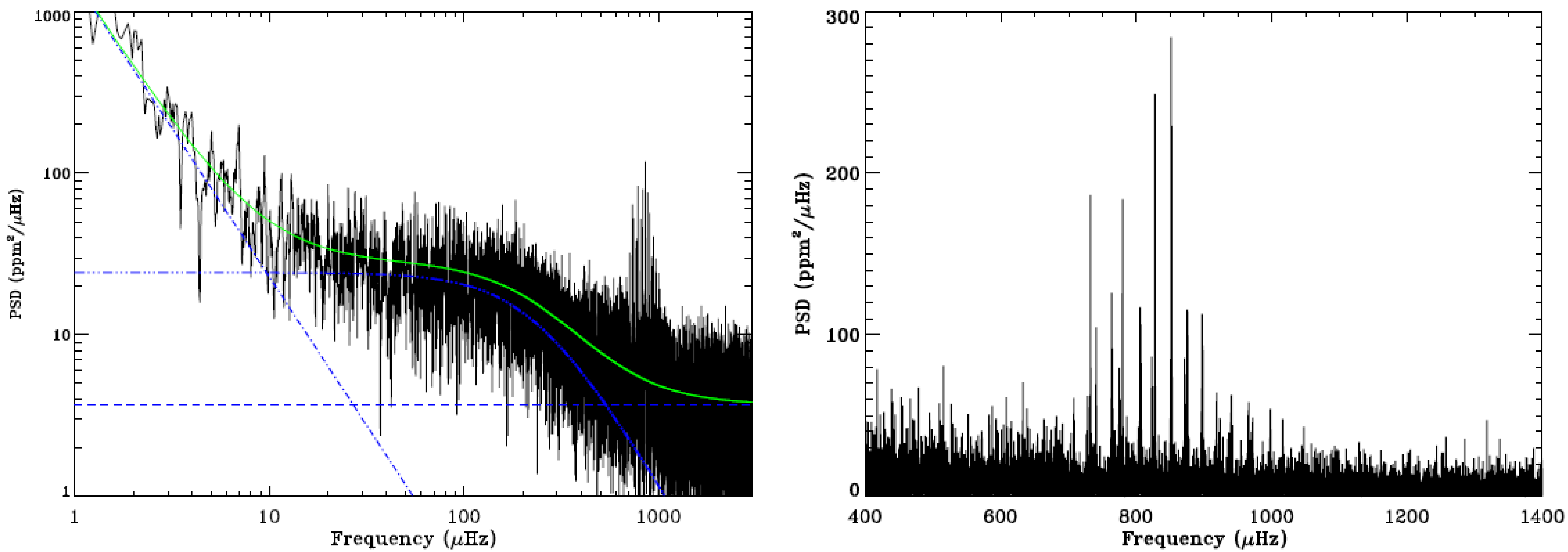
# Future Challenges….

Hans Kjeldsen
Aarhus University, Denmark

# Stellar Variability

- Minutes/hours: Oscillations, Eruptions in active regions, granulation

KIC 11395018 and KIC 11234888

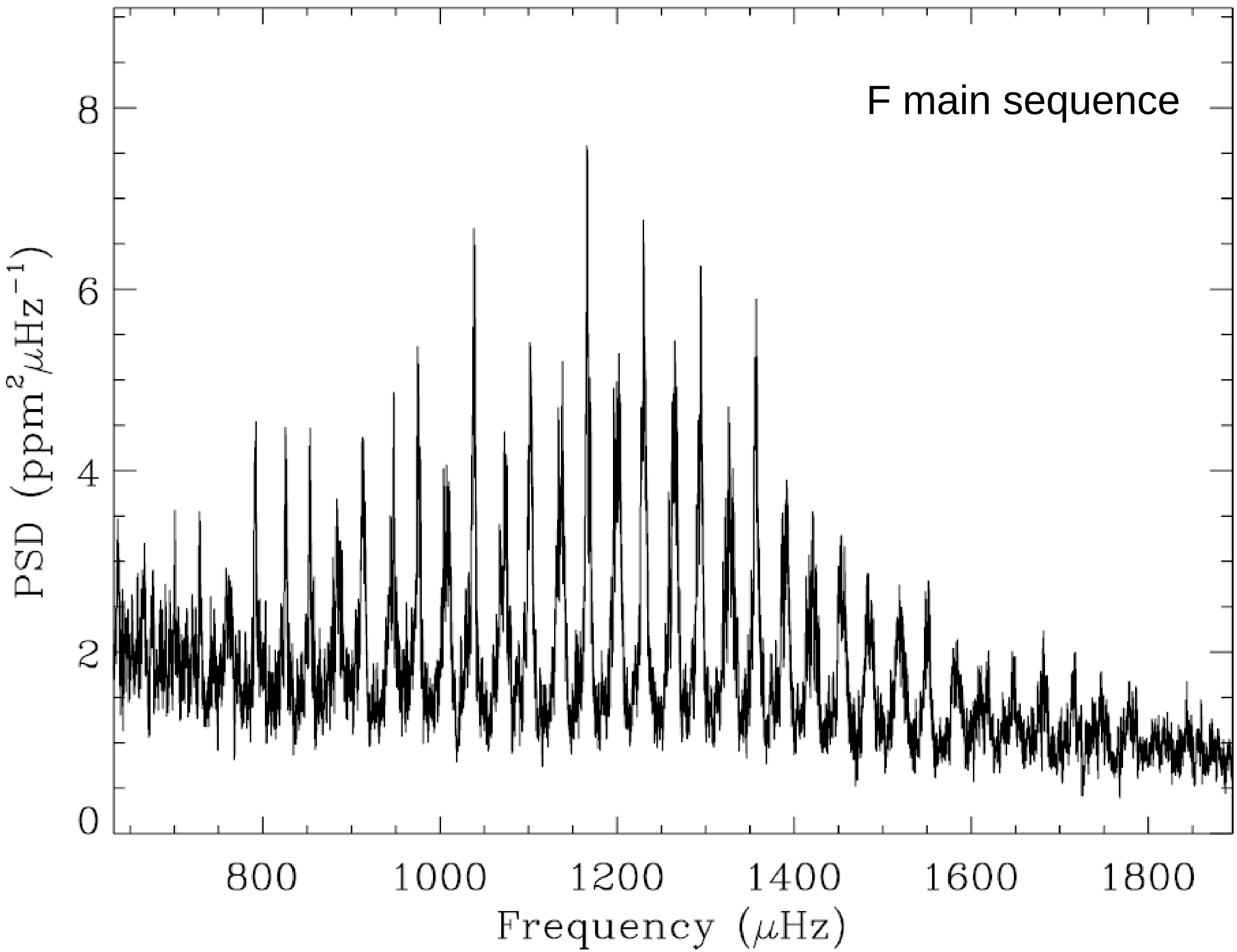



S. Mathur et al.: Solar-like oscillations in KIC 11395018 and KIC 11234888 from 8 months of Kepler data

# Stellar Variability

- Minutes/hours: Oscillations, Eruptions in active regions, granulation
- Days/months: Rotation, Spots, damping and excitation of oscillations

# 540 d, mag: 8.74

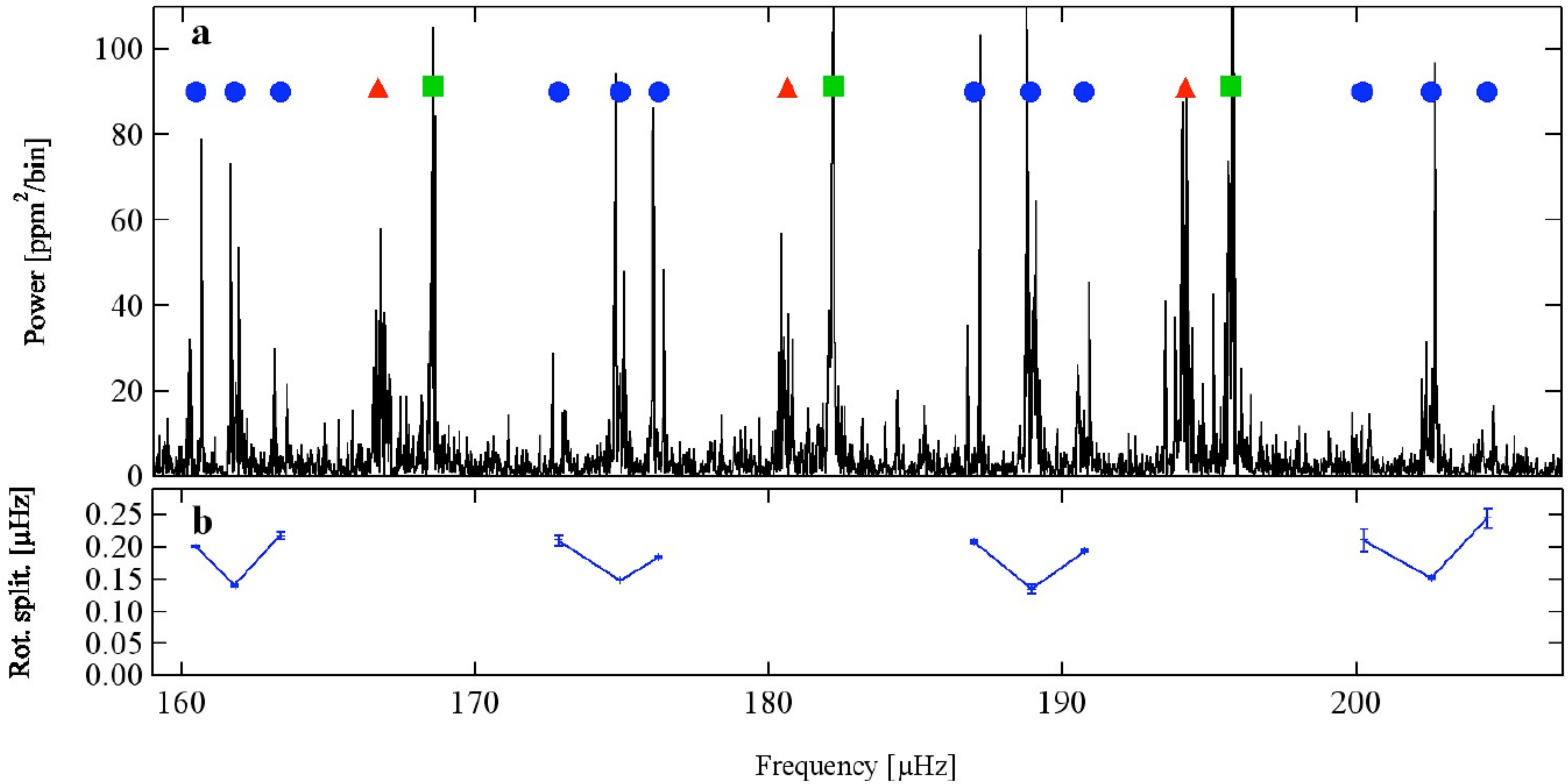



**Kepler**

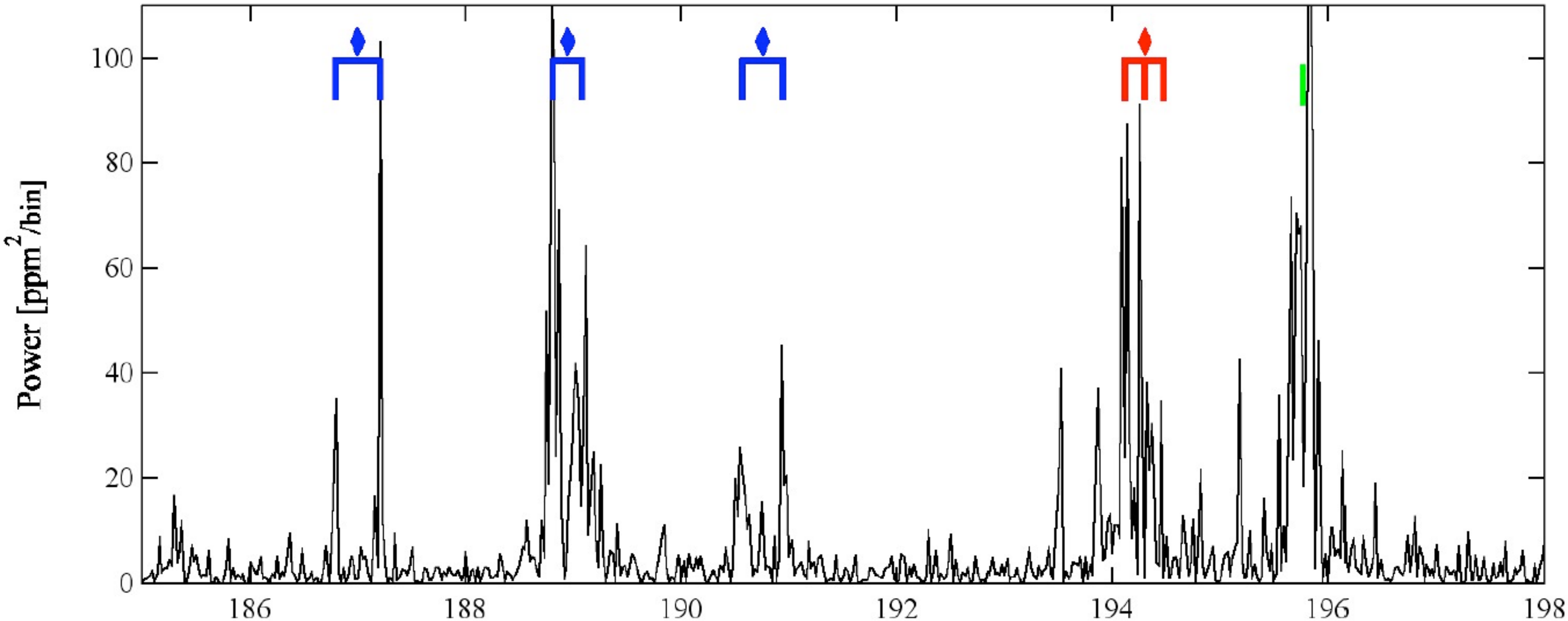
# Constraining the Core-Rotation Rate of Red-Giant stars.

Paul G. Beck[1], Josefina Montalban[2], Thomas Kallinger[1,3,4], Joris De Ridder[1], Conny Aerts[1,5], Rafael A. García[6], Saskia Hekker[7,8], Marc-Antoine Dupret[2], Benoit Mosser[9], Patrick Eggenberger[10], Dennis Stello[11], Yvonne Elsworth[8], Søren Frandsen[12], Fabien Carrier[1], Michel Hillen[1], Michael Gruberbauer[13], Jørgen Christensen-Dalsgaard[12], Andrea Miglio[8], Marica Valentini[2], Timothy R. Bedding[11], Hans Kjeldsen[12], Forrest R. Girouard[14], Jennifer R. Hall[14], Khadeejah A. Ibrahim[14]

… we report the detection of non-rigid rotation in the interiors of red-giant stars using light curves obtained by the Kepler spacecraft. We exploit rotational splittings of the recently detected mixed modes, to demonstrate an increasing rotation rate from the surface of the star to the stellar core. Comparing with theoretically predicted rotational splittings, we established that **the core must rotate at least ten times faster than the surface**.



a
b
Power [ppm$^2$/bin]
Rot. split. [μHz]
0
20
40
60
80
100
0.00
0.05
0.10
0.15
0.20
0.25
160
170
180
190
200
Frequency [μHz]



Power [ppm$^2$/bin]
100
80
60
40
20
0
186
188
190
192
194
196
198

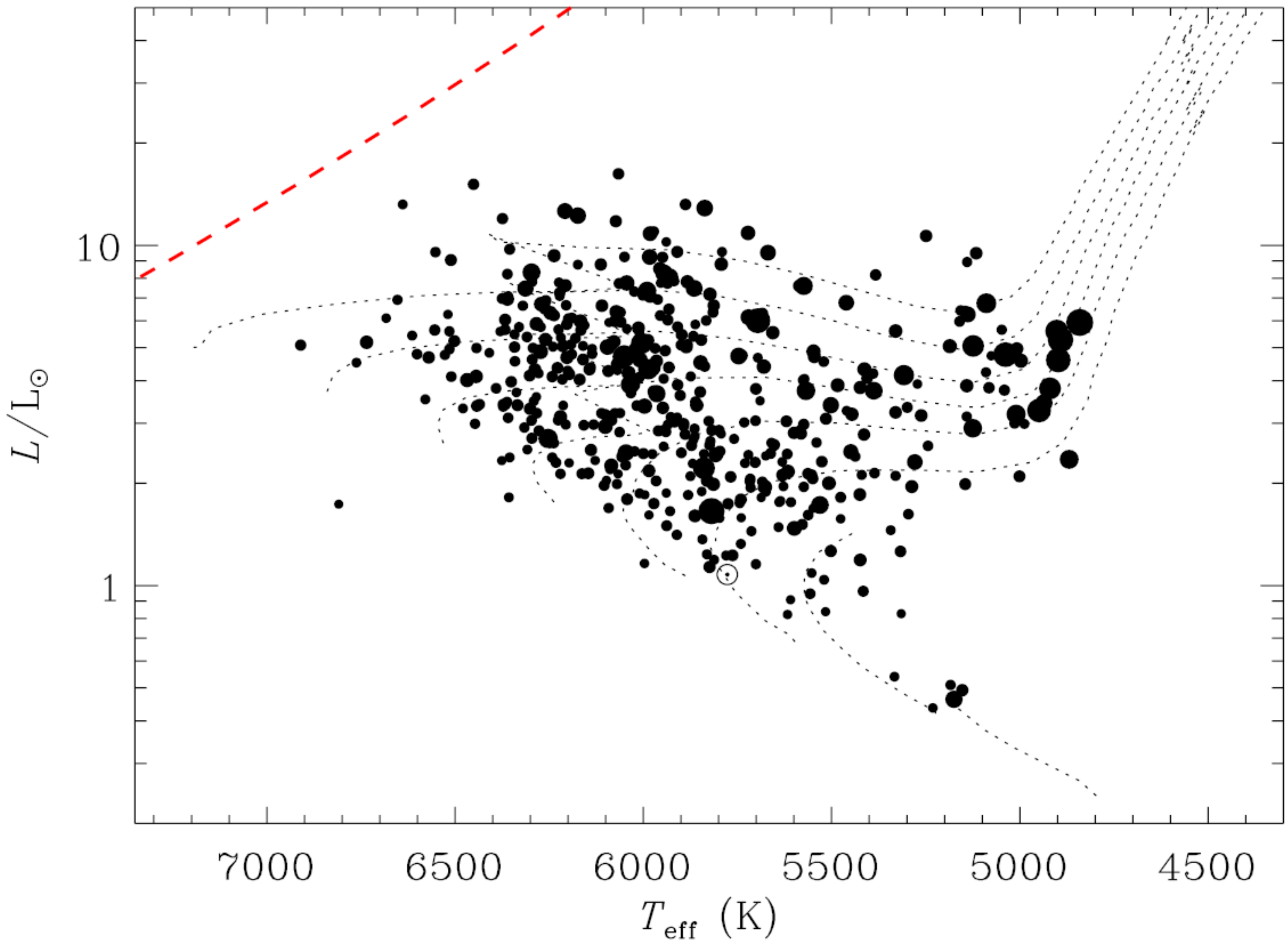
# Stellar Variability

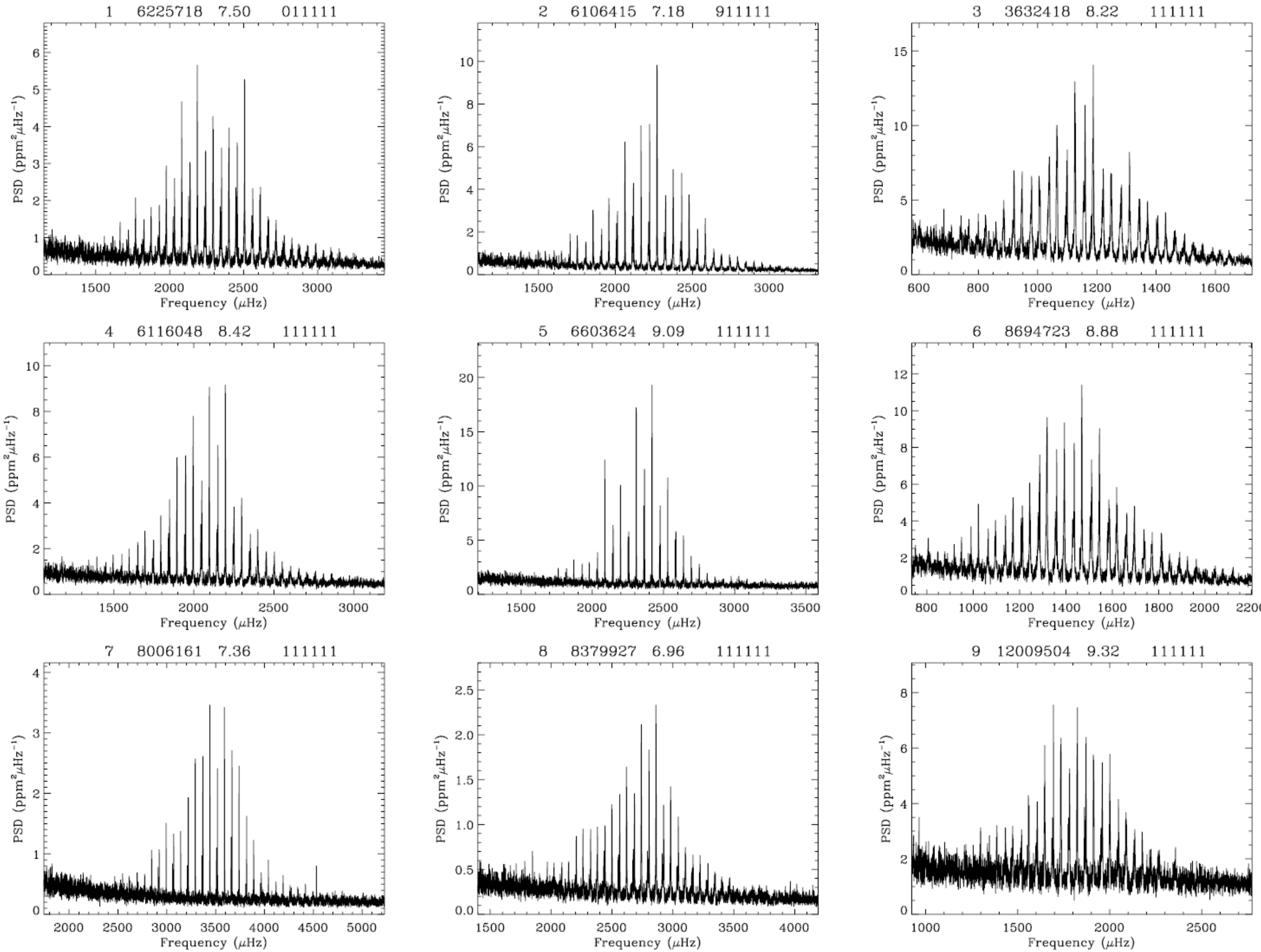
- Minutes/hours: Oscillations, Eruptions in active regions, granulation
- Days/months: Rotation, Spots, damping and excitation of oscillations
- Years: Activity cycles

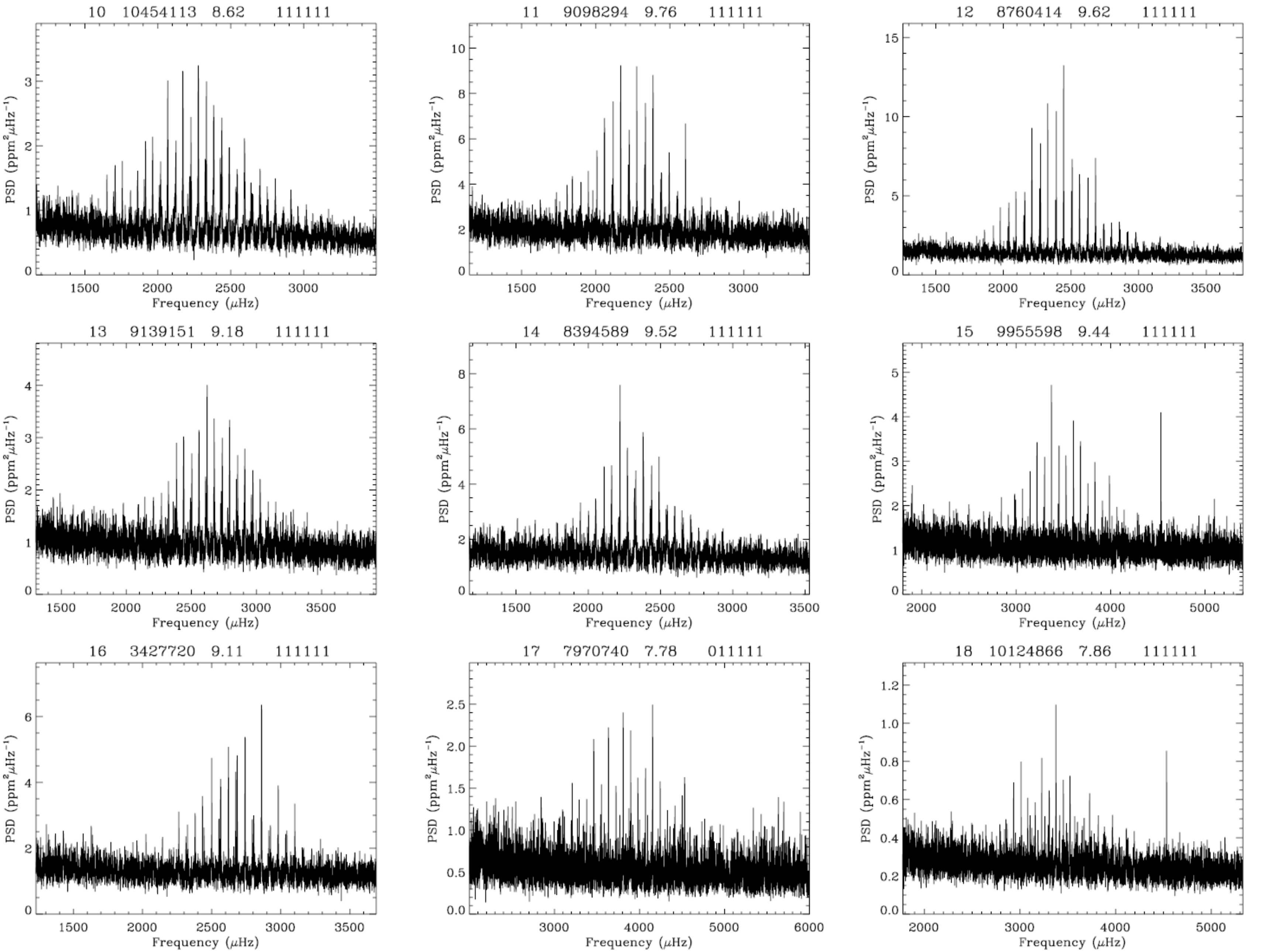
# Stellar Variability

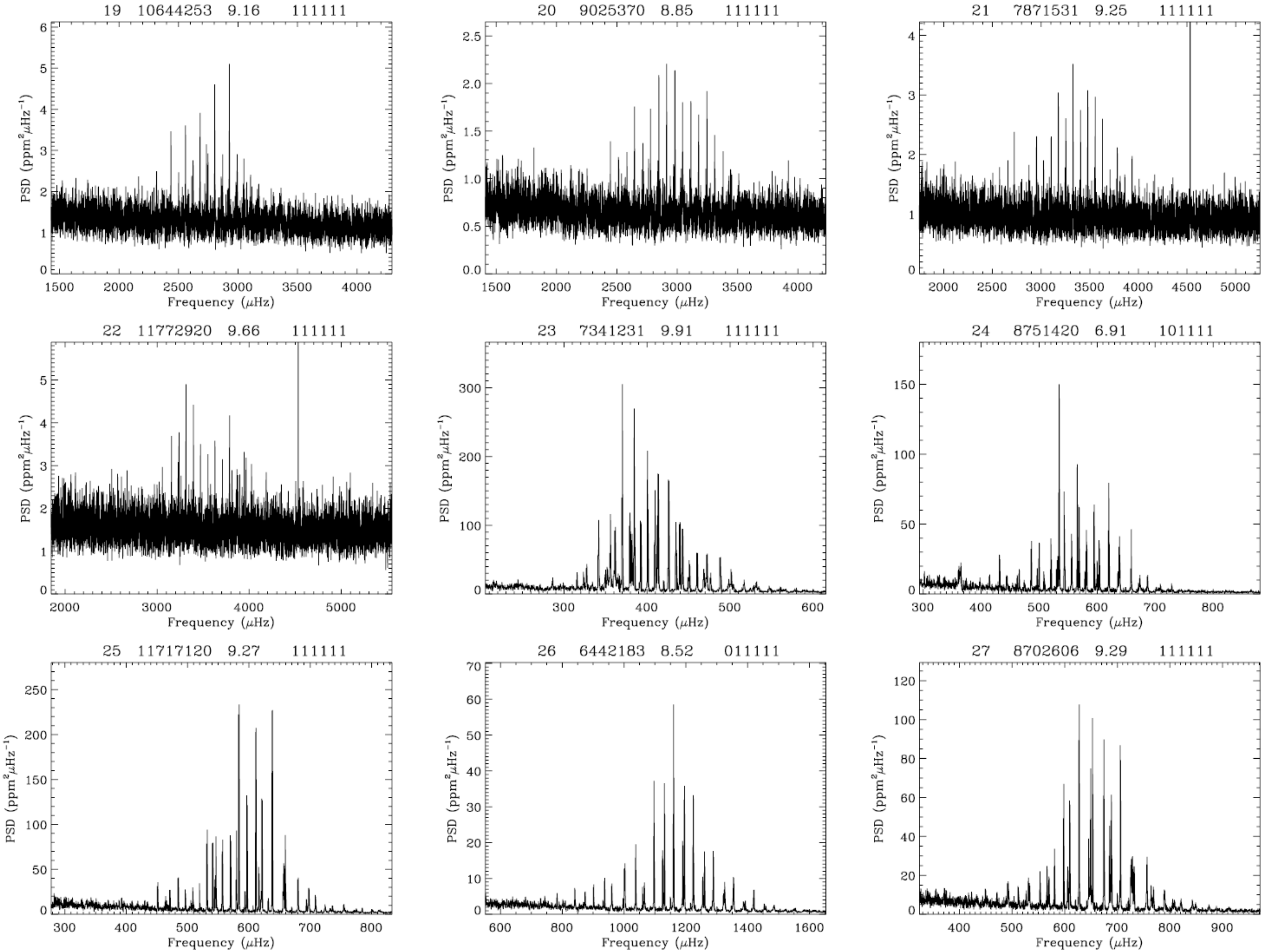
- Minutes/hours: Oscillations, Eruptions in active regions, granulation
- Days/months: Rotation, Spots, damping and excitation of oscillations
- Years: Activity cycles
- Millions and Billions of years: Structure and composition

