Inspecting Exoplanet Atmospheres with High-Resolution Spectroscopy

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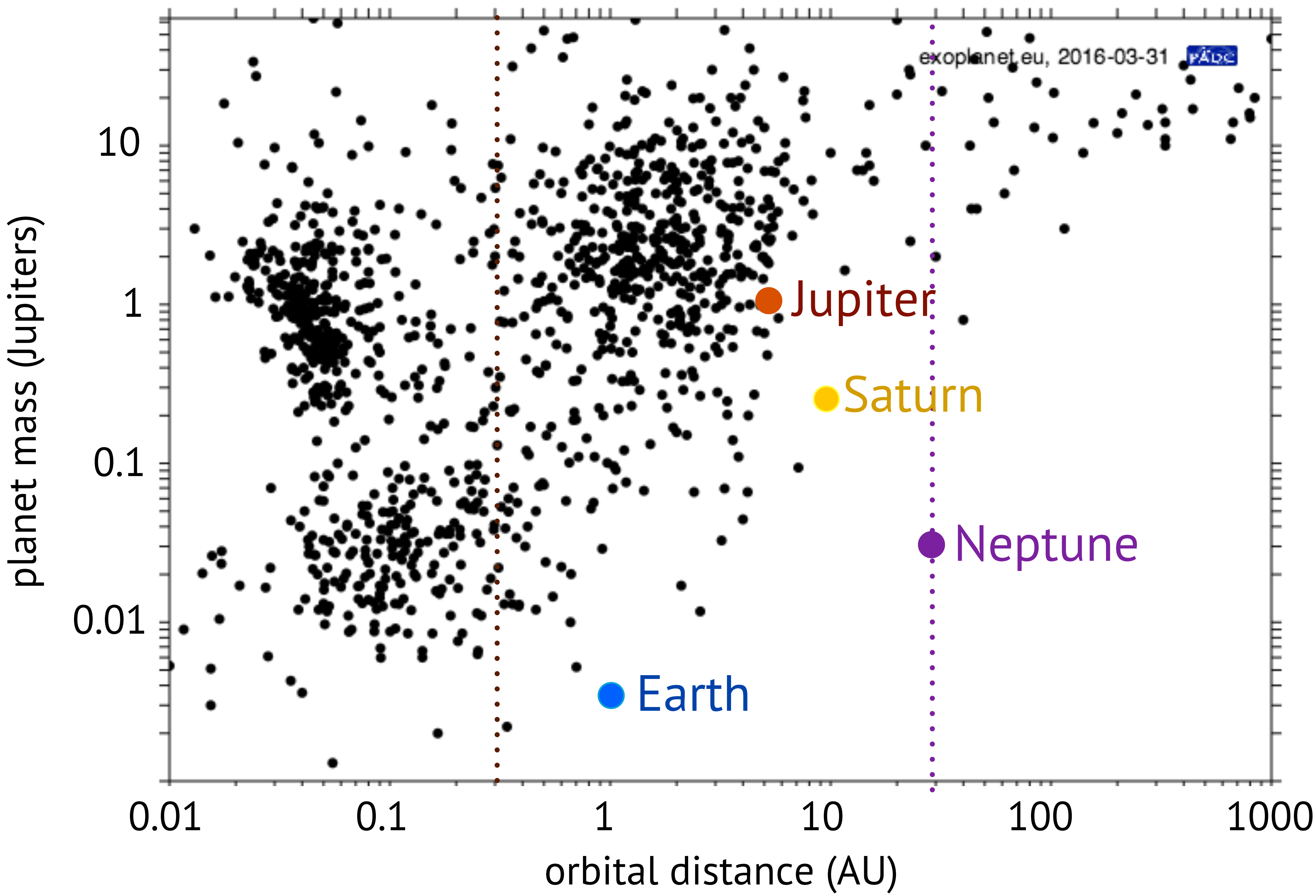
Since 1995, more than 2000 exoplanets discovered



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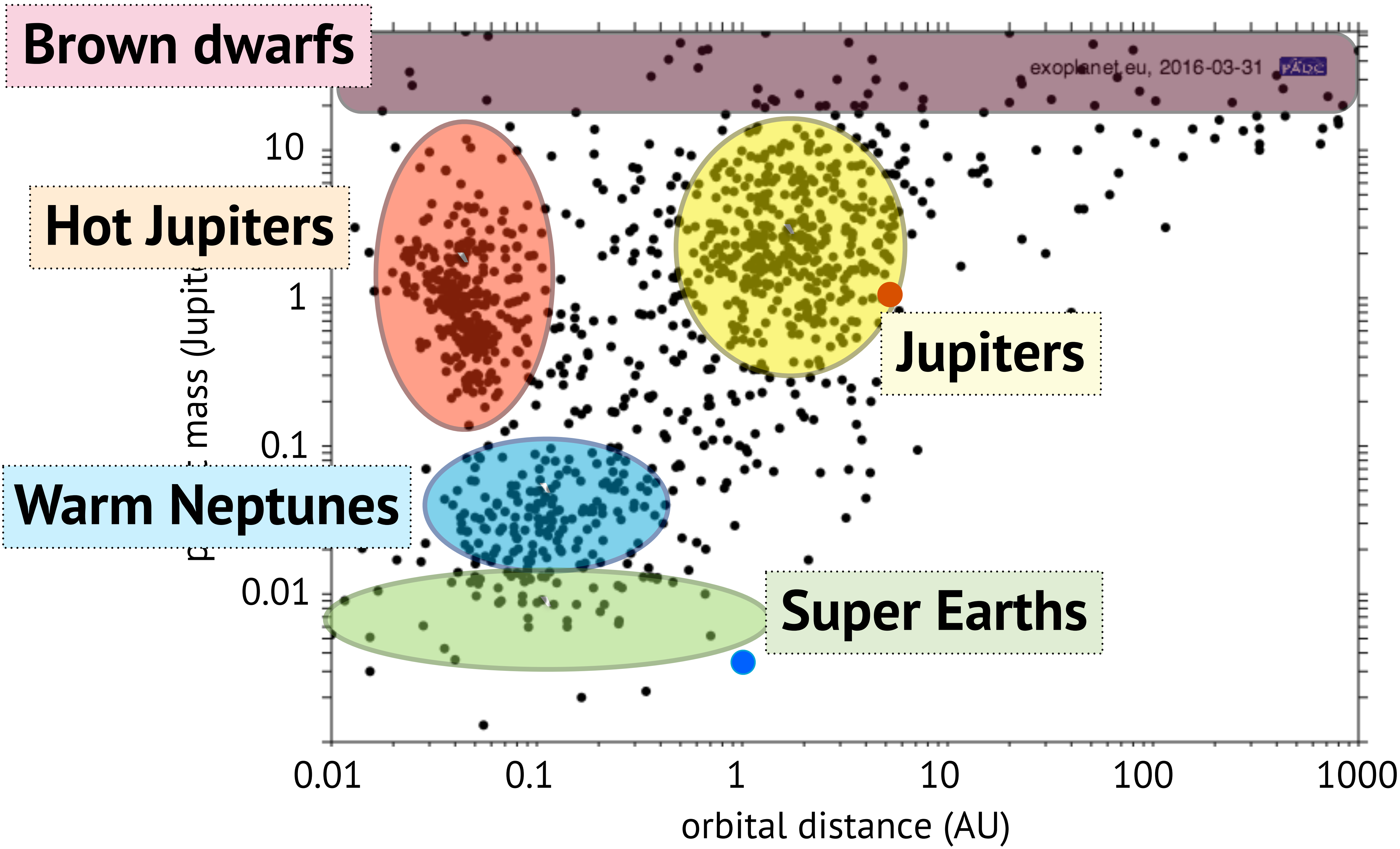

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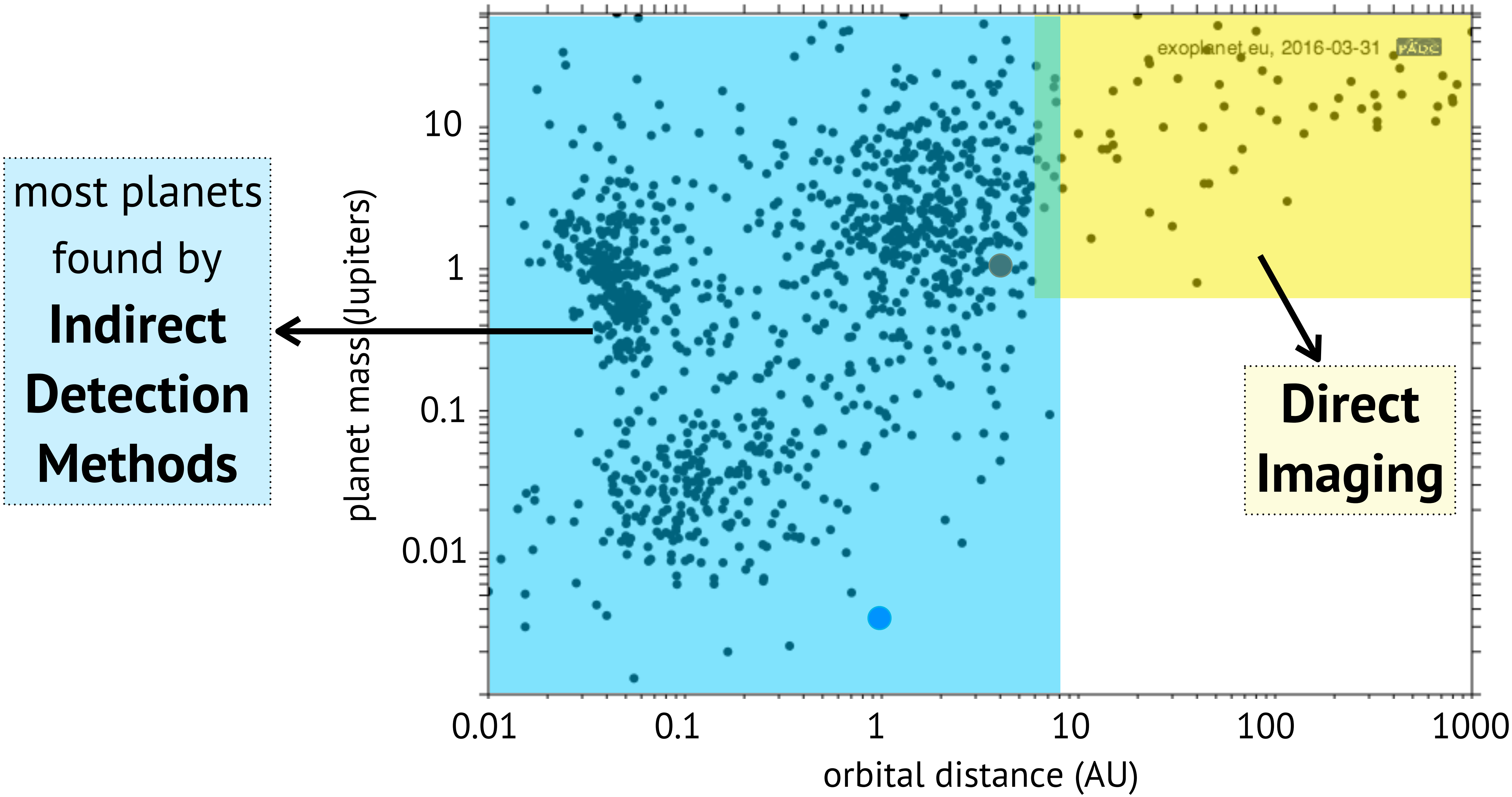
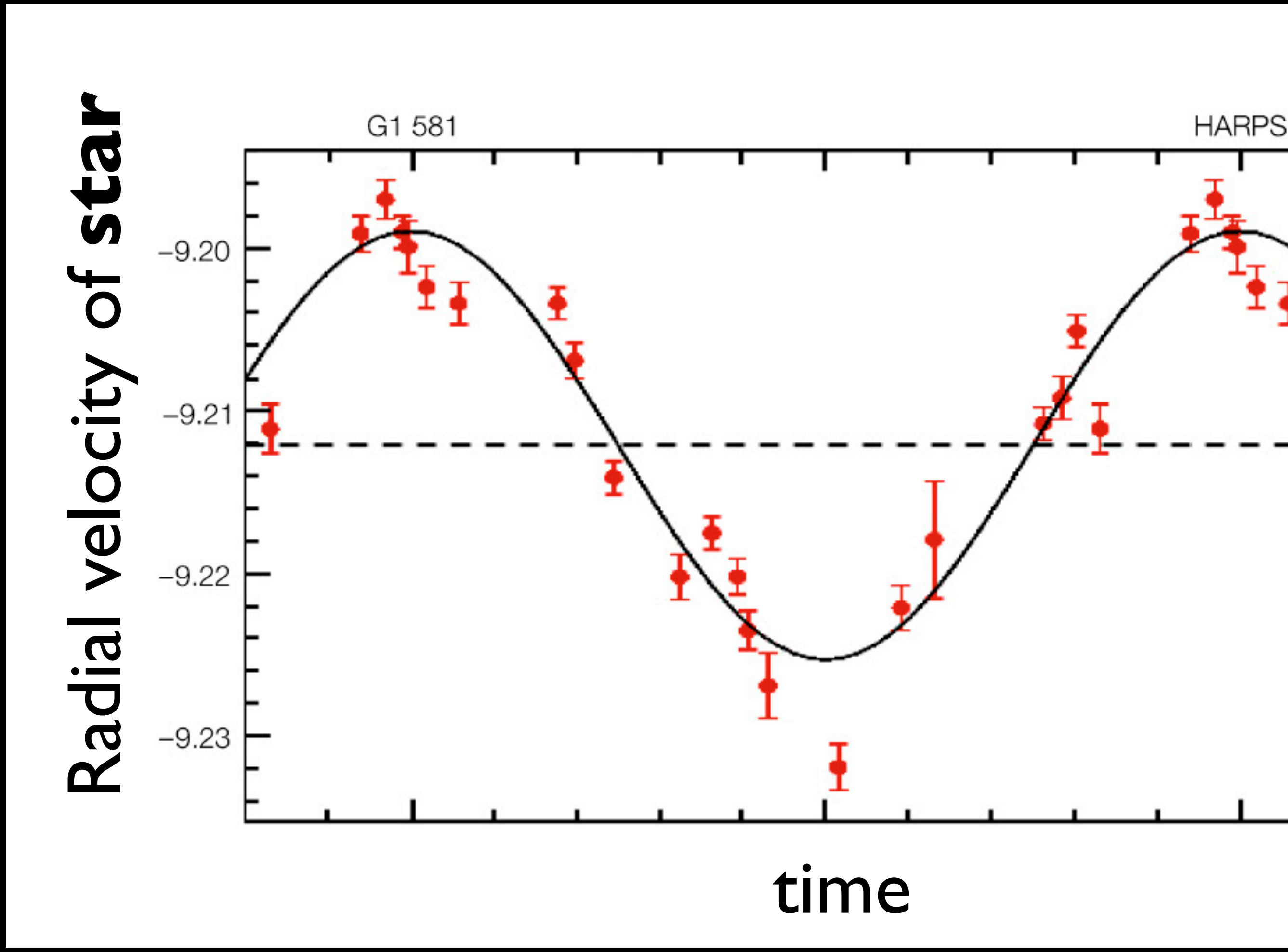


Radial Velocity Method



We do not see the planet! *Observe back-forth movement (RV) of* ***star***

Obtain:
- orbital period of planet
- only estimate of planet mass
  (orbital inclination unknown)

indirect detection methods

Radial Velocity Method

Transit Technique

Measure flux variations of star

*We do not see the planet! Observe back-forth movement (RV) of **star***

Obtain:
- orbital period of planet
- only estimate of planet mass
  (orbital inclination unknown)

+

Obtain:
- orbital period
- planet size (radius)
- orbital inclination (~90 deg)

How can we study the atmospheres of exoplanets?

