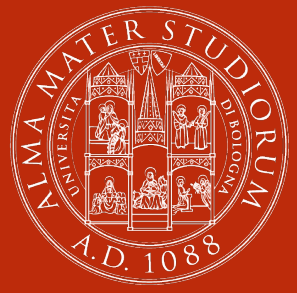
Exoplanets:
Formation, Populations, and Atmospheres



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Leonardo Testi

leonardo.testi@unibo.it

2023/2024

Dipartimento di Fisica e Astronomia

What we will cover

1. Overview
    1. Including the definition of a planet

2. Extrasolar planets
    1. Detection methods and associated biases
    2. Populations and archietcture of exosystems
    3. Comparison with Solar System

3. Extrasolar planets physics
    1. How to go beyond «detection»
    2. Physical characteristics of extrasolar planets
    3. Atmospheres
    4. Comparison with Solar System

4. Planet formation
    1. From Star Formation to protoplanetary disks
    2. Protoplanetary disks physics and chemistry
    3. Planet formation and disk-planet interaction

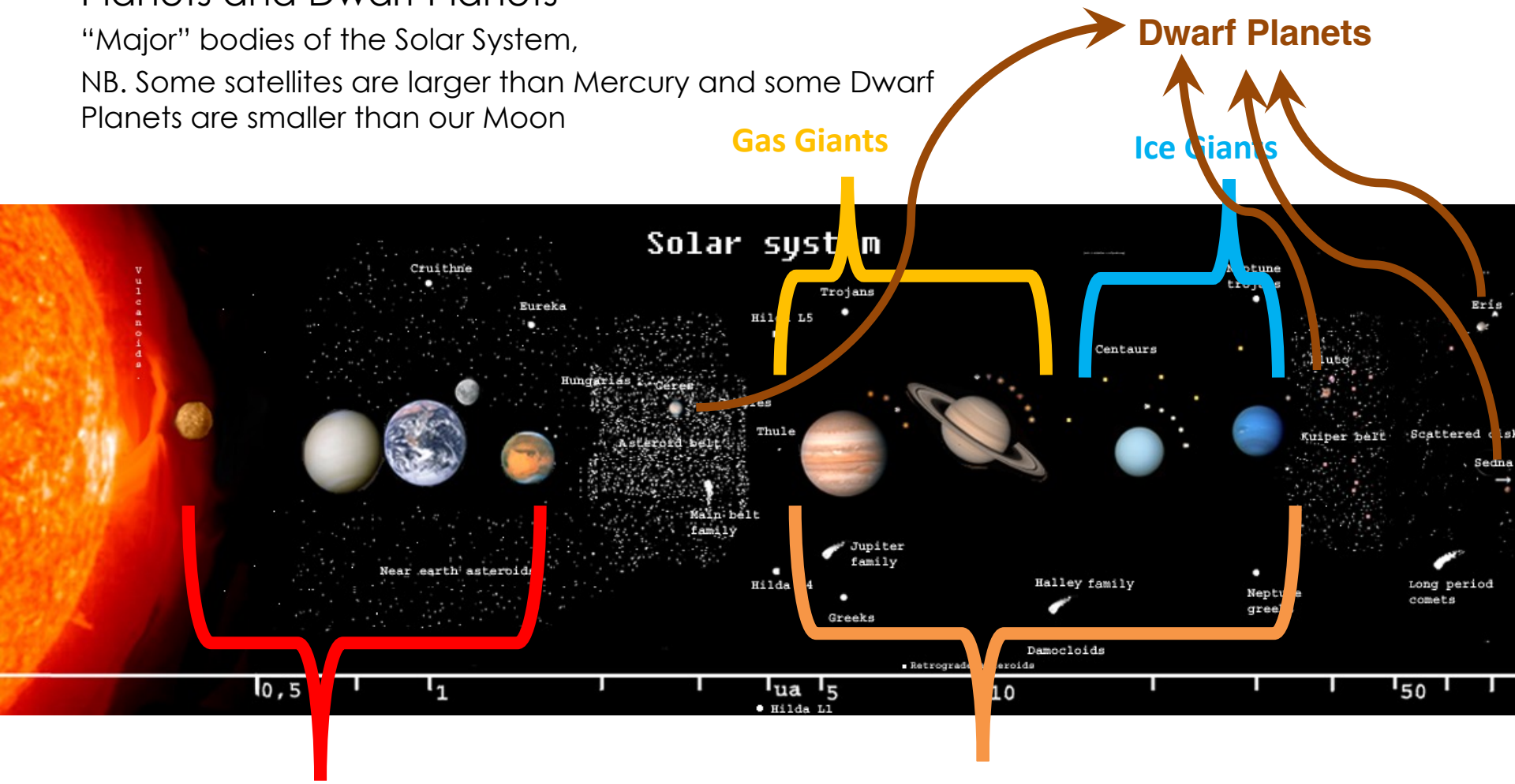
5. Astrophysical consitions for the emergence of life

Solar System

Planets and Dwarf Planets

"Major" bodies of the Solar System,

NB. Some satellites are larger than Mercury and some Dwarf Planets are smaller than our Moon