Chaplin et al. 2011

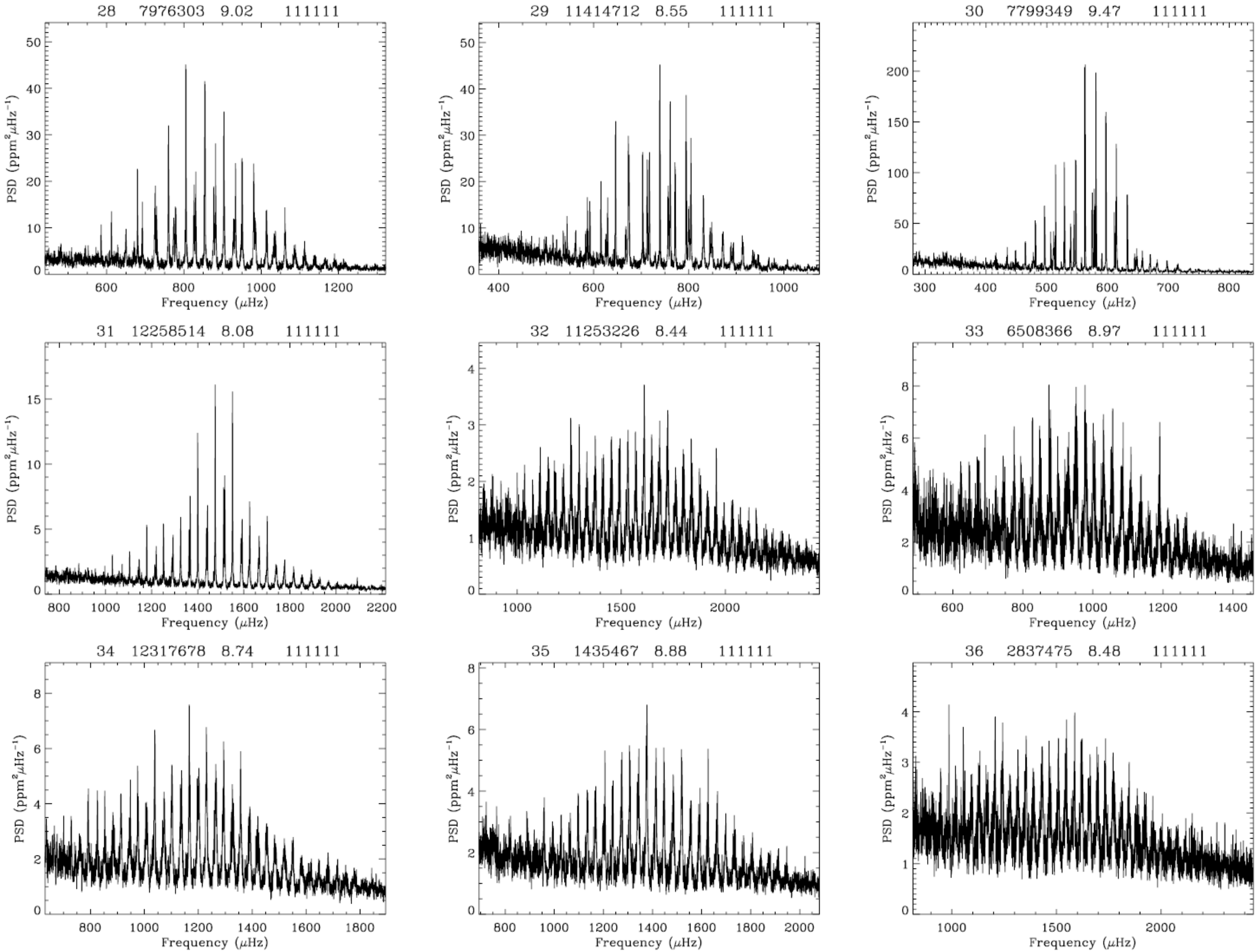



1 6225718 7.50 011111
2 6106415 7.18 911111
3 3632418 8.22 111111
4 6116048 8.42 111111
5 6603624 9.09 111111
6 8694723 8.88 111111
7 8006161 7.36 111111
8 8379927 6.96 111111
9 12009504 9.32 111111
PSD (ppm²μHz⁻¹)
Frequency (μHz)

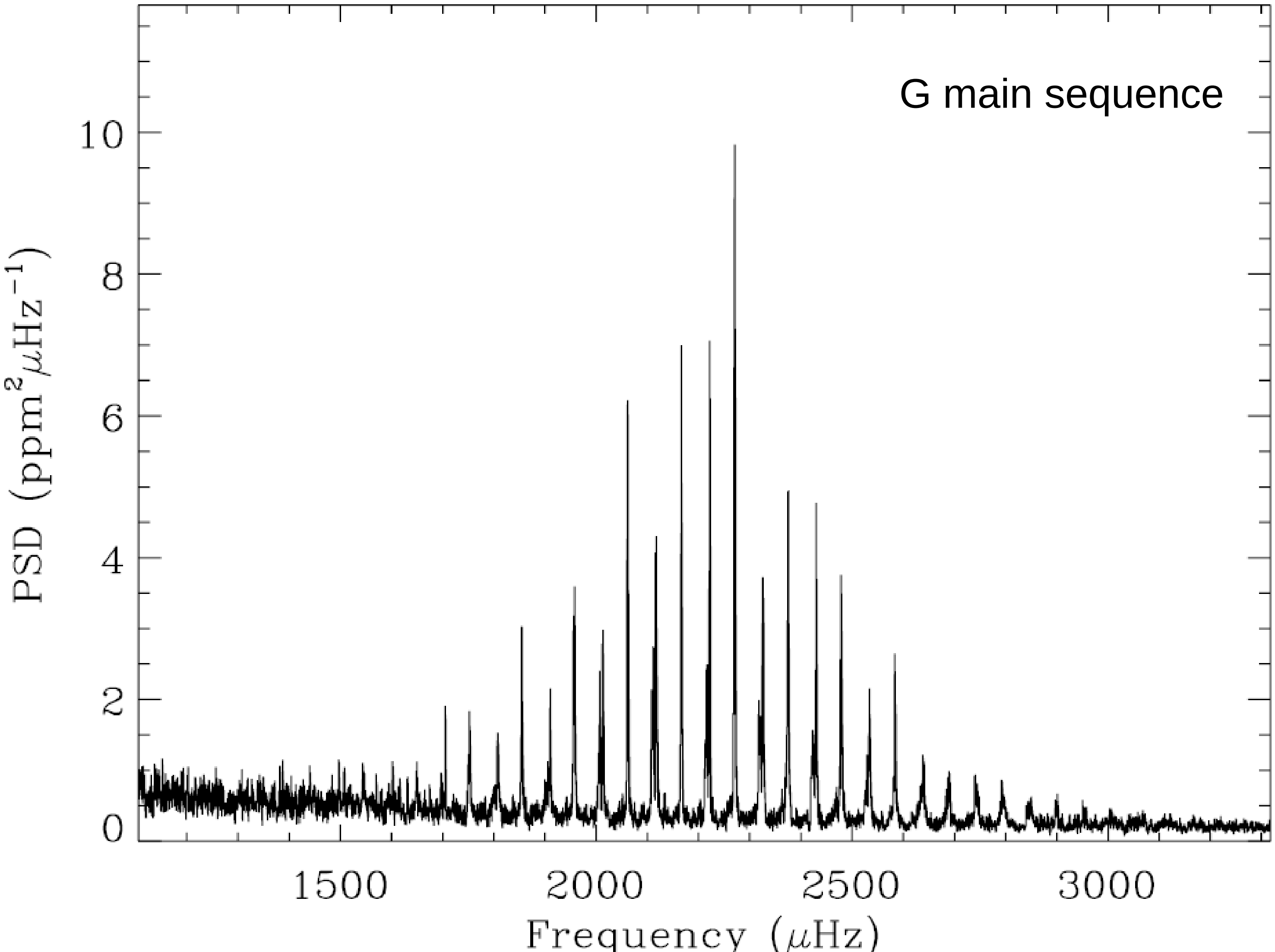

10 10454113 8.62 111111
11 9098294 9.76 111111
12 8760414 9.62 111111
13 9139151 9.18 111111
14 8394589 9.52 111111
15 9955598 9.44 111111
16 3427720 9.11 111111
17 7970740 7.78 011111
18 10124866 7.86 111111
PSD (ppm$^2\mu$Hz$^{-1}$)
Frequency ($\mu$Hz)



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 ($\mu$Hz)

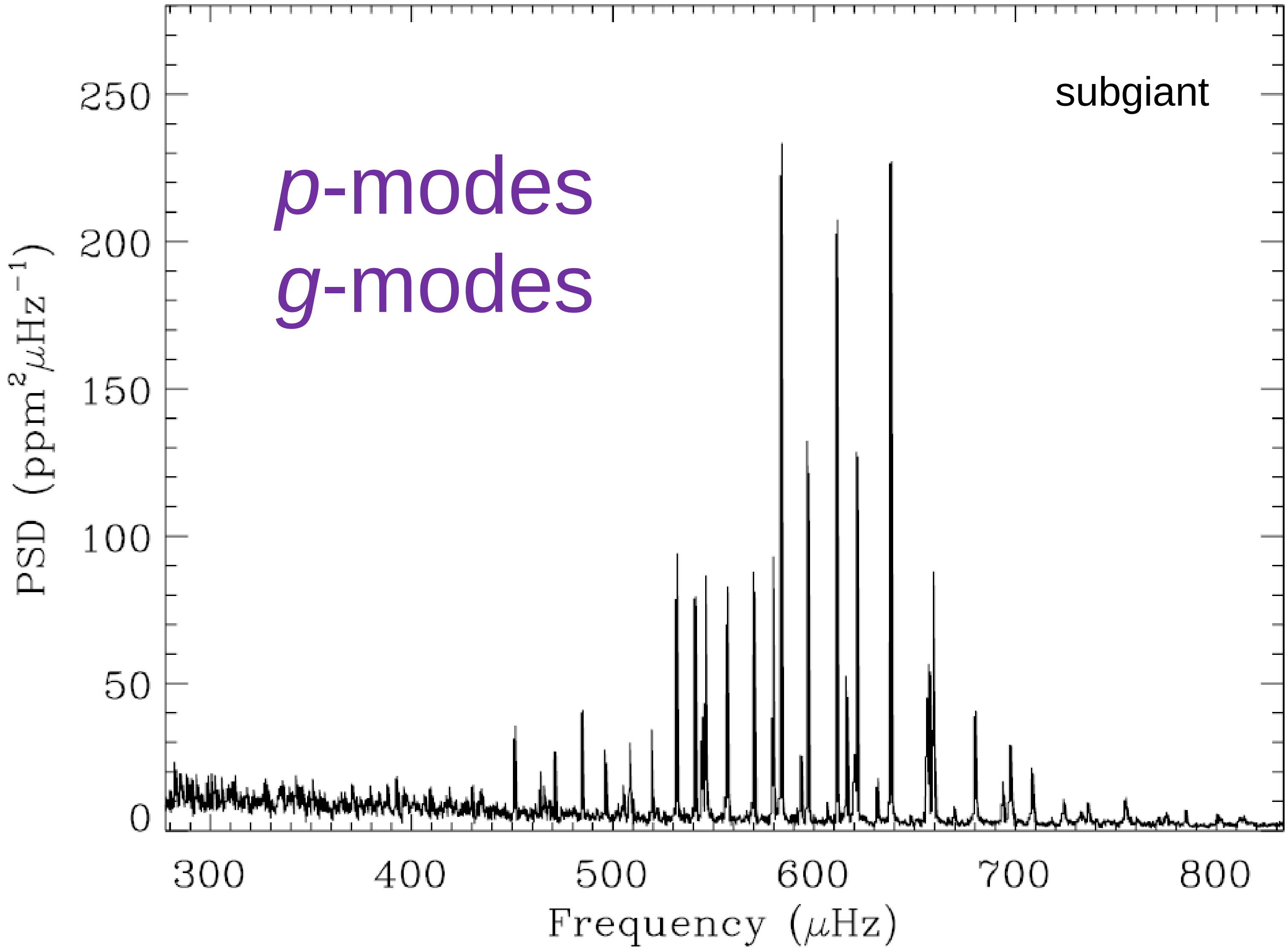

28 7976303 9.02 111111
29 11414712 8.55 111111
30 7799349 9.47 111111
31 12258514 8.08 111111
32 11253226 8.44 111111
33 6508366 8.97 111111
34 12317678 8.74 111111
35 1435467 8.88 111111
36 2837475 8.48 111111
PSD (ppm$^2\mu$Hz$^{-1}$)
Frequency ($\mu$Hz)

# 450 d, mag: 7.18




**Kepler**

# 540 d, mag: 9.27




**Kepler**

# Stellar evolution

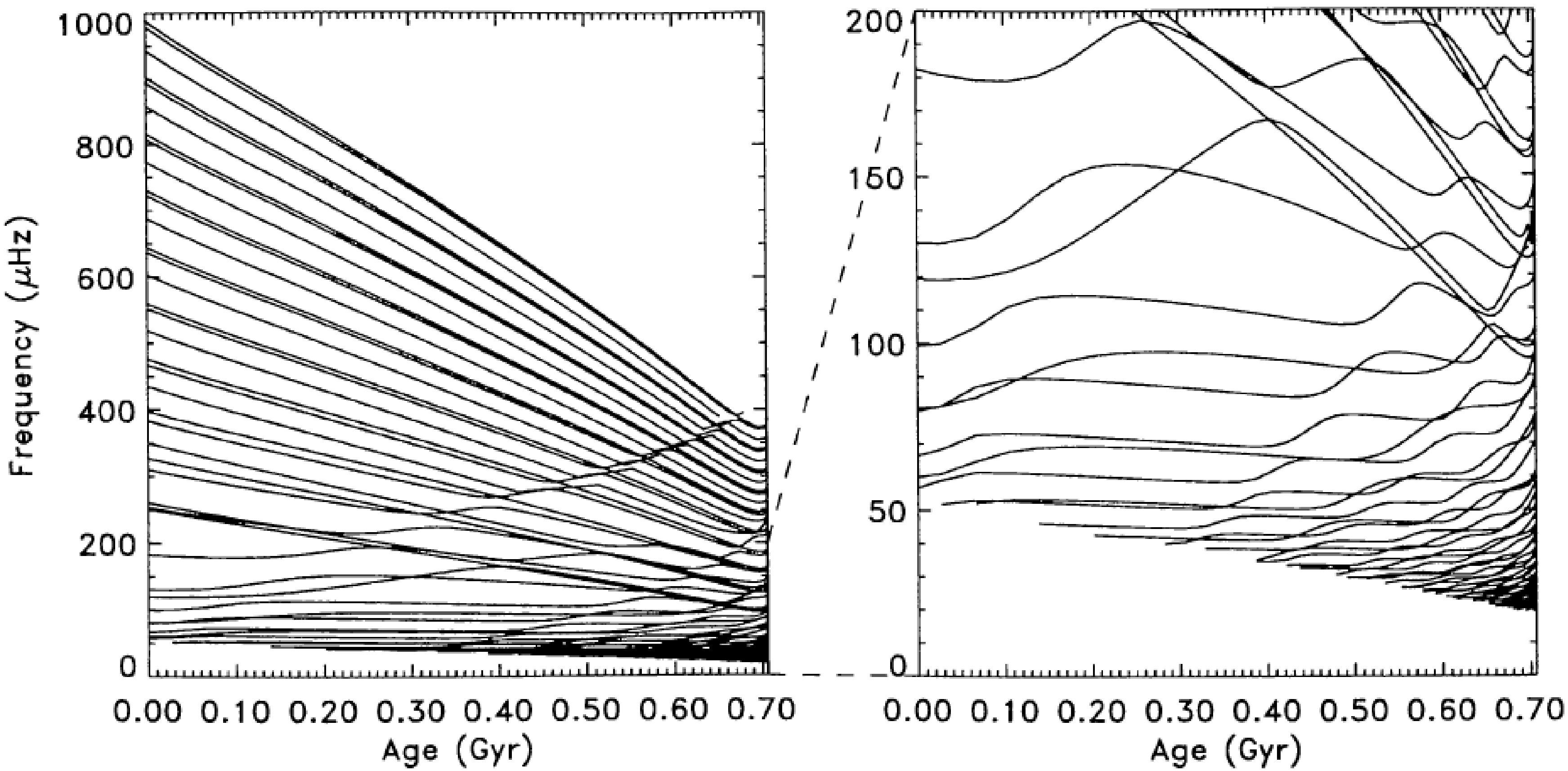
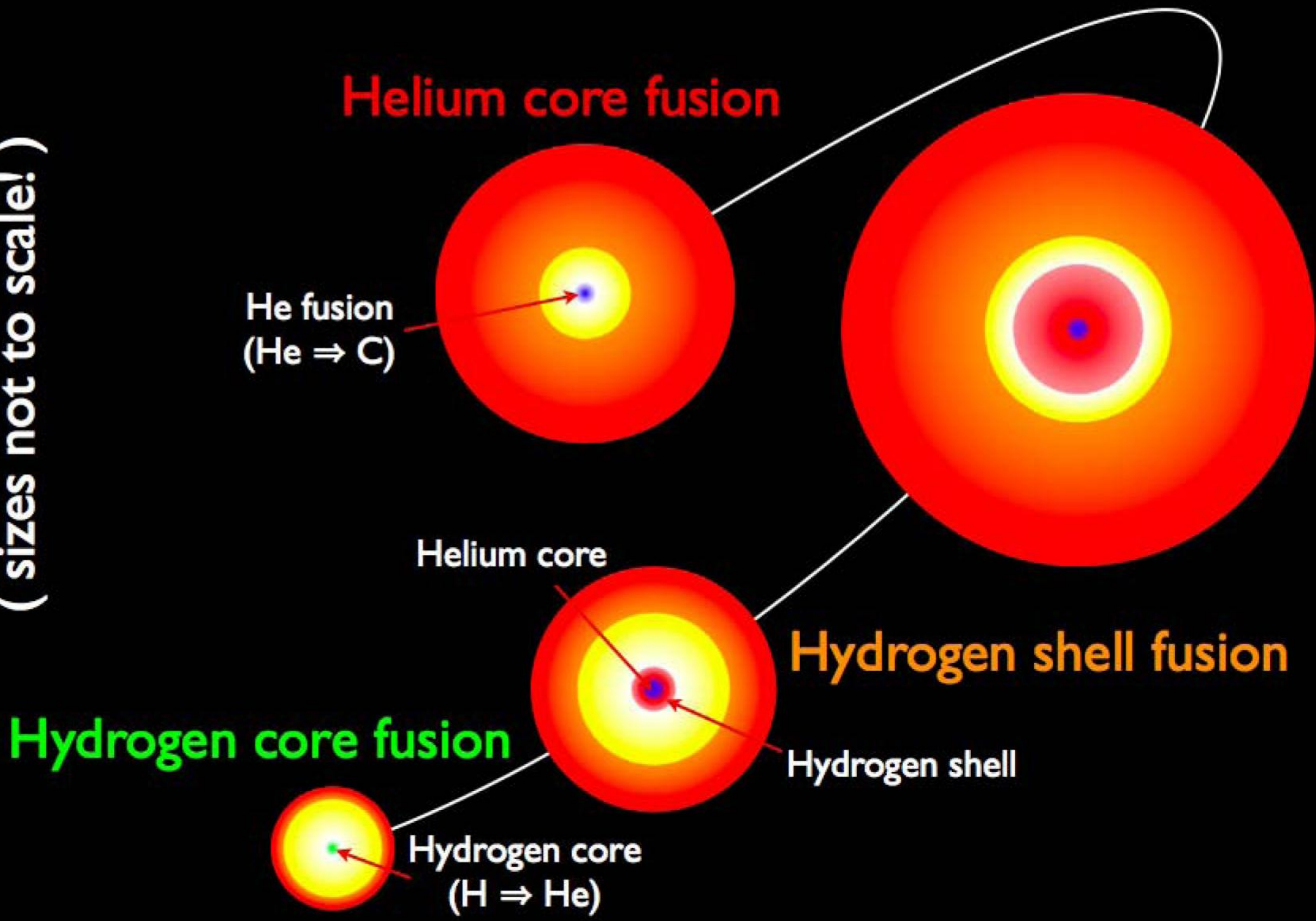
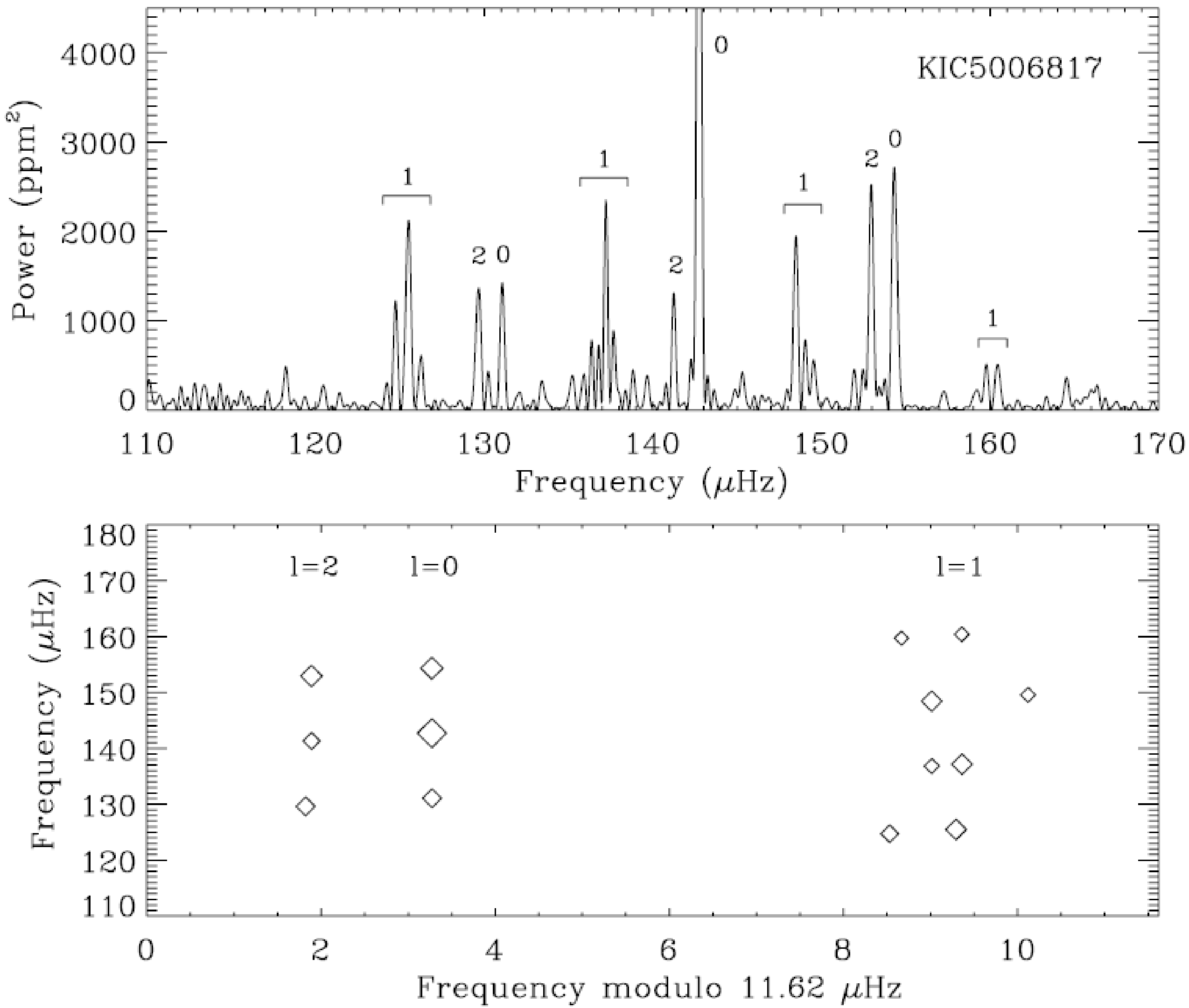



*Figure 1.* Evolution of oscillation frequencies in a $2.2\,M_\odot$ star, from model calculations by J. Christensen-Dalsgaard. Only modes with $\ell = 0, 1, 2$ and $n \leq 10$ are shown.

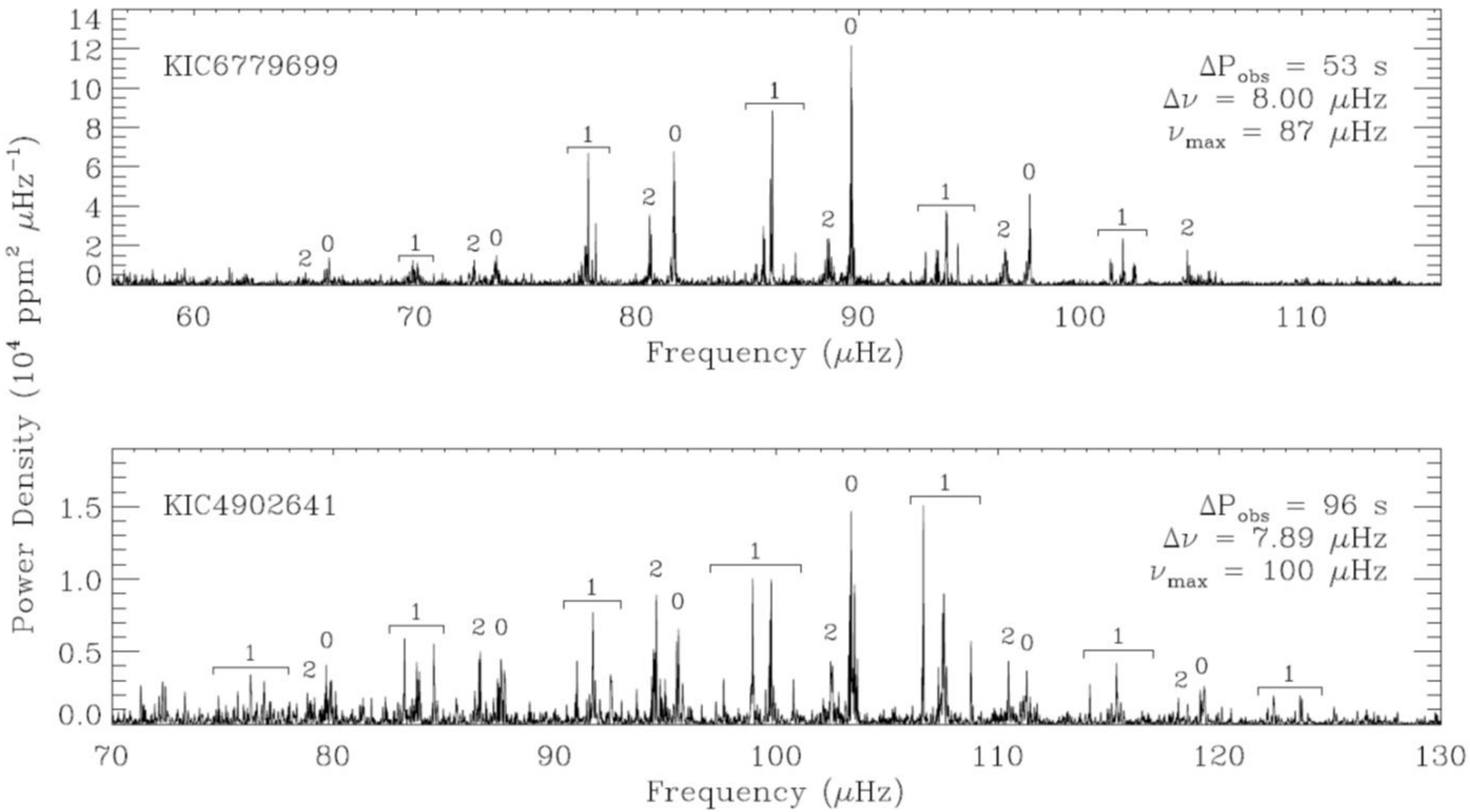
# Stellar evolution



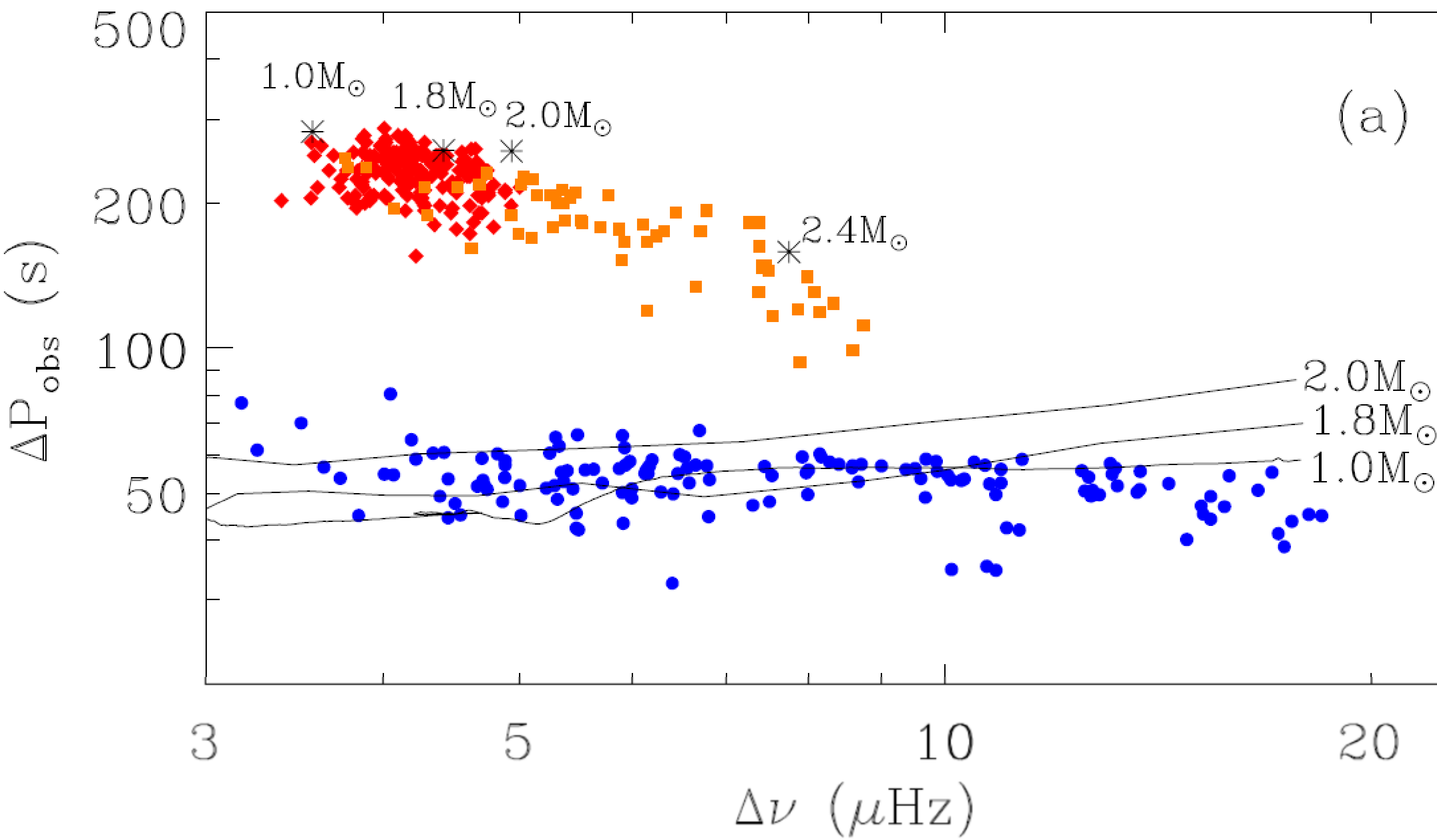

( sizes not to scale! )



KIC5006817
Power (ppm$^2$)
Frequency ($\mu$Hz)
l=2
l=0
l=1
Frequency modulo 11.62 $\mu$Hz




T. Bedding et al.: Distinguishing between hydrogen- and helium-burning red giant stars with asteroseismology using gravity-mode period spacings