Challenges:

simultaneously observe star + planet

planets are faint; stars outshine their planets by many magnitudes:

- Sun/Earth: ...... visual: $\sim 10^{10}$; IR $\sim 10^{9}$
- Sun/hot Jupiters: visual $\sim 10^{5}$; IR $\sim 10^{3}$

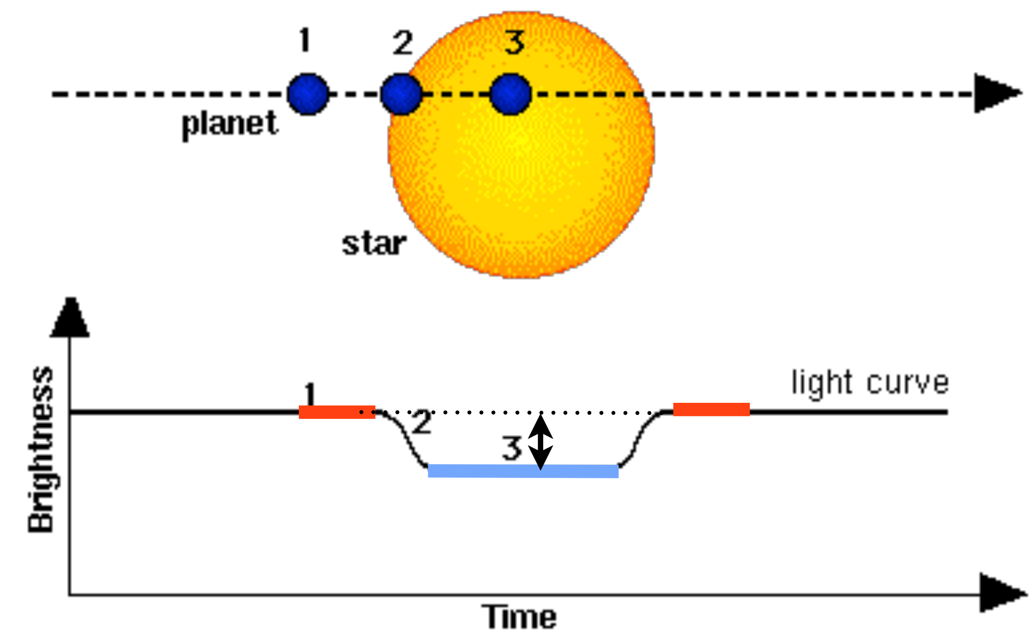
→ need strategies to identify the stellar flux and separate it from the weak planetary signal

"getting rid of the star" ...

transiting planets:

- transmission spectroscopy at transit

- secondary eclipse measurement

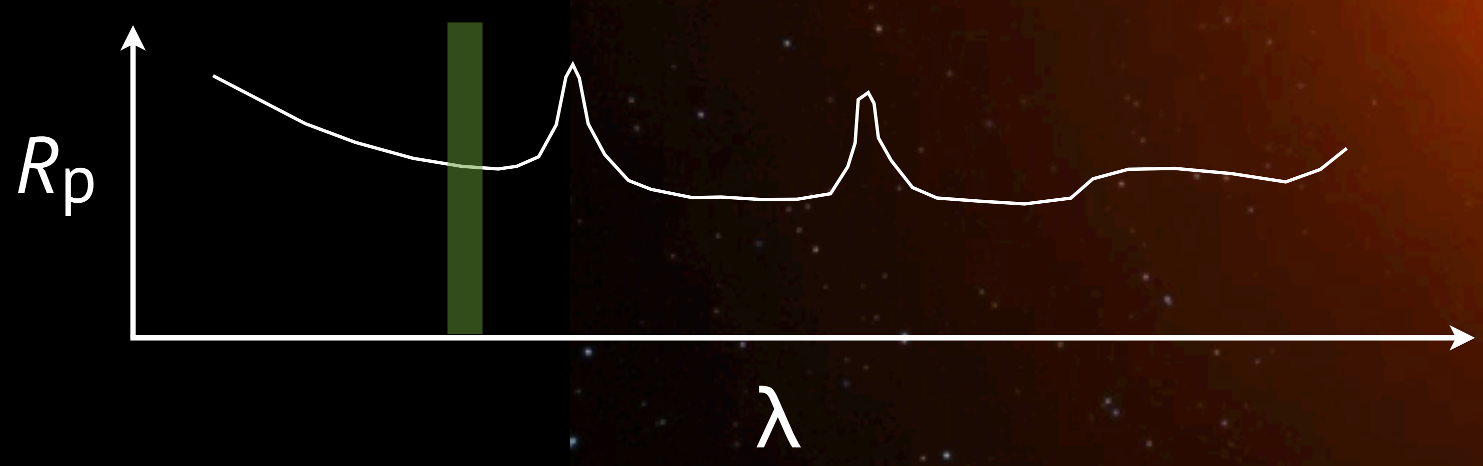


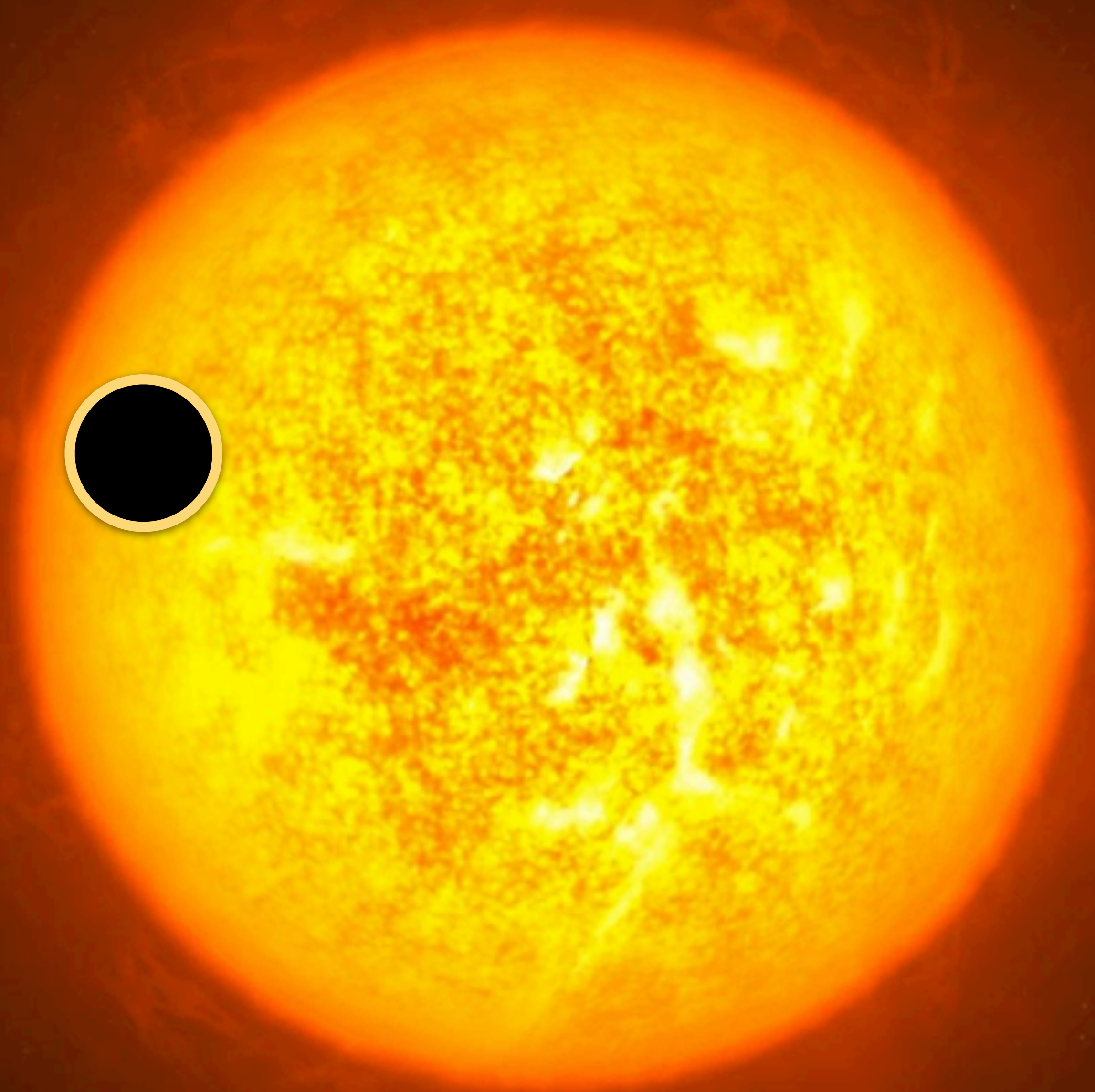
Transmission spectroscopy of transiting planets:

- measure area ratio planet / star

- atmosphere is opaque at certain λ due to molecular absorption

- planet appears larger at those λ





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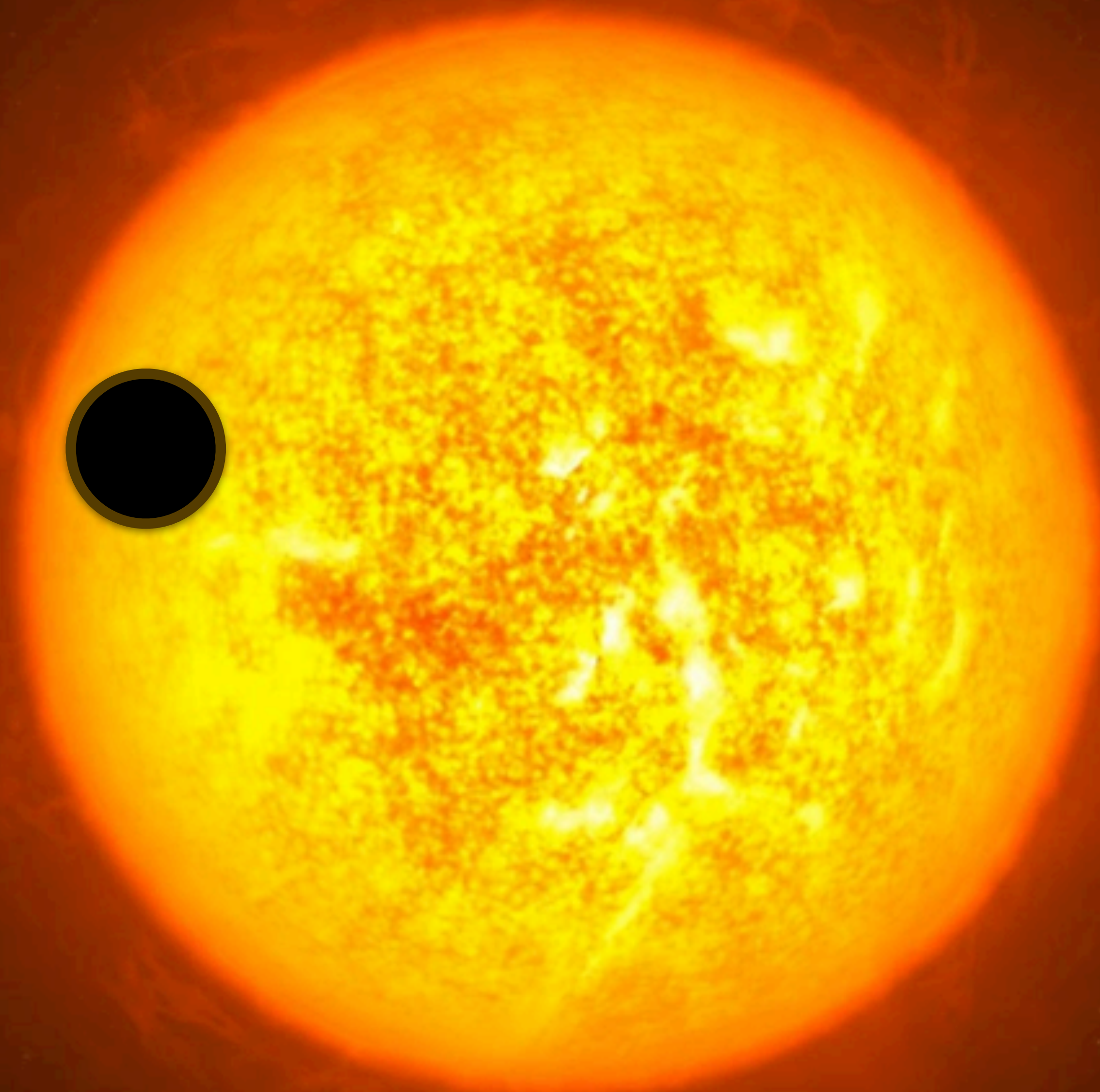
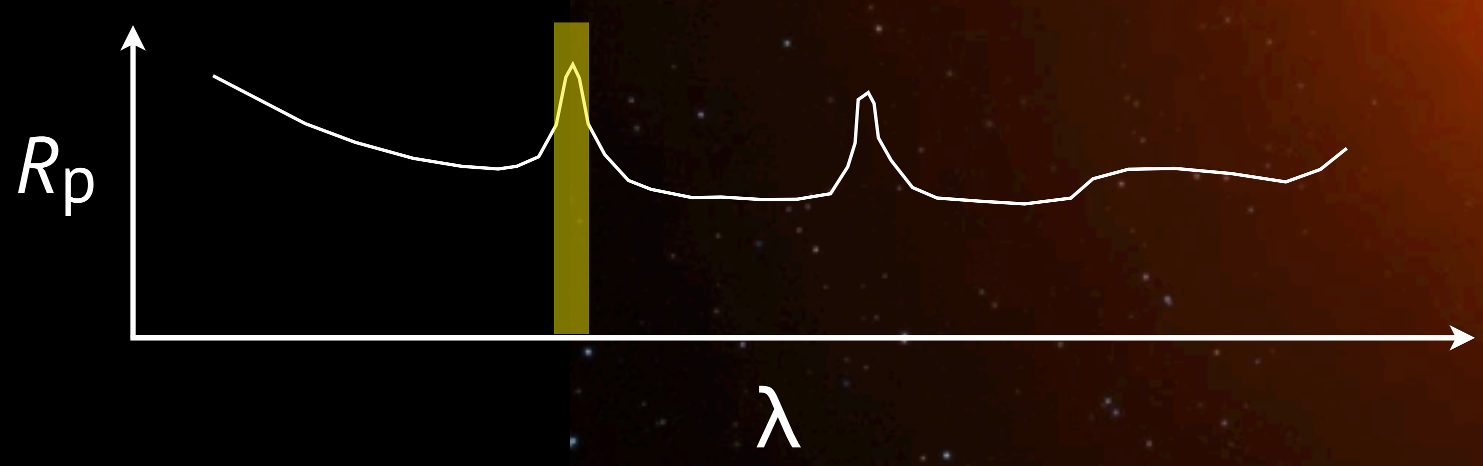


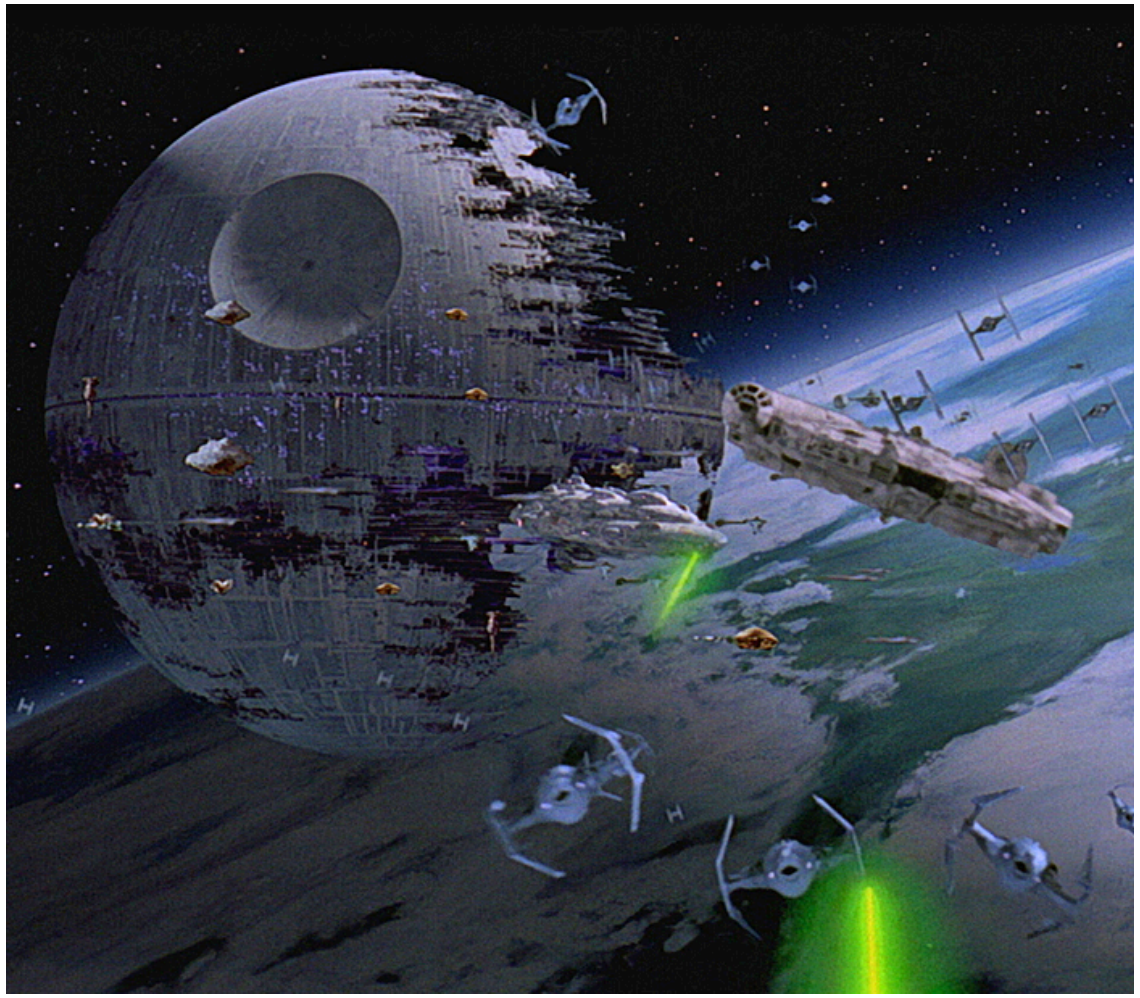


Present

From hot Jupiters ...

