Exoplanets: Why it is Hard to Find Them?

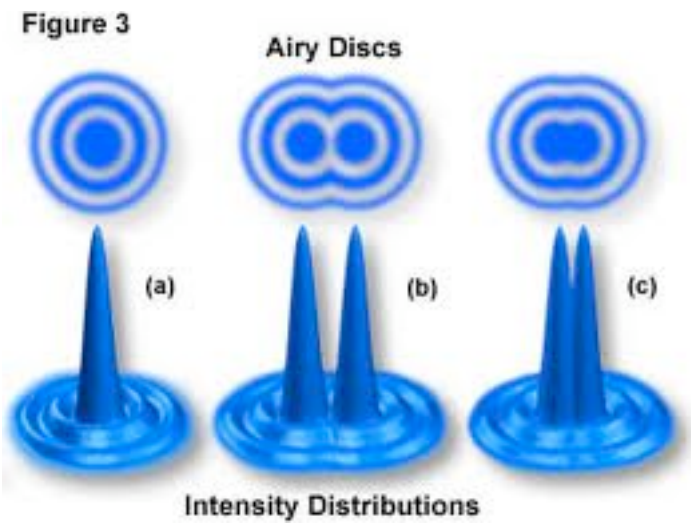
- Planets are typically 10^6 to 10^{10} times fainter than their parent star
- Astronomically speaking, they are very close to their parent star

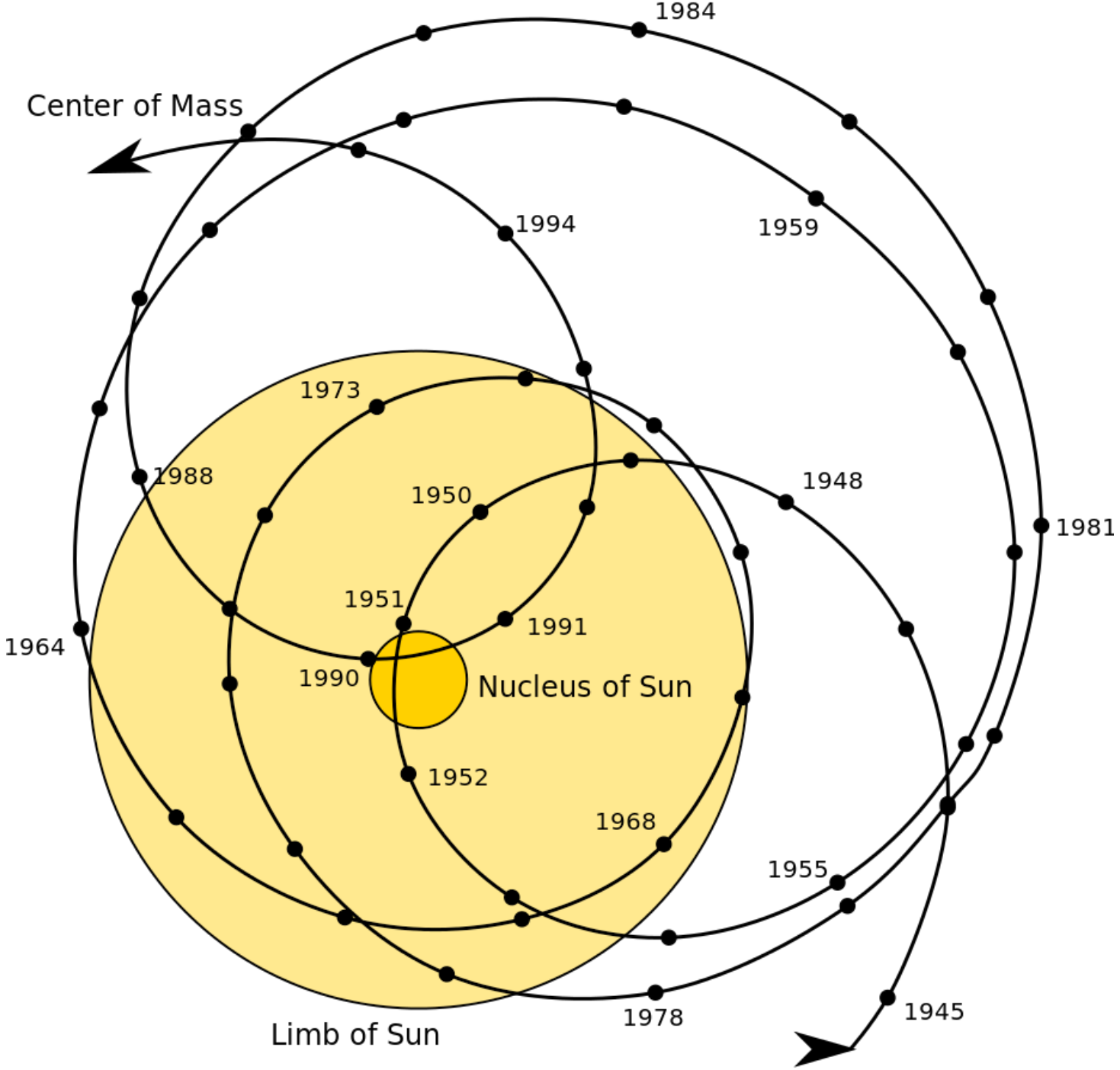
- Angle of 0.05 arcsec at 20 parsecs, for 1 AU planet

- Due to the wave nature of light, observations are diffraction-limited
  - Minimum angle that can be discerned
  - θ (radians) = 1.22 λ(cm) / D (cm)

  - For 500 nm light, 2.5 m telescope, θ=0.05 arcsec (No problem!)
  - Earth's atmosphere limits θ=0.5 arcsec, 10X worse
  - At these short wavelengths, planets are faint
  - Still have to deal with the 10^6-10^{10} faintness

  - "Direct observations" are incredibly difficult




1984
Center of Mass
1994
1959
1973
1988
1950
1948
1981
1964
1951
1991
1990
Nucleus of Sun
1952
1968
1955
1978
1945
Limb of Sun

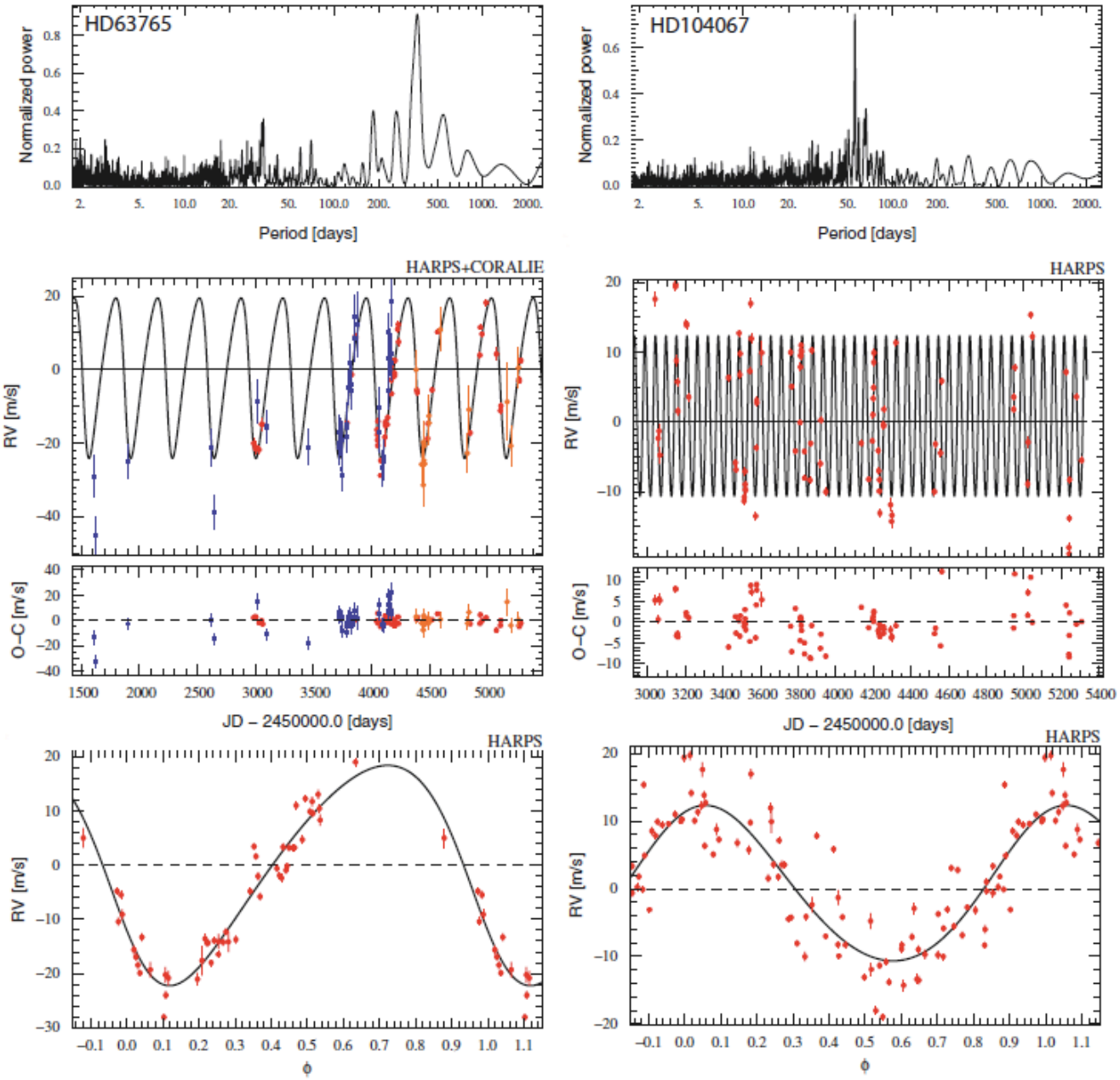
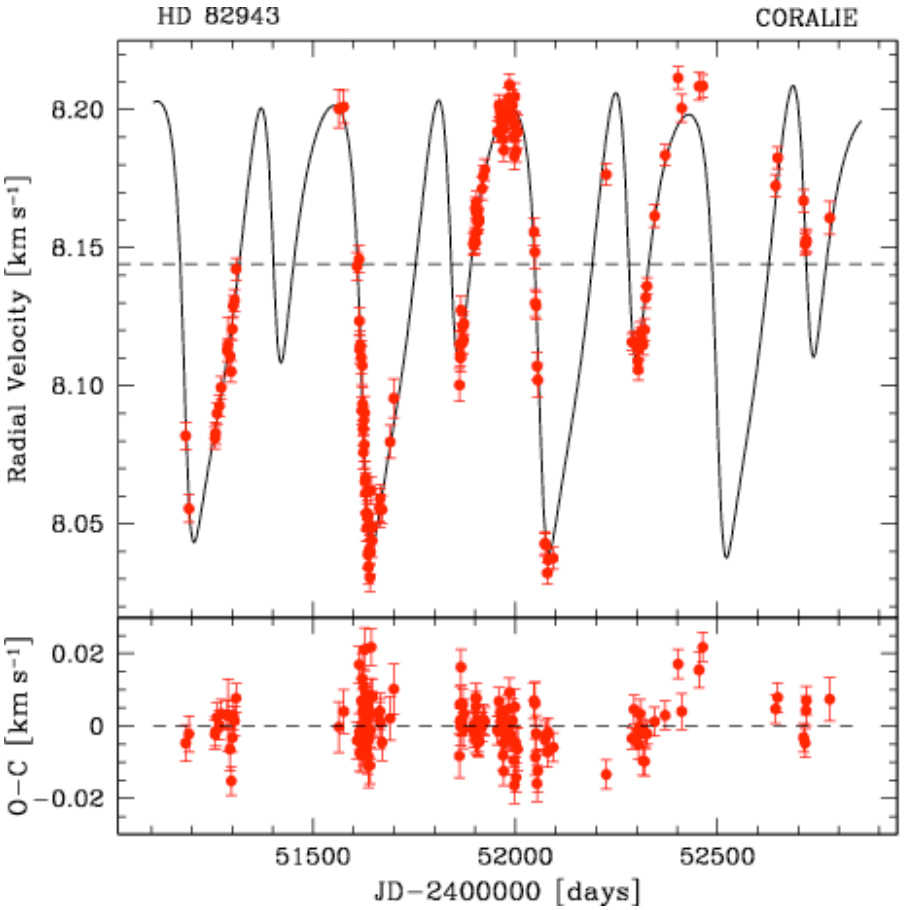
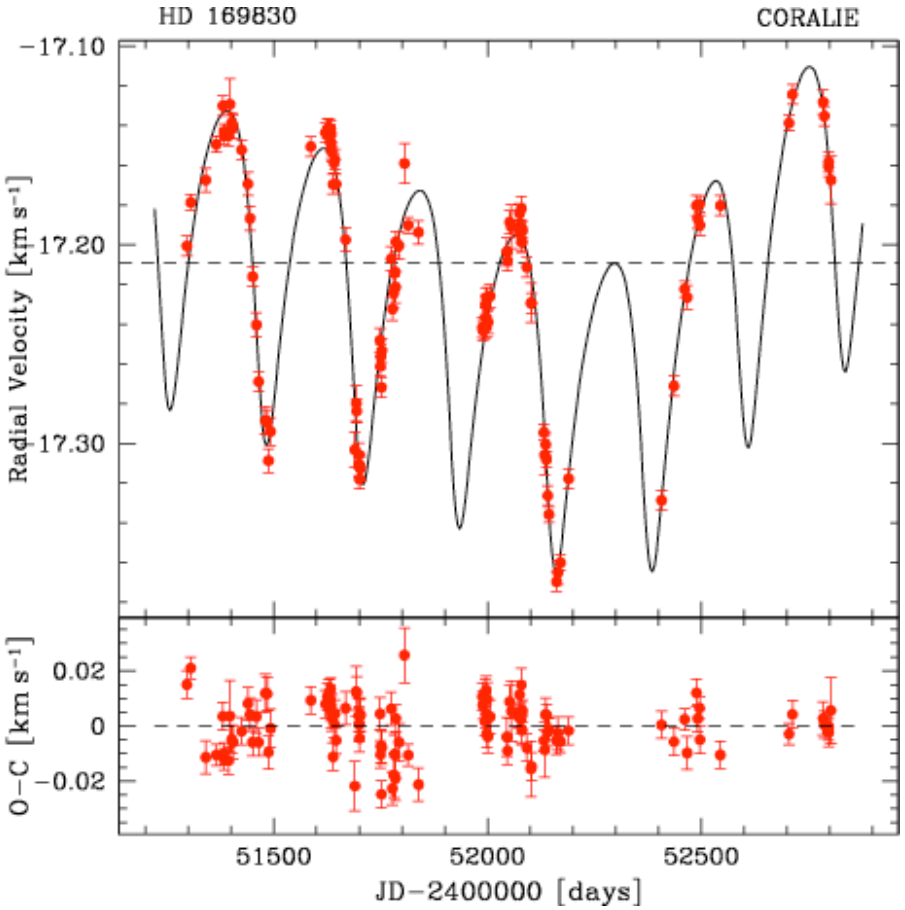
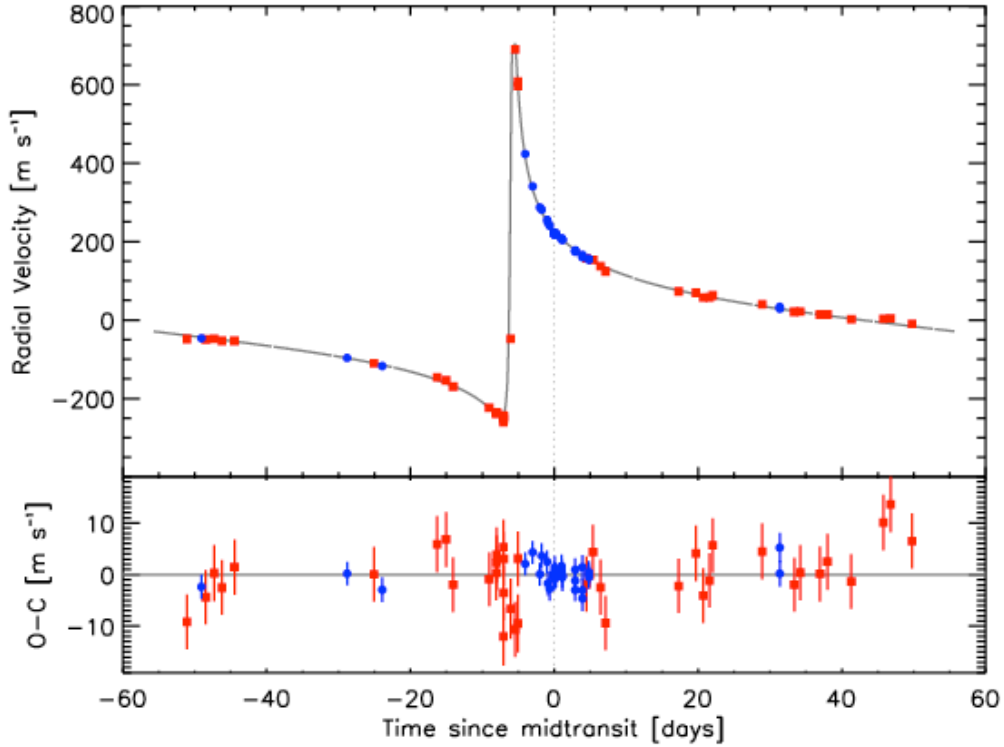
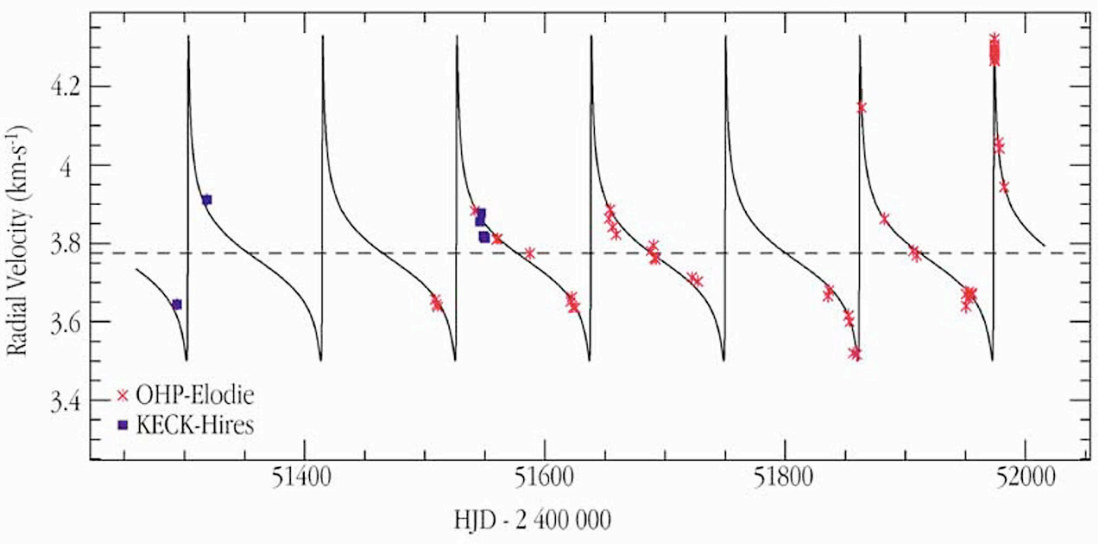


