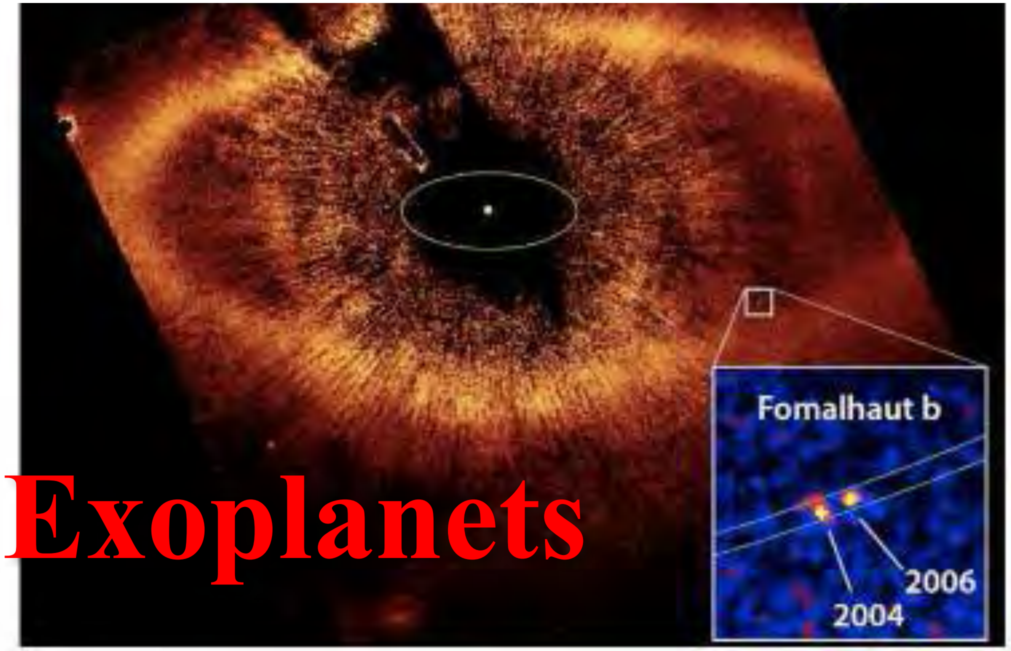
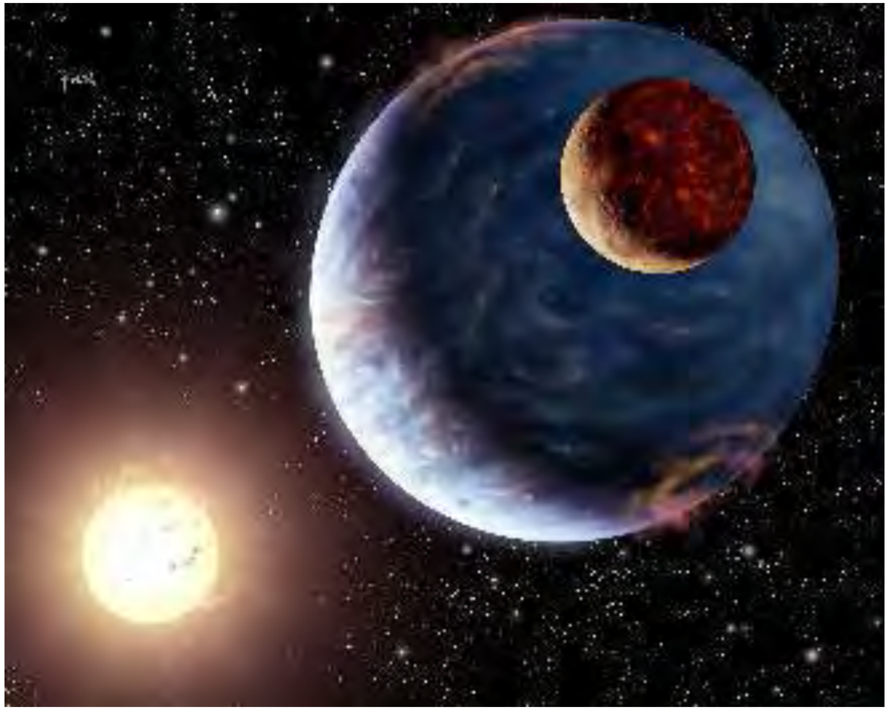


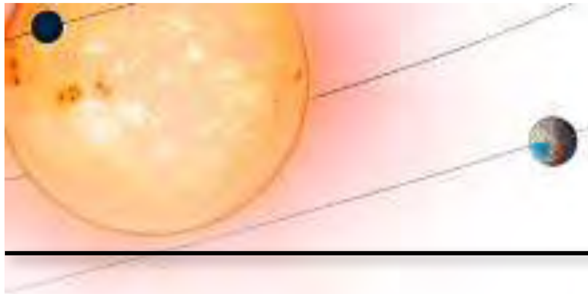
Introduction to Exoplanets



Don Pollacco
Department of Physics, Warwick University

15 September 2017

STFC School Solar System and Plasma



Overview

- Exoplanets – their discovery and characterisation
- Bulk properties
- Orbital obliquities – spin axis v's orbital alignment
- Evaporating planets
- Atmospheric characterisation and Weather
- The impact of stellar activity on small planet
- Habitable Zone planets
- The era of M dwarf hosts
- True Earth-Sun analogs
- The future!

Basic facts: some fun

1) The Universe is BIG –the fastest rocket would take >50000 yr to get to the nearest star beyond the sun. Alternatives eg ”Breakthrough *Starshot*” laser technology but extremely limited capability.
2) The Universe is 13B yr old and the Sun 4B yr old.
3) Humanoids maybe 2M yr
4) We have been technologically capable for roughly 150yr

Conclusion

Any society we can make contact with is likely to be substantially more evolved than us….

To visit the stars we will need new technology or be prepared to launch multi-generational missions.

The era of Exoplanet “Discovery”

- A number of
  e mid-20th
  Century of pl
  none of
  which were c

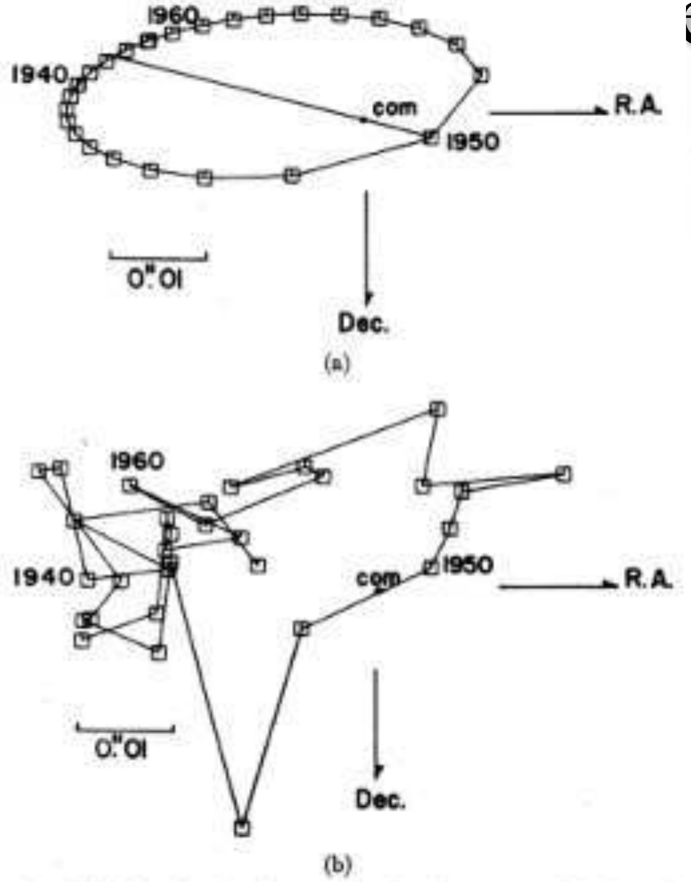
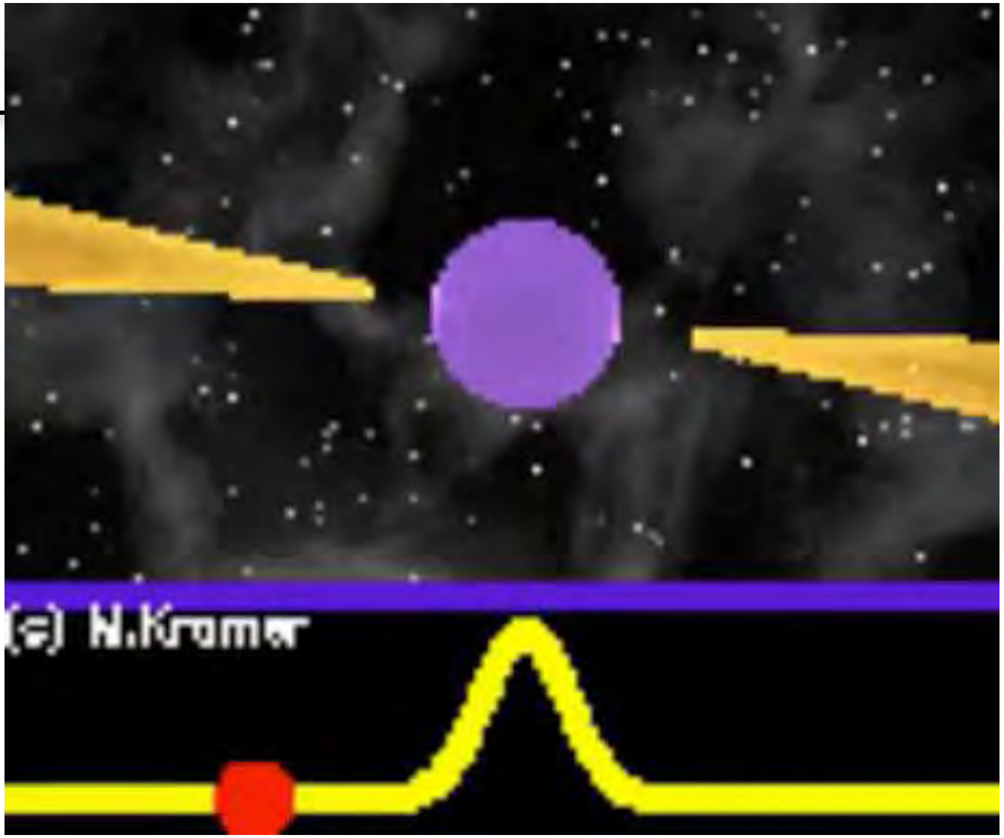
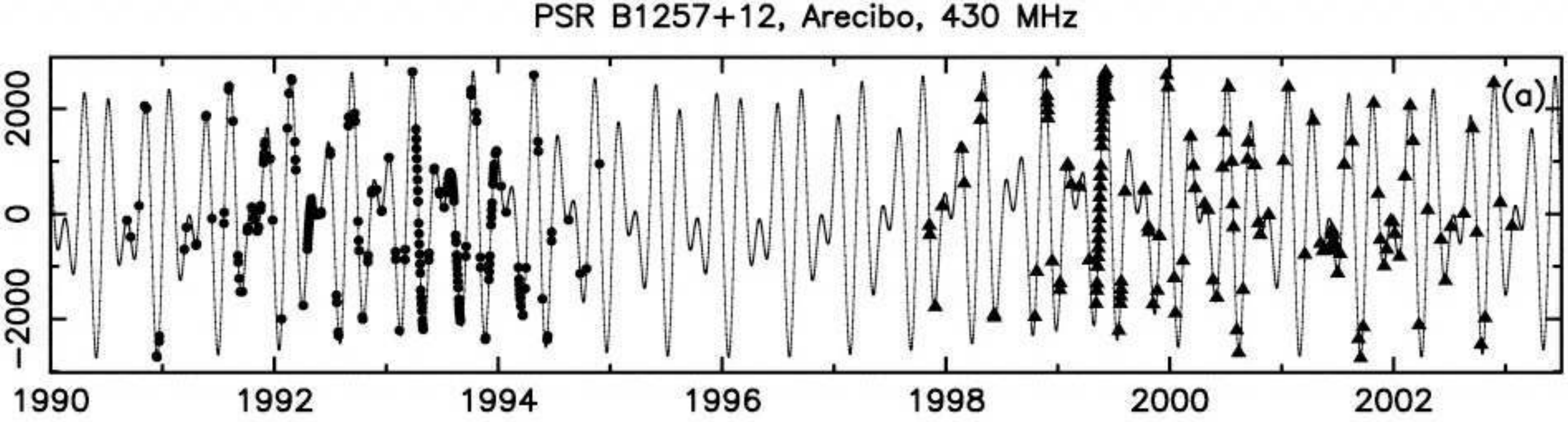


FIG. 1(a). Synthetic orbit positions based upon van de Kamps' (1969a) orbit solution. (b) Synthetic orbit positions with random error added. The first data point corresponds to 1938, the last to 1968.

First planets – Pulsar timing

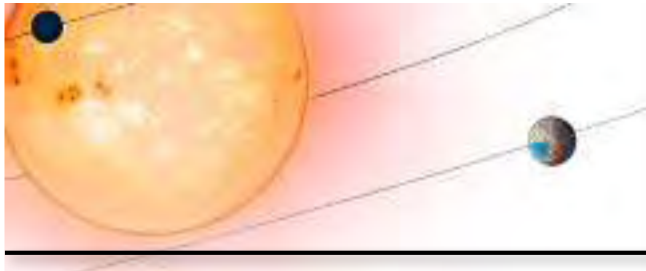
First genuine planets came from an unlikely source – pulsar timing (Wolszczan & Frail 1992)





First planet around a sun-like star

First planets around sun like star, 51 Peg, in 1995 – first hot Jupiters (Mayor and Queloz 1995)



Direct Imaging

- **Brightness:** visible due to scattered starlight or because they are self luminous. The planetary cross-section is small so that scattered starlight is faint compared to host star (table in delta mags):

	0.1AU	1AU	5.2AU
Earth	20.4	25.4	29.0
Jupiter	15.5	20.6	24.1

Ratio more favourable at IR wavelengths where planets can be self-luminous (depending on temperature). Need to block light from host star (coronagraph).

- **Resolution:** as viewed from 10pc the Earth would be 0.1 arcsec and Jupiter 0.5 arcsec from the Sun. At 100 pc the separations are 10 and 50 milli-arcsec respectively. Telescope resolution dependant on aperture and wavelength (in milli-arcsec):

	500nm	2.2μ	10μ
10m Keck	12.2	54	400
42m ELT	2.9	12.8	58

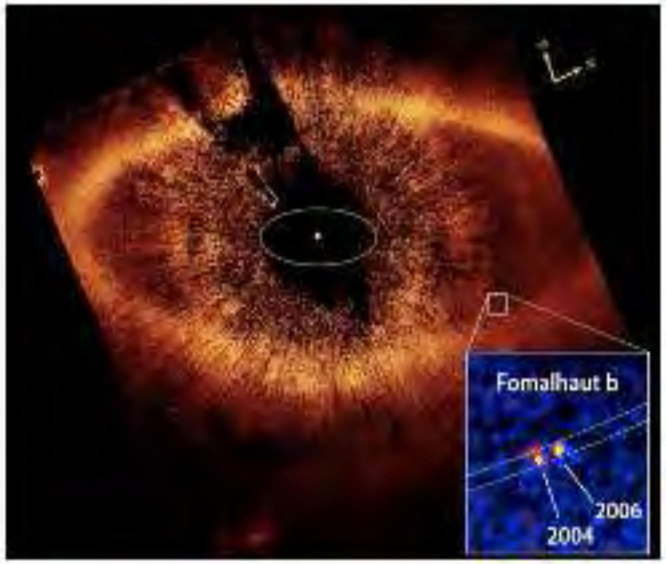
Conclusion: Optical – resolution ok, contrast bad, IR – resolution worse, contrast better

Images of exoplanets

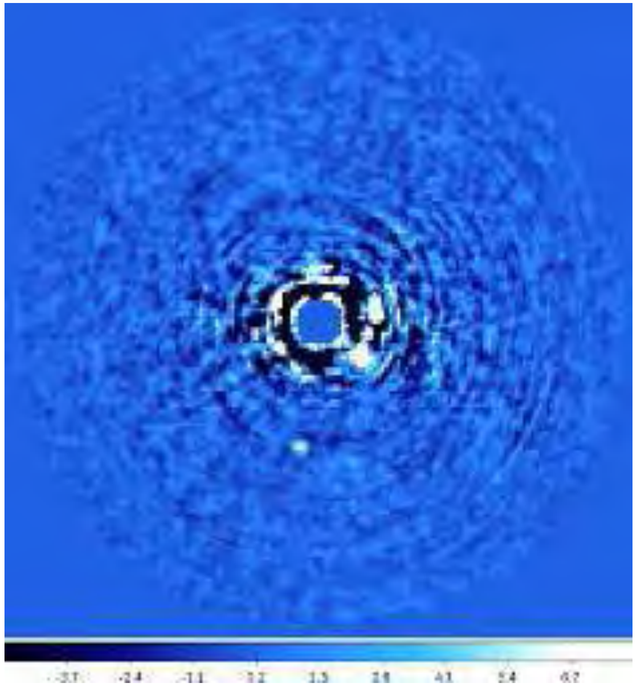
- Planets are faint and next to their stars – similar contrast difference to looking at a candle next to a football stadium light!

- None the less some planets have been imaged – but only those that are extremely large, young, and at large orbital separation.

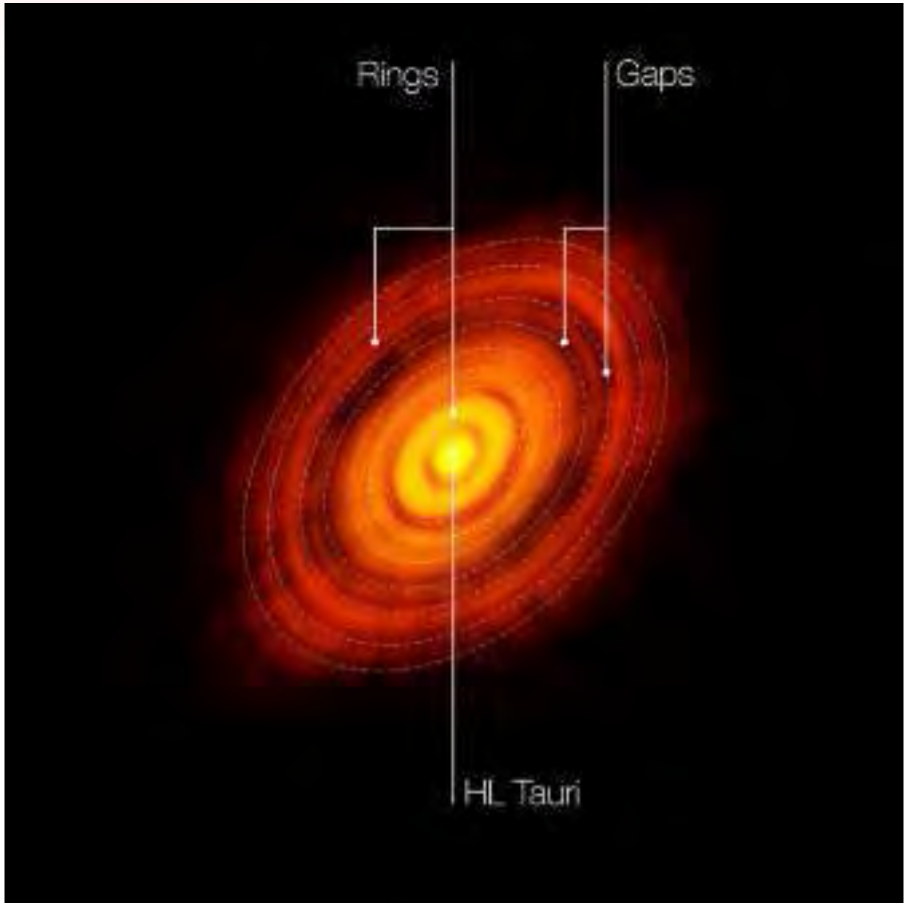
Kalas et al 2008



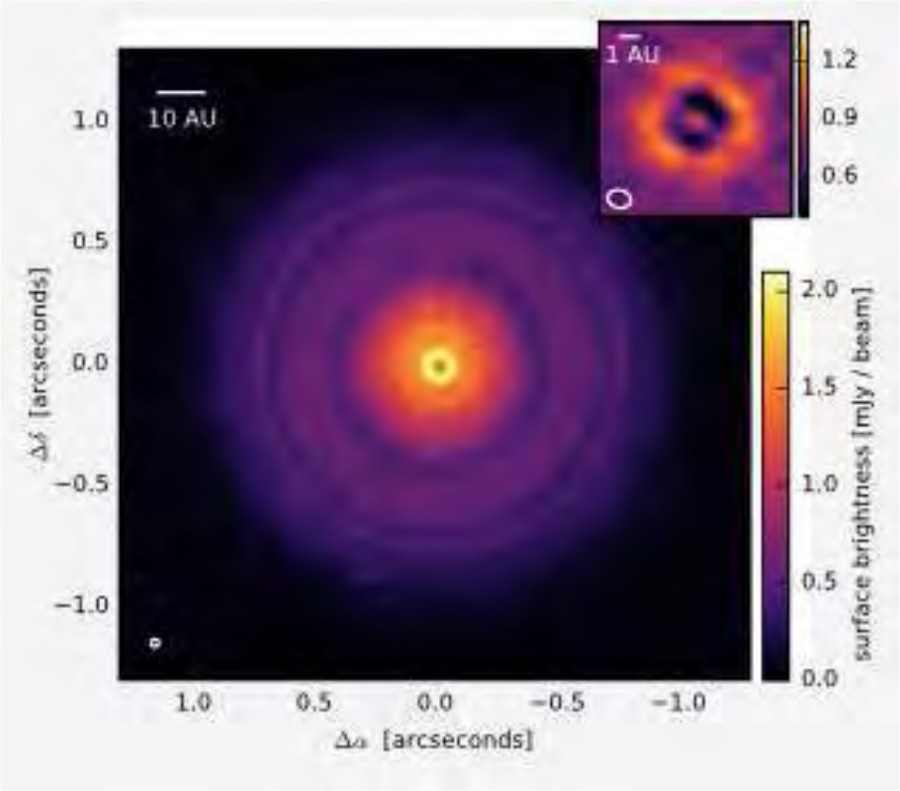
GPI
50 Eri b
Marios +
Gpi Team



Alma Disks

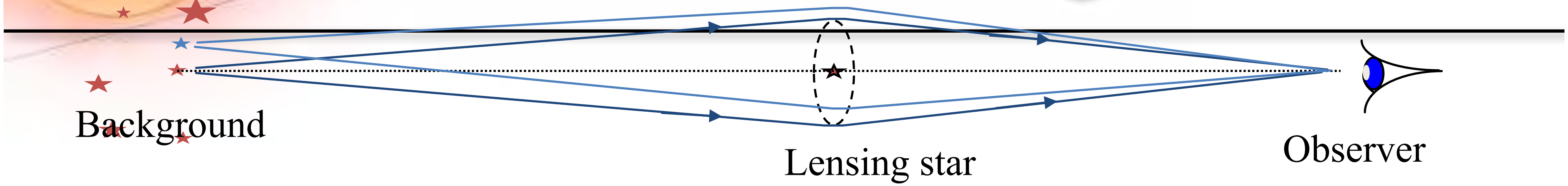


TW Hydrae



Disks bigger than solar system
Expect planets to be clearing the gaps in the disk causing rings (but cant see the planets)

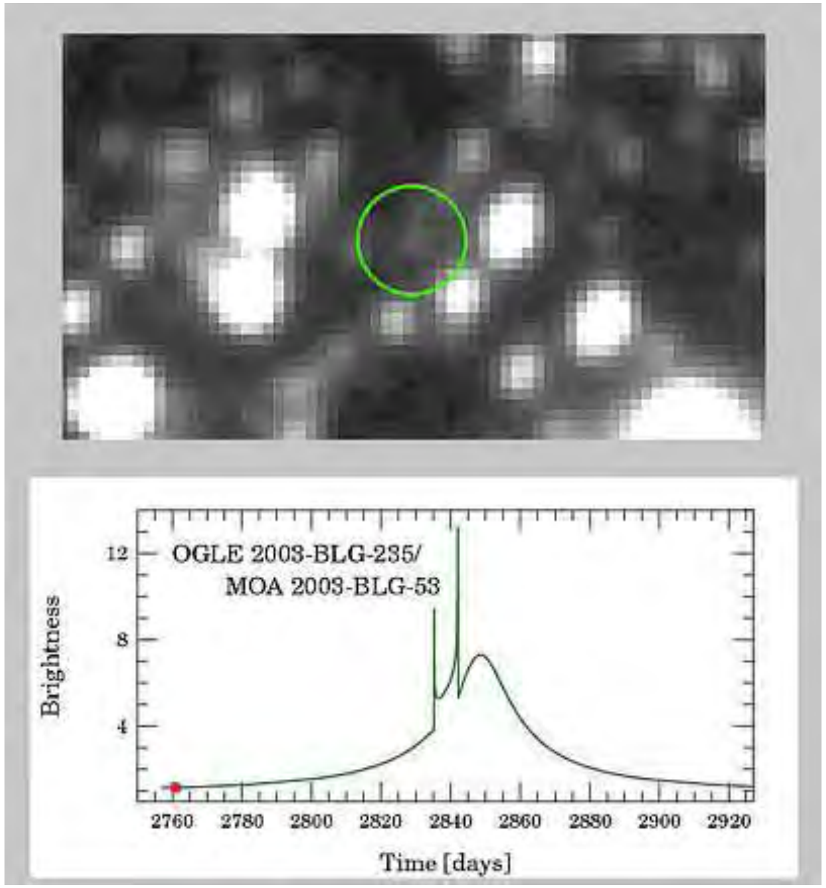
Microlensing



Light from background stars is gravitationally bent around a foreground star (+planet). First noted in images of stars near the solar limb during an eclipse.

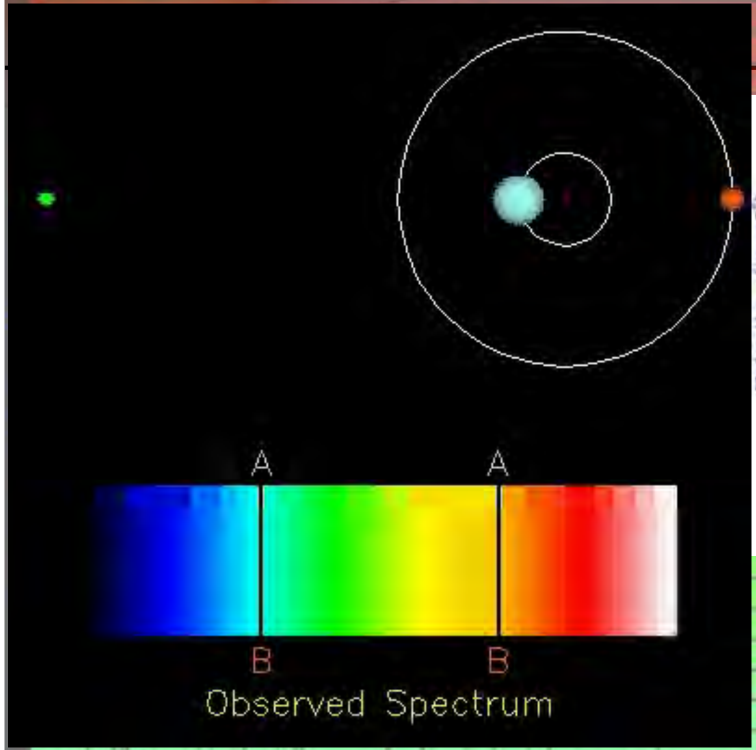
Magnification is dependant on the alignment of the lensed star and source

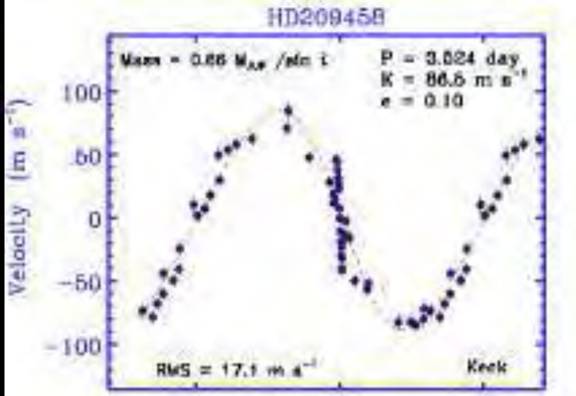
	Duration (d)	**Brightening (mags)**
Hot Jupiter	5	4
“Jupiter”	3	3
“Earth”	0.167 (4hr)	1



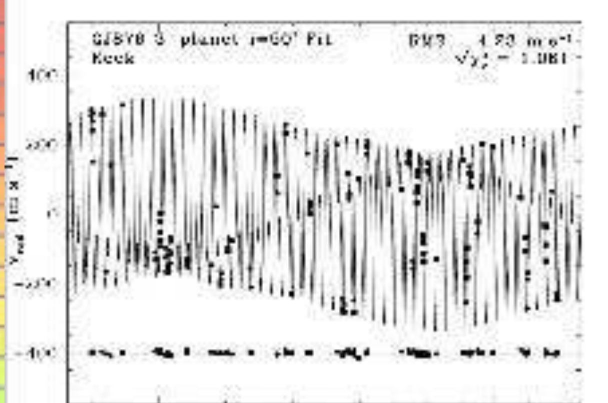
Get an estimate of the planet mass – sensitive to low mass objects at large distances

Spectroscopy: radial-velocity searches





HD209458–single planet



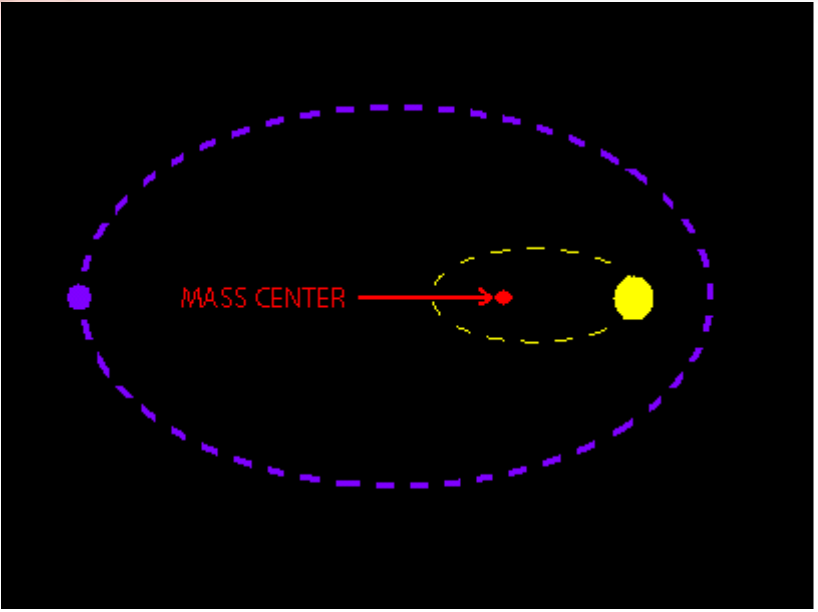
GJ876 – 3 planet model

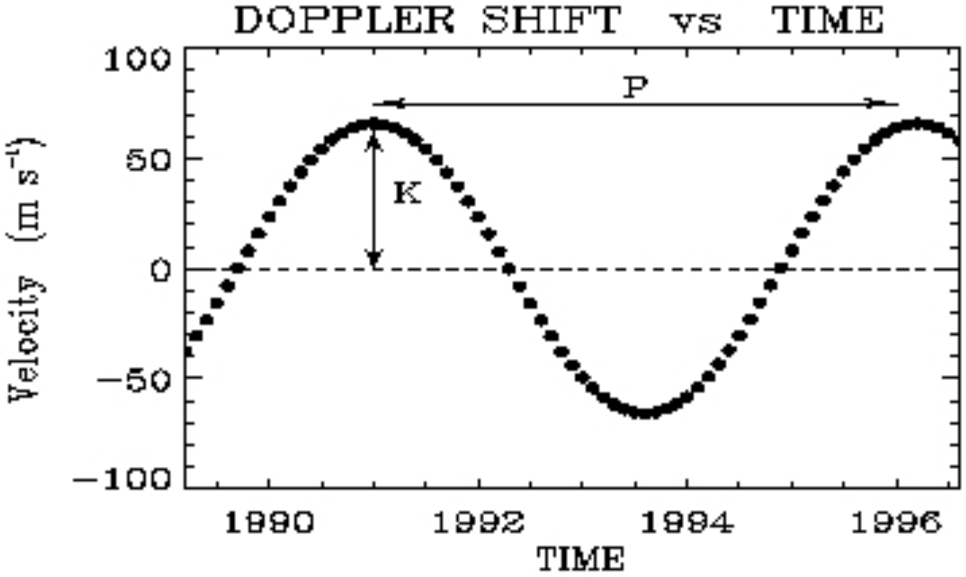
- **Need cool stars: narrow-lined (F, G, K, M) stars**

Scientifically we say we measure the velocity component perpendicular to the sky - Measure *msini* (minimum mass)

Unless you know the inclination of the planetary orbit you learn almost nothing about the planet itself…

Radial Velocities





- **Kepler 3:** $a^3 = GM_* P^2 / 4\pi^2$
- **Velocity of unseen planet:** $V_p = \sqrt{GM_* / a}$
- **Momentum conservation:** $M_p V_p = M_* V_*$
- **Observed velocity of star:** $K = V_* \sin i$
- **Collect observables:** $M_p \sin i = M_* K / V_p$

Expected RV semi-amplitudes

Radial Velocity amplitude for lower mass planets

$$k_* = \frac{28.4\,ms^{-1}}{\sqrt{1-e^2}} \frac{m_{PL}\sin i}{M_J} \left(\frac{m_* + m_{PL}}{M_{Sun}}\right)^{-2/3} \left(\frac{P}{1yr}\right)^{-1/3}$$

Example Object	**a (AU)**	**k_* (m/s)**		
Jupiter	1	28.4		
Jupiter	5	12.7	3-5m/s	
Neptune	0.1	4.8		
Neptune	1	1.5		
Super-Earth (5M_E)	0.1	1.4	1m/s	
Super-Earth (5M_E)	1	0.45		
Earth	1	0.09	Not feasible (yet)	

Current instruments able to achieve <1m/s accuracy (stability)

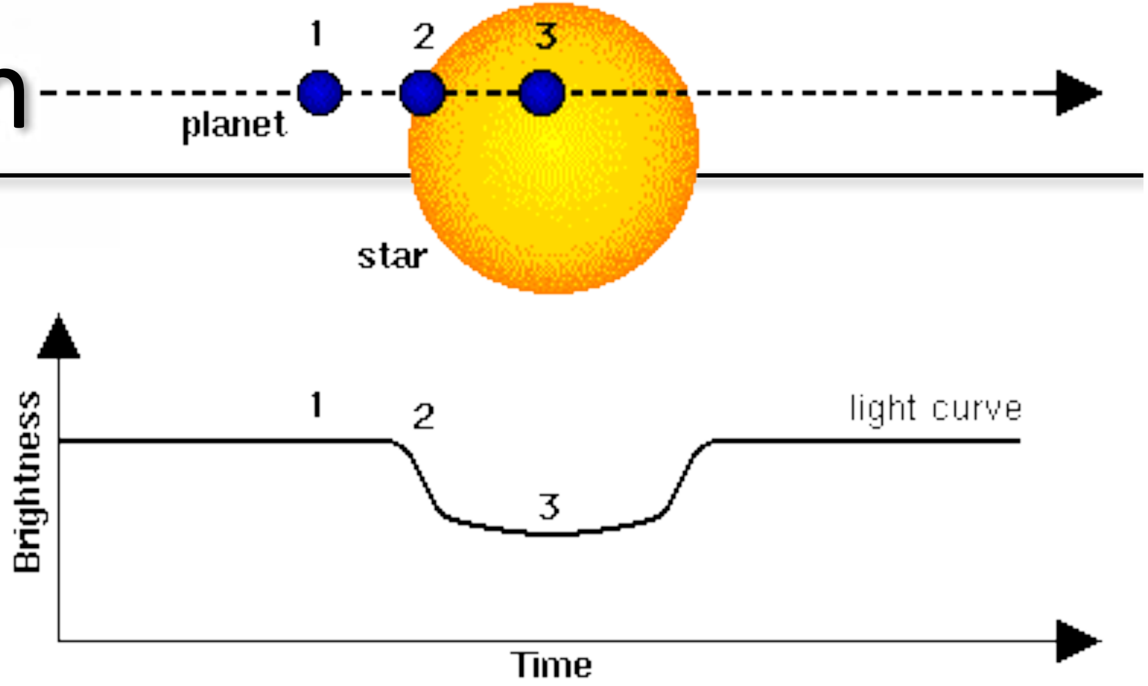
Transit Detection

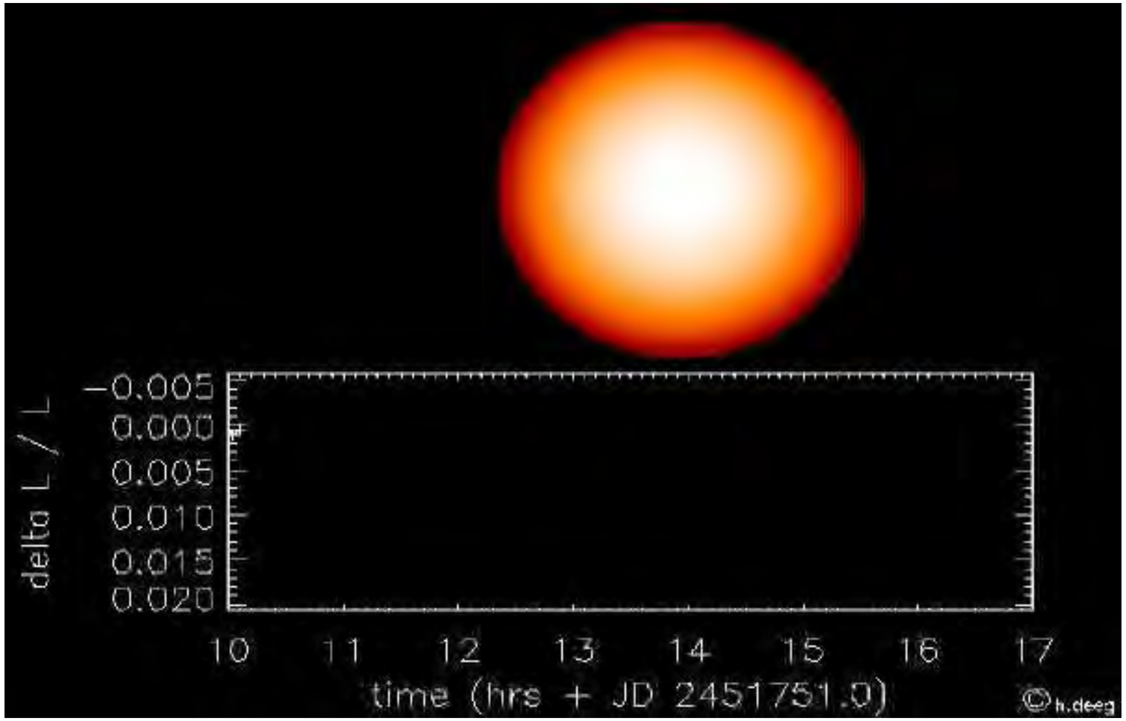
Mostly geometry - get: radius of planet/star, inclination of orbit.

Depth of transit dependent on size of planet (relative to star).

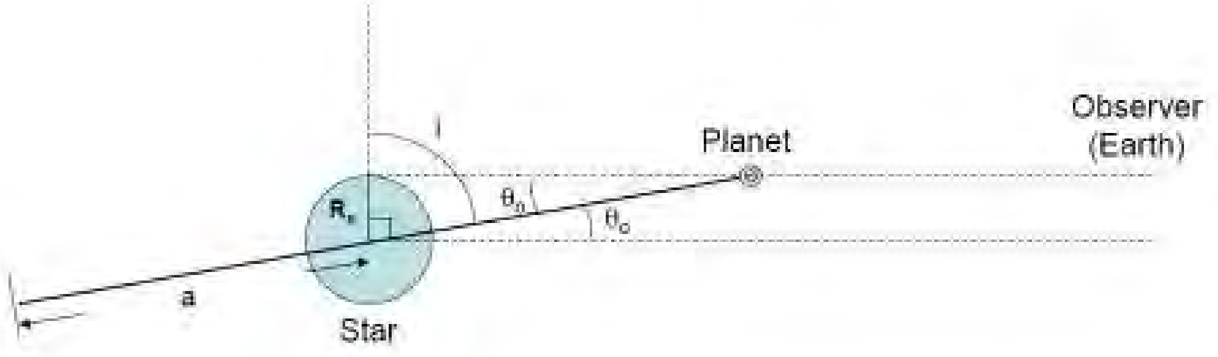
Smaller the planet (relative to star) the smaller the dip.

Jupiter sized planet transiting the sun gives a 1% drop in light. Earth transit is 100 times smaller.





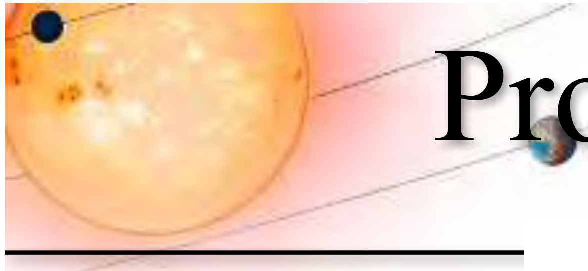
Probability of transits



i = inclination of planet's orbit to the plane of the sky
θ_o = angle of planet's orbit with respect to the observer (= 90° – i)
a = planet's semi-major axis
R_s = stellar radius

Then, the probability that a planet will transit is given by

$$P = \frac{\int_0^{\theta_0} \cos\theta d\theta}{\int_0^{\pi/2} \cos\theta d\theta} = \frac{\sin\theta|_0^{\theta_0}}{\sin\theta|_0^{\pi/2}} = \frac{\sin\theta_0}{1} = \frac{R_s}{a}$$



Probability of transits

$$P = \frac{\int_0^{\theta_0} \cos\theta \, d\theta}{\int_0^{\pi/2} \cos\theta \, d\theta} = \frac{\sin\theta \big|_0^{\theta_0}}{\sin\theta \big|_0^{\pi/2}} = \frac{\sin\theta_0}{1} = \frac{R_s}{a}$$

Probability of detecting a Jupiter transit in our solar system 700000 km/5.2 AU ~ 0.1%

⇒

To find one jupiter at 5.2 AU from a Sun like star,
one needs to look at ~ 1 / (0.1%) ~ 1000 stars !

Probability of detecting a hot-Jupiter transit around a sun-like star 700000 km/0.05 AU ~ 10%

Probability of detecting hot-Jupiter around Sun like star = $\frac{700000 \text{ Km}}{0.05 \text{ AU}} \sim 10\%$

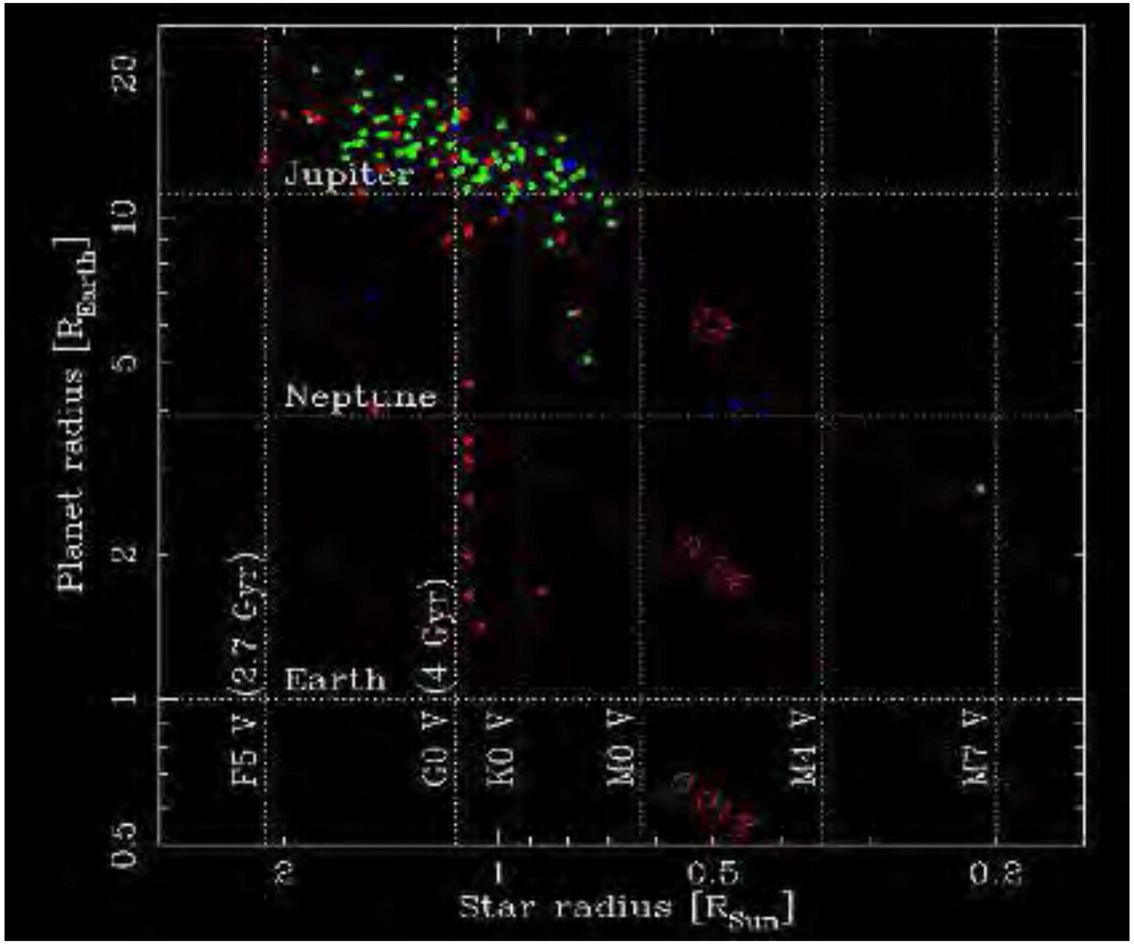
⇒

To find one hot-jupiter around a Sun like star,
one needs to look at ~ 1 / (10%) ~ 10 stars !