Future

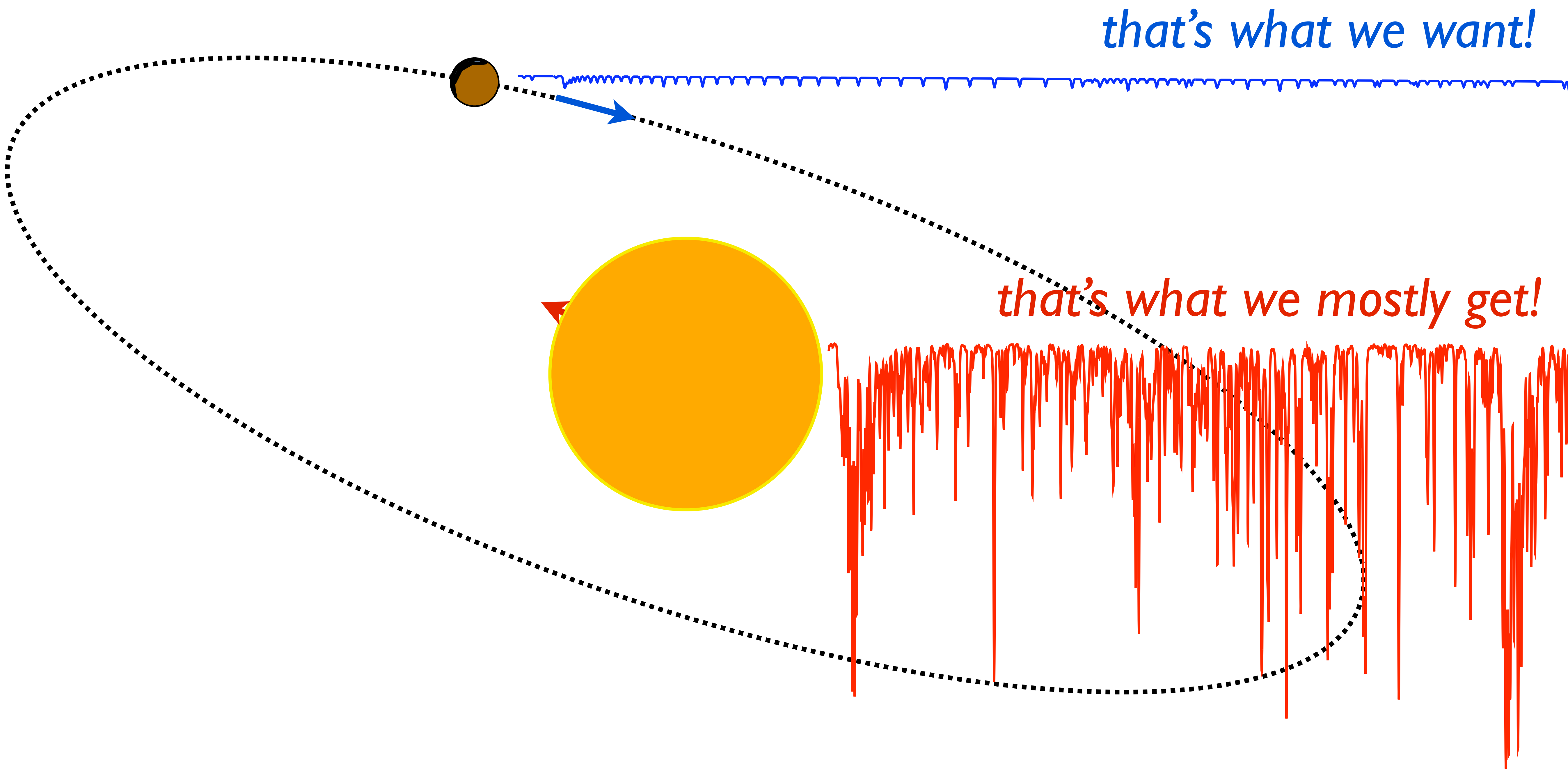
to Earth-like exoplanets



Part 1: Inspecting the Atmospheres of non-transiting Hot Jupiters

- Jupiter-sized planets a few stellar radii away from host stars
- they are hot (*T* up to 2800 K; usually around 1500 K)
- they are unique labs to study exotic atmospheres
- they glow at near-infrared λ (1 - 2.5 micron)

How can we separate the planetary signal?



How can we separate the planetary signal from the star?

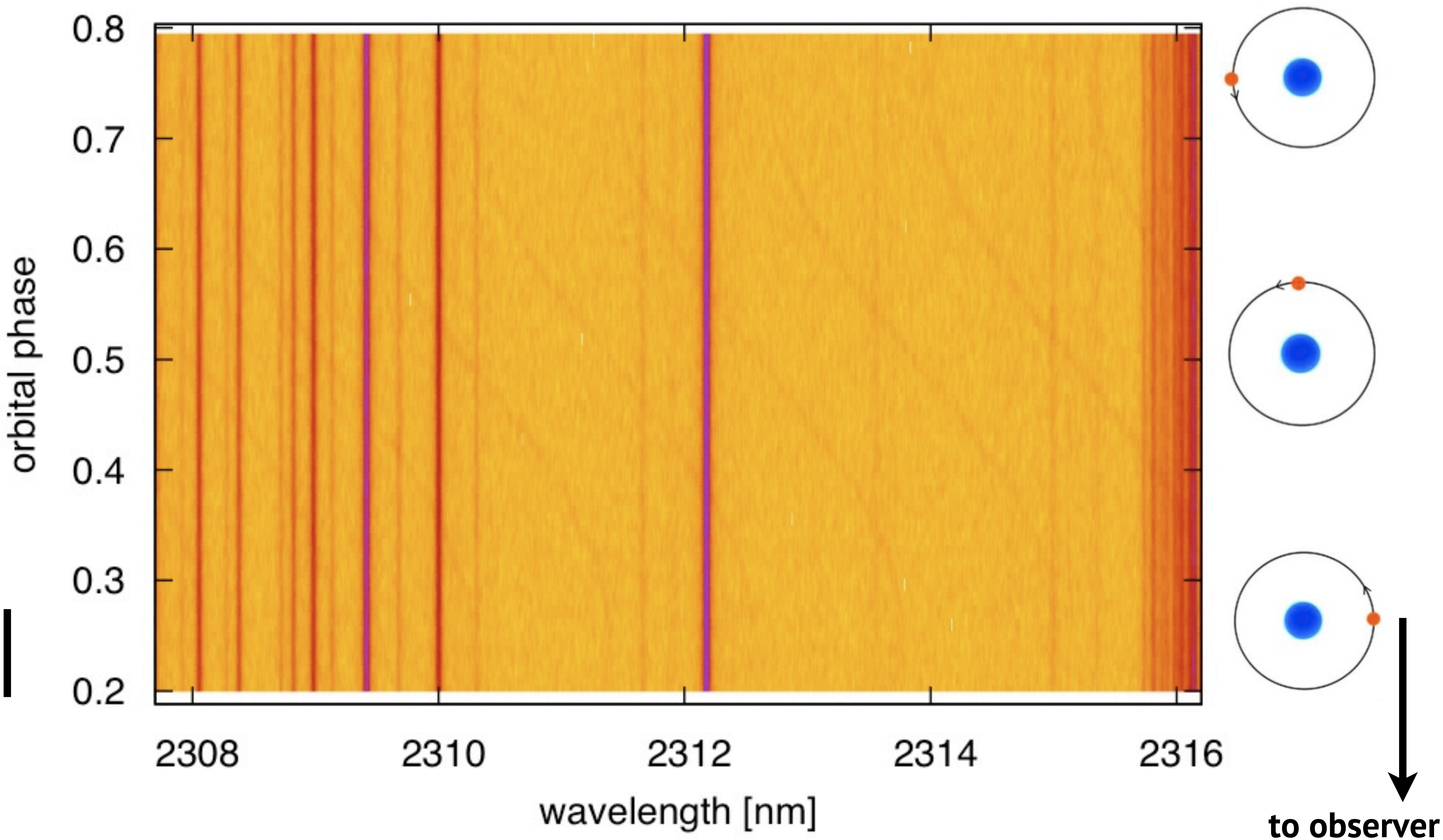
Trick:

- stellar spectrum is almost stationary (<0.5 km/s)

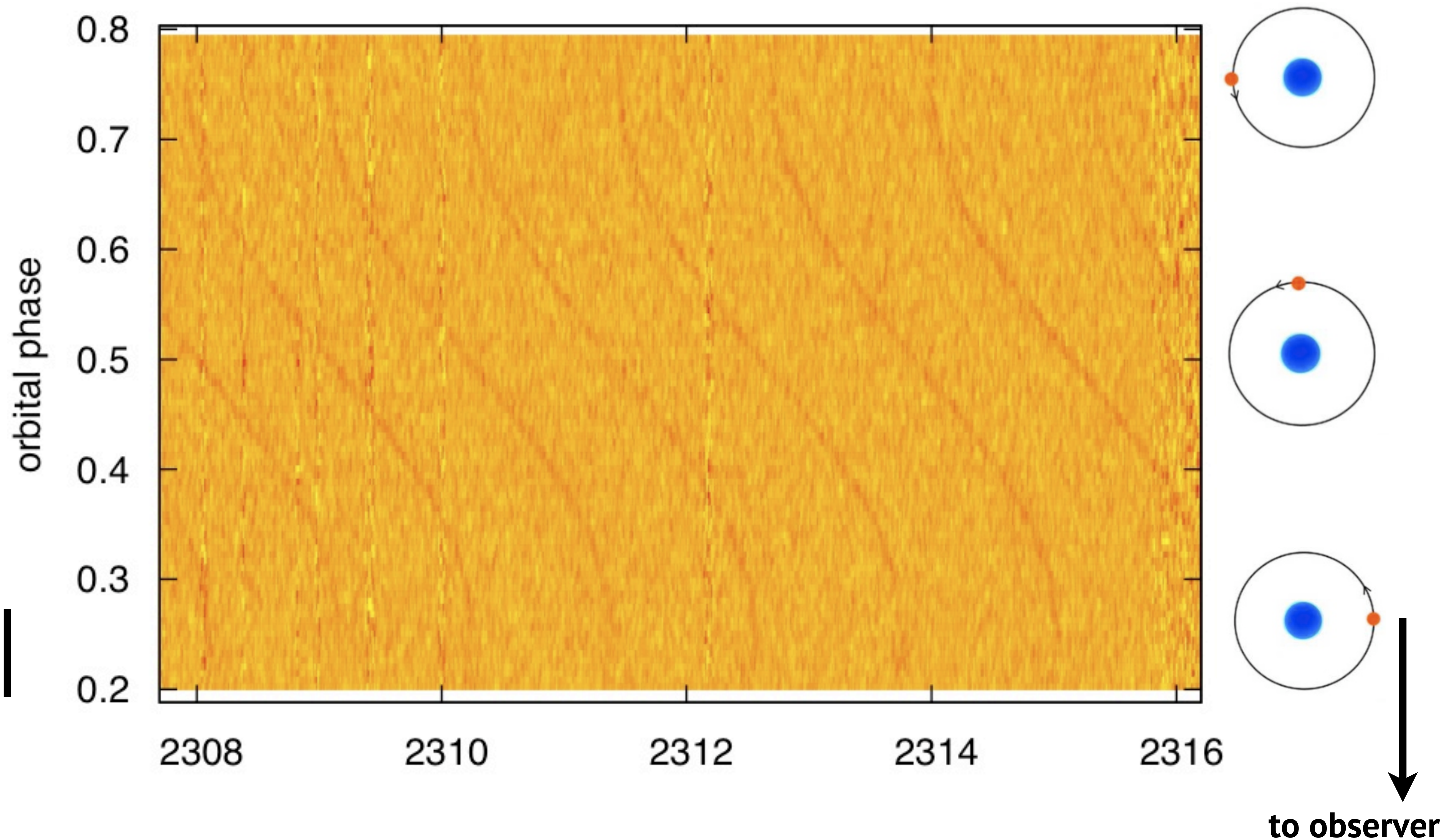
- spectrum of companion travels due to orbital motion (~100 km/s)

go to the largest telescopes and take a time-series of hi-res spectra!

disentangling the planetary signal from the stellar one



disentangling the planetary signal from the stellar one

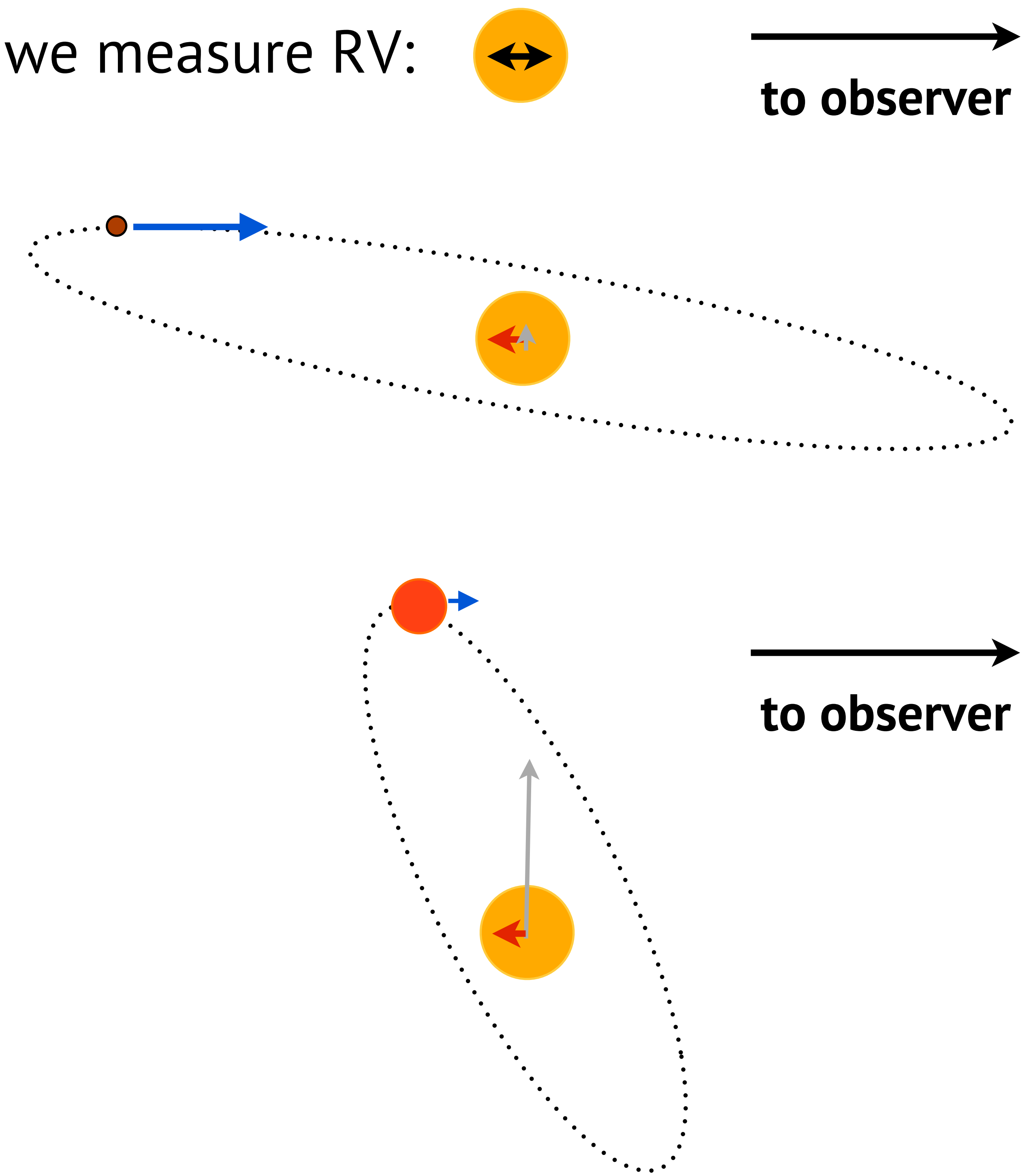


What kind of object is producing the RV shifts of the star?