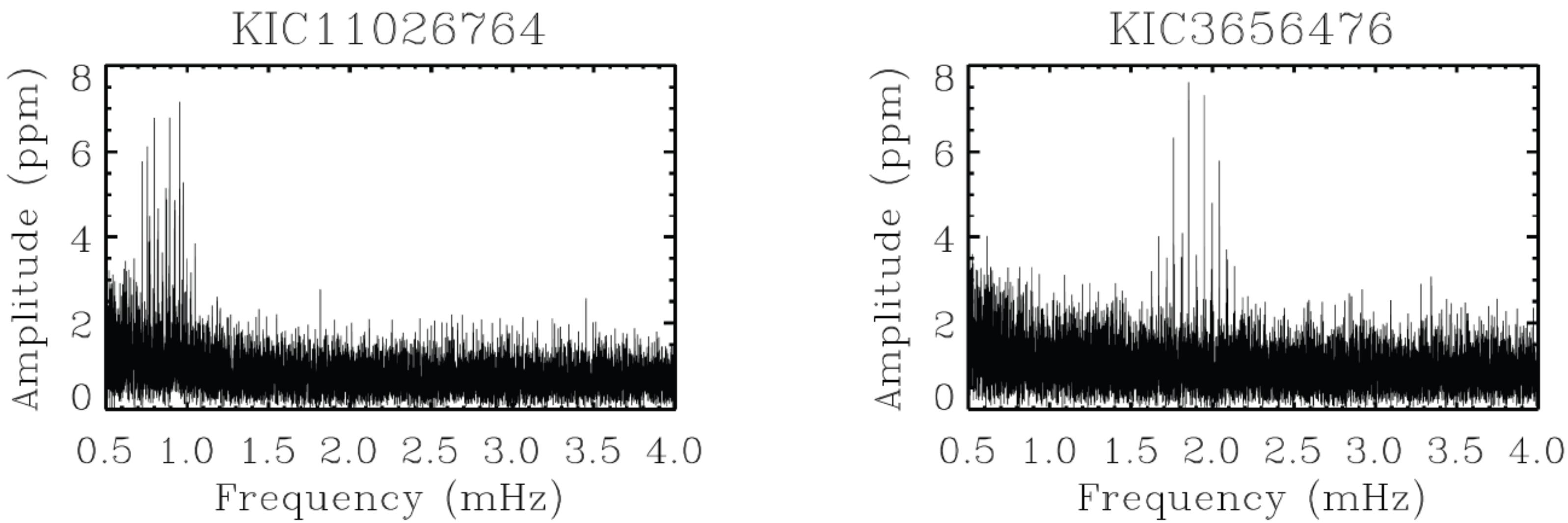

500
200
100
50
3
5
10
20
ΔP_obs (s)
Δν (μHz)
(a)
1.0M⊙
1.8M⊙
2.0M⊙
2.4M⊙
2.0M⊙
1.8M⊙
1.0M⊙

# 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, …)

# Requirements for Observational Asteroseismology:

## High-precision time series photometry with high duty cycle




$$data(t) = noise(t) + \sum_{i=1}^{n} a_i \cdot \sin(2\pi \cdot f_i \cdot t - \phi_i)$$

Following Montgomery and D. O'Donoghue, 1999

$$\sigma(a) = \sqrt{\frac{2}{\pi}} \left\langle A_{Noise}(\nu) \right\rangle = \sqrt{\frac{\left\langle P_{Noise}(\nu) \right\rangle}{2}} \approx 0.80 \cdot \left\langle A_{Noise}(\nu) \right\rangle$$

$$\sigma(\phi) = \frac{\sigma(a)}{a}$$

$$\sigma(f) = \sqrt{\frac{3}{\pi^2}} \frac{1}{T} \cdot \sigma(\phi)$$

$$\sigma(f) = \frac{\sqrt{3}}{\pi \cdot T} \frac{\sigma(a)}{a} = \sqrt{\frac{6}{\pi^3}} \frac{\left\langle A_{Noise}(\nu) \right\rangle}{a \cdot T} \approx 0.44 \cdot \frac{\left\langle A_{Noise}(\nu) \right\rangle}{a \cdot T}$$

$$\left\langle A_{Noise}(\nu) \right\rangle = \sqrt{\frac{\pi}{N}} \cdot \sigma_{Noise} \propto T^{-1/2}$$

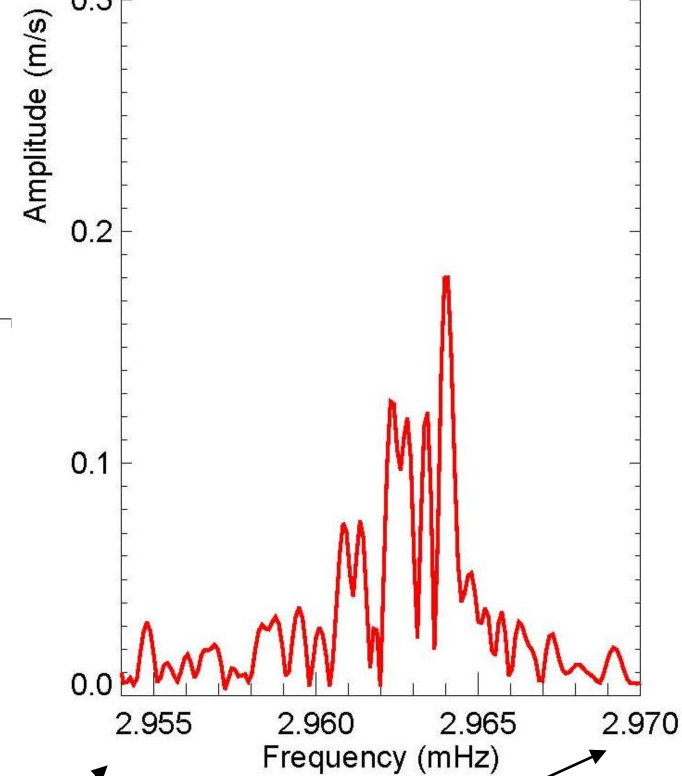
Following Montgomery and D. O’Donoghue, 1999

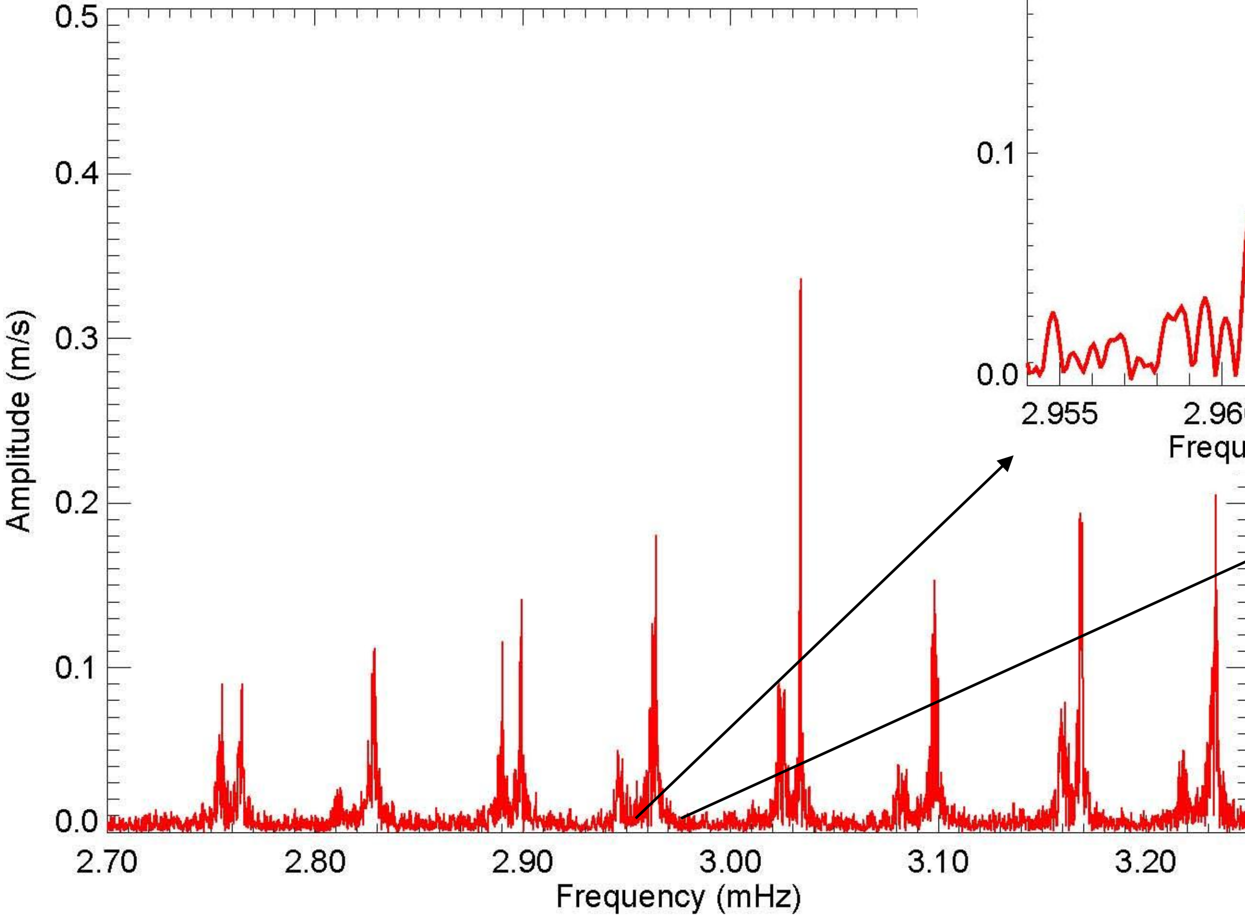
$$\sigma(a) \propto \sigma_{Noise} \cdot T^{-1/2}$$

$$\sigma(\phi) \propto \sigma_{Noise} \cdot a^{-1} \cdot T^{-1/2}$$

$$\sigma(f) \propto \sigma_{Noise} \cdot a^{-1} \cdot T^{-3/2}$$

p-mode oscillations:
Mode life-time (Damping)



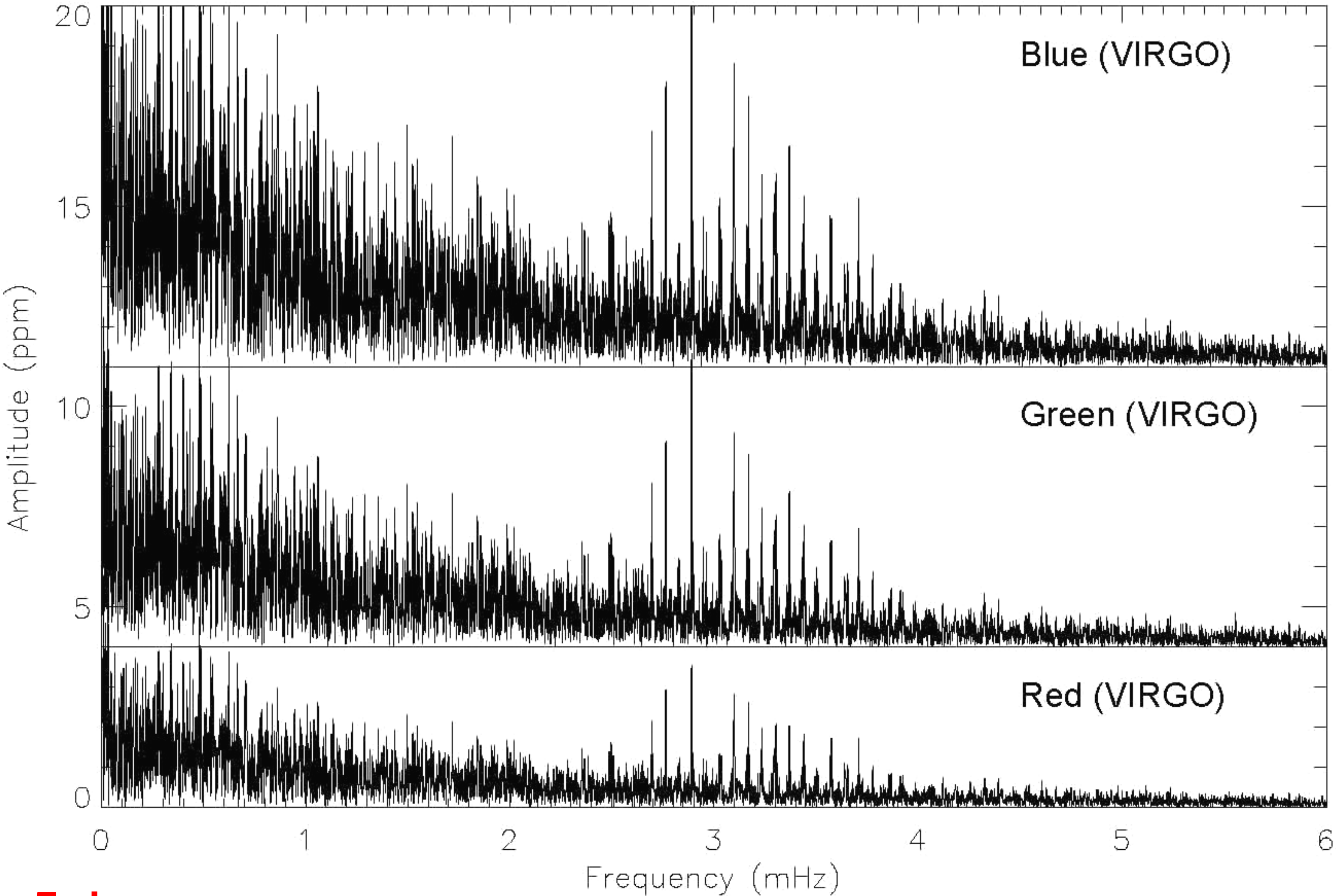



## Coherent modes

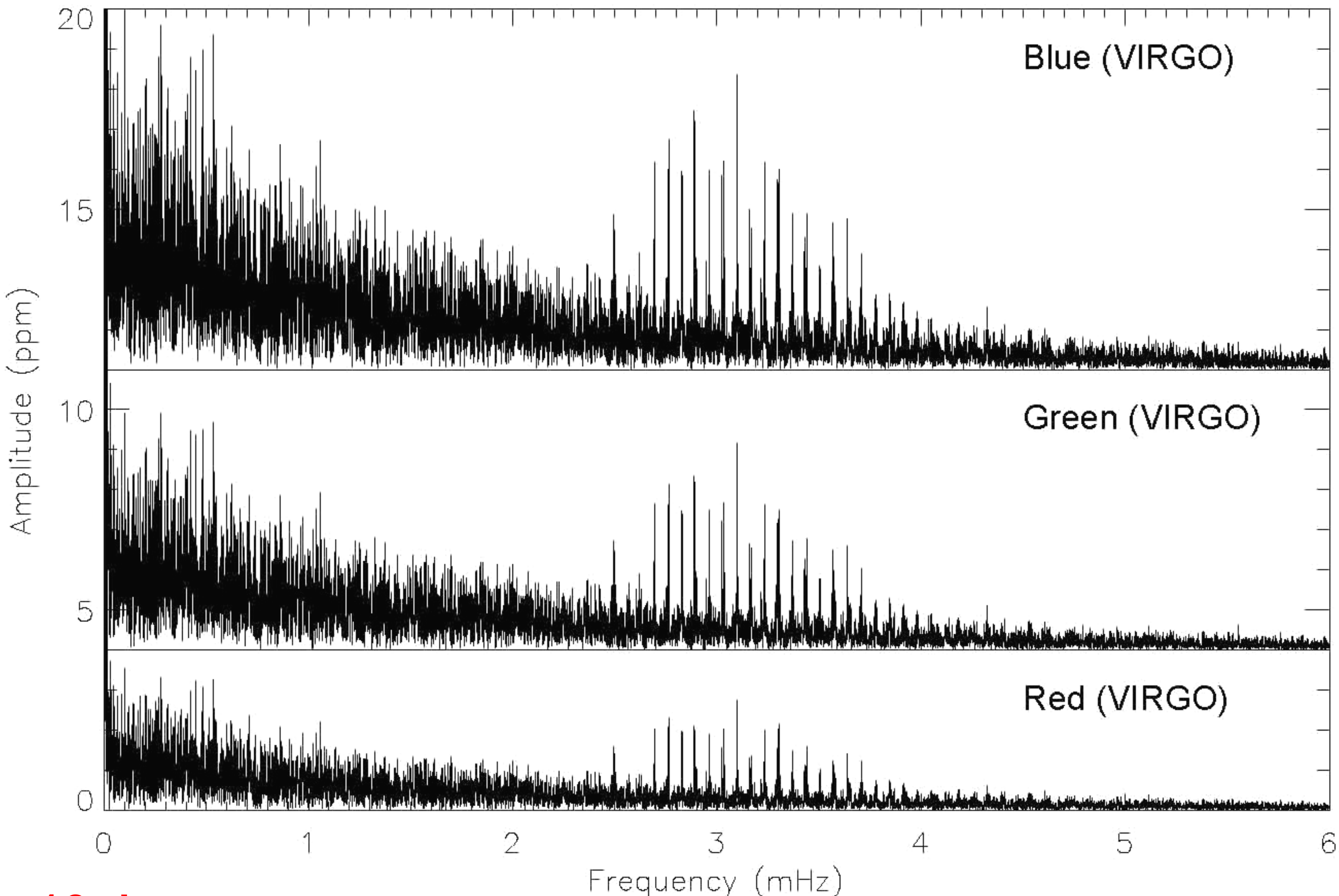
$$\sigma(f) \propto \frac{\sigma_{Noise}}{T^{3/2}}$$

## Damped and re-excited modes

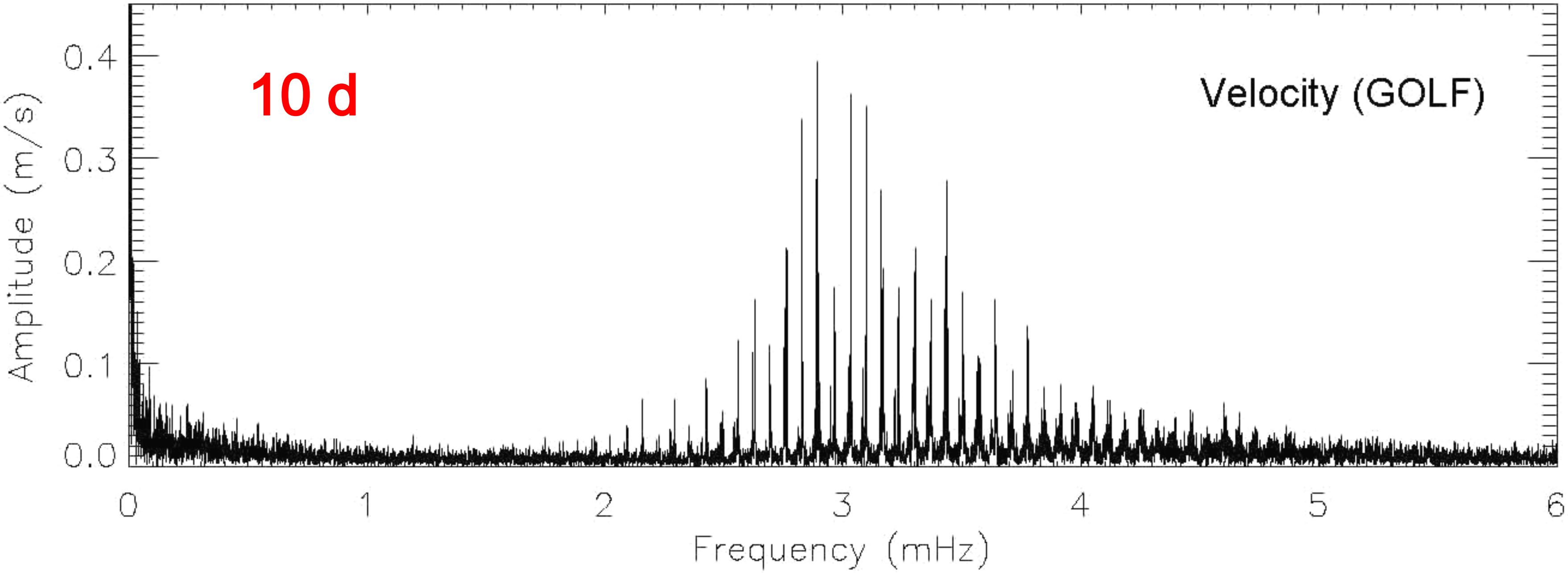
$$\sigma(f) \propto \frac{\sigma_{Noise}}{T^{1/2}}$$


Blue (VIRGO)
Green (VIRGO)
Red (VIRGO)
Amplitude (ppm)
20
15
10
5
0
0
1
2
3
4
5
6
Frequency (mHz)

5 d


Blue (VIRGO)
Green (VIRGO)
Red (VIRGO)
Amplitude (ppm)
Frequency (mHz)
20
15
10
5
0
0
1
2
3
4
5
6

10 d

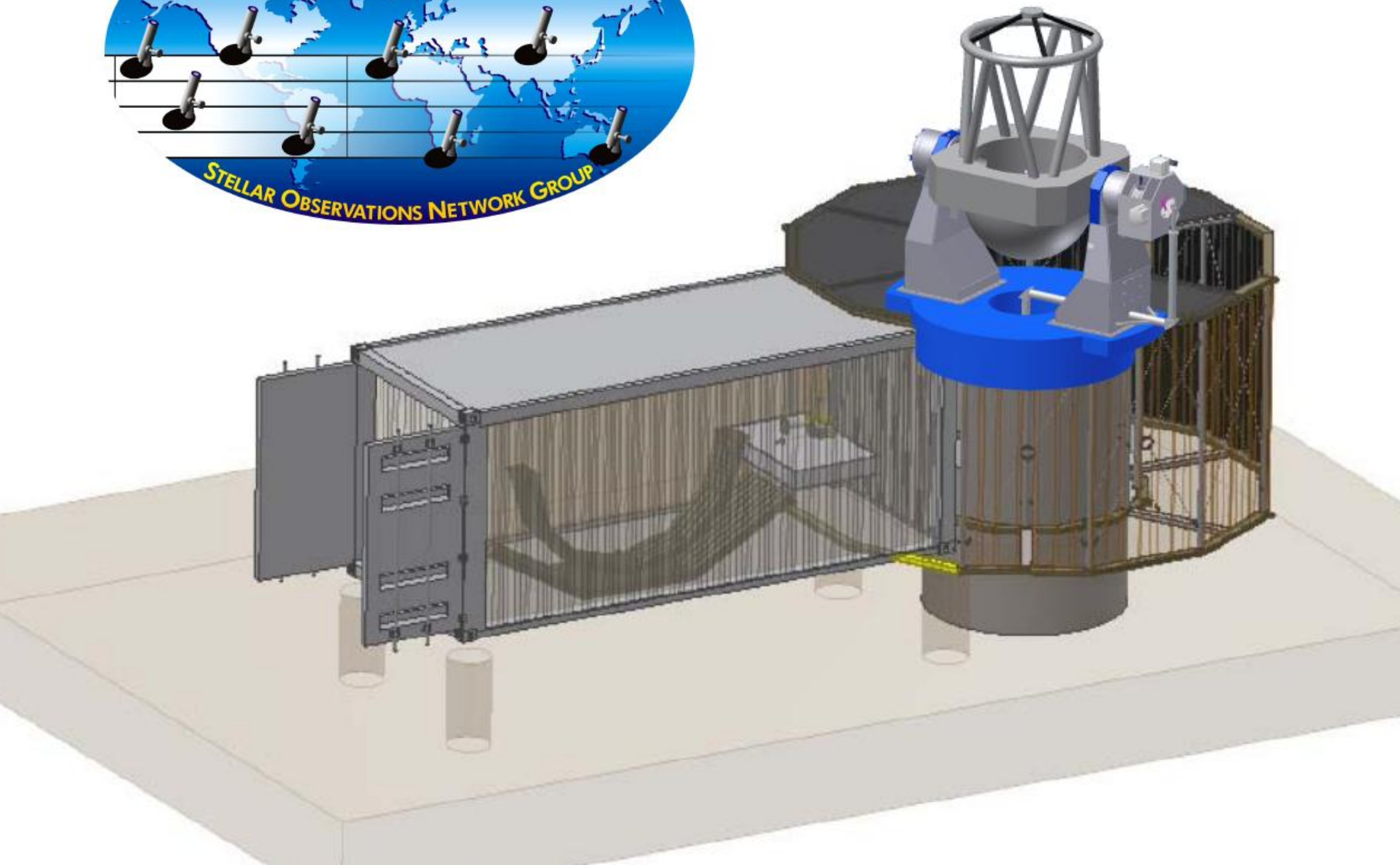



$$\sigma(a) \propto \sigma_{Noise} \cdot T^{-1/2}$$

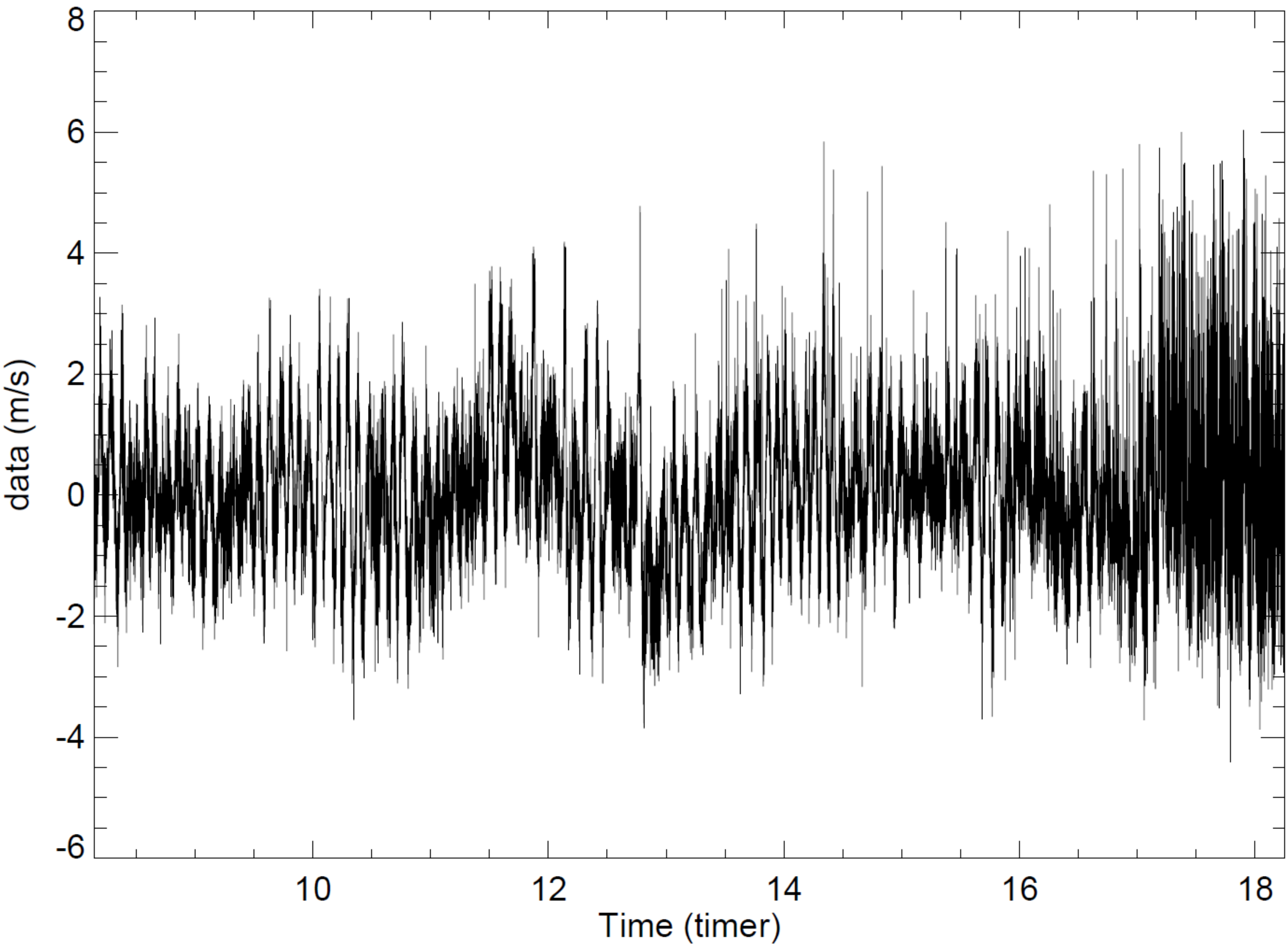
$$\sigma(f) \propto \sigma_{Noise} \cdot a^{-1} \cdot T^{-1/2}$$