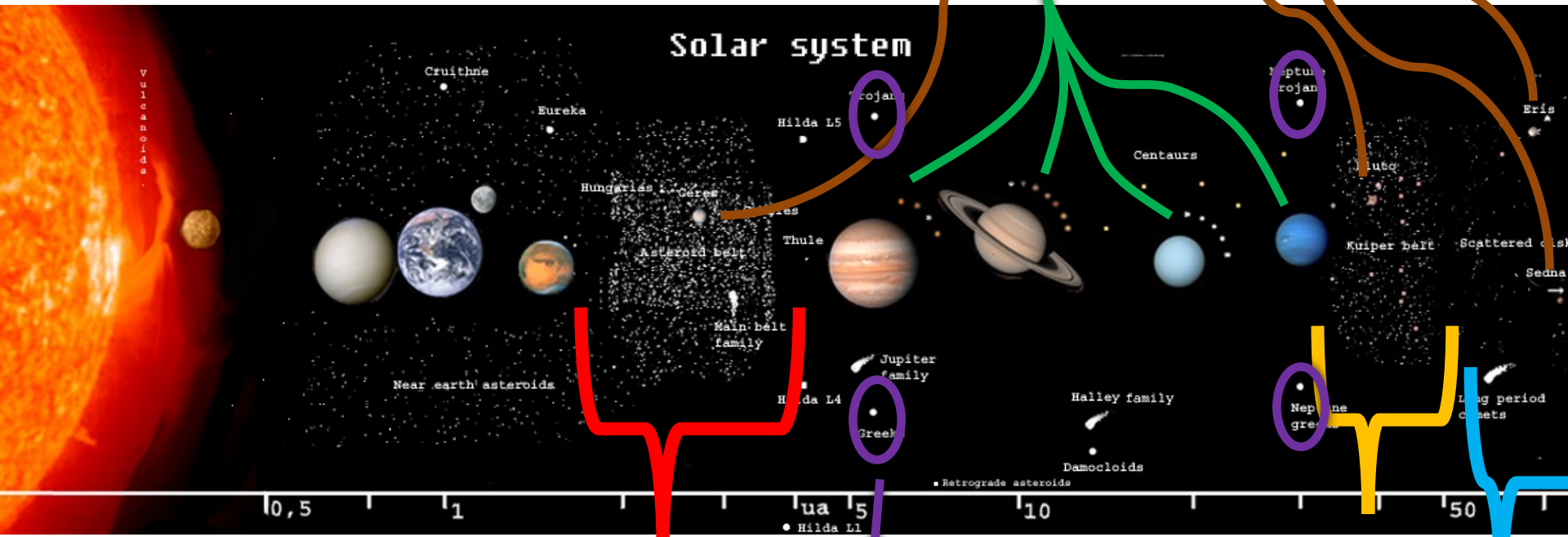
Solar System

Stable population of Minor Bodies

Stable means that their orbits have a high probability to be stable on the timescale of the age of the Solar System

Dwarf Planets

Regular and Irregular satellites



Asteroids Belt

Kuiper Belt

Scattered Disk

Jupyter and Neptune Trojans and Greeks

Oort Cloud

ALMA MATER STUDIORUM

A planetary system around the millisecond pulsar PSR1257+12

A. Wolszczan* & D. A. Frail†

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

MILLISECOND radio pulsars, which are old ($\sim 10^9$ yr), rapidly rotating neutron stars believed to be spun up by accretion of matter from their stellar companions, are usually found in binary systems with other degenerate stars[1]. Using the 305-m Arecibo radiotelescope to make precise timing measurements of pulses from the recently discovered 6.2-ms pulsar PSR1257+12 (ref. 2), we demonstrate that, rather than being associated with a stellar object, the pulsar is orbited by two or more planet-sized bodies. The planets detected so far have masses of at least 2.8 $M_\oplus$ and 3.4 $M_\oplus$, where $M_\oplus$ is the mass of the Earth. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days. Observations indicate that at least one more planet may be present in this system. The detection of a planetary system around a nearby (~ 500 pc), old neutron star, together with the recent report on a planetary companion to the pulsar PSR1829−10 (ref. 3) raises the tantalizing possibility that a non-negligible fraction of neutron stars observable as radio pulsars may be orbited by planet-like bodies.

First generally accepted exoplanets discovered in 1992 around a **pulsar**

Rapidly rotating neutron star

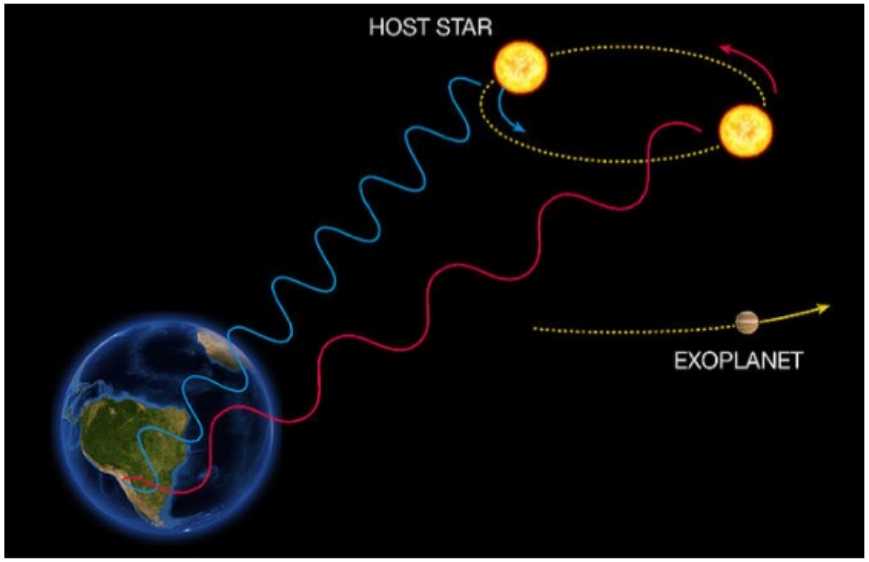
Subsequent searches show that this type of system is not common

