Exoplanets

Florian Rodler (ESO)

The first exoplanet was discovered in 1995.

The first exoplanet was discovered in 1995.

WRONG

✗

First alleged exoplanets were reported in the 1940s ...

Name	Period	a	e	M_C	$a'(M_A+M_C)/M_C$ (astr. units)	Reference
ζ Aqr	25^y	0.″080	.0	.6☉	13	5
μ Dra	3.2	.026	.4	.6	2.8	6
ξ Boo	2.2	.020	.0	1	1.5	7
61 Cyg	4.9	.020	.7	.016	2.4	8, 9

(Strand, 1944, AJ, 51, 12)

The observational concepts were laid out that ~40 years later led to exoplanet discoveries ...

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of ± 0·2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in exist-

There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This,

(Struwe, 1952, Obs, 72, 199)

Early claims of exoplanet discoveries (with astrometry):

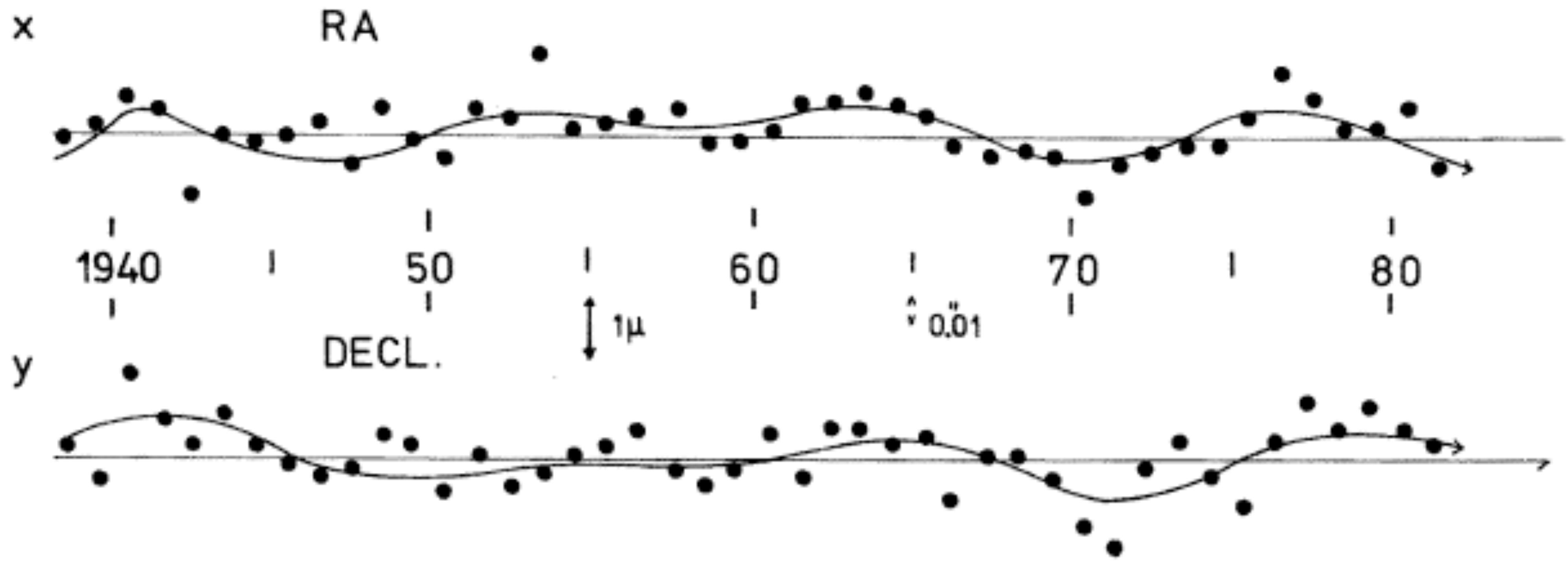


Fig. 2 Barnard's Star 1938-1981 Sproul Observatory
Yearly normal points represented by
two circular orbits; periods 12 and 20 yr.

(van de Kamp, 1982, Vistas in Ast., 26, 141)

1988: γ Cep b Campbell, Walker &Yang (ApJ 331, 902)

Radial velocities ⇒ **no firm discovery claim**

"Probable third-body variation of 25 m s^{-1} amplitude, 2.7 yr period"

⇒ in 2003 confirmed by Hatzes et al. (ApJ 599, 1383)

✓

1989: HD114762b Latham et al. (Nature 339, 38)

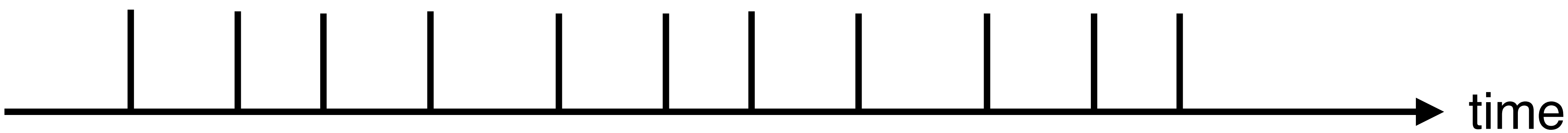
Radial velocities ⇒ **no firm discovery claim**

"The unseen companion of HD114762 - A probable brown dwarf" ... $P = 84$ d, $m \geq 11\ M_{Jupiter}$

✓

1991: PSR 1829-10 Lyne (Nature 352, 537)

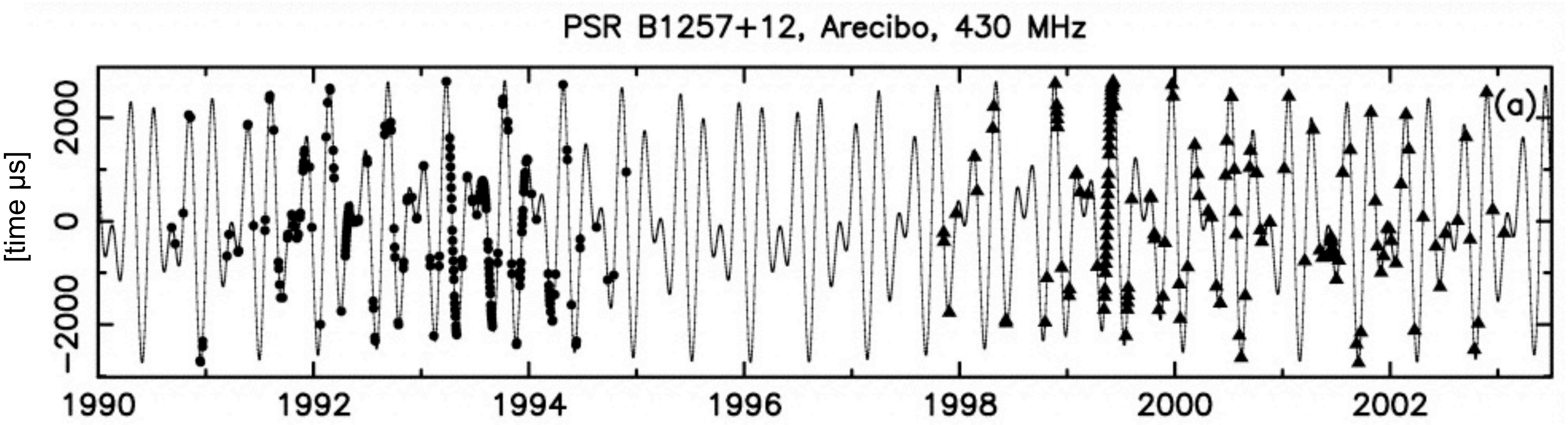
Pulsar Timing: Radio pulses arrive earlier and later at Earth



Problem: P = ½ yr ⇒ Error in the correction of the eccentricity of the Earth's movement.

1992: PSR 1257+12 Wolszczan & Frail (Nature 355, 145)

Pulsar timing ⇒ 3 M_{Earth} planets orbiting a pulsar

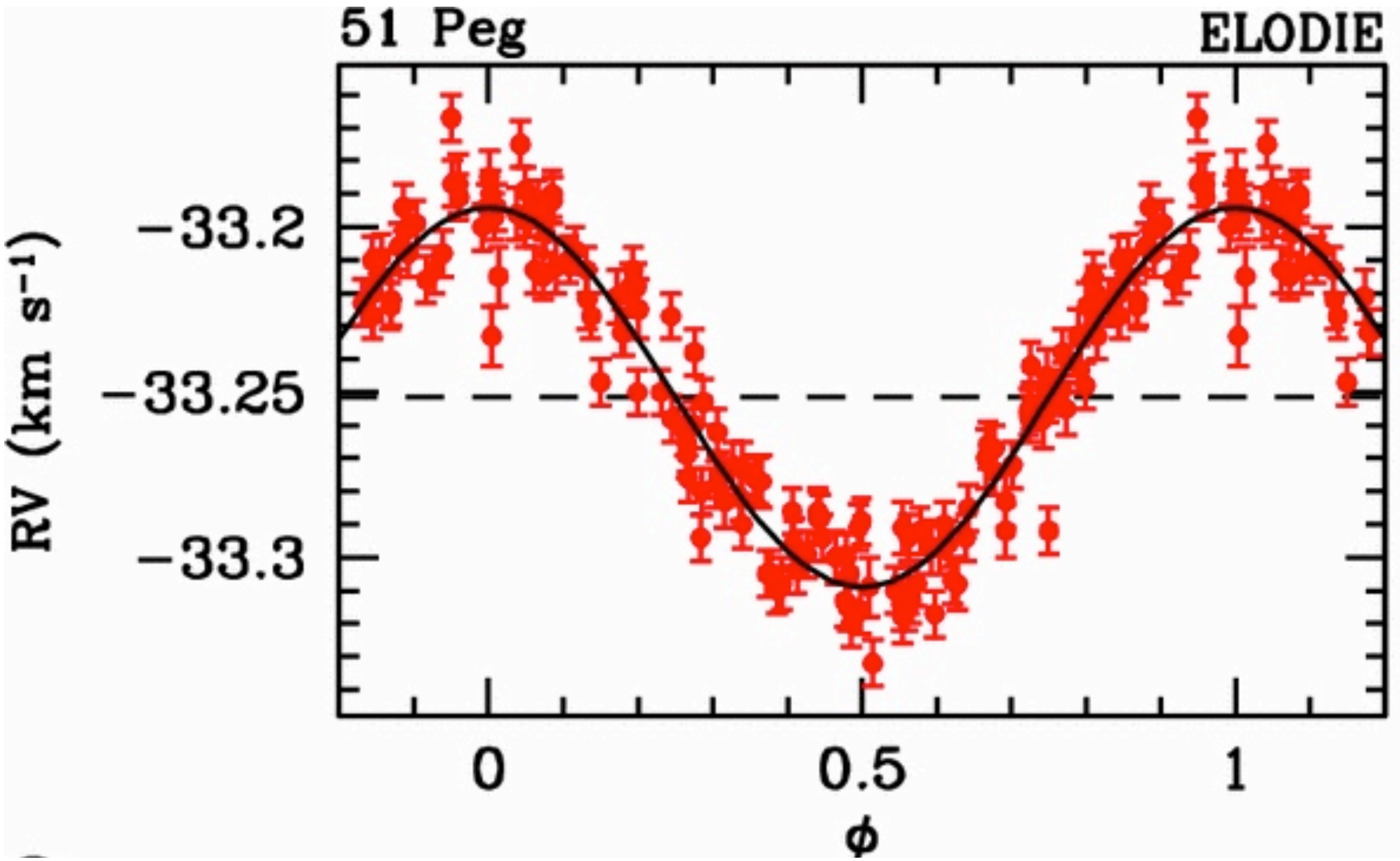


✓

1995: 51 Peg b Mayor & Queloz (Nature 378, 355)

RVs *"A Jupiter-mass companion to a solar-type star"*

$P = 4.23$ d, $a = 0.05$ AU **(!)**, $m \geq 0.47\ M_{Jupiter}$

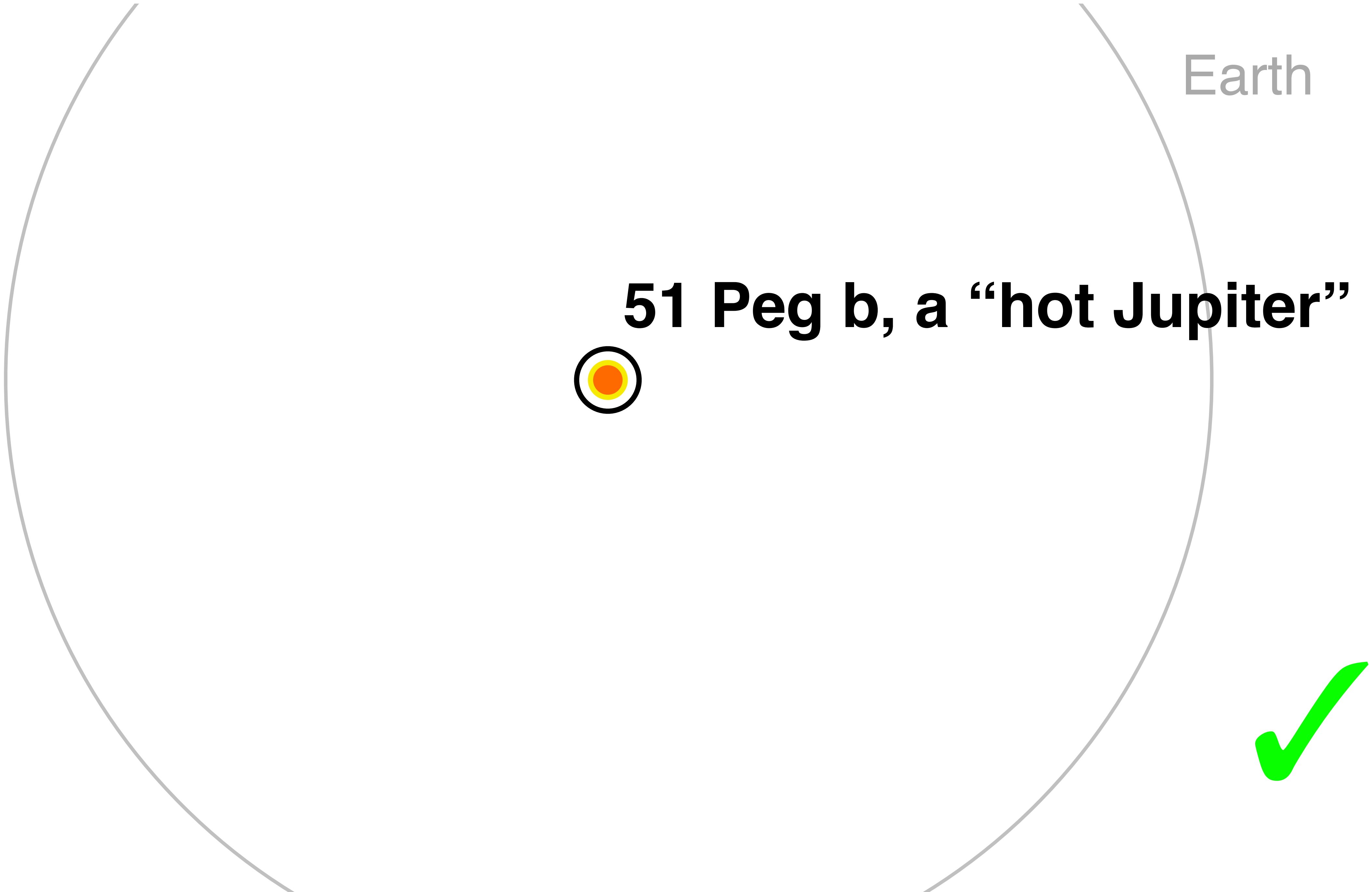


First Discoveries

1995: 51 Peg b Mayor & Queloz (Nature 378, 355)

RVs *"A Jupiter-mass companion to a solar-type star"*

*$P = 4.23$ d, $a = 0.05$ AU **(!)**, $m \geq 0.47\ M_{Jupiter}$*



The first exoplanet around a solar-type star was discovered in 1995.