Why transit surveys are popular

Small stars => smaller planets

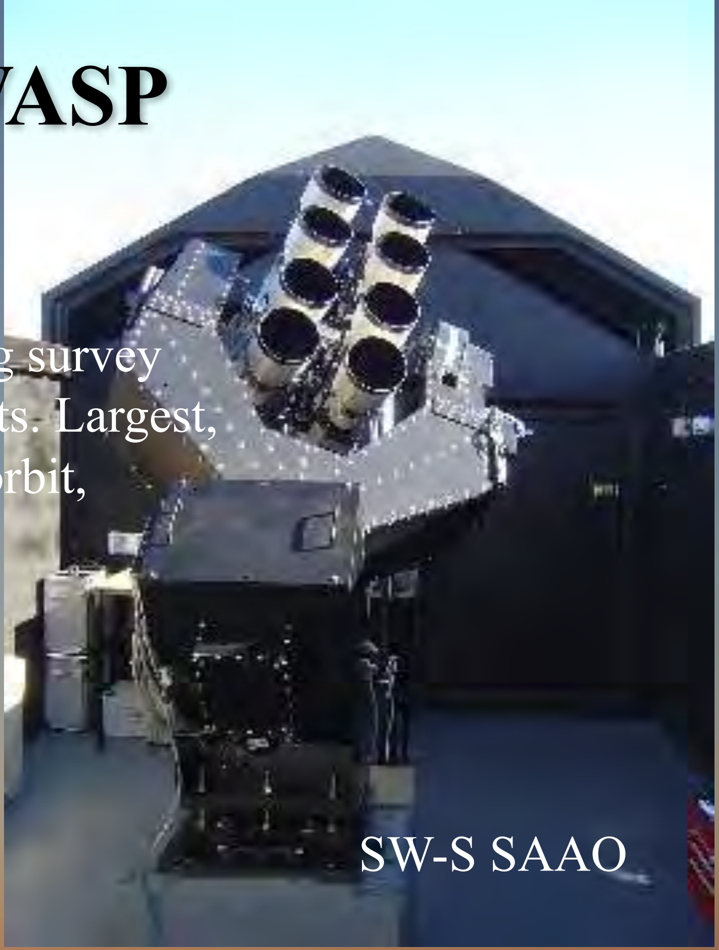
- **Transit light curve + RV curve yields planet radius, inclination, spin-orbit alignment**
- **RV measurement essential to confirm planet status : need mass ratio M_p/M_*.Hence get bulk density for model comparison.**
- **Bright transiting planets are prime targets for atmospheric analysis.**



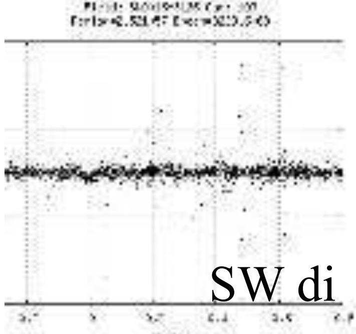
Ground based transits: SuperWASP

SW-N La Palma

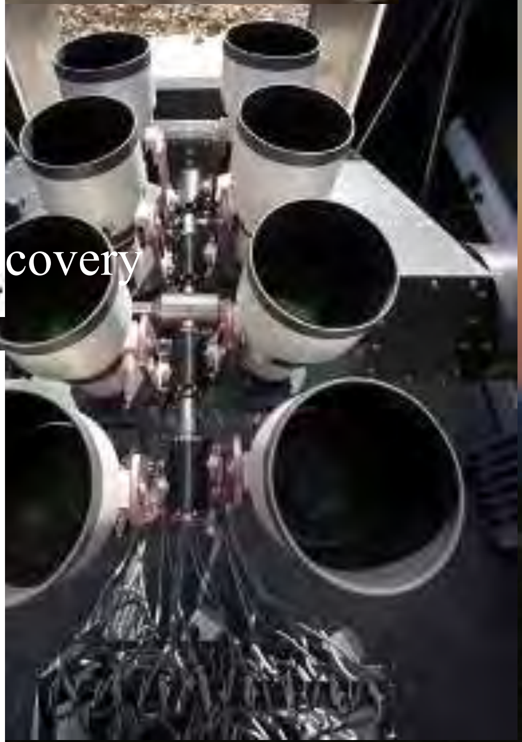
WASP project is the leading survey with >165 confirmed planets. Largest, lowest density, retrograde orbit, highest irradiation etc

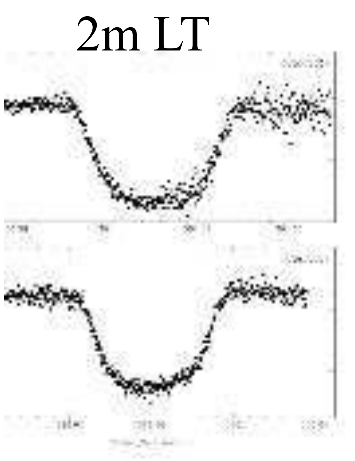


SW-S SAAO

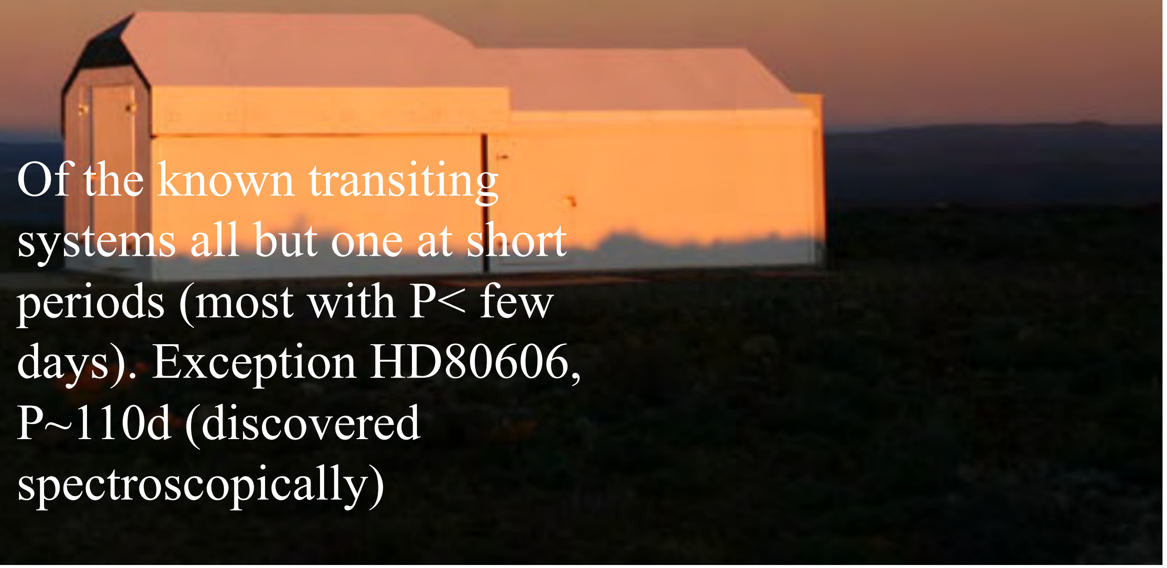


SW di covery





2m LT



Of the known transiting systems all but one at short periods (most with P< few days). Exception HD80606, P~110d (discovered spectroscopically)

Bulk Characterisation of Gas Giants

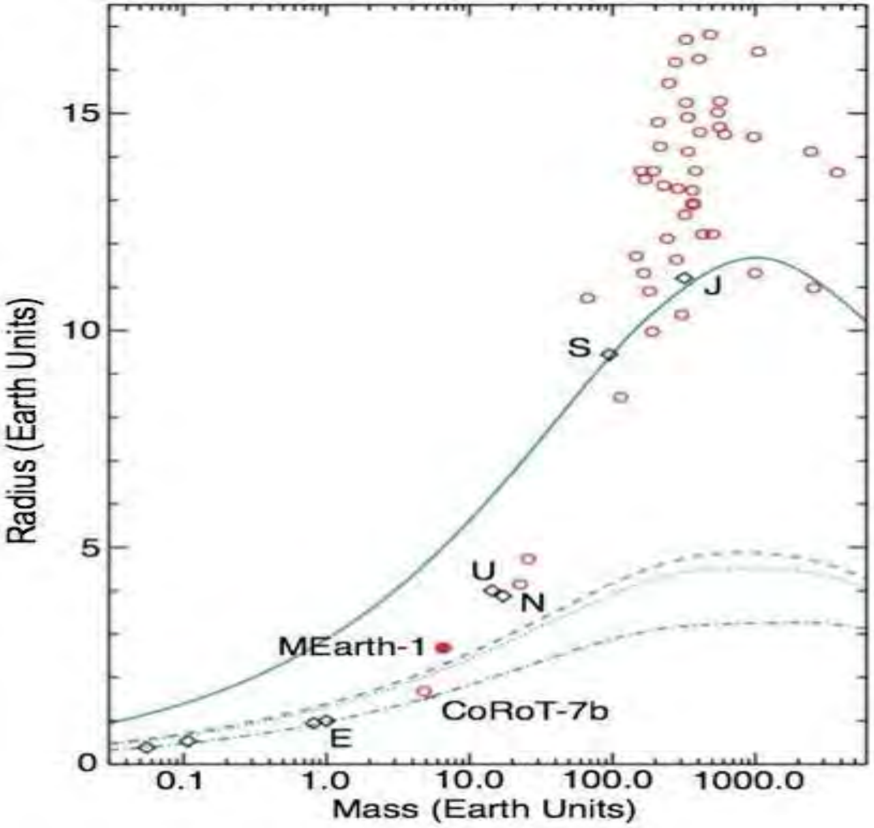
Transit surveys + RV give actual mass and radius of planet (relative to star).

Mass & Volume give density

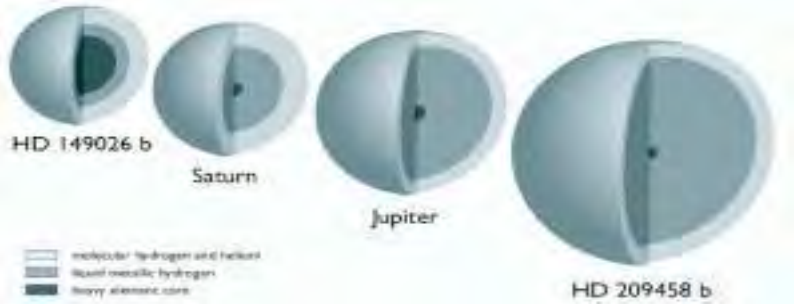
Theoretical planet models => Density

Be aware – you don’t need an *Ocean-planet* to have a *water-world*

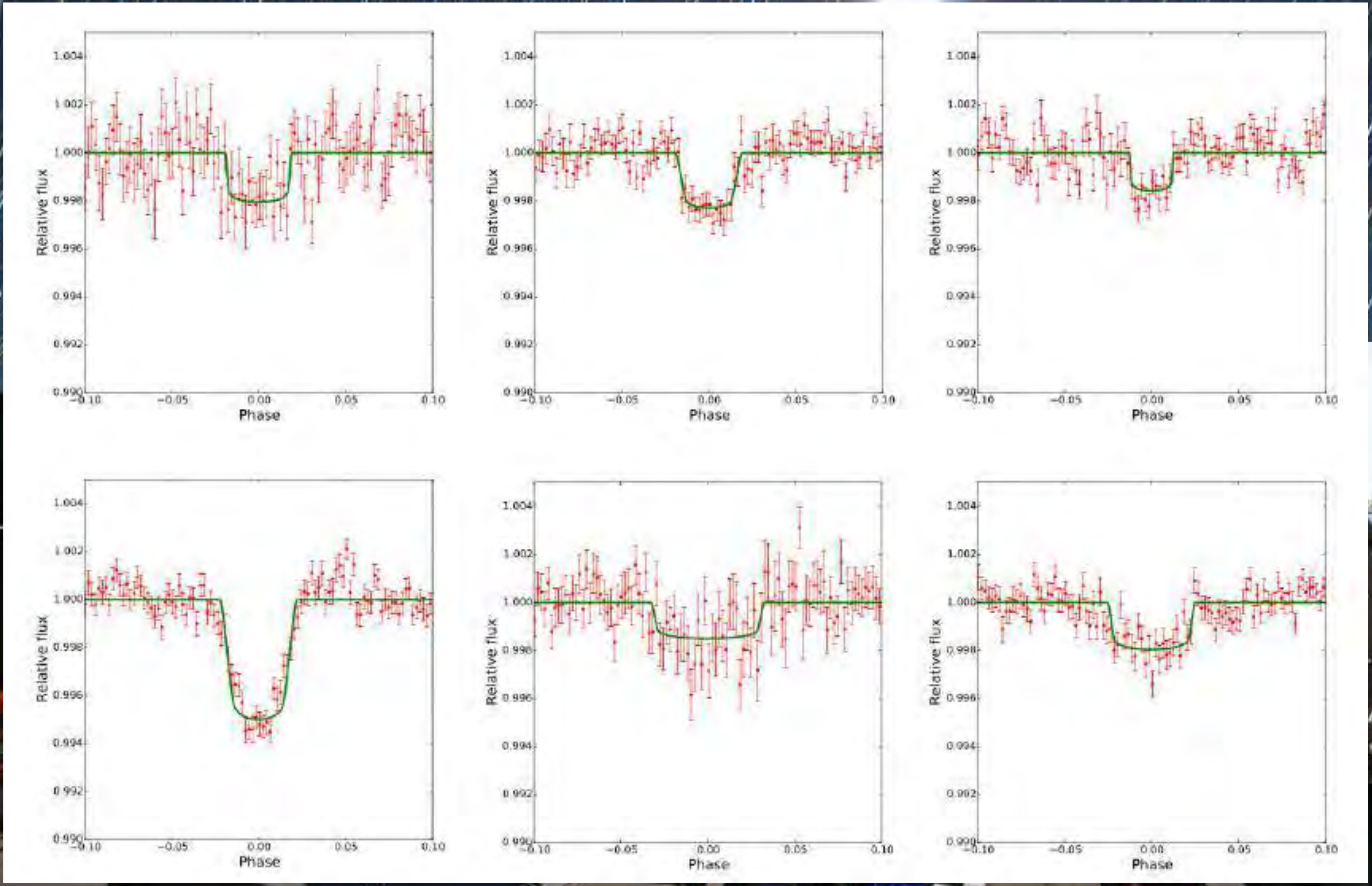
1.75Re
3Me



Much Diversity



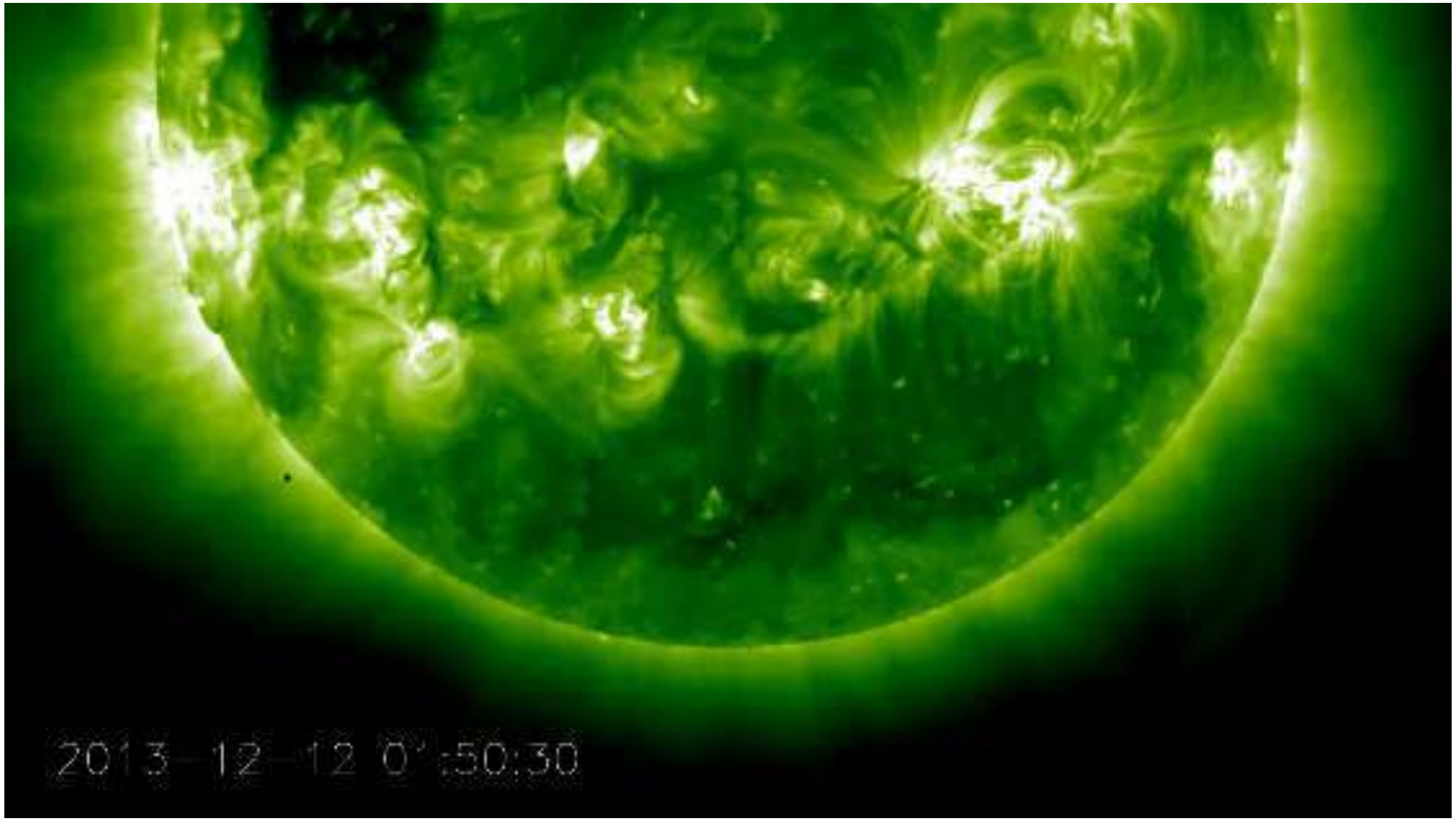
State of the Art - NGTS



Transit of Venus and extrasolar planets?

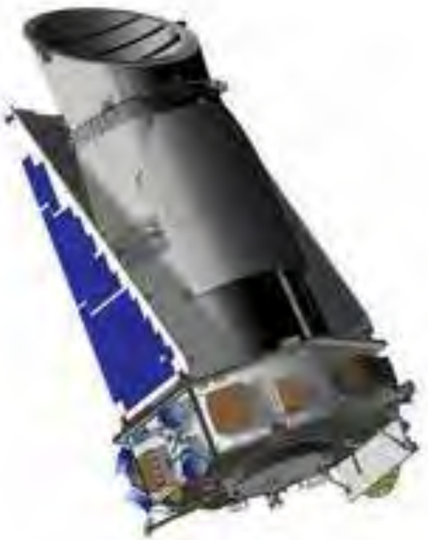
Venus transit: similar in projected size to detection of a hot-jupiter in an exoplanetary system – which we can do from the ground

Transits and more transits…



Mercury Transit similar to earth detection in exoplanetary system – can only be done from space. Even then stellar activity…..

KEPLER (launched 2009)

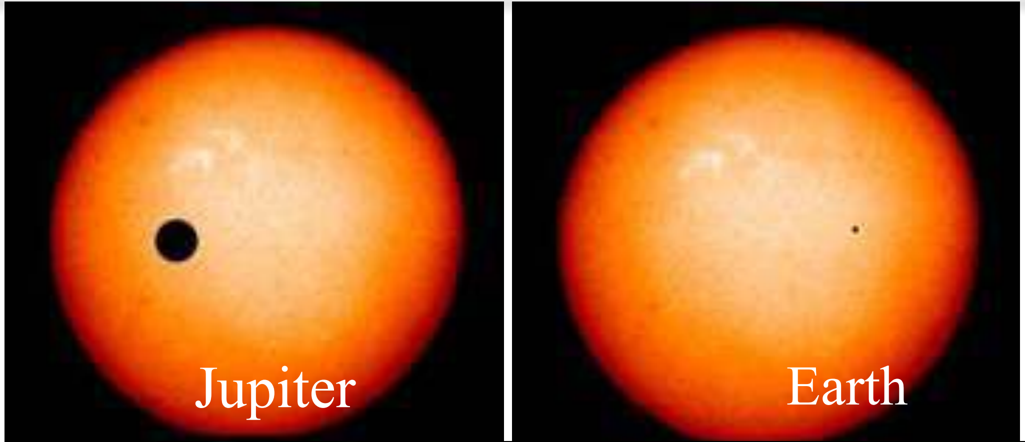


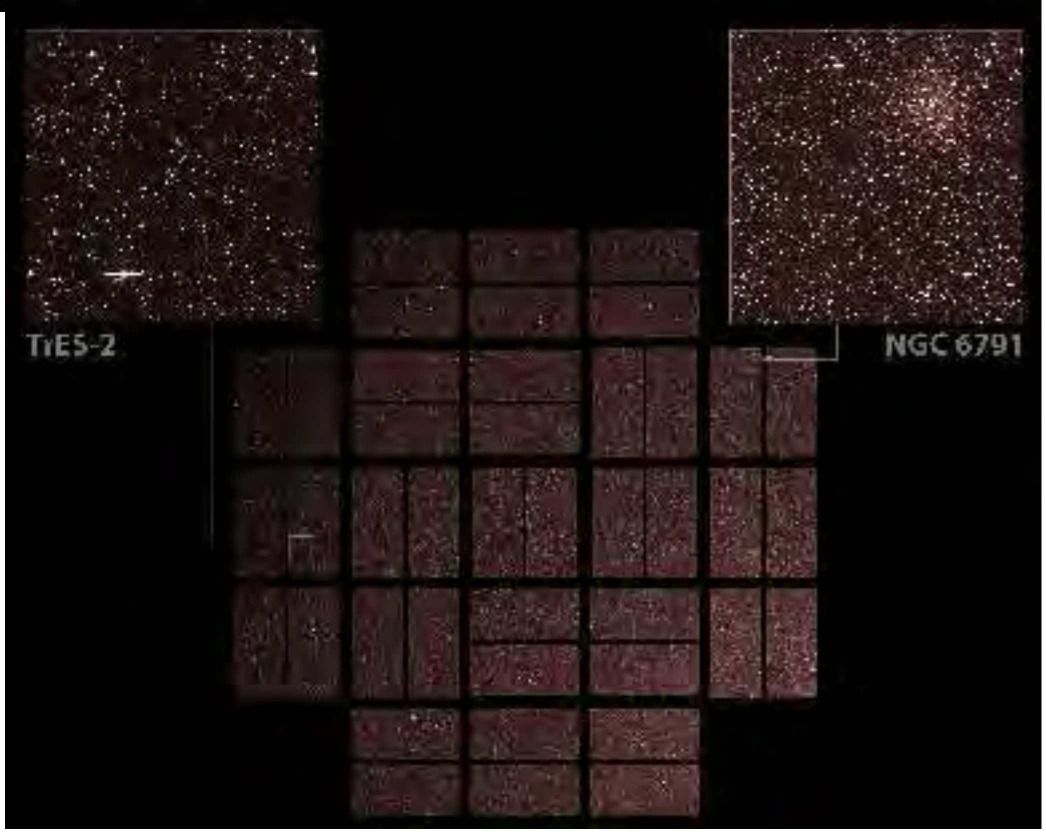
0.95m schmidt telescope
FOV ~ 105 square deg.

100000 MS stars, with V=10 - >14 mag

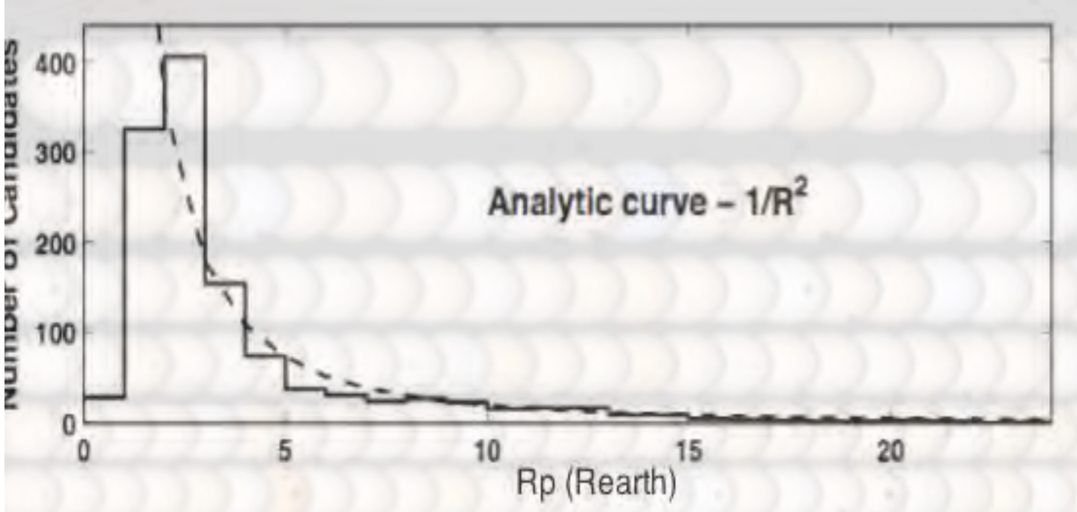
Prime mission ended with failure of 3rd gyro, now have K2 surveys

The *size* of the problem:





Big Results from Kepler

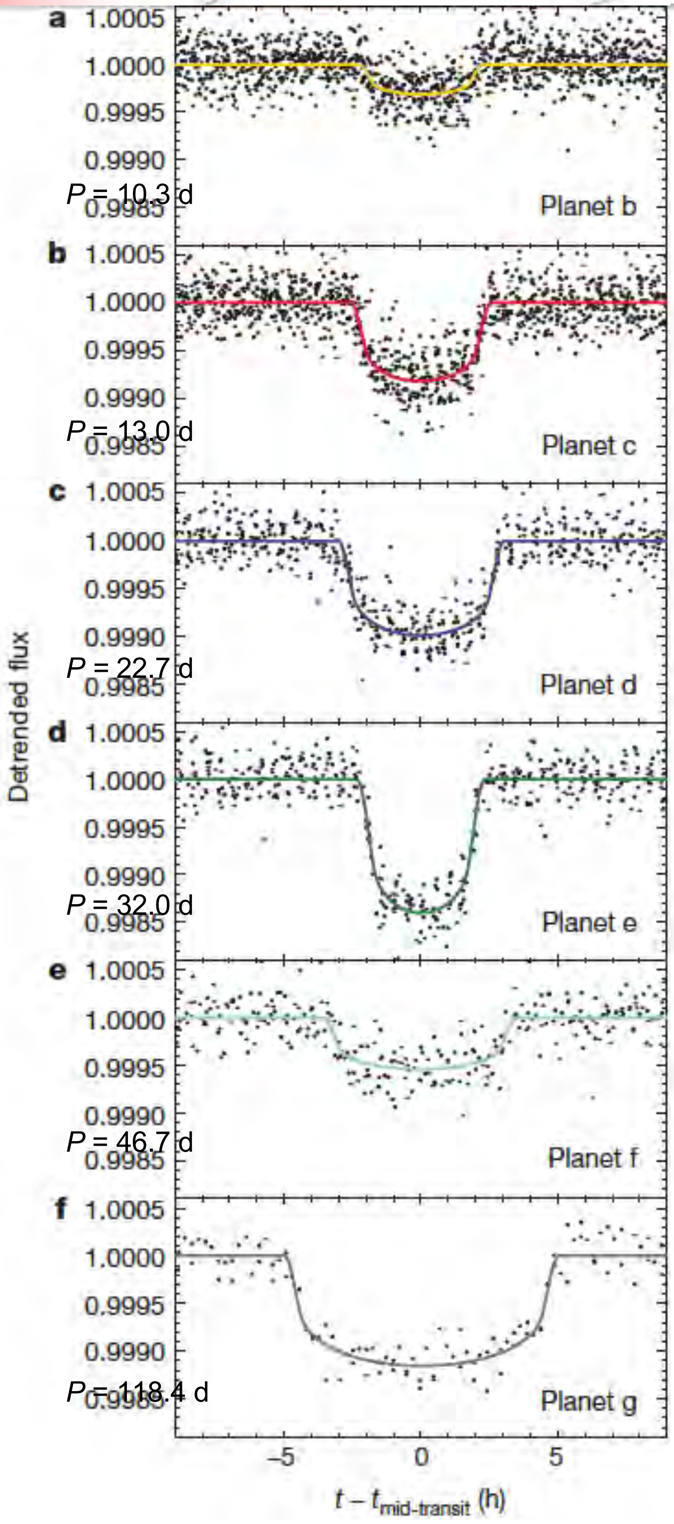


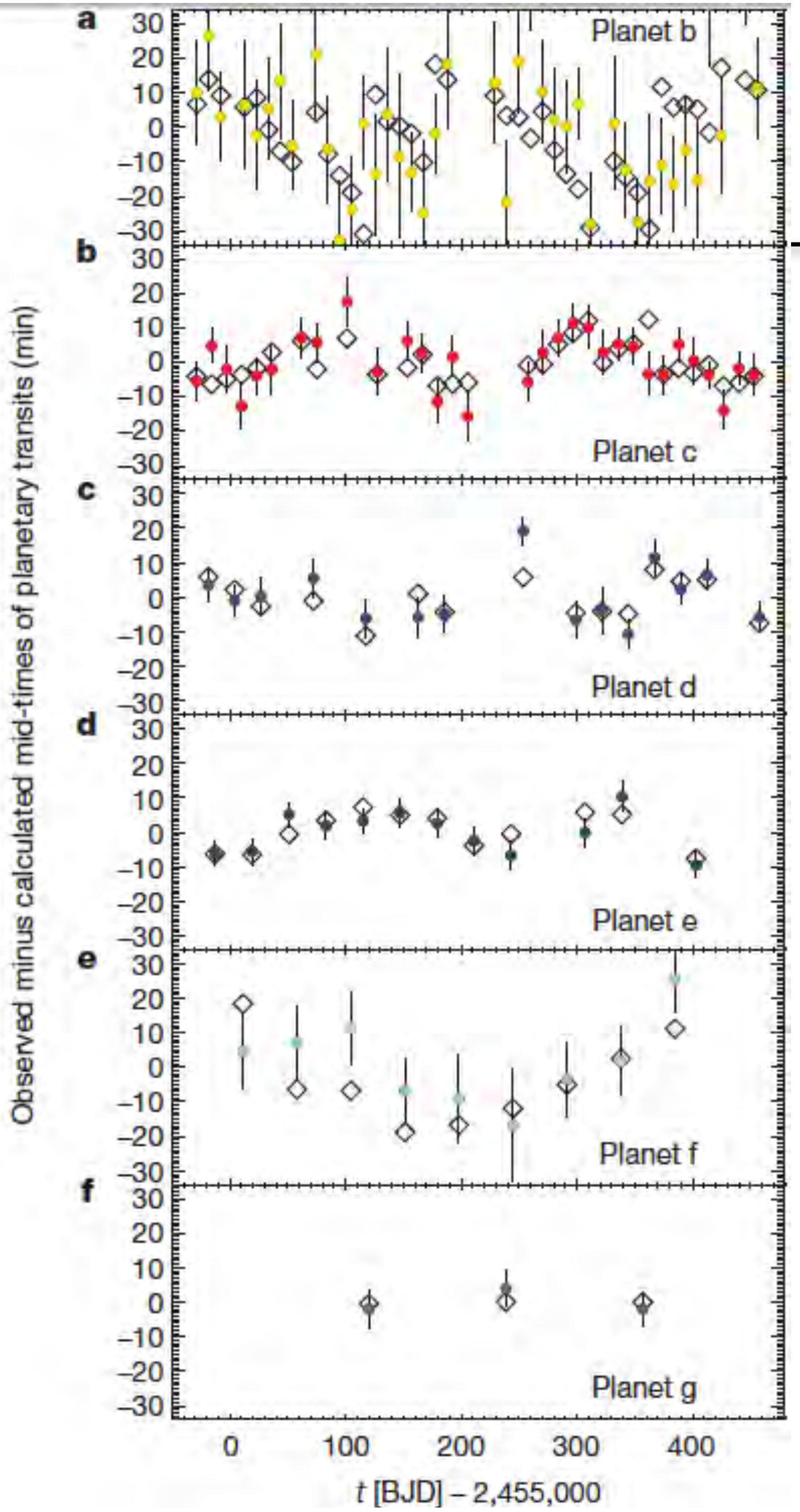
Size distribution: **dominated by small planets. Peak distribution at 2-3 Earth Radii? No surprise….**

Many small planets but very few can have their masses determined reliably. Few exceptions eg Kepler-10b/c where the host star is one of the brightest in the sample and the planetary periods are short.

Multiple Planet Systems: **17% of stars have 33% of planets ie many multiple planet solar systems.**

Kepler-11a,b,c,d,e,f

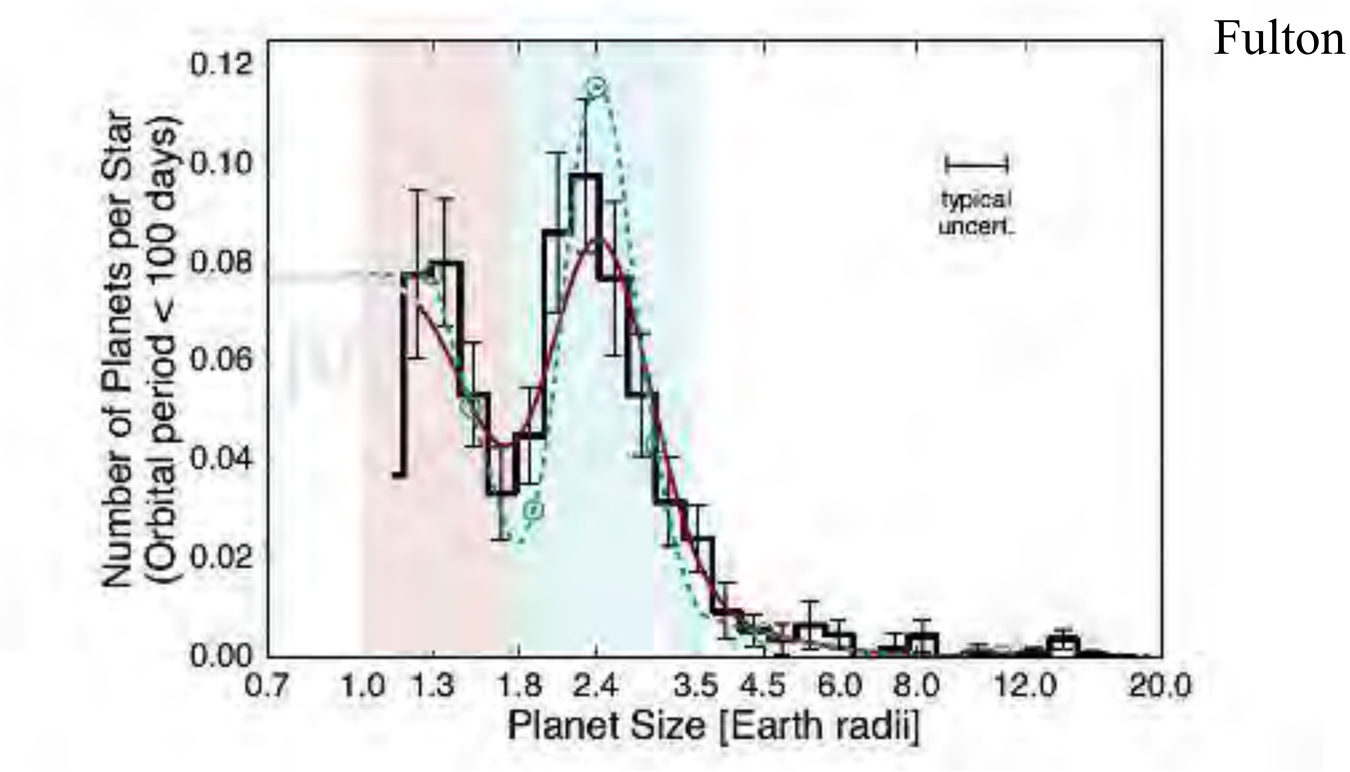




Understanding the host stars

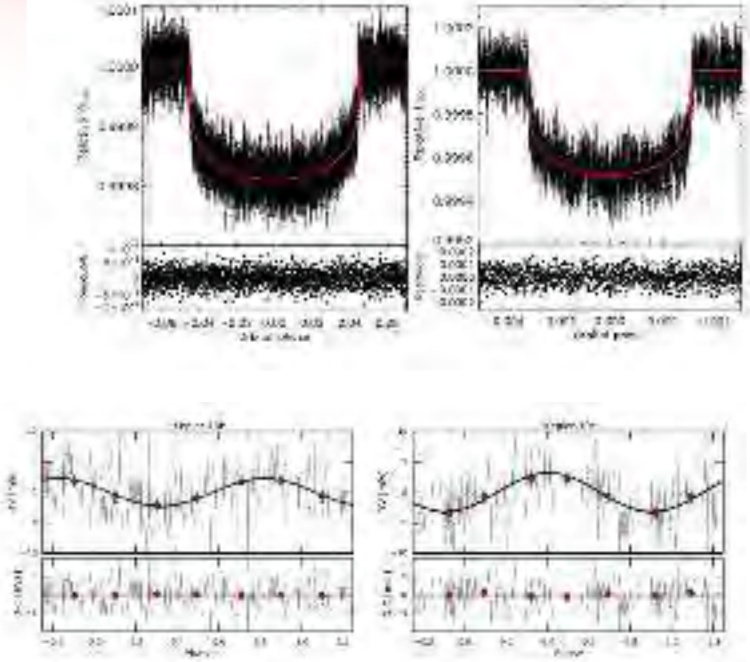
…mean's a better understanding of their planets

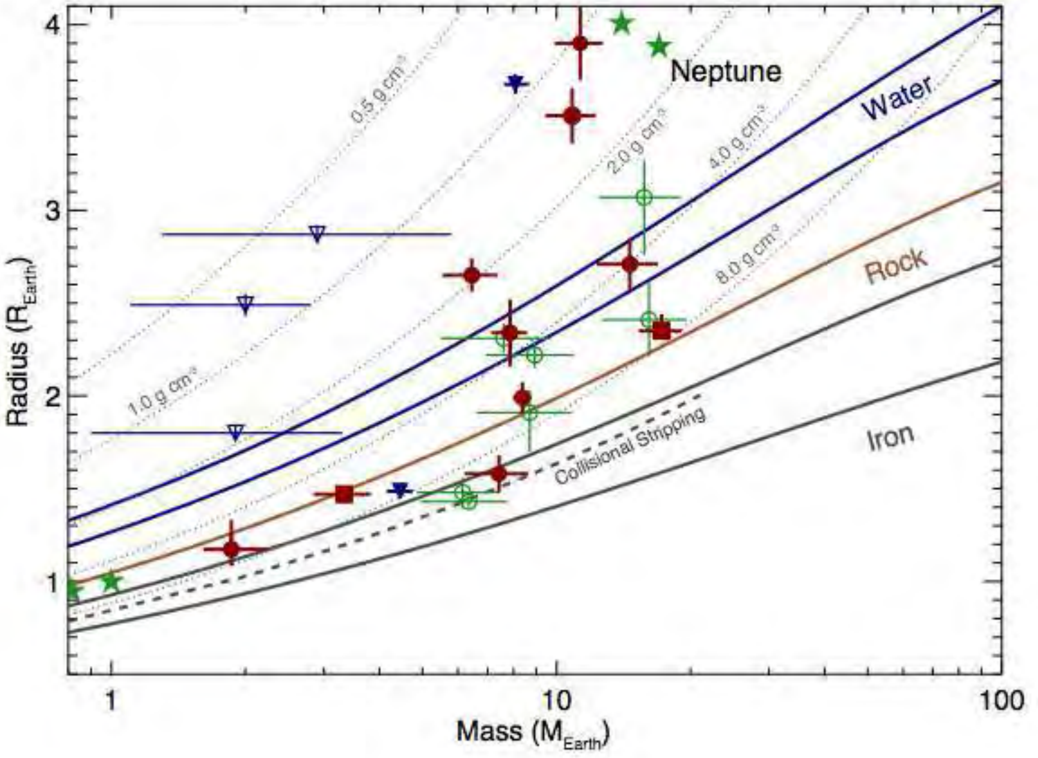
CKS stars
Fulton et al 2017



'Photo-evaporation valley' – separating rocky and gasses planets

Kepler-10b/c revisited



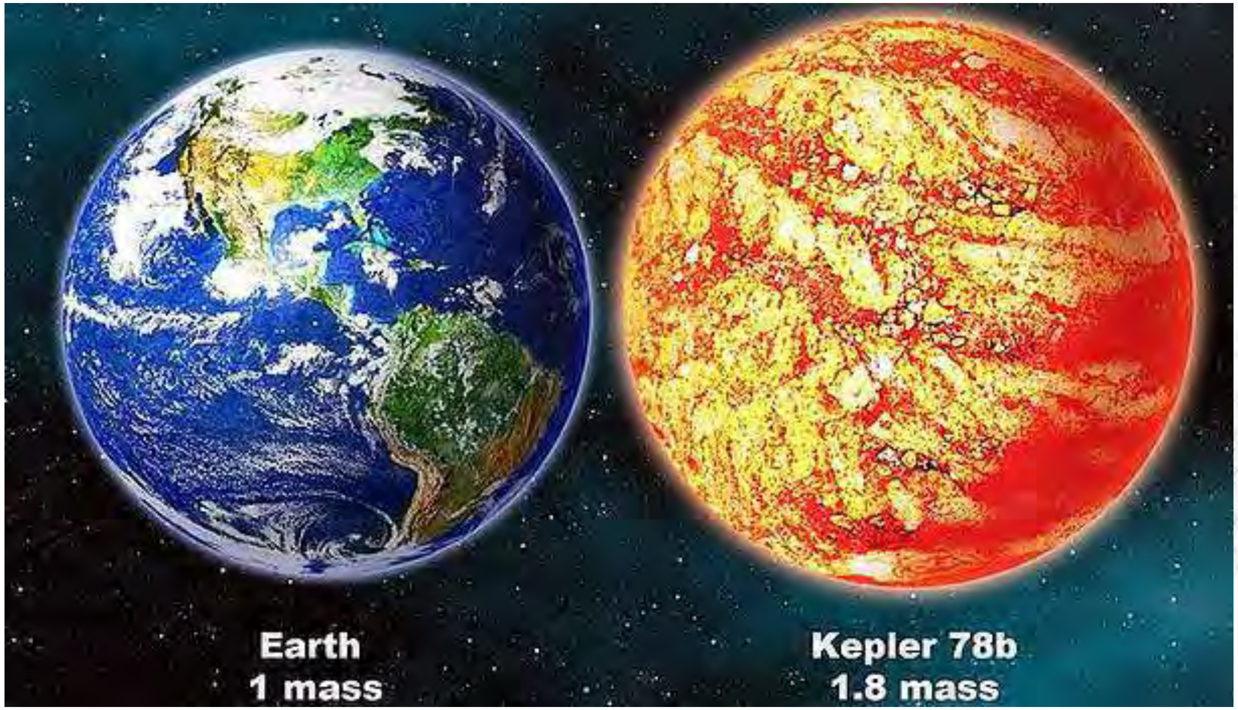


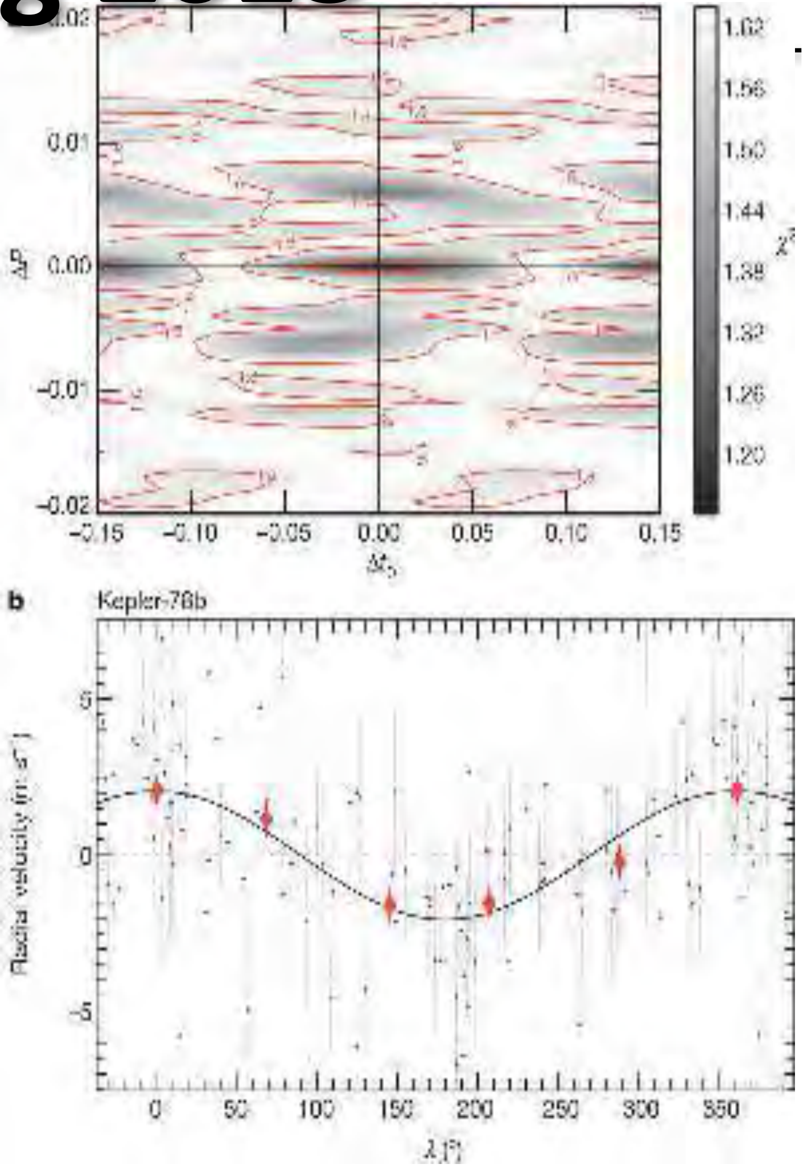
‘c’ is an extremely massive dense rocky planet – a challenge for planet formation theory

Dumusque et al 2014

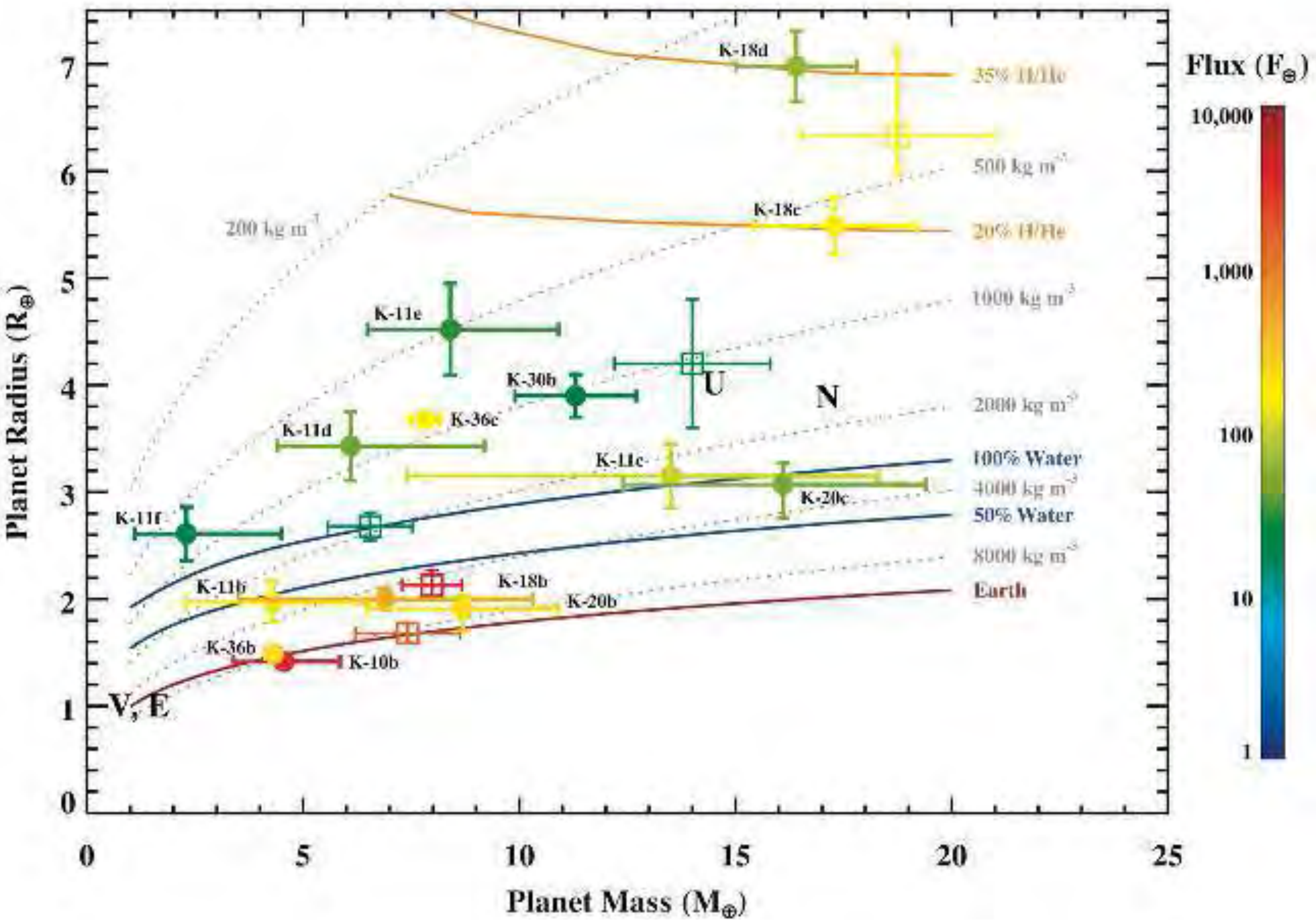
Kepler-78b Aug 2013

"Just like the earth but 2000K hotter"…..