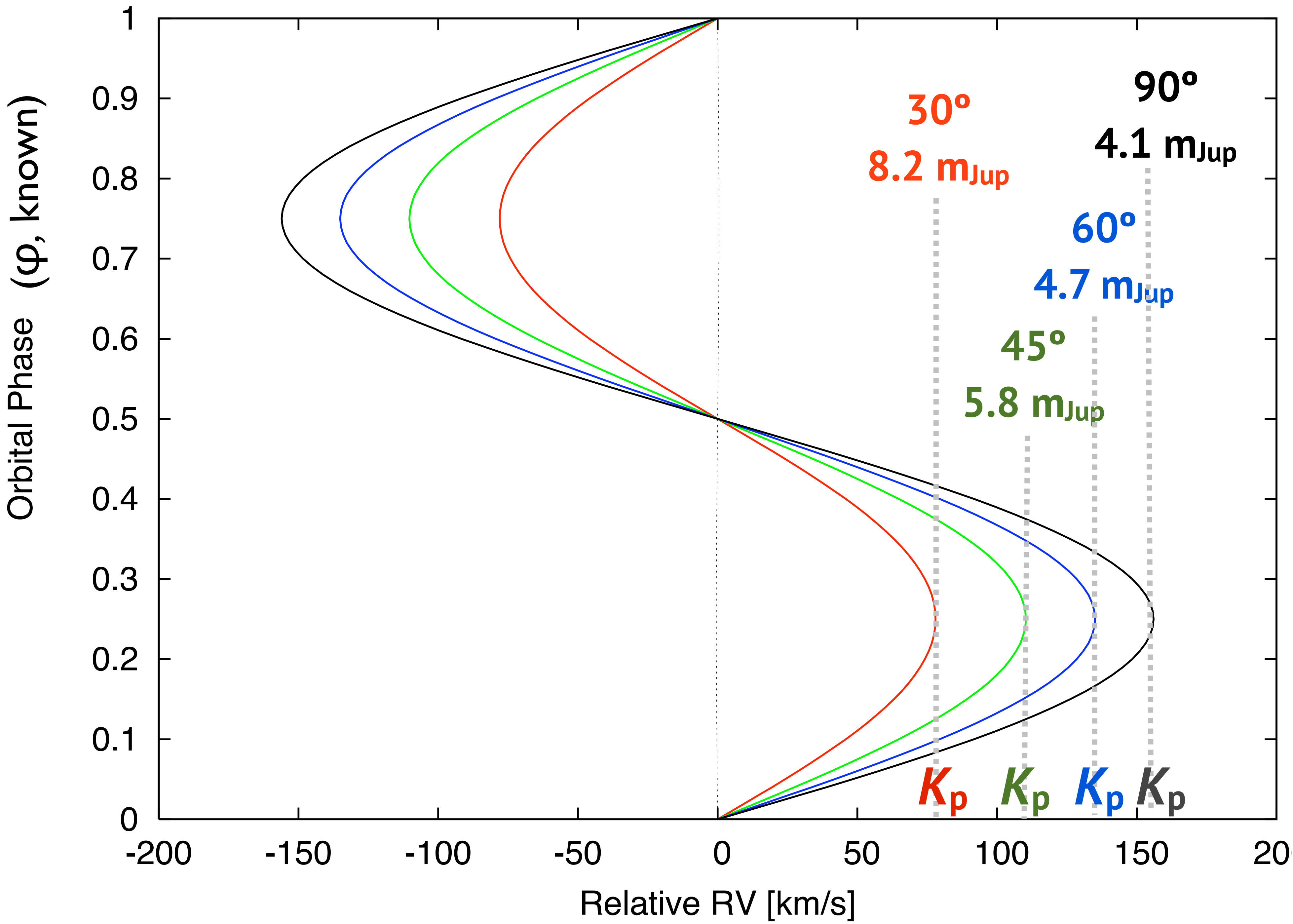
- is it a planet?
- is it a brown dwarf, or even a star?

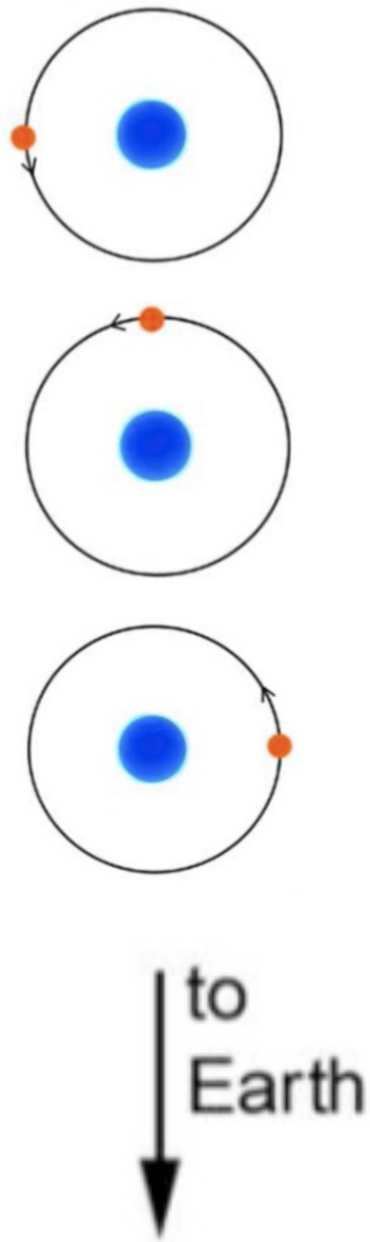
By directly measuring the RV of the companion, we can derive:

- exact mass of companion
  $m_p = m_\star K_\star / K_p$



Shape of RV curve reveals mass of companion: $m_p = m_\star K_\star / K_p$



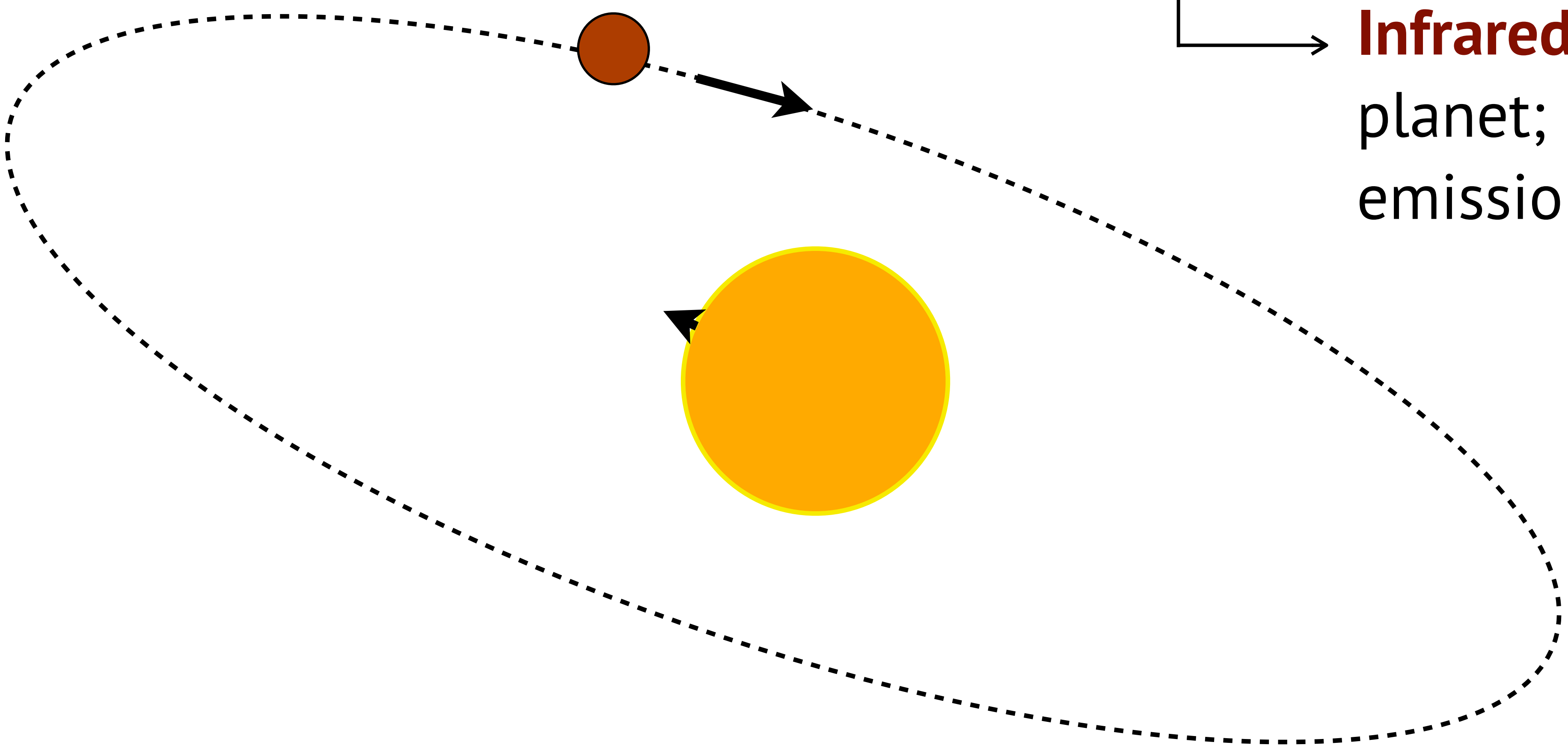


what can we observe in the planet atmospheres?

Day-side spectrum of planet

Visual: reflected starlight; revealing absorption features

Infrared: thermal emission from planet; revealing molecular emission and absorption



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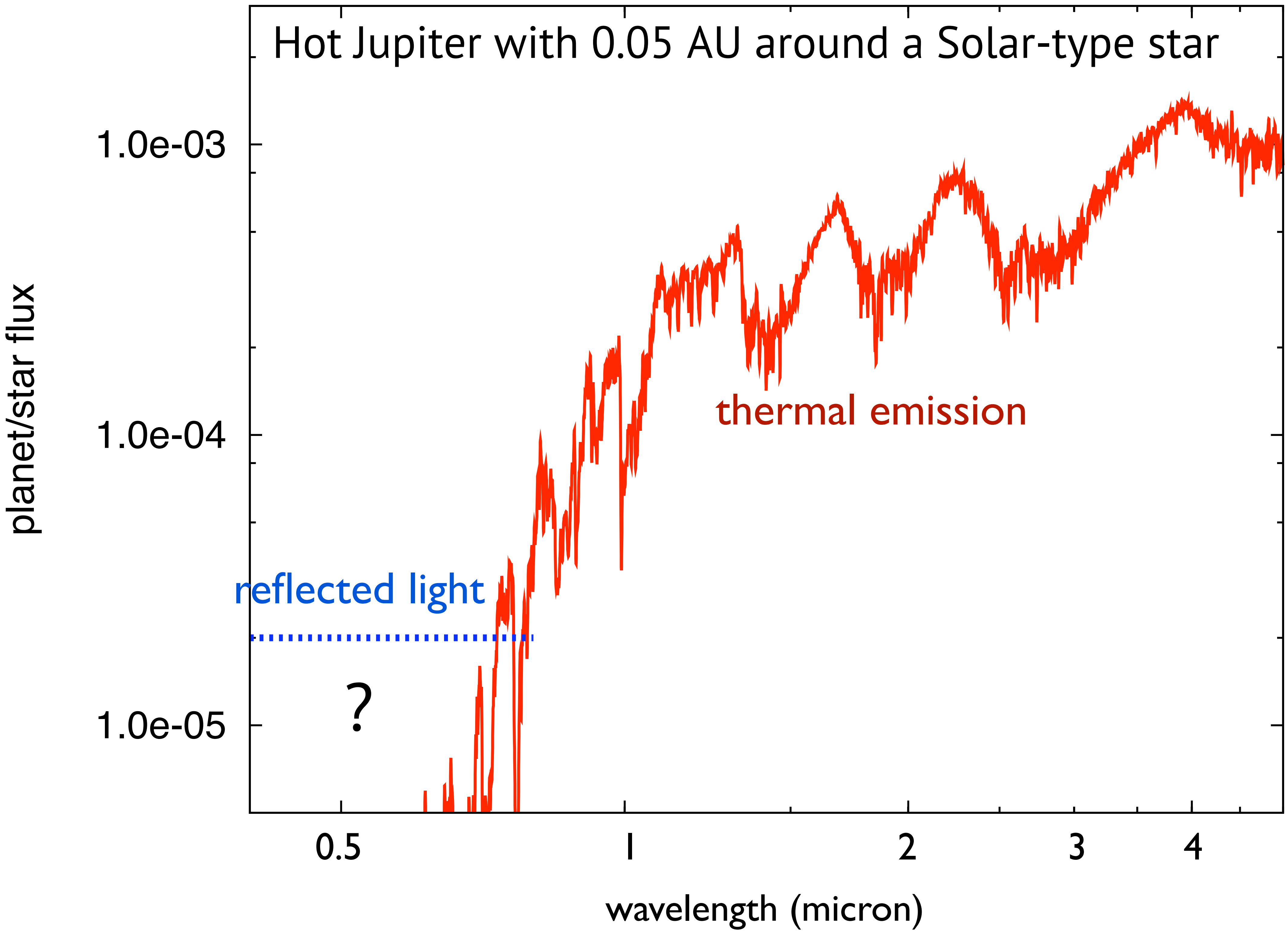


what can we observe in the planet atmospheres?

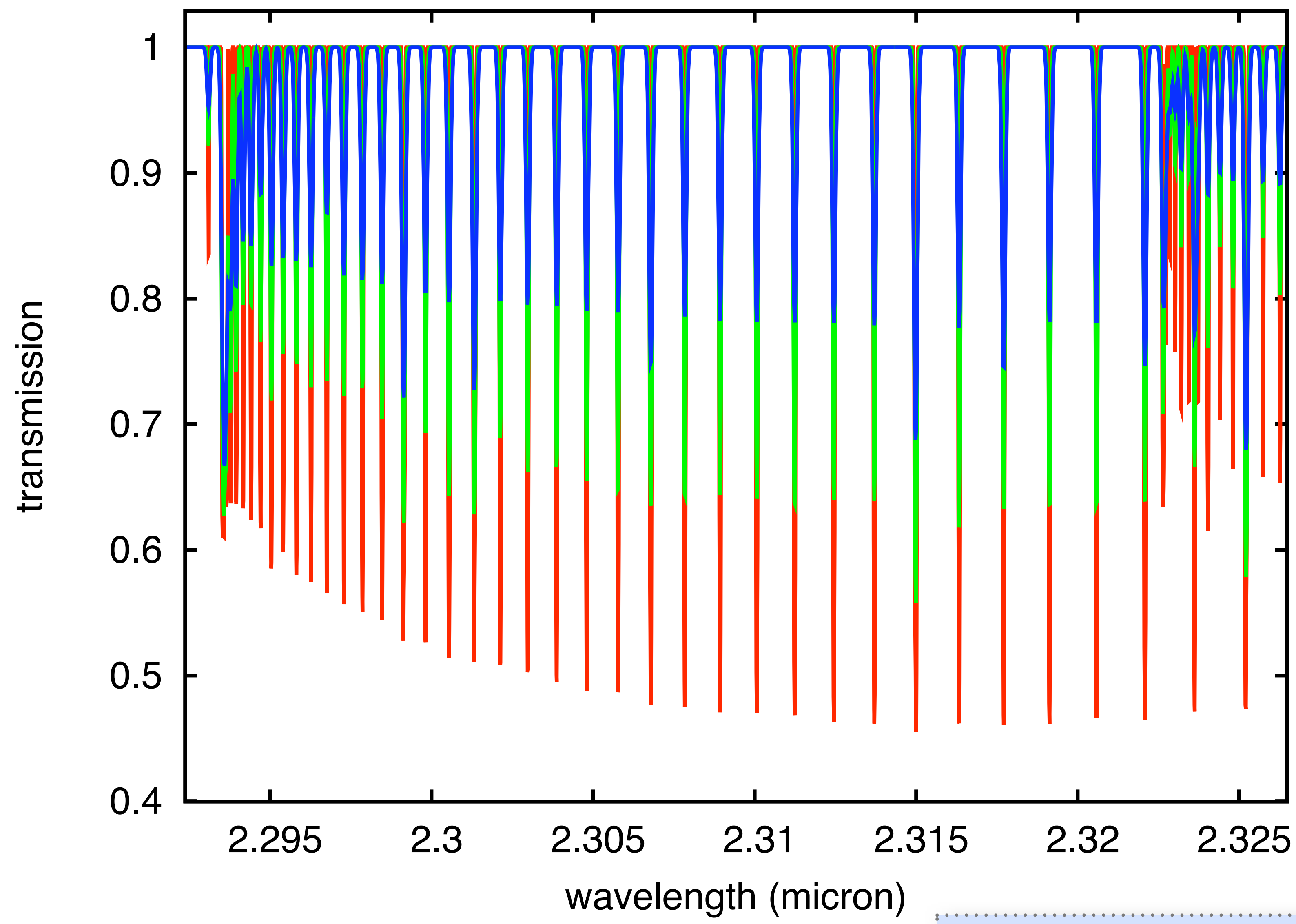
Planet spectrum in the IR:

- ★ what does it look like?
- ★ need large number of deep spectral features!
- ★ **the deeper, the better!**

↓

target molecules which are likely to be present in planet atmosphere:

