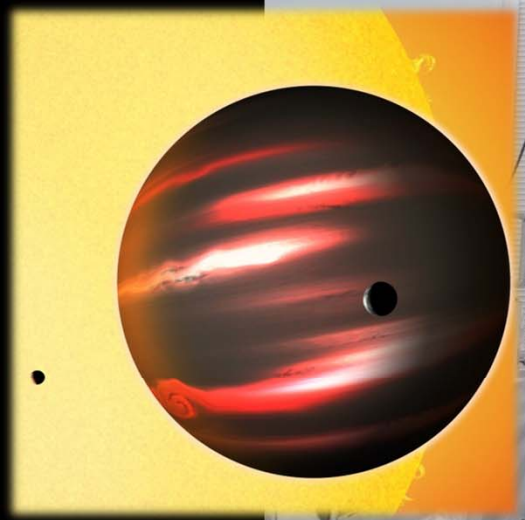
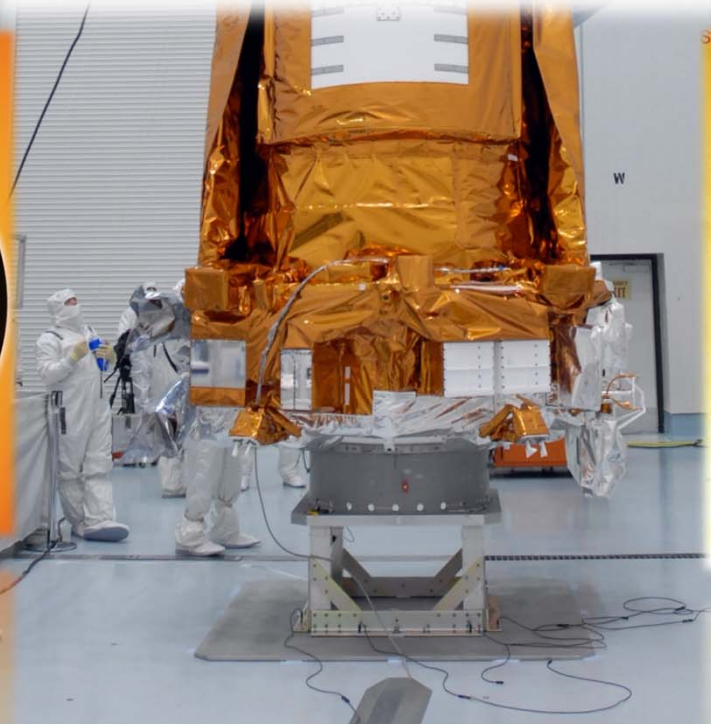
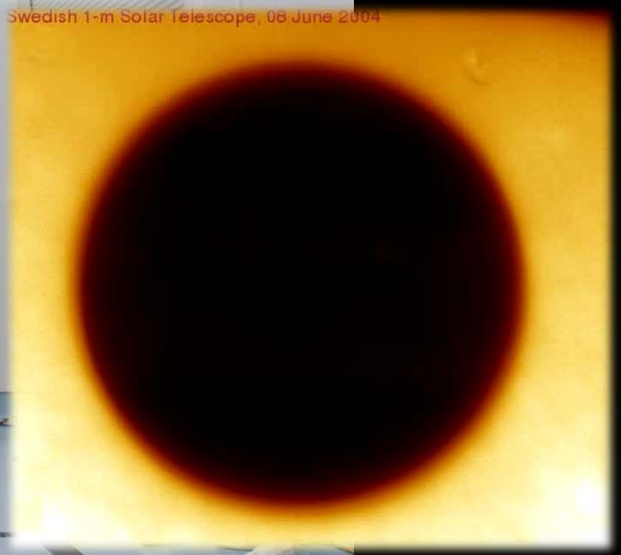
Hans Kjeldsen, Stellar Astrophysics Centre, Aarhus Universitet

The KEPLER mission:
Changing our view of stars and exoplanets

- The Kepler mission
- Asteroseismology and stars
- Transits and exoplanets

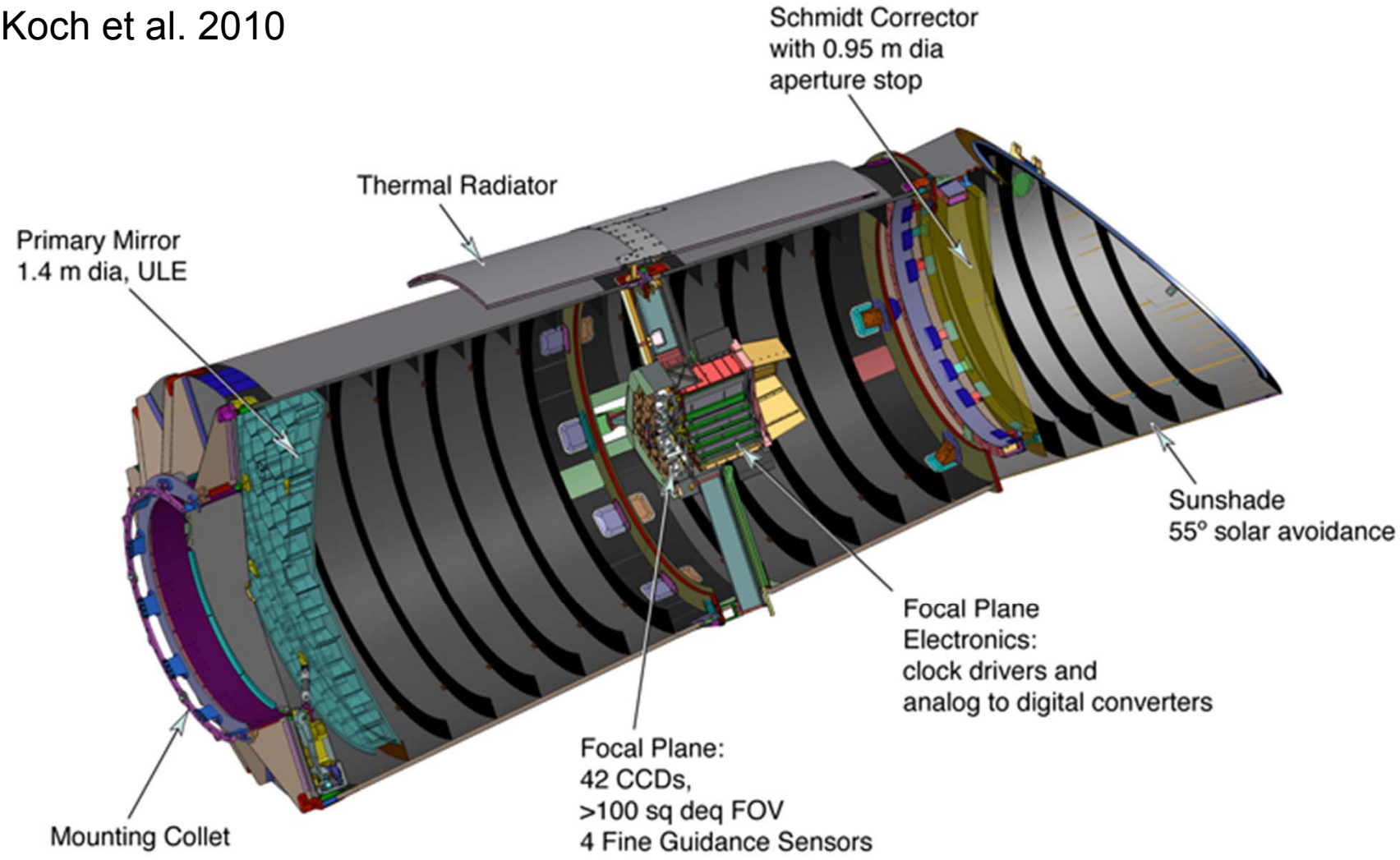






Kepler Photometer

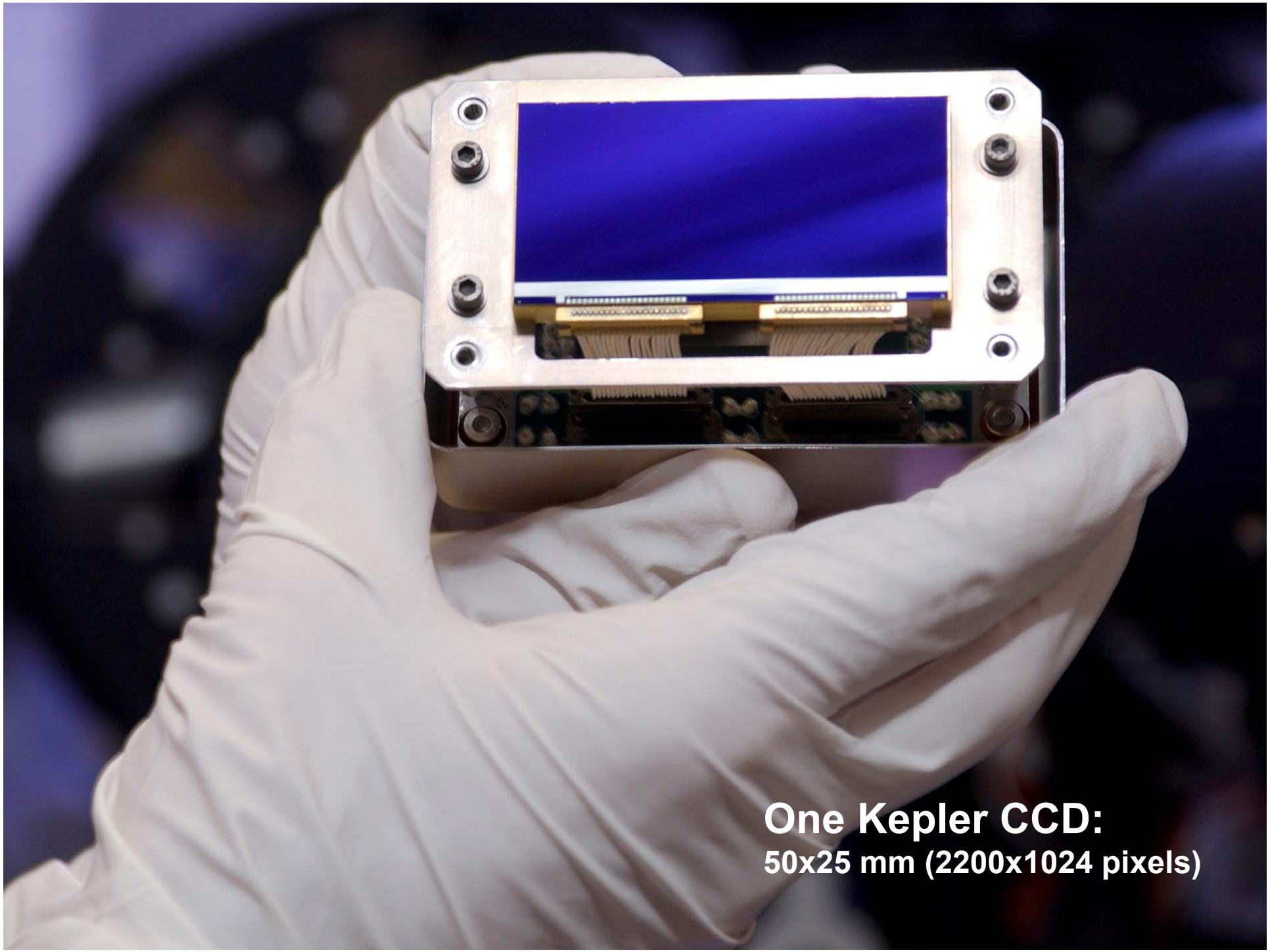
Koch et al. 2010



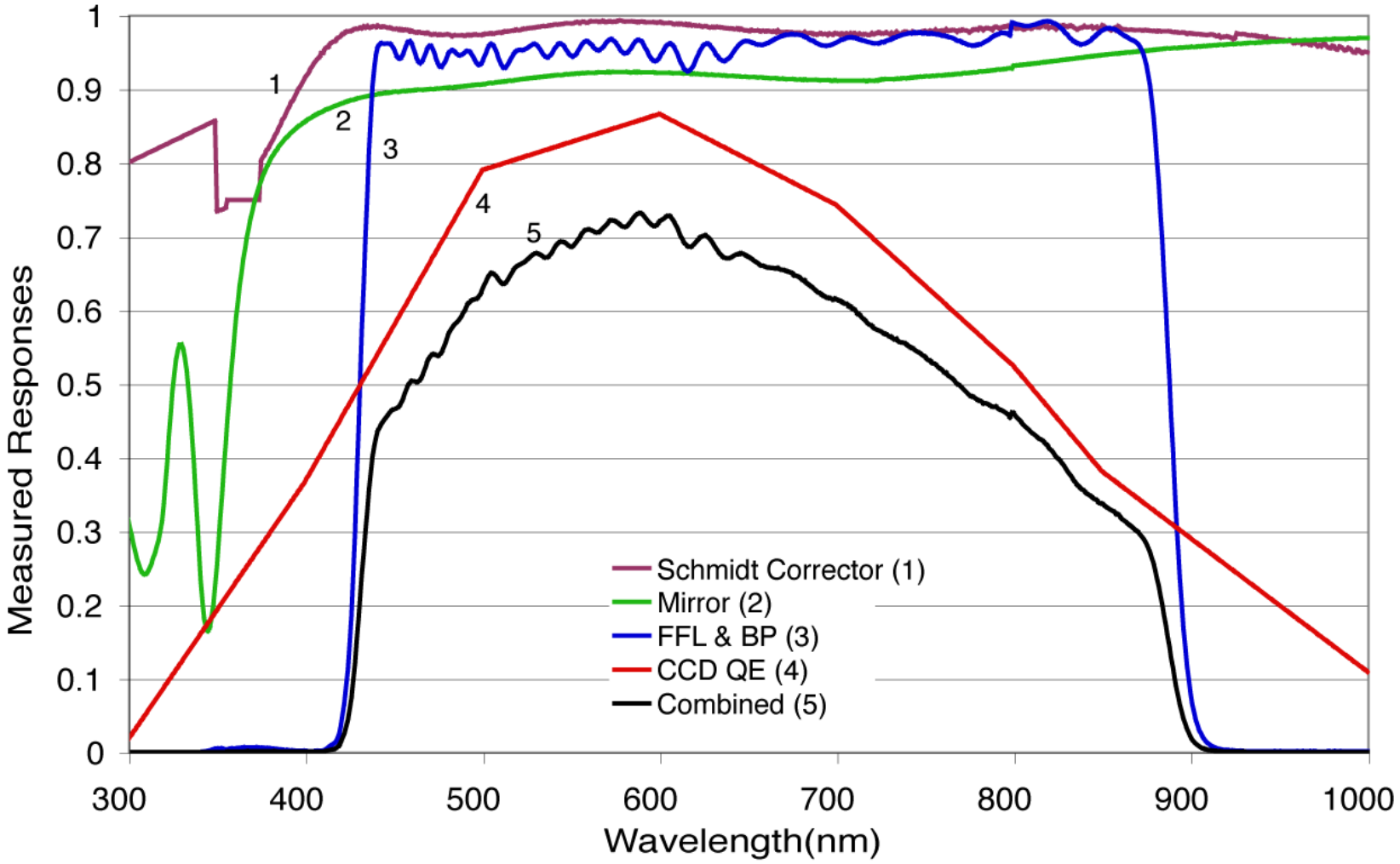
1.4 m Primary Mirror


95 cm Schmidt Corrector

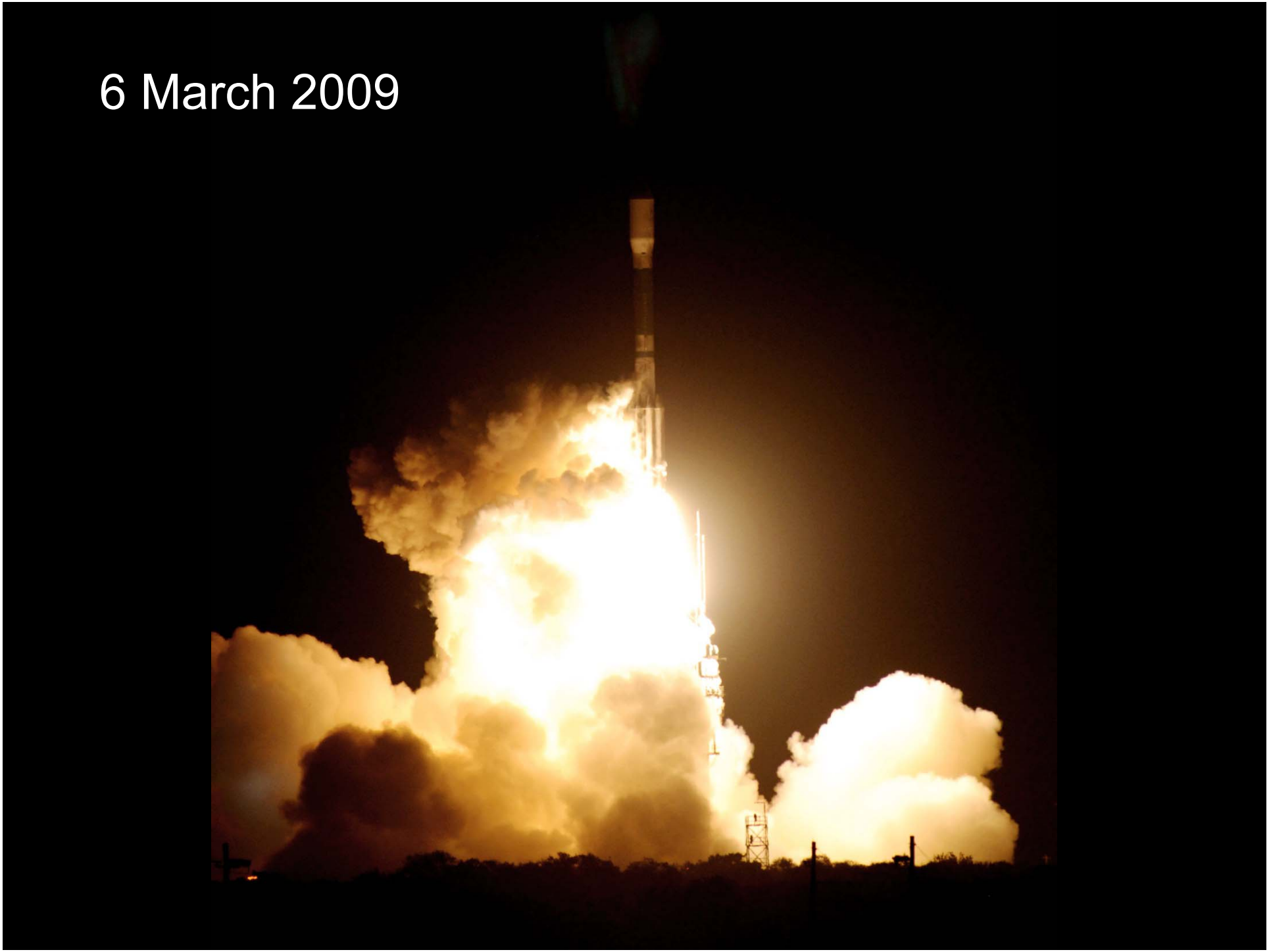

Focal Plane Assembly
42 CCDs with Field Flattener Lenses

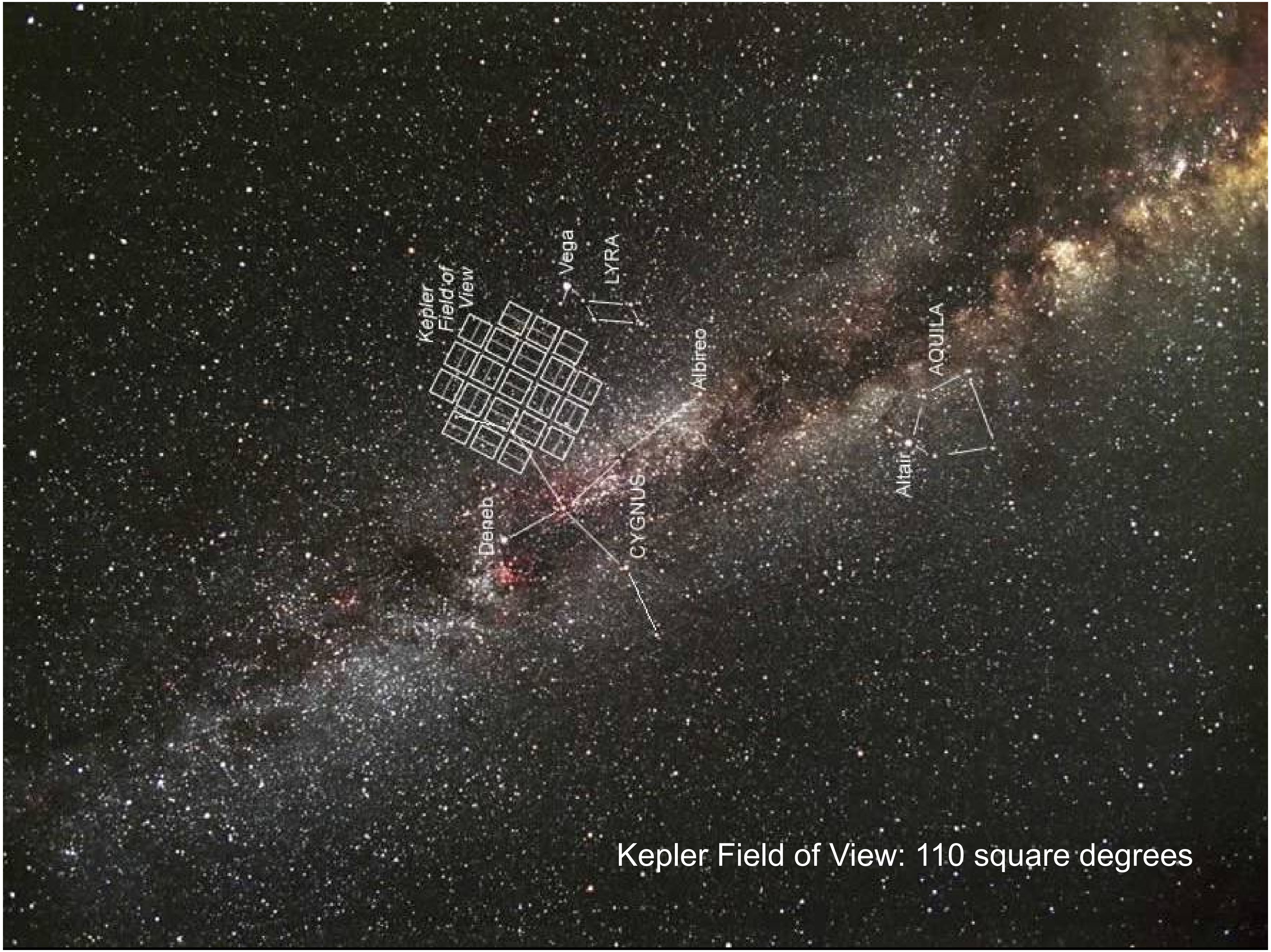

One Kepler CCD:
50x25 mm (2200x1024 pixels)