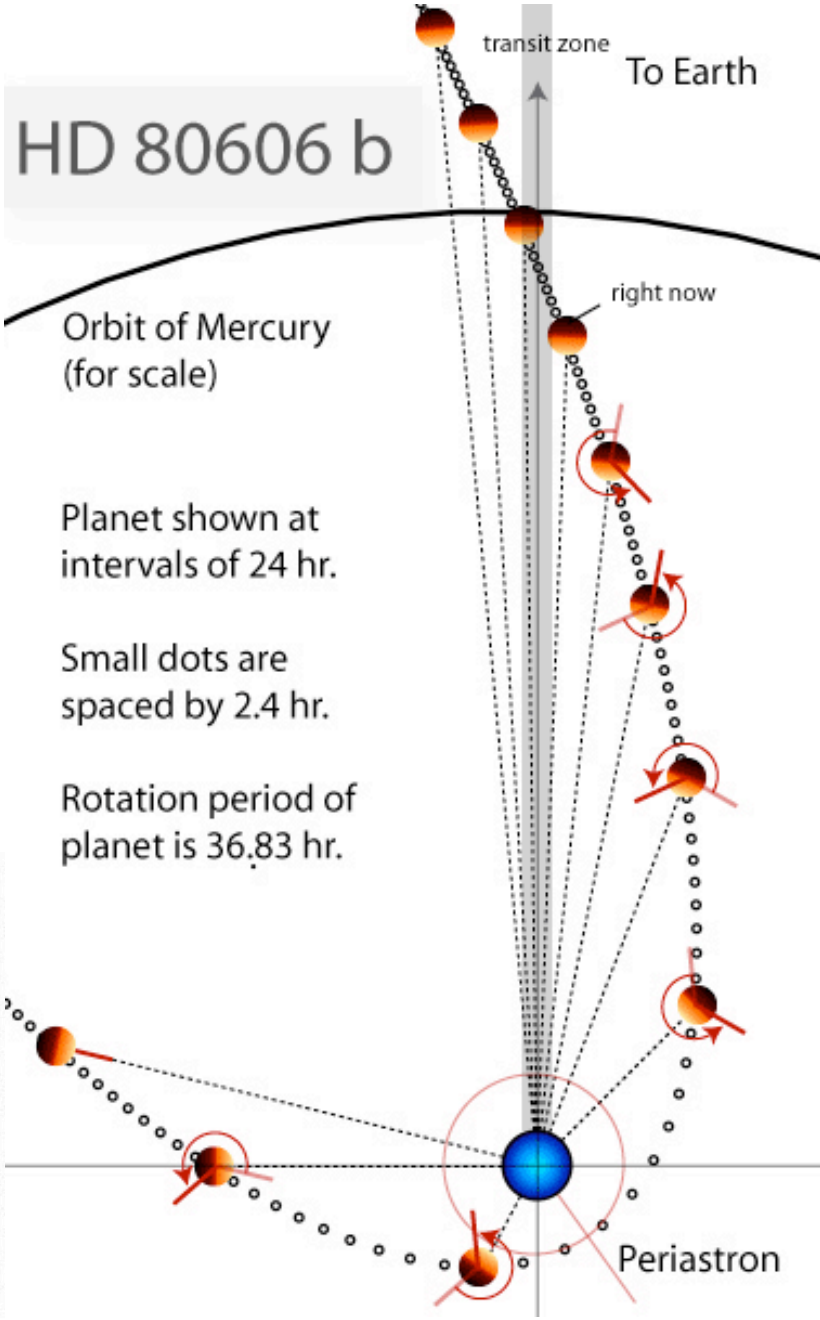
Fig. 3. *Top*: generalized Lomb-Scargle periodogram of the radial-velocity measurements for both HD 63765 (*left*) and HD 104067 (*right*). *Middle*: radial-velocity measurements as a function of Julian Date obtained with CORALIE (blue and orange dots) and HARPS (red dots). *Bottom*: HARPS' only phase-folded radial velocities. The best Keplerian, one-planet-solution is displayed as a dark curve whose corresponding orbital elements are listed in Table 2.

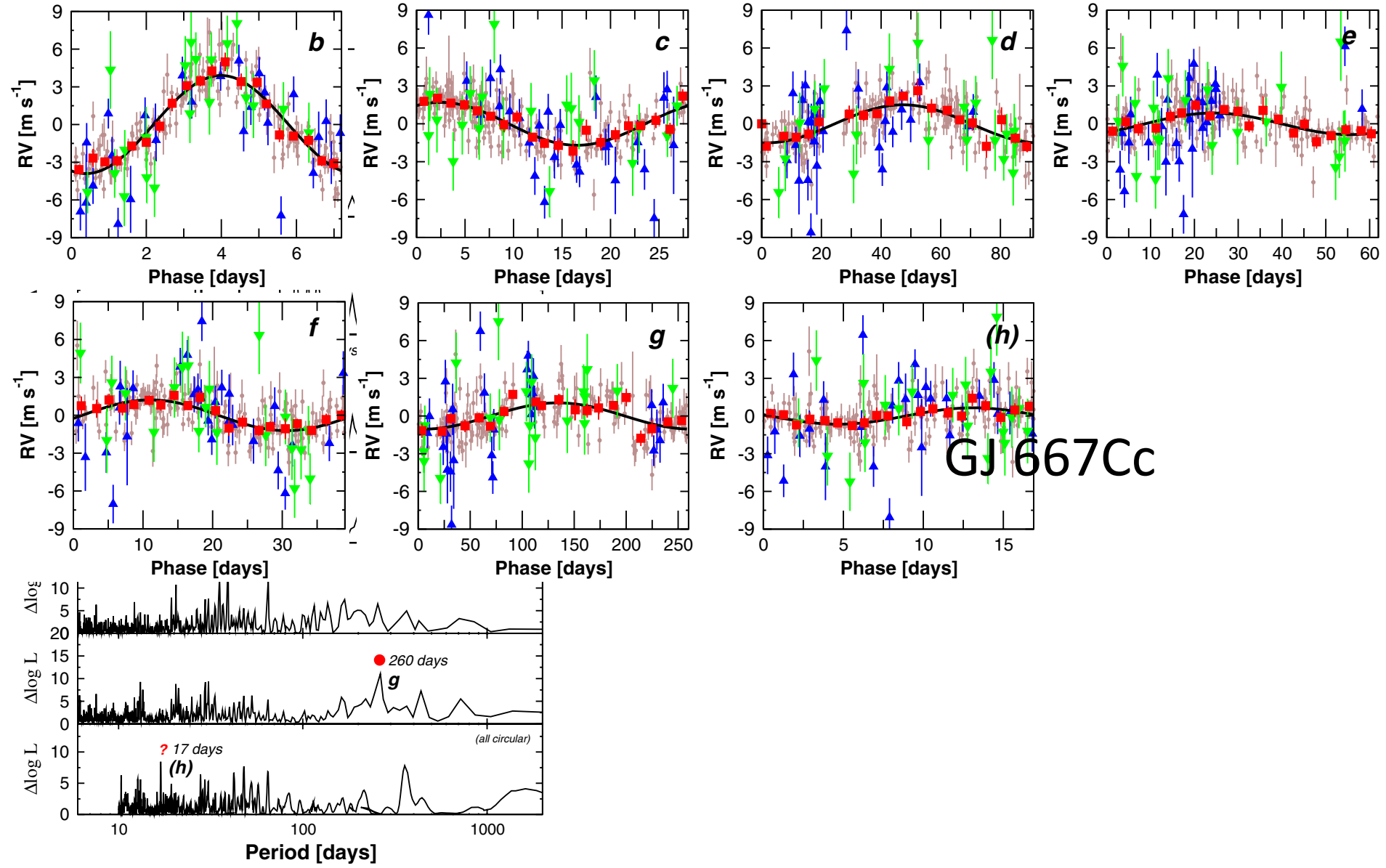

HD 82943
CORALIE
Radial Velocity [km s⁻¹]
8.20
8.15
8.10
8.05
O−C [km s⁻¹]
0.02
0
−0.02
51500
52000
52500
JD−2400000 [days]