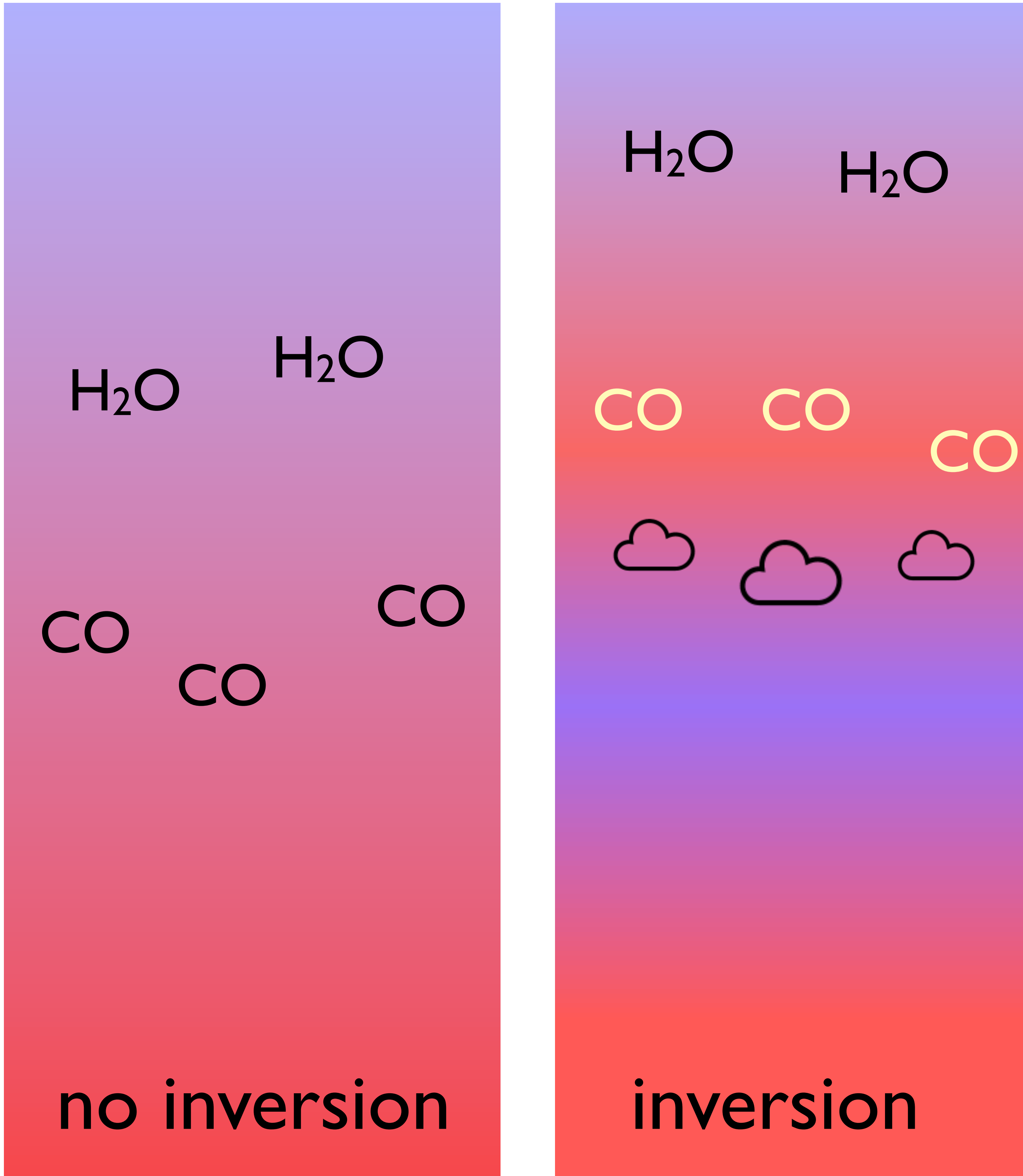
CO, H_2O, CH_4, …



blue …… 20k
green …. 35k
red …… 100k

Hi-res spectroscopy of exoplanet atmospheres:

- feasible with ground-based telescopes
- robust and unambiguous measurement of molecules
- inversion layer?



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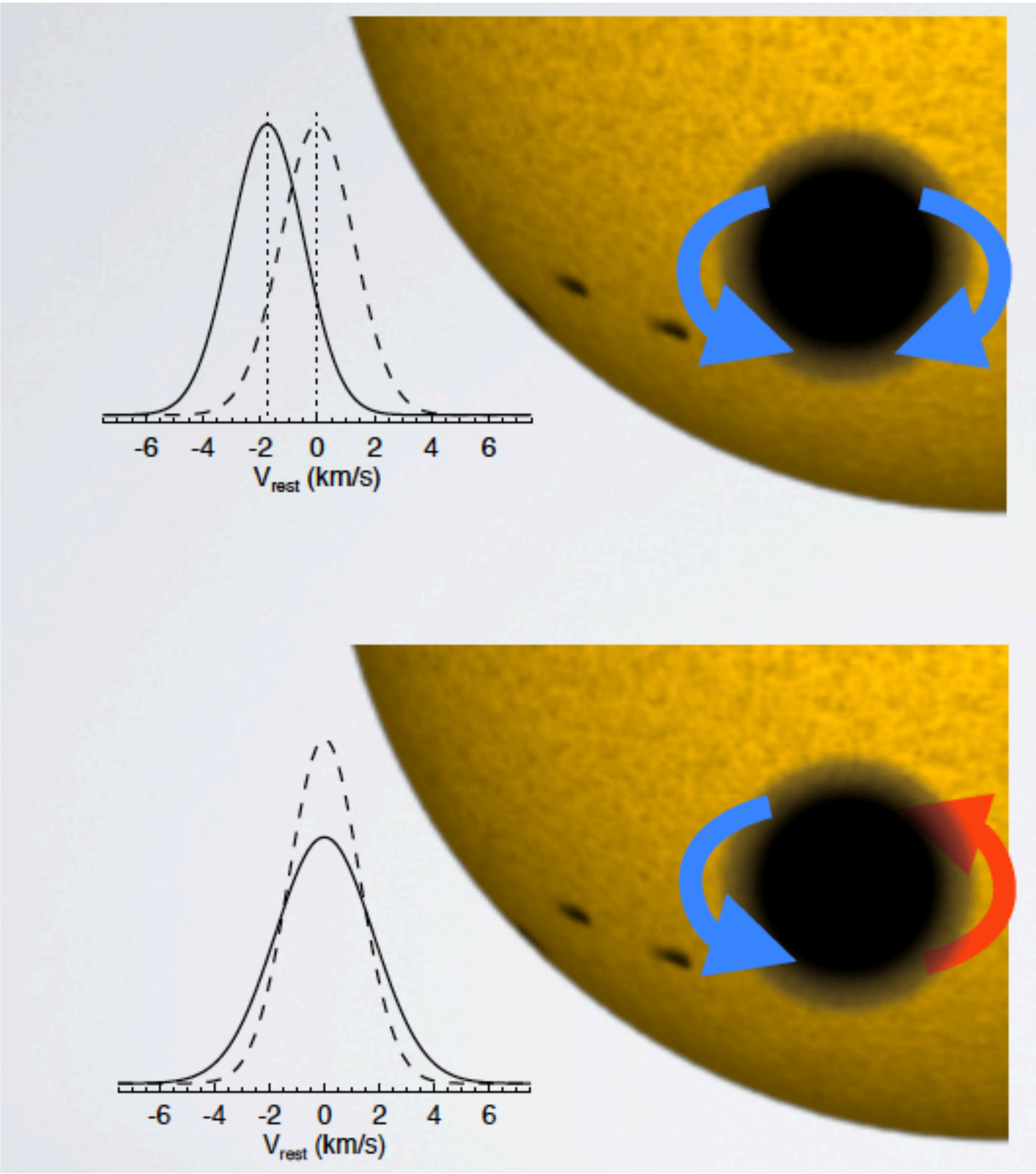


With high-res spectra, we can measure atmospheric circulation ...

Observe the presence of

★ strong winds

★ atmospheric super-rotation

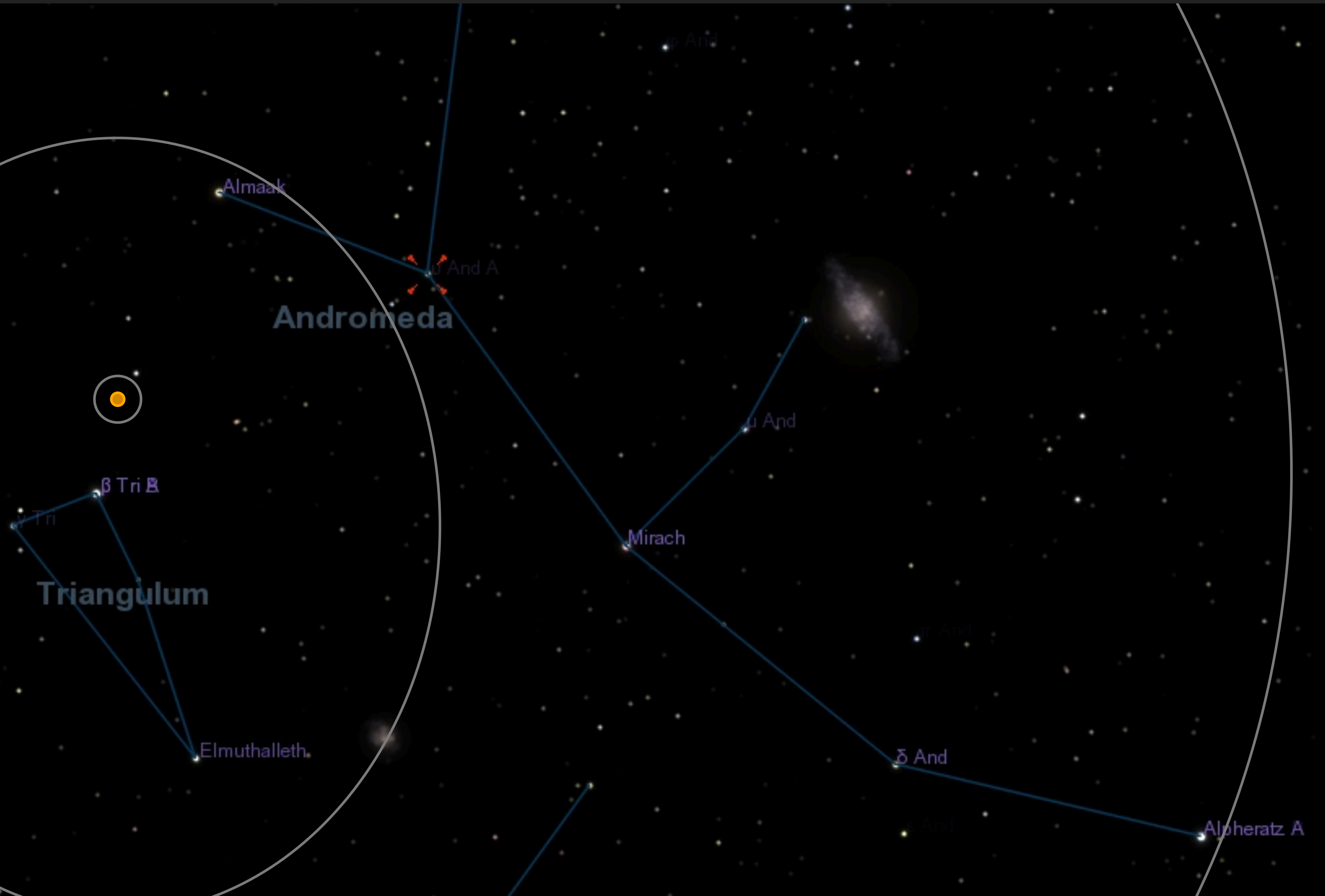
(cf. Snellen+ 2010, 2014)

In 2012, finally, this method started to work ...

- CO in the planet atmosphere of Tau Boo b (Rodler+12, Brogi+12)
- CO in HD 189733b (Rodler+ 13b, de Kok+ 13)
- CO and H_2O in 51 Peg (Brogi+ 13, 14)
- H_2O in HD 189733b (Birkby+ 13)
- H_2O in Tau Boo b (Lockwood+14)
- rotation in Bet Pic b (Snellen+14)
- CO in Ups And b, determine $i \sim 24°$ (Rodler+, in prep)

...

The Bloated Planet Upsilon Andromedae b



Multiplanet system:

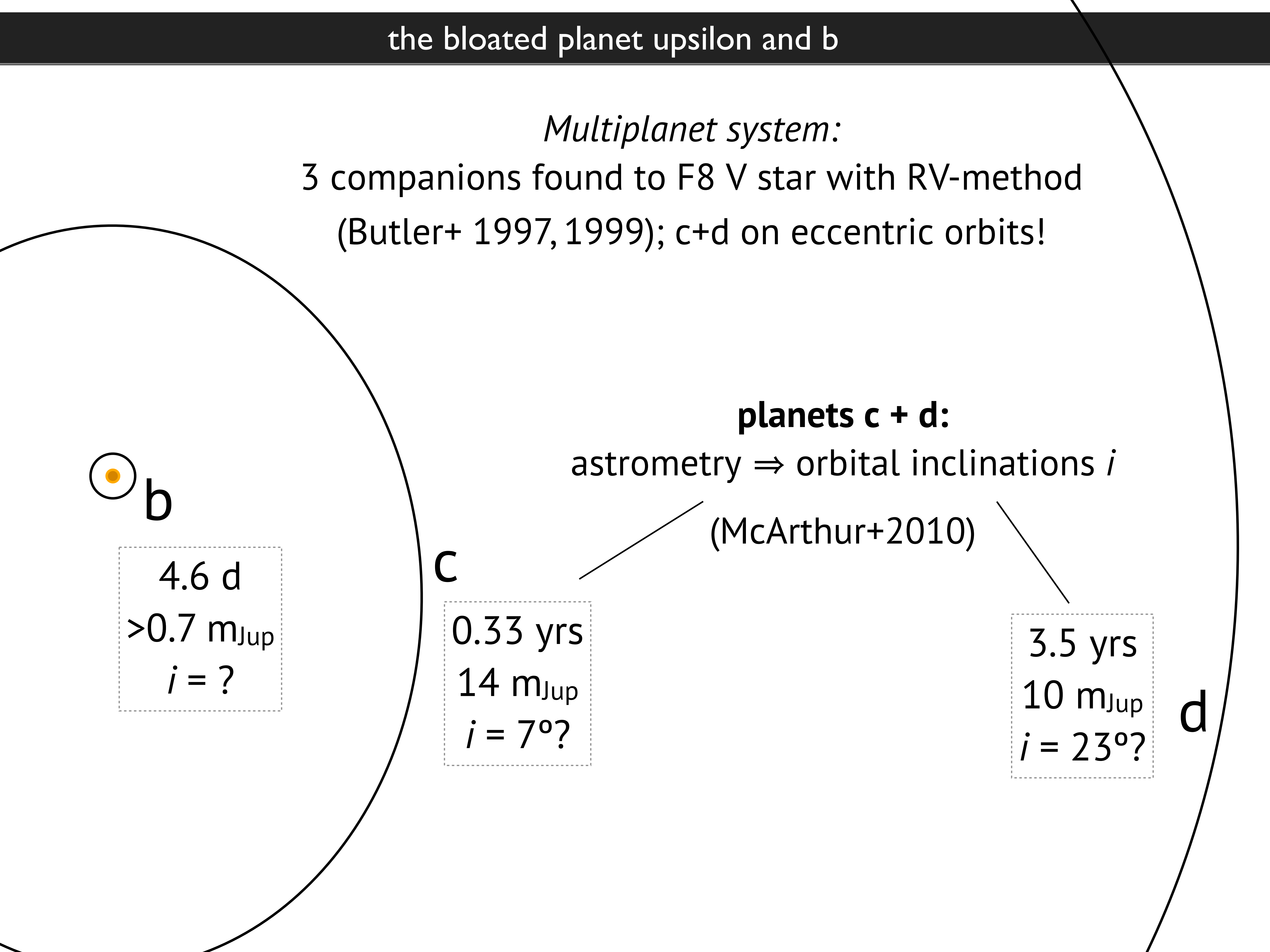
3 companions found to F8 V star with RV-method

(Butler+ 1997, 1999); c+d on eccentric orbits!

planets c + d:

astrometry ⇒ orbital inclinations *i*

(McArthur+2010)



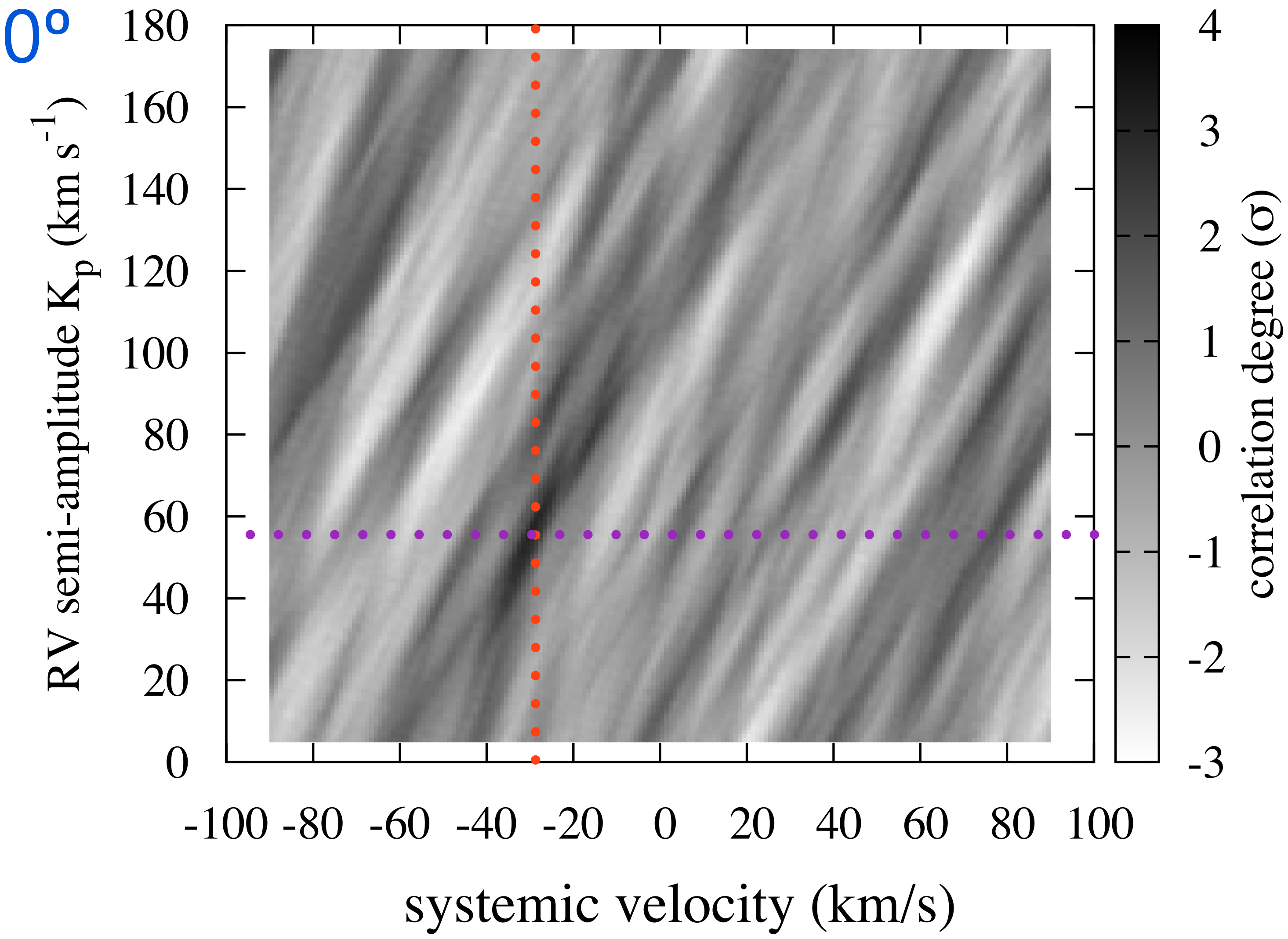
Observed Ups And b with Keck / NIRSPEC at 2.3 micron:

Detection of CO absorption in day-side spectrum of planet!

