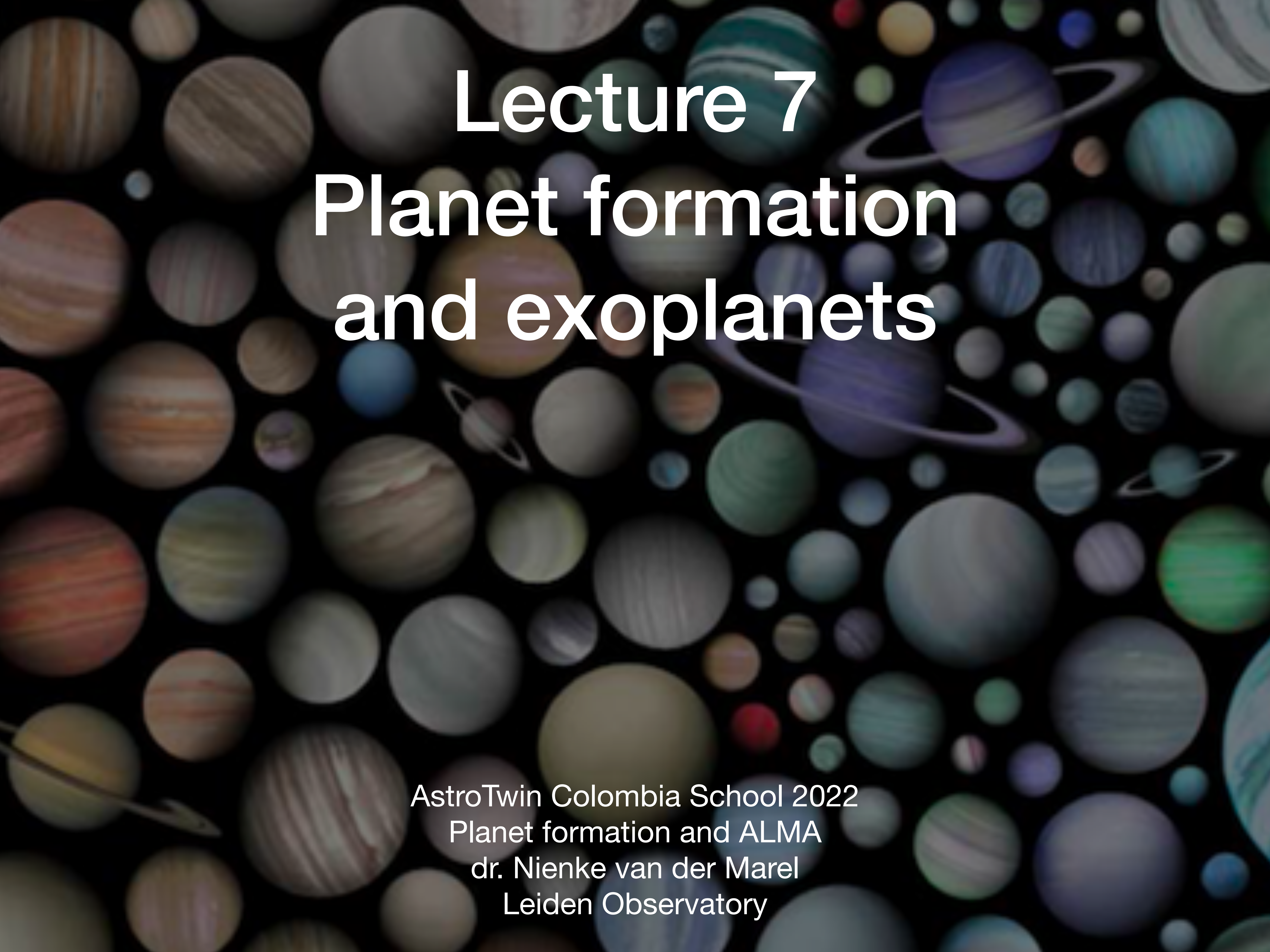
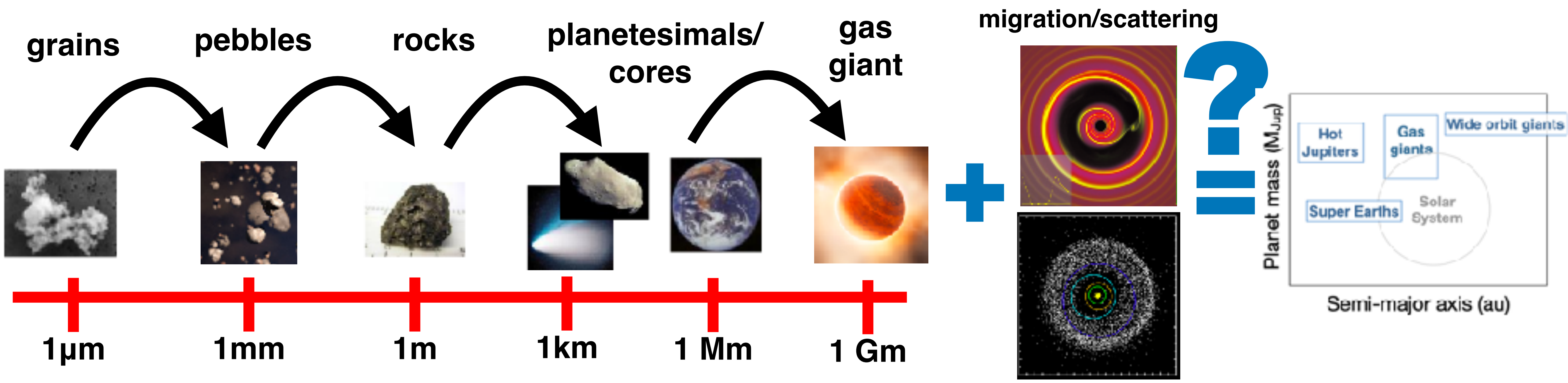


Lecture 7
Planet formation and exoplanets

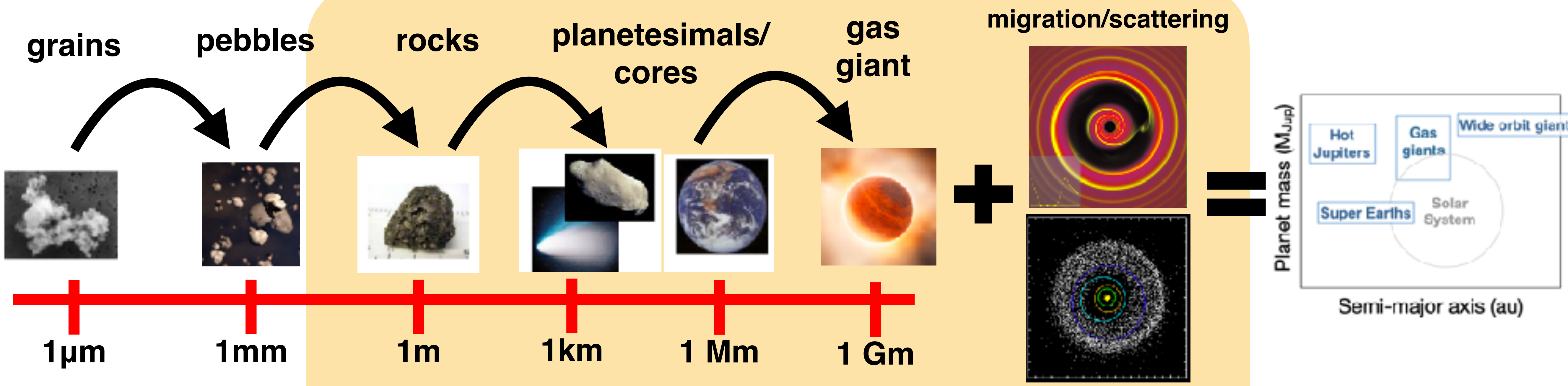
AstroTwin Colombia School 2022
Planet formation and ALMA

dr. Nienke van der Marel
Leiden Observatory

Recall: Planet formation



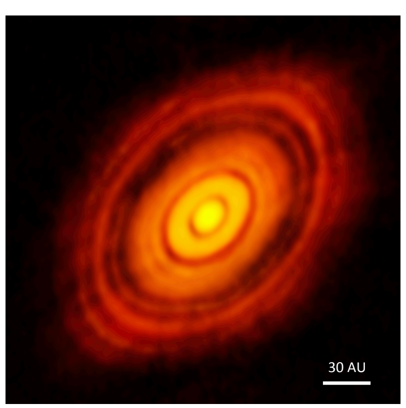
Recall: Planet formation



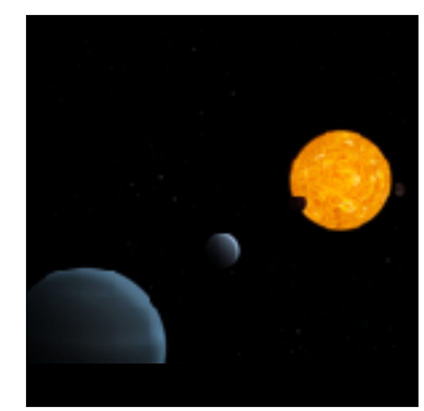
Observable

Not observable: constrained by theory

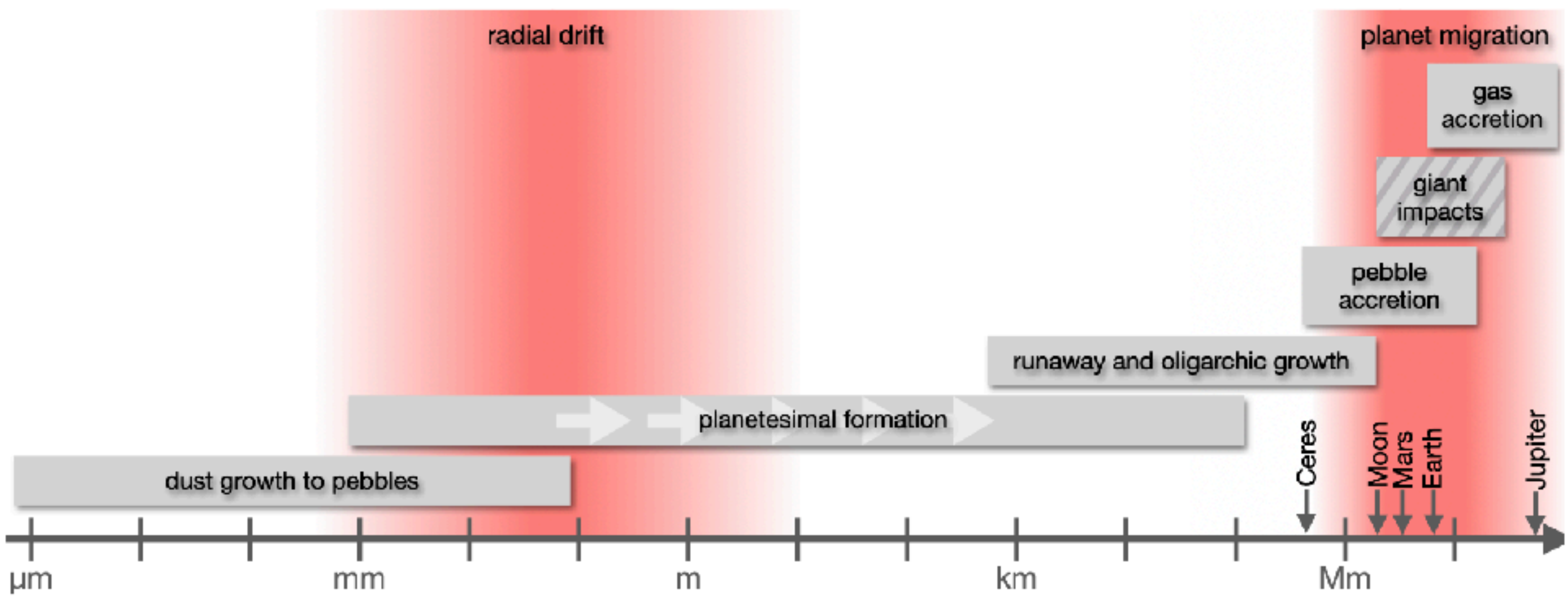
Observable



Disk masses, time scales, radial scales, trends, exoplanet populations, occurrence rates, …

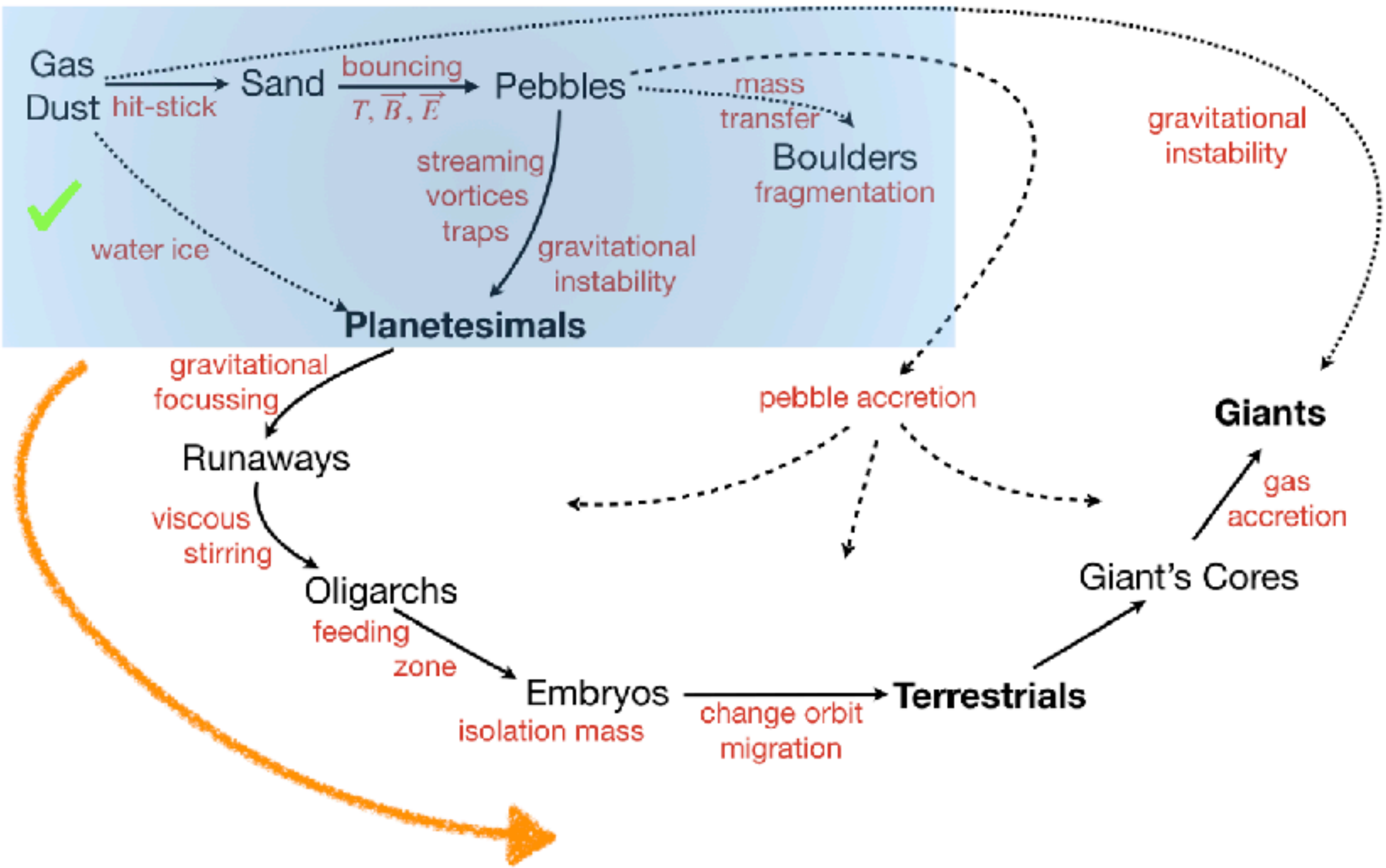


Growth steps after pebbles



Drazkowska et al. 2022 (PPVII)

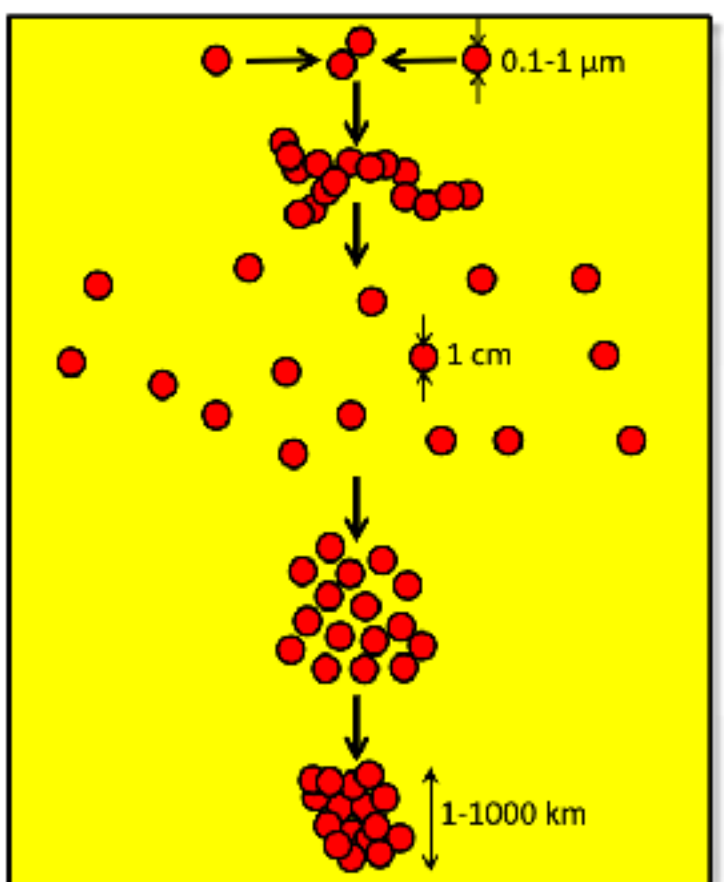
Processes for growth

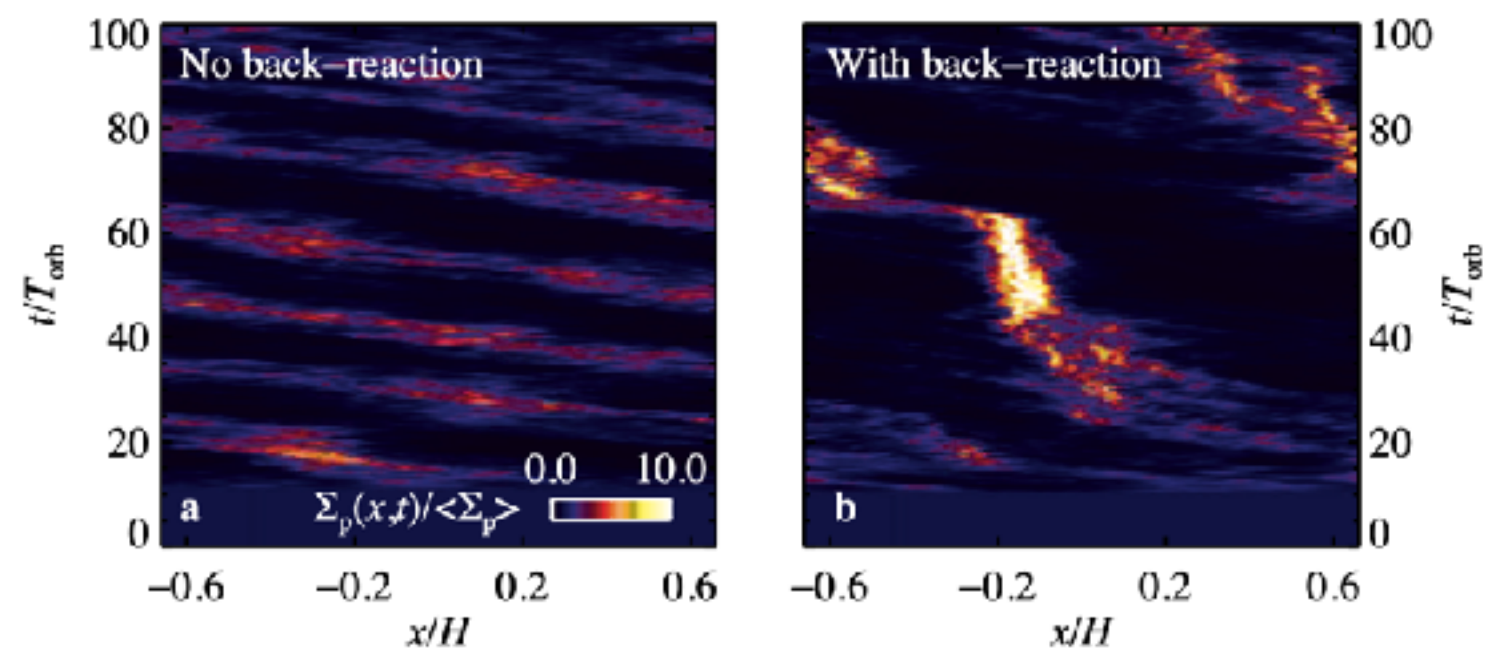


Blum 2018

Problem planetesimal formation: drift & bouncing barrier

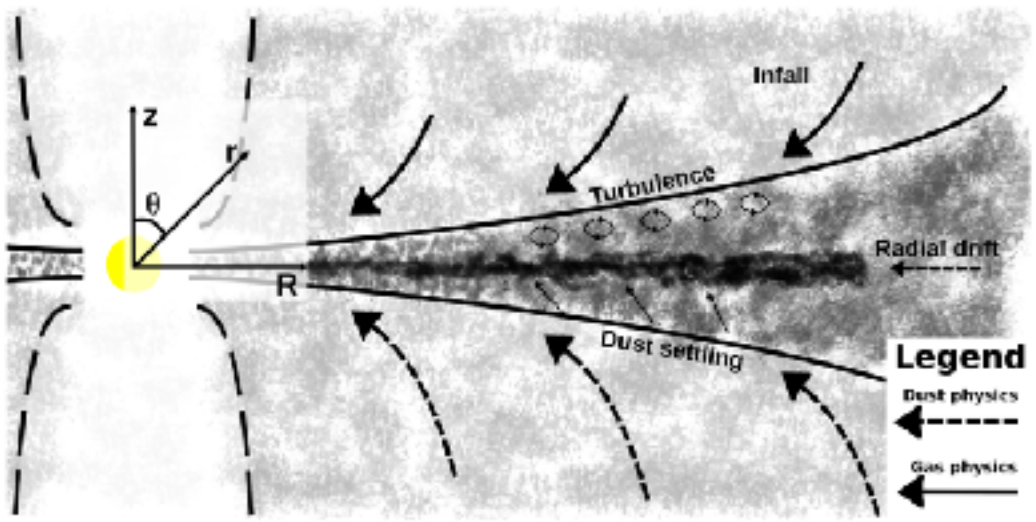
Solution: <u>streaming instability</u>
=> result of back-reaction of dust concentration on the gas, limiting the drift => pile up of material => more dust concentration => build-up of mass => local gravitational collapse

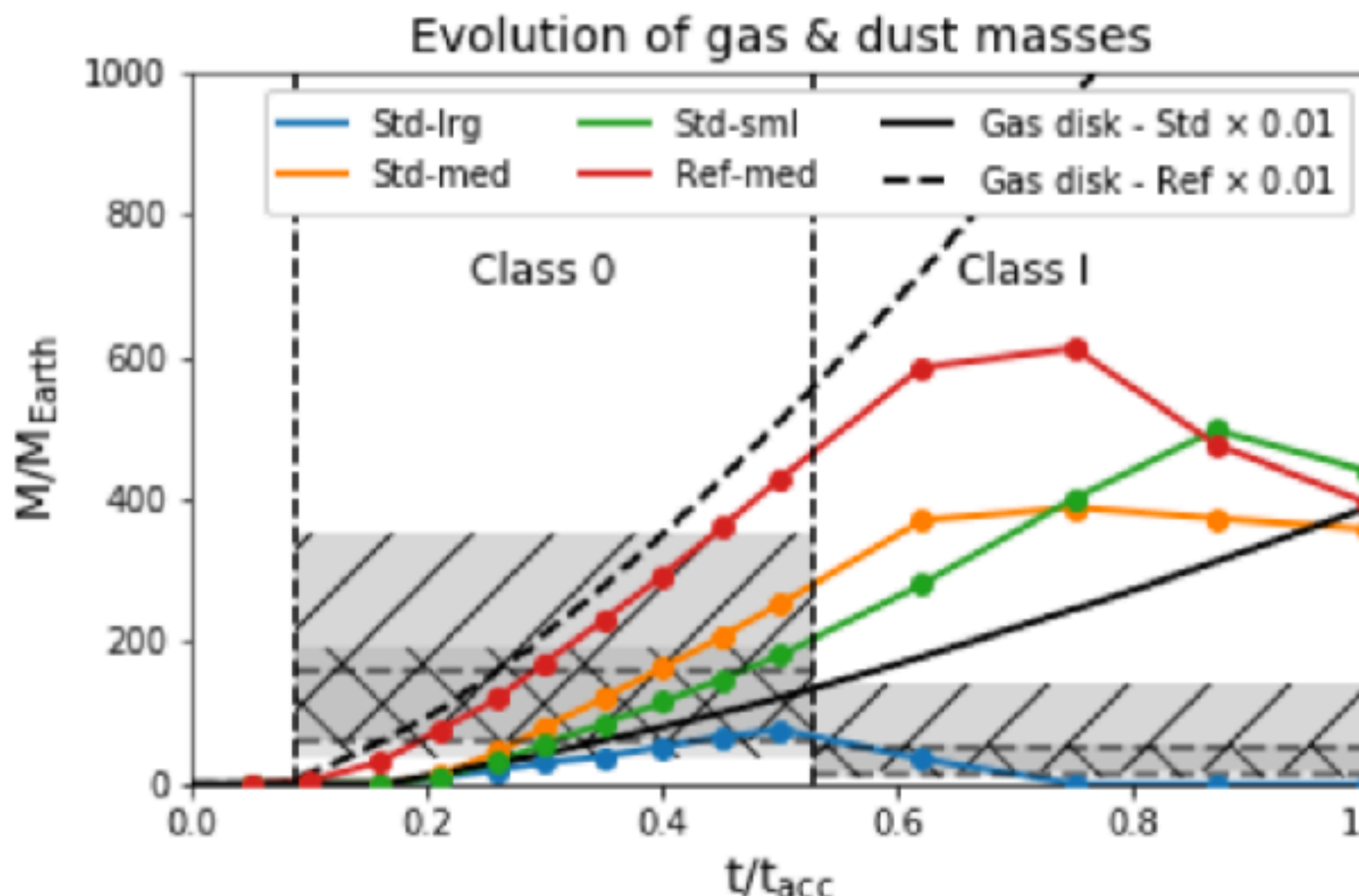




Youdin & Goodman 2005
Johansen & Youdin 2007

Early planetesimal formation





Build-up dust-to-gas ratio in infalling material: conditions for streaming instability and planetesimal formation in embedded stage