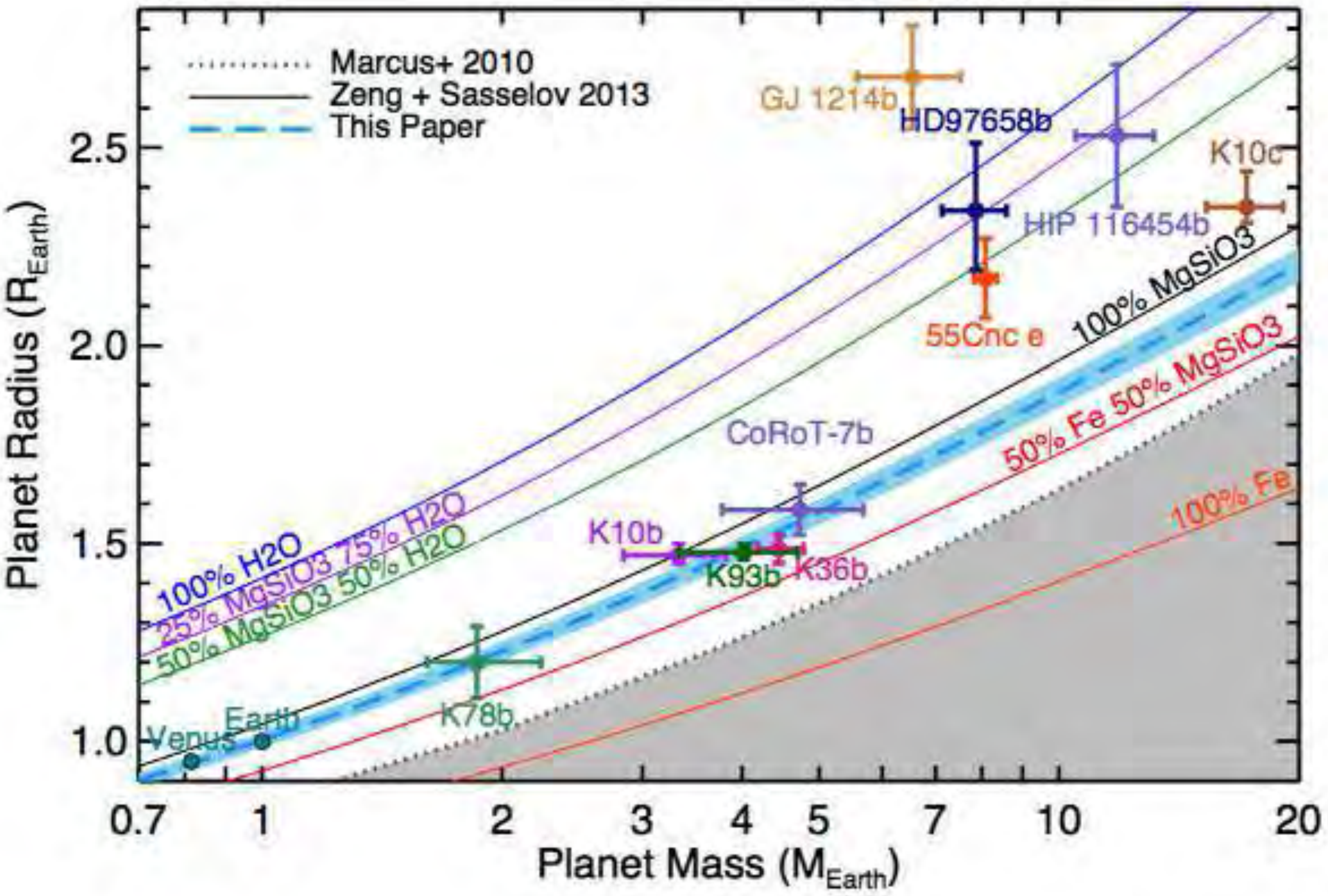




Composition of Small Planets



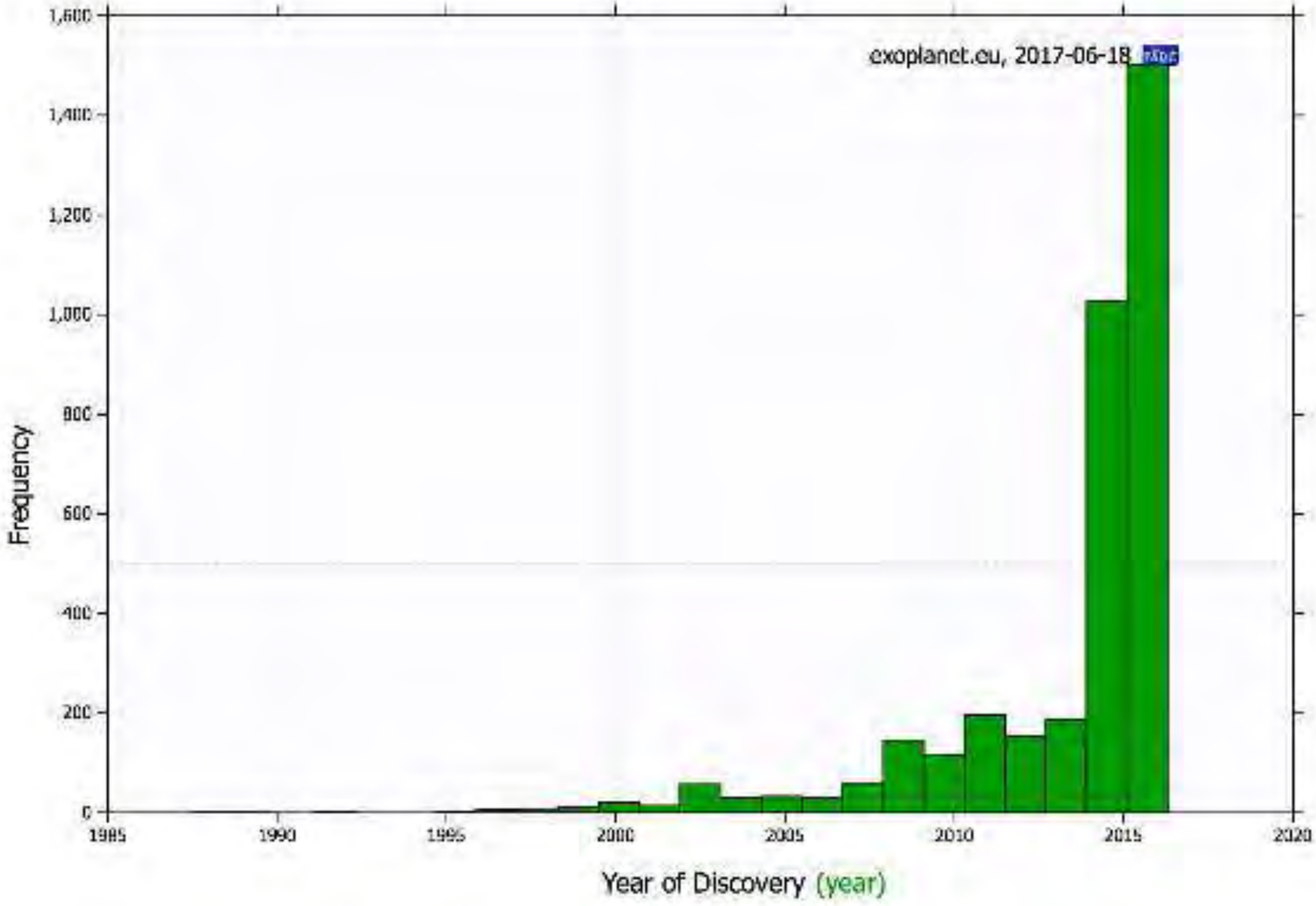
Best results so far



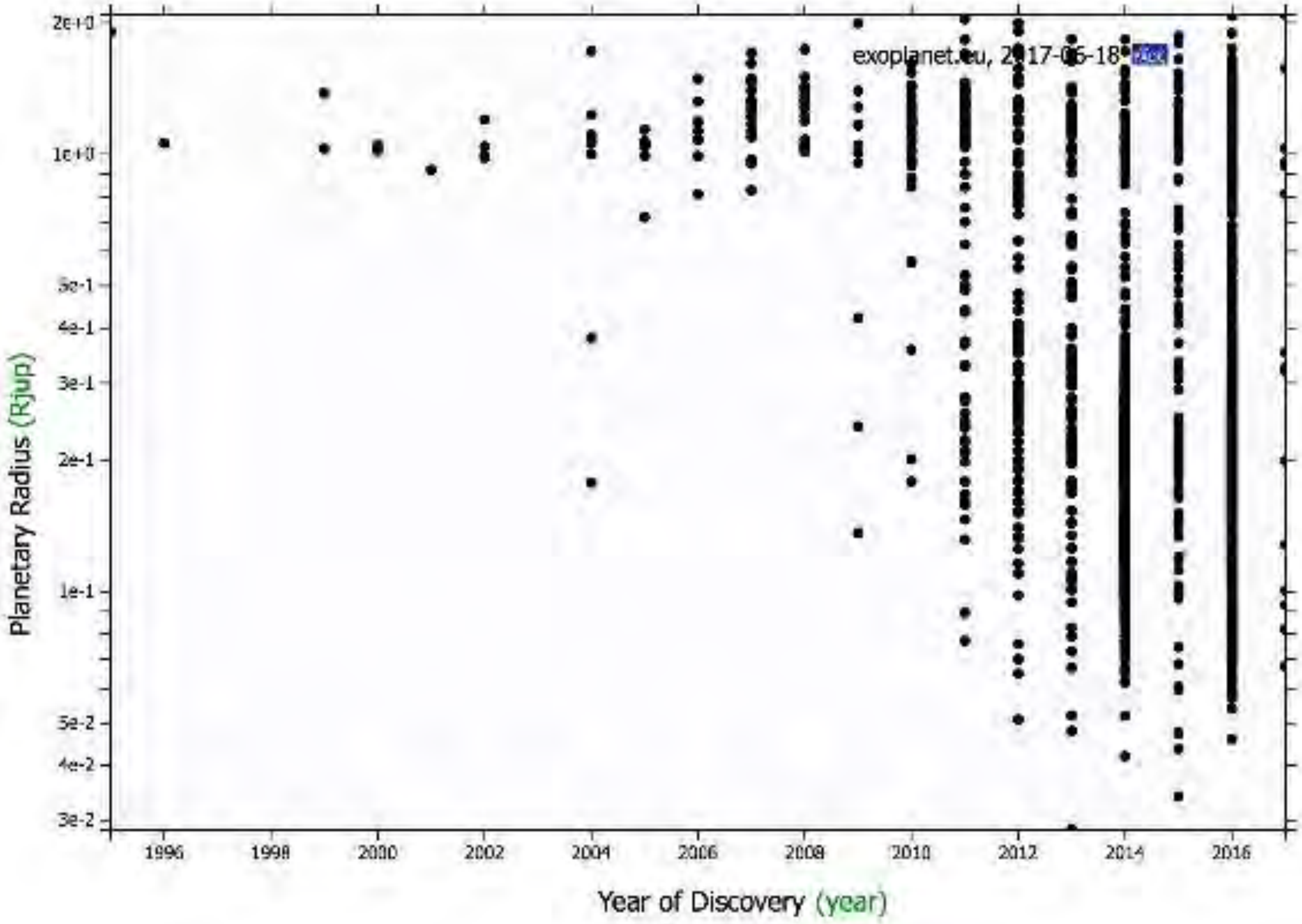
Dressing et al 2014

Only masses with better than 20% precision

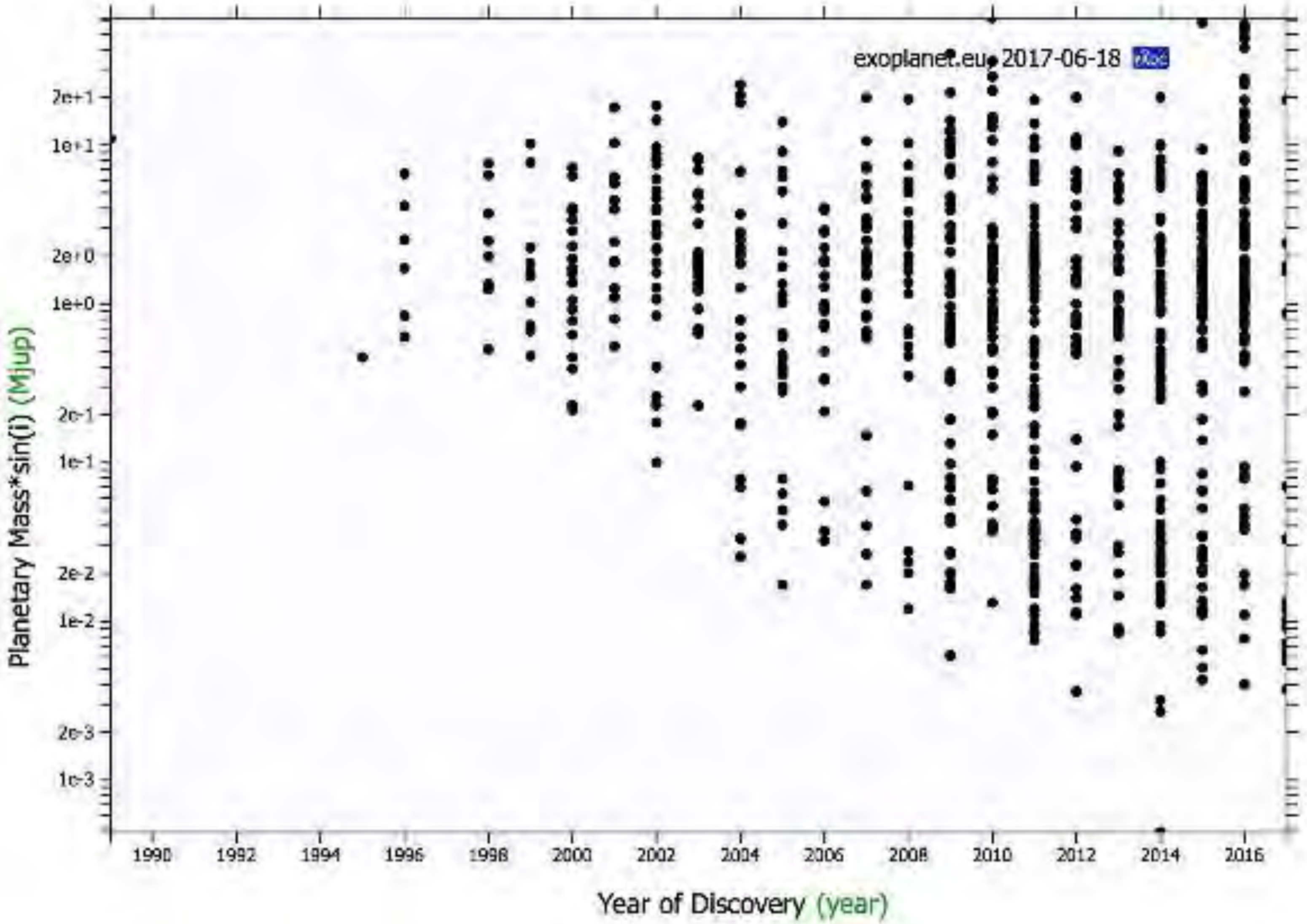
Combined discovery rate since over the last 30 years



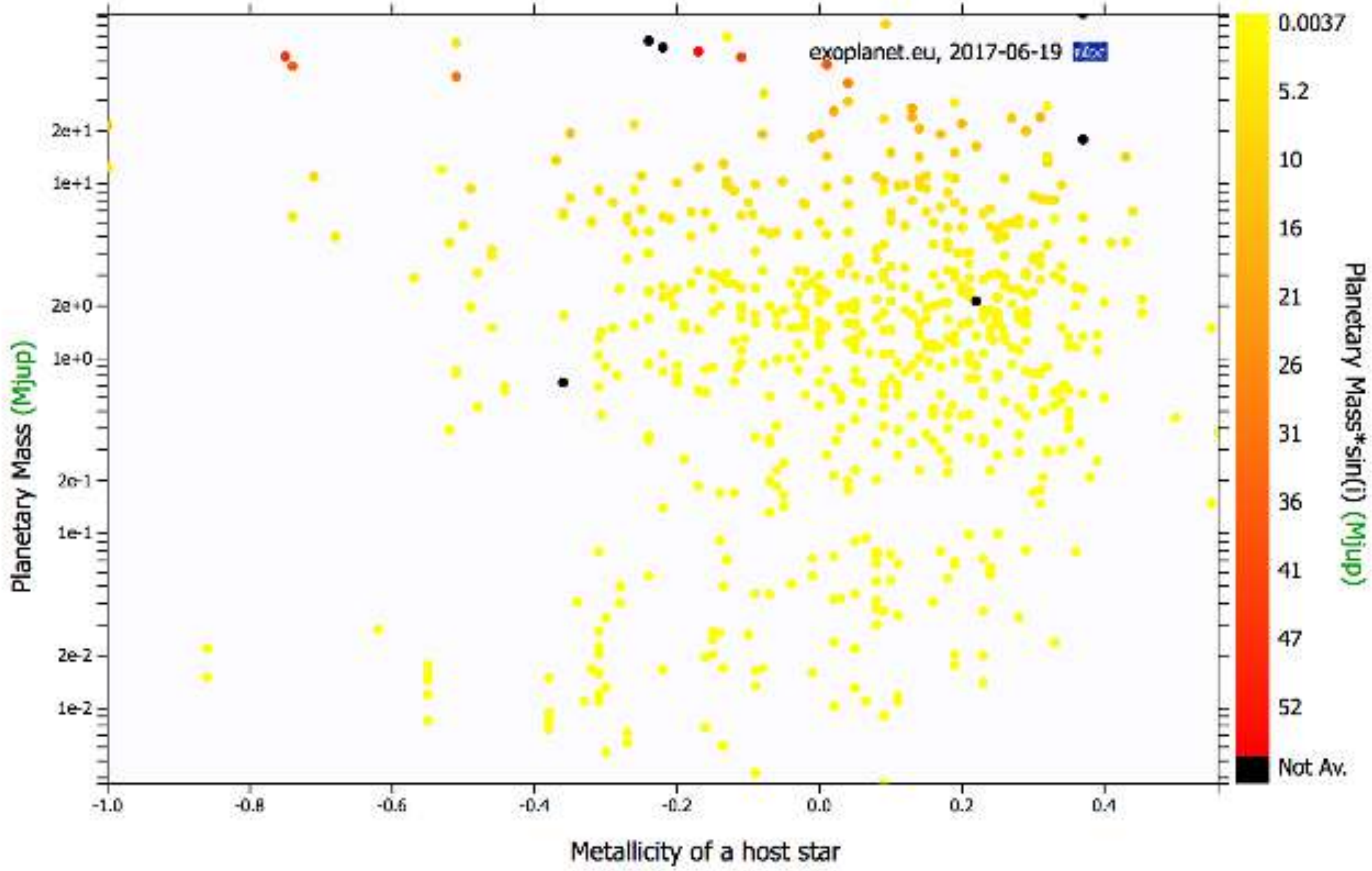
Improvement in radius sensitivity



Improvement in mass sensitivity

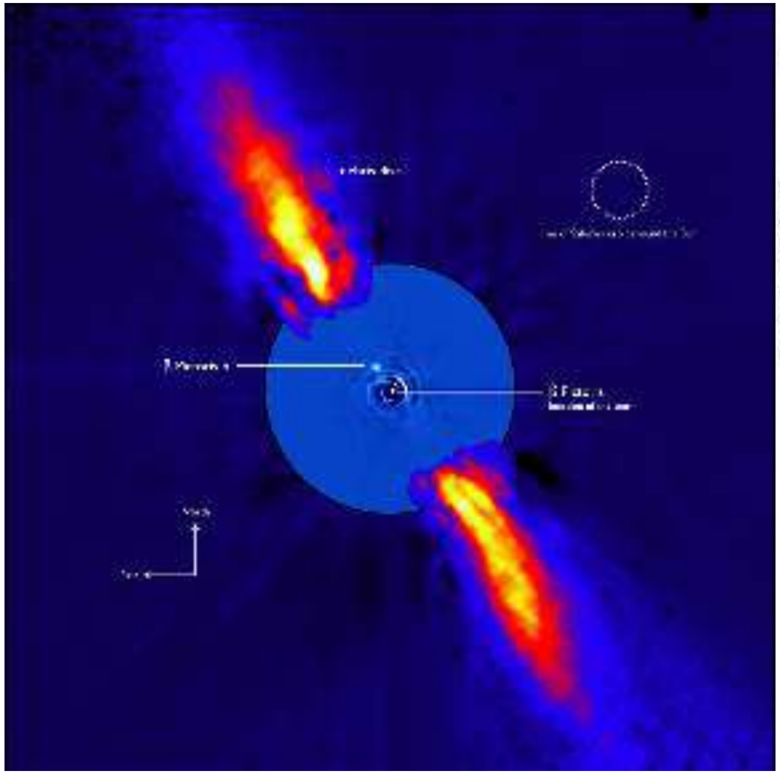


Population characteristics: metallicity of host star

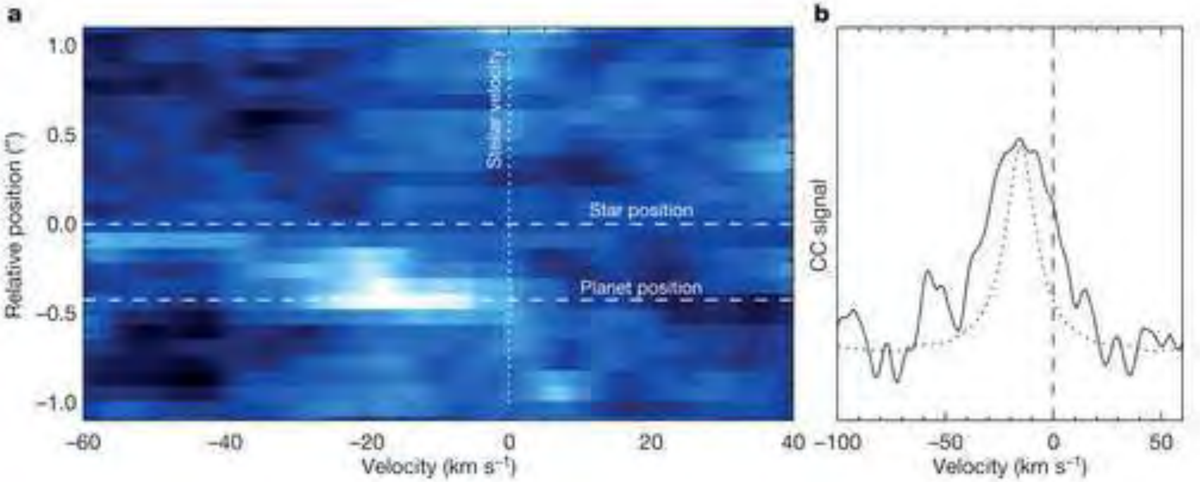


Planet Rotation

Snellen et al 2014



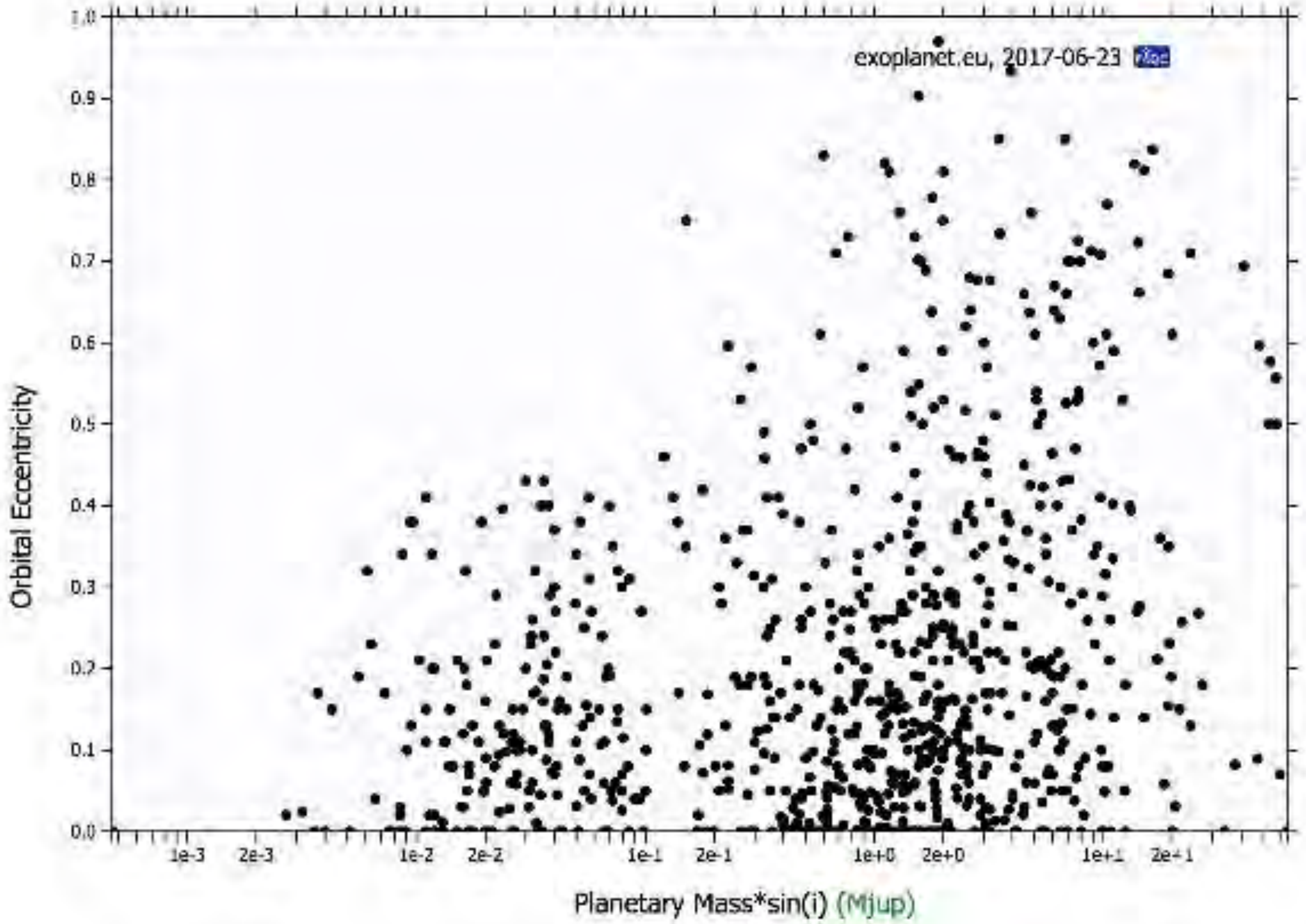
ESO VLT



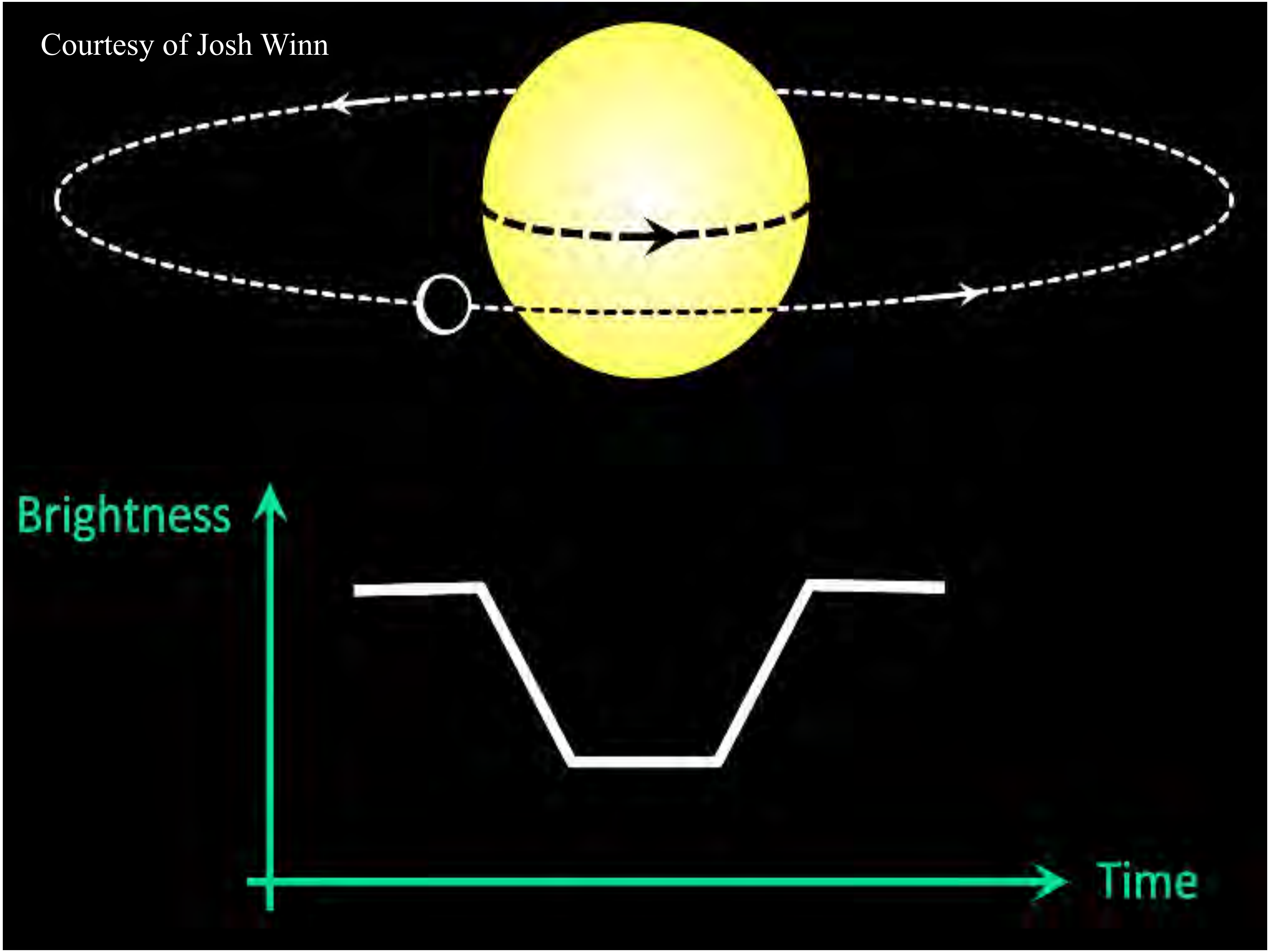
P_{rot} ~ 8 hr ($V_{equatorial}$ ~ 10^5 km/hr)

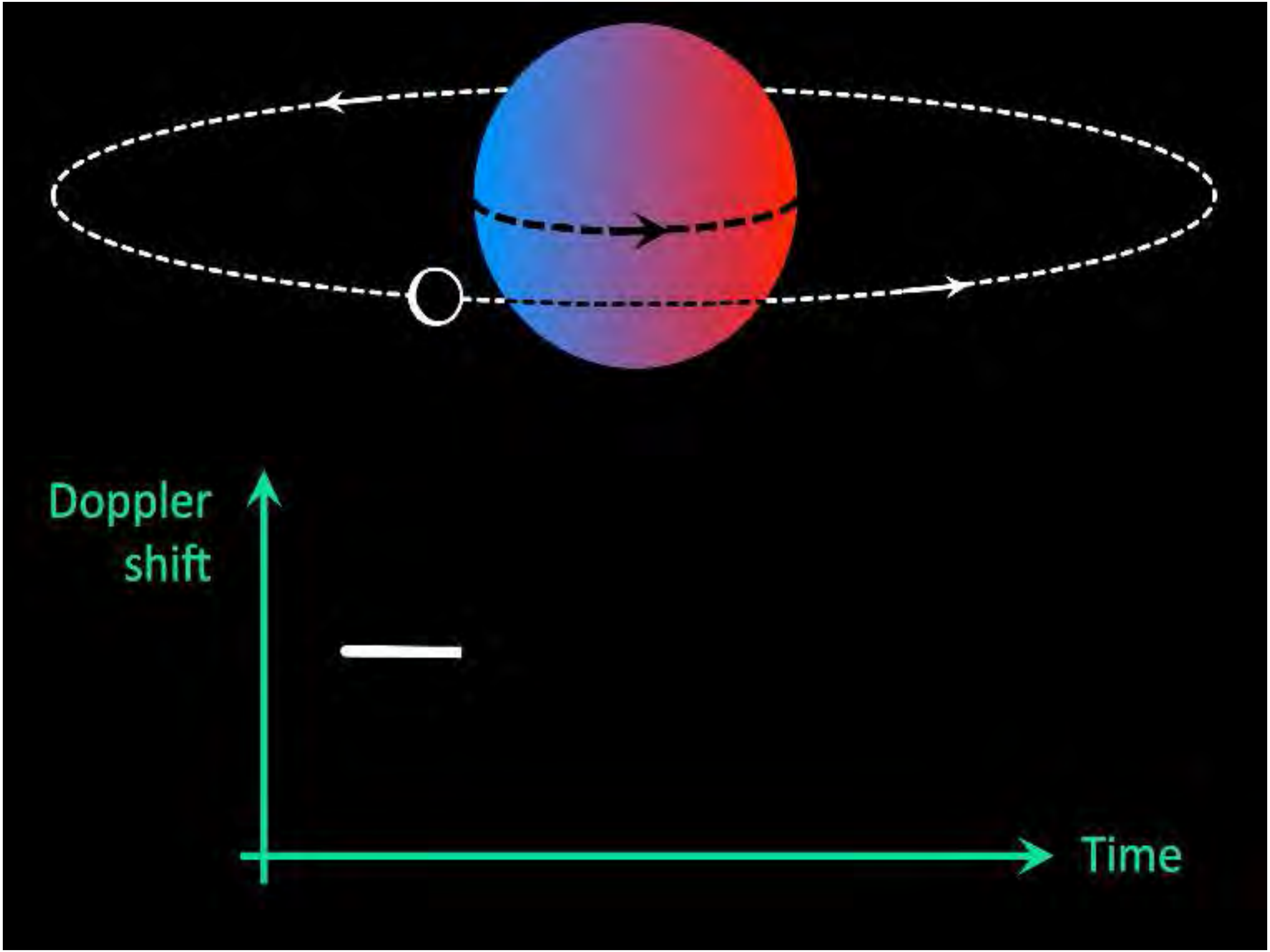
Faster than any solar system planet (but also more massive and much younger)

