Les grandes missions spatiales

Au delà du système solaire : les exoplanètes

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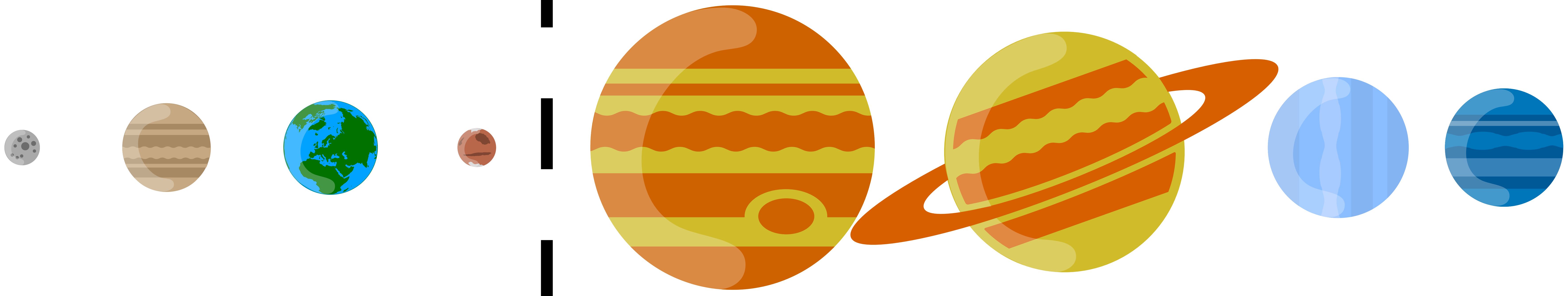
University of Geneva

https://mediaserver.unige.ch/play/161259
Utilisateur: 10A001_2021
Mot de masse: astro2021

Tour around the solar system

Telluric planets

Gas giants



Densities ranging from:
~3900 kg.m^{-3} (Mars)
to ~5500 kg.m^{-3} (Earth)

Densities ranging from:
~730 kg.m^{-3} (Saturn)
to ~1600 kg.m^{-3} (Neptune)

Tour around the solar system

Quelles sont les méthodes de détections des exoplanètes ?

NASA APOD 01/08/2012

Discovering and characterizing exoplanets

1) **Radial Velocities:** The historical method

2) **Transit:** The most prolific method

3) **Imaging:** The most natural method

4) **Astrometry:** The unsuccessful method (so far…)

5) **Microlensing:** The once-in-a-lifetime method

Discovering and characterizing exoplanets

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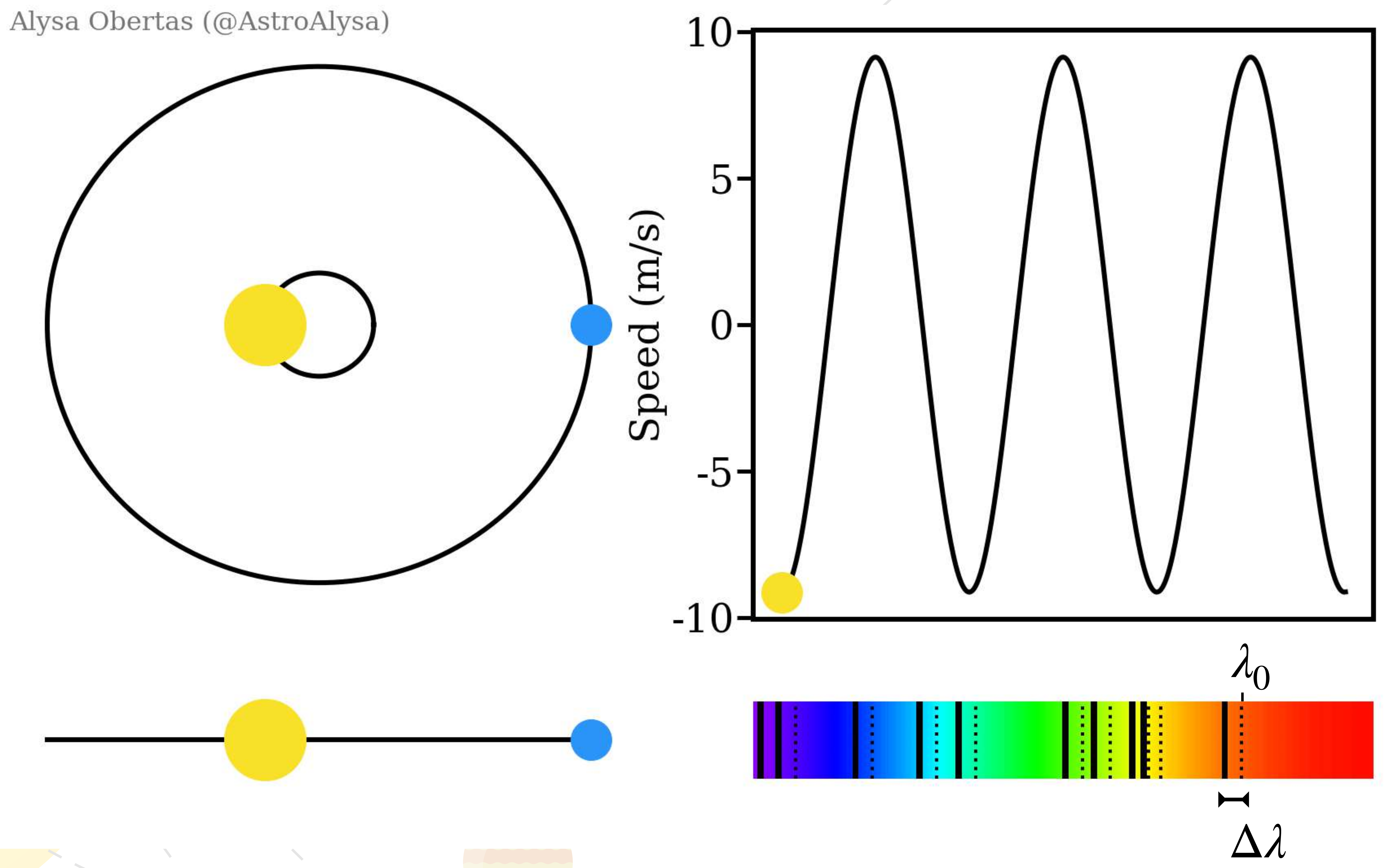
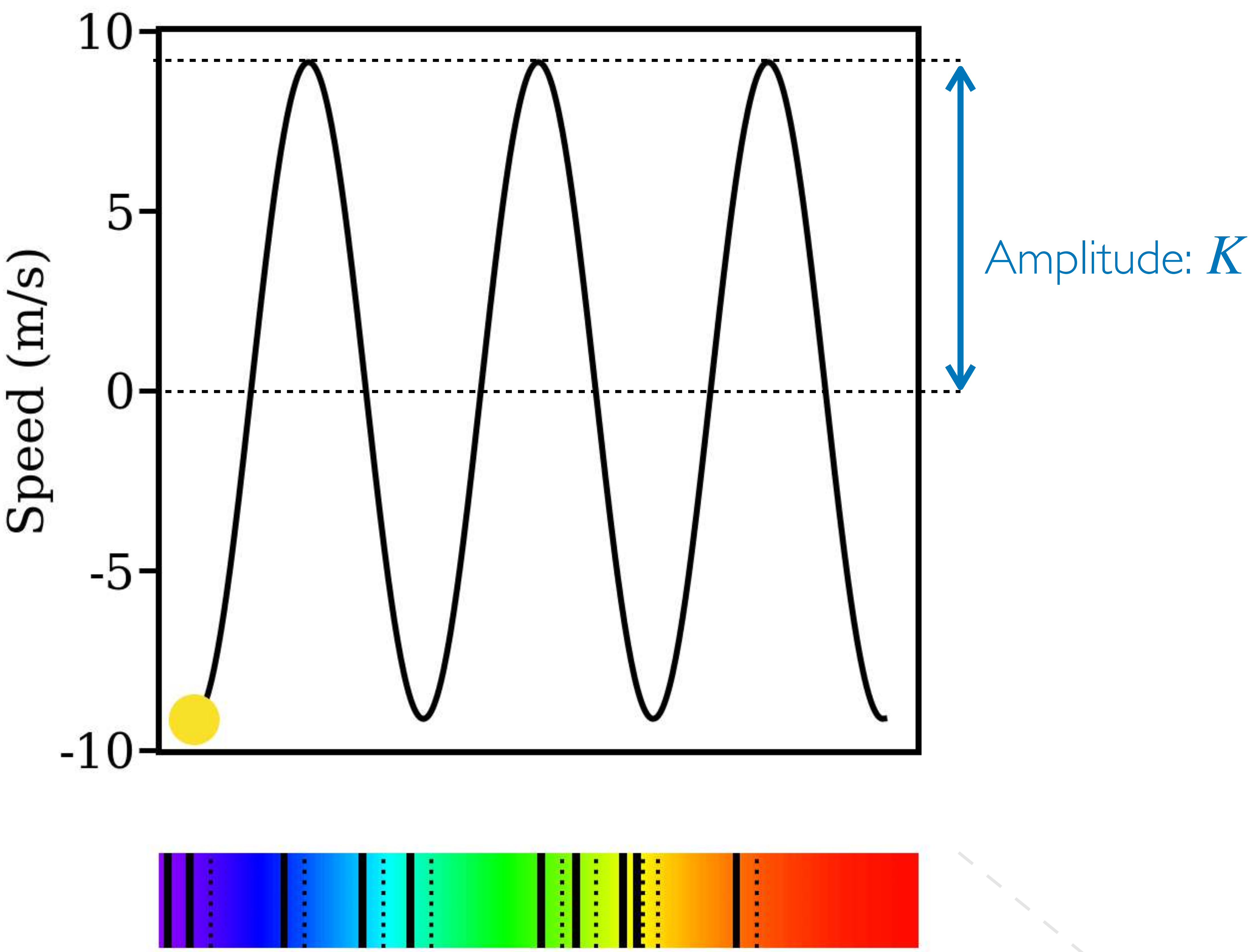
Radial velocities: the historical method



In practice, to measure the **radial velocity of a star**, we measure the **Doppler shift:** $z = \dfrac{\Delta\lambda}{\lambda_0} = \dfrac{v_\star}{c}$

Radial velocities: the historical method



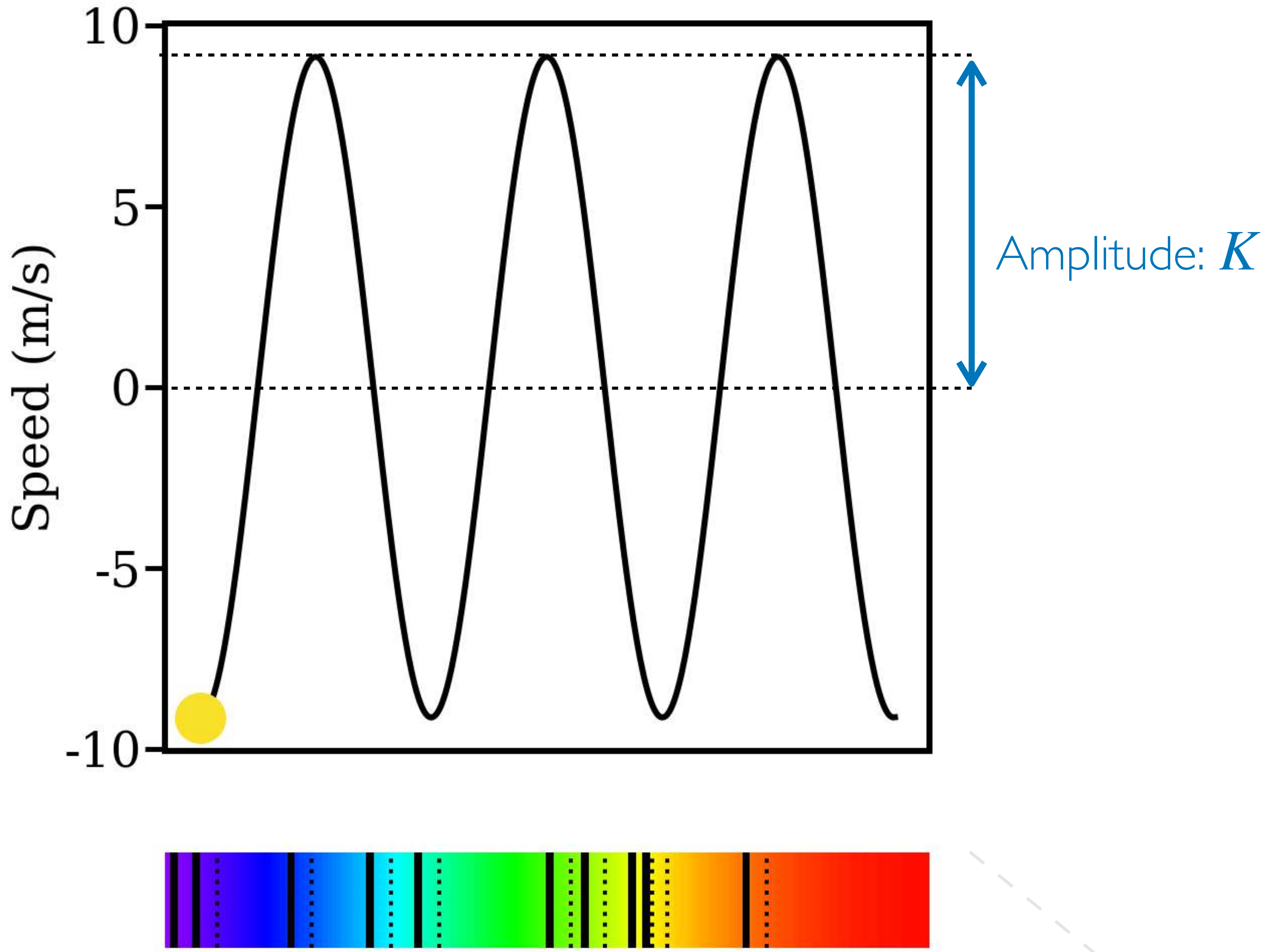
Masse minimale de la planète

$$K = (m_1 \sin i)\ m_0^{-2/3}(2\pi G)^{1/3} P^{-1/3}$$

Masse de l'étoile

Période orbitale de la planète

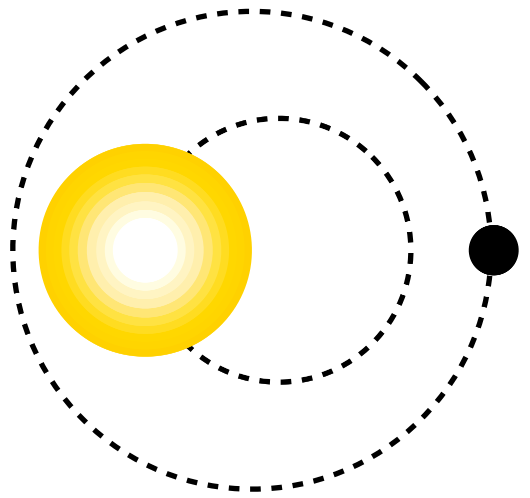
Radial velocities: the historical method



$$K = (m_1 \sin i)\ m_0^{-2/3}(2\pi G)^{1/3}P^{-1/3}$$

Quelques ordres de grandeur

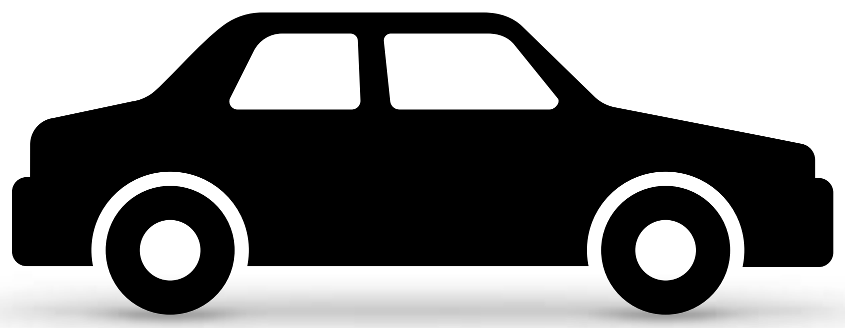
PollEv.com/emelinebolmo830



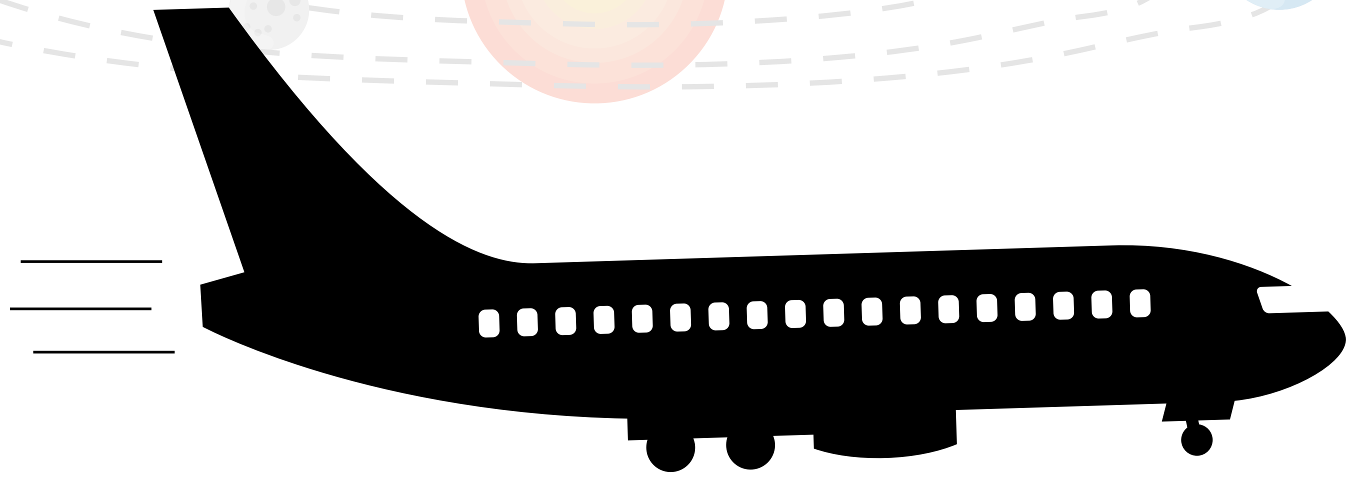
Radial velocities: the historical method

The **Earth** leads to a velocity for the Sun of **9 cm/s = 0.3 km/h**

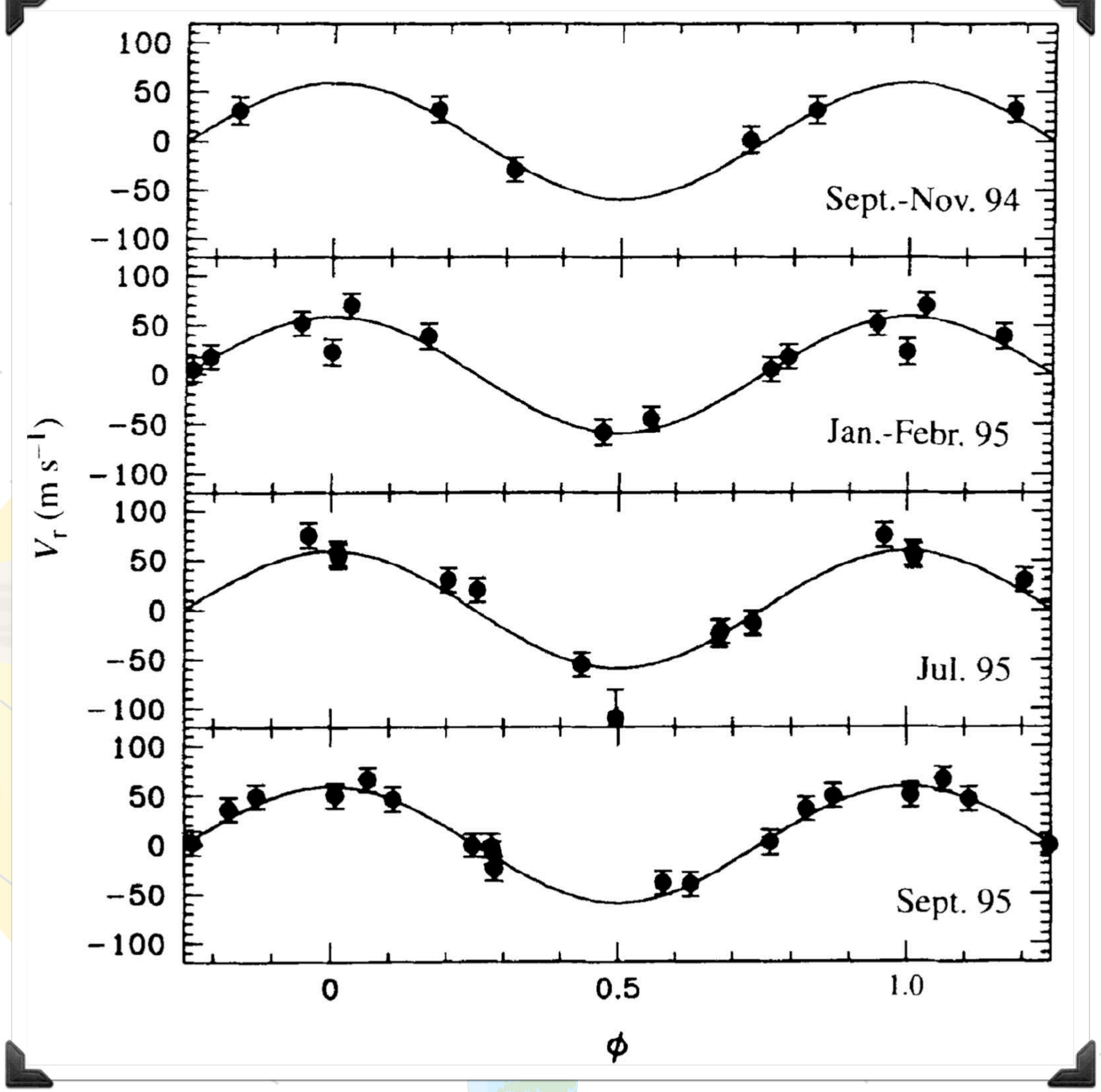
Jupiter leads to a velocity for the Sun of **12.5 m/s = 45 km/h**



A **hot Jupiter** at 0.01 AU leads to a velocity for the Sun of **285 m/s = 1026 km/h**



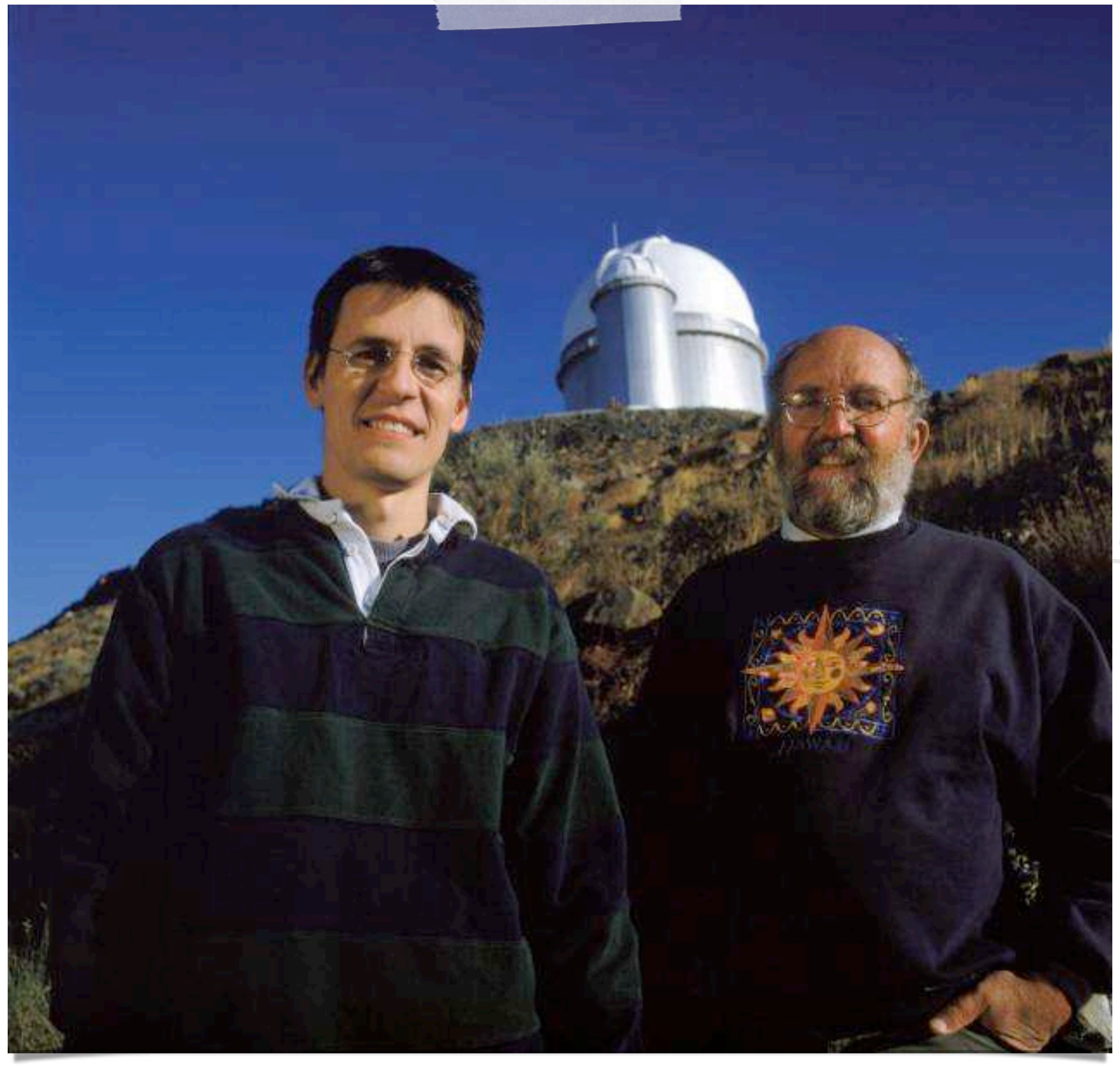
Radial velocities: the historical method



Data from **ELODIE** on the 1.93m telescope at Observatoire de Haute Provence

51 Pegasi b

The first exoplanet detected with the **radial velocity method** *[Mayor & Queloz 1995]*

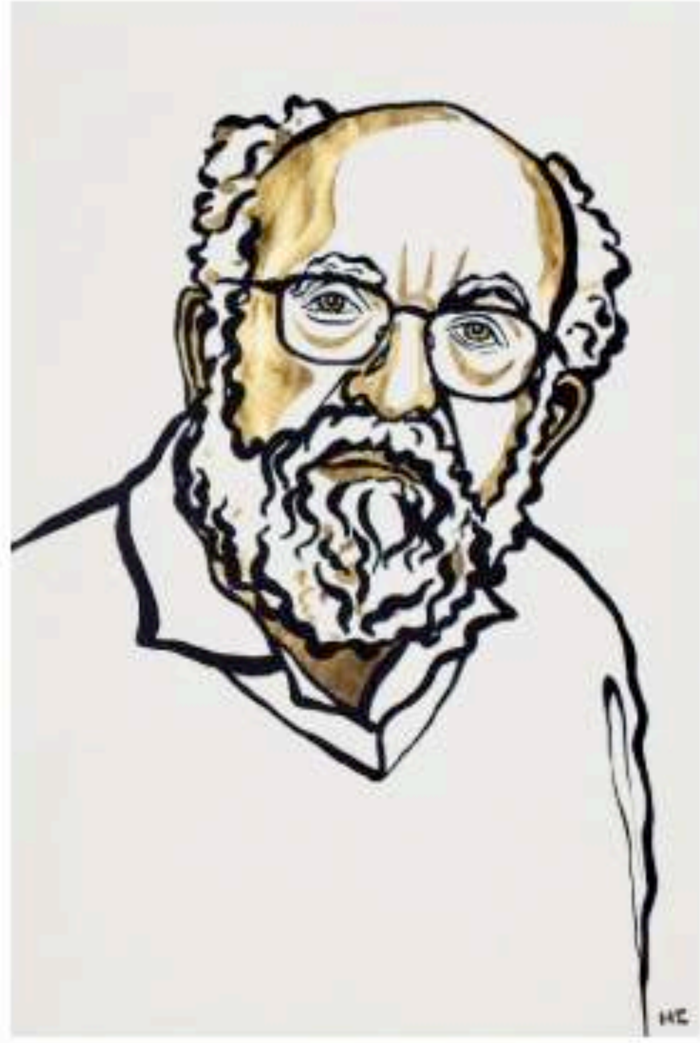


The Nobel Prize in Physics 2019

Ill. Niklas Elmedhed. © Nobel Media.

James Peebles

Prize share: 1/2



Ill. Niklas Elmedhed. © Nobel Media.

Michel Mayor

Prize share: 1/4

Ill. Niklas Elmedhed. © Nobel Media.

Didier Queloz

Prize share: 1/4

The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

UNIVERSITÉ DE GENÈVE

PRESS RELEASE

Geneva | October 8th, 2019

The 2019 Nobel Prize in Physics awarded to Michel Mayor and Didier Queloz

Professors Michel Mayor and Didier Queloz were awarded the 2019 Nobel Prize in Physics for their discovery of the first exoplanet in 1995. They have made UNIGE a global centre of expertise in this field.

© UNIGE

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Michel Mayor (picture on top), Honorary Professor of the Faculty of Science of the UNIGE. Didier Queloz, Professor in the Department of Astronomy of the Faculty of Science of the UNIGE and Professor at the University of Cambridge.

High definition pictures

On October 6, 1995, Michel Mayor, Professor at the Observatory of the Faculty of Science of the University of Geneva (UNIGE), Switzerland, and his doctoral student Didier Queloz revolutionized the world of astrophysics when they announced the discovery of the first planet located outside our solar system. Named *51 Pegasi b*, this very first exoplanet had a huge impact on the astrophysicist community. Since then, research has continued to develop, allowing for the subsequent discovery of about 2000 exoplanets so far.

"It is a fantastic recognition of the task accomplished by Michel Mayor and Didier Queloz; it shows the rigour of their scientific approach, but also their creativity and ability to think – and work – outside the box, a true pathway to great discoveries. This Nobel prize also comes as an honour for our University, for Geneva and for the whole of Switzerland, as a recognition of the quality of its research being rewarded at the highest level," says Yves Flückiger, Rector of the UNIGE.

A brief look back

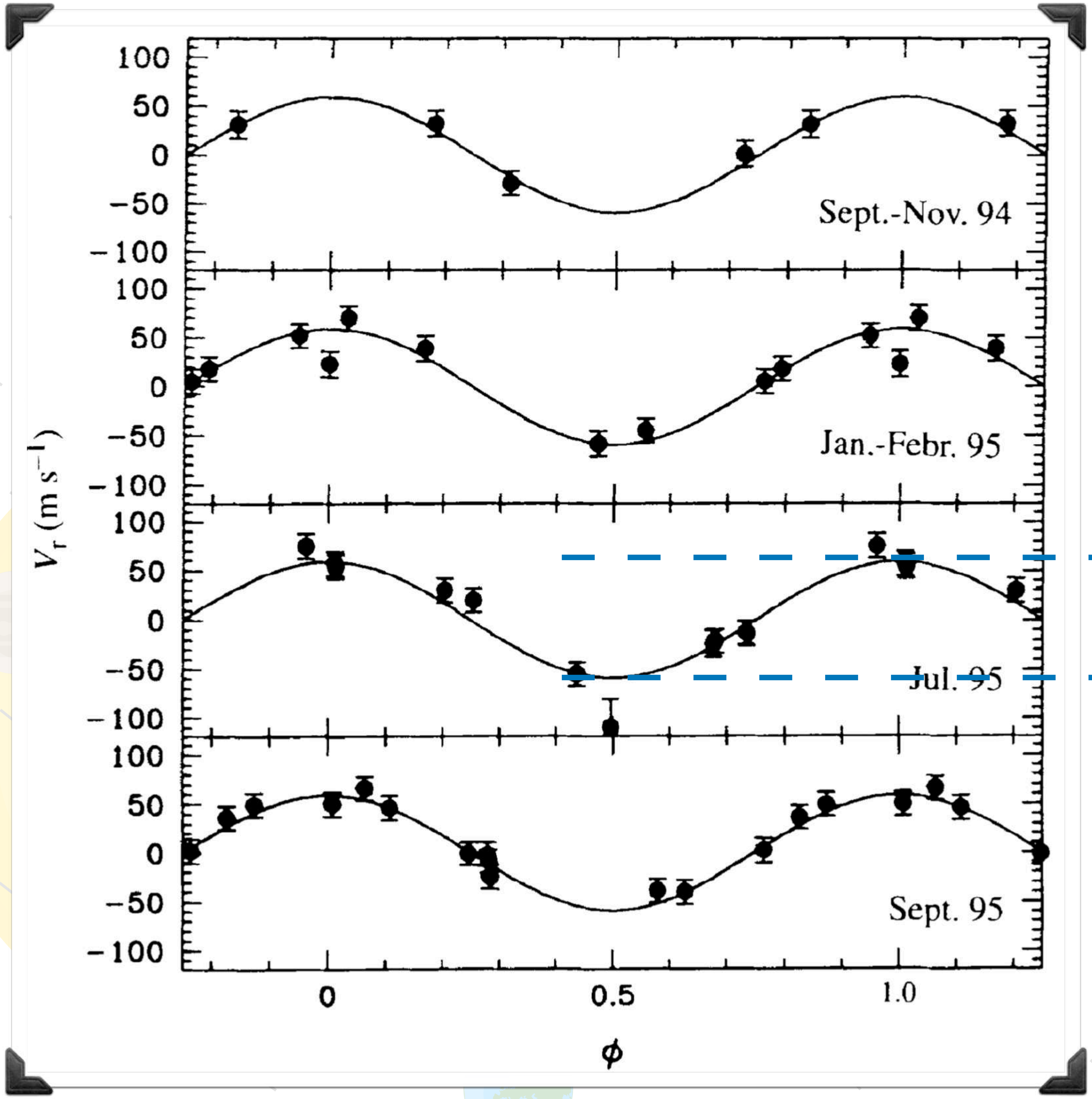
24 years ago, Michel Mayor and Didier Queloz attended a scientific conference in Florence to announce the discovery of the first planet outside the solar system: *51 Pegasi B*. "No one knew whether exoplanets existed or not," recalls Michel Mayor. For years prestigious astronomers had been looking for them in vain! "Indeed, the technologies to enable such a discovery did not exist at the time and it was necessary to wait for the Elodie spectrograph (alias super-Coravel), put into service in 1993 on a 2m diameter telescope in Haute-Provence. Thanks to the accuracy of its measurements (15m/s), Michel Mayor and Didier Queloz spotted a stellar object in 1994 that circled his star in 4.2 days. "We were so excited to have found an exoplanet, says Didier Queloz. But first we had to confirm our observations before we could reveal anything." In July 1995, the two astrophysicists no longer had any doubt: they have just discovered the first exoplanet!

