Exoplanet discoveries and ESA future missions

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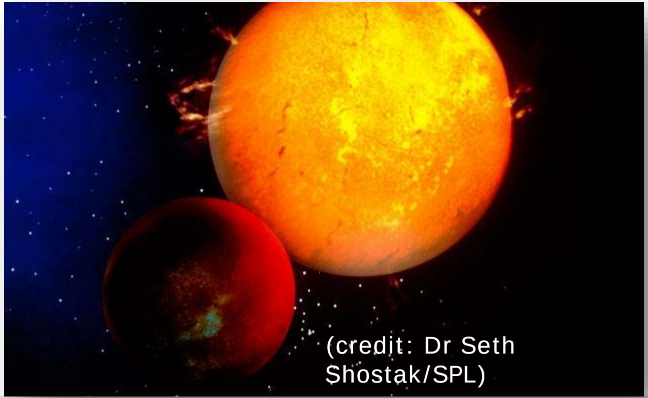
Fundamental science questions

- How do planetary systems form and evolve?
- Is our Solar System special? Are there other systems like ours?
- What makes a planet habitable?
- Is the Earth unique or has life also developed elsewhere?

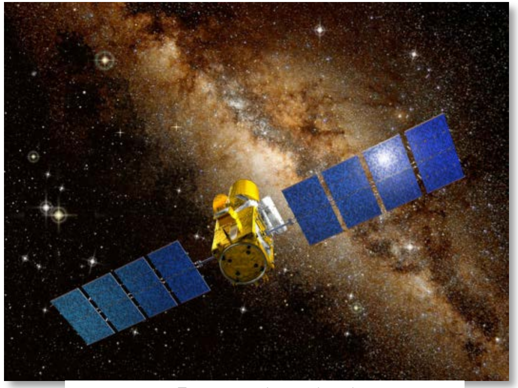
History of exoplanets – First steps

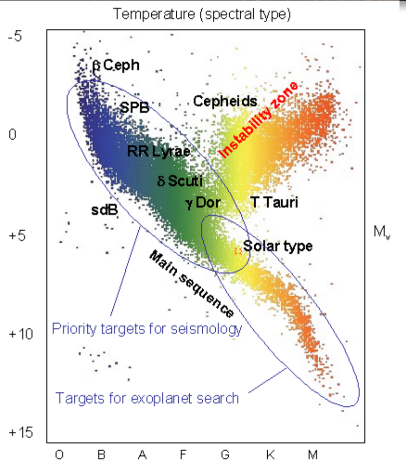
- “There are infinite worlds both like and unlike this world of ours” (Epicurus, 341–270 BCE)
- In 1584, the Catholic monk Giordano Bruno stated: “There are countless suns and countless earths all rotating around their suns”
- In 1992, Dr. Alexander Wolszczan, a radio astronomer at Pennsylvania State University, reported two or three planet-sized objects orbiting a pulsar
- In 1995, first exoplanet around a star similar to the Sun, 51 Peg, is discovered by the Swiss team of Michel Mayor and Didier Queloz
- By the end of the 20th century, several dozen worlds had been discovered


(credit: Dr Seth Shostak/SPL)

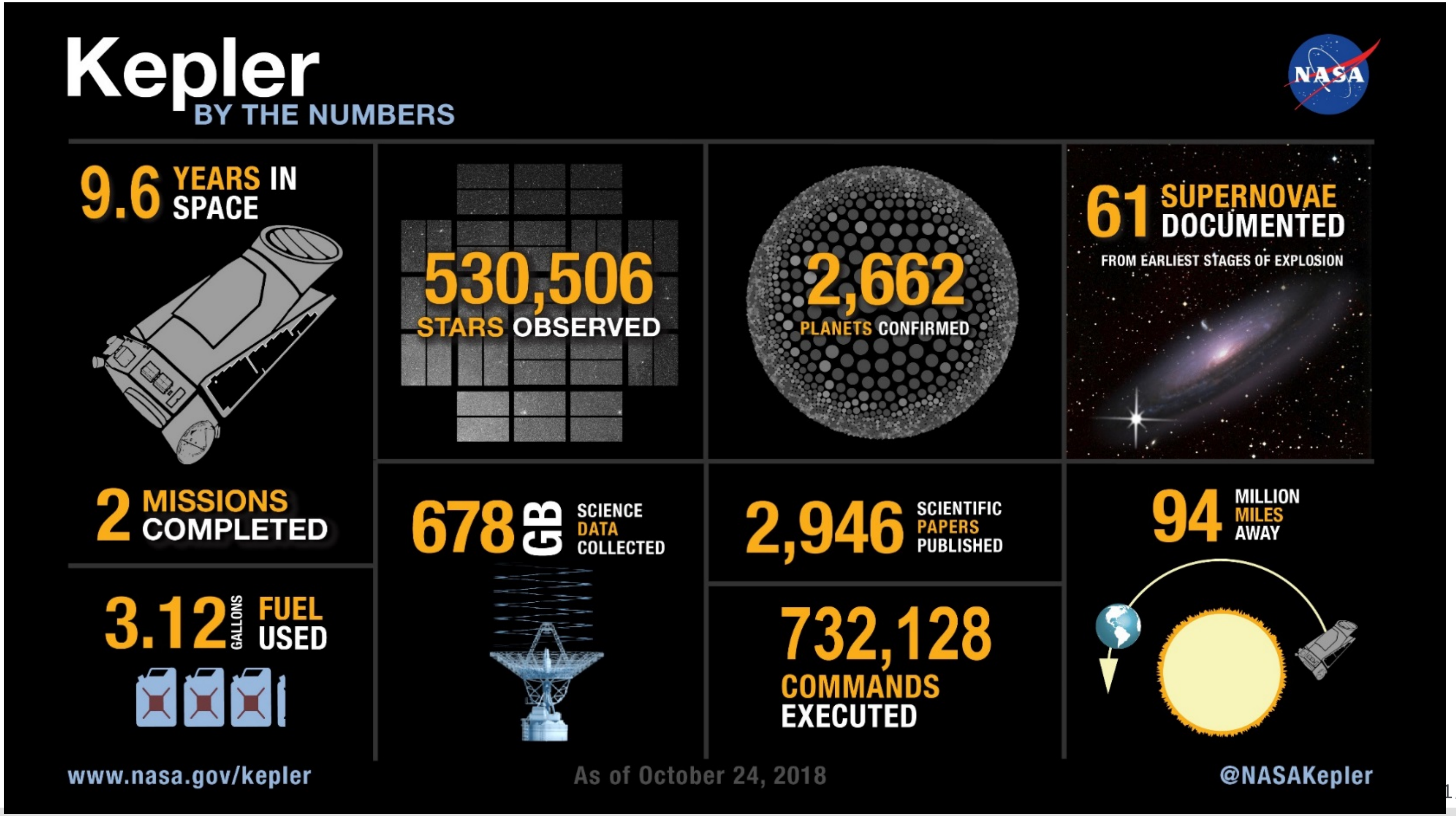
Going into space: CoRoT (CNES/ESA, 2006-2014)

- Exoplanets
- Asteroseismology
- 110,000 stars observed
- 34 confirmed exoplanets
- CoRoT-7b, first rocky exoplanet ($R = 1.7\ R_E$, $M=4.5\ M_E$)





Going into space: Kepler/K2



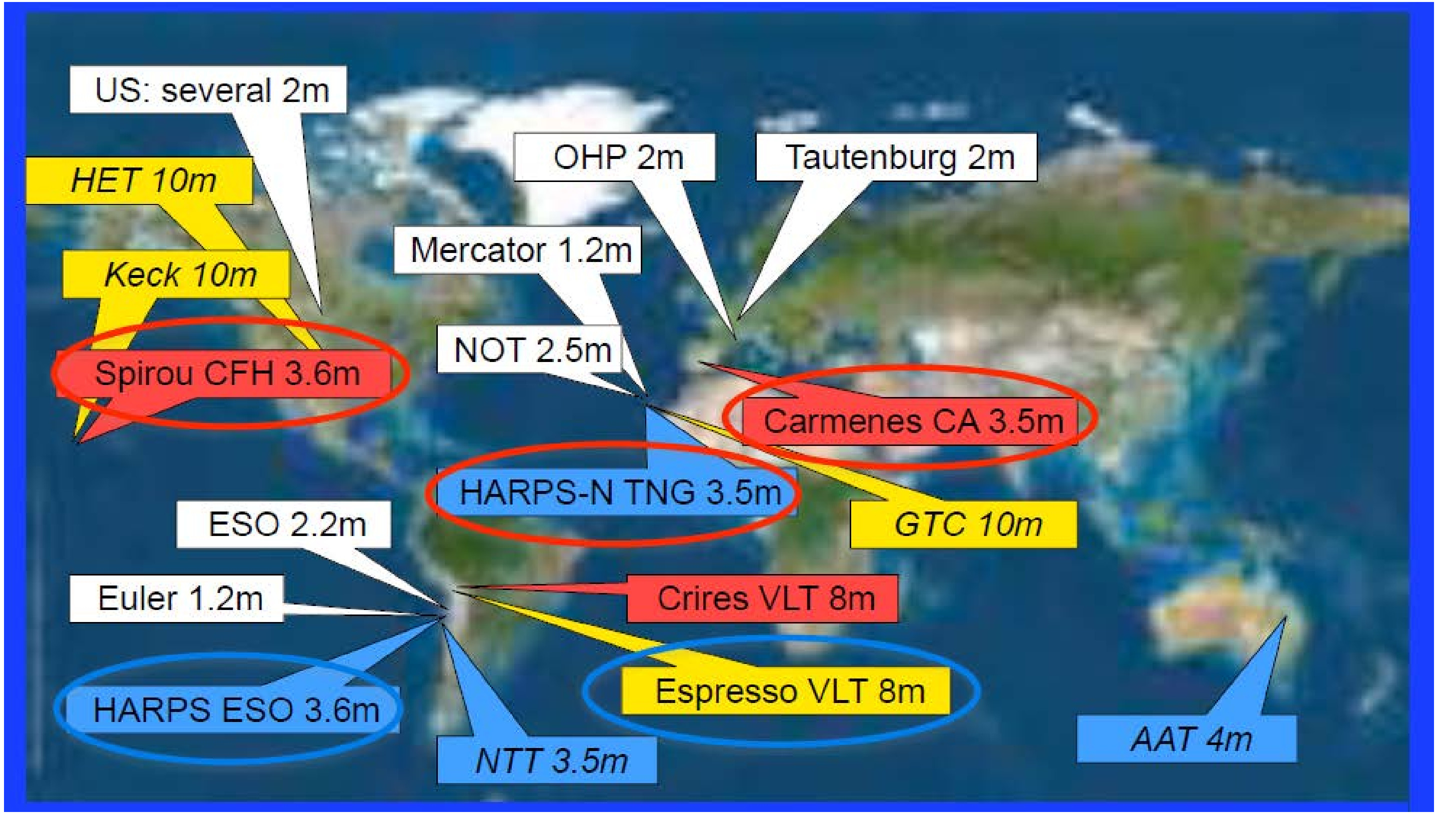
Going into space: Atmospheric characterisation

HST

Credit: NASA

Spitzer

Ground-based observatories



\+ Surveys:

- WASP
- Trappist
- NTGS
- HAT-Net
- KELT
- Qatar
- OGLE

Credit: S. Udry

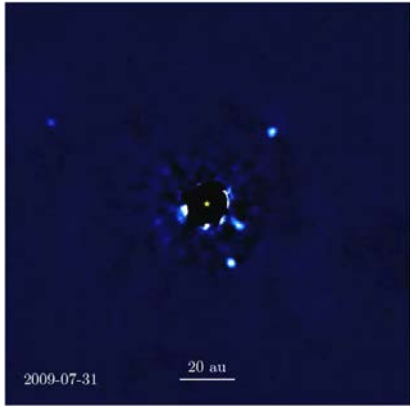
Main exoplanet detection methods (i)

Astrometry

Credit: ESA

- 1 planet discovered
  - ➢ True planet mass
  - ➢ Semi-major axis
  - ➢ Coplanarity

