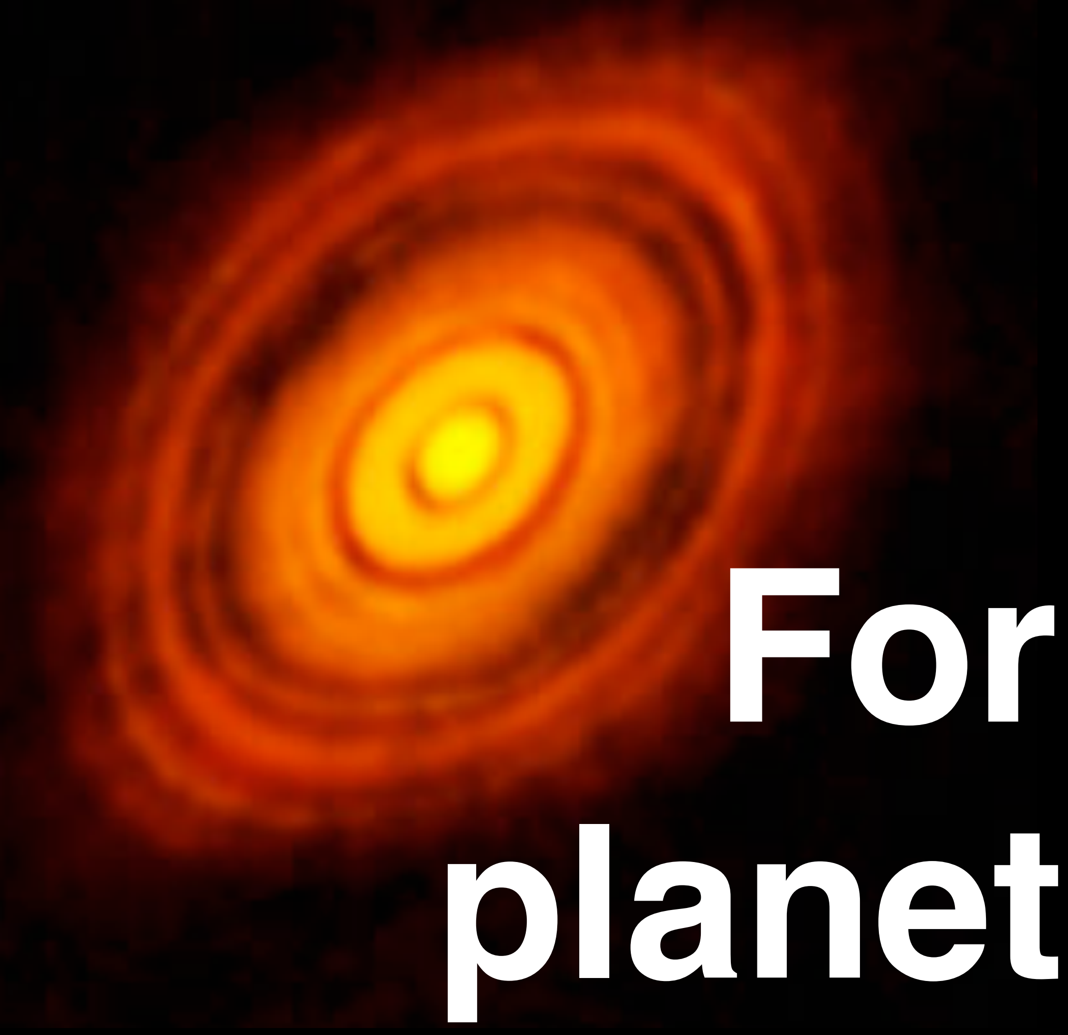
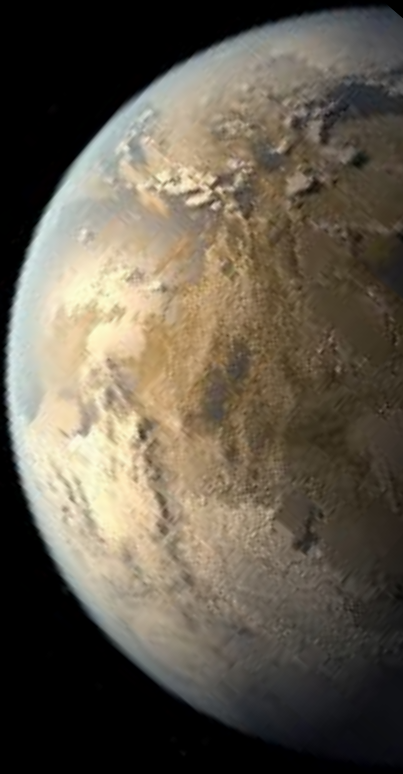