SONG

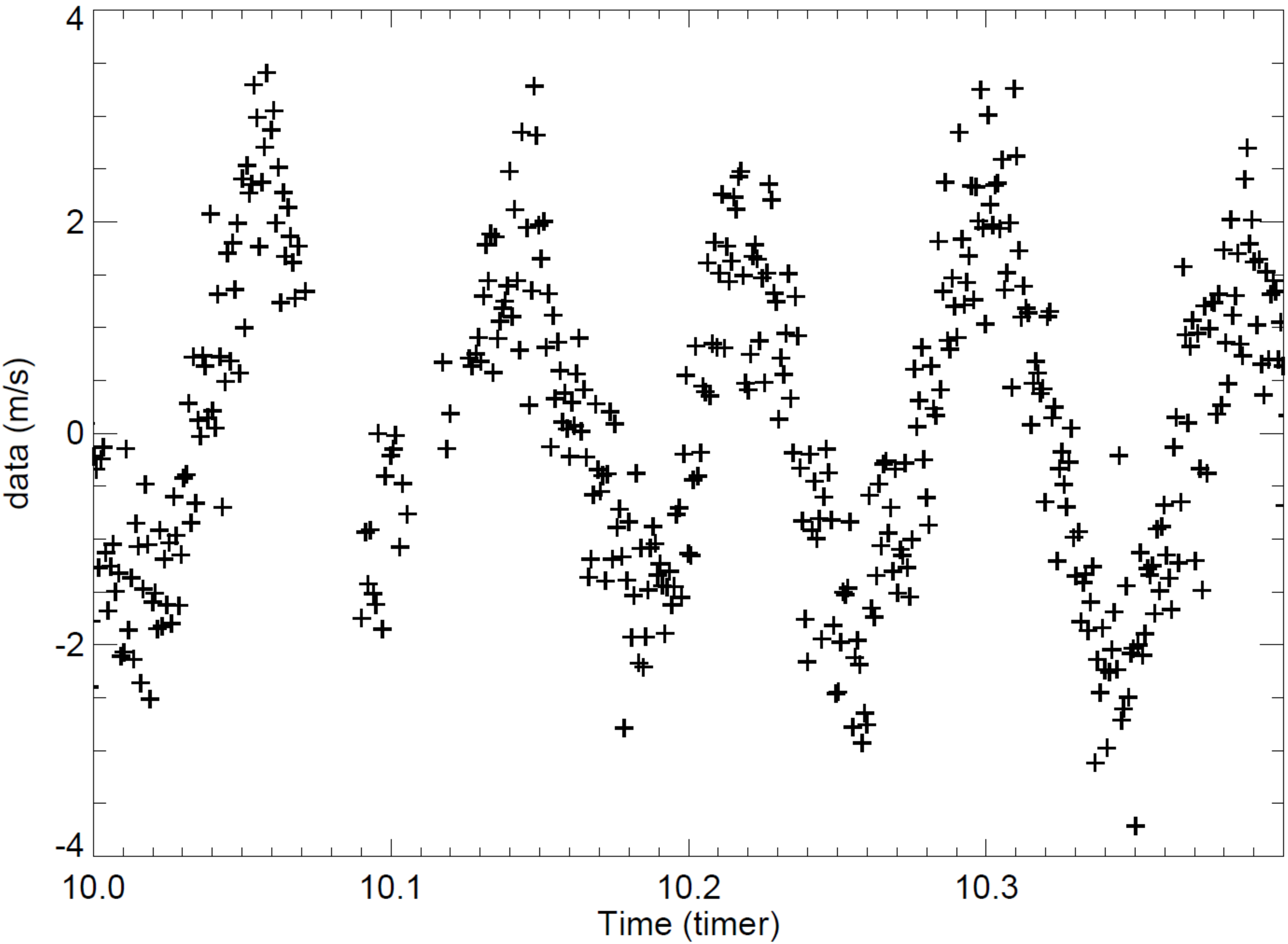
STELLAR OBSERVATIONS NETWORK GROUP



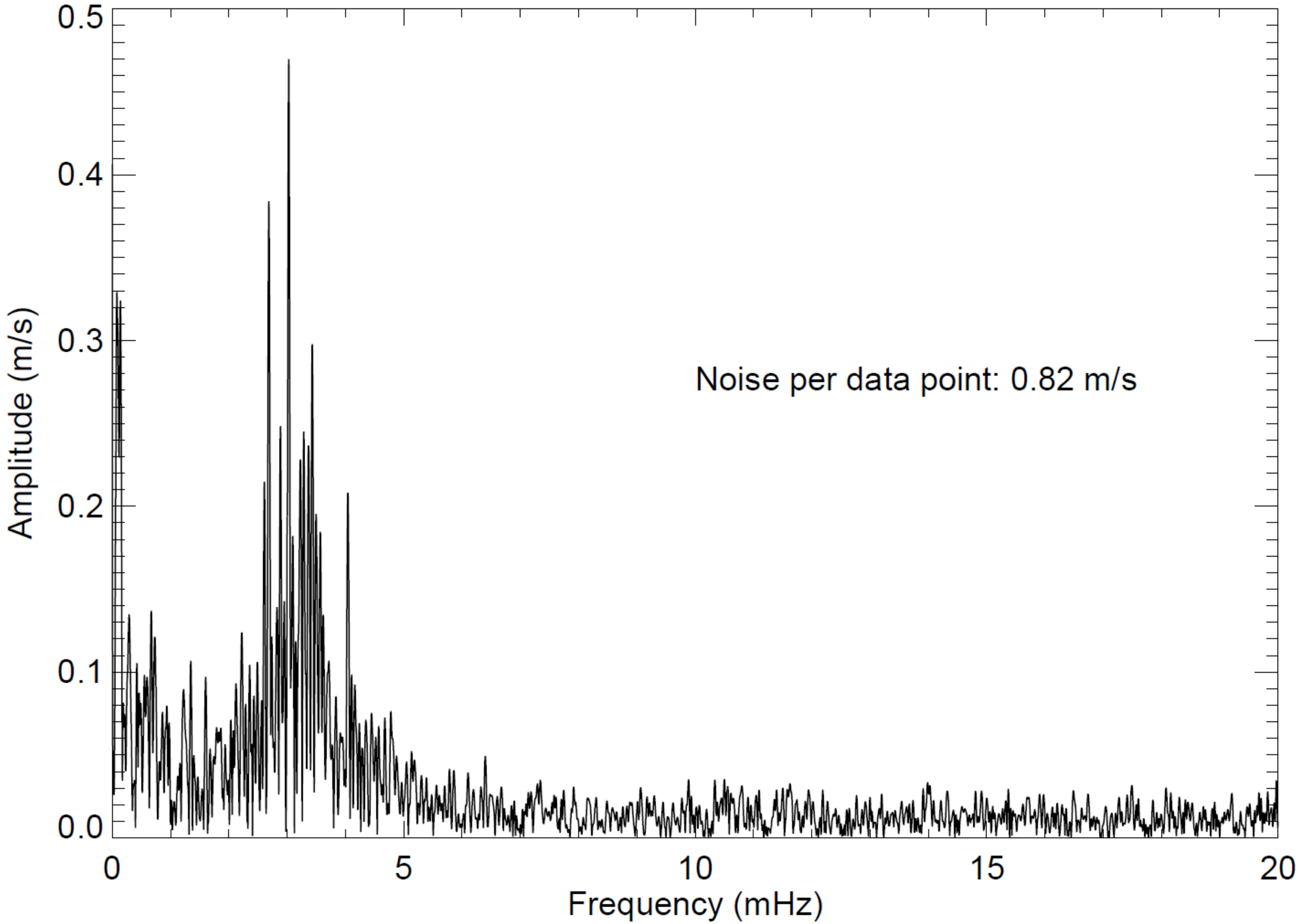

TRIAD TECHNOLOGY
TT-I-50x100-Q-AR



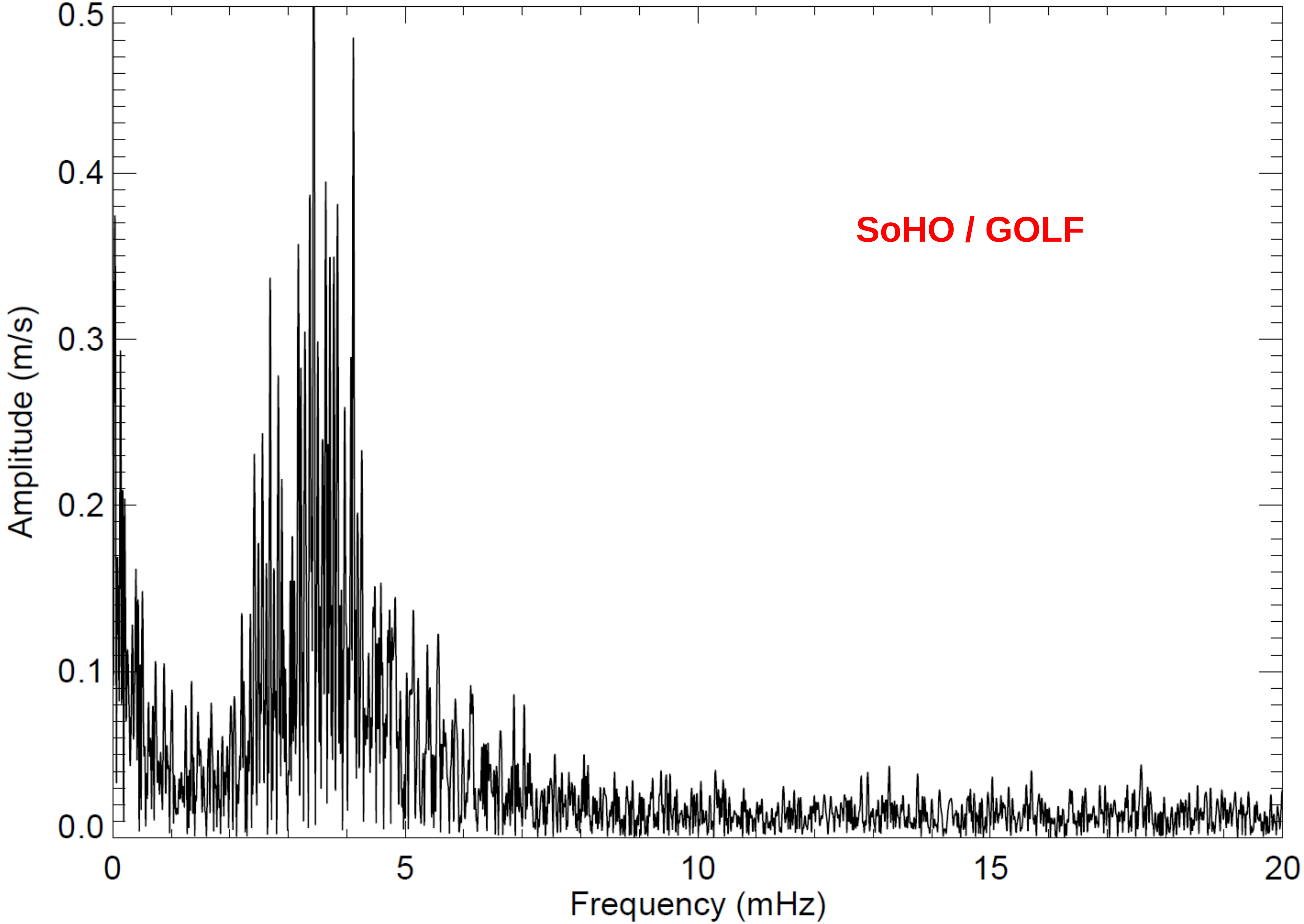
8
6
4
2
0
-2
-4
-6
data (m/s)
10
12
14
16
18
Time (timer)



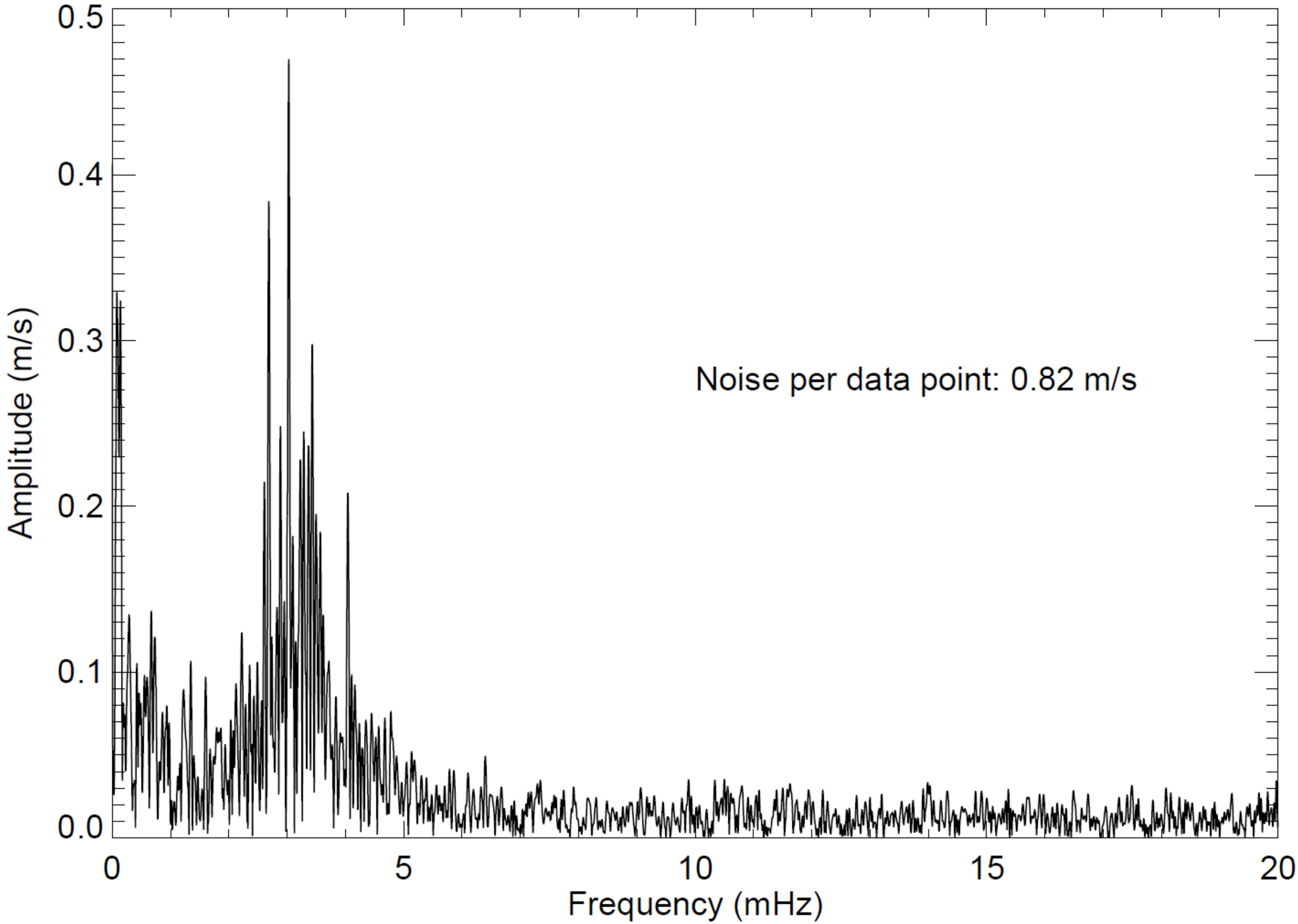
4
2
0
-2
-4
data (m/s)
10.0
10.1
10.2
10.3
Time (timer)



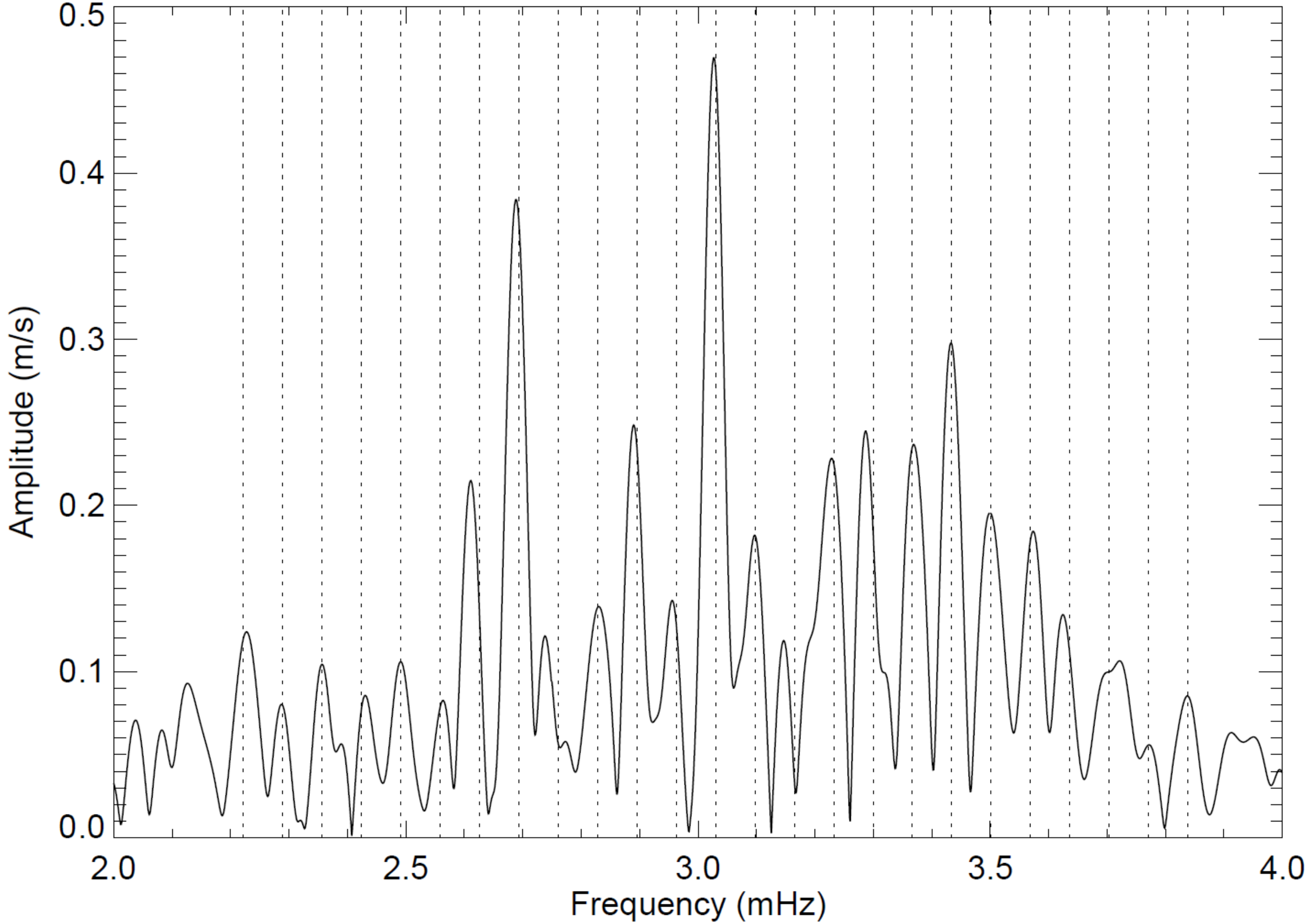
0.5
0.4
0.3
0.2
0.1
0.0
Amplitude (m/s)
Noise per data point: 0.82 m/s
0
5
10
15
20
Frequency (mHz)



SoHO / GOLF
Amplitude (m/s)
Frequency (mHz)
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20

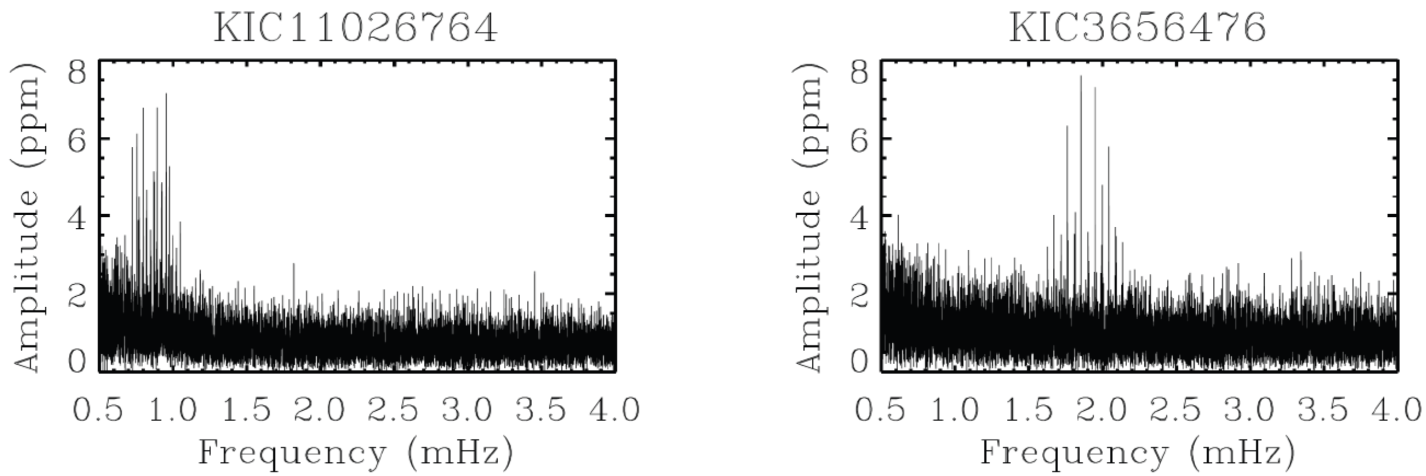


Amplitude (m/s)
0.5
0.4
0.3
0.2
0.1
0.0
Noise per data point: 0.82 m/s
0
5
10
15
20
Frequency (mHz)



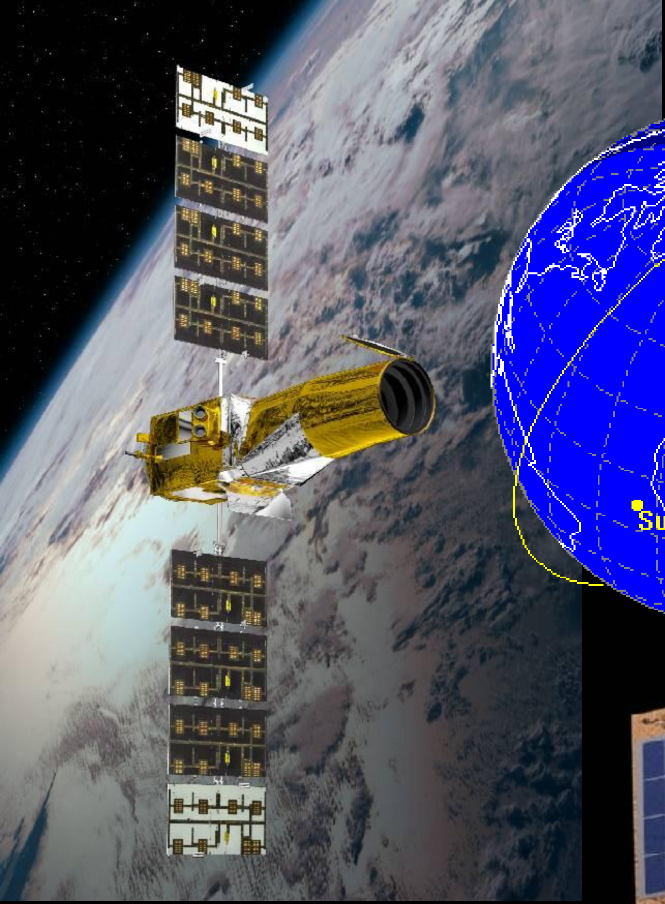
0.5
0.4
0.3
0.2
0.1
0.0
Amplitude (m/s)
2.0
2.5
3.0
3.5
4.0
Frequency (mHz)

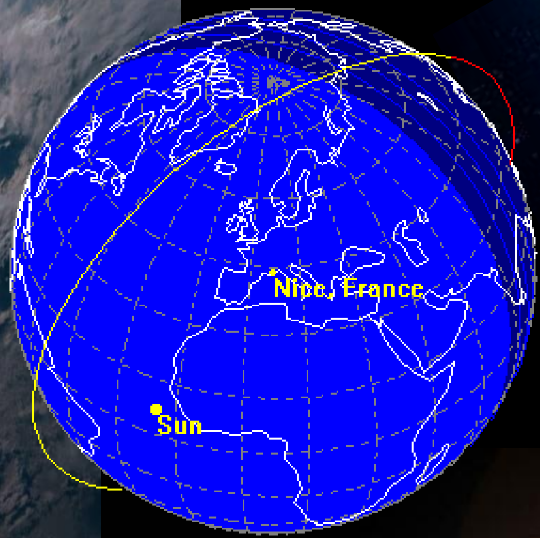
## Requirements:
## High-precision time series photometry with high duty cycle

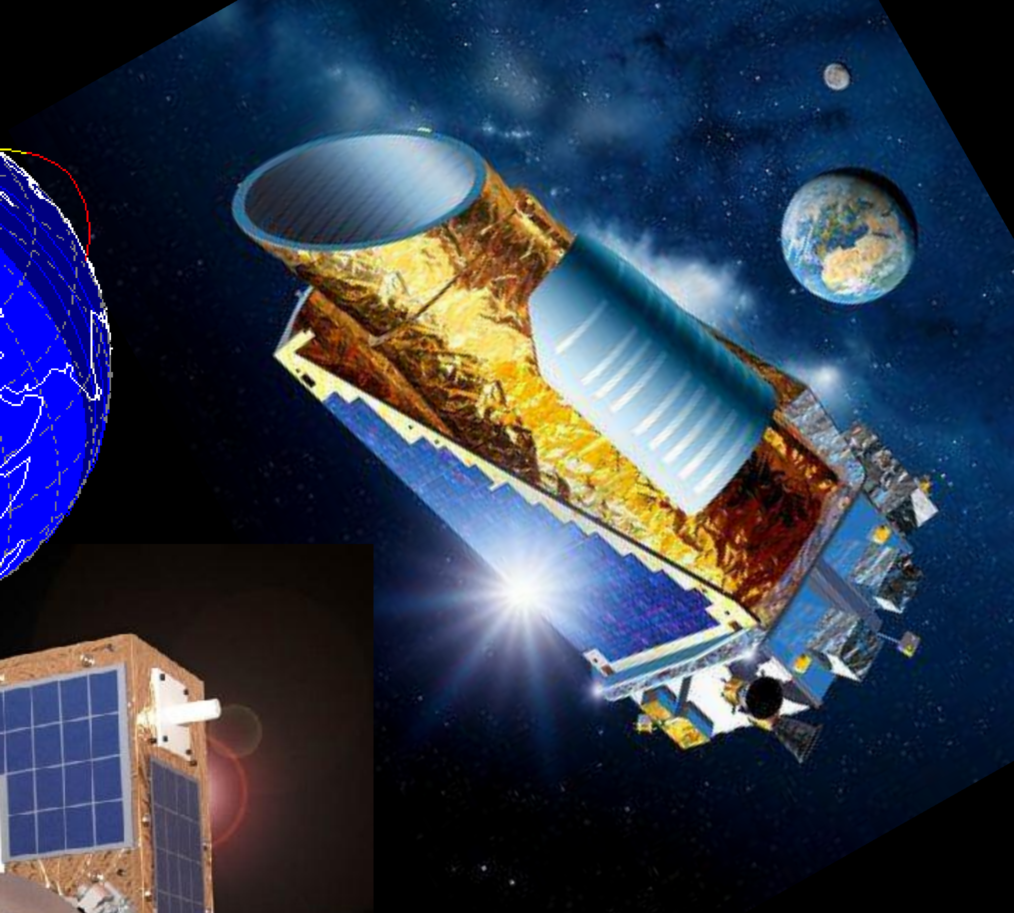



## Space:

- High Photometric Precision due to no atmospheric effects (scintillation)
- Long uninterrupted time series (high duty cycle, extended observation)
- Large number of targets observed (large FOV, high density of stars)





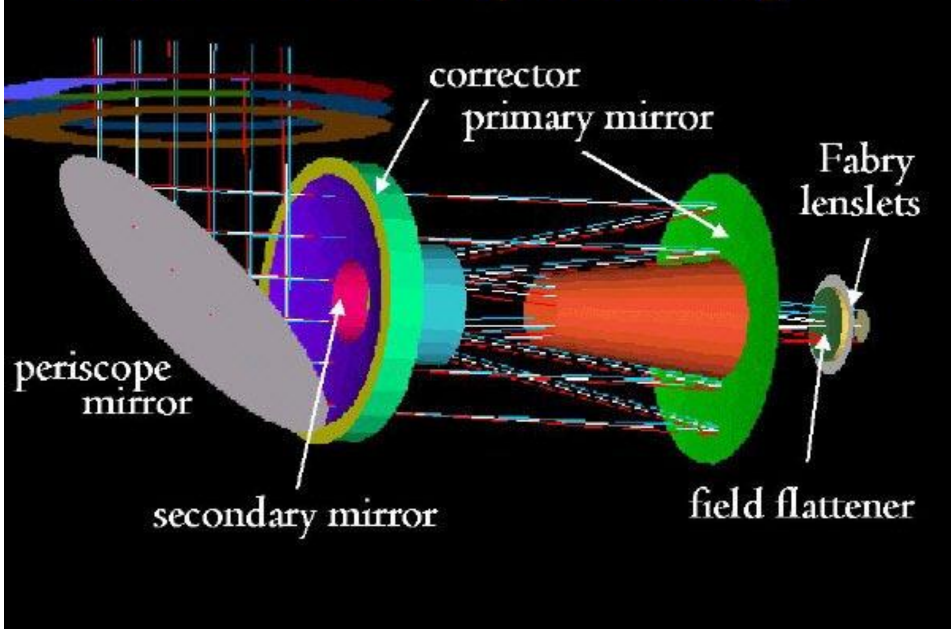
CoRoT and MOST
Low Earth Orbit (LEO)

Several pointings

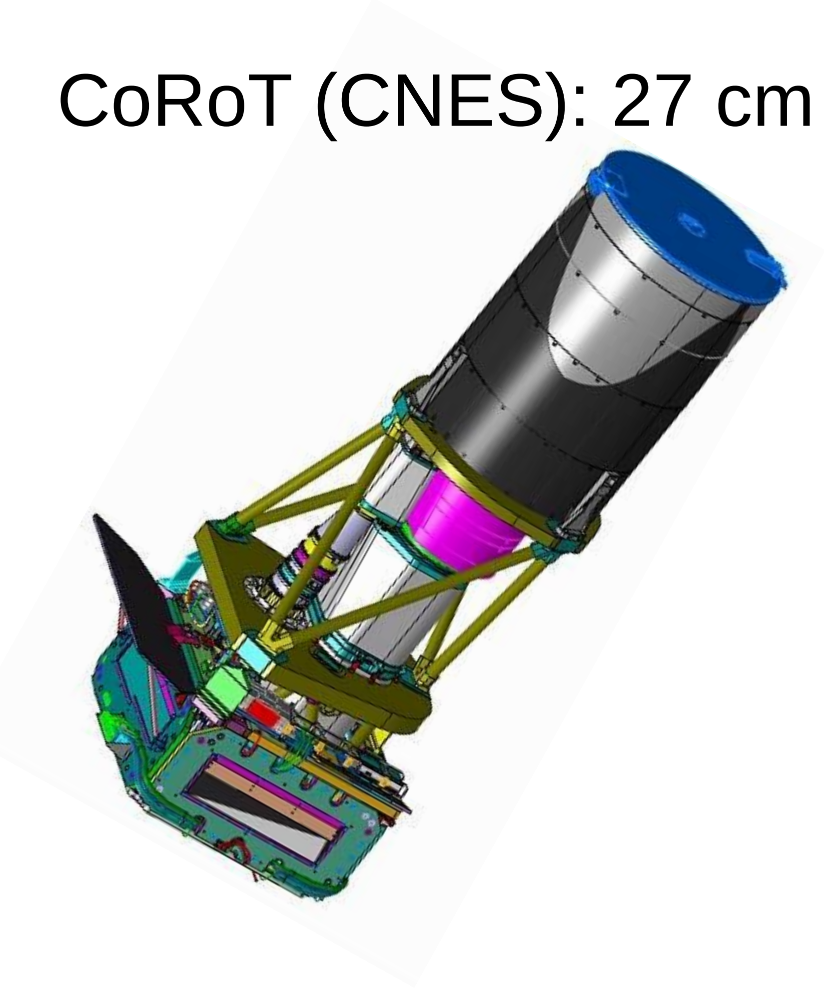
Kepler Orbit
Earth trailing Heliocentric