Koch et al. 2010

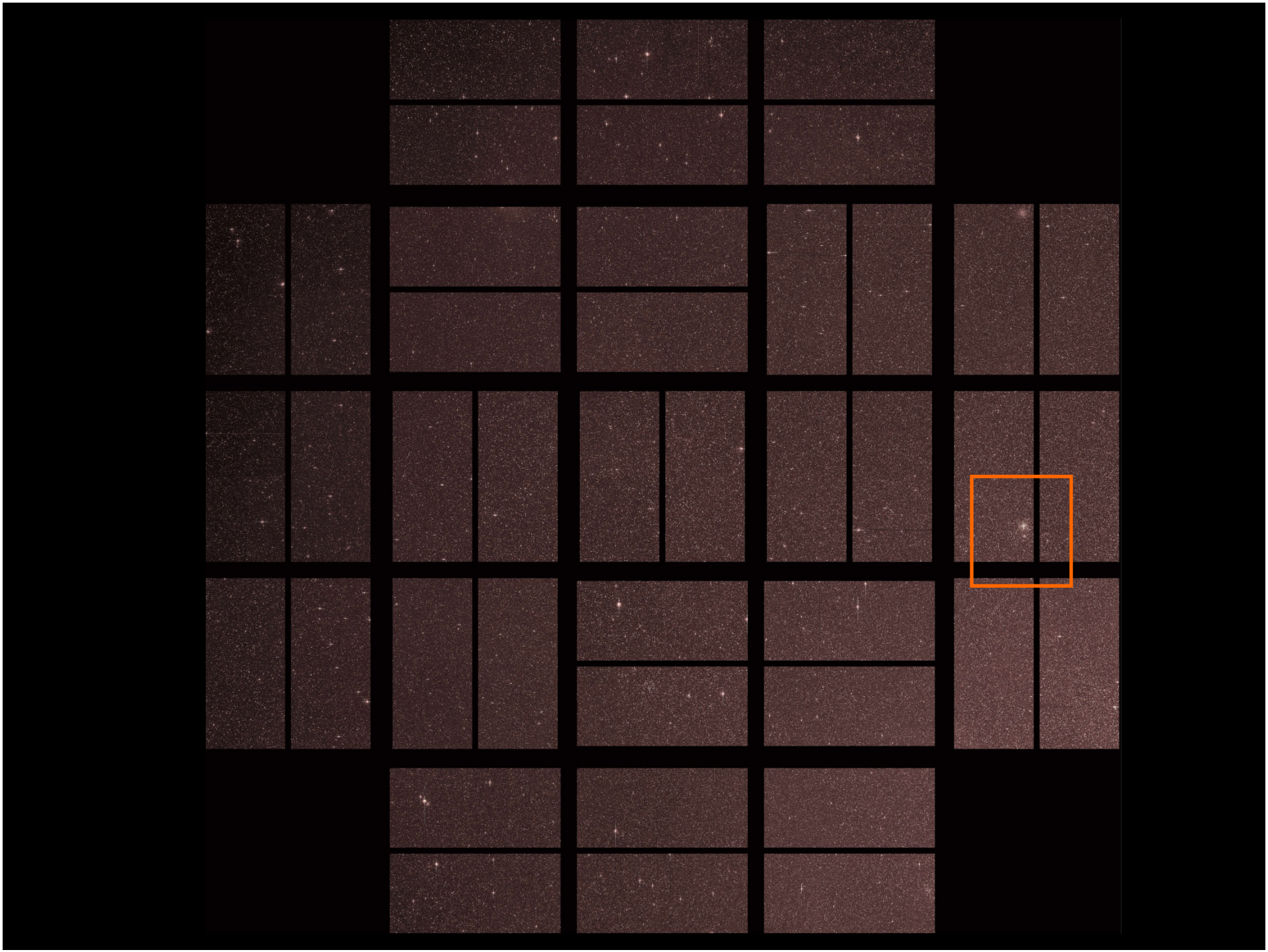


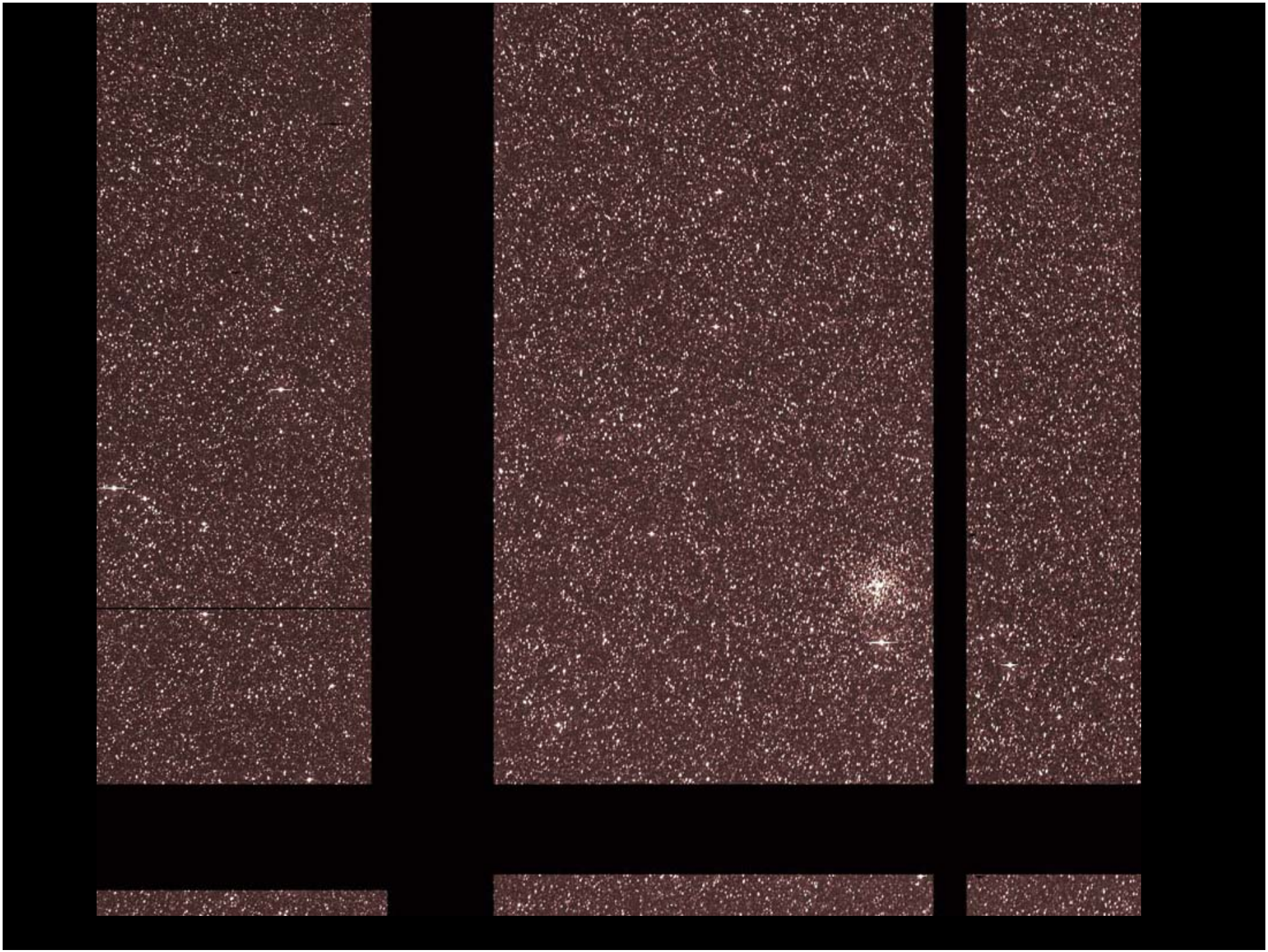
6 March 2009

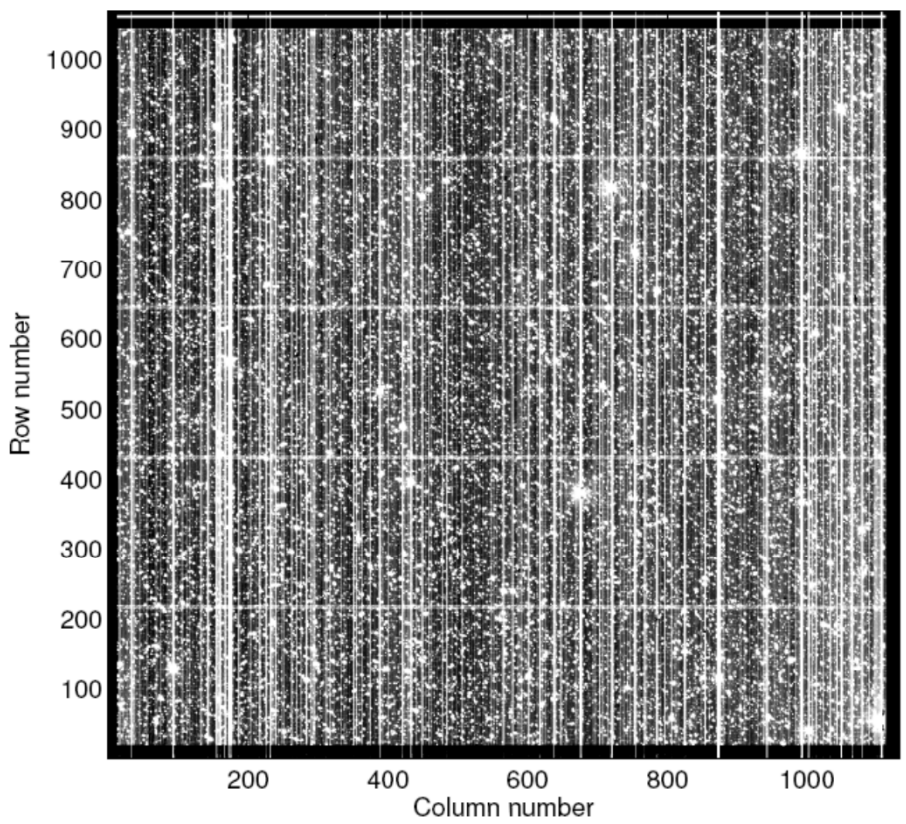




Kepler Field of View: 110 square degrees



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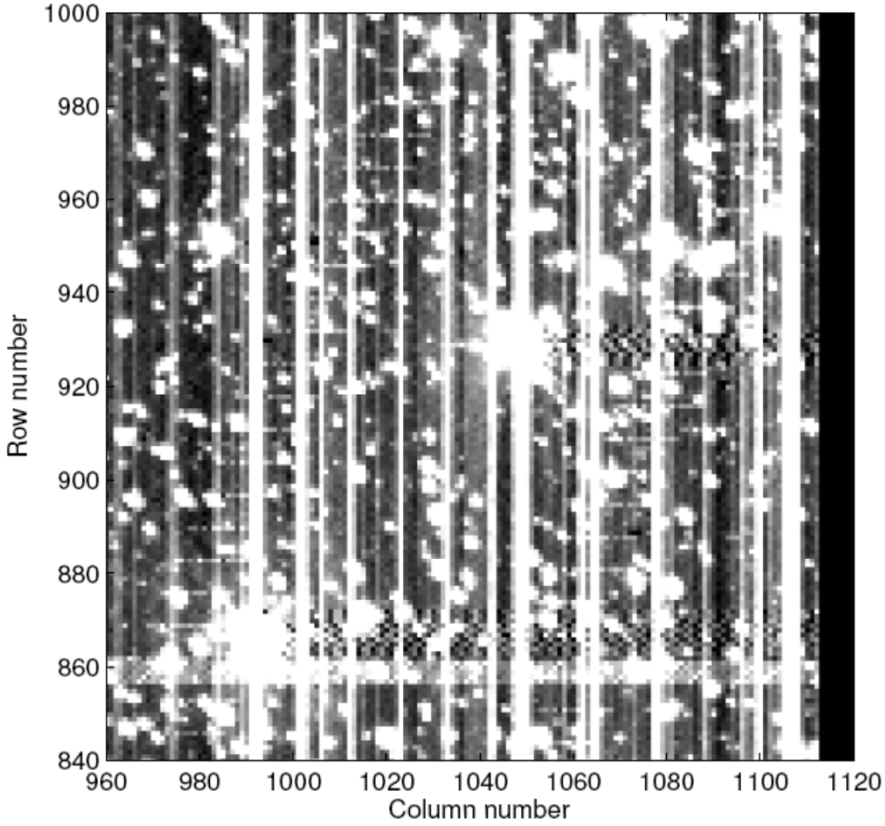
Column number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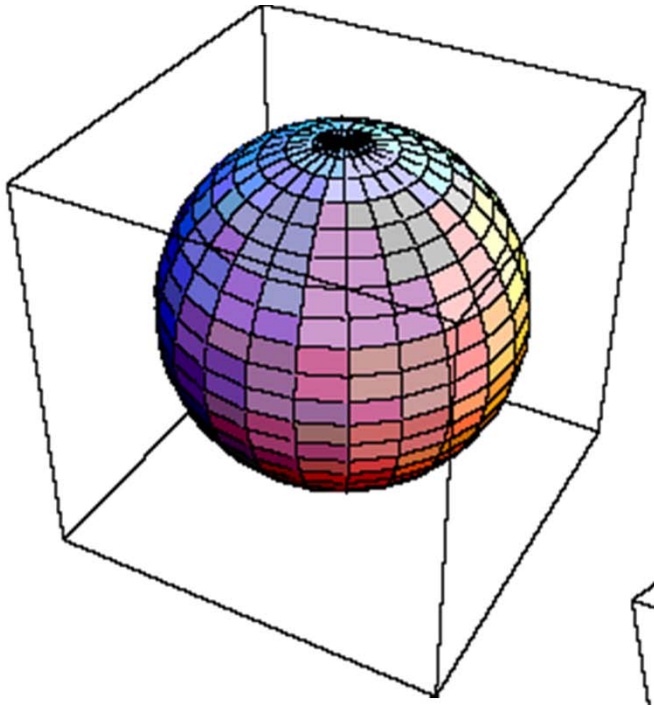
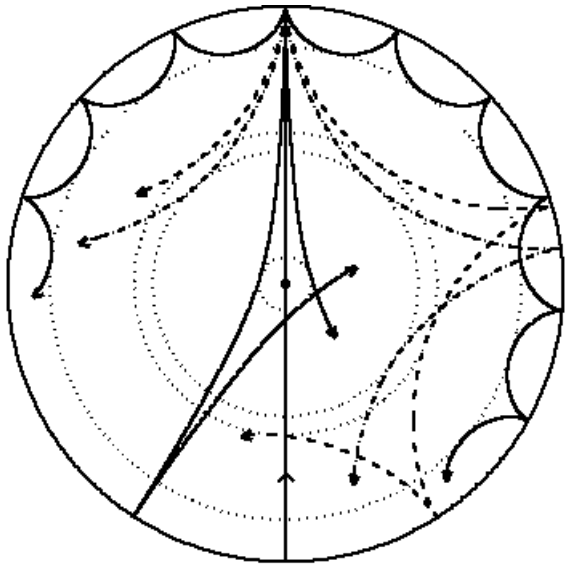
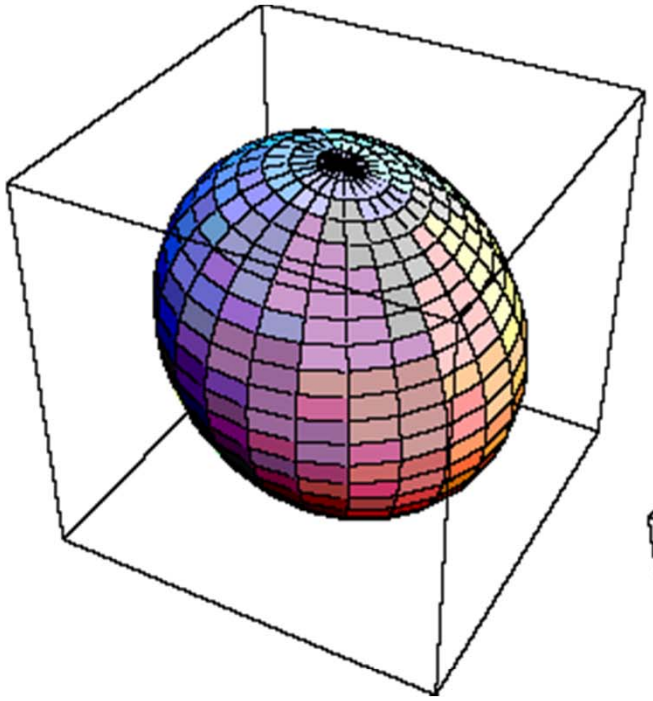
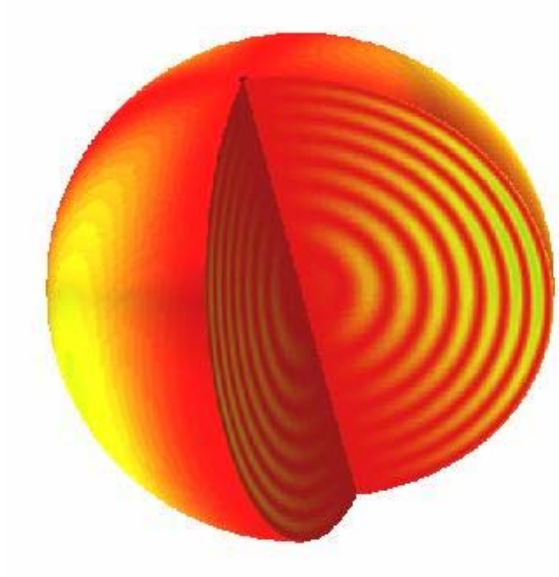
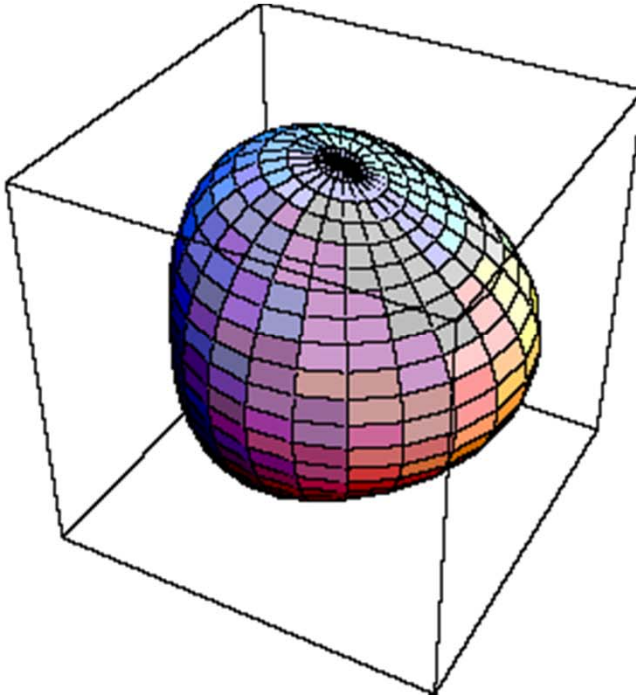
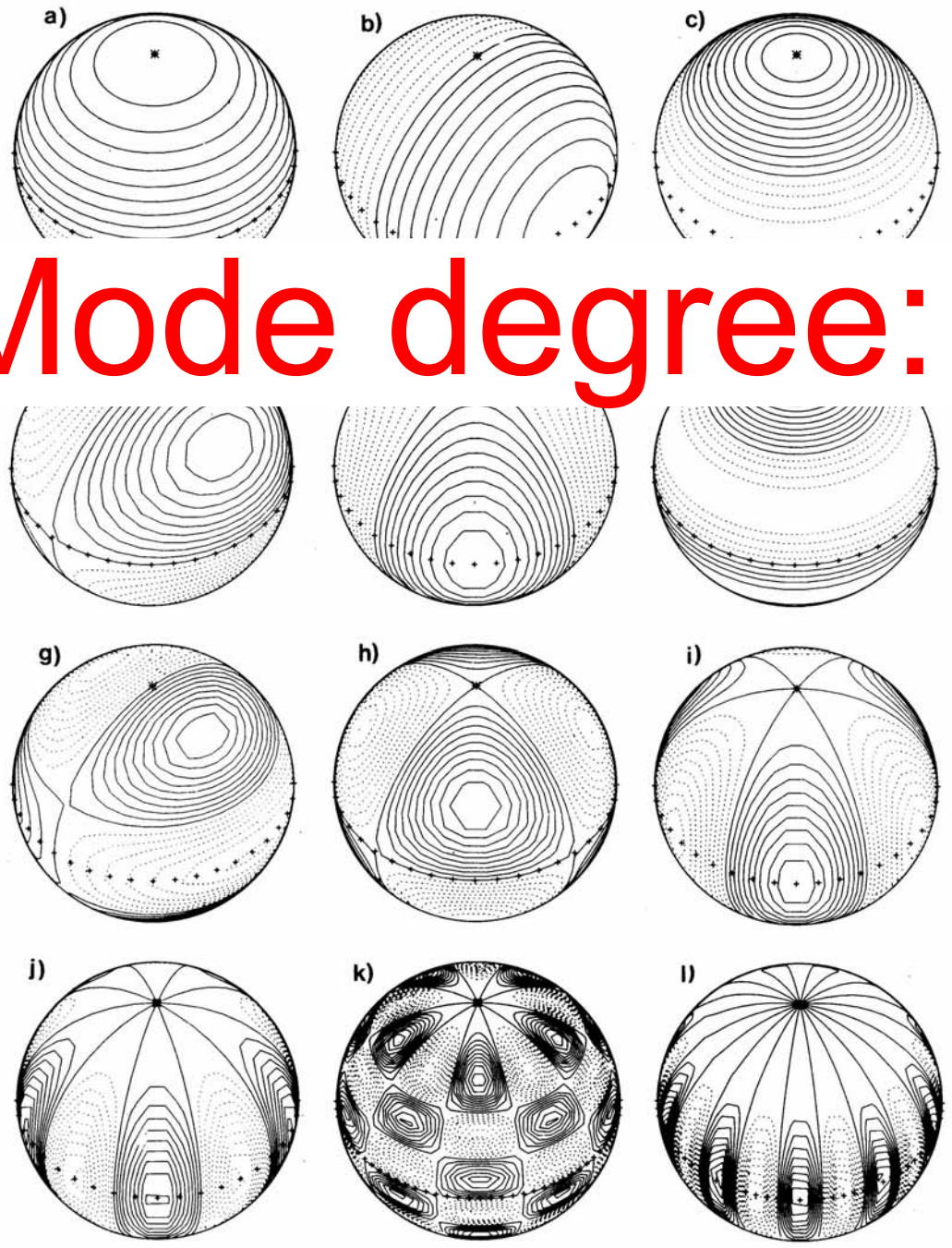








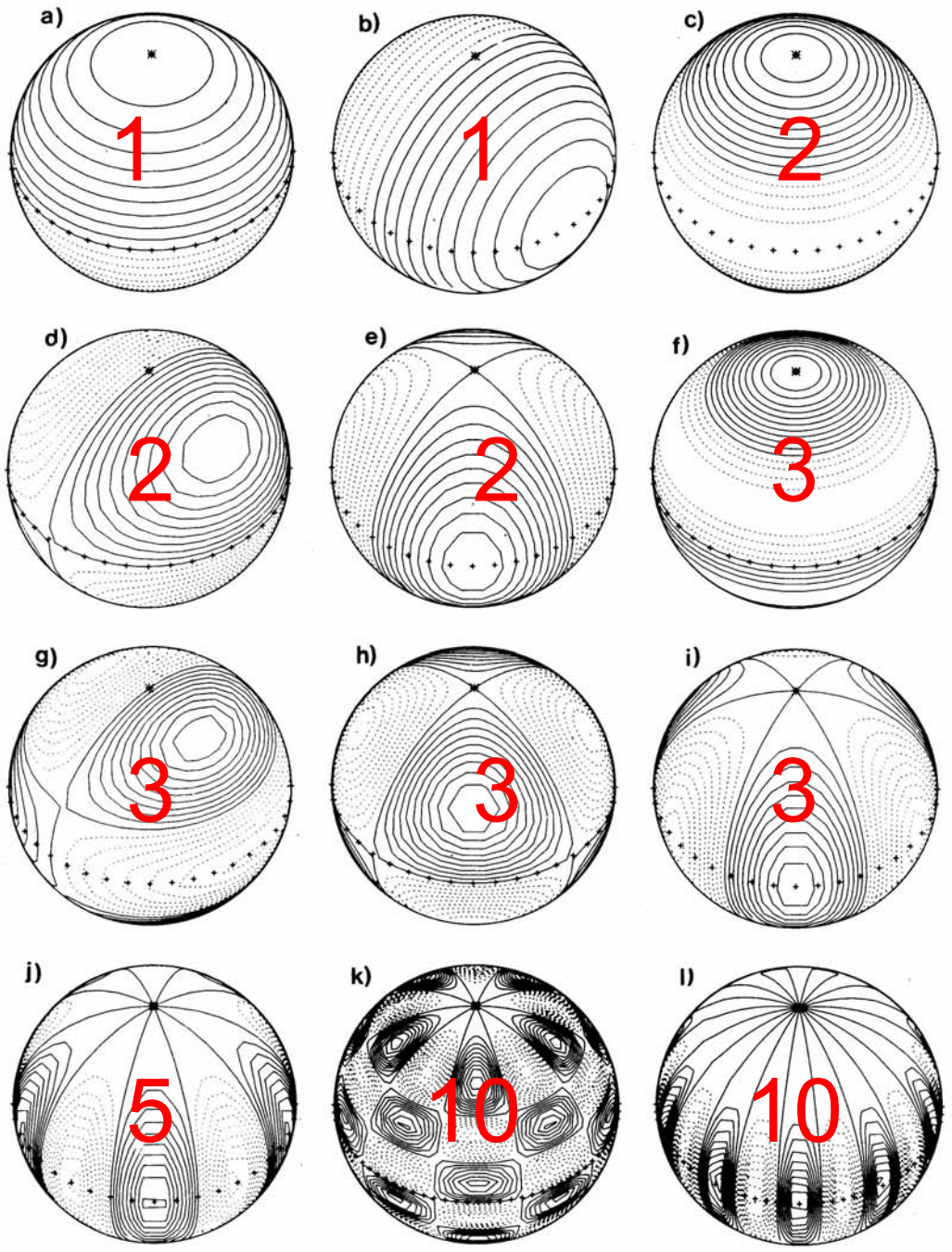


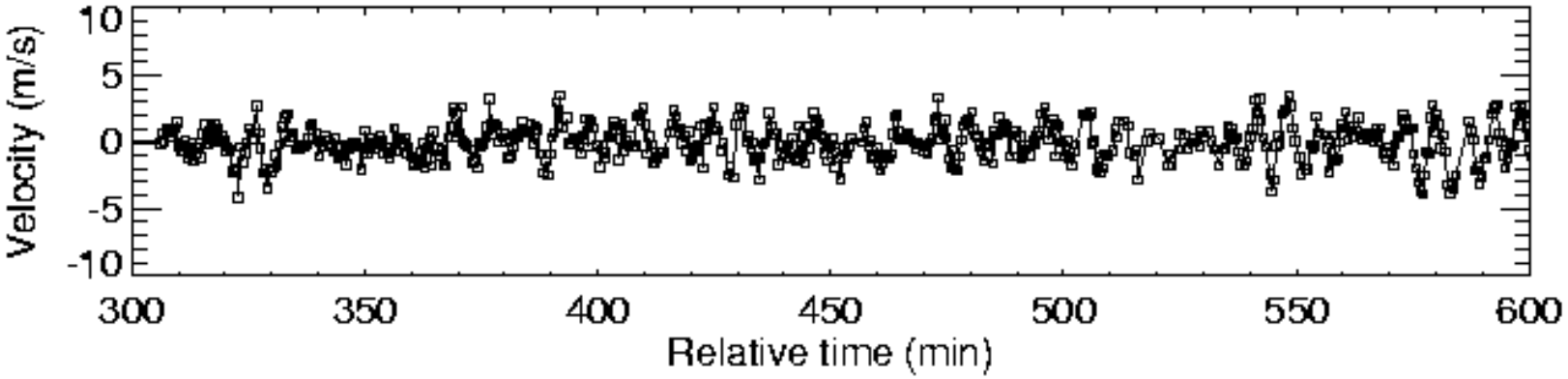


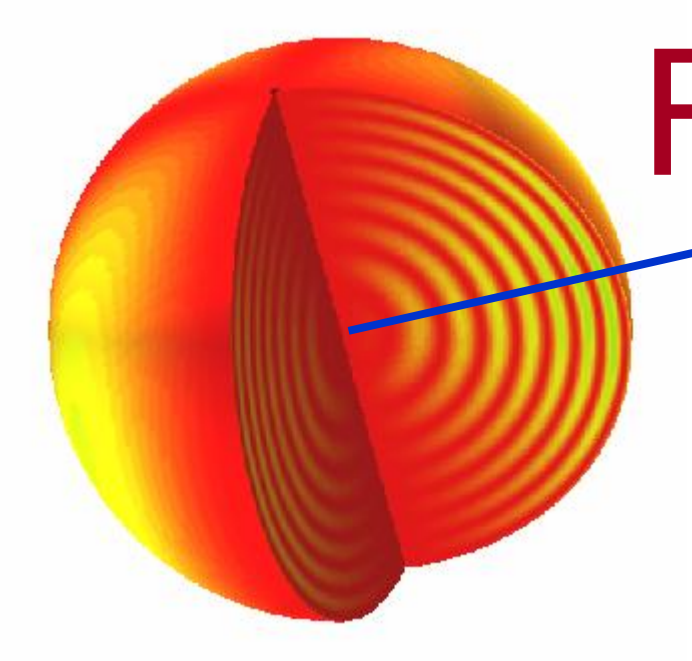
Mode degree: ℓ

ℓ=

0
Radial



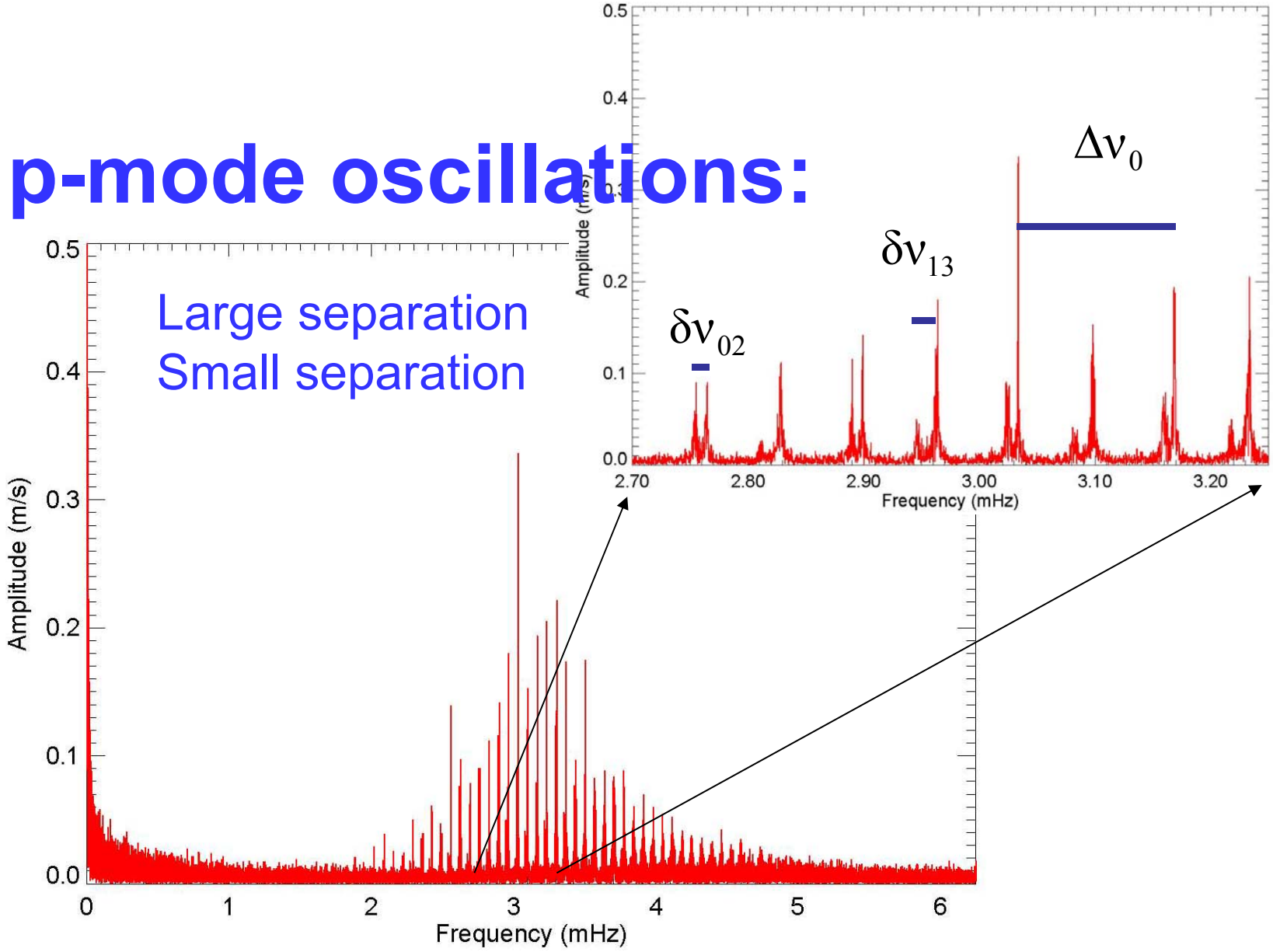


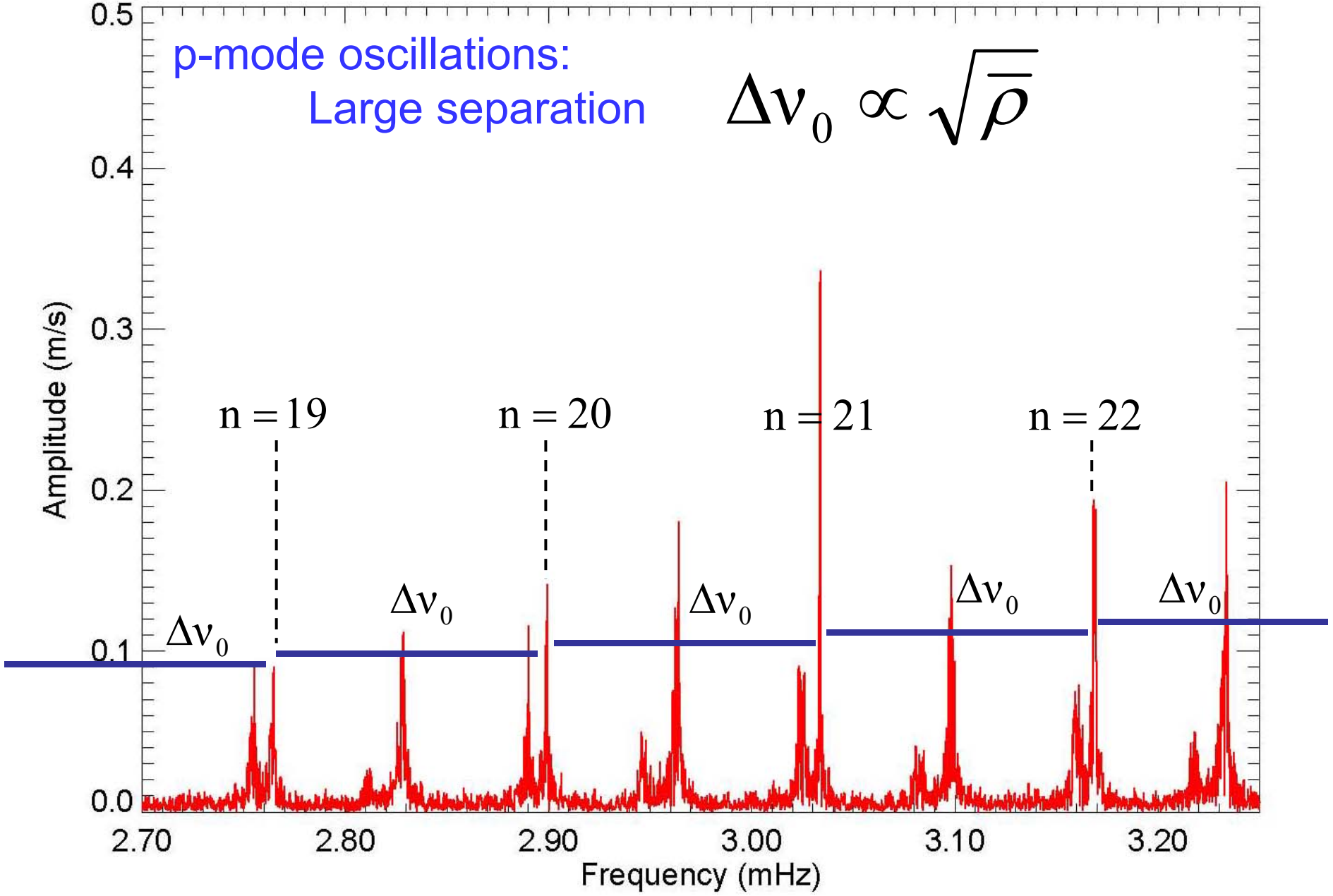


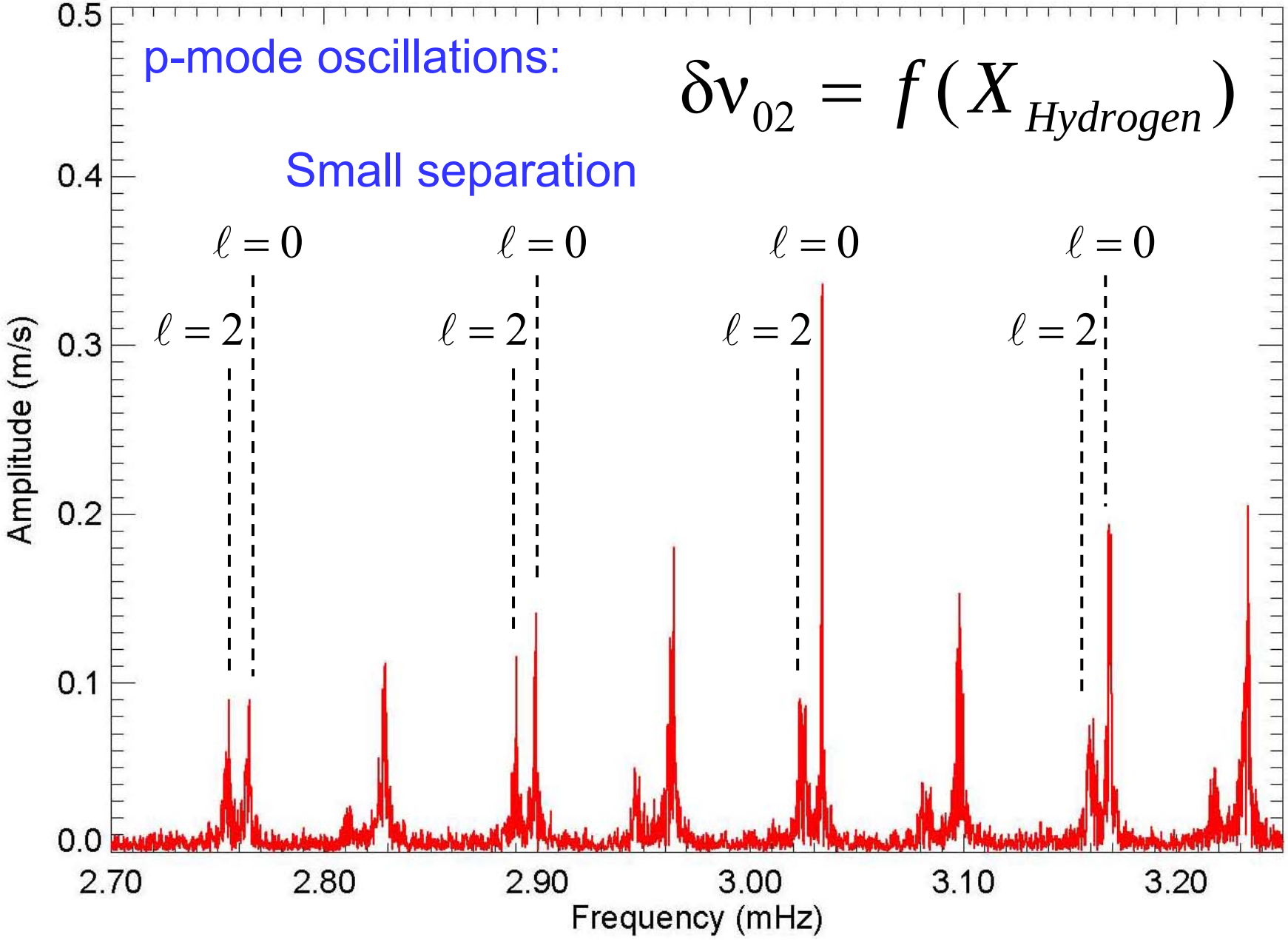
Radial order: n

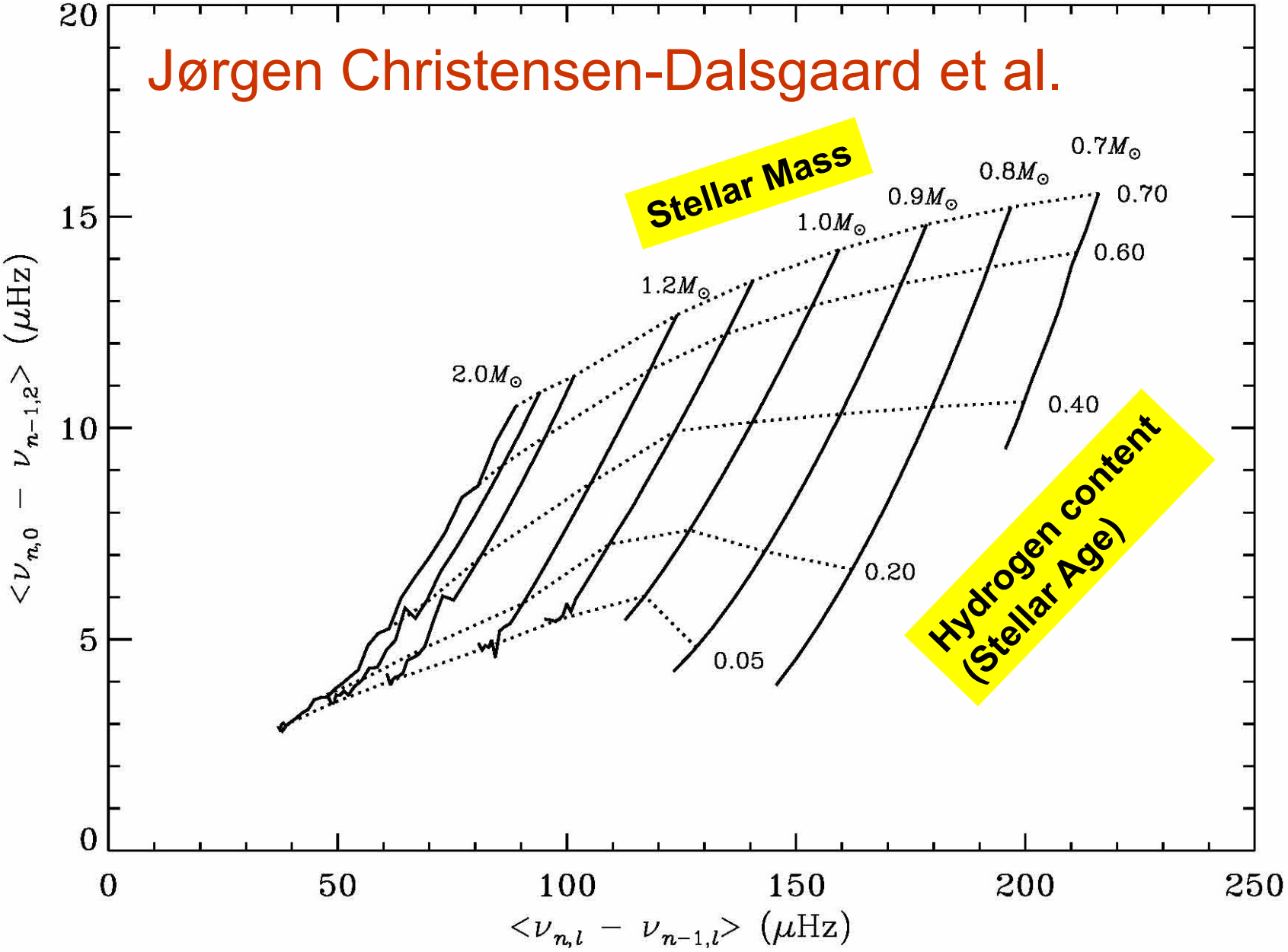
n = 17

p-mode oscillations:

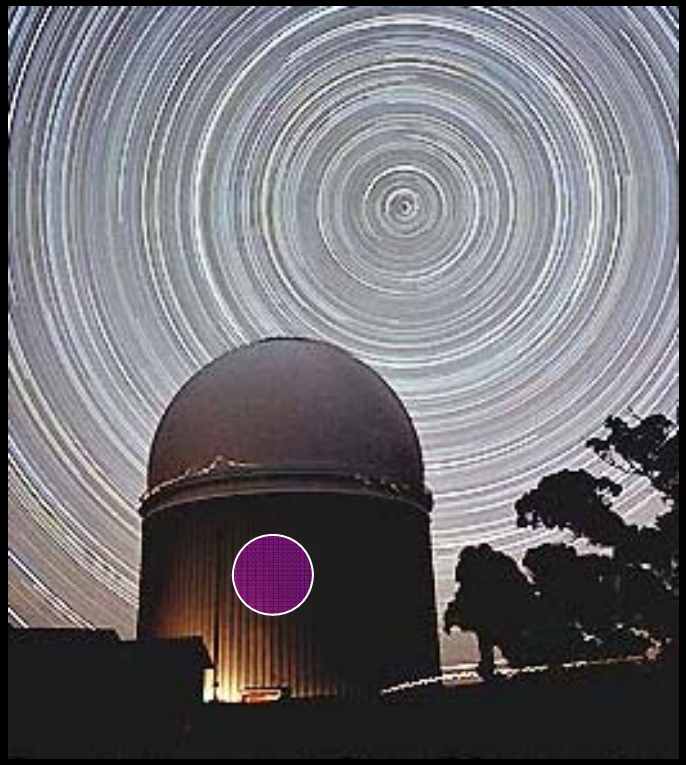



p-mode oscillations:
Large separation
$\Delta\nu_0 \propto \sqrt{\bar{\rho}}$
Amplitude (m/s)
0.0
0.1
0.2
0.3
0.4
0.5
n = 19
n = 20
n = 21
n = 22
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
$\Delta\nu_0$
2.70
2.80
2.90
3.00
3.10
3.20
Frequency (mHz)


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


Jørgen Christensen-Dalsgaard et al.
Stellar Mass
0.7$M_\odot$
0.8$M_\odot$
0.9$M_\odot$
1.0$M_\odot$
1.2$M_\odot$
2.0$M_\odot$
0.70
0.60
0.40
0.20
0.05
Hydrogen content
(Stellar Age)
$<\nu_{n,0} - \nu_{n-1,2}>$ (μHz)
$<\nu_{n,l} - \nu_{n-1,l}>$ (μHz)
0
5
10
15
20
0
50
100
150
200
250

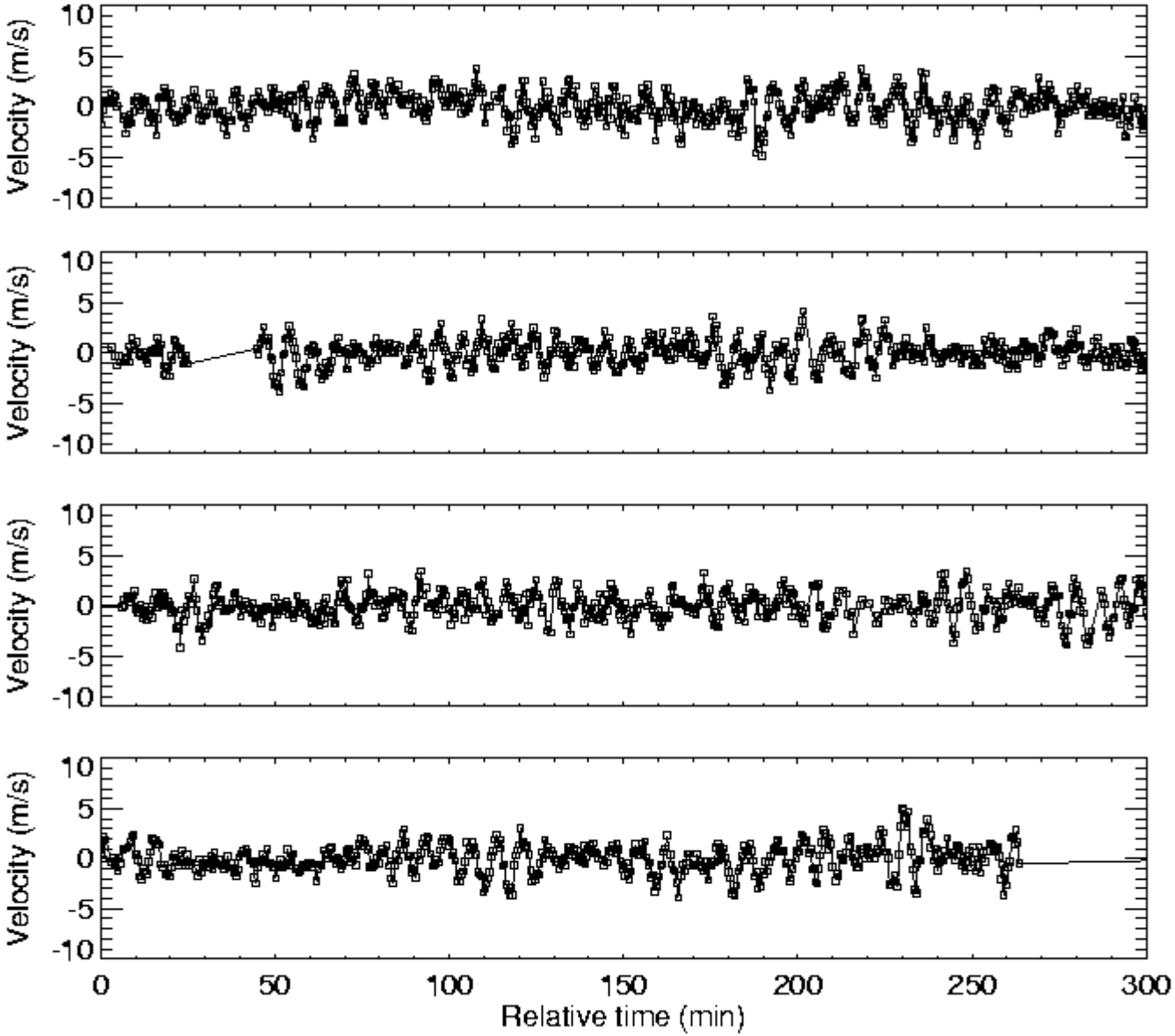
Before Kepler:
High precision radial velocities



UCLES at the AAT

UVES at the VLT

Velocities of α Cen A with UVES/VLT



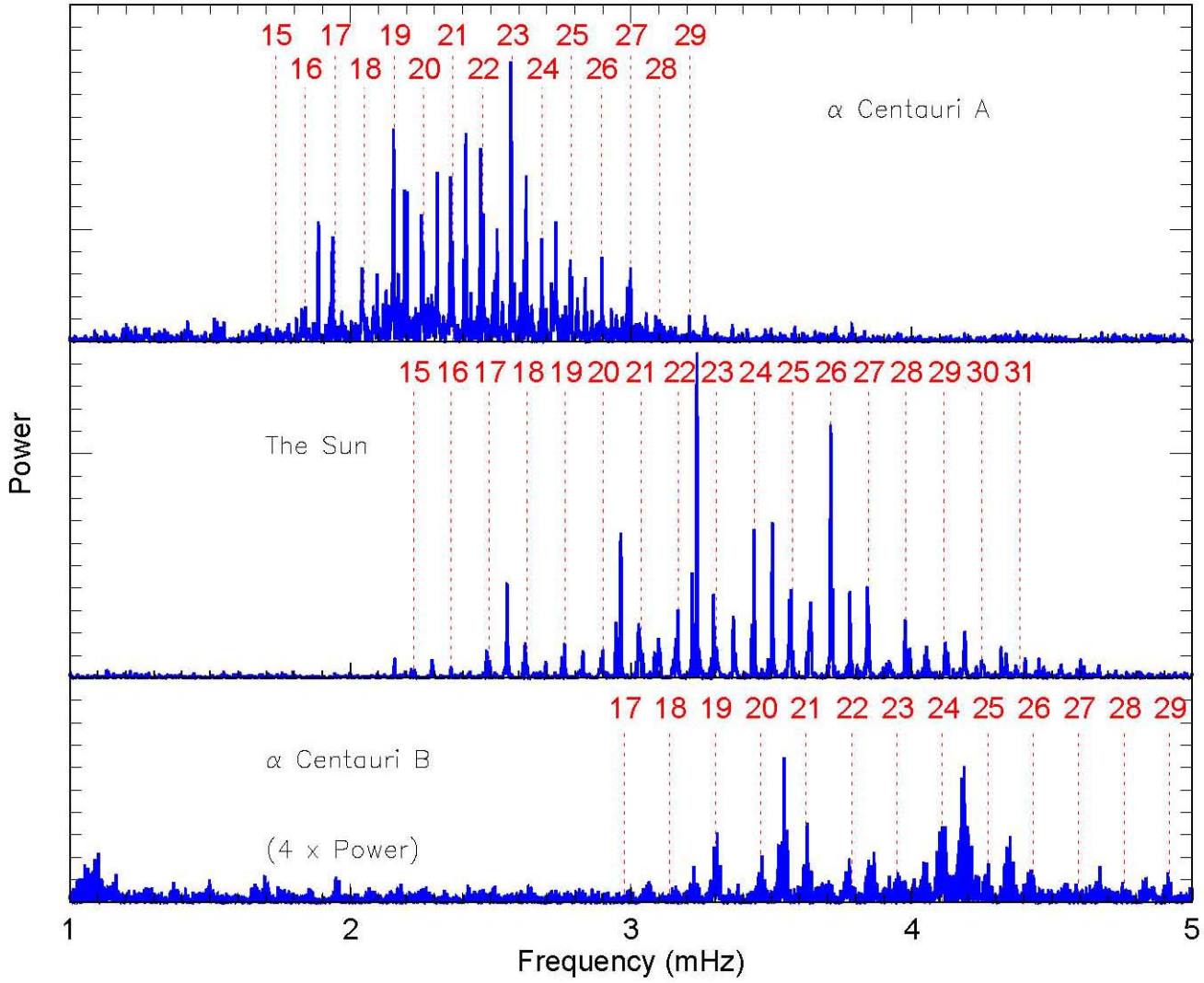
Precision: 50-70 cm/s. Cadence 26 seconds!

