GROUND CONTROL

Inaugural Event:

The Galactic Recipe for Exo-Planets

What does it take to form an Earth-like planet?

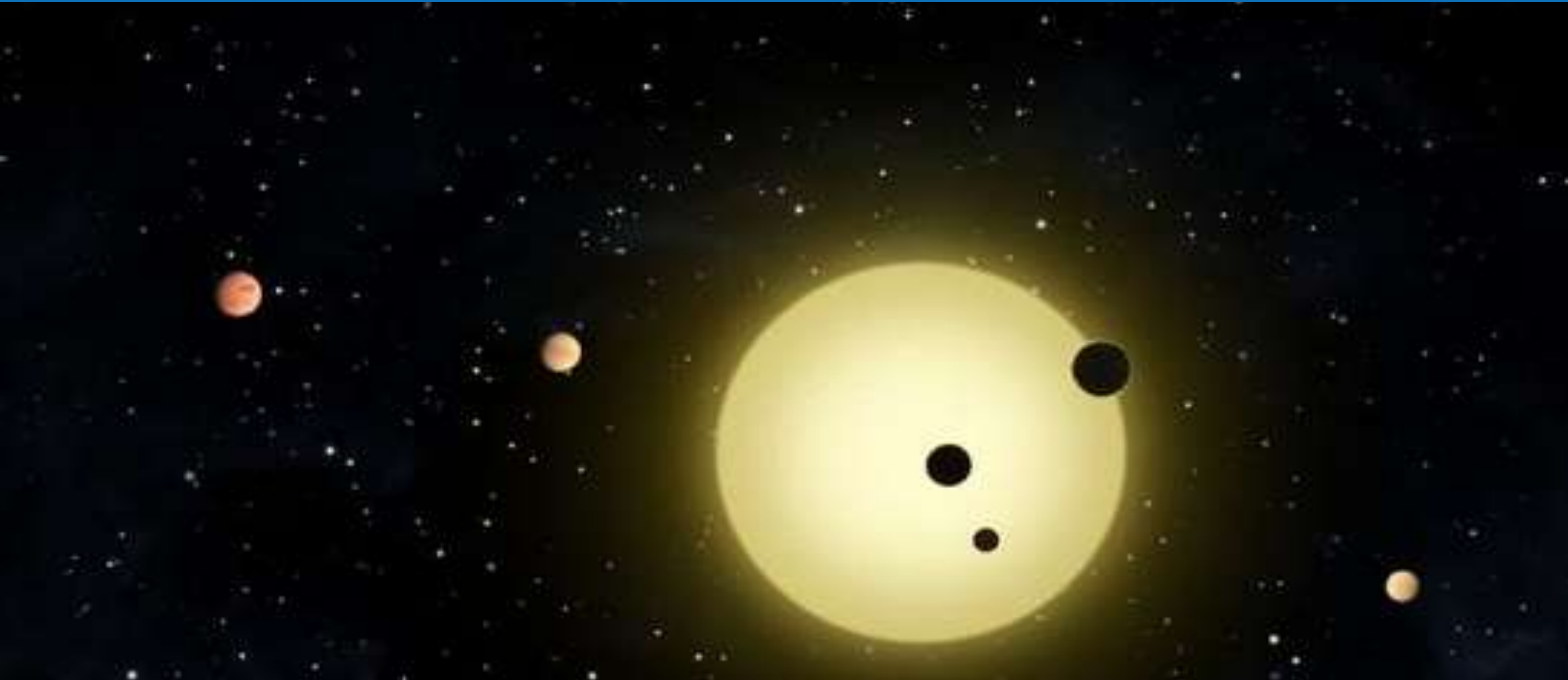
Stephanie C. Werner
Centre for Planetary Habitability, University of Oslo

Forskningsrådet

Centre for Planetary Habitability

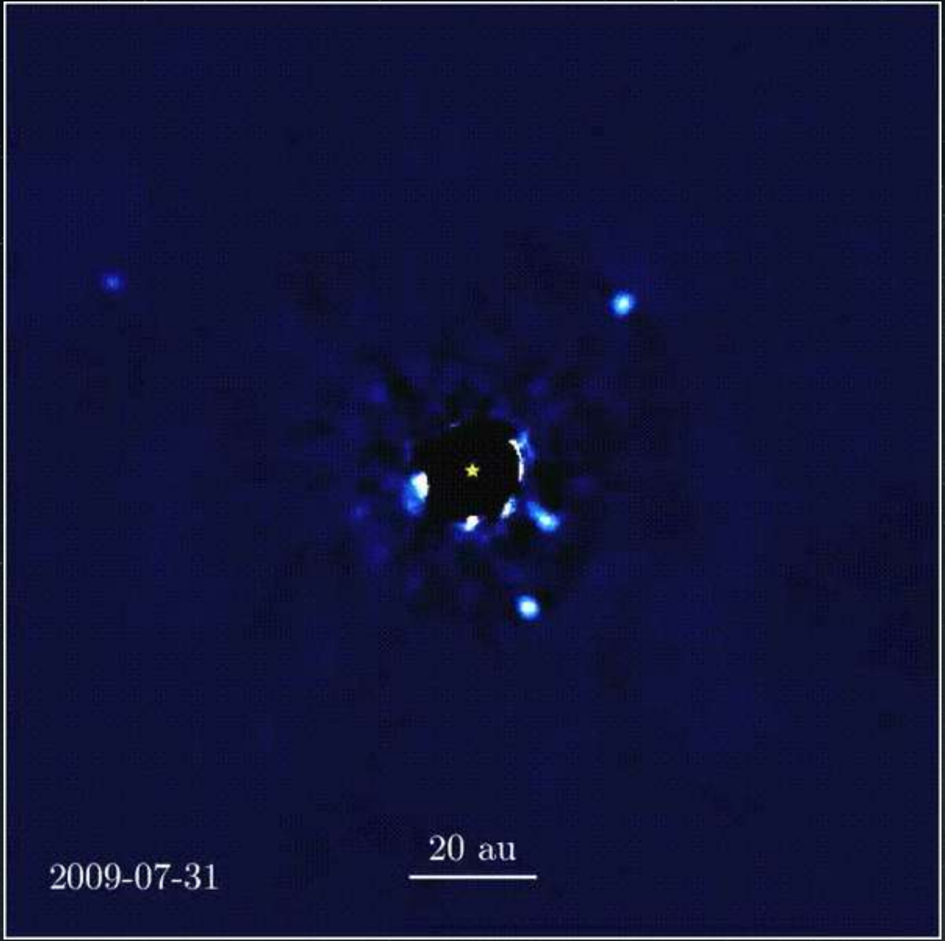
Mesh Youngstorget, February 25, 2026

What is an Exoplanet?



Planets are planets only in the solar system orbiting around the sun.
Planets that orbit around other stars are called **exoplanets**.

Exoplanets: Direct Imaging (Rare!)

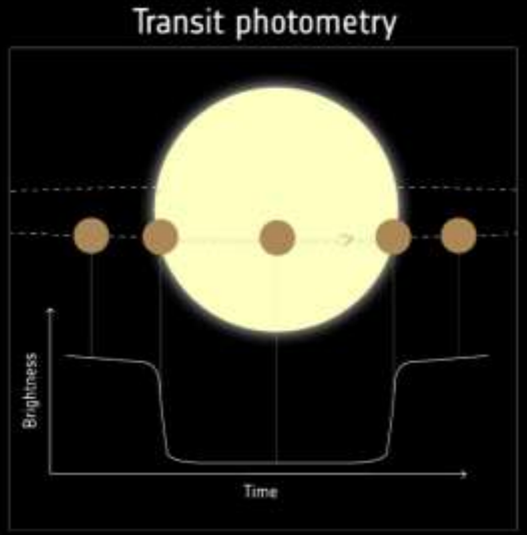


HR 8799 system
Marois et al. (2008)

The system is 30 Ma old, 133 ly away from Earth, and the star has 1.5 (or 4.9) times the Sun's mass (or luminosity).

1AU = Sun-Earth Distance= 149.597.870.700 m = 1.5813×10^{-5} light years = 4.8481×10^{-6} parsec

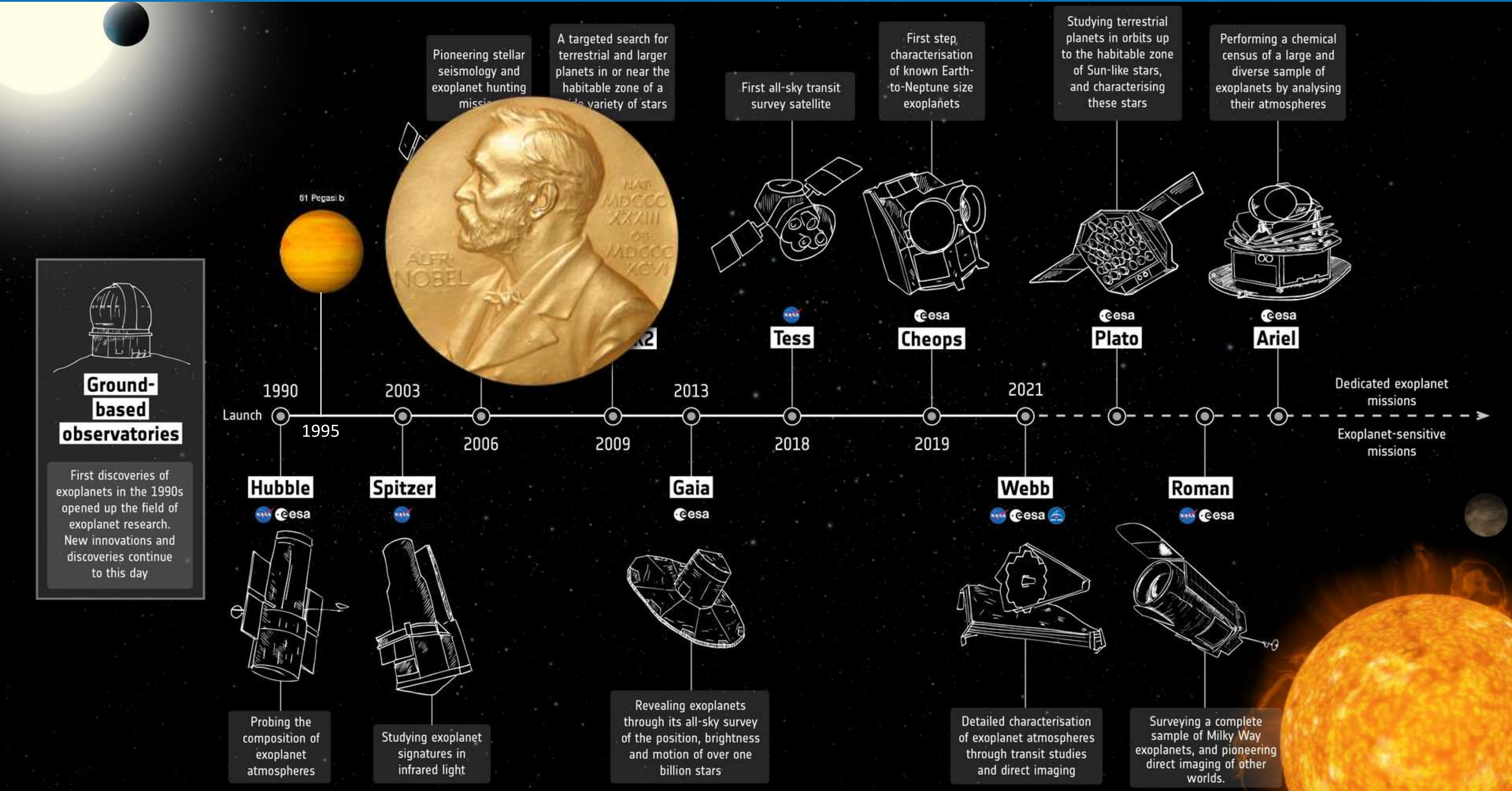
Transiting Planets – Example Venus Transit on June 6, 2012



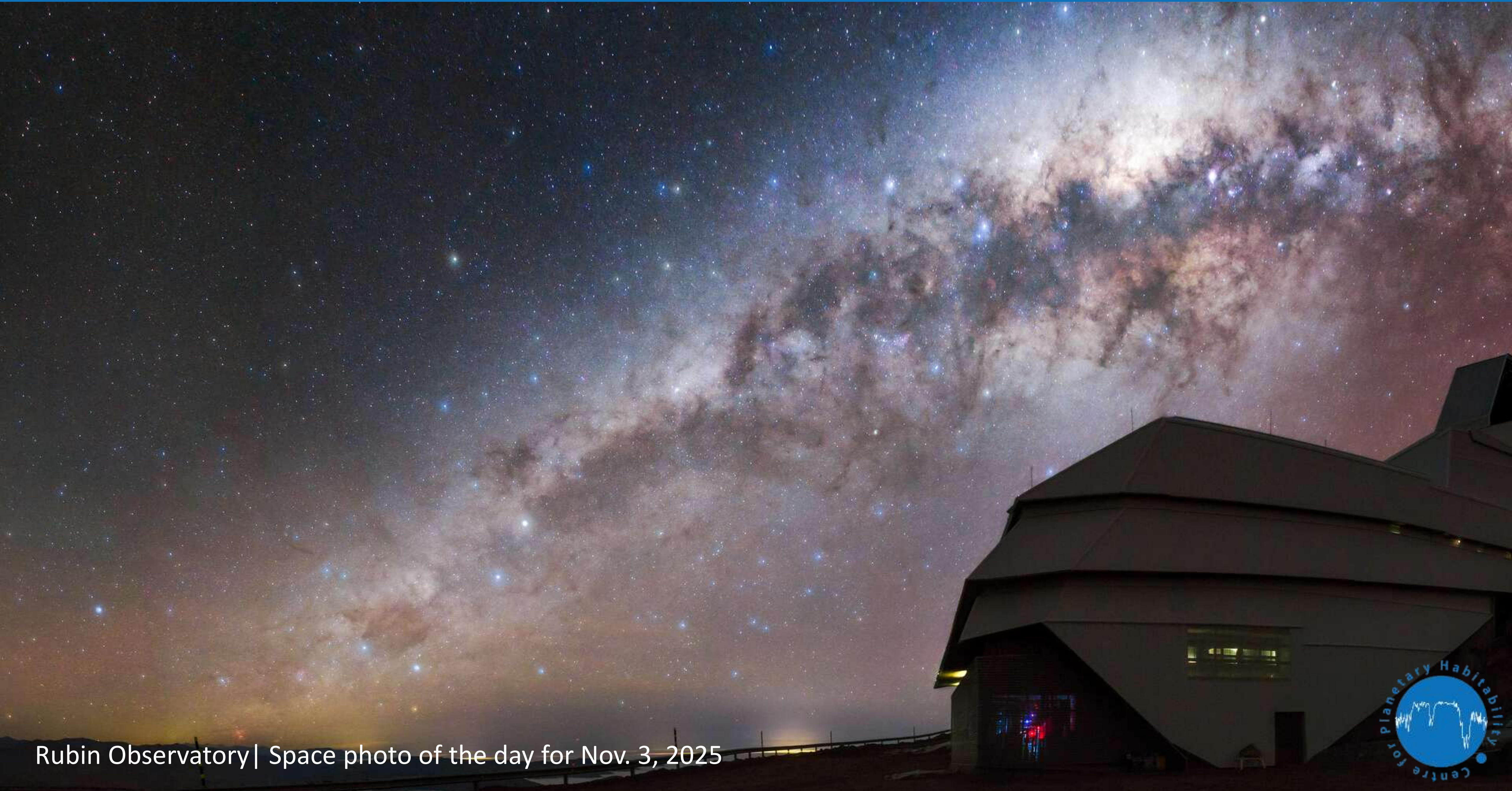
H-Alpha

Next Venus Transit December **2117**

Exoplanet Space Missions and Observatories

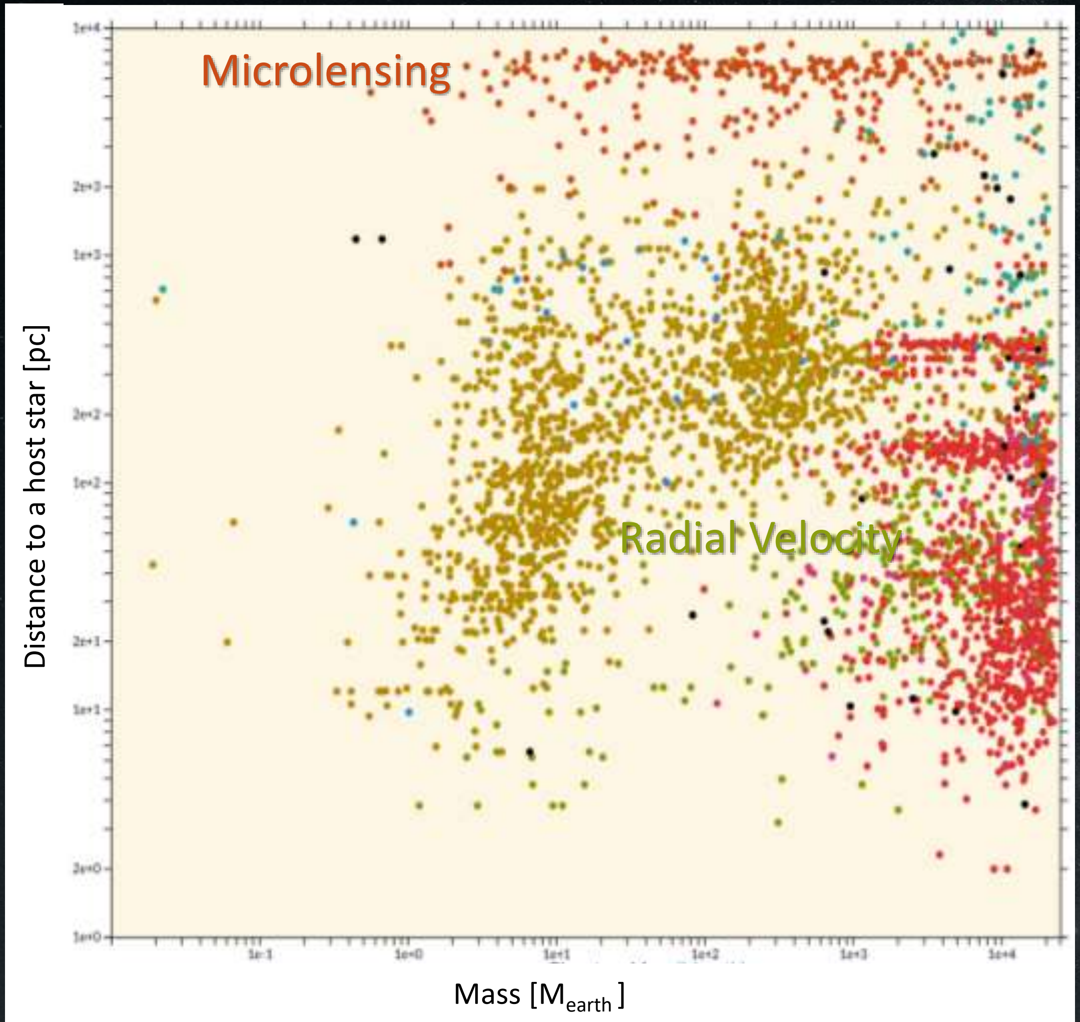


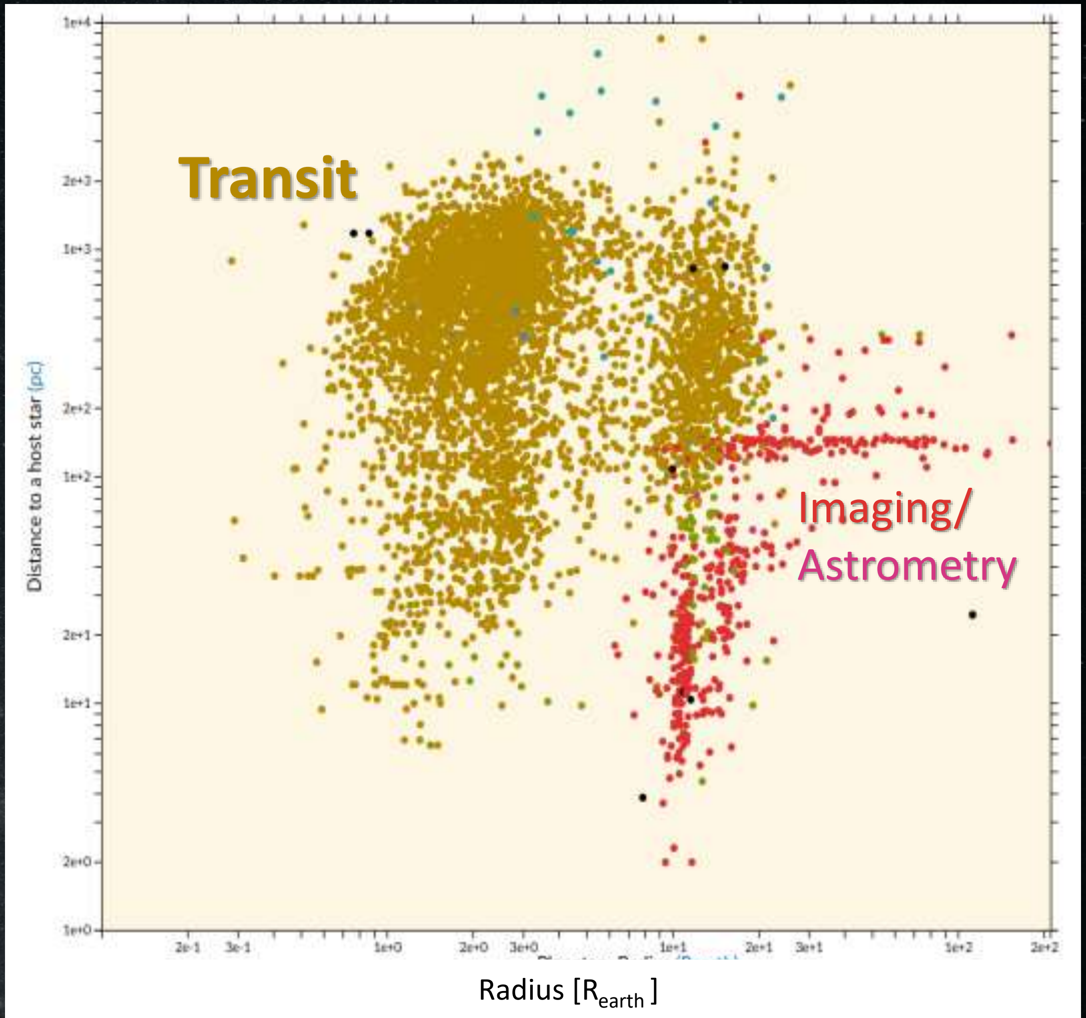
Exoplanets: Near and as far as we can 'see'