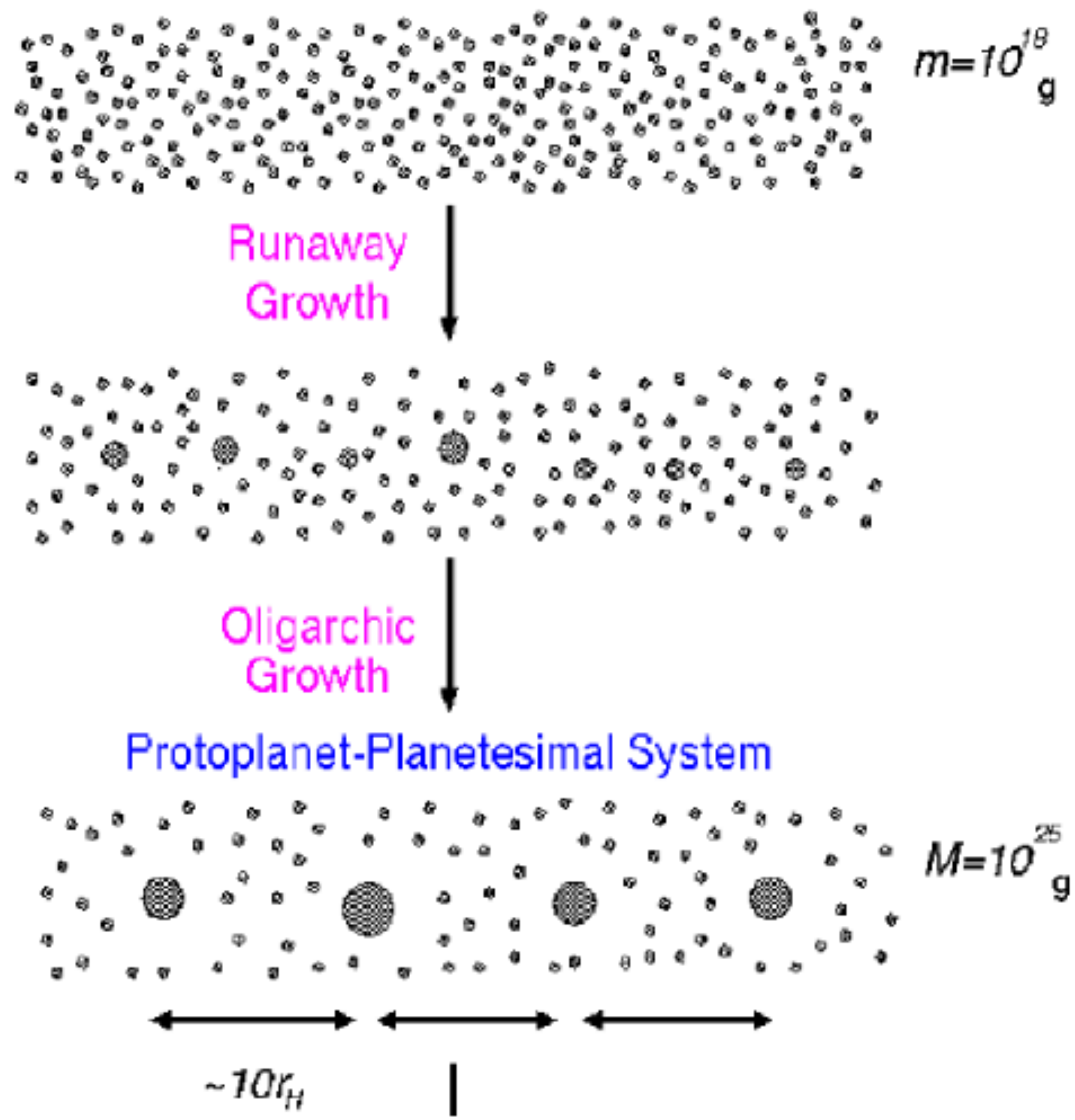
Cridland et al. 2022

Planetesimal accretion: growth planetary embryos

Initially gravitational focusing leads to <u>runaway growth</u>: massive planetesimals grow faster

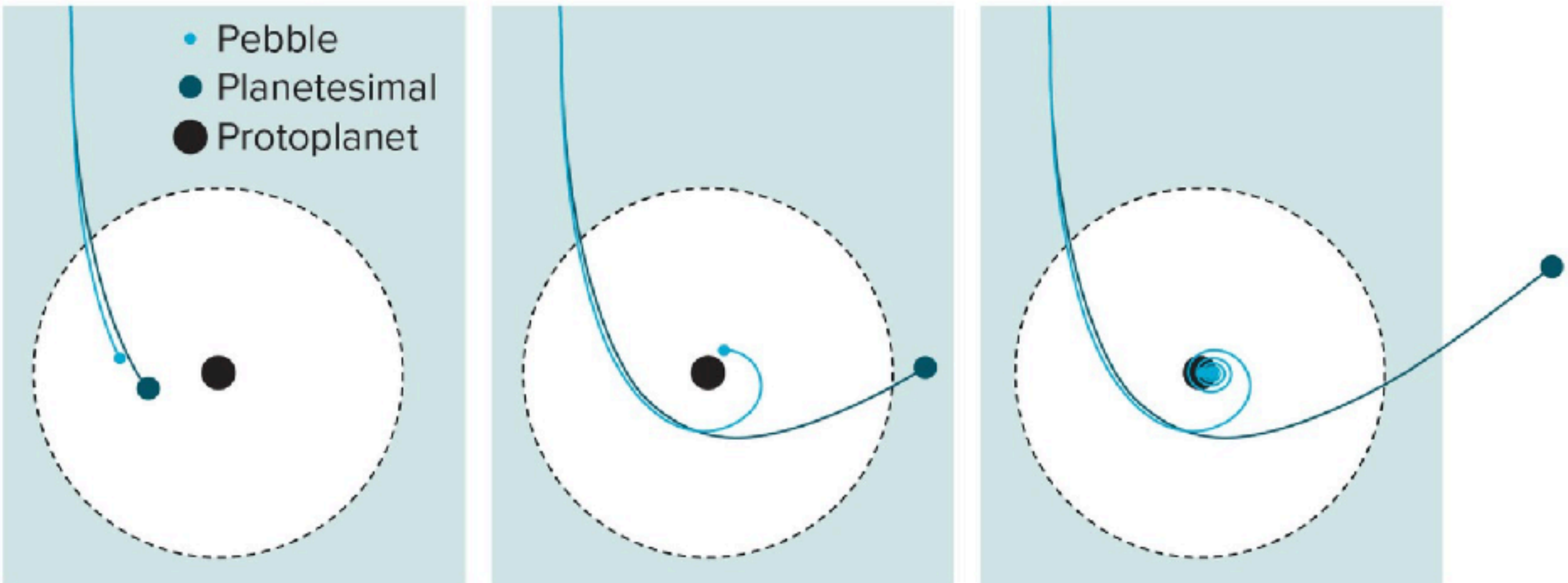
The runaway growth phase ends once the growing embryo becomes massive enough to dynamically stir the smaller planetesimals. The growth then transitions to the <u>oligarchic phase</u> which slows down growth and only most massive cores stay behind

Problem: planetesimal accretion is slow at large radii (several Myr)



e.g. Ormel et al. 2010
Armitage 2009

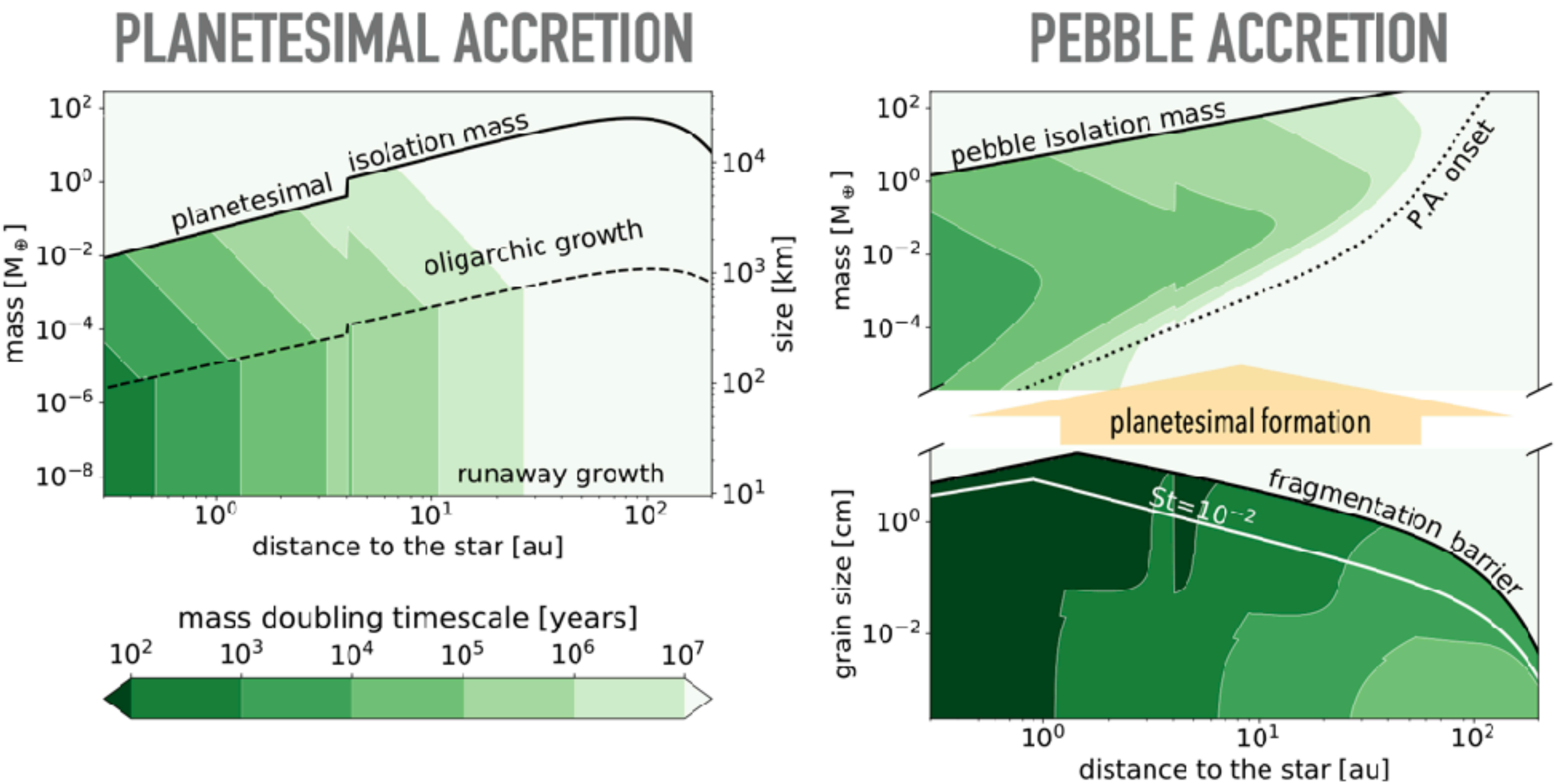
Pebble accretion



Pebbles are slowed by friction with surrounding gas as it enters planet's Hill sphere. Velocity decreases below escape velocity, spirals in. Larger planetesimal isn't slowed down enough, and flies by. Despite small mass, pebble accretion is efficient, leading to rapid increase in planet mass.

Lambrechts & Johansen 2014

Comparison timescales



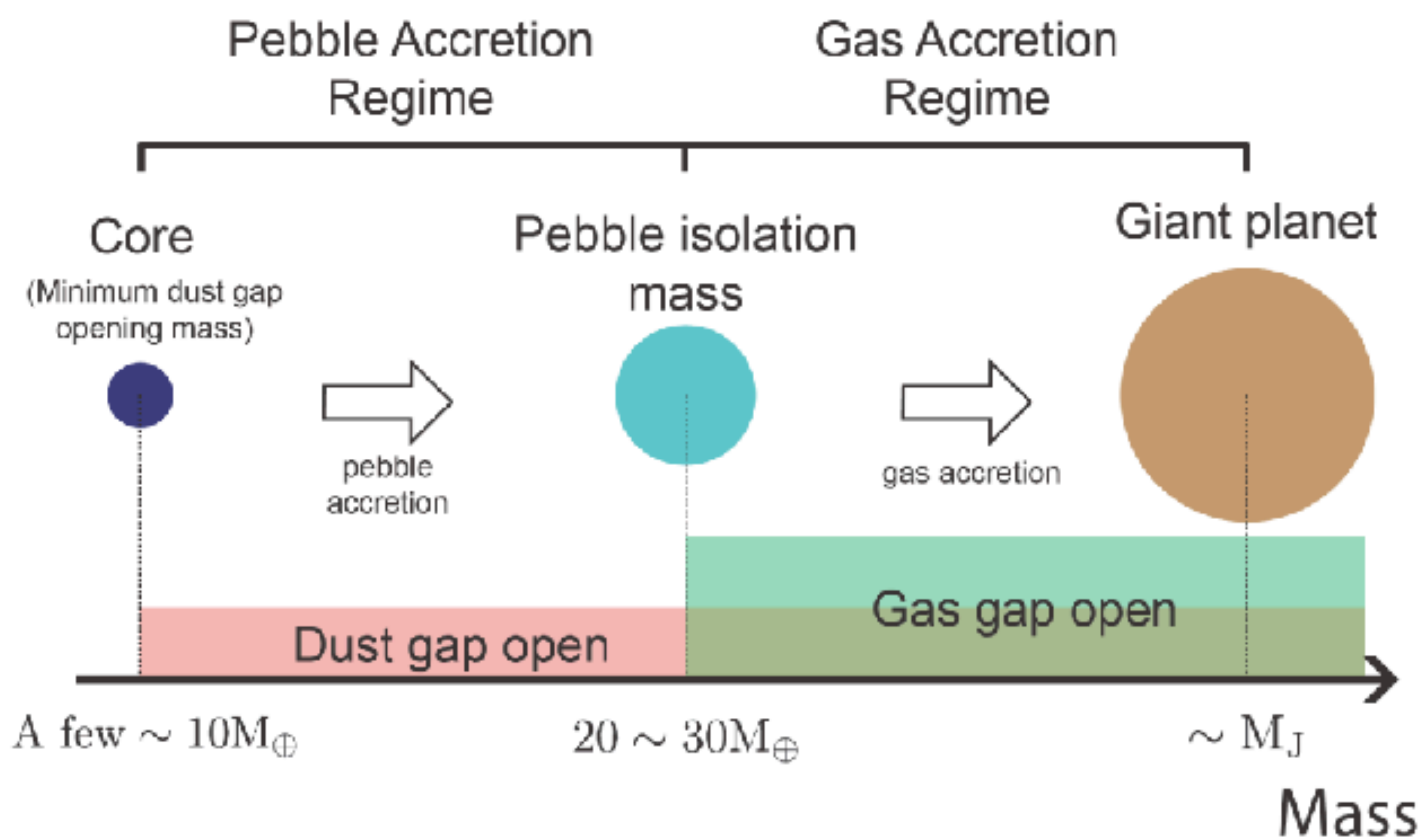
Drazkowska et al. 2022 (PPVII)

Pebble isolation mass

Minimum mass required to open up a gap in the dust (i.e. trap pebbles in the outer edge): pebble isolation mass

$$M_{\mathrm{iso,peb}} \simeq 25 M_{\oplus} \left(\frac{H/r}{0.05}\right)^3 \left(\frac{M_\star}{M_\odot}\right)$$

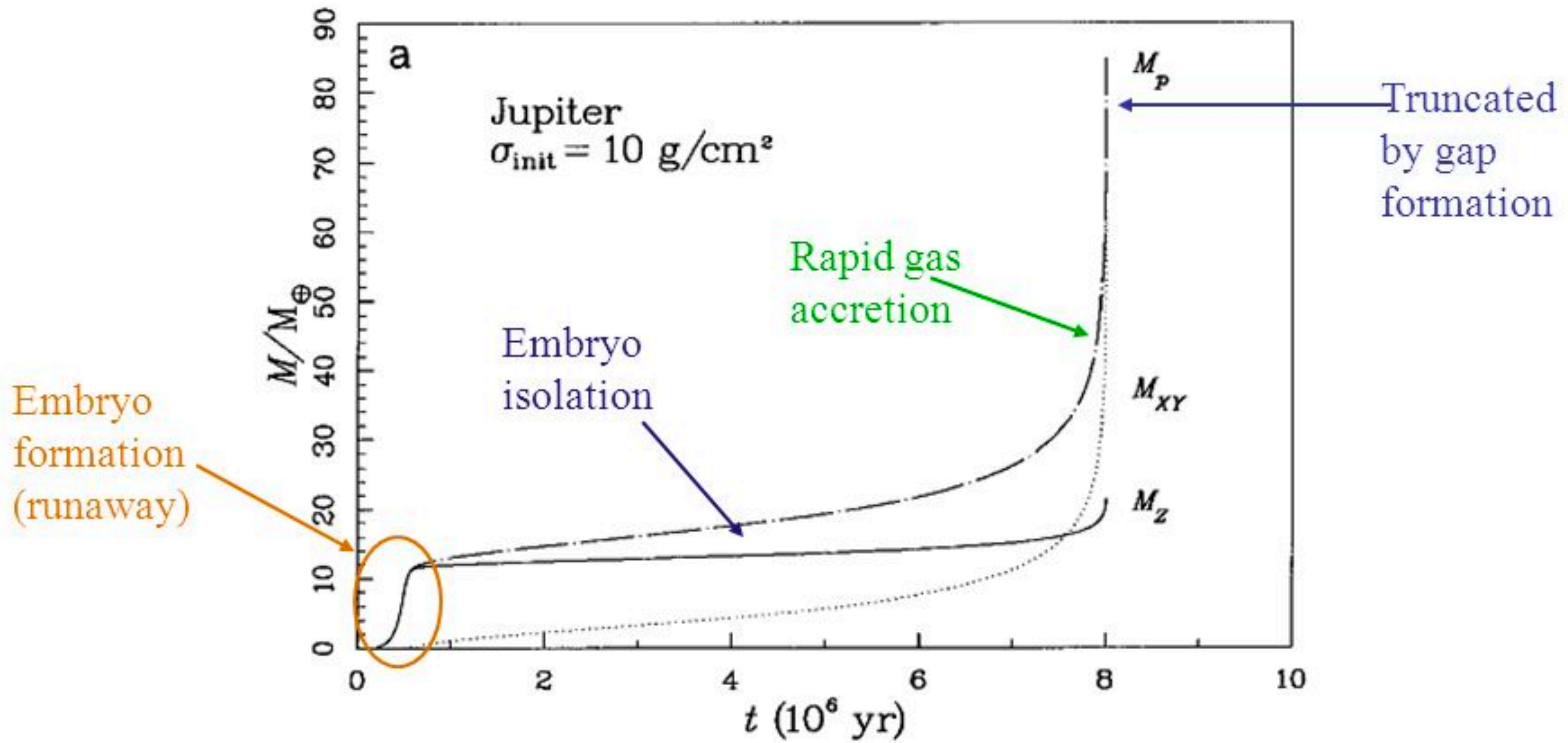
Once pebble accretion has stopped, atmosphere no longer heated: gas accretion can start as contraction is possible



Lambrechts et al. 2014
Wang et al. 2021

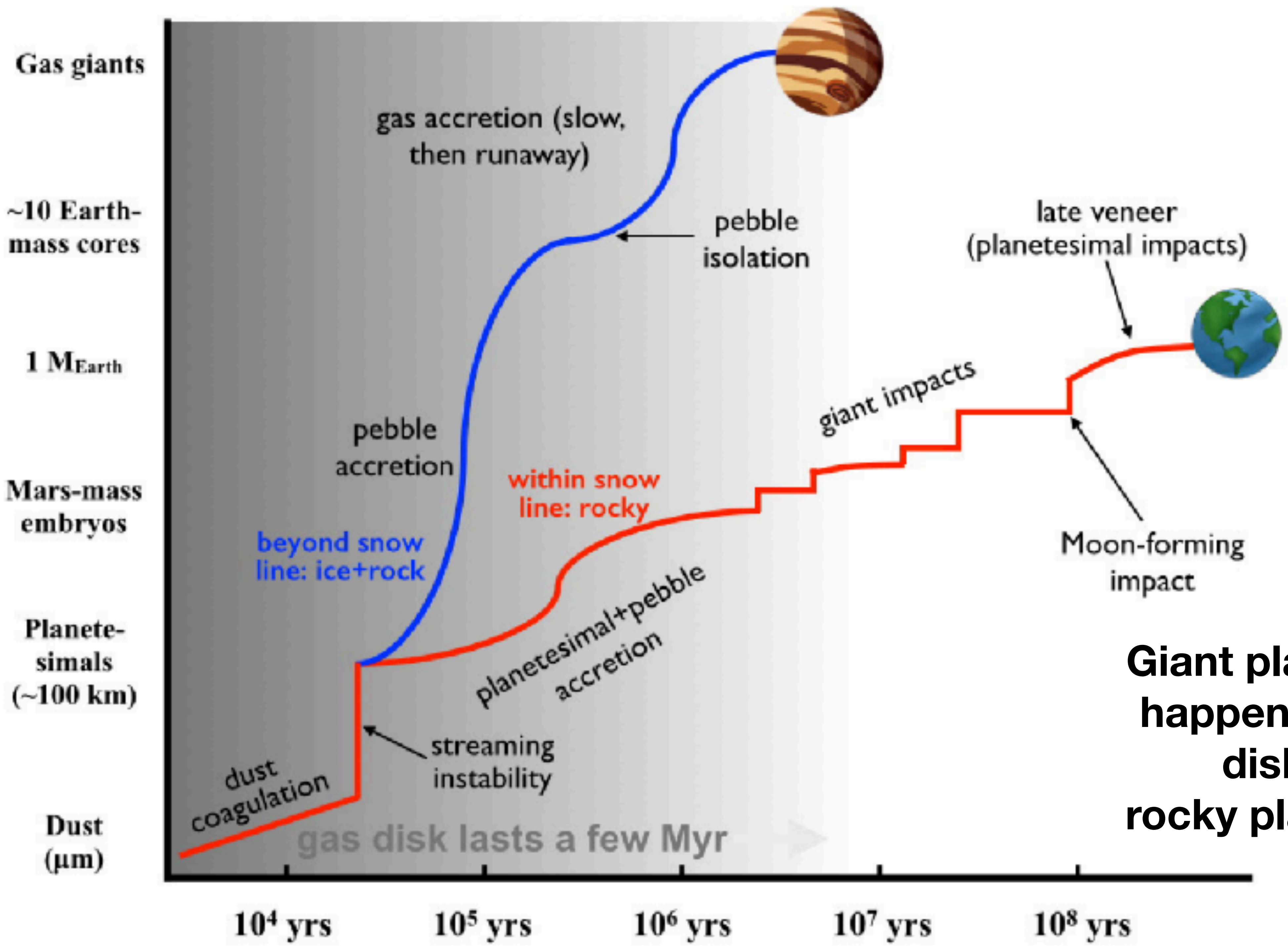
Core accretion

Gas accretion initially slow, until gas envelope ~ core mass => runaway gas accretion