Large separations **Small separations**

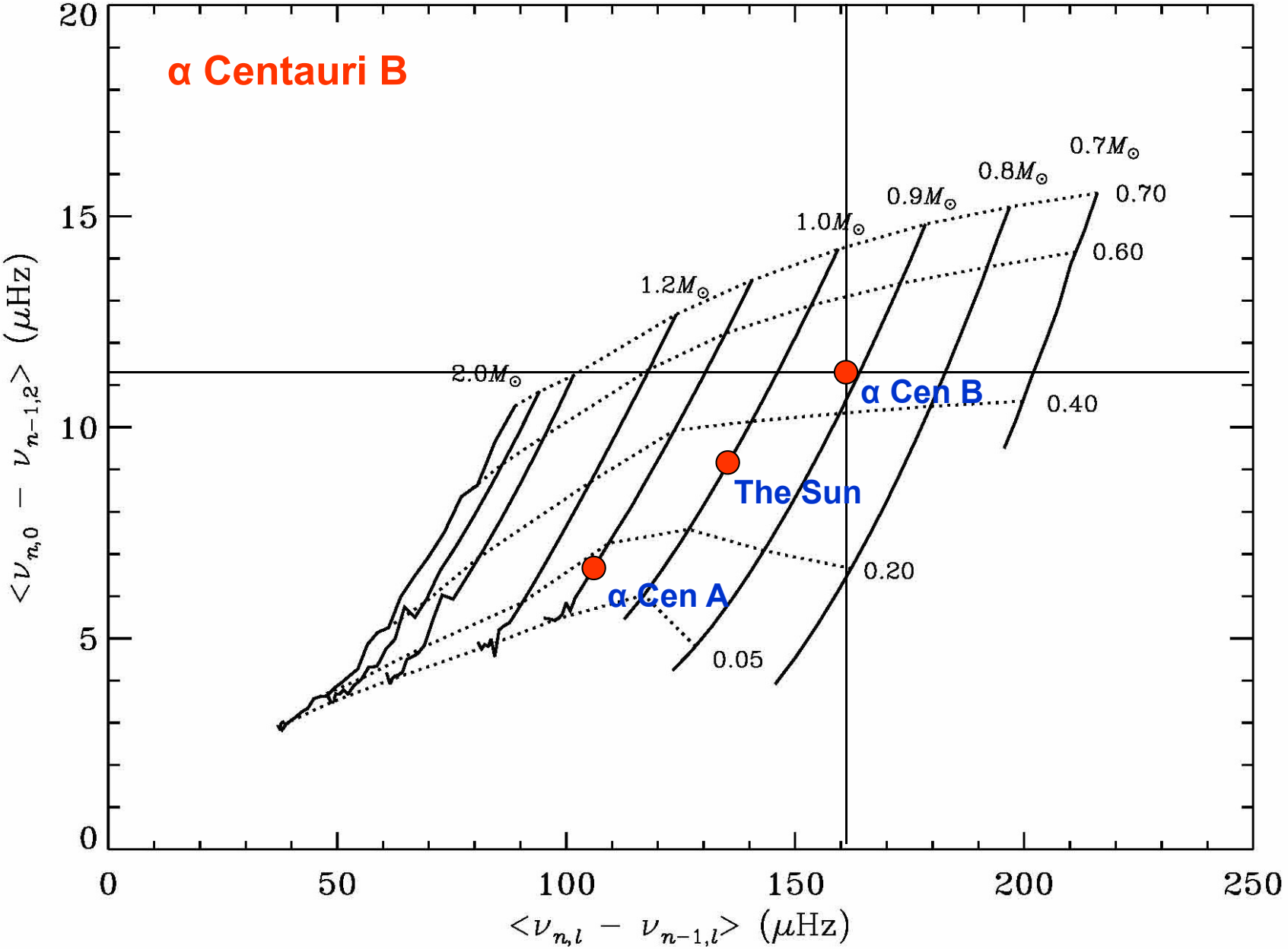
106 μHz **6.6 μHz**

135 μHz **9.2 μHz**

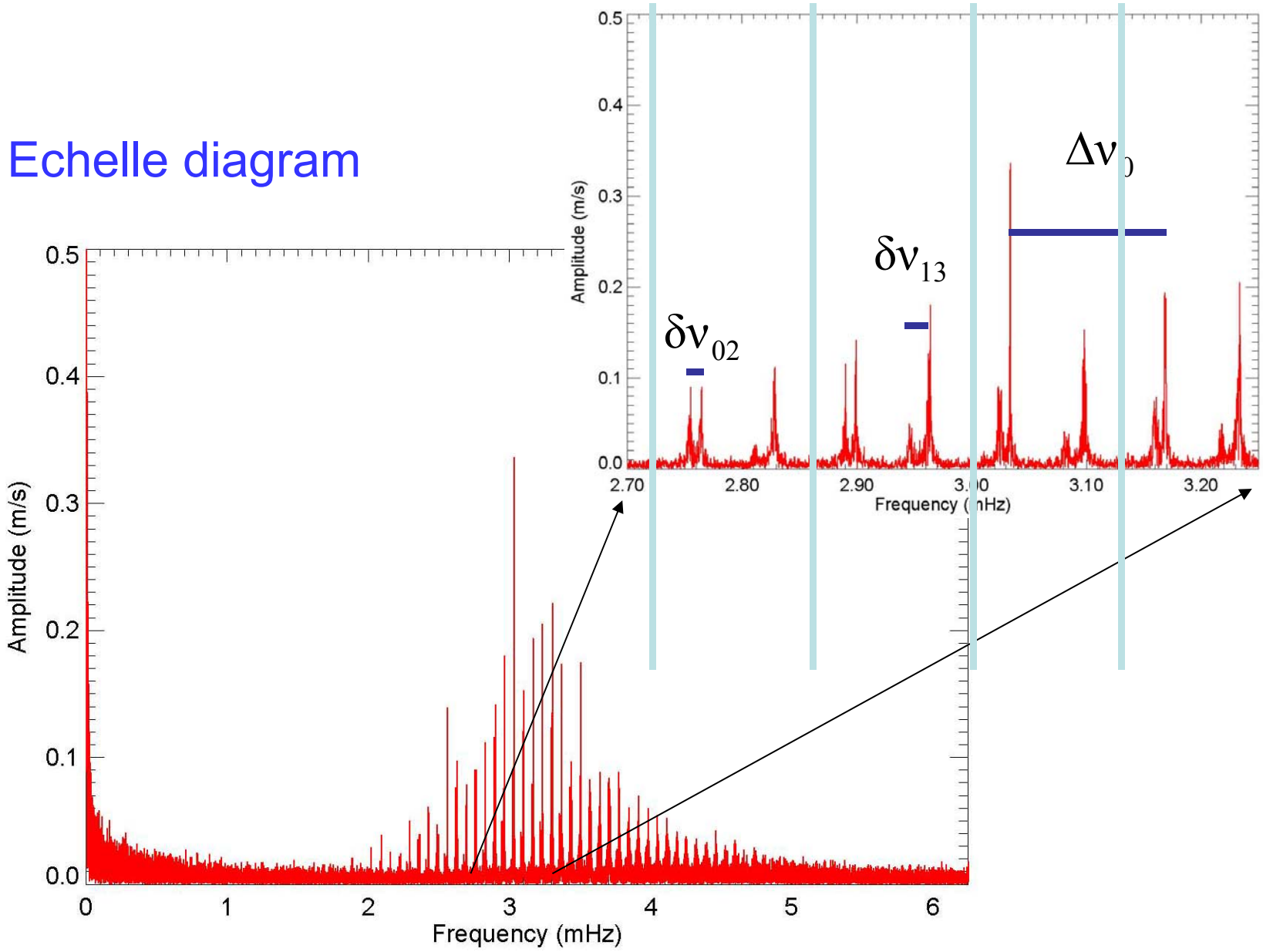
161 μHz **11.3 μHz**

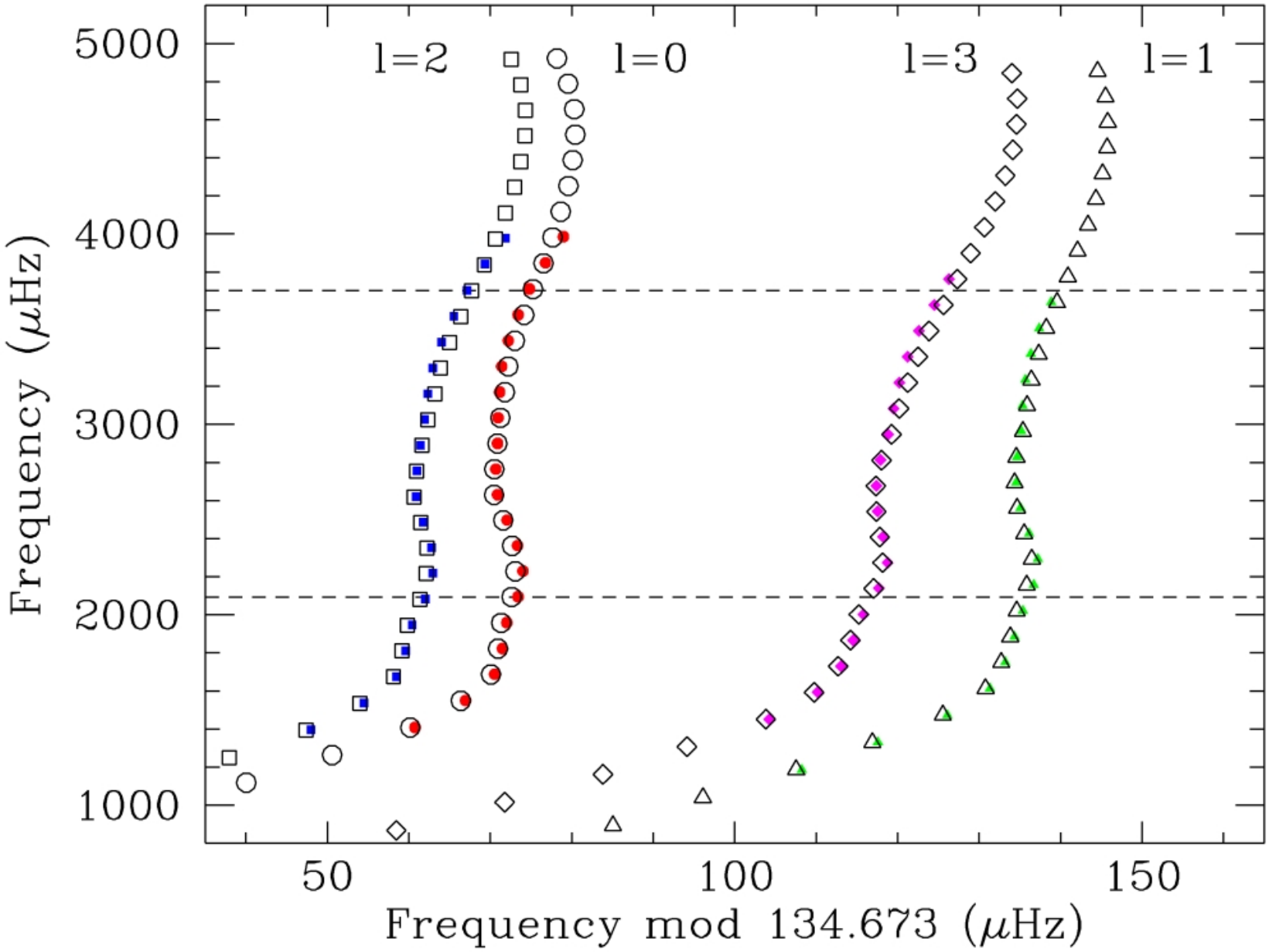


$\Delta\nu_0$ $\delta\nu_{02}$


α Centauri B
0.7$M_\odot$
0.8$M_\odot$
0.9$M_\odot$
1.0$M_\odot$
1.2$M_\odot$
2.0$M_\odot$
0.70
0.60
0.40
0.20
0.05
α Cen B
The Sun
α Cen A
$<\nu_{n,0} - \nu_{n-1,2}>$ (μHz)
$<\nu_{n,l} - \nu_{n-1,l}>$ (μHz)
0
5
10
15
20
0
50
100
150
200
250

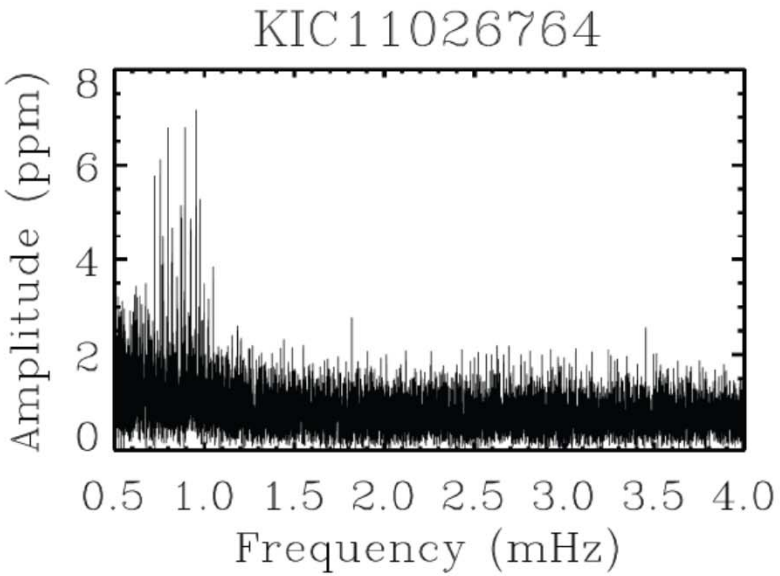
Echelle diagram

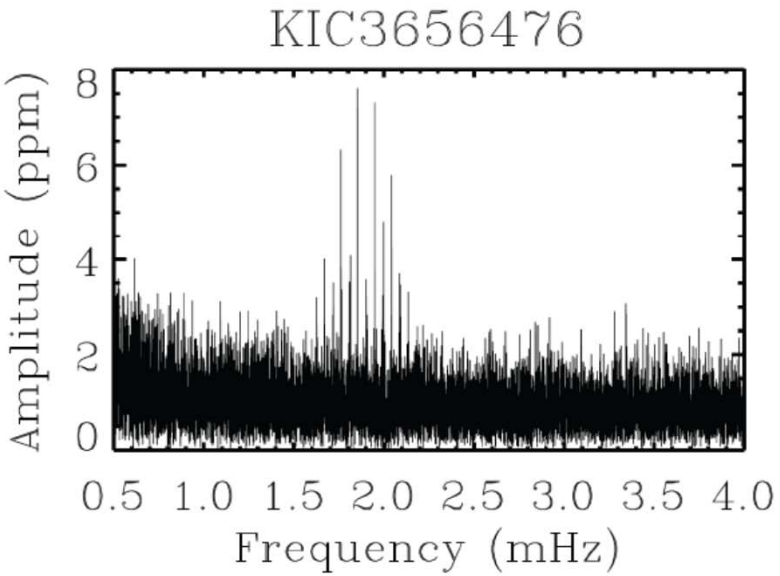


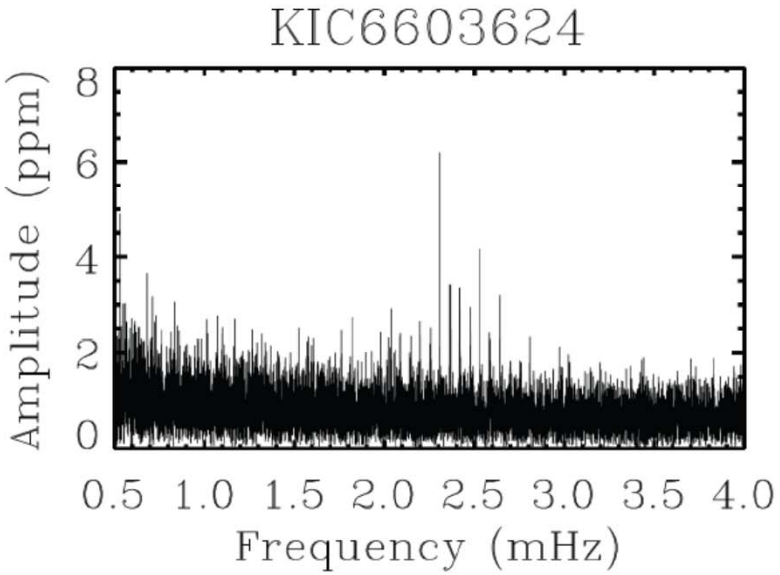


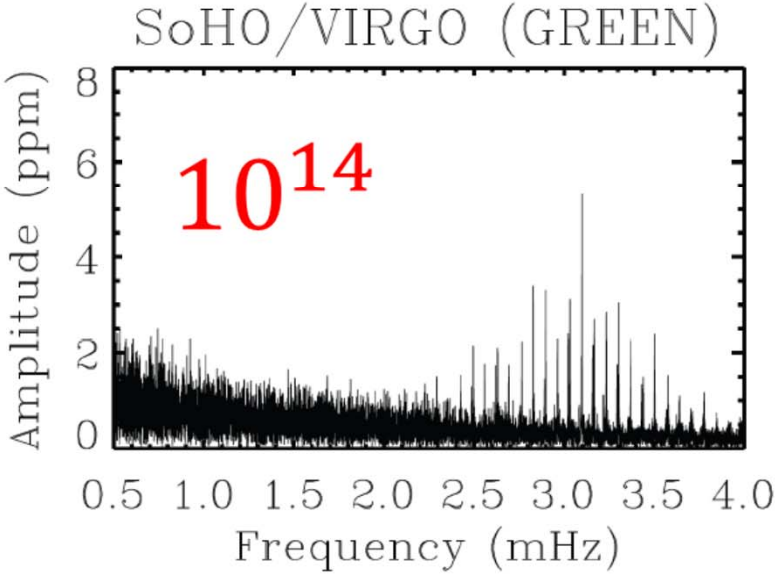
Metcalfe et al. 2010

Kepler… first month of data (2009)

