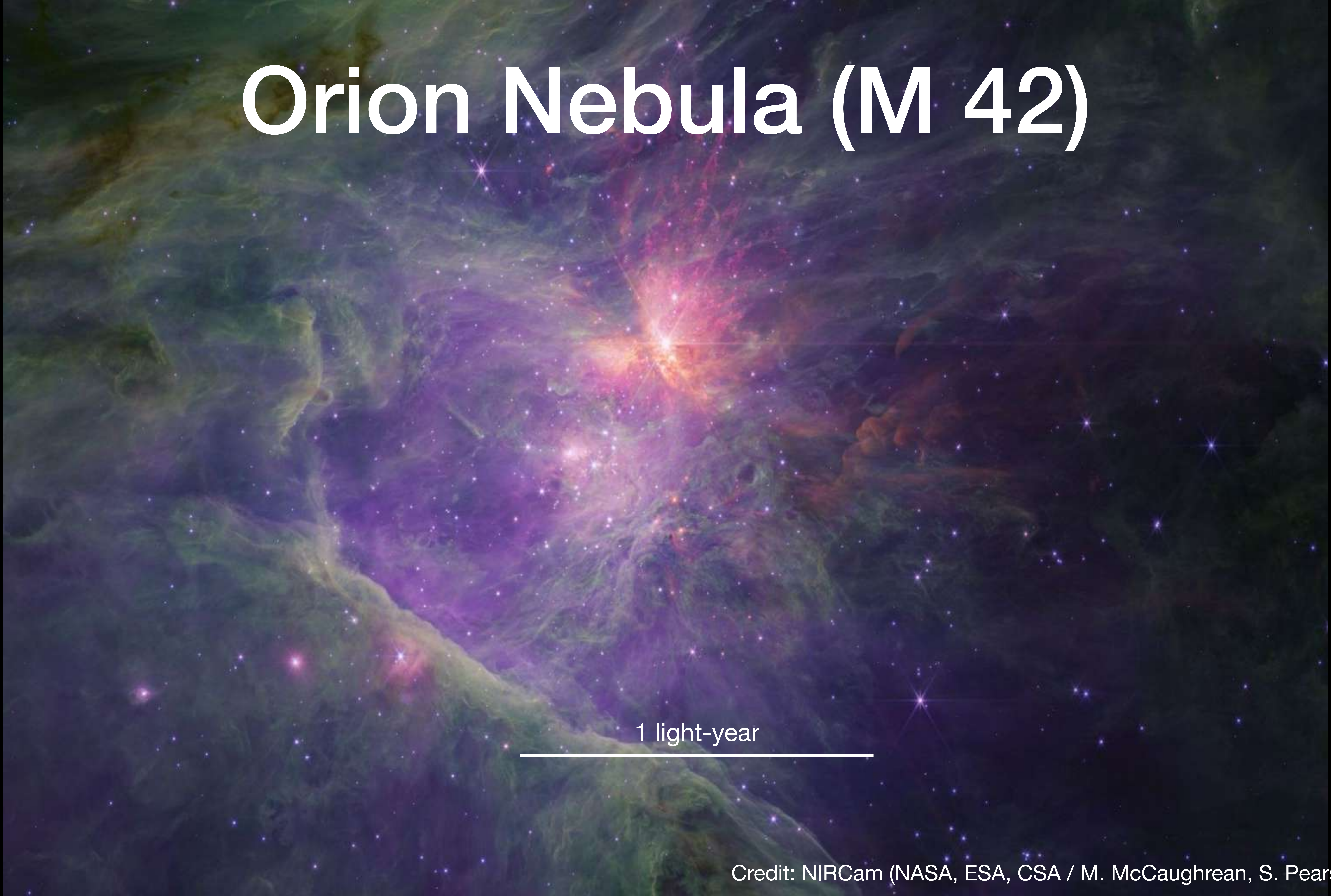
Planet Formation and Exoplanets:

From Dust to Planets

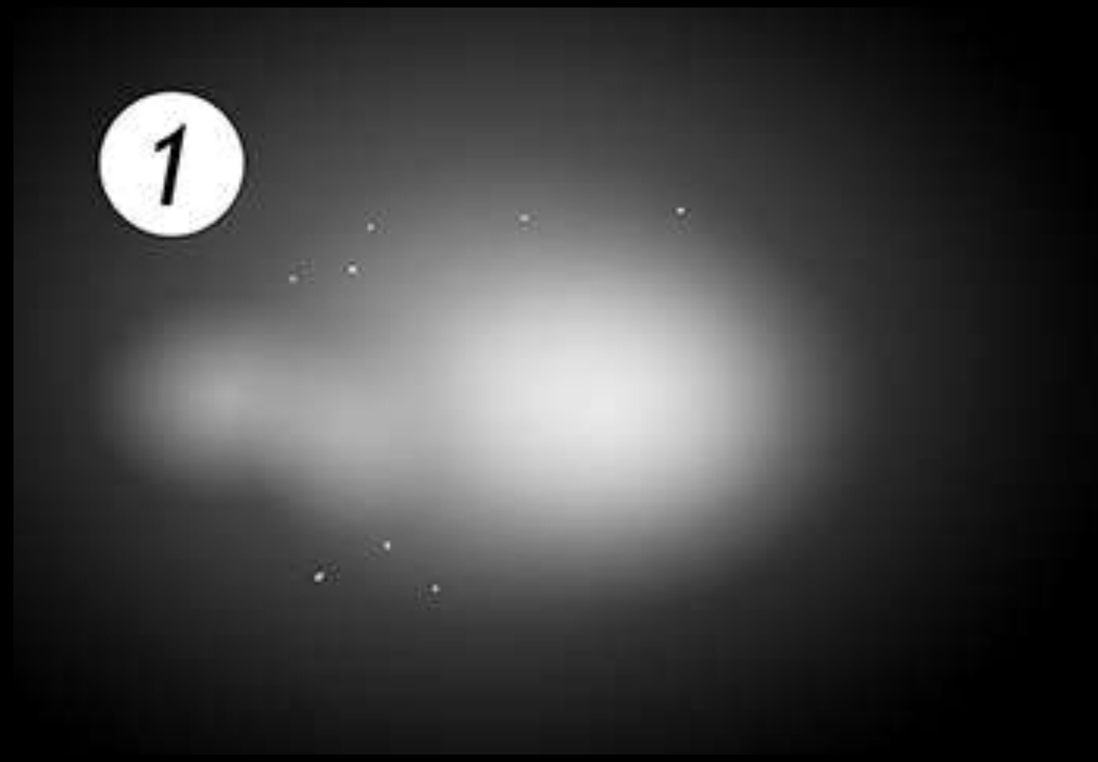
Shang-Min Tsai
ASIAA

Orion Nebula (M 42)

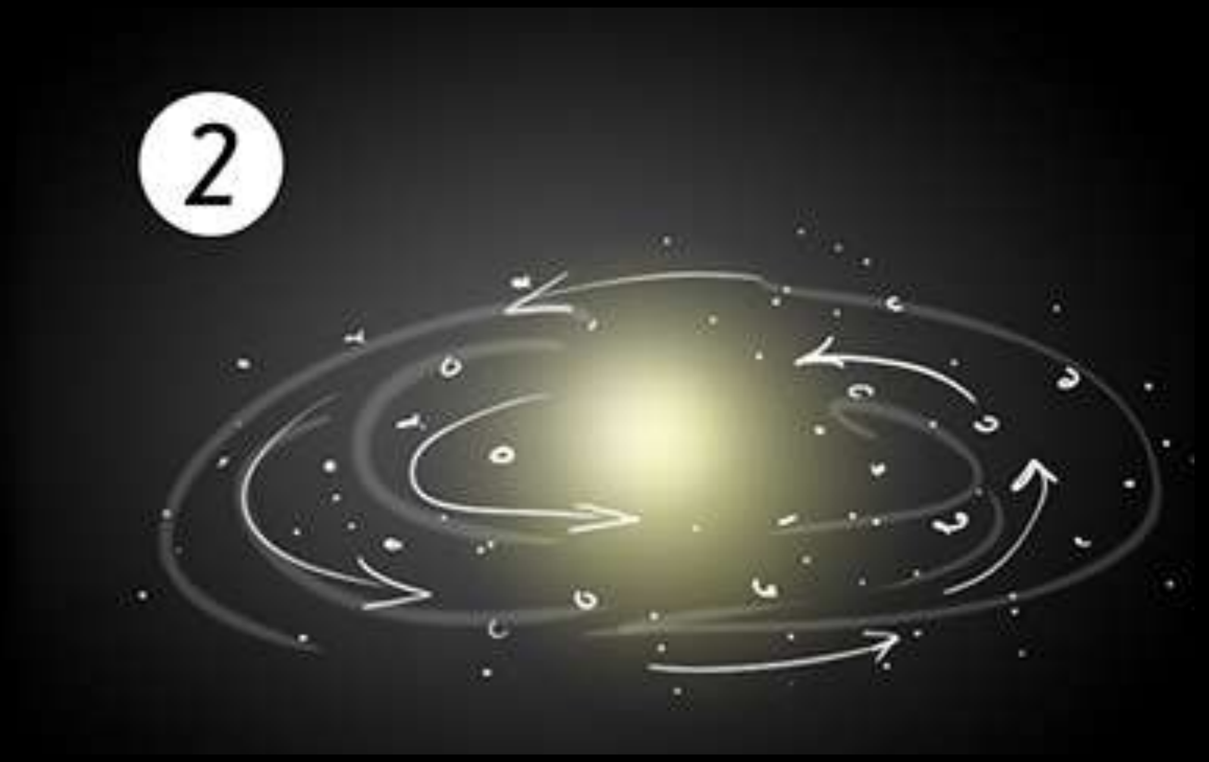


Credit: NIRCam (NASA, ESA, CSA / M. McCaughrean, S. Pearson)

The Nebular Hypothesis (Kant 1755)
— the origin story of Solar System



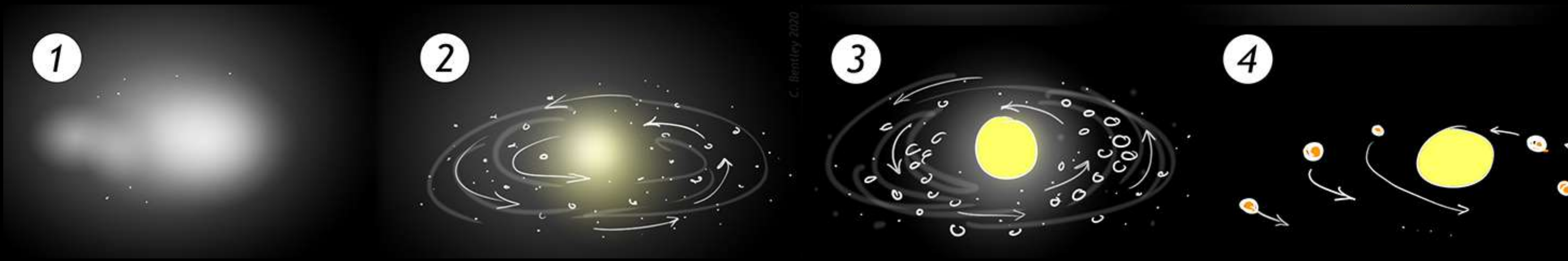
Nebula
(99% gas and 1% dust)



Proto-Sun formed
Flattening of nebula

The Nebular Hypothesis (Kant 1755)
— the origin story of Solar System

from pizza dough to pepperoni pizza



Nebula
(99% gas and 1% dust)

Proto-Sun formed
Flattening of nebula

The residual gas and dust
clump together (planetesimals)

Planets accreted from
planetesimals

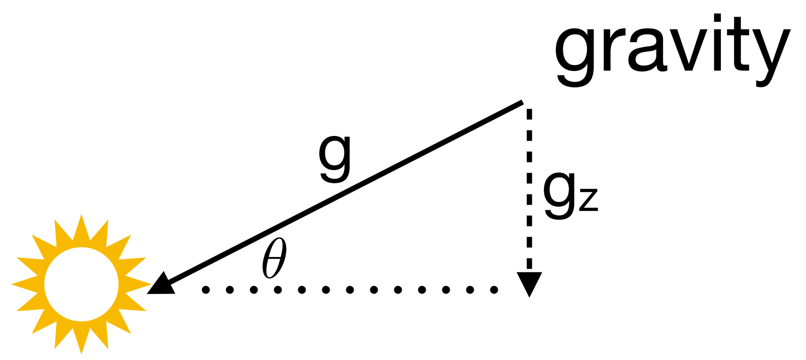
(co-planar in Solar System)

Disk structure

from observations

- **Various observation windows**
- **Truncation by photoevaporation and magnetic field**
- **Flaring geometry**

flaring geometry



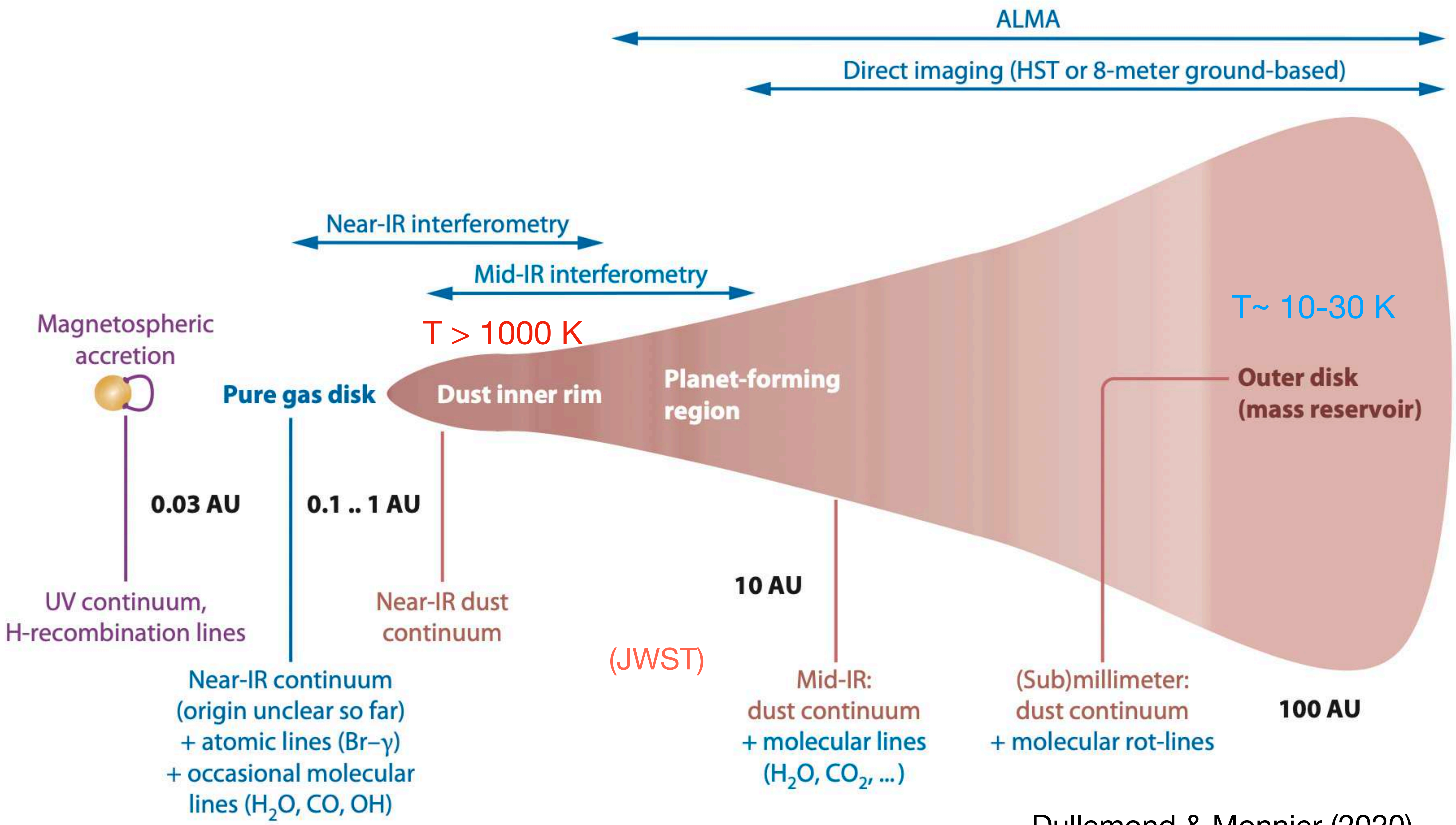
$$\frac{1}{\rho}\frac{\partial P}{\partial z} = -\frac{GM}{r^2}\left(\frac{z}{r}\right) = -\Omega^2 z$$

P gradient　　z-gravity　　angular velocity

$$P = \rho c_s^2$$ (c_s: sound speed)

density scale height: $H = \dfrac{c_s}{\Omega}$

So H increases with decreasing Ω
increasing r



Dullemond & Monnier (2020)

Mass of the disk
—Minimum Mass Solar Nebula (MMSN)

(Weidenschilling 1977)

- Can we reconstruct the disk based on the **refractory materials** (rock and metal) we see in the Solar System today?

- The giant plants dominate the mass of the planetary system: Total of giant planets' core mass ~ 0.2 $M_{Jupiter}$

- The key ingredient in the estimate is the dust to gas ratio:

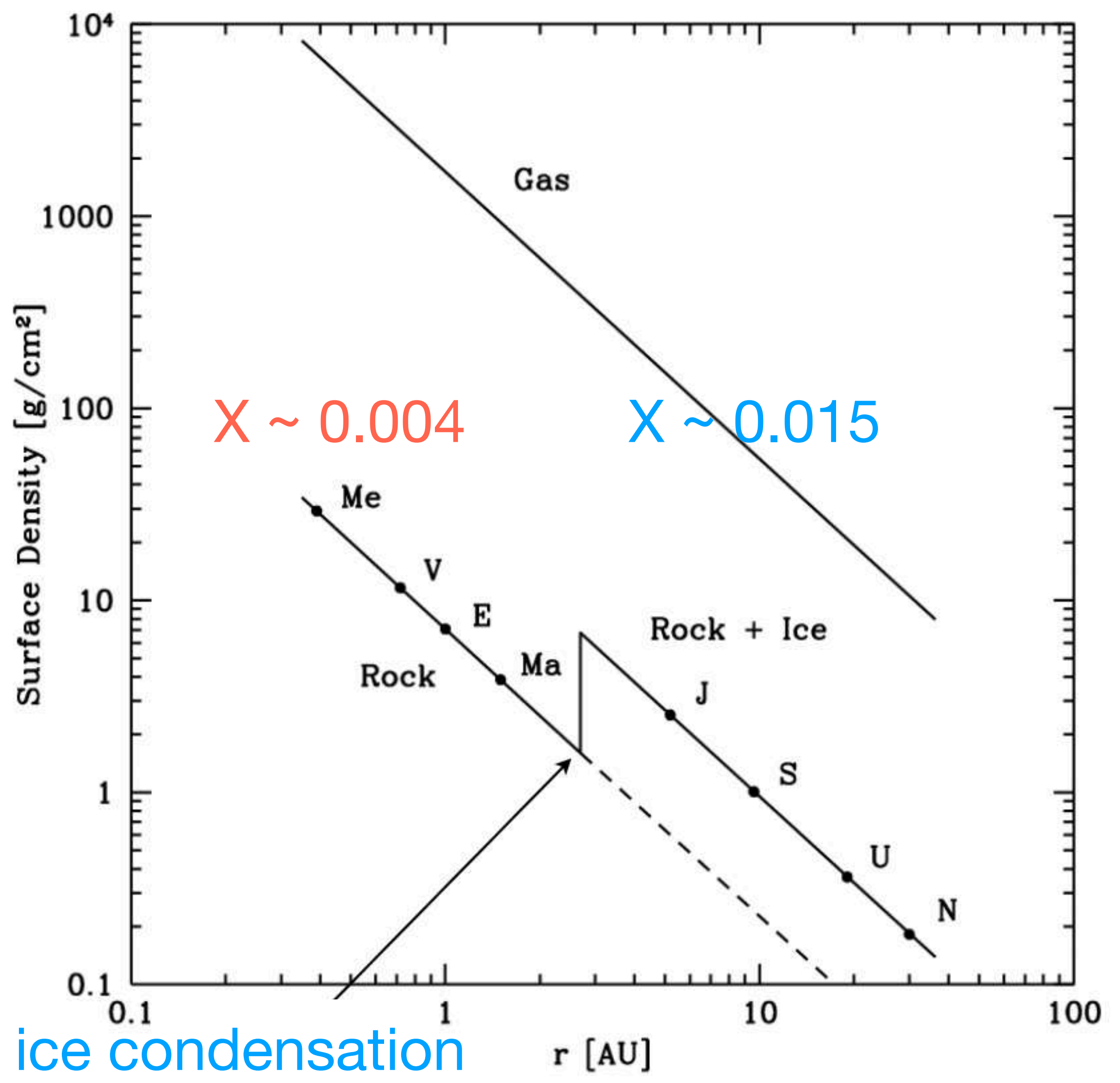
(mm)

$$x = \frac{\text{mass of dust}}{\text{mass of gas}}$$

line emission (CO)

- For x = 0.01, MMSN ~ 20 $M_{Jupiter}$ or ~ 0.02 $M_\odot$

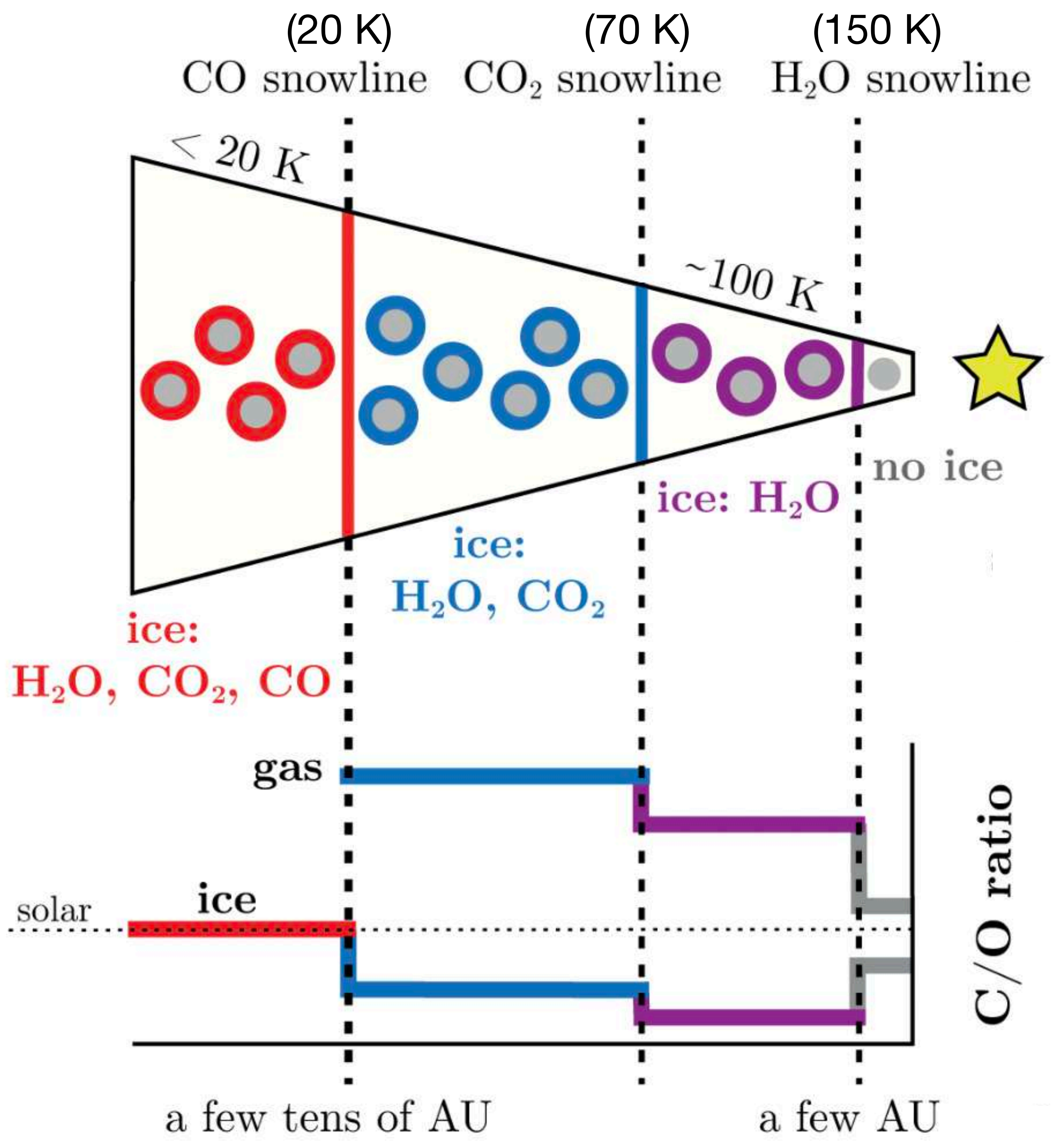
In reality, x depends on T or the distance from the Sun:



Ruden (1999)

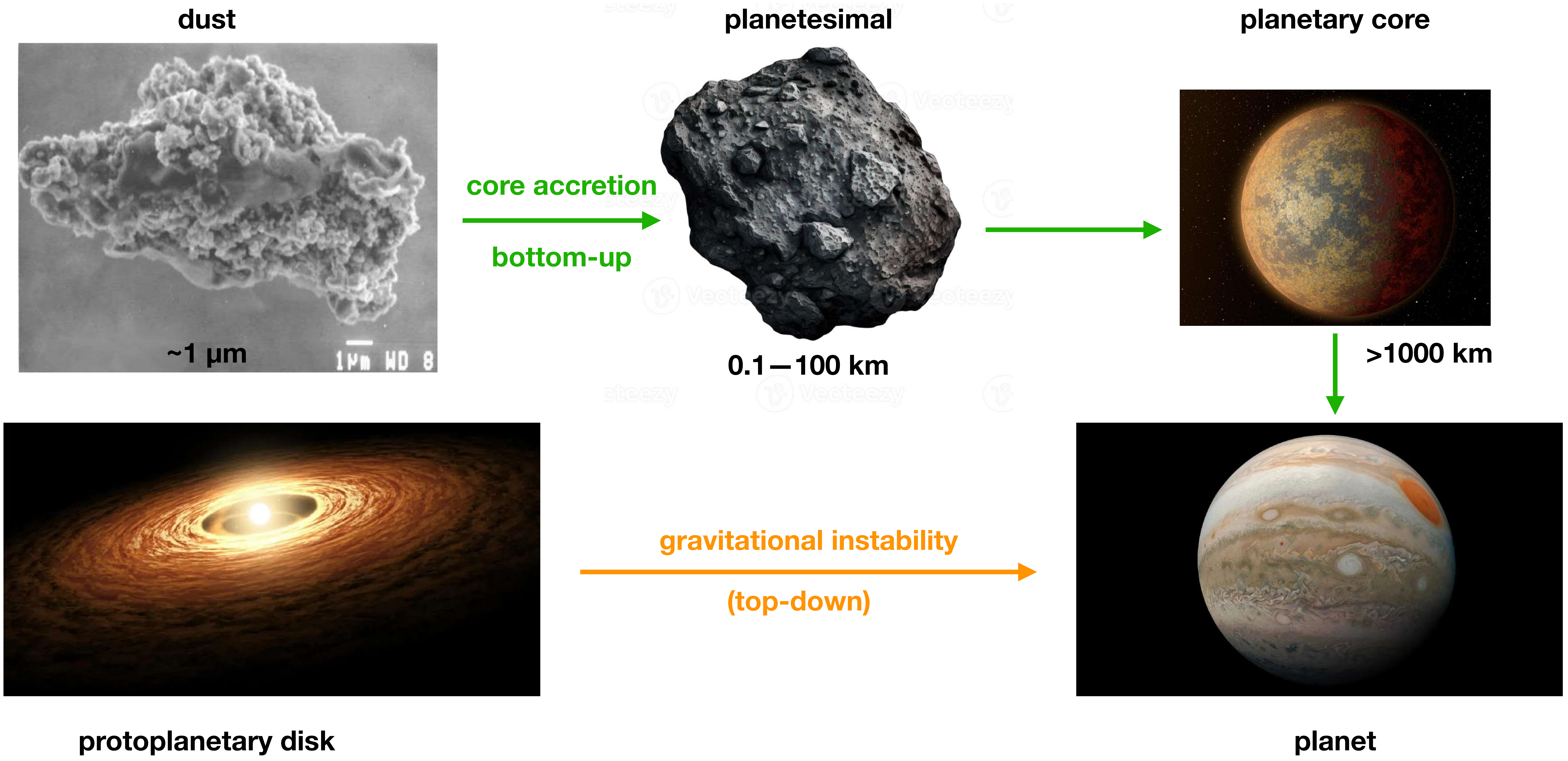
Disk Chemistry

- Determining what raw materials are available for planet formation
- Tracing back the formation history of the planets



Credit: Merel van't Hoff

Planet Formation



Core Accretion

- Predictions:
  — Jupiter has a massive core
  — metal rich stars have more gas giants

- Challenges:
  — early models suggested that the formation timescale of Jupiter > τ_{disk}
  — dust to planetesimals growth not fully understood
  — challenging to form giant planets at large orbits (>~ 20 AU)

Gravitational Instability

$$Q = \frac{c_s \Omega}{\pi G \Sigma} \sim \frac{H}{r} \frac{M*}{M_{disk}}$$

(Toomer 1964)

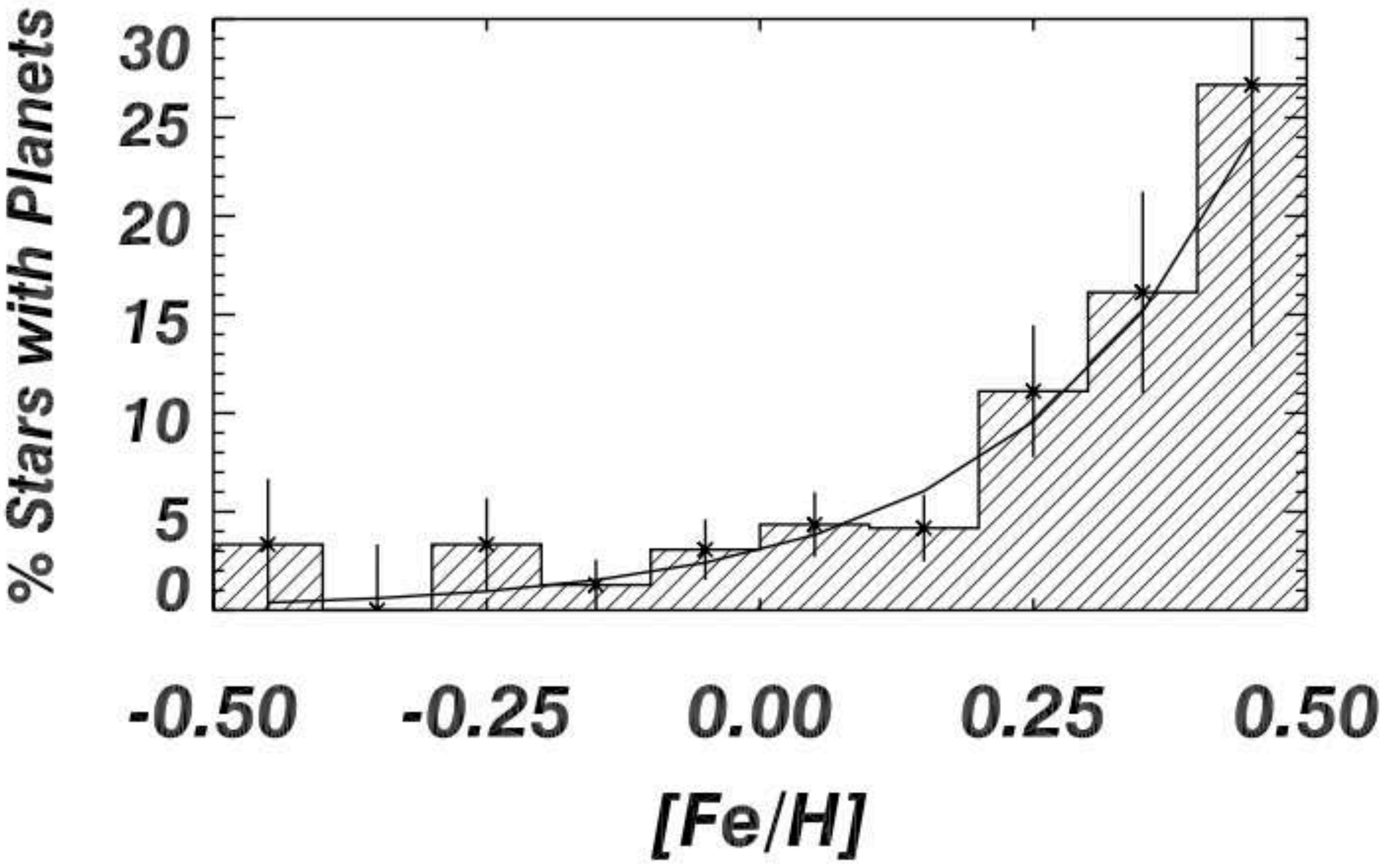
$Q \lesssim 1$, unstable

H/ r ~ 0.1 for a typical disk
so M* / M_{disk} needs to be ~ 10

- Predictions:
  — Jupiter has no or a low-mass core
  — metal rich stars should ***not*** have more gas giants
  (low metallicity cool faster)

- Challenges:
  — challenging to form giant planets at closer orbits (<~ 20 AU)
  — Requires massive disks (~0.1 M*), which might be rare

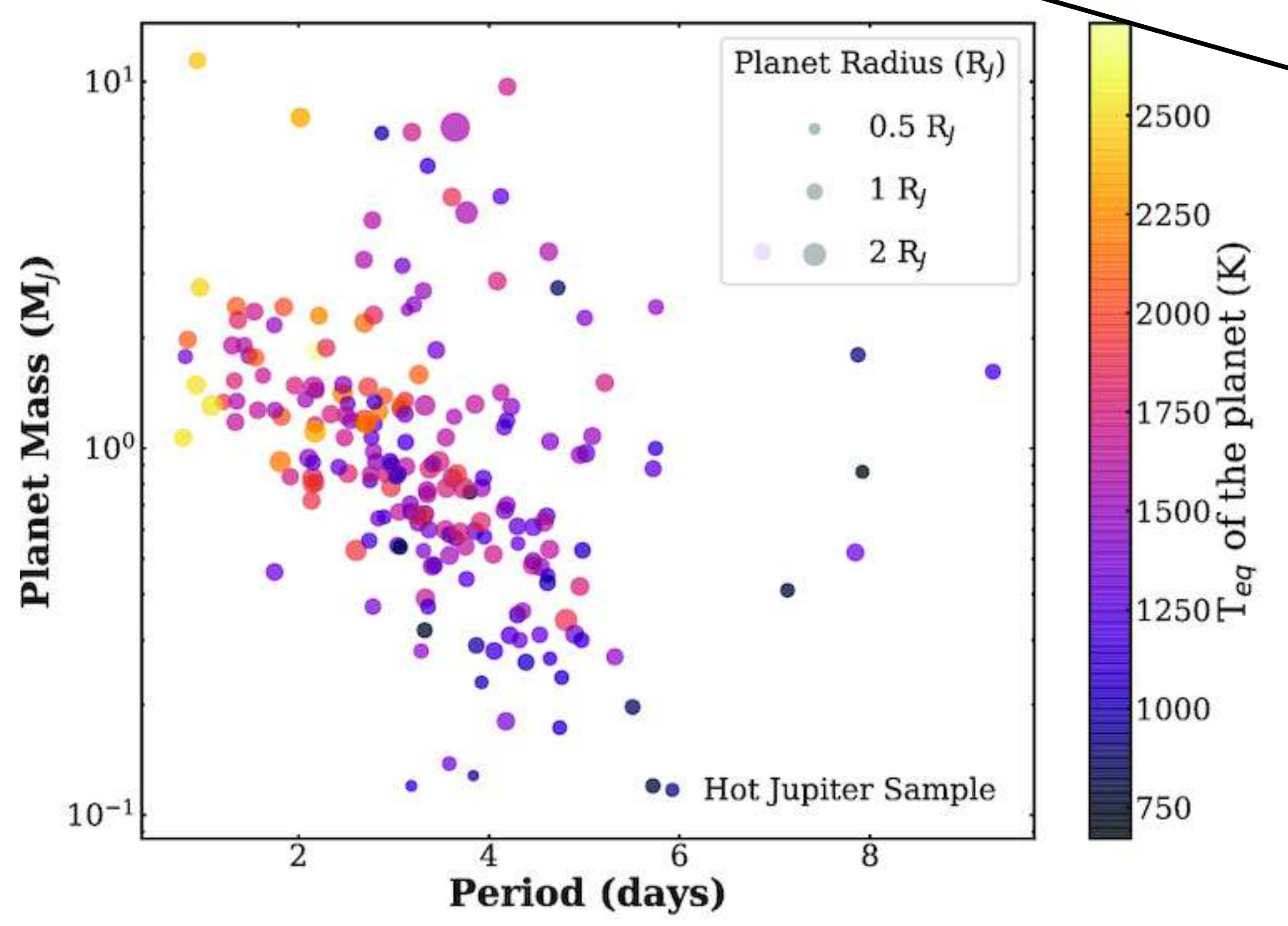
Metal rich stars have more gas giants

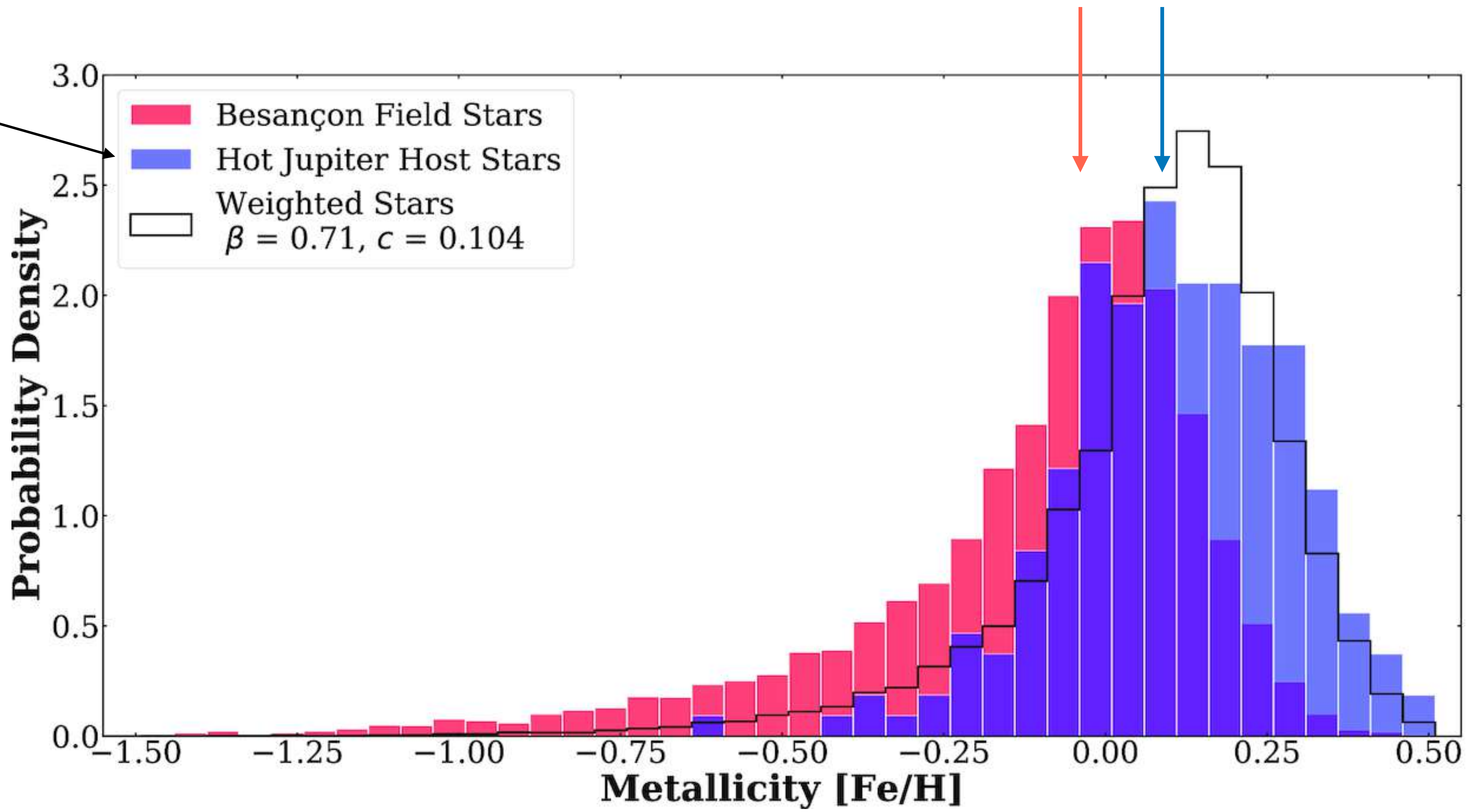


Valenti & Fischer (2005)

Metal rich stars have more gas giants

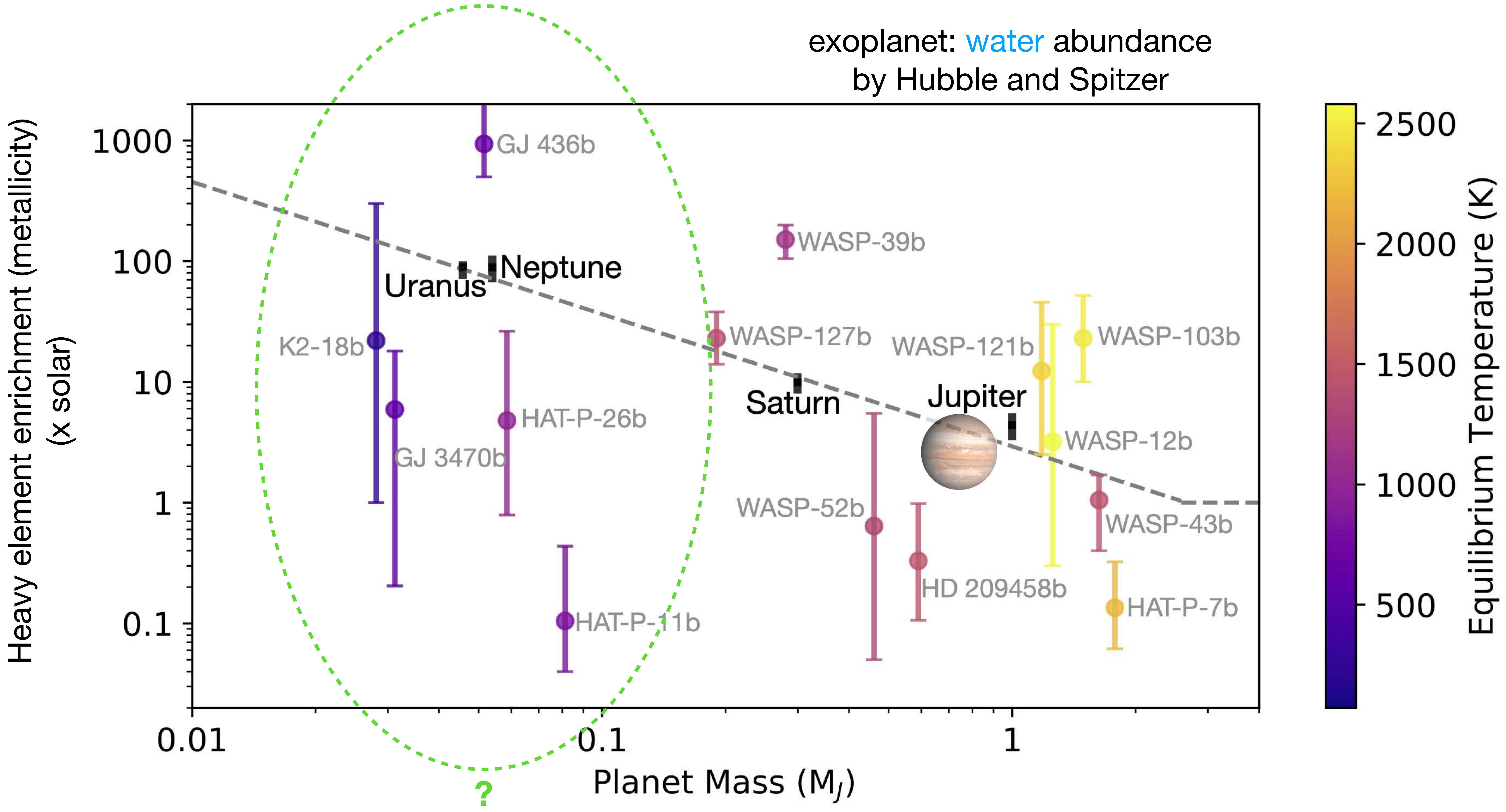
217 Hot Jupiter targets





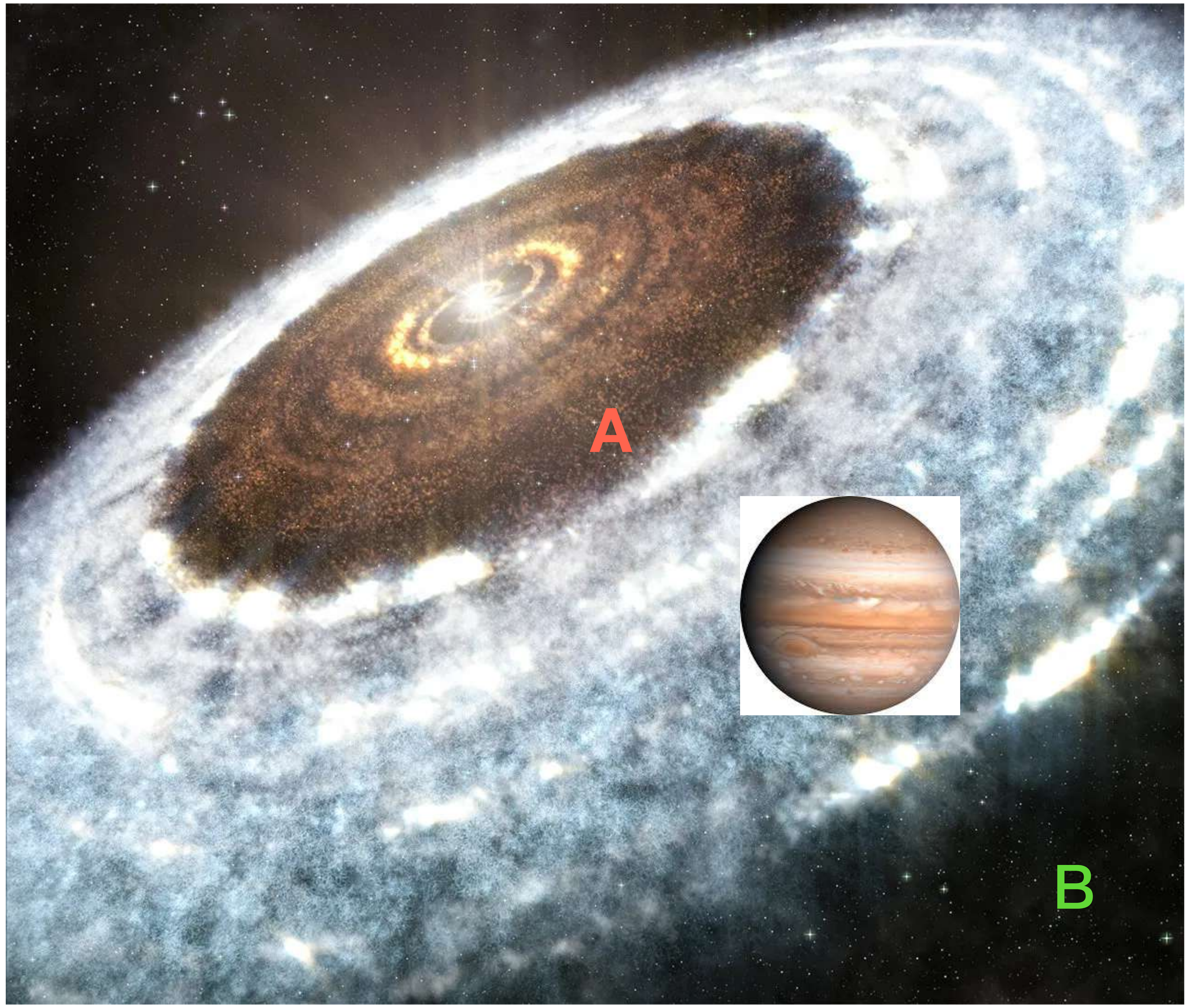
Osborn & Bayliss (2019)

More massive planets have less heavy elements?