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

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

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

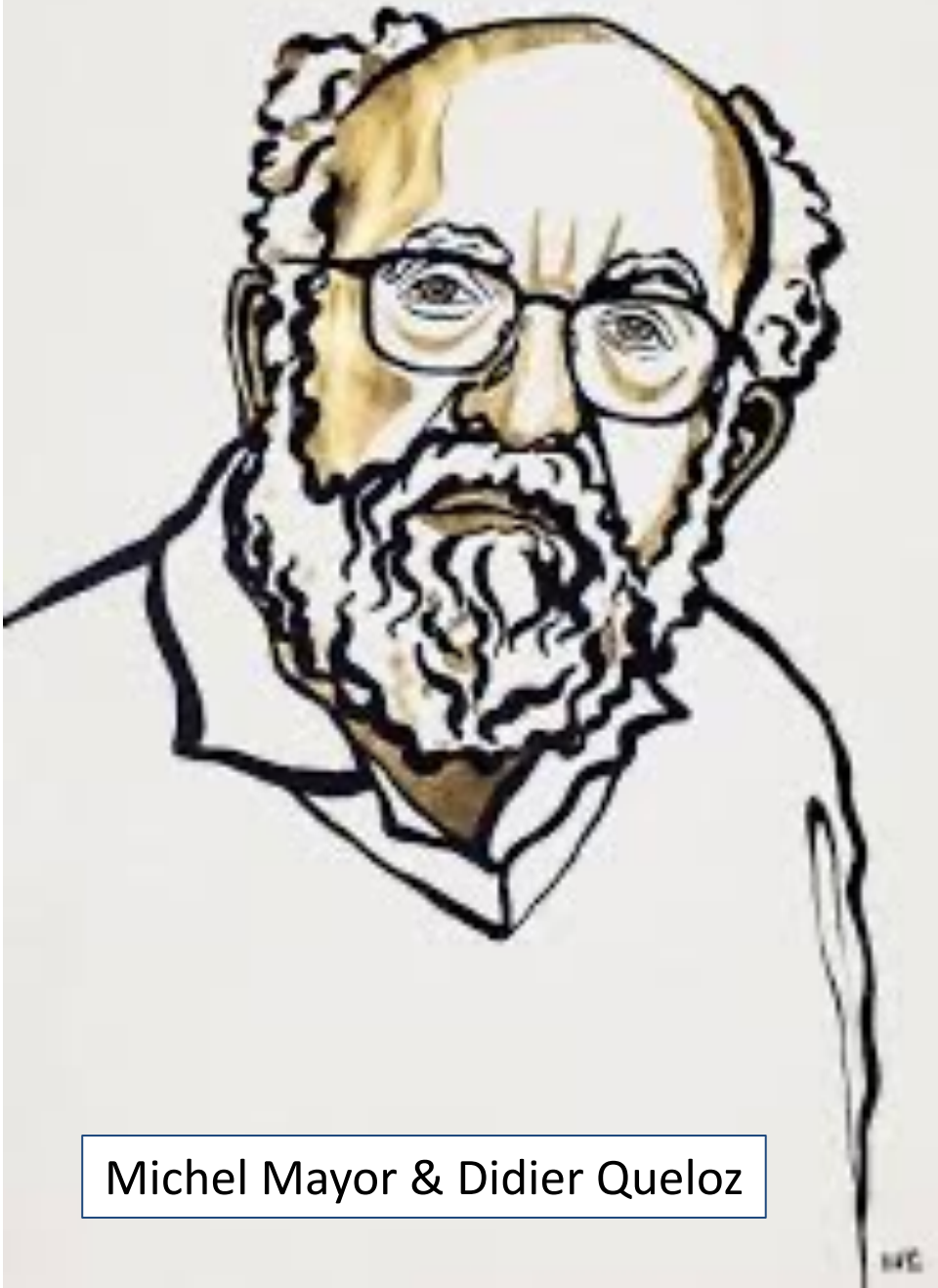


51 Peg b announced in 1995

First exoplanet found around a main sequence star, *indirectly* by measuring stellar Doppler shift