Rubin Observatory| Space photo of the day for Nov. 3, 2025

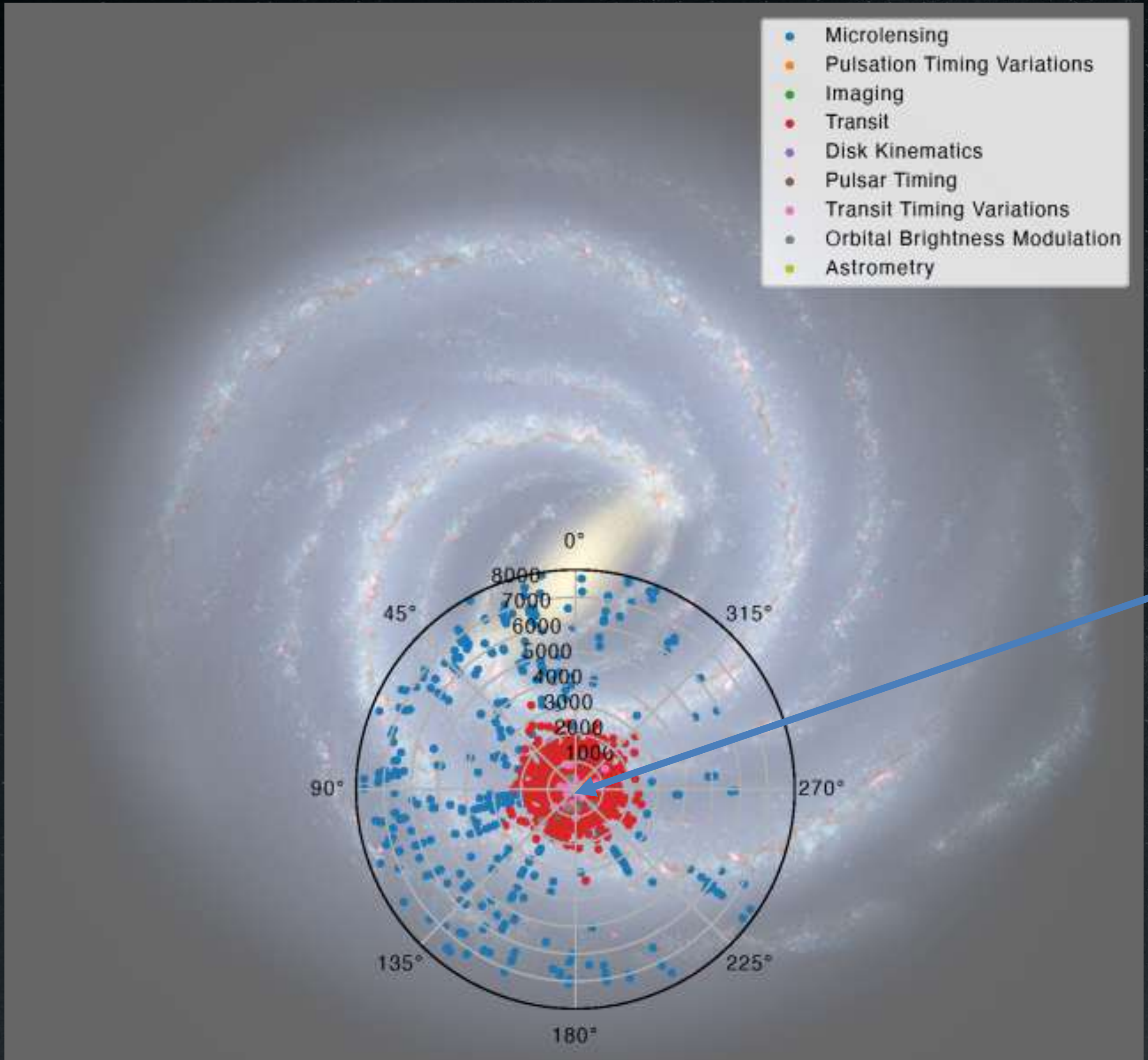
Exoplanets: Near and as far we can ‘see’ – A methodical bias





1 parsecs = 3.26 light-years = 206 165.9 AU

Exoplanets: Near and as far as within the Milky Way



1 parsecs = 3.26 light-years = 206 165.9 AU

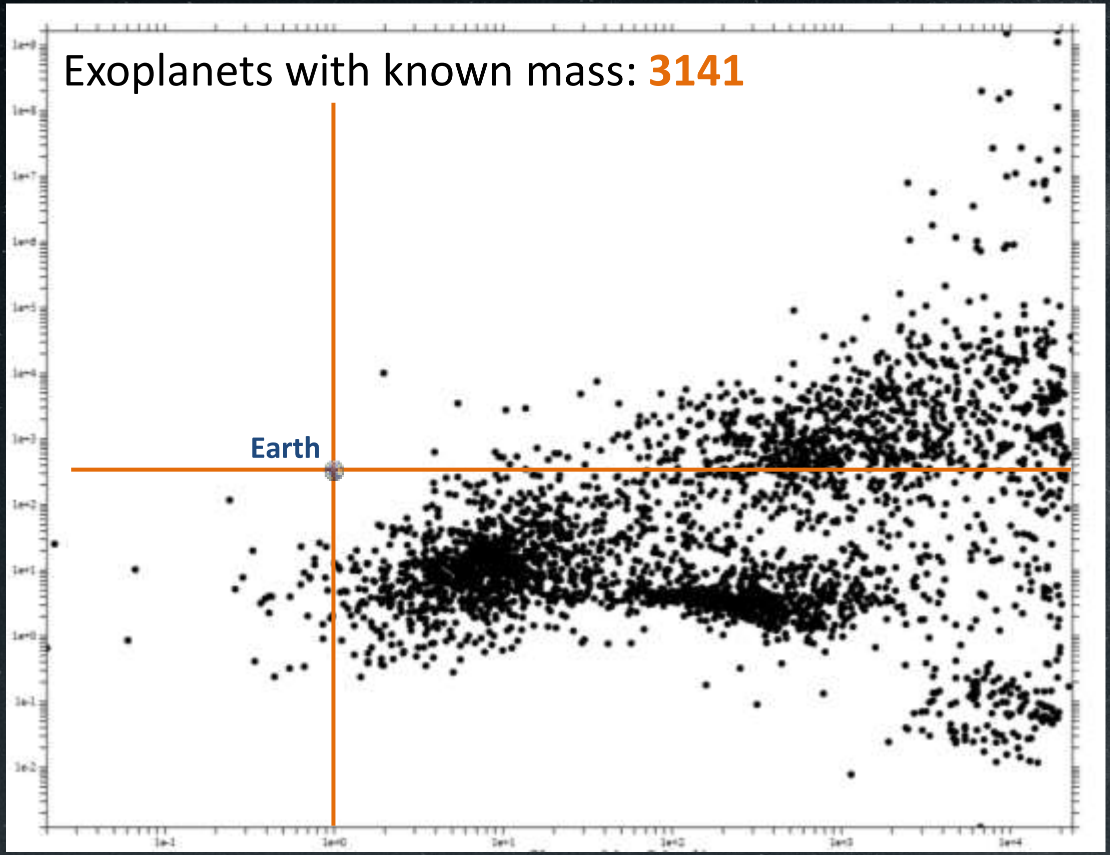
Proxima Centauri (M dwarf : 3042 (± 117) °K)
is about 4.224 light-years (1.295 parsecs) from Earth.

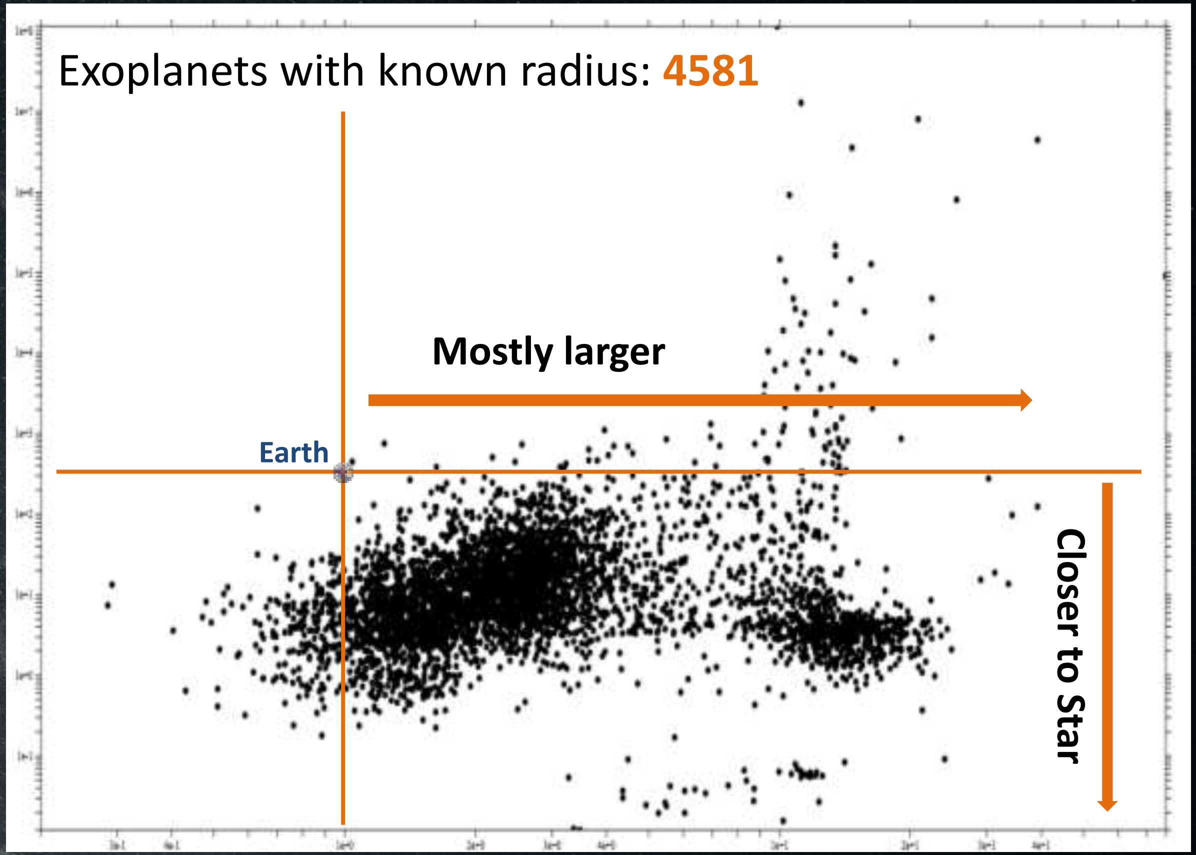
Proxima Centauri B is 1.29 (± 0.13) *M_{Earth}
Its orbit is 0.04848AU (period of 11.2 days)
within the host star's habitable zone.

Exoplanets are many (7360 known as of December 7, 2024 : exoplanet.eu) but how many?

Last Update: Feb. 25, 2026 currently 8015 planets

Orbital Period (days)





Planetary Mass (M_{earth})

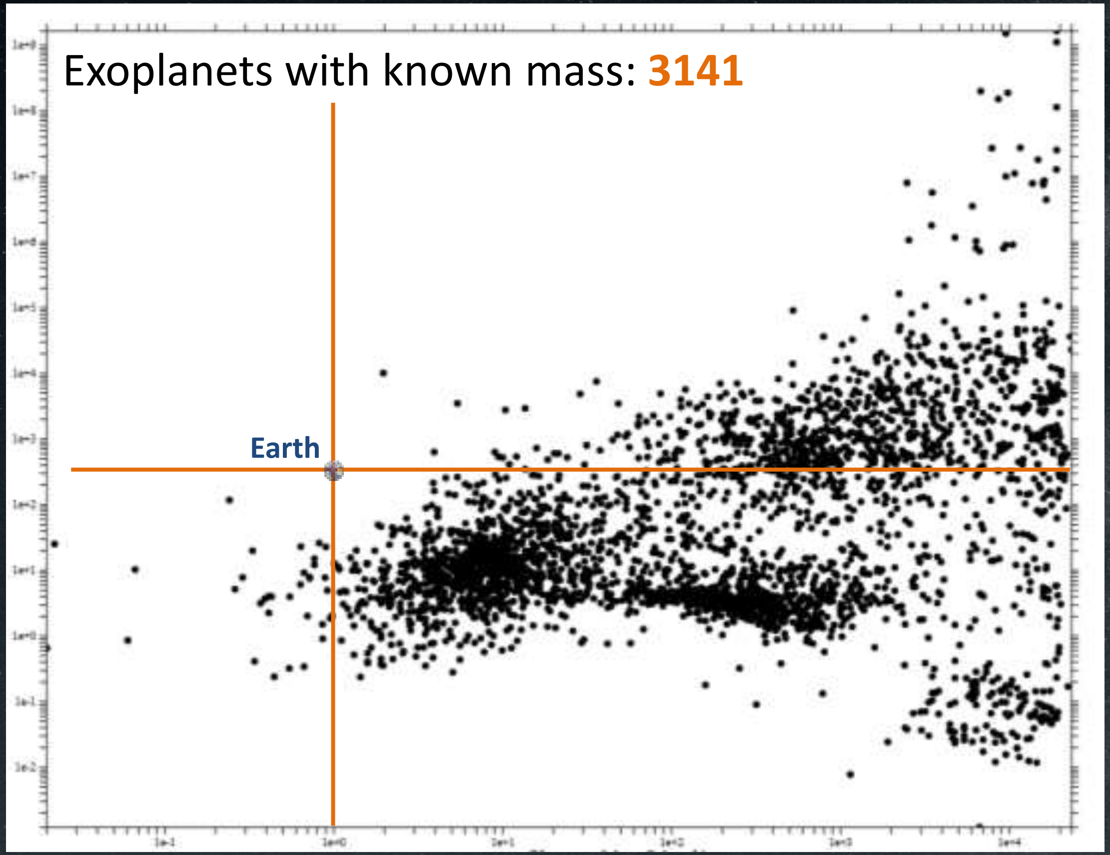
using radial velocity measurements

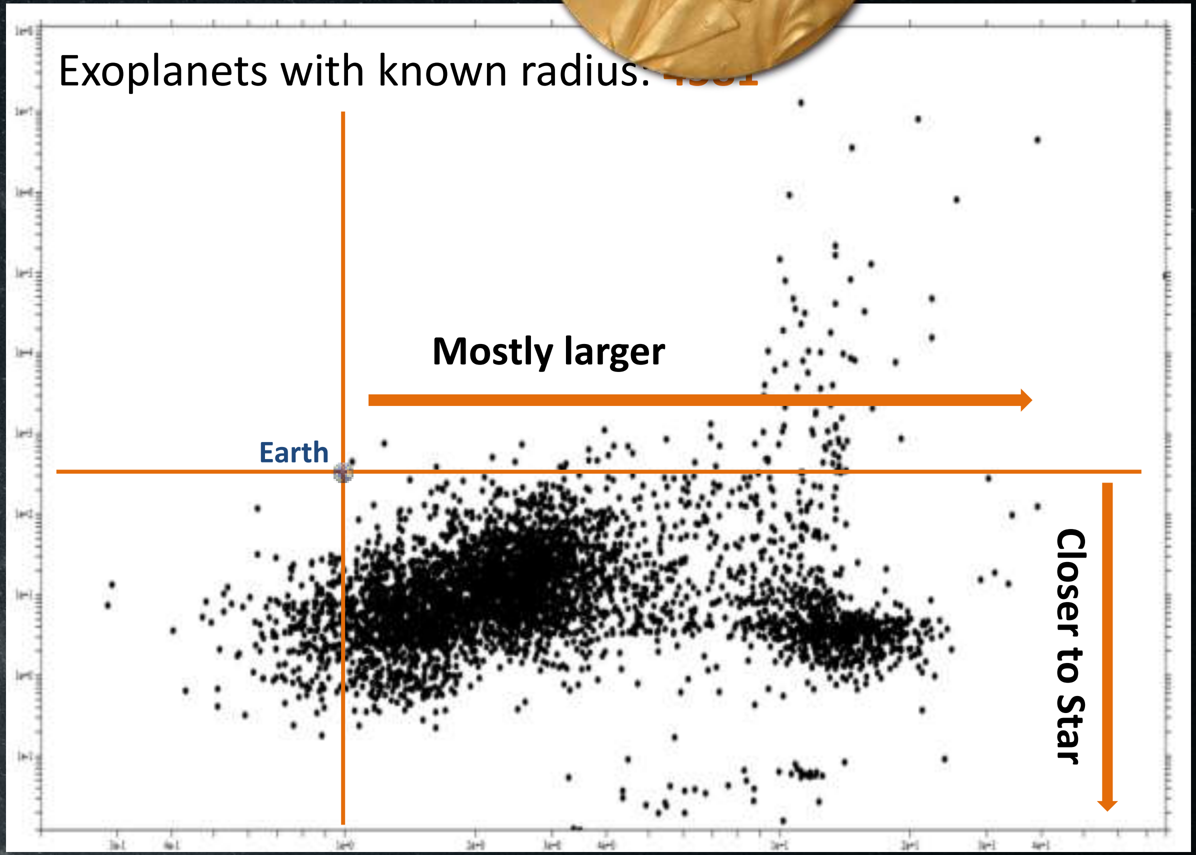
Planetary Radius (R_{earth})

using transit photometry

Statistics and Comparative Planetology

More planets around other stars raises the possibility of life elsewhere



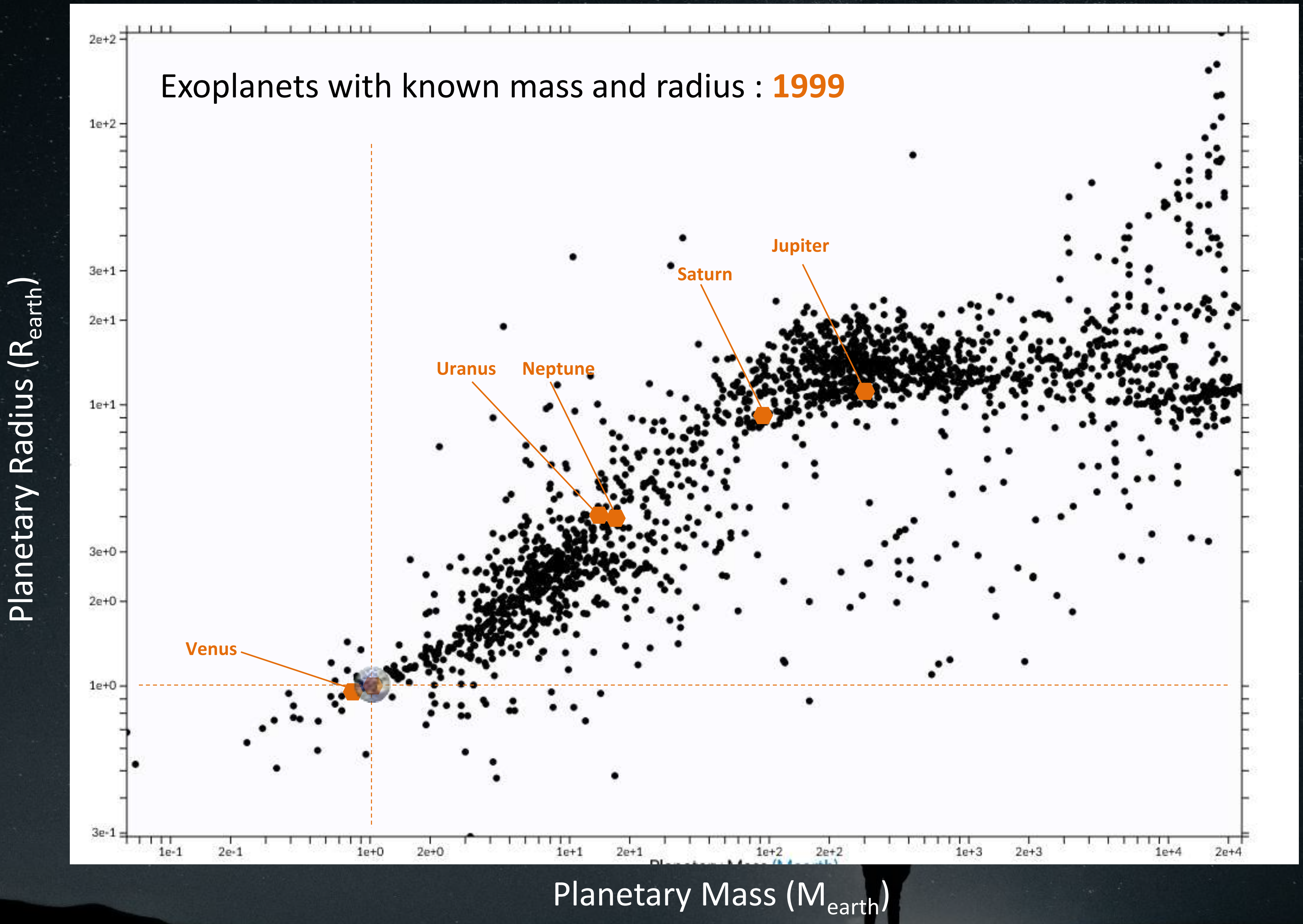


Orbital Period (days)

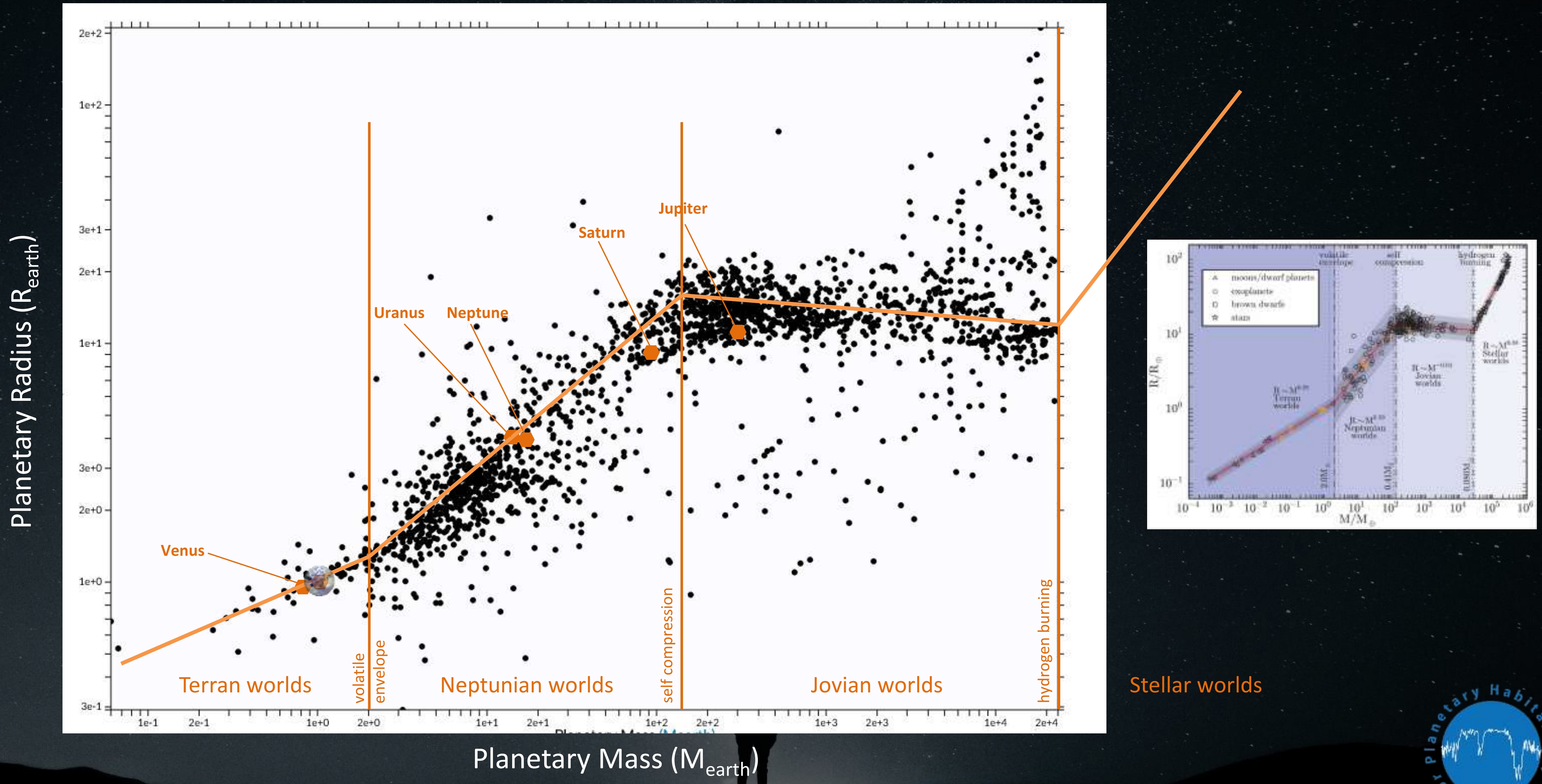
Planetary Mass (M_{earth})
using radial velocity measurements

Planetary Radius (R_{earth})
using transit photometry

Mass – radius relation in the galaxy?

