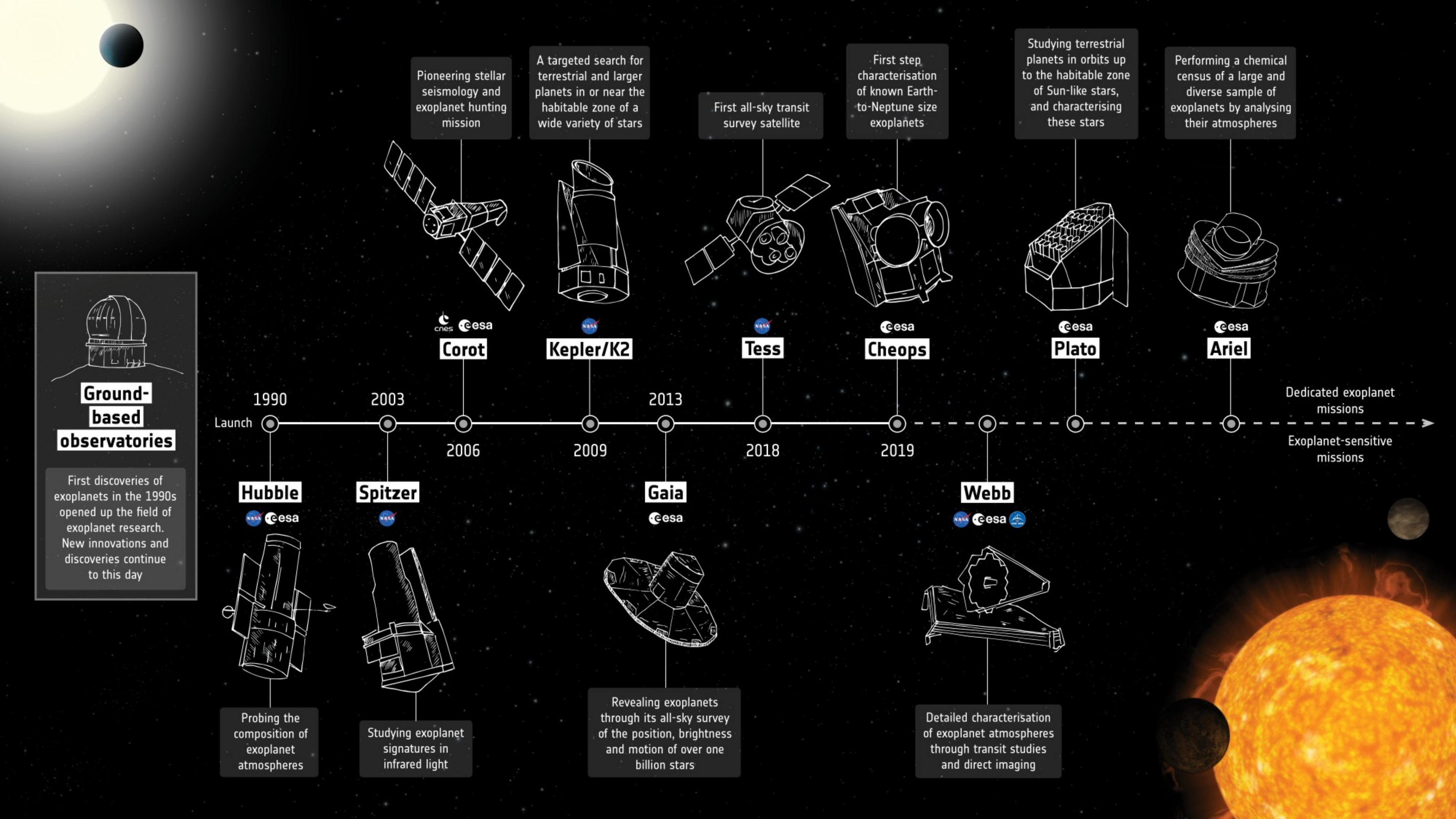
Reading list

- TESS
  Ricker 2015, doi:10.1117/1.JATIS.1.1.014003
- Plato
  https://sci.esa.int/web/plato/-/59252-plato-definition-study-report-red-book
- Cheops
  https://sci.esa.int/web/cosmic-vision/-/53541-cheops-definition-study-report-red-book
- Ariel
  https://sci.esa.int/web/ariel/-/ariel-definition-study-report-red-book



Ground-based observatories
First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day
Launch
1990
2003
2006
2009
2013
2018
2019
Pioneering stellar seismology and exoplanet hunting mission
cnes esa
Corot
A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars
NASA
Kepler/K2
First all-sky transit survey satellite
NASA
Tess
First step characterisation of known Earth-to-Neptune size exoplanets
esa
Cheops
Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars
esa
Plato
Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres
esa
Ariel
Dedicated exoplanet missions
Exoplanet-sensitive missions
Hubble
NASA esa
Probing the composition of exoplanet atmospheres
Spitzer
NASA
Studying exoplanet signatures in infrared light
Gaia
esa
Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars
Webb
NASA esa CSA
Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging

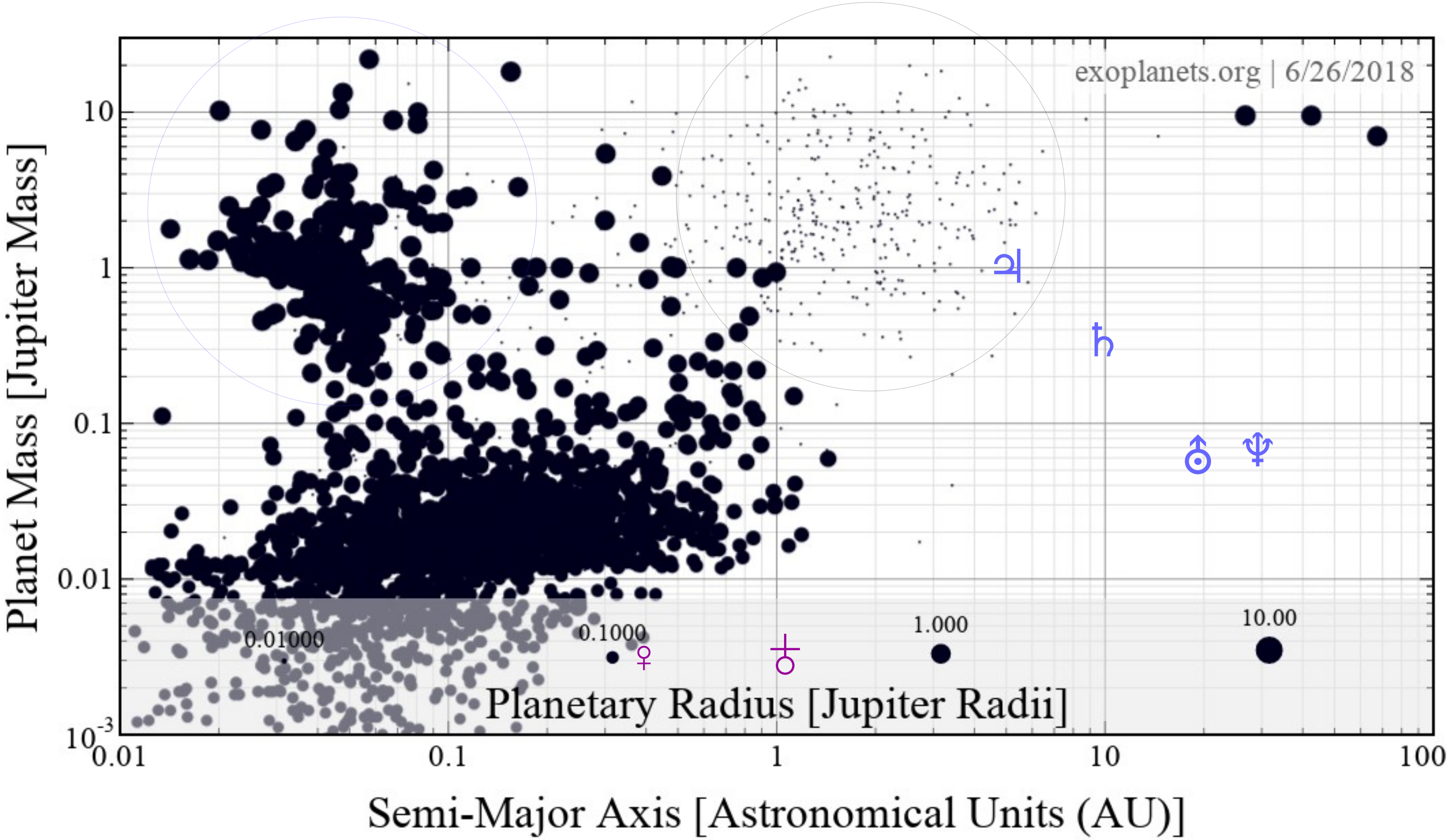
Top level comparison

Why?

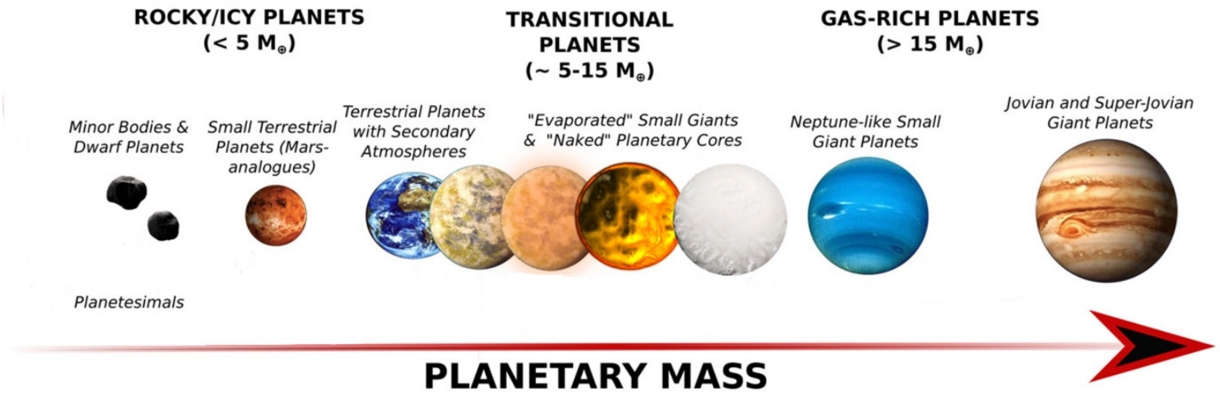
- Kepler, 1.4m primary, 10^ox10^o FoV
- TESS, 15cm lens, $(48^o)^2$ FoV
- Plato, similar to TESS
- Cheops, 30cm primary, $(0.3^o)^2$ FoV
- JWST, 6.5m primary, ~arcmin FoV
- Ariel, 1m primary, ~arcsec FoV

Mass – semi-major axis distribution

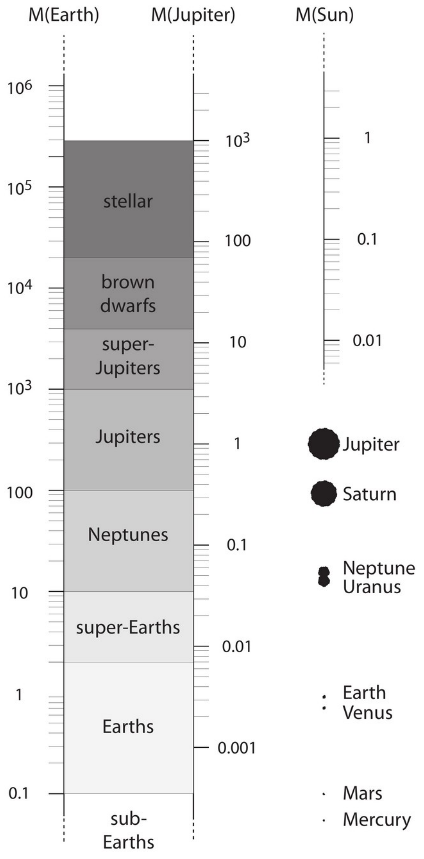
Mercury	☿
Venus	♀
Earth	♁
Mars	♂
Jupiter	♃
Saturn	♄
Uranus	⛢
Neptune	♆



Classification by size or mass

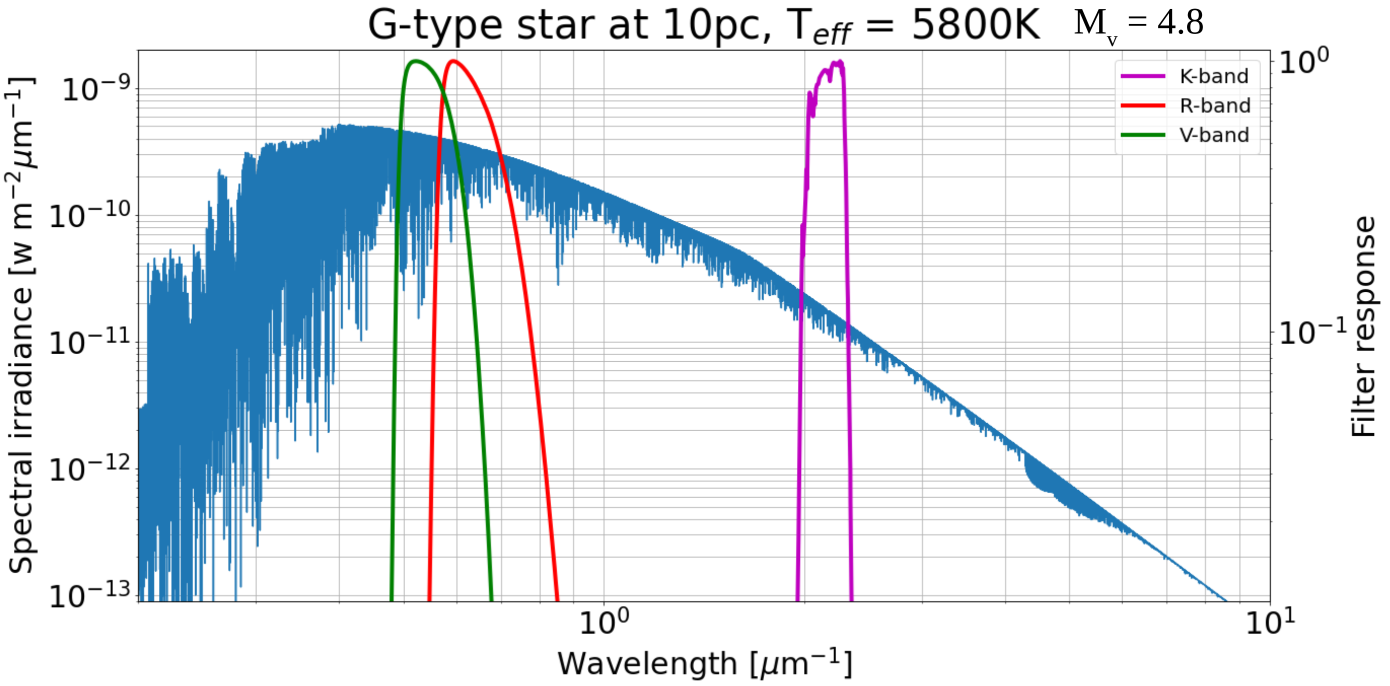


Adapted from Turrini & Riazzoli



Perryman, 2018

Typical star signals



Band V | wl: 0.55 um | S:3.8e-10 w/m2 | N:1.1e+09 ph/s /m^2
Band R | wl: 0.65 um | S:3.3e-10 w/m2 | N:1.1e+09 ph/s /m^2
Band K | wl: 2.17 um | S:1.8e-11 w/m2 | N:1.9e+08 ph/s /m^2

Solar System Fact Sheet

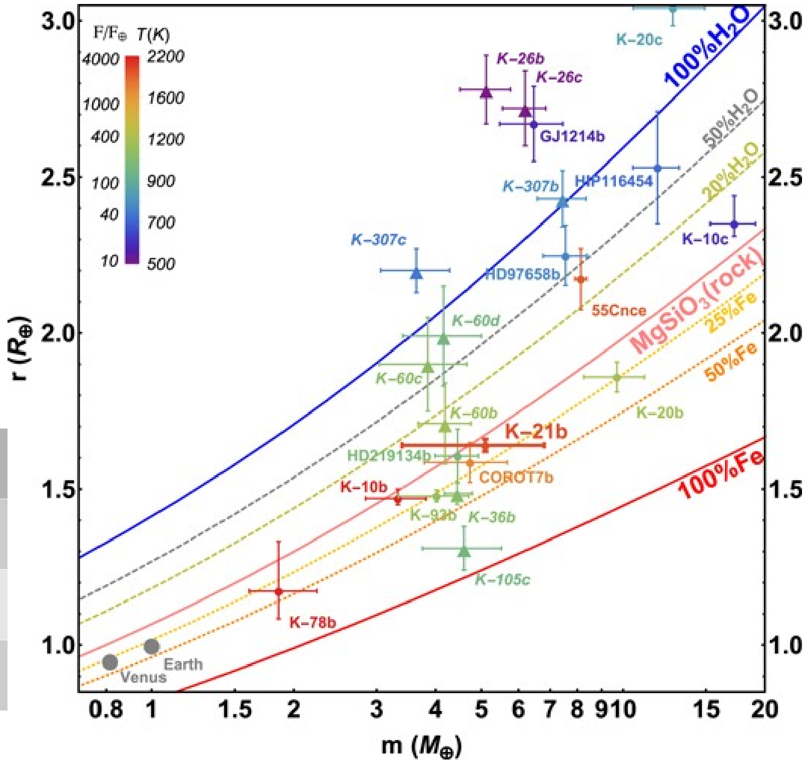
	|← ROCKY PLANETS				→|	|← GASEOUS PLANETS			→|	
Parameters* \ Planet	**MERCURY**	**VENUS**	**EARTH**	**MOON**	**MARS**	**JUPITER**	**SATURN**	**URANUS**	**NEPTUNE**	**PLUTO**
Mass	0.0553	0.815	1	0.0123	0.107	317.8	95.2	14.5	17.1	0.0025
Diameter	0.383	0.949	1	0.2724	0.532	11.21	9.45	4.01	3.88	0.186
Density (g/cm3)	5.4	5.2	5.5	3.3	3.9	1.3	0.7	1.3	1.6	2.1
Gravity	0.378	0.907	1	0.166	0.377	2.36	0.916	0.889	1.12	0.071
Rotation Period	58.8	-244	1	27.4	1.03	0.415	0.445	-0.72	0.673	6.41
Distance from Sun	0.387	0.723	1	0.00257	1.52	5.2	9.58	19.2	30.05	39.48
Orbital Period	0.241	0.615	1	0.0748	1.88	11.9	29.4	83.7	163.7	247.9
Orbital Velocity	1.59	1.18	1	0.0343	0.808	0.439	0.325	0.228	0.182	0.157
Orbital Eccentricity	12.3	0.401	1	3.29	5.6	2.93	3.38	2.74	0.677	14.6
Inclination (degrees)	7	3.4	0	5.1	1.9	1.3	2.5	0.8	1.8	17.2
Surface Pressure	0	92	1	0	0.01	–	–	–	–	0.00001
Number of Moons	0	0	1	0	2	79	62	27	14	5
Ring System?	No	No	No	No	No	Yes	Yes	Yes	Yes	No
Global Magnetic Field?	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	–

* – All parameters in Terrestrial units, except density and inclination.