Direct imaging



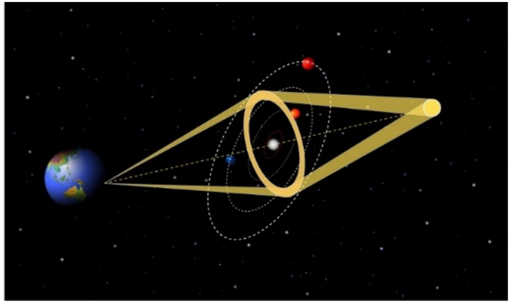
HR 8799

W.M. Keck Observatory

Credit: J. Wang/C. Marois/NExSS

- 44 planets discovered
  - ➢ Orbital parameters
  - ➢ Spectroscopy -> Radius

Microlensing



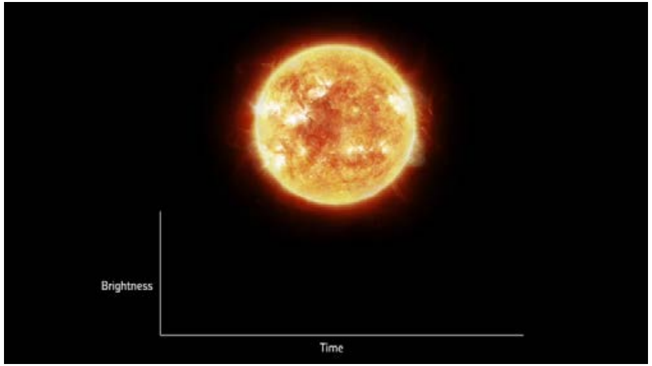
Credit: S. Gaudi and D. Bennett

- 64 planets discovered
  - ➢ Planet mass
  - ➢ Orbital distance
  - ➢ Population statistics

Main exoplanet detection methods (ii)

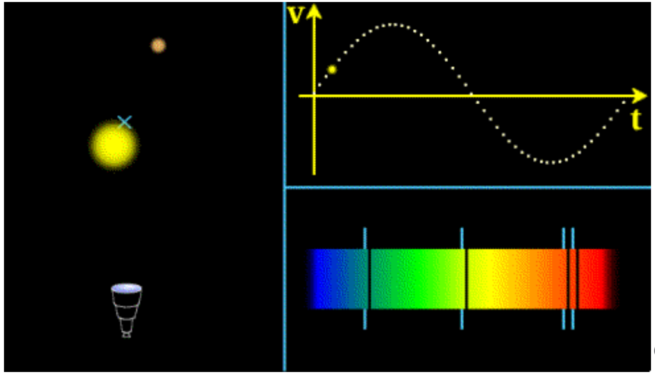
Transits (space, ground)

Credit: ESA



- 2958 planets discovered
- ➢ Semi-major axis, Planet radius
- ➢ Orbital inclination
- ➢ If TTV, also planet mass
- ➢ Depth for 1 R_E planet: 10^{-4}
- ➢ Detection probability at 1 au: 0.5%
- ➢ Spectroscopy

Radial Velocities (ground)

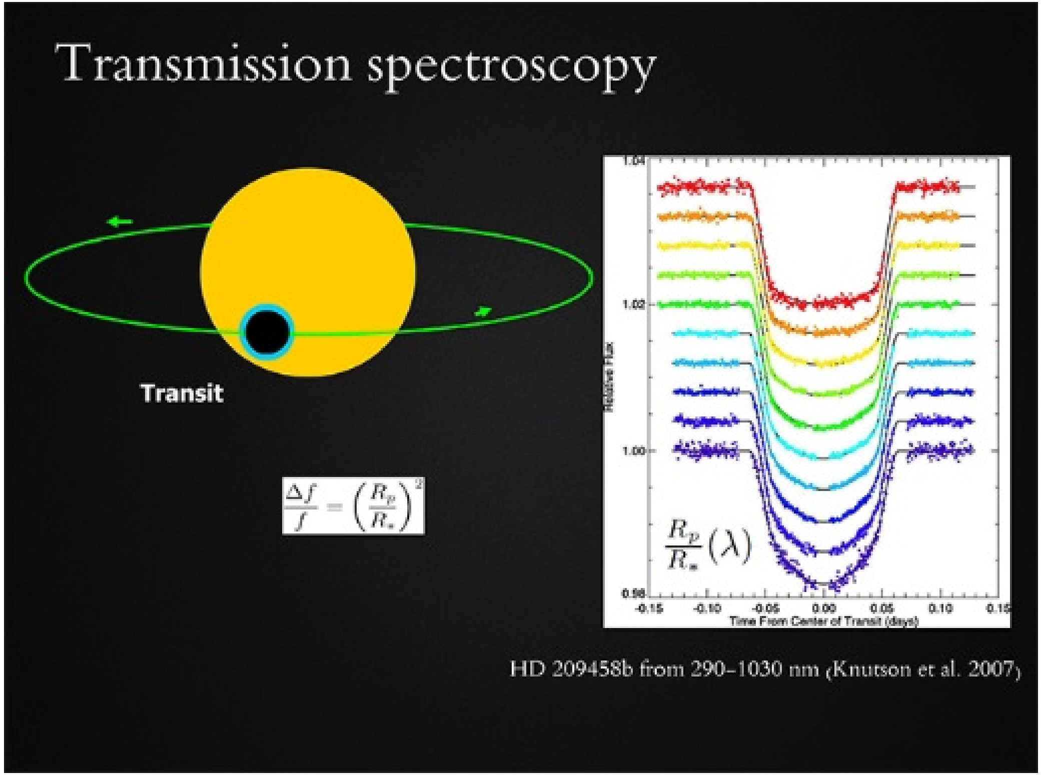


Credit: E. Pécontal

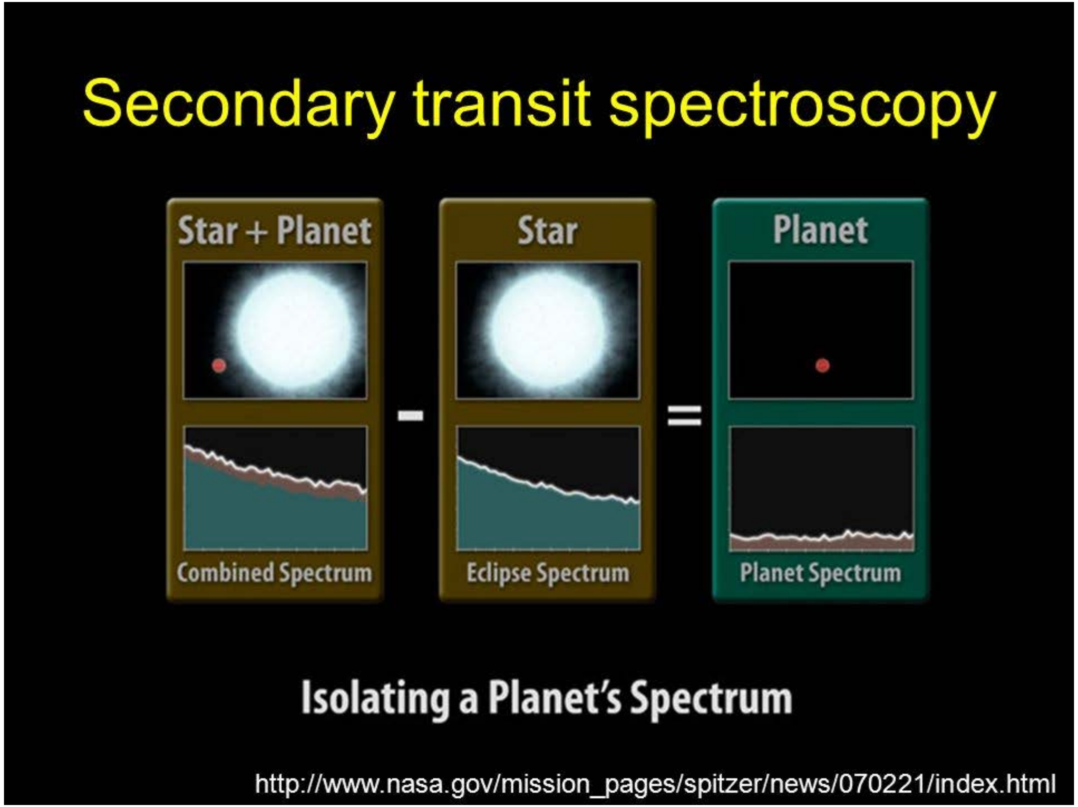
- 686 planets discovered
- ➢ M_p *sin* i: Planet mass lower limit
- ➢ Eccentricity

True planet mass and mean density

Exoplanet atmosphere characterisation (i)

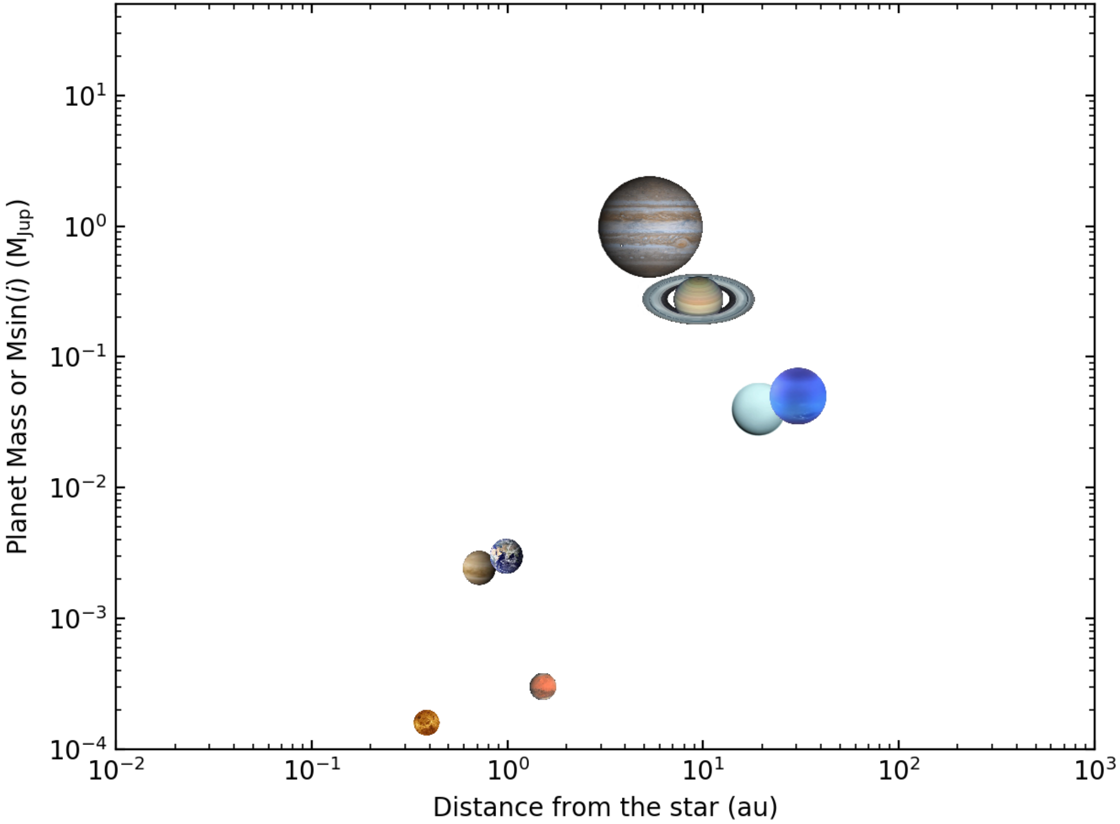


Exoplanet atmosphere characterisation (ii)

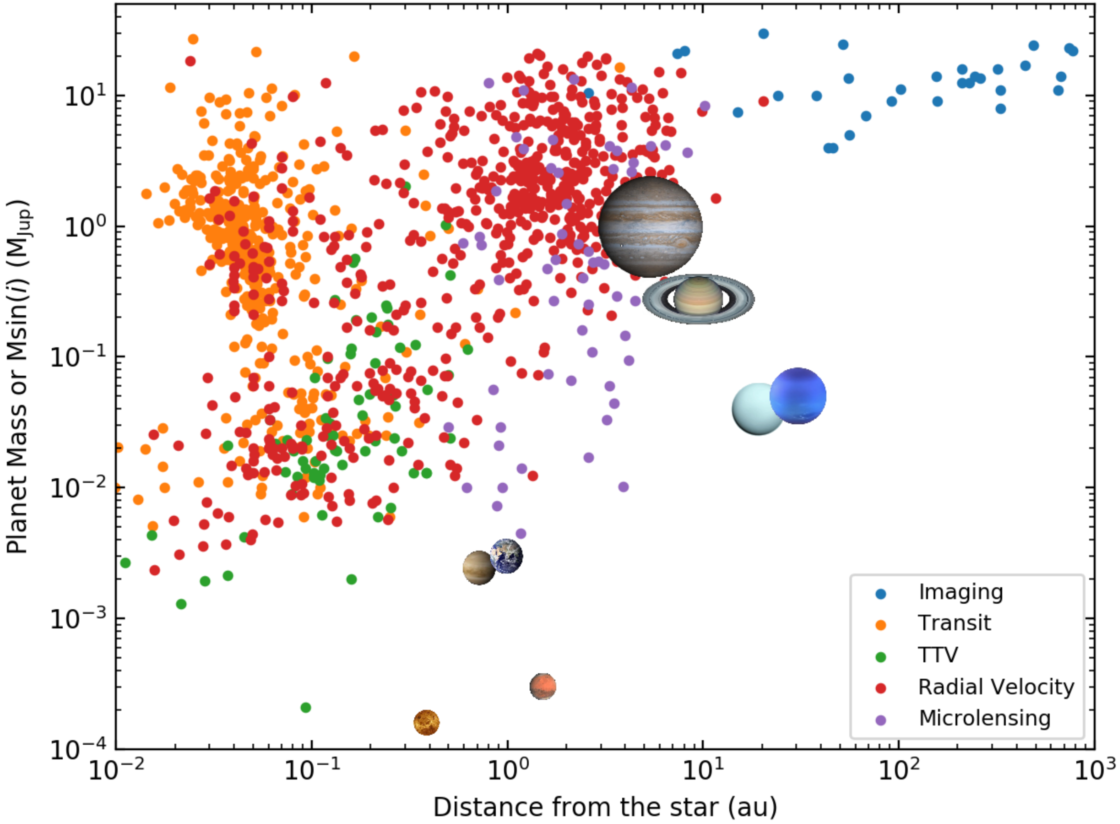


Our knowledge of the planet characteristics and habitability depends on our knowledge of the host star