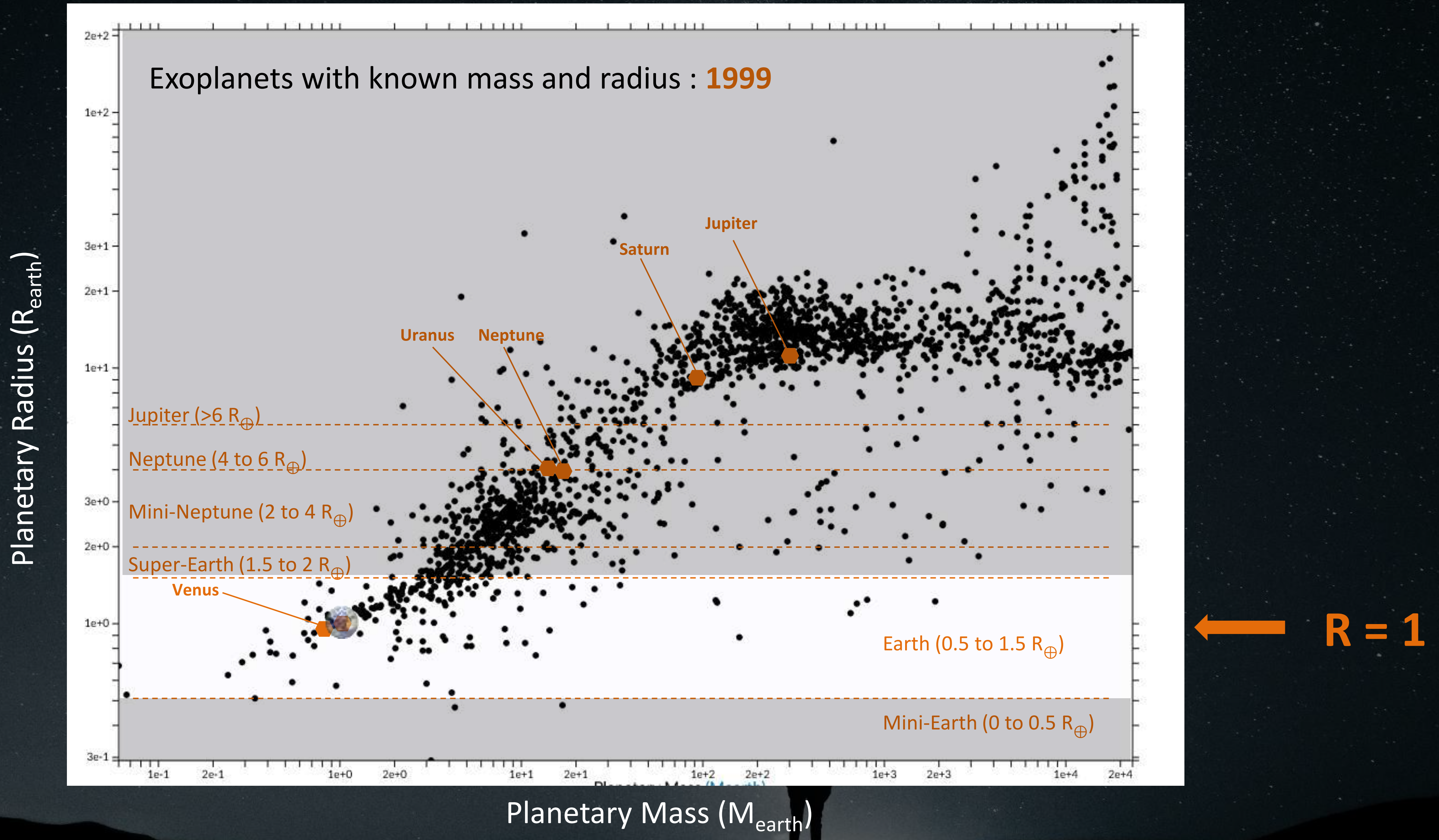


Mass – radius relation in the galaxy? An Astronomer's View

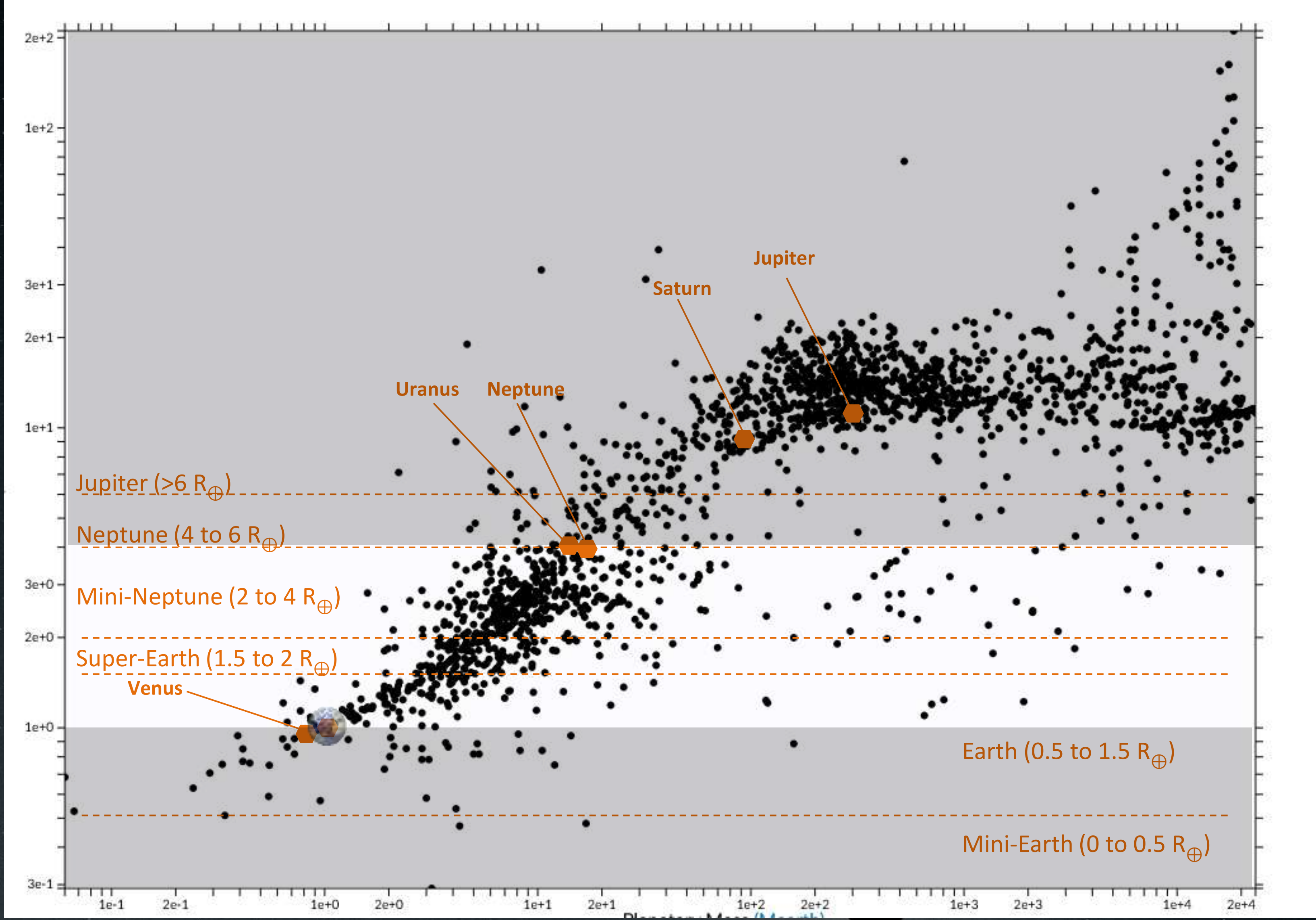


Centre for Planetary Habitability

Earth-Like Exoplanets – R = 1?



Earth-Like Exoplanets – Can it be a one-parameter view?

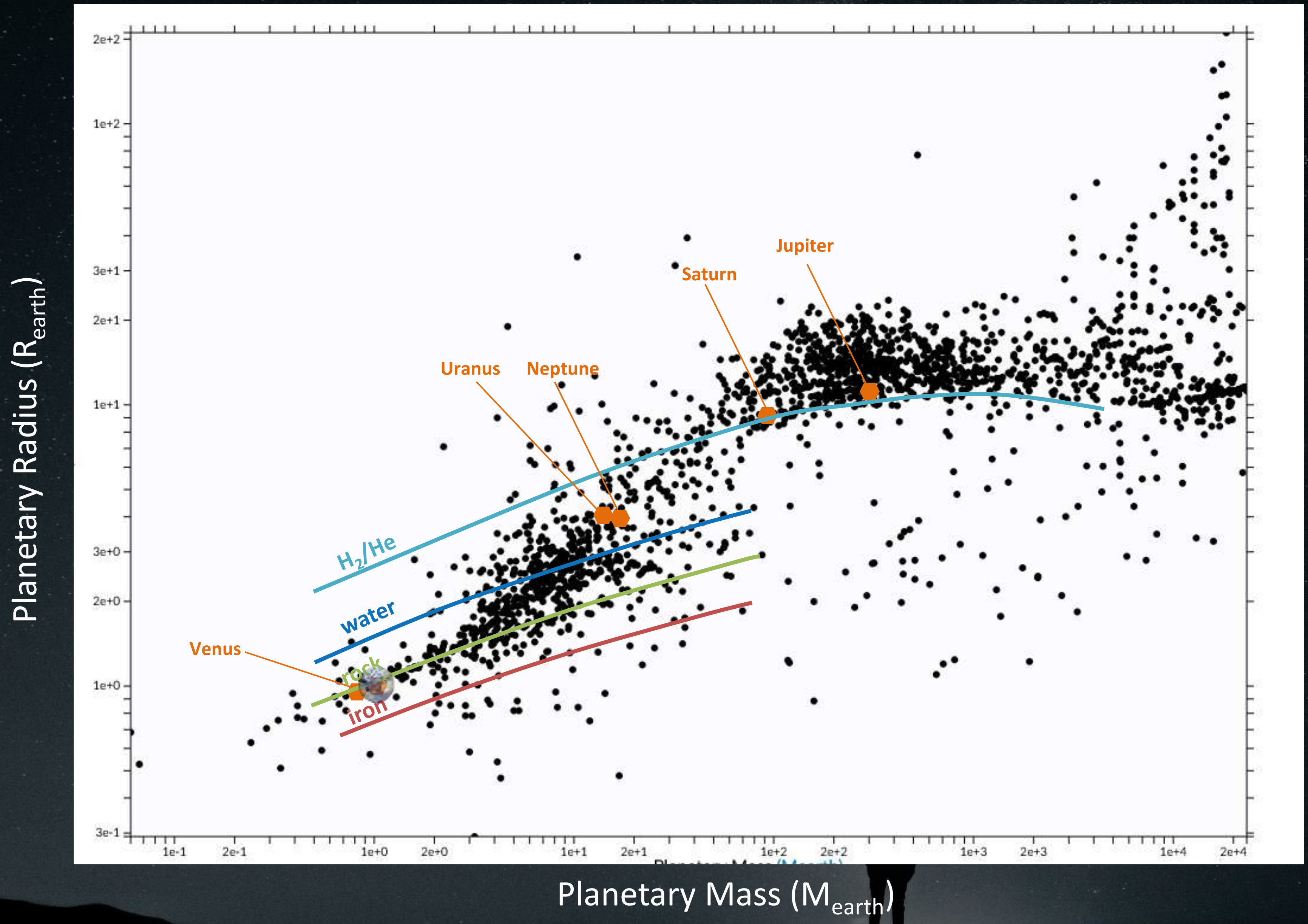


Planetary Radius (R_{earth})

Planetary Mass (M_{earth})

Neptune or Earth-like?

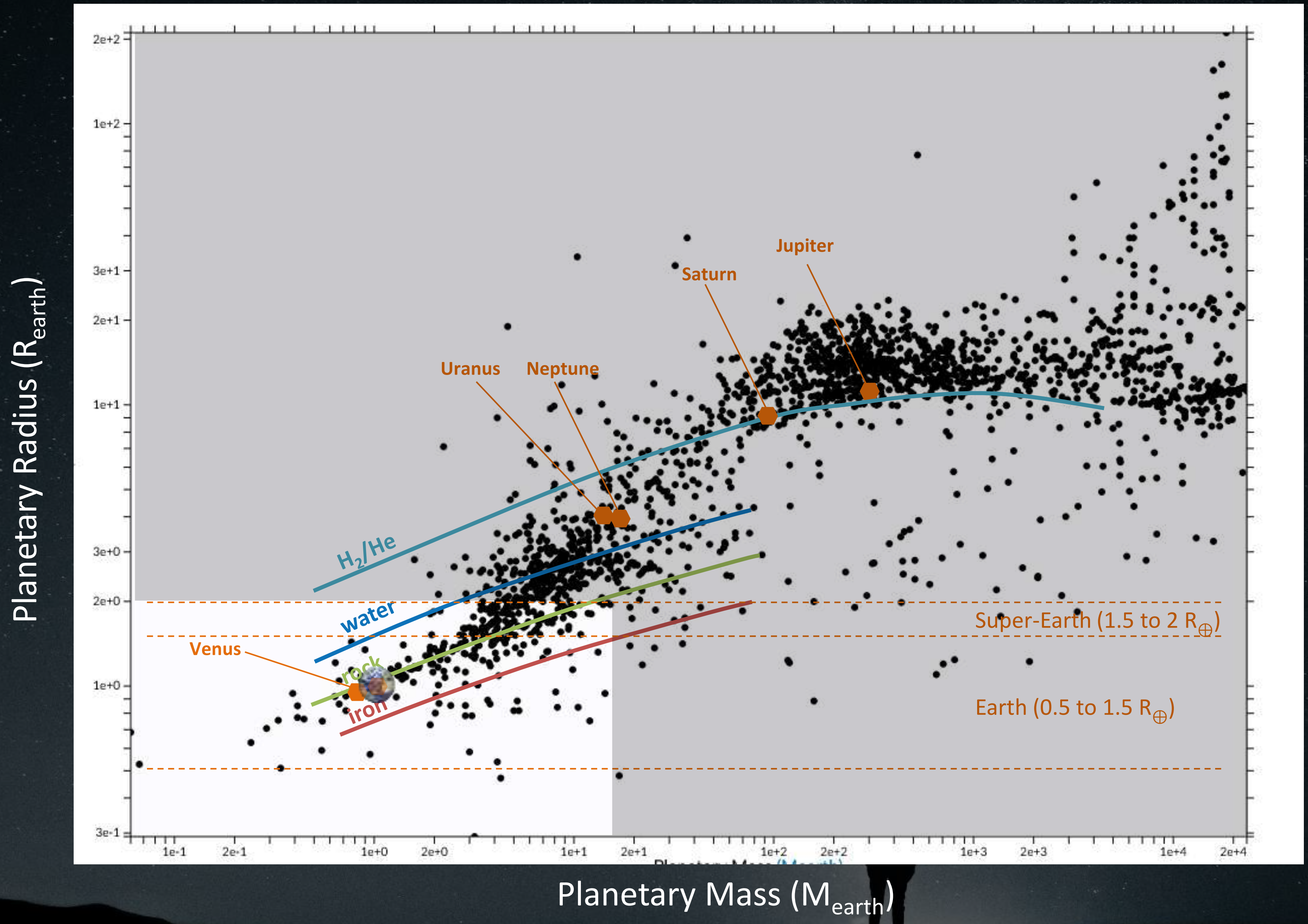
Earth-Like Exoplanets – Interior structure?



Planets do not grow linearly because of self-compression

Similar type exoplanets only along the compositional lines

Earth-Like Exoplanets: What to look for?



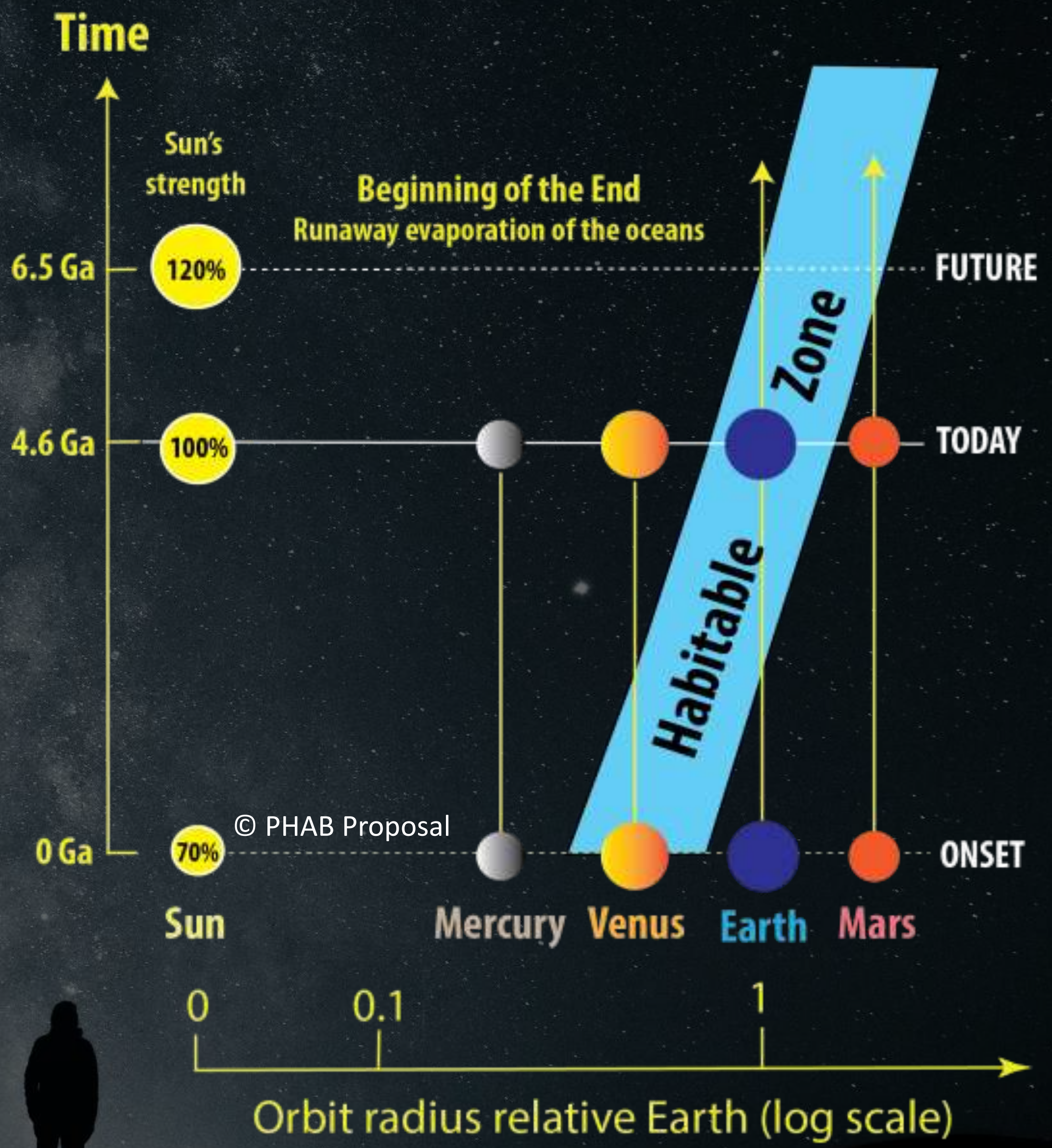
Rocky structure and Earth-like mean density imposes an upper limit for radius R <2.0 R_{earth} and masses M = 1-10 M_{earth}

in the host star's habitable zone

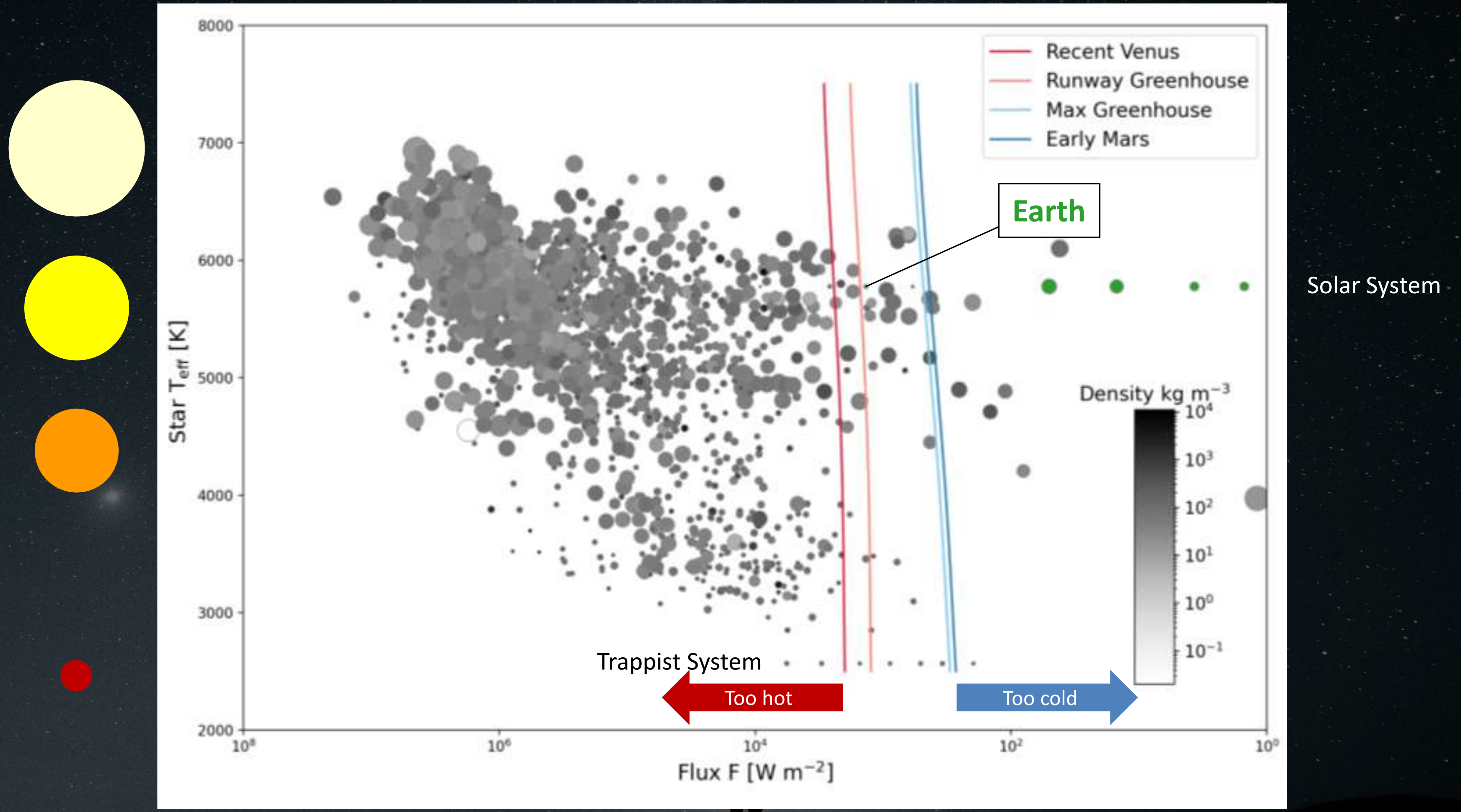
The Habitable Zone – The Astronomical definition of habitability

Presence of **liquid surface water**
for a given distance to the star,
stellar luminosity and
planet's atmosphere composition, …

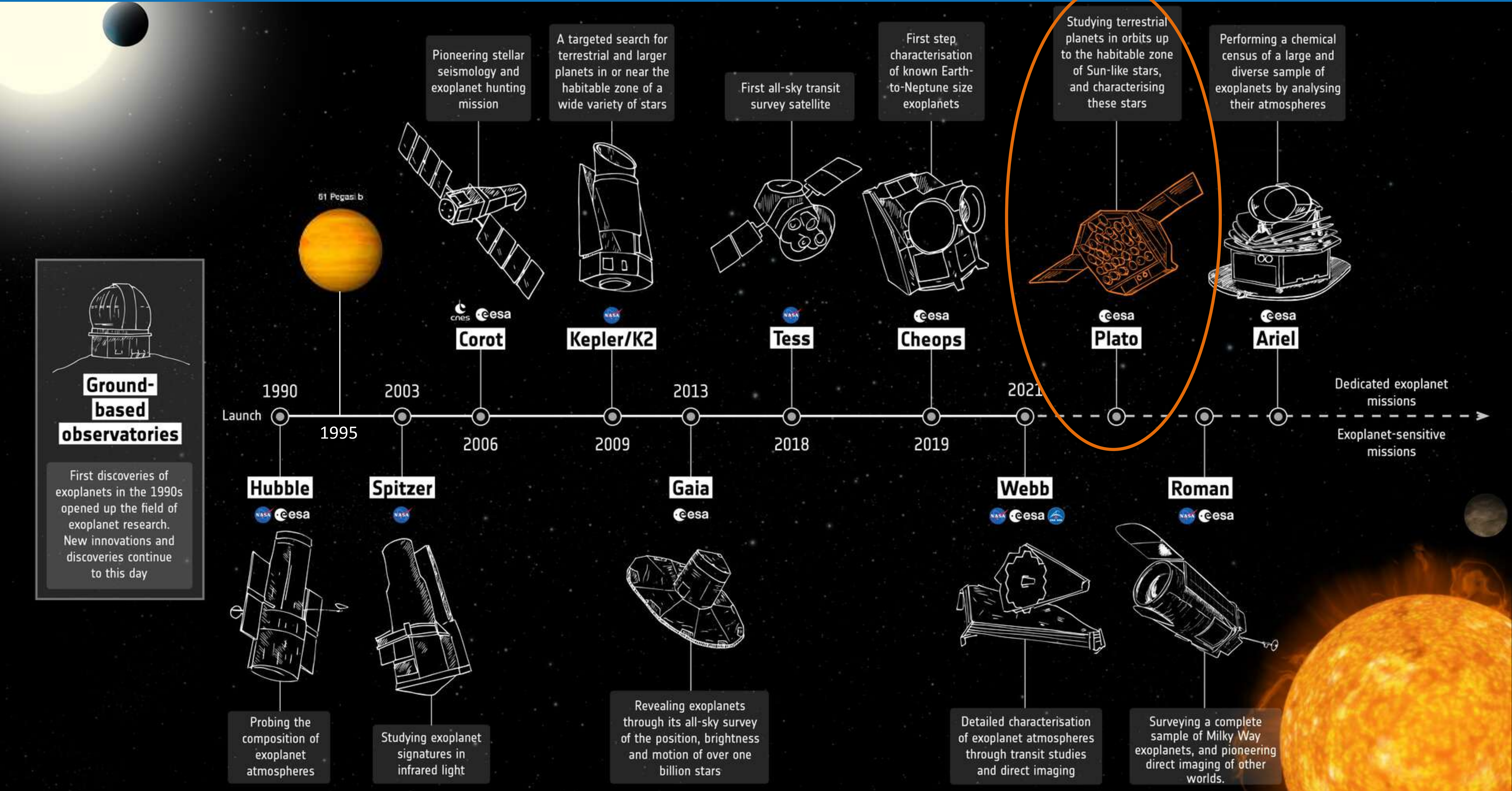
How does the star-planet interplay change these conditions through time?
How to recognise an exoplanet in its habitable phase?