Reference dimensions

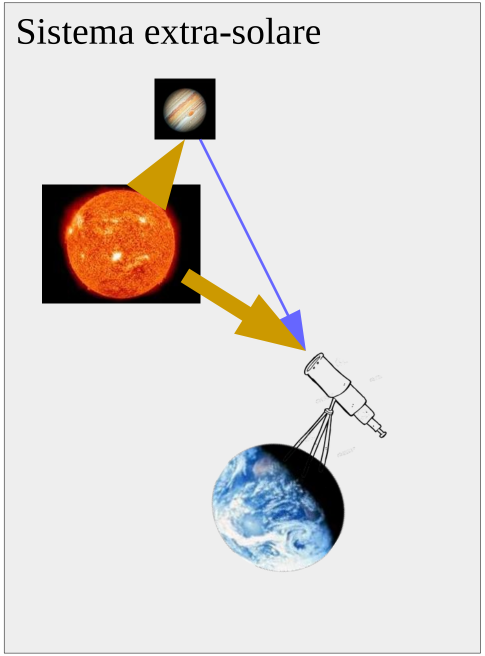
	M_P	R_P	R_p/R_*	$(R_p/R_*)^2$	a (au)	P
Earth	$1M_E$	$1R_E$	0.01	1×10^{-4}	1	1 y
Jupiter	$318M_E$	$11.2R_E$	0.1	0.01	5	12 y
Saturn	$95M_E$	$9.1R_E$	0.08	7×10^{-3}	10	30 y
Neptune	$17M_E$	$3.9R_E$	0.04	1×10^{-3}	30	168 y

	M_p	R_p	R_p/R_*	$(R_p/R_*)^2$	a (au)	P	Type
HD 189733b	$1.1M_J$	$1.13R_J$	0.16	0.03	0.03	2.2d	G
55 Cnc e	$8M_E$	$1.9R_E$	0.018	3.2×10^{-4}	0.015	0.7d	K
GJ 1214b	$8M_E$	$2.7R_E$	0.11	0.013	0.015	1.5d	M



López-Morales, et al., ApJ 152, 204, 2016

Reflected starlight (visible)



- Received by observer

$$\frac{F_p}{F_*} = \frac{2}{3}\alpha_S(\lambda)\frac{R_p^2}{a^2} = \alpha_G(\lambda)\frac{R_p^2}{a^2}$$

F_p : reflected starlight irradiance

F_* : host star irradiance

α_S: spherical albedo

α_G: geometric albedo

R_p: planet radius

a : planet – host star distance

- Twin Earth (a = 1au, $\alpha_G \sim 0.4$), $F_p/F_* \approx 7 \times 10^{-10}$
  Twin Jupiter (a = 5au, $\alpha_G \sim 0.5$), $F_p/F_* \approx 5 \times 10^{-9}$
  Twin Neputne (a = 30au, $\alpha_G \sim 0.3$), $F_p/F_* \approx 9 \times 10^{-12}$

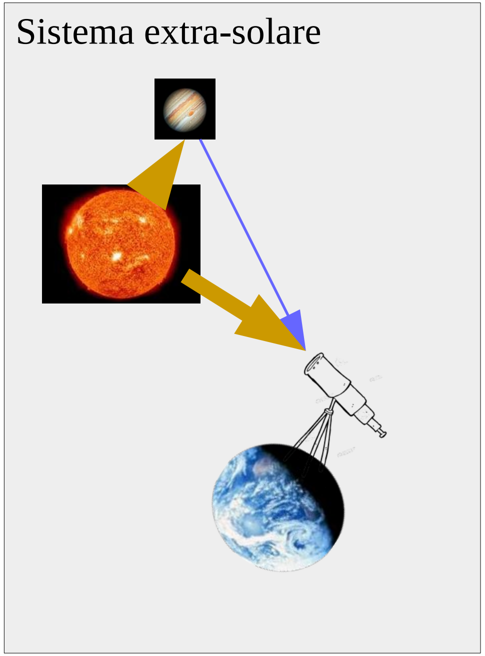
- Hot Earth (a = 0.05au, $\alpha_G \sim 0.4$), $F_p/F_* \approx 3 \times 10^{-7}$
  Hot Jupiter (a = 0.05au, $\alpha_G \sim 0.5$), $F_p/F_* \approx 5 \times 10^{-5}$
  Hot Neputne (a = 0.05au, $\alpha_G \sim 0.3$), $F_p/F_* \approx 3 \times 10^{-6}$

Planet emission (IR)

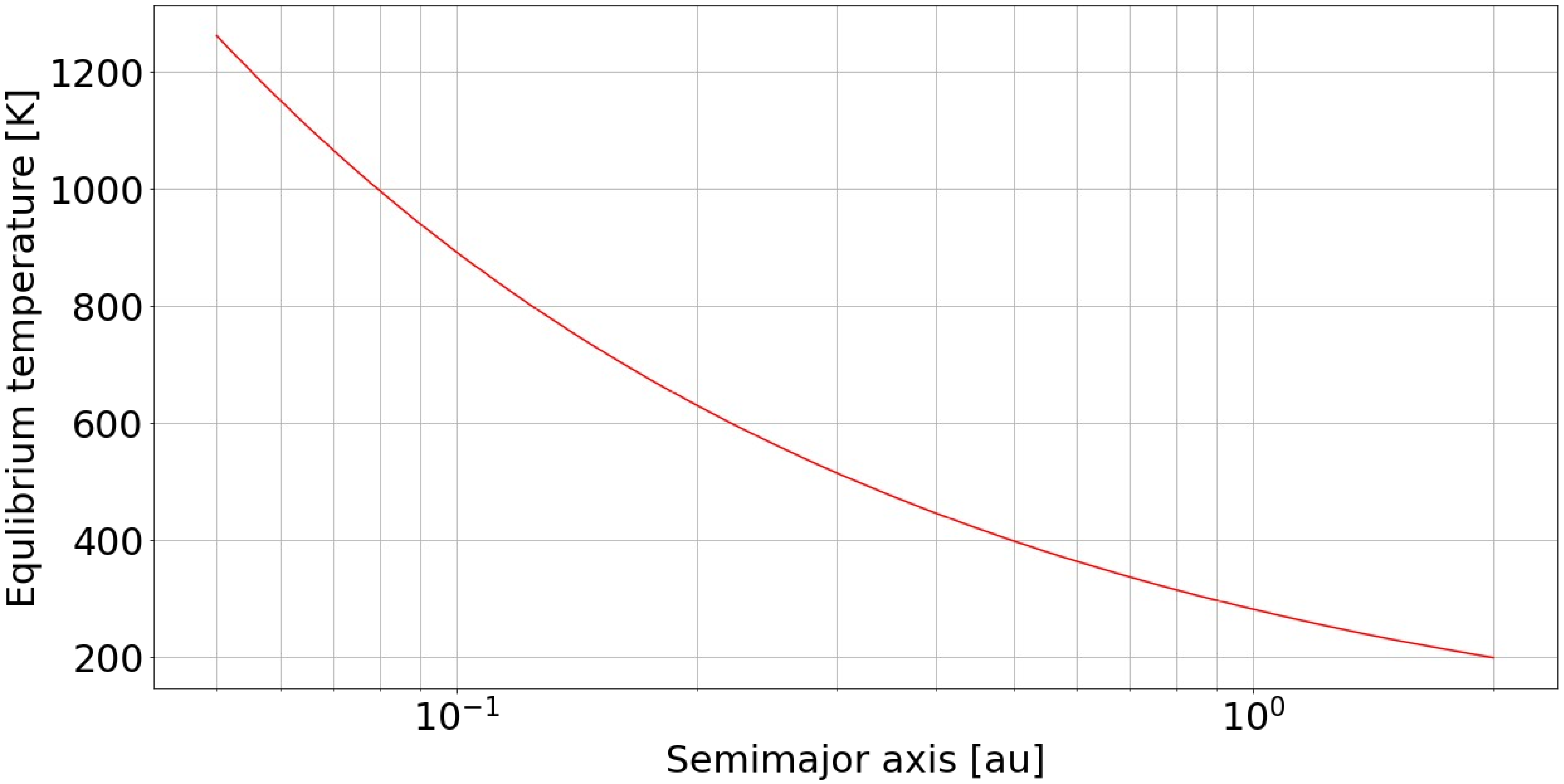
- Received by observer

$$\frac{F_{\mathrm{p}}}{F_*} \simeq \frac{R_p^2}{R_*^2} \frac{BB(T_p,\lambda)}{I_*(\lambda)} \qquad (2,4)\sigma T_p^4 = (1-\alpha_B) F_{\mathrm{bol}}$$

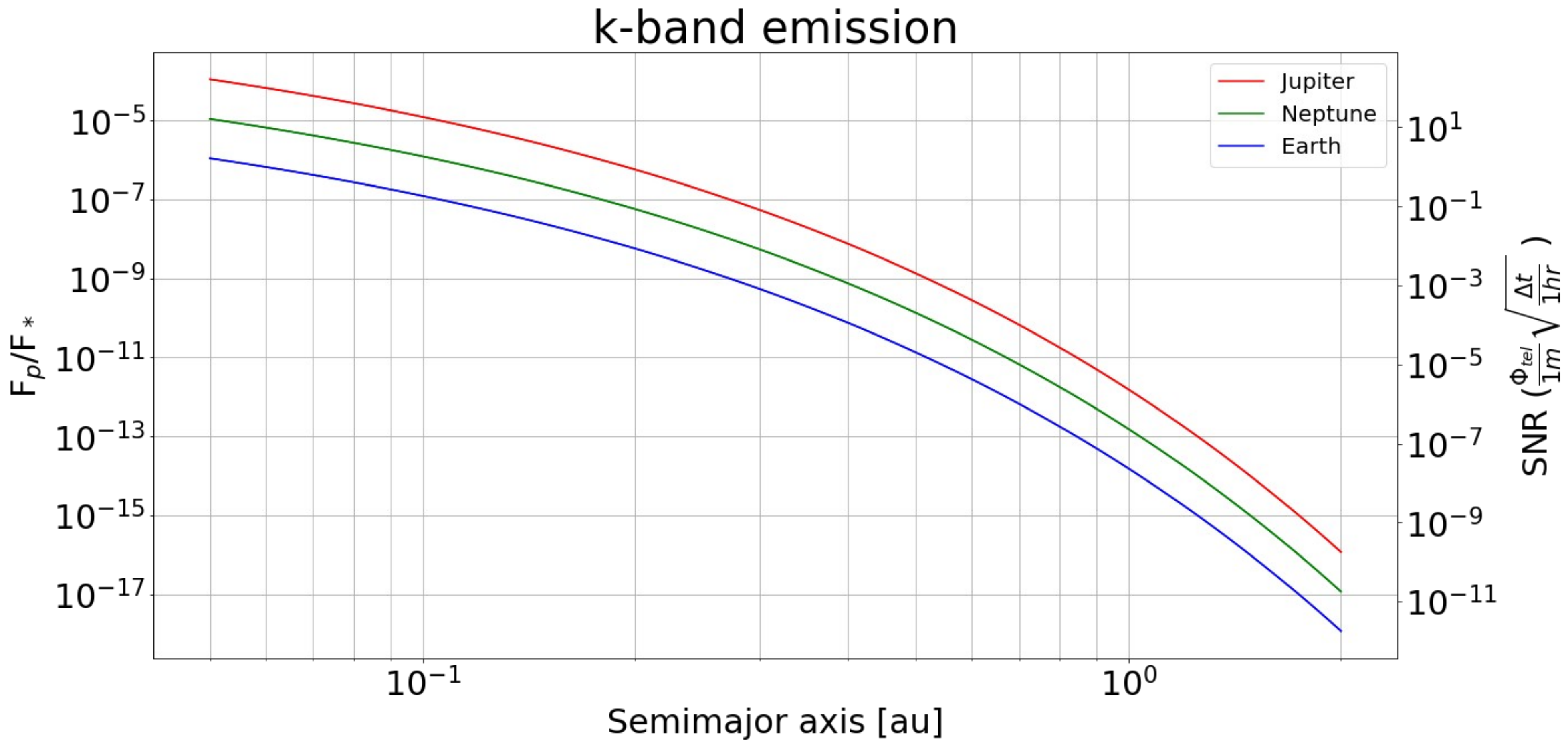
$$SNR = \frac{F_{\mathrm{p}}}{F_*}\sqrt{F_* \pi \phi_{tel}^2 \Delta t}$$



F_p : planet emission irradiance
F_* : host star irradiance
F_{bol} : host star bolometric irradiance
α_B: Bond albedo
R_p: planet radius
R_*: star radius
T_p: planet equilibrium temperature (use 2 for tidally locked planets)
SNR: Signal to Noise Ratio
Δt: observing time
Φ_{tel}: Telescope aperture

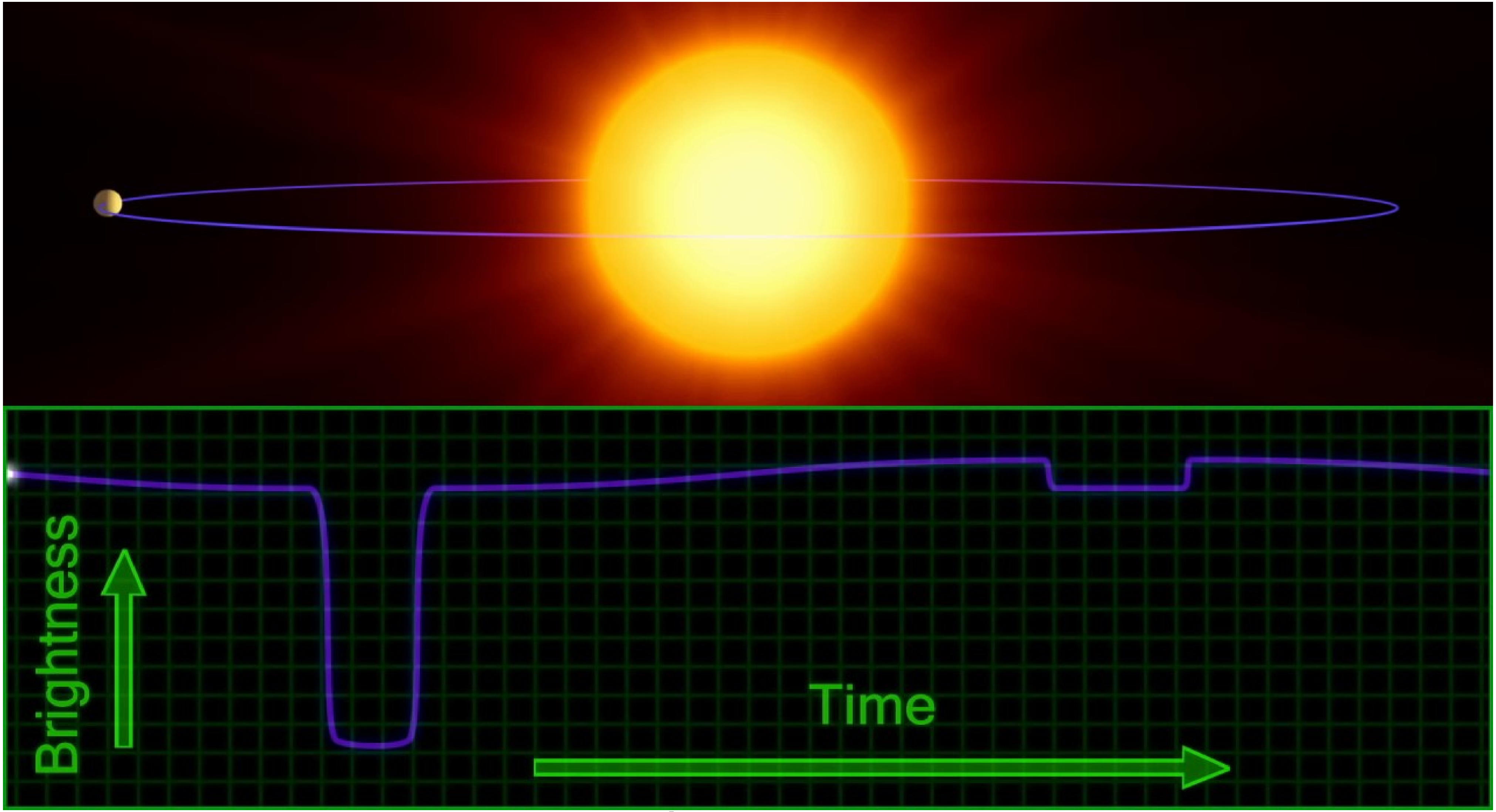


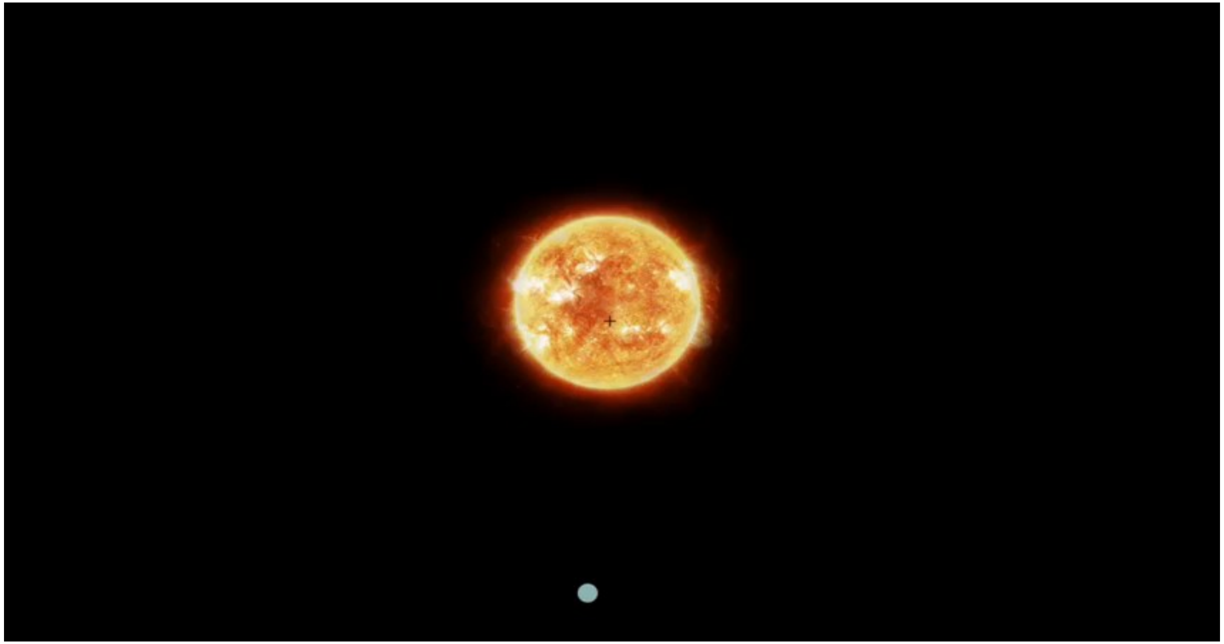
Equlibrium temperature [K]
1200
1000
800
600
400
200
10^{-1}
10^{0}
Semimajor axis [au]


k-band emission
Jupiter
Neptune
Earth
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
F_p/F_*
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
SNR $\left(\frac{\Phi_{tel}}{1m}\sqrt{\frac{\Delta t}{1hr}}\right)$
10^{-1}
10^{0}
Semimajor axis [au]