Exoplanet detection today



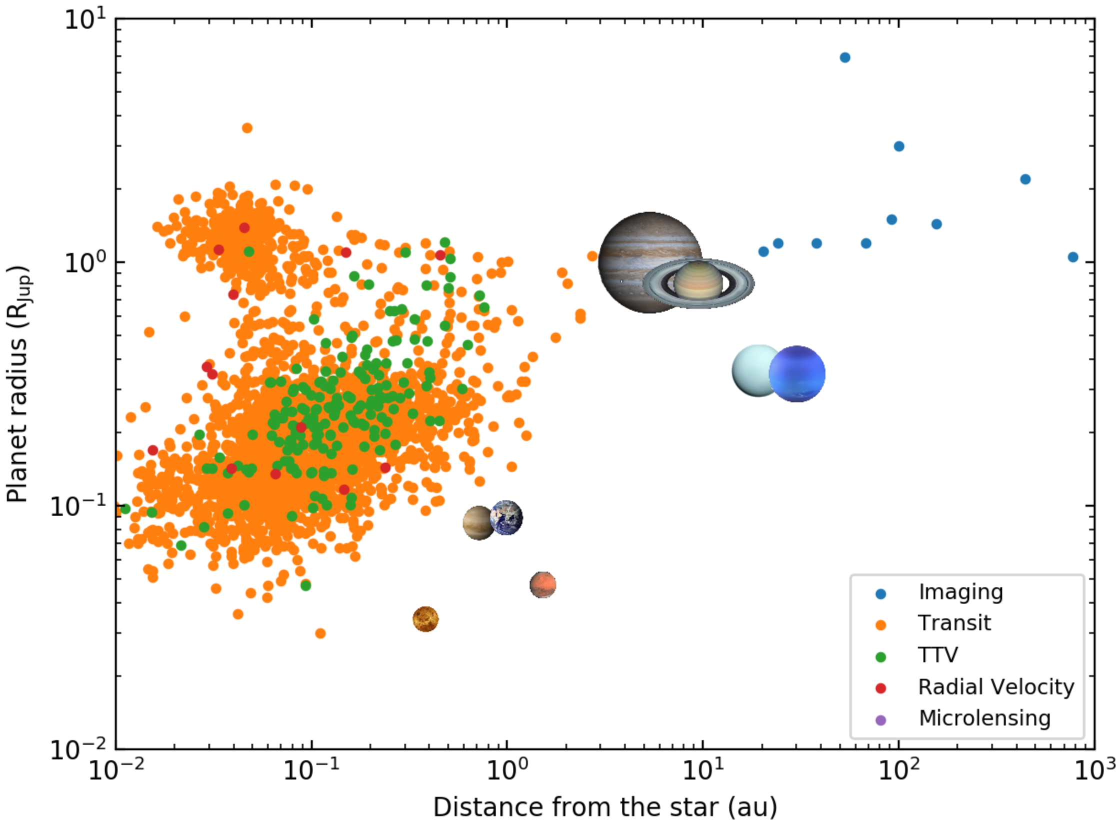
Exoplanet detection today



- ~ 3826 confirmed exoplanets
- ~ 4717 candidates
- ~ 633 multiplanet systems

Figure shows planets with known mass

Exoplanet detection today



- ~ 3826 confirmed exoplanets
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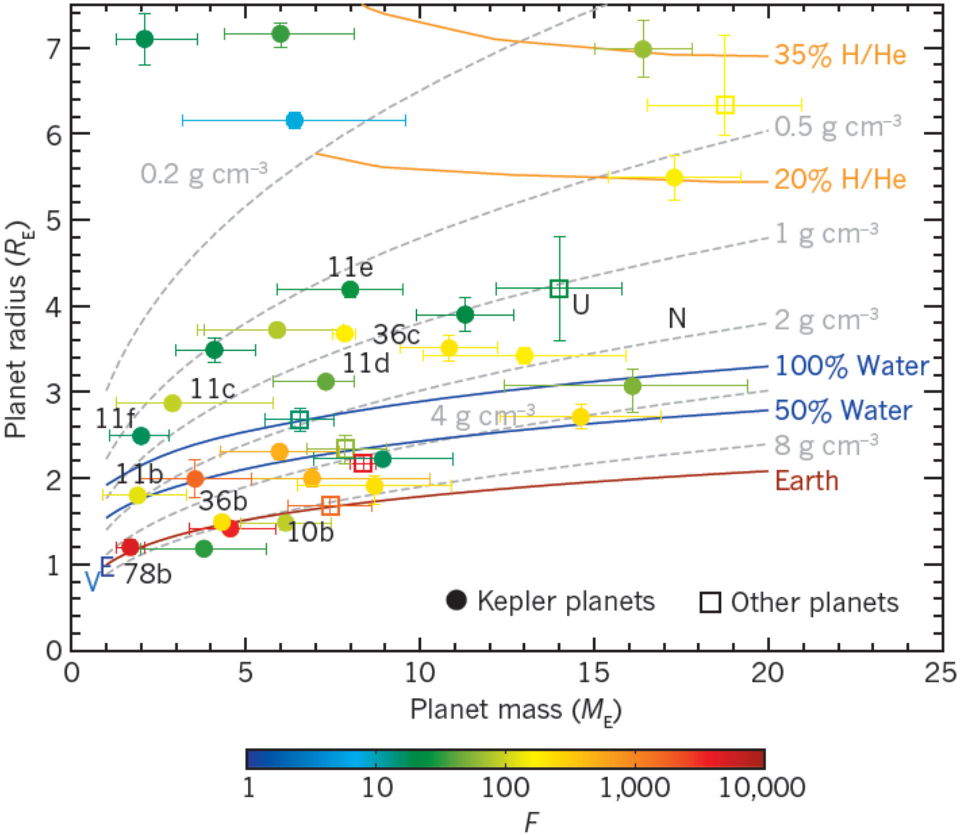
- ~ 633 multiplanet systems

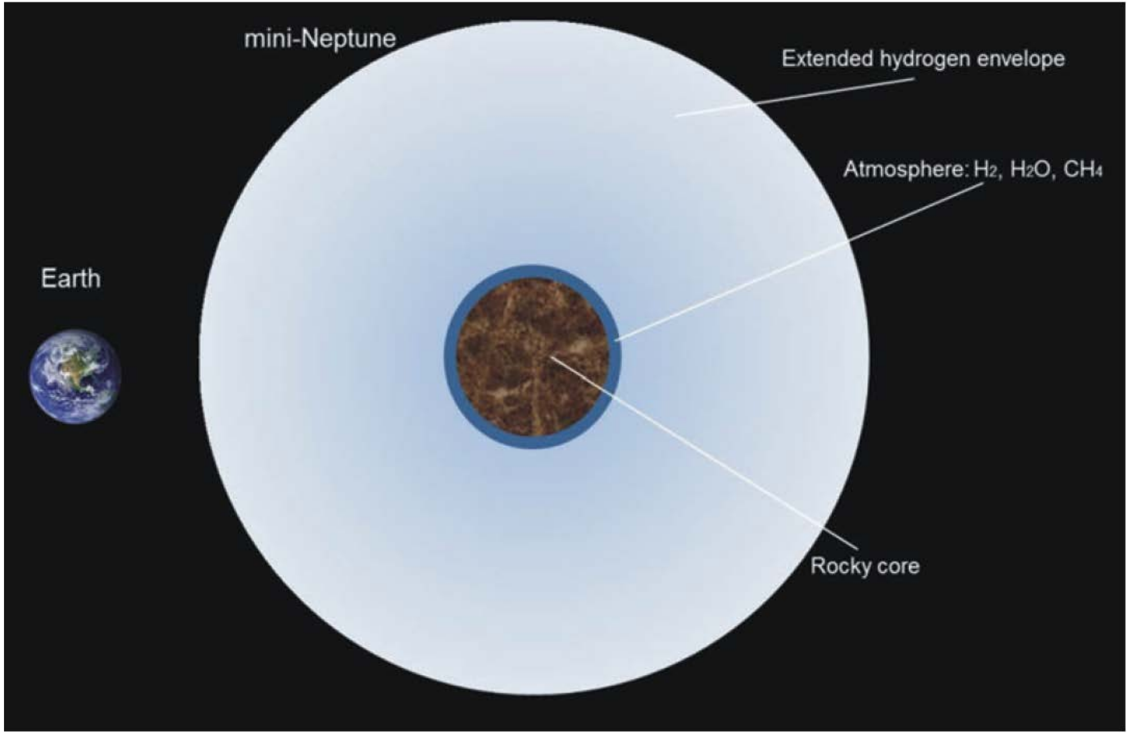
Figure shows planets with known radius

Exoplanets are diverse

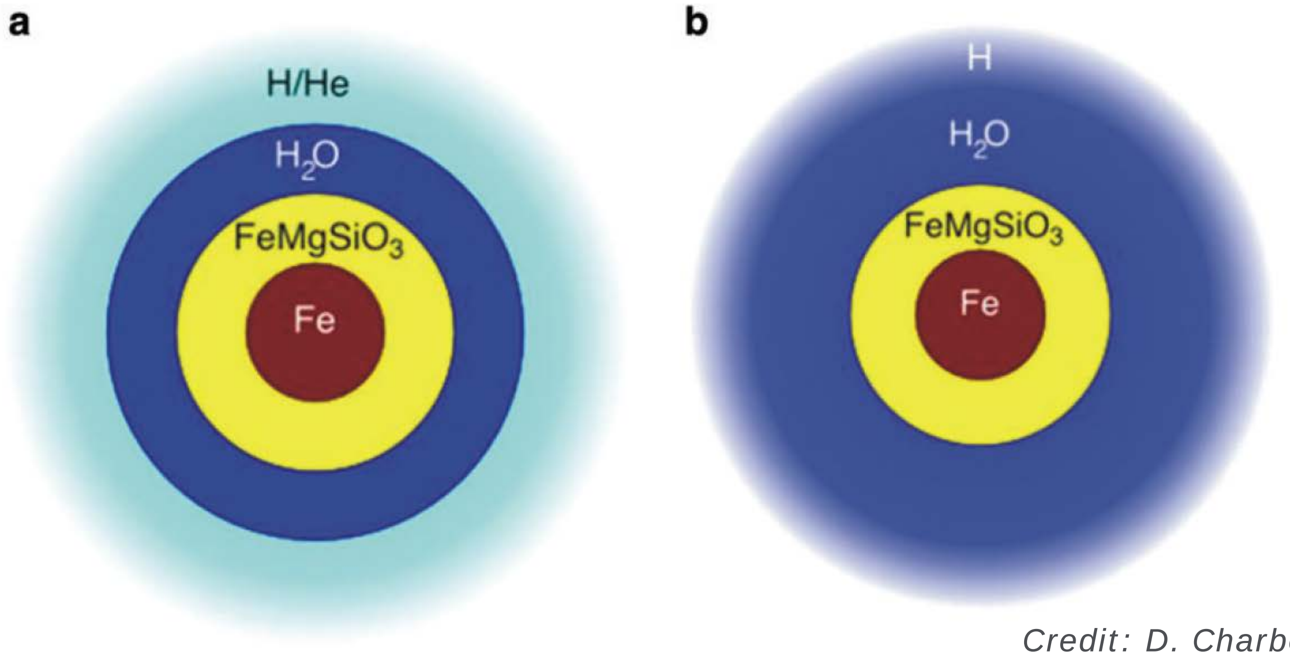


Credit: E.Lopez, Lissauer et al. (2014)