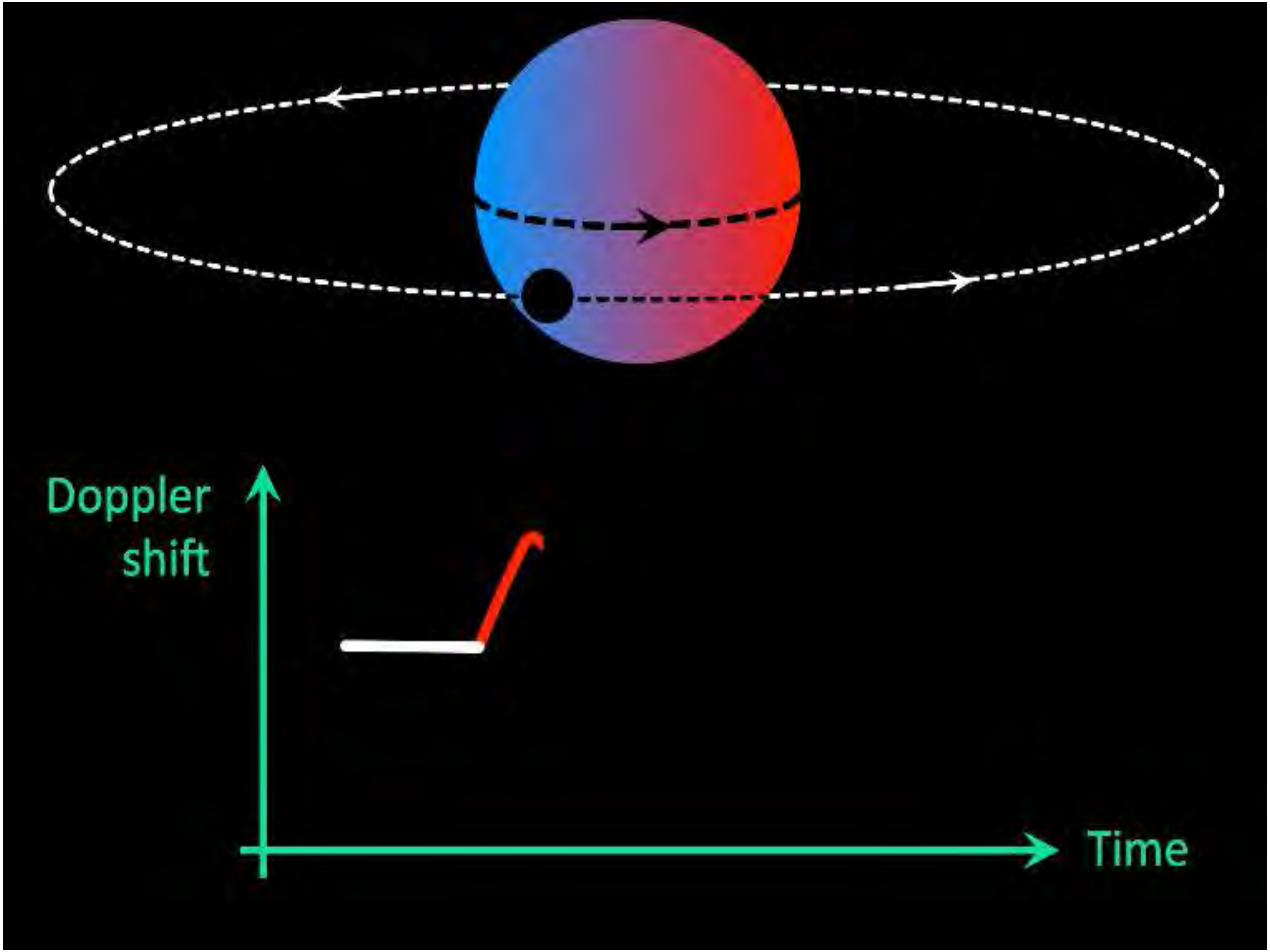
Planet Mass and Orbital Eccentricity

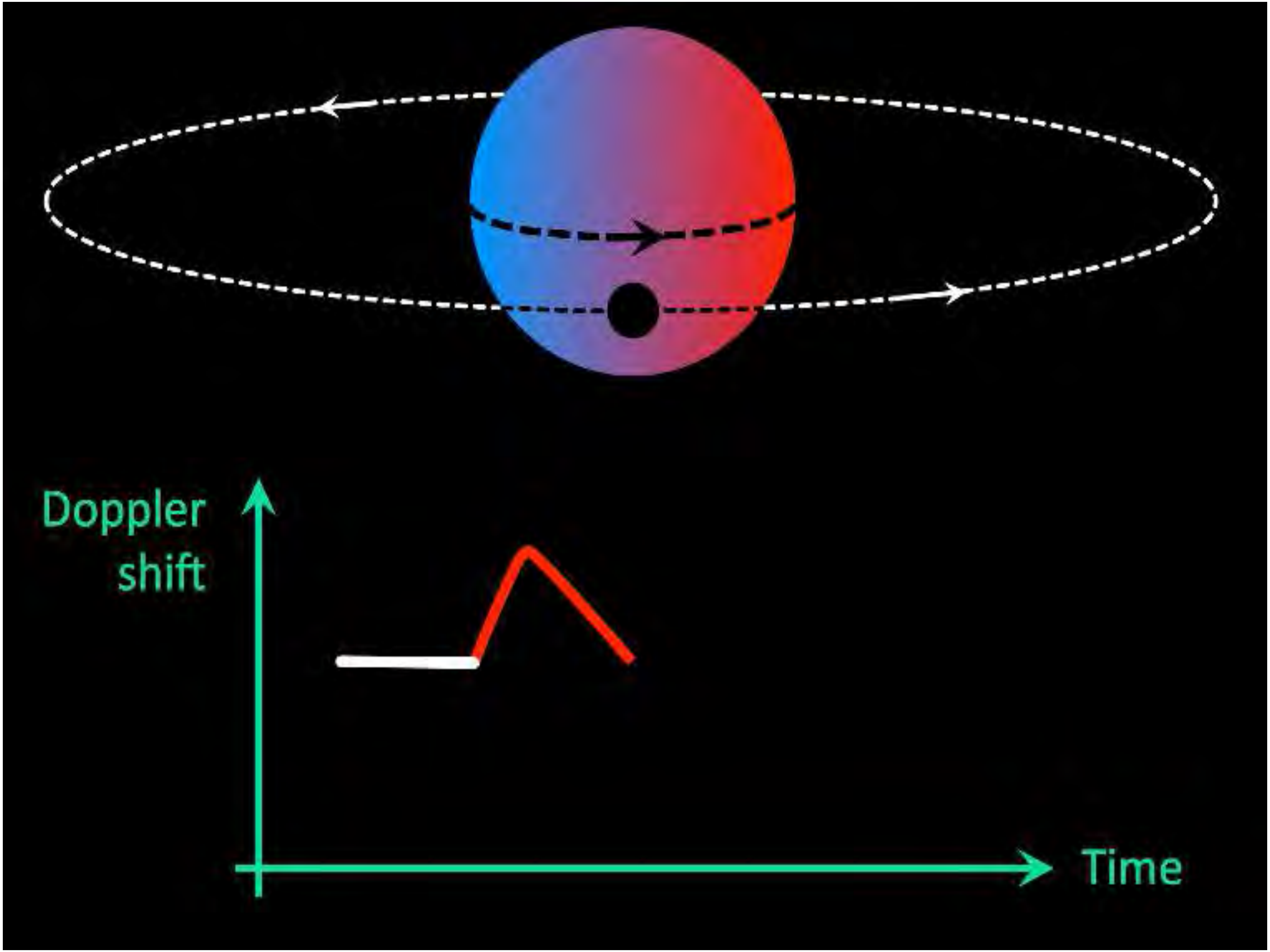


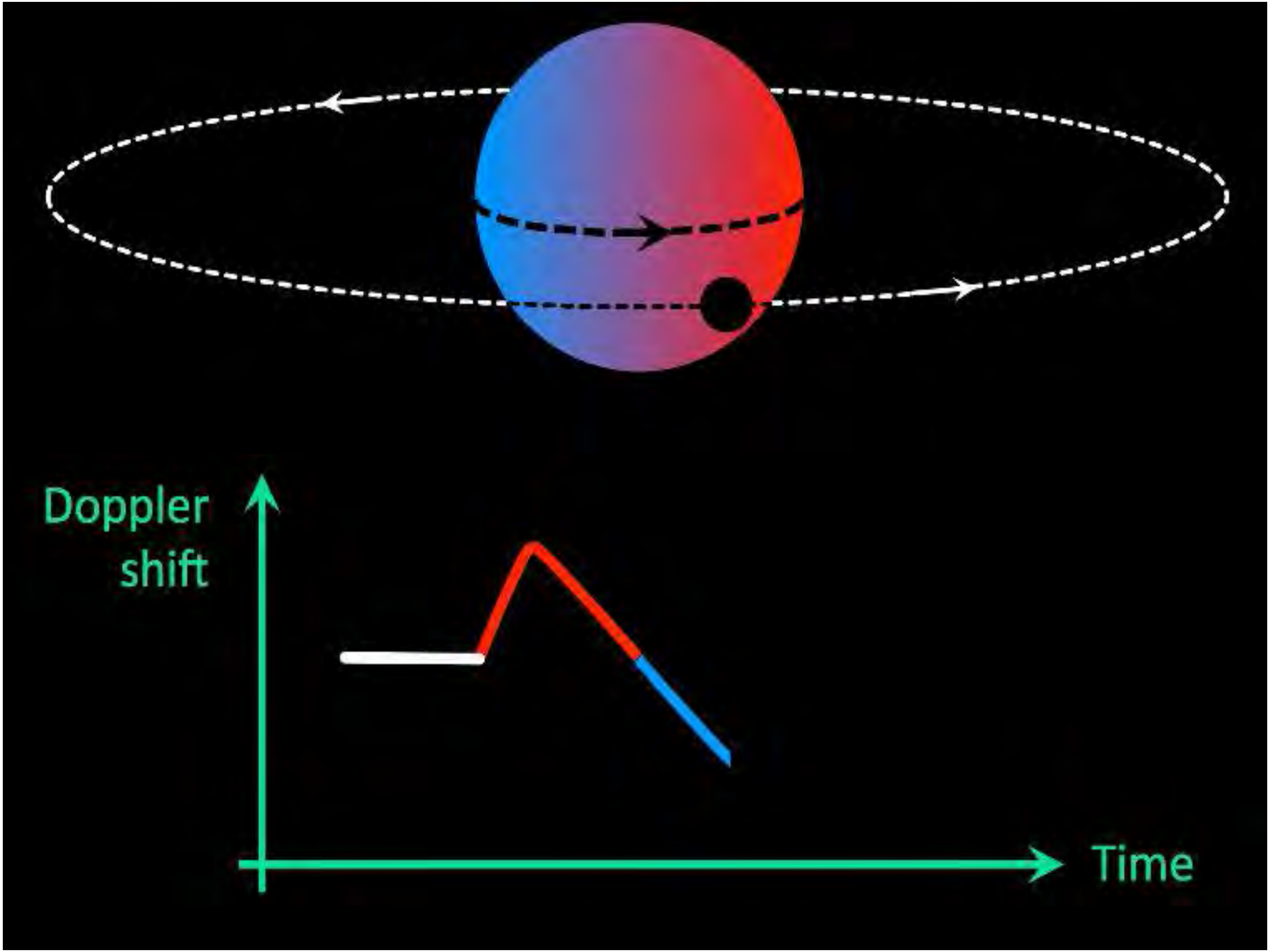
Courtesy of Josh Winn

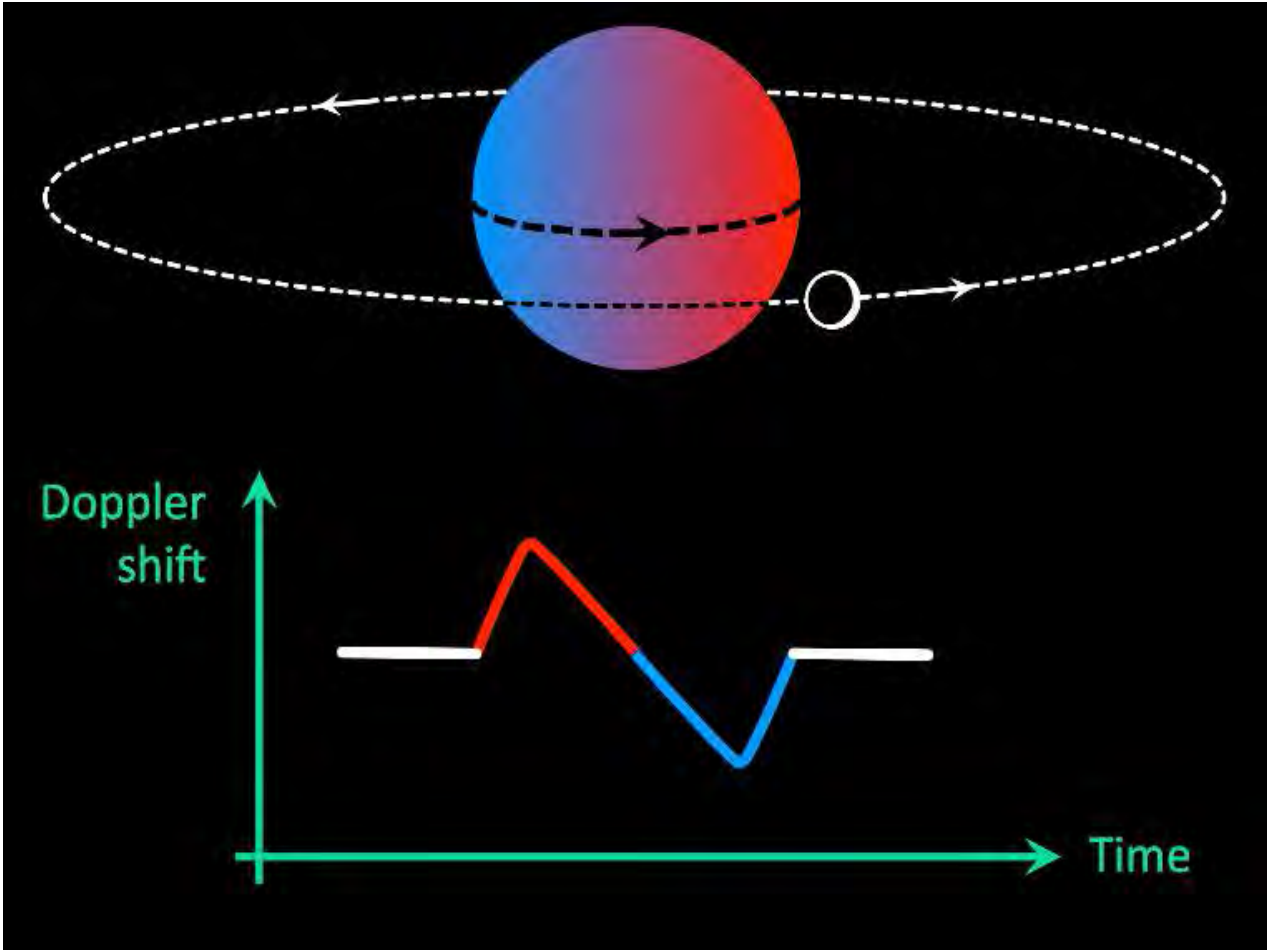


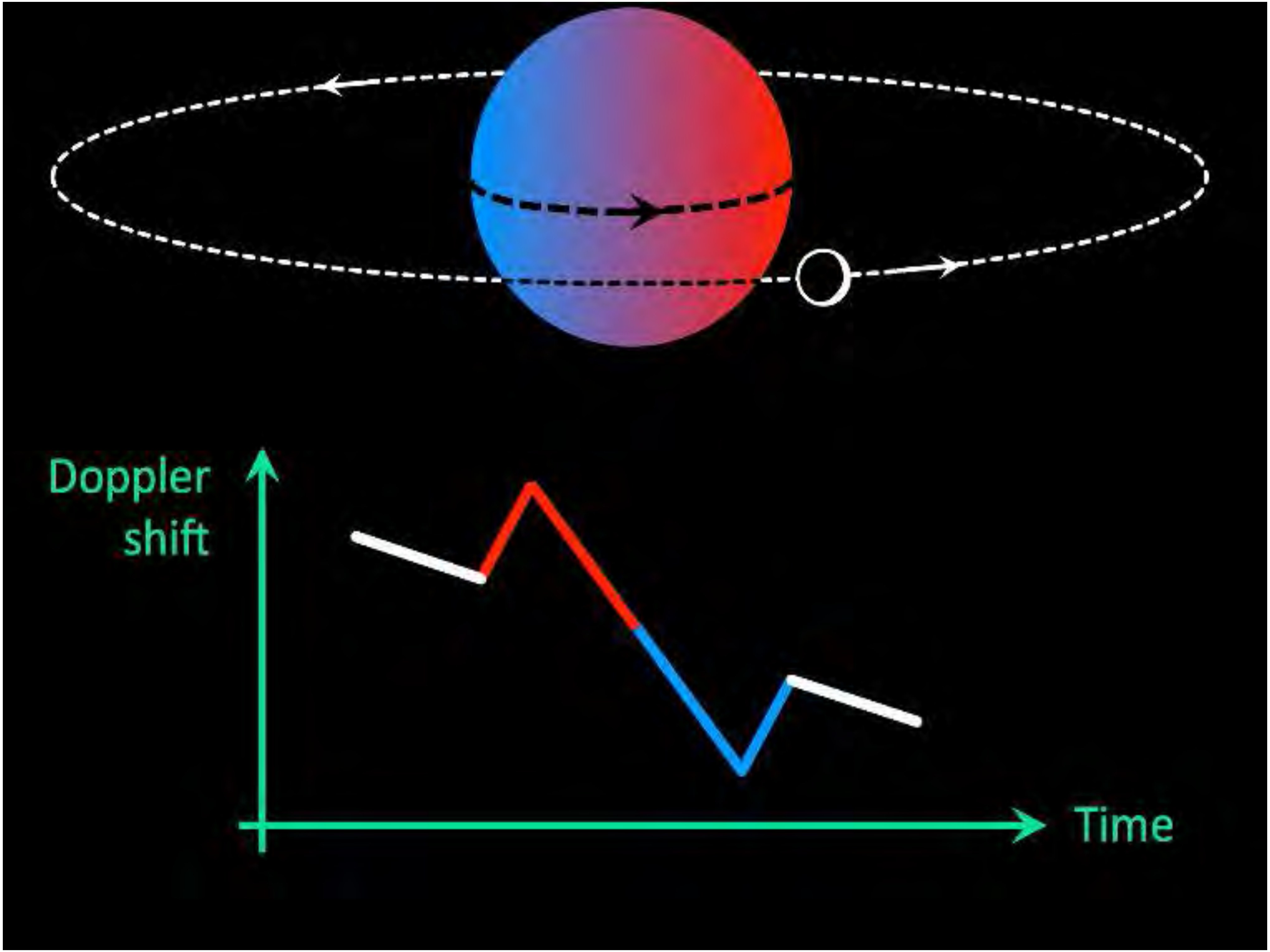

Doppler shift
Time


Doppler shift
Time

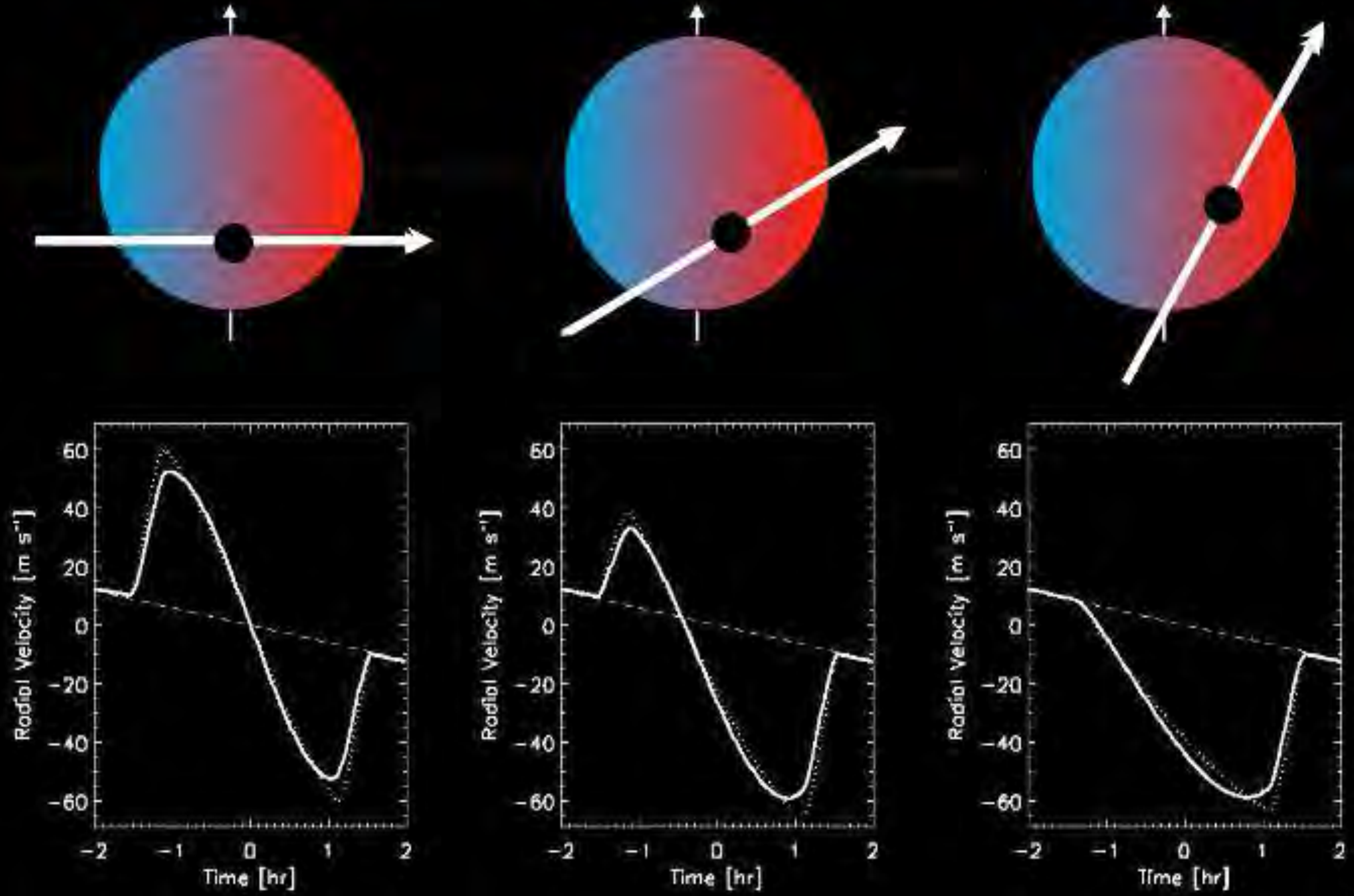

Doppler shift
Time


Doppler shift
Time

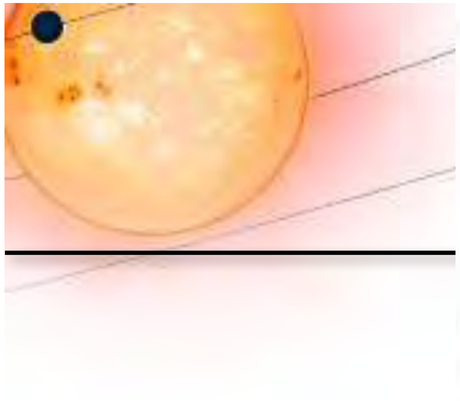

Doppler shift
Time

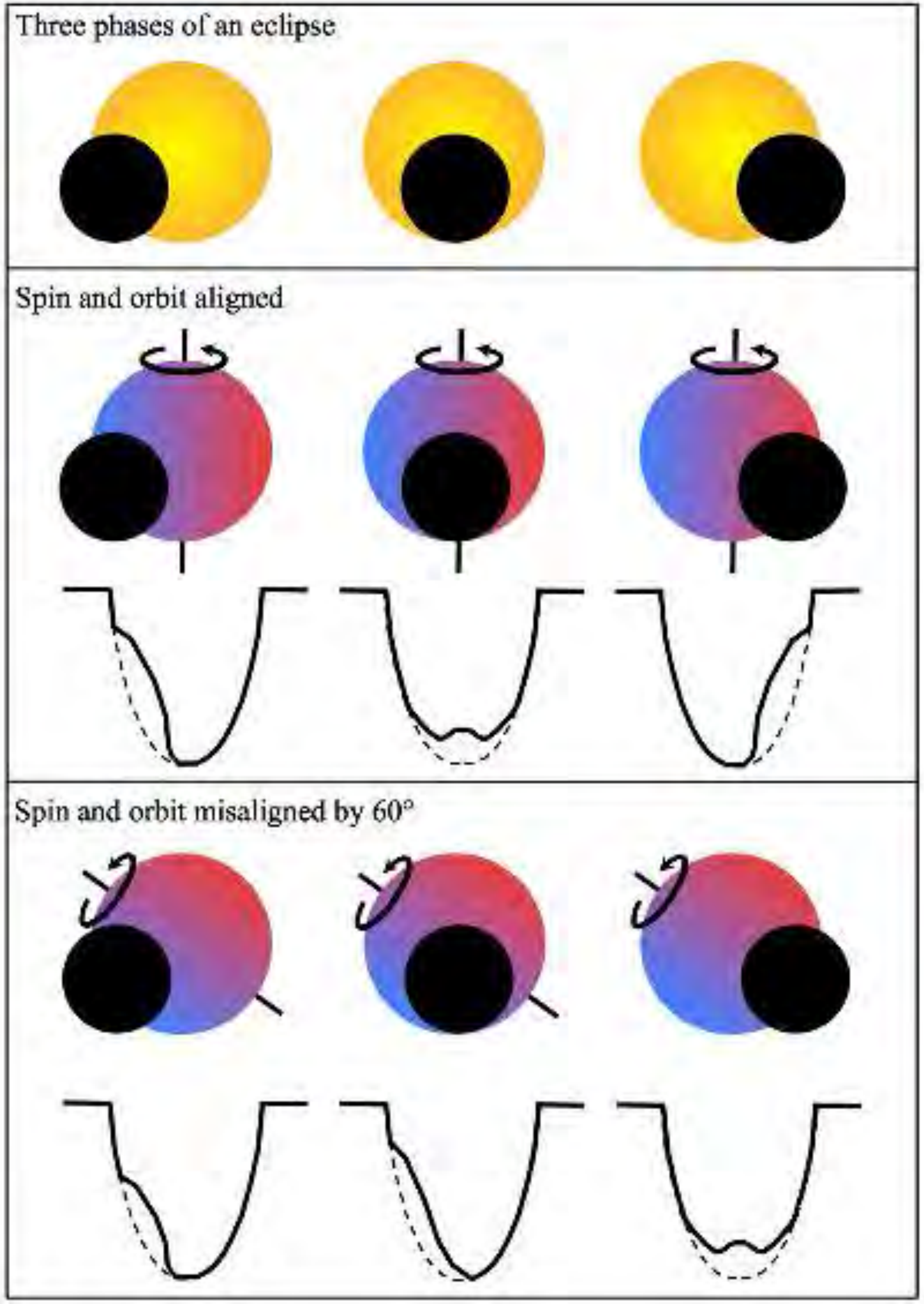

Doppler
shift
Time

Measuring the stellar obliquity



Queloz et al. (2000); Ohta, Taruya, & Suto (2005); Gaudi & Winn (2007)



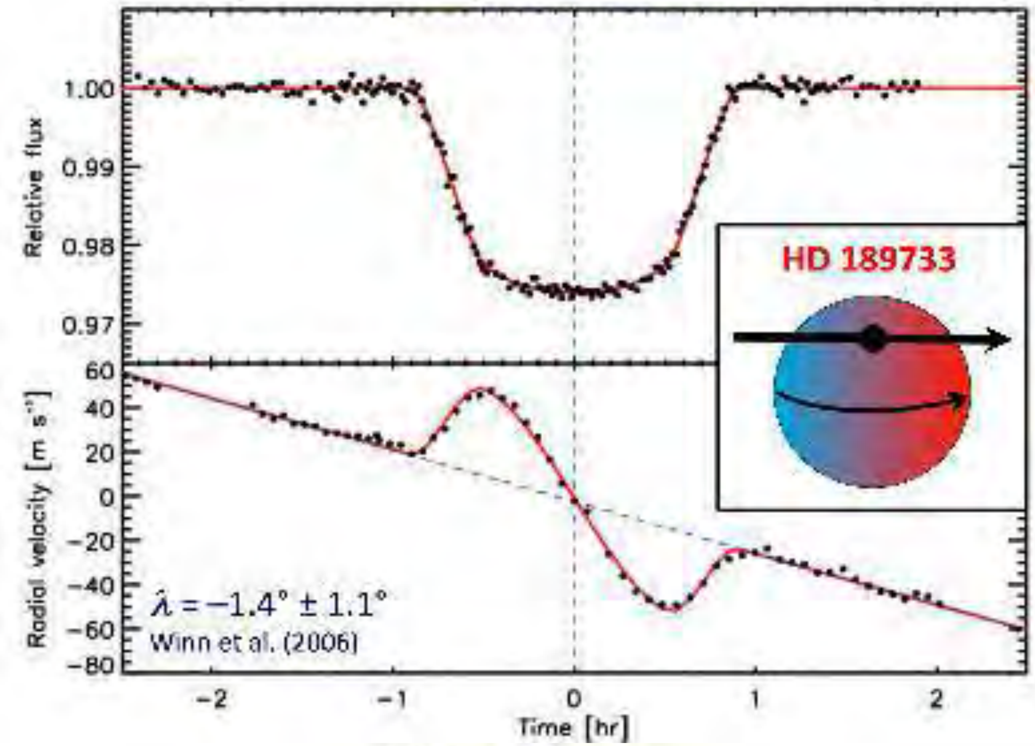


Three phases of an eclipse

Spin and orbit aligned

Spin and orbit misaligned by 60°

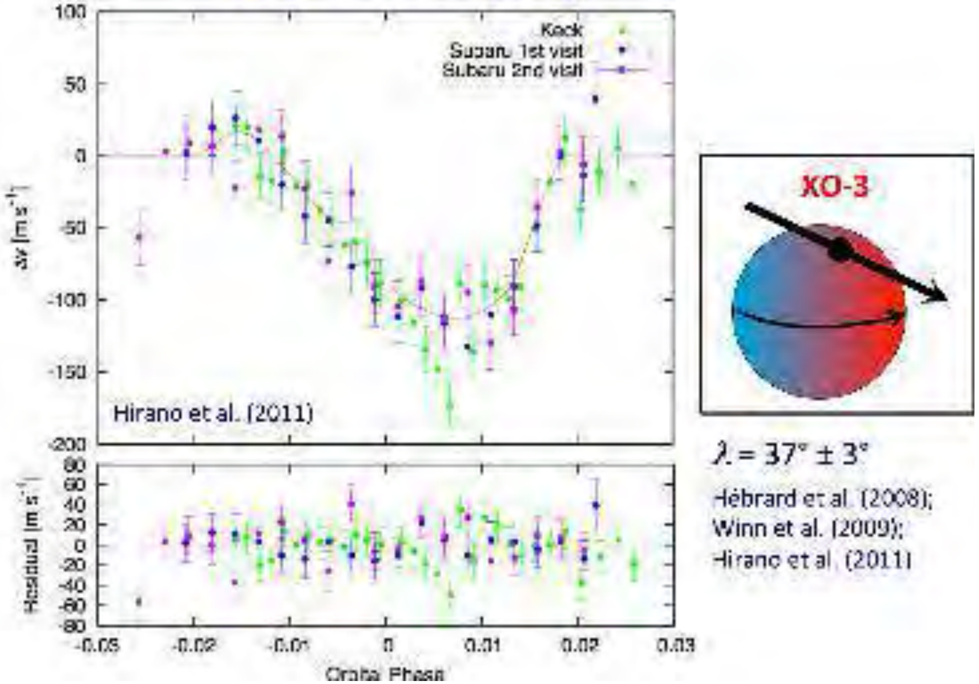
Low obliquity



$\lambda = -1.4° \pm 1.1°$

Winn et al. (2006)

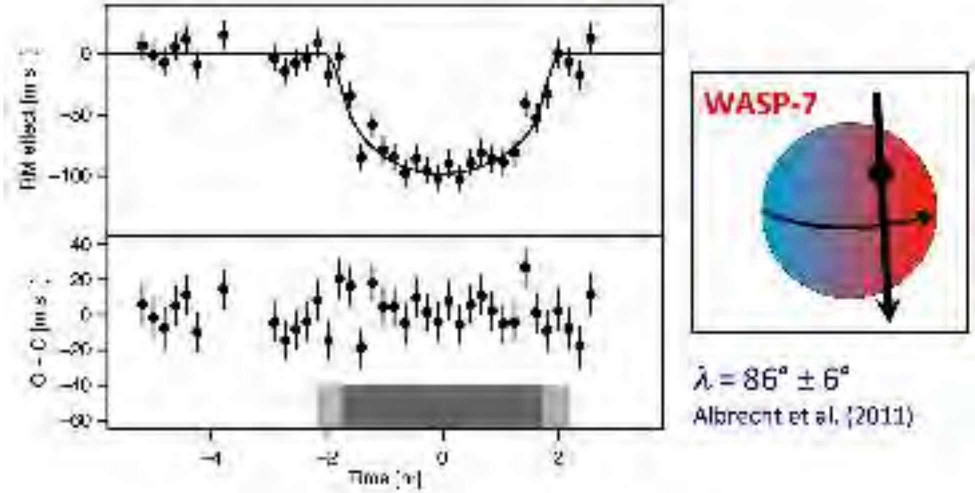
Moderate obliquity



$\lambda = 37° \pm 3°$

Hébrard et al. (2008);
Winn et al. (2009);
Hirano et al. (2011)

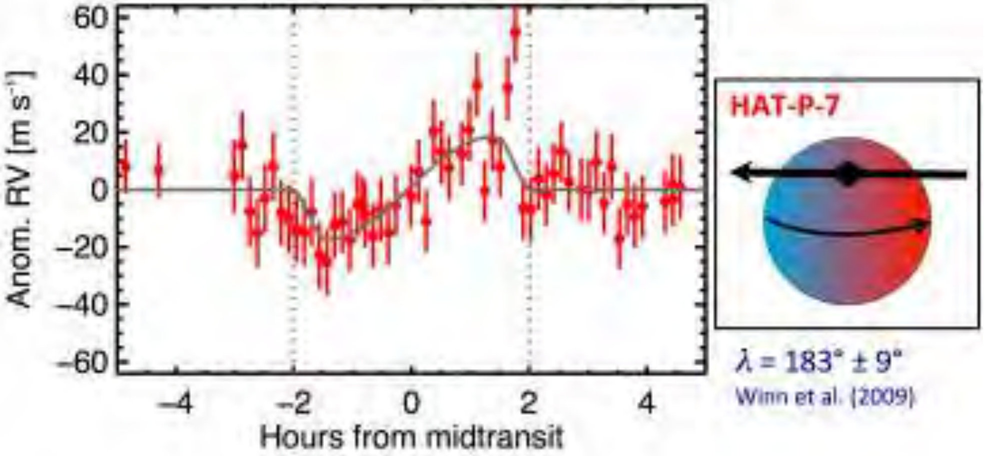
High obliquity



$\lambda = 86° \pm 6°$

Albrecht et al. (2011)

Very high obliquity (retrograde)

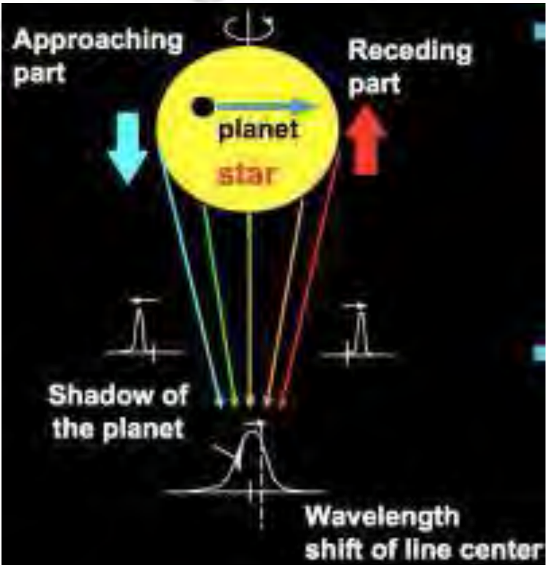


$\lambda = 183° \pm 9°$

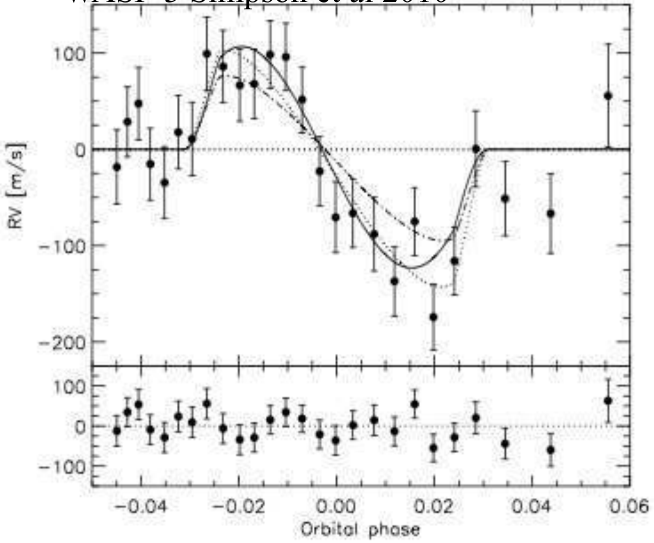
Winn et al. (2009)

Orbital Characterisation: Host star spin axis v’s orbital plane alignment I

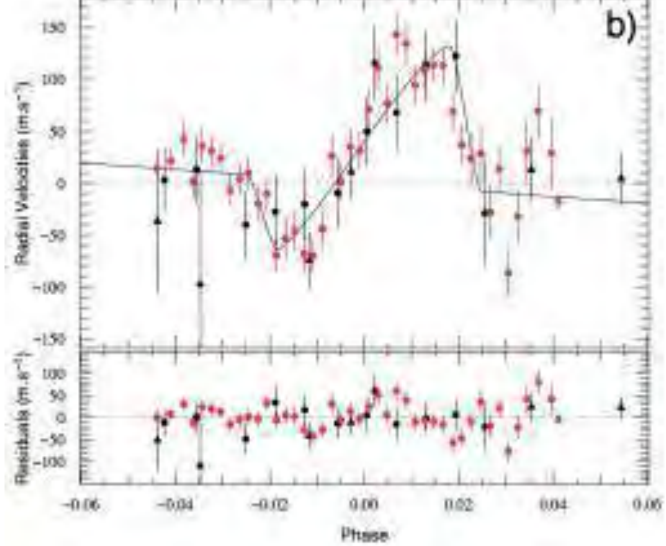
Rossiter-McLaughlin effect (



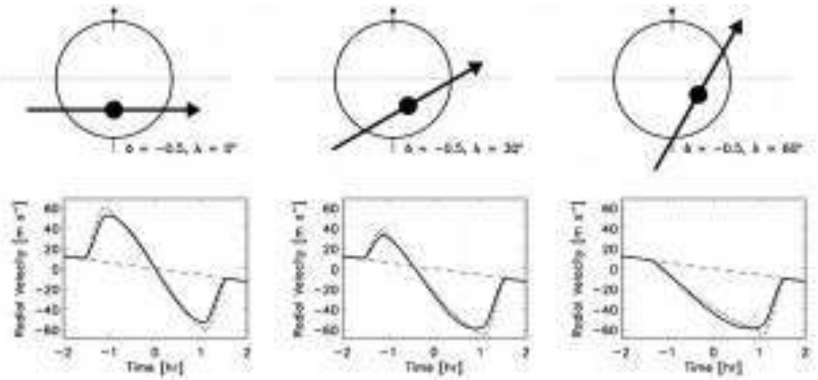
WASP-3 Simpson et al 2010



WASP-17 Triaud et al 2010

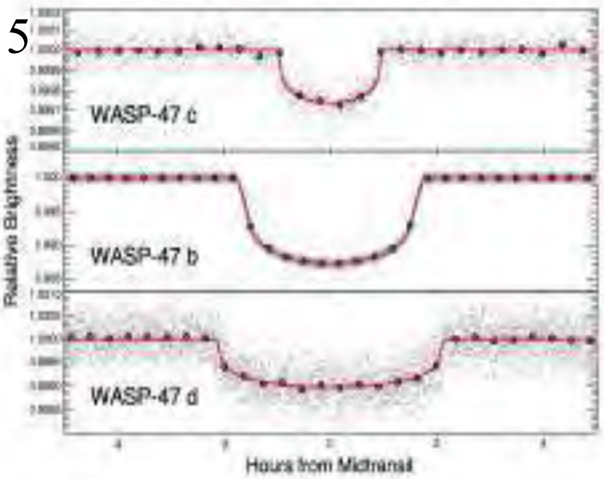


Misalignment => HJ caused by planetary scattering



But…. Becker et al 2015

K2 found additional transiting planets in HJ system
=> Disc migration



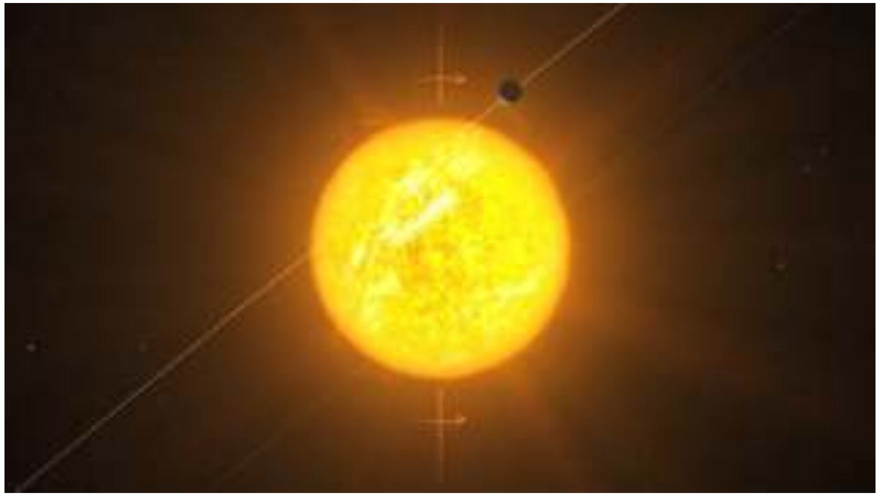
Orbital Characterisation: Host star spin axis v's orbital plane alignment

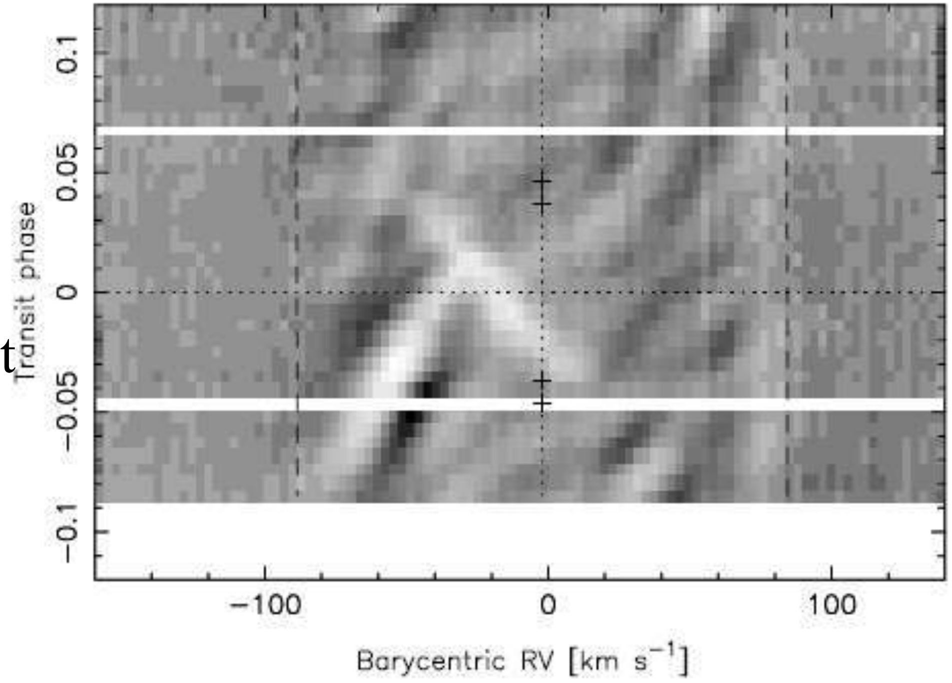
- Maybe 85% hot jupiters mis-aligned!

- Winn et al 2010: strong misalignments more common in planets orbiting hot stars: g.g. WASP-33b (A5V)

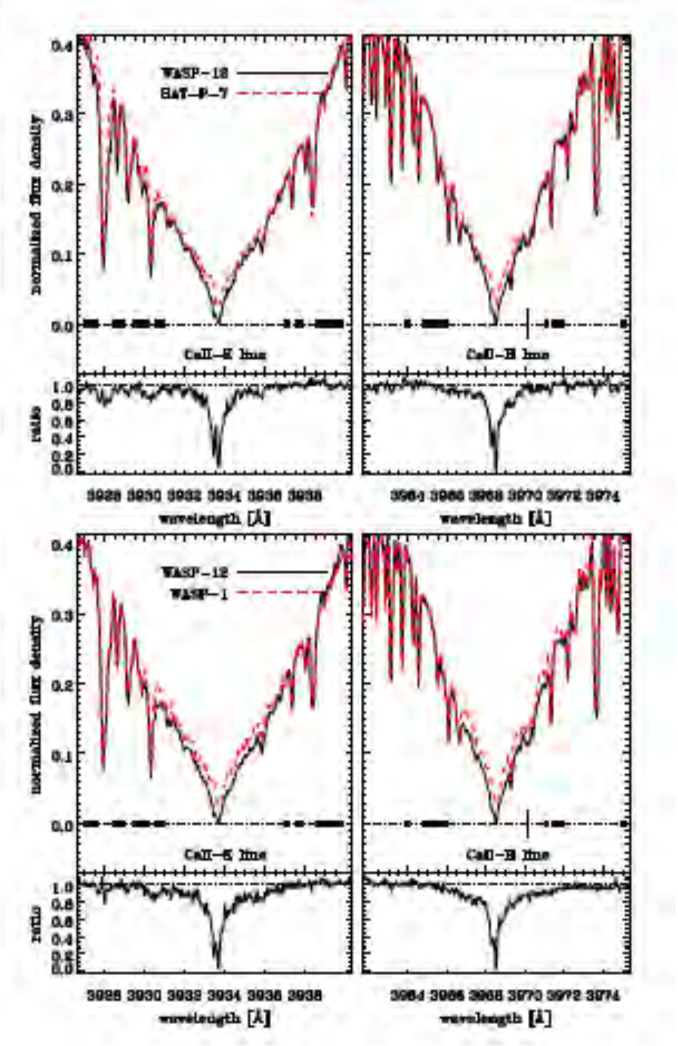
- Misalignment via seismology.

Remember Gas giants must have formed at great distance from the host and somehow migrated inwards. Clues to planet-planet scattering.





Evaporating Planets I

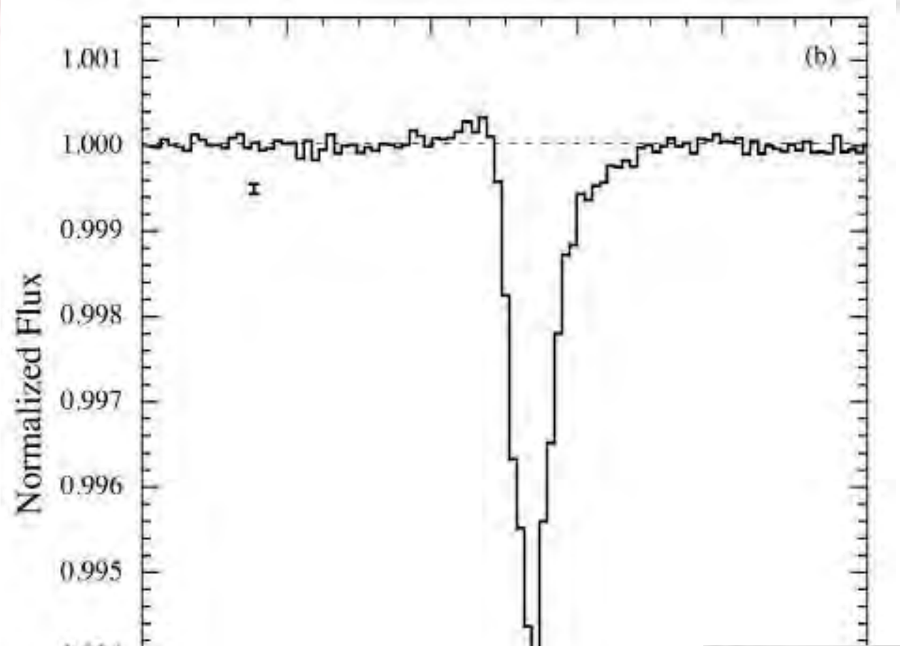


WASP-12b (2009)

What happens if you exposure a hot jupiter to intense radiation? Evaporation => compressed s-earth core

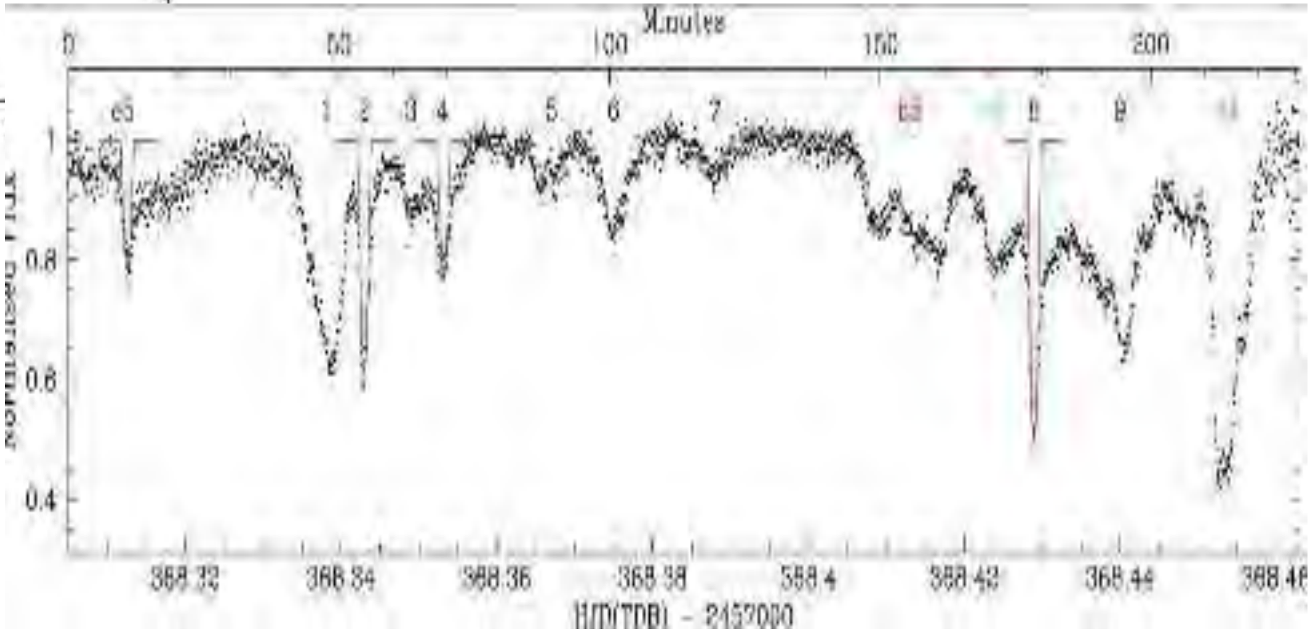
GJ436 (2015)

Evaporating Planets II



KIC 12557548 (2012)

Evaporating rocky planet



WD1145+017
White Dwarf accretion of asteroid
Gaensicke et al 2016

Atmospheric Characterisation

Often use “Scale Height” (H) to describe an atmosphere: vertical distance above the surface at which the density or pressure if the atmosphere decreases by exactly 1/e or (2.718)-1 times. So

$$P(z)=P_0\ e^{-z/H} \quad \text{where} \quad H= kT/mg$$

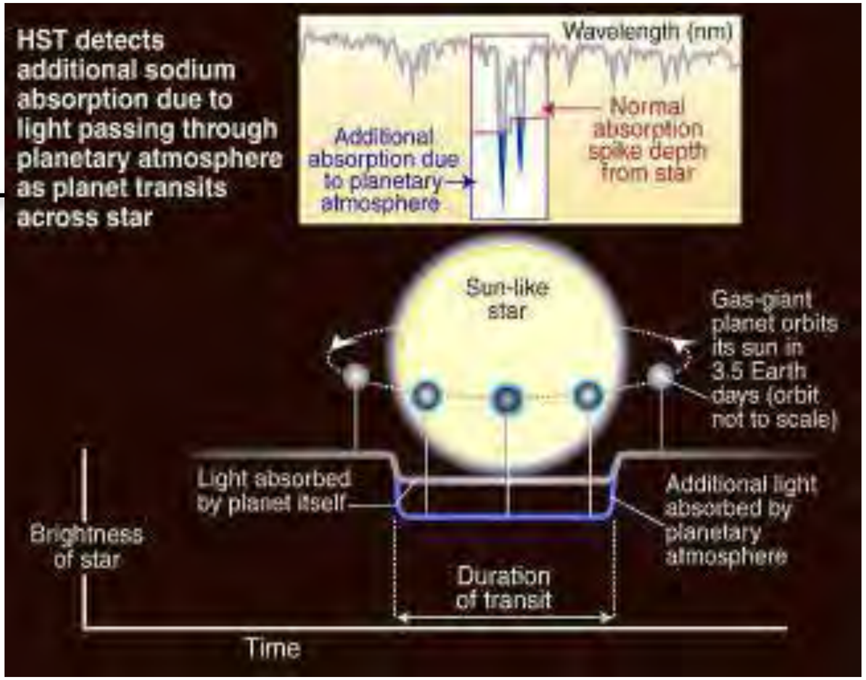
P=Presure, z=vertical height, k=Boltzmann, m=mean atomic mass, g=accl due to gravity

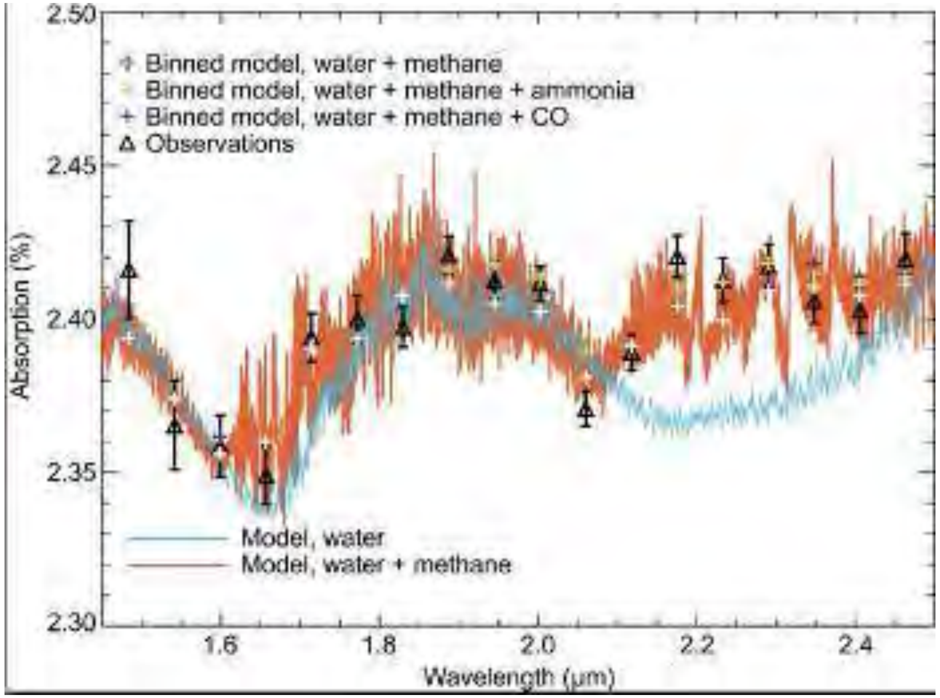
H for a hot-Jupiter ~ hundreds of km’s
H for Jupiter ~ 30km (60km for Saturn)
H for Earth < 10km

Atmospheric Characterisation of Hot-Jupiters

- Information from Transit (radius), emission spectra (close to secondary eclipse), transmission spectra (transit), reflection
- Line emission observations better established (originally done with HST Charbonneau et al 2002), repeated from the ground.
- Molecule results very controversial (Gibson et al 2011). Ground based confirmation maybe (Swain et al 2010).

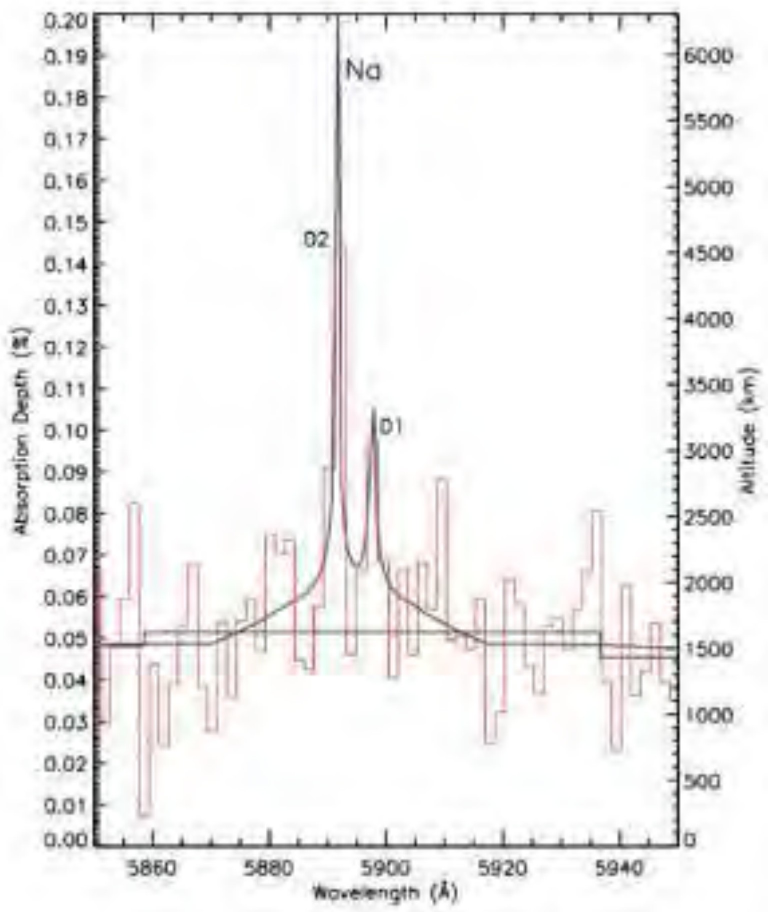
- Kepler/Corot planet hosts far too faint to be used even with an ELT





Tinetti et al 2008

Spectroscopy: Na I



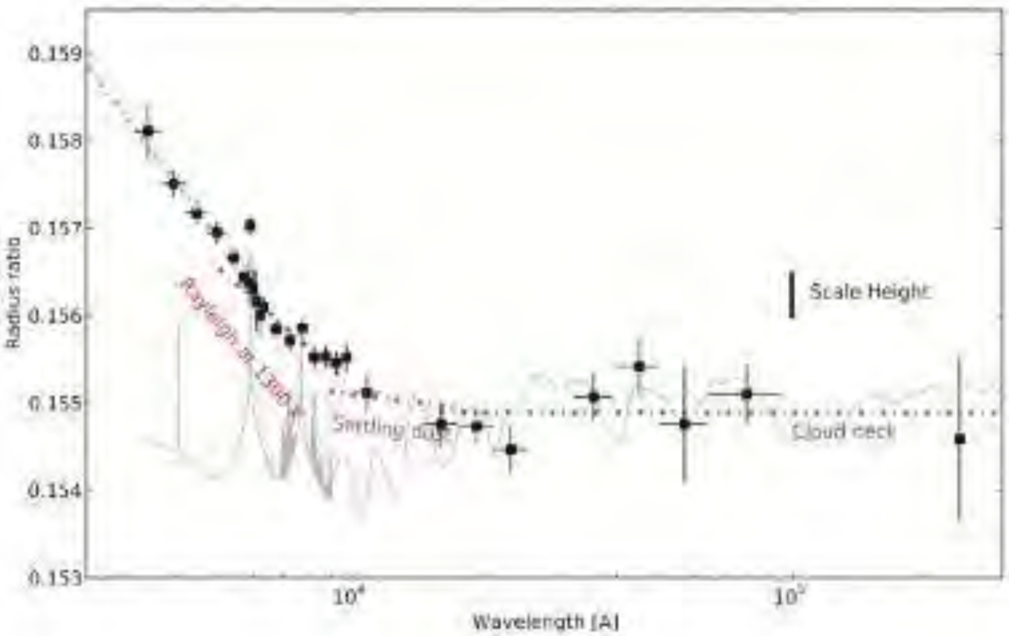
Spectrum around the sodium D doublet in the atmosphere of HD 209458 b measured by Sing et al. (2008) using archive HST STIS observations.

Some atomic features visible – Na I (Charbonneau et al 2002) observed from HST and more recently from the ground.

