Exoplanets:
population, formation, and direct imaging

Ya-Lin Wu

National Taiwan Normal University

Planets: <13 Jupiter masses (**deuterium-burning limit**)

$$D + p \rightarrow {}^3\mathrm{He} + \gamma$$

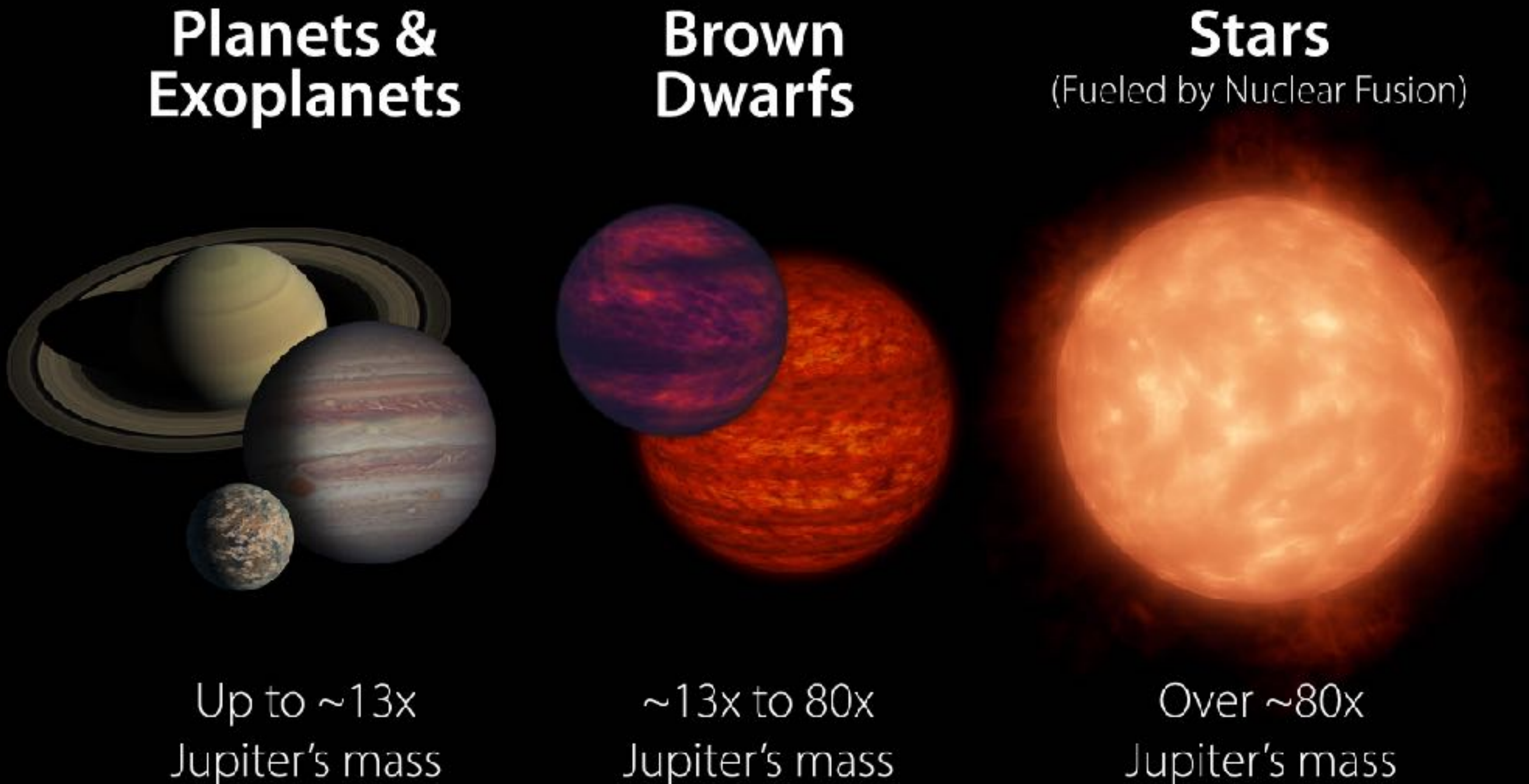
Brown dwarfs: 13~75 M_{Jup}

Stars: >75 M_{Jup} (**hydrogen-burning limit**)

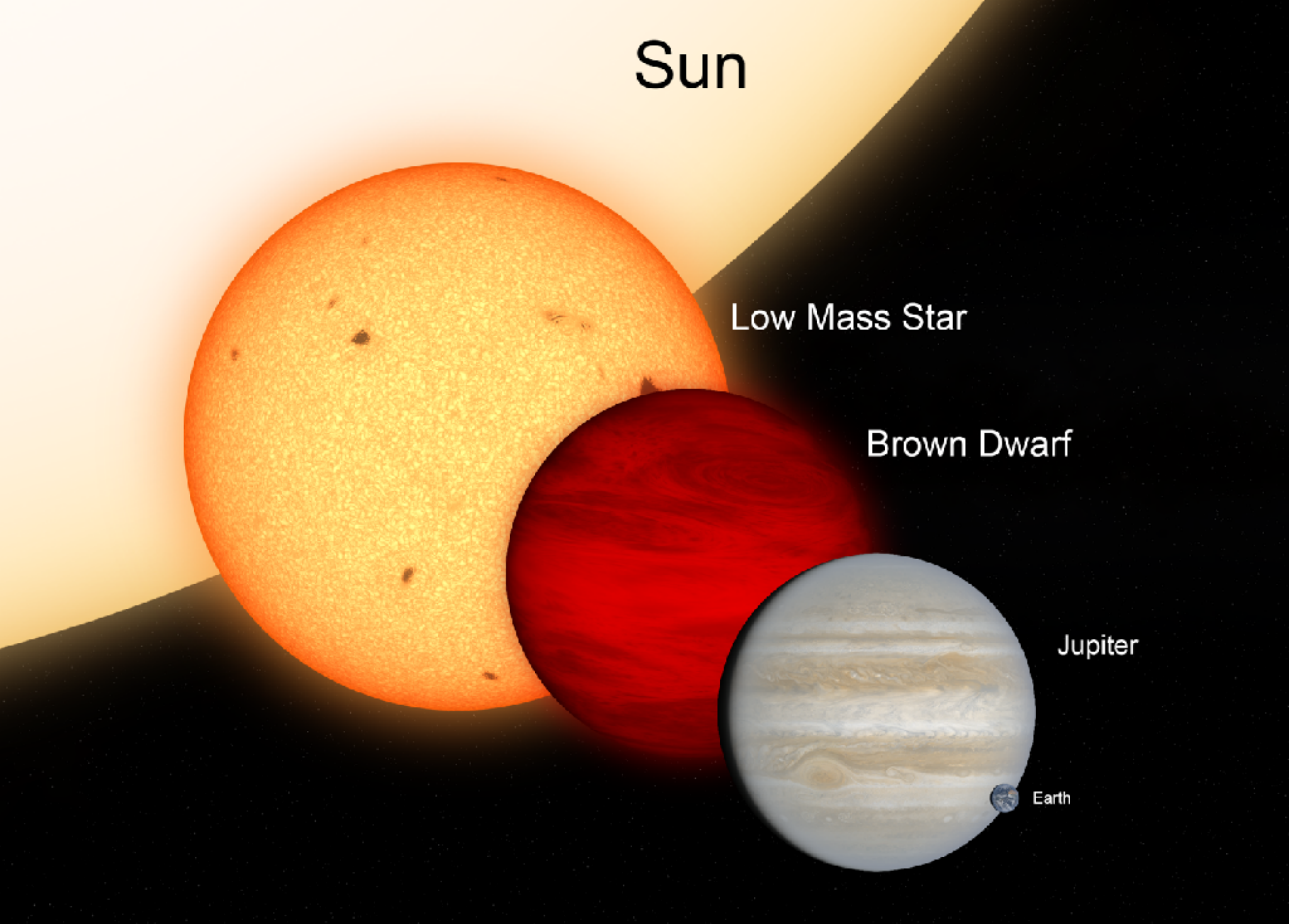
Main detection methods:

1. radial velocity (1995)
2. transit (2003)
3. microlensing (2004)
4. direct imaging (2004 or 2008)

https://en.wikipedia.org/wiki/51_Pegasi_b

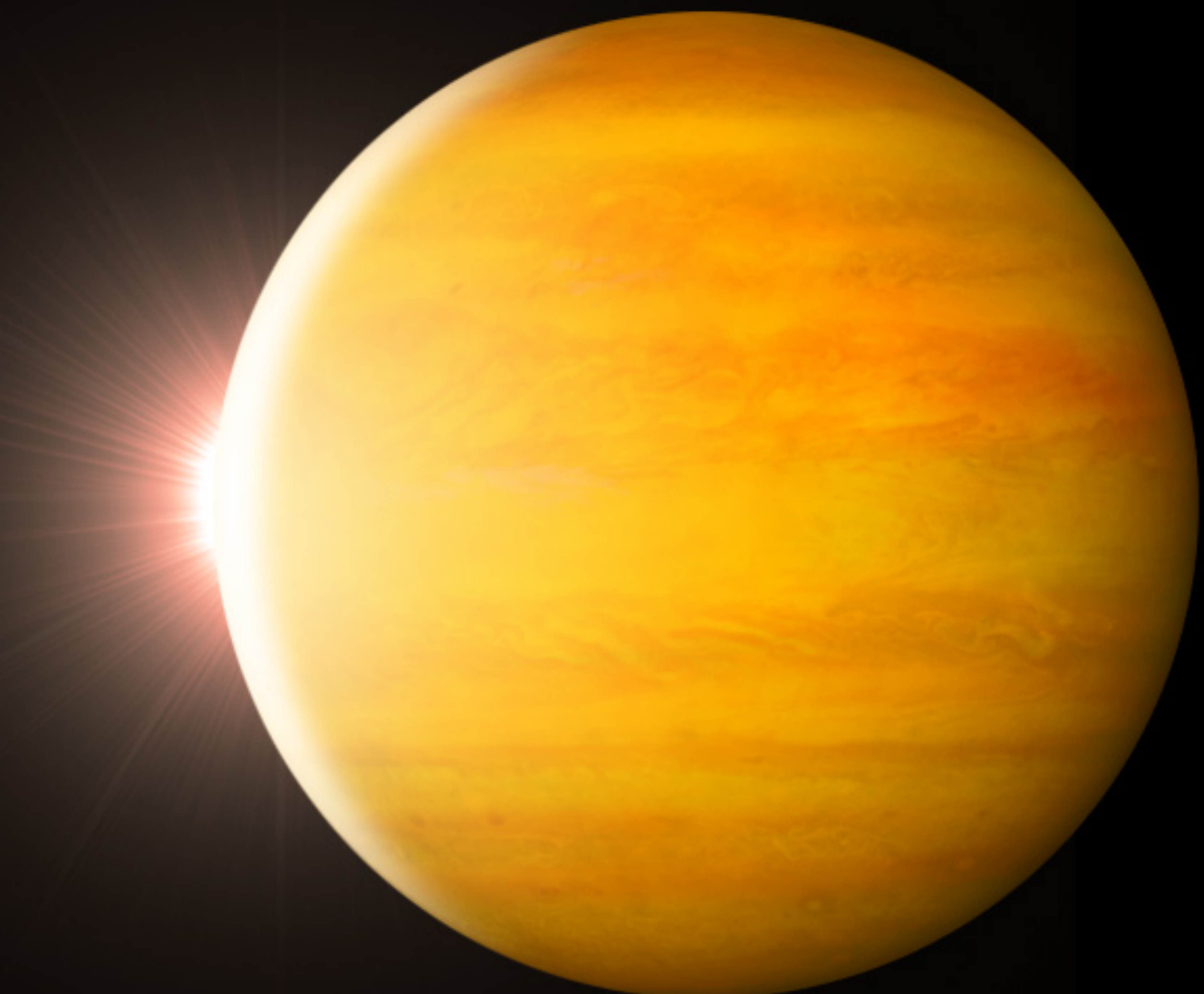


https://en.wikipedia.org/wiki/Brown_dwarf



https://en.wikipedia.org/wiki/Brown_dwarf

THE FIRST PLANET DISCOVERED AROUND A SUN-LIKE STAR



51 Pegasi b

NASA/JPL-Caltech

2019 Nobel Prize in Physics

Discovery of 51 Pegasi b

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.

Michel Mayor Didier Queloz

- ✓ 0.5 Jupiter-mass planet at 0.05 AU
- ✓ Prototype of "Hot Jupiter"