Wakeford & Dalba (2020)

Planet Formation: Location, Location, Location!



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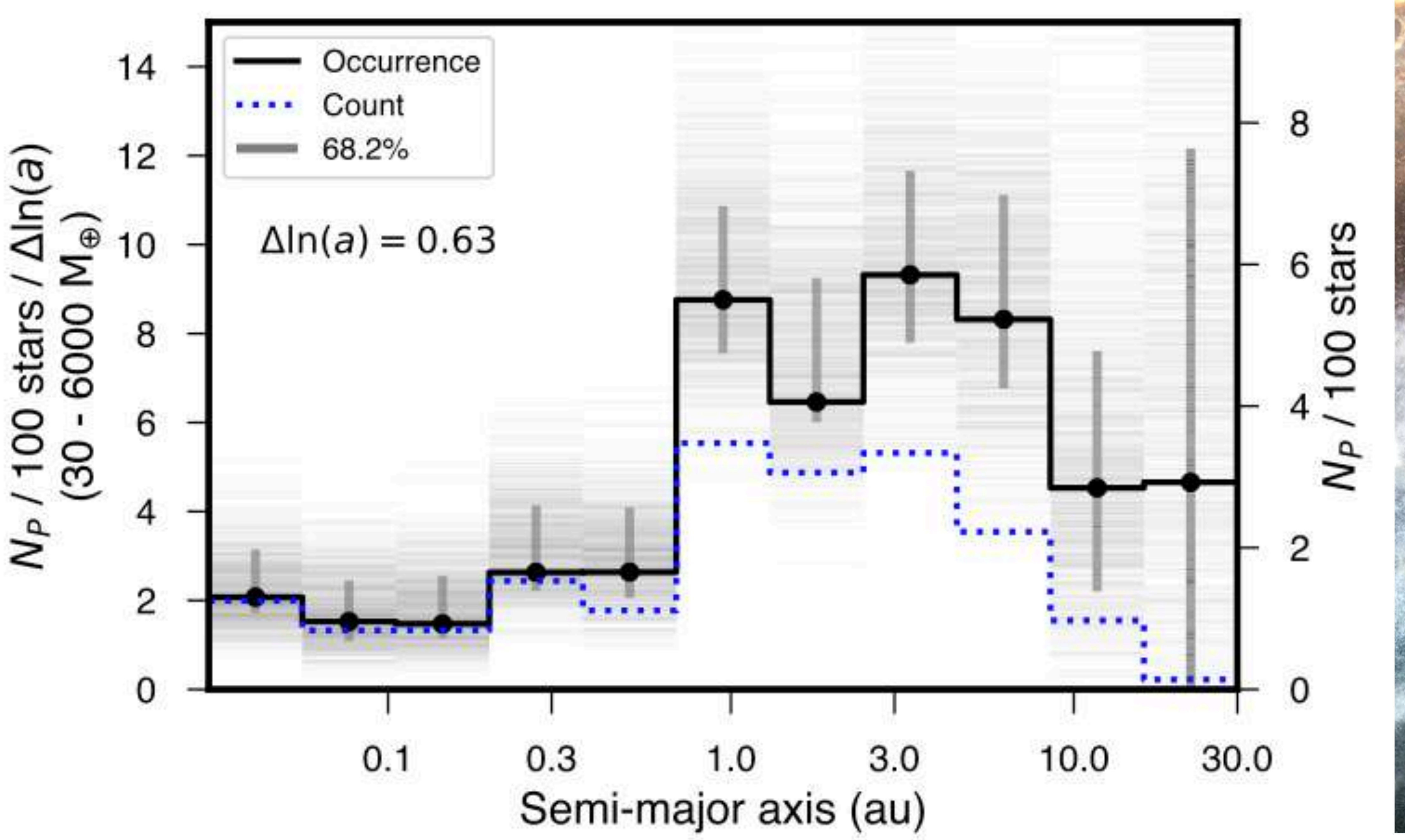
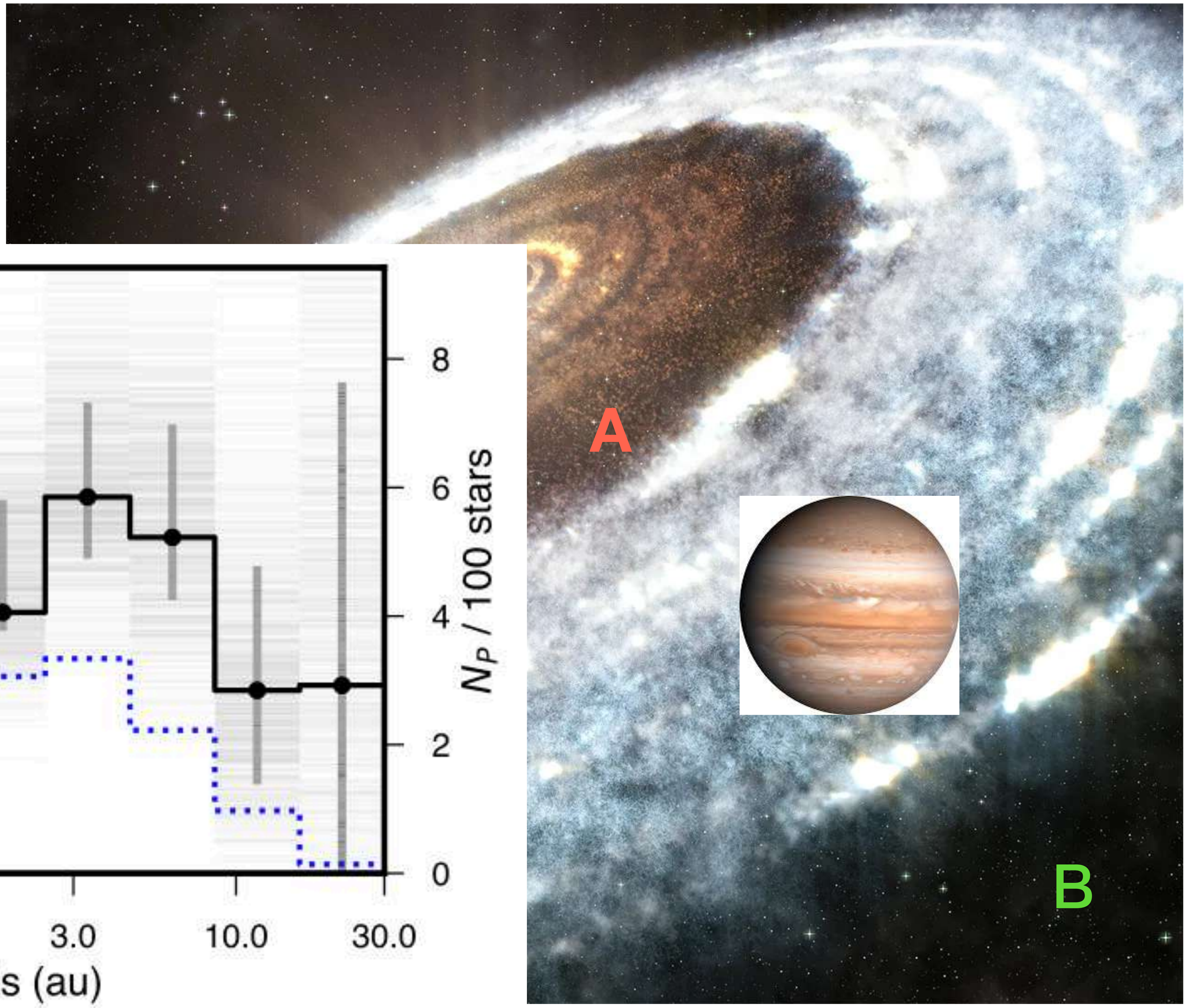
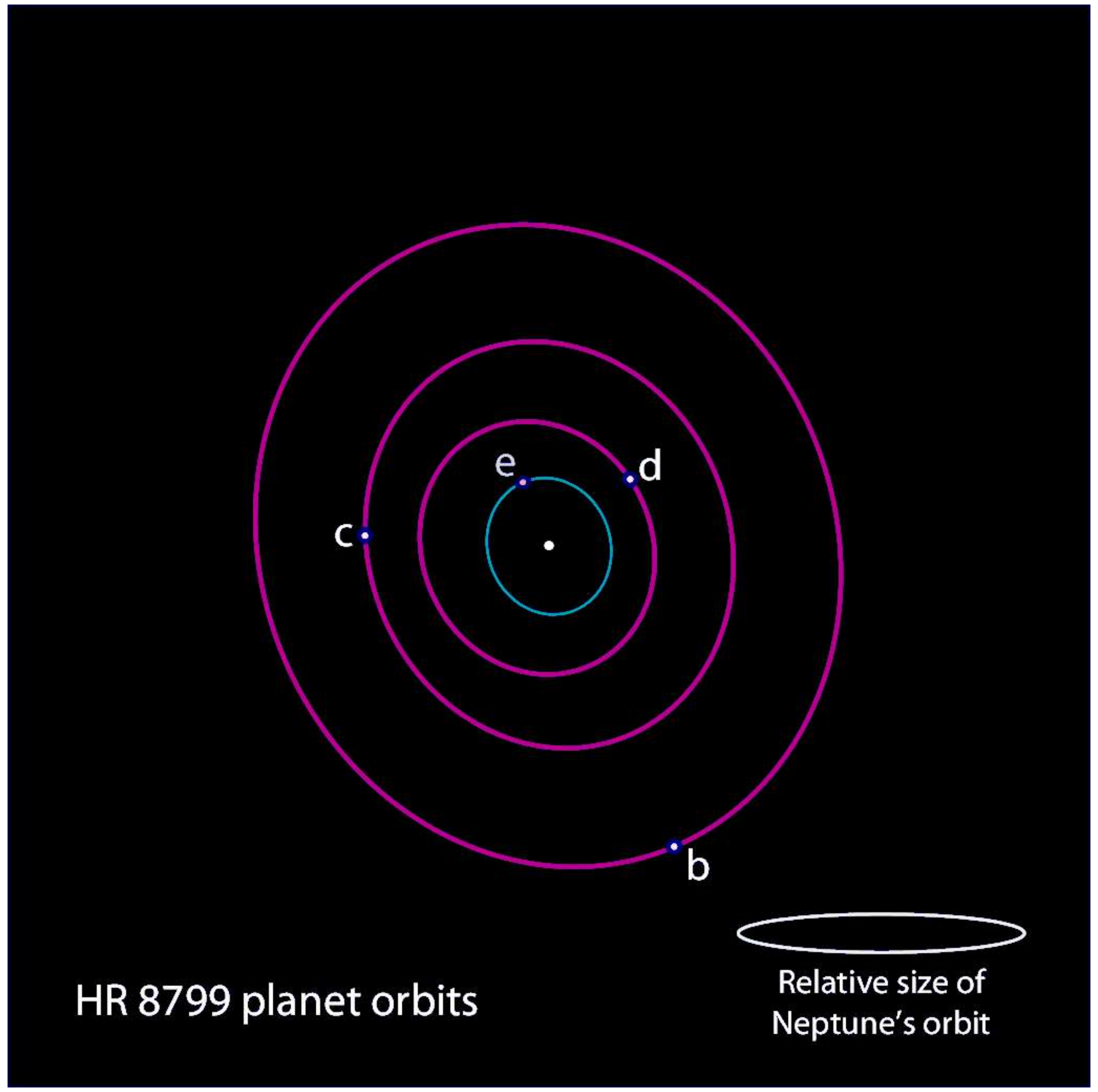


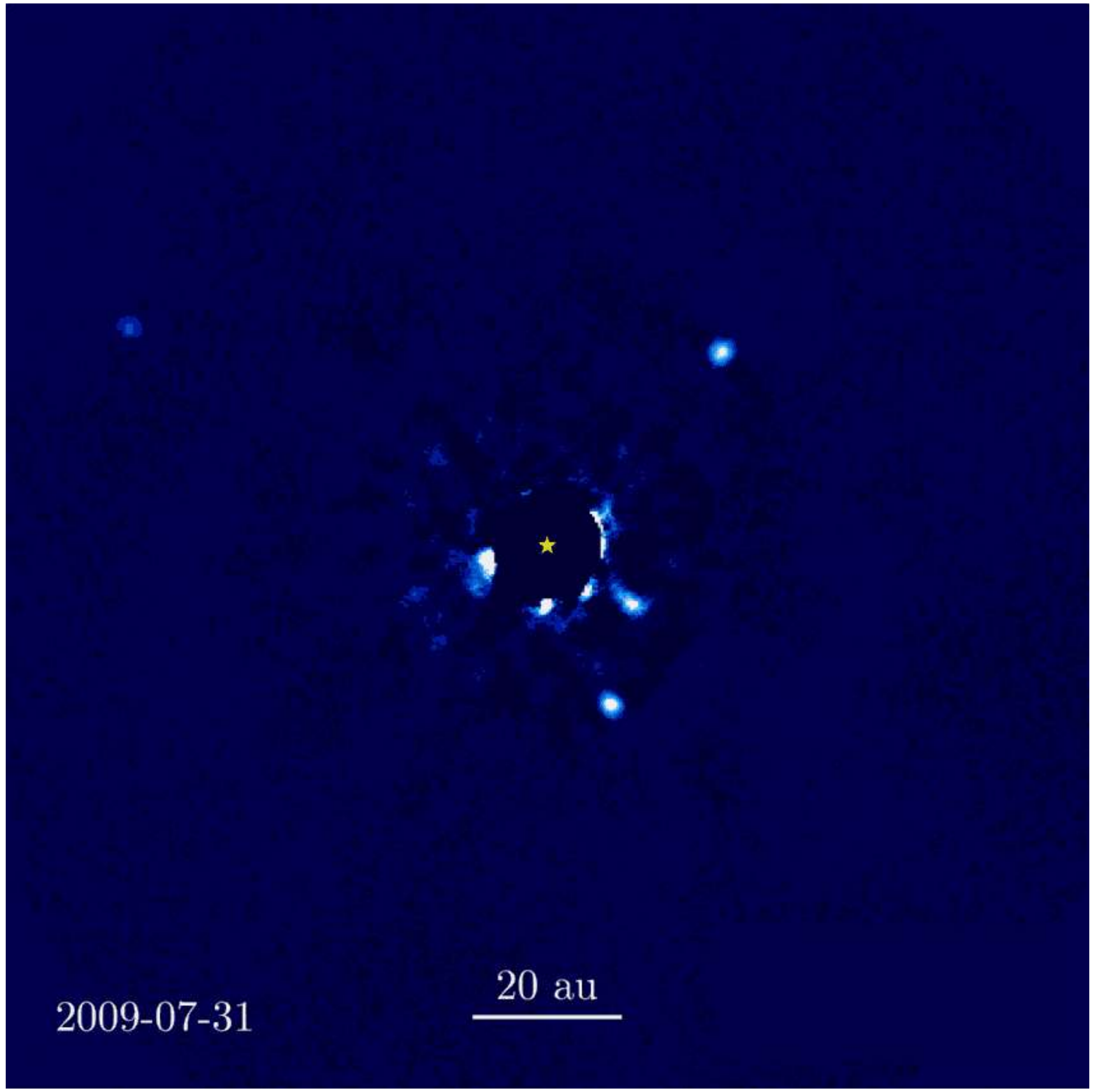


Fulton et al. (2021)

HR 8799

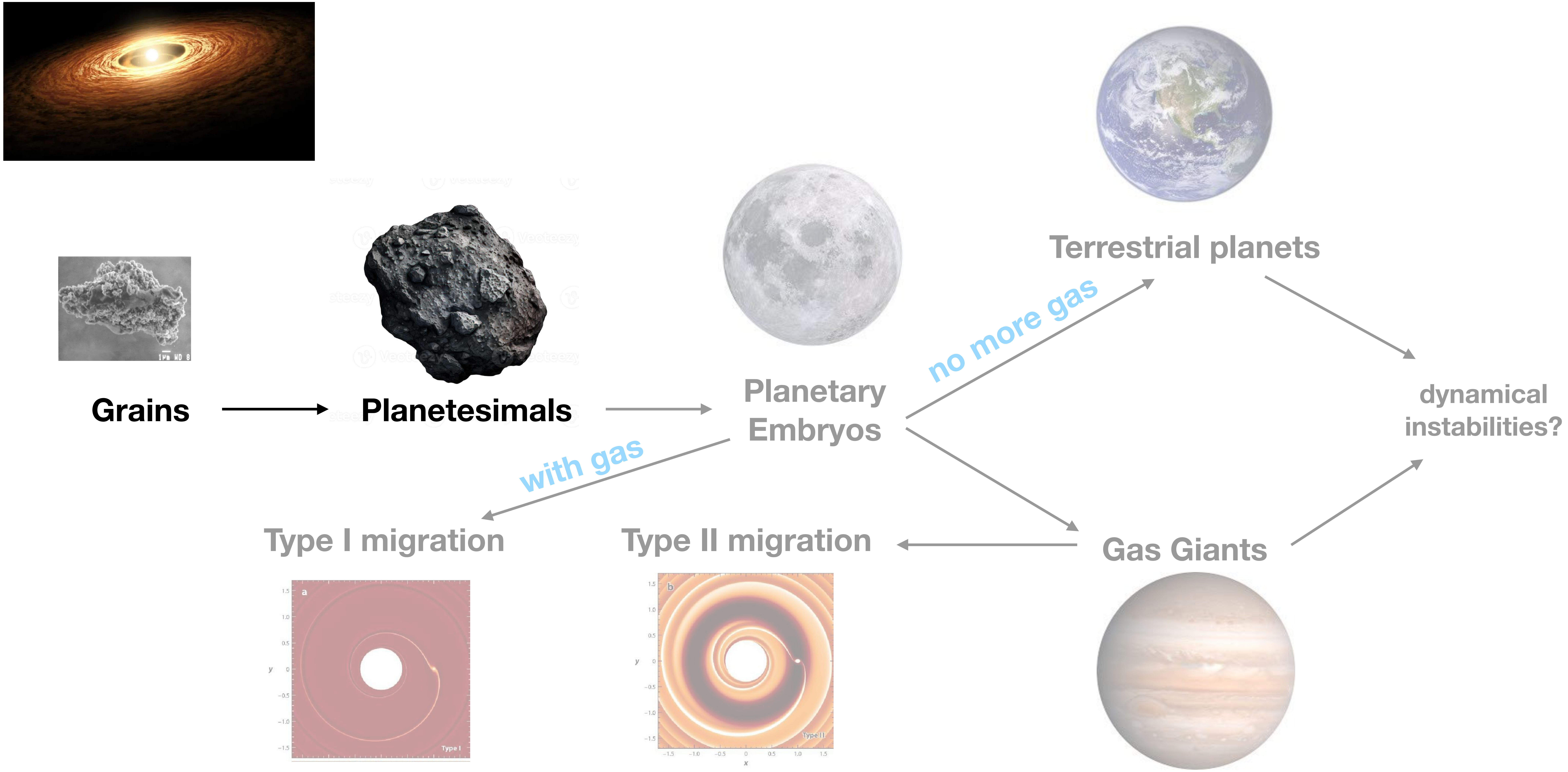
— by core accretion or gravitational instability?





Keck Observatory

Stage of Planet Formation



From dust to planetesimals

~μm

~km

- As disk cools, silicate and iron compounds first condense to small grains

- Dust particles (μm) are smaller than the **mean free path** of gas molecules (~cm):

$$\text{Knudsen number} : \frac{\lambda}{R} \qquad \lambda : \text{mean free path } R : \text{particle size}$$

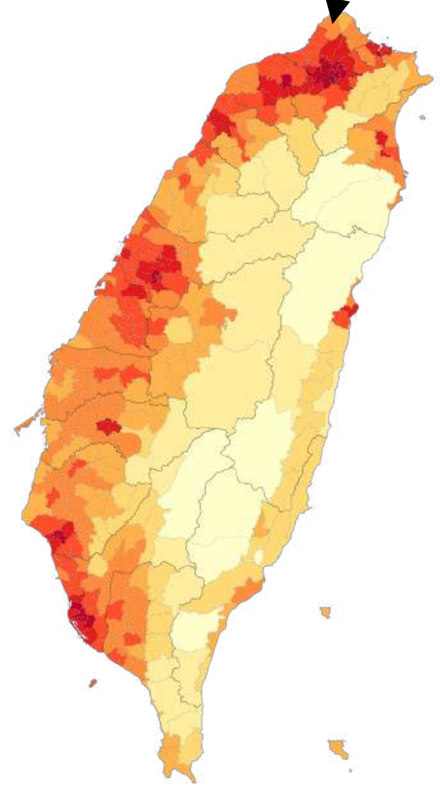
- For $\frac{\lambda}{R} \ll 1$ (fluid regime), $F_{\text{drag}} = \frac{1}{2} C_d \rho \pi R^2 v^2$ (Stokes drag)

- For small particles in a disk, $\frac{\lambda}{R} \gg 1$ (particle regime), Epstein drag applies:

$$F_{\text{drag}} = \frac{4}{3} \pi R^2 \rho_{gas} v_{th} v$$

which is **linear** in *v*

thermal velocity of gas



Dust and gas interact via drag

- Stopping time: $ts = \frac{m_{dust} v}{F_{\mathrm{drag}}}$ — gas-dust coupling timescale

inserting the Epstein drag: $t_s = \frac{m_{dust} v R}{m_{gas} v_{th} v} = \frac{\rho_{dust}}{\rho_{gas}} \frac{R}{v_{th}}$

Dust and gas interact via drag

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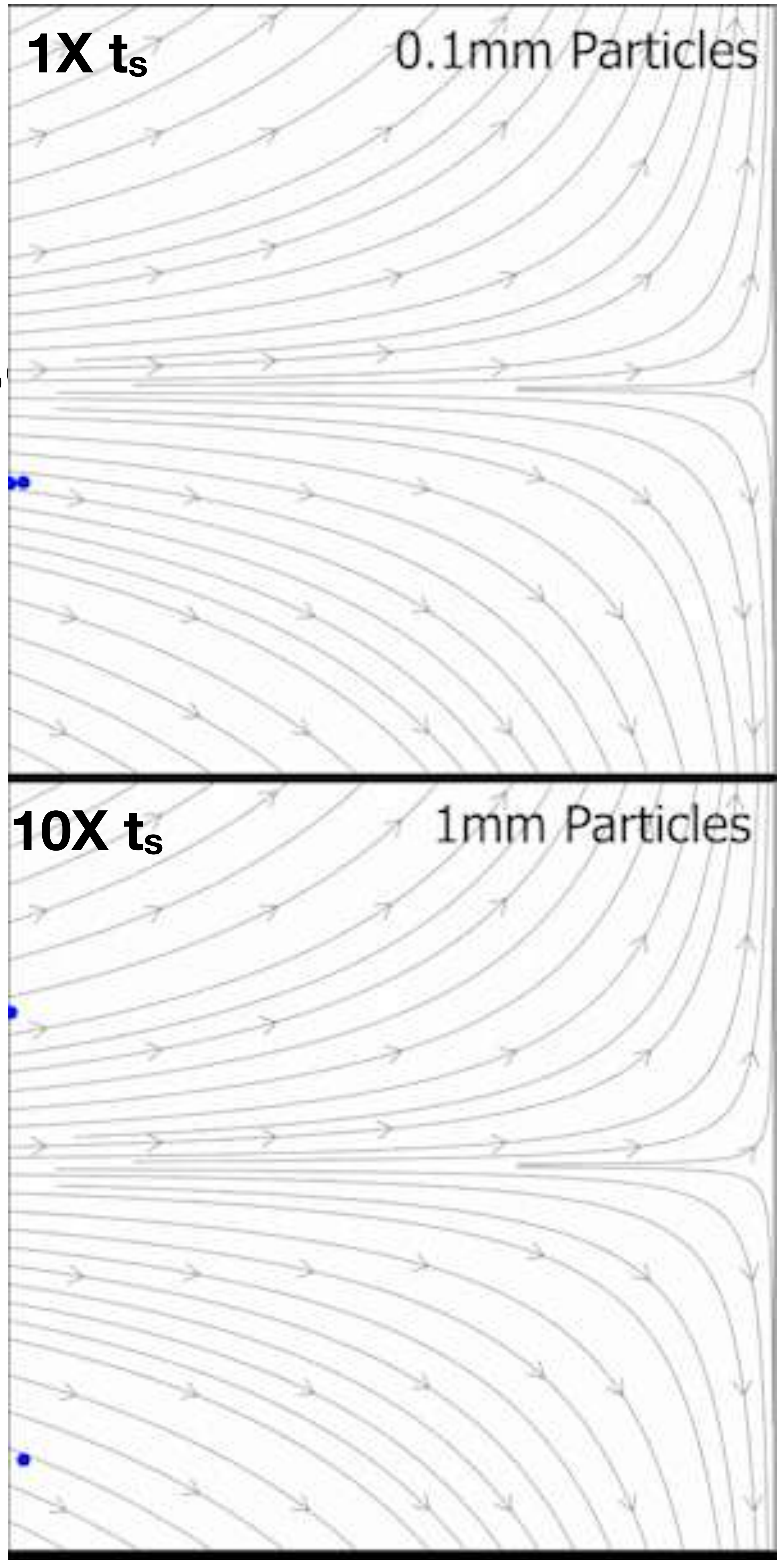
inserting the Epstein drag: $t_s = \frac{m_{dust} v R}{m_{gas} v_{th} v} = \frac{\rho_{dust}}{\rho_{gas}} \frac{R}{v_{th}}$

- Typical properties:

$$\rho_{dust} = 3 \text{ g/cm}^3 \quad \rho_{gas} = 10^{-9} \text{ g/cm}^3 \quad v_{th} = 2.5 \times 10^5 \text{cm}/s$$

For R = 1 m, $t_s \sim 10^6 s$

For R = 1 um, $ts \sim 1s$ µm-sized particles in a disk are well coupled to the gas!



Wiki: Stokes number

Coagulation (growth by collision)

- Two-body collisions can lead to growth (coagulation) and destruction (fragmentation)

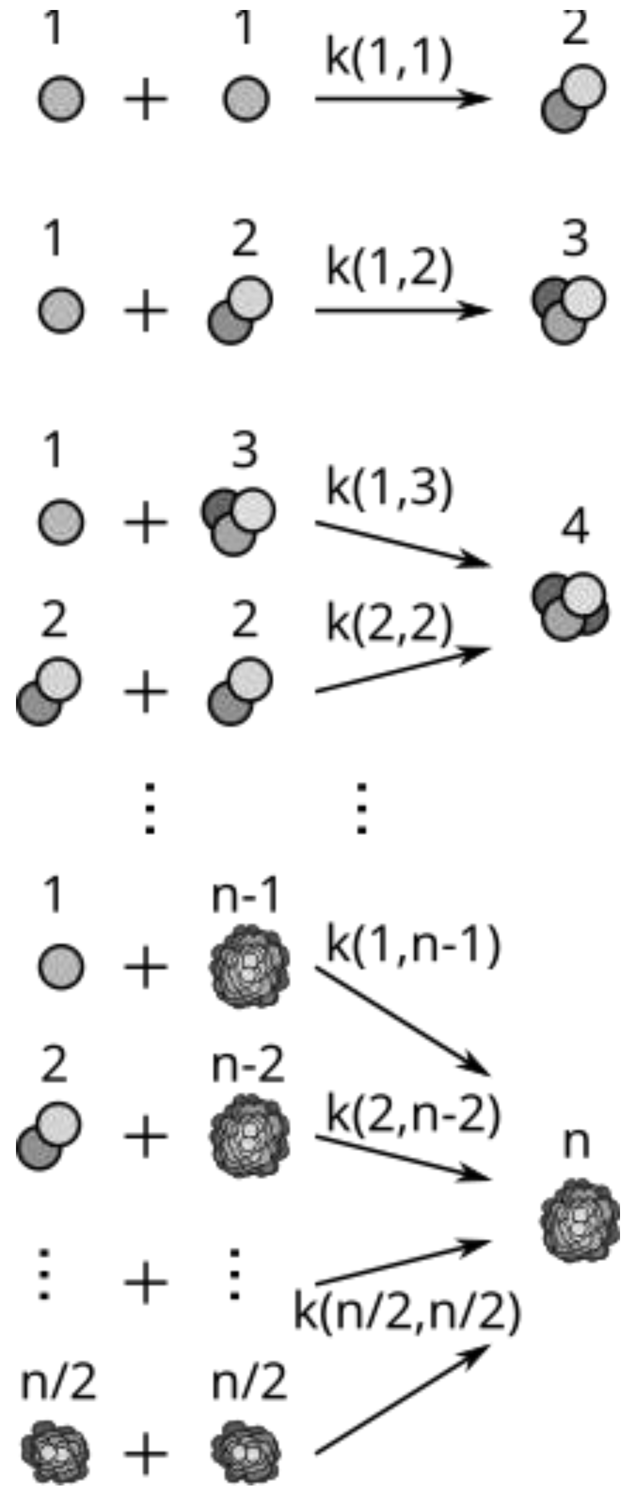
- Coagulation equation (Smoluchowski 1916):

$$\frac{\partial n_k}{\partial t} = \frac{1}{2}\sum_{i+j=k} K_{ij} n_i n_j - n_k \sum_{i=1}^{\infty} K_{ki} n_i$$

(neglecting fragmentation)

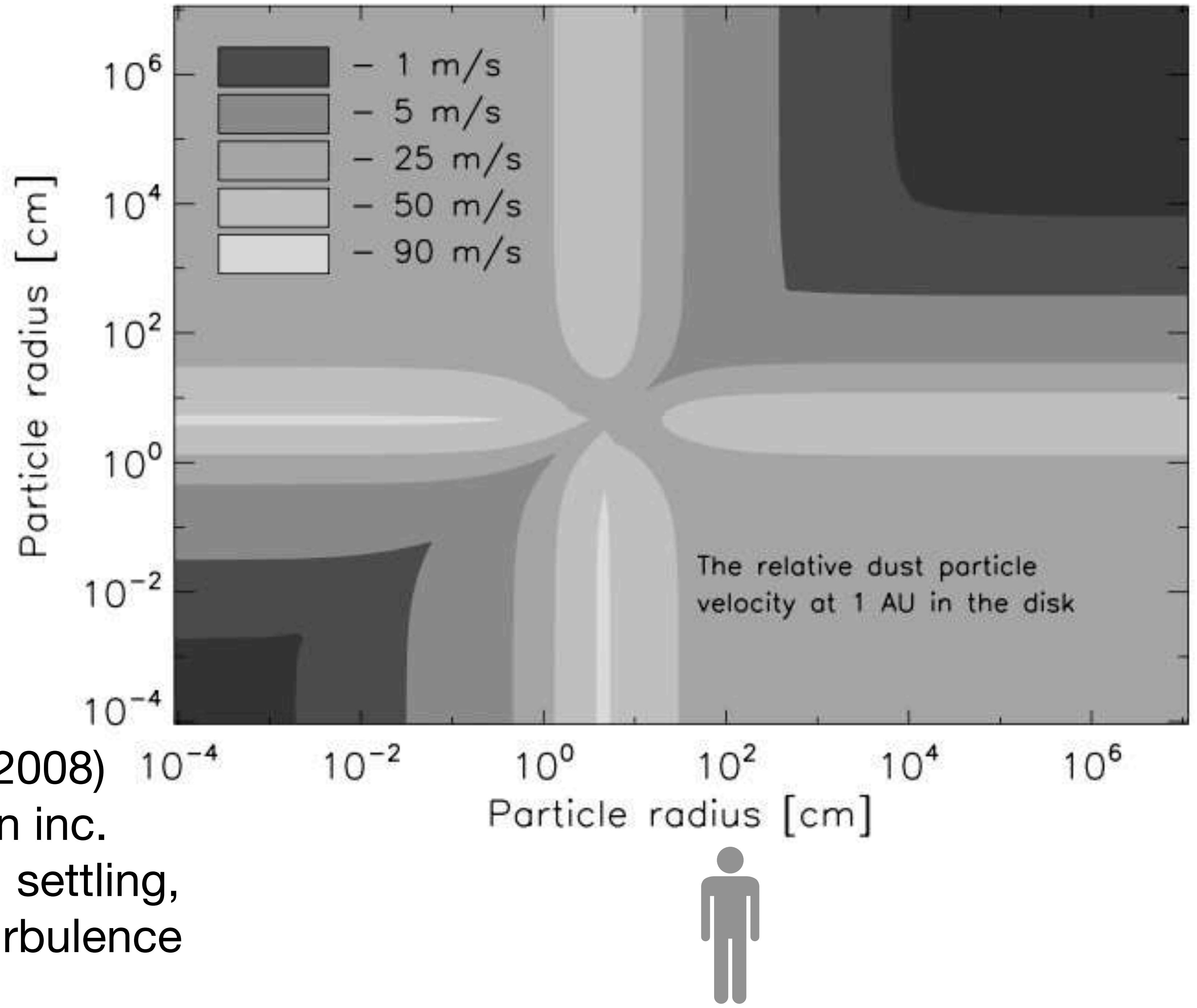
K_{ij} : interaction kernel between particles of mass i and j

depends on composition, structure, collision velocity, geometry, … etc.
typically determined by lab experiments



- Numerical models (Brauer et al. 2008; based on experiments) show that μm-sized particles can grow into cm-sized particles by coagulation within ~10^4 yrs, also consistent with the settling timescale

Meter-size barrier: Fragmentation barrier



Brauer et al (2008)
disk simulation inc.
Brownian motion, settling,
radial drift, and turbulence

- Small particles are tightly coupled to the gas. The relative velocity is dominated by Brownian motion ($\sim v_{th}$, small)
- For intermediate sizes (10–100 cm), relative velocities can become very high primarily due to to turbulence
- Large bodies are decoupled from the gas and less influenced by turbulence (lower surface-mass ratio)

Blum et al.(2014)

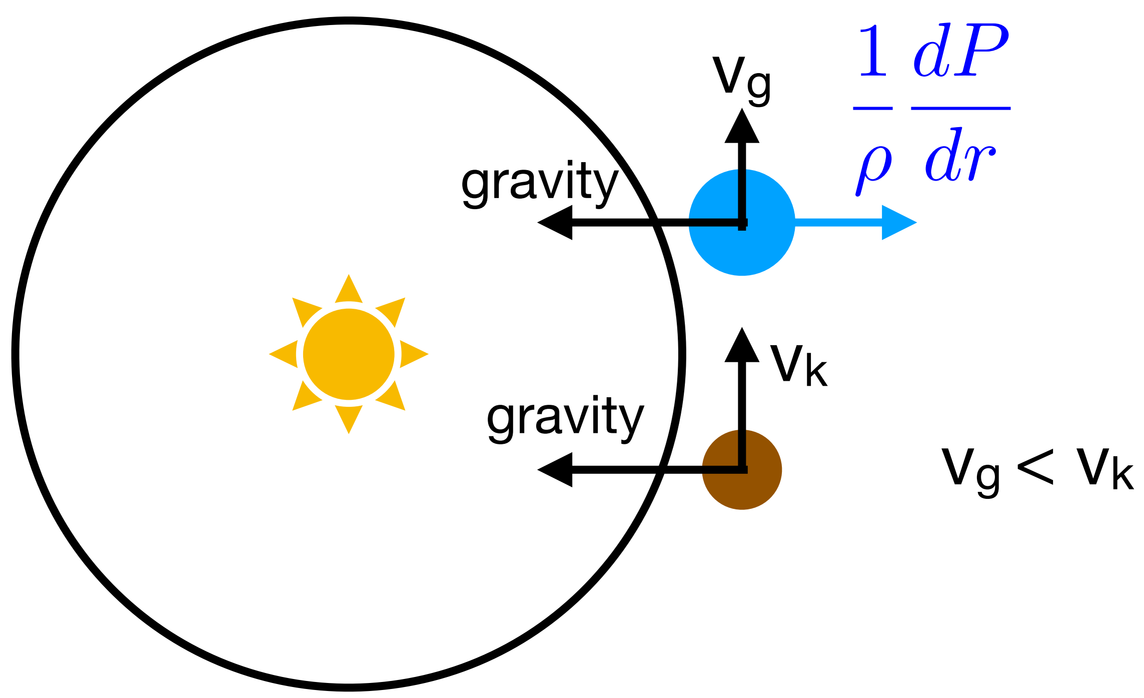
- Experiments show that for silicates, fragmentation starts from v ~ 1 m/s
- For water ice, fragmentation start from v ~ 10 m/s
- Therefore, particles with sizes 0.1-1 m do not stick, instead, they shatter in collisions

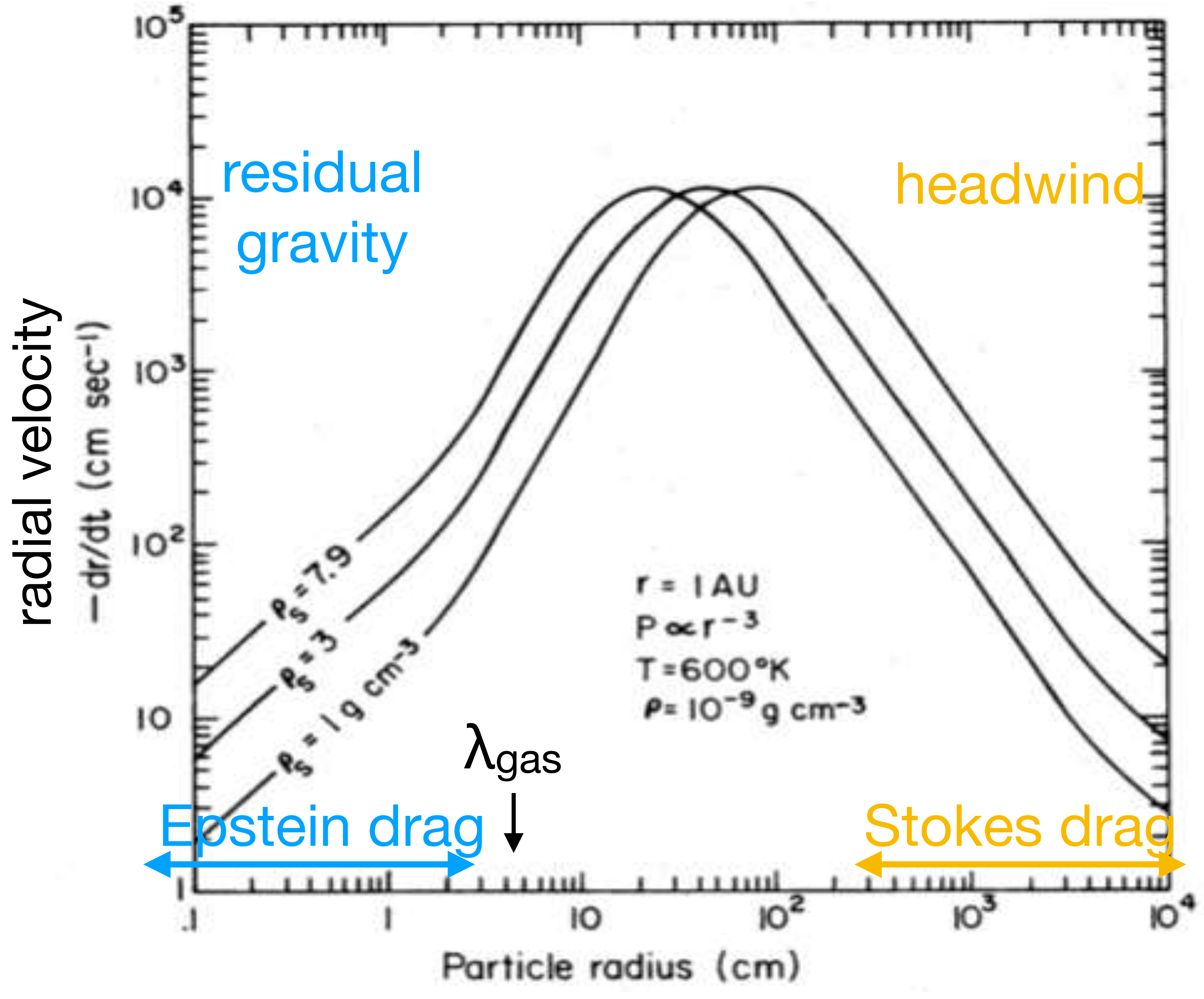
Meter-size barrier: Drift barrier

- The source of the radial drift for particles **not fully coupled** to the gas: gas moves in sub-Keplerian speed