Best established atmosphere results

Spectroscopic measurements

Because Hubble is in low earth orbit measurements are taken over a number of transits and then combined (danger from stellar variability). Combined with spitzer photometry



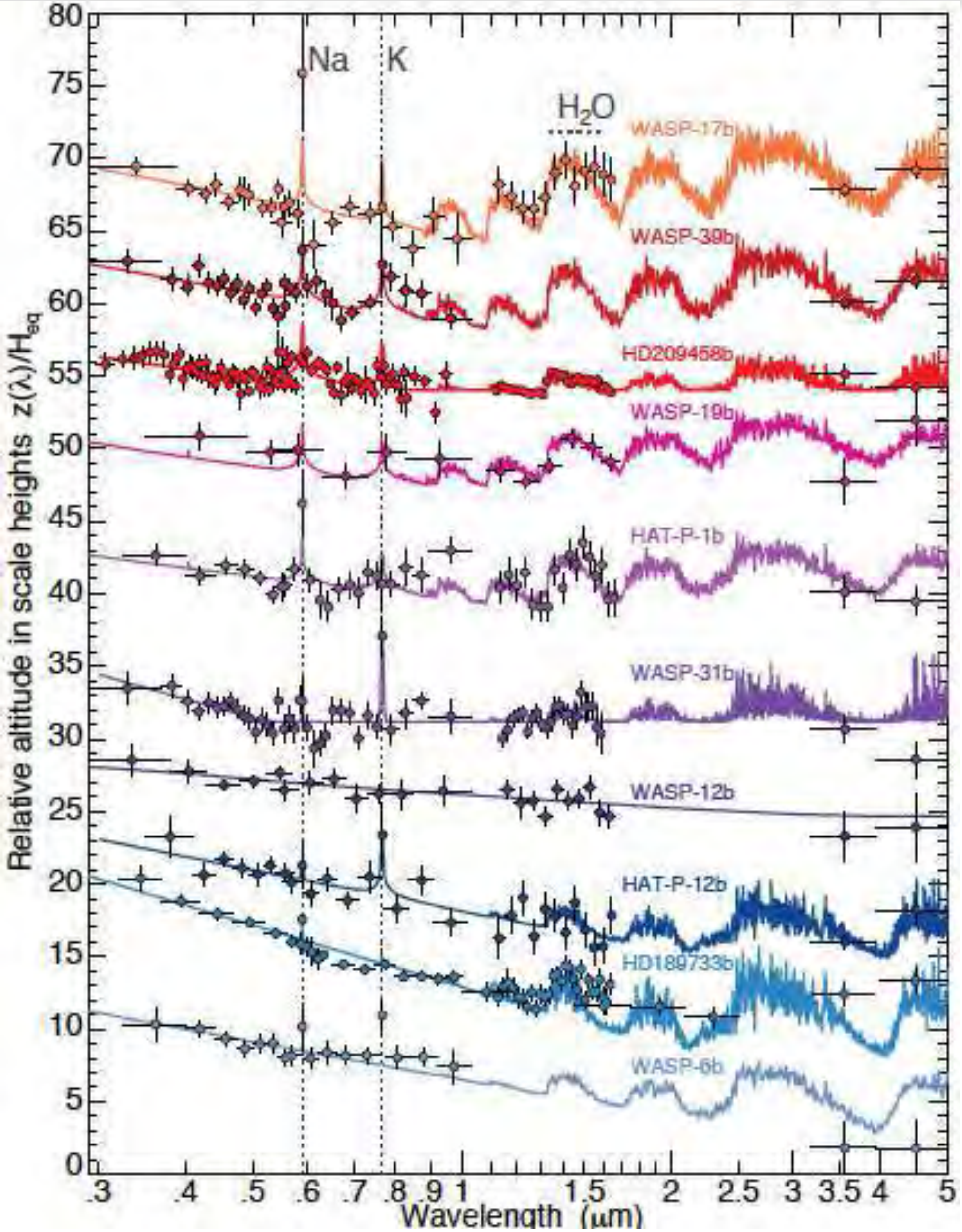
Transmission spectrum of HD 189733b, showing the core of the sodium and potassium lines, and the signature of aerosols. [Fig. 1 from the paper].

Many HJ appear cloudy, only 2-3 neptunes observed

Atmospheres of Hot Jupiters

HST + Spitzer
10 exoplanets
covering 0.3 – 5 µm
T_{eq} 950-2500K

Able to detect:
Na
K
H_2O
Haze
Clouds



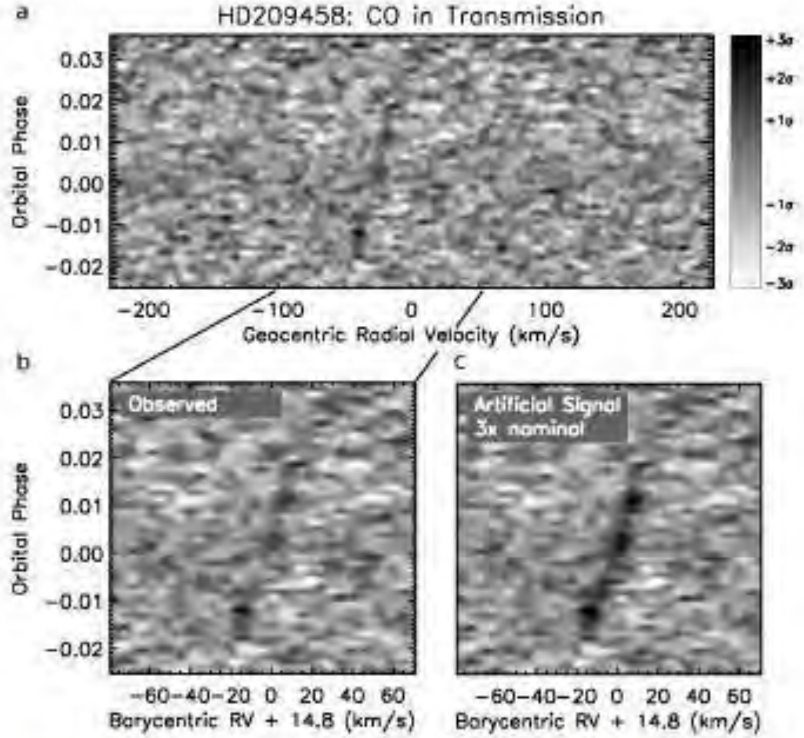
Clear

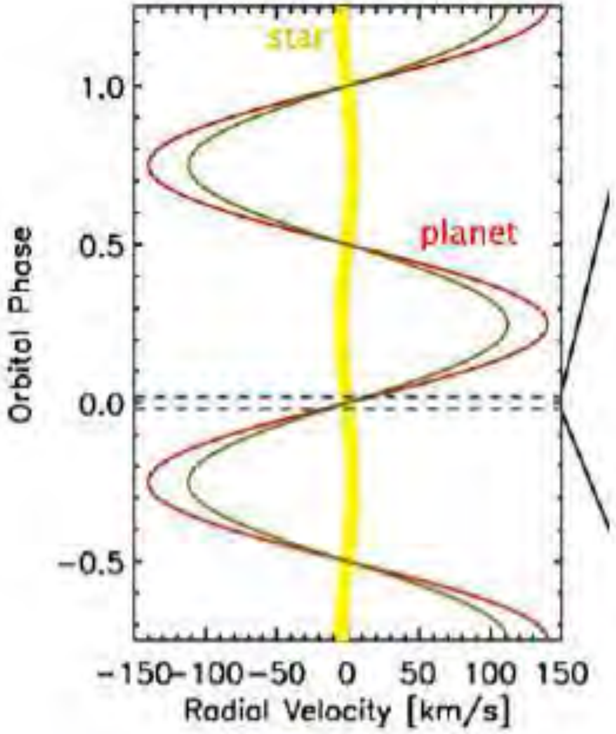
Strong Haze

Sing et al 2016 Nature

Tomography: CO transmission

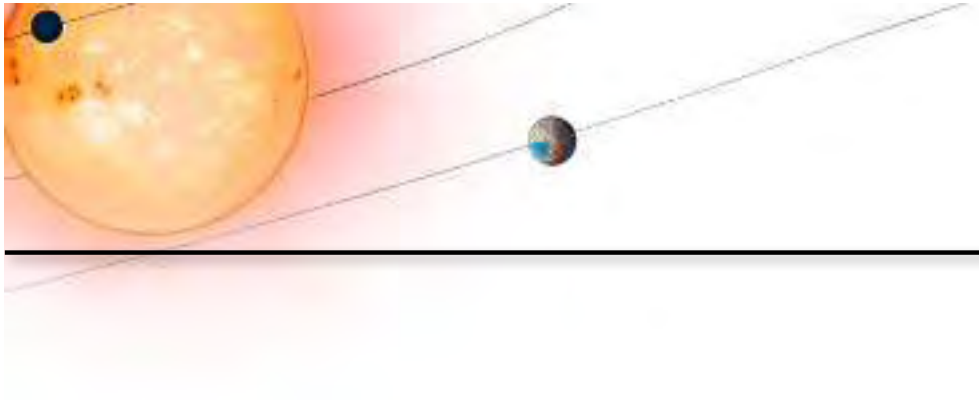
Combining thousands of CO lines in velocity space gives:





- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)

ESO VLT   Snellen et al 2010



The move towards small planets

What is an Earth Analog?

Do we use this term to mean Earth-Sun like system?
But term is often used in many other ways, for example:

a) An Earth sized planet
b) A rocky planet
c) An Earth sized planet at any distance from its host star
d) A planet with radius and mass similar to Earth

And there are others….

Here we will mean a $1M_e$ planet in the habitable zone of a sun-like star (Earth-Sun Analog)

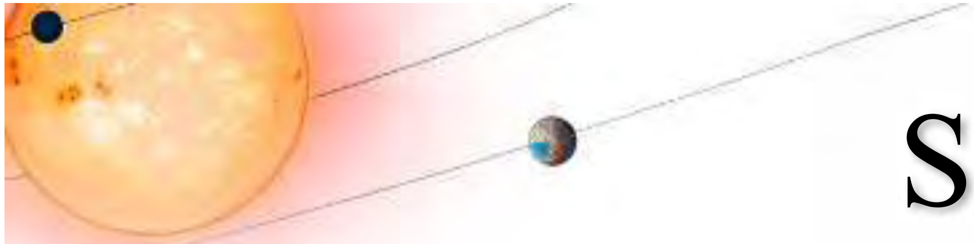
Finding *and* Characterising Earth analogs pose different questions. While finding is hard, characterising is even harder….

Earth-Analogs: What tools do we have?

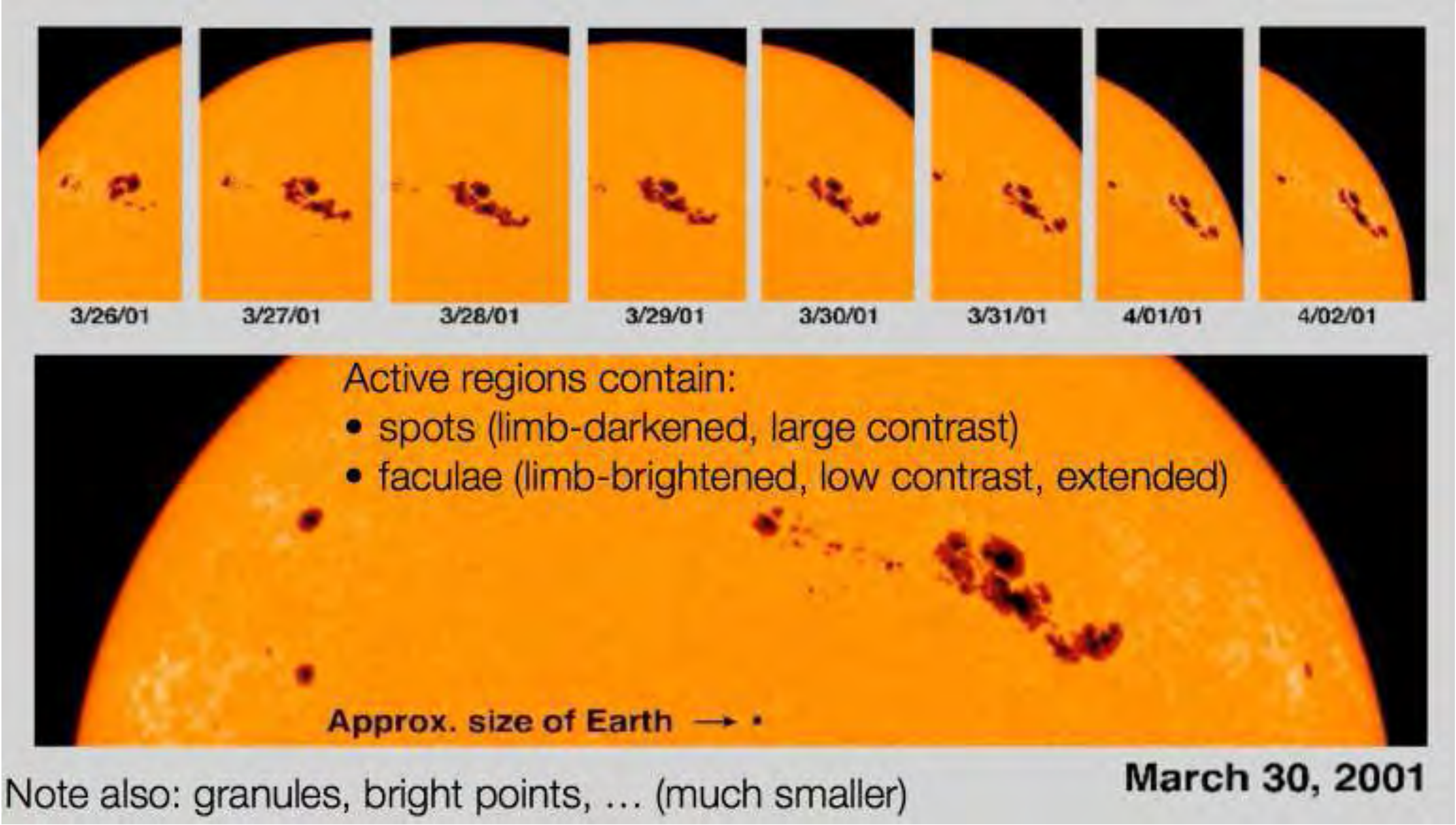
- Imaging – not currently detectable
- Spectroscopy – K~10cm/s and P~1 yr
- Microlensing – detectable, useful statistics
- Astrometry – not currently detectable
- Transit – depth 0.01% and P~1 yr

Earth-Analogs for more detailed observations could come from Transit+RV combinations – but very difficult.

Difficulties: long periods, small signals + noisy stars



Solar Activity



Active regions contain:

- spots (limb-darkened, large contrast)
- faculae (limb-brightened, low contrast, extended)

March 30, 2001

Note also: granules, bright points, … (much smaller)

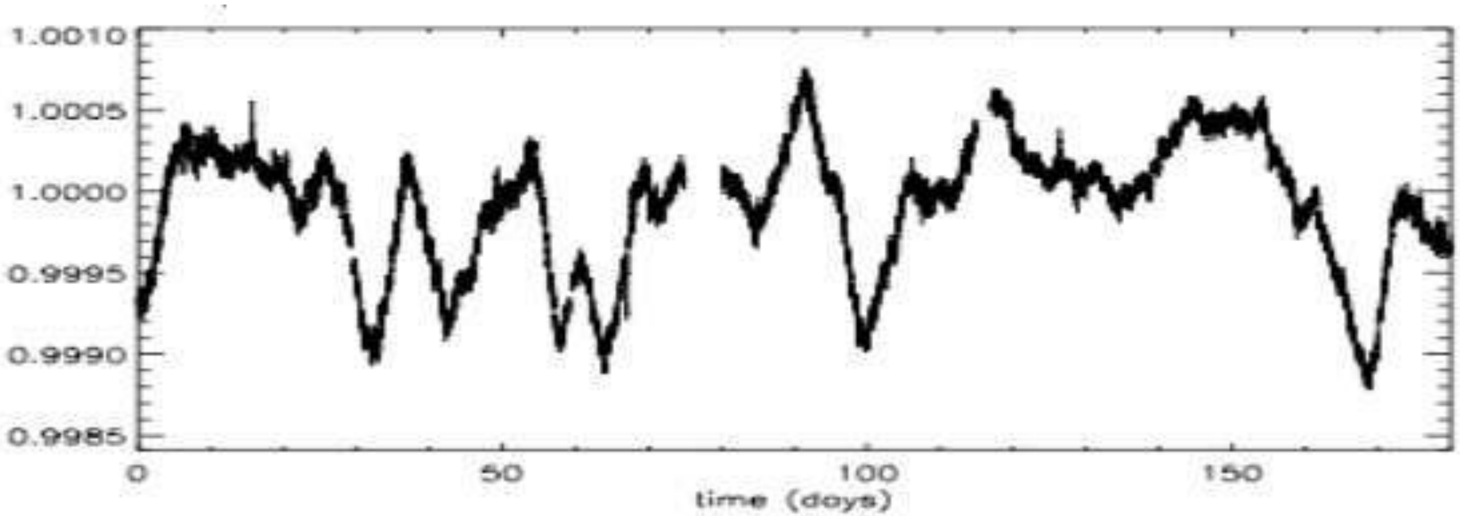
Courtesy of S.Aigrain

Solar granulation

1 hr of solar granulation

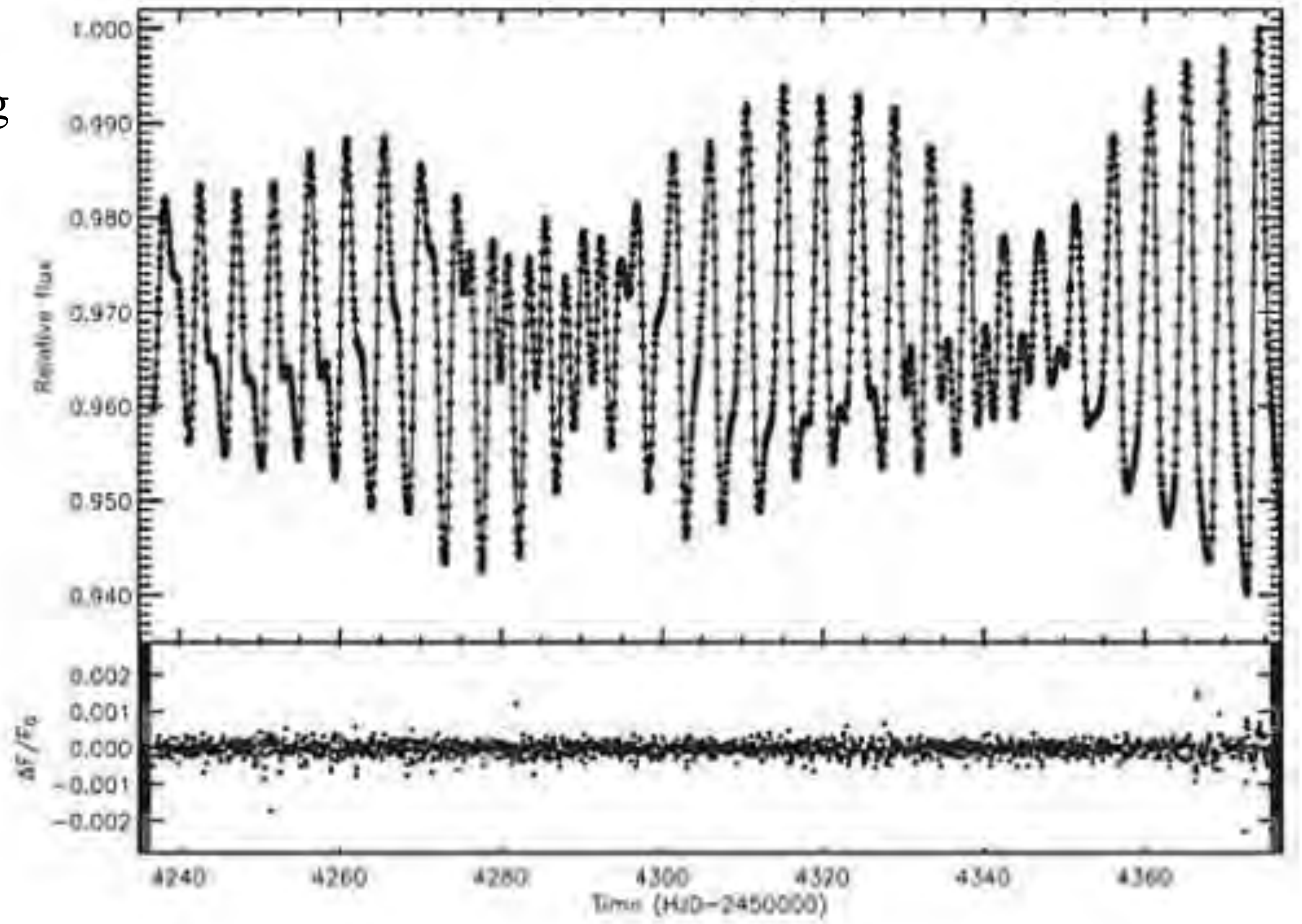
Signs of Activity in light curves

Sun



Signs of Activity in light curves

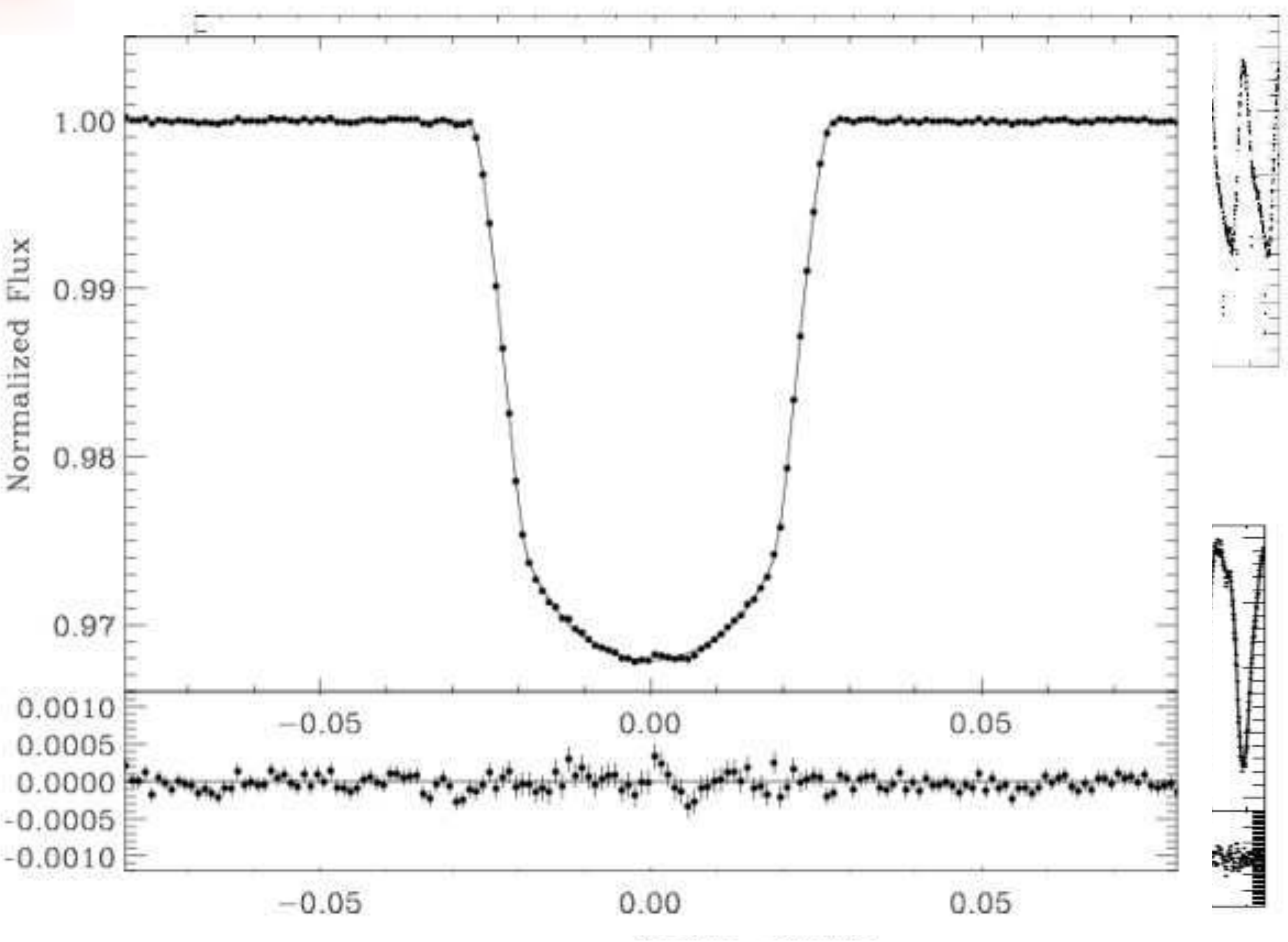
A Sun-like star (light curve fitted with model containing multiple spots)



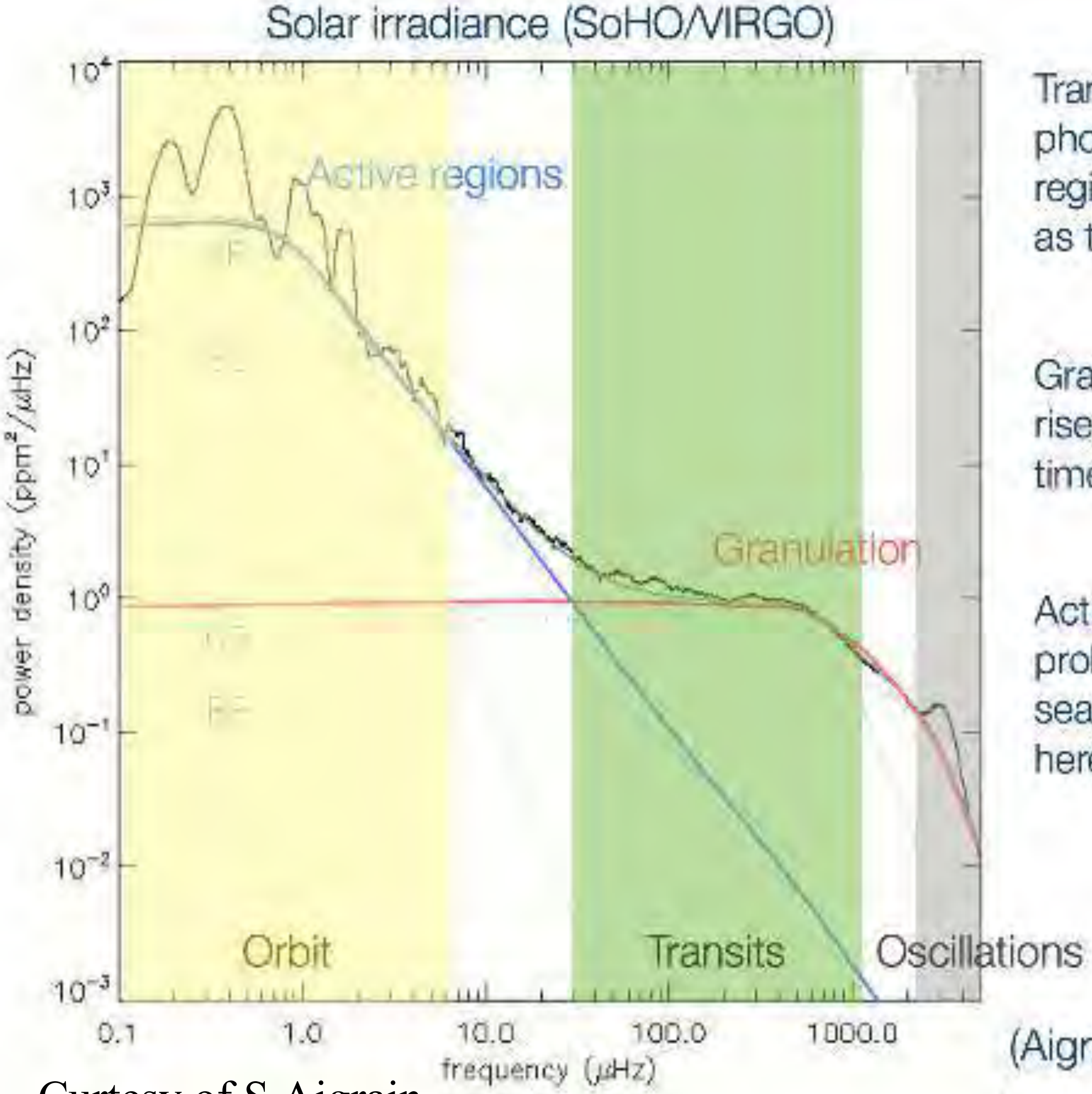
Signs of activity in light curves

CoRoT-2b

CoRoT-6



Activity Timescales



Transits can be separated from photometric variations due to active regions in the Fourier domain ... so long as the star doesn't rotate to fast!

Granulation, on the other hand, gives rise to photometric variability on similar timescales to transits (hours).

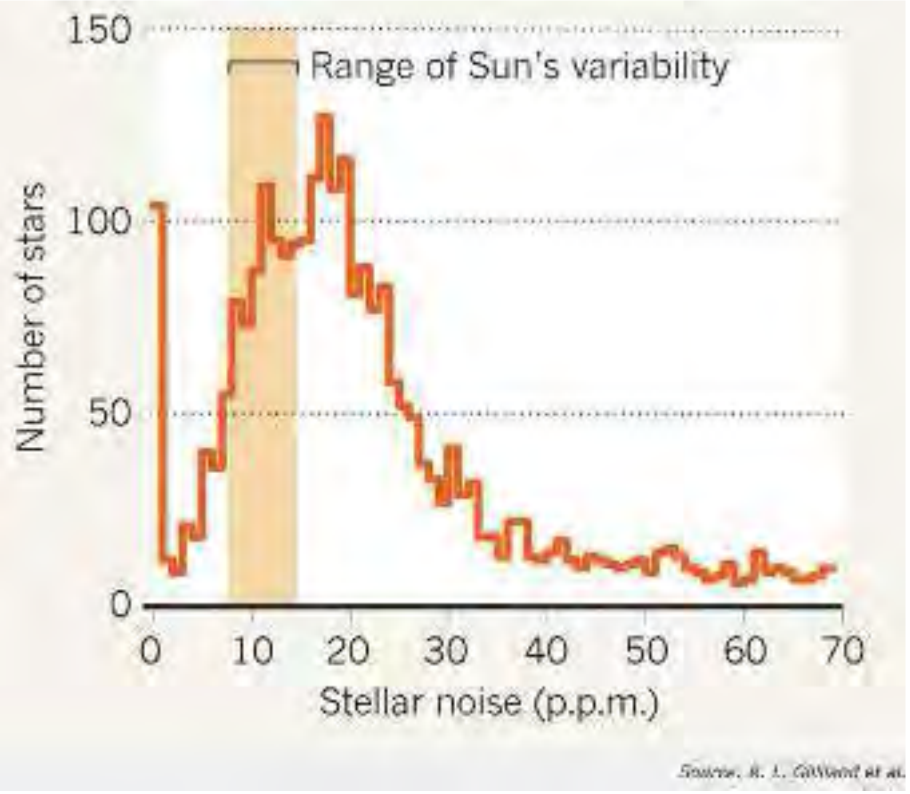
Activity-induced variability is even more problematic for radial velocity planet searches (also important but not shown here: activity cycles)

(Aigrain, Favata & Gilmore 2004)

Curtesy of S.Aigrain

Impact of stellar noise on transit detection

Stellar noise measured by Kepler (6hr time series, Gilliland et al 2011)



Source: R. L. Gilliland et al.

$$SNR_{transit} = \sqrt{(N_{transits})} D / \sigma(T_{transit})$$

$N_{transits}$ = Number of transits
D = transit depth
$T_{transit}$ = Transit duration

Given noise Kepler would have needed to detect 7 instead of 4 transits to reach SNR=10

Modelling/Filtering noise patterns in light curves is a very active area of research!

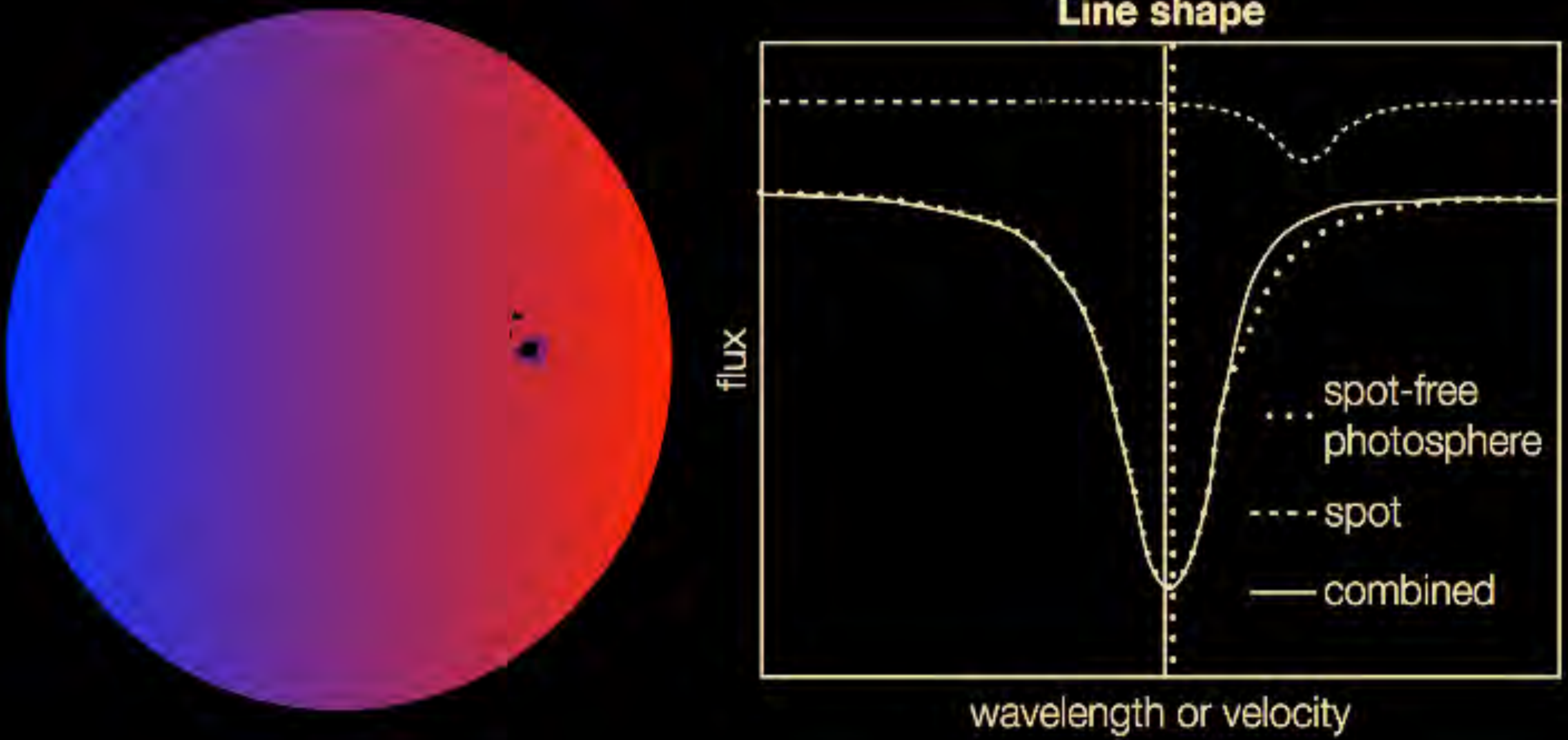
Impact of Stellar Noise on RVs

First thing to realise is quite how fine the measurements are:

3 pixels on the detector of a planet spectrograph will usually be equivalent to a velocity shift of ~2km/s so 1m/s is 0.0005 per resolution bin. To reach this level of accuracy we need to combine thousands of lines (this also explains why highly stabilized spectrographs and environments are needed).

How does activity affect a spectral line?

RV effects of activity - 1:
distortion of rotation profile (a.k.a. photometric effect)



RV effects of activity - 2:
convective blueshift suppression

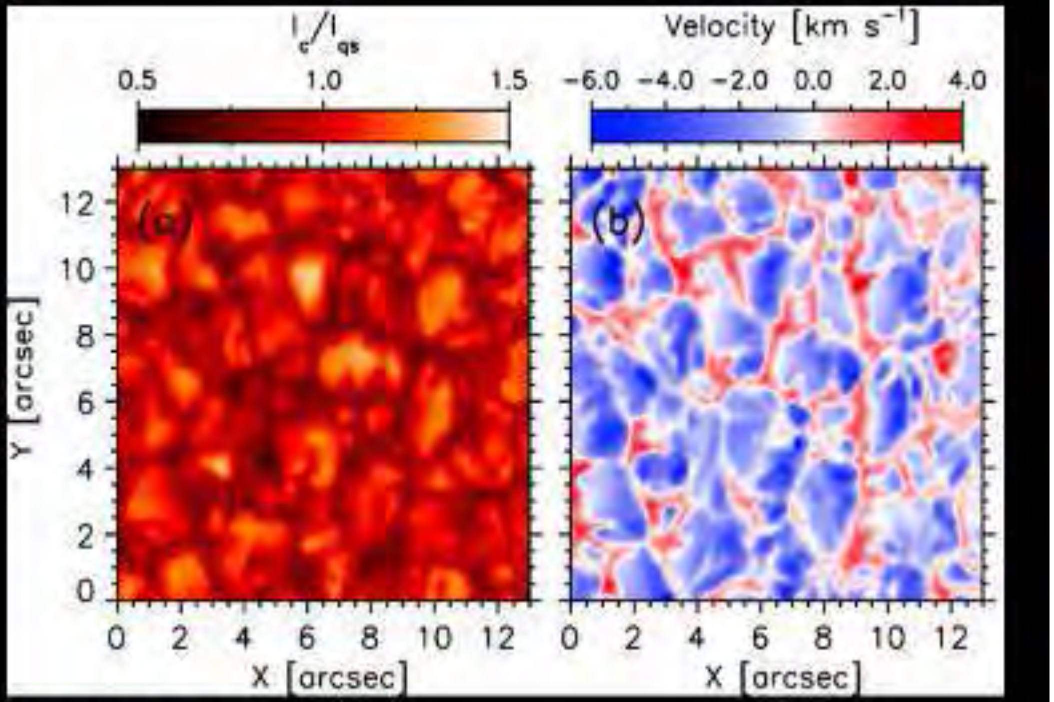
Convection is partially suppressed in regions where surface magnetic field is large

Why does this affect RVs?

RV effects of activity - 2:
convective blueshift suppression

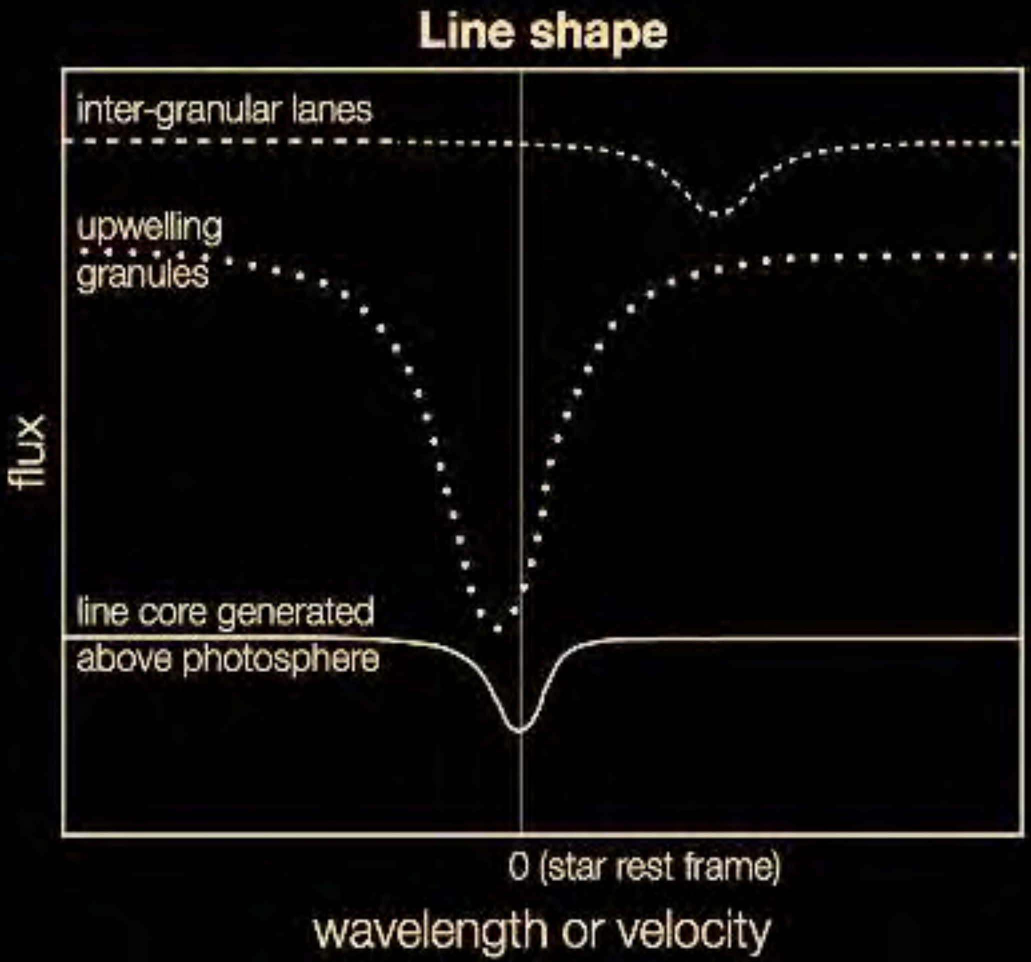
Convection is partially suppressed in regions where surface magnetic field is large

Why does this affect RVs?

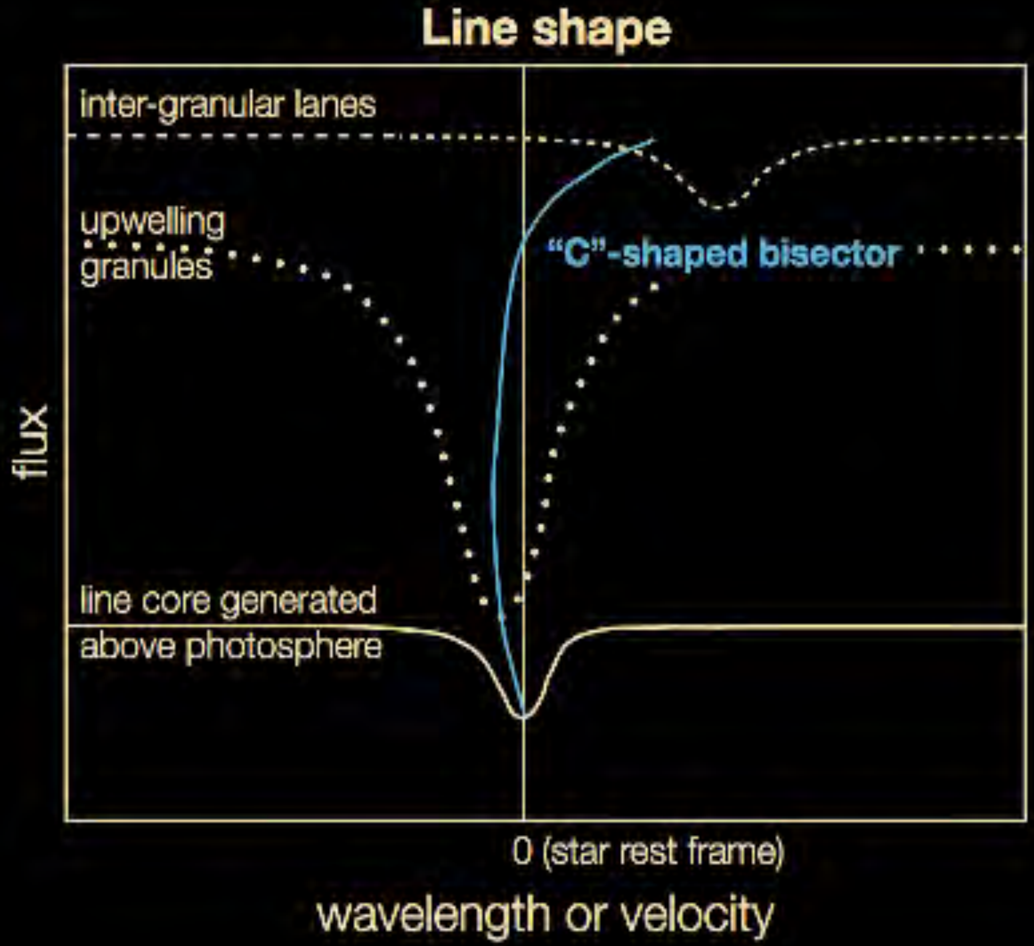


Joshi et al. (2011)

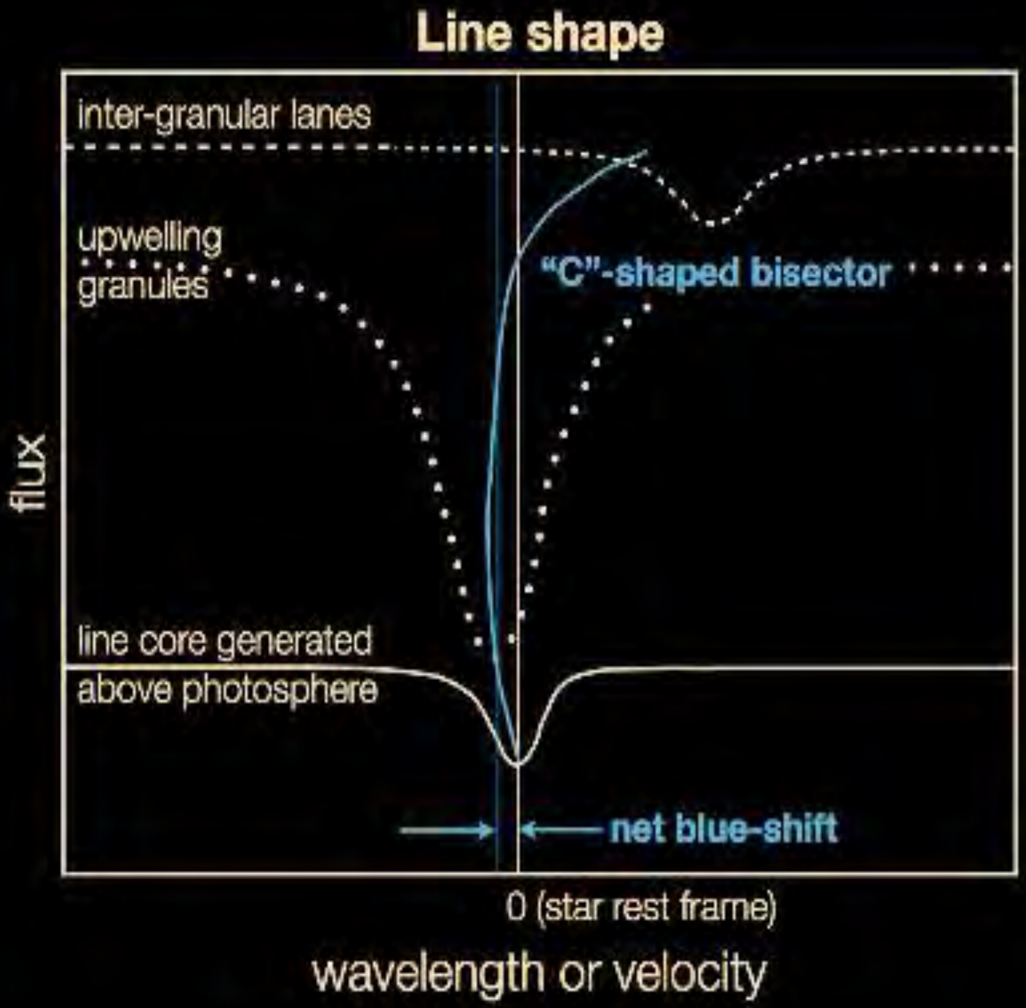
Spectral line in “normal” photosphere



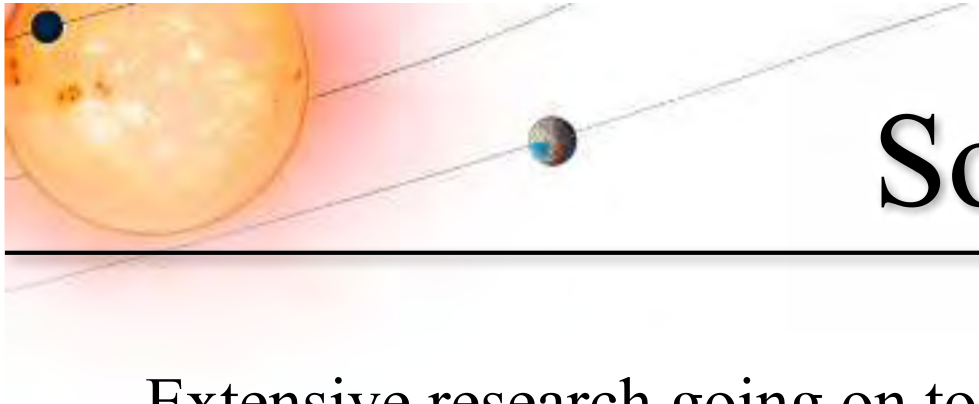
Spectral line in “normal” photosphere



Spectral line in “normal” photosphere



Line shape and absolute convective blue-shift depend on line strength (Gray 2009)



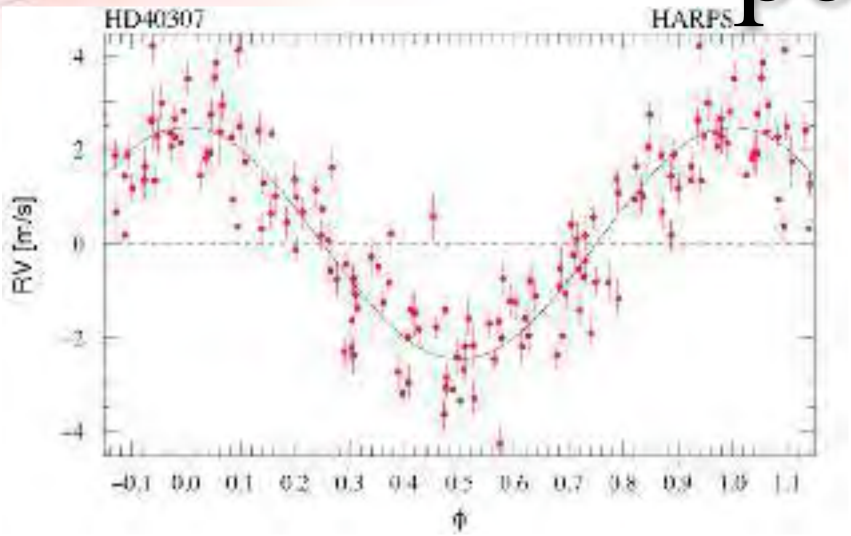
So what to do?