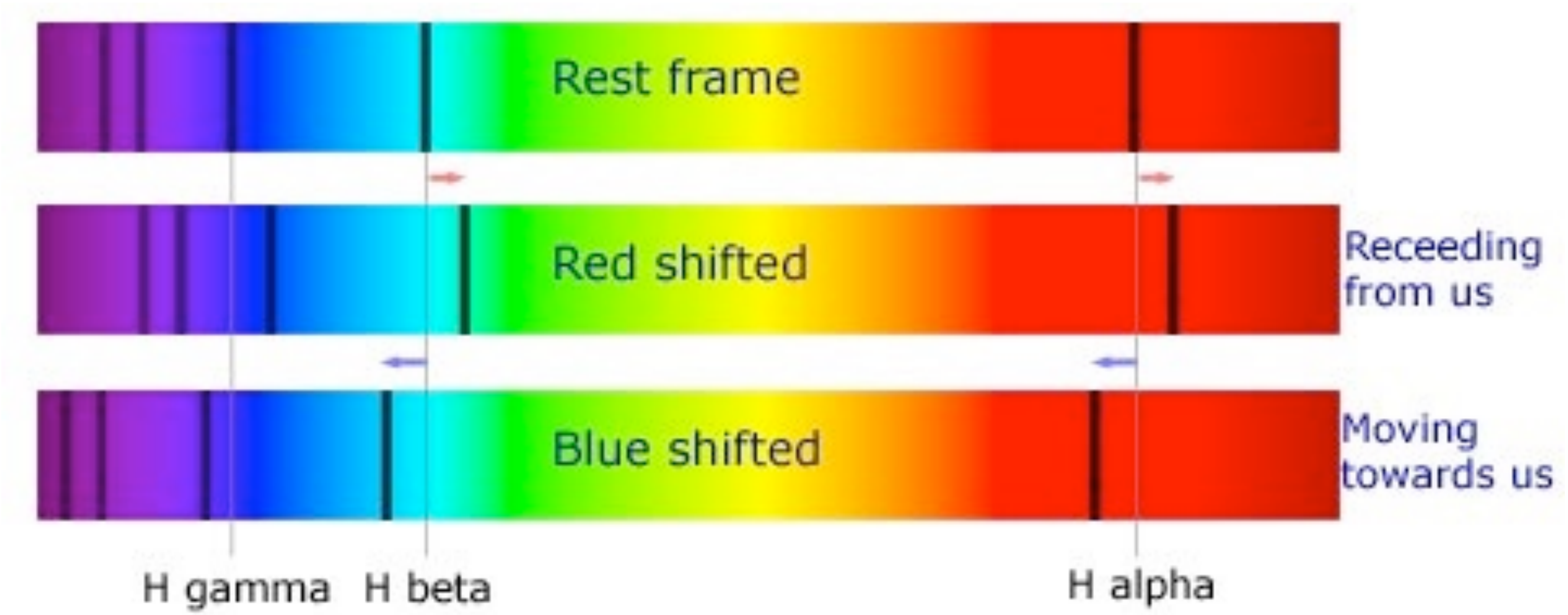
✓

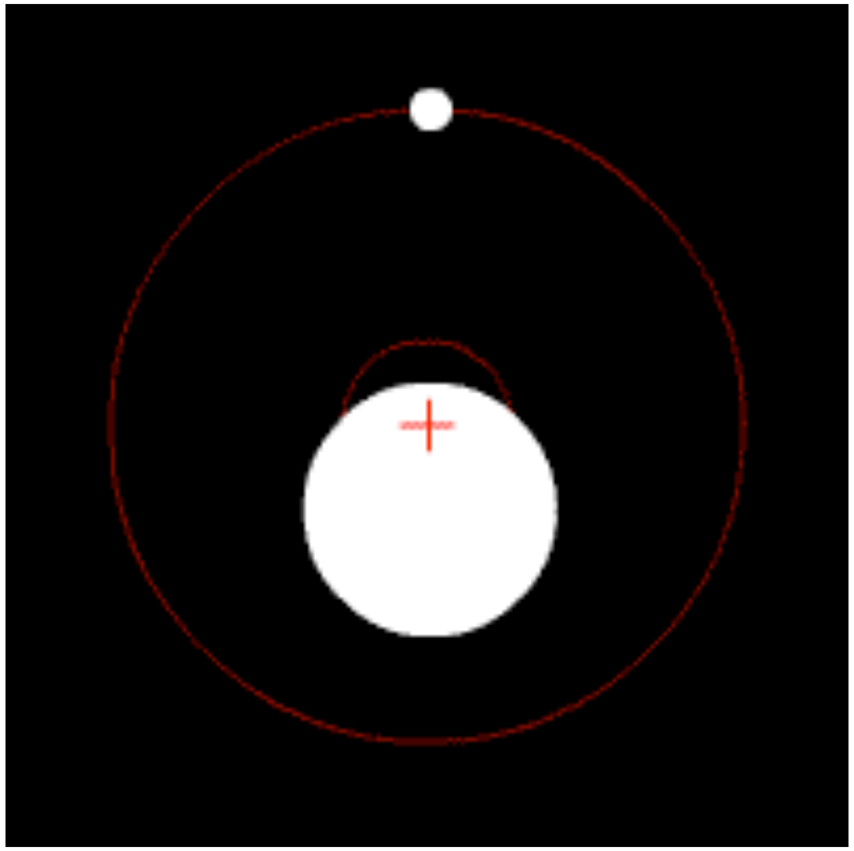
- **Radial Velocities**
- **Transits**
- **Direct Imaging**
- Astrometry
- Microlensing
- Pulsar Timing
- Transit Timing
- Interferometry

Radial Velocity technique:

measure **stellar absorption lines!**

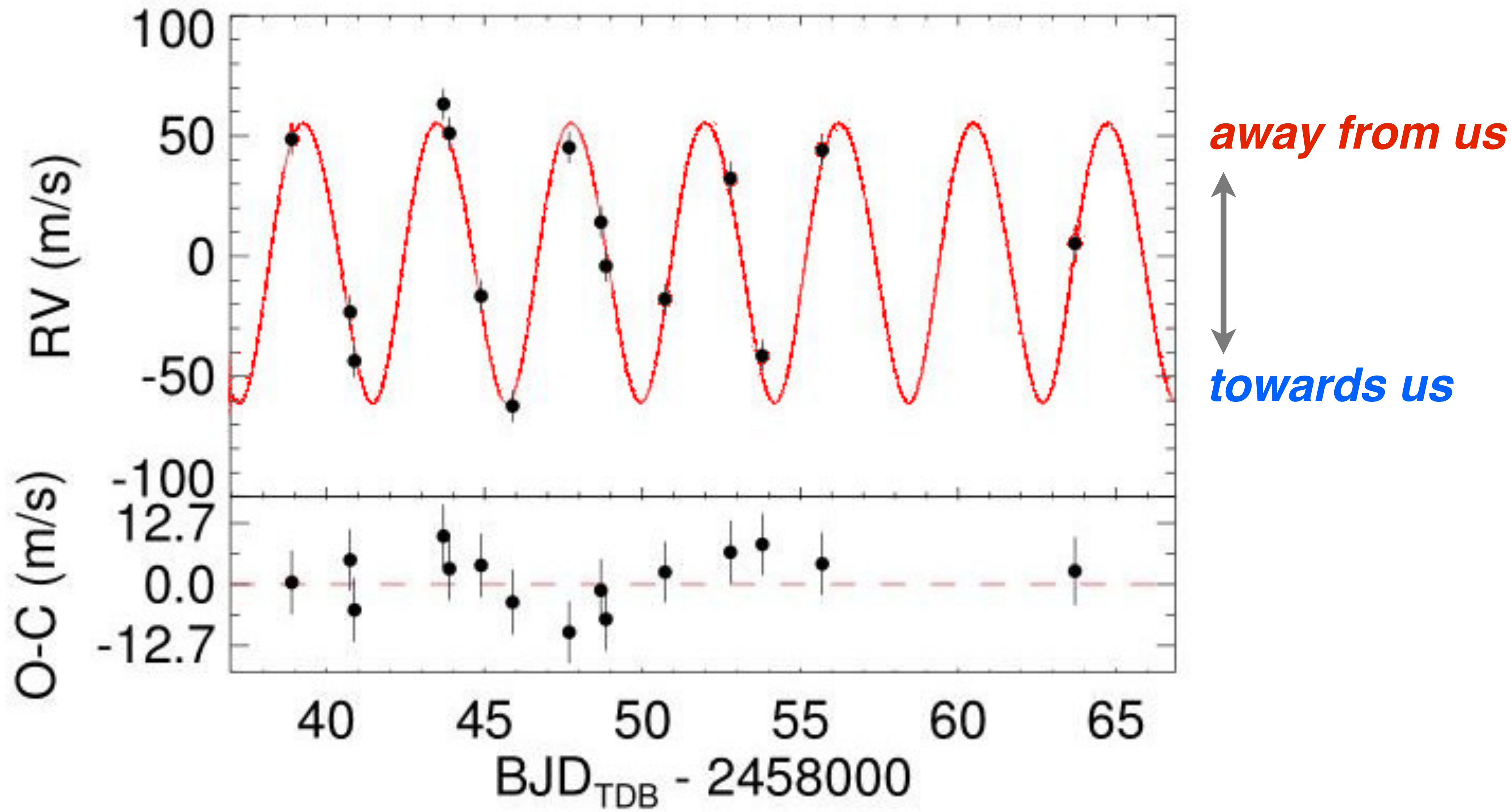
They shift as the star wobbles due to gravitational pull of the unseen planet





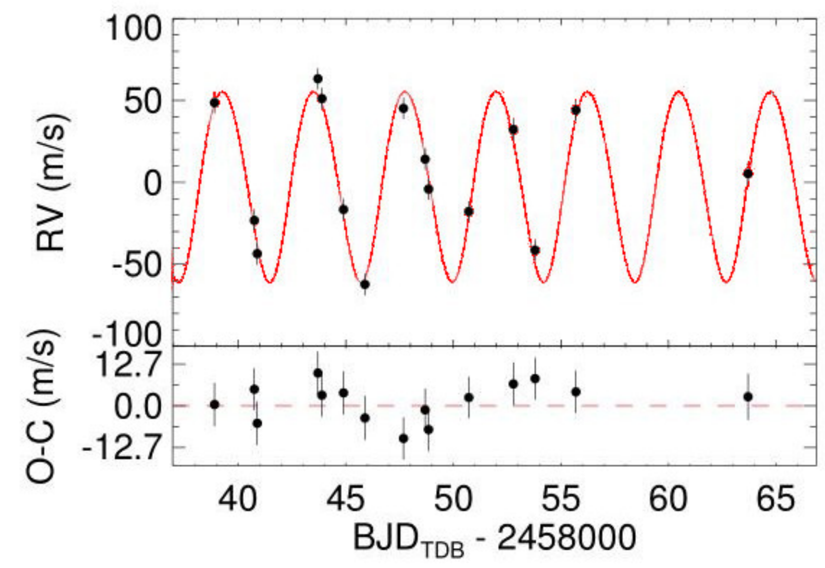
What can we measure / derive?

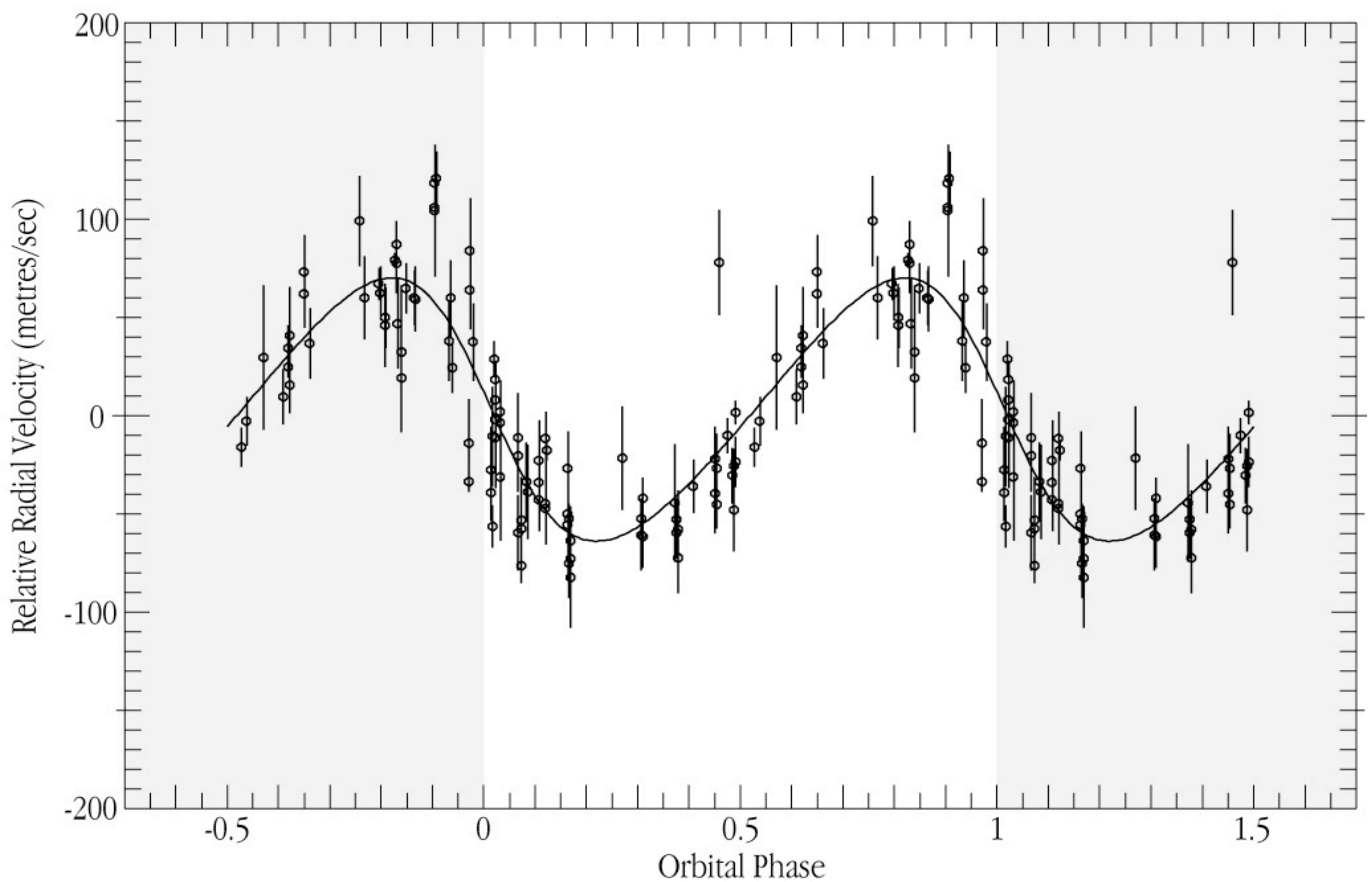
$$v_{rad} = c\ \Delta\lambda / \lambda$$



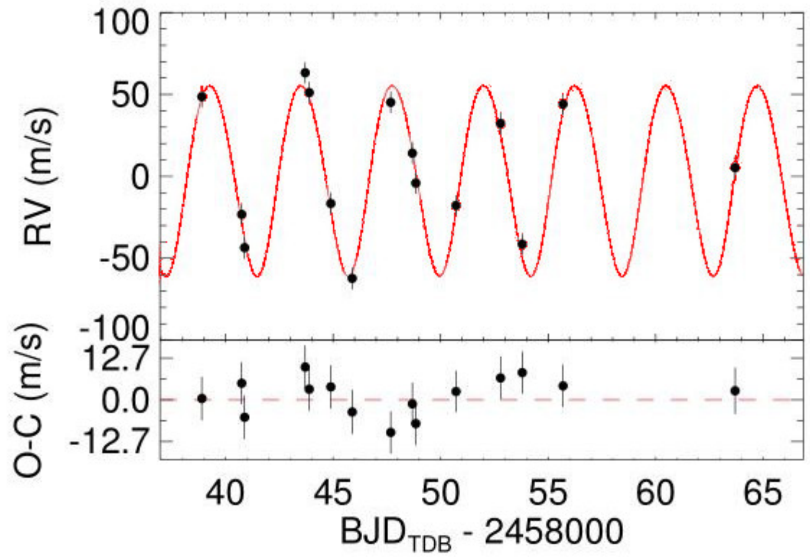
What can we measure / derive?

- orbital period *P*
- RV semi-amplitude of star ($K_\star$)
- shape of the RV curve ⇒ eccentricity ***e***





What can we measure / derive?