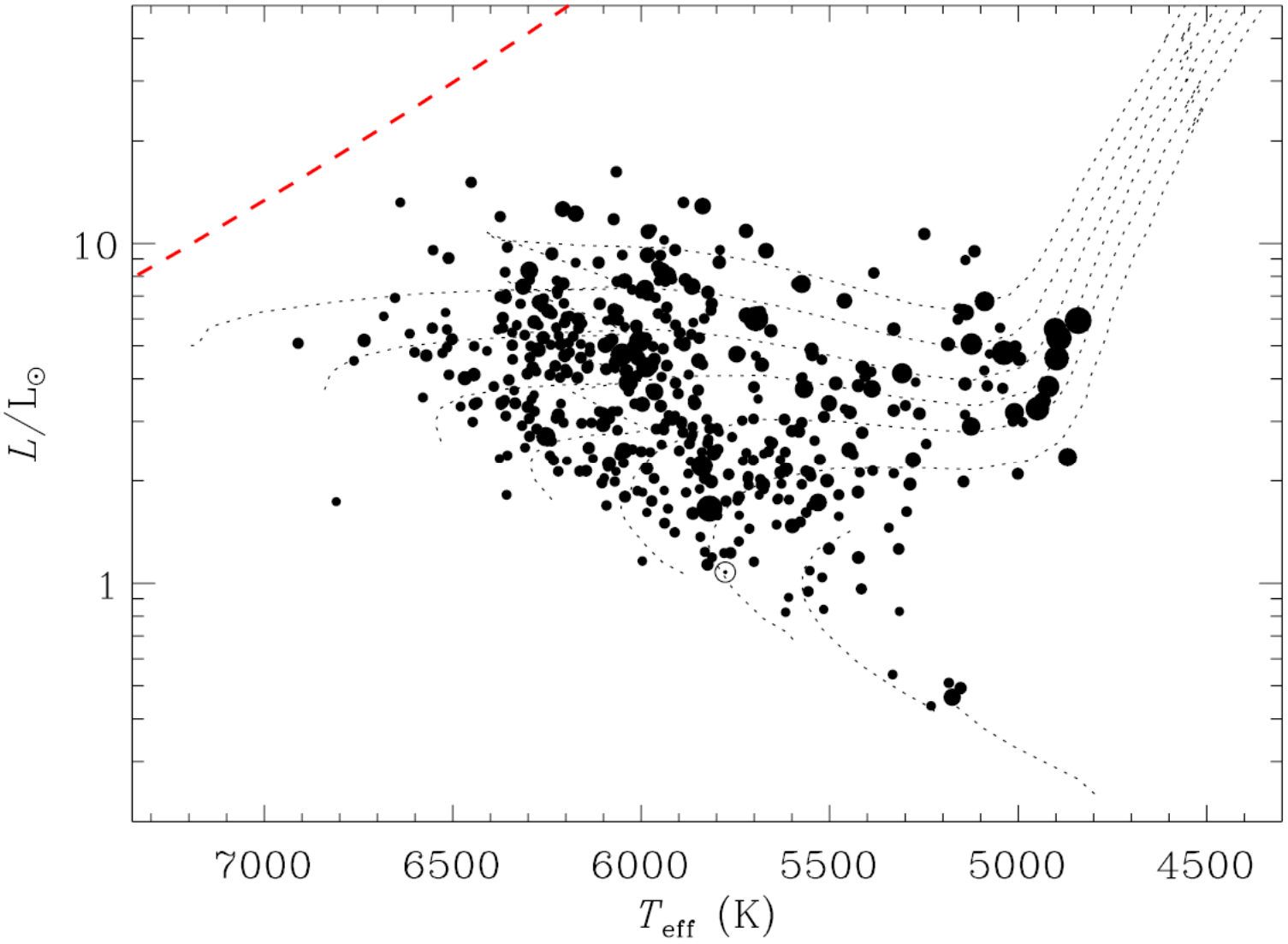


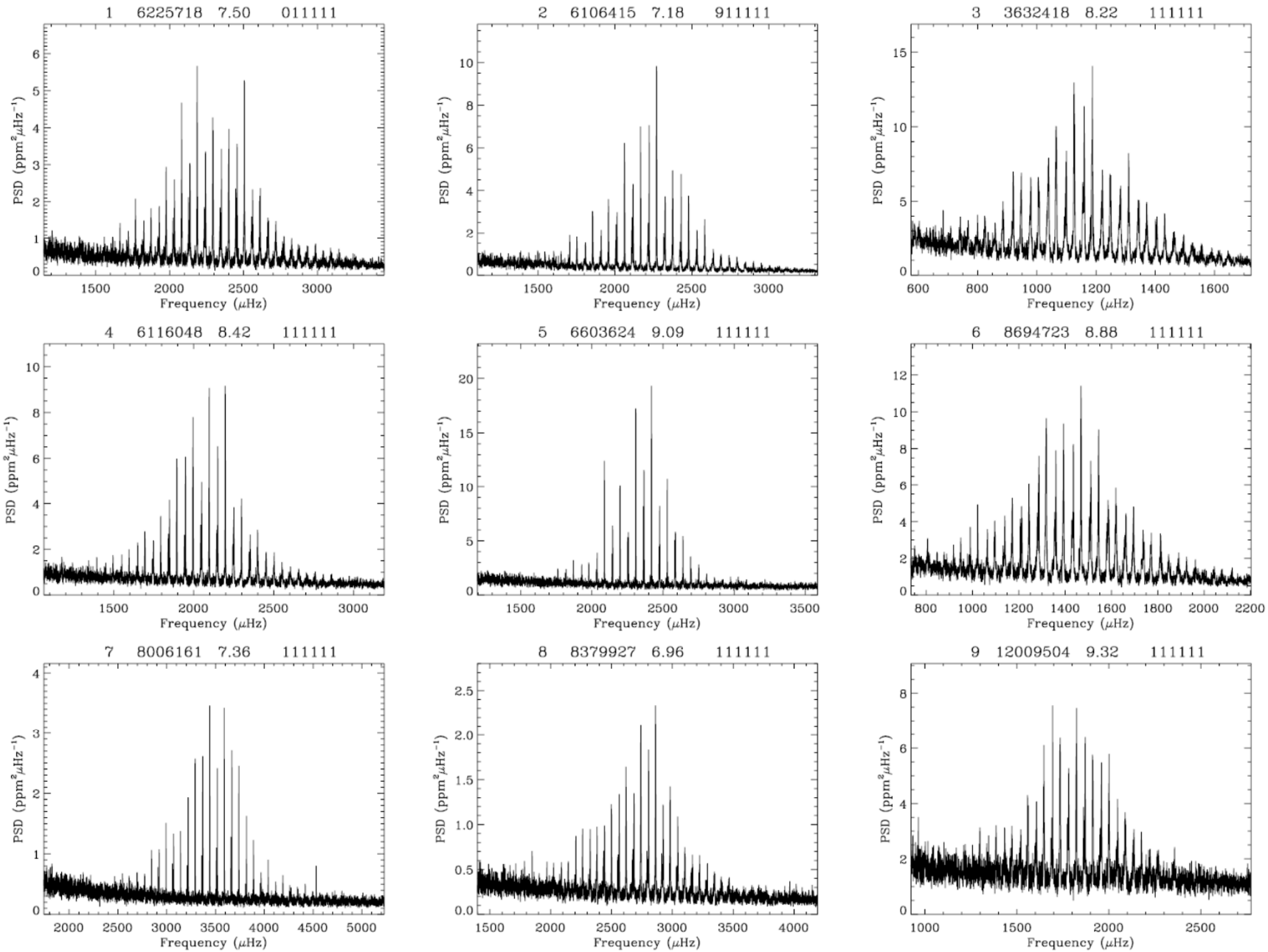


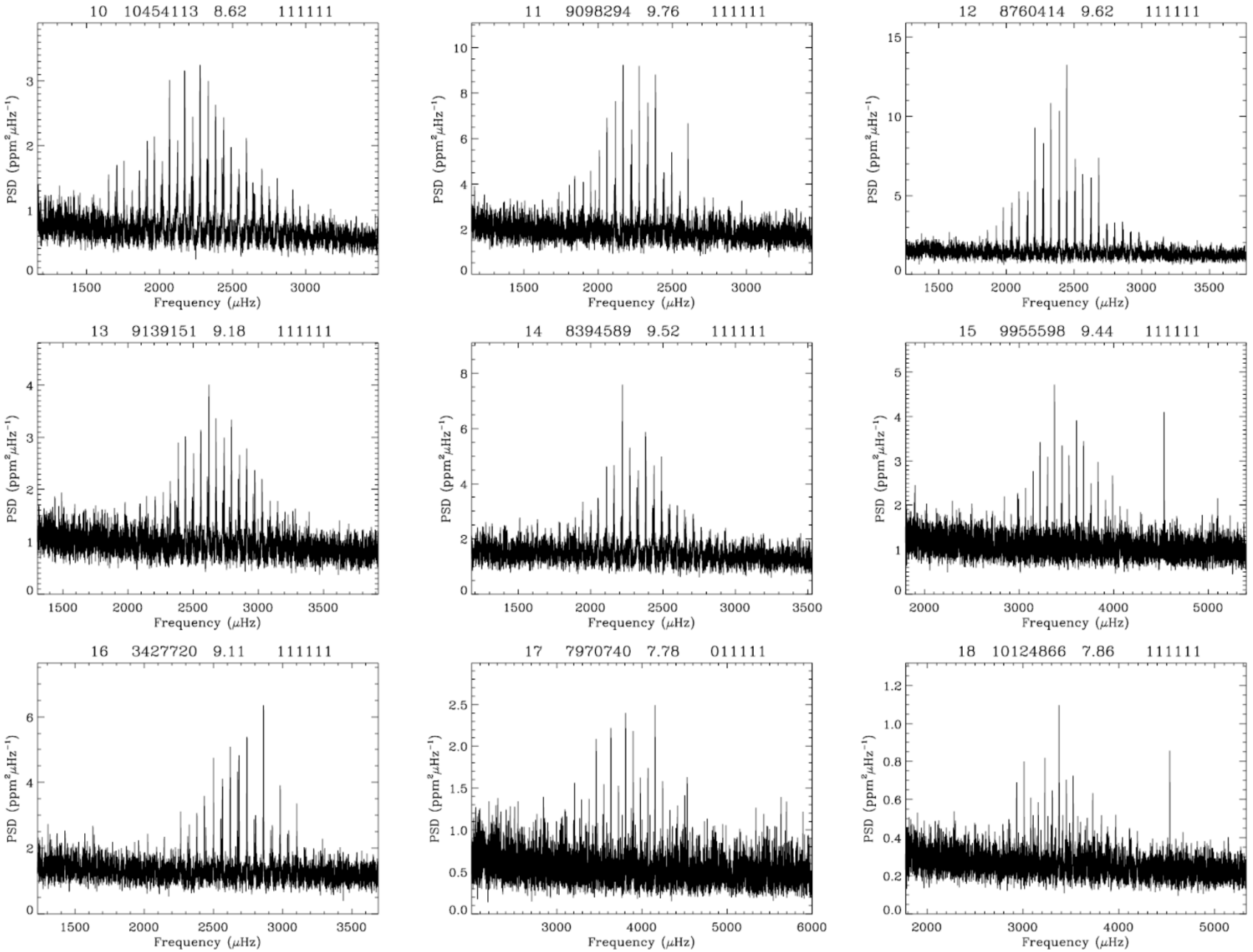


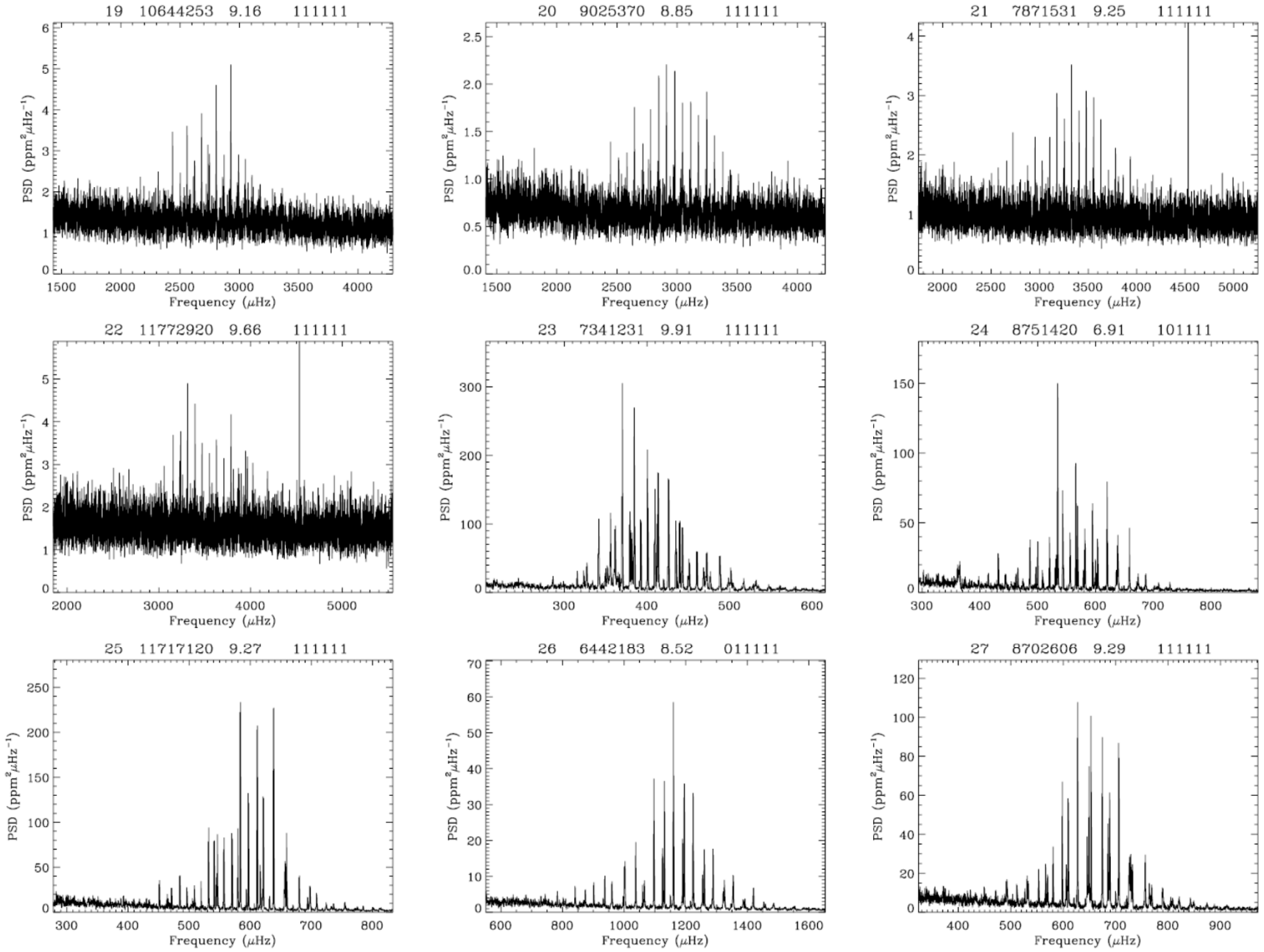


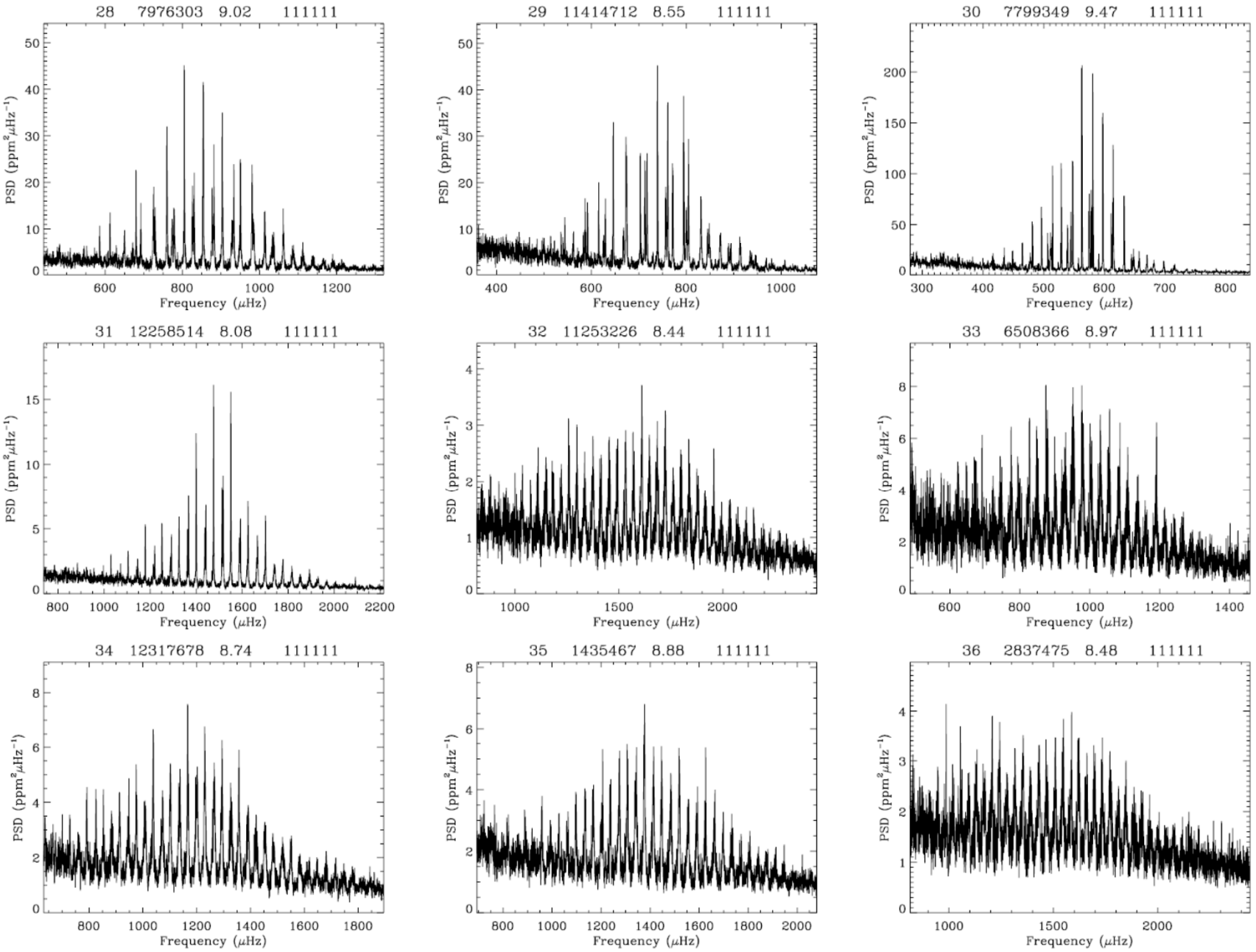
Chaplin et al. 2011



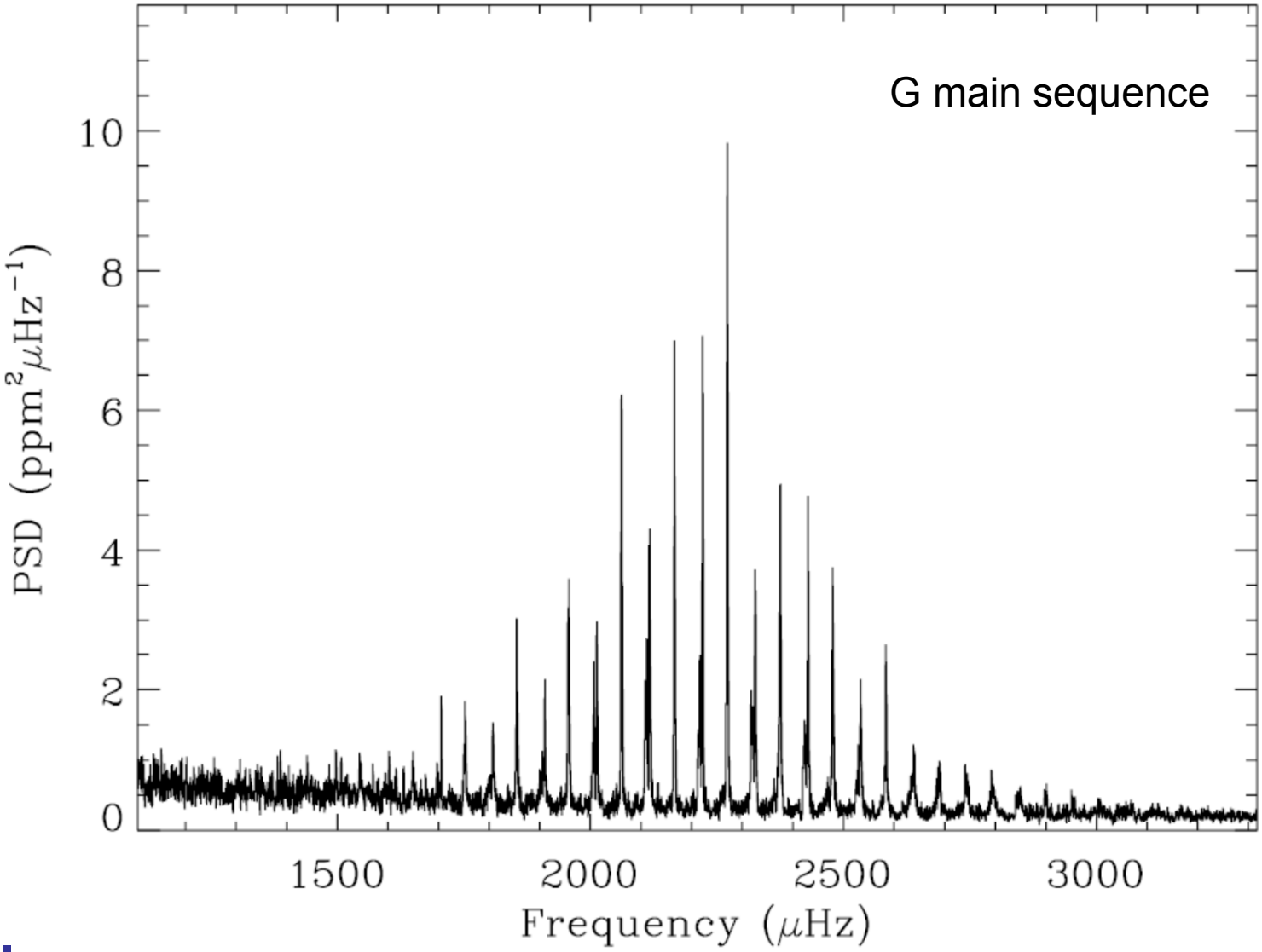

1 6225718 7.50 011111
2 6106415 7.18 911111
3 3632418 8.22 111111
4 6116048 8.42 111111
5 6603624 9.09 111111
6 8694723 8.88 111111
7 8006161 7.36 111111
8 8379927 6.96 111111
9 12009504 9.32 111111
PSD (ppm²μHz⁻¹)
Frequency (μHz)


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 (ppm² μHz⁻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 μHz^{-1})
Frequency (μHz)

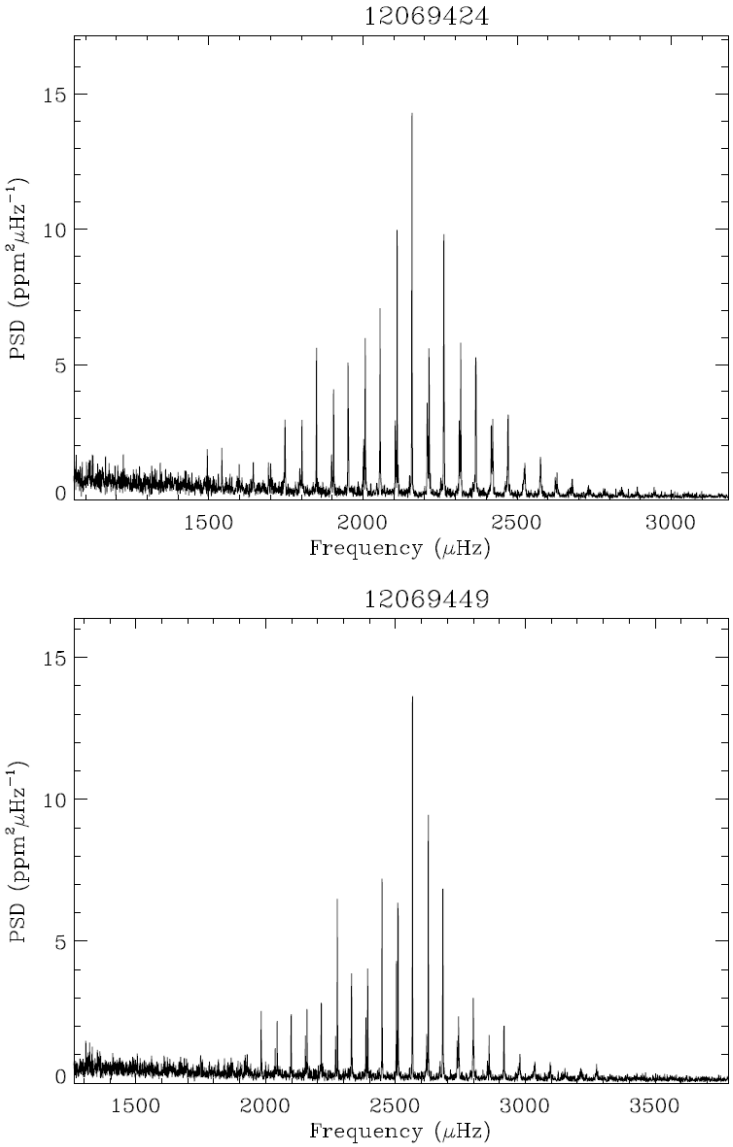

28 7976303 9.02 111111
29 11414712 8.55 111111
30 7799349 9.47 111111
31 12258514 8.08 111111
32 11253226 8.44 111111
33 6508366 8.97 111111
34 12317678 8.74 111111
35 1435467 8.88 111111
36 2837475 8.48 111111
PSD (ppm^2 μHz^{-1})
Frequency (μHz)

450 d, mag: 7.18

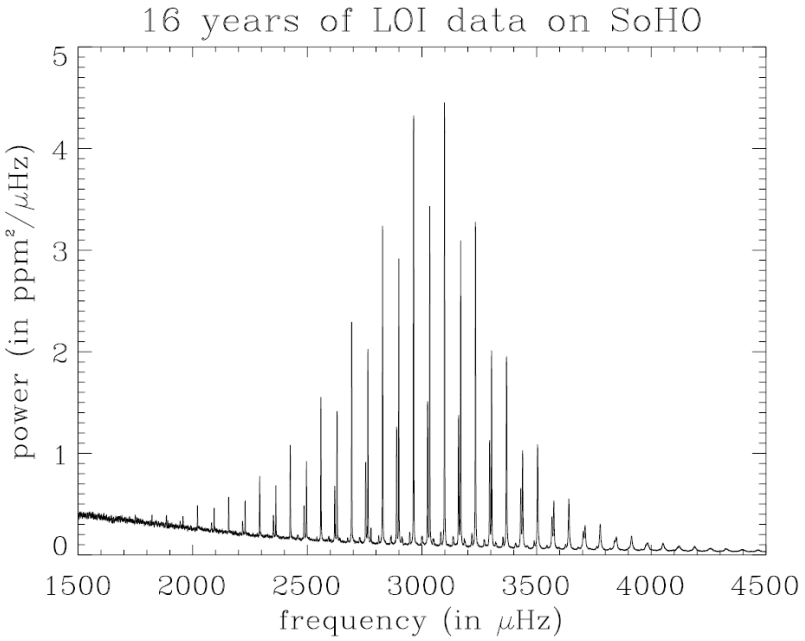


Kepler

16 Cygni A + B

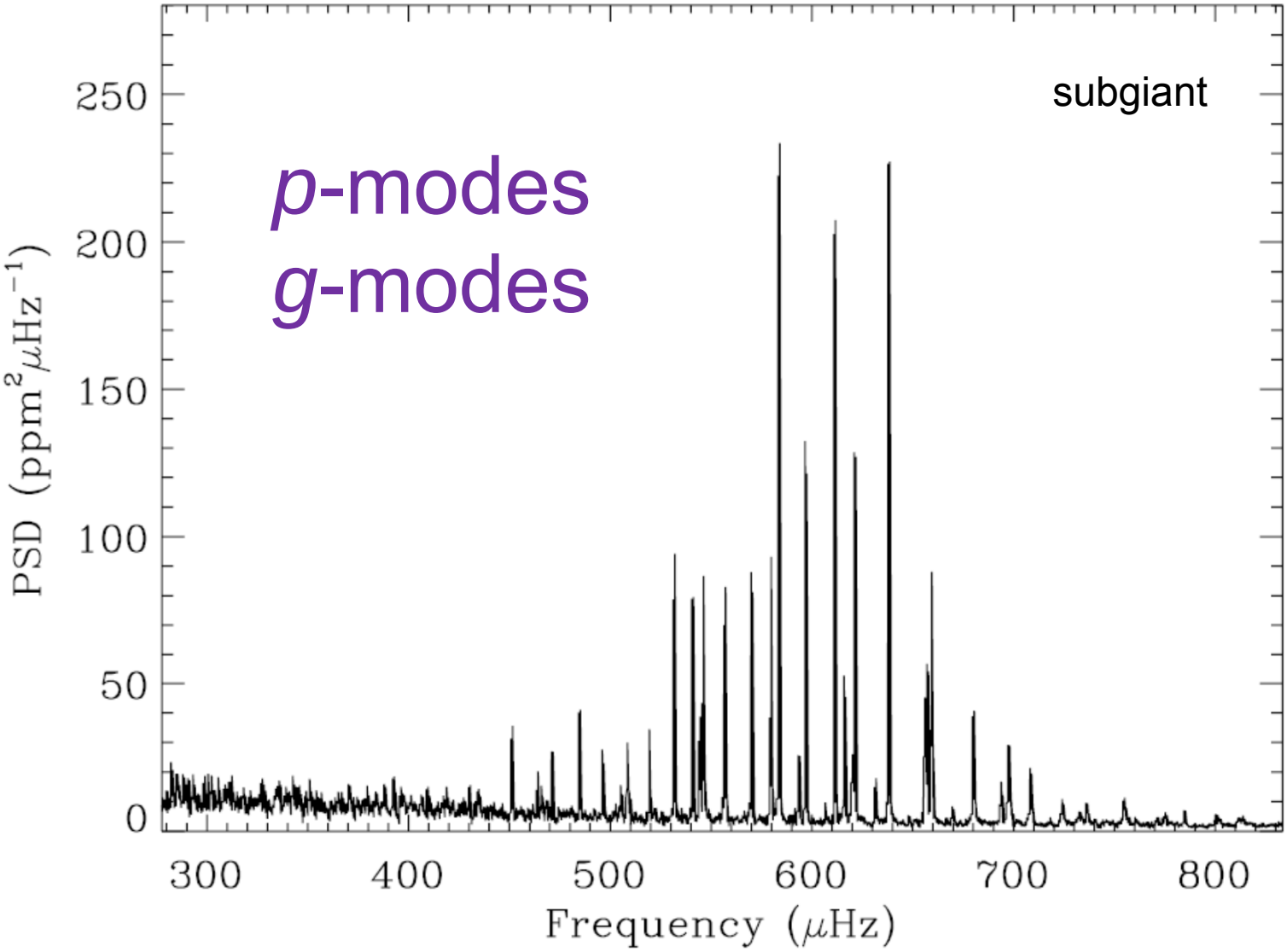


- Data quality will allow a direct comparison with the Sun
- Internal rotation and differential rotation
- Long-term phenomenon (incl. activity)
- Size of convection zone
- Excellent *classical* parameters



Thierry Appourchaux (2012)

540 d, mag: 9.27



Kepler

Stellar evolution

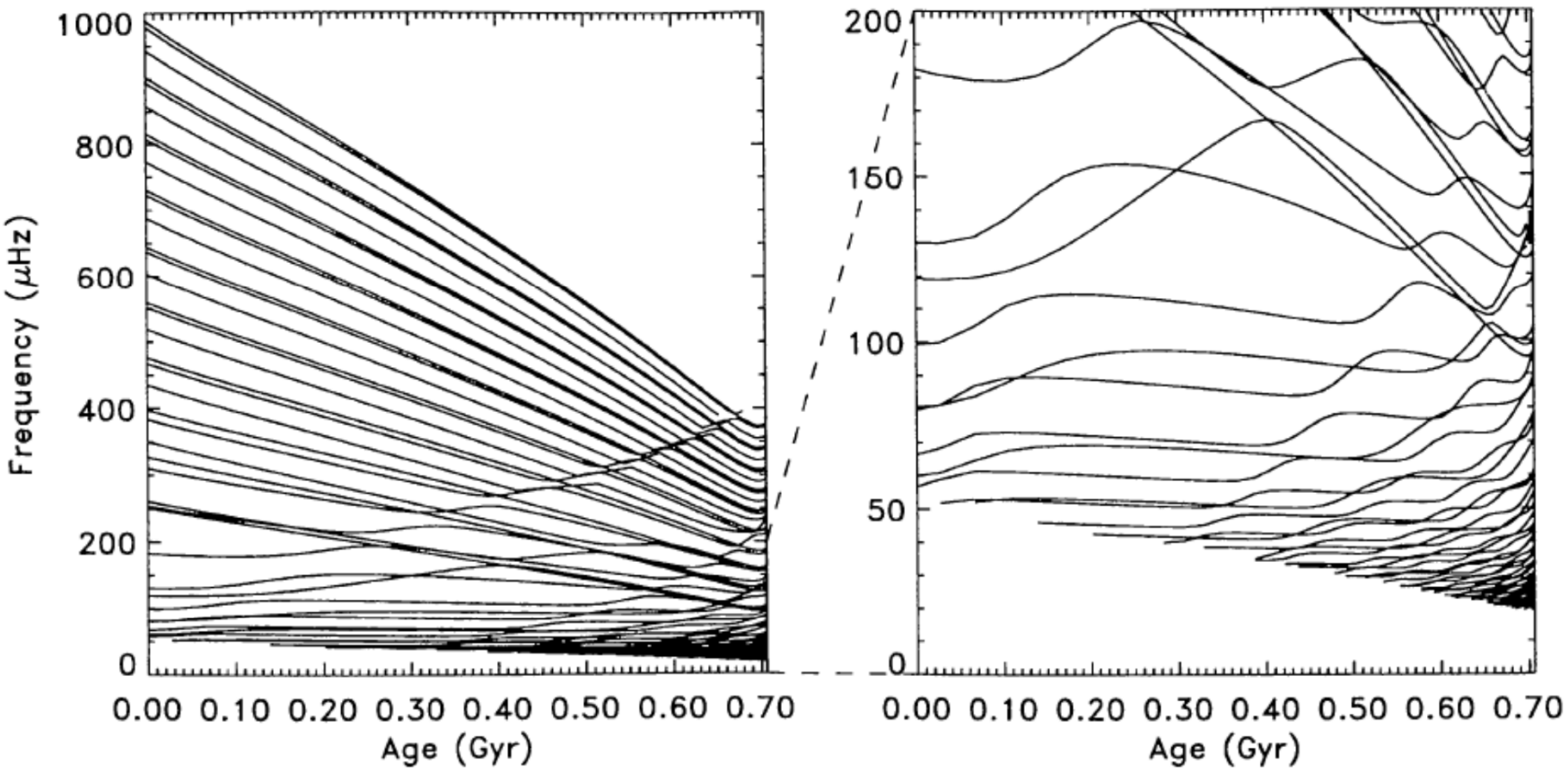


Figure 1. Evolution of oscillation frequencies in a $2.2\,M_\odot$ star, from model calculations by J. Christensen-Dalsgaard. Only modes with $\ell = 0, 1, 2$ and $n \leq 10$ are shown.

White et al. 2011

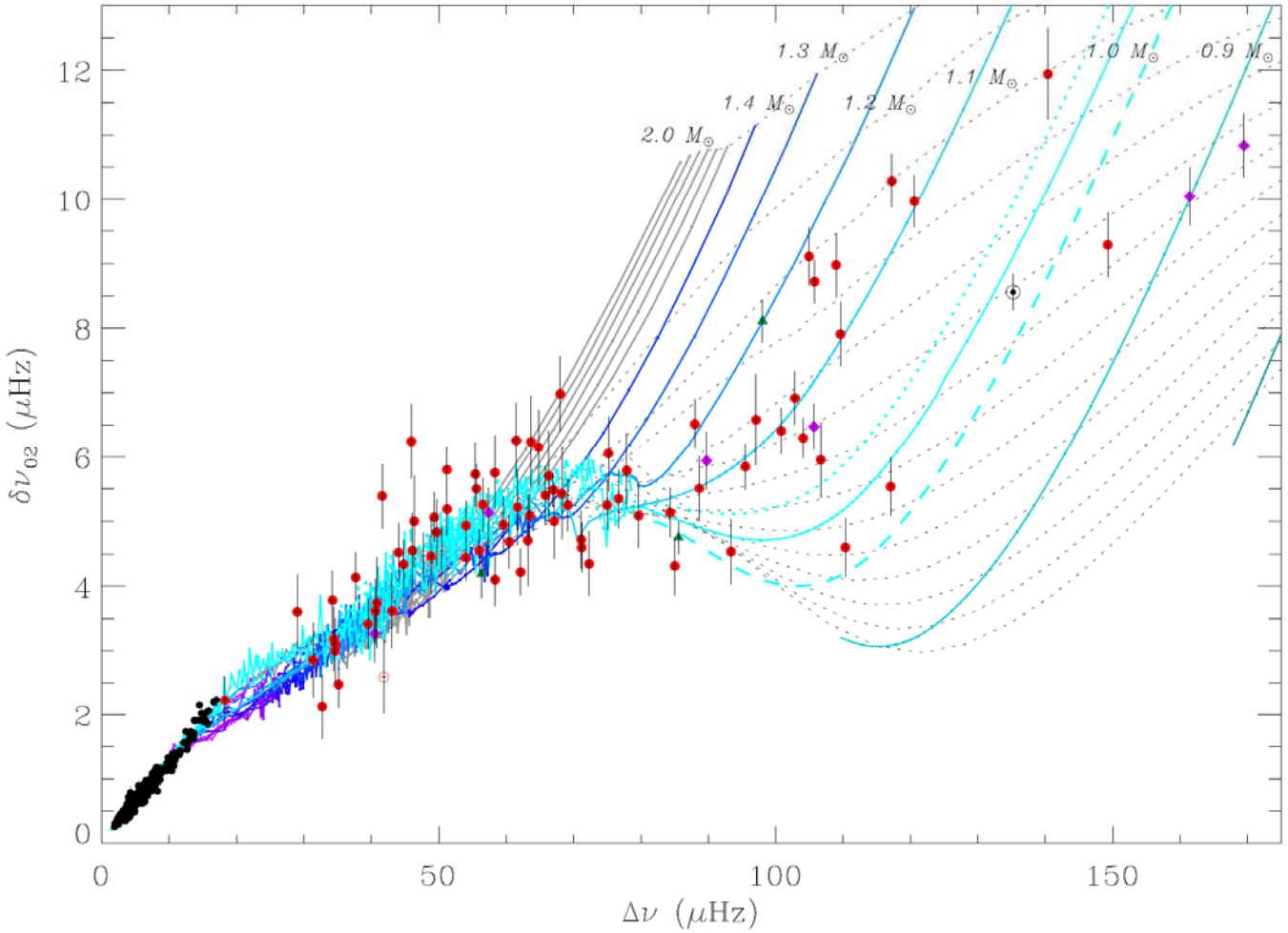
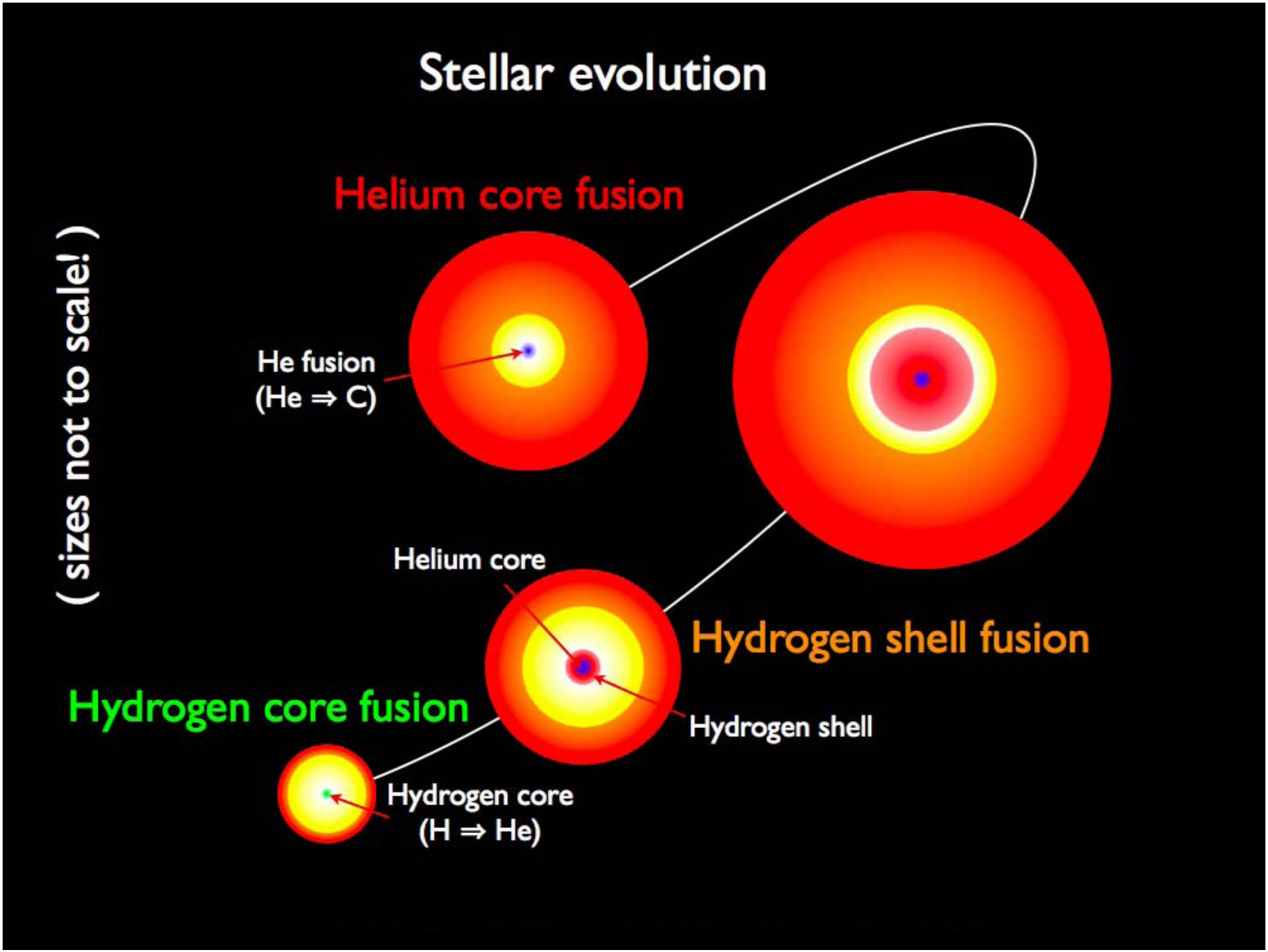
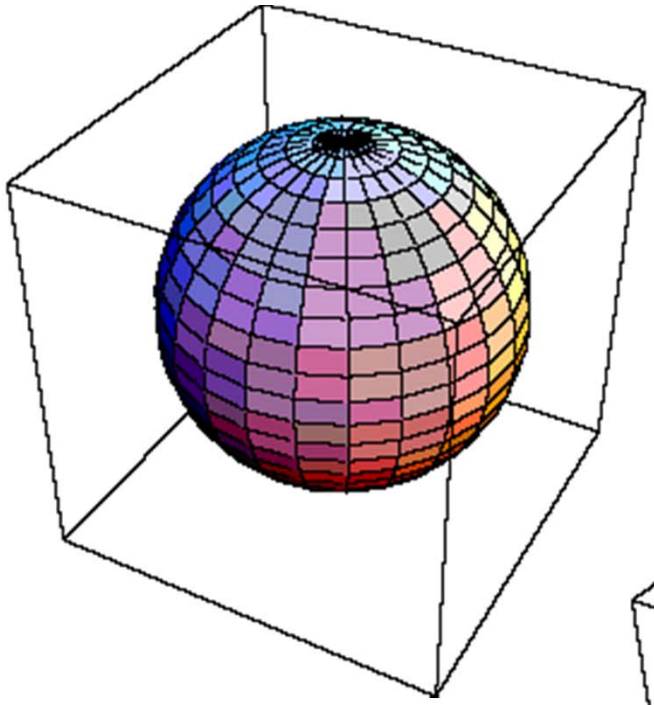
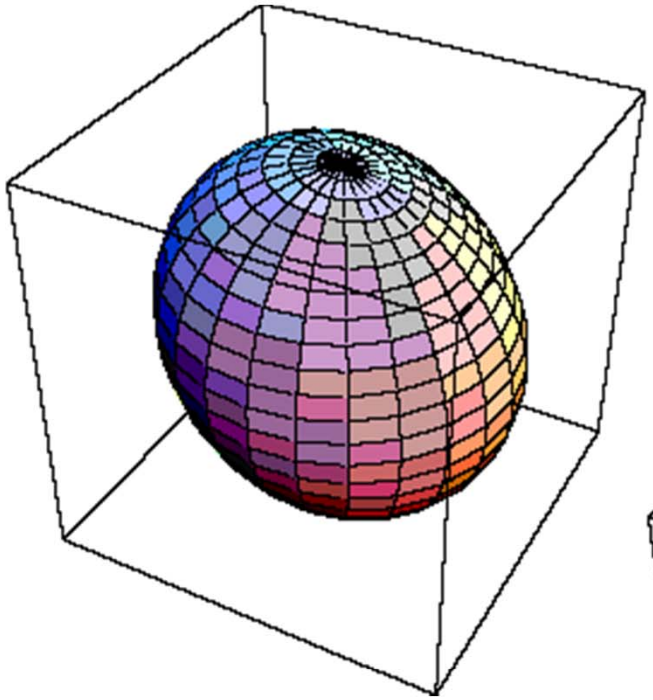
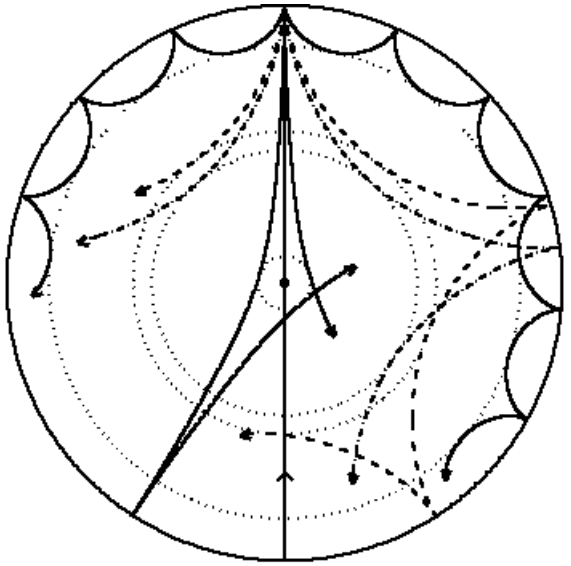


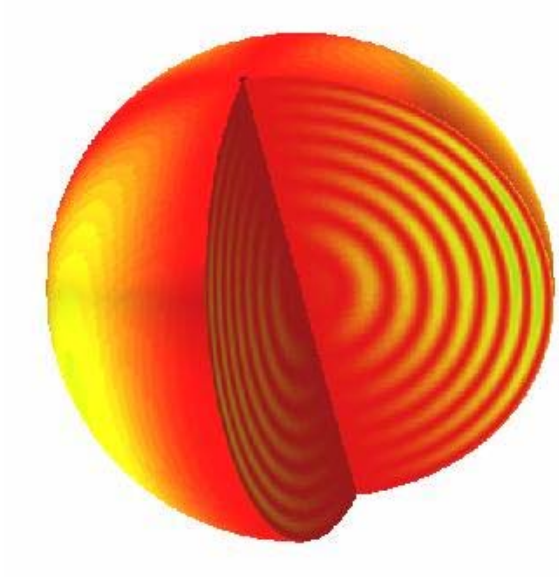
FIG. 2.— C-D diagram, with model tracks for near-solar metallicity ($Z_0 = 0.017$). Tracks increase in mass by $0.1\,M_\odot$ from $0.8\,M_\odot$ to $2.0\,M_\odot$. Also shown are tracks for metal-poor ($Z_0 = 0.014$; dotted) and metal-rich ($Z_0 = 0.022$; dashed) solar-mass models. The section of the evolutionary tracks in which the models have a higher $T_{\rm eff}$ than the approximate cool edge of the classical instability strip (Saio & Gautschy 1998) are grey: they are not expected to show solar-like oscillations. Dashed black lines are isochrones, increasing from 0 Gyr (ZAMS) at the top to 13 Gyr at the bottom. The filled red circles are the 78 *Kepler* stars from this work, while open red circles are *Kepler* stars with previously published frequency lists (see text). Also shown are *Kepler* red giants (black circles; Huber et al. 2010), and main-sequence and subgiant stars from CoRoT (green triangles; see text) and ground based observations (purple diamonds; see text). The Sun is marked by its usual symbol.