The Habitable Zone: A complex star-planet setting



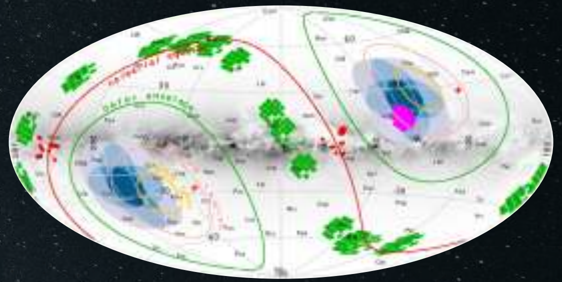
Exoplanet Space Missions and Observatories



The PLATO (PLAnetary Transits and Oscillations of stars) Mission

PLATO is a mission to detect and characterize numerous extrasolar transiting planets including **Earth-sized planets up to the habitable zone of solar-like stars** and to investigate seismic activity in stars, enabling the precise characterisation of the planets' **host star**, including its **age**

Observation Strategy: The nominal 4-year mission involves observing two distinct sky fields for two years each to detect planets with orbital periods up to one year



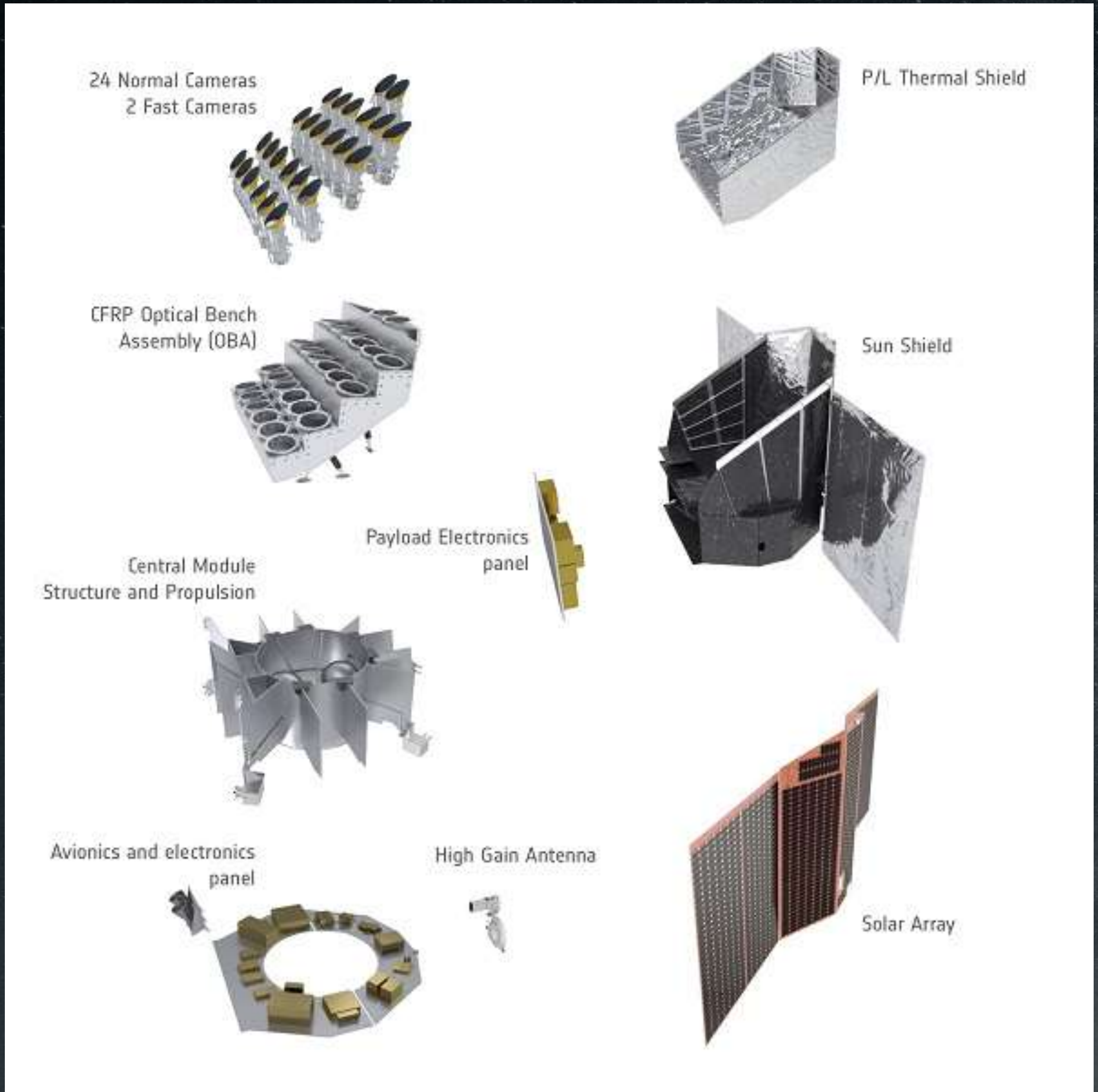
Instrumentation: 24 *normal* cameras for sky monitoring and 2 *fast* cameras for bright star observation.

Image credit: ESA/ATG medialab

Stellar Focus: Primarily targets F5-K7 spectral type dwarf and subgiant stars with magnitude $m_v \geq 11$-13

Methods: Combines **transit photometry** (to find planets) with **asteroseismology** (to analyze stellar oscillations and determine accurate stellar parameters/ages).

The PLATO mission timeline



2011: not selected for M1/M2

2014: mission selection M3

2014: My involvement started

2017: mission adoption

2018: contract with OHB signed

2018: Norwegian hardware contribution signed

2019: first CCD delivered

2022: Critical Milestone success

2022: EM tests at SRON and IAS

2024: first FMs integrated in S/C

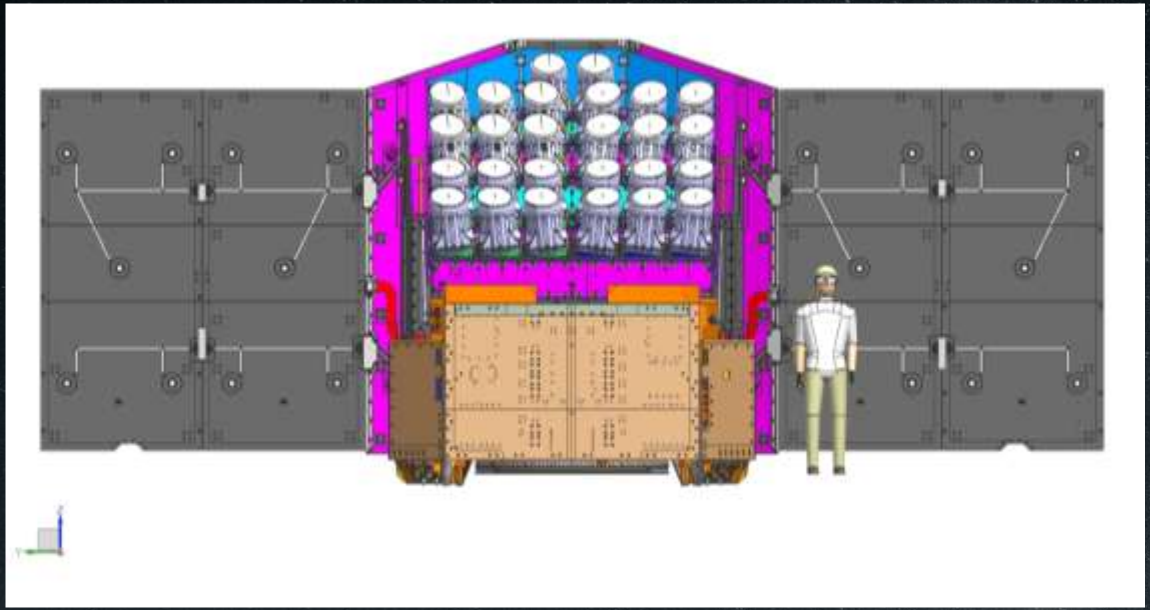
2025: Spacecraft at ESTEC

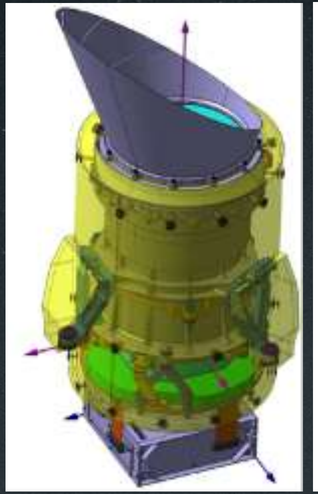
2027: launch Ariane 6

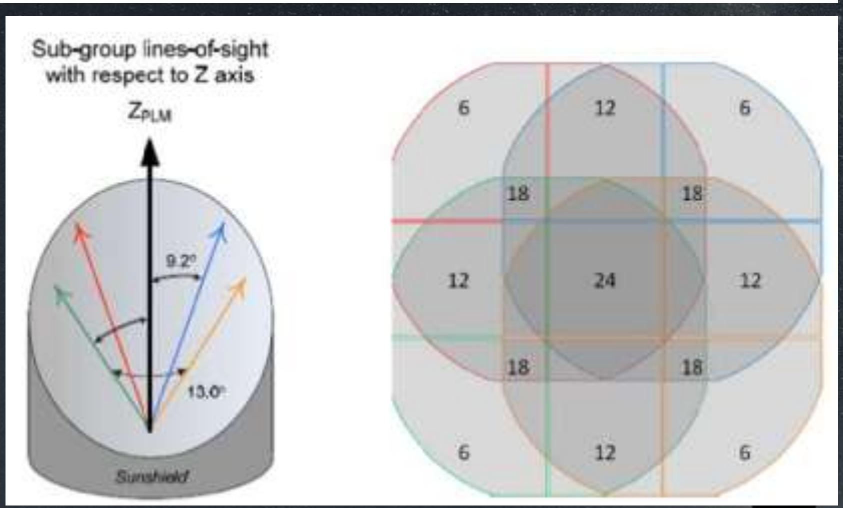
2027: start nominal operations

2028: first calibrated data

The PLATO Telescope

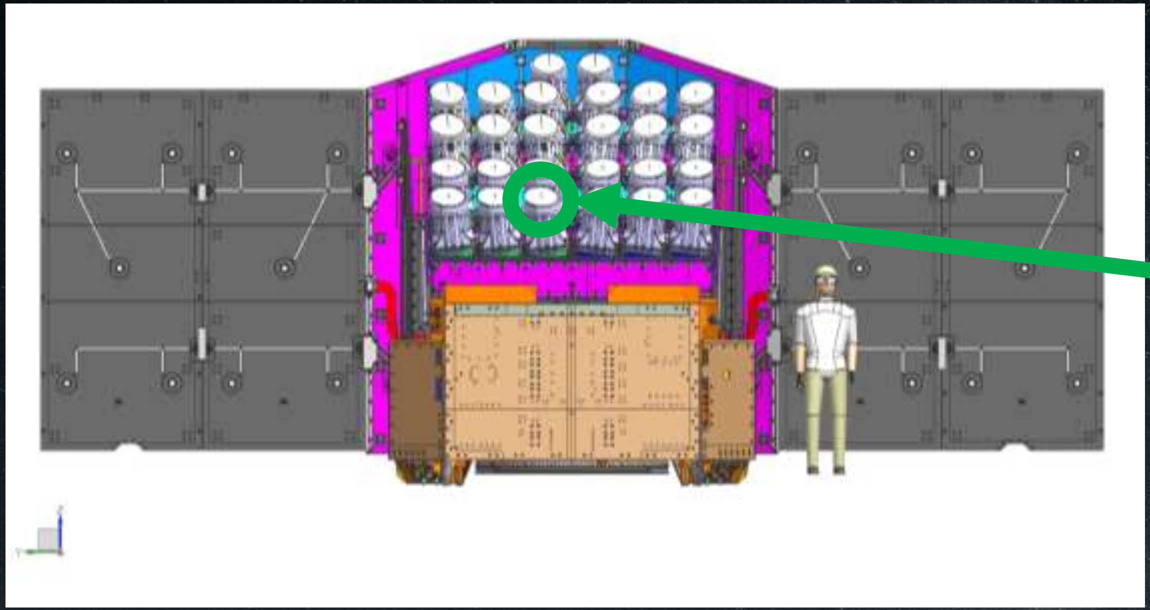




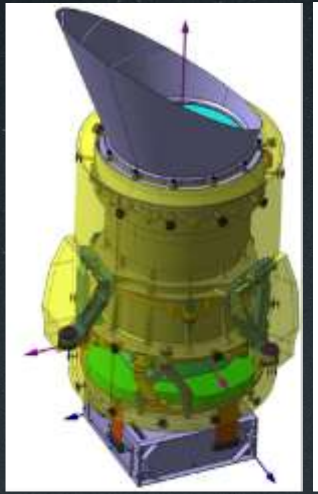


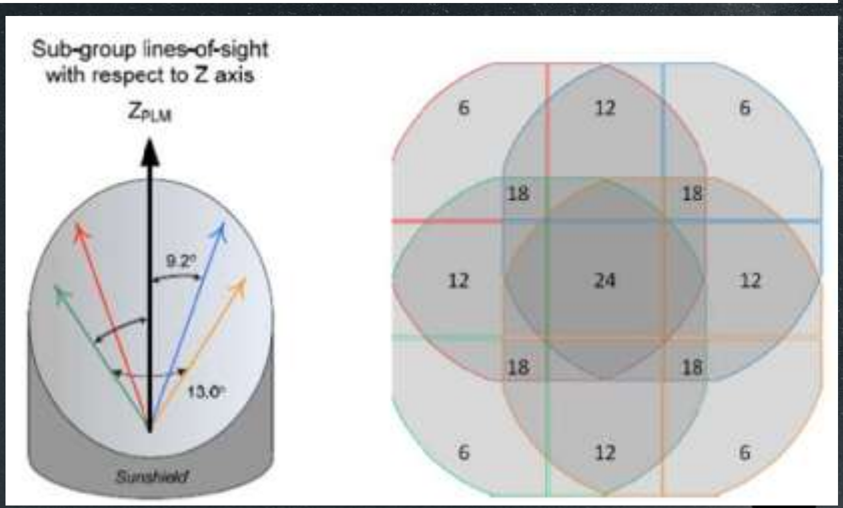
PLATO status update CW08-26:
… Plato was successfully installed in the TVAC chamber (LSS), before that the SC and cameras were once again inspected for cleanliness. …

The PLATO Telescope

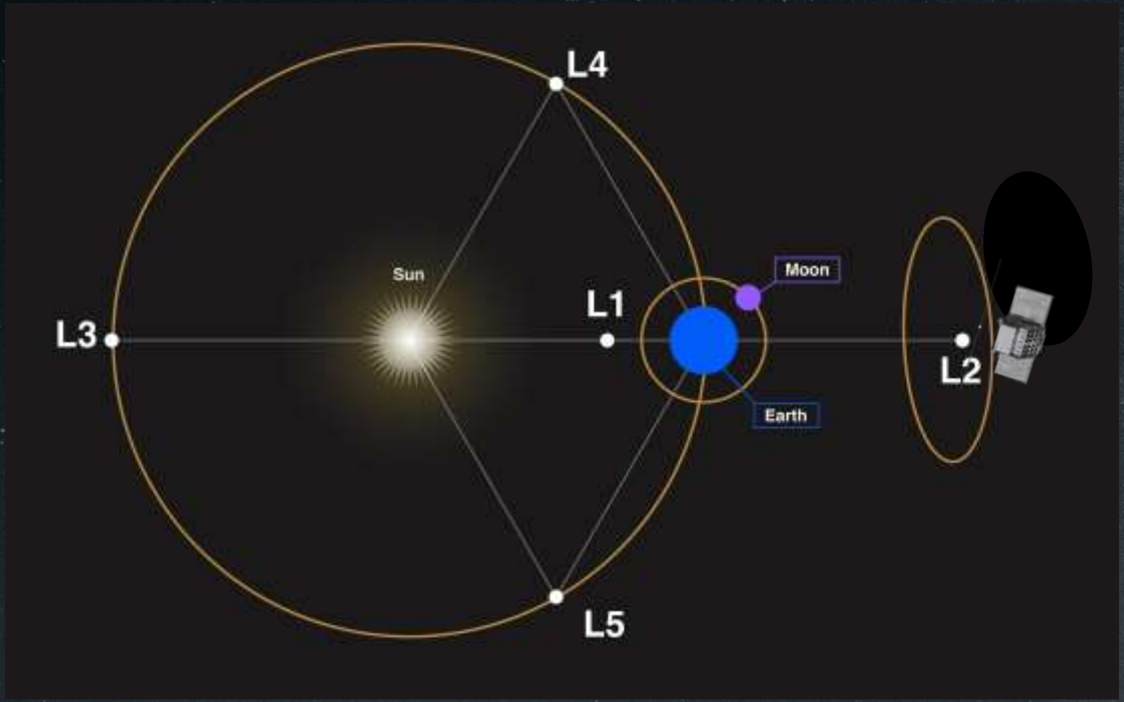


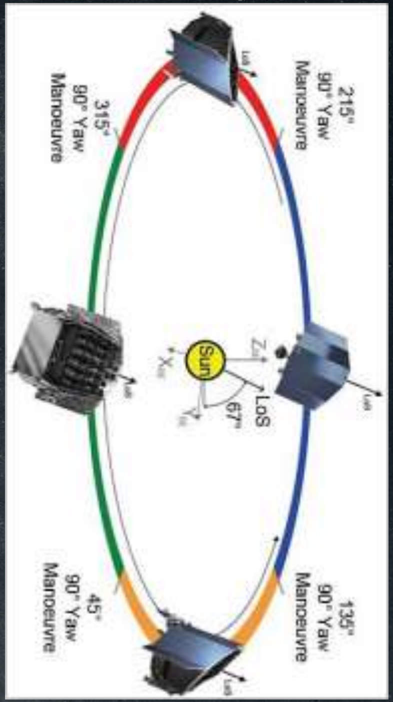
Camera named **CHansteen** after Christopher Hansteen (1784-1873) Norwegian Astronomer and Geophysicist

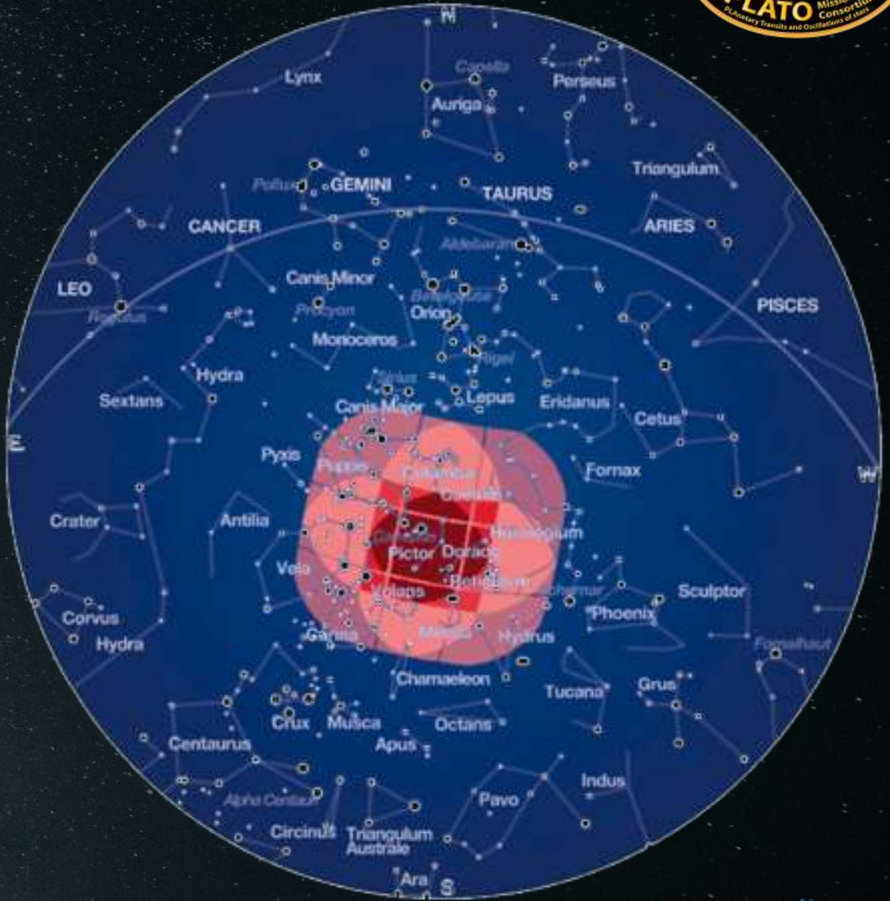




First PLATO Long-duration Observation Phase (LOP) field selected



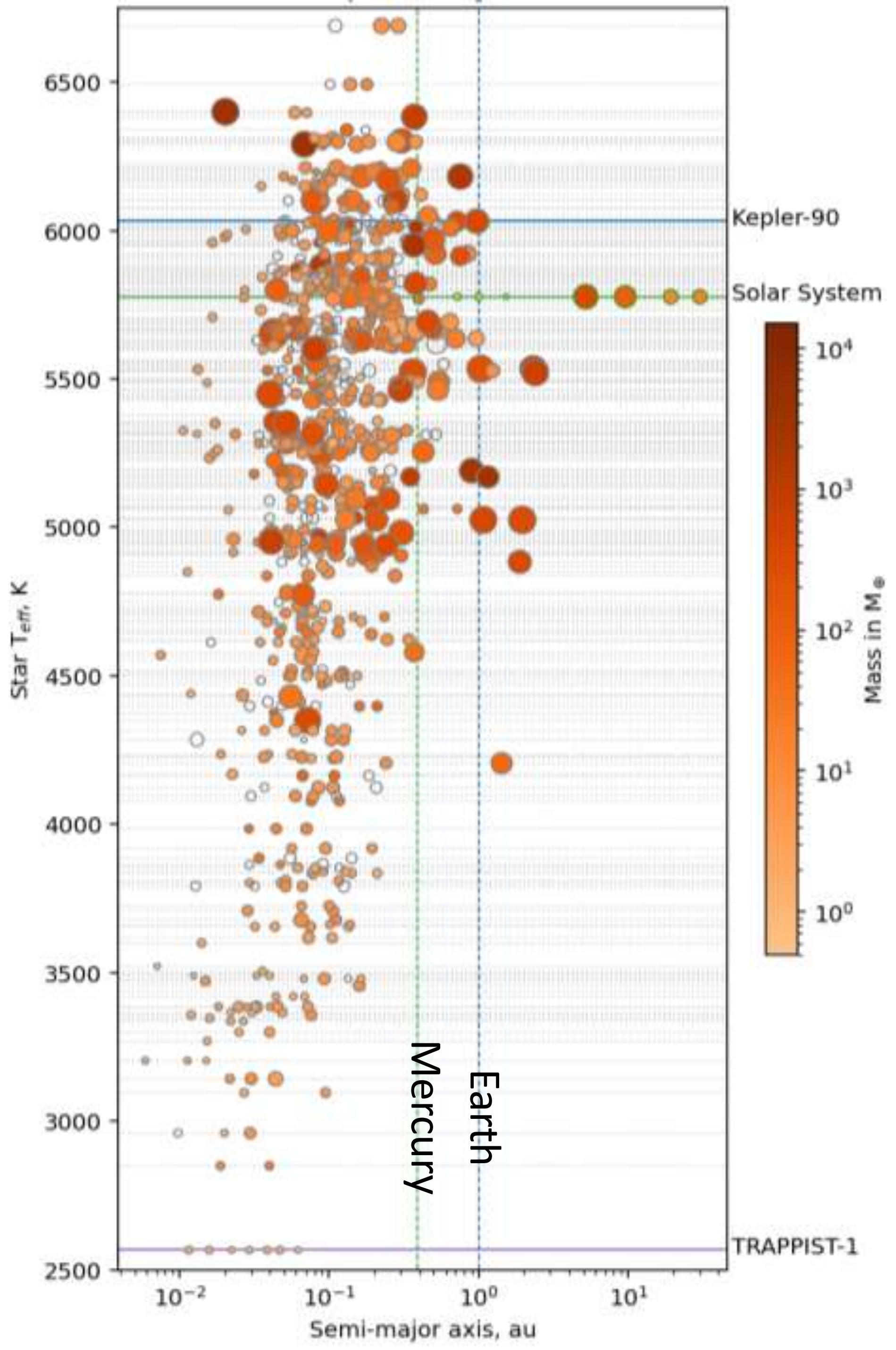




The **Galactic Recipe for Exo-Planets** Project

Our goal is
to predict and reproduce the architecture of these exoplanetary systems
and the exoplanet properties, including composition, thereby testing currently competing planet formation models against observations from PLATO.