Indirect methods

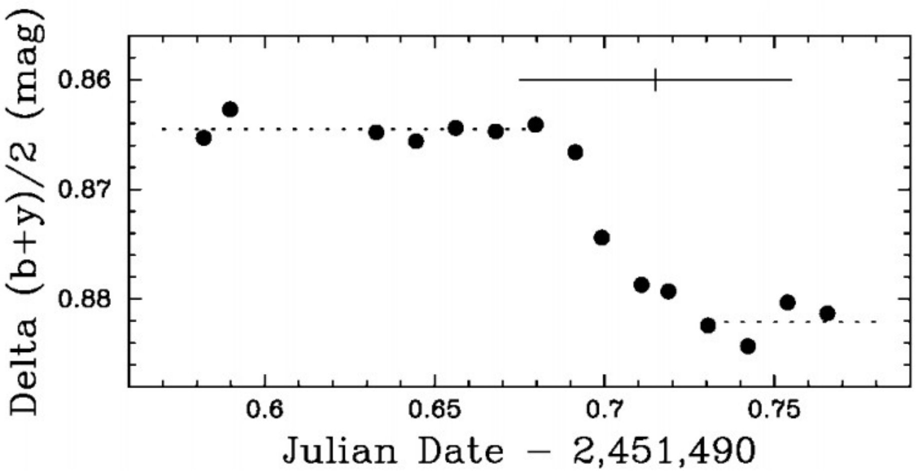
- Direct detection: challenging, and limited to bright exoplanets far from host star. But, technology improving rapidly
- Indirect methods: detection
  - Transits
  - Radial Velocities
  - Others
- Indirect methods: characterisation
  - Transits
  - Radial Velocities


Brightness
Time

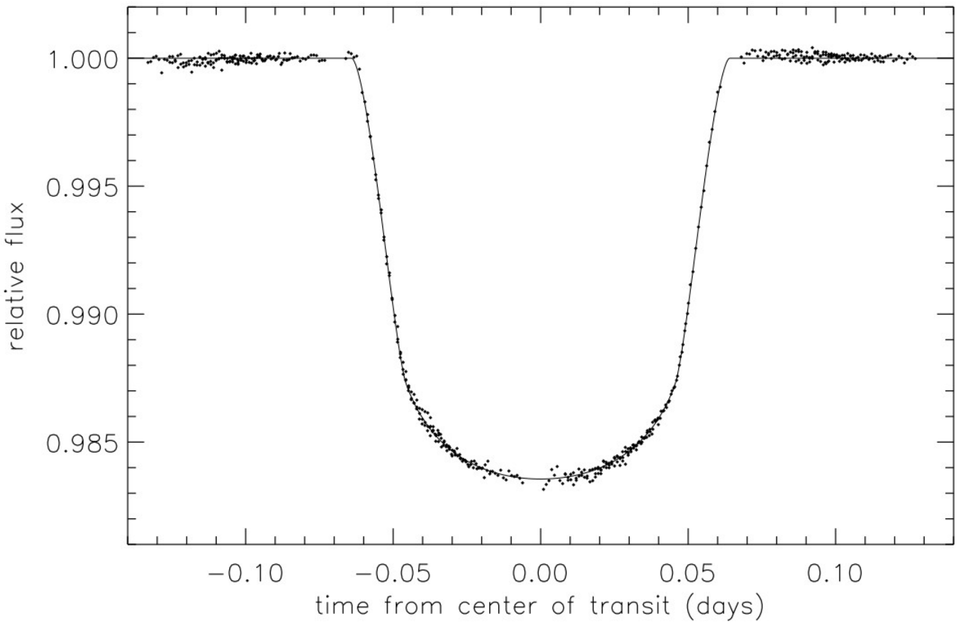


www.eso.org

Exoplanet transit light-curve [HD 209458b]

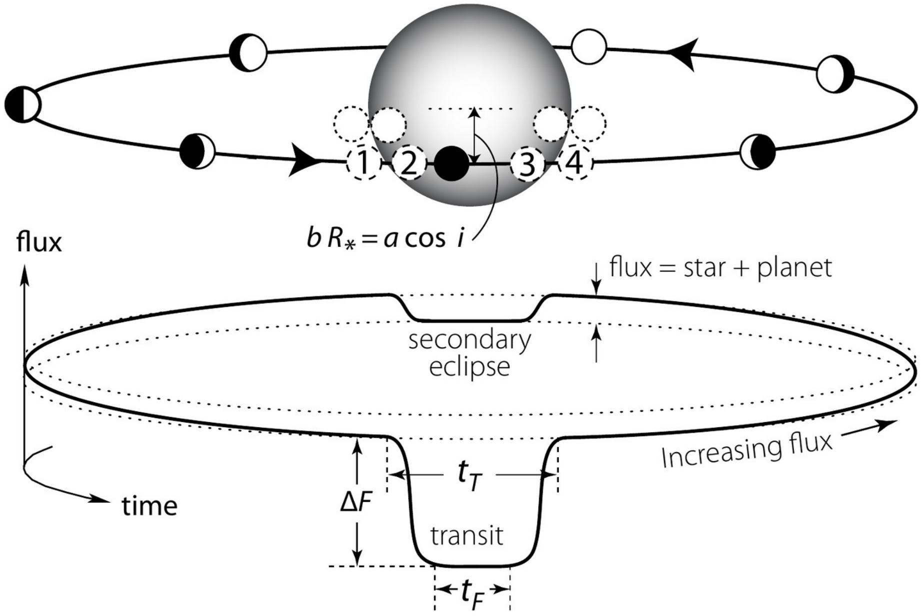


Henry, G. W., et al., ApJ 529, 41 (2000) – using a 0.8m Fairborne Observatory telescope in Arizona



Brown, M. B., et al., ApJ 552, 699 (2001) – using HST

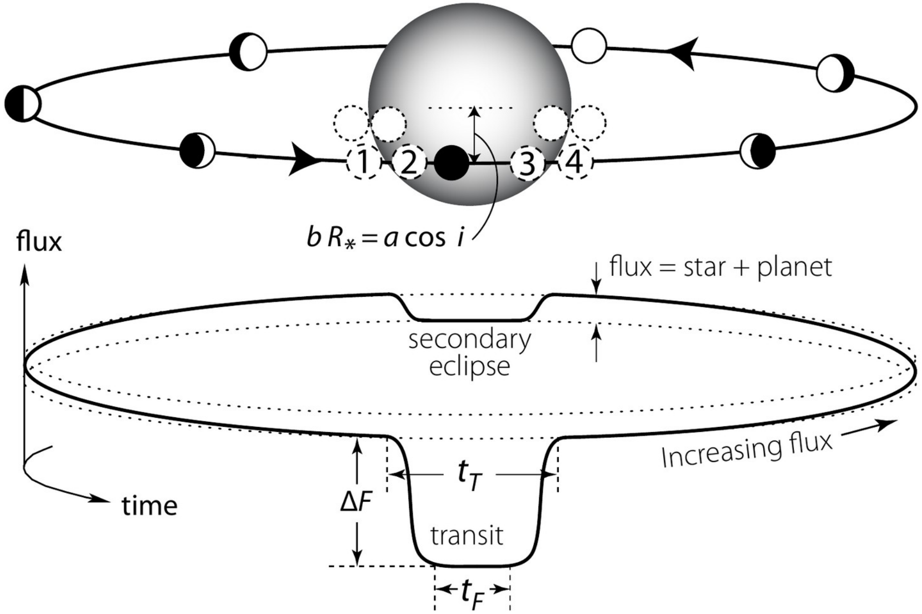
Transit Light Curves



- Things to note:
  - Points of 1st and 2nd contact (1, 2)
  - Points of 3rd and 4th contact (3, 4)
  - Transit and eclipse depths
  - Transit duration, t_T or T_{14}
  - Limb Darkening
  - Modulation of light curve with phase

- Principal observables:
  - Period
  - Transit/eclipse depths
  - Transit duration, t_T or T_{14}
  - Time between 2rd and 3th contact, t_F or T_{23}

Transit Depth



- Transit depth is the fractional dimming in the light received from the star during the transit or during the eclipse
- The signal measured is a combination of the stellar and planetary signals.
  - Stellar: emission $\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$
  - Planet: reflected stellar light + emission
- Primary transit depths:

Transit depth examples

$$k = \sigma_p / \sigma_* = \pi R_p^2 / \pi R_*^2$$
$$k_J \simeq 1\%$$

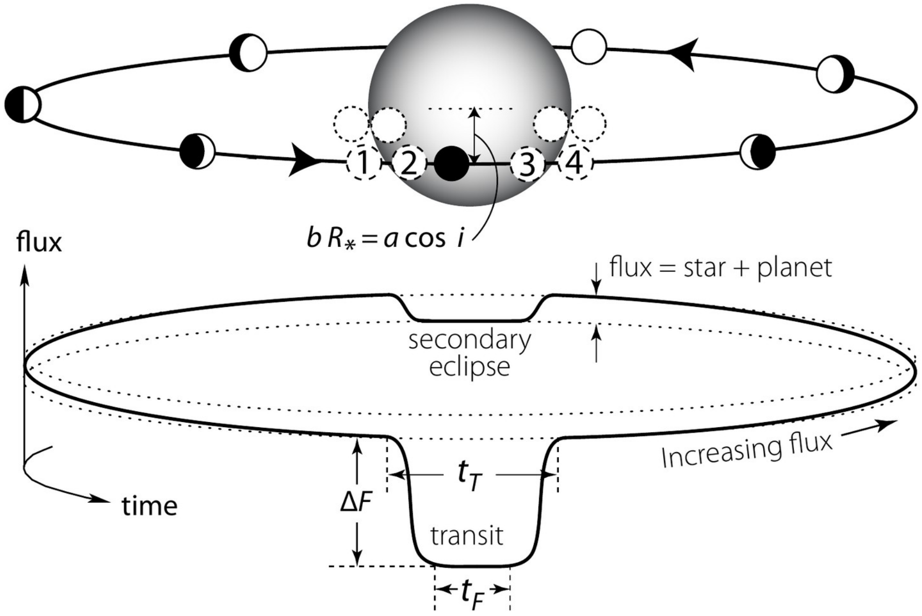
Cross-section $\sigma_* = \pi R_*^2$ for Different Stellar Types and Corresponding κ Values for the Three Planet Sizes Considered: Jupiter-like, Neptune-like, and Super-Earth

Star Type	Temperature (K)	Radius ($R_\odot$)	σ_* ($\sigma_\odot$)	$\kappa_{\mathrm{Jup.}}$ (κ_J)	$\kappa_{\mathrm{Nept.}}$ (κ_J)	κ_{SE} (κ_J)
F3V	6740 K	1.56	$\sigma_{F3} \sim 2.4$	~0.5	~0.05	~0.01
G2V	5800 K	1	$\sigma_G = \sigma_\odot$	1	~0.1	~0.02
K1V	4980 K	0.8	$\sigma_{K1} \sim 0.6$	~2	~0.2	~0.03
M1.5V	3582 K	0.42	$\sigma_{M1.5} \sim 0.18$	~6	~0.7	~0.1
M3.5V	3376 K	0.26	$\sigma_{M3.5} \sim 0.07$	~15	~2	~0.3
M4.5V	3151 K	0.17	$\sigma_{M4.5} \sim 0.03$	~35	~4	~0.7
M6V	2812 K	0.12	$\sigma_{M6} \sim 0.01$	~70	~9	~2

Notes. The reader can note that super-Earths in the orbit of late M stars have a similar ratio κ to a Jupiter in the orbit of a Sun-like star.

Tessenyi, M., et al., ApJ 746, 45 (2012)

Eclipse depths



- Secondary eclipse depths:

$$\frac{\Delta F}{F} = \frac{F_p}{F_*}$$

  - Where planet flux includes reflected star light and thermal emission.

  - $F_p = I_p(\lambda)\frac{\pi R_p^2}{D^2} \rightarrow \frac{\Delta F}{F} = \frac{I_p(\lambda)}{I_*(\lambda)}\frac{R_p^2}{R_*^2}$

  - Reflected starlight: $I_p = \alpha_G I_* \frac{R_*^2}{a^2}$

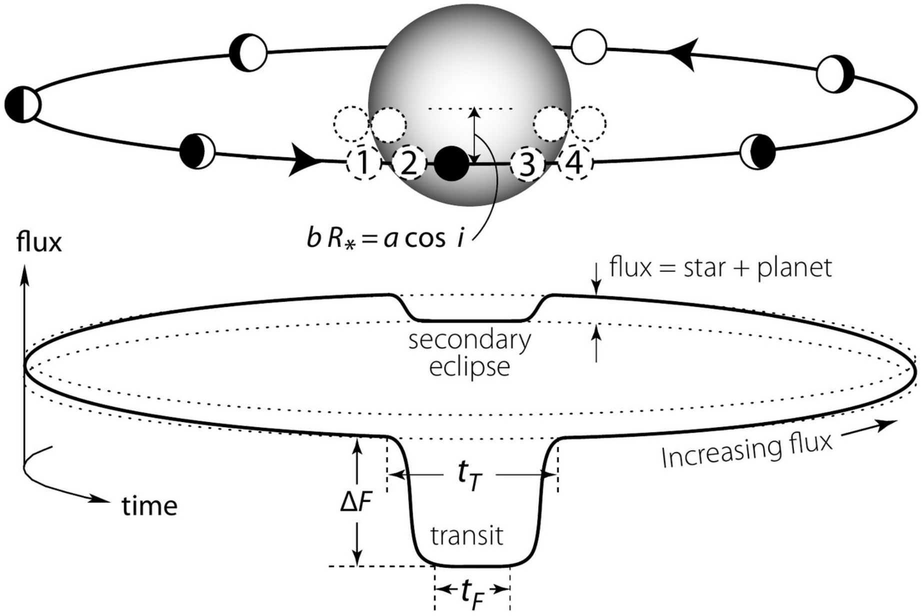
$$\frac{\Delta F}{F} = \alpha_G \frac{R_*^2}{a^2} \times \frac{R_p^2}{R_*^2}$$

    [α_G is the geometric albedo]

  - Emission (black body approximation)

$$\frac{\Delta F}{F} = \frac{BB_\lambda(T_p)}{BB_\lambda(T_*)}\frac{R_p^2}{R_*^2}$$

Phase curves



- The normalised phase curve is obtained from the modulation of the day/night sides

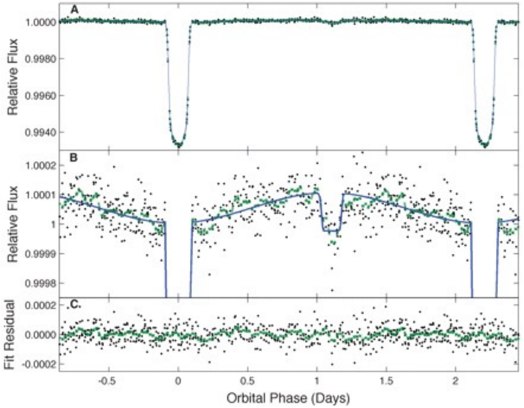
$$f_p(\lambda) = \frac{f_{\text{day}} + f_{\text{night}}}{2} + \frac{f_{\text{day}} - f_{\text{night}}}{2} \cos(\Phi)\sin(i)$$

[Burrows, A., et al., ApJ 678, 2008, Equation 1]

- For tidally locked planets observed in the infra-red

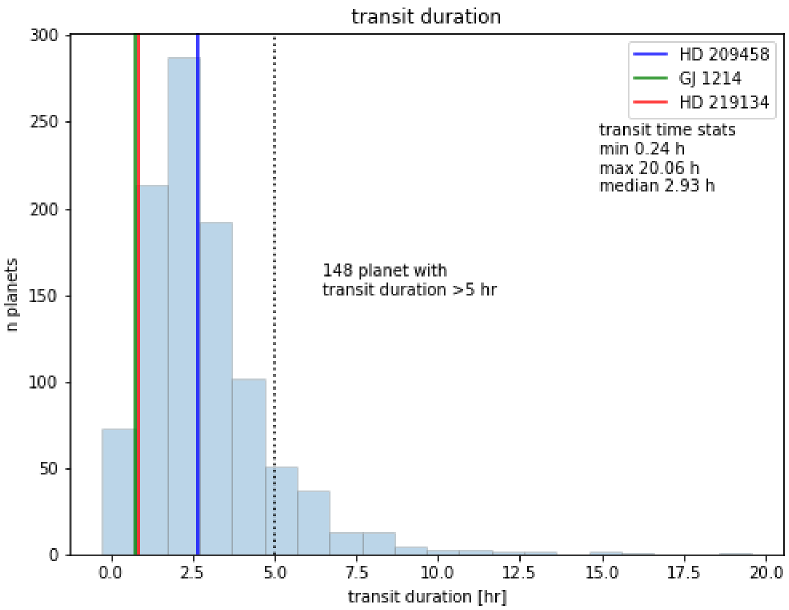
$$f_{\text{night}} \ll f_{\text{day}}$$

- At visible wavelengths, reflected stellar light from day-side is the dominant effect



Kepler's Optical Phase Curve of the Exoplanet HAT-P-7b.
W. J. Borucki et al., Science 325 (7 August 2009) 709.

SNR considerations



- For a 5σ detection of a 1% transit depth, requires

  Noise < 0.01/5 ~ 0.002

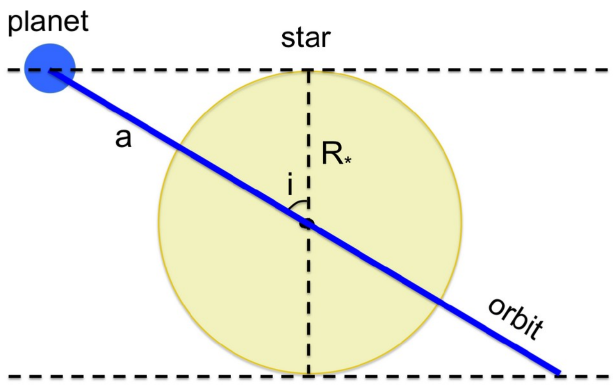
- SNR on the stellar signal

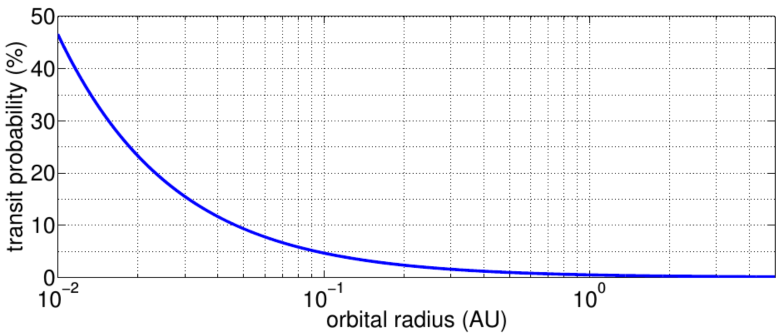
  $SNR_* > 1/0.002 \sim 500$

  Over the transit duration timescale.