Gas giant, 0.5 M_{Jup}, in 4 day orbit

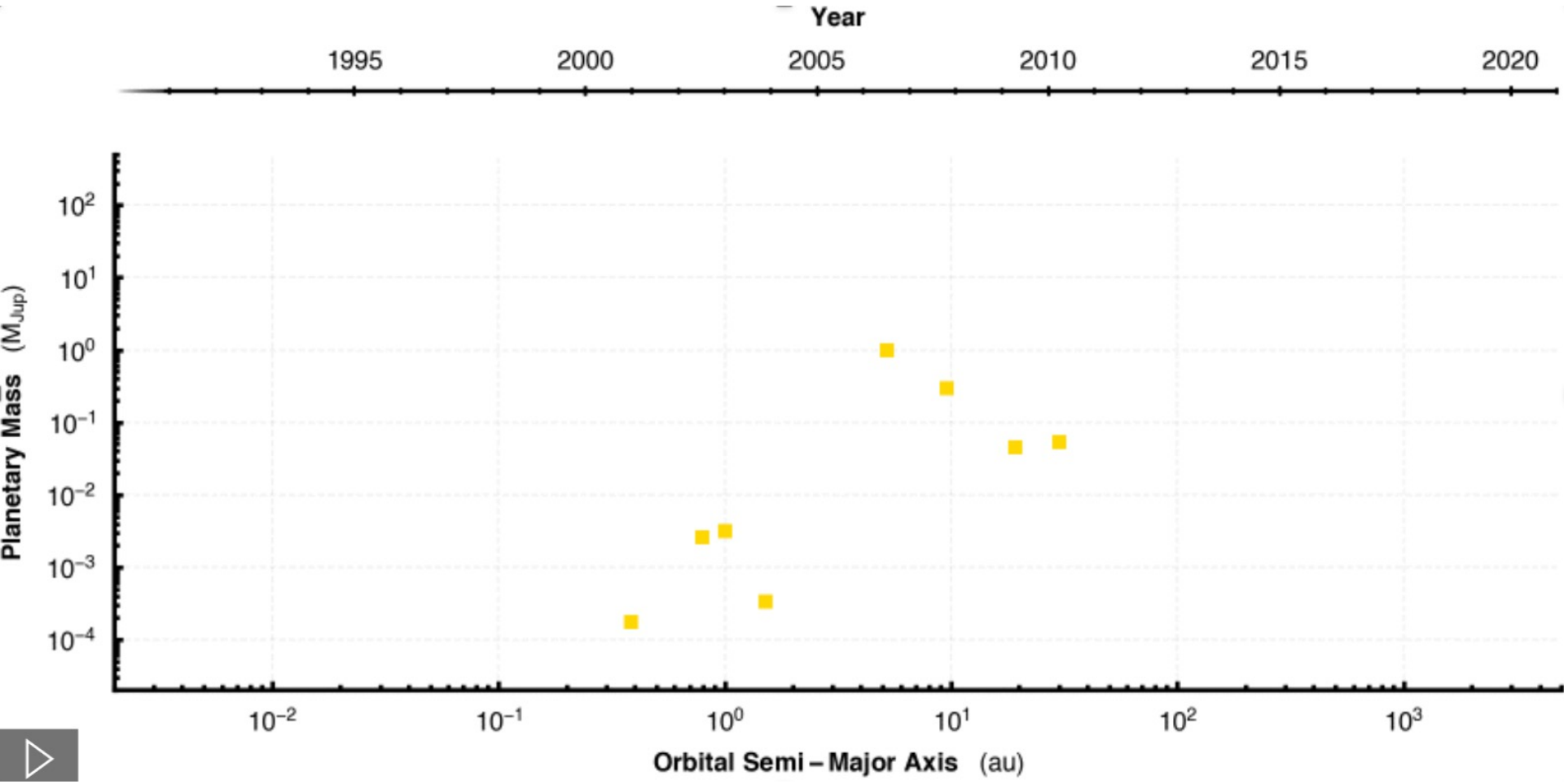
1995 – discovery of 51 Peg b



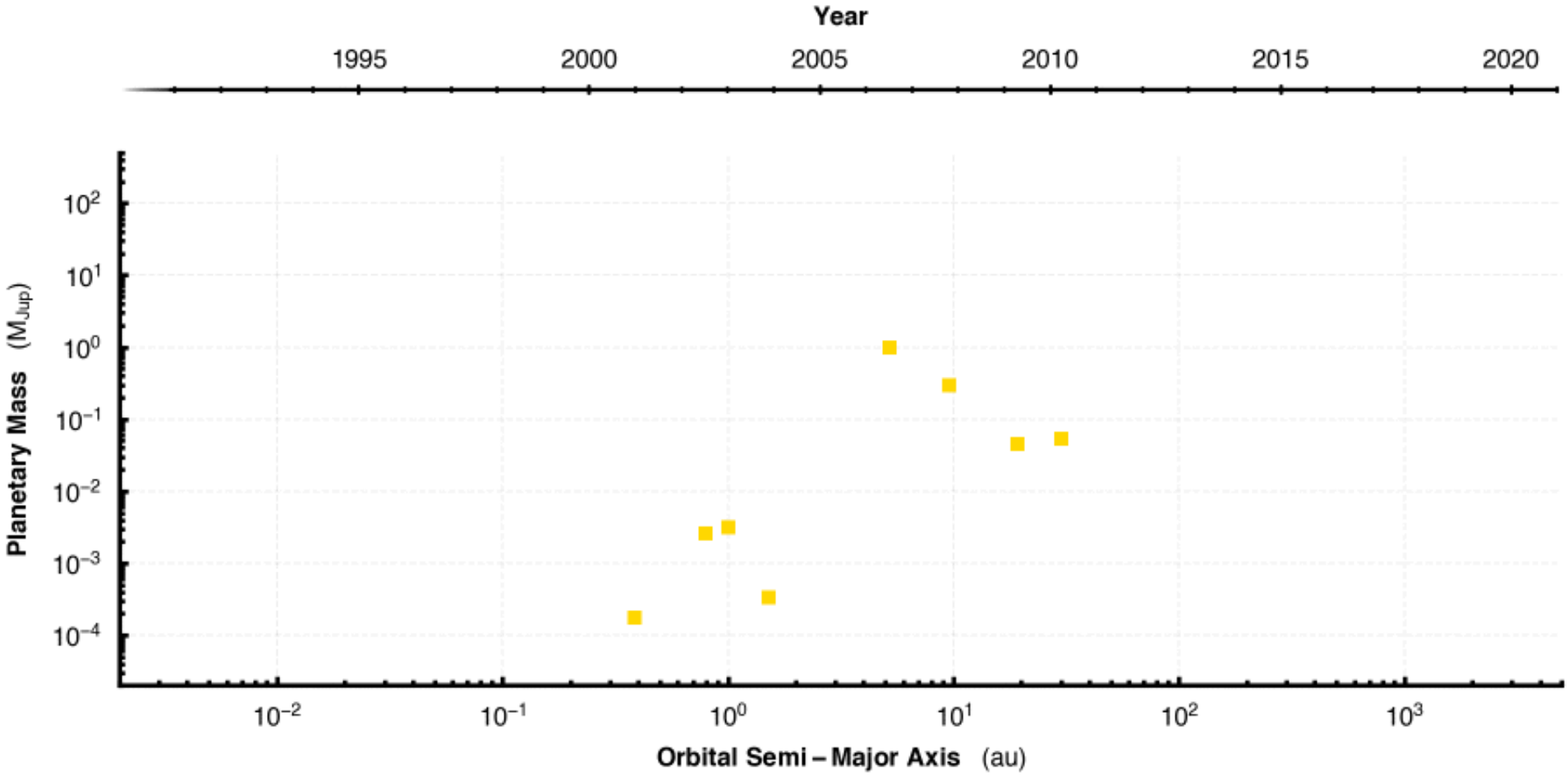
Michel Mayor & Didier Queloz

2019 Nobel Prize in Physics

Exoplanets


Year
1995
2000
2005
2010
2015
2020
Planetary Mass (M_{Jup})
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Orbital Semi – Major Axis (au)