Diversity of Exoplanetary Systems



Diversity of Exoplanetary Systems

None like the Solar System!

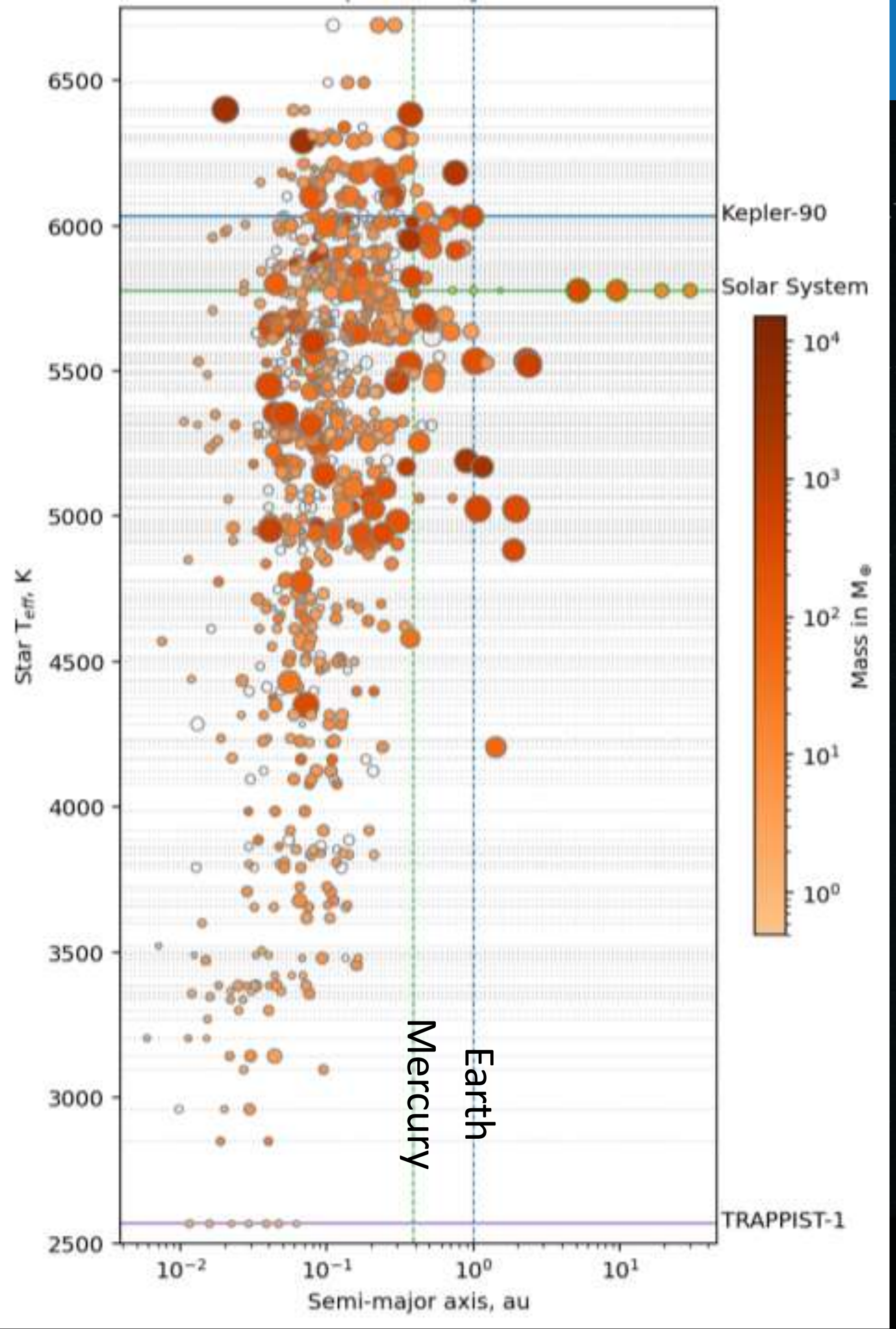
How to truly overcome observational bias?

Is it easier to form large/massive, close-in planets?

Is it easier to form compact exoplanetary systems than the extended solar system?

Can we derive properly exoplanet composition?

Is the strategy "follow the water" a good guide?



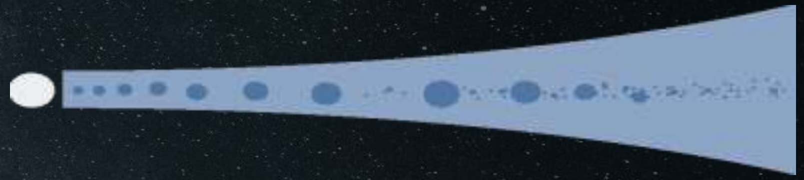
Develop predictive models from the Solar System - Dynamics

1. Gas-dust disk formation

2. Dust sedimentation

3. Planetesimal formation

4. Solid and gaseous planet formation



5. Icy planet formation

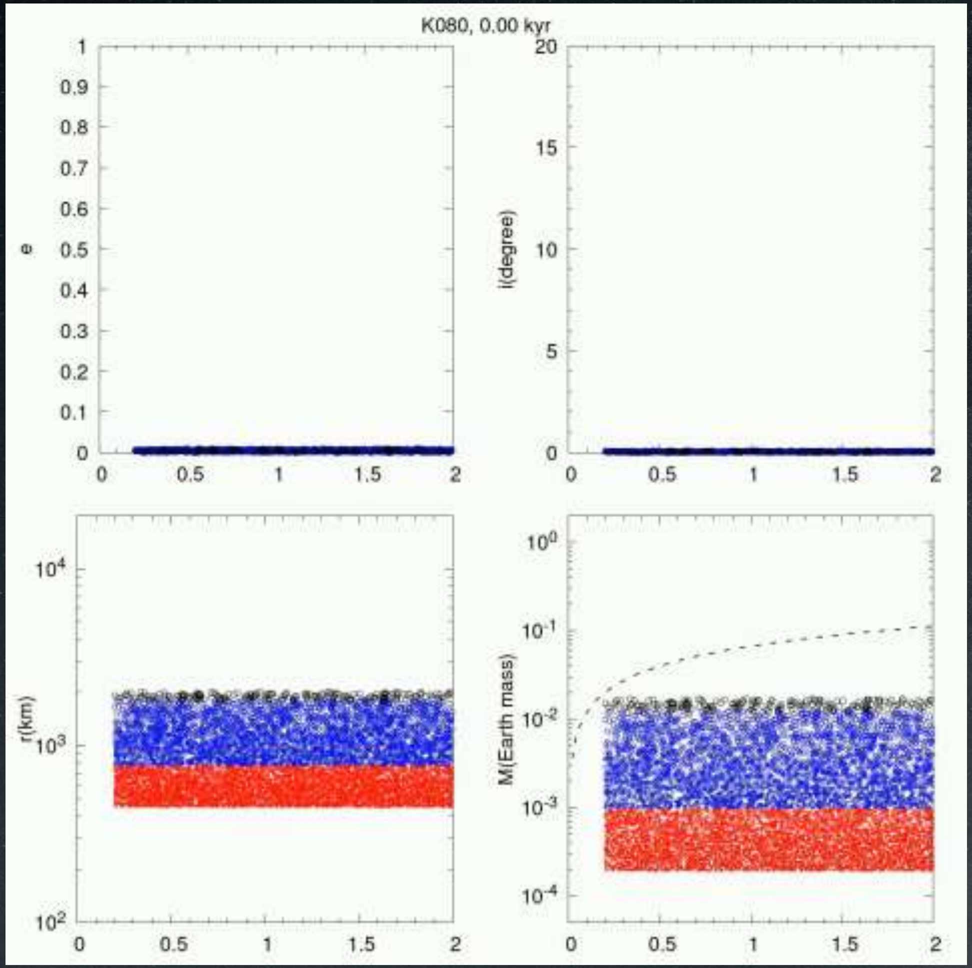
6. The Solar System

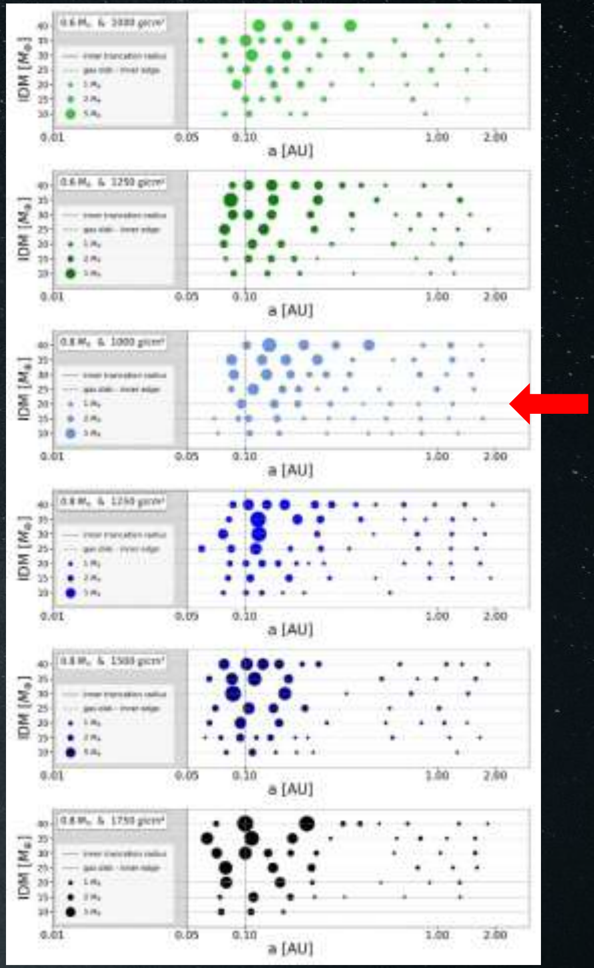
Centre for Planetary Habitability

Building Earth-like Exoplanets

Assumption: Planet formation via compositionally sorted planetesimal accretion

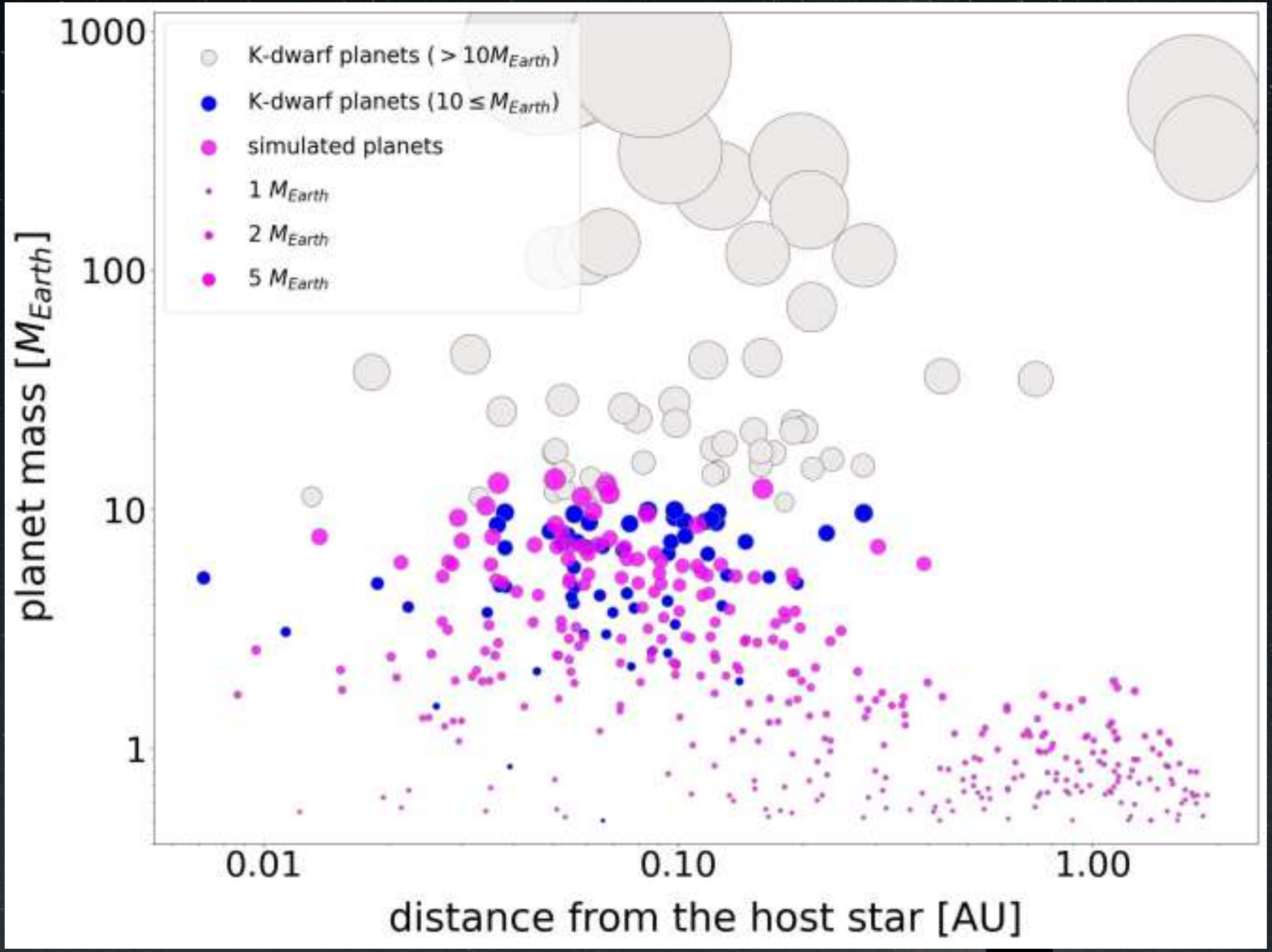
Method: High-resolution N-body simulations of late planet formation





Hatalova et al. 2023

Simulations of terrestrial planet formation around K-dwarf stars



Results:

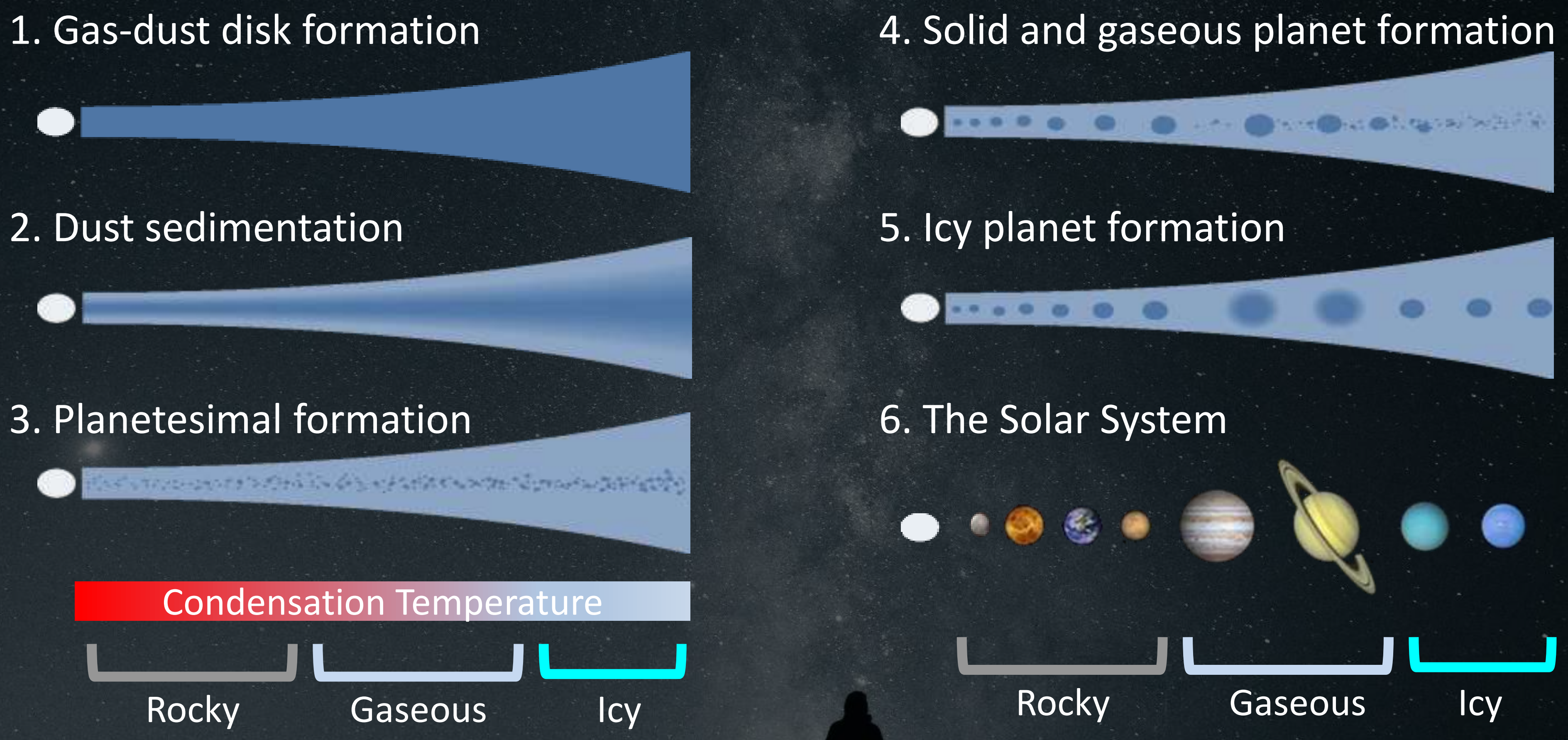
- Reproduction of the observed planet **mass** distribution using adopted solar system conditions

Next Step(s):

- **Radius** ⇦ Composition modelling: Assigning composition to the traced planetesimals using an equilibrium condensation model
- Assess whether they are really Earth-like exoplanets

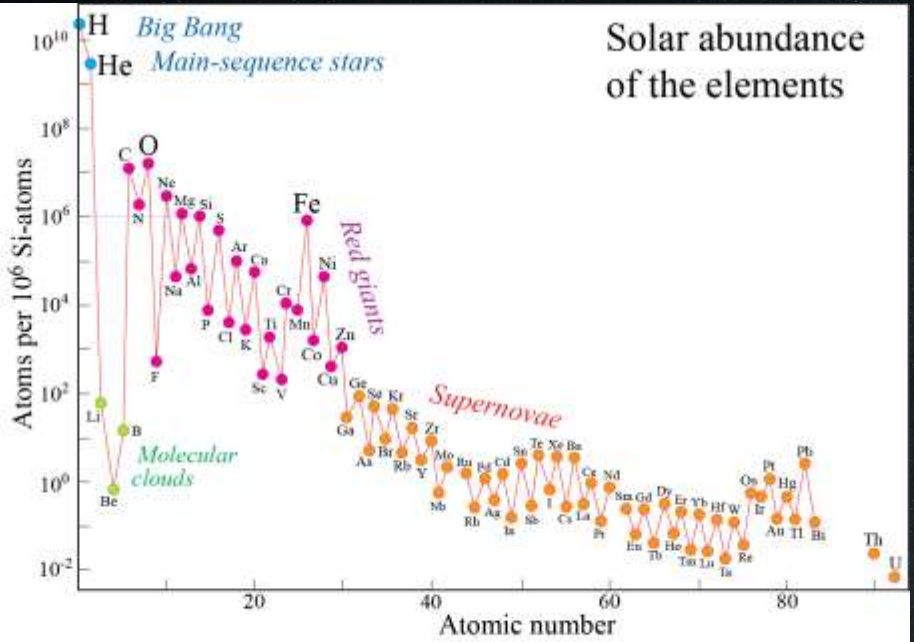
Hatalova et al. 2023

Develop predictive models from the Solar System - Composition

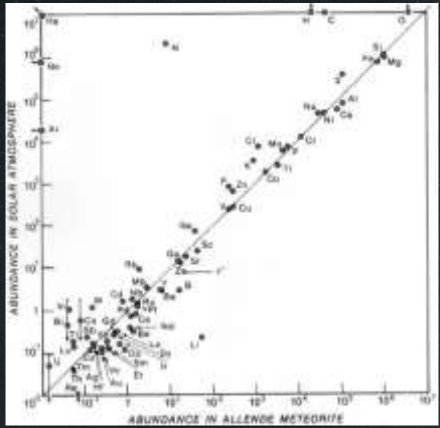


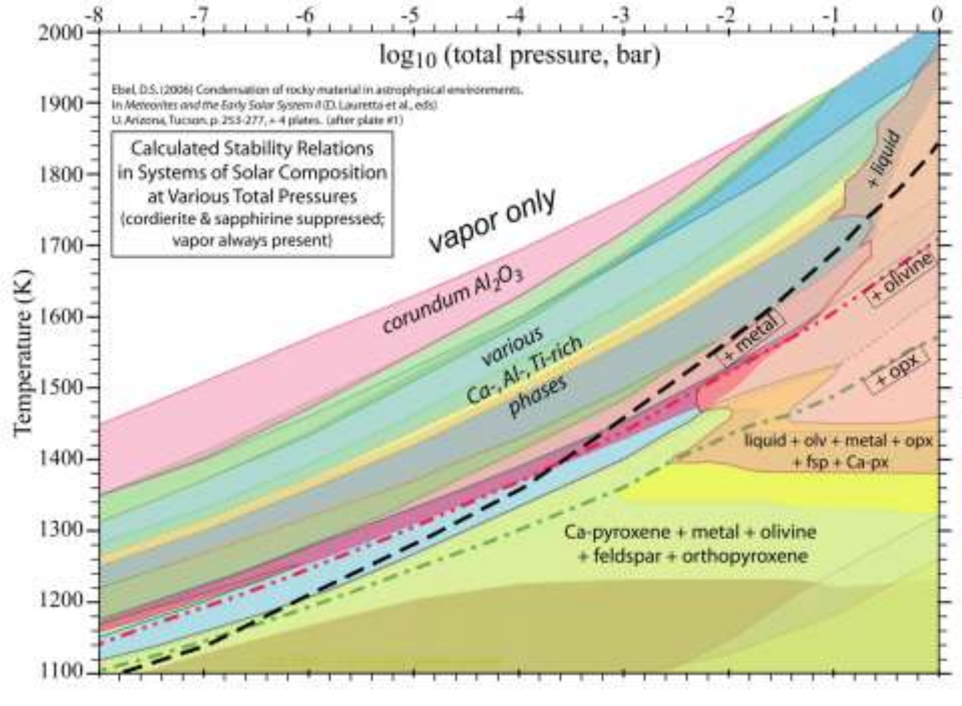
Condensation sequence is key to the *solid* planet ingredients