- orbital period P
- RV semi-amplitude of star ($K_\star$)
- shape of the RV curve ⇒ eccentricity e

⇒ **semi-major axis *a***

Kepler 3: $$a^3 = (a_* + a_p)^3 = \frac{G}{4\pi^2}(m_* + m_p)P^2$$

⇒ **estimate on the planetary mass**
(minimum mass): $m_p \sin i$

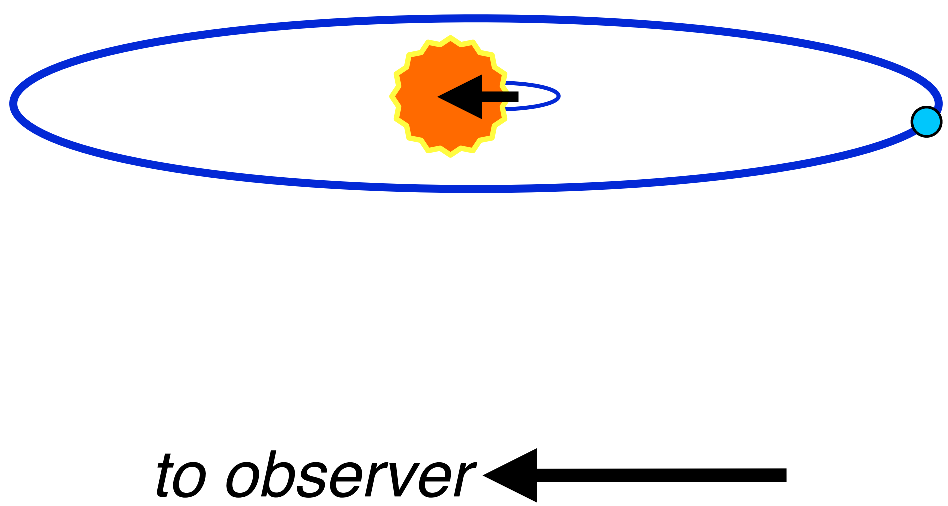
RV semi-amplitude K_*:

$$K_* \sqrt{1-e^2} = \left[\frac{2\pi G}{P}\right]^{1/3} \frac{m_p \sin i}{(m_* + m_p)^{2/3}}$$

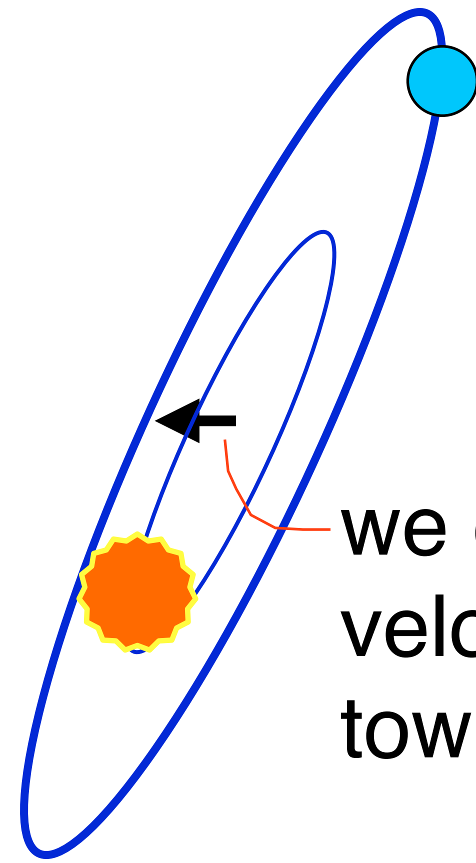
Trick: $m_p << m_\star \Rightarrow (m_p + m_\star) = m_\star$

The issue with the unknown orbital inclination *i*

i = 90° - "edge on"; companion has minimum mass

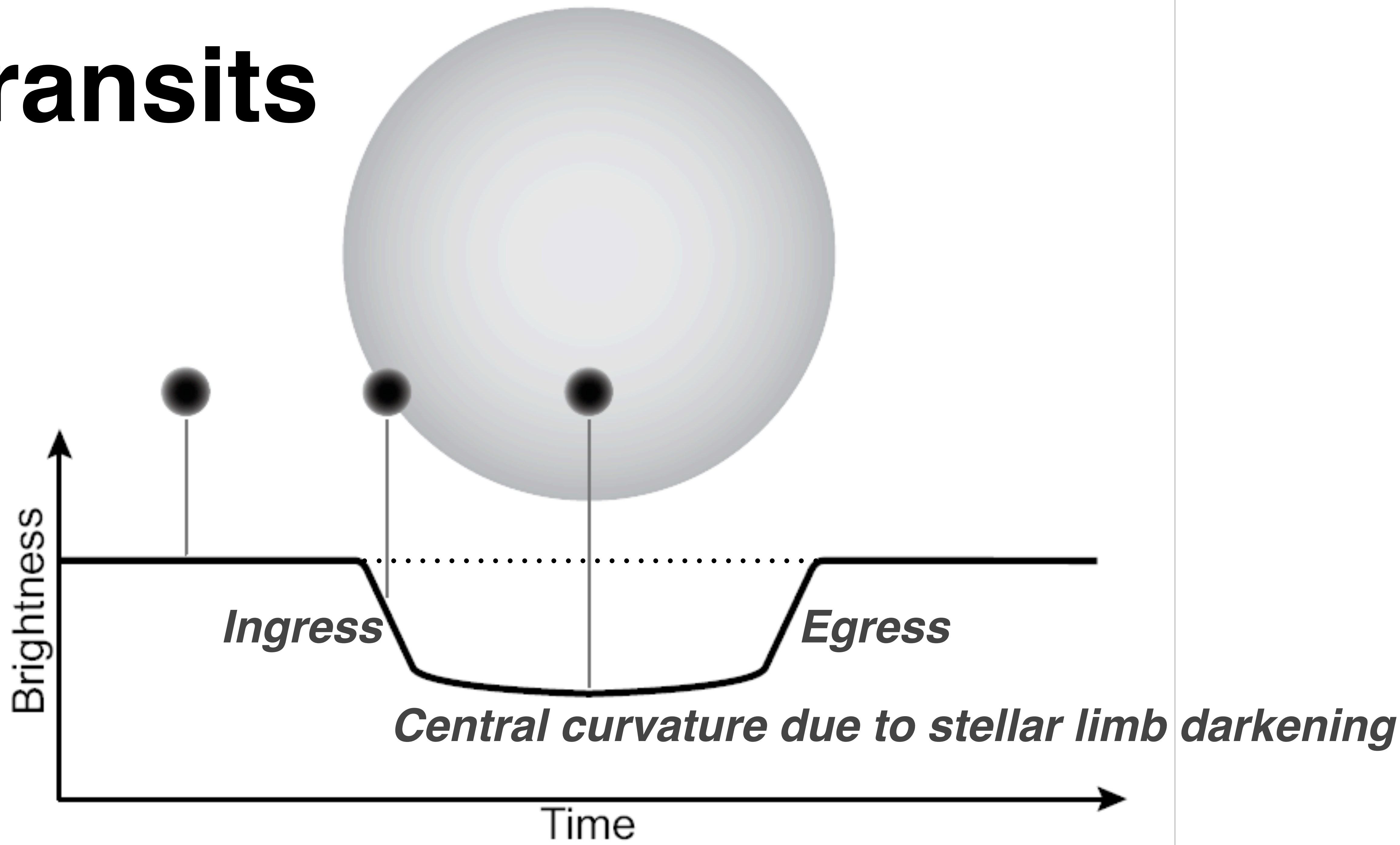


i = 25° - "face on"

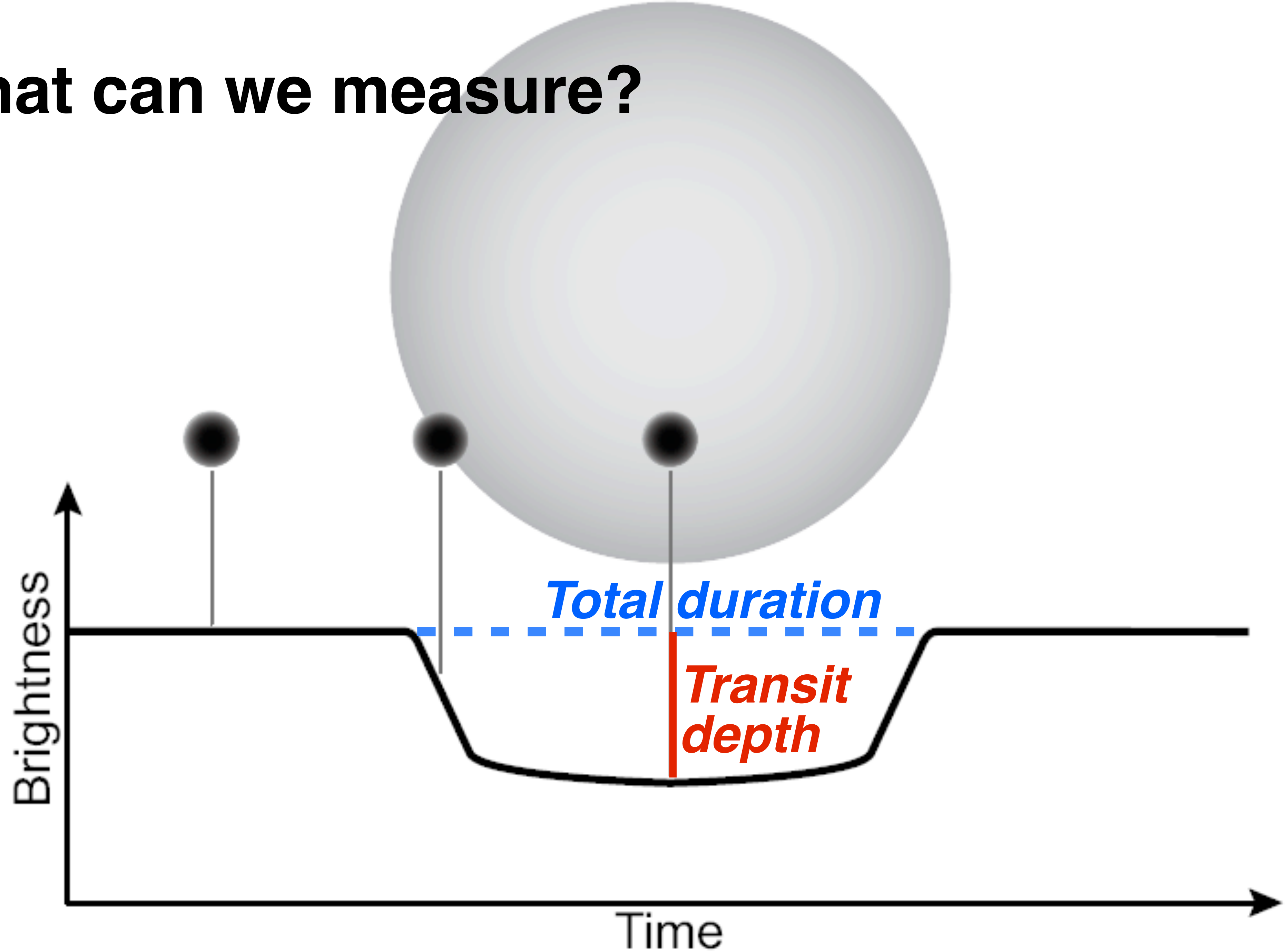


we only measure the velocity component towards Earth!

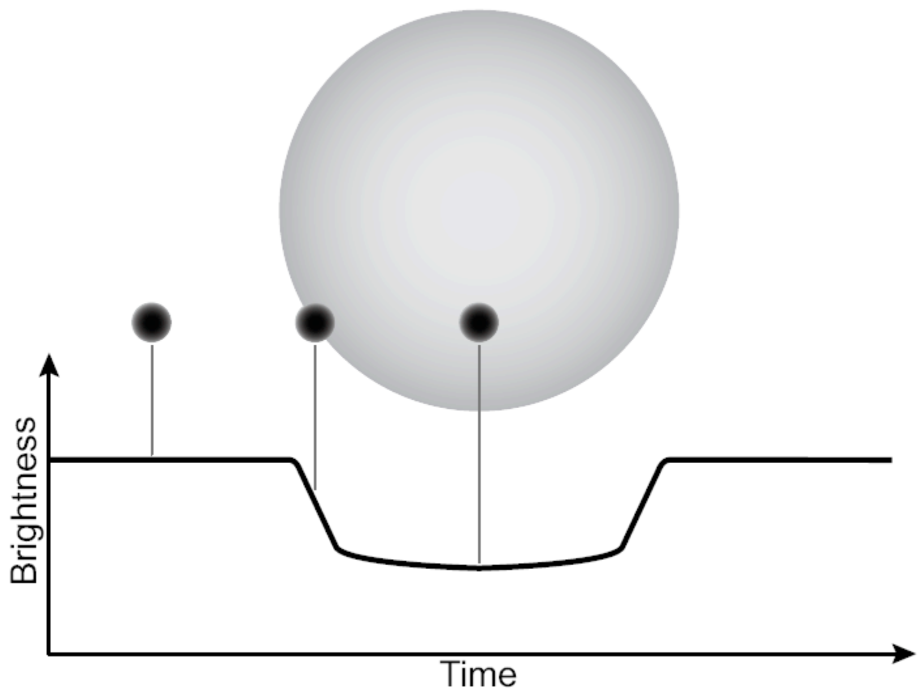
Transits


Brightness
Ingress
Egress
Central curvature due to stellar limb darkening
Time

What can we measure?



What can we measure/derive?

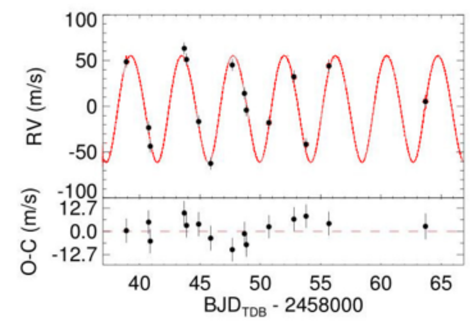


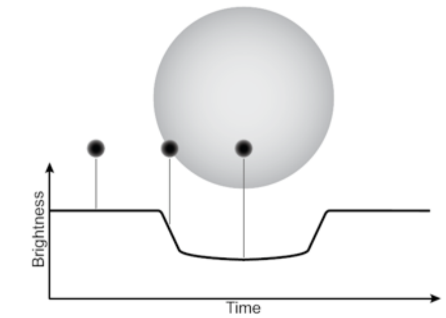
1) **planet radius R_p.**
(transit depth d corresponds to area ratio star / planet)

2) **orbital inclination** (estimate, $i \sim 90^{o}$)
(the orbit of transiting planets is "edge on")

3) **mid-transit time T_0**

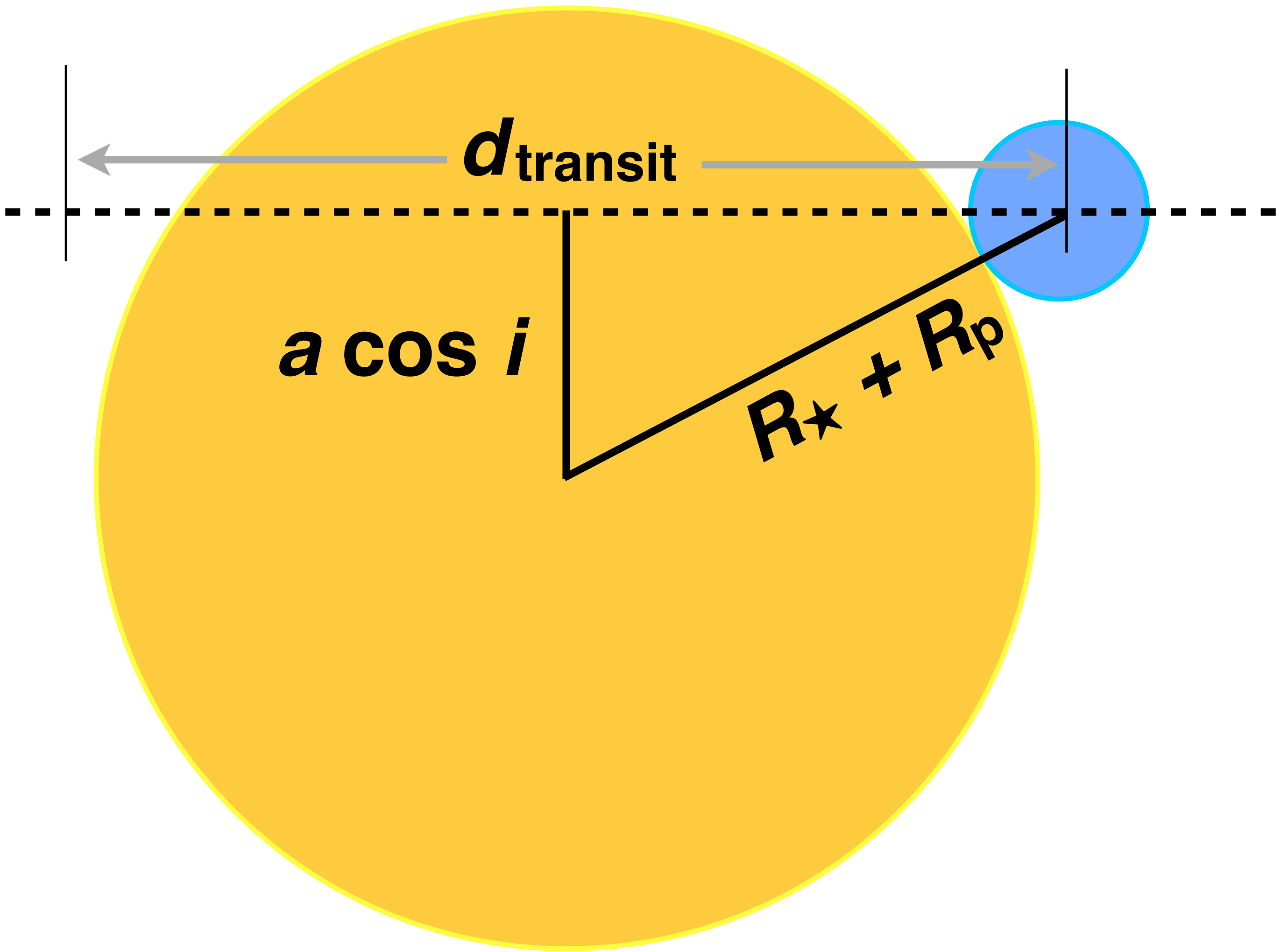
4) **orbital period P**





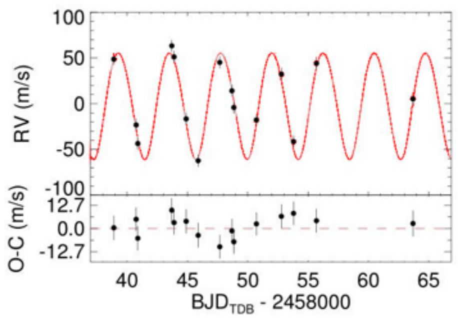
RV + transits combined ...

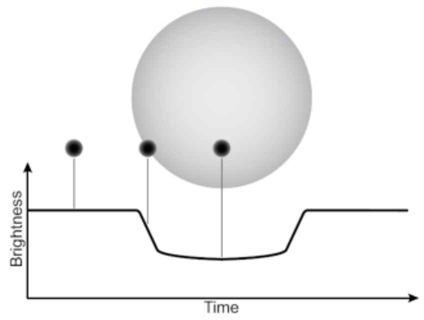
1) exact **orbital inclination *i***



$$a \cos i = \sqrt{(R_\star + R_p)^2 - l^2}$$

$$l = a\, \pi\, d_{\rm transit} / P$$





RV + transits combined ...