Exoplanets

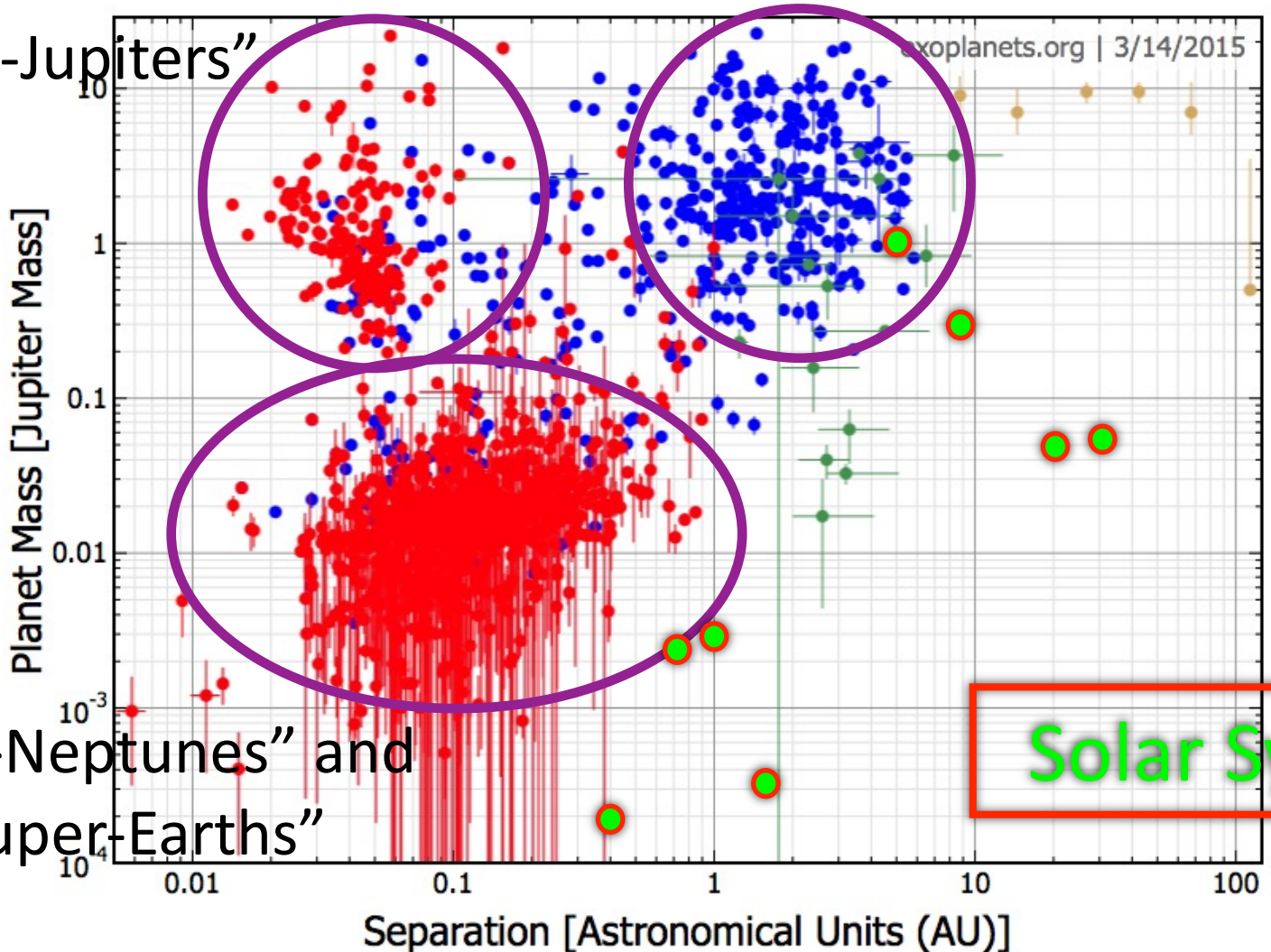

Year
1995
2000
2005
2010
2015
2020
Planetary Mass (M_Jup)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-2
10^-1
10^0
10^1
10^2
10^3
Orbital Semi – Major Axis (au)

Exoplanets populations

1. Planet populations by detection method
    1. Red: transit (mostly Kepler)

Jupiter analogs

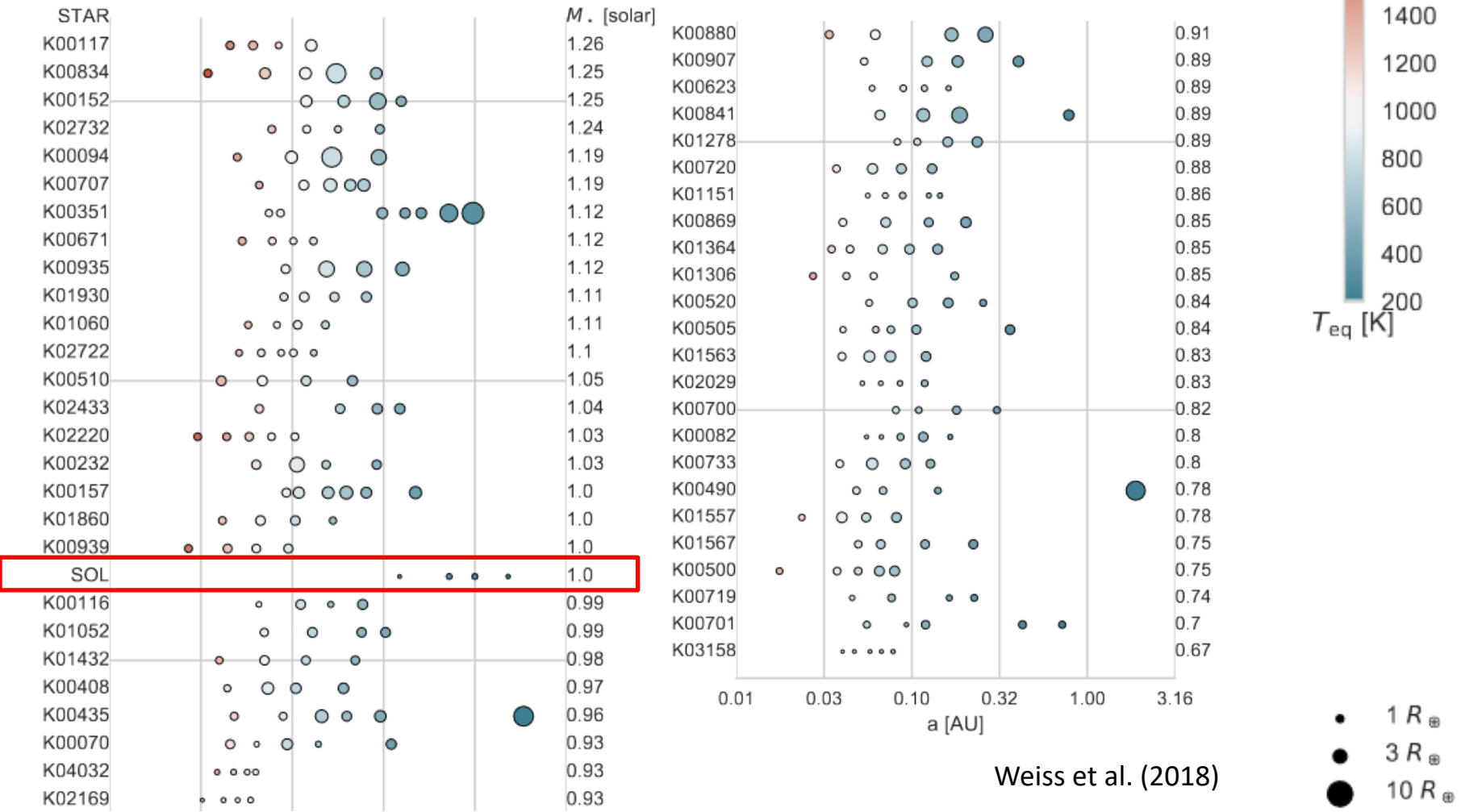
"Hot-Jupiters"