NASA/JPL-Caltech

TEMPERATURE

51 Pegasi b has a temperature of **1000C°/1800F°**.

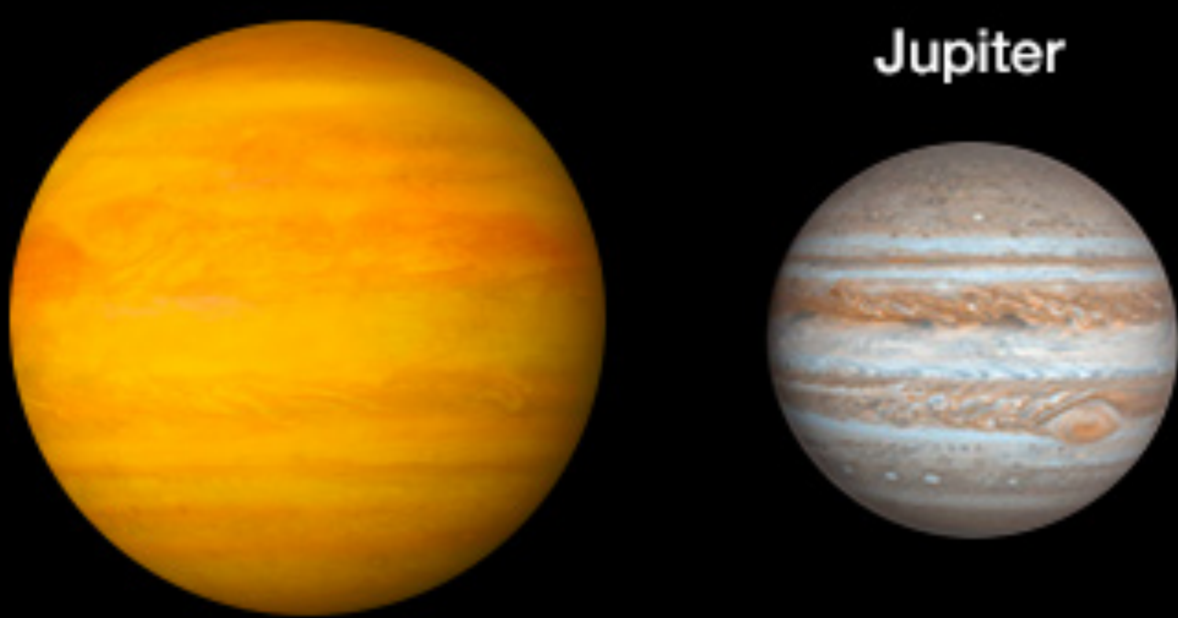
ORBITAL PERIOD

51 Pegasi b orbits its host star **every 4 days**.

PLANET COMPARISON

51 Pegasi b

Jupiter

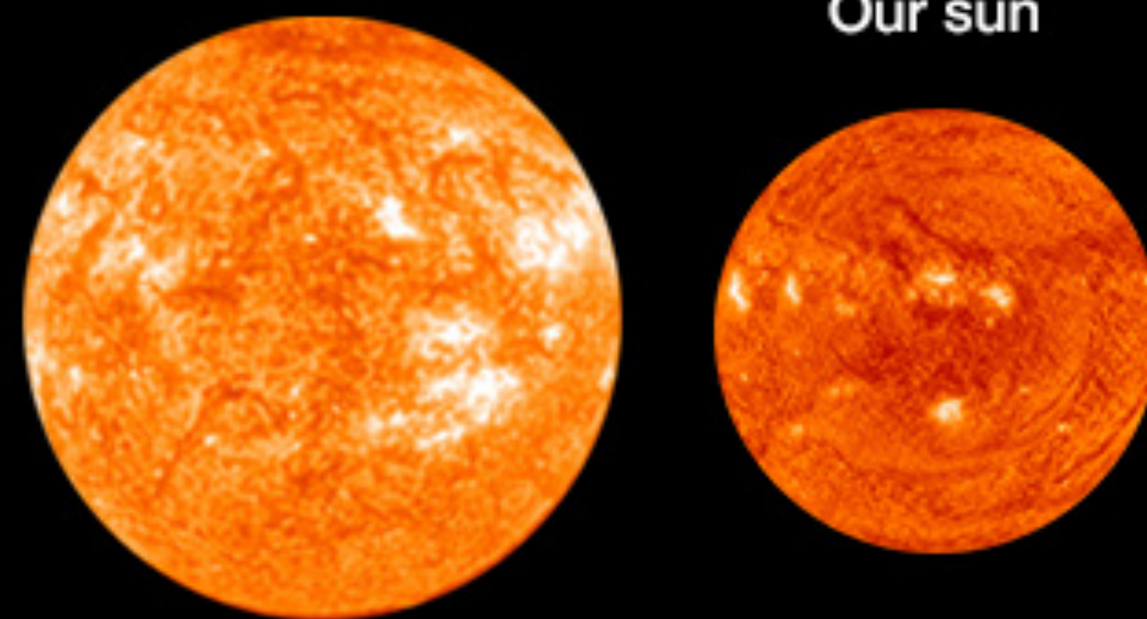


51 Pegasi b is **47% less massive**, but **50% larger** than Jupiter.

STAR COMPARISON

51 Pegasi

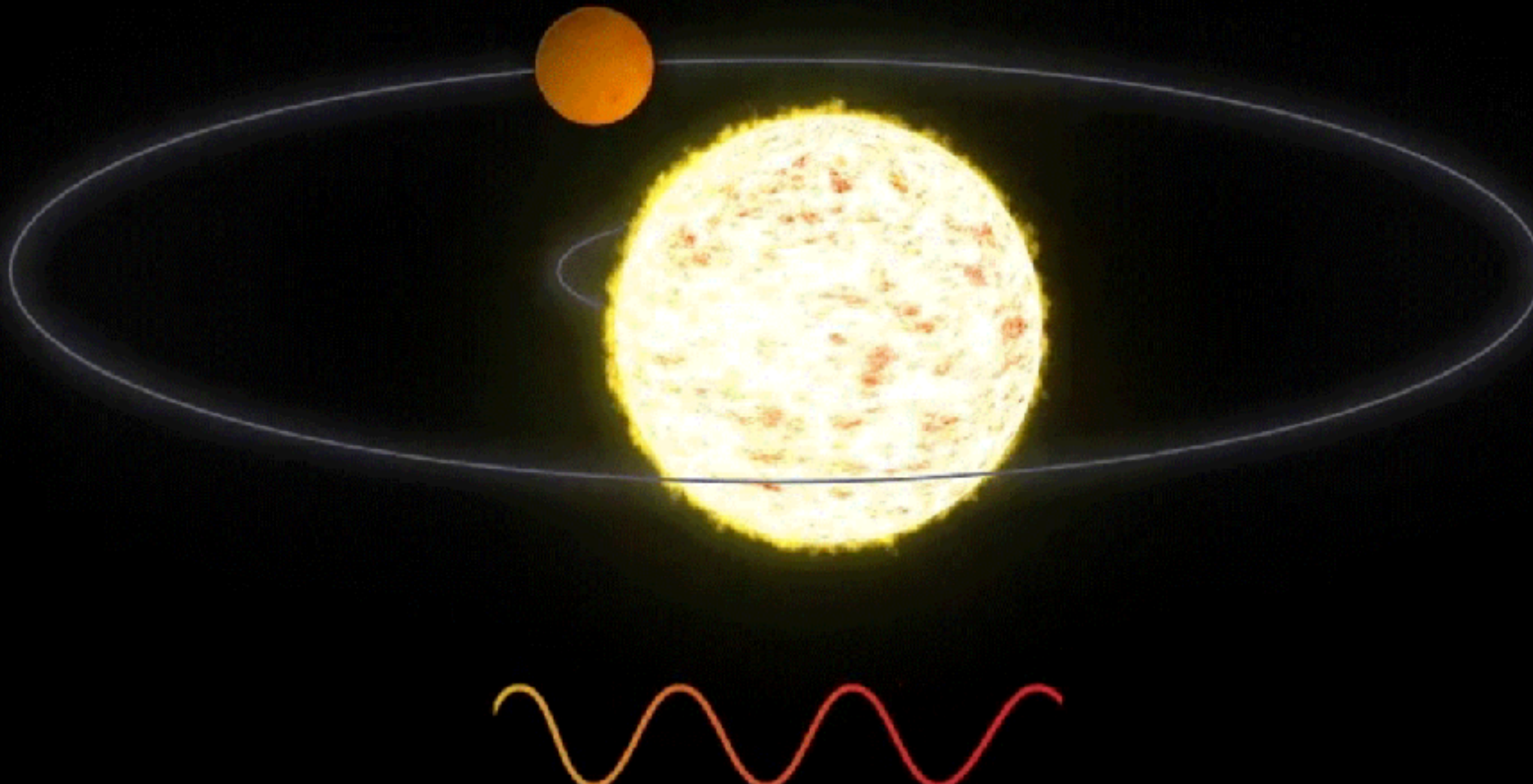
Our sun



51 Pegasi is **11% more massive** and **23% larger** than our sun.

NASA/JPL-Caltech

Detection methods

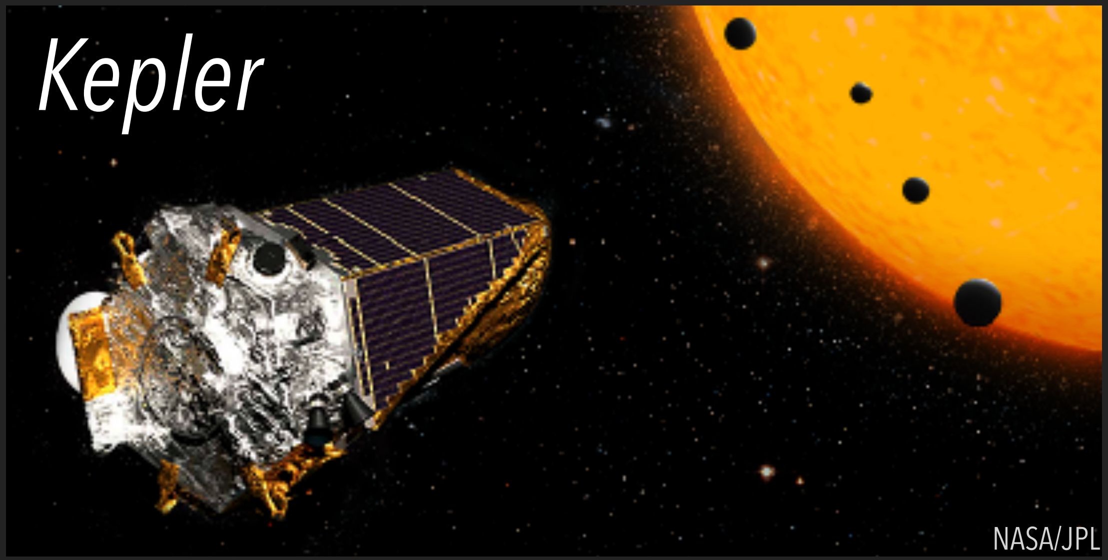


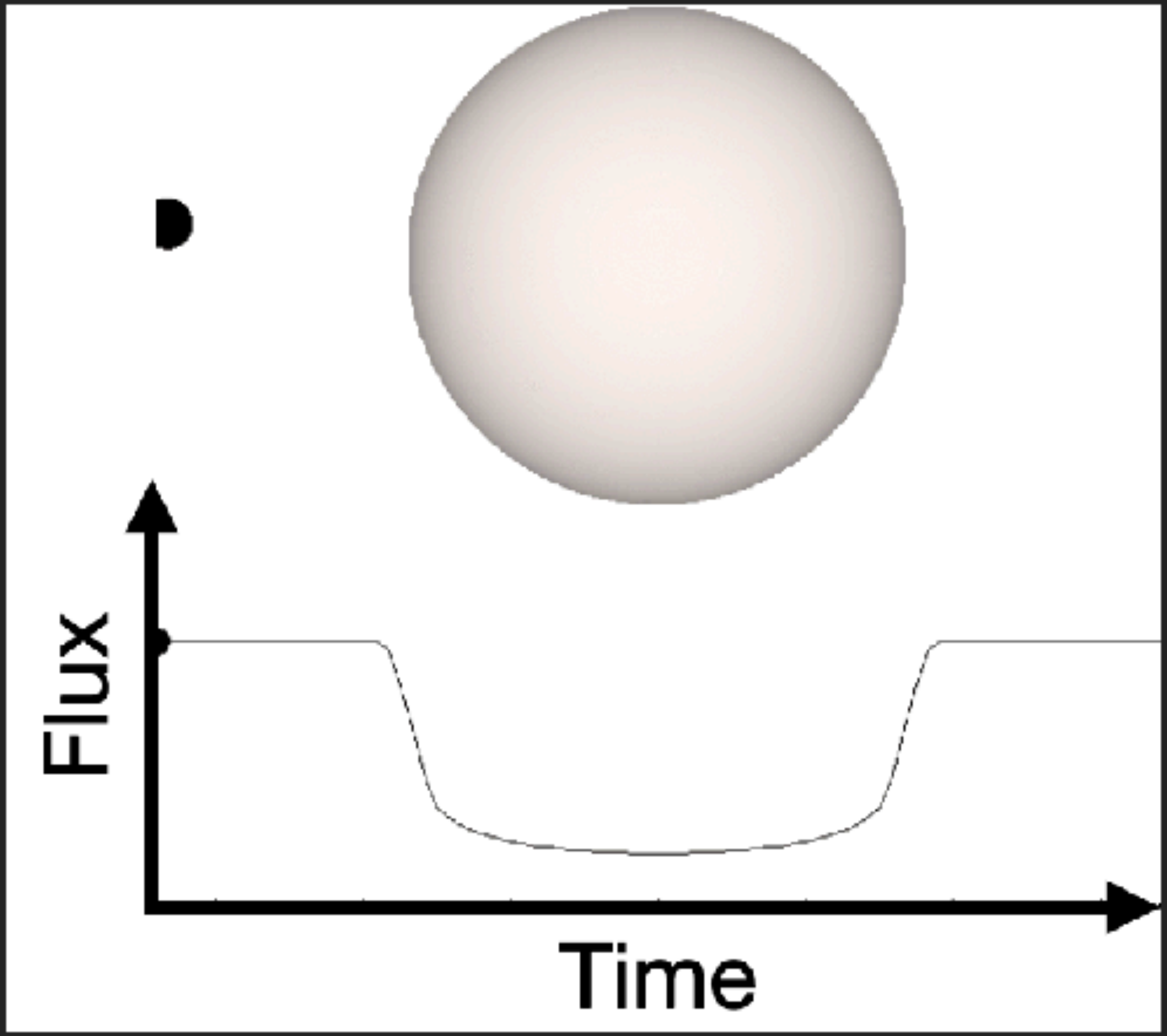
$$\text{radial velocity amplitude} \propto \frac{\text{planet mass}}{\text{period}^{1/3}}$$

RV method is more sensitive to **close** and **massive** planets

https://epl.carnegiescience.edu/file/radial-velocity-gifpostdoc-spotlightgif

Most planets are discovered by **transit**





https://lweb.cfa.harvard.edu/~avanderb/tutorial/

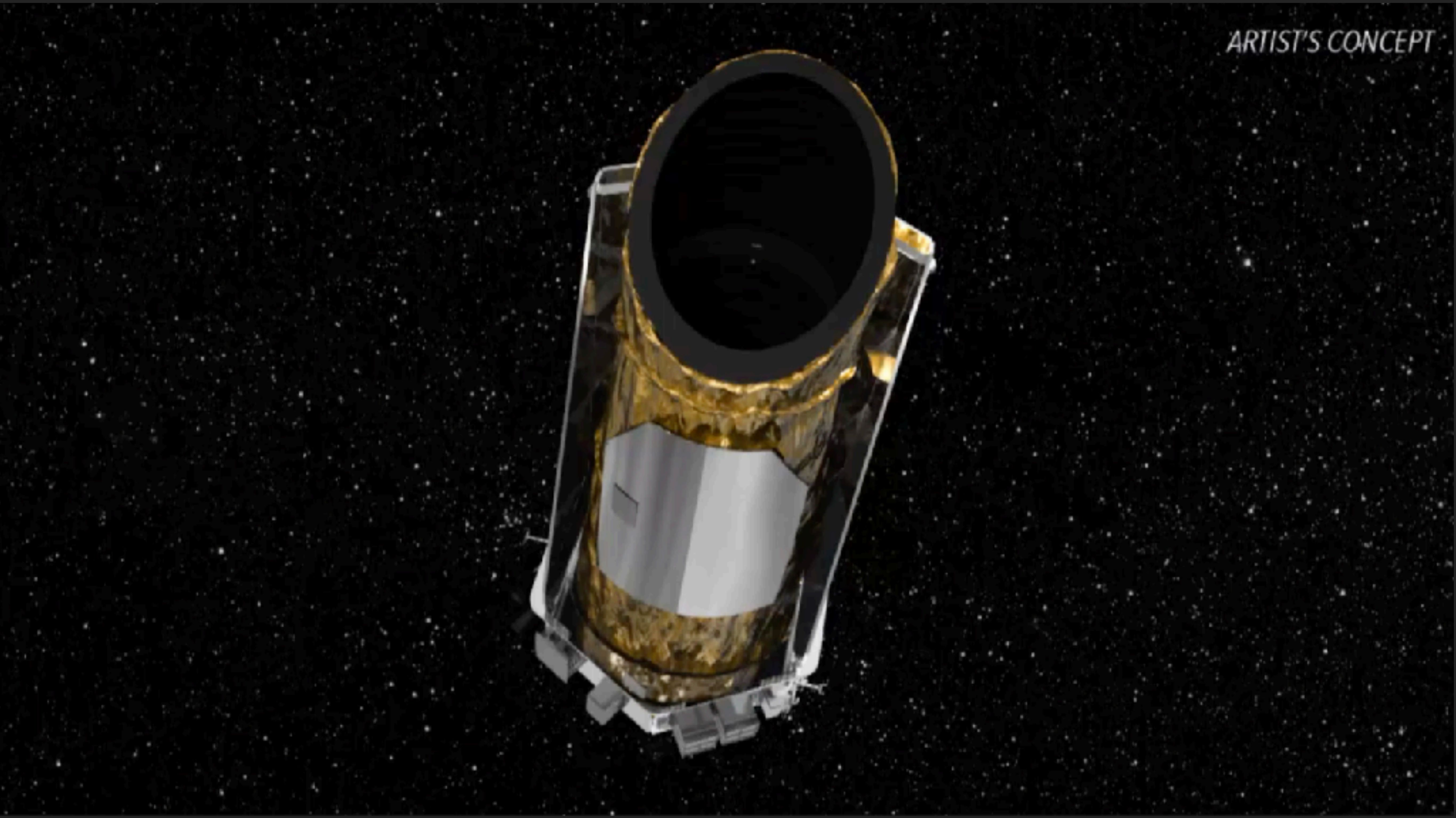
$$\text{transit depth} \propto \left(\frac{R_{\text{planet}}}{R_{\text{star}}}\right)^2$$

transit: **size** of the planet

RV: **mass** of the planet

Then we know the **density** (and possible composition) of the planet!

Most of our knowledge of the **populations** and **statistics** of exoplanets comes from the Kepler mission



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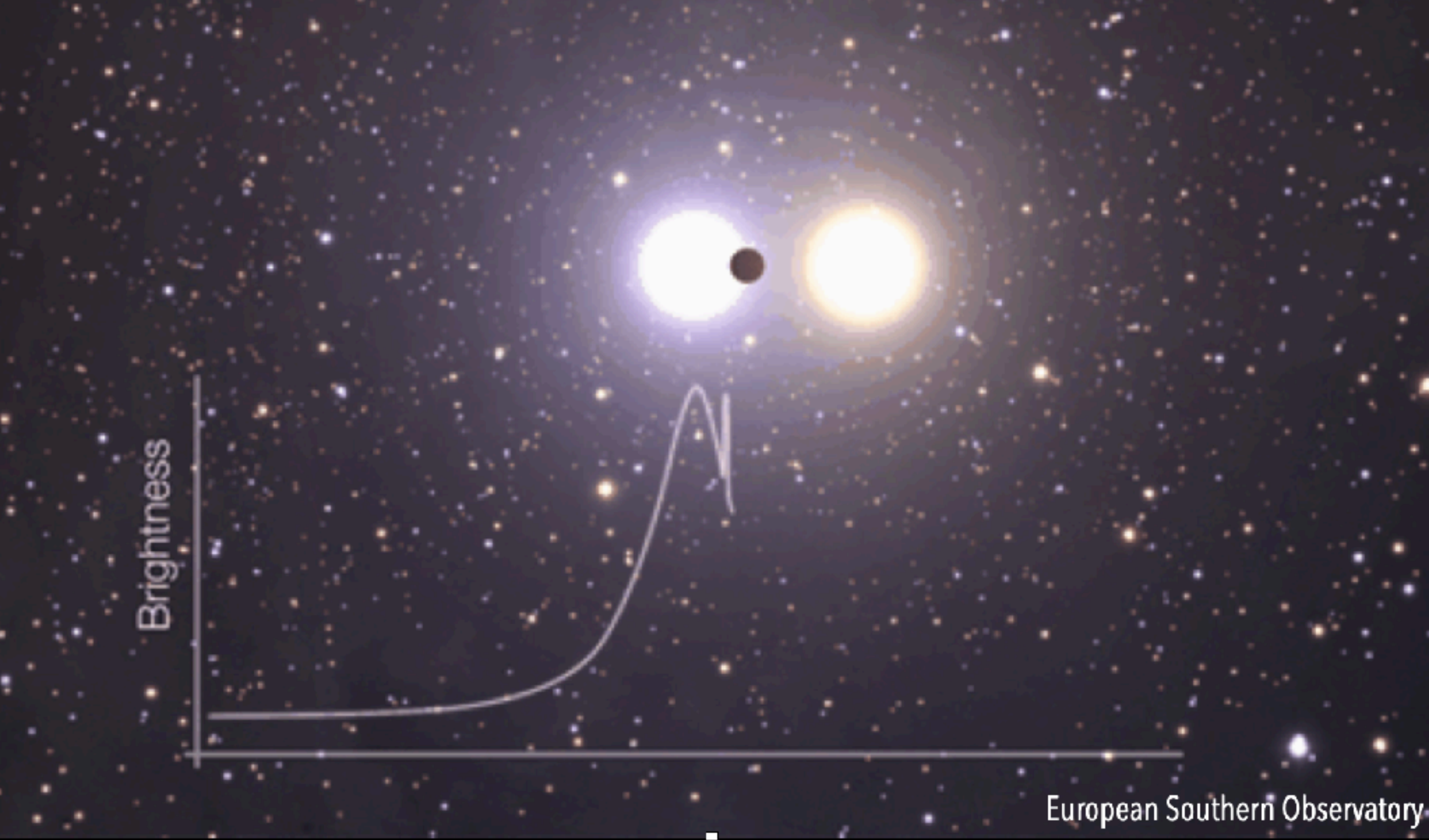
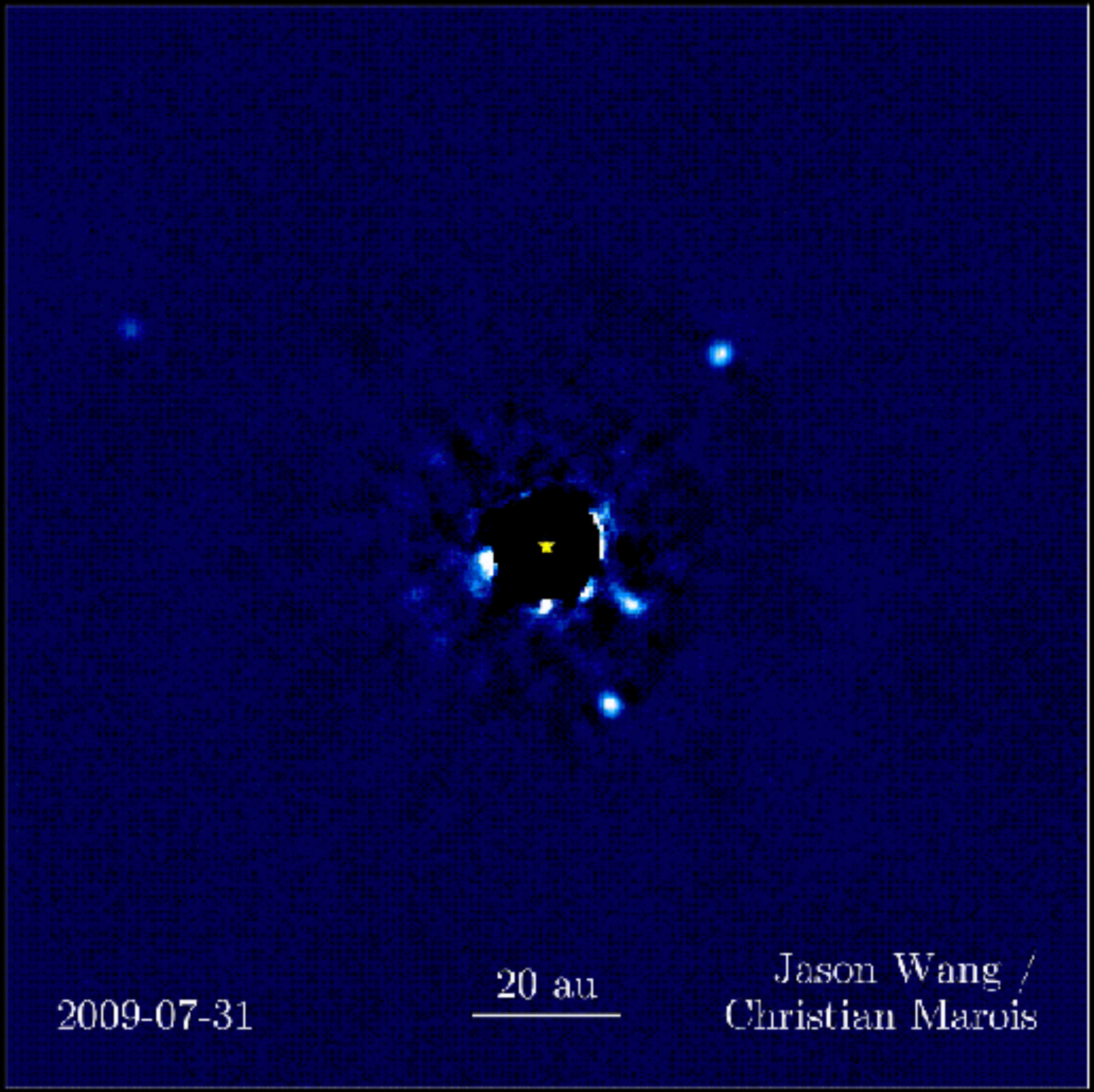