Super-Earths and mini-Neptunes



Super-Earths and mini-Neptunes



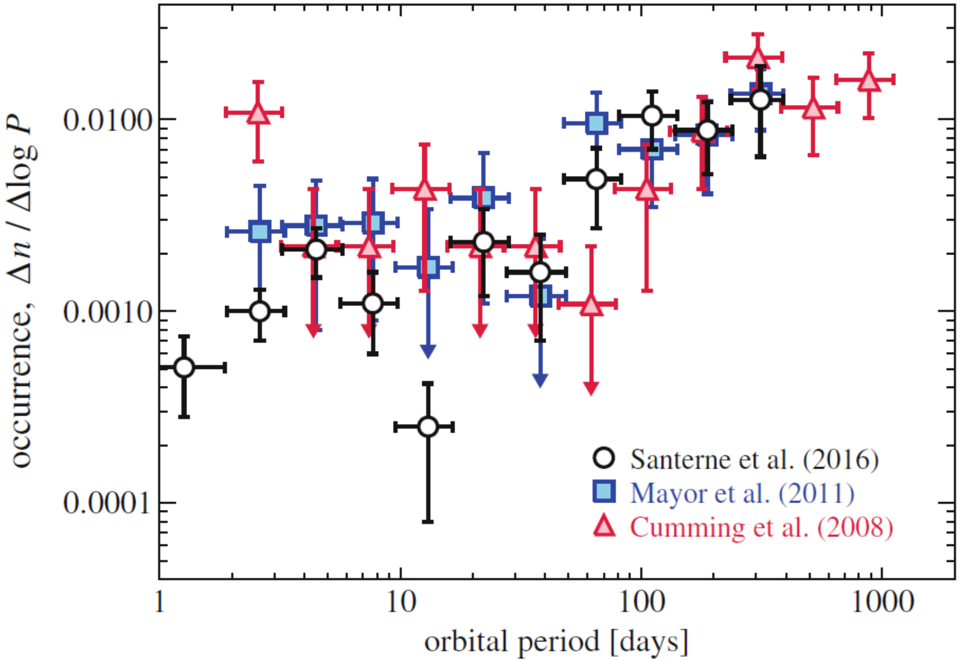
GJ 1214

Credit: D. Charbonneau

Planet occurrence – More planets than stars

Giant planets

- 10% of Sun-like stars have giant planets with periods smaller than several years
- Hot Jupiter occurrence is 0.5-1% for periods between 1 and 10 days
- Strong positive correlation with the stellar metallicity
- Broad range of eccentricities

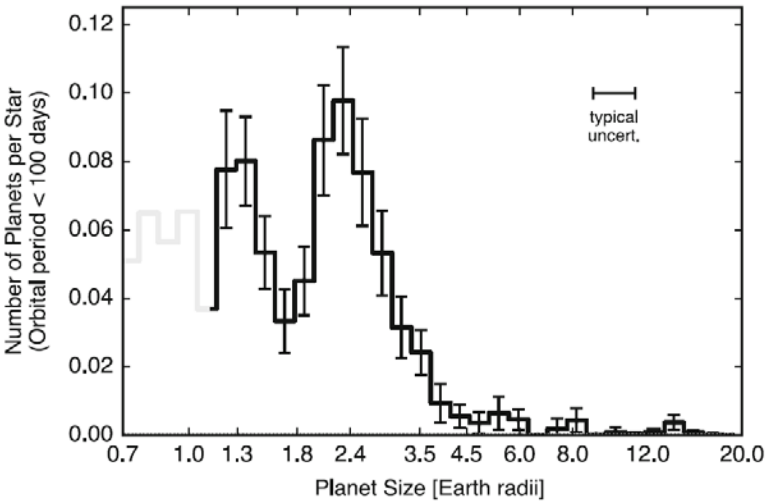


Credit: Winn (2018)

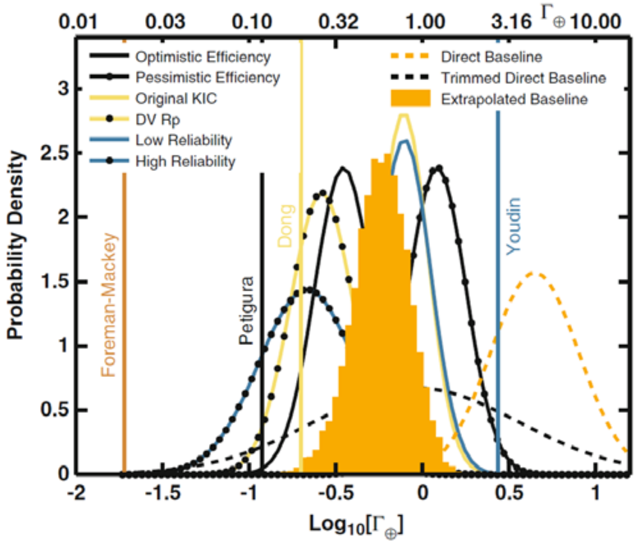
Planet occurrence – More planets than stars

Small planets

- 50% of Sun-like stars have one planet with P < 100 days and size 1-4 R_E
- No correlation with metallicity for R_p<2 R_E
- In M stars, the occurrence rate is 2-3 times higher



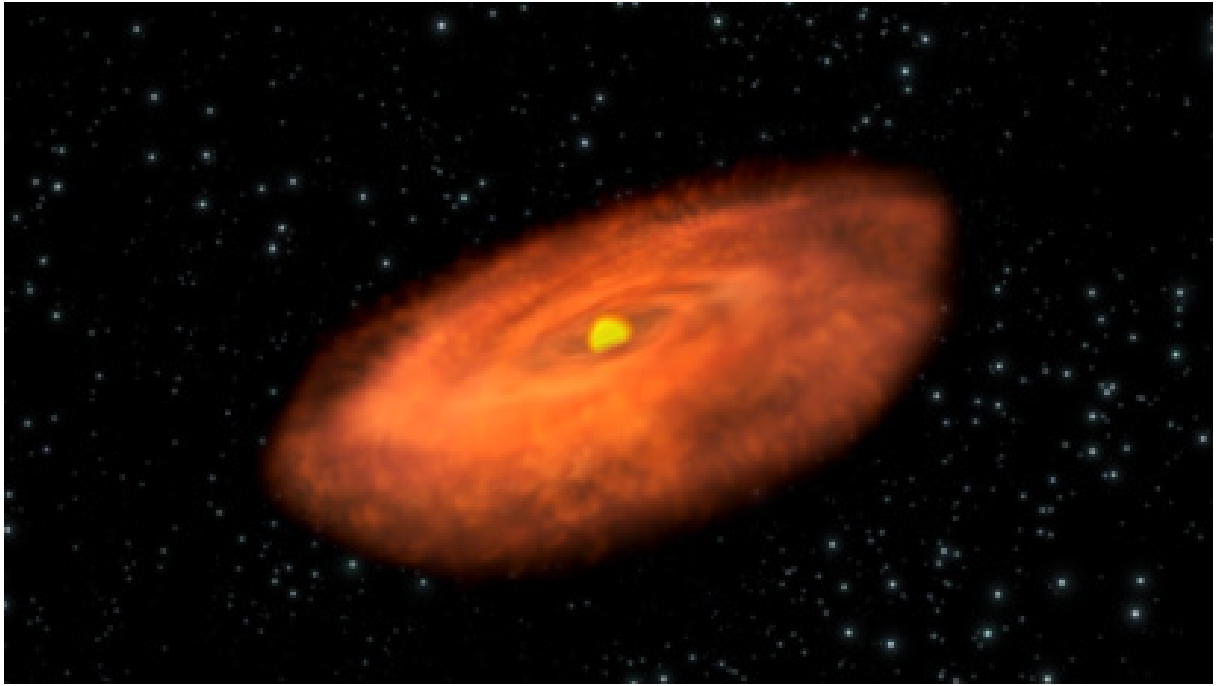
Credit: Fulton et al. (2017)



$$\Gamma_{\oplus} \equiv \left. \frac{\partial^2 n}{\partial \log P \; \partial \log R} \right|_{P=1 \text{ yr},\ R=R_{\oplus}}$$

Credit: Burke et al. (2015), Winn (2018)

Planet formation: Planets form in a disk

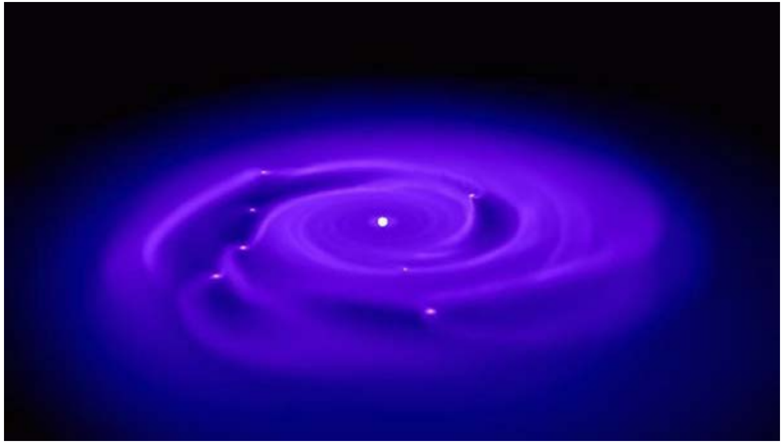


Credit: ESA

Planetary formation – Two models

Disk Instability:

- Formation as a result of gravitational fragmentation in the proto-planetary disk
- Explains formation of massive planets at large-distances from the star
- Short time-scales
- Difficult to directly form terrestrial planets: Gas envelop stripped away could explain current population?

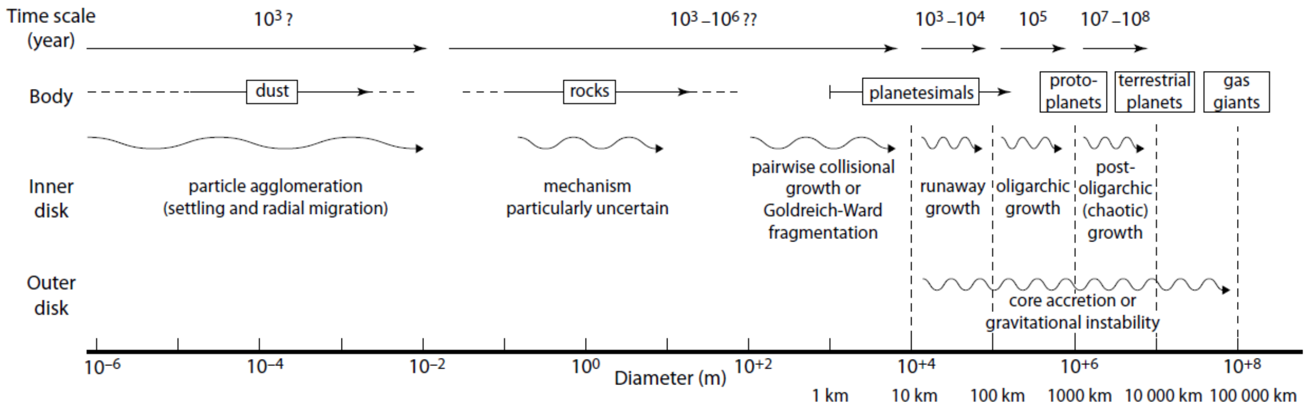


Credit: Quinn et at.