HD 169830
CORALIE
Radial Velocity [km s⁻¹]
−17.10
17.20
17.30
O−C [km s⁻¹]
0.02
0
−0.02
51500
52000
52500
JD−2400000 [days]

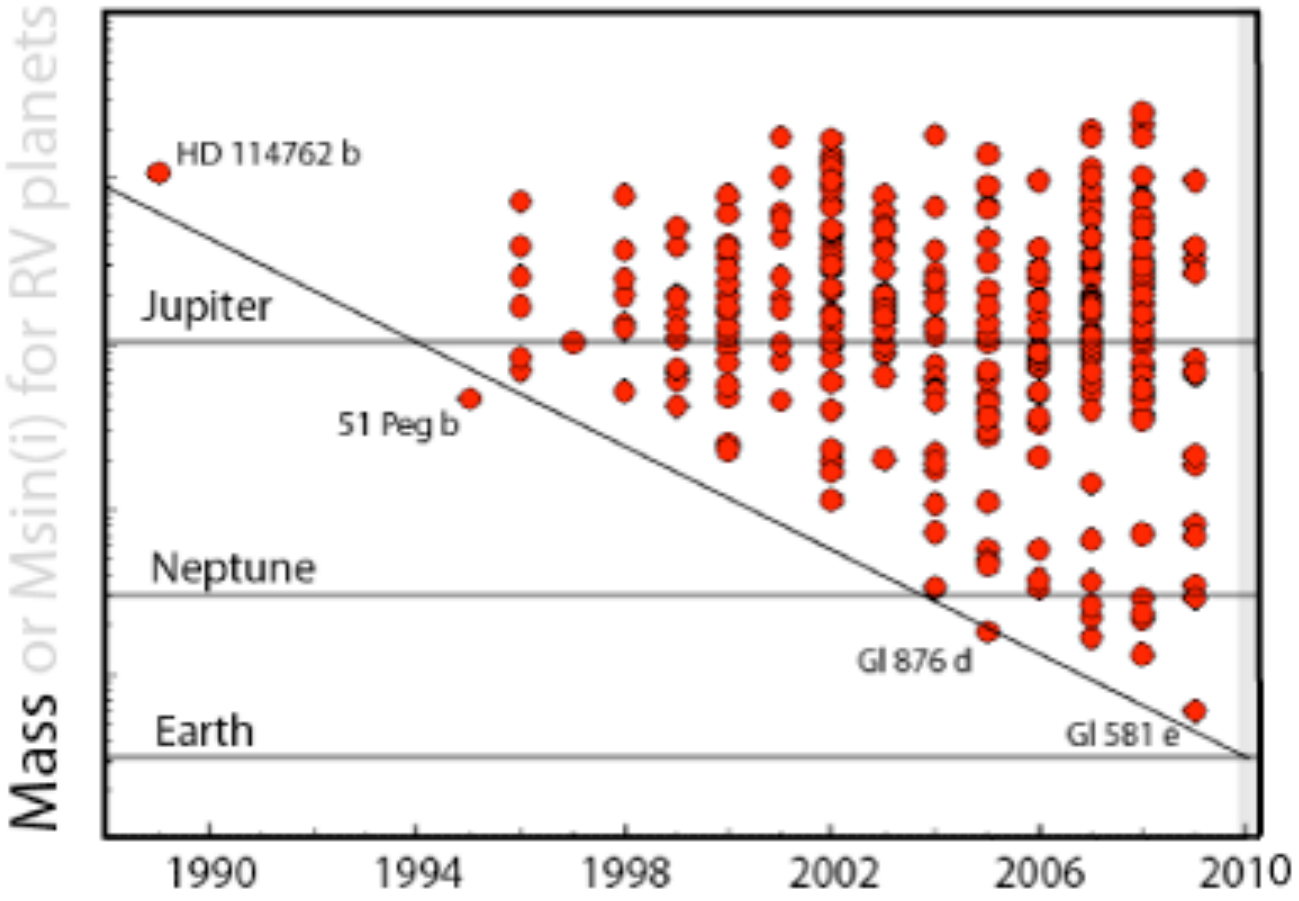

Radial Velocity [m s⁻¹]
O−C [m s⁻¹]
Time since midtransit [days]

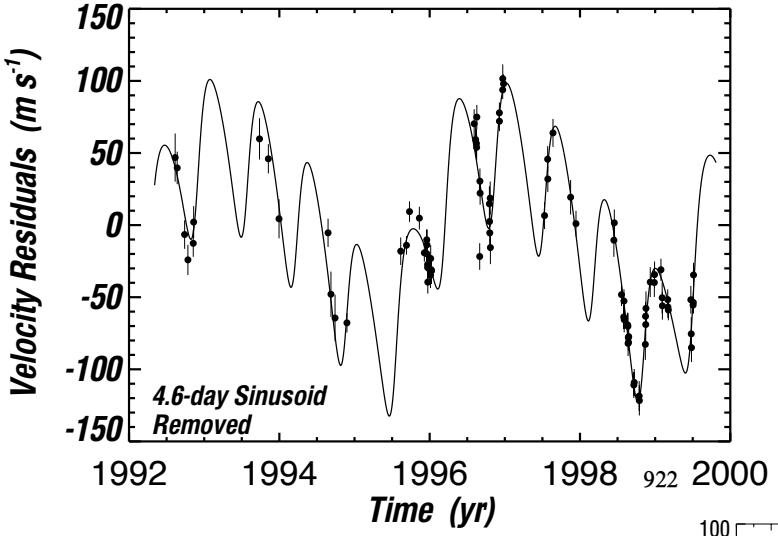

Radial Velocity (km-s⁻¹)
OHP-Elodie
KECK-Hires
HJD - 2 400 000


HD 80606 b
transit zone
To Earth
right now
Orbit of Mercury
(for scale)
Planet shown at
intervals of 24 hr.
Small dots are
spaced by 2.4 hr.
Rotation period of
planet is 36.83 hr.
Periastron


b
c
d
e
f
g
(h)
RV [m s^{-1}]
Phase [days]
GJ 667Cc
260 days
g
? 17 days
(h)
(all circular)
Δlog L
Period [days]

RV mass determinations over time




Velocity Residuals (m s-1)
150
100
50
0
-50
-100
-150
4.6-day Sinusoid
Removed
1992
1994
1996
1998
2000
Time (yr)

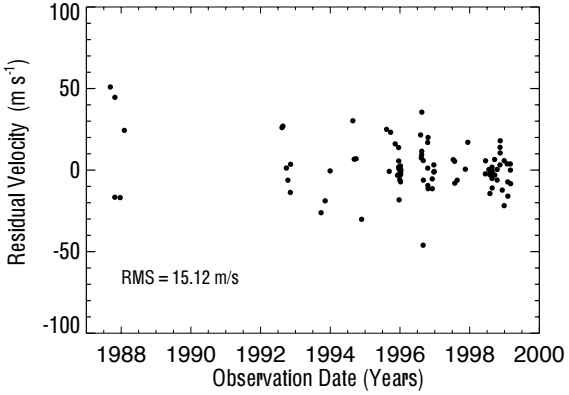

Residual Velocity (m s-1)
100
50
0
-50
-100
RMS = 15.12 m/s
1988
1990
1992
1994
1996
1998
2000
Observation Date (Years)

FIG. 4*a*

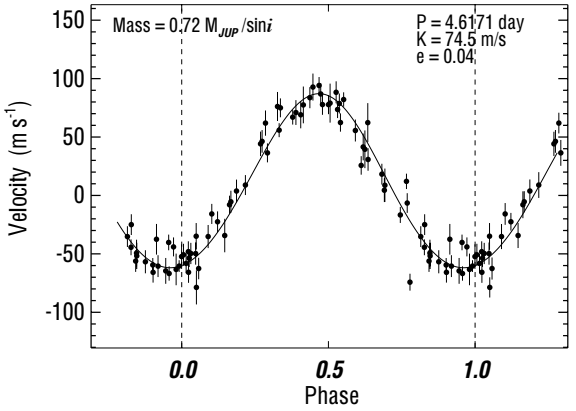
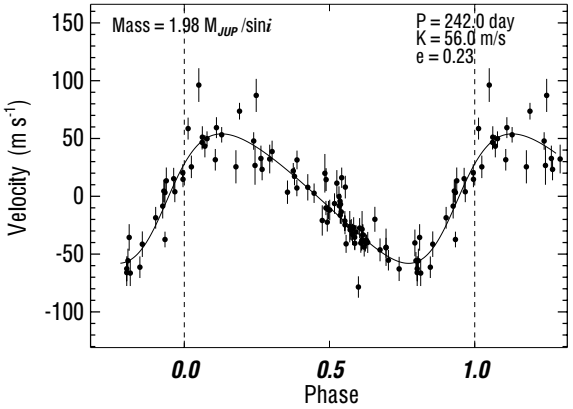
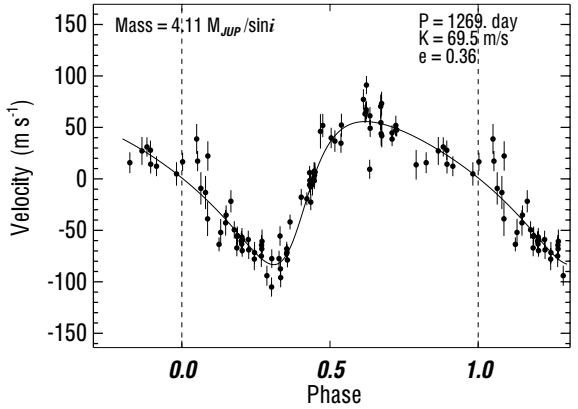

Mass = 0.72 MJUP /sini
P = 4.6171 day
K = 74.5 m/s
e = 0.04
Velocity (m s-1)
150
100
50
0
-50
-100
0.0
0.5
1.0
Phase