"This discovery is the most exciting of our entire career, and to be awarded a Nobel Prize is simply extraordinary," say Michel Mayor and Didier Queloz.

Is life hiding on exoplanets?

Current tools – such as the CHEOPS satellite or the new ESPRESSO spectrograph built in Geneva and installed on the ESO Very Large Telescope in Chile – open up new perspectives in the hunt for exoplanets. The next step is to closely analyse these planetary systems, including their origin, evolution and physical and chemical characteri-

Radial velocities: the historical method



Data from **ELODIE** on the 1.93m telescope at Observatoire de Haute Provence

51 Pegasus b

The first exoplanet detected with the **radial velocity method** *[Mayor & Queloz 1995]*

Orbital period: $P \approx 4.2$ day

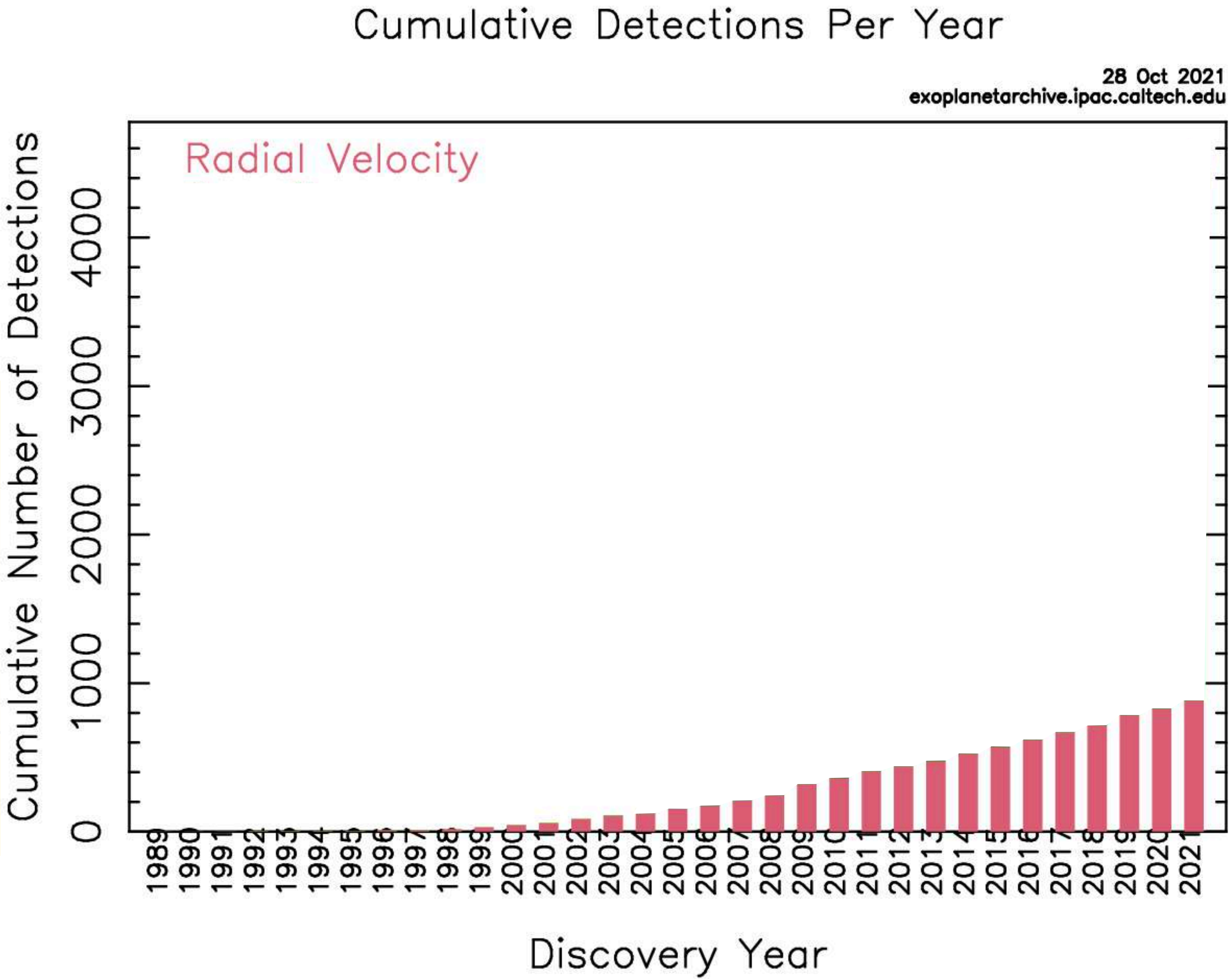
Solar mass: $M_\star \approx 1\ M_\odot$

Amplitude: $2K \approx 120$ m/s

$$K = (M_p \sin i)\ M_\star^{-2/3} (2\pi G)^{1/3} P^{-1/3}$$

The **minimal mass** of **51 Peg b** is $M_p \sin i \approx 0.47\ M_{\rm jup}$

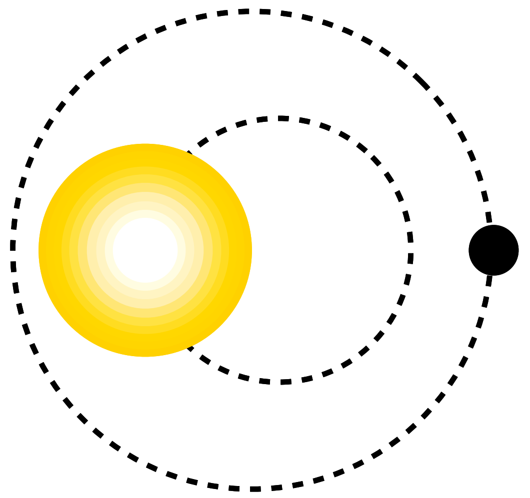
Radial velocities: the historical method

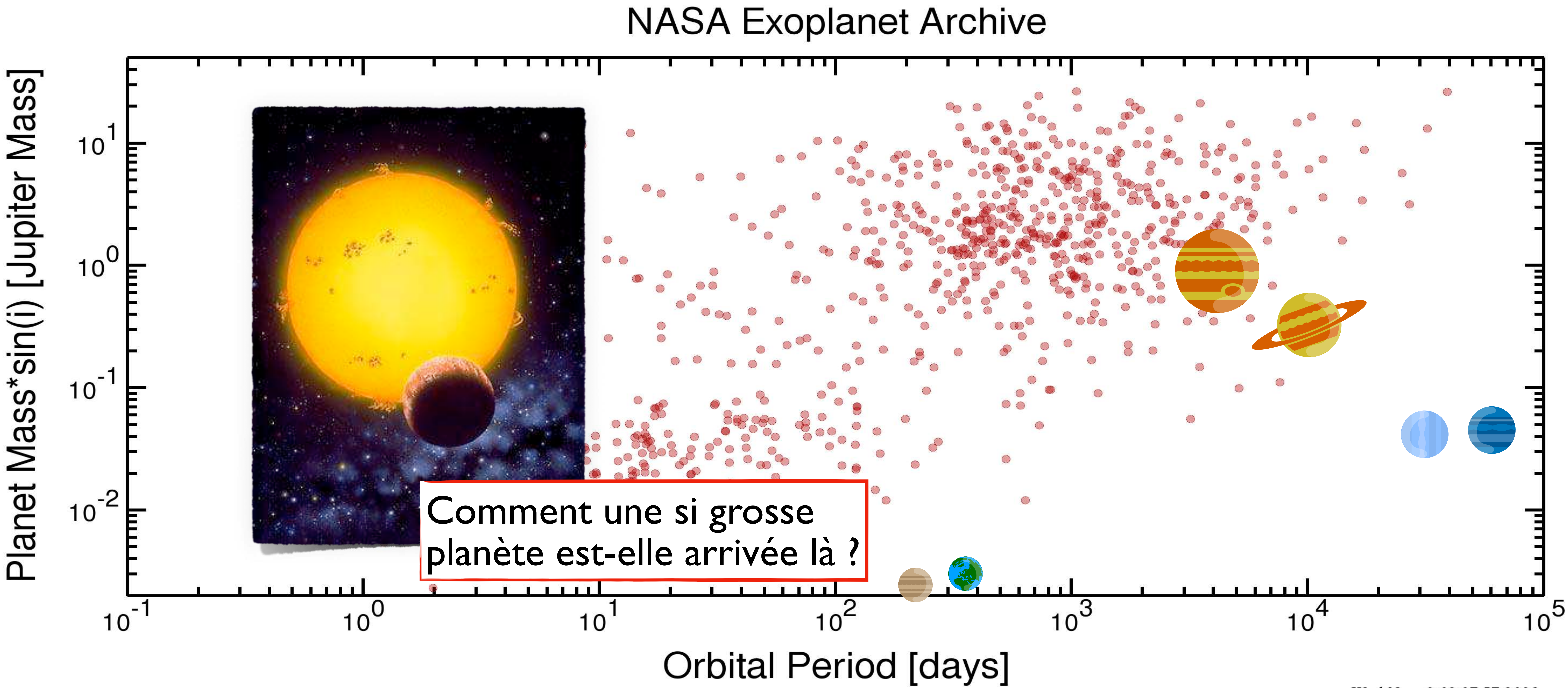


Instruments (spectrographs)

ELODIE,
HIRES,
UCLES,
CORALIE,
HARPS,
SOPHIE,
BOES,
TRES,
HARPS-N,
SPIRou,
CARMENES,
ESPRESSO,
MAROON-X,
NIRPS…

Radial velocities planets



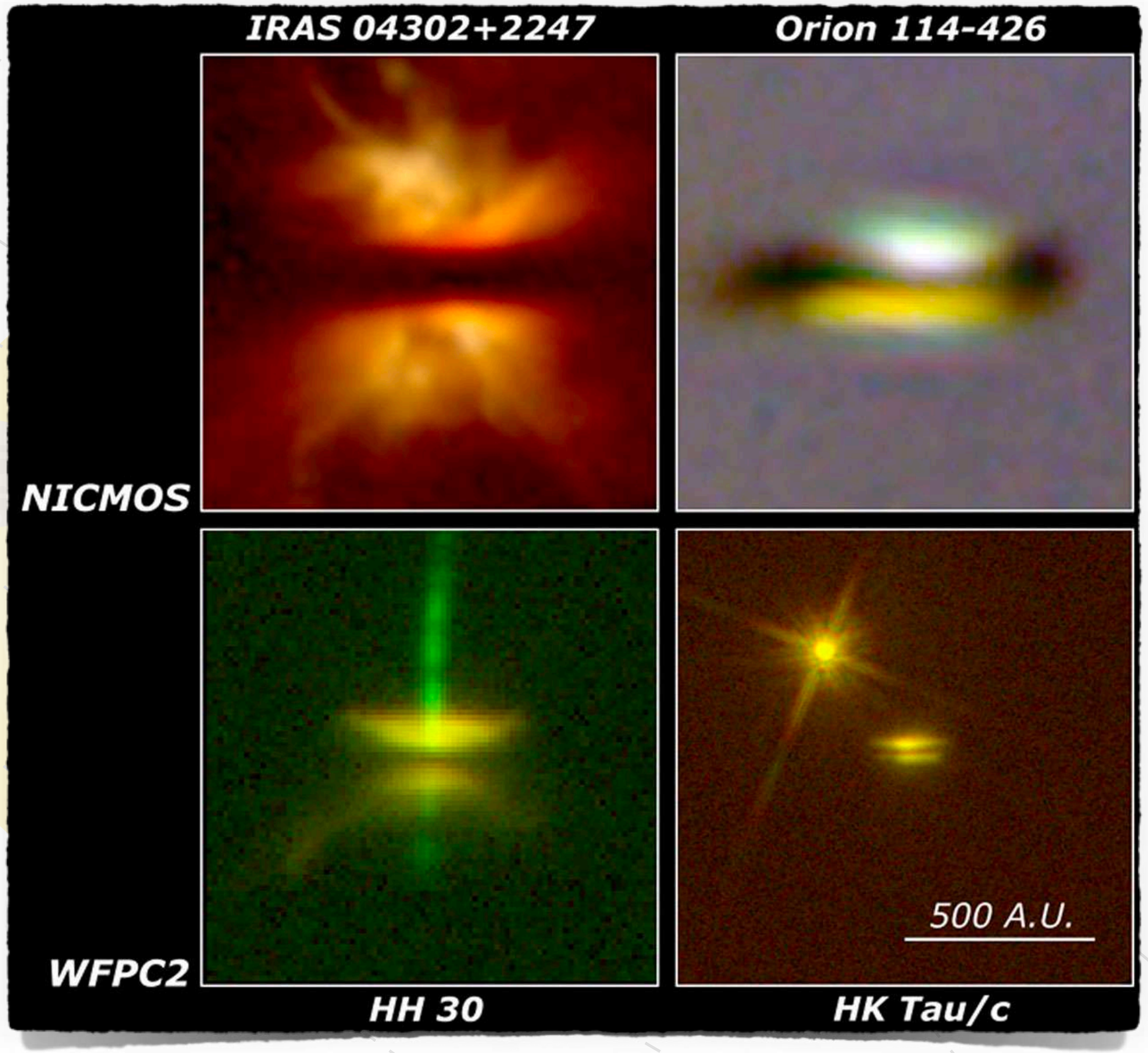


Wed Nov 3 02:07:57 2021

The “hot Jupiters” enigma

The "hot Jupiters" enigma

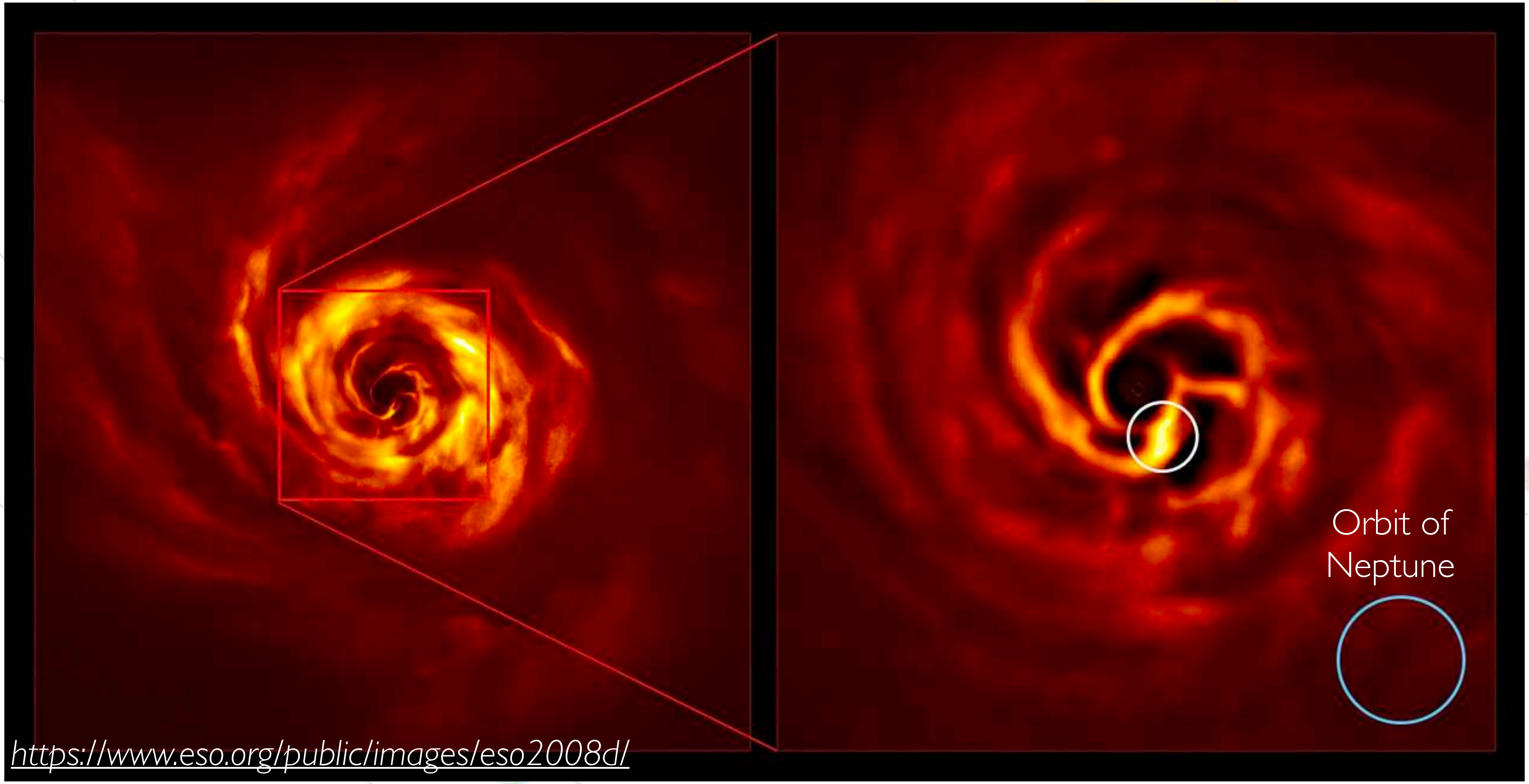
Les planètes naissent dans des disques de gaz et de poussières



Disks around young stars with Hubble

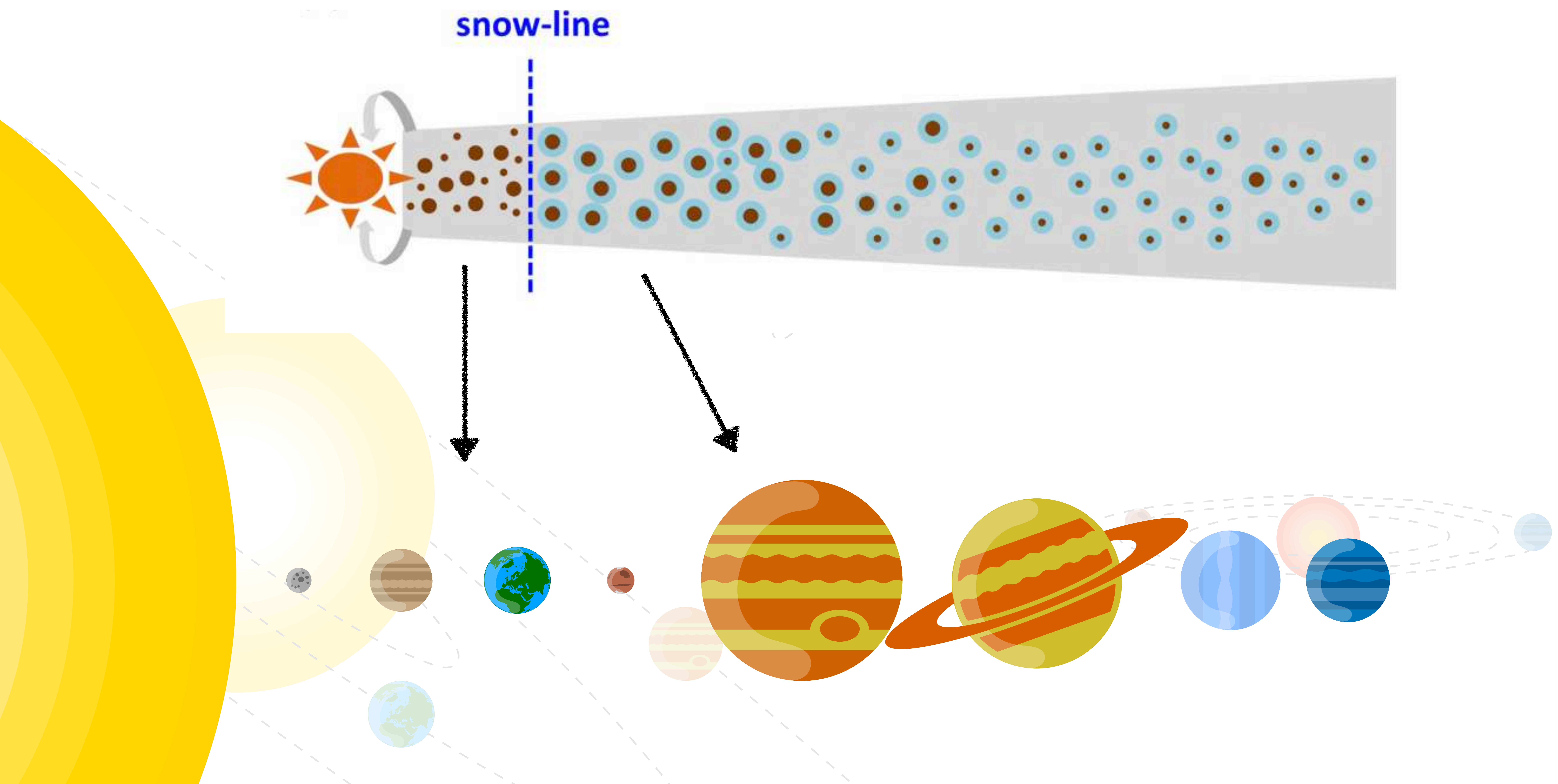
The "hot Jupiters" enigma

SPHERE images of young disks



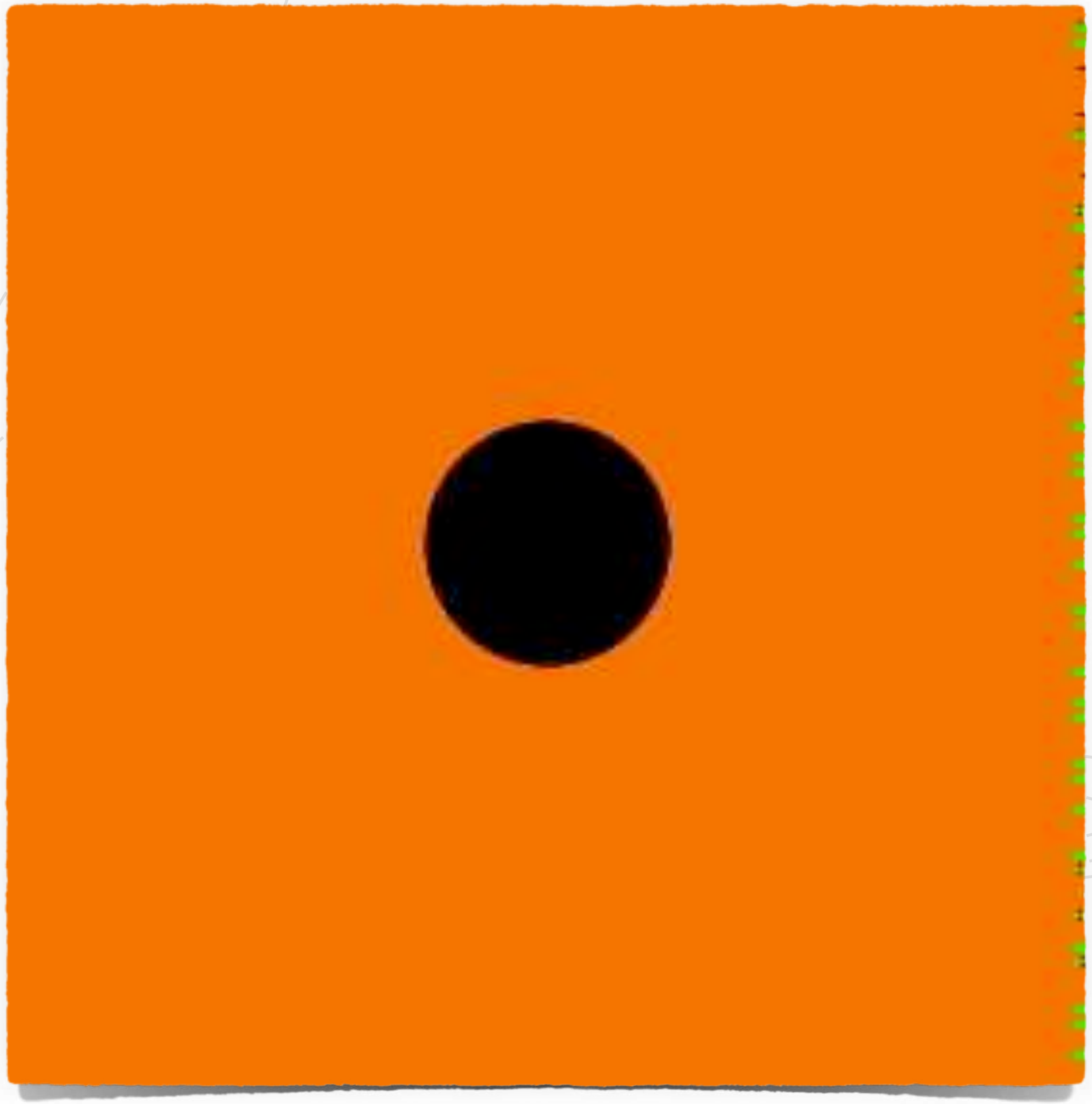
Twist in a **protoplanetary disk** which could be a **sign of planet formation**

The “hot Jupiters” enigma



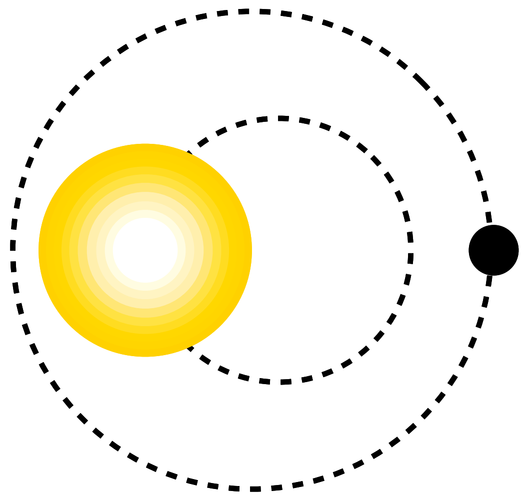
The “hot Jupiters“ enigma

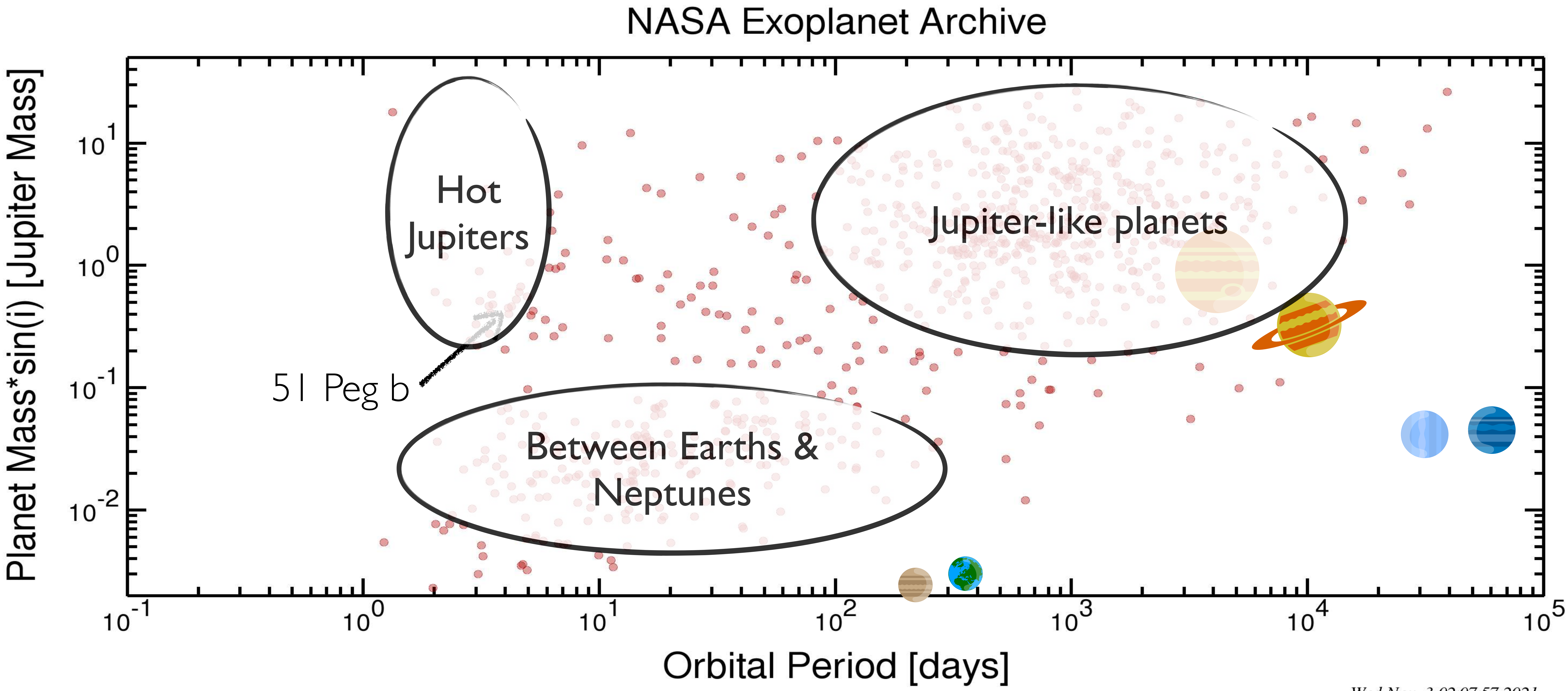
Une planète dans un disque migre !



@Masset (https://www.fis.unam.mx/~masset/moviesmpegs.html)

Radial velocities planets





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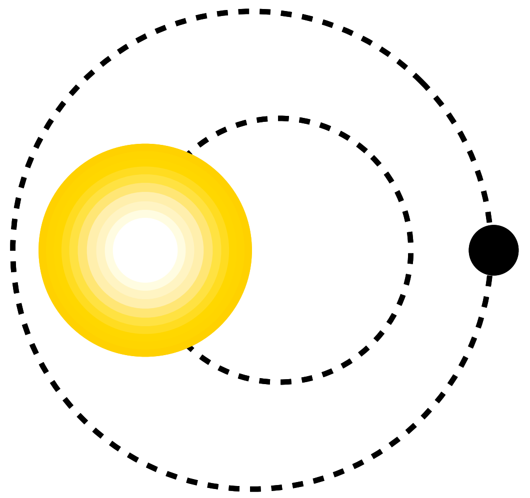
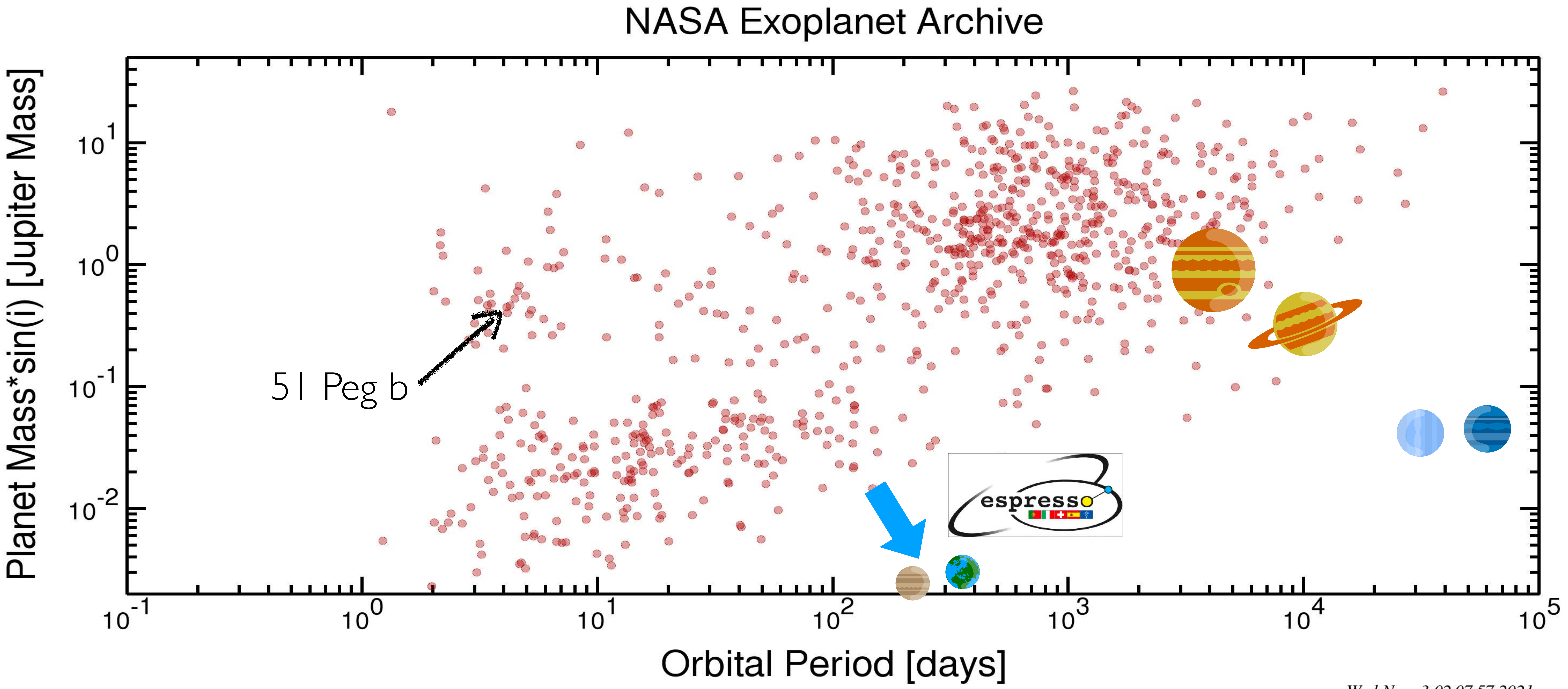
Radial velocities planets