- centrifugal balance for solids: $$\frac{v_k^2}{r} = \frac{GM}{r^2} \quad (v_k\text{: Keplerian speed})$$

- centrifugal balance for gas: $$\frac{v_g^2}{r} = \frac{GM}{r^2} + \underbrace{\frac{1}{\rho}\frac{dP}{dr}}_{<0} < \frac{v_k^2}{r}$$





Weidenschilling 1977

- Tiny particles are strongly coupled to gas and pulled inward by the small residual component of stellar gravity

- Large bodies experience a "headwind" and have their orbits decayed
But very large particles have enough inertia

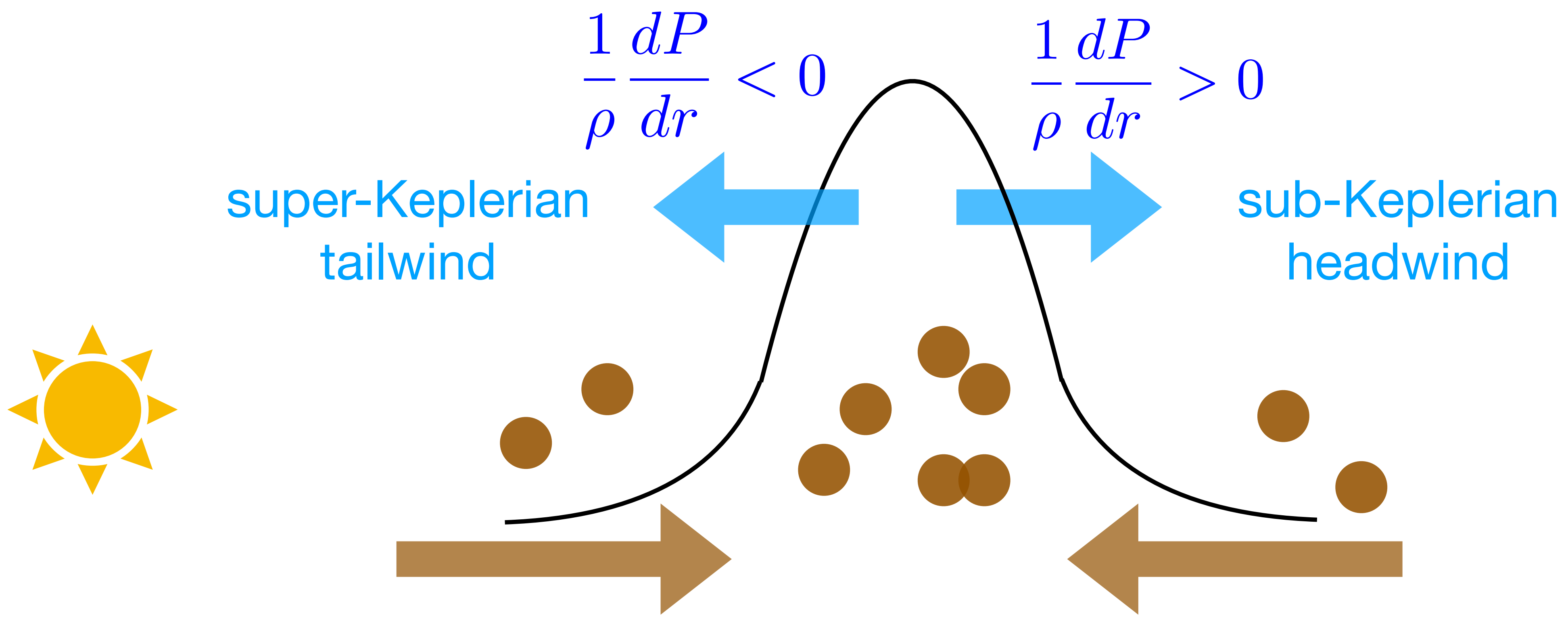
- The radial velocity reaches a peak at the transition between these two regimes, at sizes of ~ meter

- Meter-sized bodies have inward velocity ~ 100 m/s. They go towards the star from 1 AU within ~ 100 yrs

Processes to overcome the meter size barrier

— by concentrating dust particles

- Long-lived pressure bumps
  (by instabilities, vortices, sublimation, etc.)



dust particles are piled up at pressure bumps

- Streaming instability

— particles increase their own concentration via **feedback** on the gas:

Processes to overcome the meter size barrier

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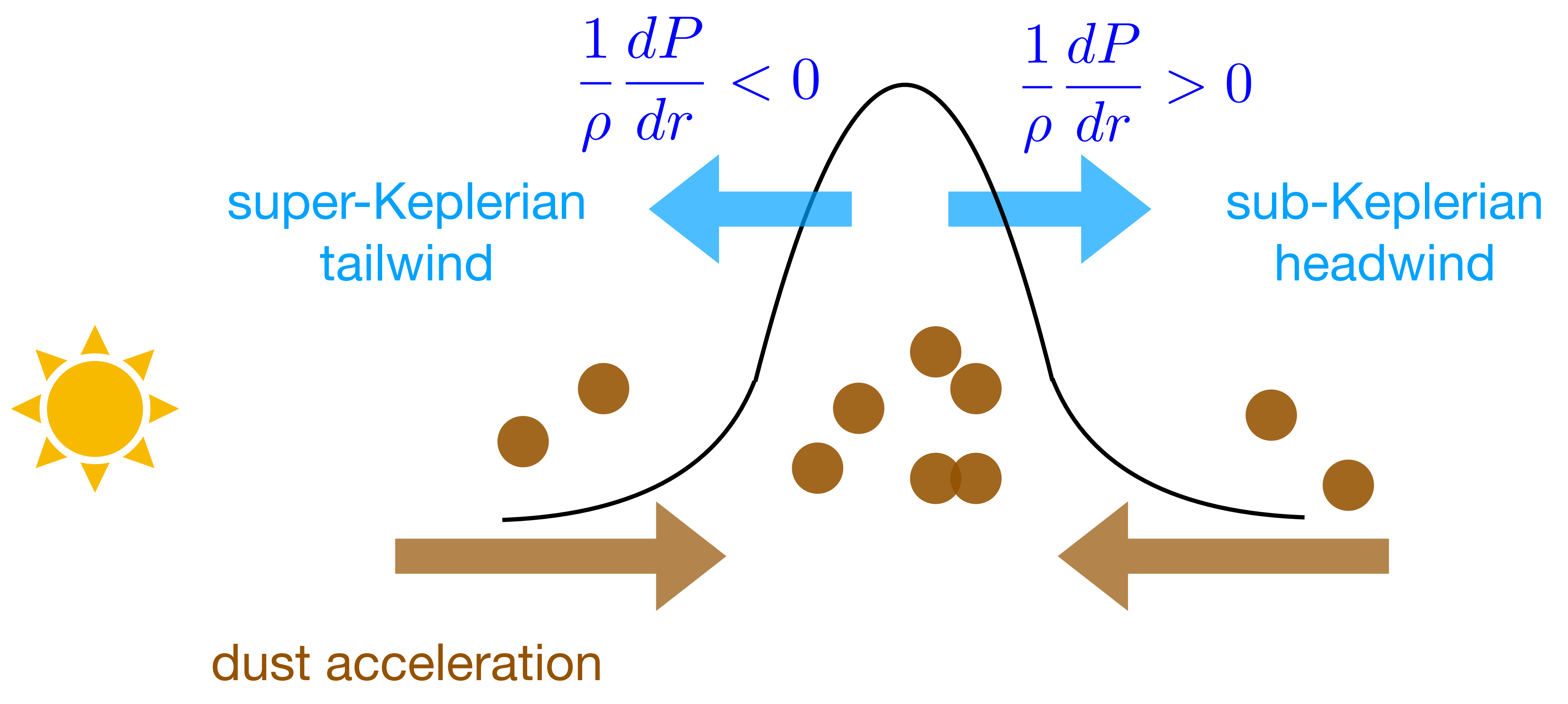
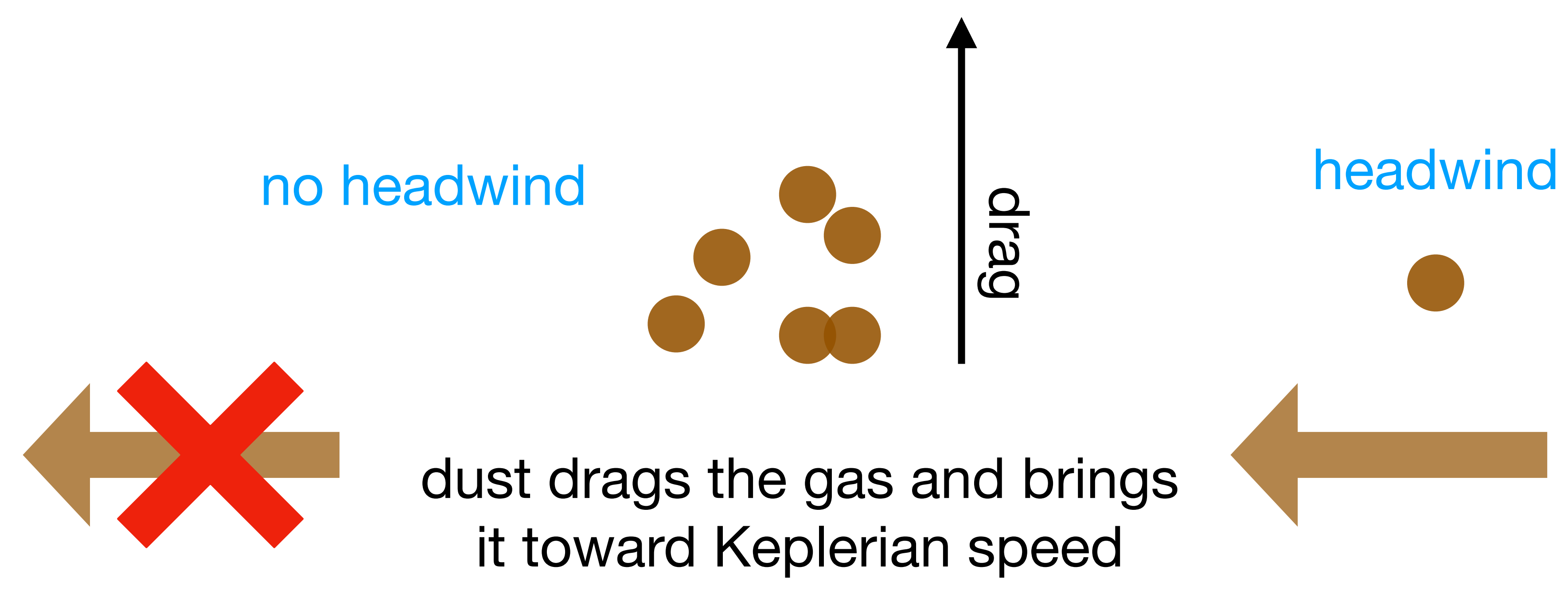


dust particles are piled up at pressure bumps

- Streaming instability

— particles increase their own concentration via **feedback** on the gas:

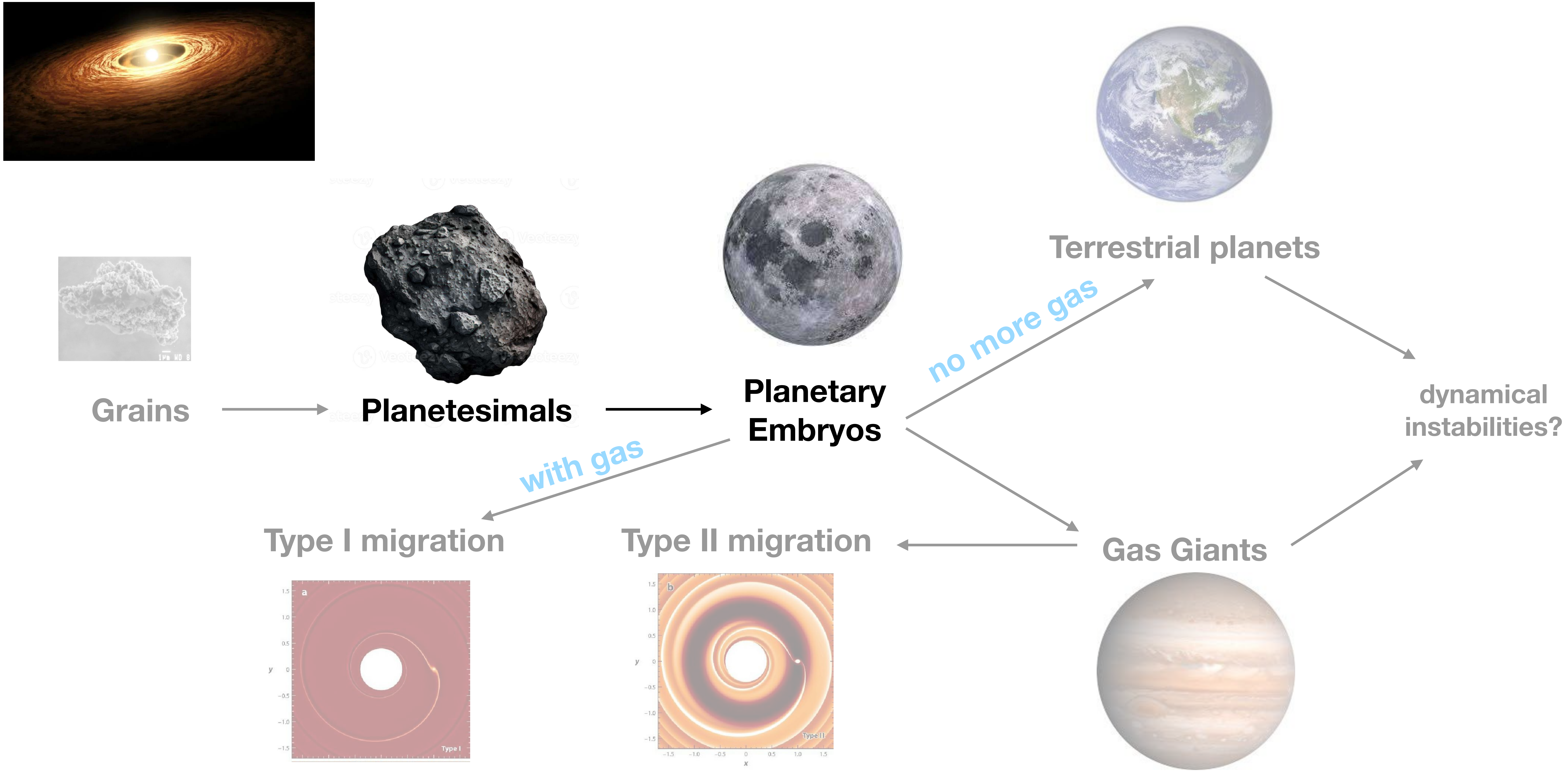
Recall $t_s \propto \rho_{dust}$



$\longrightarrow$ positive feedback for dust particles to pile up

$\longrightarrow$ leads to formation of planetesimals (~km size)
i.e. planetesimals are born big

Stage of Planet Formation



From planetesimals to planetary embryos

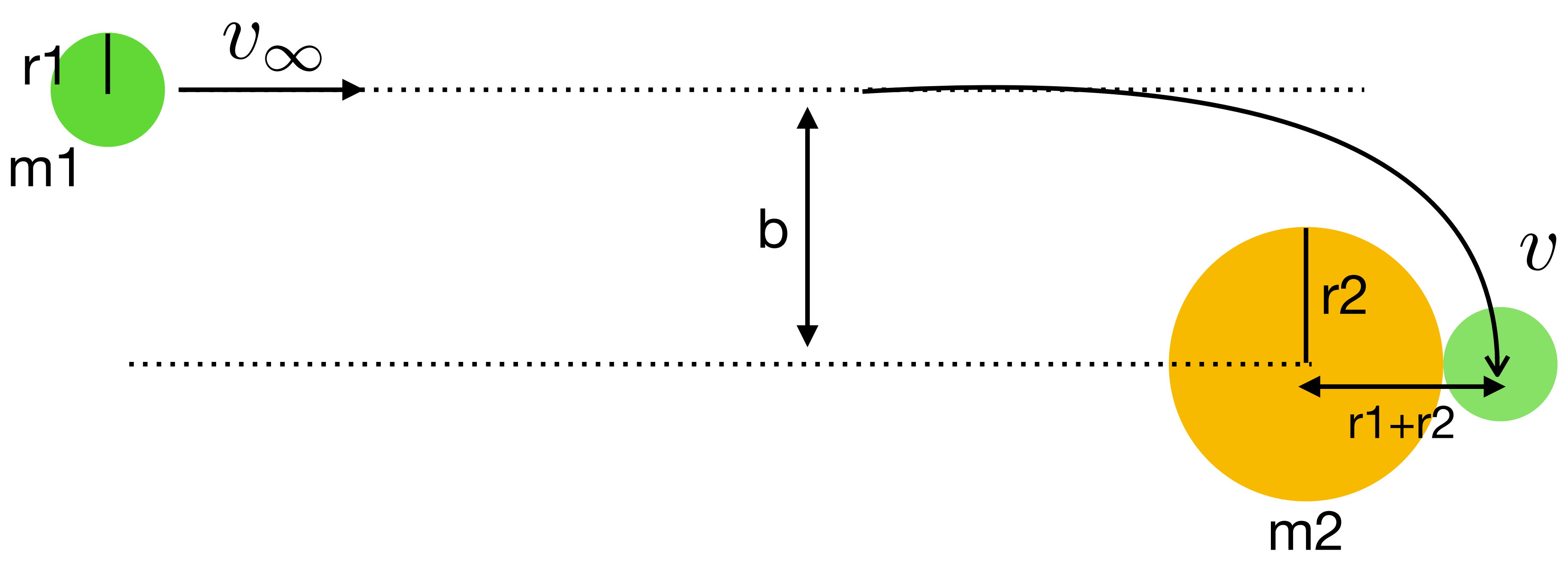
~km

~100-1000 km

Different controlling factors:

- **gravity**, rather than aerodynamic forces dominates the evolution
- mutual gravitational interactions and collisions
- gravitational encounters can excite random velocities of planetesimals

Gravitational focusing



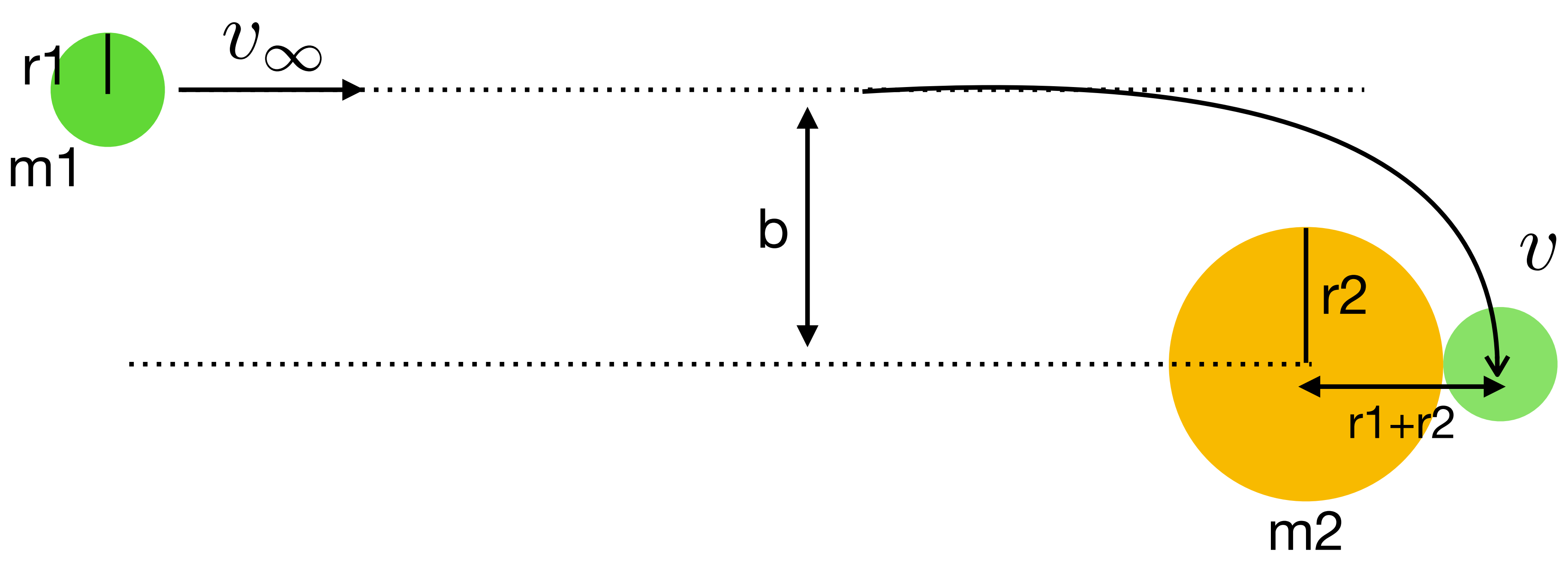
- In a pool game, the collisional cross section is simply the geometric cross section

- Gravity increases the effective collisional cross section, i.e. **gravitational focusing**
  The collisional cross section of two gravitating balls (two-body approximation): $\sigma = \pi b^2$
  Conservation of angular momentum: $\mu b v_\infty = \mu(r_1 + r_2)v \longrightarrow b^2 = (r_1 + r_2)^2 (\frac{v}{v_\infty})^2$

> 1 or < 1?

reduced mass $\mu = \frac{m_1 m_2}{m_1 + m_2}$

Gravitational focusing



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  reduced mass $\mu = \frac{m_1 m_2}{m_1 + m_2}$

  Rewriting v with the **mutual escape velocity**: $\frac{\mu v_{esc}^2}{2} = \frac{G m_1 m_2}{r_1 + r_2}$
  Conservation of energy: $\frac{\mu}{2}v_\infty^2 = \frac{\mu}{2}v^2 - \frac{v_{esc}^2}{2}\frac{m_1 m_2}{m_1 + m_2}$

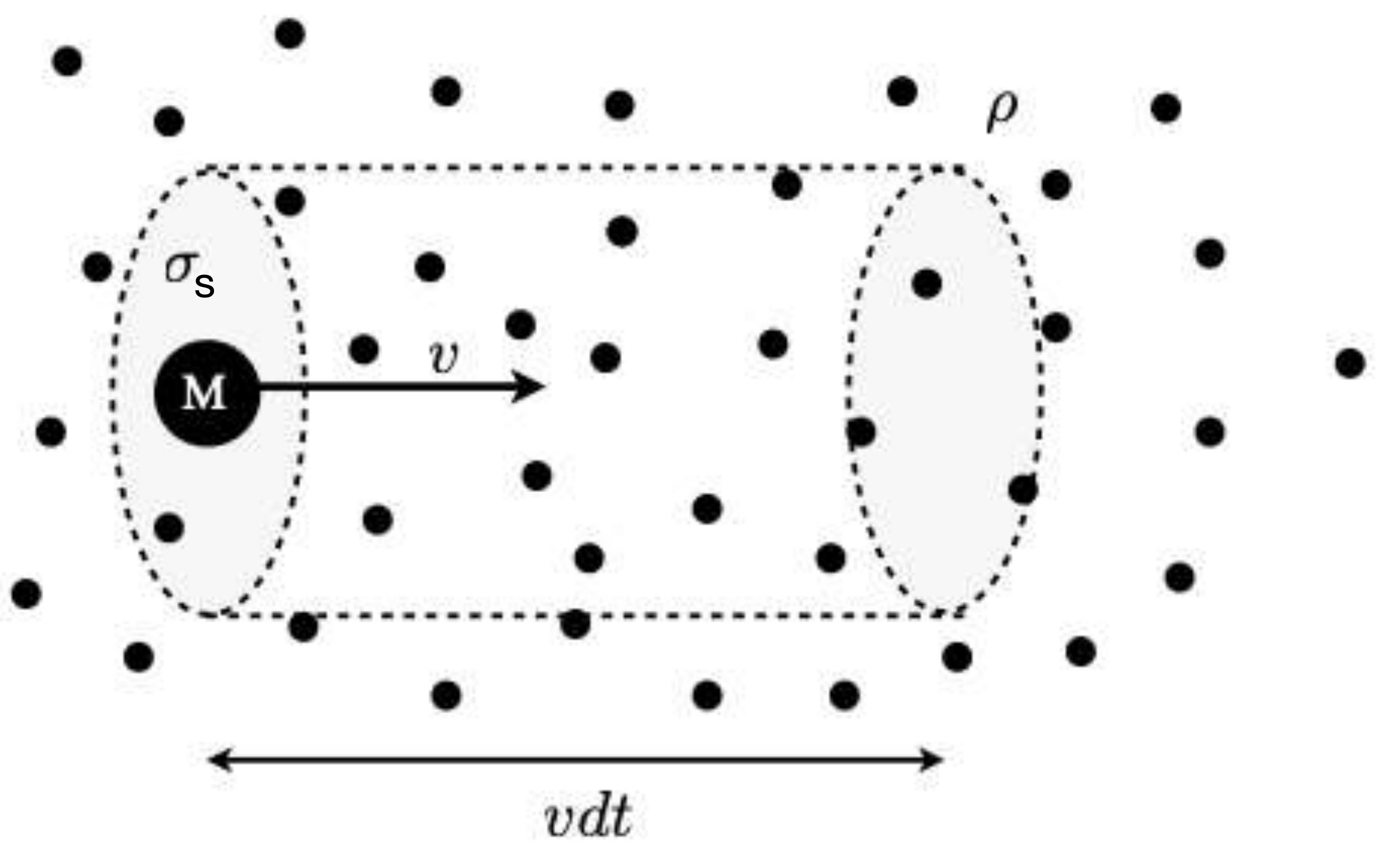
  Collisional cross section: $\sigma = \pi b^2 = \pi(r_1+r_2)^2(1 + \frac{v_{esc}^2}{v^2})$

  geometric cross section

  gravitational focusing factor

Growth rate of planetary embryos

— one large core accreting from background planetesimals



- The growth rate of a planetary embryo of of mass M accreting from a background of planetesimals with volume mass density (ρ_s):

$$dM = \rho_s \sigma v dt$$

$$\frac{dM}{dt} = \rho_s v \pi R^2 F_g \qquad \text{(R = r2 >> r1)}$$

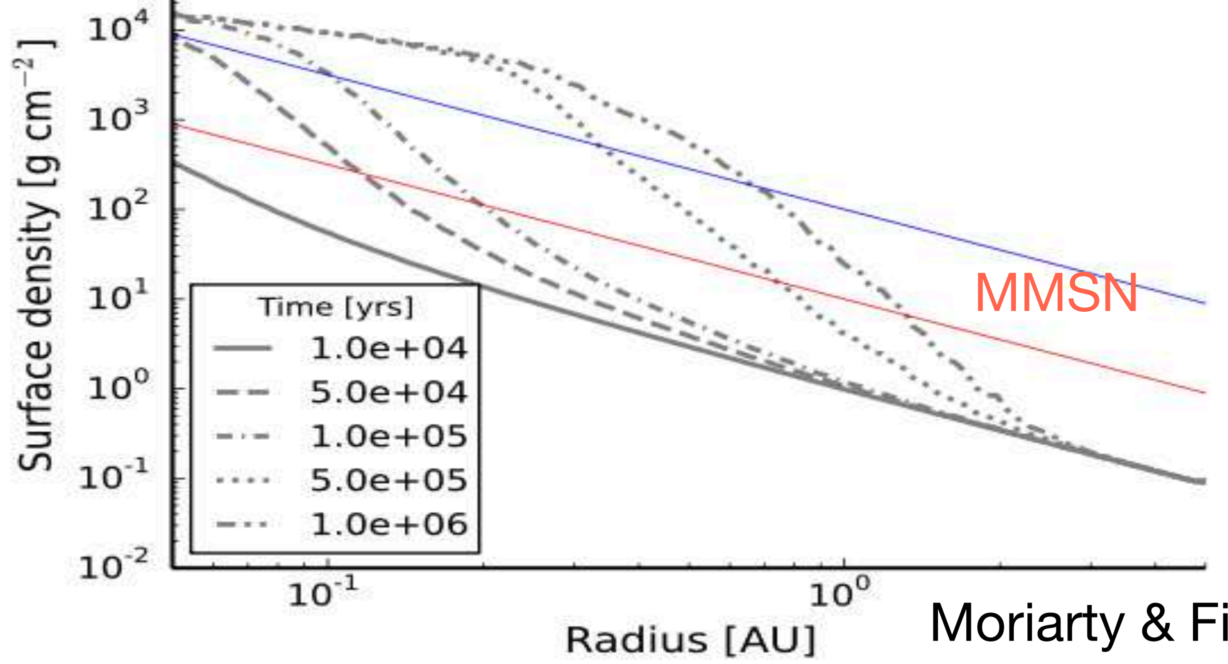
where the gravitational focusing factor $F_g = 1 + \frac{v_{esc}^2}{v^2}$

rewrite $\rho_s = \frac{\Sigma_s}{H}$ with the scaling $\frac{H}{a} \sim \frac{v}{a\Omega}$ (Σ_s: surface density Ω: orbital frequency)

, it is convenient to express the **growth rate** $\frac{dM}{dt} \sim \Sigma_s \Omega \pi R^2 F_g$

- $\Sigma_s \Omega$ decreases with distance from the star, so the growth rate is slower at larger orbits

solid surface density



Moriarty & Fischer (2015)

Runaway growth

Growth rate: $\frac{dM}{dt} \sim \Sigma_s \Omega \pi R^2 F_g$ $\quad F_g = 1 + \frac{v_{esc}^2}{v^2}$

- If $v \gtrsim v_{esc}$, $\frac{dM}{dt} \propto R^2$
- As the embryo grows, v_{esc} increases
- If $v \ll v_{esc}$, $F_g \simeq (\frac{v_{esc}}{v})^2 = \frac{1}{v^2}\frac{2GM}{R} \propto R^2$, and $\frac{dM}{dt} \propto R^2 F_g \propto R^4$

Recall $v_{esc} = \sqrt{\frac{2GM}{R}}$, $M \propto R^3$

Runaway growth

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  faster growth for lower mass

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  faster growth for higher mass

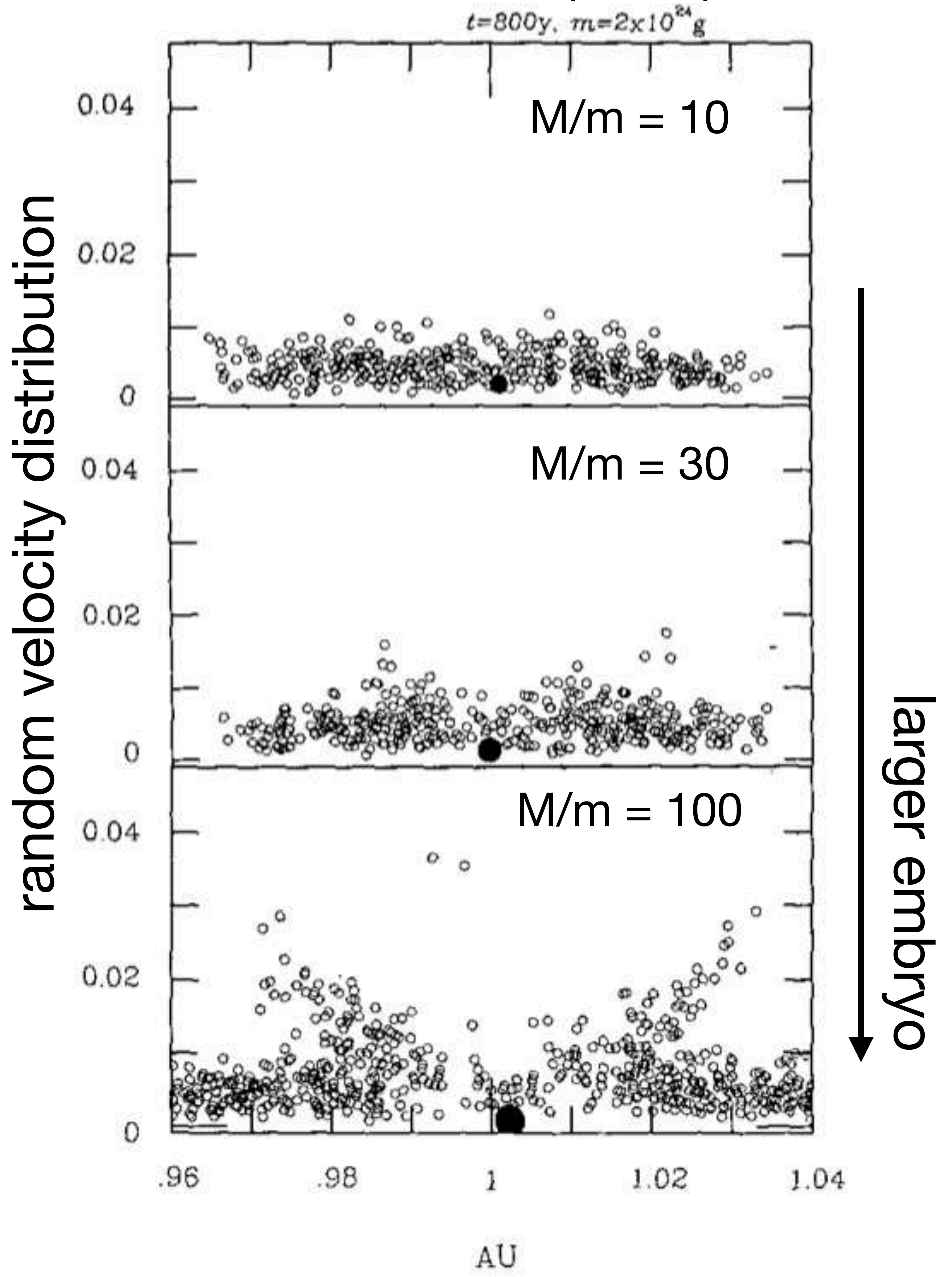
- Once in the runaway regime, more massive bodies grow faster!
  The mass ratio between small and large planetesimals increases monotonically

Oligarchic growth

Can runaway growth keeps going?

- After the large bodies have grown large enough (~100 km), they start to exert gravitational feedback on the random velocities of the smaller planetesimals
- v of planetesimals immediately around the embryo is excited
- As $\frac{dM}{dt} \propto R^2$, the growth rate is reduced to $\frac{1}{M}\frac{dM}{dt} \propto M^{-\frac{1}{3}}$
  (faster growth for lower mass)
- Eventually, the growth rate of big embryos slow down with increasing mass. This growth regime proceeds towards a set of similar mass embryos (hence "oligarchy")
- Oligarchic growth is the self-limiting mode of runaway growth

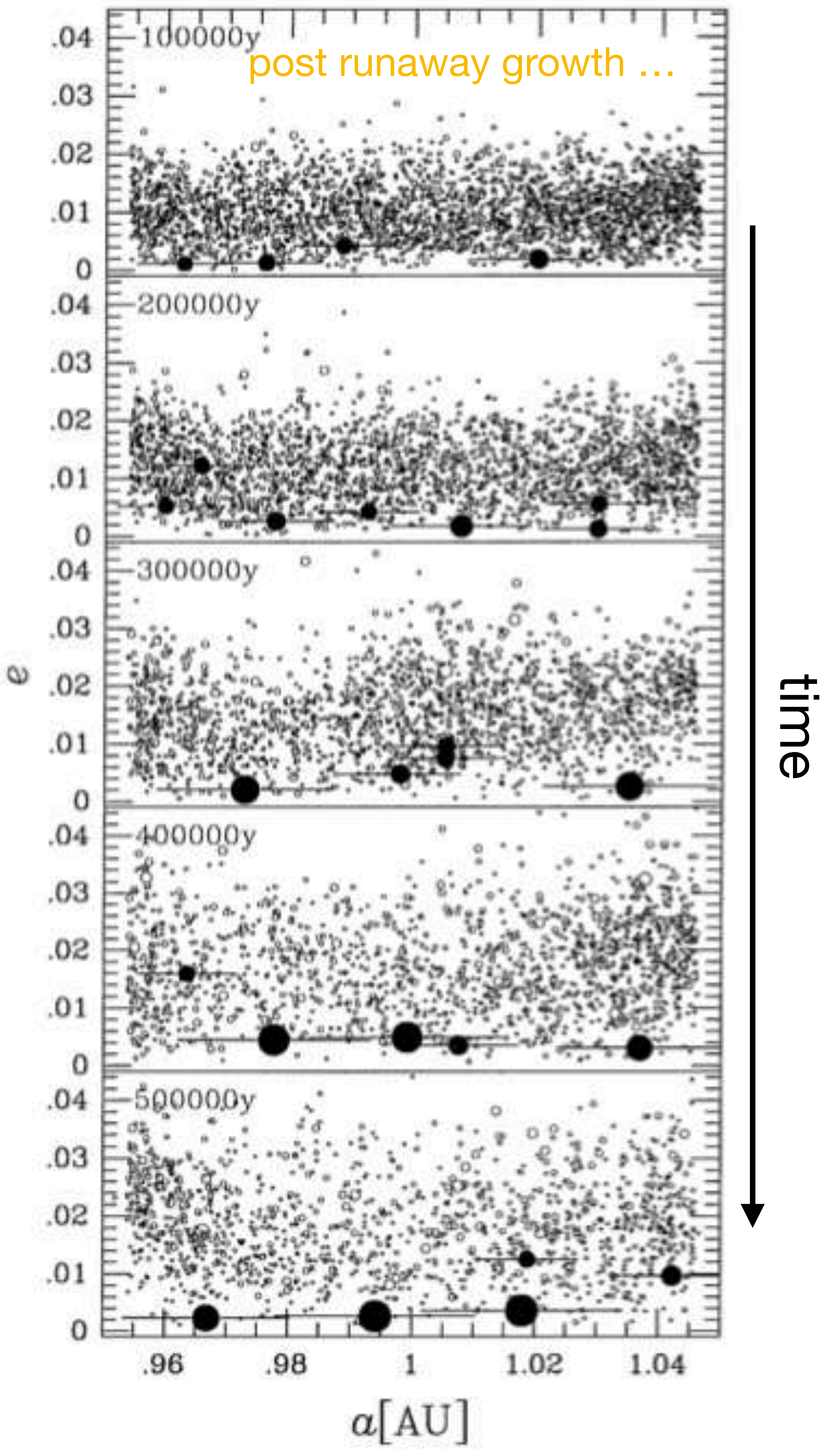
Ida & Makino (1993)



Oligarchic growth

Can runaway growth keeps going?