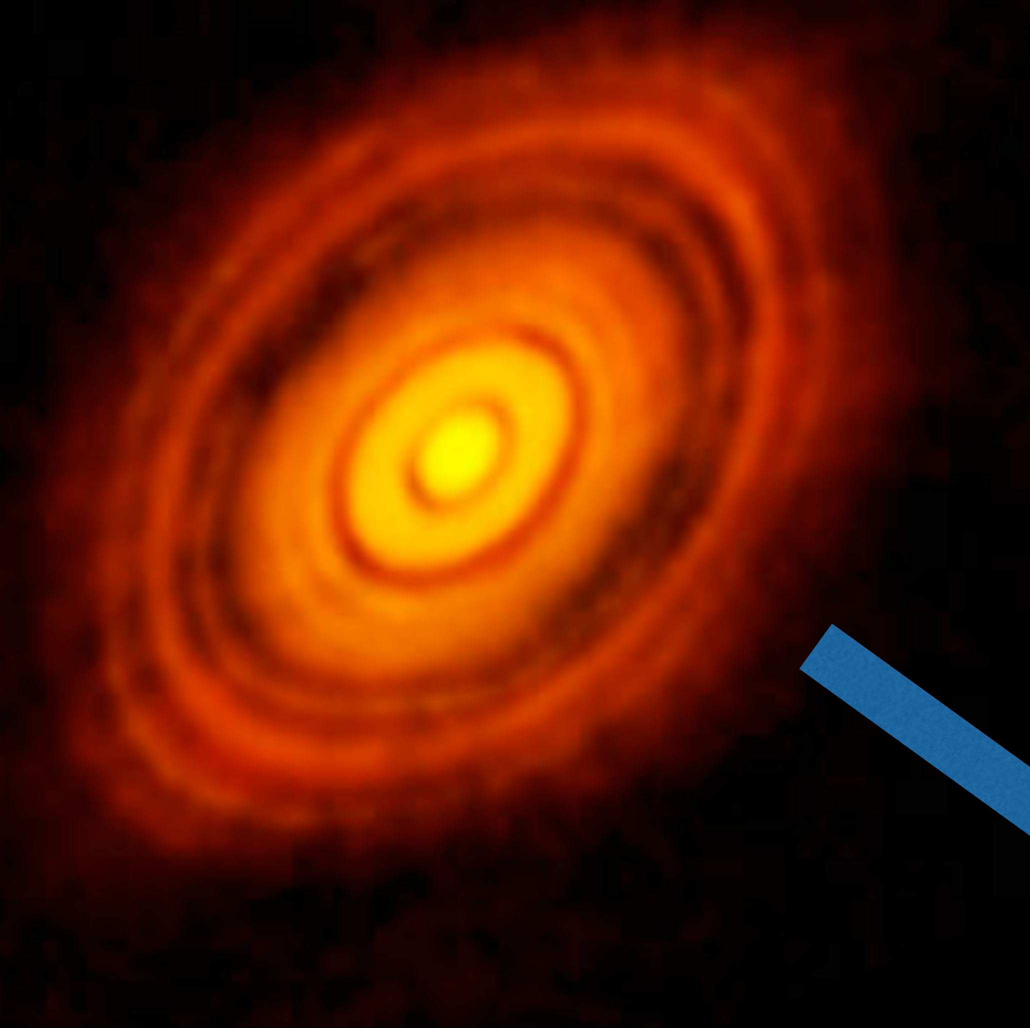
Formation of planetary systems

Sean Raymond

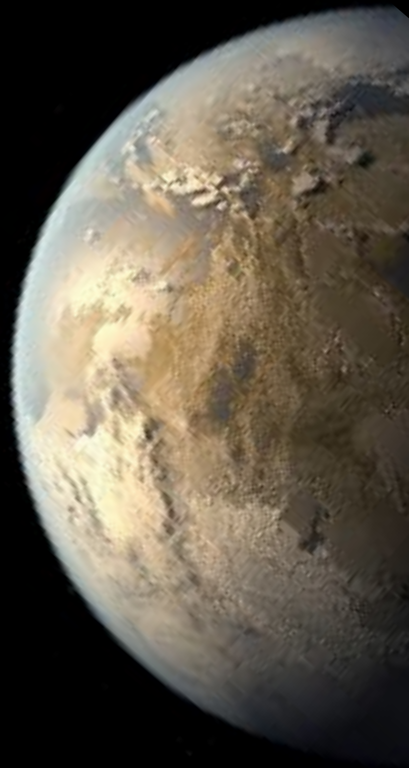
CNRS *Directeur de Recherche*
Laboratoire d'Astrophysique de Bordeaux
planetplanet.net



(with a few slides from A. Izidoro, P. Armitage, M. Lambrechts, A. Morbidelli)