Microlensing is sensitive to the planet/star mass ratio and planets more separated from the star

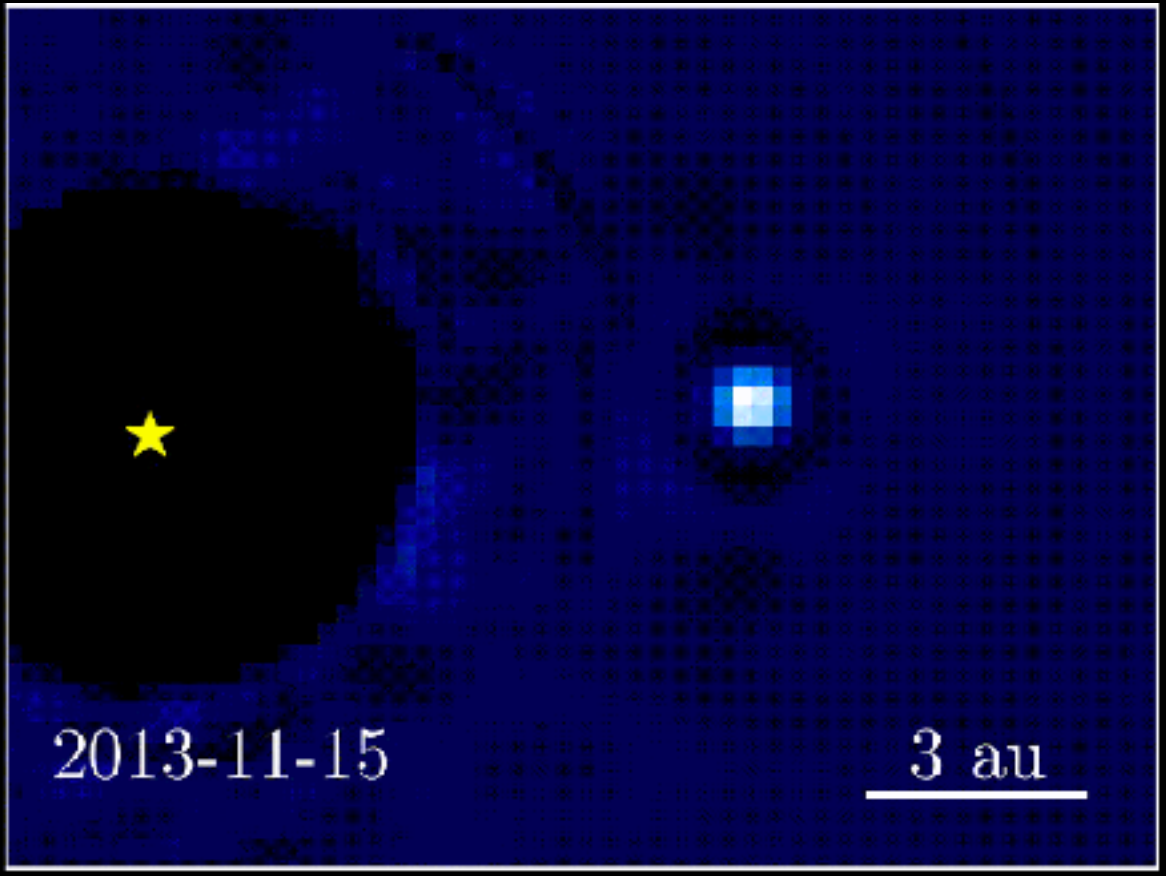
Orbital motion of giant planets

HR 8799 bcde



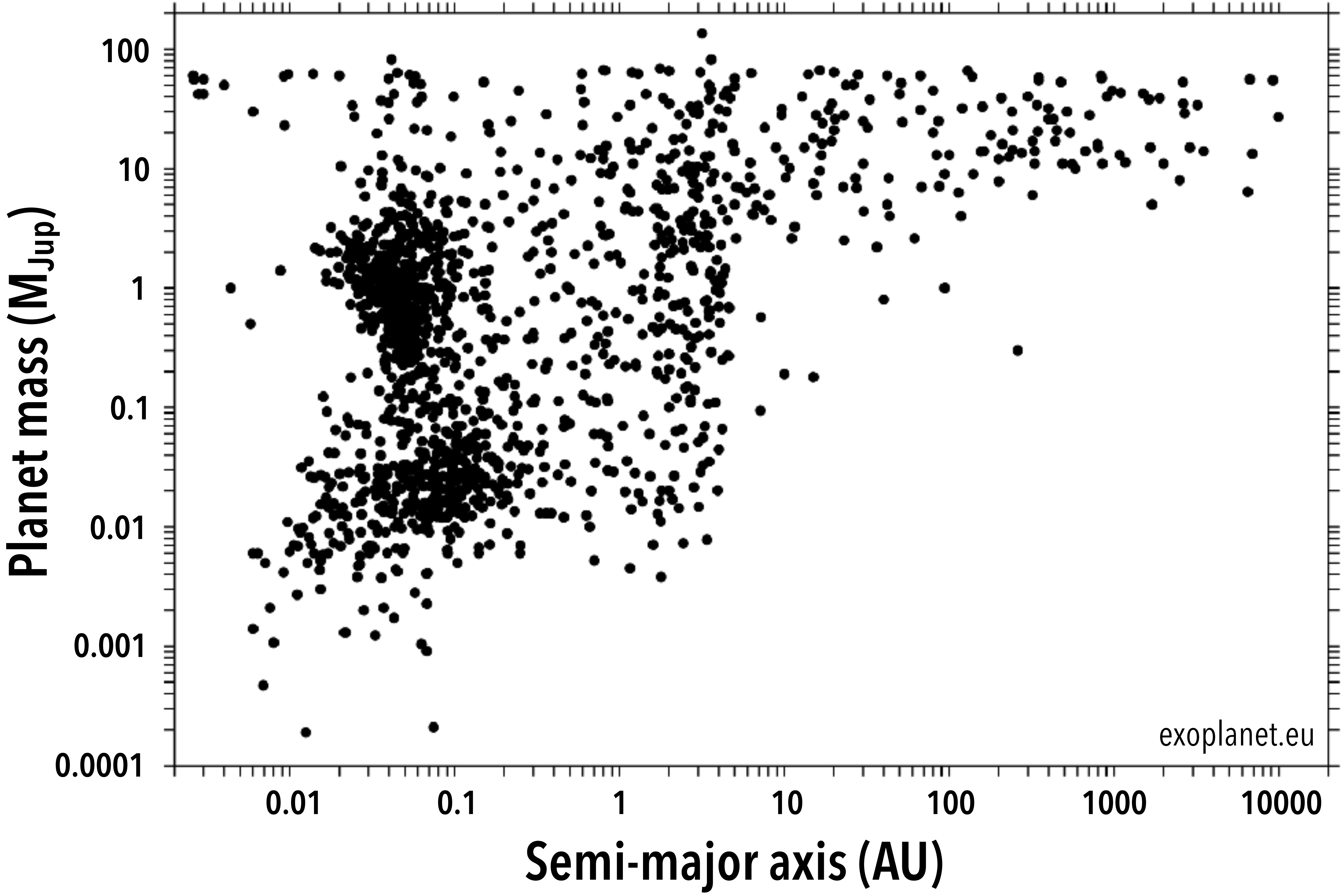
Jason Wang (UC Berkeley)/Christian Marois (NRC Herzberg)

β Pictoris b



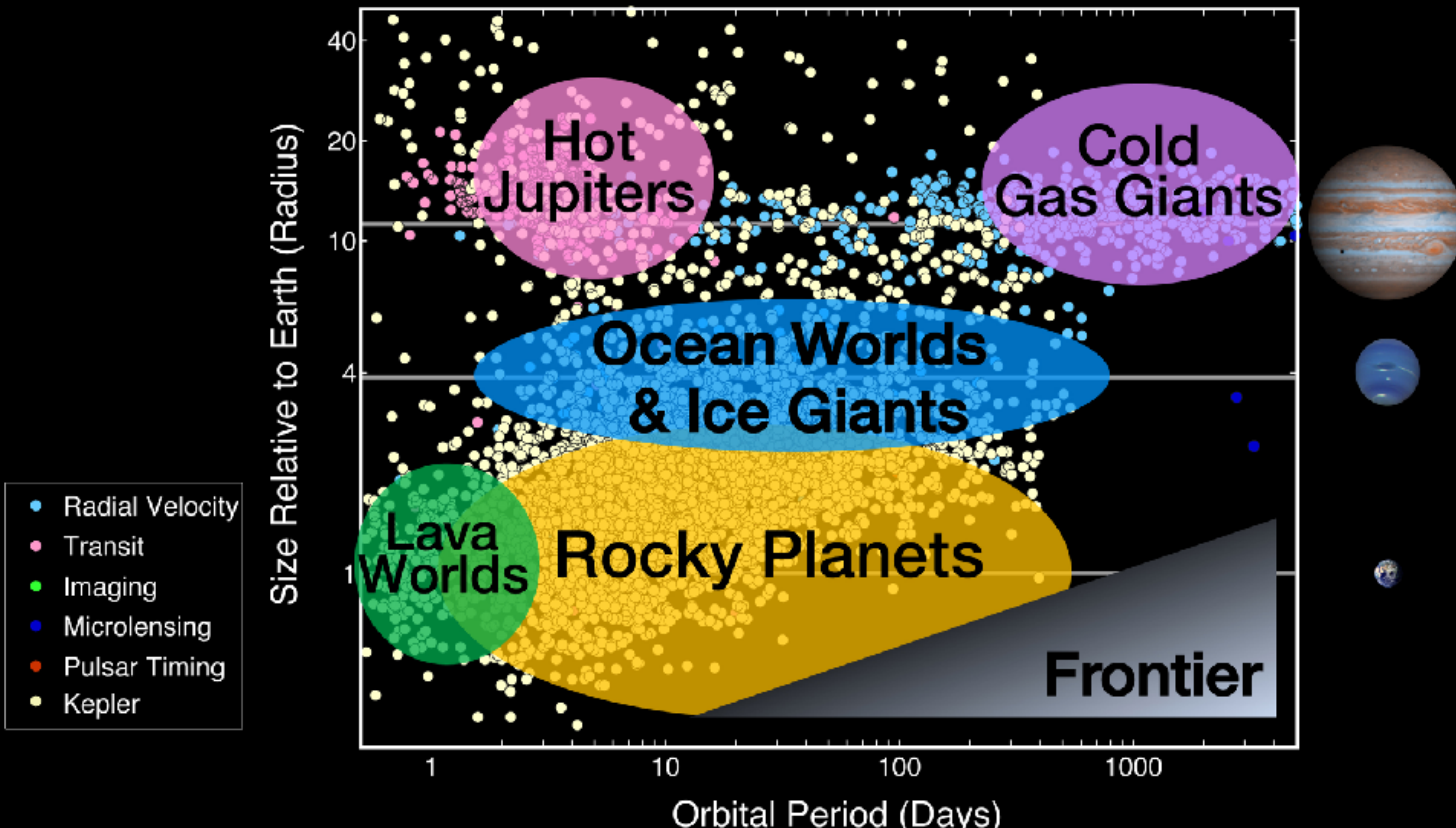
Jason Wang (UC Berkeley)/Gemini Planet Imager Exoplanet Survey

Major discoveries



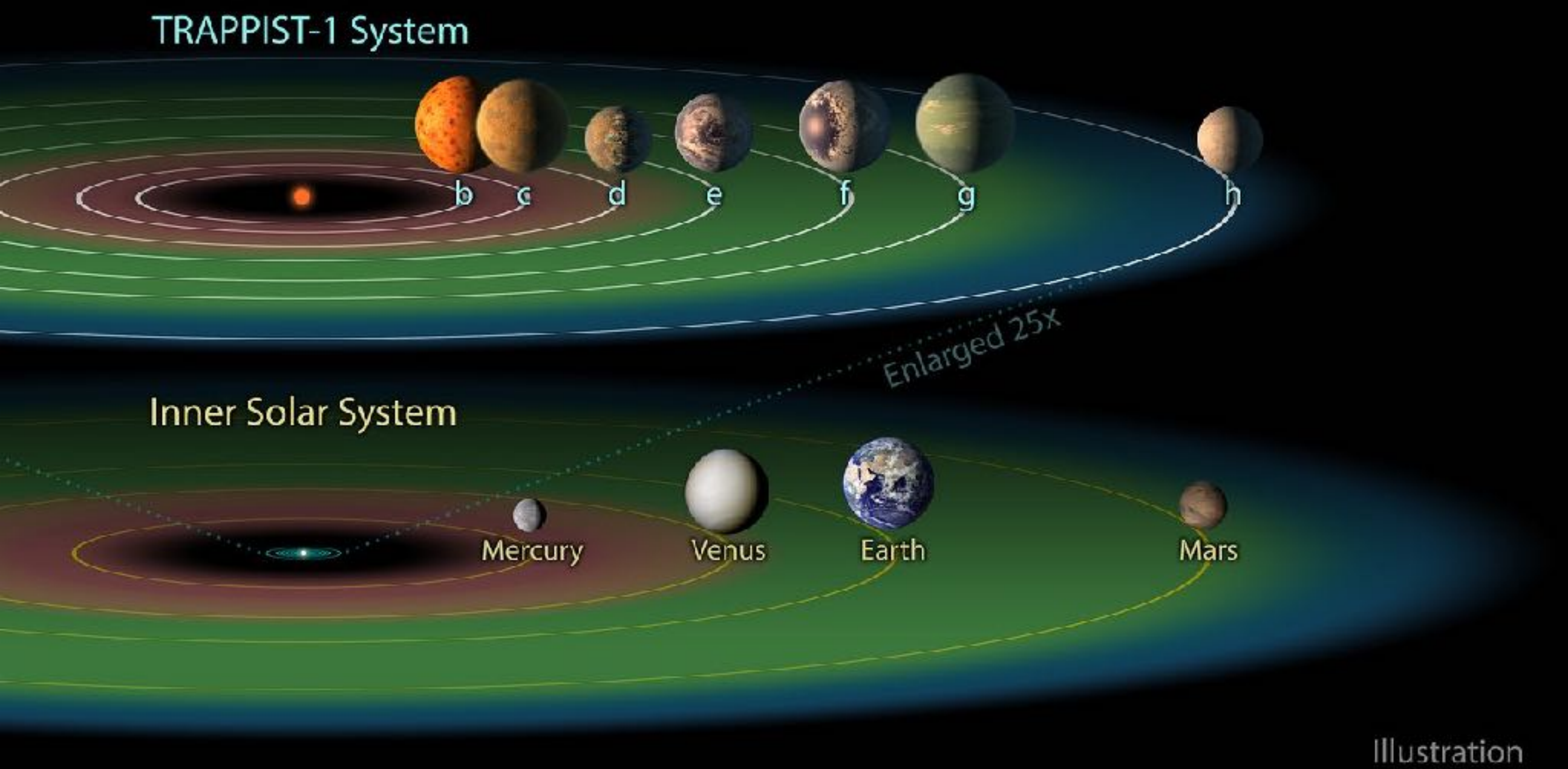
Planet mass (M_Jup)
100
10
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
1000
10000
Semi-major axis (AU)
exoplanet.eu

1. Exoplanets are common and diverse!



NASA/Ames Research Center/Natalie Batalha/Wendy Stenzel

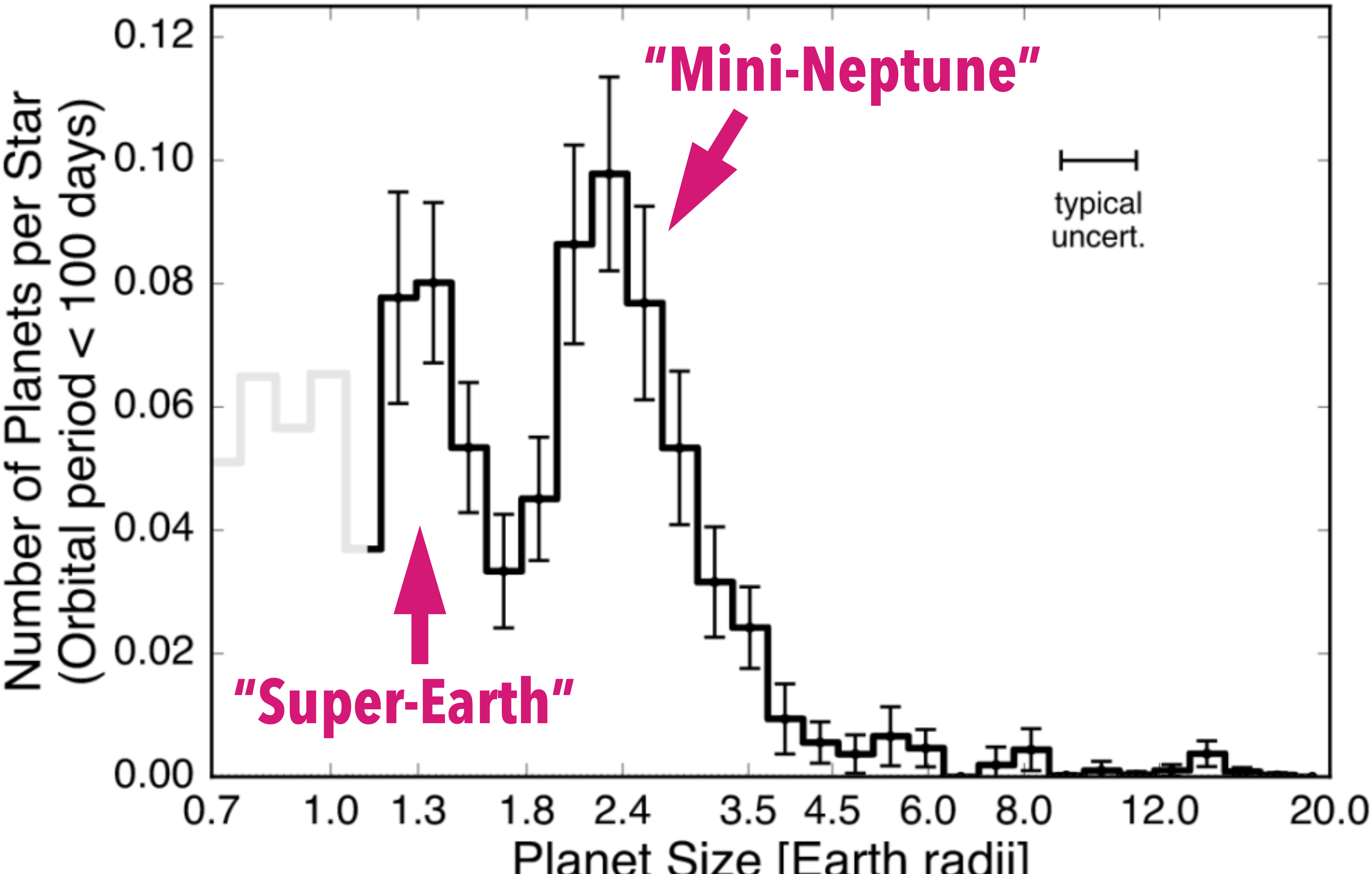
2. Multi-planet systems are common!