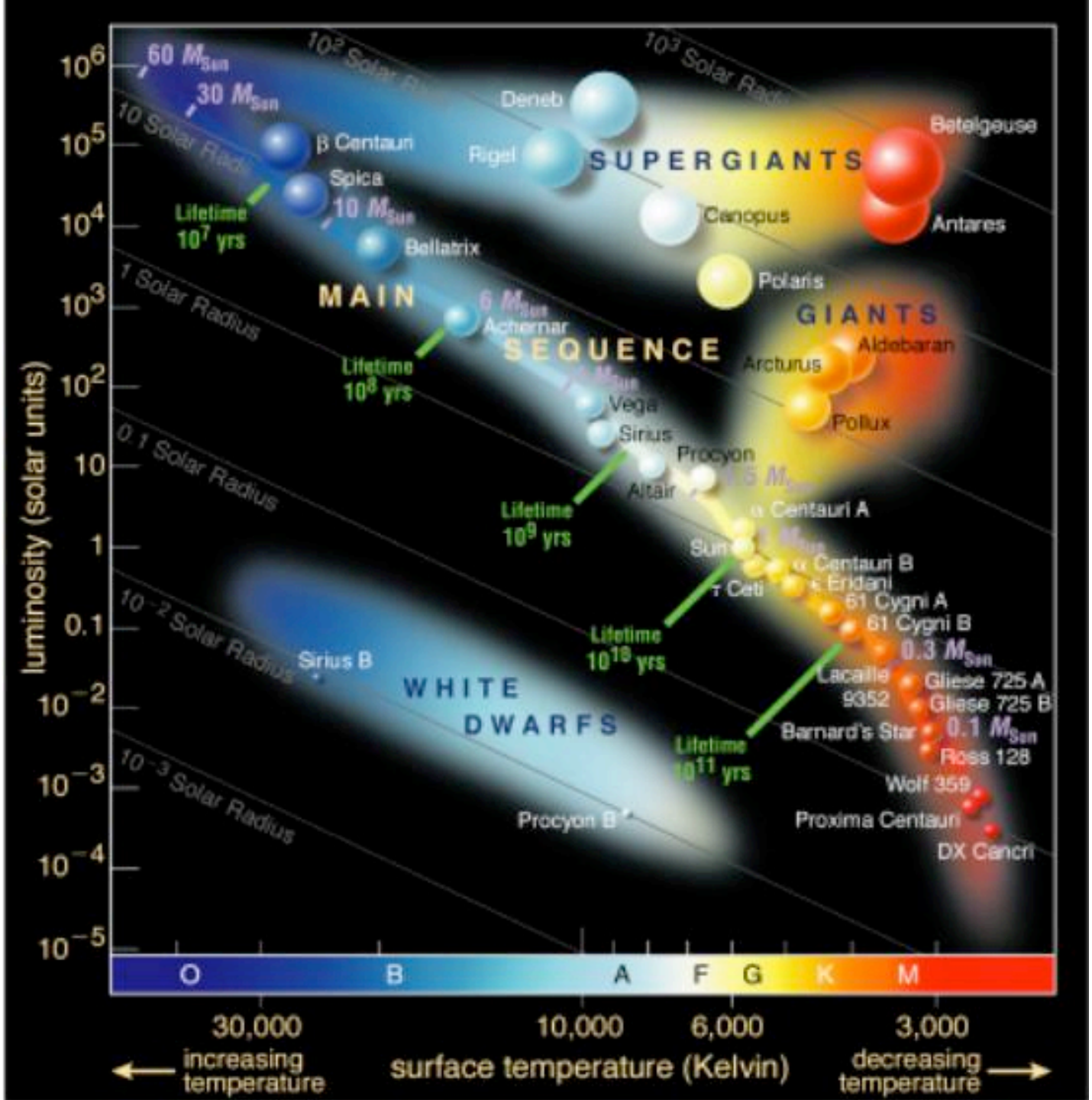
FIG. 4*b*

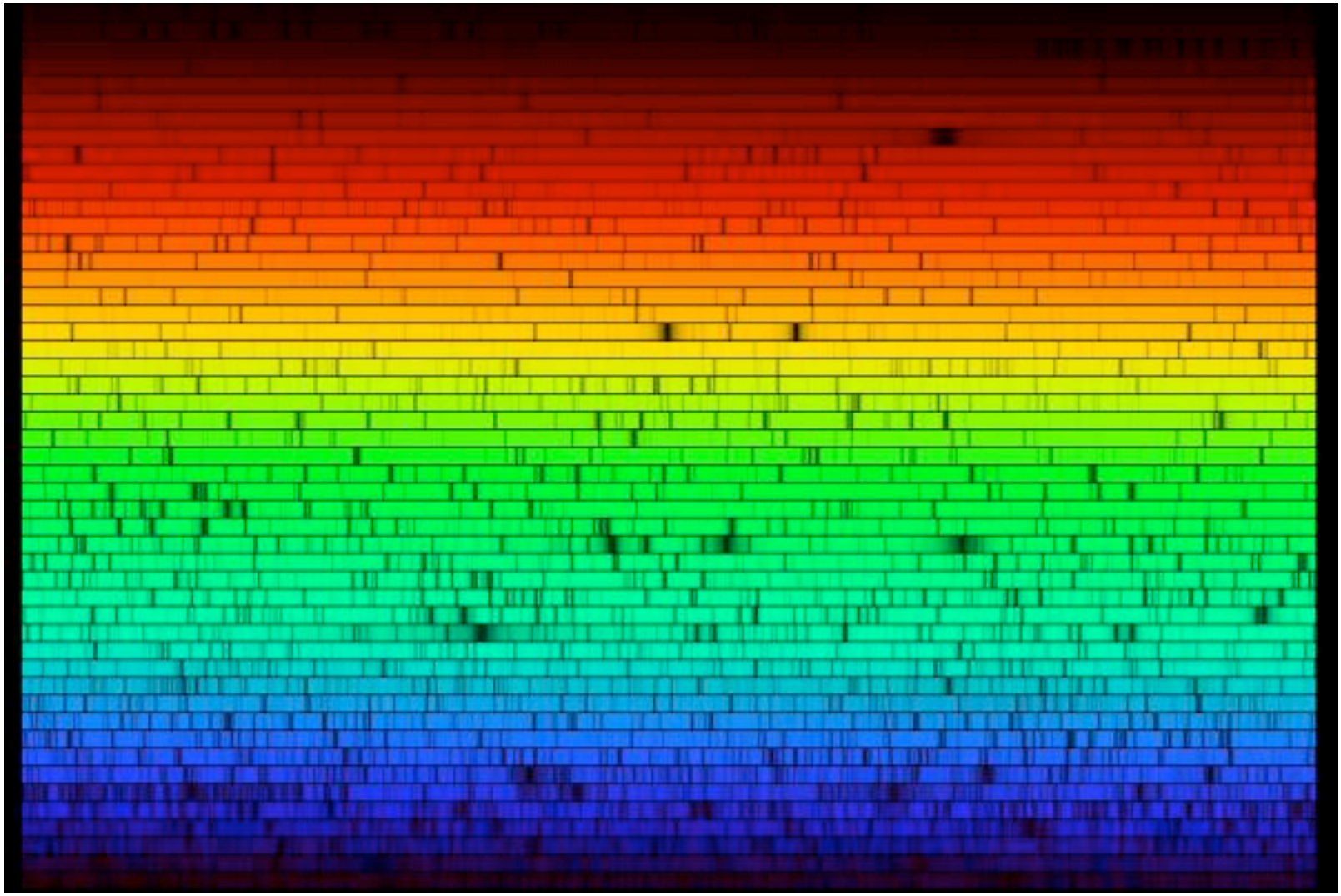

Mass = 1.98 MJUP /sini
P = 242.0 day
K = 56.0 m/s
e = 0.23
Velocity (m s-1)
150
100
50
0
-50
-100
0.0
0.5
1.0
Phase

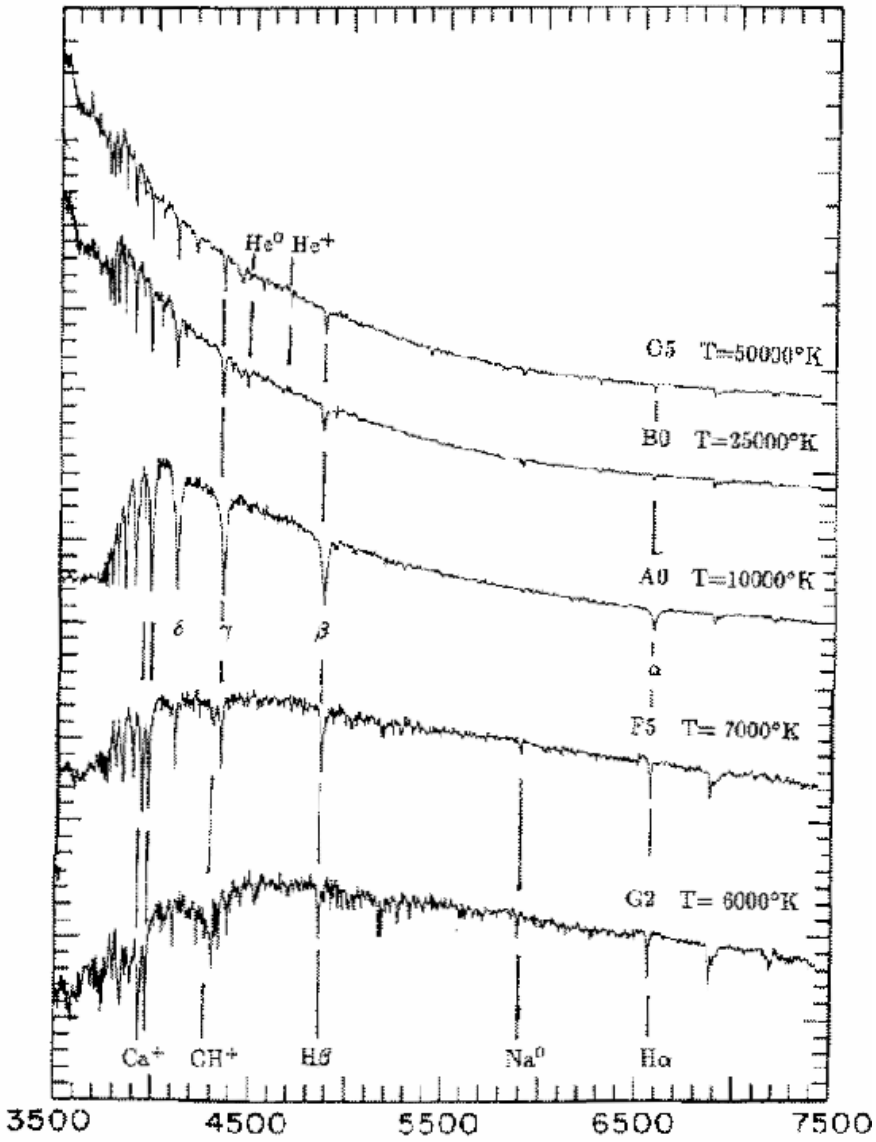

Mass = 4.11 MJUP /sini
P = 1269. day
K = 69.5 m/s
e = 0.36
Velocity (m s-1)
150
100
50
0
-50
-100
-150
0.0
0.5
1.0
Phase

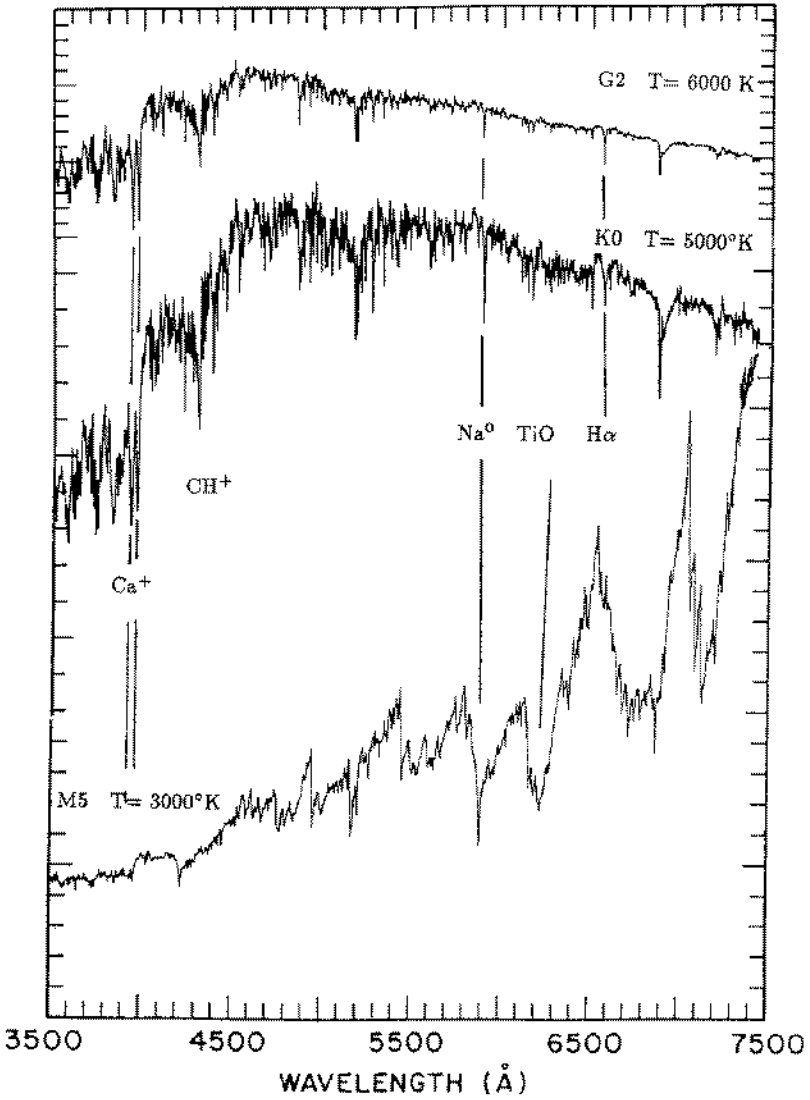
RV, main players

- HARPS (European, Southern Hemisphere)
- Keck (US, Hawaii)
- SOPHIE (France)
- HARPS North (Europe/US, Canary Islands)
- APF, Mt. Hamilton
- ESPRESSO, 2016, VLT

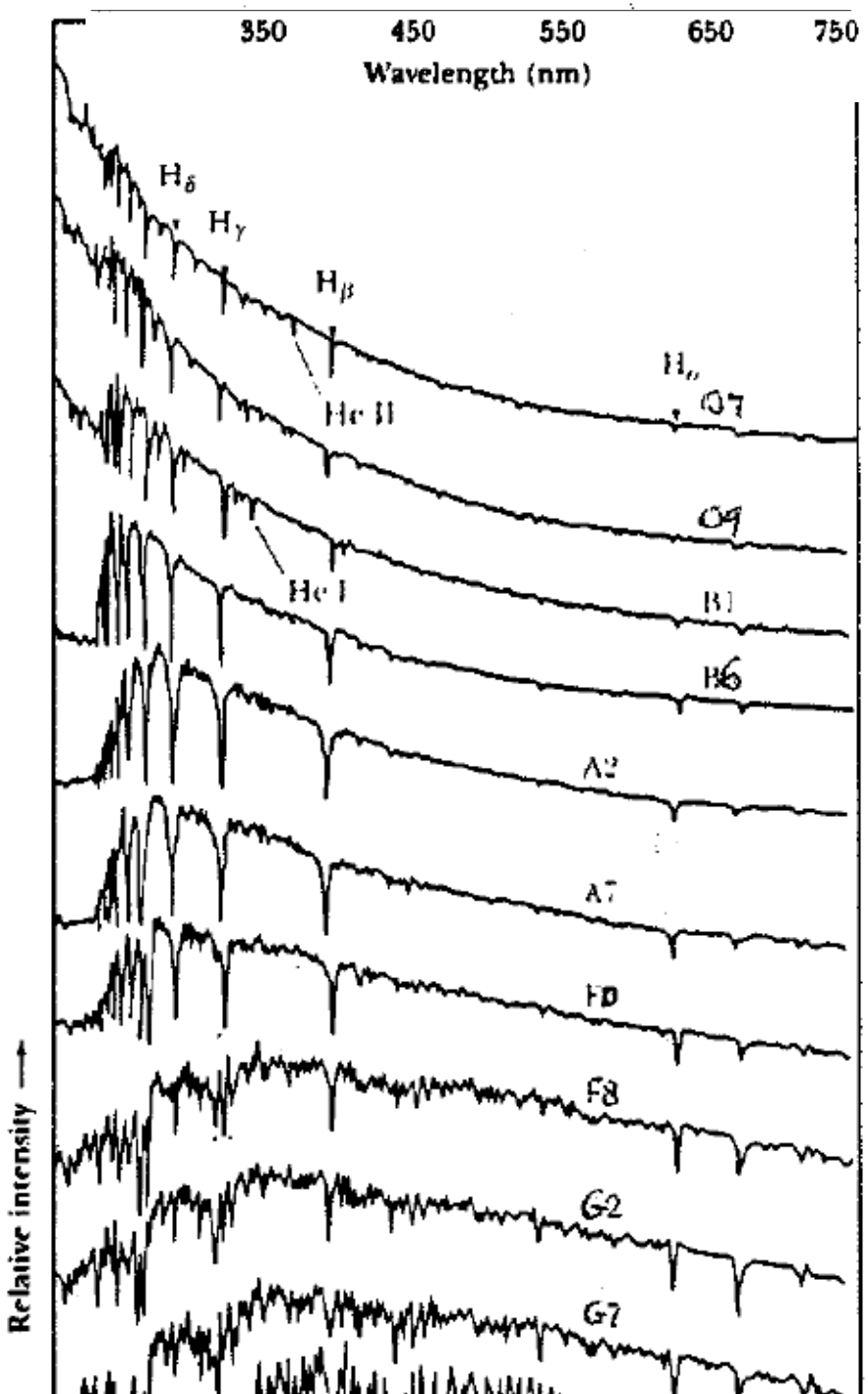

luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10 Solar Radius
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
Betelgeuse
β Centauri
Spica
Antares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