- Calibration: irrelevant
- Stability: essential

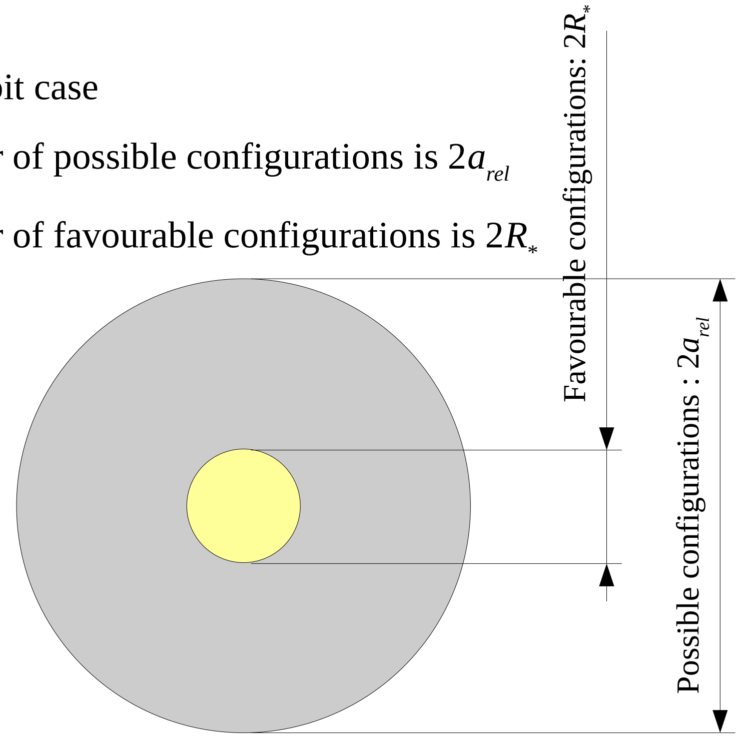
Transit probability





Credit: G. Morello, PhD thesis

- Circular orbit case
- The number of possible configurations is $2a_{rel}$
- The number of favourable configurations is $2R_*$

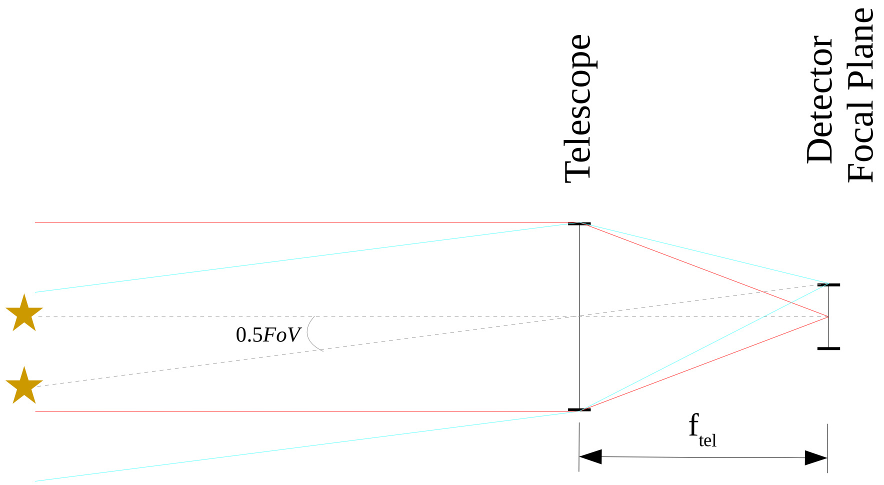


- The probability a transit occurs is $p = R_*/a_{rel}$. It's a binomial distribution (probability transit does not occur is $q = 1\text{-}p$)

Transiting exoplanet search

- Requires instruments covering large swathes of sky
  - Large FoV, and large sky surveys.
- Look for dips in photometric time-lines
- Blending
  - Large FoV means large plate scales
  - Complications from much larger numbers of stellar mass binaries [Willems, Kolb and Justham, 2006]
- Candidates need to be followed up photometrically.
- Not all Transit candidates can be followed up in RV
  - Host stars need to be bright. Only most promising candidates around brightest stars can be followed up in RV for definitive confirmation (only knowing the mass one can be certain).
- Not all RV can be followed up photometrically either
  - Only a small portion have an orbital geometry favourable to transit
  - Long-period planets are less likely to transit

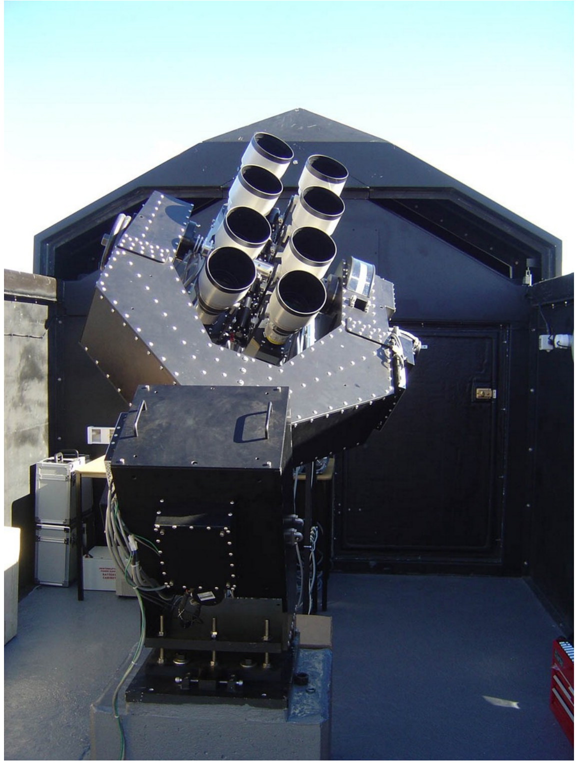
Basic instrument optical configuration

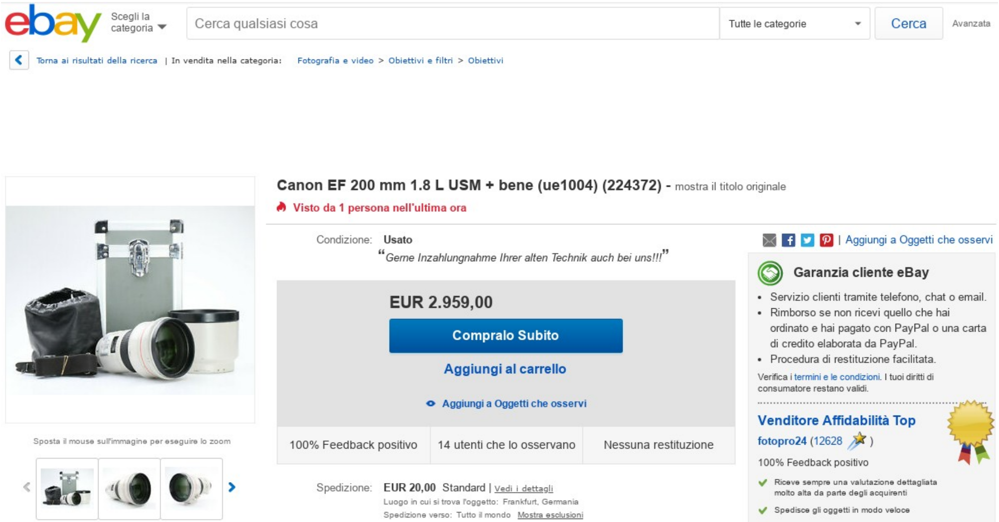


- Large sensitivity requires
  Φ_{tel} as large as needed
- Large FoV require f_{tel} as short as needed
- Therefore, it is needed a small aperture ratio
  $F_{\#} = f_{tel} / \Phi_{tel}$
- Trade-off

  Large FoV vs small enough pixel plate scale

WASP

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Canon EF 200 mm 1.8 L USM + bene (ue1004) (224372) - mostra il titolo originale
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Aggiungi a Oggetti che osservi
Garanzia cliente eBay
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Rimborso se non ricevi quello che hai ordinato e hai pagato con PayPal o una carta di credito elaborata da PayPal.
Procedura di restituzione facilitata.
Verifica i termini e le condizioni. I tuoi diritti di consumatore restano validi.
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fotopro24 (12628)
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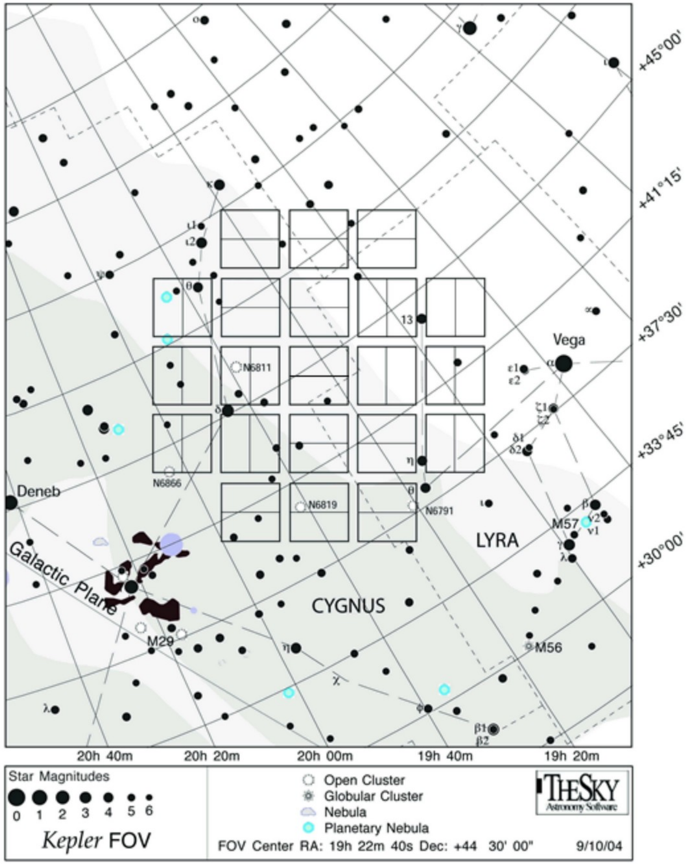
Riceve sempre una valutazione dettagliata molto alta da parte degli acquirenti
Spedisce gli oggetti in modo veloce

NASA Kepler

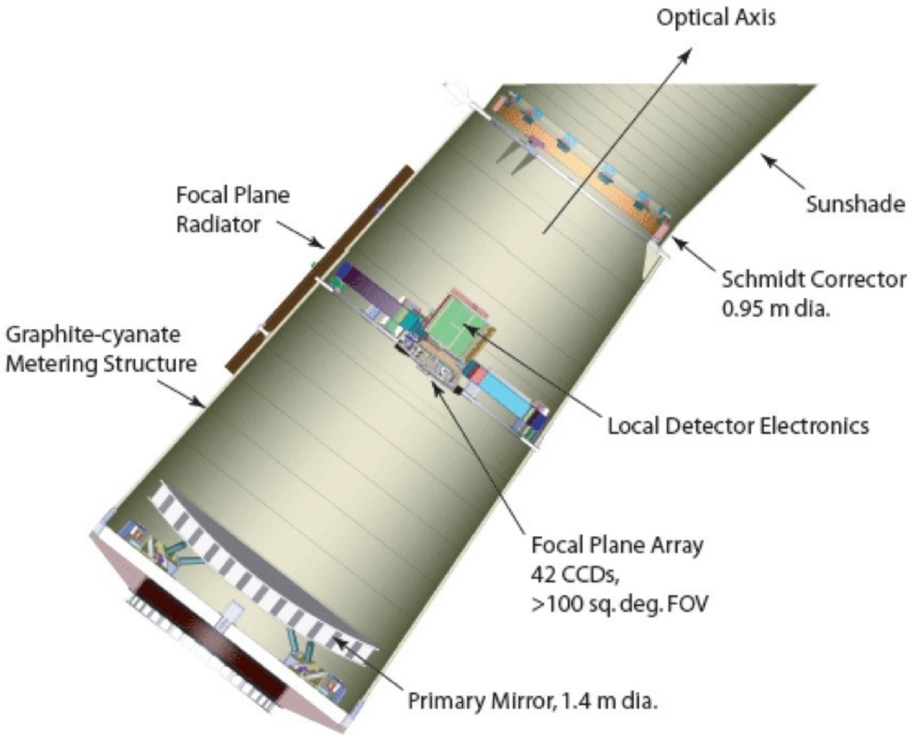
- A region of the extended solar neighbourhood in the Cygnus region along the Orion arm centred on galactic coordinates (76.32^{o},+13.5^{o}) or RA=19h 22m 40s, Dec=+44^{o} 30' 00" has been chosen.

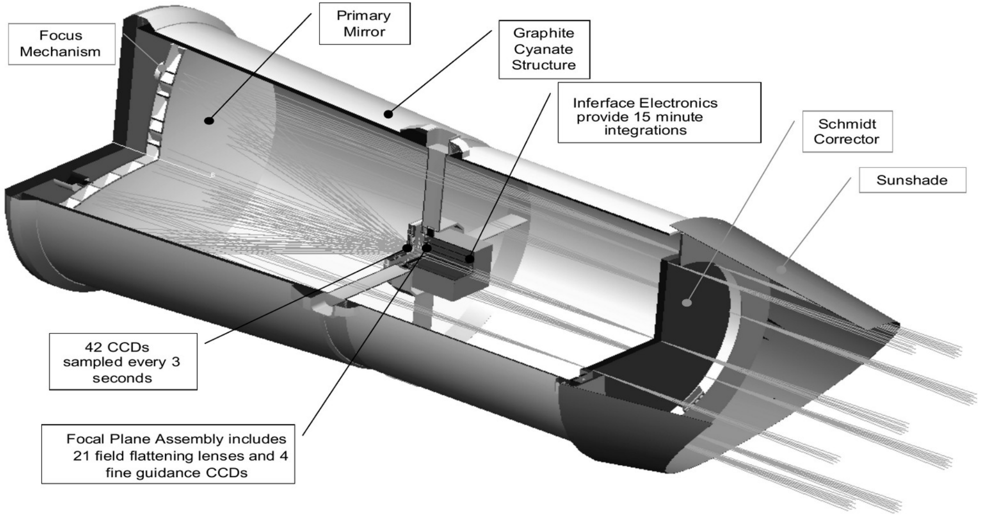
- The star field is far enough from the ecliptic plane so that the Sun does not shine into the telescope at anytime during the year.

- In addition, this FOV virtually eliminates any confusion resulting from occultation by asteroids and Kuiper-belt objects, which commonly orbit near the ecliptic plane. Comet-size objects in the Oort cloud subtend too small an angular size and move too rapidly to be a problem.



Kepler payload





Borucki, W. J., et al. Scientific Frontiers in Research on Extrasolar Planets, ASP Conference Series, Vol. 294, 2003

Kepler's legacy

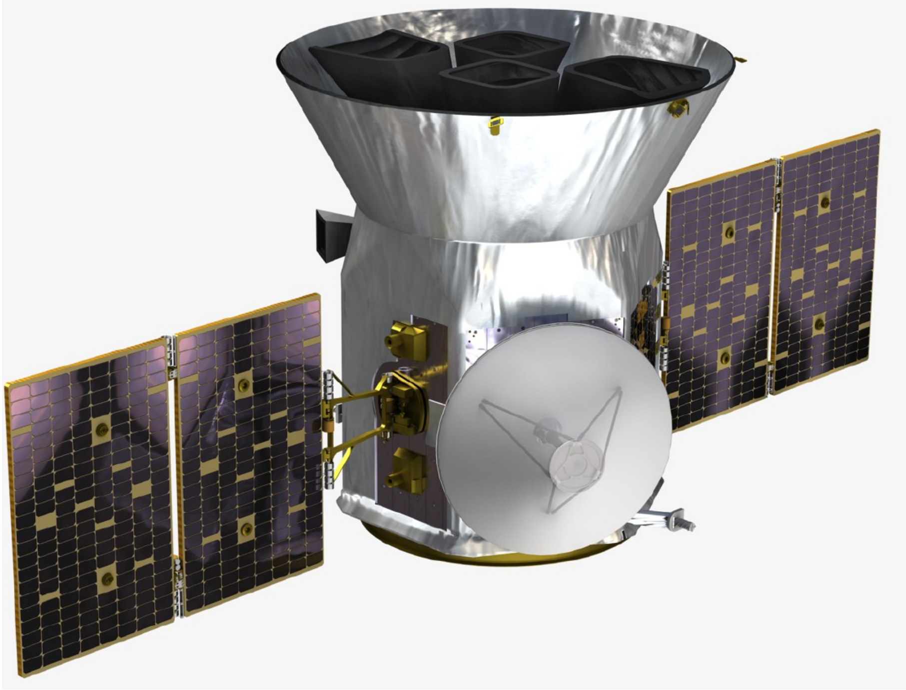
Successes

- Revolutionised the field of extrasolar planets
- Kepler
  - 2402: confirmed planets
  - 2361: candidates
- K2
  - 477: confirmed planets
  - 1022: candidates
- Major outcome
  - Exoplanets manifest a diversity unseen in our own Solar System and rise the question:
  - What are exoplanets made of? How exoplanets form and evolve? How common is the Solar System?

Lesson learned

- Large sensitivity -> small sky survey
- Exoplanets discovered around faint host stars
- Consequences
  - Difficulty in confirmation (RV or other methods
  - Difficulty in characterisation (spectroscopy or other means)
- Next step
  - Discover planets around bright stars
  - Target more M type stars (more numerous and better contrast ratios)
  - Requires all sky survey (bright star density is small compare to faint star density

NASA TESS: Mission Concept



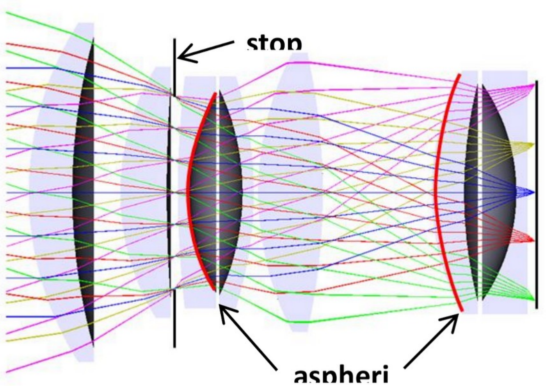
The TESS mission (Ricker et al., 2015) is designed to detect transiting planets around the nearest, brightest stars.