Extensive research going on to try and model the effects of stellar activity on RV’s. This ranges from filtering the signals (eg FF method of Aigrain et al 2012) to magnetospheric modelling of the line formation sites (Celga et al 2013). There is a lot more to come here.

Also attempts already being made to model the RV and photometric activity signals simultaneously eg Rajpaul et al 2016,Haywood et al 2016 and others.

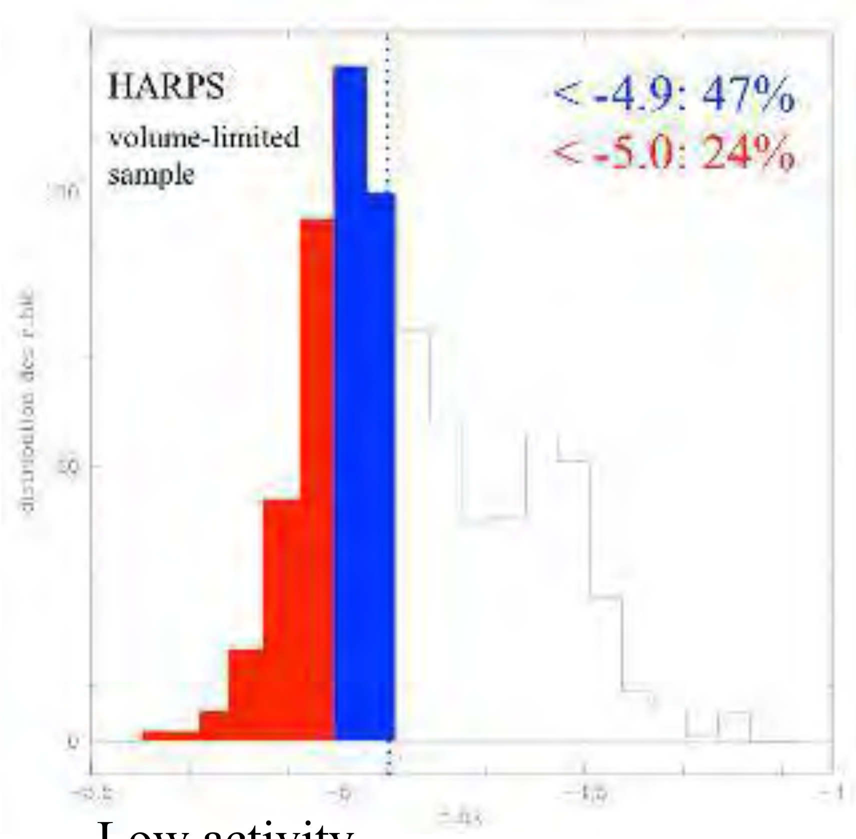
In the mean time do we just give up?

Even now high precision RV is possible



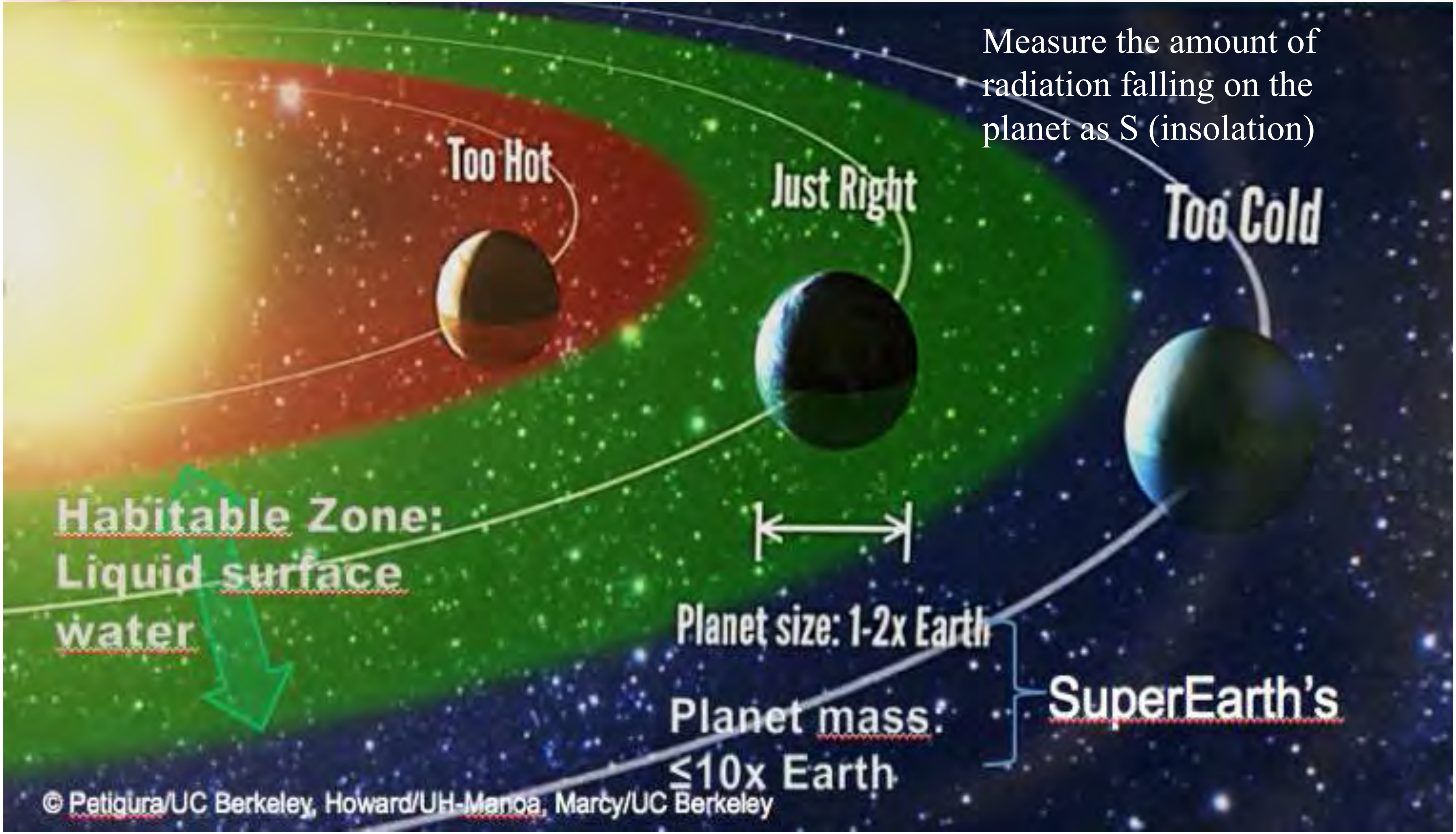
Left: HD40307 K star with 3 superearths one in 280d orbit (Mayor et al 2009).

Activity levels (log(R’$_{HK}$) index) for the HARPS volume limited stellar sample. Lowest activity objects (about 25-30%) would allow an averaging technique to be applied and reach the needed level.



Low activity stars

The Habitable Zone

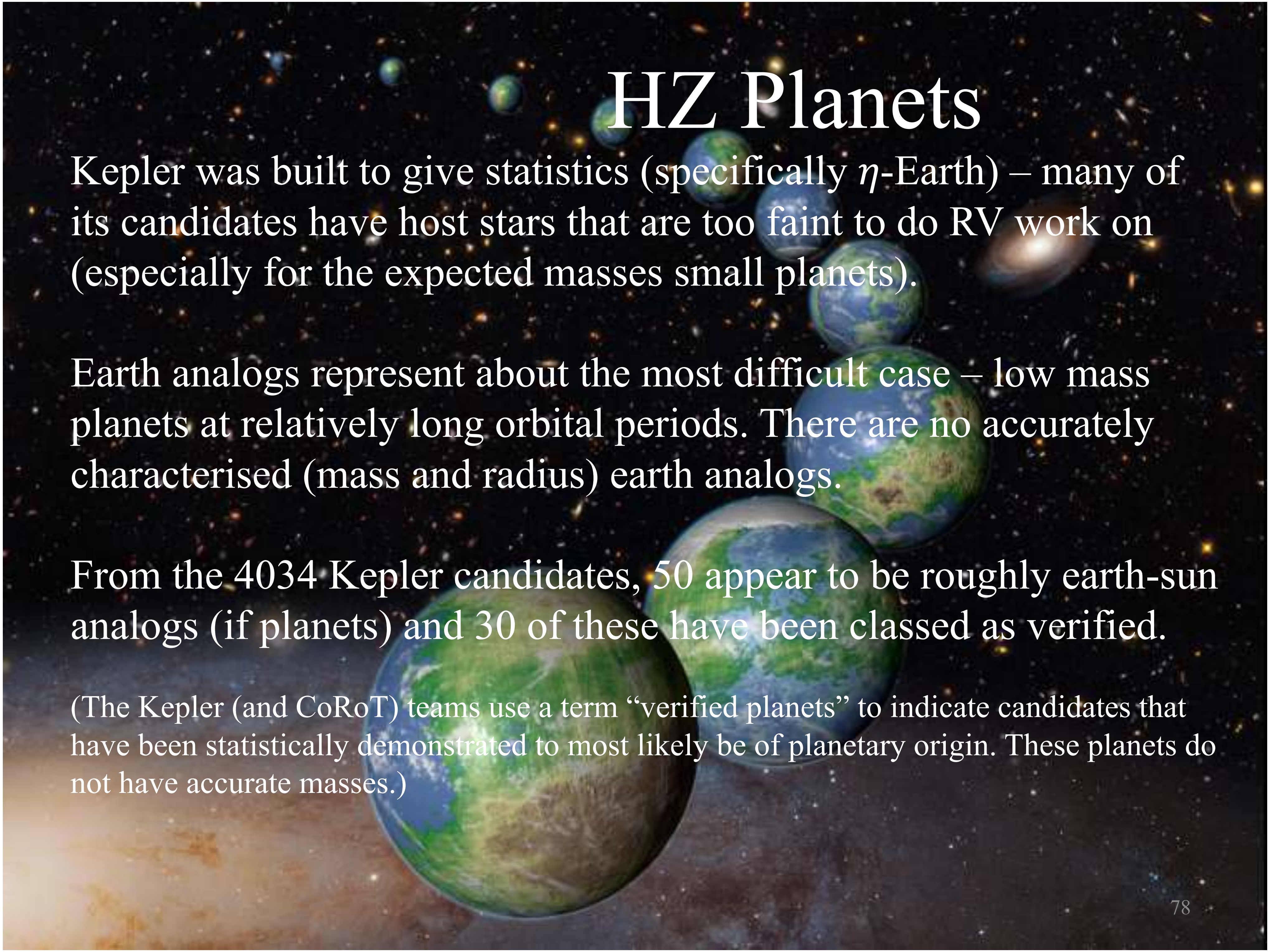


Measure the amount of radiation falling on the planet as S (insolation)

SuperEarth's

© Petigura/UC Berkeley, Howard/UH-Manoa, Marcy/UC Berkeley

Kasting et al 1993.



HZ Planets

Kepler was built to give statistics (specifically η-Earth) – many of its candidates have host stars that are too faint to do RV work on (especially for the expected masses small planets).

Earth analogs represent about the most difficult case – low mass planets at relatively long orbital periods. There are no accurately characterised (mass and radius) earth analogs.

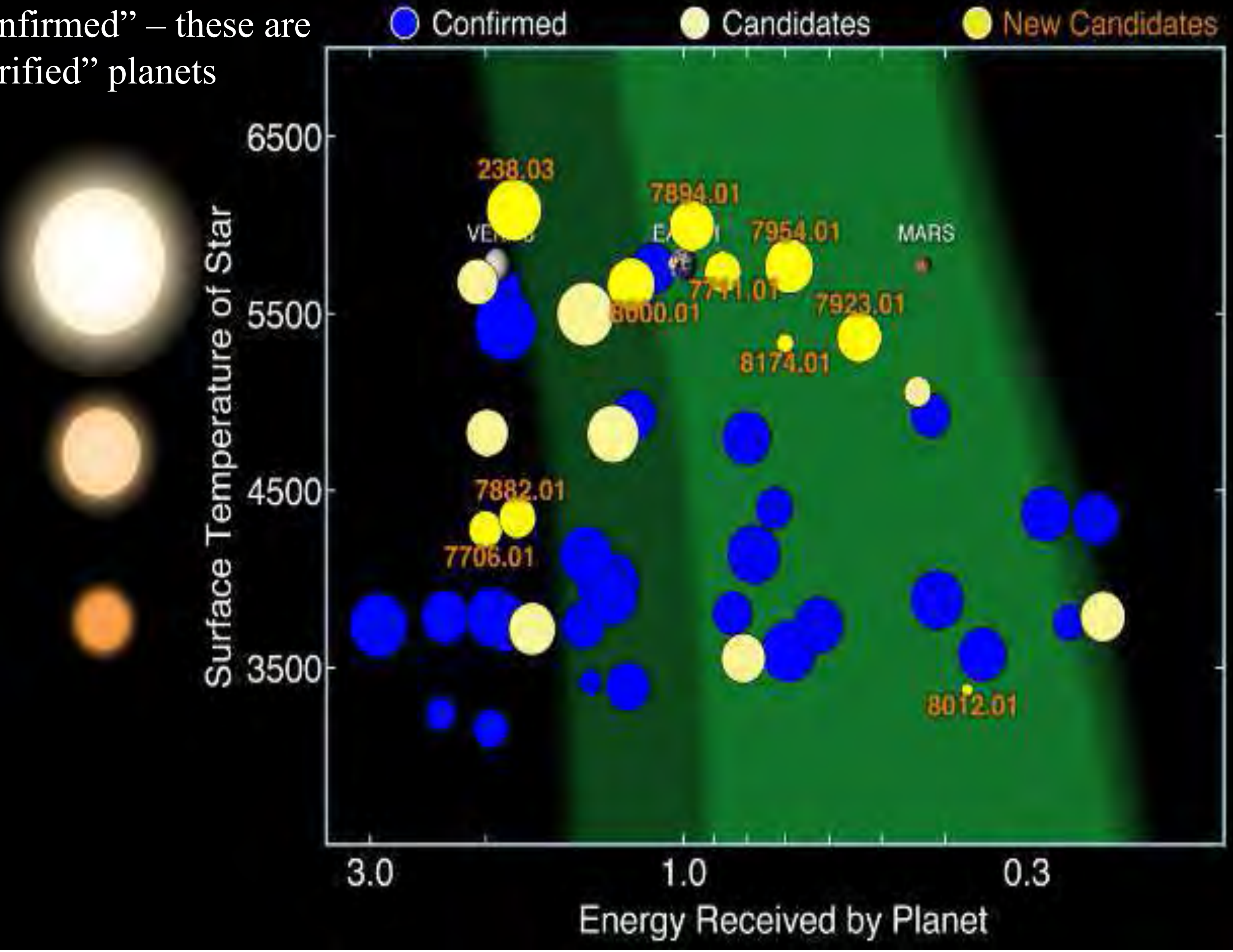
From the 4034 Kepler candidates, 50 appear to be roughly earth-sun analogs (if planets) and 30 of these have been classed as verified.

(The Kepler (and CoRoT) teams use a term “verified planets” to indicate candidates that have been statistically demonstrated to most likely be of planetary origin. These planets do not have accurate masses.)

Kepler Habitable Zone Planets

As of June 2017

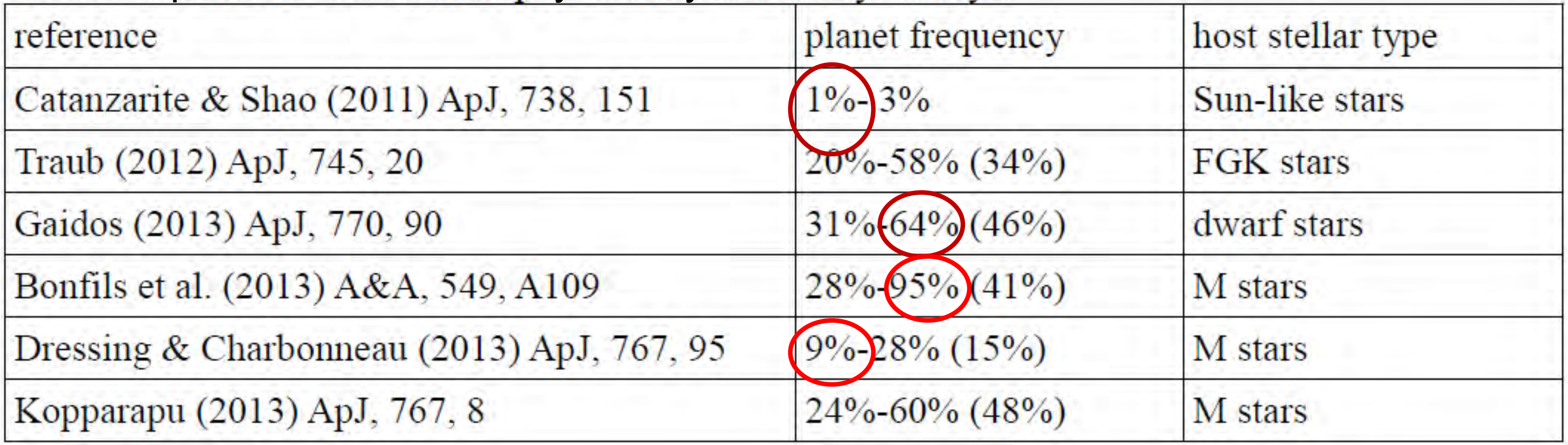
Note loose use of "confirmed" – these are "verified" planets



Values for η-Earth

η-Earth: The fraction of stars hosting Earth-like planets in their habitable zone

From Kepler and radial velocity surveys:



reference	planet frequency	host stellar type
Catanzarite & Shao (2011) ApJ, 738, 151	1%-3%	Sun-like stars
Traub (2012) ApJ, 745, 20	20%-58% (34%)	FGK stars
Gaidos (2013) ApJ, 770, 90	31%-64% (46%)	dwarf stars
Bonfils et al. (2013) A&A, 549, A109	28%-95% (41%)	M stars
Dressing & Charbonneau (2013) ApJ, 767, 95	9%-28% (15%)	M stars
Kopparapu (2013) ApJ, 767, 8	24%-60% (48%)	M stars

Batalha et al., 2014	7 – 22%	Sun-like stars

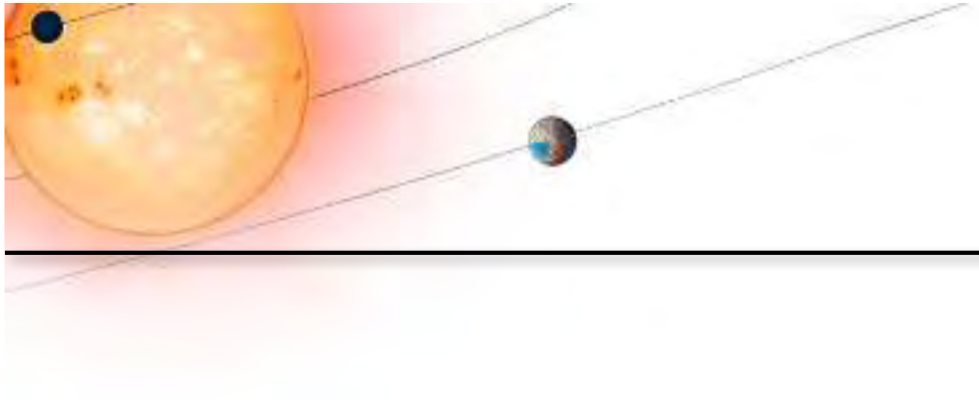
→ The fraction of (super)-Earths in the habitable zone of stars is not well known.

(Variations due to different bias corrections to data)

M dwarfs – a short cut to the HZ

We are entering the M-dwarf HZ planet era! Both for RV and transit surveys

- M-dwarfs are common!
- Intrinsically low luminosity so HZ at short periods (few days to a month or so)
- Stars are small so for a specific photometric performance ability can detect smaller planets
- Mass ratios are less extreme so RV signal bigger
- Some believe activity signals are easier to deal with in M-dwarfs (or at least for some of them).
- Some evidence that η-earth is higher in M dwarfs: planet population seems to be dominated by small (probably rocky) planets (Morton & Swift 2014)



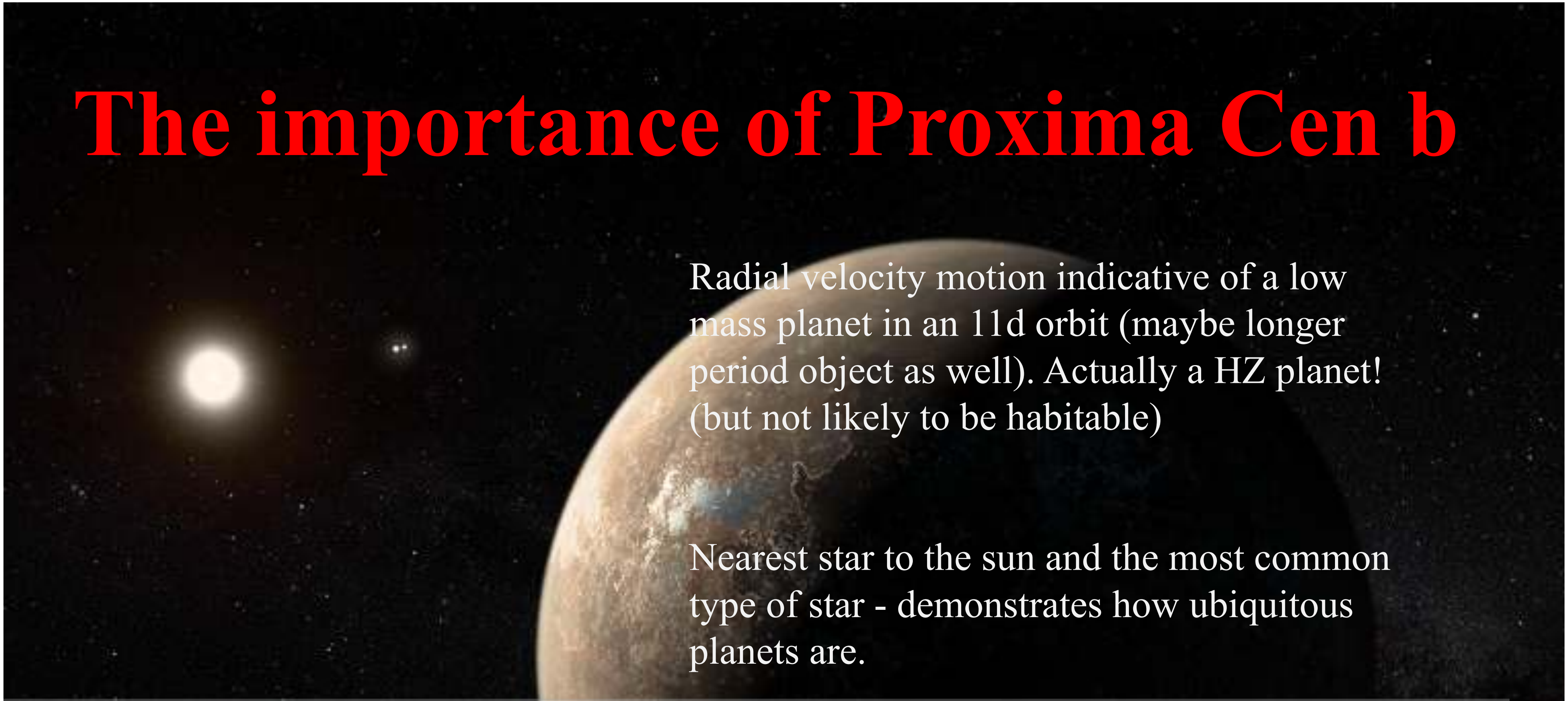
Disadvantages of M-dwarf hosts:

1. Best studied at IR wavelengths. Difficulties with instruments and the earth atmosphere)
2. Significant flaring activity
3. Retention of atmosphere
4. Intrinsic faintness of star
5. Tidally locked

Red dwarfs are an extremely broad stellar class: an M0 is quite different to an M9 star

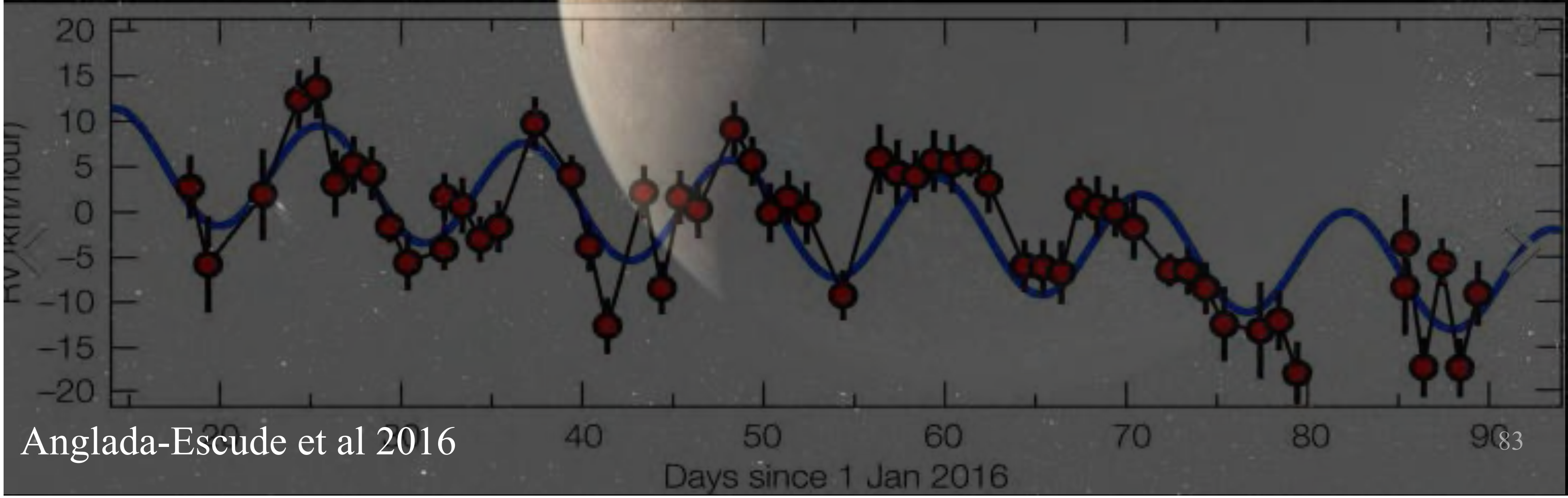
Many issues still need to be assessed regarding M-dwarfs as planet hosts but we can do this work now and it is MUCH easier than solar type stars.

The importance of Proxima Cen b

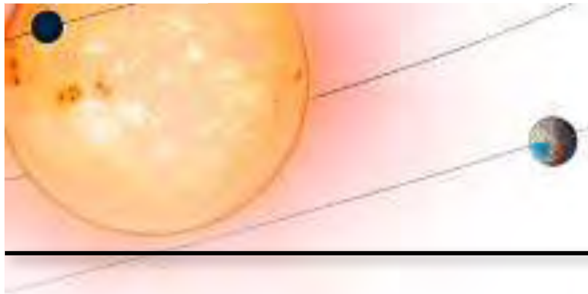


Radial velocity motion indicative of a low mass planet in an 11d orbit (maybe longer period object as well). Actually a HZ planet! (but not likely to be habitable)

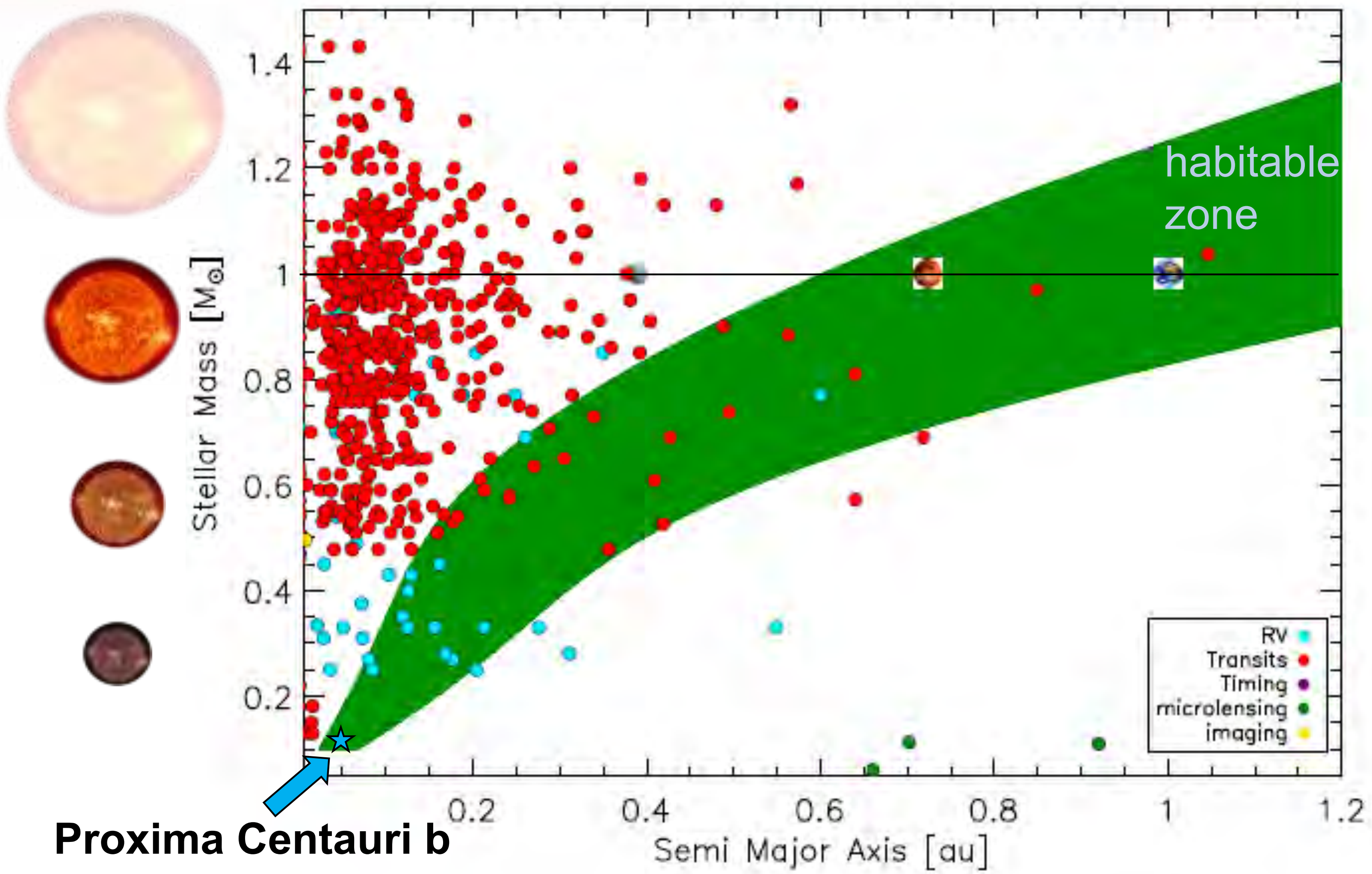
Nearest star to the sun and the most common type of star - demonstrates how ubiquitous planets are.



Anglada-Escude et al 2016



Known Small Exoplanets



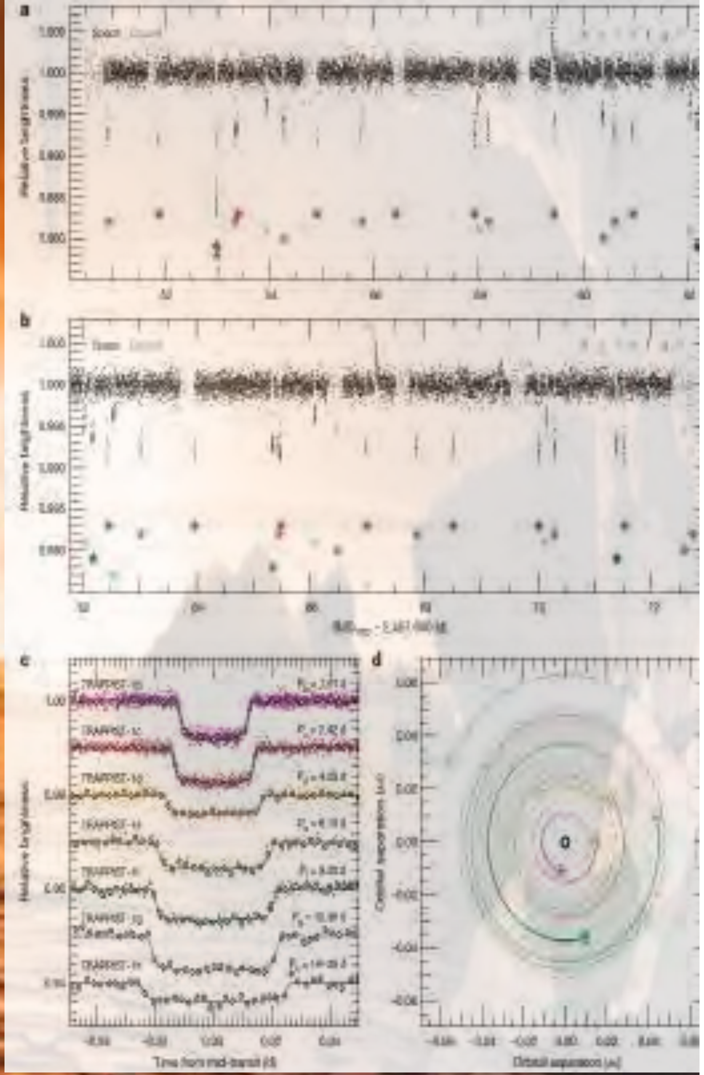
Proxima Centauri b

$M_p\sin i$: 1.27 $M_\oplus$

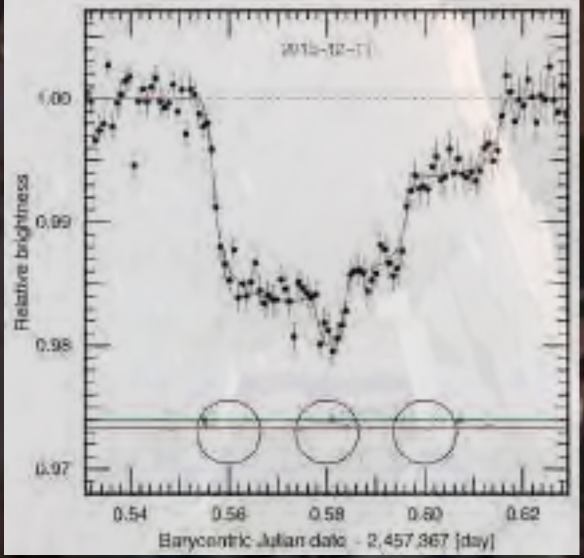
Anglada-Escudé et al 2016

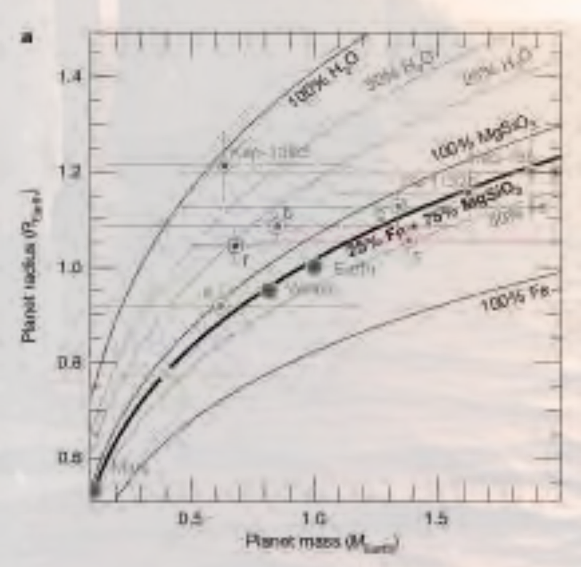
Trappist-1

The host star is a very cool and only slightly bigger than Jupiter. Star is intrinsically very low luminosity and HZ is at a period of a few days. 7 earth sized planets with orbital periods of up to 20 days – 2-3 at HZ distances. Masses uncertain.



Light curve showing multiple transits from planets



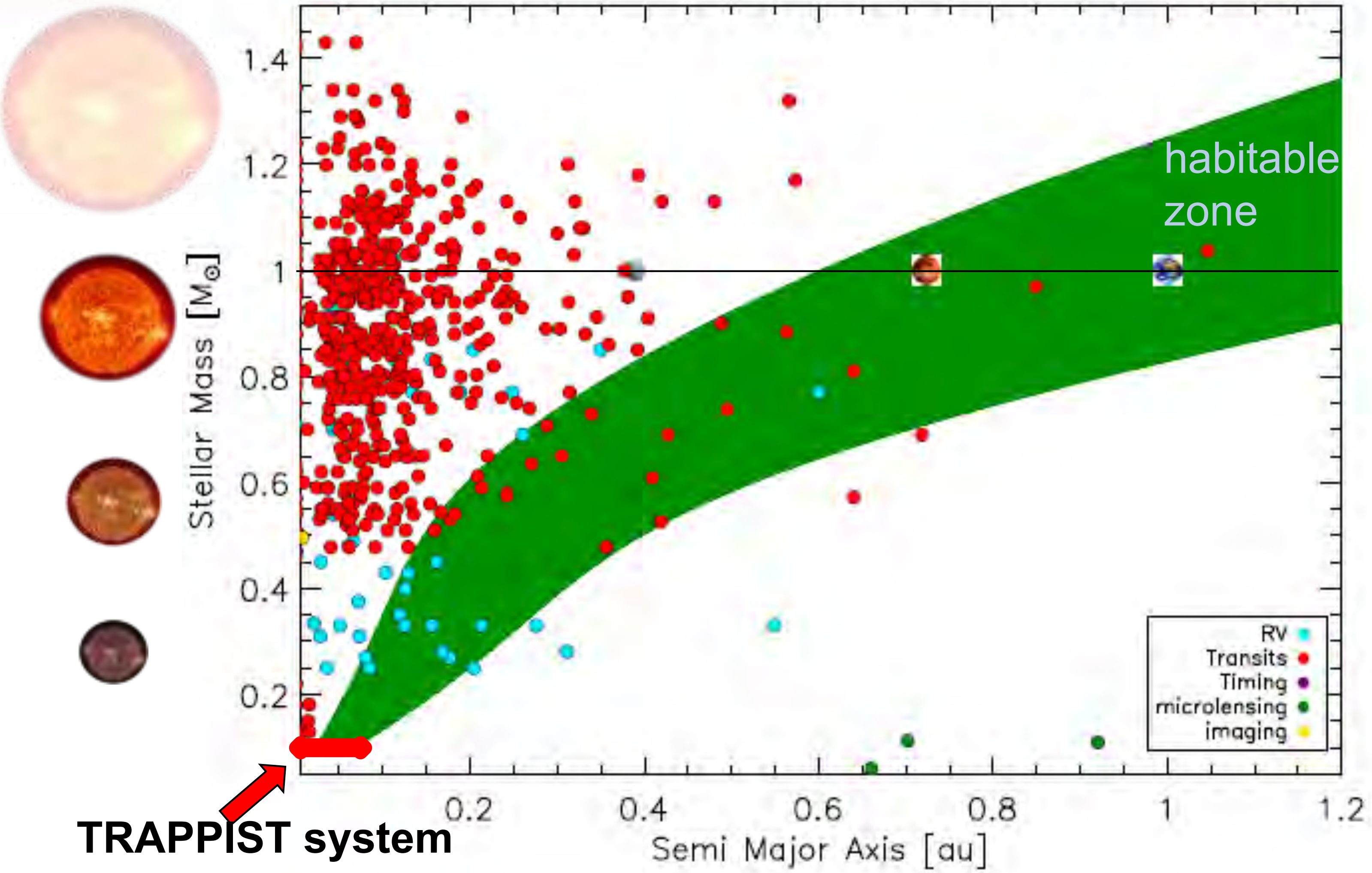


M v's r

Gillon et al 2015/17

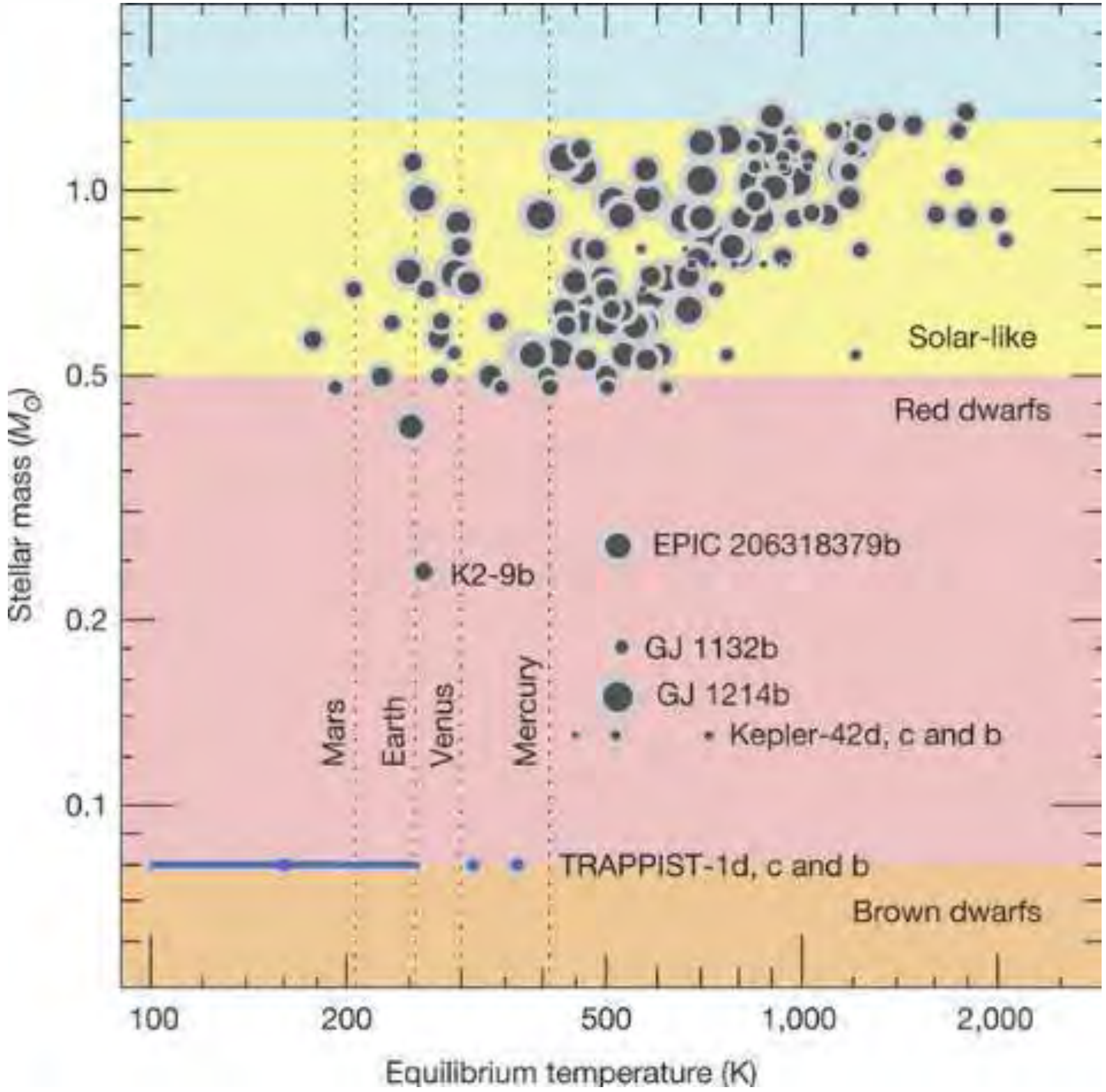
Credit: NASA, JPL-Caltech, Spitzer Team, T. Pyle (IPAC)

Known Small Exoplanets



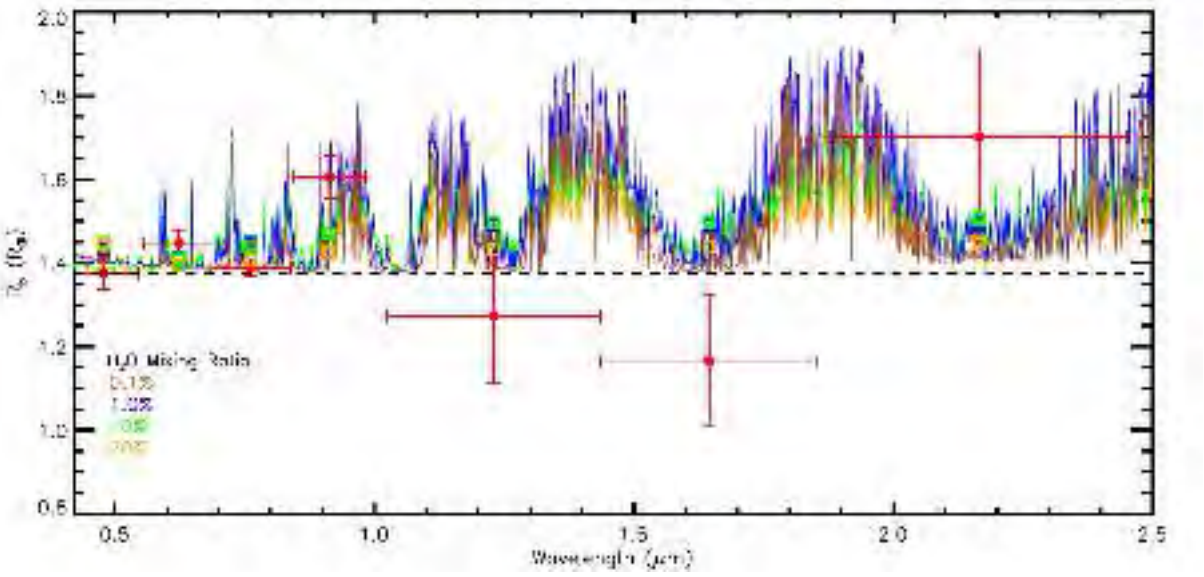
TRAPPIST system
7 super-Earth planets
(Gillon et al. 2015, 2017)

Present M-dwarf Status



Atmospheres of M dwarf planets

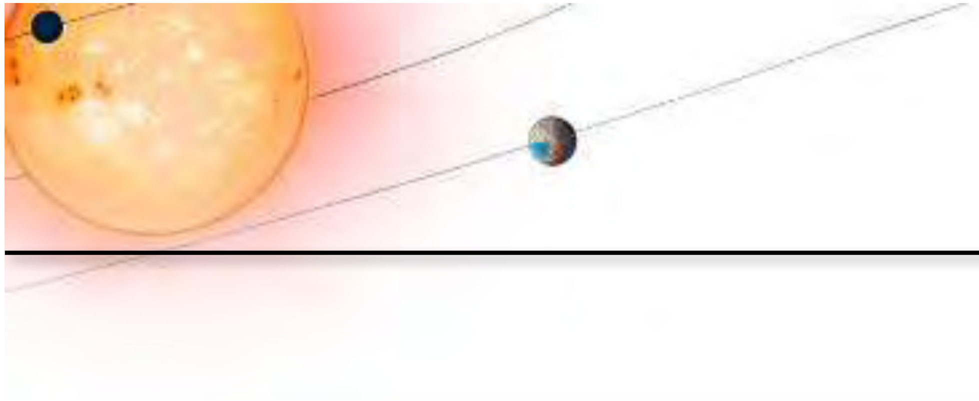
Transmission spectra of only a few M-dwarf planets have been obtained. In general these are flat and featureless indicating a cloudy planetary limb. Recently observations of GJ1132b ($T_{eq} \sim 600K$):



Planet radius much larger at ~900nm than expected.

Models are H_2O in a H_2 dominated atmosphere.
Is this a water detection?