Pollack et al. 1996

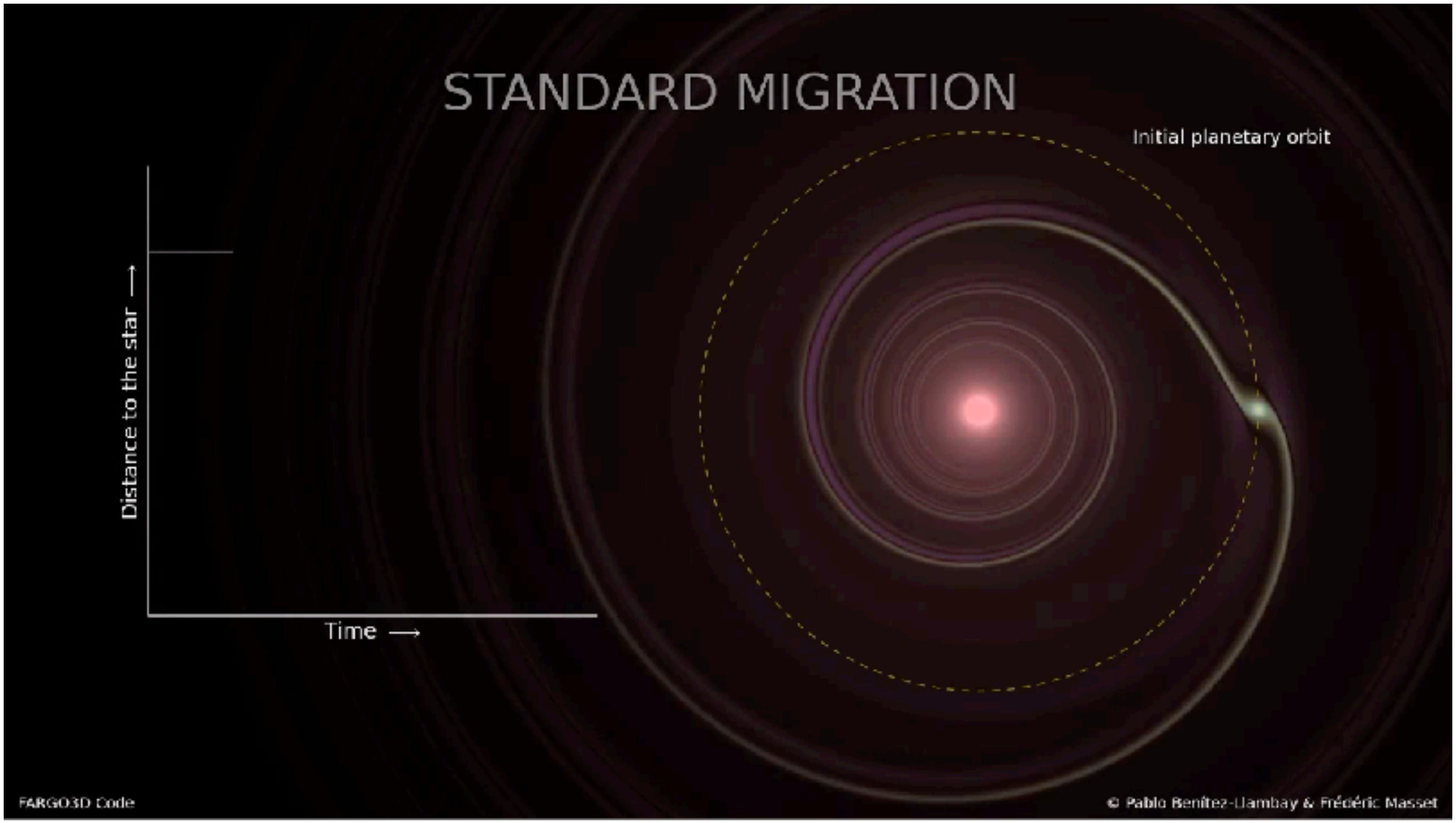
Gas giant and terrestrial planet formation



Giant planet formation must happen rapidly (before gas disk is dissipated), rocky planets can form later

Raymond & Morbidelli 2022

Migration

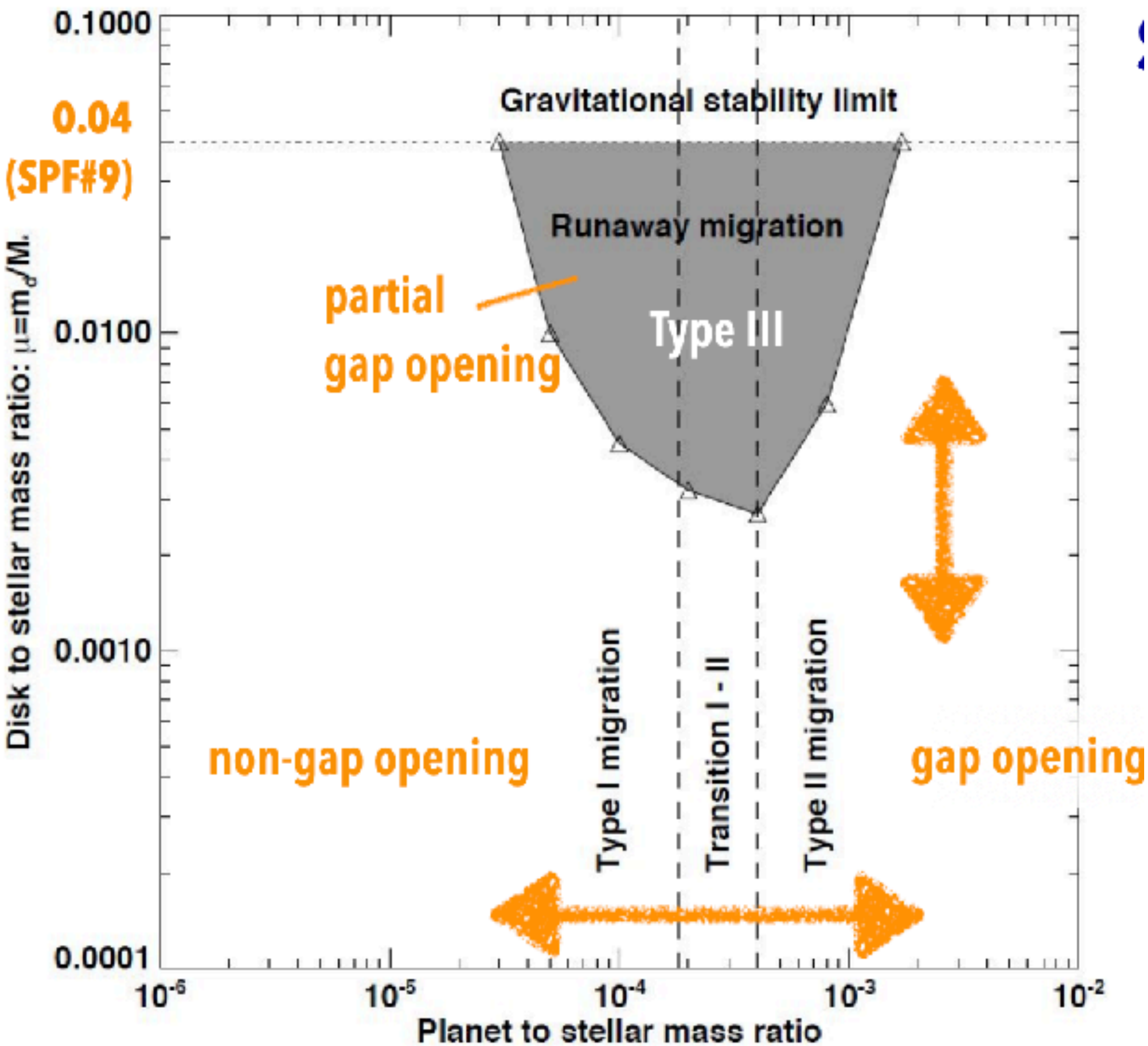


Discovery of hot Jupiters triggered possibility of inward migration: Jupiters must have formed further out. Migration happens through torques between the planet and the disk and can be inward and outward, depending on local conditions

Credits:
Pablo Benitez-Llambay

Migration

Different types of migration depending on the conditions

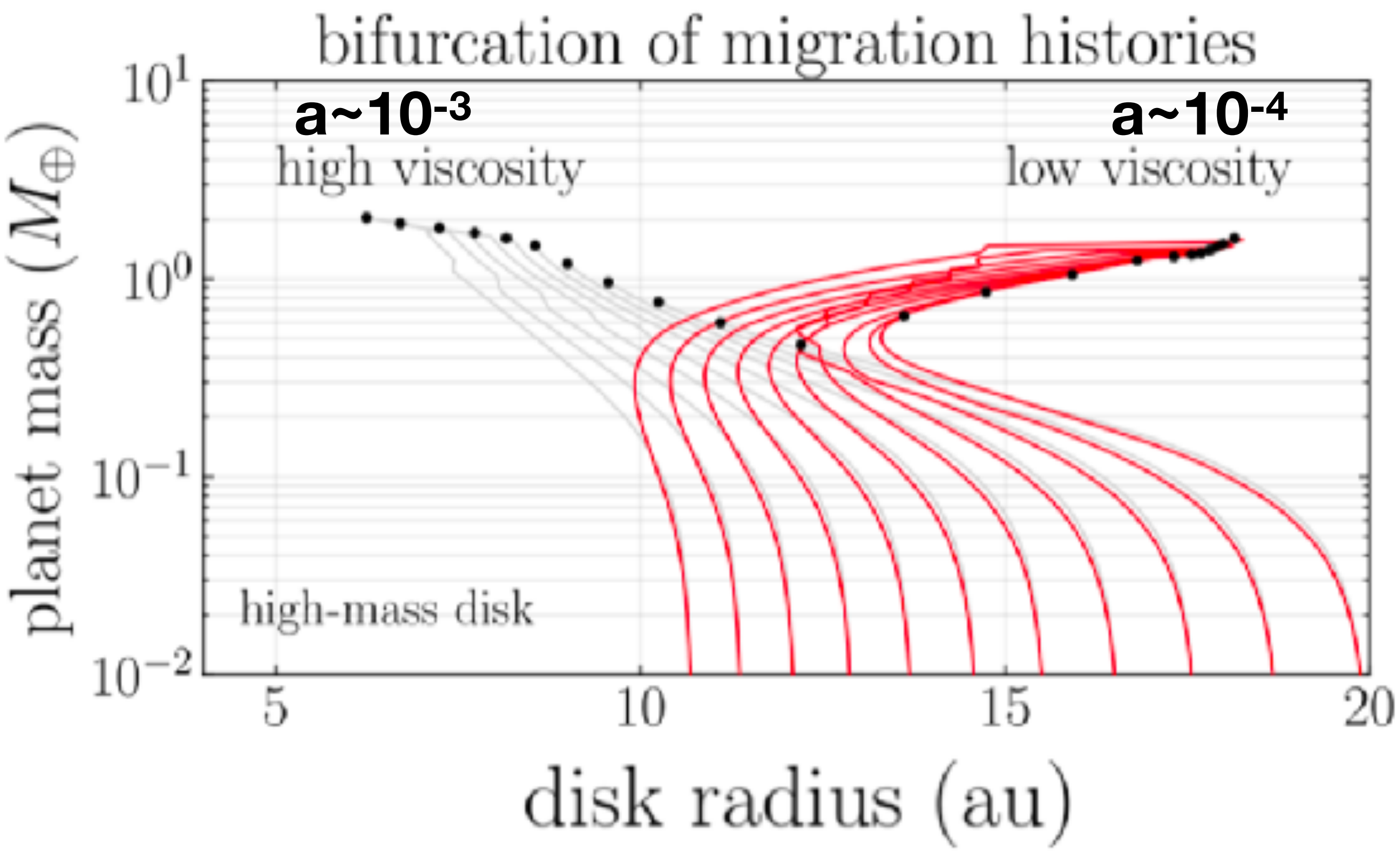


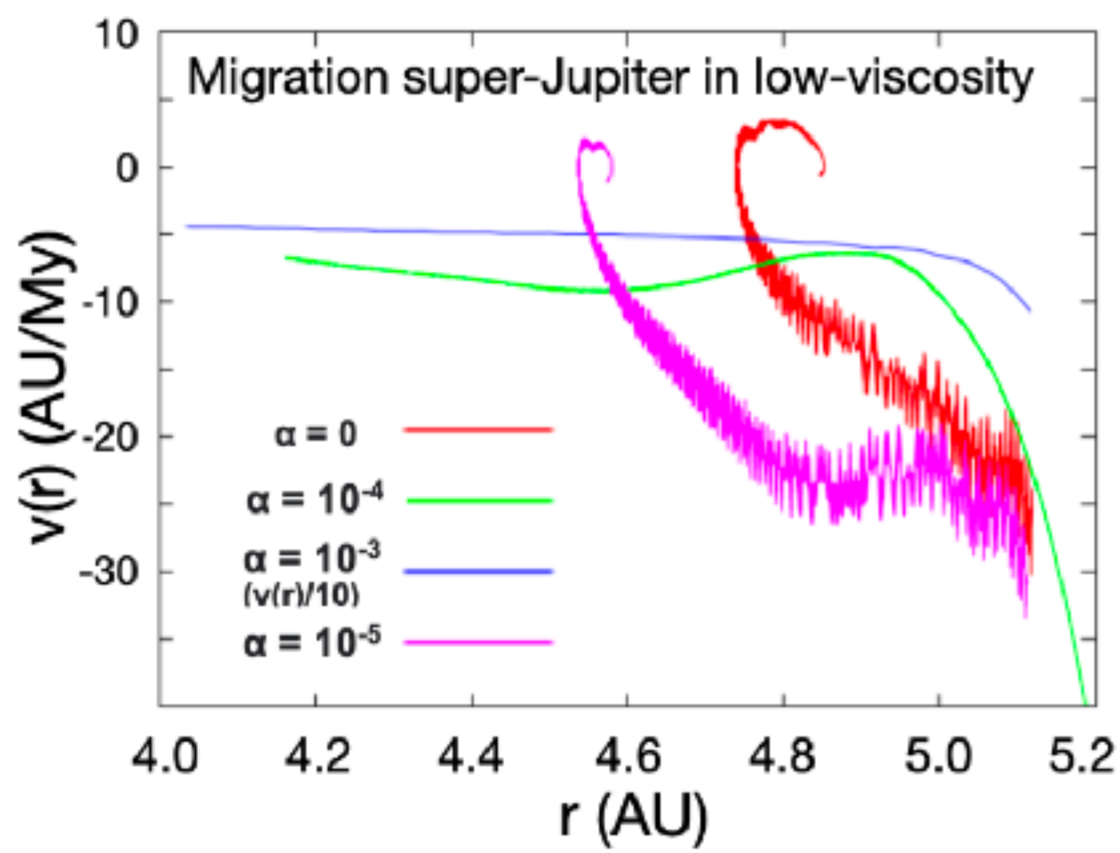
Type III depends on M_d/M_*

Type I - II depend on M_p/M_*

Kley & Nelson 2012

Many new developments in migration





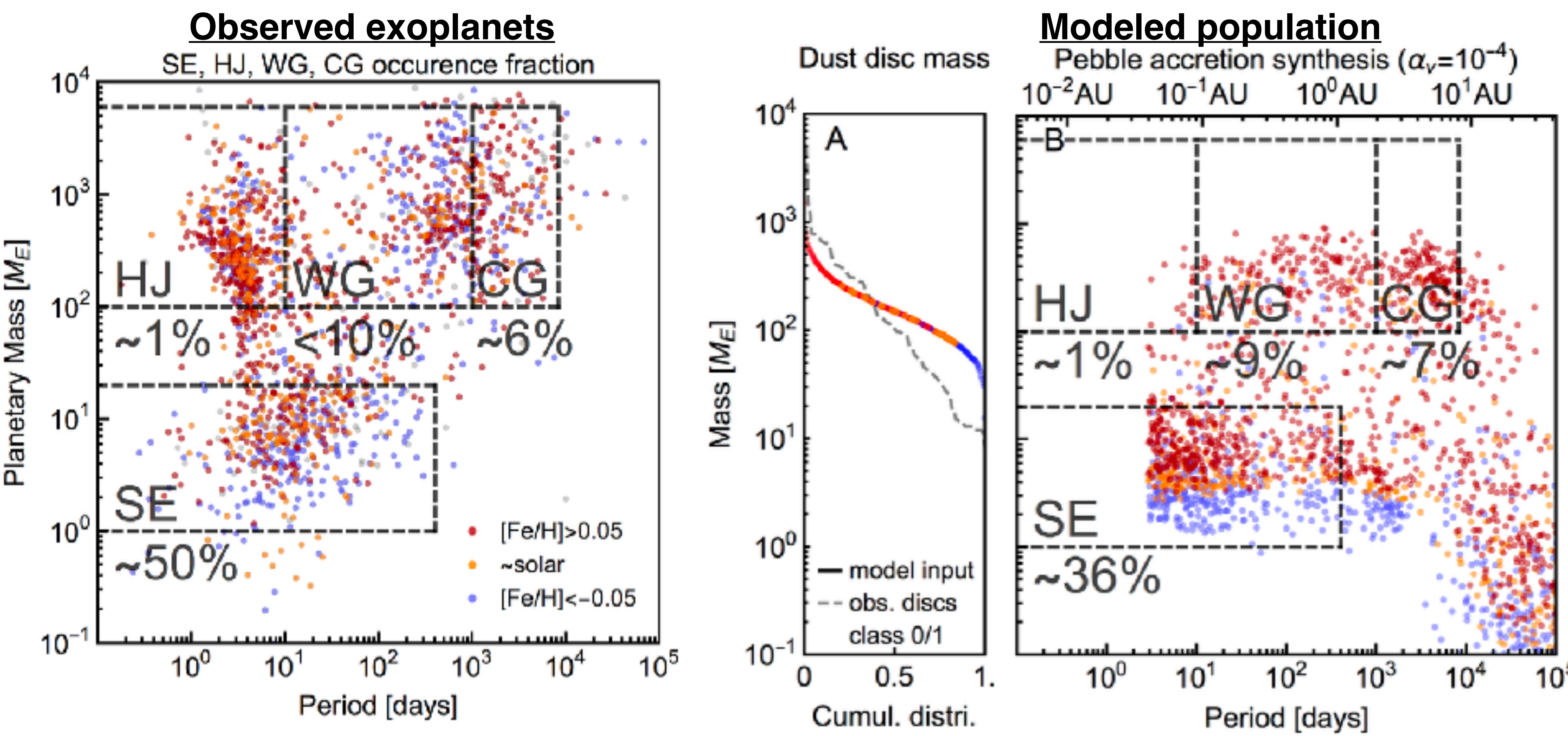
Migration may be halted or even change direction in low-viscosity disks, e.g. through the formation of vortices and eccentricity for massive planets:

no conclusive picture yet!

Speedie et al. 2021
Lega et al. 2021
Paardekooper et al. 2022 (PPVII)

Planet formation in practice

In order to test planet formation scenarios, a common approach is planet population synthesis: based on a given disk distribution and a number of prescriptions for growth and migration, where do the planets end up?



So far still difficult to get a 100% success rate

Drazkowska et al. 2022 (PPVII)

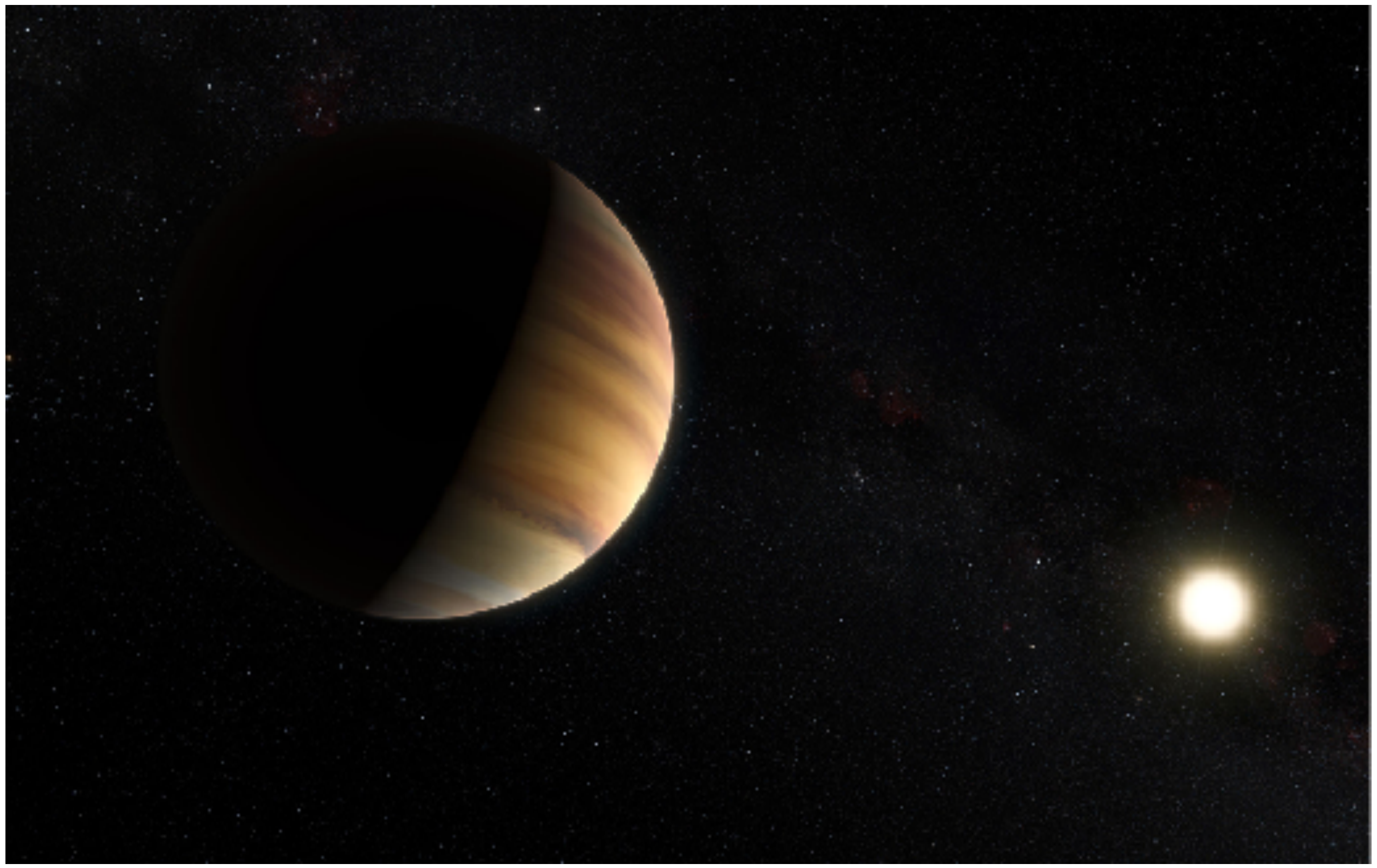
Summary

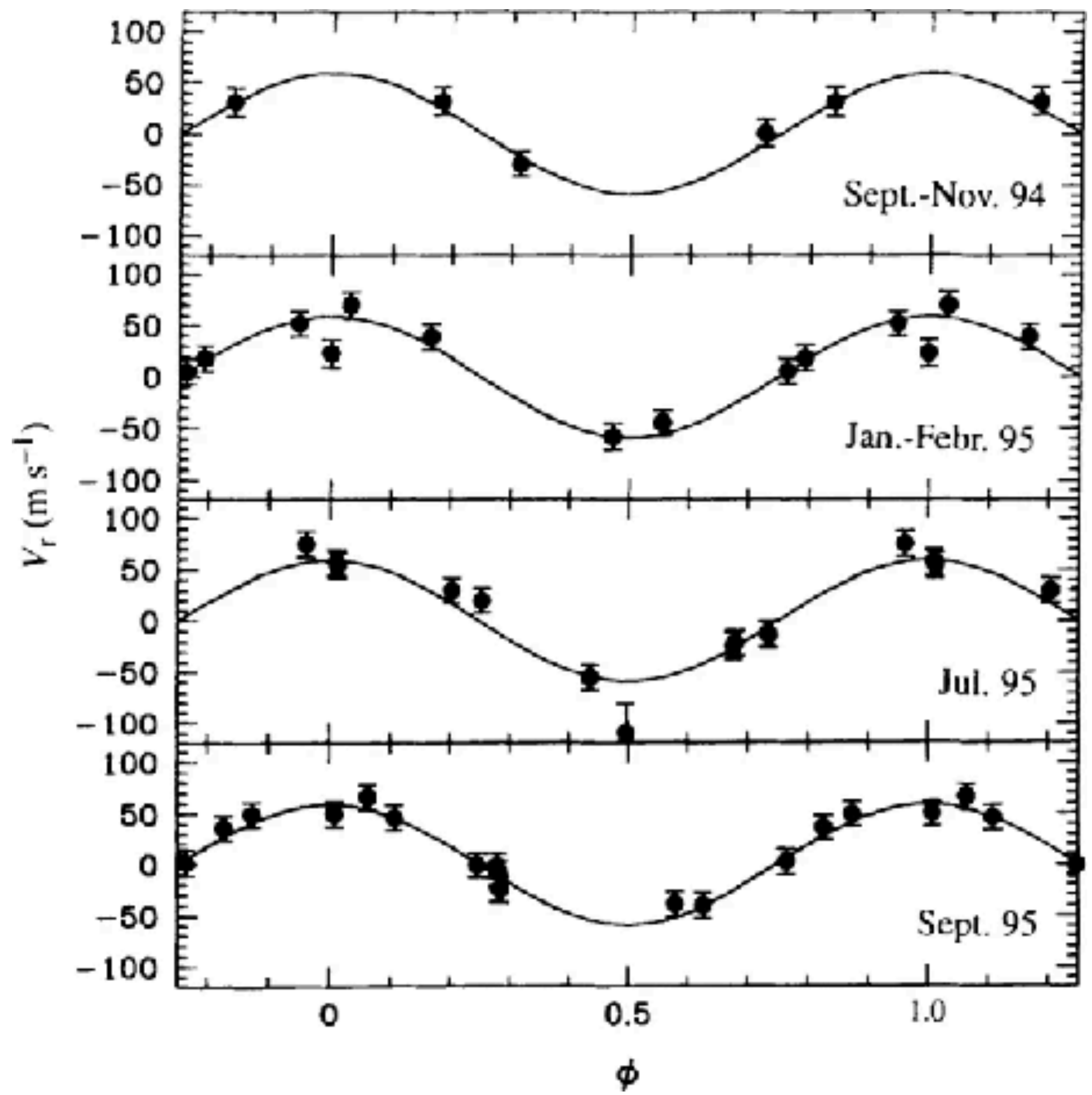
- Planet formation happens in several steps with different timescales
- No consensus yet for the exact processes
- Migration can lead to planets transported inwards and outwards: turbulence may play a key role here
- Planet population synthesis most promising approach for a full picture of planet formation, but many open questions remain