Kokubo & Ida (2000)



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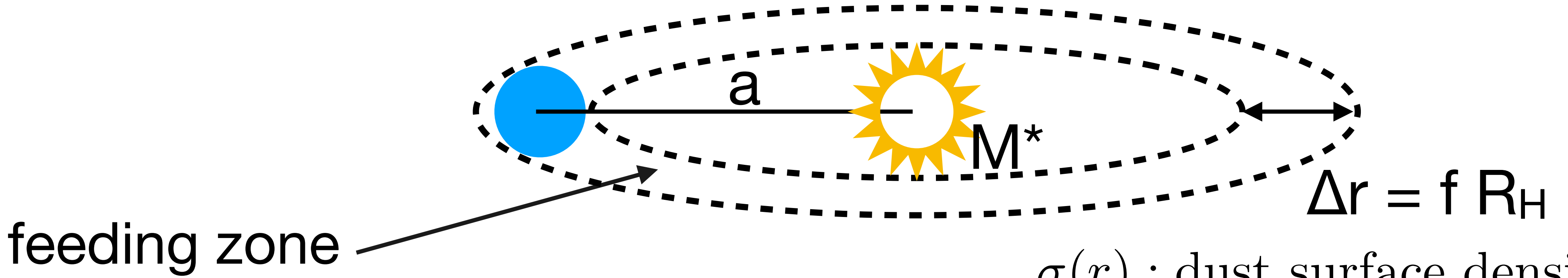
Isolation mass

— the largest mass a planetary embryo can reach



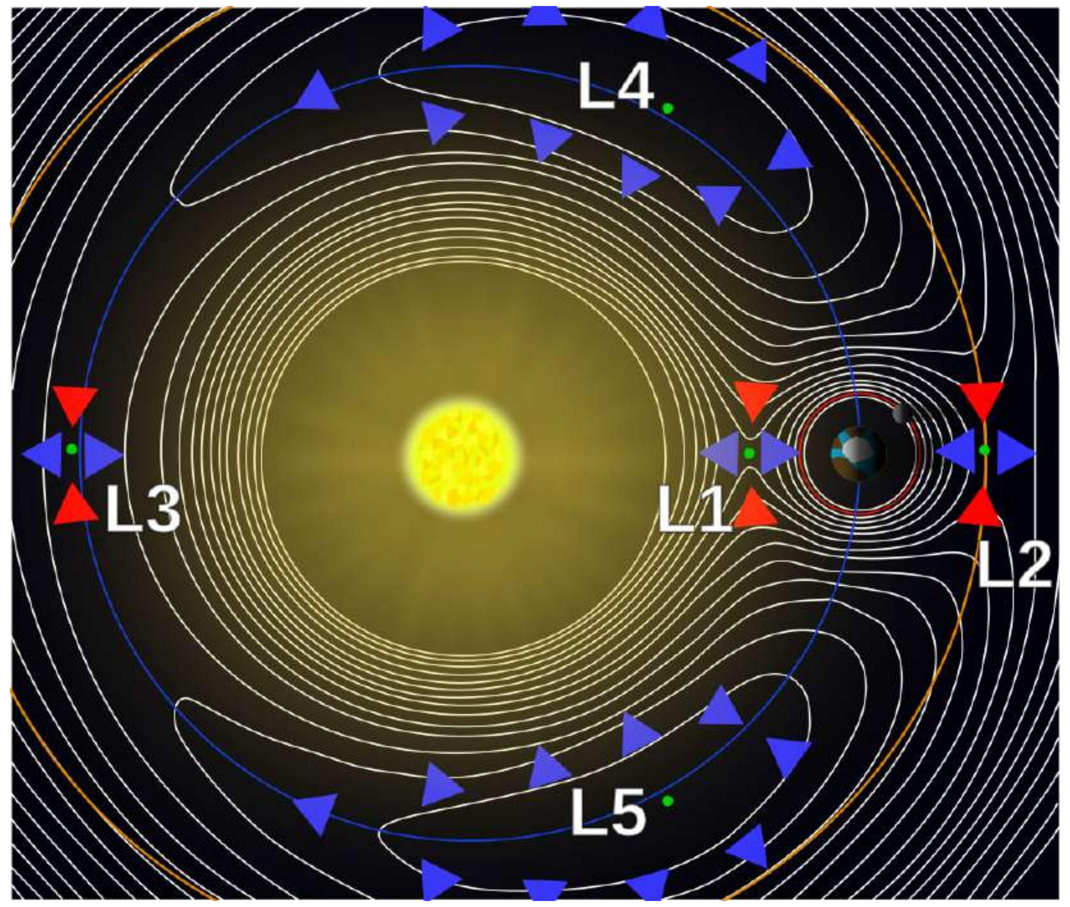
$\sigma(r)$: dust surface density

The maximum mass of a planetary embryo can accrete is

$$M = \int_{a-\Delta r}^{a+\Delta r} 2\pi r \sigma(r) dr$$

The gravitational reach Δr is given by the Hill radius $\quad \Delta r \sim f R_H, \; R_H \sim (\frac{m_p}{3M*})^{\frac{1}{3}}$

where f is typically 2—6



R_H: where the gravity of the planet dominates over the tidal influence of the star

Isolation mass

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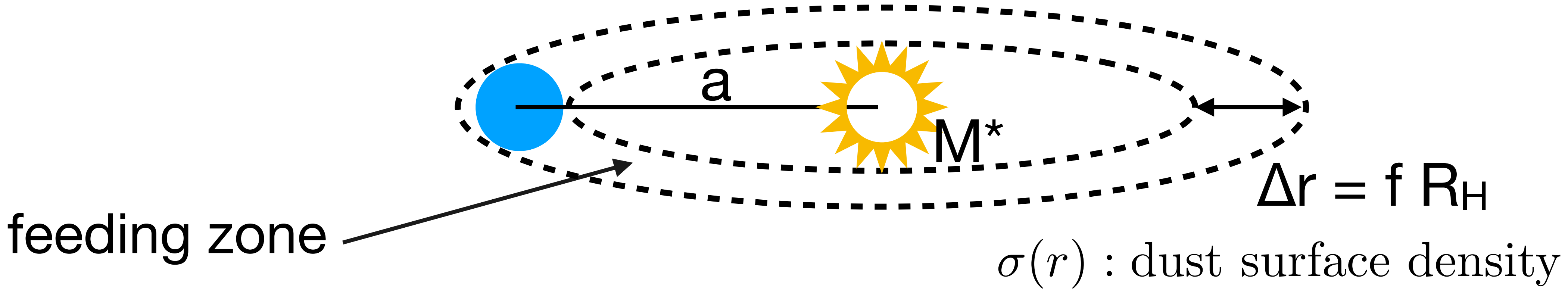
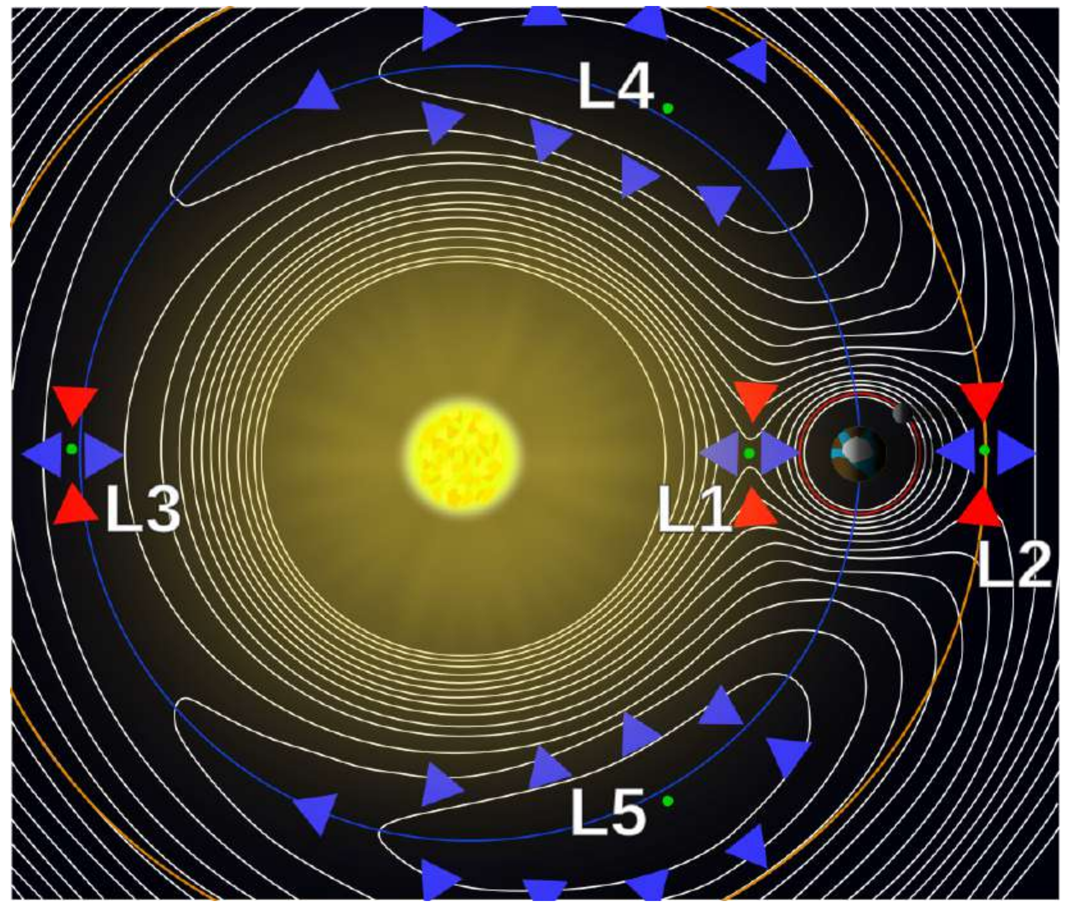


The maximum mass of a planetary embryo can accrete is

$$M = \int_{a-\Delta r}^{a+\Delta r} 2\pi r \sigma(r) dr$$

The gravitational reach Δr is given by the Hill radius $\Delta r \sim f R_H,\ R_H \approx a(\frac{m_p}{3M*})^{\frac{1}{3}}$

where f is typically 2—6



R_H: where the gravity of the planet dominates over the gravitational influence of the star

We then obtain the isolation mass by solving $M_{iso} \sim 2\pi a(2\Delta r)\sigma(a) = 4\pi a^2 f\sigma(a)(\frac{M_{iso}}{3M*})^{\frac{1}{3}}$

which yields $M_{iso} \sim (4\pi \underline{a^2} f \underline{\sigma(a)})^{3/2}(\frac{1}{3M*})^{\frac{1}{2}}$

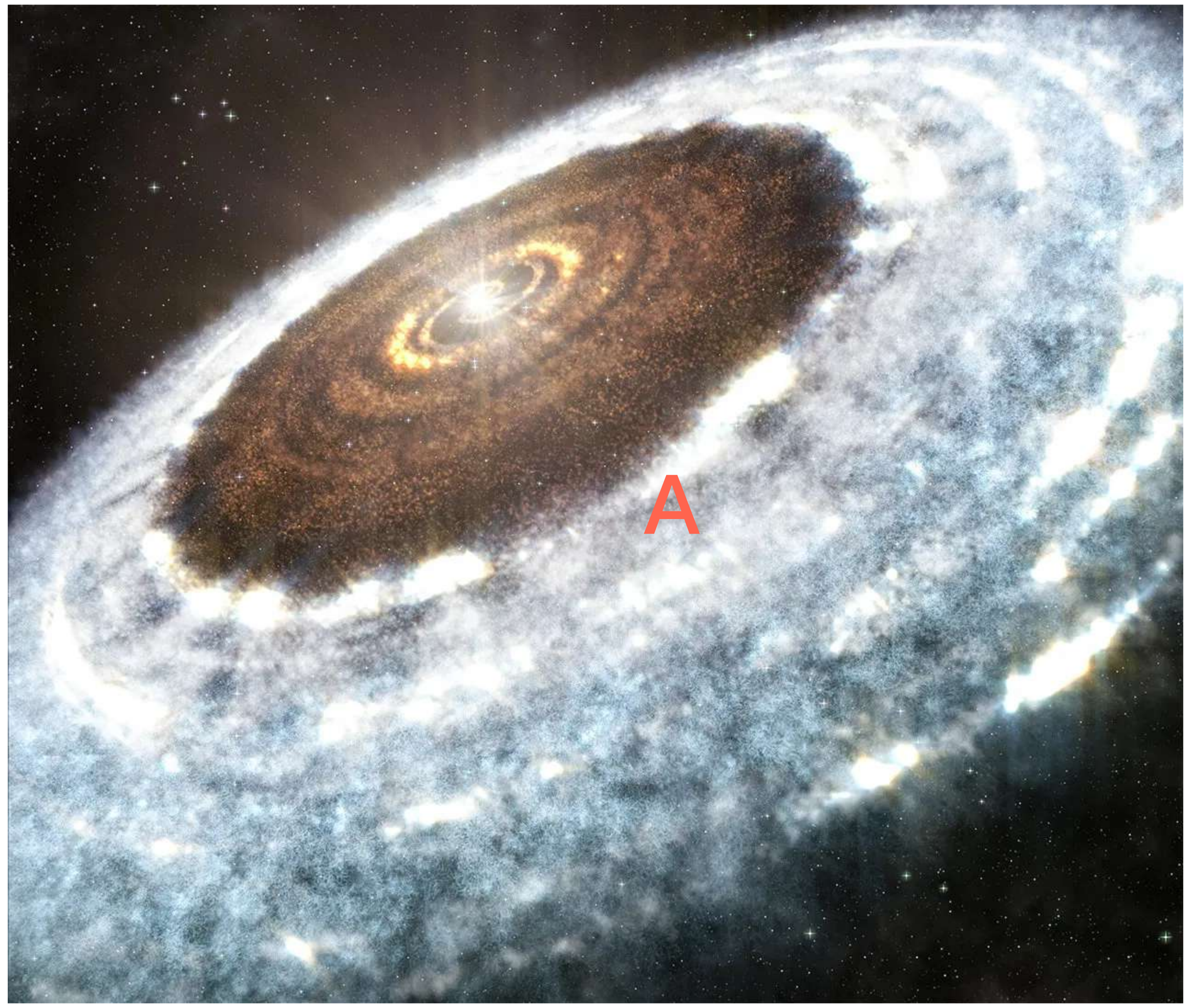
- As long as the planetesimal surface density $\sigma(a)$ falls slower than a^{-2}, M_{iso} increases with distance because of the larger feeding zone (in general $\sigma(a) \propto a^{-1.5}$)

Core accretion depending on the orbital distance

- **The feeding zone size** increases with distance from the star since the Hill radius is larger at greater distances.

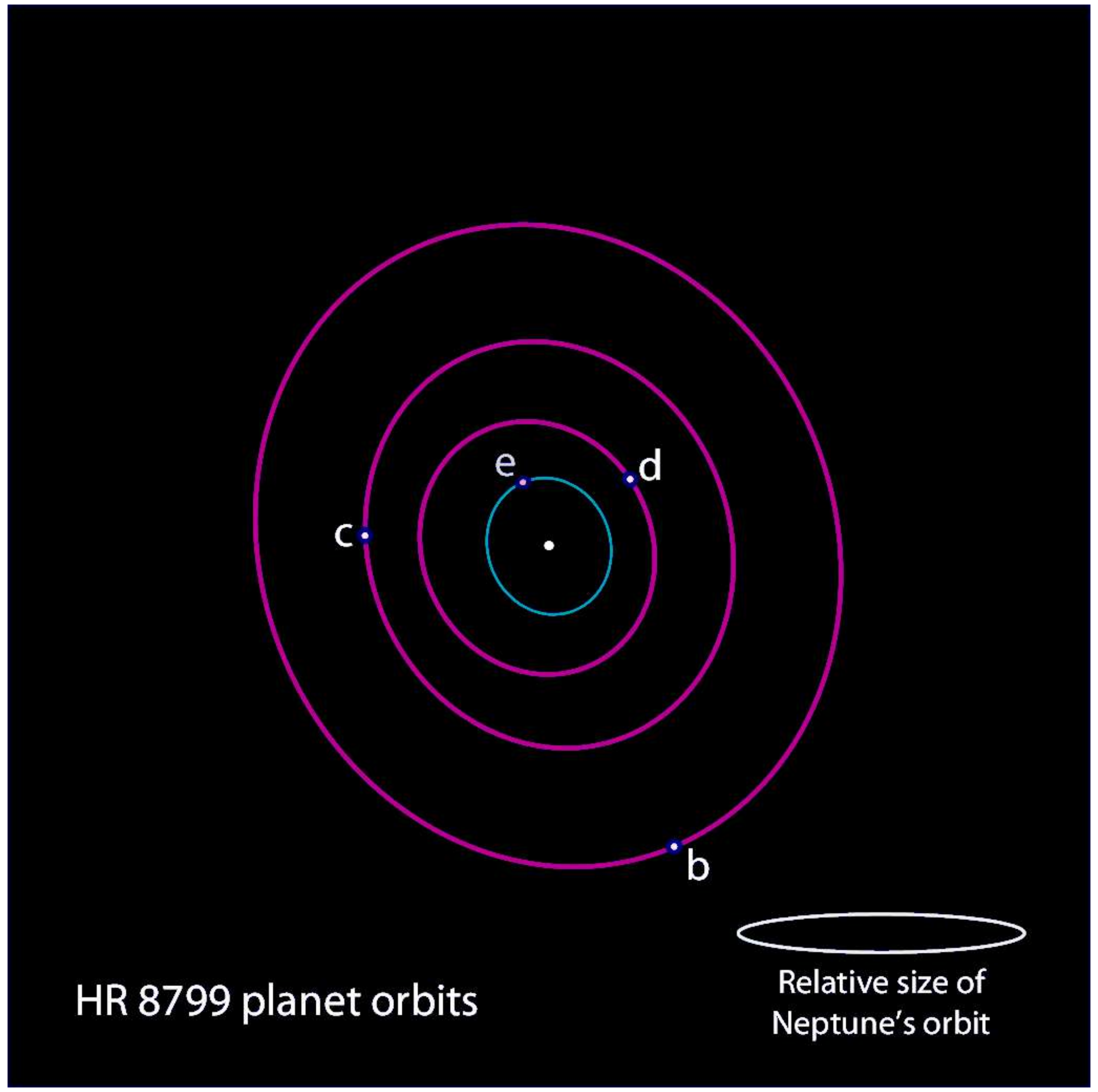
- **The Growth rate** generally decreases with increasing distance from the star due to lower surface density.

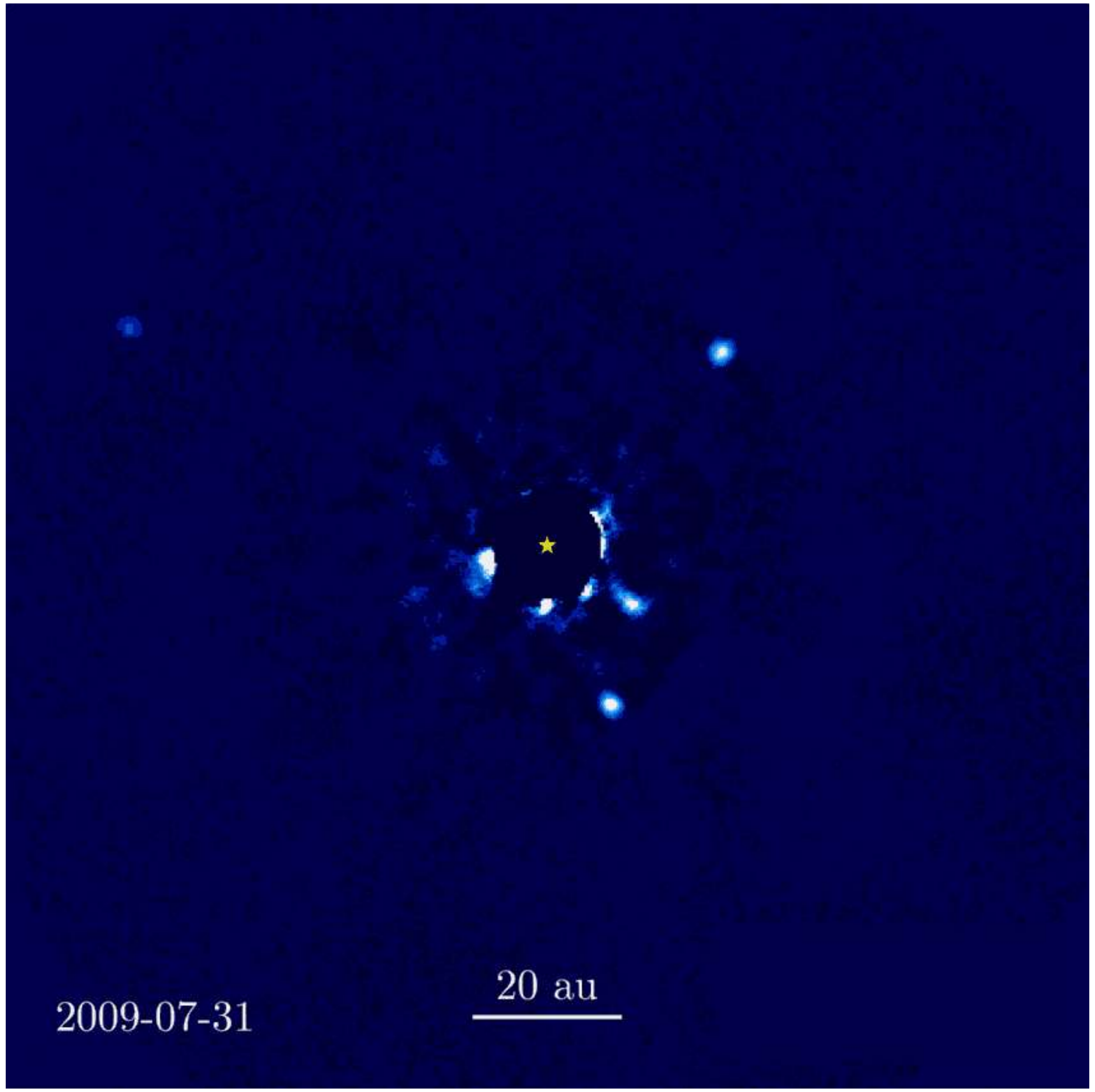
- Right beyond **the snow line** is a favorable location for planetesimal formation (~ 2—10 AU).



HR 8799

— by core accretion or gravitational instability?

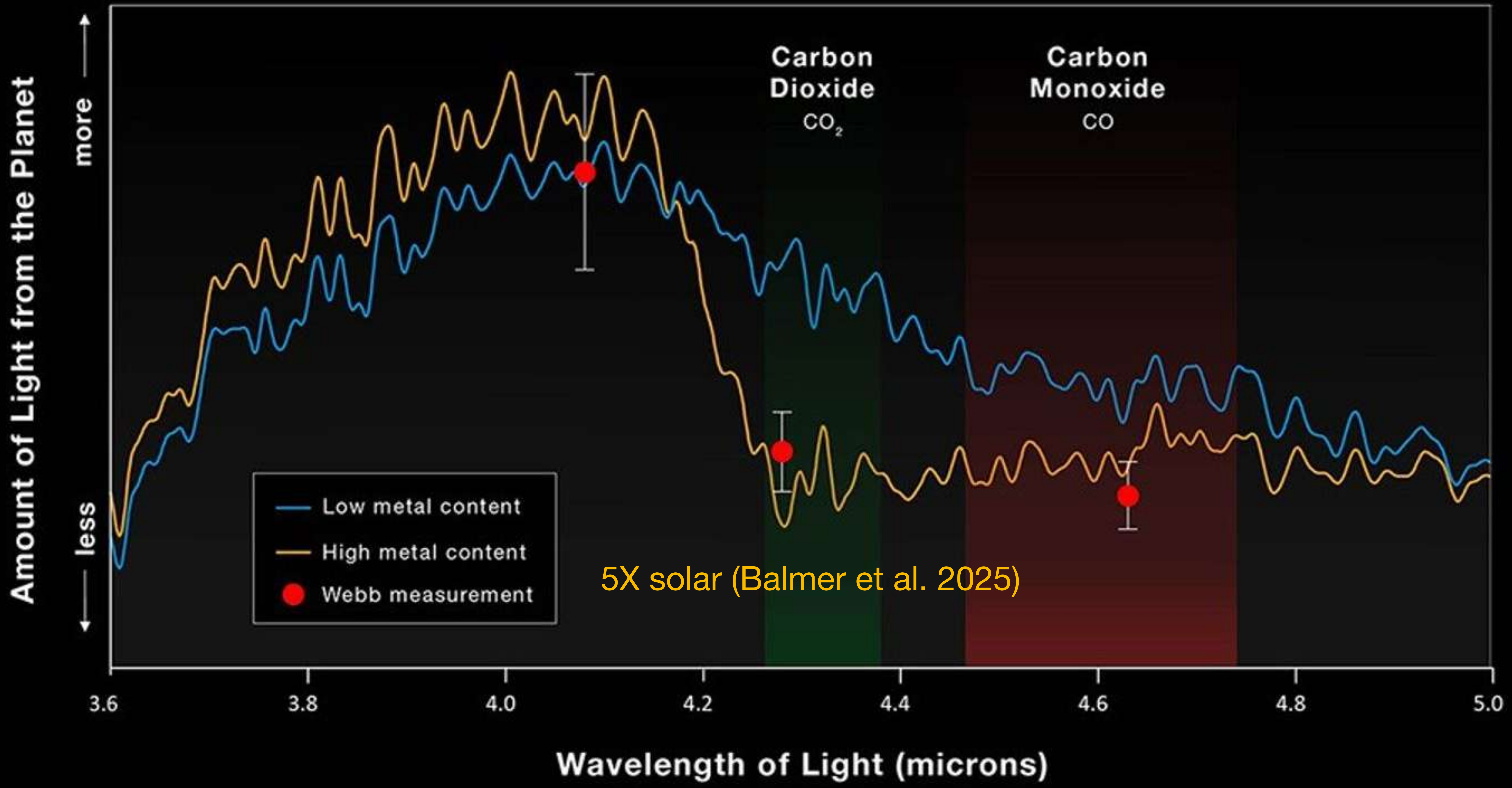




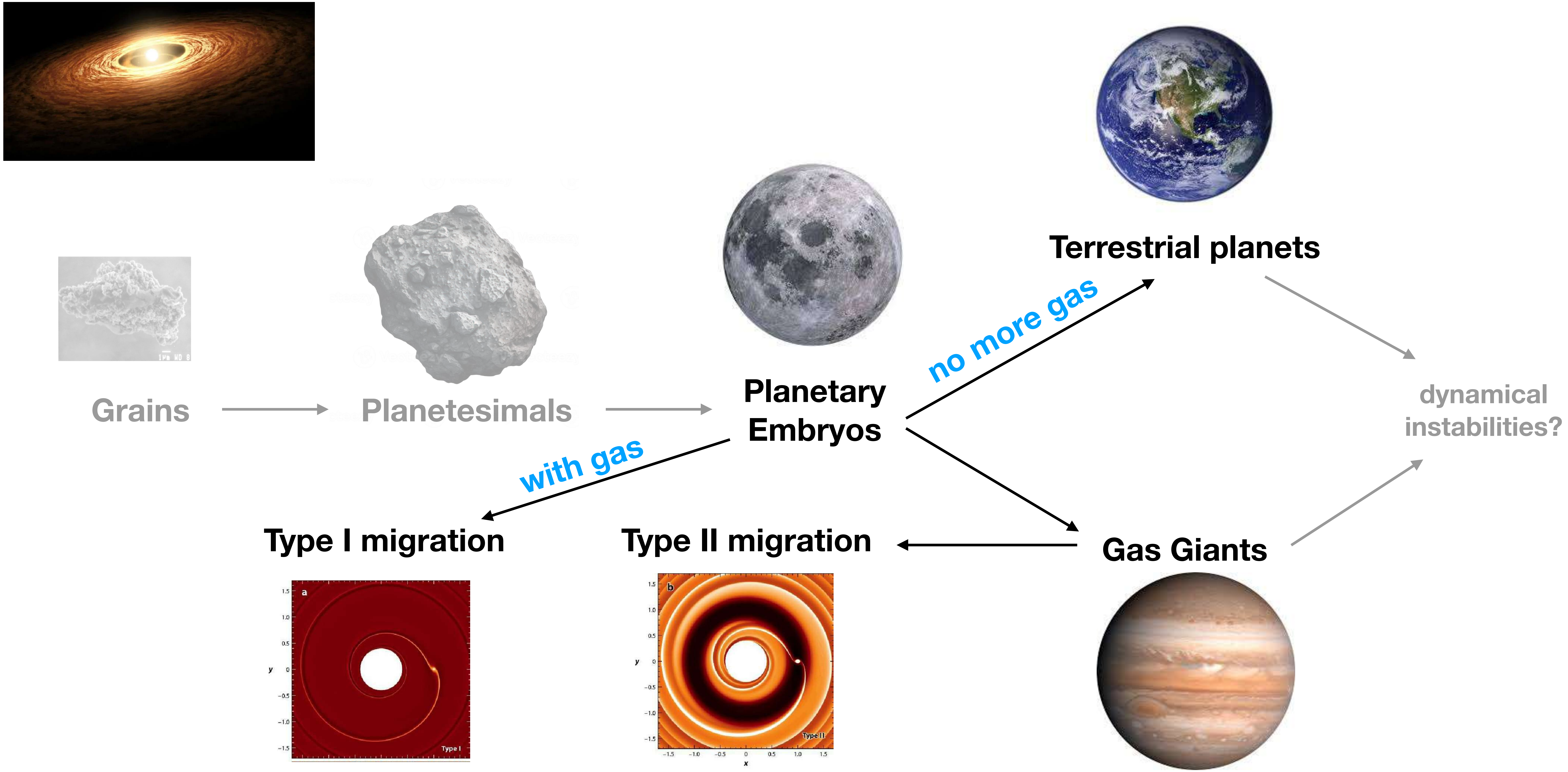
Keck Observatory

HR 8799

— by core accretion?



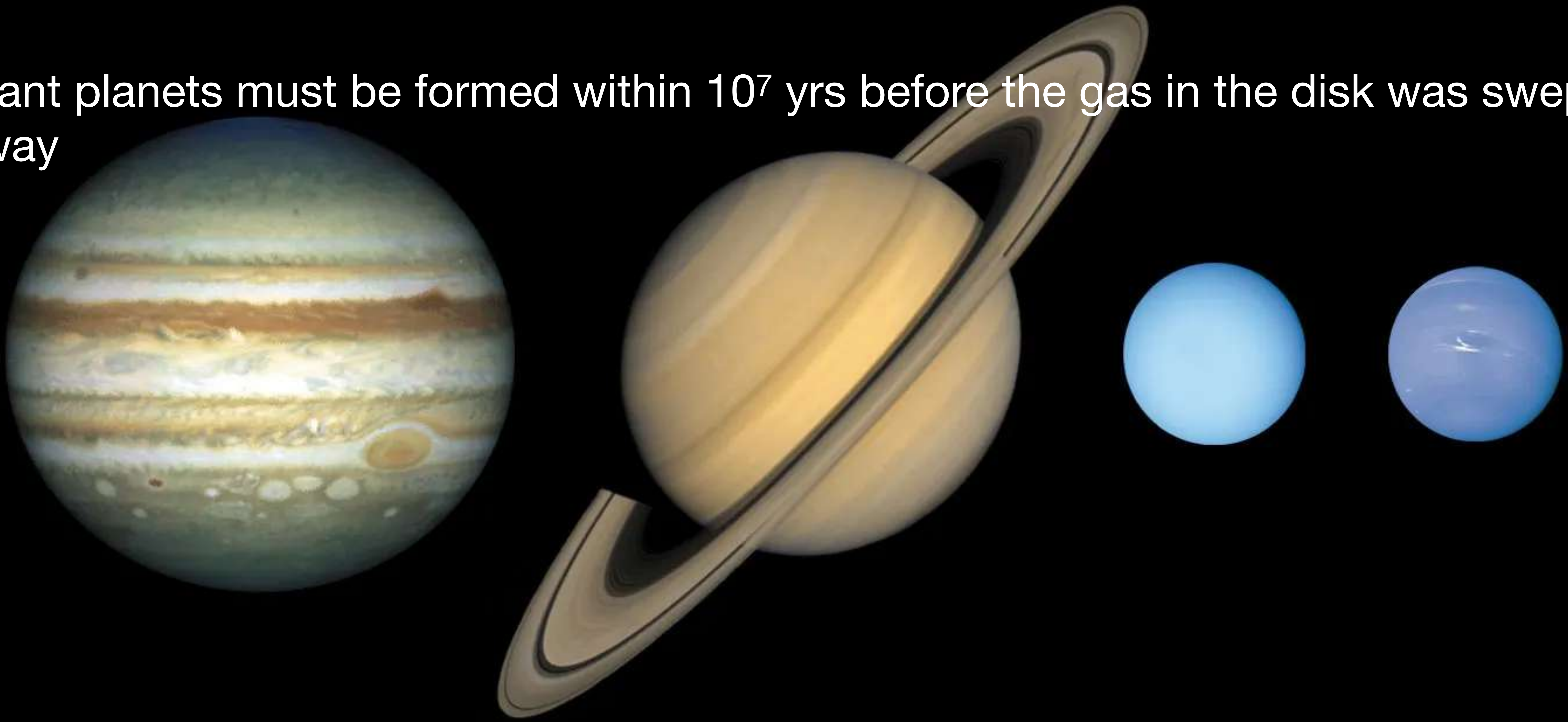
Stage of Planet Formation



Forming giant planets

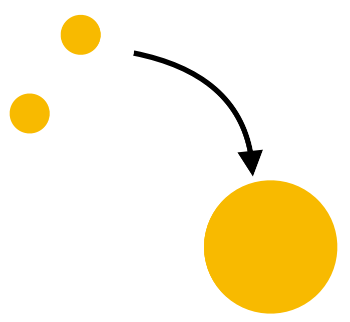
- Once the mass of a planetary core reaches ~ 5 M_{Earth}, it can gravitationally bind a gas envelope

- Giant planets must be formed within 10^7 yrs before the gas in the disk was swept away



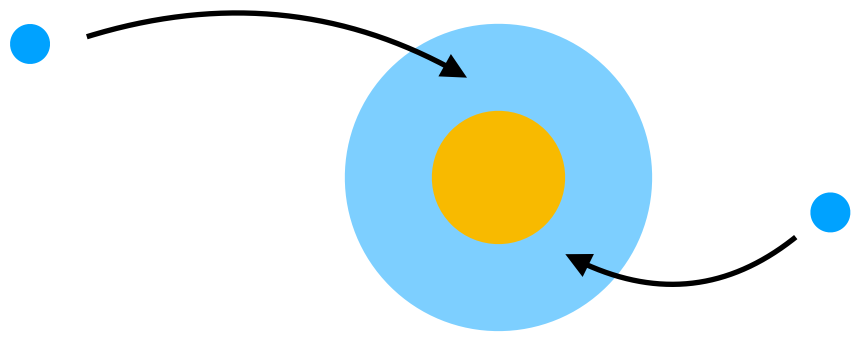
Gas accretion

Core formation
(resembling terrestrial
planet formation)