Element abundance of carbonaceous chondrites match the solar photosphere



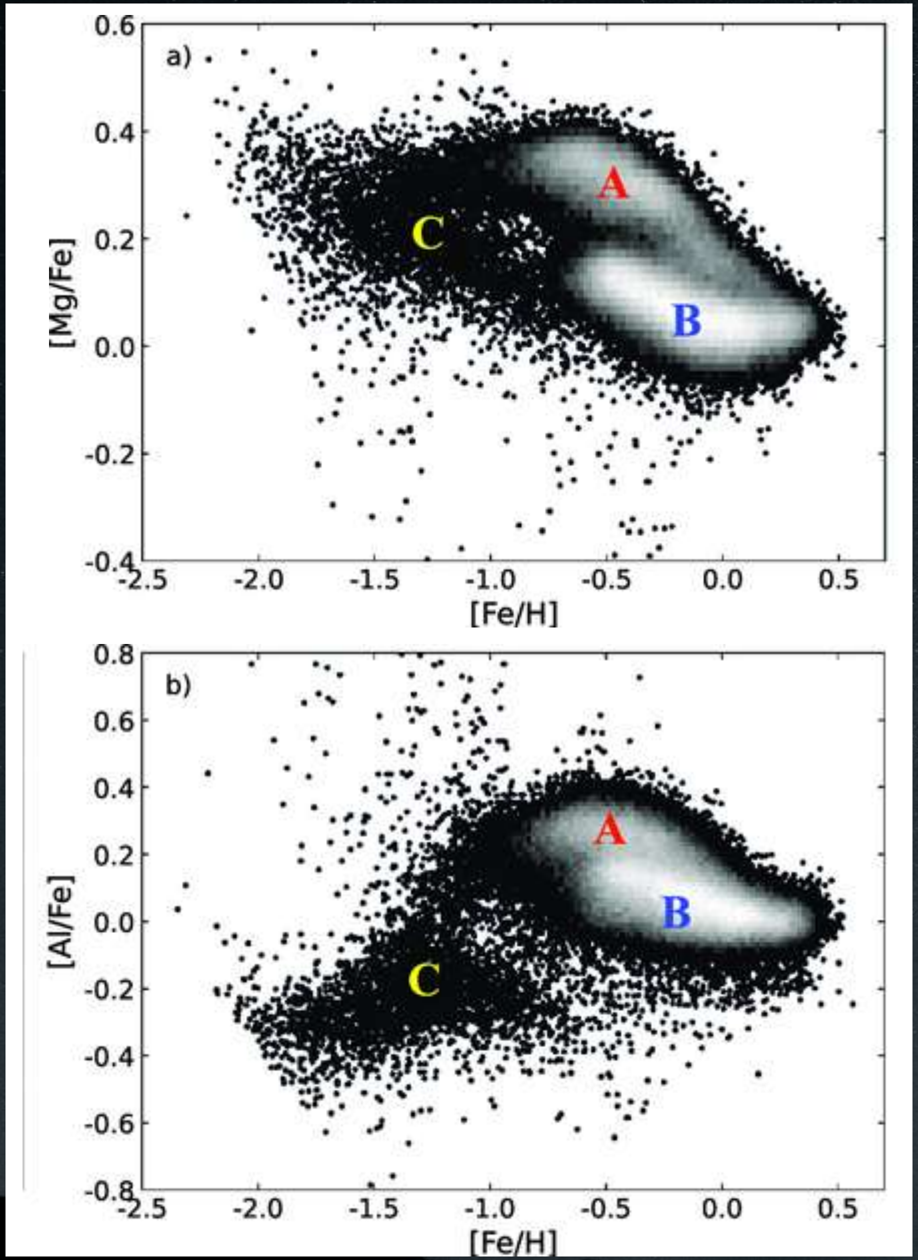
Allende Meteorite

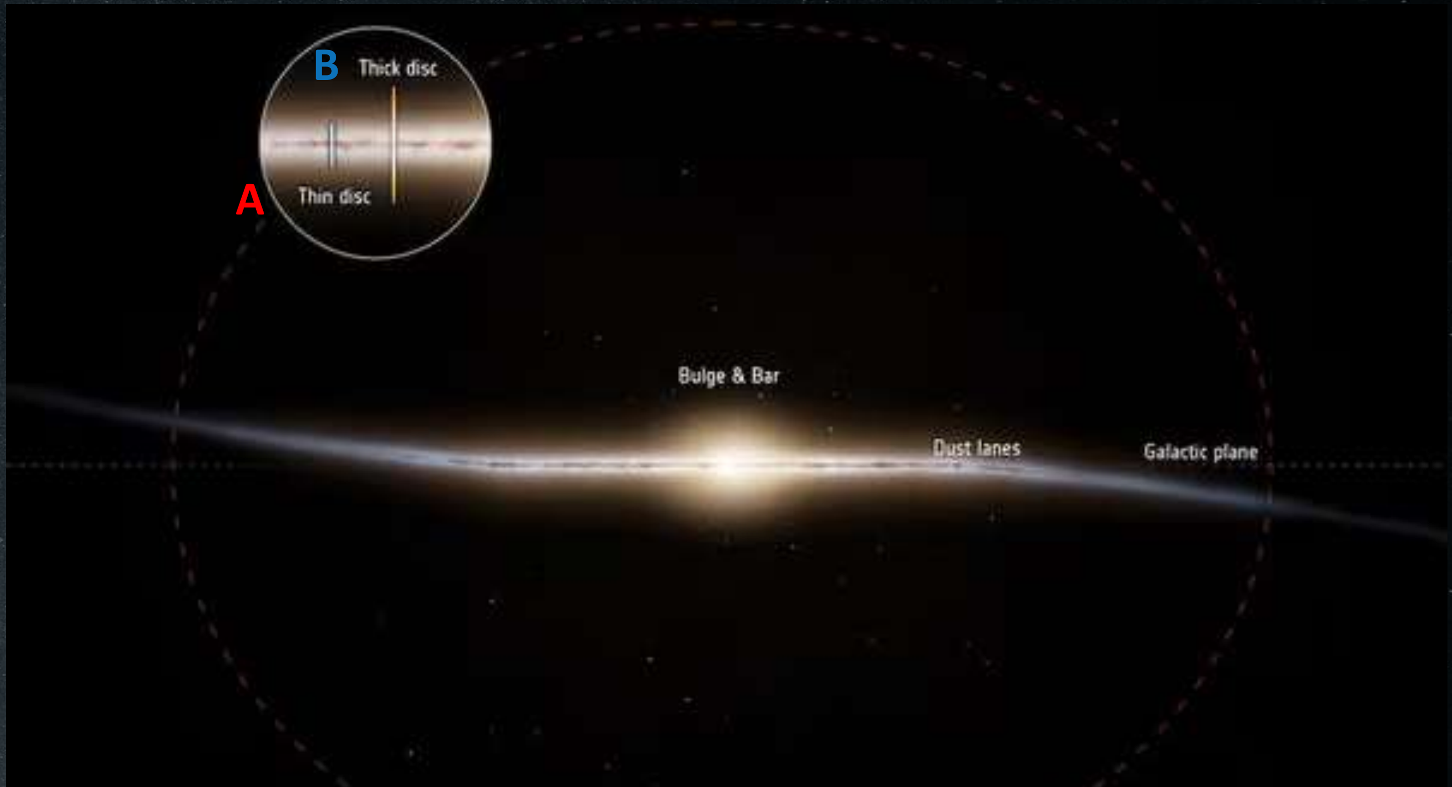




Simplified version of condensation of rocky material in astrophysical environments; e.g., Ebel (2006)

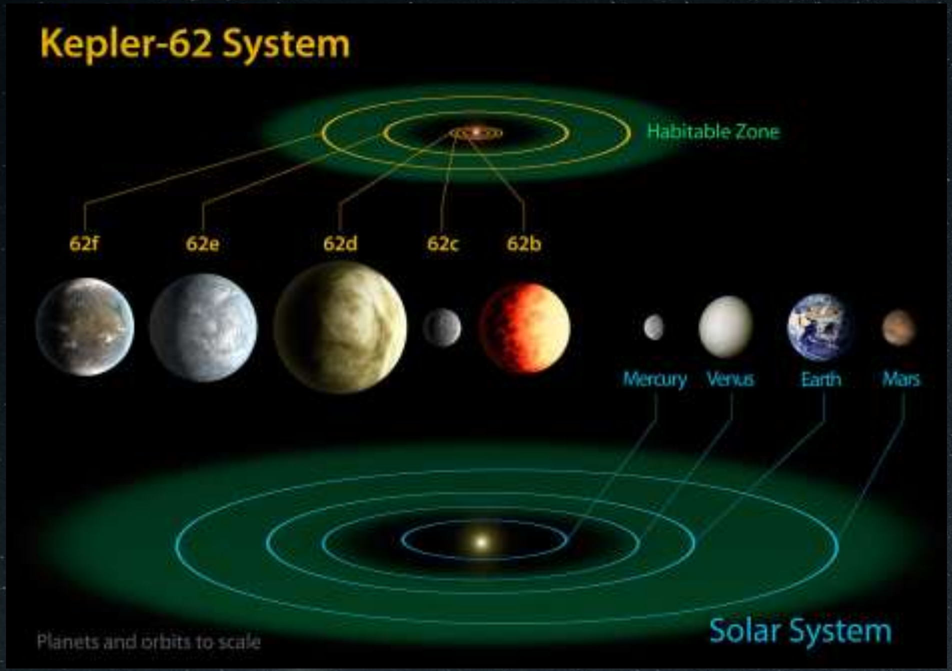
Elemental abundance distribution in the Milky Way

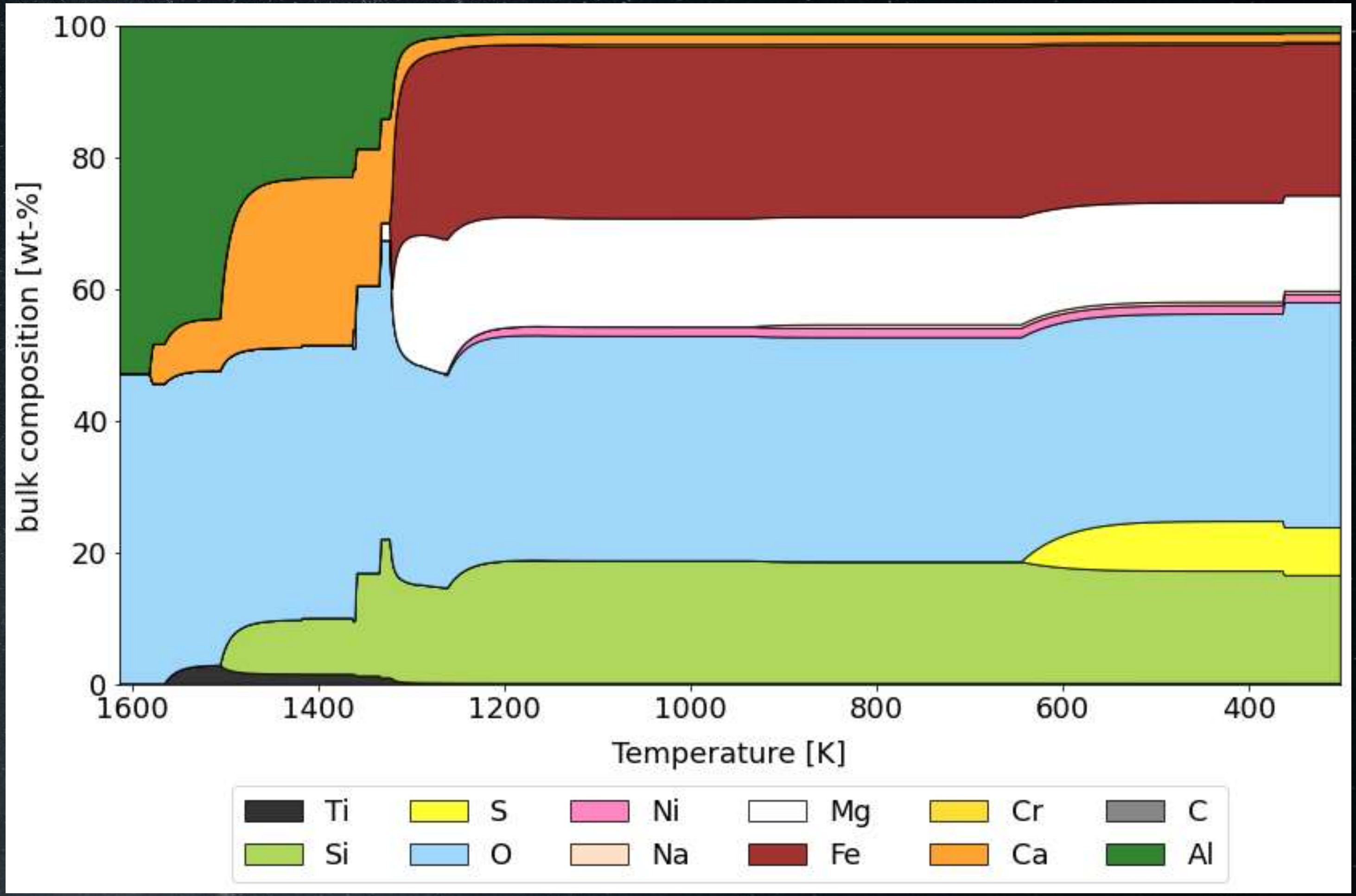




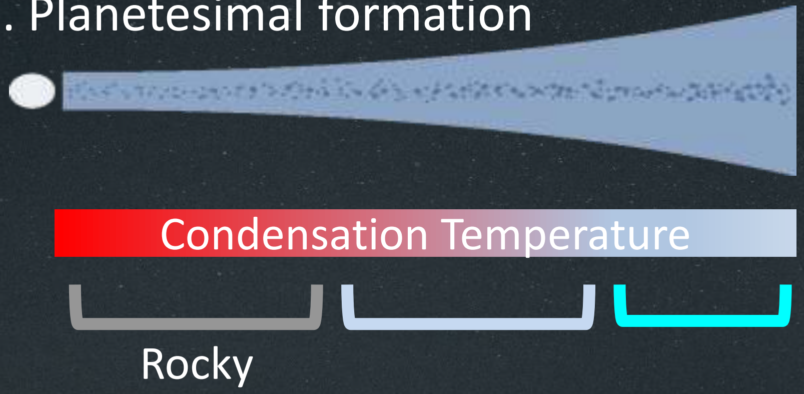
APOGEE DR17 and Gaia
A-classical thick disk,
B-classical thin disk, and
C-additional low-α component.

Each planetary system has its own condensation sequence



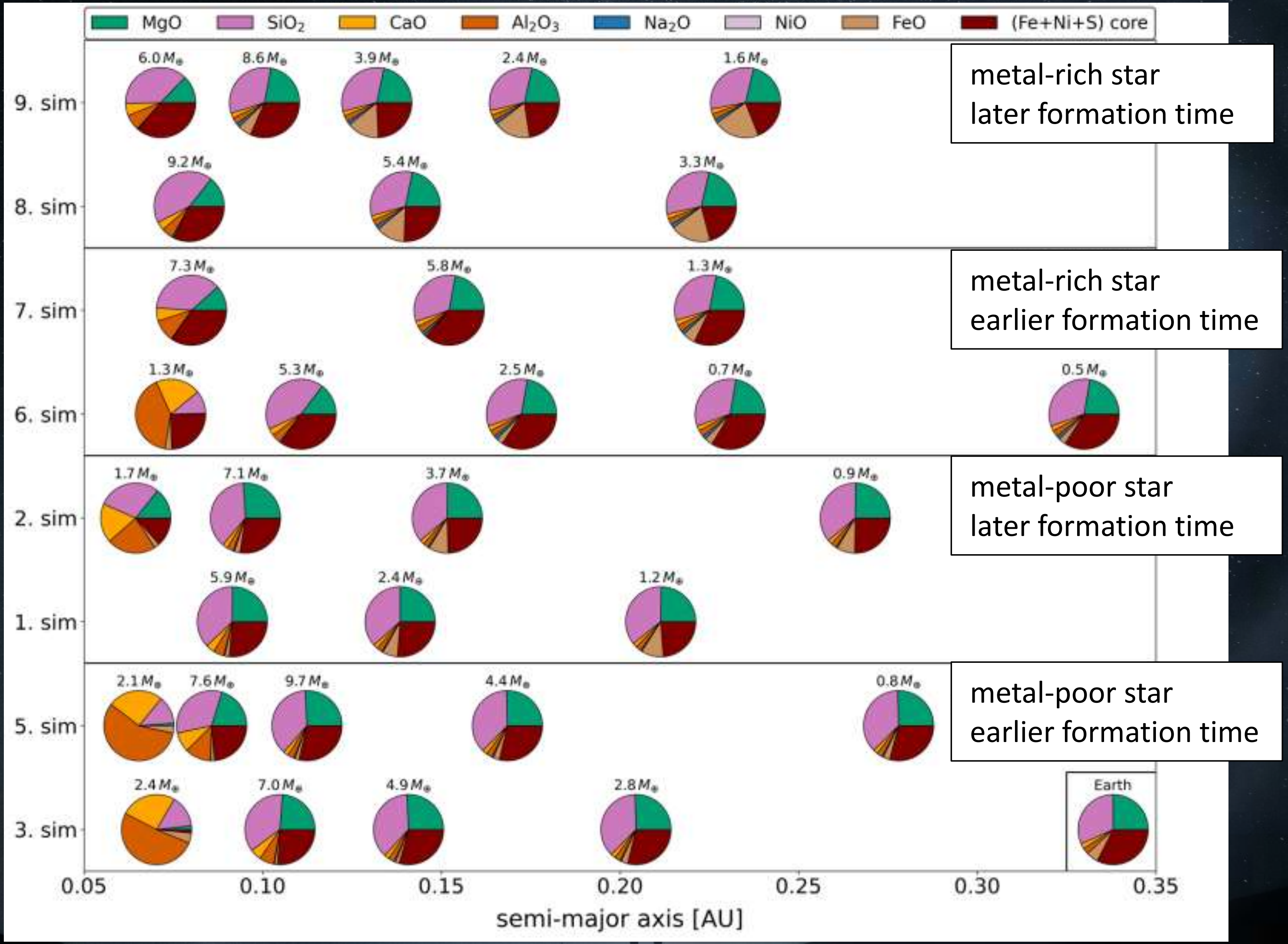


3. Planetesimal formation

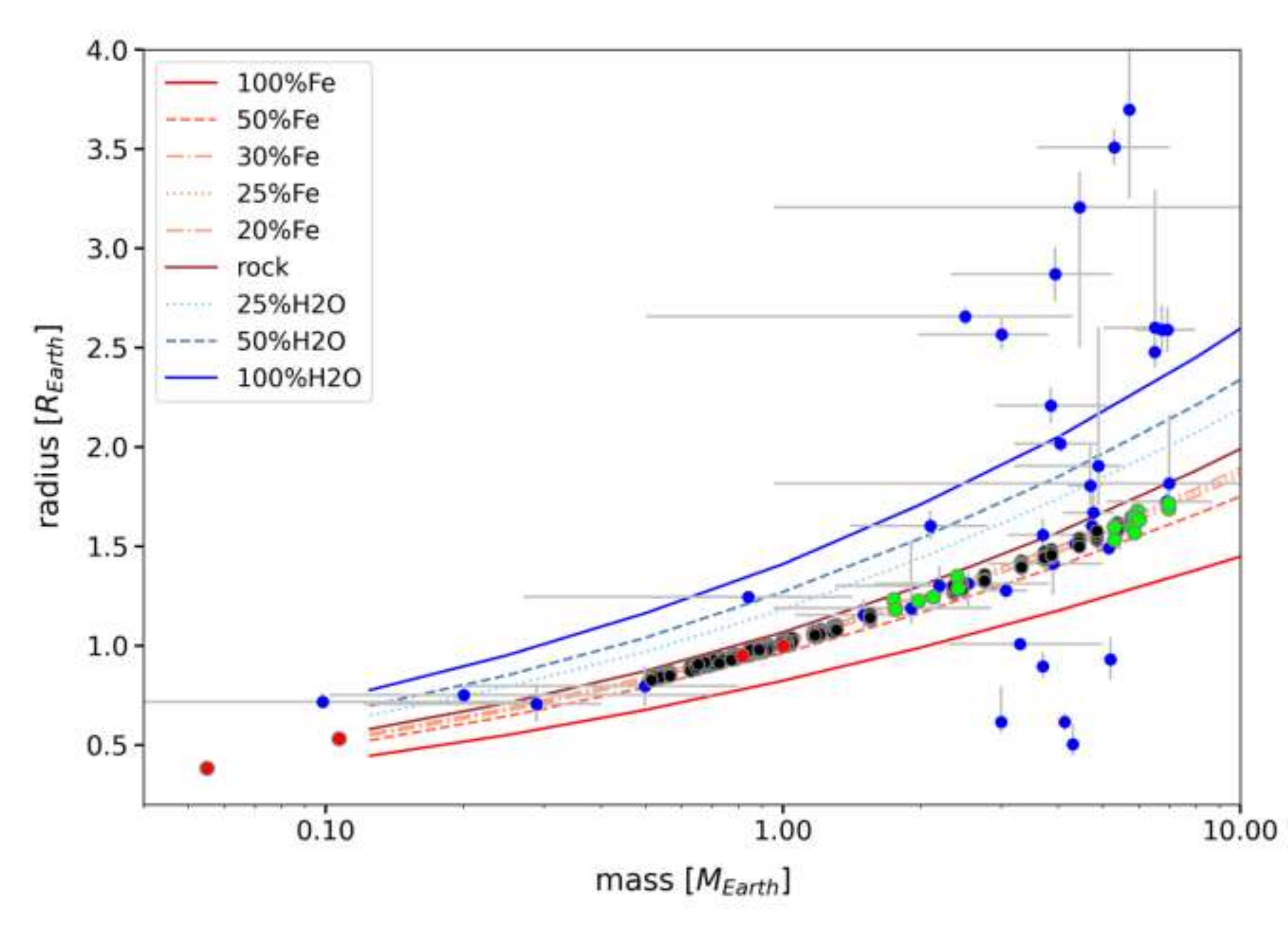


Kepler 62
K2V : 4925 K, metal poor; Age ~7 Ga; 5 planets
B 9 Me 0.055 AU 1.31 Re ; C 4 Me 0.093 AU 0.54 Re ; D 14 Me 0.120 AU 1.95 Re
E 36 Me 0.427 AU 1.670 Re ; F 35 Me 0.718 AU

Compositions of rocky exoplanets



Mass-Radius Diagram

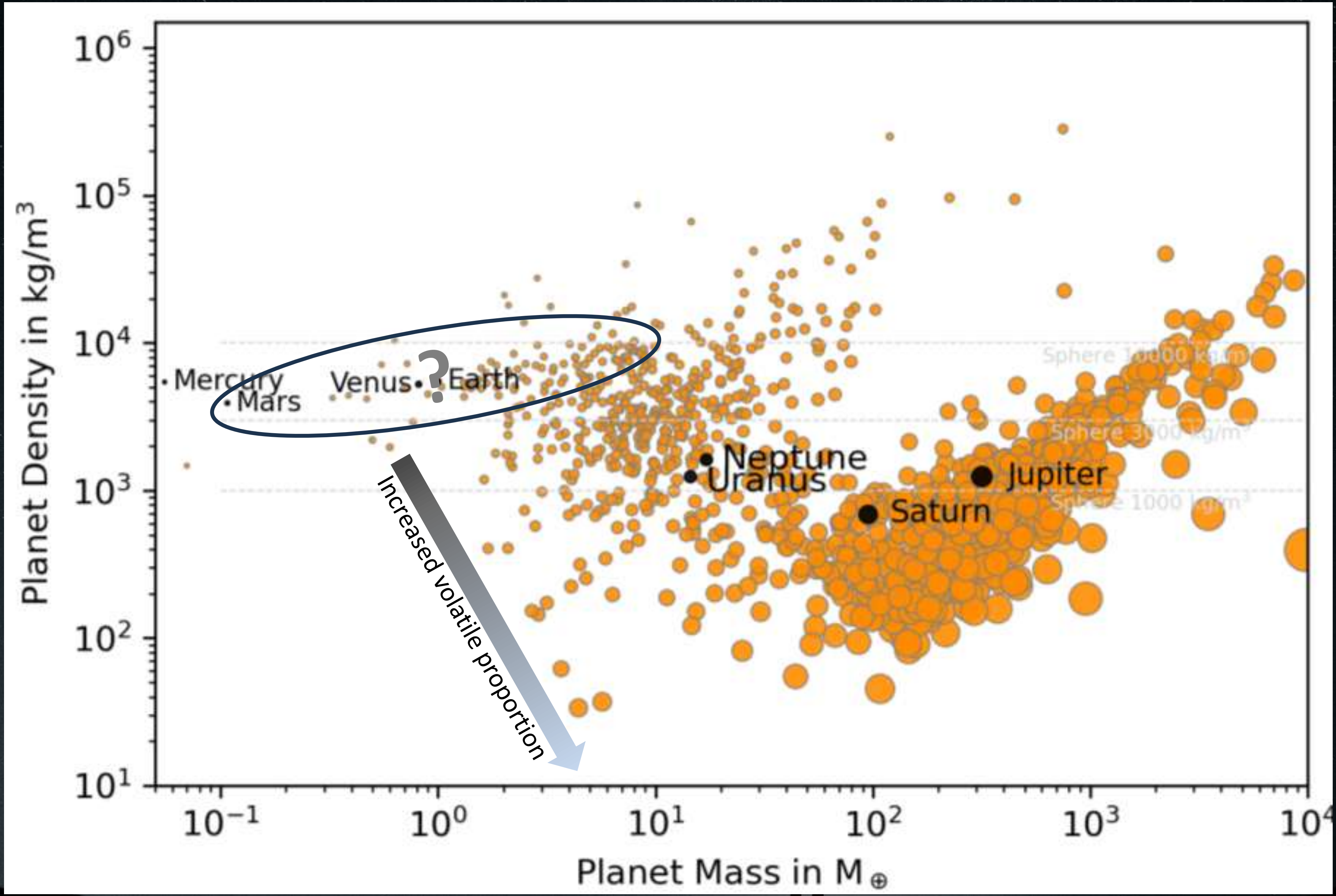


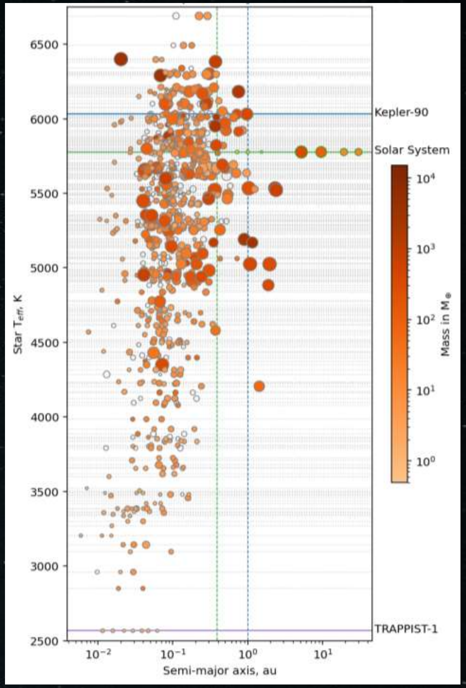
Majority of planets are compositionally like **more or less massive versions** (black) of Earth or Venus (red)