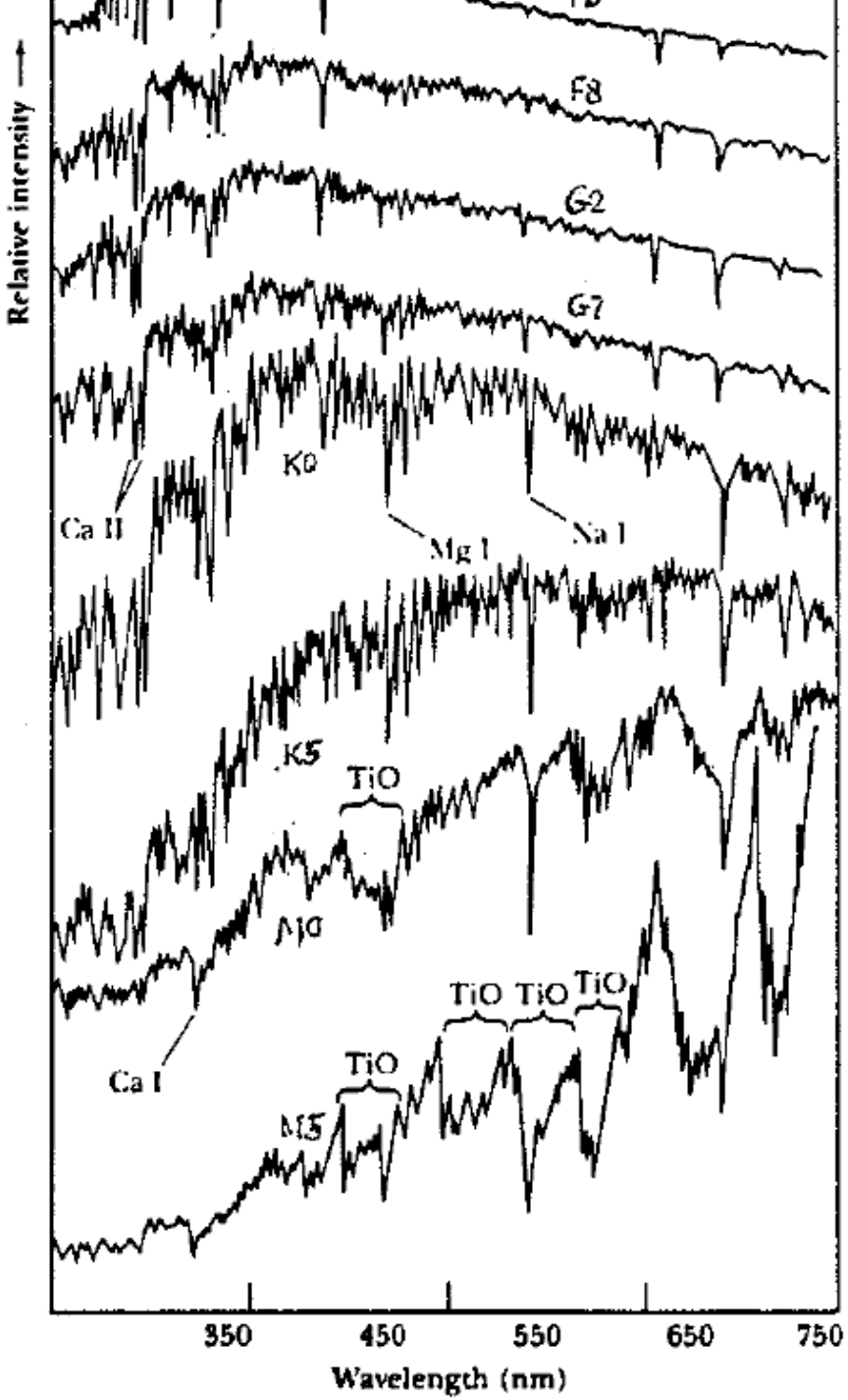


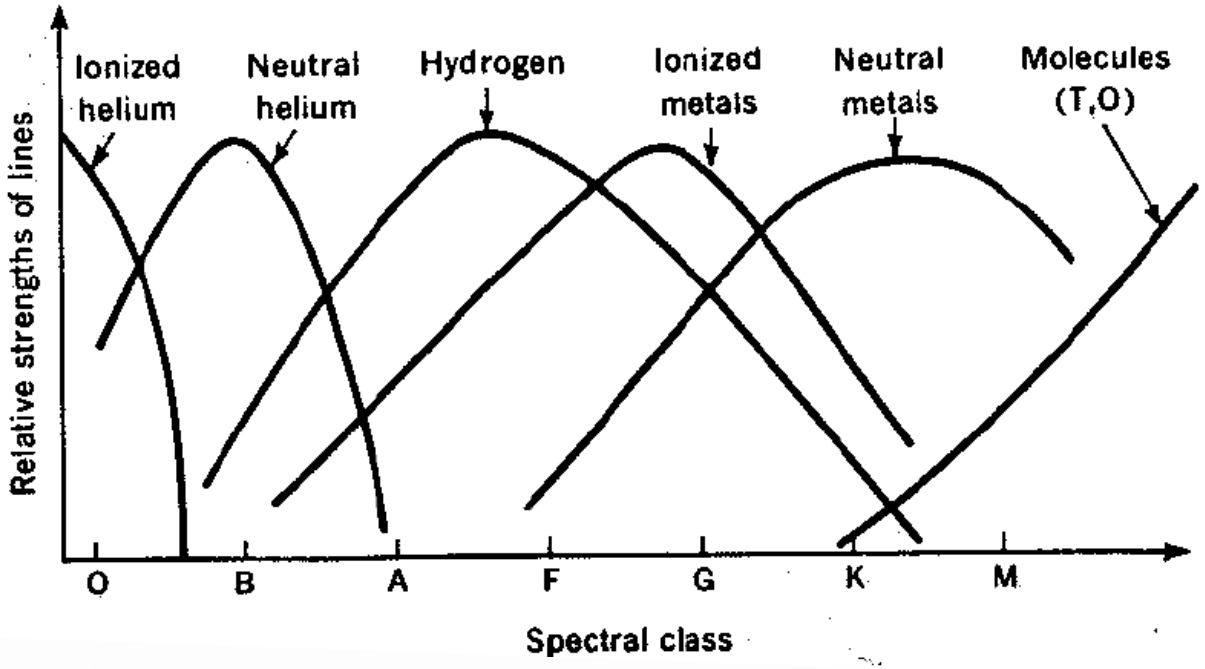


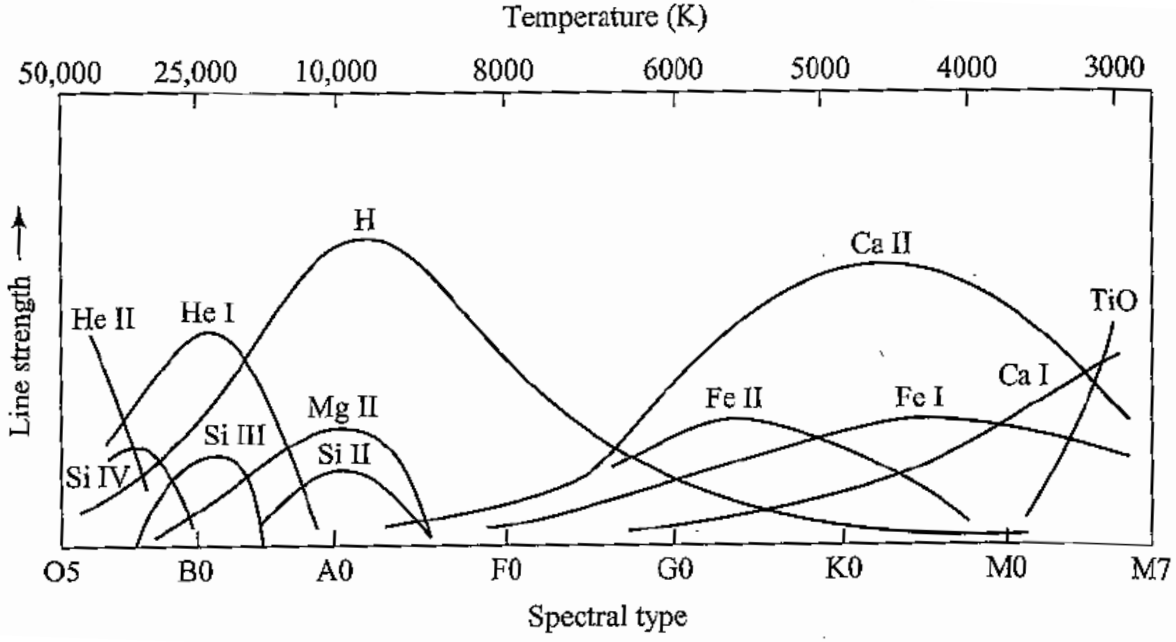


Spectra for O - G stars (left) and G - M stars (right)


350
450
550
650
750
Wavelength (nm)
Relative intensity
H_δ
H_γ
H_β
H_α
He II
He I
O7
O9
B1
B6
A2
A7
F0
F8
G2
G7


Relative intensity
F8
G2
G7
K0
Ca II
Mg I
Na I
K5
TiO
M0
Ca I
TiO
TiO
TiO
TiO
M5
350
450
550
650
750
Wavelength (nm)


Ionized helium
Neutral helium
Hydrogen
Ionized metals
Neutral metals
Molecules (T,O)
Relative strengths of lines
O
B
A
F
G
K
M
Spectral class


Temperature (K)
50,000
25,000
10,000
8000
6000
5000
4000
3000
Line strength
H
He II
He I
Si IV
Si III
Mg II
Si II
Ca II
TiO
Ca I
Fe II
Fe I
O5
B0
A0
F0
G0
K0
M0
M7
Spectral type

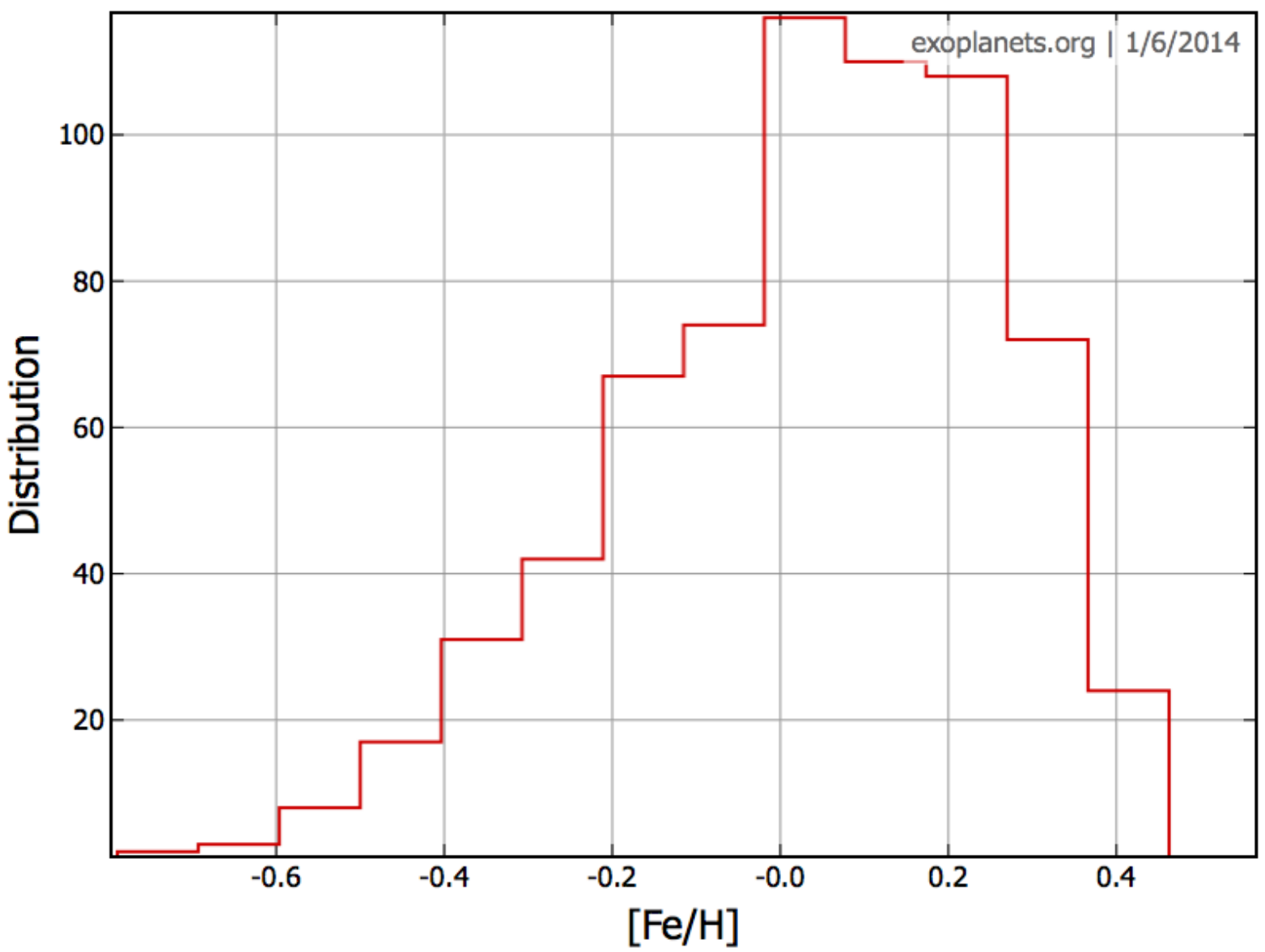
Faster Stellar Rotation Leads to Broader Lines