Southworth et al 2017



The future of planet detection

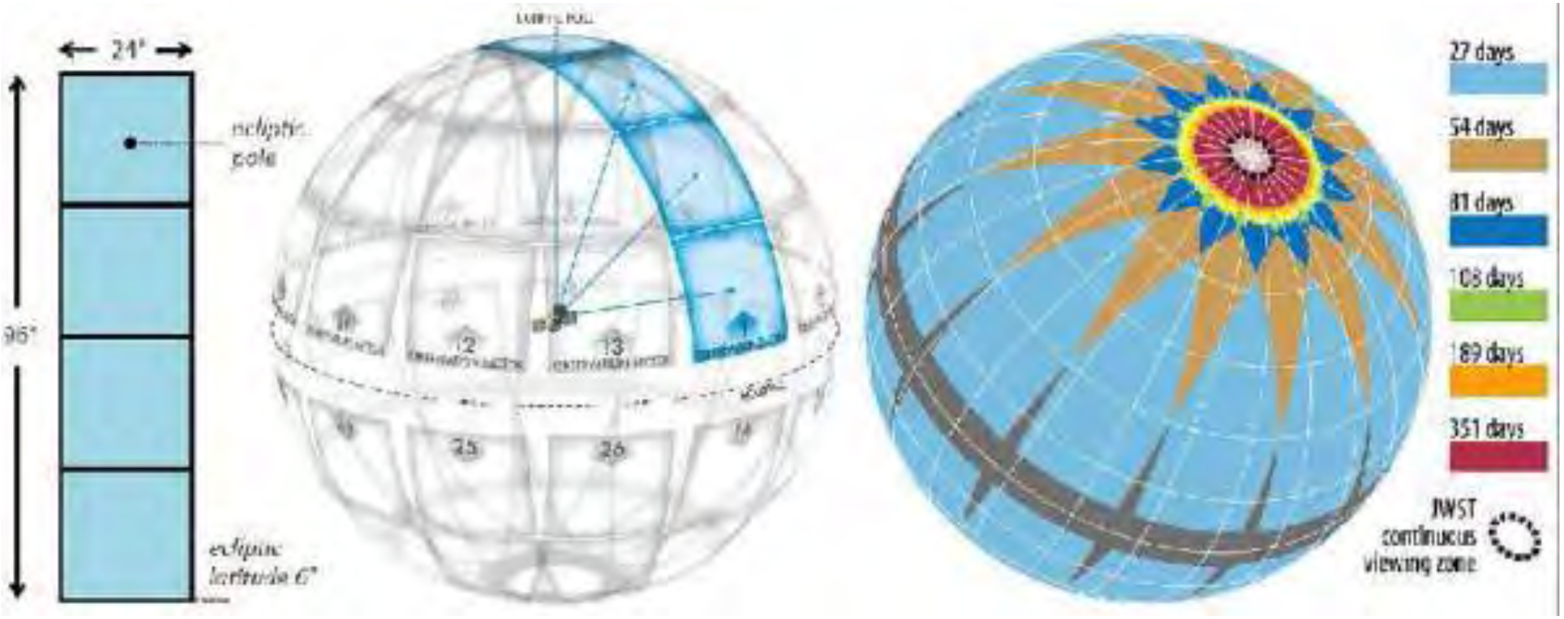
NASA's TESS: Transiting Exoplanet Survey Satellite (2018)

- Almost whole sky survey
- Bright *red* stars V=5-13 with limited sensitivity (small optics). Neptunes and super-Earths.
- Innovative orbit: Stares 28d in ecliptic and up to 100d (2% of sky) at poles => short period planets
- 1000 systems expected, ~50 will get RV characterisation
- Targets for JWST atmosphere observations

Sour grapes – wasp in space studied 2003

TESS Planetary Yield 1

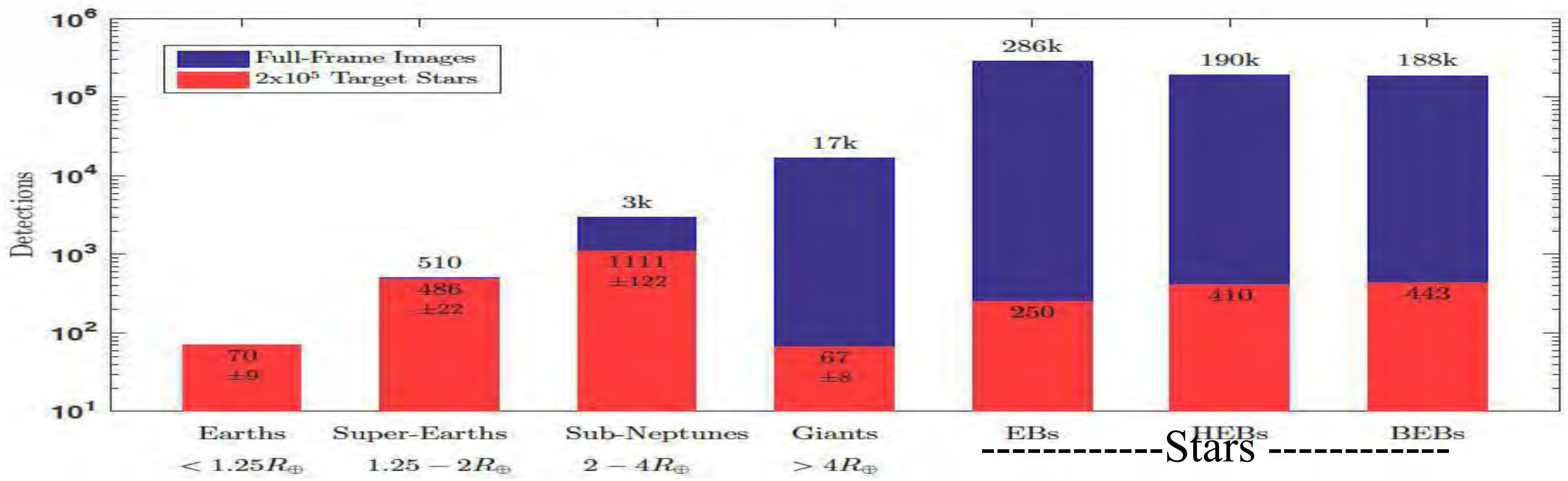
TESS is a very ingenious mission. Its orbit is highly eccentric going from near-Earth to nearly the moon’s orbit and as such it spends the bulk of its time far from the Earth – which has many advantages.



Two data products:

1) brightness measurements of $2x10^5$ pre-selected stars at 2 min cadence
2) Full sky *images* with 30 min cadence

TESS Planetary Yield 2



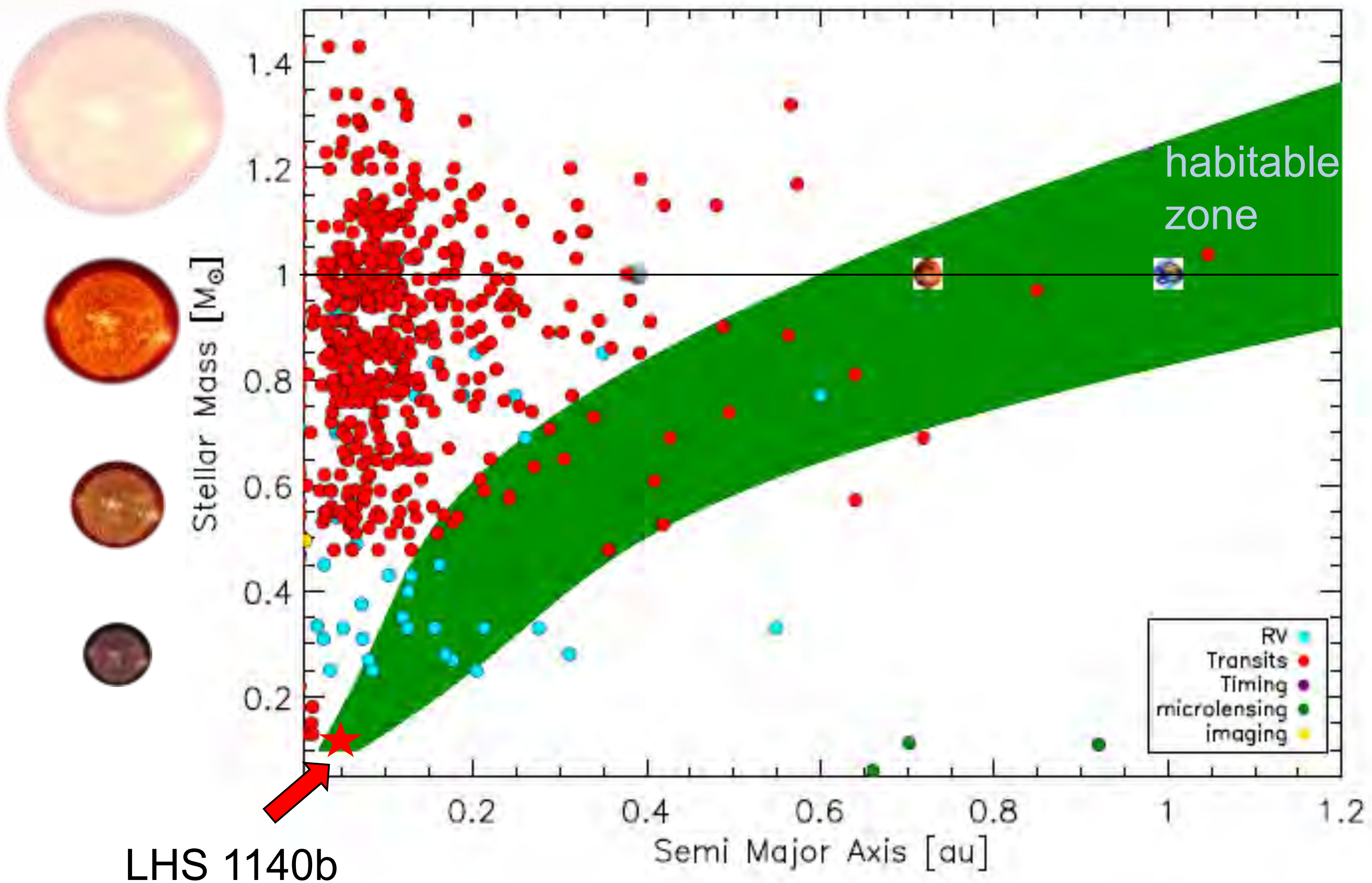
------------Stars------------

556 planets with $R_p < 2R_e$ of which 419 around M-dwarfs, 2-7 planets will have a bright host star (K<9). 137 planets with $R_p < 2R_e$ with short periods around Sun-like stars.

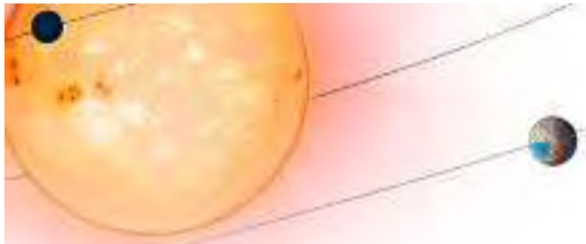
48±7 of planets with $R_p<2R_e$ near HZ with $0.2<S_e<2$ (broad HZ)
14±4 of planets with $R_p<2R_e$ near HZ with $0.2<S_e<1$ (restricted HZ Kopparapu et al 2013)

Marginal whether a bright M dwarf with HZ planet detected.
Plenty of short period planets for JWST and ELT atmospheric studies.

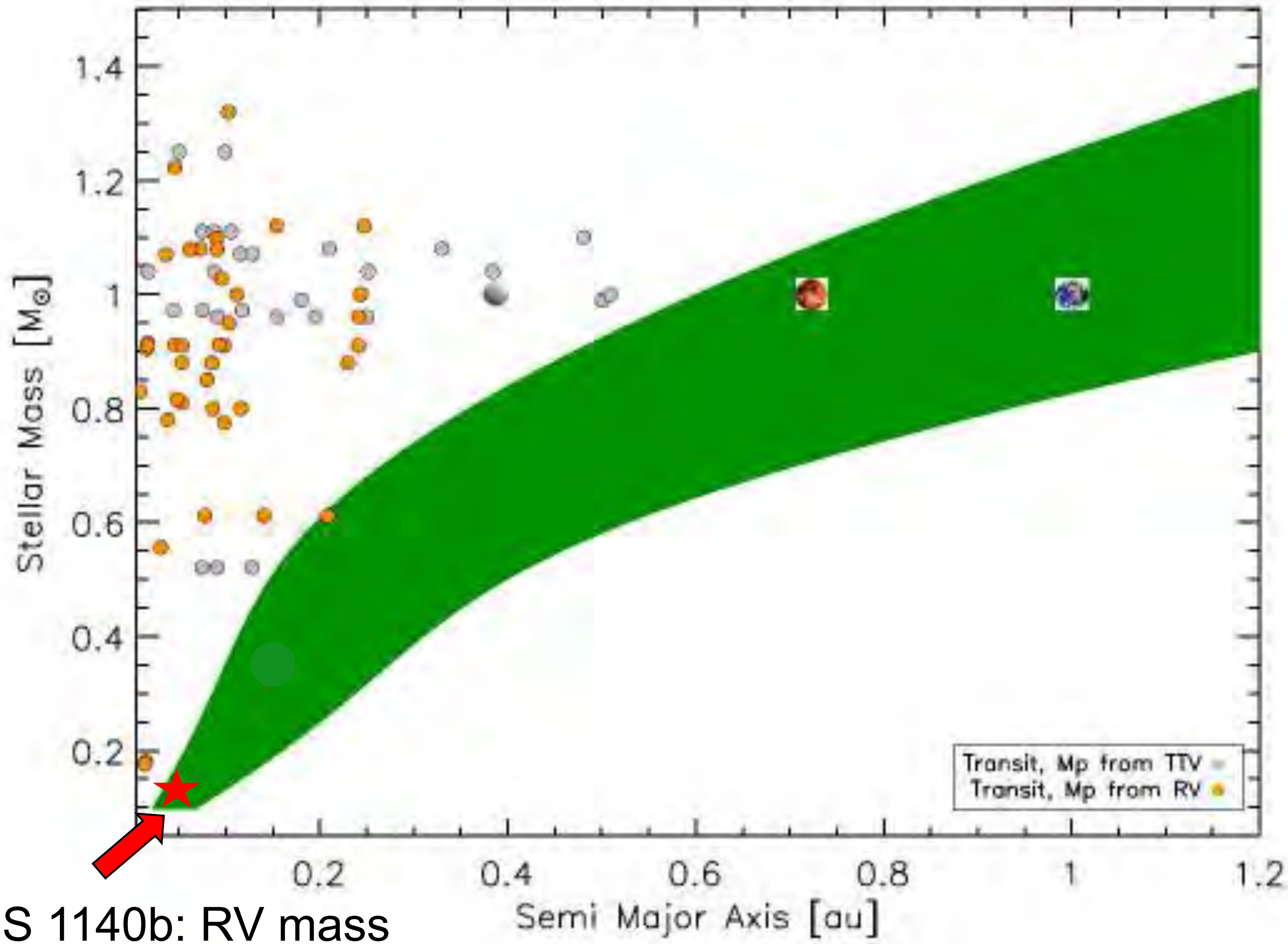
Known Small Exoplanets



LHS 1140b
$M_p \sin i$: 6.65 +/-1.82 $M_\oplus$;
R_p: 1.43 +/-0.1 $R_\oplus$ (Dittmann et al., 2017)

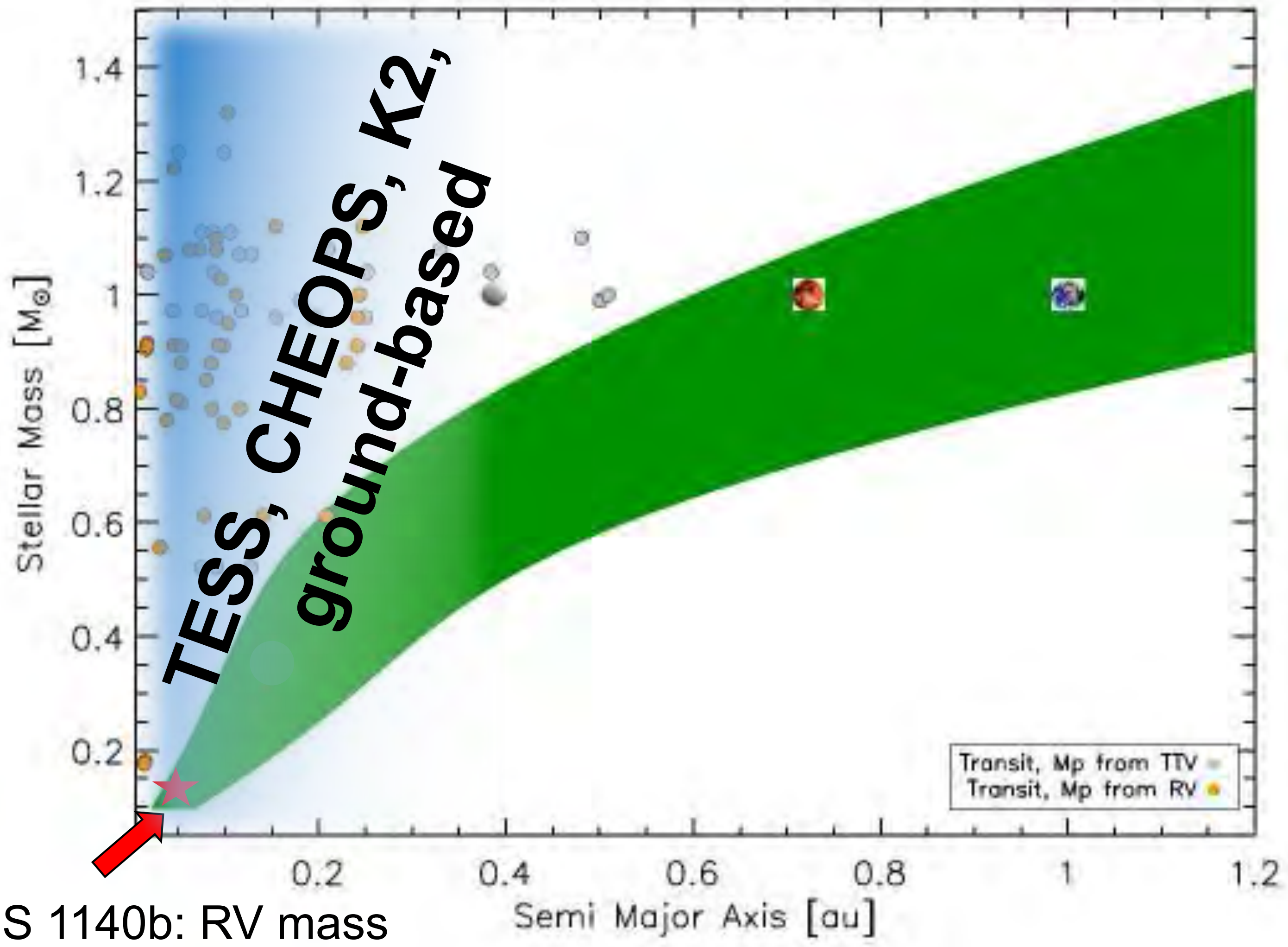


Bulk characterized super-Earths



LHS 1140b: RV mass
TRAPPIST: TTV masses

Bulk characterized super-Earths



TESS, CHEOPS, K2, ground-based

LHS 1140b: RV mass
TRAPPIST: TTV masses

The road to true earth-sun analogs

Items we will need to know:

1. The host star (M_*, R_* and age). Planet parameters from transits and RV are always determined relative to the host.

2. The host stars need to be bright. For the lowest mass planets the ground based RV observations are photon limited.

3. The activity levels (and cycles) of the host star.

PLAnetary Transits and Oscillations

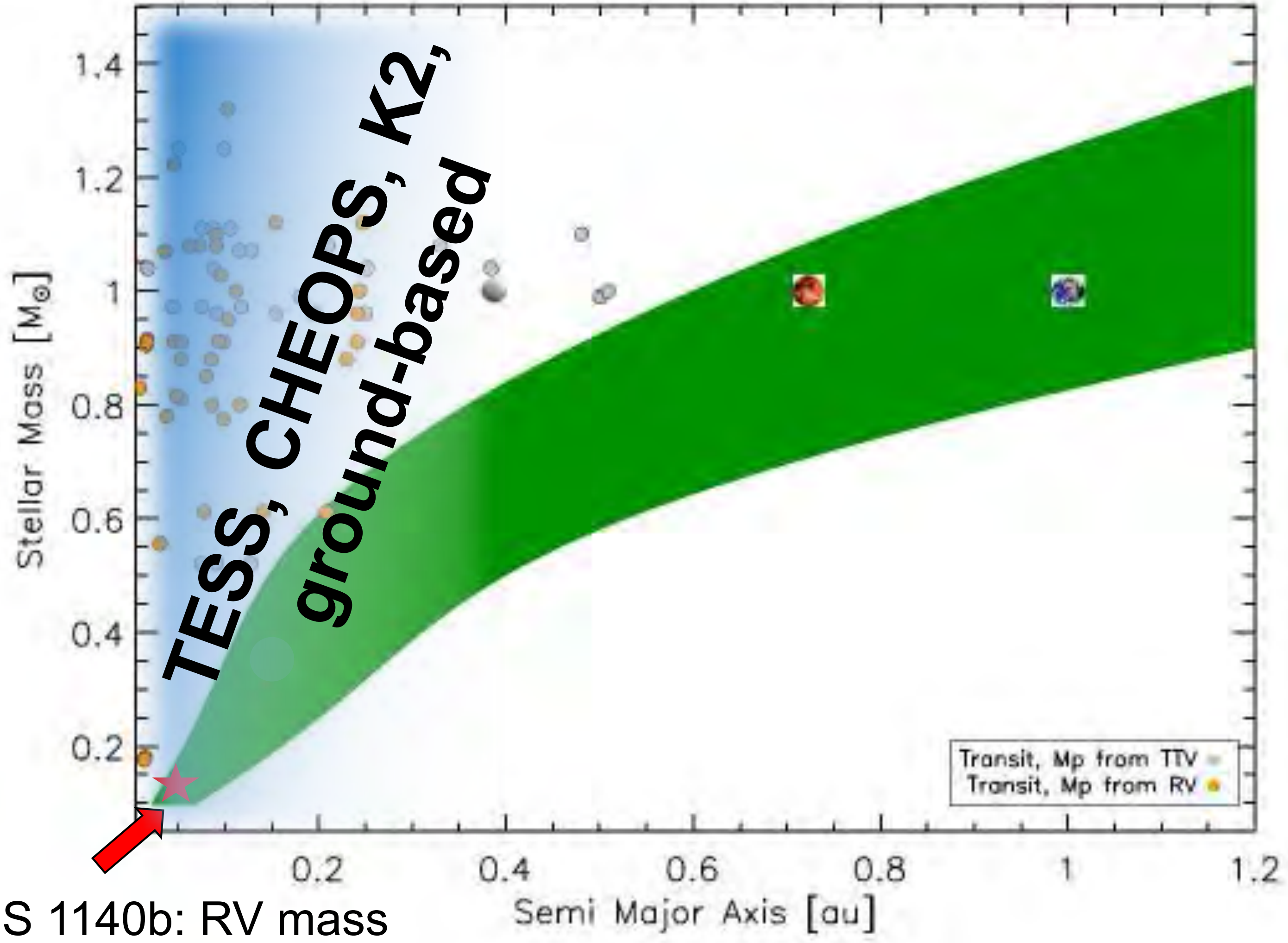
M-Class mission in ESA's Cosmic Vision (PI Rauer)
launch 2026

Concentrating on bright stars to maximize follow up potential and minimize blending/confusion issues

AIMS: *Identify bright host stars with HZ planets to search for bio-markers, atmospheres,* understand *planetary system evolution including the host star*

Transits of HZ rocky planets, asteroseismology of host stars, bright host stars.

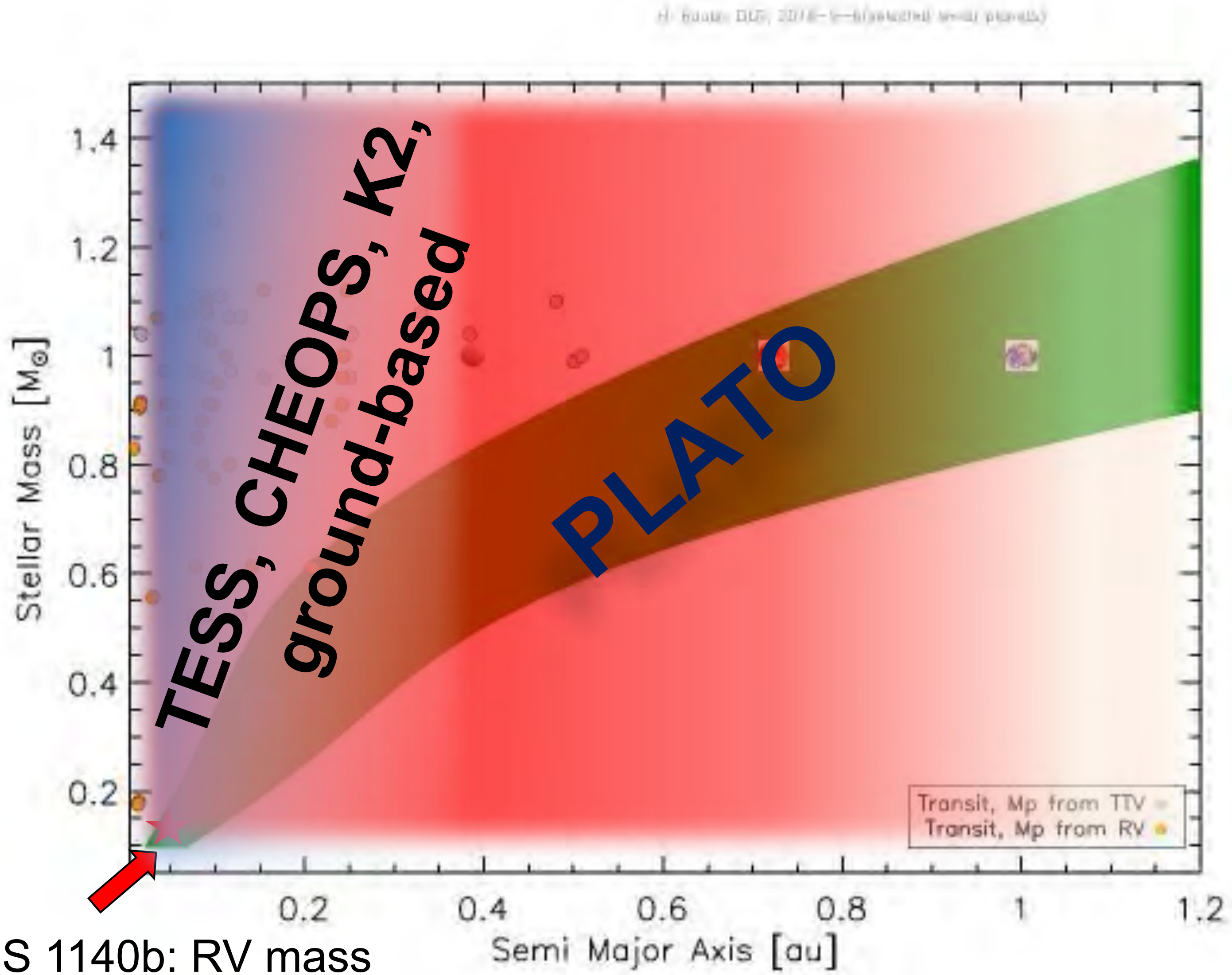
Bulk characterized super-Earths



TESS, CHEOPS, K2, ground-based

LHS 1140b: RV mass
TRAPPIST: TTV masses

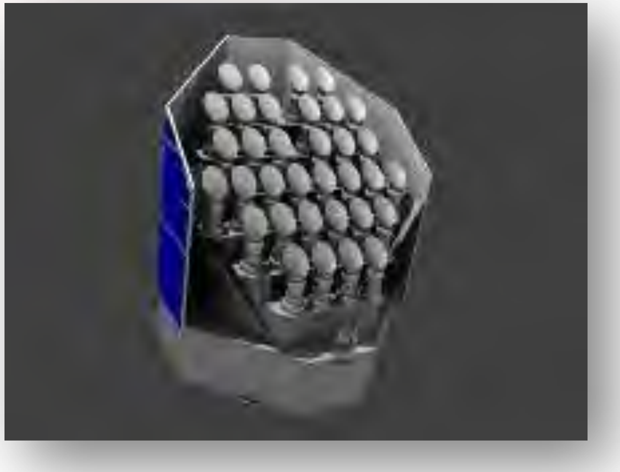
Bulk characterized super-Earths



LHS 1140b: RV mass
TRAPPIST: TTV masses

PLATO spacecraft & payload

Two designs studied in M3:



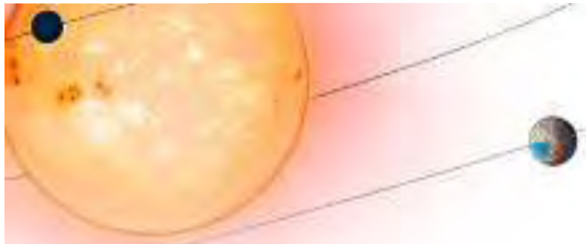
Final design to be selected early 2018.

Multi-telescope approach:

- *Large FOV (Large number of bright stars)*
- Large total collecting area *(provides high sensitivity allowing asteroseismology)*
- *Multiple telescope design mostly eliminates systematics*
- Redundancy

- **24 «normal» 20cm cameras, cadence 28 s, white light**
- **2 «fast» 20cm cameras, cadence 2.5 s, 2 colours**
- **dynamical range: $4 \leq m_V \leq 16$**

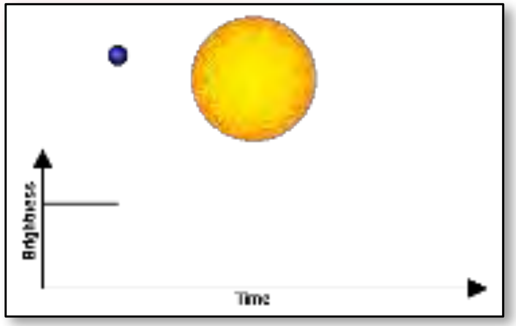
- **L2 orbit**
- **Nominal mission duration: 4+ (6.5-8) years**
- **Stares continually at just a few fields**



PLATO methods

Satellite photometry

Ground-based spectroscopy

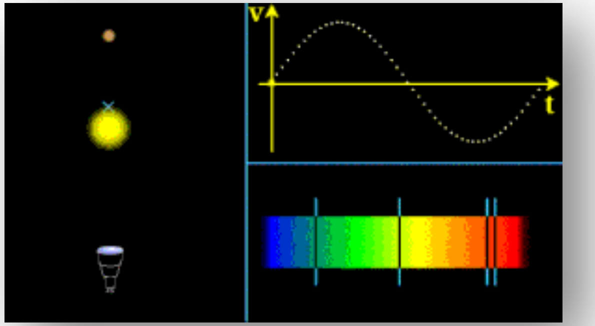


Transit detection

→ Planet/star radius ratio
→ Inclination

Asteroseismology

→ Stellar radius, mass
→ Stellar age



RV spectroscopy

→ Planet mass

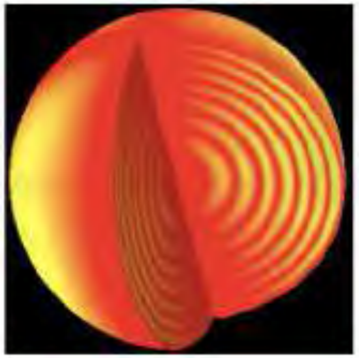
→Planet radius
→Planet age

characterized

PLATO precisions: The benchmark case: An Earth around a Sun at V= 10 mag:

→ 3% radius; → 10% mass; → 10% age

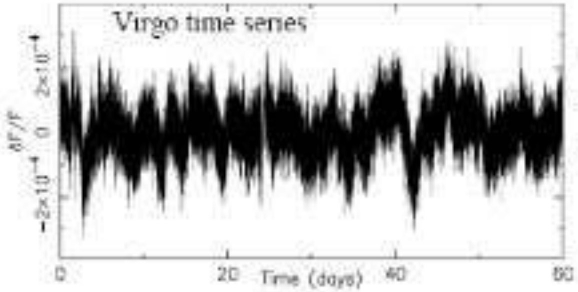
PLATO: Characterisation of host stars

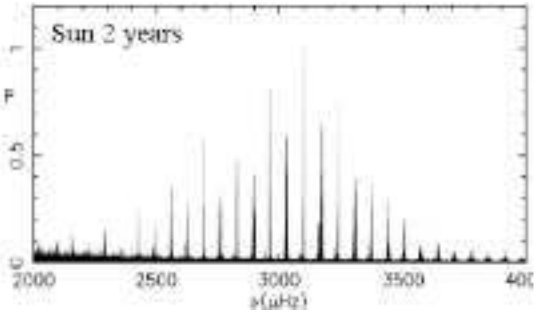


Planet parameters ← stellar parameters (asterosiesmology)

Solar-like stars oscillate in many modes, excited by convection. Sound waves trapped in interior

Resonant frequencies determined by structure:
→ frequencies probe structure
→ gives mass, angular momentum, age





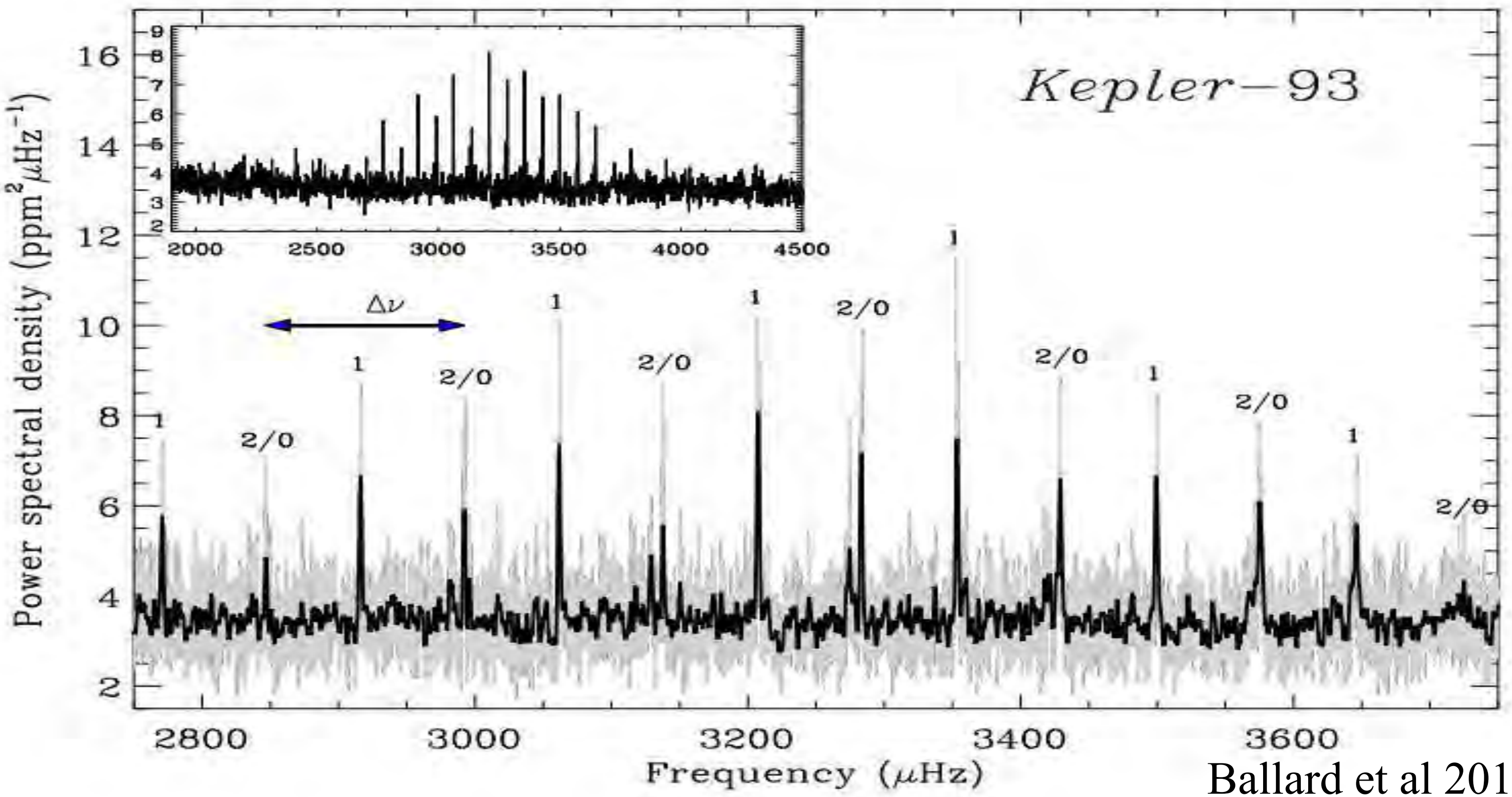
l=1, m=0

l=2, m=0

l=2, m=1

l=4, m=2

Asterosiesmology and stellar parameters



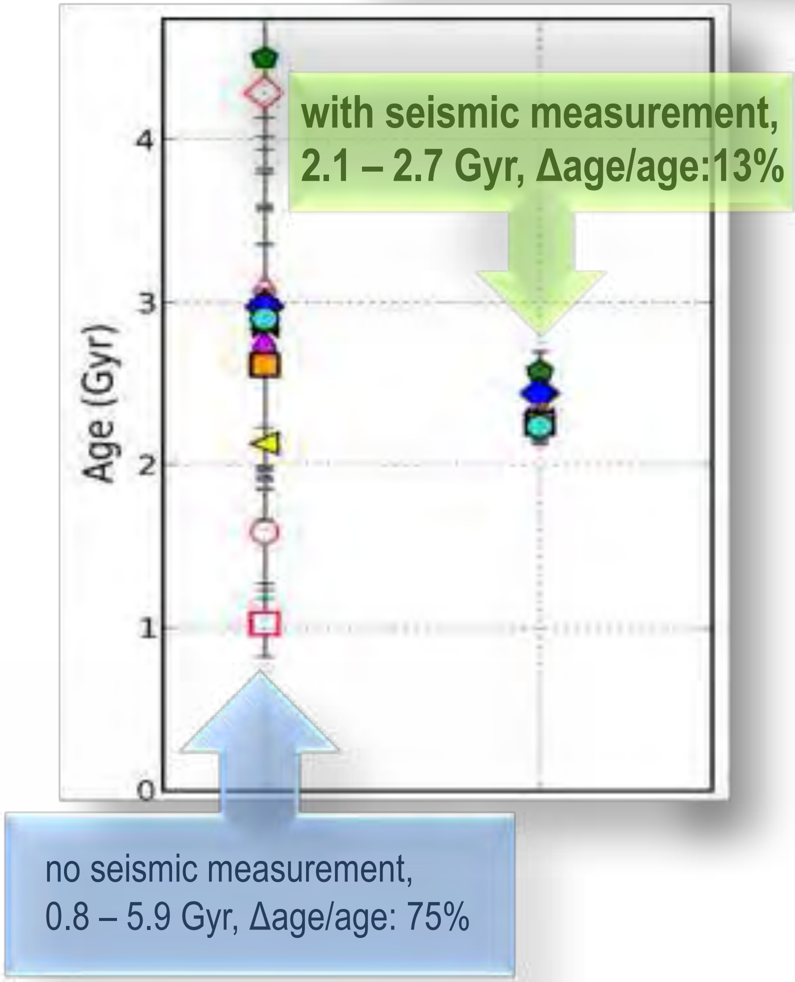
Ballard et al 2014

Large frequency separation proportional to square root of stellar mean density

Small separations sensitive to hydrogen abundance in the core => age

Host star: Age, Radius & Mass

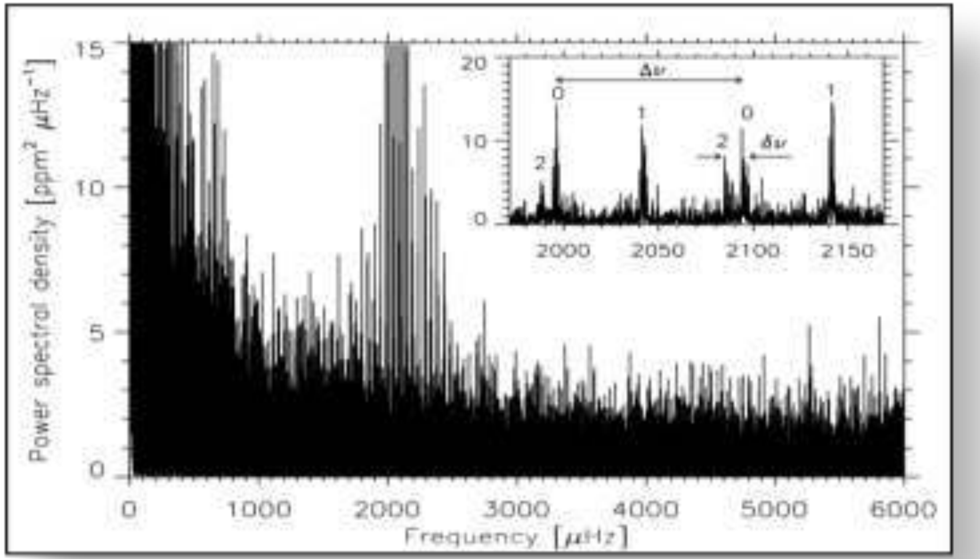
CoRoT and Kepler have demonstrated that the required accuracies can be met



with seismic measurement, 2.1 – 2.7 Gyr, Δage/age:13%

no seismic measurement, 0.8 – 5.9 Gyr, Δage/age: 75%

Example: HD 52265 (CoRoT), a G0V type, planet-hosting star, 4 months data



(Gizon et al. 2013)

Seismic parameters: Radius: 1.34 ± 0.02 R_{sun},
Mass: 1.27 ± 0.03 M_{sun},
Age: 2.37 ± 0.29 Gyr

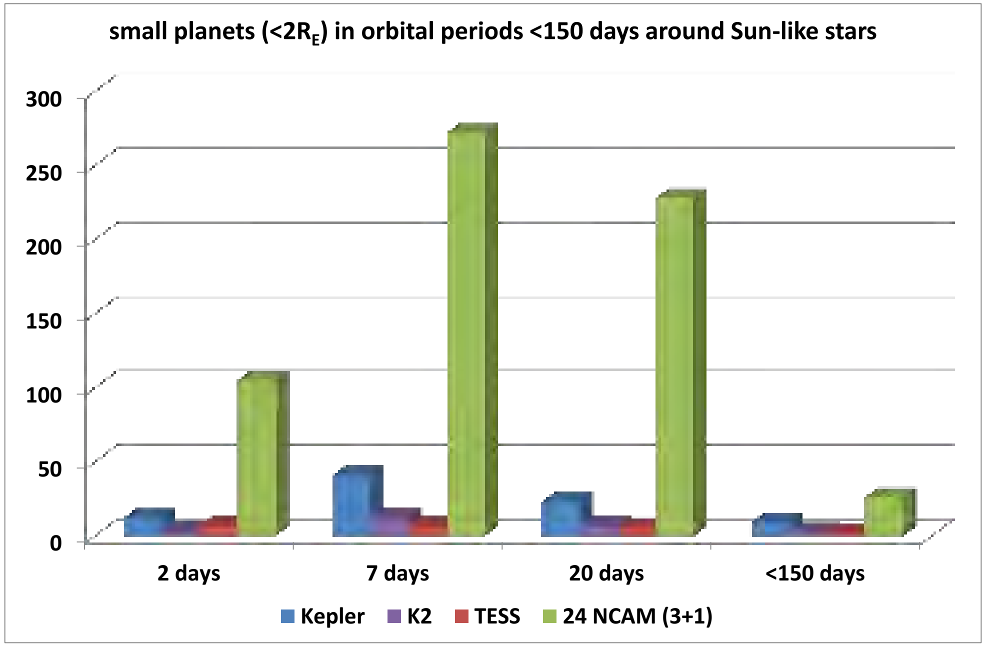
Transit signals of small planets

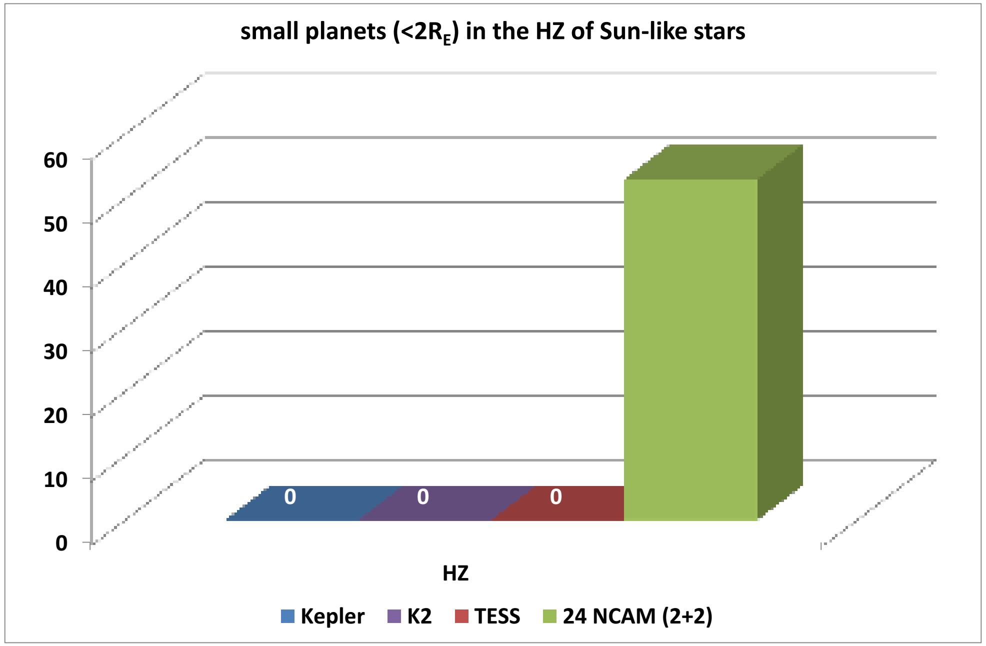
Expected transit detections in the core sample for planets **<2 Rearth**

(without considering RV follow-up, but with asteroseismology)**:**

1 Long stare +1 year observing sequence:
maximize for shorter orbital periods

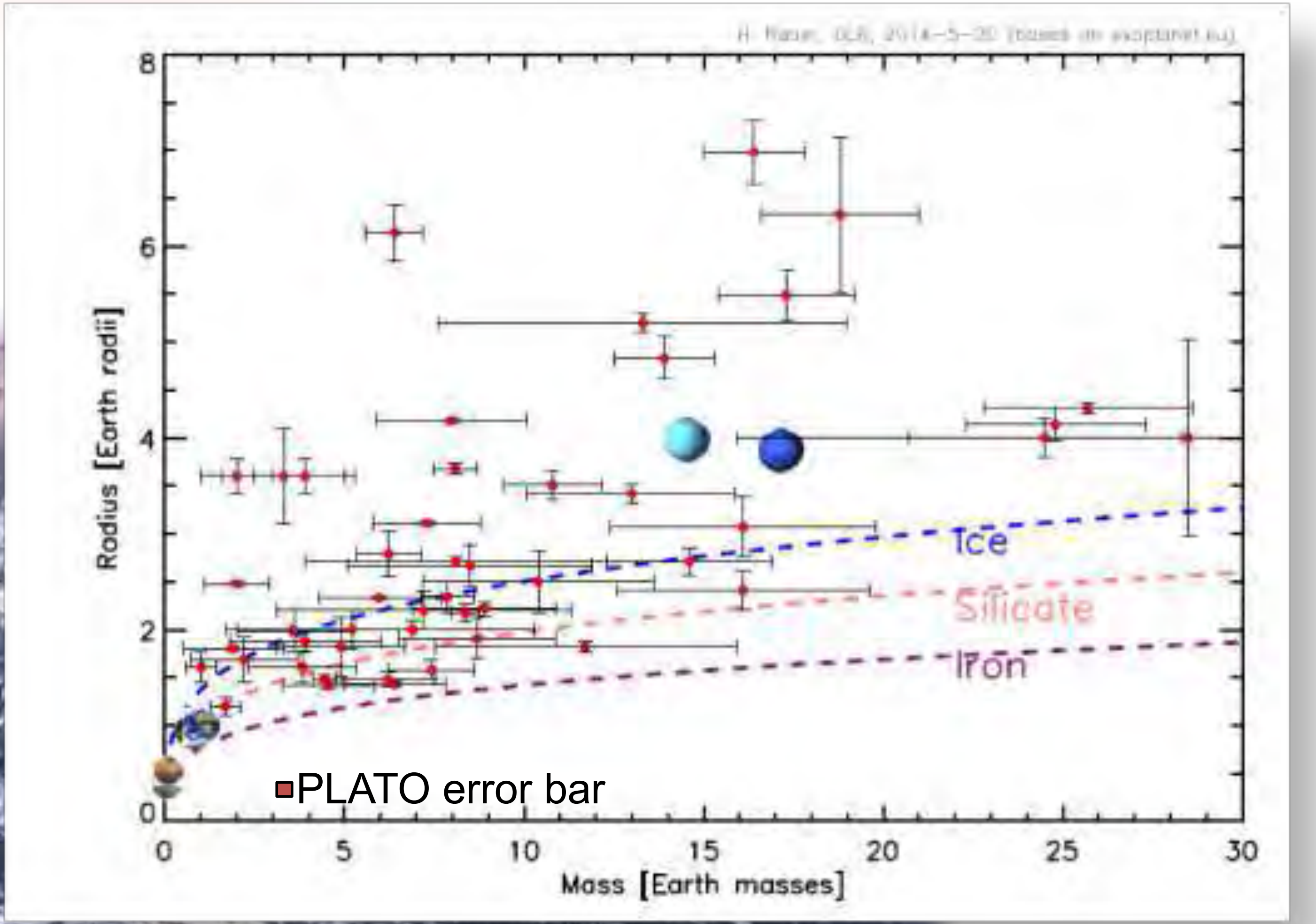
2 Long stare observing sequence:
maximize for terrestrial planets in the HZ (for 40% occurrence frequency)





→ The final yield of fully characterized planets will depend on mission extensions and available ground-based telescope time.