Exoplanets

Bias to Gijs Mulders' work: many other studies available as well

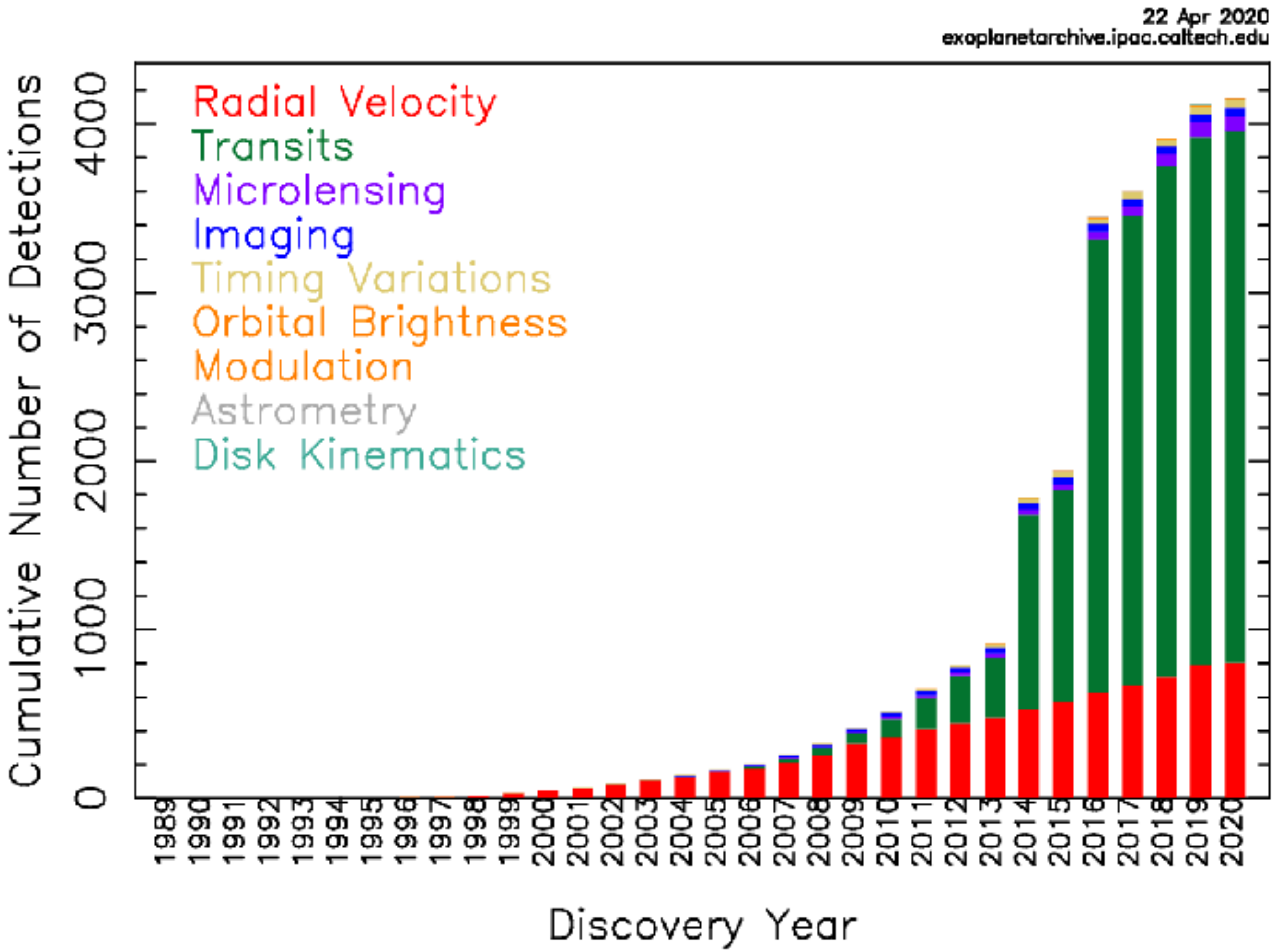
First exoplanet around star in 1995: 51 Peg b





Mayor & Queloz, 1995

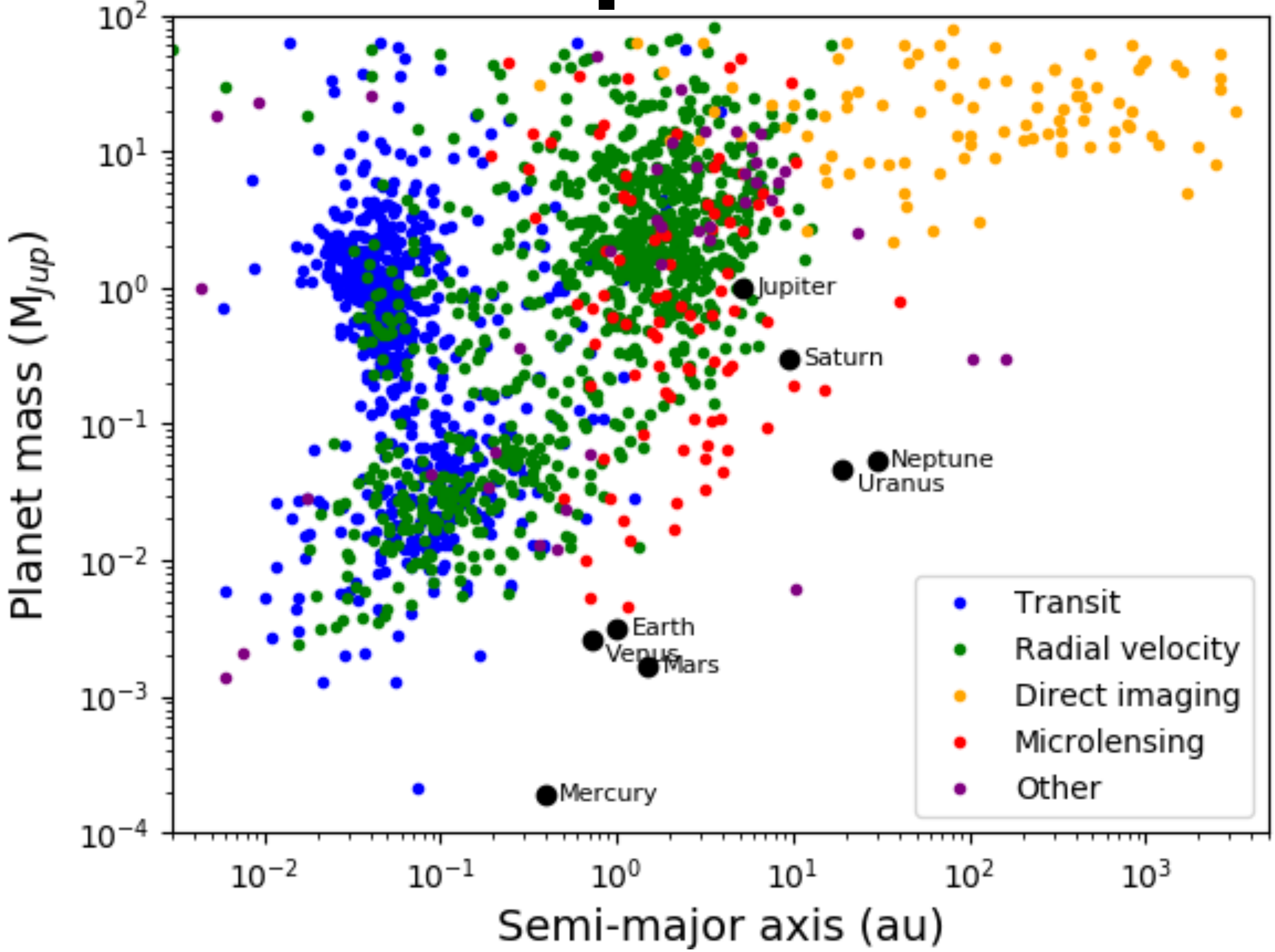
Exoplanets



Discovering exoplanets no longer special:
with the large number we can now look at demographics!

Exoplanets

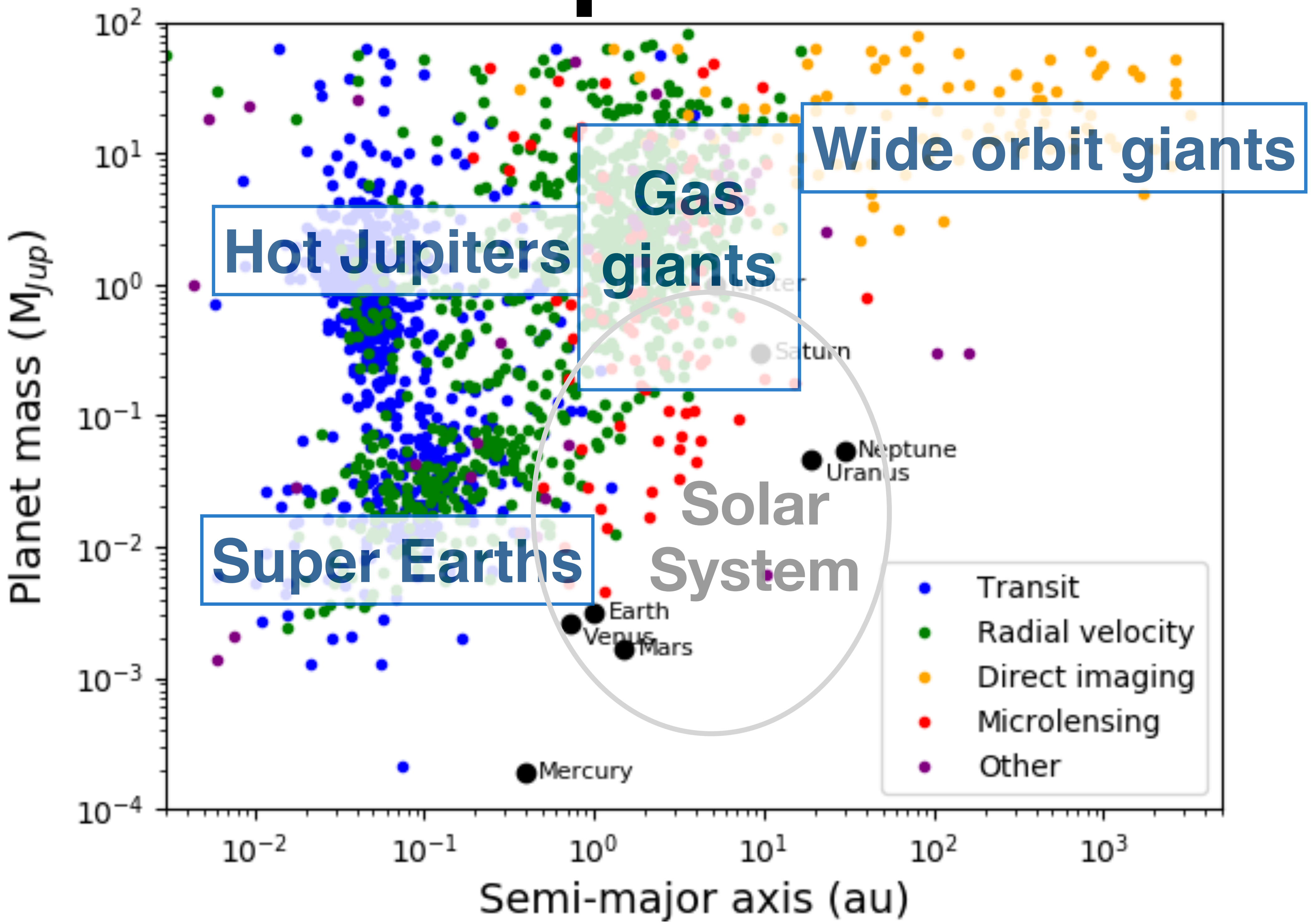
>5000 exoplanets!



http://exoplanet.eu

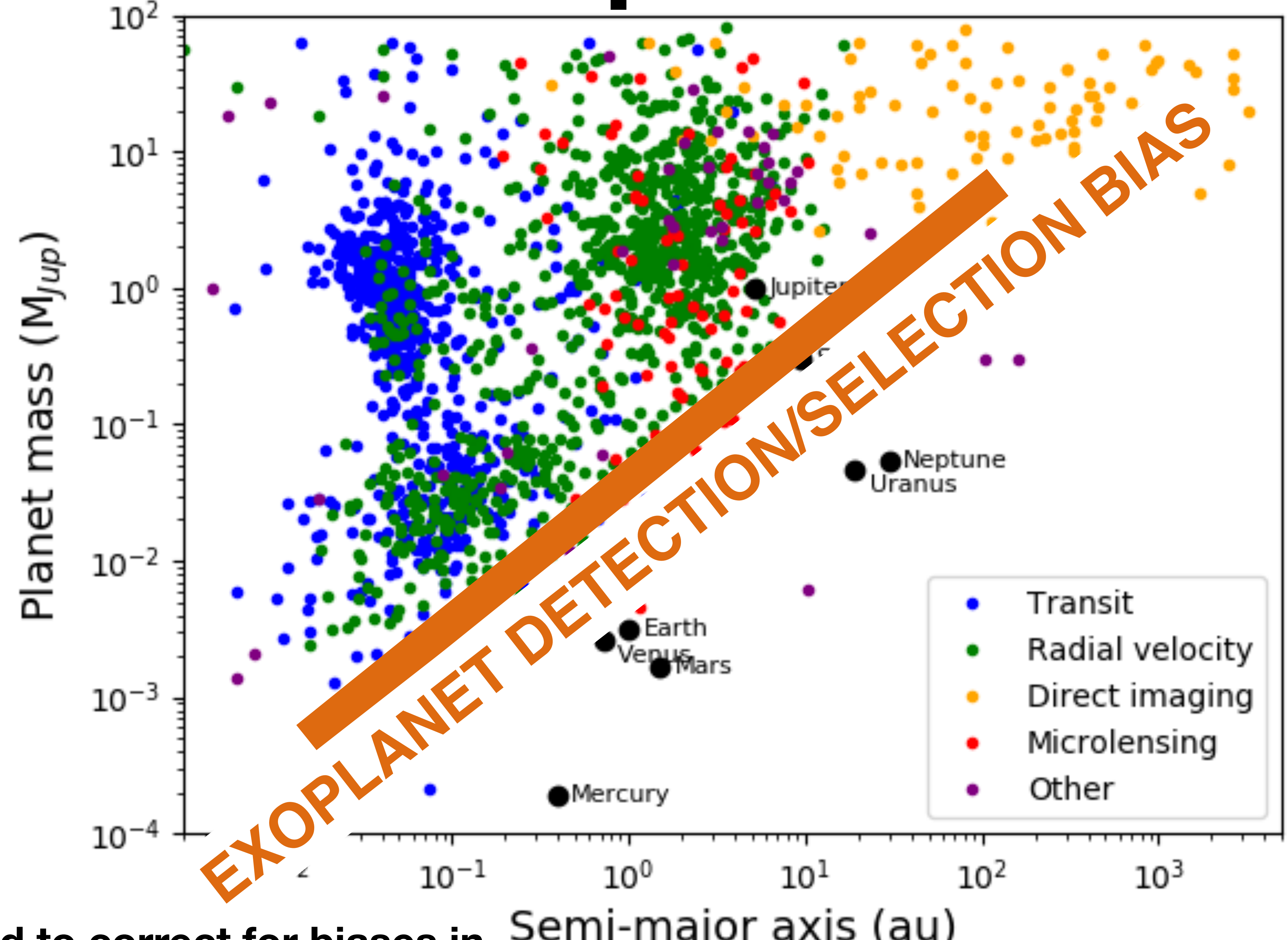
NASA exoplanet archive

Exoplanets



http://exoplanet.eu
NASA exoplanet archive

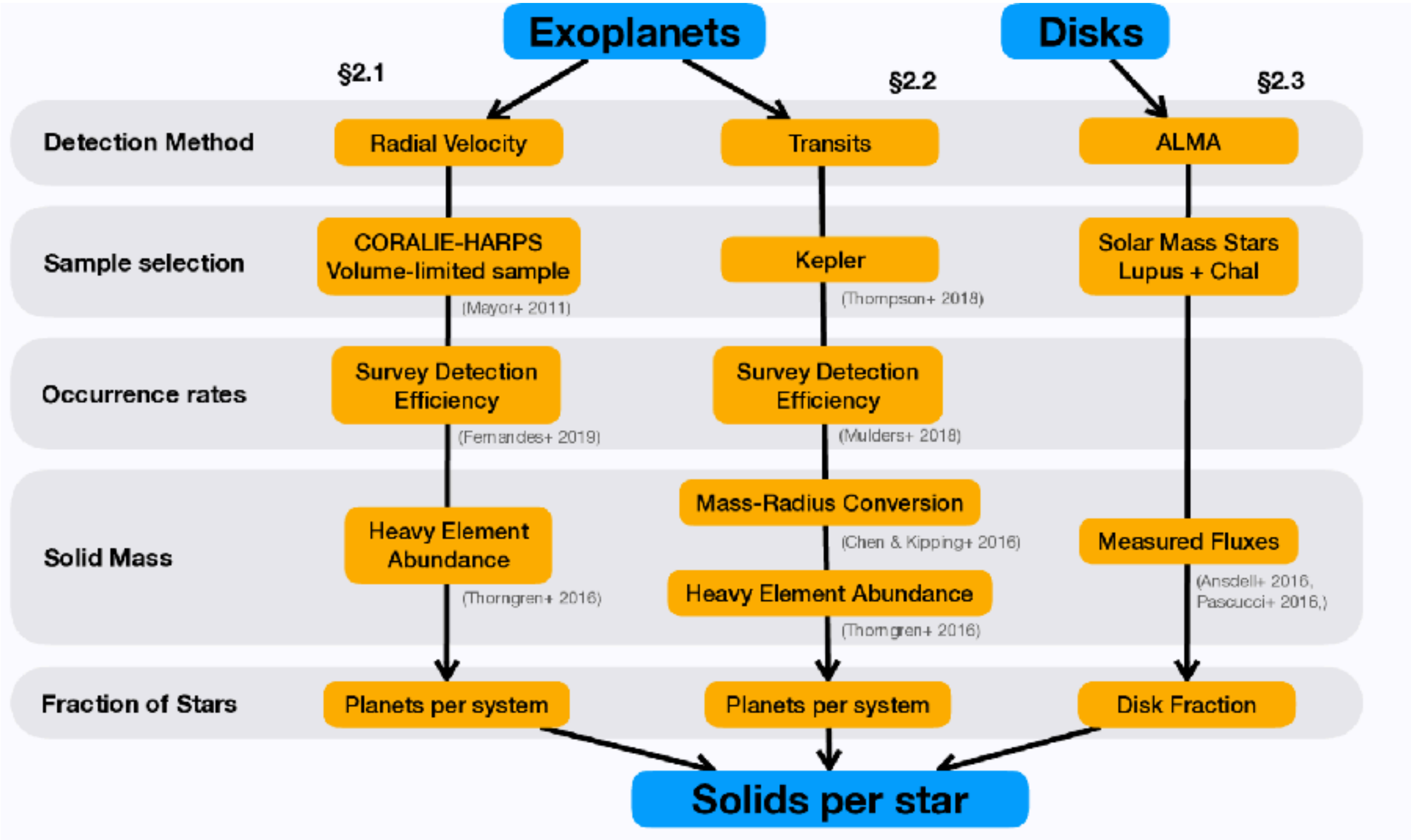
Exoplanets



Need to correct for biases in detection limit and selection criteria to derive proper occurrence rates

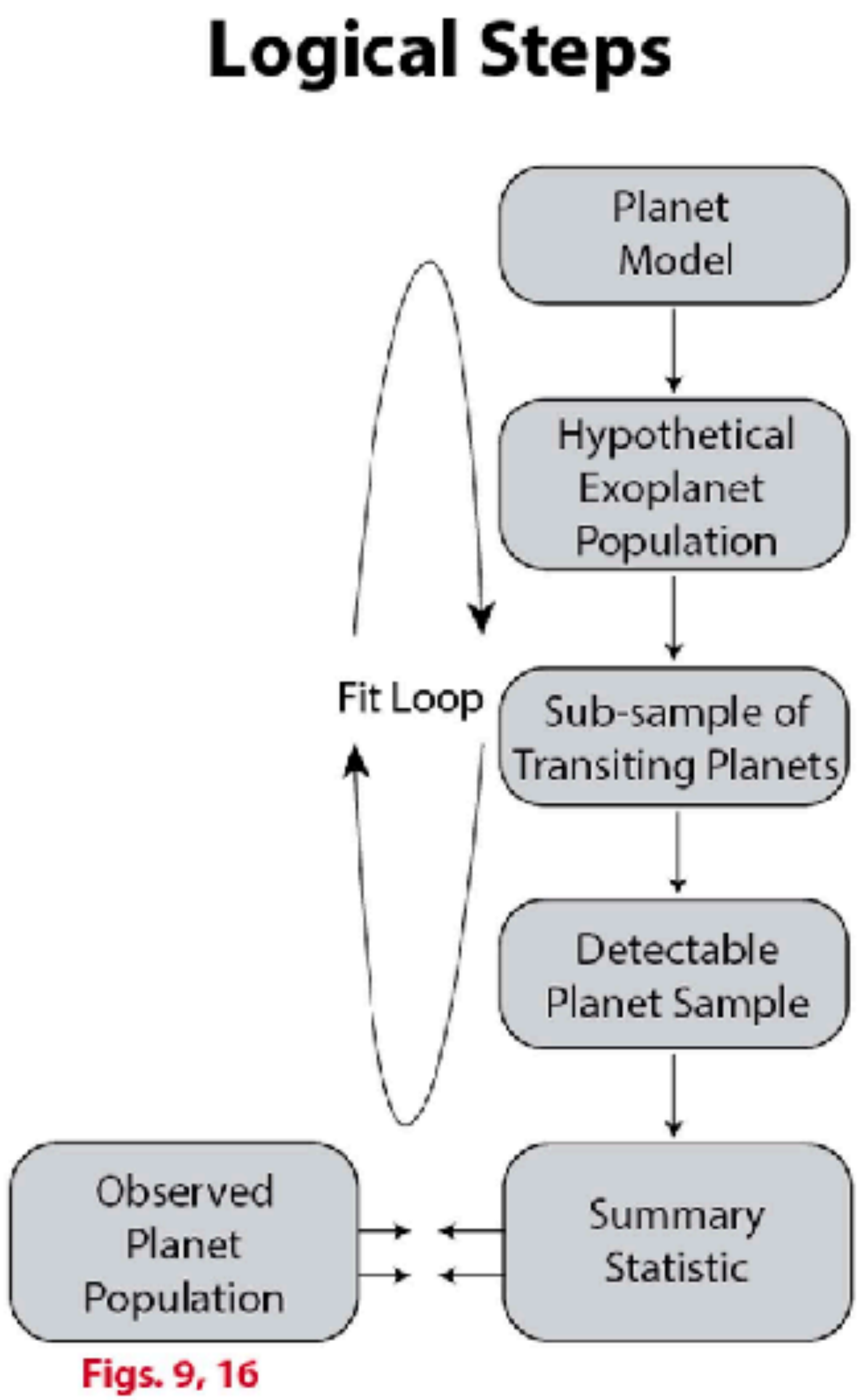
http://exoplanet.eu
NASA exoplanet archive

