Introduction of Exoplanet detection and analysis methods

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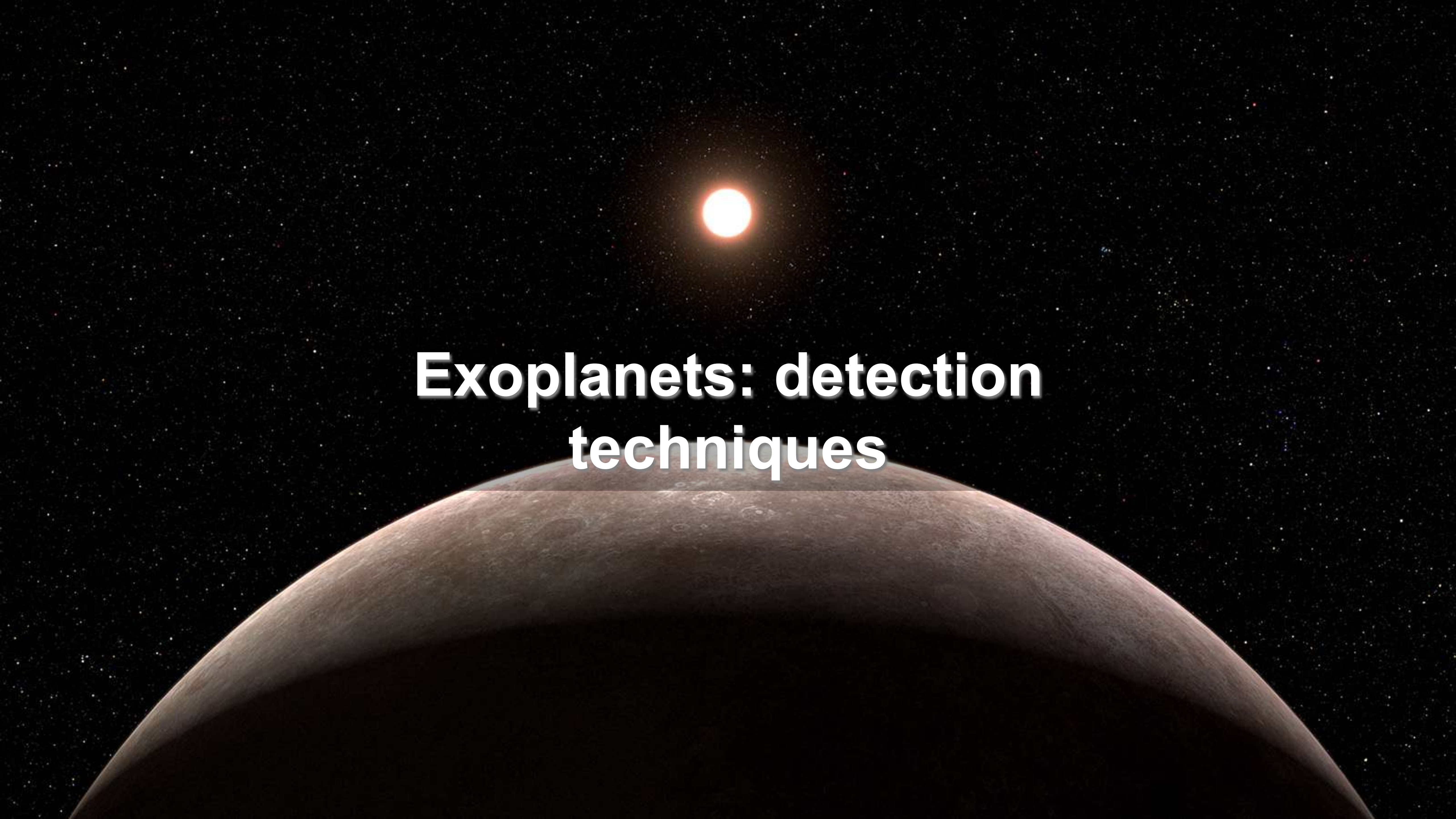
European Research Council
Established by the European Commission

Exoplanets: detection techniques



Finding planets is complicated…

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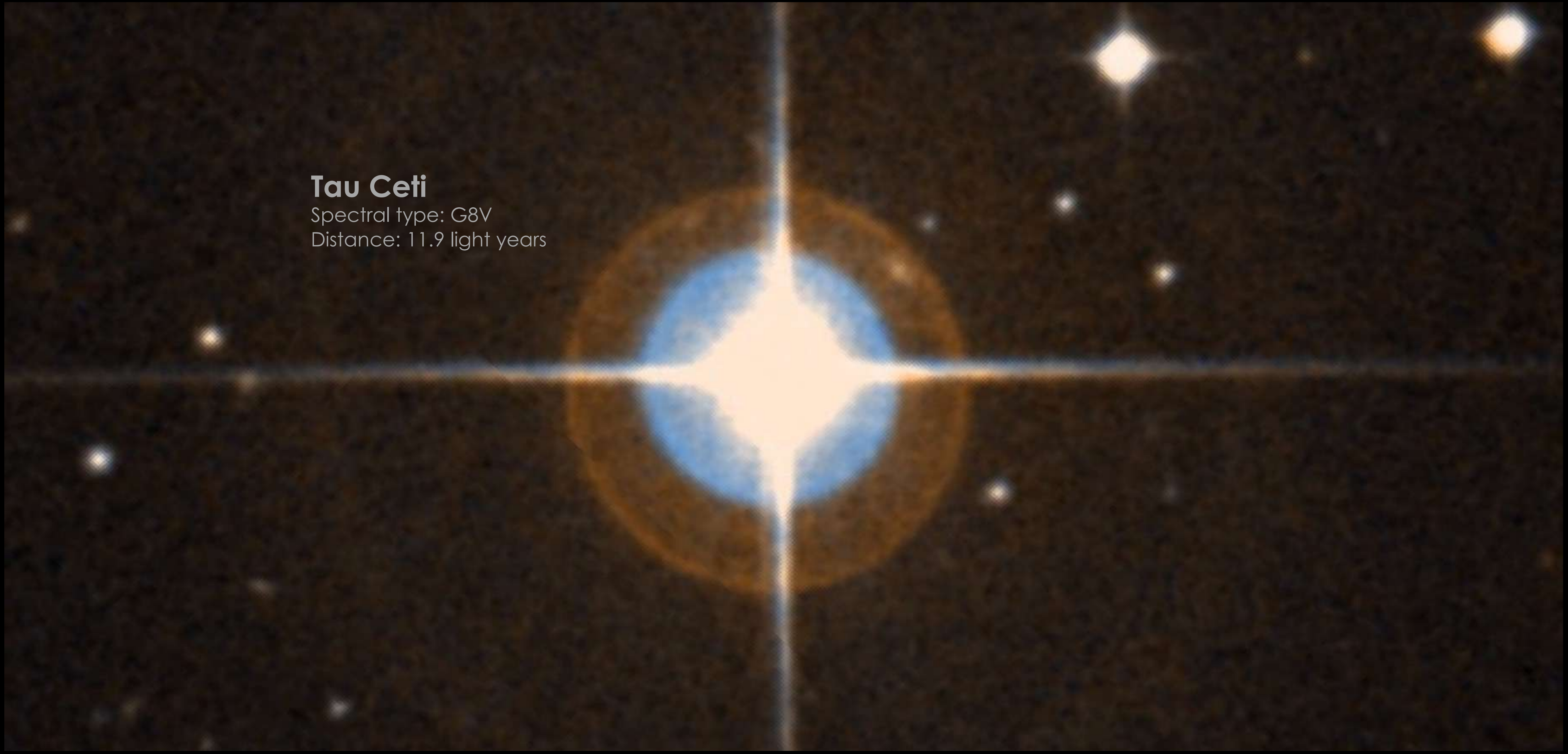
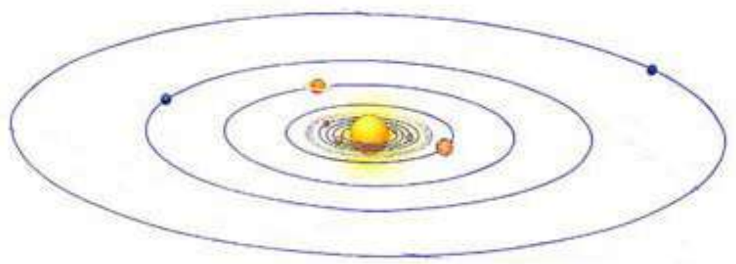
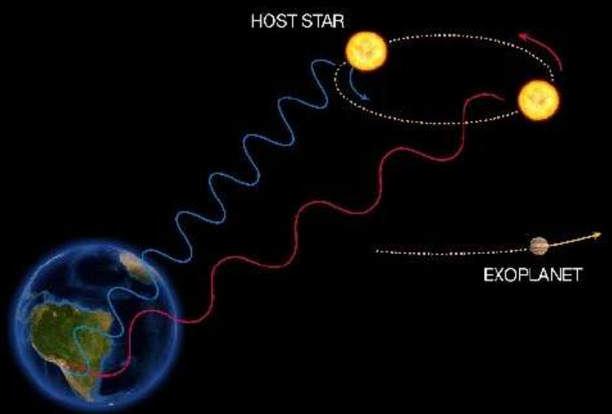


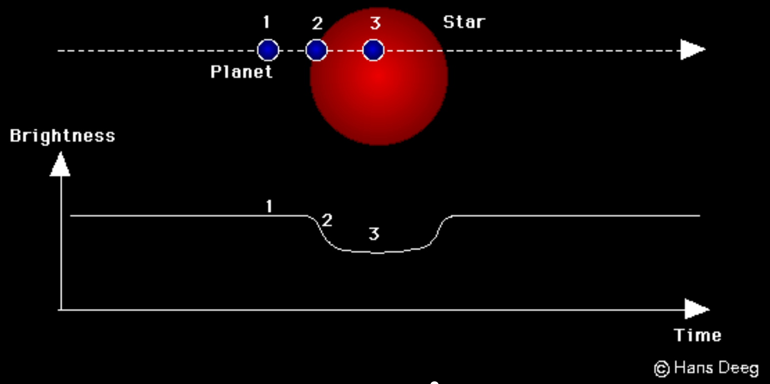


10^9 times fainter…

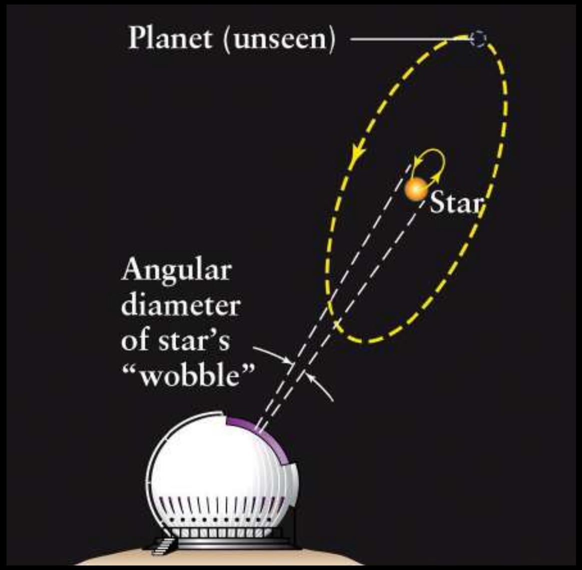
How do we find exoplanets?



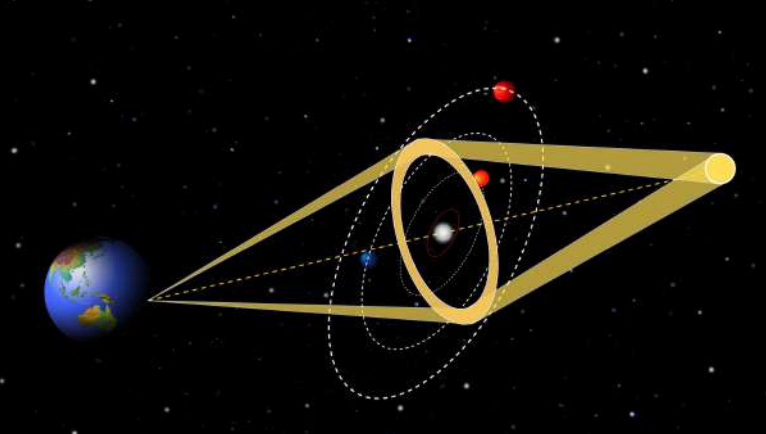
Doppler
(radial velocities)



Transits

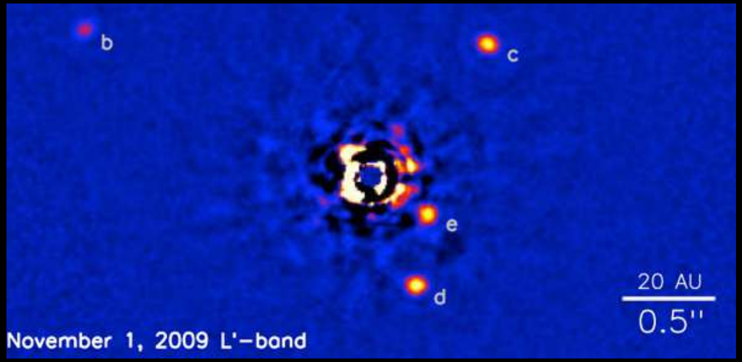


Astrometry



Gravitational lensing

Indirect methods



Direct imaging

Historical introduction

Astrometry

- **<u>70 Ophiuchi – binary star at 17 light years</u>**

Monthly Notices of the Royal Astronomical Society (1855)

On certain Anomalies presented by the Binary Star 70 Ophiuchi.
By Capt. W. S. Jacob, Madras Astronomer.

First exoplanet announced… in 1855!

Orbital period = 16 years

Other announcements referring to the same system: Thomas J.J. See (1899) & Dirk Reuyl (1943)

- **<u>Other stars: Barnard's Star, Lalande 21185, 61 Cygni, etc</u>**

Peter van de Kamp
(1901-1995)

THE ASTRONOMICAL JOURNAL VOLUME 68, NUMBER 7 SEPTEMBER 1963

Astrometric Study of Barnard's Star from Plates Taken with the 24-inch Sproul Refractor

PETER VAN DE KAMP
Sproul Observatory, Swarthmore College
(Received 21 June 1963)

Twenty-five consecutive years of photographic observations of Barnard's star show deviations from uniform proper motion and secular acceleration which can be represented by Keplerian motion with a period of 24 yr and semi-axis major of $0''.0245 \pm 0''.002$ (p.e.). Assuming a value of $0.15\odot$ for the mass of Barnard's star, the mass of the companion proves to be $0.0015\odot$, or 1.6 times the mass of Jupiter.

All these detections ended up being dismissed

Historical introduction

Radial velocities

Otto Struve
(1897-1963)

Proposal for a project of high-precision stellar radial velocity work

The Observatory, Vol. 72, p. 199-200 (1952)

We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

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,

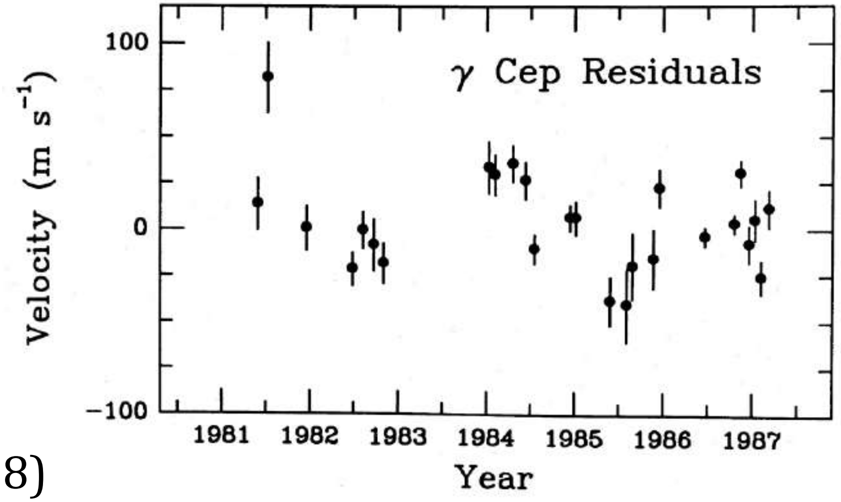
Precision ~ 750 m/s

A SEARCH FOR SUBSTELLAR COMPANIONS TO SOLAR-TYPE STARS

BRUCE CAMPBELL[1]
Department of Physics and Astronomy, University of Victoria; and Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics

AND

G. A. H. WALKER[1] AND S. YANG[1]
Department of Geophysics and Astronomy, University of British Columbia
Received 1987 December 14; accepted 1988 February 4



Precision ~ 10-15 m/s

The Astrophysical Journal (1988)

Historical introduction

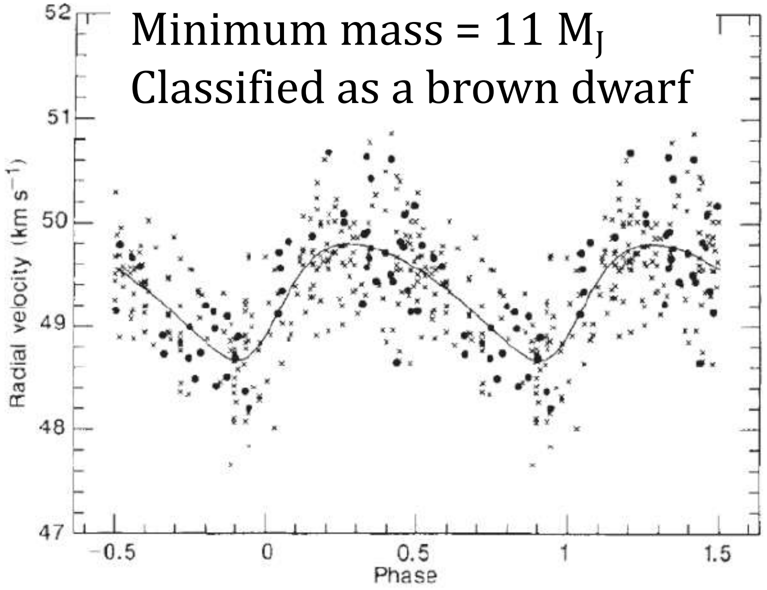
The unseen companion of HD114762: a probable brown dwarf

1989

David W. Latham*, Tsevi Mazeh†, Robert P. Stefanik*, Michel Mayor‡ & Gilbert Burki‡

* Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
† School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Science, Tel Aviv University, Tel Aviv 69978, Israel
‡ Observatoire de Genève, Chemin des Maillettes 51, Ch-1290 Sauverny, Switzerland

Orbital period = 84 days
Minimum mass = 11 M_J
Classified as a brown dwarf



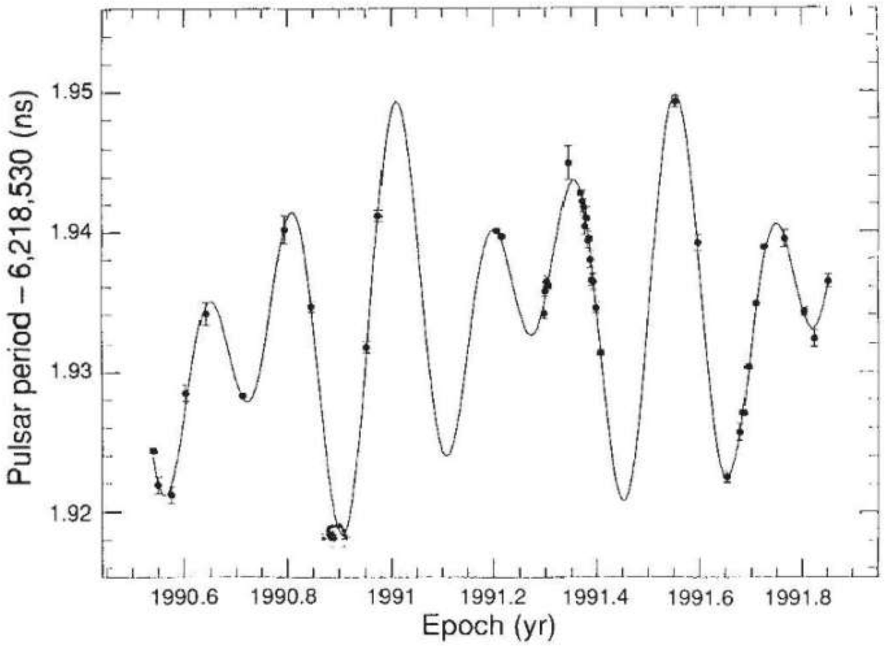
A planetary system around the millisecond pulsar PSR1257+12

1992

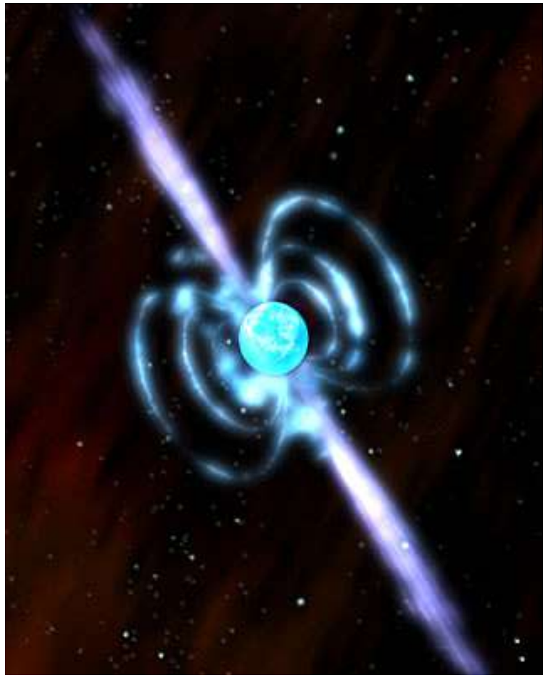
A. Wolszczan* & D. A. Frail†

* National Astronomy and Ionosphere Center, Arecibo Observatory, Arecibo, Puerto Rico 00613, USA
† National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA

Millisecond pulsar
Radio observations (Arecibo)



2 planets ≥ 3 M_{Earth}
Second generation planets?



Historical introduction

A Jupiter-mass companion to a solar-type star

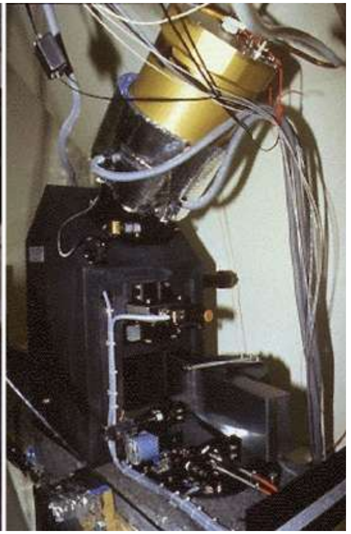
Michel Mayor & Didier Queloz

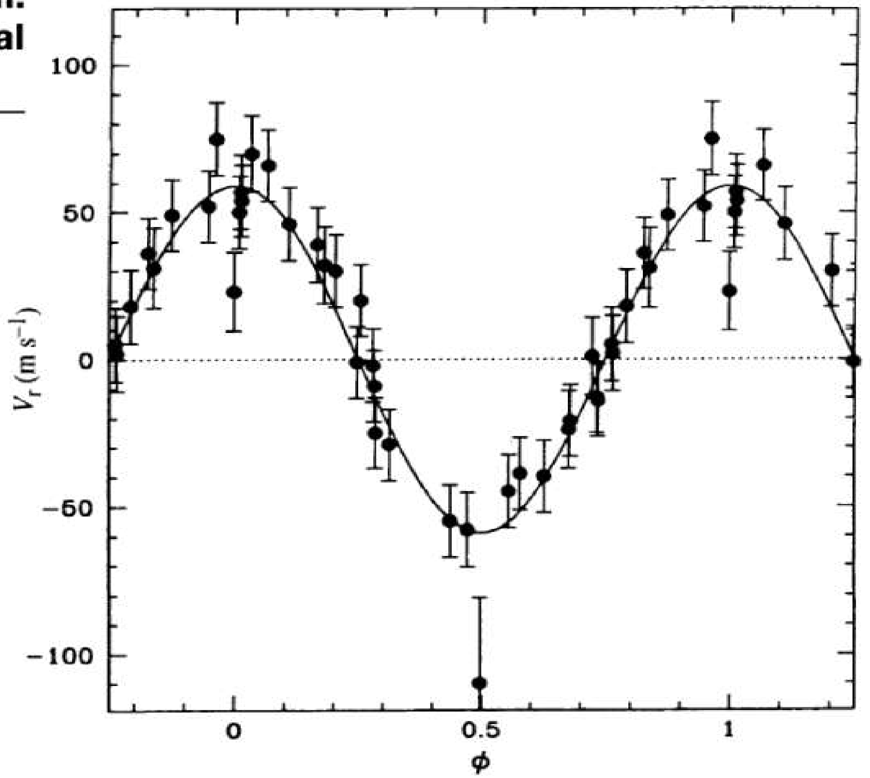
Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

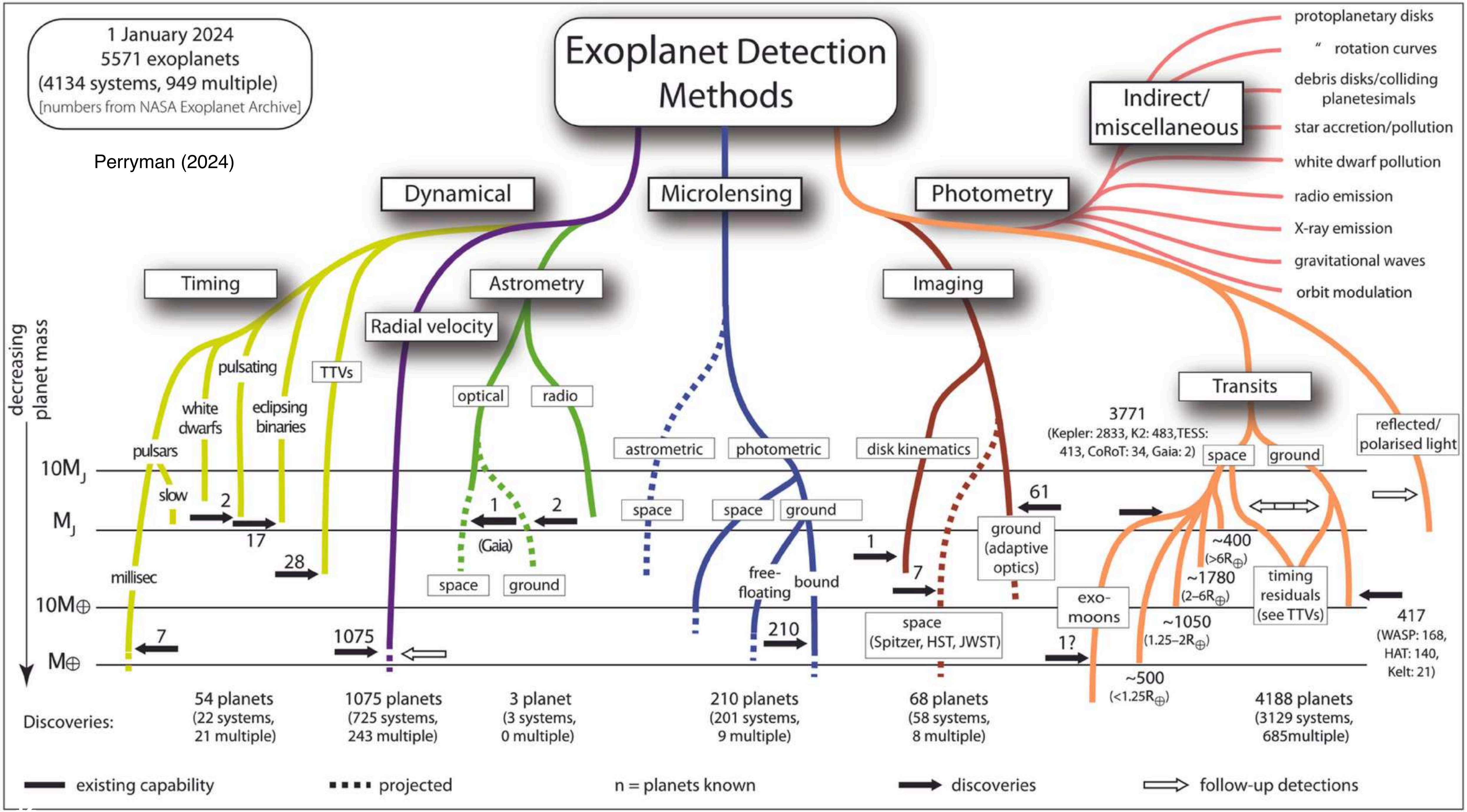
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