Planetary formation – Two models

Core Accretion:

- Planetesimal coagulation and core formation followed by accretion of a gaseous envelope
- Critical mass to accrete H/He must be reached before the planetary disk has disappeared

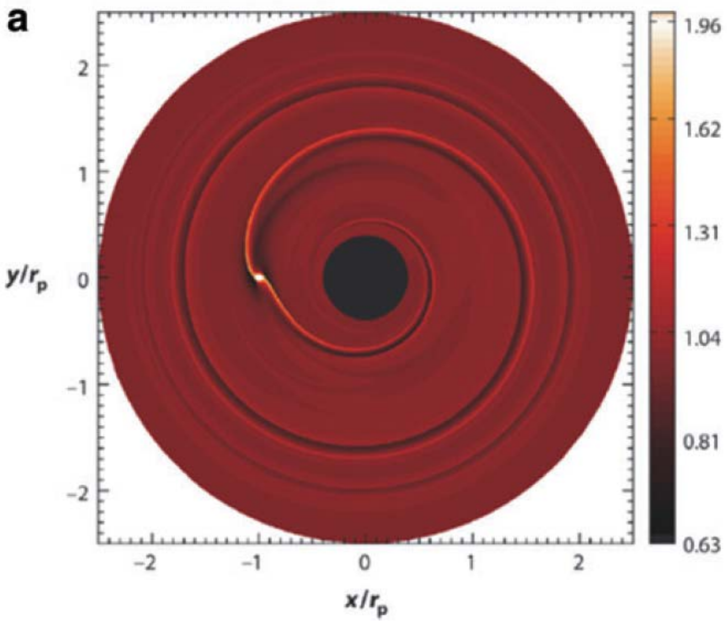


Credit: Perryman 2011

Planetary Migration models

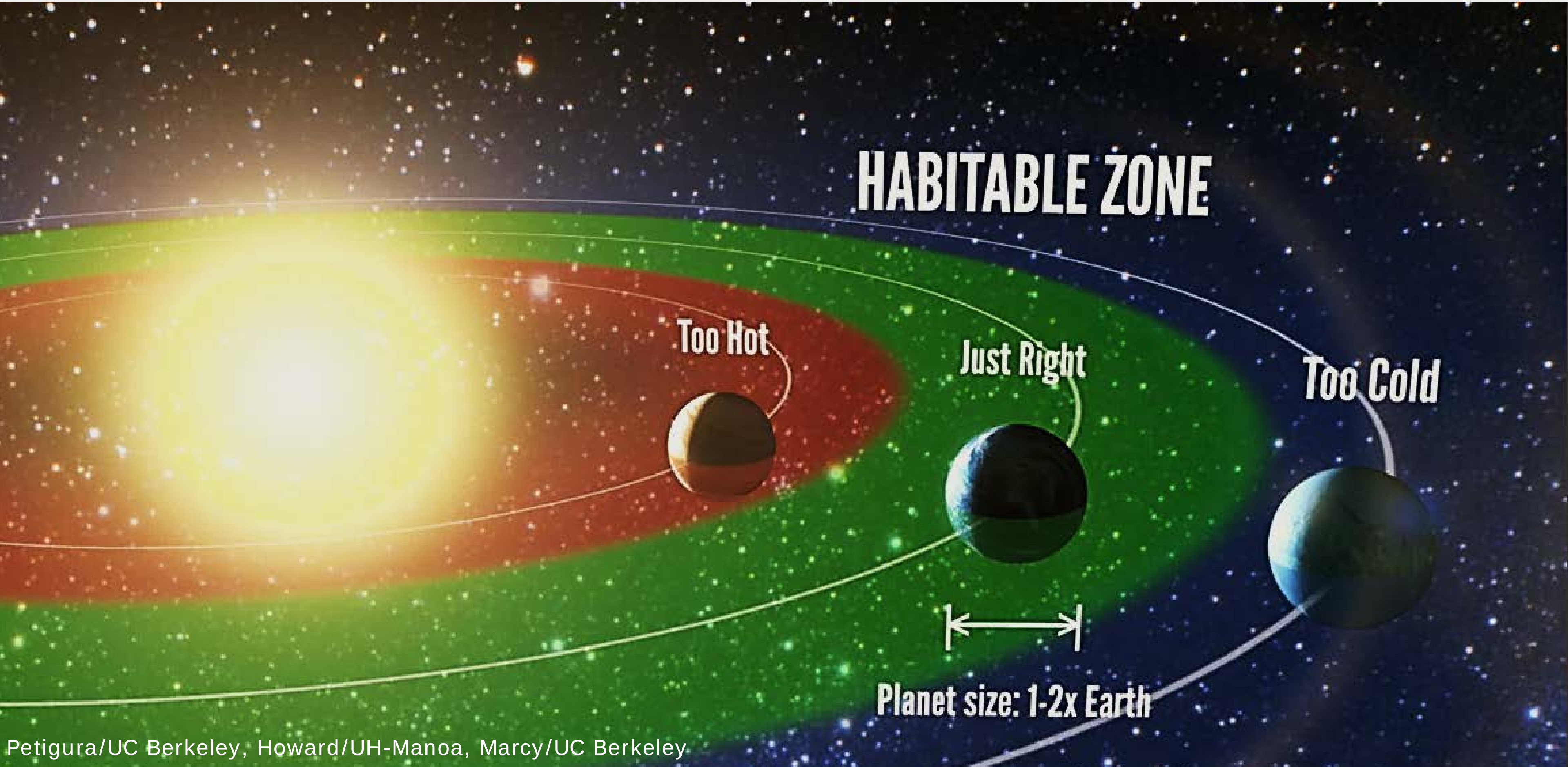
- Caused by gravitational interaction between forming planet and parent disks
- Inward migration more probable
- Low-mass planets in the habitable zone accrete most of their mass from outer cold parts of the disk ➪ Water-rich planets

- Planetary composition is different for planets forming interior or beyond the iceline
- Beyond the iceline: Faster core growth, faster accretion of solids and gas, accretion of larges amount of water



Credit: Kley and Nelson 2012

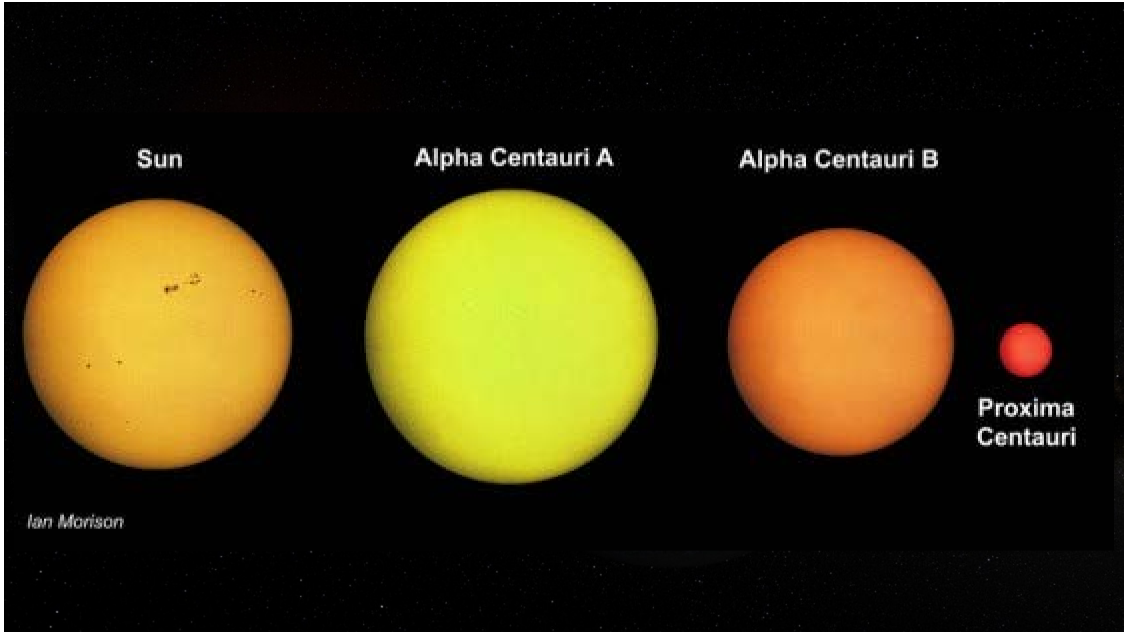
Habitable Zone



Petigura/UC Berkeley, Howard/UH-Manoa, Marcy/UC Berkeley

Closest exoplanet – Proxima Centauri b

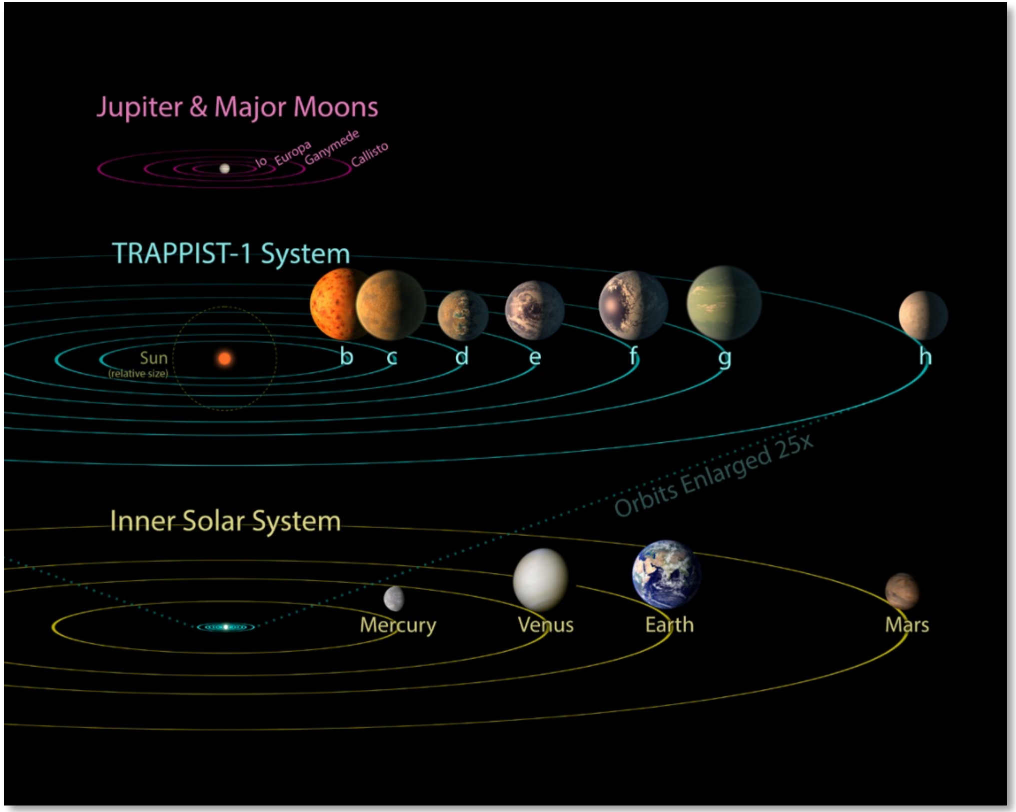
- Red dwarf star
- Planet of 1.3 Earth masses
- Closest exoplanet in the habitable zone



Credit: ESO/M. Kornmesser

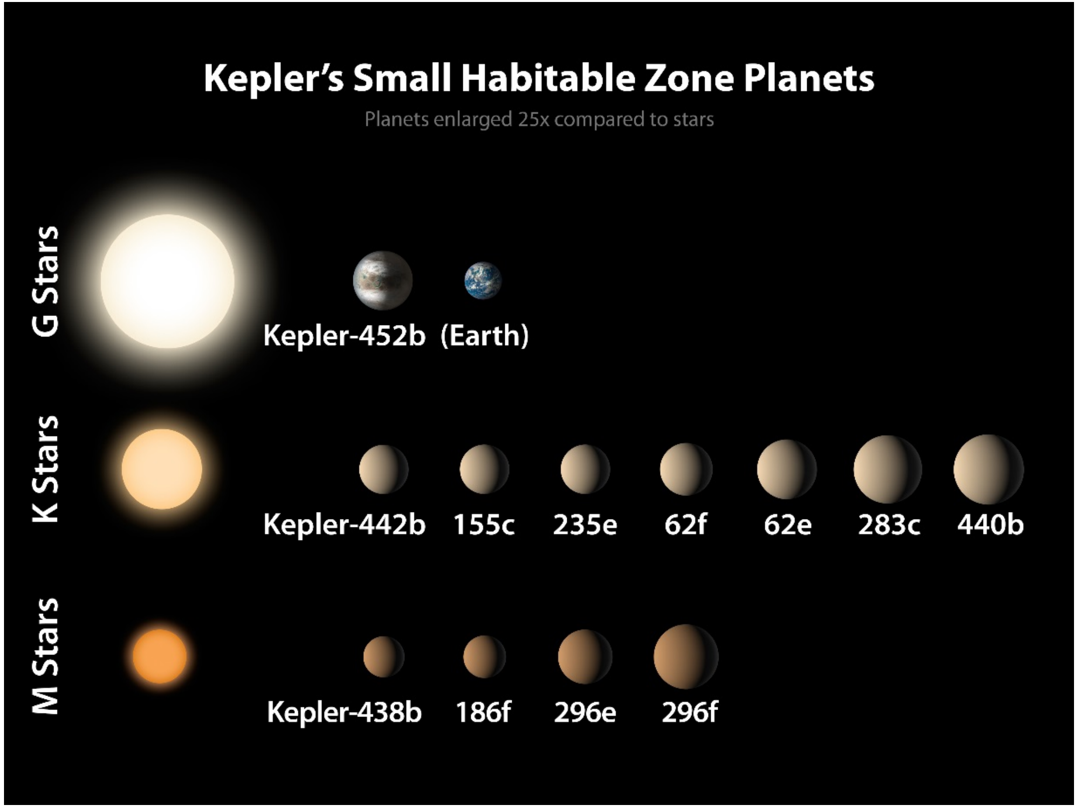
The Trappist-1 system

- Ultra-cold red dwarf star (M8V)
- 7 temperate rocky planets
- Tidally locked
- Total planetary mass is 0.02% of the stellar mass
(similar to Galilean satellites)

