Extra-solar planets and their parent stars

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European Northern Observatory

La Palma Observatory (ORM)

2590 meter a.s.l.

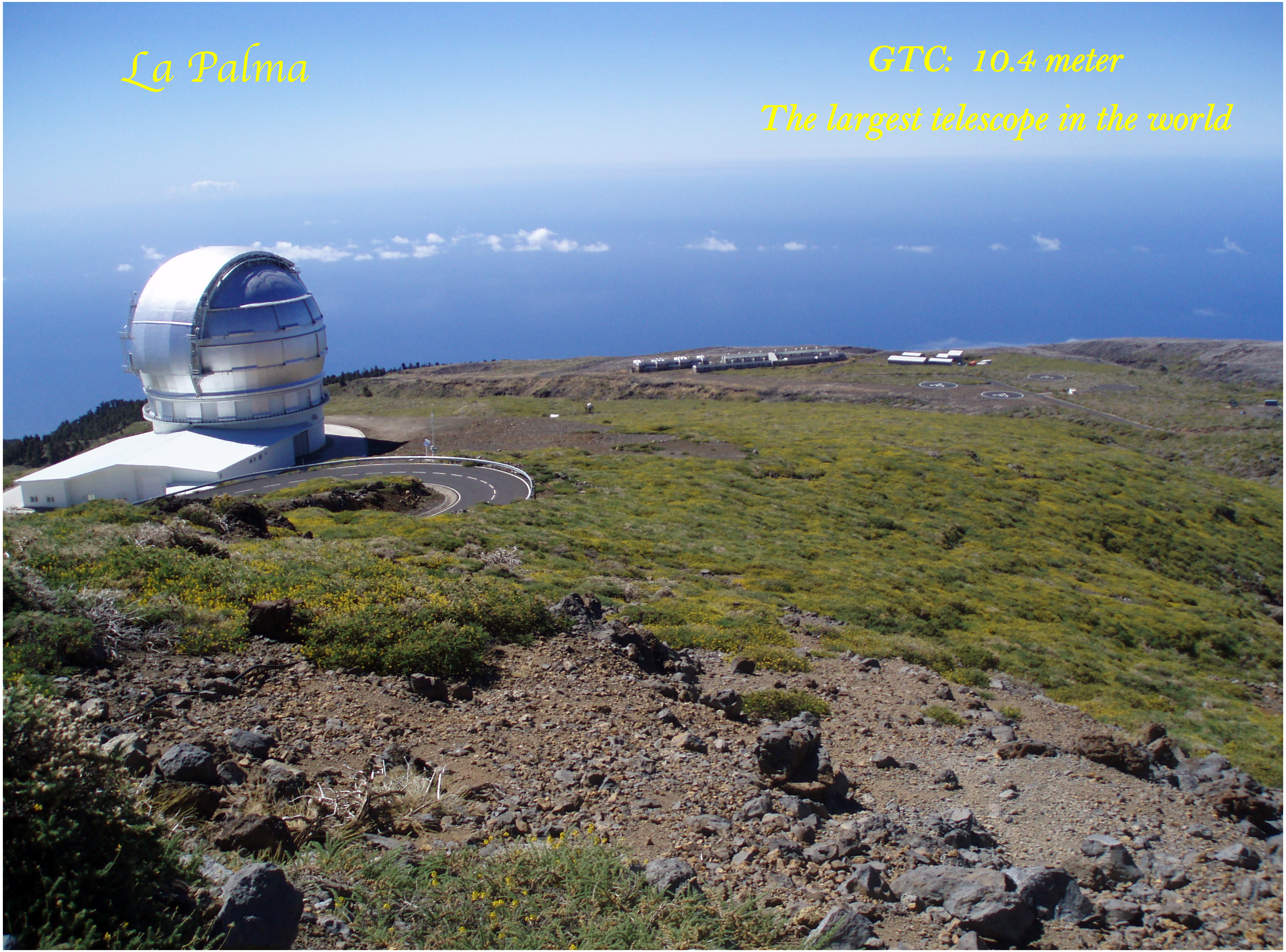
Teide Observatory

2590 meter a.s.l.

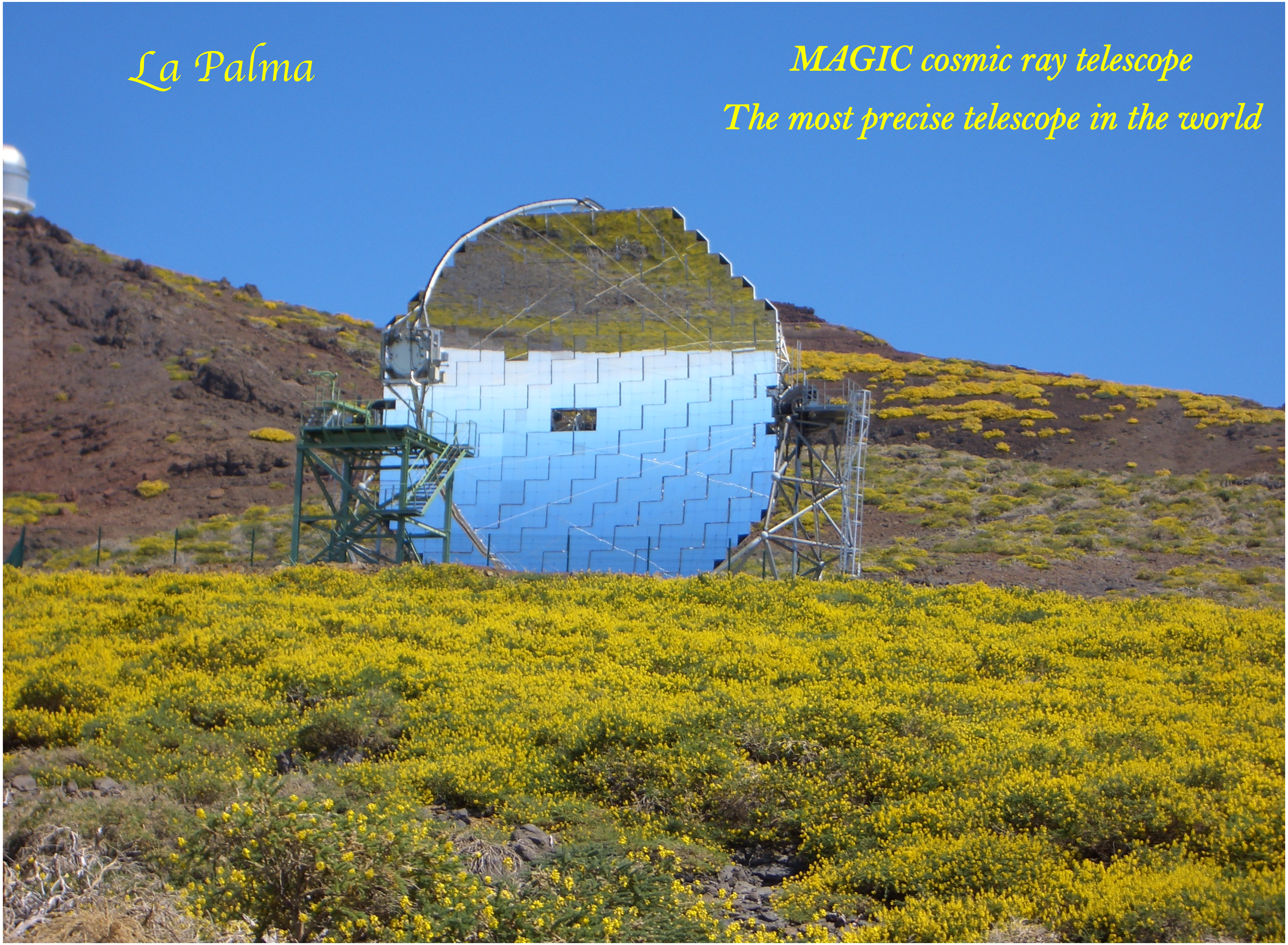
Teide Observatory

2590 meter a.s.l.

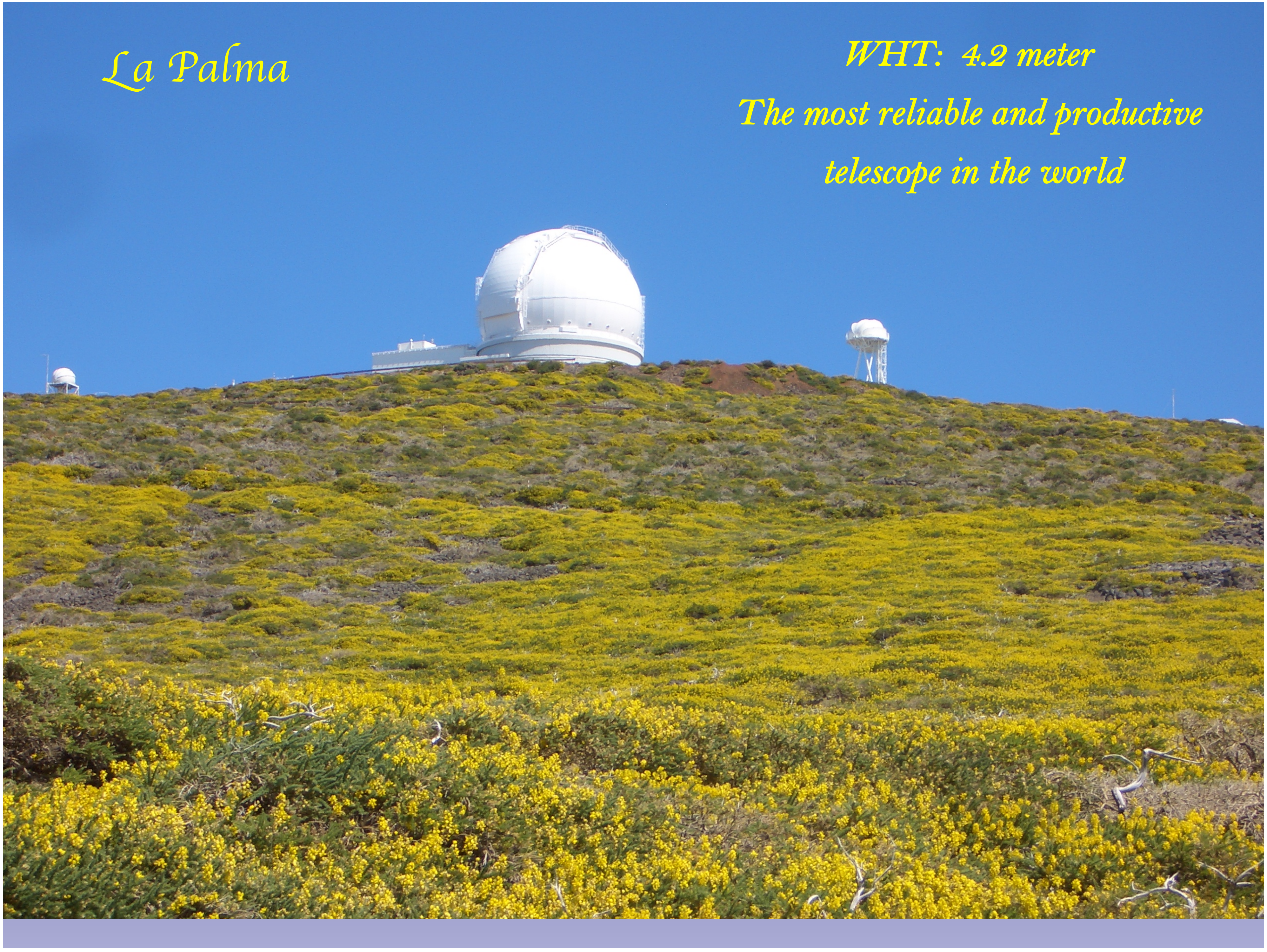

La Palma


La Palma
GTC: 10.4 meter
The largest telescope in the world

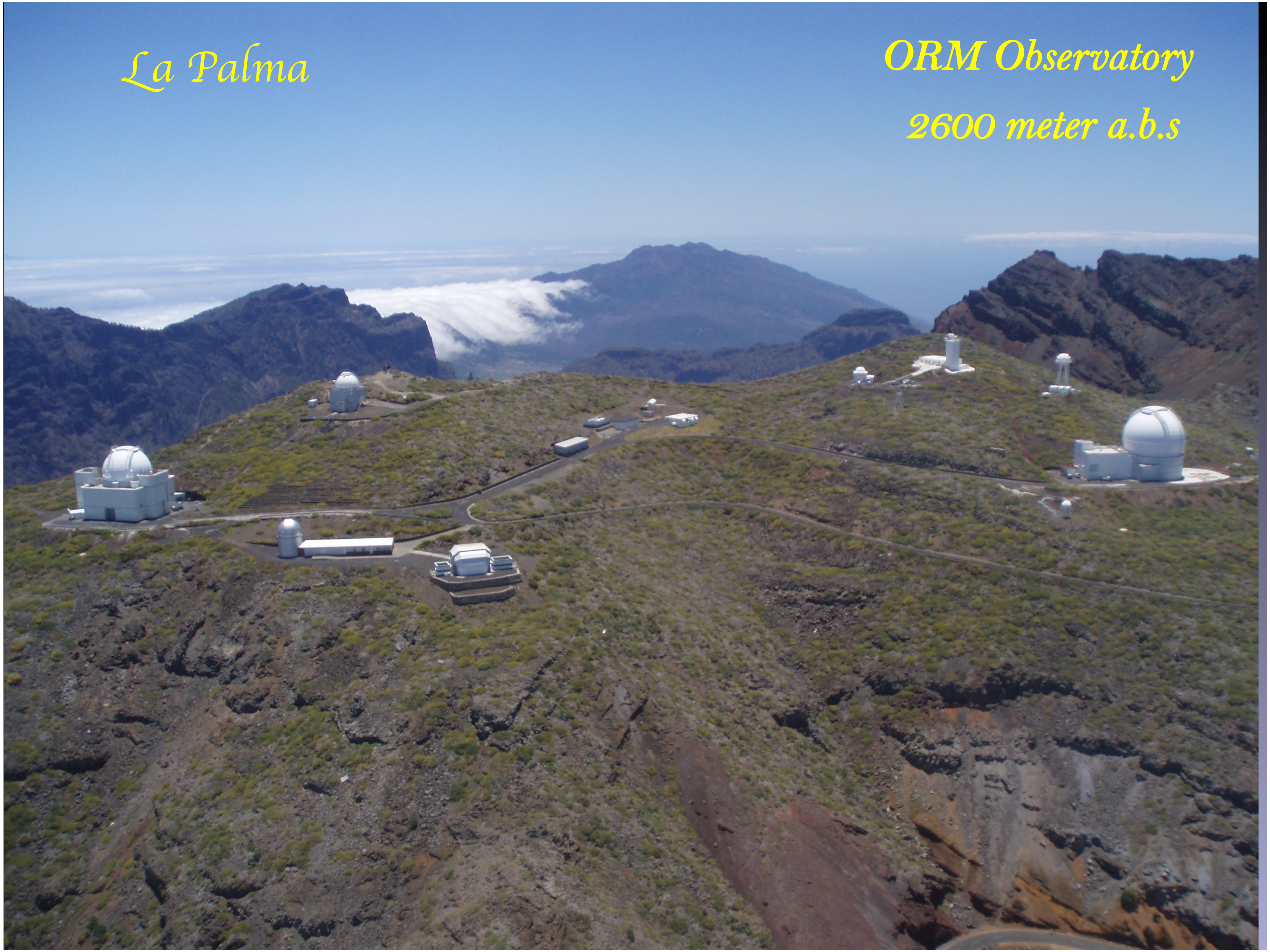
Galileo: 3.5 meter
Italian National Telescope
La Palma


La Palma
MAGIC cosmic ray telescope
The most precise telescope in the world


La Palma
MERCATOR Swiss-Belgian
1.2 meter robotic telescope


La Palma
WHT: 4.2 meter
The most reliable and productive
telescope in the world


La Palma
ORM Observatory
2600 meter a.b.s


La Palma
ORM Observatory
2600 meter a.b.s

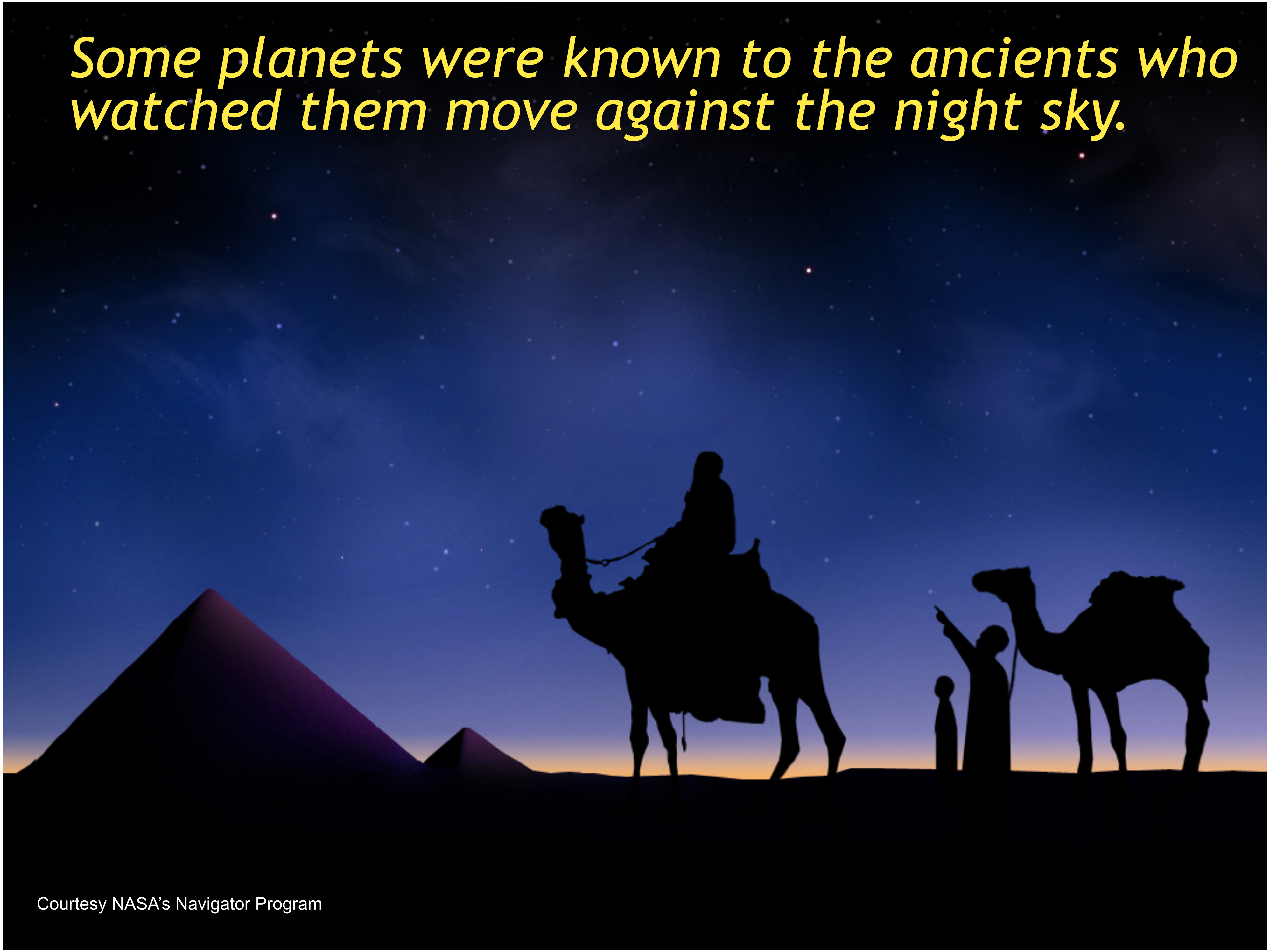

La Palma
GTC: 10.4 meter
The largest telescope in the world

Tenerife

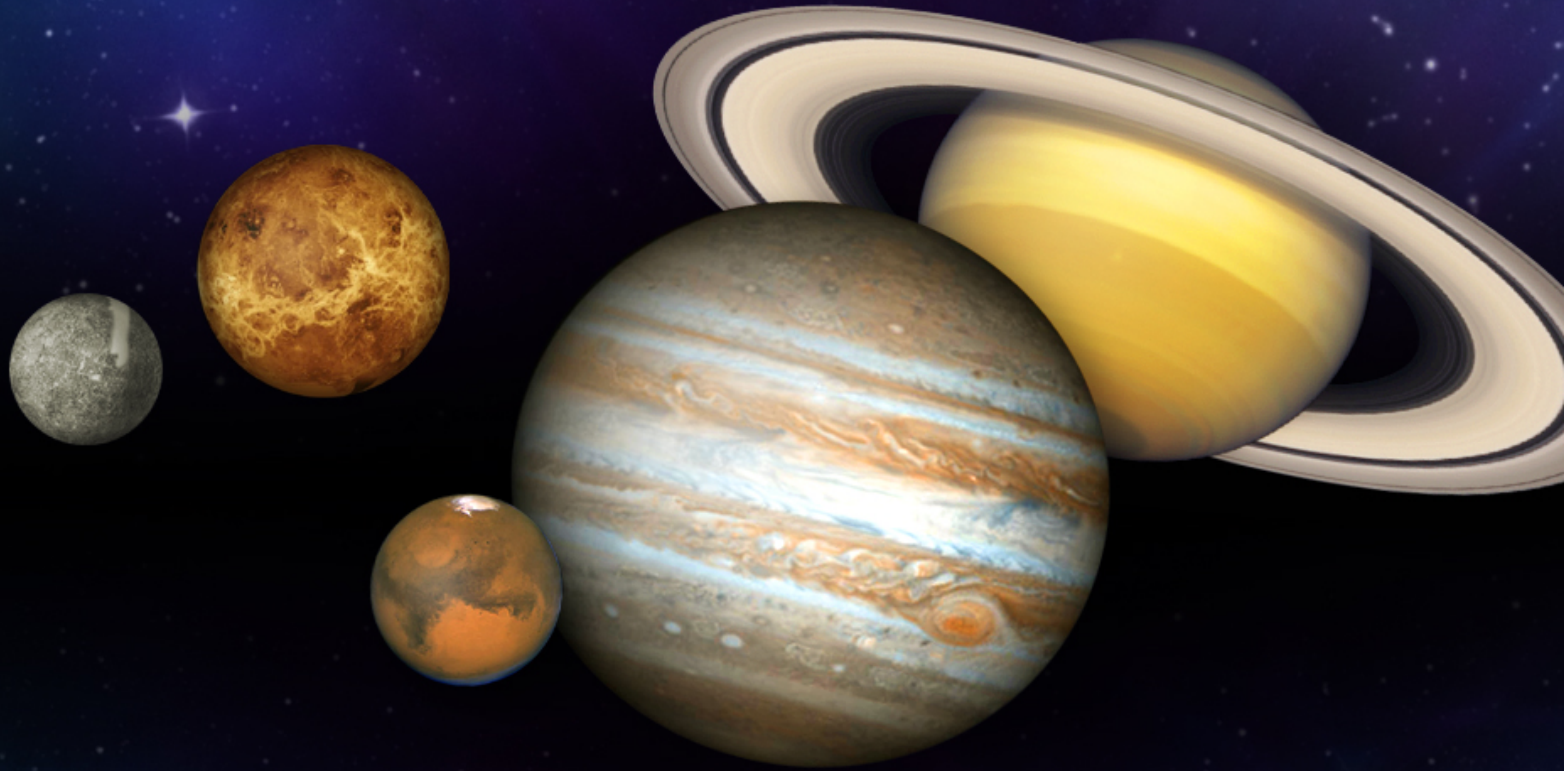
Teide Observatory

2590 meter a.s.l.


Tenerife
Teide Observatory
2590 meter a.s.l.


Some planets were known to the ancients who watched them move against the night sky.
Courtesy NASA’s Navigator Program

Mercury, Venus, Mars, Jupiter, and Saturn were the “Wandering Stars.”



“Planet” comes from the Greek word for “wanderer.”

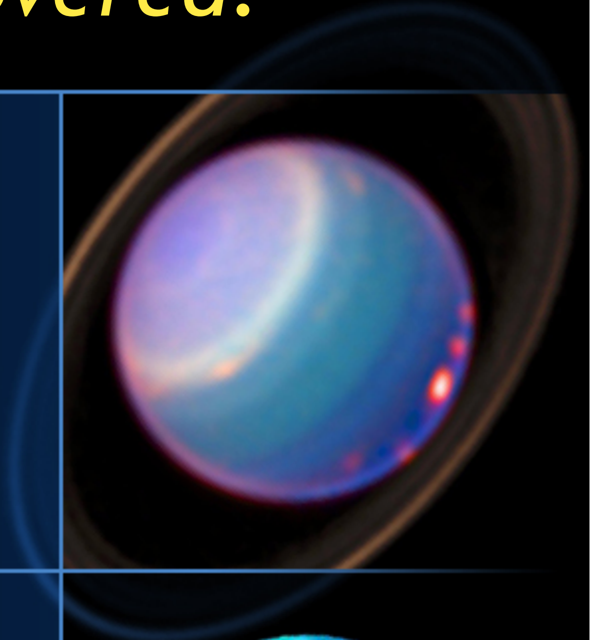
Courtesy NASA’s Navigator Program

And other planets were “discovered.”

Uranus

The year 1781

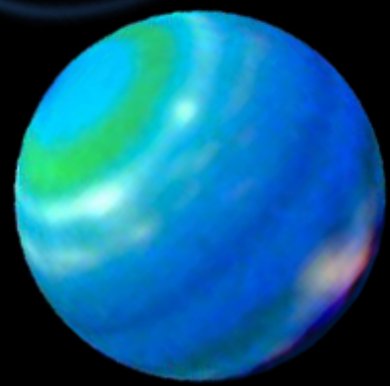
The first planet “discovered.”
William and Caroline Herschel



Neptune

The year 1846

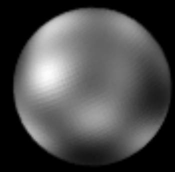
First observed by Galle and d'Arrest (based on calculations by Adams and Le Verrier).



Pluto

The year 1930

Discovered by Clyde Tombaugh



Courtesy NASA’s Navigator Program

But what about more distant worlds? Thousands of years ago, Greek philosophers speculated.

"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and planets and other things we see in this world."

Epicurius
c. 300 B.C

Courtesy NASA's Navigator Program

And so did medieval scholars.

The year 1584

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth”

Giordano Bruno
in De L'infinito
Universo E Mondi

Courtesy NASA’s Navigator Program

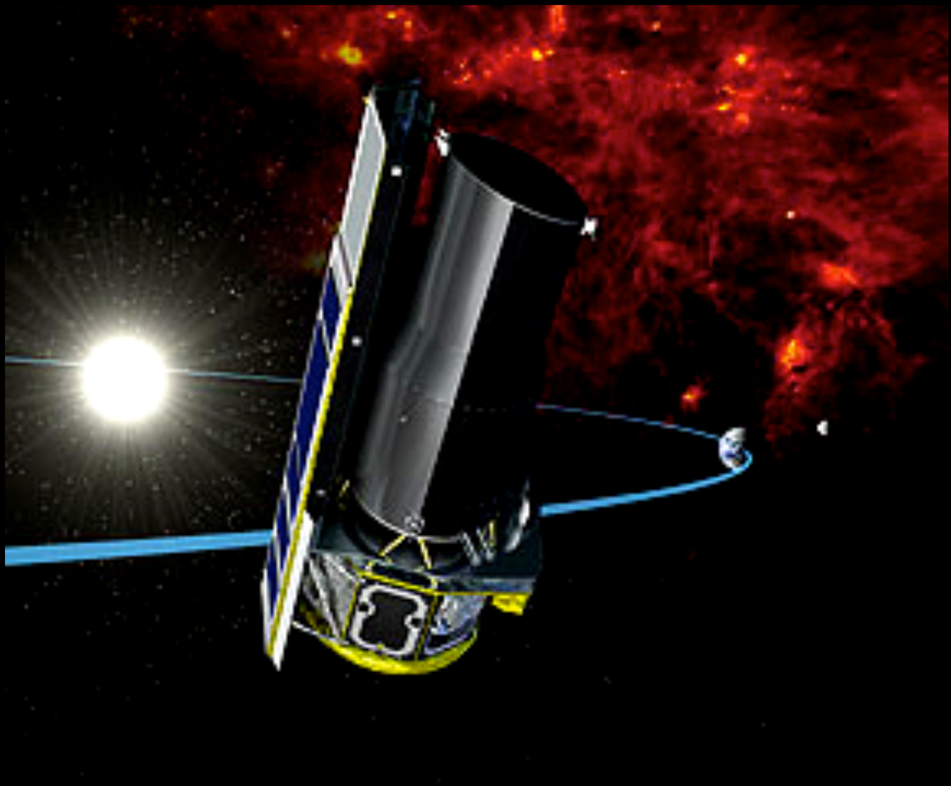
In 1995, a breakthrough: the first planet around another star.