NATURE · VOL 378 · 23 NOVEMBER 1995

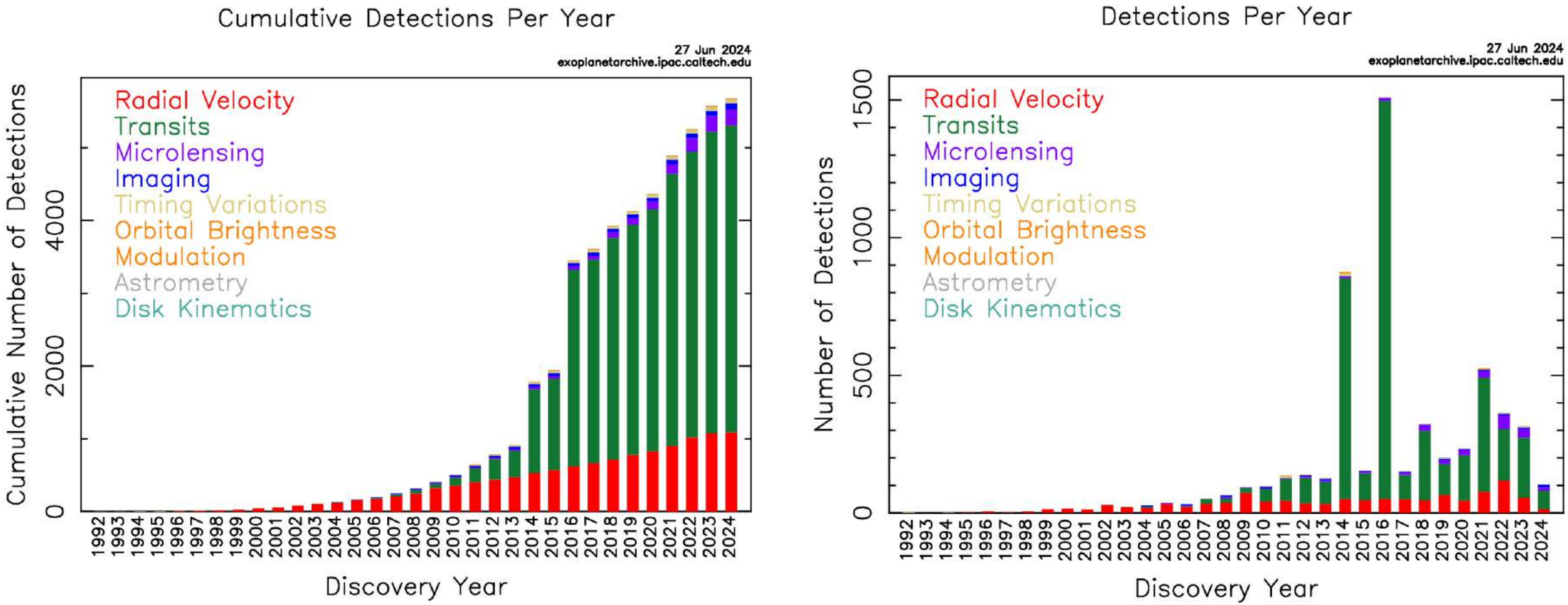
Precision
~10-15 m/s







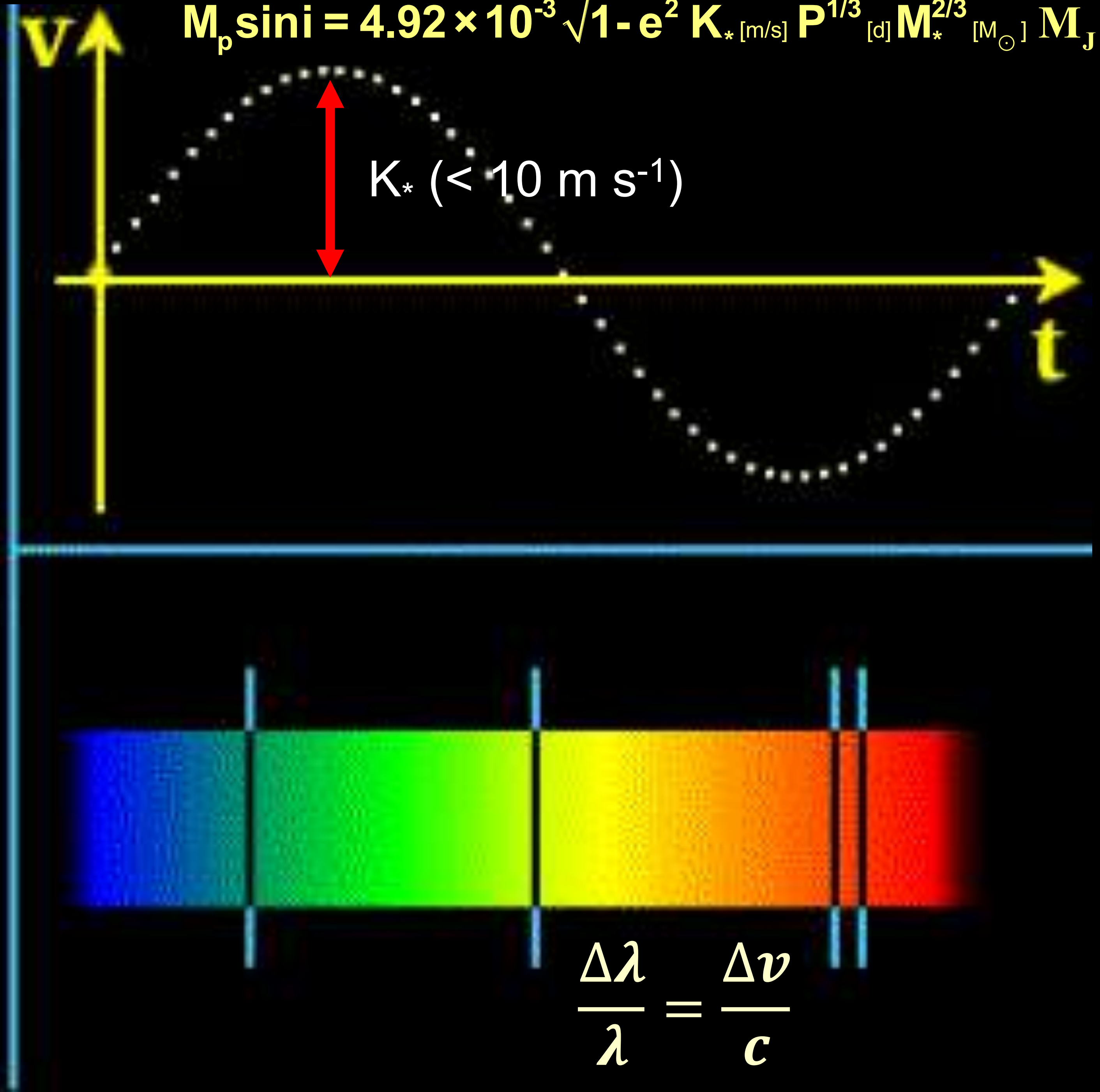
1 January 2024
5571 exoplanets
(4134 systems, 949 multiple)
[numbers from NASA Exoplanet Archive]
Perryman (2024)
Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Indirect/ miscellaneous
protoplanetary disks
" rotation curves
debris disks/colliding planetesimals
star accretion/pollution
white dwarf pollution
radio emission
X-ray emission
gravitational waves
orbit modulation
Timing
Astrometry
Radial velocity
Imaging
Transits
decreasing planet mass
pulsating
TTVs
white dwarfs
eclipsing binaries
pulsars
slow
millisec
optical
radio
(Gaia)
space
ground
astrometric
photometric
space
space
ground
free-floating
bound
disk kinematics
ground (adaptive optics)
space (Spitzer, HST, JWST)
3771
(Kepler: 2833, K2: 483, TESS: 413, CoRoT: 34, Gaia: 2)
space
ground
reflected/ polarised light
~400 (>6R⊕)
~1780 (2–6R⊕)
~1050 (1.25–2R⊕)
~500 (<1.25R⊕)
exo-moons
timing residuals (see TTVs)
417
(WASP: 168, HAT: 140, Kelt: 21)
10MJ
MJ
10M⊕
M⊕
2
17
28
7
1075
1
2
1
7
61
210
1?
Discoveries:
54 planets (22 systems, 21 multiple)
1075 planets (725 systems, 243 multiple)
3 planet (3 systems, 0 multiple)
210 planets (201 systems, 9 multiple)
68 planets (58 systems, 8 multiple)
4188 planets (3129 systems, 685multiple)
existing capability
projected
n = planets known
discoveries
follow-up detections



Source: NASA Exoplanet Archive

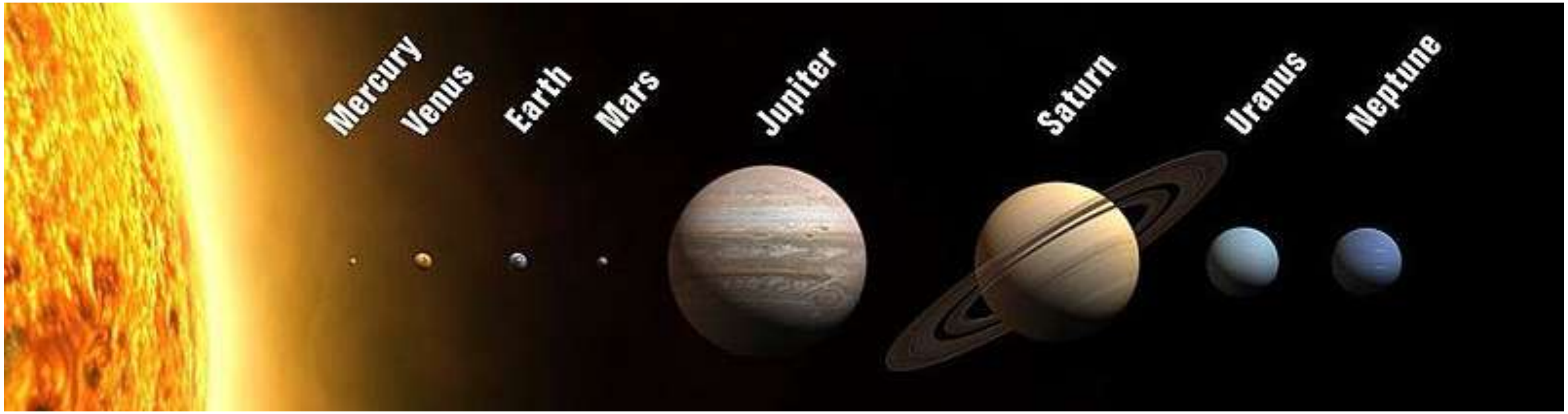
Radial velocities

$$M_p \sin i = 4.92\times10^{-3}\sqrt{1-e^2}\,K_{*\,[m/s]}\,P^{1/3}_{[d]}\,M_{*}^{2/3}{}_{[M_\odot]}\,M_J$$



$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}$$

The radial velocity method

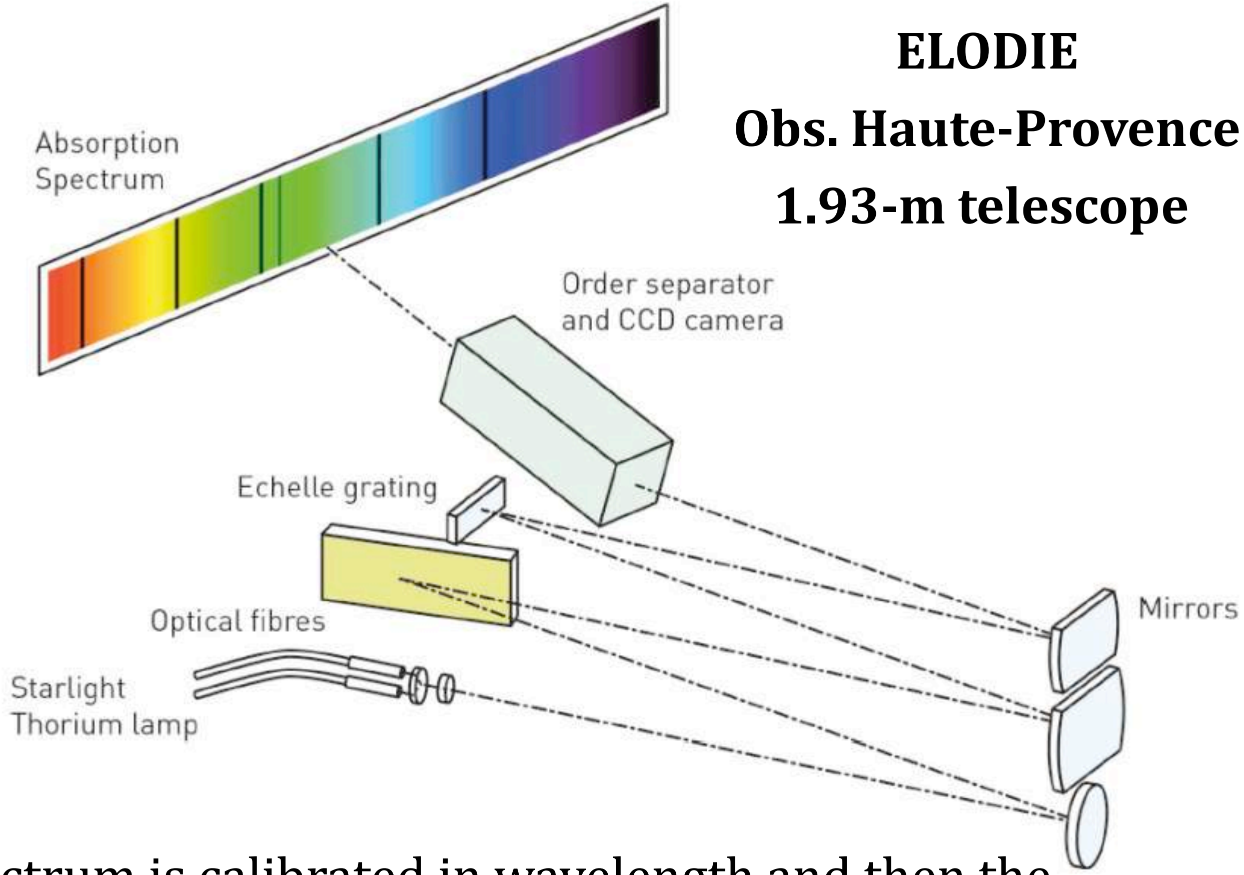


P (yr)	0.24	0.62	1	1.9	11.9	29.4	83.7	163.7
K (m s^{-1}) for i=90°	**0.008**	0.085	0.09	**0.008**	**12.5**	2.8	0.3	0.3

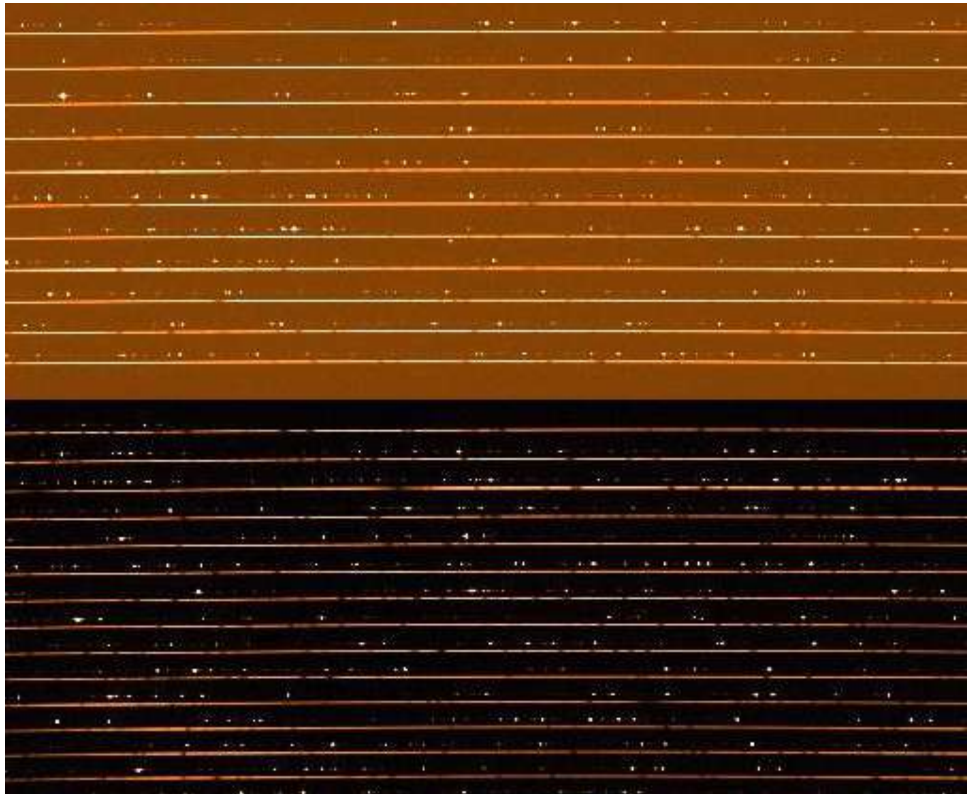
- **Tech not available until 90s**
- **Current best precision ~ 0.2 m s^{-1} = 0.7 km/h**

The instrument: spectrometer

Simultaneous calibration: A lamp sends light to the telescope and then it is transported to the spectrometer, together with the star light, using fibres



ELODIE
Obs. Haute-Provence
1.93-m telescope



The spectrum is calibrated in wavelength and then the radial velocity is measured from cross-correlation

Cathode made from a heavy element (Th, U) with a substrate gas (Ar, Ne) → narrow and stable emission lines

The first exoplanet!

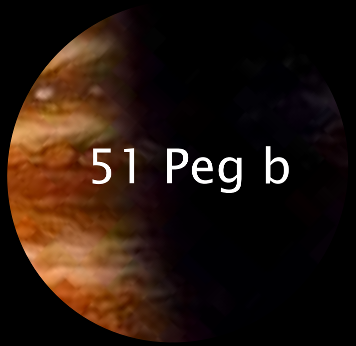
Mercury

Venus

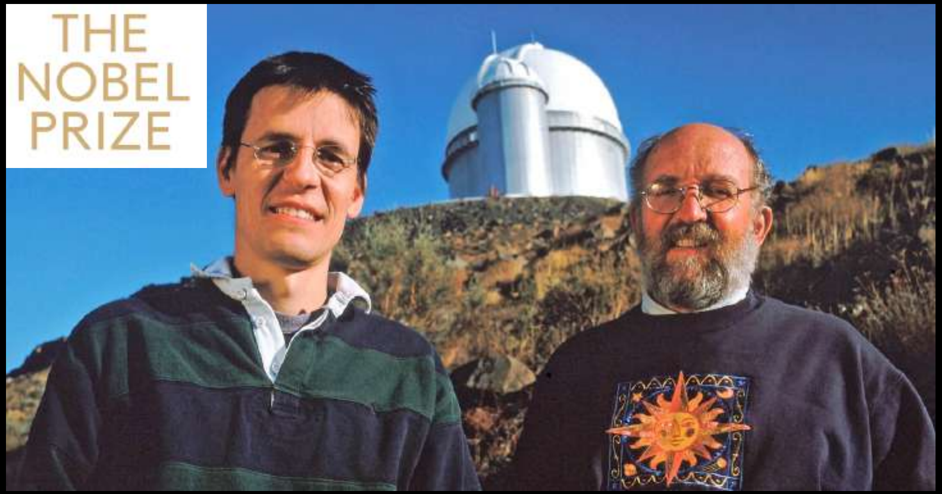
Earth

Solar System:

small rocky planets close to the Sun
gas/ice giants farther away



51 Pegasi b: a gas giant close to its star (hot Jupiter)



High-precision spectrometers (HARPS)

ΔRV = 1 m/s

⇕

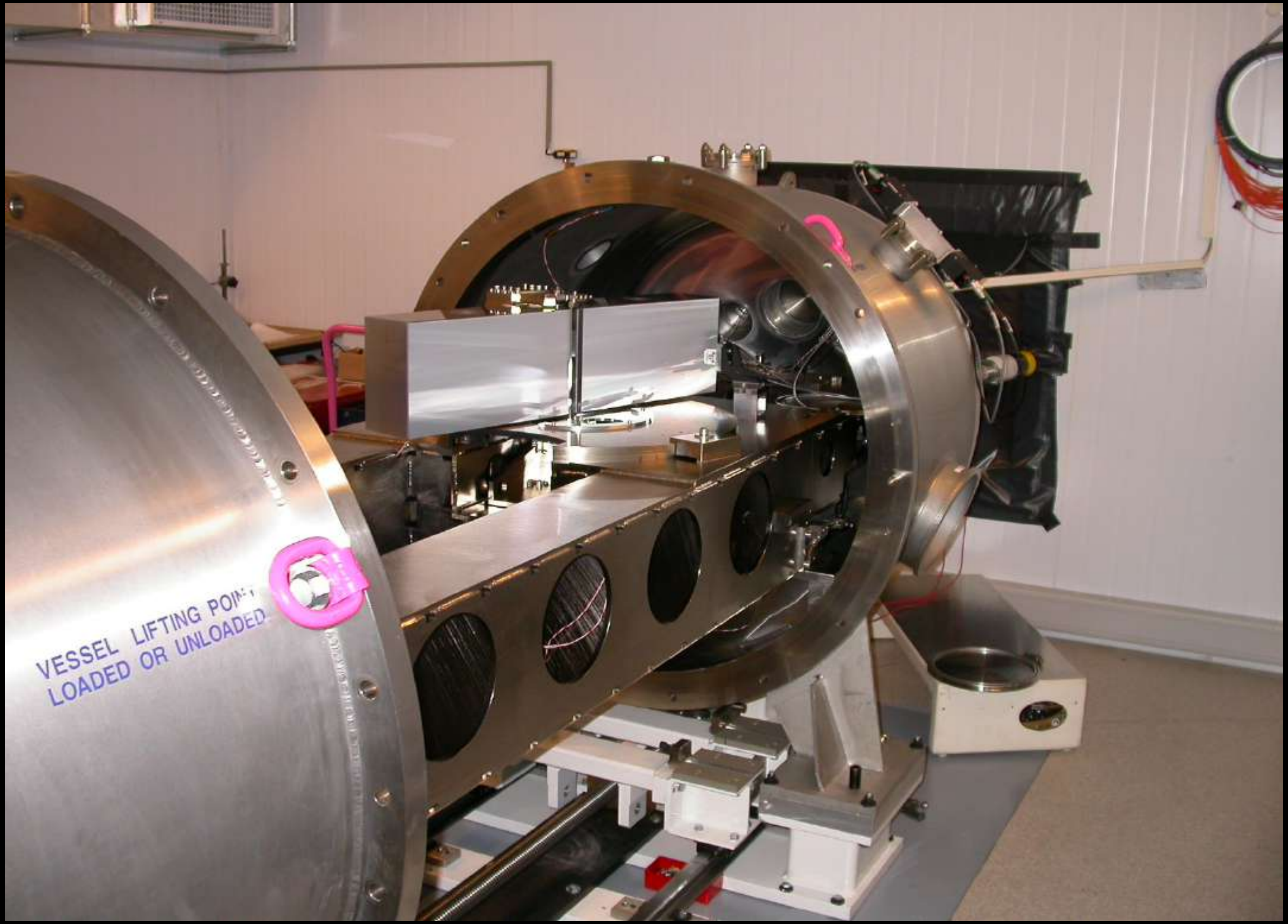
$\Delta\lambda = 2 \cdot 10^{-5}$ Å
➜ 15 nm on the detector
➜ 1/1000 pixel
➜ 30 Si atoms

⇕

➜ ΔT = 0.001 K
➜ ΔP = 0.01 mbar

⬇

Pressure and temperature control



carmenes

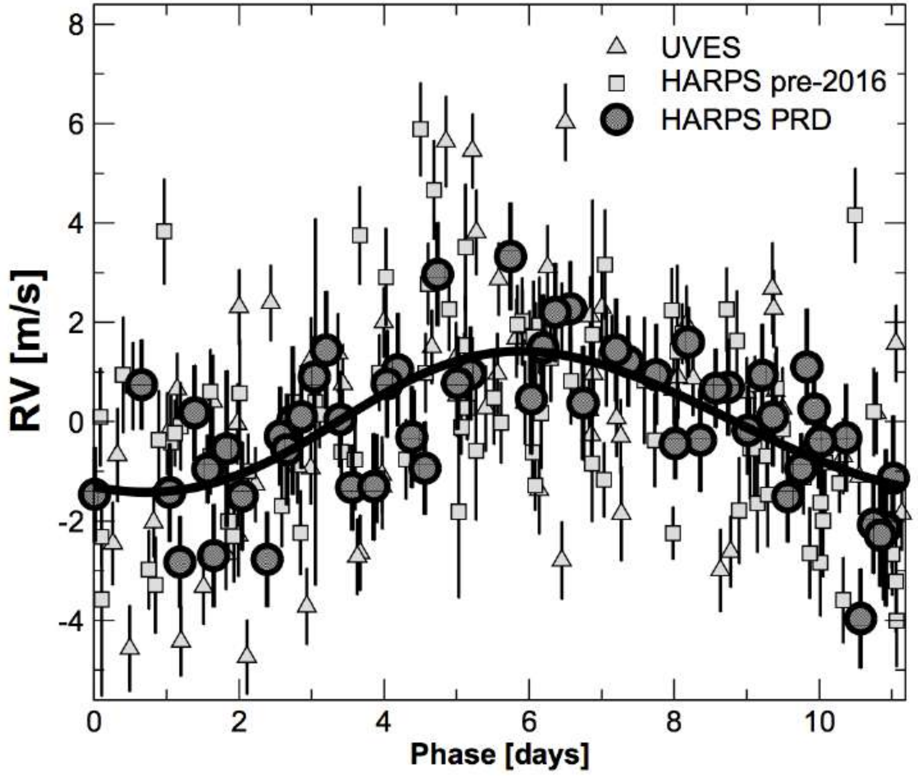
- 3.5-m @ CAHA
- VIS (520-970 nm) & NIR (970-1710 nm) channels
- Goal: low-mass planets in M-dwarfs

Proxima Centauri

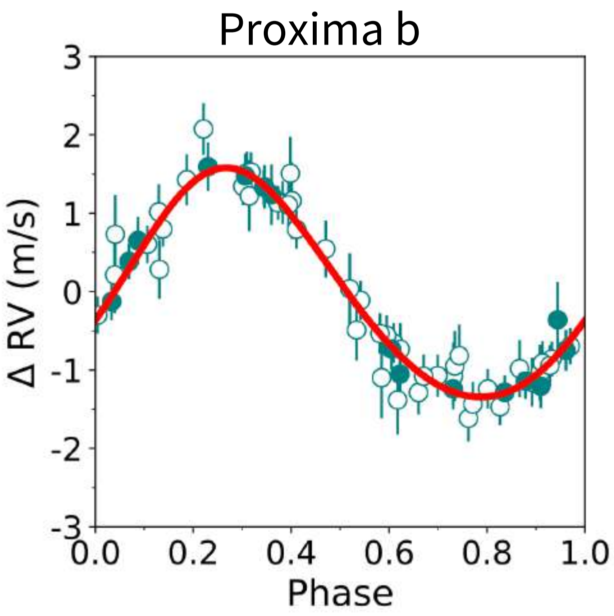
Nearest neighbor has planets!