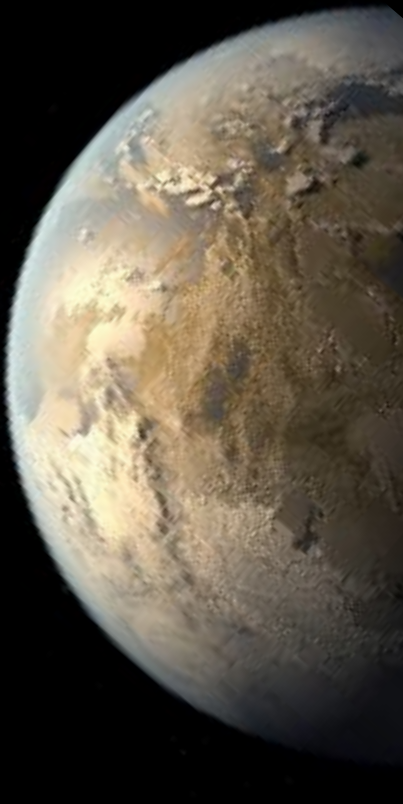


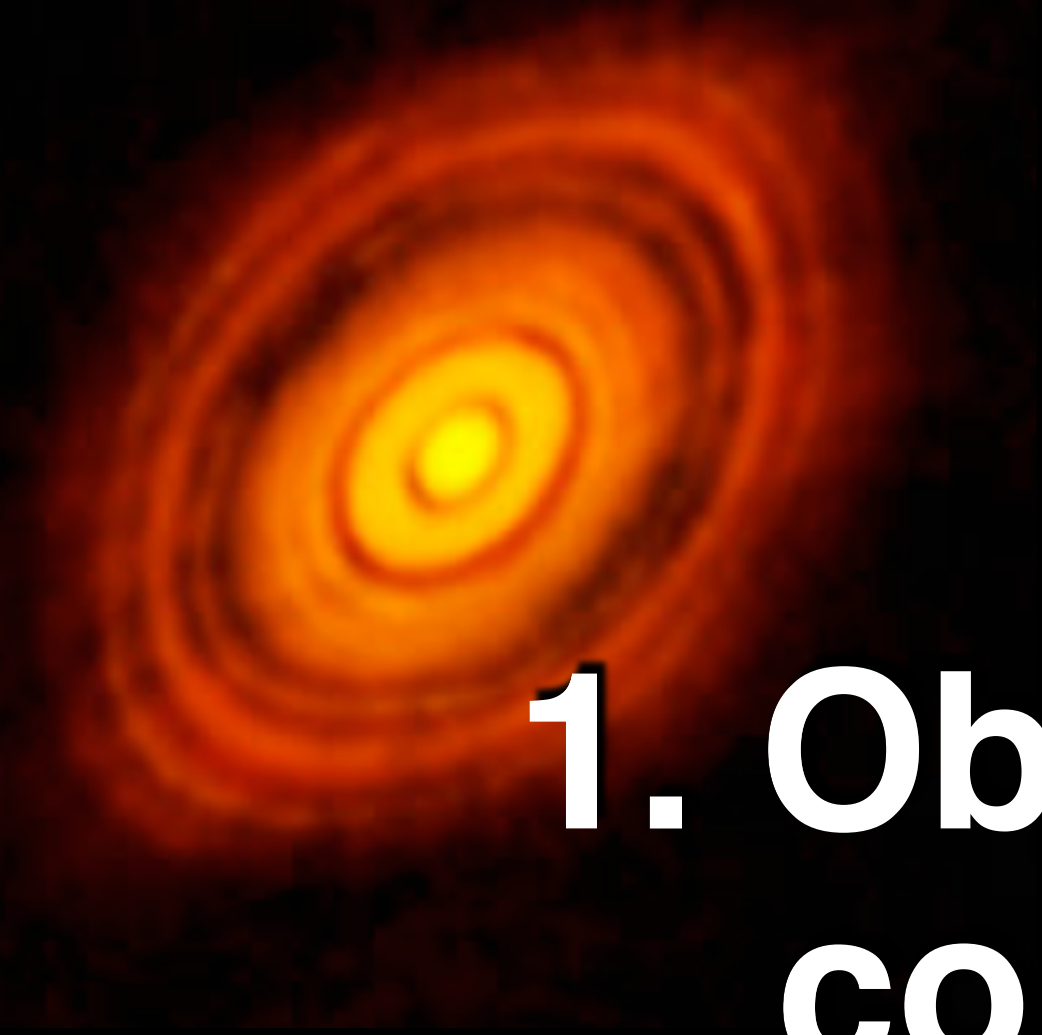
“planet formation”

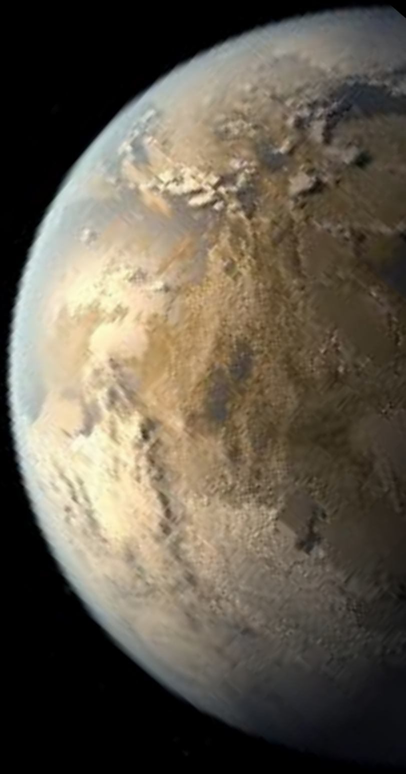


Outline

1. Observational constraints (and the Solar System in context)
2. Stages of planet formation
3. Formation models: exoplanets
4. Formation models: Solar System