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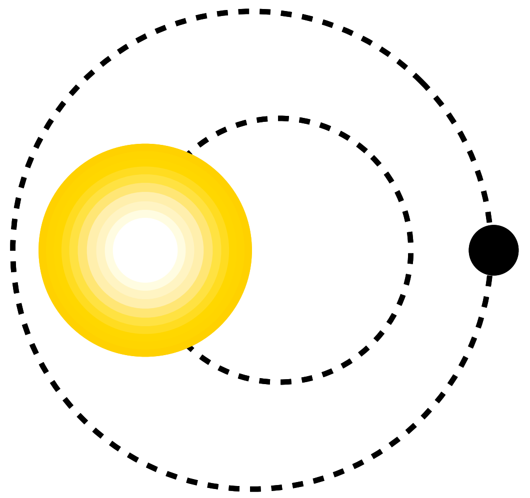
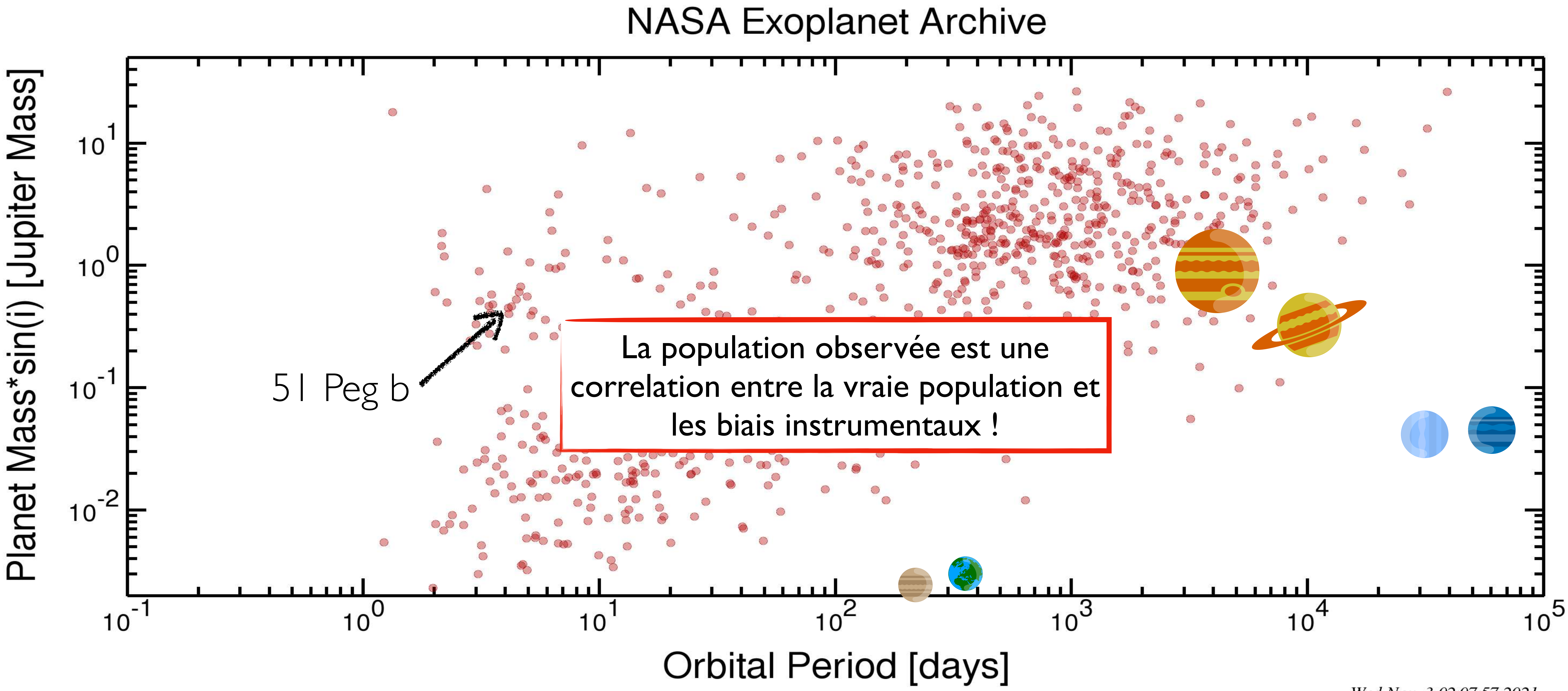


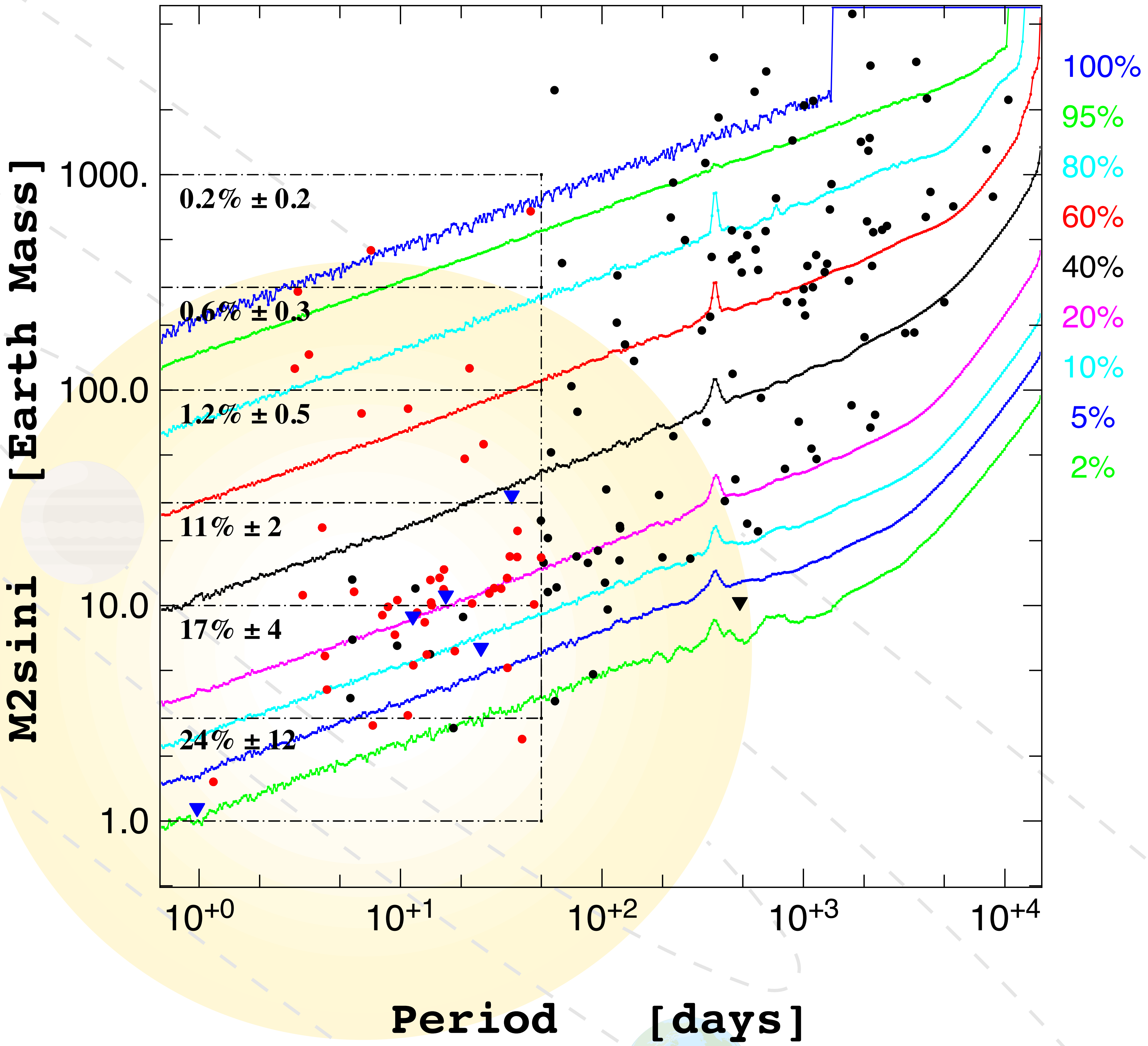
Radial velocities planets



La population observée est une correlation entre la vraie population et les biais instrumentaux !

Wed Nov 3 02:07:57 2021

Radial velocities planets

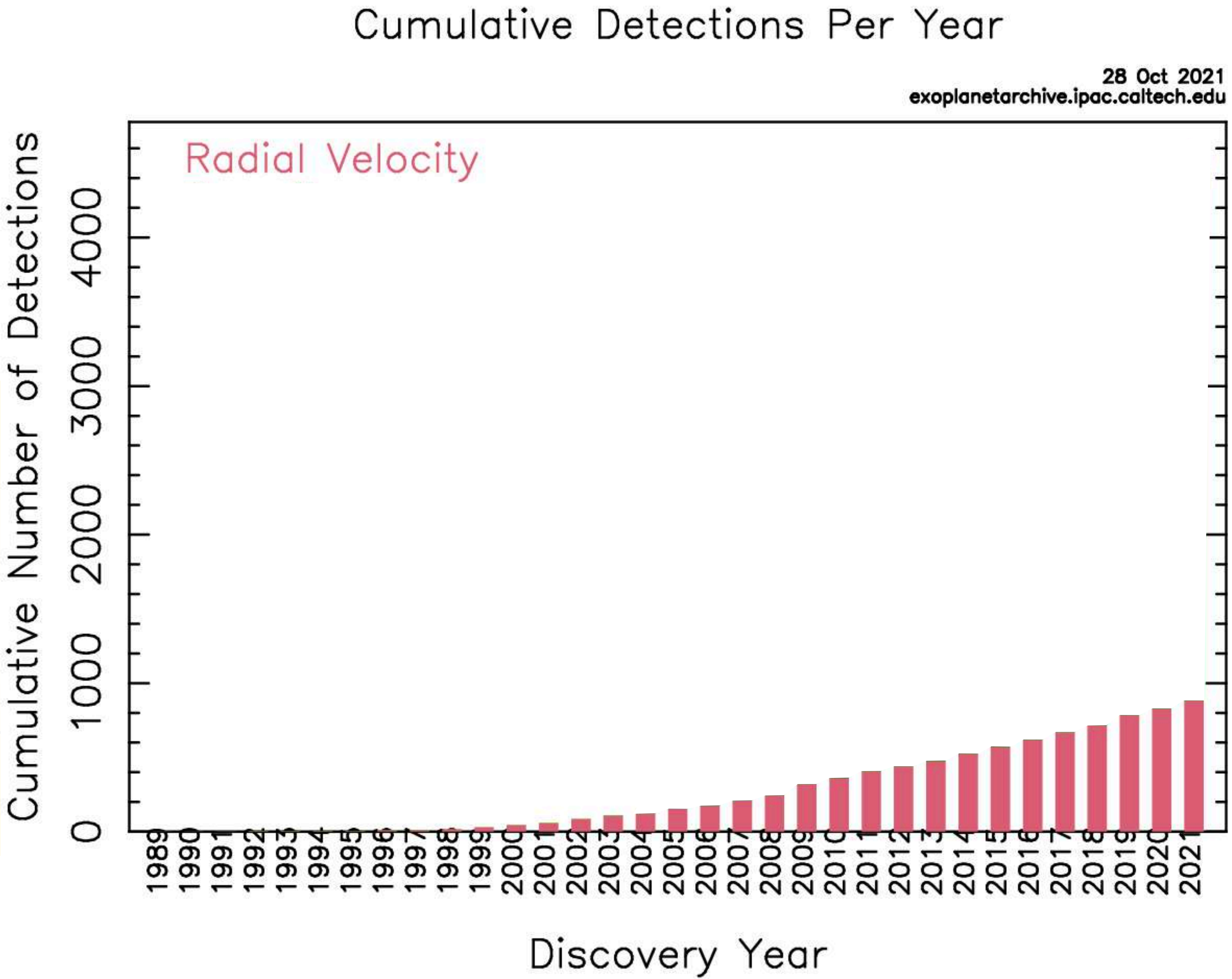


Completeness for HARPS and Coralie surveys

[Mayor+11]

Mass limits	Period limit	Planetary rate based on published planets	Planetary rate including candidates	Comments
$> 50\ M_\oplus$	< 10 years	13.9 ± 1.7 %	13.9 ± 1.7 %	Gaseous giant planets
$> 100\ M_\oplus$	< 10 years	9.7 ± 1.3 %	9.7 ± 1.3 %	Gaseous giant planets
$> 50\ M_\oplus$	< 11 days	0.89 ± 0.36 %	0.89 ± 0.36 %	Hot gaseous giant planets
Any masses	< 10 years	65.2 ± 6.6 %	75.1 ± 7.4 %	All "detectable" planets with $P < 10$ years
Any masses	< 100 days	50.6 ± 7.4 %	57.1 ± 8.0 %	At least 1 planet with $P < 100$ days
Any masses	< 100 days	68.0 ± 11.7 %	68.9 ± 11.6 %	F and G stars only
Any masses	< 100 days	41.1 ± 11.4 %	52.7 ± 13.2 %	K stars only
$< 30\ M_\oplus$	< 100 days	47.9 ± 8.5 %	54.1 ± 9.1 %	Super-Earths and Neptune-mass planets on tight orbits
$< 30\ M_\oplus$	< 50 days	38.8 ± 7.1 %	45.0 ± 7.8 %	As defined in Lovis et al. (2009)

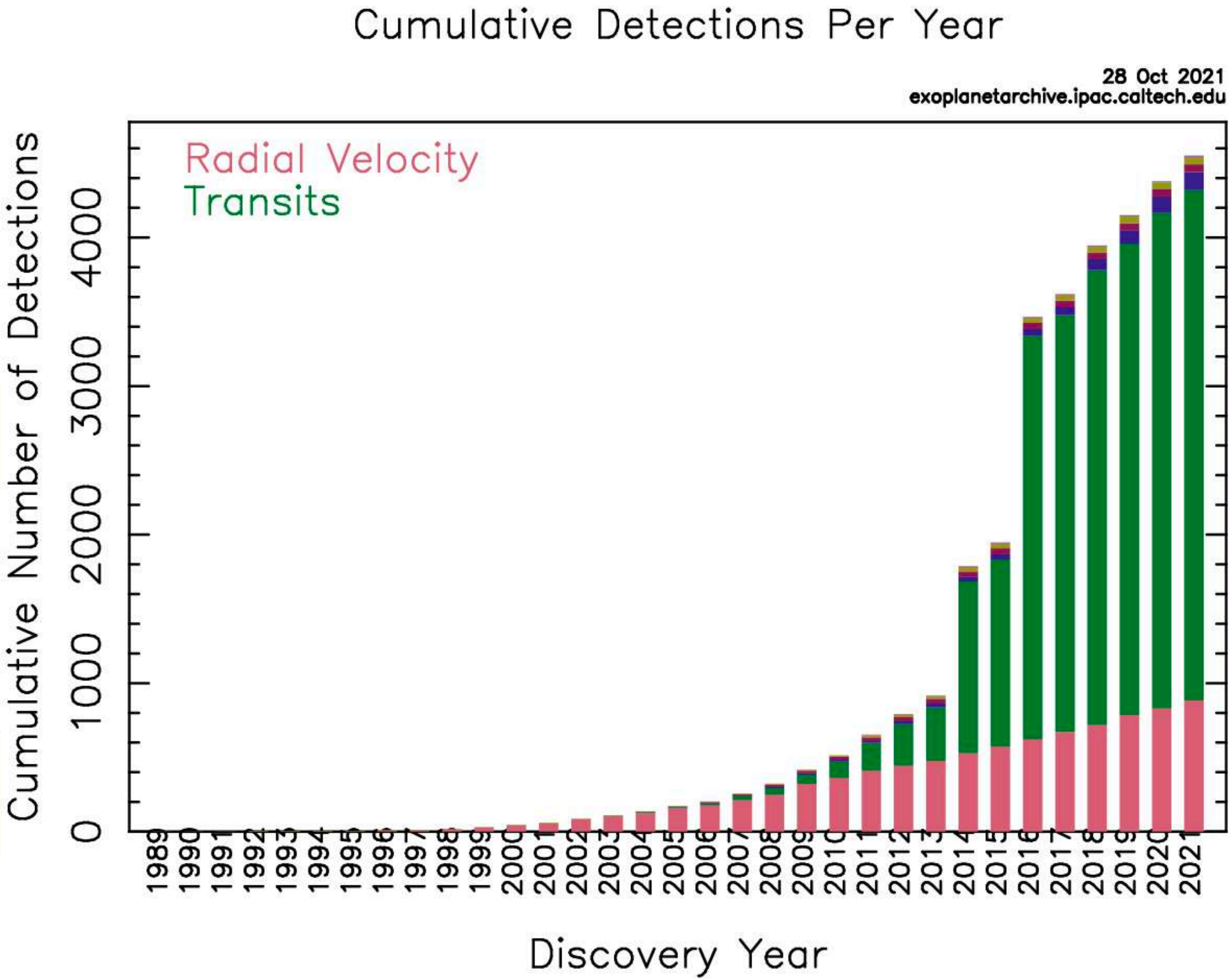
Radial velocities: the historical method



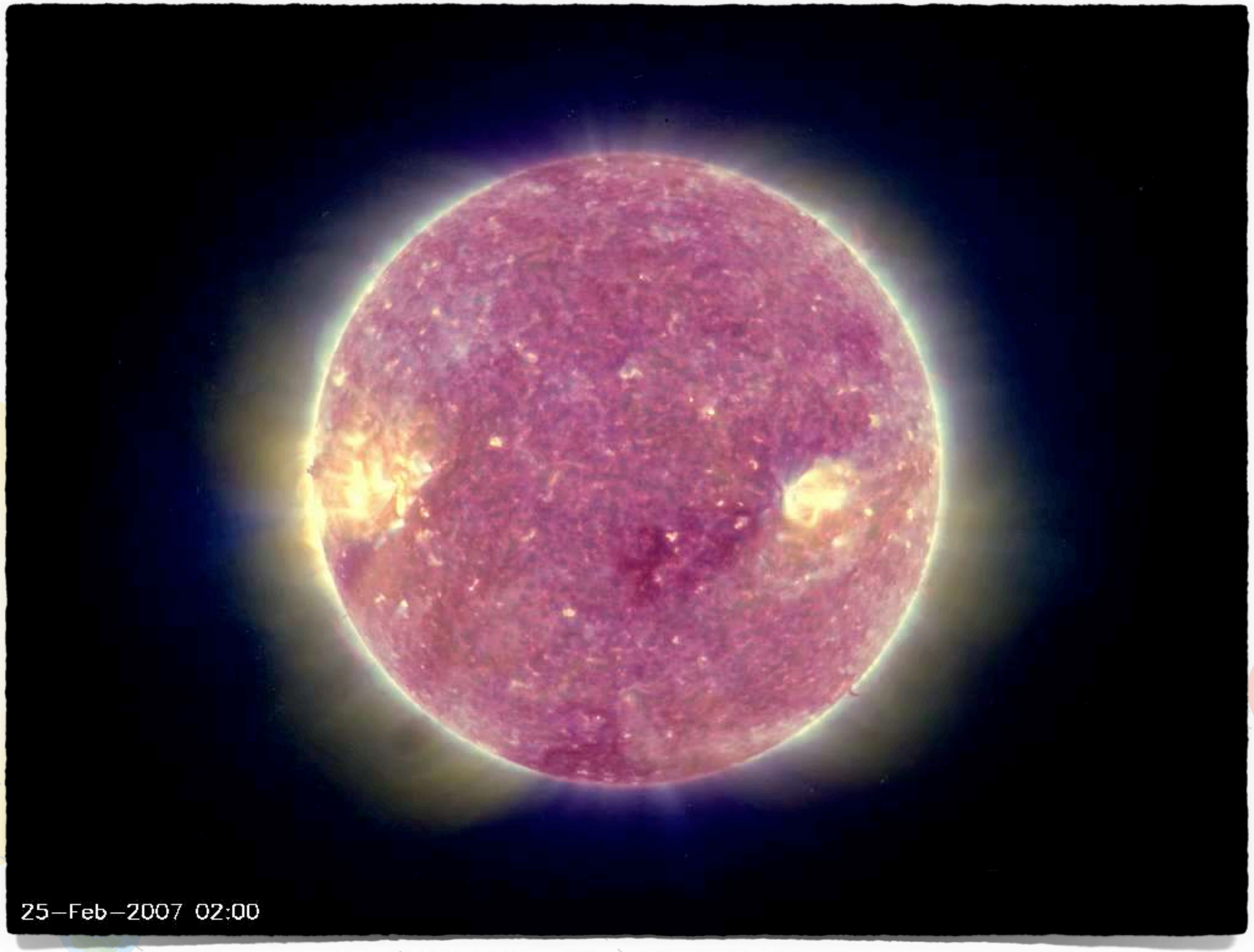
Instruments (spectrographs)

ELODIE,
HIRES,
UCLES,
CORALIE,
HARPS,
SOPHIE,
BOES,
TRES,
HARPS-N,
CARMENES,
ESPRESSO,
MAROON-X…

Transit: the most prolific method



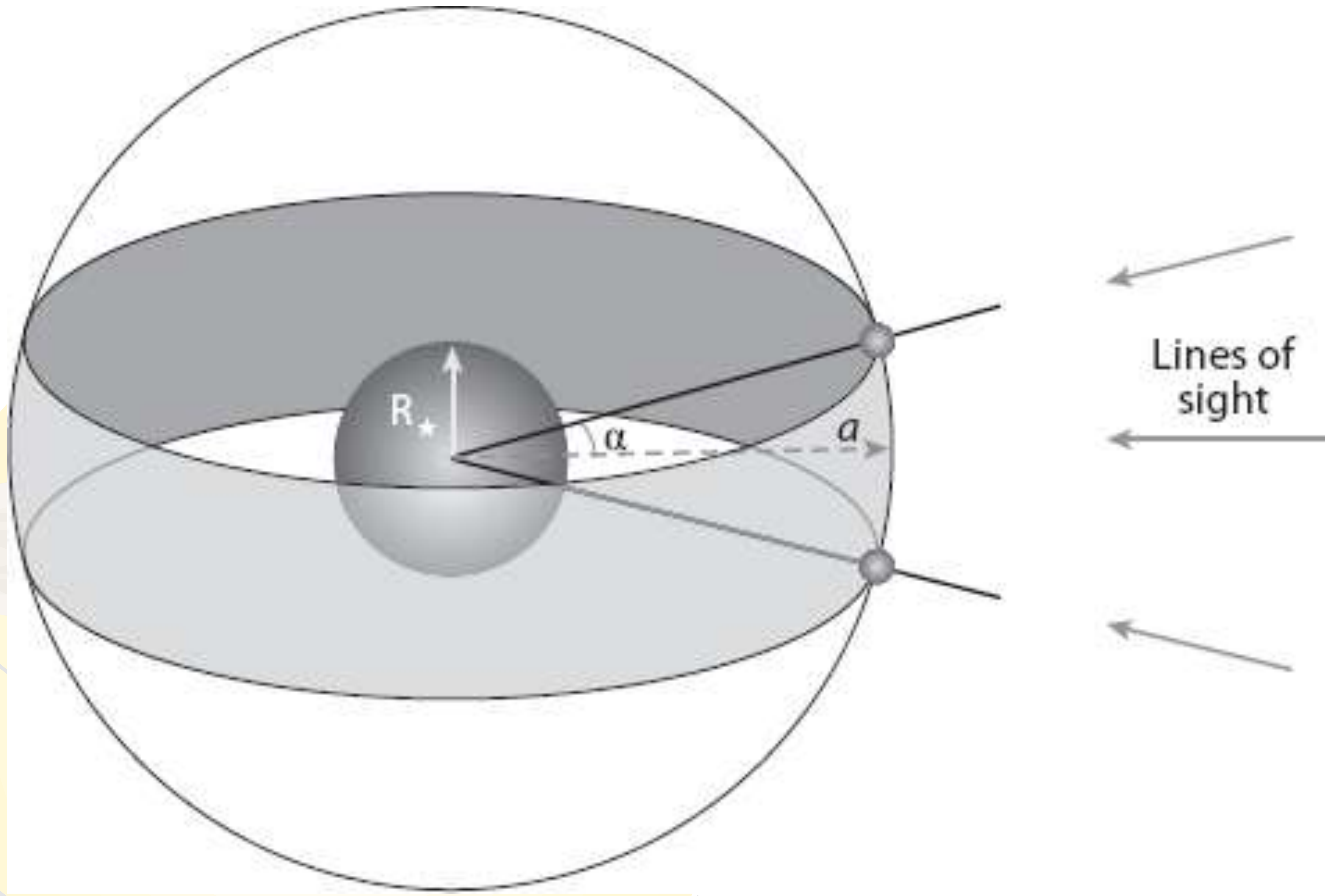
Transit: the most prolific method



@NASA (instrument STEREO B)

Transit: the most prolific method

Transit probability is the **ratio** of the **solid angles allowing for transit** over the **total solid angle**



$$\boxed{\text{Transit probability: } P_{transit} = \frac{R_p + R_\star}{a}}$$

In practice, $R_p \ll R_\star$, so: $P_{transit} \approx \dfrac{R_\star}{a}$

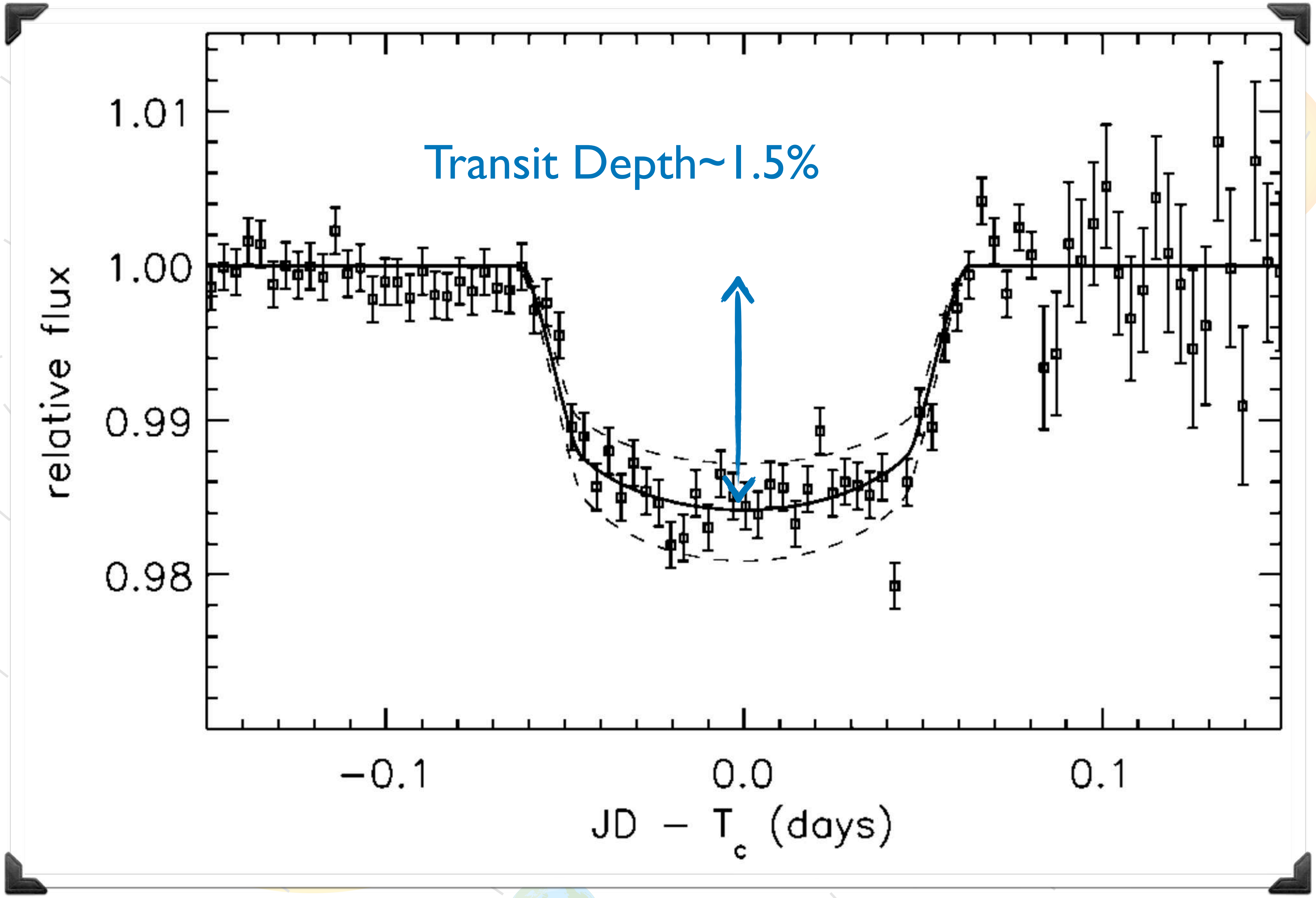
Quelle est la probabilité de transit de la Terre pour un observateur extra-terrestre ?

$(R_\star = 0.0046\ \text{AU})$

PollEv.com/emelinebolmo830

Transit: the most prolific method

Transit: the most prolific method



HD209458b

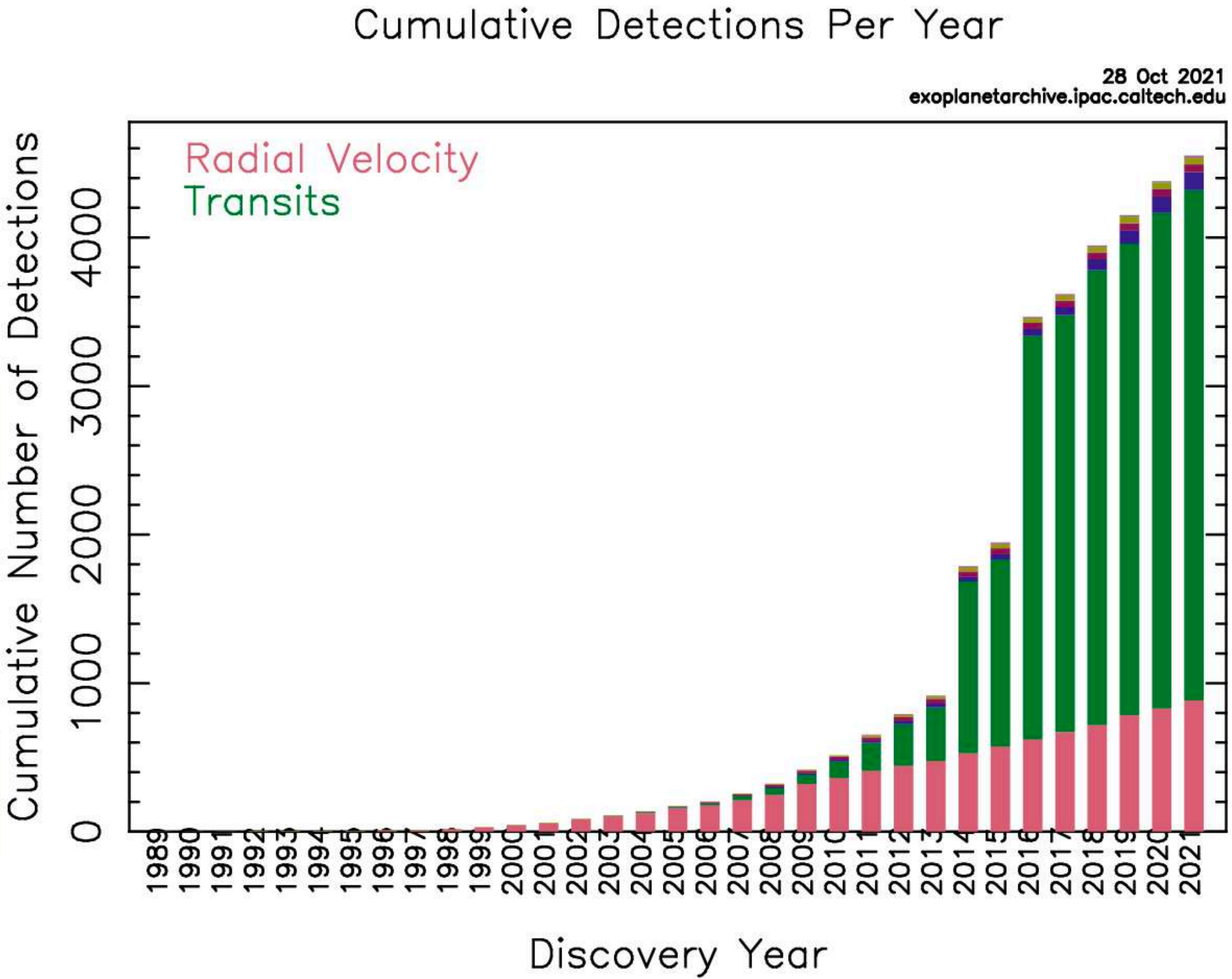
The first transit observed from the ground *[Charbonneau+2000]*

Data was binned into 5 min averages and phased according to the best-fit orbit

Best-fit orbit: $R_p = 1.27 R_{Jup},\ i = 87.1^{\circ}$

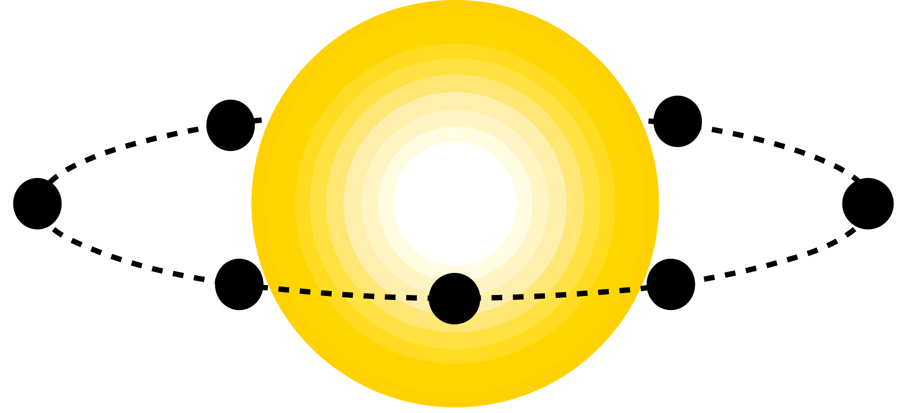
Photometric data from the **STARE** instrument, wide field CCD based telescope

Transit: the most prolific method

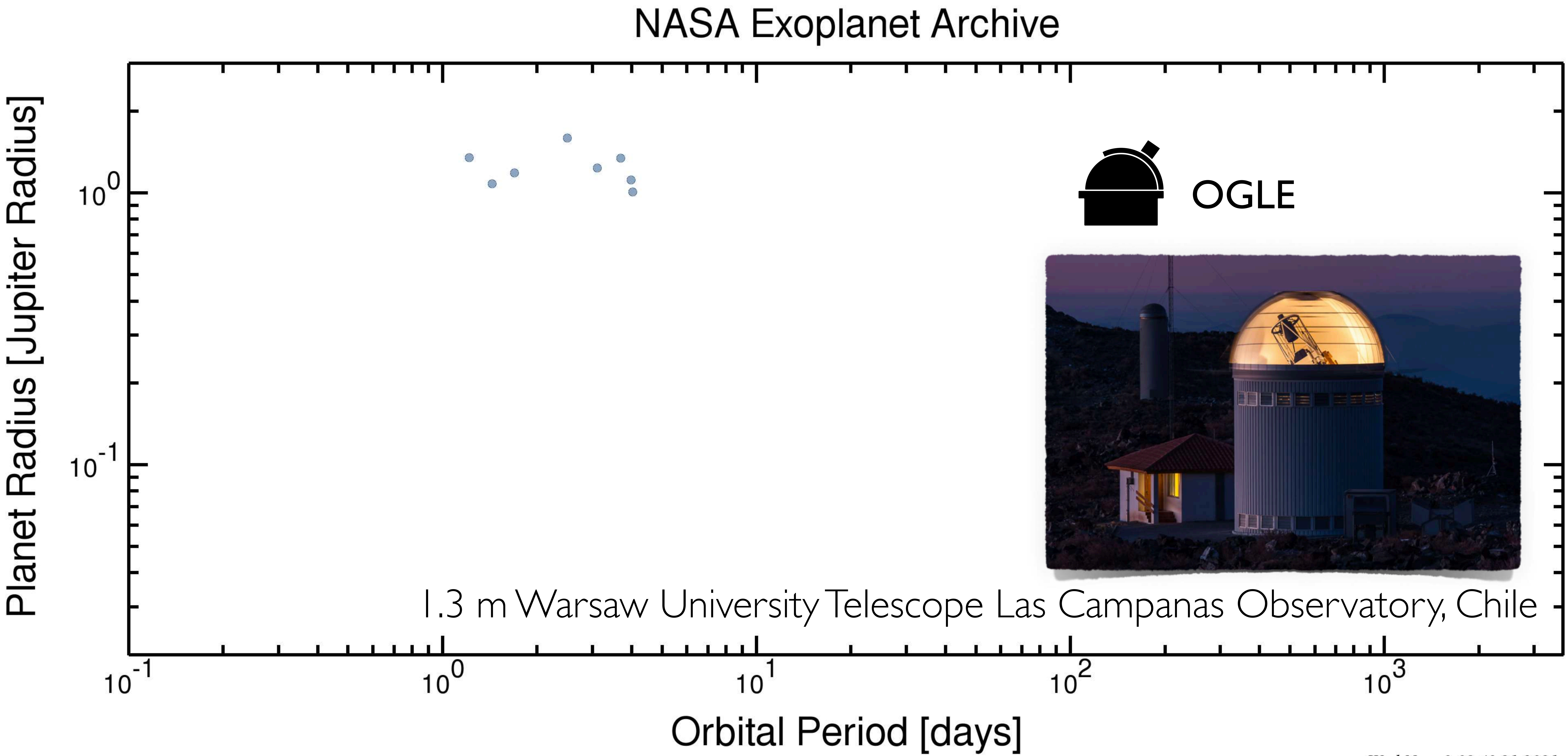


Instruments (photometry)