Ca- and Al-rich innermost planets (green) almost reach the rock (core-less planets) and 50%Fe curves

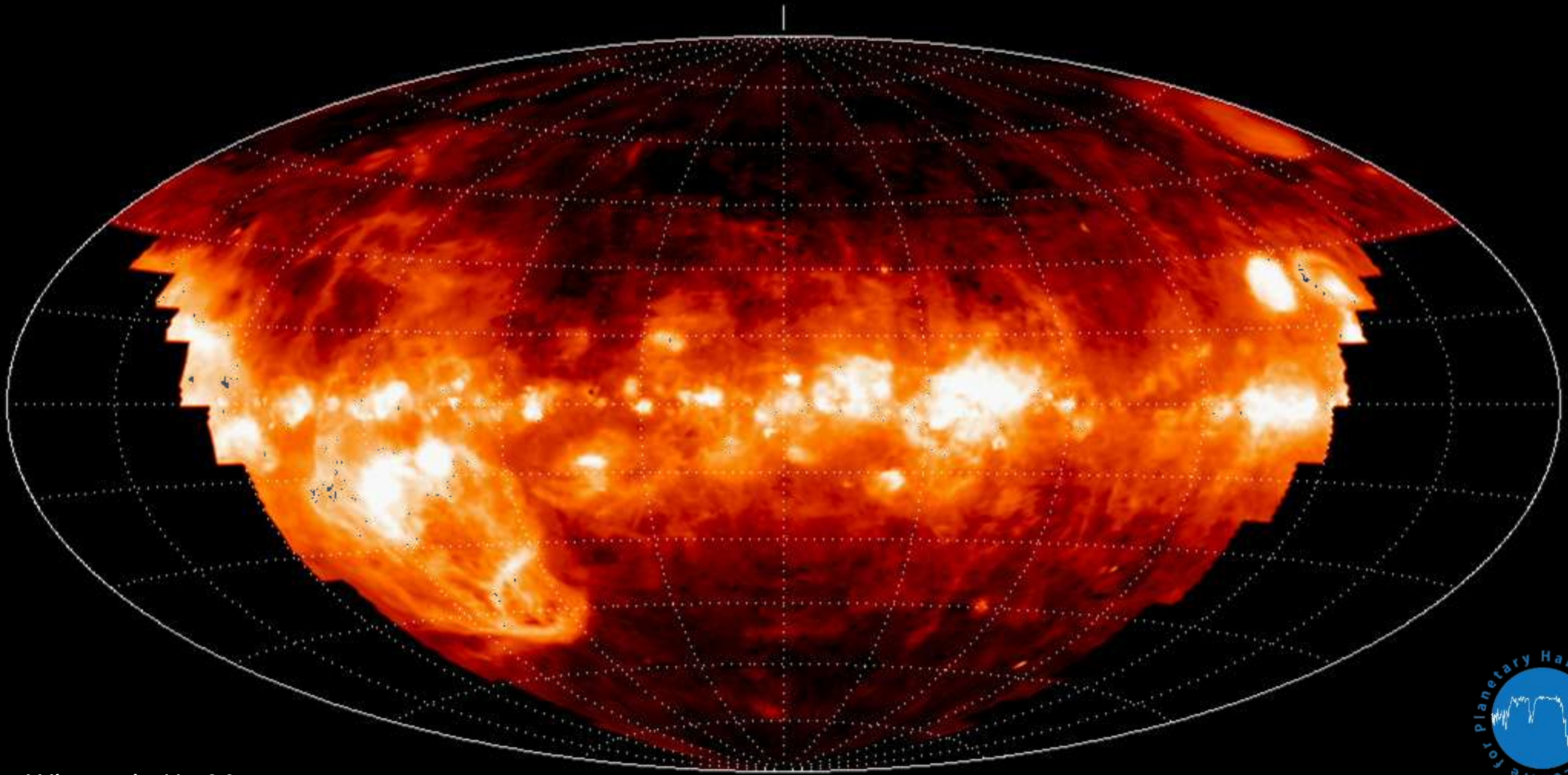
However, we do not capture those with low average density (which probably have thick atmospheres) …

Why are there so few rocky exoplanets?



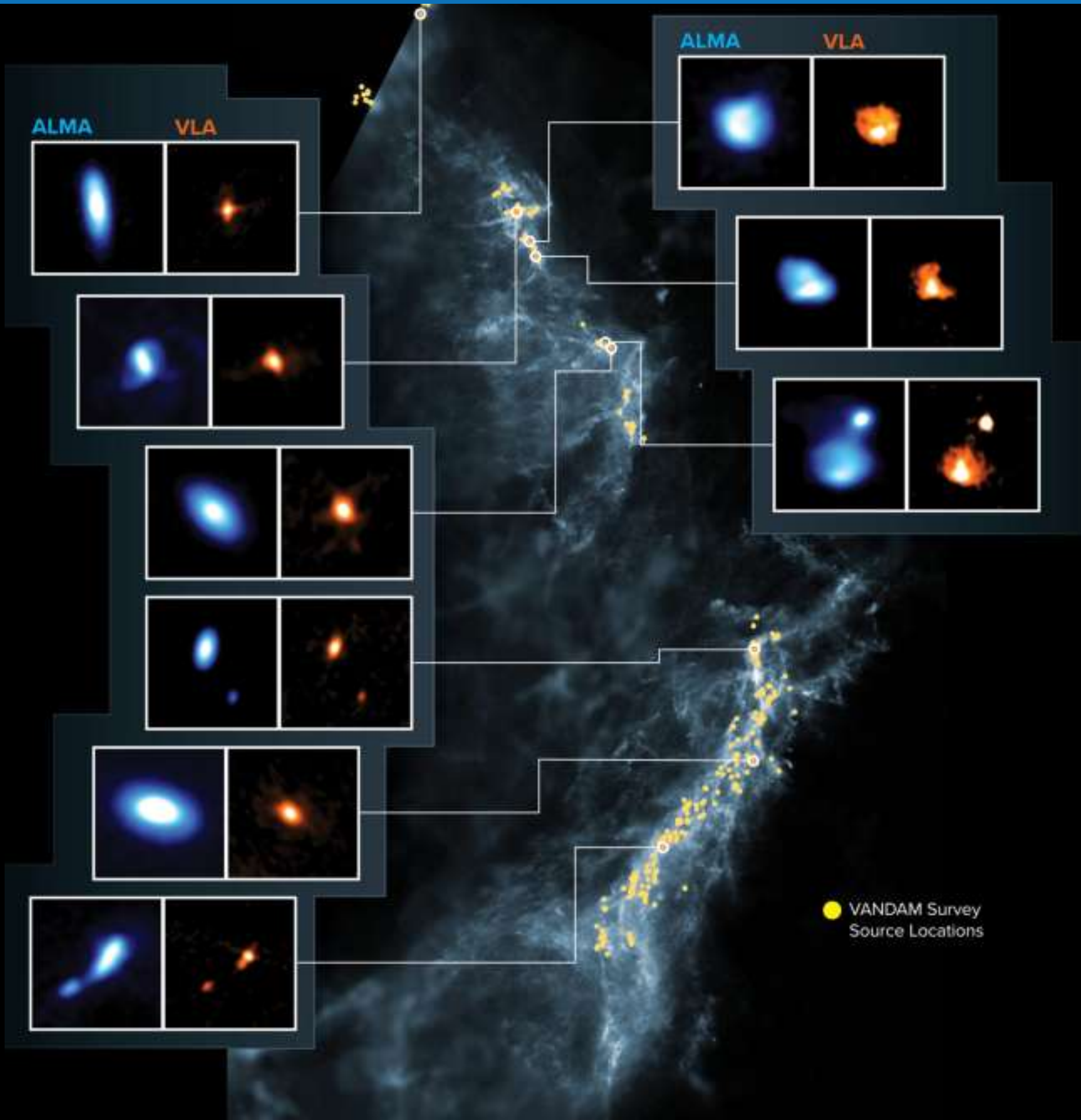


Interstellar Medium mapped by ionized H – Cradle of stars and planets

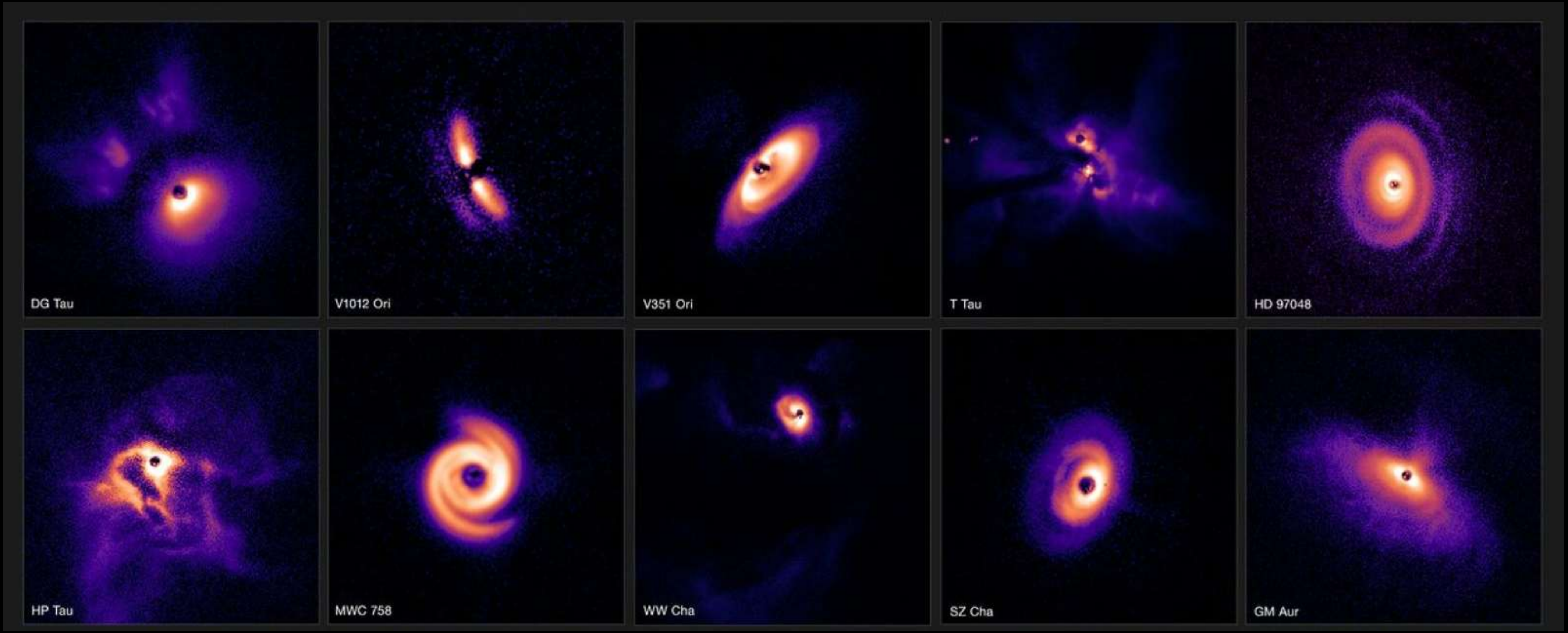


Wisconsin Hα Mapper

Planet formation in the Orion Nebula

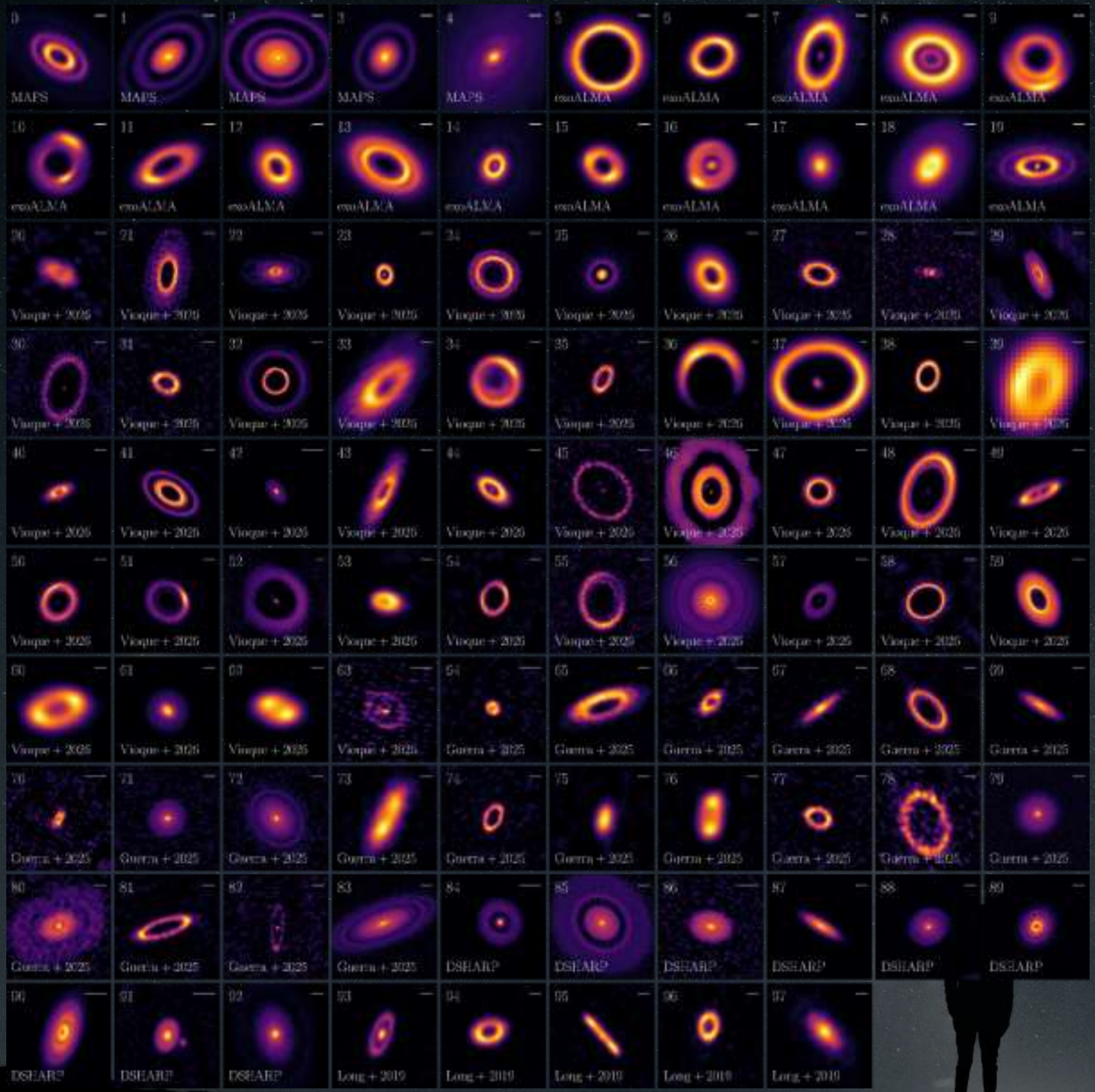


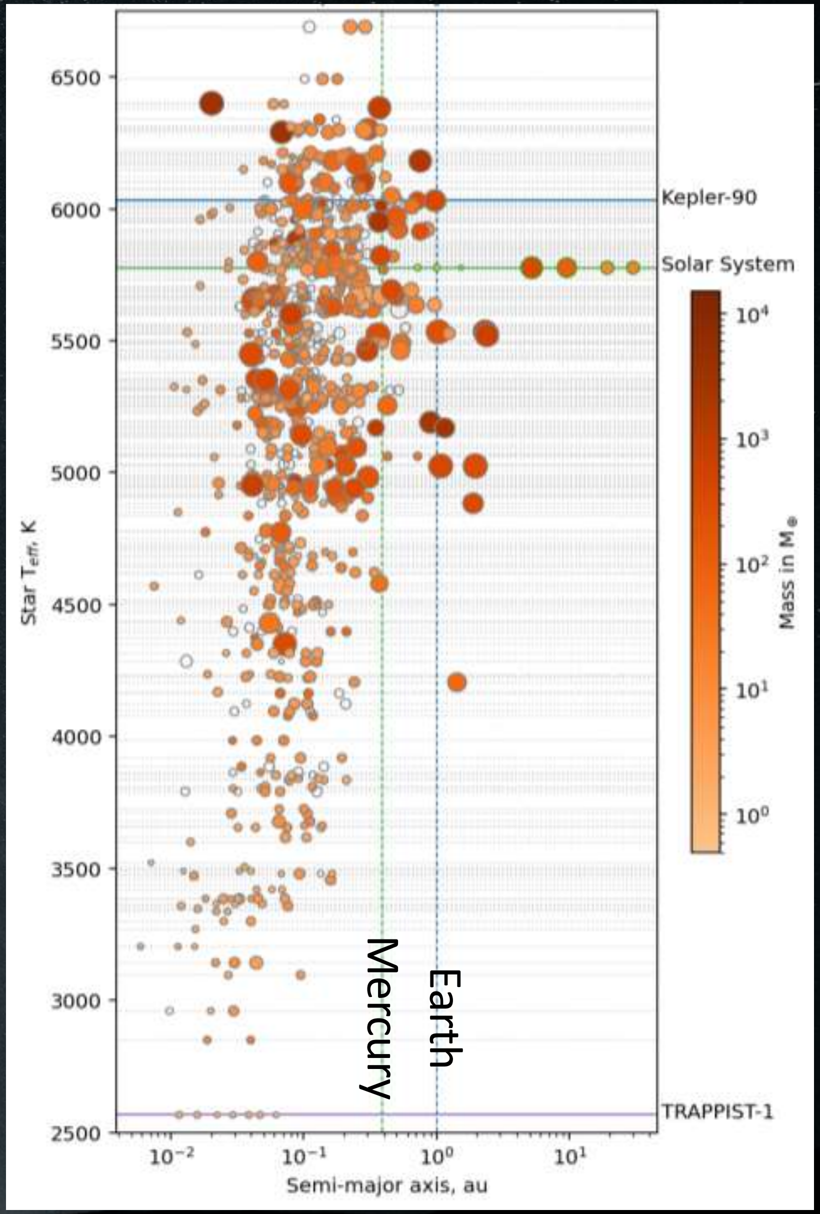
Various shapes of star-forming regions



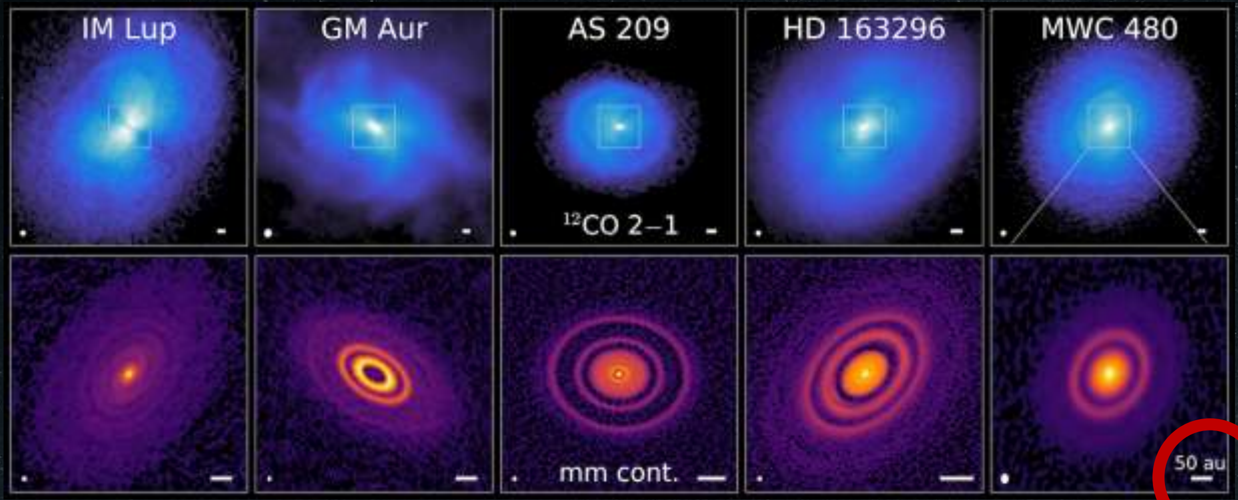
Unveiling diverse environments in star-forming regions, these observations shed light on how planets are born across the galaxy. (ESO) Observed by the ALMA telescope

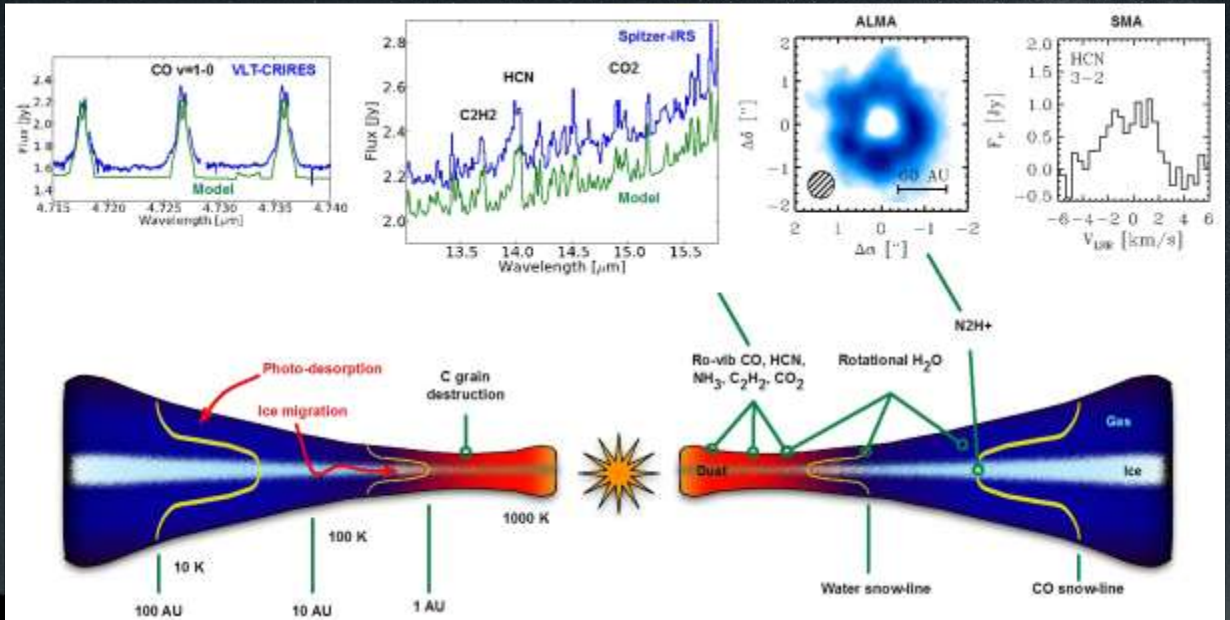
Diversity of protoplanetary disks and relation to exoplanetary systems