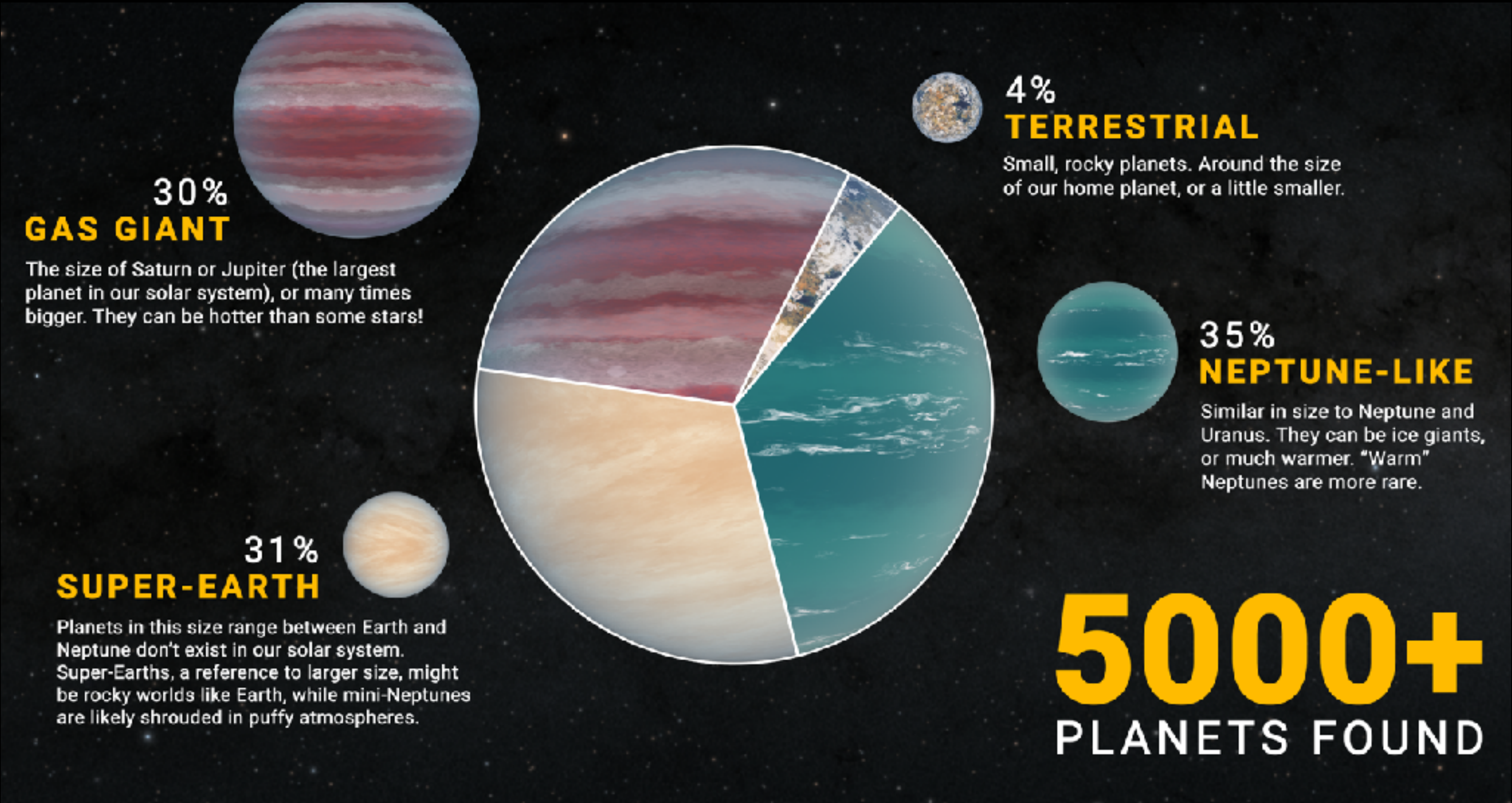


Most stars in the universe likely have multiple planets

NASA/JPL-Caltech

3. Small planets come in two sizes (Fulton+2017)





Caution: each detection method has its own **selection bias**!

NASA/JPL-Caltech

Planet formation

grain growth in protoplanetary disks

motion of dust and gas

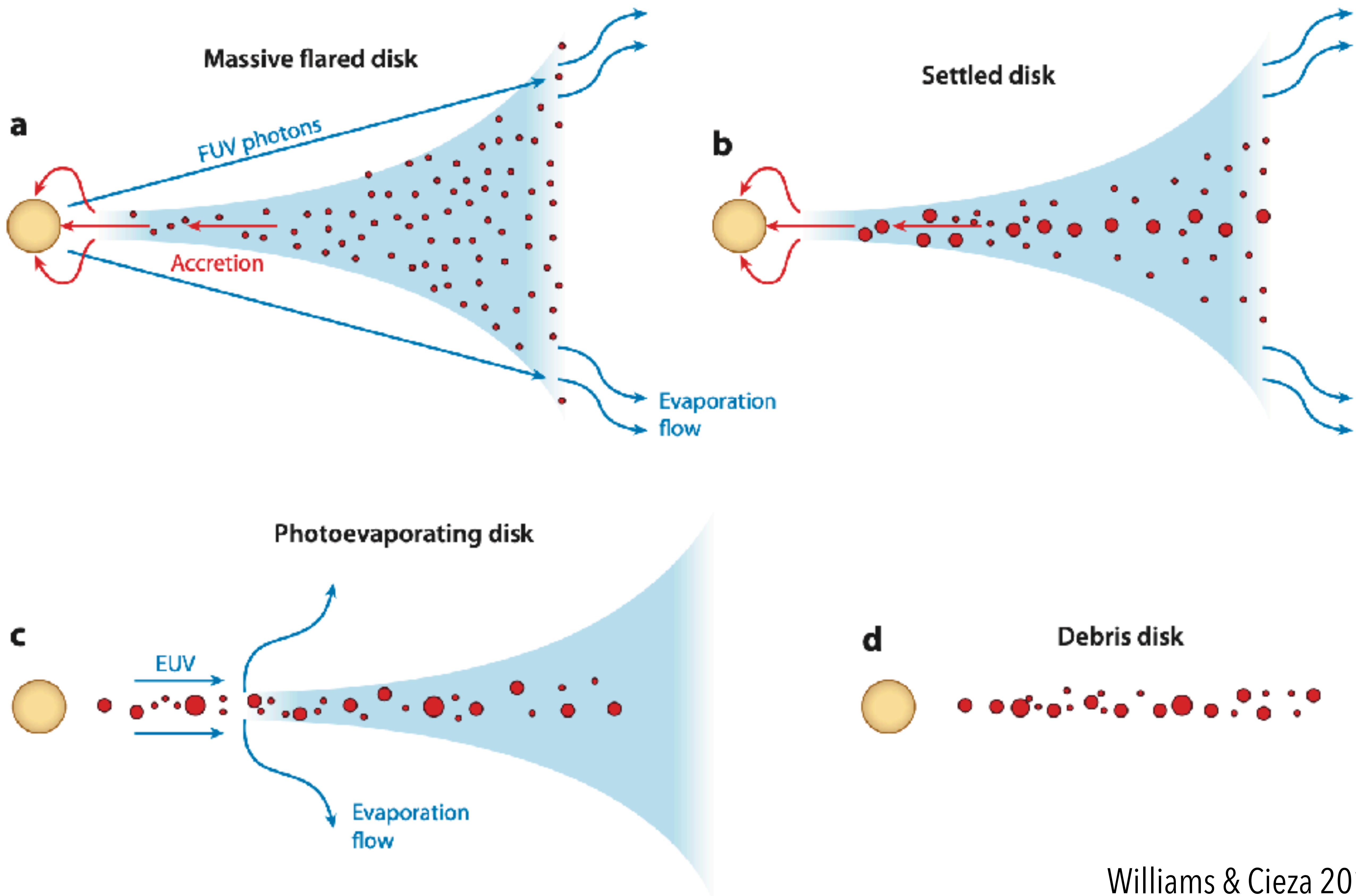
meter-size barrier and streaming instability

from planetesimals to runaway accretion

alternative scenario: top-down formation of giant planets

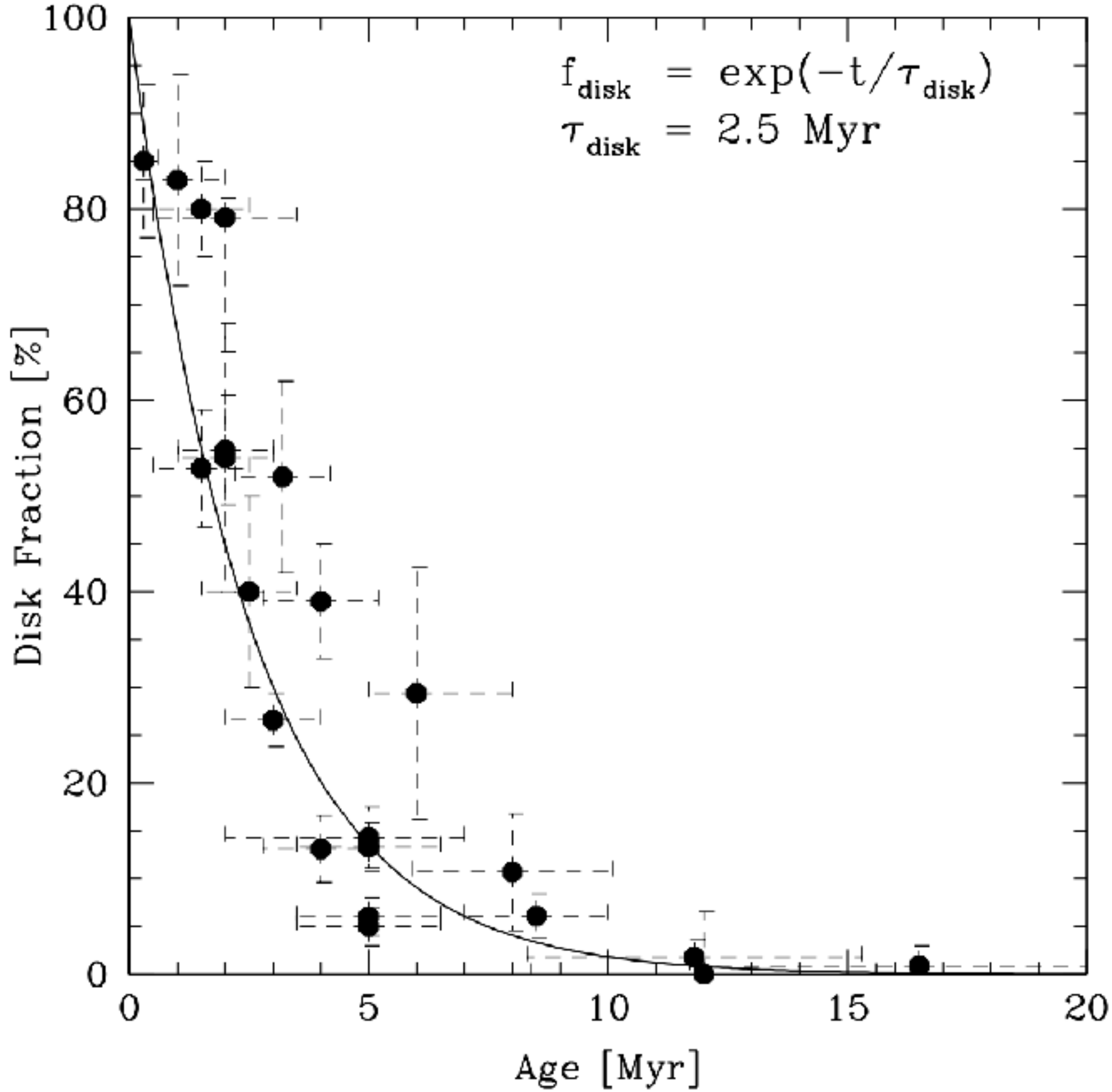
origin of the radius valley

Evolution of a protoplanetary disk



Williams & Cieza 2011

Protoplanetary disks are dissipated in few Myr



Mamajek 2009

Motion of gas and dust: Stokes number

Mass of a protoplanetary disk: ~99% gas & ~1% dust

Coupling between gas and dust can be described by Stokes number *St*

how quickly a particle adjust its velocity to the surrounding fluid

$$\text{Stokes number} = \frac{\text{relaxation timescale}}{\text{fluid characteristic timescale}}$$

orbital period in the context of protoplanetary disks

St << 1 : object moves with gas (e.g., micron-sized grains)

St >> 1 : object goes its own way (e.g., km-sized planetesimals)

Grain growth in protoplanetary disks

Micron-sized grains flow with gas and have very low relative velocities

They can stick together and grow to mm/cm-size via **van der Waals force** (induced electric dipole)

The growth of larger bodies then faces two fatal challenges:

1. **The fragmentation and bouncing barrier**: larger grains have higher inertia and are less likely to stick; collisions tend to cause bouncing or fragmentation rather than merging

2. **The radial drift barrier**: as *St* approaches unity, the velocity mismatch between gas and dust reaches its peak, driving rapid inward radial drift

Motion of gas and dust in protoplanetary disks

Motion of gas: **gravity** + **pressure gradient**

$$\frac{v^2}{r} = \frac{GM}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

Pressure is higher in the inner disk (denser & warmer): pressure gradient decreases with radius $\frac{dP}{dr} < 0$

Orbital velocity of gas is slightly lower (<0.5%) than Keplerian velocity (sub-Keplerian)

However, dust grains tend to move in Keplerian motion: $\frac{v^2}{r} = \frac{GM}{r^2}$

Meter-size barrier

This velocity difference between gas and dust has a catastrophic impact on planet formation

Dust moves faster than gas and feels a **headwind**: dust will slow down, lose angular momentum, and drift inward

mm/cm-sized grains have $St \sim 1$ and the highest radial drift: **all dust will fall onto the central star on the order of 100 yr!**

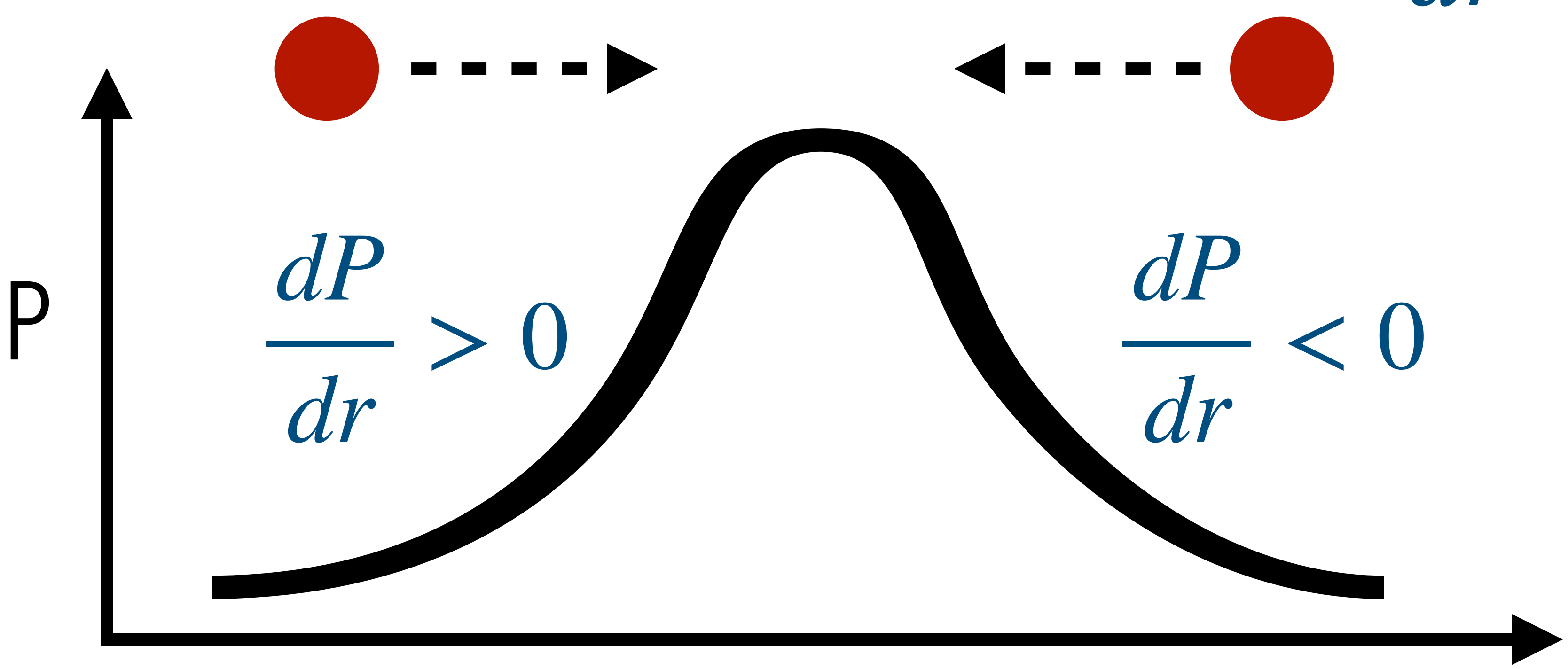
No meter-sized or larger planetesimals could form

Without a mechanism to bypass this meter-size barrier, planet formation would terminate here–**the catastrophic radial drift must be stopped**

Pressure bump

Stopping radial drift requires **pressure bumps (local pressure maxima)**

to create an **inverse pressure gradient** $\dfrac{dP}{dr} < 0$



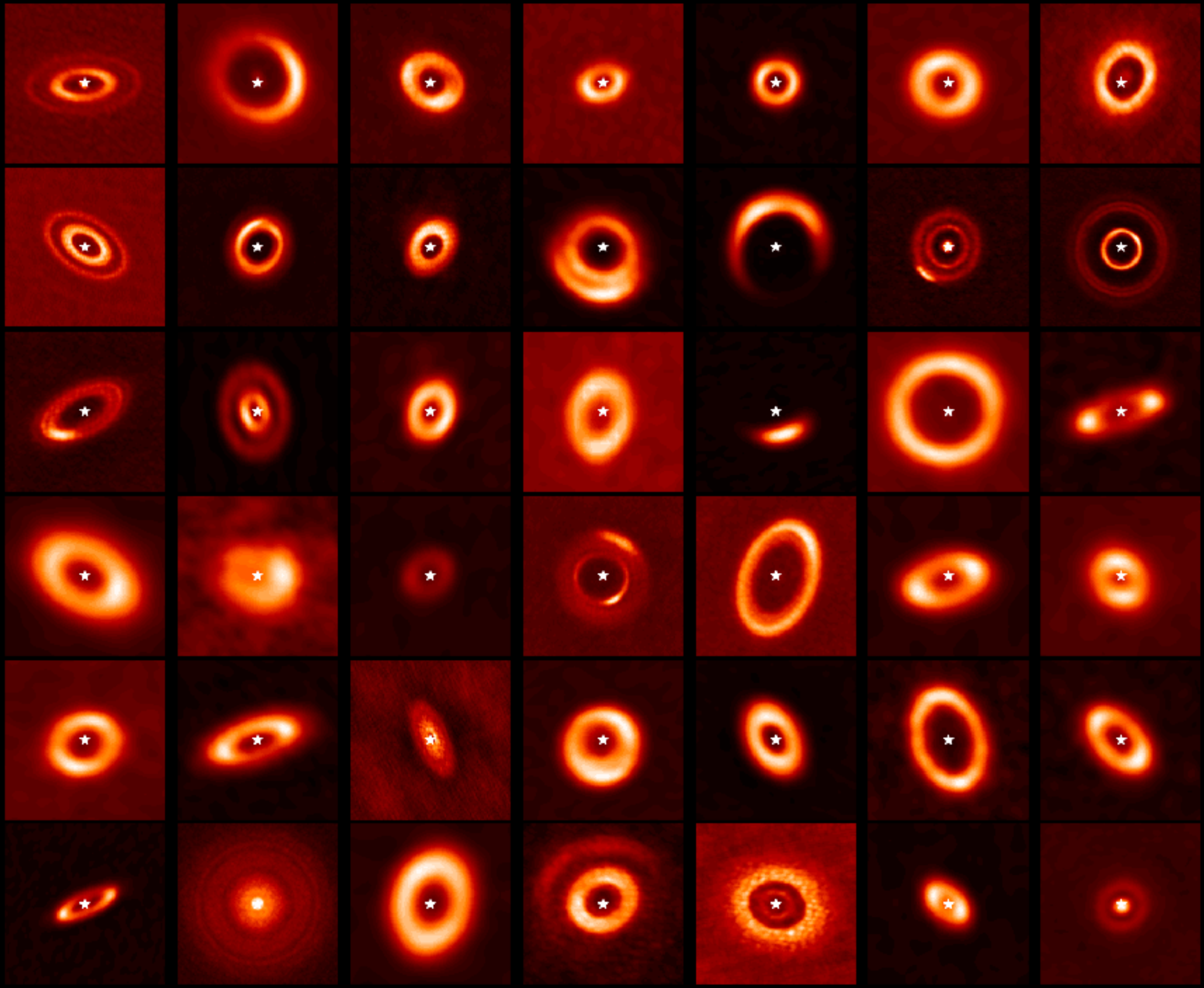
$$\frac{v^2}{r} = \frac{GM}{r^2} + \frac{1}{\rho}\frac{dP}{dr}$$