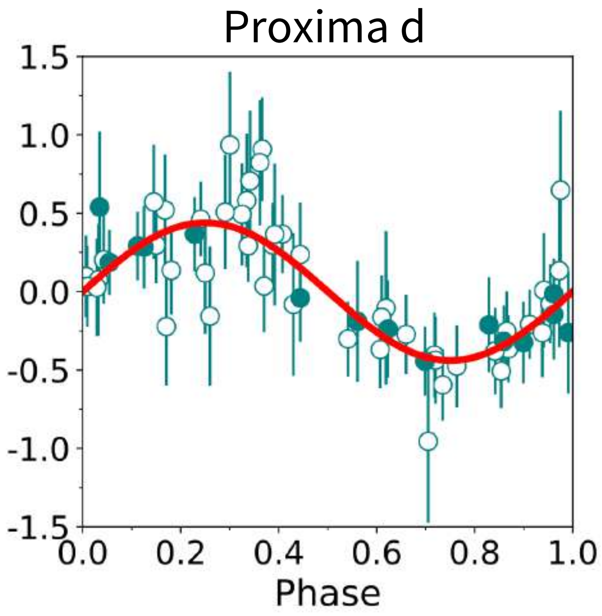
⇨ Proxima b (HARPS) $K = 1.5$ m s^{-1}

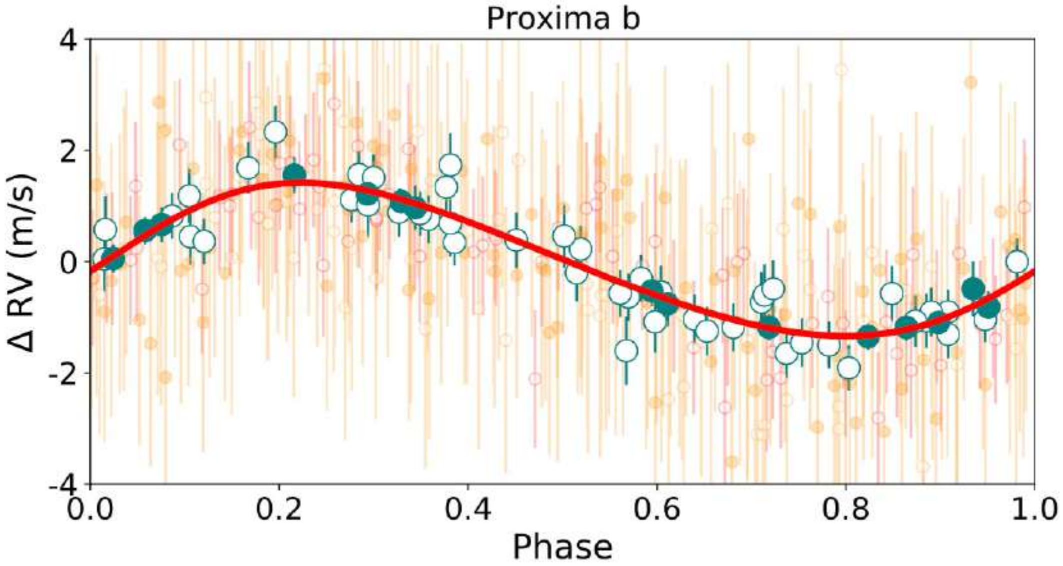
⇨ Proxima d (ESPRESSO) $K = 0.35$ m s^{-1}



Anglada-Escudé et al. (2016, Nature)
Suárez-Mascareño et al. (2020, A&A)





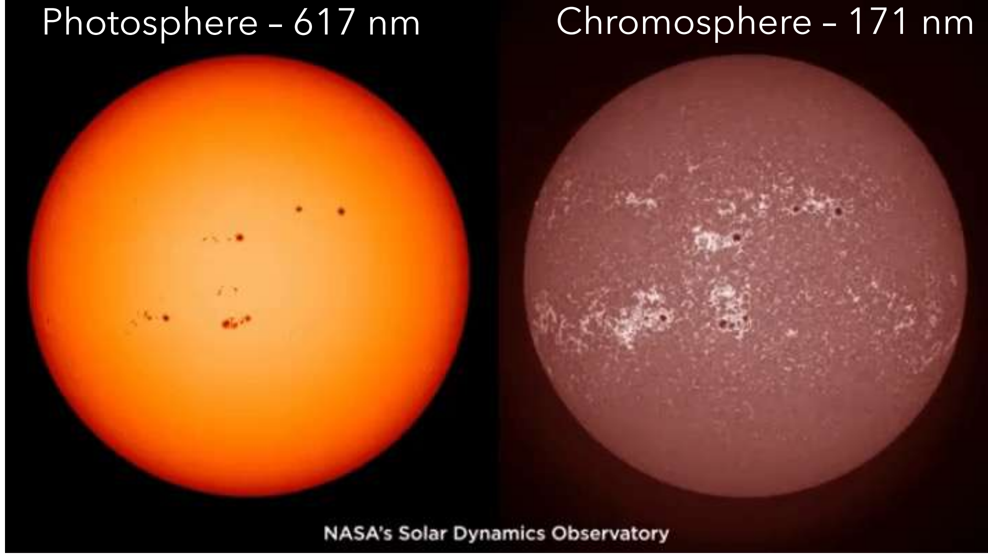


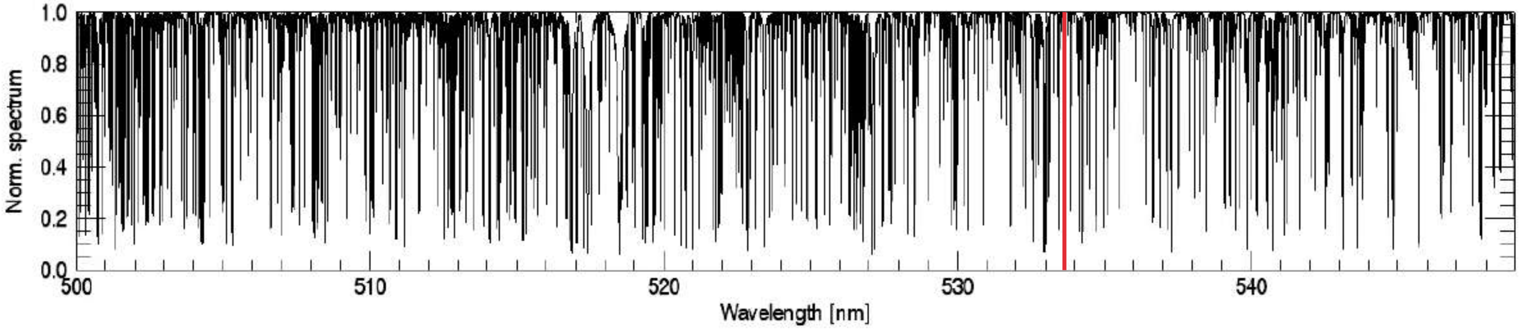
Keplerian motions & stellar activity

SPOTLESS project

Funded by the European Union

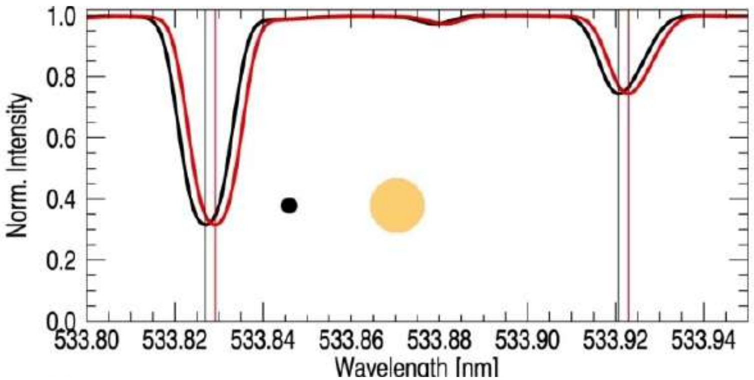
European Research Council
Established by the European Commission





RV measurements generally use an **average** profile for all lines, ignoring **unknown** shape changes expected for individual lines

Planet-induced Doppler shifts are invariant from line to line



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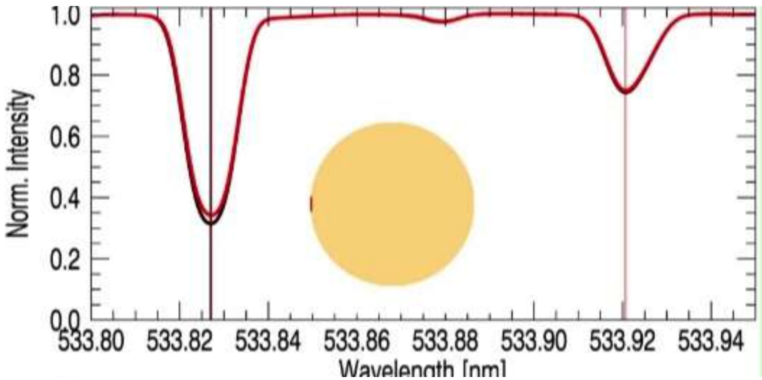
Activity-driven changes are local to individual spectral lines



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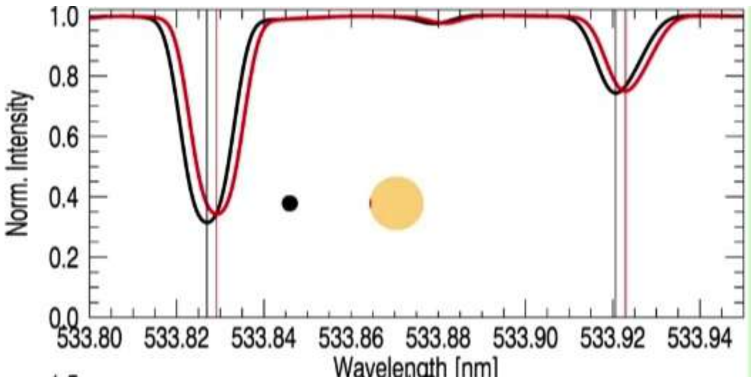
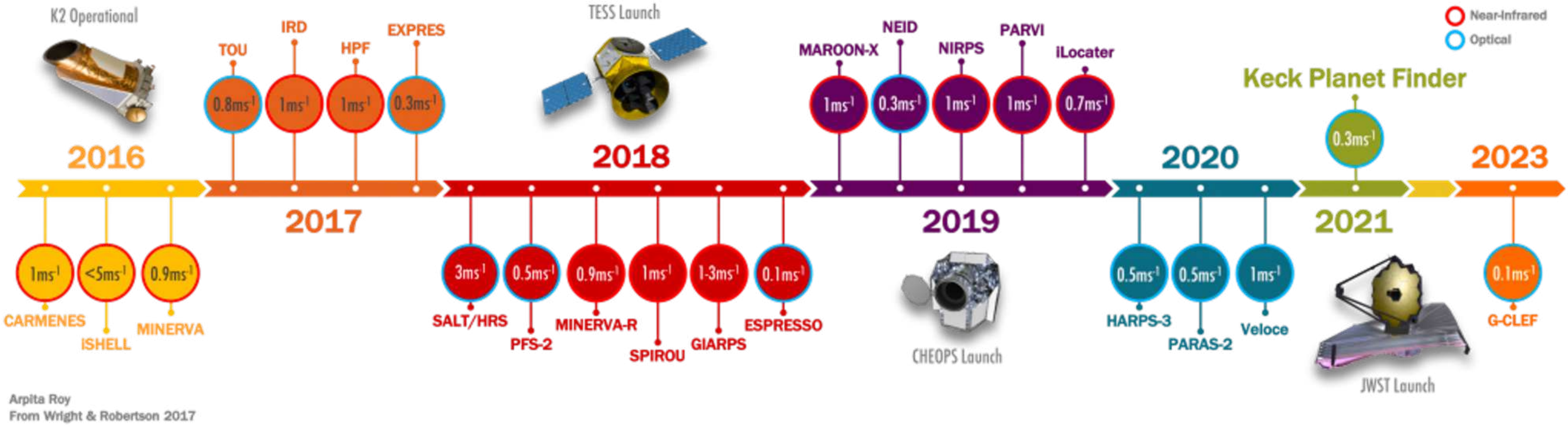
Observations





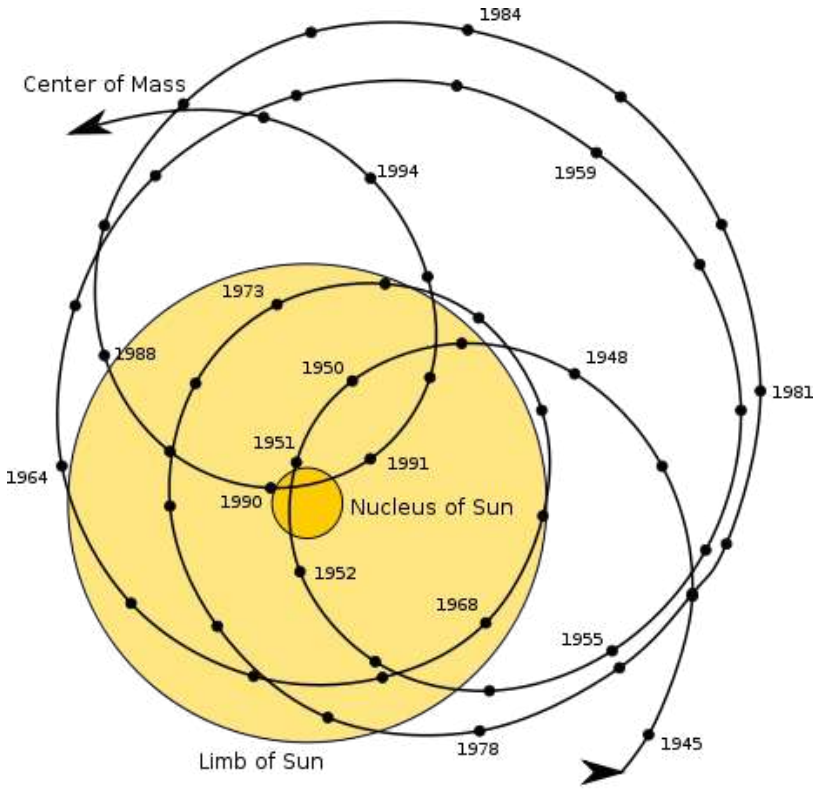
ADDITIONAL:

Ongoing:
HARPS
HARPS-N
(APF, PFS, SOPHIE, CORALIE,...)

Planned:
MARVEL
ANDES
GTC-CHORUS

The astrometric method

Motion of the star on the plane of the sky (circular orbit)

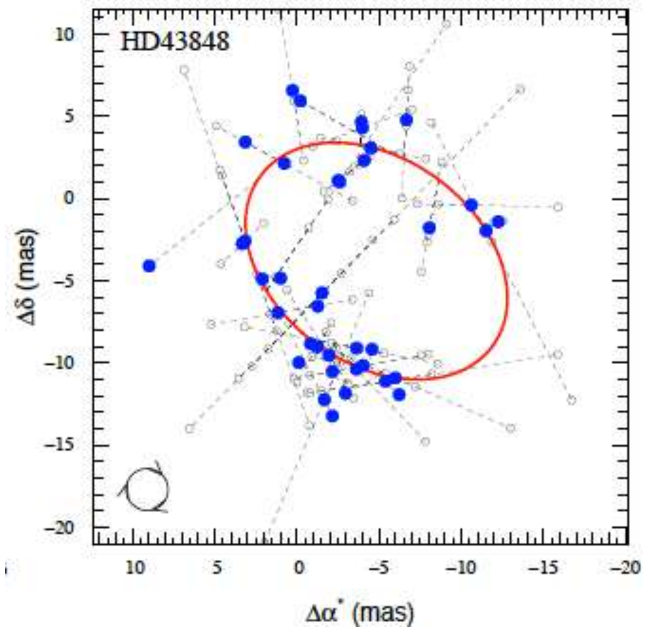


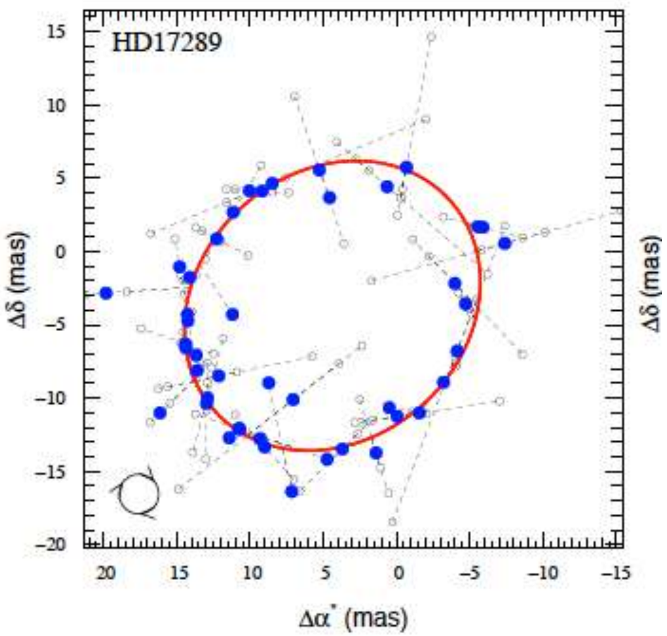
$$\theta = \frac{a}{d}\frac{m_p}{m_*} = \left(\frac{G}{4\pi^2}\right)^{1/3} \frac{m_p}{m_*^{2/3}} \frac{P^{2/3}}{d}$$

$$\theta = 5mas \frac{m_p}{M_J} \left(\frac{m_*}{M_{sun}}\right)^{-2/3} \left(\frac{P}{11.8yr}\right)^{2/3} \left(\frac{d}{pc}\right)^{-1}$$

$$\theta = 3\mu as \frac{m_p}{M_\oplus} \left(\frac{m_*}{M_{sun}}\right)^{-2/3} \left(\frac{P}{1yr}\right)^{2/3} \left(\frac{d}{pc}\right)^{-1}$$

$m_p << m_*$

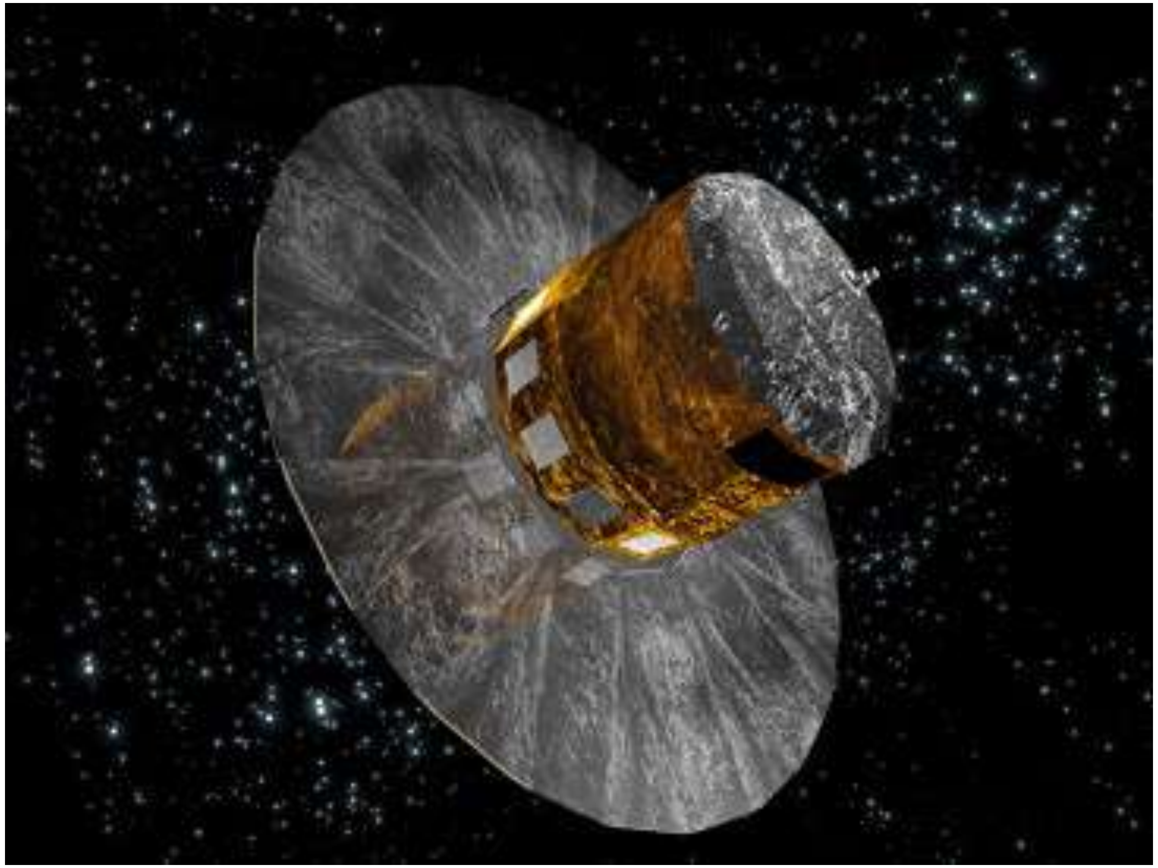




The astrometric method: the future

Gaia

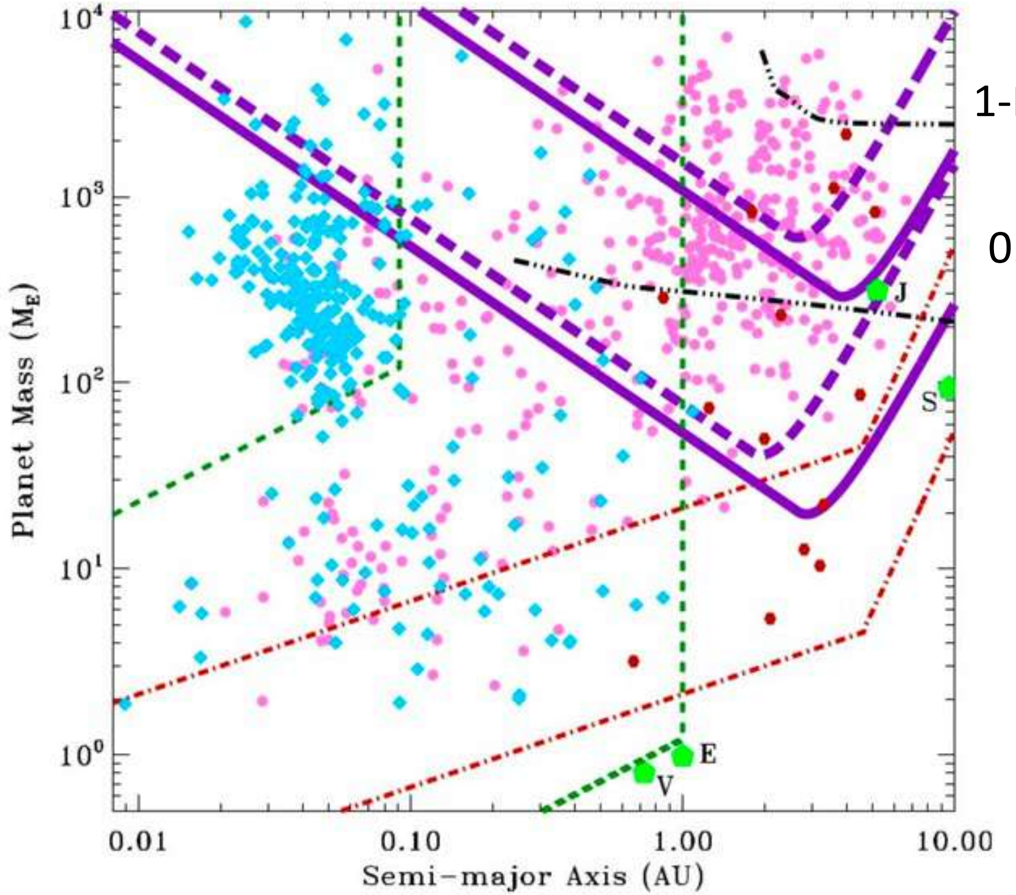
- ESA mission
- Launched on Dec 19th, 2013
- 2 telescopes of 1.45-m aperture
- Additional telescope for spectroscopy
- Orbit: Earth-Sun L2 point
- Positions and motions **for over 10^9 stars**
- Photometry + astrometry + RV for 10^6 stars
- Maximum magnitude ~ 20
- For each star: ~70 measurements over 5 years
- Astrometric precisions:
  - 20 µas @ mag 15
  - 200 µas @ mag 20



Angle between the fields: 106.5°
At the end, absolute position measurements

The astrometric method: the future

Gaia



1-$M_\odot$ G dwarf at 200 pc

0.4-$M_\odot$ M dwarf at 25 pc

Sozzetti (2018)

Expected harvest: ~1000 long-period massive planets
Strong constraints on the frequency of Jupiter analogs

Gaia DR4 release date: 2026

The timing method

Principle: delay or advance of a periodic signal due to the orbital motion of the source and the finite speed of light (*light travel time*)

Targets = source with a very stable periodic signal:

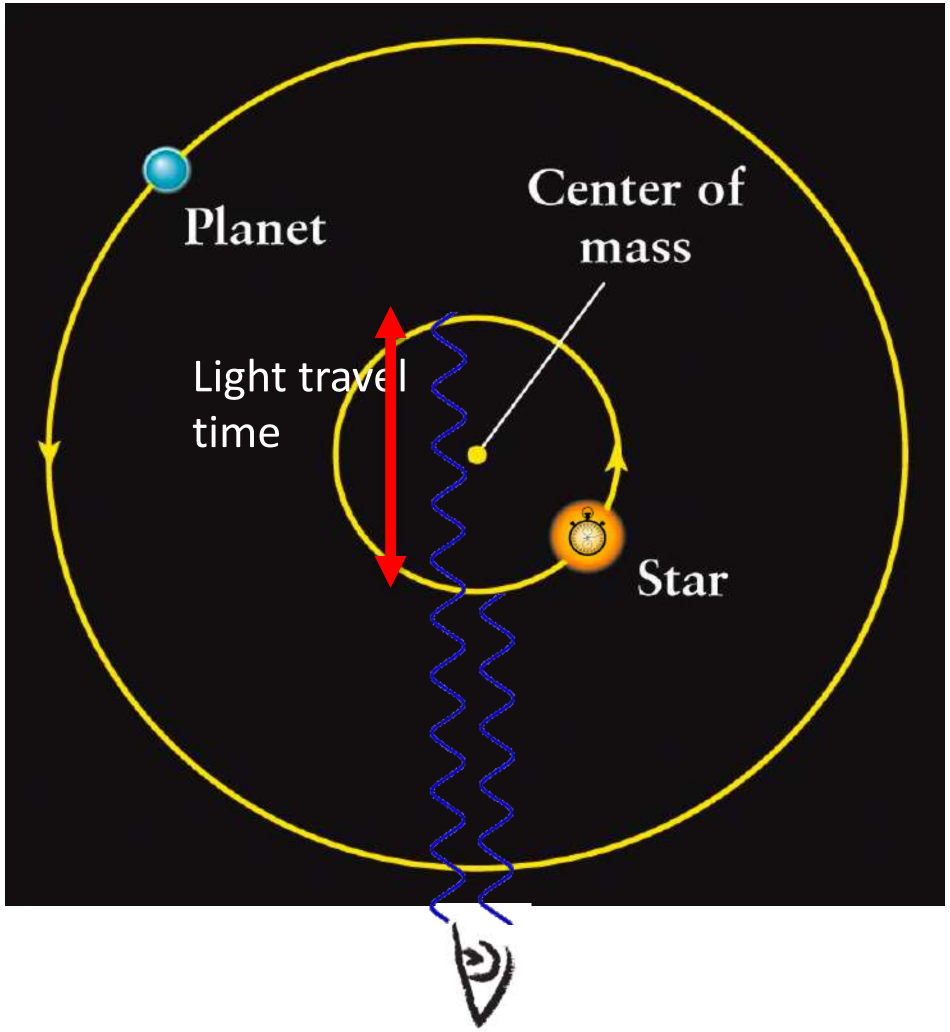
pulsars
pulsating stars
eclipsing binaries

Amplitude : $$\Delta t = \frac{1}{c}\frac{a \times M_p \sin i}{M_*}$$

Earth + Sun = 1.5 ms
Jupiter + Sun = 2.5 s

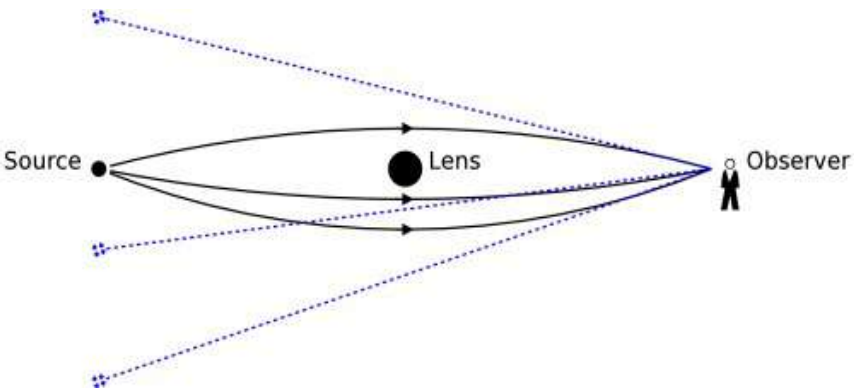
$$\Delta T = \frac{a_{12} \sin i_3}{c}\left[\frac{1 - e_3^2}{1 + e_3 \cos \nu_3} \sin(\nu_3 + \omega) + e_3 \sin \omega\right]$$

Irwin (1959)



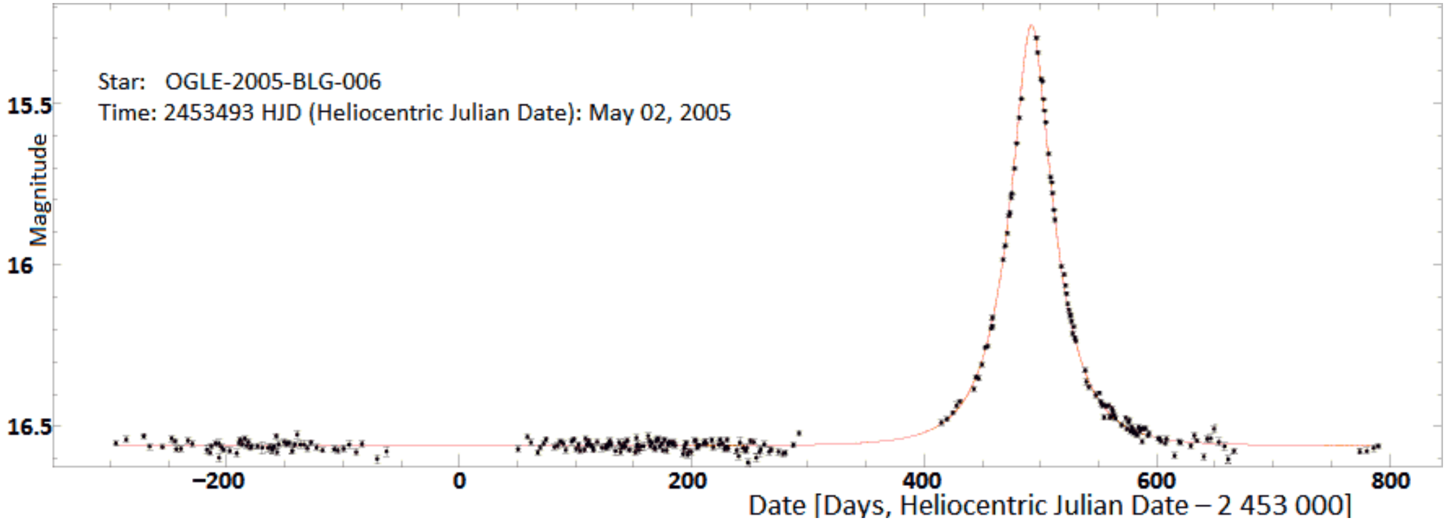
The gravitational microlensing method

Principle: General Relativity predicts that light rays are deflected by gravitational fields. The light of a distant source grazing a lens (e.g. star, planet) can be deflected towards Earth. The source appears then brighter.



The different images of the source are not resolved. The most significant effect is photometric.

- **Required alignment** ~1 mas → very rare. Detection makes it necessary to observe very dense stellar fields.
- **Typical source:** 1 star of the galactic bulge at ~ 8 kpc
- **Typical lens:** 1 star of the galactic disk ~ 4 kpc
- **Typical duration:** determined by the relative motion of the two stars. A few weeks to a few months. ONE TIME ONLY!