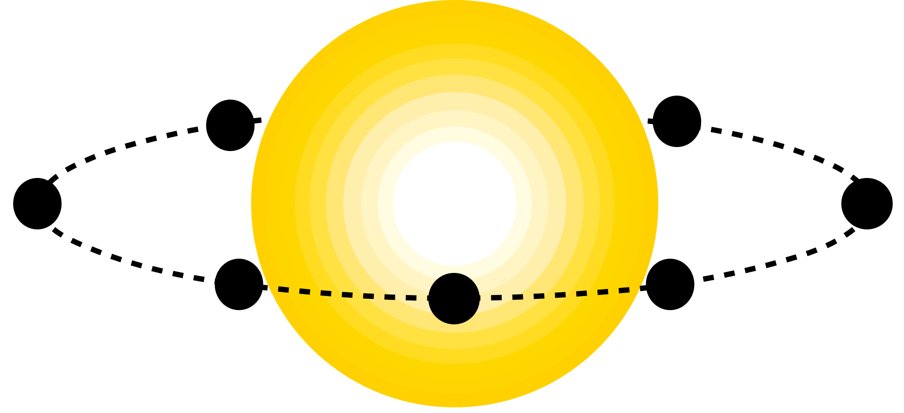
OGLE,
HATNet,
SuperWASP,
MEarth,
TRAPPIST,
SPECULOOS,
Kepler,
K2,
TESS,
CHEOPS…



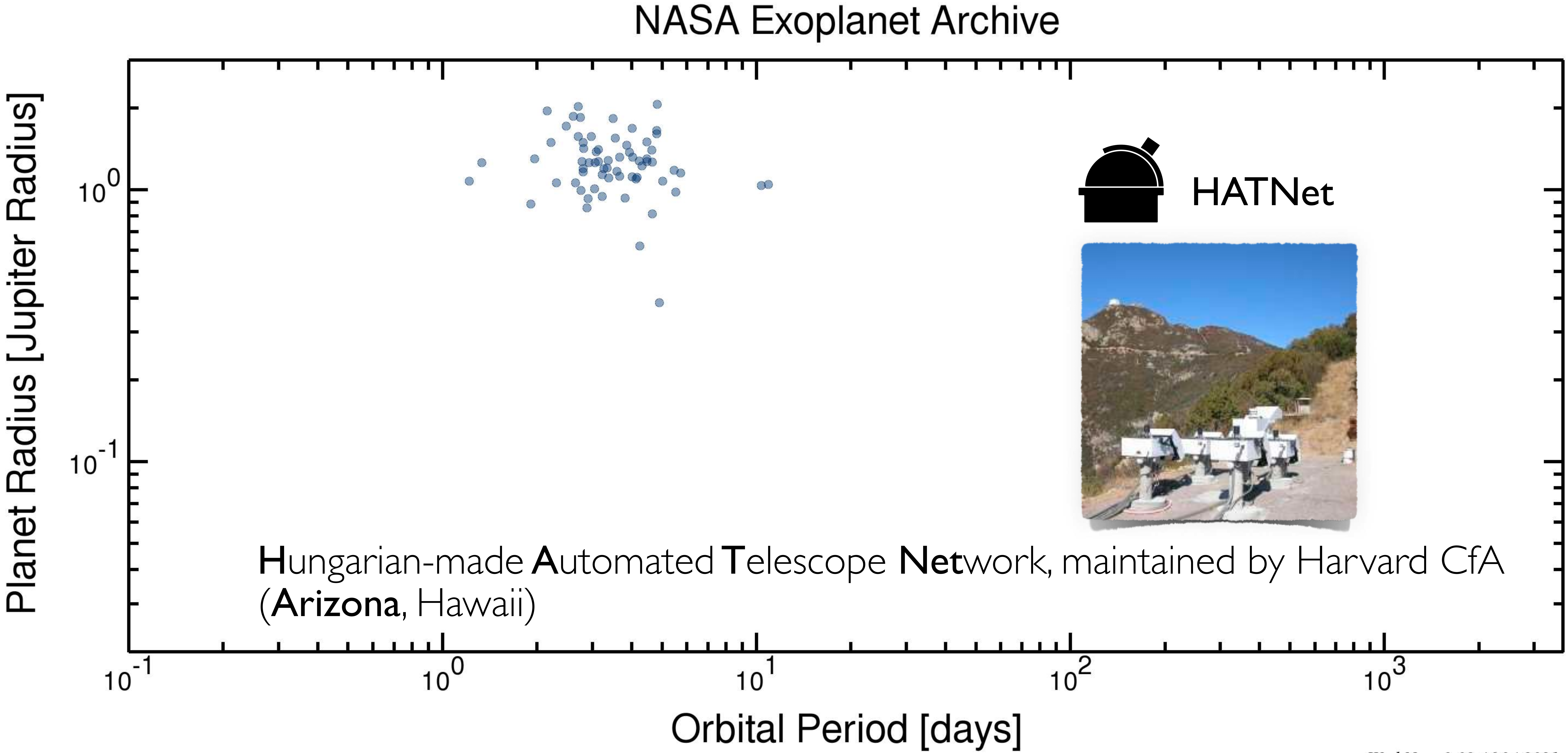
Transit: the most prolific method



1.3 m Warsaw University Telescope Las Campanas Observatory, Chile



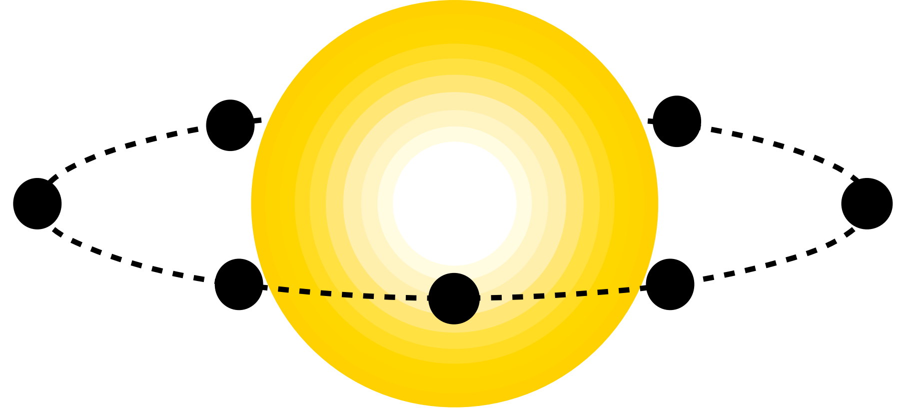
Transit: the most prolific method

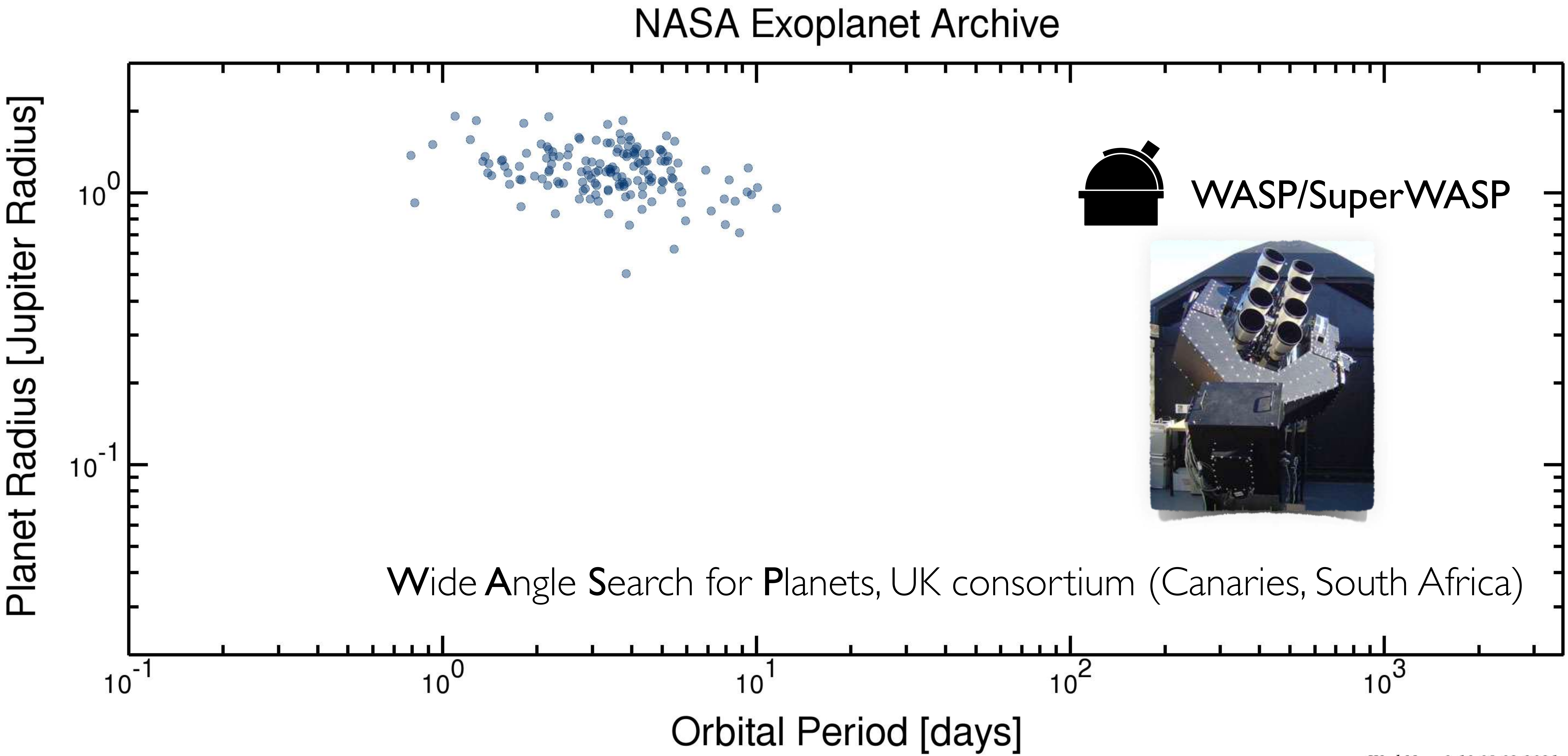


HATNet

Hungarian-made **A**utomated **T**elescope **Net**work, maintained by Harvard CfA (**Arizona**, Hawaii)

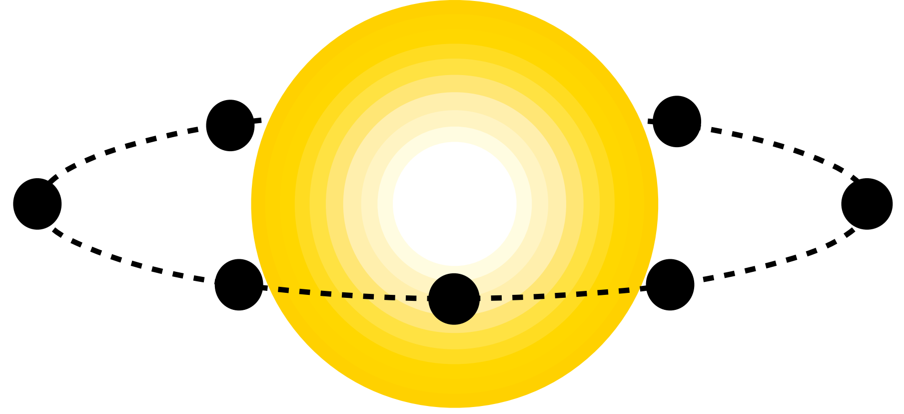
Transit: the most prolific method



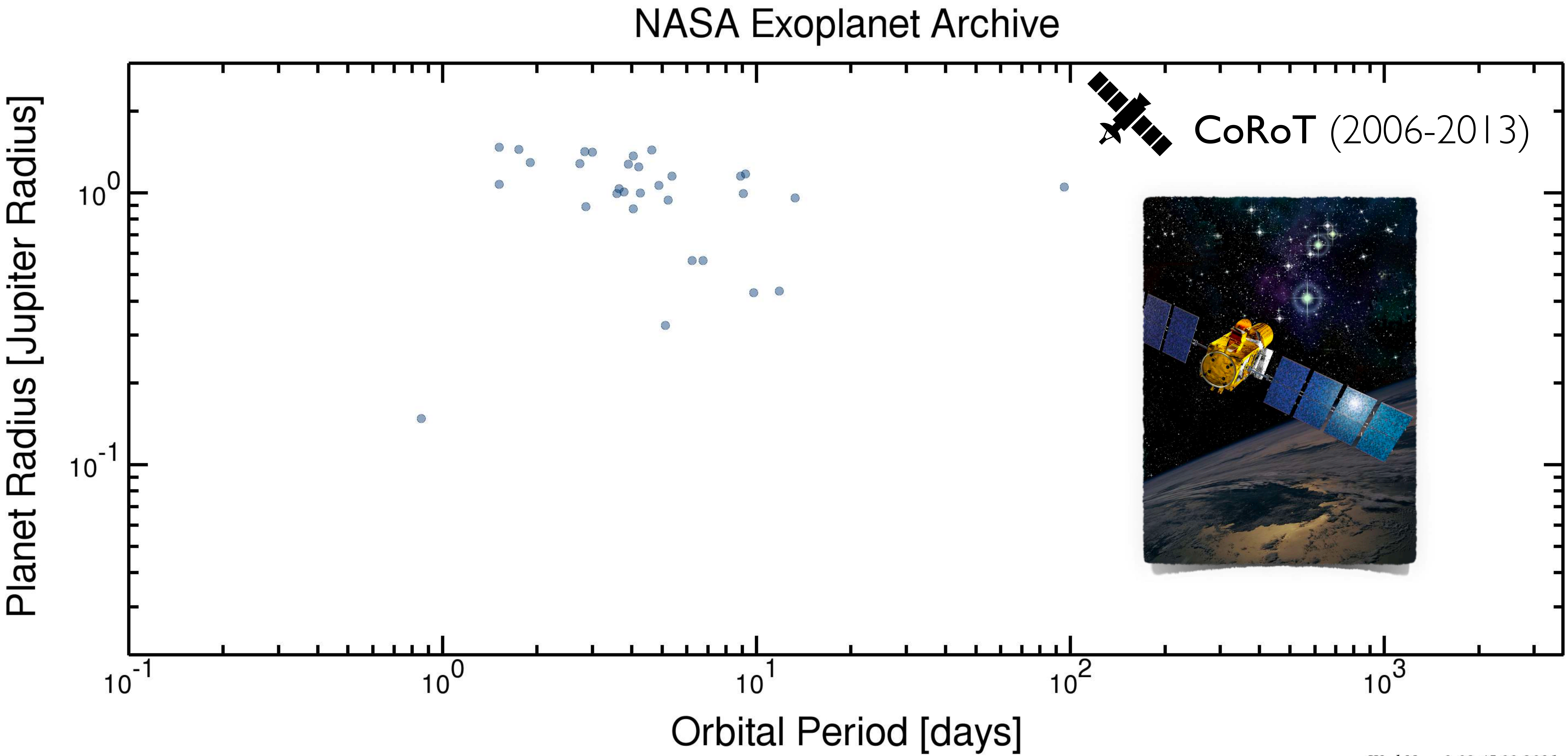


WASP/SuperWASP

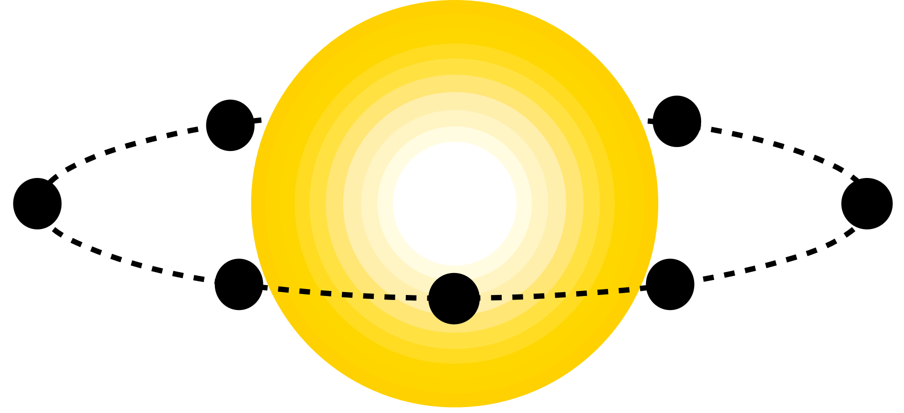
Wide Angle Search for Planets, UK consortium (Canaries, South Africa)

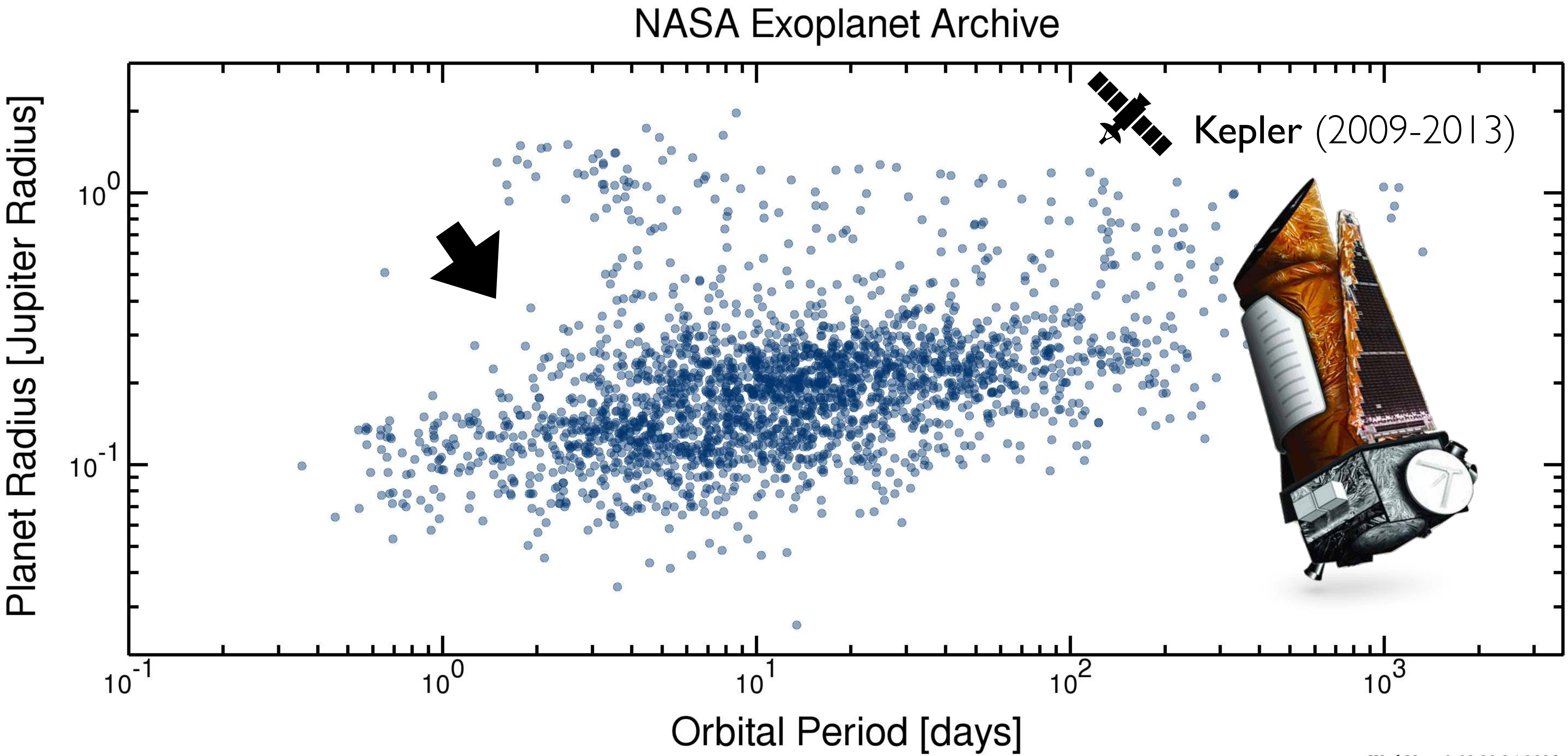


Transit: the most prolific method

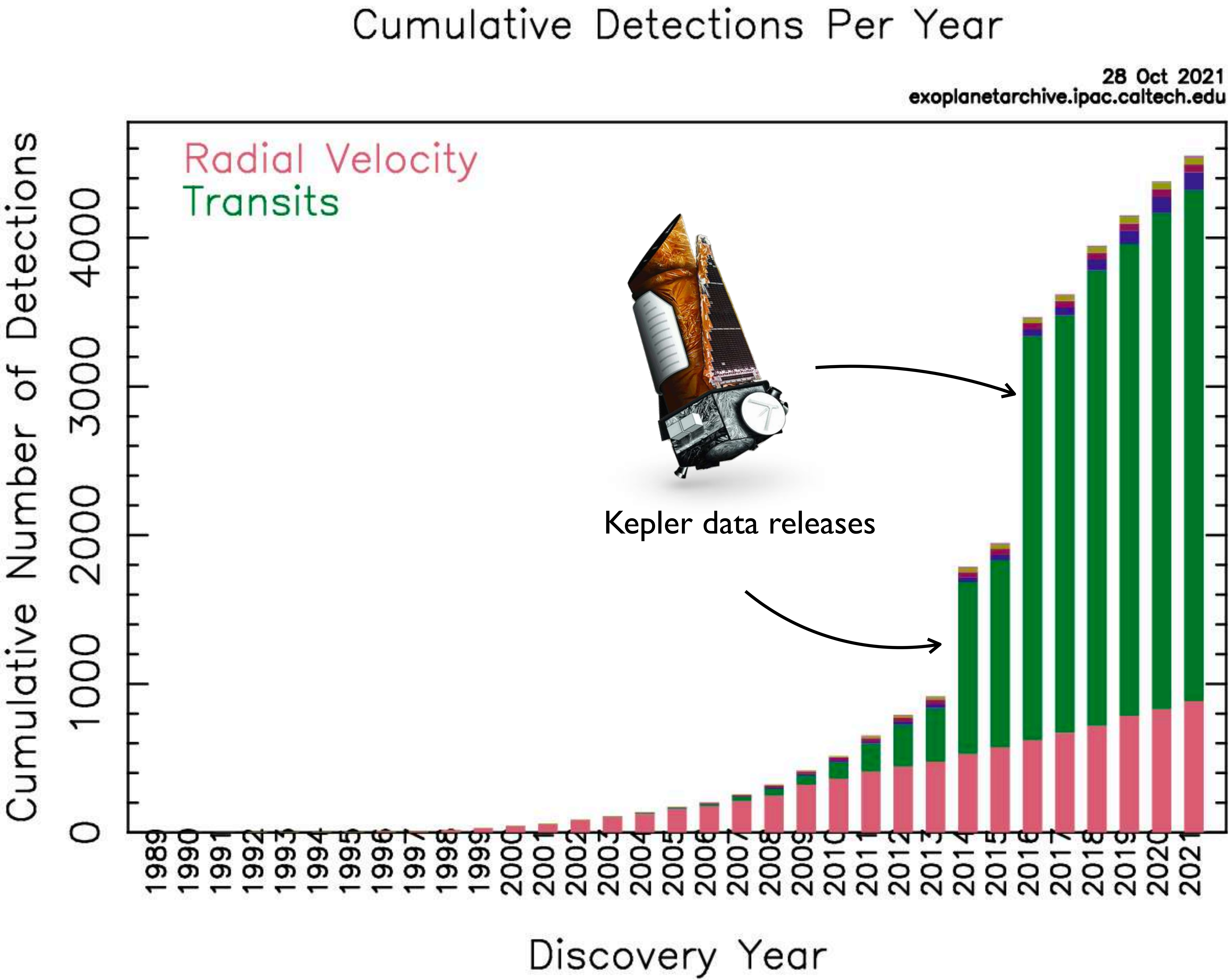


Transit: the most prolific method





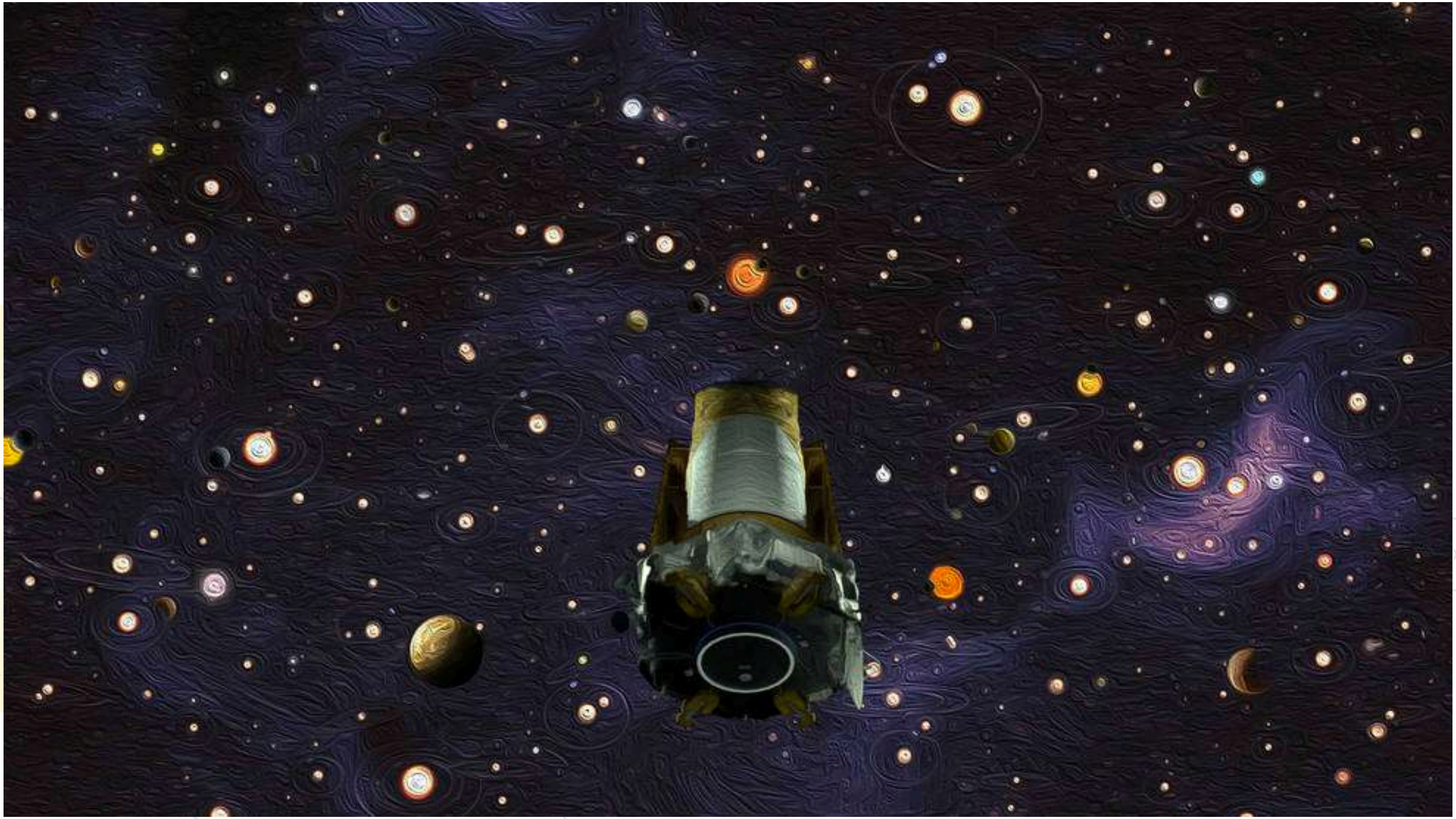
Transit: the most prolific method

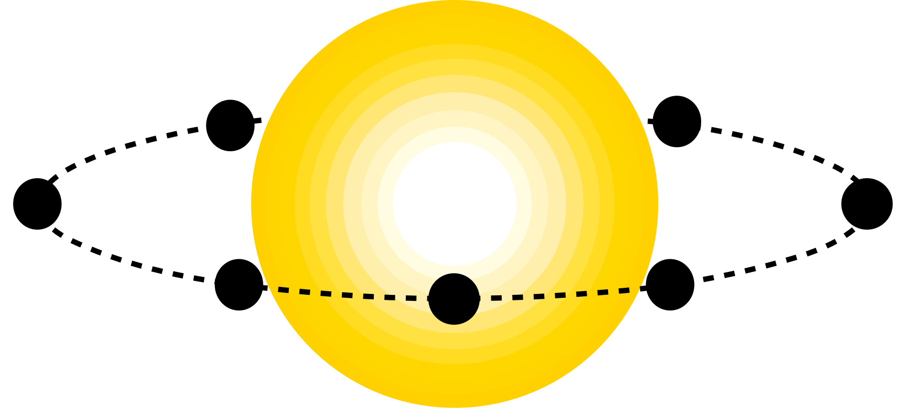


Instruments (photometry)

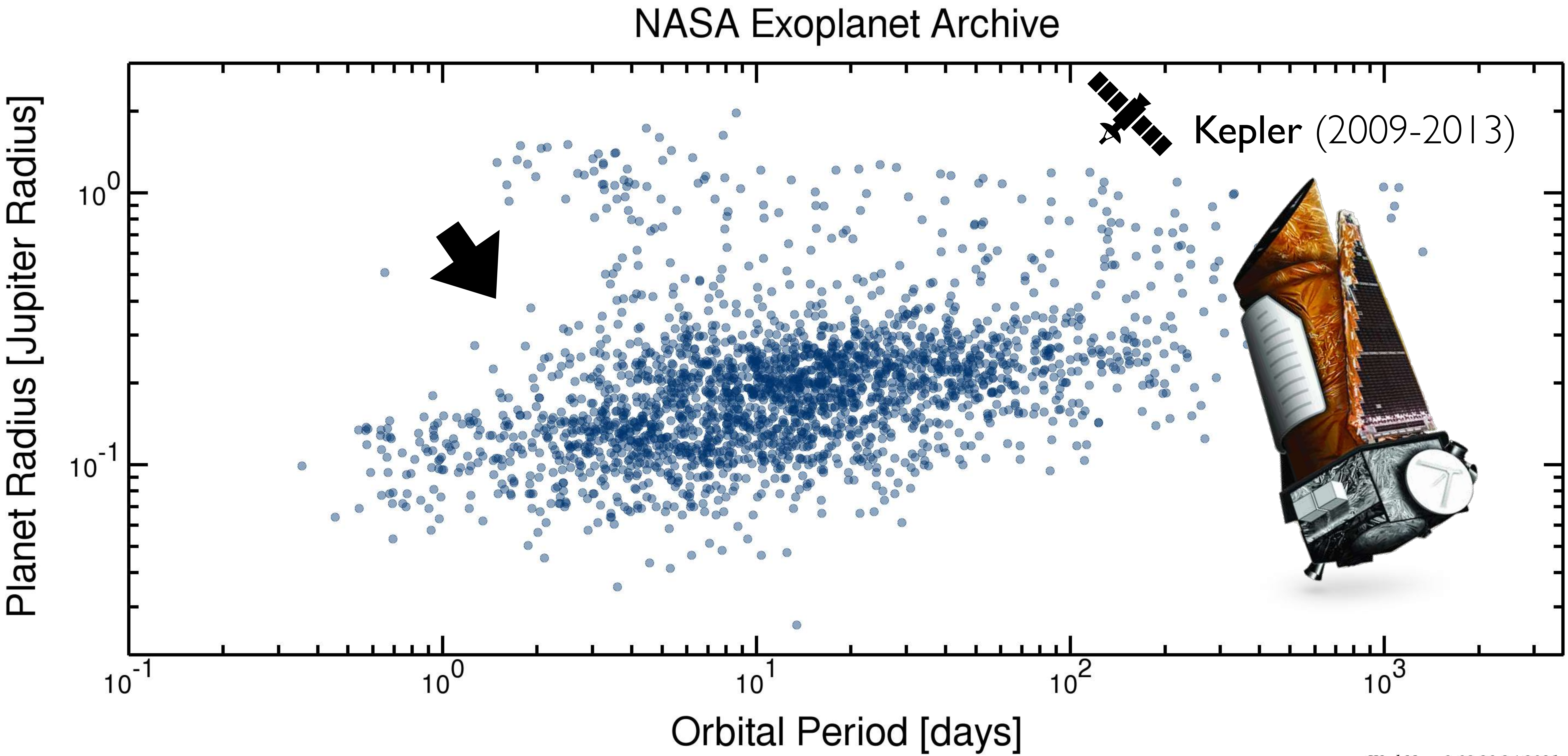
OGLE,
HATNet,
SuperWASP,
MEarth,
TRAPPIST,
SPECULOOS,
Kepler,
K2,
TESS,
CHEOPS…

Transit: the most prolific method





Transit: the most prolific method



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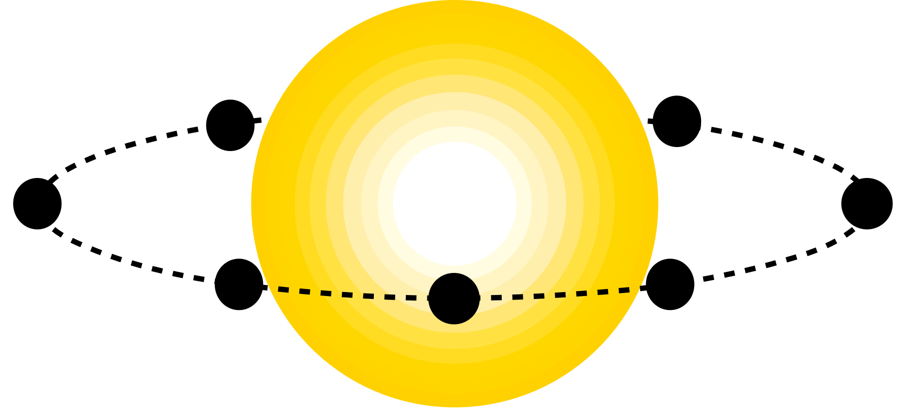