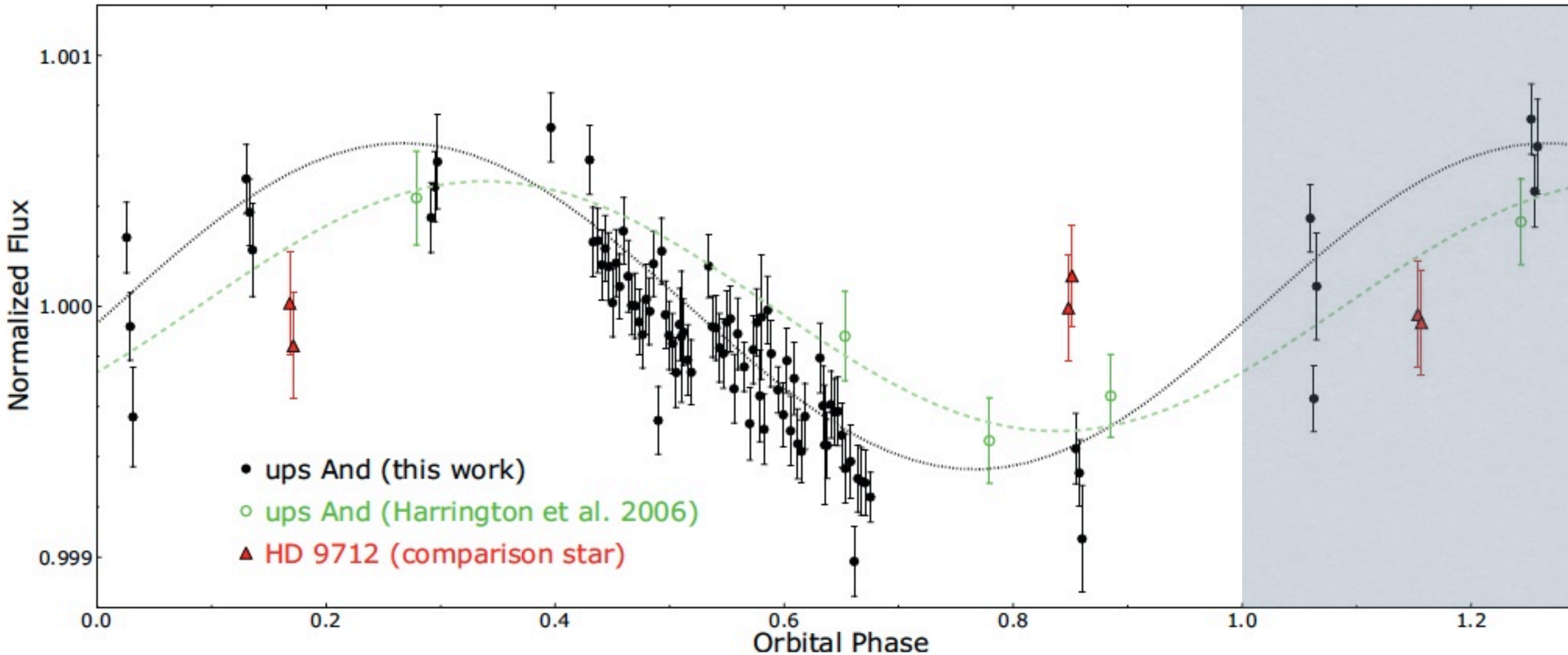
1) measure orbital motion and find orbital inclination 18-30º

2) determine planet mass m_p = 1.6-1.8 Jup

(Rodler+ in prep.)



the bloated planet upsilon and b

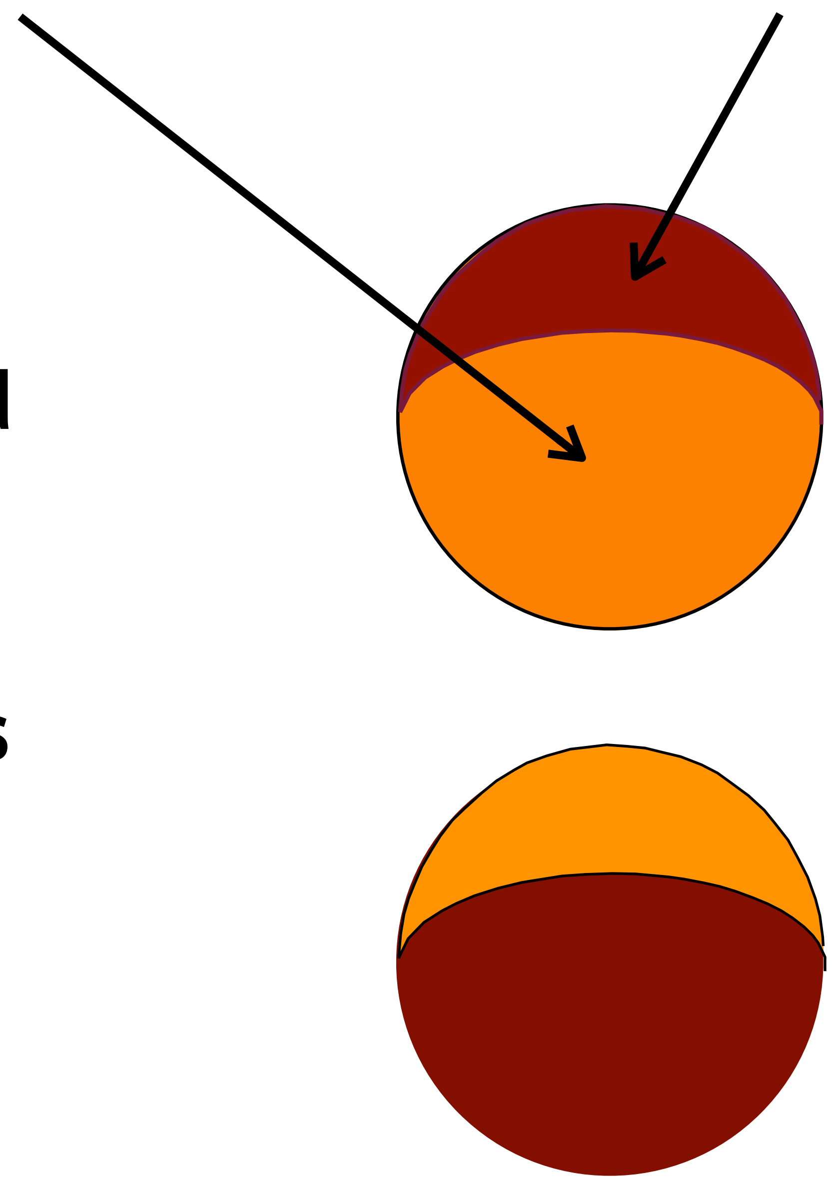


24 micron Spitzer lightcurve

(Crossfield+ 2010)

Phase curve of Ups And b can be explained by large radius):

$R_{p,\,min}$ = 1.8 R_{Jup} (assuming day side T = 1600 K, night side T = 900 K, spin-orbit alignment)



- **this planet is probably extremely inflated**

- **among the largest exoplanets!**

- **observe CO in absorption, which suggests the absence of a thermal inversion layer**

High-res spectroscopy of exoplanet atmosphere reveals ...

1) **orbital motion** of companion
→ *orbital inclination i, solve for exact mass* m_p

2) **molecule species** in planet atmosphere

3) **thermal inversion** layer in planetary atmosphere

4) Doppler broadening: **circulation pattern** in planet atmosphere

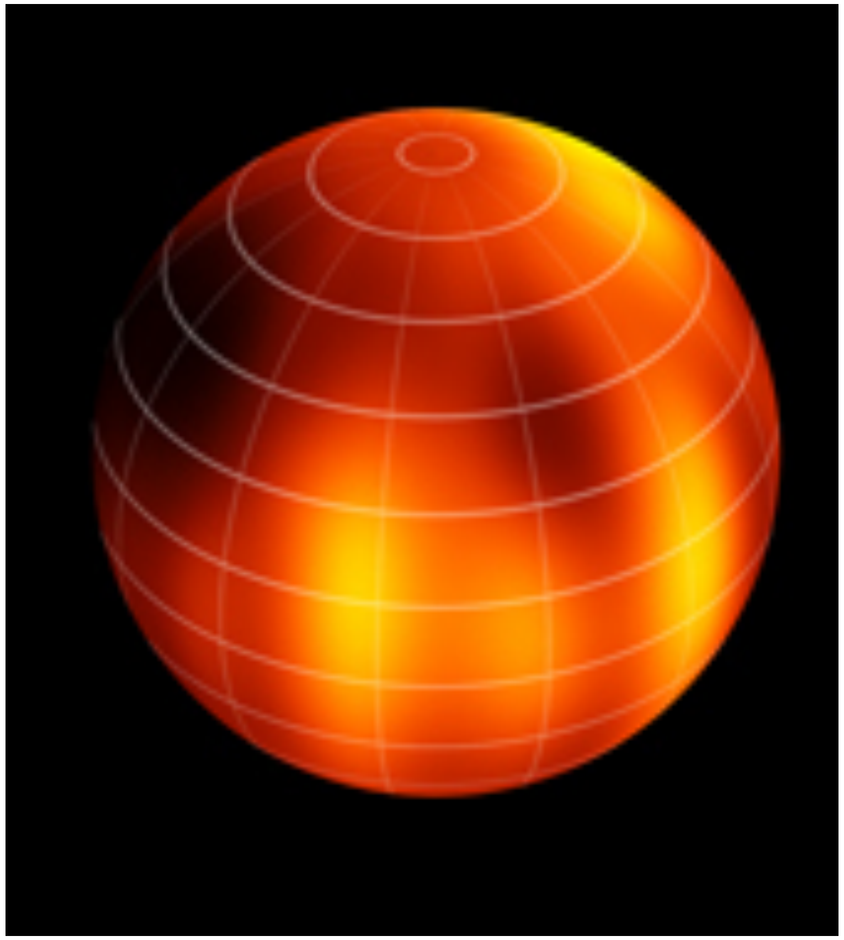
5) planet radius (with phase curve)!

Outlook:

With current instrumentation, we can only investigate hot Jupiters with bright host stars (K<6; ~10 hot Jupiters)!

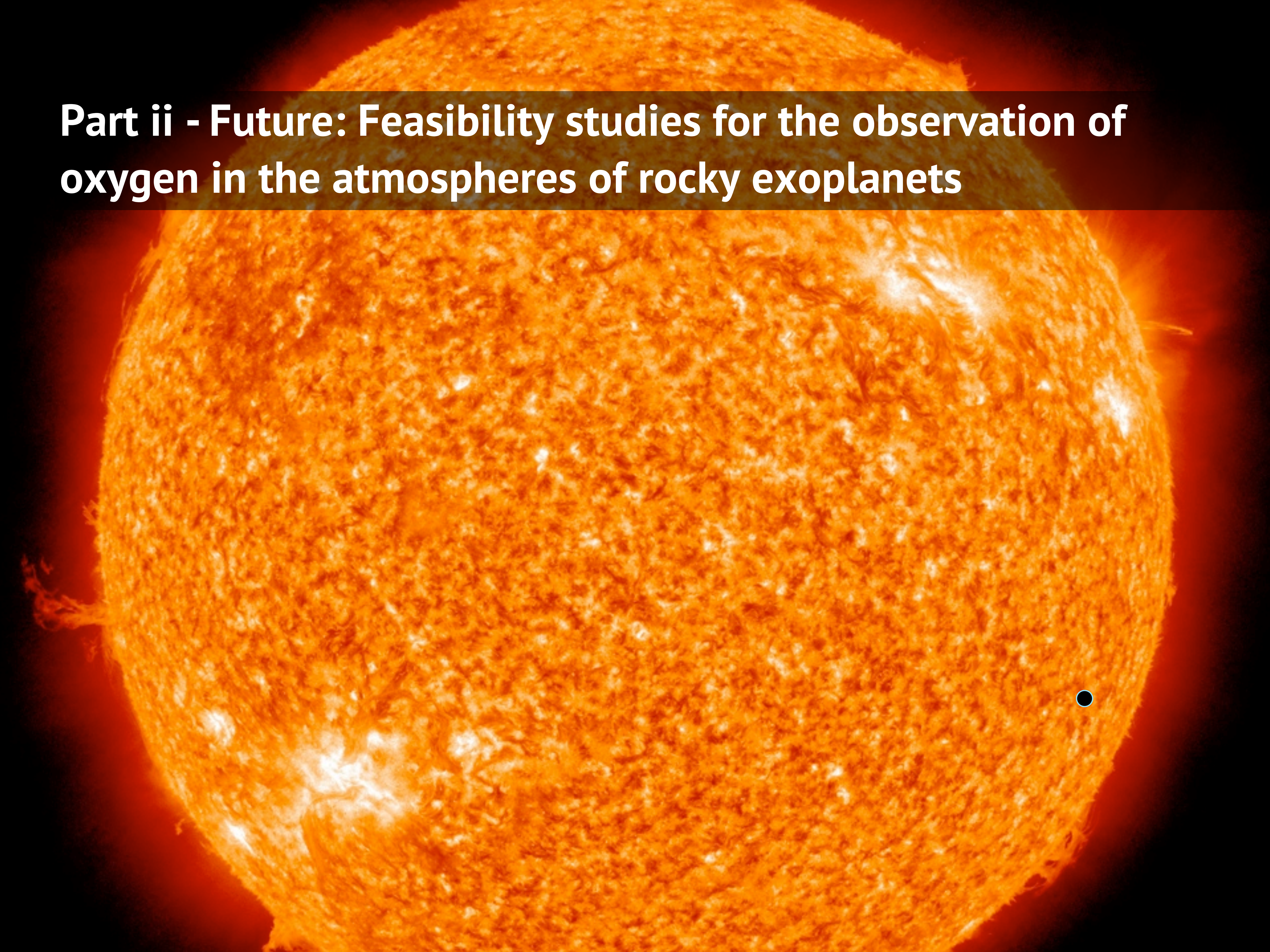
With the upcoming **ELTs** we will:

- ⋆ inspect ~80 hot Jupiters orbiting fainter host stars (K<11)
- ⋆ investigate smaller planets: super-Earths, hot Neptunes, and warm Jupiters around bright host stars
- ⋆ map the planet atmospheres of hot Jupiters with Doppler imaging



Crossfield+ 2014

Part ii - Future: Feasibility studies for the observation of oxygen in the atmospheres of rocky exoplanets



The key to find habitable planets is to study the atmospheres of rocky exoplanets:

- presence of biomarkers (O_2, O_3, CH_4)

- greenhouse gases (CO_2, H_2O, CH_4)

We focus on rocky, dense exoplanets with radii 1-1.5 Earths, in the “habitable zone” (i.e. surface temperatures allowing water to be in liquid state)

How can we study the atmospheres of small exoplanets?

Challenges:

simultaneously observe star + planet

planets are faint; stars outshine their planets by many magnitudes:

- Sun/Earth: .... visual: ~10^{10}; IR ~10^{9}

... that's pretty faint!

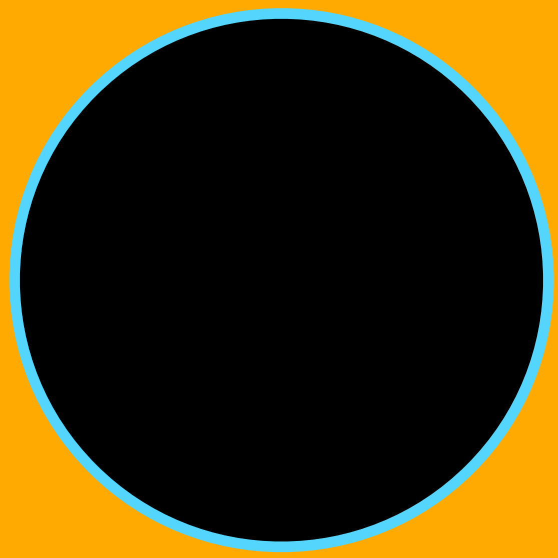
How can we study the atmospheres of small exoplanets?