Stellar evolution
(sizes not to scale!)
Helium core fusion
He fusion
(He ⇒ C)
Helium core
Hydrogen shell fusion
Hydrogen core fusion
Hydrogen shell
Hydrogen core
(H ⇒ He)



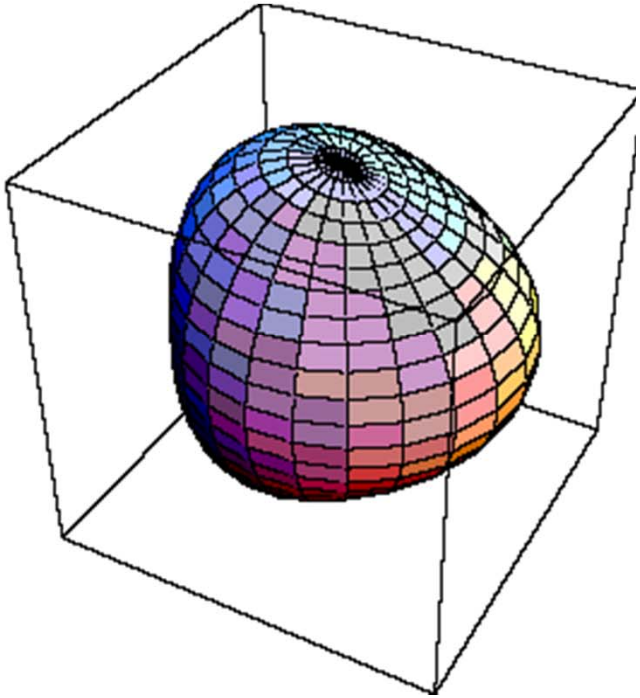






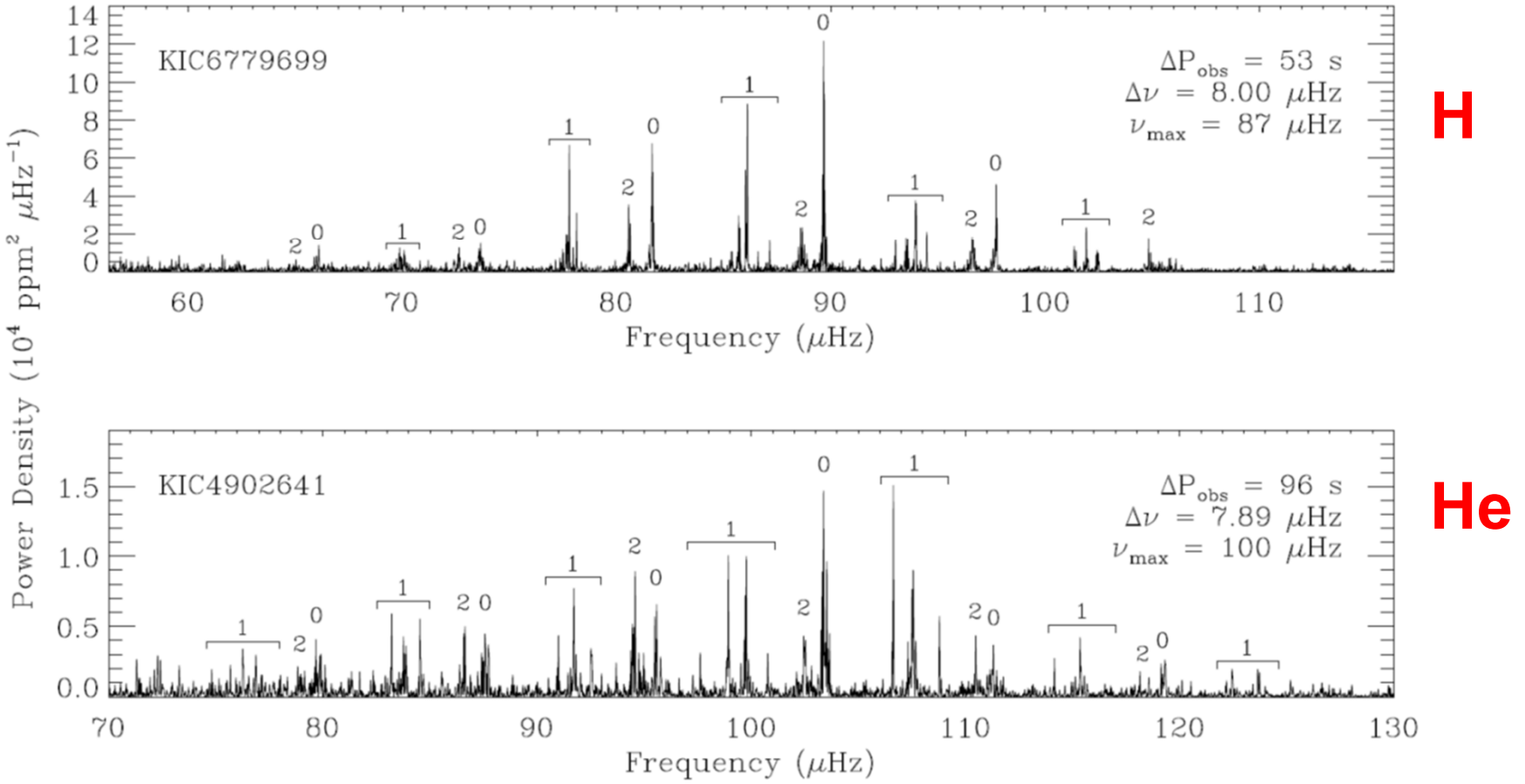
p-modes

g-modes



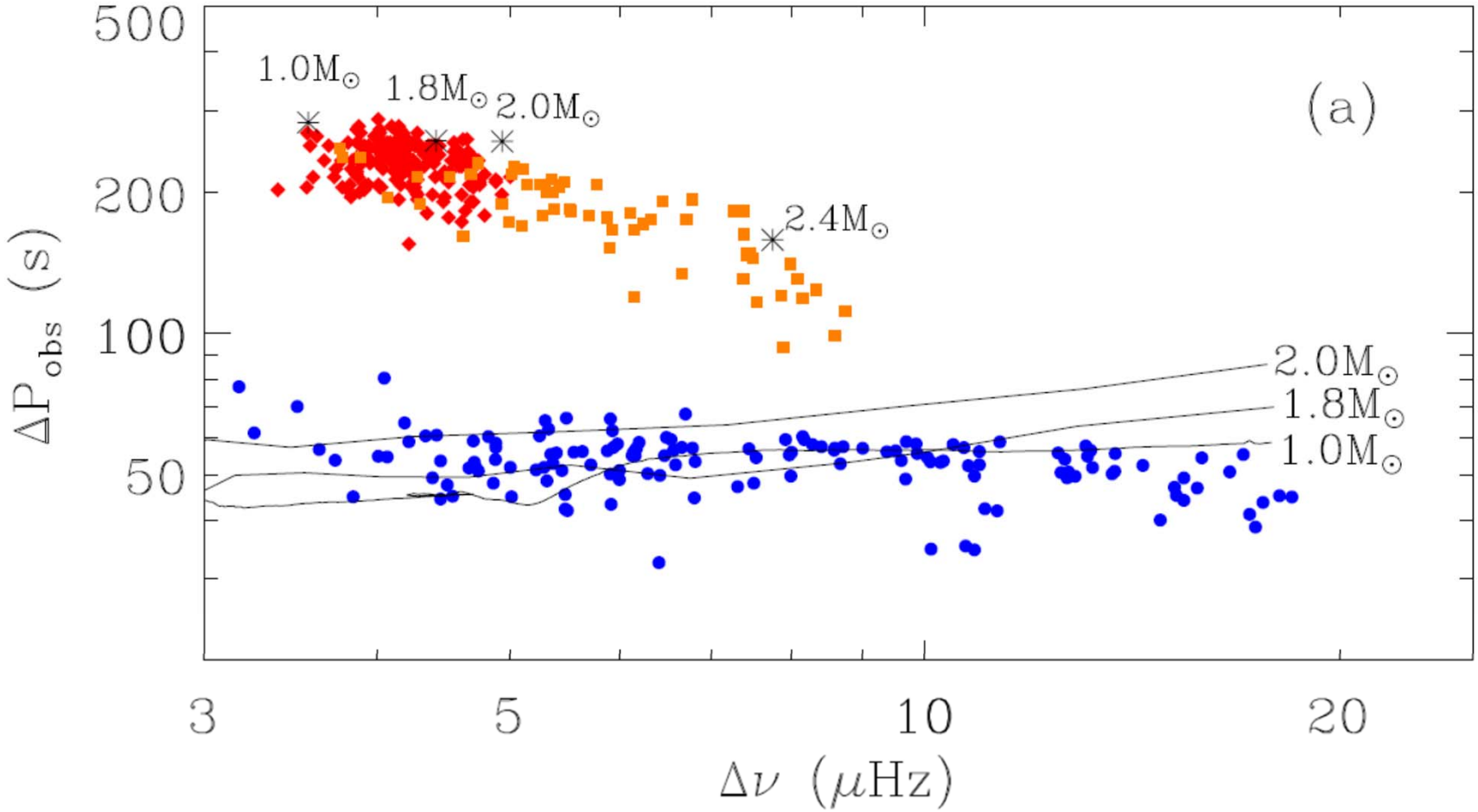
Gravity modes as a way to distinguish between hydrogen- and helium-burning red giant stars

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]



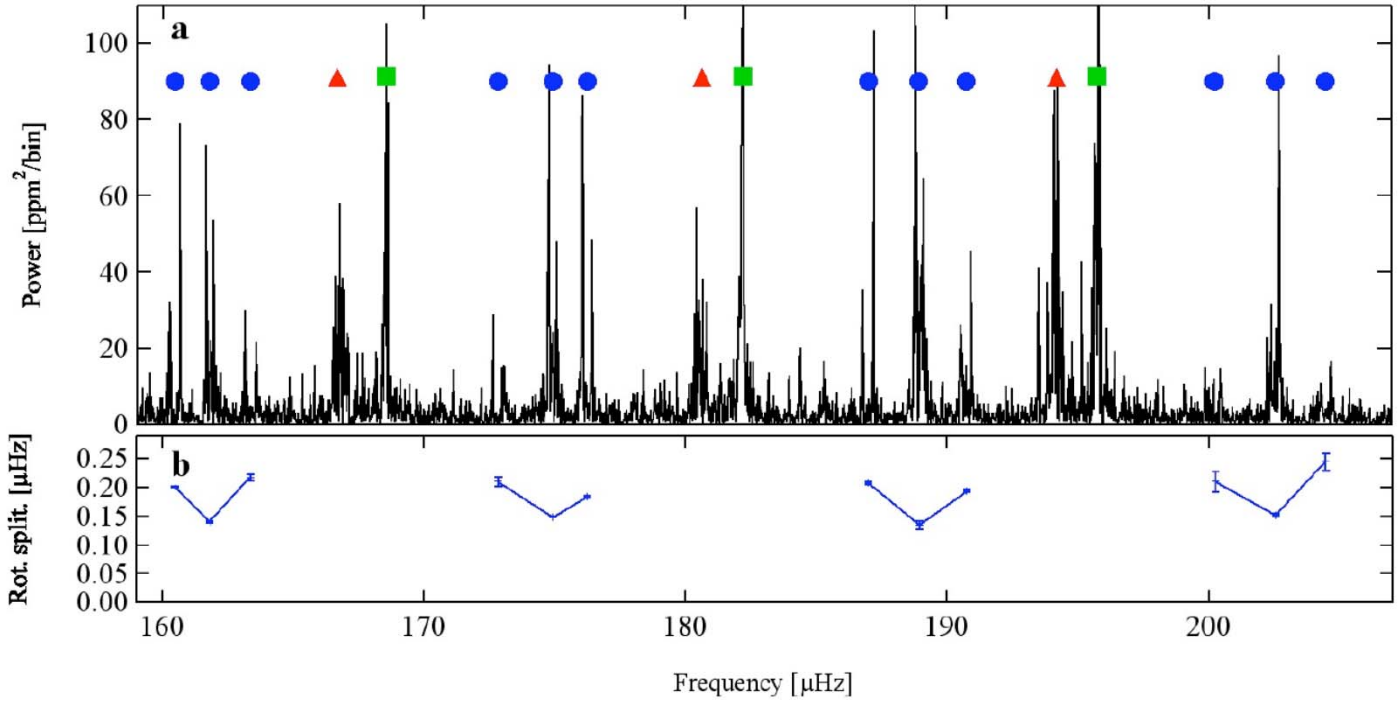
H

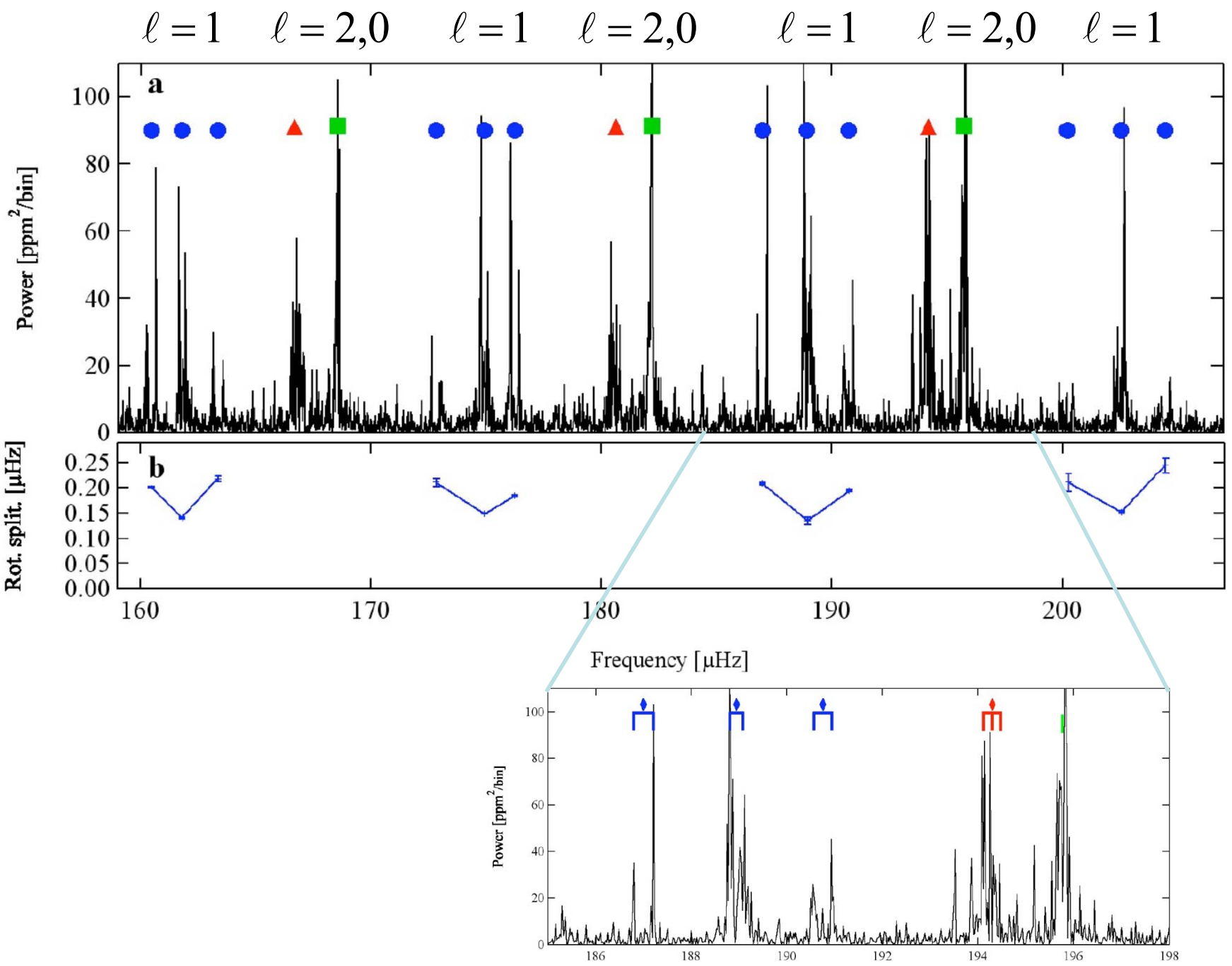
He

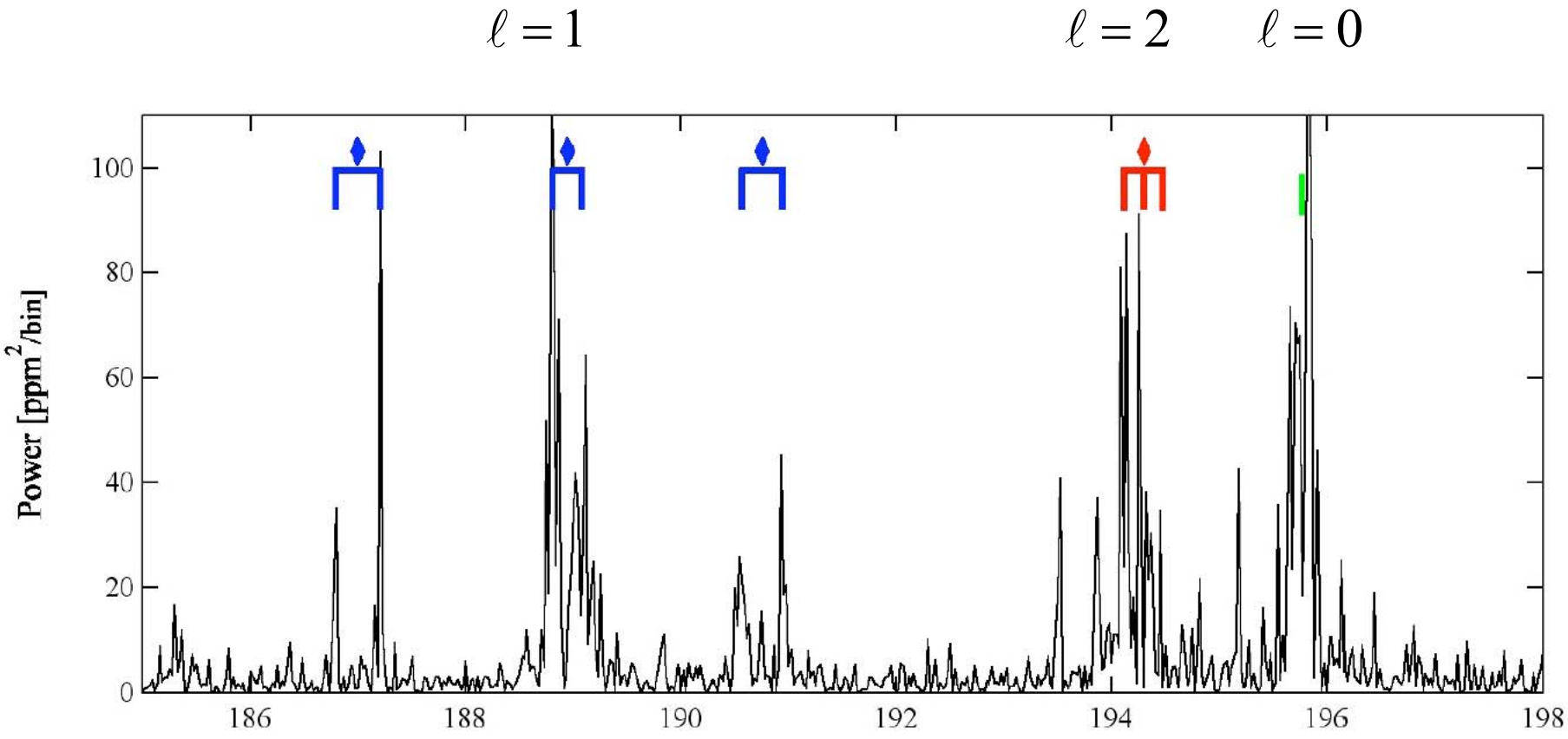

500
200
100
50
ΔP_{obs} (s)
1.0M$_\odot$
1.8M$_\odot$
2.0M$_\odot$
2.4M$_\odot$
(a)
2.0M$_\odot$
1.8M$_\odot$
1.0M$_\odot$
3
5
10
20
$\Delta\nu$ (μHz)

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

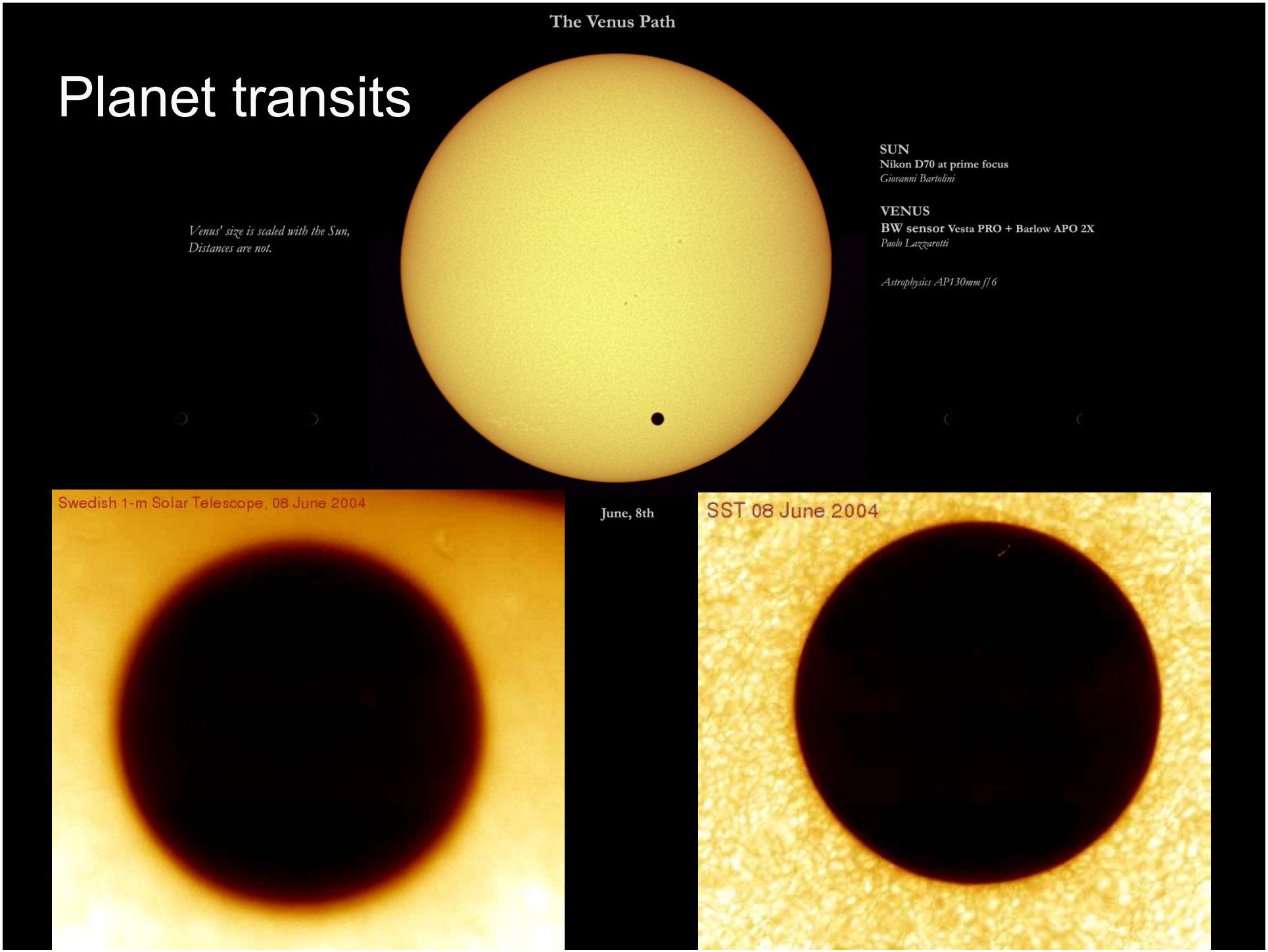
Paul G. Beck[1], Josefina Montalban[2], Thomas Kallinger[1,3,4], Joris De Ridder[1], Conny Aerts[1,5], Rafael A. García[6], Saskia Hekker[7,8], Marc-Antoine Dupret[2], Benoit Mosser[9], Patrick Eggenberger[10], Dennis Stello[11], Yvonne Elsworth[8], Søren Frandsen[12], Fabien Carrier[1], Michel Hillen[1], 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]

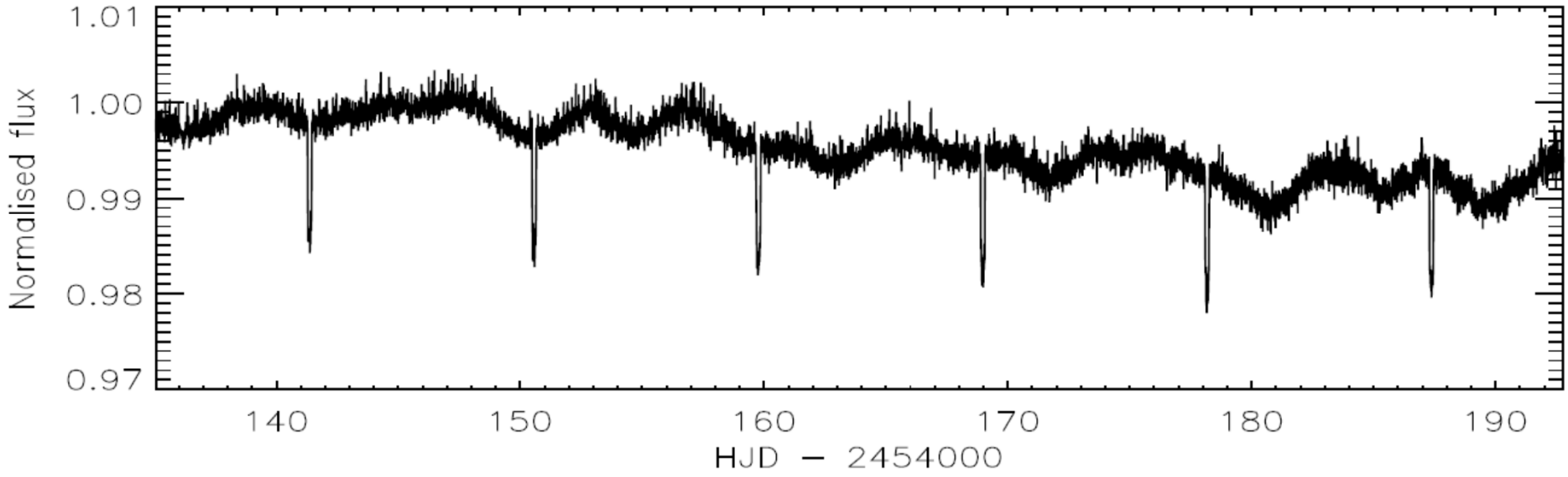


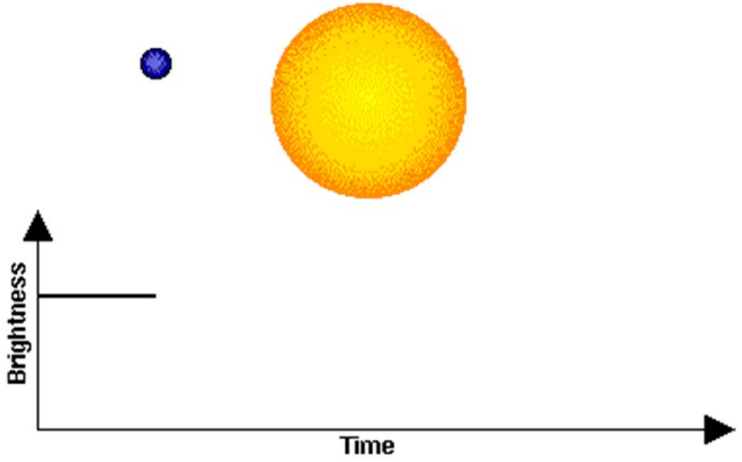

ℓ = 1
ℓ = 2,0
ℓ = 1
ℓ = 2,0
ℓ = 1
ℓ = 2,0
ℓ = 1
a
b
Power [ppm²/bin]
Rot. split. [μHz]
Frequency [μHz]
160
170
180
190
200
186
188
190
192
194
196
198

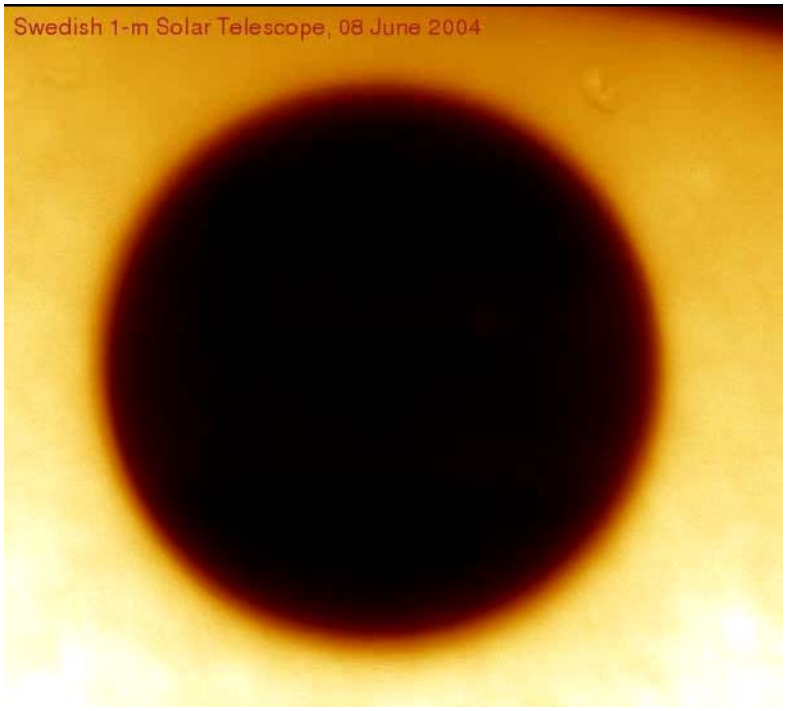

$\ell = 1$
$\ell = 2$
$\ell = 0$
Power [ppm^2/bin]
0
20
40
60
80
100
186
188
190
192
194
196
198

