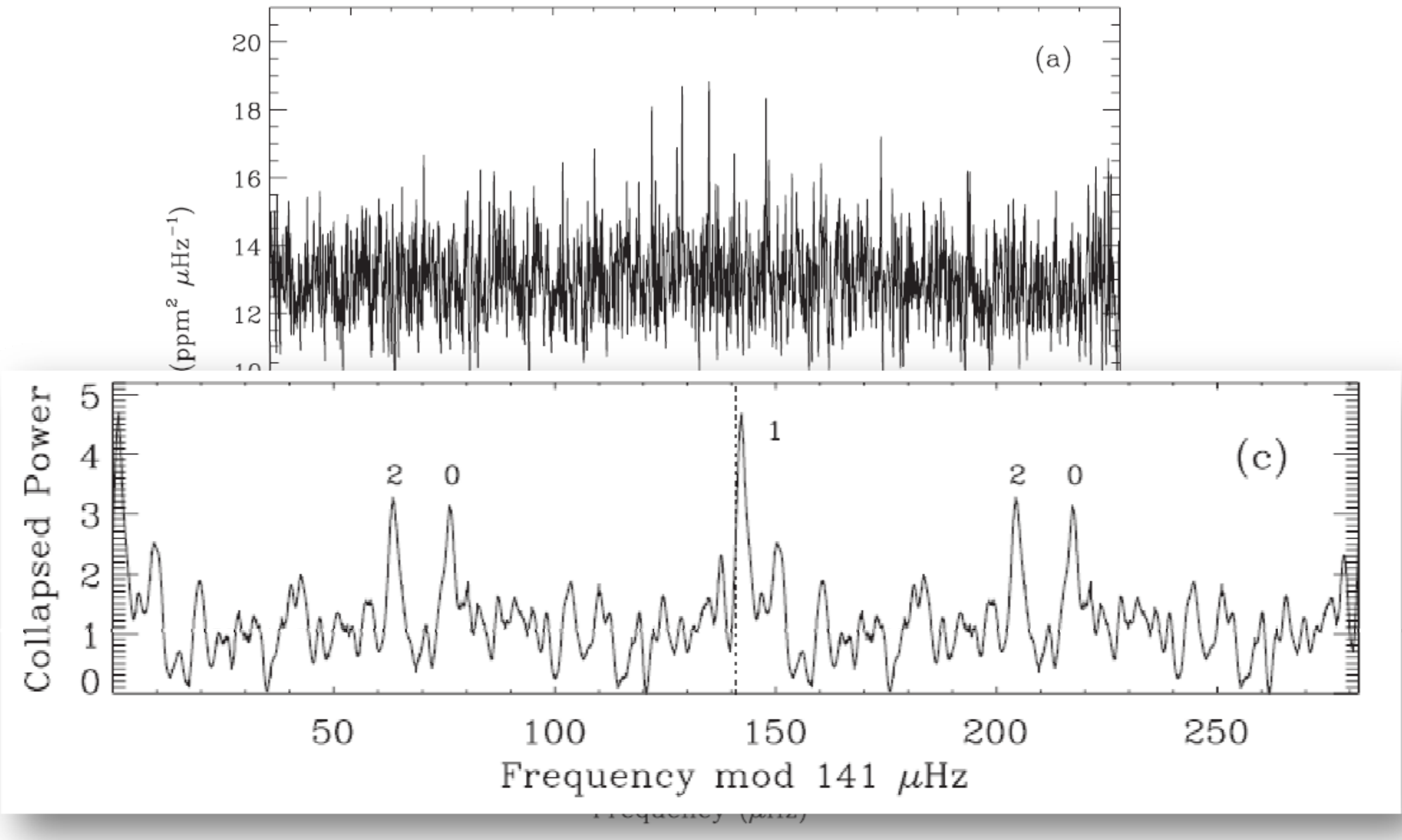
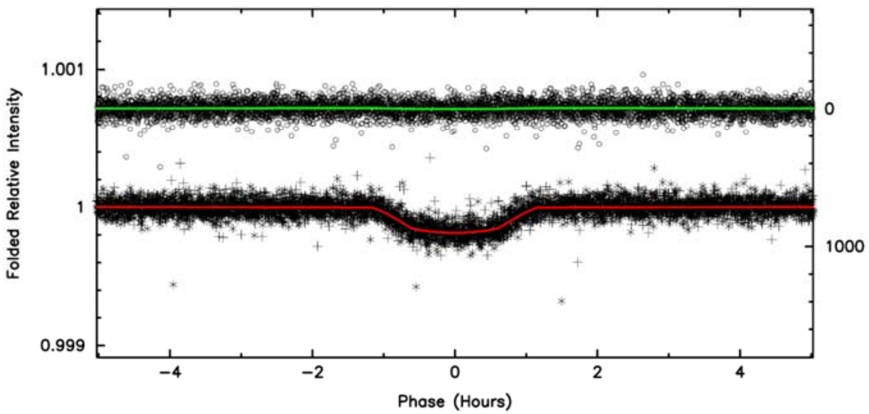
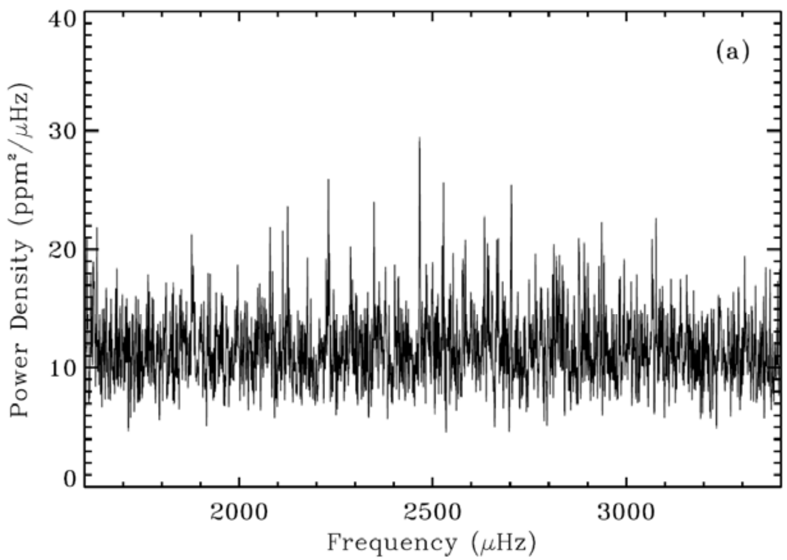


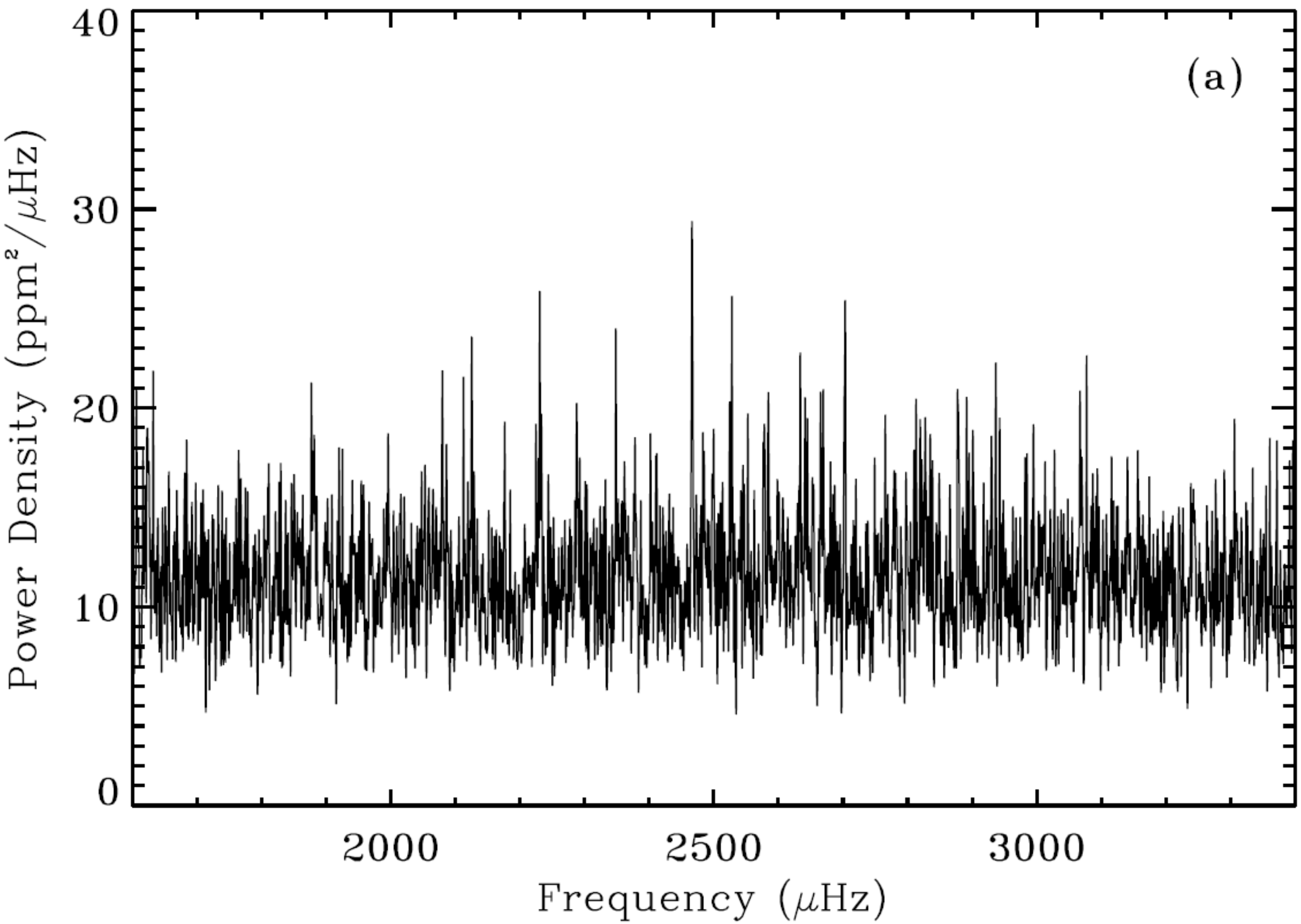
The Astrophysical Journal, 729:27 (21pp), 2011 March 1 doi:10.1088/0004-637X/729/1/27

KEPLER'S FIRST ROCKY PLANET: KEPLER-10b*

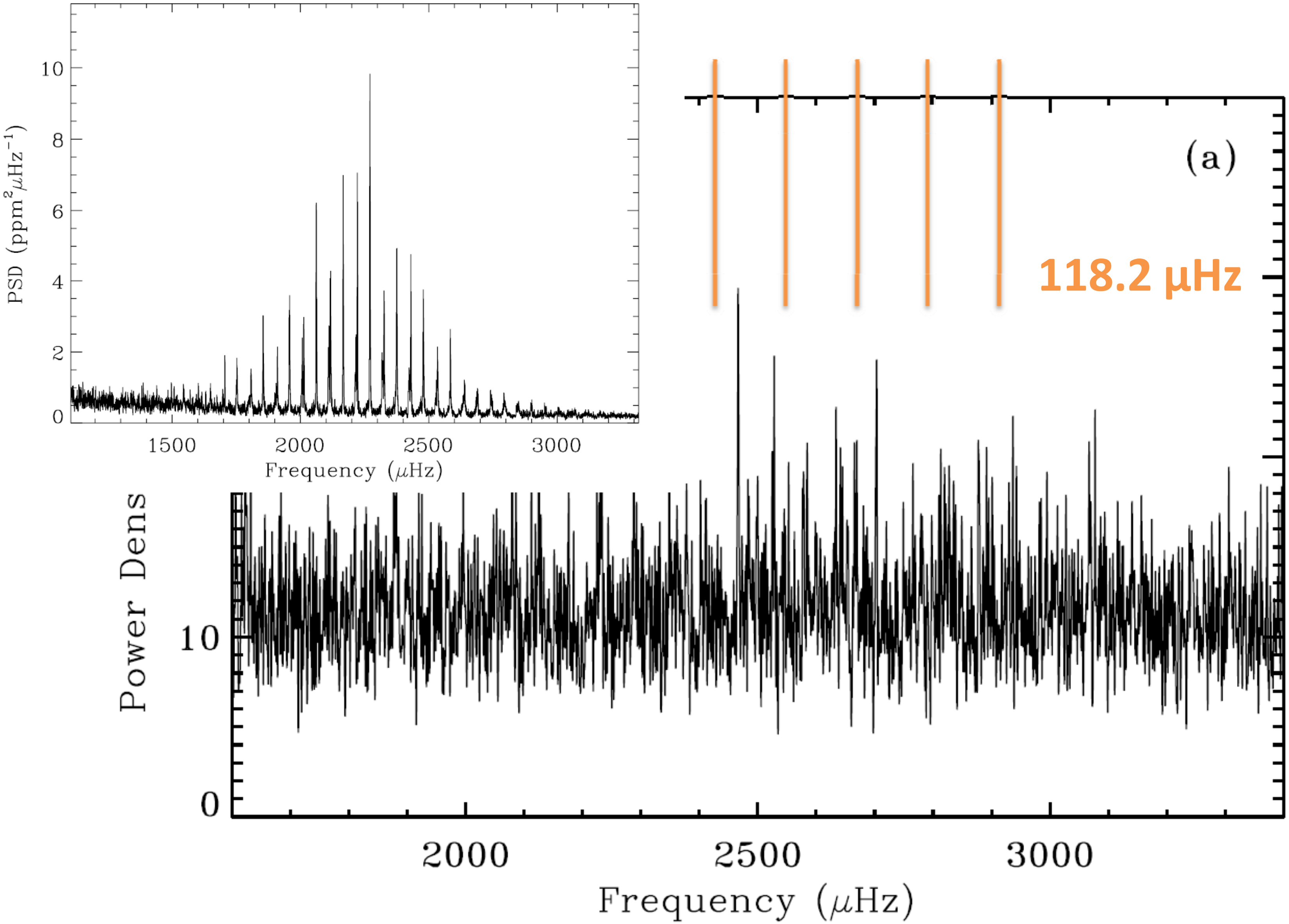
Natalie M. Batalha[1], William J. Borucki[2], Stephen T. Bryson[2], Lars A. Buchhave[3], Douglas A. Caldwell[4], Jørgen Christensen-Dalsgaard[5,6], David Ciardi[7], Edward W. Dunham[8], Francois Fressin[3], Thomas N. Gautier III[9], Ronald L. Gilliland[10], Michael R. Haas[2], Steve B. Howell[11], Jon M. Jenkins[4], Hans Kjeldsen[5], David G. Koch[2], David W. Latham[3], Jack J. Lissauer[2], Geoffrey W. Marcy[12], Jason F. Rowe[2], Dimitar D. Sasselov[3], Sara Seager[13], Jason H. Steffen[14], Guillermo Torres[3], Gibor S. Basri[12], Timothy M. Brown[15], David Charbonneau[3], Jessie Christiansen[2], Bruce Clarke[4], William D. Cochran[16], Andrea Dupree[3], Daniel C. Fabrycky[3], Debra Fischer[17], Eric B. Ford[18], Jonathan Fortney[19], Forrest R. Girouard[20], Matthew J. Holman[3], John Johnson[21], Howard Isaacson[12], Todd C. Klaus[20], Pavel Machalek[4], Althea V. Moorehead[18], Robert C. Morehead[18], Darin Ragozzine[3], Peter Tenenbaum[4], Joseph Twicken[4], Samuel Quinn[3], Jeffrey VanCleve[4], Lucianne M. Walkowicz[12], William F. Welsh[22], Edna Devore[4], and Alan Gould[23]