Challenges:
simultaneously observe star + planet

planets are faint; stars outshine their planets by many magnitudes:
- Sun/Earth: .... visual: $\sim 10^{10}$; IR $\sim 10^{9}$

Transmission spectroscopy of small transiting planets better?
- With transmission spectroscopy, we only care about the area ratio planet atmosphere / stellar disk!

Transmission spectroscopy:
exo-Earth around solar-type star



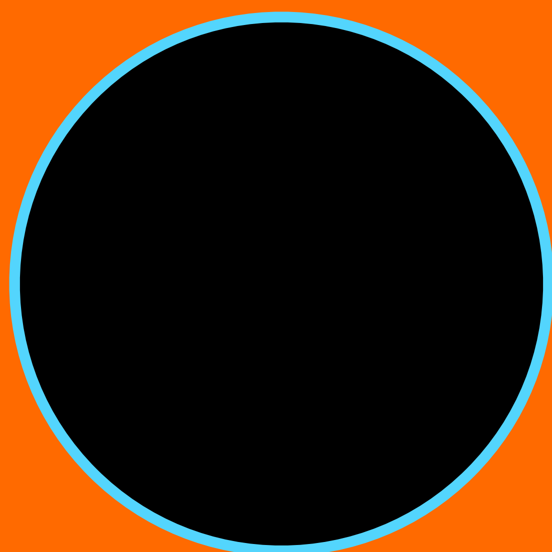
Question: imagine, the Sun emits 10^6 photons

How many photons pass through the planet atmosphere?

a) 2
b) 20
c) 200

Transmission spectroscopy

Earth-like planet around an M4-dwarf



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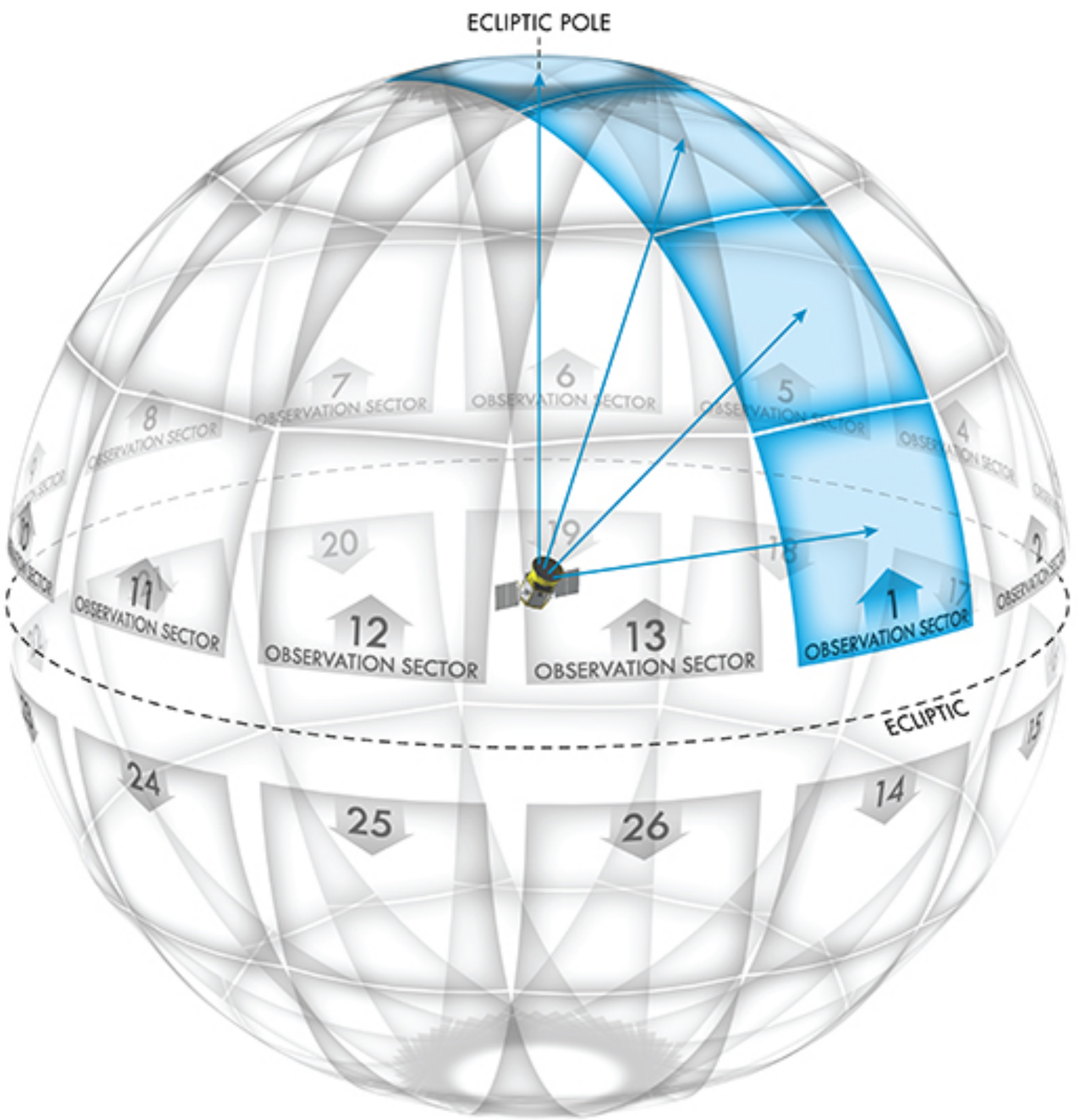
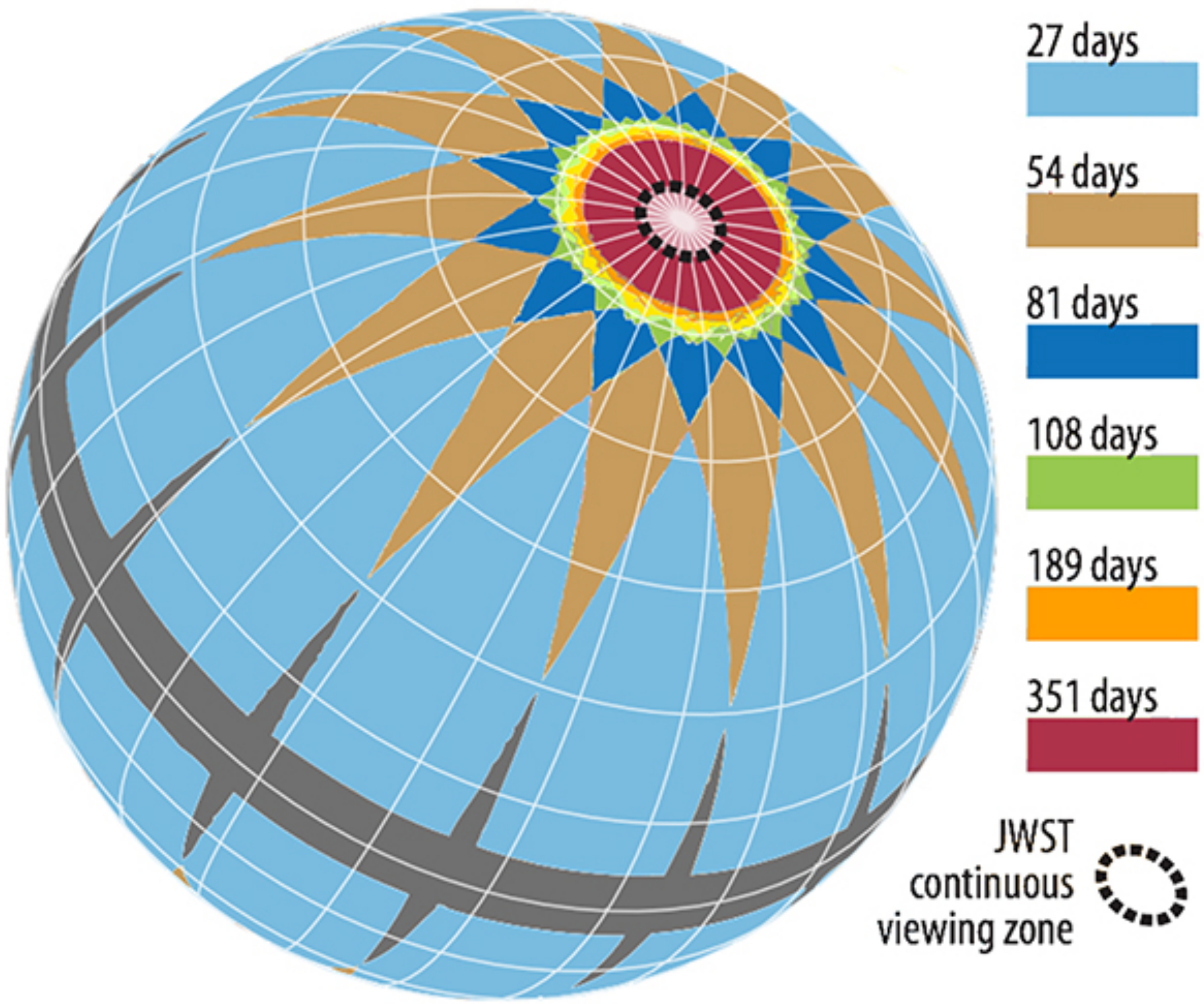
Roadmap for the discovery and characterization of potentially habitable exoplanets:

TESS (2017) - 6.5 m JWST (2018) - the three ELTs (mid-2020?)





Roadmap for the discovery and characterization of potentially habitable exoplanets:

TESS (2017)

- will discover hundreds of transiting super-Earths (exoplanets with radii 1-2 Earths)

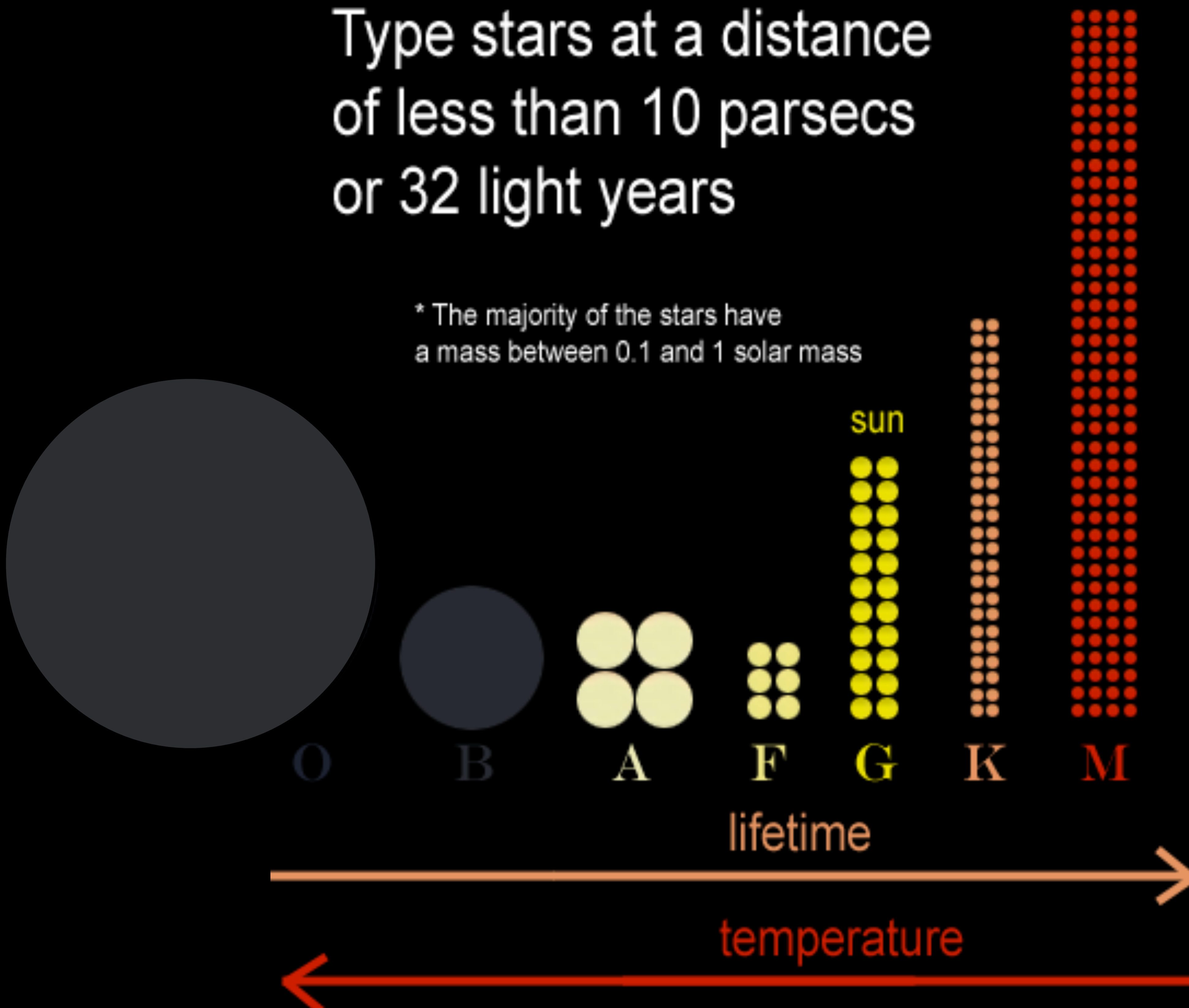
- most of them with orbital periods < 20 days

- most of them around relatively "bright" planet host stars

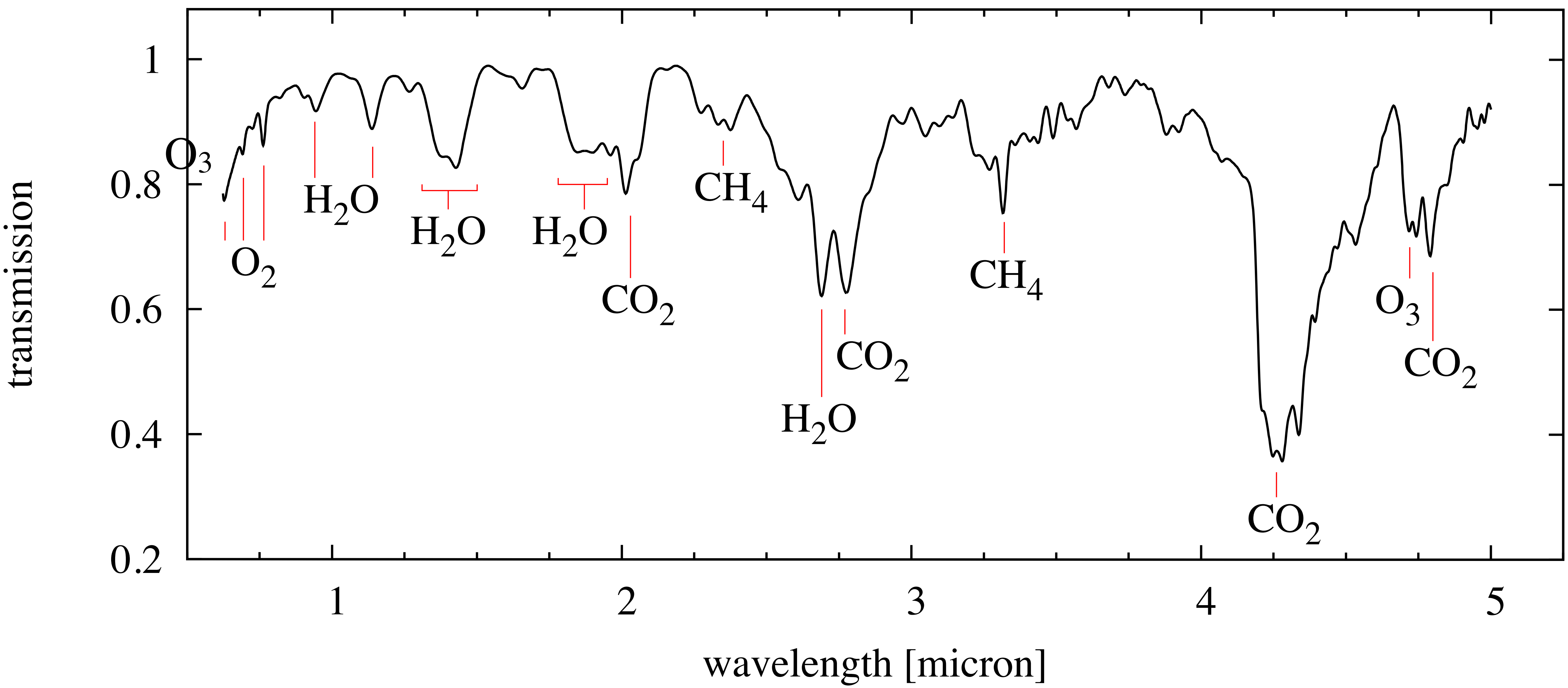
- **planets around cool M-dwarfs will be potentially habitable**