1) exact **orbital inclination *i***

2) **exact mass m_p** *(solve for $m_p \sin i$)*

3) mean **density of planet** $\sim m_p / R_p^3$

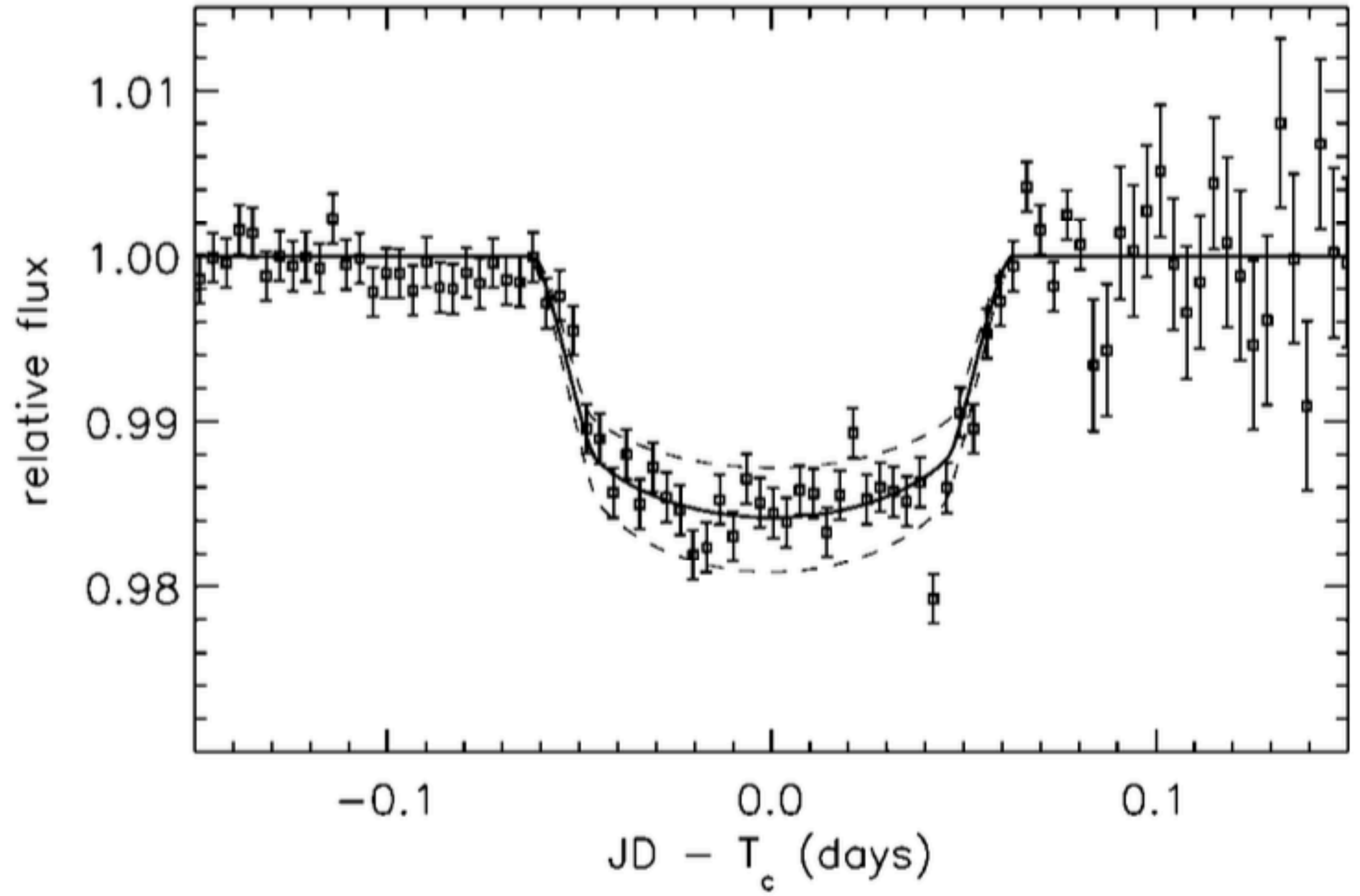
2000: HD 209458 The first transiting planet

Charbonneau et al. (ApJ 529, L45)
Henry et al. (ApJ 529, L41)

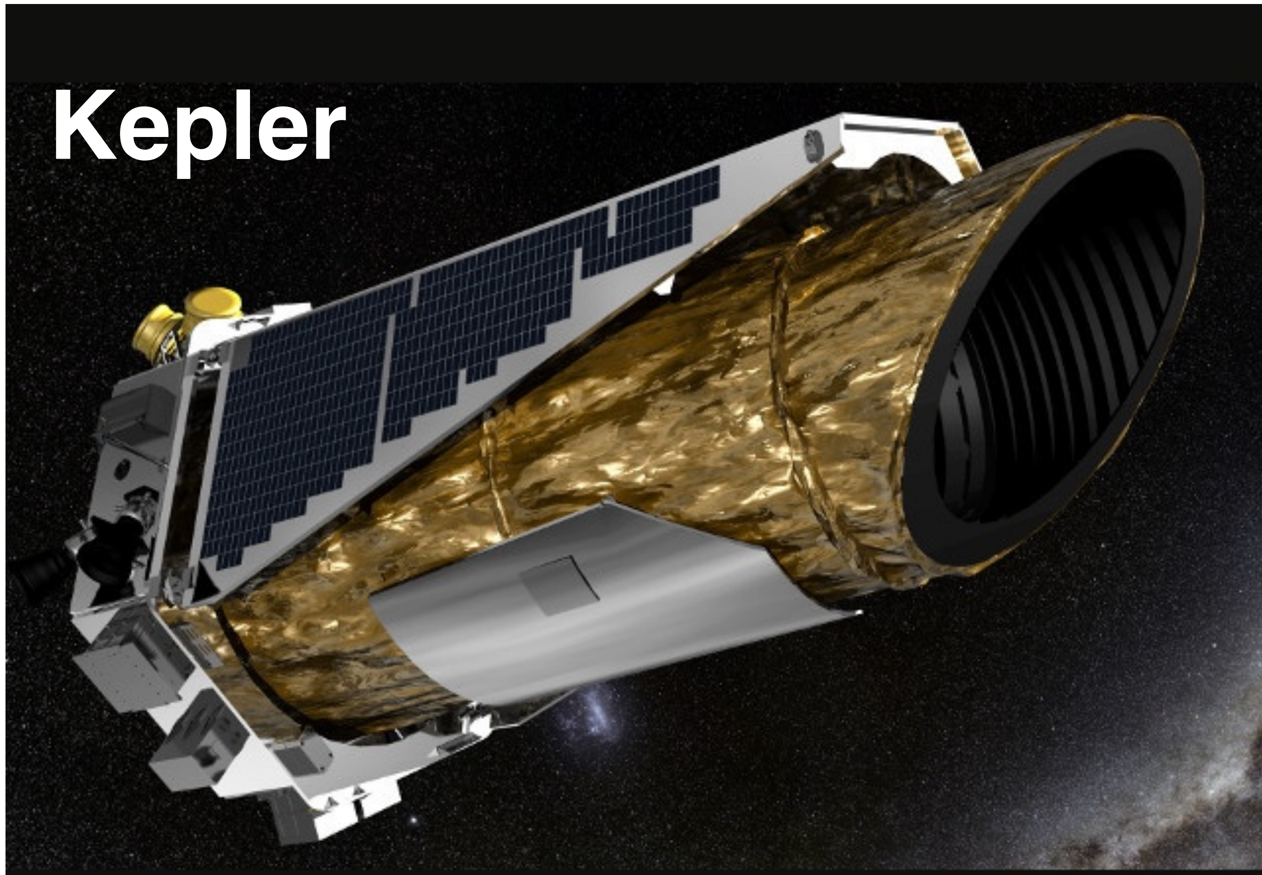
⇒ $i = 86.9°$

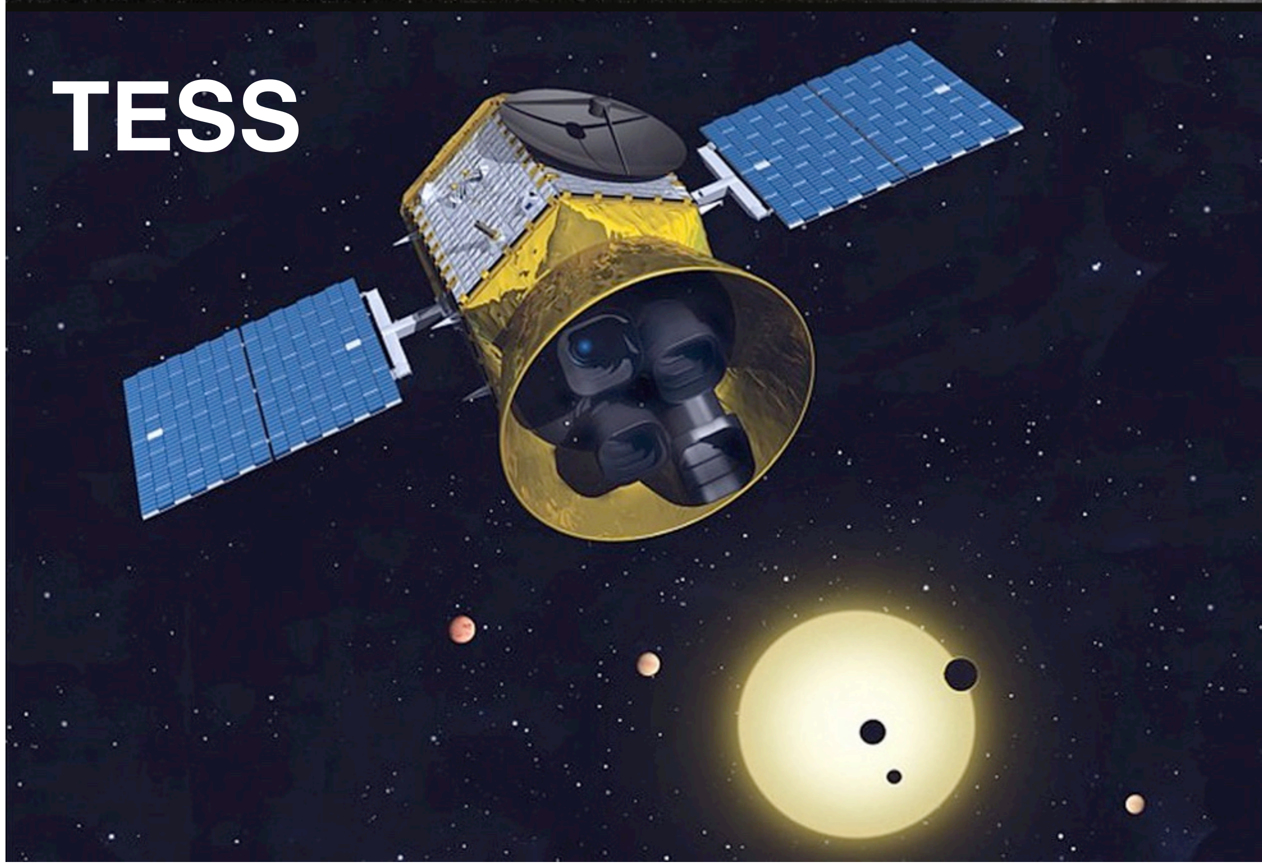
⇒ $m_p = 0.69\ M_{jup}$

⇒ $R_p = 1.4\ R_{jup}$



Transit surveys to detect transiting planets





... from the ground and from space

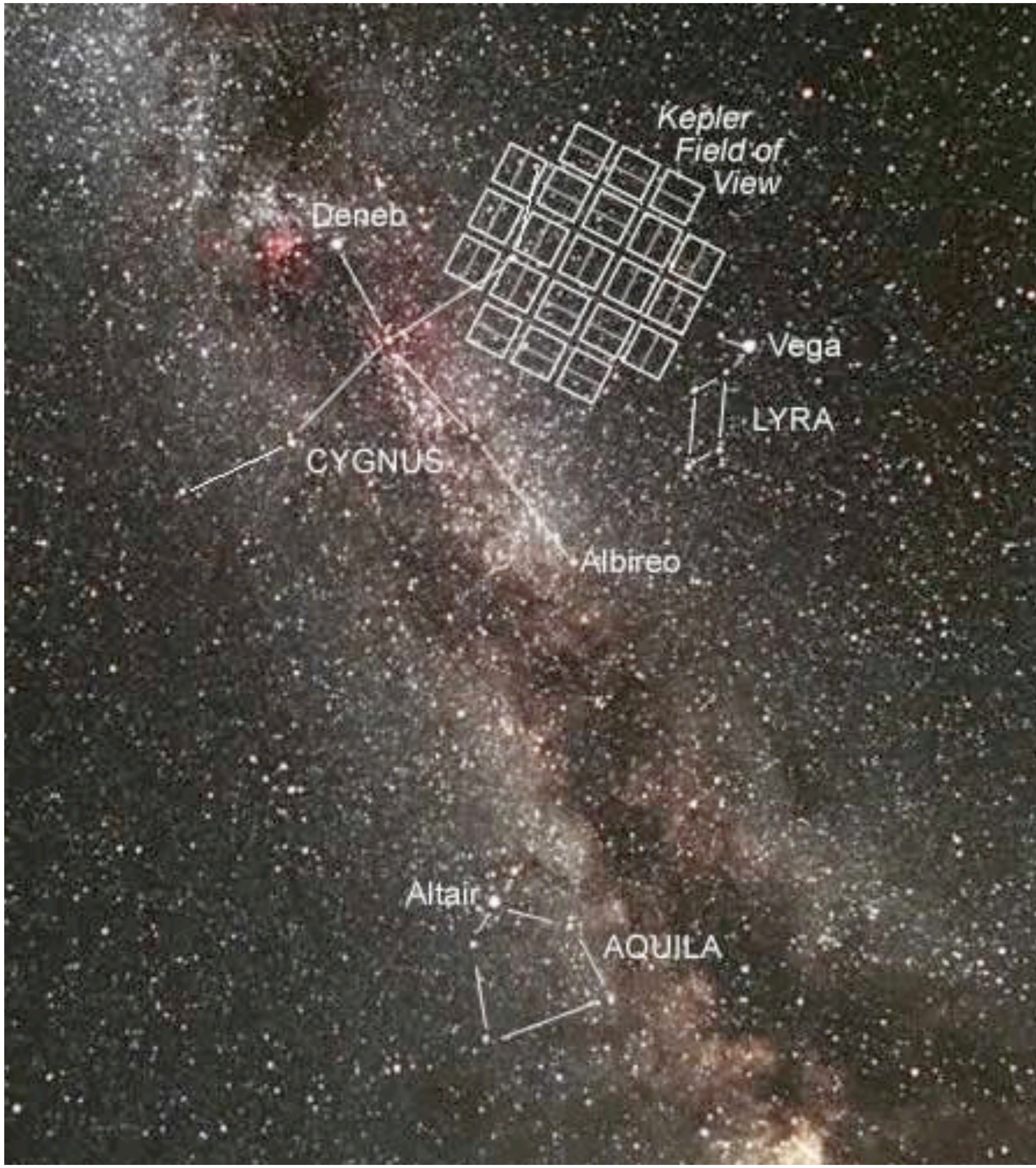
Kepler satellite mission

2010 - 2015 (2018)

- 95cm aperture; monitored the brightness of ~150 000 stars

- found over 2600 planets!

Stars with planets are the rule, not the exception!