Diversity of Rocky Planets



Status:

- Masses vary
  by a factor of ~4
  (with large errors)
- Radii vary
  by a factor of ~3

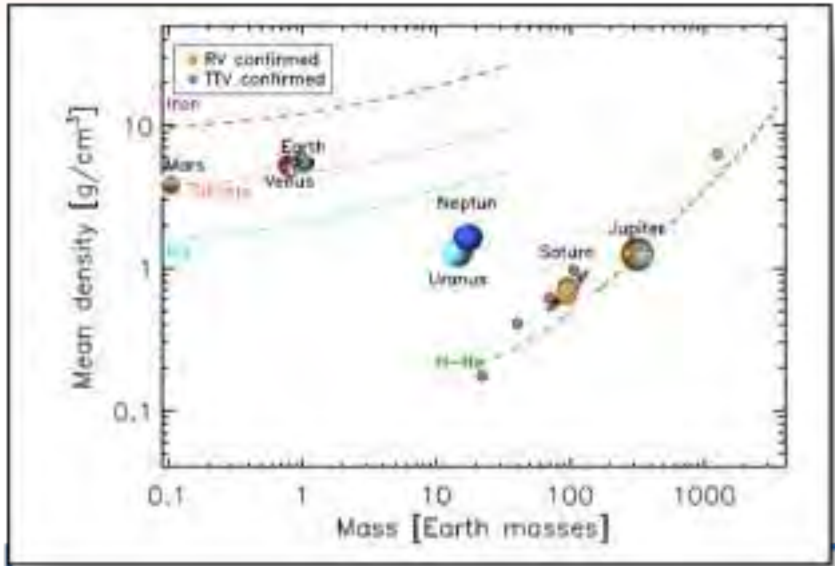
Accuracy needed to break composition degeneracy

→ **PLATO goals**:

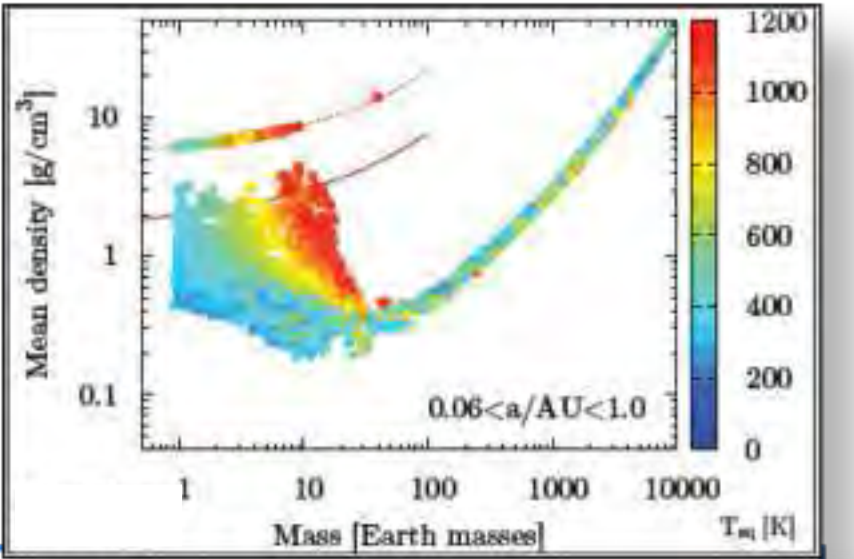
- Radius: ~3%
- Mass: ~10%

Planet diversity and planet formation

Observations



Planet formation model predictions



Mordasini et al.

PLATO will allow us to:

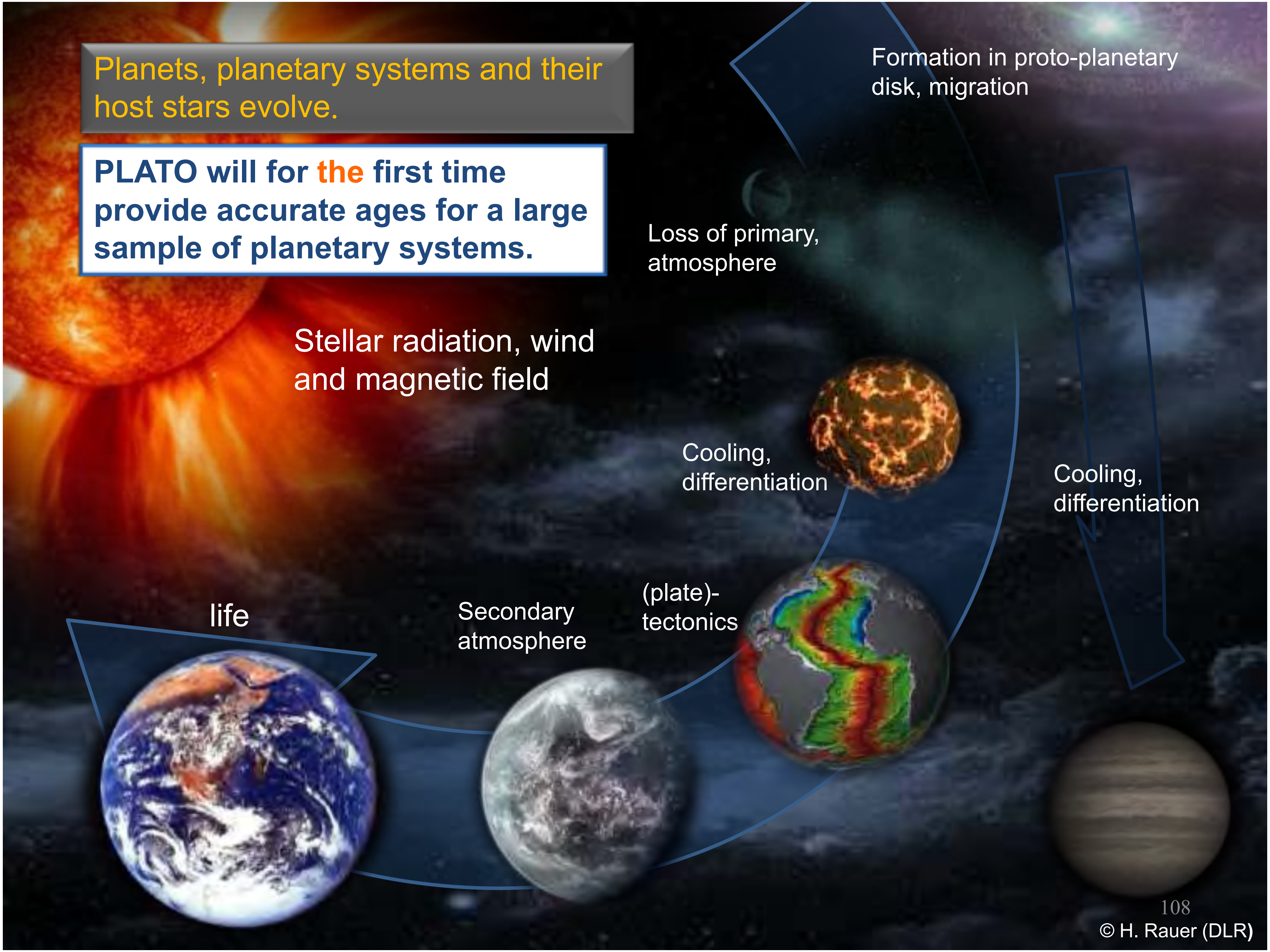
- Measure how planet density and mass vary with
  - orbital distance and planetary system architectures
  - host star parameters (spectral type, composition, age…)

→ gain new insights into planet formation and evolution processes

Theory integrated into PLATO

Planets, planetary systems and their host stars evolve.

PLATO will for the first time provide accurate ages for a large sample of planetary systems.



Stellar radiation, wind and magnetic field

Formation in proto-planetary disk, migration

Loss of primary, atmosphere

Cooling, differentiation

Cooling, differentiation

(plate)-tectonics

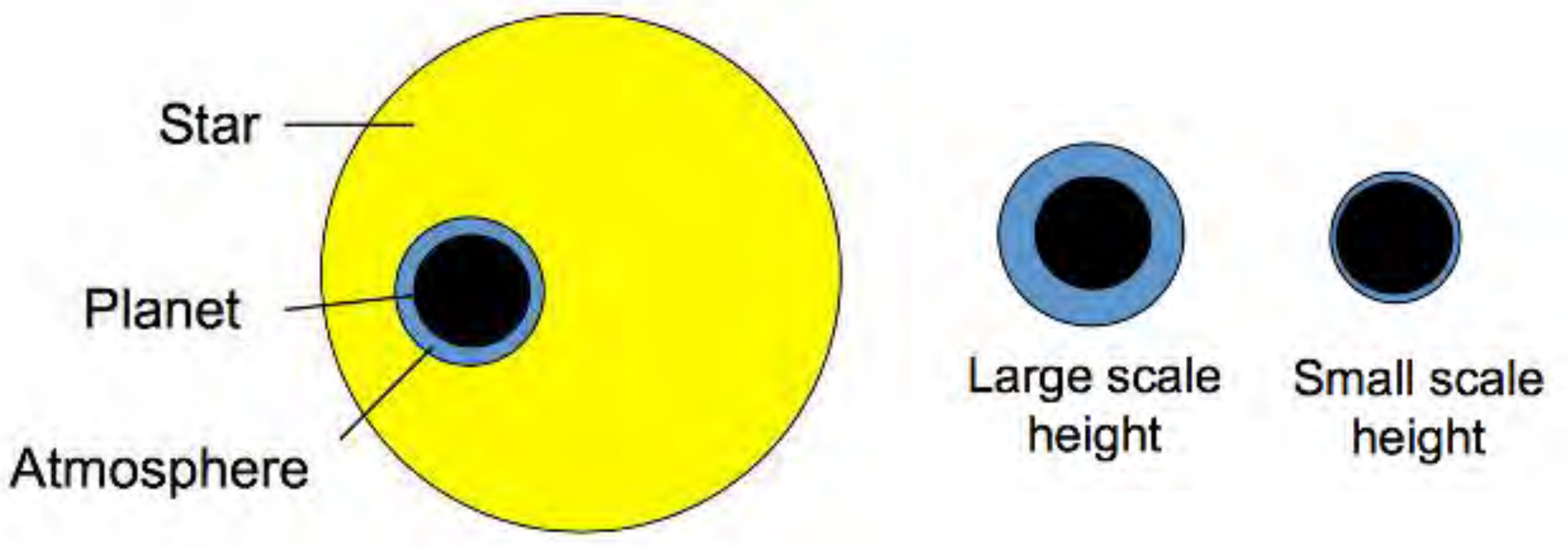
Secondary atmosphere

life

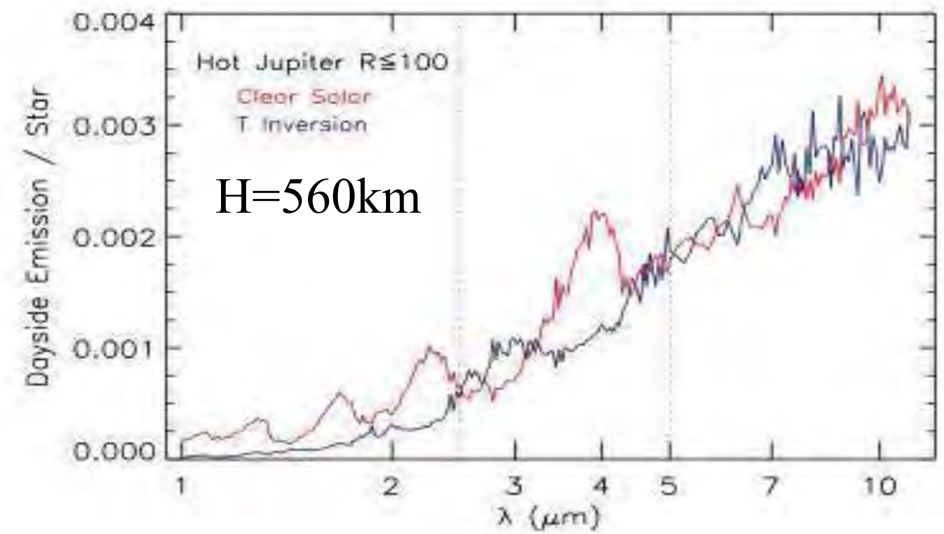
© H. Rauer (DLR)

Atmospheres of Rocky Planets with JWST

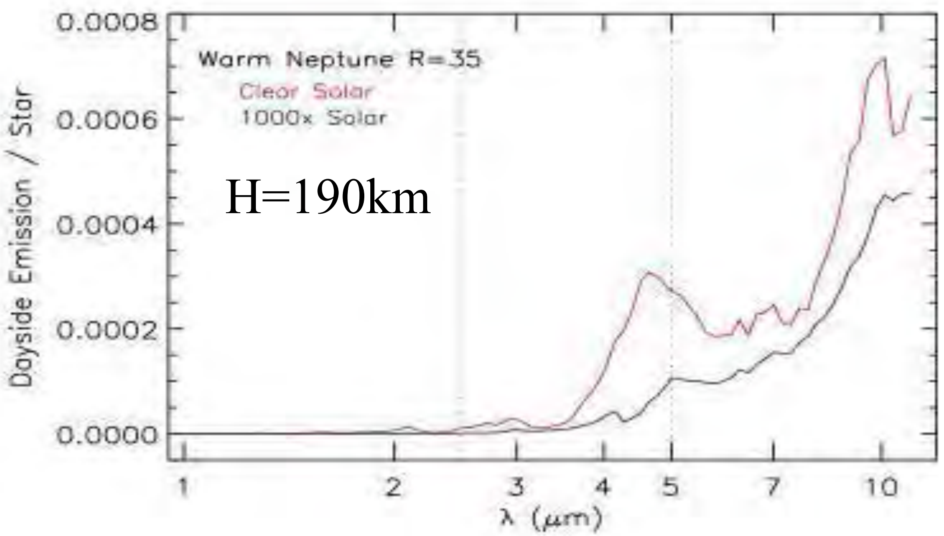
Transmission Spectra - a reminder:



Atmospheres of large Rocky Planets with JWST (Green et al 2015) 1

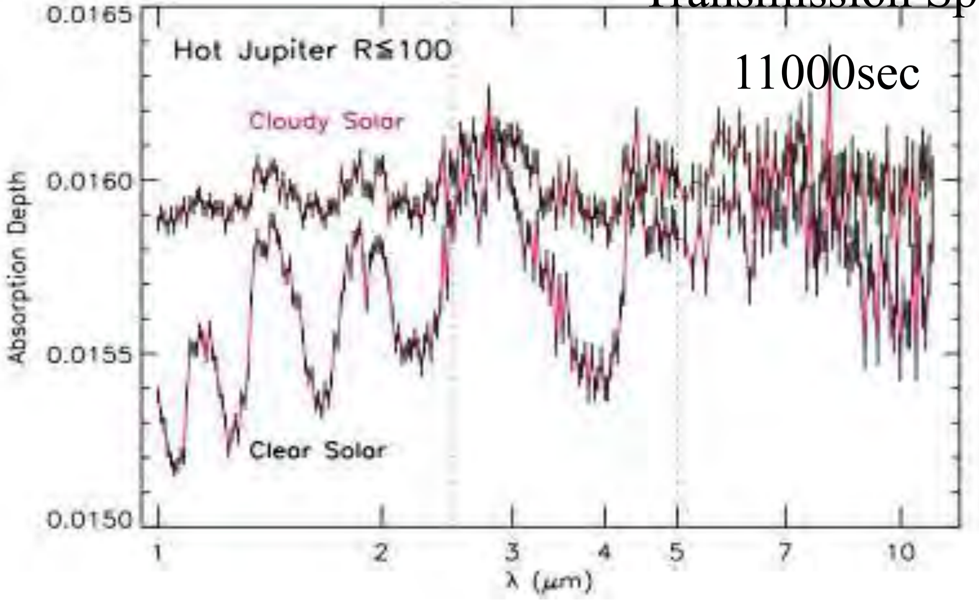


H=560km

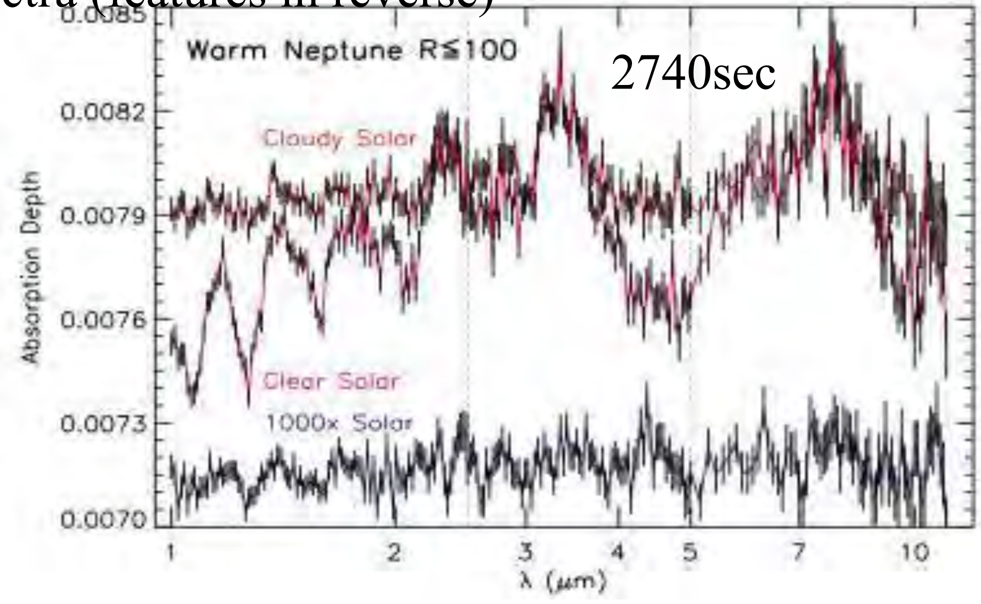


H=190km

Transmission Spectra (features in reverse)

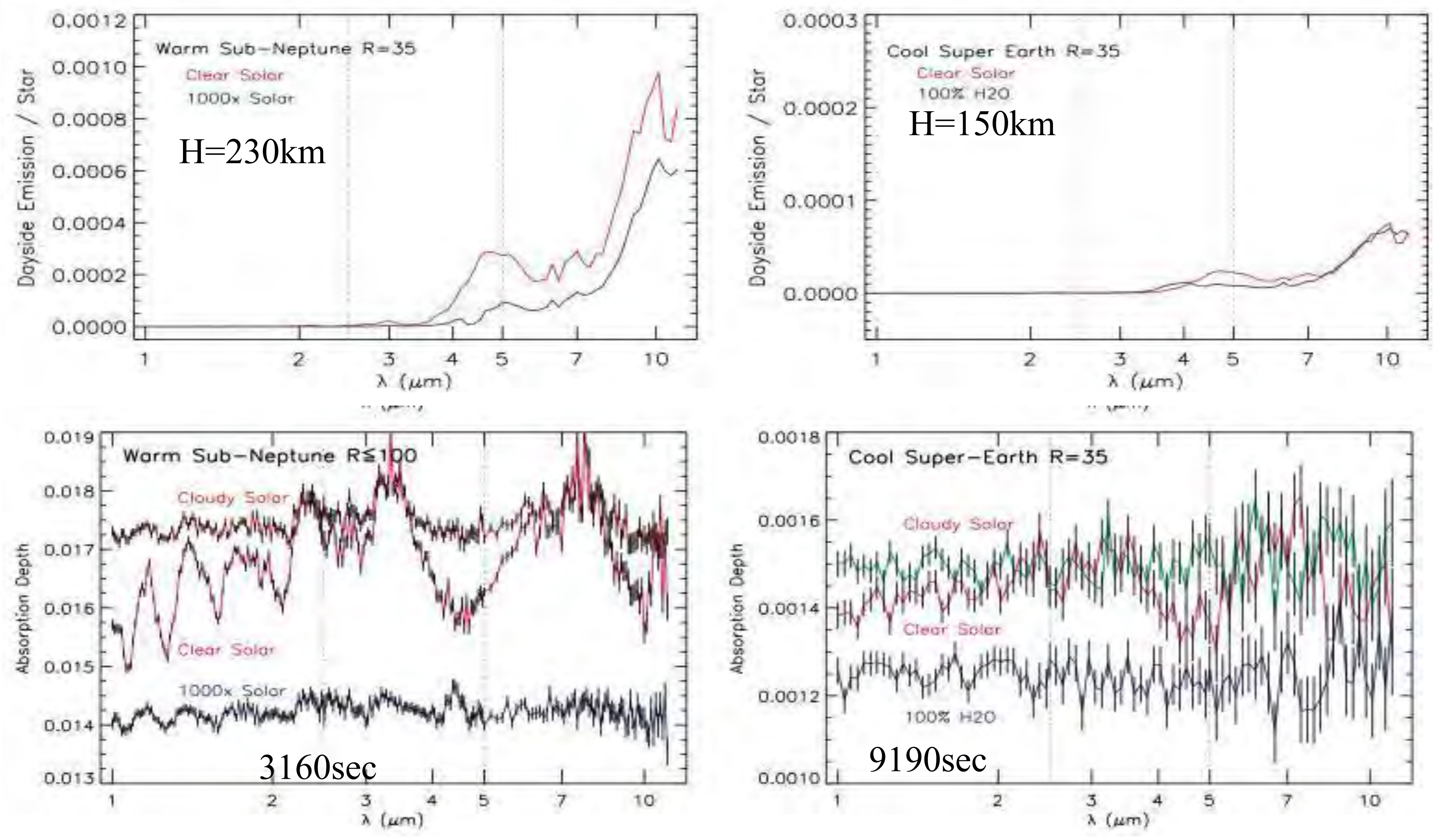


11000sec



2740sec

Atmospheres of large Rocky Planets with JWST (Green et al 2015) 2



H=230km

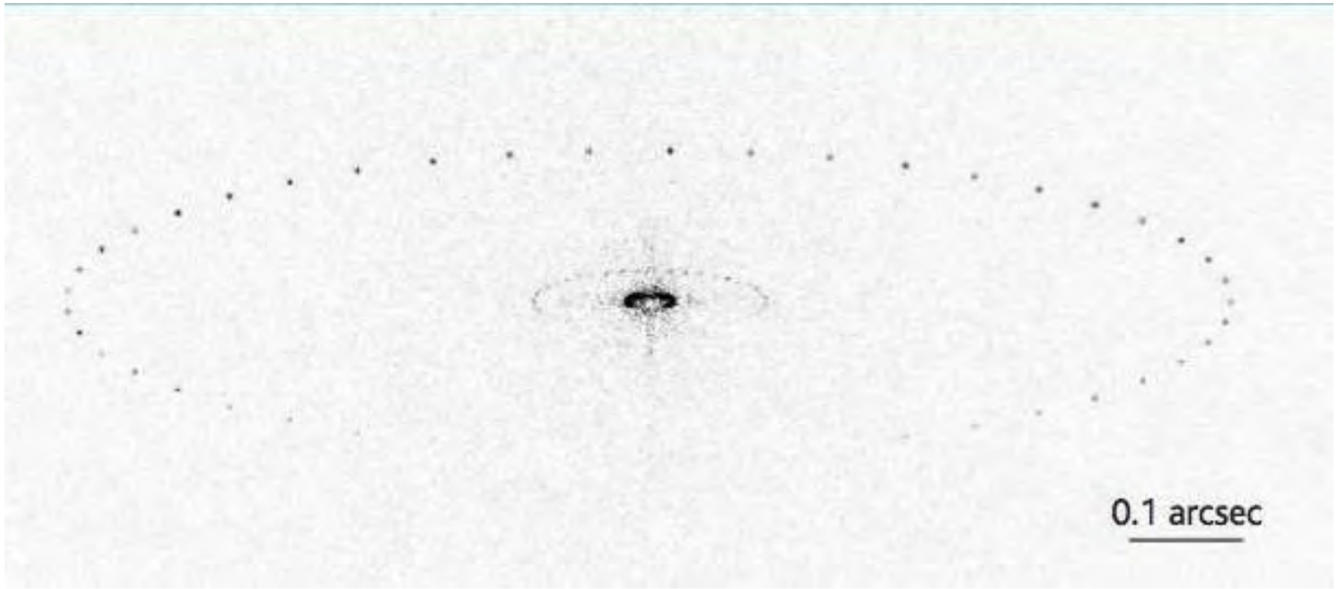
H=150km

3160sec

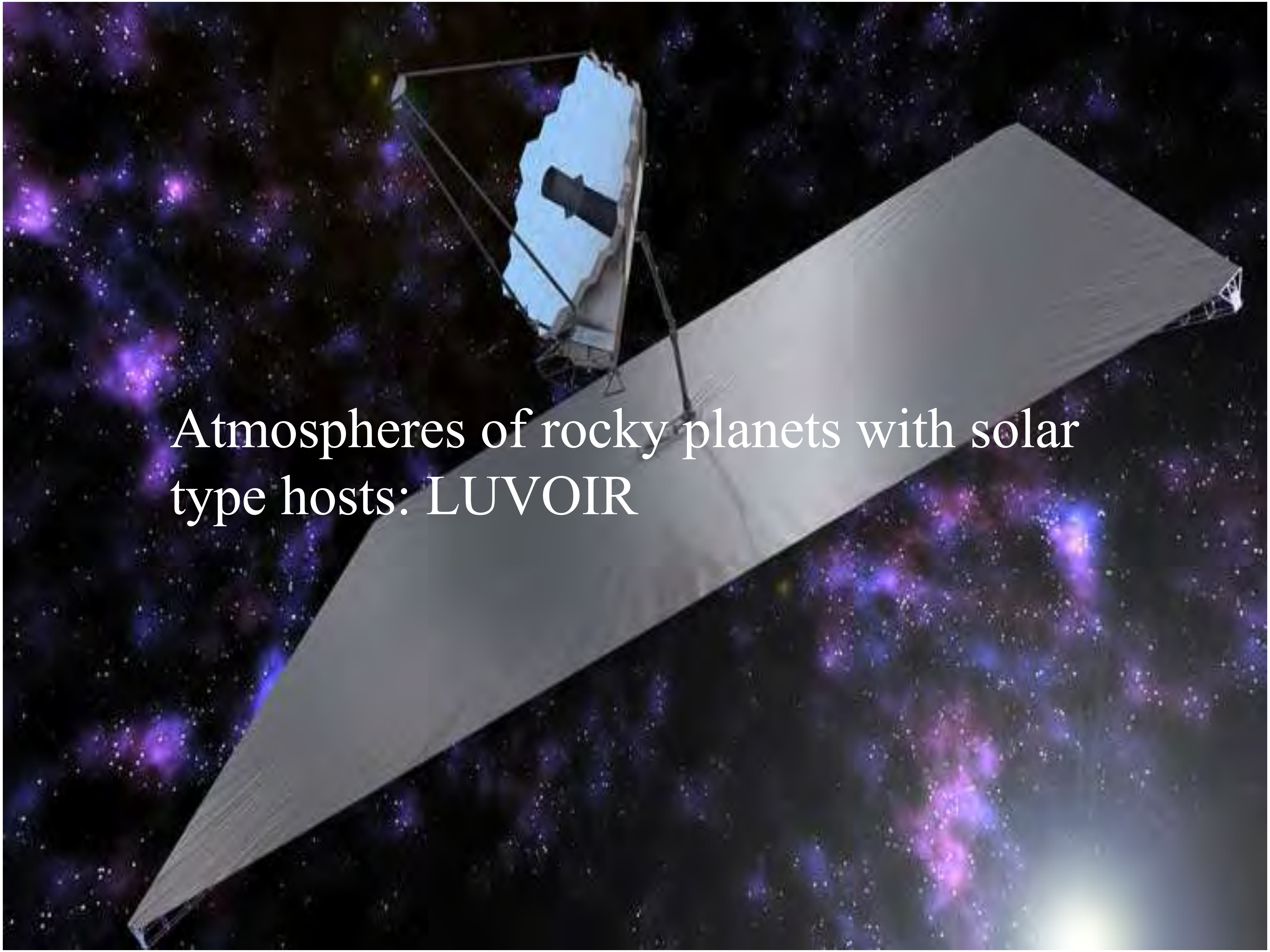
9190sec

What about PLATO HZ planets?

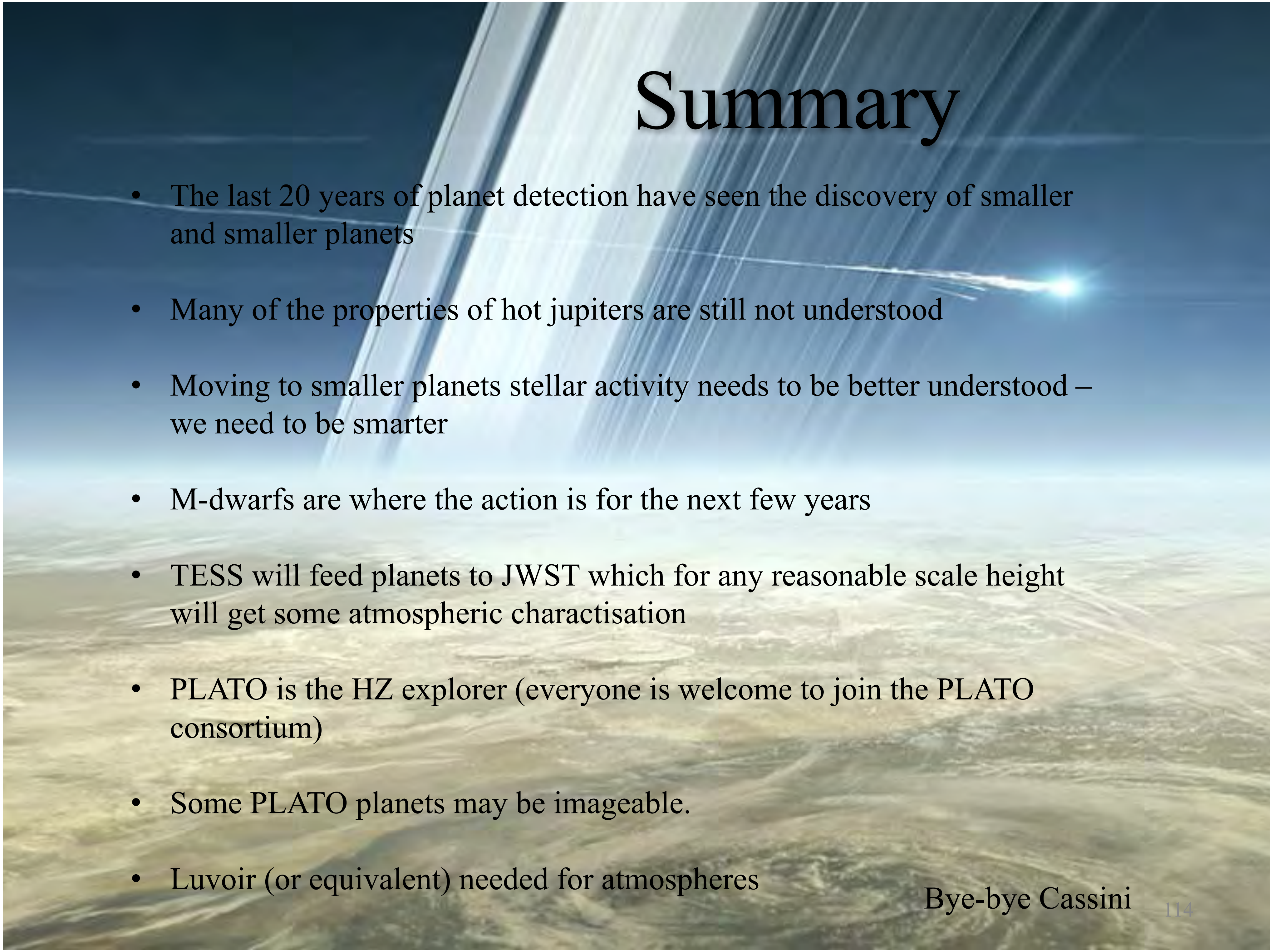
Nearest solar type stars (say 10pc), would have resolvable HZ planets: Imaging and spectroscopy possible.



Hainaut, Rahoui, & Gilmozzi 2004



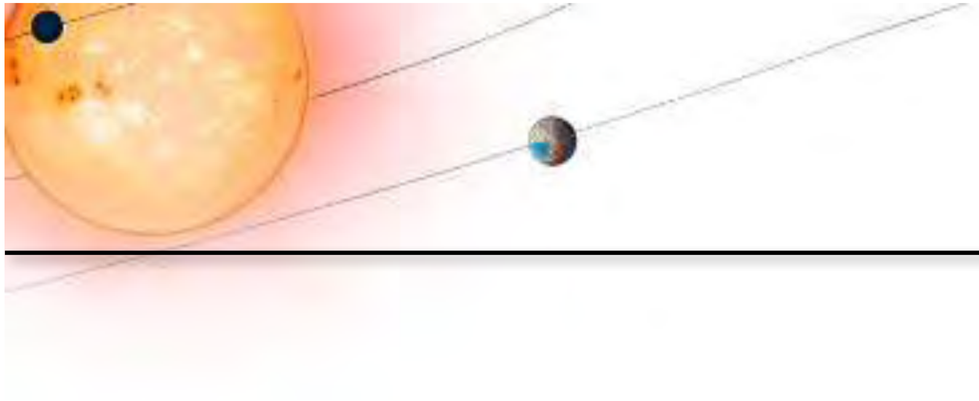
Atmospheres of rocky planets with solar type hosts: LUVOIR



Summary

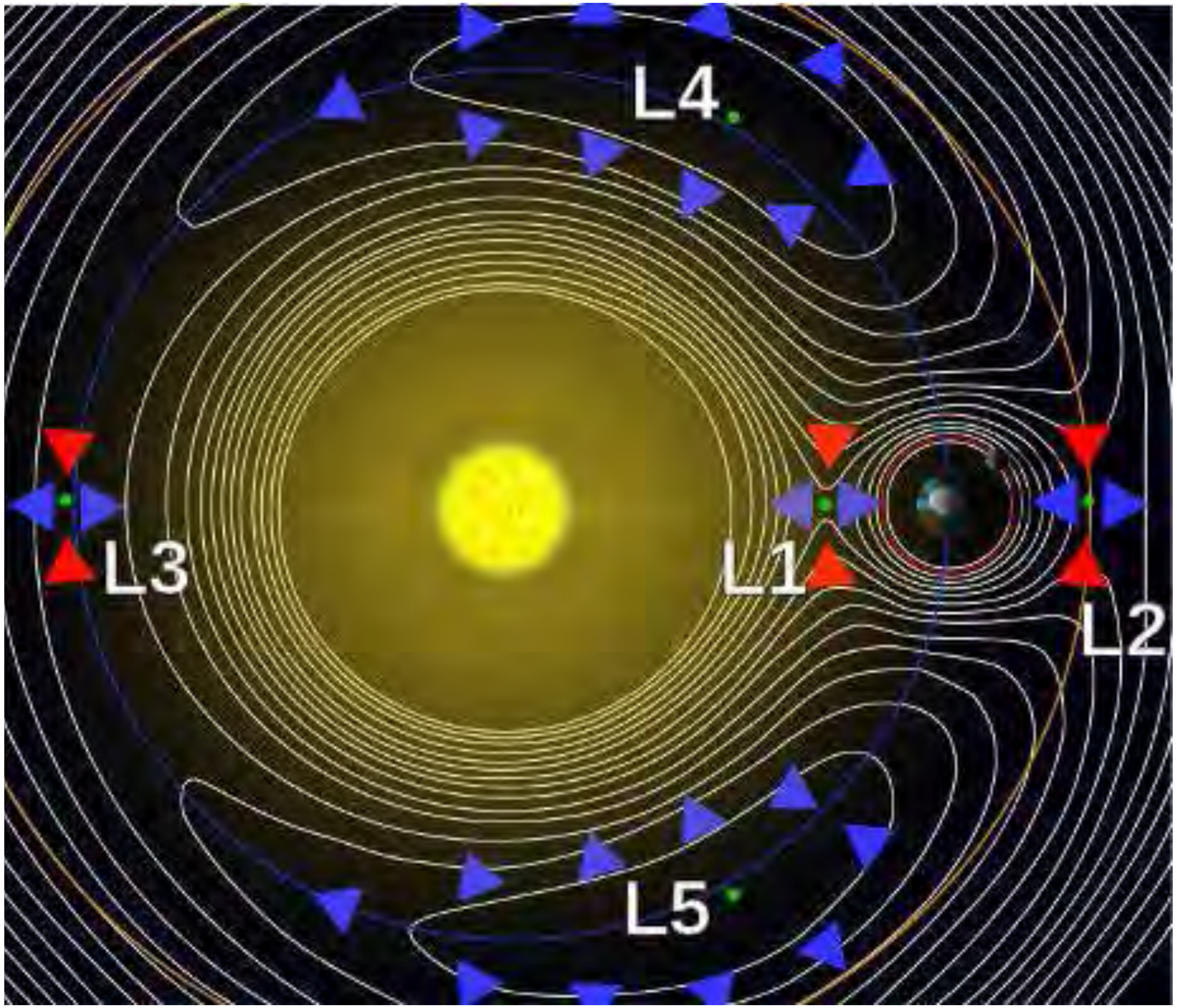
- The last 20 years of planet detection have seen the discovery of smaller and smaller planets
- Many of the properties of hot jupiters are still not understood
- Moving to smaller planets stellar activity needs to be better understood – we need to be smarter
- M-dwarfs are where the action is for the next few years
- TESS will feed planets to JWST which for any reasonable scale height will get some atmospheric charactisation
- PLATO is the HZ explorer (everyone is welcome to join the PLATO consortium)
- Some PLATO planets may be imageable.
- Luvoir (or equivalent) needed for atmospheres

Bye-bye Cassini



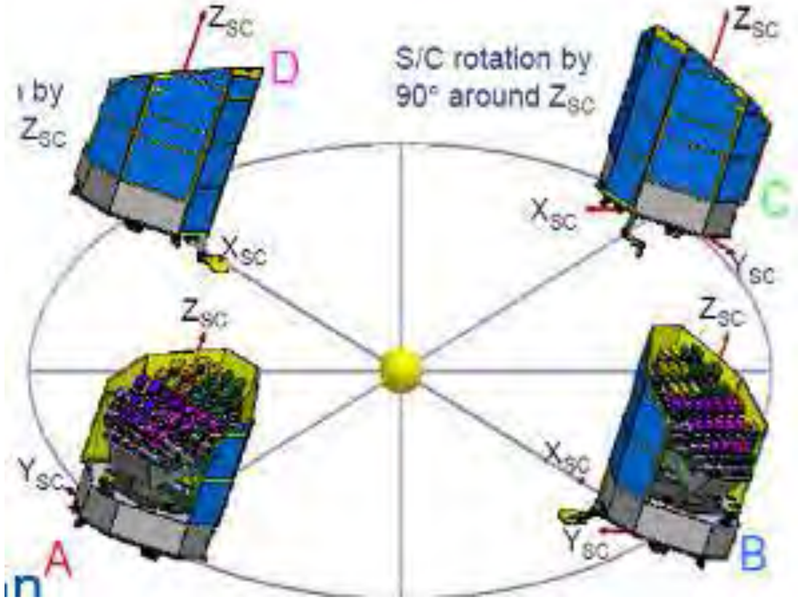
PLATO’s L2 Orbit

Surfaces of equipotential in Sun-Earth system

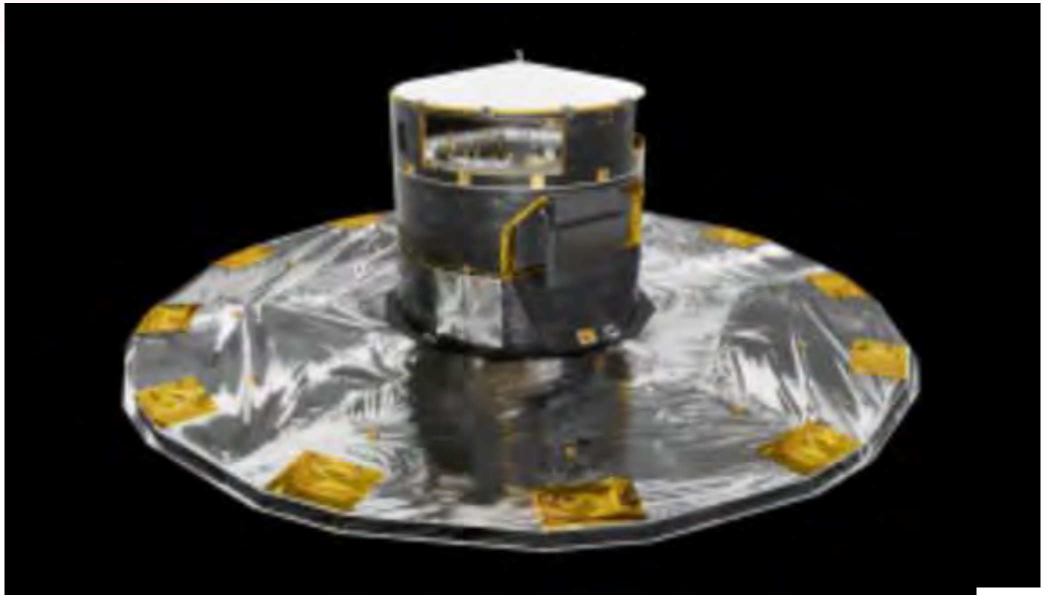


Launched from Kourou and transferred to large amplitude (1.5 Mkm orbit around L2 (Several over missions there).

Spacecraft rotated every 3 months



Gaia Coming!

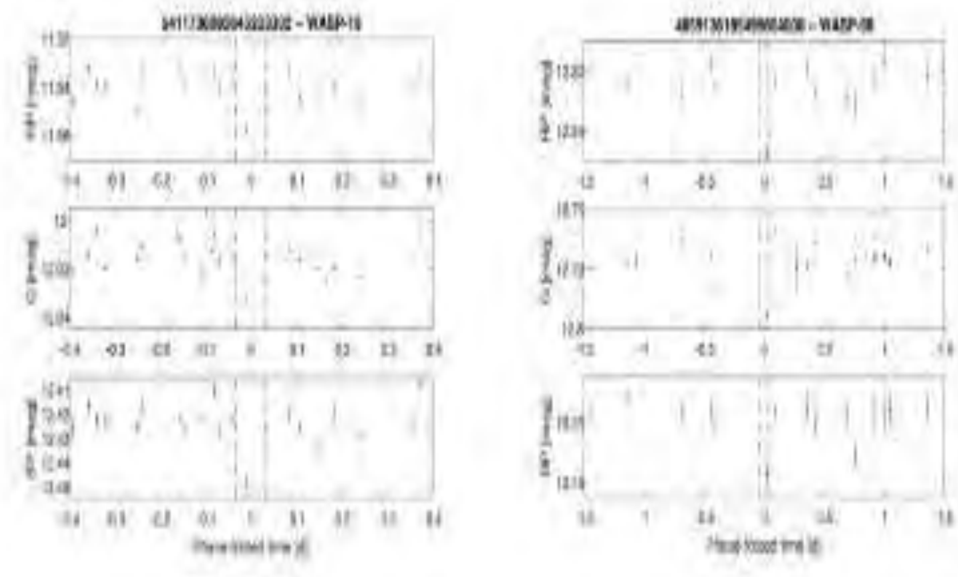


Astrometric mission

Been flying since about 2015 and last year had DR1.

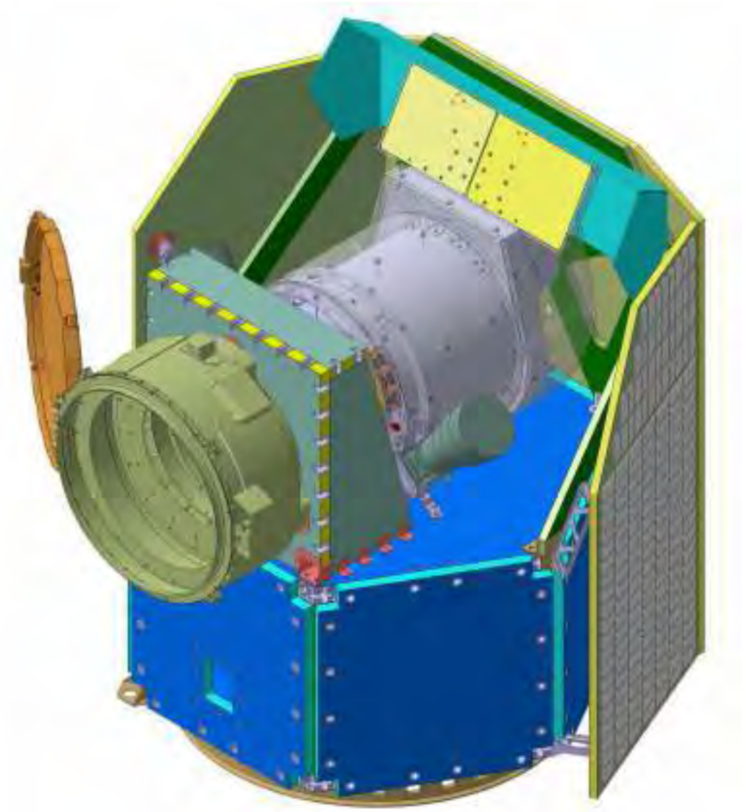
Precision ~10 microarcsec => tens of thousands of exoplanets out to 500pc, mostly large. DR2 2020.

Can also do light curves.



CHEOPS (2018)

ESA S1 Mission *Characterisation of Exoplanets* (Swiss led)

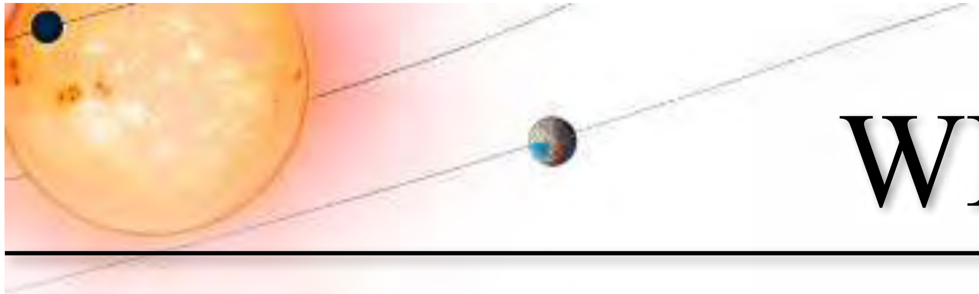


The mission goals are:
To search for shallow transits on stars already known to host planets with accuracy sufficient to identify a significant atmosphere.

To provide precision radii for a number of hot Neptune planets orbiting stars brighter than 12th V magnitude and to search for co-aligned smaller mass planets.

To measure the phase modulation due to the different contribution of the dayside of hot Jupiter planets and in some cases to measure the secondary eclipse.

Pointed mission (not a wide angle survey) known targets from RV searches and ground based transit surveys.



WFIRST/AFTA

WFIRST is a wide field imaging telescope. It has been proposed to do a microlensing survey with concurrent (maybe simultaneous) ground based observations. This will break the near-low mass v’s far high-mass degeneracy.

In principle this would give definitive statistics of the planetary mass distribution mostly at large orbital distances and mostly around low mass stars.

WAFTA: The WFIRST Coronagraph Instrument (CGI) will enable the first space-based program to directly image planets orbiting the nearest sunlike stars and to spectroscopically characterize their atmospheres at optical and near-IR wavelengths. Also baseline is a launch for a star-shade to be used for star occultation (in addition to the CGI).
Claimed to be able to image and take spectra of possible superearths around nearby stars but much will depend on technology development.