Michel Mayor and Didier Queloz

A Swiss team discovers a planet – 51 Pegasi – 48 light years from Earth.

Courtesy NASA's Navigator Program

Methods to Detect Planets



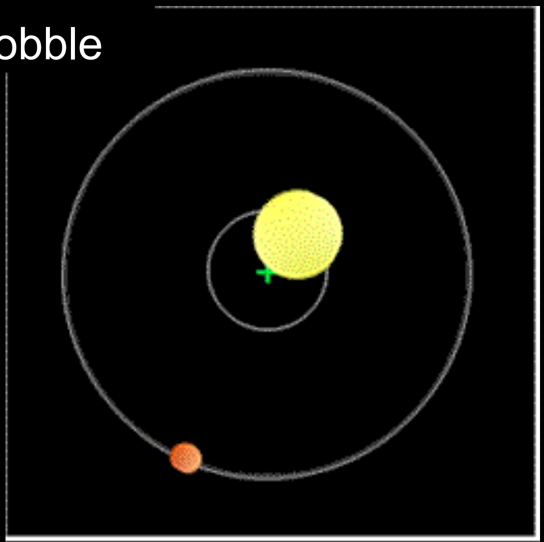
Artist Concept:
NASA's Spitzer Infrared Telescope

Spitzer, for the first time, captured the light from two known planets orbiting stars other than our Sun. But so far, most of the extra-solar planets are being detected using INDIRECT methods.

Methods to Detect Planets

There are several complementary methods for detecting planets orbiting distant stars.

Wobble

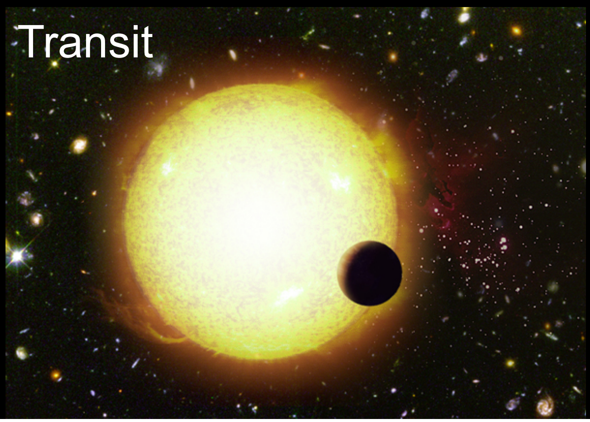


Doppler – *detecting the star wobbling in the line of sight due to the planet's gravitational pull*

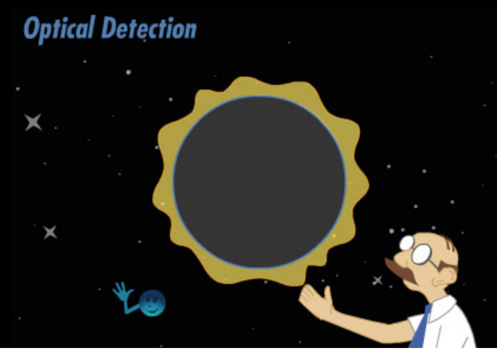
Astrometry – *detecting tiny wobble of stars against other stars in the background.*

Planet Transit – *detecting a tiny drop in brightness of the star as a planet passes in front*

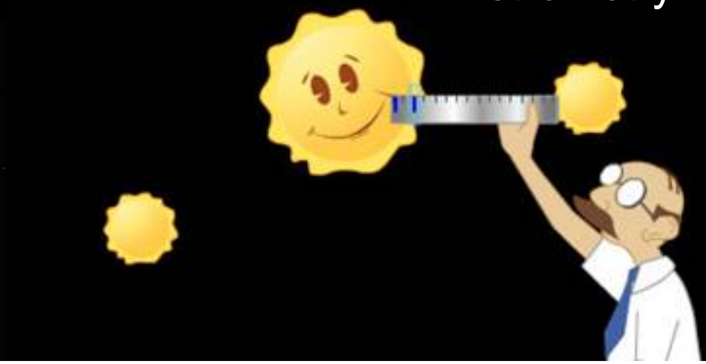
Coronograph – *blotting out the light of the star so planets can be "seen"*



Coronograph



Astrometry



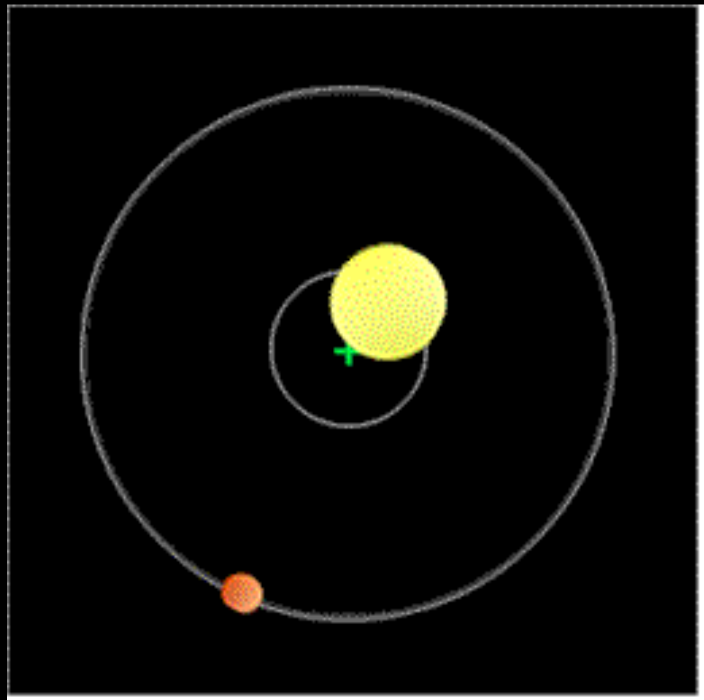
Massive Planets Cause Stars to Wobble

Stars and their planets also move about the common center of mass.

Since the mass of a star is so much greater than the mass of a planet, the “center of mass” (i.e. “balance point”) is located close to (but not at the center) of the parent star.

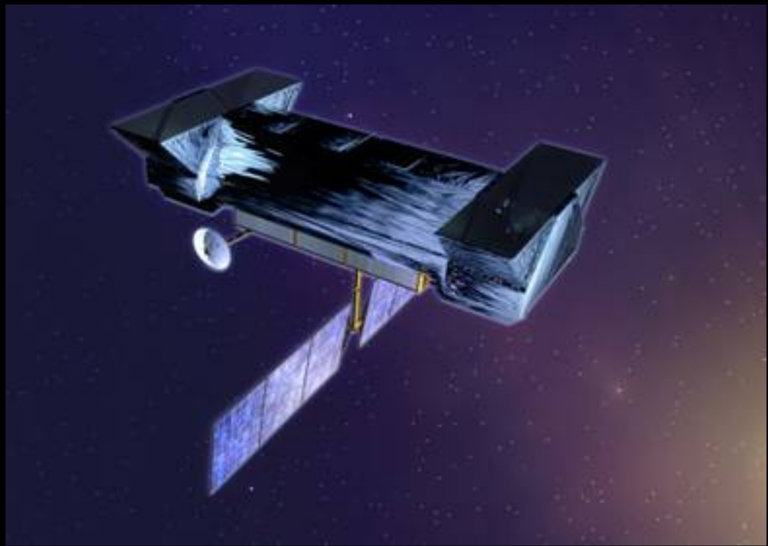
This means that stars with planets in orbit around them are not stationary. Rather, they move slightly about this balance point producing a gravitational wobble!

The gravitational wobble of the Sun is dominated by the gravity of the most massive planet Jupiter.

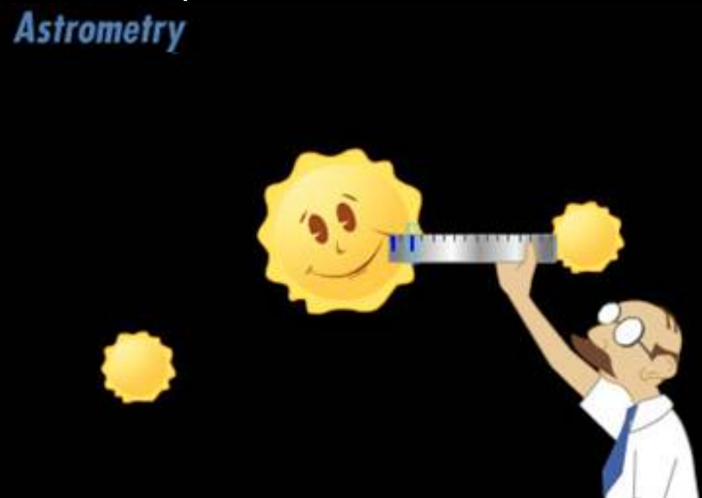


NASA's SIM PlanetQuest Mission

Are there terrestrial planets orbiting nearby stars?



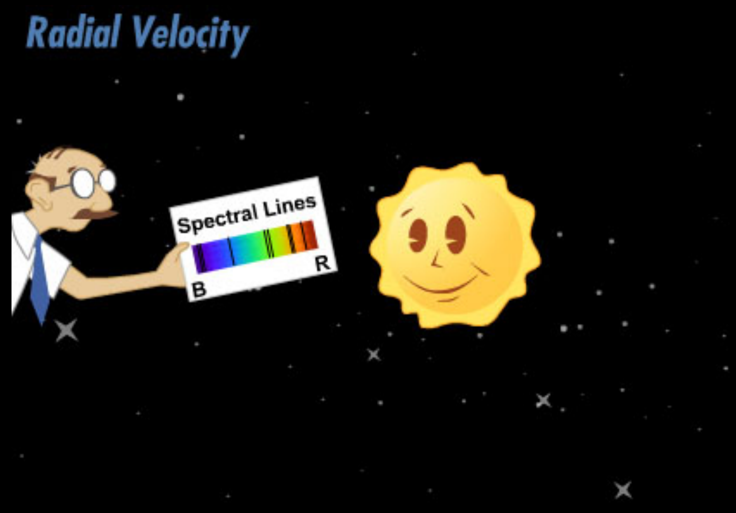
Artist Conception: NASA's SIM PlanetQuest



NASA's SIM PlanetQuest Mission will survey nearby stars for Earth-size planets by measuring the wobble of stars against other stars in the background.

This method of detection is called astrometry.

Doppler shift to measure the tug of planets on stars. Here is how it works:



So far, nearly all extra-solar planets have been discovered with this technique

If an unseen planet tugs the star back and forth…

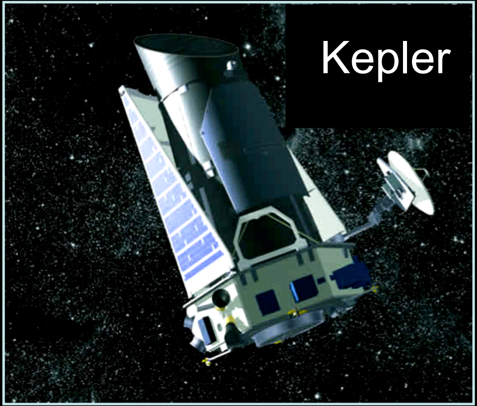
…the light from the star shifts slightly to the red as the star moves away from you.

…and slightly to the blue as it moves toward you.

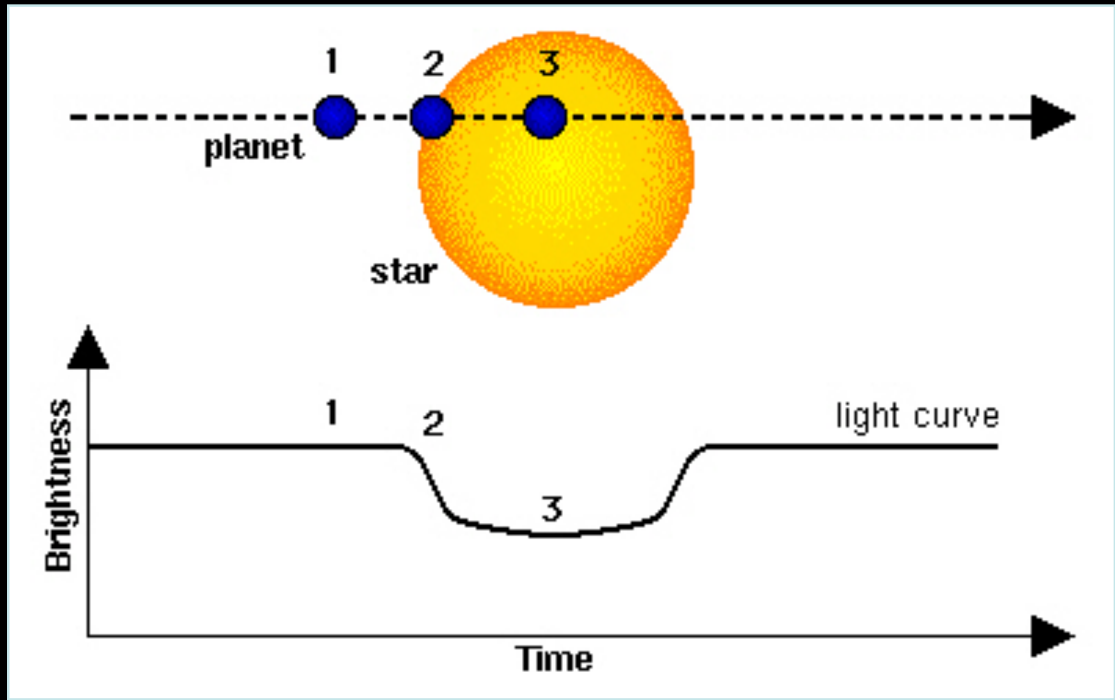
Astronomers can detect these shifts by very carefully observing the spectra (or colors) of the stars.

Courtesy NASA's Navigator Program

Detecting Planets: Transit Method



NASA's Kepler mission will use the transit method.



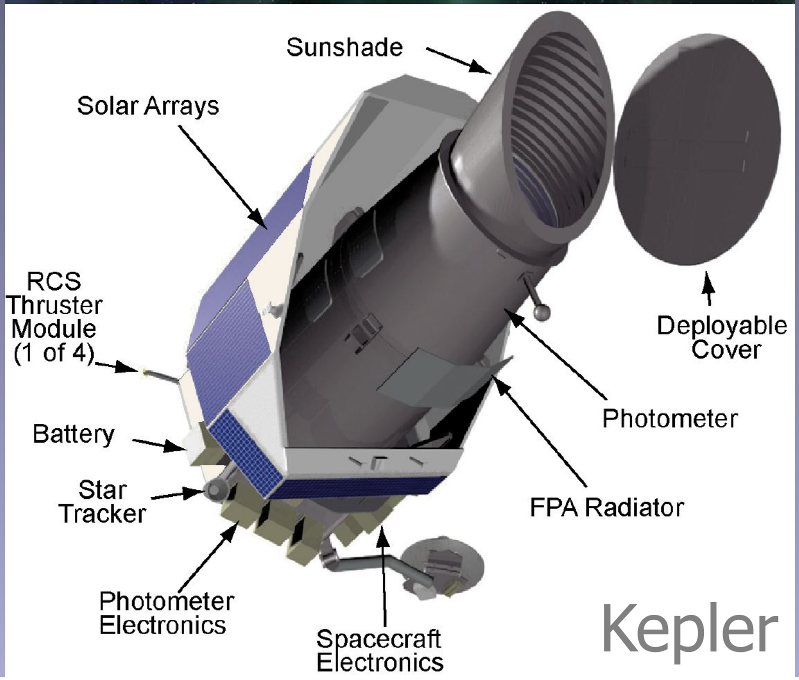
When a planet passes by (or transits) a star, we can detect a slight decrease in the amount of light from the star.

Space Missions: COROT_Kepler

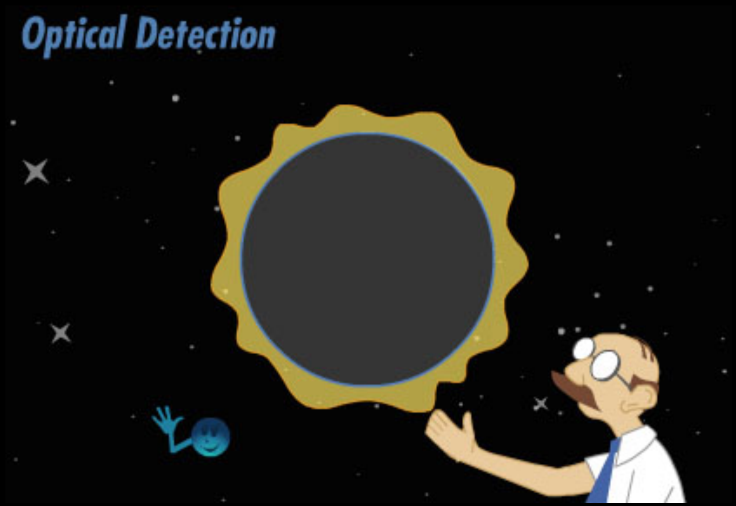
- COROT（2007）
  - 60,000 stars
  - field: 3 deg^2
  - precision: ~10^{-4} mag
- Kepler（2010）
  - 100,000 stars
  - field: 10 deg^2
  - precision: ~5×10^{-5} mag

➢ Hundreds of new transits of giant planets?

➢ A few terrestrial planets?

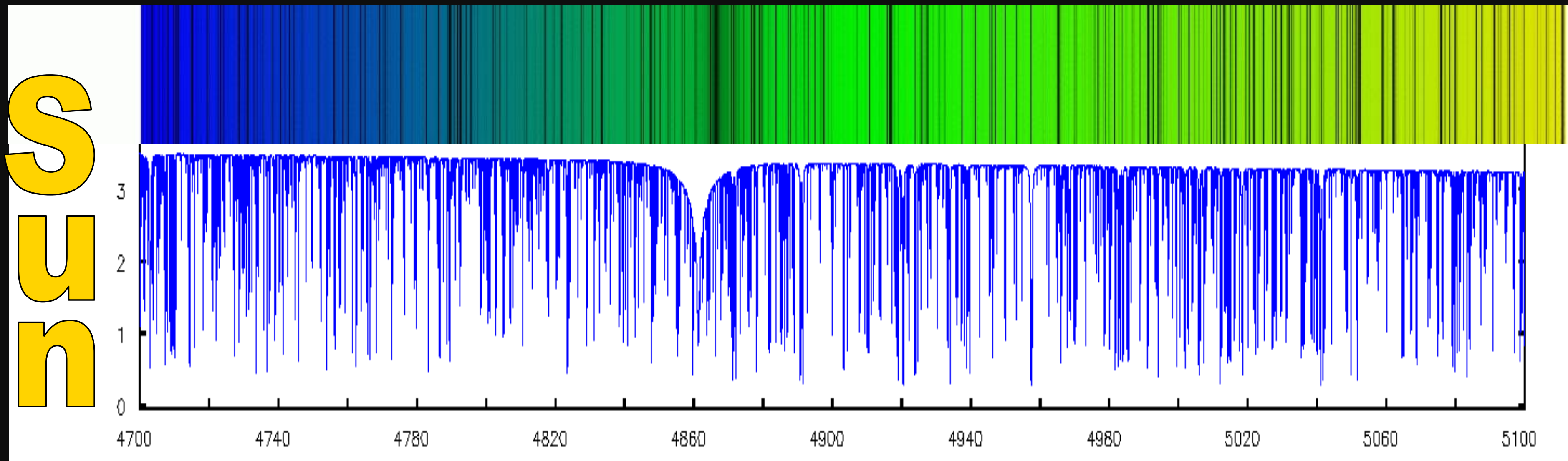


Coronograph: We will block out the bright light from the star.



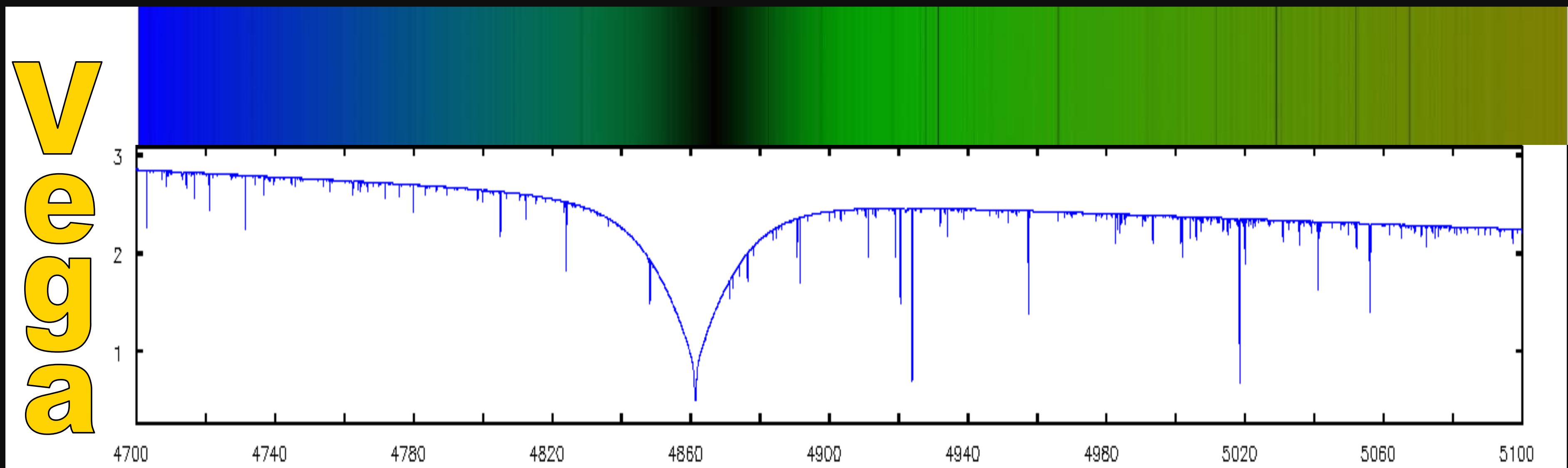
Keck Interferometer

The Keck Interferometer combines the light of two 10-meter telescopes to take images of hot Jupiter-size planets that shine bright in infrared light.



T_{eff} = 5800 K

24000 lines in the optical spectrum of the Sun. 15 % not yet identified !



T_{eff} = 9900 K

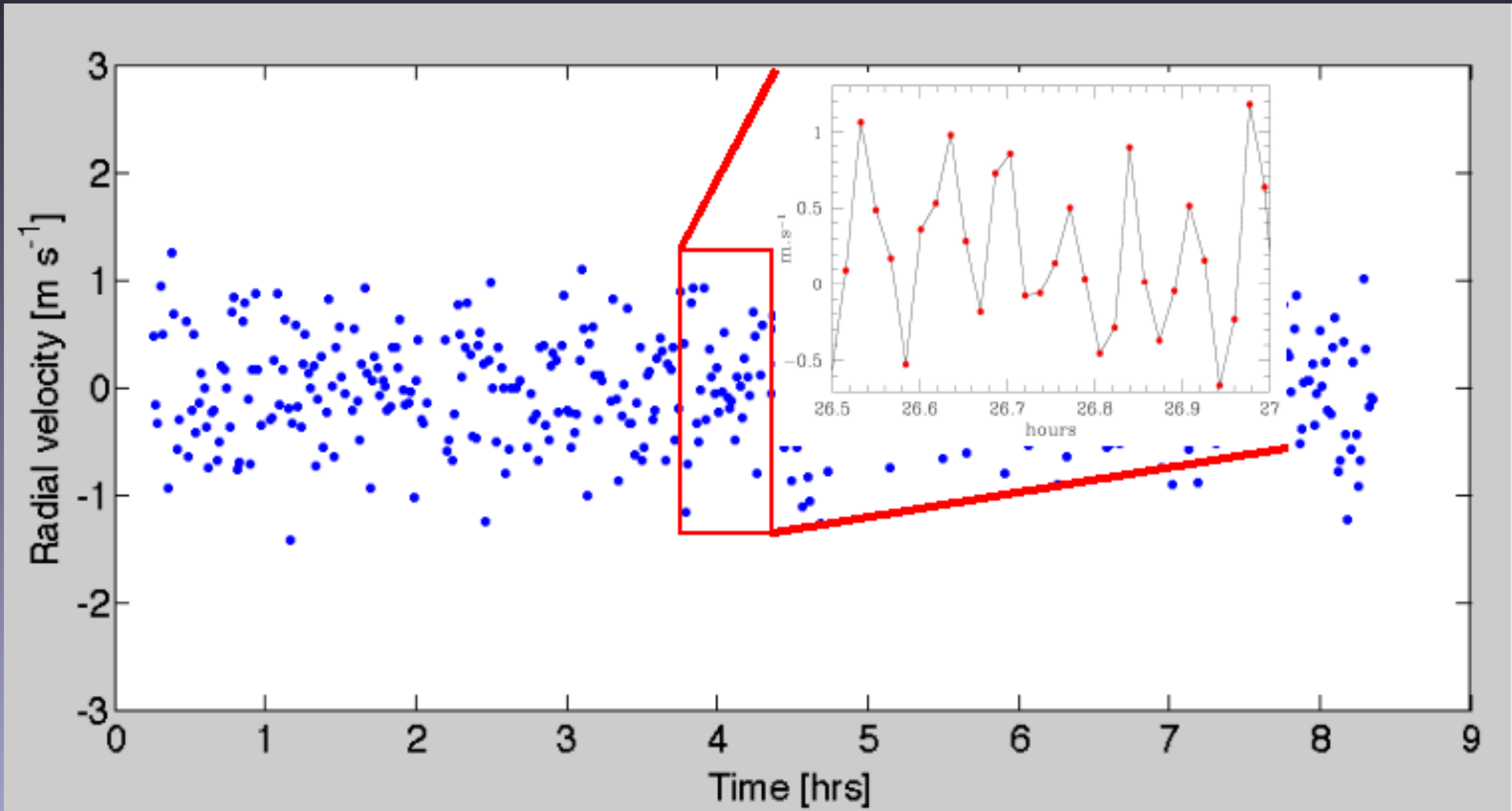
Wavelength

How precise ?