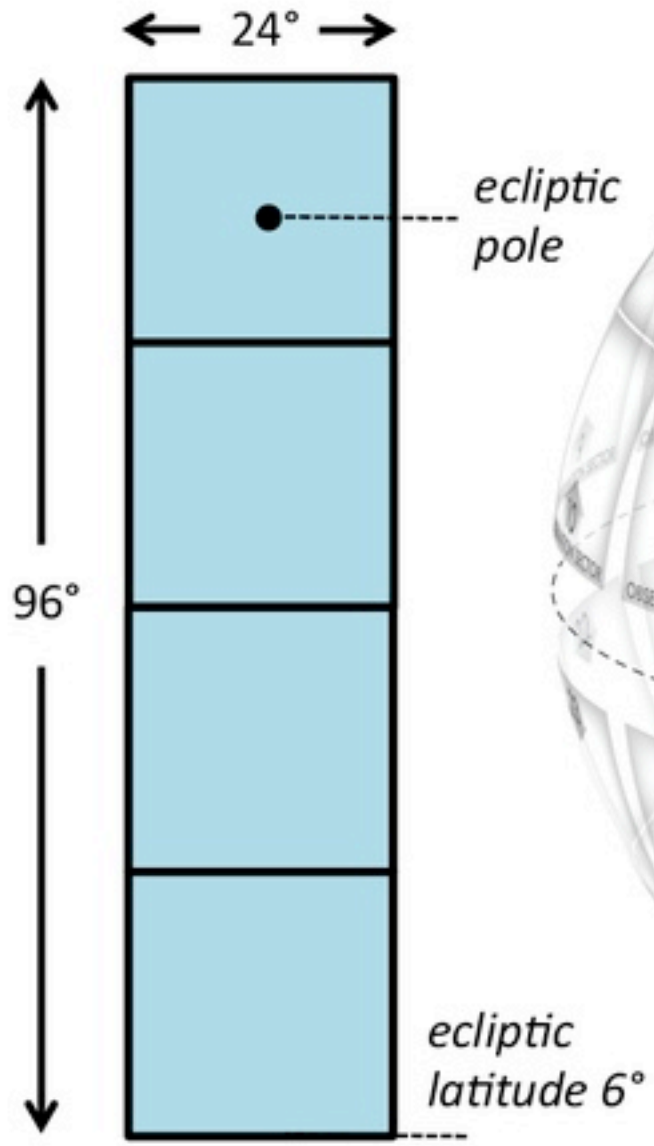


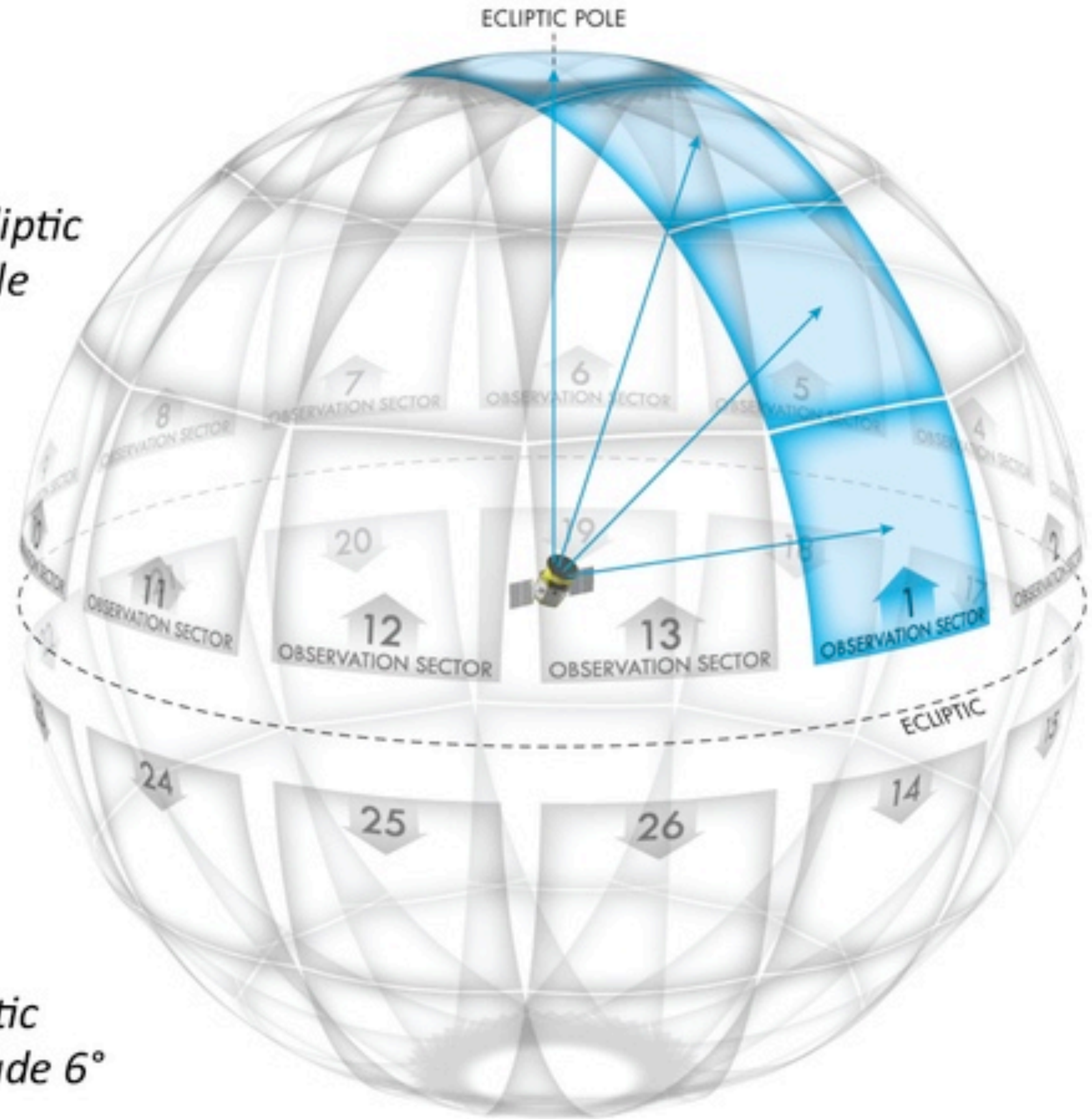
TESS mission

since 2018

- all-sky survey

- short-period planets around brighter stars (atmospheres!)

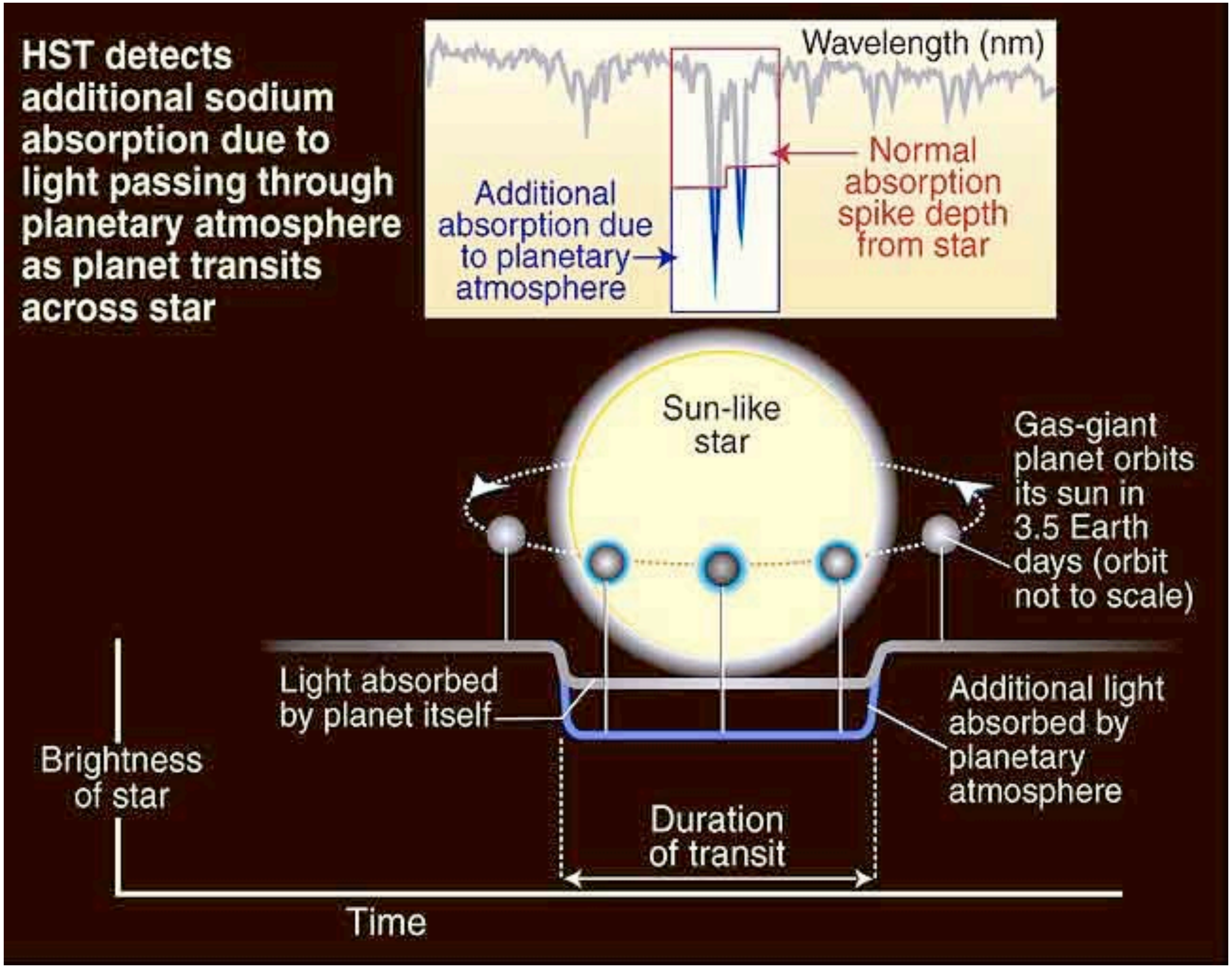




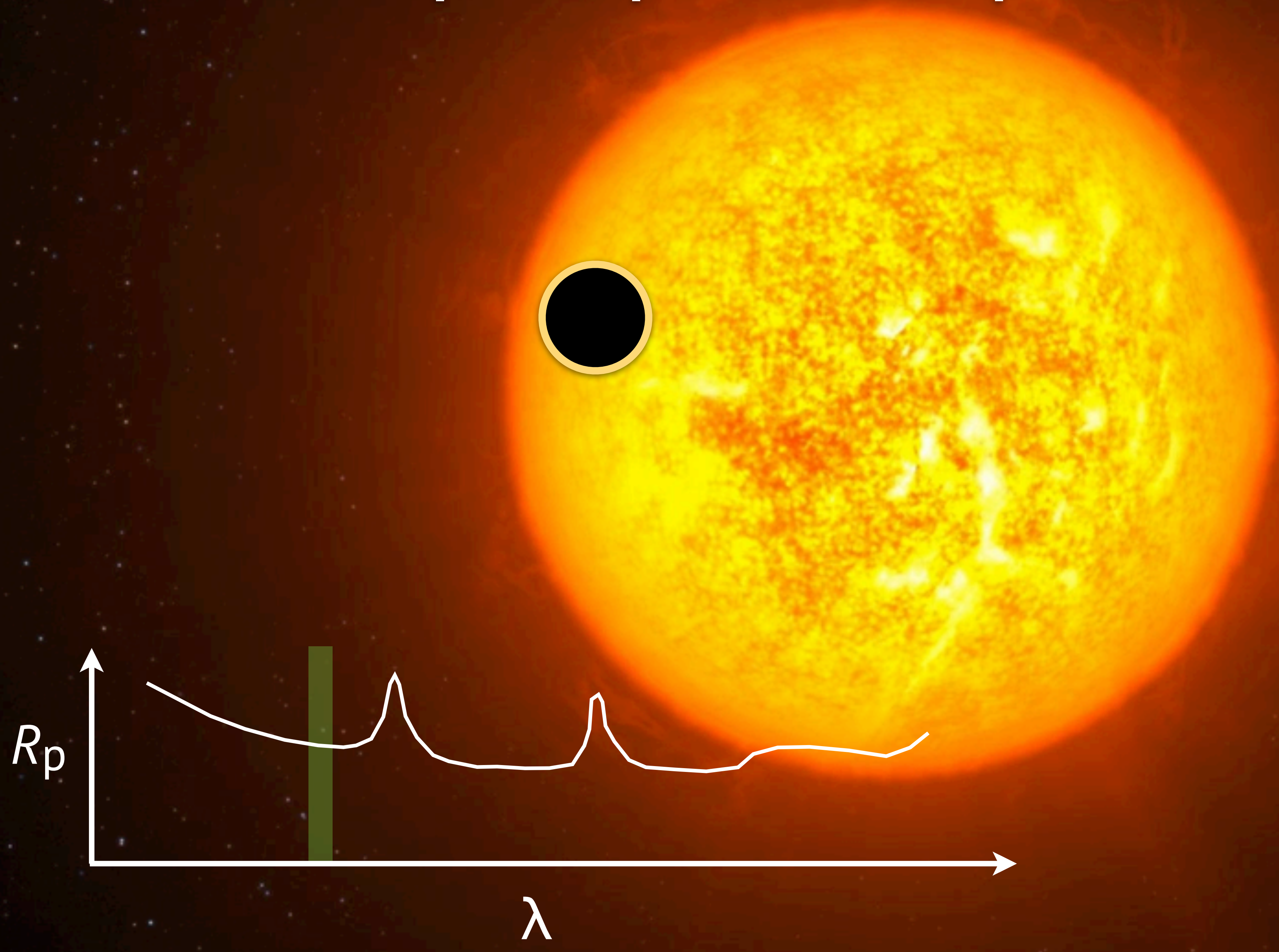
2002: first exoplanet atmosphere detected

Transmission spectroscopy of HD209458b

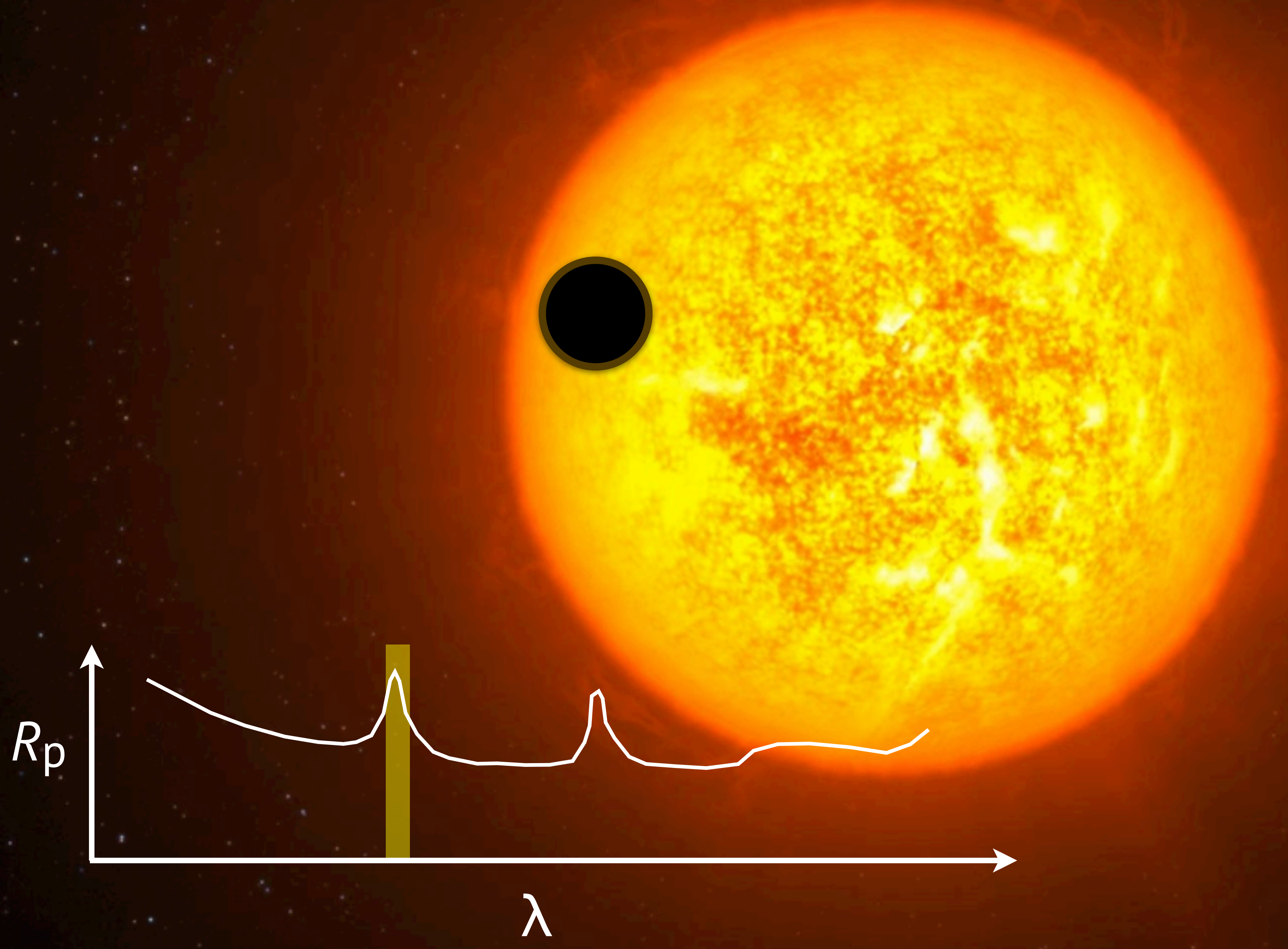
Charbonneau et al. (ApJ, 568, 377)



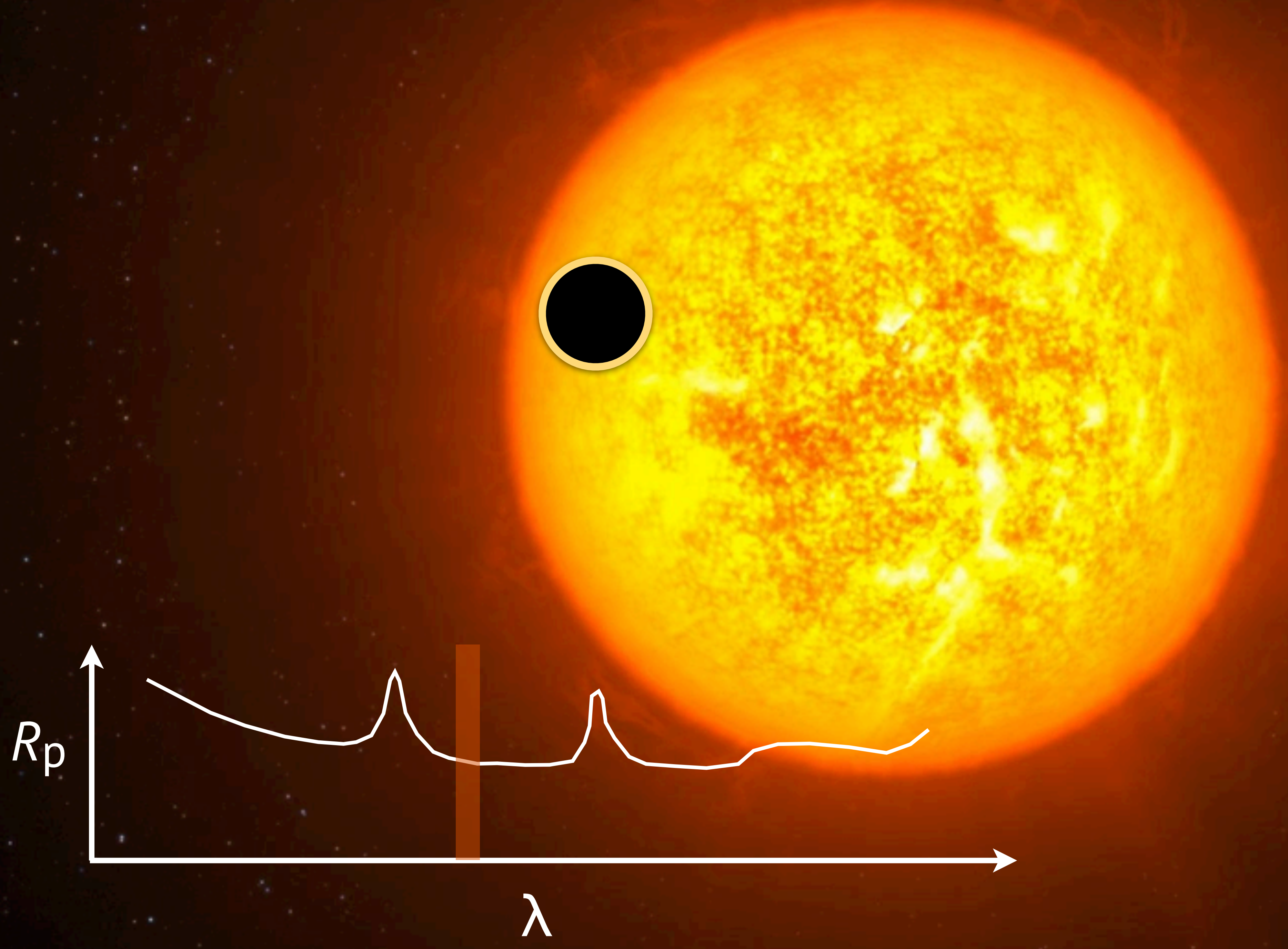
For transmission spectroscopy, we only care about the area ratio **transparent planet atmosphere** / stellar disk