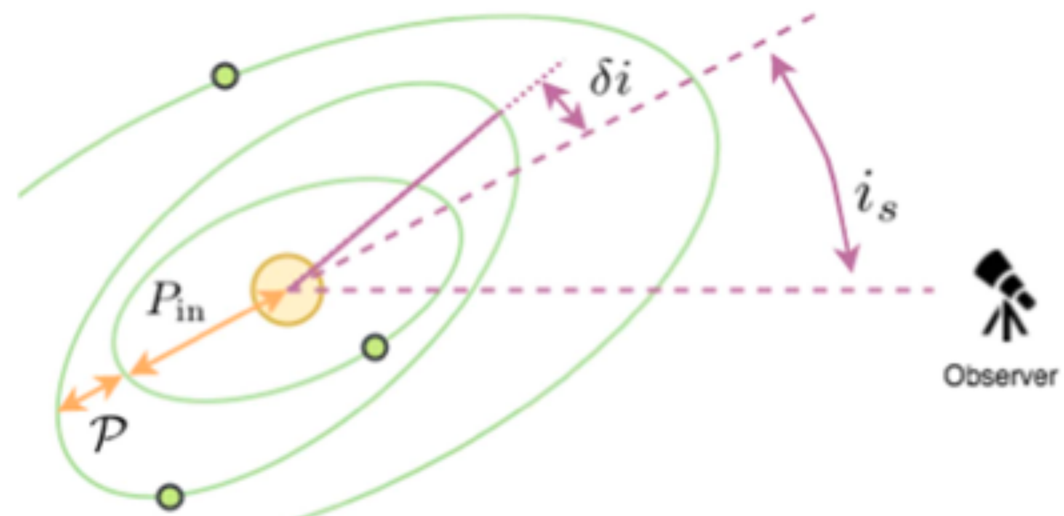
Debiasing exoplanet catalogs

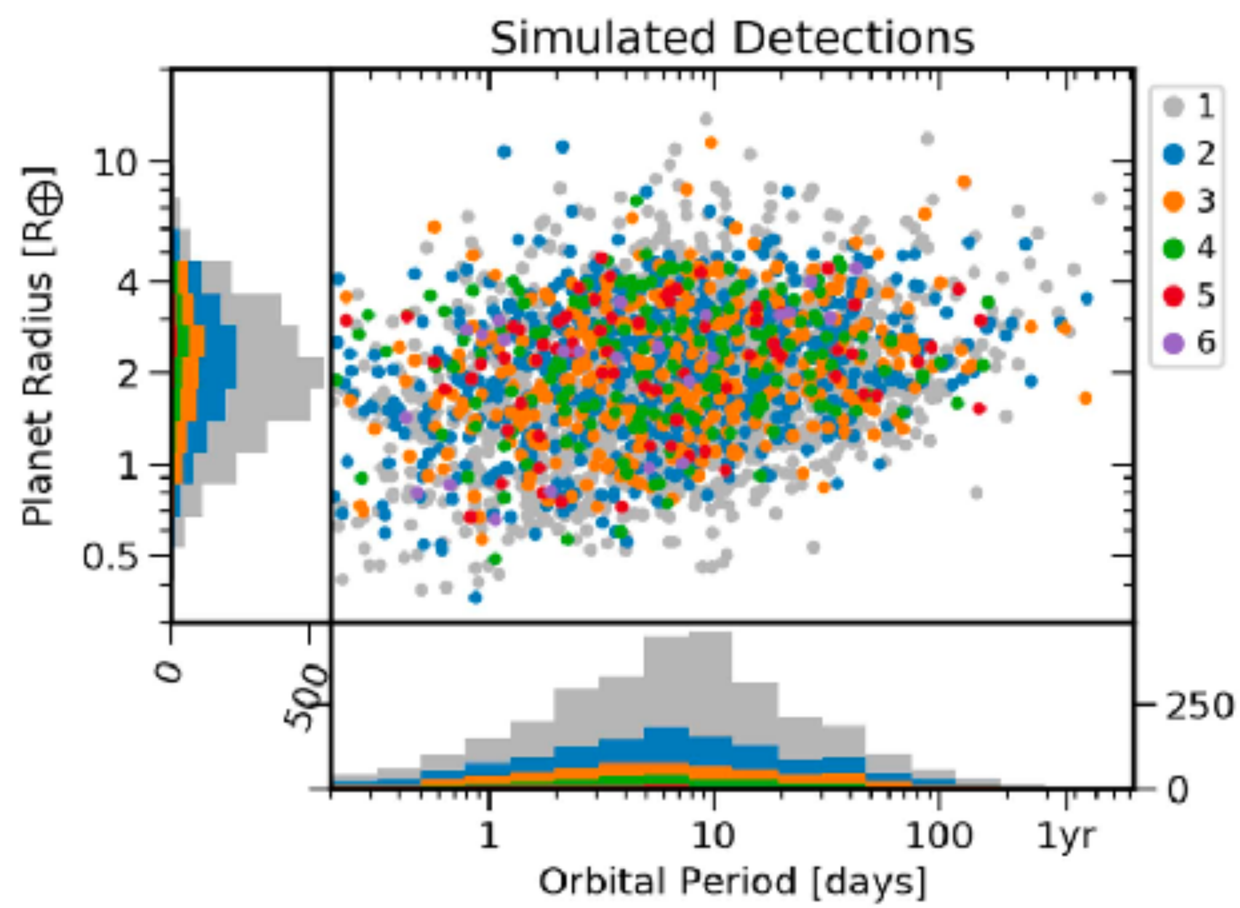


Mulders et al. 2021

Example: EPOS

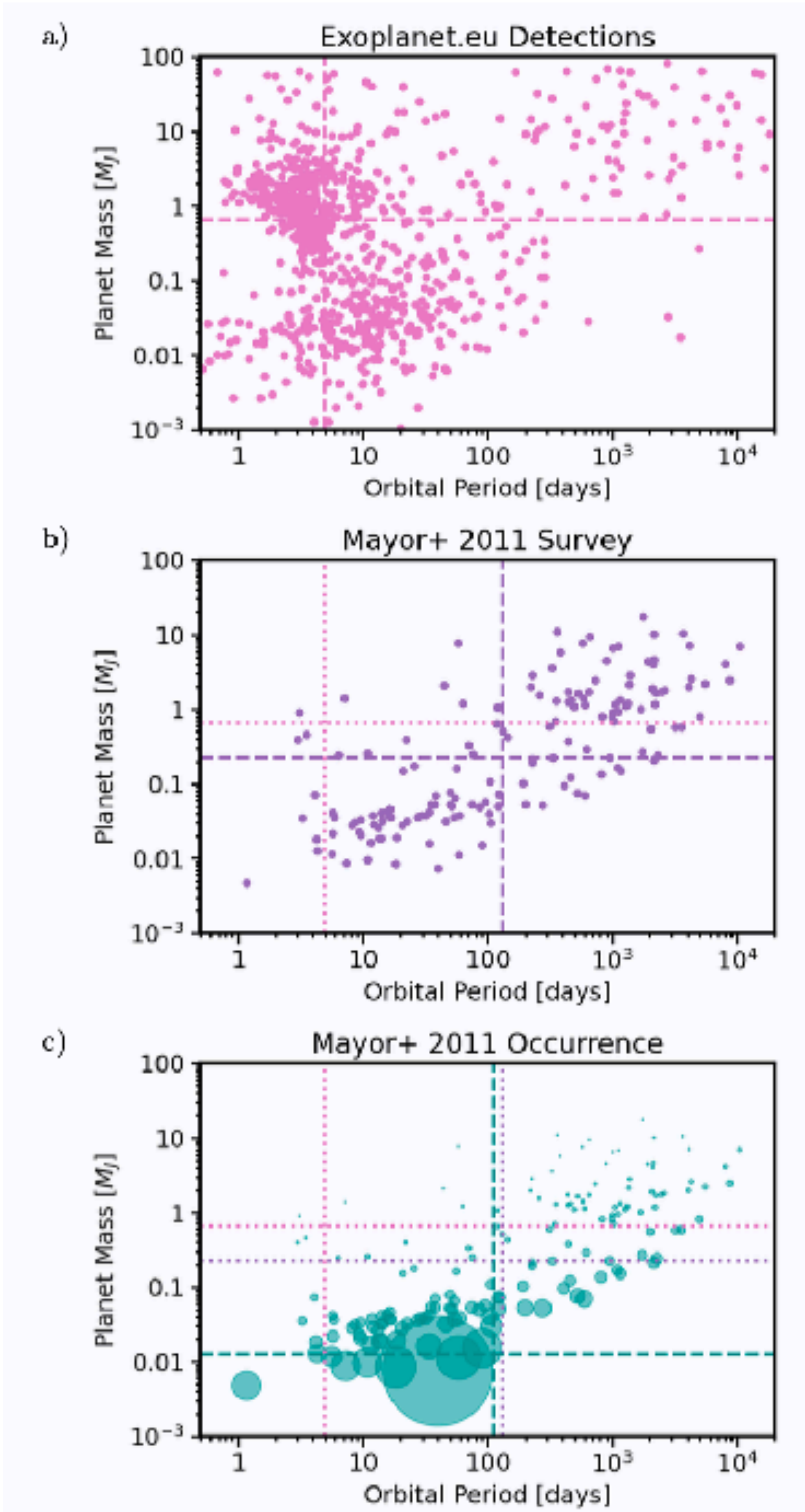




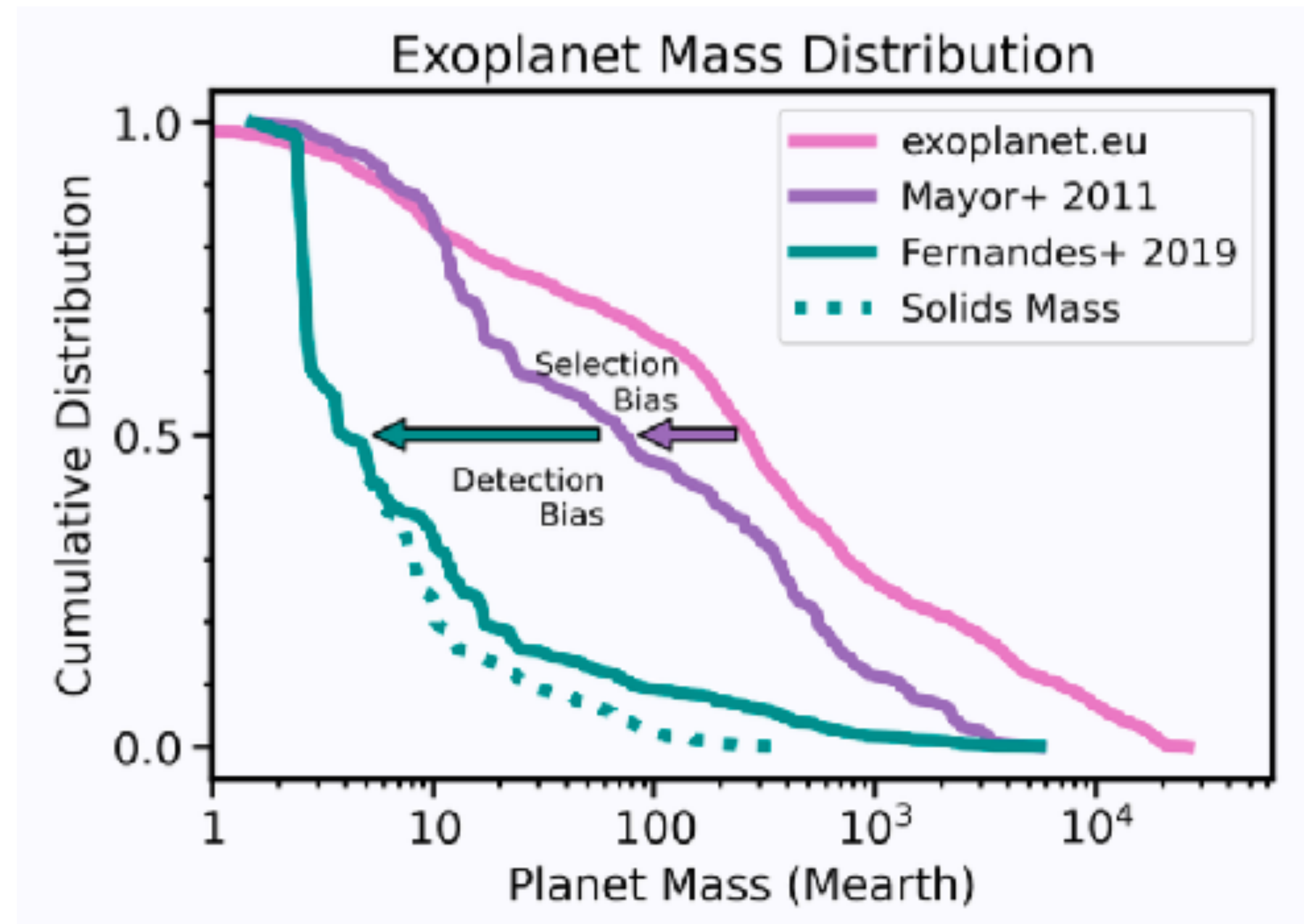


Mulders et al. 2018

Recall: dust mass budget



Careful! Exoplanet detection catalog is not a complete or unbiased survey

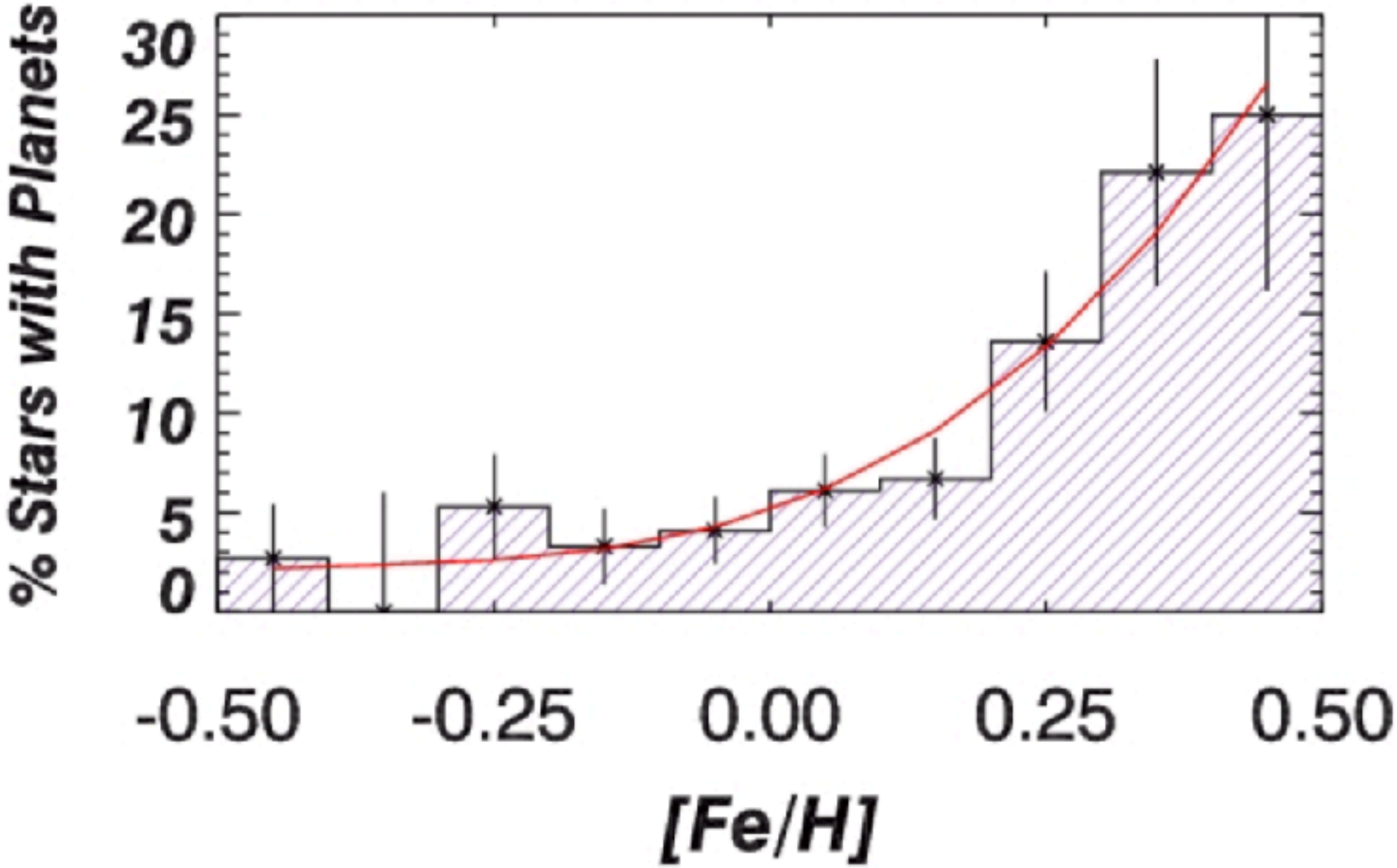


Need to correct for selection and detection biases to get the 'true' exoplanet mass budget

Mulders et al. 2021

Occurrence rates

*Giant plane**t** vs metallicity*

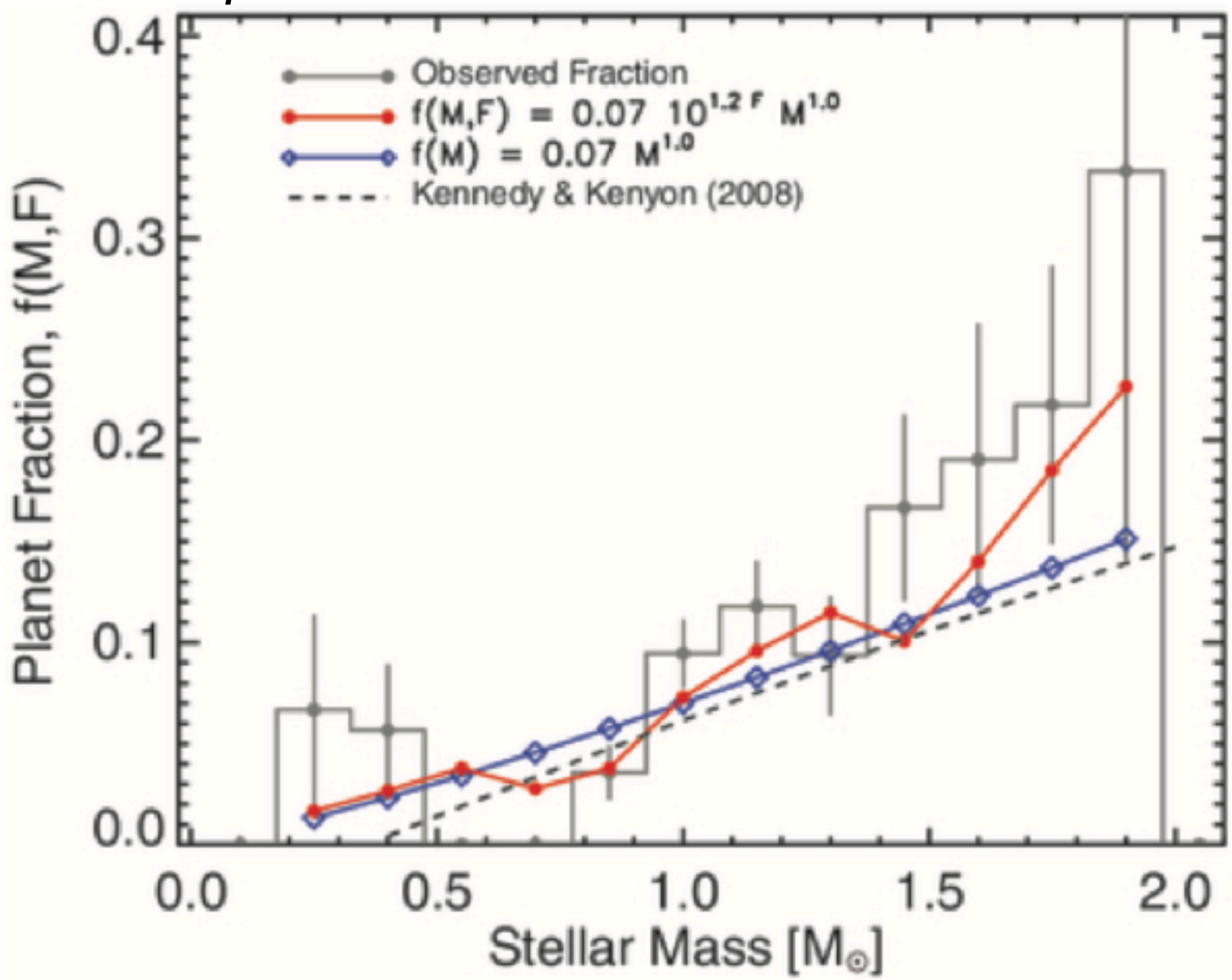


Giant planets more common around higher metallicity stars (but overall occurrence remains small, <30%!): linked to formation preferences in cloud?

Fischer & Valenti 2005

Occurrence rates

Giant planet vs stellar mass

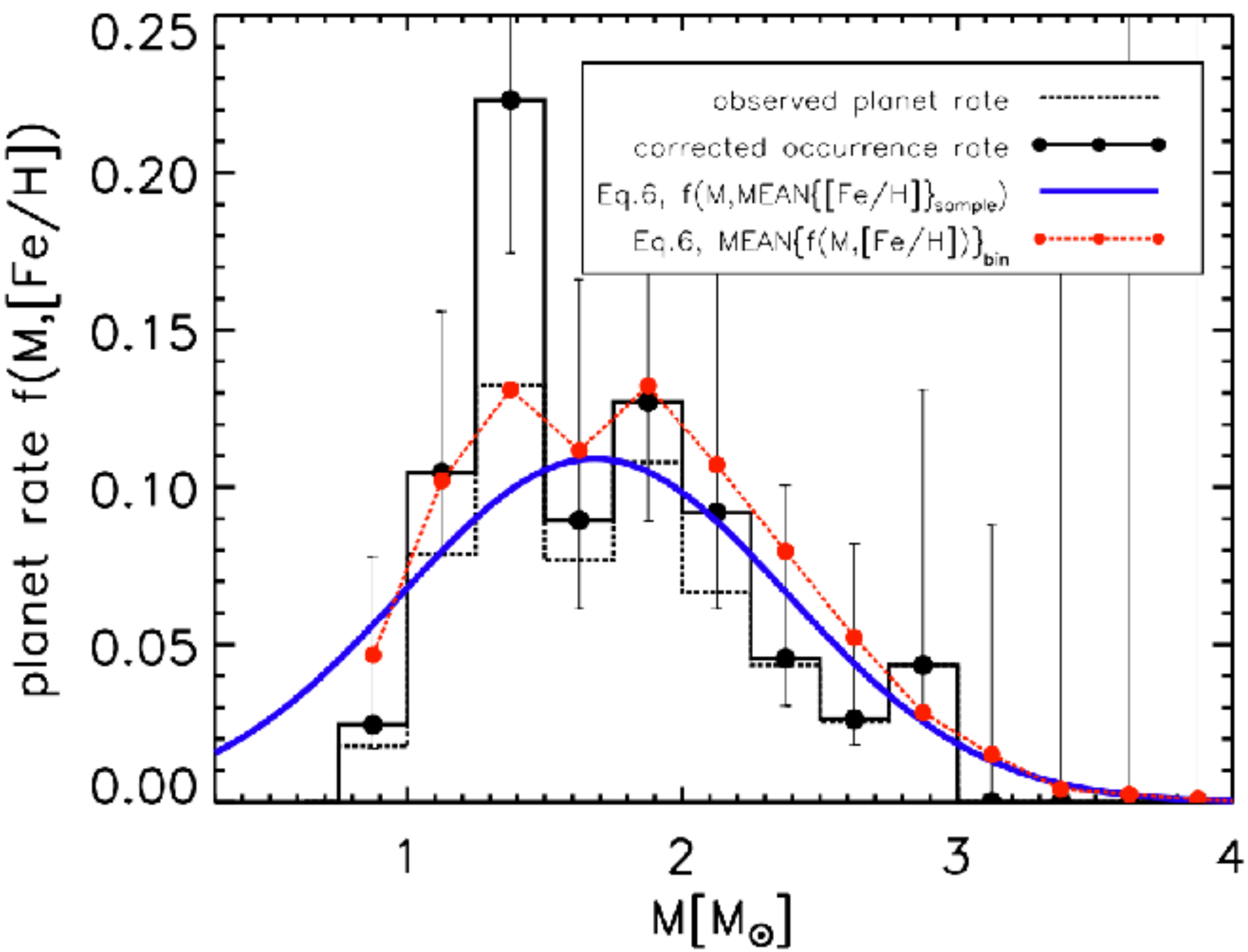


Giant planets more common around higher mass stars (but overall occurrence remains small, <30%!): linked to higher mass stars having higher mass disks?