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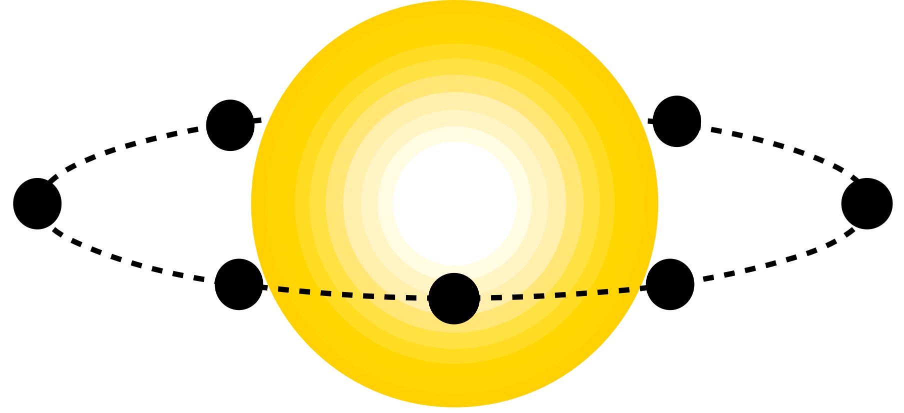
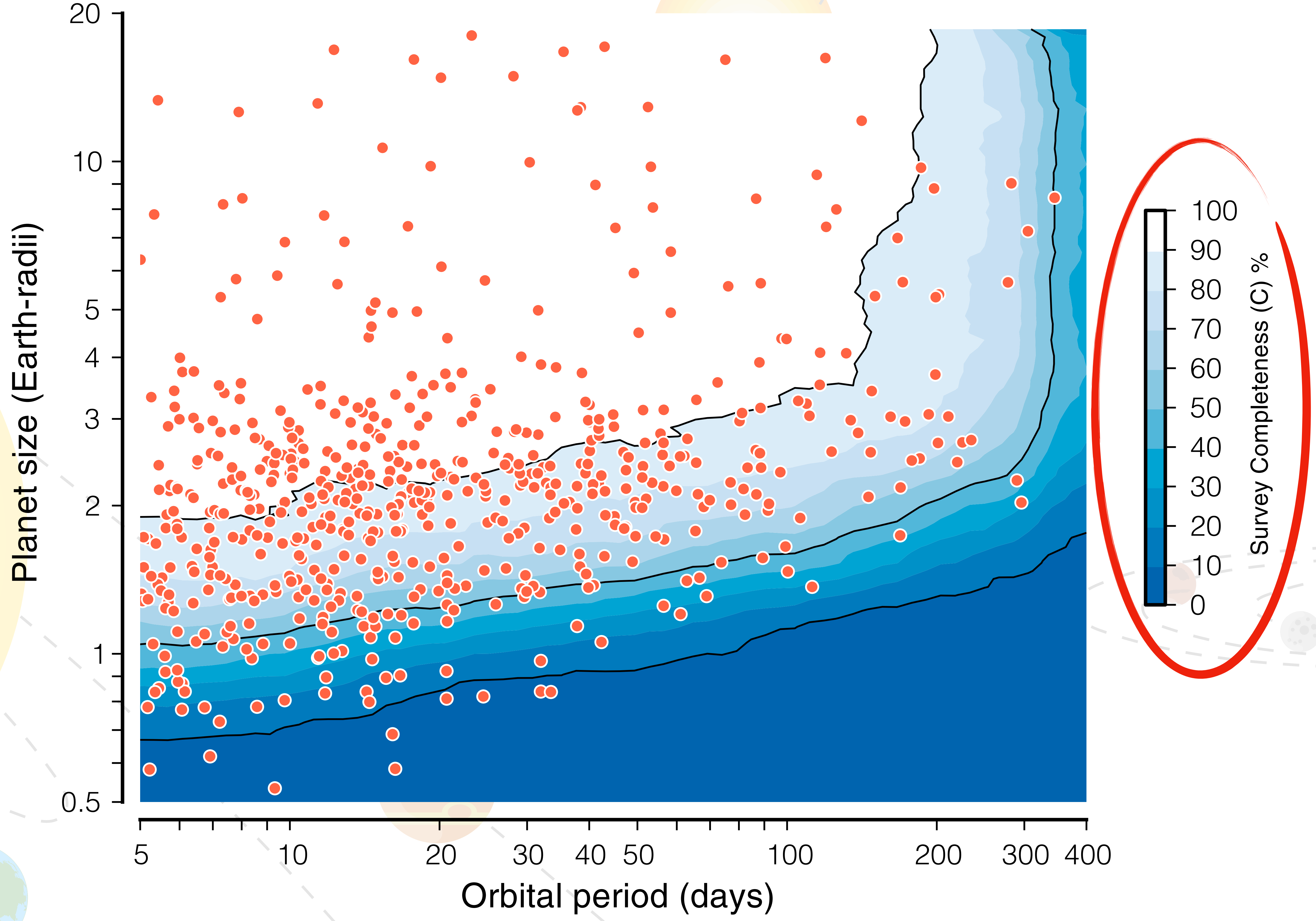
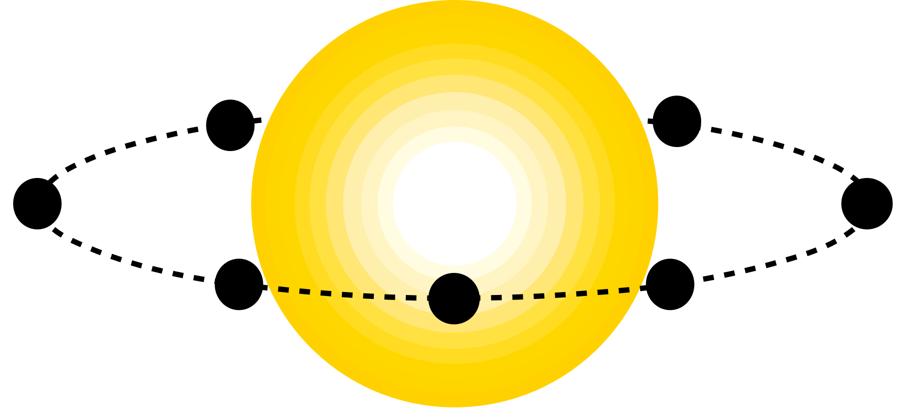


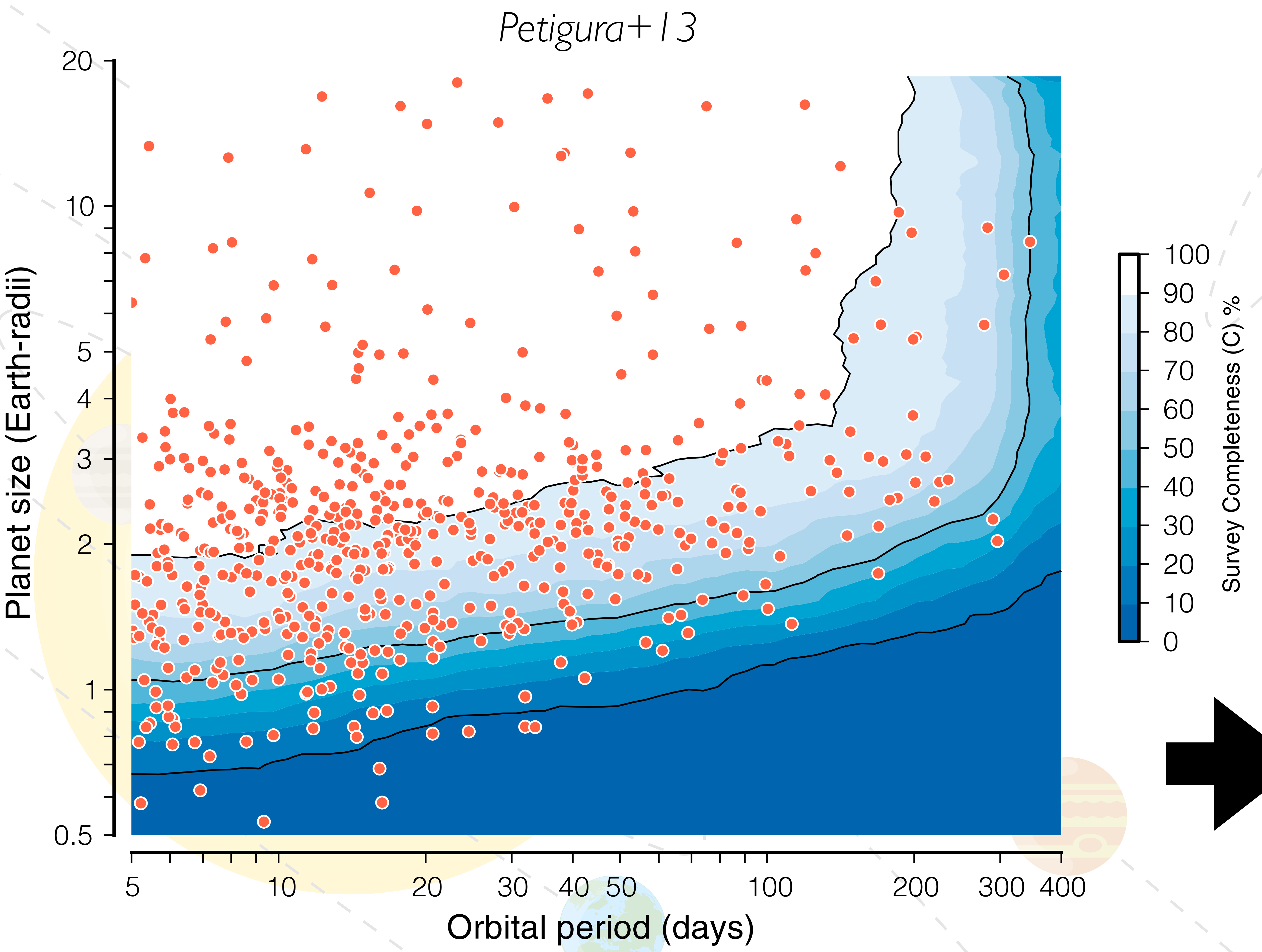
Transiting planets

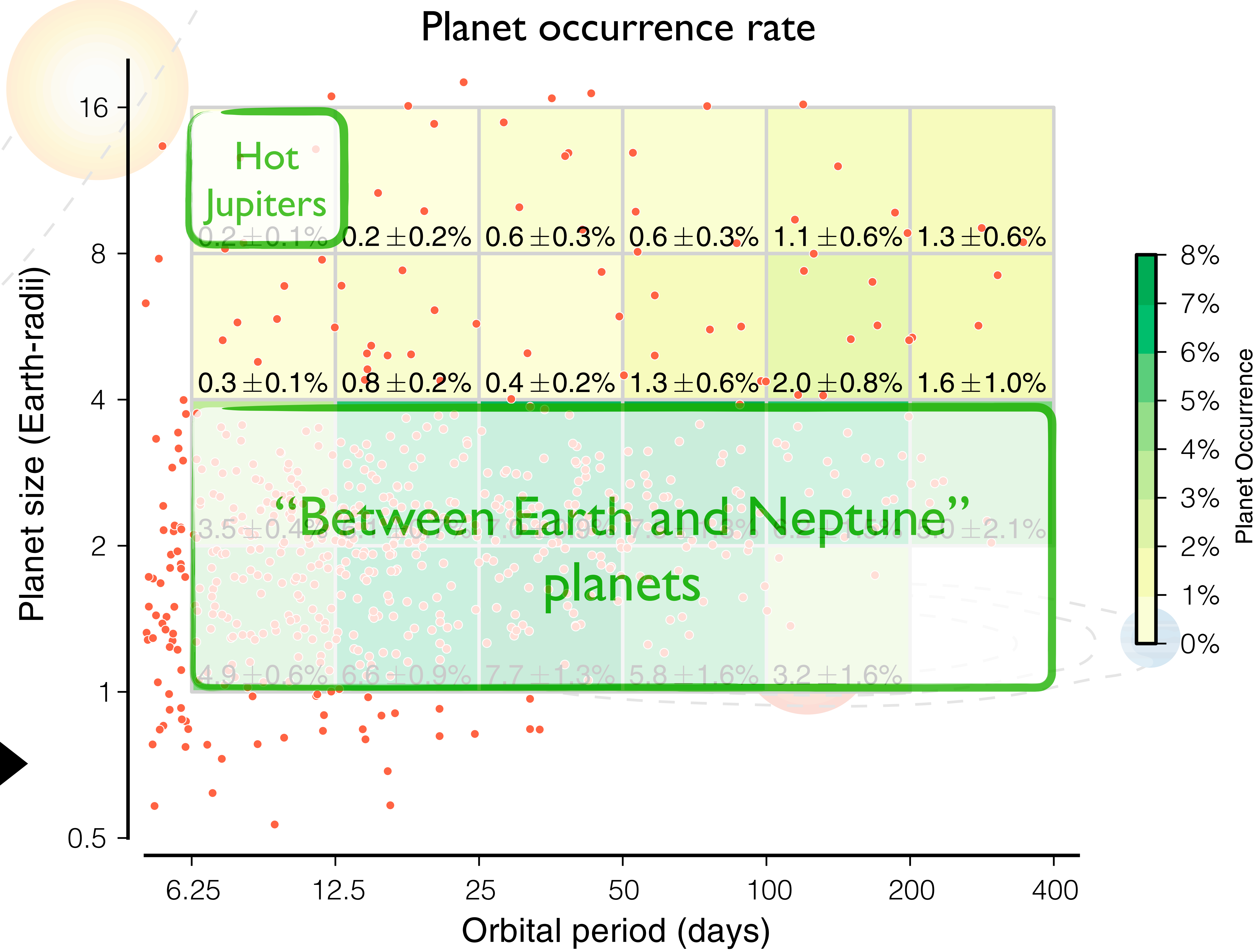


Petigura+13

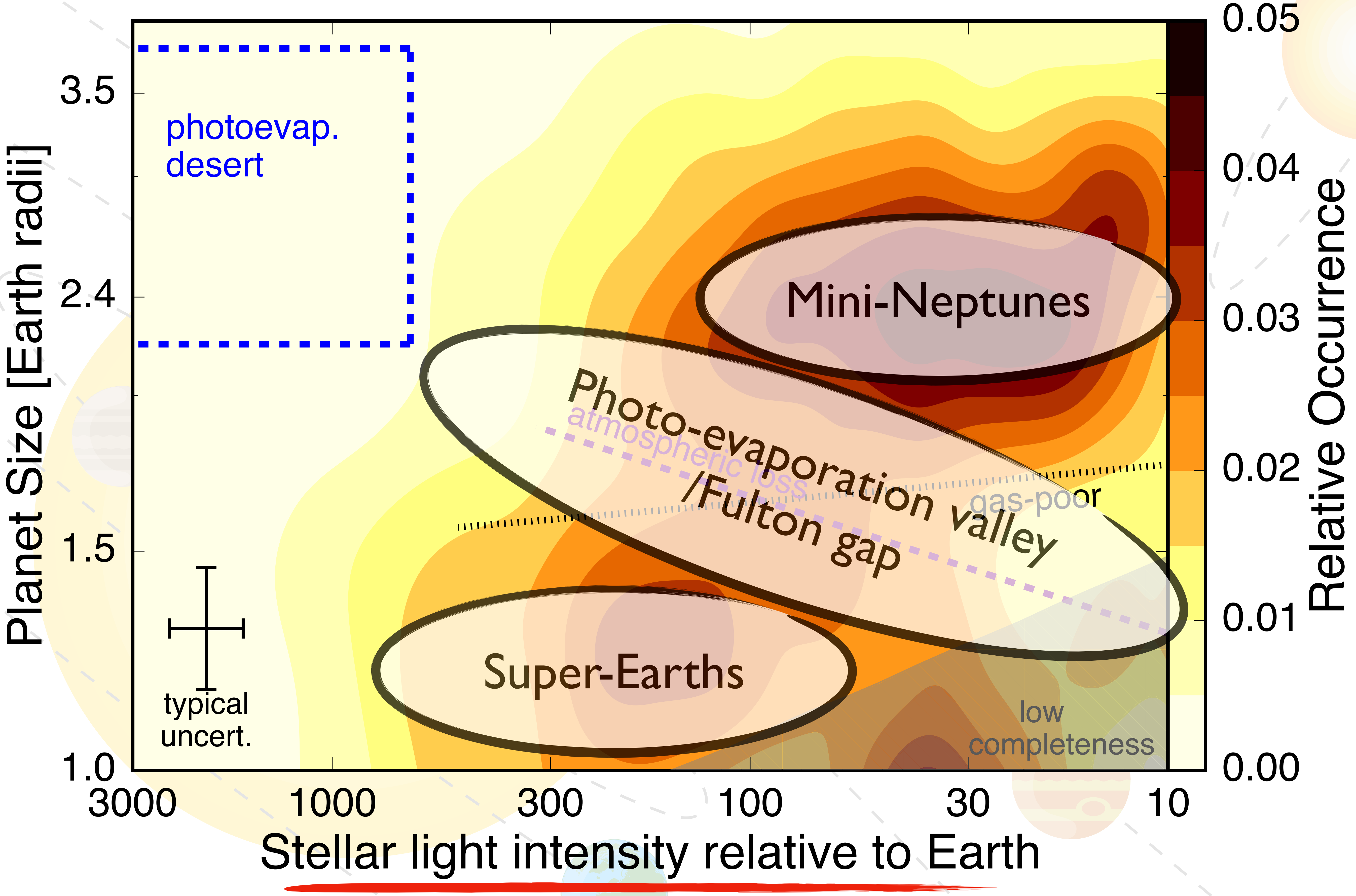
Transiting planets







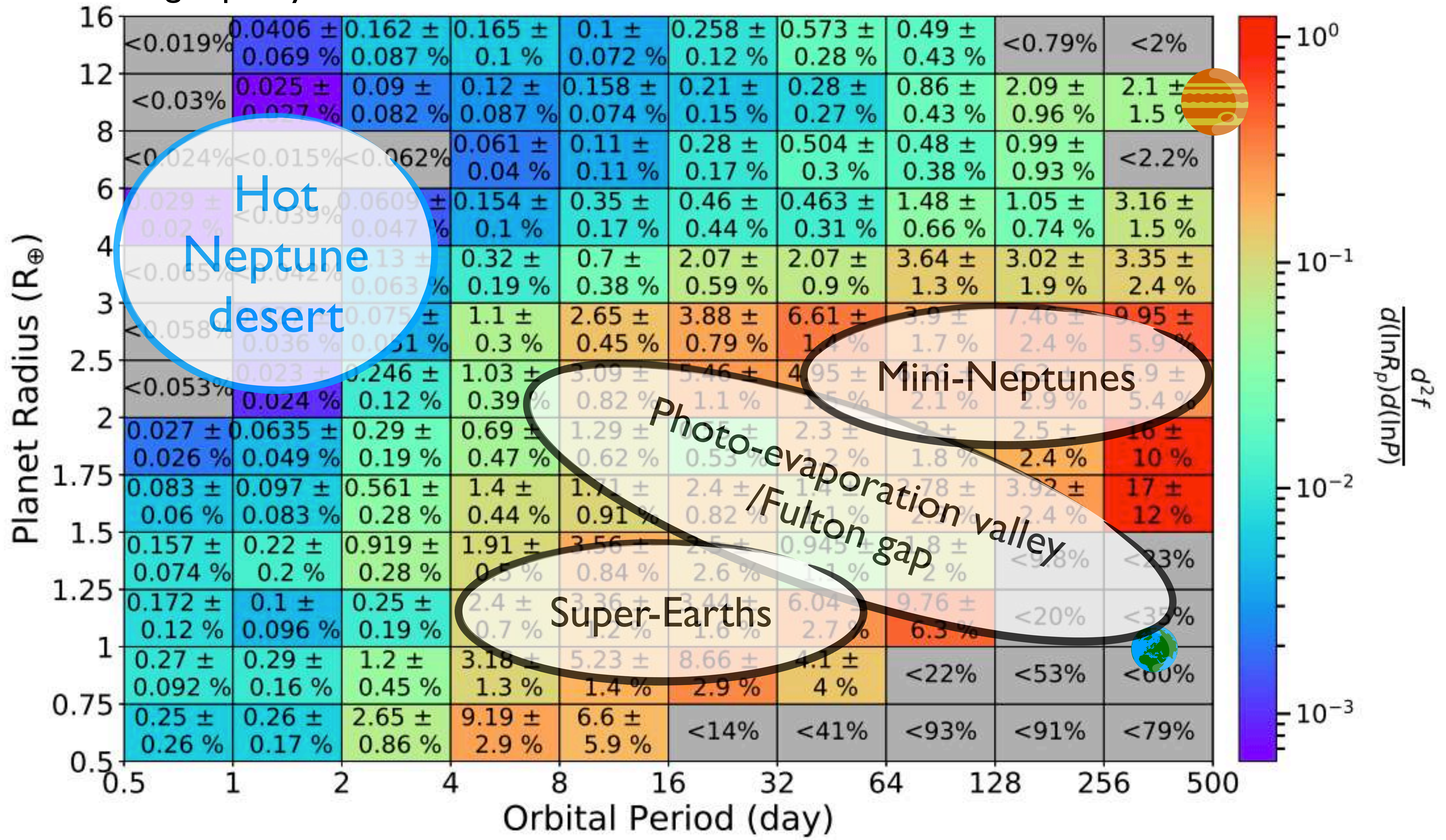
Transiting planets



Kepler detections with **updated stellar radius** determined using **Gaia DR2** *[Fulton+17, 18]*

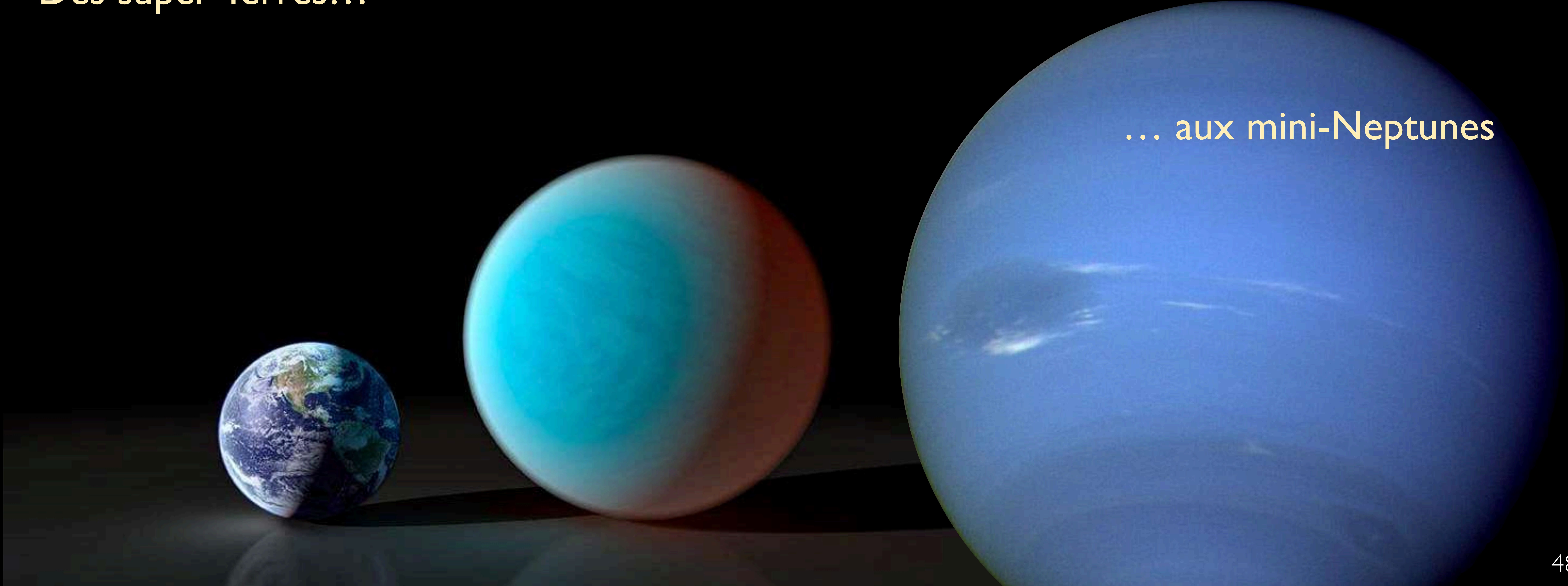
Transiting planets

High-quality dataset of FGK stars

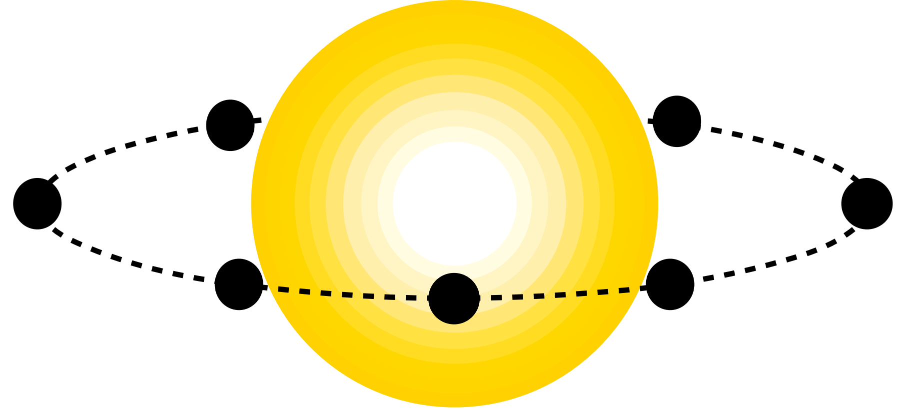


Occurrence rates for **Kepler** based on a **combined detection** and **vetting efficiency model** *[here: Hsu+19, see also Kunimoto & Matthews, 20]*