For transmission spectroscopy, we only care about the area ratio **transparent planet atmosphere** / stellar disk

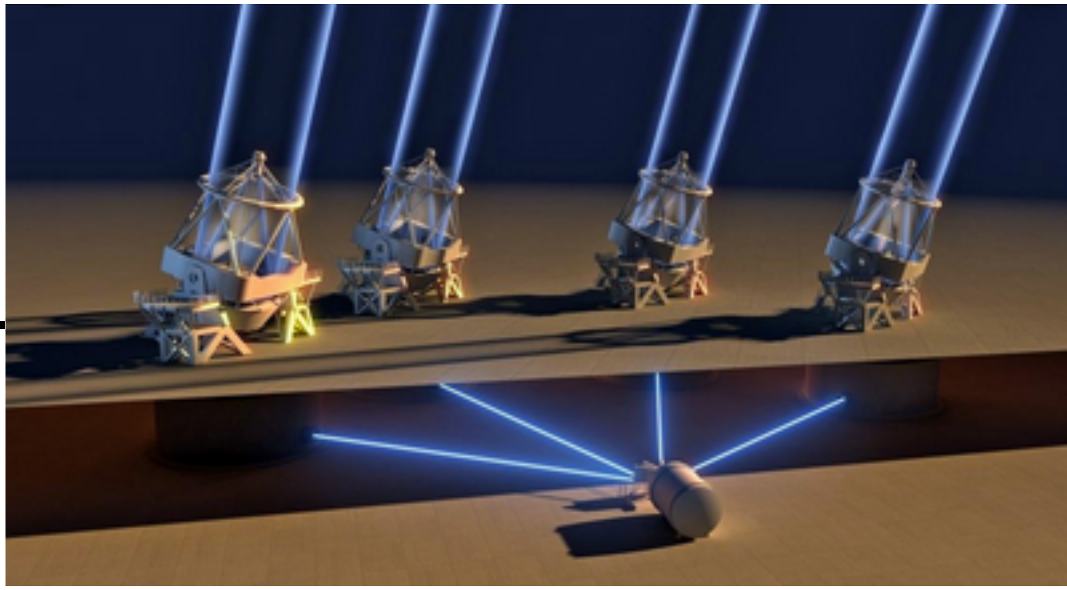


For transmission spectroscopy, we only care about the area ratio **transparent planet atmosphere** / stellar disk



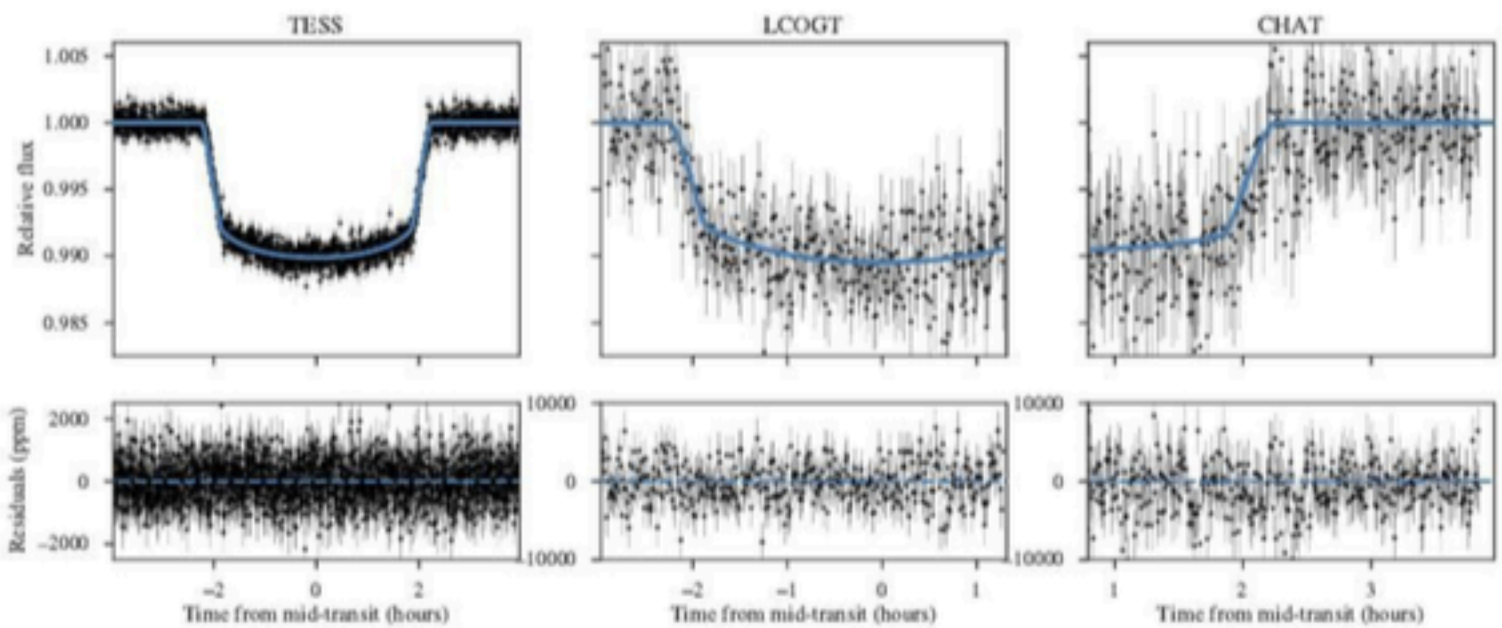
Instruments at ESO for RV observations and atmosphere studies:

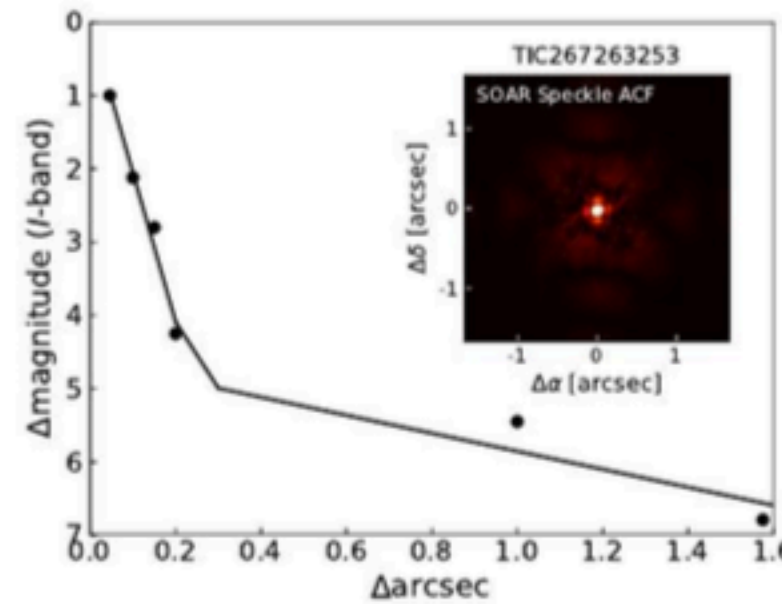
- UVES (VLT, since 2000)
- FORS2 (VLT, since 2000) *spectro-photometry*
- HARPS (La Silla, since 2003)
- ESPRESSO (VLT, since 2018) -----
- NIRPS (La Silla, 2021)
- CRIRES (VLT, 2021)

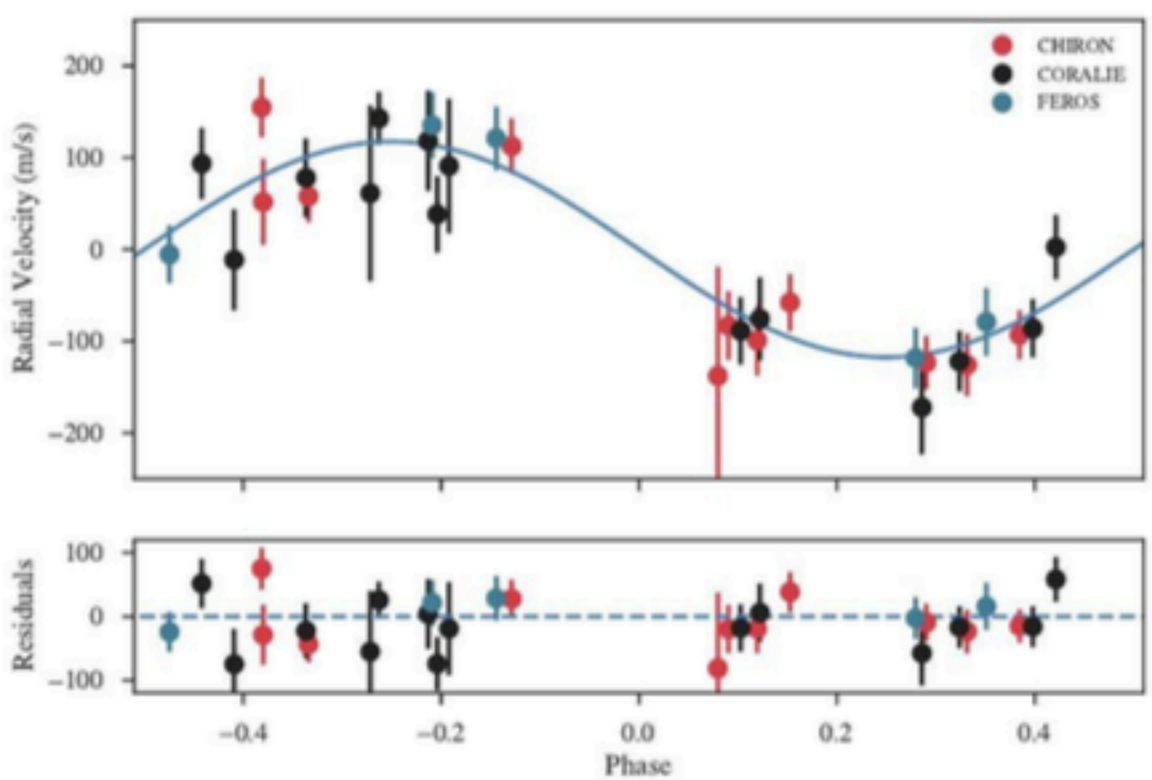


Questions?

Matias Jones: detecting the TESS planet HD2685b



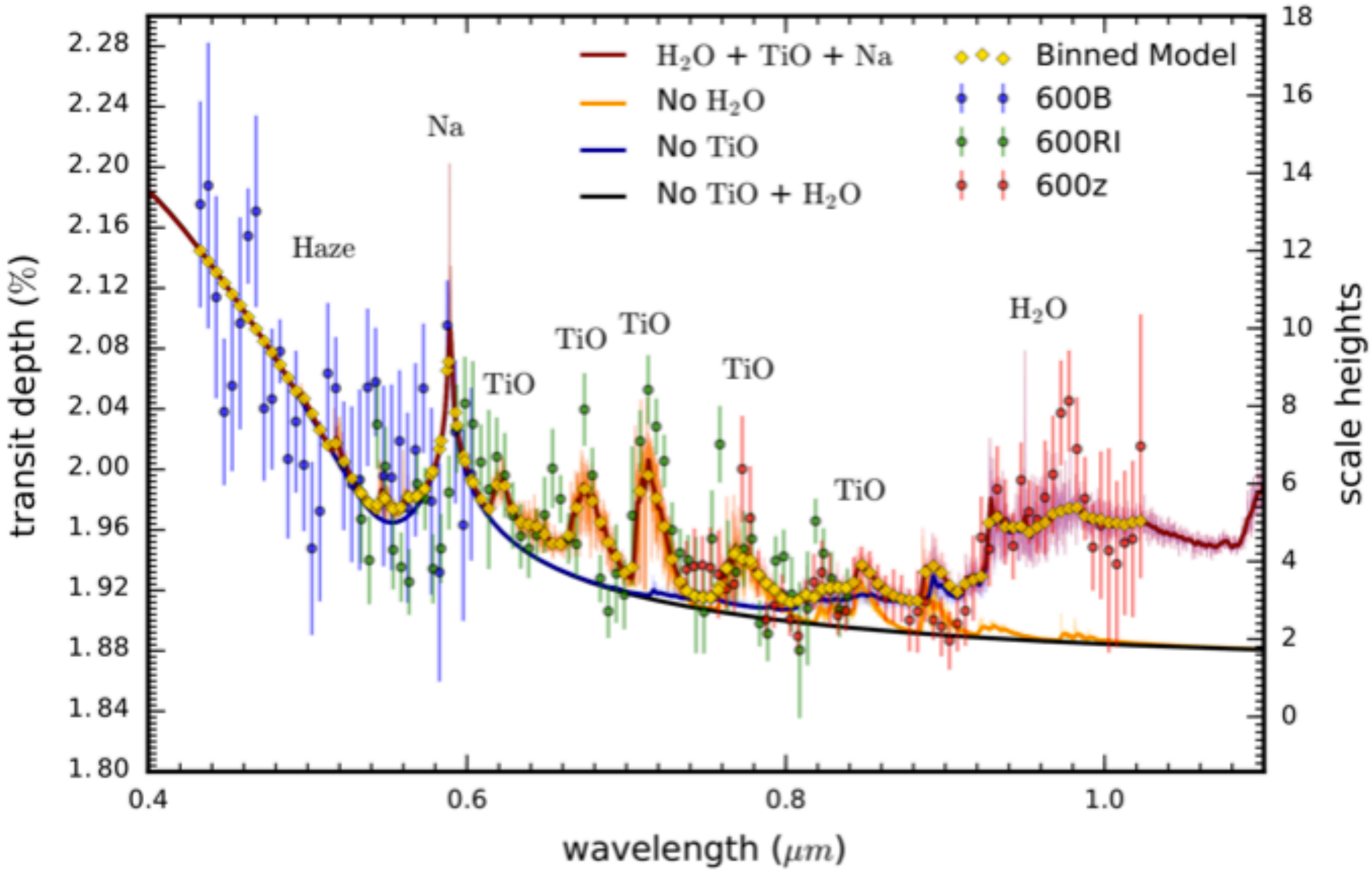




Planetary parameters	
M_P (M_J)	1.17 ± 0.12
R_P (R_J)	1.44 ± 0.05
a (AU)	0.0568 ± 0.0006
T_{eq} (K)	2061 ± 28