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

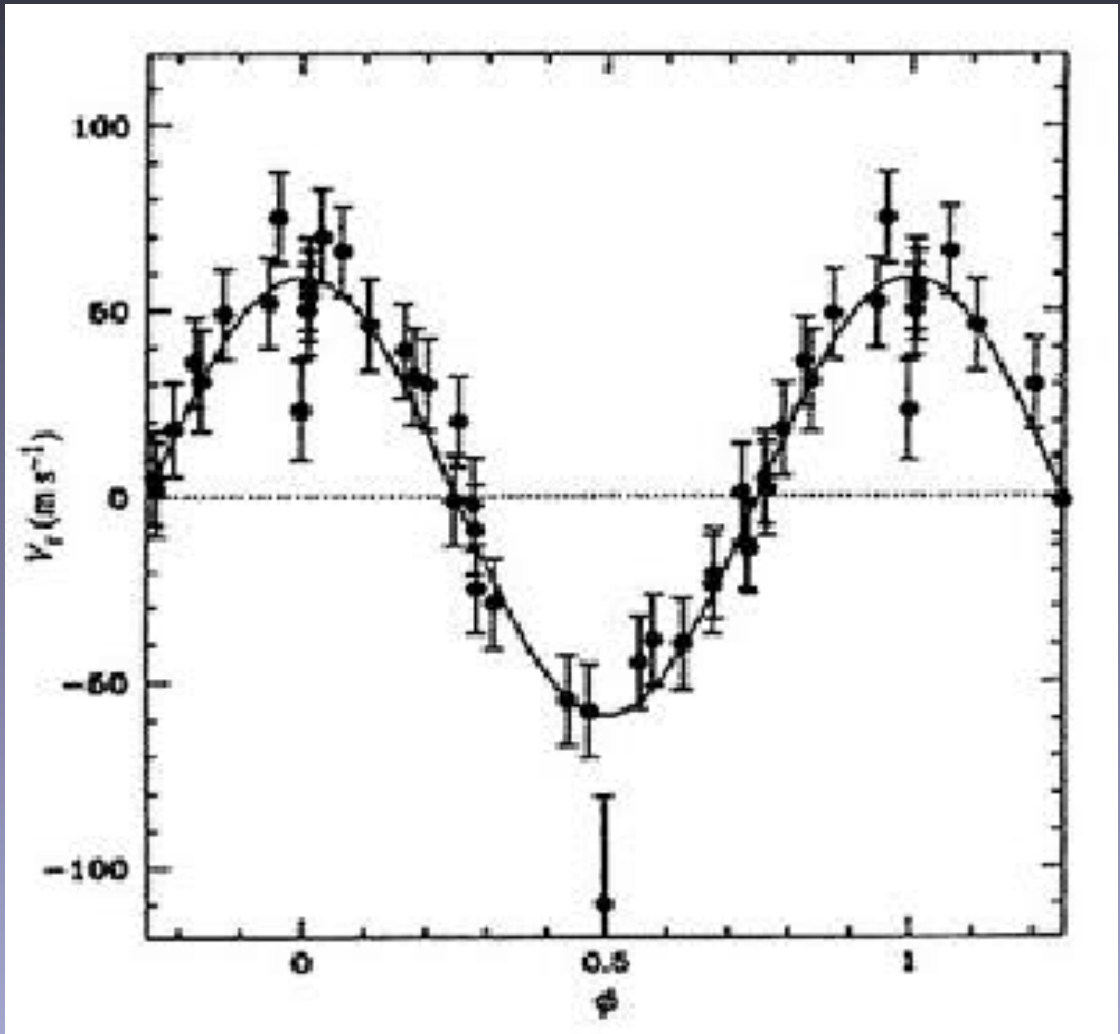
accuracy

Stellar challenges



First planets and first “problems”

Mayor & Queloz (1995)



Strange world:

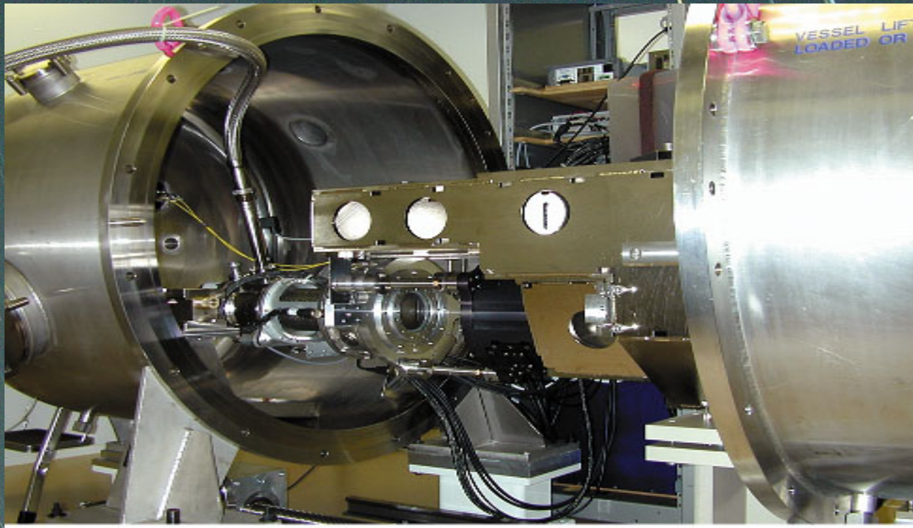
$m\sin(i)=0.47M_{Jup}$

P=4.2 days

Separation=0.05 AU

The HARPS Project

- Better than 1m/s long term precision



The HARPS Spectrograph

ESO PR Photo 08b/03 (27 March 2003)

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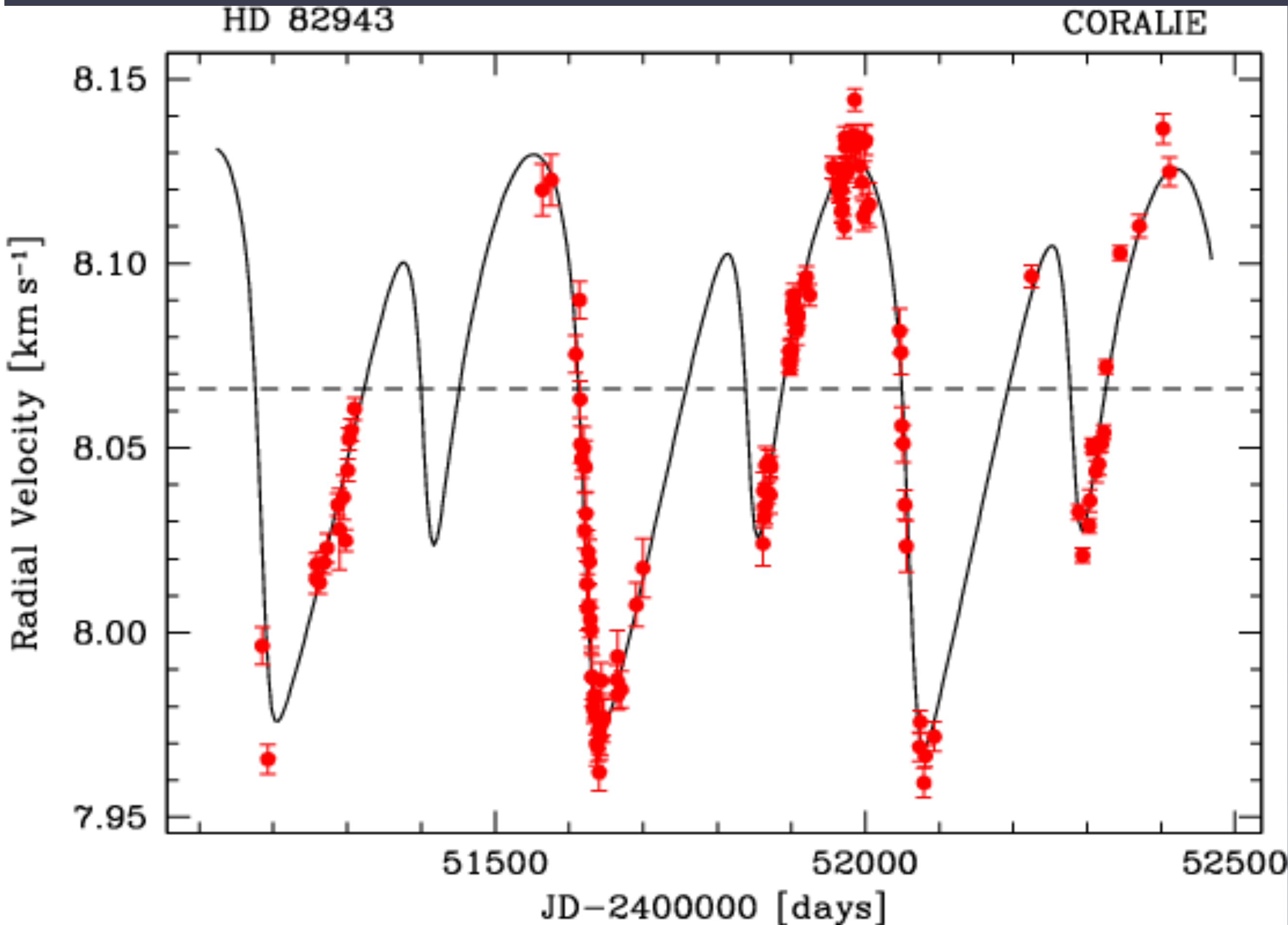
HD82943: a two planet system

(Mayor et al. 2000, A&A), Israelian et al., (2001, Nature)



- Resonant orbits!!!

	b	c
m2 (Jup)	1.63	0.88
P (days)	444	222
Ecc.	0.41	0.54
Sep. (AU)	1.16	0.73

Huge eccentricity

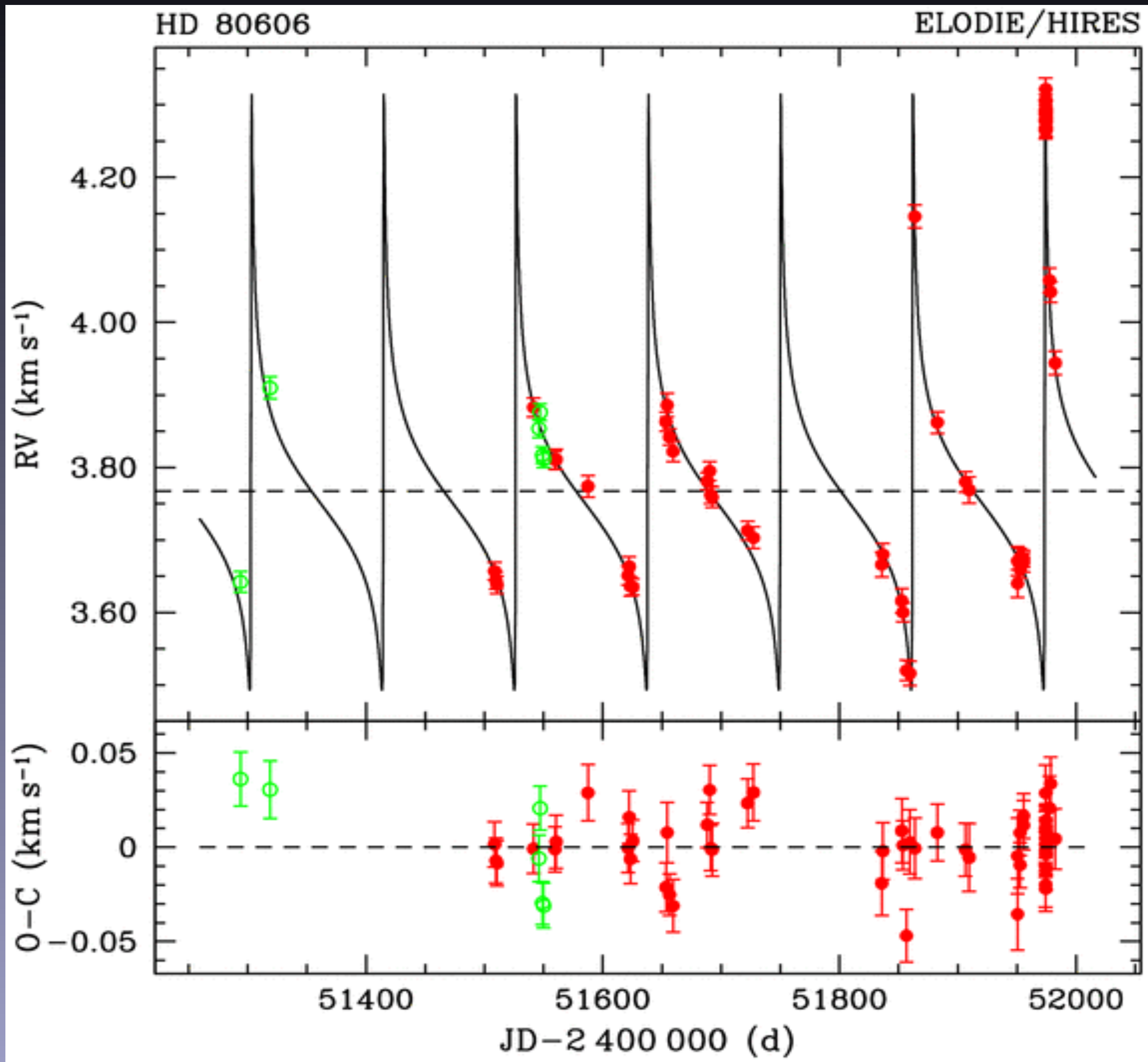
HD80606

(Naef et al. 2001)

ecc.=0.93

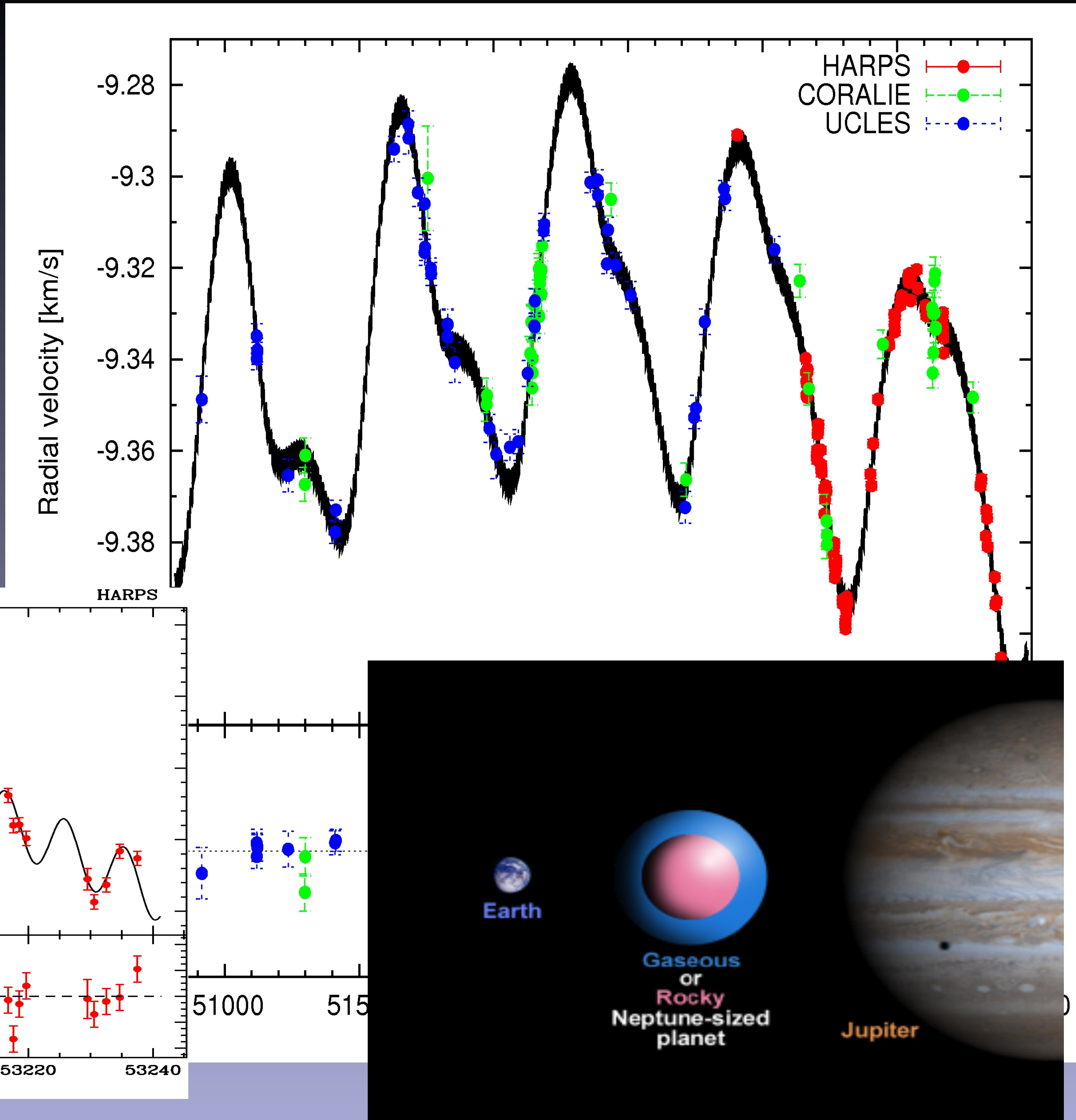
P=112 days

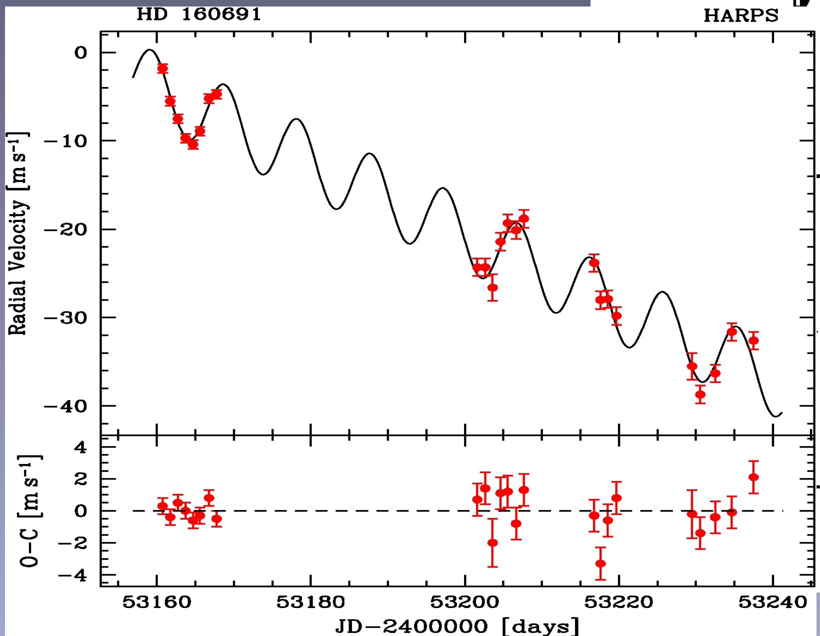
msini=4M(Jup)



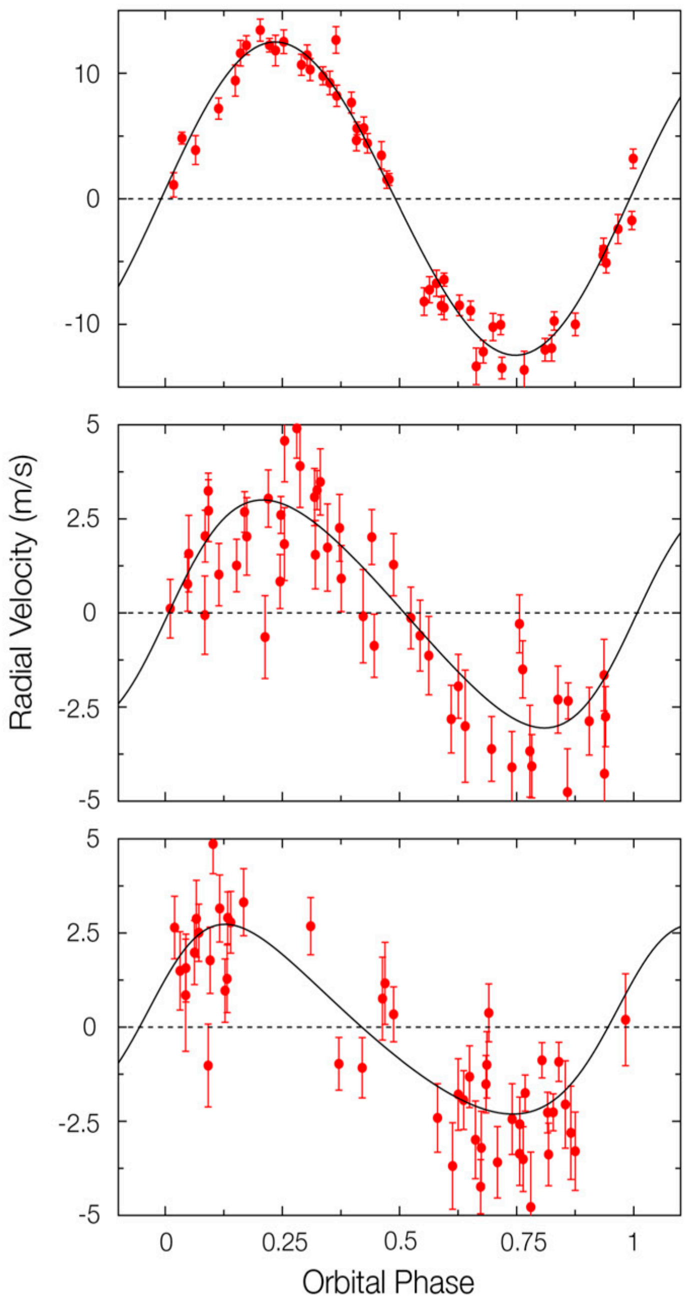
μ Ara: a 4_planet system

(Santos et al. 2004; Pepe et al. 2006)



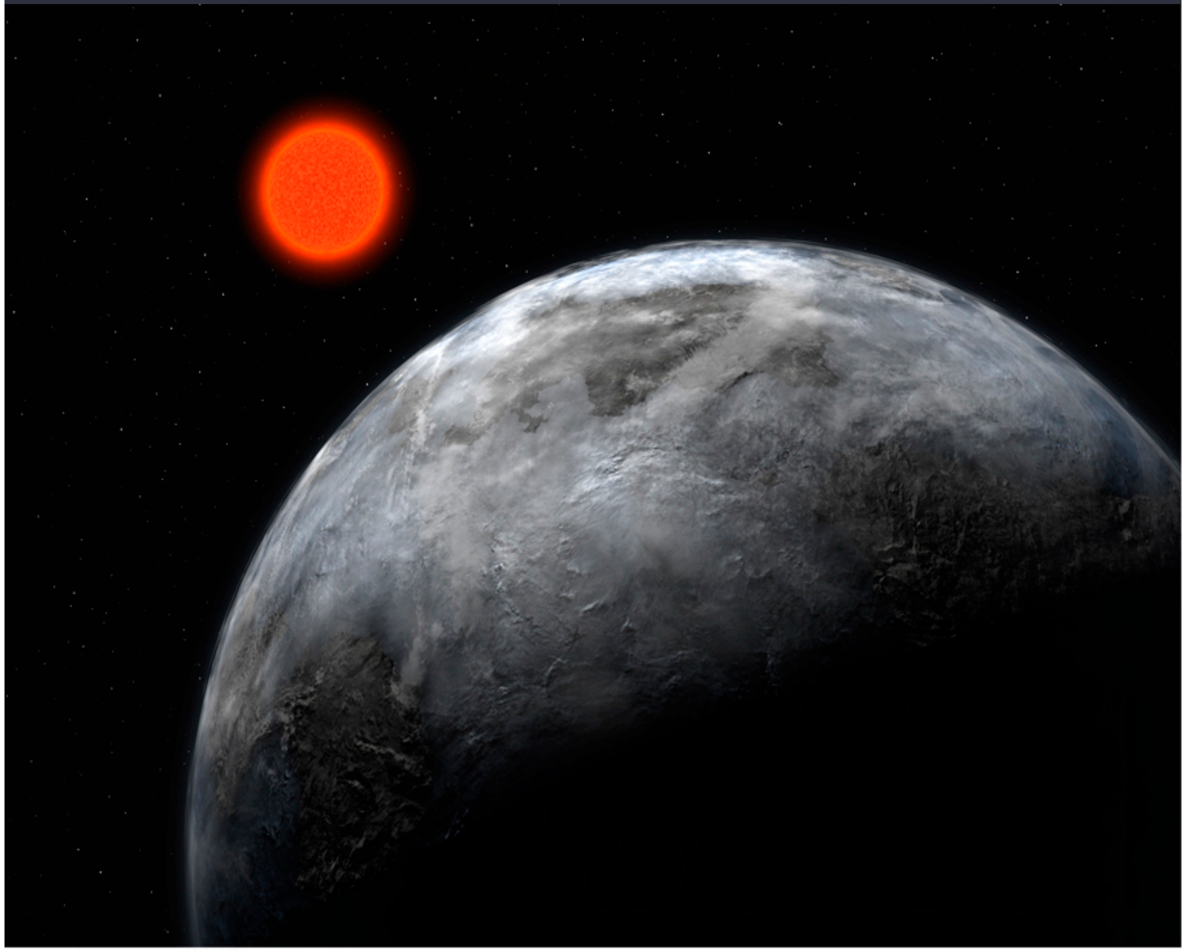


Gl581c (Udry et al. 2007)
5 Earth-masses in the habitable zone!



Observed Velocity Variation of Gliese 581

ESO Press Photo 22d/07 (25 April 2007)

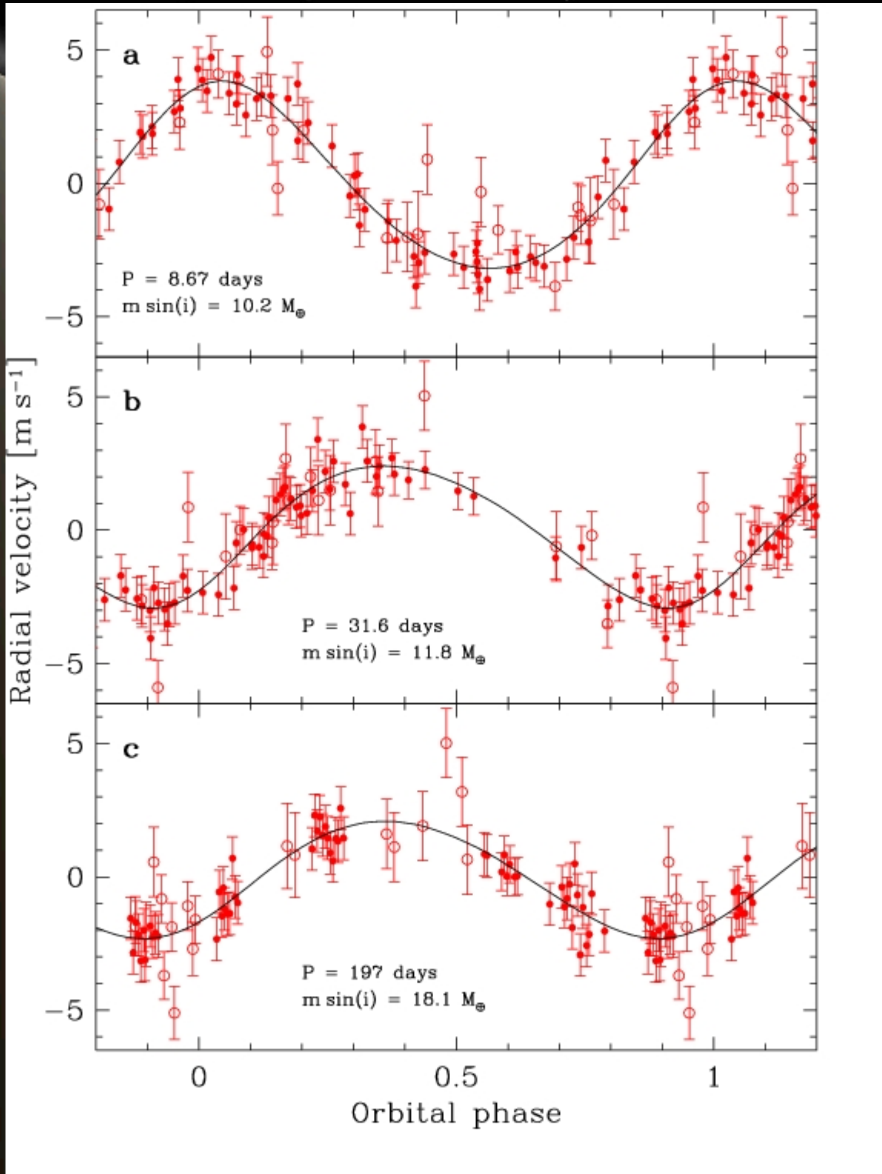


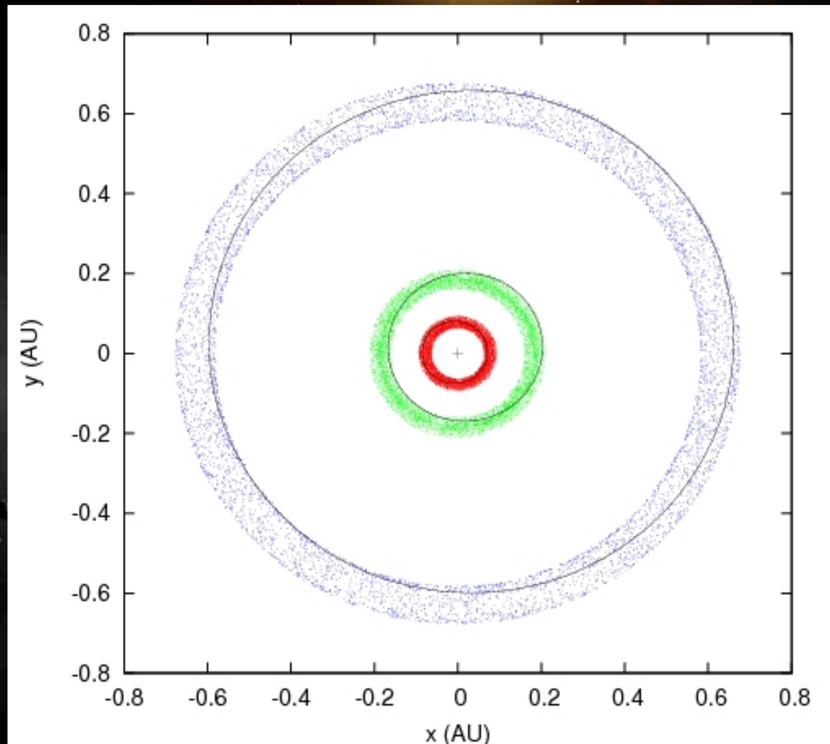
A Super-Earth around Gliese 581

(Artist's Impression)