Characteristic	Value
Number of cameras	4
Camera FOV	$24° \times 24°$
CCDs	MIT/LL CCID-80
CCDs per Camera	4
CCD Dimensions	2048×2048 pixels in imaging array
Pixel Size	15 μm square
Pixel Depth	100 μm
Lens	Custom 146 mm, f/1.4 lens (MIT/LL Design)
Bandpass	600-1040 nm
Camera Temperature	$-85°$C (lens), $-80°$C (CCDs)

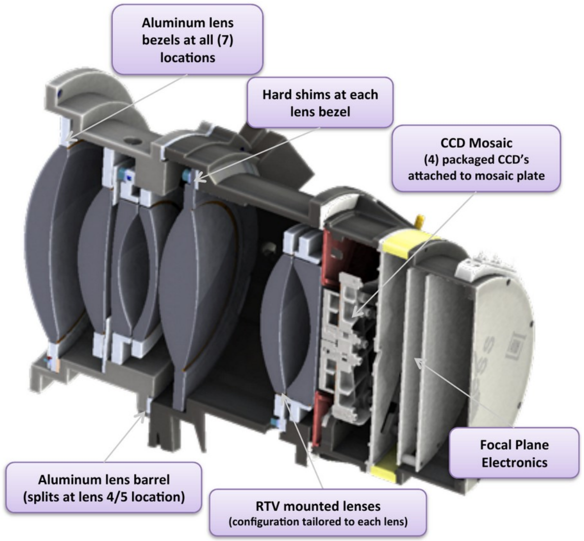
TESS Launch

- Launch 18th April 2018
- Mission life time: 2 years
- Mission extended, operations ongoing
- On 24th November 2021 there are
  - 4704 TESS candidates
  - 172 Tess Confirmed planets

Optics

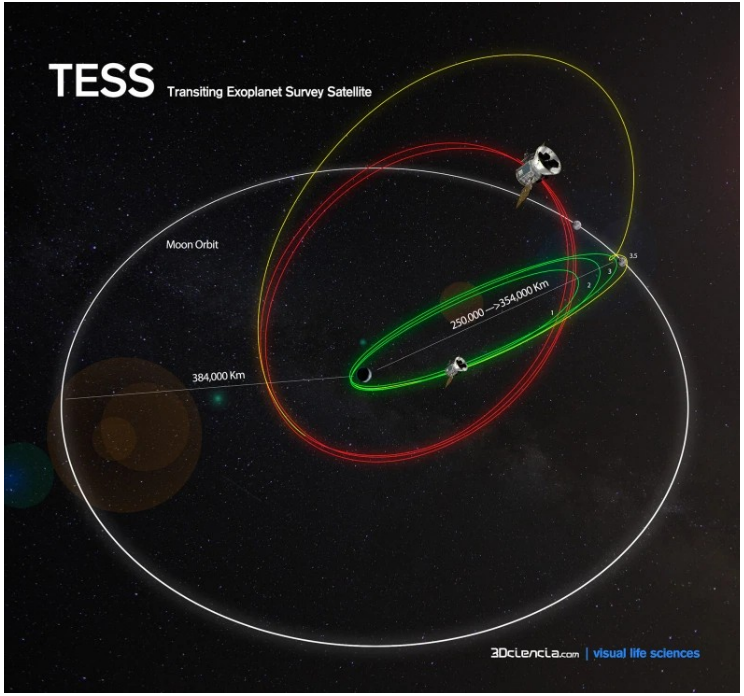


Parameter	Value
FOV	24° x 24°
FL, f/#	146 mm, f/1.4
EPD	105 mm
Wavelengths	600-1000 nm
CCD	2 x 2 detector arrays 4k x 4k pixels
Detector arrays	2048 x 2048 15 micron pixels
Transmittance	86.5% (with filter)
Mass	9.3 kg
Dimensions	17.0 cm diameter 21.1 cm long

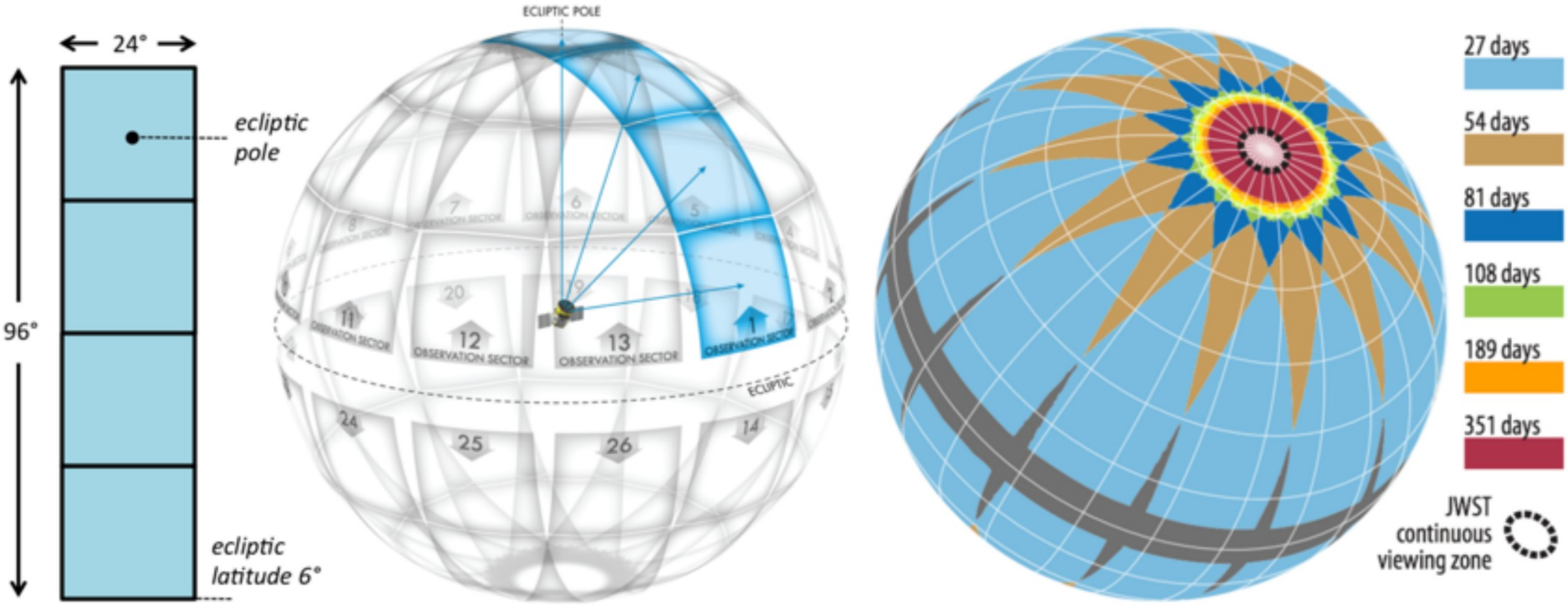


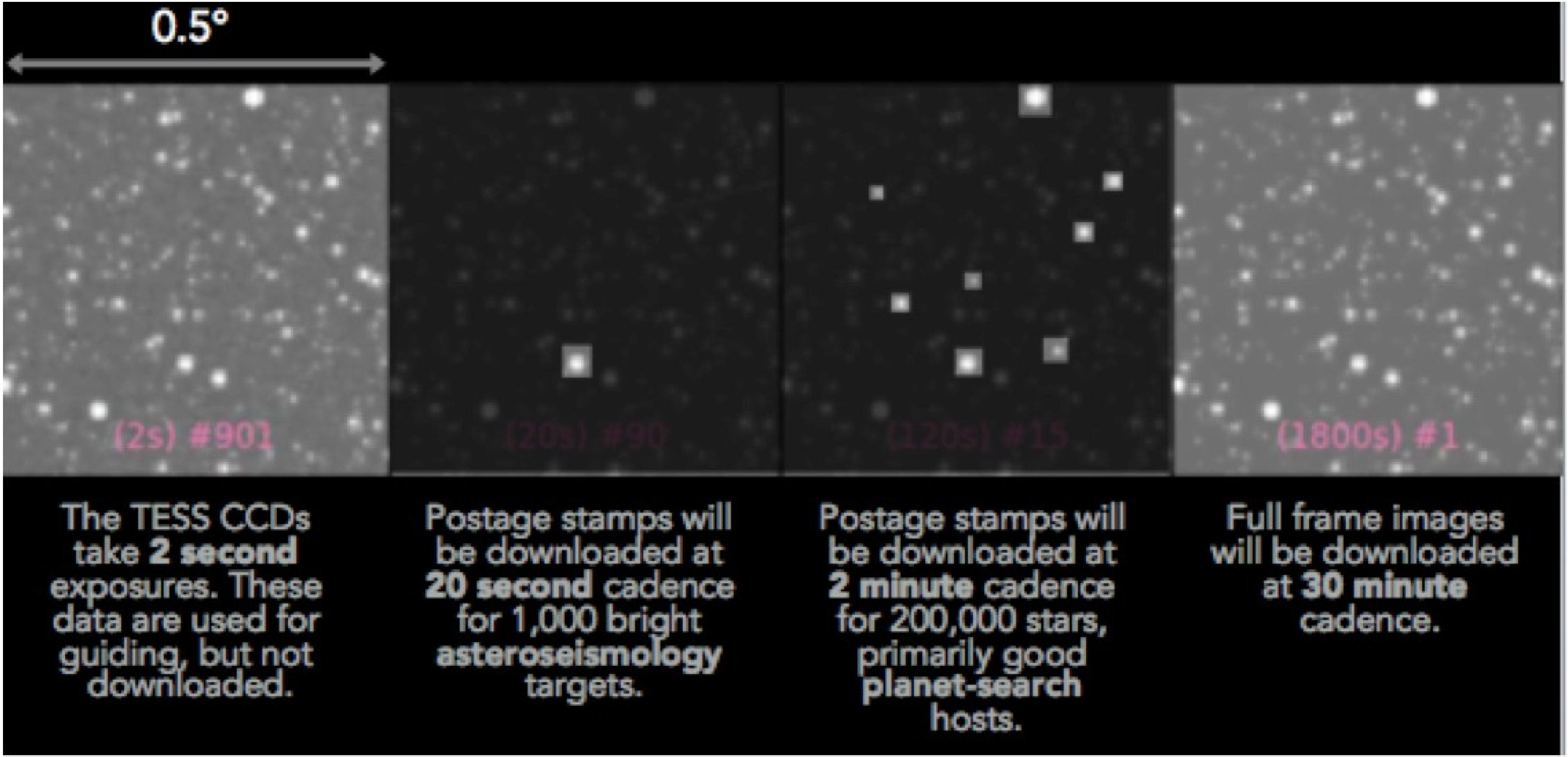
Orbit

- Elliptical, 2:1 lunar-synchronous orbit
- Period: 13.7 days
- Perigee: 17 R_E .   Apogee: 59 R_E
- Moon leading or lagging the spacecraft apogee by ~ 90^o averaging out lunar perturbation
- Orbit above Earth radiation belts --> low-radiation environment
- Nearly constant thermal environment



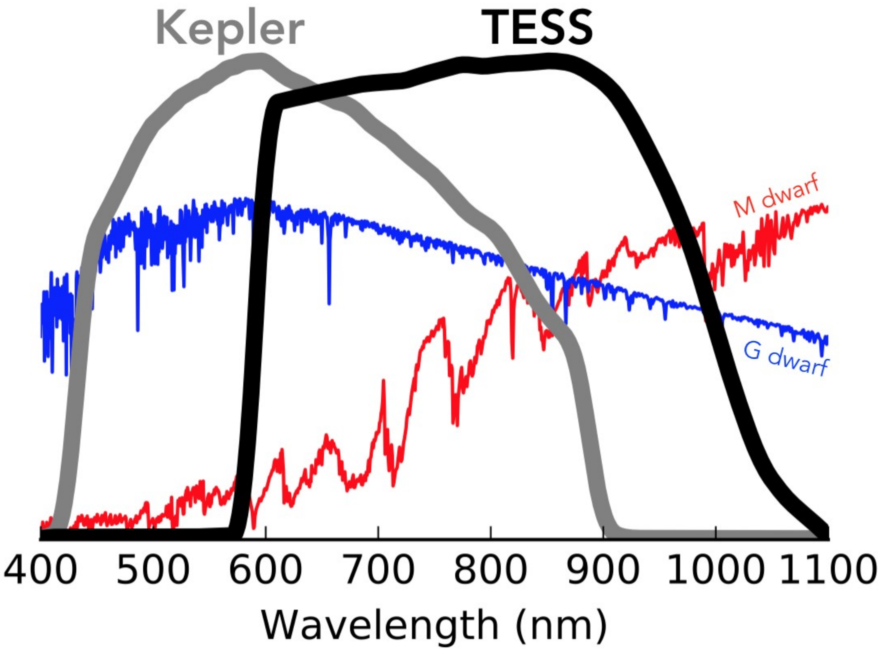
Observing strategy





0.5°
(2s) #901
(20s) #90
(120s) #15
(1800s) #1
The TESS CCDs take **2 second** exposures. These data are used for guiding, but not downloaded.
Postage stamps will be downloaded at **20 second** cadence for 1,000 bright **asteroseismology** targets.
Postage stamps will be downloaded at **2 minute** cadence for 200,000 stars, primarily good **planet-search** hosts.
Full frame images will be downloaded at **30 minute** cadence.

TESS photometry



- 70% of stars in the Milky Way are M-dwarfs
- Bright in the near-IR
- TESS extends its photometric sensitivity in the red to detect planets arounf M-type stars
  - More bright target
  - Larger contrast ratios
  - Allows characterisation

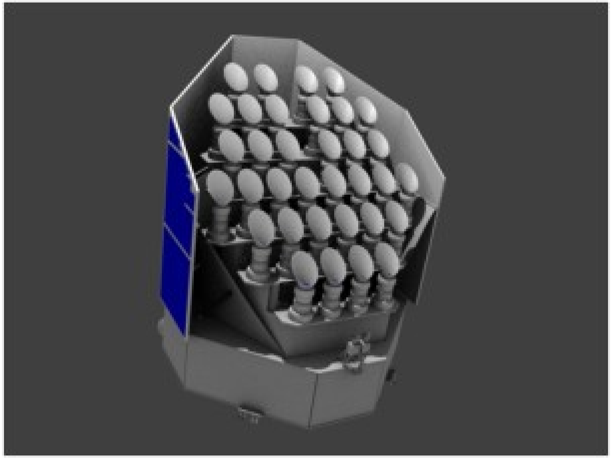
Plato (ESA)

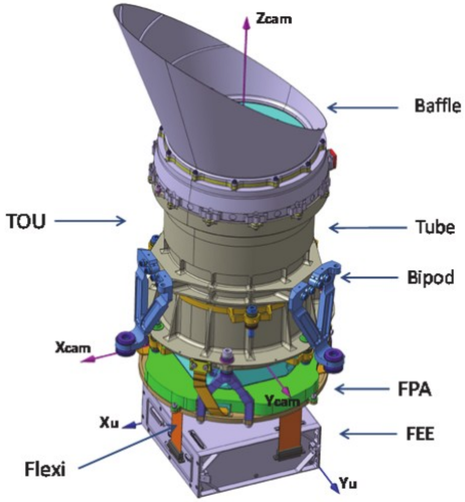
PLATO Definition Study – Mission Summary	
Key scientific goals	Detection of terrestrial exoplanets up to the habitable zone of solar-type stars and characterisation of their bulk properties needed to determine their habitability. Characterisation of hundreds of rocky (including Earth twins), icy or giant planets, including the architecture of their planetary system, to fundamentally enhance our understanding of the formation and the evolution of planetary systems. These goals will be achieved through: 1) planet detection and radius determination (3% precision) from photometric transits; 2) determination of planet masses (better than 10% precision) from ground-based radial velocity follow-up, 3) determination of accurate stellar masses, radii, and ages (10% precision) from asteroseismology, and 4) identification of bright targets for atmospheric spectroscopy.
Observational concept	Ultra-high precision, long (at least two years), uninterrupted photometric monitoring in the visible band of very large samples of bright ($V \leq$11-13) stars.
Primary data products	• High cadence optical light curves of large numbers of bright stars. • Catalogue of confirmed planetary systems fully characterised by combining information from the planetary transits, the seismology of the planet-host stars, and the ground-based follow-up observations.
Payload	
Payload concept	• Set of 24 normal cameras organised in 4 groups resulting in many wide-field co-aligned telescopes, each telescope with its own CCD-based focal plane array; • Set of 2 fast cameras for bright stars, colour requirements, and fine guidance and navigation.
Optical system	6 lenses per telescope (1 aspheric)
Focal planes	104 CCDs (4 CCDs per camera) with 4510 × 4510 18 µm pixels
Instantaneous field of view	~ 2232 deg², with 4 groups of cameras respectively looking on 301 deg², 247 deg², 735 deg², and 949 deg².

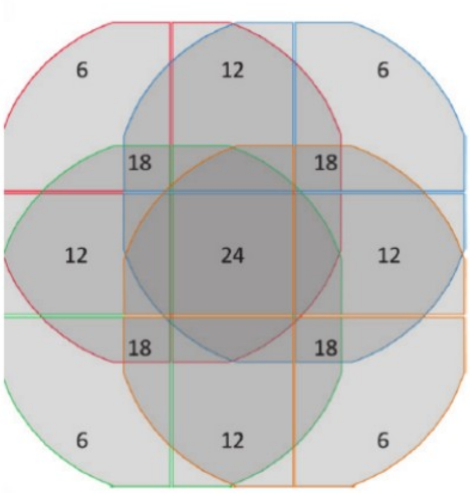
Overall mission profile	
Operations reference scenario	Nominal in-orbit science operations with a Long duration observation phase including two single fields monitored for two years each. Optionally a split into 3 years long duration pointing and 1 year "step-and-stare" phase.
Lifetime	Satellite built and verified for an in-orbit lifetime of 6.5 years and to accommodate consumables for 8 years.
Duty cycle	≥ 93% per target in a year
Launcher	Launch by Soyuz-Fregat2-1b from Kourou in 2025
Orbit	Transfer to L2, then large amplitude libration orbit around L2
Description of Spacecraft	
Stabilisation	3-axis
Telemetry band	X and K-band
Average downlink capacity	~ 435 Gb per day
Pointing stability	0.2 arcsec $(Hz)^{-1/2}$ over time scales of 25 s to 14 hours
Pointing strategy	A 90° rotation around the line of sight every 3 months

Plato red book:
http://sci.esa.int/plato/59252-plato-definition-study-report-red-book

24 cameras covering a combine 2232 deg^2 FoV







resulting field-of-view configuration

Plato red book:
http://sci.esa.int/plato/59252-plato-definition-study-report-red-book

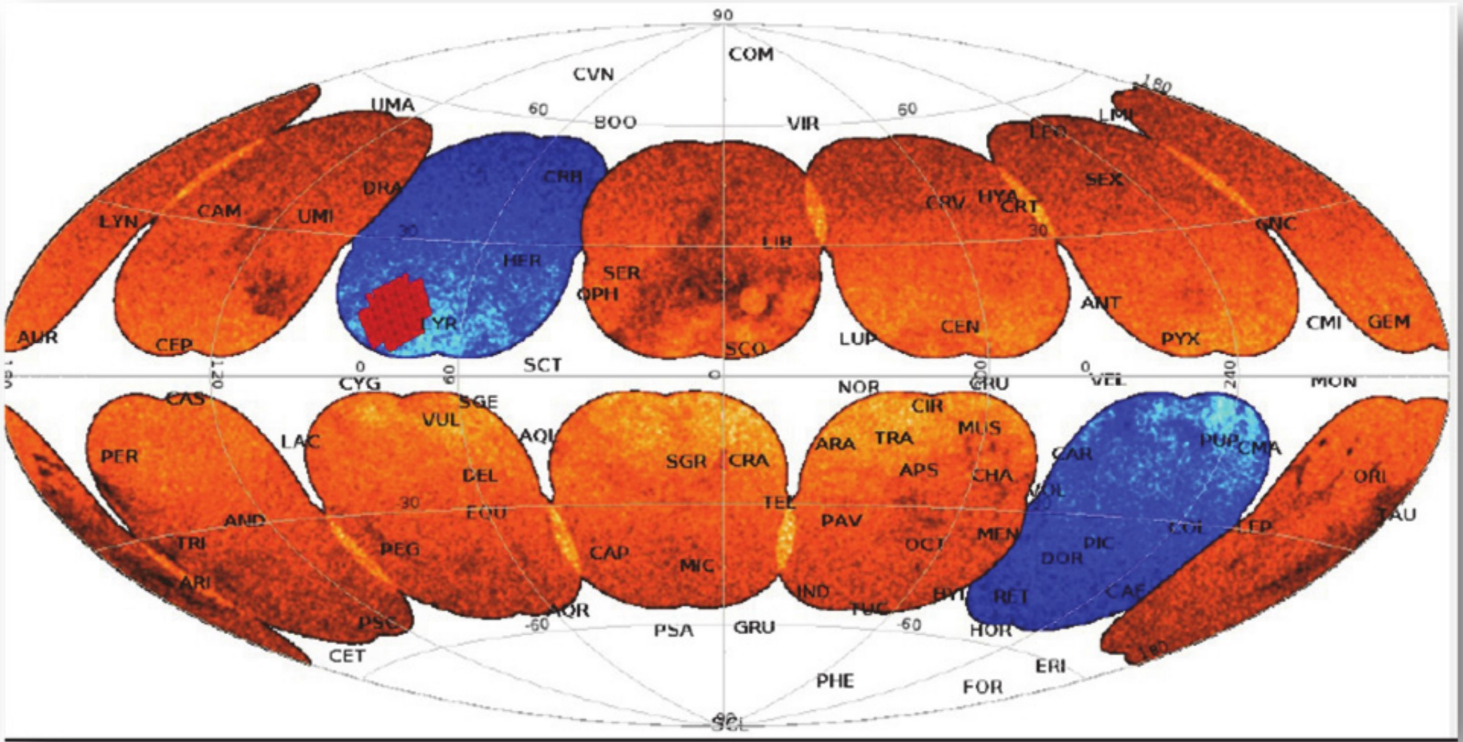
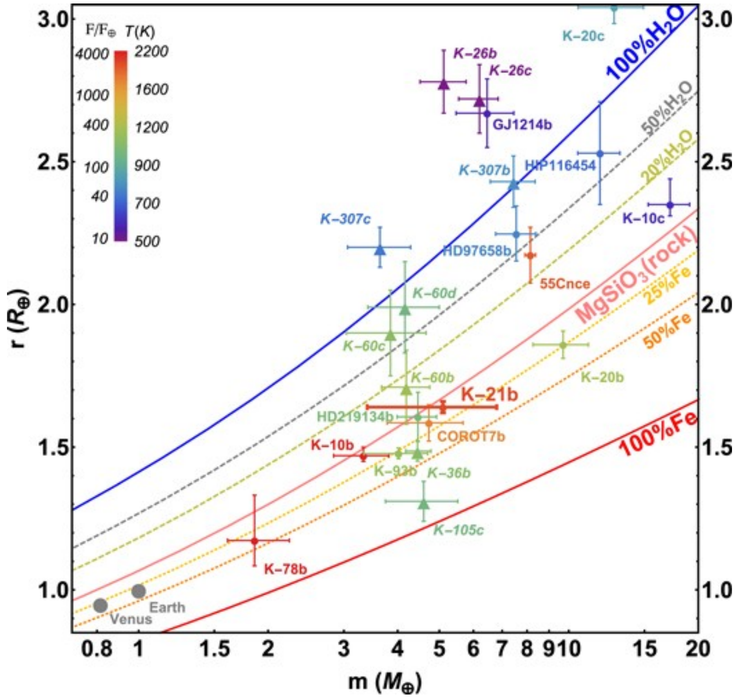


Figure 5.4: Schematic comparison of observing approaches. Red area: the Kepler target field. Large areas: size of the PLATO field. A combination of short (orange) and long (blue) duration pointings is able to cover a very large part of the sky. Note that the final locations of long duration and step-and-stare fields will be defined two years before launch and are drawn here for illustration only.

Characterisation, mass-radius relation



- R_p, M_p -> density -> composition
- Observables: R_p/R_* (transit), $M_p/M_*^{2/3}$(RV)
- Requires small error bars on transit depths, and RV.
- Requires knowledge of stellar parameters
- A (optimistic) 20% knowledge of mass and 10% on radius leads to a 30% uncertainty on density

$$\frac{\delta\rho}{\rho}=\sqrt{\left(\frac{\delta M}{M}\right)^2+9\left(\frac{\delta R}{R}\right)^2}$$

- Requires improving
  - Knowledge on R_p, R_* and M_*

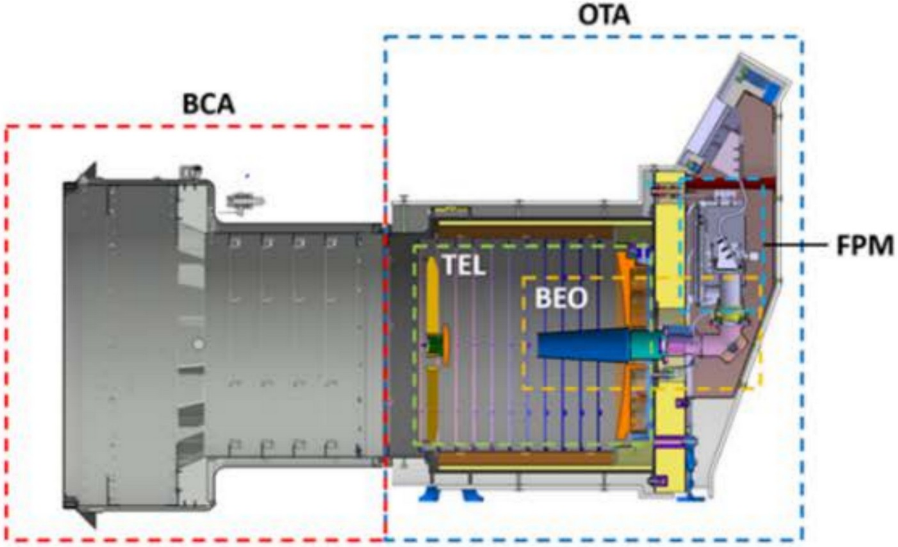
Plato needs RV

- Only brightest Plato detections can be followed up spectroscopically
- Main characterisation perspective is by RV
- Plato programme aims at
  - RV for about 100 to 152 super-earth (10% at ~ 1 AU)
  - RV for about 22 earth size planets (30% at ~ 1 AU)
  - Planet sizes to ~3% accuracy
- This means density estimates at 30% to 14% (assuming a RV mass estimate at 30% to 10%).

$$\frac{\delta\rho}{\rho} = \sqrt{0.3^2 + 9 \times 0.03^2} \simeq 30\,\% \qquad \frac{\delta\rho}{\rho} = \sqrt{0.1^2 + 9 \times 0.03^2} \simeq 14\,\%$$

Cheops (ESA)

- Key science goal:
  - Measure bulk density of super-Earths and Neptunes around bright stars
  - Improve upon the knowledge of the planet radius, or measure it when not know (e.g. RV detection)
- Sun-synchronous orbit
- Ritchey-Cretien optical telescope, 30cm diameter, f/8
- Optical photometry (330 to 1100nm)
- FoV 0.32 deg
- Launch Autumn 2019
- Precise characterisation of the radii of known transiting planets with RV detection, and of their host star
- Planned mission lifetime: 3.5 years



Open questions

Tens to hundreds of thousands planets detected by end of next decade: it’s time to answer:

- What are exoplanets made of ?
- How do planets and planetary systems form ?
- How do planets and their atmospheres evolve with time ?

Also

- Is our Solar system unique ?
- Are there habitable planets ?

Spectroscopy

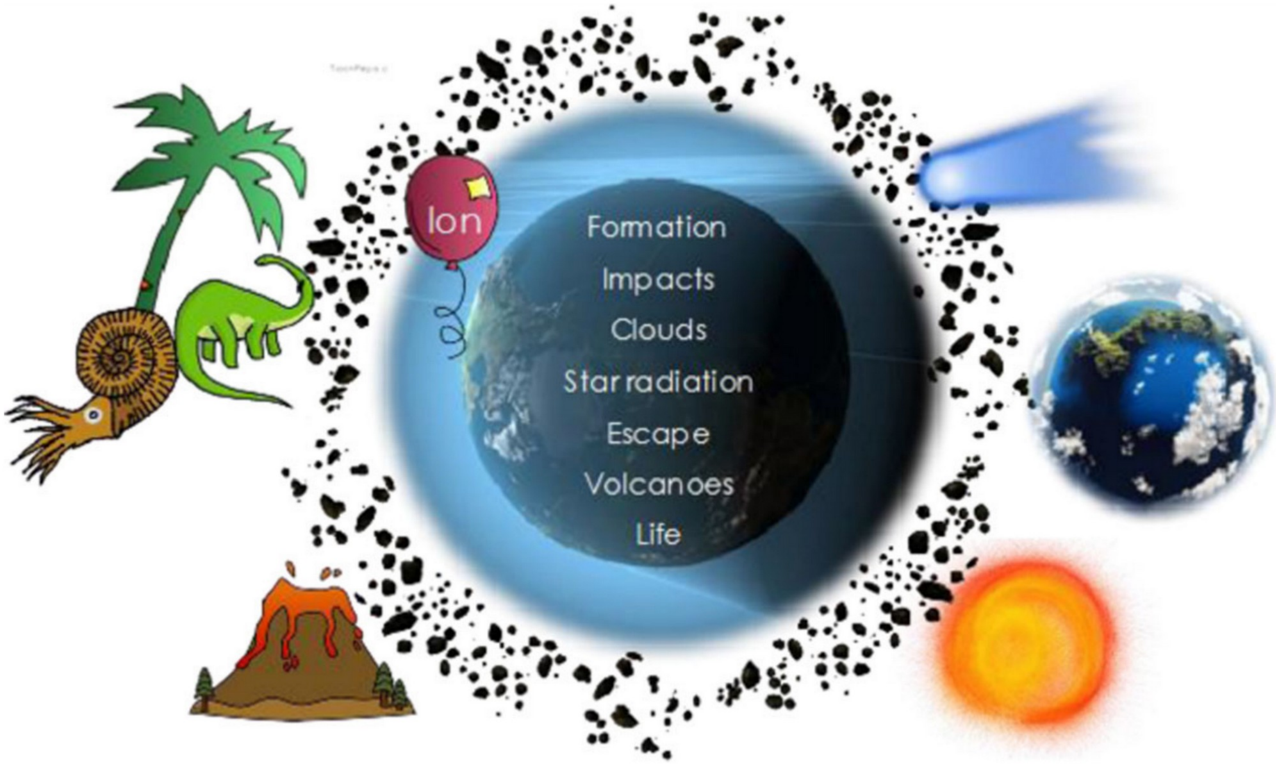
In OUR Solar System

Spectroscopy revealed true nature of planets in our Solar System, unravelling the story of their formation and evolution.

Exoplanetary science

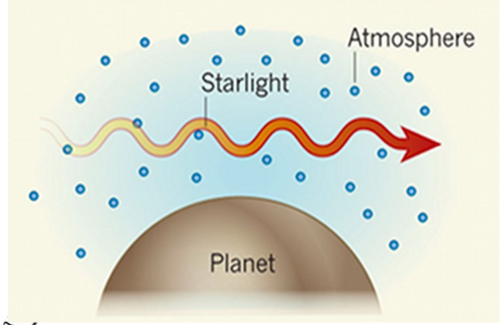
Stands on the threshold of an exciting revolution
spectroscopy holds the key to decipher the true nature of these far away worlds

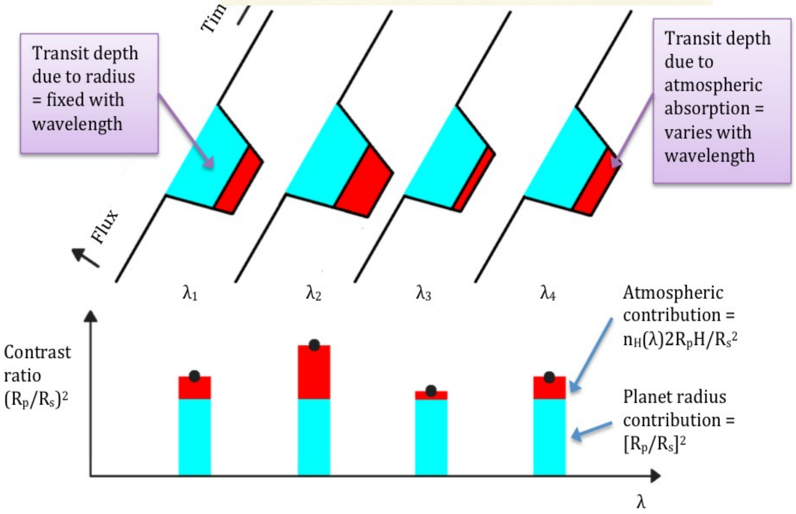
Characterisation: spectroscopy



Transit spectroscopy

Both planet body and atmosphere block starlight, but atmospheric contribution changes with wavelength, due to absorption (or scattering) by molecules





Credit: S. Sarkar

$$k^2(\lambda)=\frac{[R_p+\Delta h(\lambda)]^2}{R_*^2}\simeq\frac{R_p^2}{R_*^2}+\frac{2R_p\Delta h(\lambda)}{R_*^2}=k_0^2\left(1+2\frac{\Delta h(\lambda)}{R_p}\right)$$

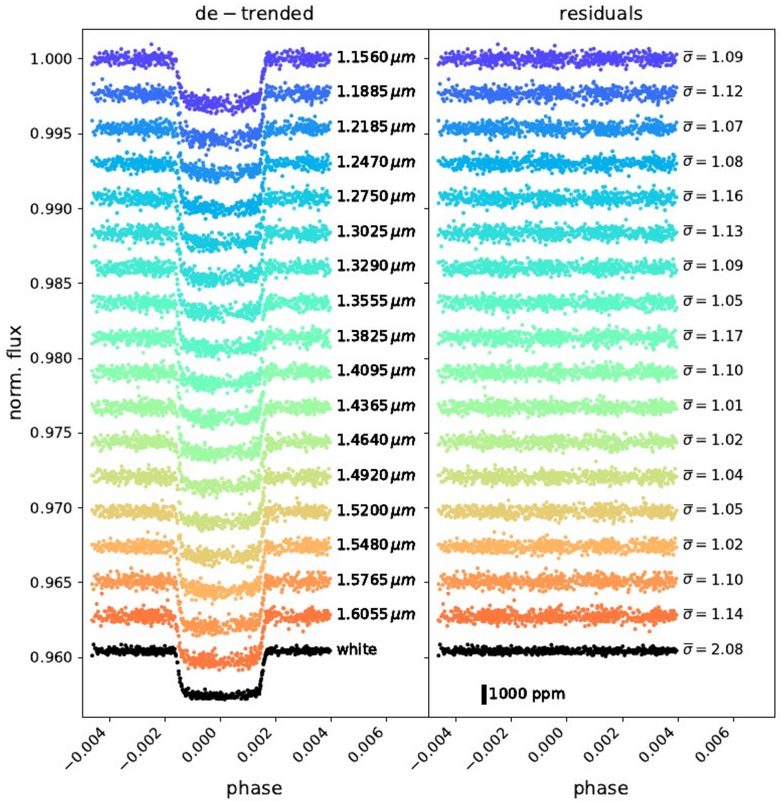
- R_p is the radial distance from the planet centre where the disk of the planet is optically thick at all wavelengths.
- Δh is the height where the atmosphere becomes optically thin at a given wavelength

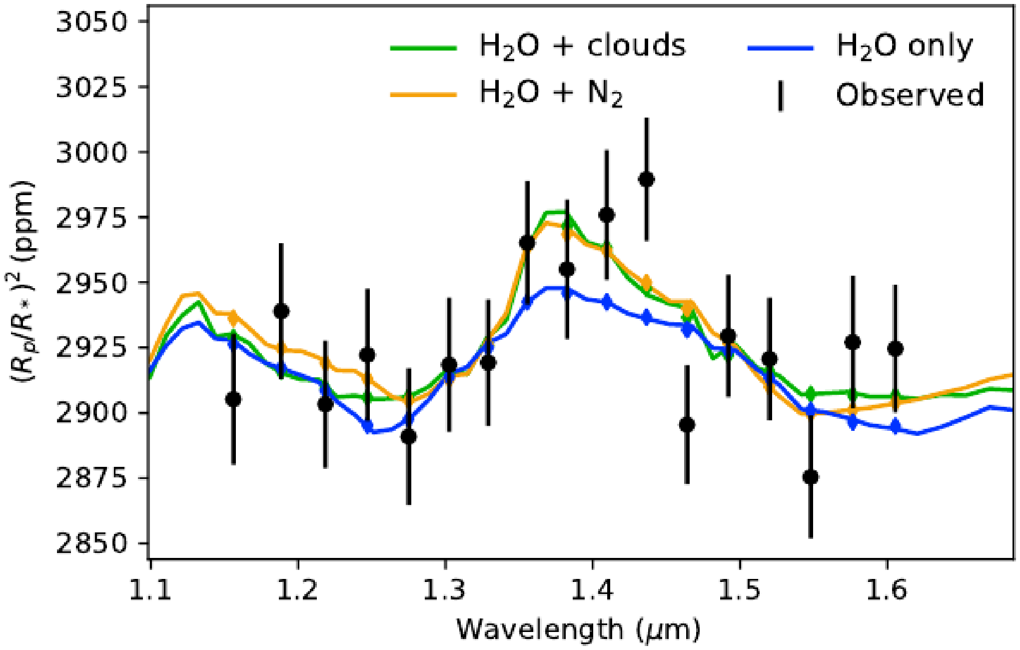
$$\Delta h(\lambda)=n(\lambda)H=n(\lambda)\frac{k_B T}{mg}$$

with $n(\lambda)$ takes value around 4 ~ 5 depending from the wavelength, and the atomic and molecular species mixed in the atmosphere.

Example: K-18 b transit spectroscopy

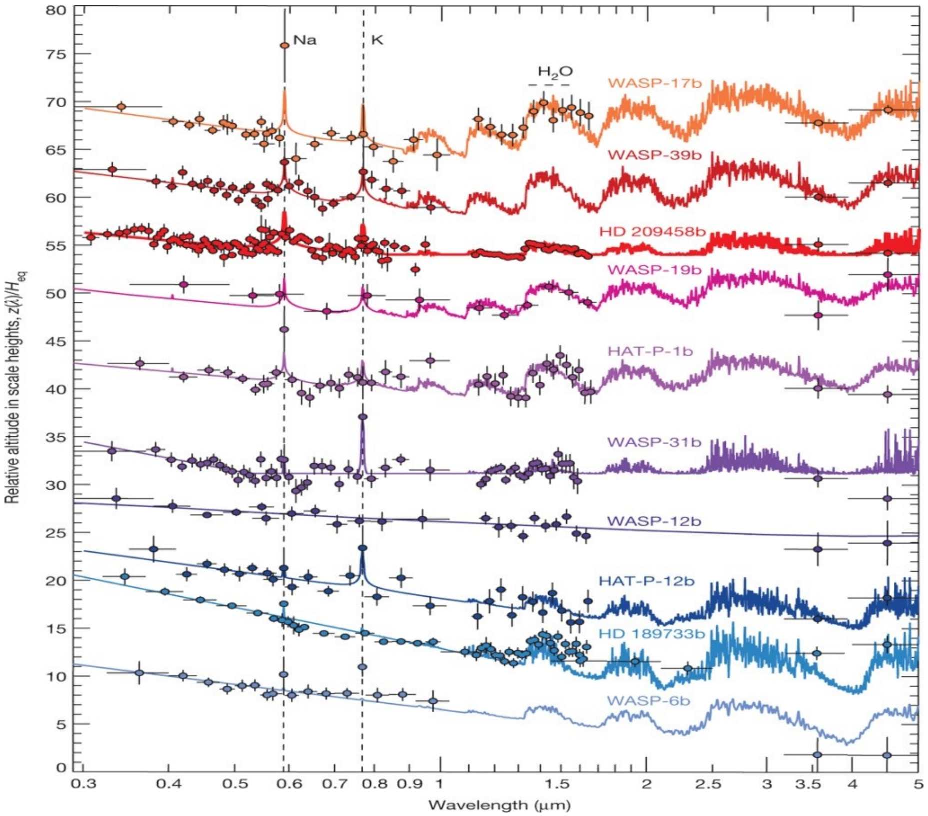
HST WFC3 observations from 1.1 to 1.7 micron





Tsiaras et al., Nat. 2019

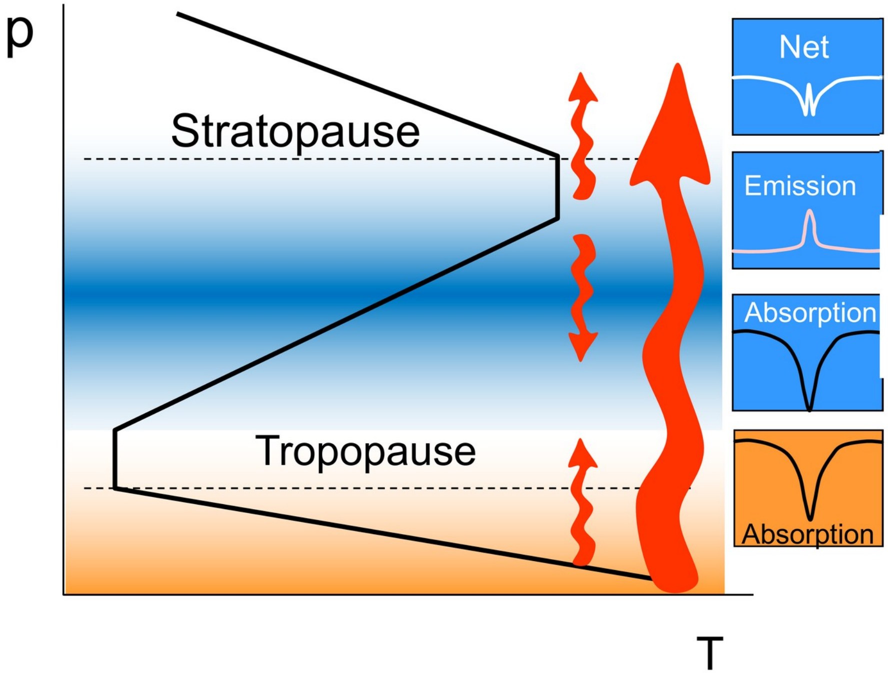
HST/Spitzer spectroscopy

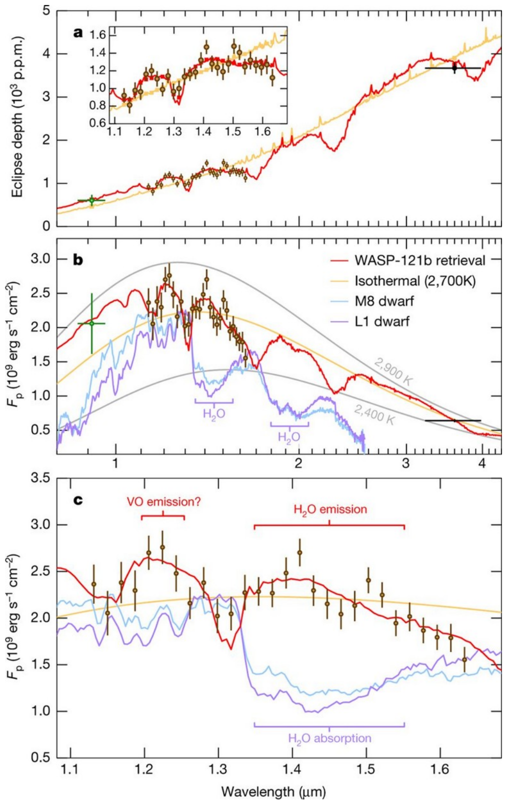


DK Sing *et al. 2016* doi:10.1038/nature16068

- Had proven possible spectroscopy of the atmospheres of exoplanets
- Limited by the wavelength coverage
- Requires instrumentation dedicated and optimised for both sensitivity and spectral coverage.

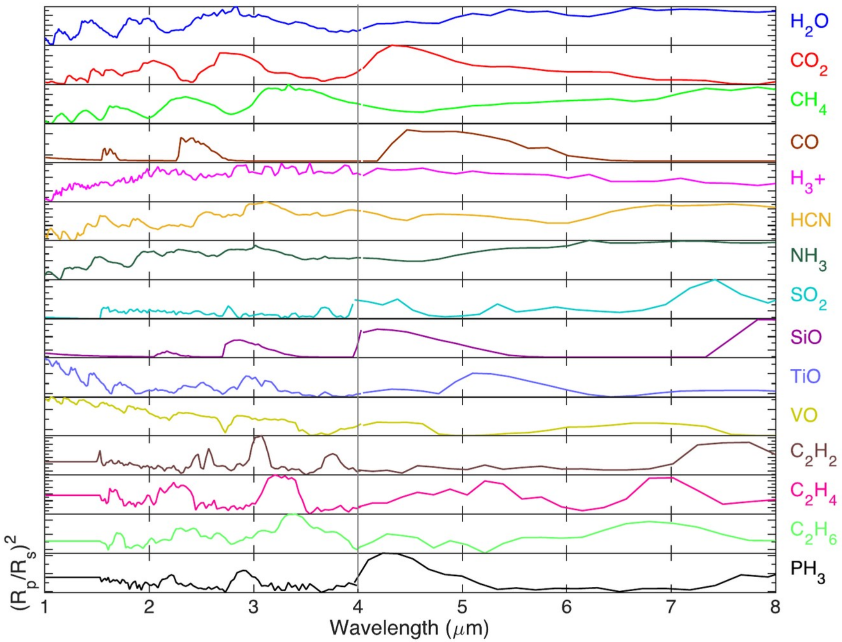
Eclipse spectroscopy





WASP 121b, Evans et al. Nat. 548, 2017

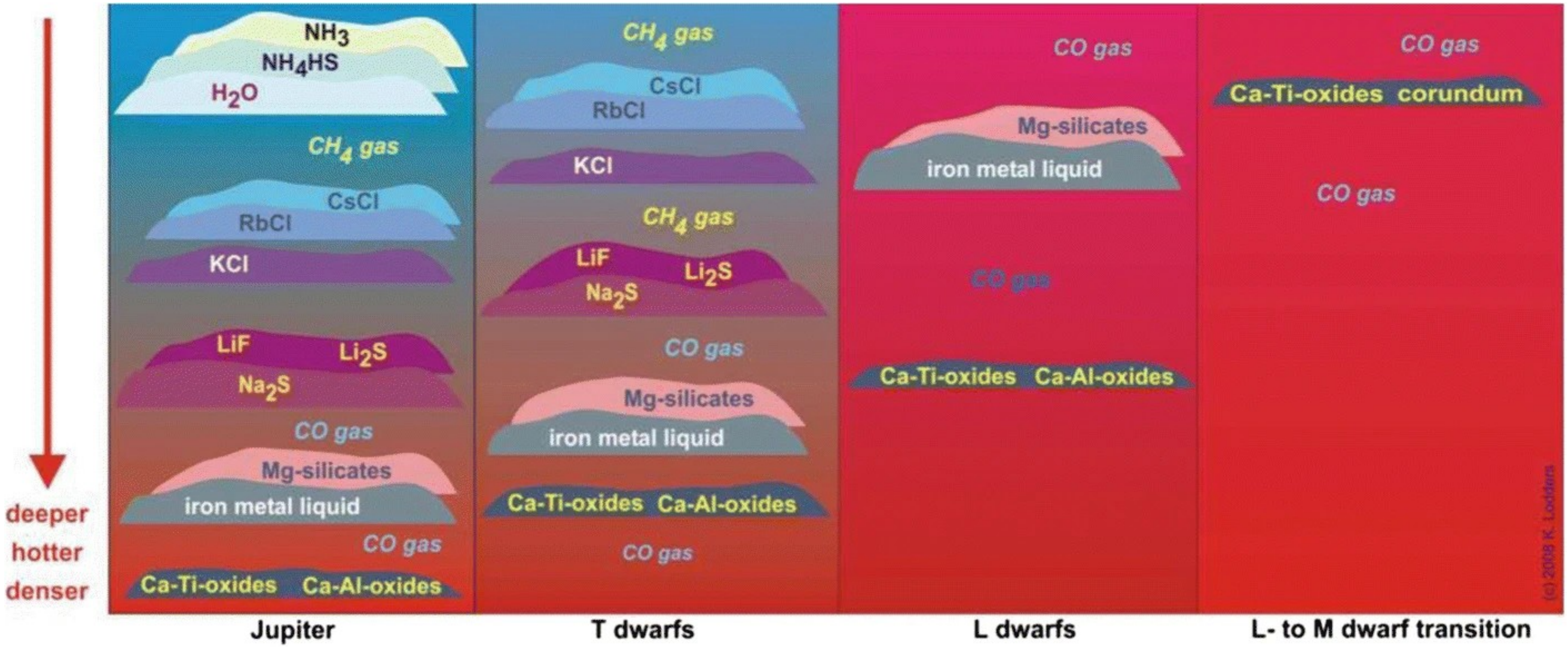
Molecular signatures



Tinetti et al.

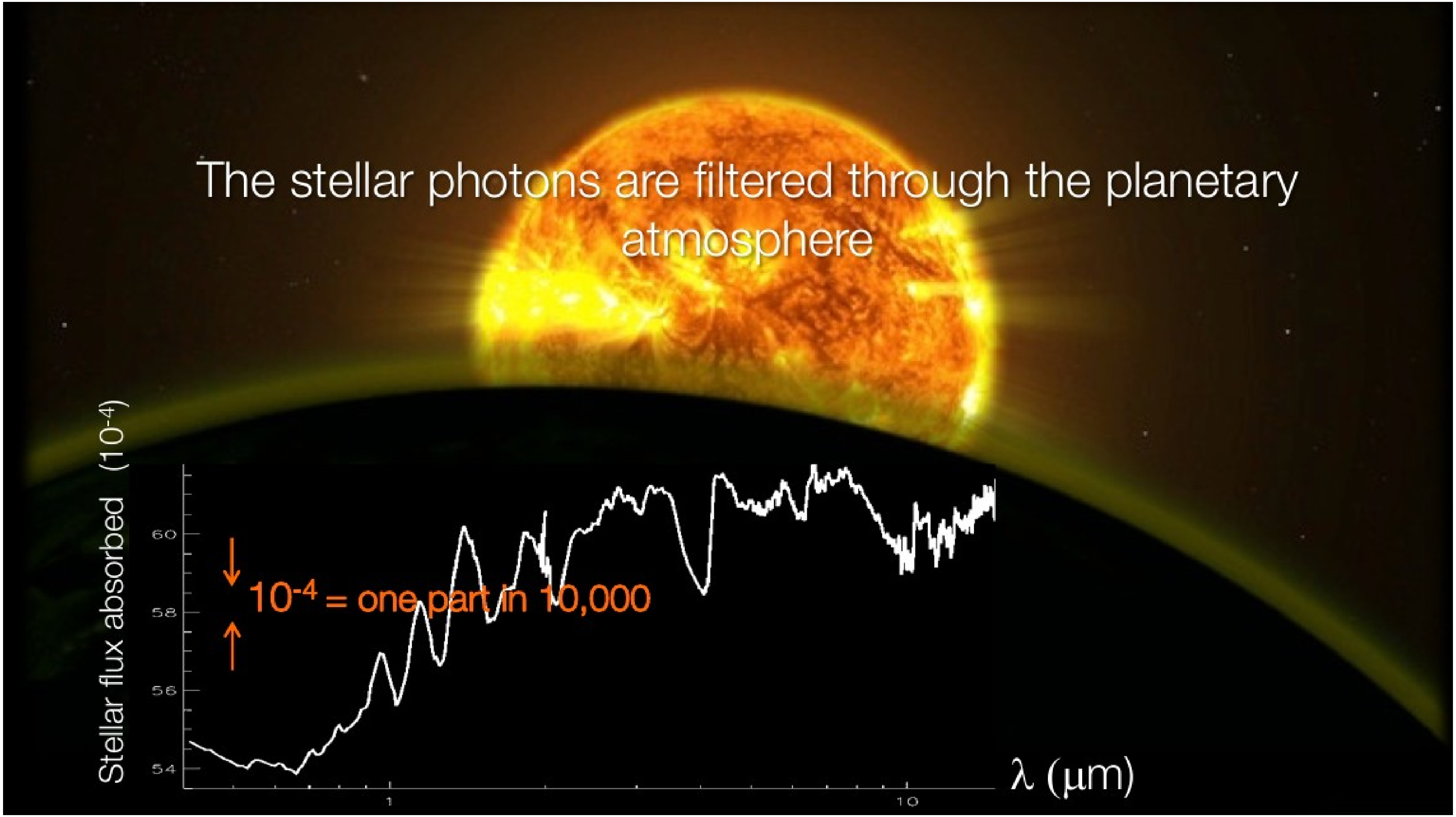
- Roto-vib signatures from molecules among the most abundant in the Galaxy
- Observations in low spectral resolution (10s to 100s) are sufficient to detect their signatures
  - Advantages: small volume instrumentation, more photons
- Observations in high spectral resolution
  - Fewer photons, require: large volume, large aperture instrumentation, typically exploited in combination with RV from the ground

Condensation and sequestration

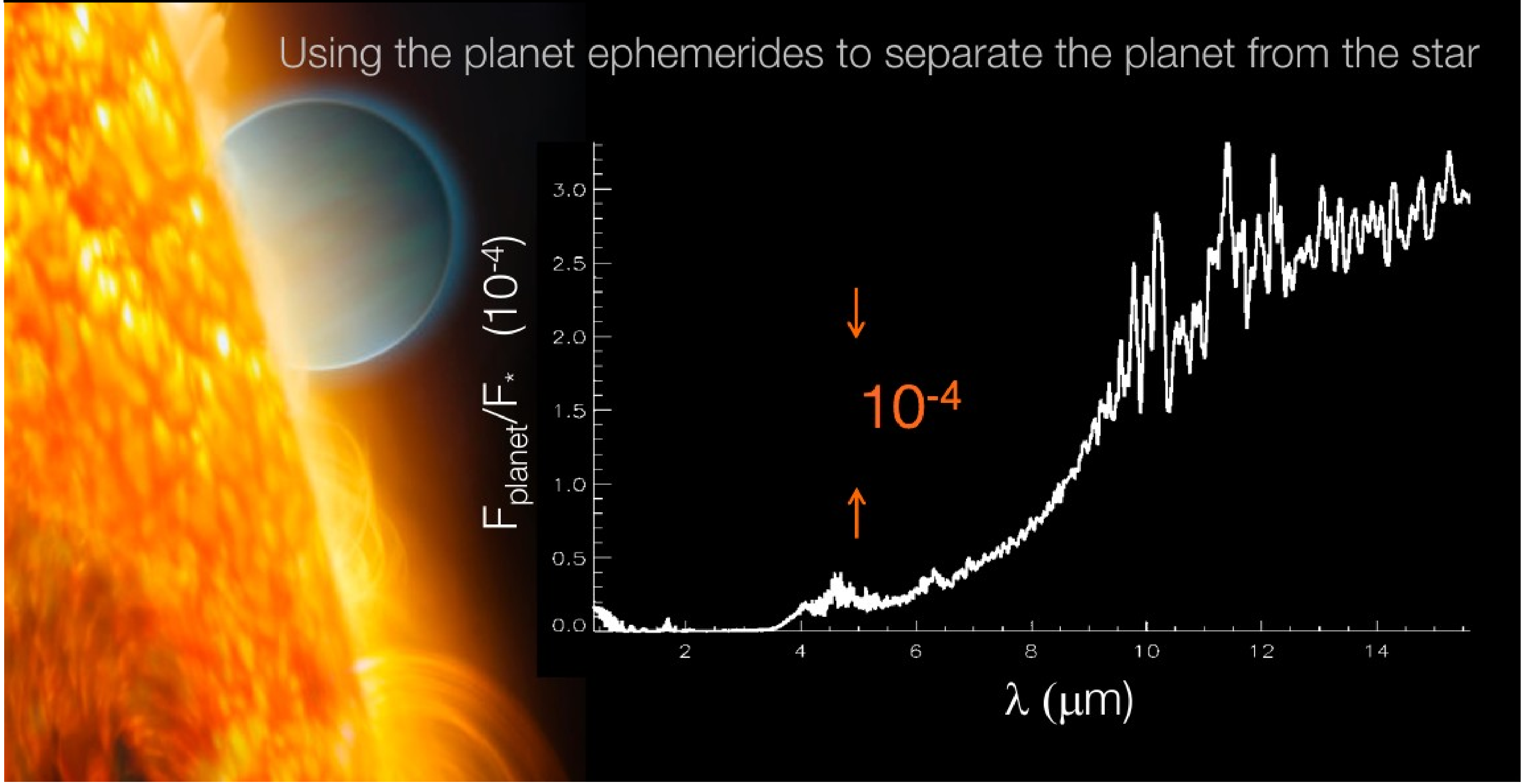


Cloud layers in atmospheres ranging from our Jupiter to the hottest brown dwarfs. Condensate clouds of various species form at specific points in the temperature-pressure profile. As atmospheres cool, these clouds sink deeper, falling below the observable gaseous layer.

Lodders & Fegley, ‘Chemistry of Low Mass Substellar Objects’, Springer (2006)


The stellar photons are filtered through the planetary atmosphere
Stellar flux absorbed (10-4)
60
58
56
54
10-4 = one part in 10,000
λ (μm)
1
10

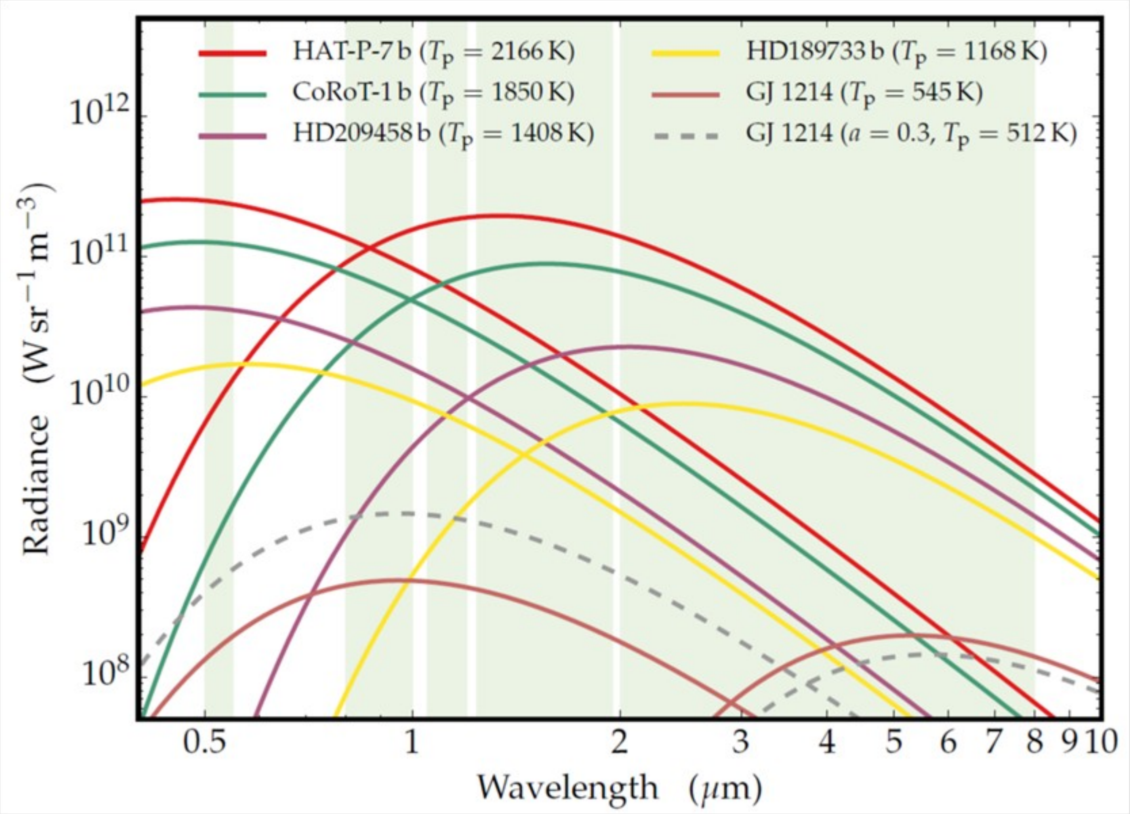
Eclipse Spectroscopy



Important points

- Exoplanets discovered show a large diversity in any parameter (radius, mass, stellar type, orbital parameters)
- If we hope to make sense of this diversity we need to characterise spectroscopically a large and diverse sample of exoplanets and probe the largest possible parameter space in terms of
  - Planet type
  - Host star spectral type
  - Orbital configuration
- These are Ariel's main science requirements: a statistical survey of a large and diverse sample of exoplanet atmospheres.

Characterisation: from VIS to mid-IR



- Observations at VIS wavelengths: reflected component, near peak of stellar irradiance
- Observations in the near-IR and mid-IR: molecular signature and peak of planet emission spectrum.
- Signal: ~ 100ppm
- Requires SNR of stellar signal of the order of 50000 for a 5 sigma detection, i.e. ~100 more than for discovery.

SNR considerations

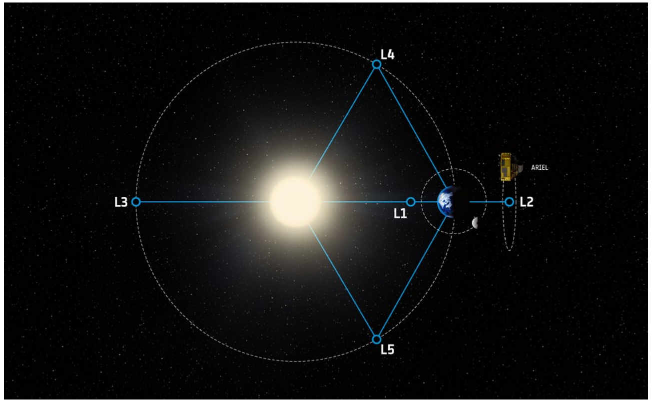
- Large SNR on the stellar signal is needed in order to detect the small variations caused by the exoplanet atmosphere
- SNR_* ~ 50000, at the transit duration timescale (a few hrs)
- This requires bright stars, and this is why a lot of effort is being put in detecting planets around bright and small stars (TESS)
- Sensitivity (random noise) is not an issue for these targets.
- The name of the game is: control of systematics

Most treacherous systematics

- The star: stellar variability
  - All measurements relative to star. Star knowledge and stability (over the observation time) is essential.
- The instrument:
  - temperature variations
  - Pointing stability
- Key to success is to design-out these systematics or provide the instrument with the capability to deal with them.

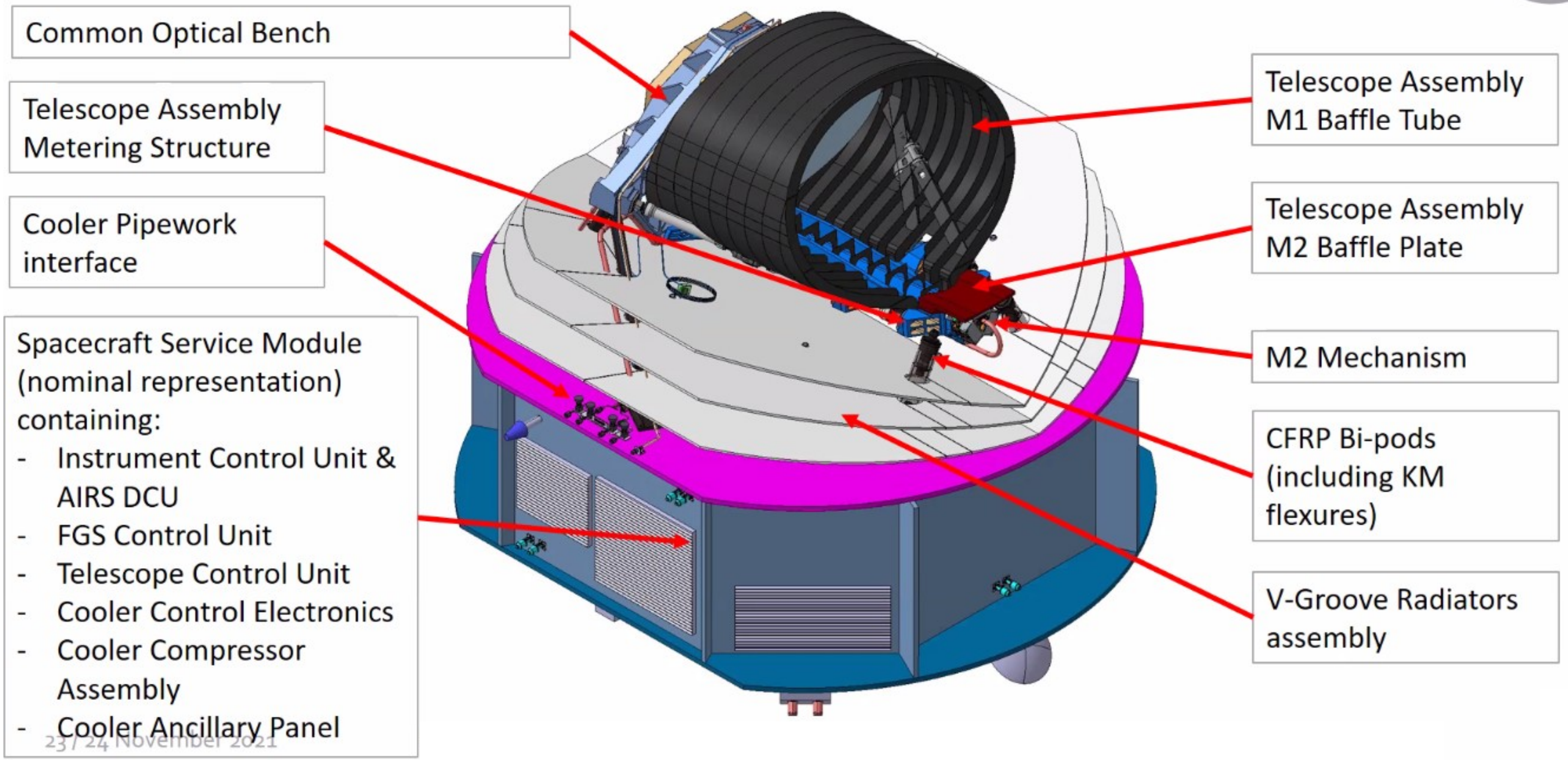
Ariel fact sheet

- Simultaneous observation from 0.5 to 7.8 micron
- 1m – class telescope
- In L2 for thermal stability (needed for mid-IR observations)
- Launch: 2029
- Mission lifetime 3.5yr + 2yr extended



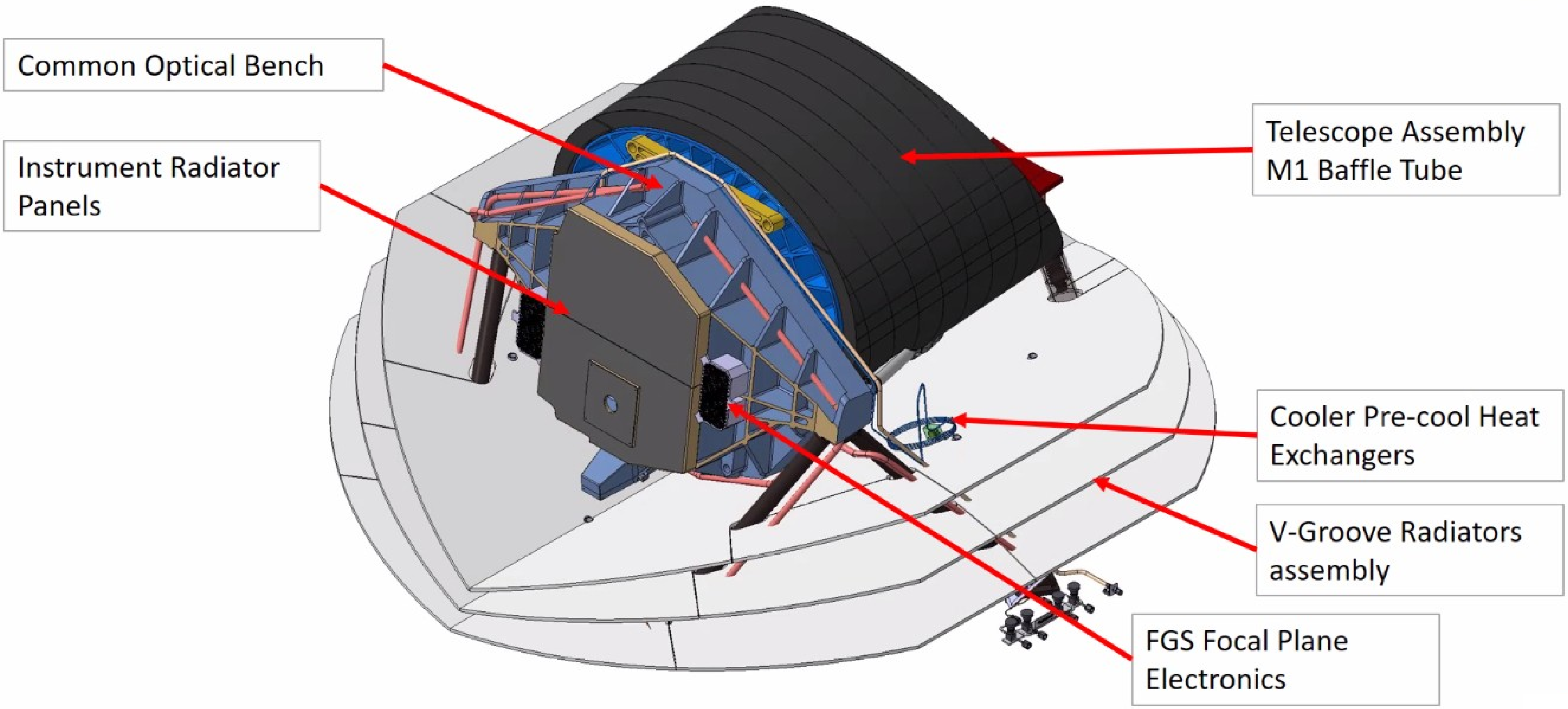
Name	Wavelength (um)	Type
VisPhot	0.5 – 0.6	Photometer
FGS1	0.6 – 0.9	Photometer
FGS2	0.9 – 1.1	Photometer
NIRSpec	1.1 – 1.95	Spec. R > 15
AIRS CH0	1.95 – 3.9	Spec. R > 100
AIRS CH1	3.9 – 7.8	Spec. R > 30

Overview of Payload Module - Front



23/24 November 2021

Overview of Payload Module - Rear



Overview of Payload Module - Rear

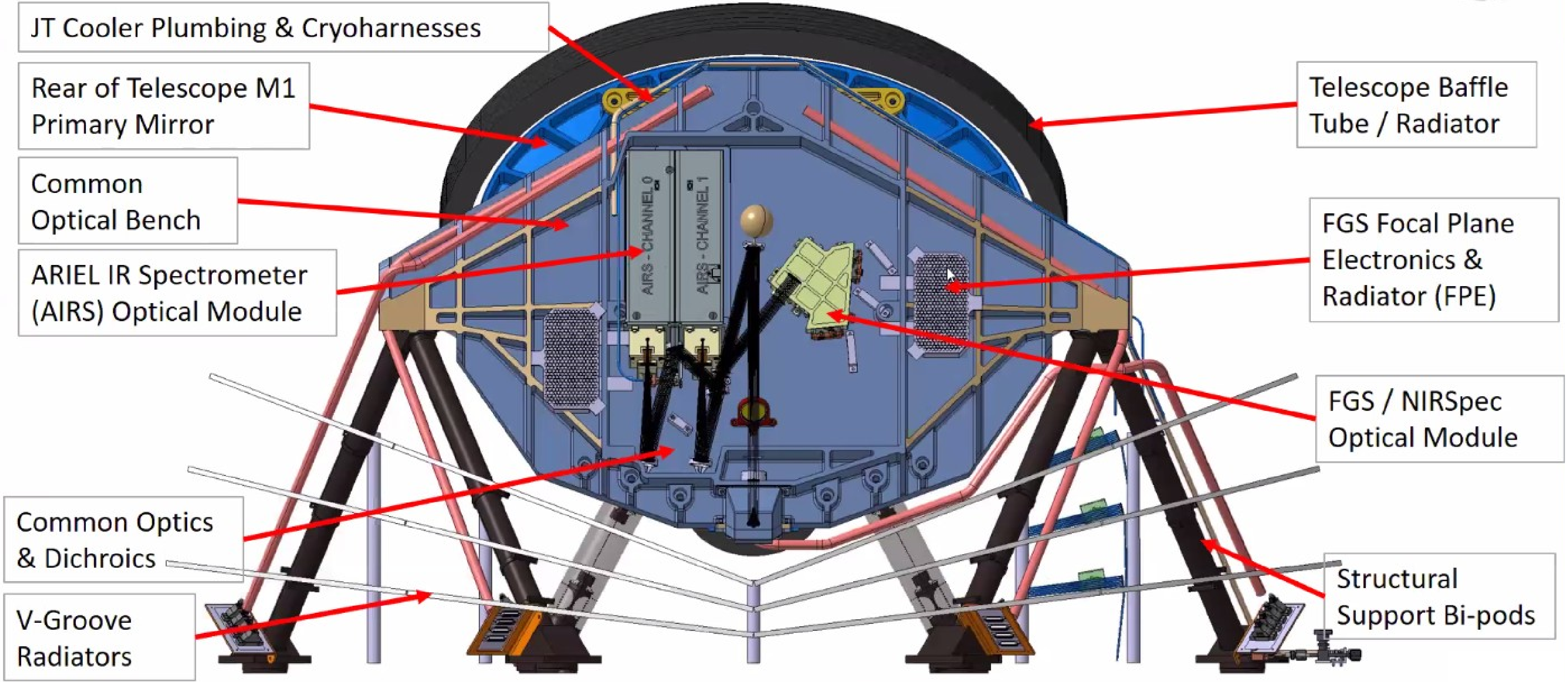


Table 4-1: Summary of noise sources and systematic errors

Type of uncertainty	Source	Mitigation Strategy
Detector noise	Dark current noise	Choice of low-noise detectors
	Readout noise	
	Gain stability	Calibration, post- processing data analysis, choice of stable detectors.
	Persistence	Post-processing decorrelation. Continuously staring at a target for the whole duration of the observation.
Thermal noise	Emission from telescope, common optics and all optical elements	Negligible due to surface emissivity properties and in-flight temperatures of the payload.
	Temperature fluctuations in time	Negligible impact by design
Astrophysical noise	Photon noise arising from the target	Fundamental noise limit, choice of aperture size (M1 diameter).
	Photon noise arising from local zodiacal light	Negligible over ARIEL band
	Stellar variability with time	Multi-wavelength stellar monitoring, post-processing decorrelation
Pointing jitter	RPE and PDE effects on the position, Spectral Energy Distribution, and detector intra/inter pixel response	Small RPE and PDE, Nyquist sampling, post-processing decorrelation
	Slit losses	Spectrometer input slit sufficiently large