One FOV for whole mission

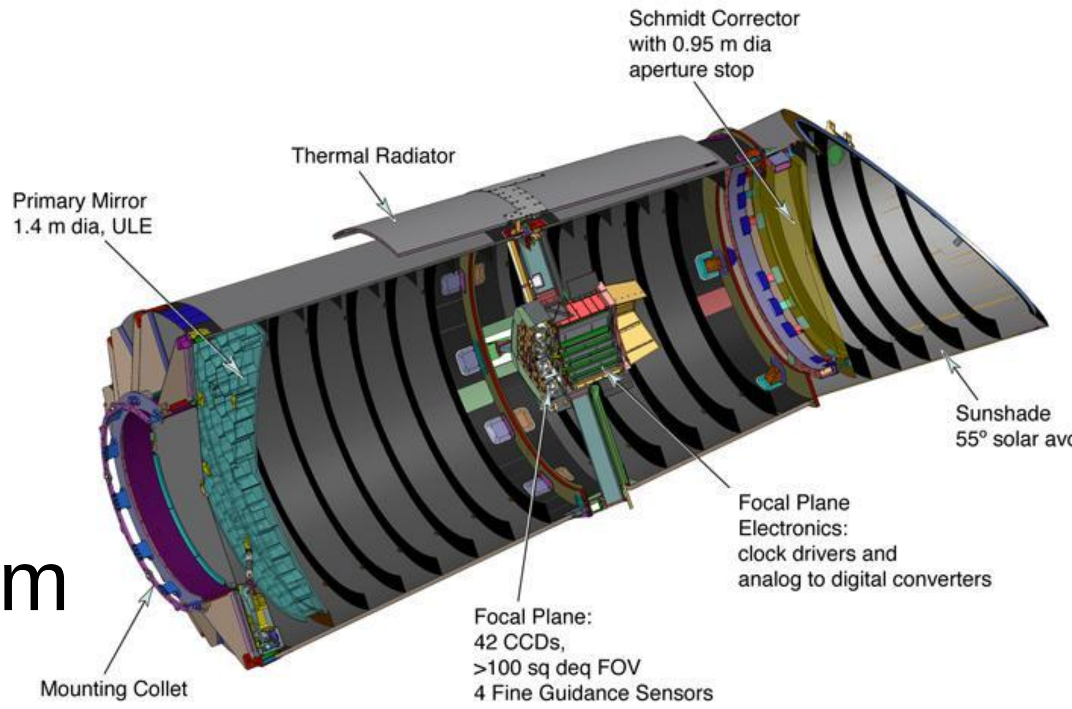
MOST (CSA): 15 cm



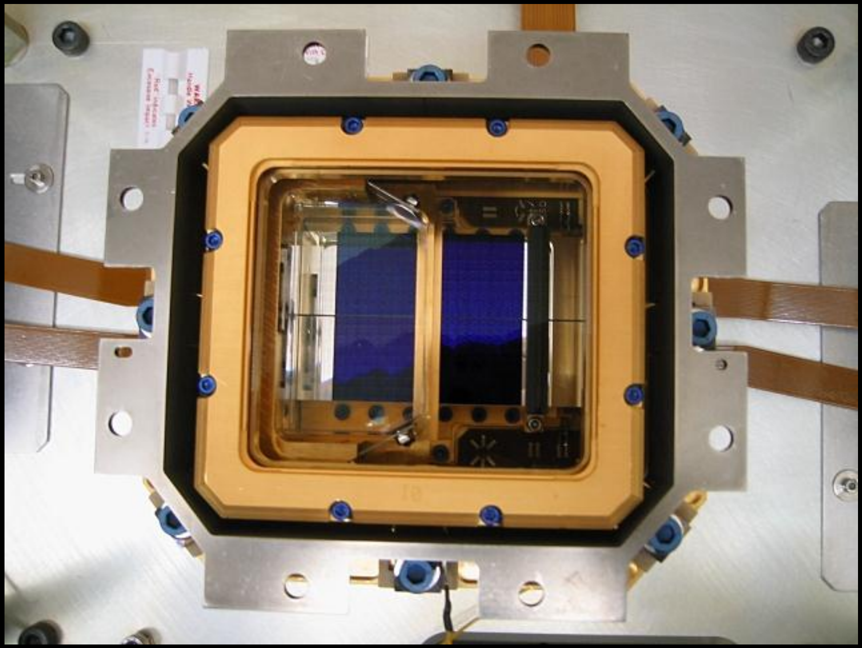

CoRoT (CNES): 27 cm



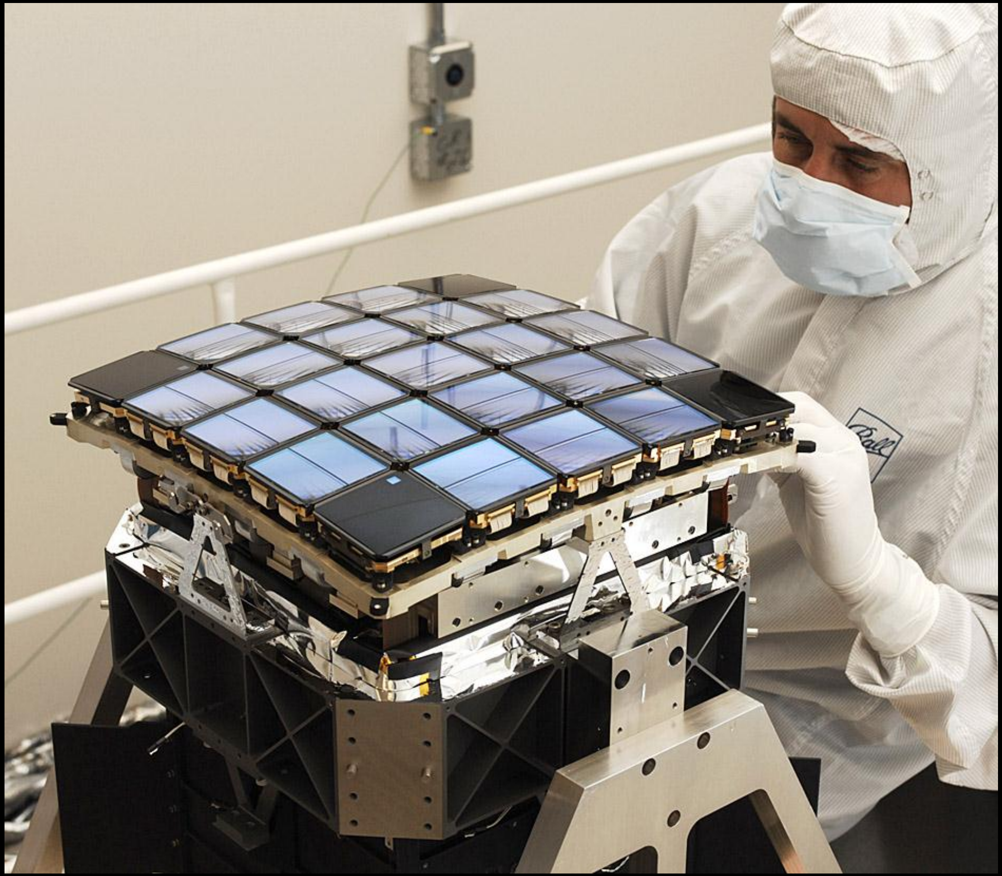
Kepler (NASA): 95 cm



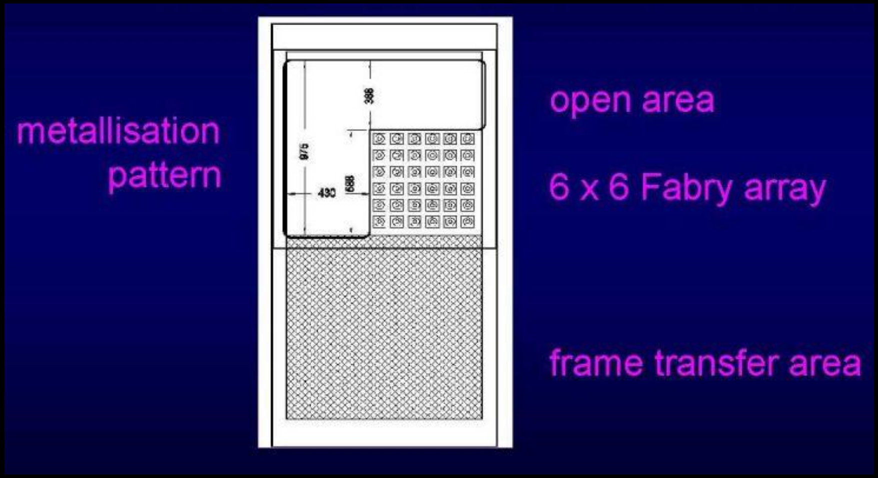
CoRoT: 4 CCD's



Kepler: 42 CCD's



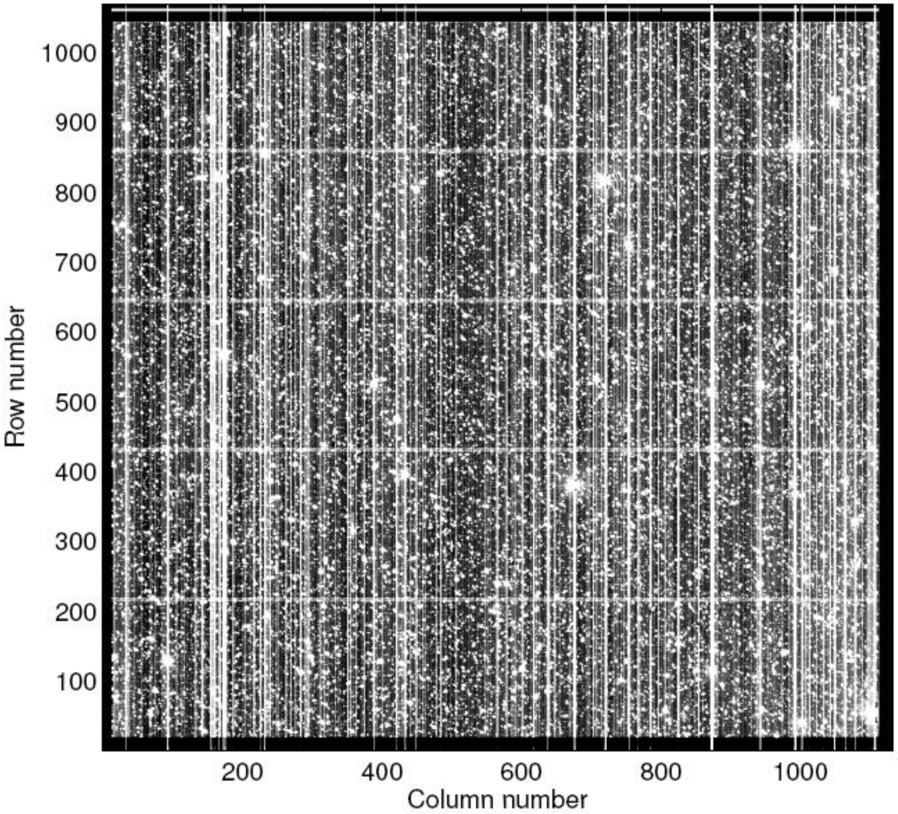
MOST: 1 CCD

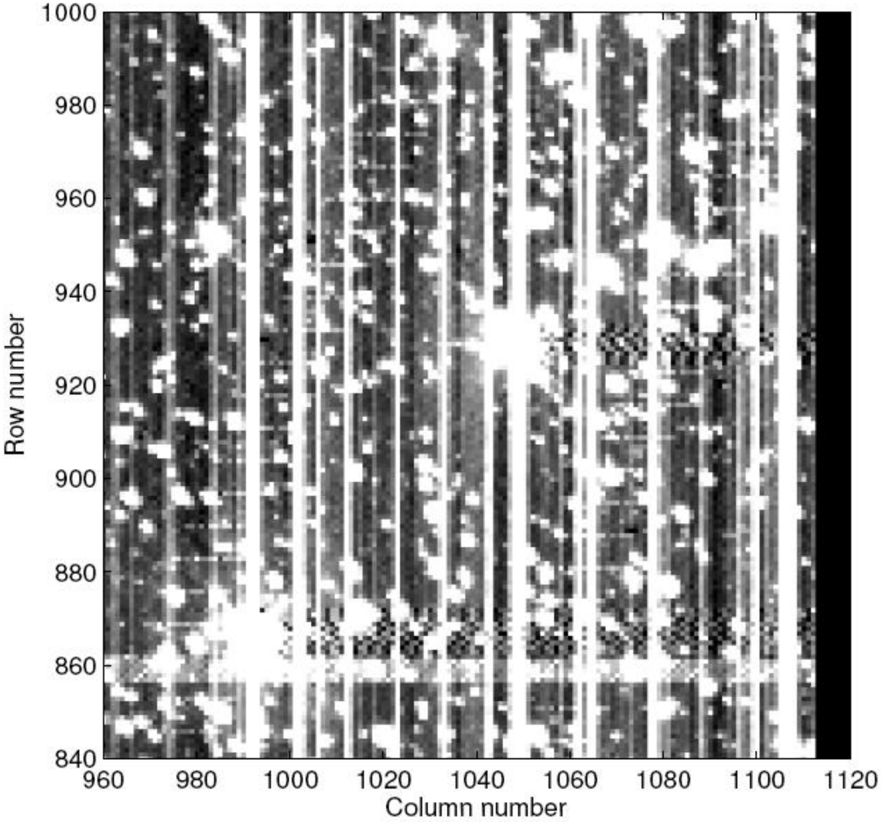


# The three Space Missions

- **MOST**: Precursor for dedicated time series missions. Focus is on bright stars.
- **CoRoT**: More than 100,000 targets for exoplanet studies ( T(obs) < 180d ). Few hundred stars observed for asteroseismology.
- **Kepler**: Very extended time series data (years). Relatively low crowding effects. High dynamical range (V: 7-16)

# The data …

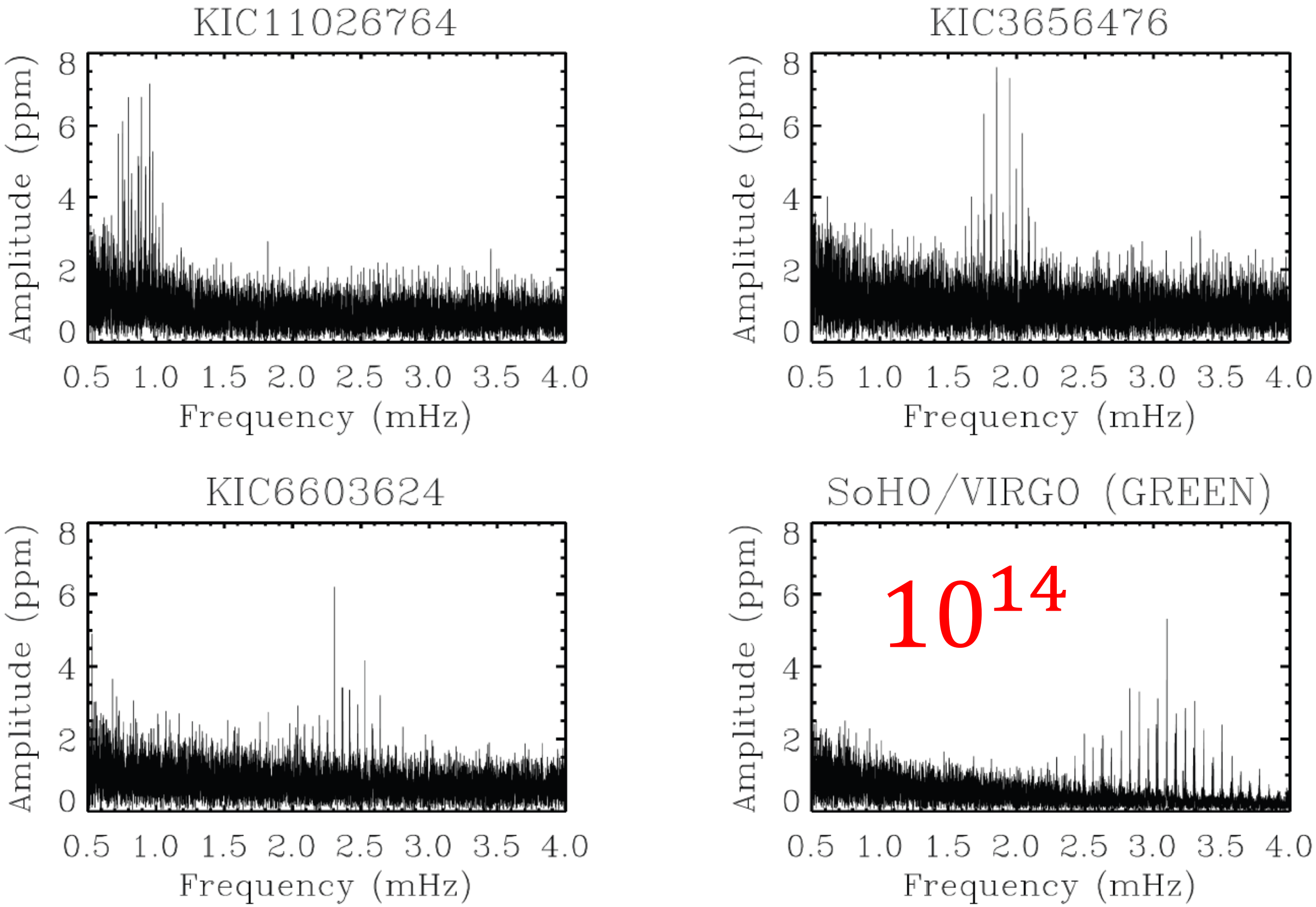



Jenkins et al. 2010

**Kepler**

# Can the data meet the challenges?
# …. a series of examples …




Kepler

# Noise levels

- Magnitude 7: 15 ppm / min
  2.8 ppm / 30-min
  0.40 ppm / day
  0.04 ppm / Q (90-d)

Amplitude Spectrum Noise (90-d):
0.08 ppm

# Stellar evolution

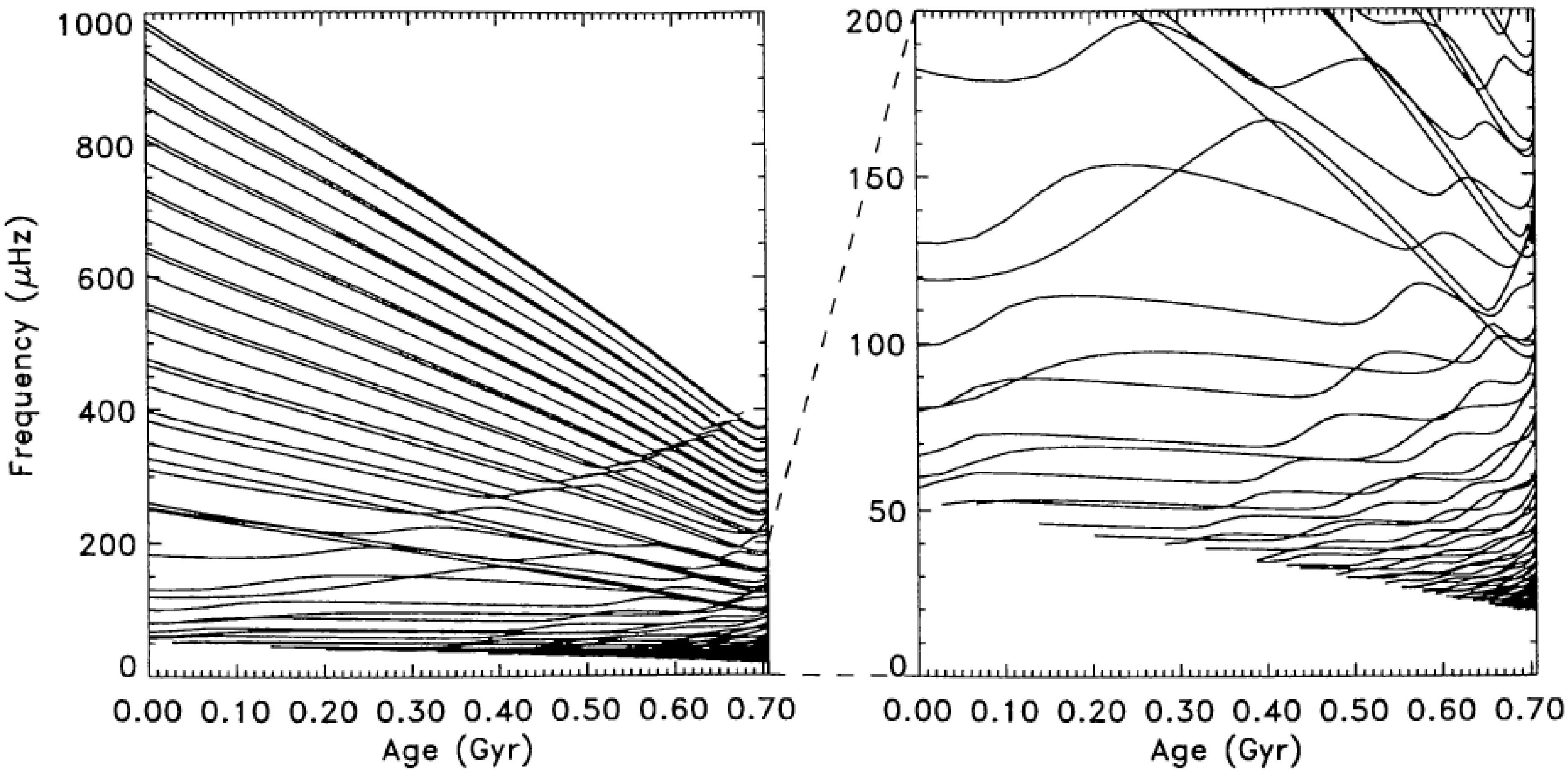


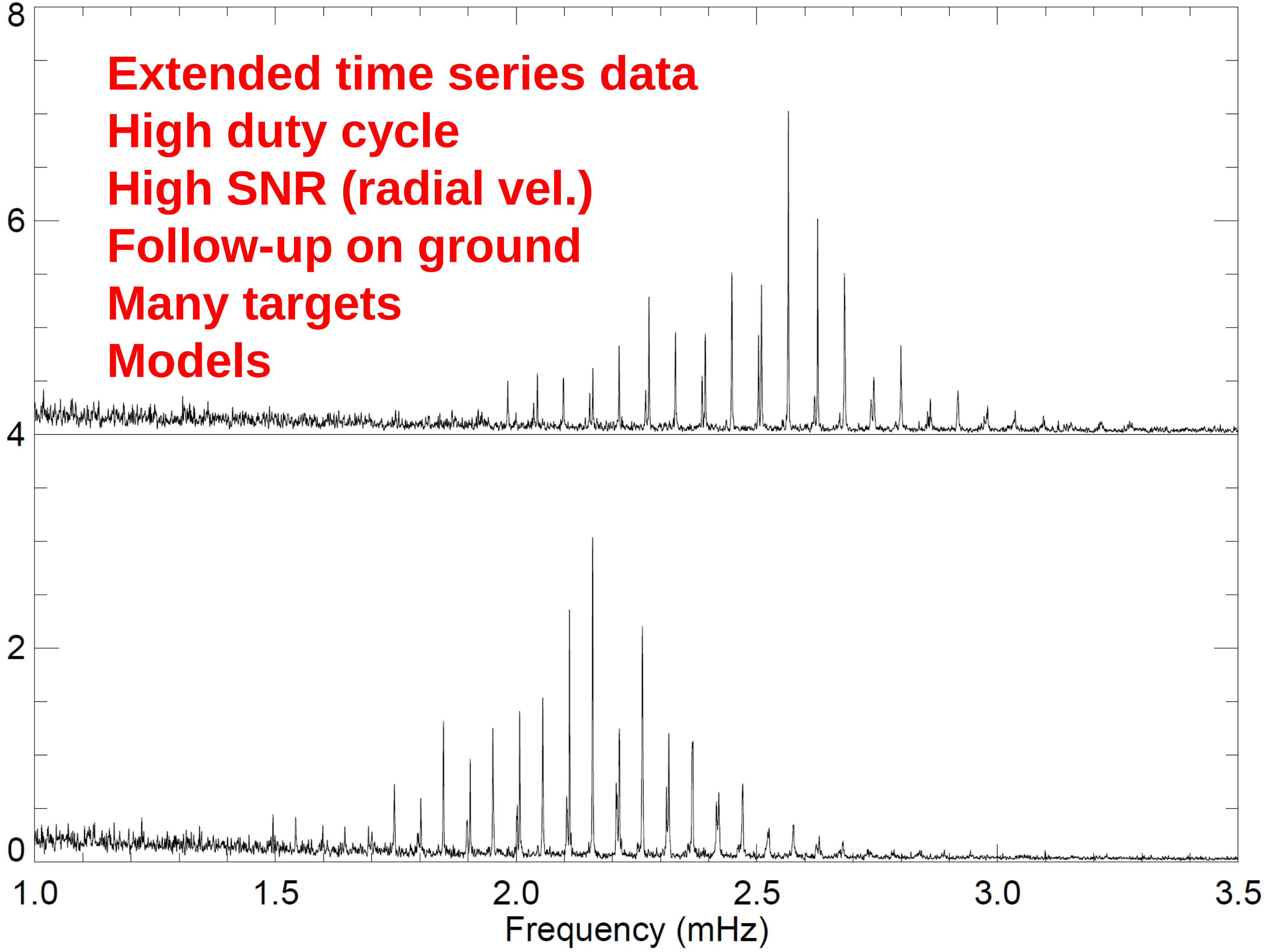

*Figure 1.* Evolution of oscillation frequencies in a $2.2\,M_\odot$ star, from model calculations by J. Christensen-Dalsgaard. Only modes with $\ell = 0, 1, 2$ and $n \leq 10$ are shown.

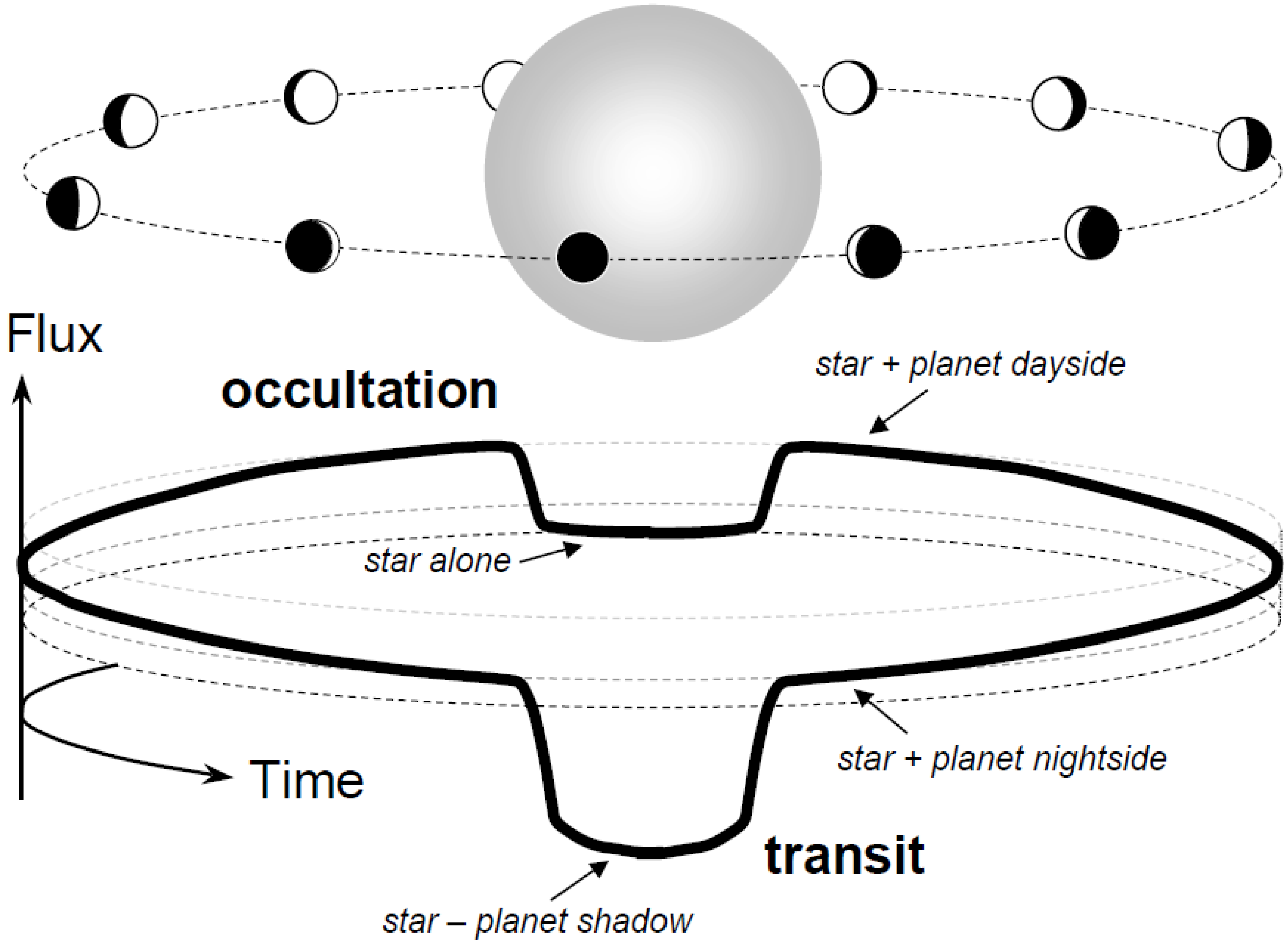
**Table 1.** Frequency accuracy for a $V = 8$ target observed by KEPLER

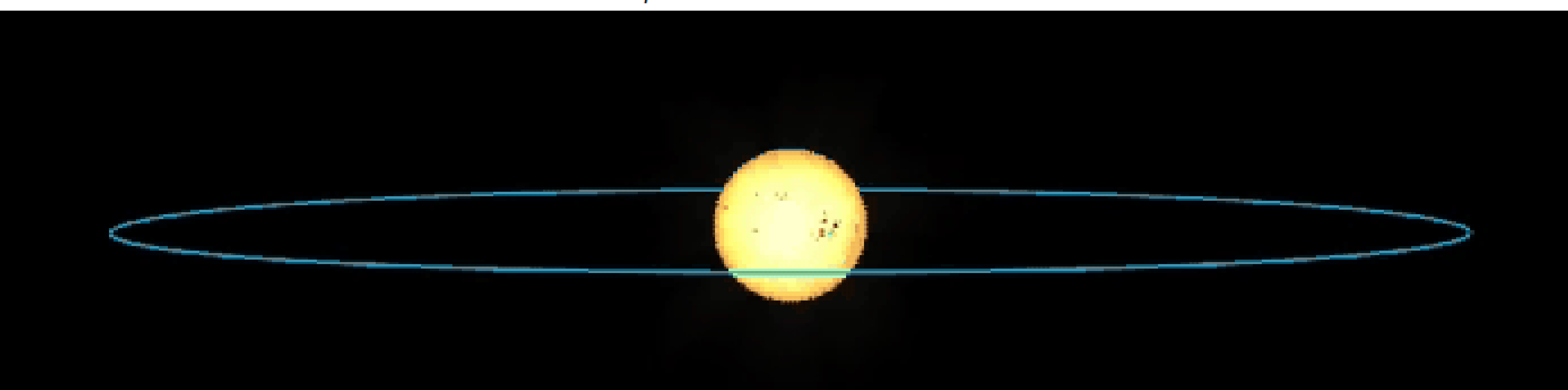
| | Coherent | | Damped | | |
|---|---|---|---|---|---|
| | | | $\tau = 10$ d | $\tau = 3$ d | $\tau = 6$ hr |
| $T$ | $a = 0.01$ | $a = 100$ ppm | $a = 50$ ppm | $a = 5$ ppm | $a = 5$ ppm |
| 90 d | 0.7 pHz | 70 pHz | 0.0013 μHz | 0.040 μHz | 0.50 μHz |
| 3 yr | 0.02 pHz | 2 pHz | 0.0004 μHz | 0.013 μHz | 0.16 μHz |
| 7 yr | 0.005 pHz | 0.5 pHz | 0.0002 μHz | 0.008 μHz | 0.10 μHz |

$$\sigma\left(\frac{1}{P}\frac{dP}{dt}\right) \approx \frac{\sigma(f)}{f}\frac{1}{T} \propto \sigma_{\rm noise}\, a^{-1}\, f^{-1}\, T^{-5/2}$$

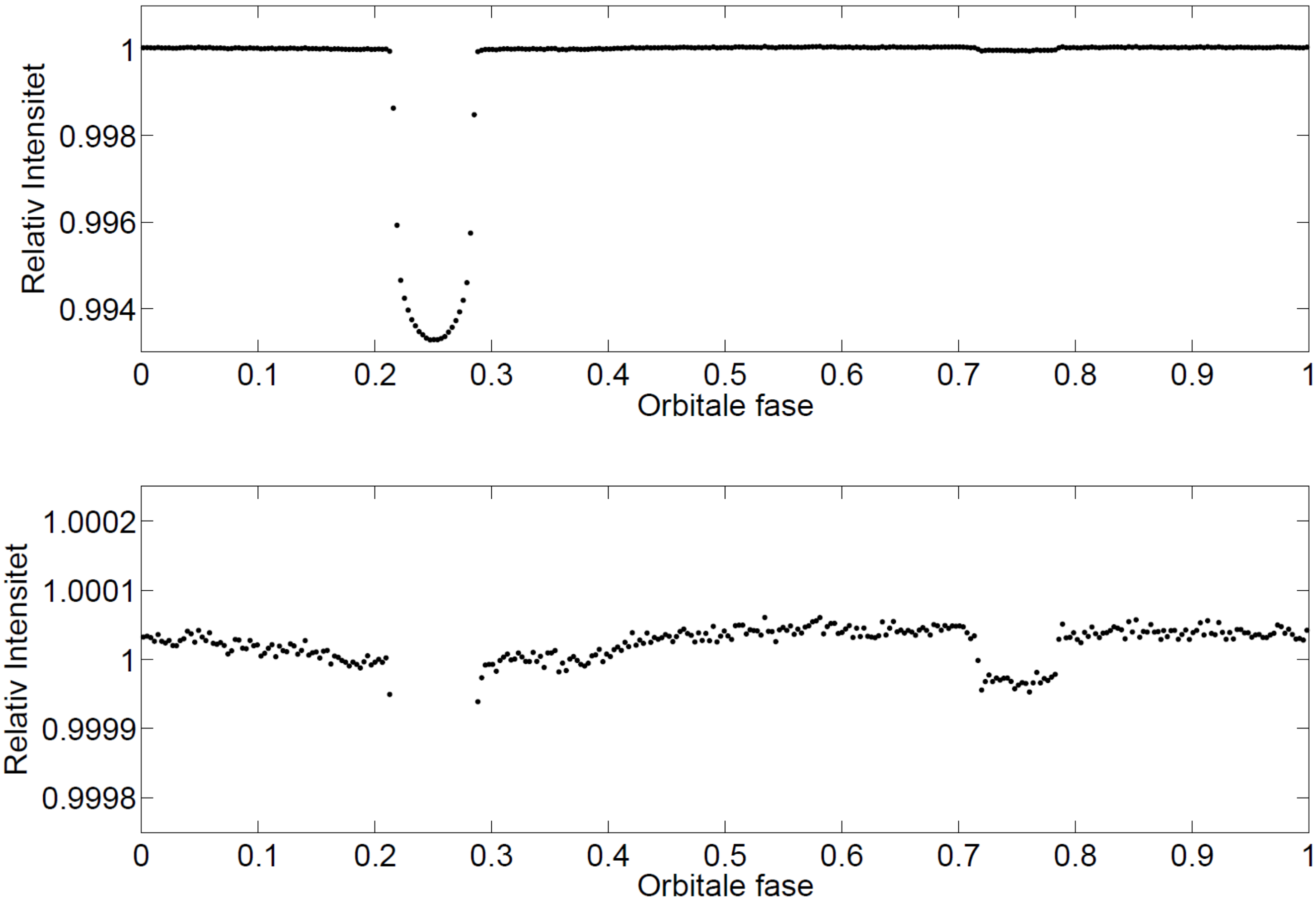
$$\sigma\left(\frac{1}{P}\frac{dP}{dt}\right) < 10^{-10}\, yr^{-1}$$