Gas outside the bump is sub-Keplerian: dust grains are dragged by headwind and drift inward toward the bump

Gas **inside** the bump moves **faster** than Keplerian: dust grains are pushed by **tailwind** and drift outward toward the bump

Pressure bumps seen with ALMA

https://en.wikipedia.org/wiki/HL_Tauri



https://www.nienkevandermarel.com/research.html

Streaming instability

A pressure bump gathers pebbles, creating an overdense region; **streaming instability (Youdin & Goodman 2005) then amplifies this overdensity**

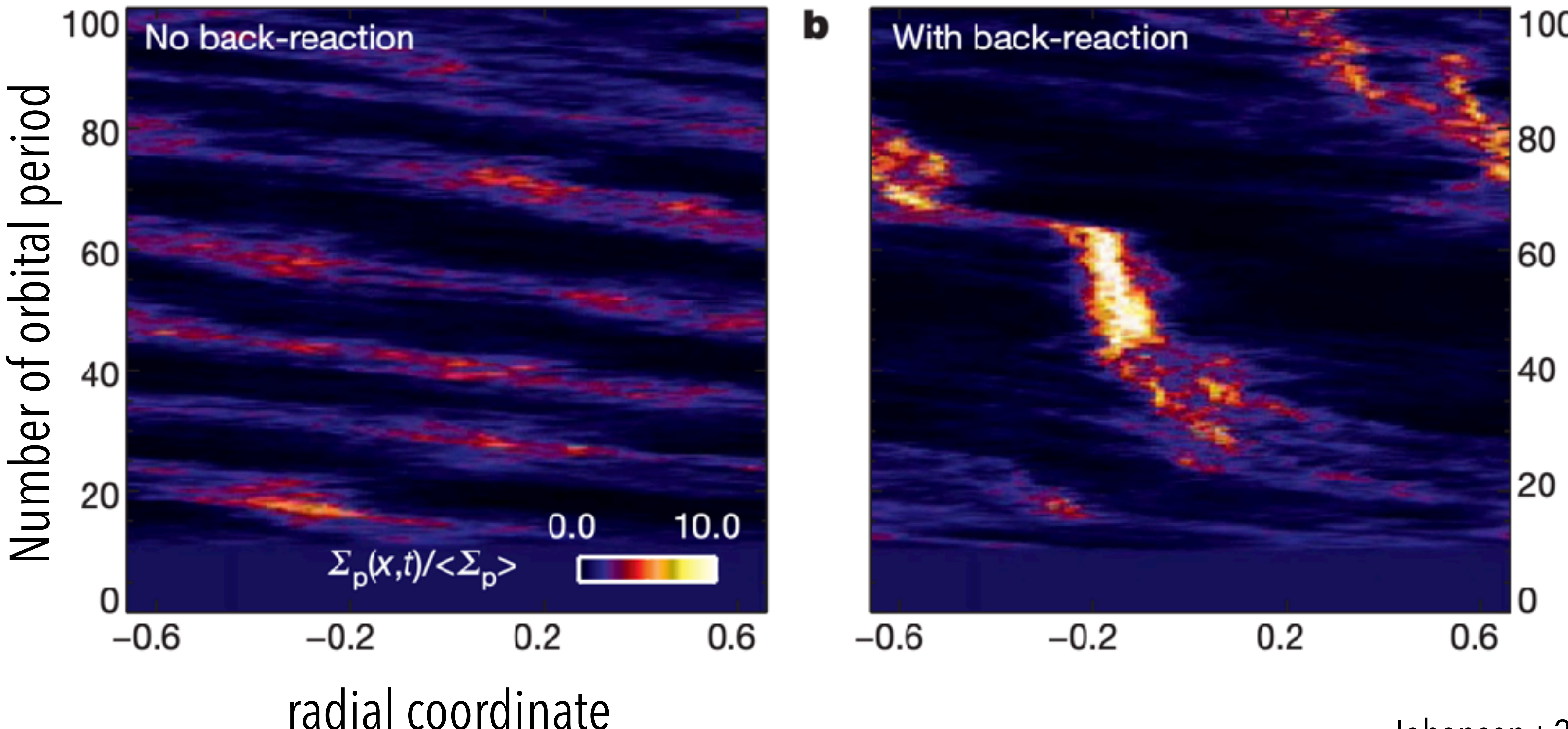
Spirit of streaming instability: Newton's 3rd law

Dust is dragged by gas; gas is pushed by dust

A positive feedback: sub-Keplerian gas is accelerated toward Keplerian → weaker headwind → slower radial drift → pebbles crowd together and pile up to form clumps → higher dust density → stronger acceleration for gas → even weaker headwind → even slower radial drift …

Without Newton's 3rd law

With Newton's 3rd law: strong density enhancement



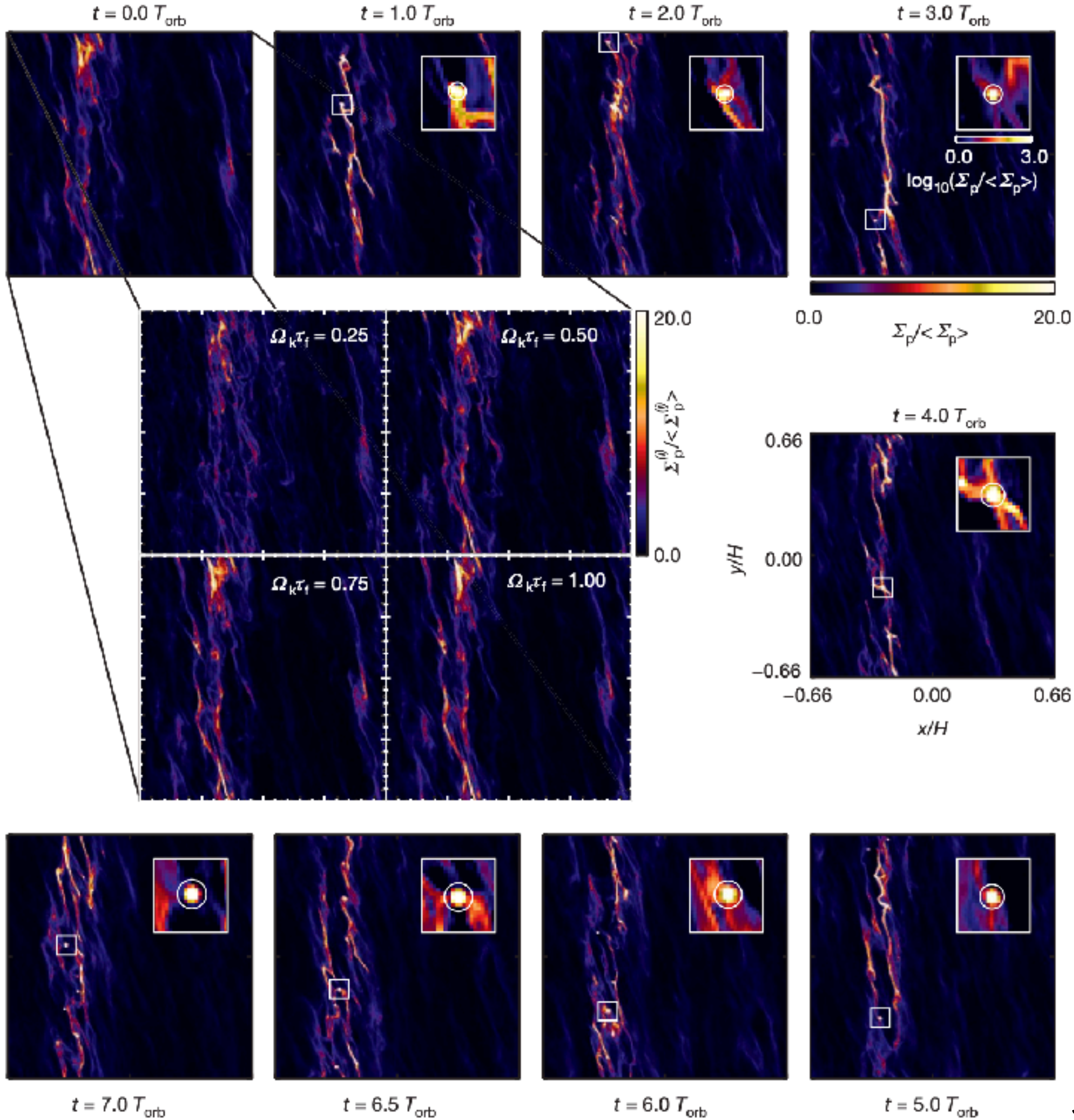
Johansen+2007

Streaming instability

Within a few orbital periods, local dust-to-gas ratio is amplified by a factor of thousands, forming dense clumps and filaments

Self-gravity of these accumulated pebbles triggers gravitational collapse, **directly forming 10–100 km-sized planetesimals**

Streaming instability allows solids to bypass the classical meter-size barrier, instantly creating large planetesimals without suffering from fragmentation or radial drift



Johansen+2007

Streaming instability bridges the gap between microphysics and macrophysics

Collision physics/aerodynamics (van der Waals force, gas drag, bouncing, fragmentation…)

↓

Streaming instability

↓

Celestial mechanics (gravity)

When km-sized planetesimals are formed, their Stokes number is >>1 and will decouple from gas and move independently

After the meter-size barrier

Planet formation is now (mainly) governed by gravity

Runaway growth (Kokubo & Ida 1996): larger planetesimals grow **exponentially** in mass by accreting smaller ones in their vicinity

escape velocity

Cross section of gravitational focusing: $\sigma = \pi R^2 \left(1 + \frac{v_{\mathrm{esc}}^2}{v_\infty^2} \right)$

relative velocity when two objects are infinitely apart

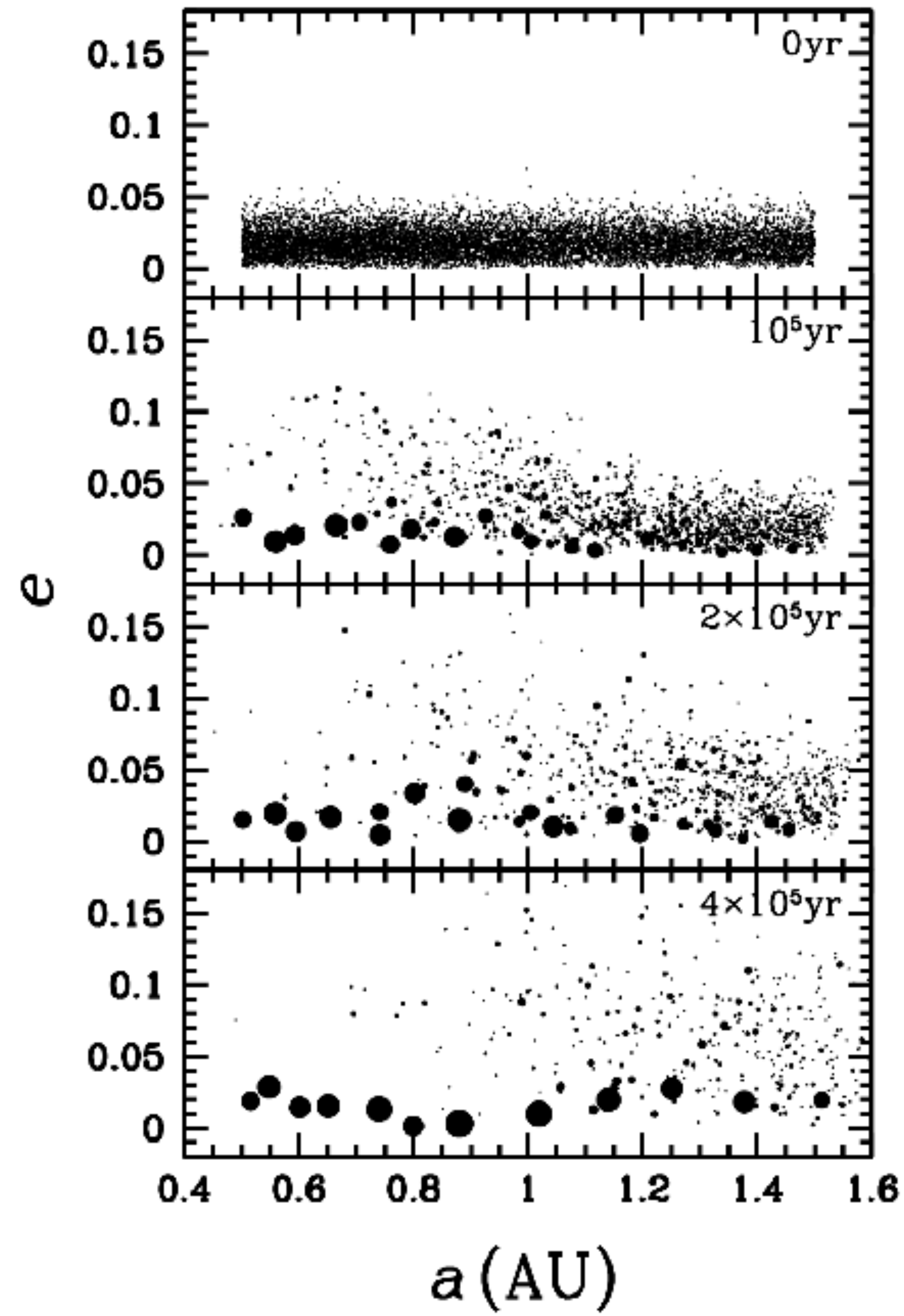
The richer gets richer: larger planetesimals possess higher escape velocities and larger cross-sections, allowing them to rapidly grow into **planetary embryos** of a few thousand km

Oligarchic growth

Following runaway accretion, a few dominant embryos emerge

Their immense gravity stirs the surrounding planetesimals, causing v_∞ to increase and weakening the effect of gravitational focusing

These leading embryos experience a reduced growth rate, each occupying a distinct feeding zone in the disk and remaining well-separated from one another (**oligarchic growth; Kokubo & Ida 1998**)



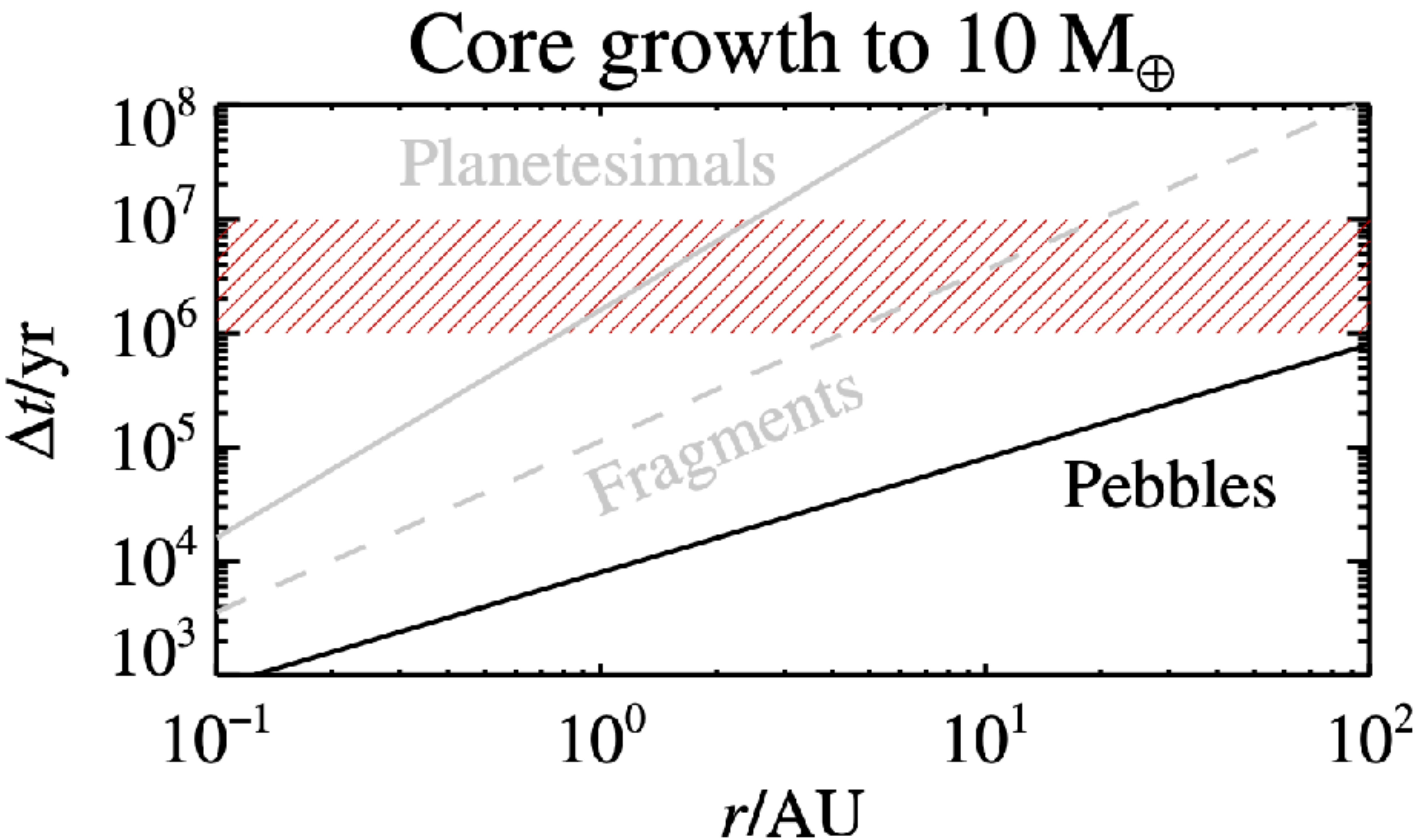
Kokubo & Ida 2002; Raymond+2014

Pebble accretion

Traditional planetesimal accretion (runaway/oligarchic) is **too slow (>10 Myr)** to form a massive core (~10 Earth masses) before the gas disk dissipates