Harder to see small wavelength shifts

Limits Doppler RV searches to mid F and later

Average Stellar Rotational Velocities

Class	V(km/s)
O5	190
B0	200
B5	210
A0	190
A5	160
F0	95
F5	25
G0	12



Stars that are richer in heavy elements more commonly have **giant planets**

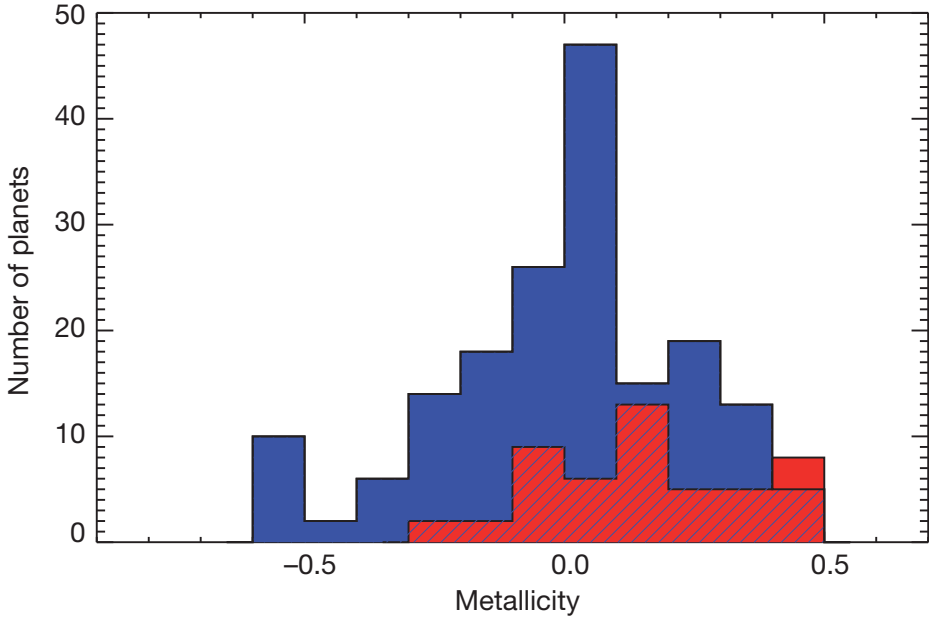
LETTER

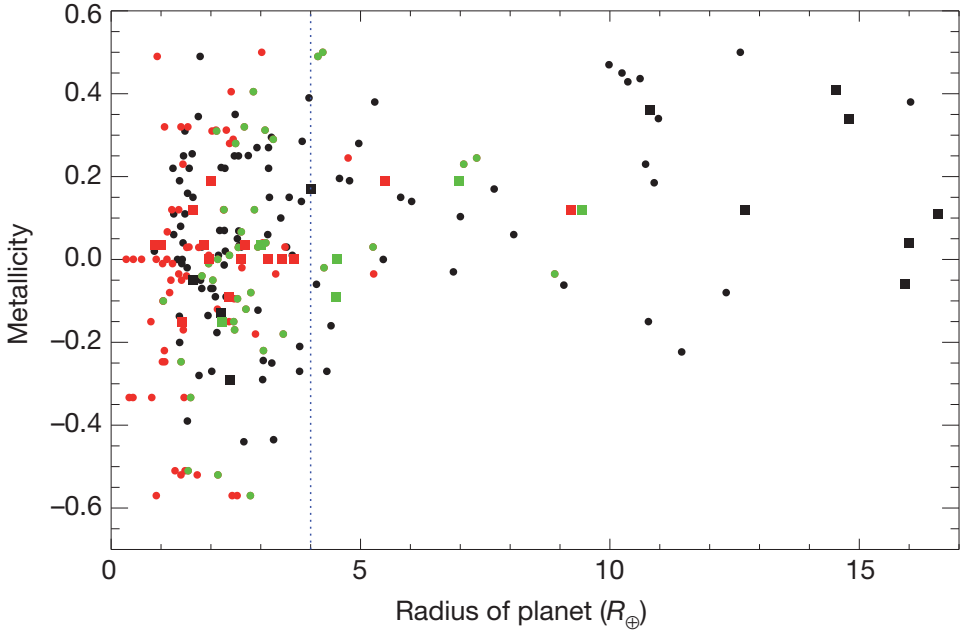
doi:10.1038/nature11121

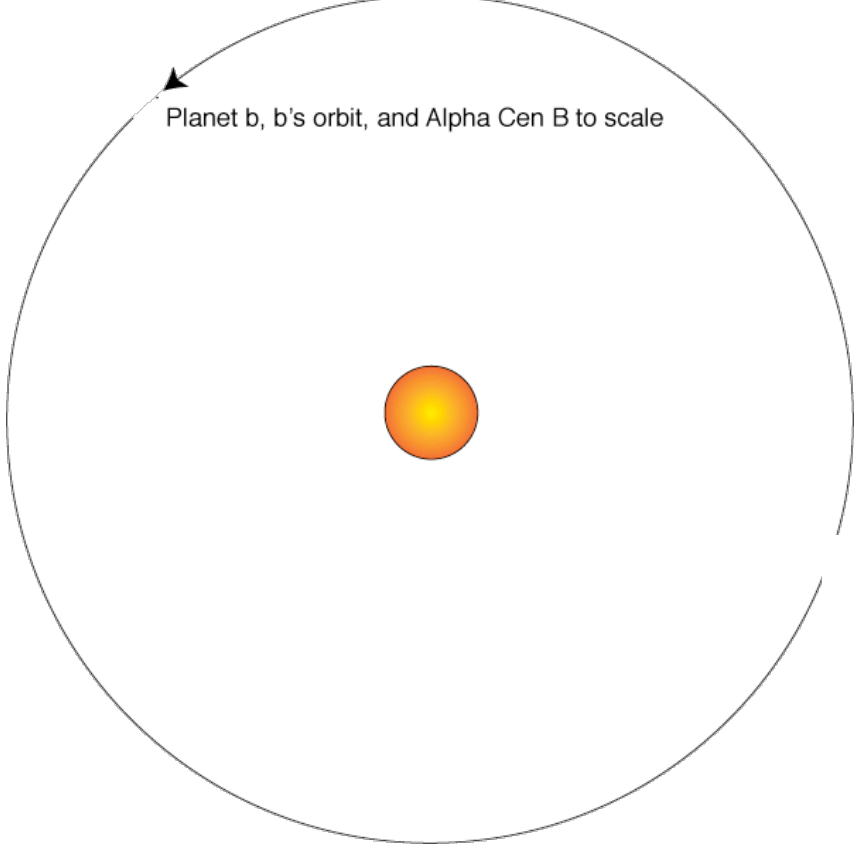
An abundance of small exoplanets around stars with a wide range of metallicities

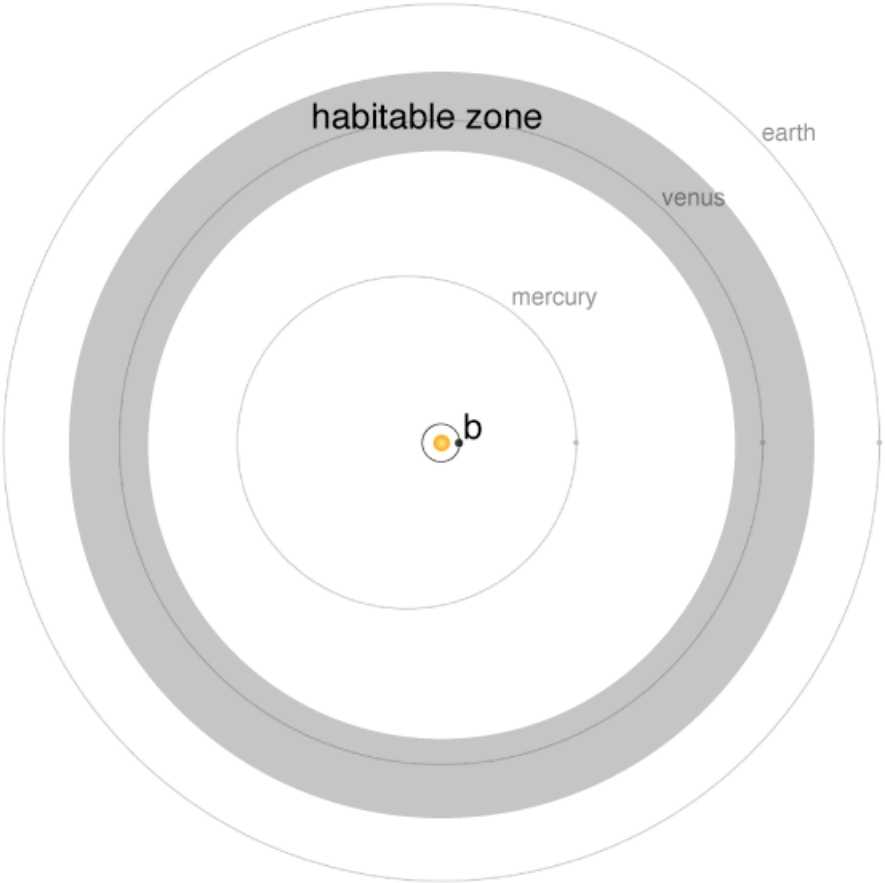
Lars A. Buchhave[1,2], David W. Latham[3], Anders Johansen[4], Martin Bizzarro[2], Guillermo Torres[3], Jason F. Rowe[5], Natalie M. Batalha[6], William J. Borucki[7], Erik Brugamyer[8], Caroline Caldwell[8], Stephen T. Bryson[7], David R. Ciardi[9], William D. Cochran[8], Michael Endl[8], Gilbert A. Esquerdo[3], Eric B. Ford[10], John C. Geary[3], Ronald L. Gilliland[11], Terese Hansen[1], Howard Isaacson[12], John B. Laird[13], Philip W. Lucas[14], Geoffrey W. Marcy[12], Jon A. Morse[15], Paul Robertson[8], Avi Shporer[16,17], Robert P. Stefanik[3], Martin Still[18] & Samuel N. Quinn[3]

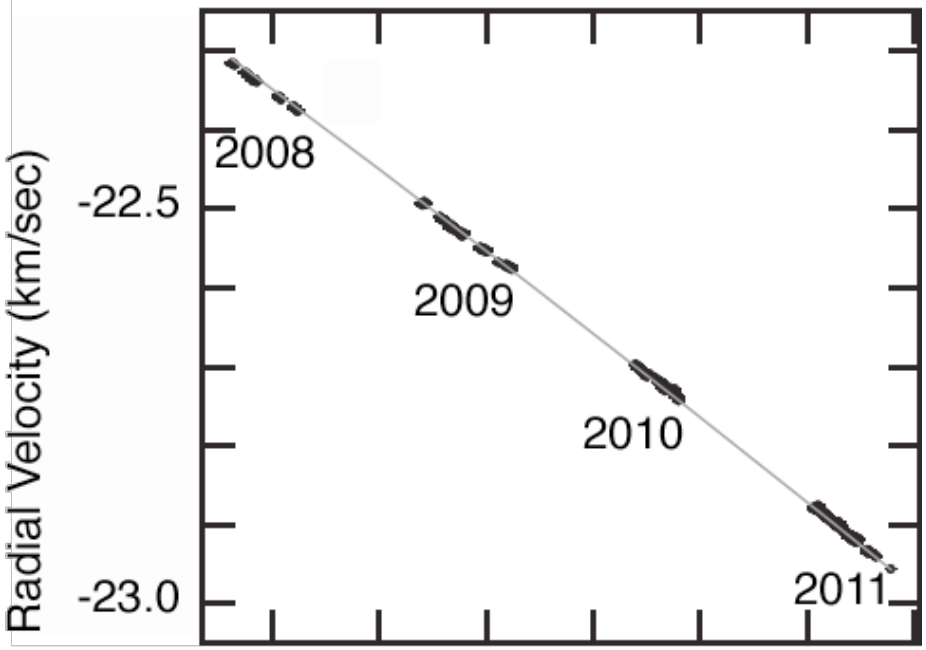
$$[\mathrm{m/H}] = \log_{10}(N_\mathrm{m}/N_\mathrm{H})_\mathrm{star} - \log_{10}(N_\mathrm{m}/N_\mathrm{H})_\mathrm{Sun},$$