SO Press Photo 22b/07 (25 April 2007)

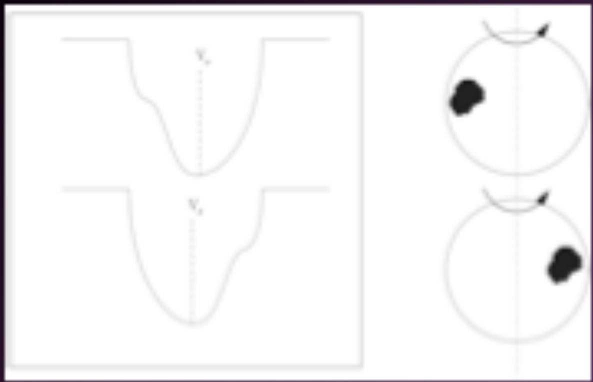
HD69830: a HARPS system of 3 Neptunes（Lovis et al. 2006）

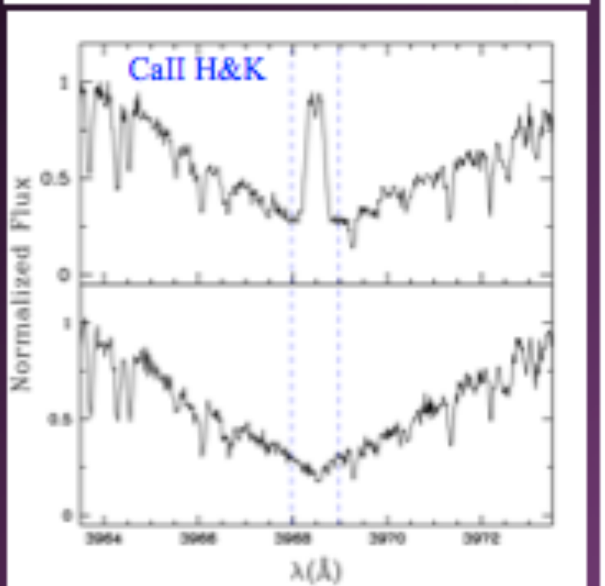


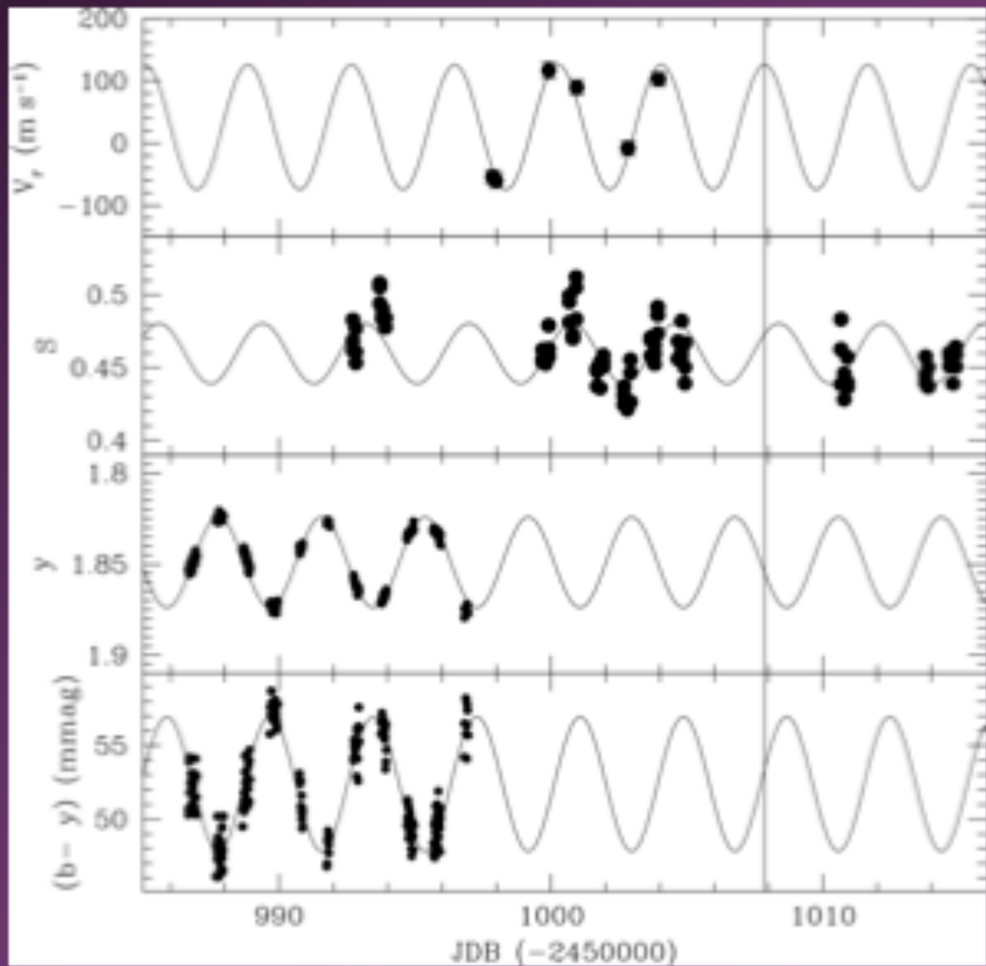


Stellar activity

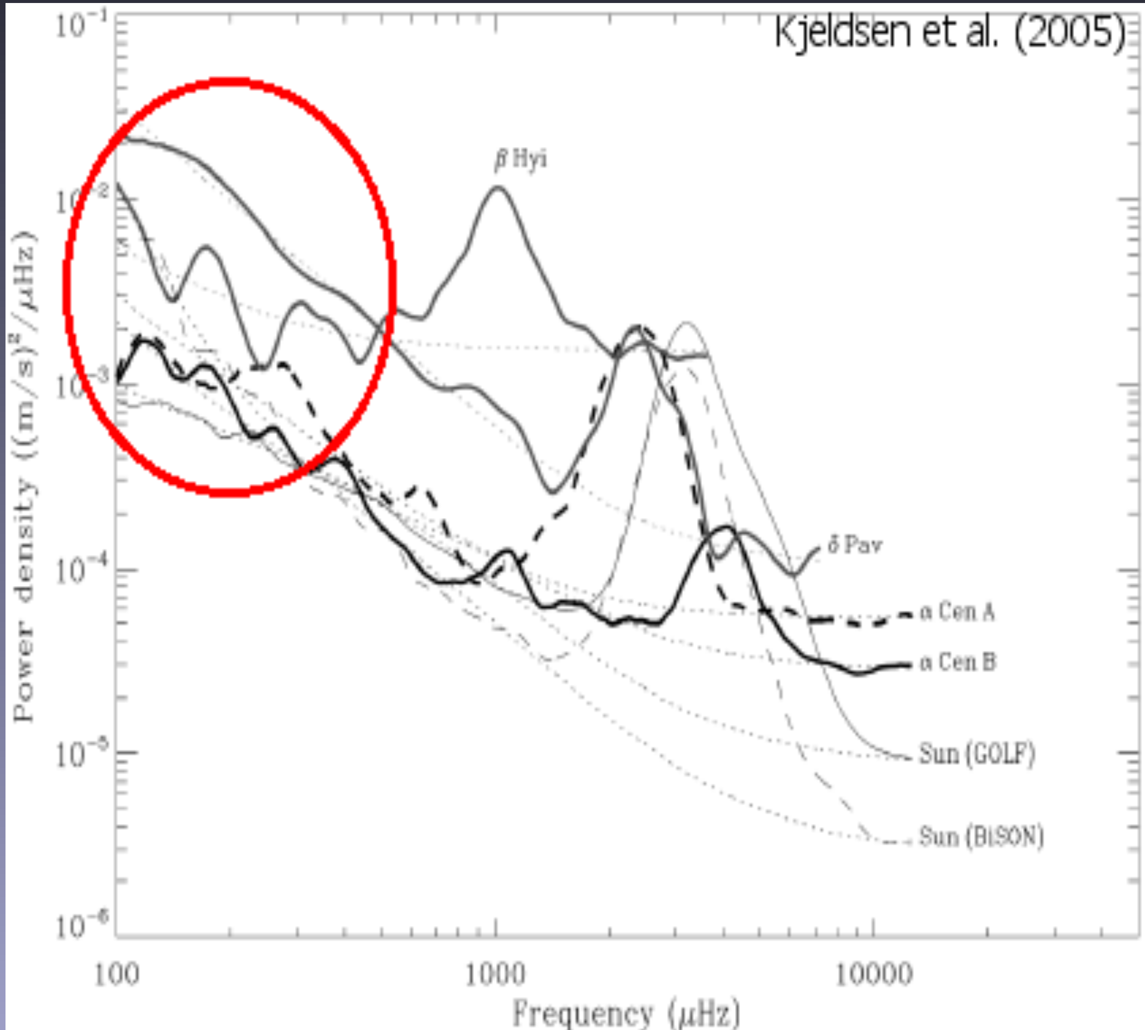
Texbook case: HD166435 (Queloz et al. 2000)







Stellar challenges



- Granulation ($\tau \sim$ 6 min)
- Mesogranulation ($\tau \sim$ 3h)
- Supergranulation ($\tau \sim$ 1 day)
- Active regions ($\tau \sim$ 10 days)

Current situation on exoplanet searches

- 865 exoplanets found, mostly by Radial–velocity surveys
- At least 60% of sun–like stars have planets
    - 134 multi–planet systems
    - 230 planets transit their host–stars
    - 87 Neptuns and Super–Earth.
    - 13 planets detected by direct imaging.
    - 8 planets with molecules detected
    - 13 Free floating planets

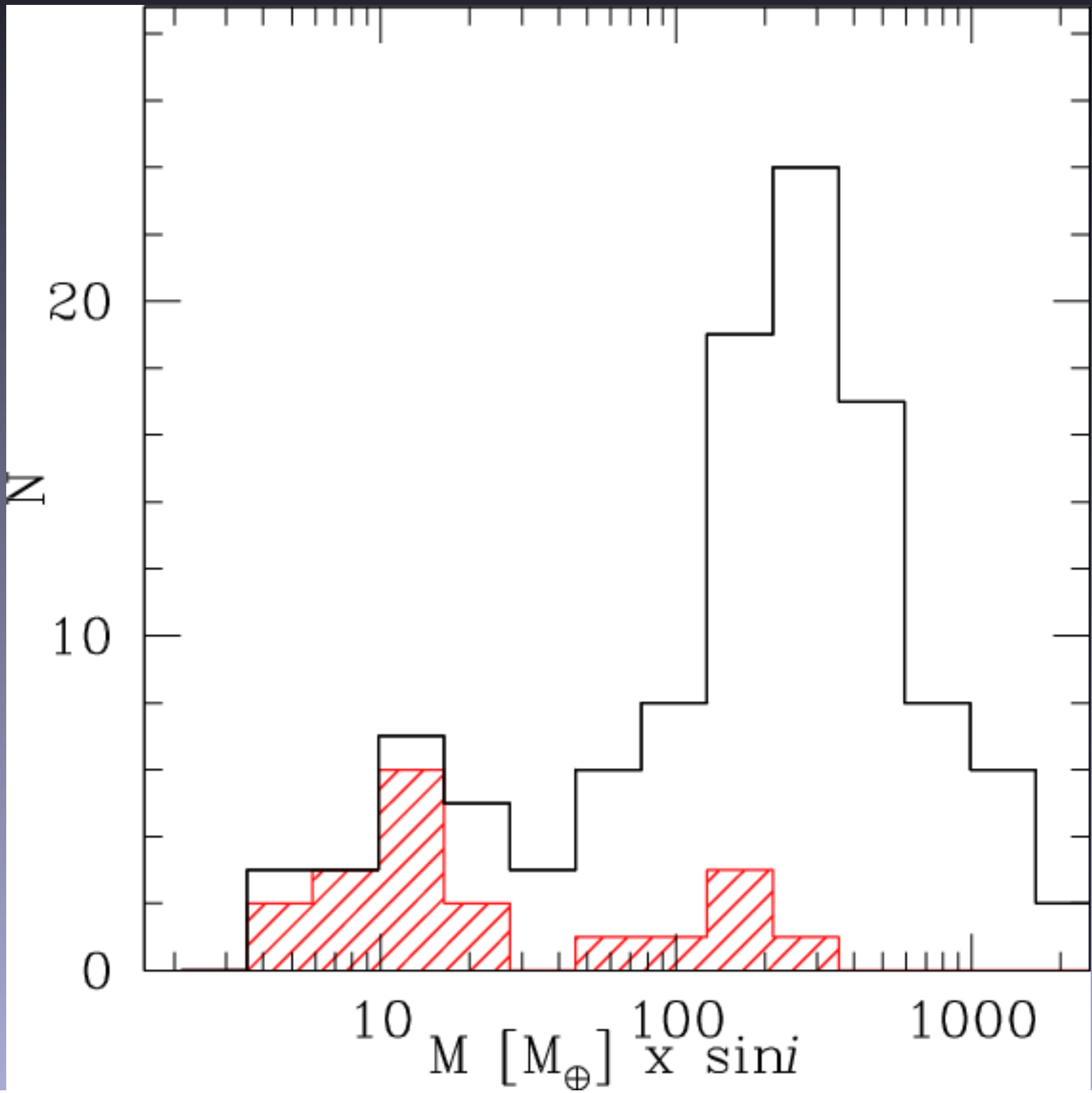
New worlds, new problems

- Varied and strange properties!
- Very different from Solar System!
- Not supposed to exist!!!

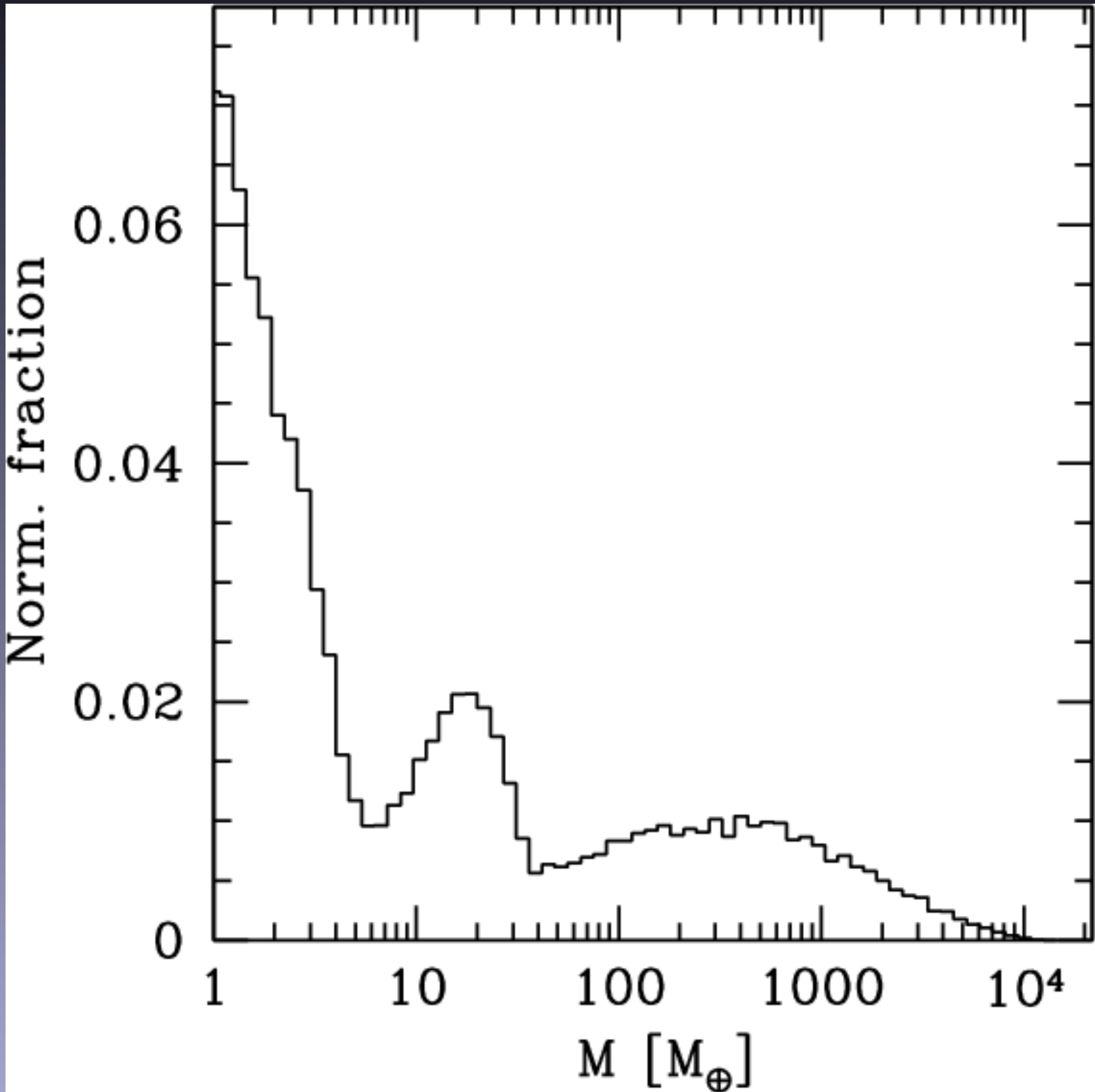
Need to revise theories of planet formation and evolution

Look at the statistical properties

Mass distribution (HARPS)

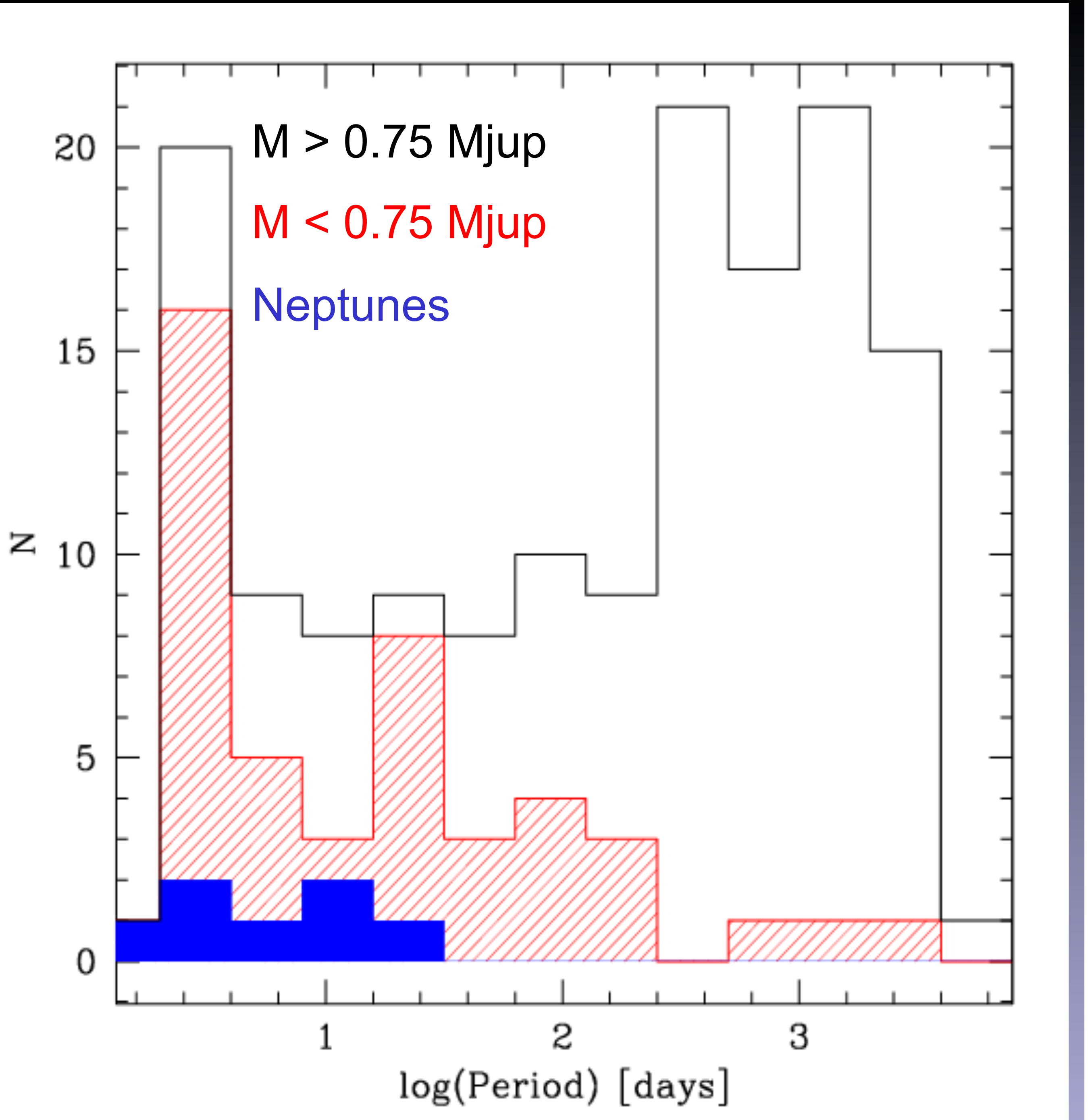


Benz et al. (2009)



Period Distribution:3-day peek and period valey

（Cumming et al. 1999; Udry et al. 2003）



Mayor et al. 2012

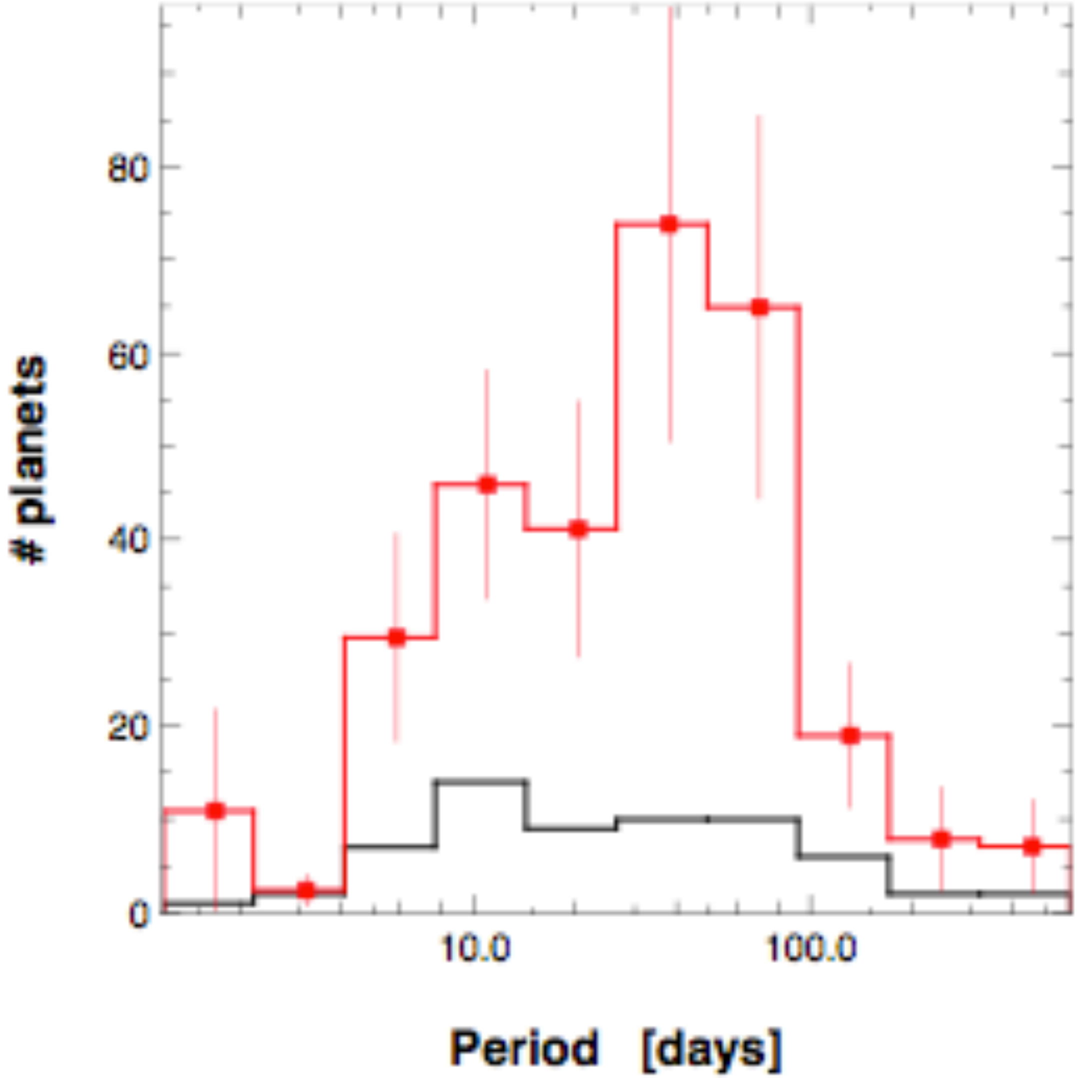
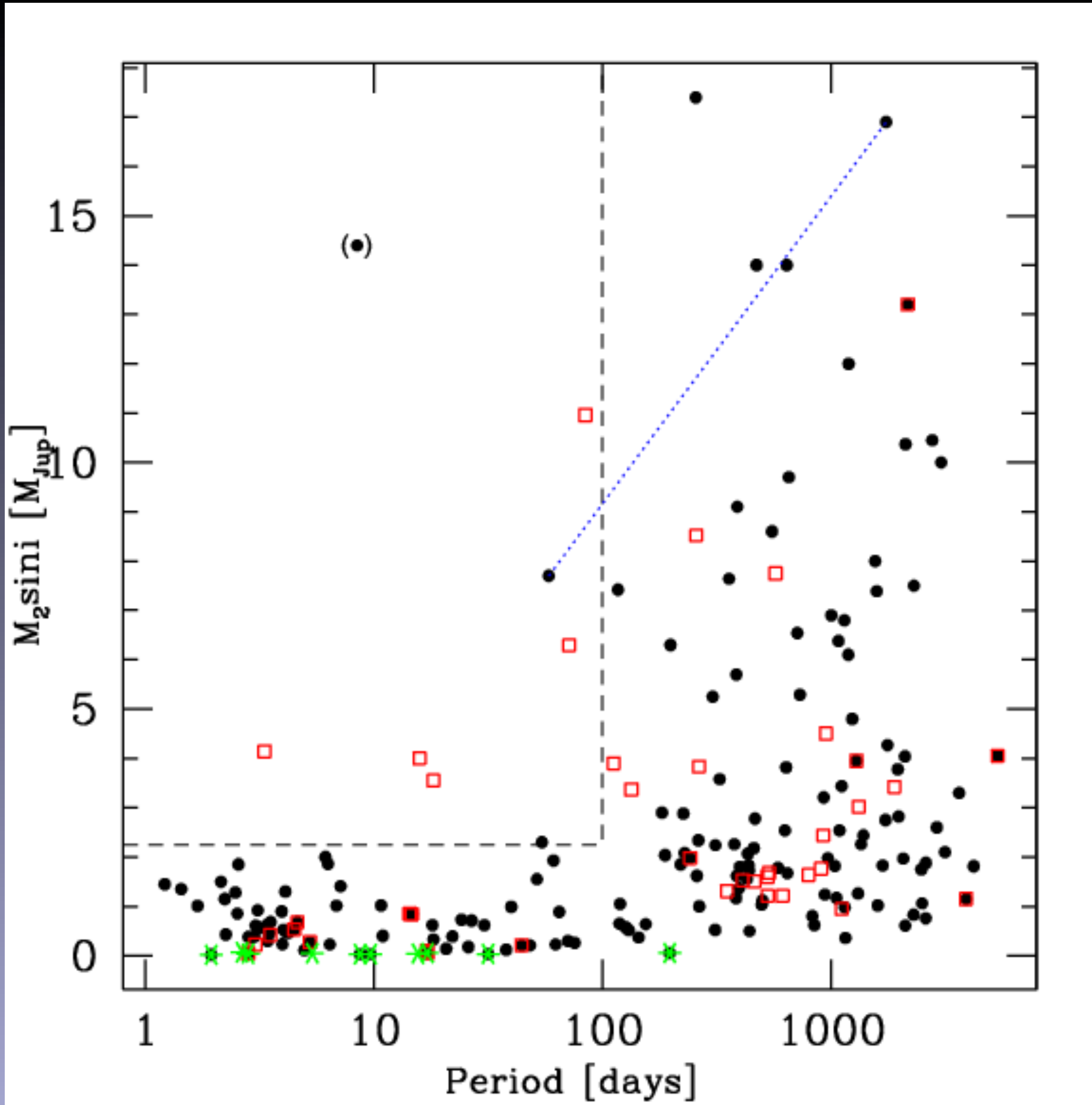


Fig. 14. Observed period distributions for low-mass planets ($m_2 \sin i < 30\,M_\oplus$) before (black histogram) and after (red histogram) correction for the detection bias. Most of the low-mass planets are confined on short period orbits. The mode of the distribution appears just over 40 days.