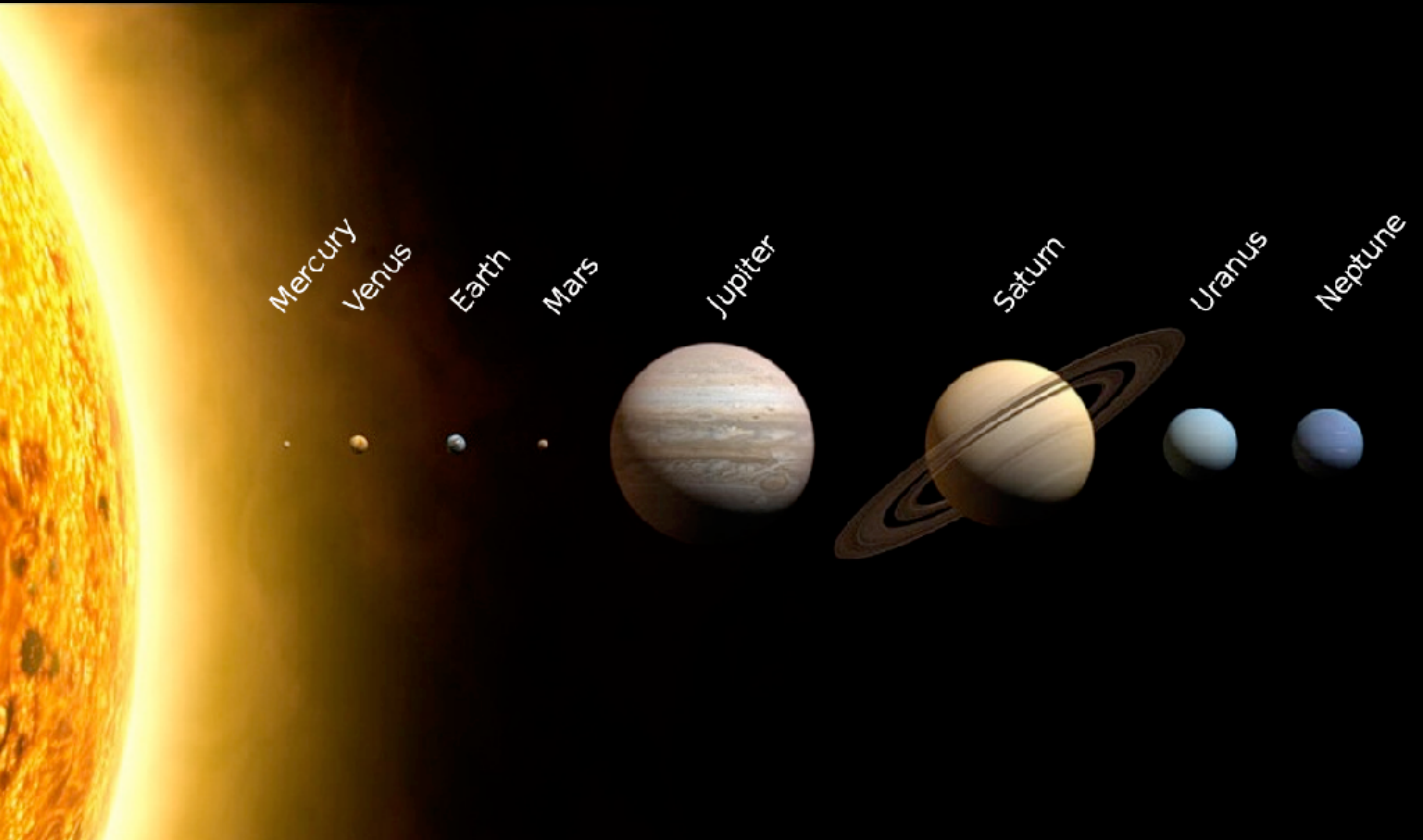




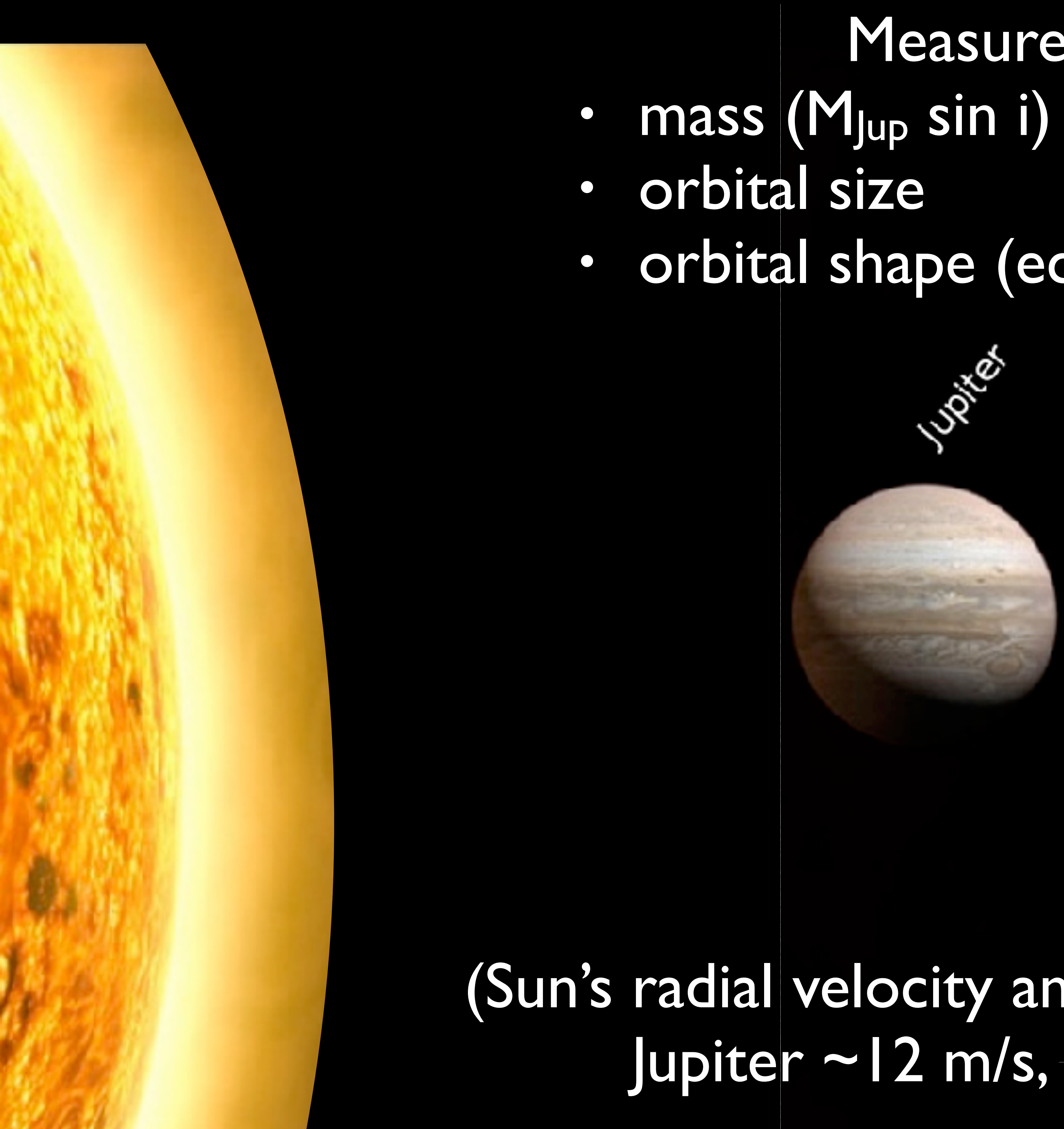
1. Observational constraints

- Solar System in context
- Solar System
- Exoplanets