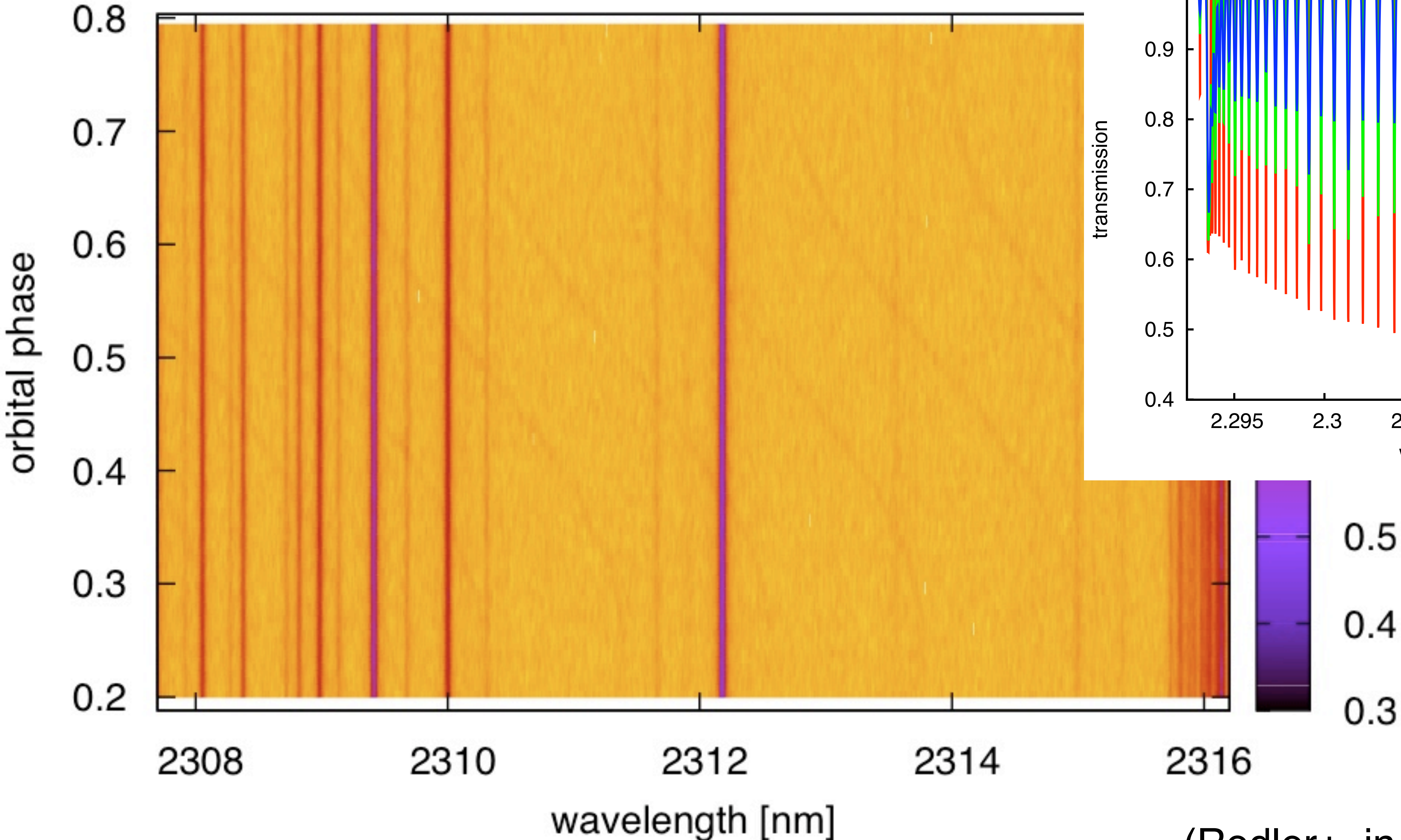
(Jones+2019, A&A)

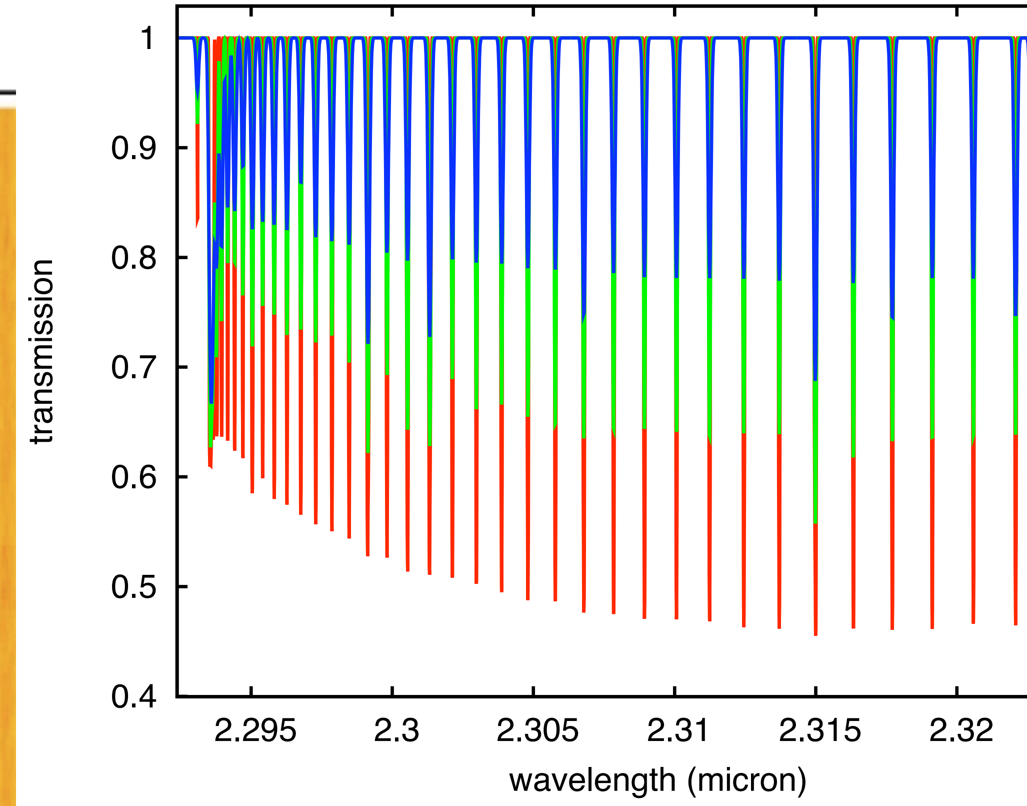
Elyar Sedaghati: transmission spectrum of WASP19b



(Sedaghati+2017, Nature)

Florian Rodler: CO in day-side spectrum of Ups And b





(Rodler+, in prep)

Direct Imaging

Two challenges:

- planets appear close to star
- planets are *relatively* small / faint

(flux ratio Jupiter/Sun ~ 10^{-9} in the vis

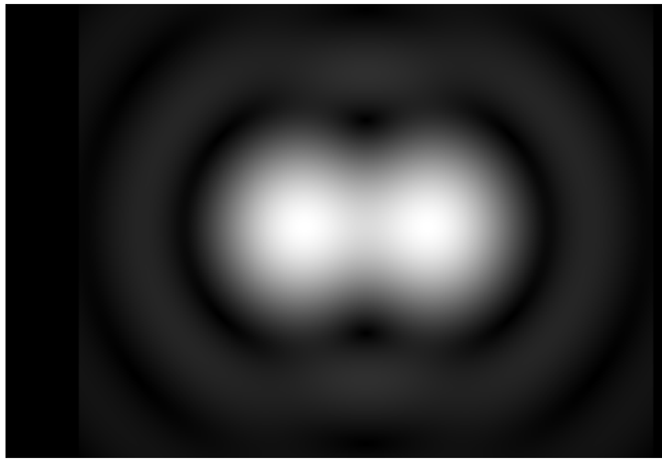
Detection Methods: Direct Imaging


...than the planet
...hidden
in the glare.

Challenge: angular resolution on sky

- planet in 10 AU orbit around star 10 pc away from us: separation on sky = **1”**.
- at 100 pc distance: separation on sky = **0.1”**.

Diffraction limits angular resolution of telescope:
$r['']$ = 1.22 λ/D 206,265

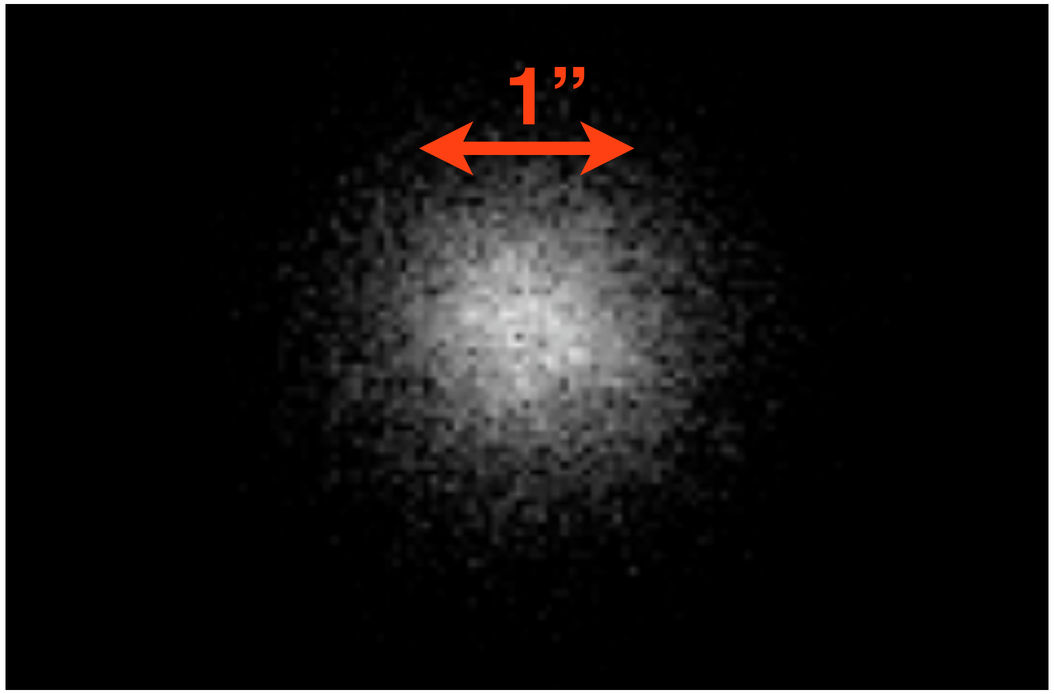


That’s the smallest possible value to separate two sources with a telescope with an aperture *D*

Example: VLT(8.2m) at λ=1µm: **0.031”**

However, there is a *little* problem ...

Atmospheric turbulence?!

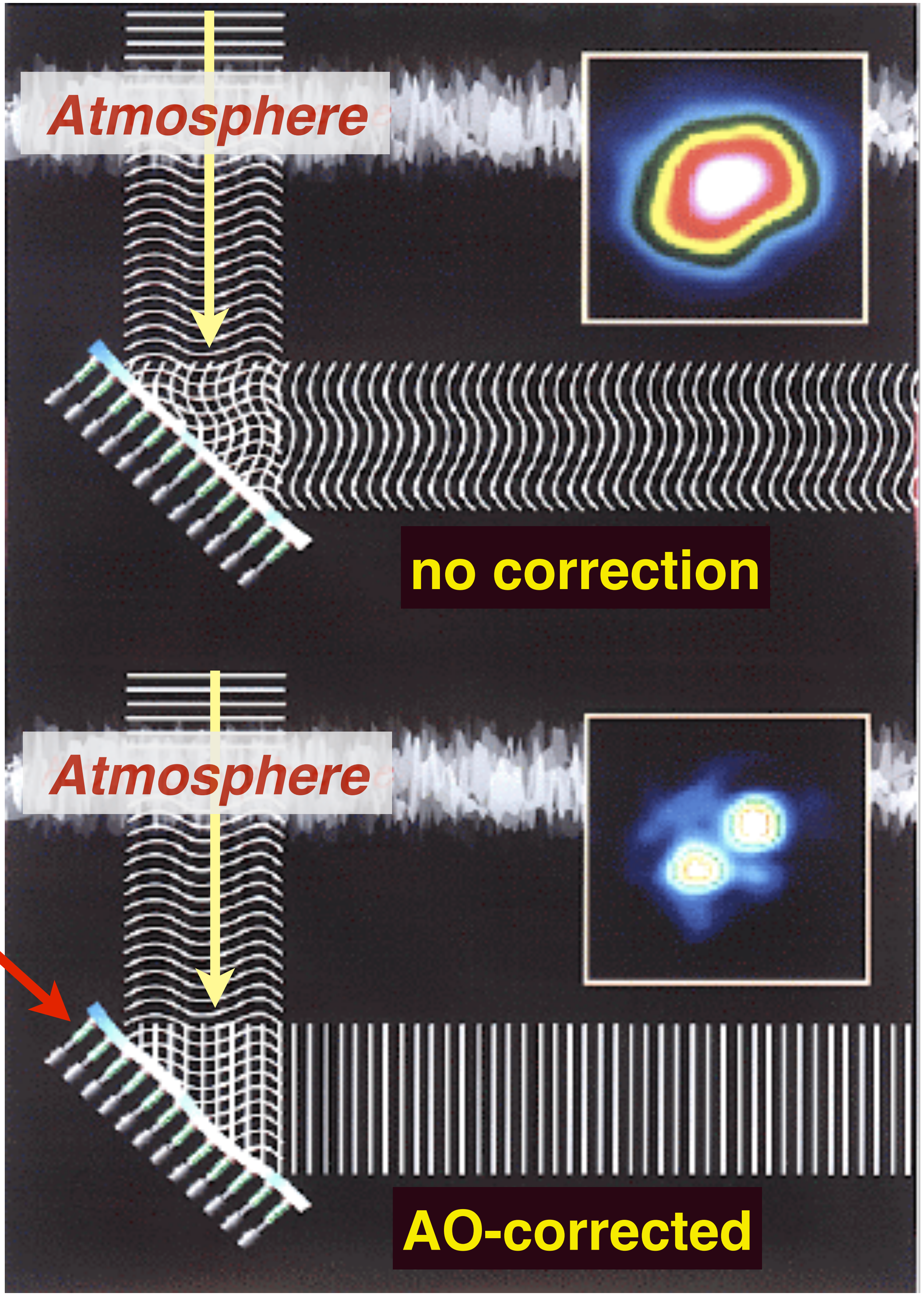


You don’t like it?

- **go to space**, or
- do **lucky imaging**, or
- do some magic ...

Adaptive Optics (AO):
- correct distortions in wavefront
- use a deformable mirror (at 1 kHz)

AO allow to attain angular resolutions of ~0.1" at the VLT!



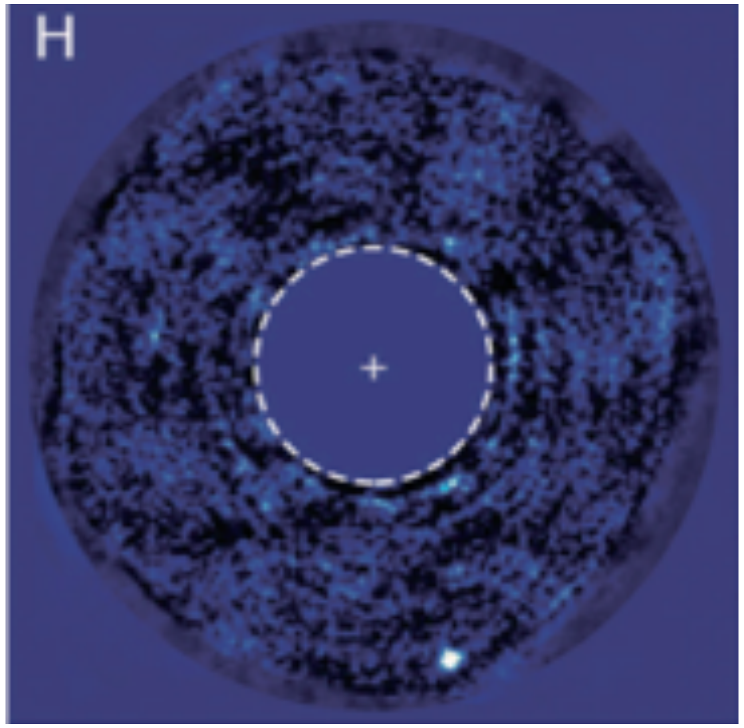
Enhancing the contrast ...

- what targets?
  young planets are hot: they shine bright in the NIR (~10^{-4})

Enhancing the contrast ...

- what targets?
  young planets are hot: they shine bright in the NIR (~10^{-4})

- **coronagraph**: a mask that blocks most of the star light (~99%)

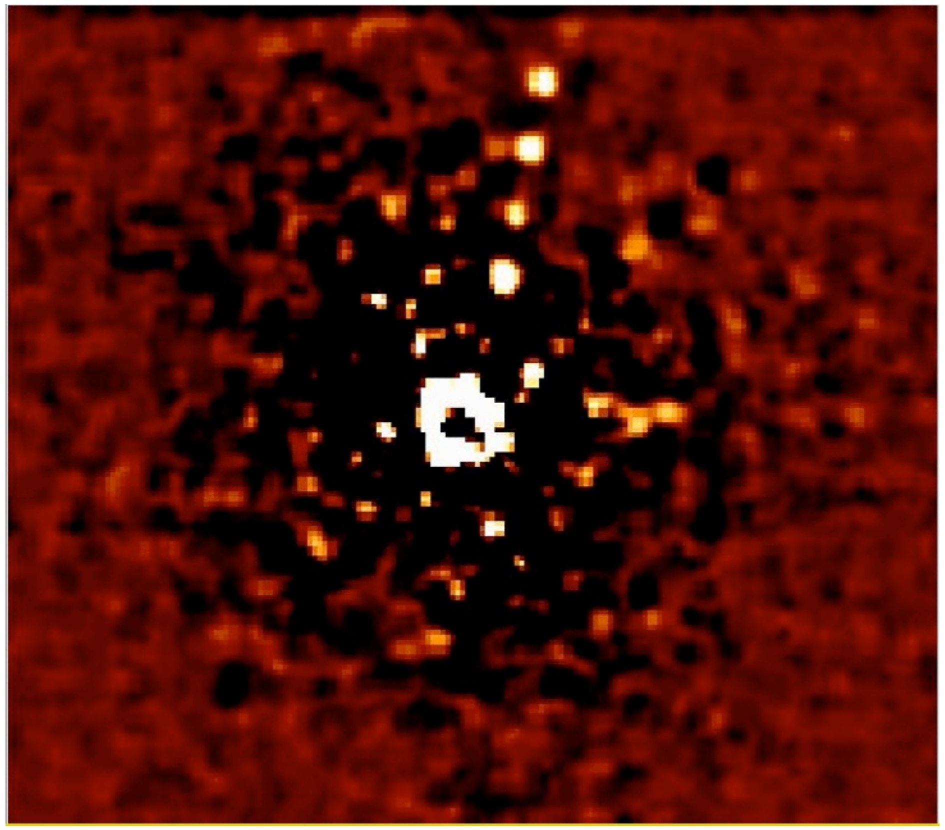


Enhancing the contrast ...