The gravitational microlensing method

$$\theta_E \approx 0.4\left(\frac{M_L}{0.3M_{Sun}}\right)^{1/2}\left(\frac{D_L}{2kpc}\right)^{-1/2}\left(\frac{D_{LS}}{D_S}\right)^{1/2} mas,$$

$$R_E = \theta_E D_L \approx 2.2\left(\frac{M_L}{0.3M_{Sun}}\right)^{1/2}\left(\frac{D_L}{2kpc}\right)^{1/2}\left(\frac{D_{LS}}{D_S}\right)^{1/2} au$$

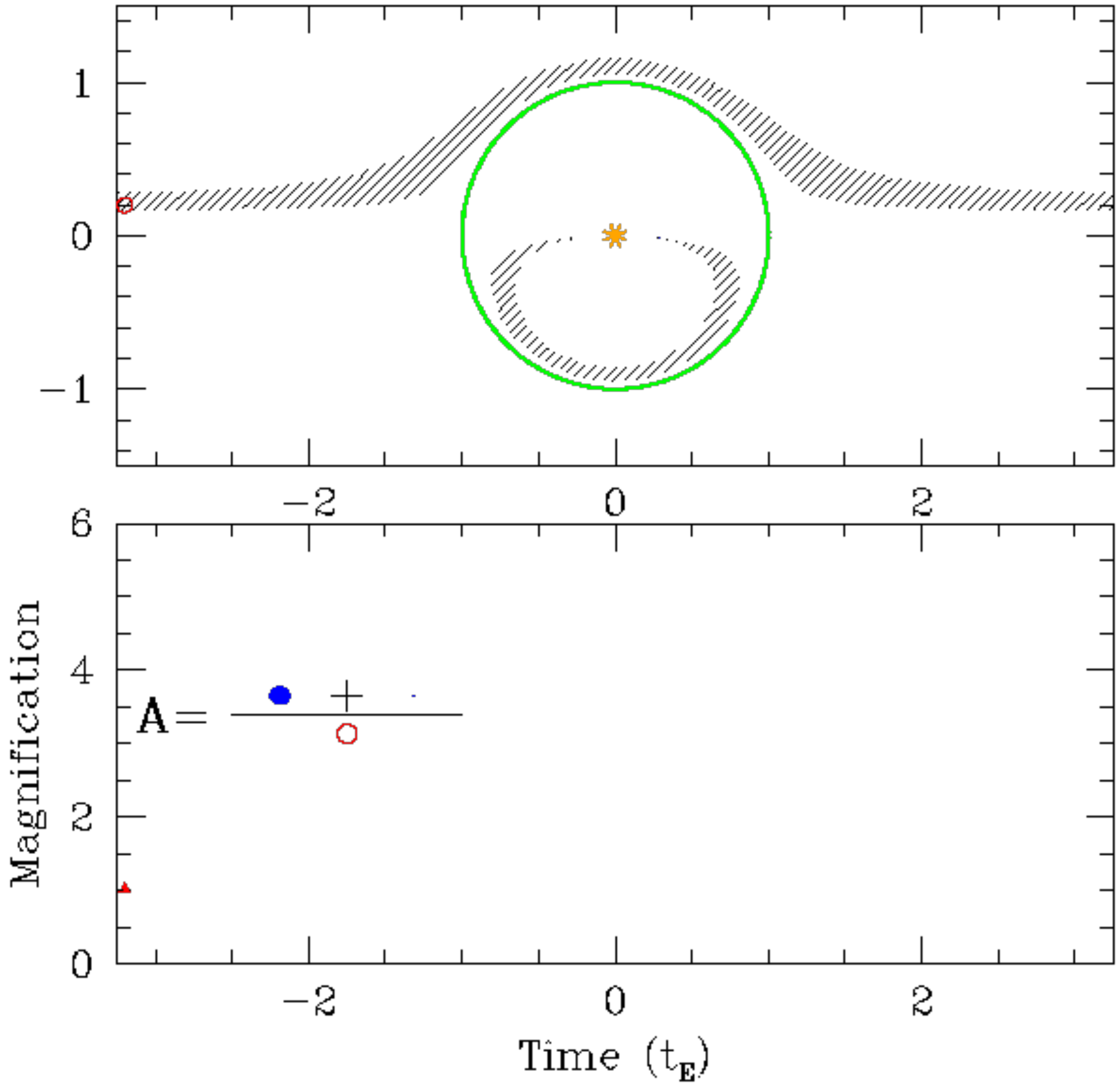
For a typical stellar lens, the Einstein ring corresponds to the size of a planetary system

Magnification A

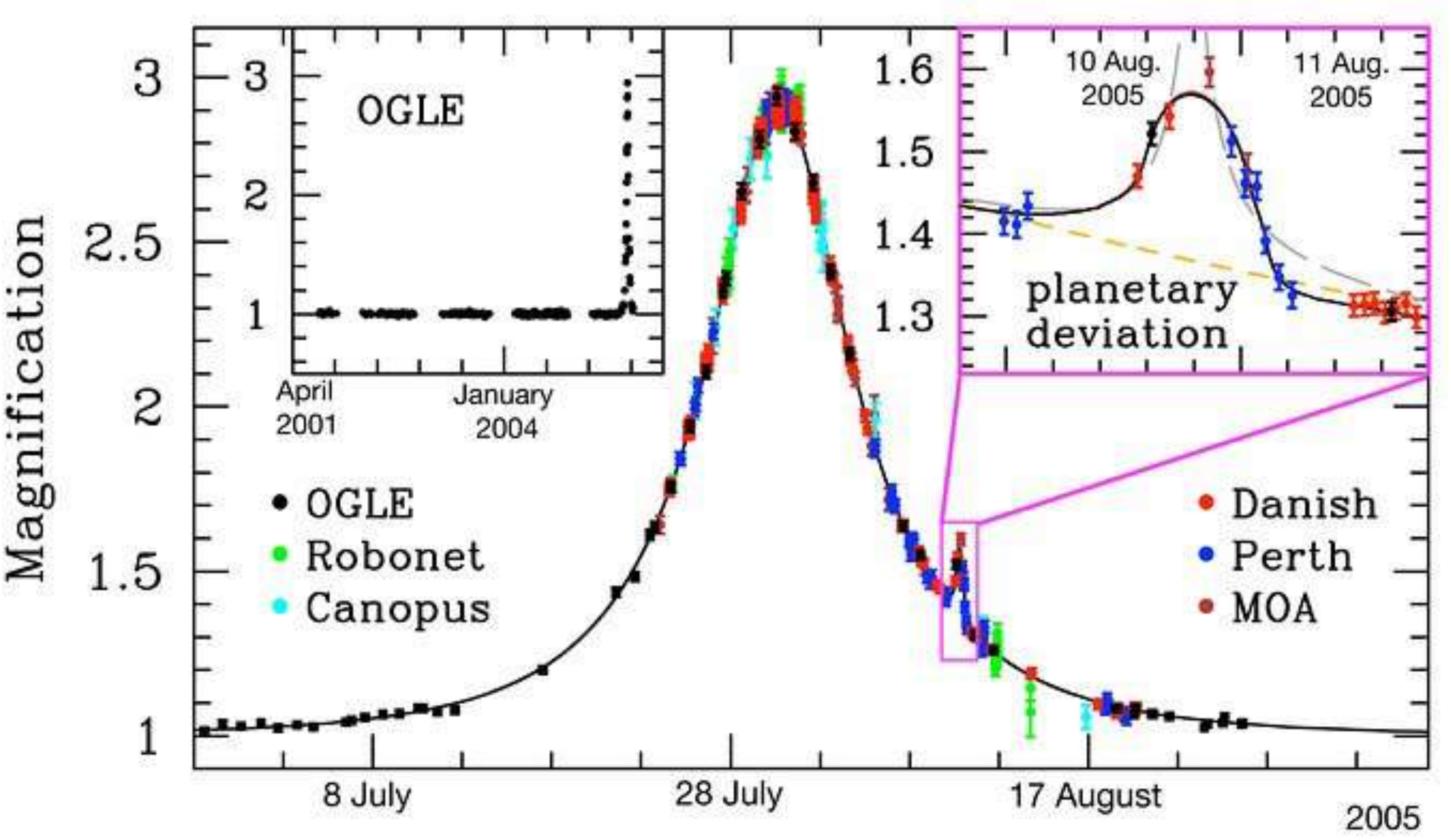
$$A = \frac{u^2+2}{u\sqrt{u^2+4}}, u \equiv \frac{\theta_S}{\theta_E}$$

Lensing preserves surface brightness but changes surface

Maximum recorded: A = 3000



The gravitational microlensing method

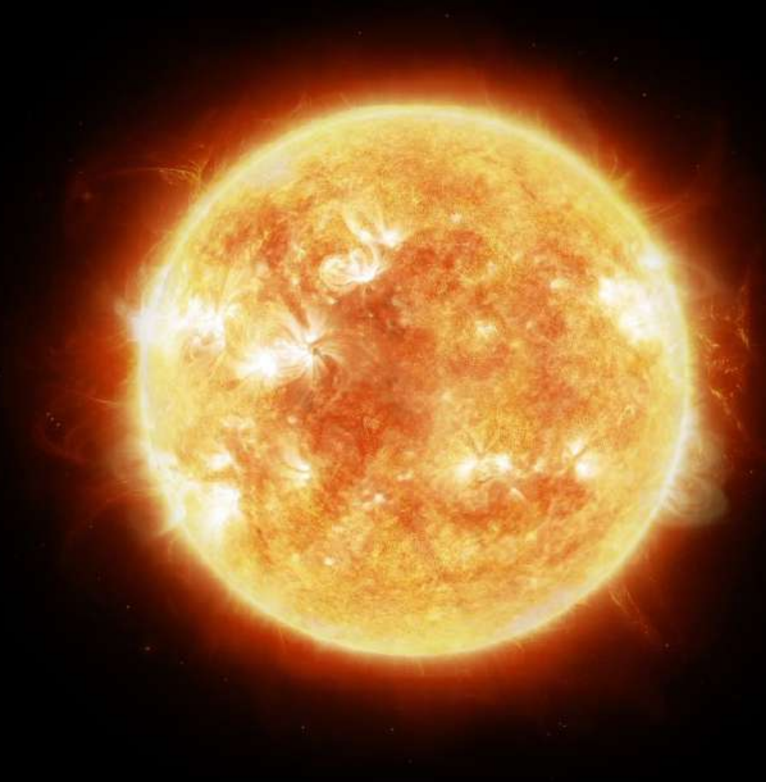


Beaulieu et al. (2006, Nature)

Transits

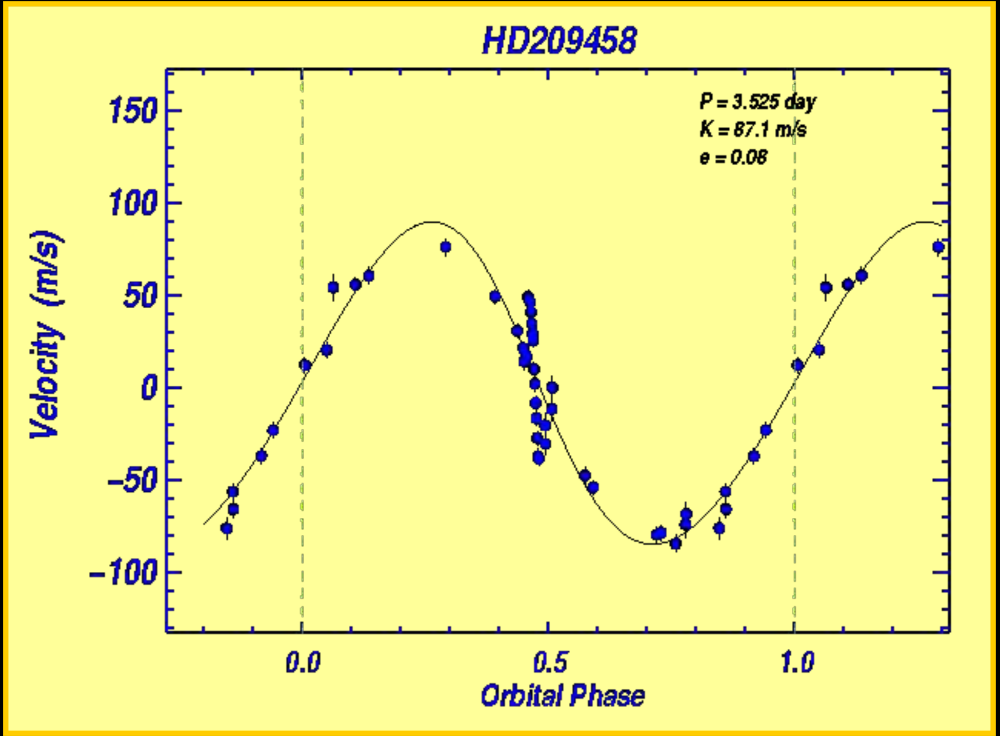
- **Transit parameters:**
  - **Period** $P^2 M_* = a^3$
  - **Depth** $\Delta f \approx \left(\frac{R_p}{R_*}\right)^2$
  - **Duration**

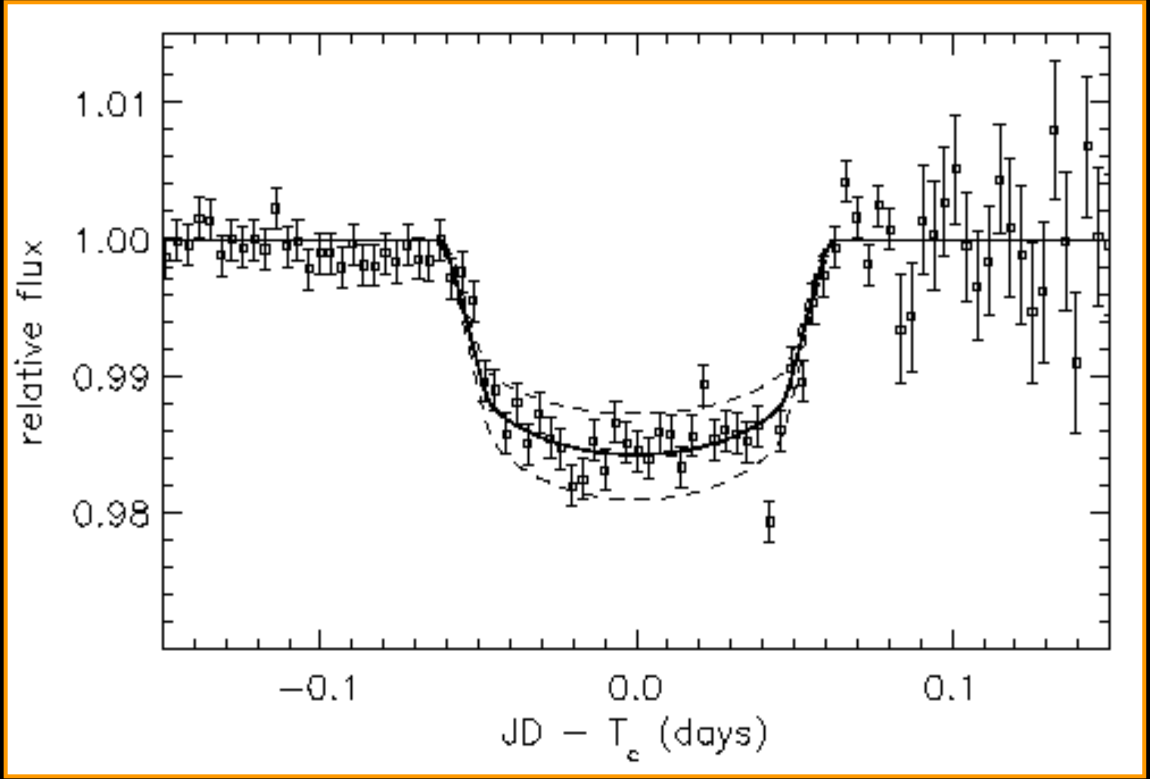
$$\tau_c = 26 R_* \sqrt{\frac{a}{M_*}} \cong 13\sqrt{a}\ \text{hrs}$$



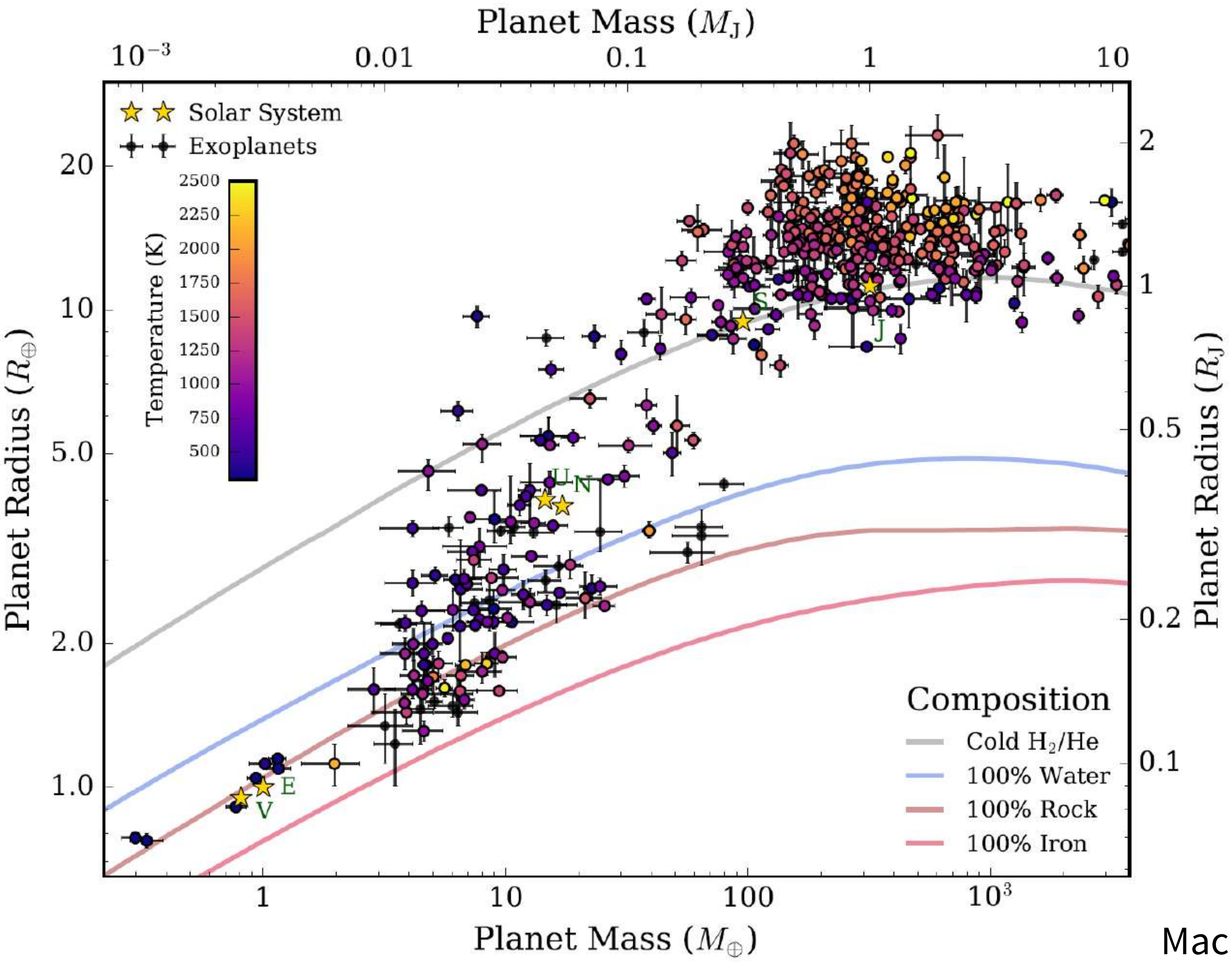
First in 1999: planet already known from radial velocities – HD 209458 (David Charbonneau)

↳ Depth of 1–2% for Jupiter-Sun



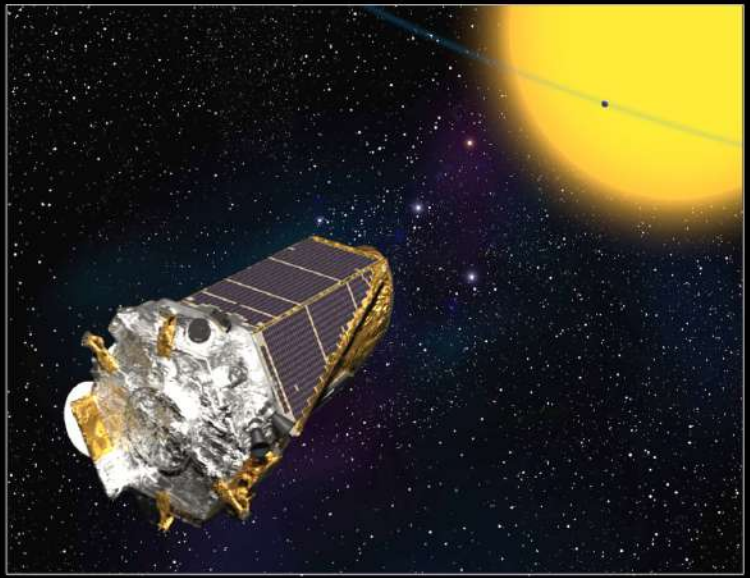


- **Planet data:**
  - $M = 0.7\ M_{Jup}$
  - $R = 1.35\ R_{Jup}$
  - $i = 86.6°$
  - $\rho = 0.35\ g/cm^3$ (!)



MacDonald (2021)

Transits from space



COROT (CNES/ESA)
mission ended
(December 2006-October 2012)

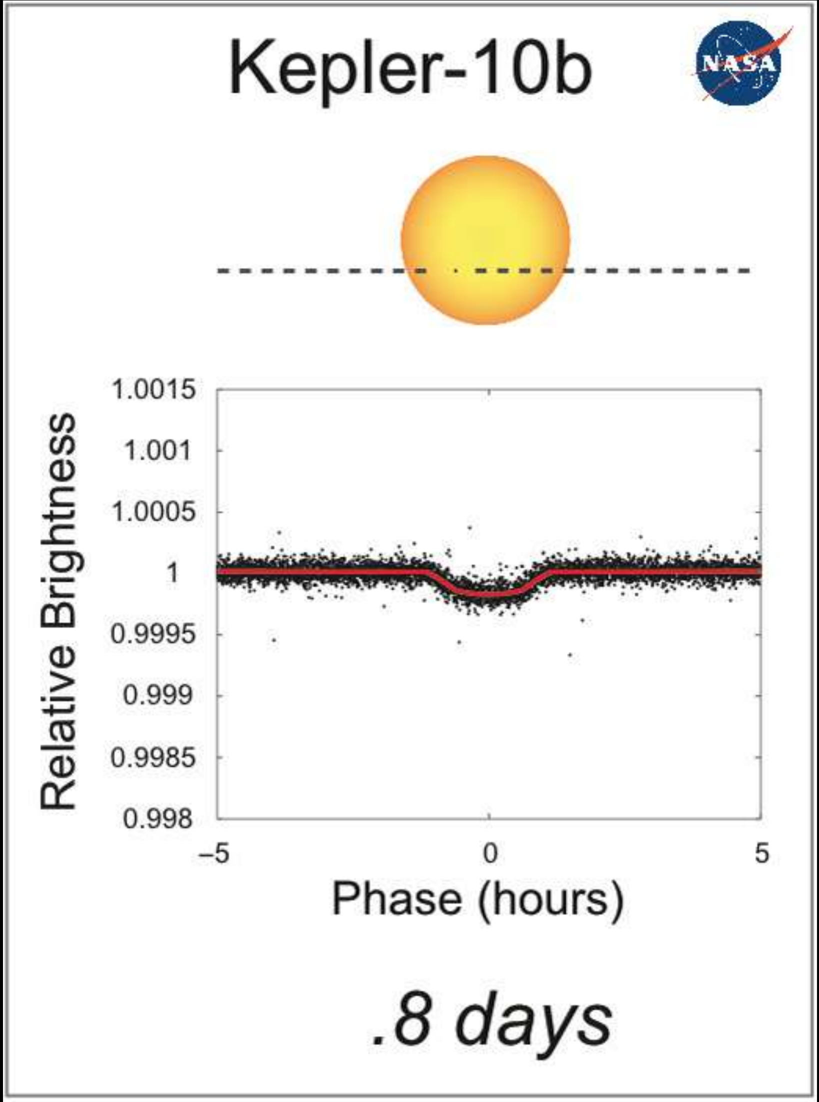
Kepler + K2 (NASA)
mission ended
(March 2009-May 2013;
June 2014-October 2018)

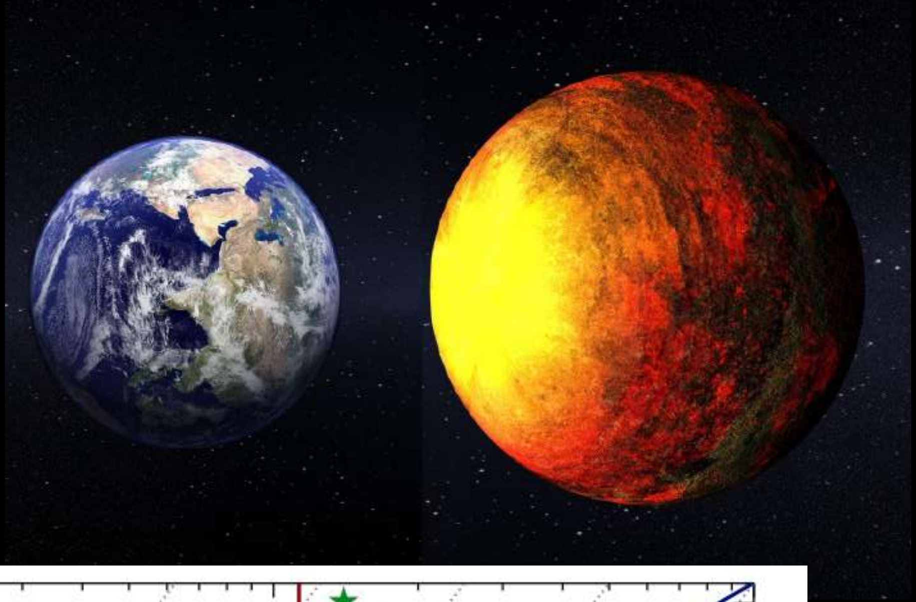
TESS (NASA)
mission in operation
(April 2018-)

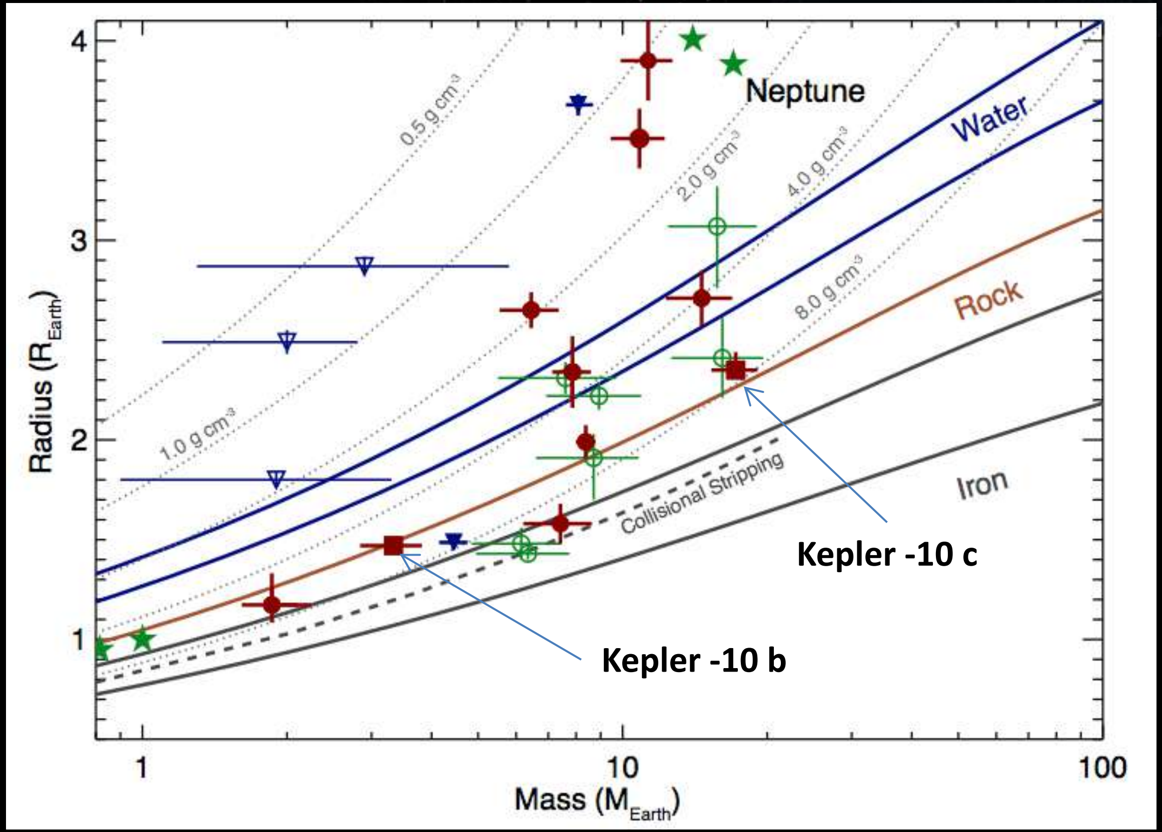
CHEOPS (ESA)
Mission in operation
(December 2019-)

The first super-Earth discovered by Kepler

$M \sim 4.5\ M_\oplus$ & $R = 1.4\ R_\oplus$







The PLATO mission

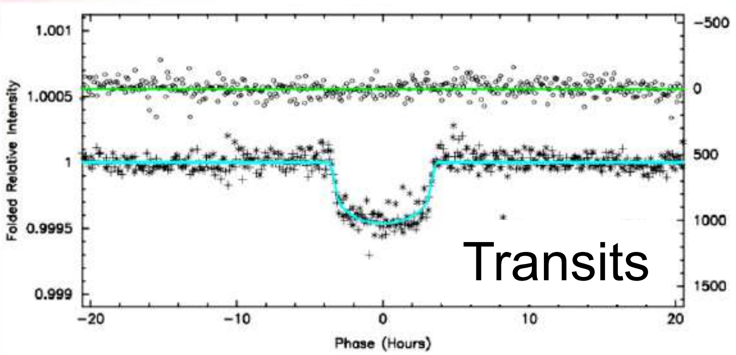
PLAnetary Transits and Oscillations of stars (PLATO) is a mission to detect and characterise exoplanets and study their host stars

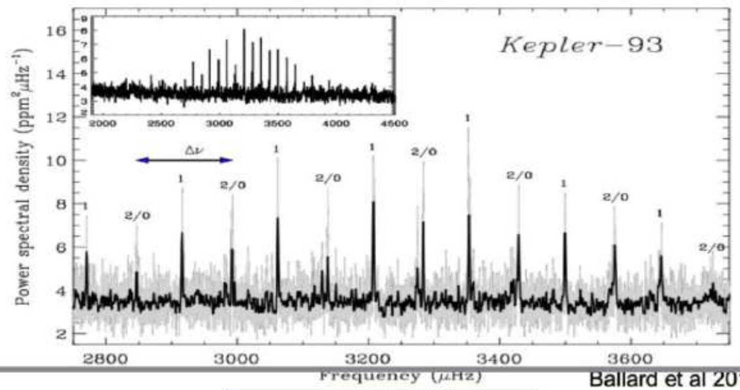
Focus on Earth-size planets in orbits up to the habitable zone of bright Sun-like stars to address these main questions:

1. How do planets and planetary systems form and evolve?
2. Is our Solar system special or are there others like ours?
3. Are there potentially habitable planets?