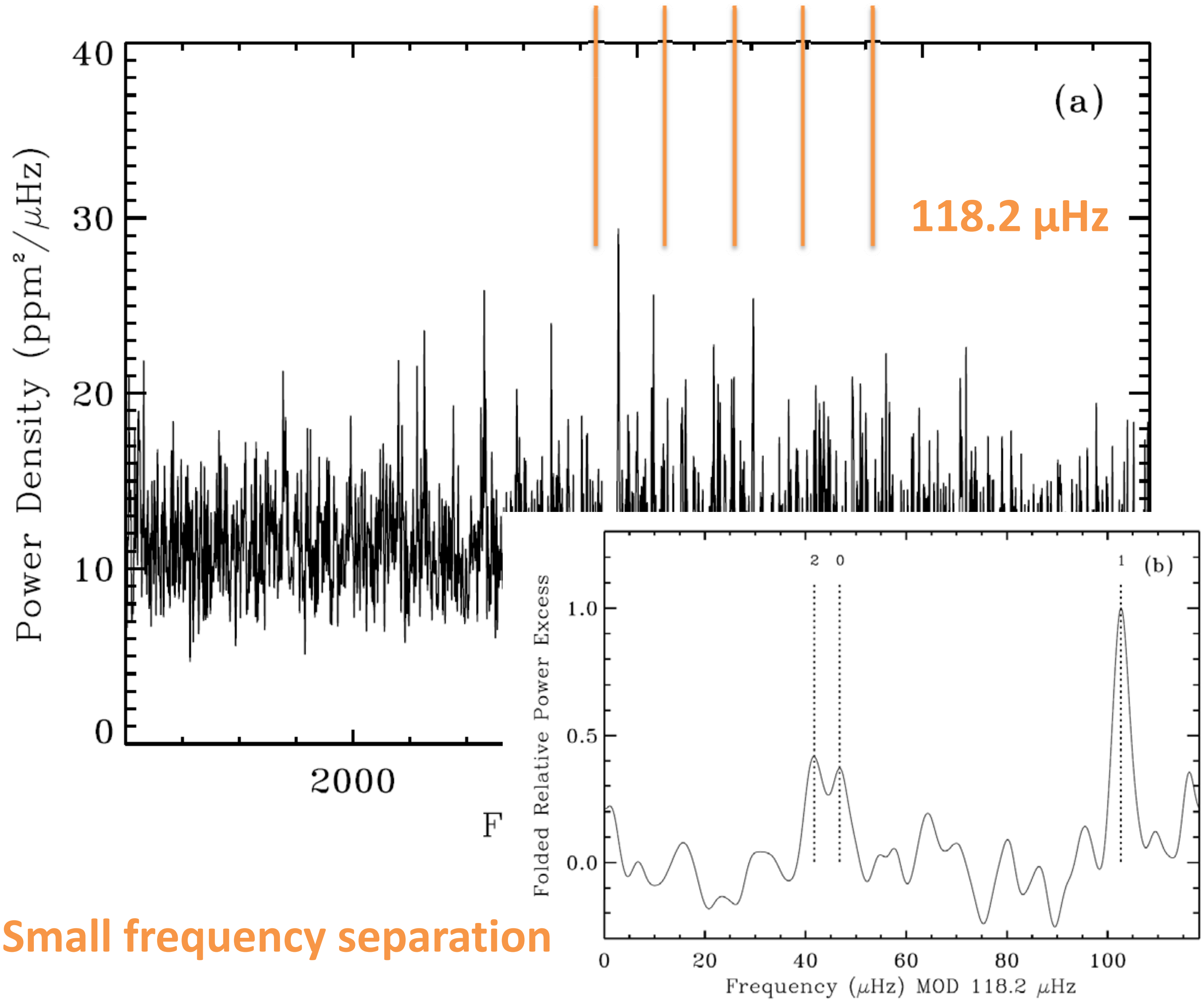




Batalha et al. 2011: 275d



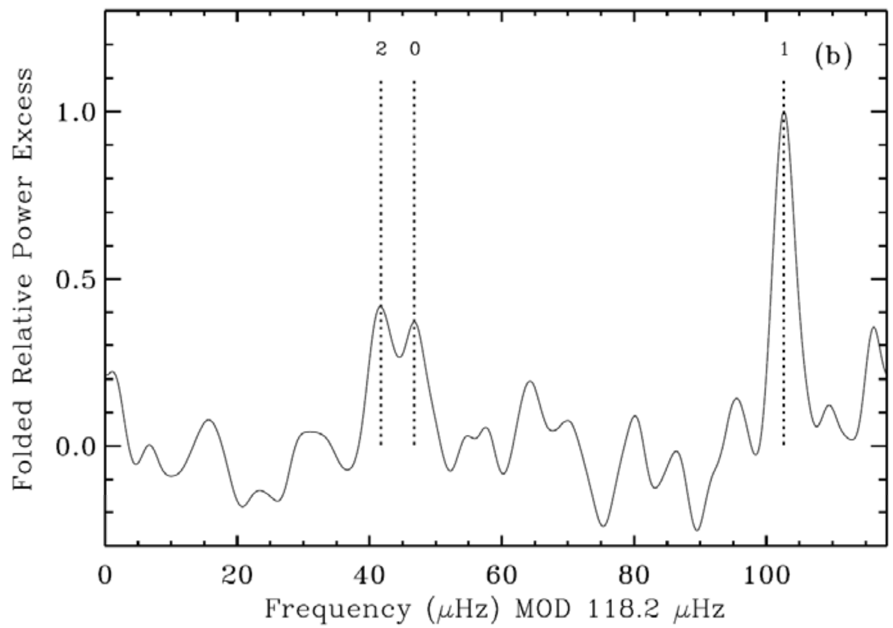
Large frequency separation



Small frequency separation

Mass (Msun)	0.995 ± 0.060	(6%)
Radius (Rsun)	1.056 ± 0.021	(2 %)
Age (Gyr)	11.9 ± 4.5	(38%)

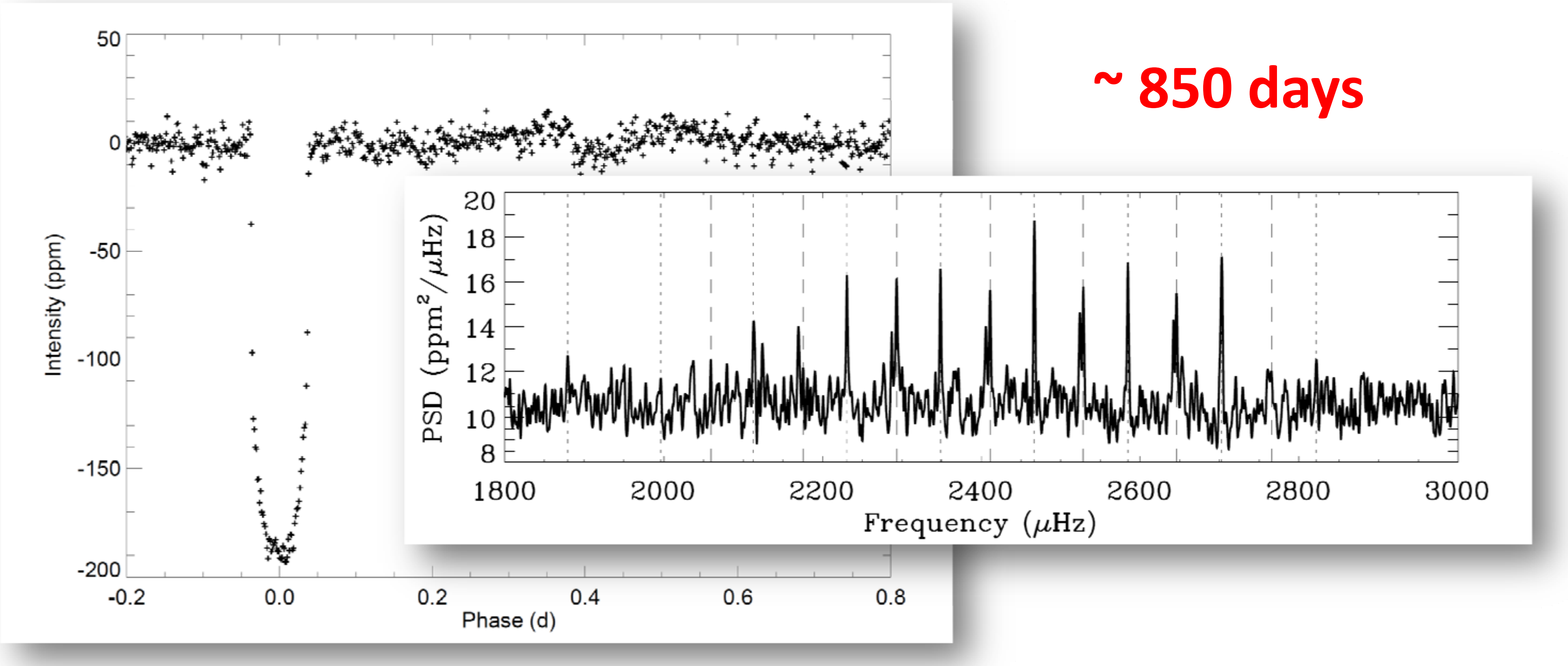
- Batalha et al. 2011



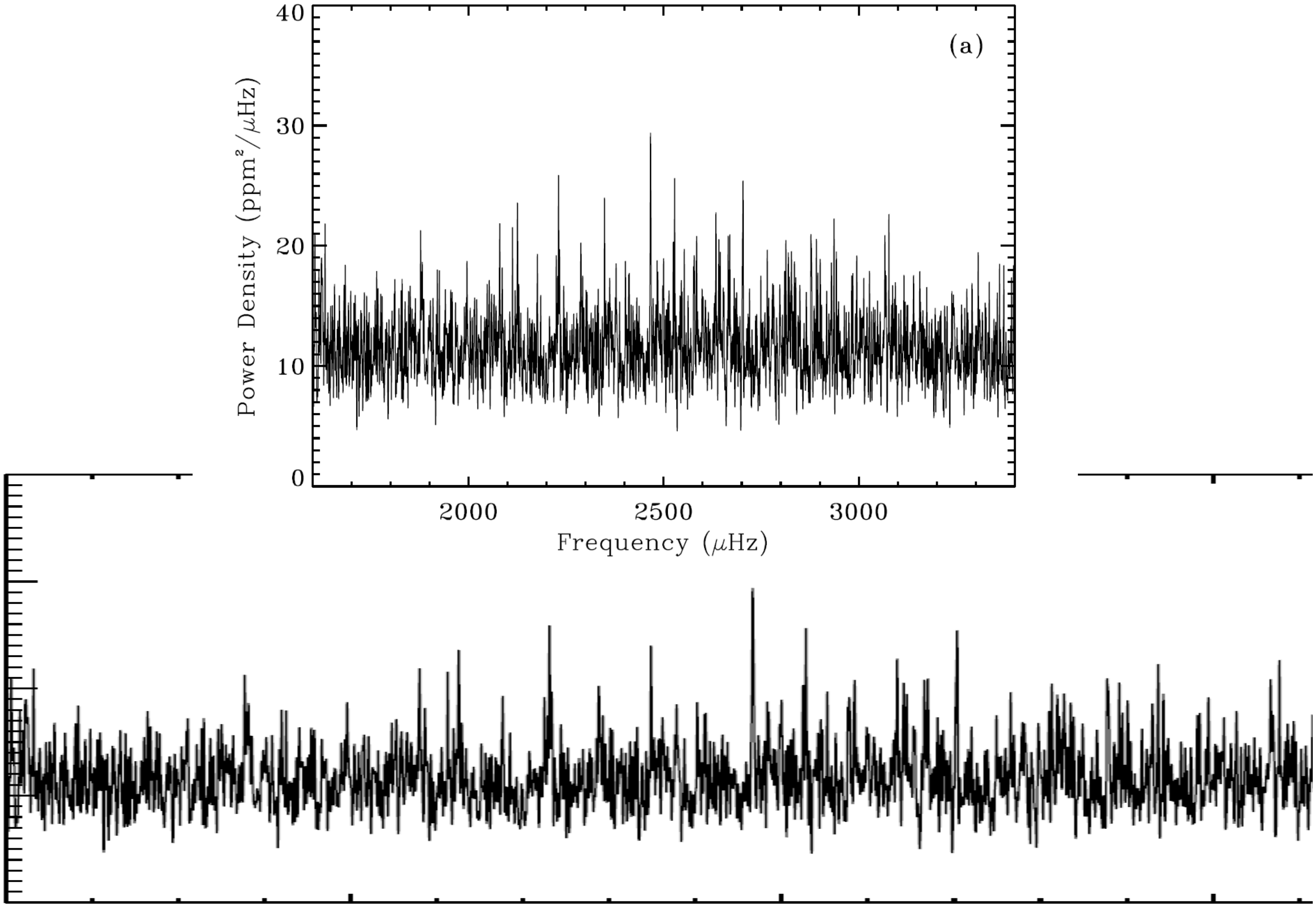
Analysis of more than two years of data….

Accurate parameters of the oldest known rocky-exoplanet hosting system: Kepler-10 revisited

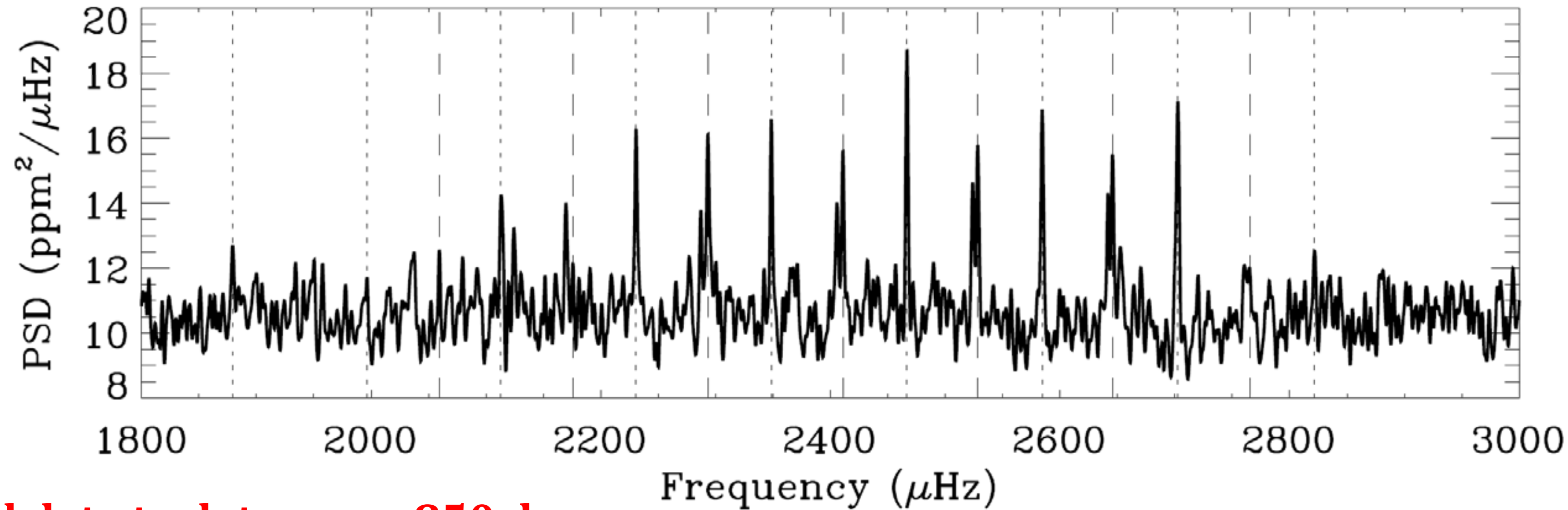
Alexandra Fogtmann-Schulz, Brian Hinrup, Vincent Van Eylen, Jørgen Christensen-Dalsgaard, Hans Kjeldsen, Víctor Silva Aguirre, and Brandon Tingley
Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark.



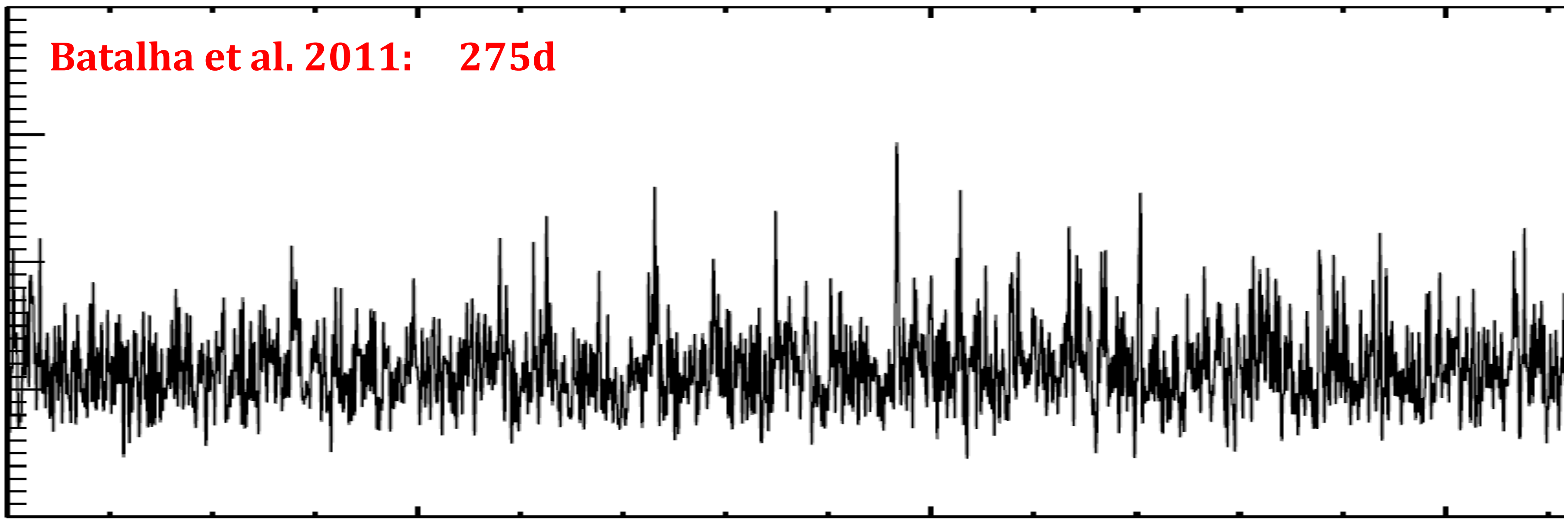
~ 850 days

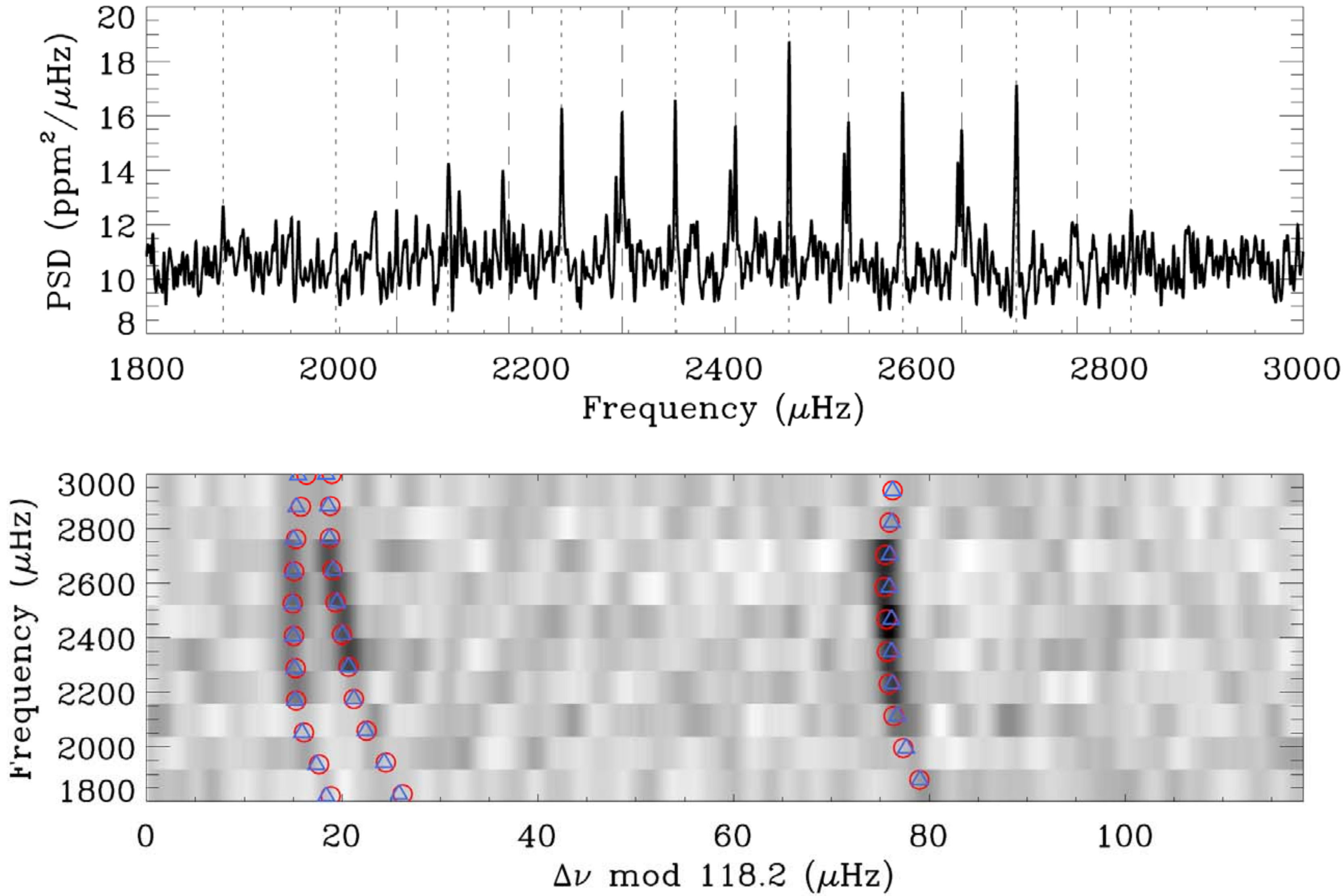


(a)
Power Density (ppm²/μHz)
40
30
20
10
0
2000
2500
3000
Frequency (μHz)