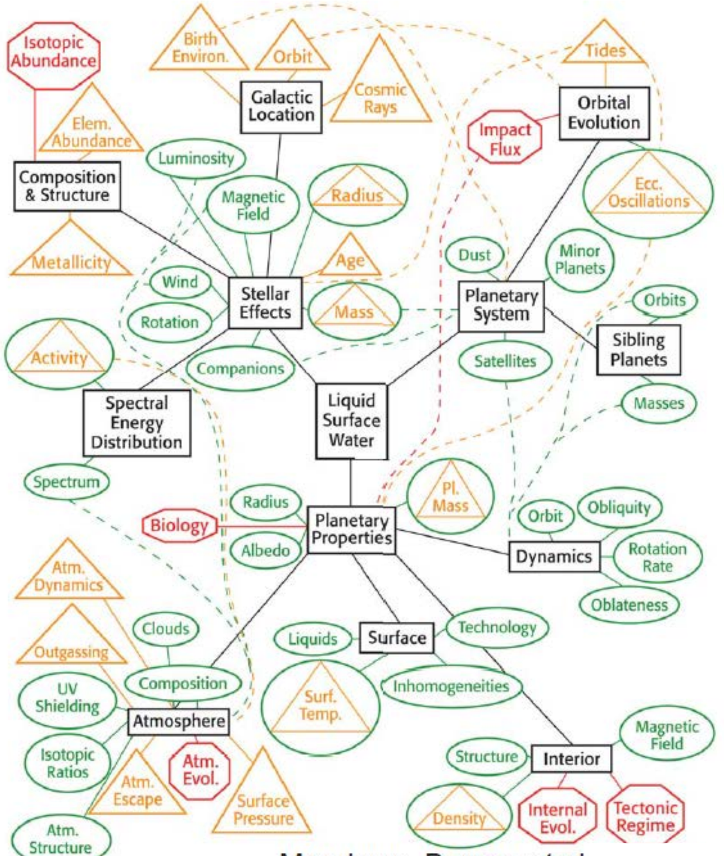


NASA/JPL-Caltech

Kepler terrestrial planets in the HZ



Habitability

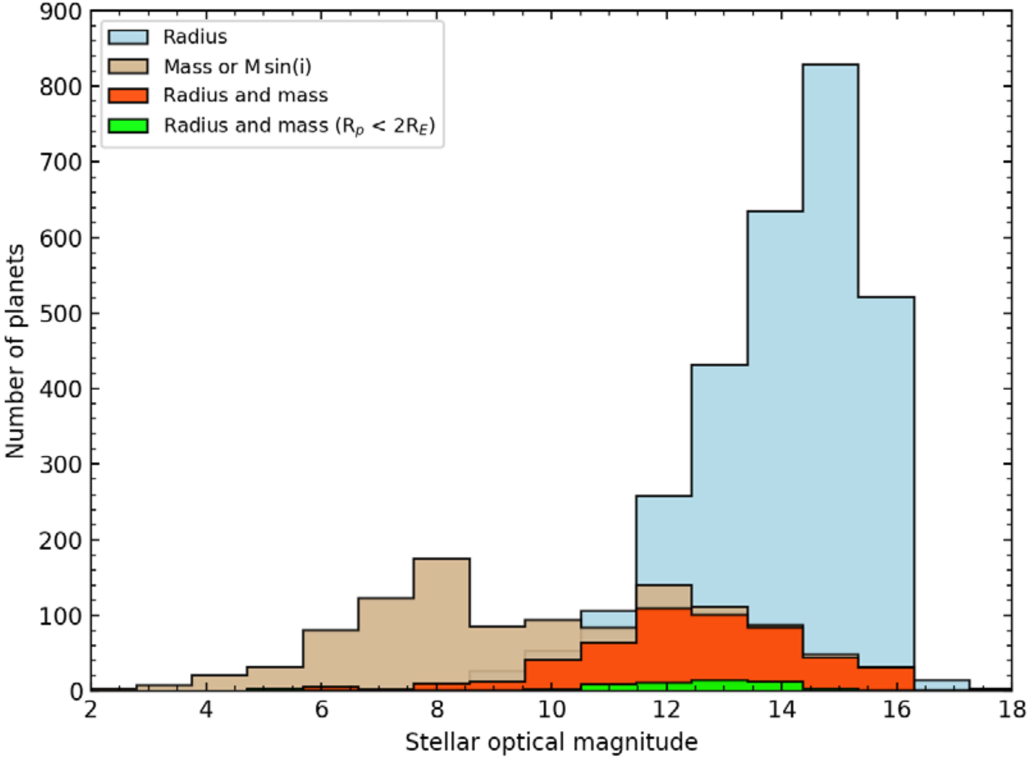


Meadows, Barnes et al.

Habitability is a multiparameter study

Habitability evolves over time and requires knowledge of the age and evolution of the system

Need to observe bright stars

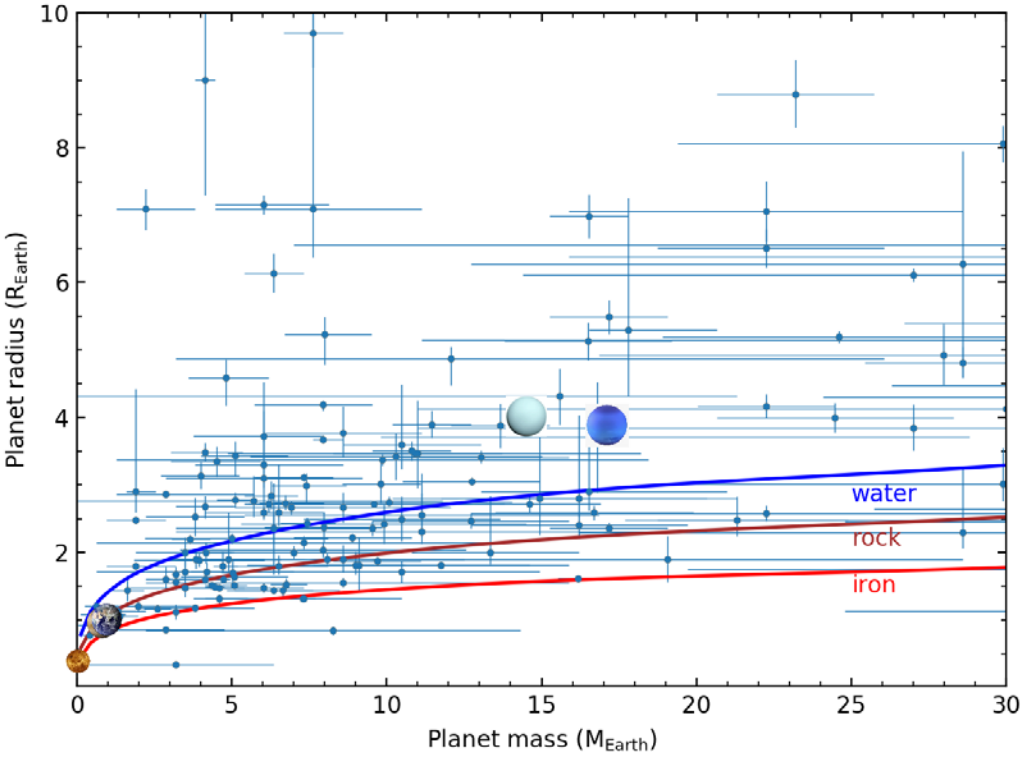


3826 confirmed exoplanets

48 small planets ($R_p < 2\ R_E$) with known radius and mass

RV mass determination and spectroscopy follow-up require bright stars

We need better radius and mass accuracies



Planet properties and diversity

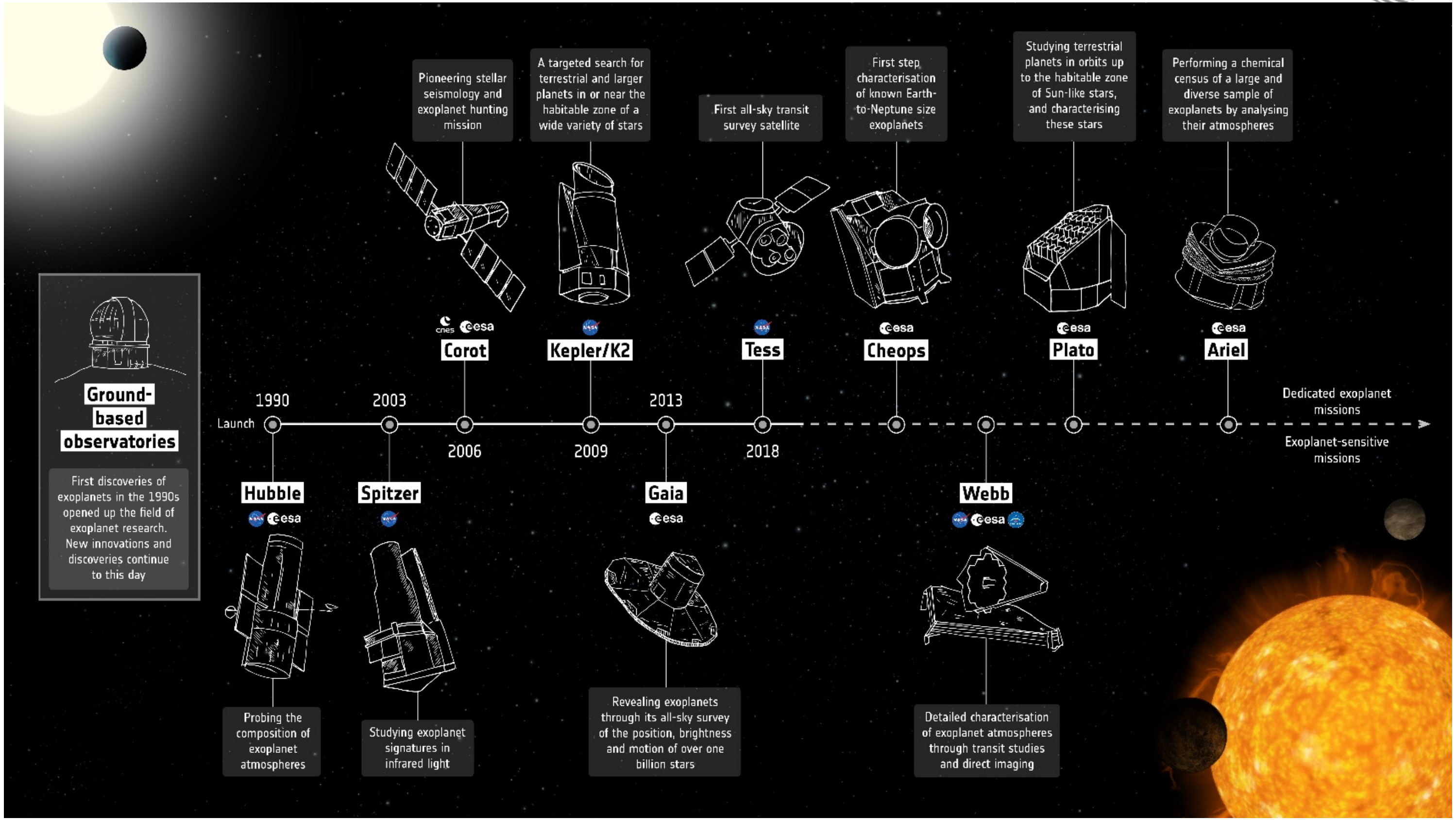
Planet formation

Planet evolution

Habitability

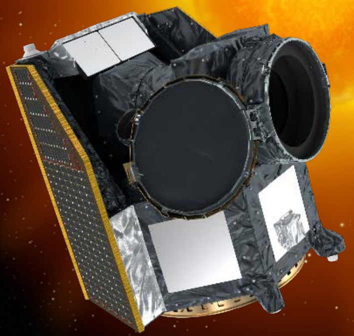
Influence of the environment

Exoplanets related missions



CHEOPS Characterising Exoplanet Satellite

cheops esa

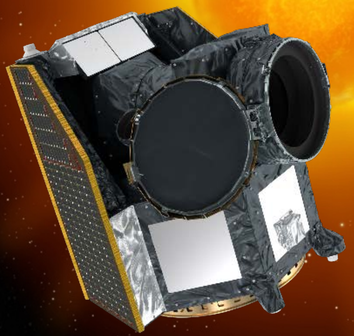


- Using ultra-high precision, broadband vis/IR photometry to measure the radii of known exoplanets orbiting bright stars → combined with mass → bulk density, first-step characterisation
- ”s”-class mission → new type of mission in science programme → programmatic constraints
- Cooperation between ESA Science Programme and Swiss Space Office , Consortium PI from UBern
  - Many mission components typically under ESA for larger missions under Consortium responsibility.
- Design optimised to minimise systematics and to maximise photometric stability

Courtesy of Kate Isaak

CHEOPS

Science in a Nutshell...



- Structure of the nearest, brightest transiting super-Earths and Neptunes
- Mass—radius relationship for planets in the low-mass range → relating to planet formation and evolution models
- New planets - around stars already known to host a planetary system (inner plants, TTVs), trojans, around A-stars
- Geometric albedos and phase curves of hot Jupiters (energy transport)
- Detailed analysis of light curves during transit – planet shape, exomoons, rings

+pot-pourri: stellar variability, stellar occultation by TNO/centaur, recovery of ephemerids...