- PLATO is ESA's M3 Mission
- Launch planned for end of 2026

The PLATO mission: methods





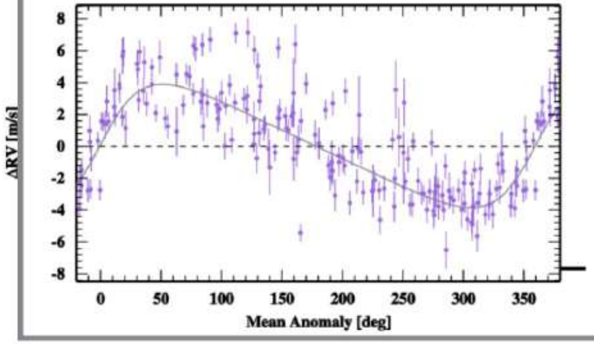
Ballard et al 2014

High-precision photometry

Planet radius
Period,
inclination

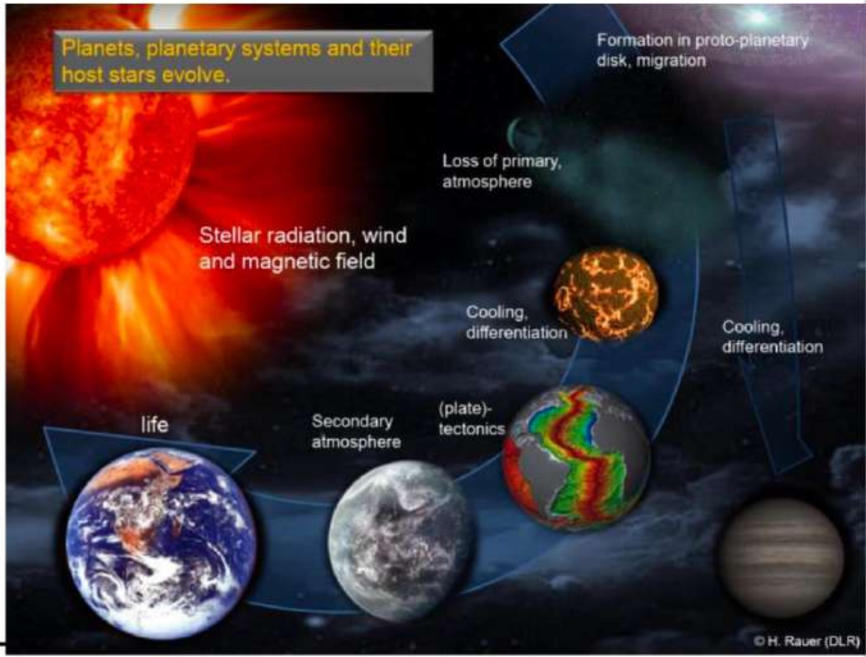
R⋆, M⋆
age

High precision
radial velocity



Planet mass
Eccentricity

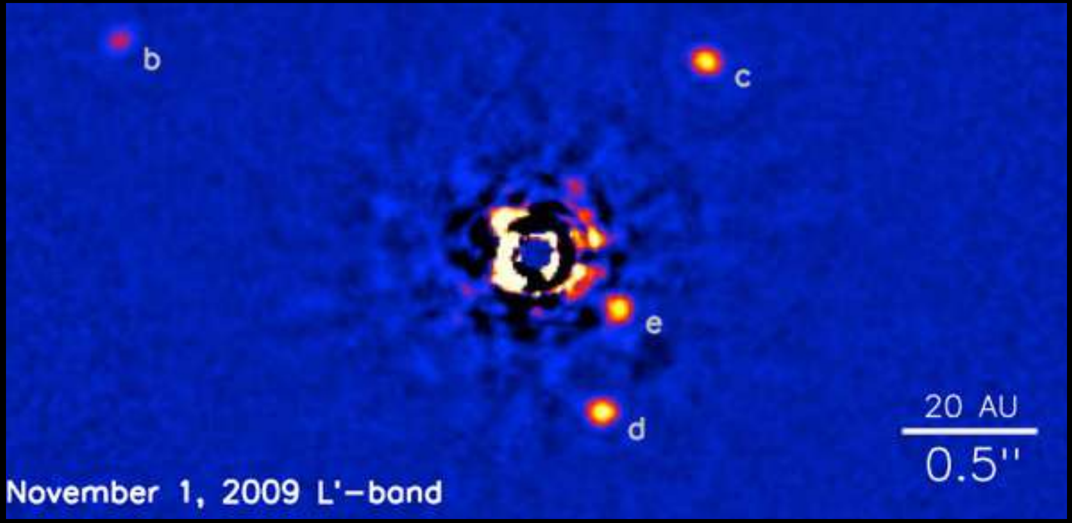
- Radius ~3%
- Mass ~10%
- Age ~ 10%

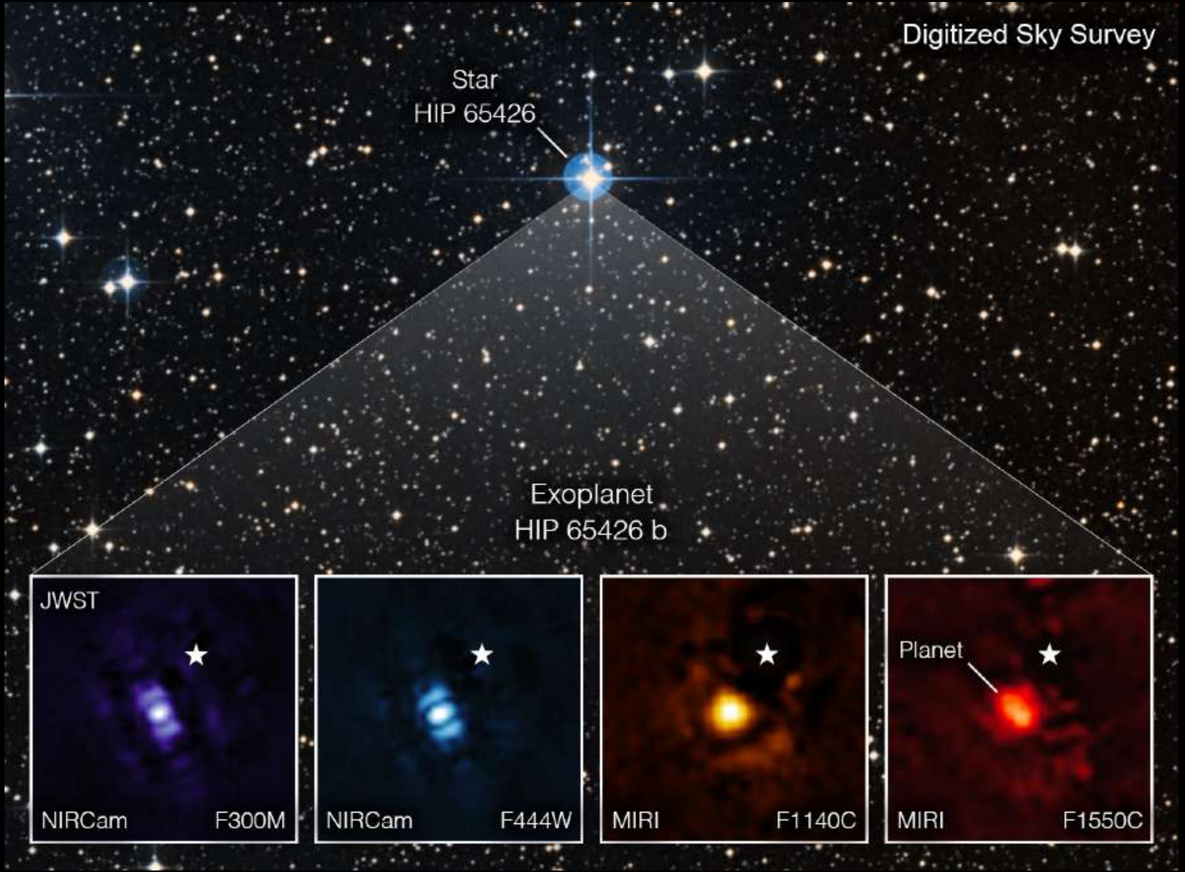


+ orbital parameters + architecture

Direct imaging

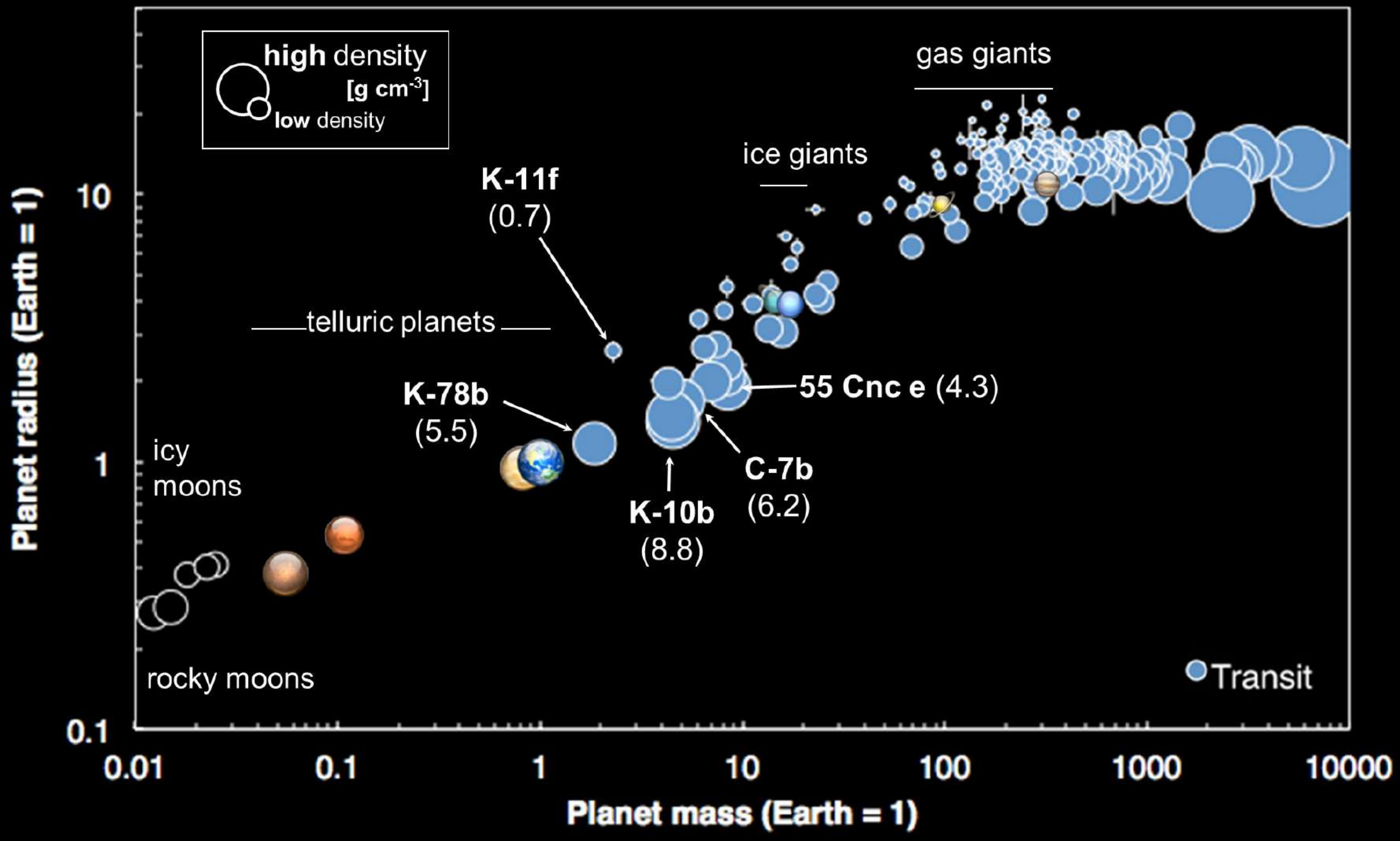
- Severe contrast problem
  - In the visible (reflected light) contrast is 10^6 o more (for Jupiter)
  - In the IR (emitted light) the contrast is more favourable (10^4)
- Several successes! HR 8799, β Pic, Fomalhaut, HIP 65426, ...





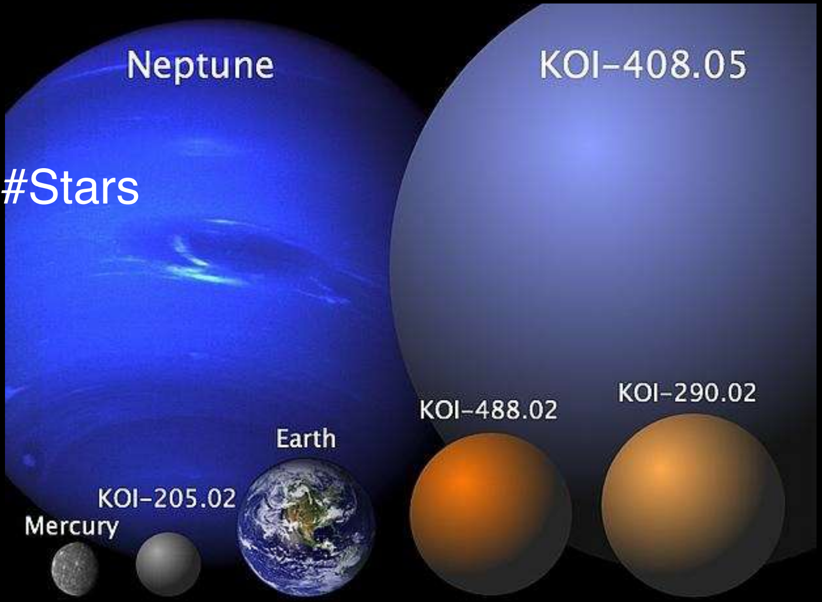
Statistics and results

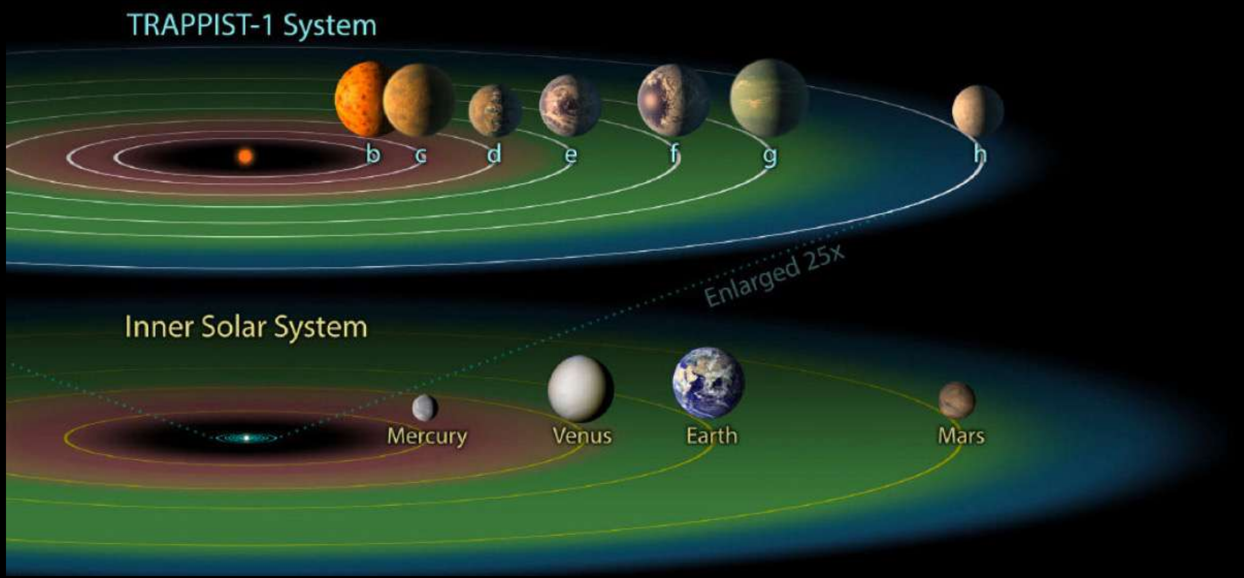
Credit: Martin Vargic


high density
[g cm-3]
low density
gas giants
ice giants
K-11f
(0.7)
telluric planets
K-78b
(5.5)
55 Cnc e (4.3)
icy
moons
C-7b
(6.2)
K-10b
(8.8)
rocky moons
Transit
Planet radius (Earth = 1)
10
1
0.1
0.01
0.1
1
10
100
1000
10000
Planet mass (Earth = 1)

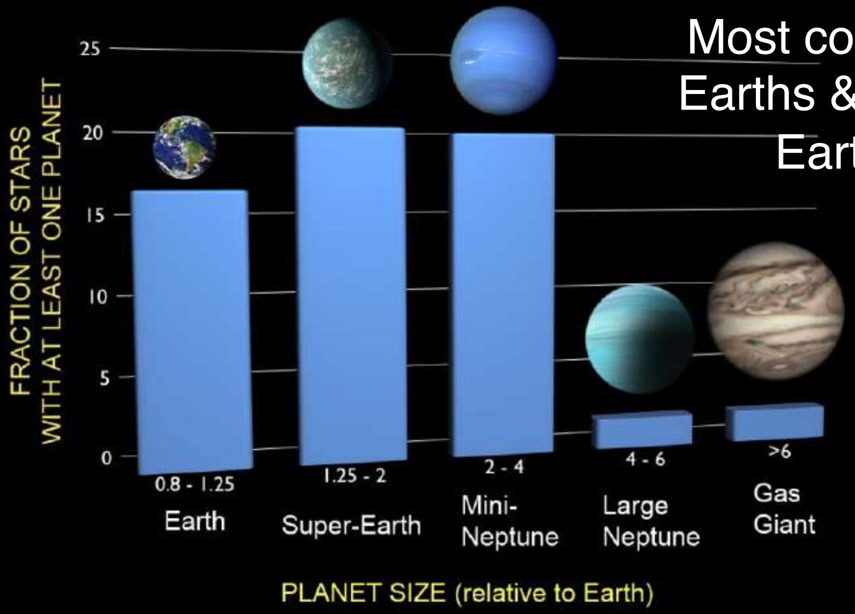
What is known?

#Planets > #Stars



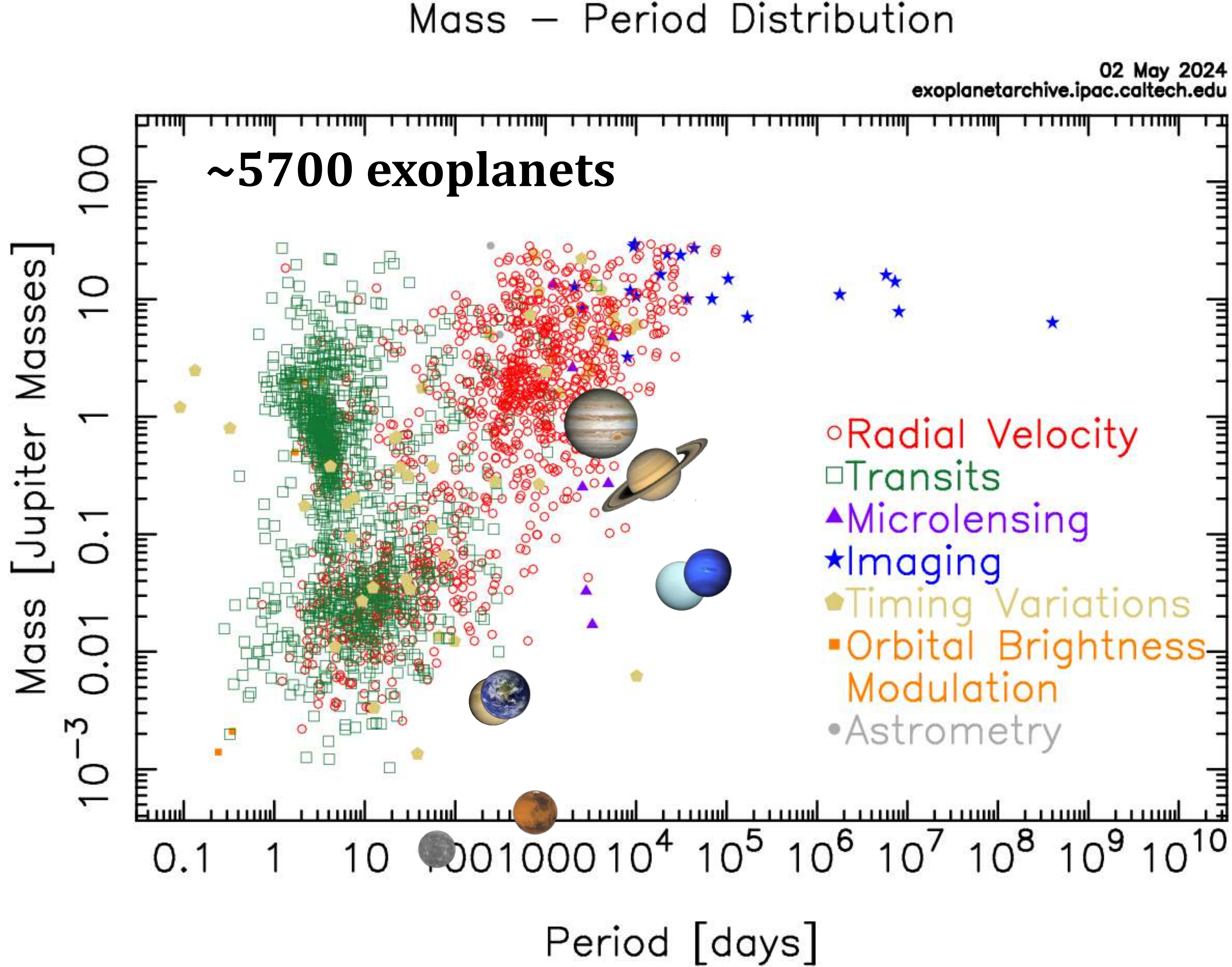


Multiple systems are common, especially around low-mass stars



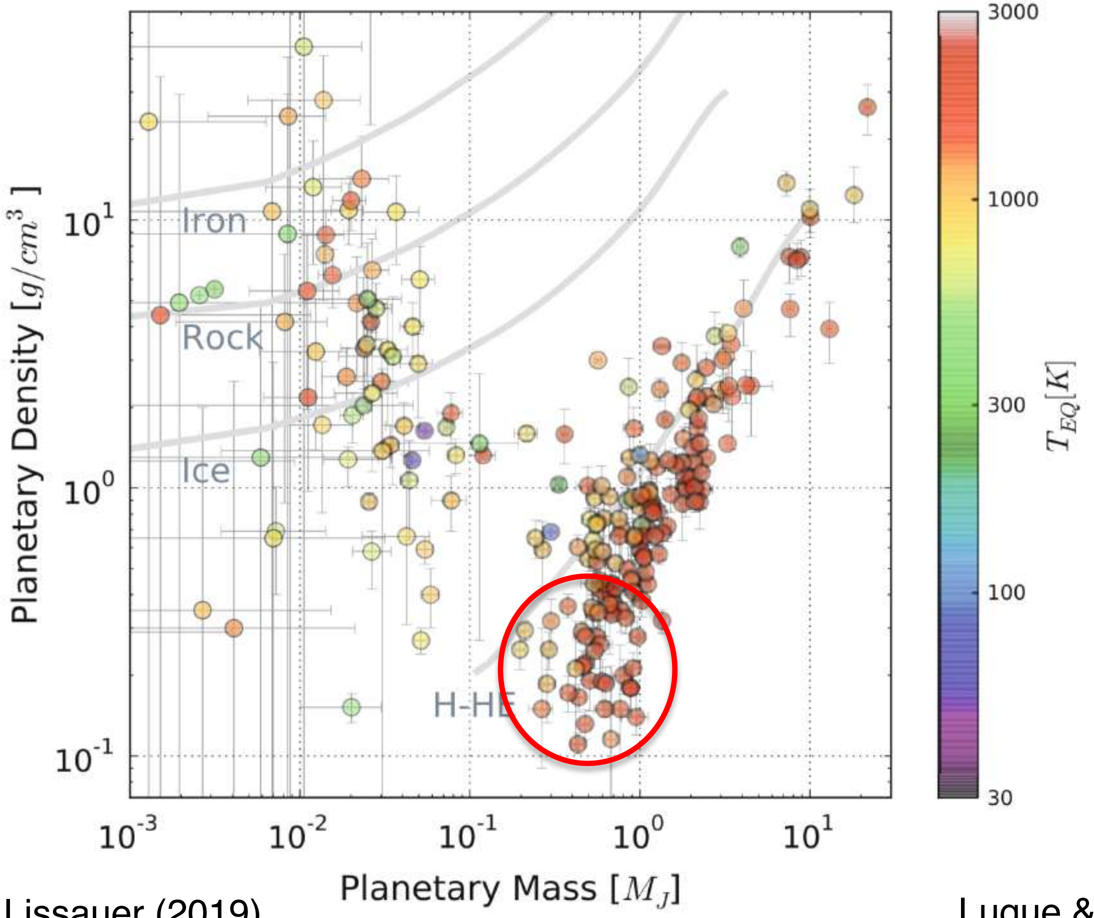
Most common: Earths & super-Earths

Even the closest star has a planet in the habitable zone


Mass – Period Distribution
02 May 2024
exoplanetarchive.ipac.caltech.edu
~5700 exoplanets
Mass [Jupiter Masses]
Period [days]
Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness Modulation
Astrometry

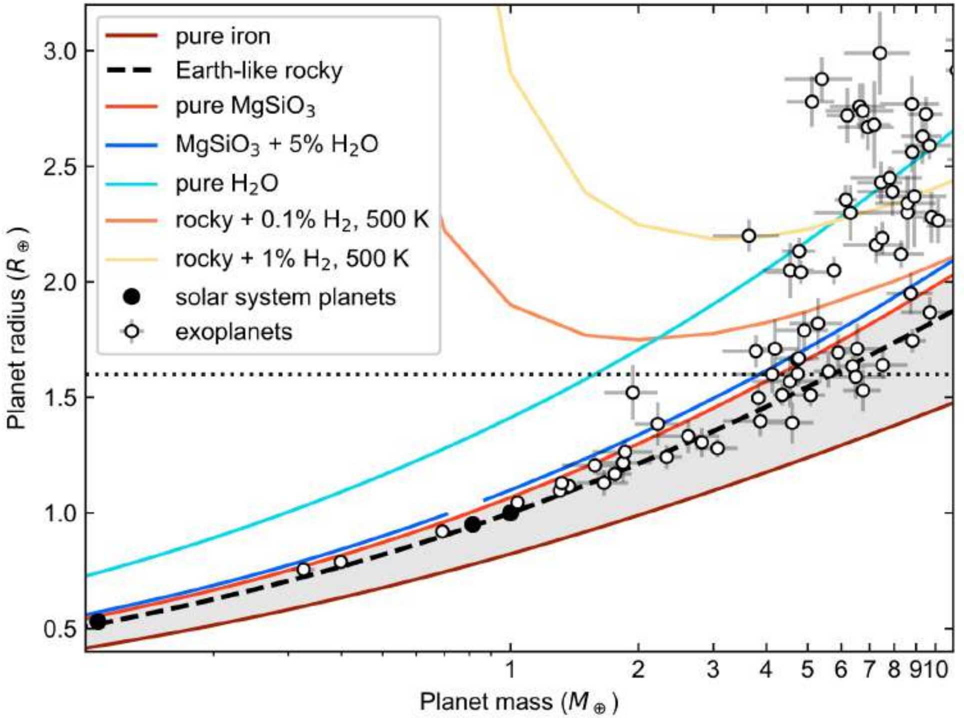
Mysteries

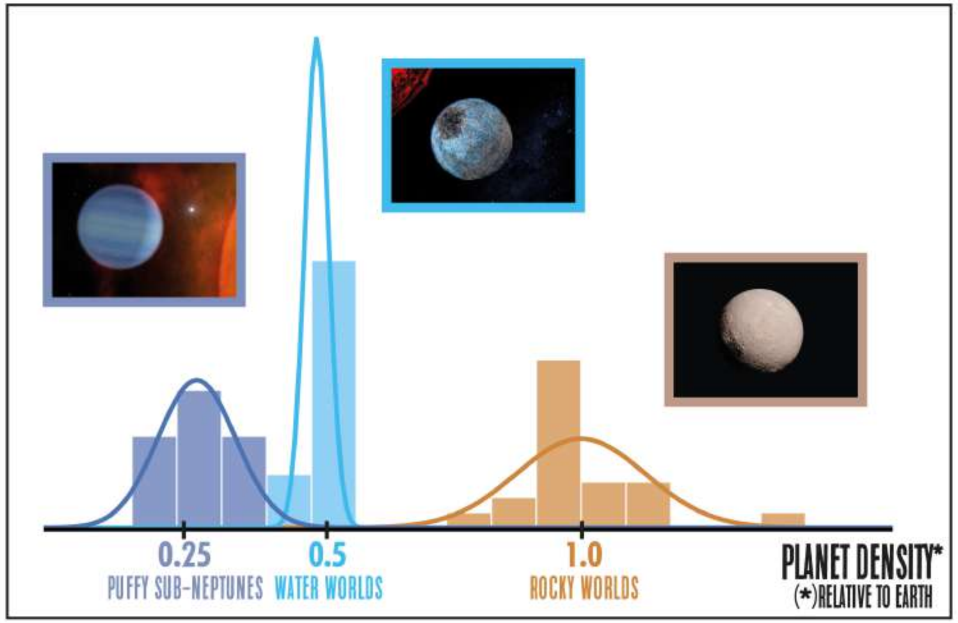
Many hot Jupiters have very low densities and are inflated, with radii > 2 R_{jup}