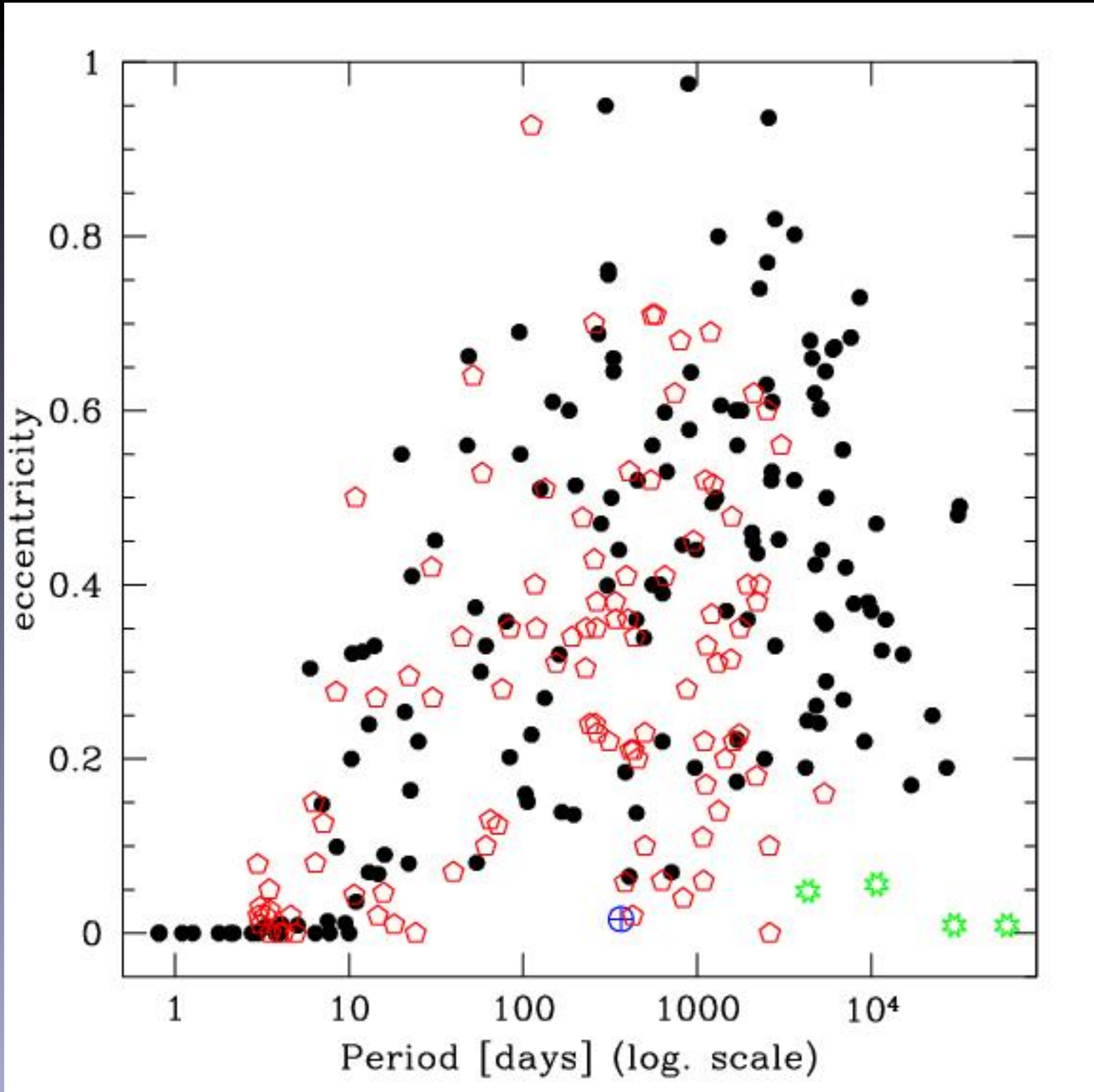
Mass-Period relation

No planets with short P and high Mass!



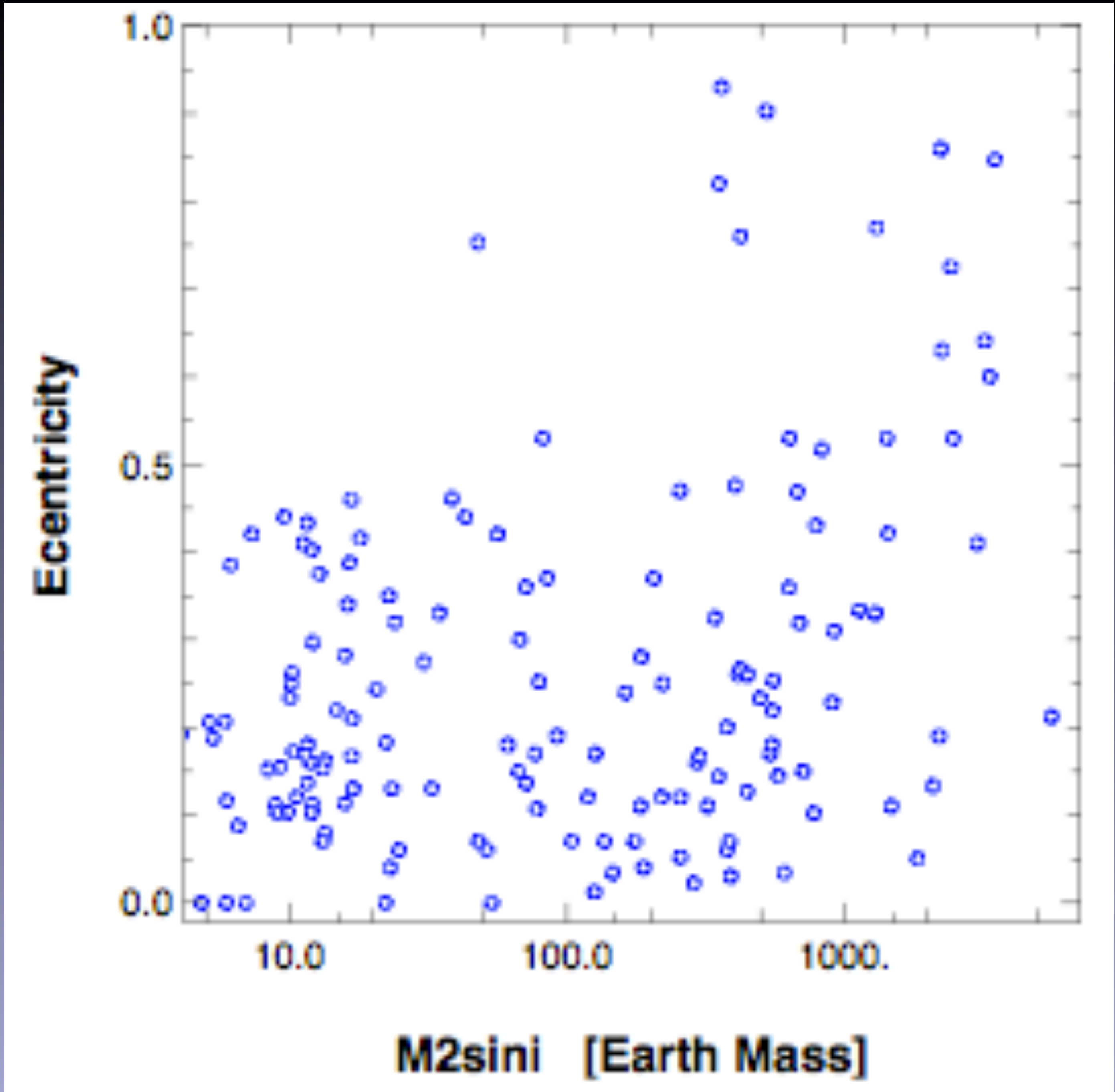
Eccentricity Distribution!

Only small difference between binary stars and planets!



Eccentricity Distribution!

Mayor et al 2012

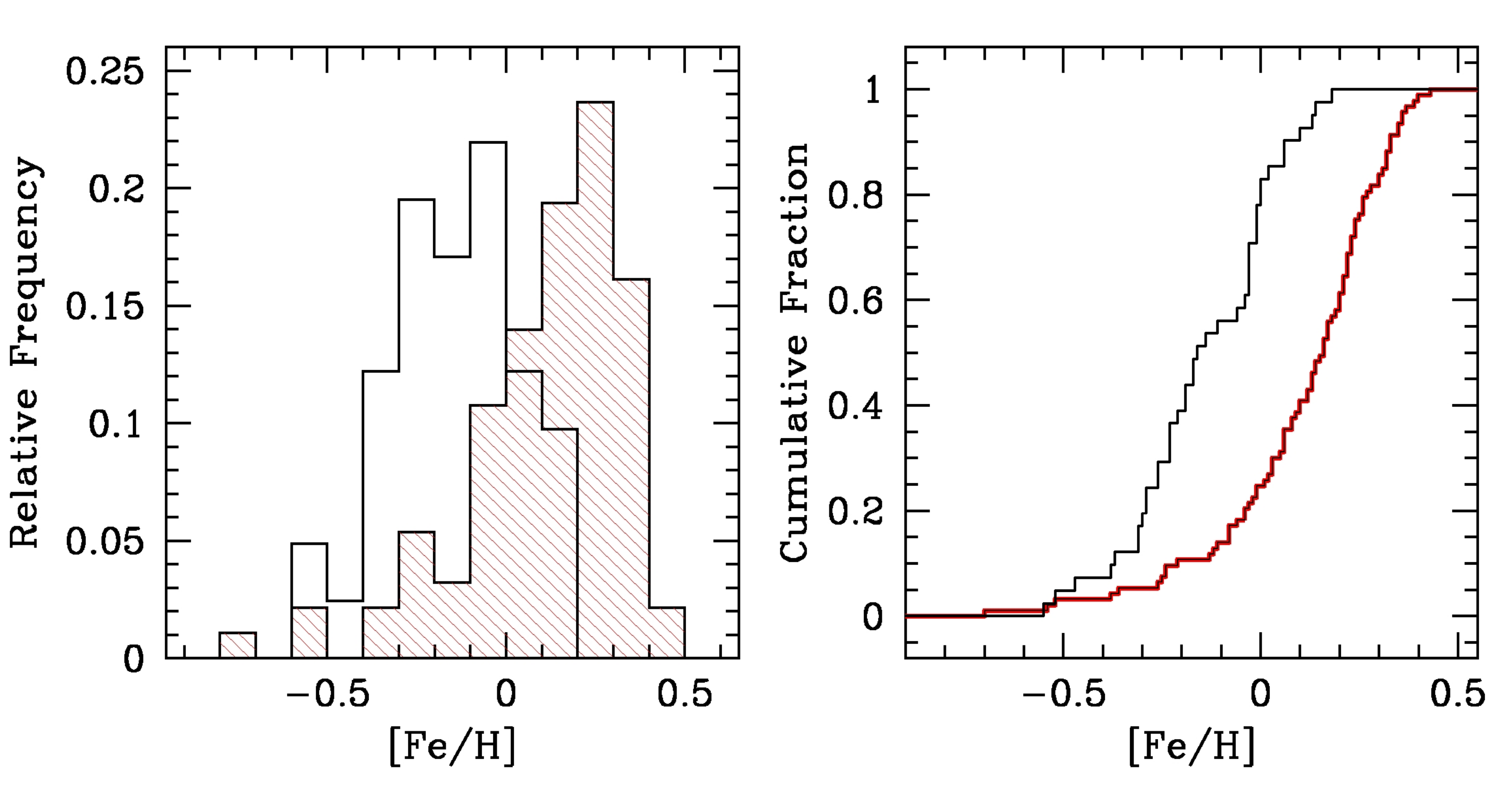


The point is...

- Mass distribution
  - Stars and planets formed by different process
  - Upper mass-limit for planet?
- Need for migration mechanisms
  - Migration is mass-dependent
  - How to stop migration?
- Eccentricity pumping mechanisms needed

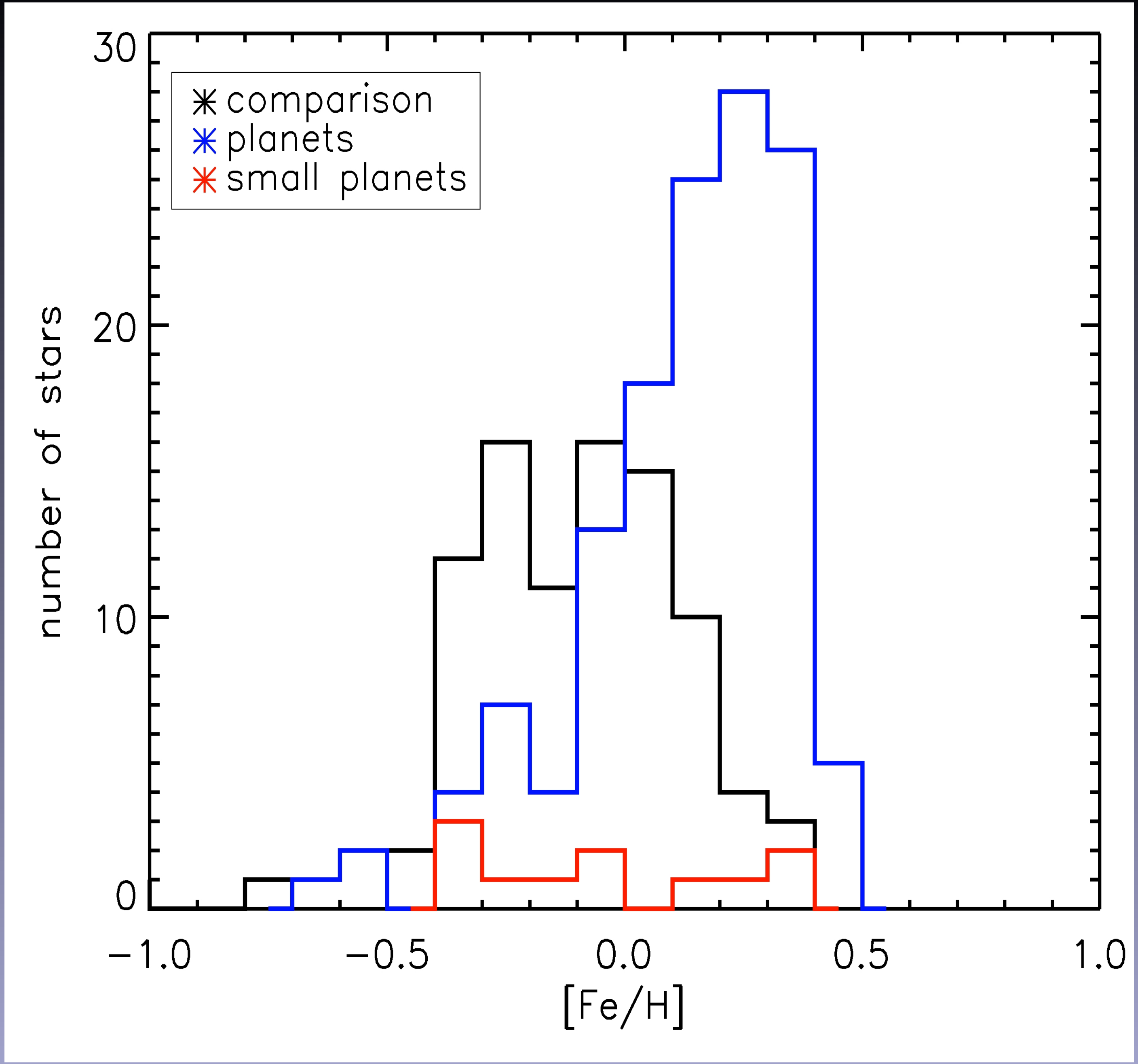
Planet frequency and stellar [Fe/H]

Santos, Israelian & Mayor (2001-2005)



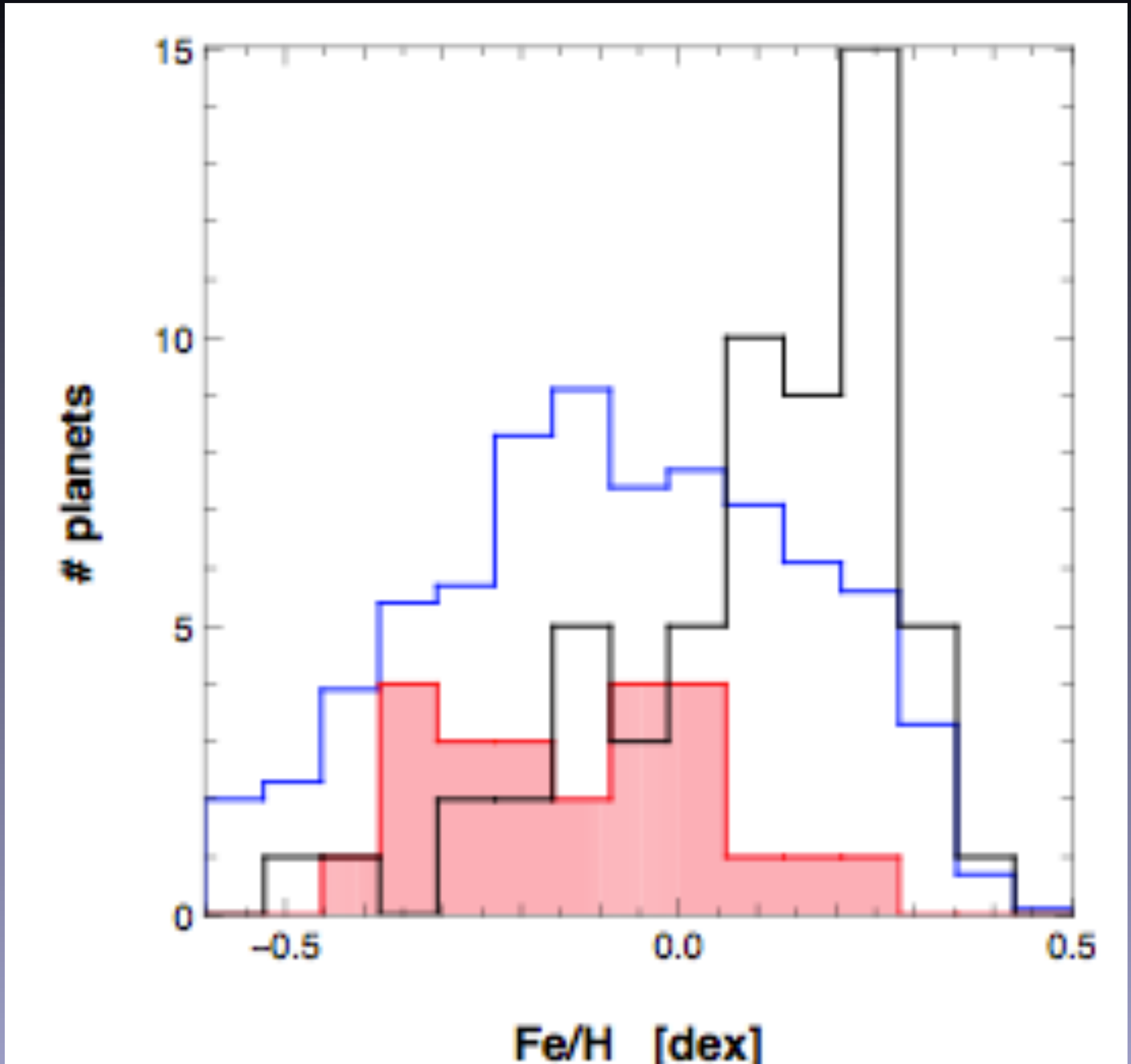
Is the same true for Neptunes?

Sousa et al 2011

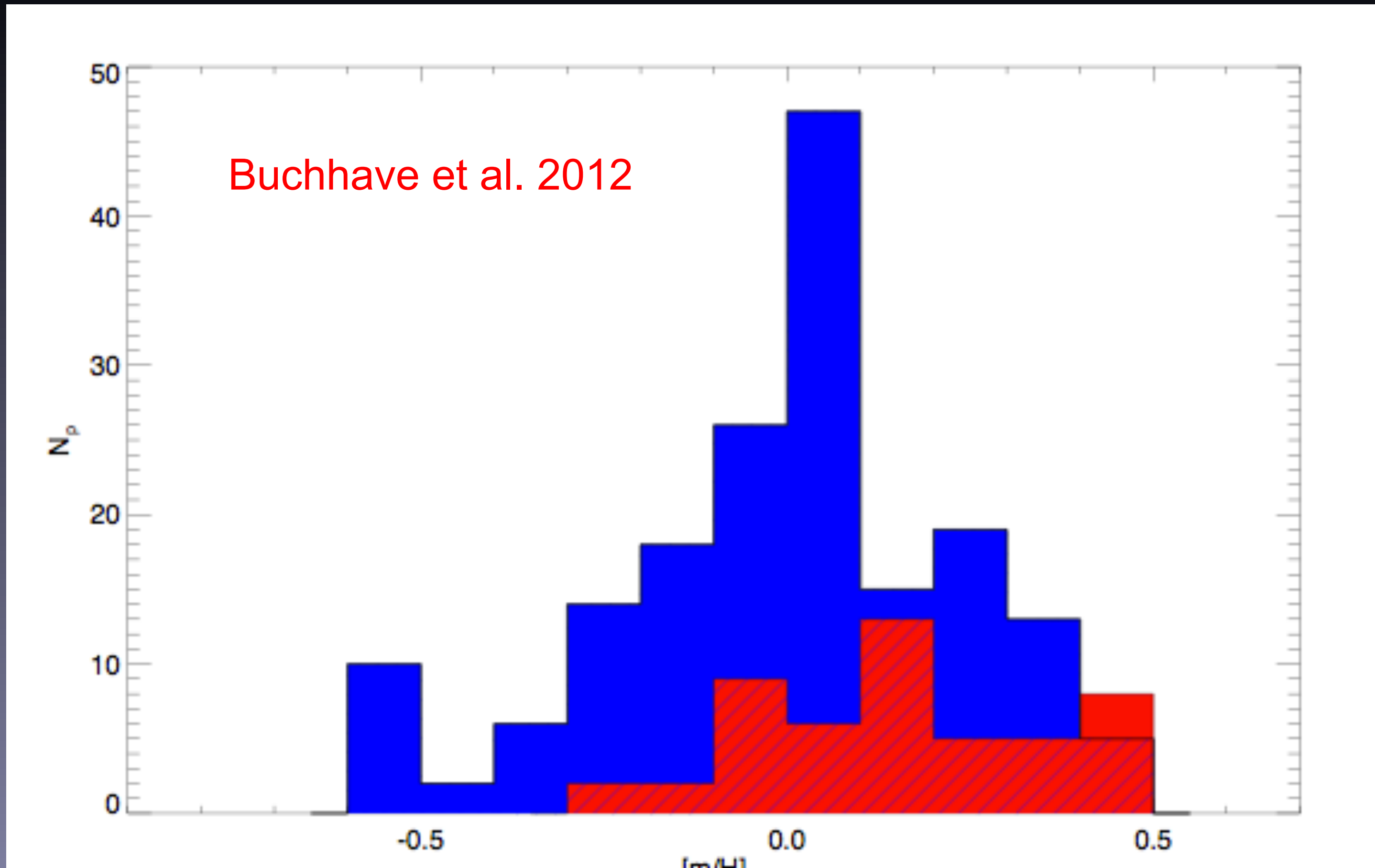


Is the same true for Neptunes?

Mayor et al 20l2



Is the same true for Earths?