Hydrostatic growth

$$\frac{dP}{dr} = -\frac{GM\rho}{R}$$

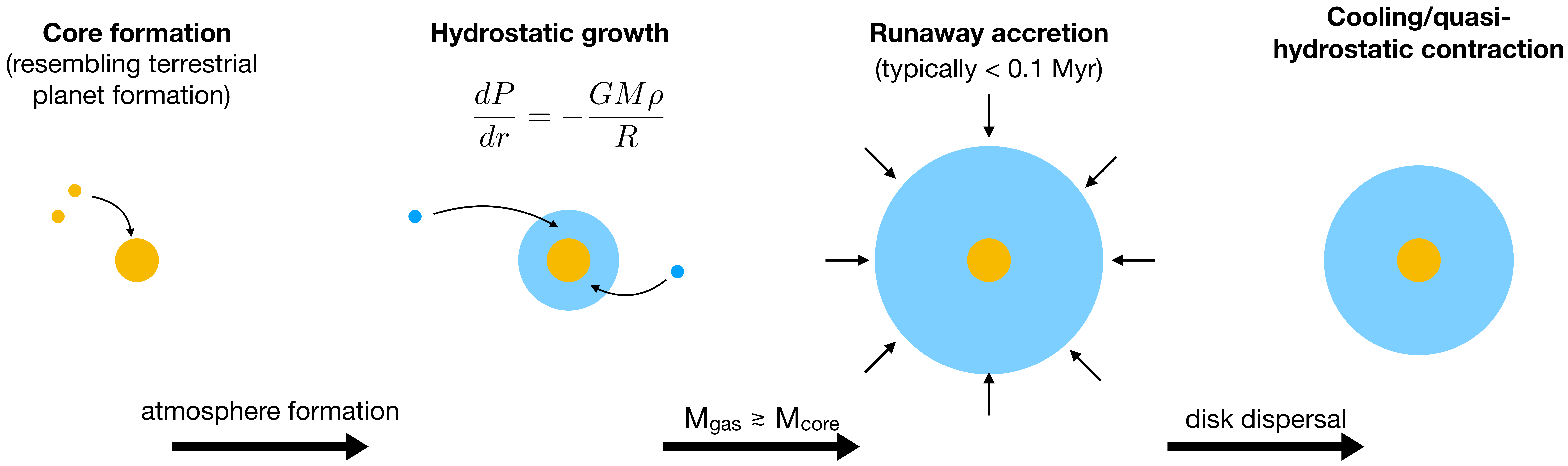


atmosphere formation

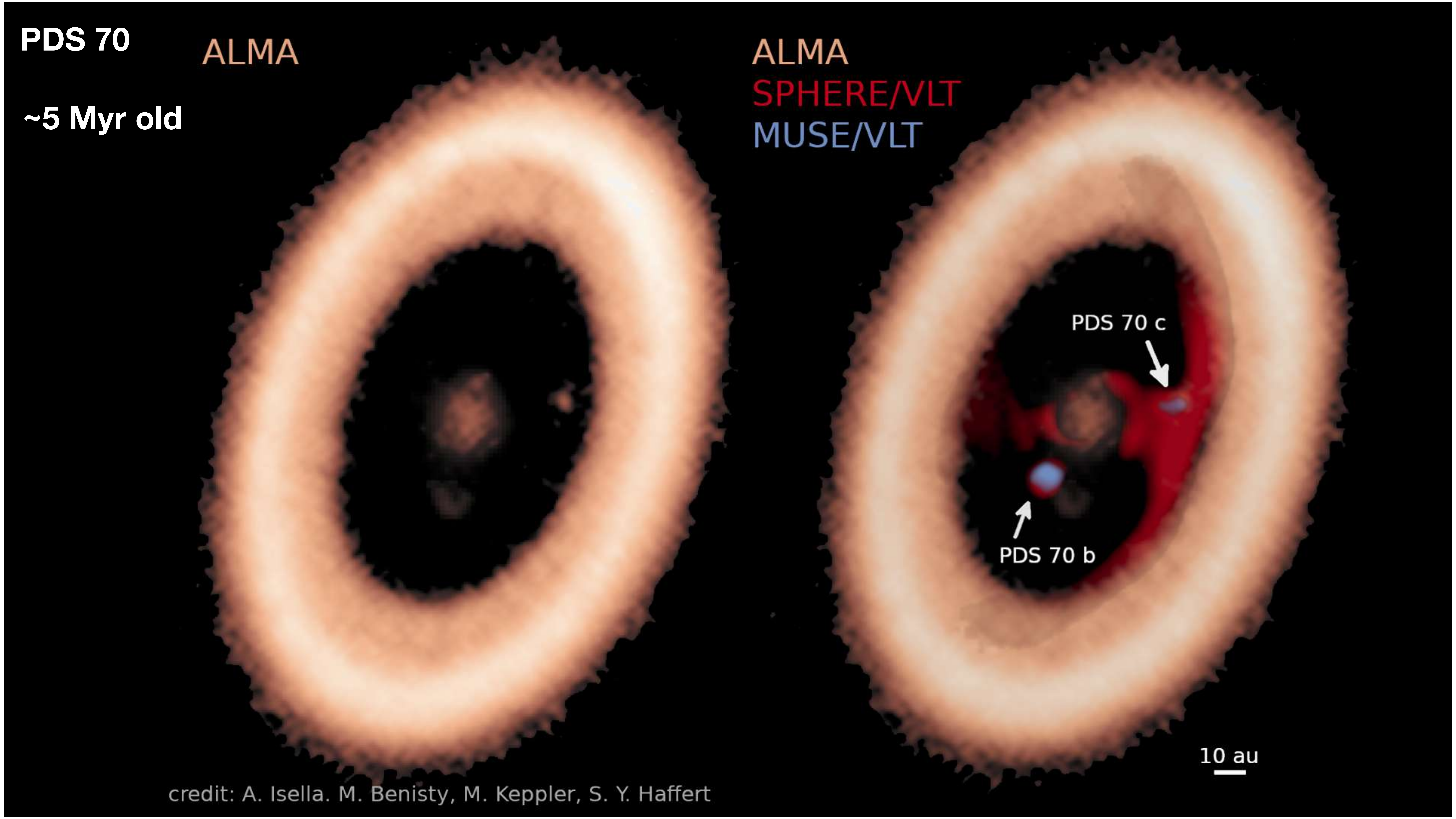
disk dispersal

Neptune-like planets

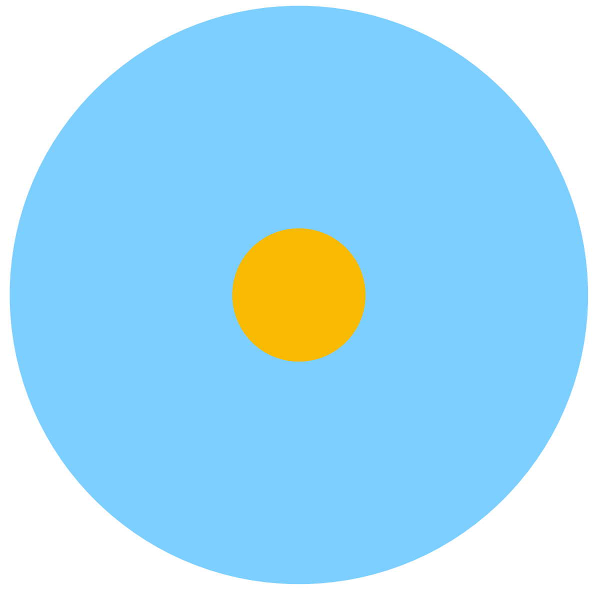
Gas accretion



Gas accretion

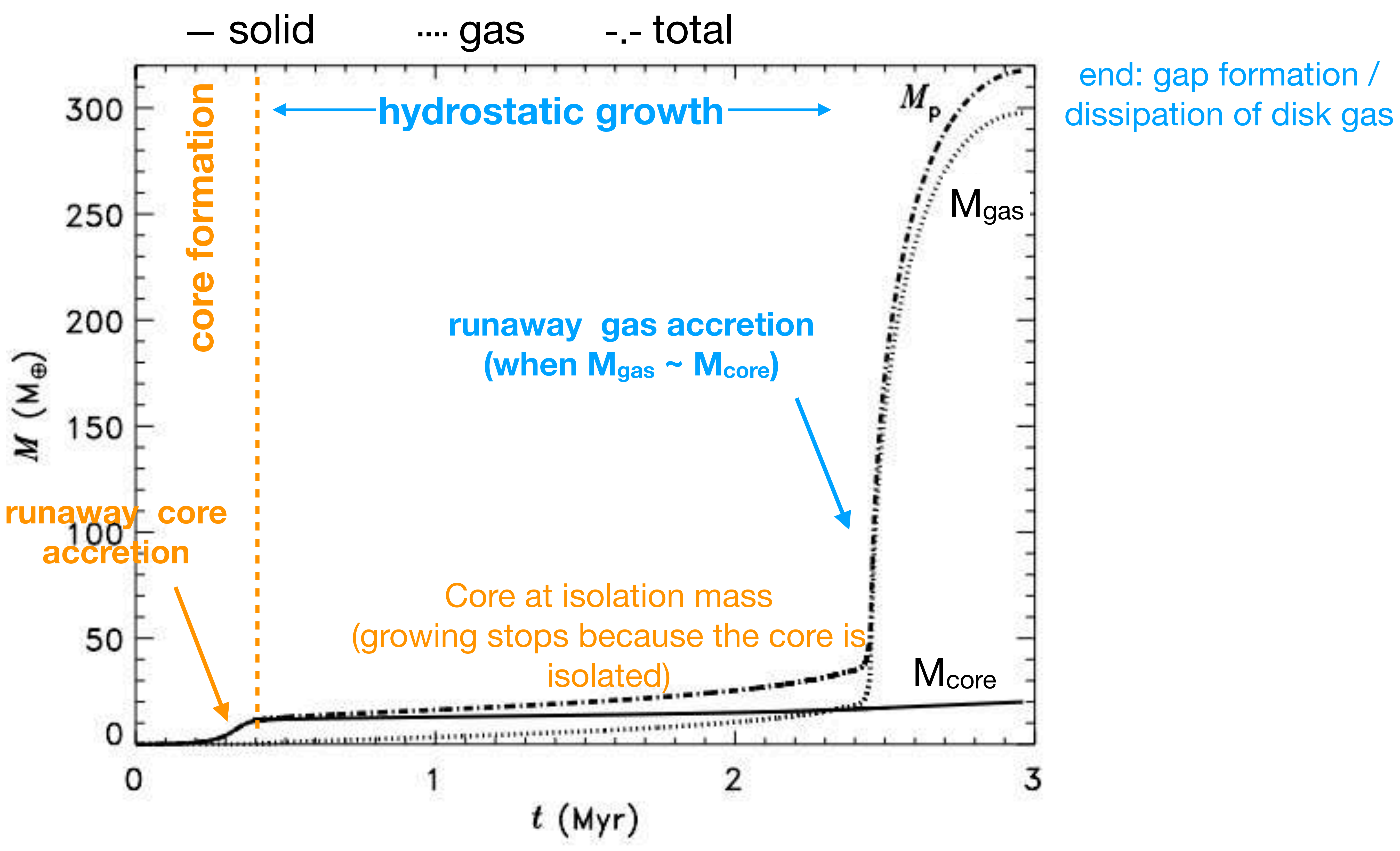


Cooling/quasi-hydrostatic contraction



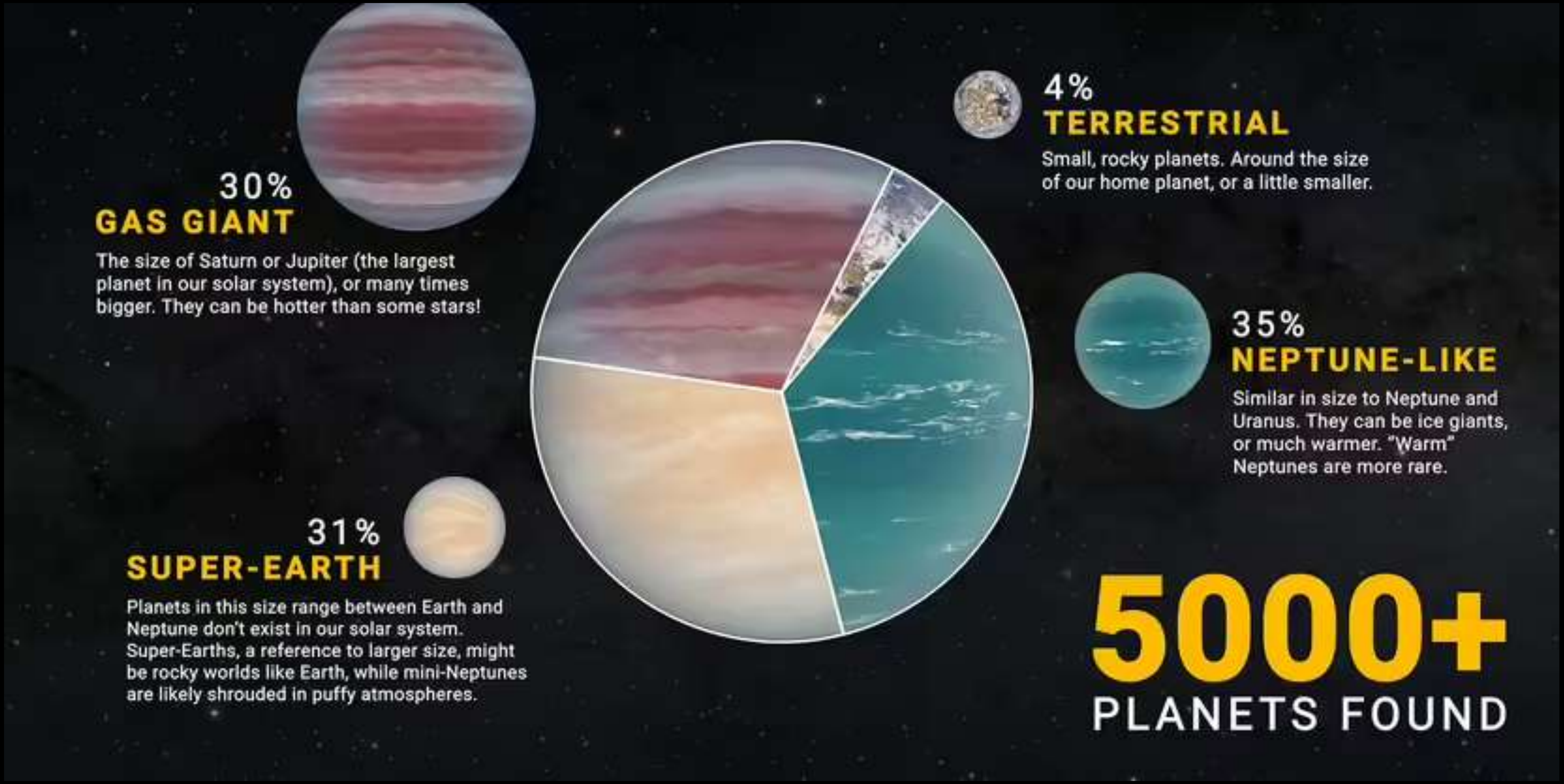
Stages of forming giant planets

— making Jupiter with a core accretion model via 3D hydrodynamic calculations



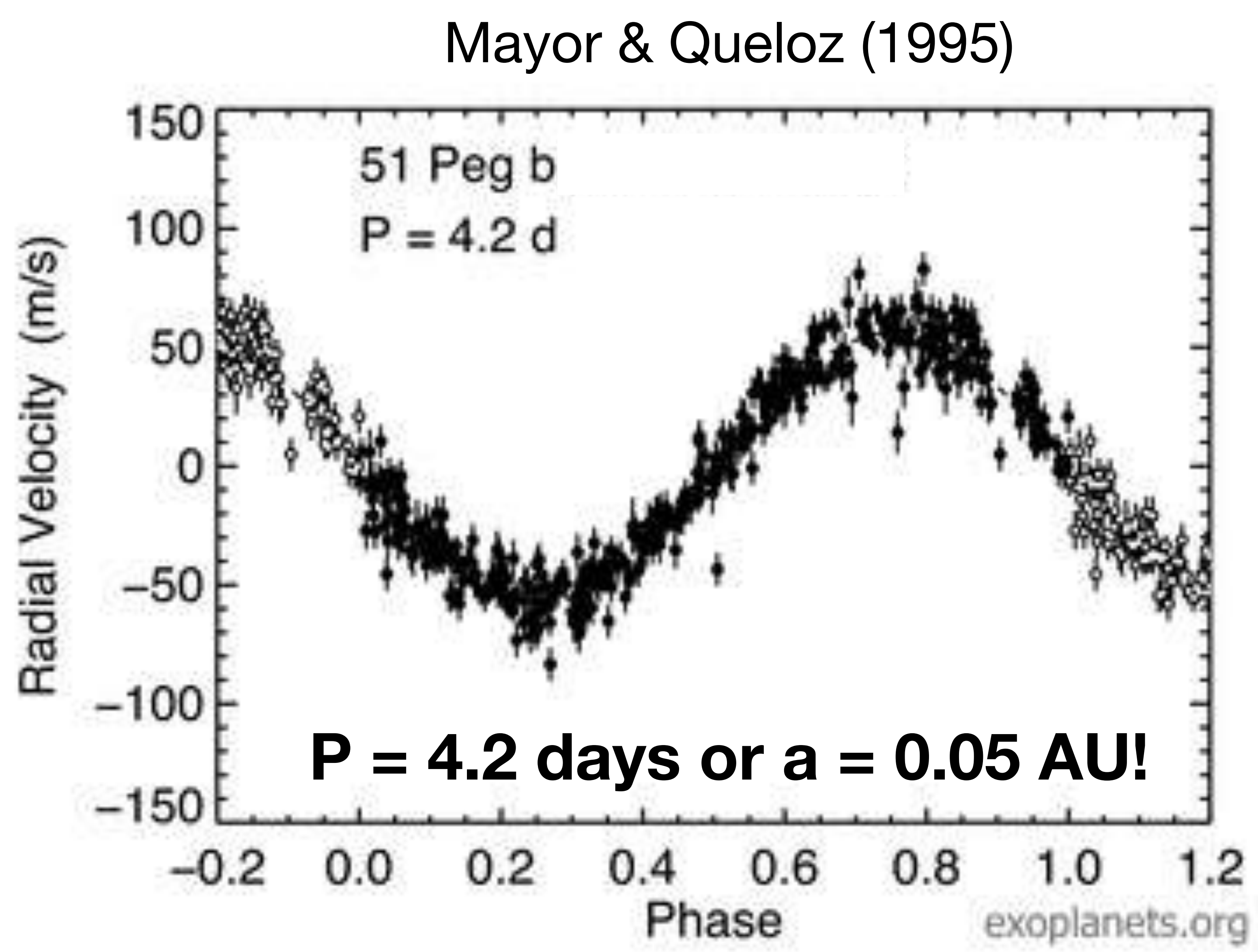
Lissauer et al. (2009)

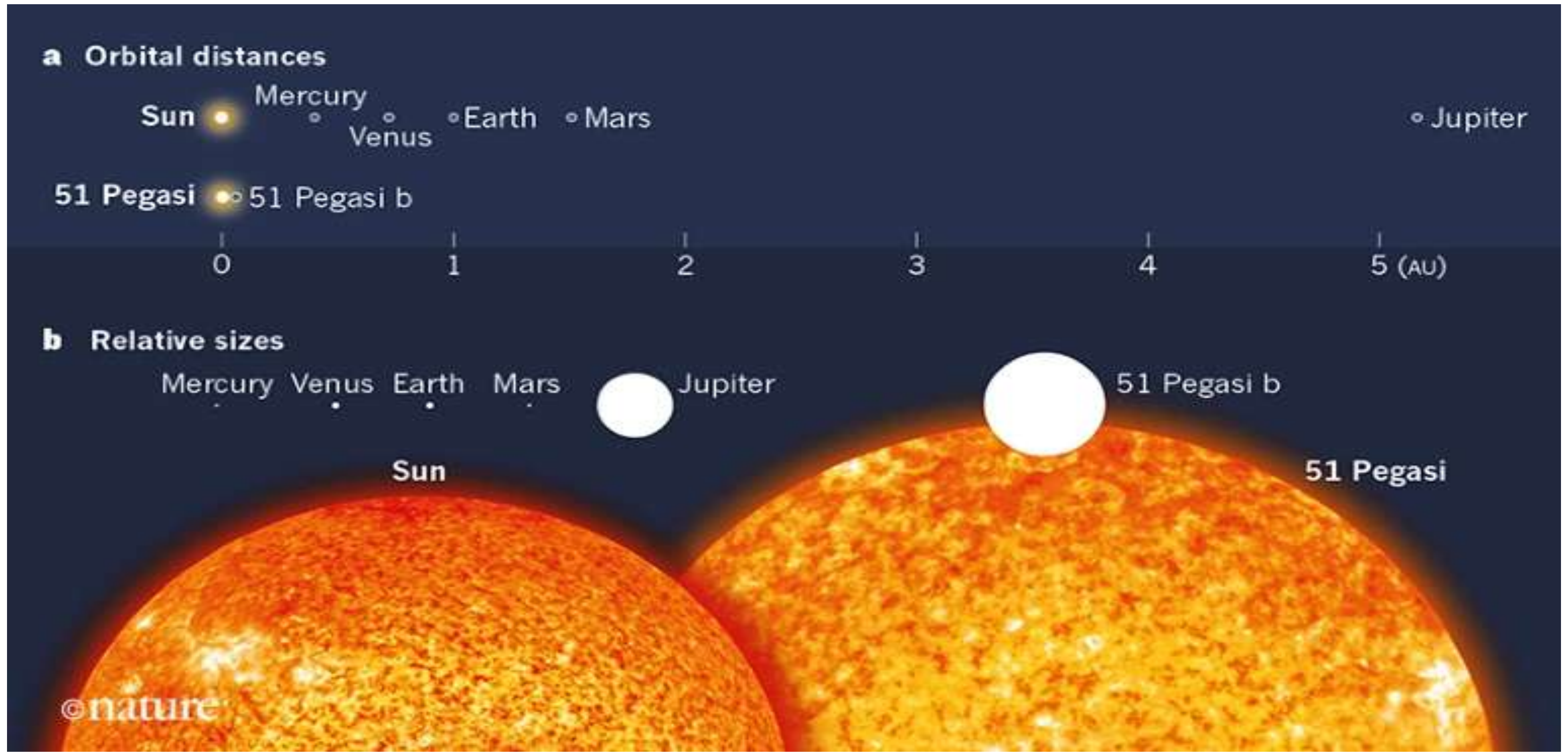
Exoplanets: planets outside the solar system

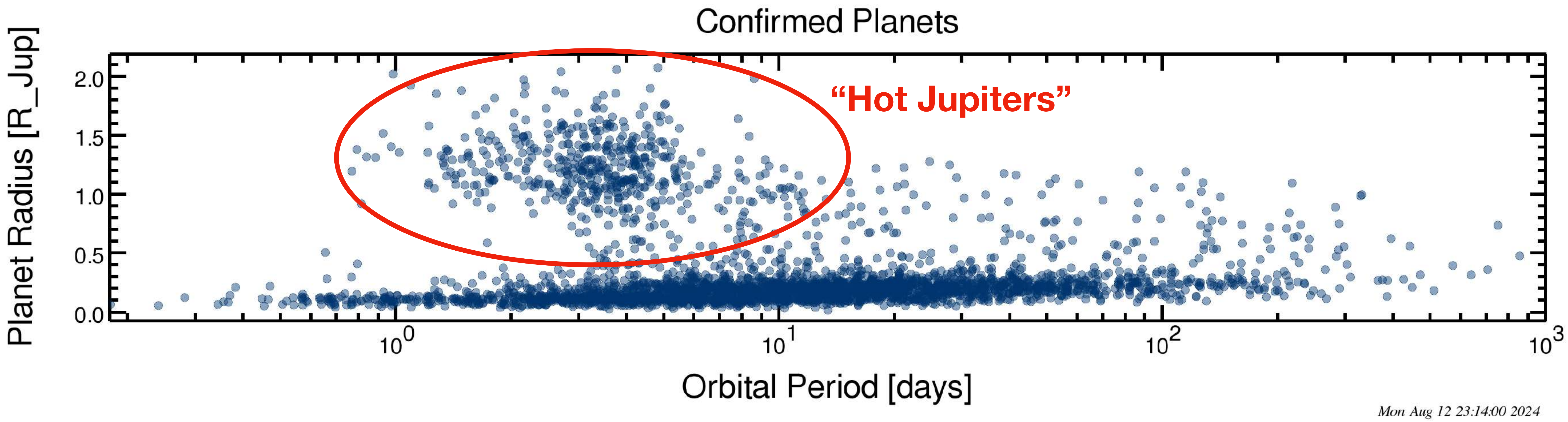


NASA/JPL-Caltech

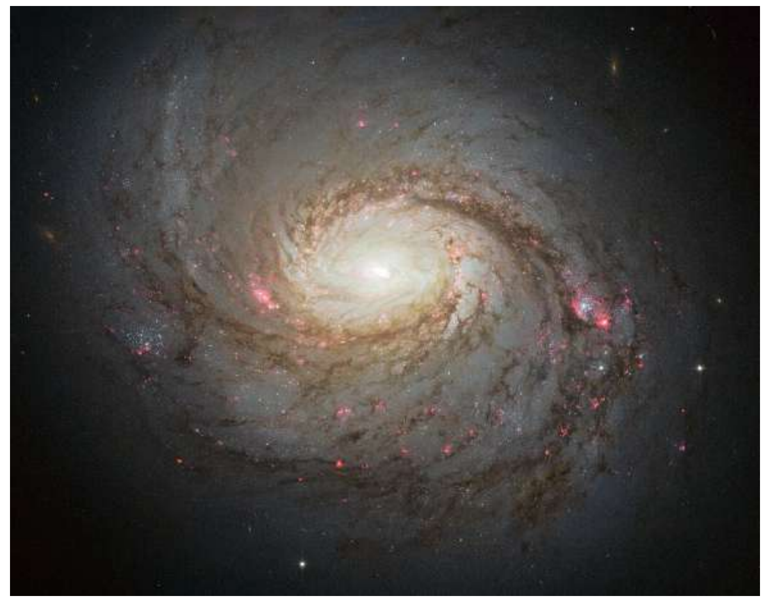
First exoplanet around a Sun-like star



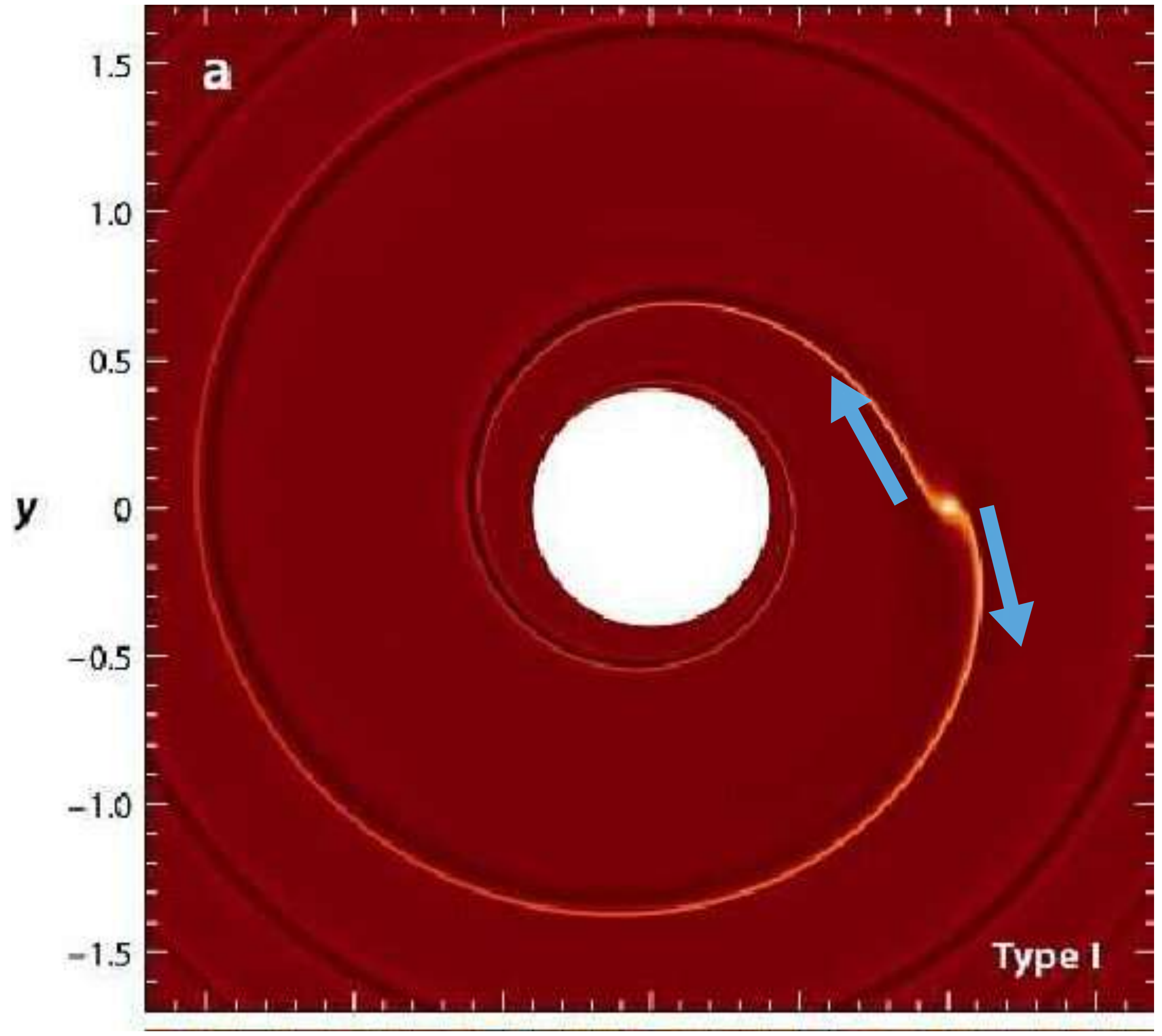




Planet migration



Type I

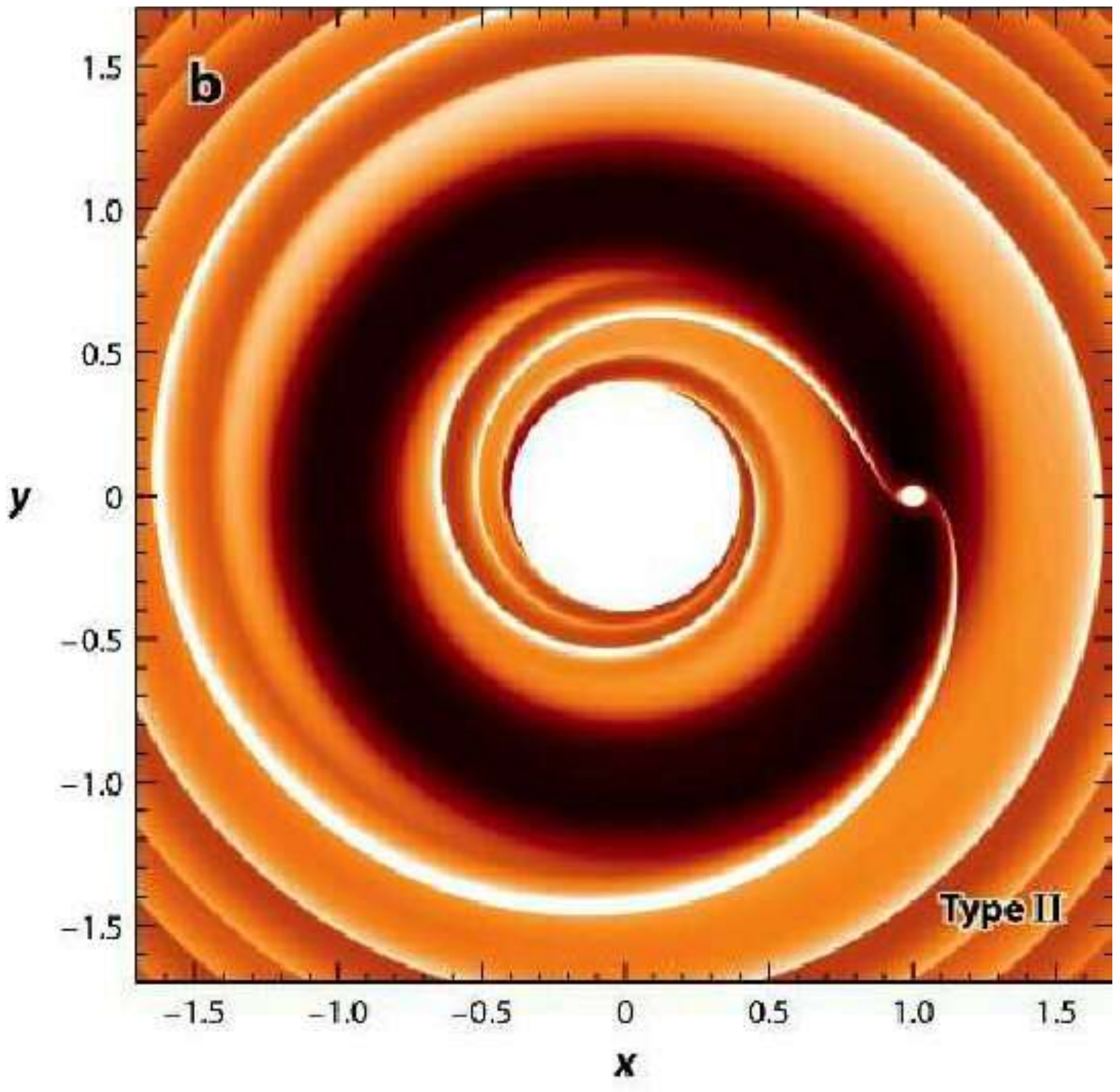


M < 10 M_{Earth}

- Planet creates spiral density waves which exert a torque on the planet
- The **outer** spiral wave applies a bigger torque than the **inner** one
- The planet loses its angular momentum and migrates **toward the star**
- Short timescale: For M < 10 M_{Earth} at 5 AU in a MMSN, the planet would reach the star ~10^5 yrs

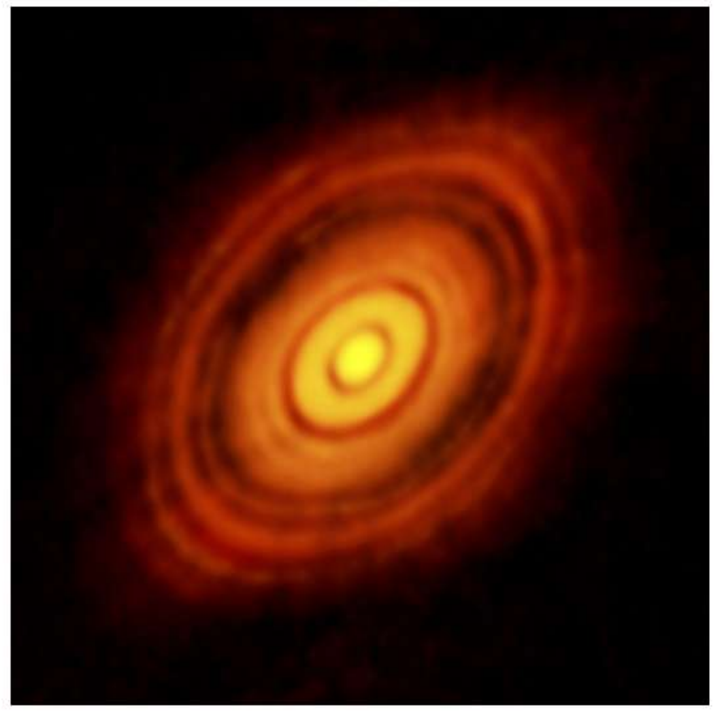
Planet migration

Type II



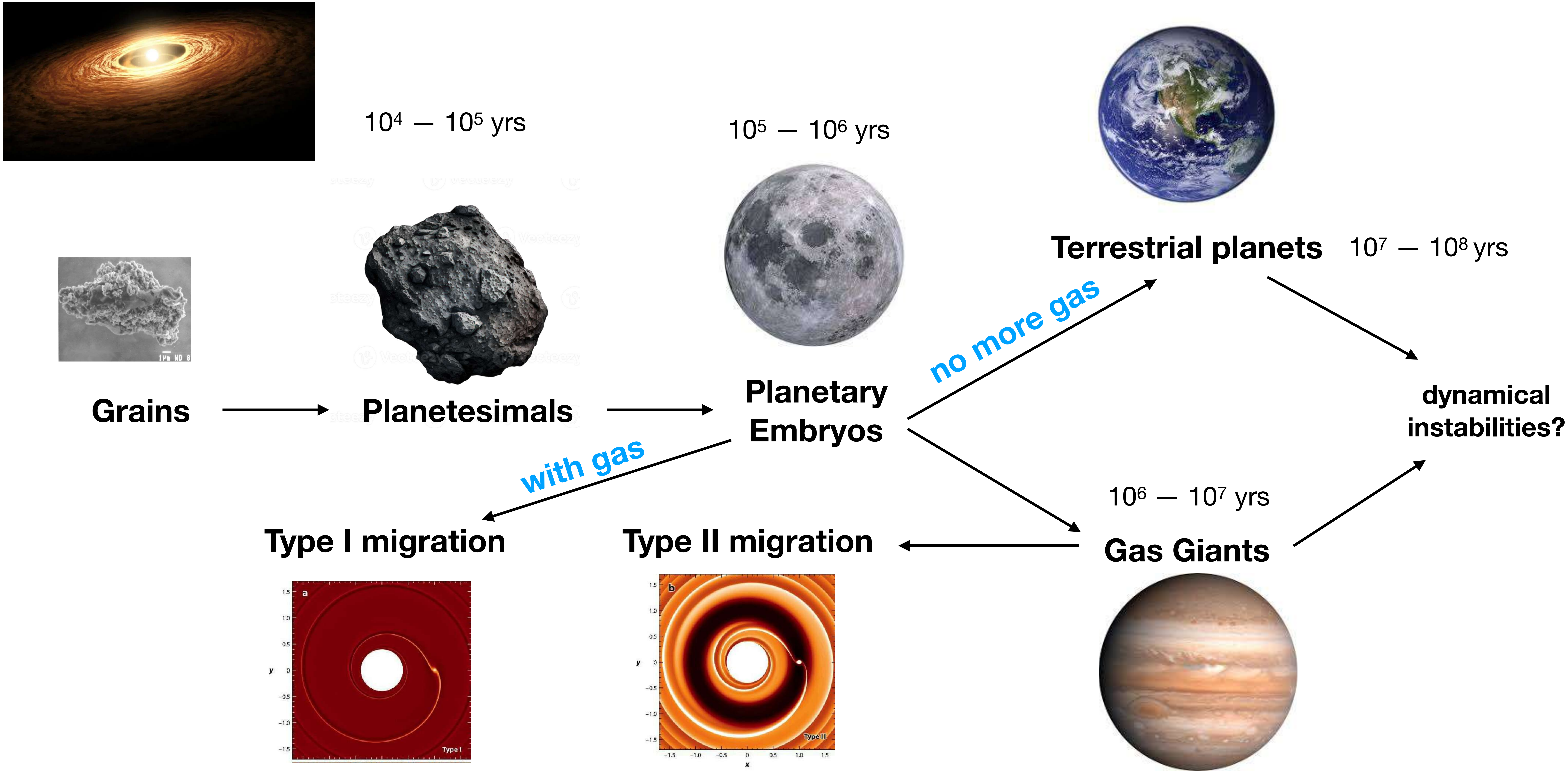
Mp ≳ Saturn mass (~100 M_{Earth}), with a Hill sphere greater than the disk scale height and therefore opens up a gap

- The width of the gap is determined by the T and viscosity of the disk and the mass of the planet => infer planets



- Planet migrates with the viscous evolution of the disk
- Longer timescale: Planet's orbit evolves on a similar timescale as the disk is evolves on the viscous timescale $\tau = \frac{R^2}{\nu} \sim 10^6 \mathrm{yrs}$
- Most likely explanation of how hot Jupiters form

Stage of Planet Formation

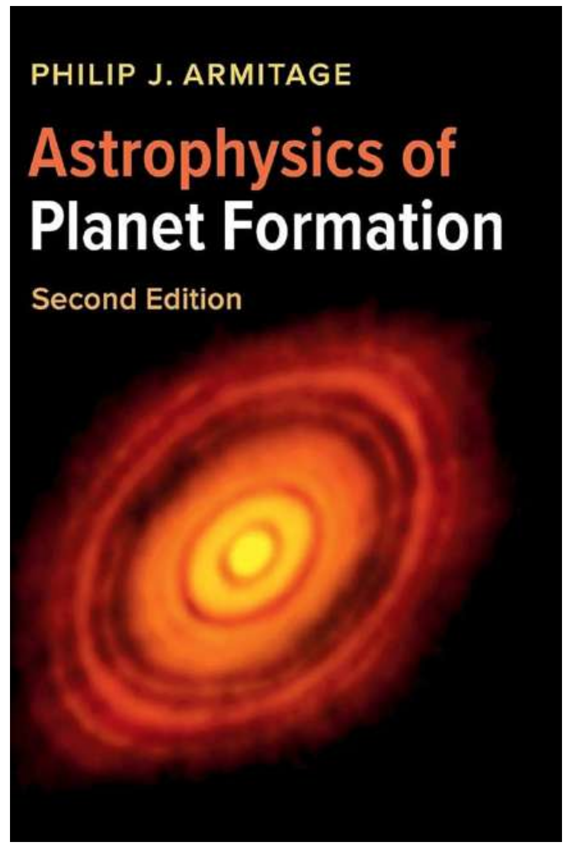


Reading materials

- Digestable notes (Philip Armitage)
  https://solarsystemorigins.wordpress.com

- Comprehensive with equations
  Ch. 13 of “Planetary Sciences” by de Pater and Lissauer, Cambridge University Press
  Review by Johansen and Lambrechts (2017): Forming Planets via Pebble Accretion

- Self-sufficient and didactic:

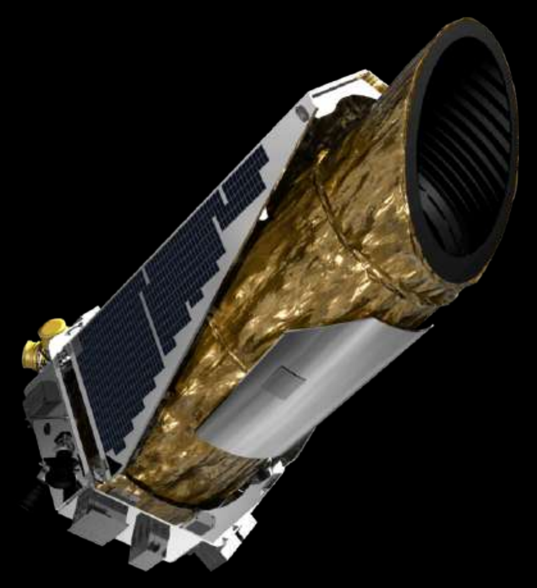


An Incomplete Story of Planet Formation Told by Exoplanet Atmospheres

Exoplanet science has come a long way!

confirmed exoplanets: N = 0 before 1992 ⟶ N > 5000 today

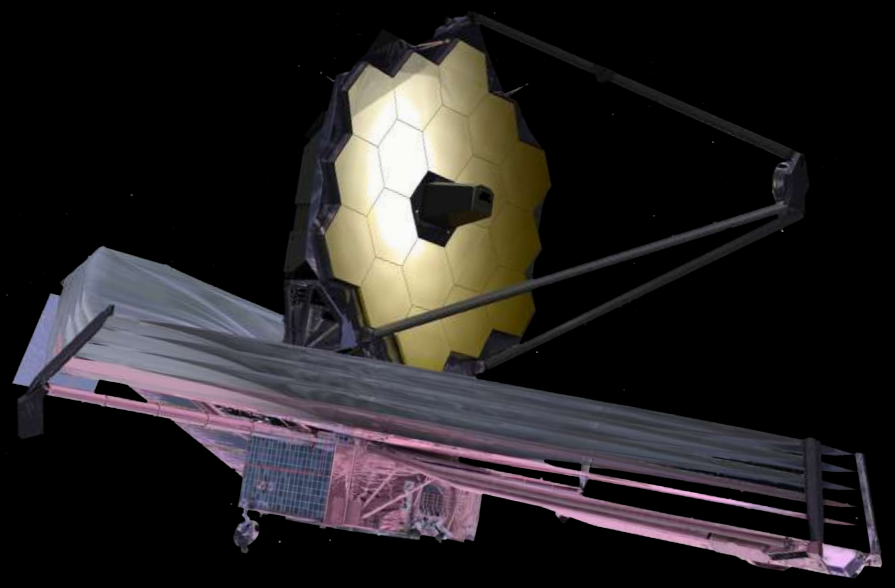
Planet hunters:



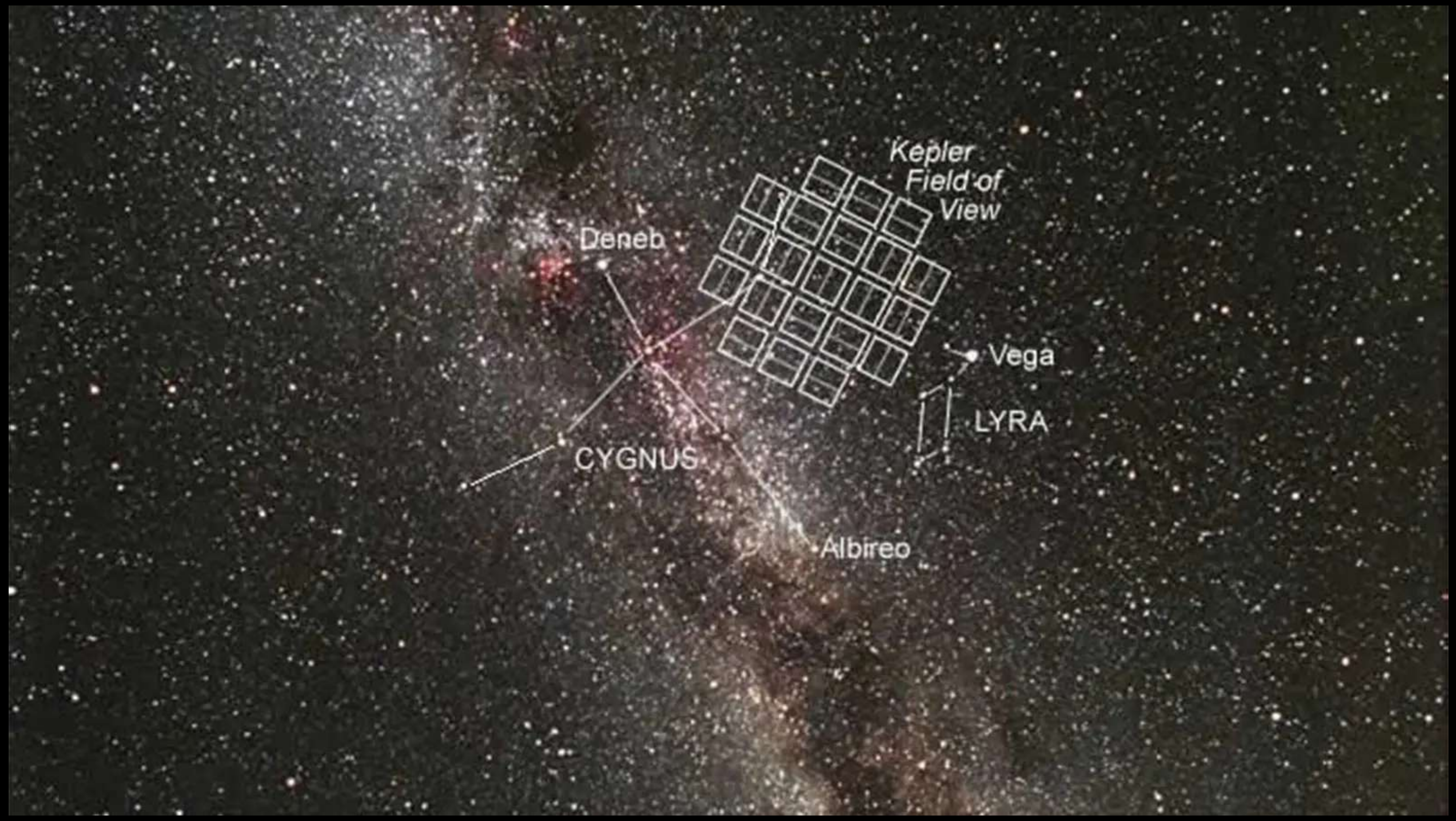
Kepler

TESS

Characterization:



JWST



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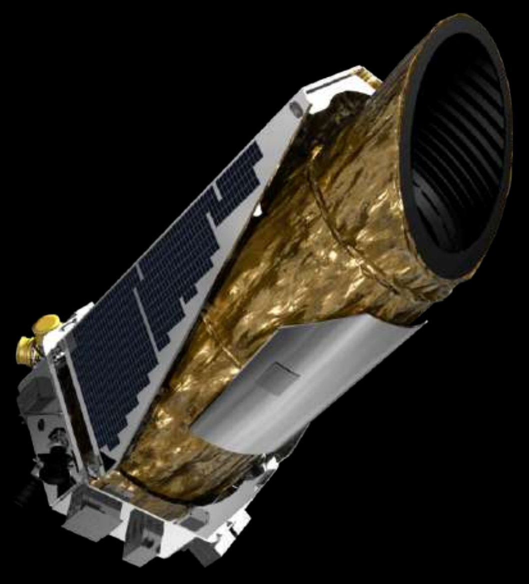
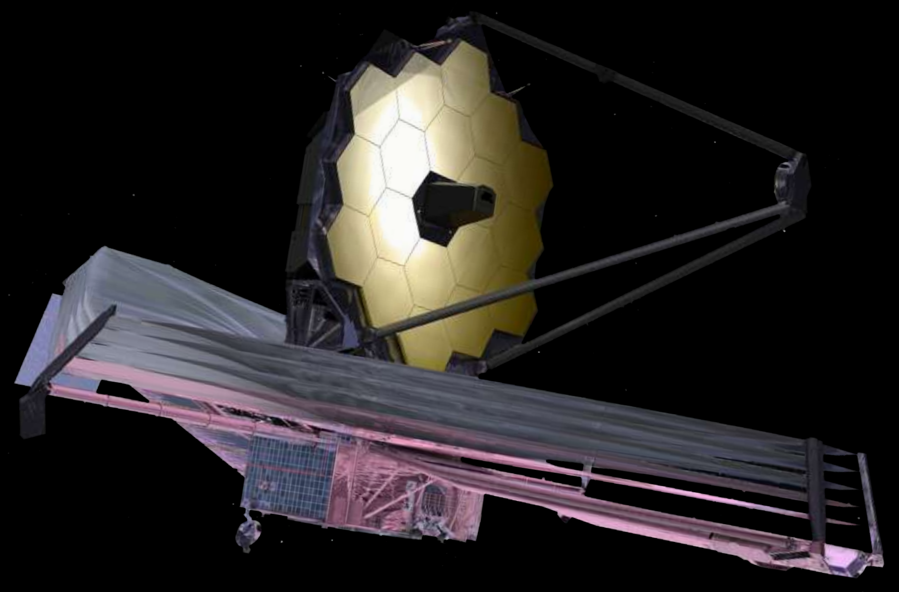


Kepler

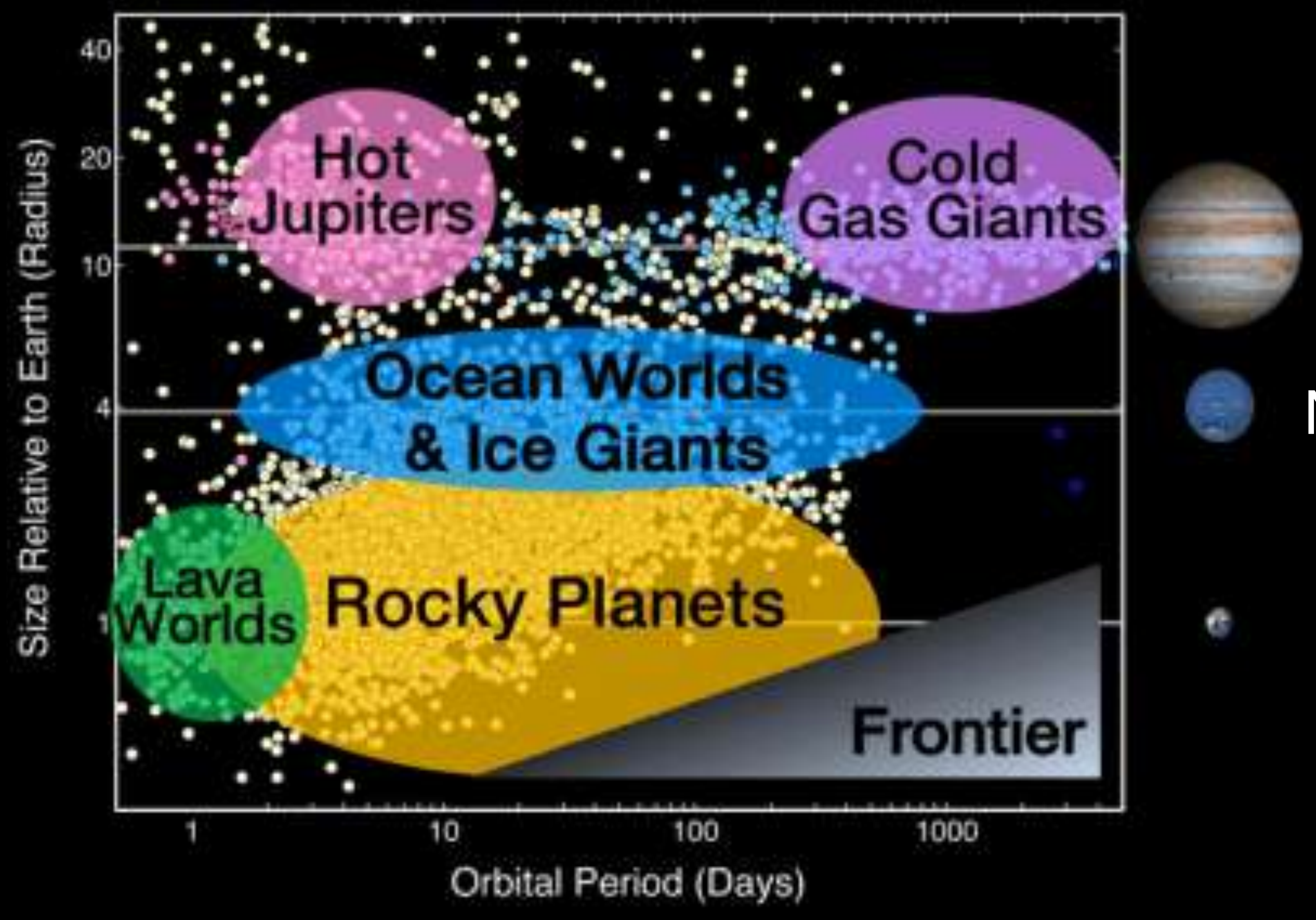
TESS

Characterization:



JWST

Exoplanet population



Jupiter

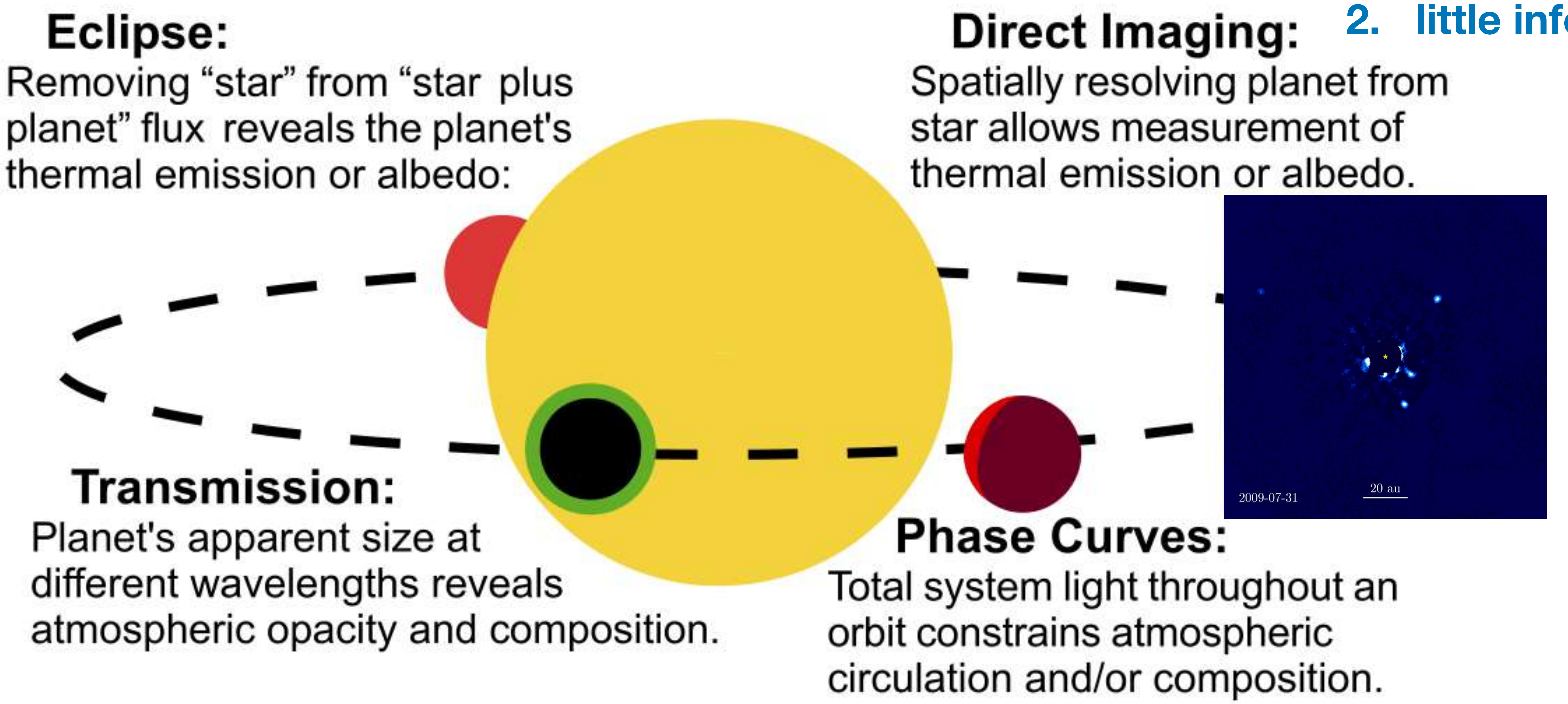
Neptune

Earth

credit: Natalie Batalha

Exploring exoplanet atmospheres from afar

1. **two for the price of one**
2. **little info about R, M, T**



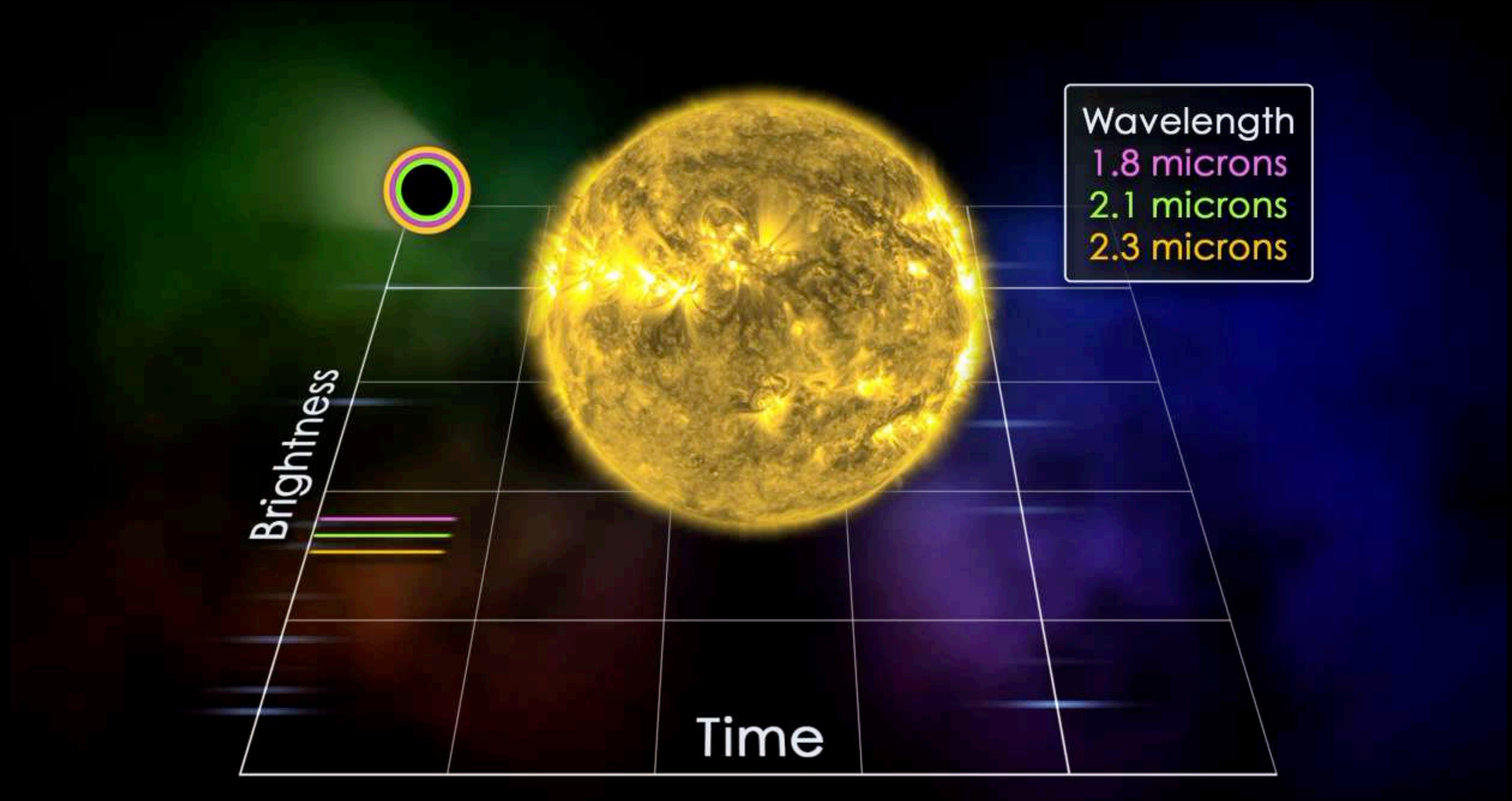
credit: https://gapt.iaa.es/

Transit

—4000+ exoplanets discovered

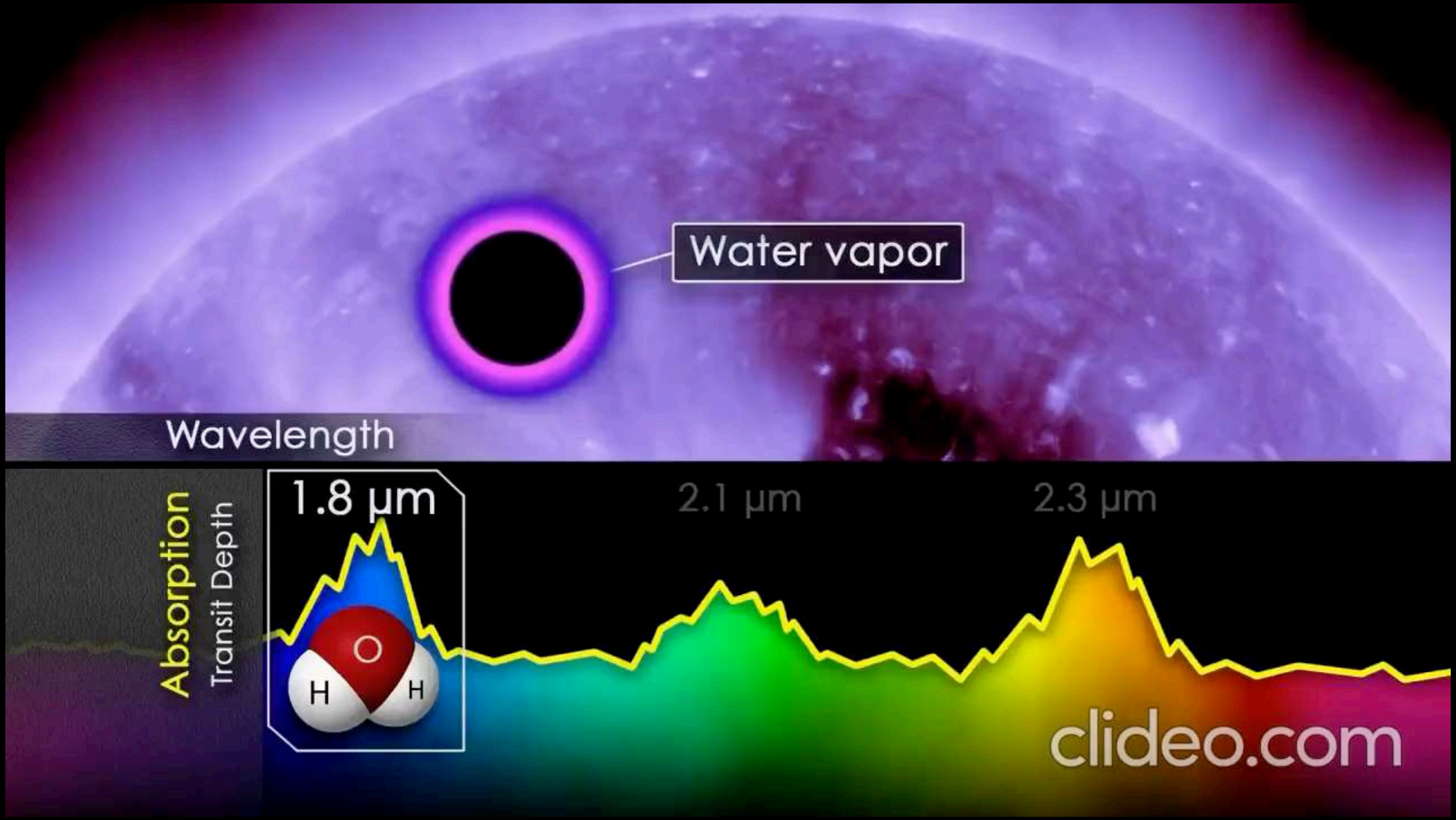
https://exoplanets.nasa.gov/alien-worlds/ways-to-find-a-planet/

Transmission spectroscopy



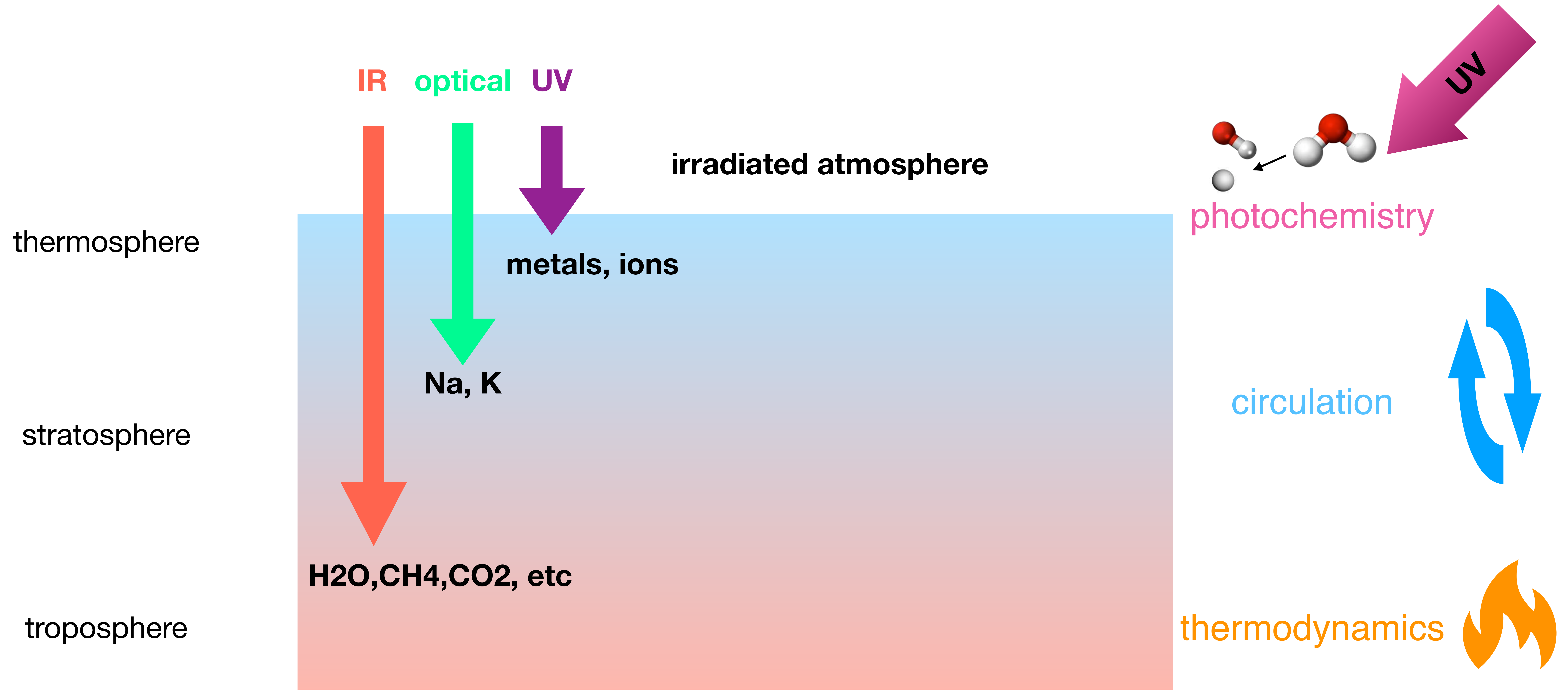
credit: NASA's Goddard Space Flight Center

Transmission spectroscopy

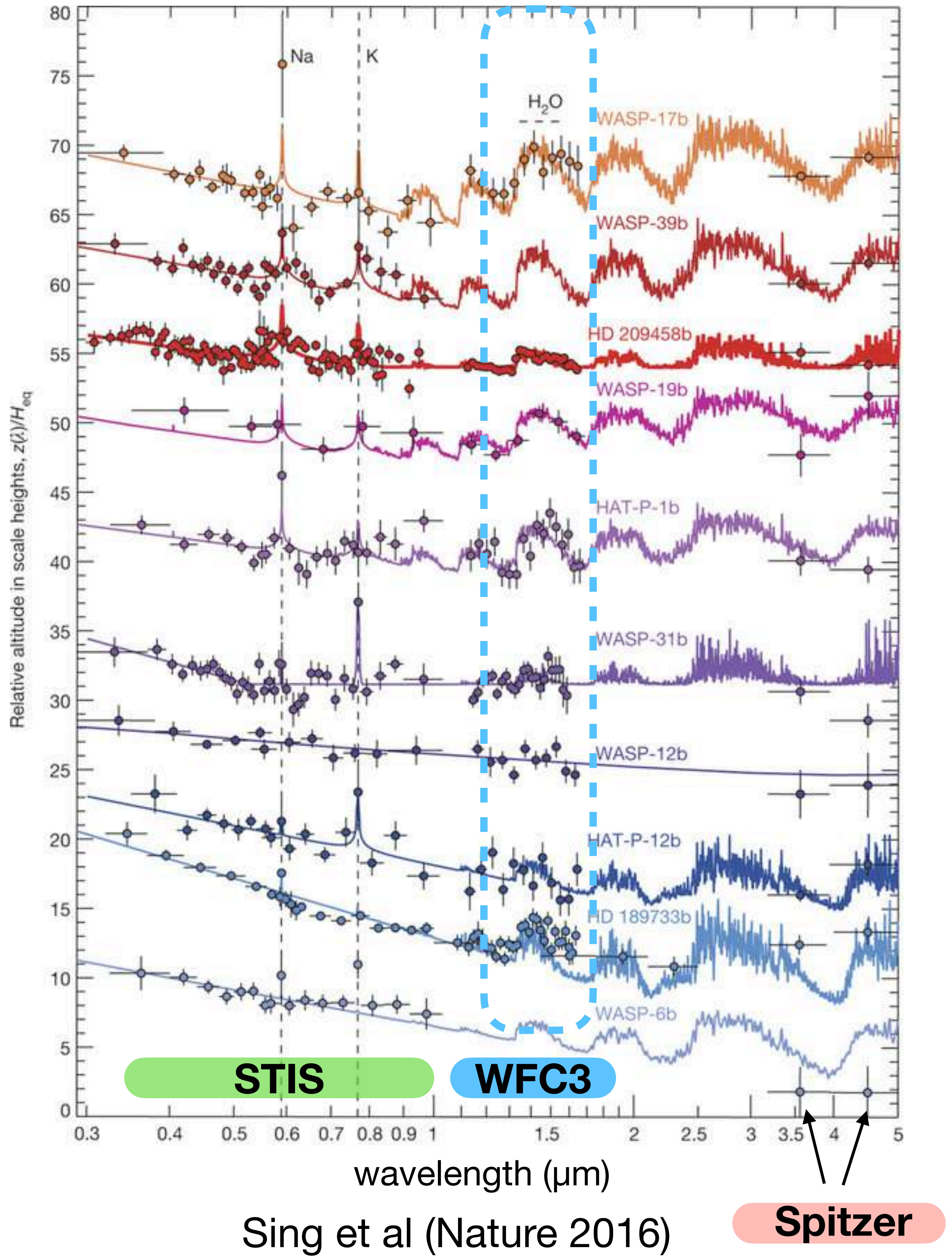


credit: NASA Goddard Media Studios

What governs the atmospheric composition?



Water is easier to measure for hot giant exoplanets

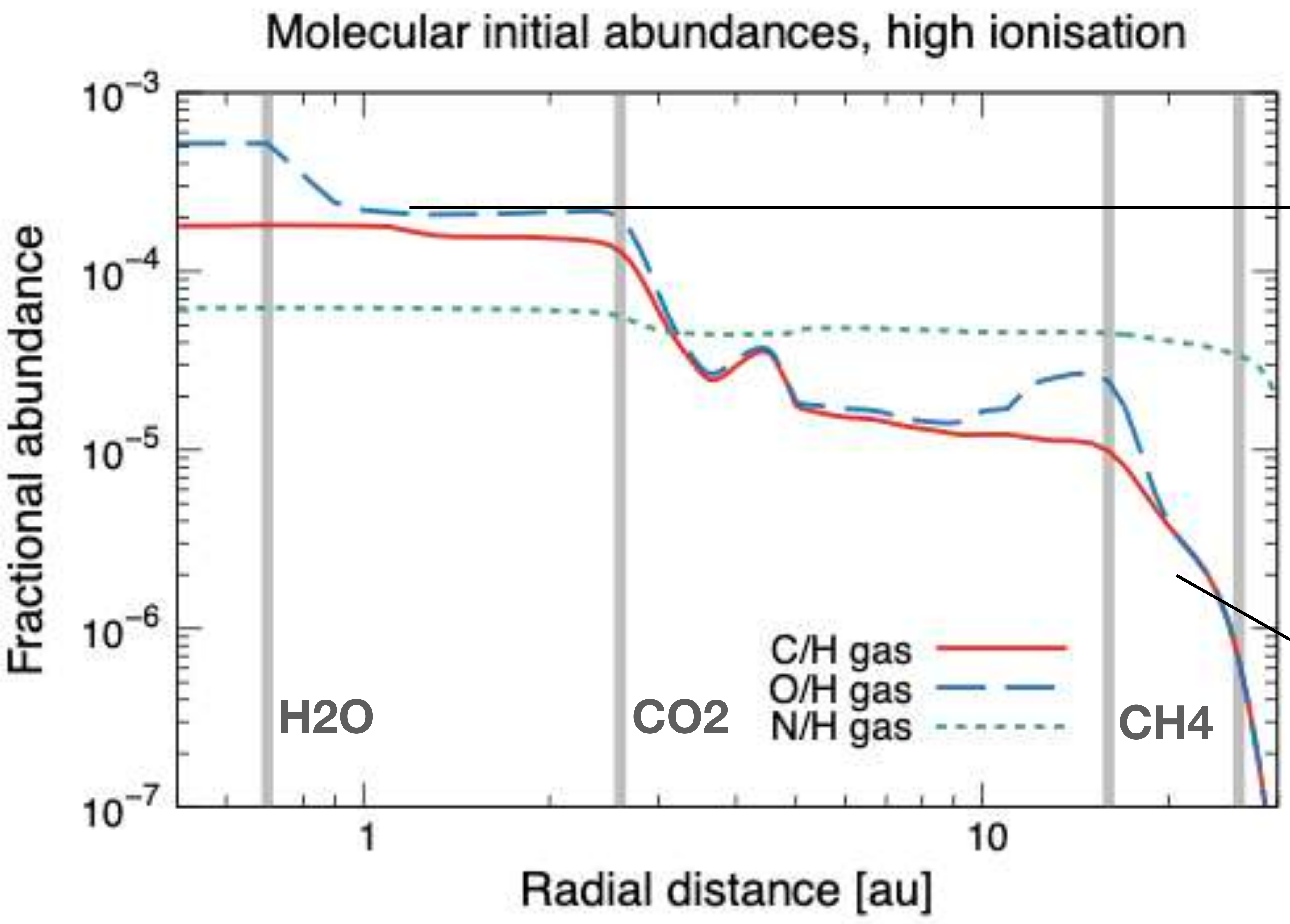


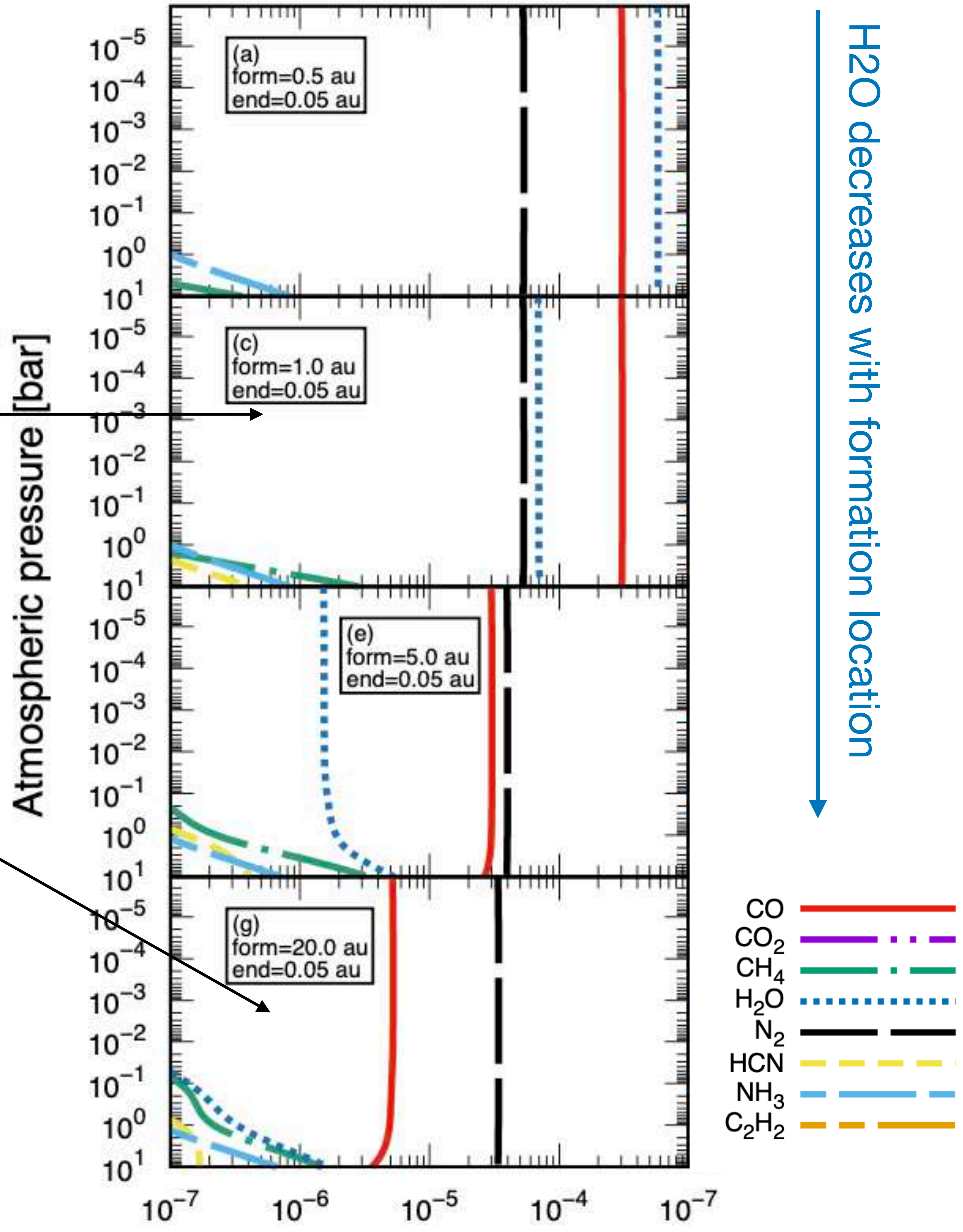
Sing et al (Nature 2016)

- Water is ubiquitous
  with varying absorption strength

- Enhanced optical scattering slopes

Formation locations relative to snowline positions

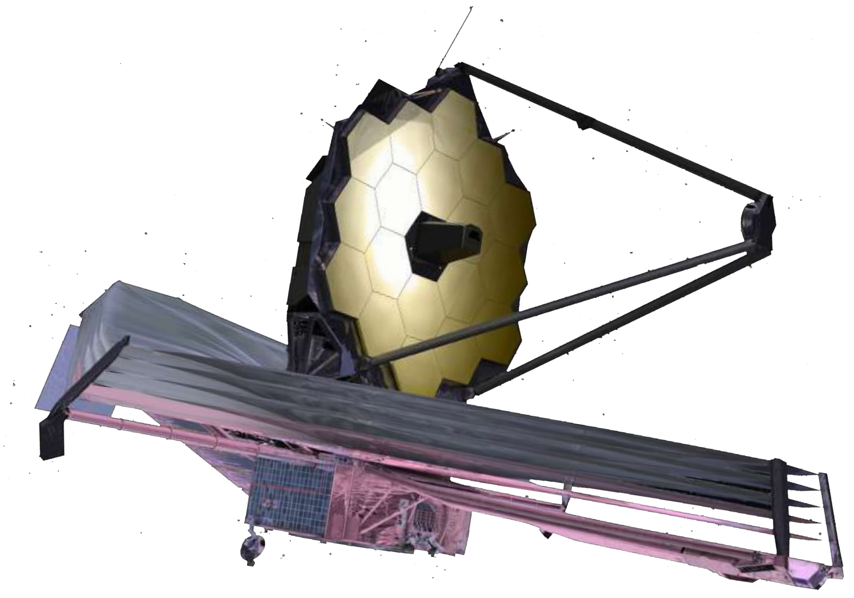




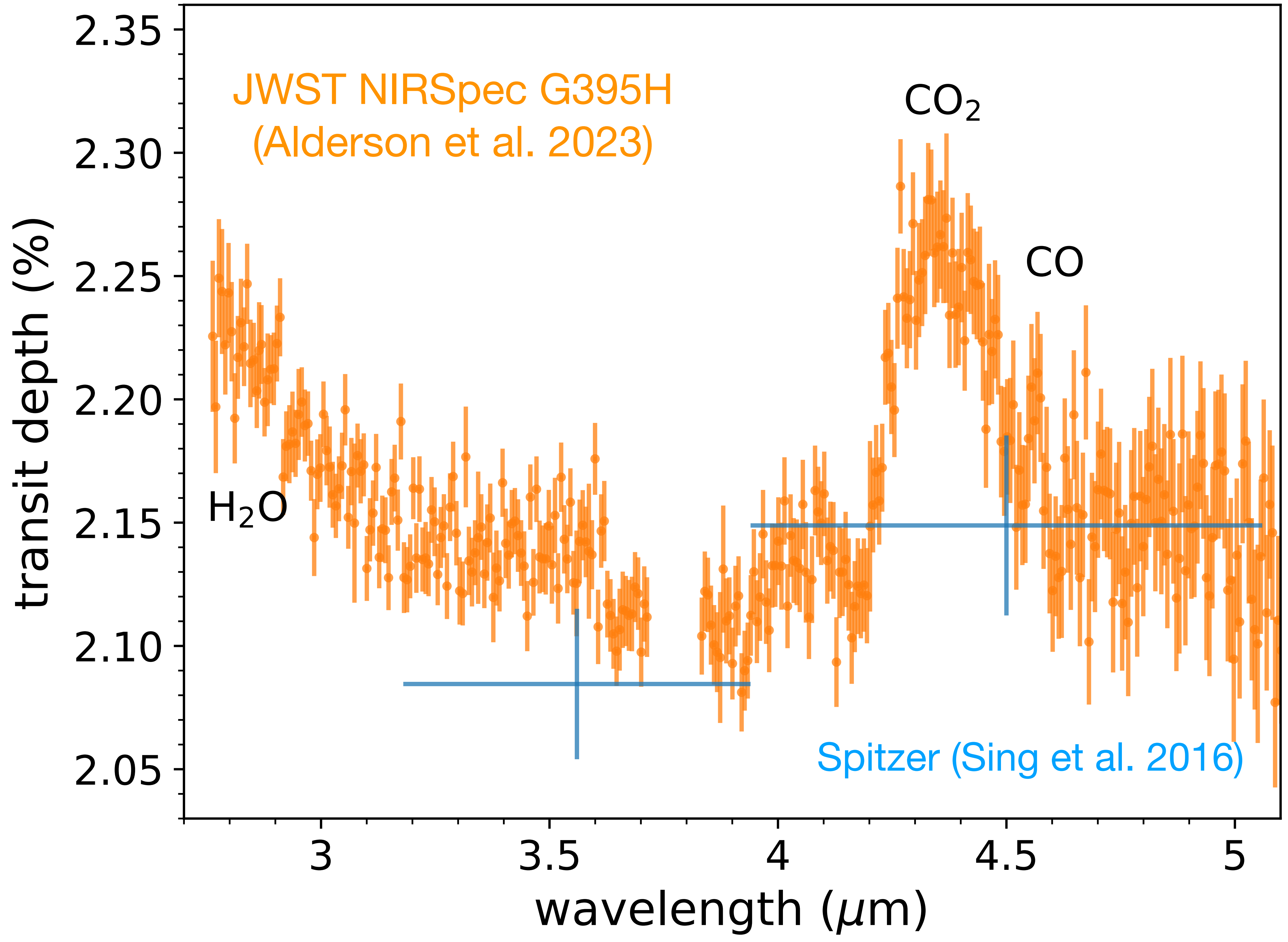
H2O decreases with formation location

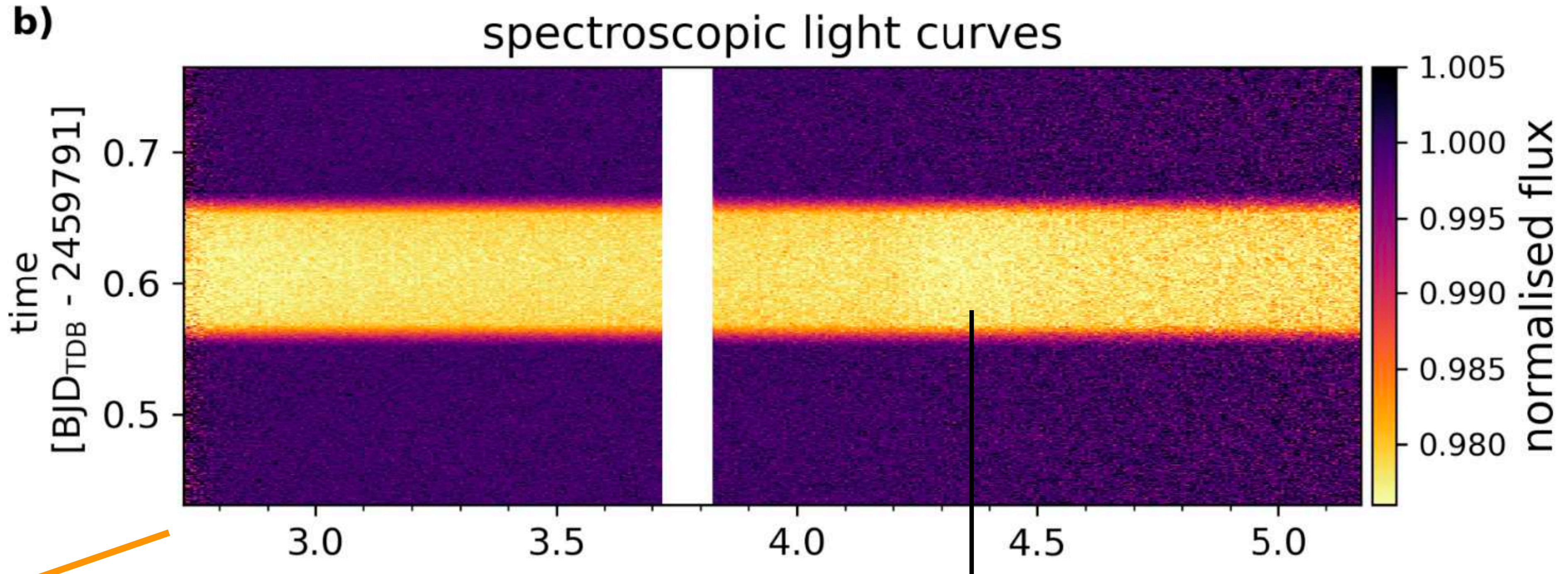
—100% from midplane gas

Notsu et al. (2020)



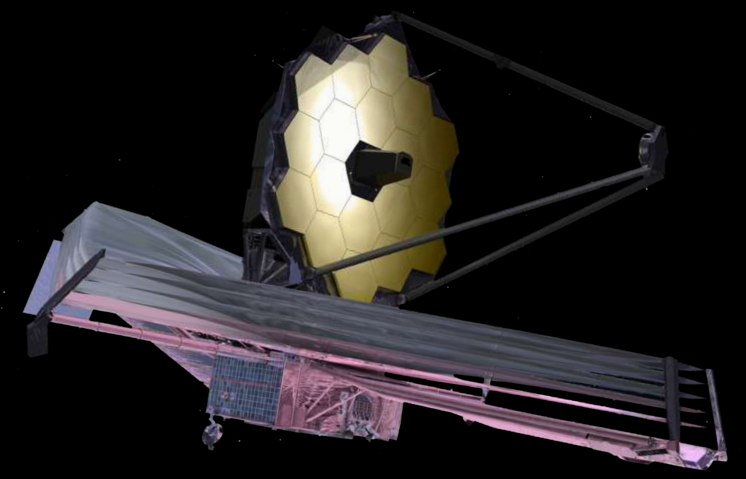
JWST opens the IR window





CO2

Mysterious Molecule



WASP-39 b

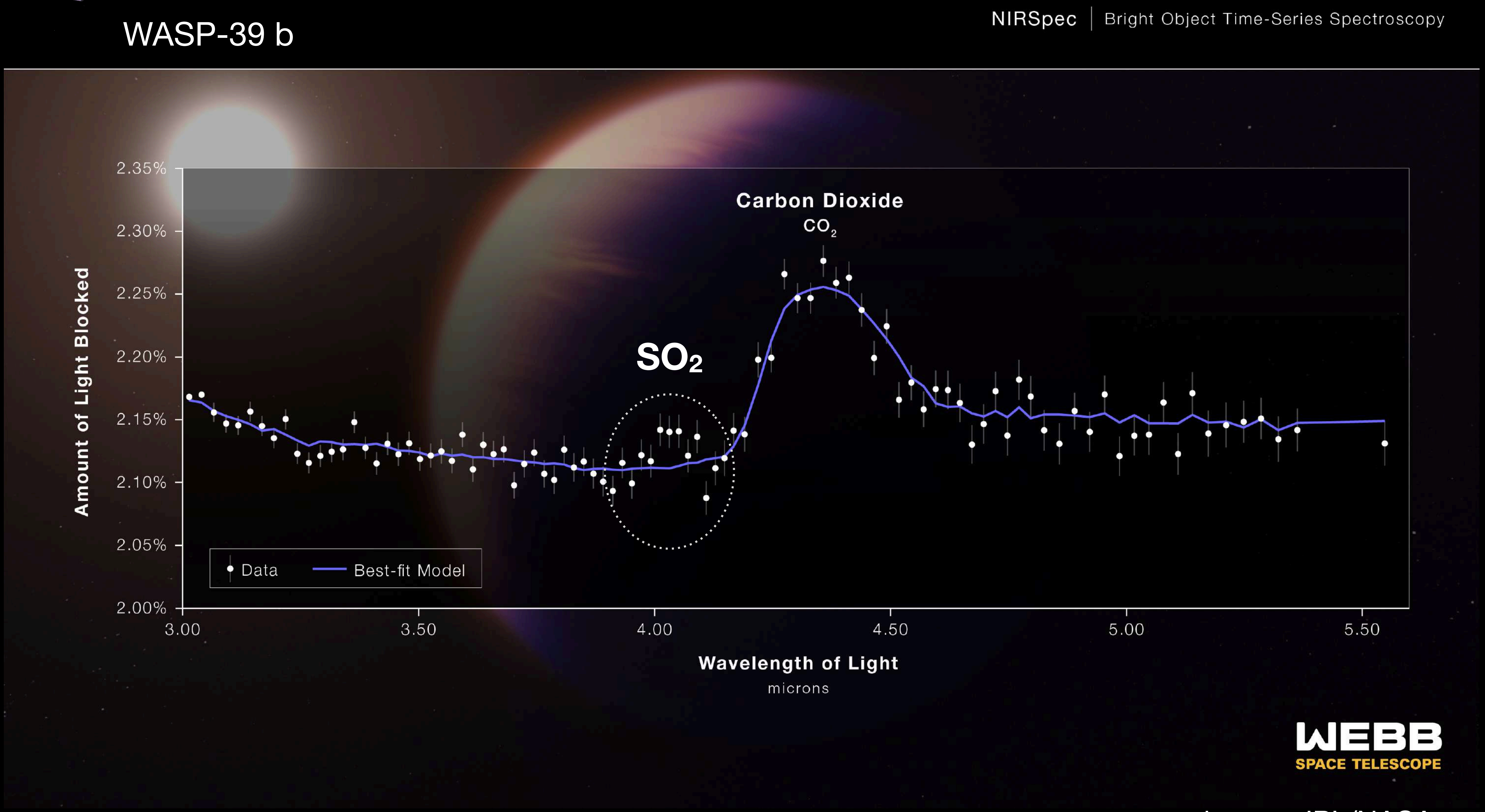
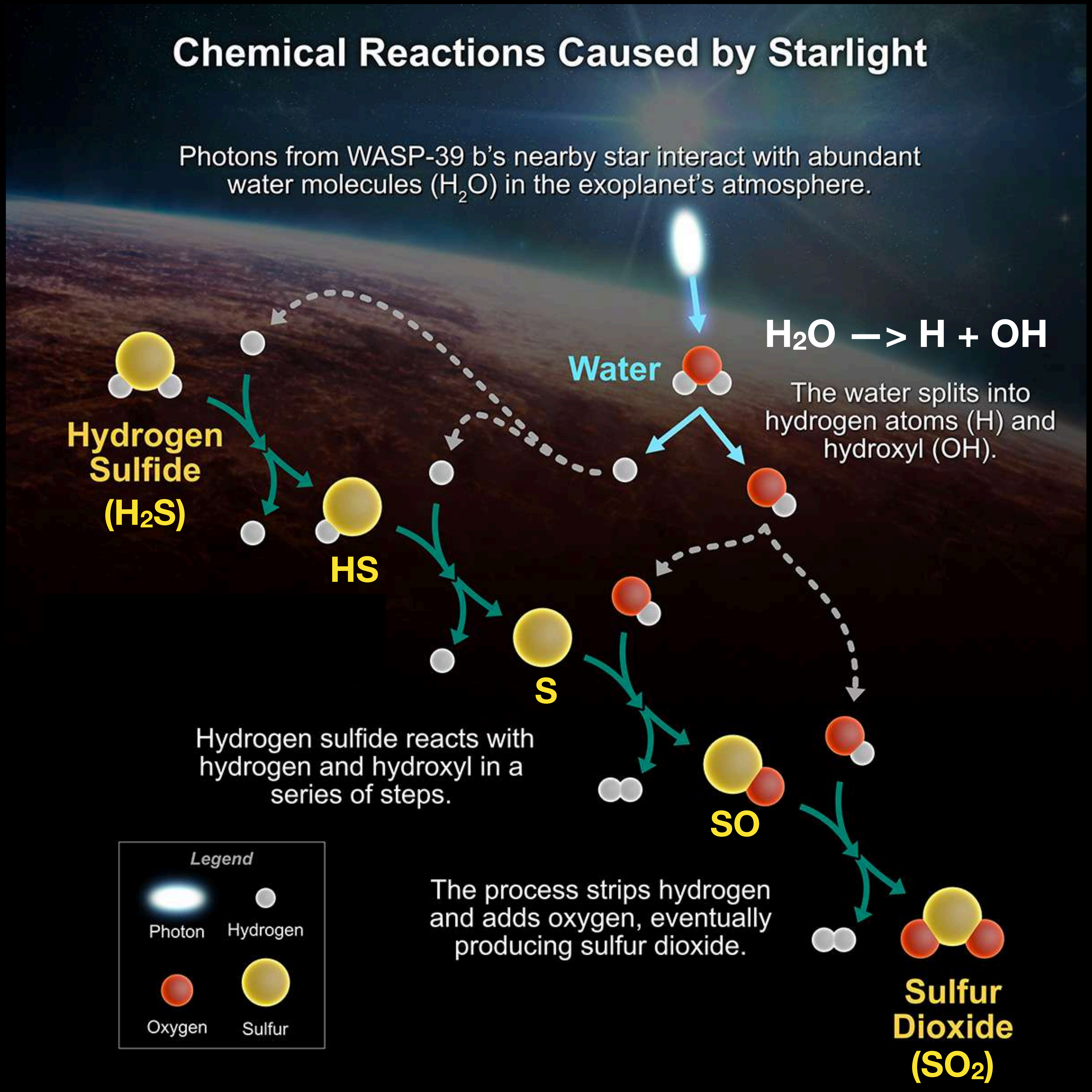
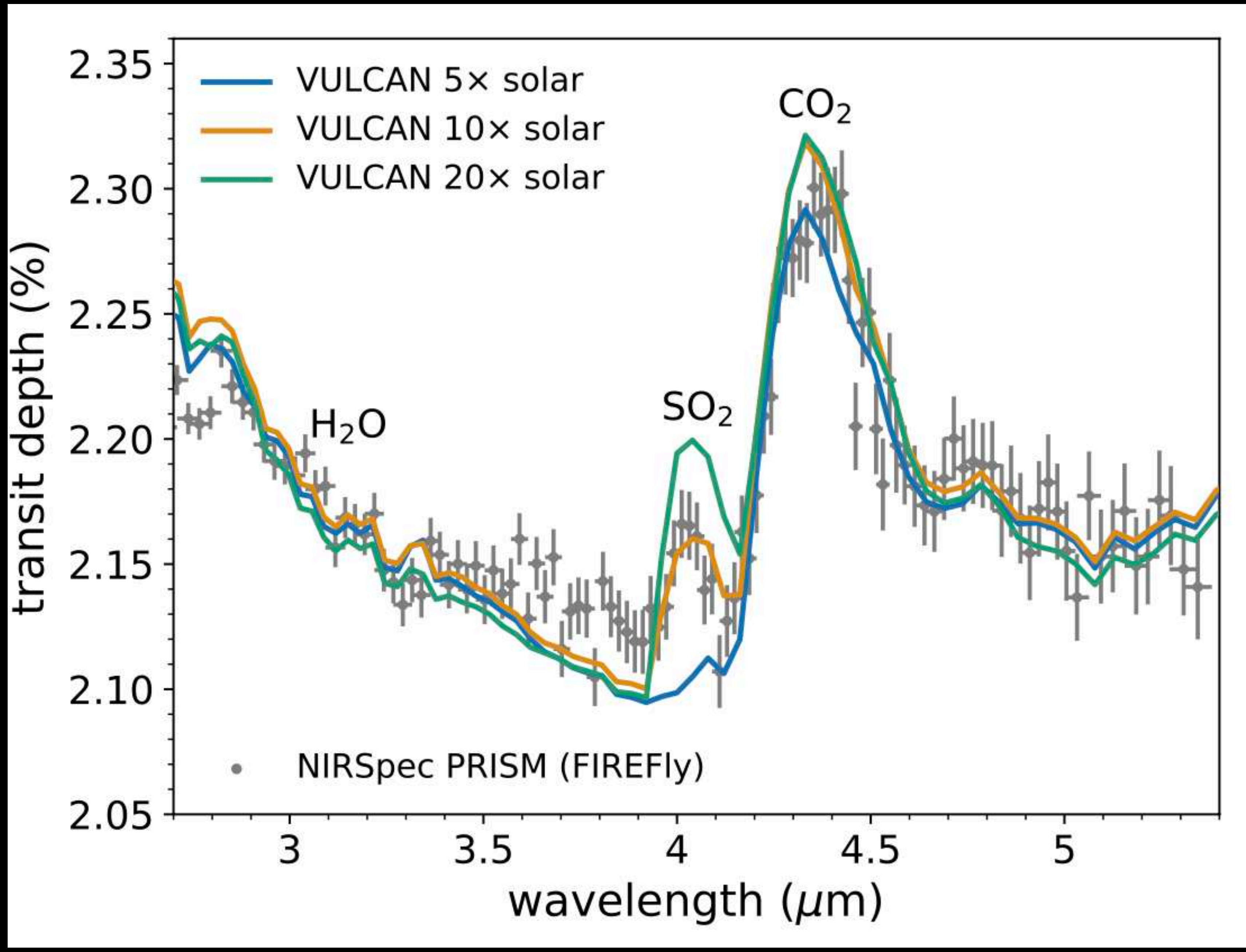