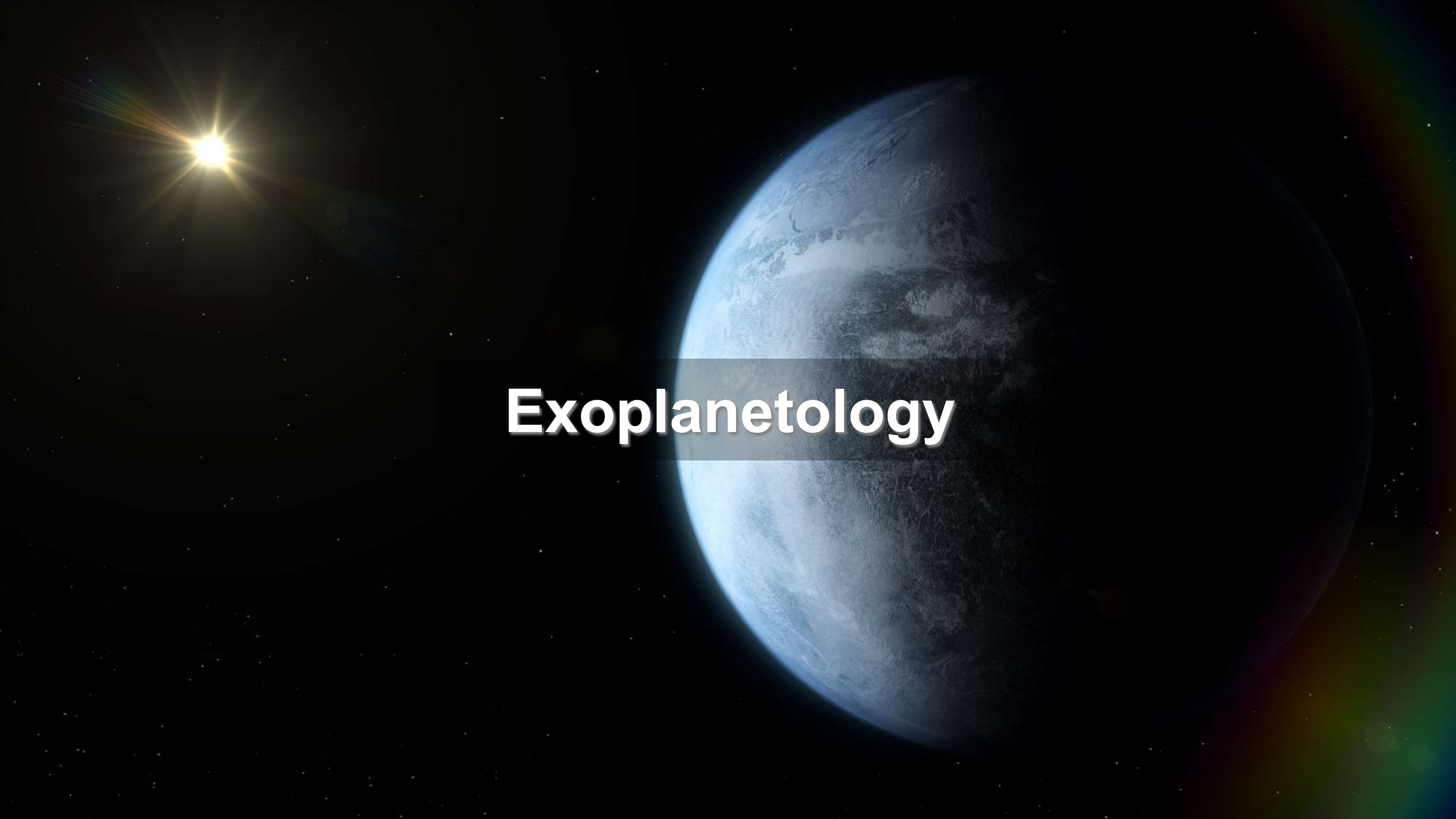
Lissauer (2019)

Where is the rocky/gaseous transition?



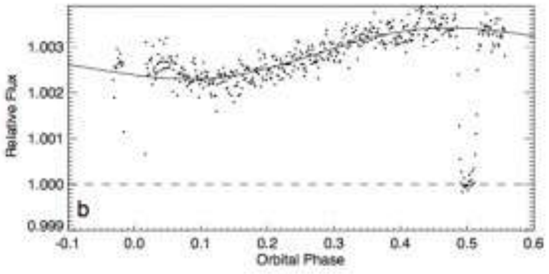


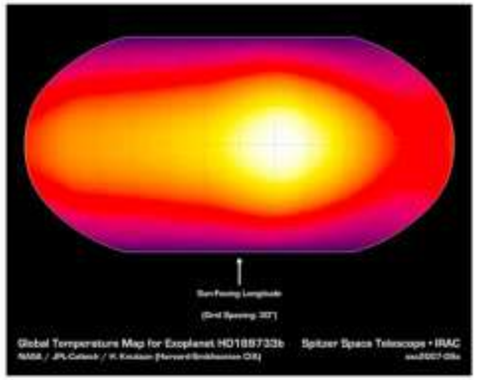
Luque & Pallé (2022)


Exoplanetology

Studying the atmospheres of transiting planets

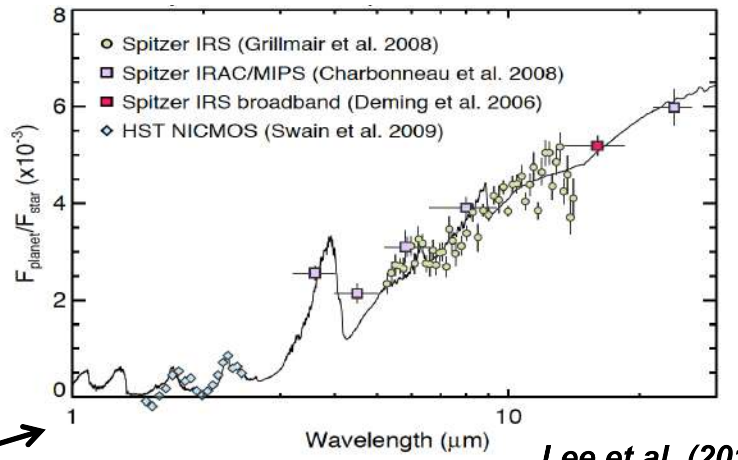
Phase curve





Knutson et al. (2008)

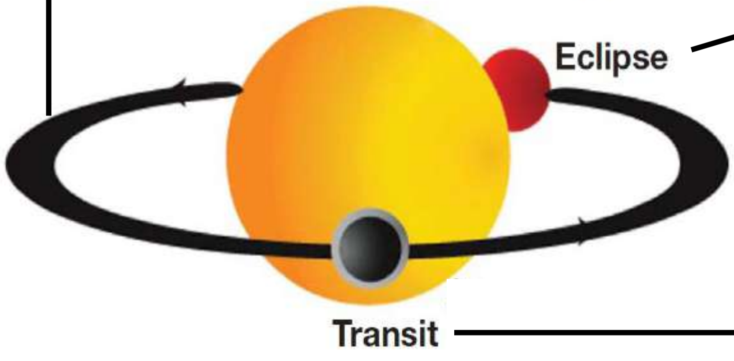
Emission spectrophotometry (dayside)



Lee et al. (2011)

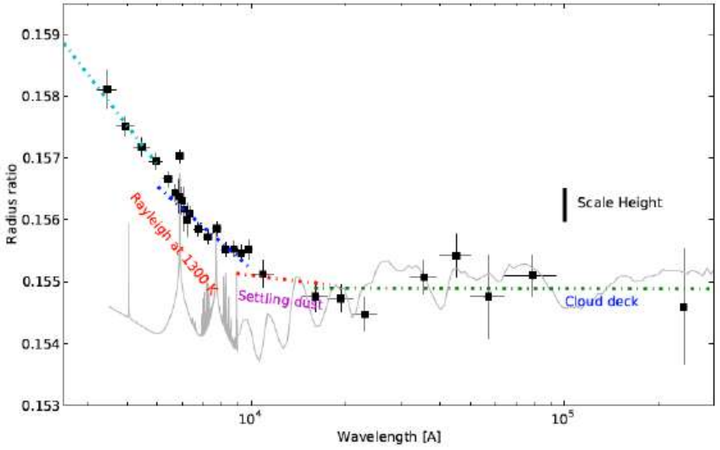
Planet's spectrum without the need for ultra-high spatial resolution

Bonus: mass, radius, orbit, obliquity, etc…



Deming & Seager (2009)

Transmission spectrophotometry (limb)

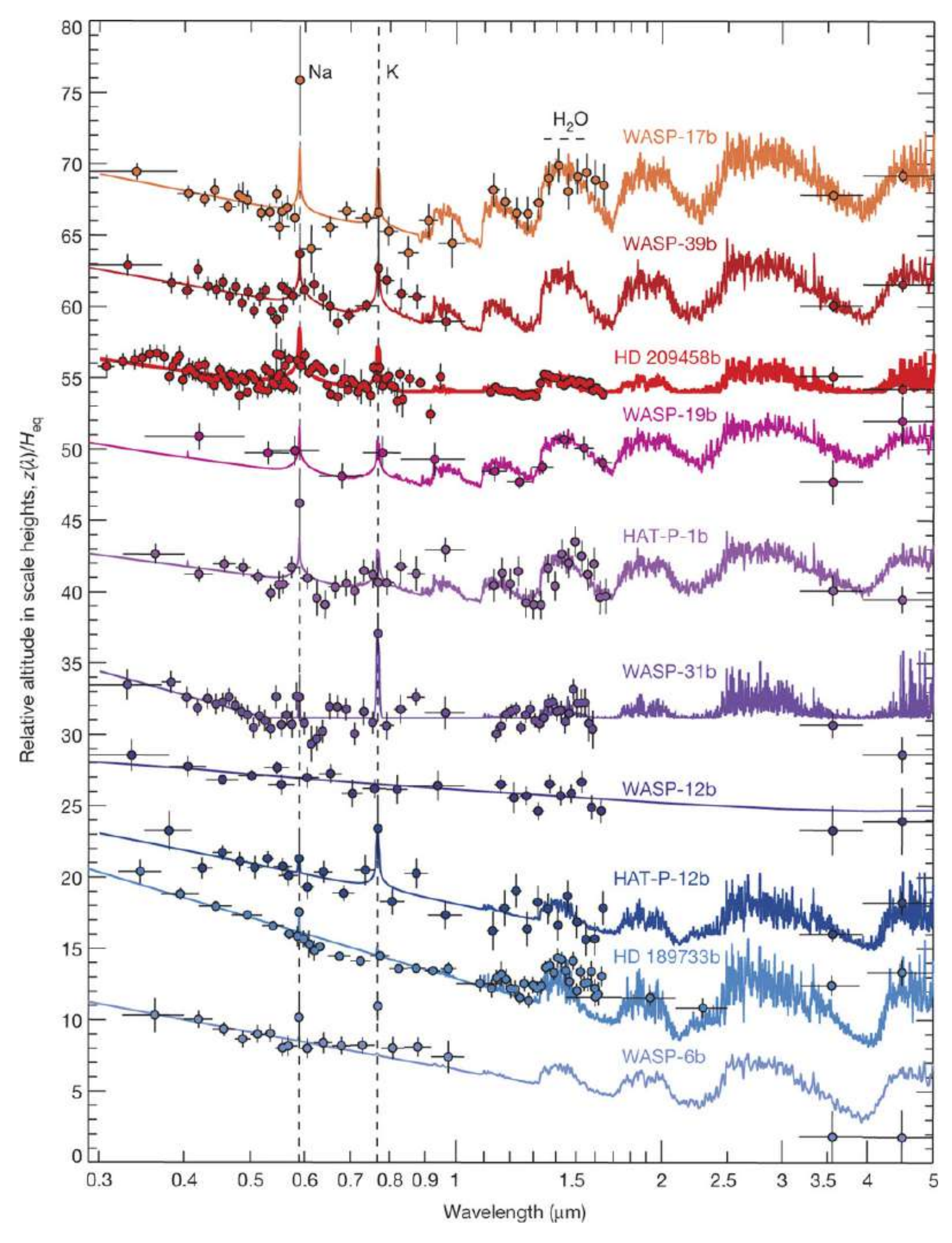


Pont et al. (2013)

On-off method

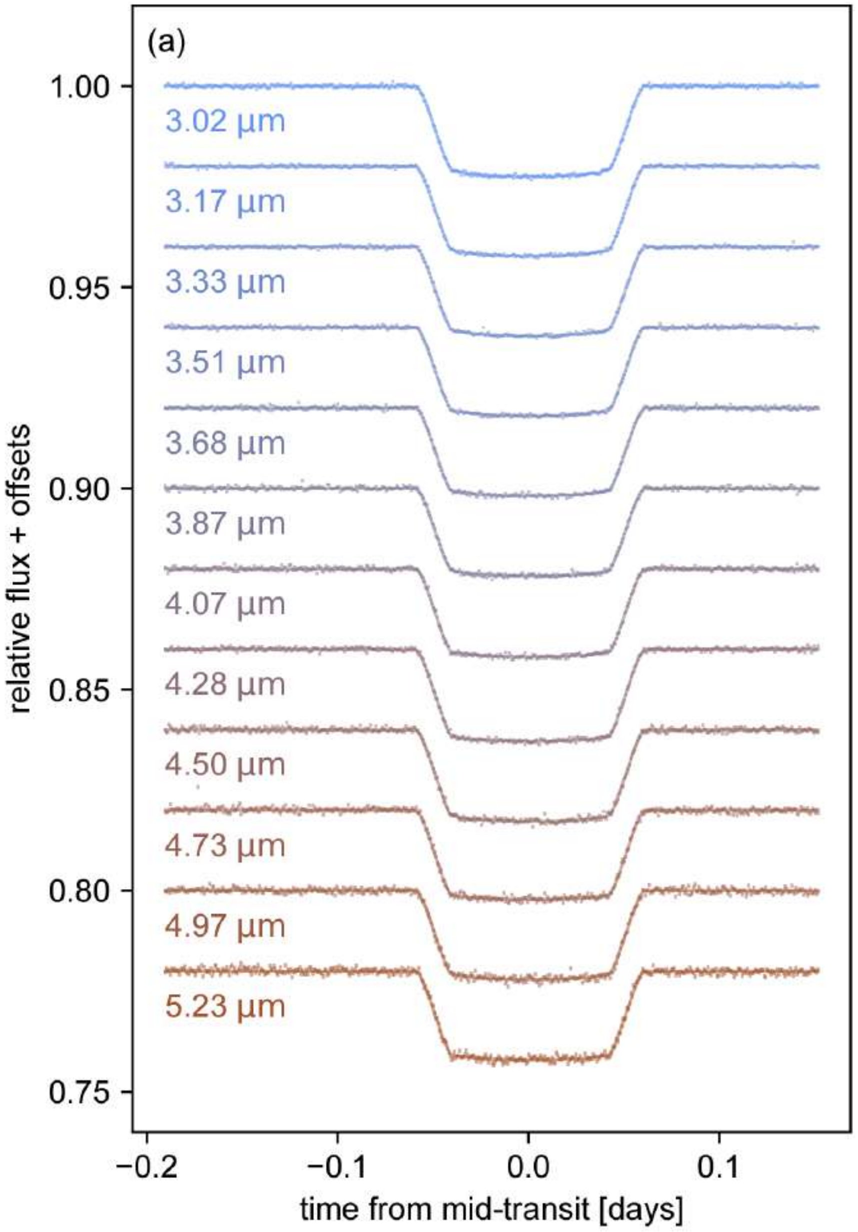
Transmission spectroscopy

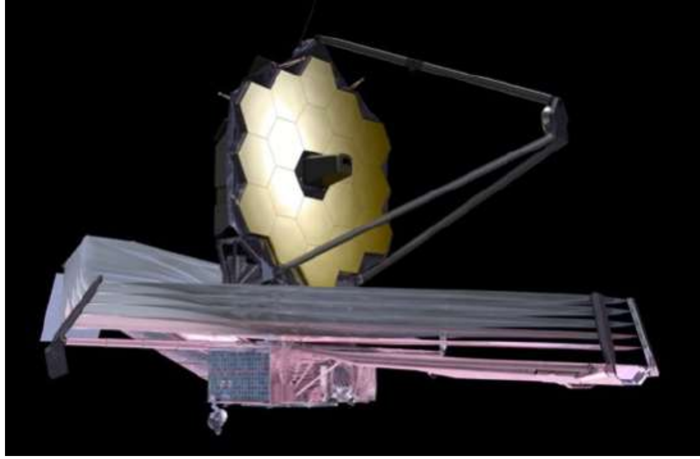
Artist's Impression of "Hot Jupiter" Exoplanets
NASA and ESA ▪ STScI-PRC15-44a

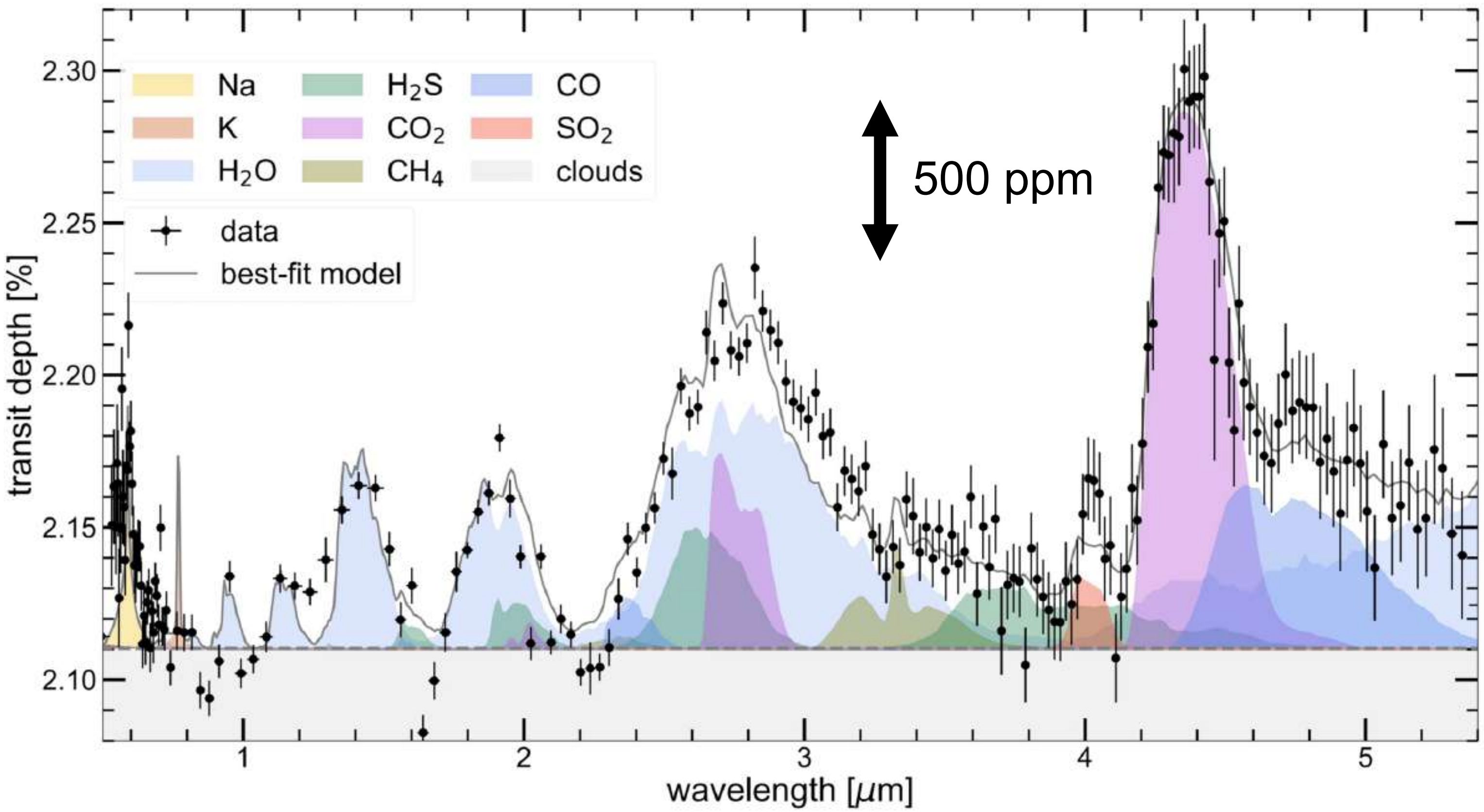


Sing et al. (2016)

Transmission spectrum of WASP-39 b





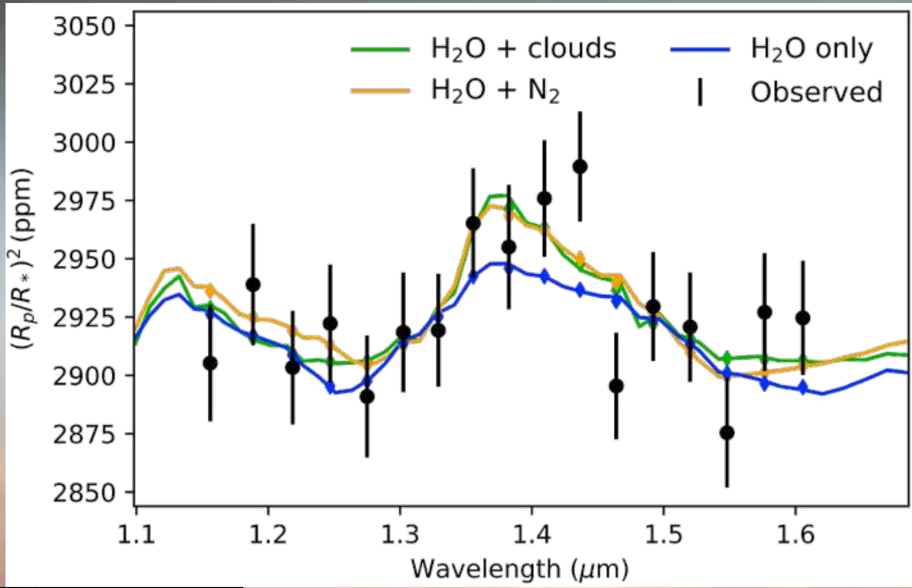


JWST Transiting Exoplanet Community Early Release Science Team, 2023, Nature

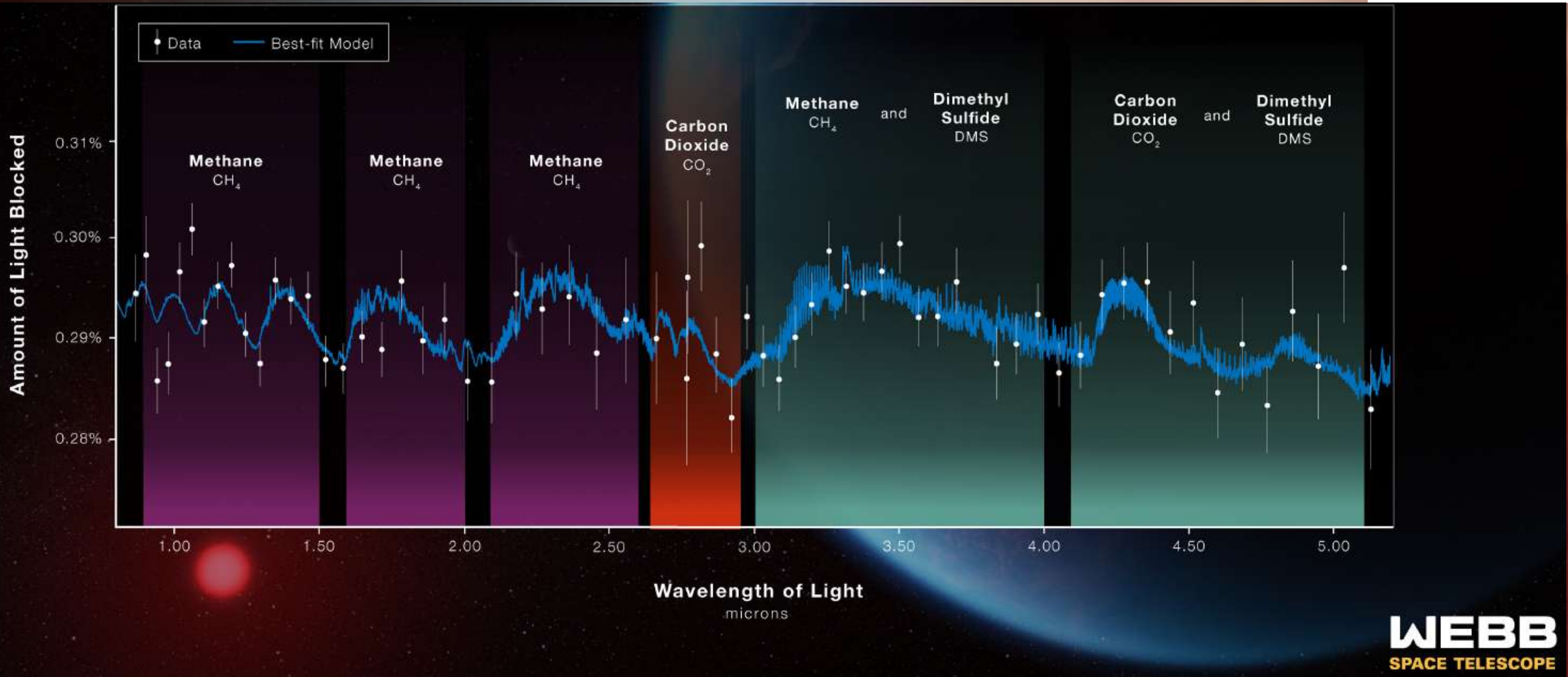
Transit transmission spectroscopy

K2-18 b

Near-IR: water vapor?



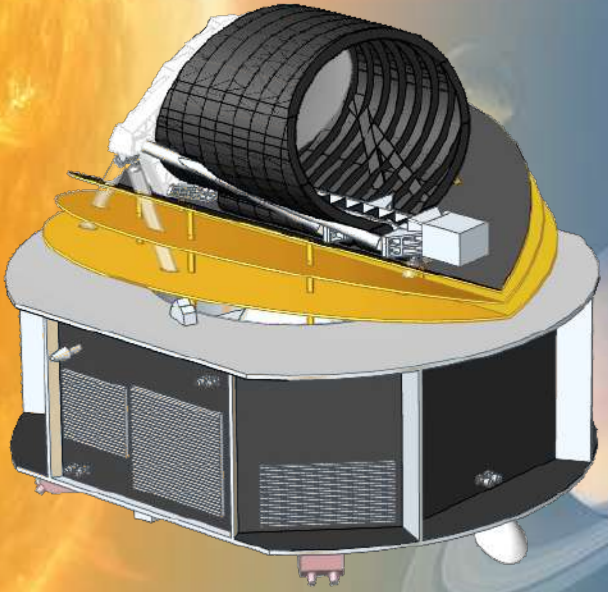
Tsiaras et al. (2019); Benneke et al. (2019)



No! Methane!

