Planet S

National Centre of Competence in Research

THE FORMATION OF GAS-RICH PLANETS

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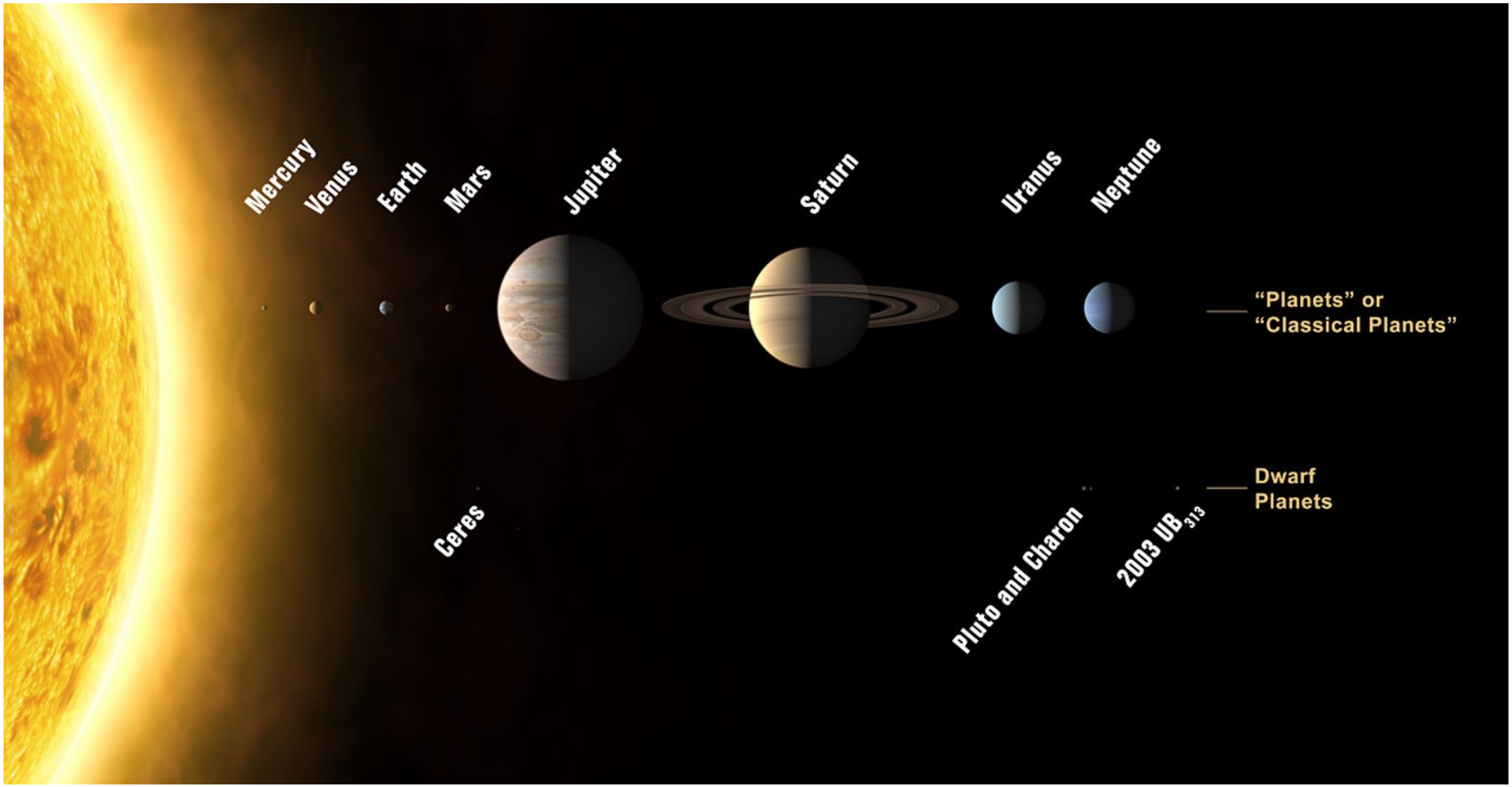
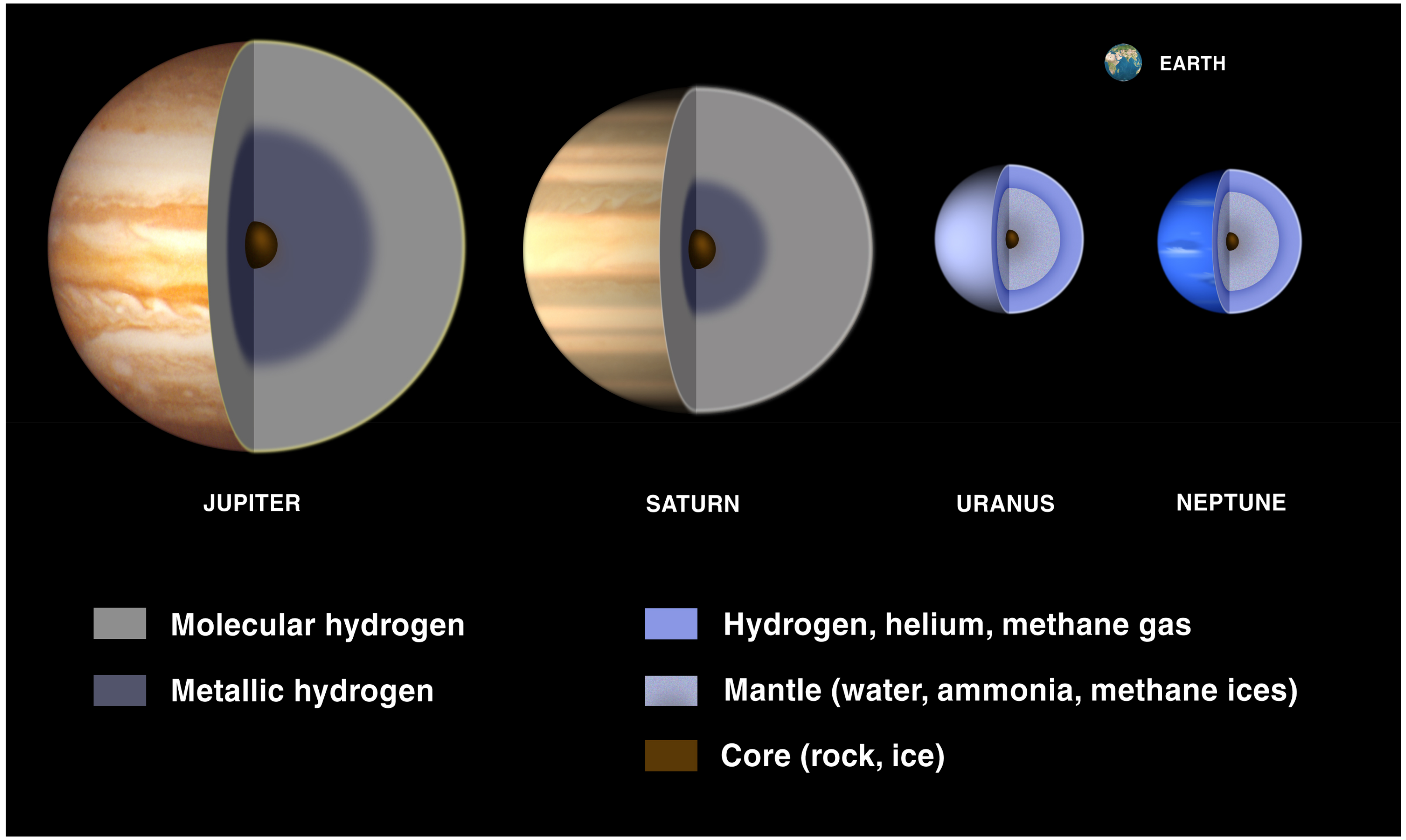
PLANETS IN THE SOLAR SYSTEM



Credit: The International Astronomical Union/Martin Kornmesser

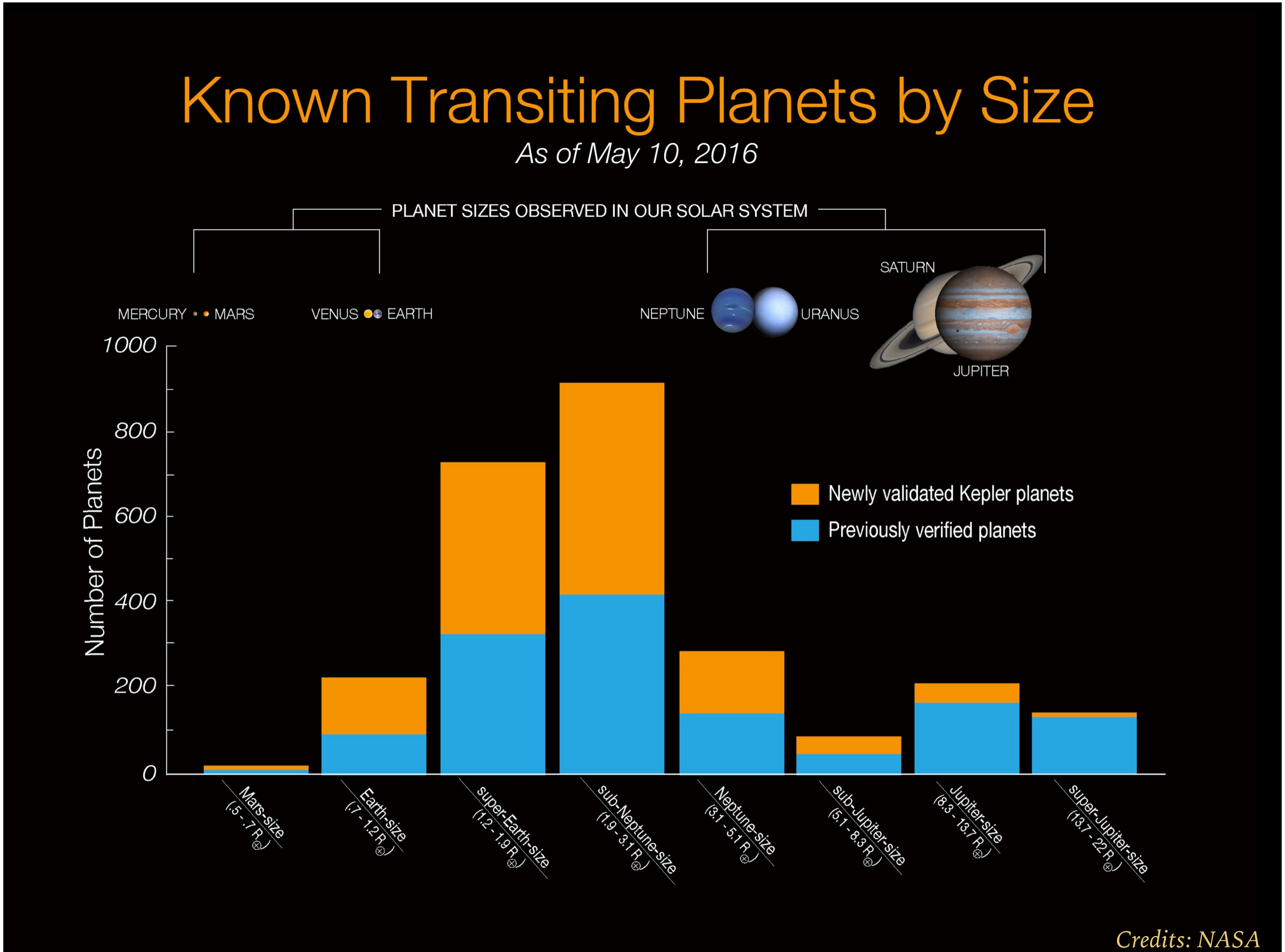
GAS-RICH PLANETS IN THE SOLAR SYSTEM



(credits: Wikiwand)

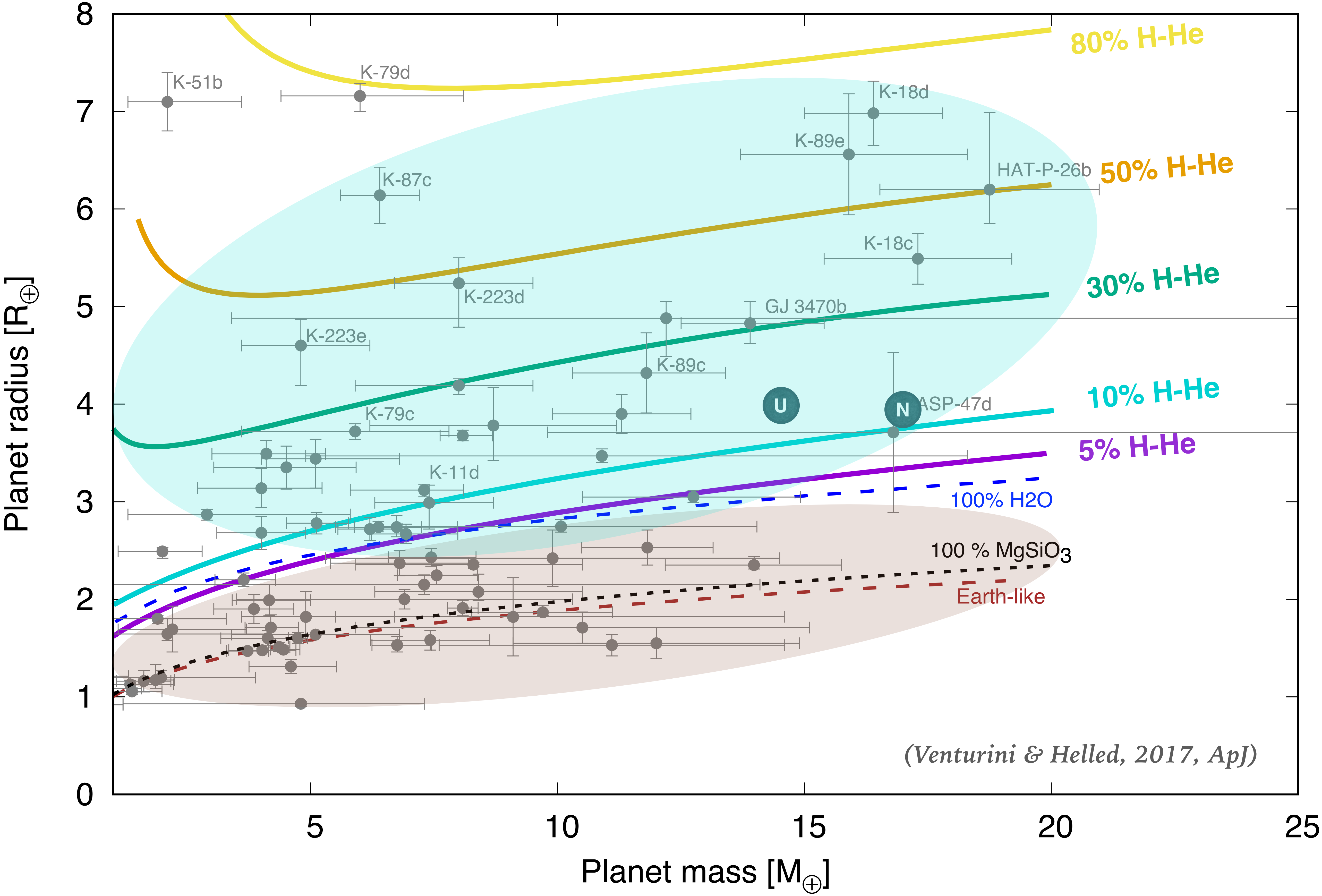
	Jupiter	Saturn	Uranus	Neptune
Mass [$M_\oplus$]	318	95	14.5	17
Radius [$R_\oplus$]	11	9.1	3.98	3.87
mass fraction of H-He	~87 - 95%	~ 68 - 91%	~10-25%	~10-25%