image: JPL/NASA

Sulfur dioxide (SO_2) reveals photochemistry and formation history

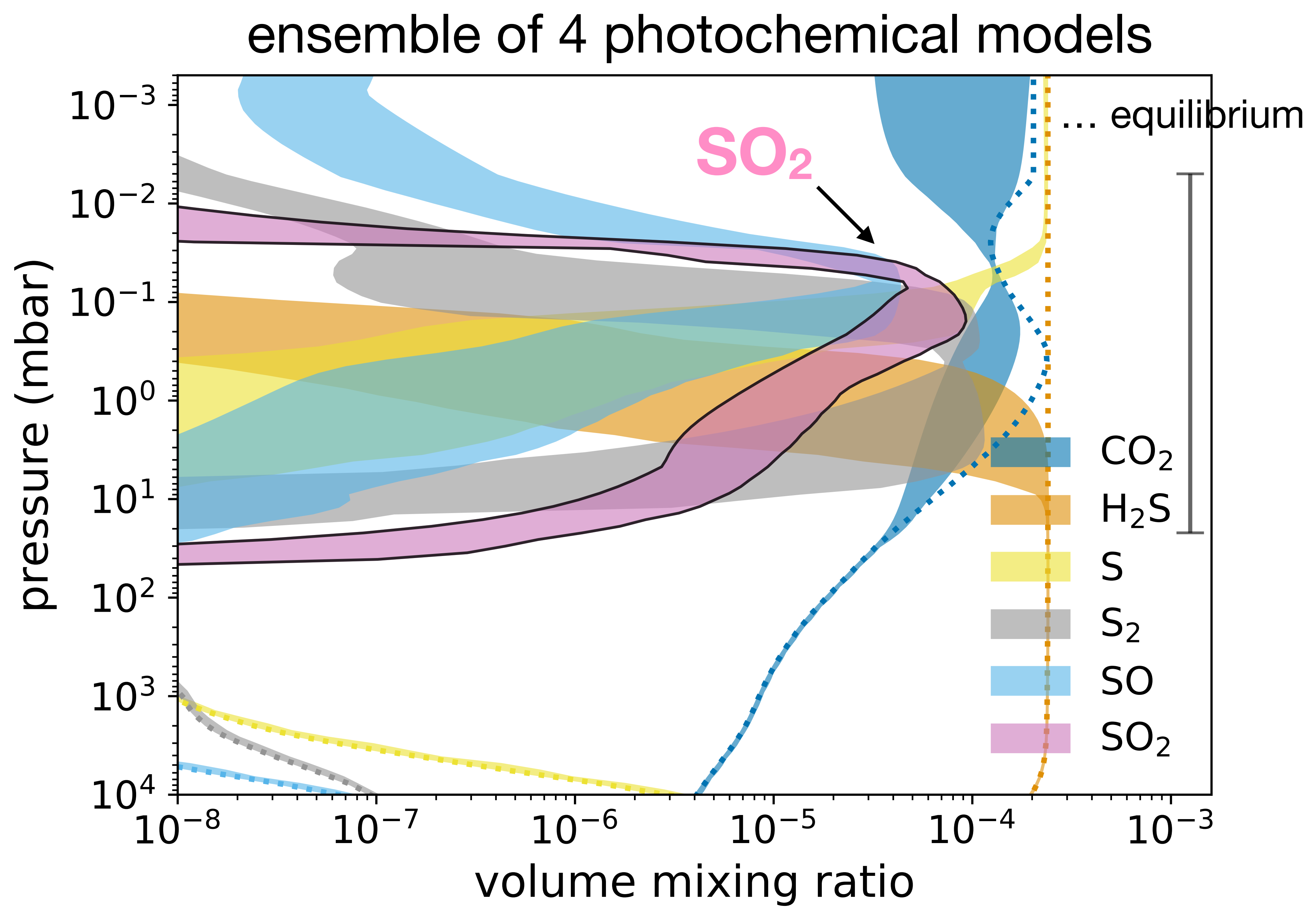


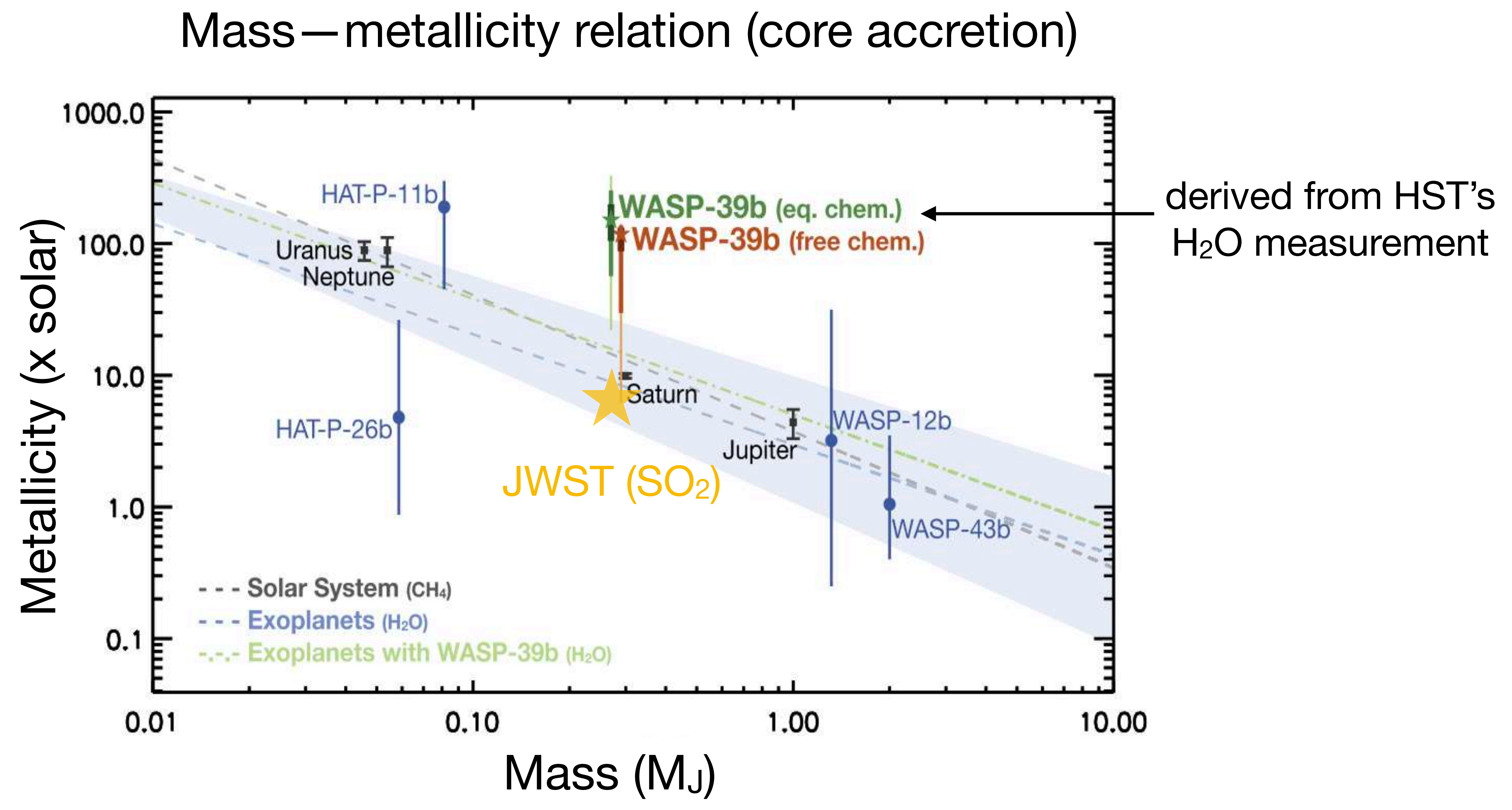
SO_2 is a good tracer for **metallicity** (heavy elements)



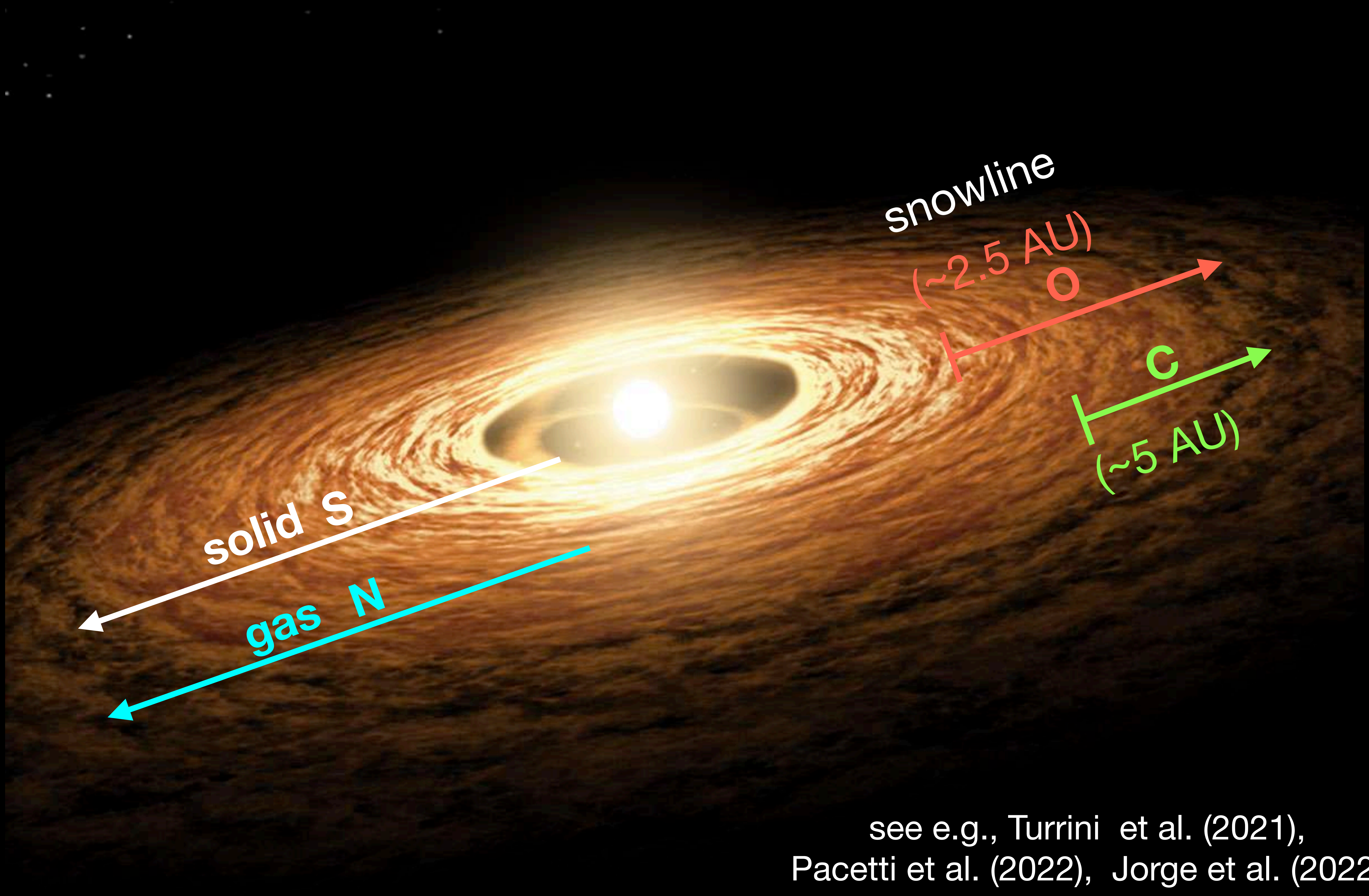
Tsai et al. (2023a, Nature)

Refined mass-metallicity relation



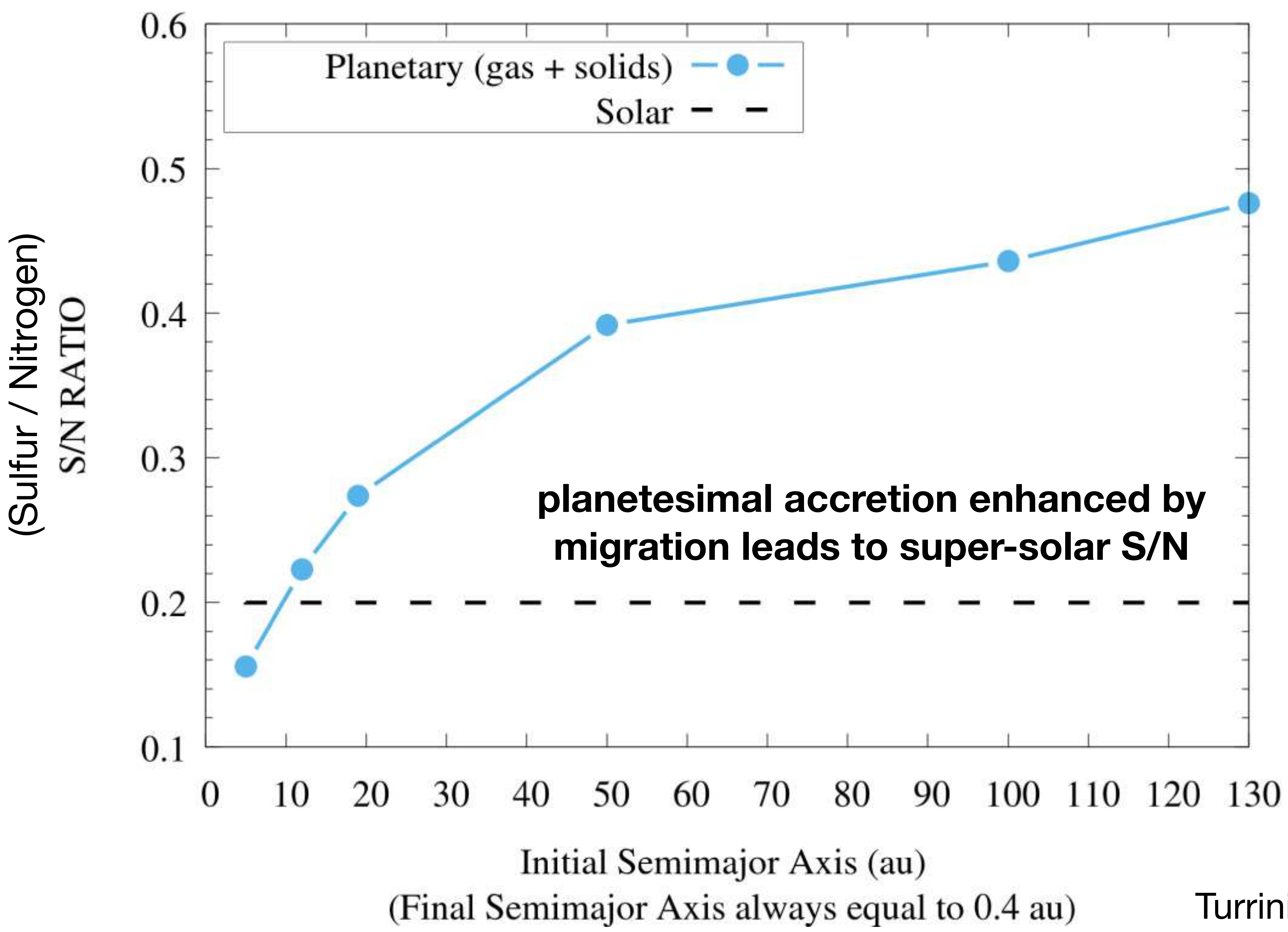


Insights into solid accretion



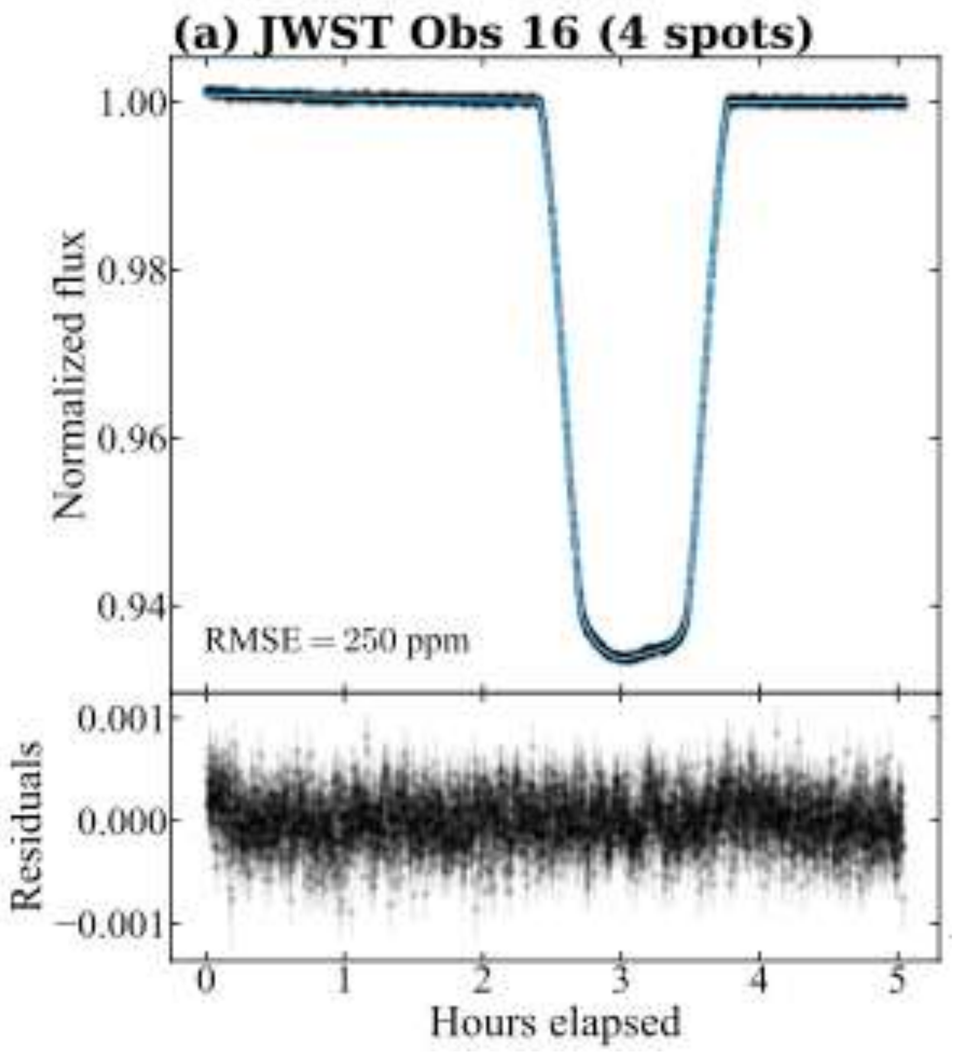
see e.g., Turrini et al. (2021),
Pacetti et al. (2022), Jorge et al. (2022)

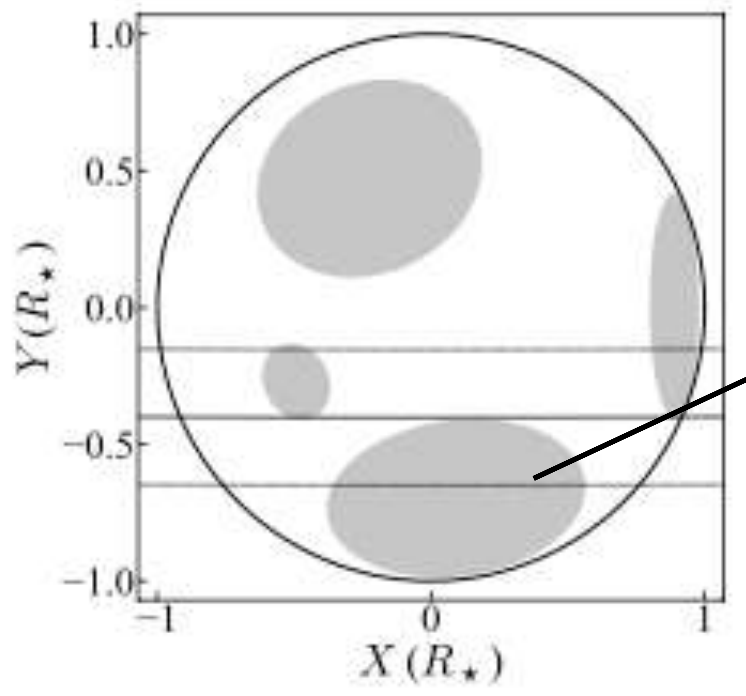
Sulfur provides insights into planetary migration history



Turrini et al. (2021)

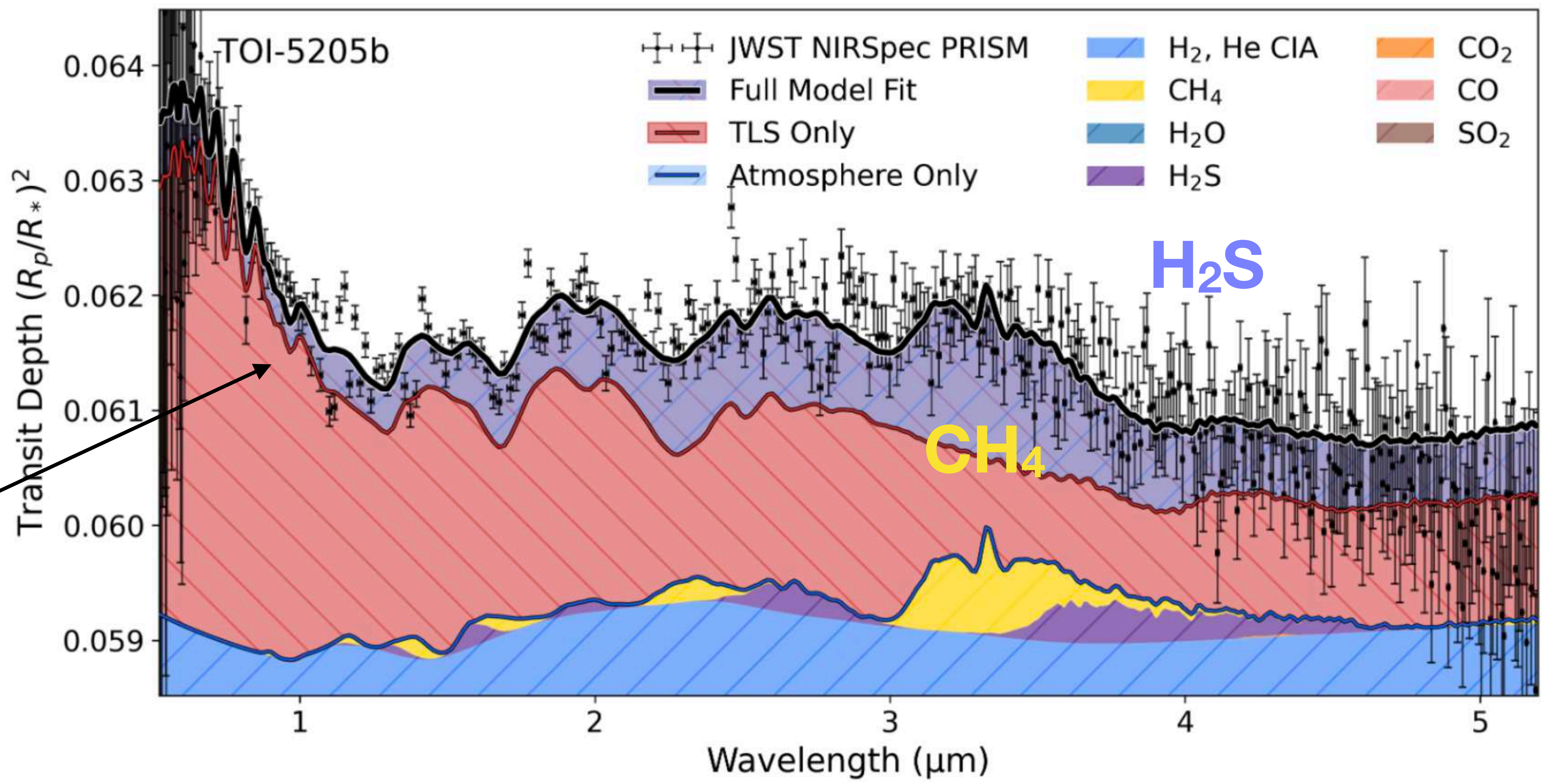
Very low metallicity and super-solar C/O revealed on a M-star giant?





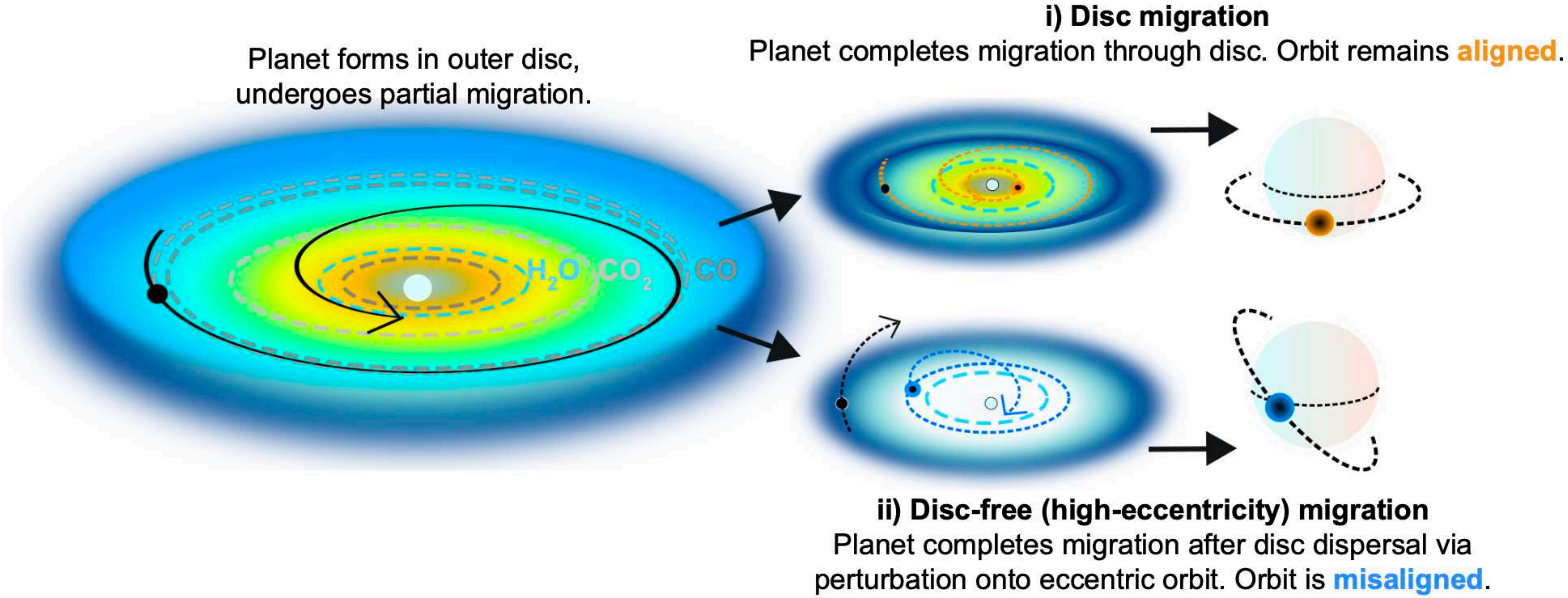
GEMS (**7 M-star giants**) JWST Cycle 2 GO #3171

— Detection of CH_4 and H_2S on a M-star gas giant suggests low metallicity and high S/H, C/O ratios which implies extensive **migration** and solid enrichment



Cañas, Lustig-Yaeger, **Tsai** et al. submitted

Distinguish different migration pathways

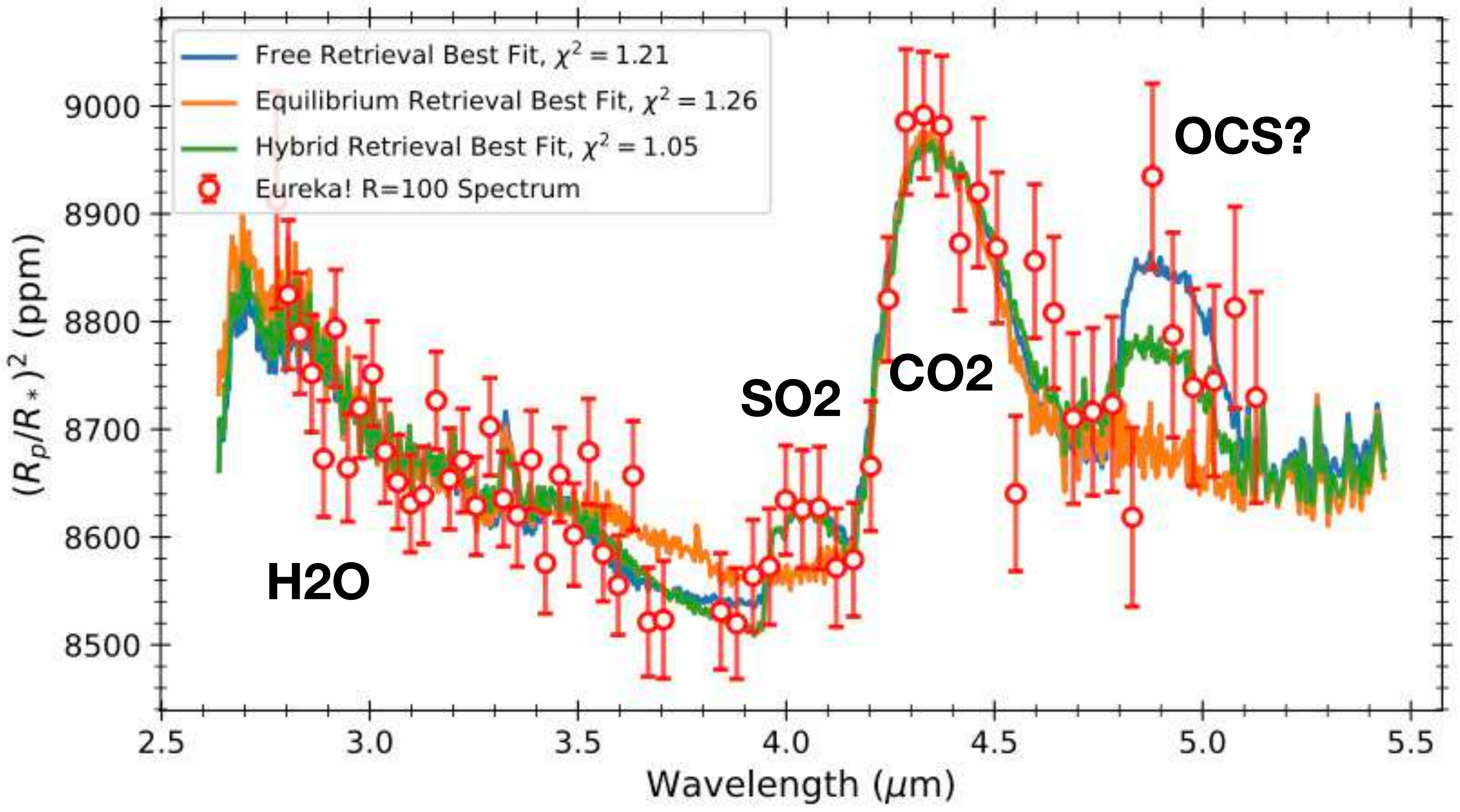


Kirk et al. (2024)

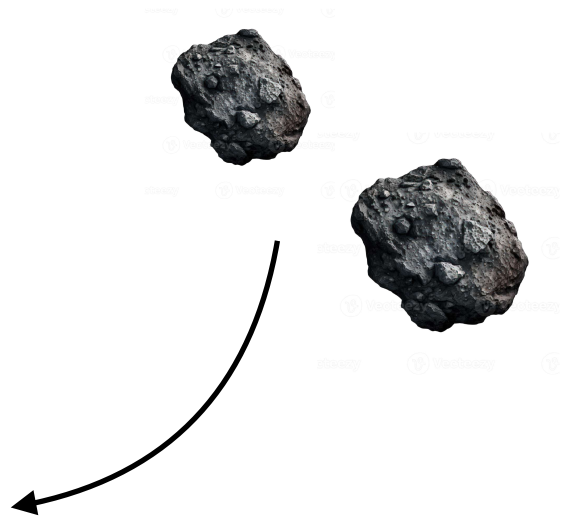
Distinguish different migration pathways

WASP-15 b obliquity = - 139.6

super-solar metallicity (~15X solar)



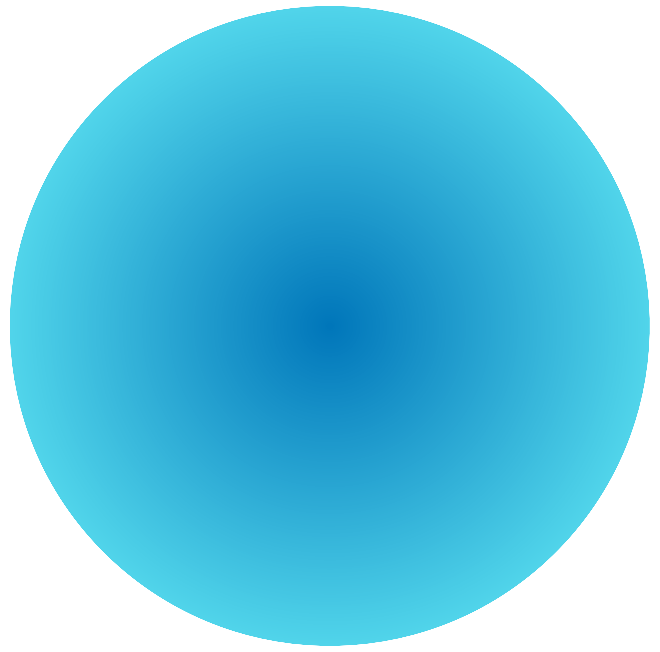
late accretion of solids?