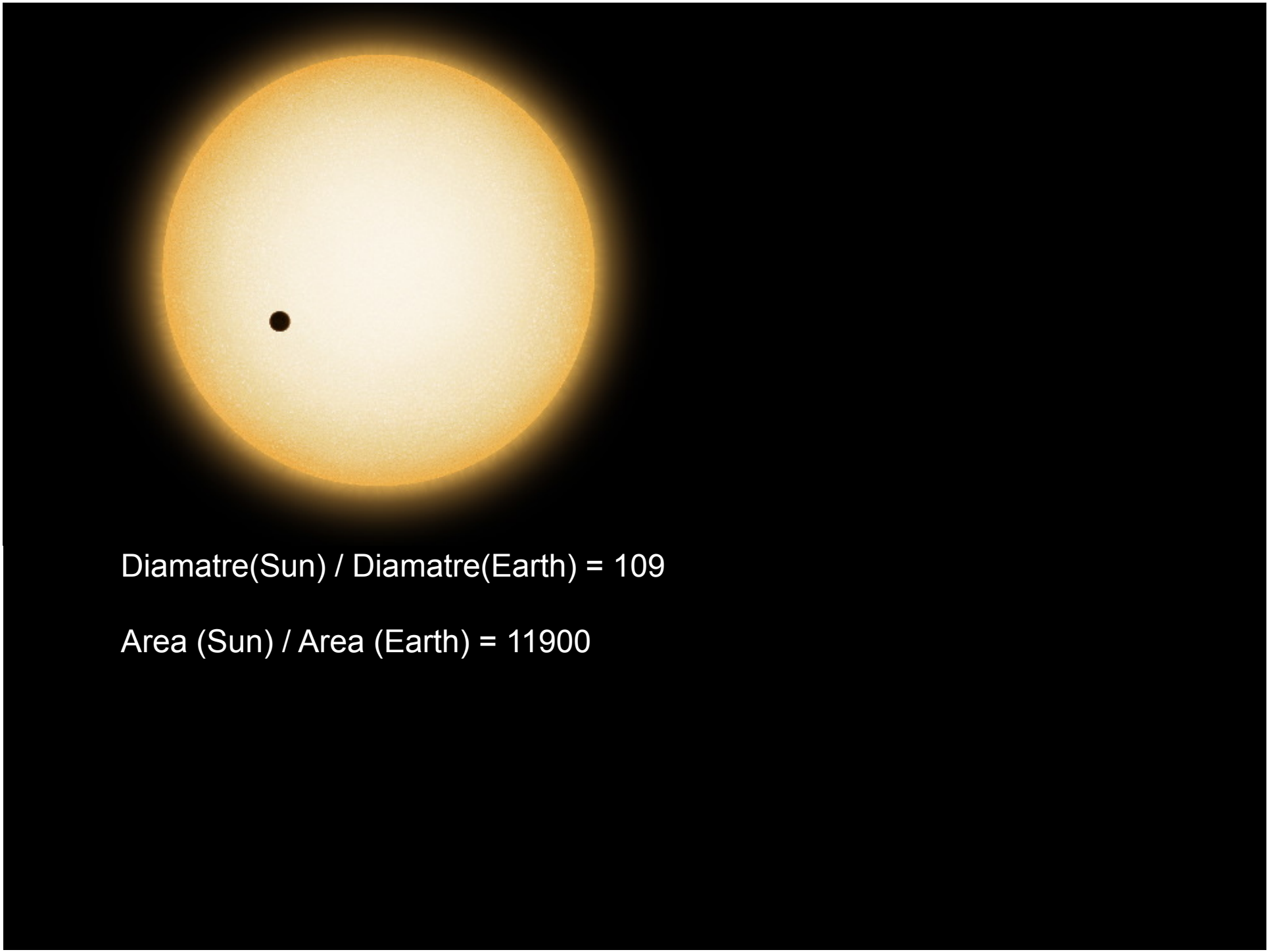
Planet transits




Normalised flux
1.01
1.00
0.99
0.98
0.97
140
150
160
170
180
190
HJD − 2454000

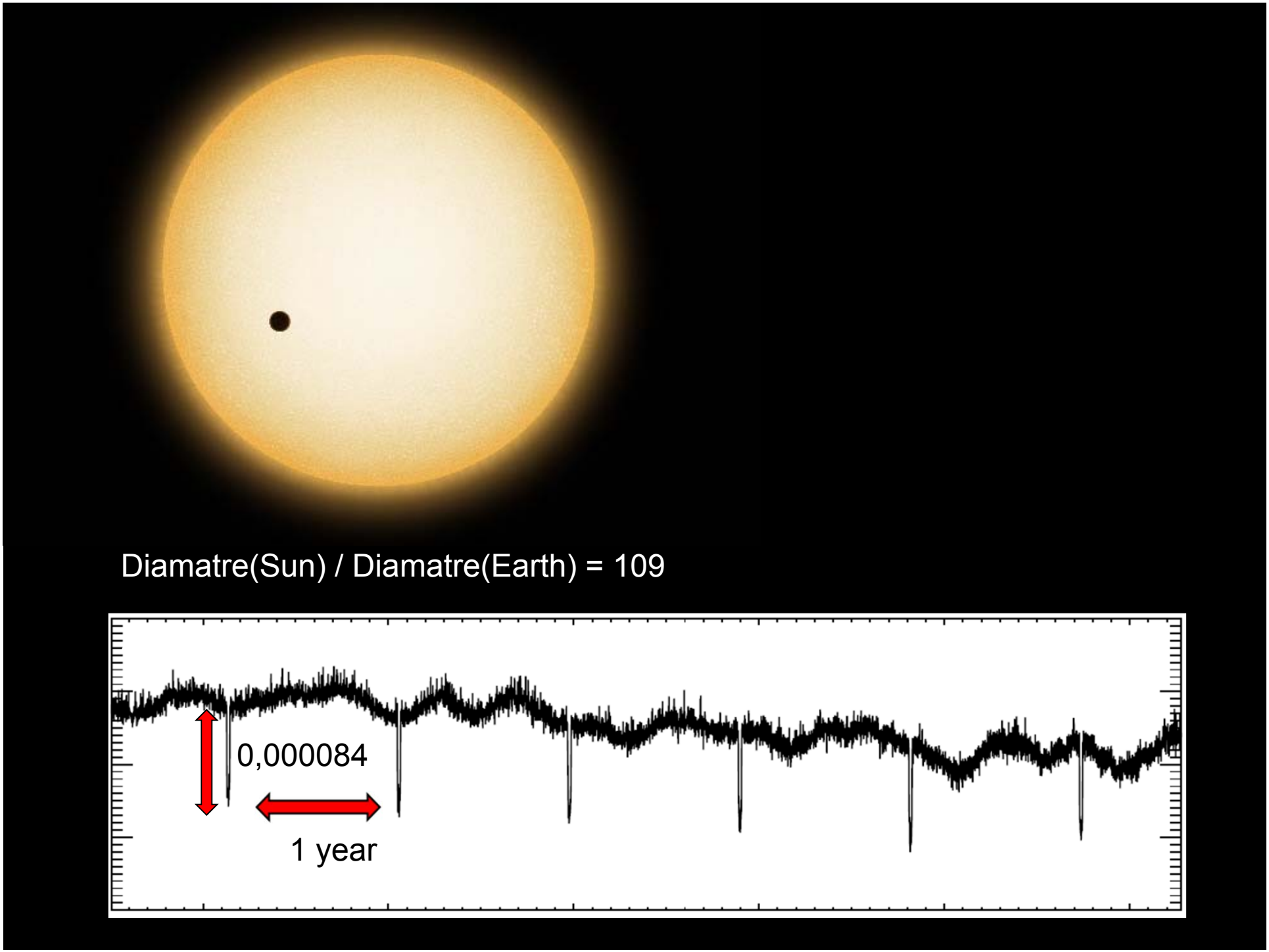

Brightness
Time

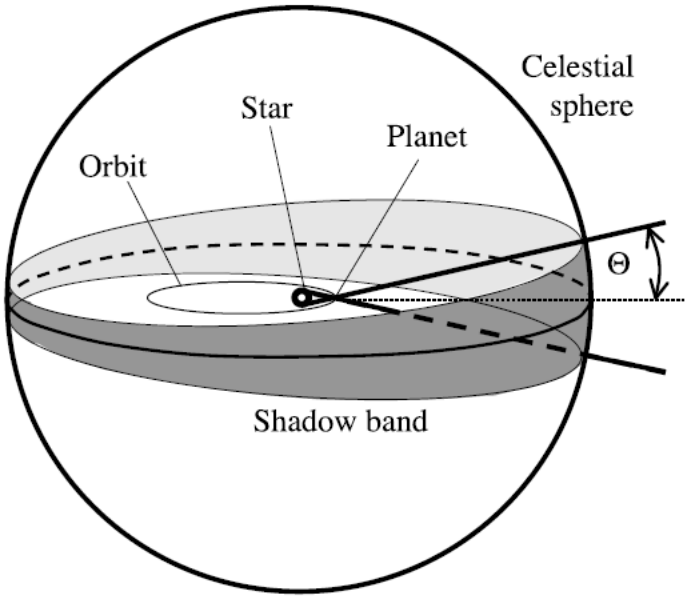

Swedish 1-m Solar Telescope, 08 June 2004

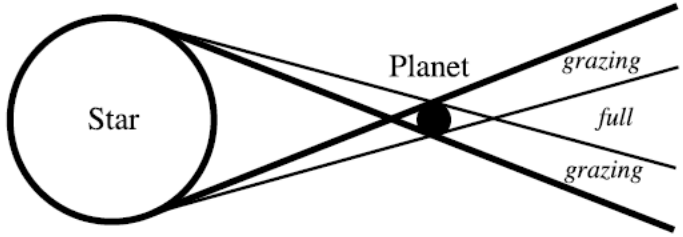


Diamatre(Sun) / Diamatre(Earth) = 109

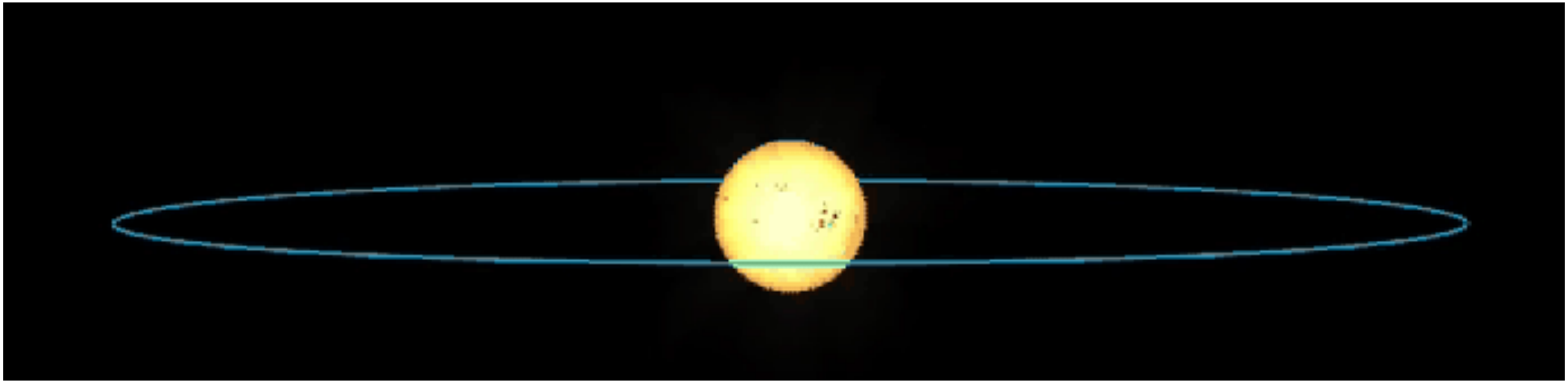
Area (Sun) / Area (Earth) = 11900

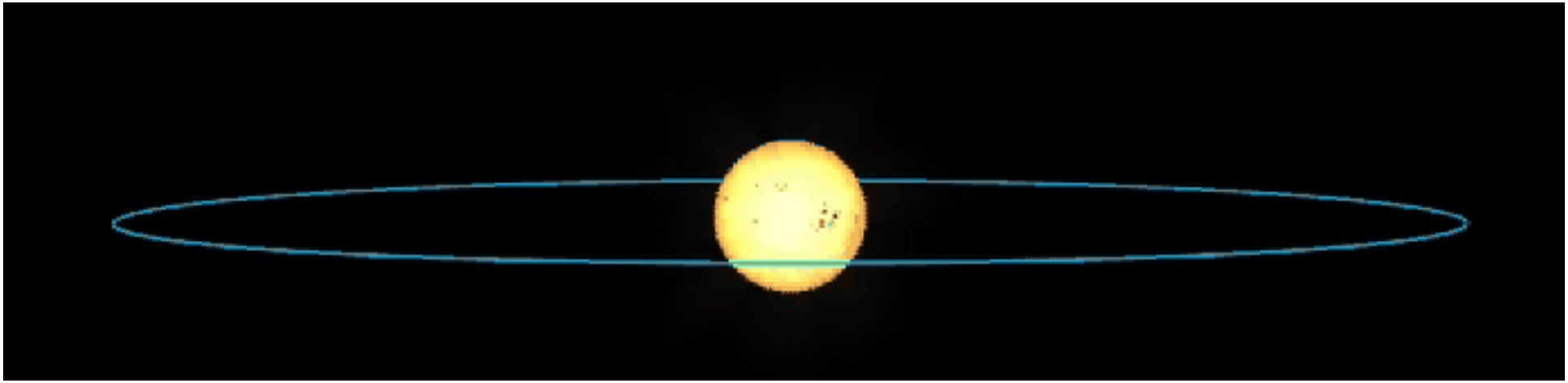

Diamatre(Sun) / Diamatre(Earth) = 109
0,000084
1 year

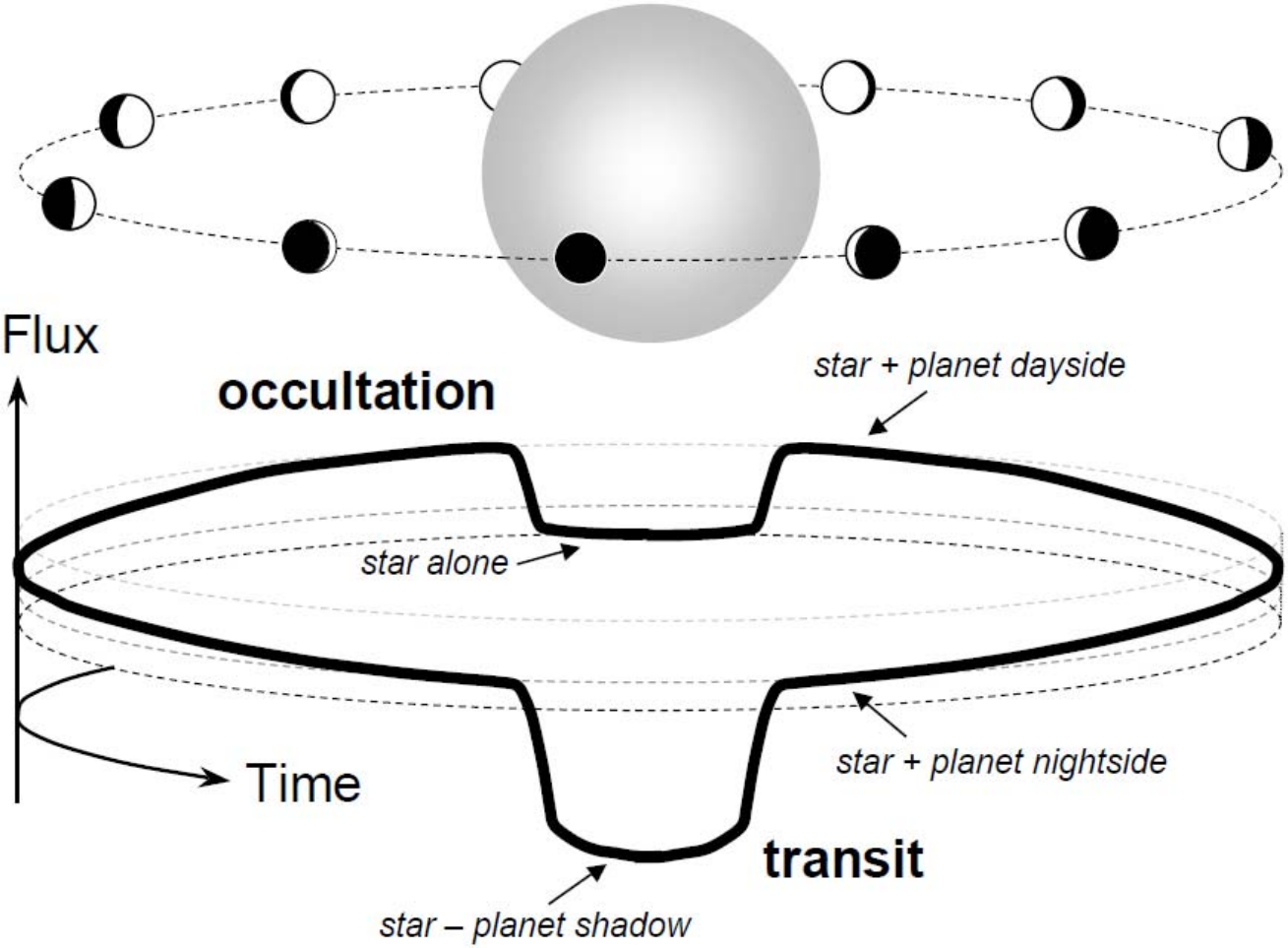

Celestial
sphere
Star
Planet
Orbit
Θ
Shadow band


Star
Planet
grazing
full
grazing

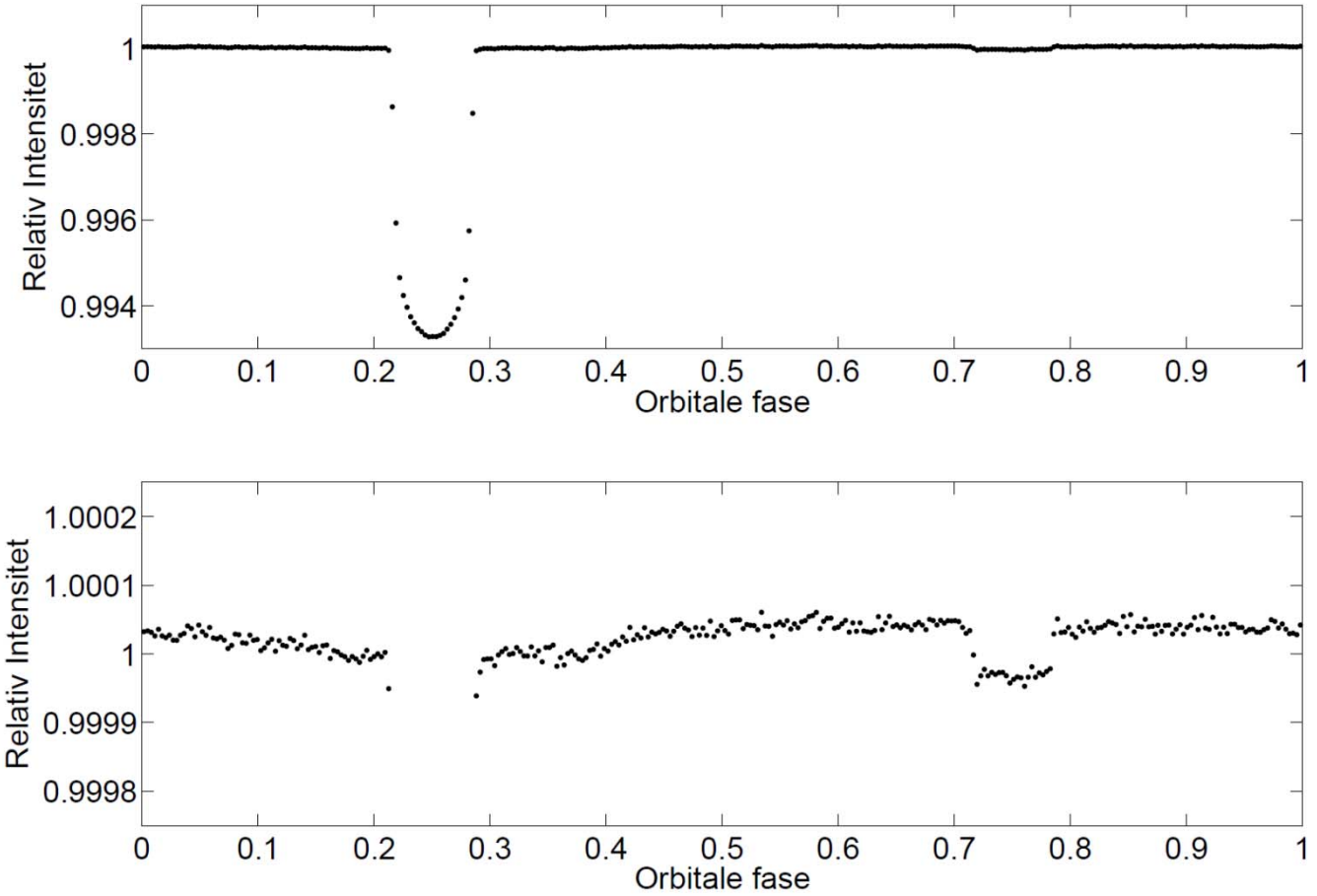
Close-up



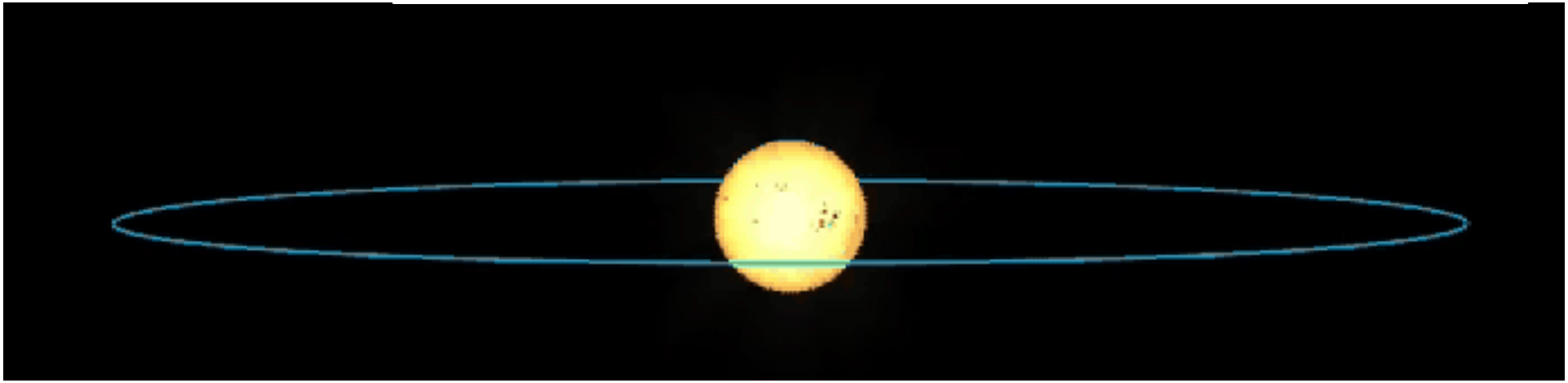



Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow

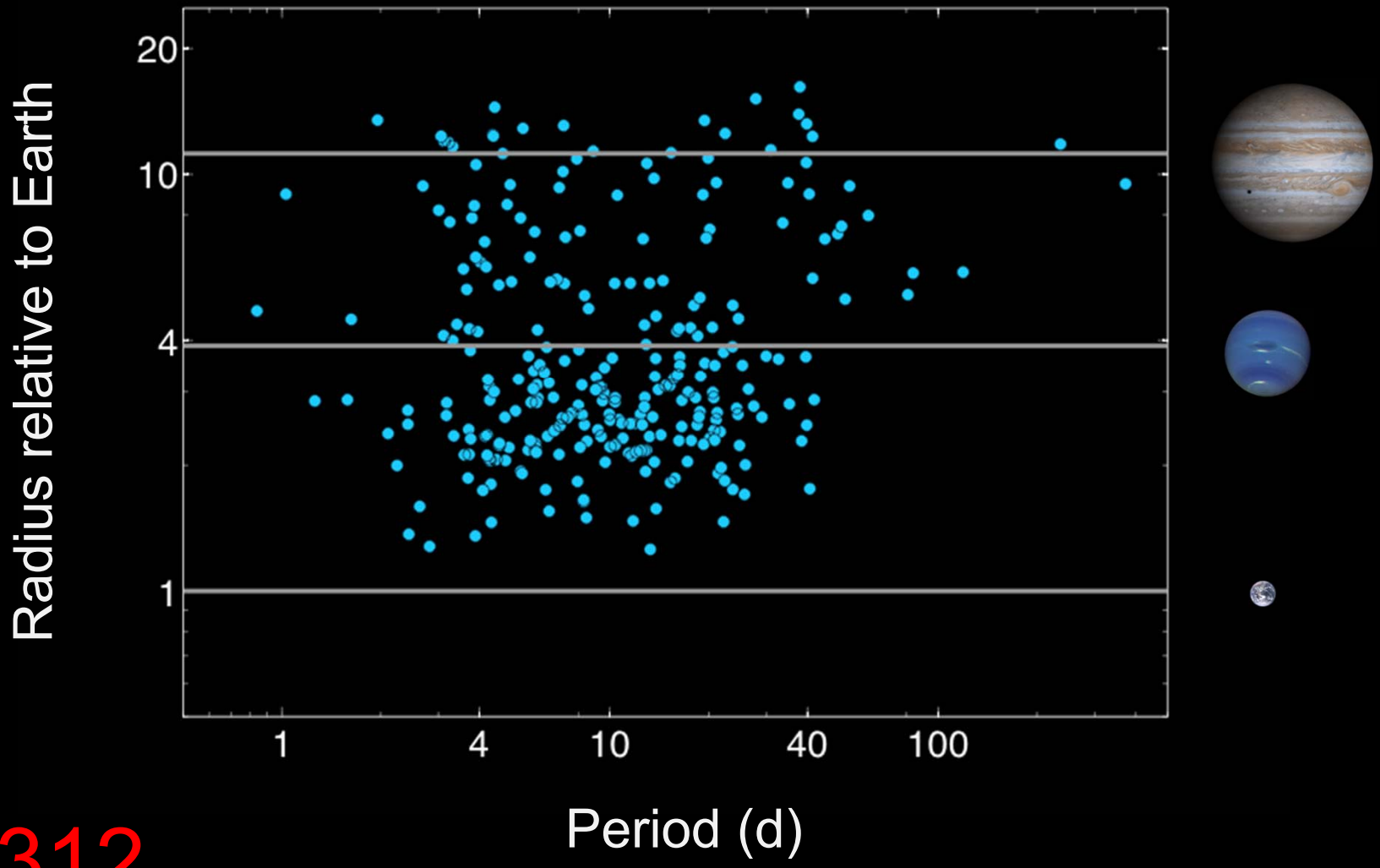
HAT-P-7



Nielsen et al. 2012

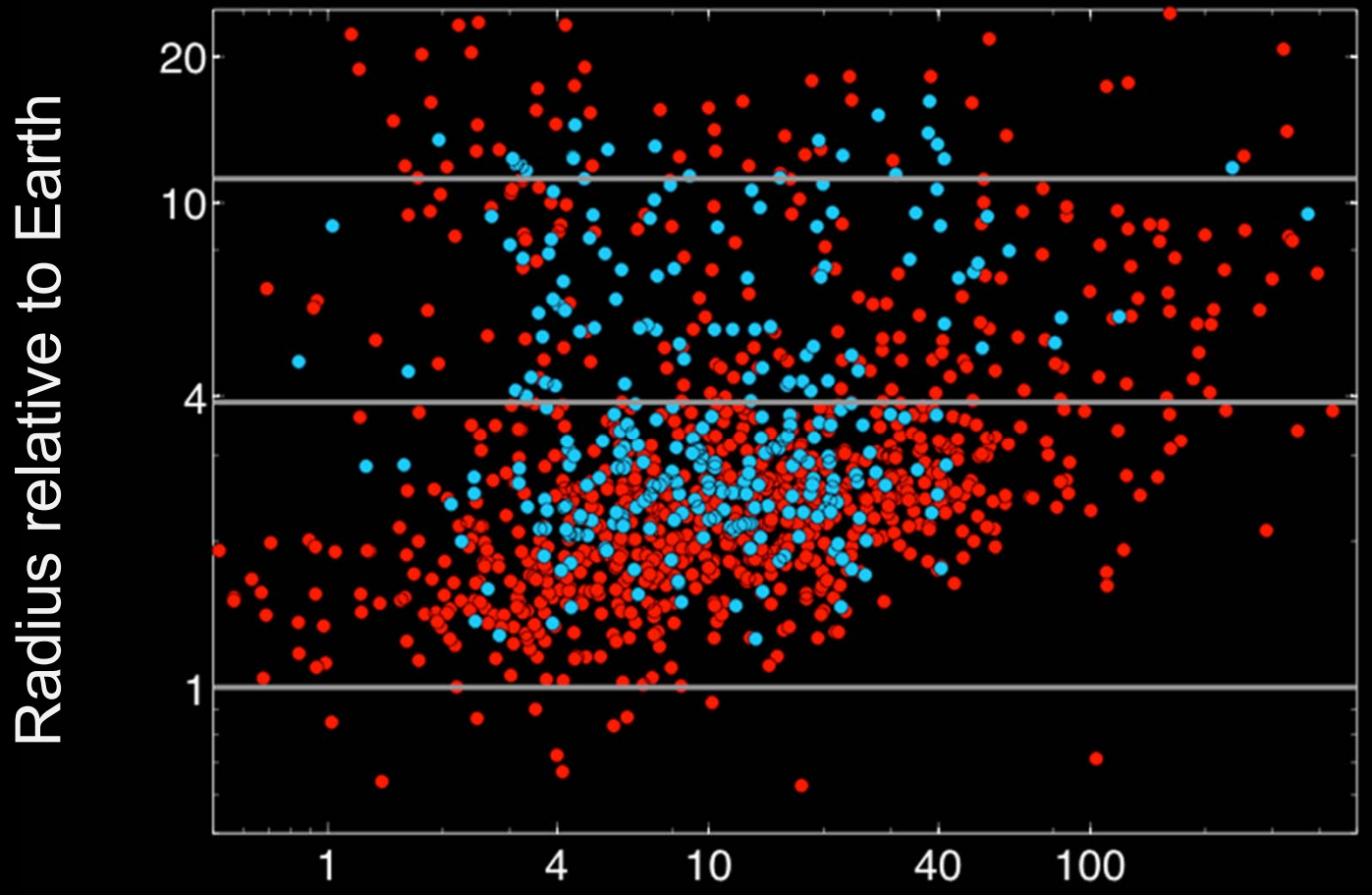


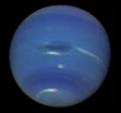
Kepler Exoplanet Candidates – June 2010



312

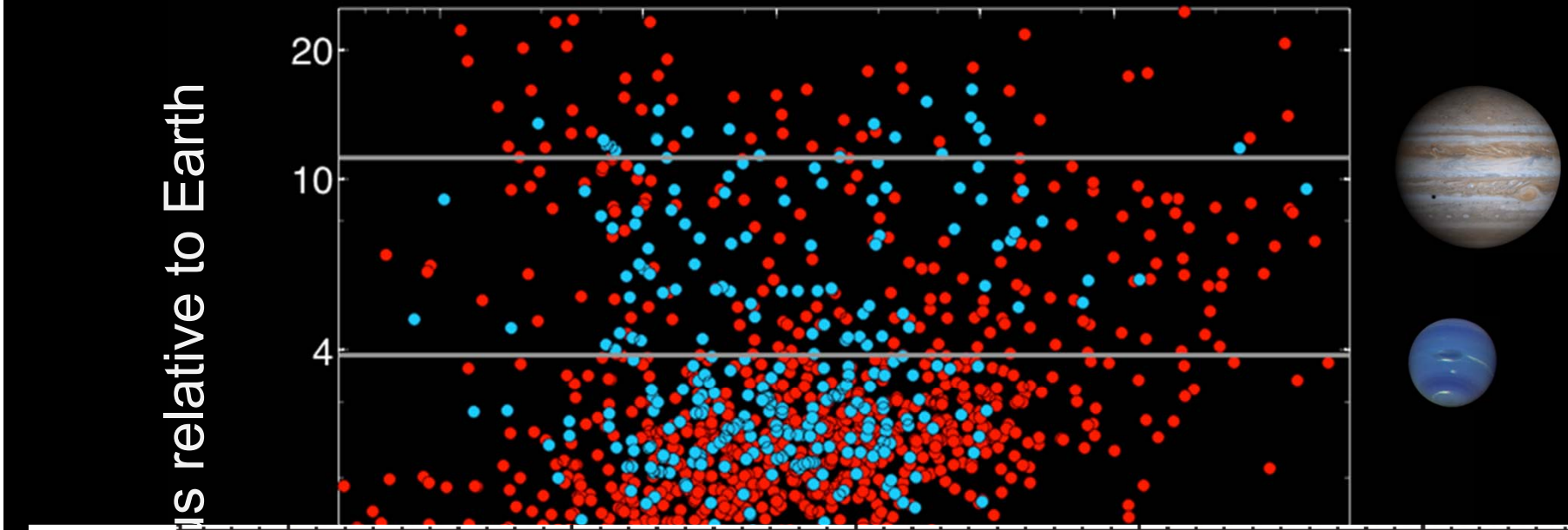
Kepler Exoplanet Candidates – Feb 2011

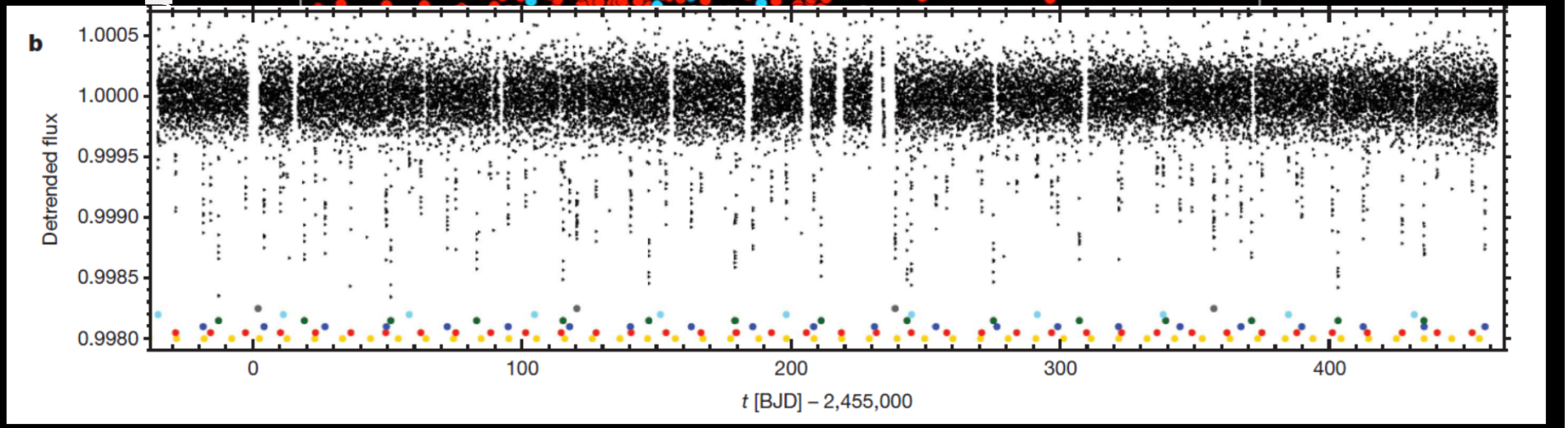




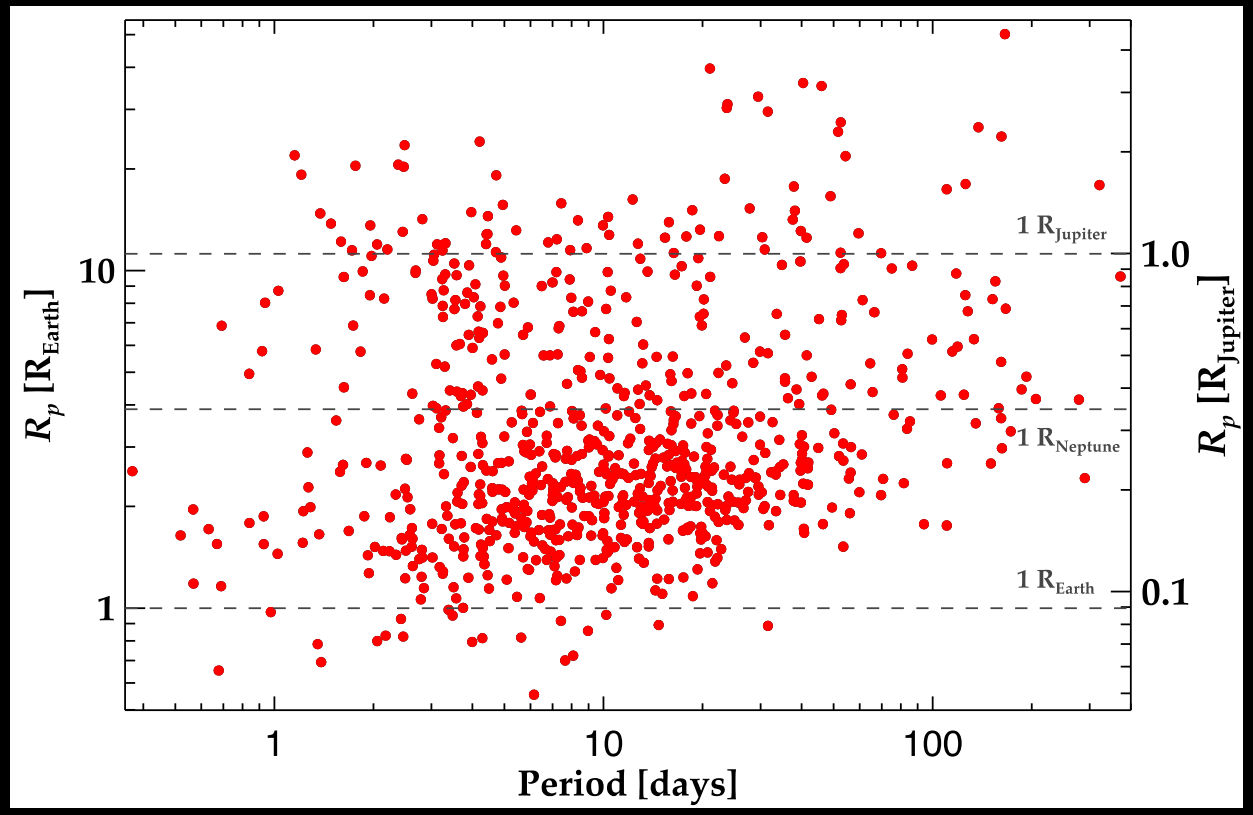
1235

Kepler Exoplanet Candidates – Feb 2011



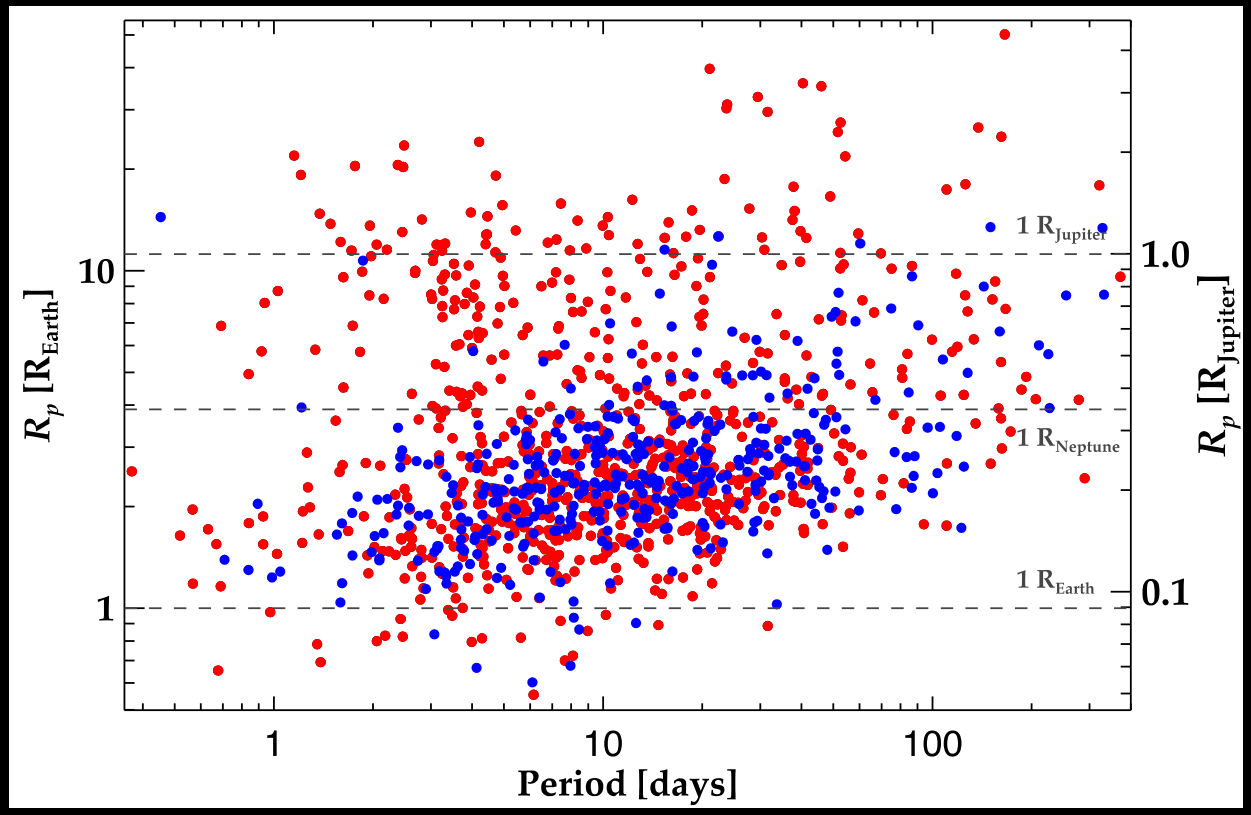


Kepler: 827 Single Planet Systems Detected



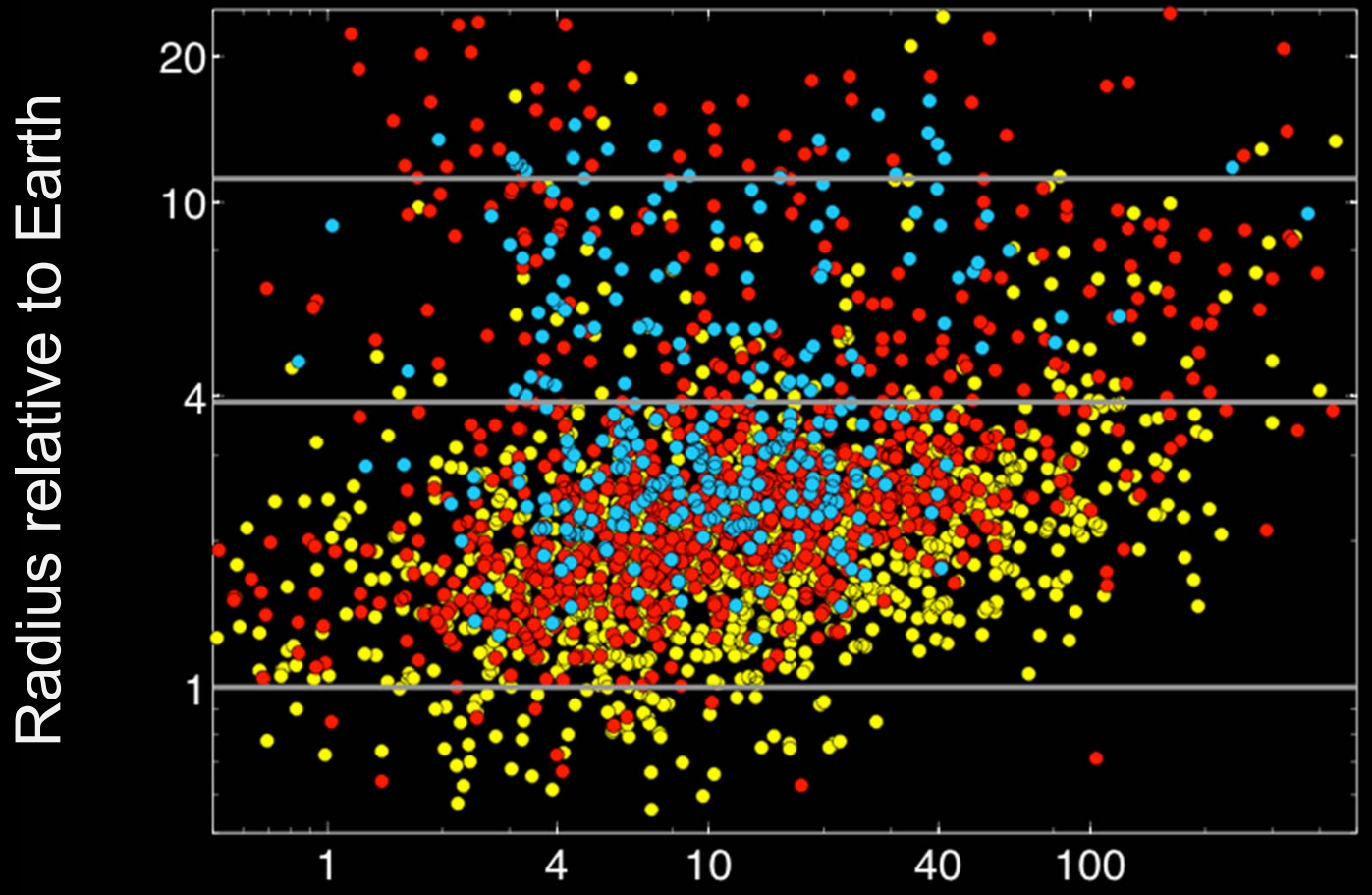
Letham et al. 2011

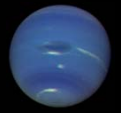
Kepler: 827 Single Planet Systems Detected