Pebble accretion (Lambrechts & Johansen 2012): gas drag slows down mm/cm-sized pebbles as they approach an embryo, causing them to rapidly spiral down and collapse onto its surface

This aerodynamic assistance allows embryos to bypass slow oligarchic phases and **reach several Earth masses in <1 Myr**



Lambrechts & Johansen 2012

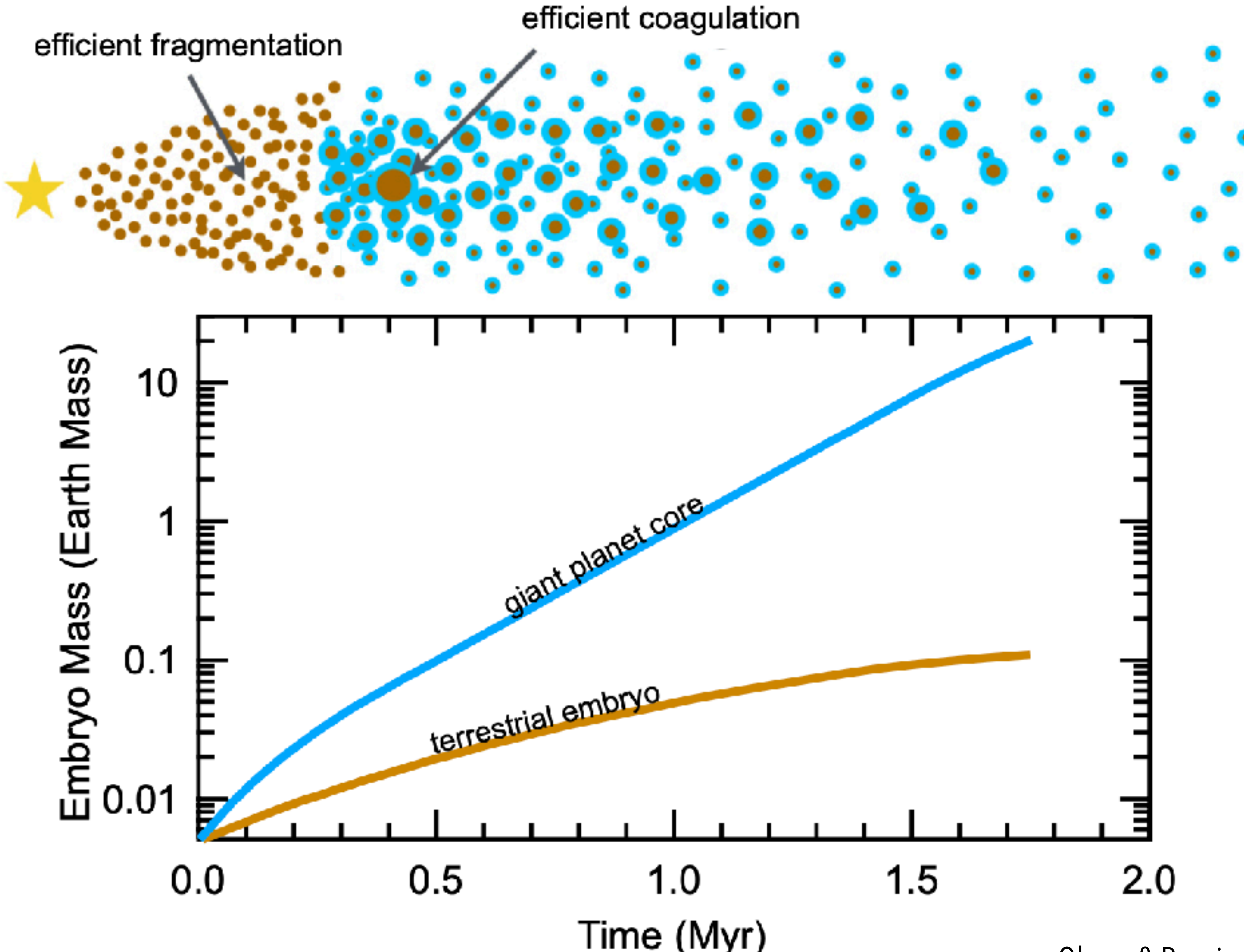
Pebble accretion inside/outside the snowline

Inside the snowline:

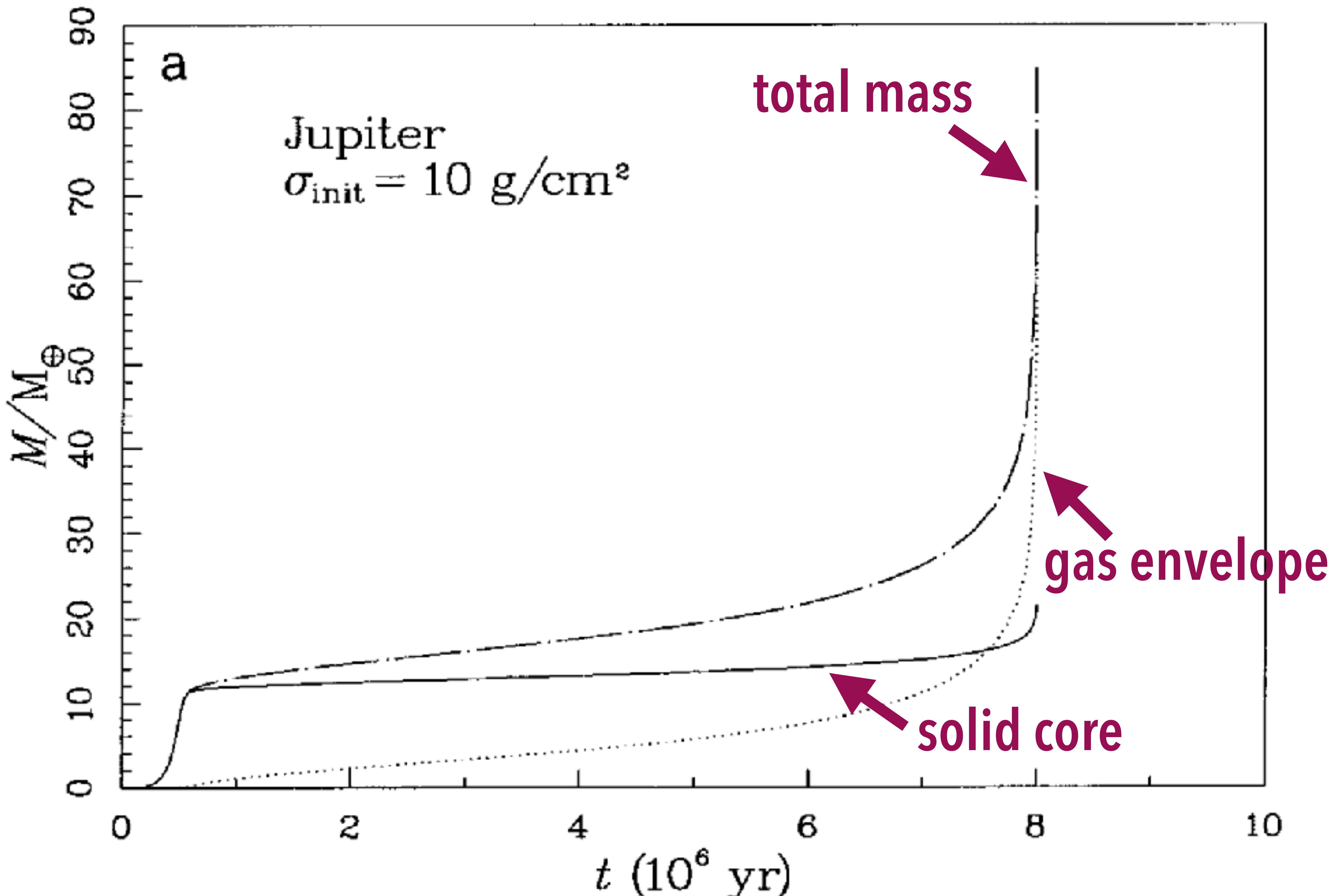
- dry silicate pebbles limit embryos to a few Earth masses, followed by **giant impacts**
- **mini-Neptunes**: cores assemble before disk dissipation, capturing a light H/He envelope
- **super-Earths**: cores finalize after disk dissipation, or lose their atmospheres later via **photoevaporation** (stellar XUV stripping)

Outside the snowline:

- sufficient icy pebbles accelerate core growth beyond the **critical mass threshold (~10 Earth masses)**
- this triggers **runaway gas accretion**, rapidly forming gas giants like Jupiter (**core accretion; Pollack+1996**)



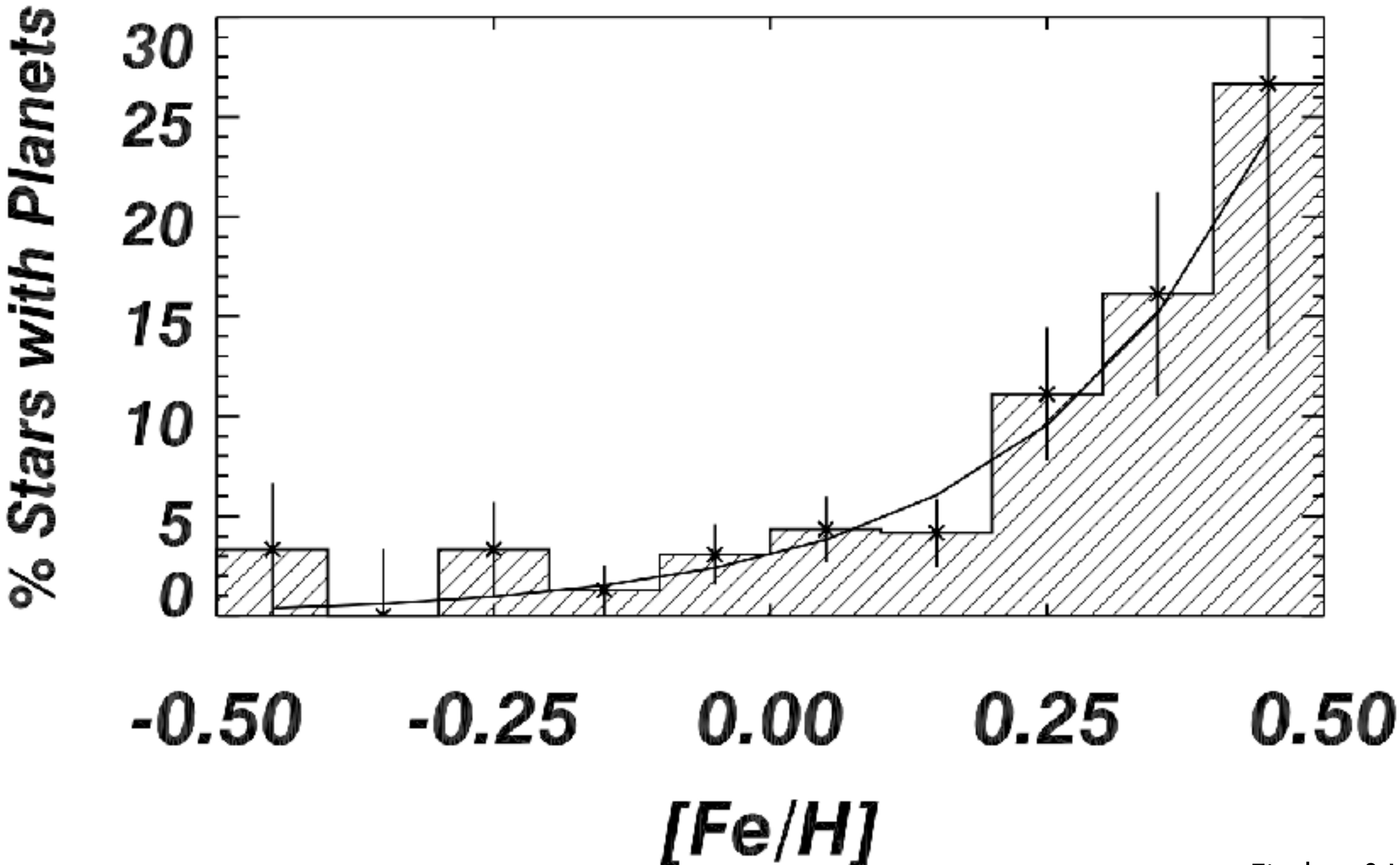
Oberg & Bergin 2021



Pollack+1996

Observational proof: planet-metallicity correlation

Metal-rich stars are more likely to have giant planets



Fischer & Valenti 2005

Observational proof: planet-metallicity correlation

Metal-rich stars are more likely to have giant planets

Higher metallicity → more solid material (pebbles) → easier for pebbles to clump together via streaming instability → rapid formation of large planetesimals → efficient pebble accretion onto embryos → reaching critical core mass (~10 Earth masses) before disk dissipation → runaway gas accretion

Core accretion is a **bottom-up** process

Can giant planets form directly from the top down?

Top-down formation of giant planets

Gravitational instability (Toomre 1964; Boss 1997) occurs when a sufficiently **massive and cold protoplanetary disk** becomes **self-gravitating (Toomre $Q \lesssim 1$)**, leading to rapid fragmentation of the gas disk directly into a giant plant

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

c_s: sound speed (thermal pressure to prevent collapse)

κ: epicyclic frequency (~Keplerian frequency; shear to stretch the clump)

Σ: surface density

Top-down formation of giant planets

Toomre *Q* is defined conceptually as **stabilizing forces/self-gravity**

It quantifies the balance between thermal/rotational support and gravitational collapse

When *Q*<1, self-gravity dominates over thermal pressure and rotational shear: any density fluctuation cannot be suppressed; it will continually grow and eventually collapse into bounded clumps

Gravitational instability (also known as disk instability/fragmentation) favors the **outer disk (>50 AU)**:

- low temperatures → low sound speed and weak pressure
- optically thin → efficient cooling

Core accretion vs. gravitational instability

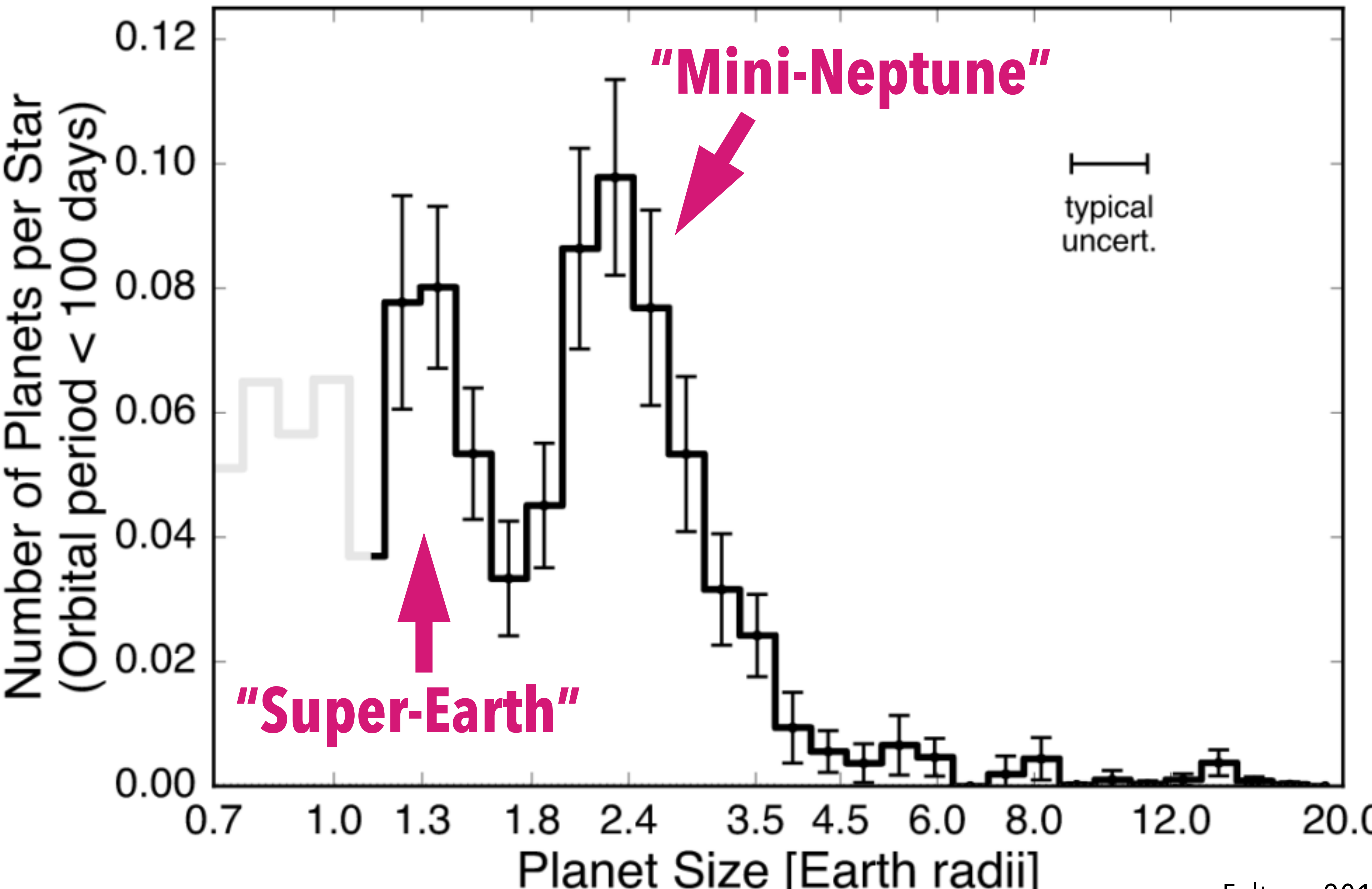
1. Mechanism
    - CA: bottom-up process. Dust grain collide and stick, building a ~10 $M_\oplus$ rocky core before sweeping up gas
    - GI: top-down process. Sudden, direct fragmentation of a massive, cold disk into giant planets

2. Timescale
    - CA: slow (~Myr). Giant cores must from before the disk dissipates
    - GI: instantaneous (~decades to centuries)

Core accretion vs. gravitational instability

3. Preferred location
    - CA: inner disk where solid material is concentrated, and orbit times are short, enhancing collision and accretion rates
    - GI: outer disk where low temperatures and long orbital periods enable rapid radiative cooling
4. Observational evidence
    - CA: strongly supported by the planet-metallicity correlation (metal-rich stars are more likely to harbor giant planets due to higher pebble supply). Some directly-imaged giant planets also has higher metallicity than their host stars (e.g., HR 8799 planets)
    - GI: may explain wide-orbit giant planets, which are located too far out for CA to efficiently work