Madhusudhan et al. (2023)

The ARIEL mission

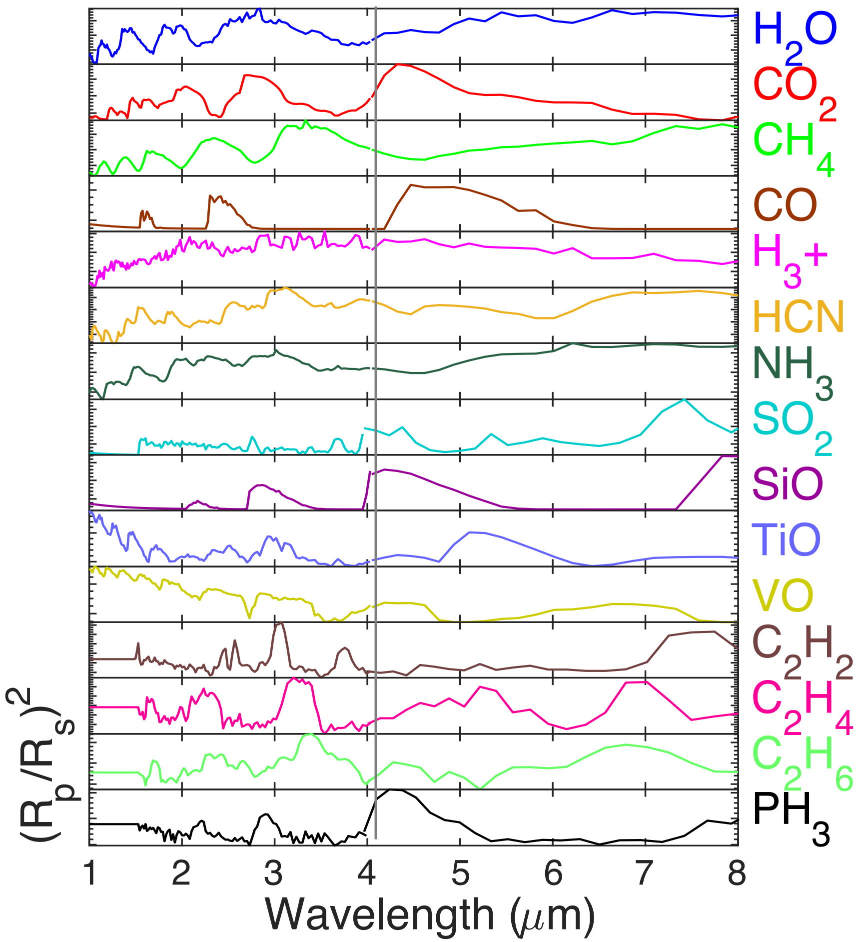


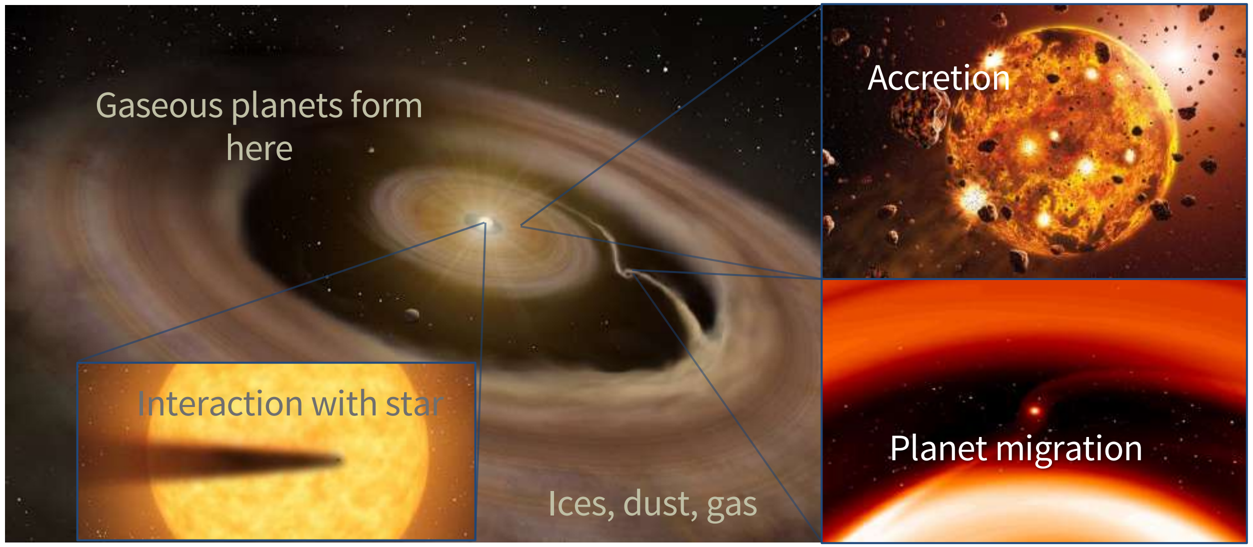
- ESA M4 mission
- Launch in late 2029
- 3.5 years @ L2
- ~1000 transiting exoplanets

European Space Agency

The ARIEL mission

- First chemical census of a large sample of diverse exoplanets

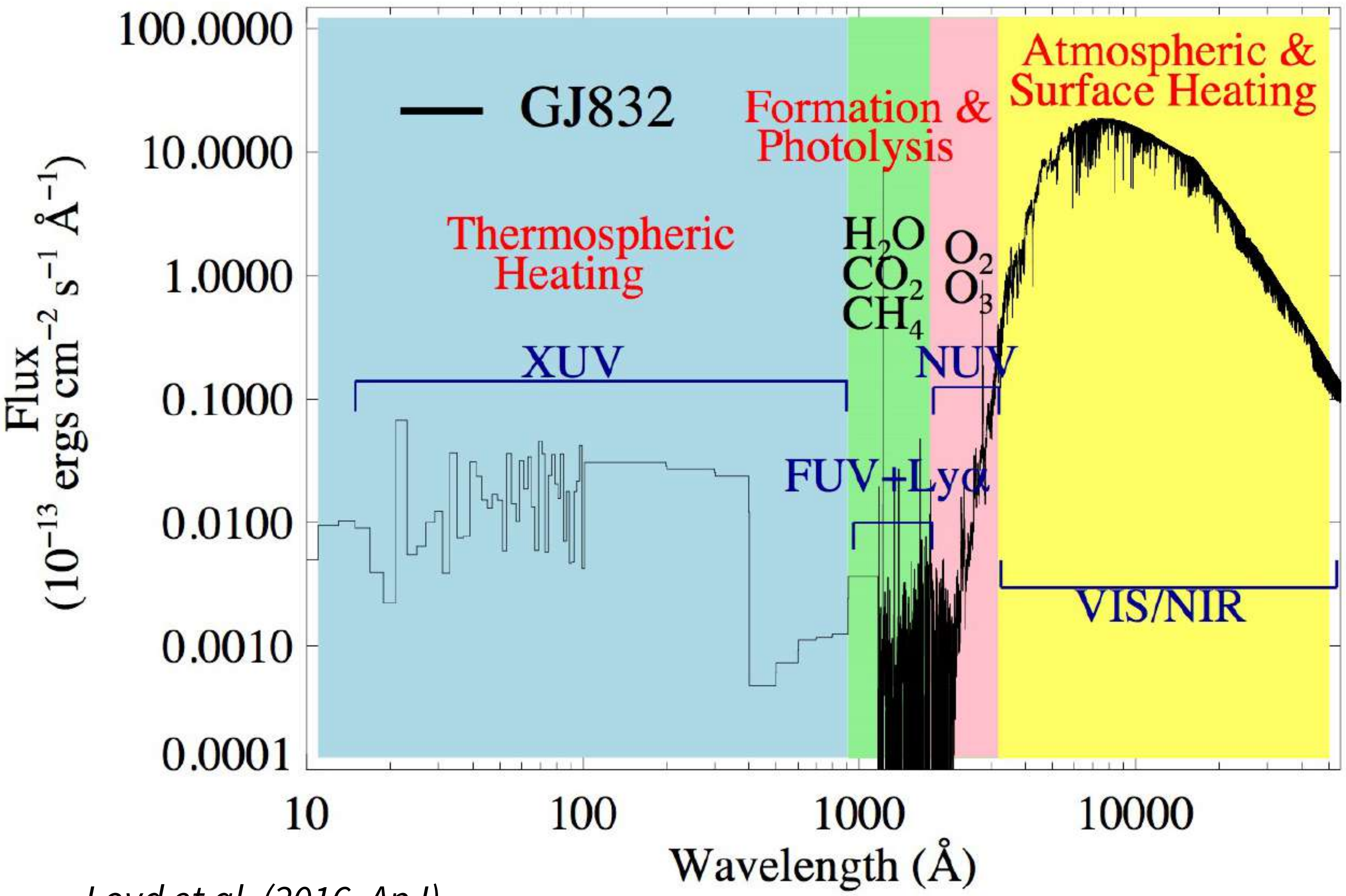




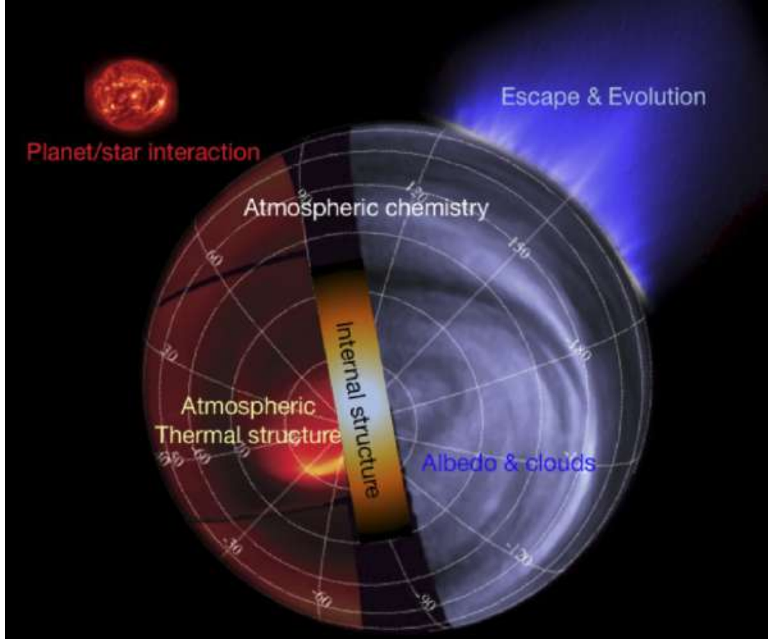
- Elliptical mirror telescope: 1.1 x 0.7 m^2
- Cryogenic instrument with simultaneous coverage 0.5-7.8 mm

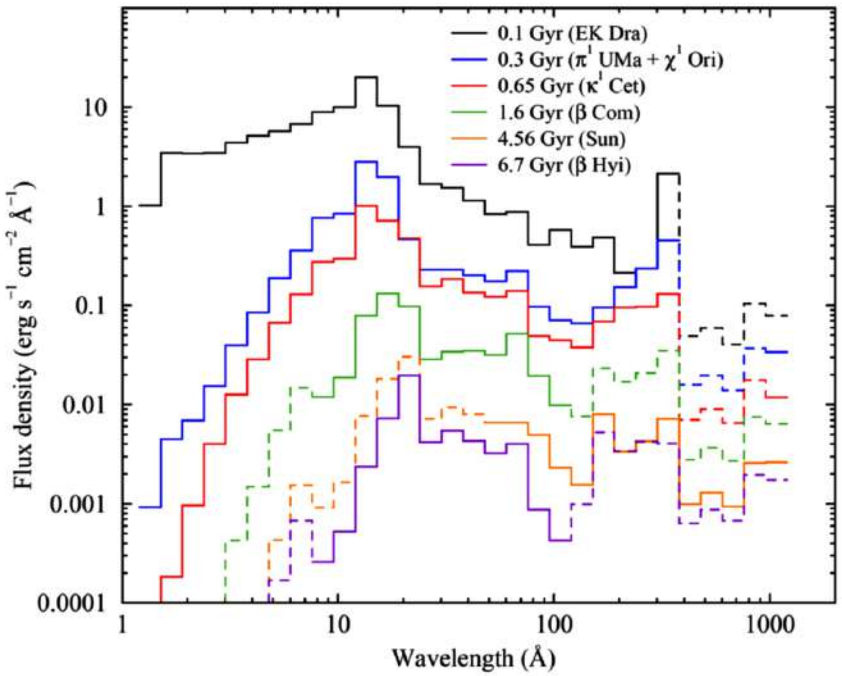
- Key questions
  - How diverse are exoplanets chemically?
  - Does chemical diversity correlate with other parameters?
  - Formation & evolution processes?
  - Migration? Interaction with star?

Stars have an impact on planet atmospheres



Loyd et al. (2016, ApJ)





Sun in time: Ribas et al. (2005, ApJ)

- Are there other planets out there?
- How did they form and evolve?
- What are they made of?
- Are they habitable?
- Are they inhabited?

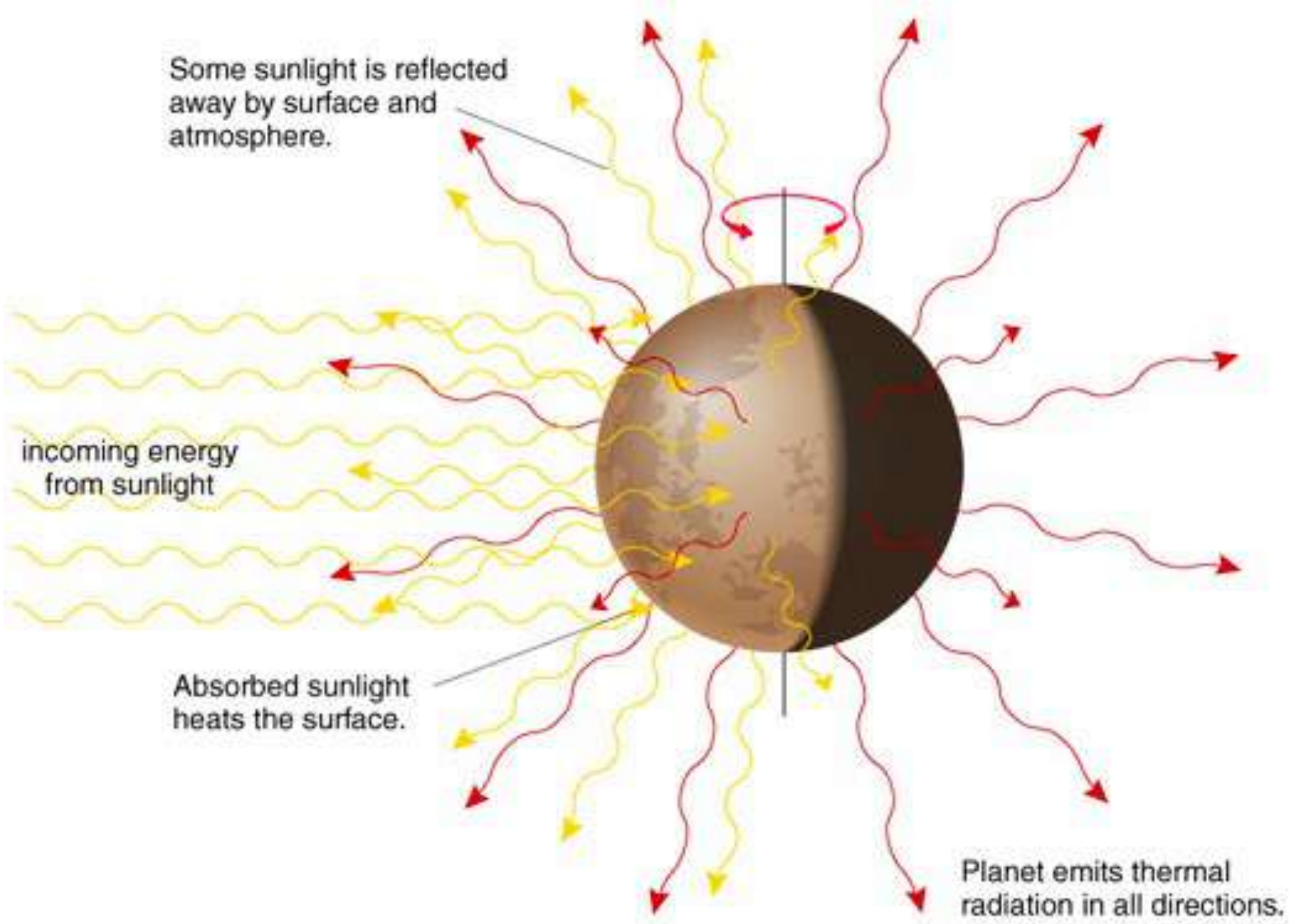
4 centuries after the Copernican revolution, this is a new revolution: Our context in the living Universe

Habitability

The stellar habitable zone

Requirement: liquid water on its surface → surface temperature between 0 and 100 ºC (273 – 373 K)

It depends on the stellar irradiation balance between absorbed and emitted energy.



First approximation

- Absorbed energy: $E_{abs} = \pi R_p^2 (1 - A) \cdot S$

  S: solar (or stellar) irradiance
  $S_\odot$= 1360 W m^{-2} (solar constant, at 1 au) $S = \frac{L}{4\pi a^2}$

  A: Bond albedo, reflected energy $A_{\rm Earth}$ ~ 0.3

- Emitted energy: black body radiation $E_{em} = f \pi R_p^2 \sigma T_{eq}^4$

$$E_{abs} = E_{em} \qquad \pi R_p^2 (1 - A) \cdot S = f \pi R_p^2 \sigma T_{eq}^4$$

f: redistribution factor

- *f*=4 if energy is uniformly redistributed on the planetary sphere (~Earth)
- *f*=2 if the energy is distributed over the starlit hemisphere
- *f*=1/cos θ if there is no redistribution (no atmosphere)

$$T_{eq} = \left(\frac{(1 - A)L}{4\pi a^2 f \sigma} \right)^{1/4} \qquad a = \left(\frac{(1 - A)L}{4\pi f \sigma T_{eff}^4} \right)^{1/2}$$

The stellar habitable zone

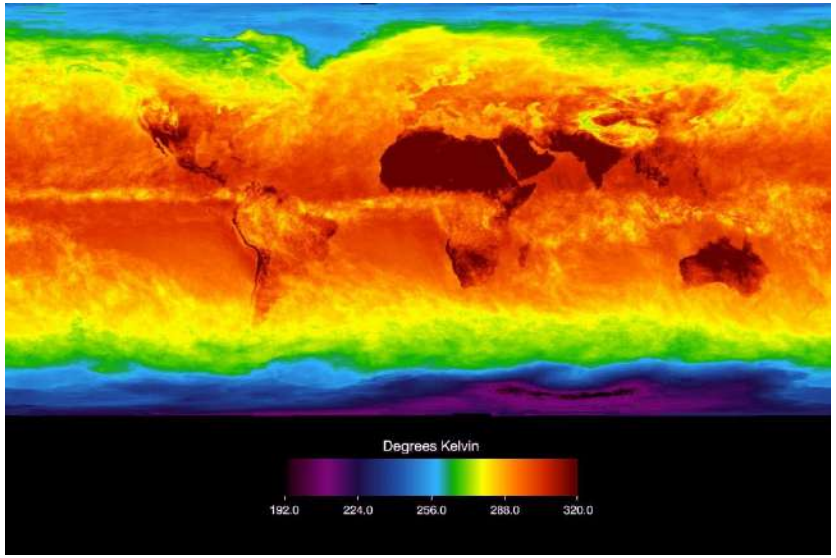
Solar System HZ

Assume $A \sim 0.3$:

HZ inner limit: T_{eq}= 100 °C = 373 K → a_{in} = *0.47 au*

HZ outer limit: T_{eq}= 0 °C = 273 K → a_{out} = *0.87 au!*

Only Venus is inside this region…



Caution! The equilibrium temperature corresponds to a black body with the same emission, but with dense atmospheres, it does not indicate a physical temperature at the surface or the atmosphere

Planet equilibrium temperatures

Venus (a = 0.72 au, $A \sim 0.75$): T_{eq}= –42 °C

Earth (a = 1.0 au, $A \sim 0.29$): T_{eq}= –18 °C

Mars (a = 1.5 au, $A \sim 0.22$): T_{eq}= –60 °C

But we know that surface temperatures are:

Venus ~ 464 ºC (+506 °C)

Earth ~ 15 ºC (+33 °C)

Mars ~ –55 ºC (+5 °C)

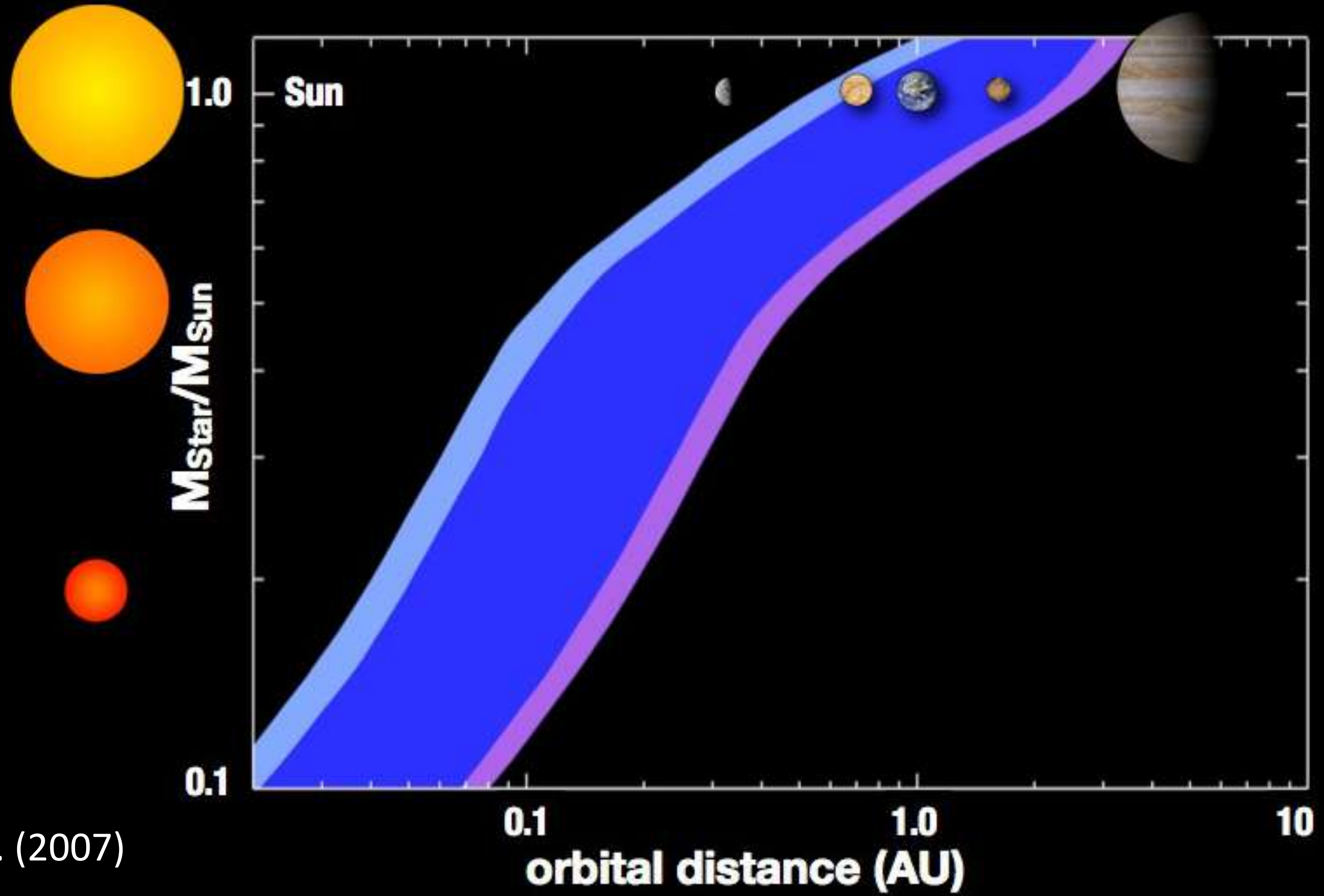
$$T_s = T_{eq} + \Delta T_{GH}$$

Earth case, $A \sim 0.3$, ΔT_{GH} = 33 °C

HZ inner limit: T_s= 100 °C = 373 K → a_{in} = *0.56 au*

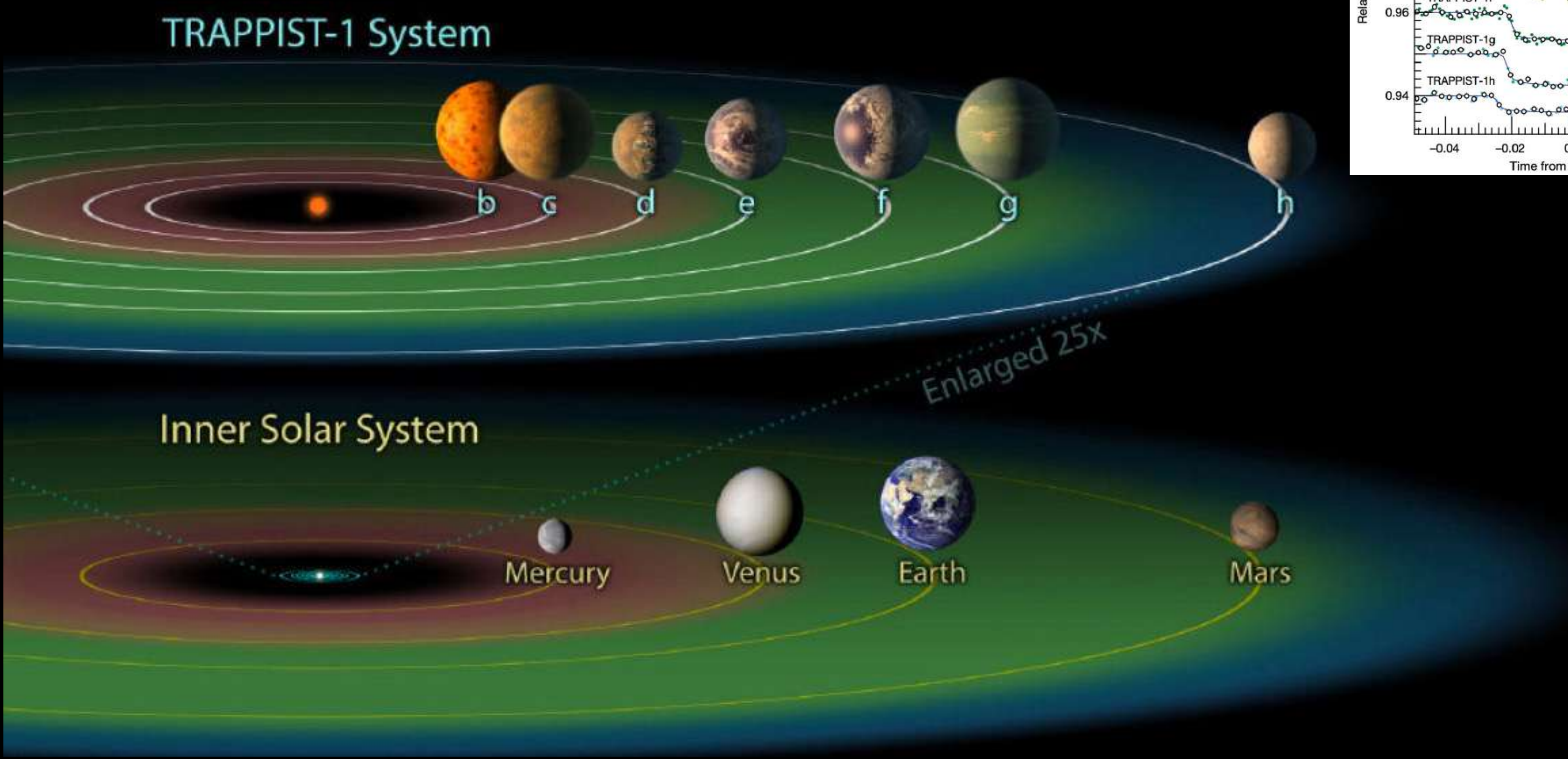
HZ outer limit: T_s= 0 °C = 273 K → a_{out} = *1.12 au*

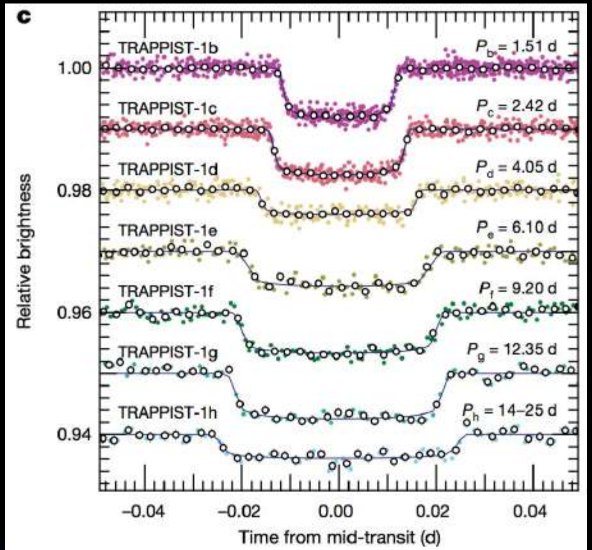
Habitable zone for different stellar masses



Selsis et al. (2007)

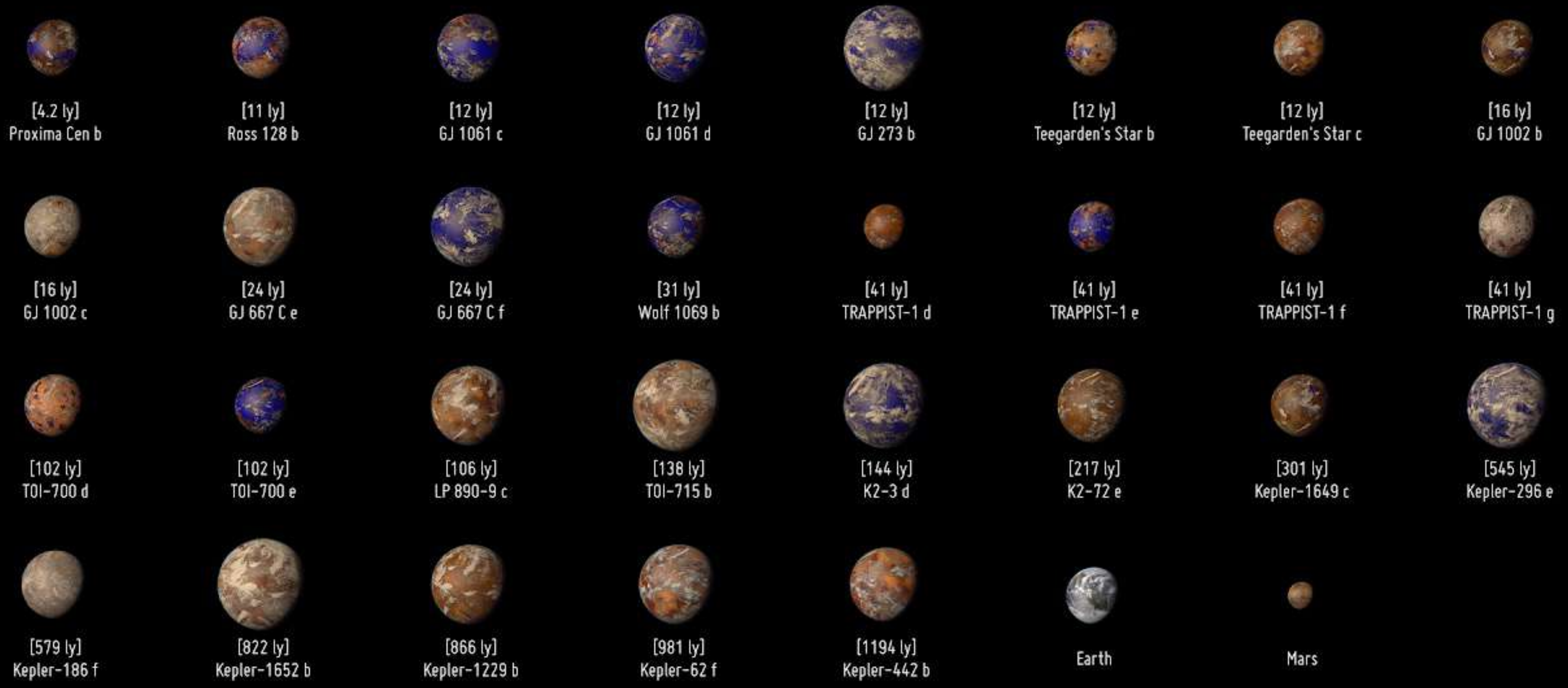
TRAPPIST-1: Seven Earth cousins





Potentially Habitable Worlds

PHL



Artistic representations. Earth and Mars for scale.