- Planet-forming disks

The Solar System



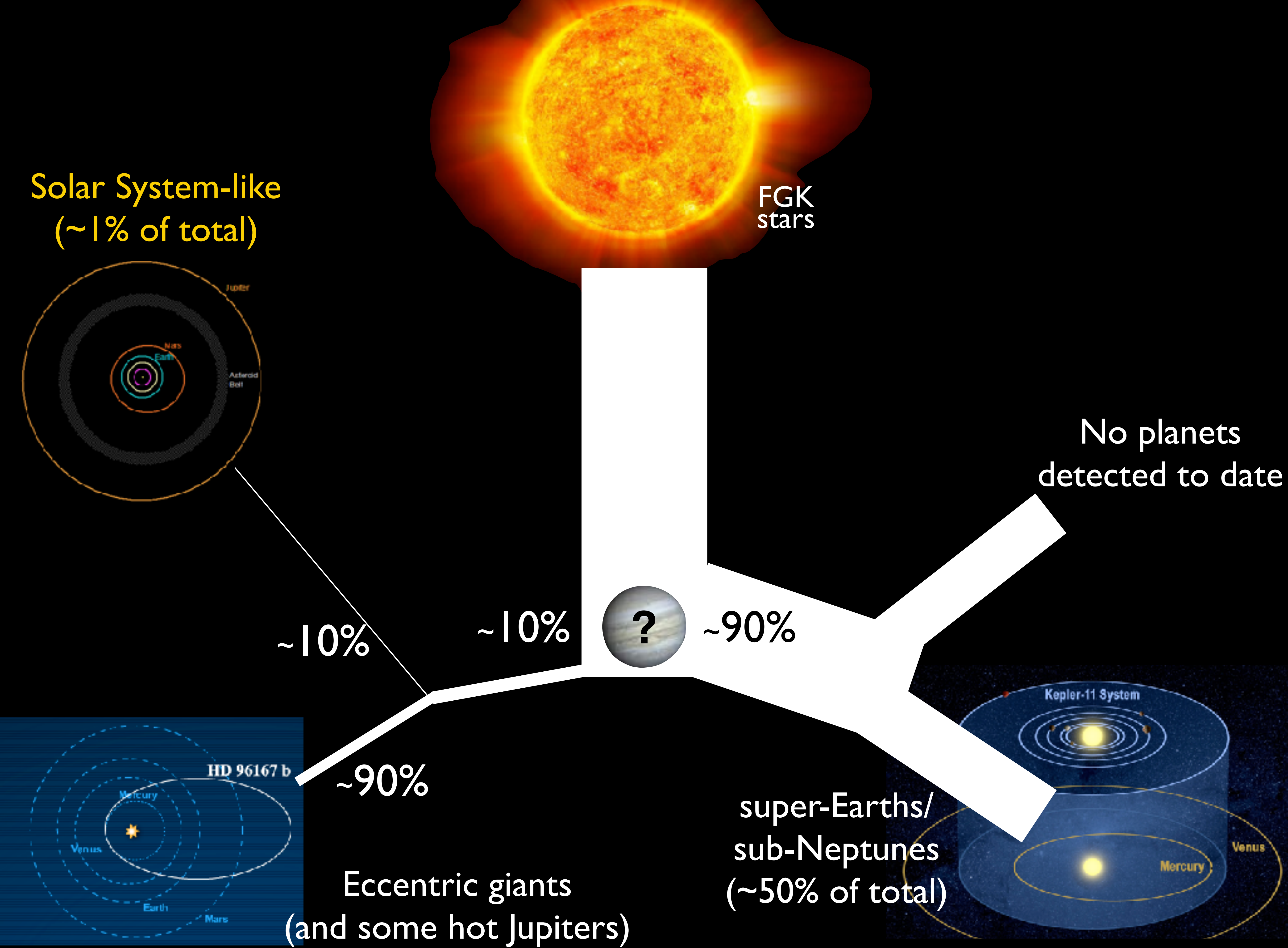
The exo-Solar System



Measure:

- mass (M_{Jup} sin i)
- orbital size
- orbital shape (eccentricity)