- what targets?
  young planets are hot: they shine bright in the NIR (~10^{-4})

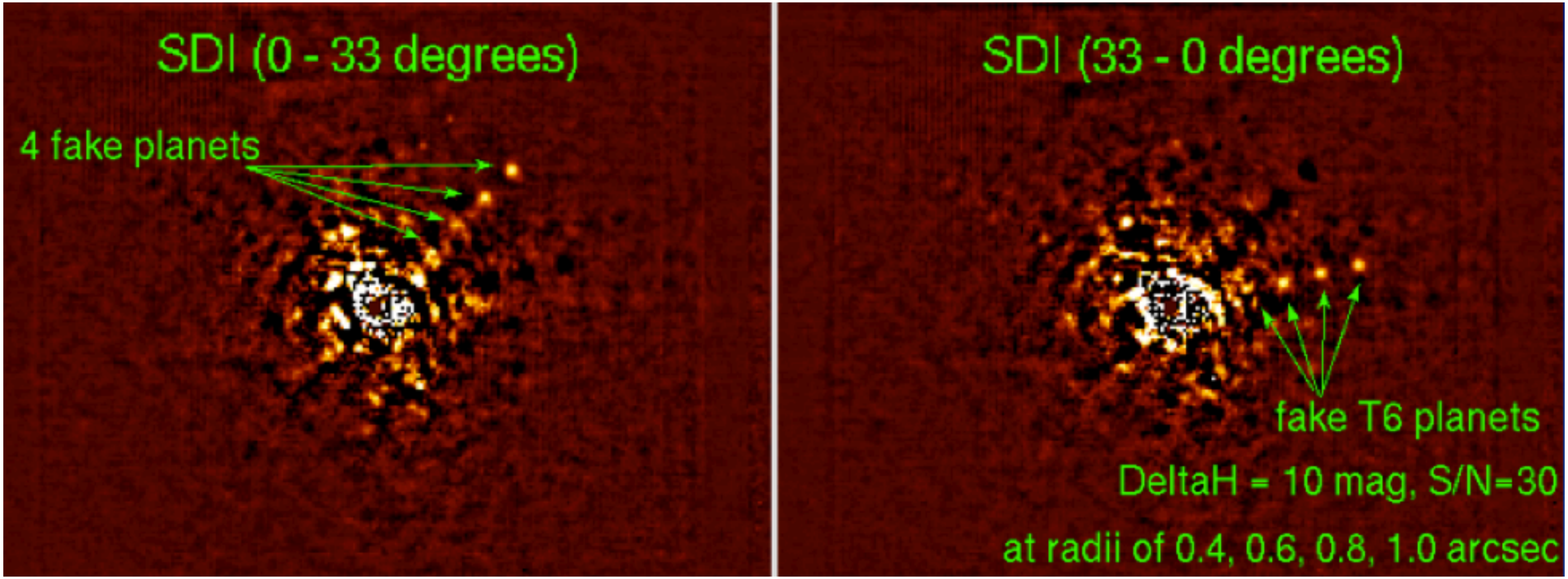
- **coronagraph**: a mask that blocks most of the star light (~99%)

- **angular differential imaging** (ADI) to identify instrumental noise.



Which one of these dots is a planet?

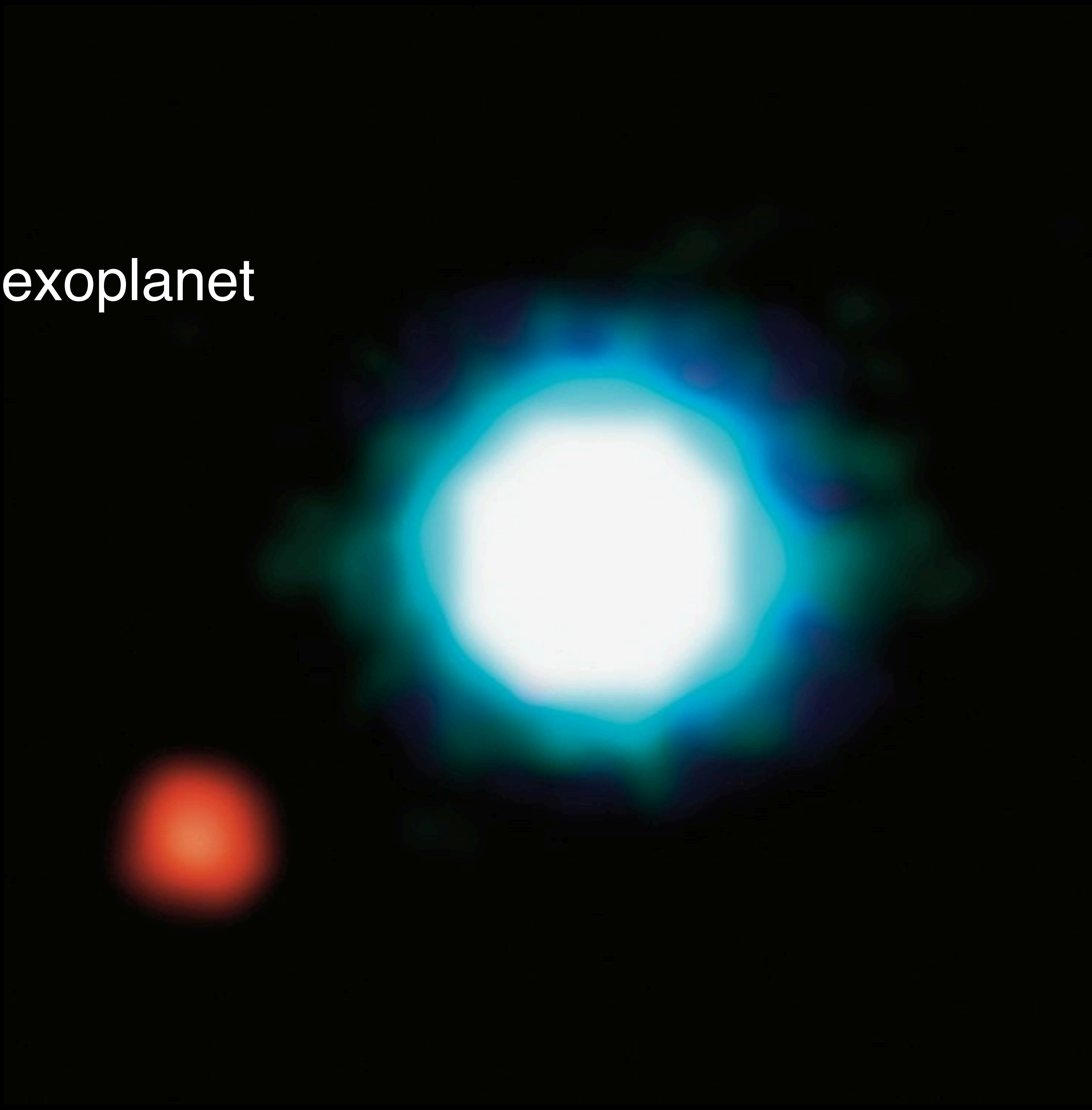
- **angular differential imaging** (ADI) to identify instrumental noise: due to telescope mounting, **sky field rotates** over time on detector, while **instrumental noise ("speckles") is static.**



2M1207

- 2004: the first directly imaged exoplanet
  a ~ 40 AU (0.78” on sky)
  m_p = 3-10 m_{Jup}
  age < 10 Myr
  instrument: VLT/NACO

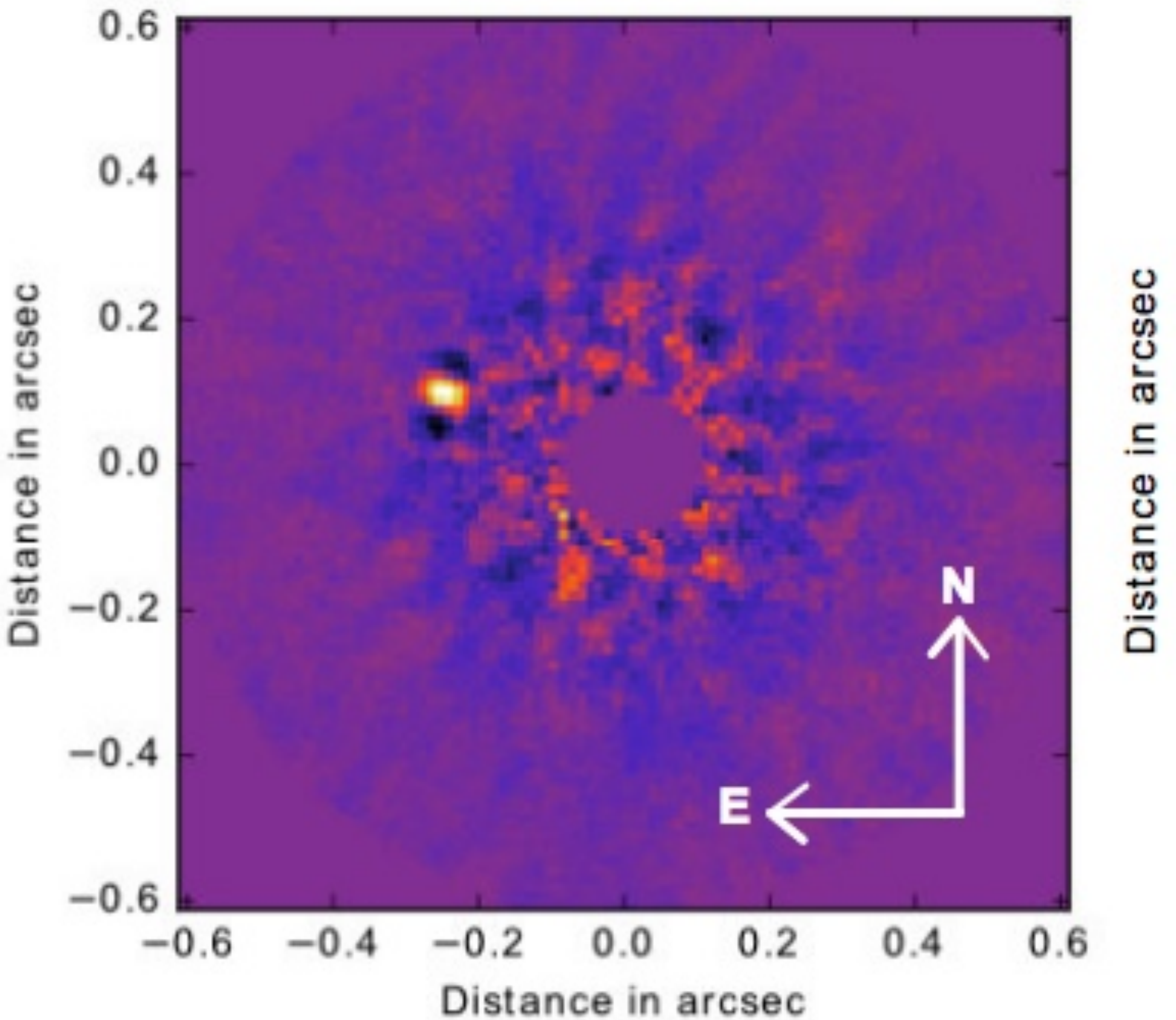
  (Chauvin+2004, A&A)



Instruments at ESO for direct imaging with extreme AO:

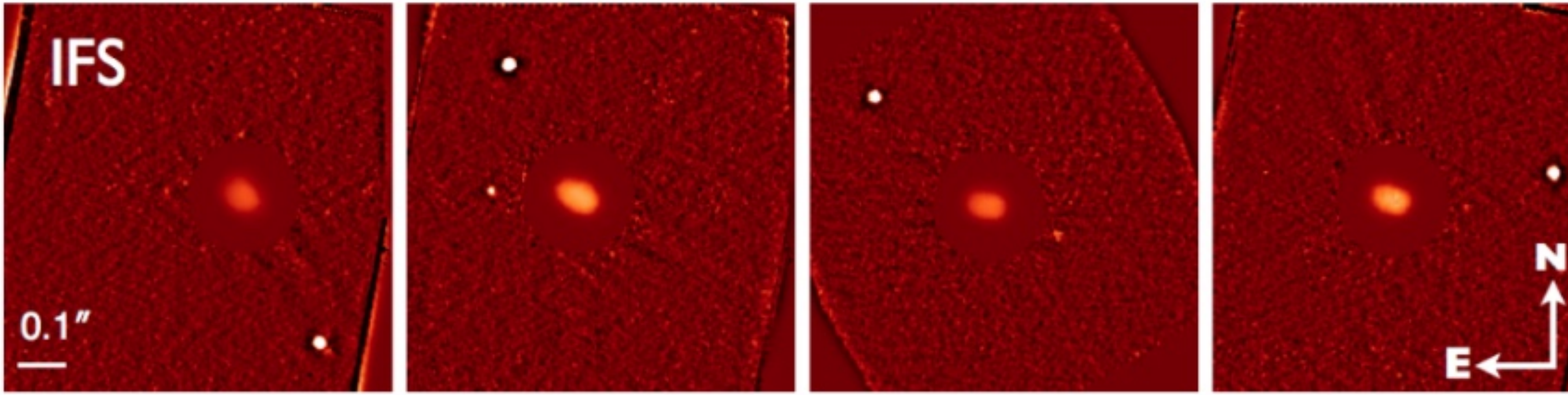
- **SPHERE** (since 2015)
  in VIS and NIR; Allows also low-res spectroscopy.

Julien Milli, Zahed Wahhaj:
detecting a brown dwarf in a debris disk



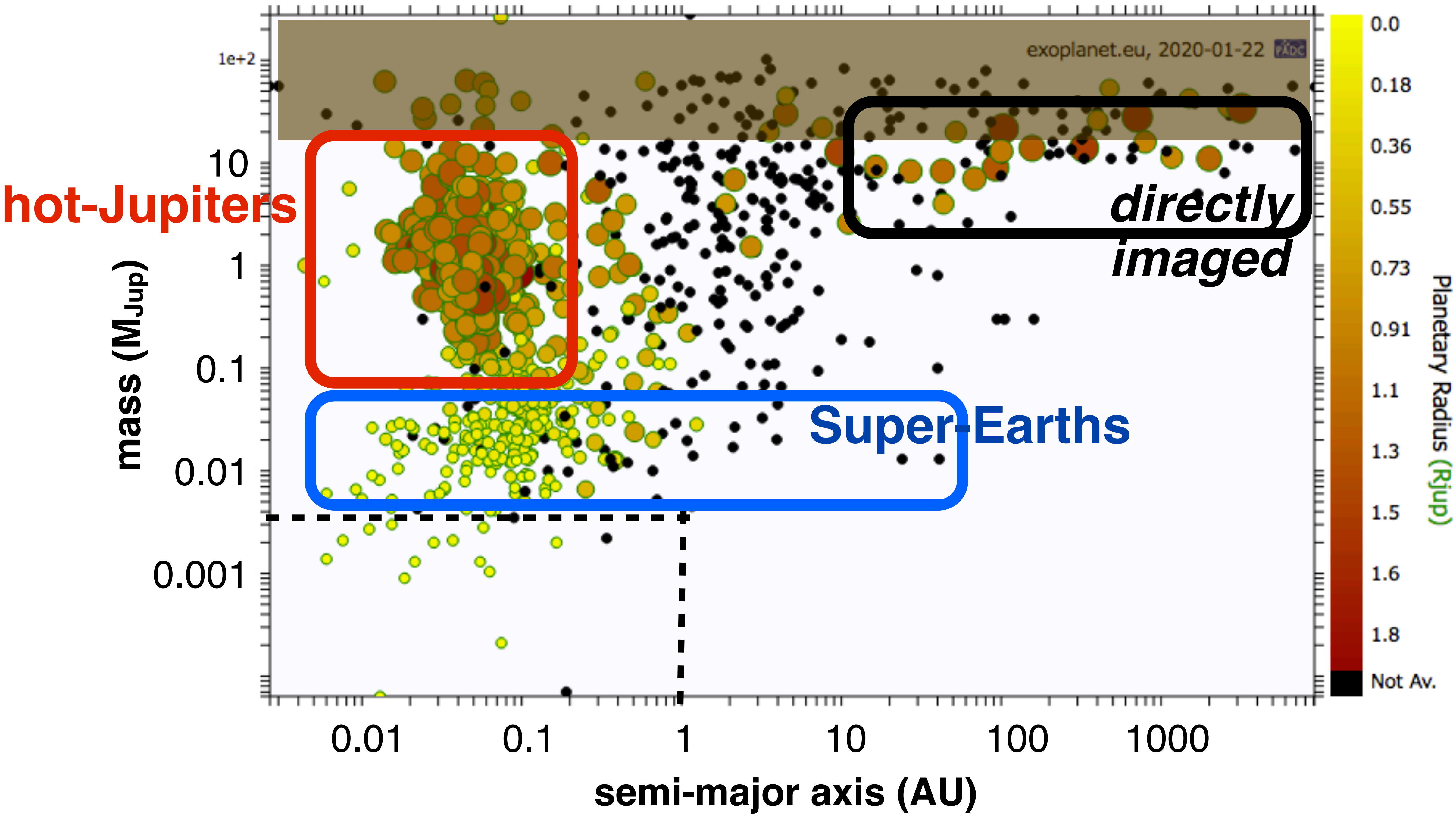
(Milli+2017)

Bin Yang: detecting a moon of an asteroid



(Yang+2016)

~4200 exoplanets confirmed:



~4200 exoplanets confirmed: