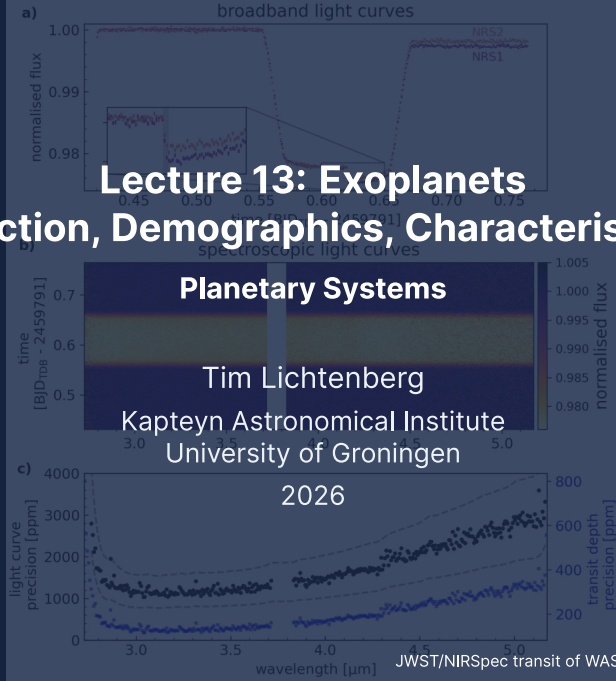


Lecture 13: Exoplanets

Detection, Demographics, Characterisation



Learning Objectives

By the end of this lecture, you will be able to:

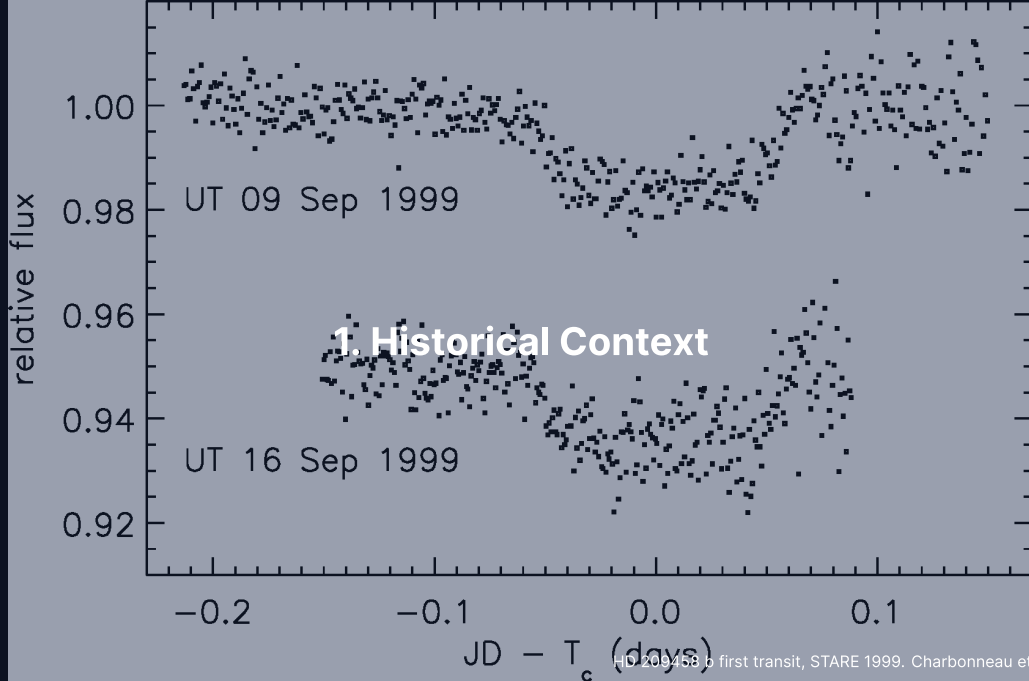
- Describe the main exoplanet detection methods and their biases
- Combine transit and radial-velocity geometry into a bulk density, and read the radius valley
- Evaluate JWST-era atmospheric results and biosignature claims

From zero confirmed exoplanets in 1991 to more than 6000 in 2026.

Recap: Where We Are in the Course

- Lectures 9–11 surveyed the geology, atmospheres, and interiors of the solar planets
- Lecture 12 decoded small bodies and meteorites as planet formation fossils
- This lecture turns outward to thousands of exoplanets to test if these patterns are universal

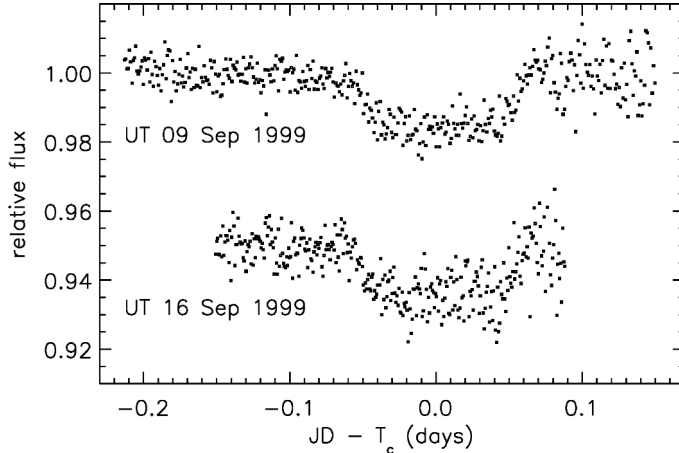
Today: How do we detect, weigh, and characterise worlds beyond our solar system?



HD 209458 b first transit, STARE 1999. Charbonneau et al. (2000)

From Zero to Six Thousand in Three Decades

- **1992 (PSR B1257+12):** first exoplanets, around a pulsar, by timing (Wolszczan & Frail)
- **1995 (51 Pegasi b):** first planet around a Sun-like star; a 4.23-day orbit forced migration theory (Mayor & Queloz)
- **1999 (HD 209458 b):** first transit of an RV planet: a gas-giant radius and bulk density



The first ground-based detection of a transiting exoplanet, HD 209458 b, on two nights in 1999. Charbonneau et al. (2000).

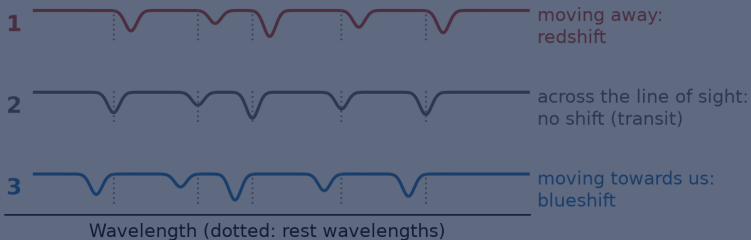
Successive transits dropped the flux by about 1.7% (independent detection by Henry et al. 2000): exoplanets became physical objects with measurable radii.

(a) Star and planet orbit the barycentre

yellow: star; grey: planet
arrows: velocity of the star
star orbit not to scale

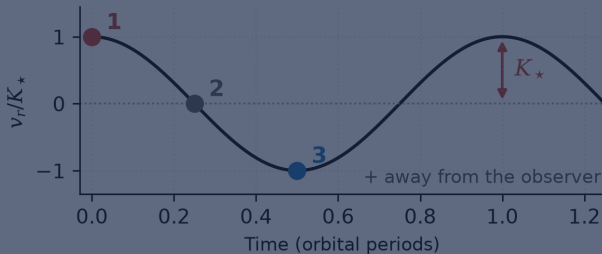


(b) Stellar absorption lines (shifts exaggerated)

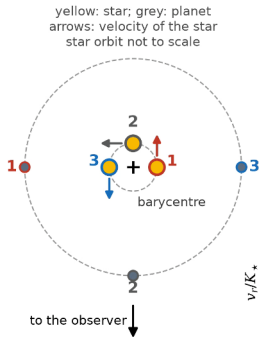


2. Detection Method 1: Radial Velocity

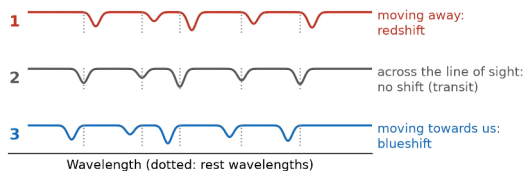
(c) Radial velocity of the star



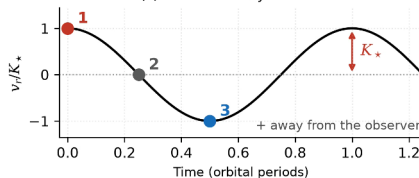
(a) Star and planet orbit the barycentre



(b) Stellar absorption lines (shifts exaggerated)



(c) Radial velocity of the star



Star and planet orbit the barycentre; over one orbit the stellar lines shift to the red, not at all, and to the blue. Course figure.

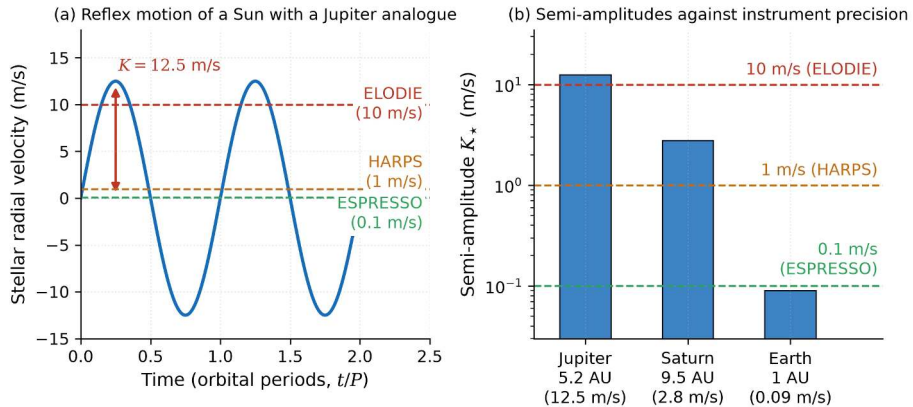
Only the line-of-sight component of the star's velocity shifts the lines; the amplitude of the velocity curve is the semi-amplitude K_* .

Radial Velocity: Doppler Reflex of the Star

- Star and planet orbit a common barycentre: $a_{\star} = (m_p / M_{\star}) a_p$
- The periodic Doppler shift of the stellar absorption lines gives the reflex velocity
- Semi-amplitude $K_{\star}$ for inclination i (edge-on: $\sin i = 1$; circular: $e = 0$):

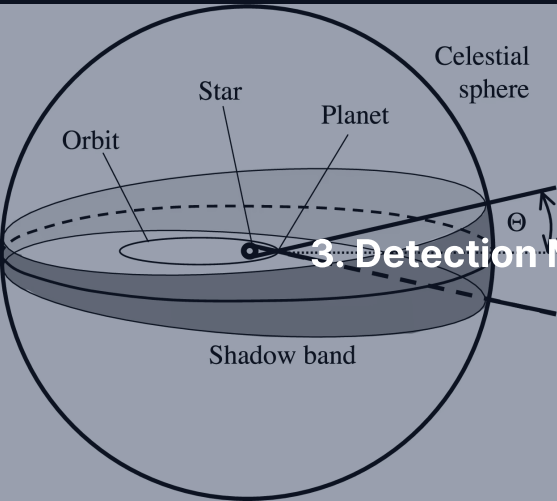
$$K_{\star} = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{m_p \sin i}{M_{\star}^{2/3}} \frac{1}{\sqrt{1 - e^2}}$$

Jupiter at 5.2 AU: $K_{\star} \approx 12.5 \text{ m s}^{-1}$; Earth at 1 AU: $K_{\star} \approx 9 \text{ cm s}^{-1}$.

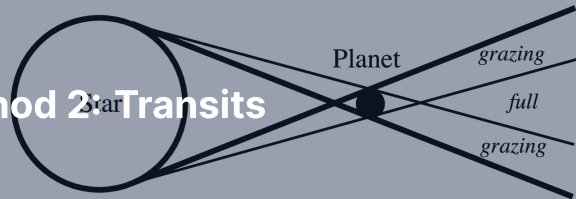


(a) Reflex velocity of a Sun with a Jupiter analogue against ELODIE, HARPS and ESPRESSO precisions; (b) semi-amplitudes of Jupiter, Saturn and Earth analogues. Course figure.

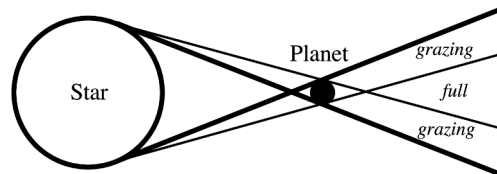
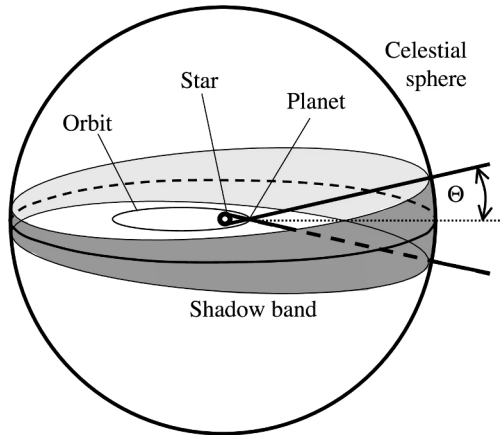
An Earth analogue at 0.09 m s^{-1} sits below the instrumental floor and within the $0.1\text{--}1 \text{ m s}^{-1}$ stellar jitter; RV alone gives only the minimum mass $m_p \sin i$.



3. Detection Method 2: Transits



Close-up



Close-up

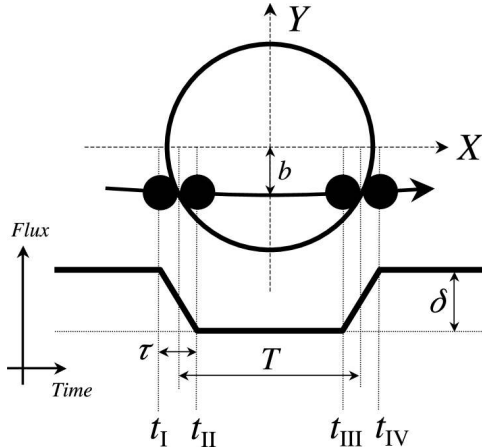
Transit geometry: a planet on an orbit near the line of sight crosses the stellar disk.
Winn (2010).

Transit depth $\delta = (R_p/R_*)^2$ and geometric probability $p \approx R_*/a$: a strong selection bias toward short periods and large R_p/R_* .

Quick Scales

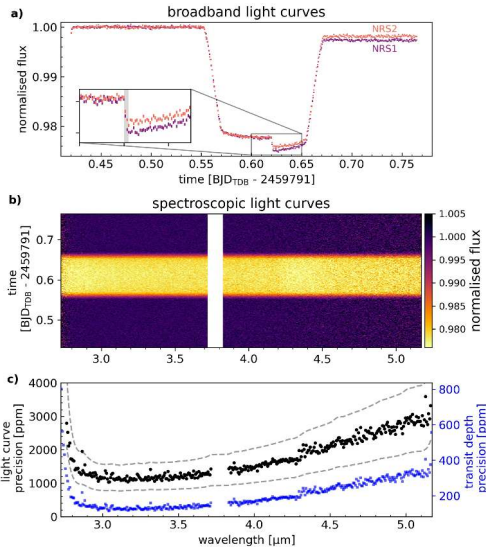
Transit depth scales inversely with the square of the stellar radius, so small planets around small stars are far easier to detect.

- **Jupiter around Sun:** $\delta \approx 1.01\%$, easily detected from ground-based telescopes
- **Earth around Sun:** $\delta \approx 84$ ppm, requires ultra-precise space photometry
- **Earth around M dwarf ($0.15 R_{\odot}$):** $\delta \approx 4000$ ppm, accessible from ground and space



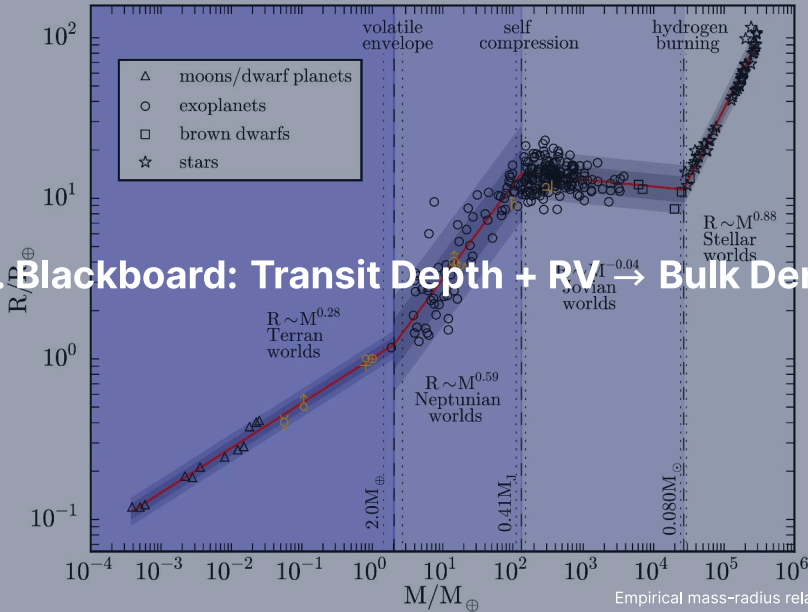
Anatomy of a transit light curve with its four contact times t_I to t_{IV} . Winn (2010).

The depth gives the radius ratio R_p/R_* ; the total duration and the ingress time give the impact parameter b and the inclination. A real transit bottom curves from stellar limb darkening.

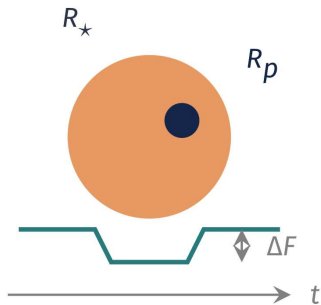


JWST/NIRSpec transit photometry of WASP-39 b: depths measured to 200–600 ppm per spectroscopic bin, below typical exoplanet absorption features. Alderson et al. (2023).

4. Blackboard: Transit Depth + RV $\rightarrow$ Bulk Density



Goal and strategy



Goal: a radius and a mass for the same planet, hence a density.

- Transit alone: the radius R_p , but no mass
- RV alone: the minimum mass $m_p \sin i$, but no radius
- Combined: **both**, so the bulk density $\bar{\rho}_p$

Bulk density turns an astronomical detection into a physical, geological body. To the board.

Steps 1 to 3 and the Density

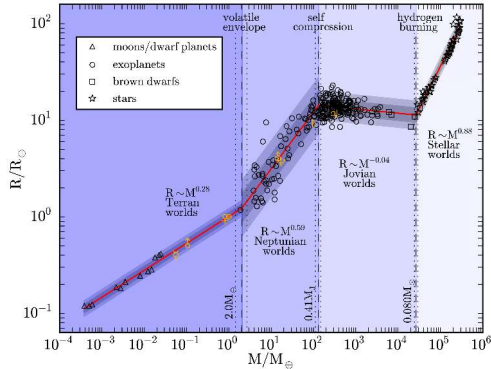
Transit depth $\delta = (R_p/R_\star)^2$ gives R_p ; the reflex velocity

$K_\star = (2\pi G/P)^{1/3} m_p \sin i M_\star^{-2/3}$ gives $m_p \sin i$ (broad).

- A transit forces $\sin i \approx 1$ and collapses the $m_p \sin i$ degeneracy
- Both R_p and m_p measured for the same object
- Bulk density follows from elementary geometry:

$$\bar{\rho}_p = \frac{m_p}{(4/3)\pi R_p^3} = \frac{3m_p}{4\pi R_p^3}$$

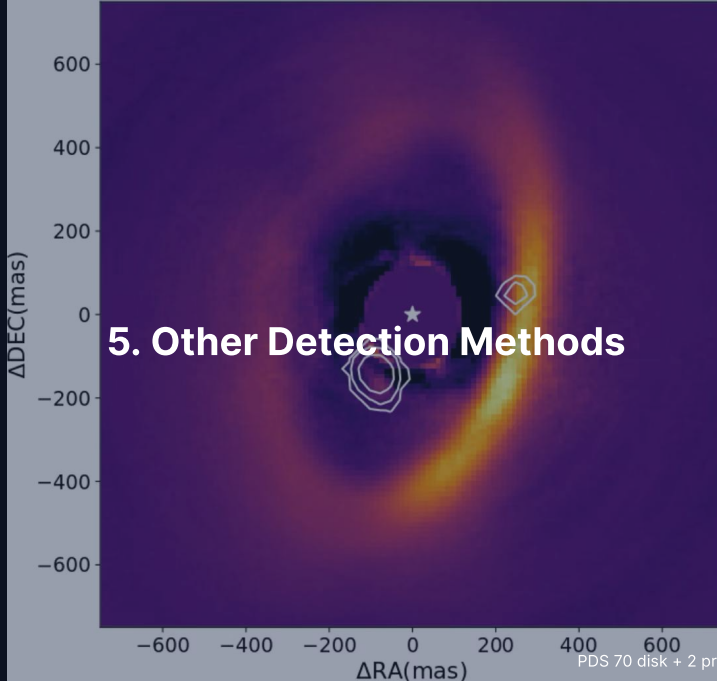
Transit plus RV turns a detection into a physical object: radius, mass and density from one planet.



The empirical mass-radius relation of exoplanets and solar-system bodies.
Chen & Kipping (2017).

Density maps to composition: $\bar{\rho} \approx 5.5 \text{ g cm}^{-3}$ rocky (Earth, Venus), 1.3 g cm^{-3} gas giant (Jupiter), 0.5 g cm^{-3} an inflated envelope, and $1\text{--}3 \text{ g cm}^{-3}$ the sub-Neptunes, a size class the solar system lacks.

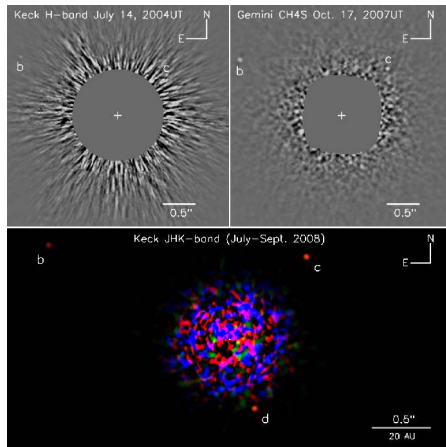
5. Other Detection Methods



PDS 70 disk + 2 protoplanets. Haffert et al. (2019)

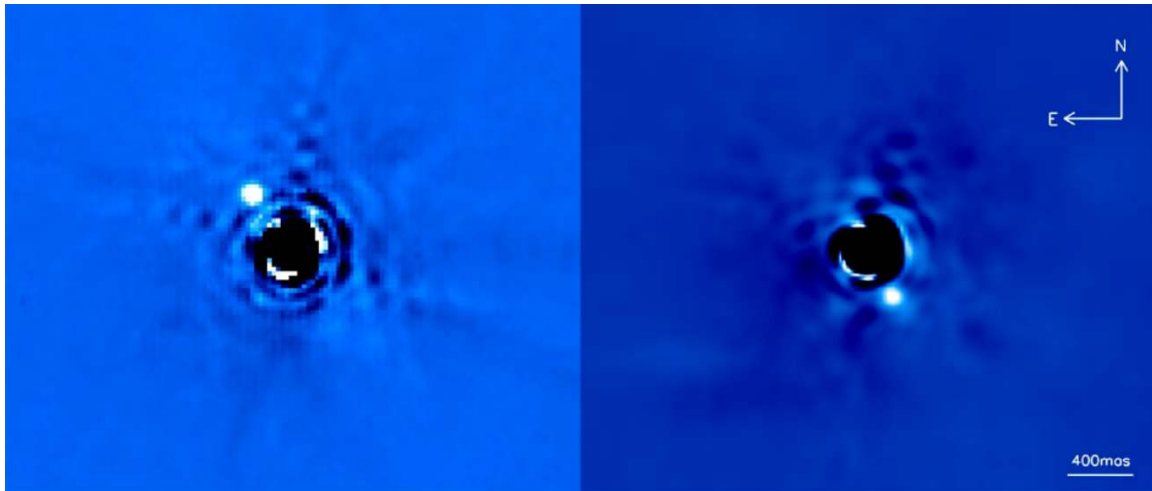
Direct Imaging: Spatial Separation of Photons

- **Contrast:** suppress the star by 10^{-9} (Jupiter) to 10^{-10} (Earth twin) at separation $\theta = a/d$
- **Technology:** extreme adaptive optics plus coronagraphs against diffraction and speckle noise
- **Bias:** young, massive, self-luminous giants on wide orbits ($a > 10$ AU)

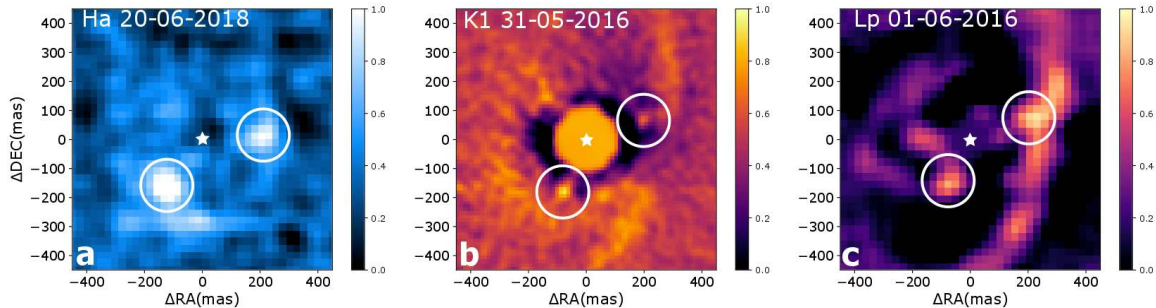


Keck and Gemini adaptive-optics discovery images of the HR 8799 planets.
Marois et al. (2008).

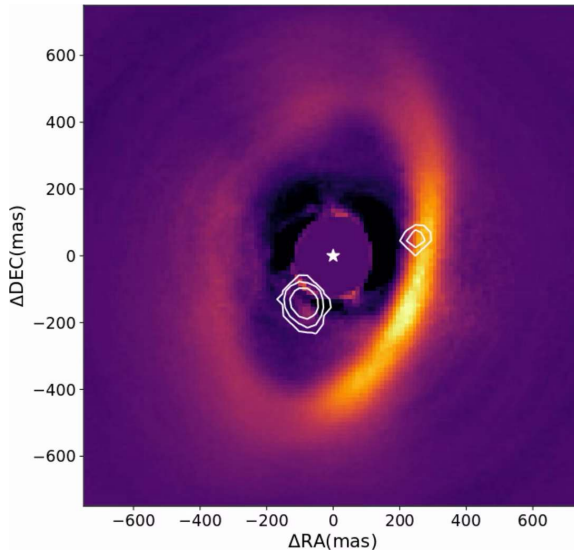
Four co-moving planets of 5–10 M_J at 14–68 AU (planet e added in 2010) around a 30–60 Myr star: they still glow from their contraction heat.



Direct image of β Pictoris b: orbital motion between 2003 and 2009 confirms a bound $\sim 9 M_J$ companion at ~ 9 AU. Lagrange et al. (2010); credit: ESO/A.-M. Lagrange et al.



PDS 70 b and c inside the disk gap in MUSE H α (a), SPHERE K1 (b) and NACO L' (c): both protoplanets are accreting within the cleared cavity. Haffert et al. (2019).



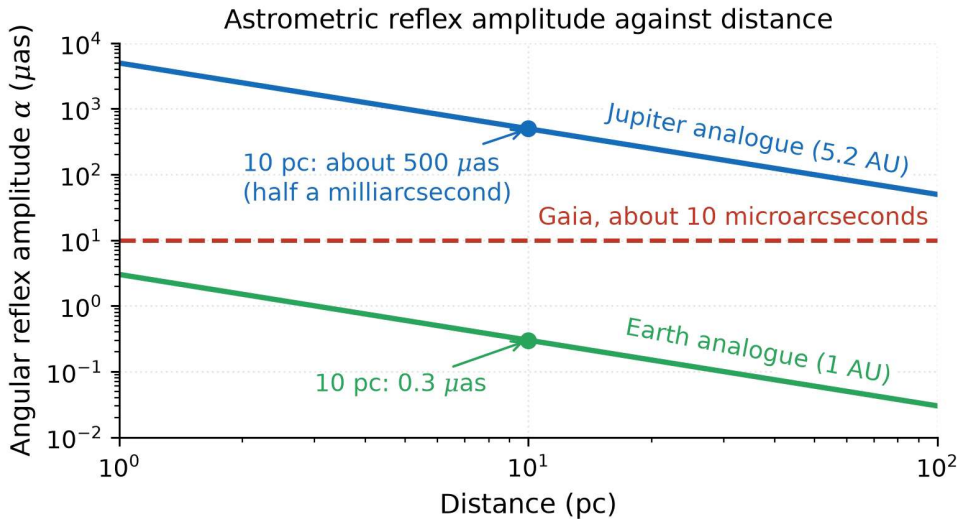
Composite scattered-light image of the PDS 70 protoplanetary disk with the two embedded protoplanets inside the cleared gap. Haffert et al. (2019).

Astrometry: Gaia Will Find Jupiter Analogues

Astrometry follows the star's reflex wobble on the sky and gives true masses.

$$\alpha = \frac{m_p}{M_\star} \cdot \frac{a_p}{d}$$

- **Signal:** a Jupiter analogue at 10 pc gives $\alpha \sim 500 \mu\text{as}$; an Earth analogue $\sim 0.3 \mu\text{as}$
- **Gaia DR4 (2026):** thousands of cold giants expected; $\sim 10 \mu\text{as}$ final precision
- **True mass:** the inclination i is measured, so no $m \sin i$ degeneracy



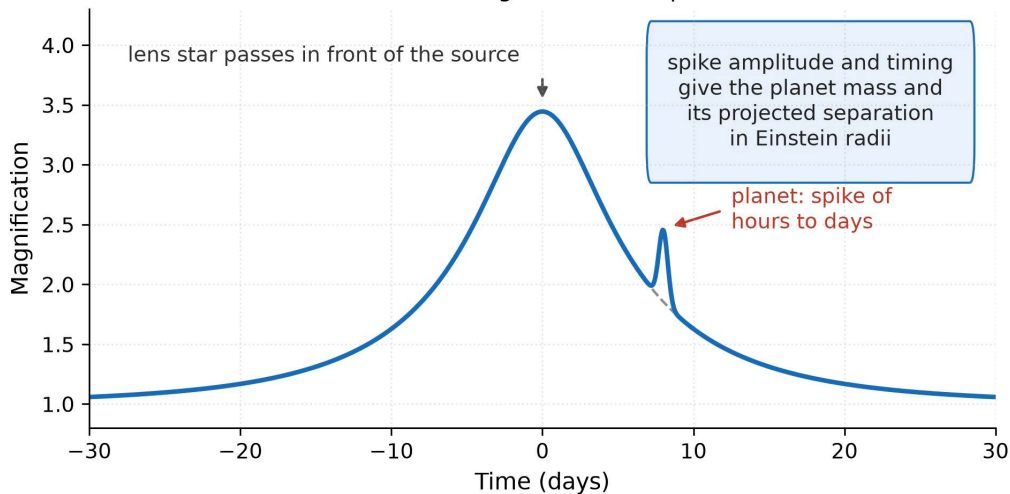
Astrometric reflex amplitude against distance for Jupiter and Earth analogues, with Gaia's final precision of about 10 microarcseconds as the dashed line. Course figure.

Microlensing, Timing, and Detection Biases

- **Microlensing (Roman):** cool planets at 1–10 AU and unbound rogue worlds
- **Timing variations (TTVs):** dynamical masses for faint hosts such as TRAPPIST-1
- **Together:** transits and RV probe close-in orbits; imaging, astrometry and microlensing the wide ones

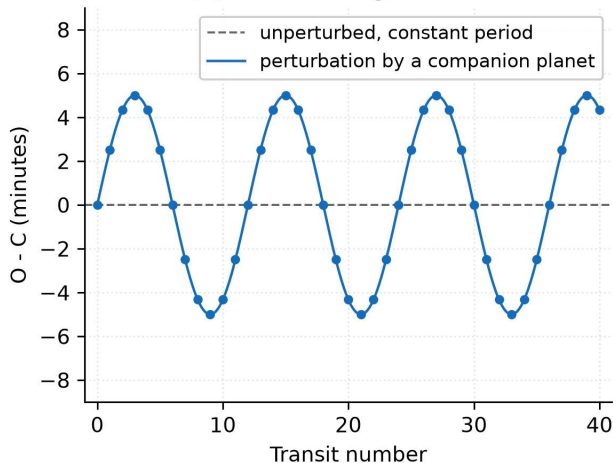
Each method covers its own part of parameter space, so the archive carries the biases of the methods.

A microlensing event with a planet



A microlensing event with a planet: the magnification of a background source by a lens star, and the spike of hours to days that a planet around the lens adds. Course figure.

(a) Transit timing variations



(b) Timing methods

transit timing variations:

dynamical masses (TRAPPIST-1)

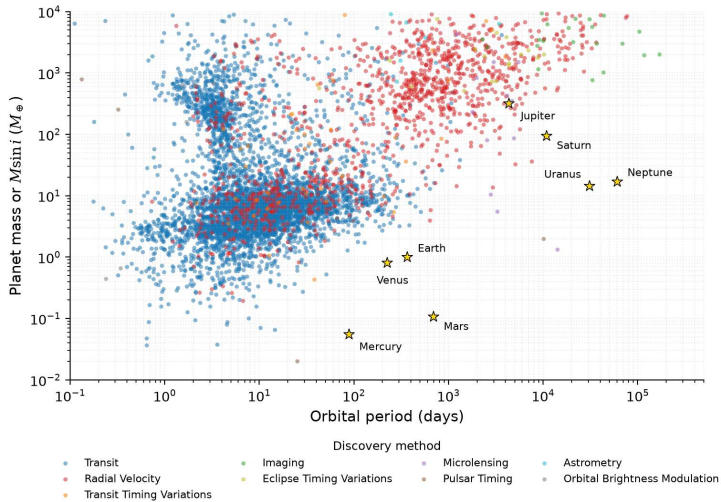
pulsar timing:

the first exoplanets (1992)

eclipse timing in binaries:

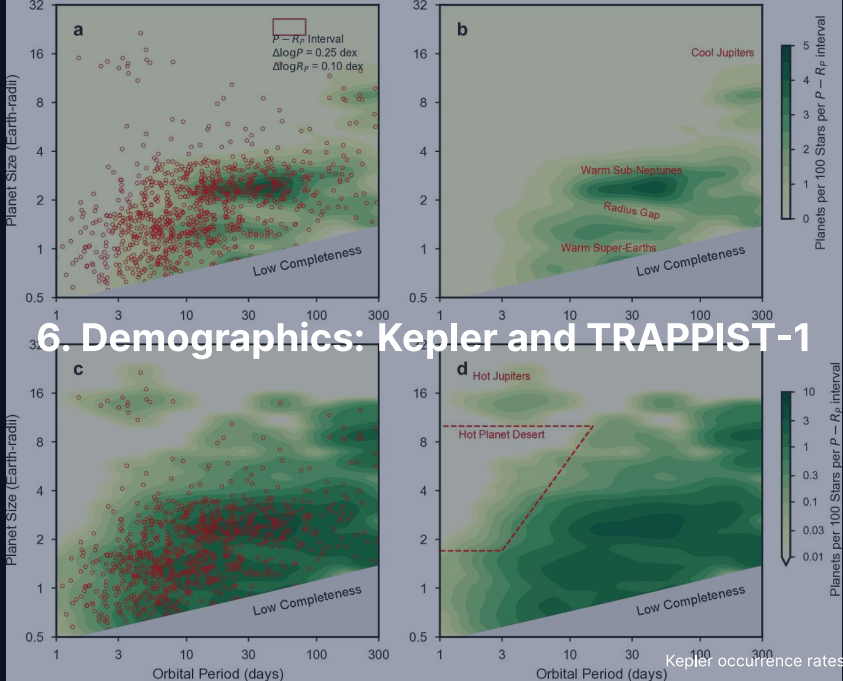
circumbinary planets
(Kepler-16 b, 2011)

(a) Observed minus calculated transit times of a planet perturbed by a companion (5 minute amplitude, schematic); (b) the three timing methods: transit timing, pulsar timing and eclipse timing in binaries. Course figure.



Confirmed exoplanet masses (or $m_p \sin i$) against orbital period by detection technique, with the solar-system planets: discoveries pile up at high mass and short period.

Credit: NASA Exoplanet Archive (2026). Course figure.

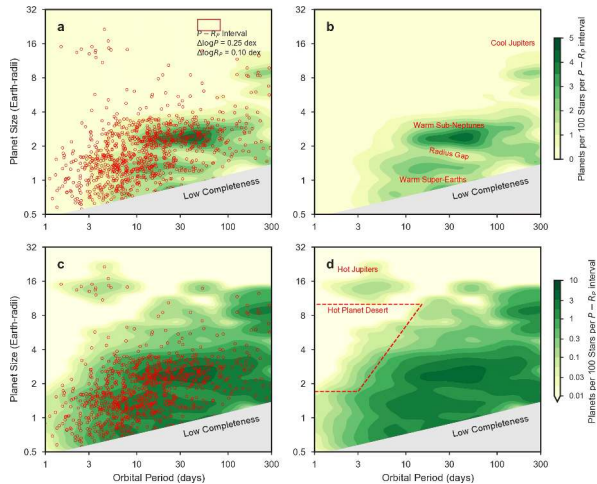


6. Demographics: Kepler and TRAPPIST-1

The Kepler Revolution

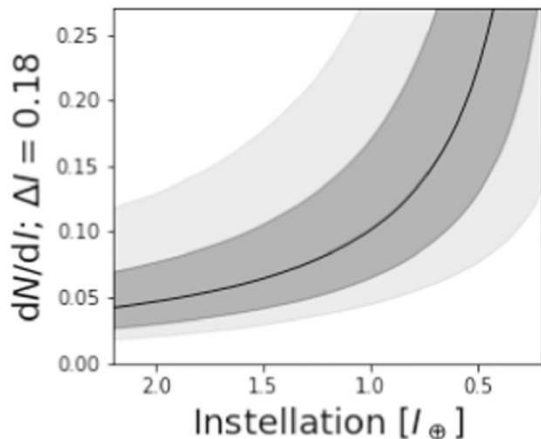
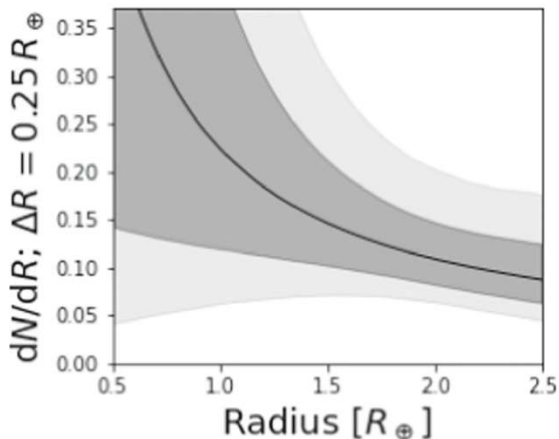
- **Planets are ubiquitous:** on average more than 1 planet per main-sequence star (Petigura et al. 2018)
- **Small planets dominate:** super-Earths and sub-Neptunes are common; hot Jupiters are rare (0.5–1%)
- **Habitable terrestrial rate:** Earth-sized planets in the habitable zone occur at $\eta_{\oplus} \sim 0.4$ (Bryson et al. 2021)

Kepler's computable detection efficiency gave the first bias-corrected occurrence rates: planets outnumber stars in the Milky Way.



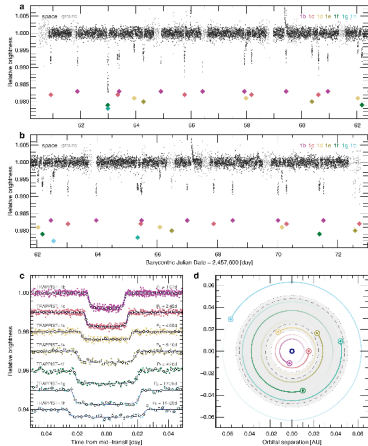
Planet occurrence against period and size, California-Kepler Survey. Petigura et al. (2018).

Small planets outnumber giants at every period; the fall-off beyond ~ 100 days is partly completeness-limited.



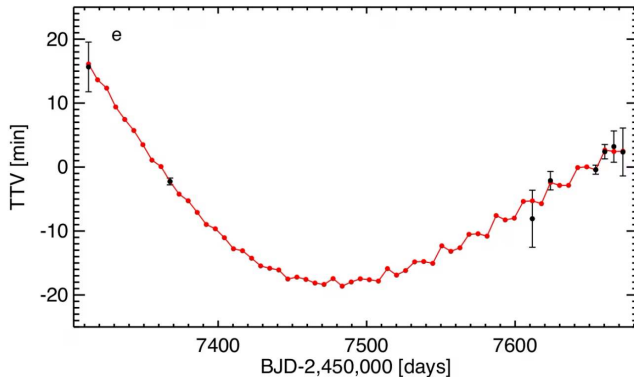
Marginalised occurrence of small planets per unit radius (left) and per unit instellation (right), with 68% and 95% credible bands. Bryson et al. (2021).

The central estimate $\eta_{\oplus} \sim 0.4$: terrestrial planets in habitable zones are common.



Transits of the seven TRAPPIST-1 planets. Gillon et al. (2017).

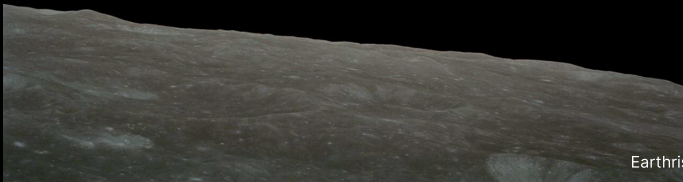
An M8 ultra-cool dwarf at 12 pc with seven Earth-sized planets within about 0.06 AU in a resonant chain, consistent with early inward migration; e, f and g orbit in the temperate habitable zone.



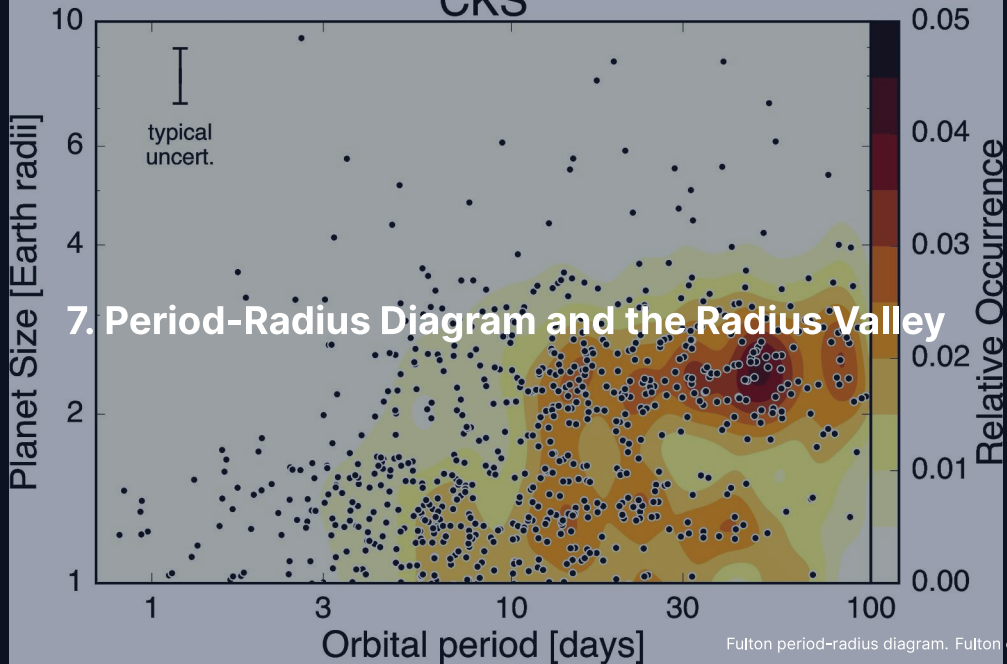
Transit-timing variations of TRAPPIST-1 e against a seven-planet dynamical model.
Gillon et al. (2017).

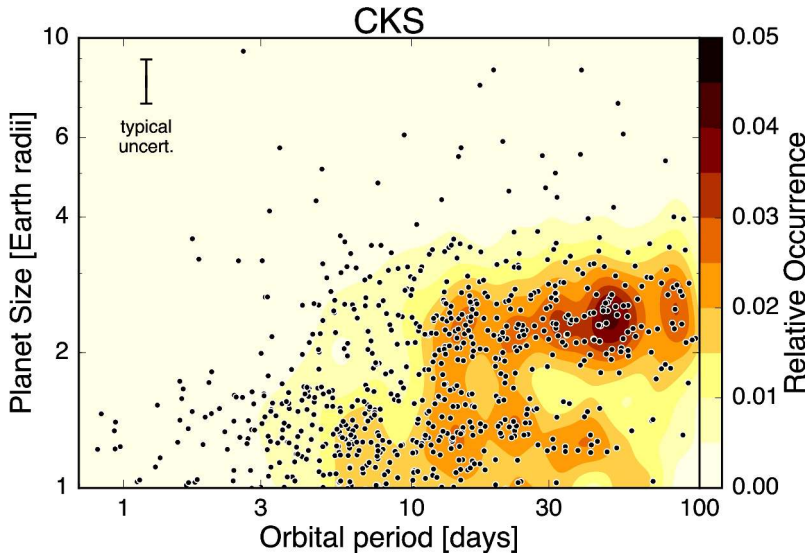
Timing variations of tens of minutes, fitted with simultaneous N-body models, break the mass degeneracies and give individual masses and densities without radial velocities.

Break

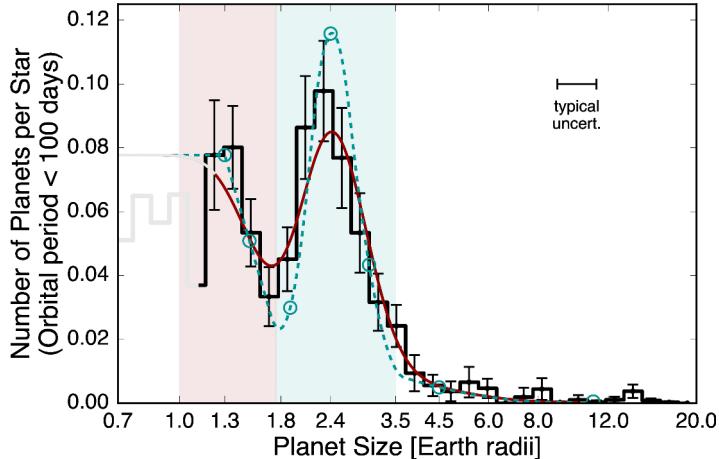


CKS





Period-radius distribution of small Kepler planets after stellar parameter refinement: super-Earths and sub-Neptunes separated by a deficit at $\sim 1.8 R_{\oplus}$. Fulton et al. (2017).



The radius valley: small Kepler planets have a bimodal size distribution. Fulton et al. (2017).

A deficit at $1.5\text{--}2.0 R_{\oplus}$ separates super-Earths near $1.3 R_{\oplus}$ (bare rocky cores) from sub-Neptunes near $2.4 R_{\oplus}$ (volatile envelopes); photoevaporation or core-powered mass loss carves it.

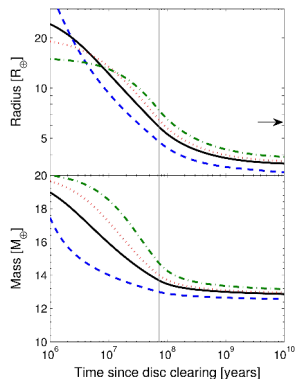
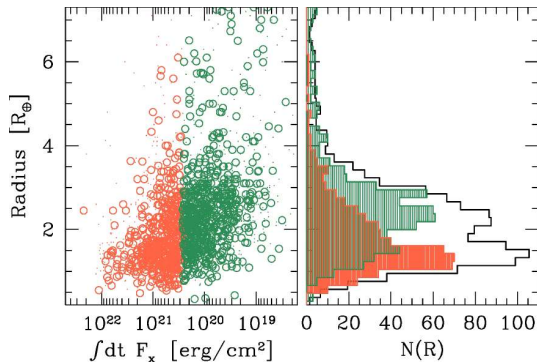
Photoevaporation Strips H/He Envelopes

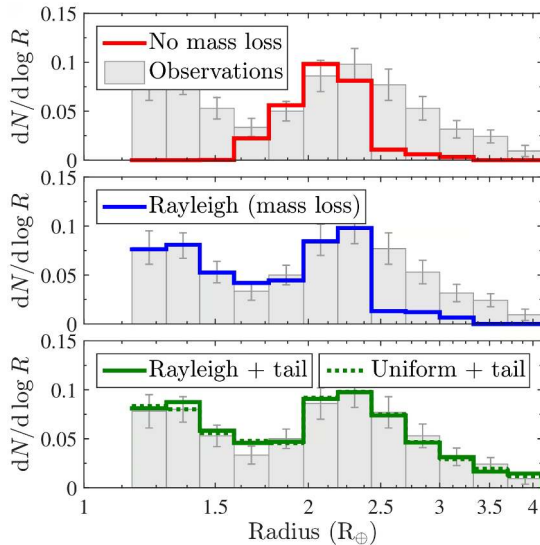
Energy-limited hydrodynamic escape driven by high stellar X-ray and EUV irradiation:

$$\dot{M} \approx \frac{\epsilon \pi F_{\text{XUV}} R_p^3}{GM_p}$$

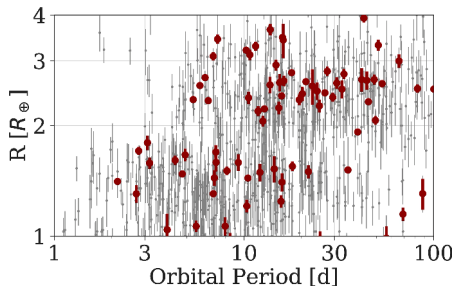
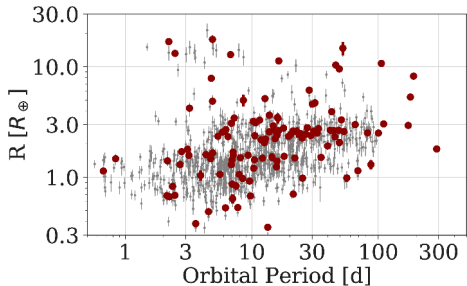
- Young stars saturate XUV flux at $\sim 10^3 \times$ modern levels for ~ 100 Myr
- Strips light primordial H/He envelopes from lower-mass cores at close-in orbits
- Owen & Wu (2013): naturally carves the bimodal radius valley

Photoevaporation Model + Mass-Loss Tracks



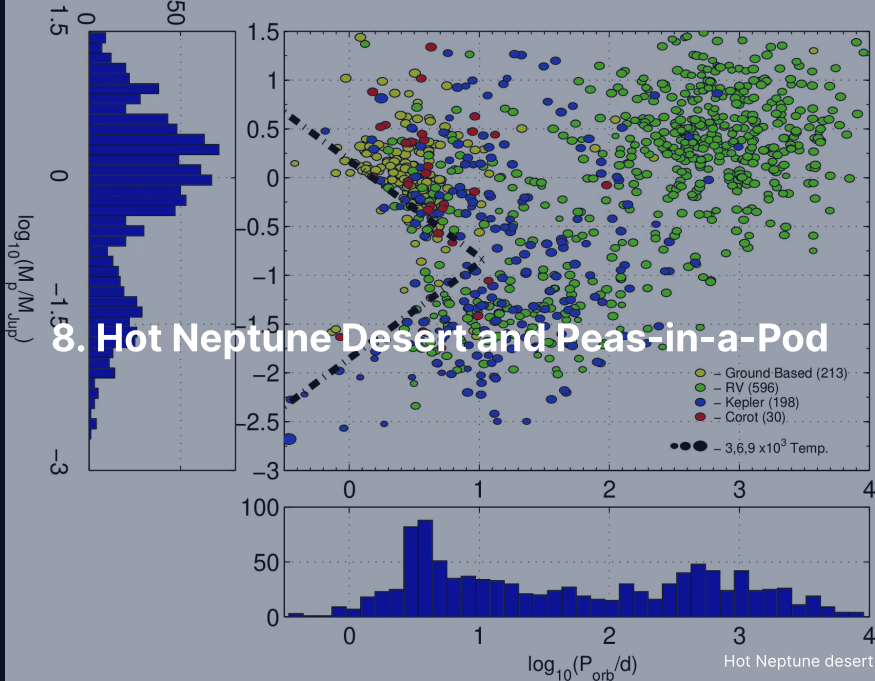


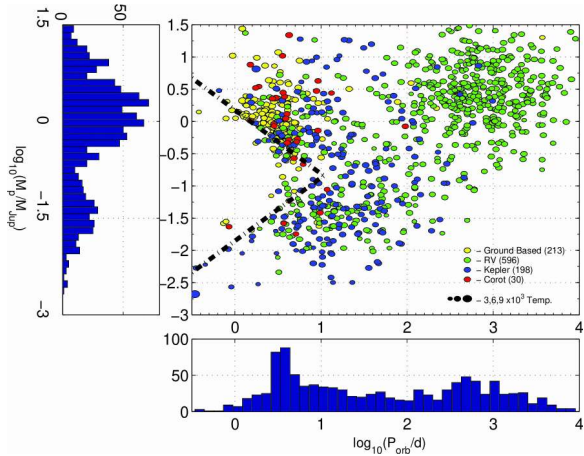
Core-powered mass loss: envelope loss driven by heat from the cooling rocky interior also produces a bimodal distribution with a gap at $\sim 1.8 R_{\oplus}$. Ginzburg et al. (2018).



The radius valley with asteroseismic stellar radii: its position shifts with orbital period. Van Eylen et al. (2018).

The valley slopes to smaller R_p at longer periods, as photoevaporation and core-powered cooling predict: many close-in super-Earths are stripped cores rather than primordial rocky worlds.

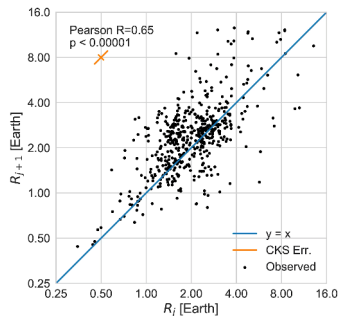




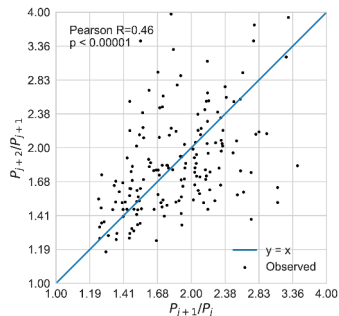
The hot Neptune desert in the mass-period plane. Mazeh et al. (2016).

A deficit of $10\text{--}100 M_{\oplus}$ planets at $P < 5$ d: at the **bottom edge** photoevaporation strips low-mass envelopes and leaves super-Earths, at the **top edge** tidal Roche-lobe overflow strips inflated giants.

Peas-in-a-Pod Architectures



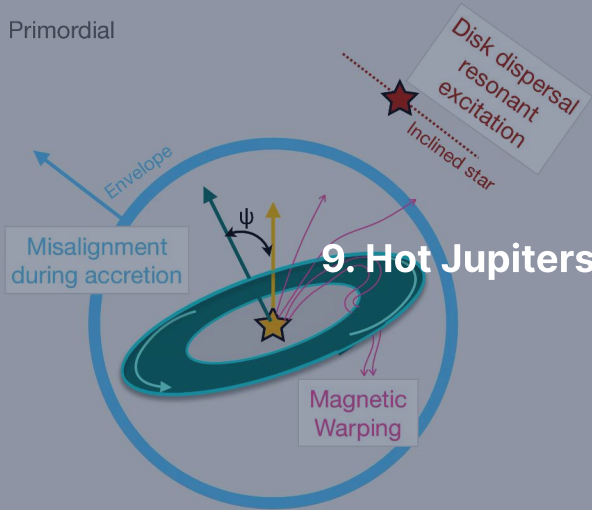
Adjacent radii: Pearson $r = 0.65$



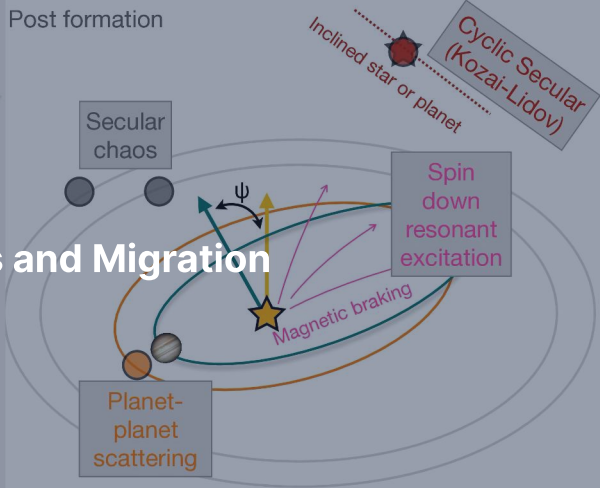
Adjacent period ratios: clustered

- Planets in compact multi-systems tend to have similar sizes and uniform orbital spacing (Weiss et al. 2018)
- Favours quiet in-situ growth or migration over chaotic giant impacts

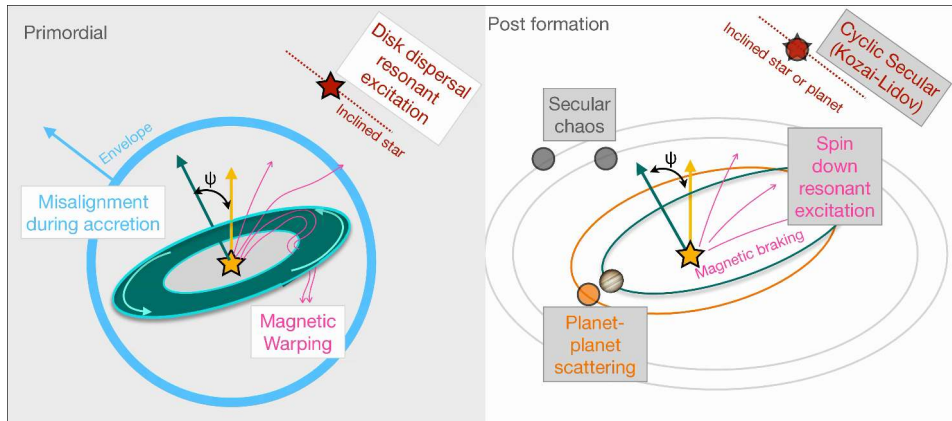
Primordial



Post formation

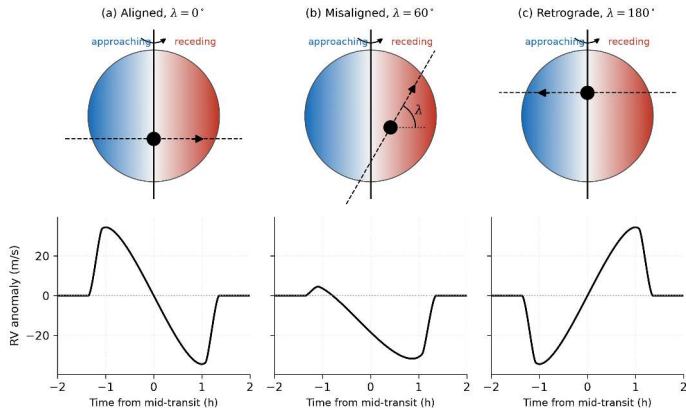


9. Hot Jupiters and Migration



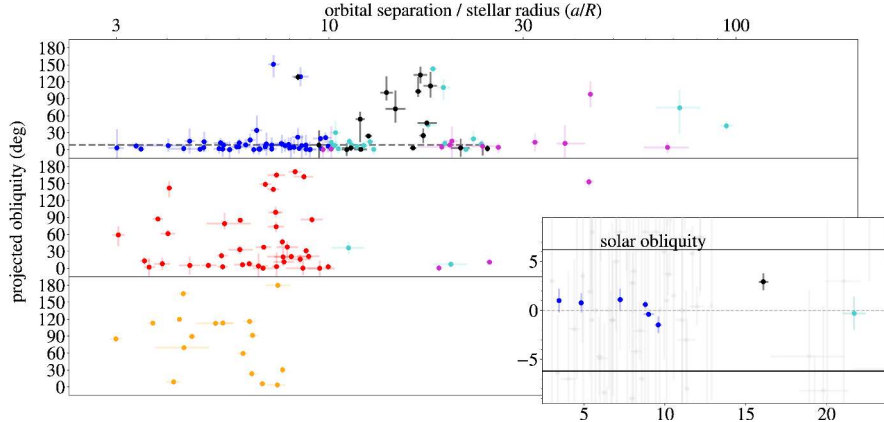
Three pathways to a hot Jupiter and the stellar obliquity each one leaves.
Albrecht et al. (2022).

Disk migration (Type II) keeps a low obliquity; **high-eccentricity** Kozai-Lidov migration and **planet scattering** leave wide misalignments; in situ growth at 0.05 AU is disfavoured.



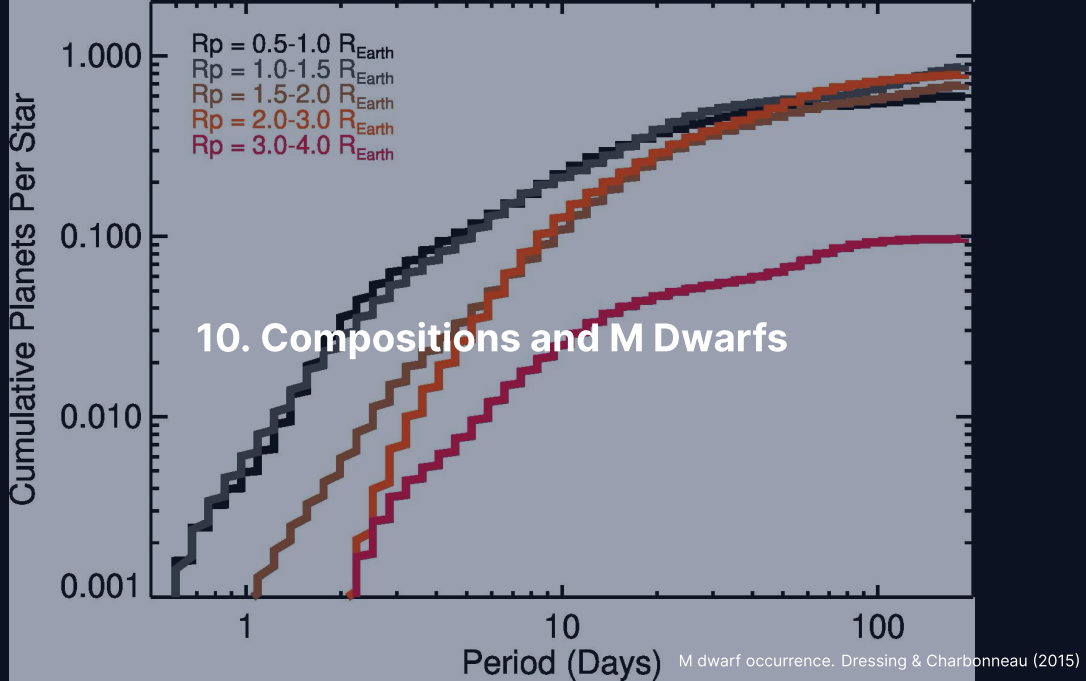
The Rossiter-McLaughlin anomaly of a hot Jupiter on an aligned, a misaligned and a retrograde orbit. Course figure.

The shape of the anomaly gives the sky-projected spin-orbit angle λ , which separates disk migration from dynamical migration; the transit light curve gives the inclination i .



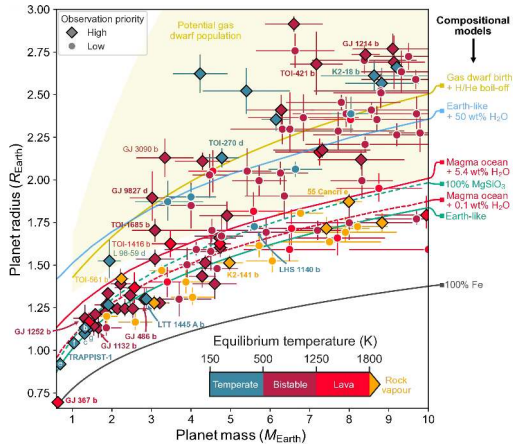
Stellar obliquities of hot Jupiter hosts against a/R_* , by effective temperature.
Albrecht et al. (2022).

Cool stars ($T_{\text{eff}} < 6250$ K) realign tidally through their convective envelopes; **hot stars** keep high obliquities; the wide dispersion at large a/R_* shows that dynamical migration occurs.



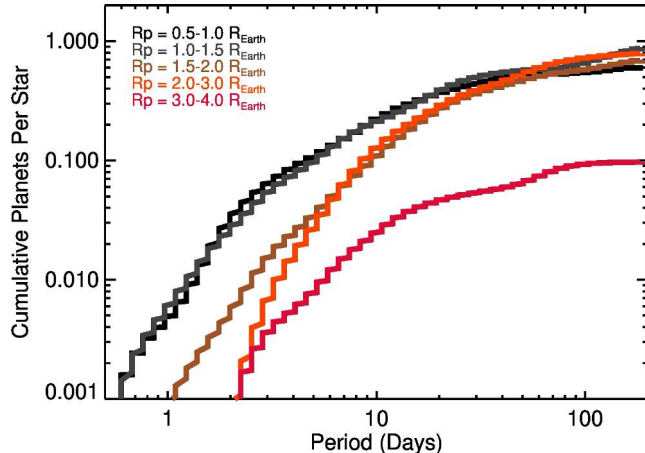
Sub-Neptunes: Water World or H/He?

- **Density split:** super-Earths ($\bar{\rho} \sim 4\text{--}8 \text{ g cm}^{-3}$) are rocky; sub-Neptunes ($\bar{\rho} \sim 1\text{--}3 \text{ g cm}^{-3}$) require volatile envelopes
- **Degeneracy:** density cannot separate a 1% H/He envelope from a 50% water-rich mantle
- **Spectroscopic test:** transmission spectroscopy gives the atmospheric mean molecular weight



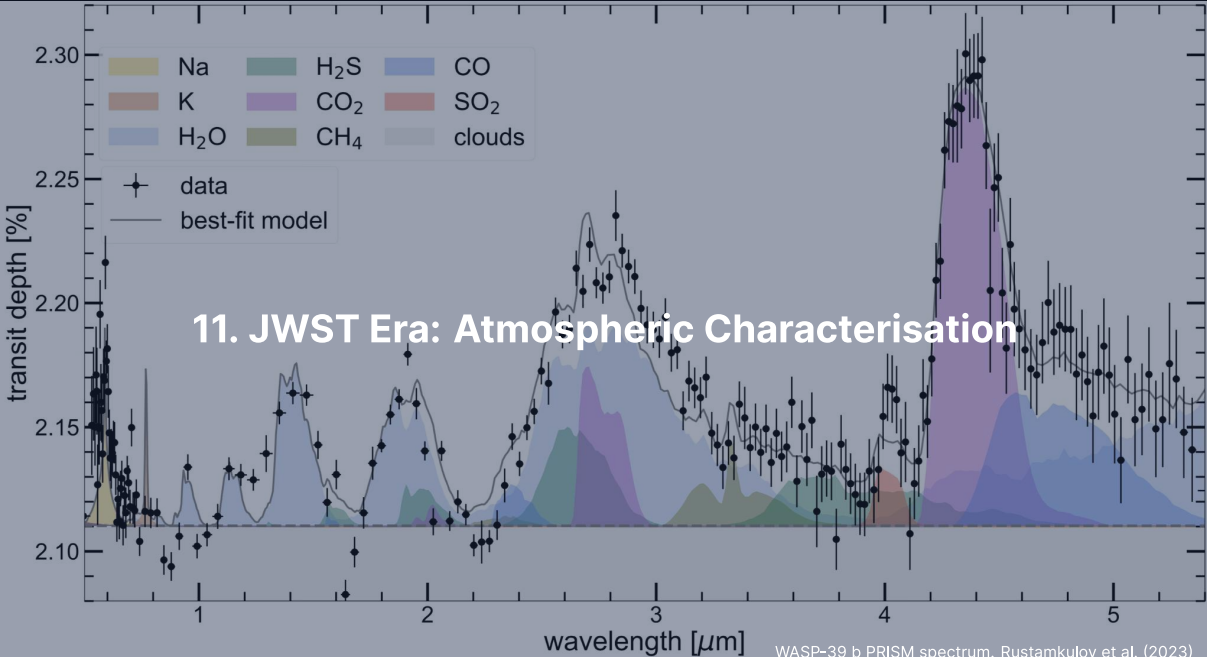
Mass against radius for small exoplanets with interior models from pure iron to volatile-rich envelopes, sorted by thermal regime. Lichtenberg et al. (2025).

Rocky super-Earths follow the silicate-iron curves; sub-Neptunes need substantial volatile envelopes or water-rich layers to explain their larger radii.



Planet occurrence around M dwarfs from Kepler. Dressing & Charbonneau (2015).

M dwarfs host ~ 2.5 small planets each and favour transits and RV, but **XUV desiccation** in the long pre-main sequence can strip whole oceans (Luger & Barnes 2015) and **tidal locking** fixes day and night sides.

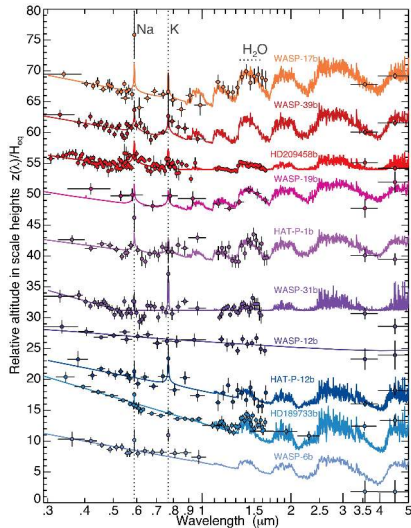


Transmission Spectroscopy

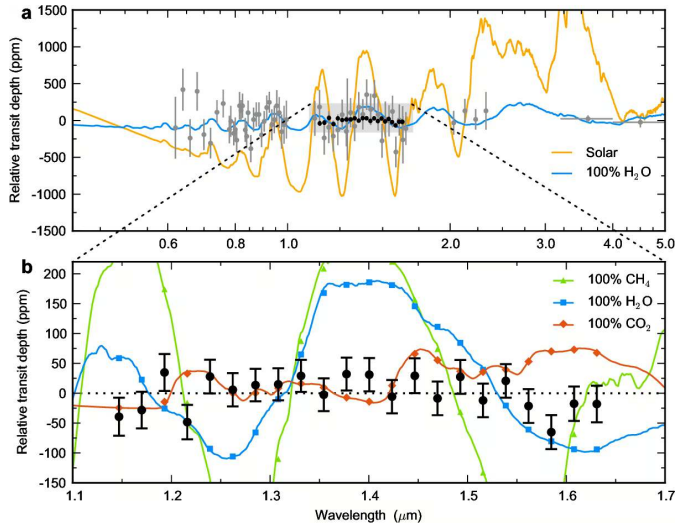
Starlight filtered through an atmosphere during transit encodes molecular absorption; with the scale height

$$H = \frac{k_B T}{\mu m_u g}, \quad \delta(\lambda) \approx \frac{(R_p + n_H(\lambda) H)^2}{R_\star^2}, \quad \frac{\Delta\delta}{\delta} \approx \frac{2n_H H}{R_p}.$$

- Hot Jupiter ($T = 1500$ K, $\mu = 2.3$, $g = 25 \text{ m s}^{-2}$): $H \approx 200$ km, $\Delta\delta/\delta \approx 2\%$, absolute modulation $\Delta\delta \sim 200$ ppm (JWST-routine)
- Sub-Neptunes: 10–100 ppm; terrestrial atmospheres: < 10 ppm
- High clouds or hazes flatten the spectrum (GJ 1214 b): a flat spectrum does not mean no atmosphere

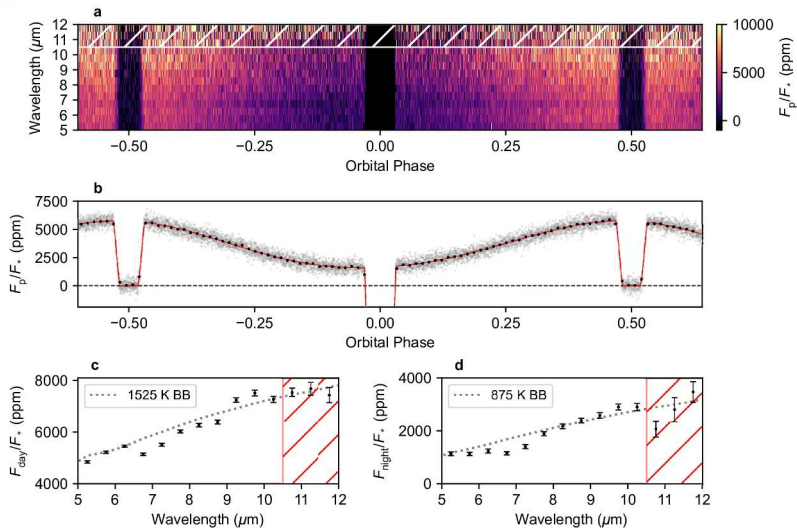


Transmission spectra of ten hot Jupiters from HST and Spitzer across $0.3\text{--}5\ \mu m$: a continuum from clear atmospheres with water absorption to cloudy scattering slopes. Sing et al. (2016).

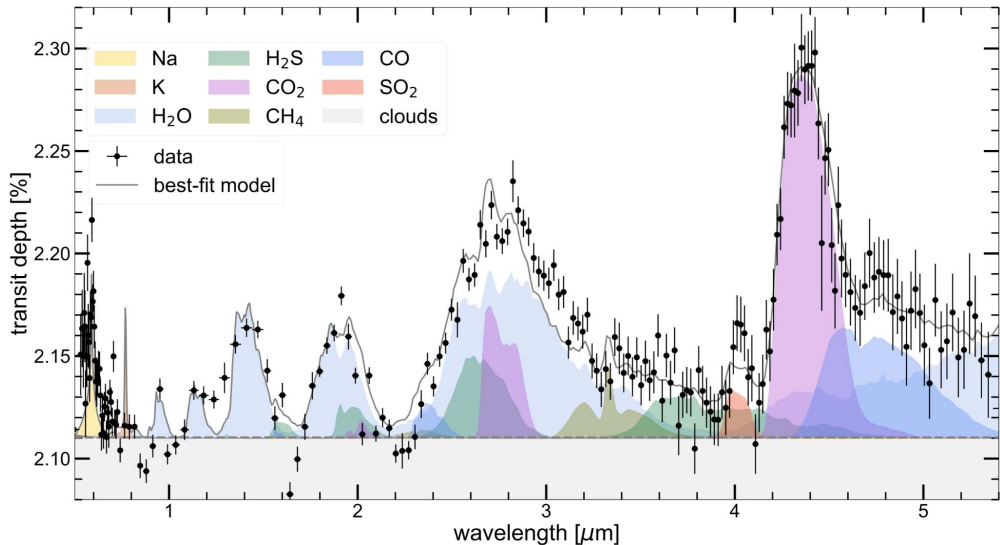


Featureless HST transmission spectrum of the warm sub-Neptune GJ 1214 b: cloud-free H_2O , CH_4 and CO_2 atmospheres are ruled out, so high clouds or hazes are present.

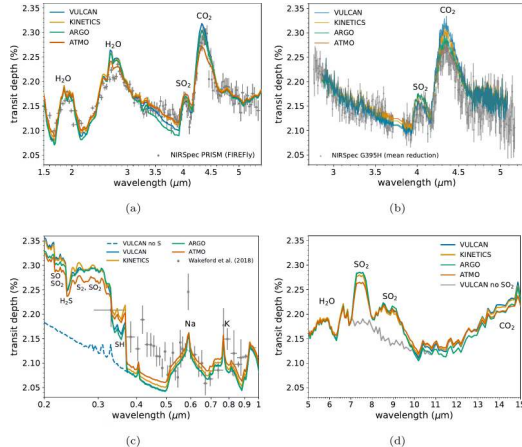
Kreidberg et al. (2014).



JWST/MIRI spectroscopic phase curve of WASP-43 b: thermal emission from dayside to nightside constrains the atmospheric heat redistribution. Bell et al. (2024).



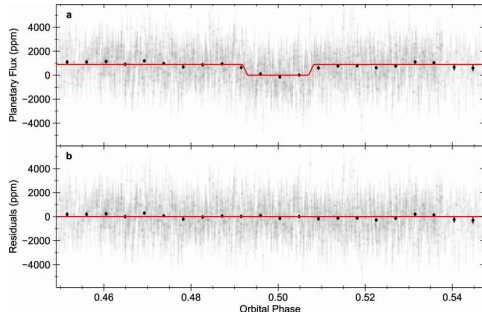
JWST/NIRSpec PRISM transmission spectrum of WASP-39 b with model opacity bands: H₂O (33 σ), CO₂ (28 σ), clouds (21 σ), Na (19 σ) and CO (7 σ). Rustamkulov et al. (2023).



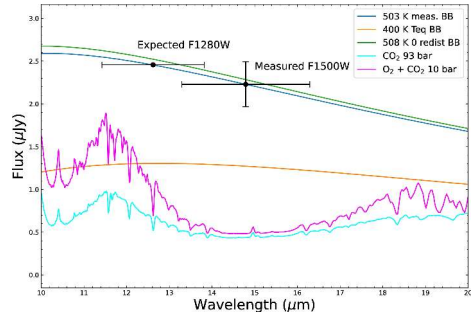
The $4.05\ \mu\text{m}$ absorption feature of SO_2 in the JWST spectrum of the hot Saturn WASP-39 b ($0.28\ M_J$). Tsai et al. (2023).

Photochemical SO_2 from UV photolysis of H_2S : the first photochemical product identified in an exoplanet atmosphere, proof of disequilibrium chemistry.

TRAPPIST-1 b: Bare Rock Dayside

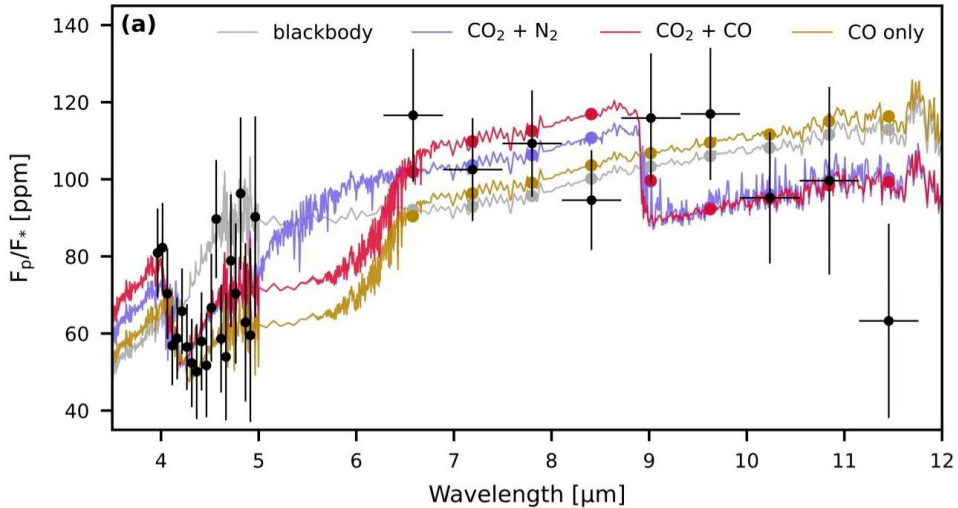


15 μm secondary eclipse

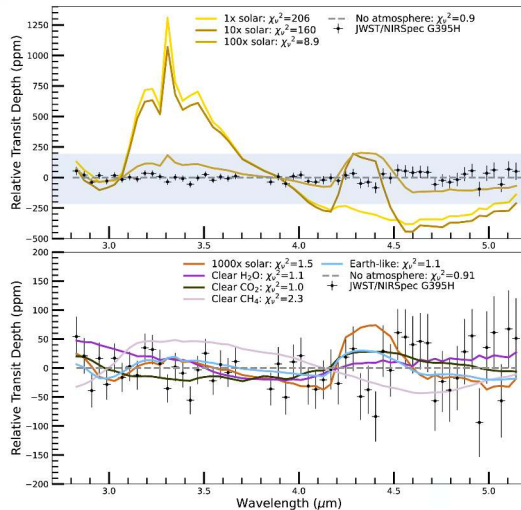


Compared to model atmospheres

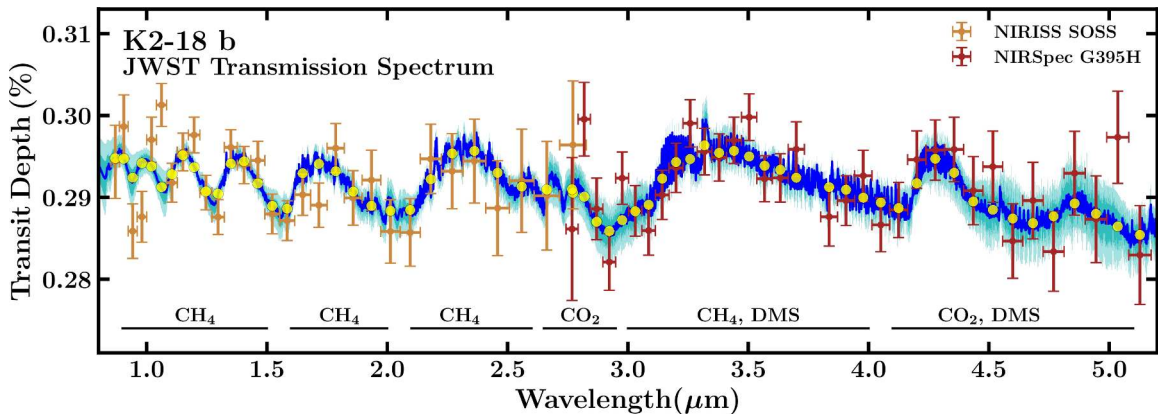
$T_B = 503^{+26}_{-27}$ K, consistent with bare rock; a **thick CO₂ atmosphere is ruled out** (Greene et al. 2023). With TRAPPIST-1 c and LHS 475 b, inner M dwarf rocky planets show a widespread lack of thick atmospheres.



JWST NIRCам and MIRI emission spectrum of 55 Cancri e: the data fall below the bare-rock blackbody and favour CO and CO_2 , tentative evidence for a secondary atmosphere outgassed from a molten surface. Hu et al. (2024).

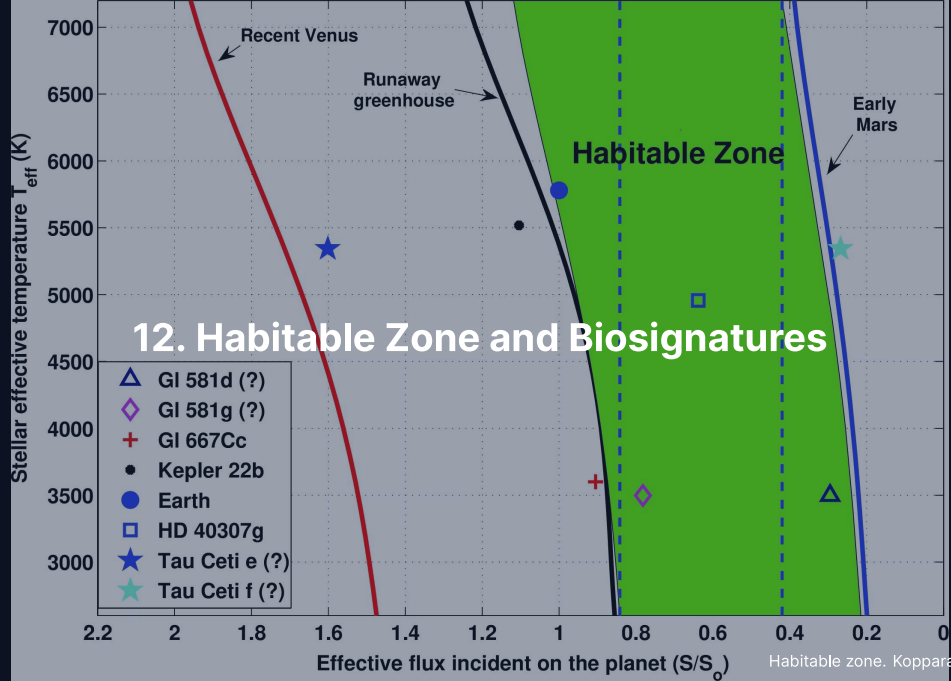


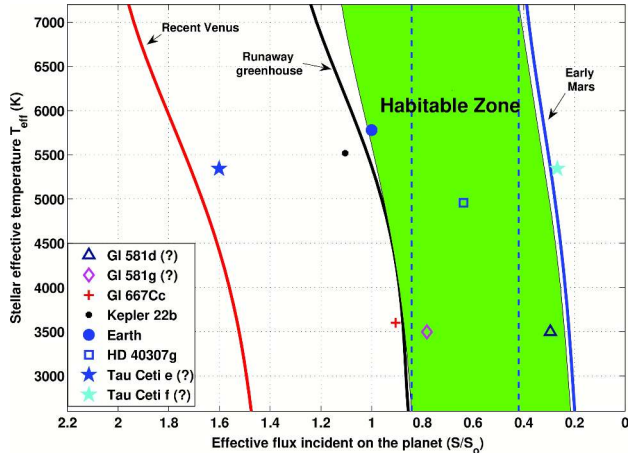
JWST NIRSpec G395H transmission spectrum of the Earth-size M dwarf planet LHS 475 b at about 12 pc: flat, so hydrogen-helium and pure CH_4 atmospheres are ruled out and a Venus-like CO_2 atmosphere stays marginally consistent. Lustig-Yaeger et al. (2023).



JWST transmission spectrum of the sub-Neptune K2-18 b in the habitable zone of its M dwarf. Madhusudhan et al. (2023).

CH_4 and CO_2 detected, DMS disputed and tentative ($\lesssim 2\sigma$); Hycean ocean, mini-Neptune envelope and magma ocean models compete: candidate biosignatures need rigorous real-time vetting.





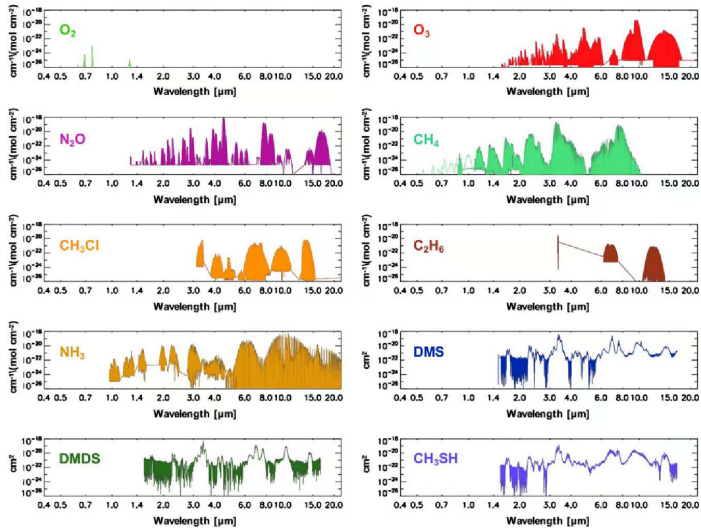
The classical habitable zone from a 1D radiative-convective grid. Kopparapu et al. (2013).

Inner edge: the moist greenhouse limit; outer edge: the maximum CO_2 greenhouse, where Rayleigh scattering by more CO_2 outweighs its extra warming; both scale with stellar temperature and luminosity.

Habitable Zone Evolution and Biosignatures

- **Dynamic trajectory:** HZ boundaries shift with stellar evolution; pre-MS M dwarfs subject planets to prolonged runaway desiccation
- **Disequilibrium pairs:** atmospheric biosignatures demand chemical disequilibrium ($\text{O}_2 + \text{CH}_4$), not lone gas species
- **False positives:** abiotic O_2 can build up by H_2O photolysis with hydrogen escape, or by CO_2 photolysis

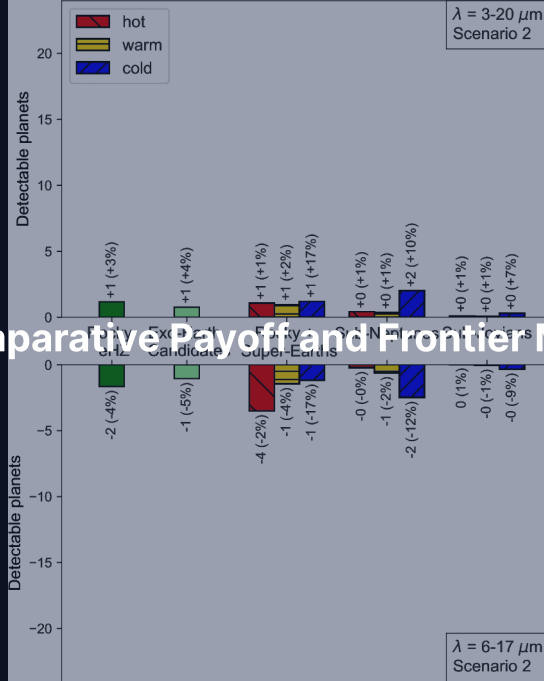
Life detection is an inverse problem requiring exclusion of all abiotic pathways.

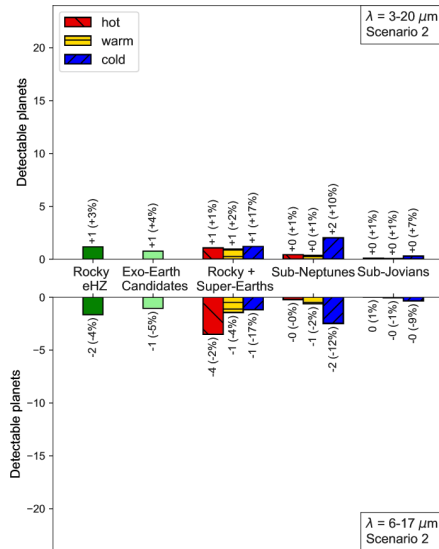


Absorption cross-sections from 0.4 to 20 μm for ten candidate biosignature gases: oxygen absorbs only in narrow optical bands, the others mostly in the infrared.

Schwieterman et al. (2018).

13. Comparative Payoff and Frontier Missions





Predicted detection yields of the LIFE mid-infrared space interferometer for exoplanets within 20 pc, by radius and insolation. Quanz et al. (2022).

Summary: Today's Course-Level Takeaways

1. **Detection:** transit plus radial velocity breaks $m \sin i$ and yields the true bulk density; every method carries its own bias
2. **Demographics:** small planets dominate ($\eta_{\oplus} \sim 0.4$); photoevaporation or core-powered mass loss carves the radius valley at $\sim 1.8 R_{\oplus}$; resonant chains and peas-in-a-pod systems record smooth disk migration
3. **Characterisation:** JWST detects photochemistry and bare rocks; biosignatures require ruling out false positives

Next: Lecture 14



Questions?

Next: Lecture 14. Synthesis & Astrobiology

Lecture notes: formingworlds.github.io/IntroductionToPlanetaryScience