The radius valley



Fulton+2017

The radius valley

Possible origin: atmospheric loss driven externally or internally

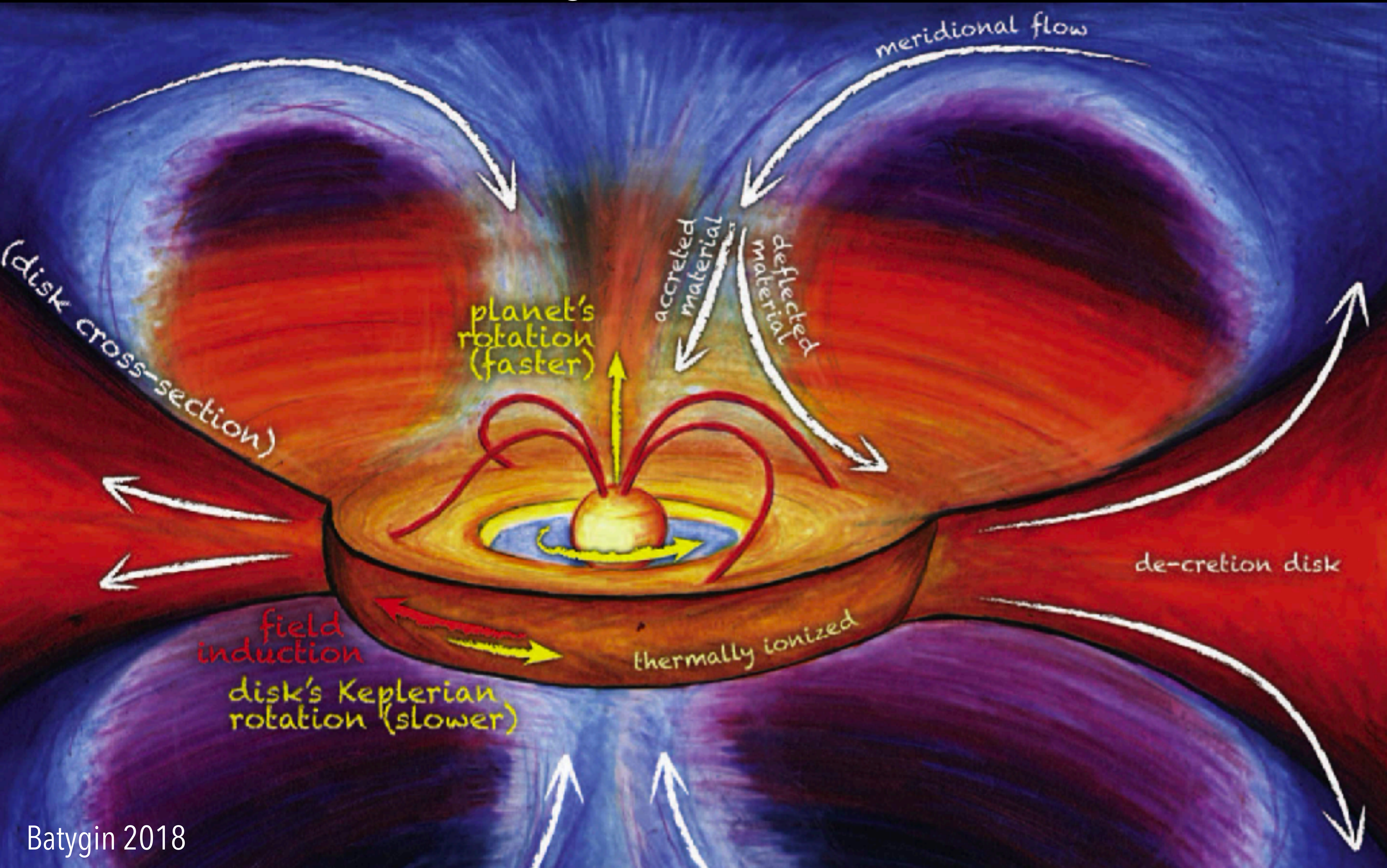
H/He atmosphere is extremely puffy due to its low density. Stripping even a tiny fraction of this atmosphere causes the planet's radius to drop, driving it across the valley from the right peak to the left peak

Photoevaporation (external heating): intense X-ray and UV photons from the young host star heat the upper atmosphere, blasting the gas into space

Core-powered mass loss (internal heating): the cooling rocky core releases residual accretion heat and radioactive decay energy, heating the atmosphere to drive mass loss (e.g., Ginzburg+2018)

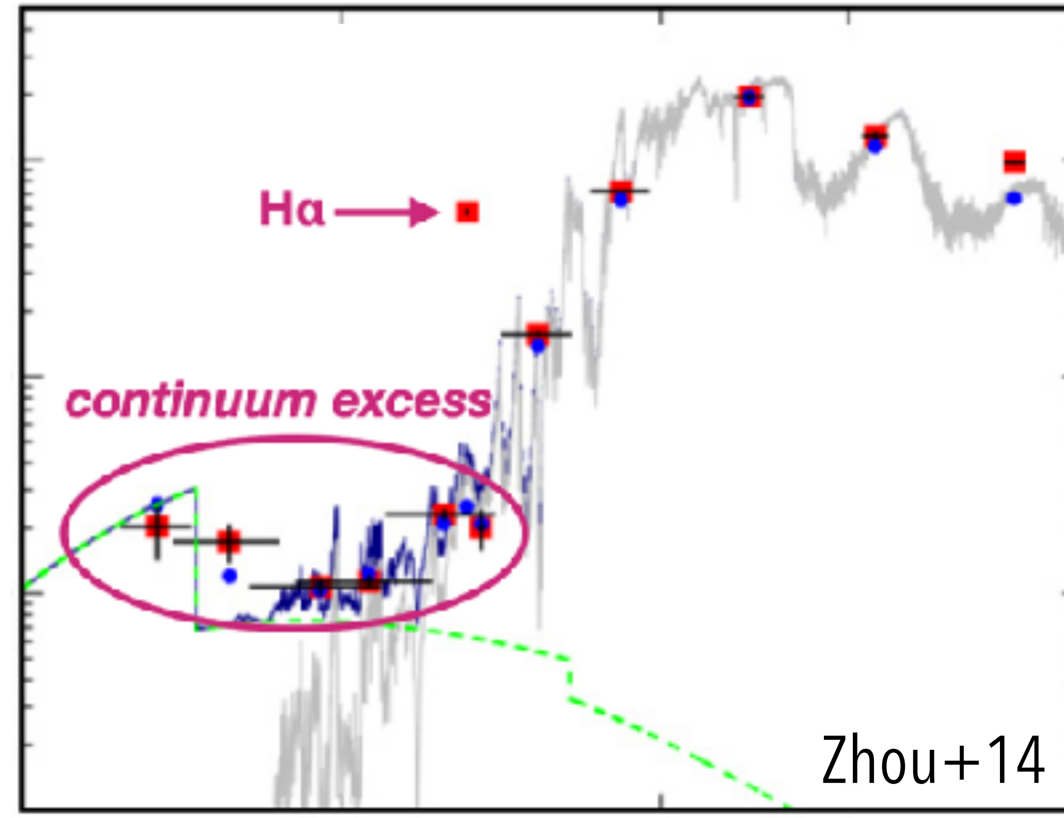
Direct-imaging of young giant planets

Protoplanets can emit strong hydrogen emission (e.g., Hα at 6563 Å) when gas falls onto their surfaces



Batygin 2018

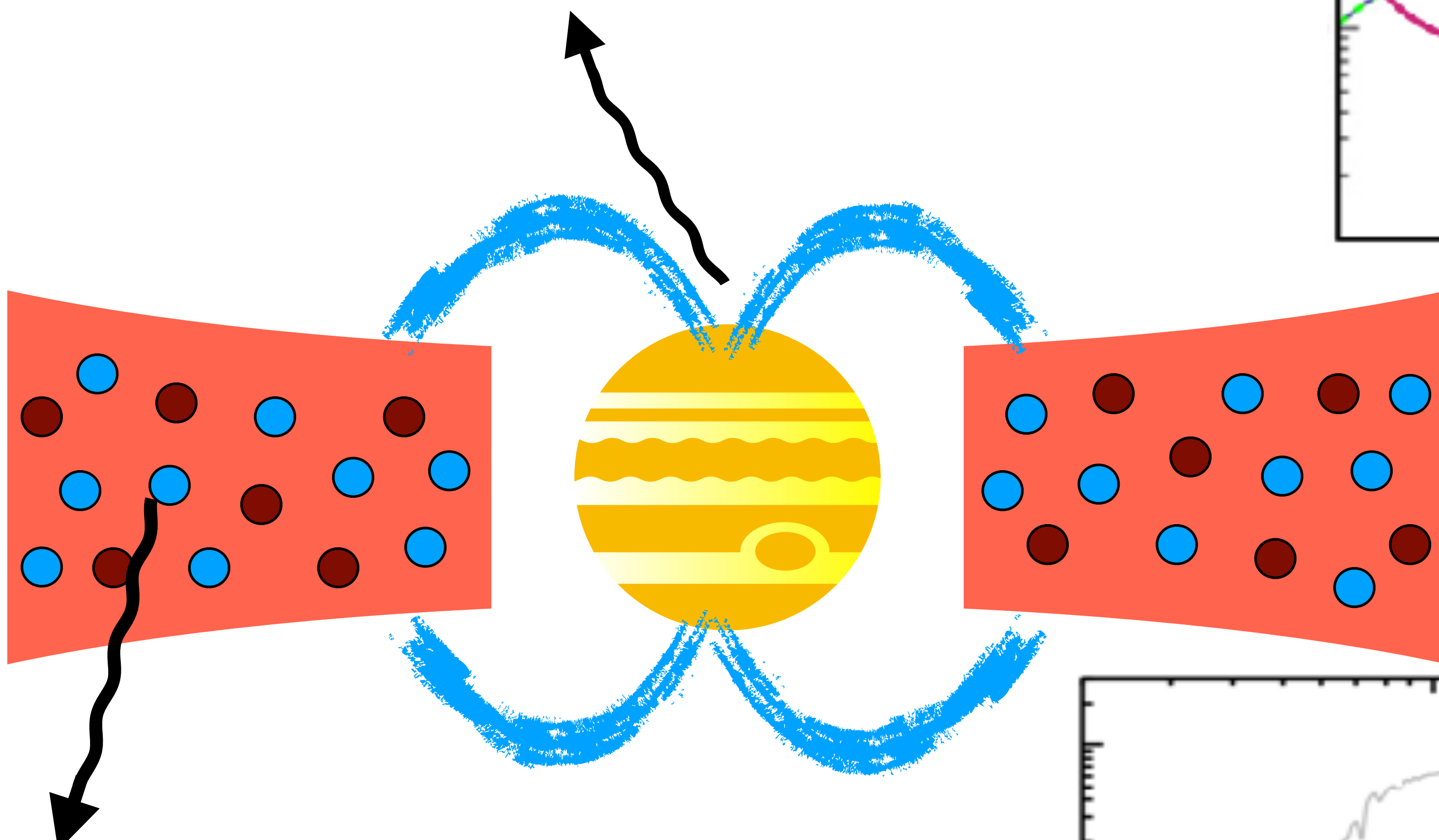
Signatures of young giant planets



UV/optical/near-infrared

hydrogen lines (Hα, Paβ, Brγ)

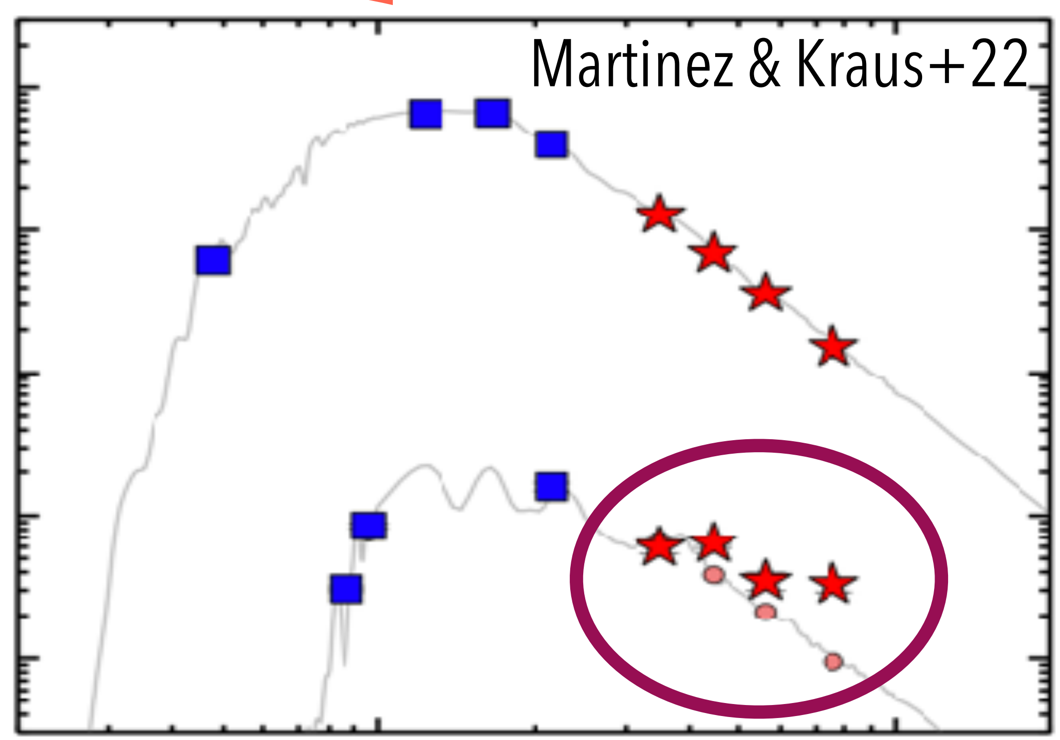
accretion shock continuum



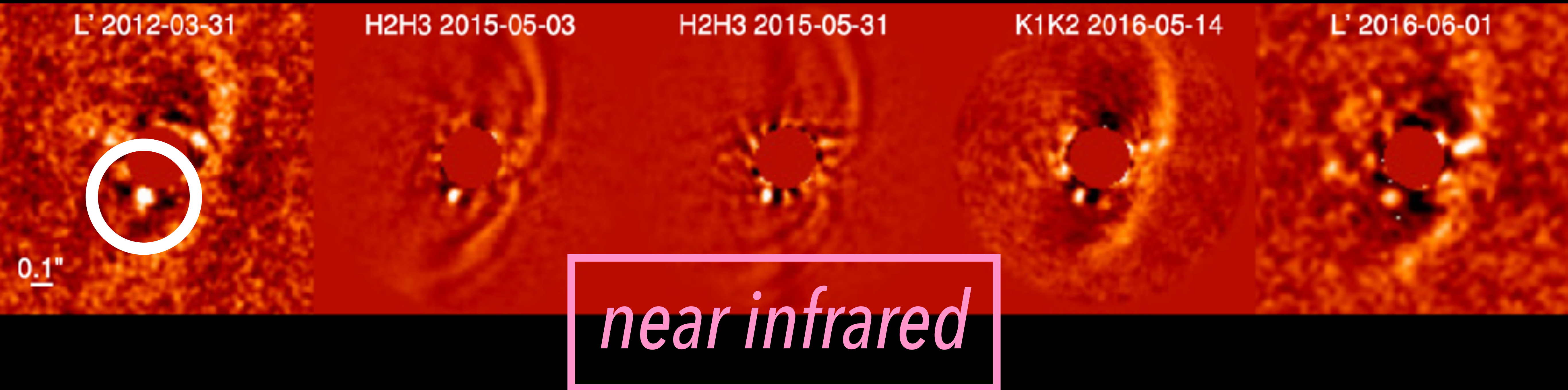
mid-infrared & millimeter

dust thermal continuum

molecular lines



A protoplanet around PDS 70 discovered in 2018



A&A 617, A44 (2018)
https://doi.org/10.1051/0004-6361/201832957

Astronomy & Astrophysics

Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70⋆,⋆⋆

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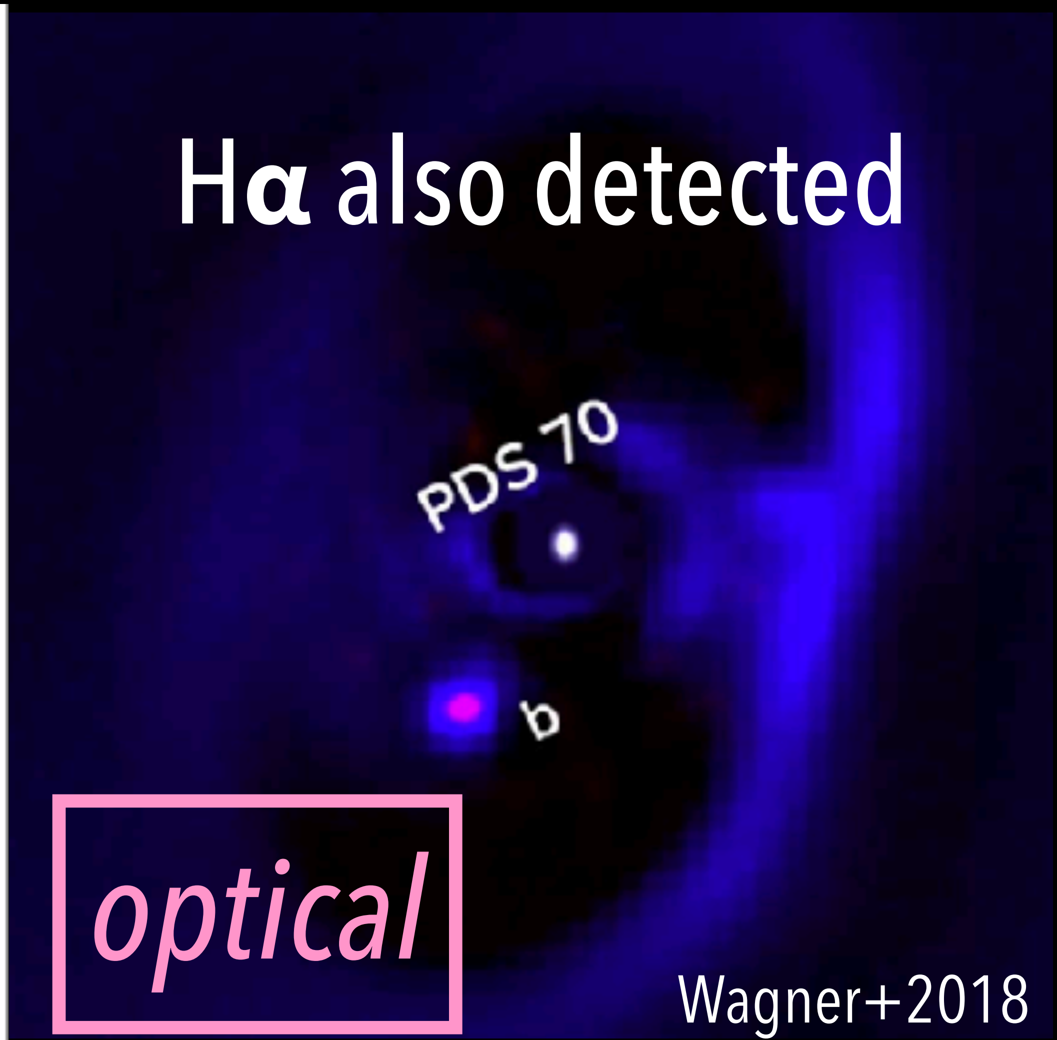