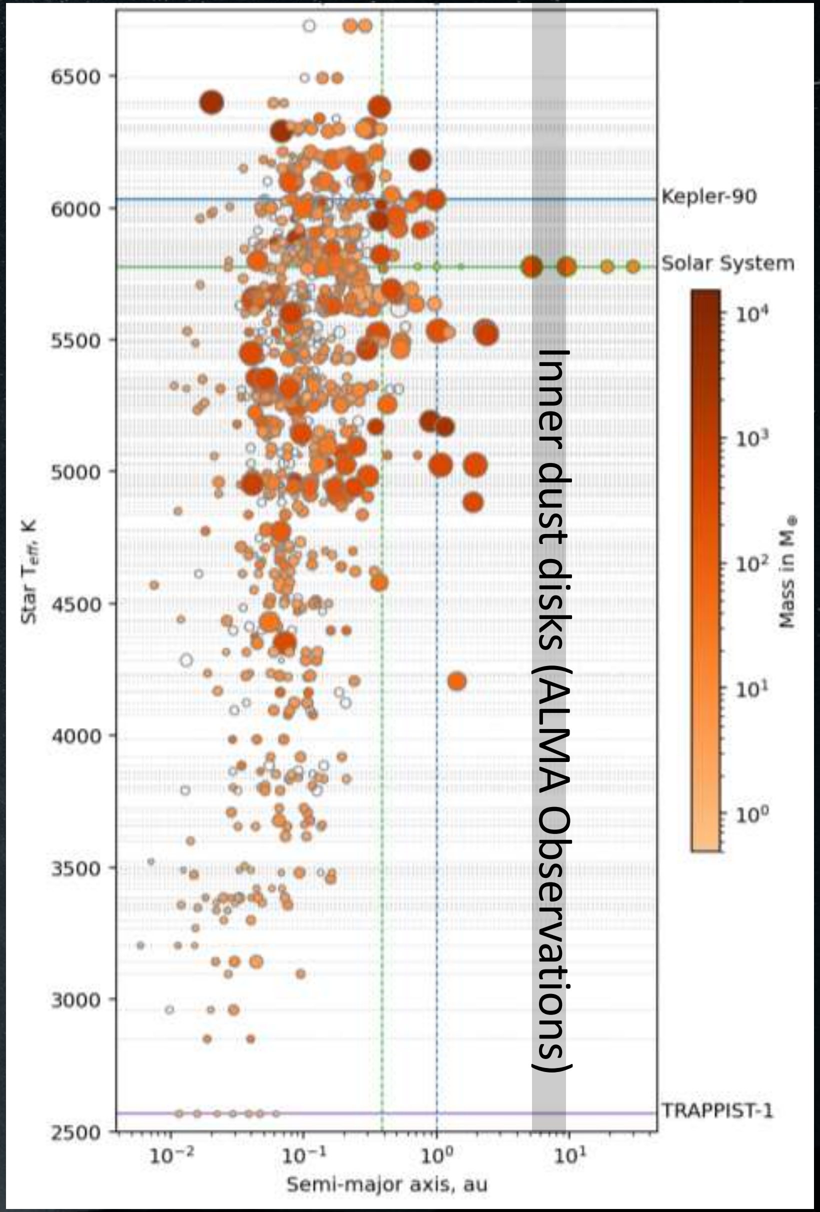




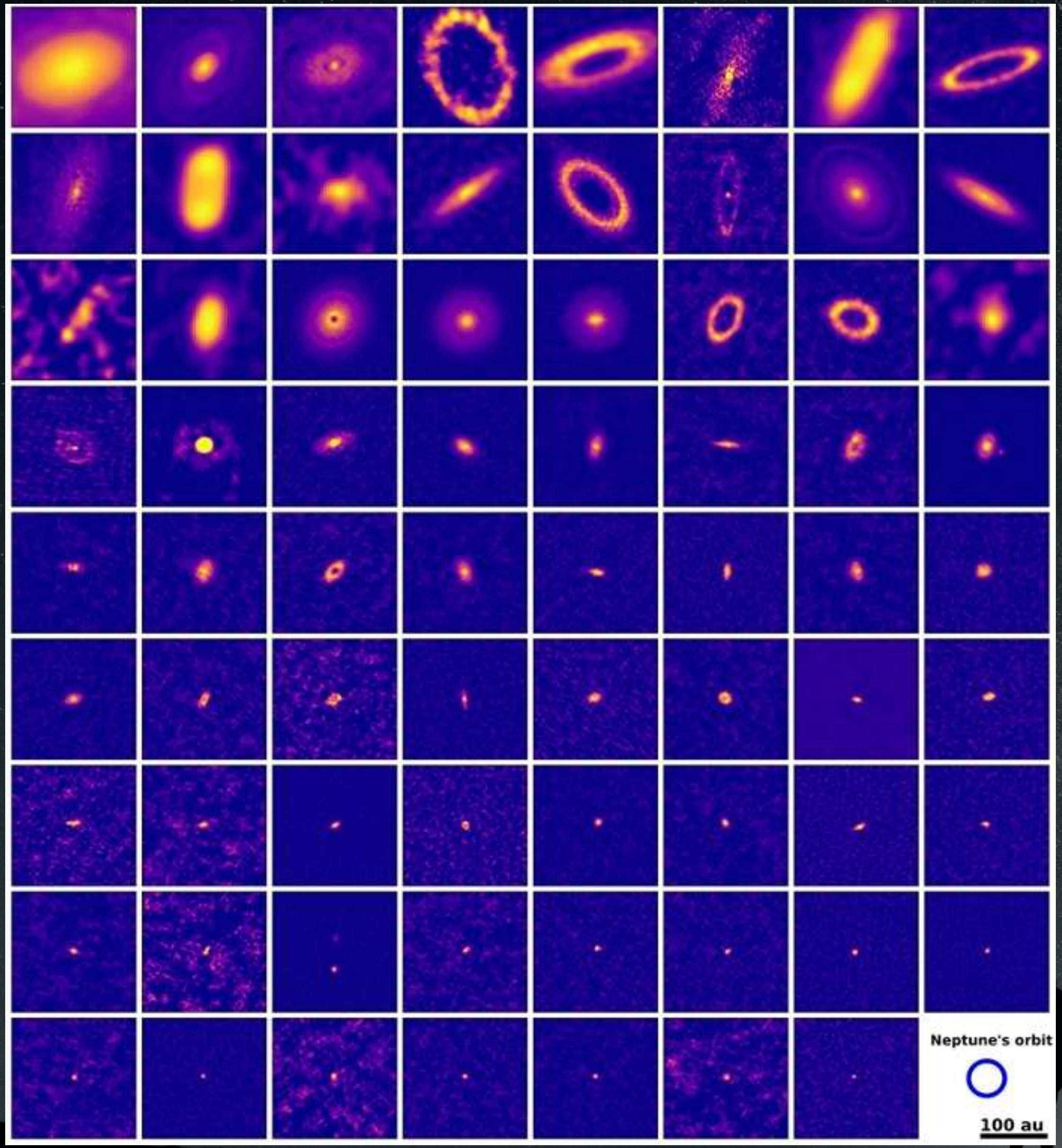
Mismatch in dimensions

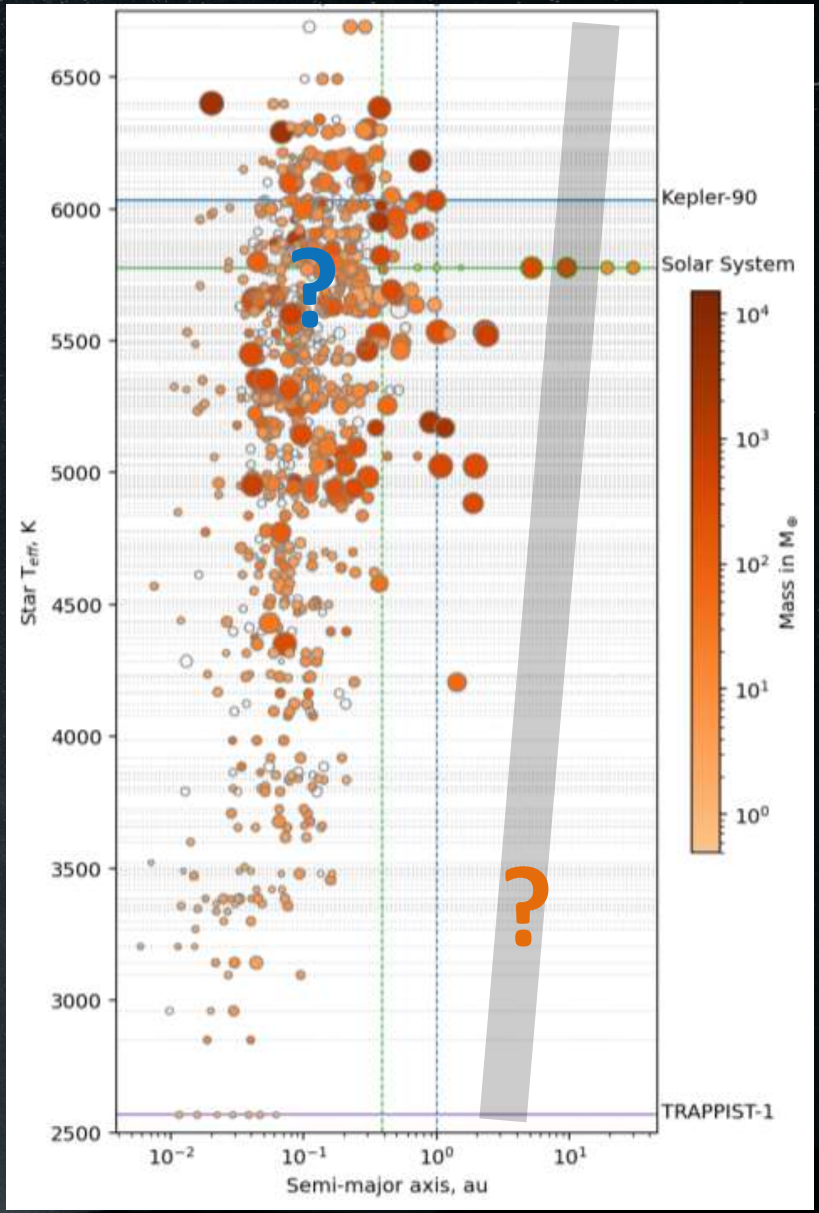






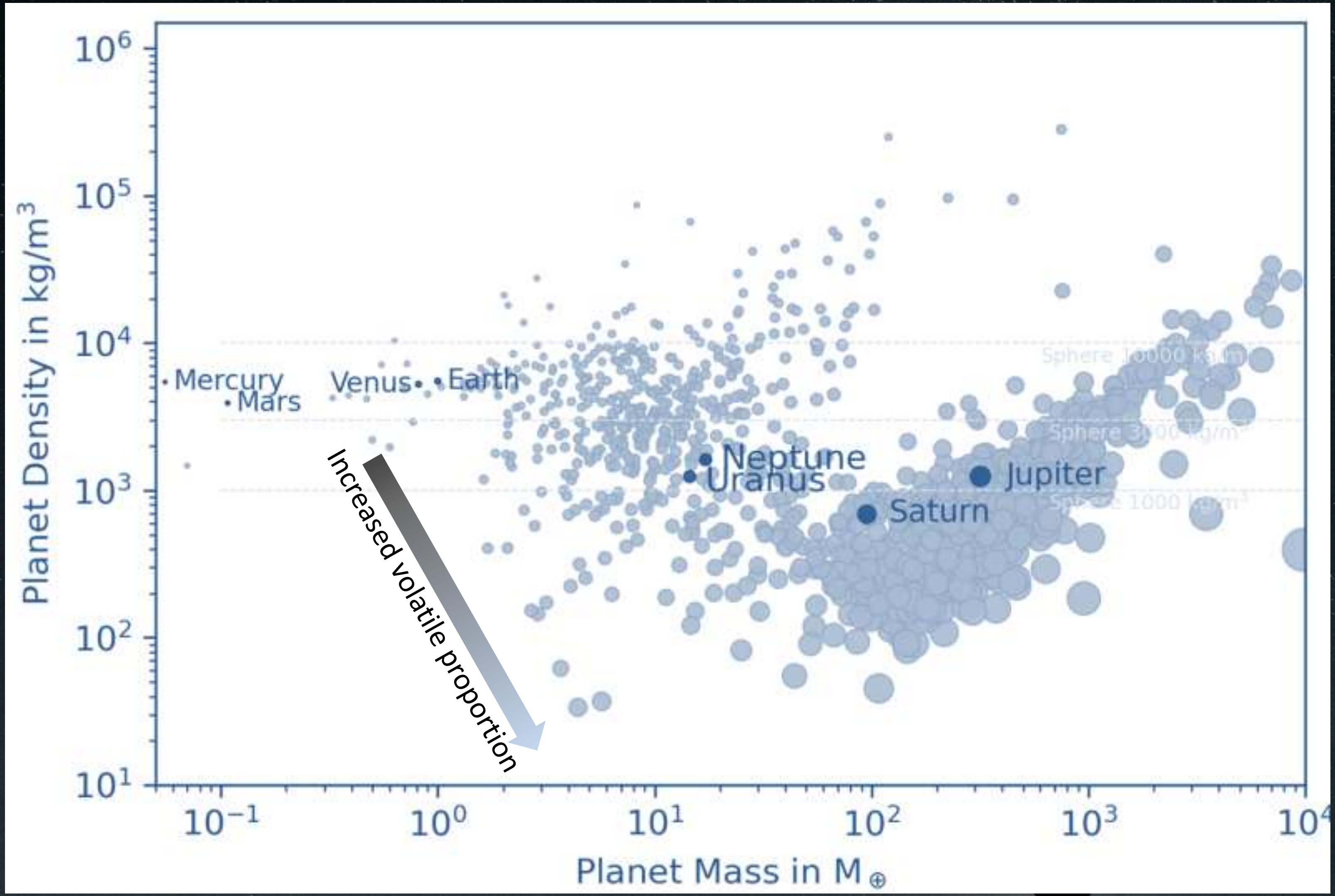
Observed smaller protoplanetary disks

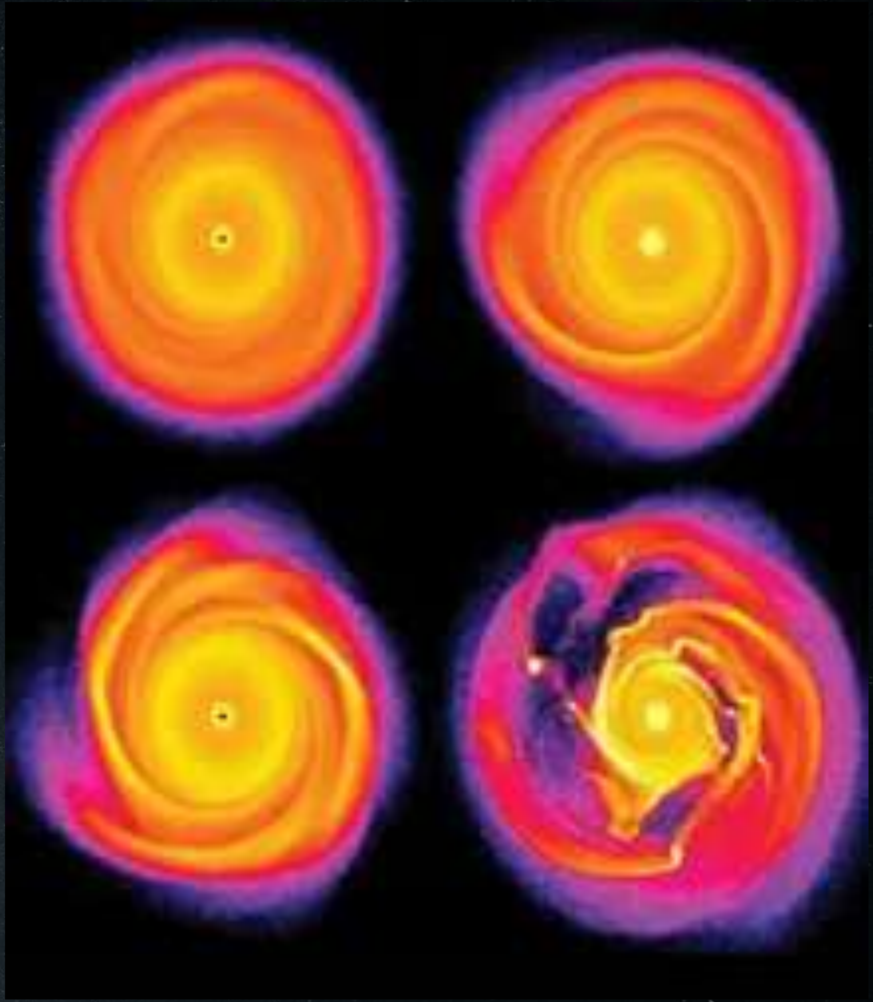




How do these planets get their substantial atmospheres to begin with?

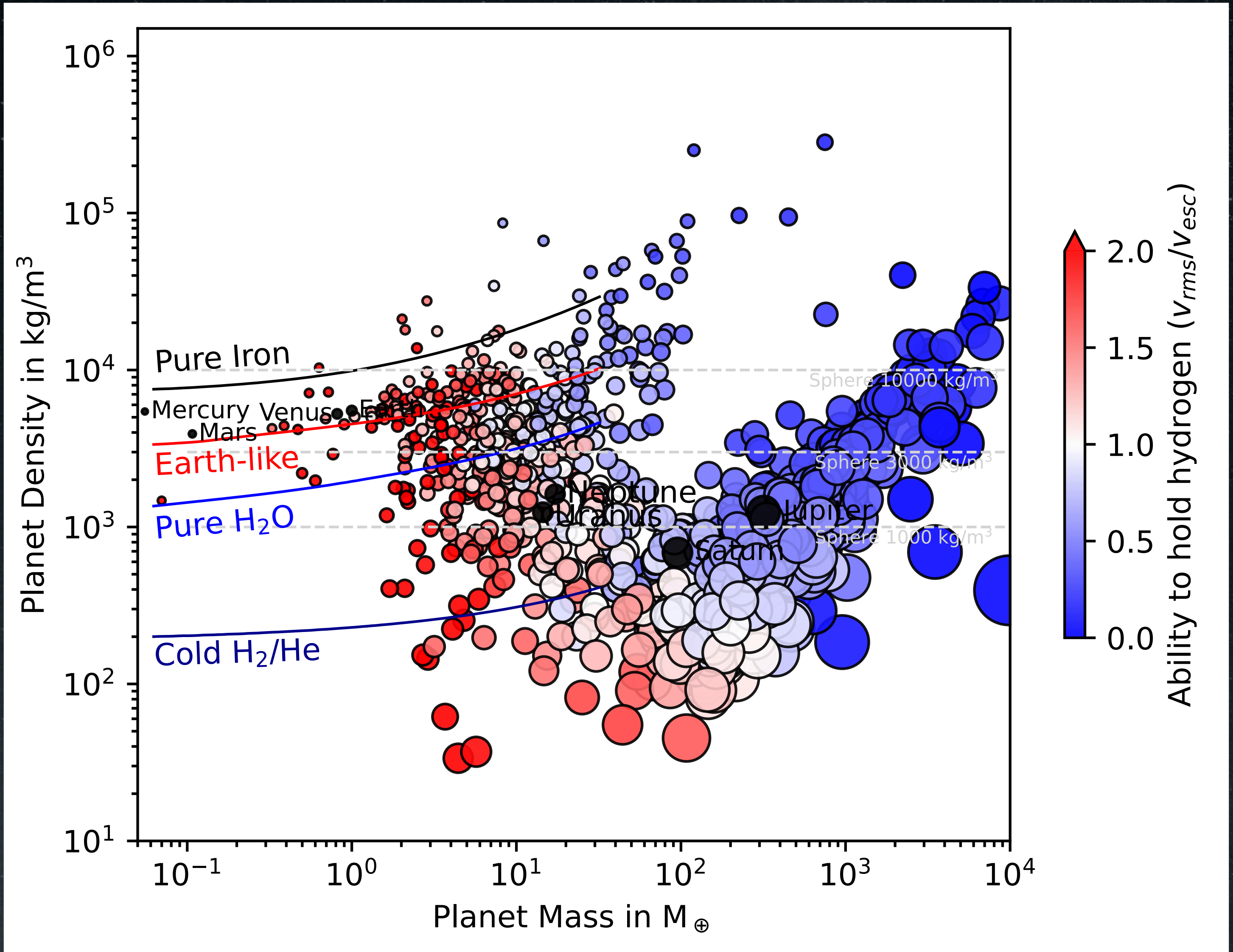
Planet formation by gravitational instability and collapse ?





Centre for Planetary Habitability

Exoplanet – Atmospheres are not easily blown away…



Werner et al. (unpublished)

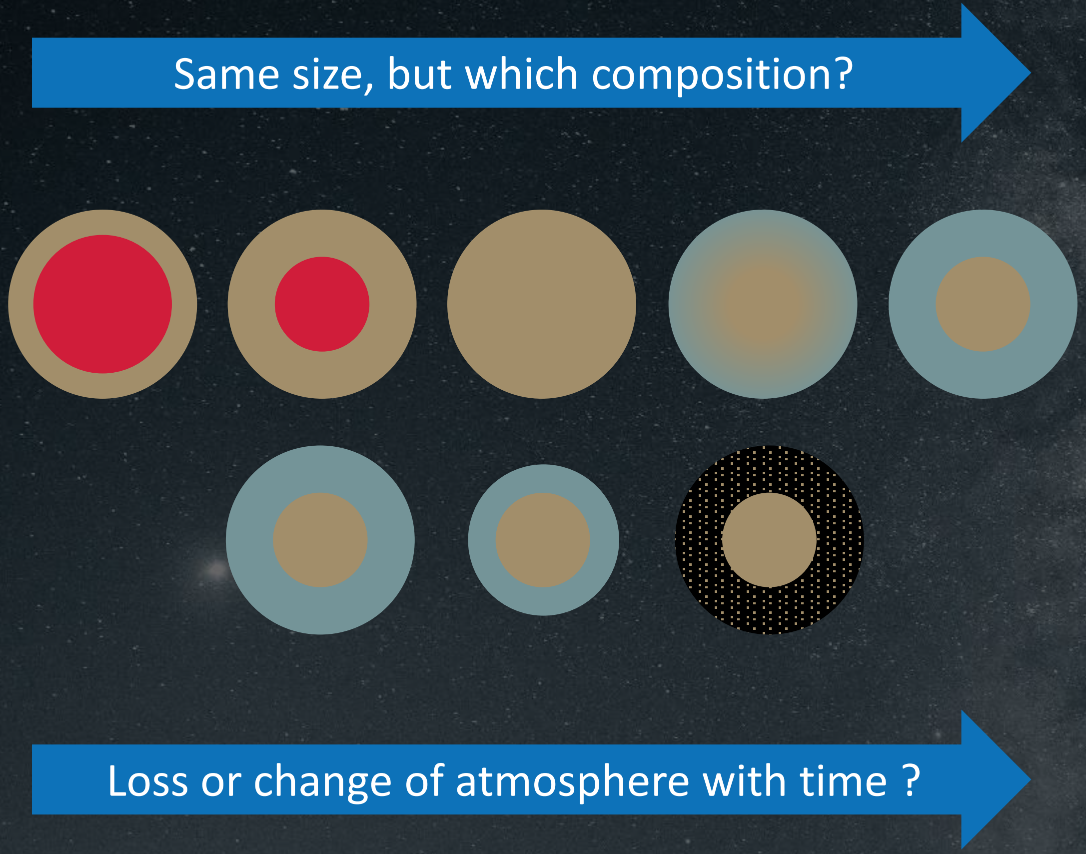
Atmosphere loss is related to:

- the star-planet distance,
- temperature of the star,
- magnetic activity of the star,
- mass of the planet, and the
- planet's atmospheric molecular weight, and
- time.

The density of a planet would indicate whether a planet kept its volatiles.

But: More complicated and a matter of chemistry

Evolutionary changes are challenging to capture



The *Galactic Recipe for Exo-Planets*.

Objective 1: Derive exoplanet population and exoplanetary system structures, including the PLATO LOPS2 field results, thereby covering the galactic stellar composition variety and range of system ages.

Objective 2: Develop a self-consistent, dynamical N-body simulation suite of exoplanet formation also in multi-planet systems.

Objective 3: Consider the evolution of the protoplanetary disk during planetesimal and pebble formation, respectively, including (volatiles) elemental abundances for estimating exoplanet compositions.

Objective 4: Predict and reproduce the architecture of exoplanetary systems and exoplanet composition, structure, and density as defined by stellar heritage, and to validate the updated planet formation model suite against PLATO observations.

The Galactic Recipe for Exo-Planets

We know many exoplanet systems,
none is similar to the solar system,
and we have not found life elsewhere!

Do we need to declare Earth «unique»?
Are the initial conditions to form the solar system unique?
Is life on Earth and are our habitability criteria unique?

Stay tuned !

Forskningsrådet

Centre for Planetary Habitability


Centre for Planetary Habitability