(Sun's radial velocity amplitude due to Jupiter ~12 m/s, P=12 yr)



FGK stars

Solar System-like
(~1% of total)

No planets
detected to date

~10%

~10%

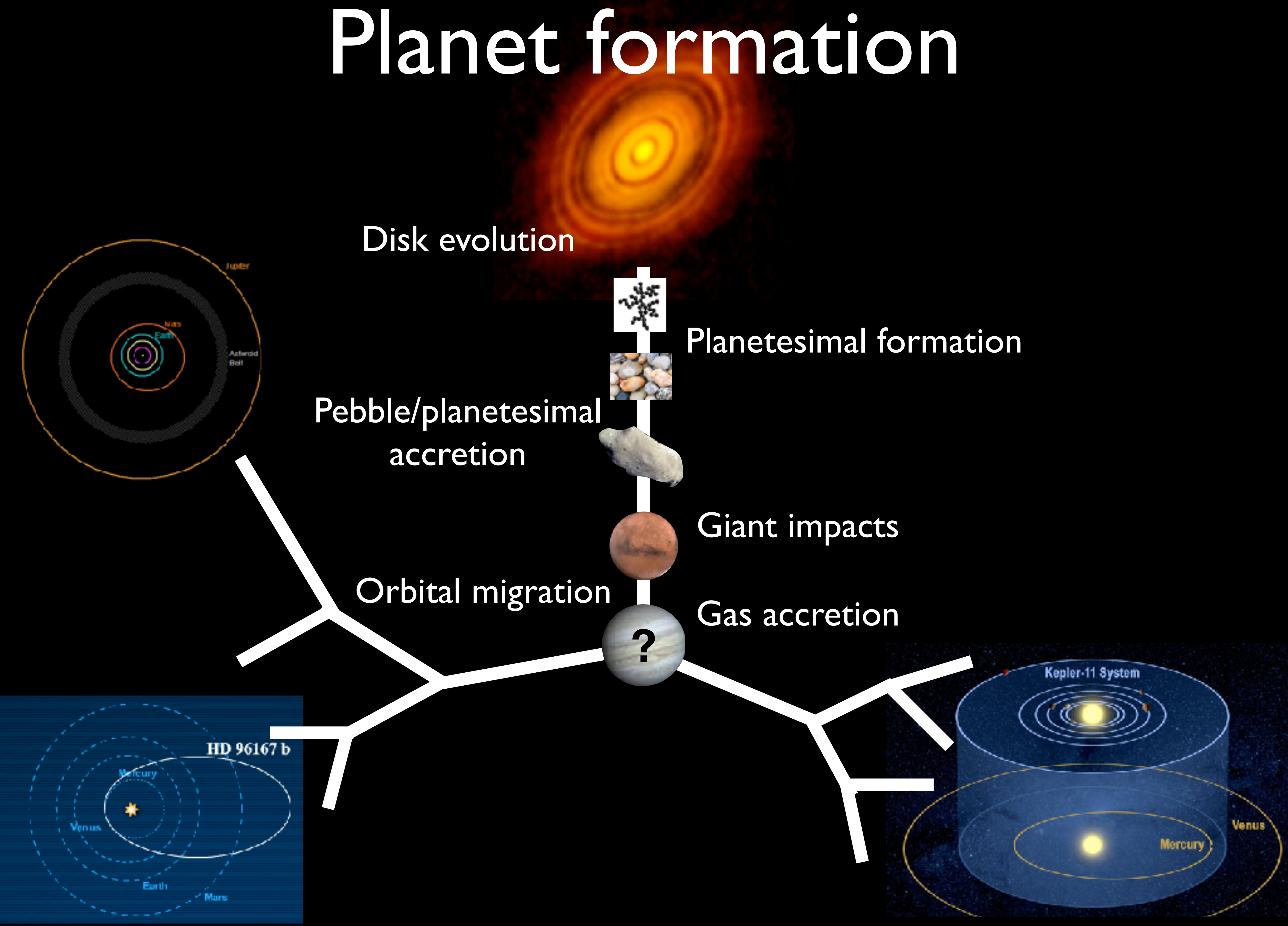
~90%

~90%

Eccentric giants
(and some hot Jupiters)

super-Earths/
sub-Neptunes
(~50% of total)