Extended time series data
High duty cycle
High SNR (radial vel.)
Follow-up on ground
Many targets
Models
8
6
4
2
0
1.0
1.5
2.0
2.5
3.0
3.5
Frequency (mHz)

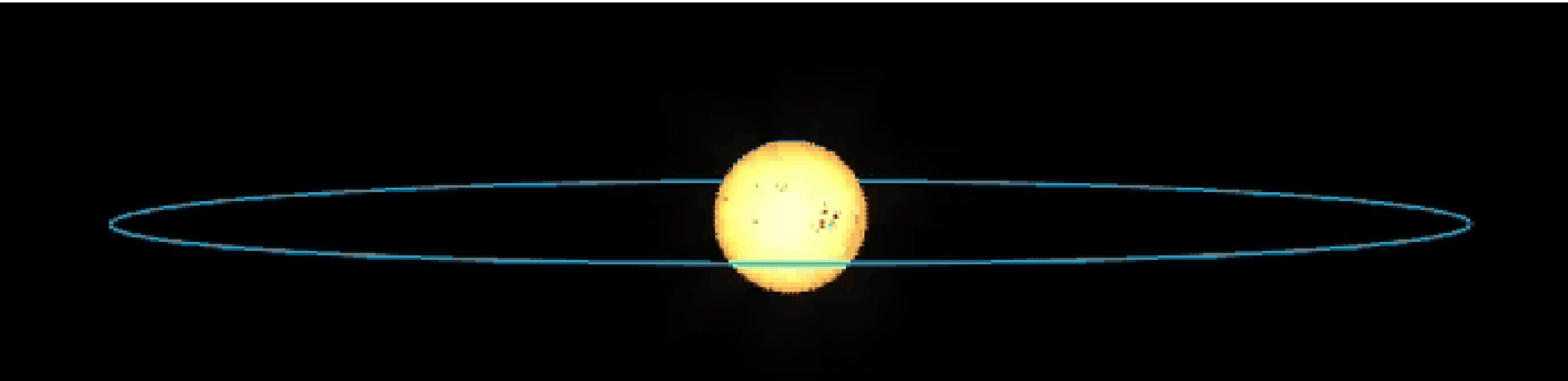

Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow



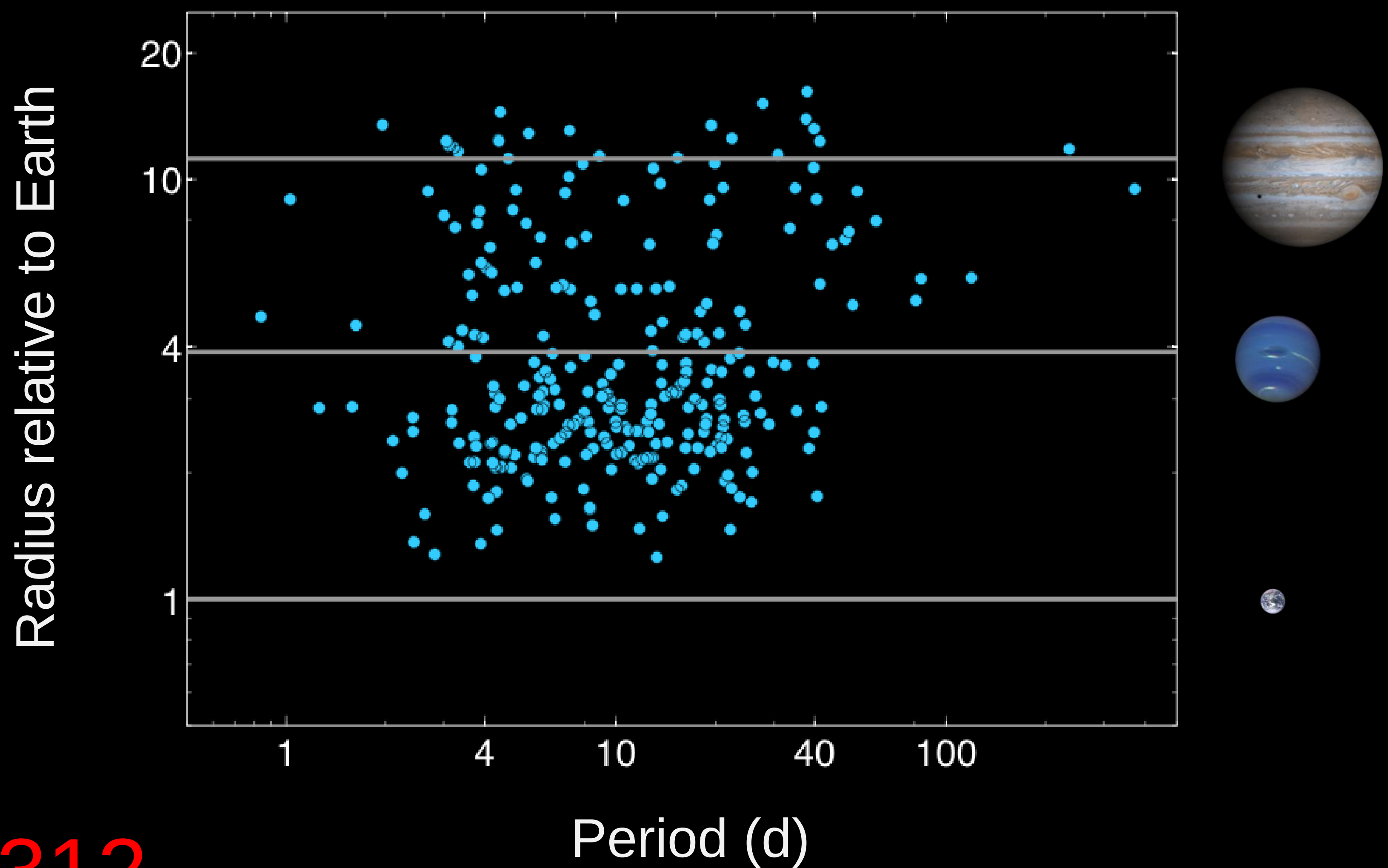
# HAT-P-7




Nielsen et al. 2012

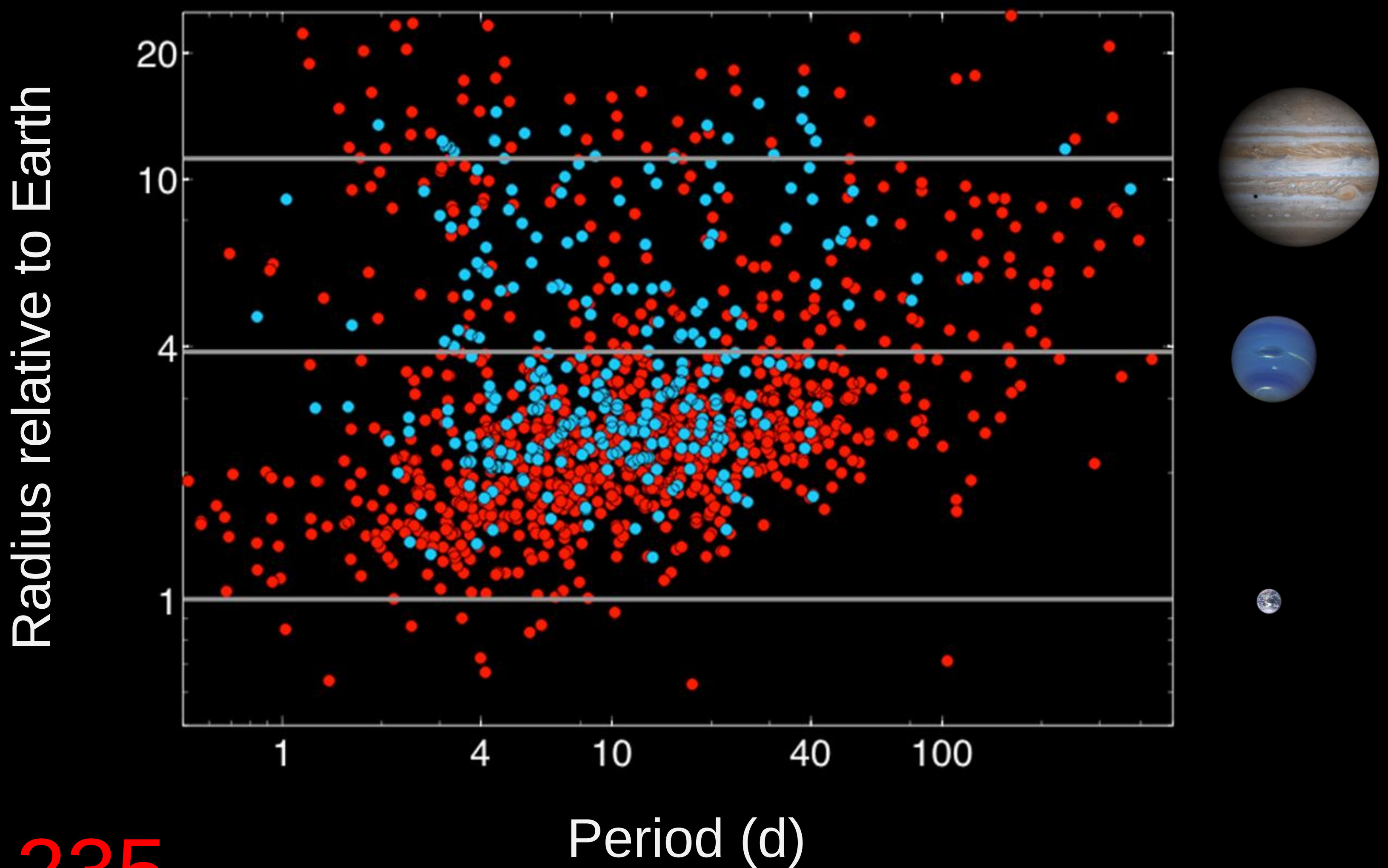


# Kepler Exoplanet Candidates – June 2010



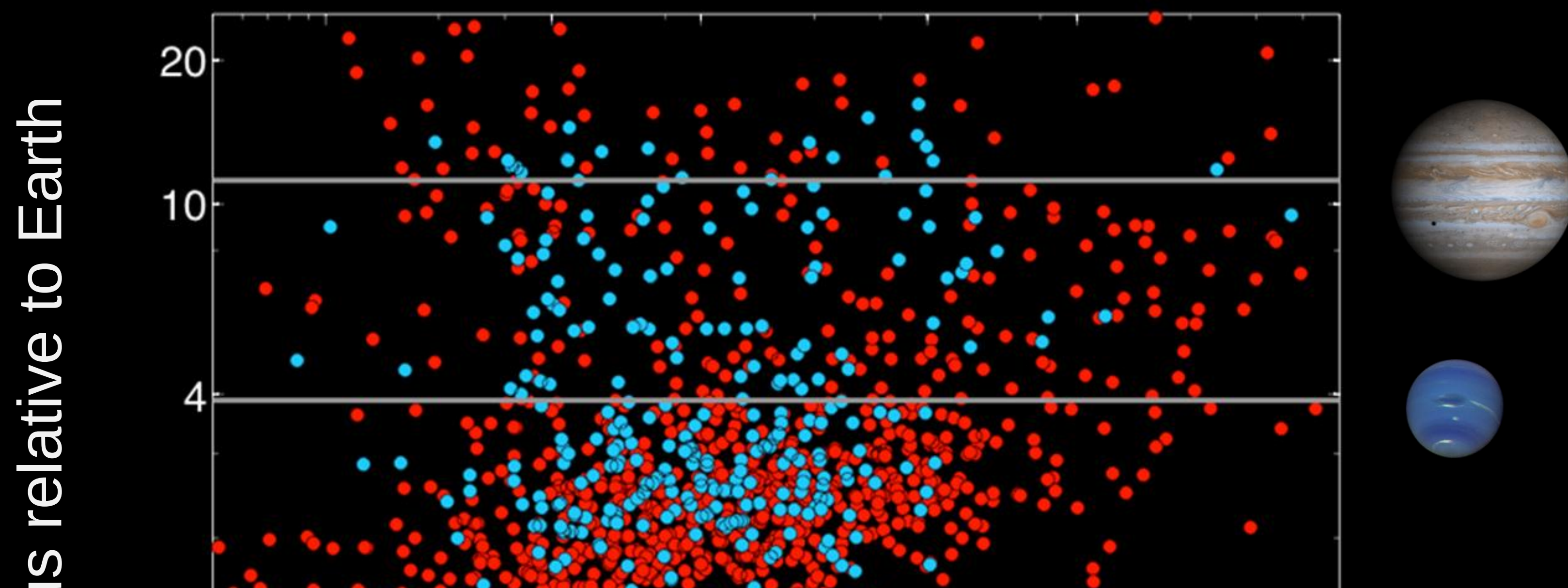

312

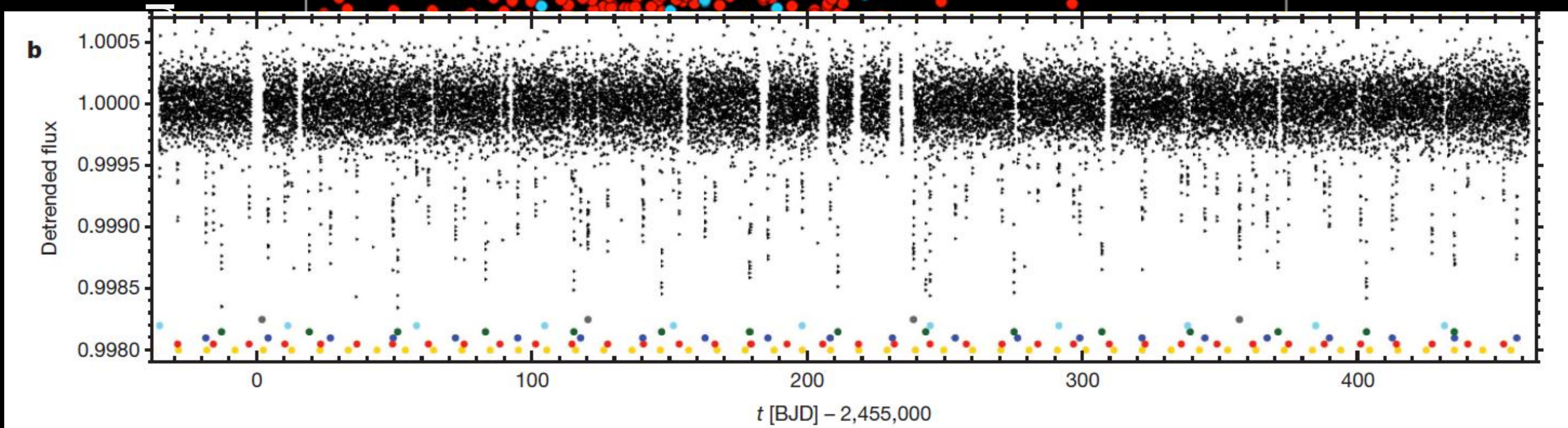
# Kepler Exoplanet Candidates – Feb 2011



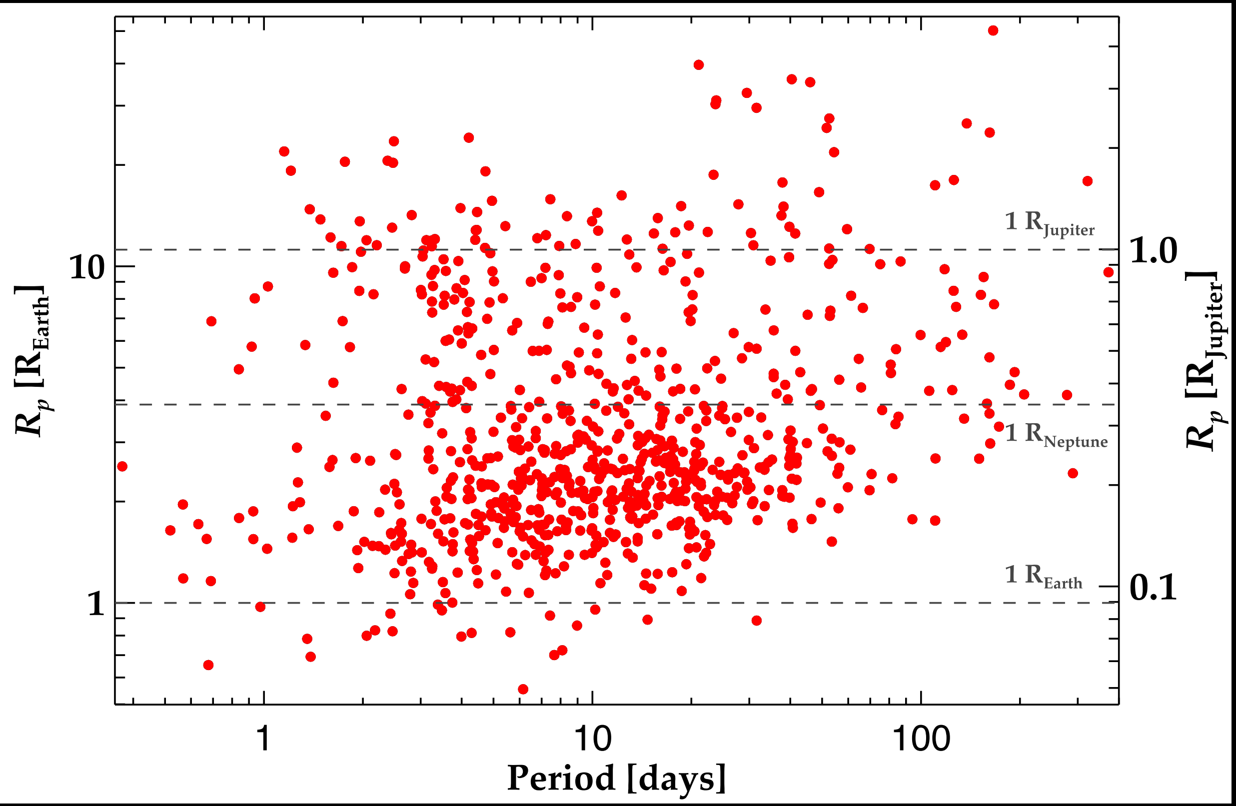

1235

# Kepler Exoplanet Candidates – Feb 2011



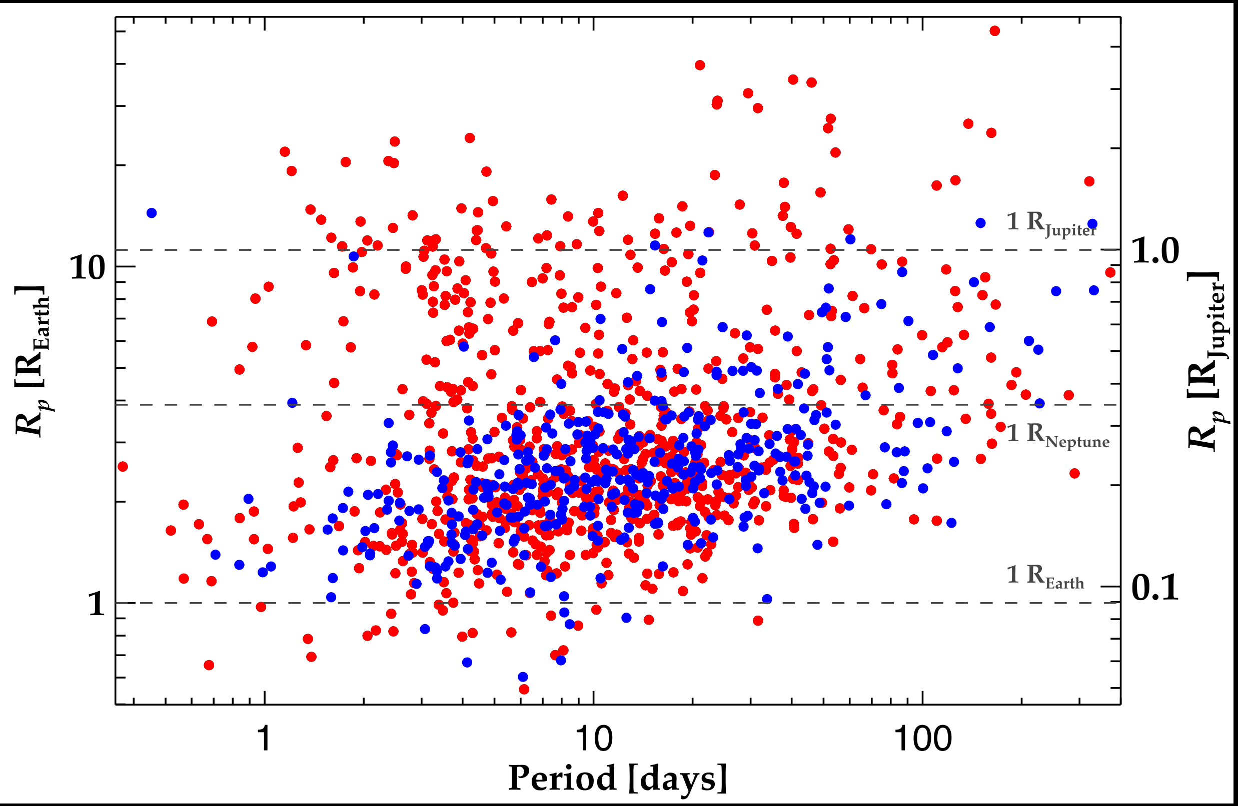



# Kepler: 827 Single Planet Systems Detected

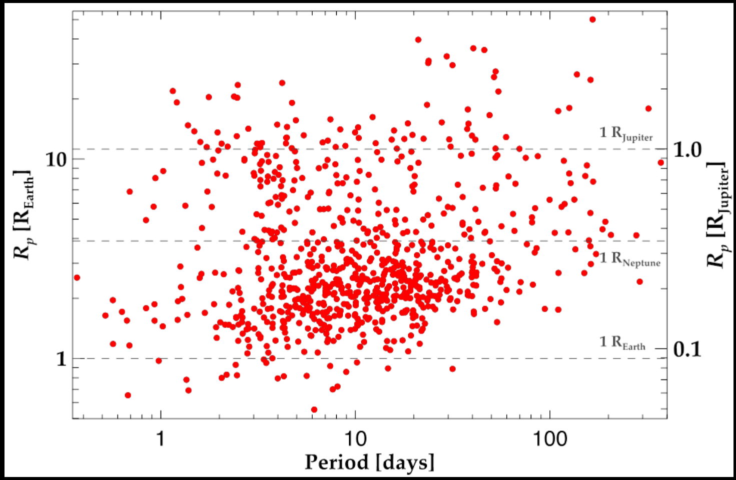


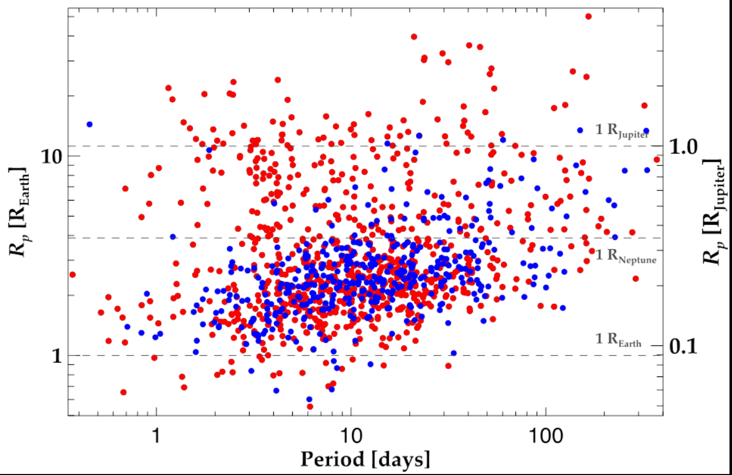

Letham et al. 2011

# Kepler: 827 Single Planet Systems Detected



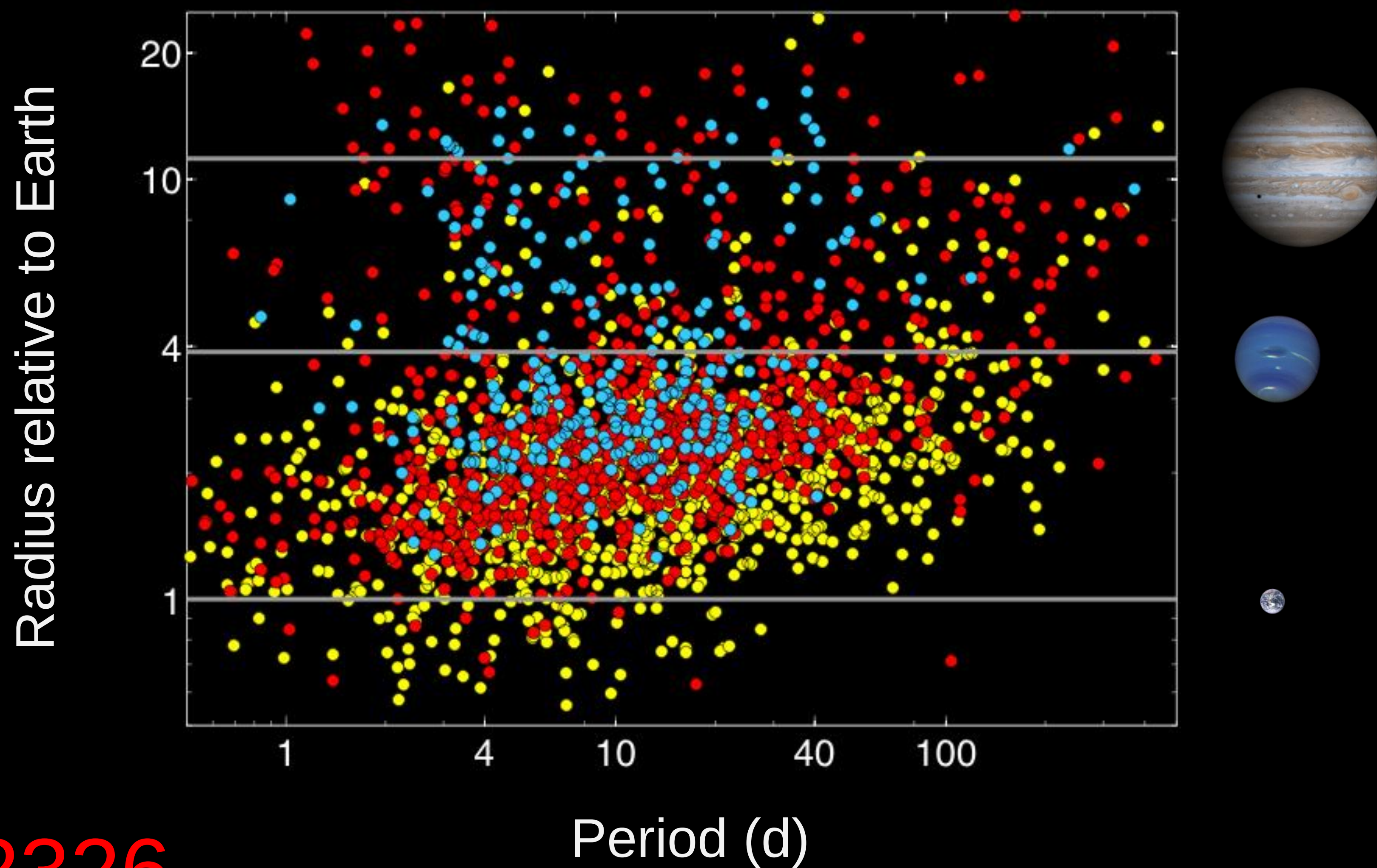

408 candidates in 170 multiple systems




(from Spitzer)

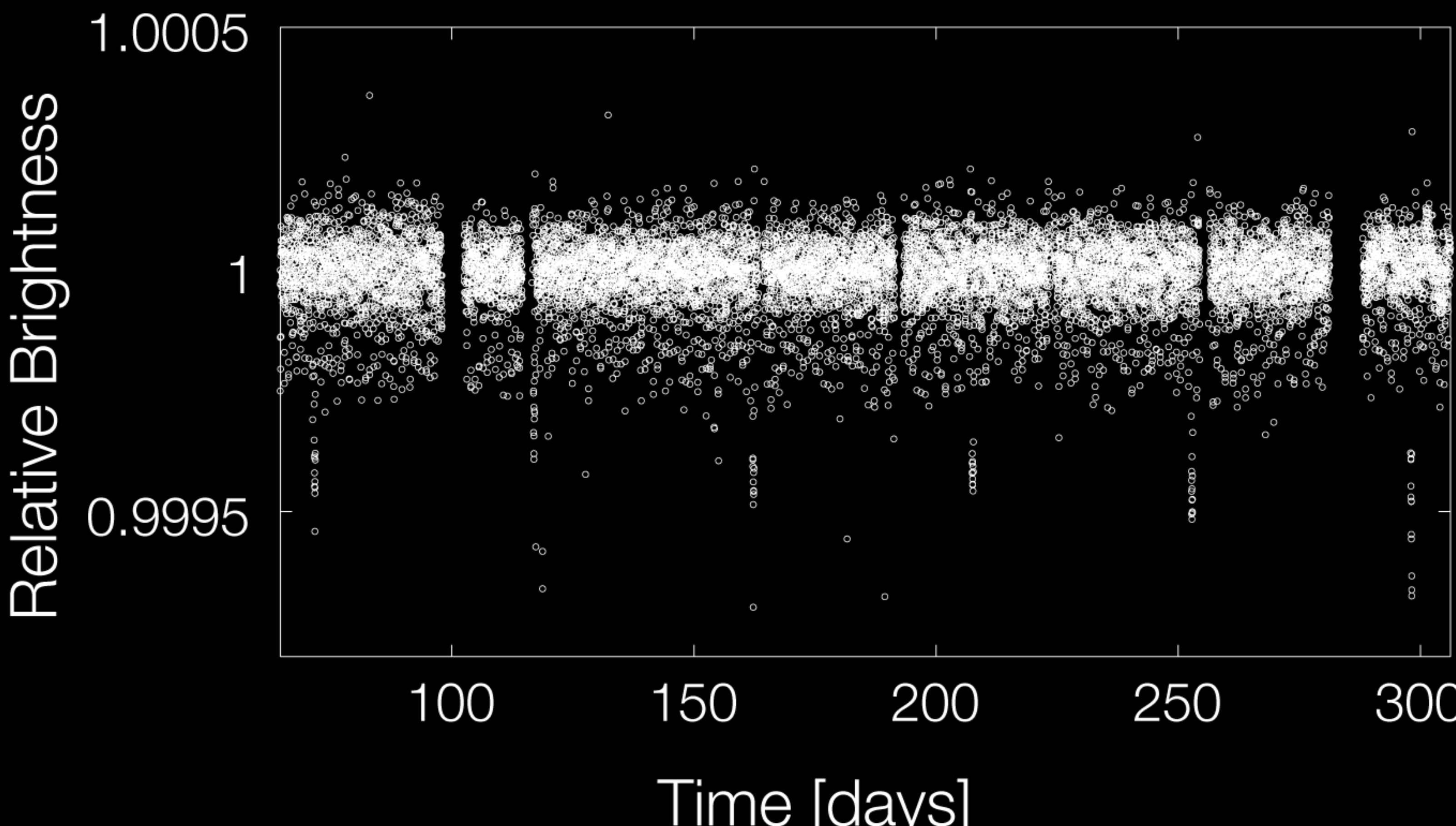
# Kepler Exoplanet Candidates – Dec 2011