Another protoplanet around PDS 70 discovered in 2019

Both PDS 70 b and c are emitting Hα

Two accreting protoplanets around the young star PDS 70

S. Y. Haffert, A. J. Bohn, J. de Boer, I. A. G. Snellen, J. Brinchmann, J. H. Girard, C. U. Keller & R. Bacon

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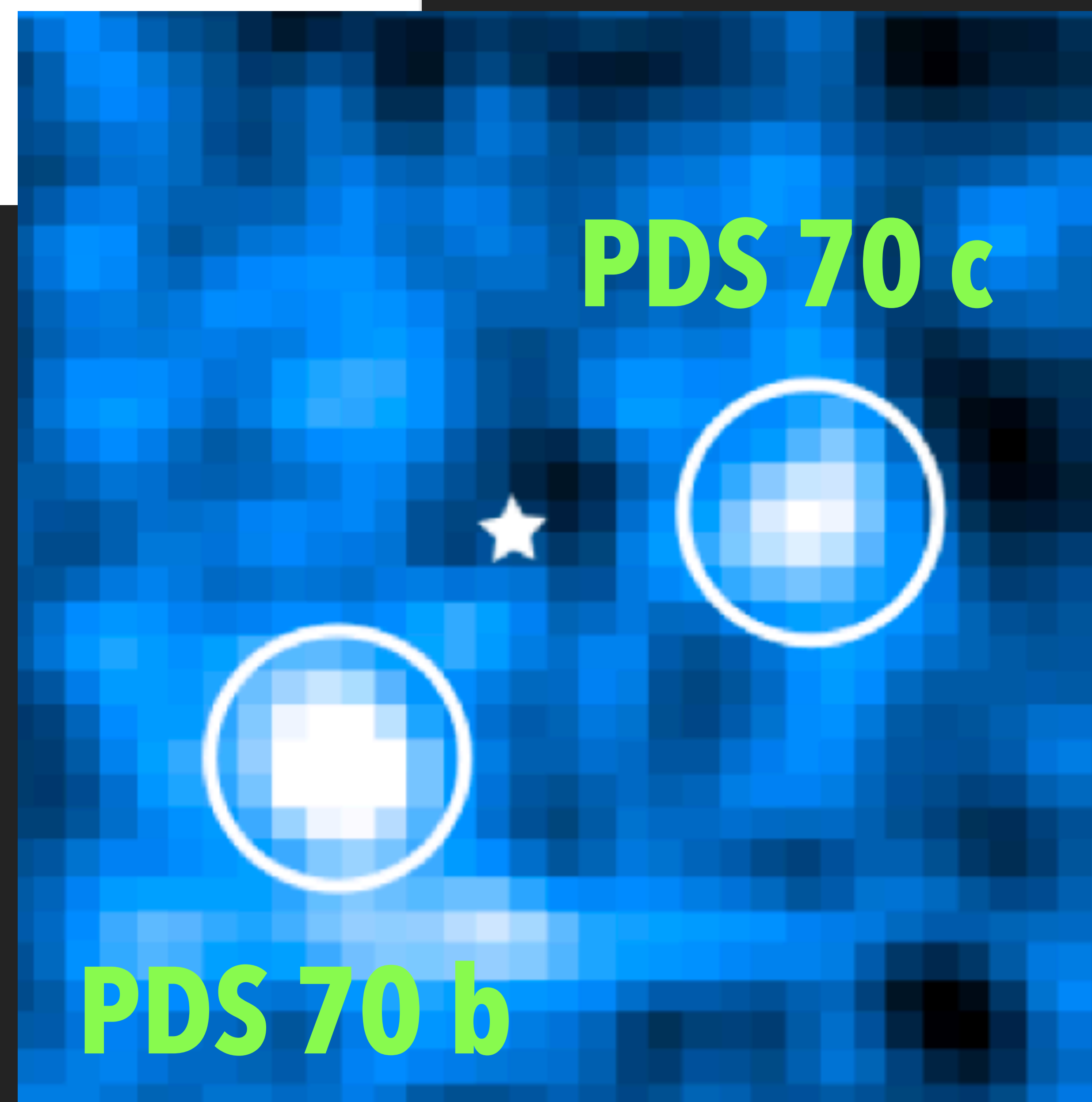
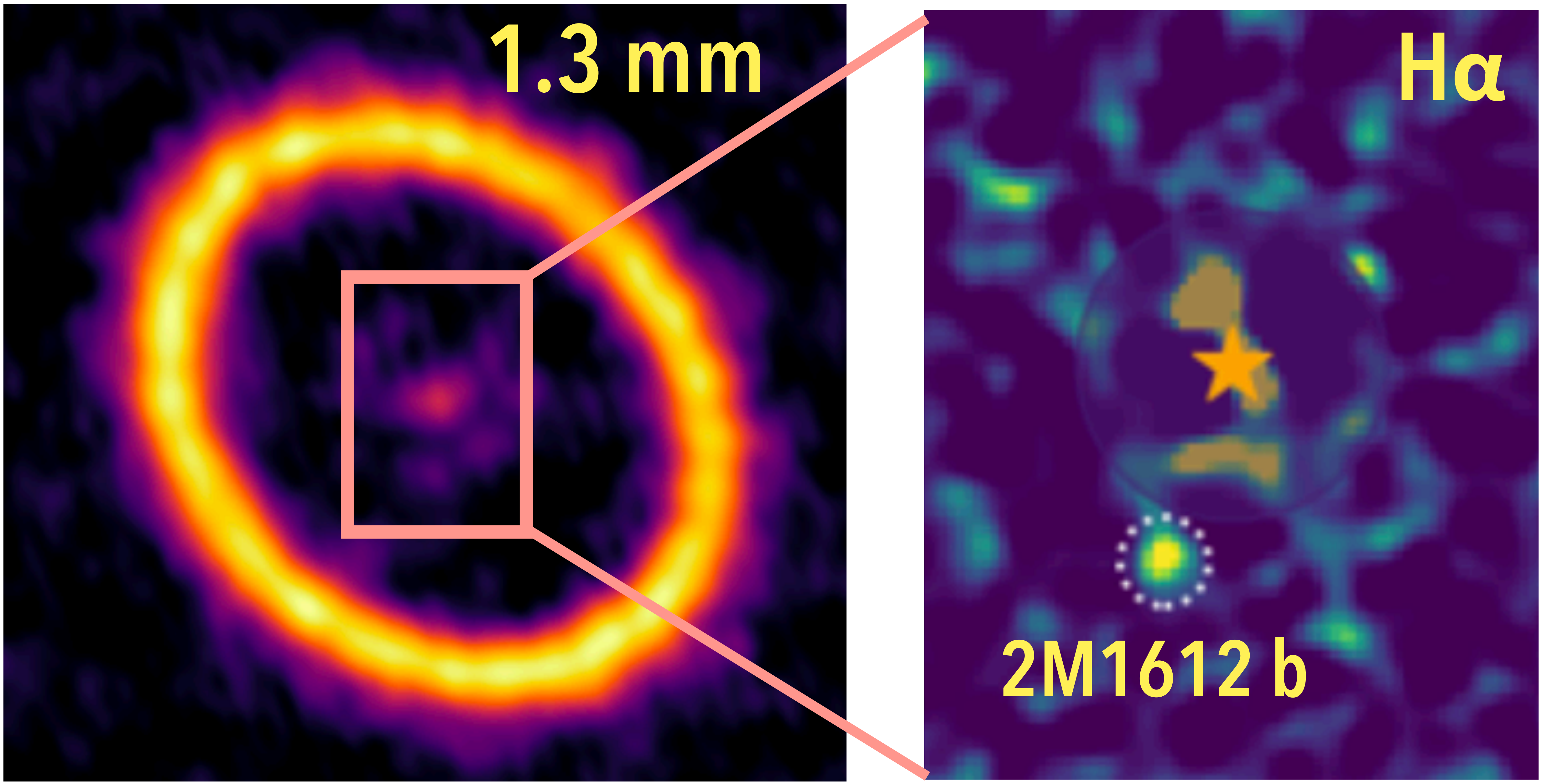
Both planets have masses of 2~4 M_{Jup}

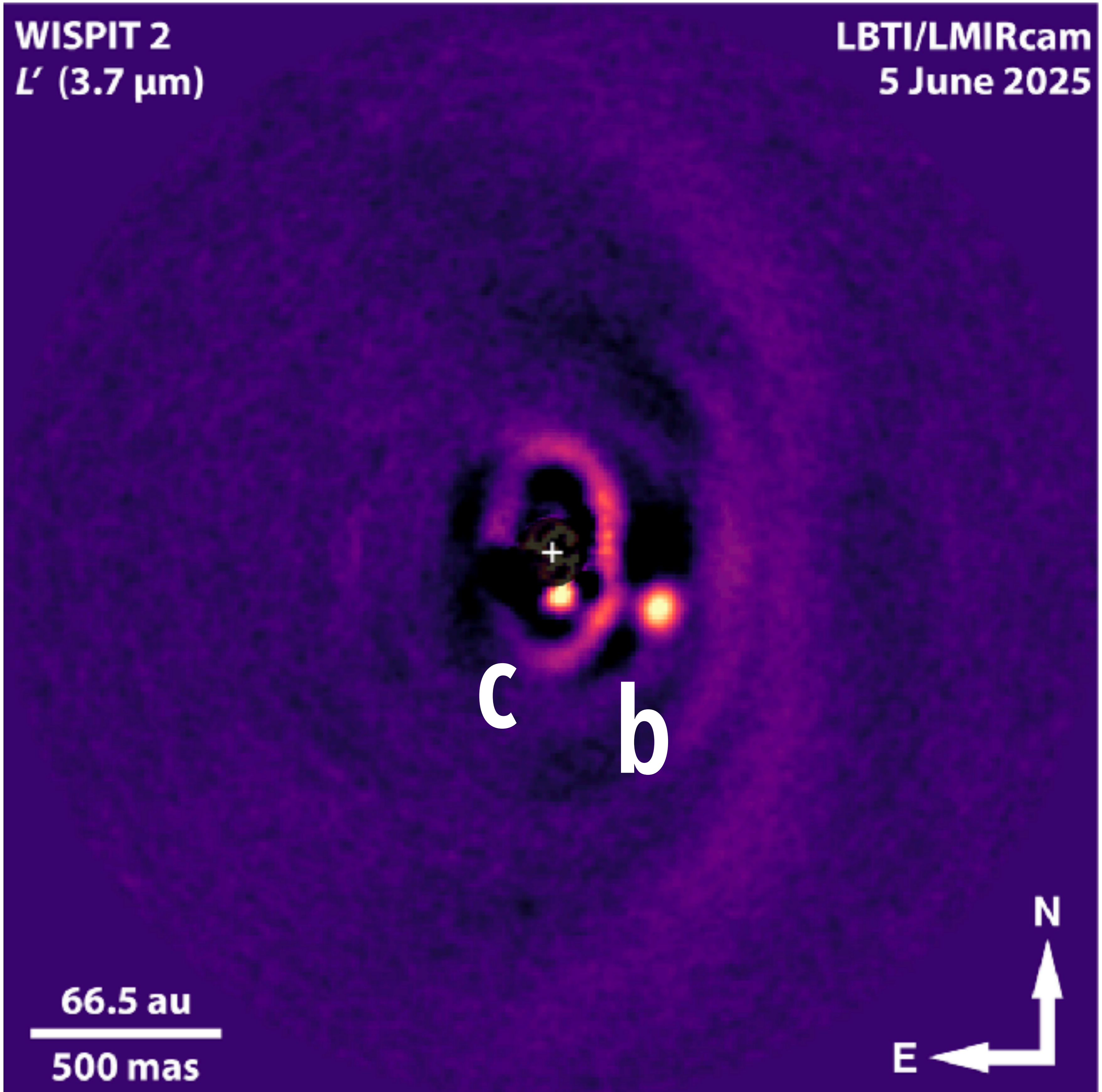


A ~4 M_{Jup} protoplanet around 2MASS J1612–3010



Li+2025

Two protoplanets around WISPIT 2



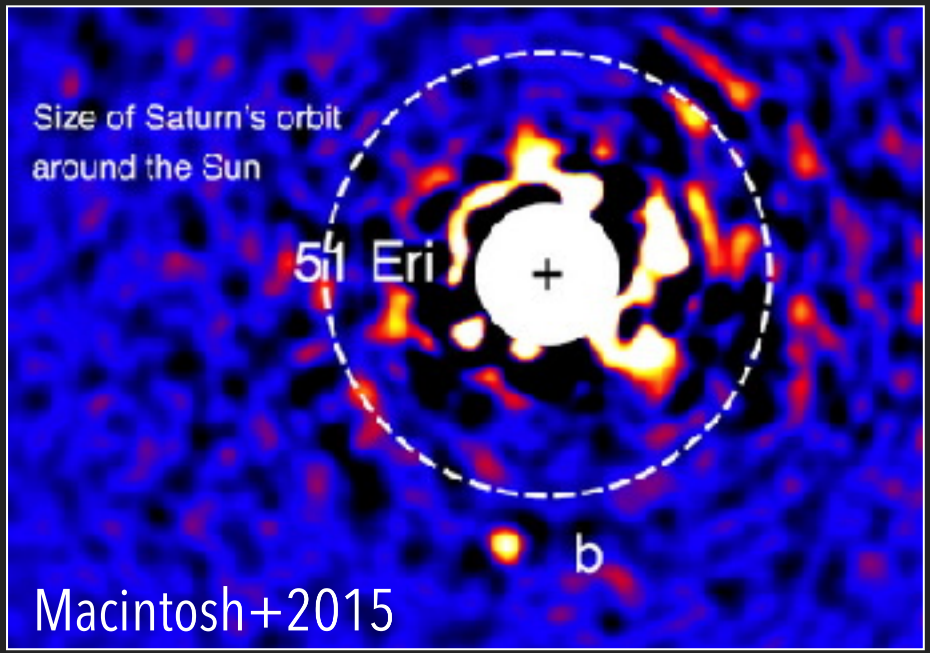
WISPIT 2 b: ~5 M_{Jup}

WISPIT 2 c: ~10 M_{Jup}

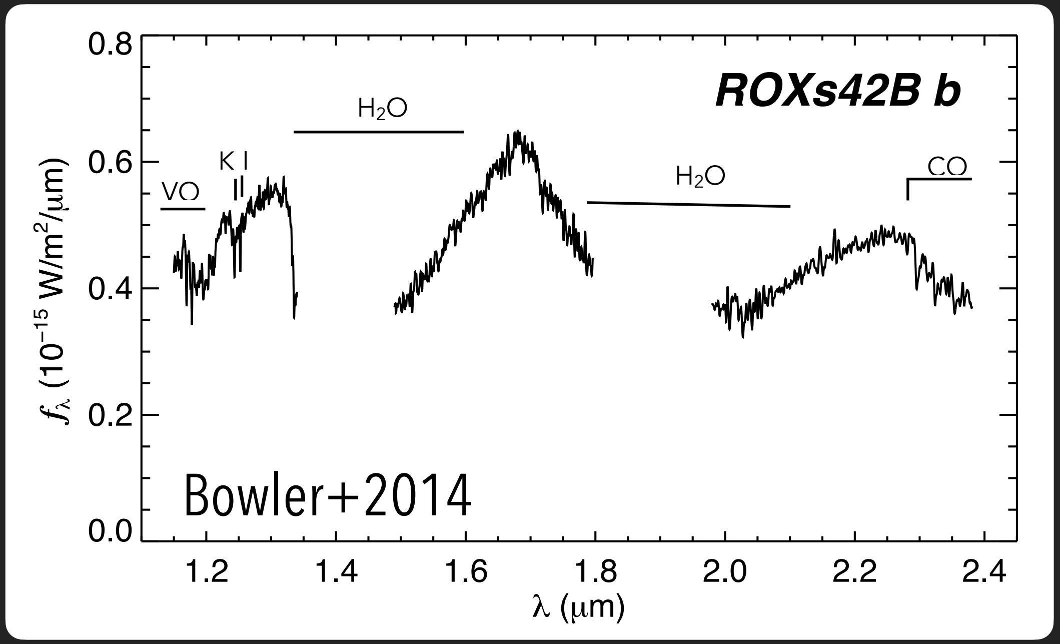
Close+2025;
van Capelleveen+2025;
Lawlor+2026

Key advantages of direct imaging

architecture

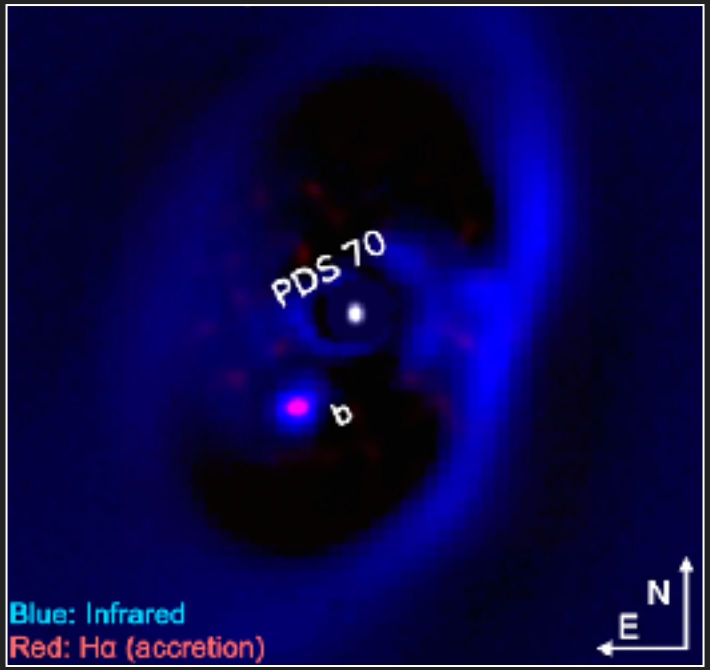


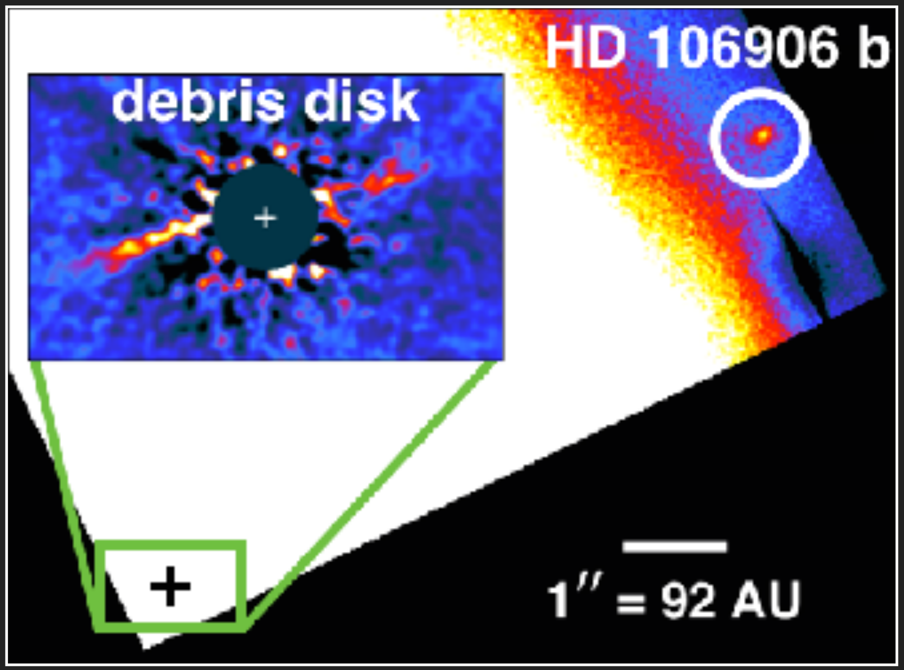
atmosphere



planet-disk interaction

Wagner+2018





Wu+2016

Summary

1. detection methods

2. major discoveries (demographics, multi-planet systems, radius valley)

3. planet formation (meter-size barrier, streaming instability, core accretion, gravitational instability, origin of radius valley)

4. direct imaging of accreting giant planets (PDS 70 bc, WISPIT 2 bc, 2M1612 b)