EXOPLANETS: ~ 4000 CONFIRMED



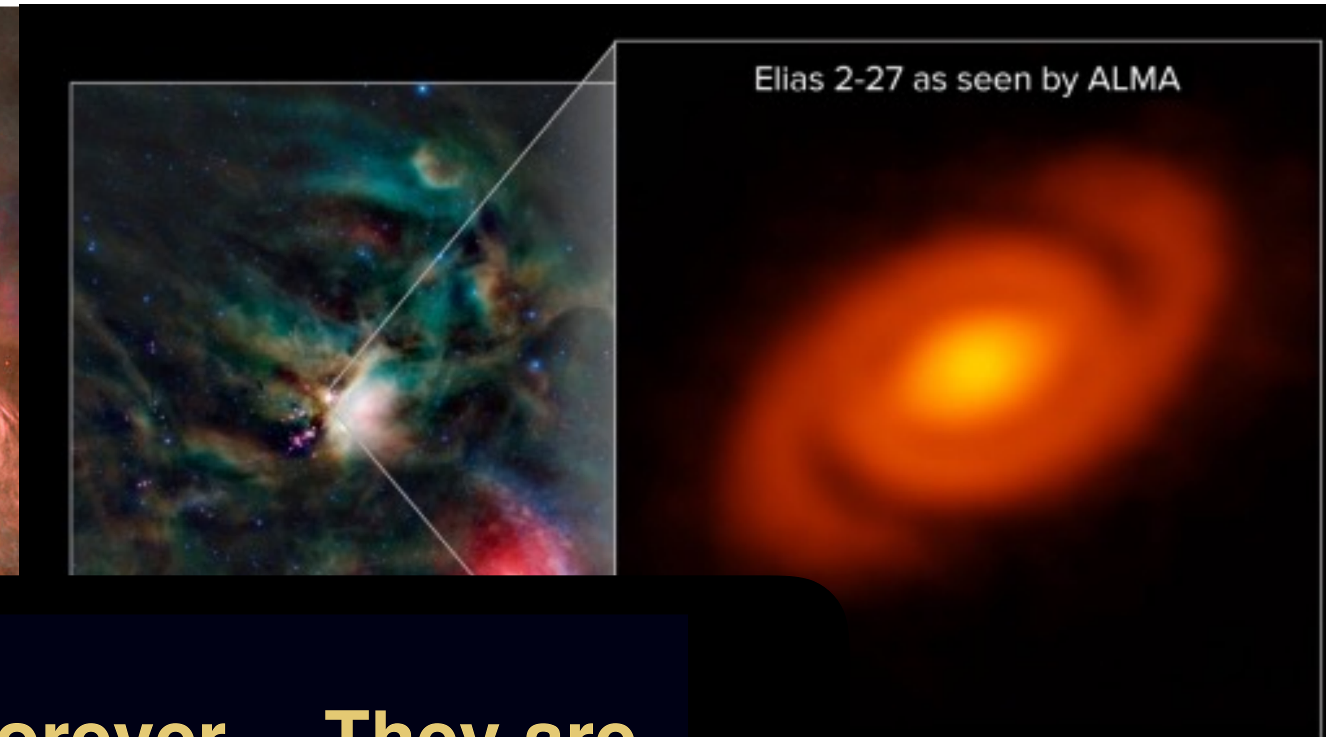
planets with sizes between Earth and Neptune are VERY common

DIVERSITY IN COMPOSITION FOR LOW-MASS PLANETS



HOW DO PLANETS FORM?

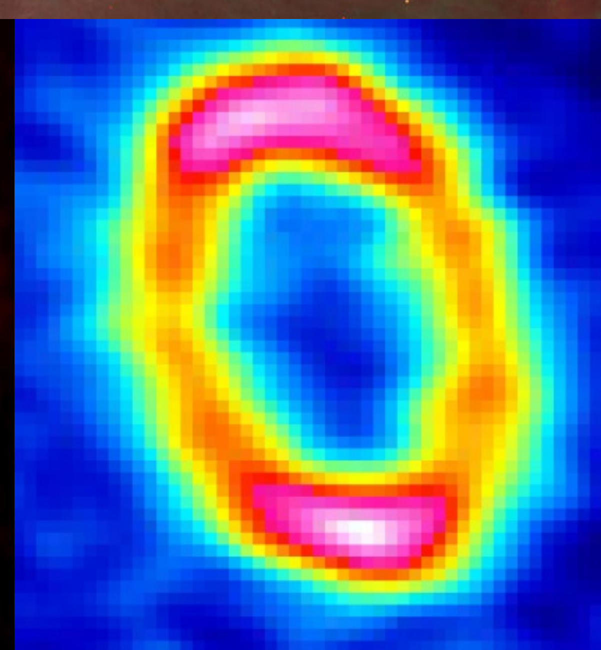
Orion nebula. Credit: NASA, ESA, M. Robberto (STSI/ESA), the HST Orion Treasury Project Team and L. Ricci (ESO)



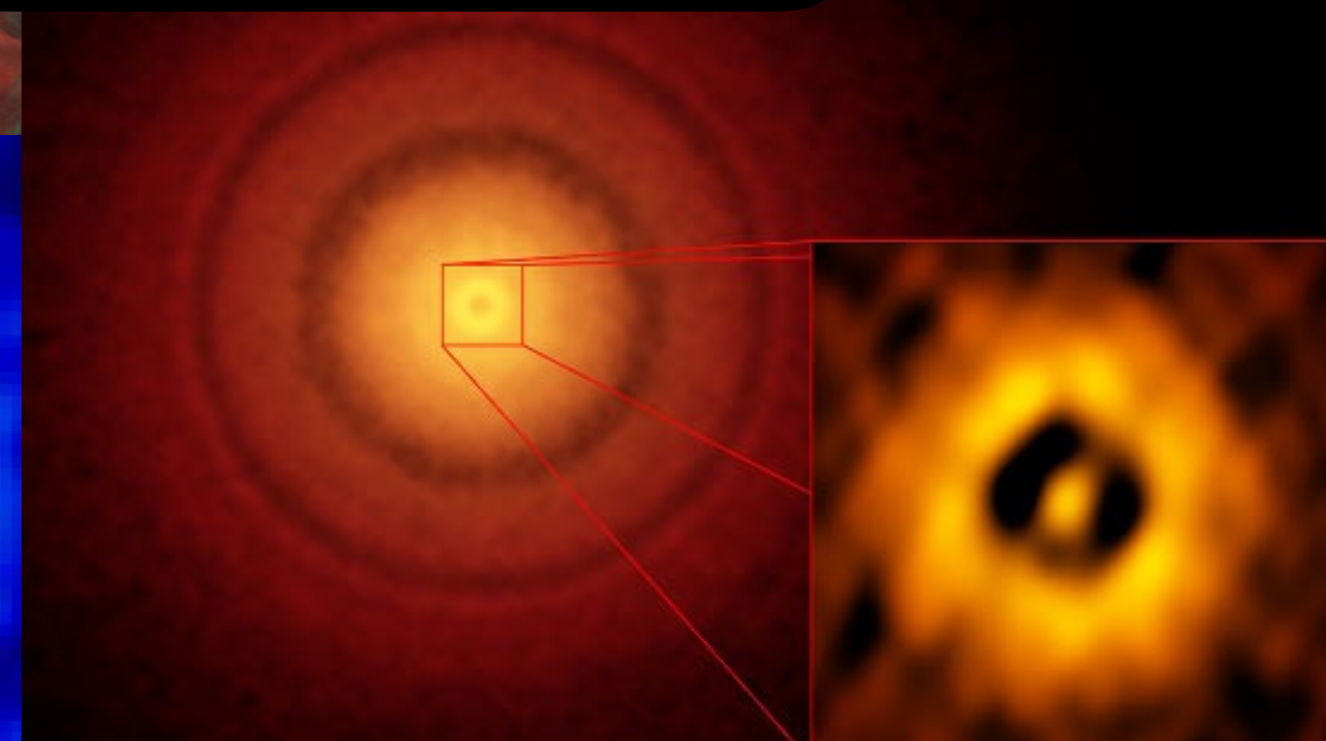
Credit: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO), L. Pérez (MPIfR)

But disks don't last forever… They are observed to have lifetimes of a few Myr

HL Tau. Credits: ALMA



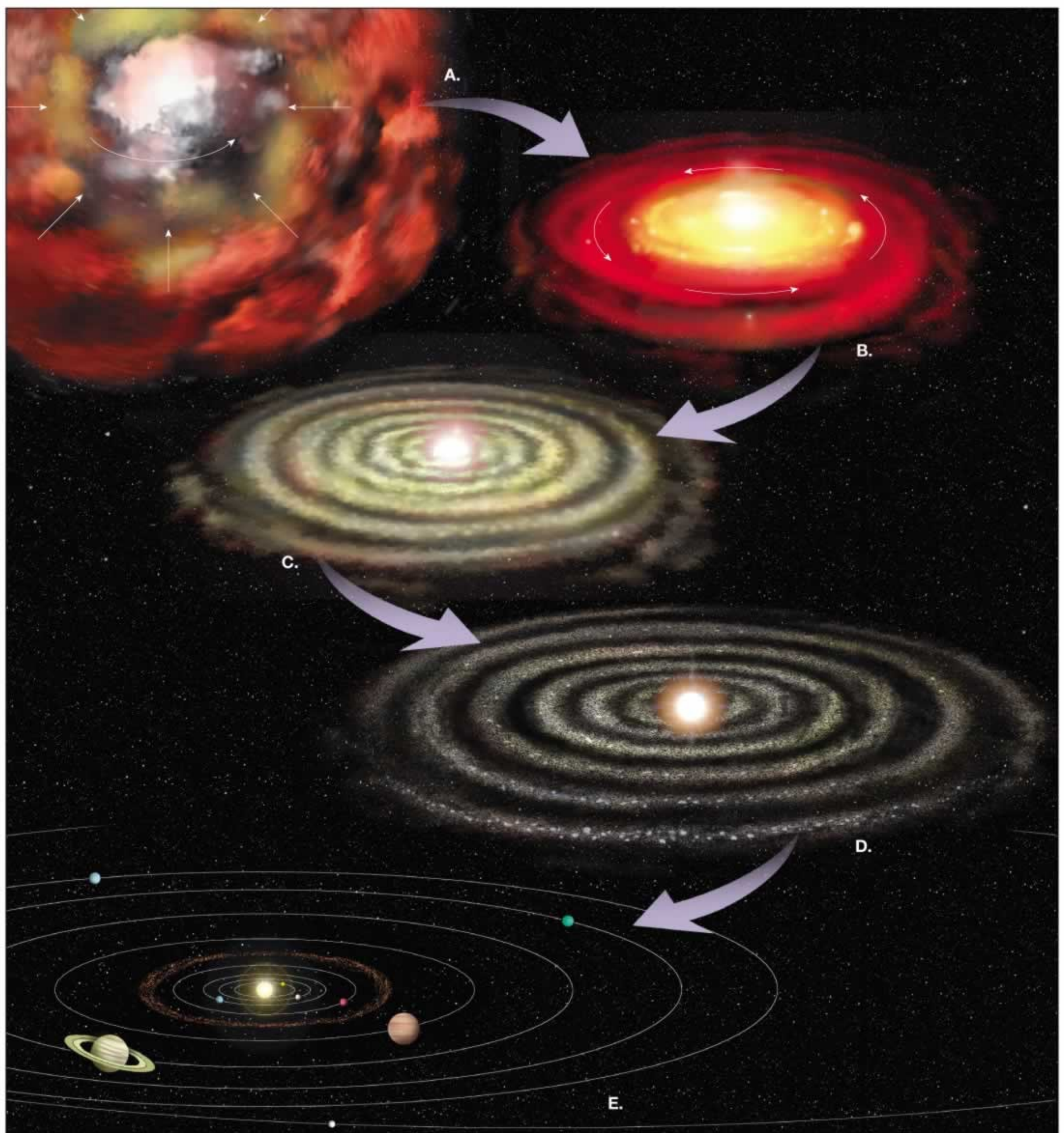
Credits: ALMA



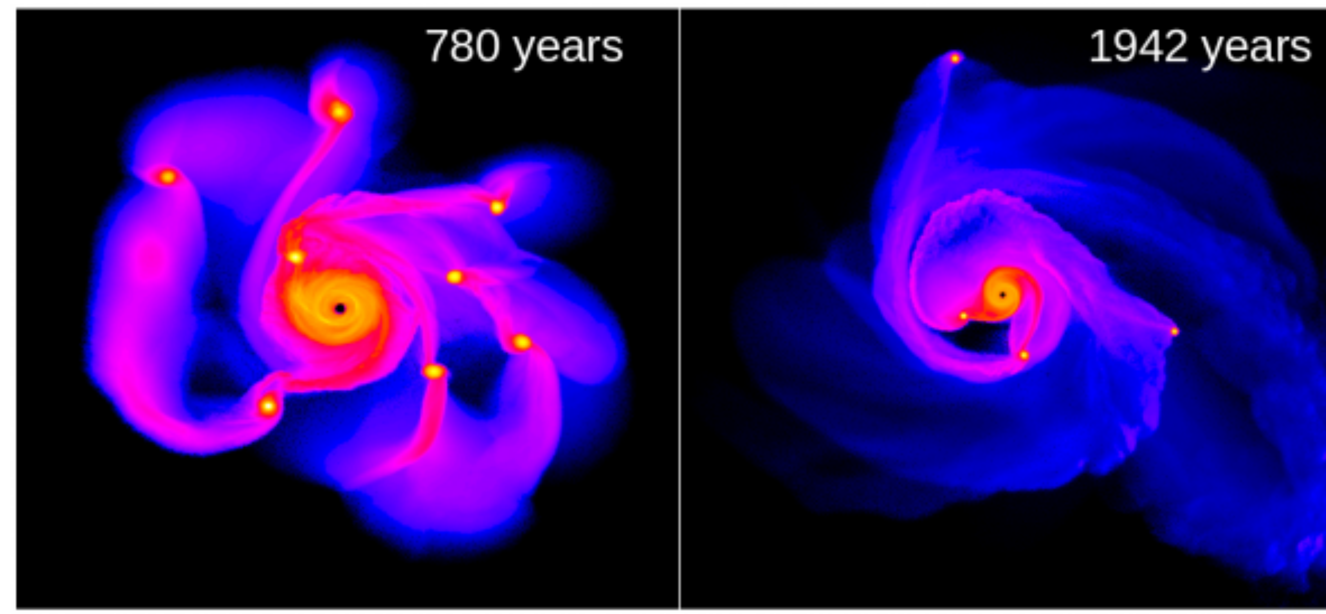
TW Hydrae. Image credit: S. Andrews, Harvard-Smithsonian Center for Astrophysics / ALMA / ESO / NAOJ / NRAO.