Johnson et al. 2010

Occurence rates

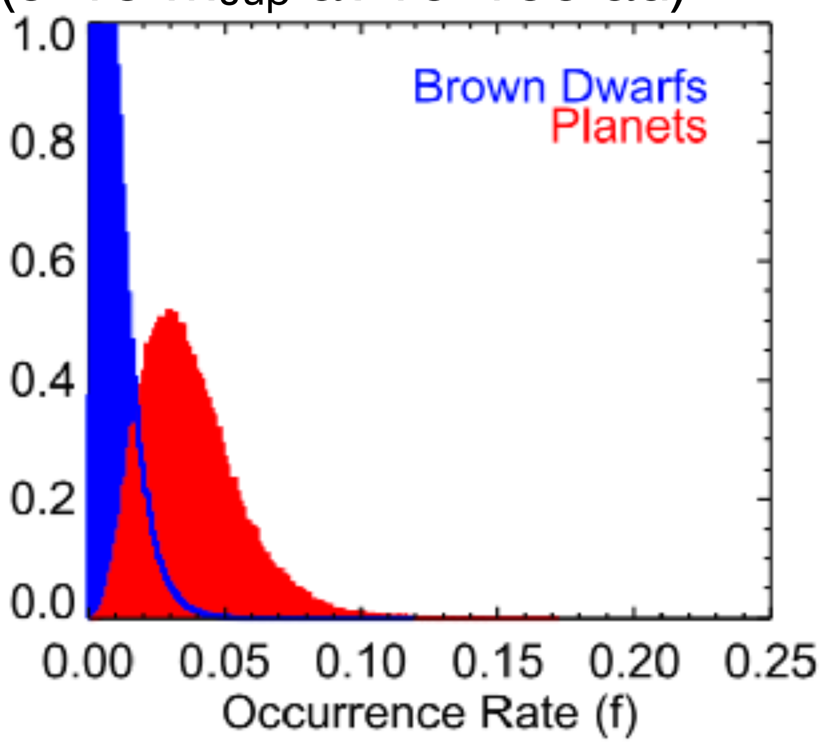
More recent studies of giant planets show similar trend



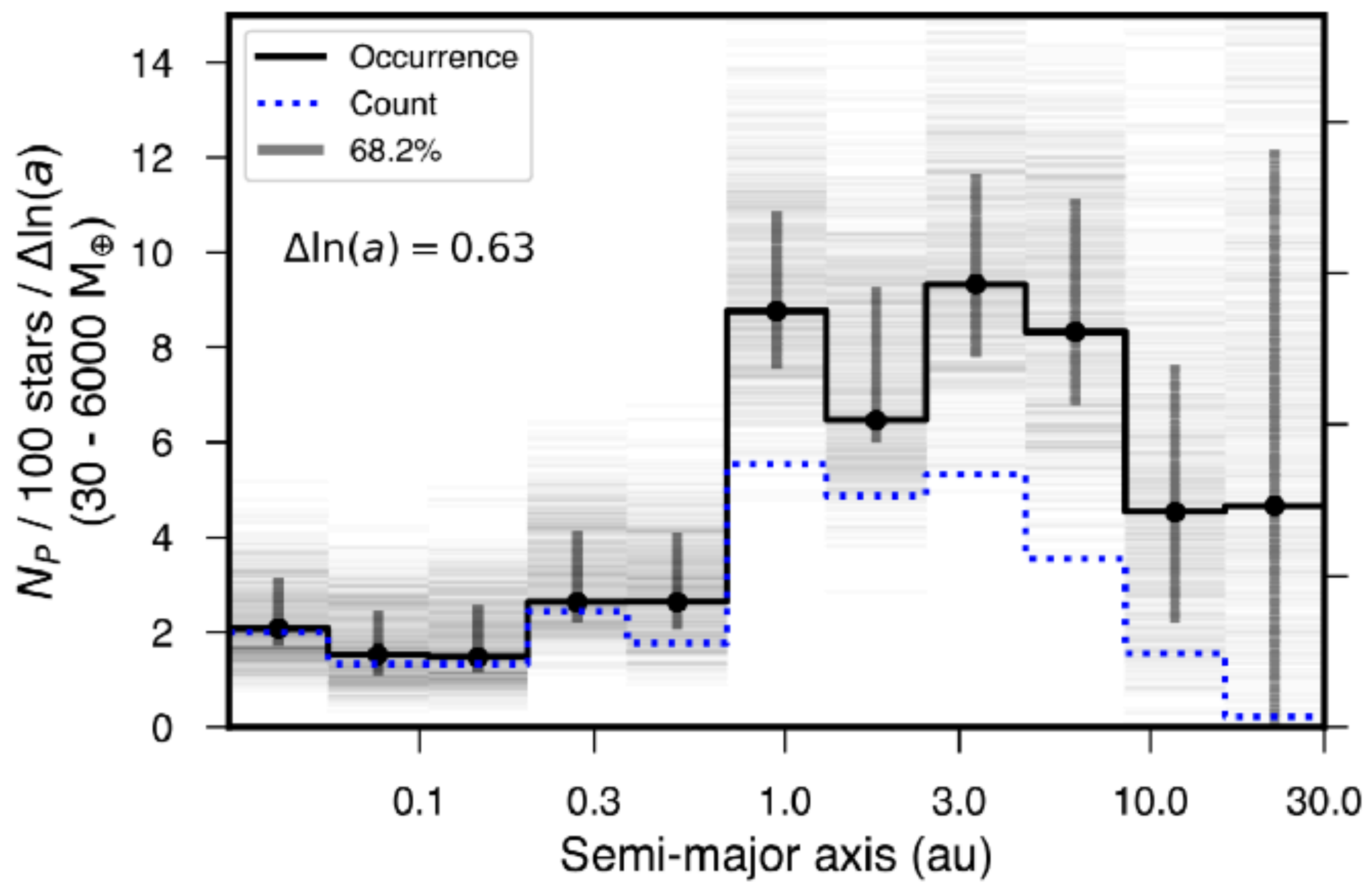
Fulton et al. 2021 (CLS)
Wolthoff et al. 2022

Giant planet orbital radii

Direct imaging:
(5-13 M_{Jup} at 10-100 au)



Radial velocity surveys:
(0.1-18 M_{Jup} at 0.1-20 au)



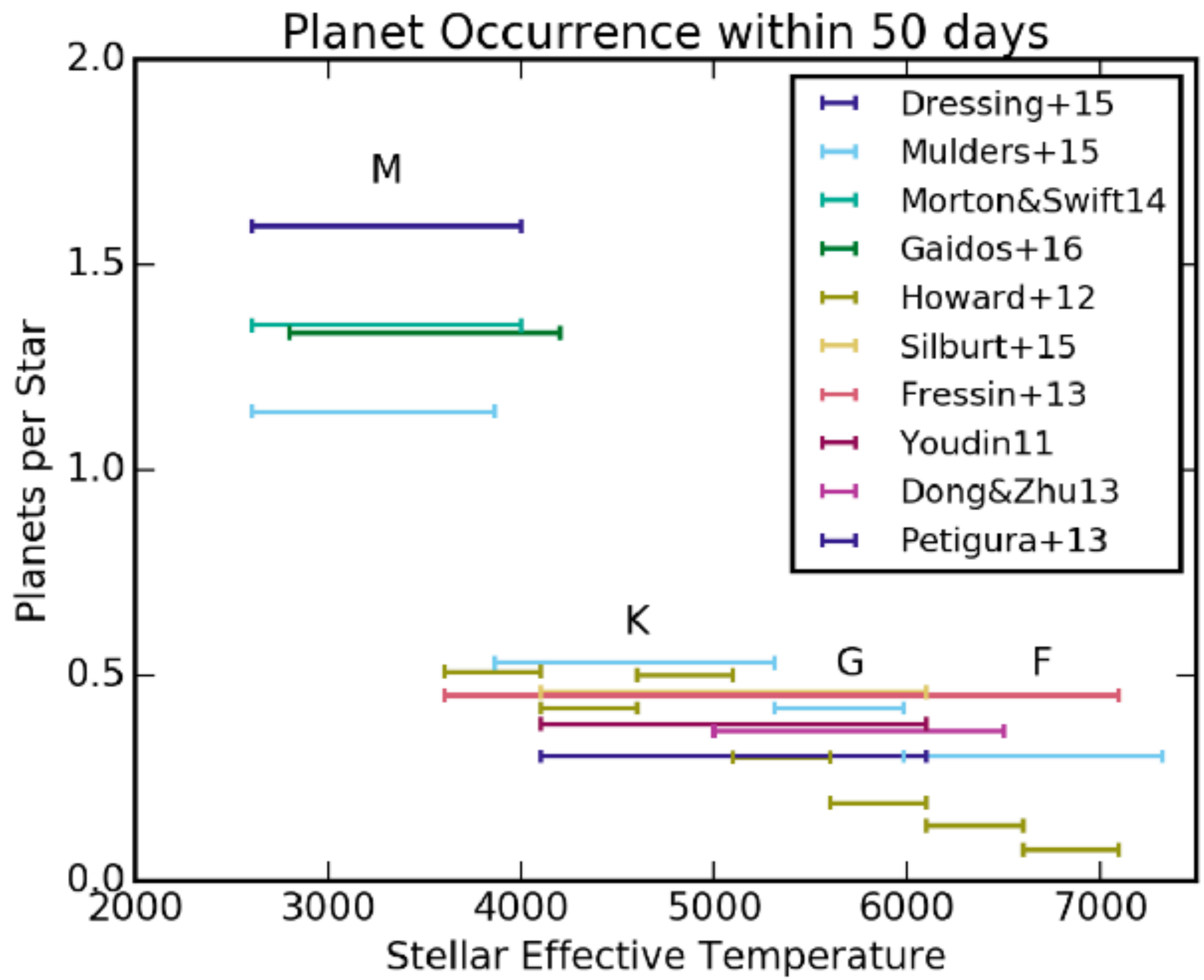
Giant planets are most commonly found at 3-8 au: preferential formation location (snowline) or migration halted here?

Nielsen et al. 2019 (GPIES)
Fulton et al. 2021 (CLS)

Close-in super-Earths

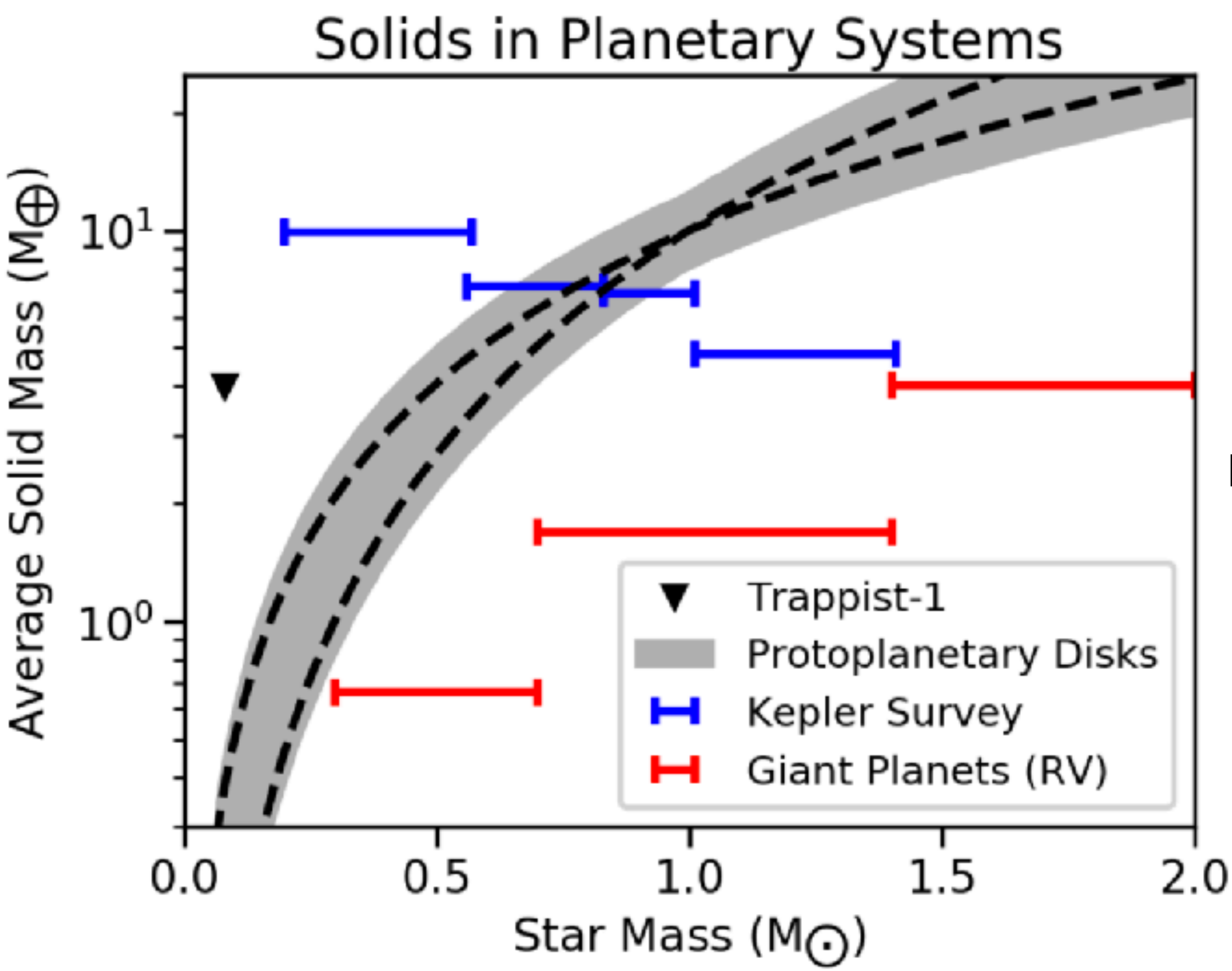
Super-Earths on <50 day orbits ('Kepler planets') are much more common around M-dwarfs than around solar type stars:

what is special about M-dwarfs that these planets grow more preferentially?



Mulders et al. 2015, 2018

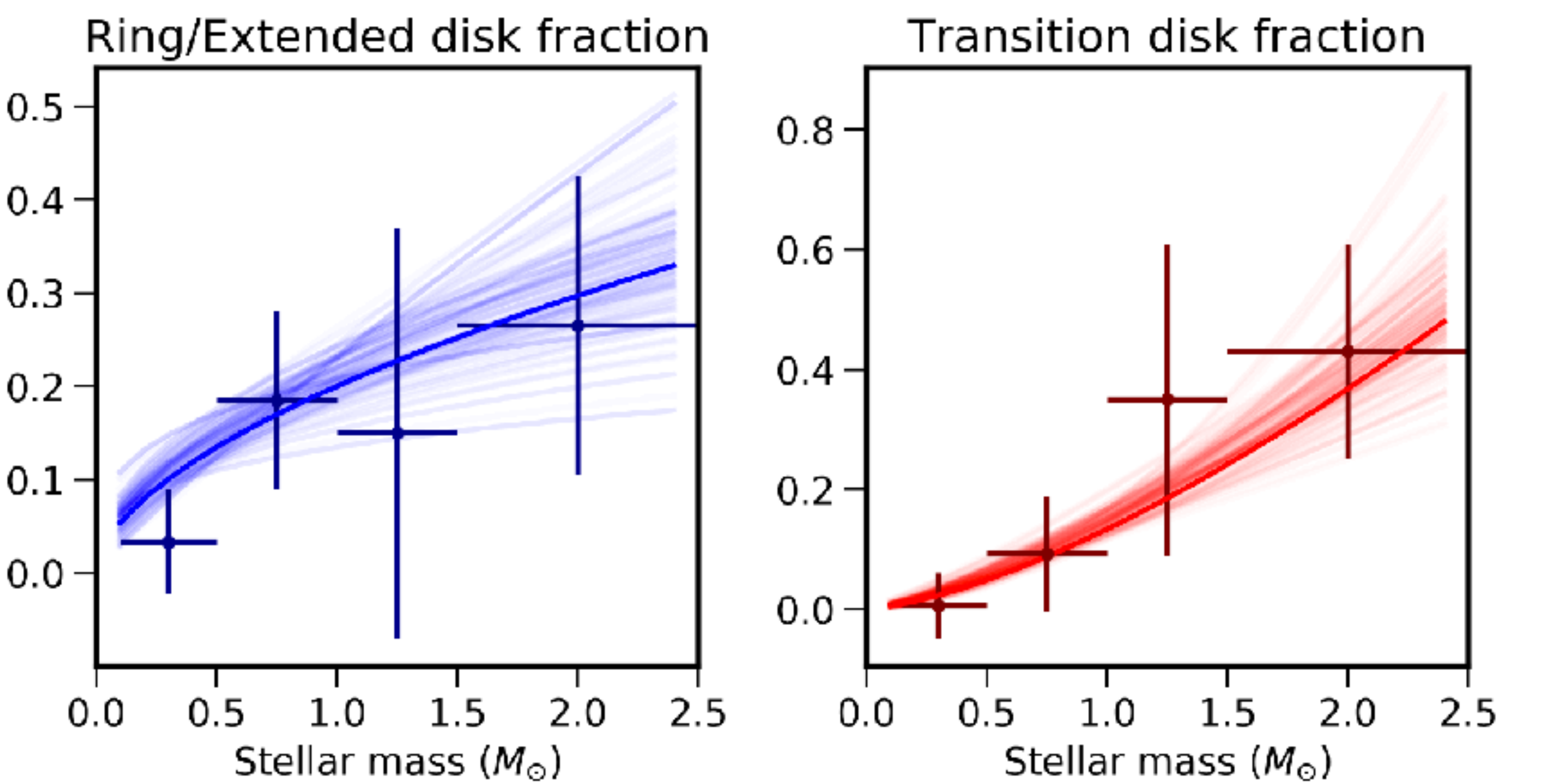
Combined trends



Interesting: opposite trends of planet populations, combined mass budget?

Mulders et al. 2021

Recall: disk demographics



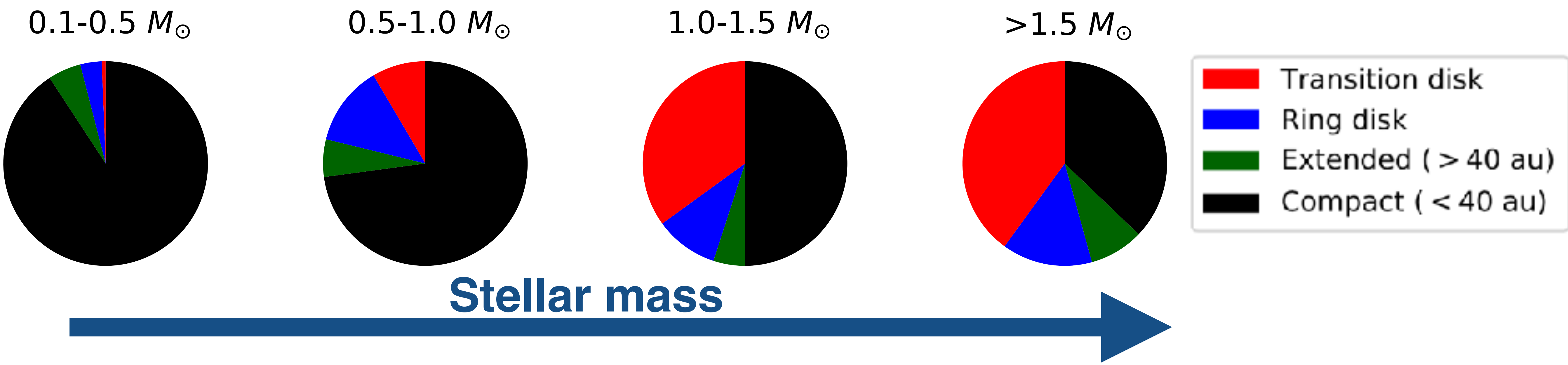
$$f(M_*) = C \cdot M_*^{\alpha}$$

Gapped disk occurrence is correlated with stellar mass

Van der Marel & Mulders 2021
Stapper et al. 2022

Disk demographics

Stellar mass dependence of disks



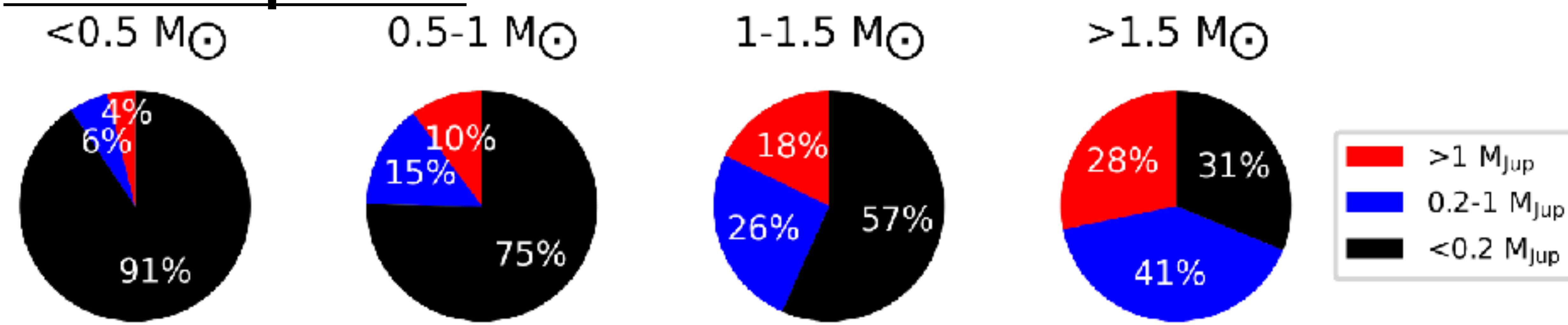
Gapped disks are more common around more massive stars

Van der Marel & Mulders 2021

Disk demographics: giant planets

Disks

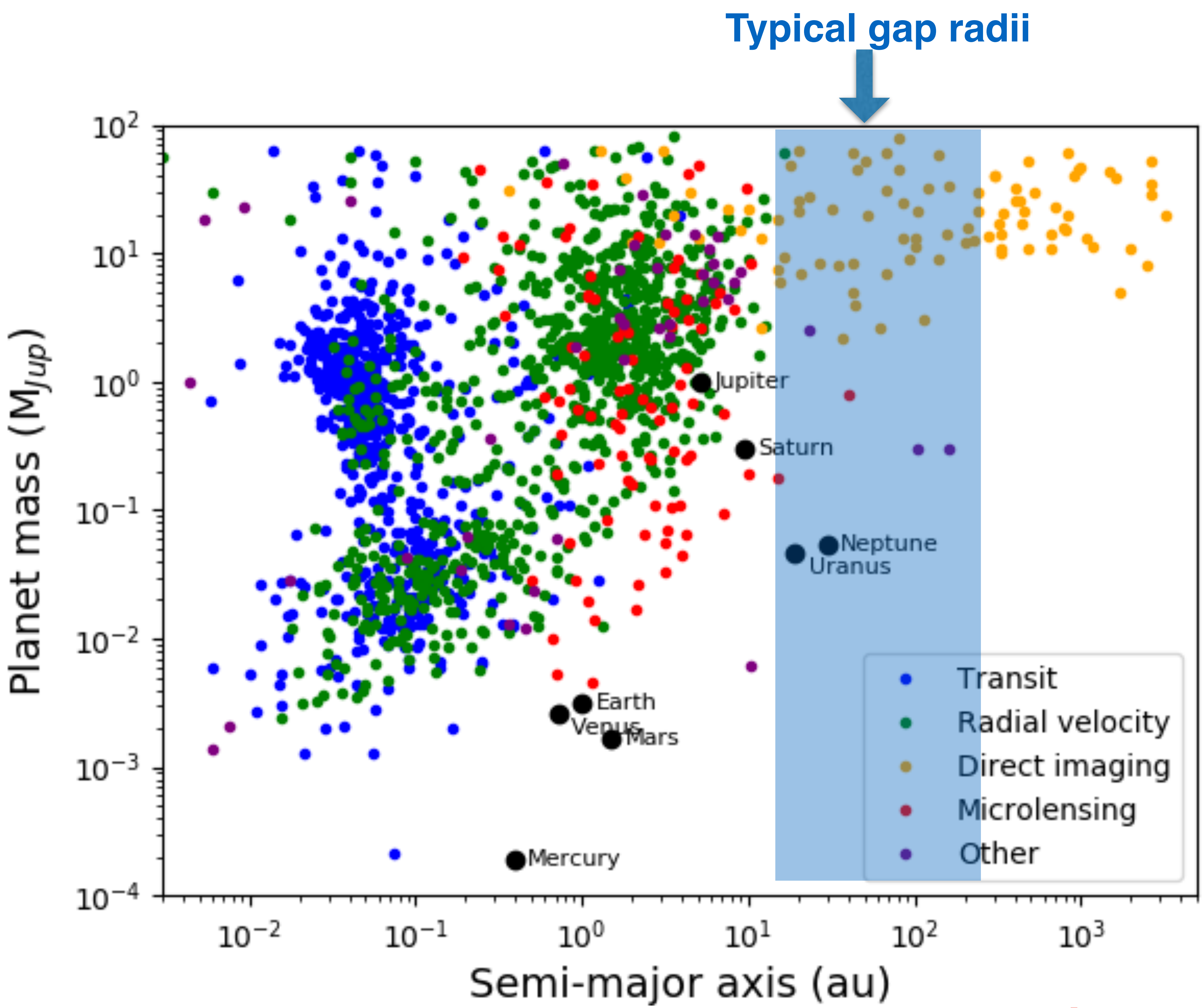
Giant exoplanets



Match: disk gaps can be linked to giant planets (when there is migration)!

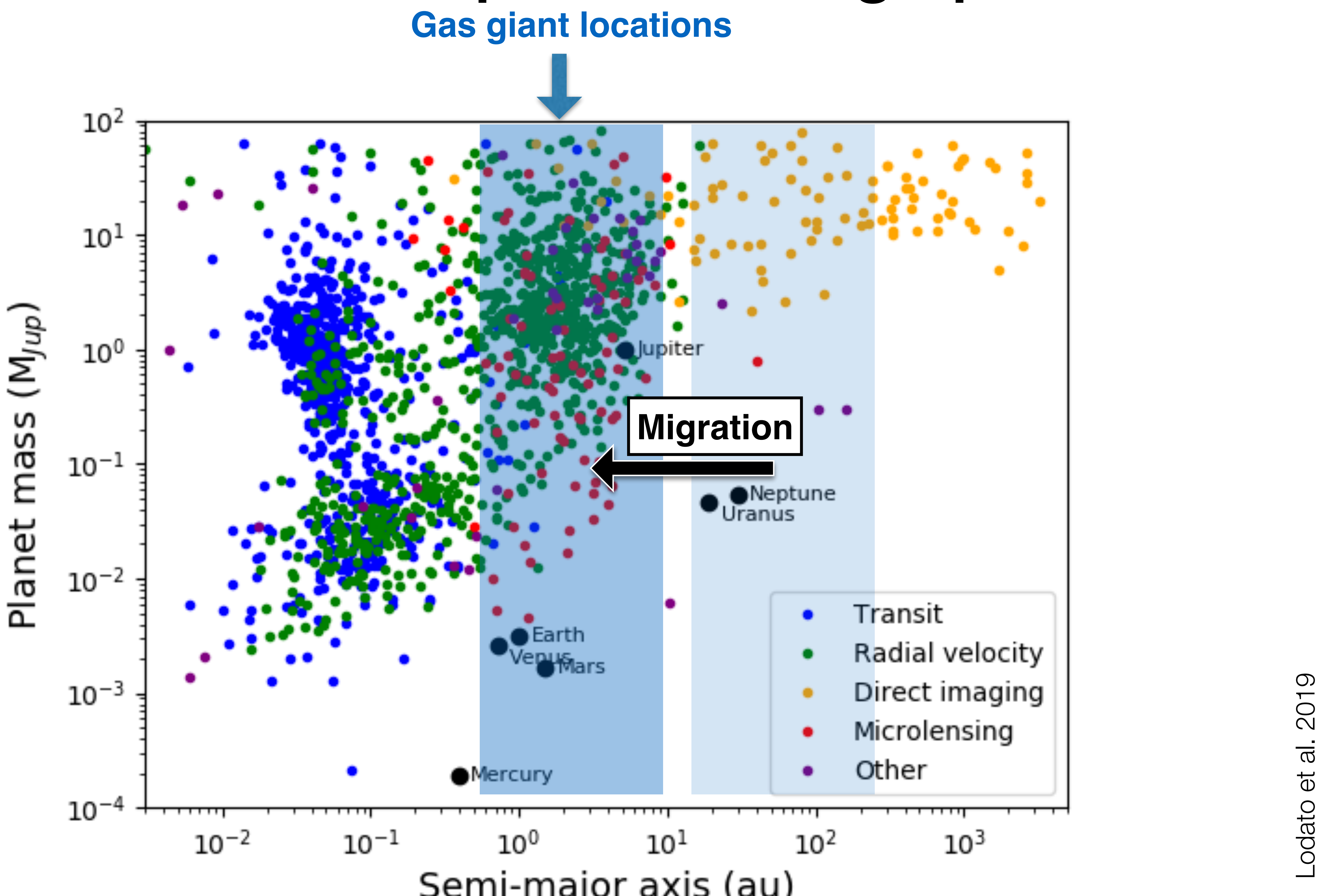
Mayor et al. 2011
Fernandes et al. 2019
van der Marel & Mulders 2021

How to link with exoplanet demographics?



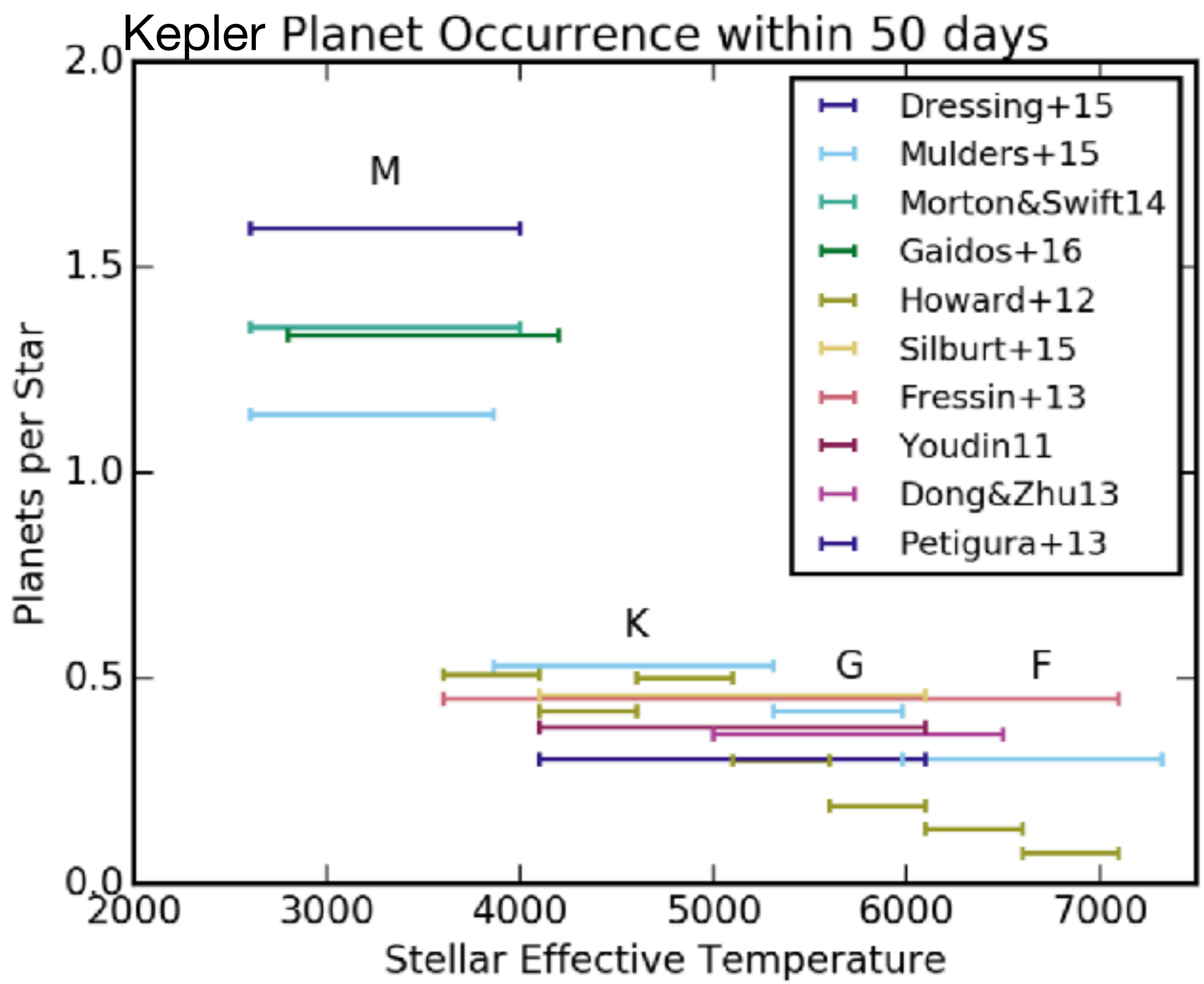
Problem: giant planets at wide orbits are rare (few %)

How to link with exoplanet demographics?



Problem: giant planets at wide orbits are rare: inward migration

Exoplanet demographics: super-Earths

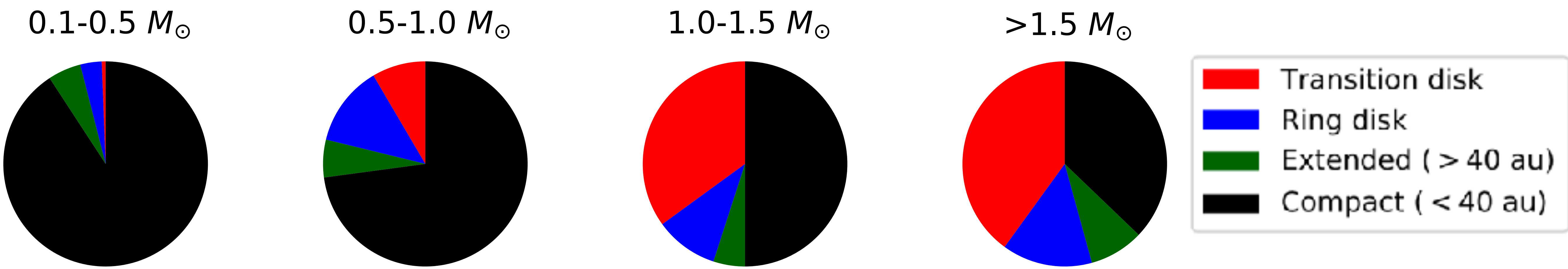


Super-Earth occurrence **decreases** with stellar mass

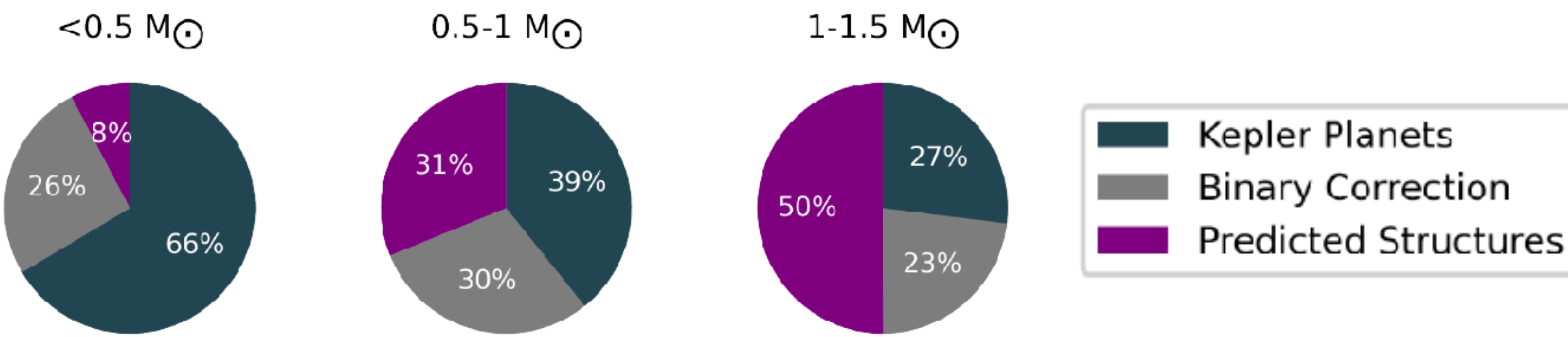
Mulders et al. 2015, 2018, 2019

Disk demographics: super-Earths

Disks



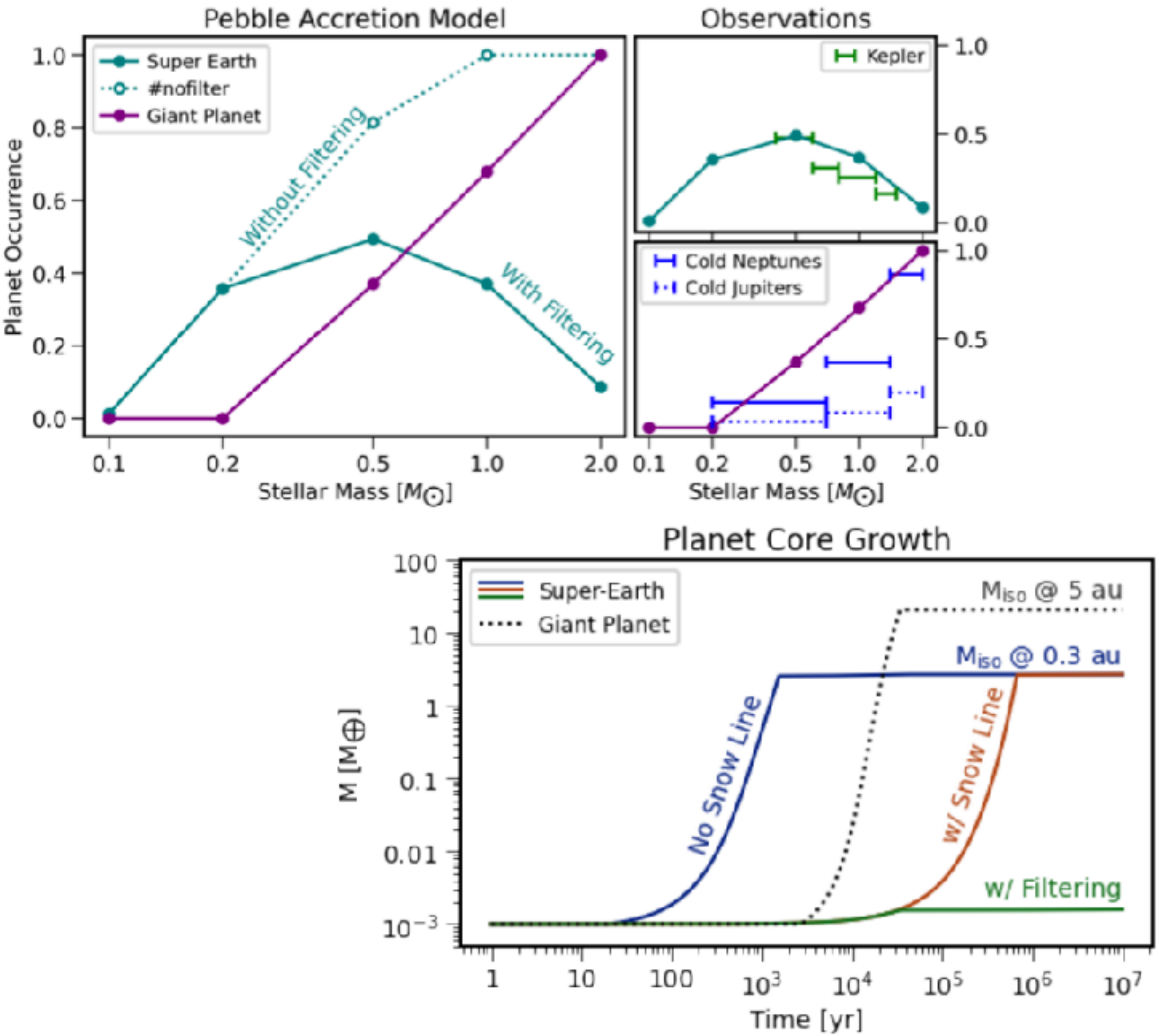
Close-in super-Earths ('Kepler planets')



Match: compact disks can be linked to super-Earths: increased pebble flux

Moe & Kratter 2019
Lambrechts et al. 2019
van der Marel & Mulders 2021

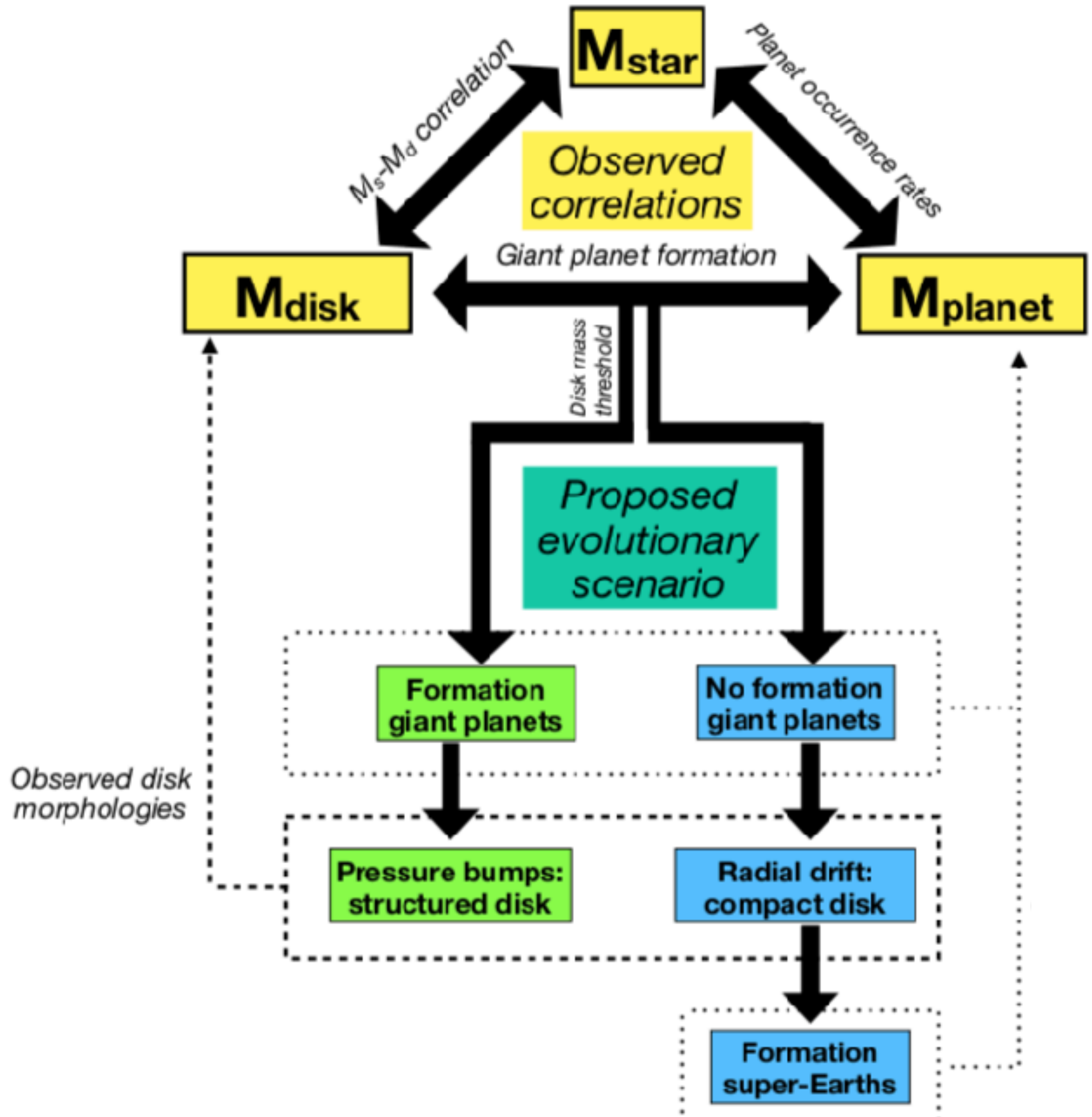
Super-Earth formation due to pebble flux



Explanation Solar System: no super-Earth

Lambrechts et al. 2019
Appelgren et al. 2020
Mulders et al. 2021b

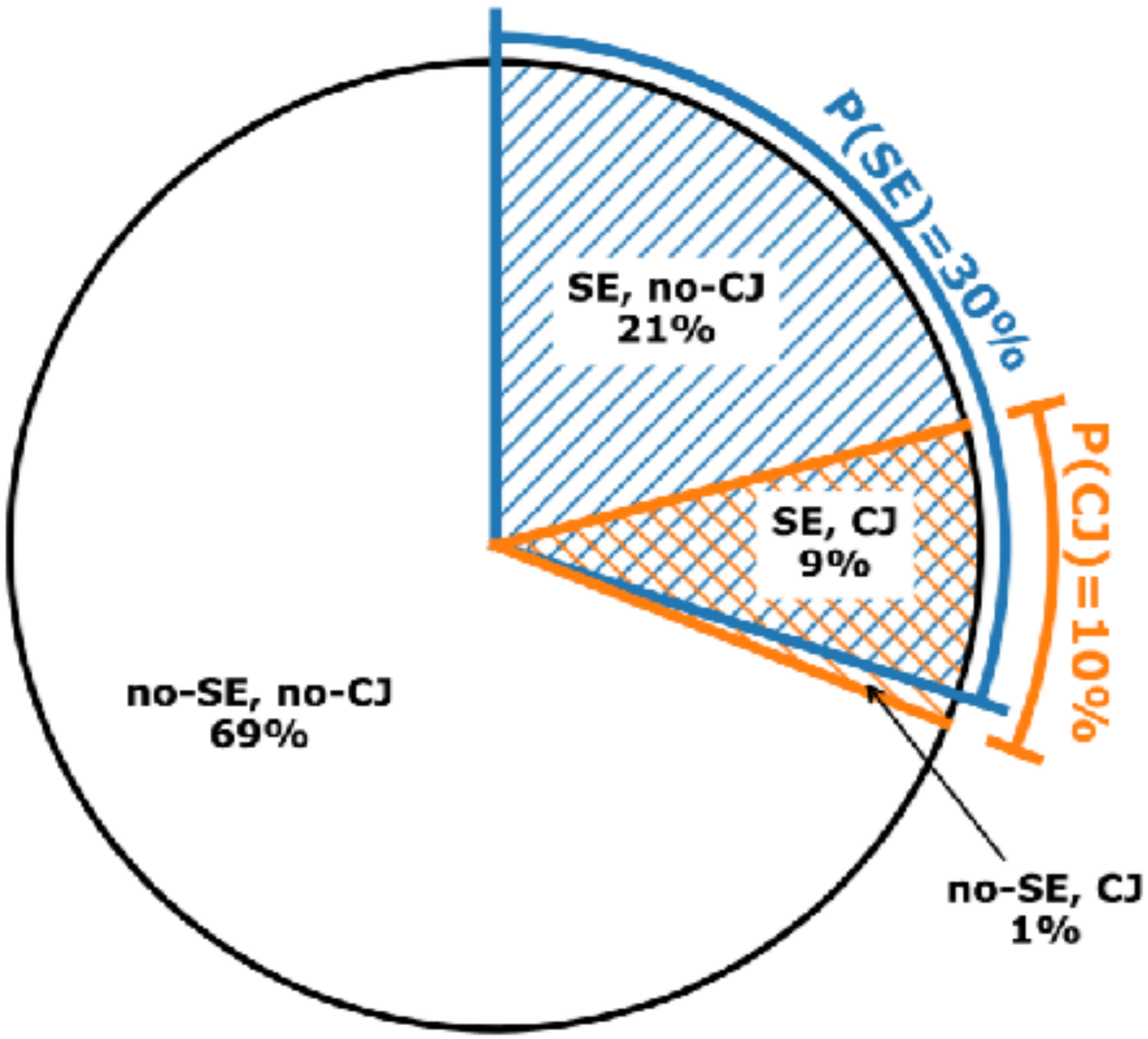
How does planet formation affect disk evolution?

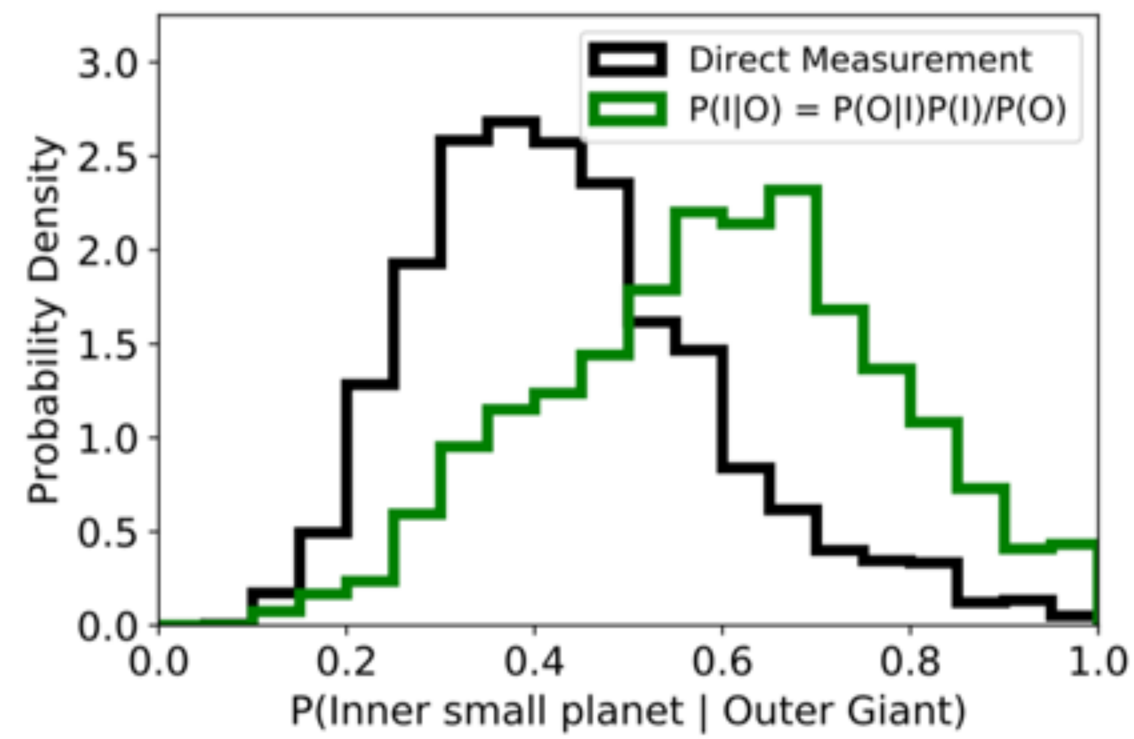


Van der Marel & Mulders 2021

Close super-Earth - cold Giant correlation?