Chemical Composition

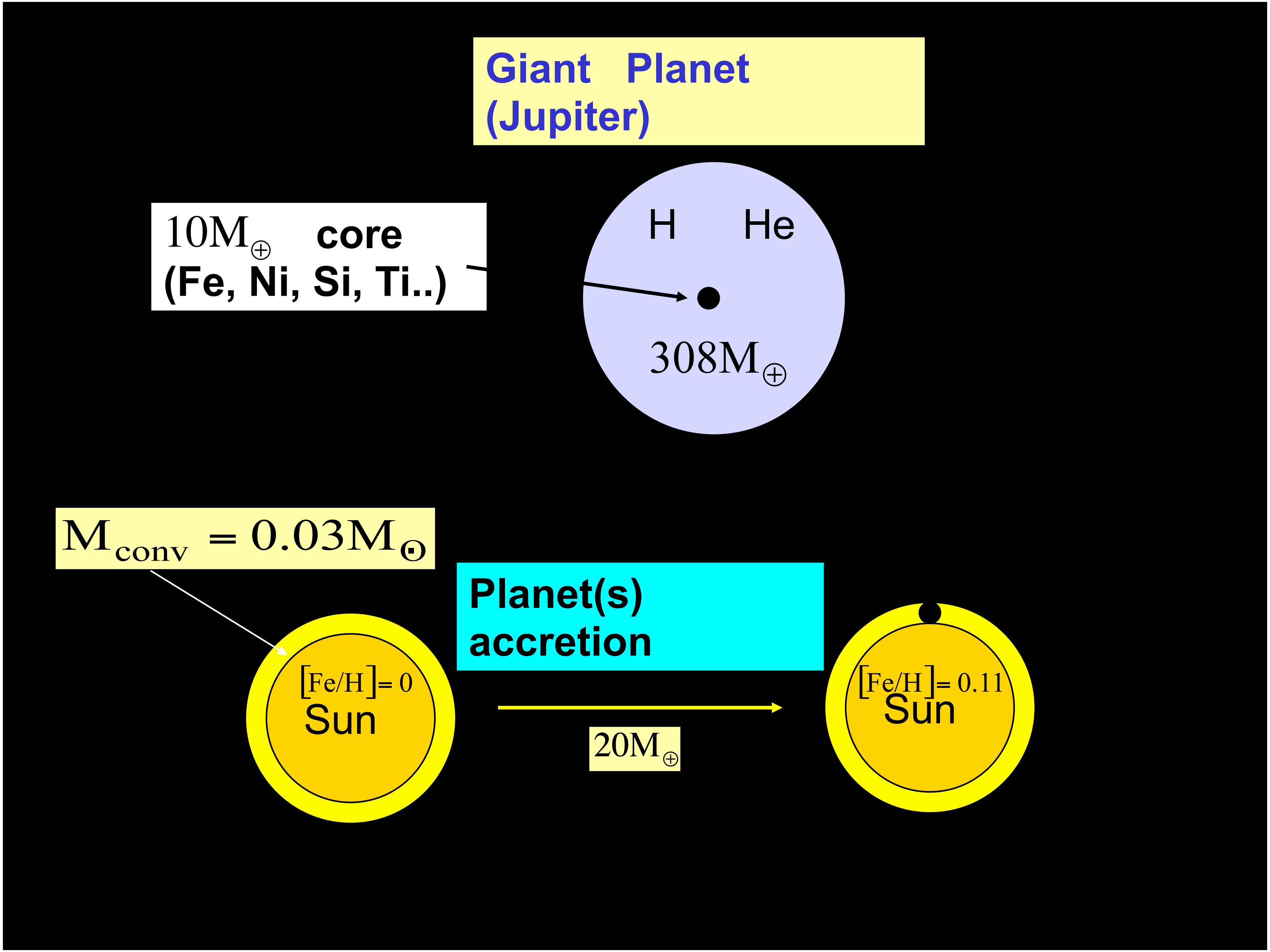
Primordial

Planet formation and stellar evolution does not modify stellar surface abundance

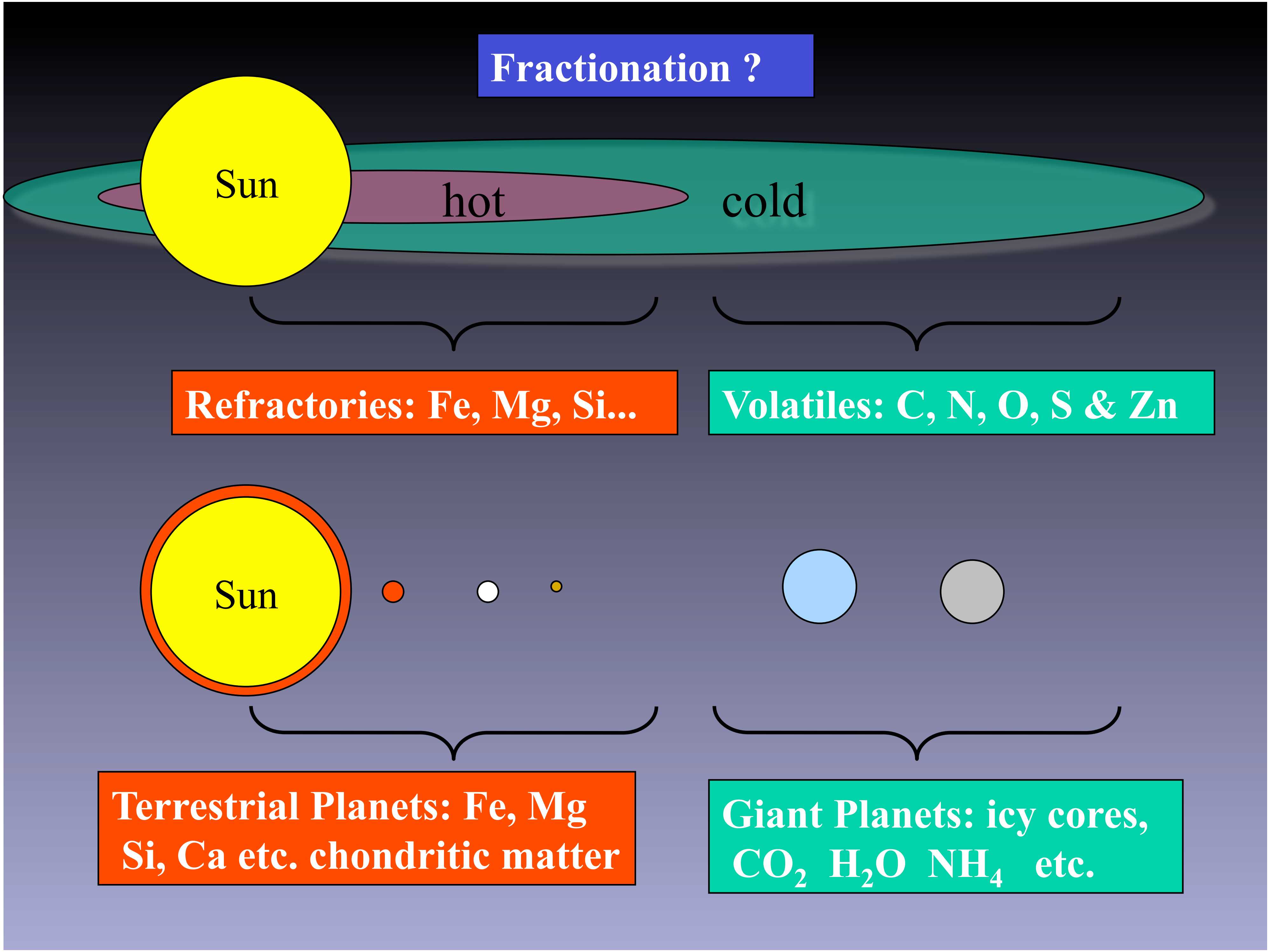
Secondary

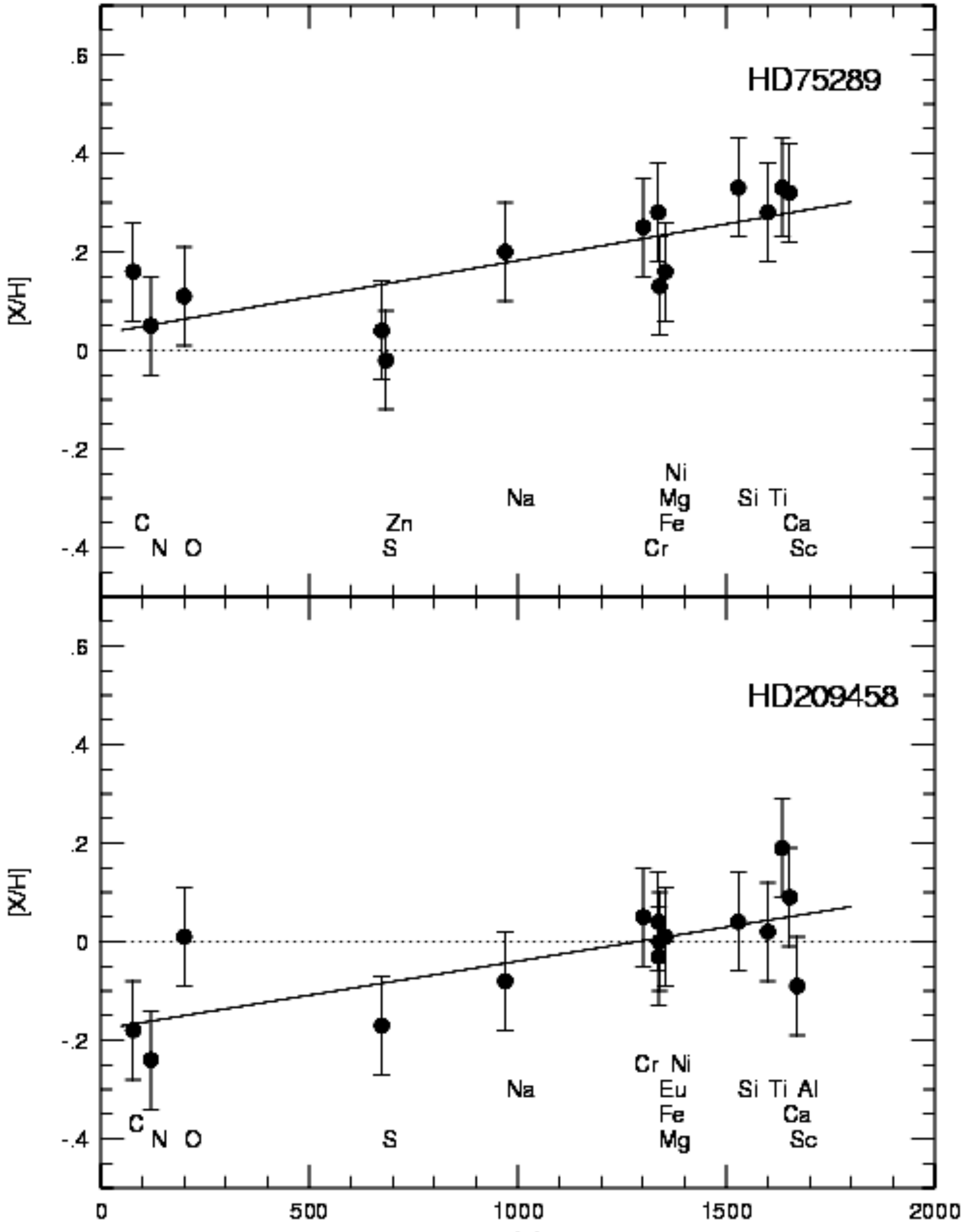
pollution

Grav. settling, etc



Giant Planet (Jupiter)
$10M_{\oplus}$ core (Fe, Ni, Si, Ti..)
H He
$308M_{\oplus}$
$M_{conv} = 0.03M_{\odot}$
Planet(s) accretion
$[Fe/H] = 0$
Sun
$20M_{\oplus}$
$[Fe/H] = 0.11$
Sun


Fractionation ?
Sun
hot
cold
Refractories: Fe, Mg, Si...
Volatiles: C, N, O, S & Zn
Sun
Terrestrial Planets: Fe, Mg
Si, Ca etc. chondritic matter
Giant Planets: icy cores,
CO_2 H_2O NH_4 etc.

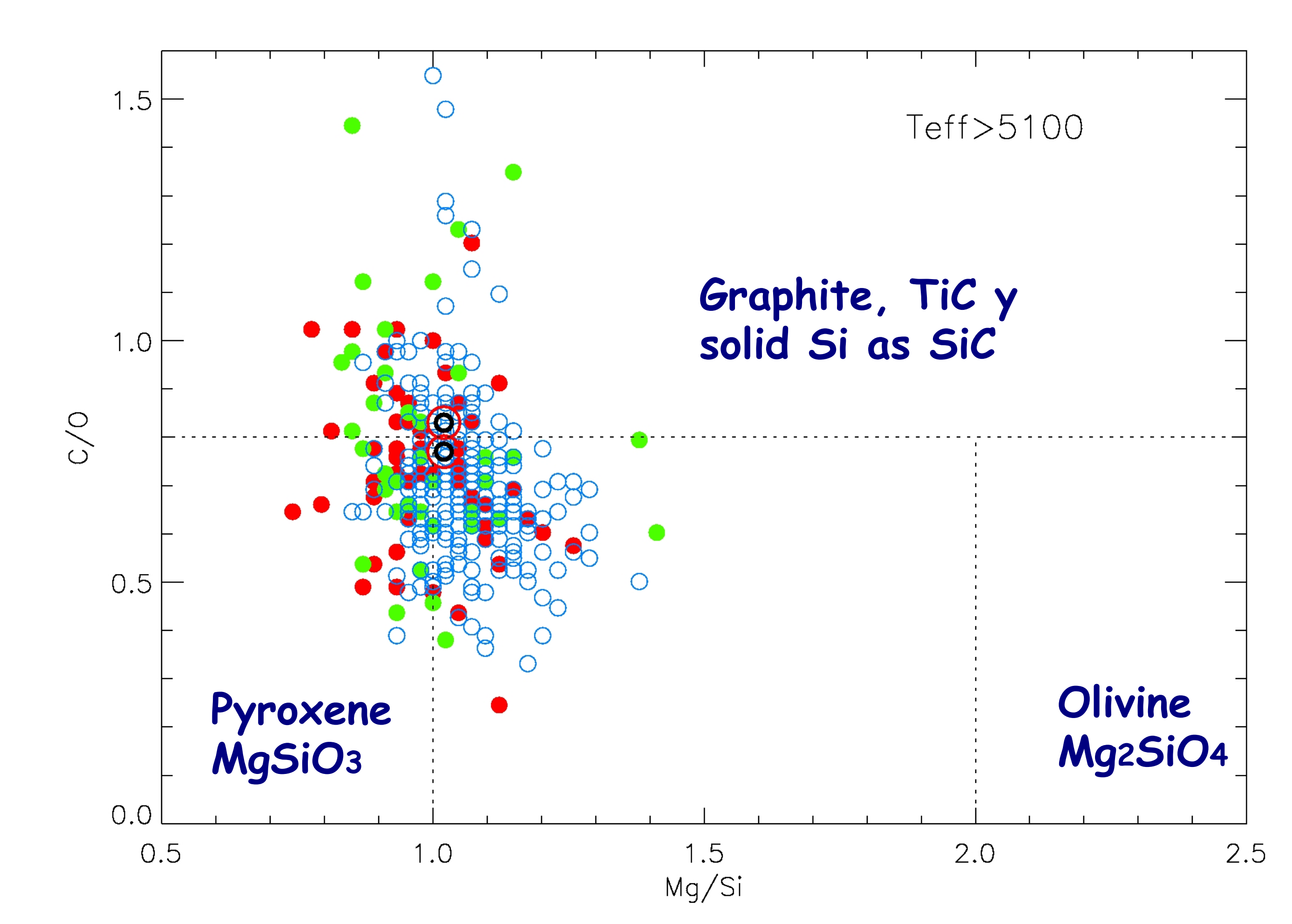


Smith et al. (2000)

Not confirmed by
Sadakane et al. (2002),
Takeda et al. (2001)

$T_c(K) \longrightarrow$ **Condensation temperature**

C/O versus Mg/Si



Mg/Si abundance ratios are larger in planet-host stars than in stars without known planets, although part of this signature is probably due to chemical evolution effects since planet-host stars are on average more metal-rich than single stars.

Delgado-Mena et al. (2010, ApJ, 725, 2349)

Light elements Li and Be

Angular momentum exchange:

Momentum locked in planets
Transfered to the star by accreted objects
Tidal effects

MS accretion of planetesimals, ingulfment of planets ^{6}Li **-test**

Flare activity (spallation reactions: Li & Be))

Light element tests

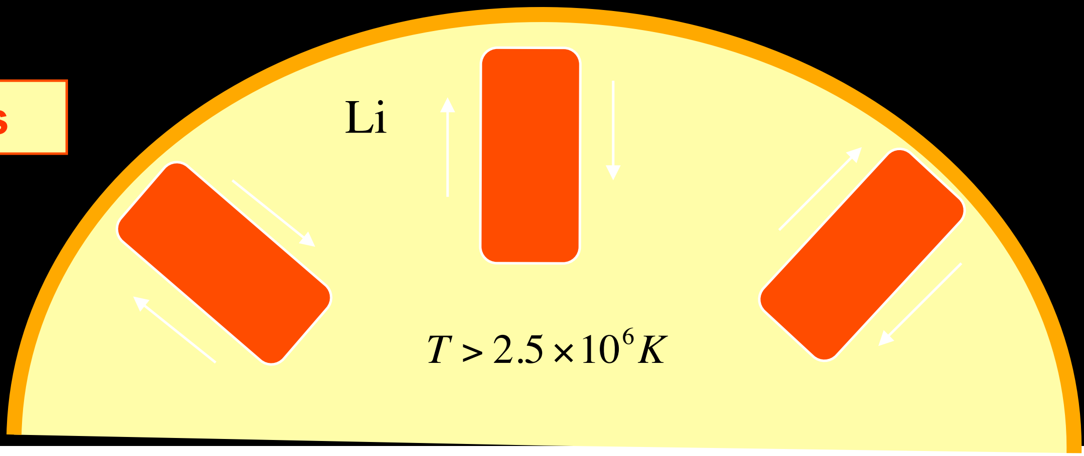
$$T > 2.5 \times 10^6 K \Rightarrow \ {}^7\mathrm{Li} \text{ is destroyed}$$
$$T < 2.5 \times 10^6 K \Rightarrow \ {}^7\mathrm{Li} \text{ is preserved}$$

$$T > 2.0 \times 10^6 K \Rightarrow \ {}^6\mathrm{Li} \text{ is destroyed}$$
$$T < 2.0 \times 10^6 K \Rightarrow \ {}^6\mathrm{Li} \text{ is preserved}$$

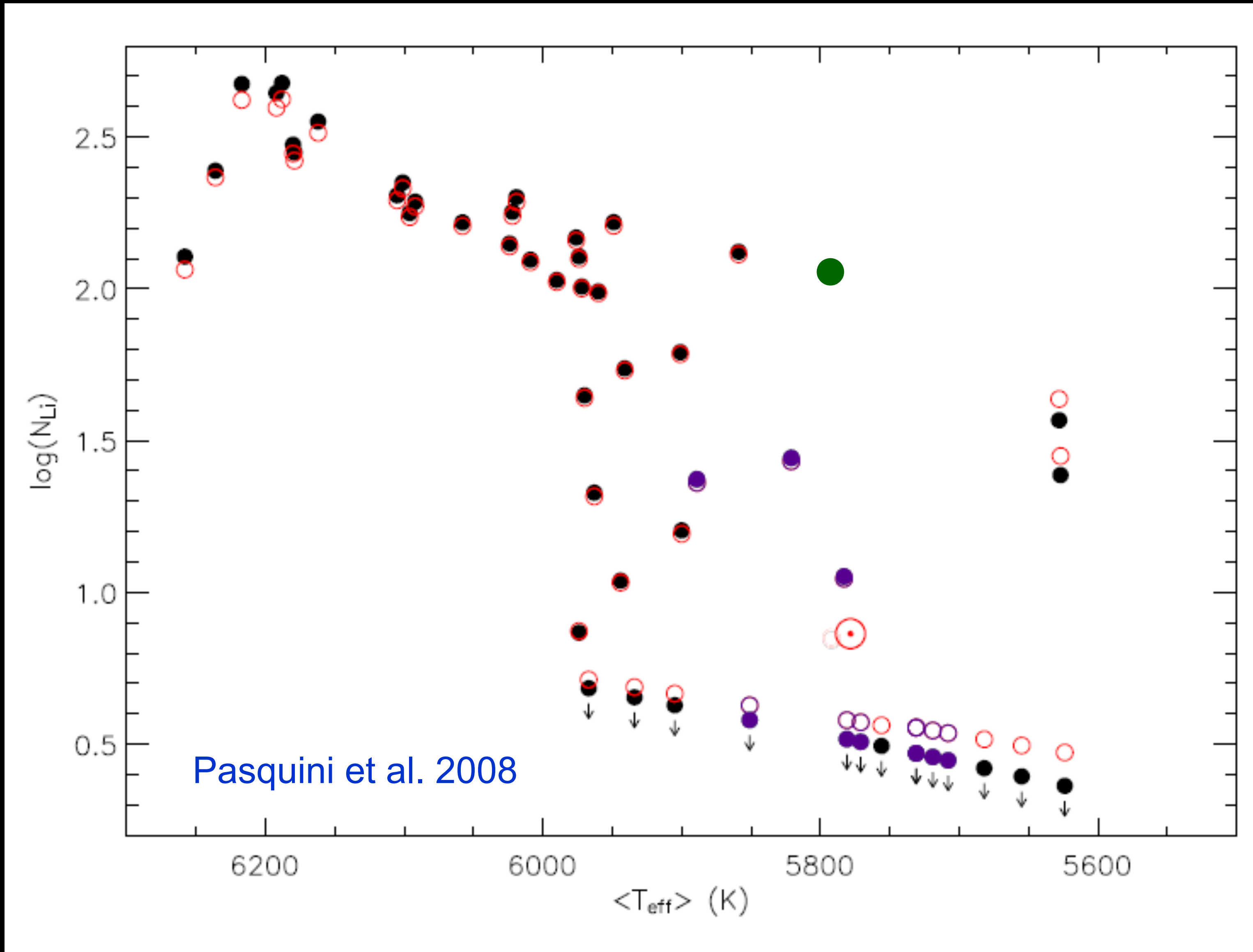
$$T > 3.0 \times 10^6 K \Rightarrow \ \mathrm{Be} \text{ is destroyed}$$
$$T < 3.0 \times 10^6 K \Rightarrow \ \mathrm{Be} \text{ is preserved}$$

$$T > 3.5 \times 10^6 K \Rightarrow \mathrm{B} \text{ is destroyed}$$
$$T < 3.5 \times 10^6 K \Rightarrow \mathrm{B} \text{ is preserved}$$

Convective cells



M67 open cluster

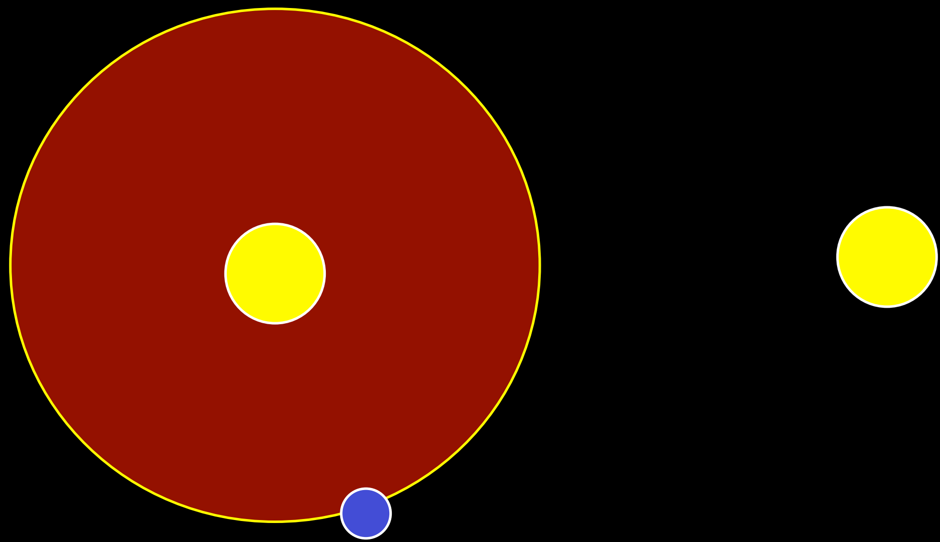


It is possible, in principle anyway, that the low Li abundances of the Sun and 16 Cyg B with respect to 16 Cyg A may be related to the presence of planetary companion. Li abundances of 47 UMa, and HD114762 might further support such a connection between planets/disks, angular momentum evolution, and photospheric Li abundance.

King et al. (AJ, 113, 1871, 1997)

16 Cyg B

Log Li ~ 0.6



16 Cyg A

Log Li ~ 1.3

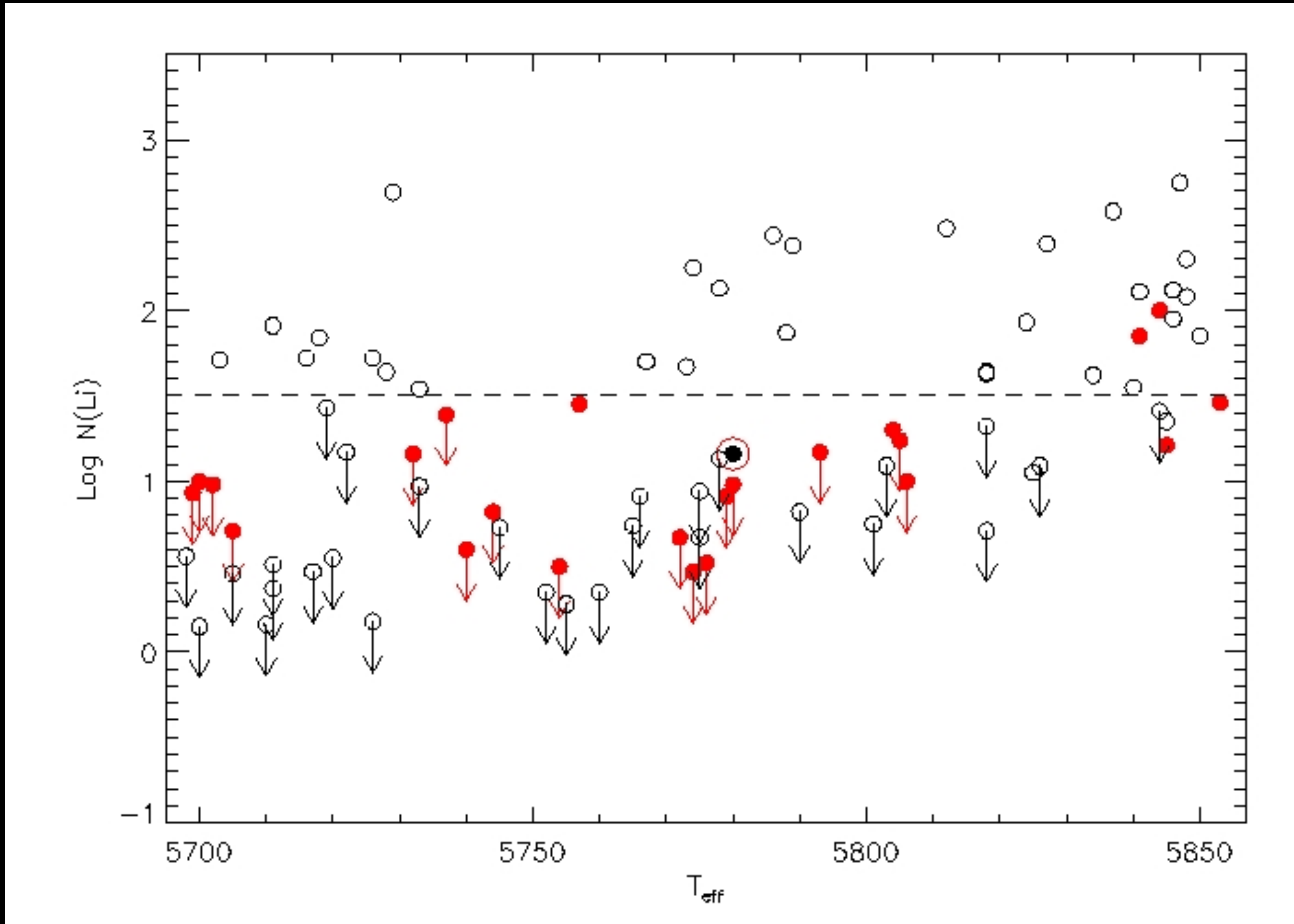
YES or NO

Gonzalez & Laws (2000)	yes
Ryan (2000)	no
Israelian et al. (2004)	yes
Takeda & Kawanomoto (2005)	yes
Chen & Zhao (2006)	yes
Luck & Heiter (2006)	no
Takeda et al. (2007)	yes
Gonzalez (2008)	yes

YES or NO

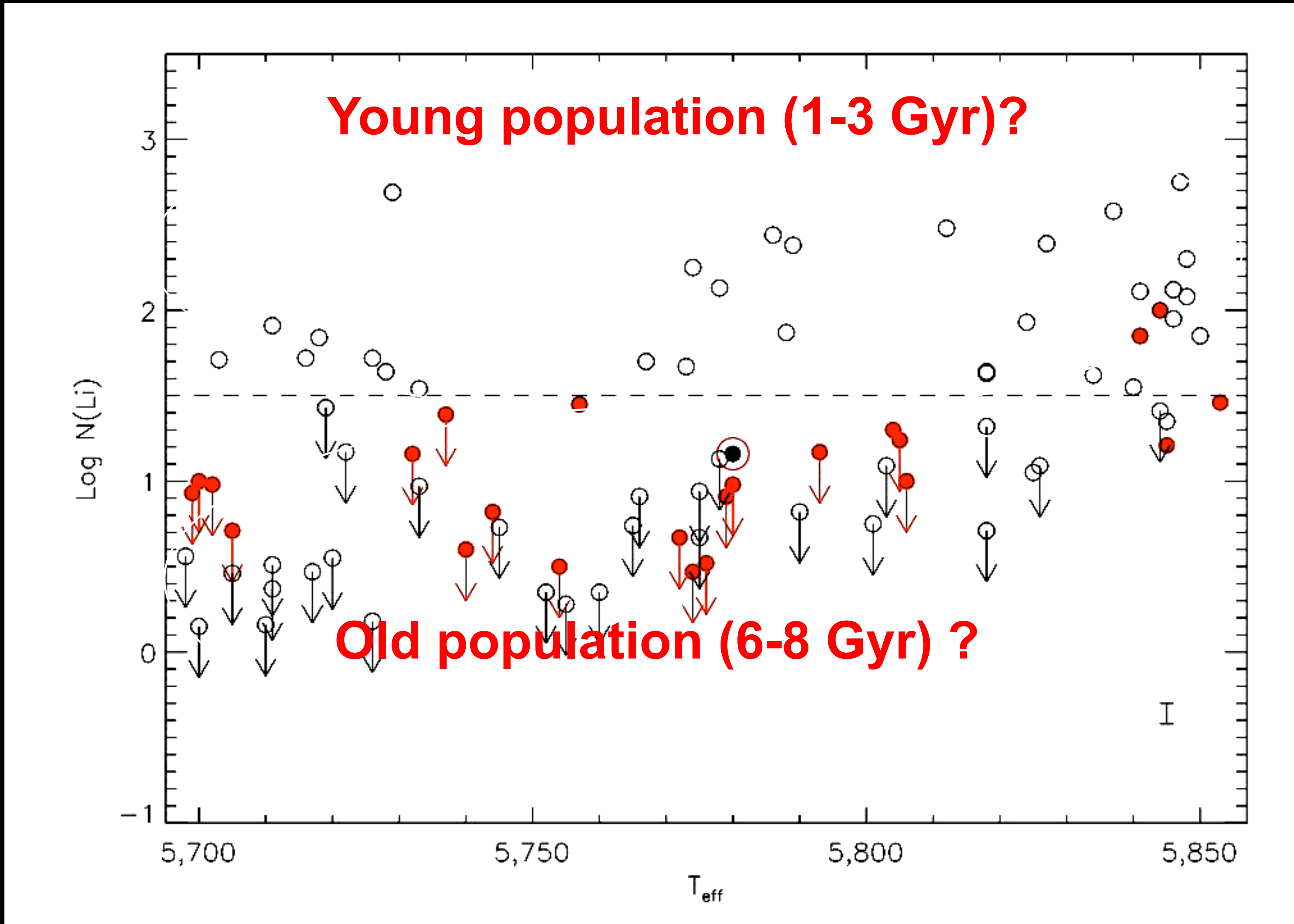
Israelian et al. (2009)	yes
Gonzalez (2010)	yes
Takeda et al. (2010)	yes
Baumann et al (2010)	no
Ghezzi et al. (2010)	no
Sousa et al. (2010)	yes
Delgado Mena et al. (2011)	yes