HOW ARE PLANETS FORMED INSIDE DISKS?

Bottom-up: solids sediment and coagulate. When they grow large enough they can attract gas from the disk (**Core accretion**).

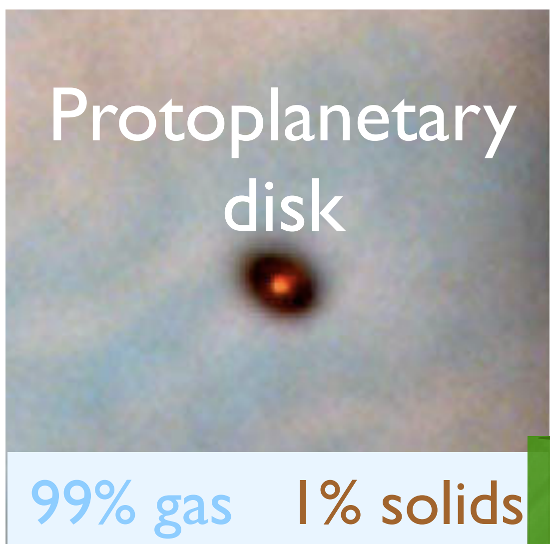


Top-down: disk formed around the star collapses under its own gravity. Planets form from the disk fragments (**Disk Instability**) ⟶ they are born gaseous.

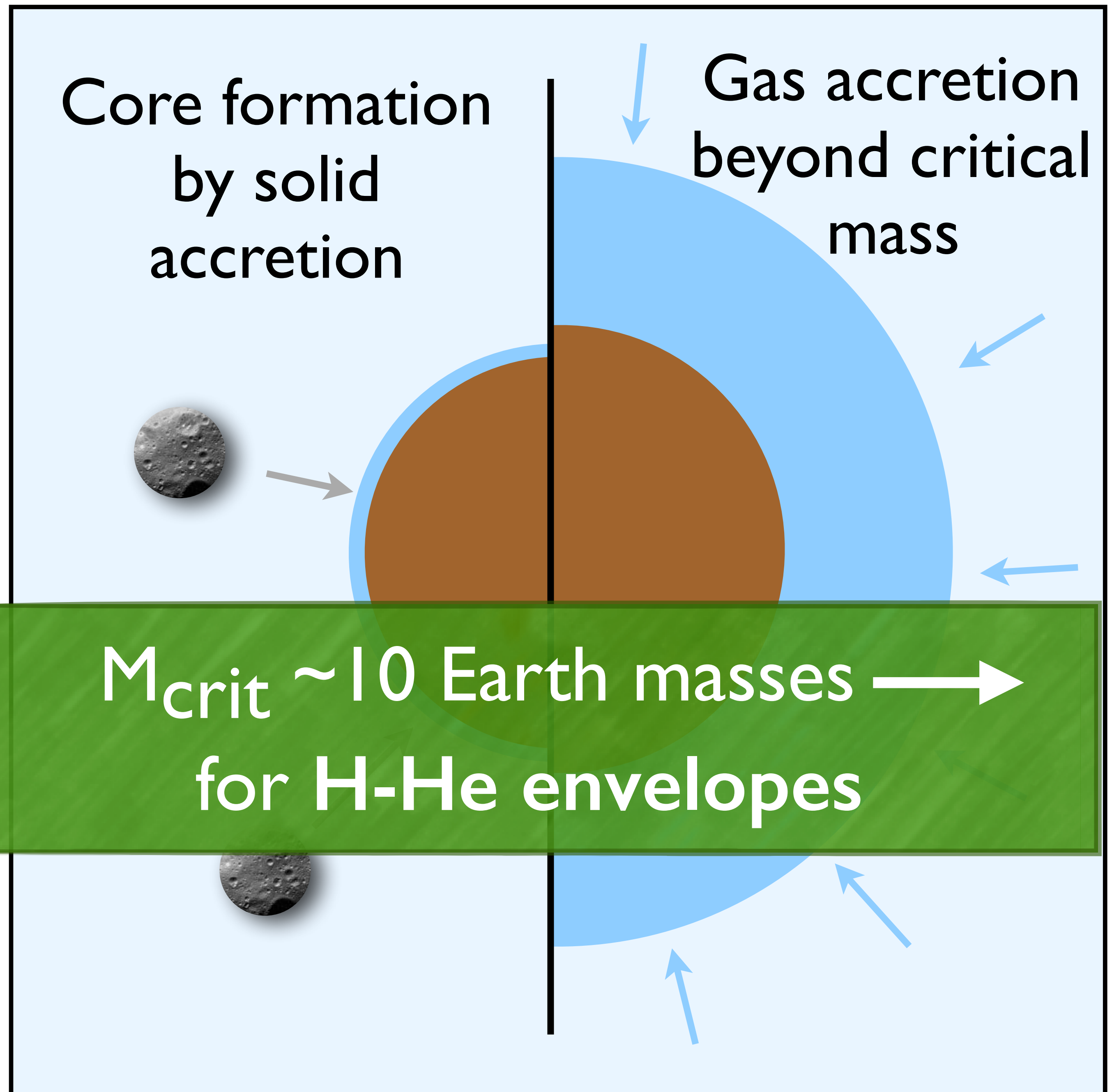


Credit: Lucio Mayer & T. Quinn, ChaNGa code

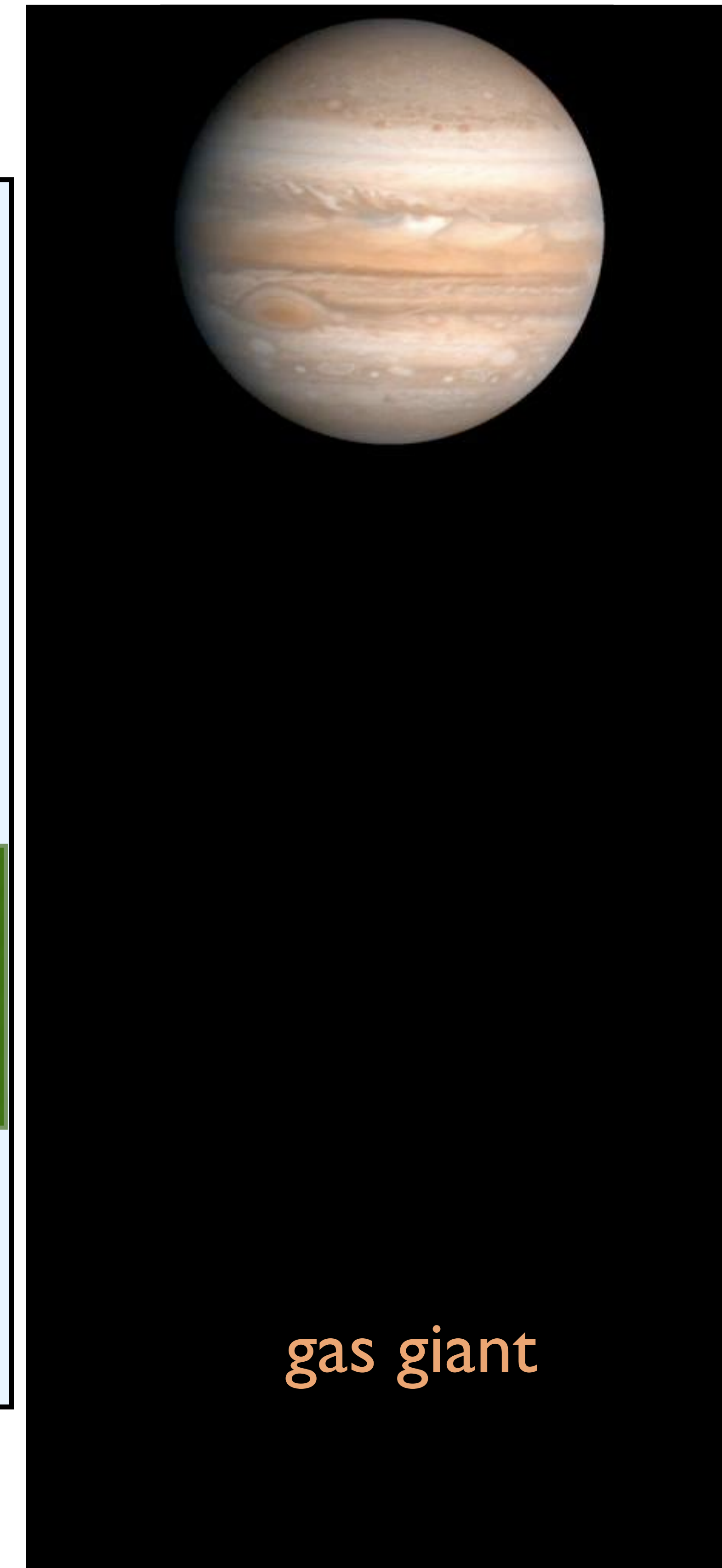
PLANET FORMATION: CORE ACCRETION MODEL



$T_{\mathrm{disk}} < 10^7 \mathrm{yr}$

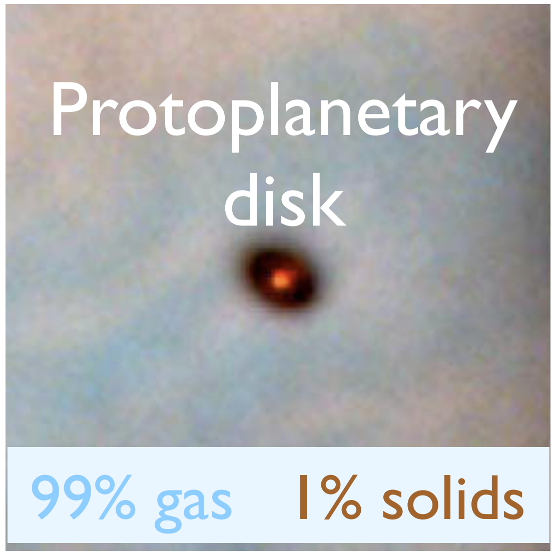


M_{crit} ~10 Earth masses ⟶
for **H-He envelopes**



(Perri & Cameron 1974, Mizuno 1978, Bondeheimer & Pollack 1986, Pollack et al. 1996)

PLANET FORMATION: CORE ACCRETION MODEL



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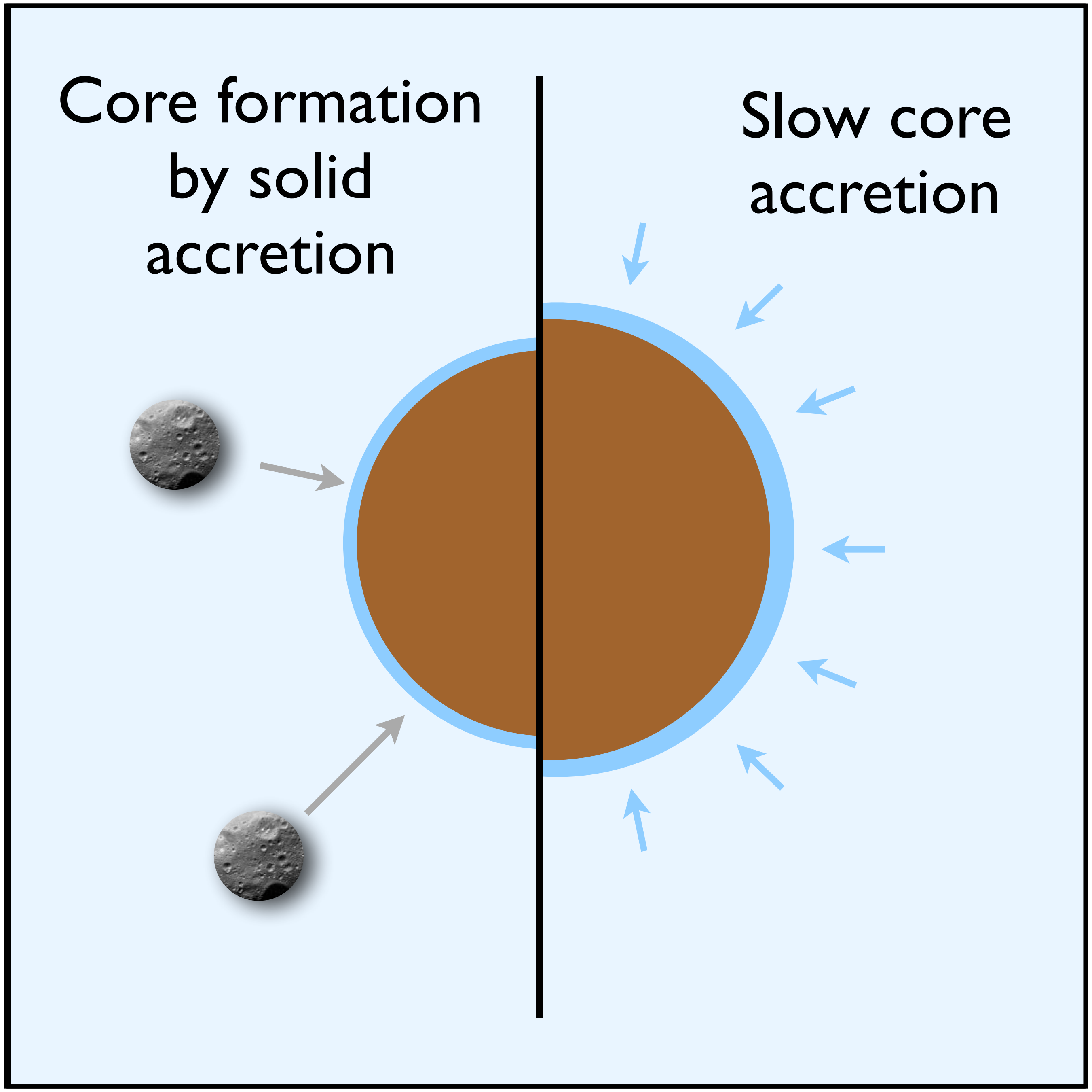
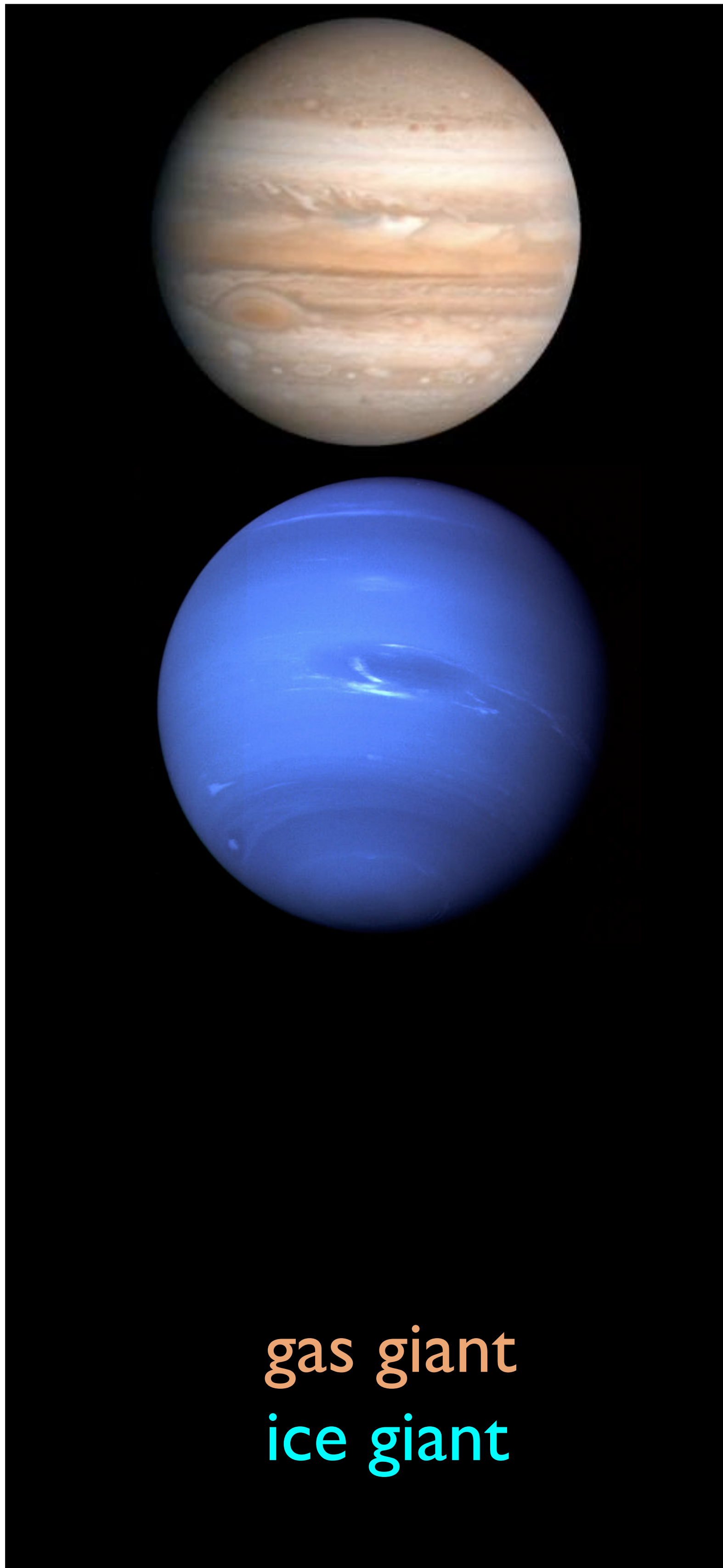
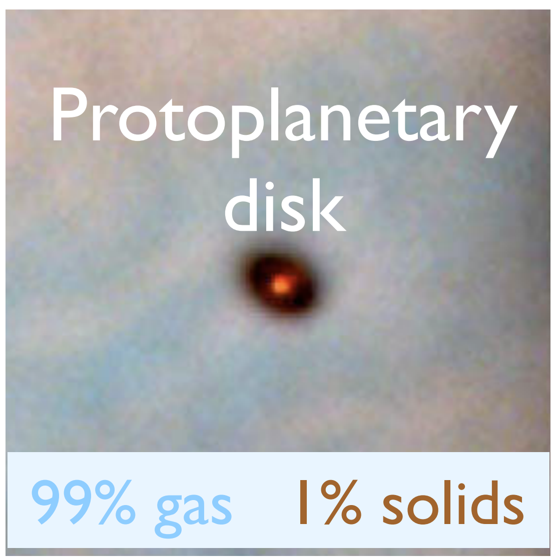




Fine-tuning problem: disk must disappear when the planet acquired a non-negligible amount of H-He, but usually at this stage the planet is already in the runaway gas phase (Helled & Bodenheimer, 2014; Venturini & Helled, 2017).

PLANET FORMATION: CORE ACCRETION MODEL



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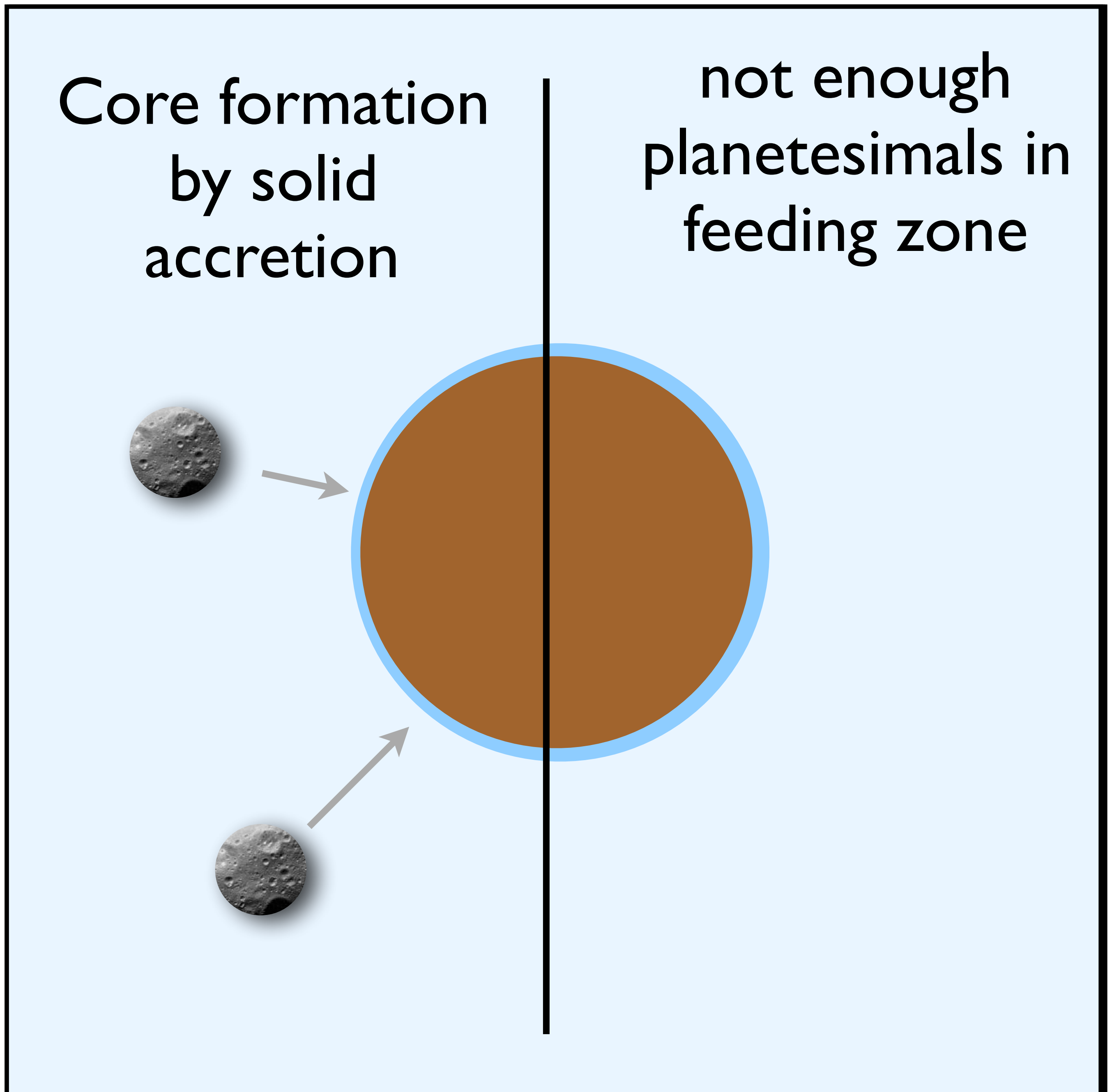
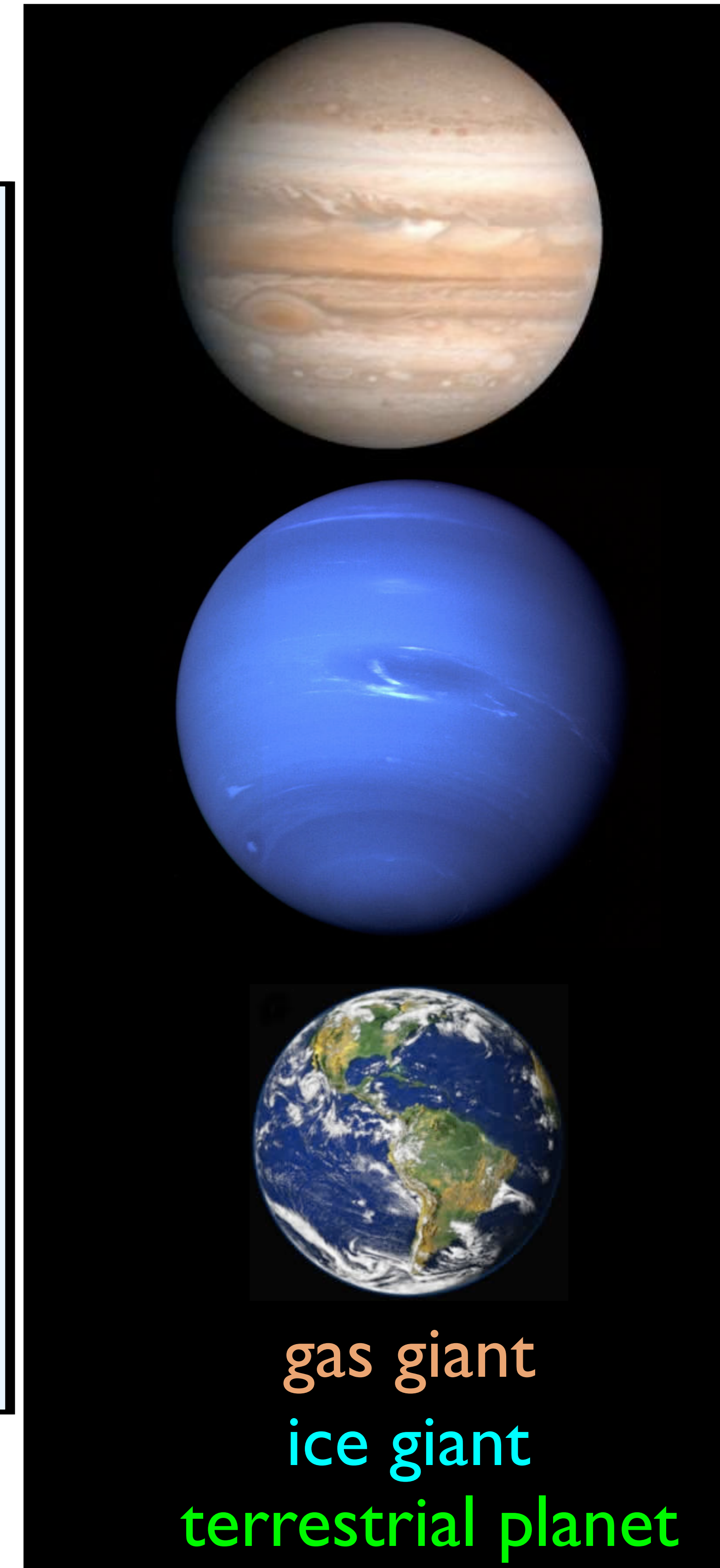
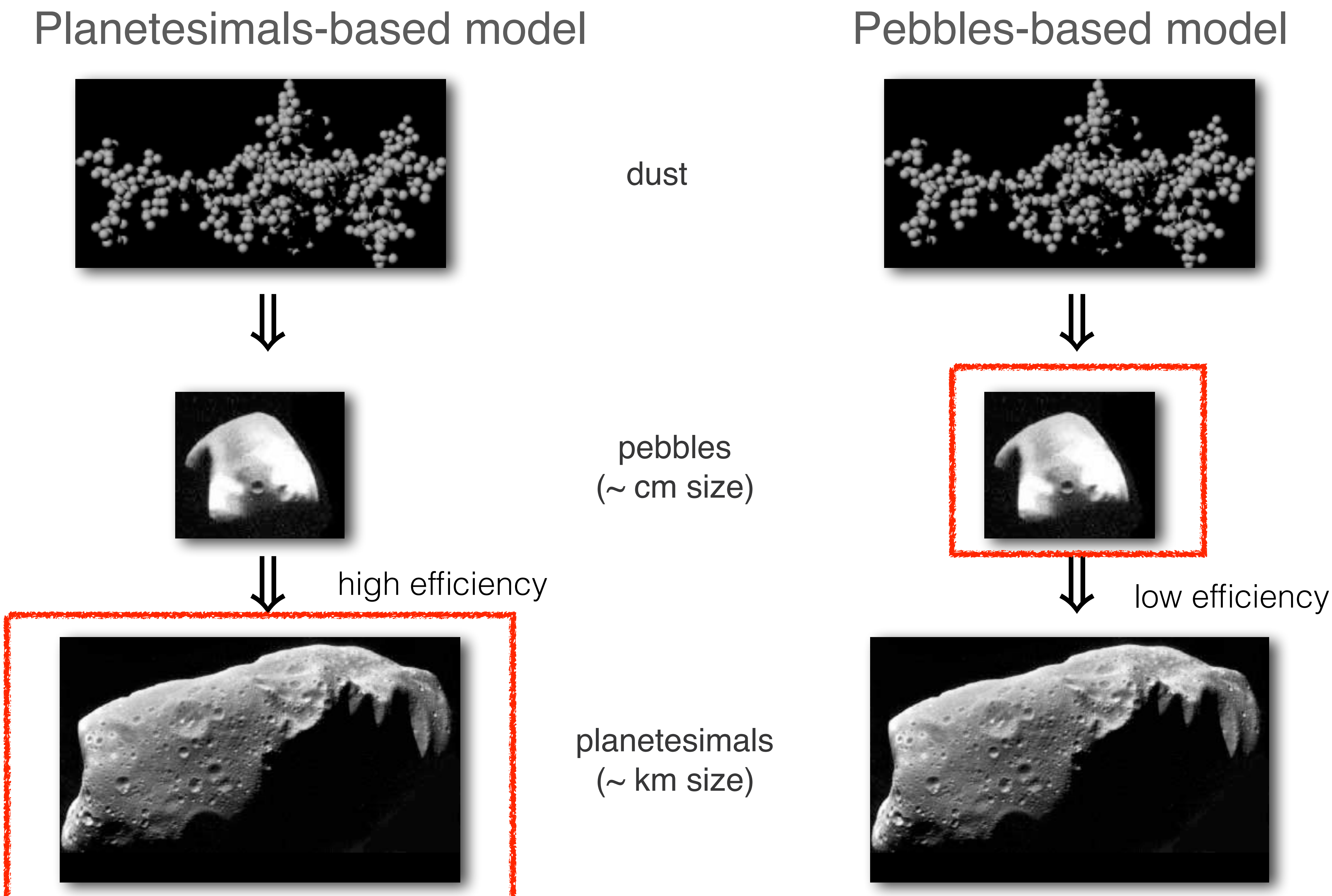


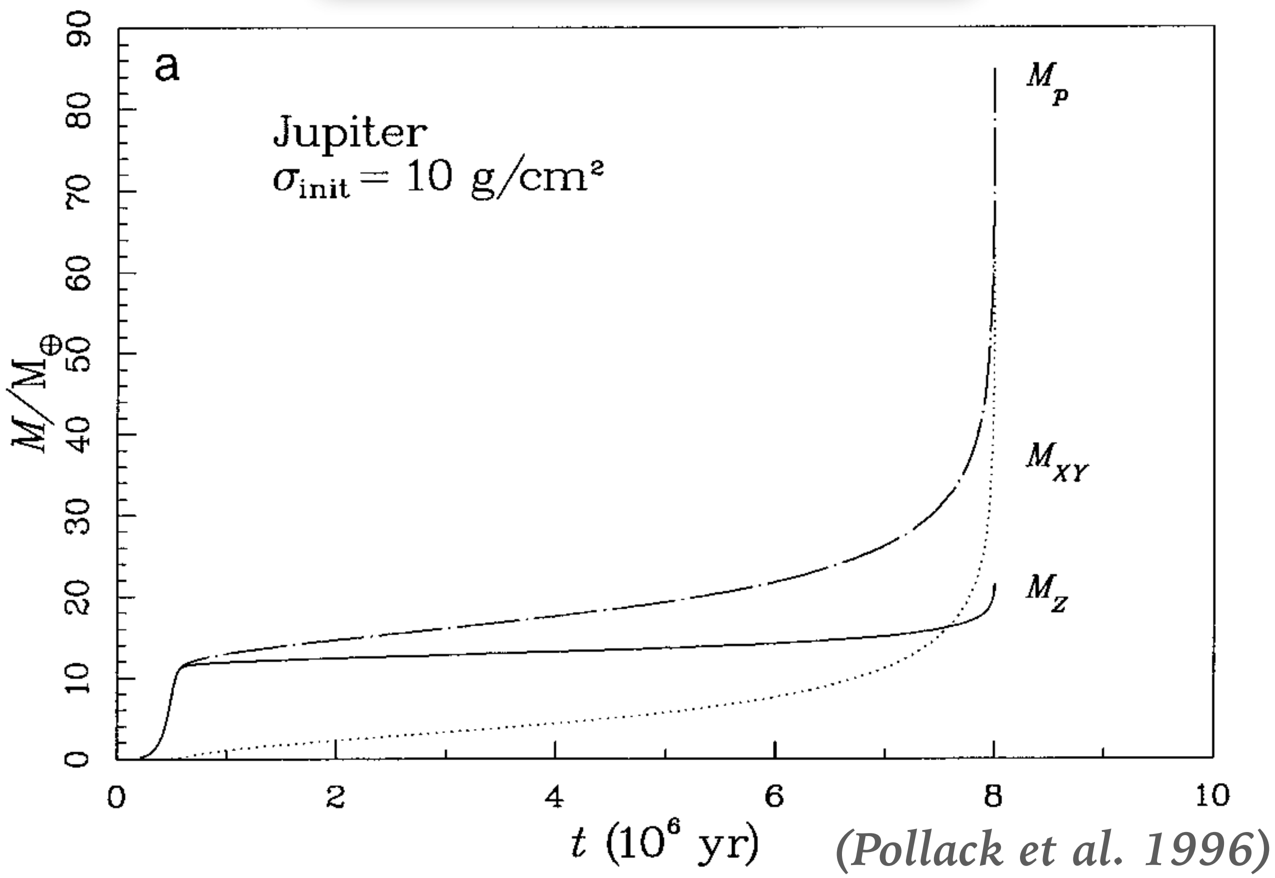


WHAT ARE THESE SOLIDS?



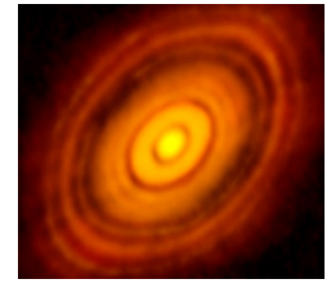
(courtesy of Y. Alibert)

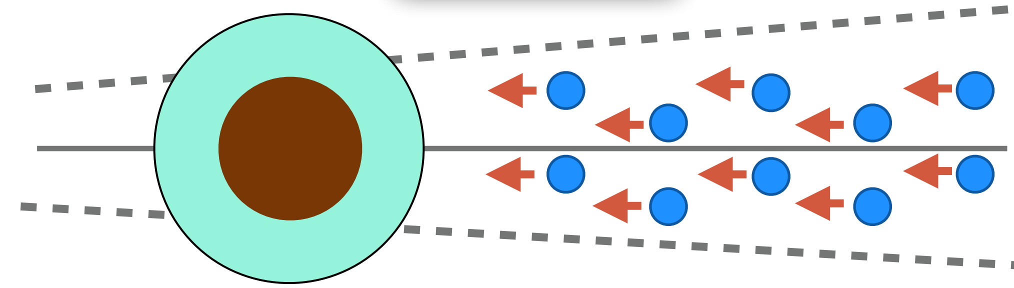
Planetesimals-based model

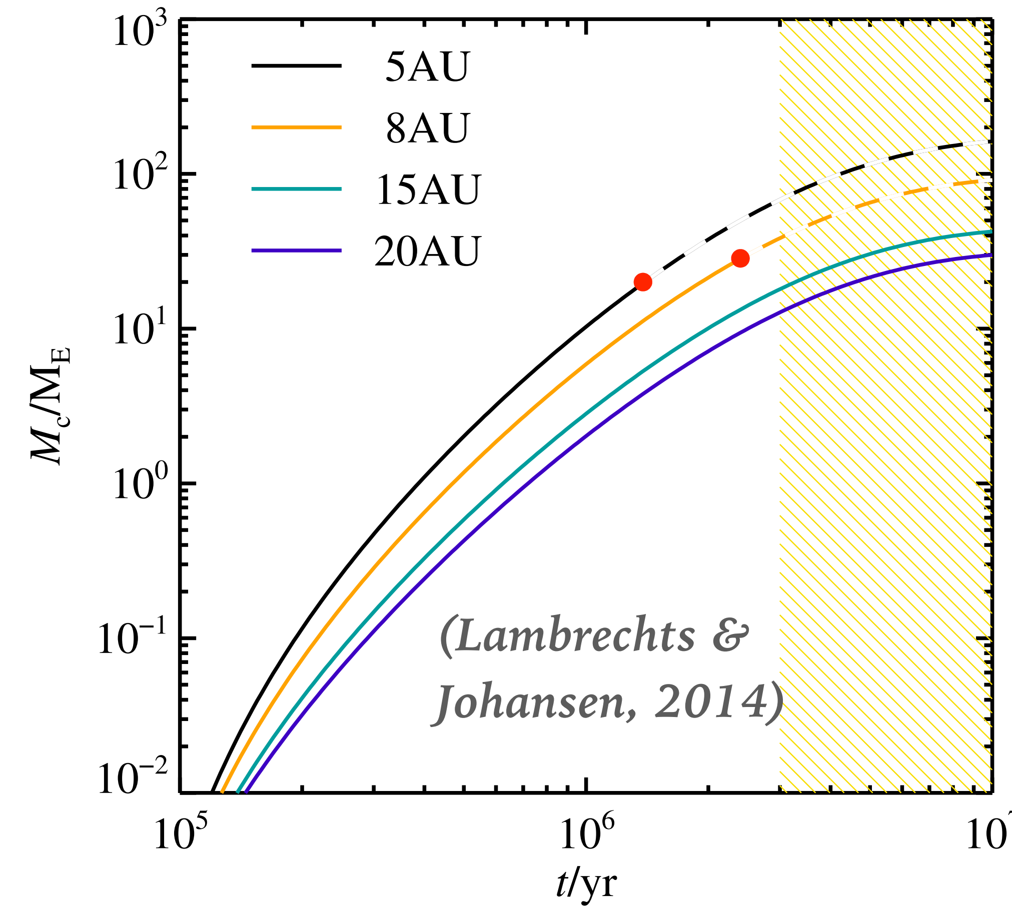


- **Too long formation timescales** unless planetesimals are small (100 m - 1 km: *Fortier et al. 2013*).
- Difficult to accrete planetesimals (Sho Shibata's talk).
- Substantial H-He accretion onto a ~2 M_E core requires very special conditions (*Ikoma & Hori, 2012, Bodenheimer & Lissauer 2014*).

Pebbles-based model

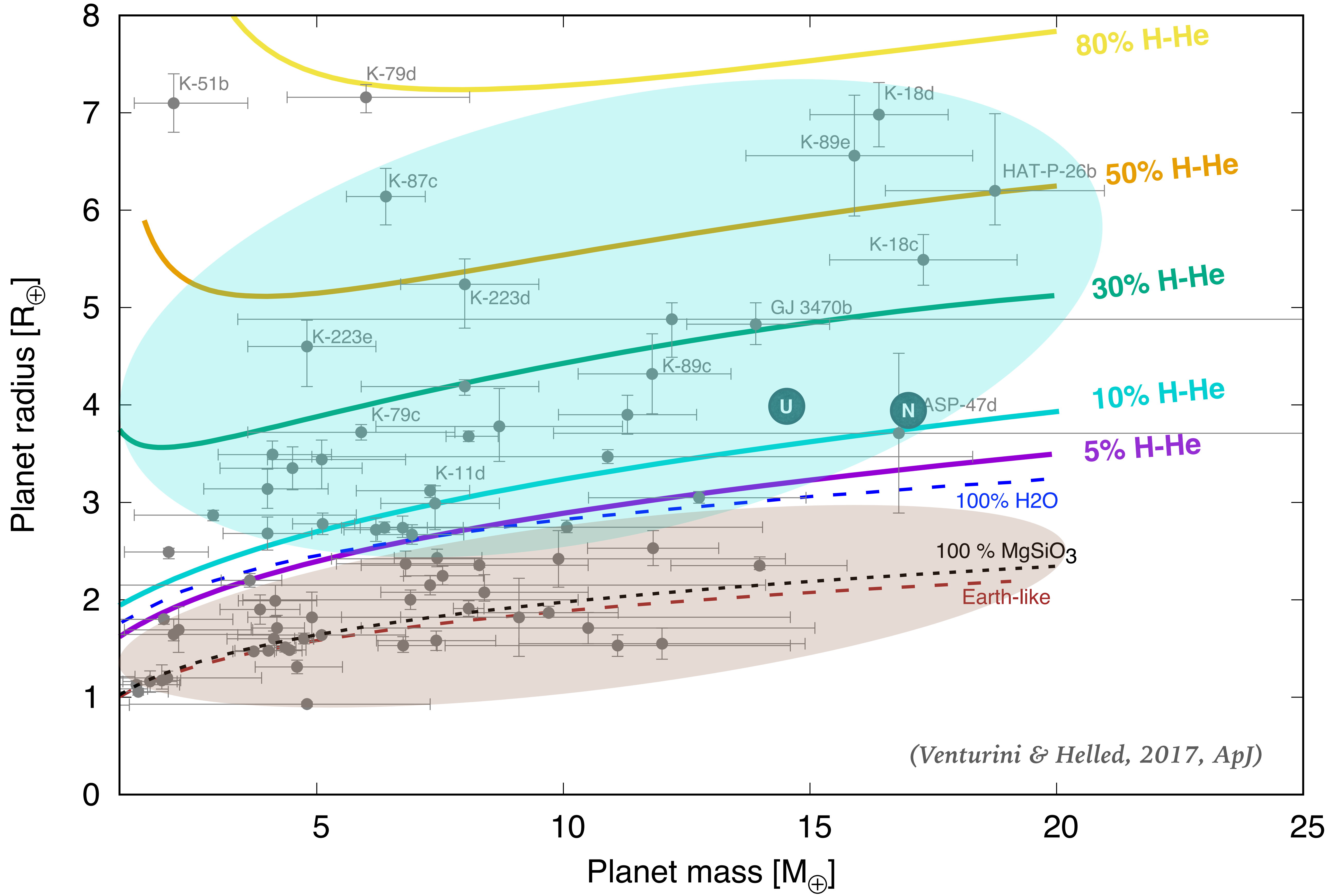




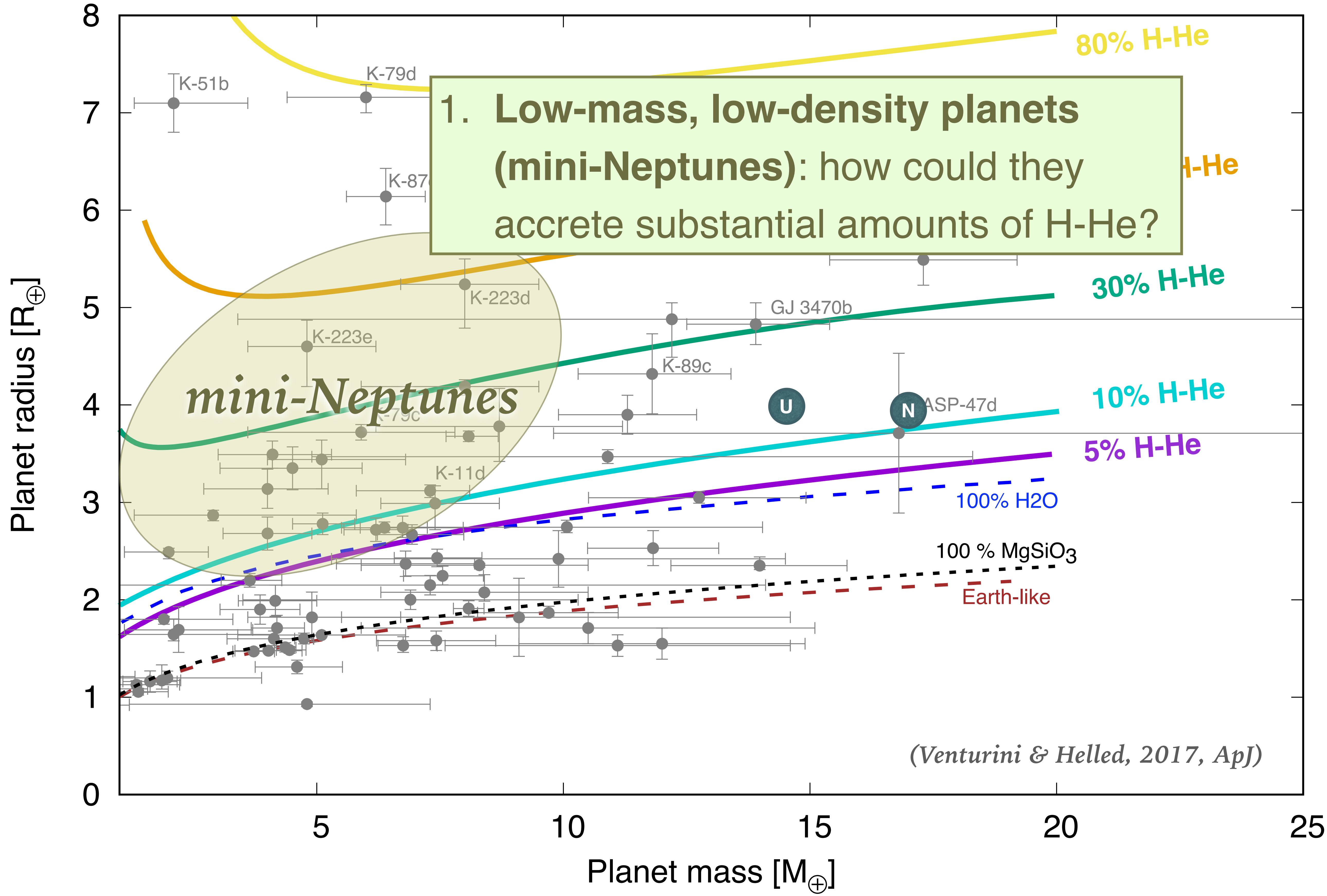


- **Formation of gas giants too efficient**, unless:
  - ➡ high disk viscosity (*Ormel 2017*).
  - ➡ large orbital distances + high envelope opacities (*Venturini & Helled, 2017*).

DIVERSITY IN COMPOSITION FOR LOW-MASS PLANETS



CURRENT PROBLEMS WITH FORMATION MODELS:



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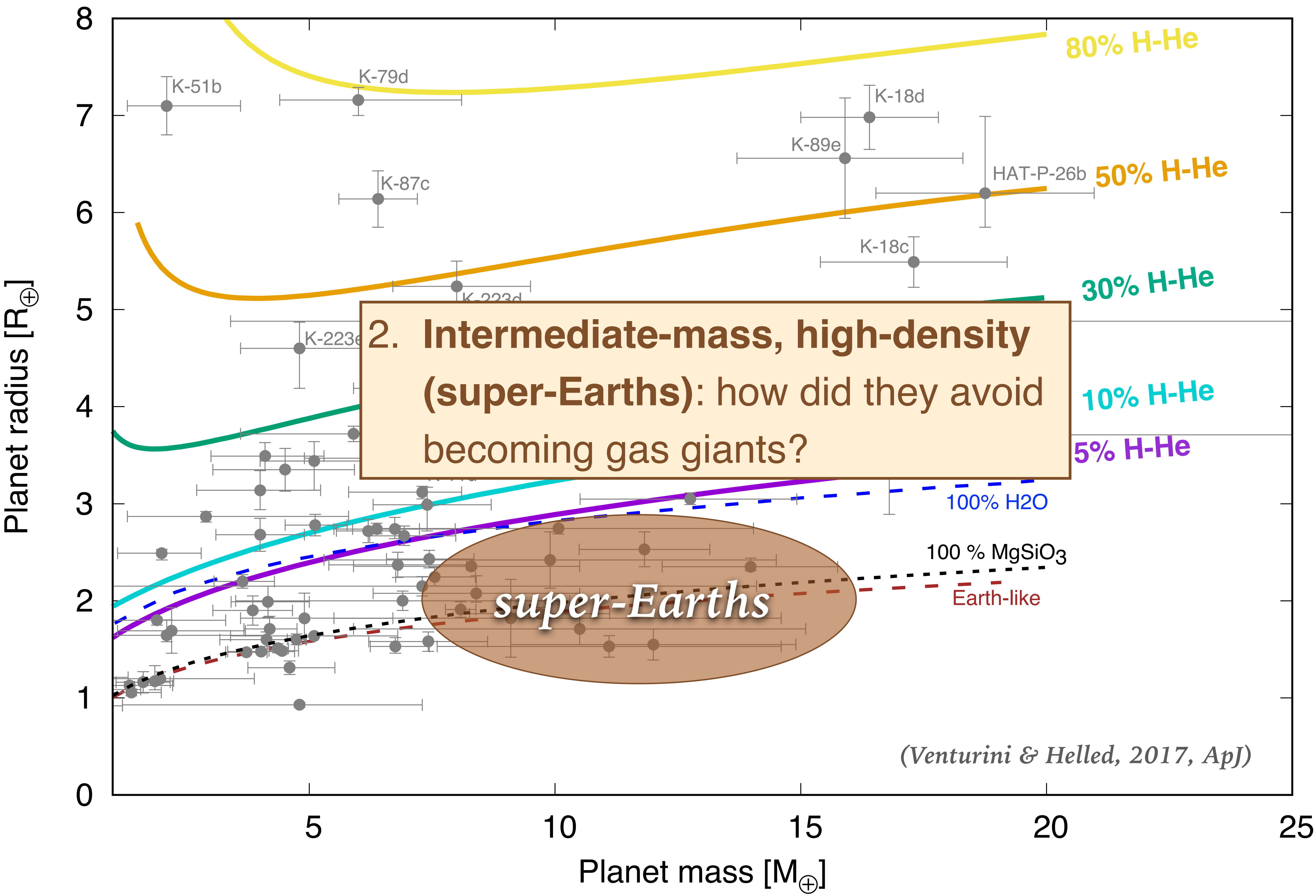

2. **Intermediate-mass, high-density (super-Earths)**: how did they avoid becoming gas giants?

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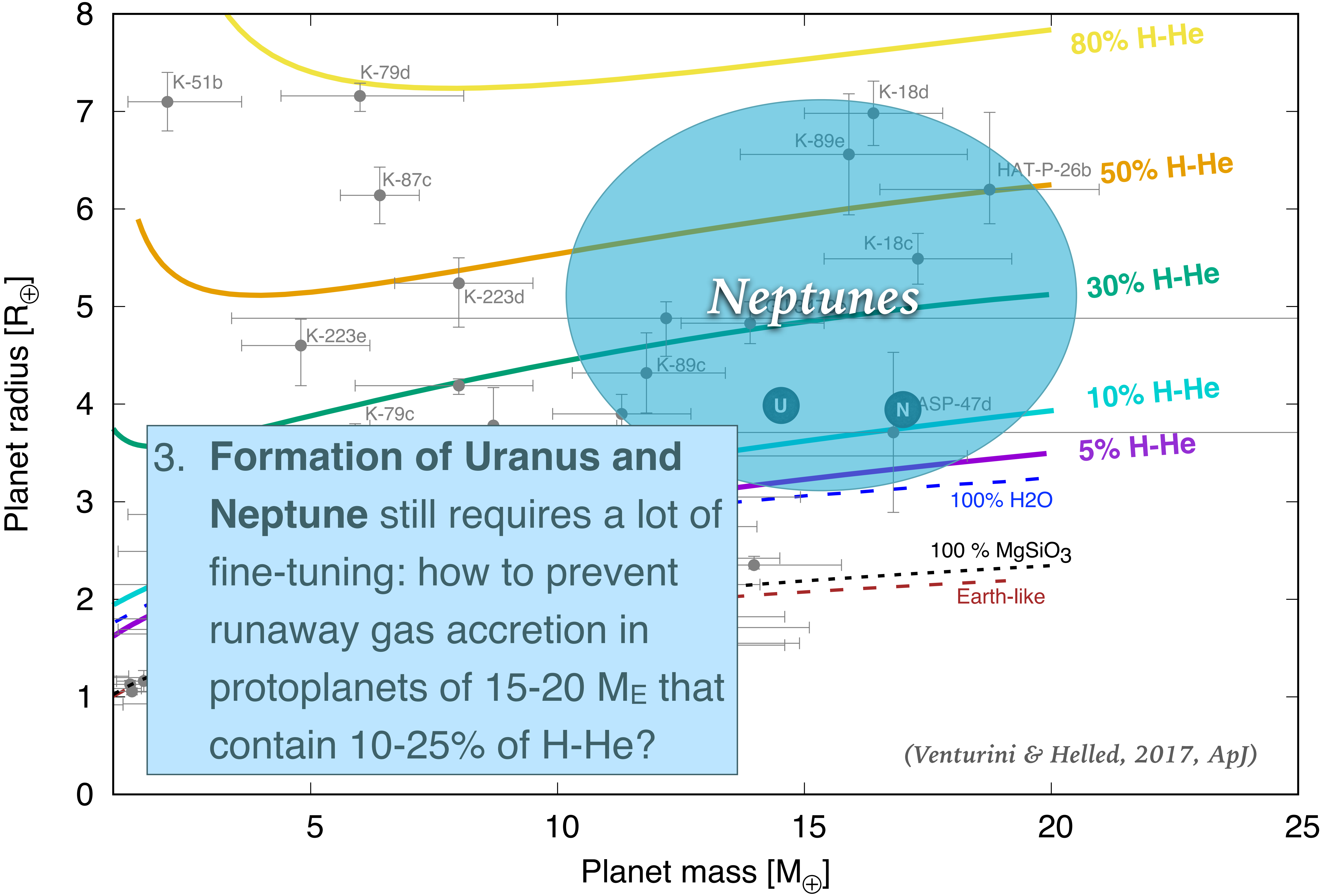


3. **Formation of Uranus and Neptune** still requires a lot of fine-tuning: how to prevent runaway gas accretion in protoplanets of 15-20 M_E that contain 10-25% of H-He?

CURRENT PROBLEMS WITH FORMATION MODELS

How do we explain the formation of:

1. **Low-mass, low-density planets (mini-Neptunes)**: how could they accrete substantial amounts of H-He?

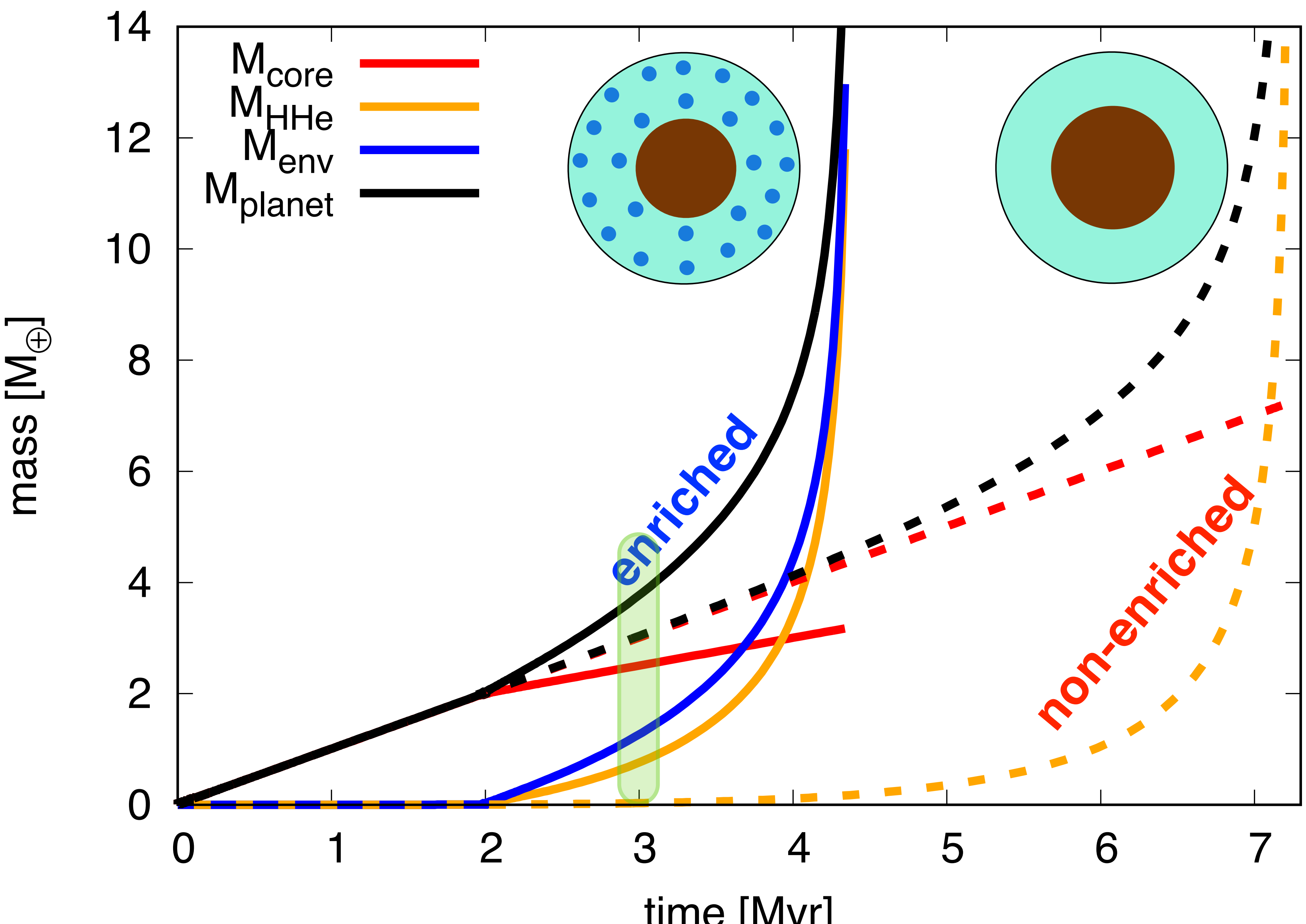
2. **Intermediate-mass, high-density (super-Earths)**: how did they avoid becoming gas giants?

3. **Formation of Uranus and Neptune** still requires a lot of fine-tuning: how to prevent runaway gas accretion in protoplanets of 15-20 M_E that contain 10-25% of H-He?

4. **Apparently *dry* composition of short period plantes —>** formation models favour gas accretion beyond the iceline.

1. FORMATION OF MINI-NEPTUNES: aided by envelope enrichment

From static calculations, envelope enrichment is expected to play a role in reducing the timescale to form a gas giant:
Stevenson (1982), P&SS; Hori & Ikoma (2011), MNRAS; Venturini et al. (2015), A&A



Not all solids reach the core => icy planetesimals/pebbles sublimate and mix with the primordial H-He atmosphere: two main effects during planetary growth:

1) **Timescale to form a gas giant reduced** by a factor of at least 2.
2) **Small protoplanets with ~20% of H-He in mass can be formed.**

Venturini et al.(2016), A&A
Venturini & Helled (2017), ApJ

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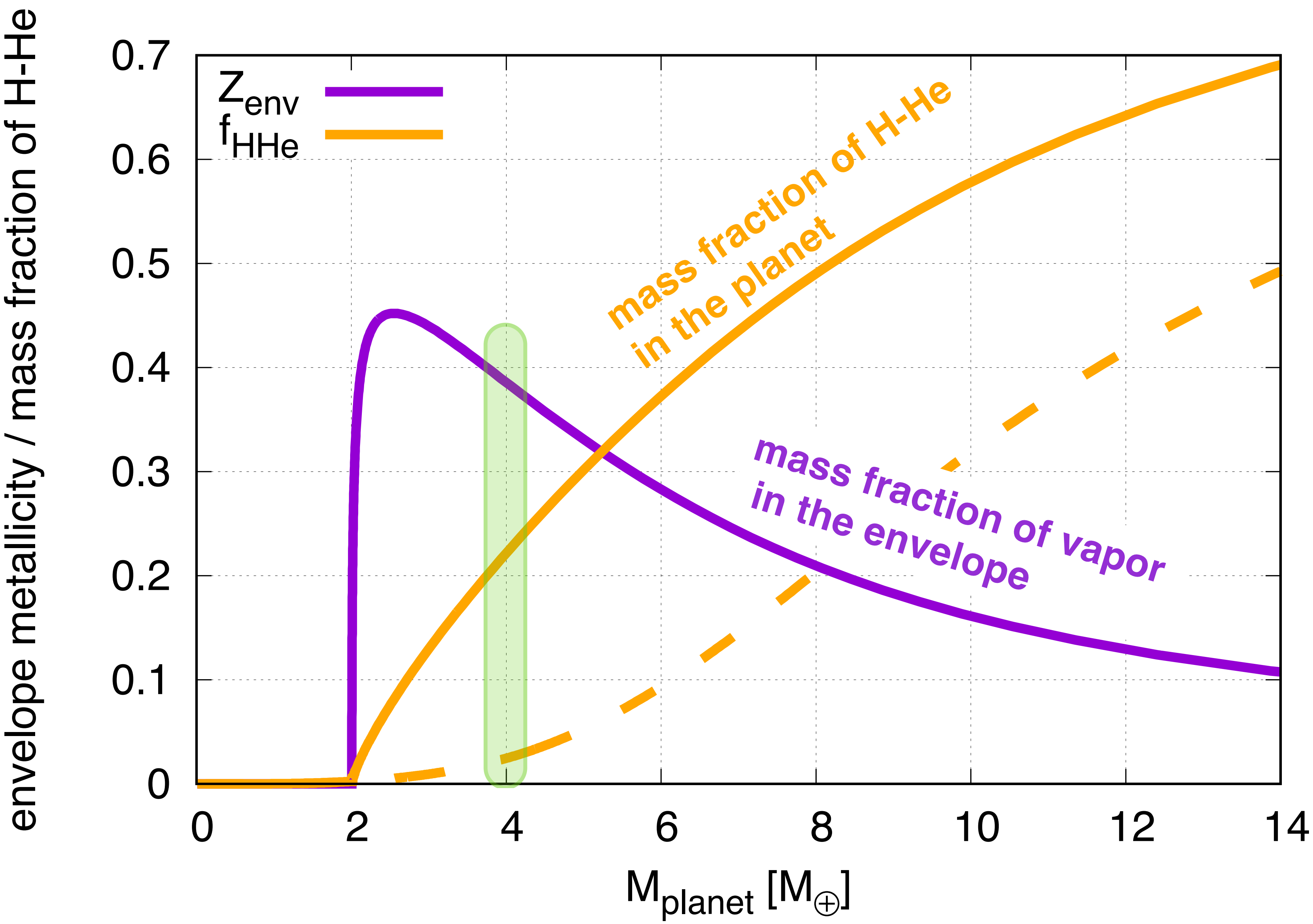

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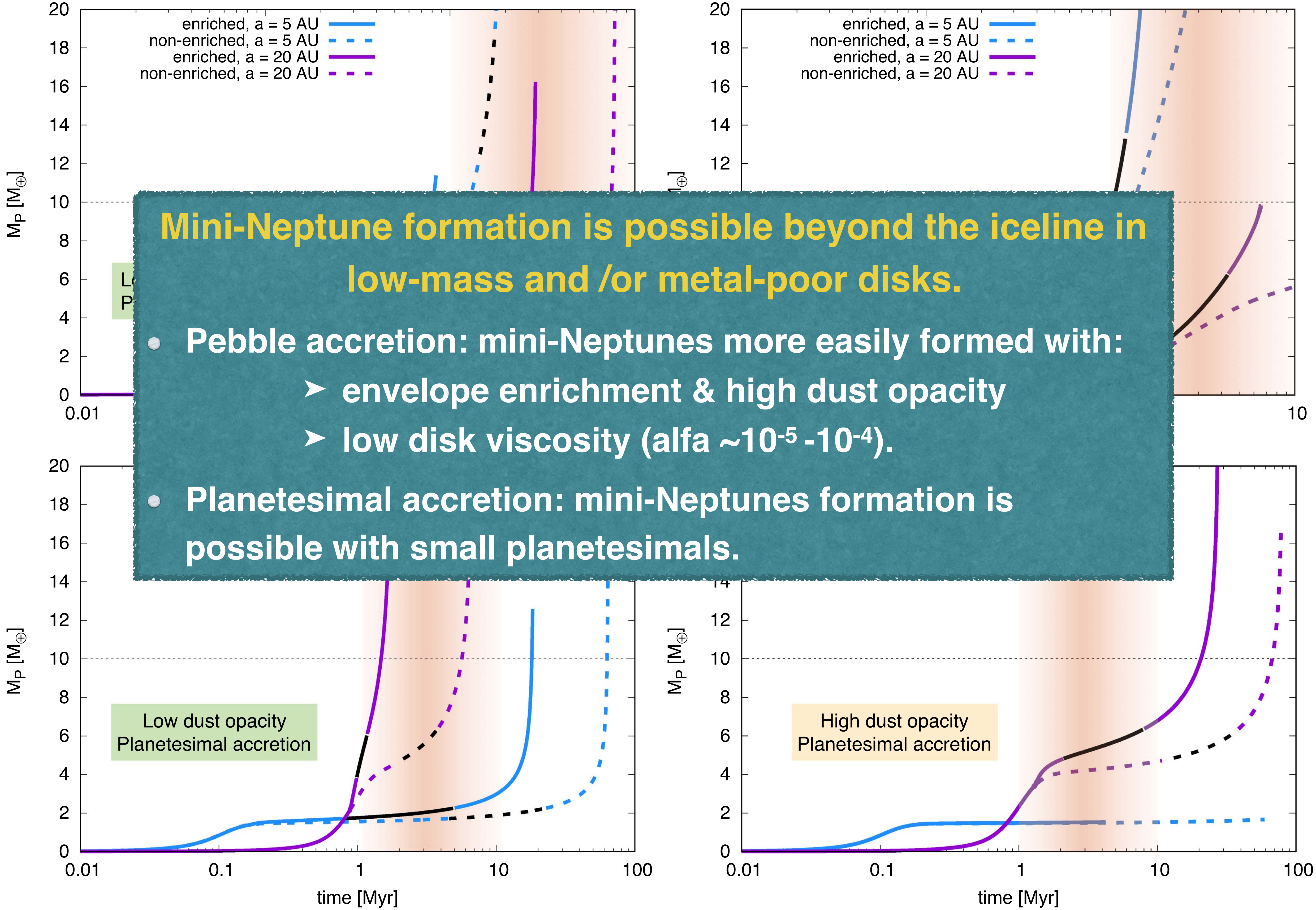


Mini-Neptune formation is possible beyond the iceline in low-mass and /or metal-poor disks.

- **Pebble accretion: mini-Neptunes more easily formed with:**
  - ➤ **envelope enrichment & high dust opacity**
  - ➤ **low disk viscosity (alfa ~10^{-5} -10^{-4}).**
- **Planetesimal accretion: mini-Neptunes formation is possible with small planetesimals.**

Venturini & Helled (2017), ApJ

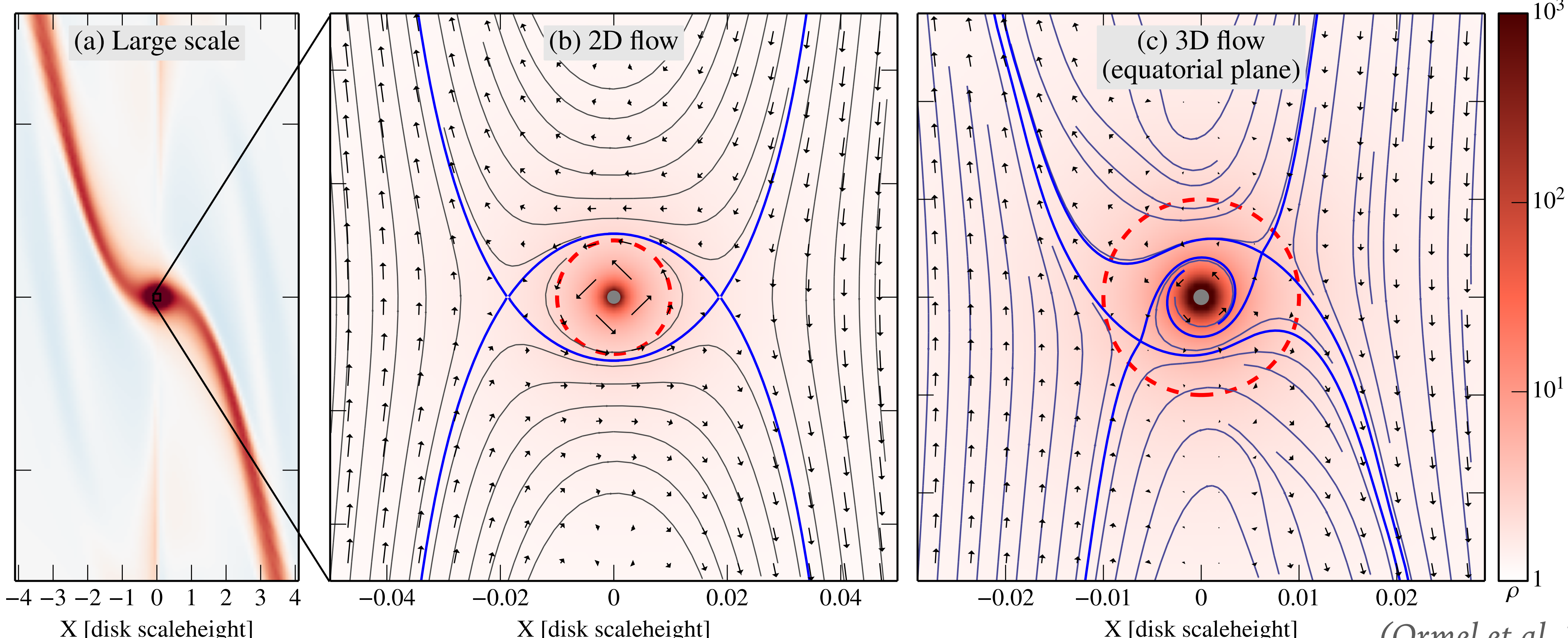
2. INTERMEDIATE-MASS, HIGH-DENSITY (SUPER-EARTHS)

Recycling scenario:

Ormel et al. (2015), MNRAS

Lambrechts & Lega (2017), A&A

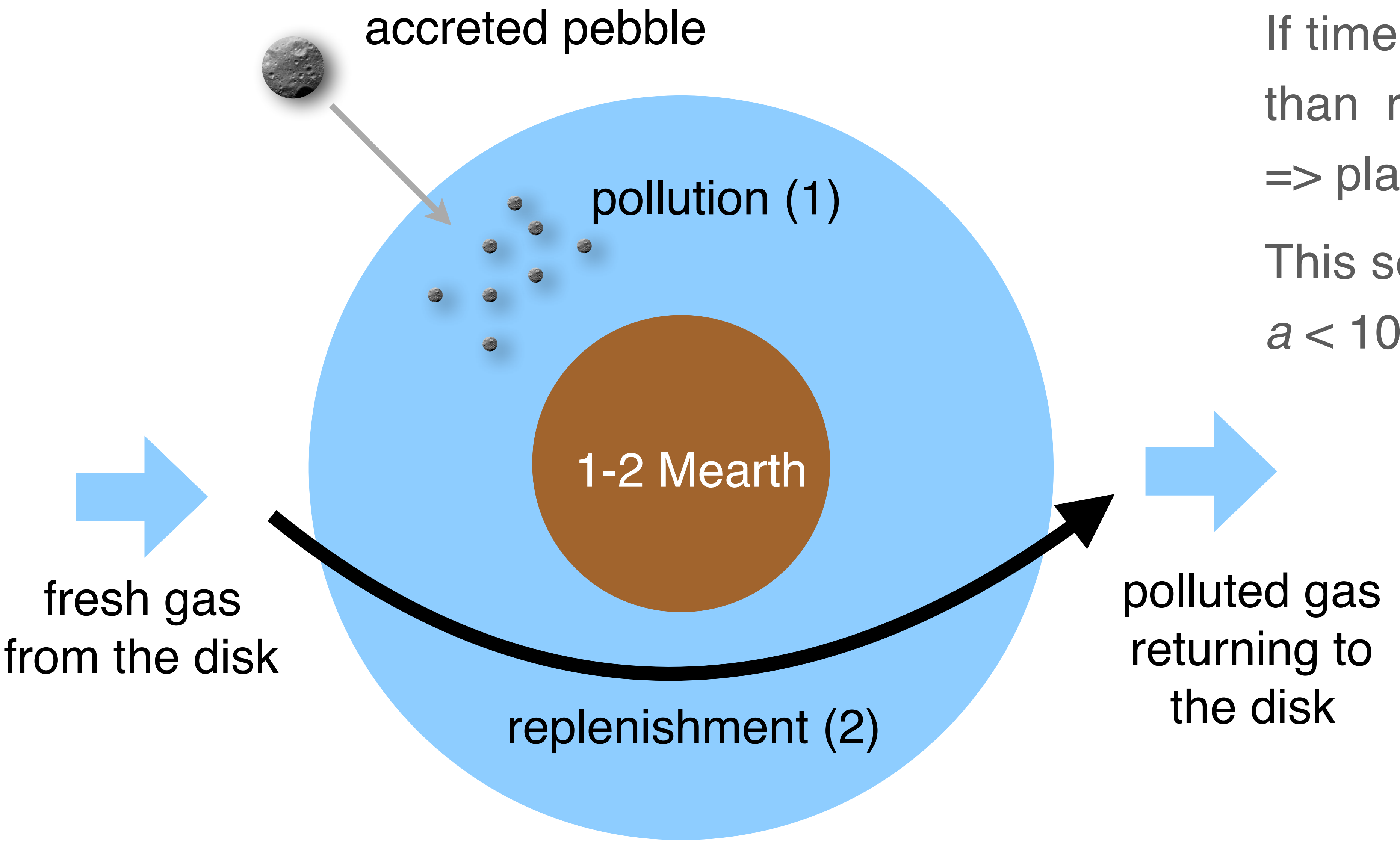
Cimerman et al. (2017), MNRAS



(Ormel et al. 2015)

3D hydrodynamical simulations show that low-entropy gas within the Bondi radius flows back to the disk, and high-entropy gas from the disk replenishes the envelope => **gas is not cooled, and therefore not accreted, but recycled into the disk**.

CONSEQUENCES OF RECYCLING WHILE ACCRETING PEBBLES: MAXIMUM PLANETARY MASS?



If timescale to pollute is longer than replenishment timescale => planet will stop growing.

This seems to happen for $a < 10$ AU.

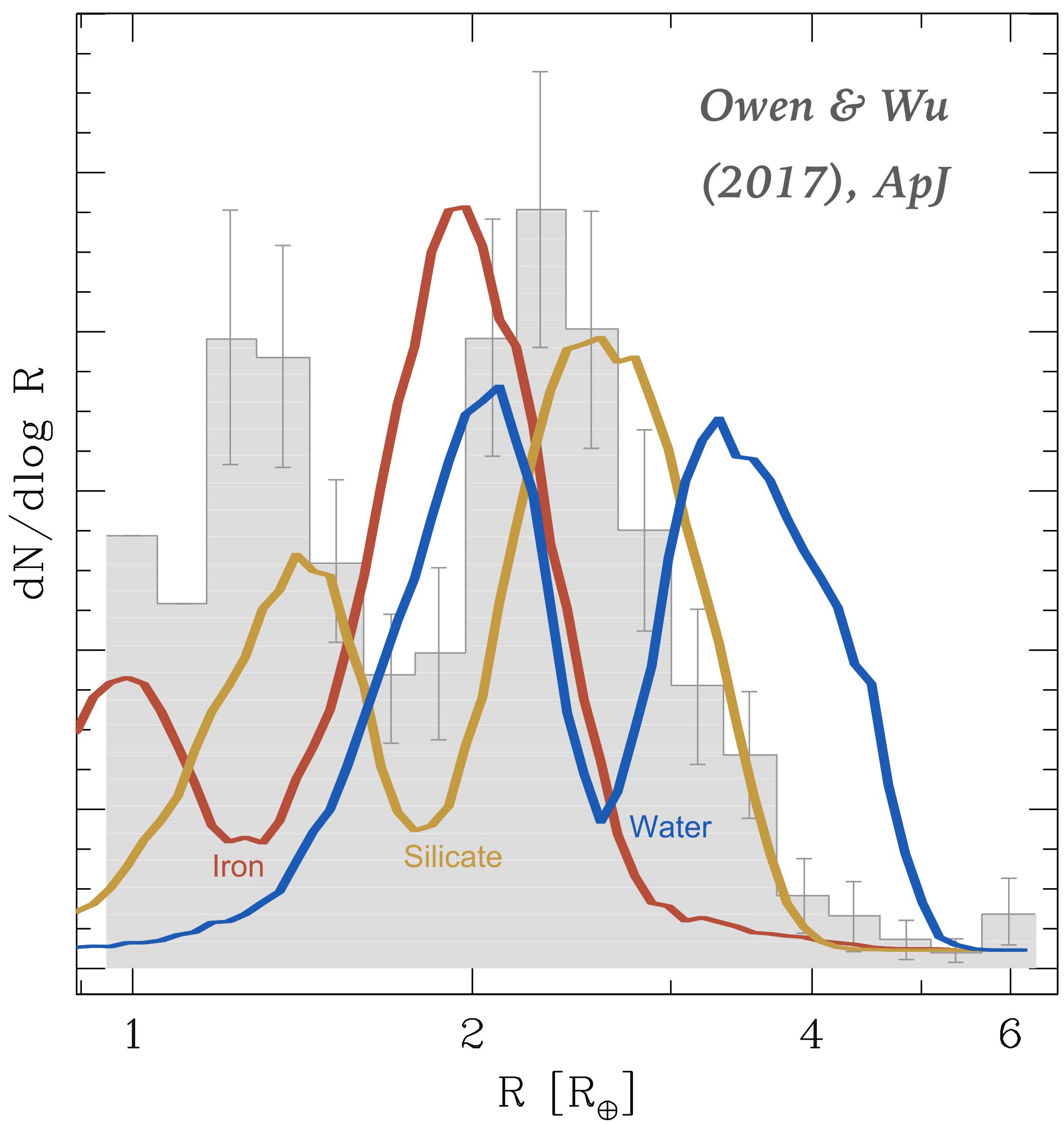
(Alibert 2017, A&A)

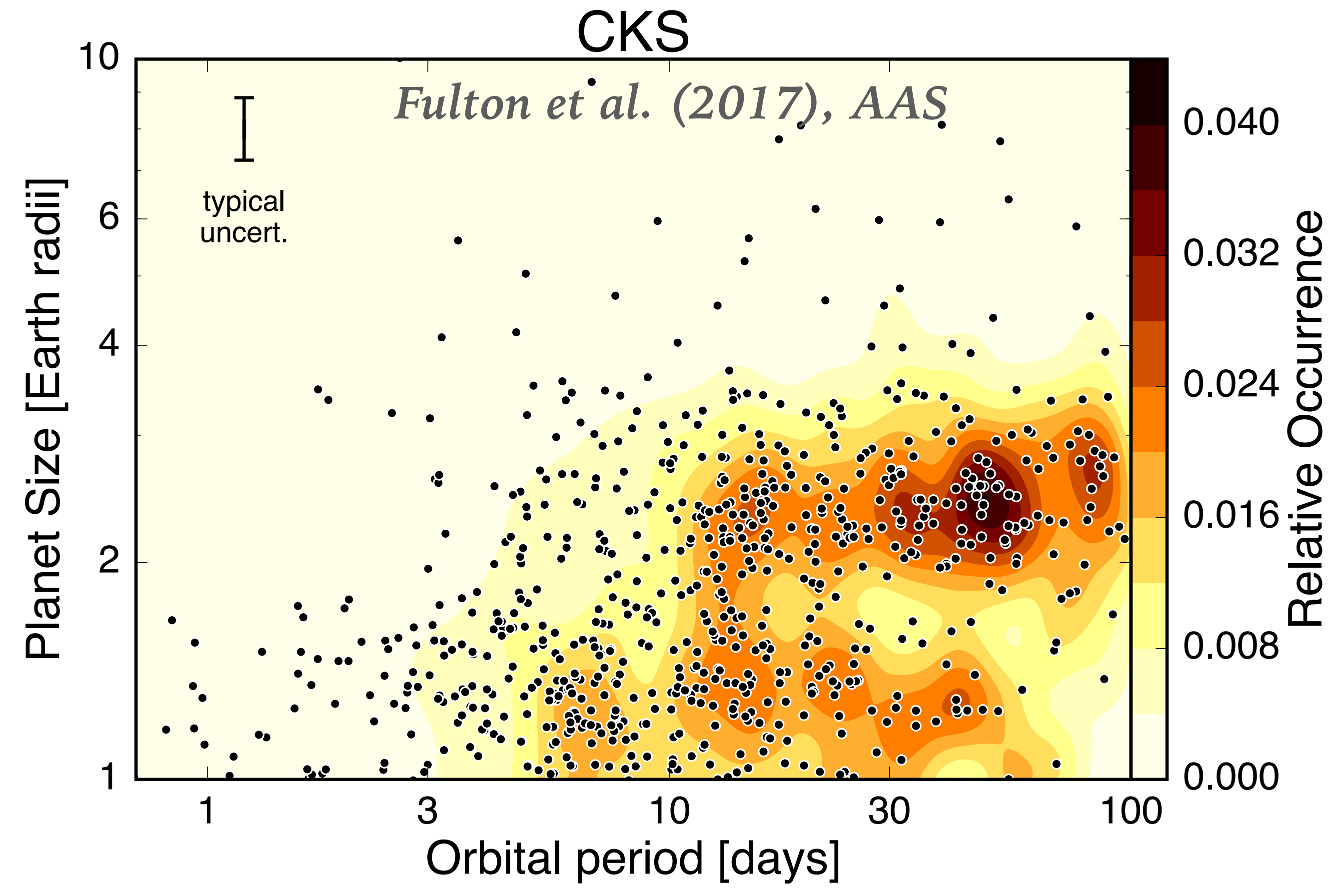
Details still unclear due to lack of resolution of 3D simulations and combination of effects of envelope enrichment with gas-flow dynamics.
Open questions:
How much gas is the planet able to retain? How does this depend on:

- **distance to the star?**
- **core mass?**

SMALL PLANETS AT SHORT PERIODS: THE EVAPORATION VALLEY

Re-analysis of the Kepler data (Fulton et al. 2017) shows a **bimodal distribution** of **sizes** of short period exoplanets, **peaked at 1.3 and 2.4 R_E.**





Photoevaporation can predict the 2 peaks, and their values are very sensitive to the composition of the core —> **cores seem to be Earth-like in composition.**

(Owen & Wu 2017; Jin & Mordasini 2017)

- **Formation inside the iceline?**
- **Icy envelope enrichment + loss of water? (Ormel's talk, Ikoma's talk)**

SUMMARY:

* New measurements of mass and radius of exoplanets are challenging our theories of planet formation.
* **Low-mass, low-density exoplanets can be explained more naturally when envelope enrichment** is accounted for. "Sweet spots" to form mini-Neptunes: disk that allow a protoplanet to accrete solids at an accretion rate of ~10^{-6} $M_{\oplus}$/yr:
    * small planetesimals (~100 m size) and low surface density of solids.
    * pebbles in small-mass/low metallicity disks.
* **Intermediate mass, rocky exoplanets** could have prevented runaway gas accretion by exchange of gas with the disk **(*recycling scenario*)**.
* The formation of Neptunes still requires a lot of fine-tuning: cores of 10-15 M_E accrete gas in a runaway fashion, and recycling should not be effective at large semi-major axes.
    * Merging of mini-Neptunes? (Izidoro et al. 2015)
    * High opacities? (Venturini et al. 2016) + high solid accretion? (Lambrechts et al. 2014, Yann Alibert's talk).
* Conflict between observations (rocky cores) and predictions from theory (gas-rich objects should have non-negligible amounts of water): how can we explain the second peak of the Kepler planets with in-situ formation models (inside iceline)? How did they manage to accrete substantial H-He (given the recycling)?

Thank you!