Planet formation



Disk evolution

Planetesimal formation

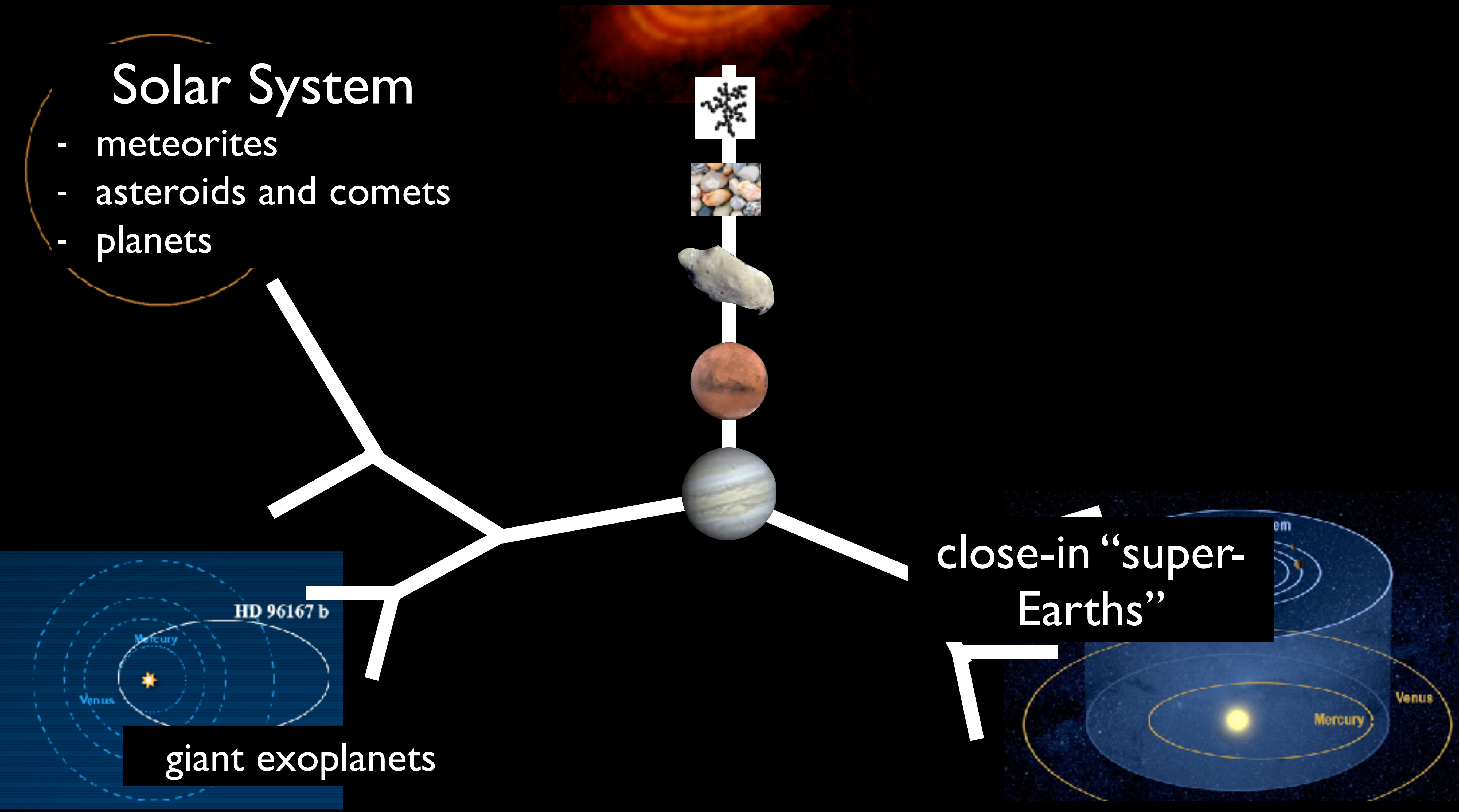
Pebble/planetesimal accretion

Giant impacts

Orbital migration

Gas accretion

Constraints



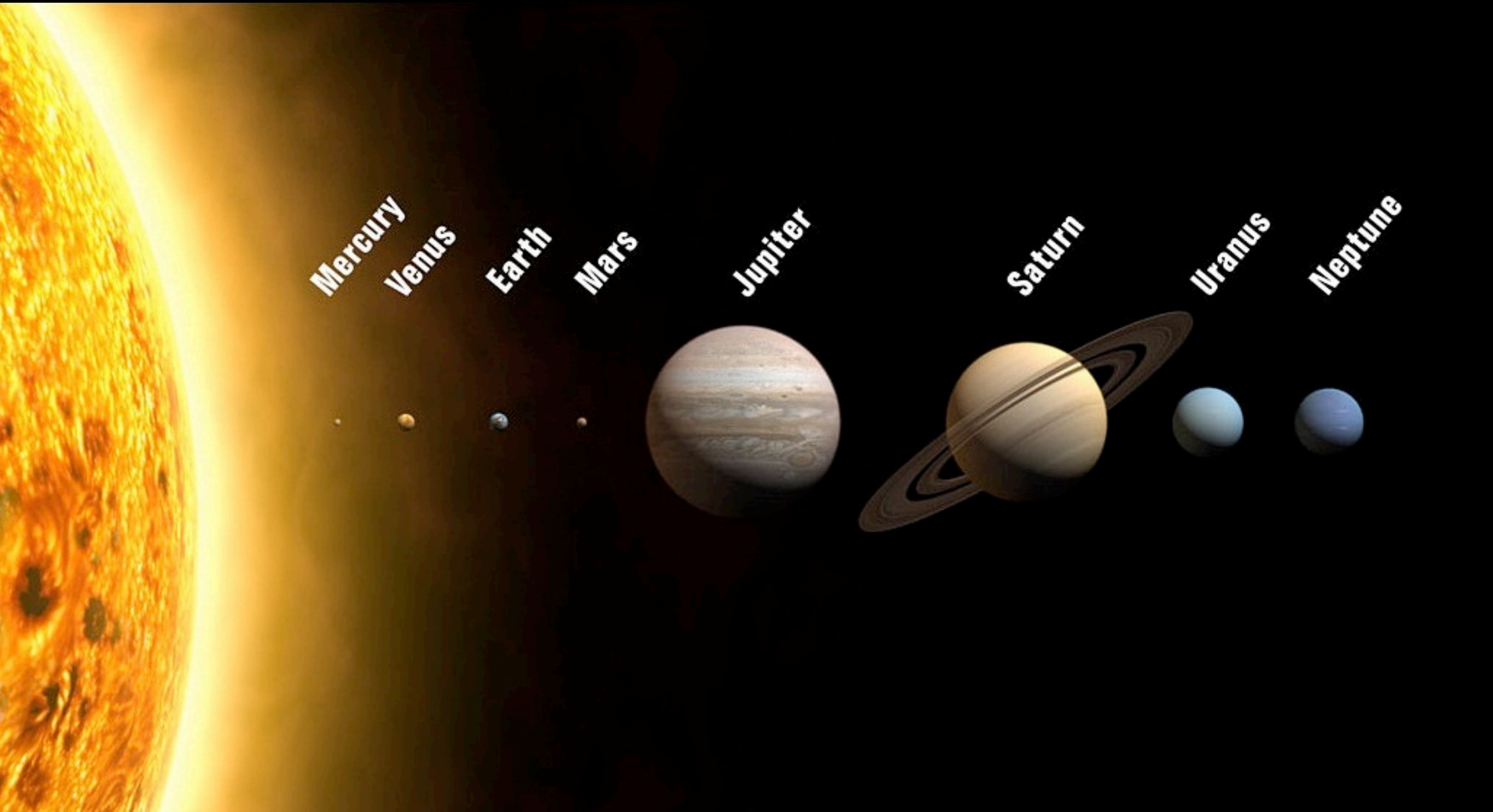