Li versus T_{eff}

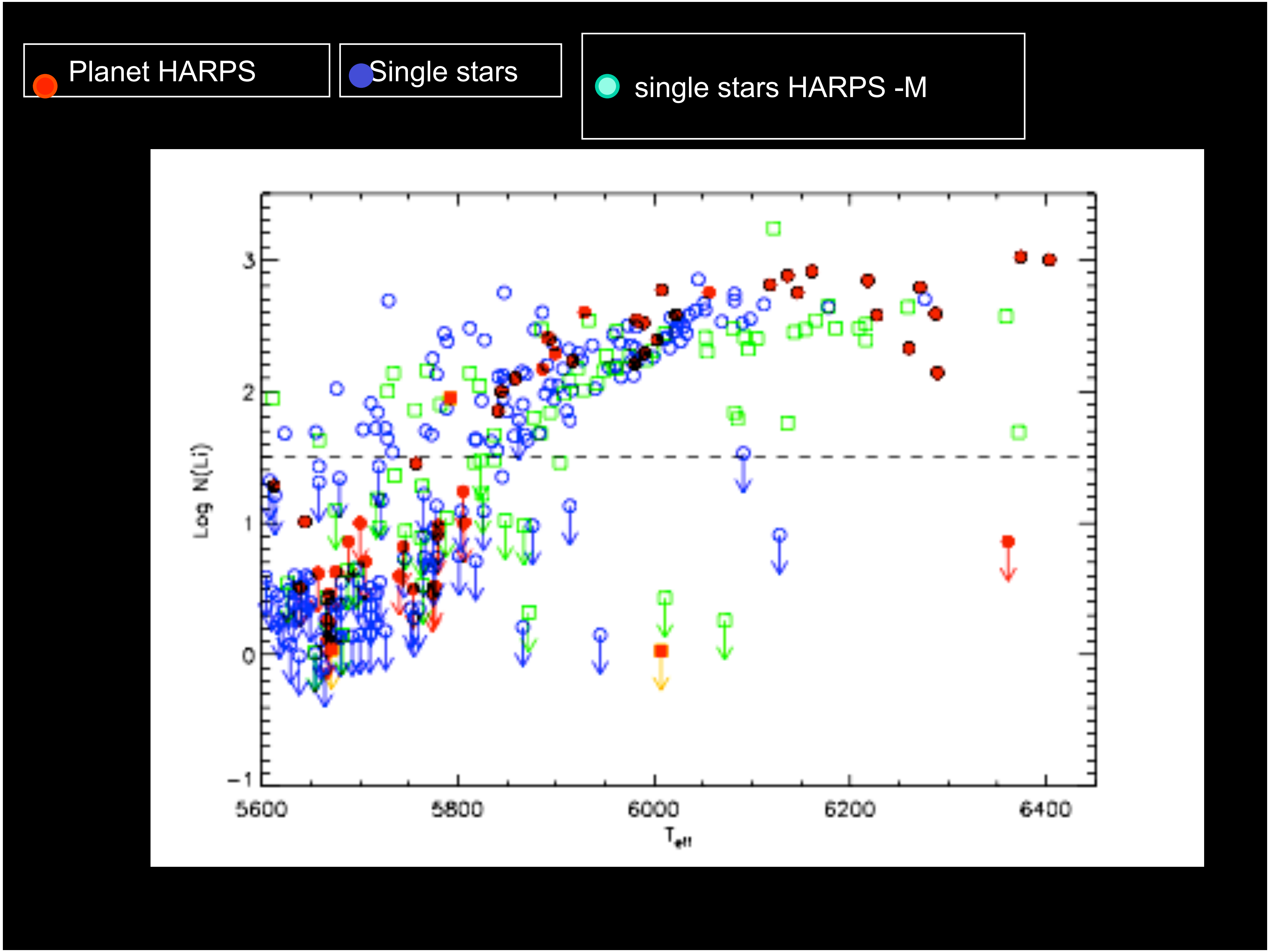


Li abundances for 23 planet-host stars and 60 stars without planets from HARPS GTO program and CORALIE program

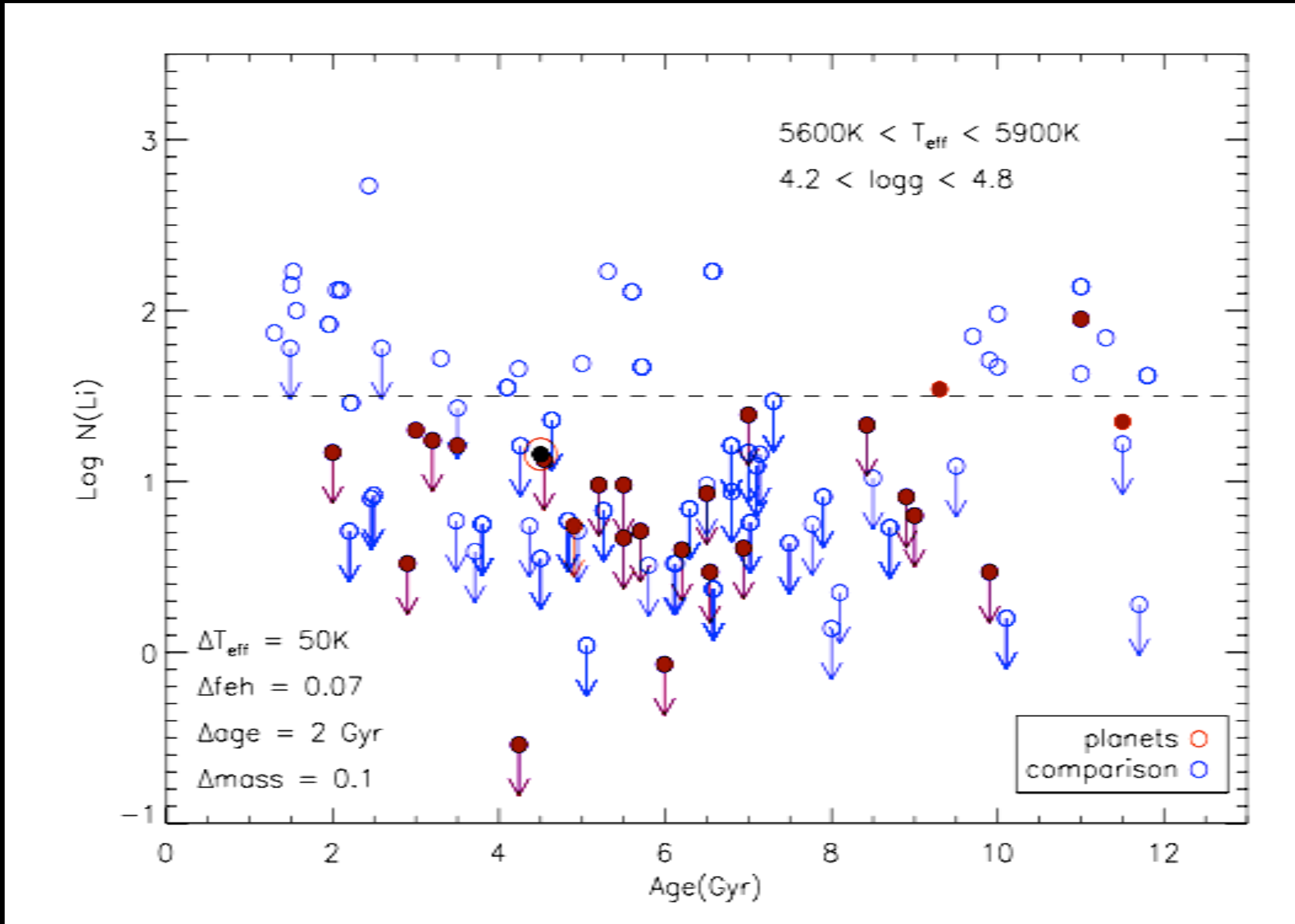
Israelian et al. (2009, Nature, 462, 189)

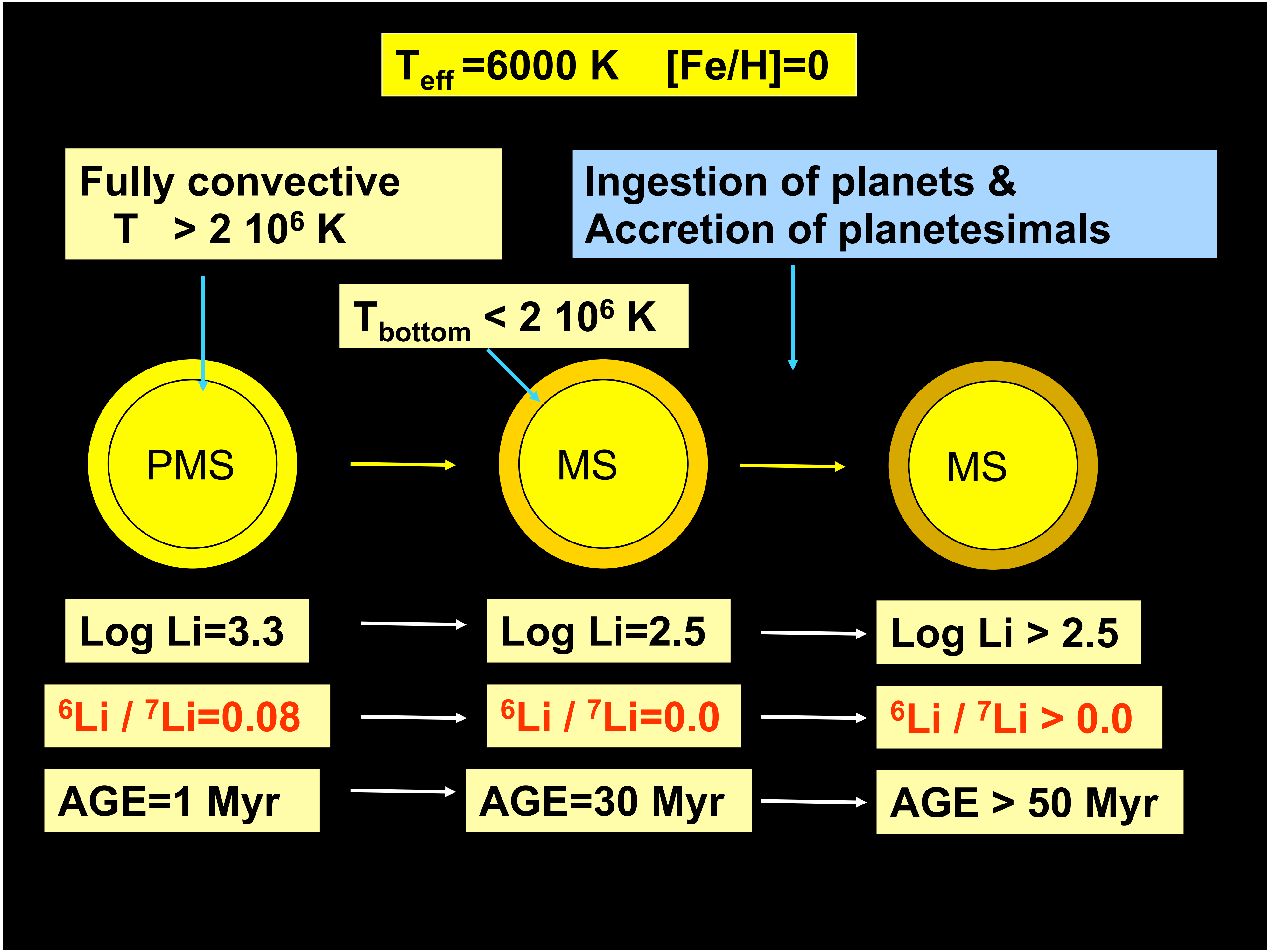


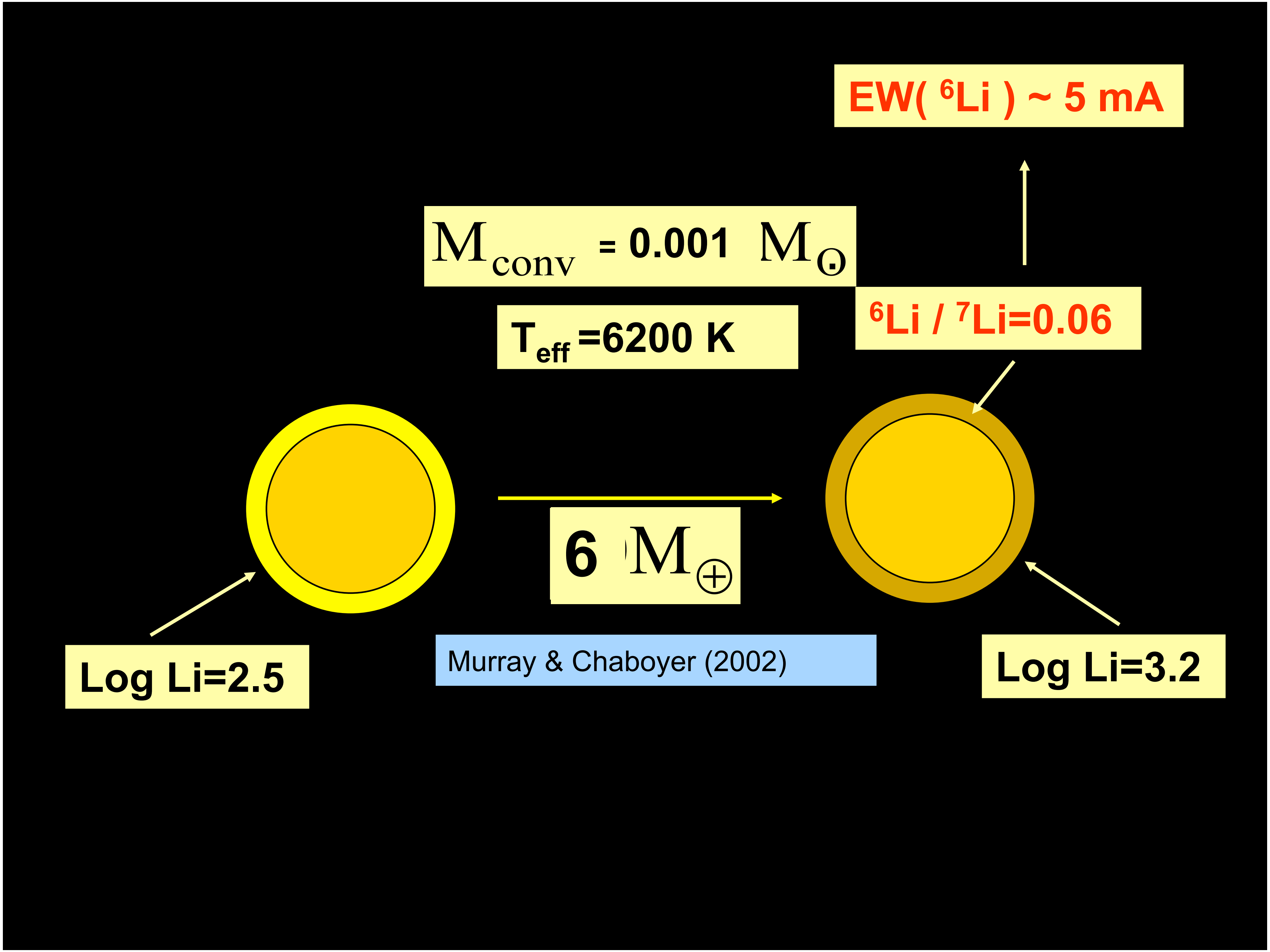
Age effect/bias ?



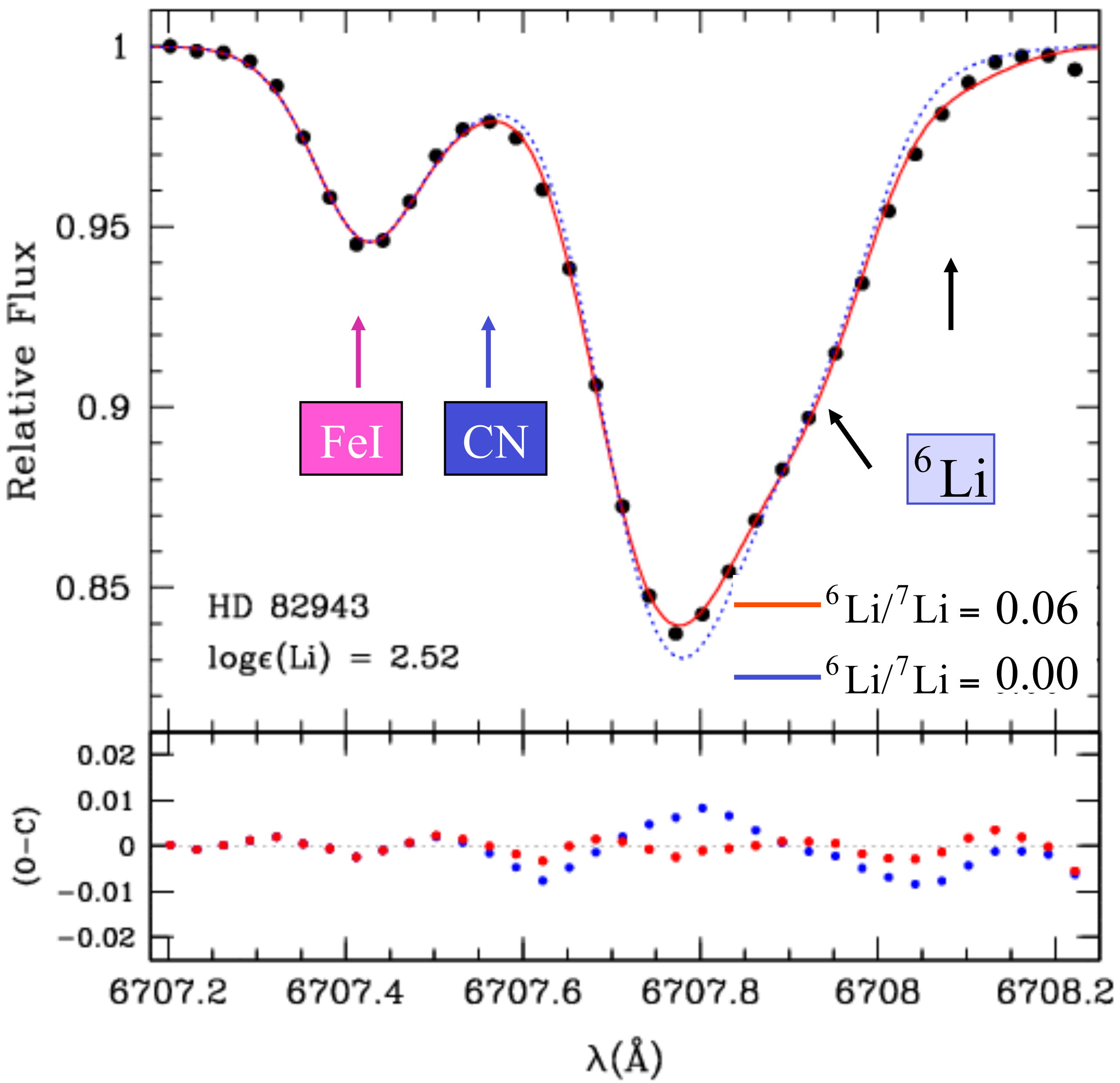
Planet HARPS
Single stars
single stars HARPS -M
Log N(Li)
3
2
1
0
−1
5600
5800
6000
6200
6400
T_eff


5600K < T_{eff} < 5900K
4.2 < logg < 4.8
ΔT_{eff} = 50K
Δfeh = 0.07
Δage = 2 Gyr
Δmass = 0.1
planets
comparison
Log N(Li)
Age(Gyr)


T_{eff} =6000 K [Fe/H]=0
Fully convective
T > 2 10^6 K
Ingestion of planets &
Accretion of planetesimals
T_{bottom} < 2 10^6 K
PMS
MS
MS
Log Li=3.3
Log Li=2.5
Log Li > 2.5
^{6}Li / ^{7}Li=0.08
^{6}Li / ^{7}Li=0.0
^{6}Li / ^{7}Li > 0.0
AGE=1 Myr
AGE=30 Myr
AGE > 50 Myr


EW(^{6}Li) ~ 5 mA
M_{conv} = 0.001 $M_\odot$
^{6}Li / ^{7}Li=0.06
T_{eff} =6200 K
6 $M_\oplus$
Log Li=2.5
Murray & Chaboyer (2002)
Log Li=3.2

HD 82943 Israelian et al. (Nature, 2001)



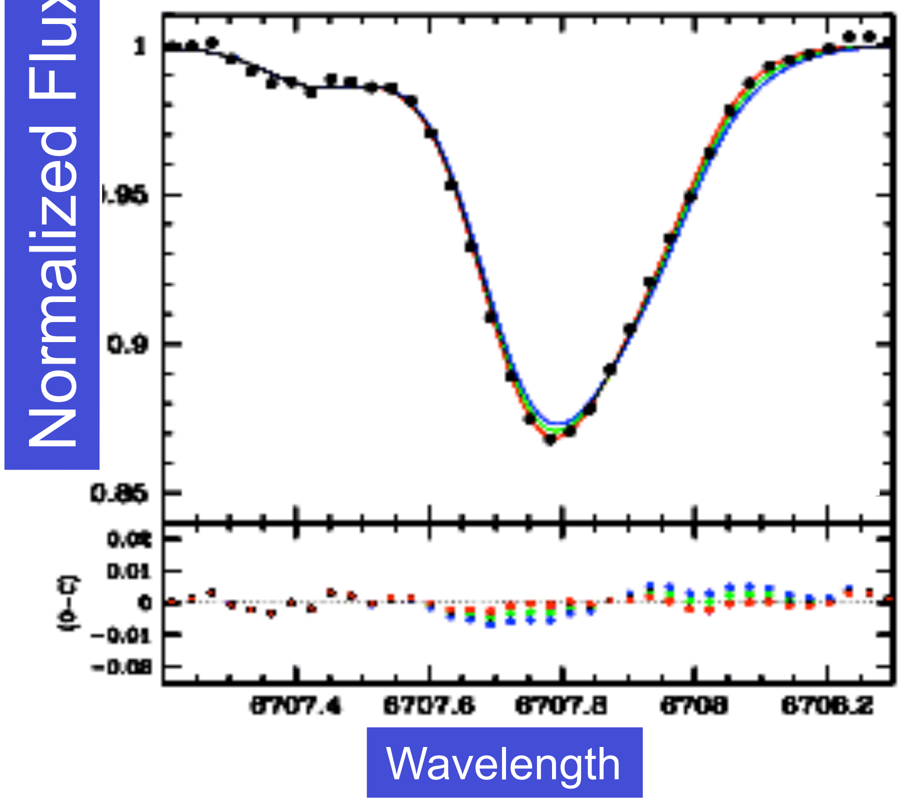
HD 91889

$\log\varepsilon(\mathrm{Li}) = 2.52$

$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.06$

$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.03$

$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.00$

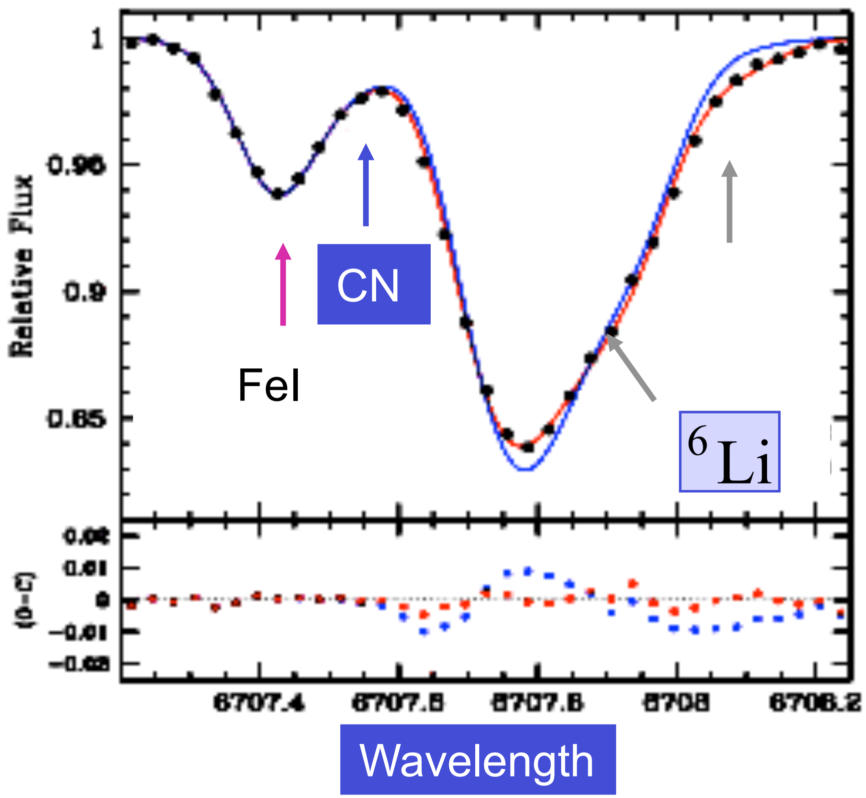


HD 82943

$\log\varepsilon(\mathrm{Li}) = 2.51$

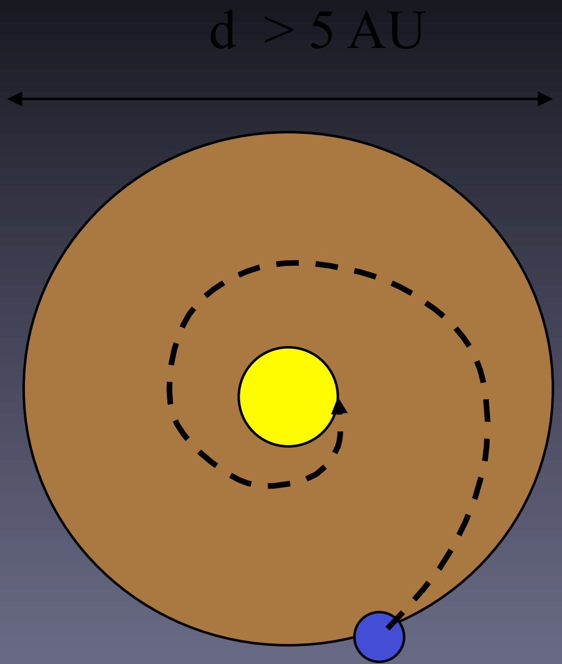
$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.12$

$^{6}\mathrm{Li}/^{7}\mathrm{Li} = 0.00$



The Li6-test (Israelian et al. Nature, 411, 163, 2001)

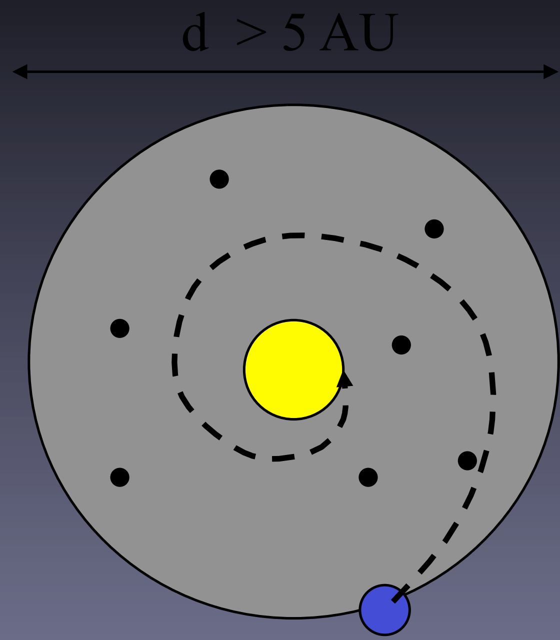
Planetary migration



Time-scale ~ 10-20 Myr

Dense gas/dust accretion disk
drag effect, torque etc

Planetary migration: dynamical friction



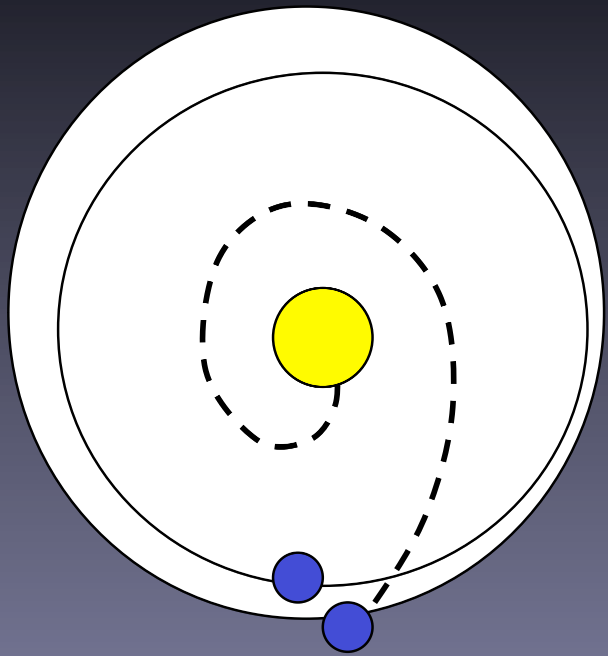
Time-scale: up to 1 Gyr

planetesimals

NO gas

$$0.0001M_{sun} < M_{disk} < 0.1M_{sun}$$

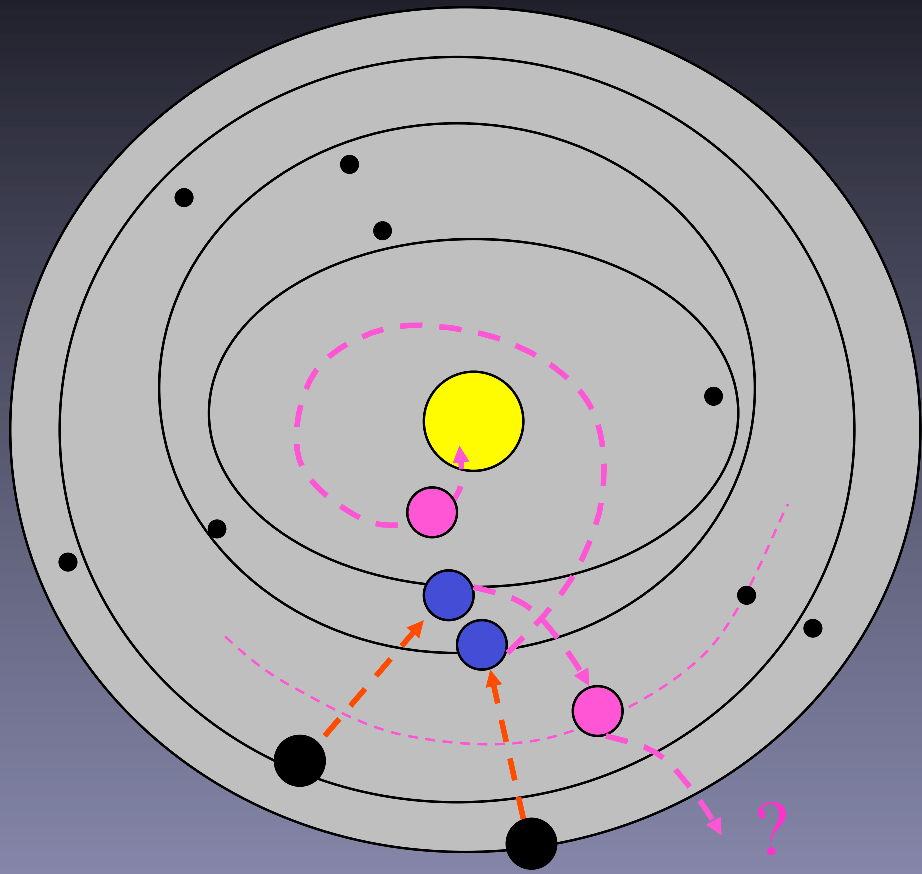
Multi-body interactions: no gas/dust, no planetesimals



Time-scale: up to 100 Myr

Few large planets, orbital radii evolve at different rates.