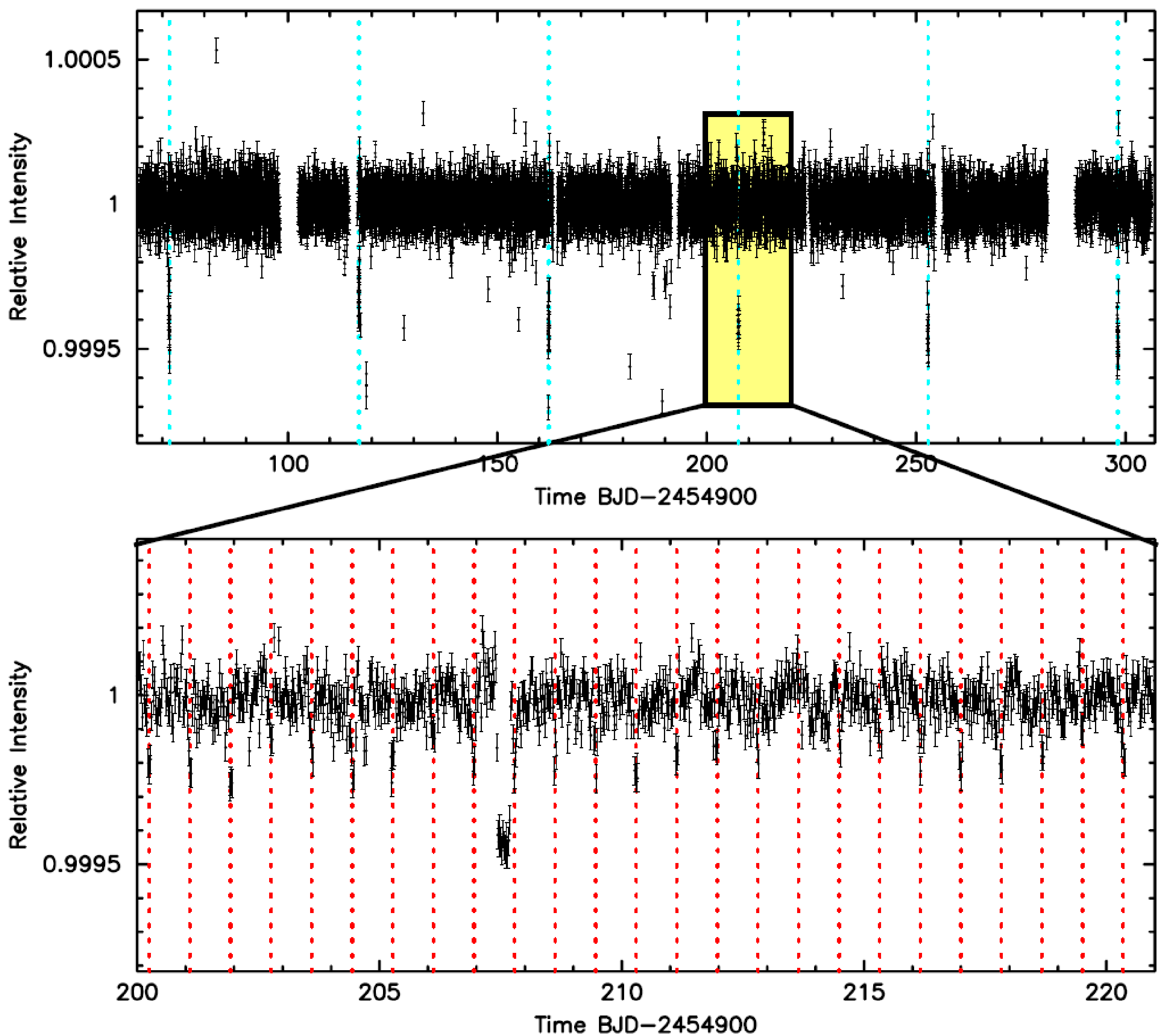



2326

# Kepler-10 Light Curve

Batalha et al. 2011

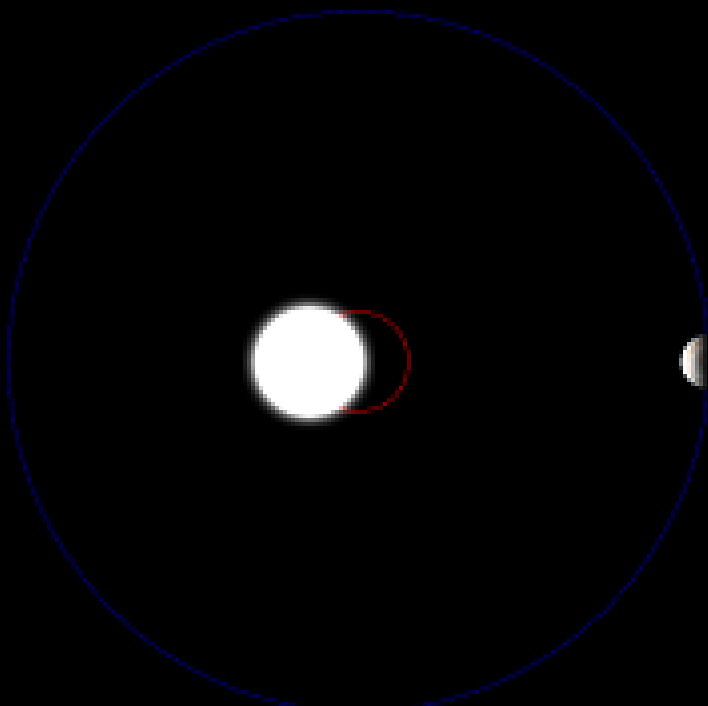


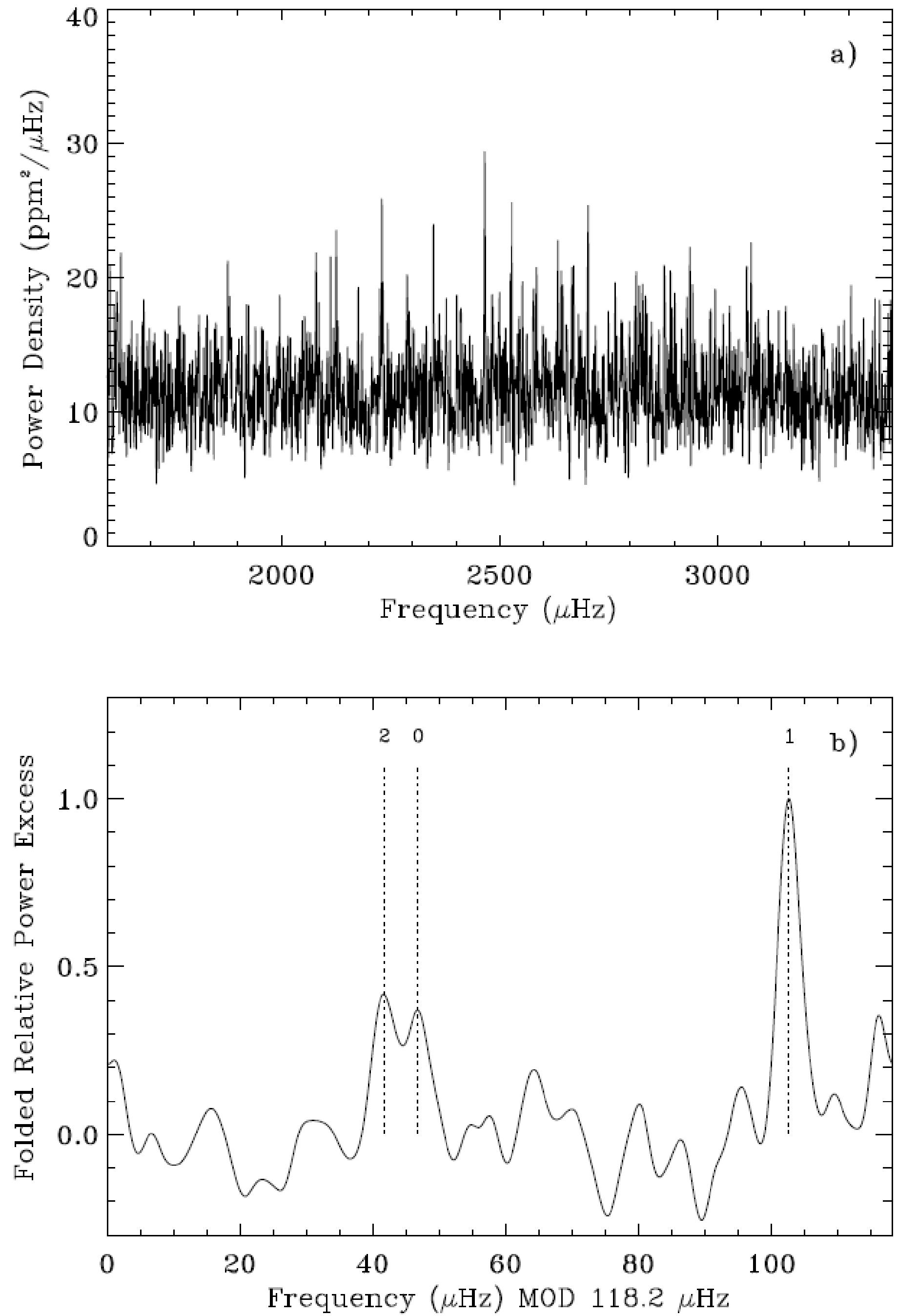


1.0005
1
0.9995
Relative Intensity
100
150
200
250
300
Time BJD−2454900
1
0.9995
Relative Intensity
200
205
210
215
220
Time BJD−2454900

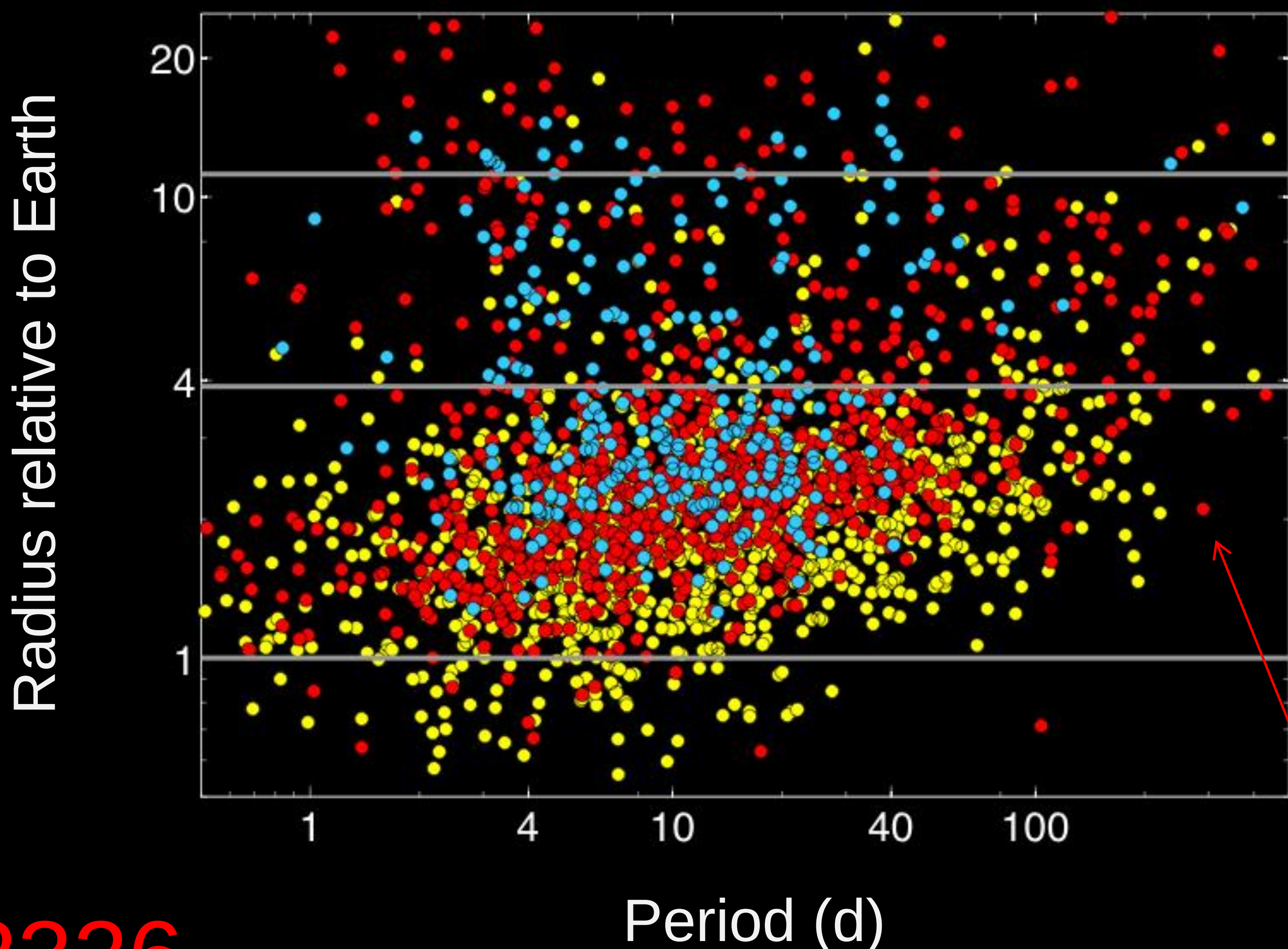
Kepler-10

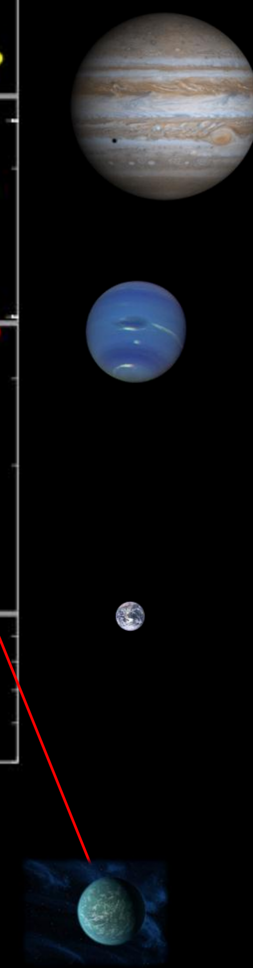
V = 11.2





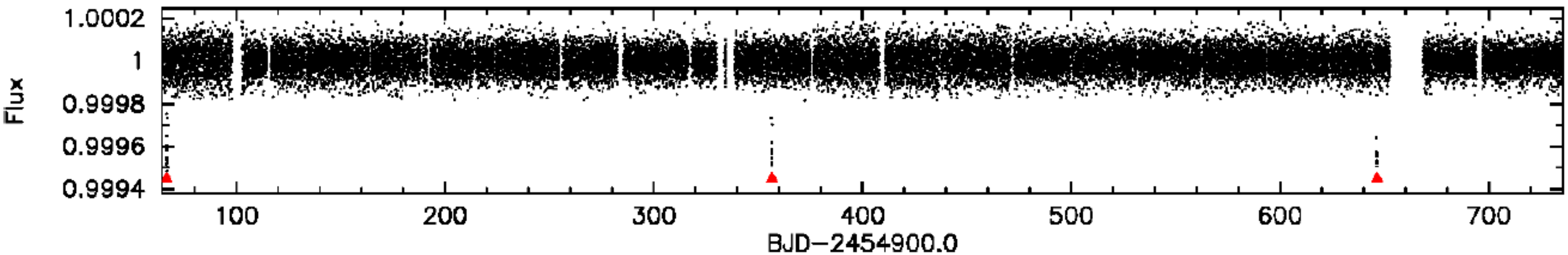
# Kepler Exoplanet Candidates – Dec 2011

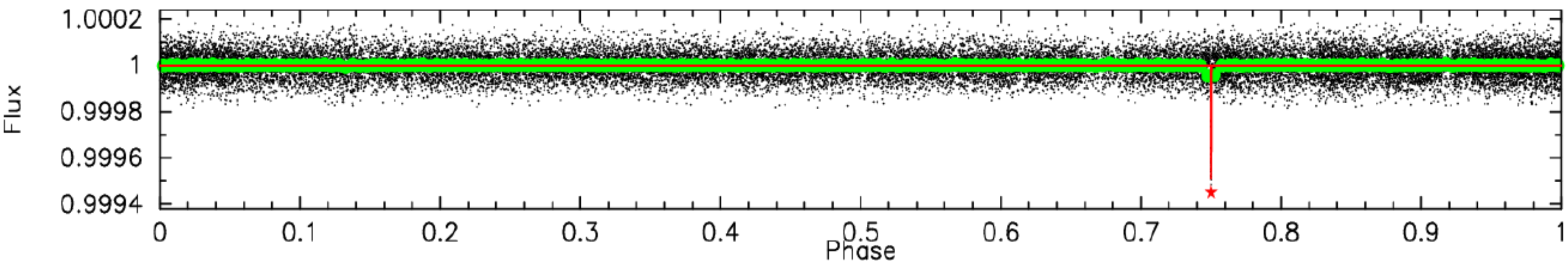


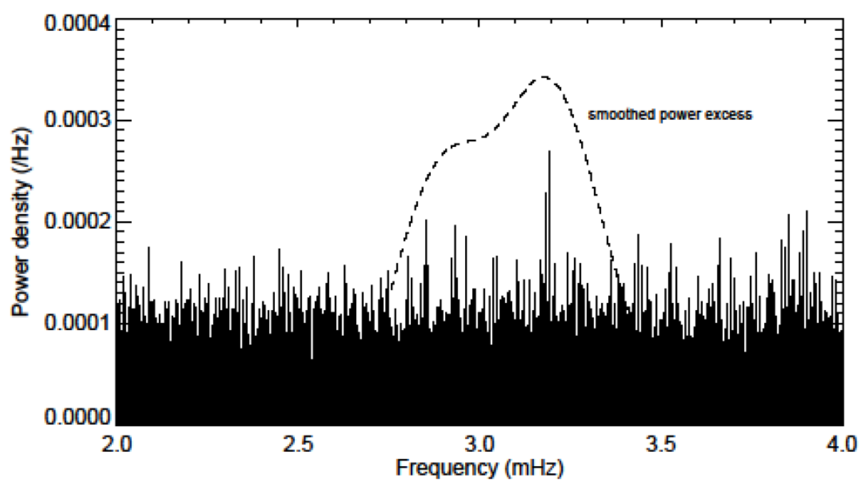



2326

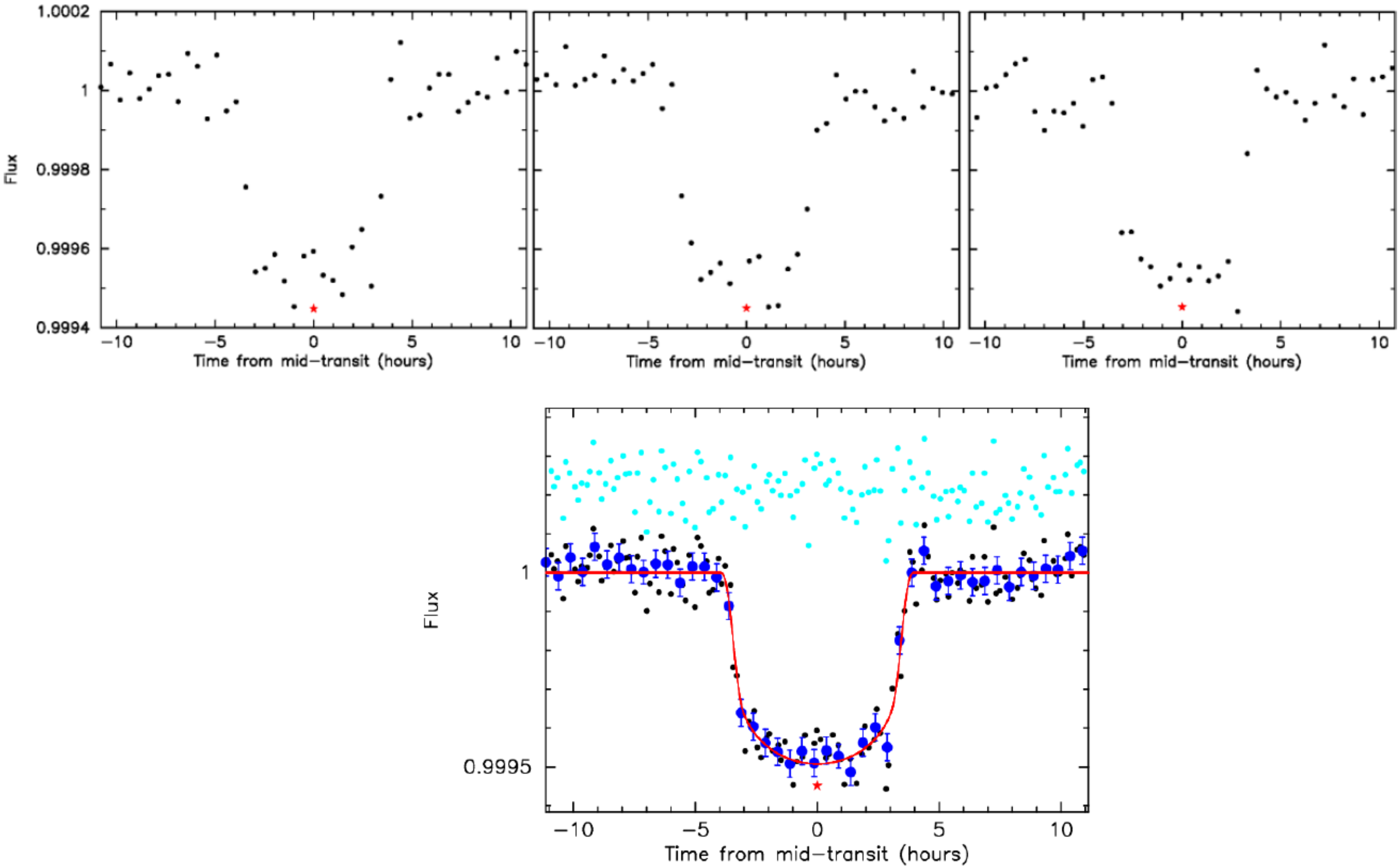
# Kepler-22b



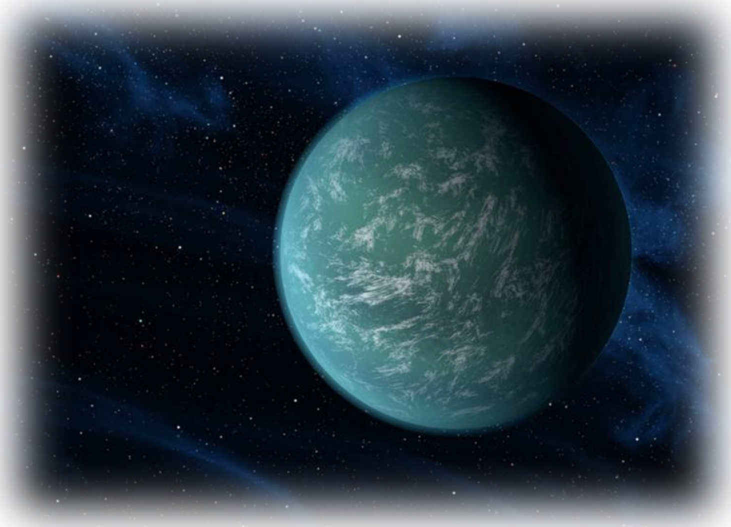




Batalha et al. 2011



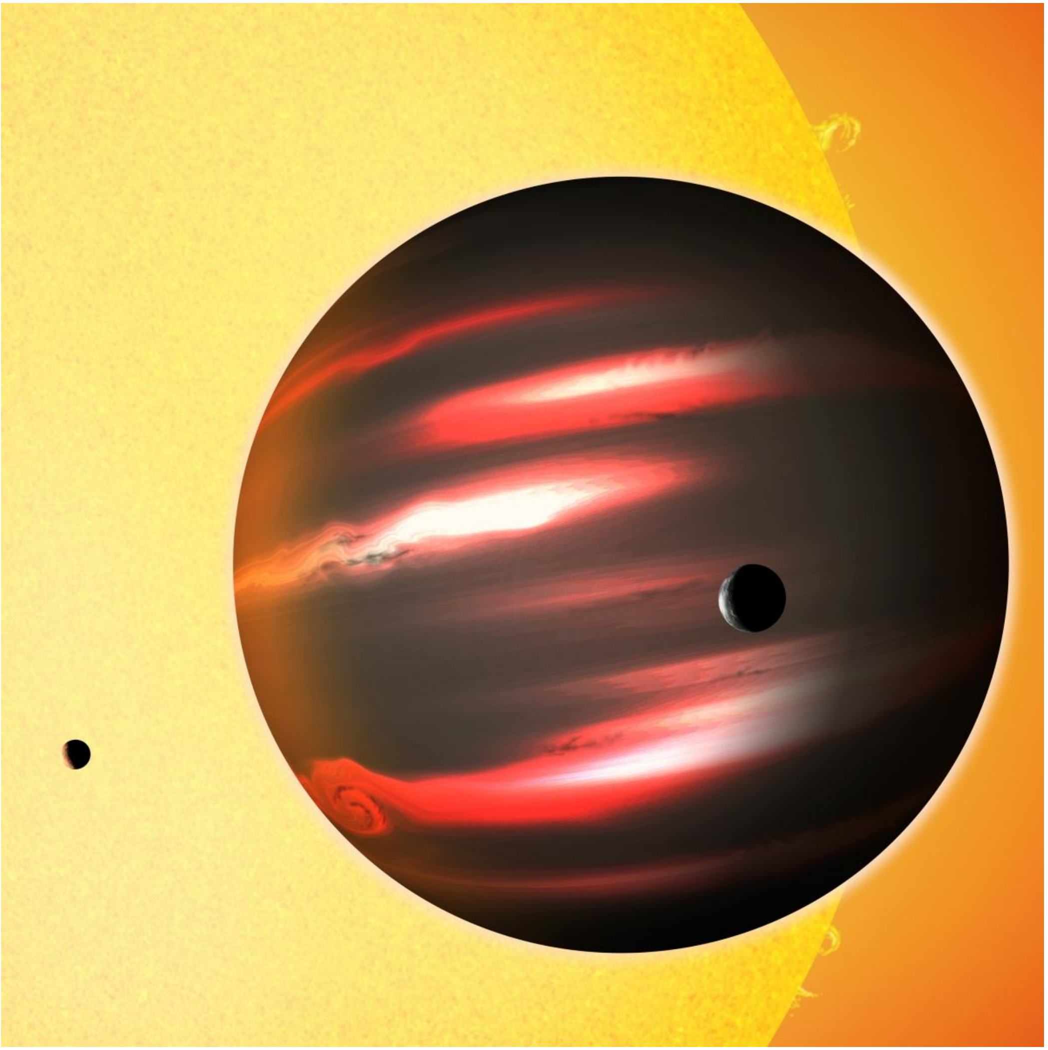
Flux
1.0002
1
0.9998
0.9996
0.9994
−10
−5
0
5
10
Time from mid−transit (hours)
Time from mid−transit (hours)
Time from mid−transit (hours)
Flux
1
0.9995
Time from mid−transit (hours)

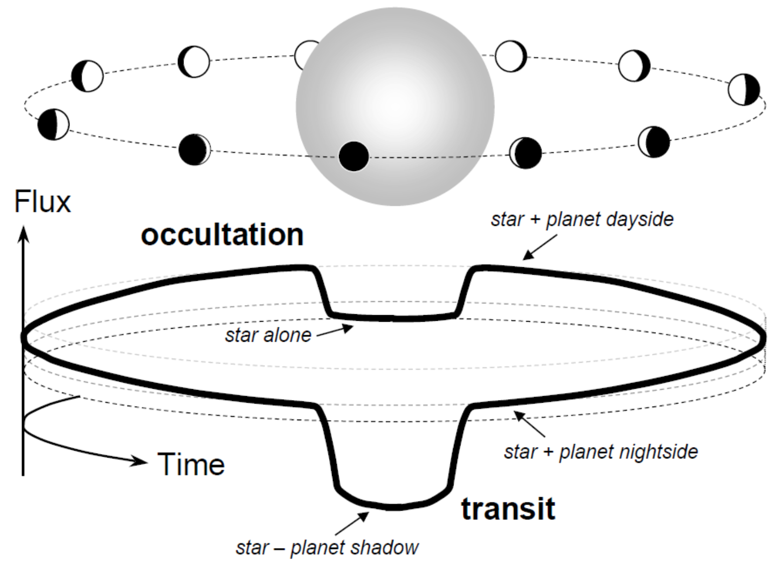


# Kepler-22b

| | |
|---|---|
| Mass, $M_\odot$ | $0.970 \pm 0.060$ |
| Radius, $R_\odot$ | $0.979 \pm 0.020$ |
| Luminosity, $L_\odot$ | $0.79 \pm 0.04$ |
| Distance (pc) | 190 |
| Orbital period, P (days) | 289.8623 +0.0016/-0.0020 |
| Radius, $R_\oplus$ | $2.38 \pm 0.13$ |
| Mass, $M_\oplus$ ,($1\sigma$, $2\ \sigma$, & $3\sigma$ upper limits) | 36, 82, 124 |
| Orbital semi-major axis, $a$ (AU) | 0.849 + 0.018/-0.017 |
| Equilibrium temperature, $T_{eq}$ (K) | 262 |