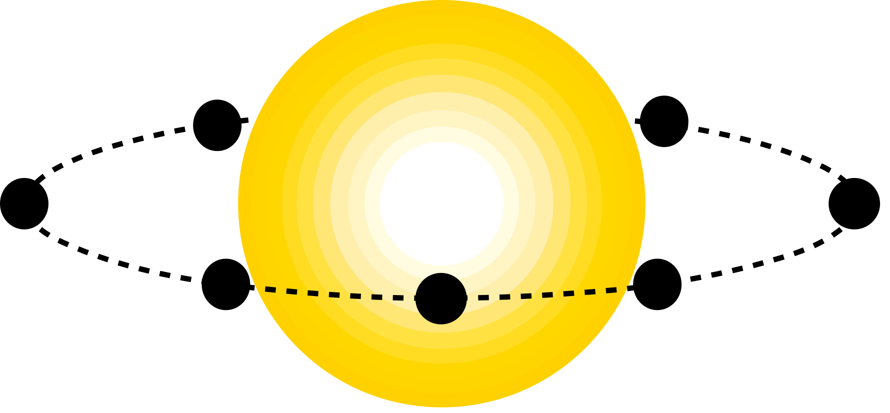
Des super-Terres…



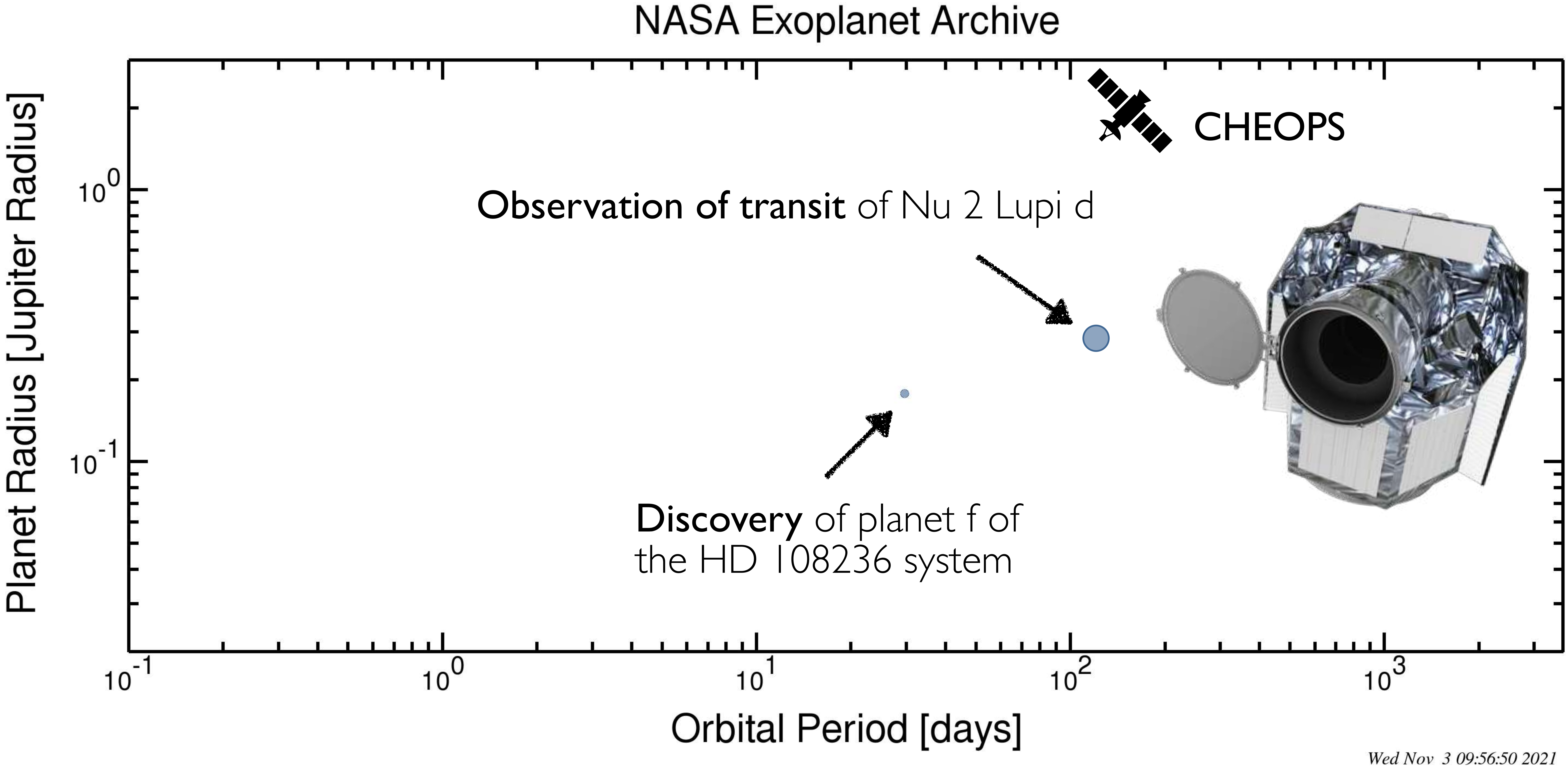
… aux mini-Neptunes



Transit: the most prolific method

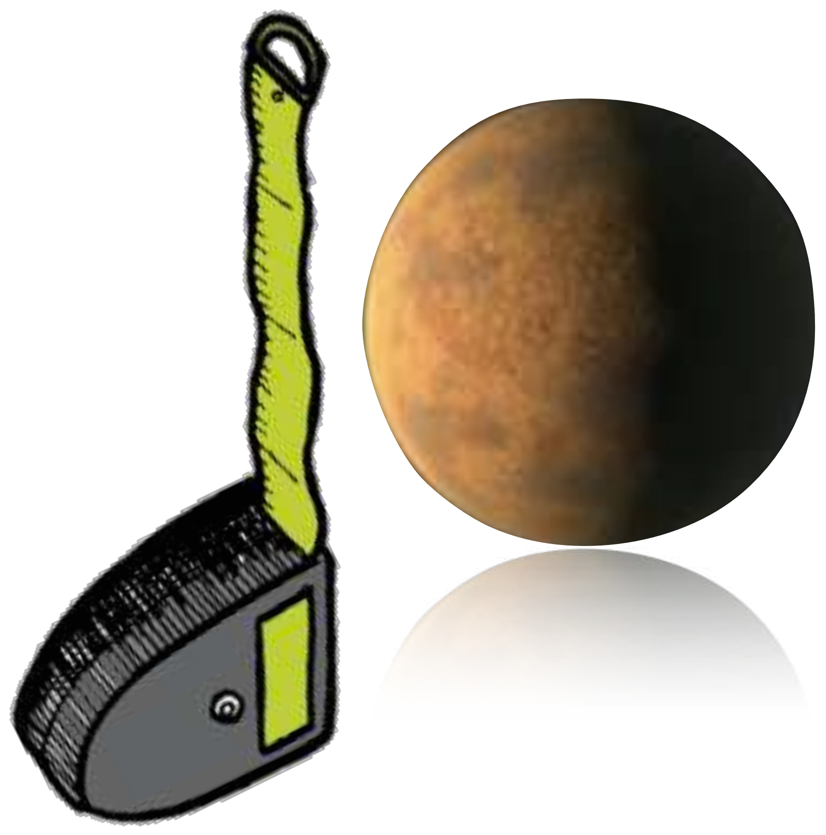


Transiting planets



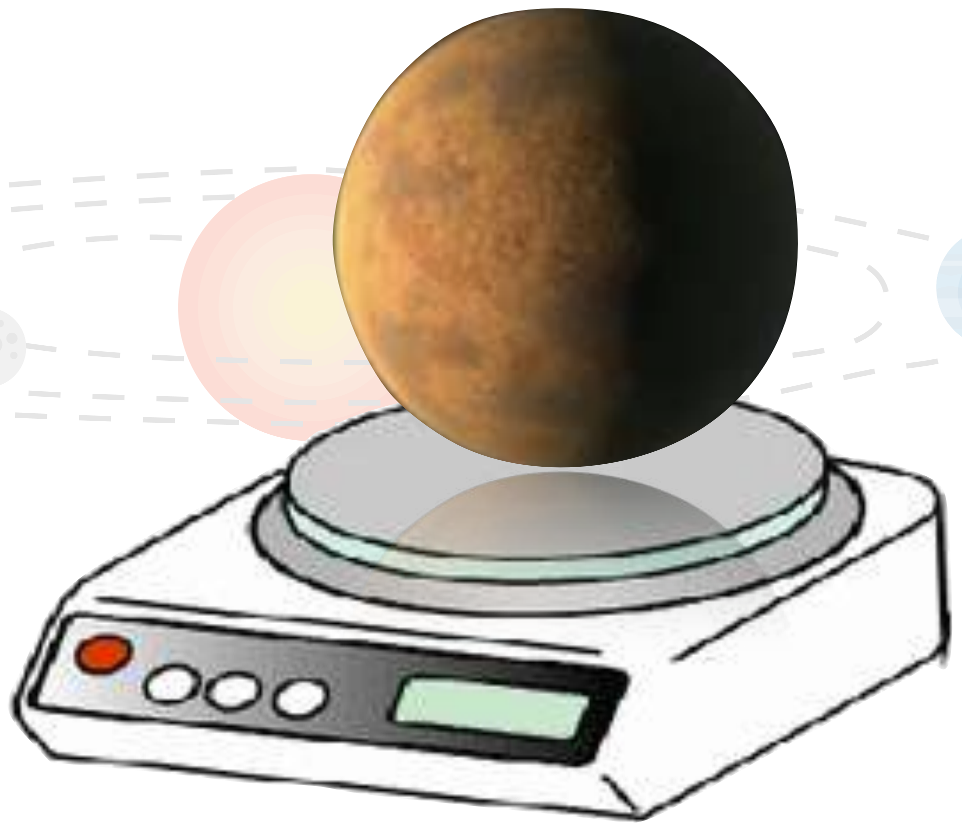
Planets characterization

Transit → Période orbitale
Taille de la planète



+

Vitesse radiale → Période orbitale
Masse de la planète



→ **Densité/composition** de la planète

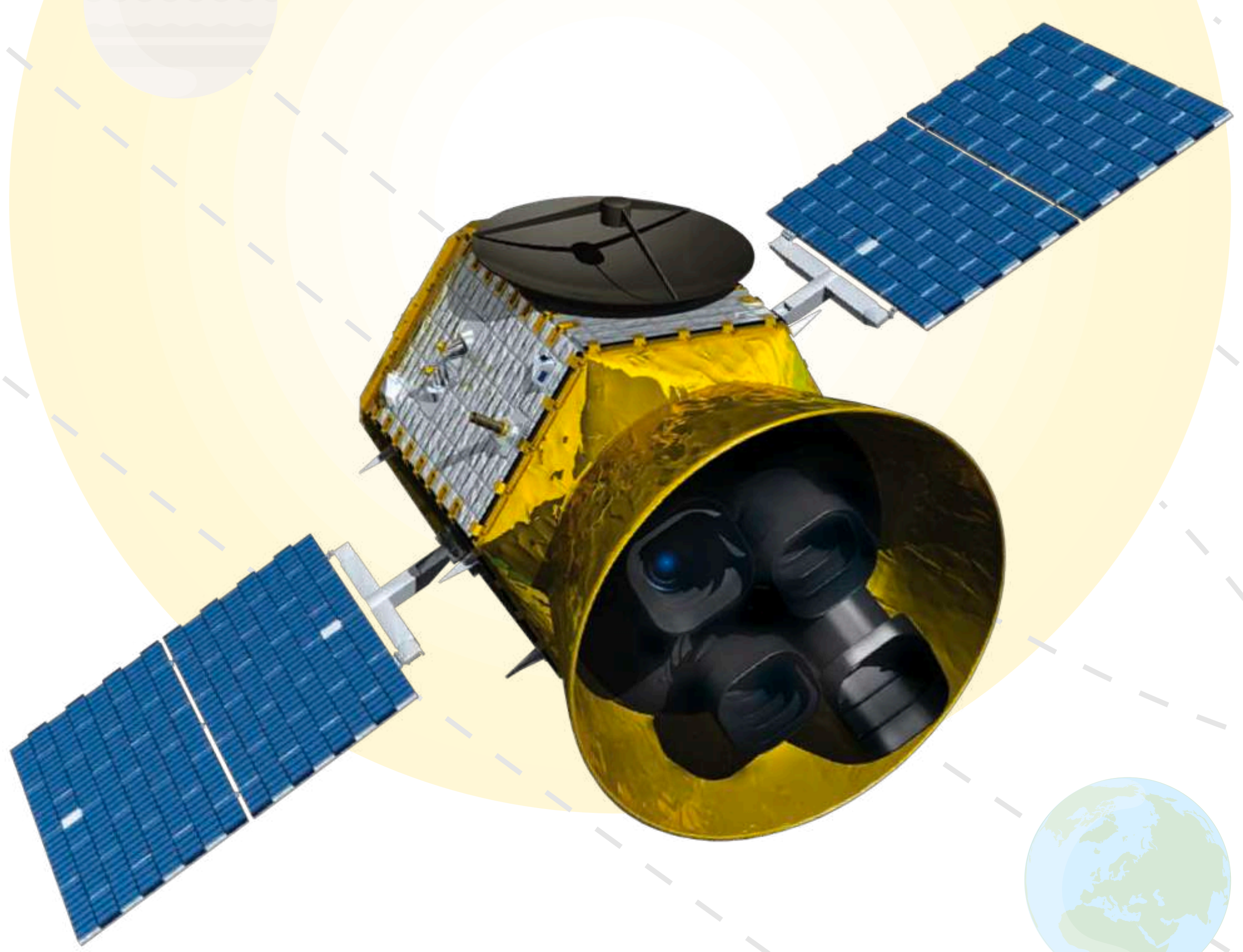
Planets characterization

Transit

Vitesse radiale

→ Densité/composition de la planète

TESS

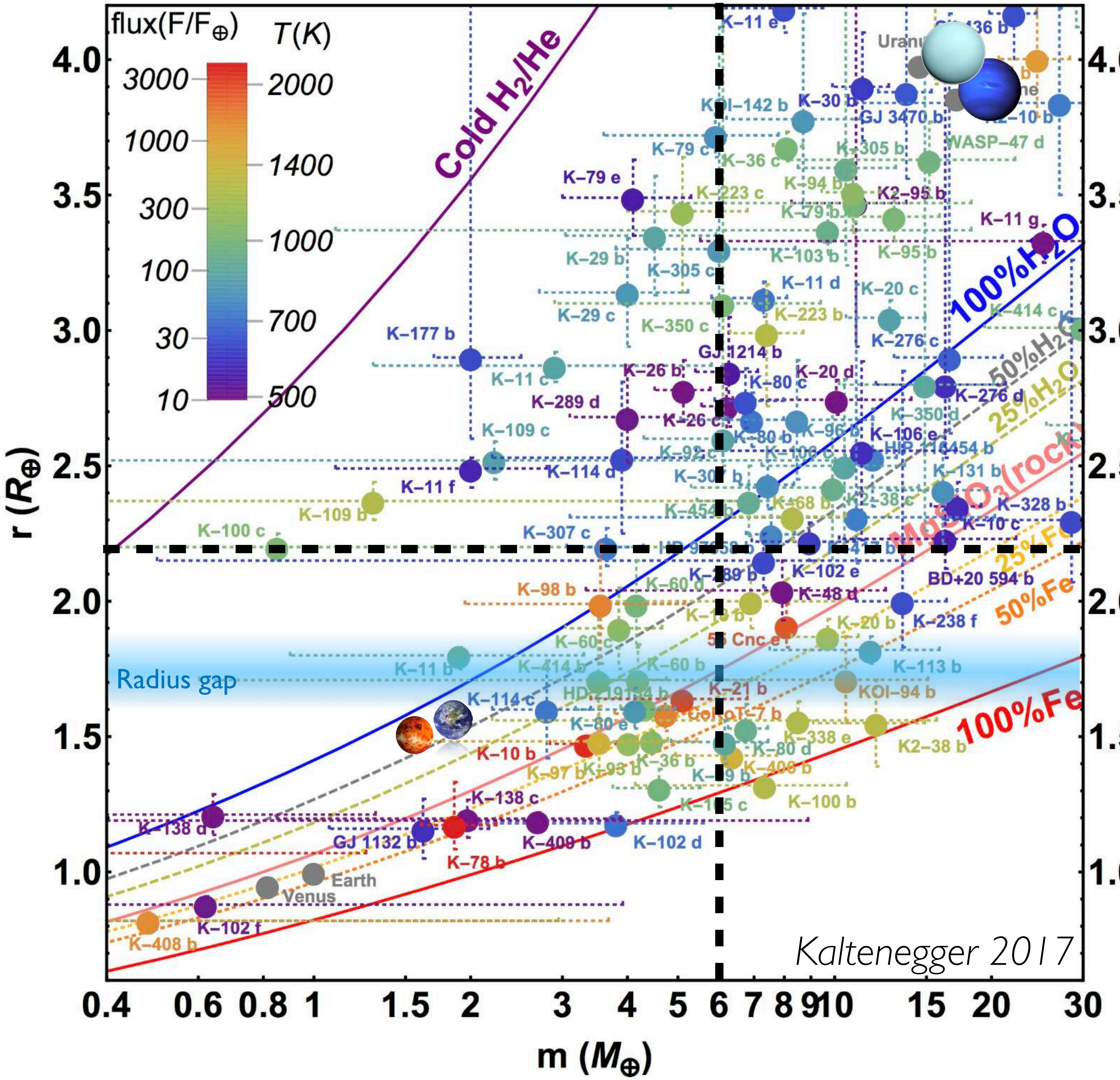


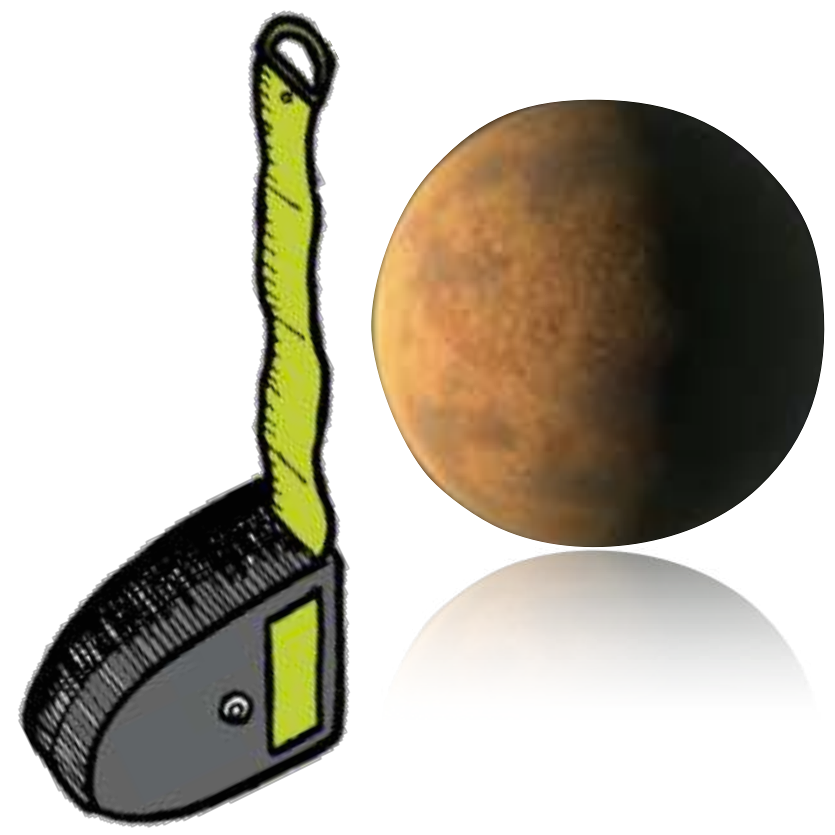
CHEOPS

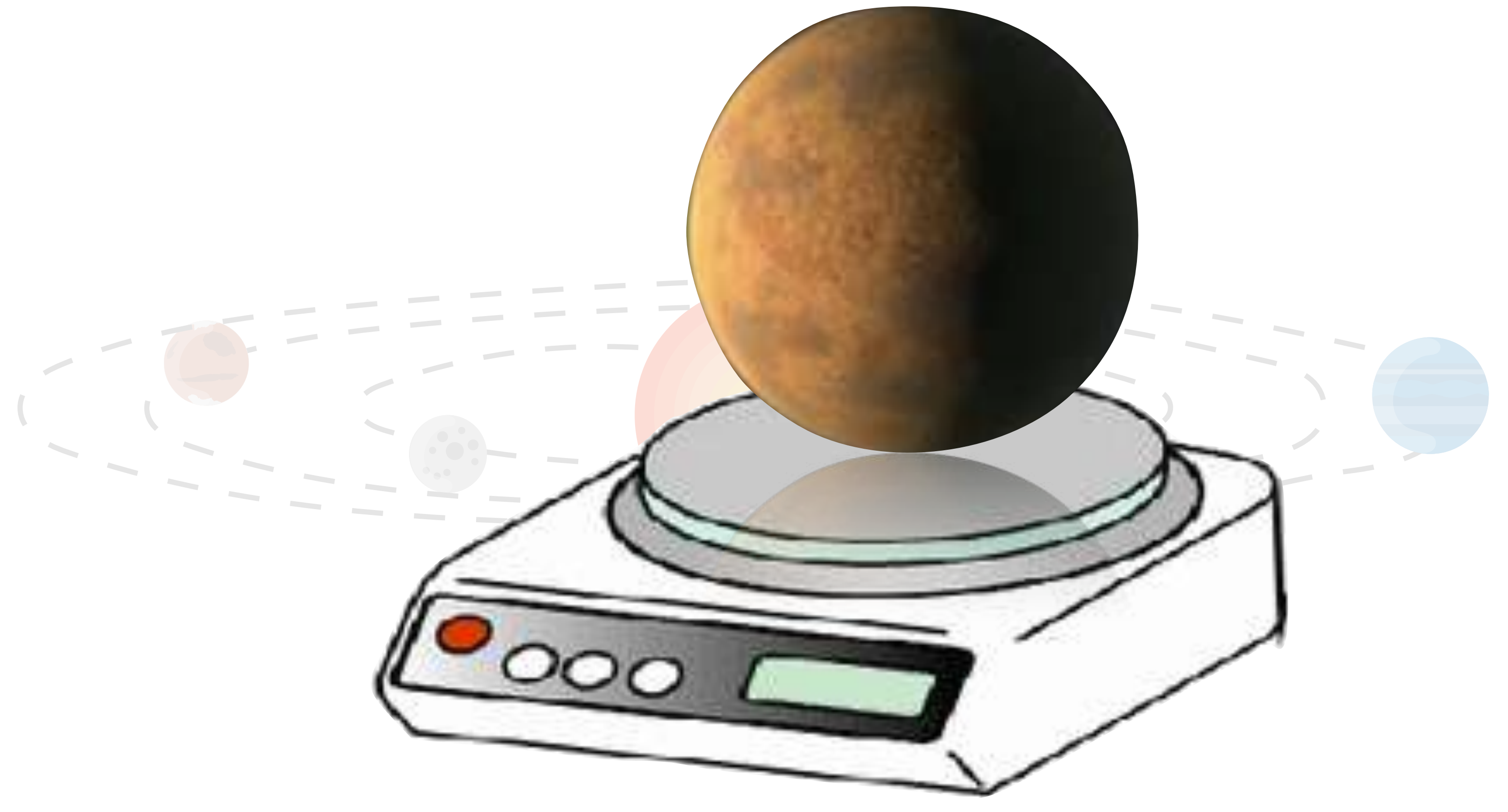
PLATO

Planets characterization

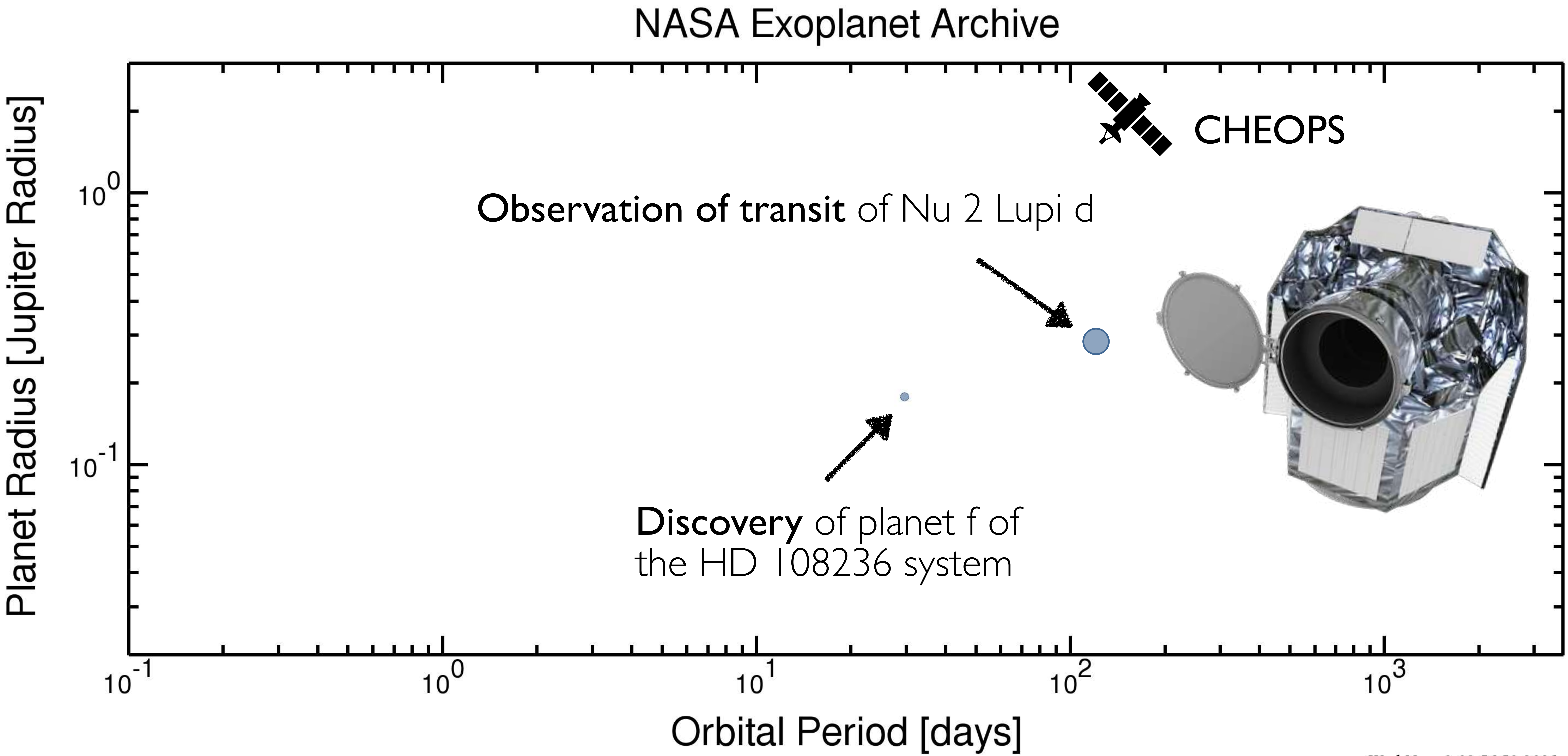
Huge degeneracy



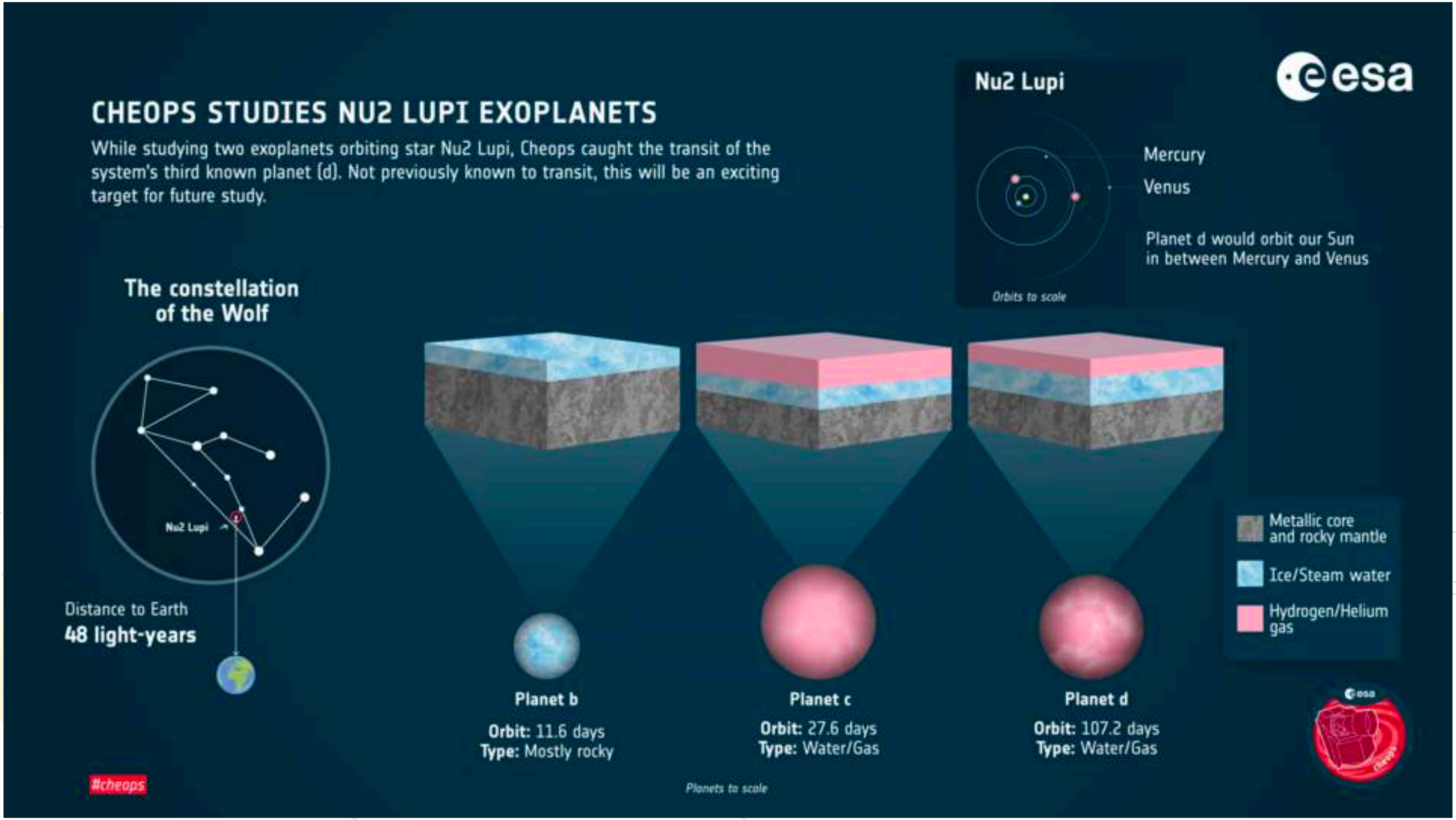




Planets characterization

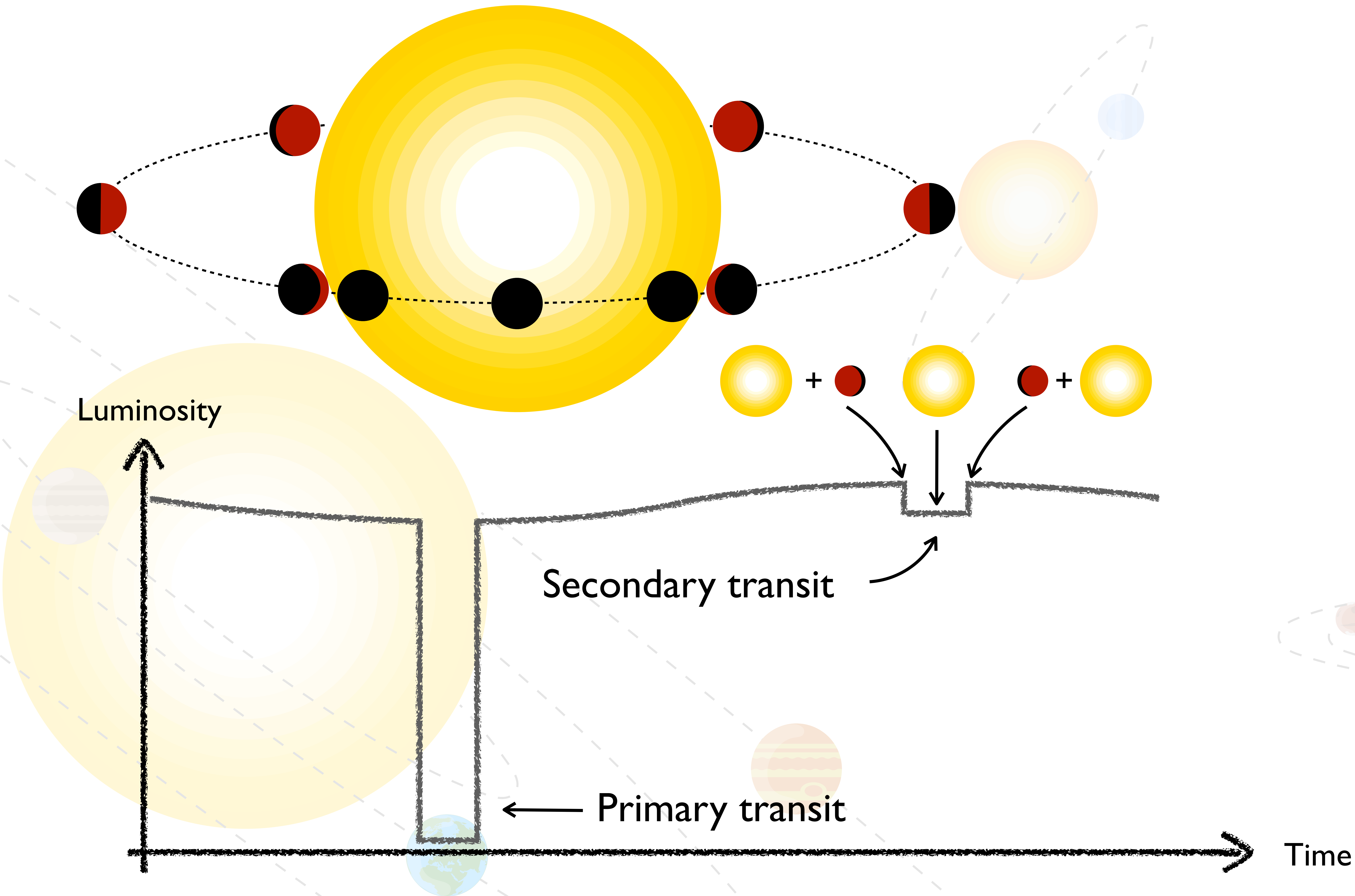


Planets characterization

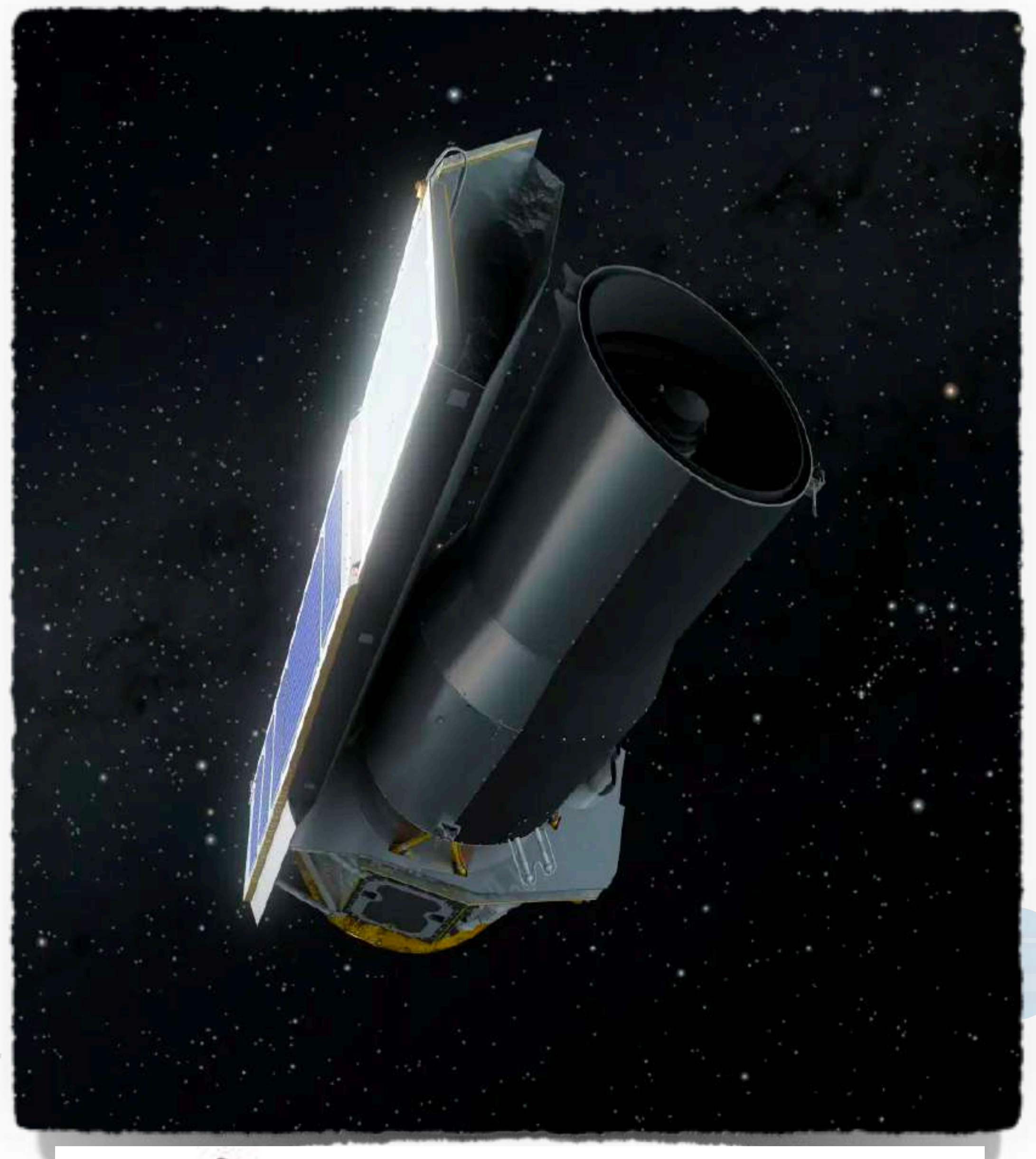


Delrez+21

Planets atmospheric characterization

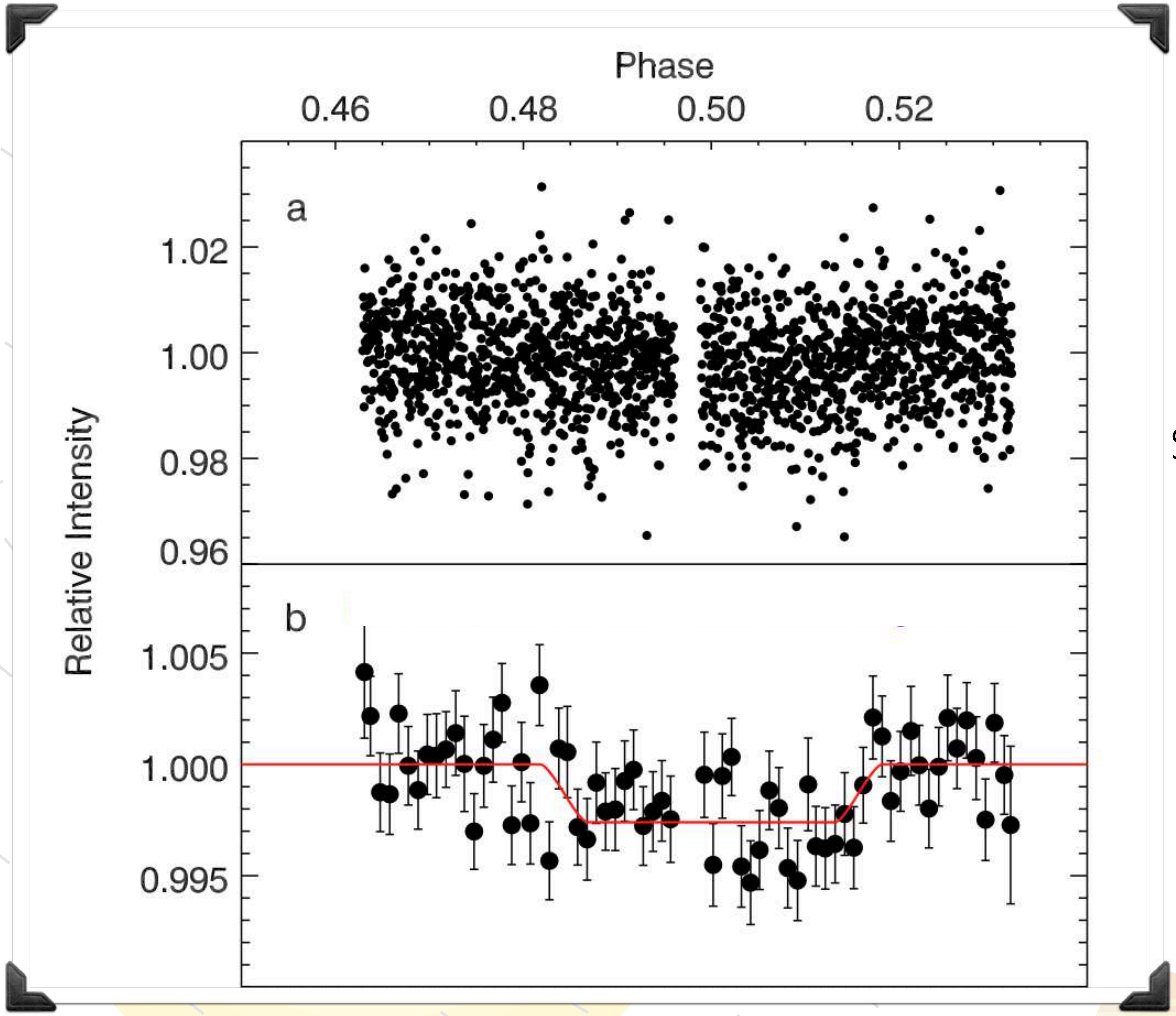


Spitzer (2003-2020)



SPITZER SPACE TELESCOPE

Planets atmospheric characterization



Data from the 24 μm channel of the Multiband Imaging Photometer for **Spitzer** (MIPS)

HD209458b

The first secondary transit of an exoplanet *[Deming+2005]*
[See also Charbonneau+2005: TrES-1*]*

Signal is hidden in noise

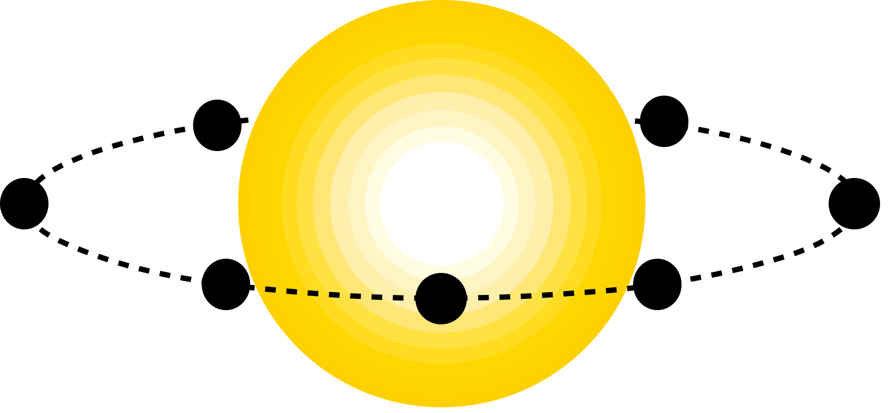
Data was binned into bins of phase width 0.001