Multi-body interactions & planetesimals disk



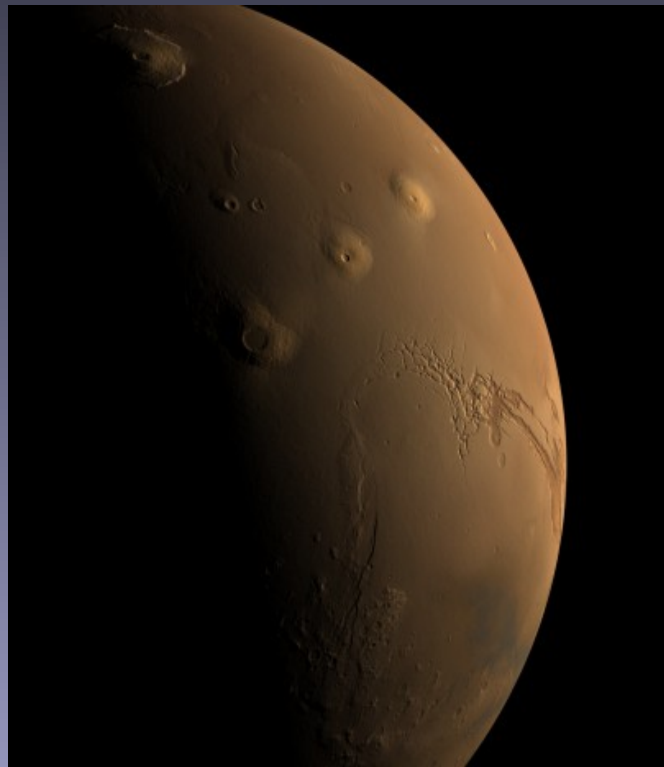
Time-scale: up to 1 Gyr or more

No accretion disk, dust & gas

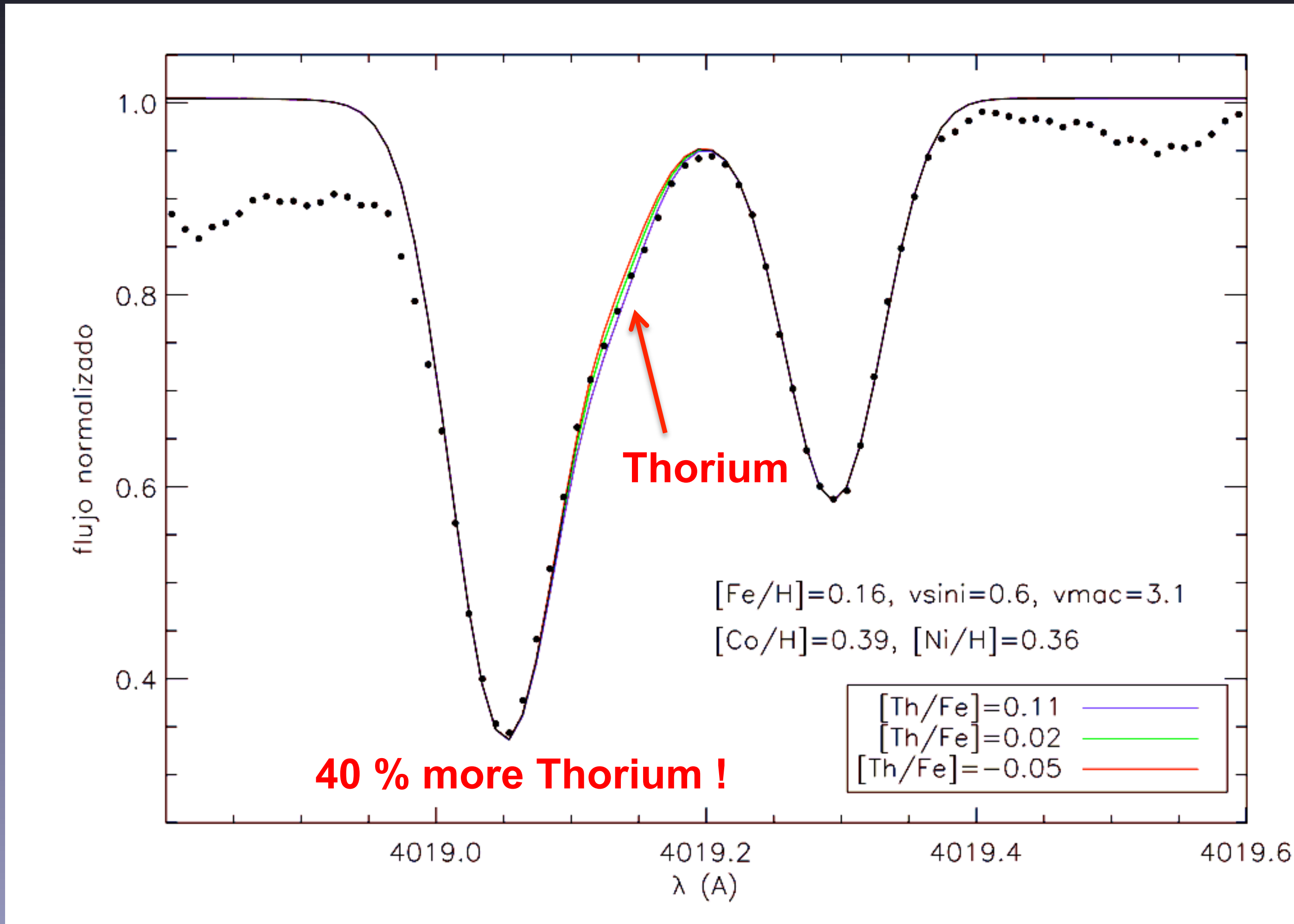
only planetesimals

Tectonic & Volcanic activity

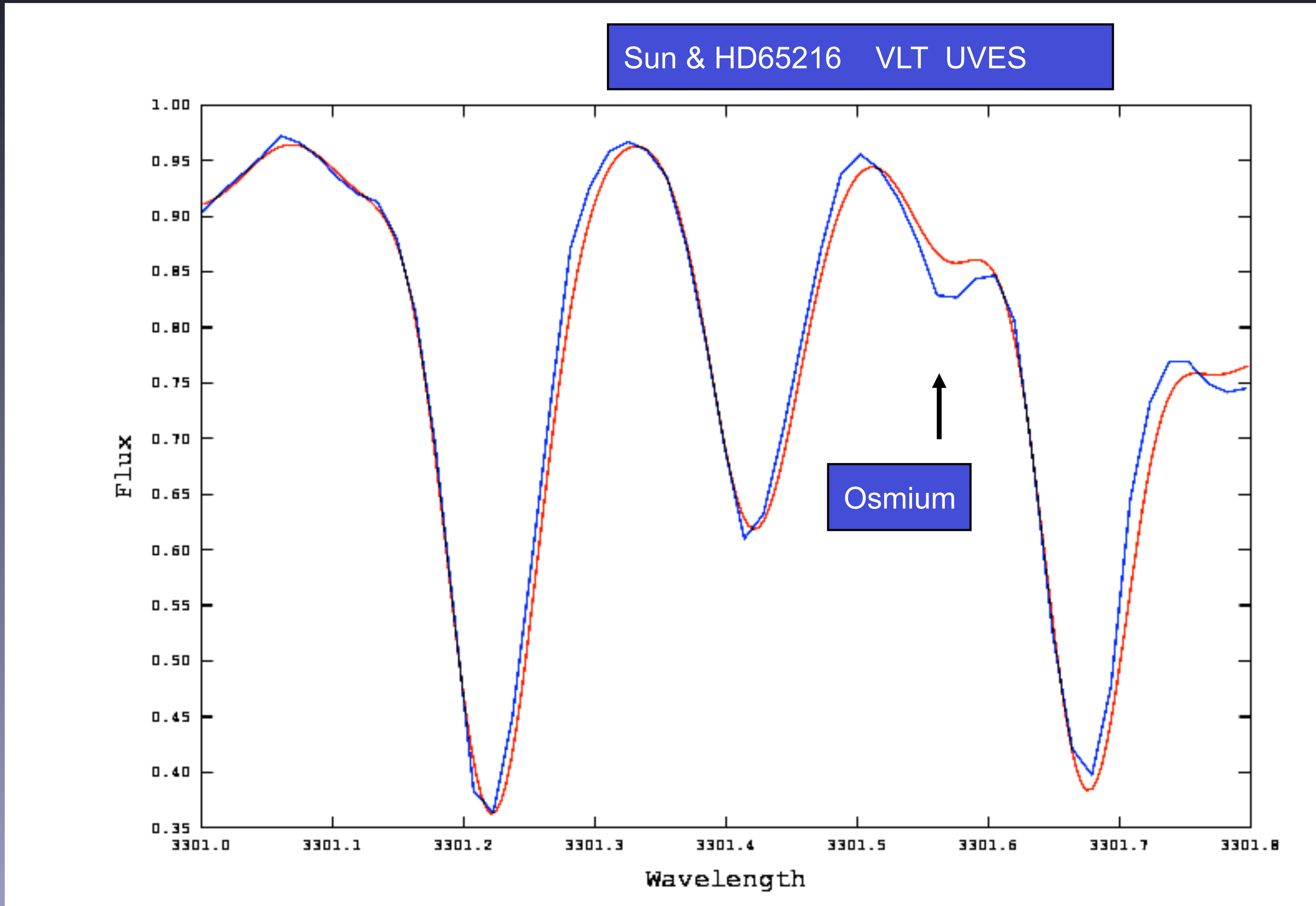
Is there enough Th, U and K ?



HD115585
Sun like star with a planetary system

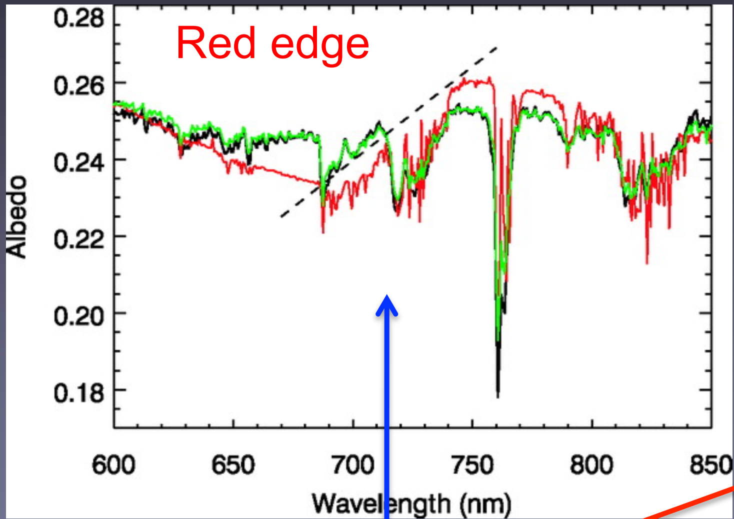


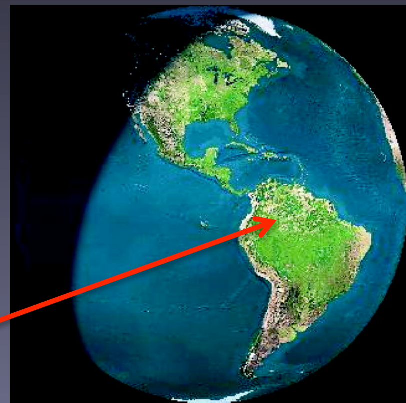
No planets and no life without SUPERNOVAE



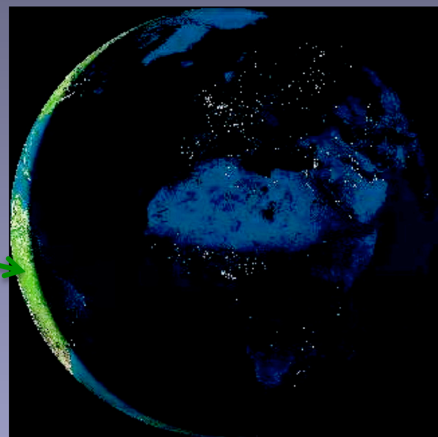
Biomarkers !

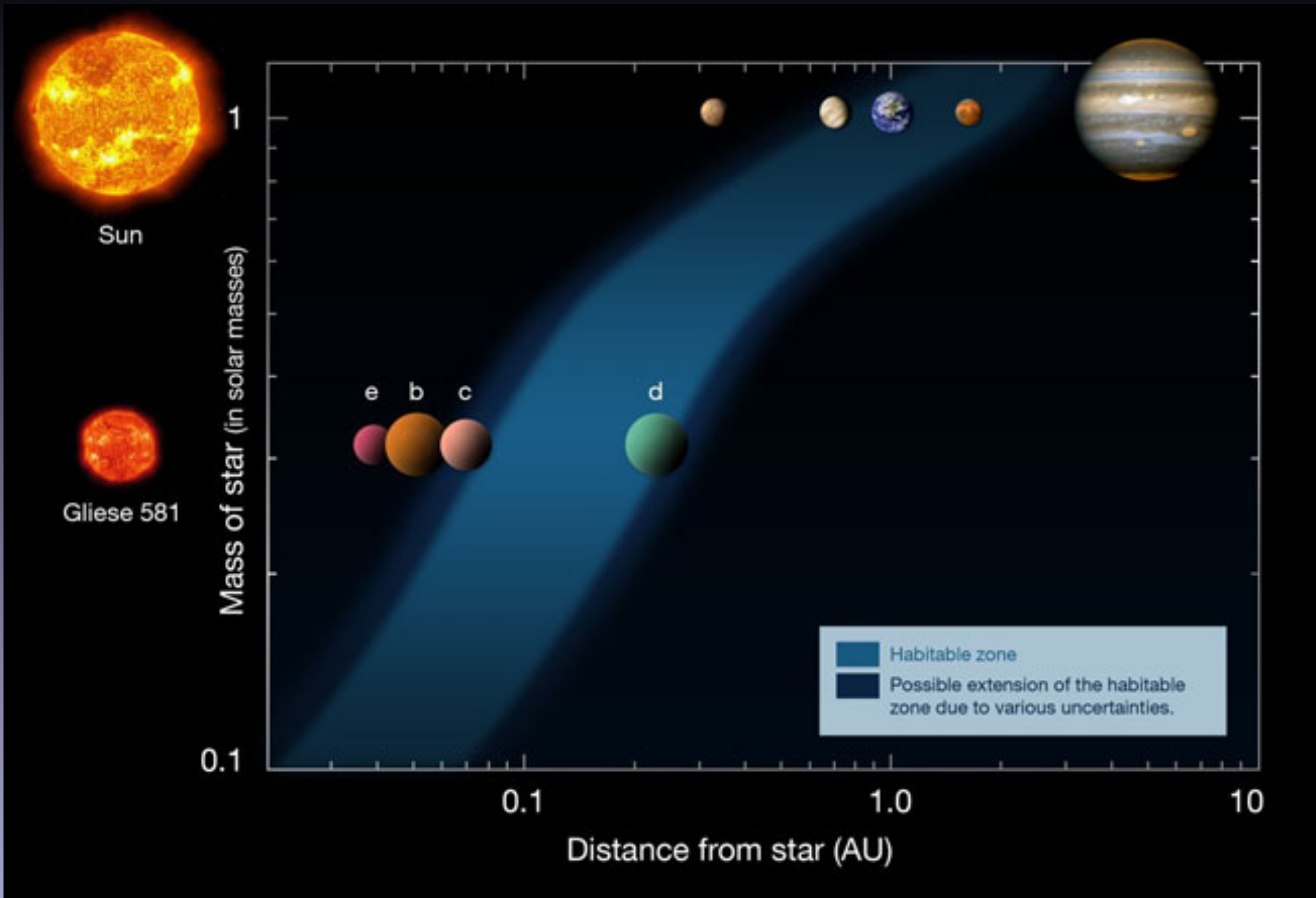
Earthshine spectrum





Cloud free vegetated area

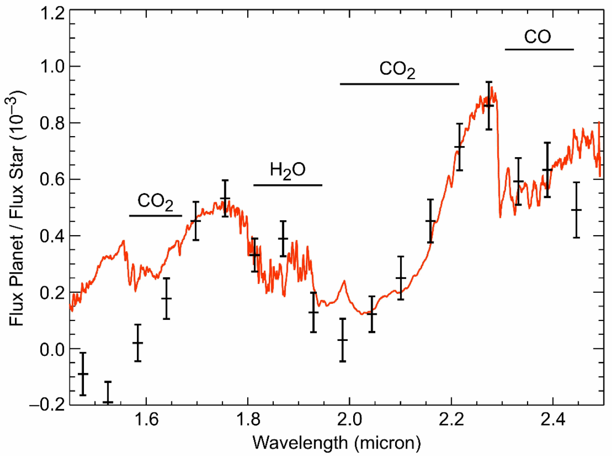



Sun
Gliese 581
Mass of star (in solar masses)
1
0.1
e
b
c
d
Habitable zone
Possible extension of the habitable zone due to various uncertainties.
0.1
1.0
10
Distance from star (AU)

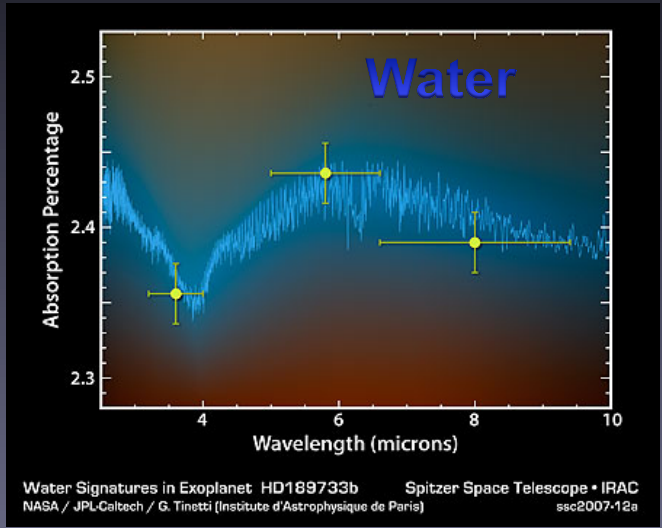
Biomarkers !

Spectroscopy of extrasolar planets

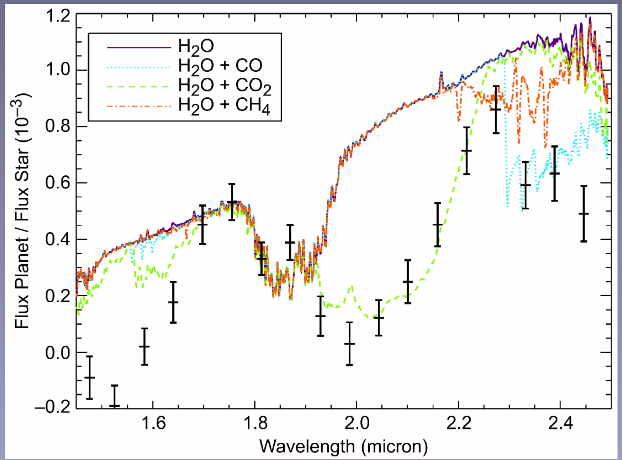
HD189733 b

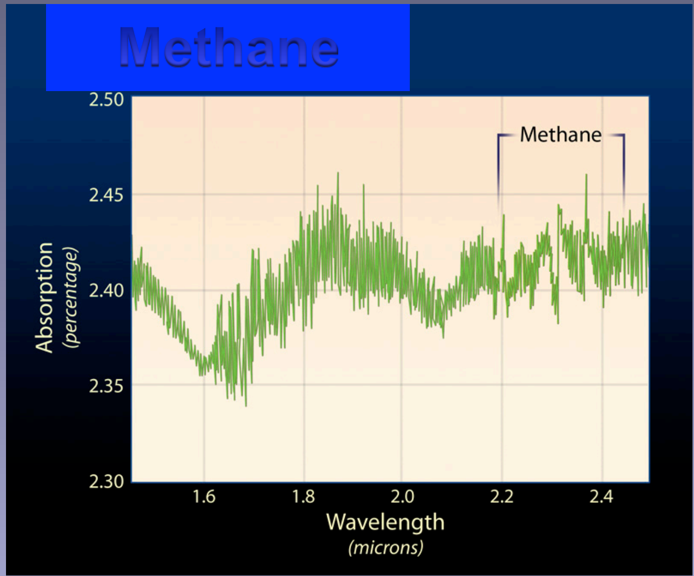


Hubble & Spitzer
Space telescopes

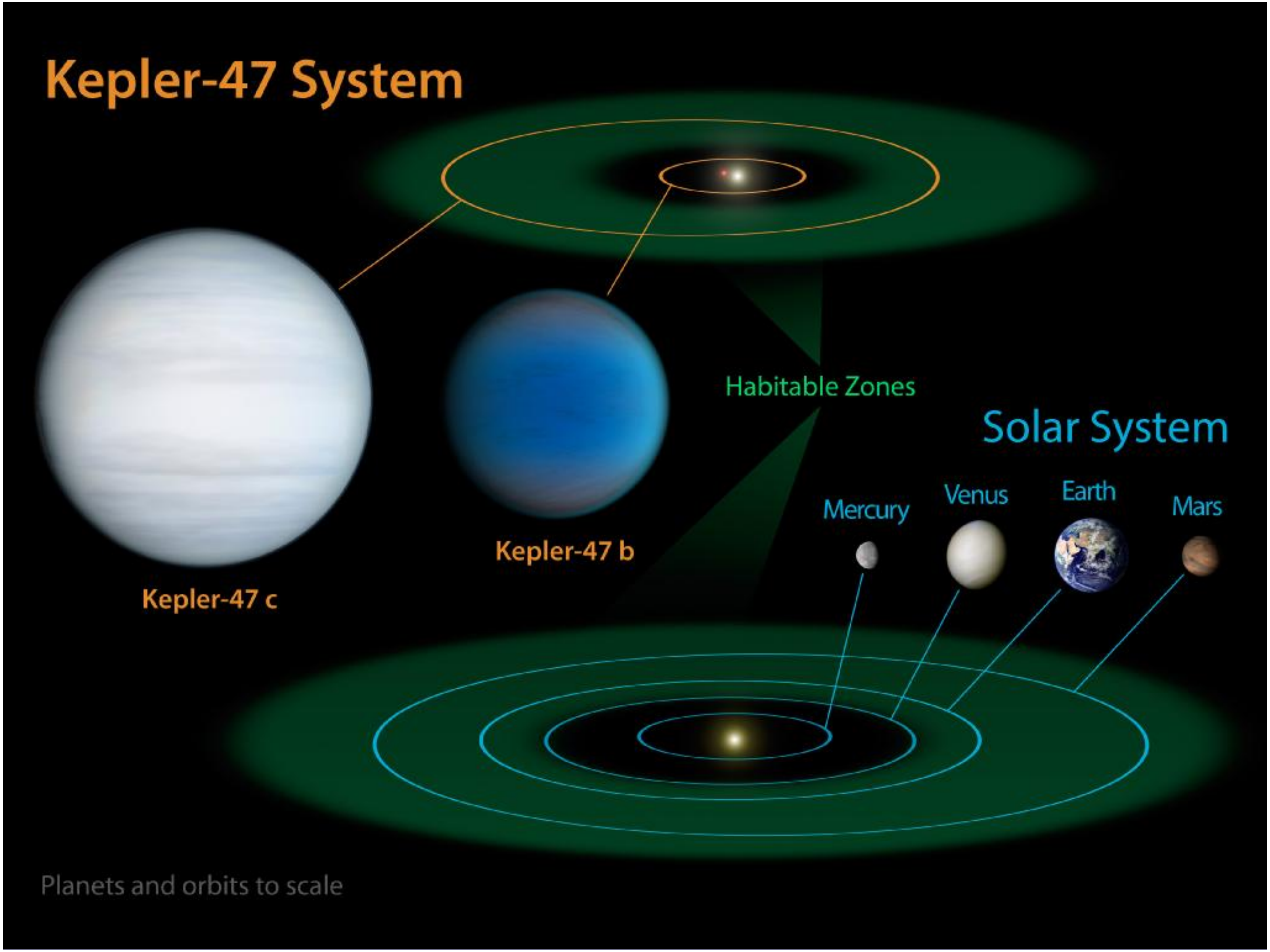


CO_2 Carbon Dioxide





And soon O_2 and/or O_3 ?


Kepler-47 System
Kepler-47 c
Kepler-47 b
Habitable Zones
Solar System
Mercury
Venus
Earth
Mars
Planets and orbits to scale

Future instruments like ESPRESSO and HIRES (ESO VLT/ELT)

- ESPRESSO@VLT (2014)
  - Proposed to ESO (pre-CODEX instrument)
  - Goal RV precision: 10cm/s precision
  - Goals: detection of Earth-like planets, asteroseismology, fundamental physics, cosmology
- HIRES@E-ELT (2018)
  - 1cm/s precision over 20 years

Thank You!