408 candidates in 170 multiple systems

Kepler Exoplanet Candidates – Dec 2011

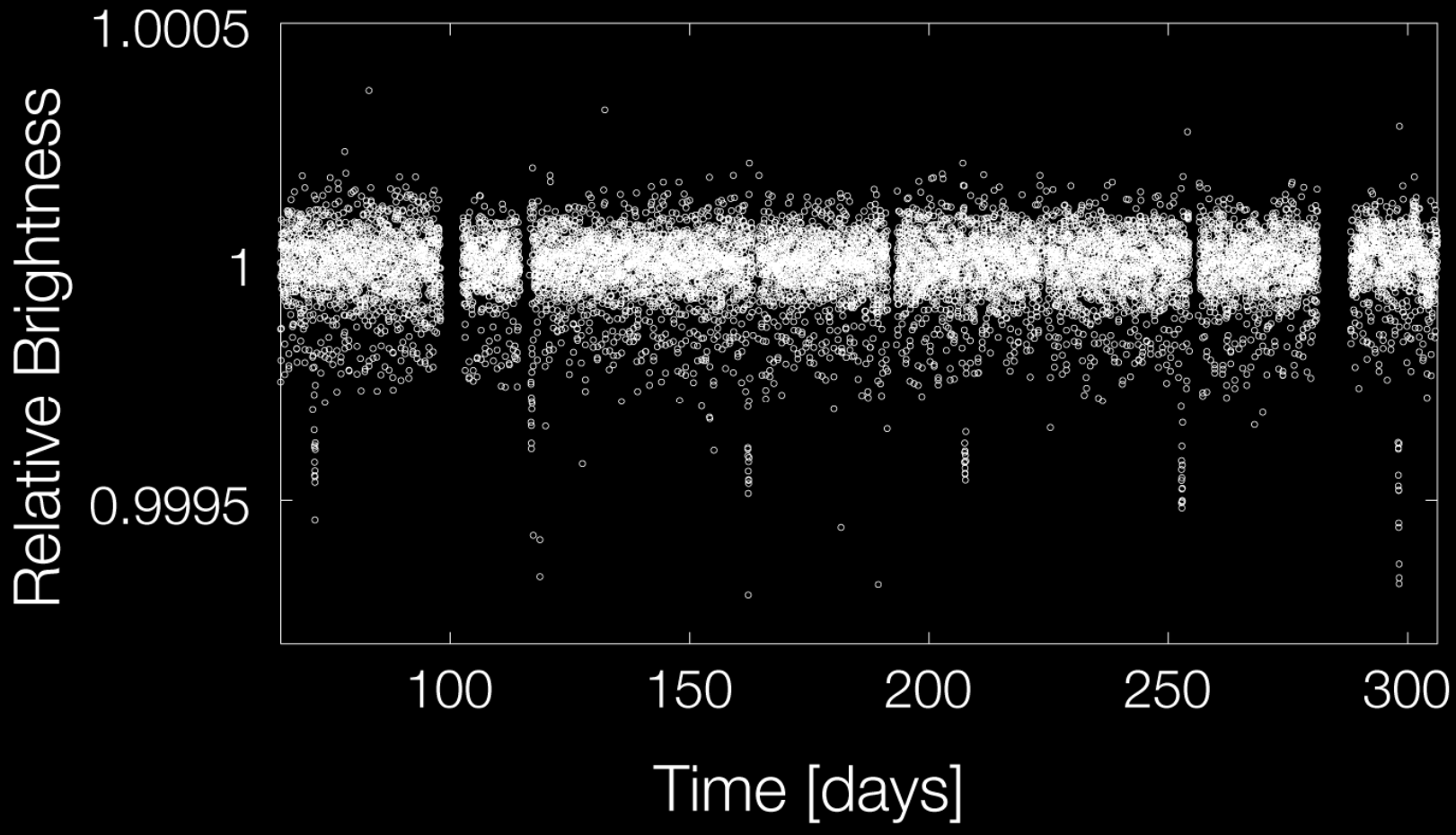


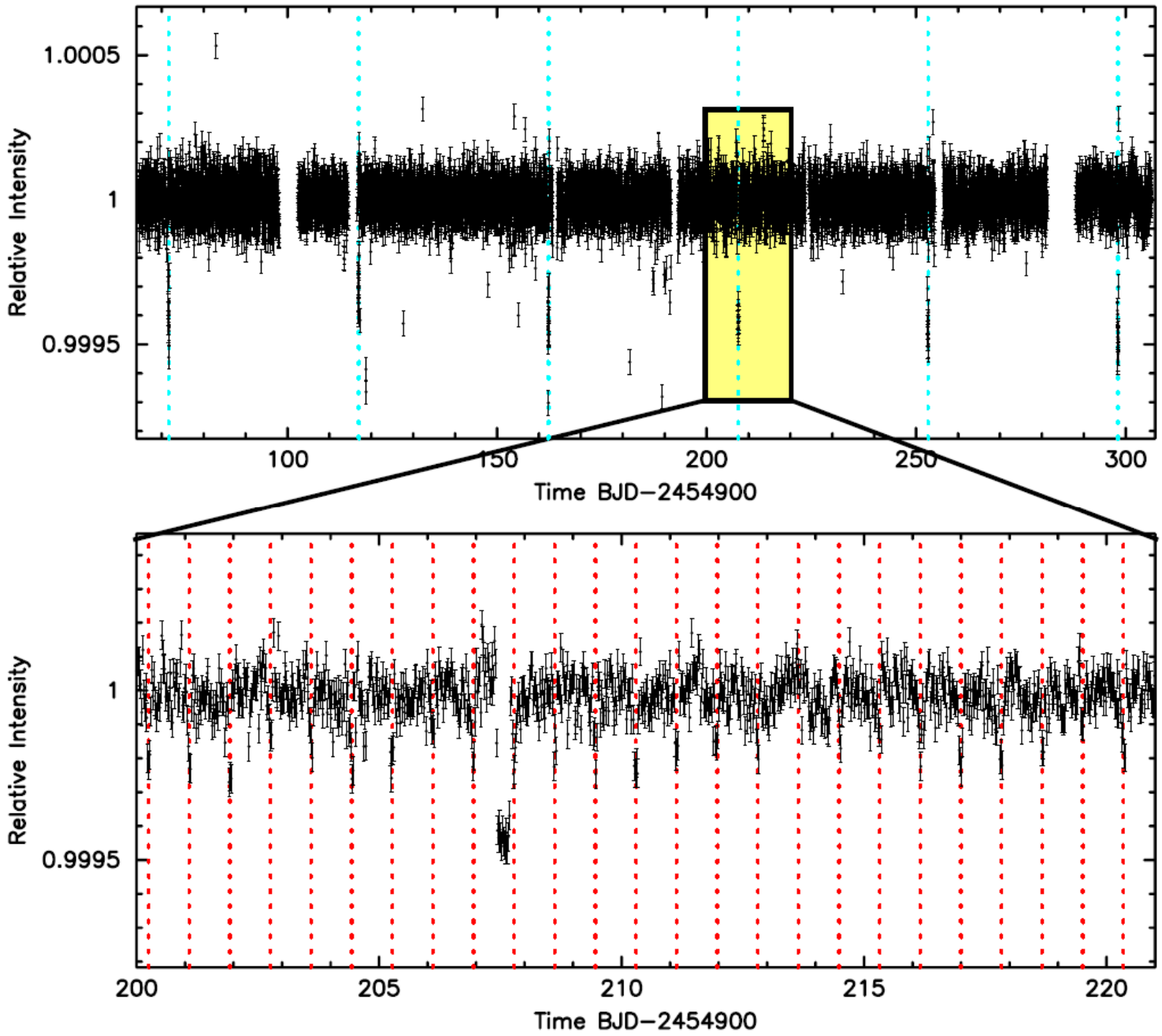


2326

Kepler-10 Light Curve

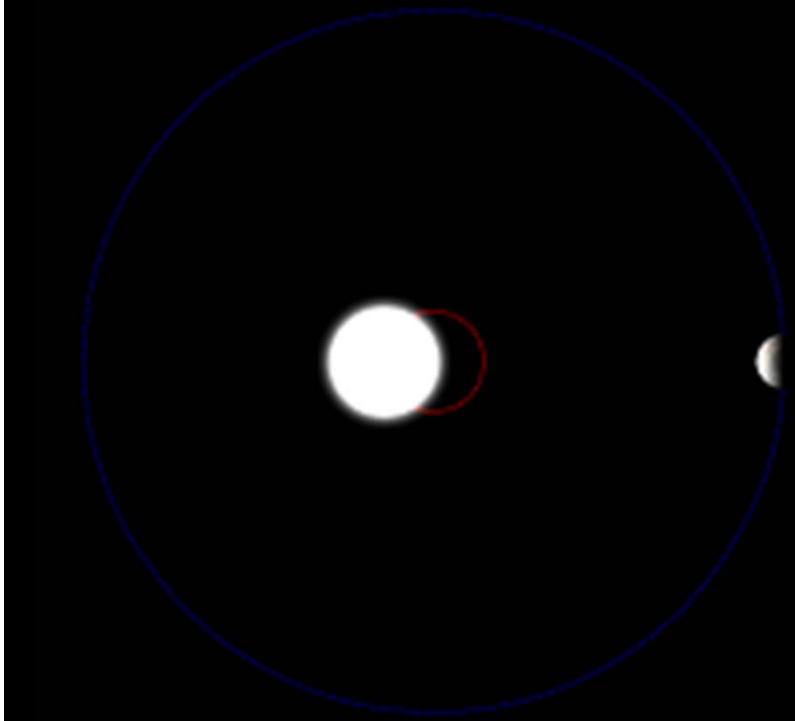
Batalha et al. 2011

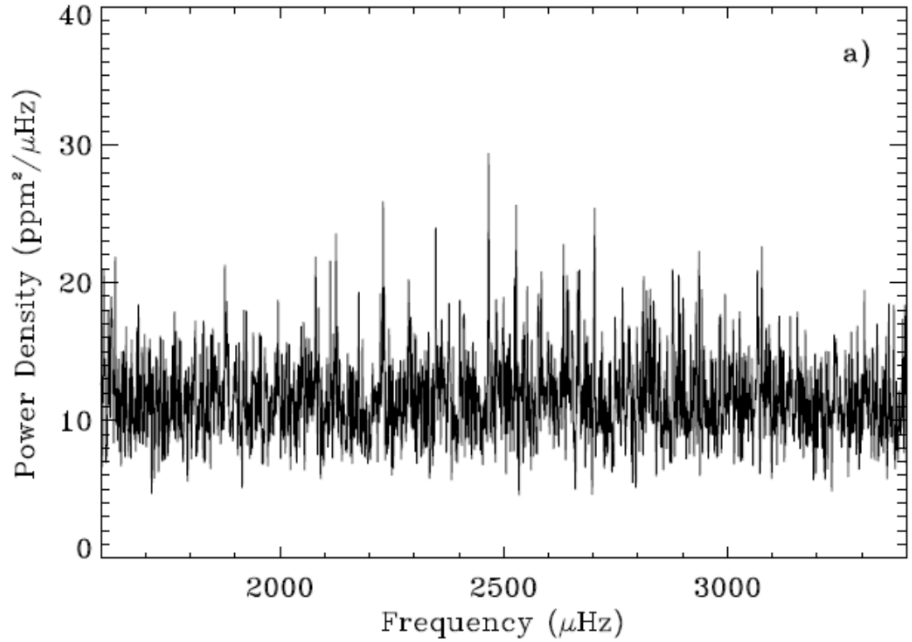


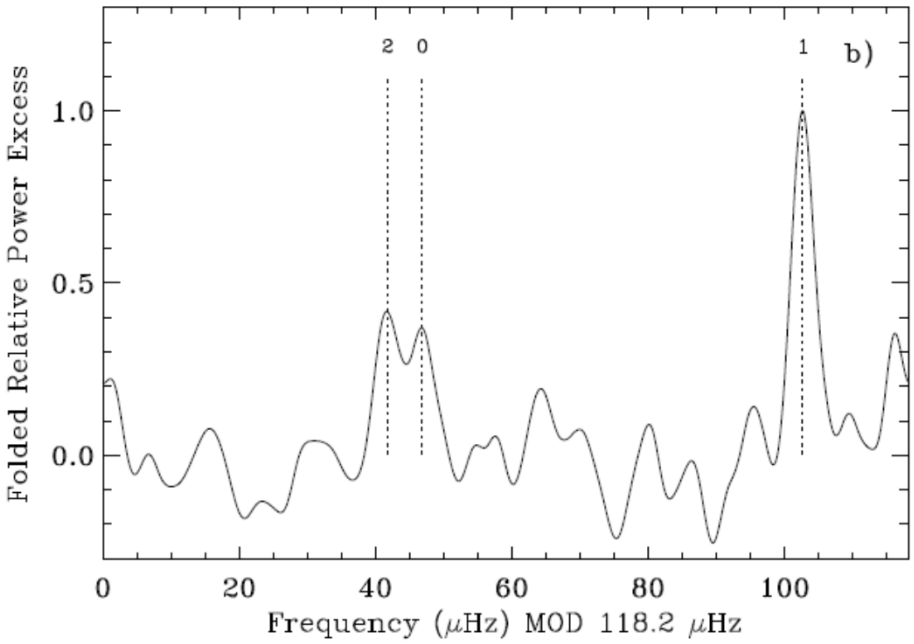

1.0005
1
0.9995
Relative Intensity
100
150
200
250
300
Time BJD−2454900
1
0.9995
Relative Intensity
200
205
210
215
220
Time BJD−2454900

Kepler-10

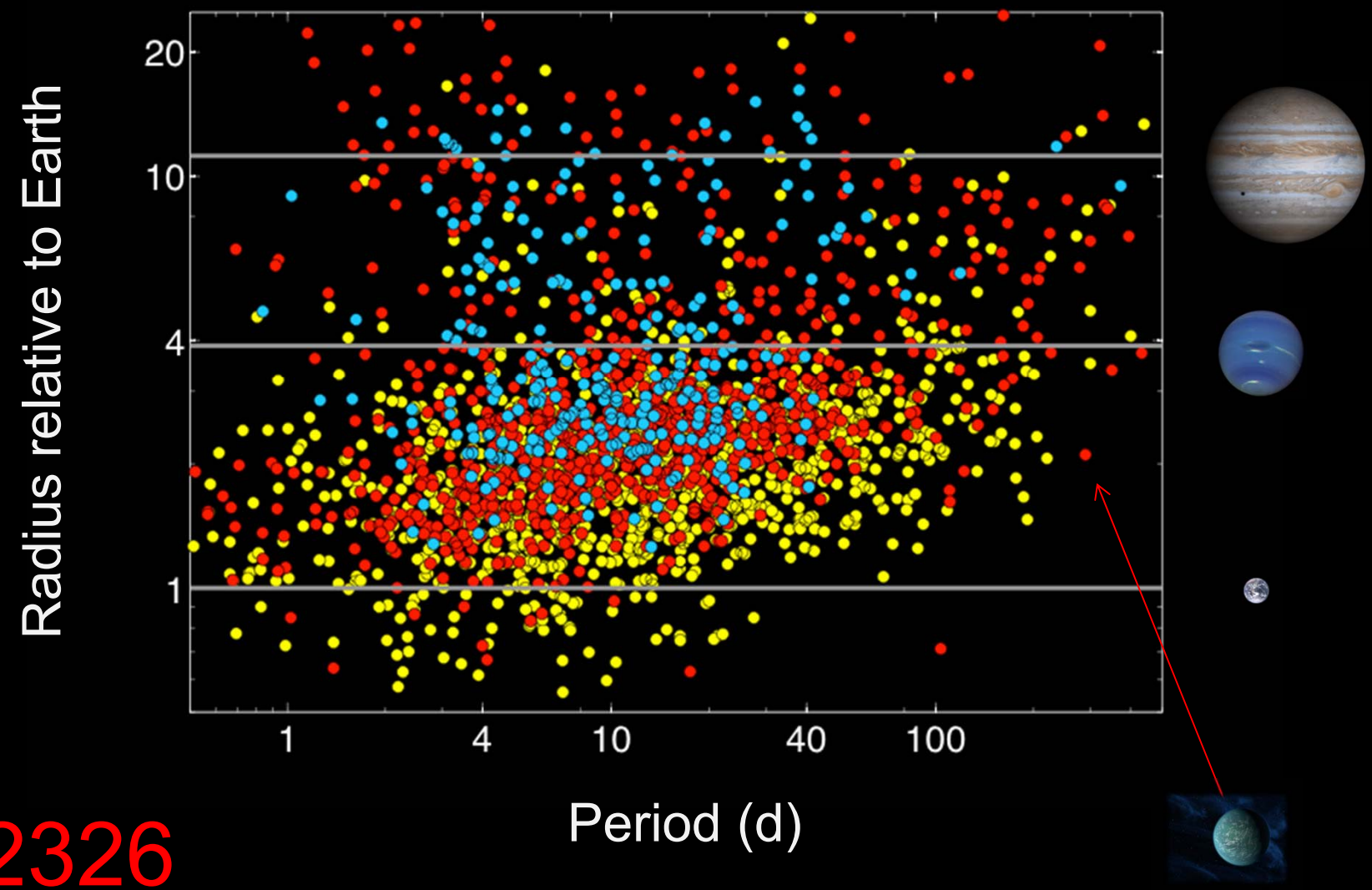
V = 11.2



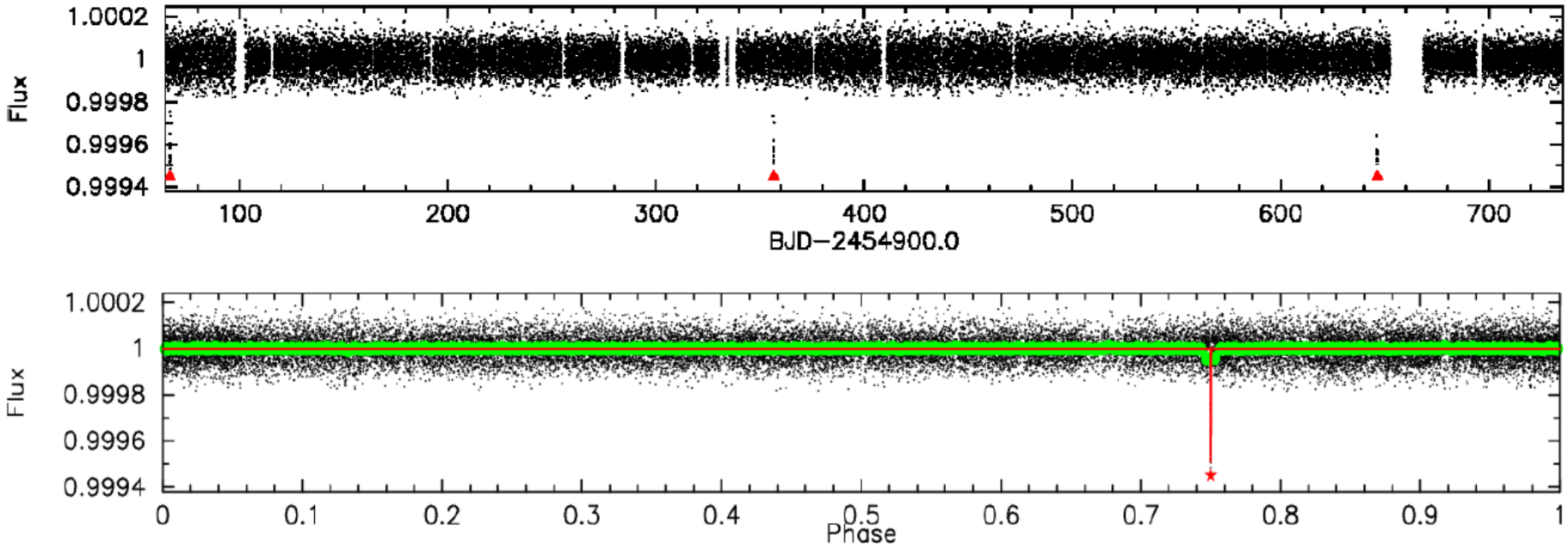


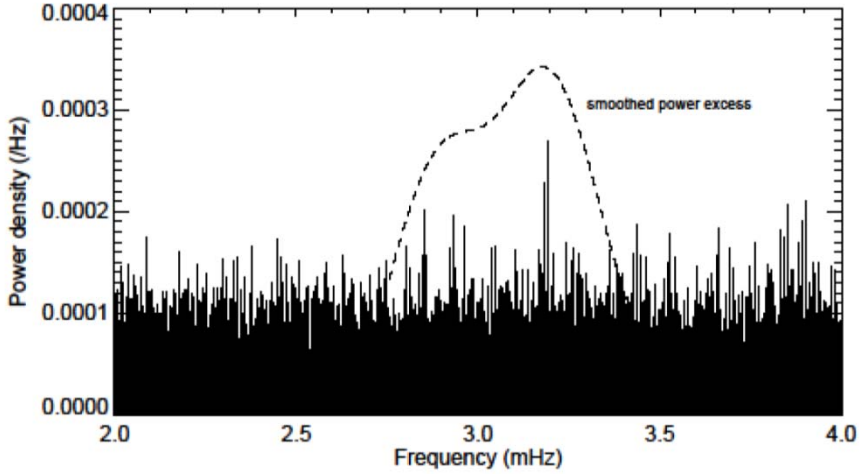


Kepler Exoplanet Candidates – Dec 2011

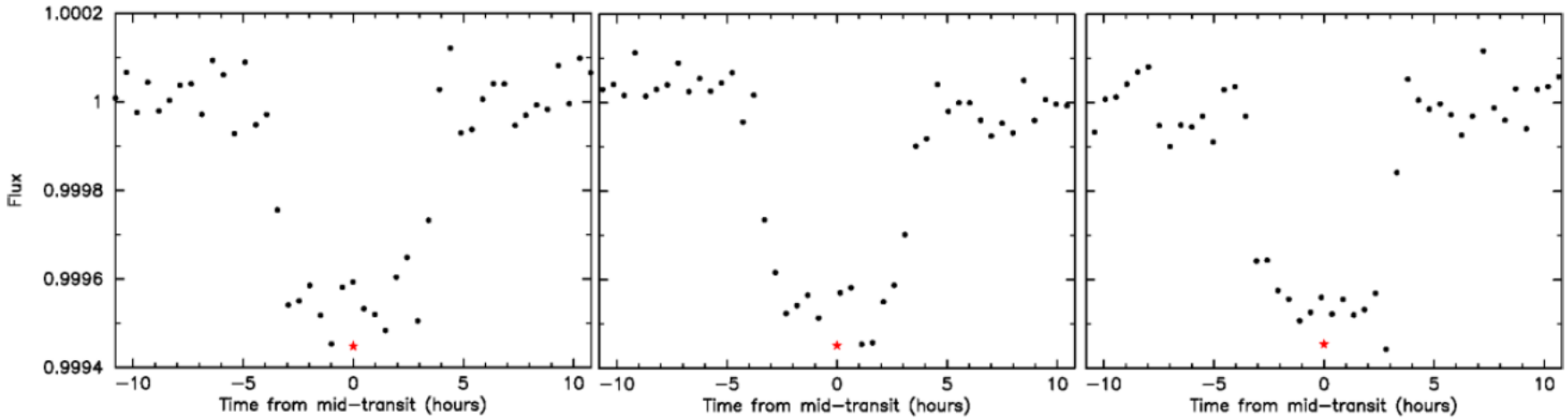


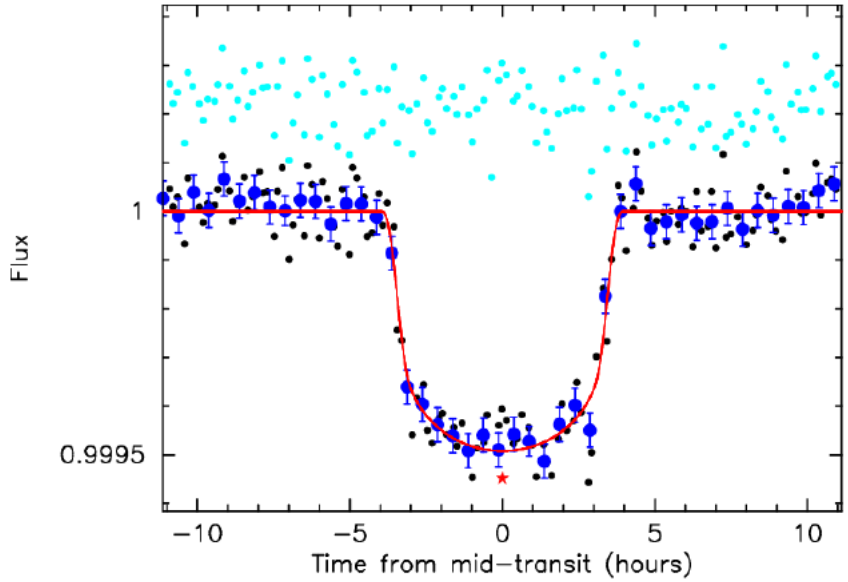
Kepler-22b

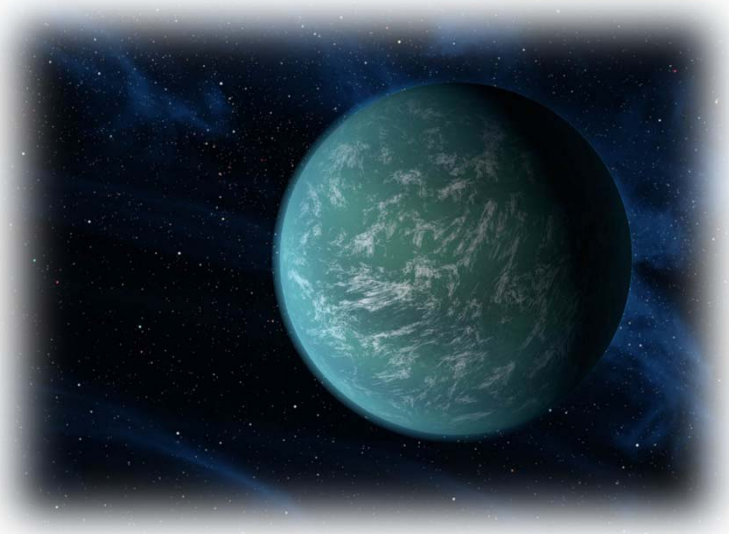




Batalha et al. 2011

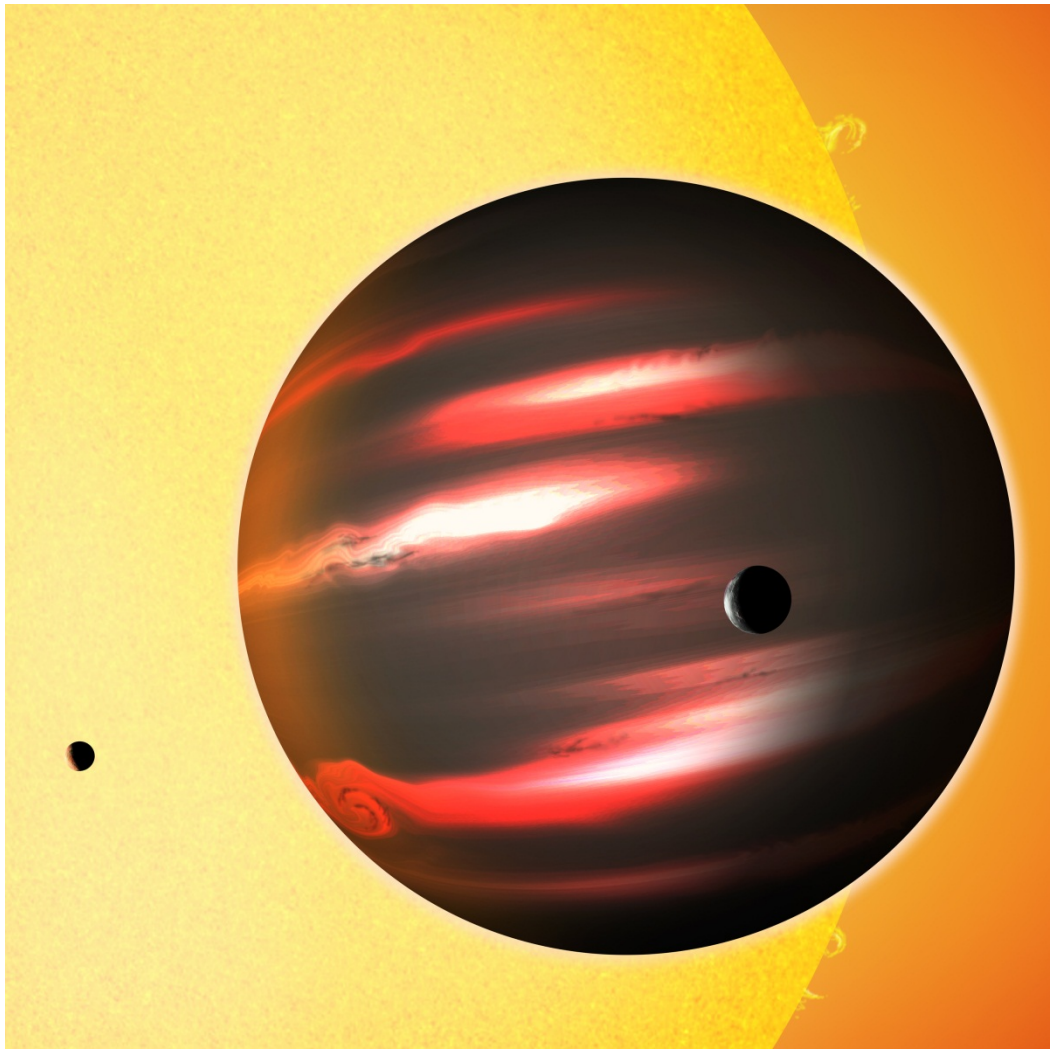

1.0002
1
0.9998
0.9996
0.9994
Flux
−10
−5
0
5
10
Time from mid−transit (hours)
Time from mid−transit (hours)
Time from mid−transit (hours)


1
0.9995
Flux
−10
−5
0
5
10
Time from mid−transit (hours)

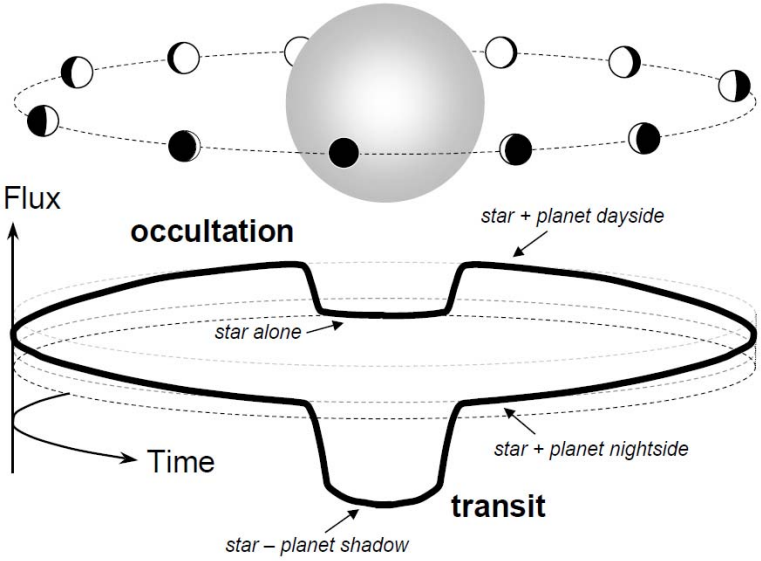


Kepler-22b

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

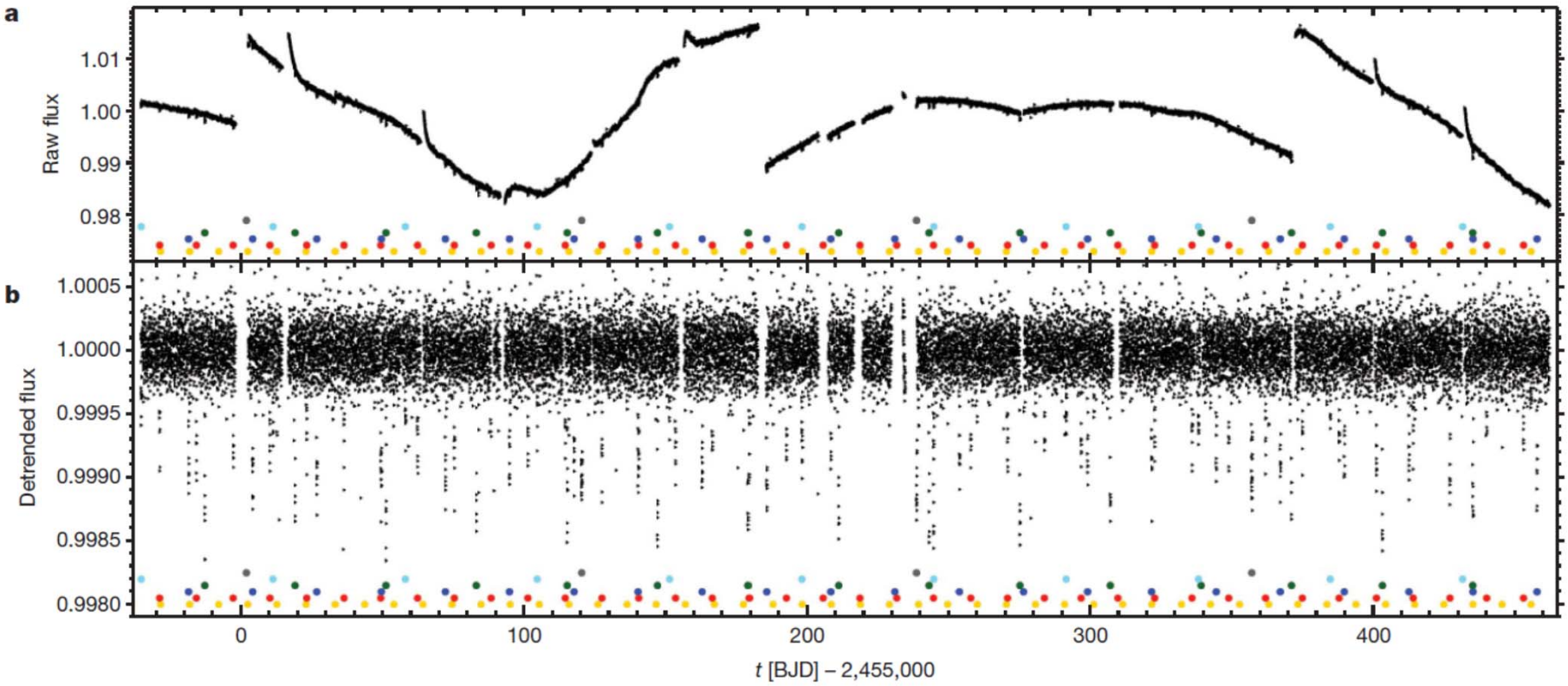


TrES-2b

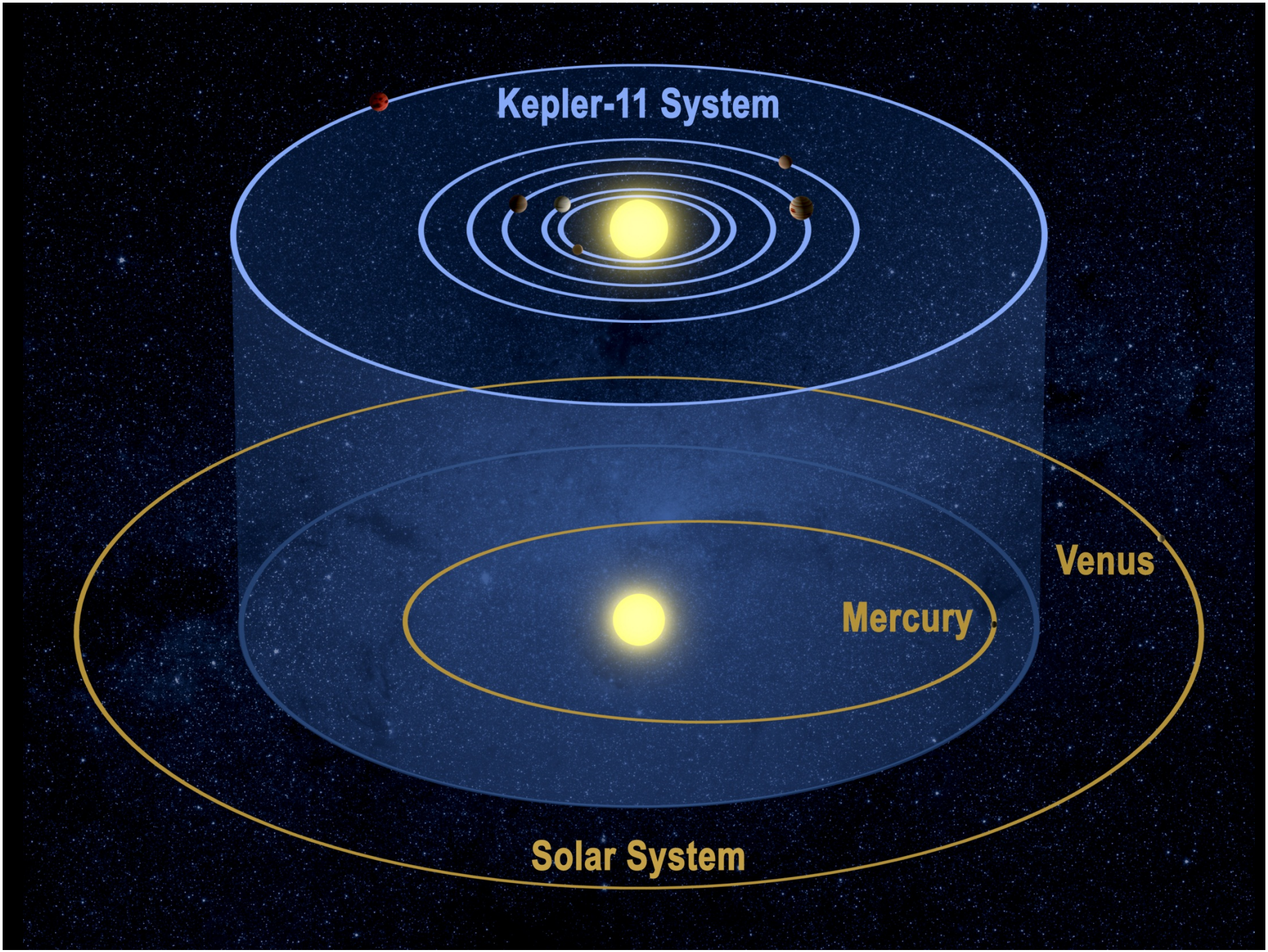


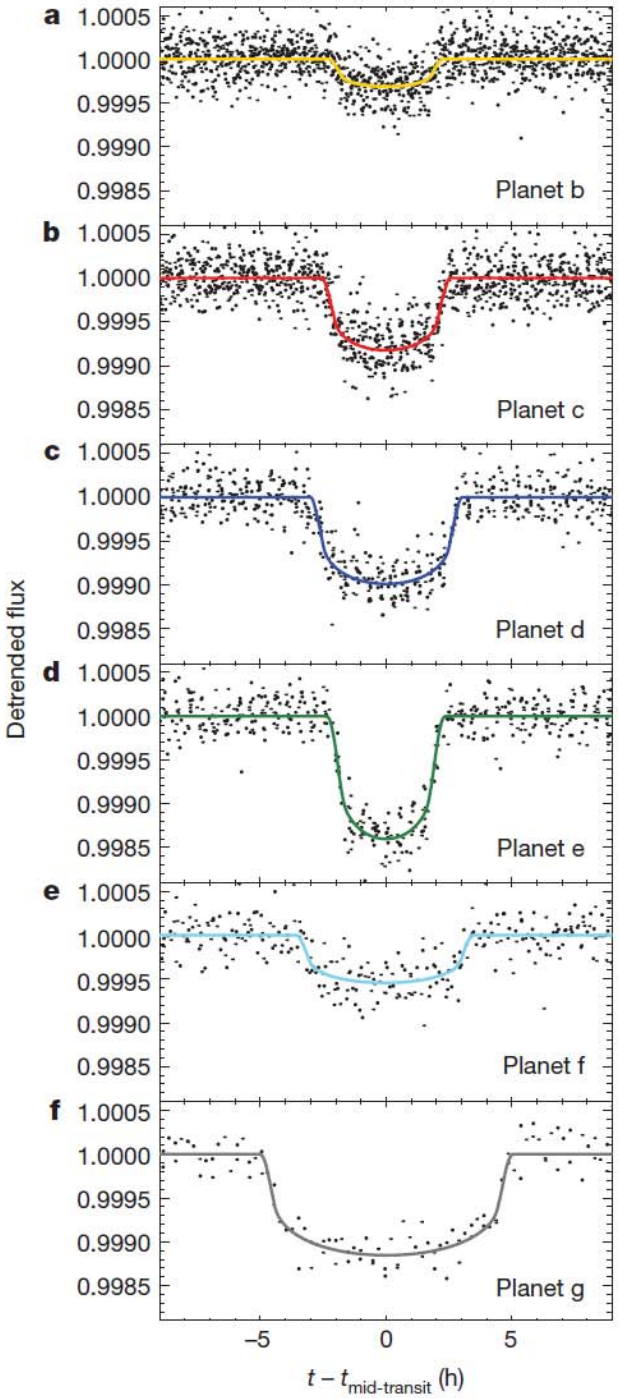
David M. Kipping & David S. Spiegel. *Monthly Notices of the Royal Astronomical Society*. For all models, the geometric albedo is < 1%, and for the best-fit models it is ~0.04%

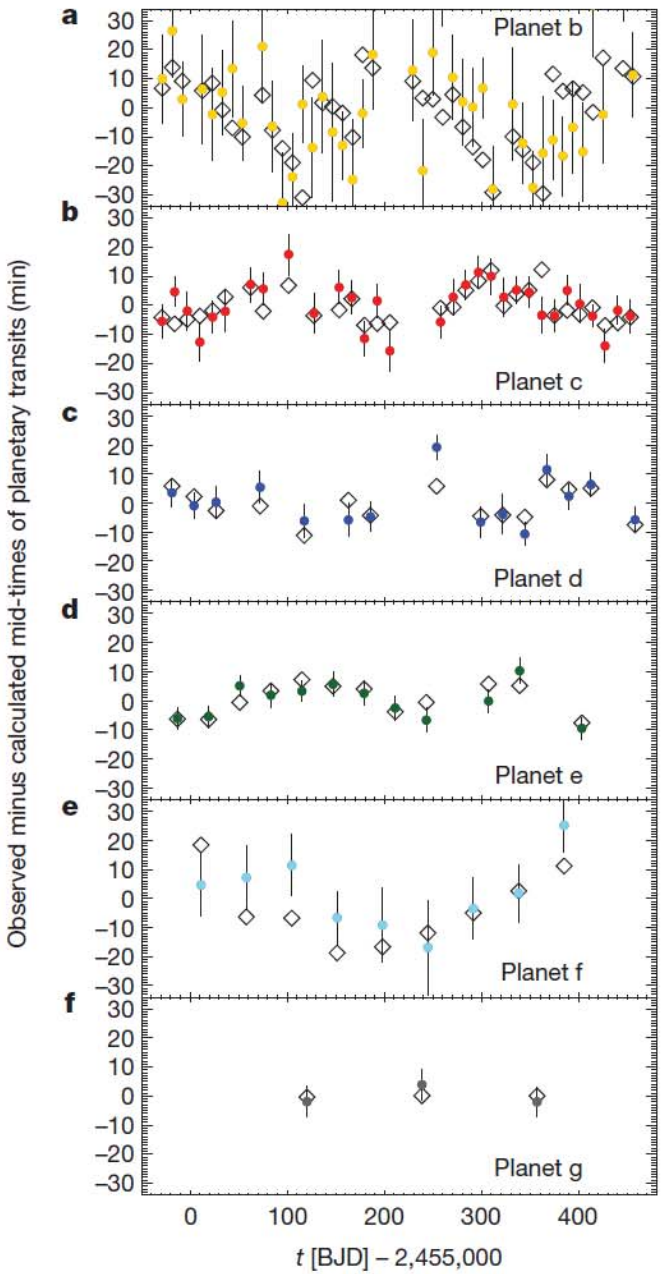
Kepler-11

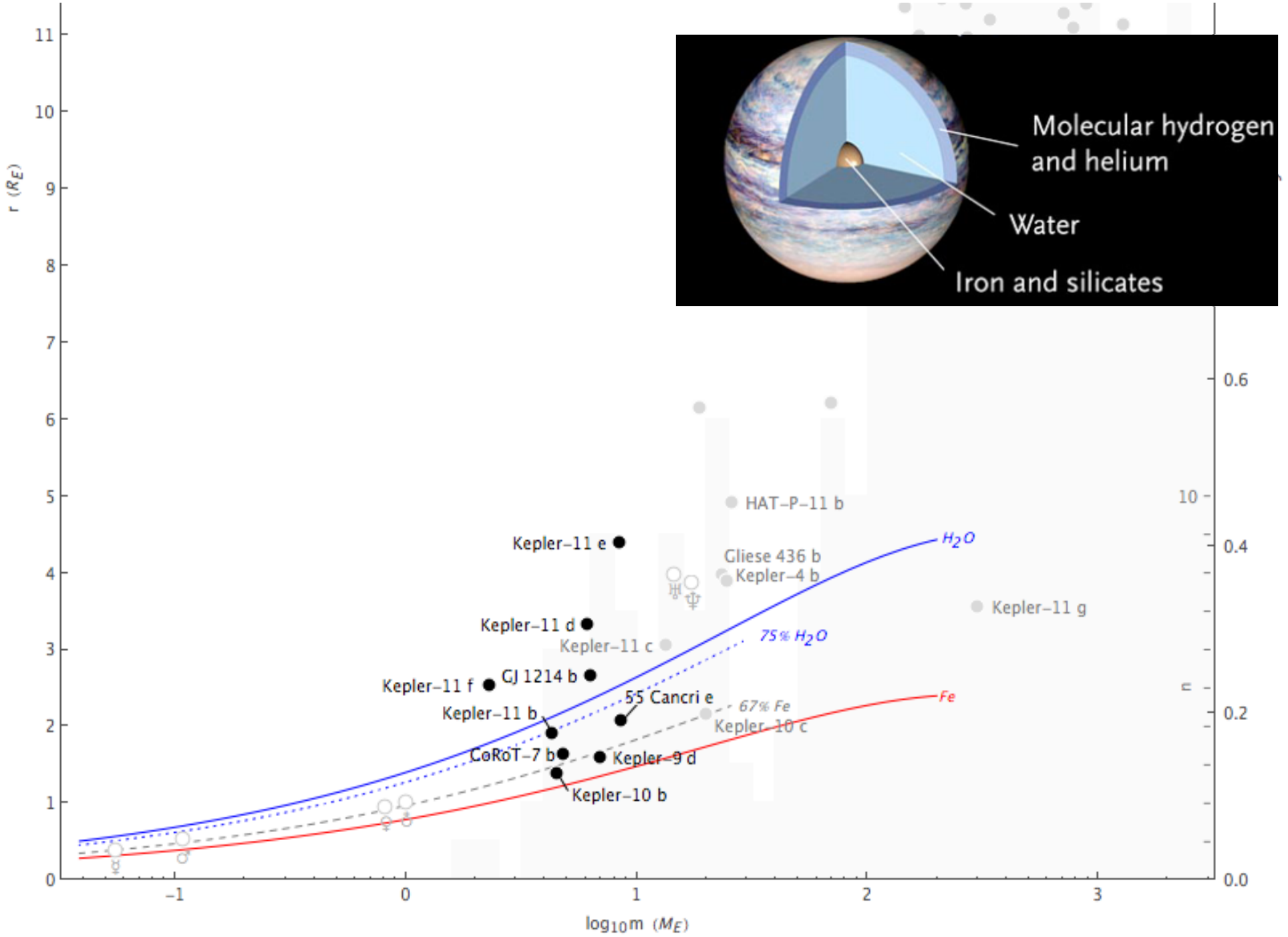


Lissauer et al. 2011


Kepler-11 System
Venus
Mercury
Solar System

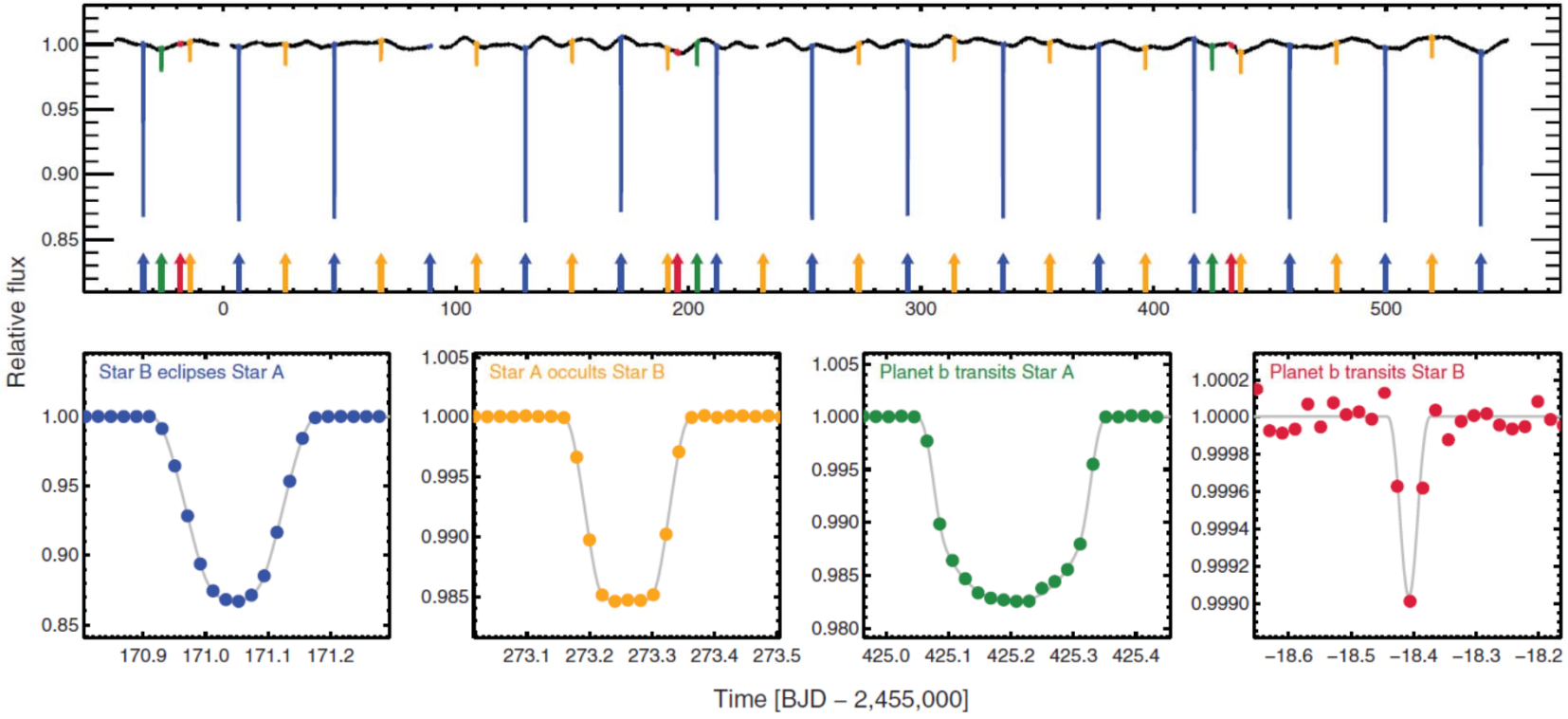

a
b
c
d
e
f
1.0005
1.0000
0.9995
0.9990
0.9985
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
Detrended flux
−5
0
5
t − t mid-transit (h)

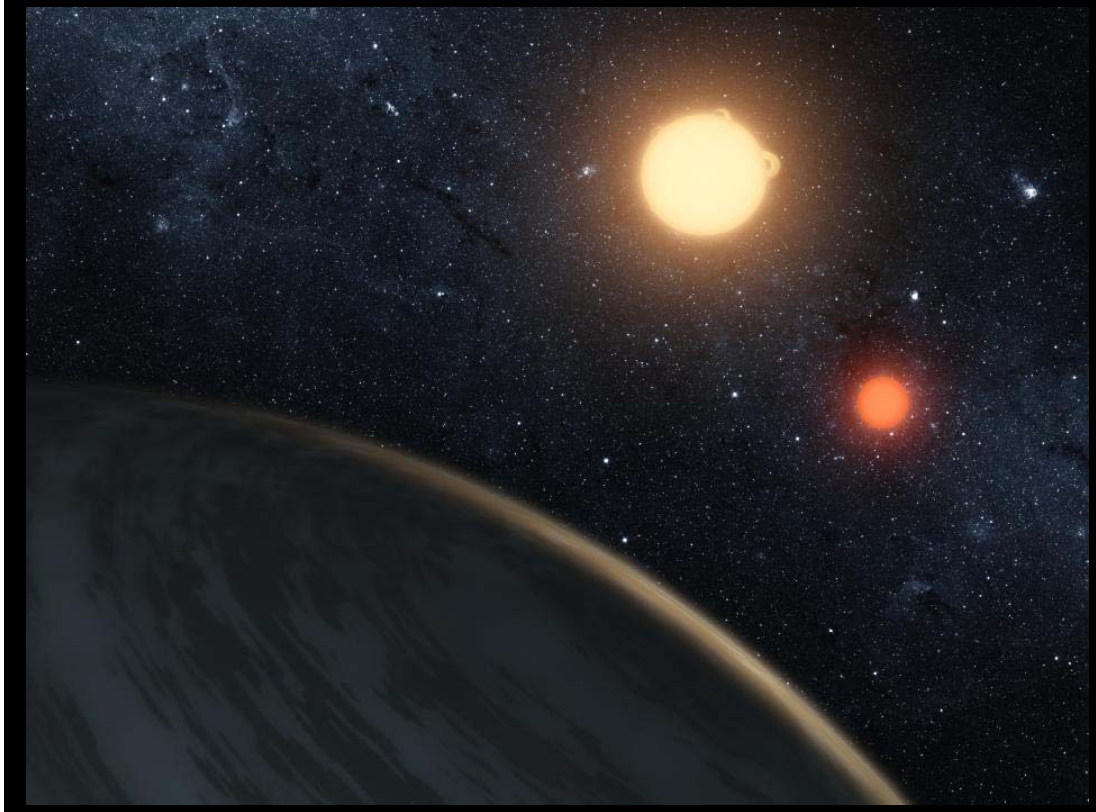

a
b
c
d
e
f
30
20
10
0
−10
−20
−30
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
Observed minus calculated mid-times of planetary transits (min)
0
100
200
300
400
t [BJD] − 2,455,000

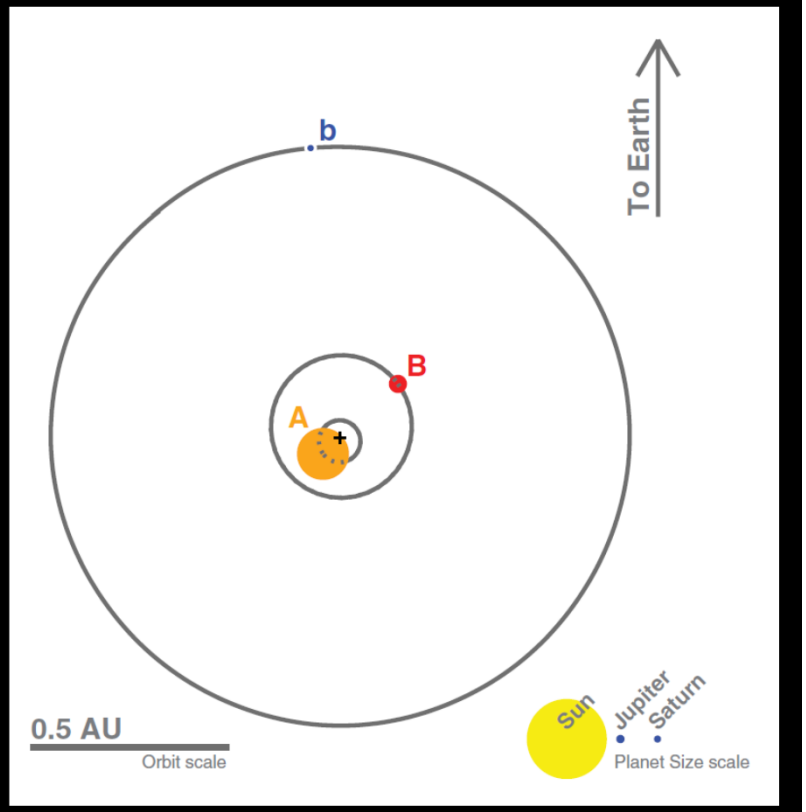

Molecular hydrogen and helium
Water
Iron and silicates
r (R_E)
$\log_{10}$m (M_E)
n
H_2O
75% H_2O
Fe
67% Fe
HAT-P-11 b
Kepler-11 e
Gliese 436 b
Kepler-4 b
Kepler-11 g
Kepler-11 d
Kepler-11 c
Kepler-11 f
GJ 1214 b
55 Cancri e
Kepler-11 b
Kepler-10 c
CoRoT-7 b
Kepler-9 d
Kepler-10 b

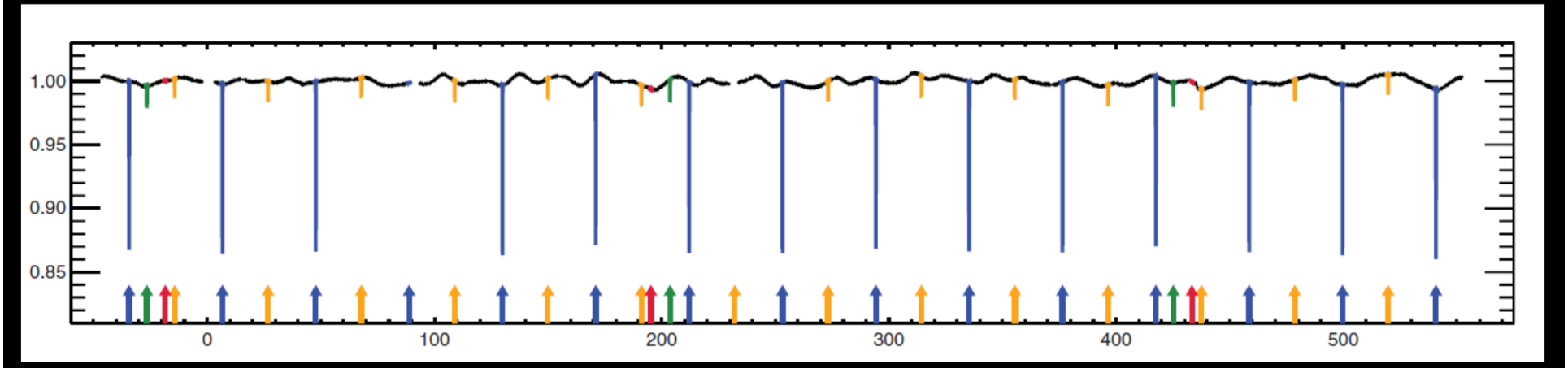
Kepler-16: A Transiting Circumbinary Planet

Laurance R. Doyle,[1*] Joshua A. Carter,[2] Daniel C. Fabrycky,[3] Robert W. Slawson,[1] Steve B. Howell,[4] Joshua N. Winn,[5] Jerome A. Orosz,[6] Andrej Prˇsa,[7] William F. Welsh,[6] Samuel N. Quinn,[8] David Latham,[8] Guillermo Torres,[8] Lars A. Buchhave,[9,19] Geoffrey W. Marcy,[11] Jonathan J. Fortney,[12] Avi Shporer,[13,14] Eric B. Ford,[15] Jack J. Lissauer,[4] Darin Ragozzine,[2] Michael Rucker,[16] Natalie Batalha,[16] Jon M. Jenkins,[1] William J. Borucki,[4] David Koch,[4] Christopher K. Middour,[17] Jennifer R. Hall,[17] Sean McCauliff,[17] Michael N. Fanelli,[18] Elisa V. Quintana,[1] Matthew J. Holman,[8] Douglas A. Caldwell,[1] Martin Still,[18] Robert P. Stefanik,[8] Warren R. Brown,[8] Gilbert A. Esquerdo,[8] Sumin Tang,[8] Gabor Furesz,[8,10] John C. Geary,[8] Perry Berlind,[20] Michael L. Calkins,[20] Donald R. Short,[21] Jason H. Steffen,[22] Dimitar Sasselov,[8] Edward W. Dunham,[23] William D. Cochran,[24] Alan Boss,[25] Michael R. Haas,[4] Derek Buzasi,[26] Debra Fischer[27]

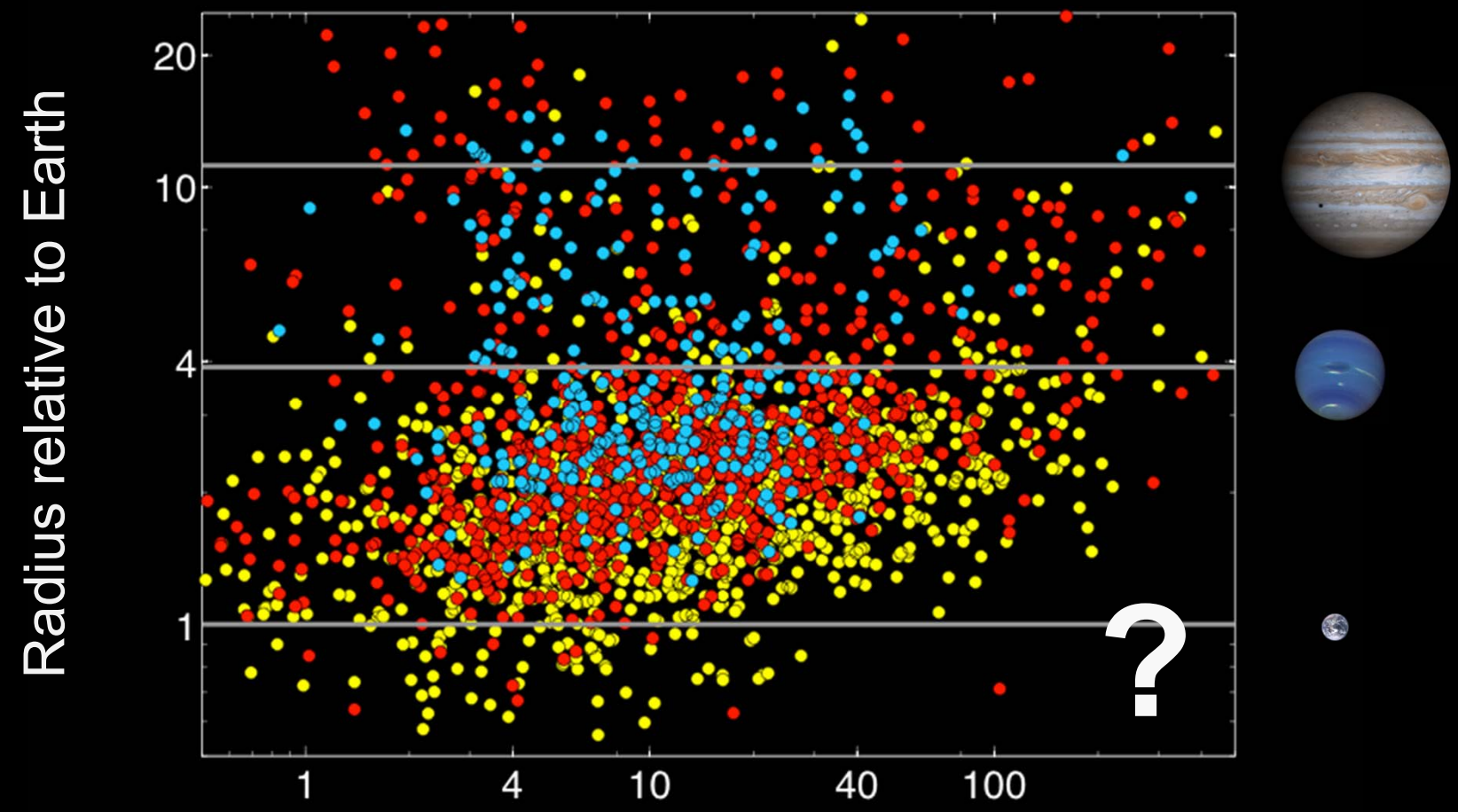





To Earth
b
B
A
0.5 AU
Orbit scale
Sun
Jupiter
Saturn
Planet Size scale


1.00
0.95
0.90
0.85
0
100
200
300
400
500

Kepler is extended to end 2016



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Gustav Kirchhoff and Robert Bunsen

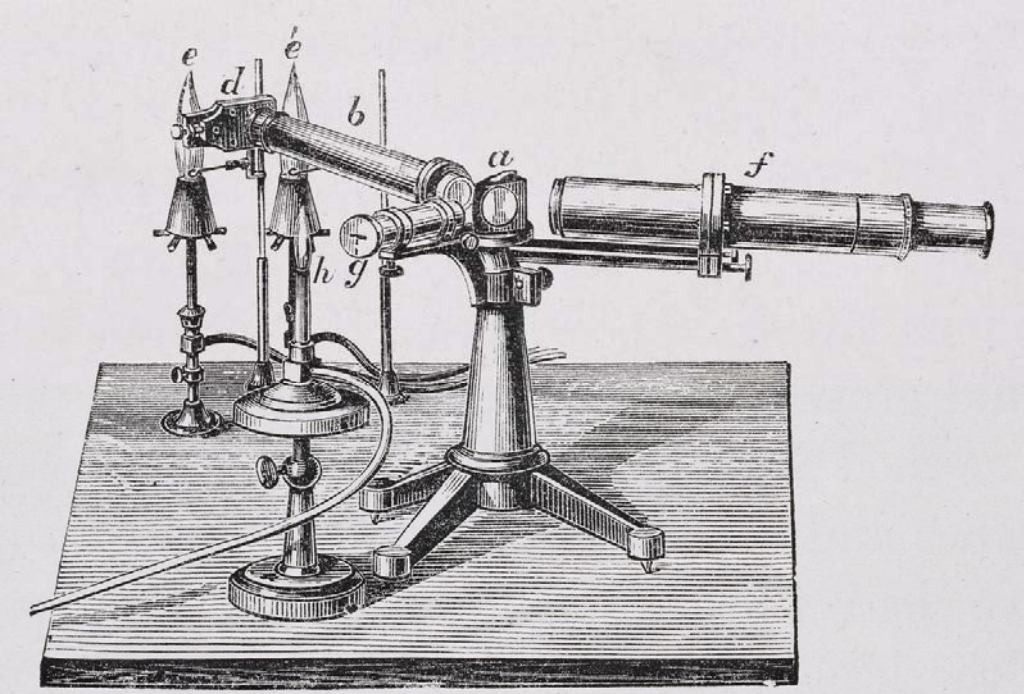
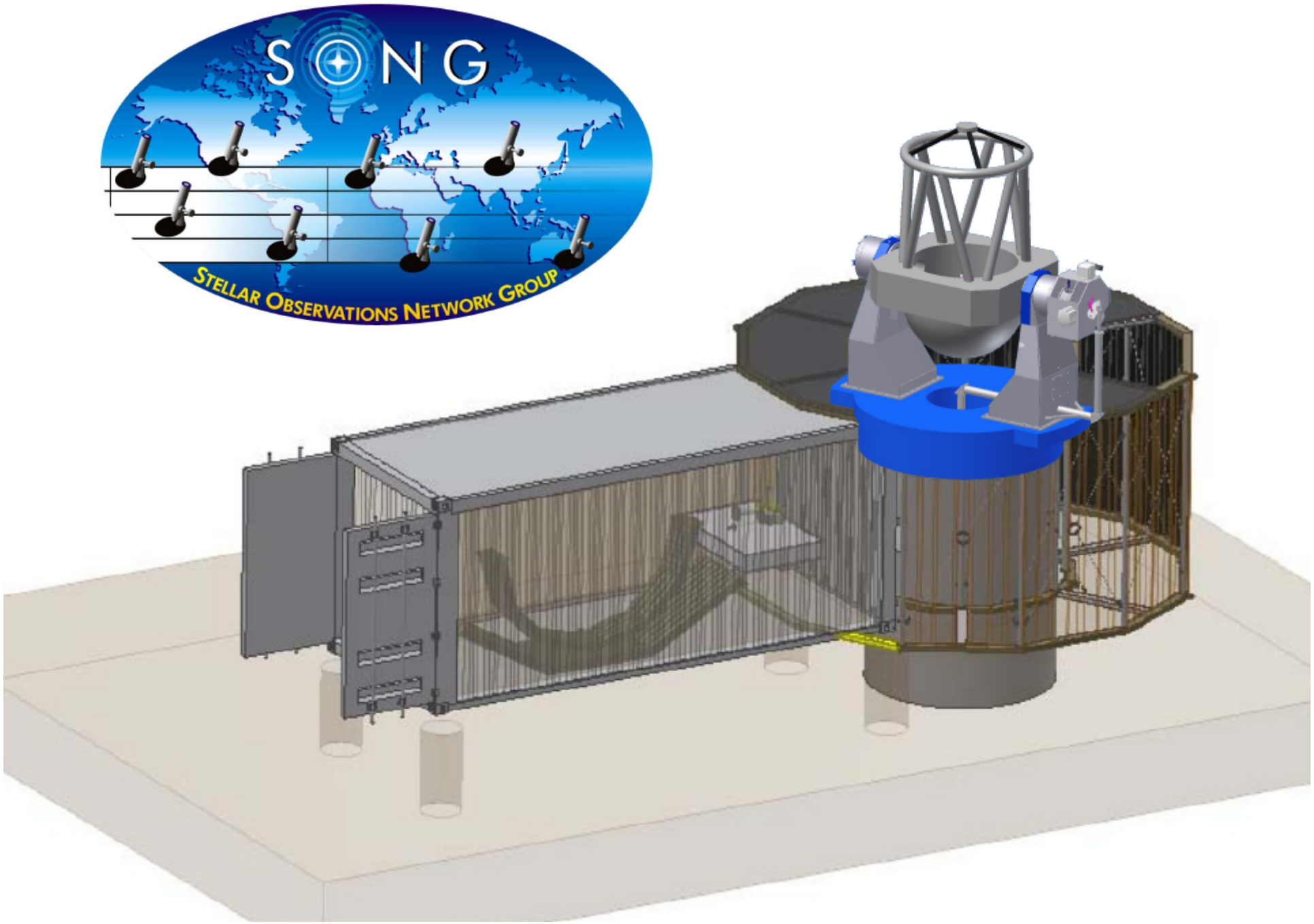


FIG. 21.


SONG
STELLAR OBSERVATIONS NETWORK GROUP

The first SONG node is ready at Tenerife