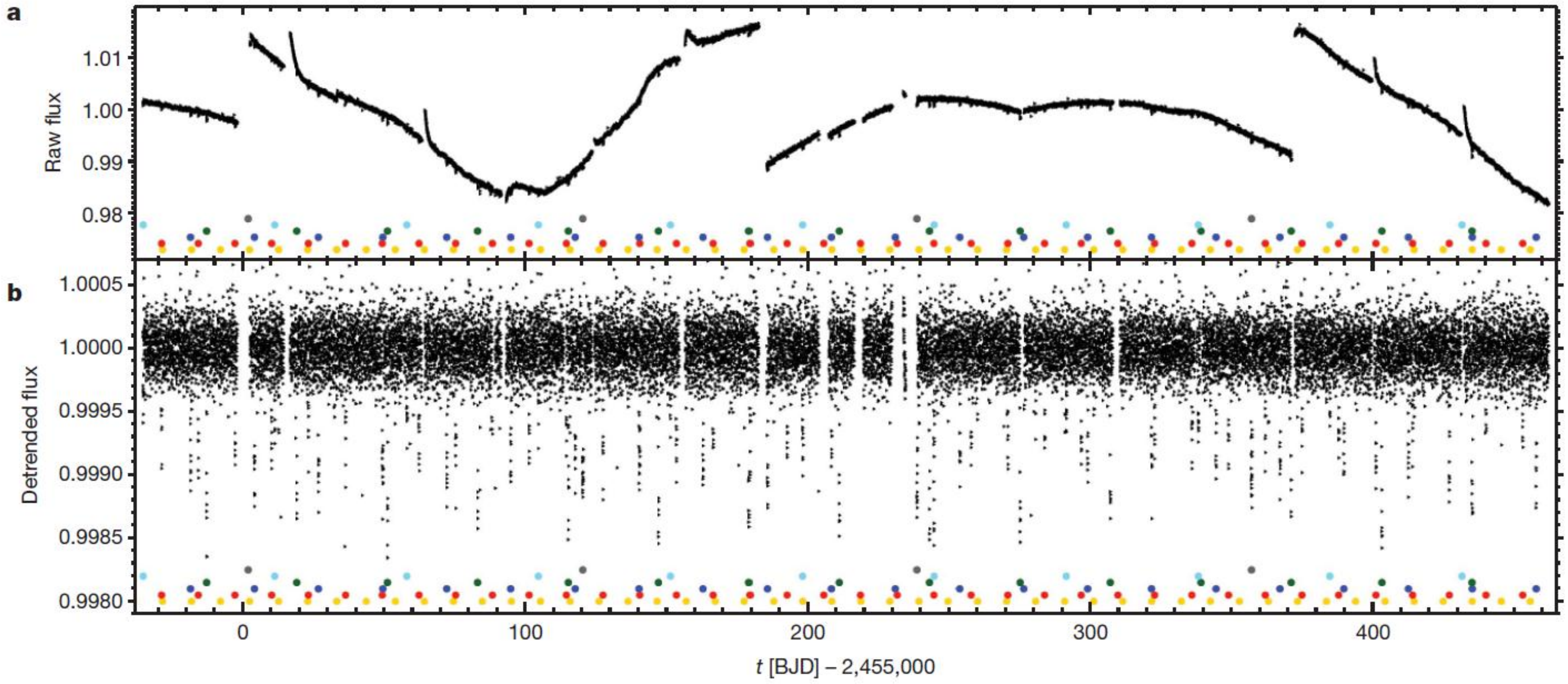
# TrES-2b



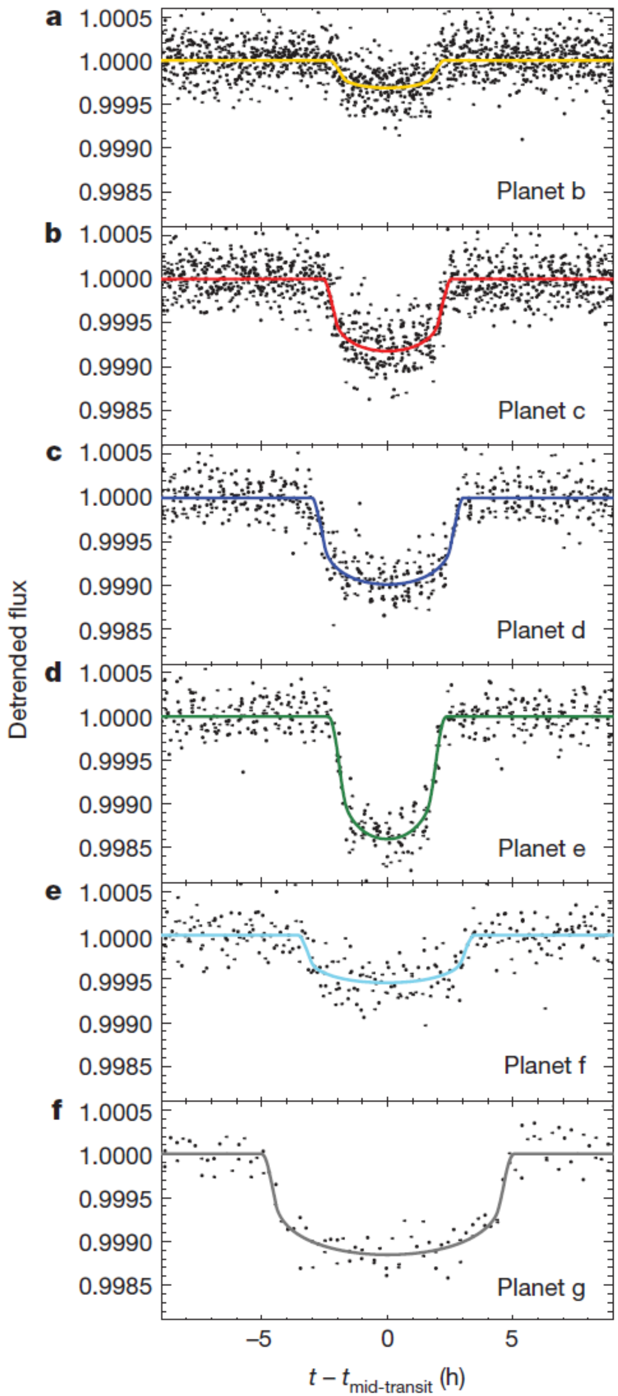



David M. Kipping & David S. Spiegel. *Monthly Notices of the Royal Astronomical Society*. For all models, the geometric albedo is < 1%, and for the best-fit models it is ~0.04%

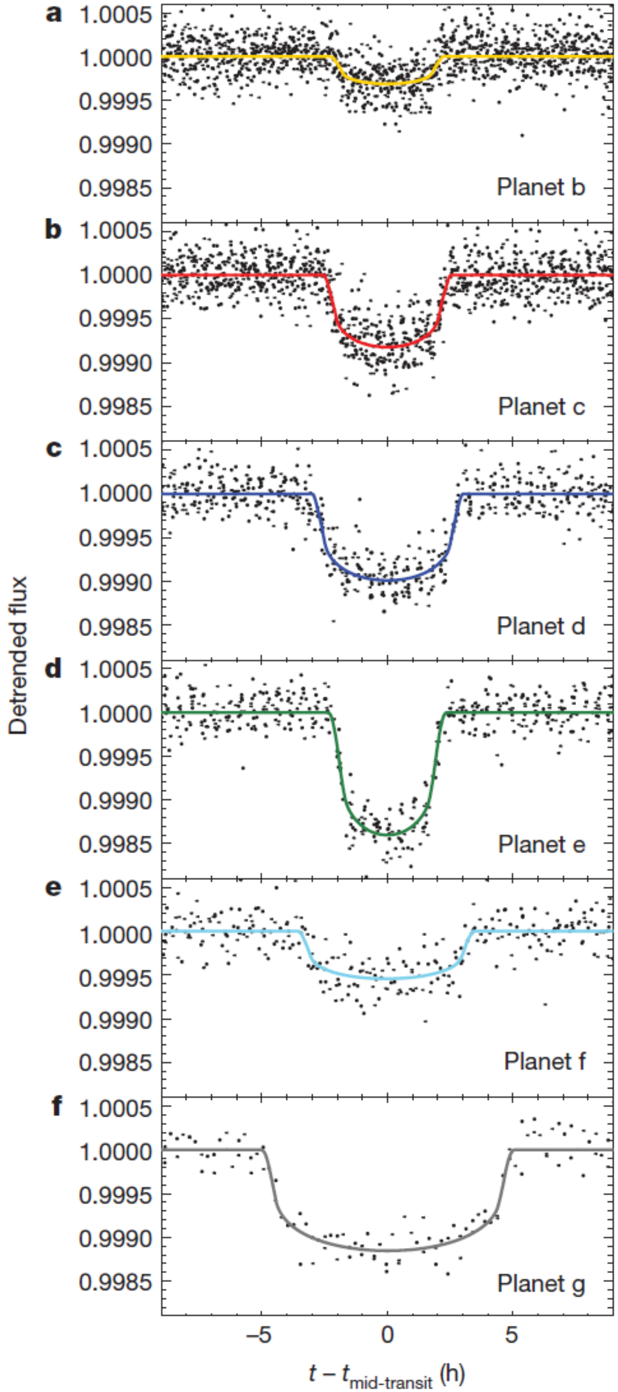
# Kepler-11

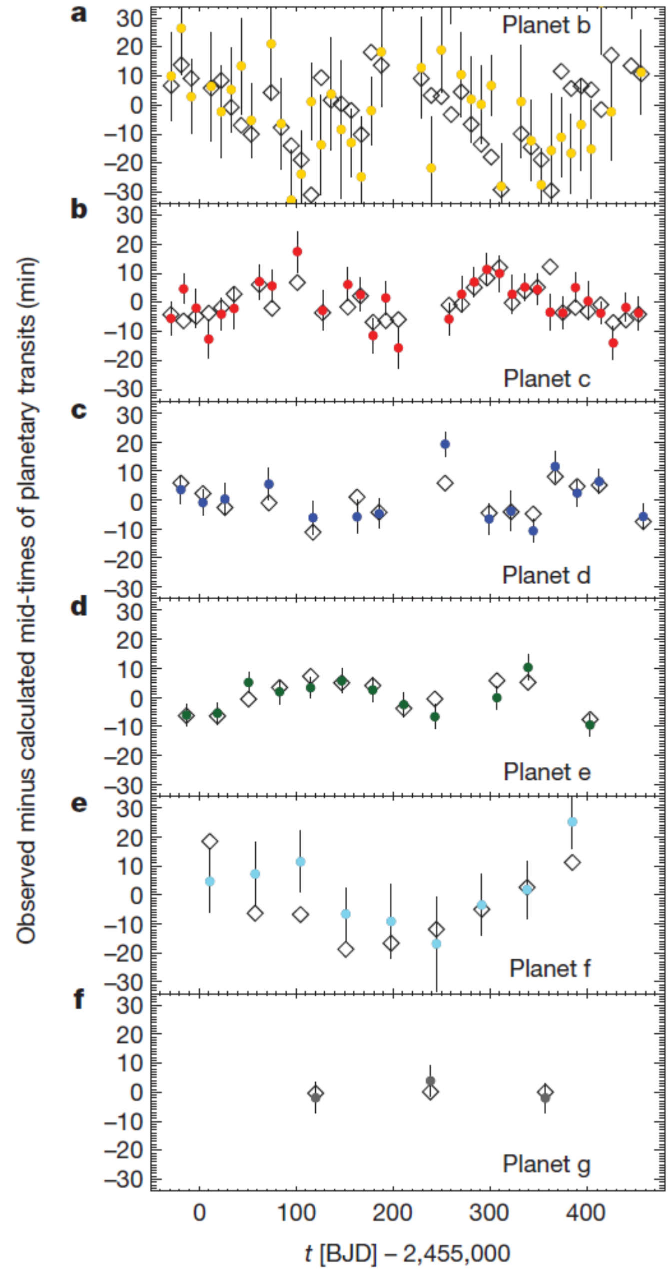


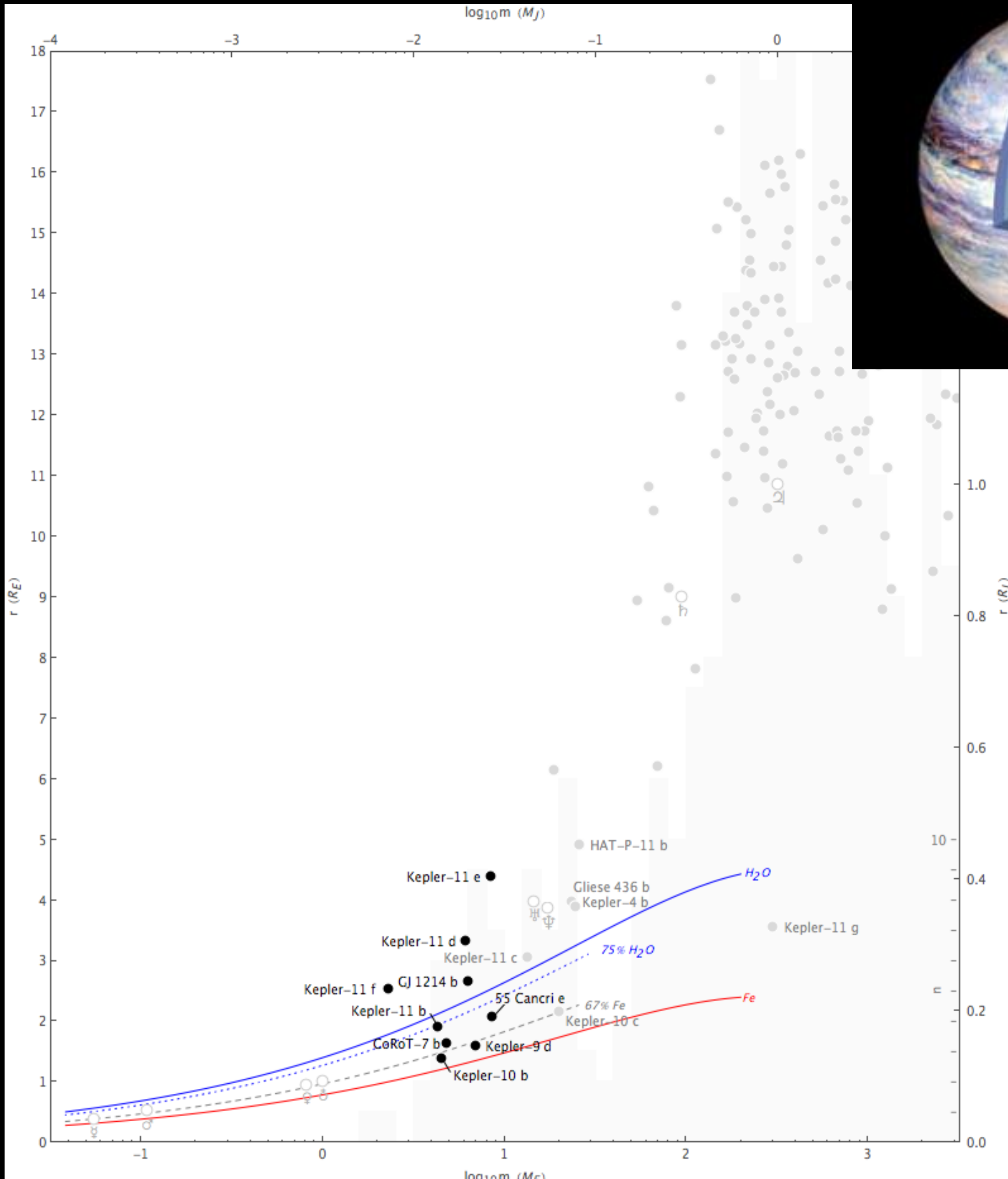

Lissauer et al. 2011

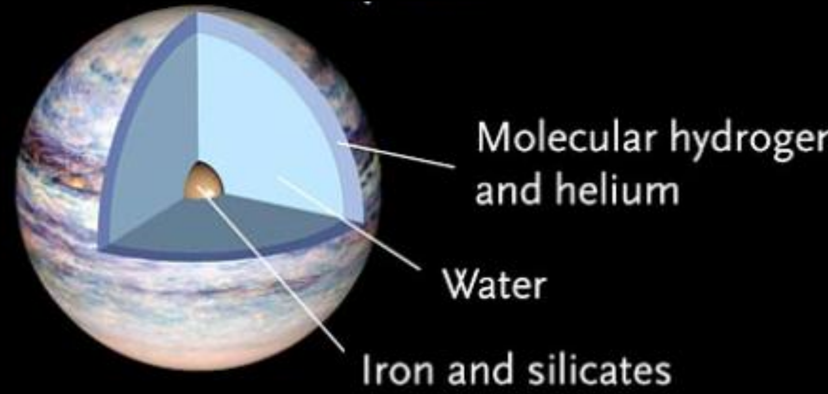


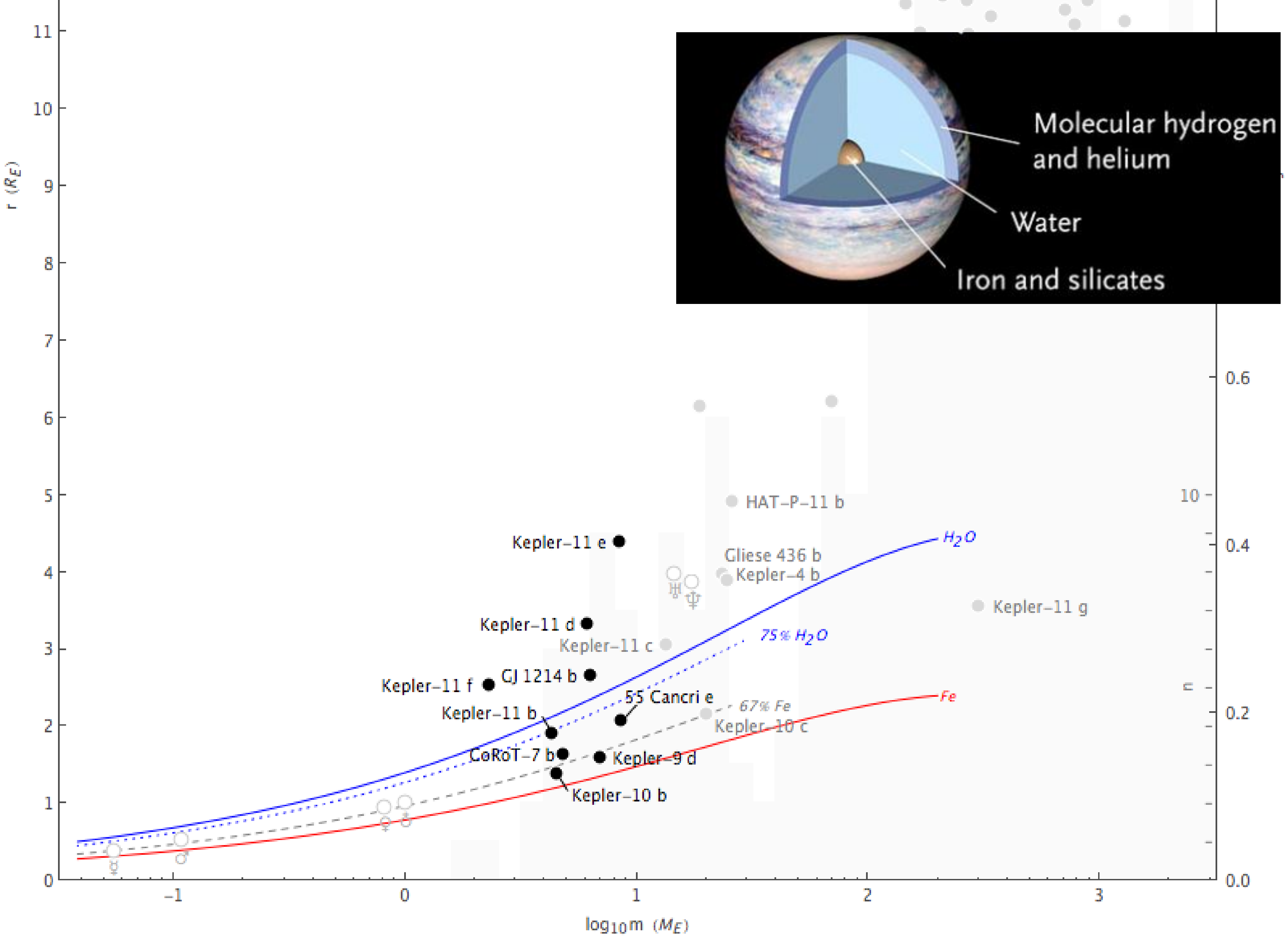
a
b
c
d
e
f
Detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
–5
0
5
t – t mid-transit (h)


a
b
c
d
e
f
1.0005
1.0000
0.9995
0.9990
0.9985
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
Detrended flux
−5
0
5
$t - t_{\mathrm{mid\text{-}transit}}$ (h)


a
b
c
d
e
f
30
20
10
0
−10
−20
−30
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
Observed minus calculated mid-times of planetary transits (min)
0
100
200
300
400
t [BJD] − 2,455,000

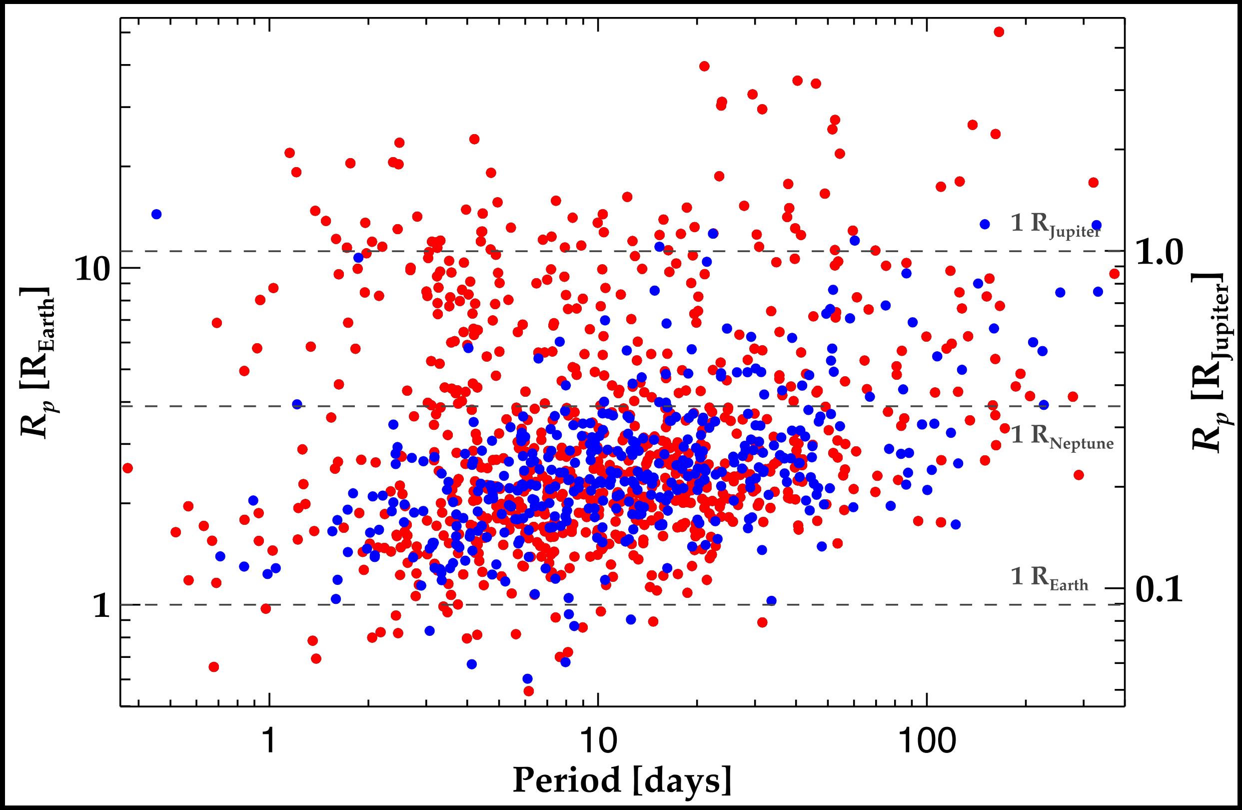

log10m (MJ)
r (RE)
r (RJ)
log10m (ME)
HAT-P-11 b
Gliese 436 b
Kepler-4 b
Kepler-11 e
Kepler-11 d
Kepler-11 c
Kepler-11 f
GJ 1214 b
Kepler-11 b
55 Cancri e
CoRoT-7 b
Kepler-9 d
Kepler-10 b
Kepler-10 c
Kepler-11 g
H2O
75% H2O
67% Fe
Fe


Molecular hydrogen and helium
Water
Iron and silicates



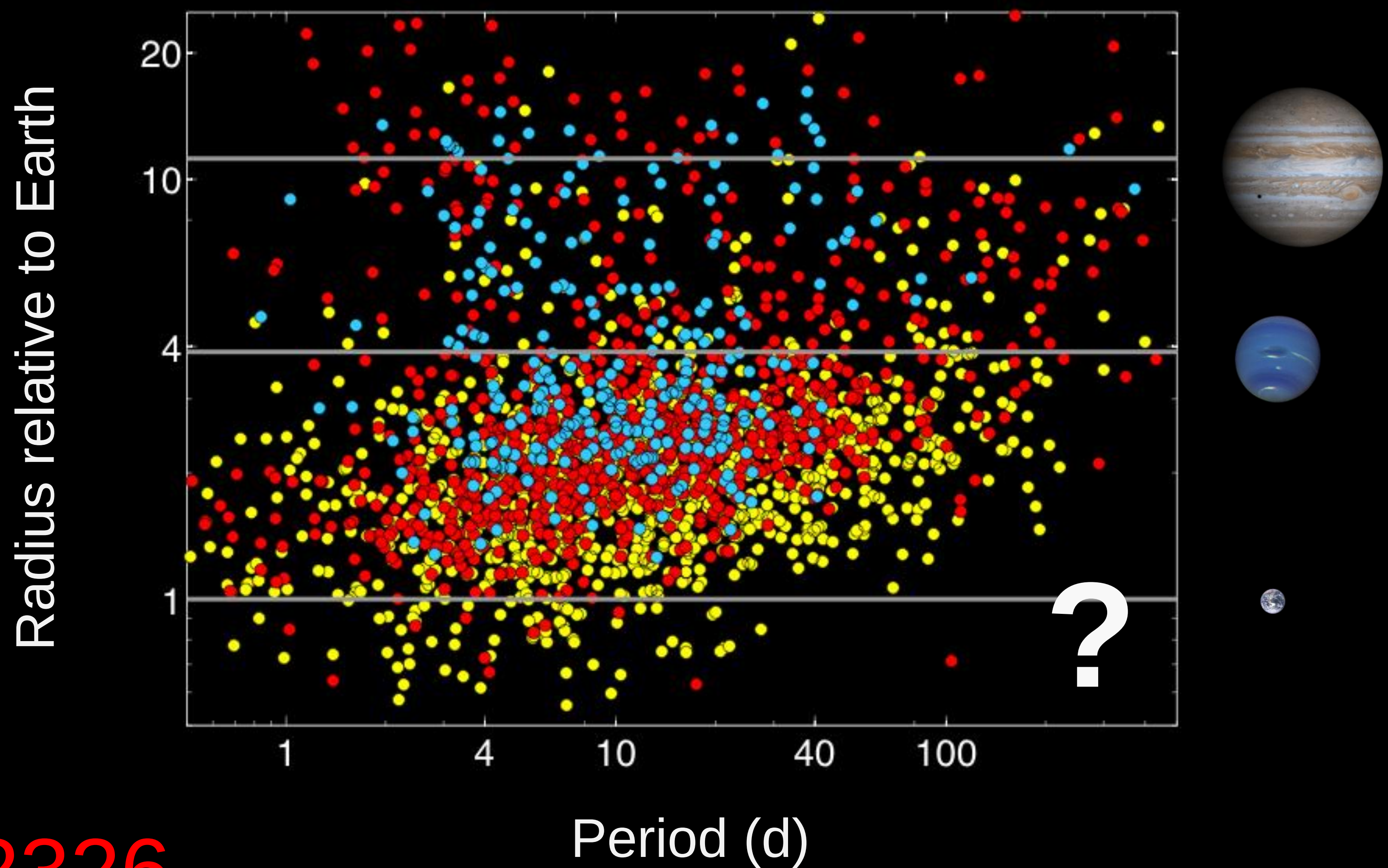
Molecular hydrogen and helium
Water
Iron and silicates
r $(R_E)$
$\log_{10} m$ $(M_E)$
$H_2O$
75% $H_2O$
67% Fe
Fe
Kepler–11 e
Kepler–11 d
Kepler–11 c
Kepler–11 f
GJ 1214 b
Kepler–11 b
55 Cancri e
CoRoT–7 b
Kepler–9 d
Kepler–10 b
Kepler–10 c
HAT–P–11 b
Gliese 436 b
Kepler–4 b
Kepler–11 g

# Kepler: 827 Single Planet Systems Detected

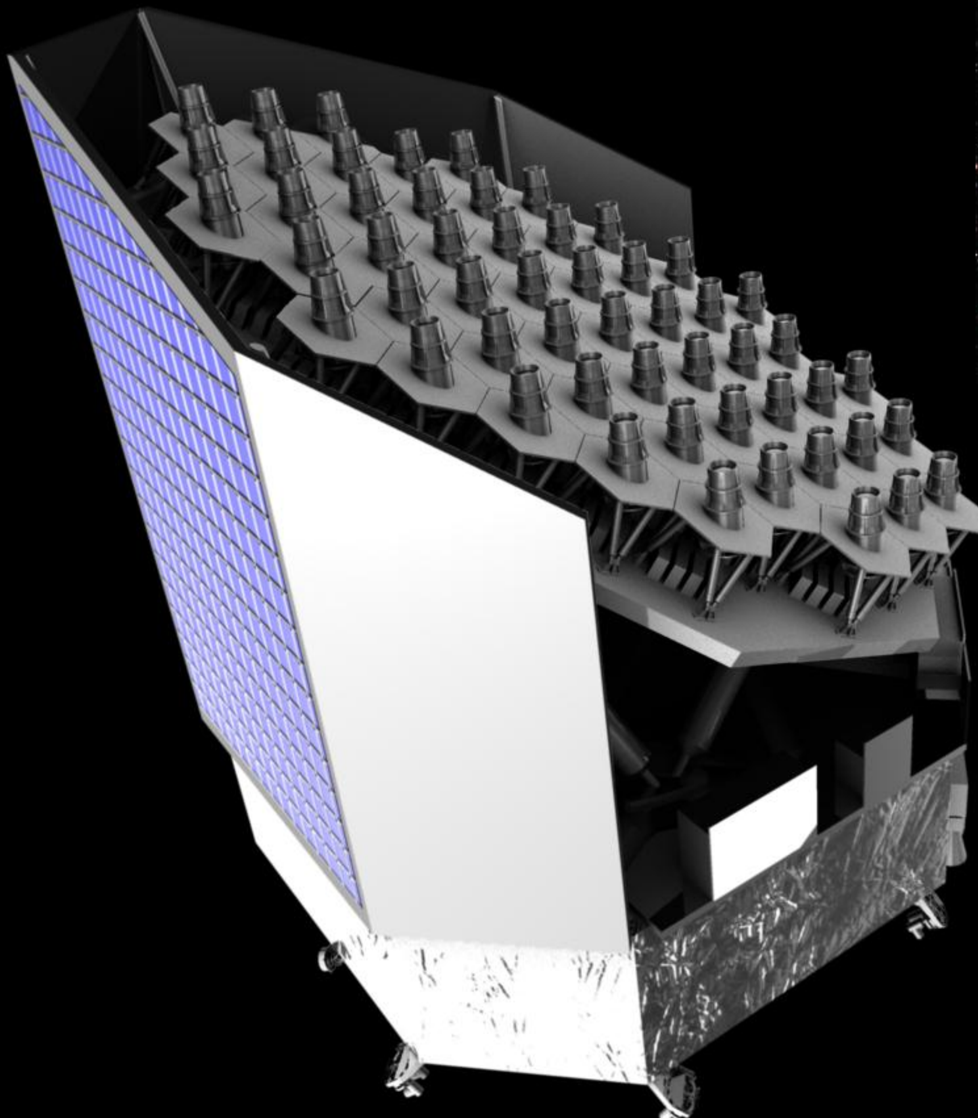


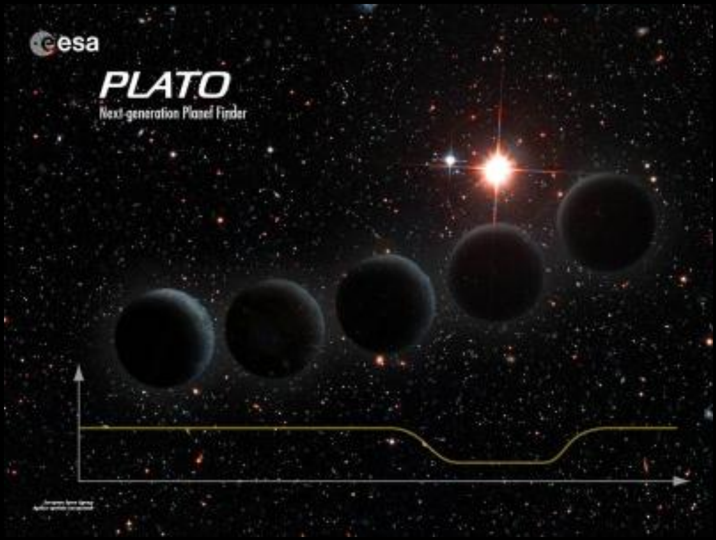

408 candidates in 170 multiple systems

# Kepler is extended to the end 2016




2326




esa
PLATO
Next-generation Planet Finder