"Mini-Neptunes" and "Super-Earths"

Solar System

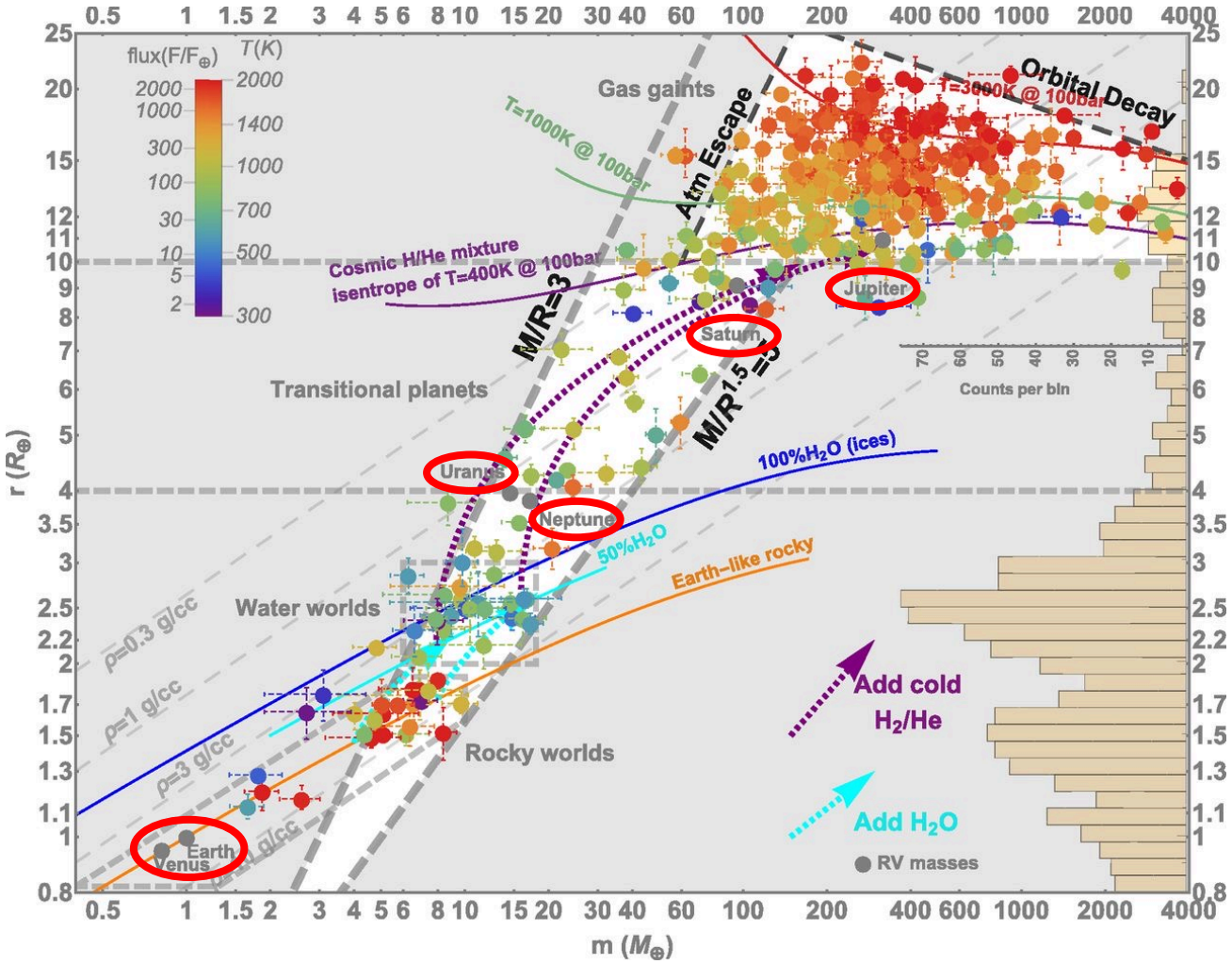
Planetary architectures



Weiss et al. (2018)