Planets are organized in order of their increasing distance from Earth (shown between brackets in light-years).

CREDIT: The Habitable Worlds Catalog, PHL @ UPR Arecibo (phl.upr.edu) Jan 2024

Potentially habitable | 29
(in habitable zone and rocky)

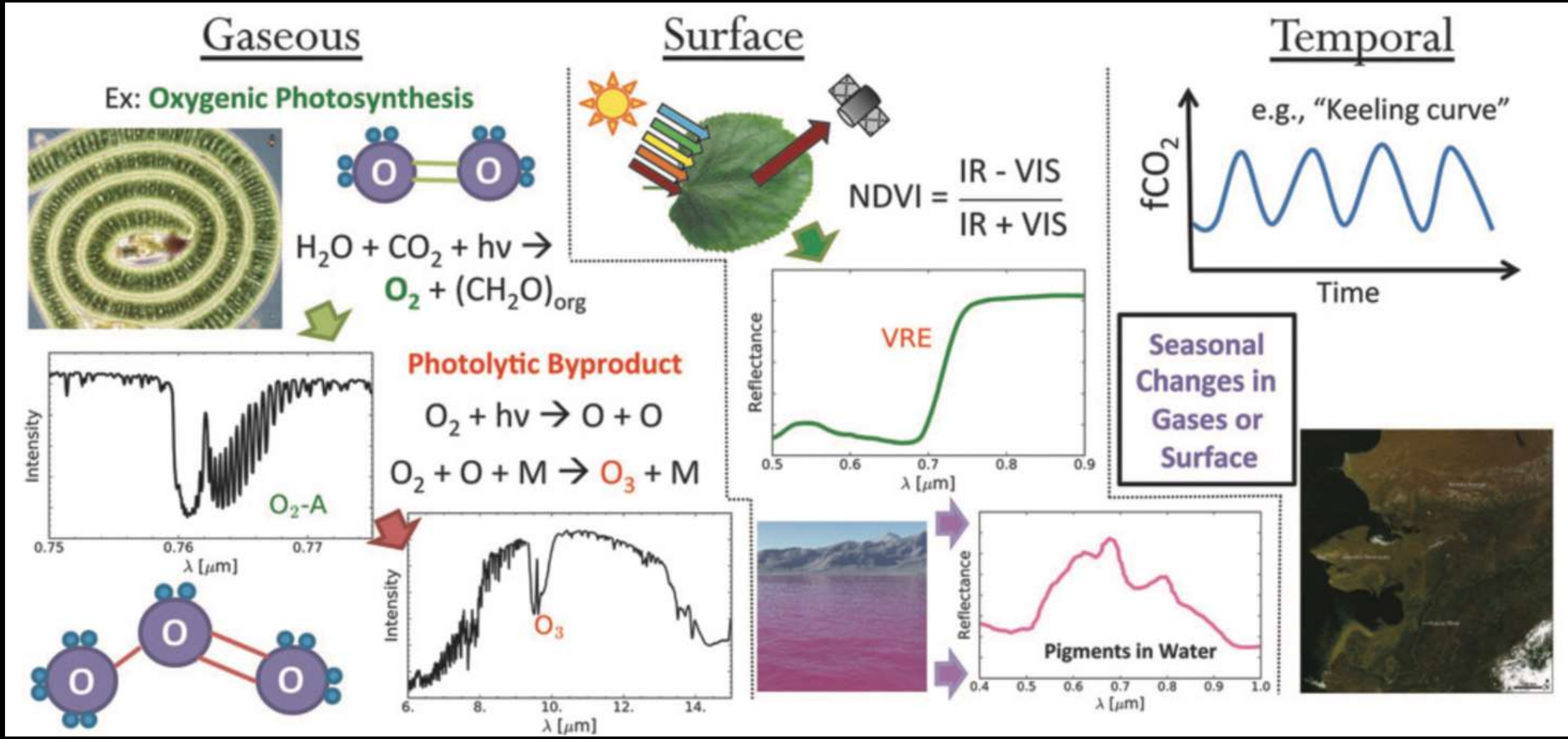
Habitable | ?
(with surface liquid water)

Inhabited | ??
(with a biosphere)

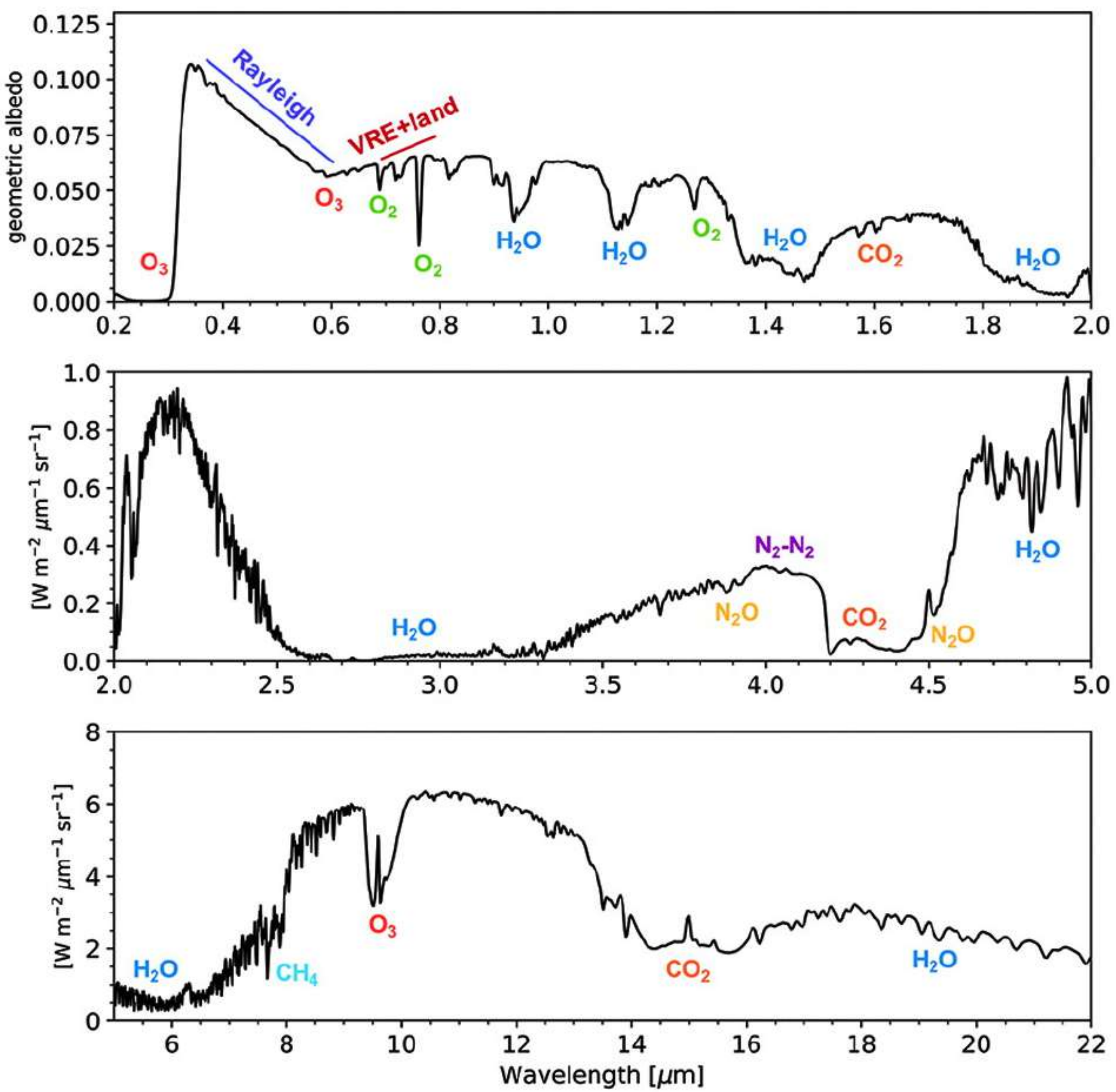
Suitable for humans | ???
(we can breathe)

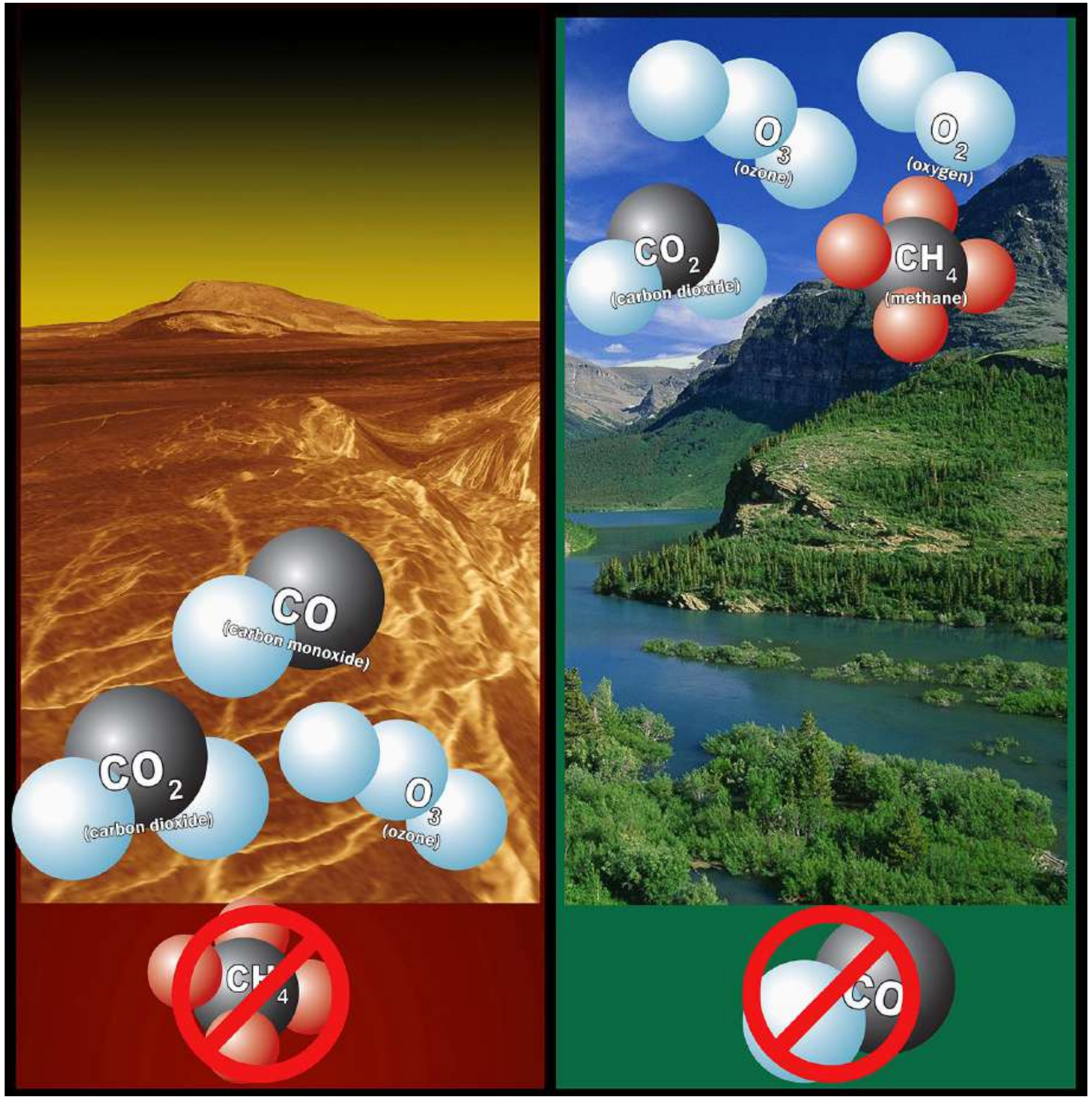
- Biosignature ⇨ object, substance and/or pattern that requires a biological agent

- Remote sensing ⇨ We will not resolve an exoplanet ⇨ Life signs should be a global phenomenon

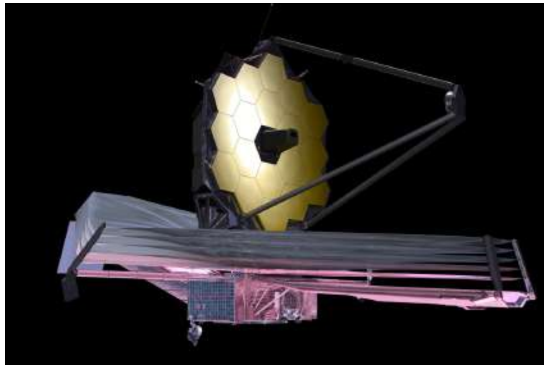


Biosignatures



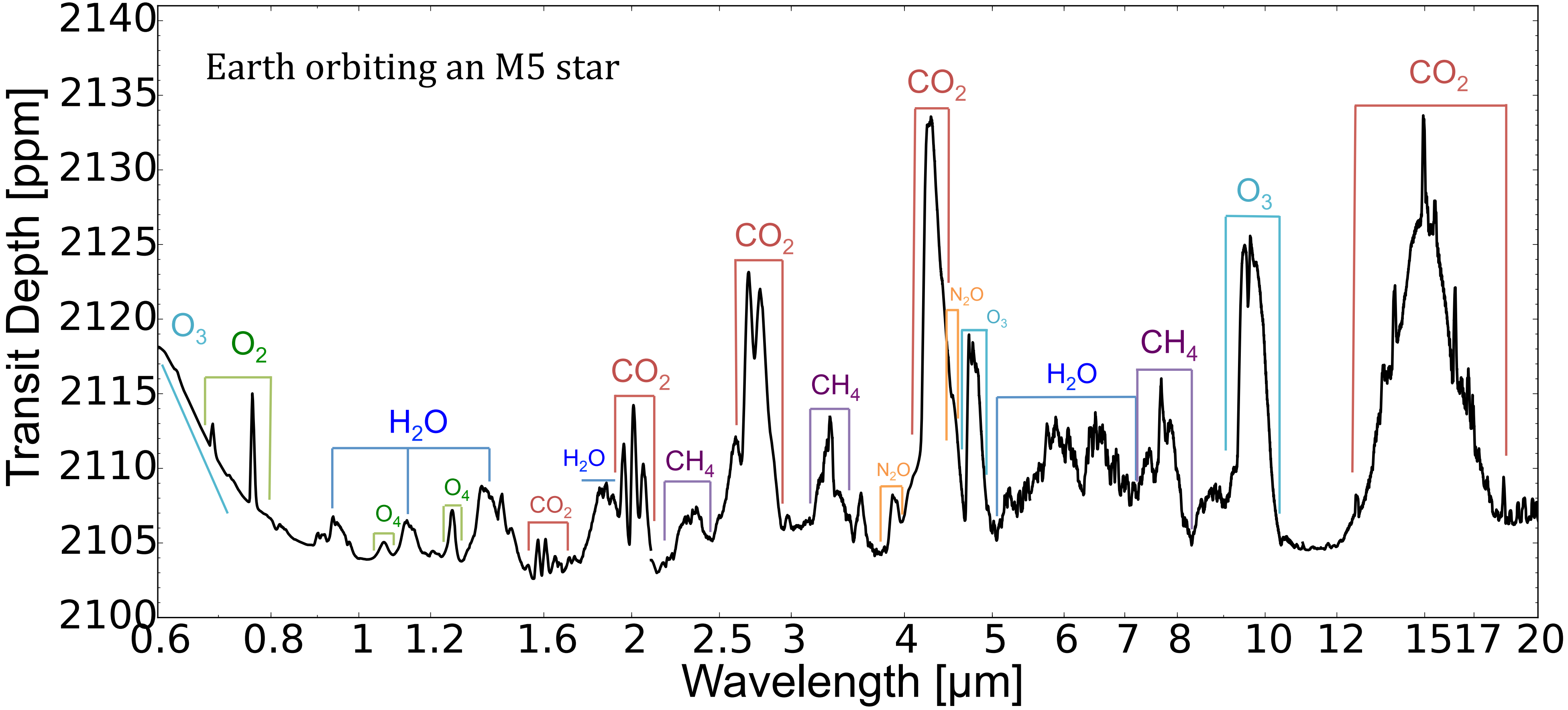


Biosignature detection with JWST

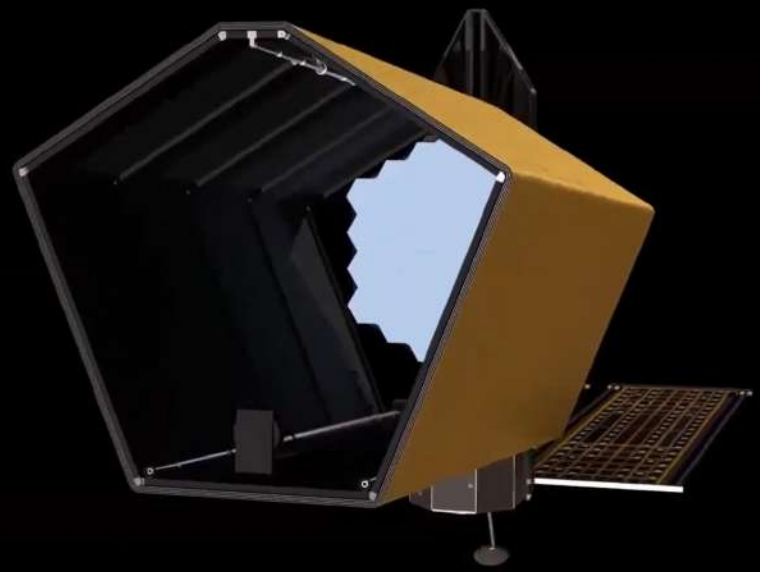


Transmission spectroscopy

Misra et al. (2014)



Signals of 2-30 ppm. Water vapour a few ppm.



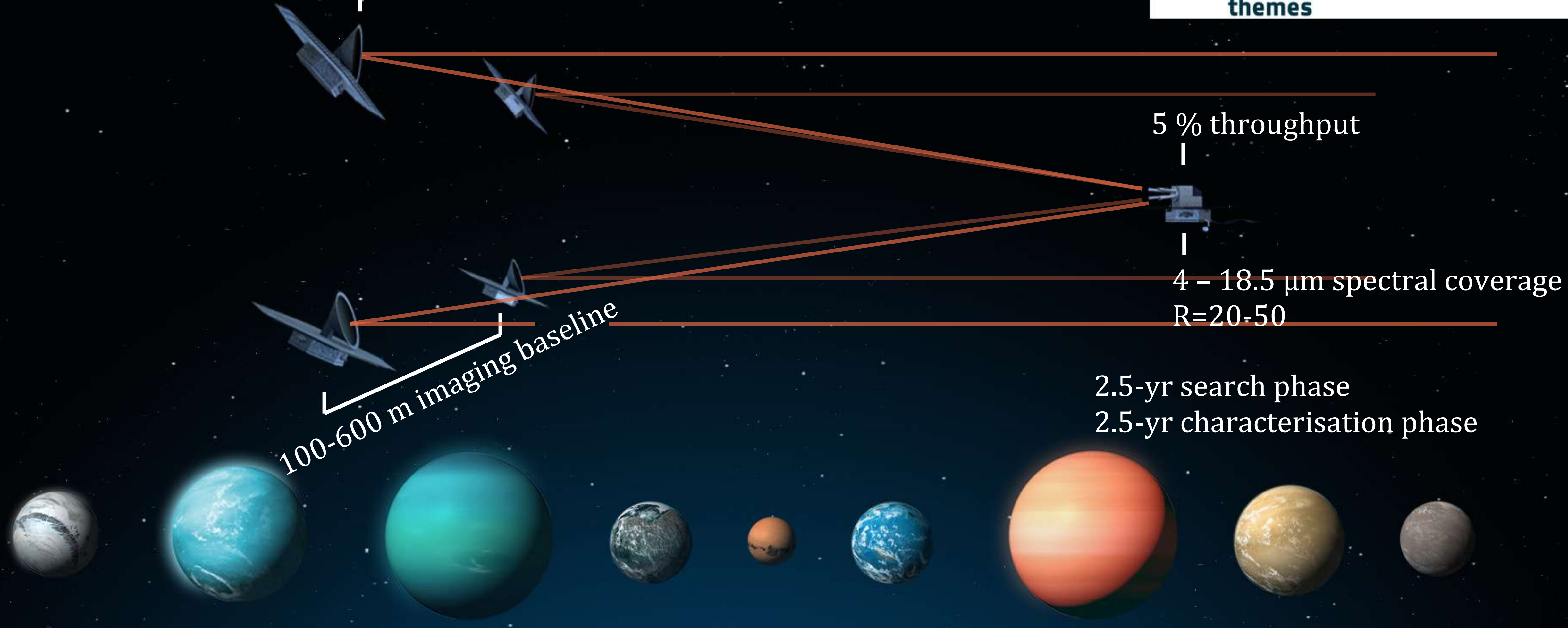
Habitable Worlds Observatory
Simulated Solar System Time-lapse
Observed from 33 light-years away
Time = 10 years, 1 second = 72 days

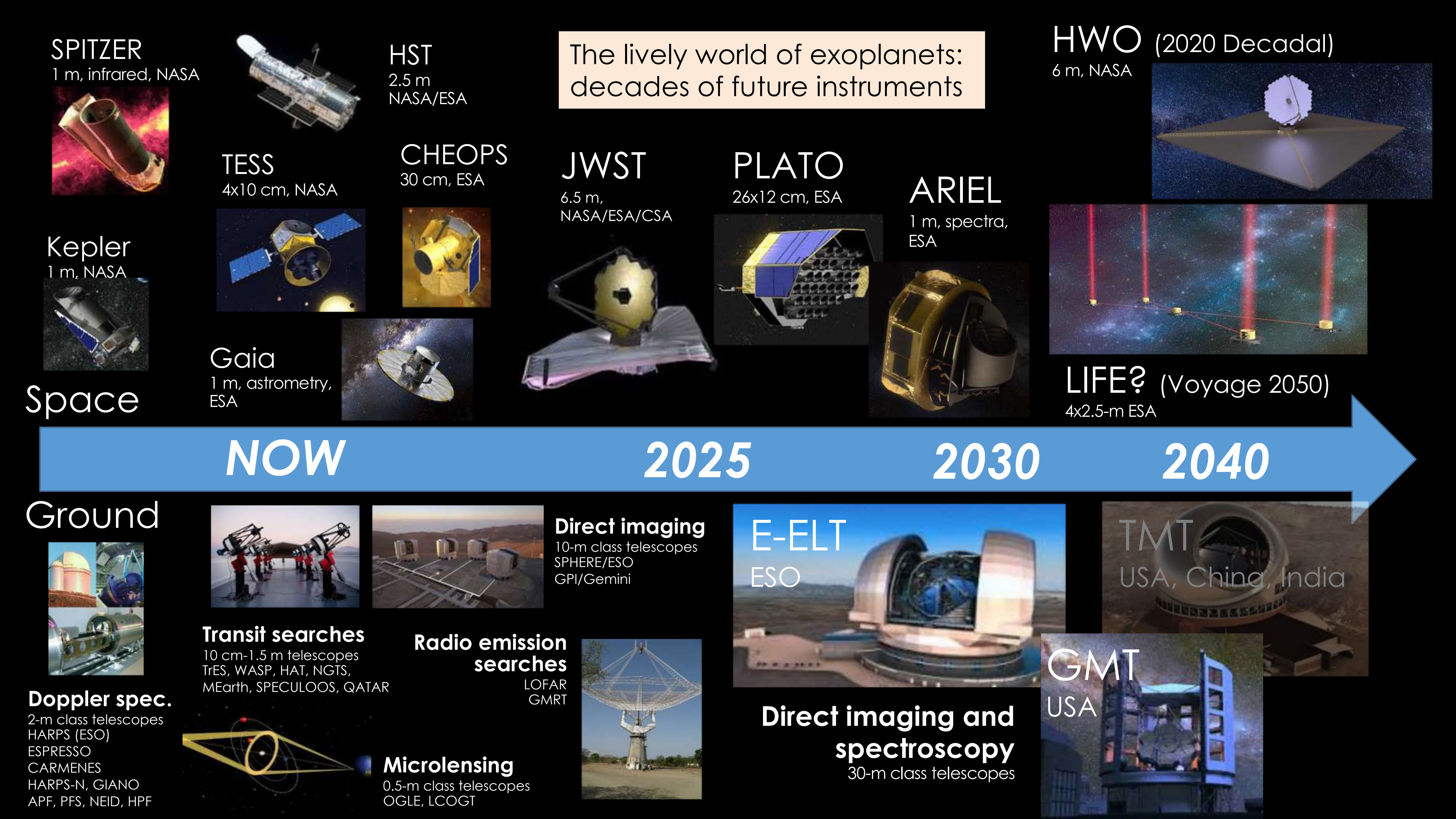
LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Goals:
- Assess habitability
- Search for biosignatures
- Study the diversity of terrestrial planets


SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

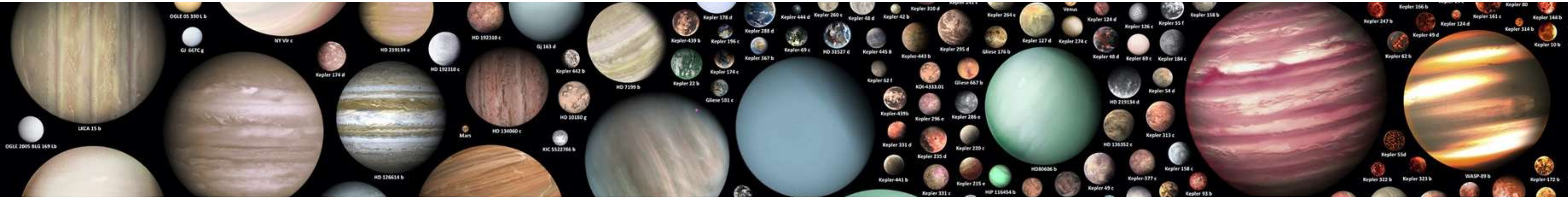



The lively world of exoplanets: decades of future instruments
SPITZER
1 m, infrared, NASA
HST
2.5 m
NASA/ESA
Kepler
1 m, NASA
TESS
4x10 cm, NASA
CHEOPS
30 cm, ESA
Gaia
1 m, astrometry, ESA
Space
JWST
6.5 m, NASA/ESA/CSA
PLATO
26x12 cm, ESA
ARIEL
1 m, spectra, ESA
HWO (2020 Decadal)
6 m, NASA
LIFE? (Voyage 2050)
4x2.5-m ESA
NOW
2025
2030
2040
Ground
Doppler spec.
2-m class telescopes
HARPS (ESO)
ESPRESSO
CARMENES
HARPS-N, GIANO
APF, PFS, NEID, HPF
Transit searches
10 cm-1.5 m telescopes
TrES, WASP, HAT, NGTS,
MEarth, SPECULOOS, QATAR
Direct imaging
10-m class telescopes
SPHERE/ESO
GPI/Gemini
Radio emission searches
LOFAR
GMRT
Microlensing
0.5-m class telescopes
OGLE, LCOGT
E-ELT
ESO
TMT
USA, China, India
GMT
USA
Direct imaging and spectroscopy
30-m class telescopes

The big challenges

- Planetary architectures in solar-type stars
- Atmospheres of a great diversity of planets
- Climates + physical-chemical processes + geology
- Main constituents of rocky temperate exoplanets:
  - Atmospheres dominated by N_2/CO_2?
  - Presence of H_2O?
  - Presence of biosignature gases O_2 – CH_4?
  - Biosignature gases due to biotic or abiotic processes?

Orders of magnitude in science




Pale Blue Dot
Voyager 1, 1990