Early studies suggesting strong correlation: this argues against pebble drift scenario and in favor of overall disk mass ~ formation efficiency



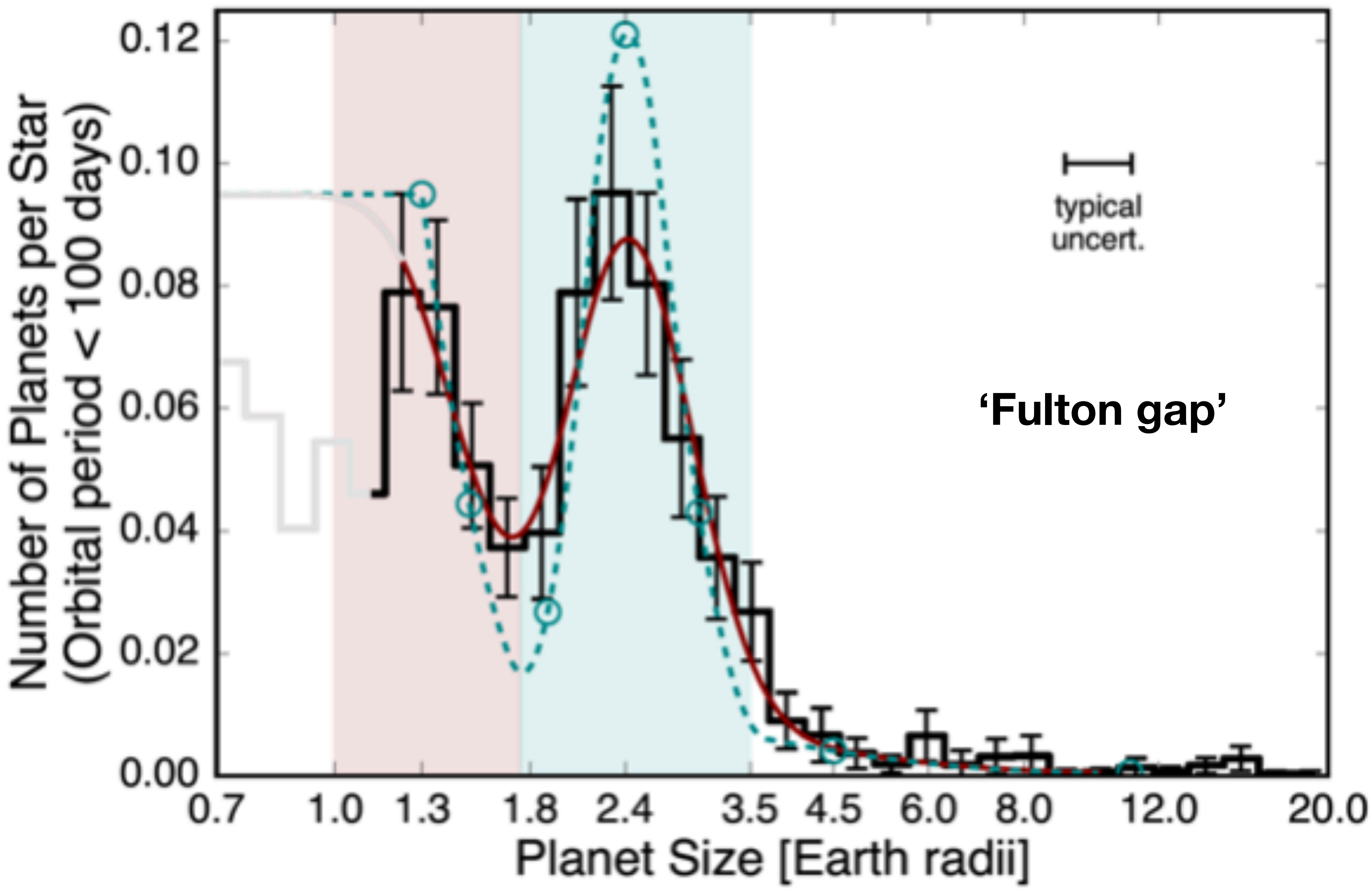


Problem: small, biased samples: large errorbars!

Rosenthal (CLS): correlation actually weaker, and disappears fully for higher threshold giant (>120 M_E)

Barbato et al. 2018
Zhu & Wu 2018
Rosenthal et al. 2021

The radius valley

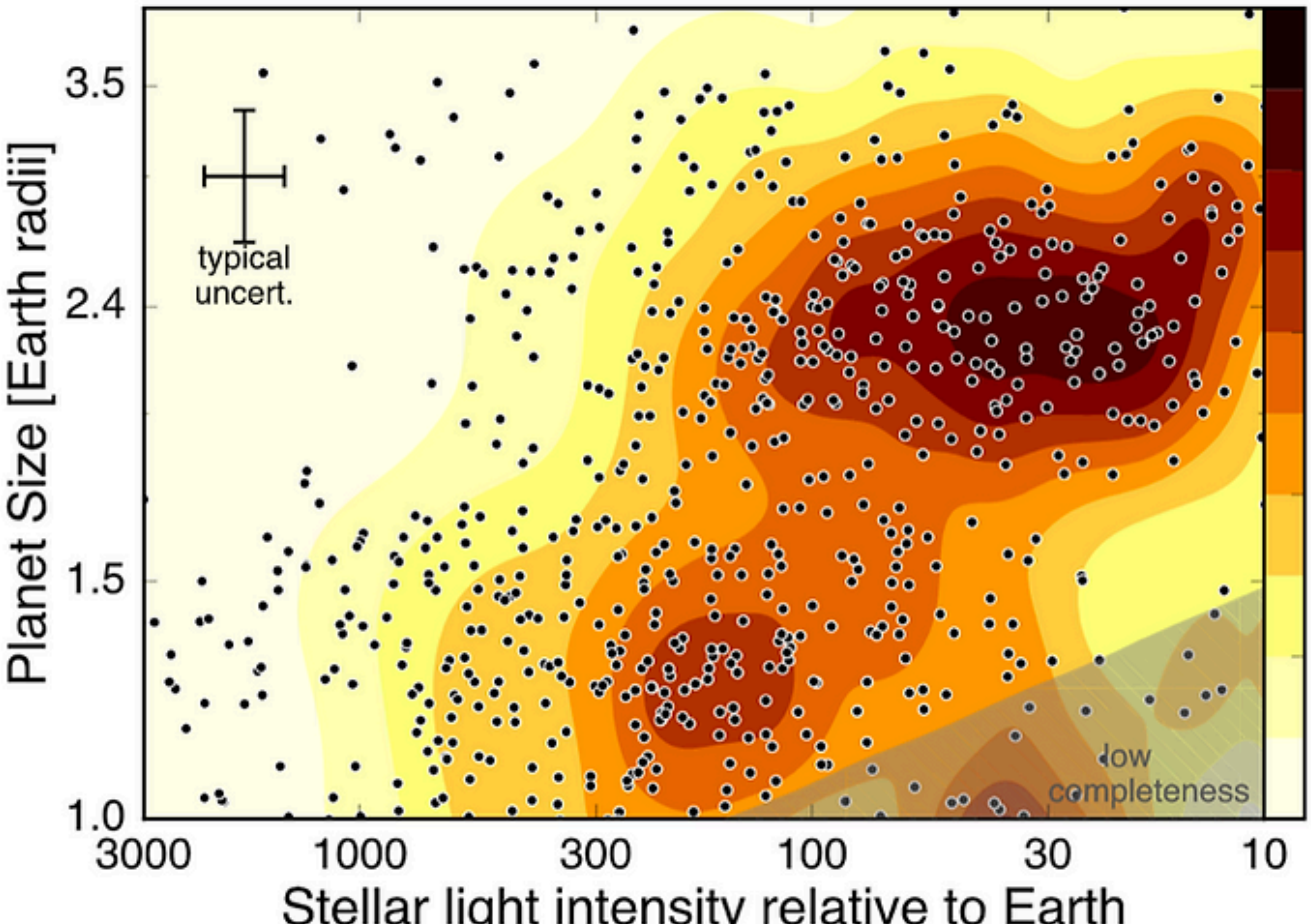


For the super-Earth/sub-Neptune planet population, a gap was found in the occurrence between small (<1.8 R_E) and large (>1.8 R_E) planets

Fulton et al. 2017
Fulton & Petigura 2018
Owen & Wu 2013, 2017

The radius valley

Gap can be seen in 2D in this occurrence diagram depending on the incident flux



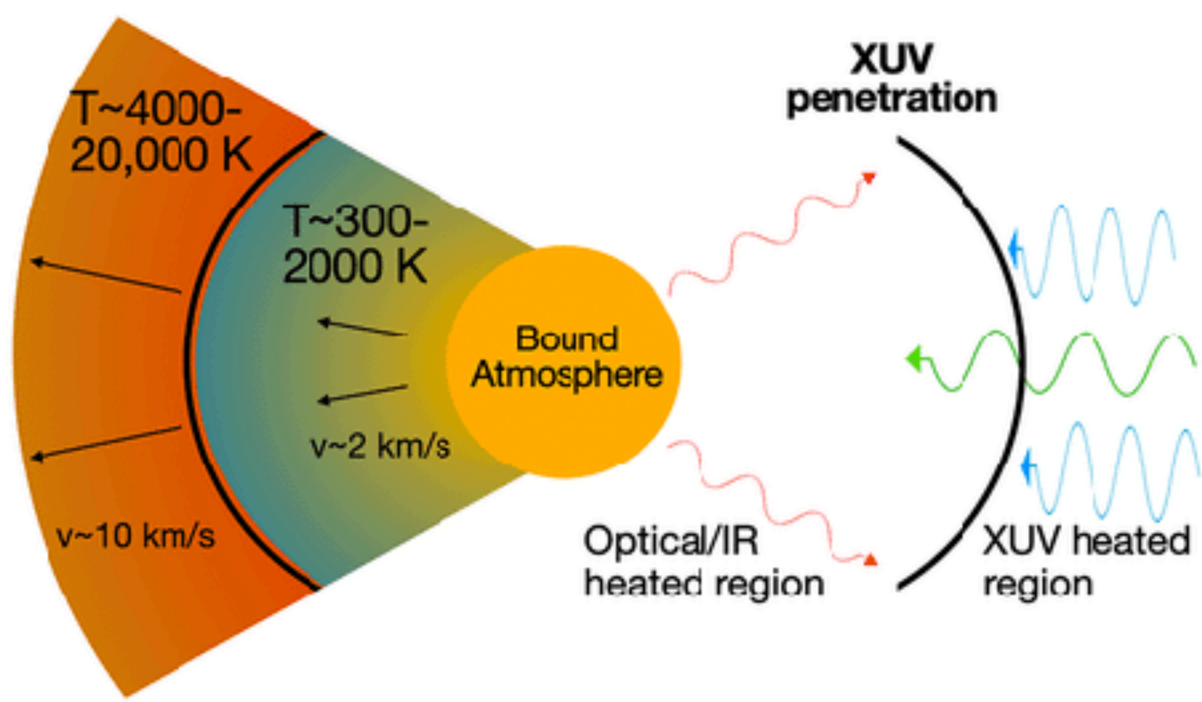
Fulton et al. 2017

The radius valley

<u>Explanations</u>:

- Photoevaporation (<100 Myr)
- Core-power mass loss (~Gyr)
- Gas-poor formation

The first two explanations are processes that happen (well) after the formation of the planet: how well can we exoplanets compare with disk properties if post-processing is important?

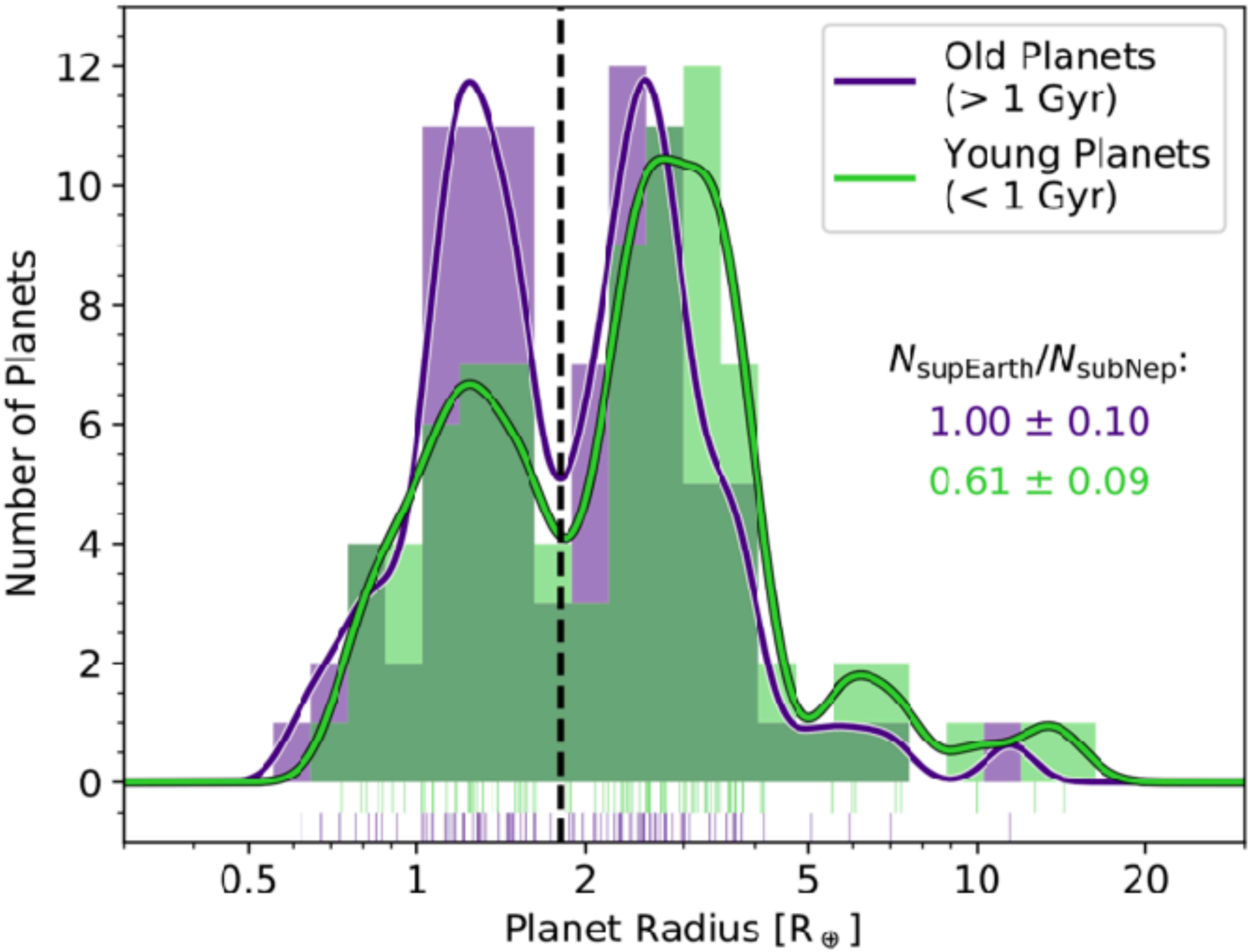


All processes are realistic in typical conditions, but they predict different trends in the radius valley

Fulton et al. 2017
Fulton & Petigura 2018
Owen & Wu 2013, 2017
Ginzburg et al. 2018
Lee & Chiang 2016

The radius valley

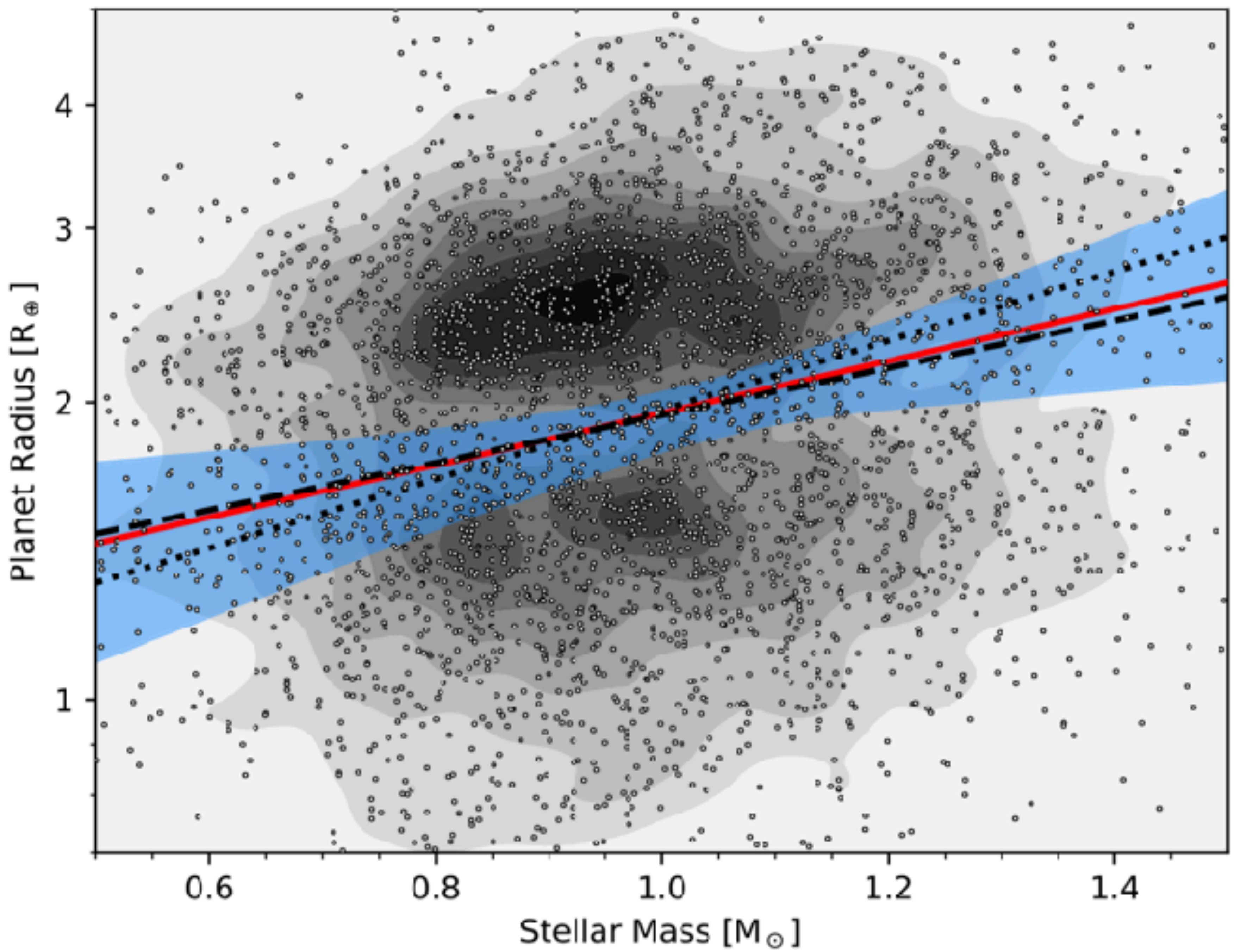
Ratio changes with stellar age: seems to argue for core-powered mass-loss with a timescale of ~Gyr



Berger et al. 2020

The radius valley

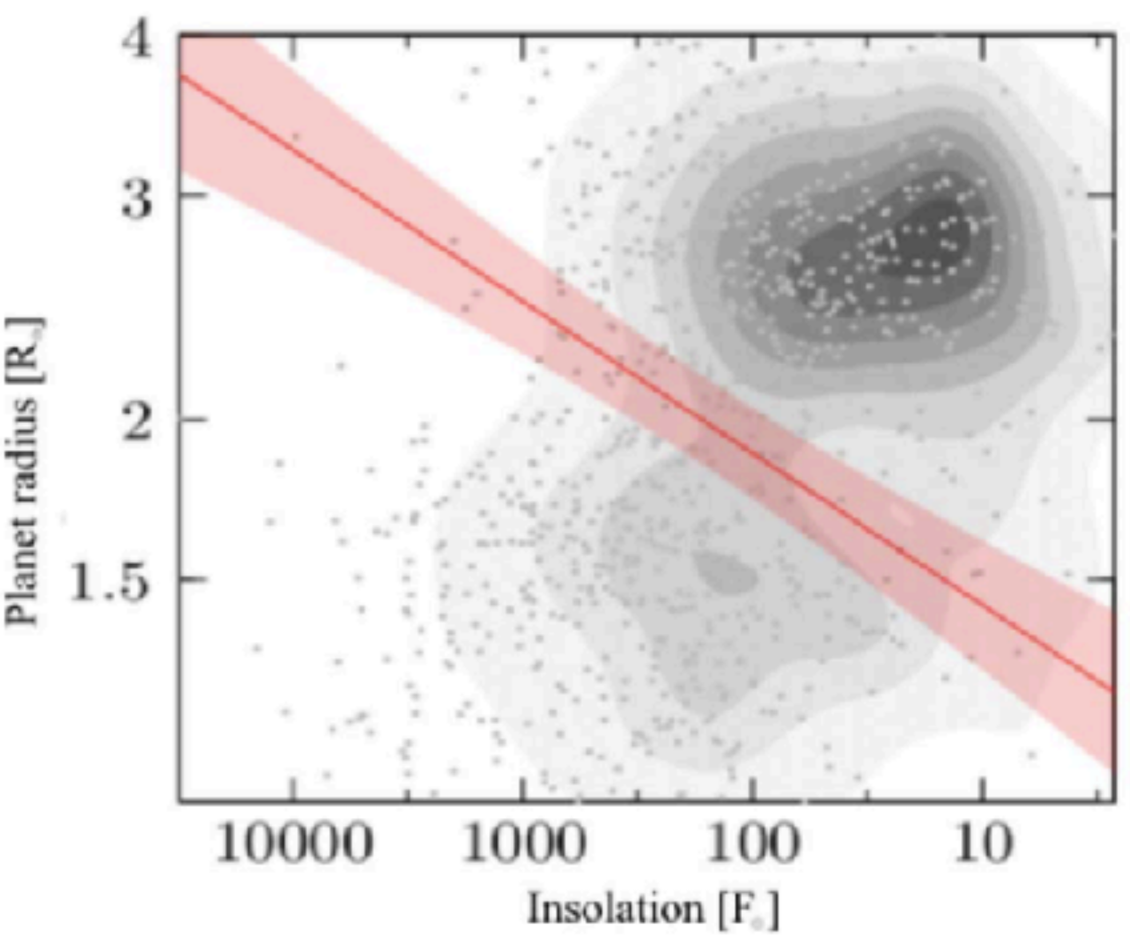
Gap width and centre change with stellar mass:
different processes dominant at different stellar masses?



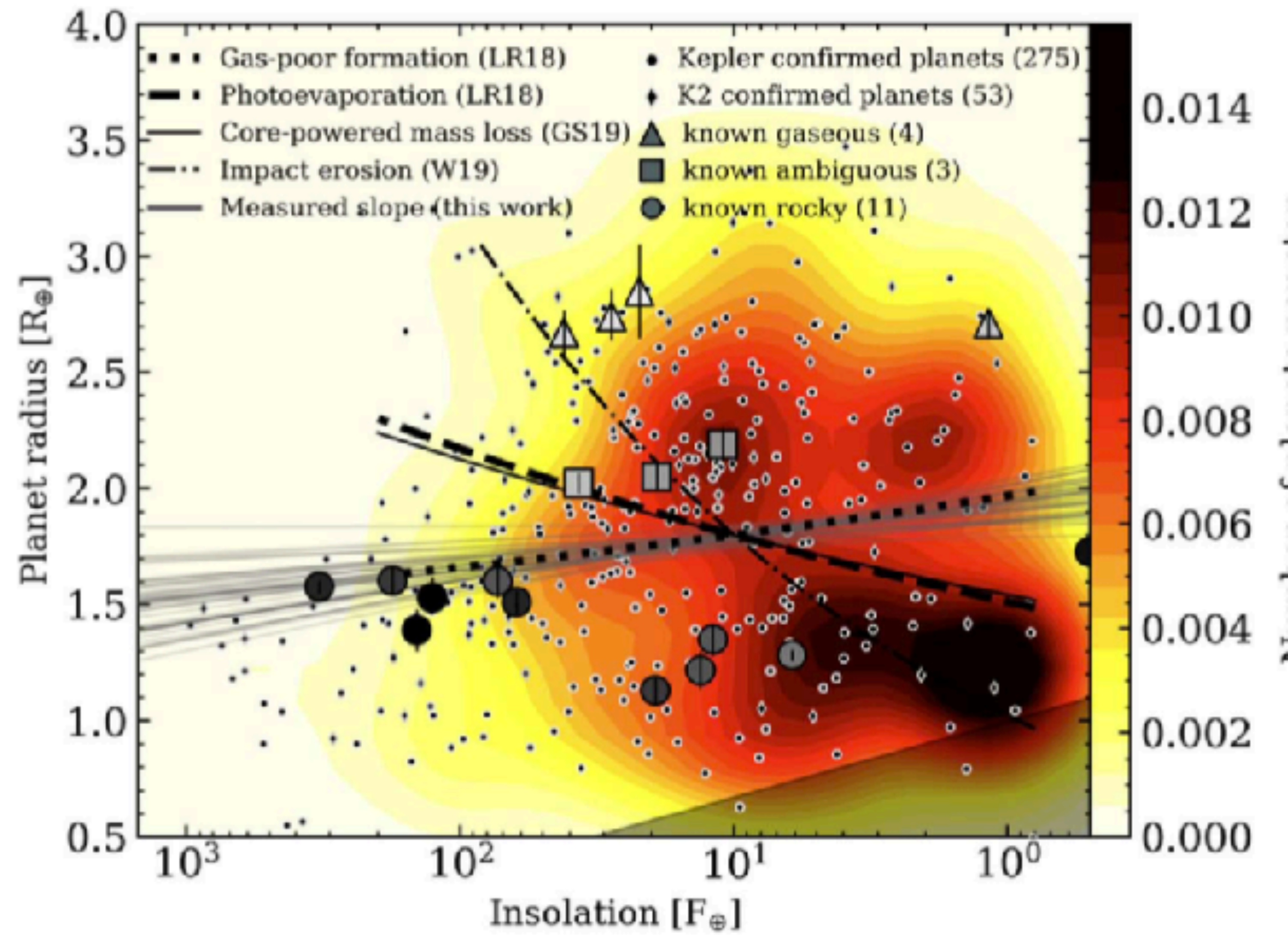
Berger et al. 2020

The radius valley

The slope in the incident flux diagram also changes with stellar mass: evidence for gas-poor formation for the planets around low-mass stars



Solar-mass stars



sub-Solar-mass stars

Cloutier et al. 2020

Summary

- When comparing exoplanet properties with disks, use occurrence rates which have been corrected for selection and detection biases
- Giant planets have a stellar mass dependence which may correspond to the gapped disk occurrence
- Close-in super-Earths have an inverse stellar mass dependence which may correspond to compact disk occurrence => formation due to increased pebble drift
- The observed radius valley may be caused by post-formation mechanisms, at least for solar mass stars

Questions?

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