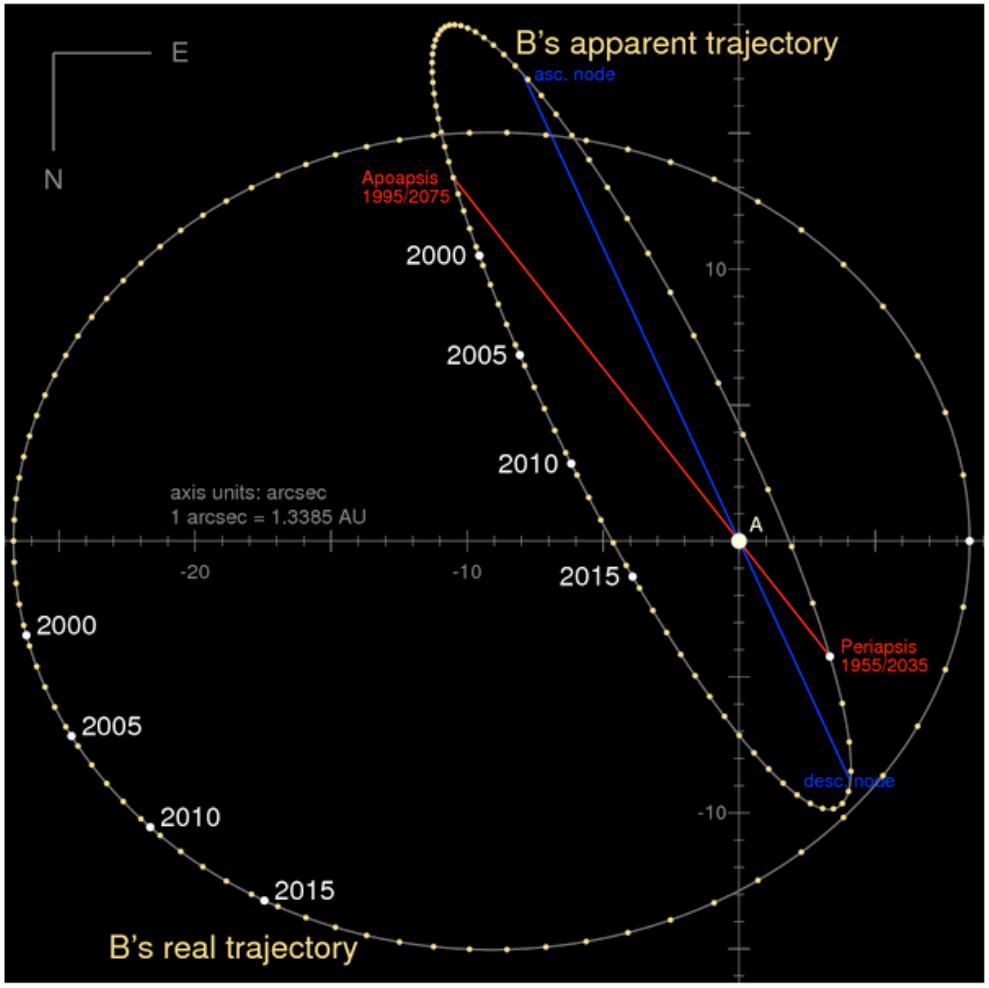


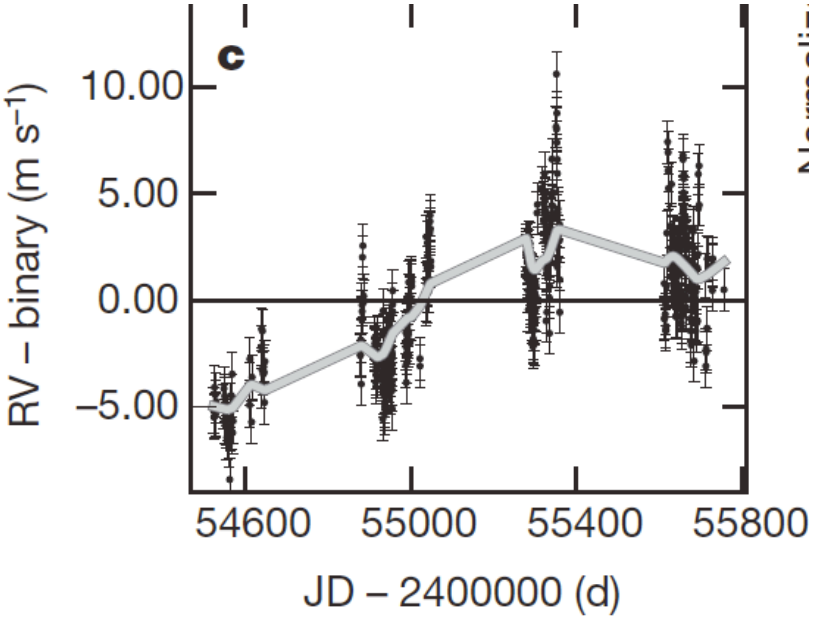



Planet b, b's orbit, and Alpha Cen B to scale


habitable zone
earth
venus
mercury
b

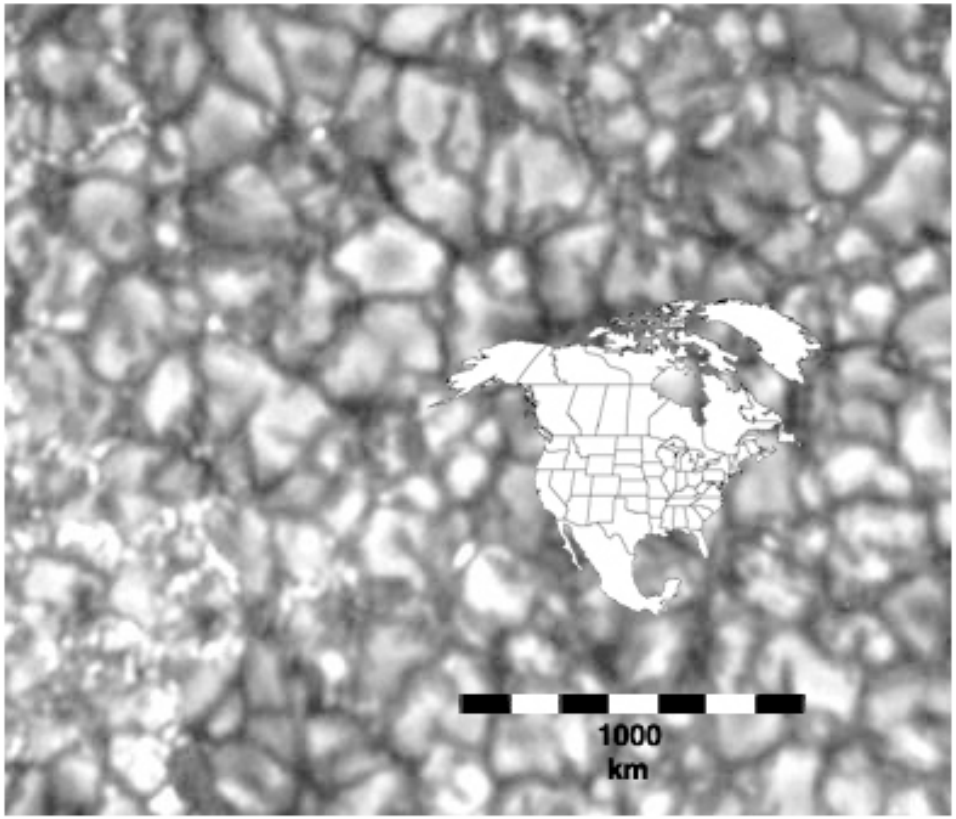


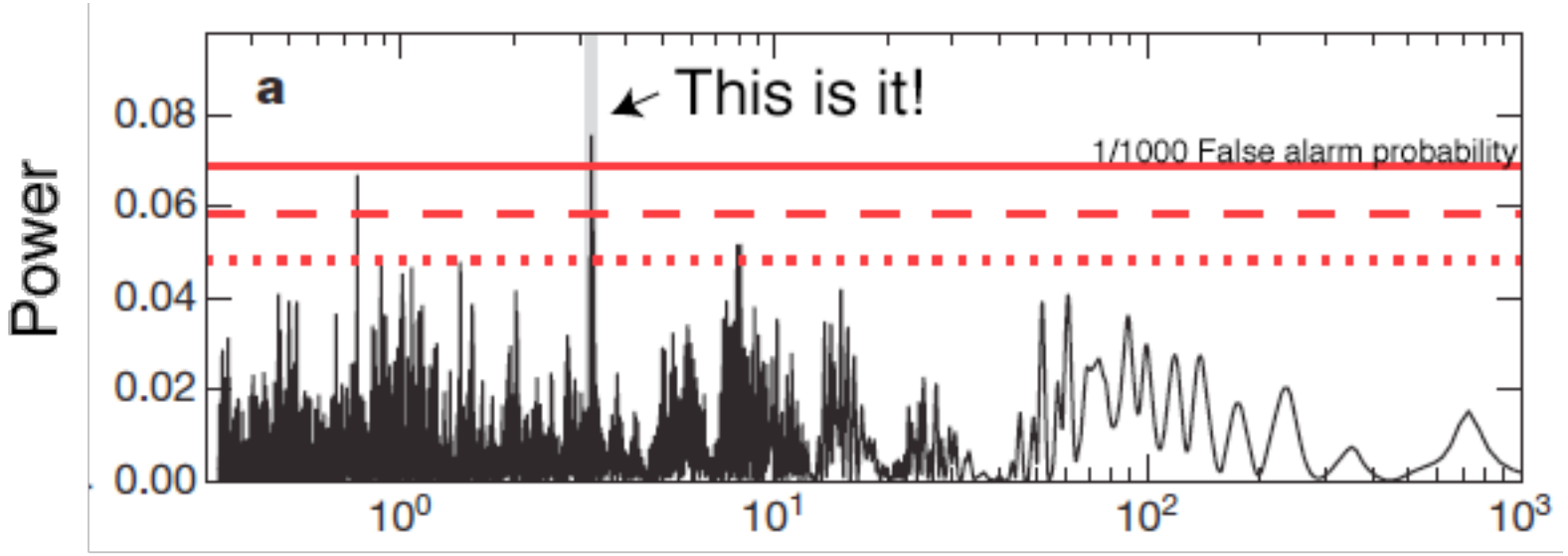


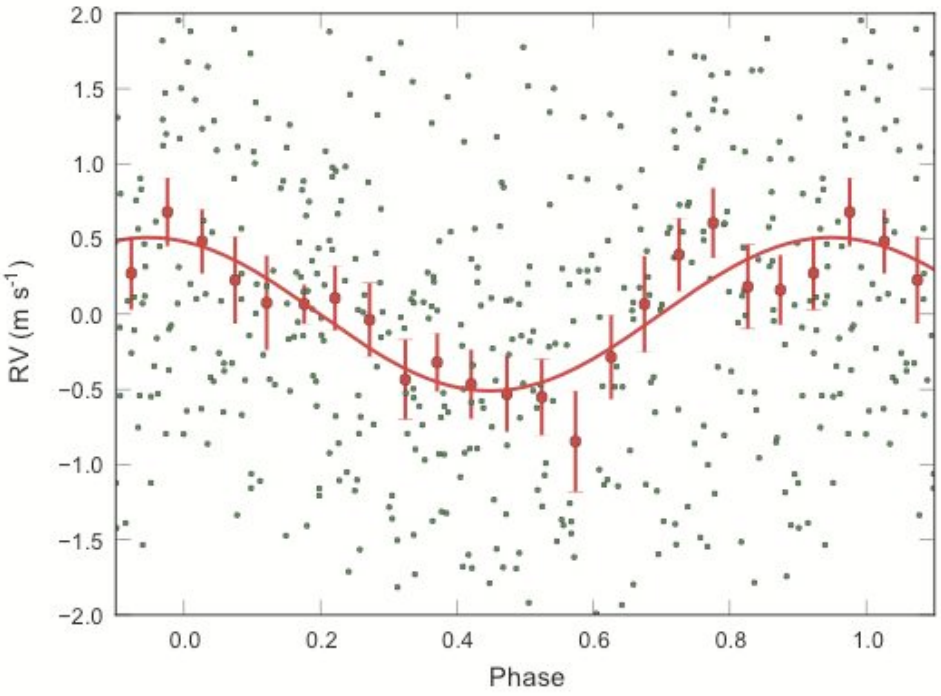


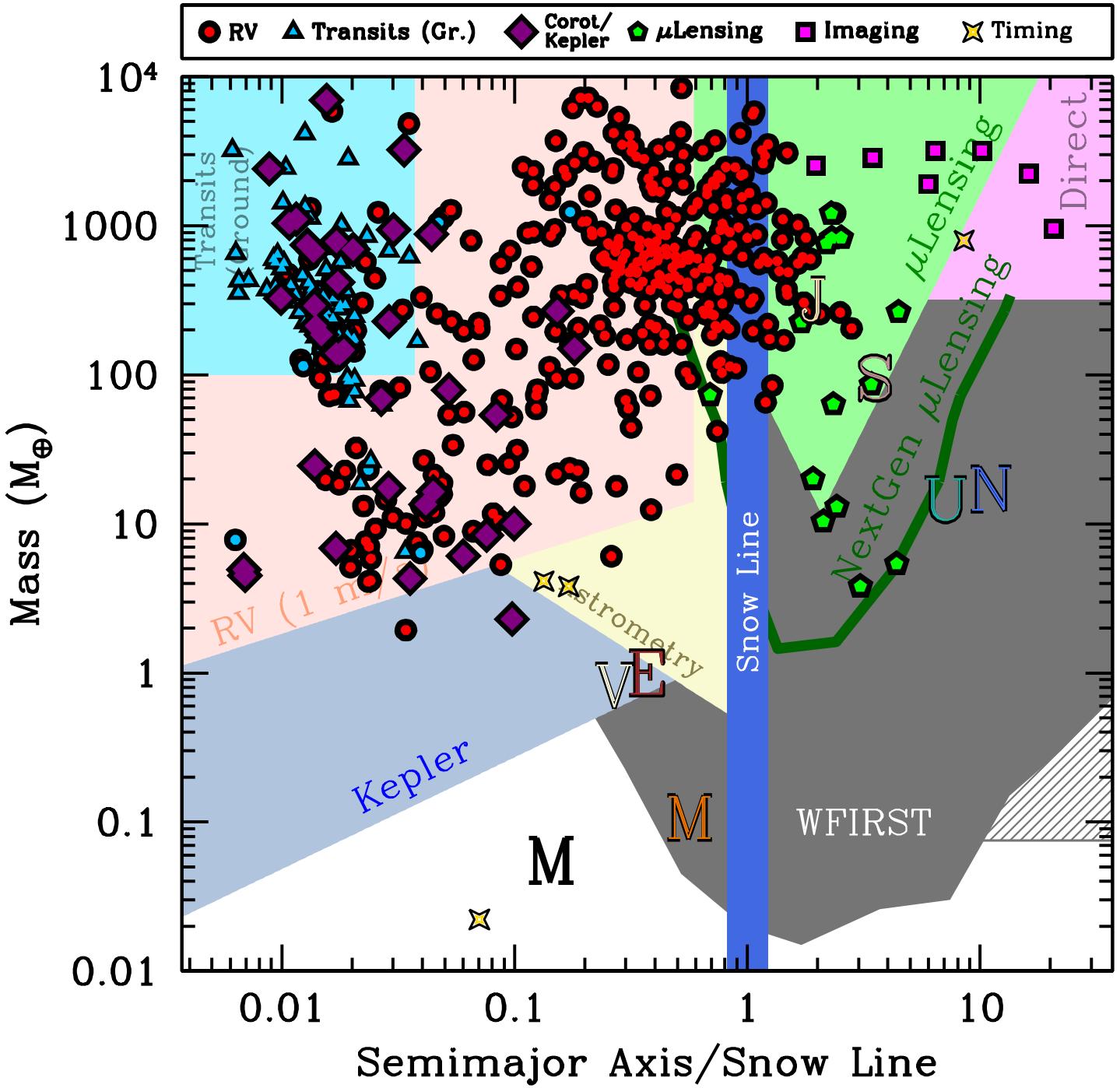
Alpha Centauri B has a velocity component in our direction of more the 50,000 miles per hour.