Courtesy of Kate Isaak

CHEOPS

Mission in a nutshell…

cheops esa

Payload:

- Singleband ultra-high precision photometer (0.3 - 1.1 um).
- Compact Ritchey Chrétien telescope, 30cm effective diameter, defocussed PSF to minimise impact of pointing jitter.
- Single, frame-transfer CCD 1kx1k, 1”/pix

Platform:

- Based on an existing Airbus platform: compact c. $(1.5\text{m})^3$, 300 kg
- Pointing accuracy < 4 “ rms with payload in the loop
- Rolling around the line of sight

Launch, orbit and operations:

- Shared launch on Soyuz from Kourou (2019), 3.5 yrs (5 yrs goal) lifetime
- Sun-synchronous orbit: ~ 100 mins, dawn-dusk, 700 km attitude
- Ground stations at Villa Franca and Torrejon (ES)
- MOC at INTA (ES) , SOC in Geneva (CH), mission manager at UBern (CH)
- 80%:20% split of observing time between Consortium and ESA Guest Observers Programme.

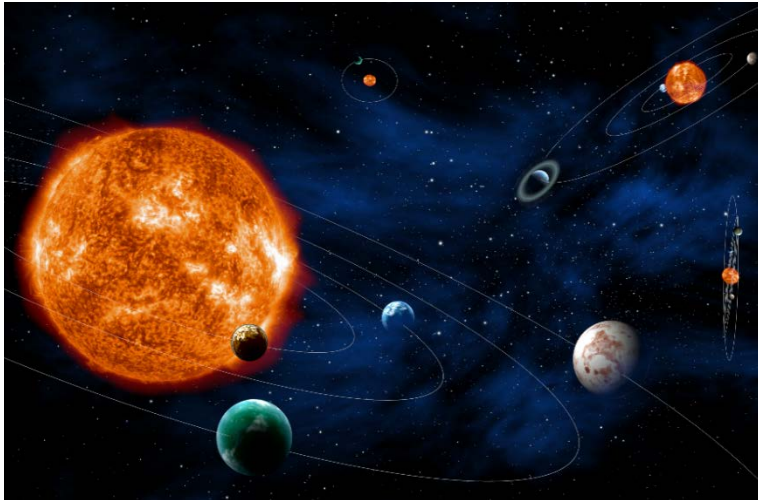
Use

Courtesy of Kate Isaak

PLATO science objectives

PLATO is a mission to detect and characterise exoplanets and study their host stars

- Bulk properties (mass, radius, mean density) and ages of planets, including terrestrial planets in the habitable zone of Sun-like stars: Earth-Sun analogues
- Planetary systems architecture and evolution
- Planet properties and frequencies as a function of stellar parameters and environment
- Internal structure and evolution of stars
- Identify good targets for atmospheric spectroscopic follow-up



PLATO techniques and observing strategy

Techniques

1. Transit method
   - Planet radius (~3% error)
2. Asteroseismology analysis
   - Stellar radius, mass, and age
   - Planet age (~10% error)
3. Radial velocity observations with ground-based telescopes
   - Planet mass (~10% error)

Accuracies for an Earth-size planet orbiting a G0V star at 1 au

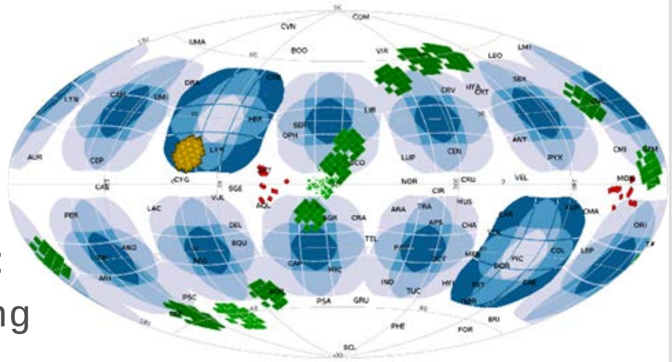
Stellar samples

- Core sample: ~15,000 F5-K7 dwarf and subgiant stars of m_V < 11 (*follow-up with radial velocity ground-based observations*)
- Statistical sample: >245,000 stars of m_V <13(16)

Strategy

Nominal mission:
2 long pointings lasting 2 years each

Alternative scenario:
1 long pointing during 3 years + 1 year step-and-stare



Credit: V. Nascimbeni

PLATO description

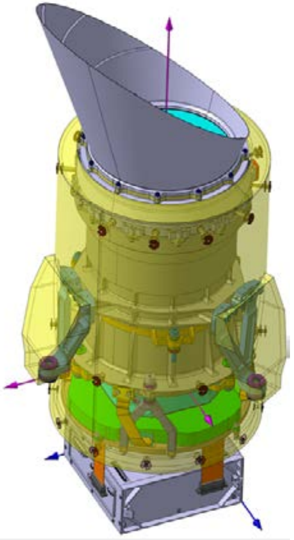
Mission definition

- Launch in 2026 into orbit around L2
- Mission nominal science operations: 4 years
- Satellite/instrument designed to last with full performance for 6.5 years
- Consumables will last 8 years

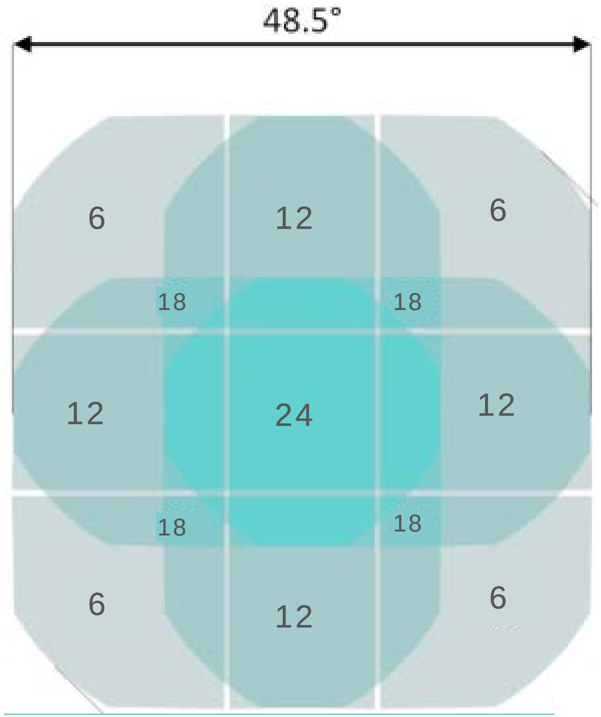
Multi-telescope approach

- Large FOV (large number of bright stars)
- Large total collecting area (high sensitivity)
- Redundancy

PLATO payload



One of the 24 “normal cameras”



PLATO FoV

24 «normal» cameras, cadence 25 sec, operate in “white light” (500 – 1050 nm)

2 «fast» cameras, cadence 2.5 sec, 2 colours

Stellar magnitudes: $4 \leq m_V \leq 13$ (16)

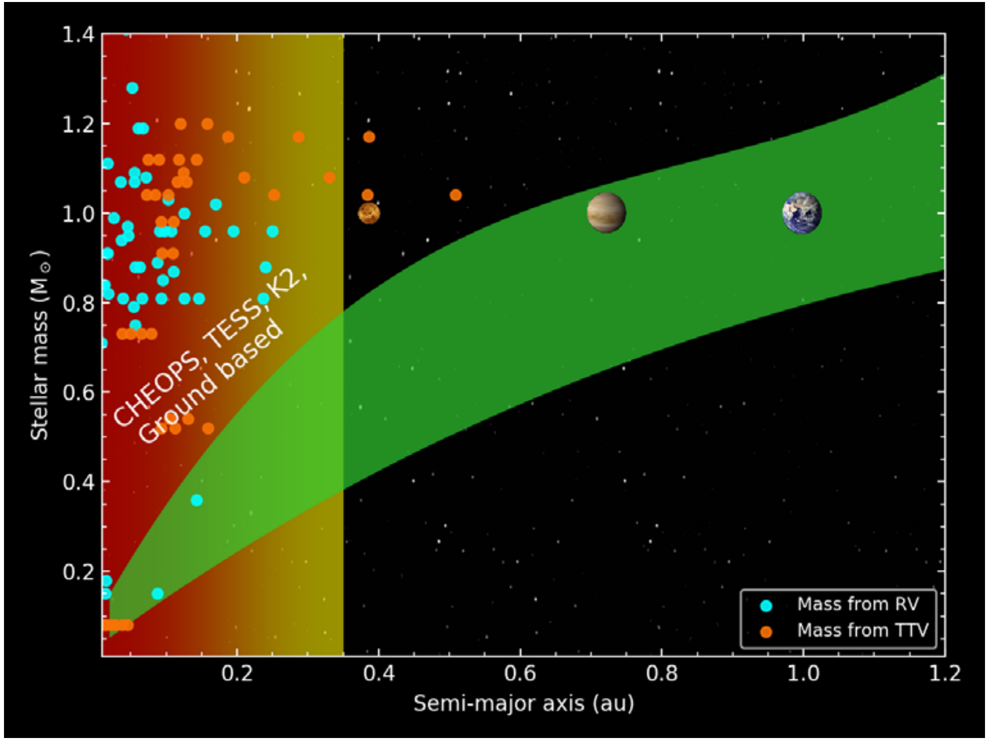
Focal plane: 104 CCDs (4 CCDs per camera) with 4510 x 4510 18 µm pixels

Instantaneous field of view ~ 2250 deg^2

PLATO and habitability

TESS and CHEOPS will detect and characterise small planets in the habitable zone of M dwarfs.

$1 < M_{planet} \leq 10 M_E$
$R_{planet} \leq 2 R_E$



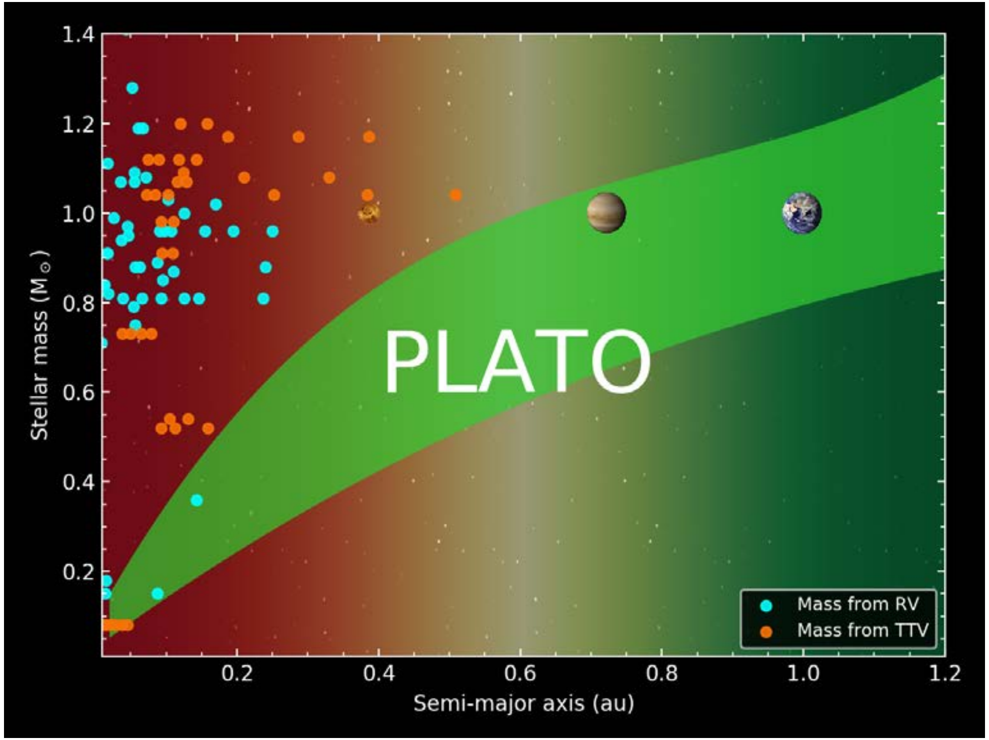
Rauer et al. (2014)

PLATO and habitability

TESS and CHEOPS will detect and characterise small planets in the habitable zone of M dwarfs.

The habitable zone of Sun-like stars is the objective of PLATO.