Best-fit orbit: $D = 0.26\,\%$

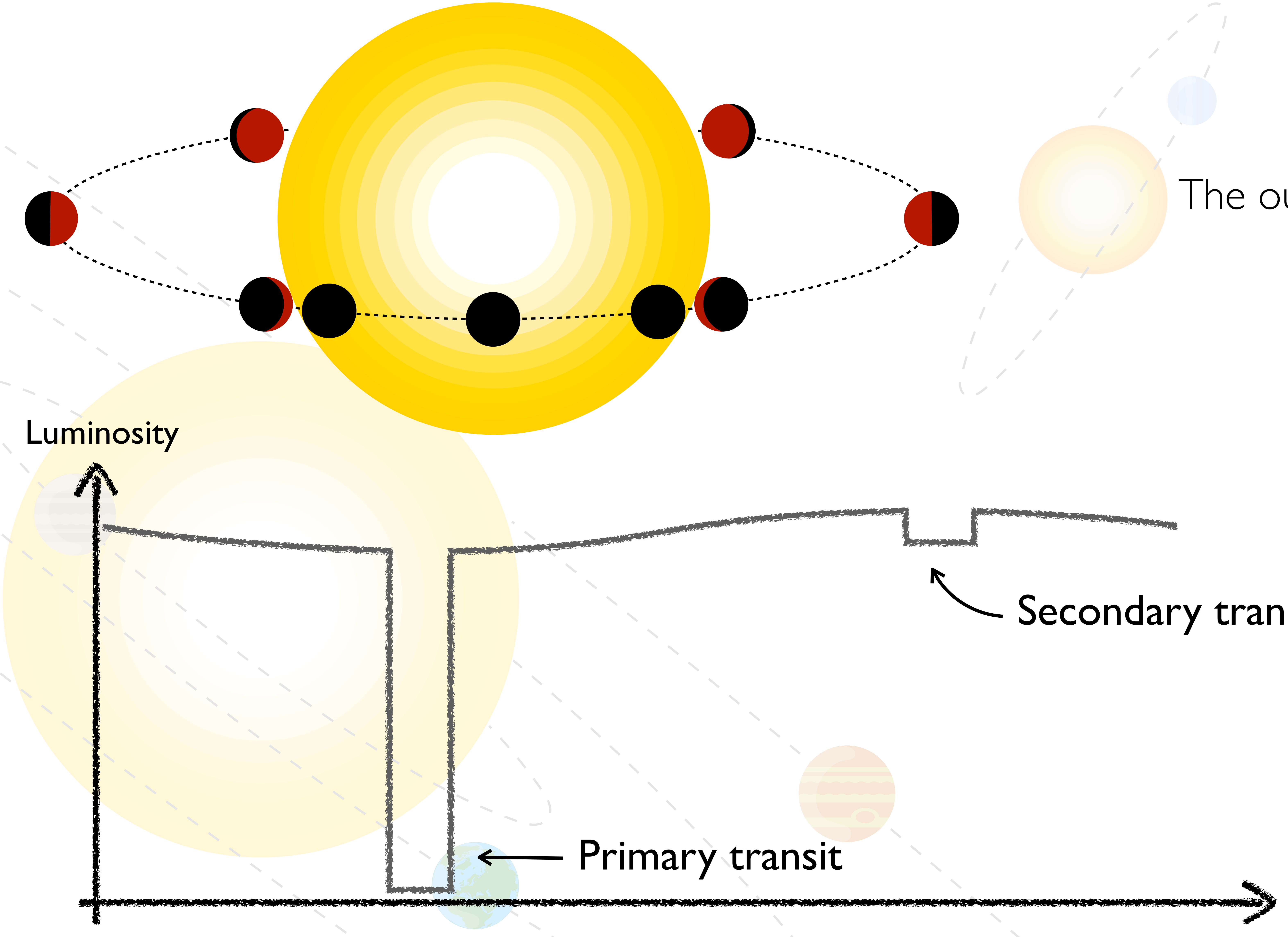
Flux at 24 μm from the planet: **55 μJy**
Brightness temperature of **1130 K**

$(1\ \mathrm{Jy} = 10^{-26}\ \mathrm{W \cdot m^{-2} \cdot Hz^{-1}})$

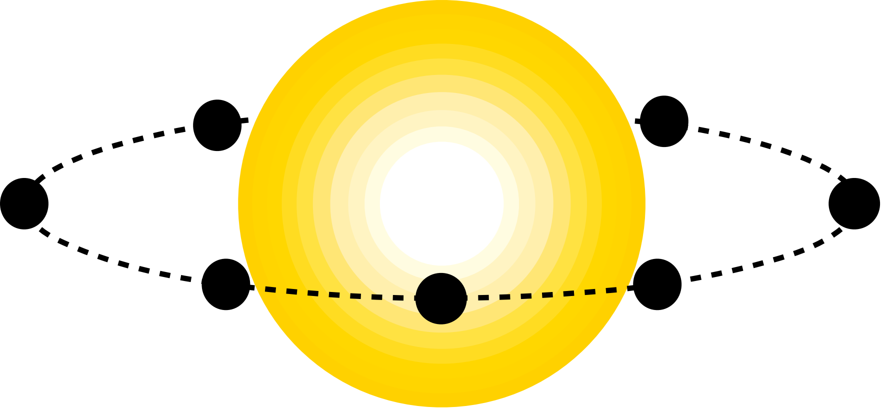
Planets atmospheric characterization

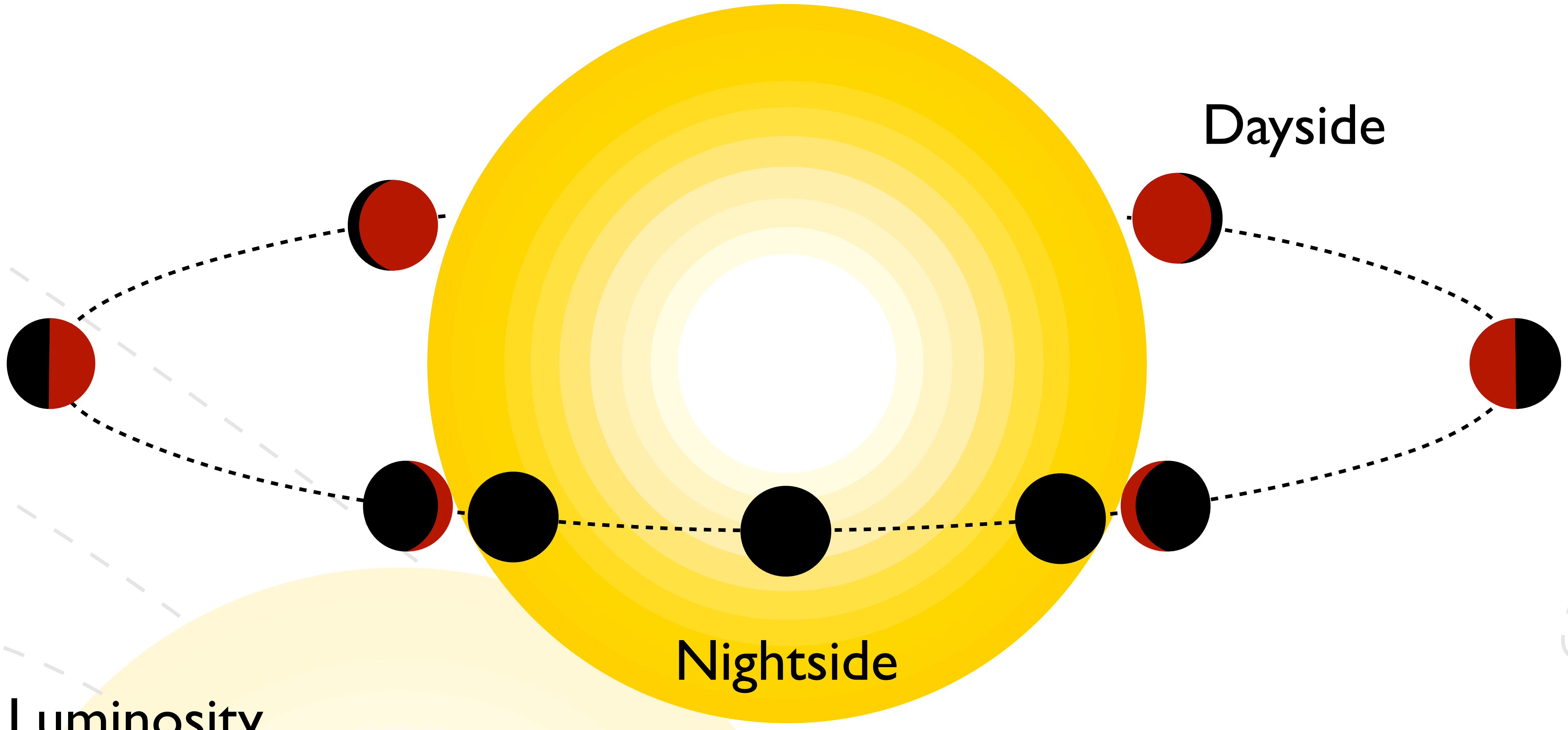


The out-of-transit wobble is a **phase-curve**



Planets atmospheric characterization





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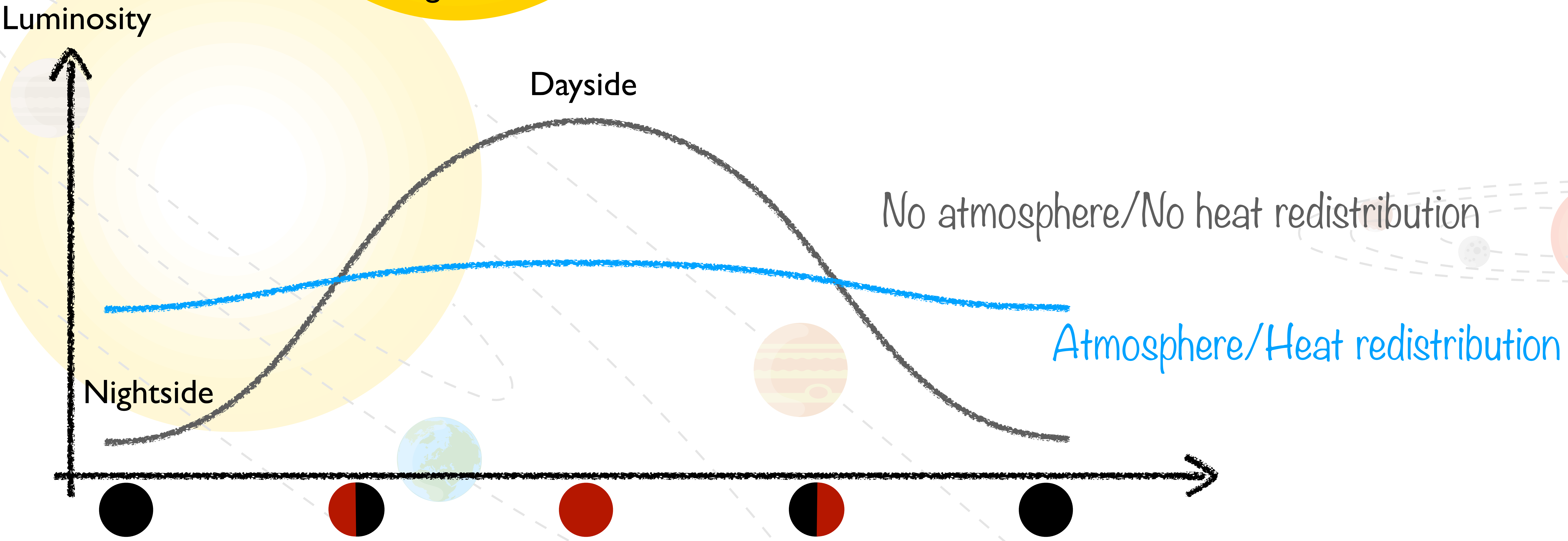
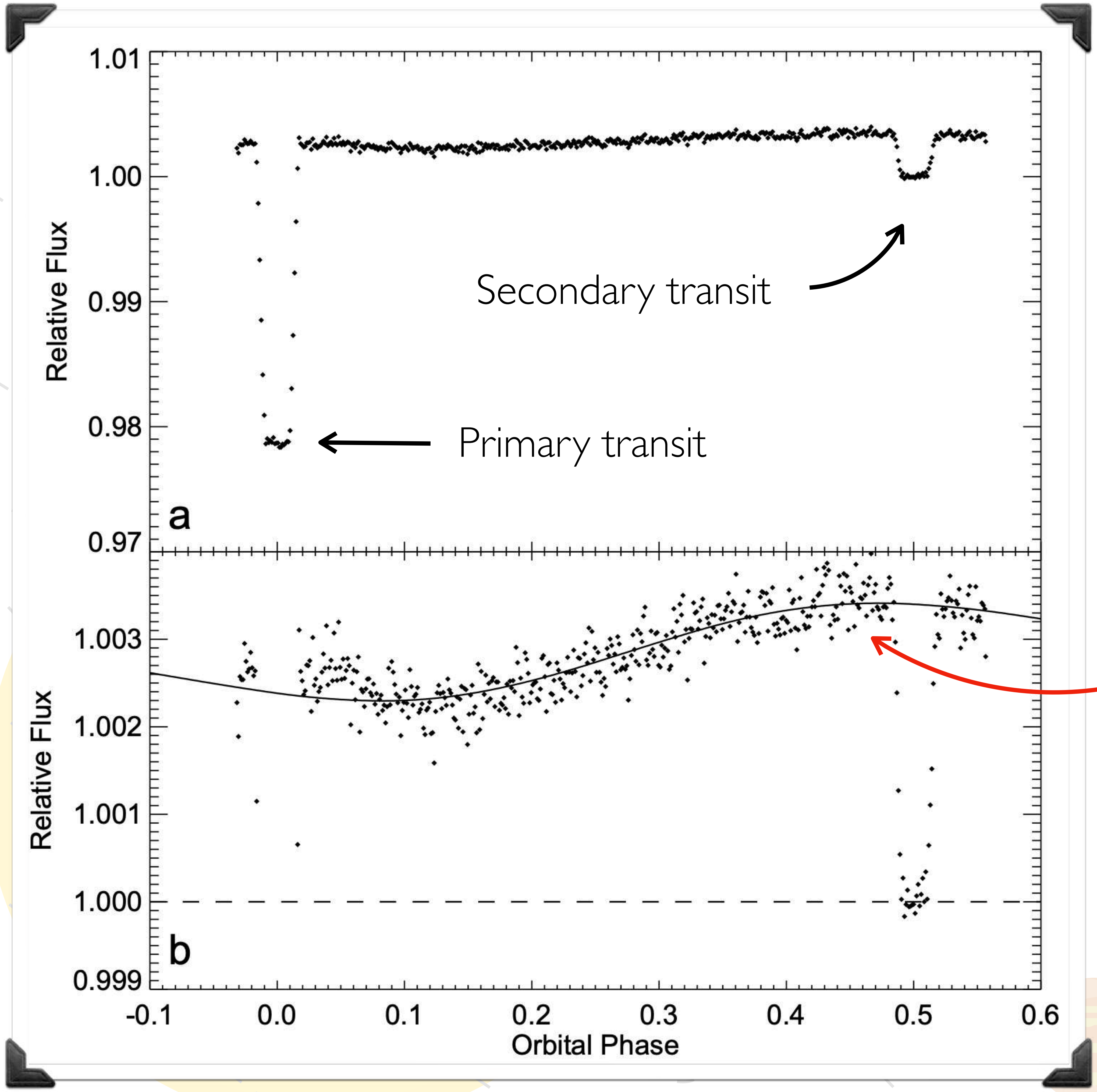


Planets atmospheric characterization



Data from the 8 μm channel of the InfraRed Array Camera for **Spitzer** (IRAC)

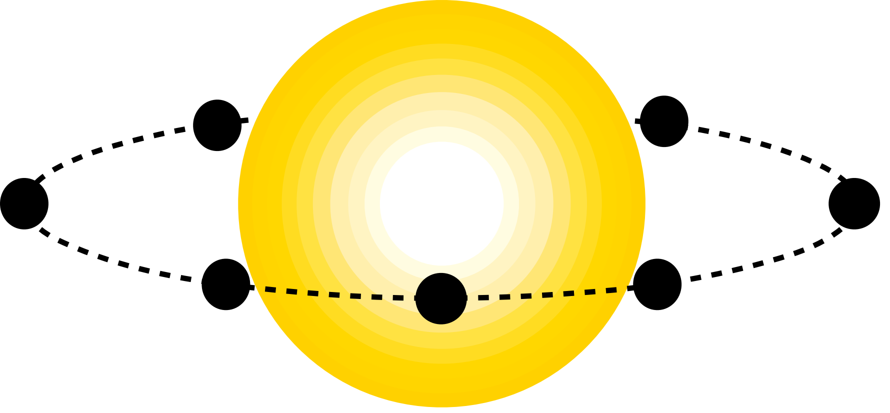
HD189733b *[Bouchy et al. 2005]*

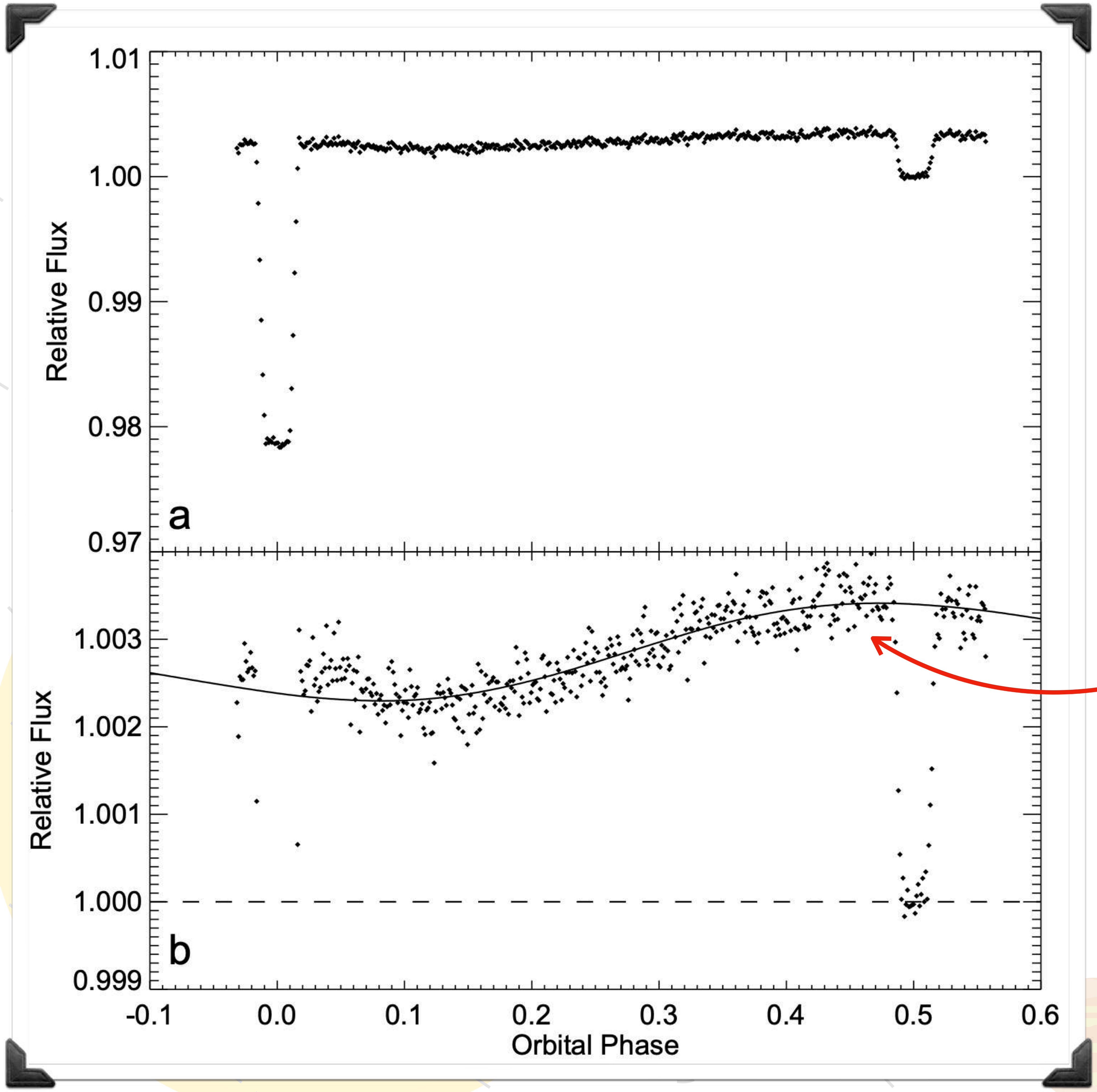
The first phase curve of an exoplanet *[Knutson+2007]*

Note that the **maximum of the phase curve** does not occur at secondary transit but is **shifted in phase**

A quoi ce décalage peut être dû ?

Planets atmospheric characterization





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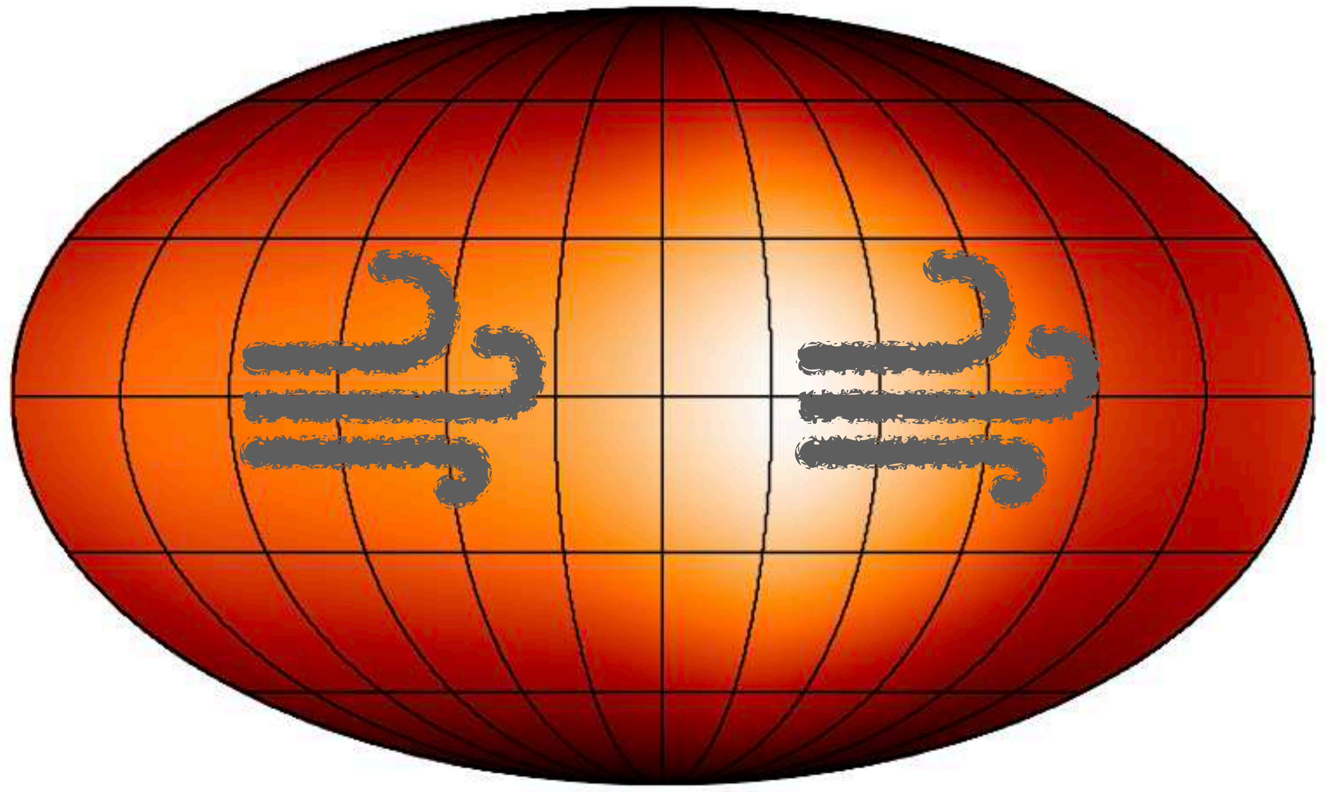
HD189733b *[Bouchy et al. 2005]*

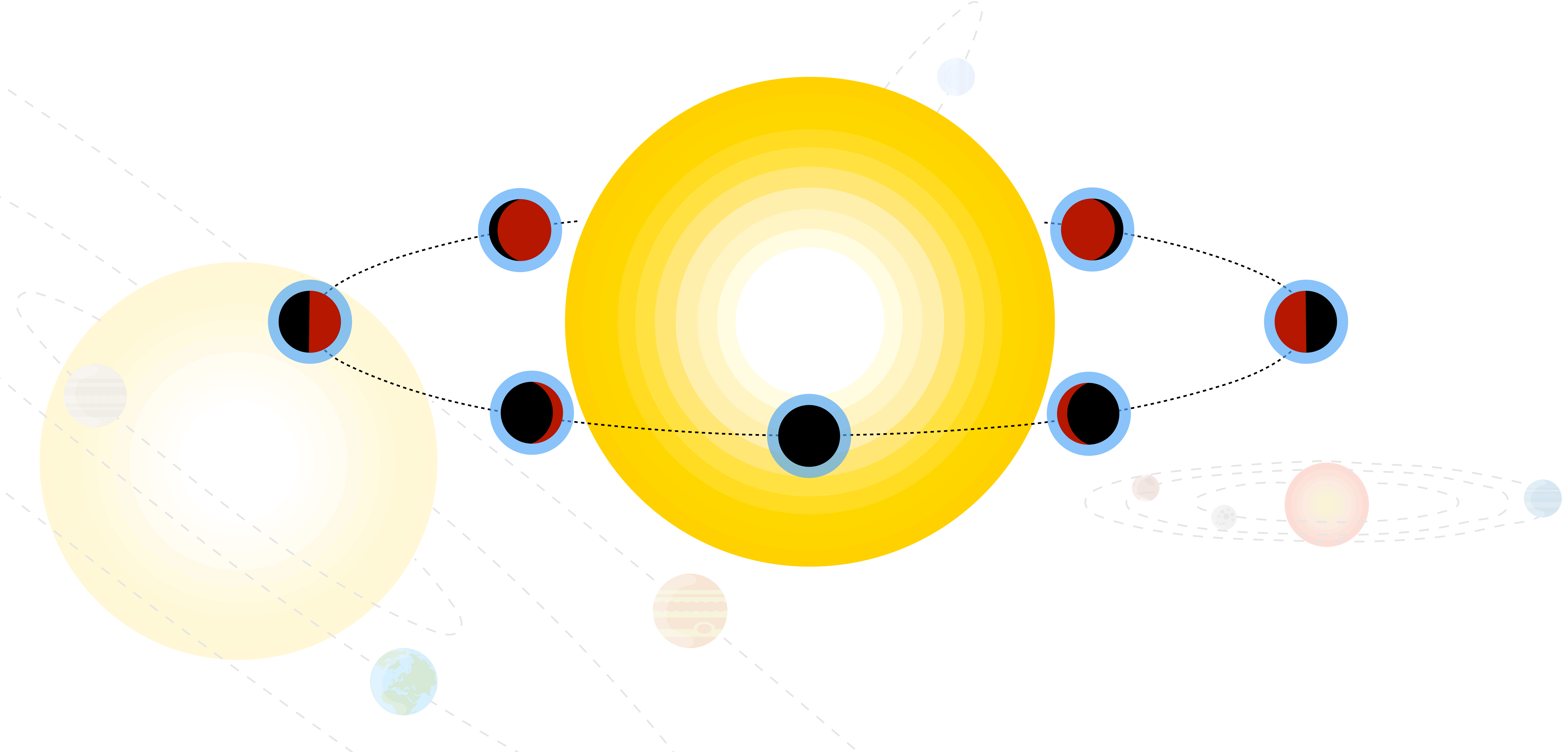
The first phase curve of an exoplanet *[Knutson+2007]*

Note that the **maximum of the phase curve** does not occur at secondary transit but is **shifted in phase**

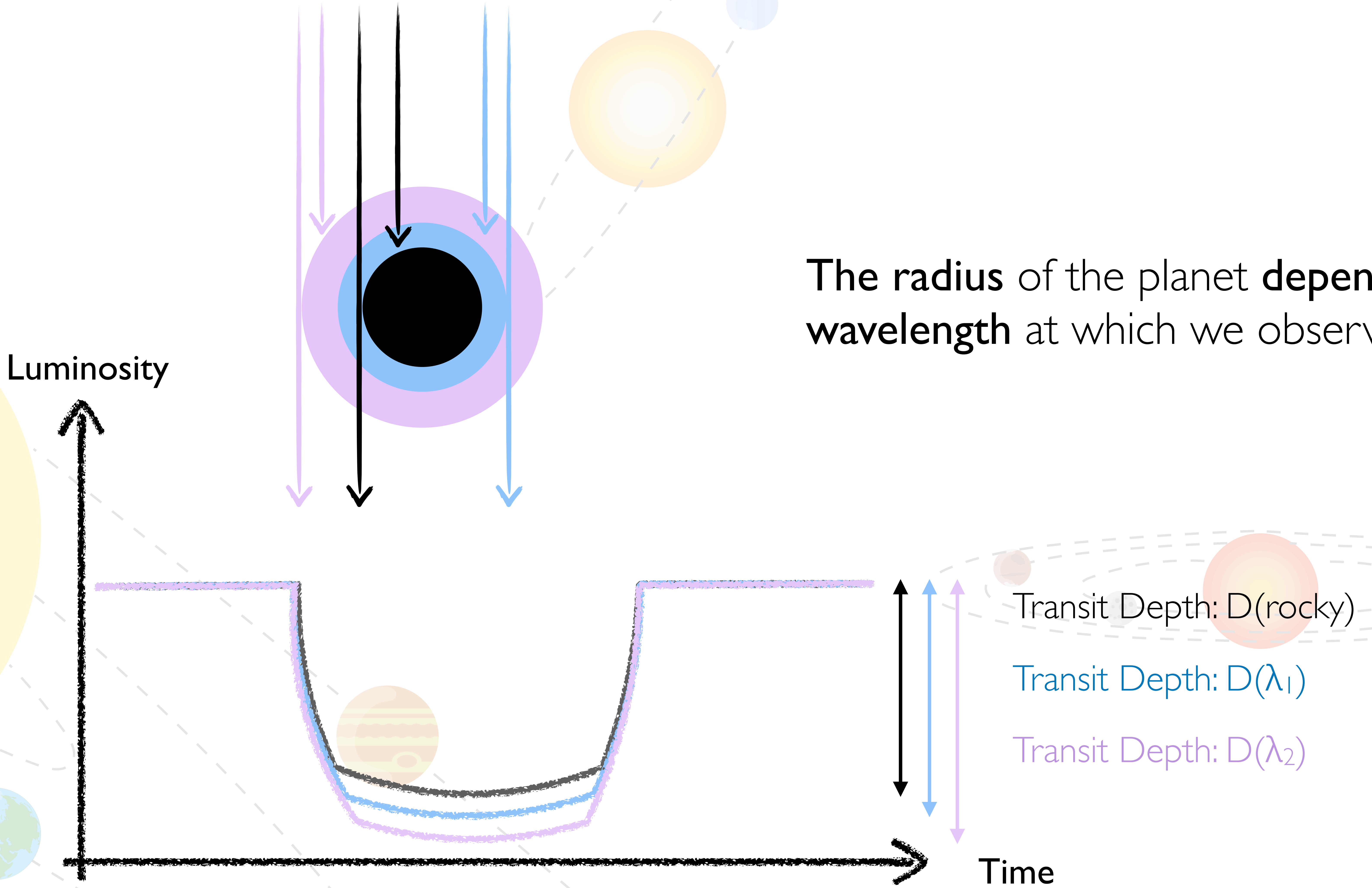
Hottest point is not the substellar point: it is **shifted eastward**, which is a **sign of heat redistribution**