Kirk et al. (2025, inc. Tsai)

Most common class of planets is missing in our solar system

Earth

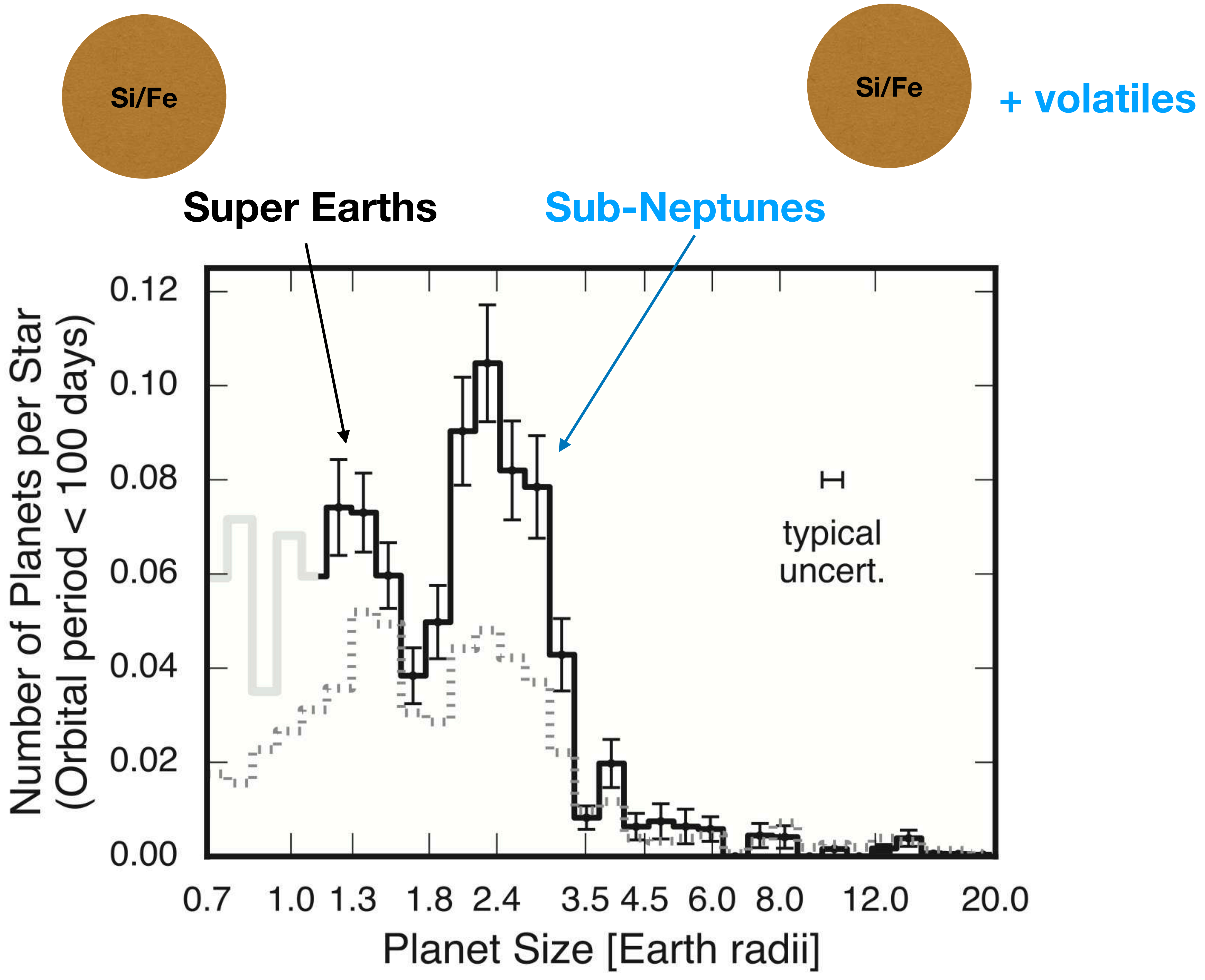


A common exoplanet size
$R_{Earth} < R < R_{Neptune}$

Neptune
R ~ 4 Earth radii

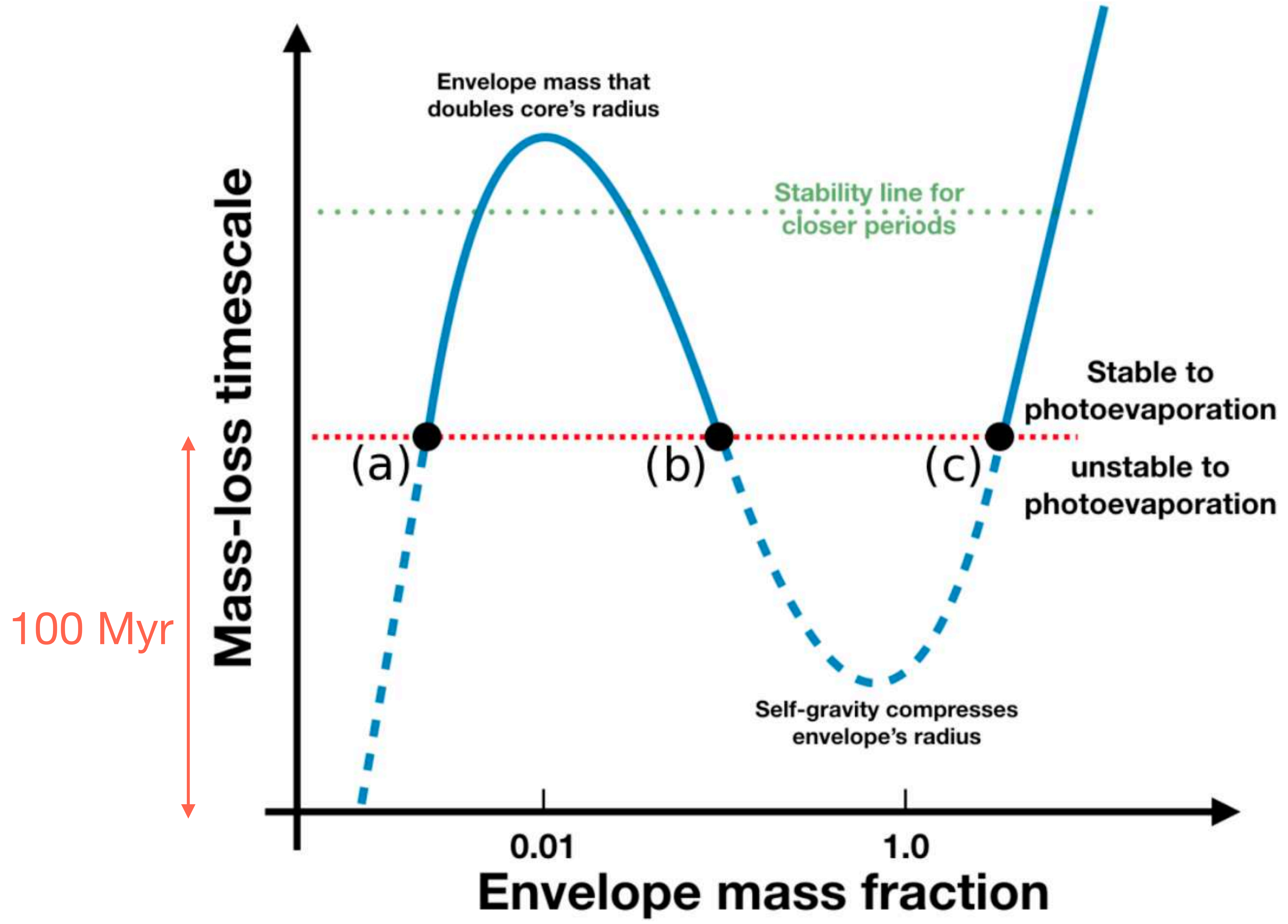
e.g., Fulton et al. (2017), Thompson et al. (2018)

Small planets come in two sizes



Fulton & Petigura (2018)

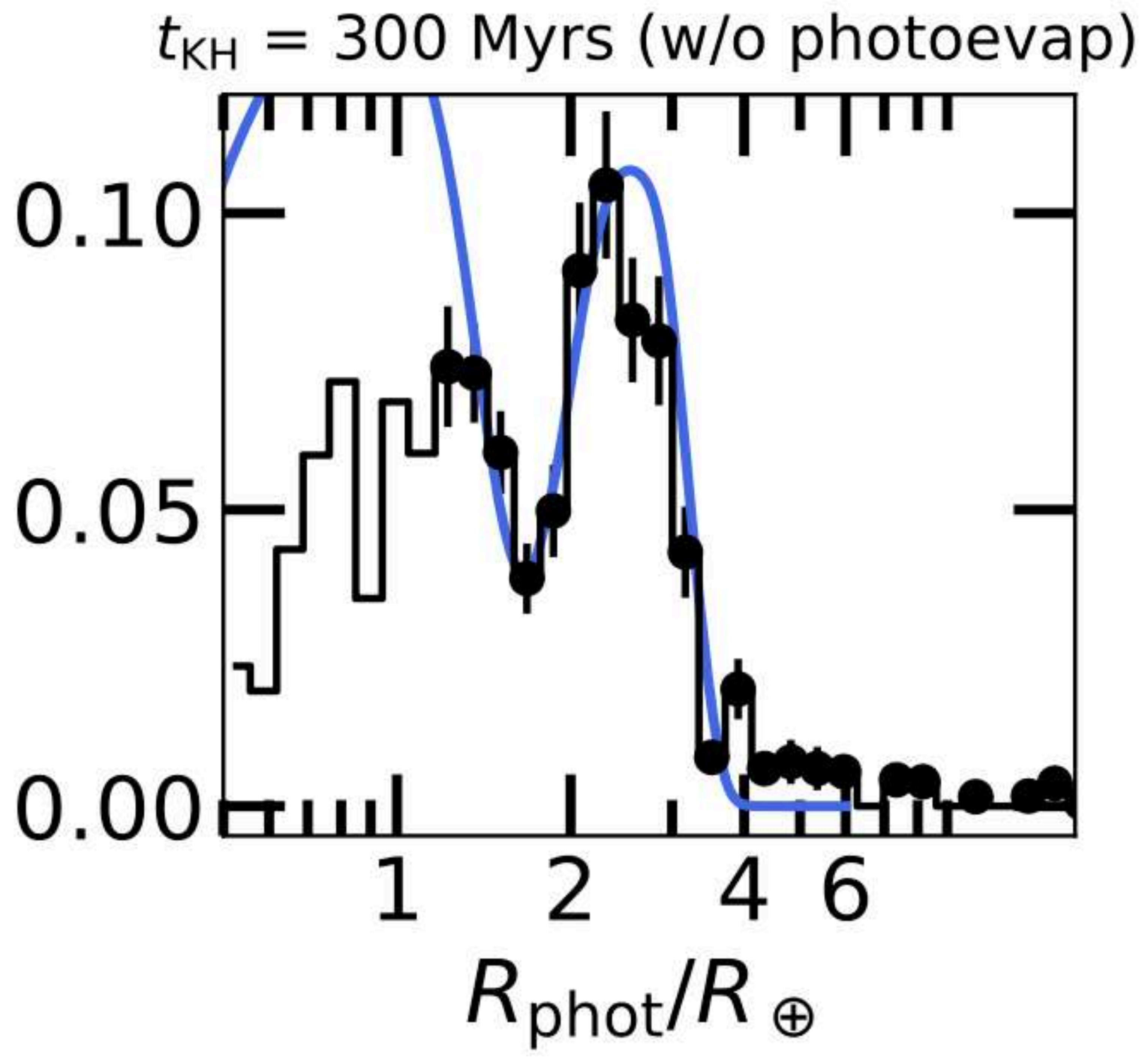
Mass loss timescale of photoevaporation



Owen & Lai (2018)

Primordial Radius Gap

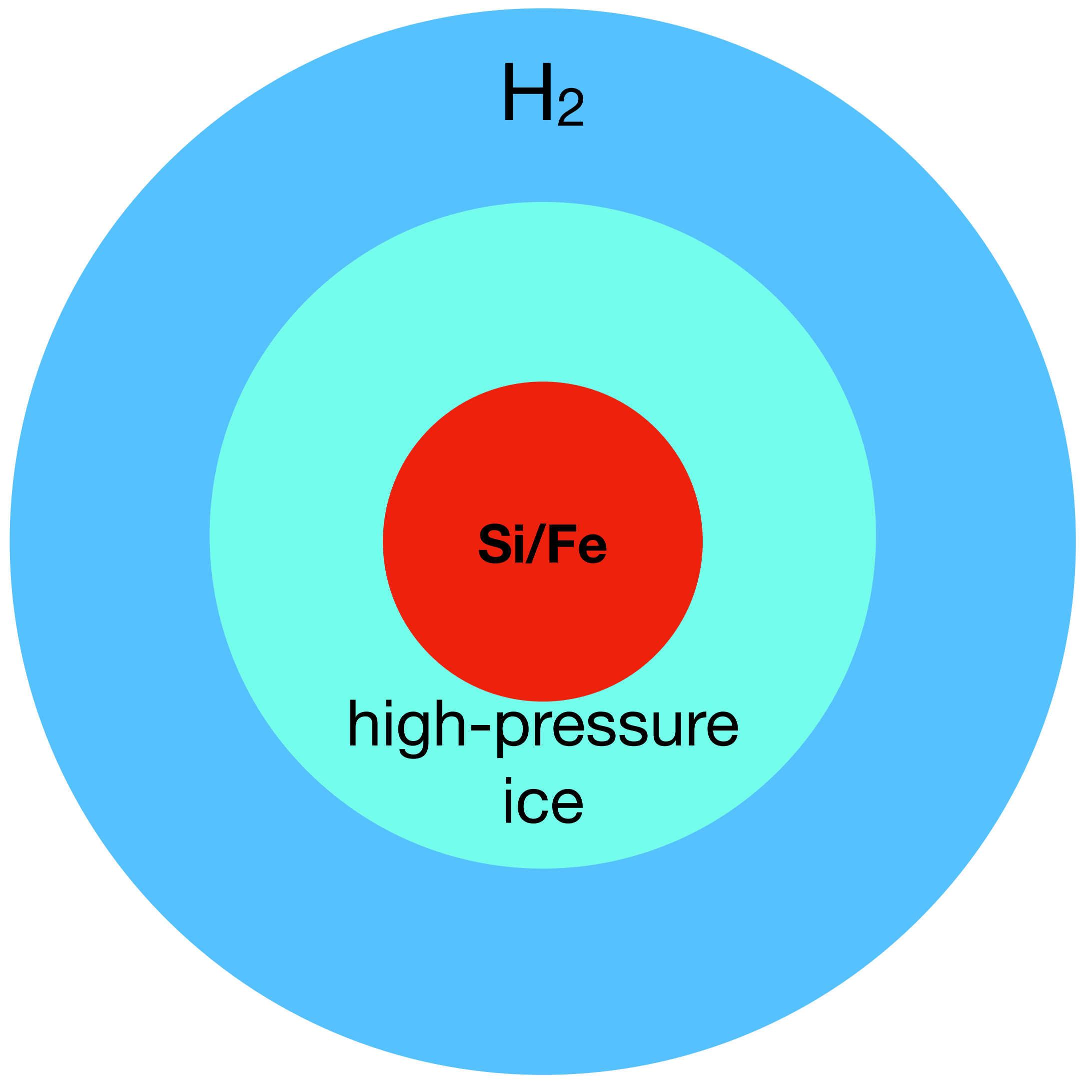
- Super-Earth cores are formed late in gas-poor environments
- Dusty atmosphere delays cooling

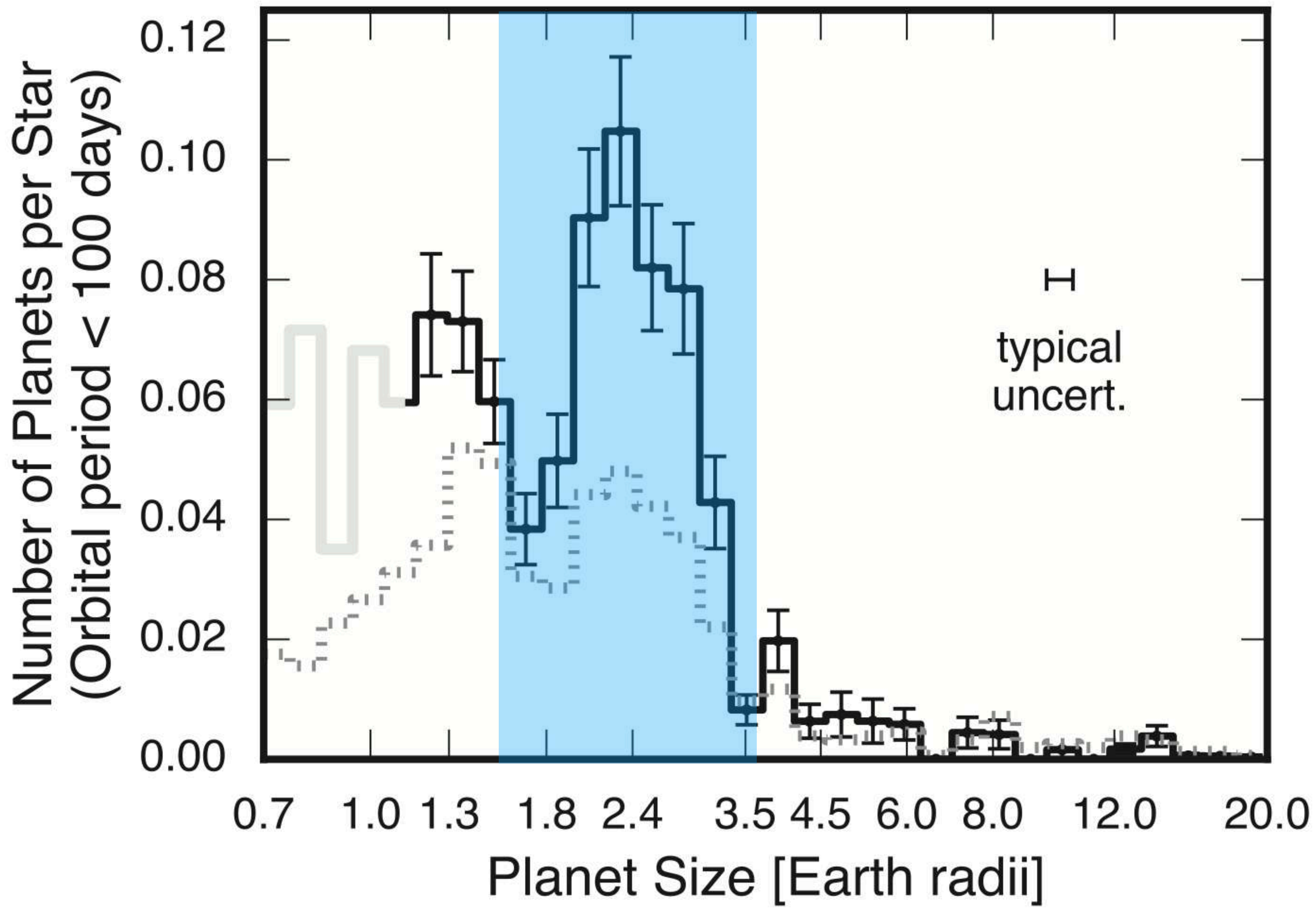


Lee & Chiang (2016), Lee & Connors (2021)

Rocky worlds or sub-Neptunes?

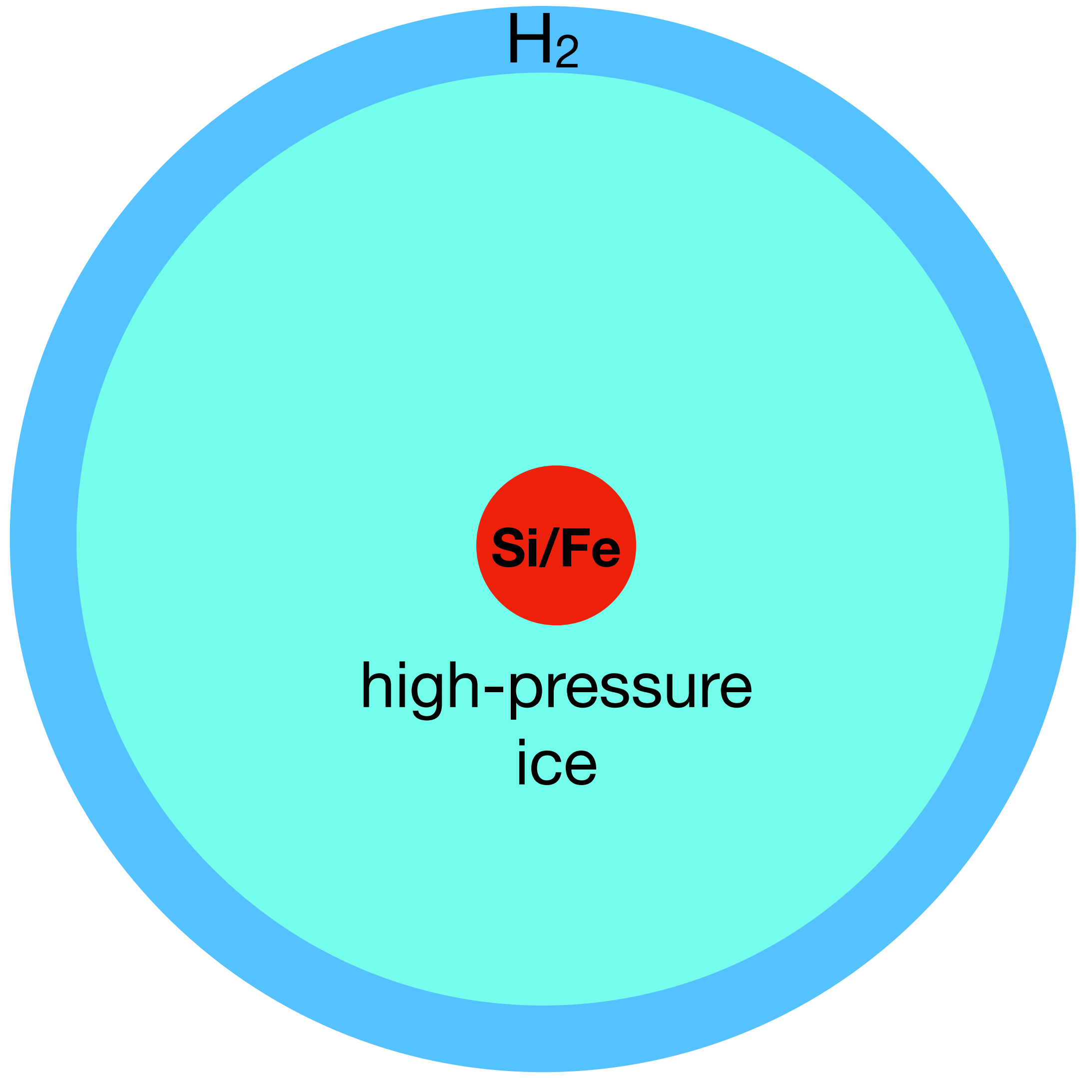
dense core
thick atmosphere



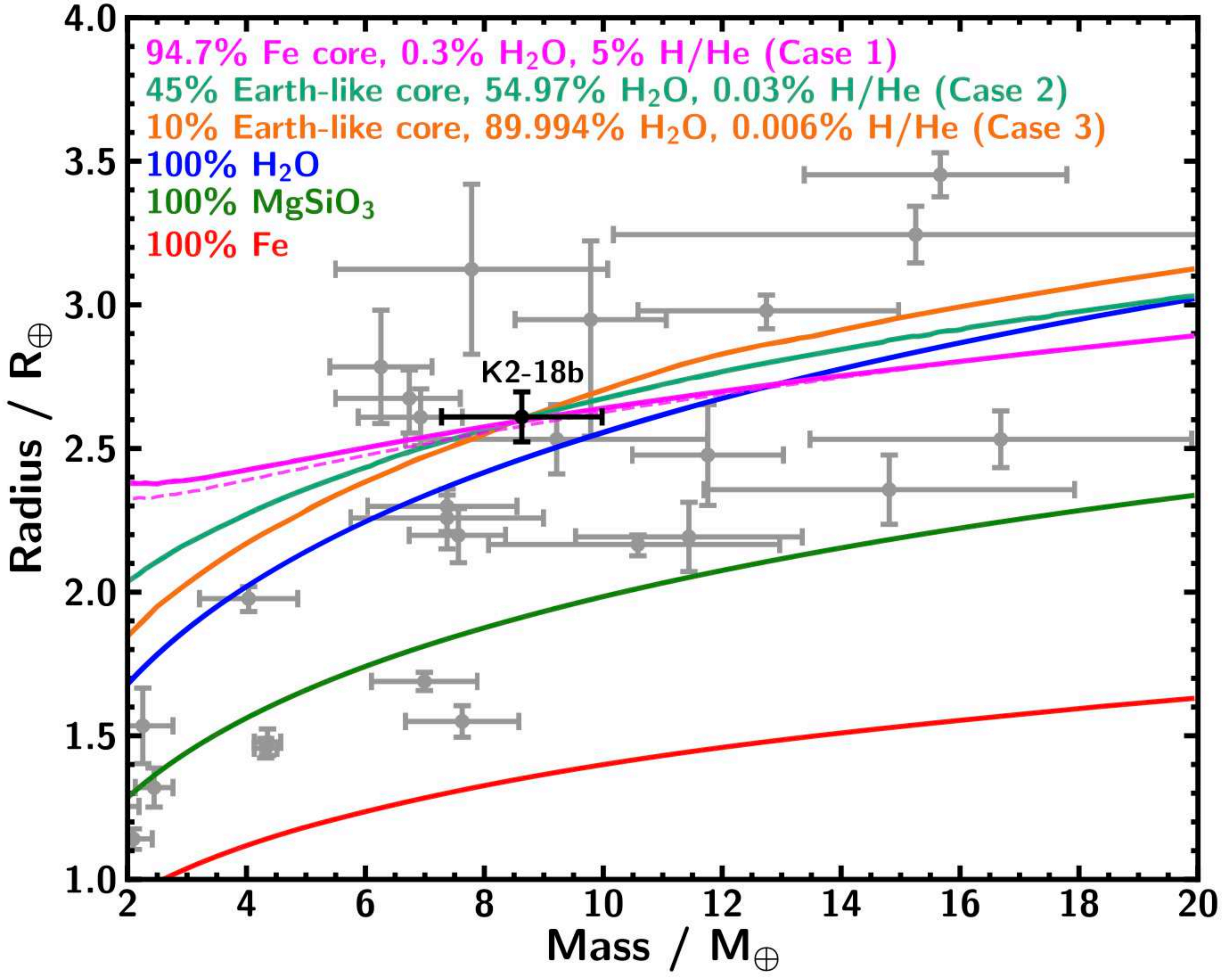


Fulton & Petigura (2018)

light core
thin atmosphere

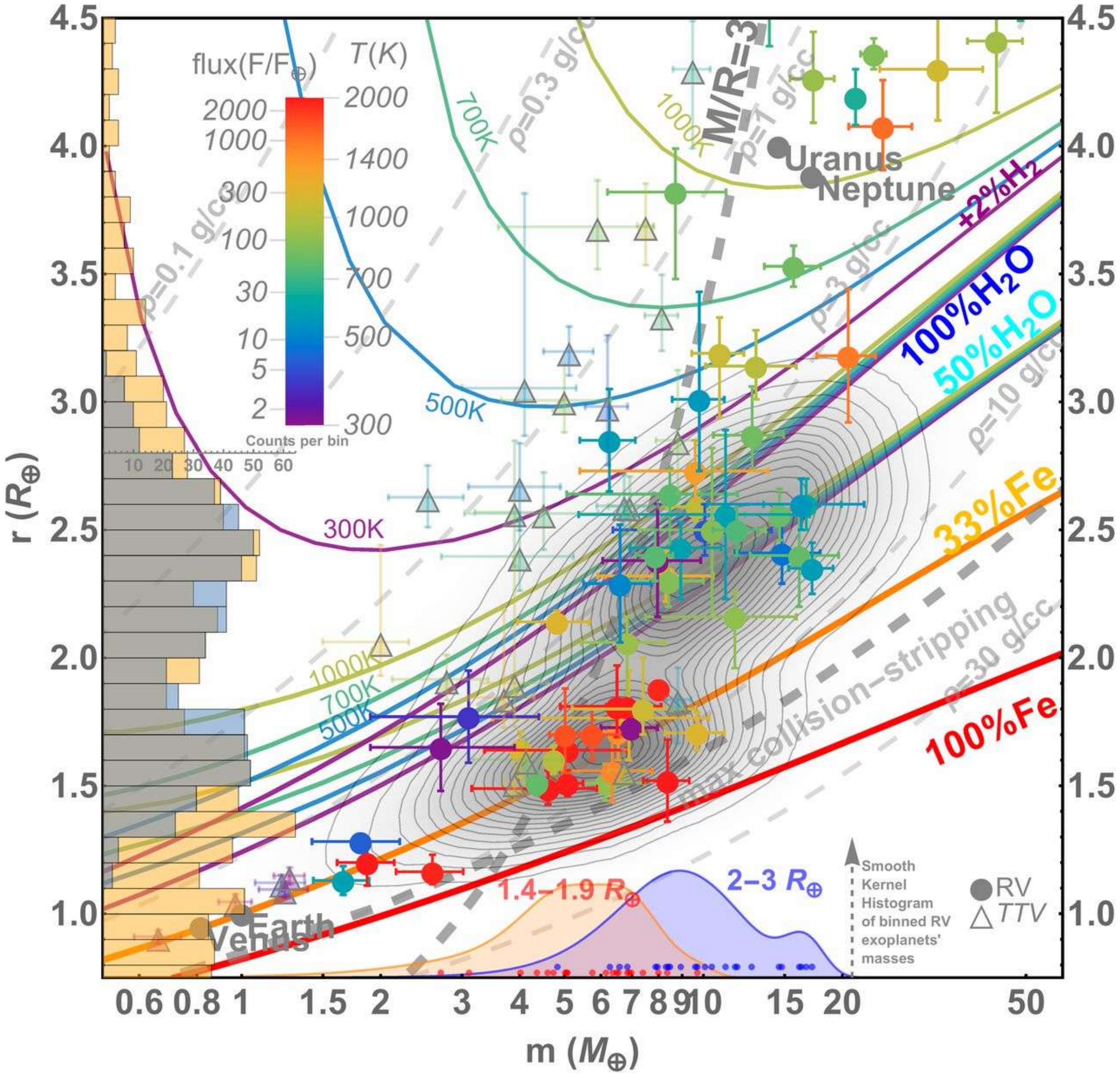


Internal composition degeneracy



Madhusudan et al. (2020)

The population above the gas is water worlds (> 1/4 H2O)

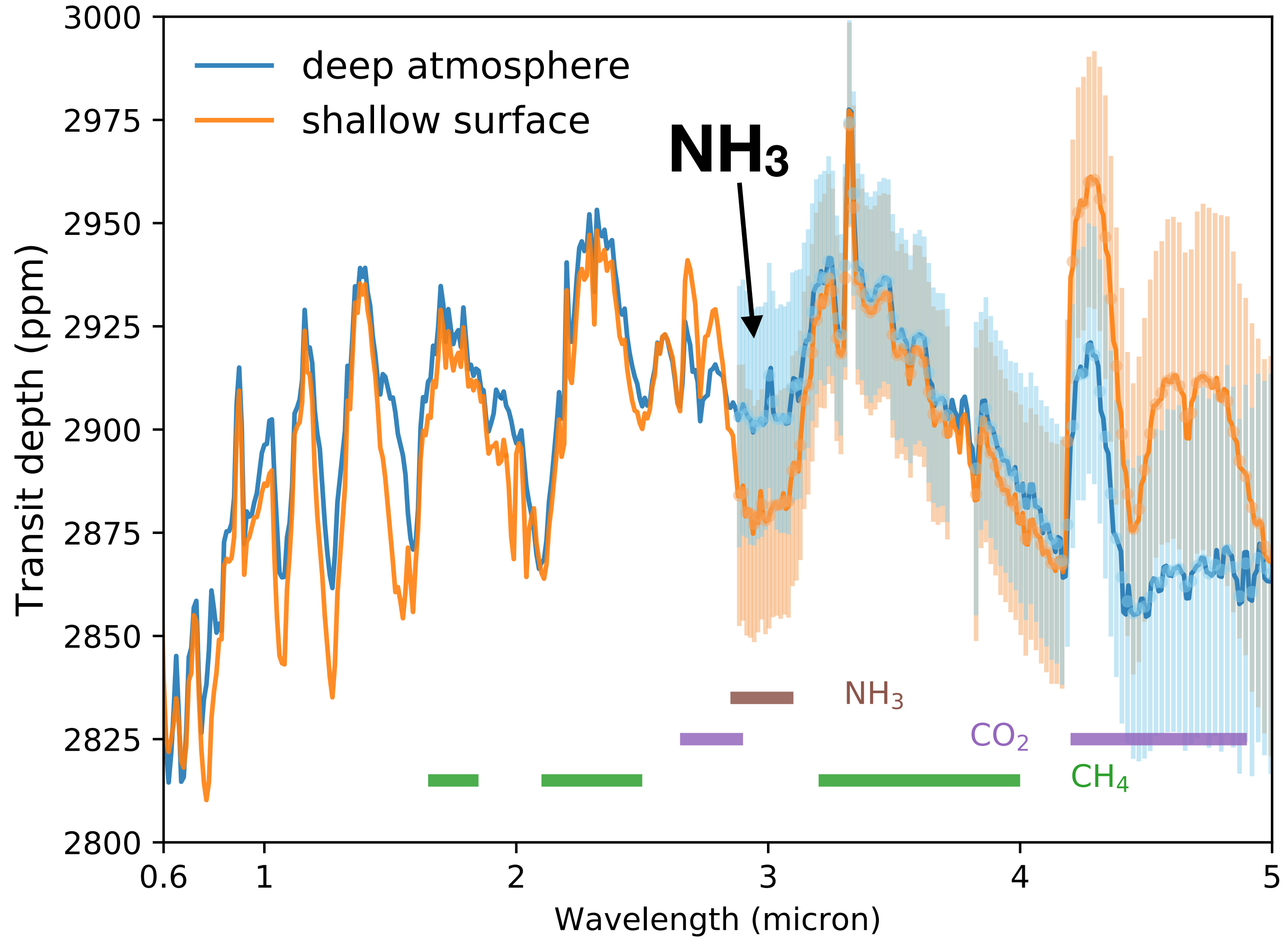


Zeng et al. (2019)

Atmospheric composition to differentiate between rocky worlds and sub-Neptunes

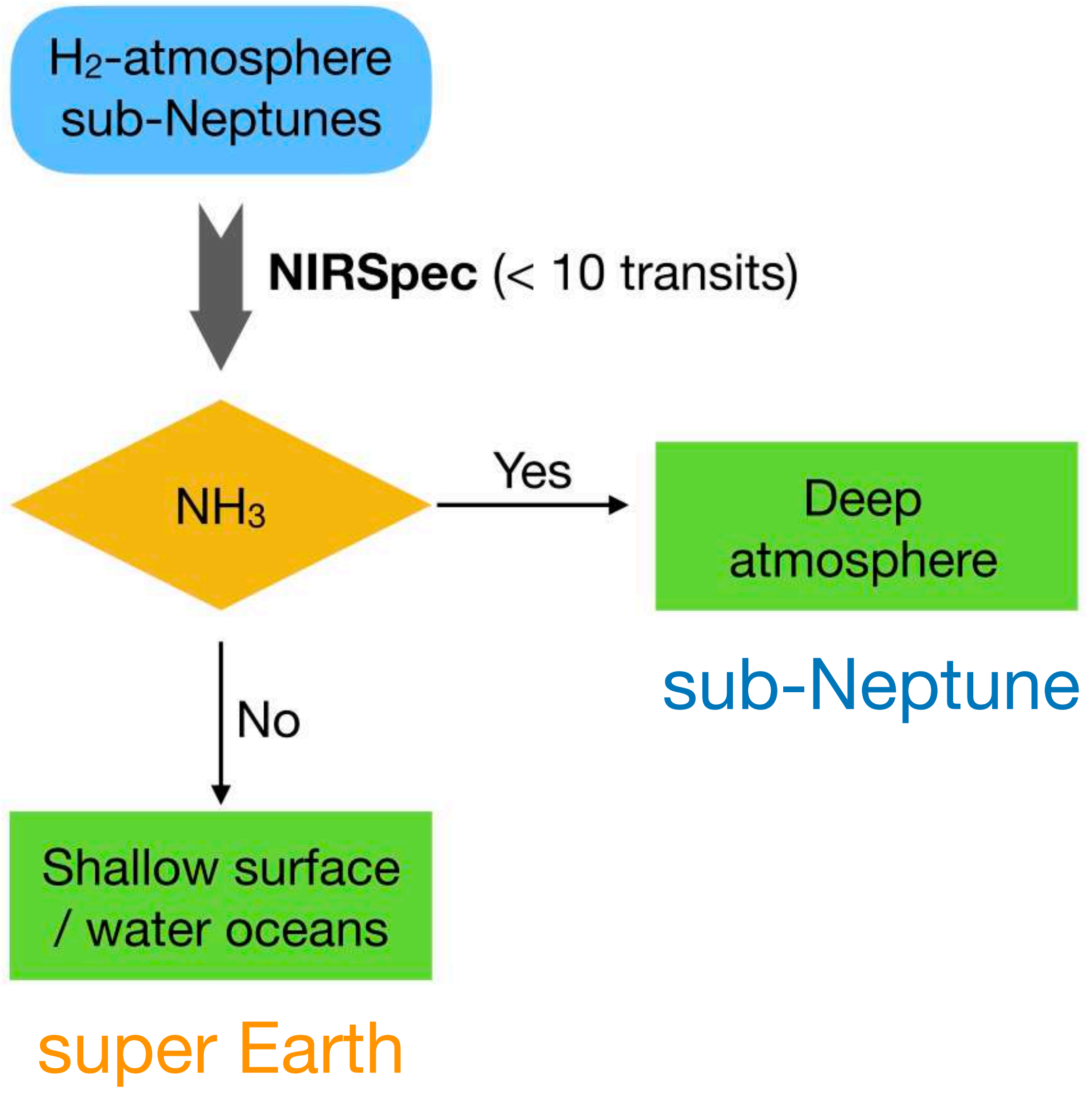
NH_3 remains abundant in Jupiter's troposphere but is depleted on Titan
— atmospheric composition offers insights into the **presence of a surface**

On sub-Neptunes, NH_3 is abundant by resupply from the deep atmosphere
In thin atmospheres, NH_3 is photochemically converted to N_2

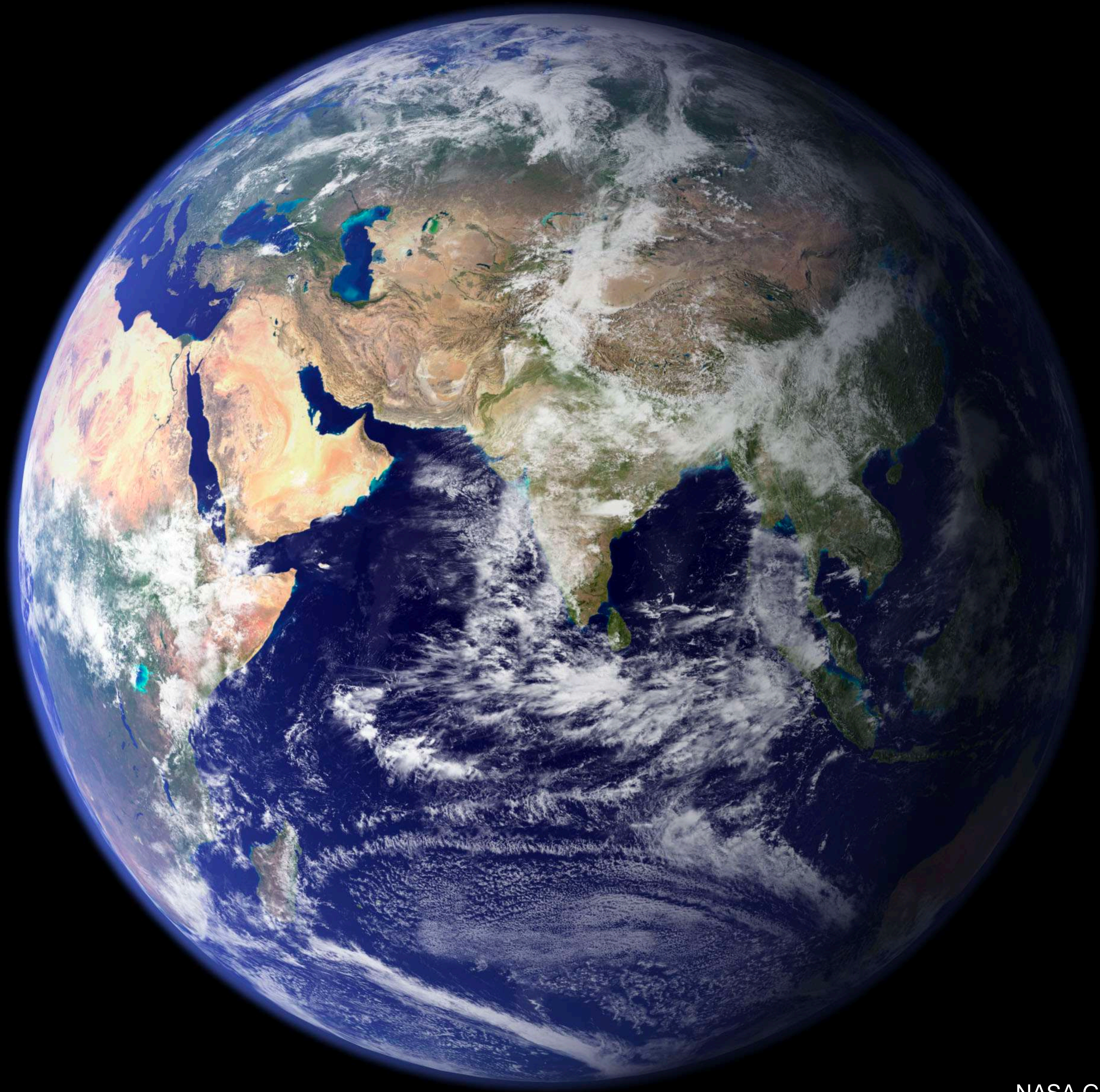


thin atmosphere

deep atmosphere



Tsai et al. (2021); Yu et al. (2021)



NASA Goddard Space Flight Center / Reto Stöckli


The Pale Blue Dot
The Pale __ Dot?

Exoplanet references

- Exoplanet Atmospheres: Physical Processes
  Sara Seager
  — a classic book; pedagogical and covering a good range of exoplanet characterization

- Exoplanetary Atmospheres: Theoretical Concepts and Foundations
  Kevin Heng
  — more advanced; a good read for radiative transfer

- Atmospheric Evolution on Inhabited and Lifeless Worlds Book
  David Catling & James F. Kasting
  — focused on terrestrial atmospheres; very readable and self-contained,

Back up

A main challenge for planetesimal accretion

— giant plants in the Solar System are formed too slow

- The surface densities of planetesimals required to build the core of Jupiter and Saturn at their current locations are too high (Pollack et al. 1996), especially including the realistic oligarchic regime
- The growth rate outside of 10 AU drops sharply, making it very challenging to form the cores of Uranus and Neptune within the lifetime of the protoplanetary disk (Safronov 1969)

$$\frac{dM}{dt} \sim \Sigma_s \Omega \pi R^2 F_g$$

➡ increase the surface density of solids

observational constraints; fate of the remaining (~80%) planetesimals?

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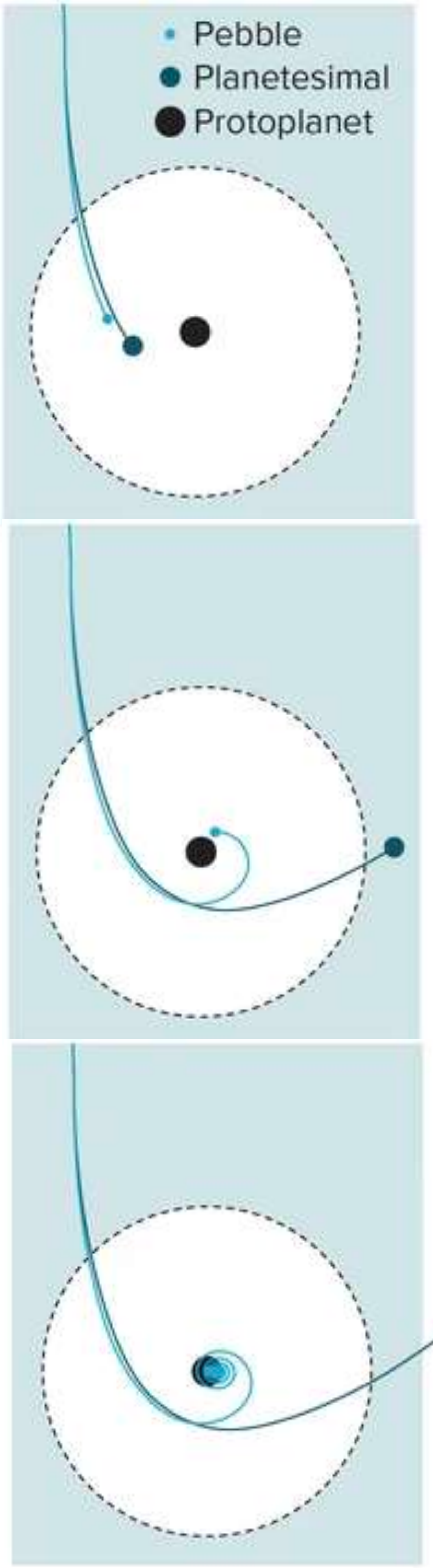
➡ increase the accreting radius of the planet — pebble accretion ✔

Pebble accretion

Lambrechts & Johansen 2012



- Observation: The observation of large populations of pebbles in protoplanetary disks
- The meter-size barrier makes disks very efficient factories for producing pebbles of mm—cm sizes!
- An embryo can accrete pebbles at a much higher rate because of the gas drag, which causes pebbles to spiral toward the growing embryo. This is highly efficient, as the planet's gravity pulls pebbles over a much larger area than would be the case for planetesimal-planetesimal collisions

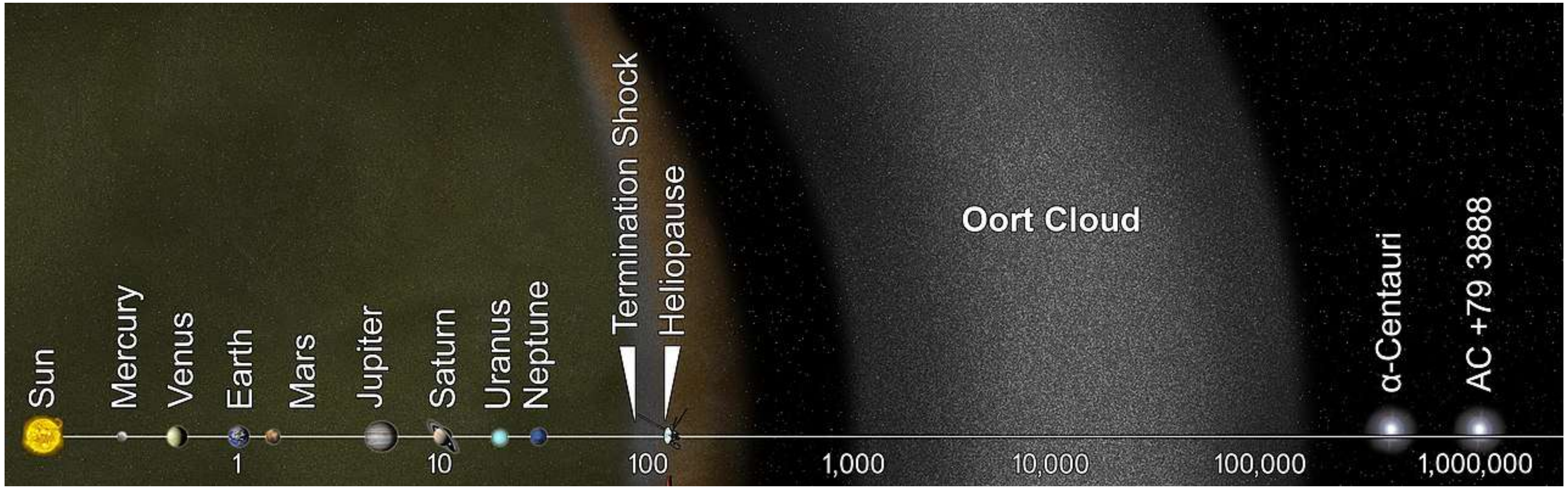
General accretion rate of pebbles: $$\frac{dM}{dt} \sim R_H \Sigma_p v$$

- Pebble accretion rate increases with orbital radius: higher R_H, larger H (flared disk), smaller v (slower radial drift)

Small Bodies in the Solar System

- The missing mass of the Kuiper belt:
  The total mass of the astroid belt ~ 10^-3 Earth masses — why so little?
  Jupiter perturbation: many small bodies were scattered into Jupiter-crossing orbits and then vaporized, collided into Jupiter, or ejected from the Solar System

- Theory of Oort cloud: planetesimals formed between 3 and 30 AU were ejected by the giant planets. Estimate the mass of solid material ejected?
  — based on observed comet number distribution?
  — based on dynamical calculations? … just list references



credit: NASA / JPL-Caltech

- Based on the Number of observed long-period comets and Dynamical simulations, there are about 10^11 — 10^12 comets in Oort clouds

- typical comet density ~ 0.6 g/cm3, a comet is ~10^-10 earth mass

On the origin of the 'hot' Kuiper-belt population