1. Most known planetary systems have a very different architecture than the Solar System
   Reality or bias?

Ineternal structure of planets

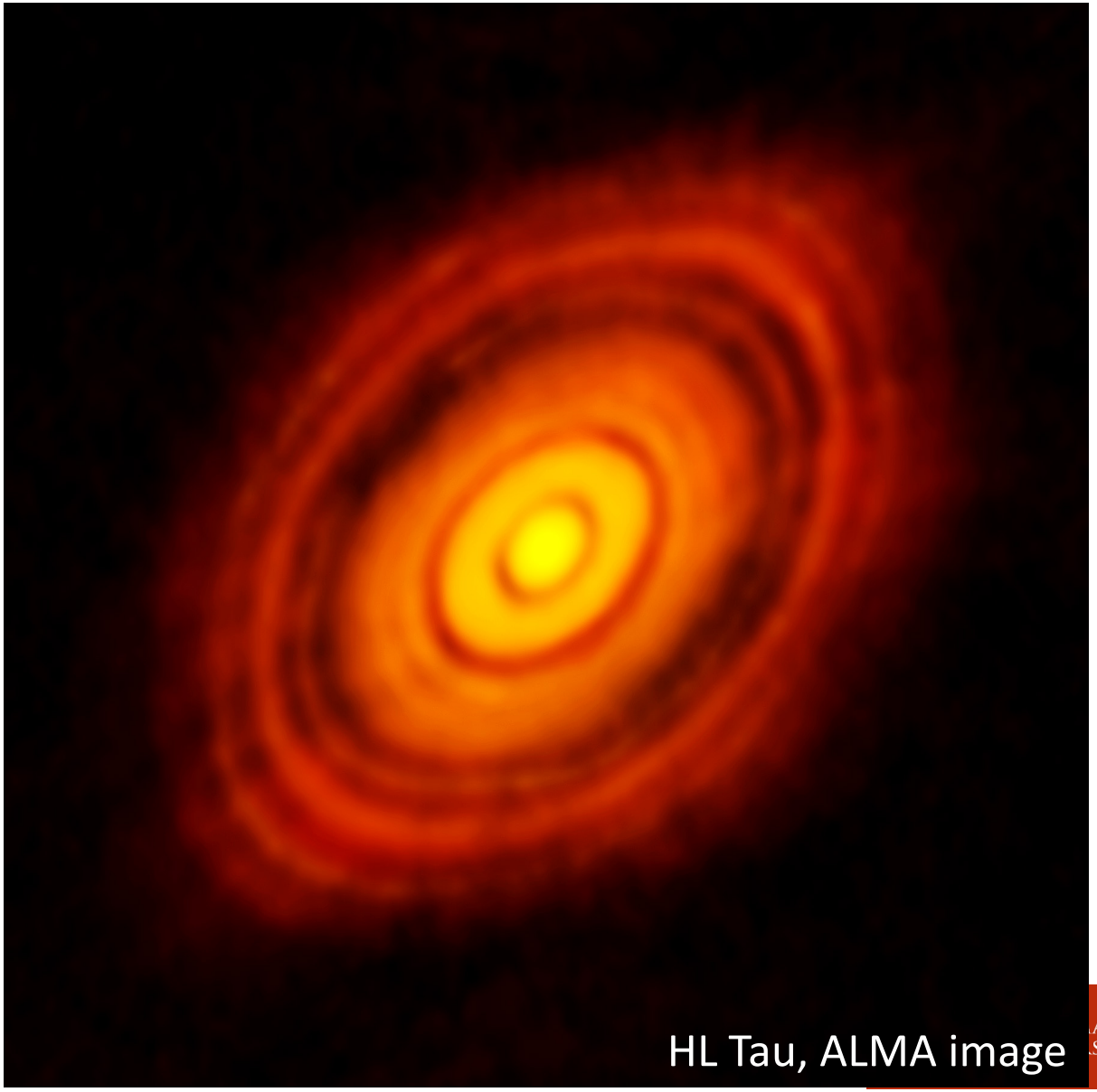


A common type of planet has (M,R) *intermediate* between the Solar System's terrestrial and giant planets

"super-Earths", "mini-Neptunes"

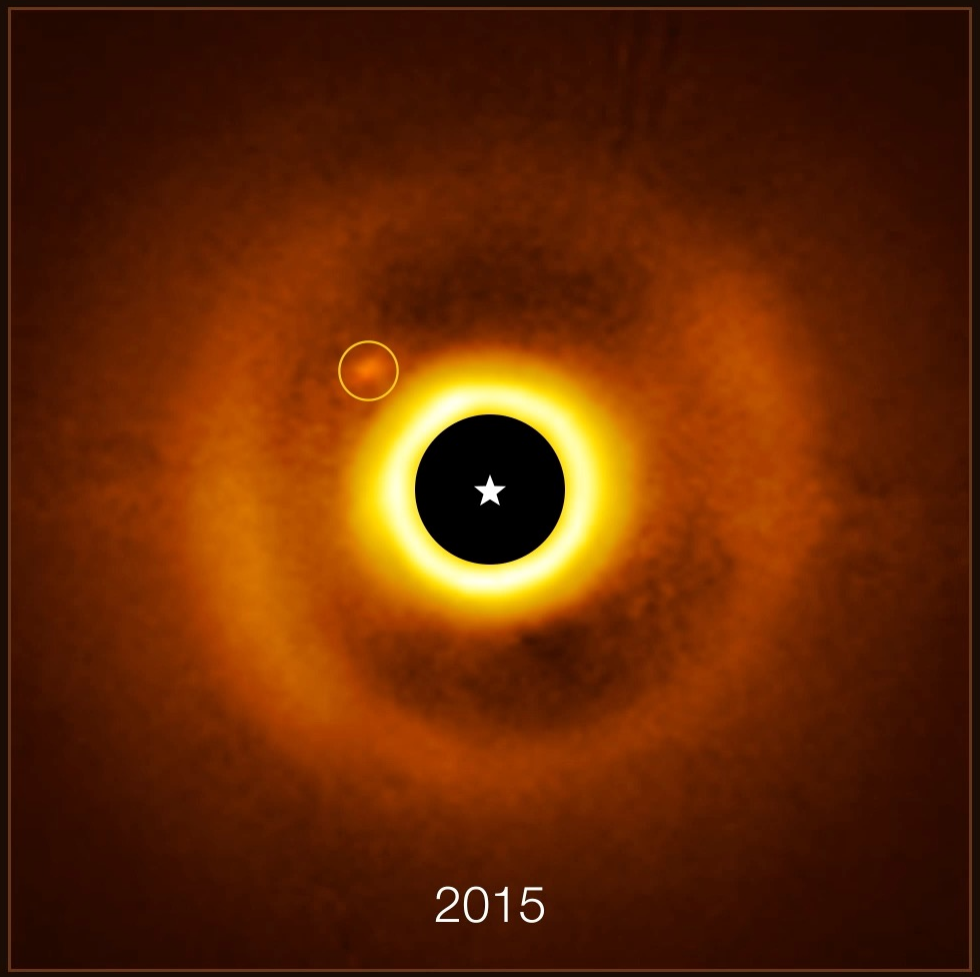
Zeng et al. (2019)

Planet formation



HL Tau, ALMA image

Planet formation



ALMA image

Habitability

What makes a planet habitable?

Difficult and contentious question!