Type stars at a distance of less than 10 parsecs or 32 light years

* The majority of the stars have a mass between 0.1 and 1 solar mass



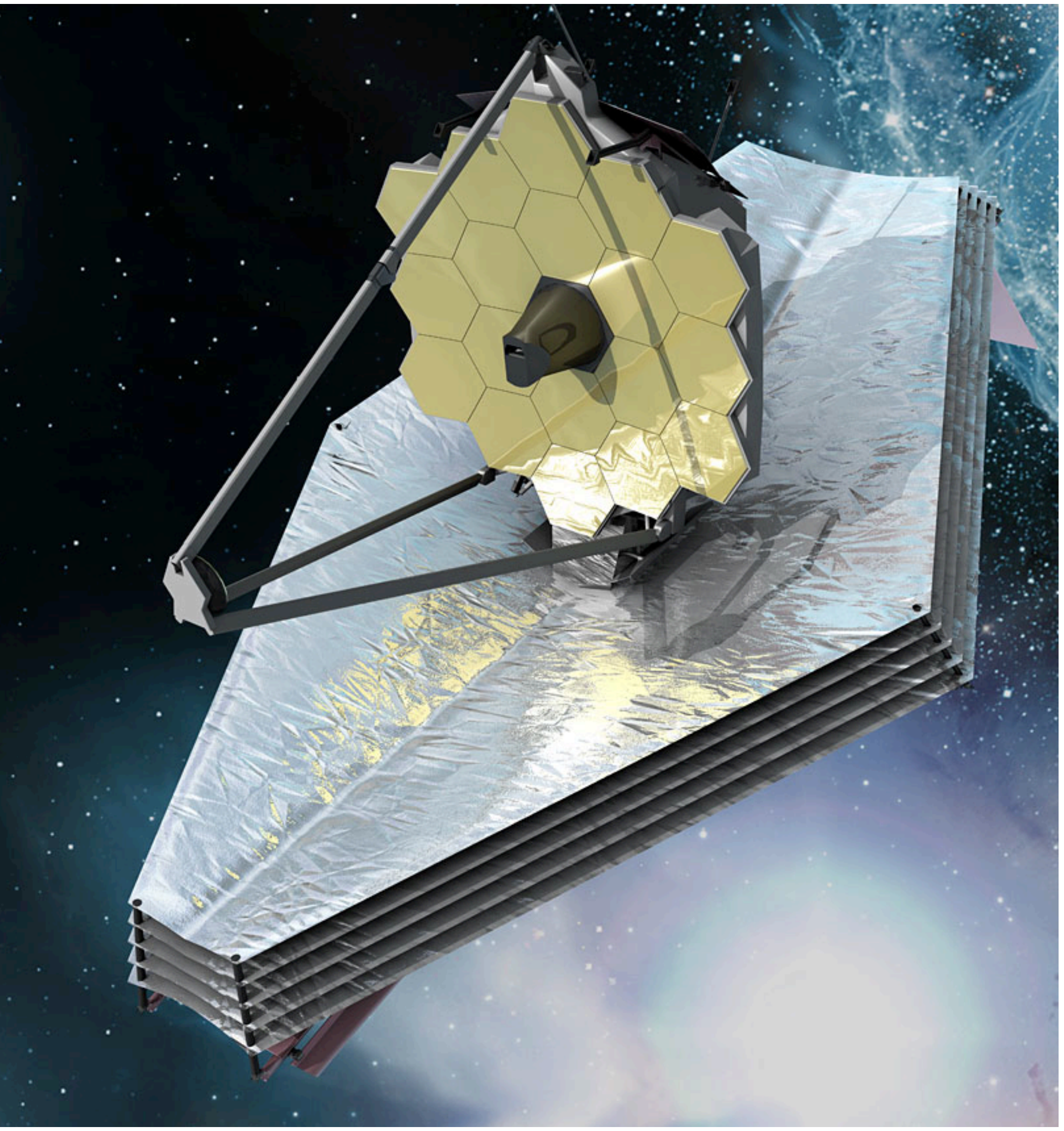
Transmission spectrum of Earth seen by some aliens ...



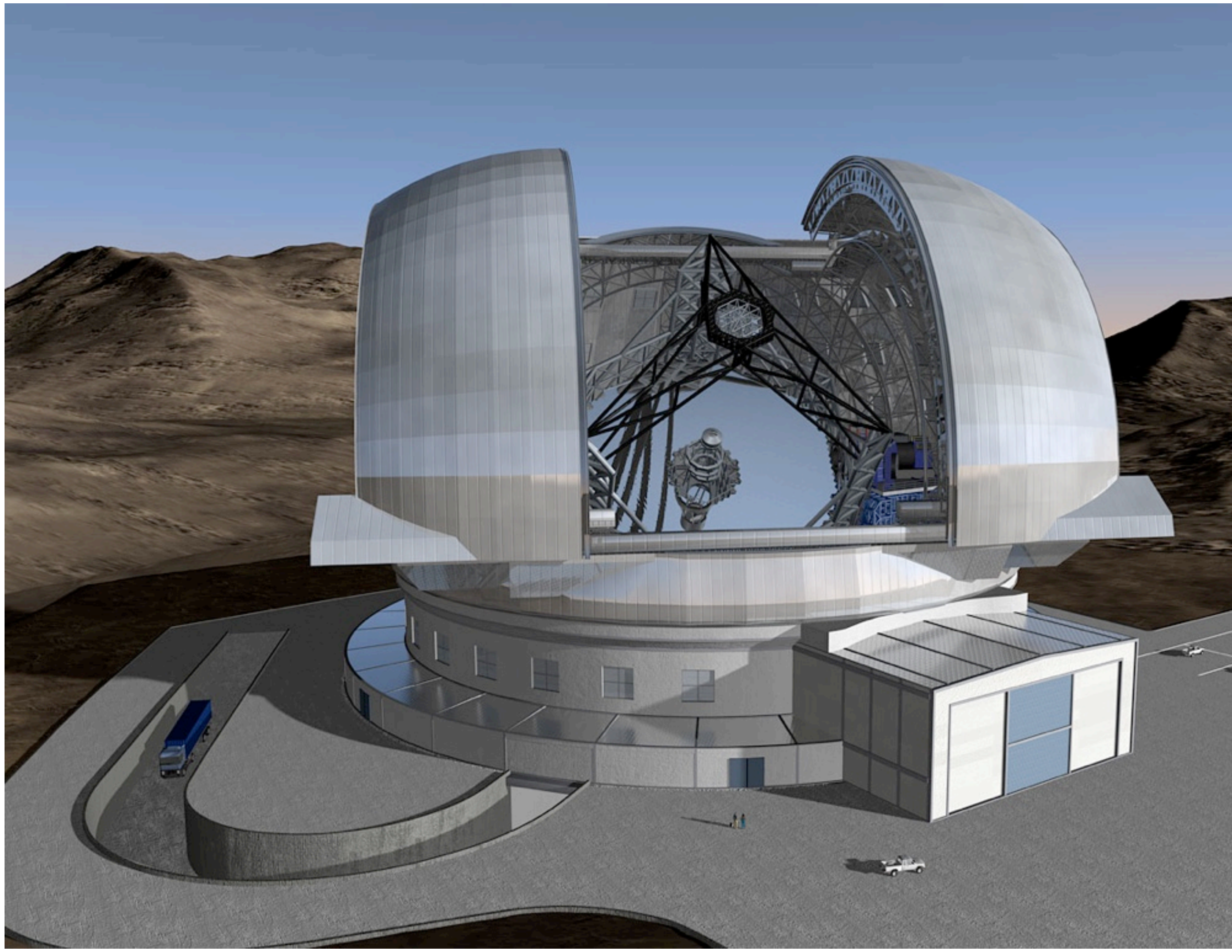
? **How much time would we need to observe oxygen in the atmosphere of a rocky super-Earth (1.5 Earth radii) orbiting an M-dwarf star?** ?

What telescope/instrument/setup is most efficient to detect oxygen?

- carry out feasibility studies for the **JWST** and the 39m **E-ELT**



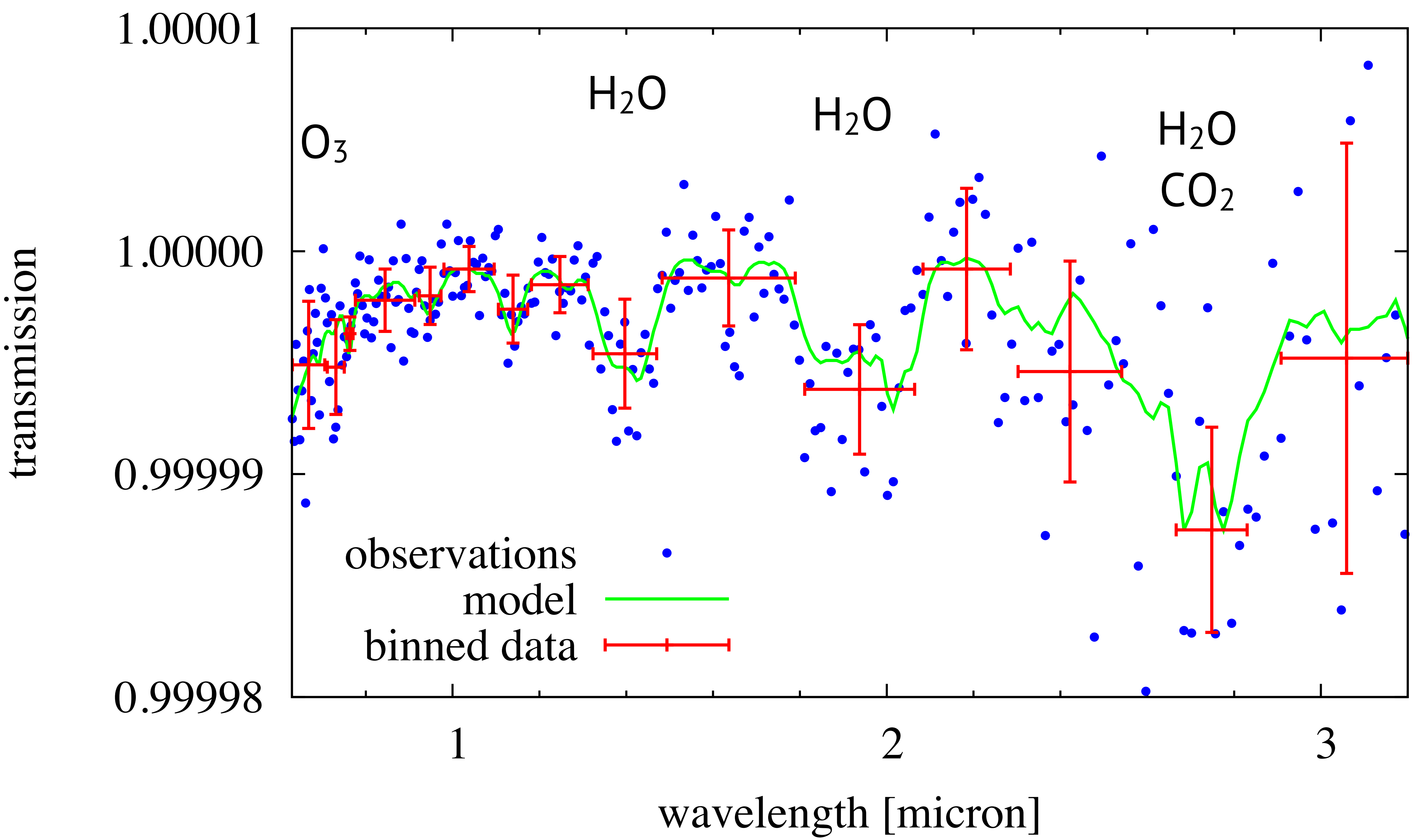
JWST, 2018



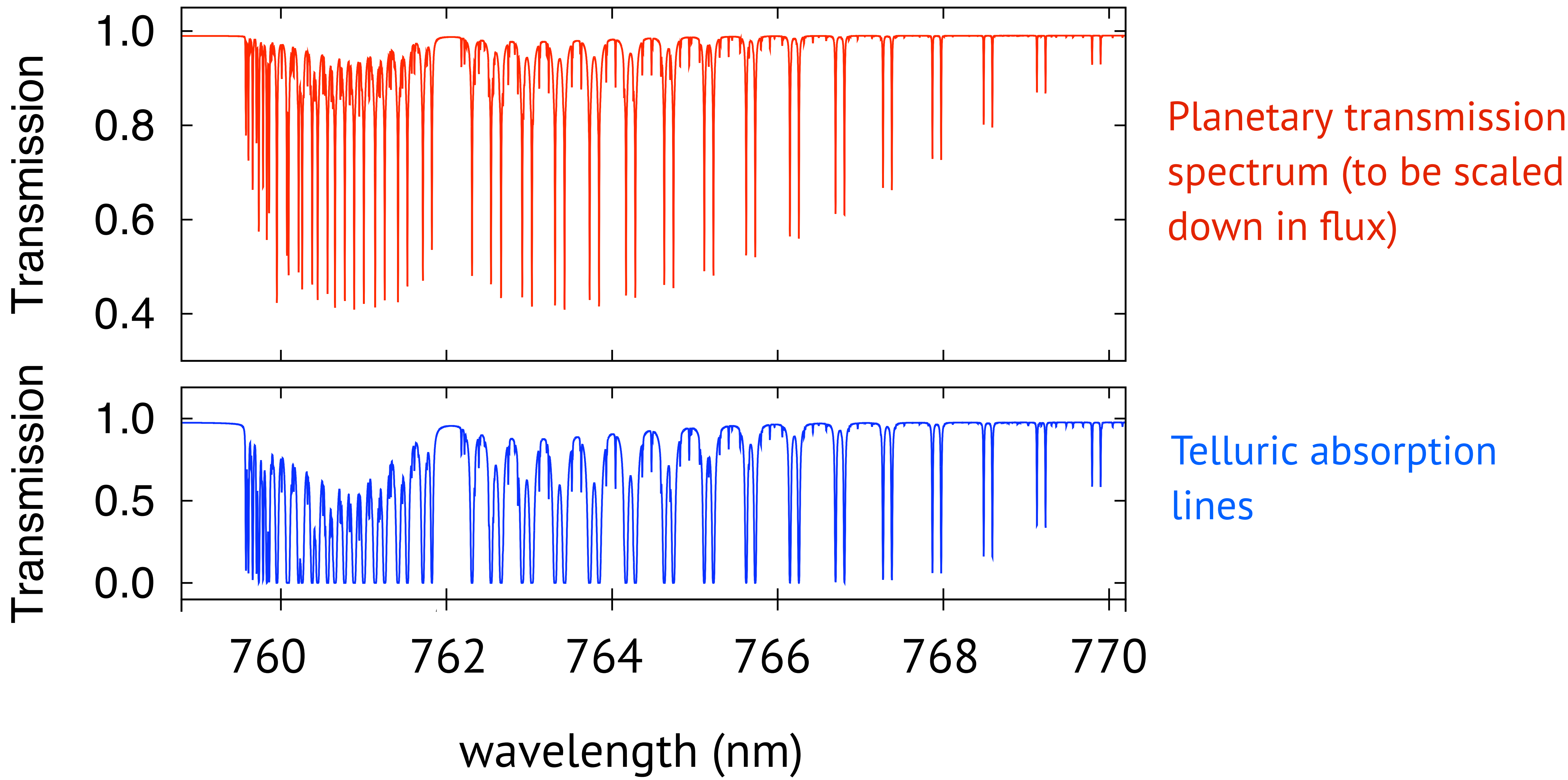
E-ELT, 2025+

150 hours with JWST (transmission spectroscopy, low-res) ...

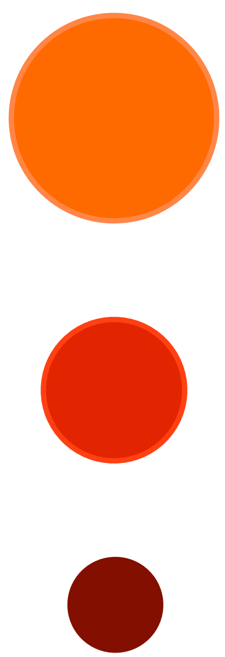
... and still **no** oxygen. Instead hints for water, CO_2 and ozone absorption.



The O_2 band around 760 nm (R = 100k)



Observing time needed to attain a 3σ detection with the 39m E-ELT …



	area ratio	M_I	P (days)	transit duration (h)	number transits	**on target hours**
M1V	85000	7.7	43	4.0	14	**~56**
M2V	67000	8.3	33	3.4	16	**~54**
M3V	53000	8.8	27	3.0	16	**~48**
M4V	30000	10.0	16	2.1	12	**~25**
M5V	14000	11.2	10	1.5	18	**~27**
M6V	8000	12.4	6	1.1	26	**~29**

… at a distance of 5 pc (16 ly)

Conclusions

- detection of O_2 in the atmosphere of a super-Earth is feasible with the E-ELT in 25+ hours.

- most suitable for M4V at < 8 pc.

- with JWST we won't be able to measure O_2 in the atmosphere of a super-Earth.

- JWST will allow us to measure water, ozone and CO_2 therein

Check out literature:

Rodler + López-Morales (2014), Snellen+ (2013), Kaltenegger + Traub (2009)