All data to date: 850 d





PSD (ppm²/μHz)
20
18
16
14
12
10
8
1800
2000
2200
2400
2600
2800
3000
Frequency (μHz)
Frequency (μHz)
3000
2800
2600
2400
2200
2000
1800
0
20
40
60
80
100
Δν mod 118.2 (μHz)

Mass (Msun)	0.995 ± 0.060
Radius (Rsun)	1.056 ± 0.021
Age (Gyr)	11.9 ± 4.5

- Batalha et al. 2011

Mass (Msun)	0.913 ± 0.022
Radius (Rsun)	1.065 ± 0.009
Age (Gyr)	10.4 ± 1.4

- All data to date

Kepler-10:

Mass (Msun)	0.913 ± 0.022	(2.4%)
Radius (Rsun)	1.065 ± 0.009	(0.85%)
Age (Gyr)	10.4 ± 1.4	(13%)

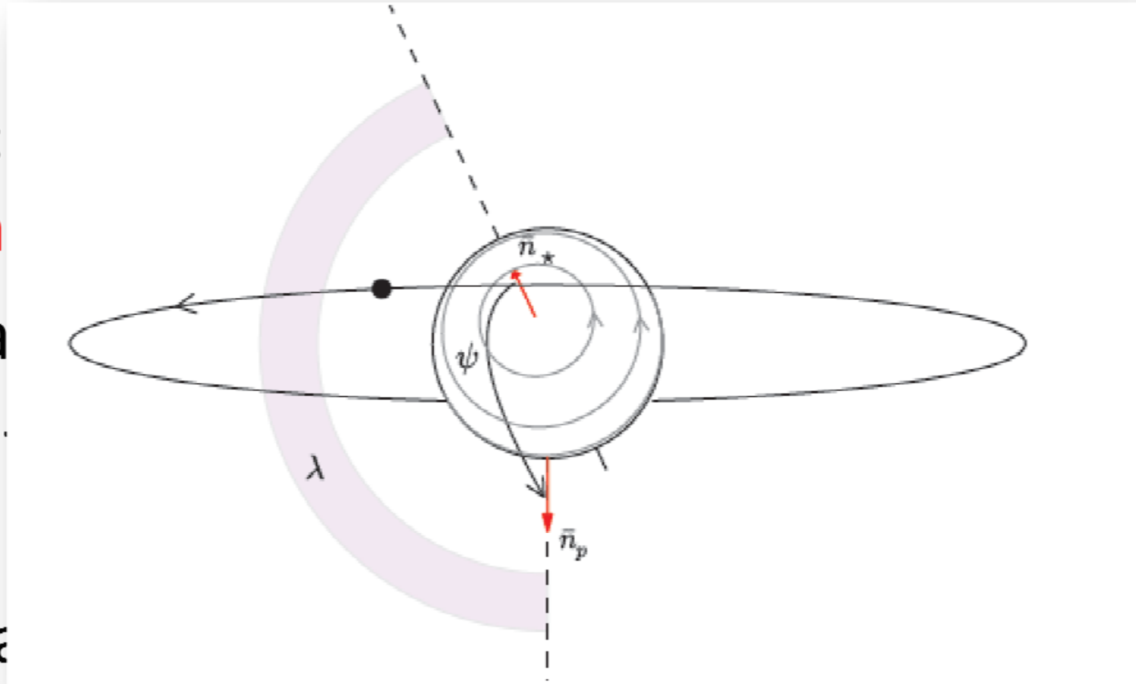
Kepler-10b:

R_{planet}/R_{star}	0.01254 ± 0.00013	(1.0%)
R_{planet}/R_{Earth}	1.451 ± 0.019	(1.3%)

The key is to extend the length of the time series or observe bright targets with high SNR

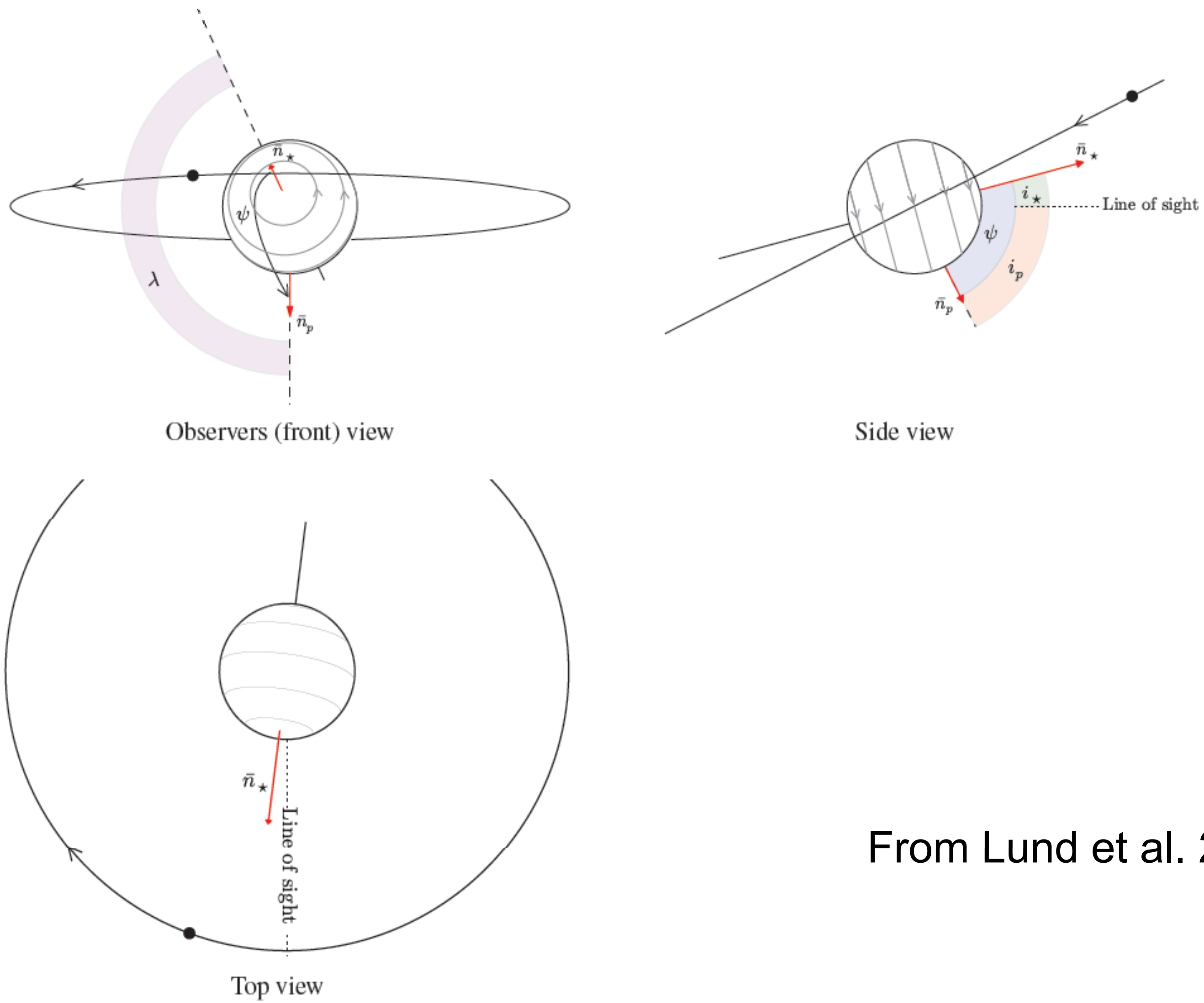
Asteroseismology

- Mean **density** –
- **Mass** (more acc
  Teff) – better th
- **Radius** from Ma
- **Surface gravity**
  than 3%
- **Age** / Evolutiona
  off age



- Rotation period, inclination axis, differential rotation

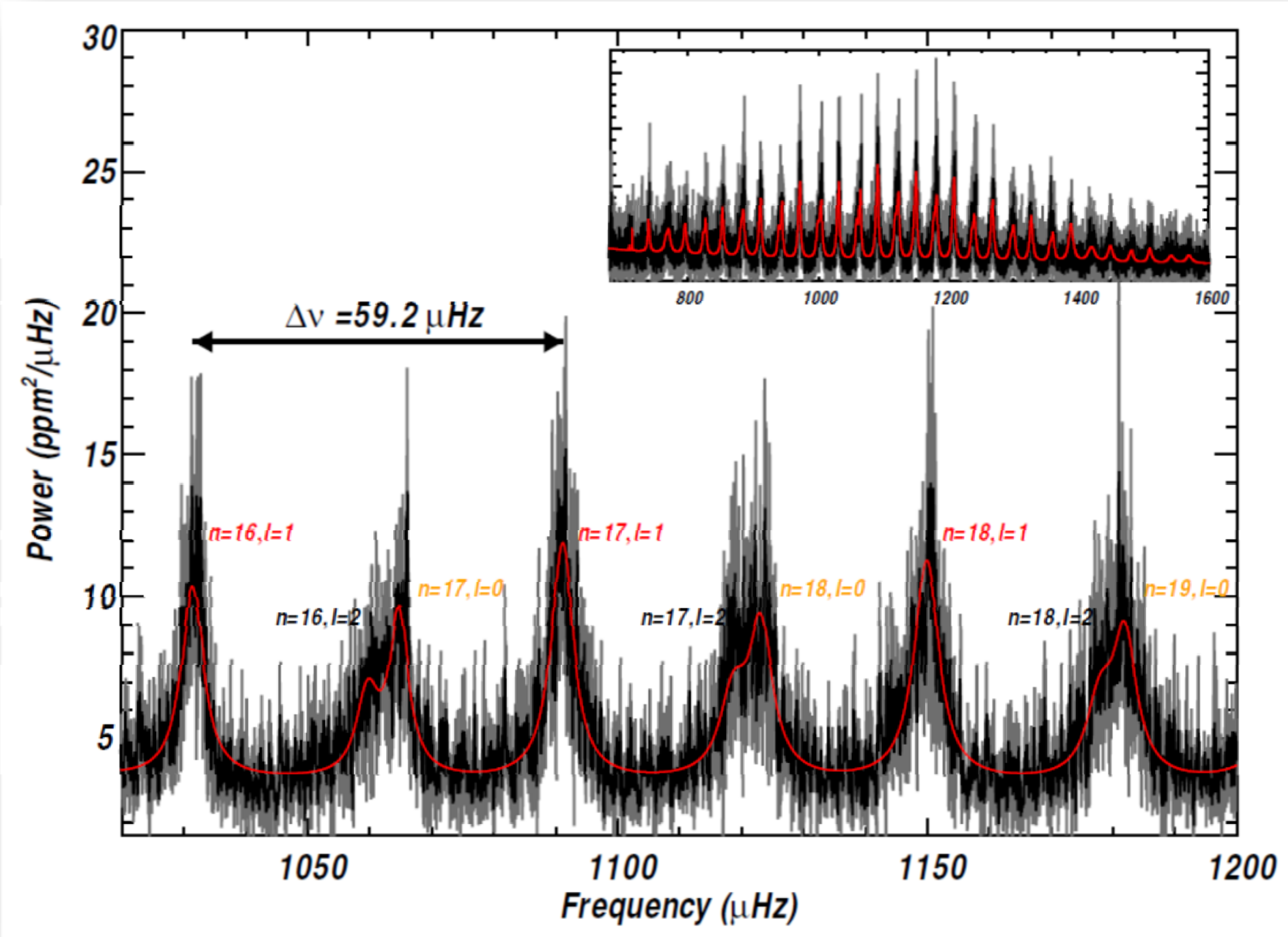
HAT-P-7b



From Lund et al. 2014

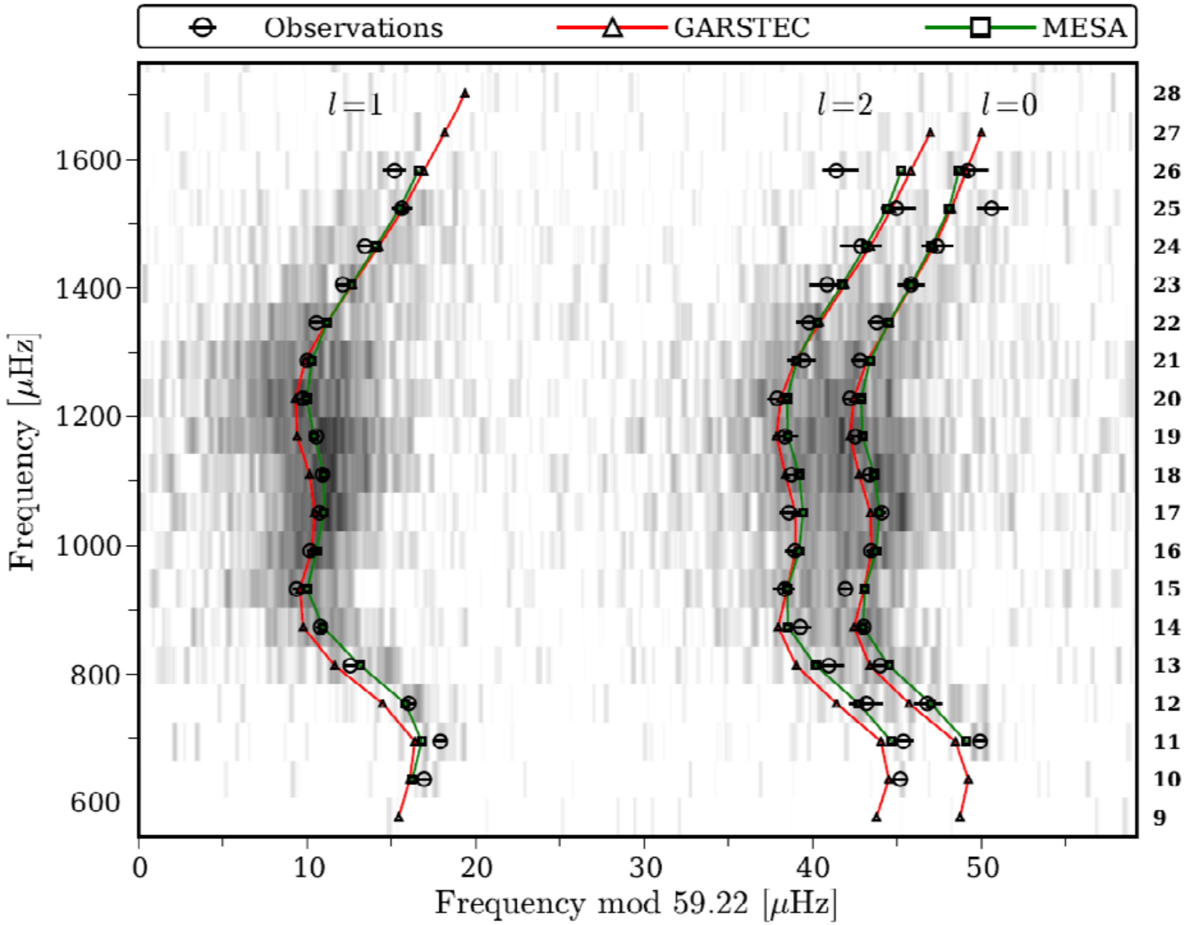
Determination of Three-dimensional Spin–orbit Angle with Joint Analysis of Asteroseismology, Transit Lightcurve, and the Rossiter–McLaughlin Effect: Cases of HAT-P-7 and Kepler-25

Othman BENOMAR[1], Kento MASUDA[2], Hiromoto SHIBAHASHI[1], and Yasushi SUTO[2,3]



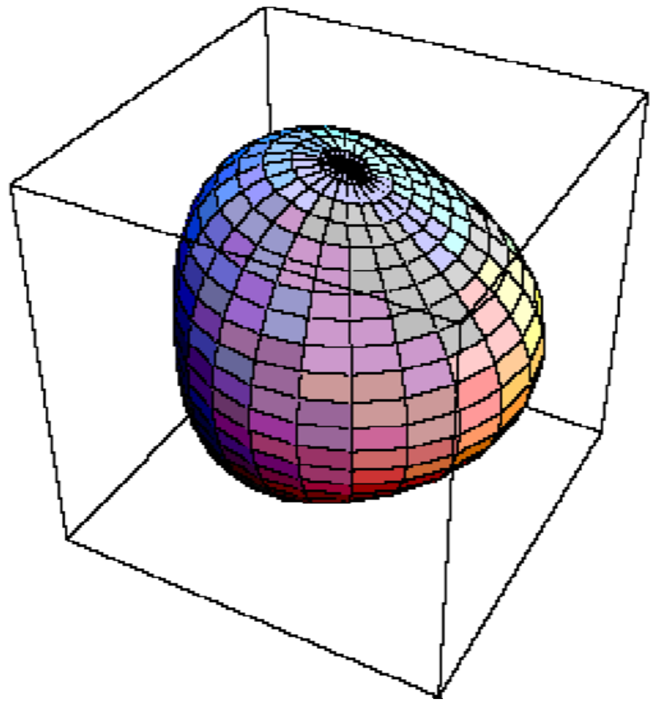
Asteroseismic inference on the spin-orbit misalignment and stellar parameters of HAT-P-7

Mikkel N. Lund[1★], Mia Lundkvist[1,2], Victor Silva Aguirre[1], Günter Houdek[1], Luca Casagrande[3], Vincent Van Eylen[1], Tiago L. Campante[5,1], Christoffer Karoff[4,1], Hans Kjeldsen[1], Simon Albrecht[1], William J. Chaplin[5,1], Martin Bo Nielsen[6,7], Pieter Degroote[8], Guy R. Davies[5,1], and Rasmus Handberg[5,1]



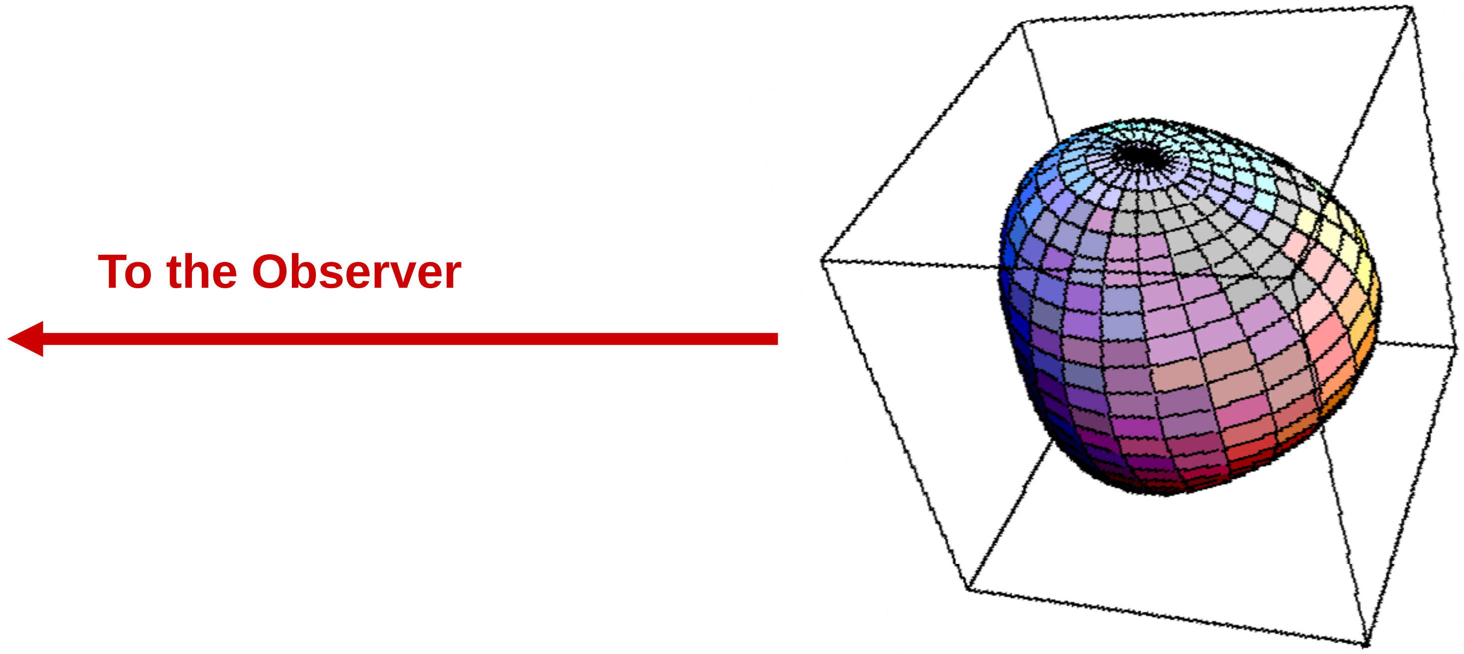
Inclination of rotational axis?

To the Observer



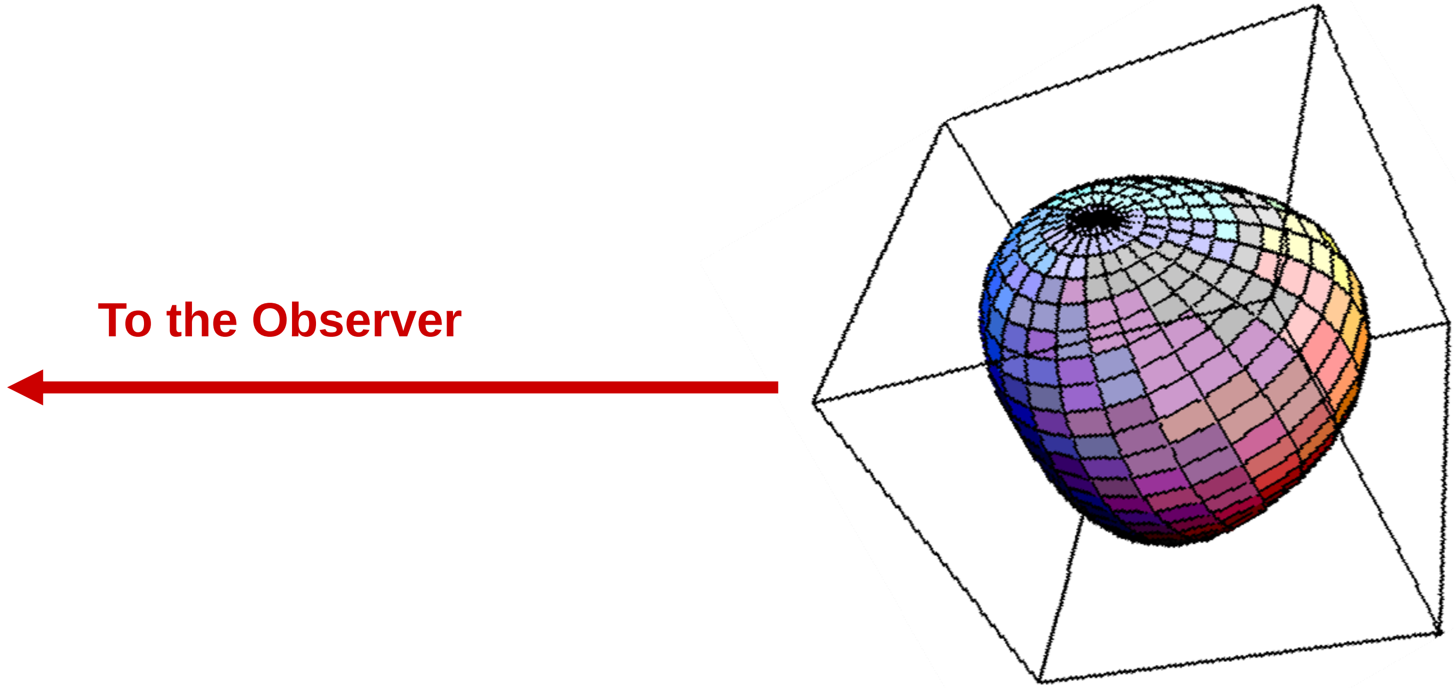
90°

Inclination of rotational axis?



75°

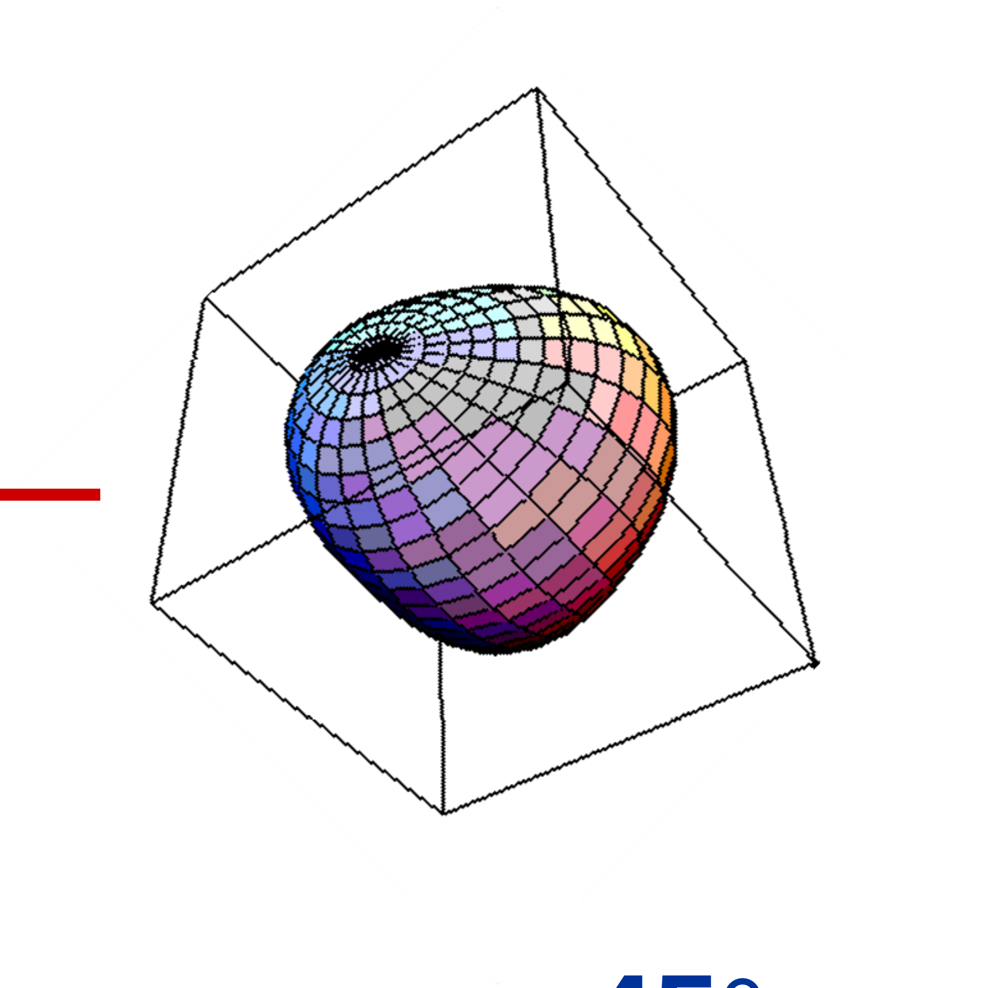
Inclination of rotational axis?



60°

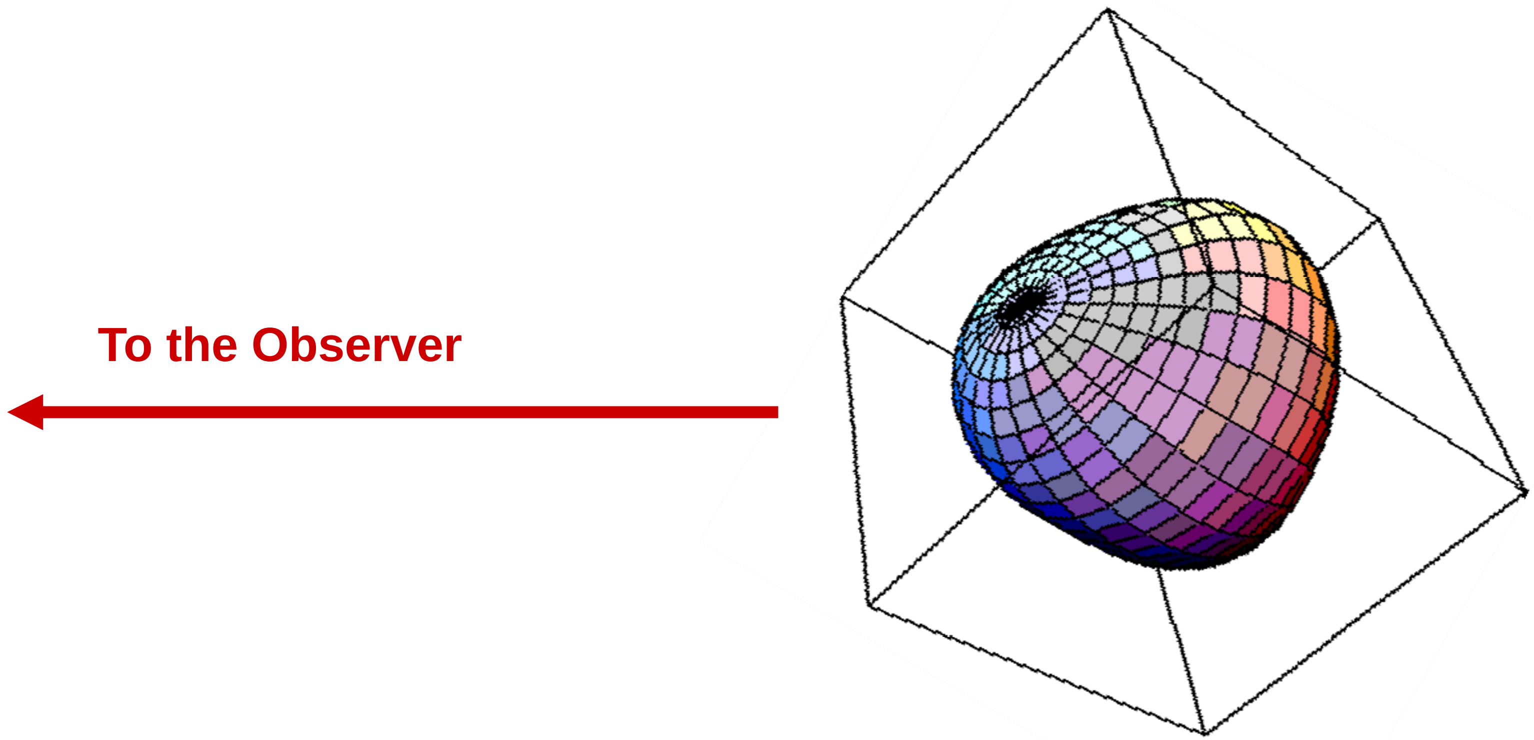
Inclination of rotational axis?

To the Observer



45°

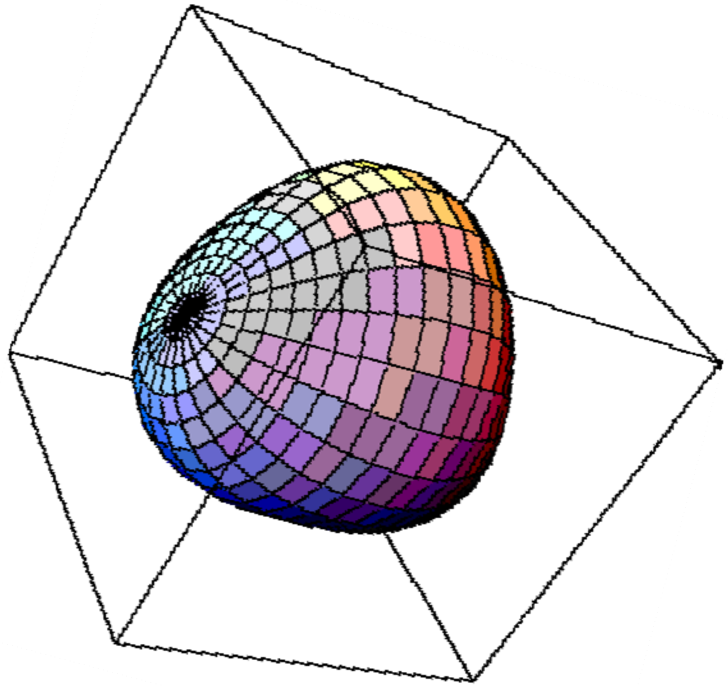
Inclination of rotational axis?



30°

Inclination of rotational axis?

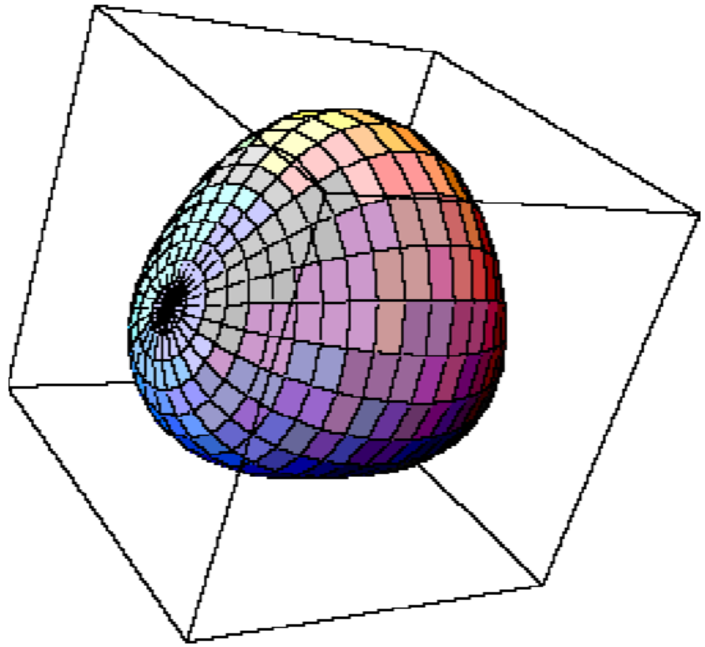
To the Observer



15°

Inclination of rotational axis?

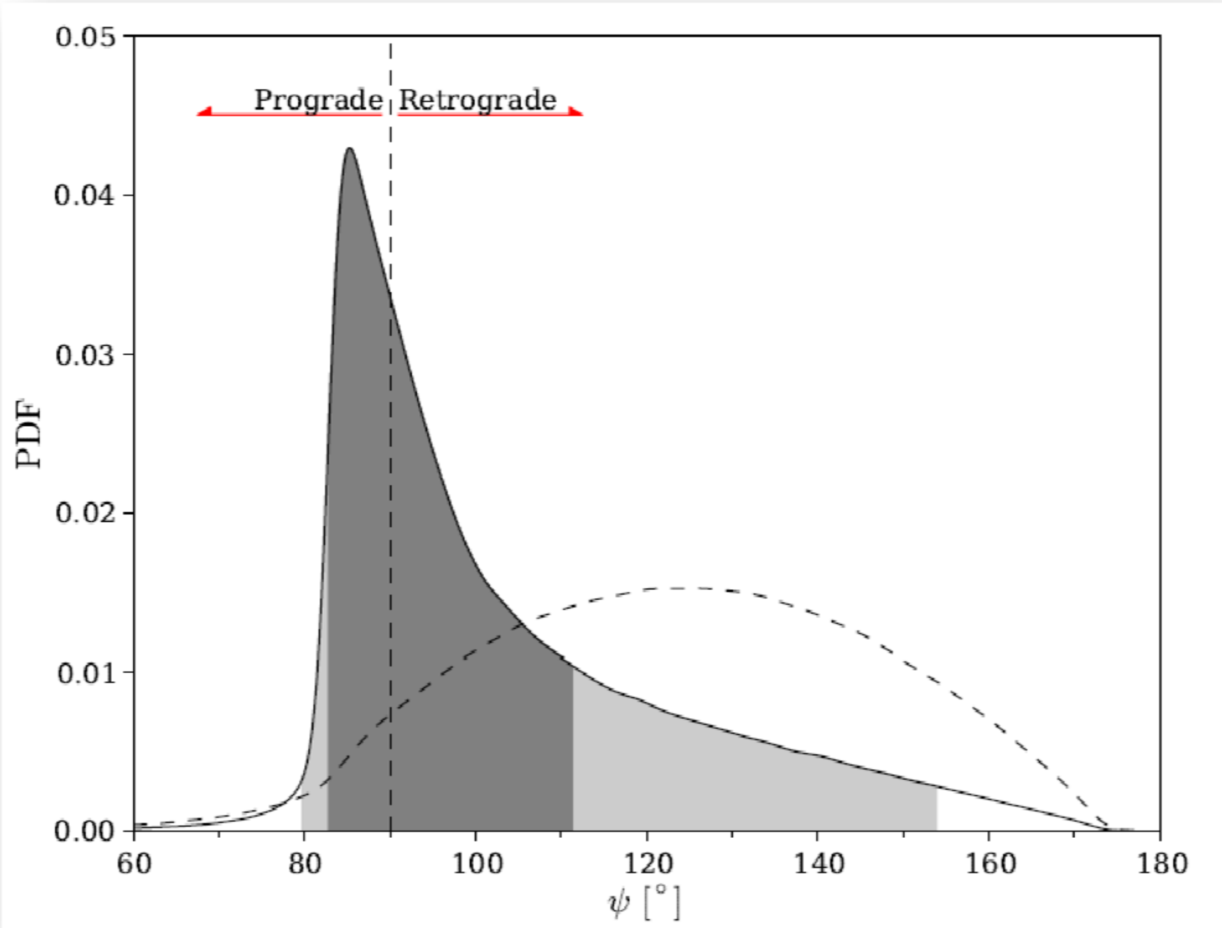
To the Observer



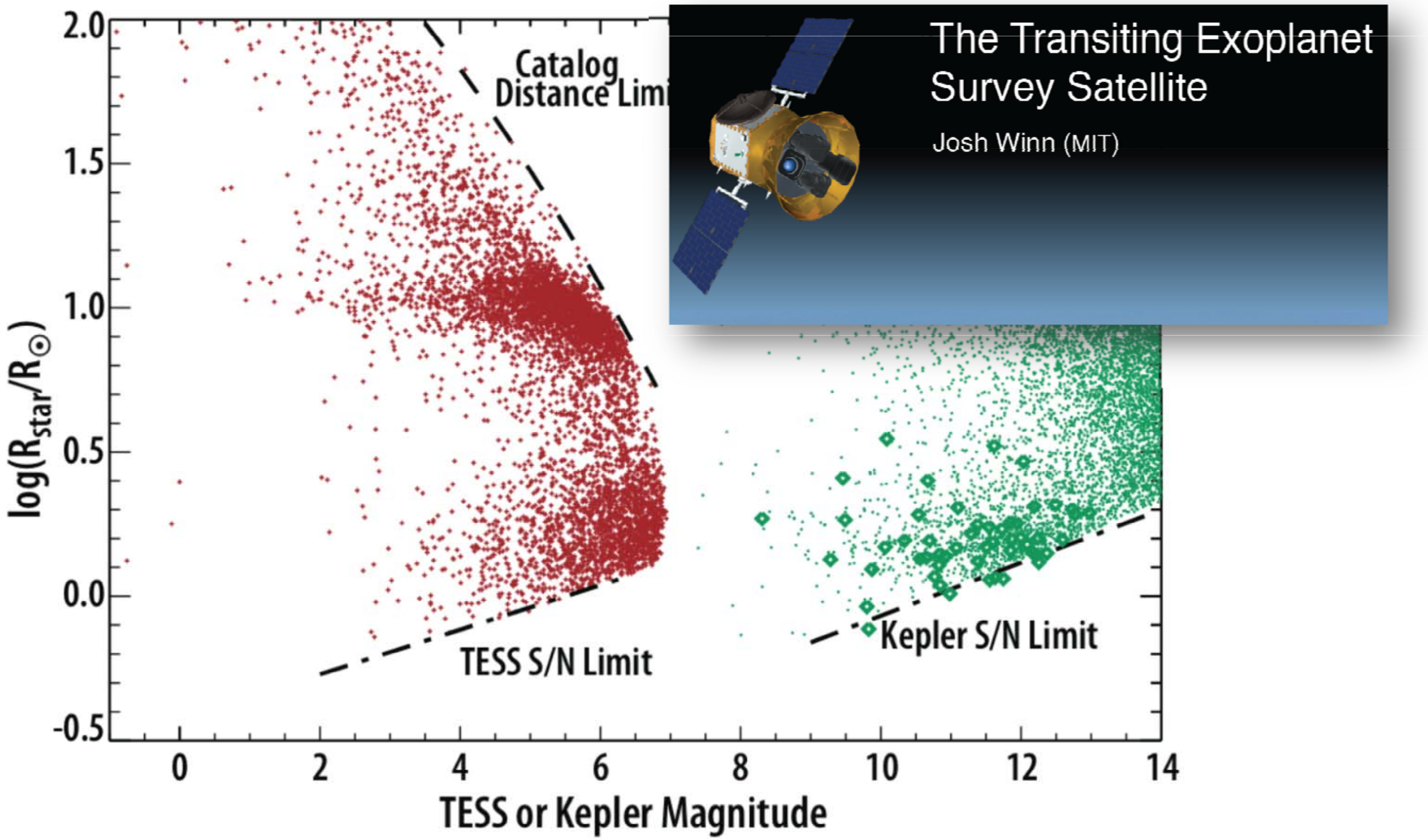
0°

Asteroseismic inference on the spin-orbit misalignment and stellar parameters of HAT-P-7

Mikkel N. Lund[1★], Mia Lundkvist[1,2], Victor Silva Aguirre[1],
Günter Houdek[1], Luca Casagrande[3], Vincent Van Eylen[1], Tiago L. Campante[5,1],
Christoffer Karoff[4,1], Hans Kjeldsen[1], Simon Albrecht[1], William J. Chaplin[5,1],
Martin Bo Nielsen[6,7], Pieter Degroote[8], Guy R. Davies[5,1], and Rasmus Handberg[5,1]

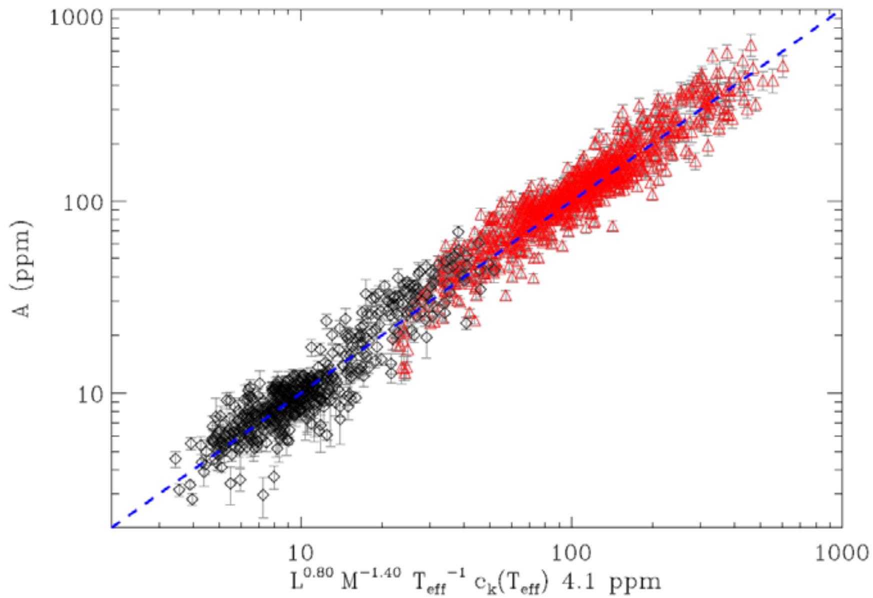


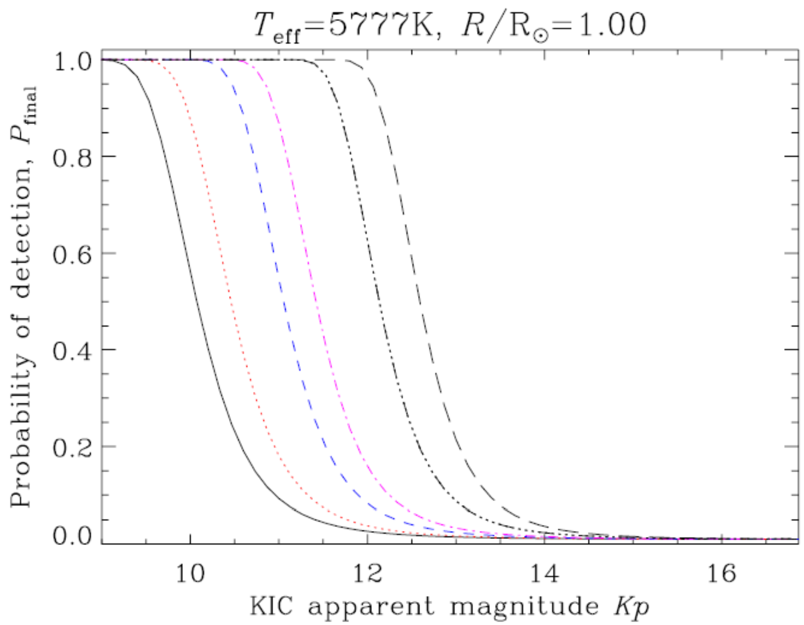
Prospects for *p*-mode detection

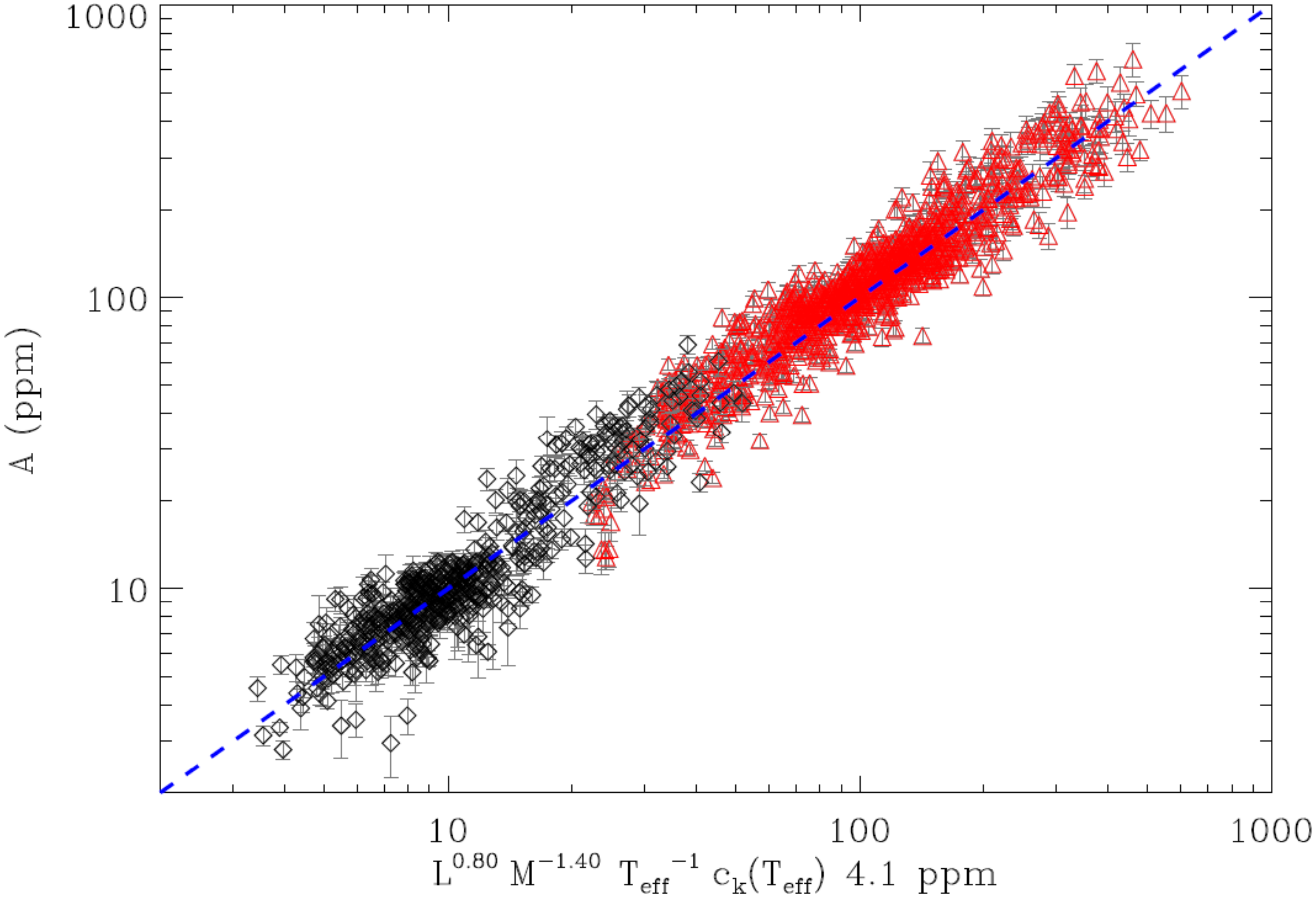


Detection of p-modes

- Amplitude
- SNR

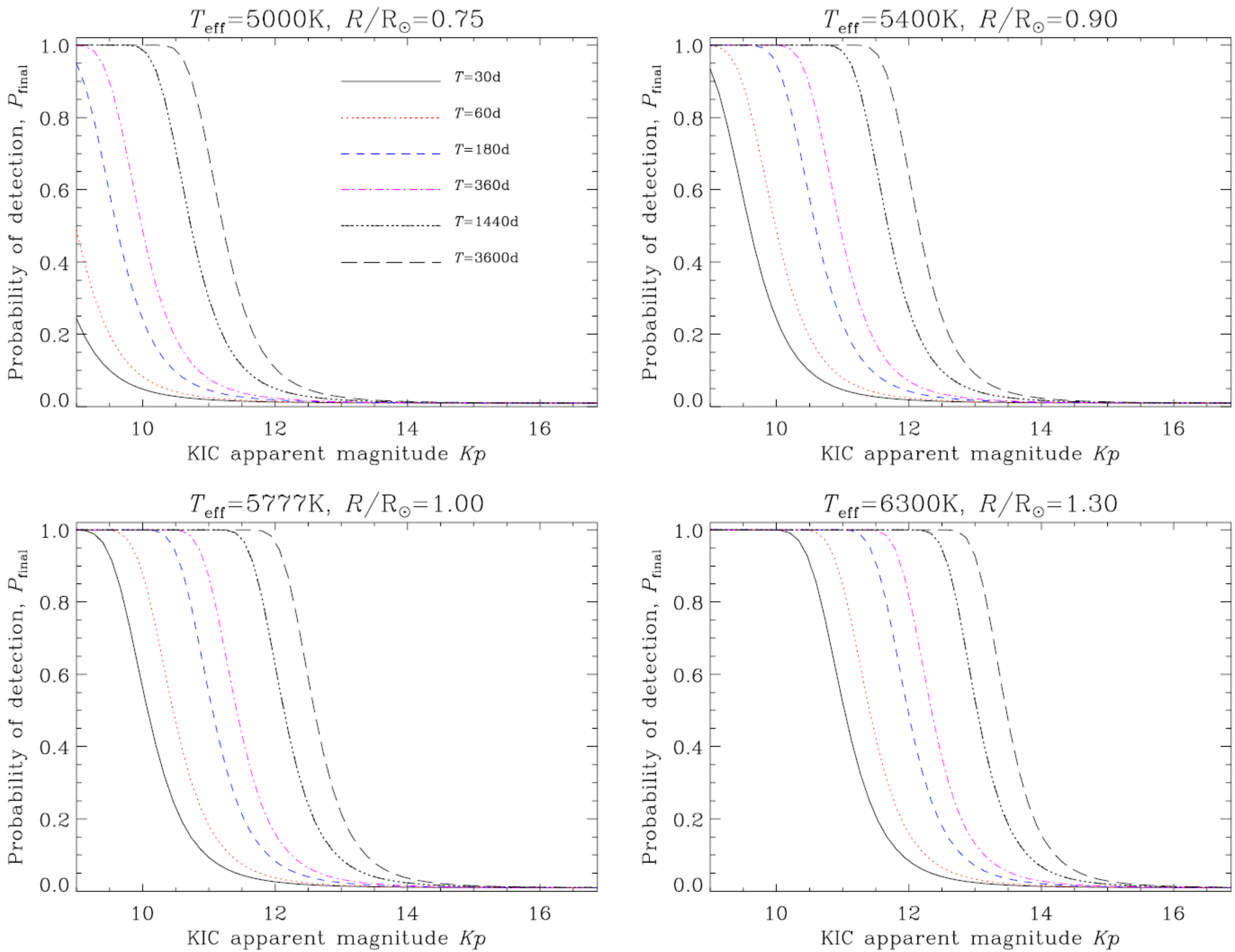




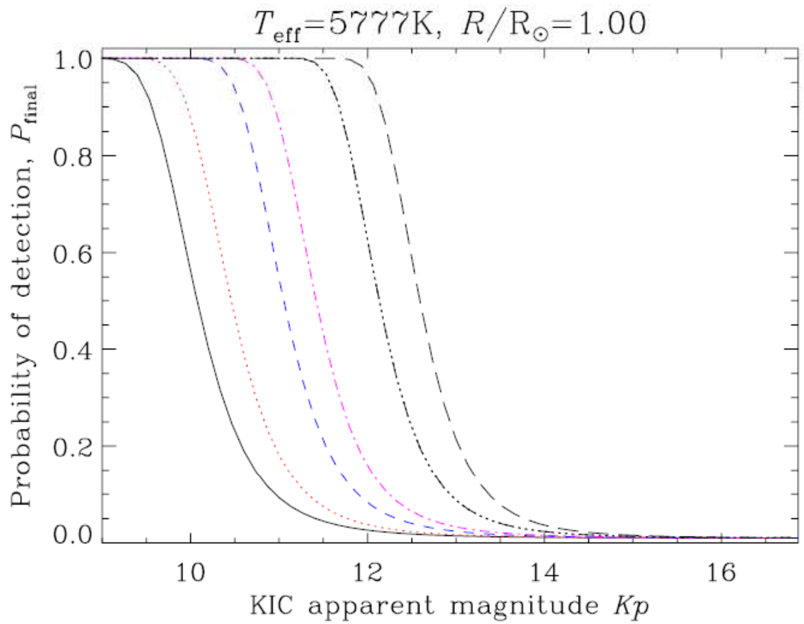


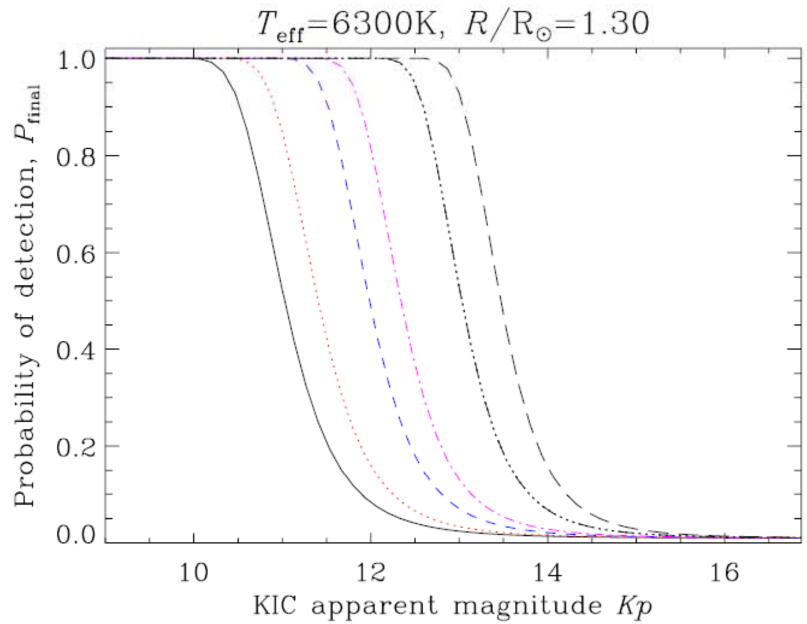
Huber et al. 2011

Chaplin et al. 2011

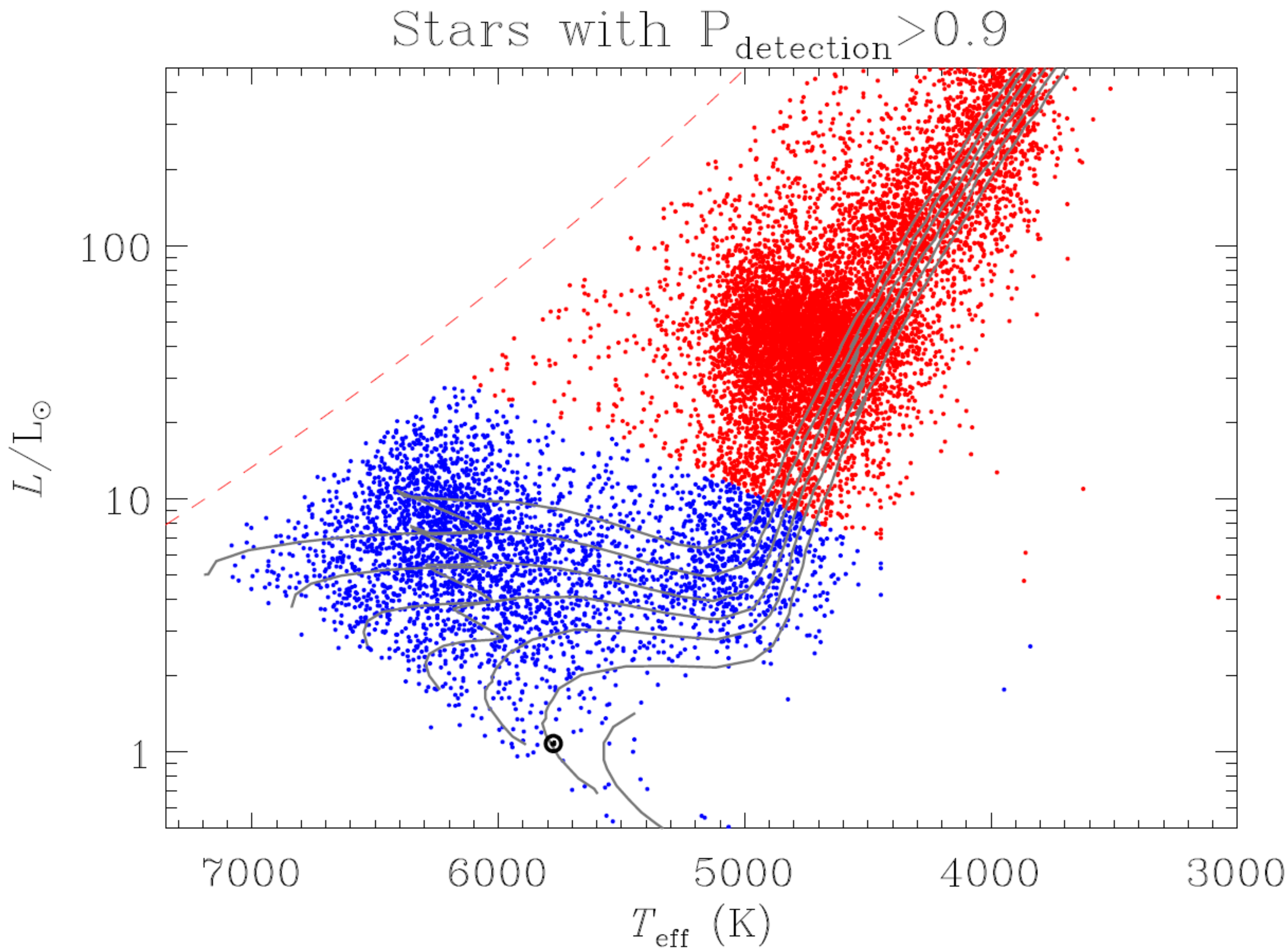


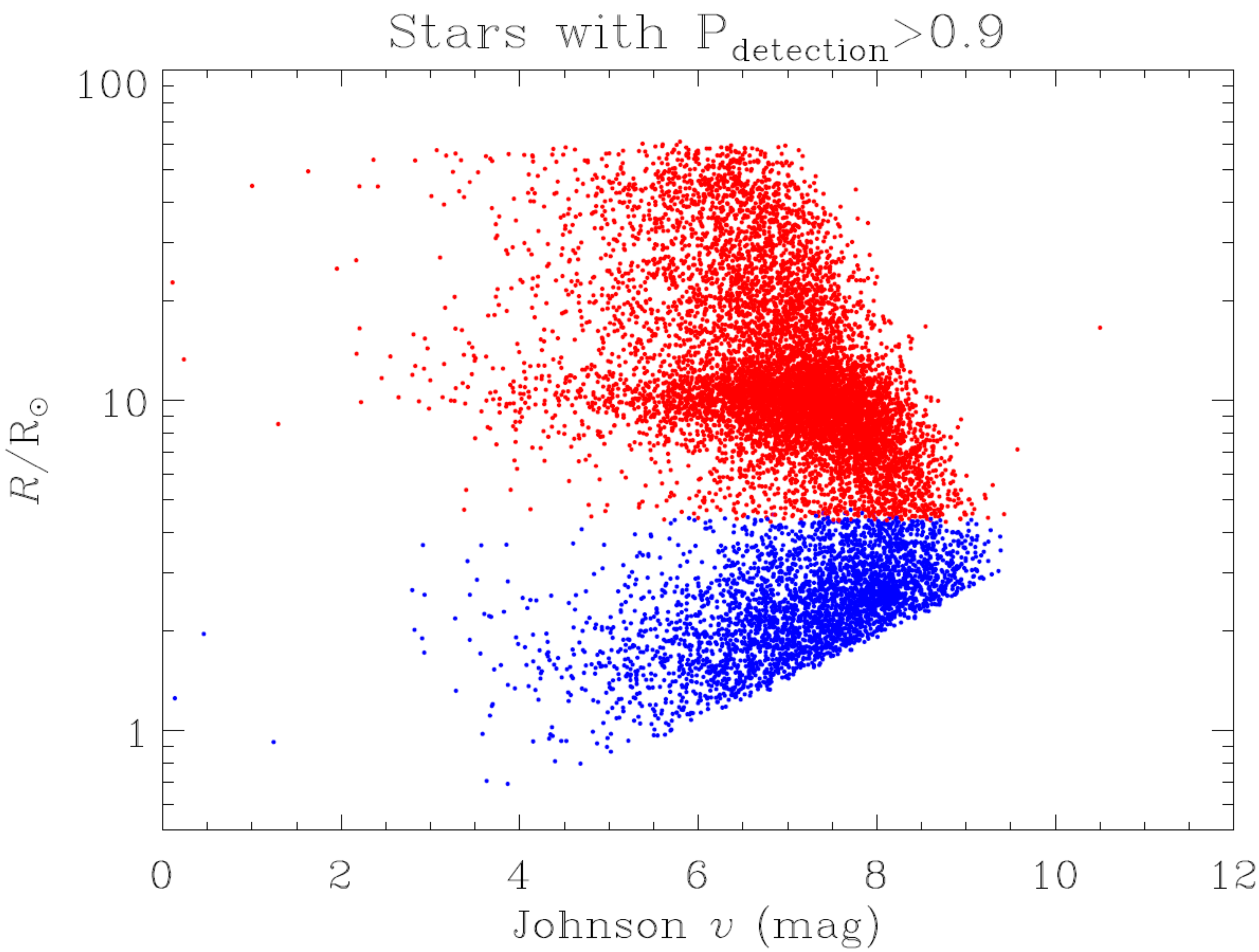
$$V_{\mathrm{limit}} = 11.6 + 1.25 \cdot \log_{10}(T_{obs} / yr) + 4 \cdot \log_{10}(L / L_{sun})$$
$$- 7 \cdot \log_{10}(M / M_{sun}) - 5 \cdot \log_{10}(T_{eff} / 5778K)$$
$$+ 5 \cdot \log_{10}(D / m)$$





TESS targets based on HIPPARCOS (Chaplin 2013)





Stars with $P_{detection}$>0.9
100
10
1
$R/R_{\odot}$
0
2
4
6
8
10
12
Johnson v (mag)

Amplitudes of stellar oscillations and granulation will be lower in TESS than in Kepler/K2

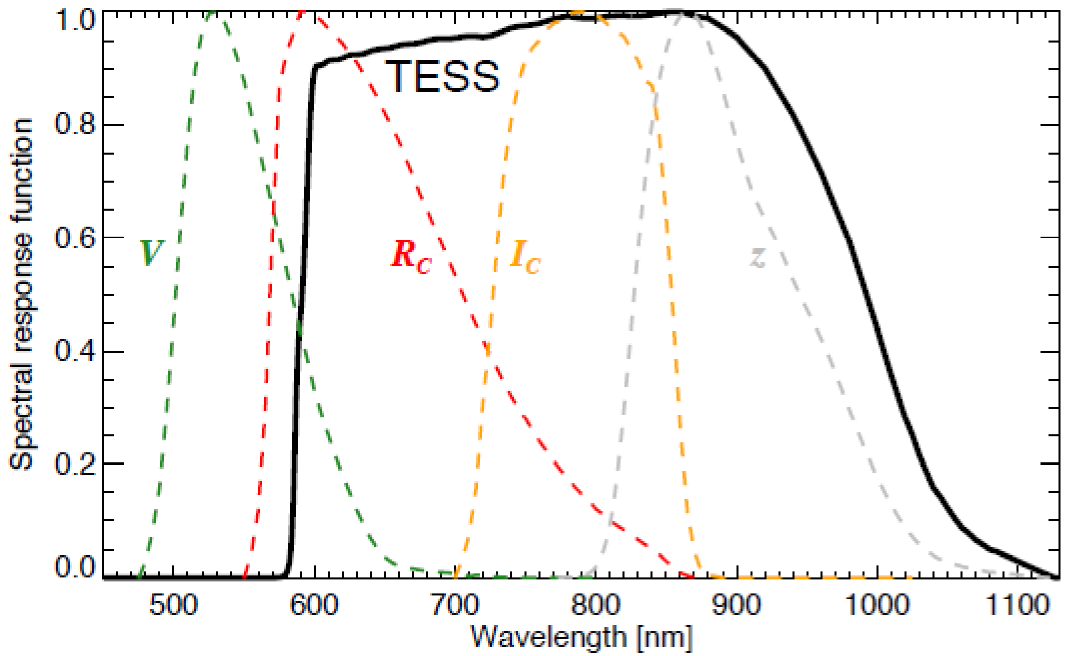


Figure 1. The TESS spectral response function (black line), defined as the product of the long-pass filter transmission curve and the detector quantum efficiency curve. Also plotted, for comparison, are the Johnson-Cousins V, R_C, and I_C filter curves and the SDSS z filter curve. Each of the functions has been scaled to have a maximum value of unity.

From: Ricker, Winna, Vanderspek and Latham et al.

arXiv:1406.0151v1 [astro-ph.EP] 1 Jun 2014

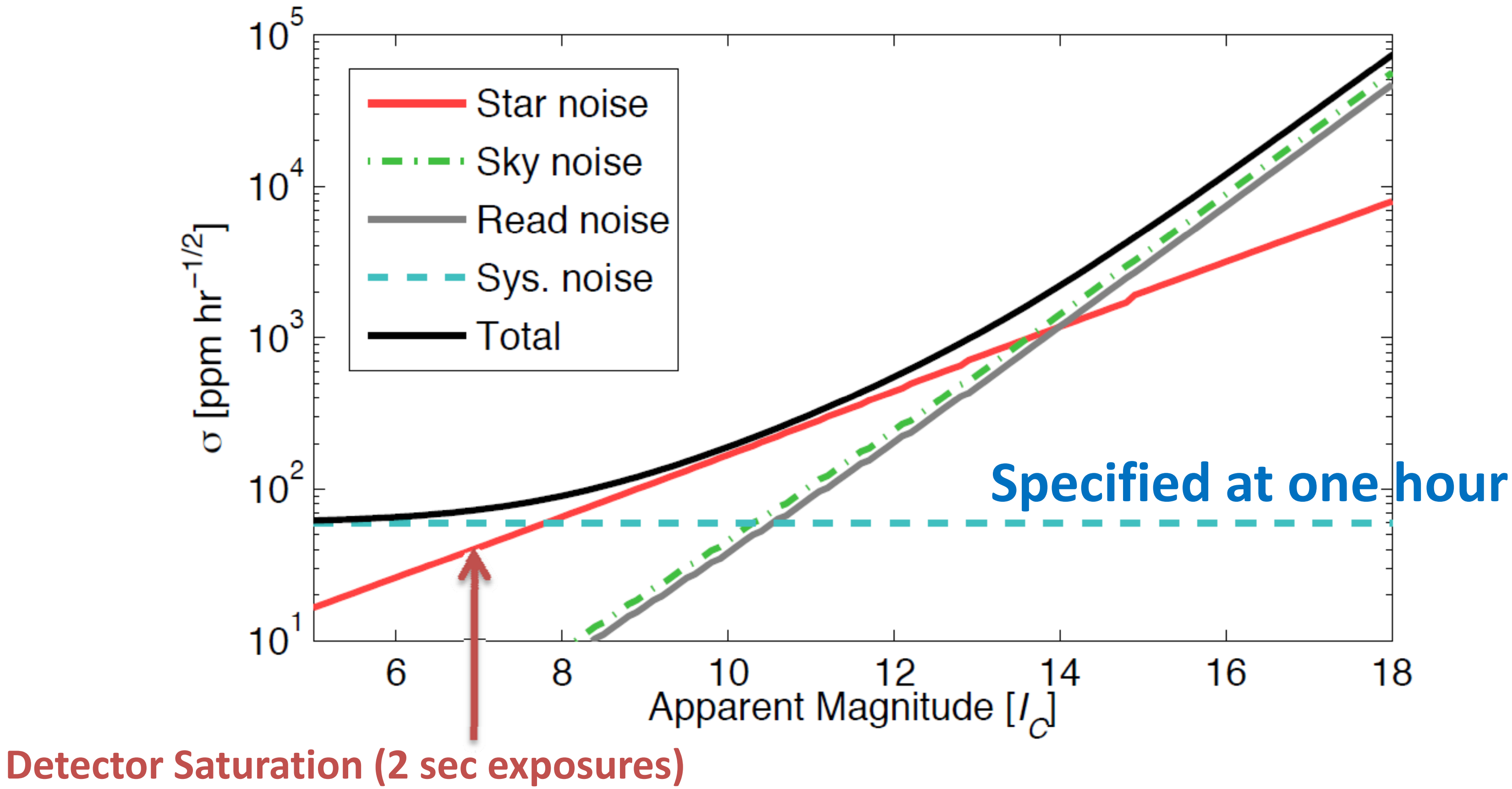
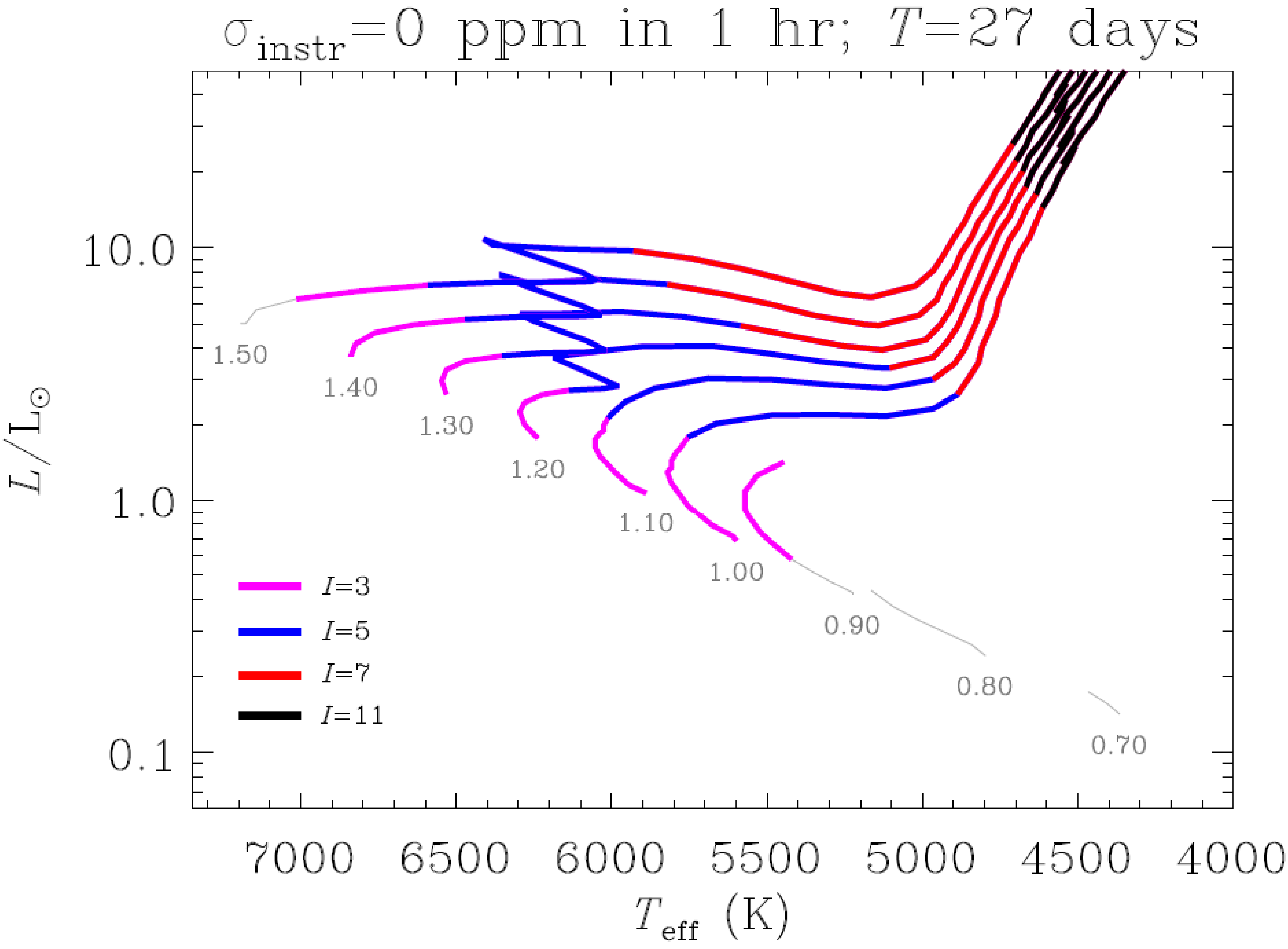


Figure 8. *Top.*—Expected 1σ photometric precision as a function of stellar apparent magnitude in the I_C band. Contributions are from photon-counting noise from the target star and background (zodiacal light and unresolved stars), detector read noise ($10\ e^-$), and an assumed 60 ppm of incorrigible noise on hourly timescales.

From: Ricker, Winna, Vanderspek and Latham et al.

arXiv:1406.0151v1 [astro-ph.EP] 1 Jun 2014



Simulations done by Bill Chaplin (2014)

A number of stars will be observed for extended periods

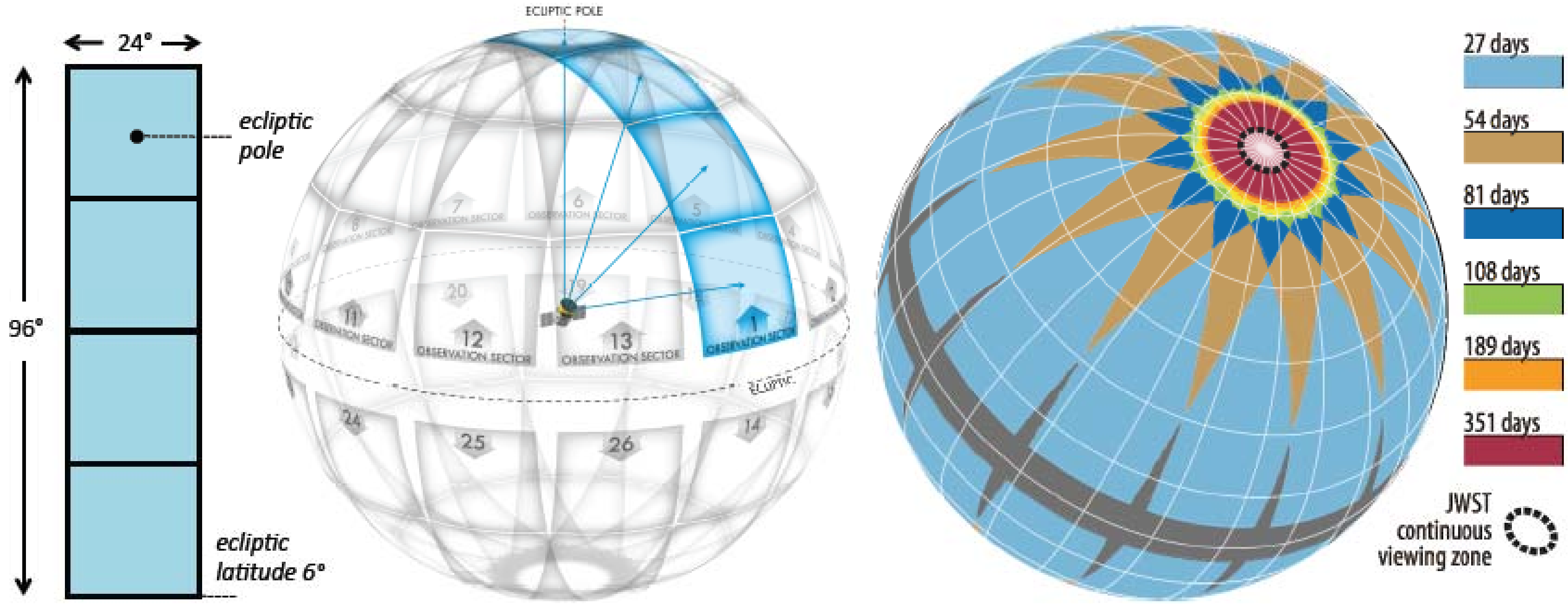
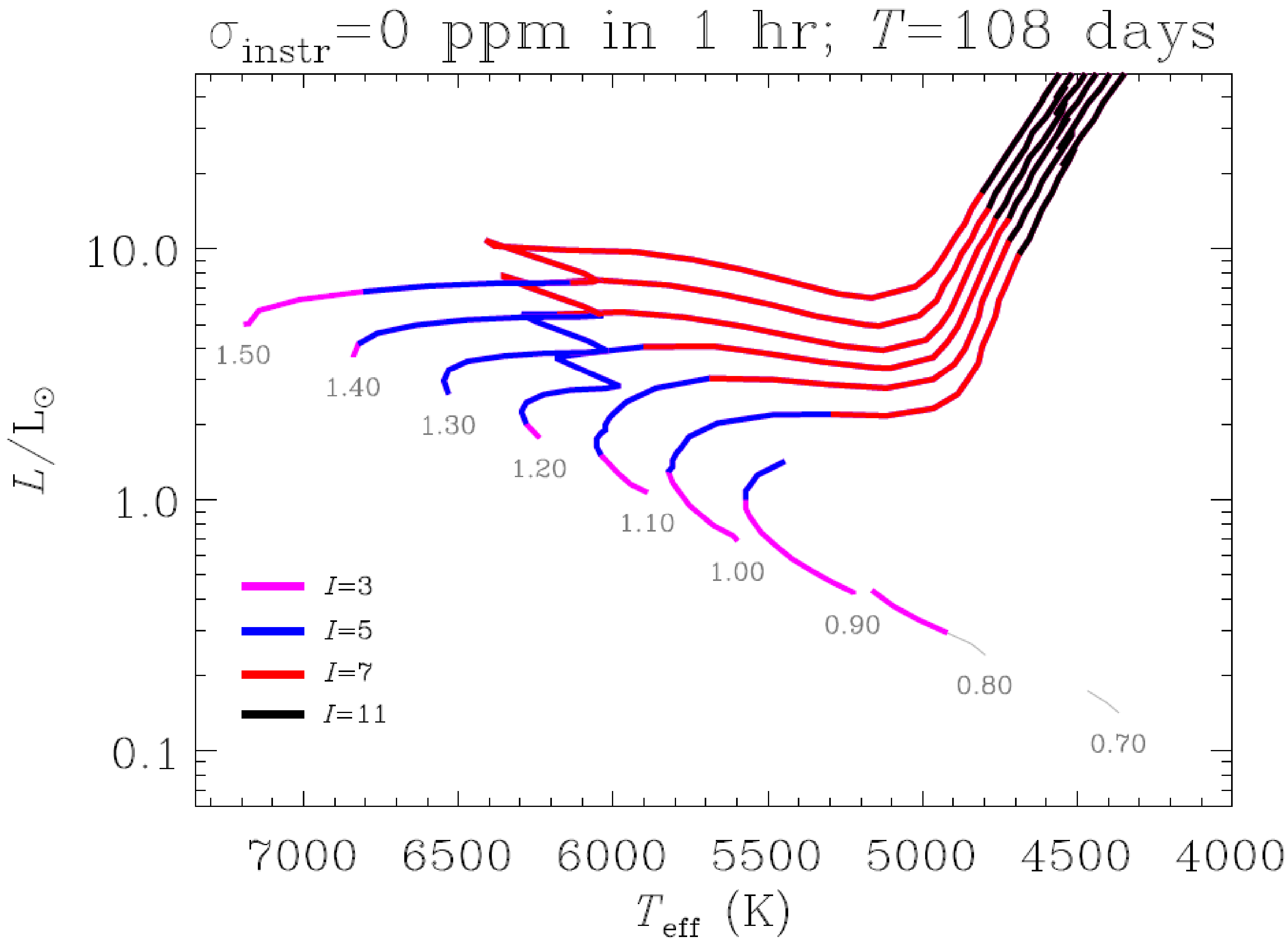


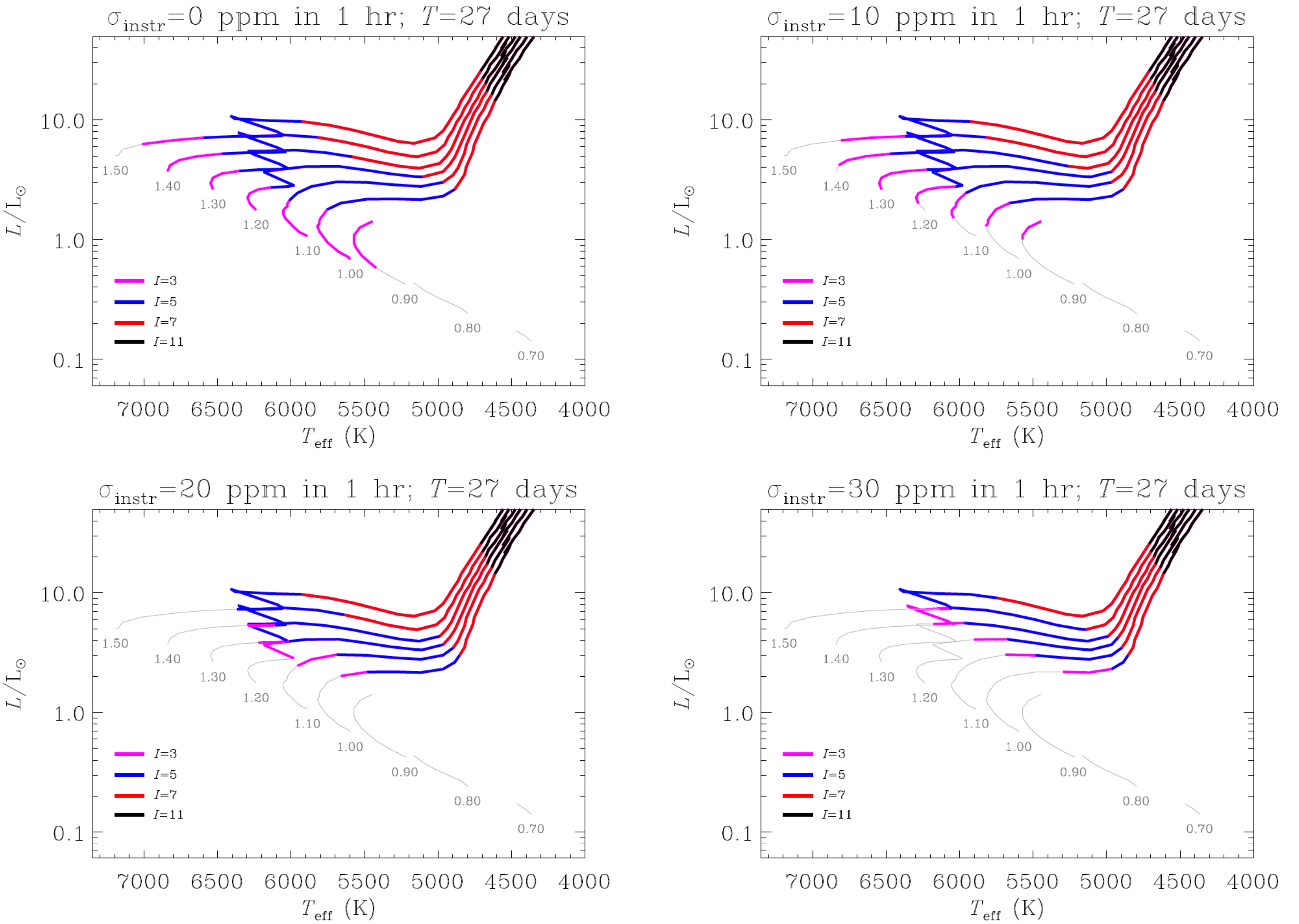
Figure 7. *Left.*—The instantaneous combined field of view of the four *TESS* cameras. *Middle.*—Division of the celestial sphere into 26 observation sectors (13 per hemisphere). *Right.*—Duration of observations on the celestial sphere, taking into account the overlap between sectors. The dashed black circle enclosing the ecliptic pole shows the region which *JWST* will be able to observe at any time.

From: Ricker, Winna, Vanderspek and Latham et al.

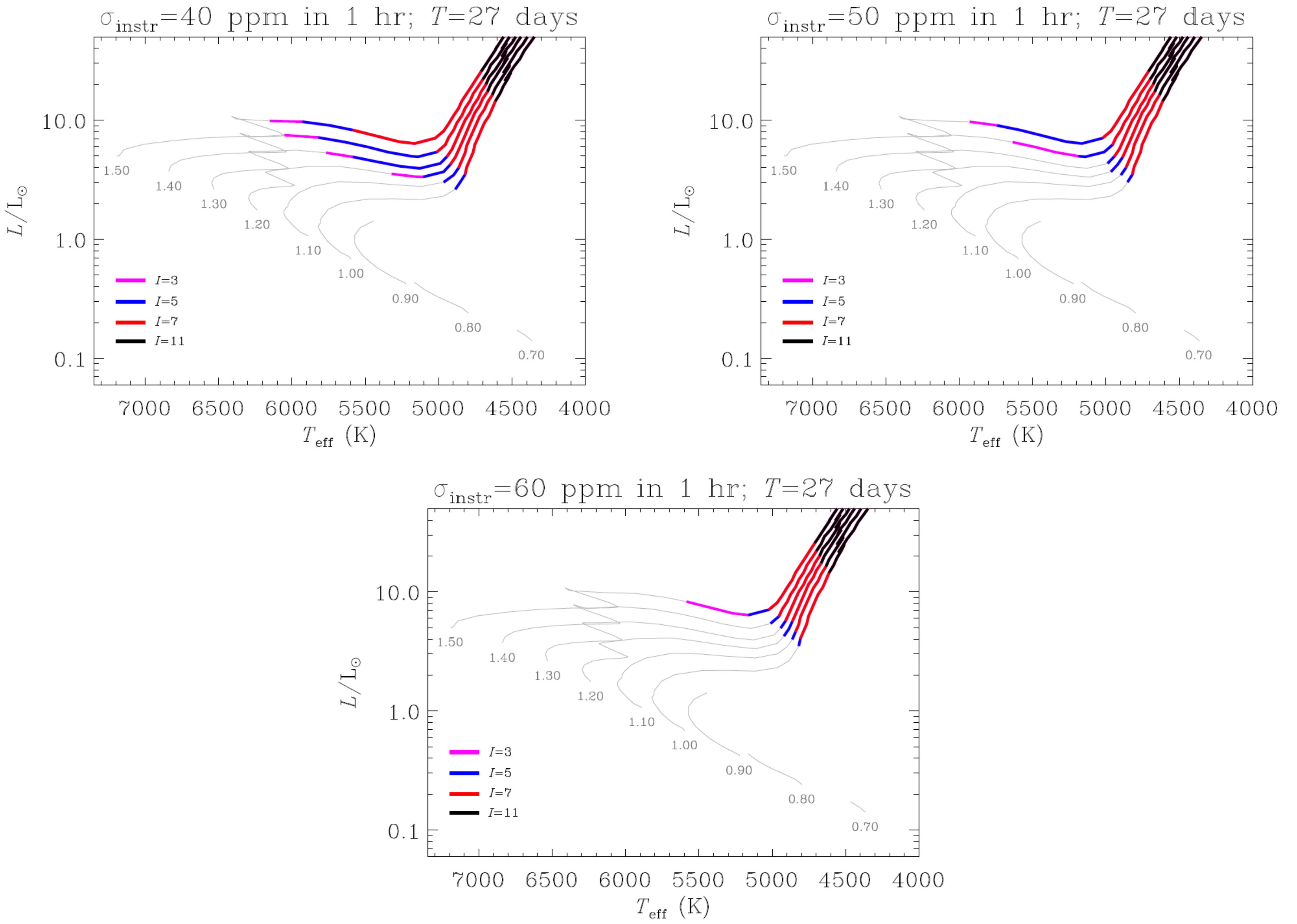
arXiv:1406.0151v1 [astro-ph.EP] 1 Jun 2014



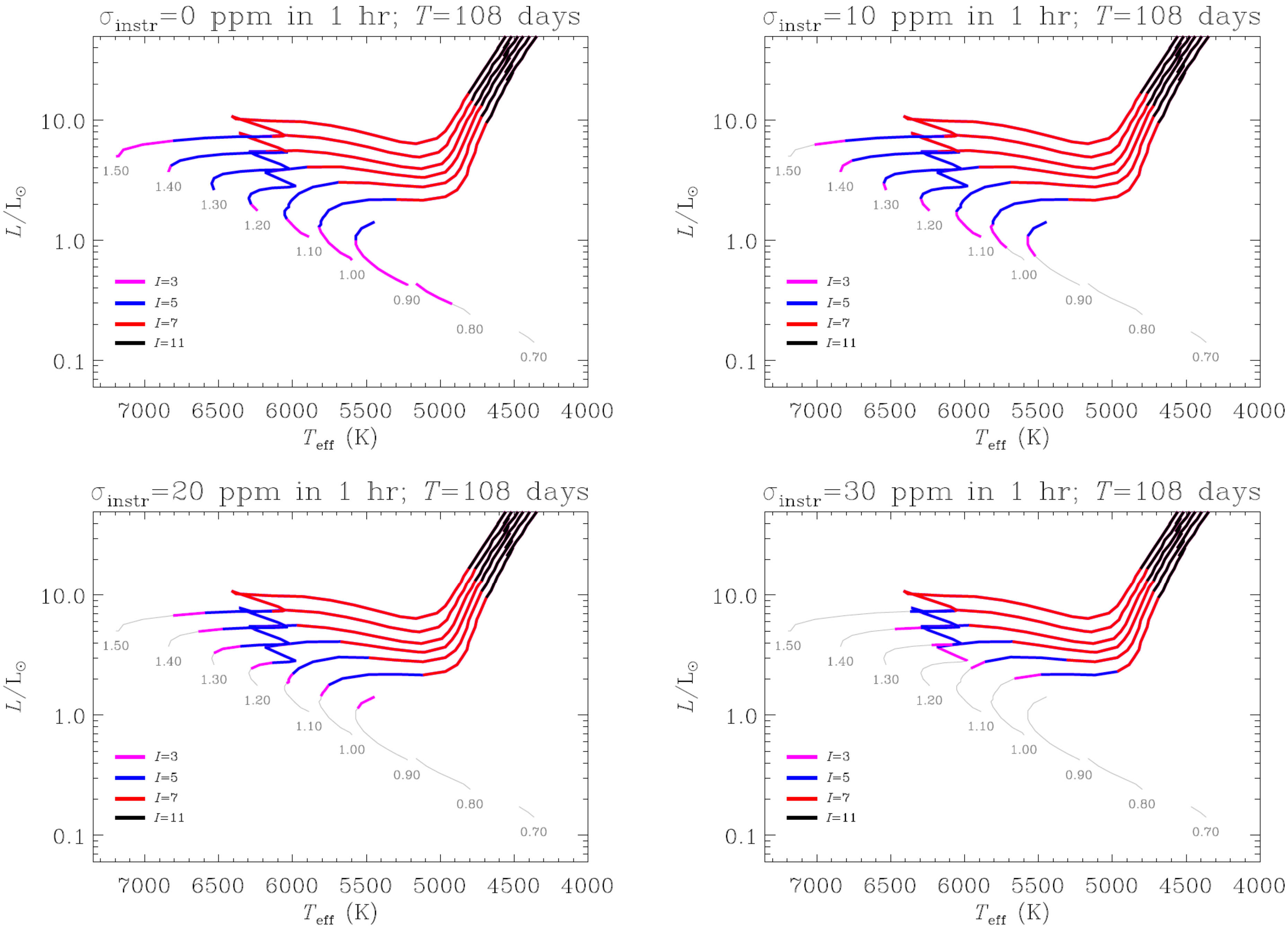
Simulations done by Bill Chaplin (2014)



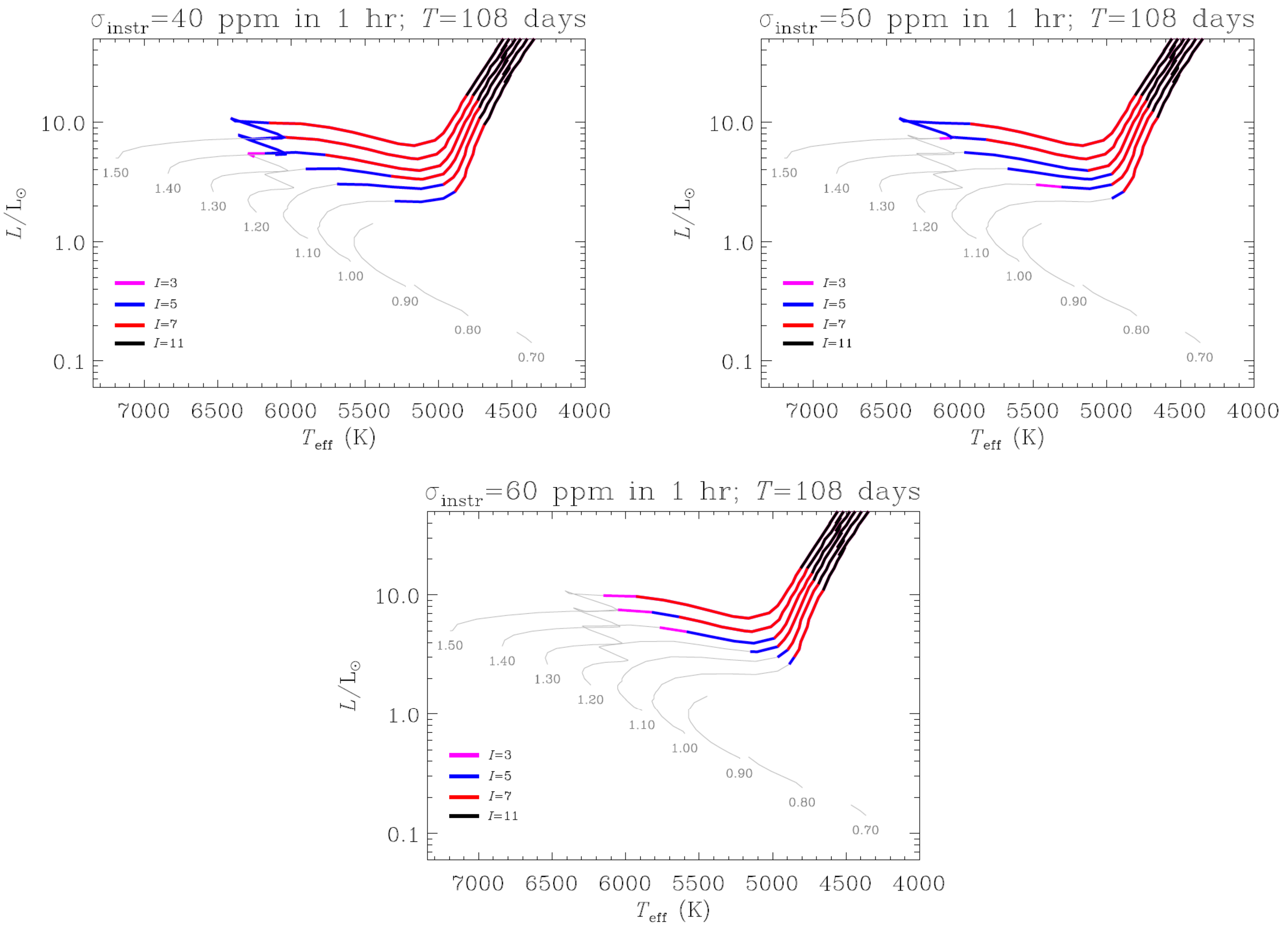
σinstr=0 ppm in 1 hr; T=27 days
σinstr=10 ppm in 1 hr; T=27 days
σinstr=20 ppm in 1 hr; T=27 days
σinstr=30 ppm in 1 hr; T=27 days
L/L⊙
Teff (K)
I=3
I=5
I=7
I=11
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
10.0
1.0
0.1
7000
6500
6000
5500
5000
4500
4000

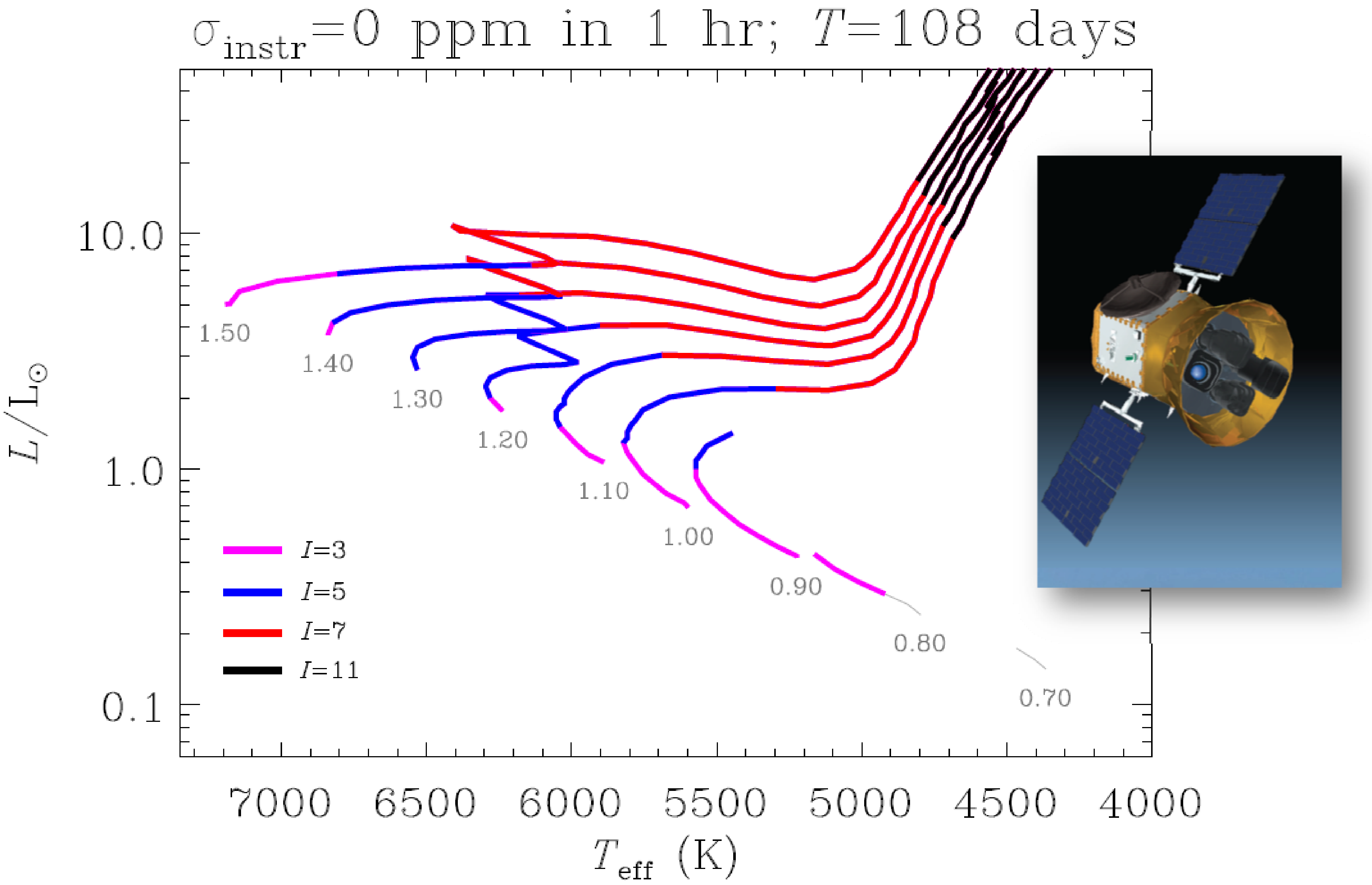


$\sigma_{\rm instr}$=40 ppm in 1 hr; T=27 days
$\sigma_{\rm instr}$=50 ppm in 1 hr; T=27 days
$\sigma_{\rm instr}$=60 ppm in 1 hr; T=27 days
$L/L_\odot$
$T_{\rm eff}$ (K)
I=3
I=5
I=7
I=11
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70

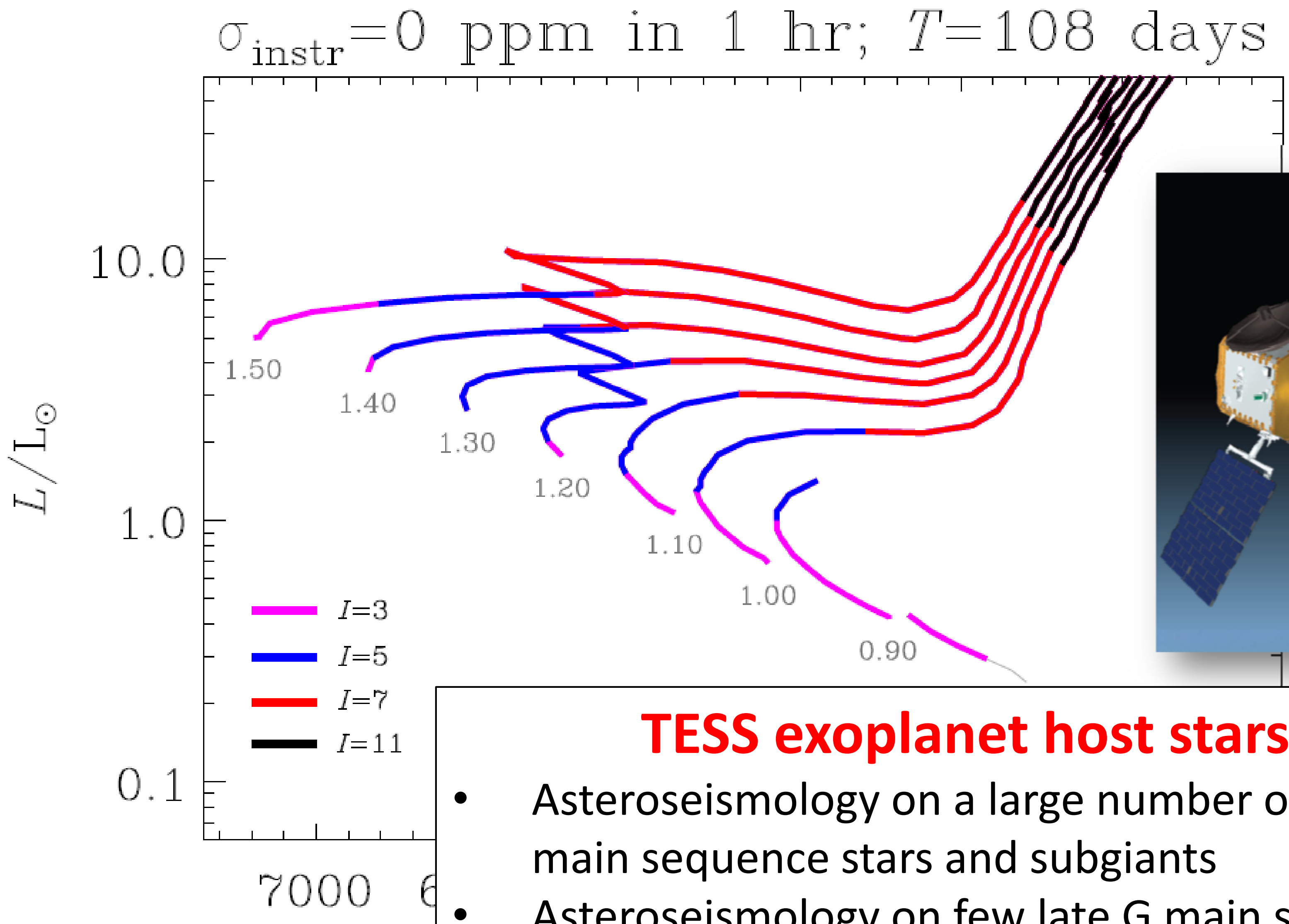


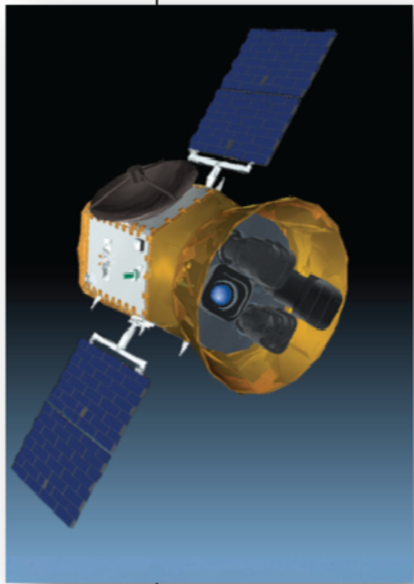
σ_{instr}=0 ppm in 1 hr; T=108 days
σ_{instr}=10 ppm in 1 hr; T=108 days
σ_{instr}=20 ppm in 1 hr; T=108 days
σ_{instr}=30 ppm in 1 hr; T=108 days
$L/L_\odot$
T_{eff} (K)
10.0
1.0
0.1
7000
6500
6000
5500
5000
4500
4000
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
I=3
I=5
I=7
I=11


σinstr=40 ppm in 1 hr; T=108 days
σinstr=50 ppm in 1 hr; T=108 days
σinstr=60 ppm in 1 hr; T=108 days
L/L⊙
Teff (K)
10.0
1.0
0.1
7000
6500
6000
5500
5000
4500
4000
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0.80
0.70
I=3
I=5
I=7
I=11



Simulations done by Bill Chaplin (2014)





TESS exoplanet host stars

- Asteroseismology on a large number of F and G main sequence stars and subgiants
- Asteroseismology on few late G main sequence stars near the ecliptic poles.
- Testing models for M < M(sun)