$1 < M_{planet} \leq 10 M_E$
$R_{planet} \leq 2 R_E$



Rauer et al. (2014)

PLATO ground-based follow-up

There are two kinds of follow-up observations:

1) Observations designed to detect false positives (filtering observations)

2) Observations needed to characterise the planetary orbit and mass (radial velocity observations)

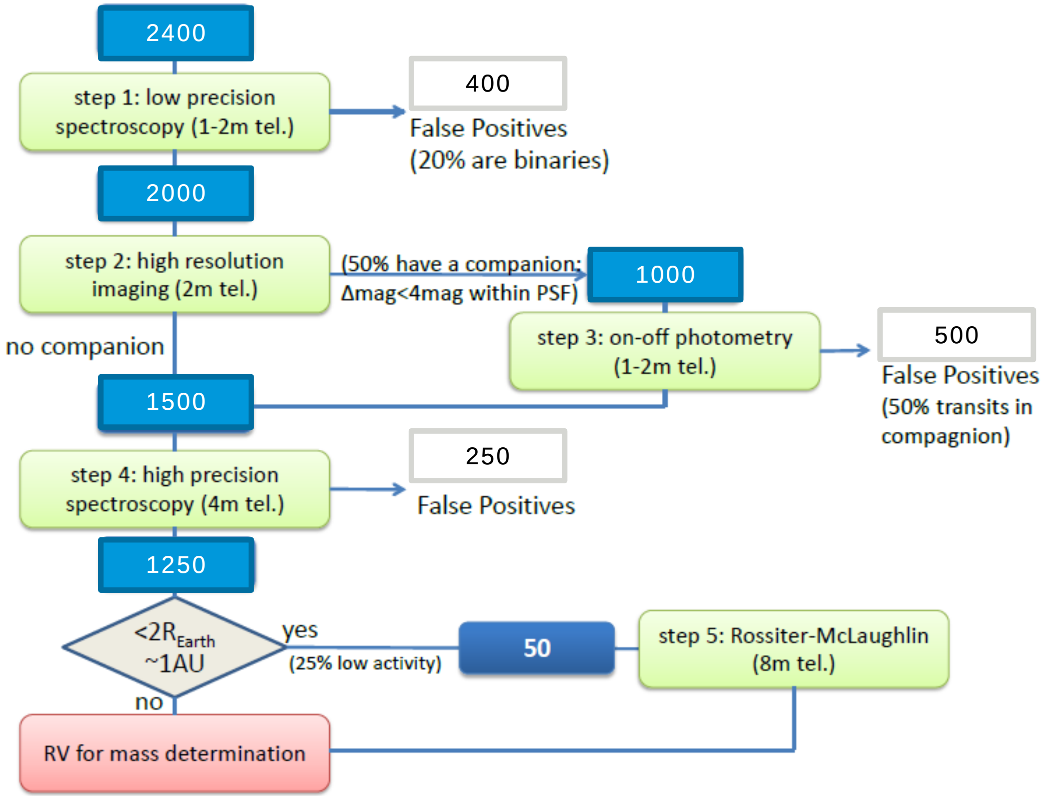
- The team performing these observations for the core sample (GOP Team) will be selected through an open call by ESA
- The issue of the AO is planned for 3 years (TBC) before the PLATO launch
- The GOP Team will organise their respective telescope resources and execute the observations following the PLATO Mission Consortium requirements

Follow-up estimates for core sample

Assuming current baseline of 2 fields, 2+2 yr, dwarf and subgiants F5-K7 with *V* < 11 mag

Centroid filtering not included

Estimates under revision



PLATO Guest Observer programme

- ESA will issue calls for proposals for complementary science programmes
- The targets must be within the PLATO sky fields defined by the SWT
- The duration of the proposed observations cannot exceed the observation durations of the corresponding sky fields.
- The first call will be issued nine months before launch
- More open calls will be issued during the mission (once per year, TBC)
- At any given time, 8% of the science data rate (excluding calibration data) will be allocated to the guest observers
- Proposals on targets of opportunity possible, but they will be executed on a best effort basis

Ariel

Chemical census of a LARGE diverse sample of KNOWN exoplanets

Observations

- Probe atmospheric chemistry & dynamics
- IR transit & eclipse spectroscopy (1.1-7.8 um)
- VNIR multiband photometry (0.5-1.1 um)

Targets

- ~1000 known exoplanets, transiting stars brighter than mag_K=9.5
- Diverse sample from gas giants to super-earths (possibly reaching earths)
- Focus on warm & hot planets, T >500 K, to constrain bulk elemental composition

Courtesy of Göran Pilbratt

Targets: migration our ally

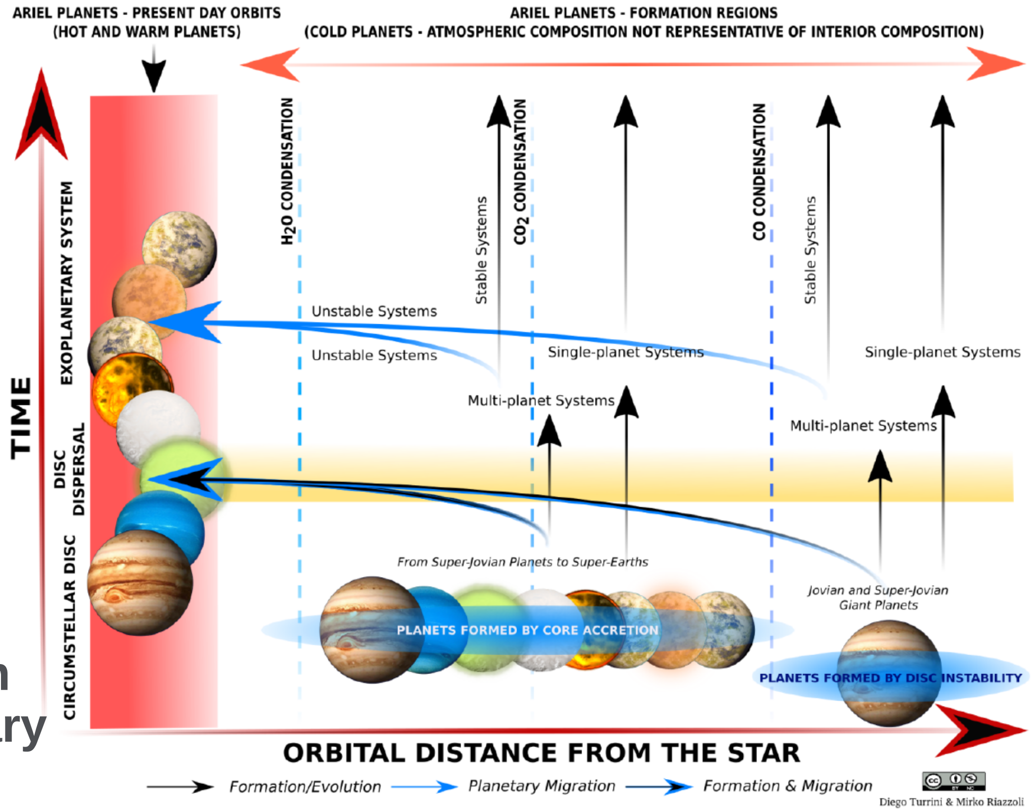
ARIEL will preferentially observe warm & hot planets

- Very limited sequestration
- Linking atmospheric to bulk elemental composition enabled

Planetary migration

- Common – but beware of bias!
- ~½ of known planets <0.1 AU
- Can take place at different times
  - In protoplanetary disk
  - After disk dispersal

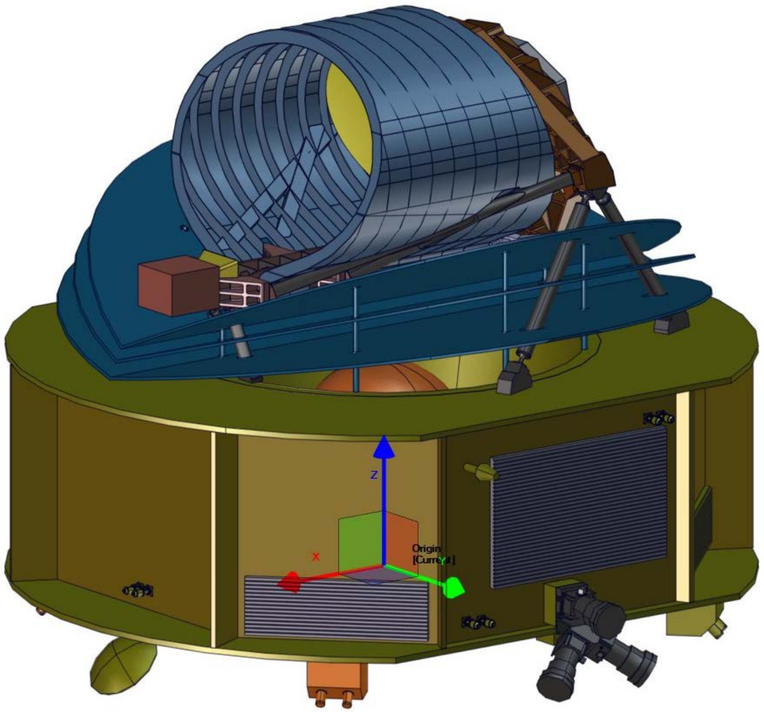
'Delivers' warm & hot planets from different formation and evolutionary tracks forming representative sample



Courtesy of Göran Pilbratt

Spacecraft & mission

Under study by industry (x2) and ARIEL Consortium (PLM)



Courtesy of Göran Pilbratt

Instrument

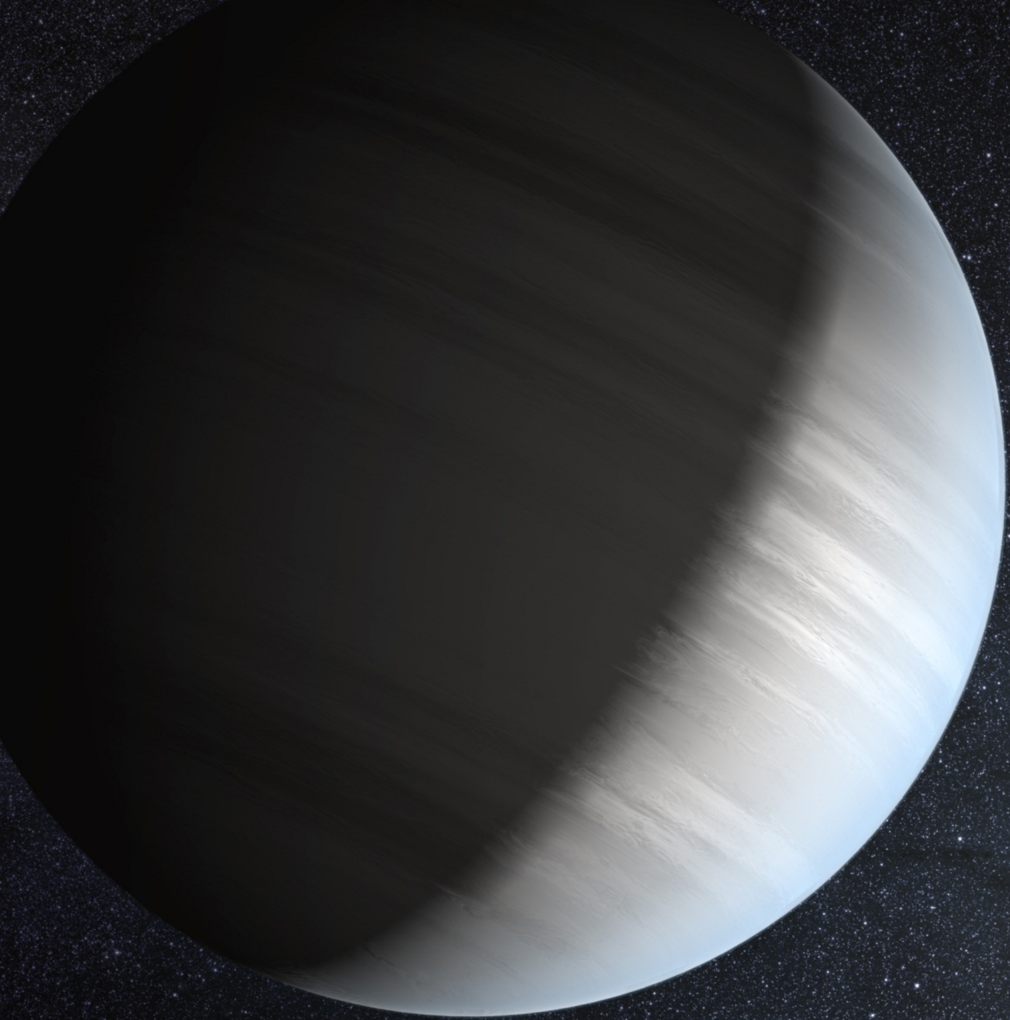
- Spectrometers:
  - NIRSpec 1.1-1.95 μm R~10
  - AIRS0 1.95-3.9 μm R~100
  - AIRS1 3.9-7.8 μm R~30
- Photometer:
  - 3 VNIR channels 0.5-1.1 μm

Telescope

- 3-mirror off-axis, 1.1 x 0.7 m aperture

Spacecraft & mission

- Payload module (PLM) passively cooled
- AIRS detectors actively cooled
- A62 launch to large halo-orbit around L2
- Nominal lifetime 4 years, extended 6 years
- Liberal data policy
- Consortium with 11+ ESA countries



We are in a golden era for the study of new worlds