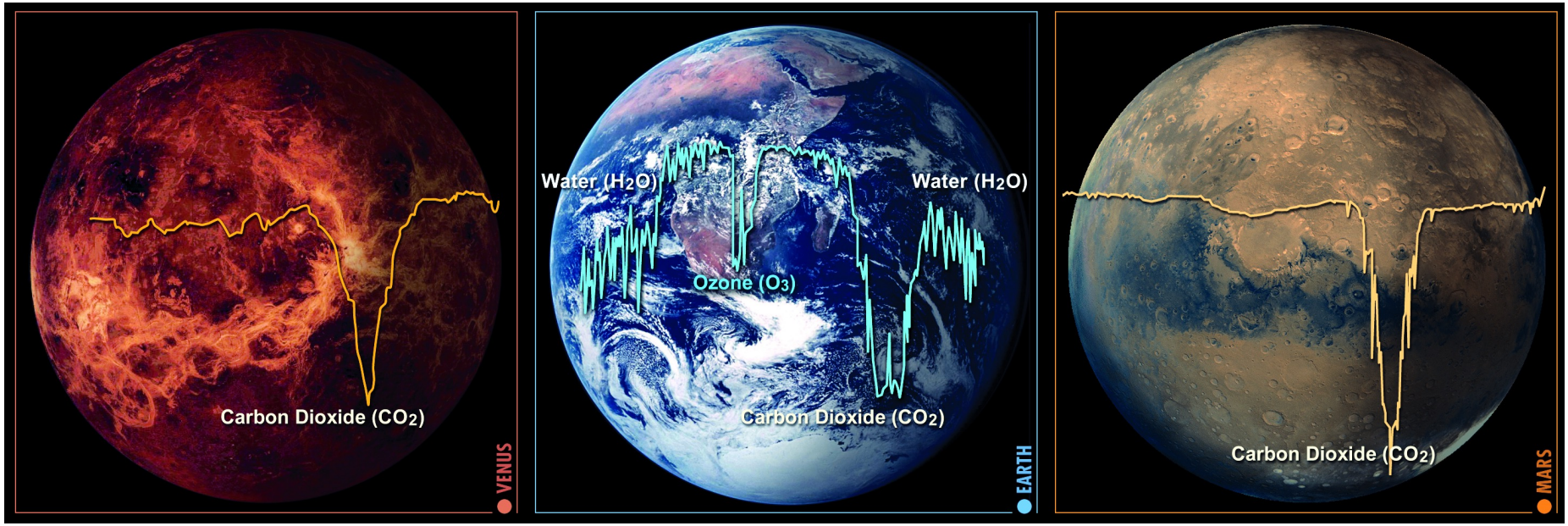
Define **habitable zone** as range of orbital distances where liquid water can be stable on the surface

- Few if any “Earth analogs” (Earth mass, Earth orbital radius, Sun-like star) have been found
- Possibly habitable planets are known around lower mass stars

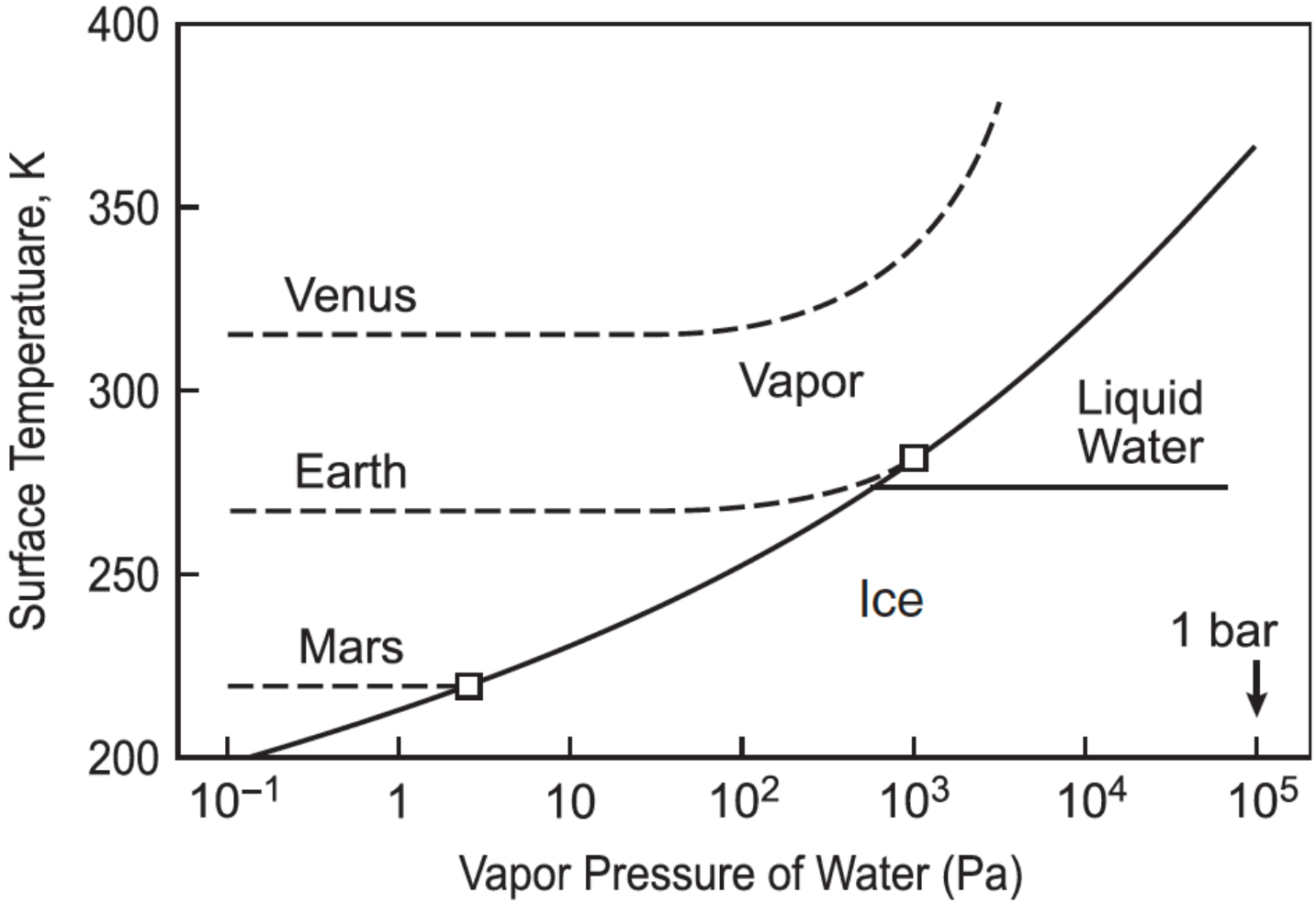
Habitability

Long-term goal: observe potentially habitable exoplanet atmospheres and search for presence / absence of
biomarkers – constituents that on Earth are only present because of life

O_2 and O_3 are generally considered best candidates



Atmospheres evolution



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Exoplanets: Formation, Populations, and Atmospheres

2023/2024

Leonardo Testi