Planets atmospheric characterization



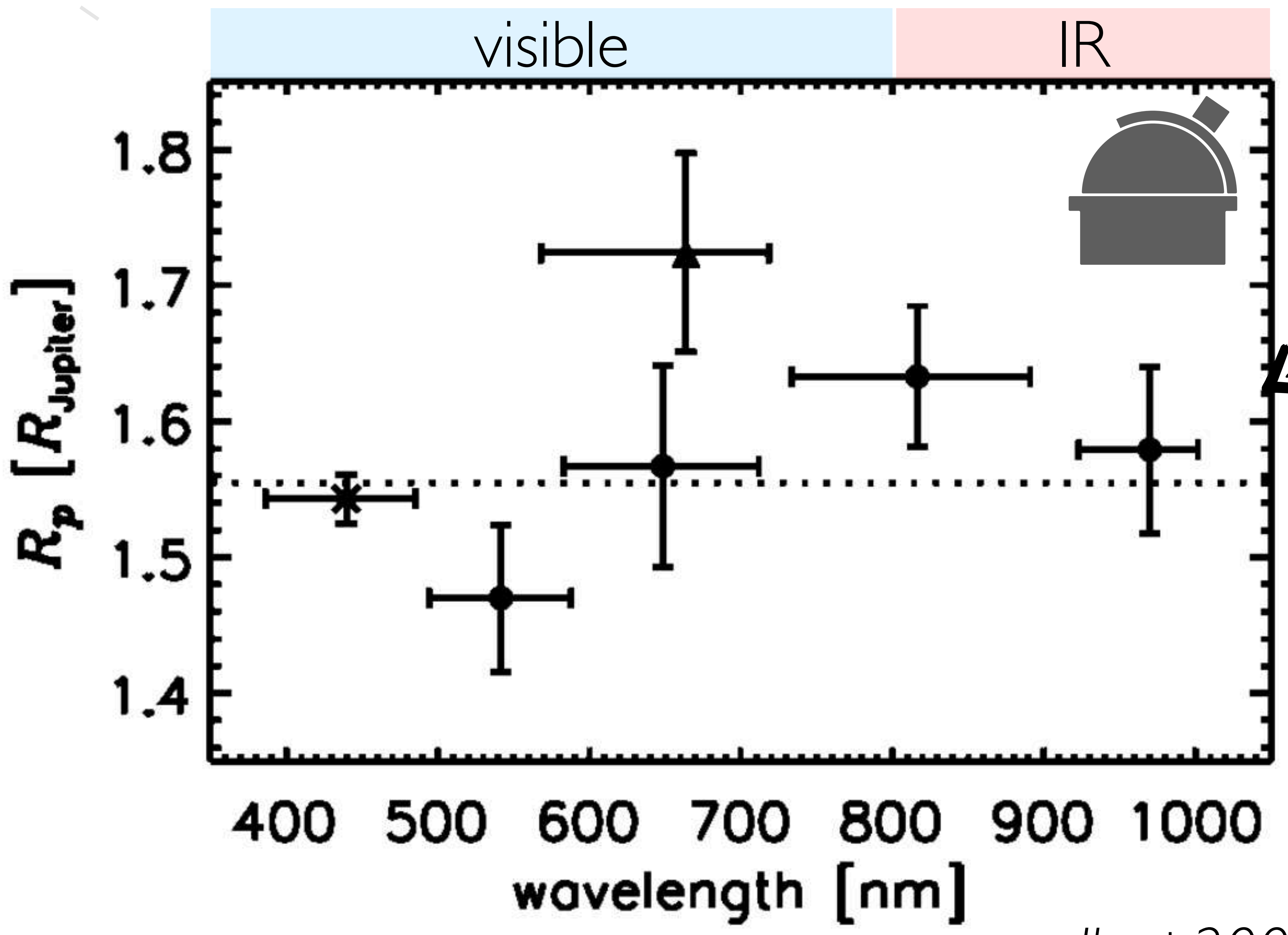
Planets atmospheric characterization



The radius of the planet **depends** on the **wavelength** at which we observe

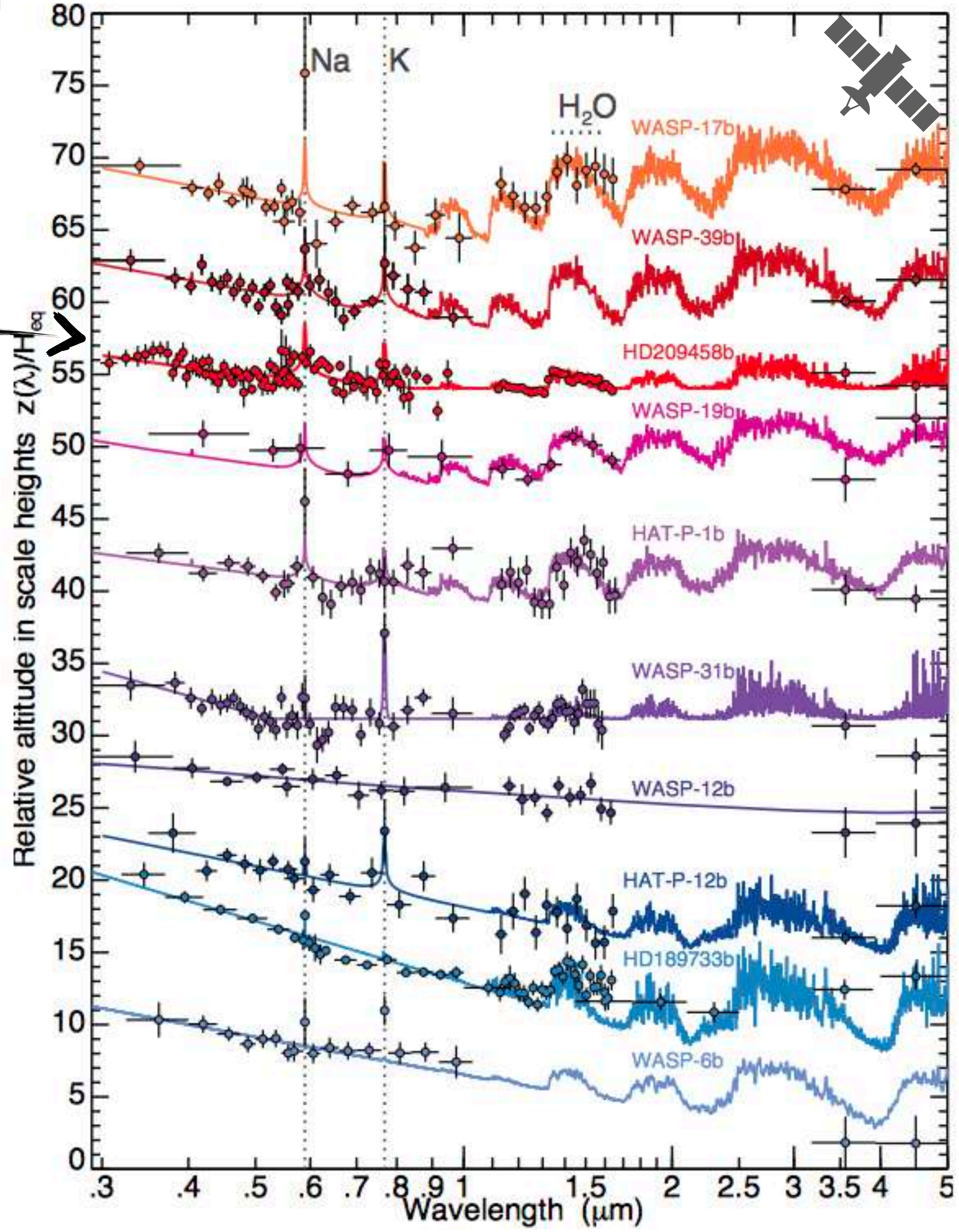
Planets atmospheric characterization

HD 209458 b



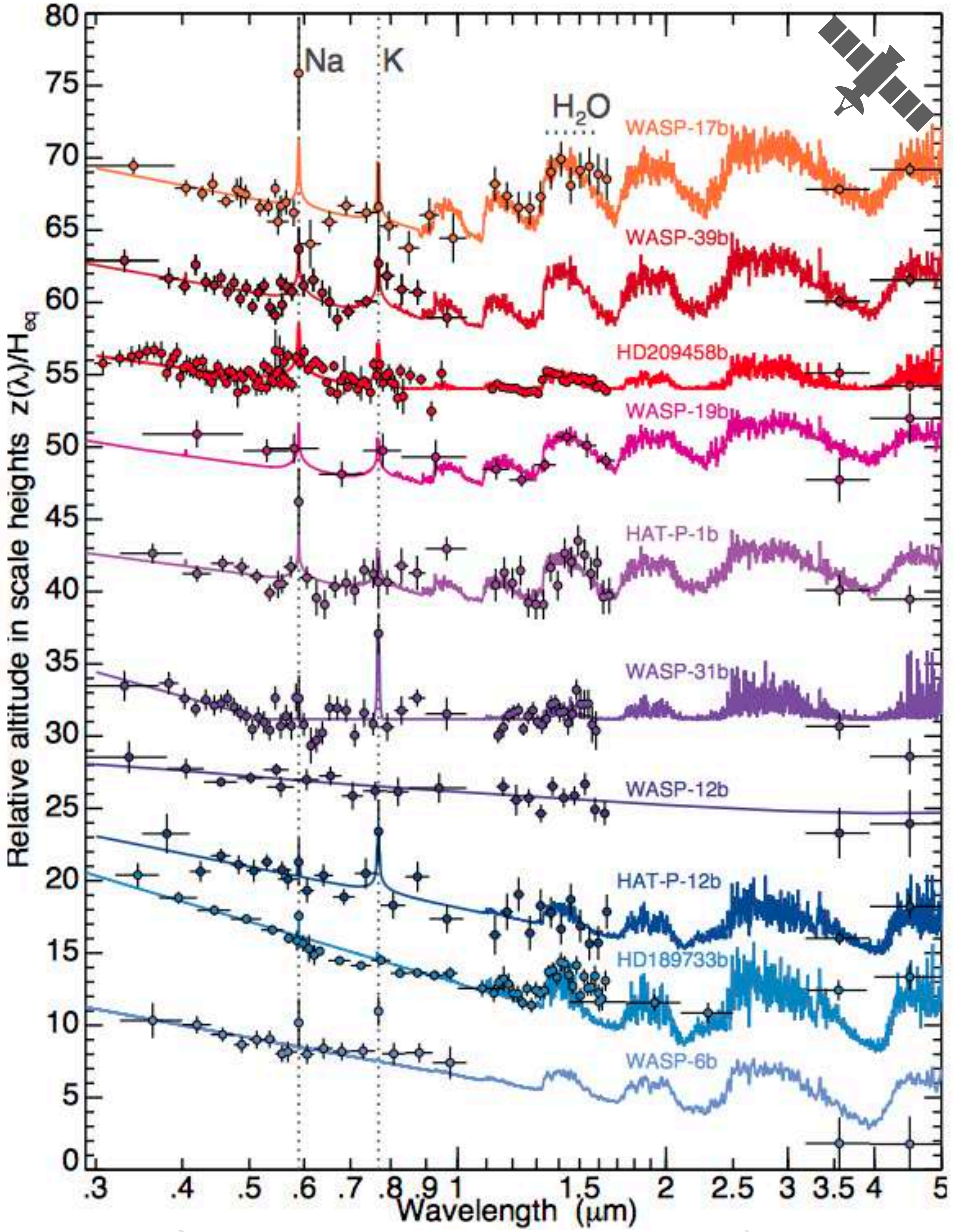
Jha+2000

What a difference of 16 years makes



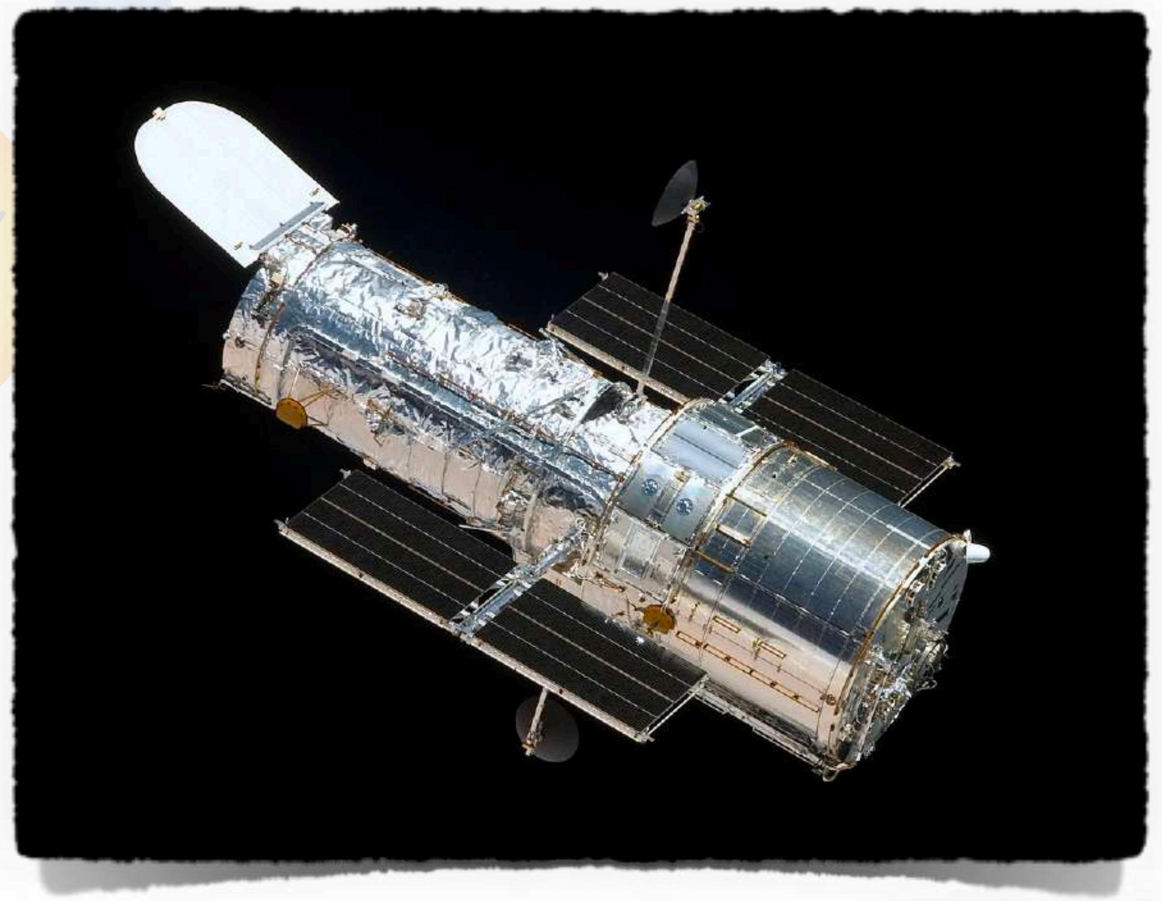
Sing+2016

Planets atmospheric characterization

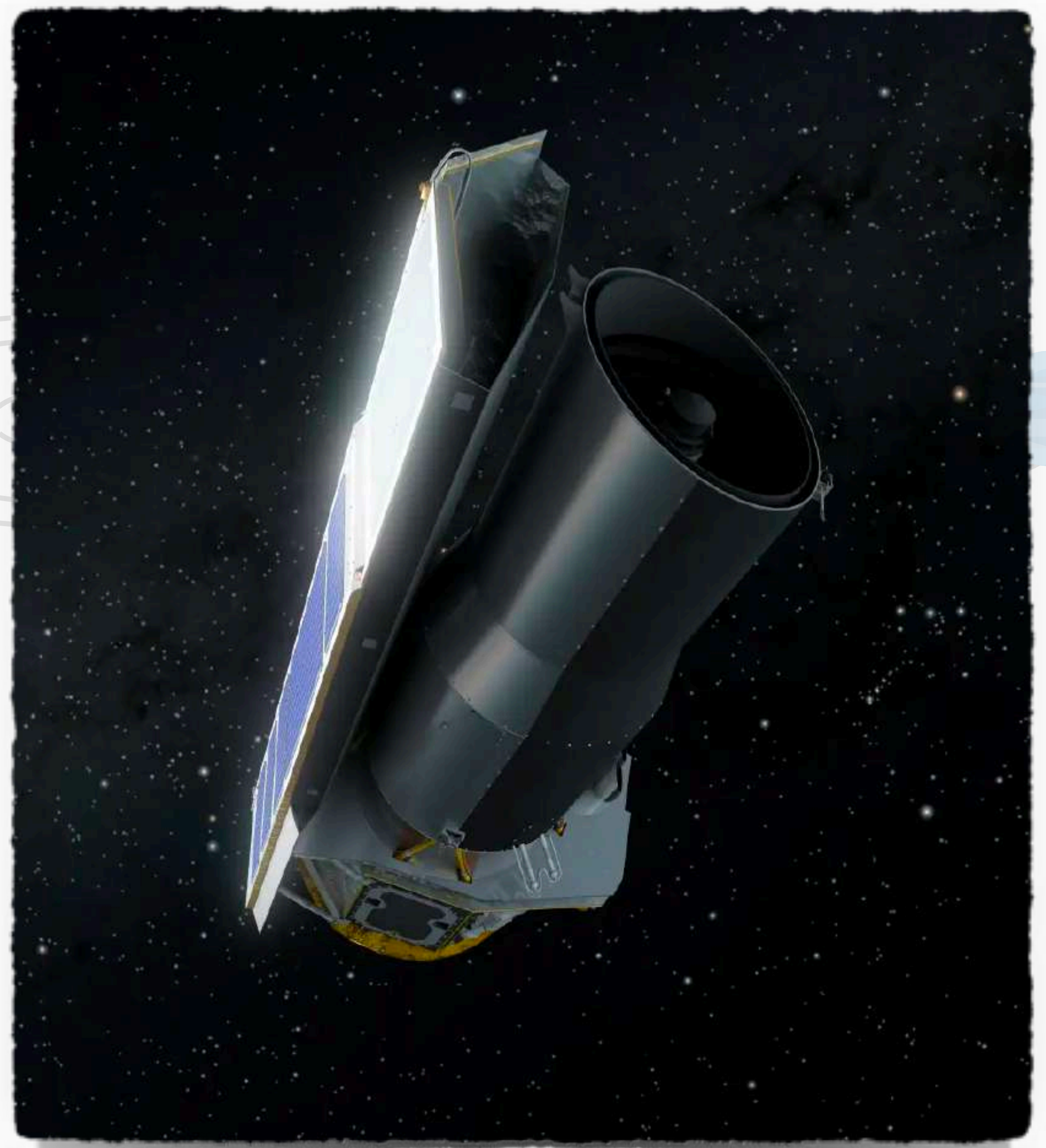


Sing+2016

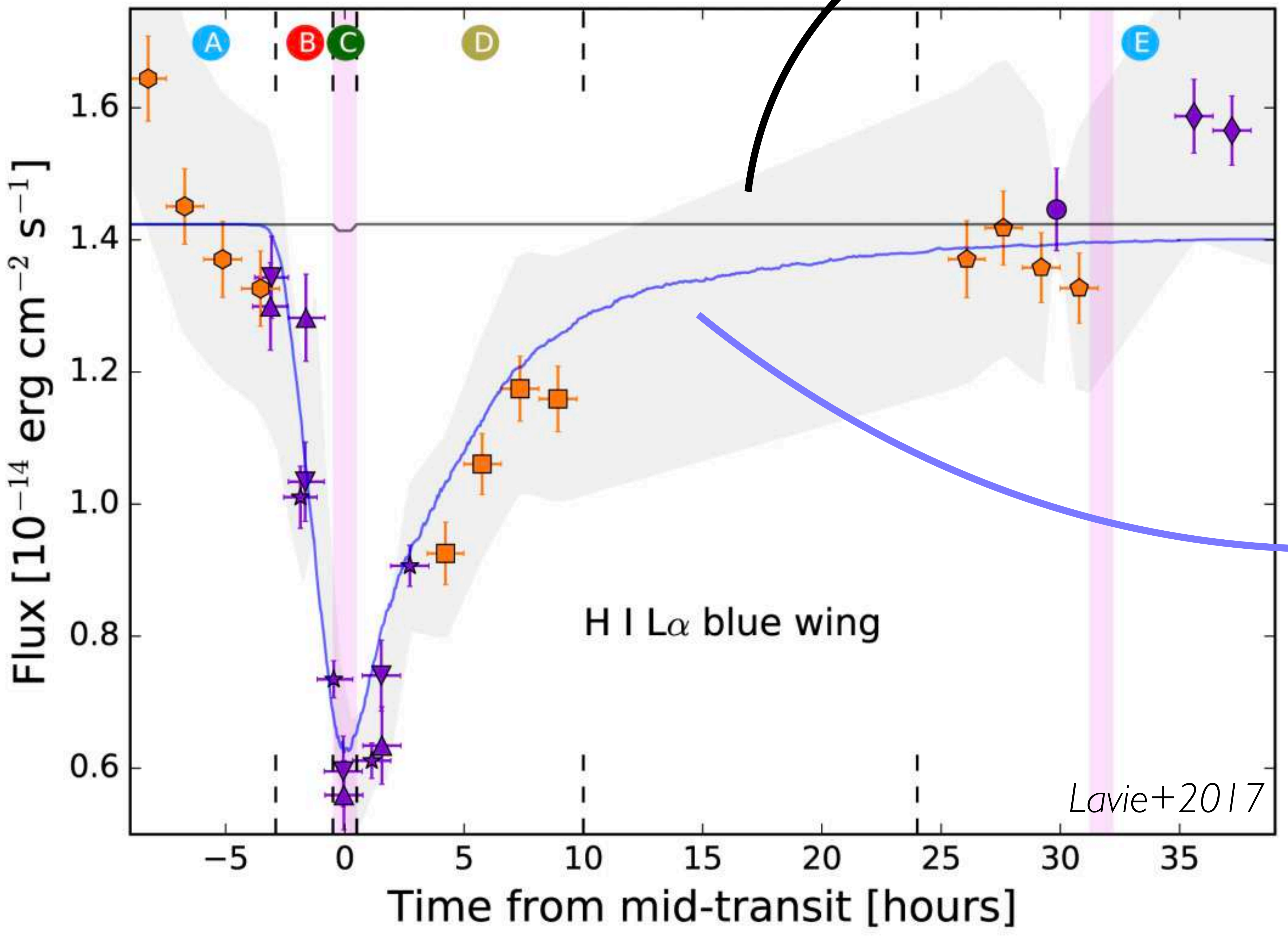
Hubble Space Telescope



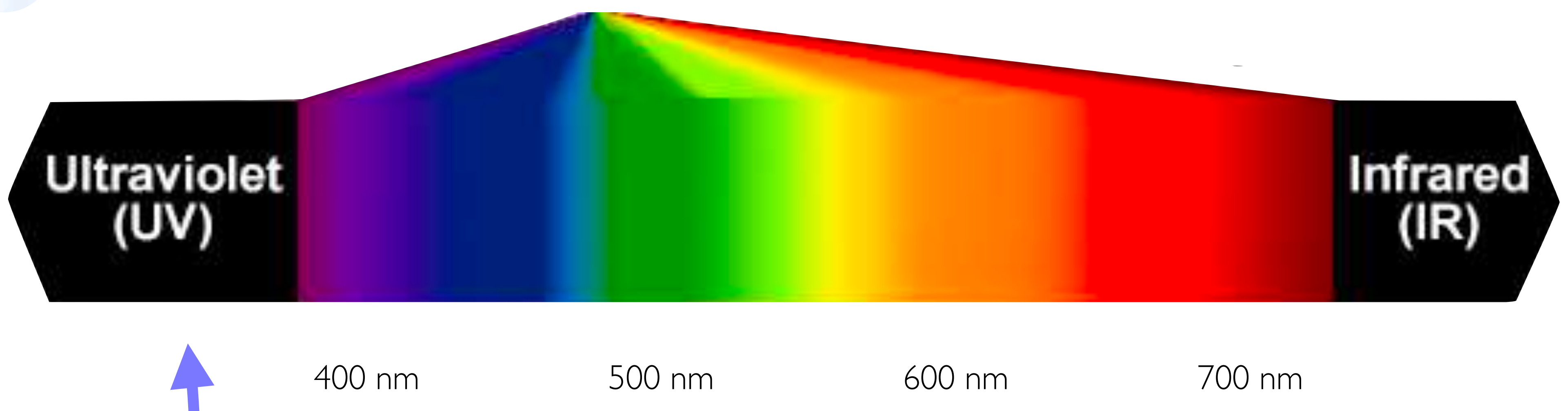
Spitzer



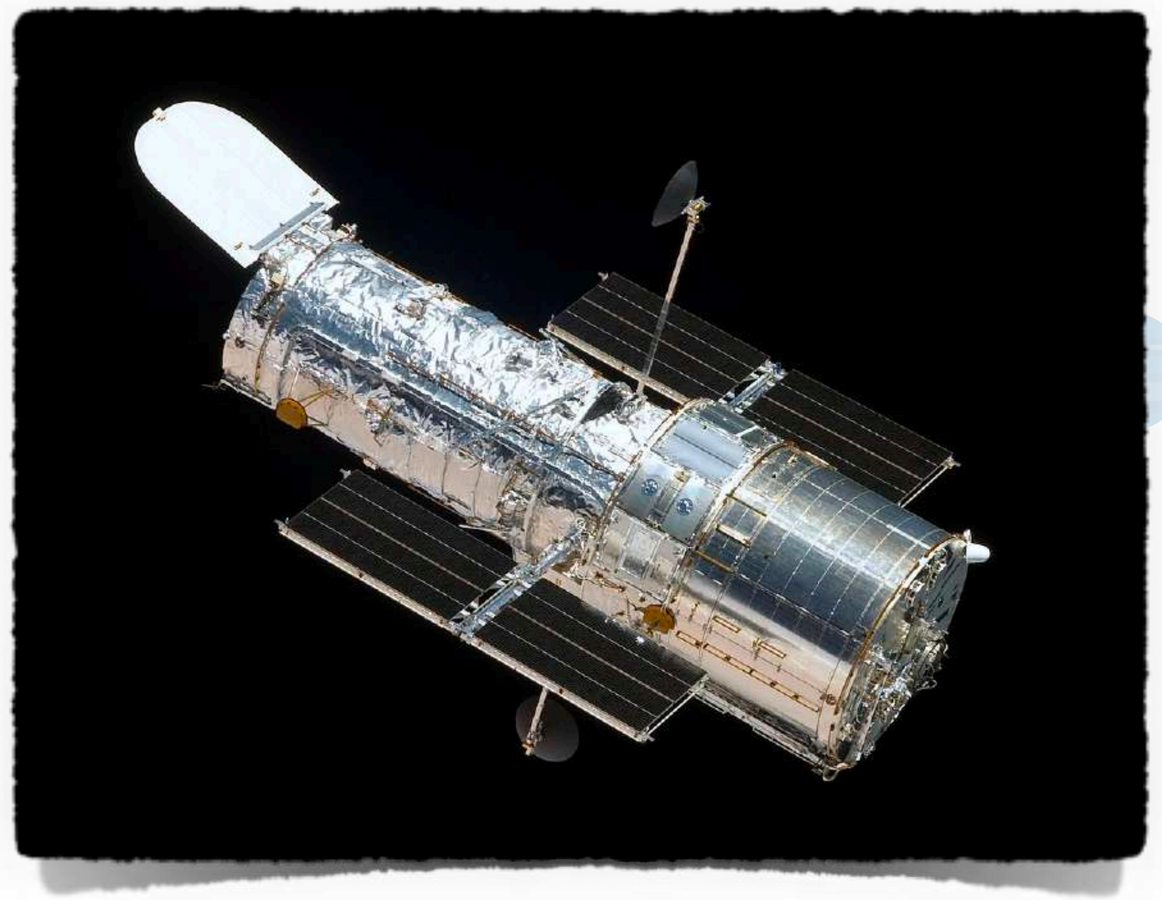
Planets atmospheric characterization



Transit dans le visible

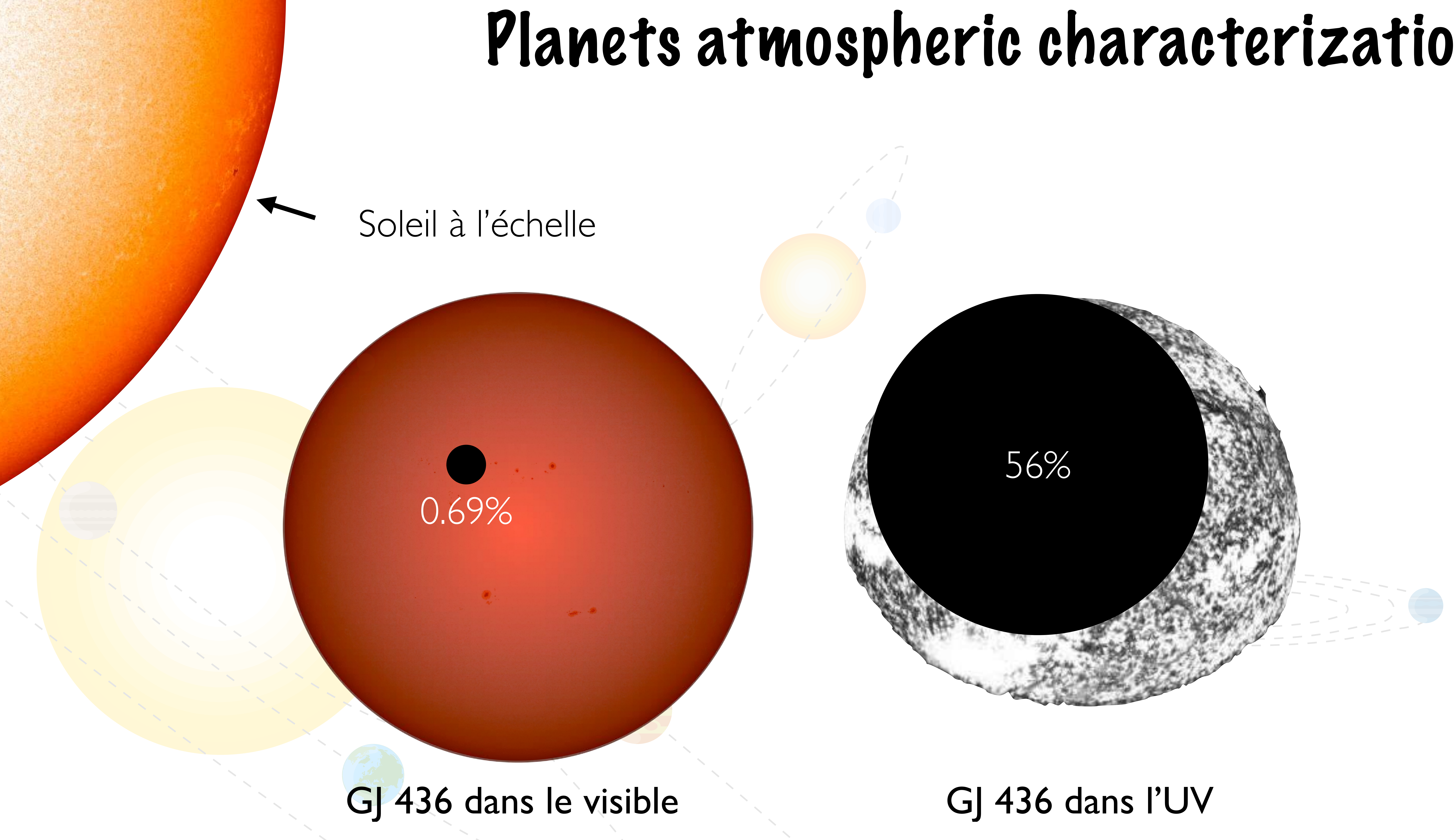


Transit dans l'UV



Hubble Space Telescope

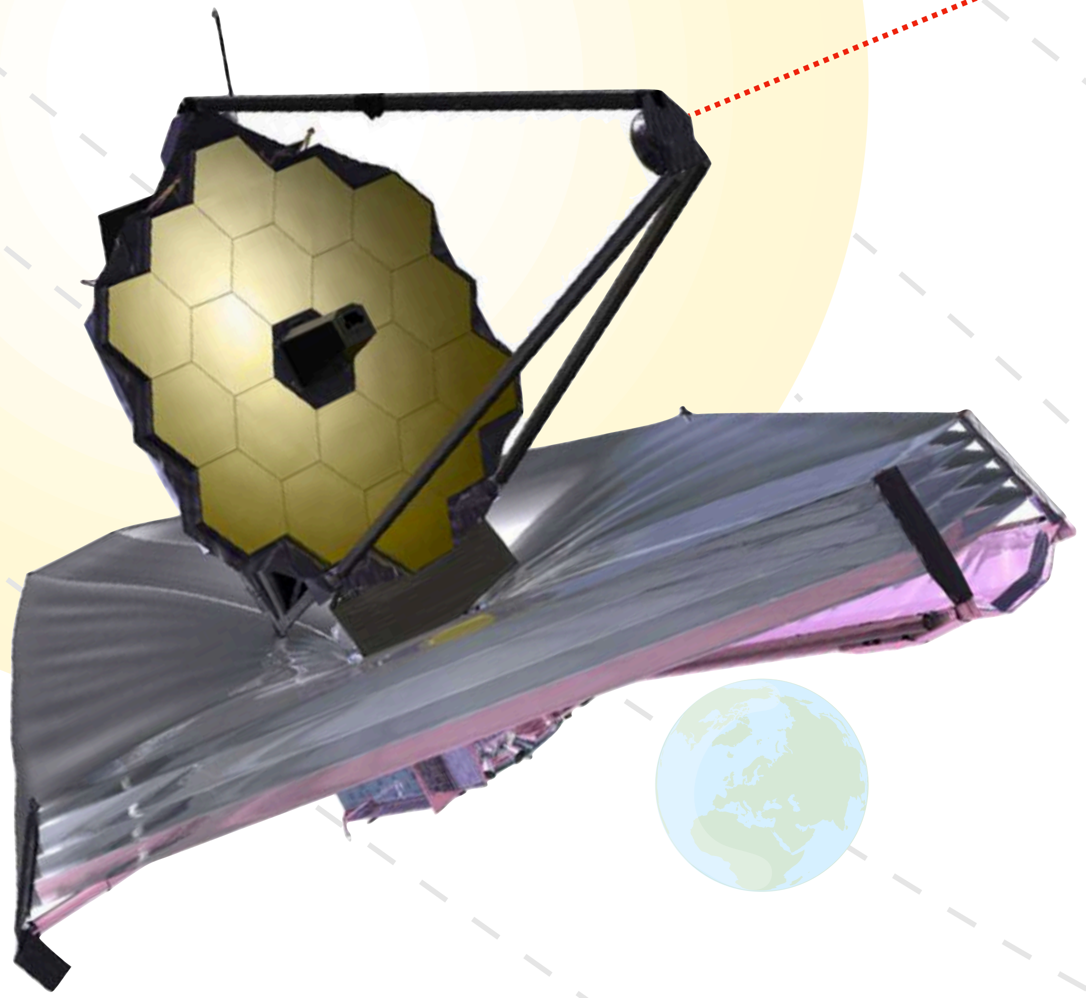
Planets atmospheric characterization

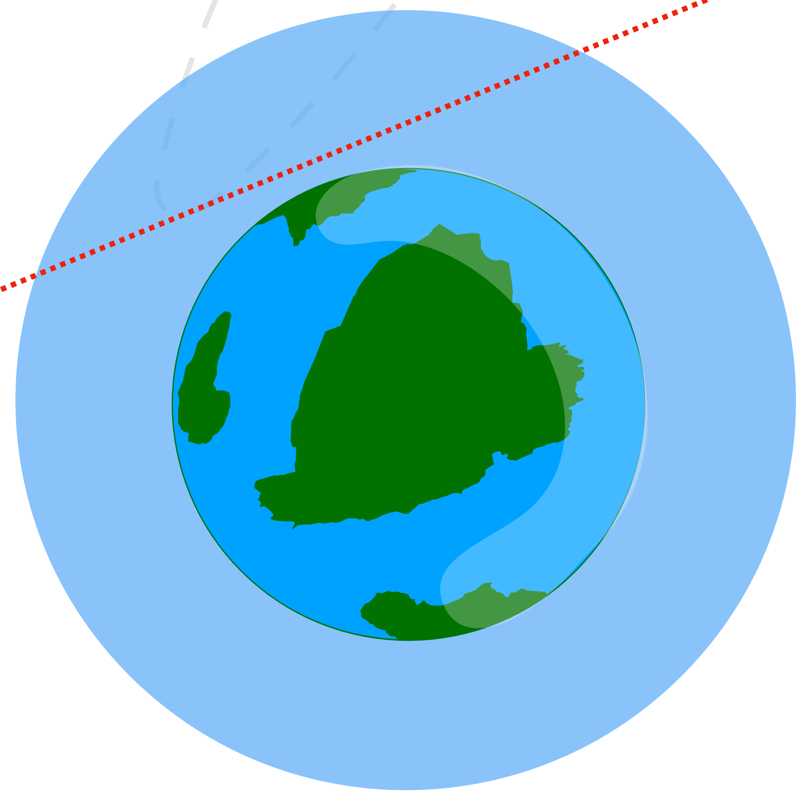


Planets atmospheric characterization

Planets atmospheric characterization

The James Webb Space Telescope (JWST)





Launch in Dec. 2021

Planets atmospheric characterization

TRAPPIST-1
[Gillon+16, 17]

Planets atmospheric characterization

The end!