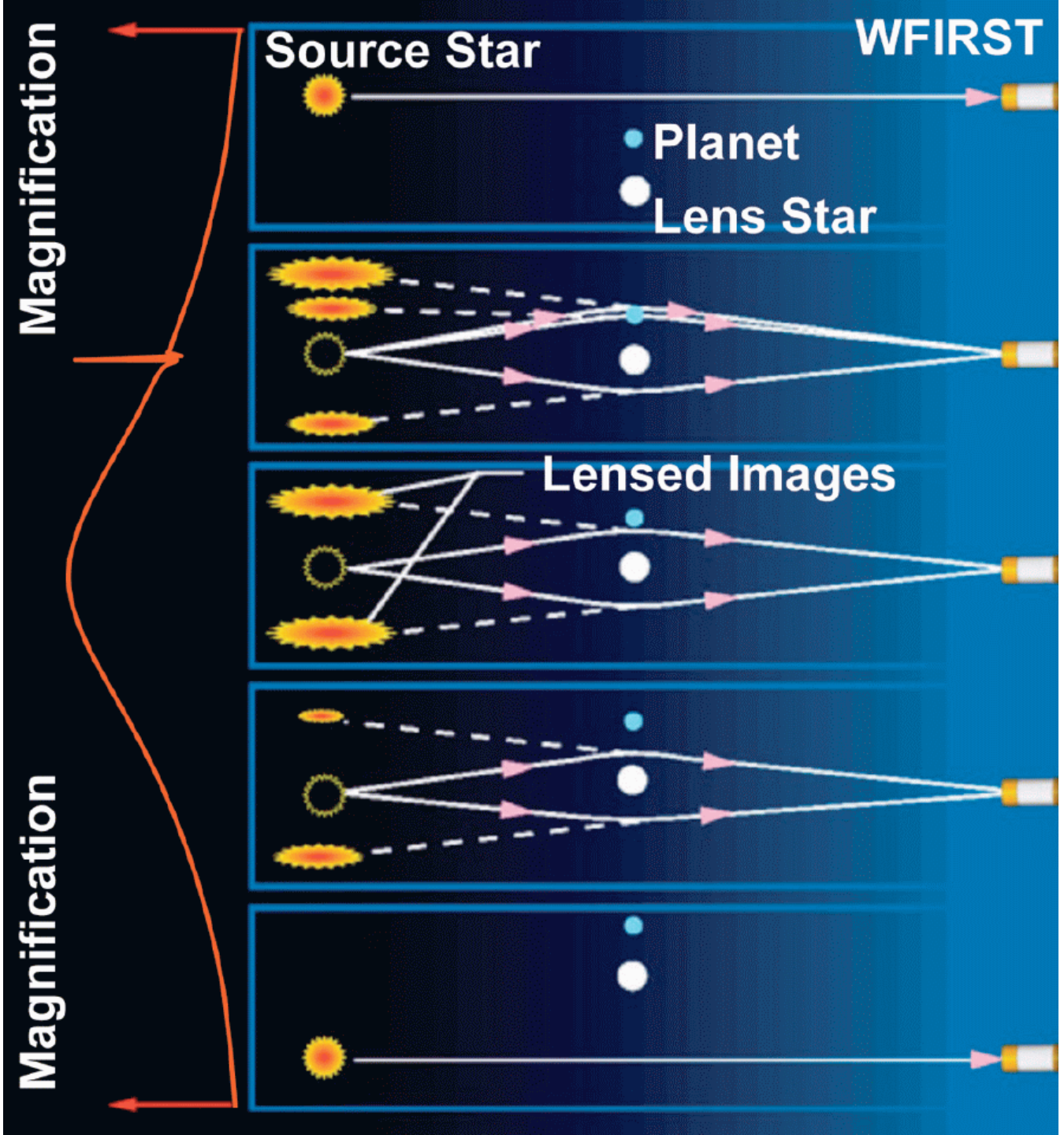
Generic Stellar Noise

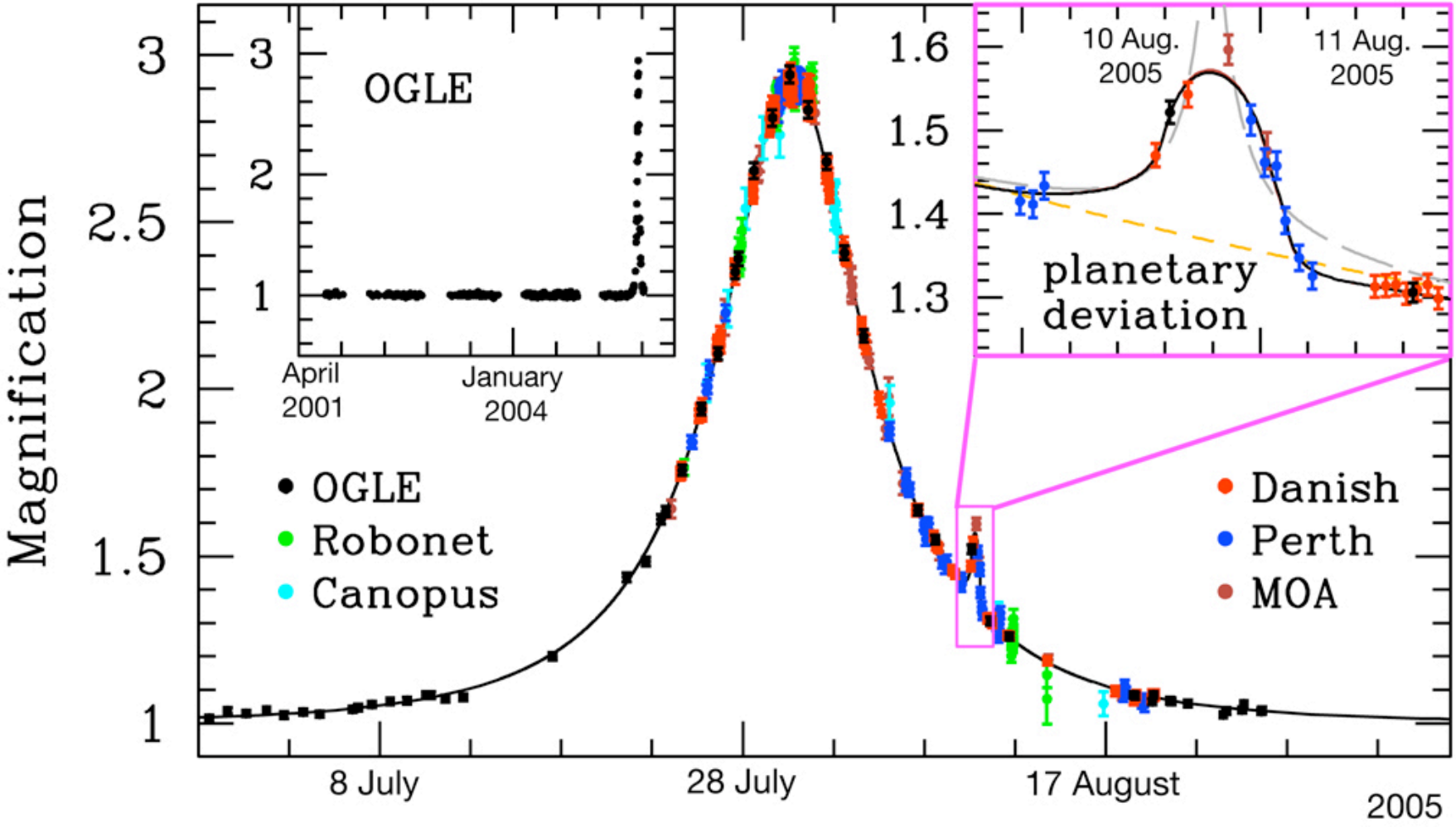



a
This is it!
1/1000 False alarm probability
Power
0.08
0.06
0.04
0.02
0.00
10^0
10^1
10^2
10^3
Period


RV (m s^{-1})
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0.0
0.2
0.4
0.6
0.8
1.0
Phase

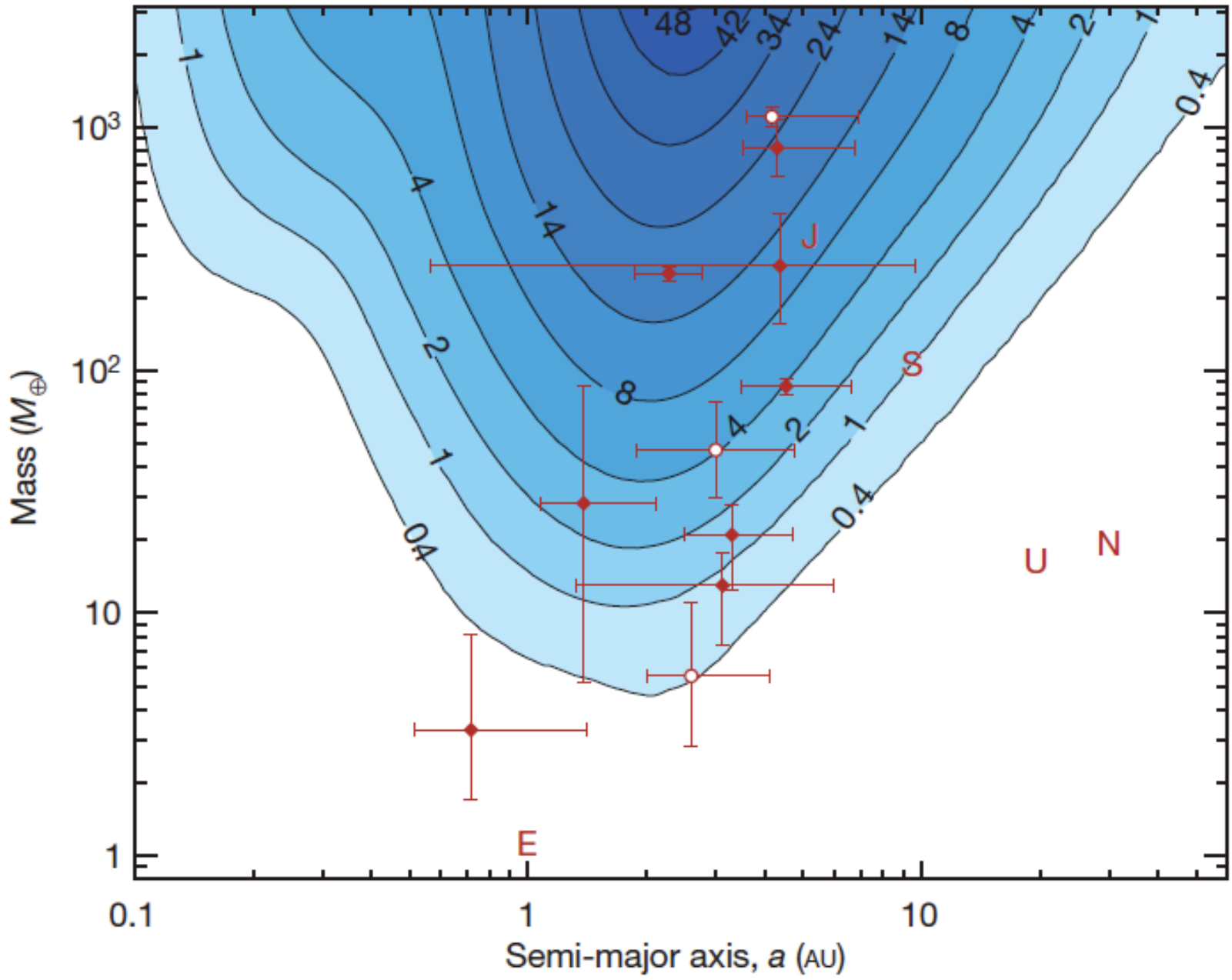

RV
Transits (Gr.)
Corot/ Kepler
μLensing
Imaging
Timing
Mass (M⊕)
Semimajor Axis/Snow Line
10⁴
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
Transits (Ground)
RV (1 m/s)
Astrometry
Kepler
Snow Line
μLensing
NextGen μLensing
Direct
WFIRST
J
S
UN
VE
M
M


Magnification
Source Star
WFIRST
Planet
Lens Star
Lensed Images
Magnification



Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)


48
42
34
24
14
8
4
2
1
0.4
J
S
U
N
E
Mass ($M_\oplus$)
10^3
10^2
10
1
0.1
1
10
Semi-major axis, a (AU)