protoplanetary
disks

Solar System
- meteorites
- asteroids and comets
- planets

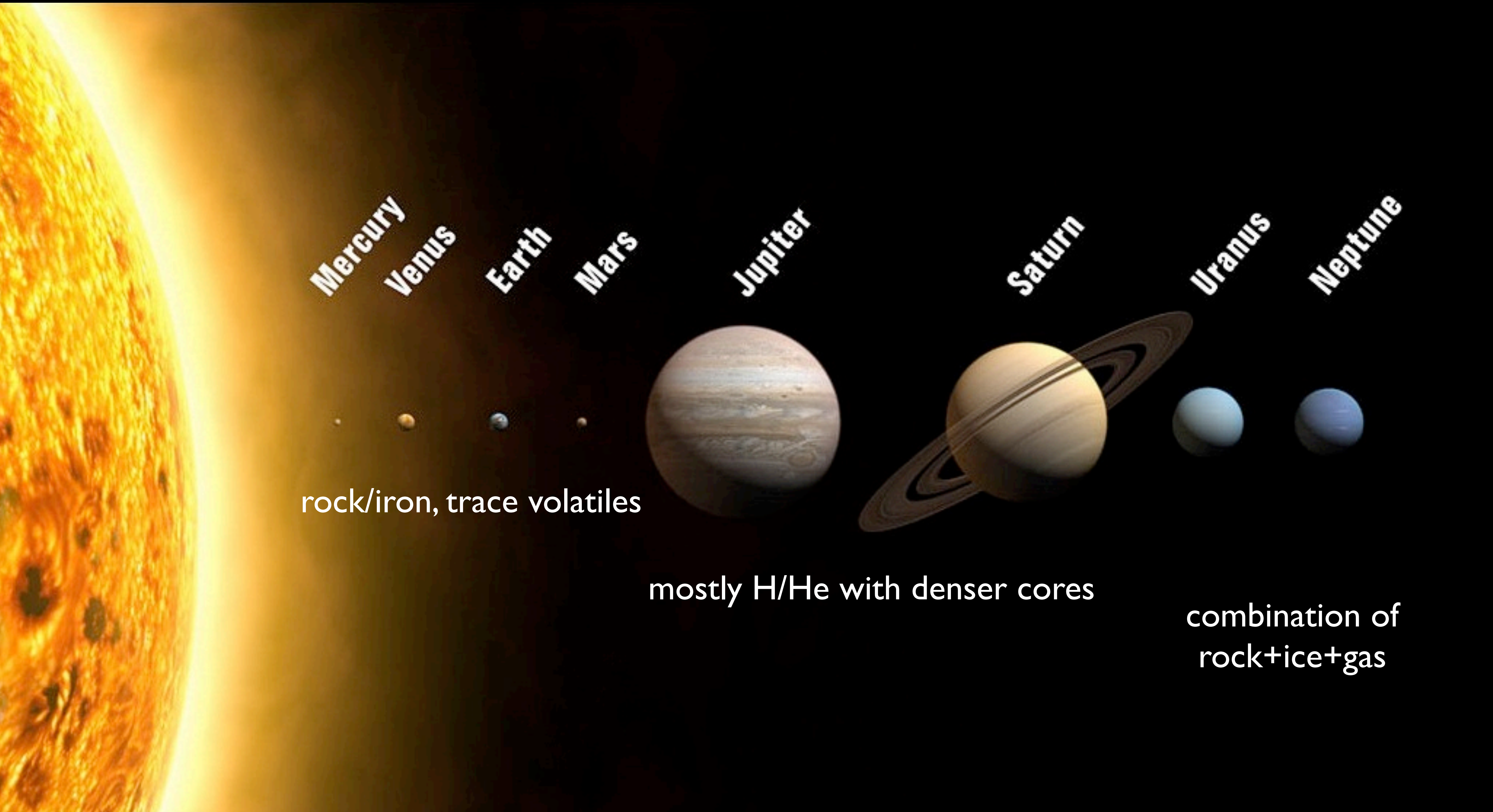
close-in “super-
Earths”

giant exoplanets

Solar System constraints



Planetary masses and compositions



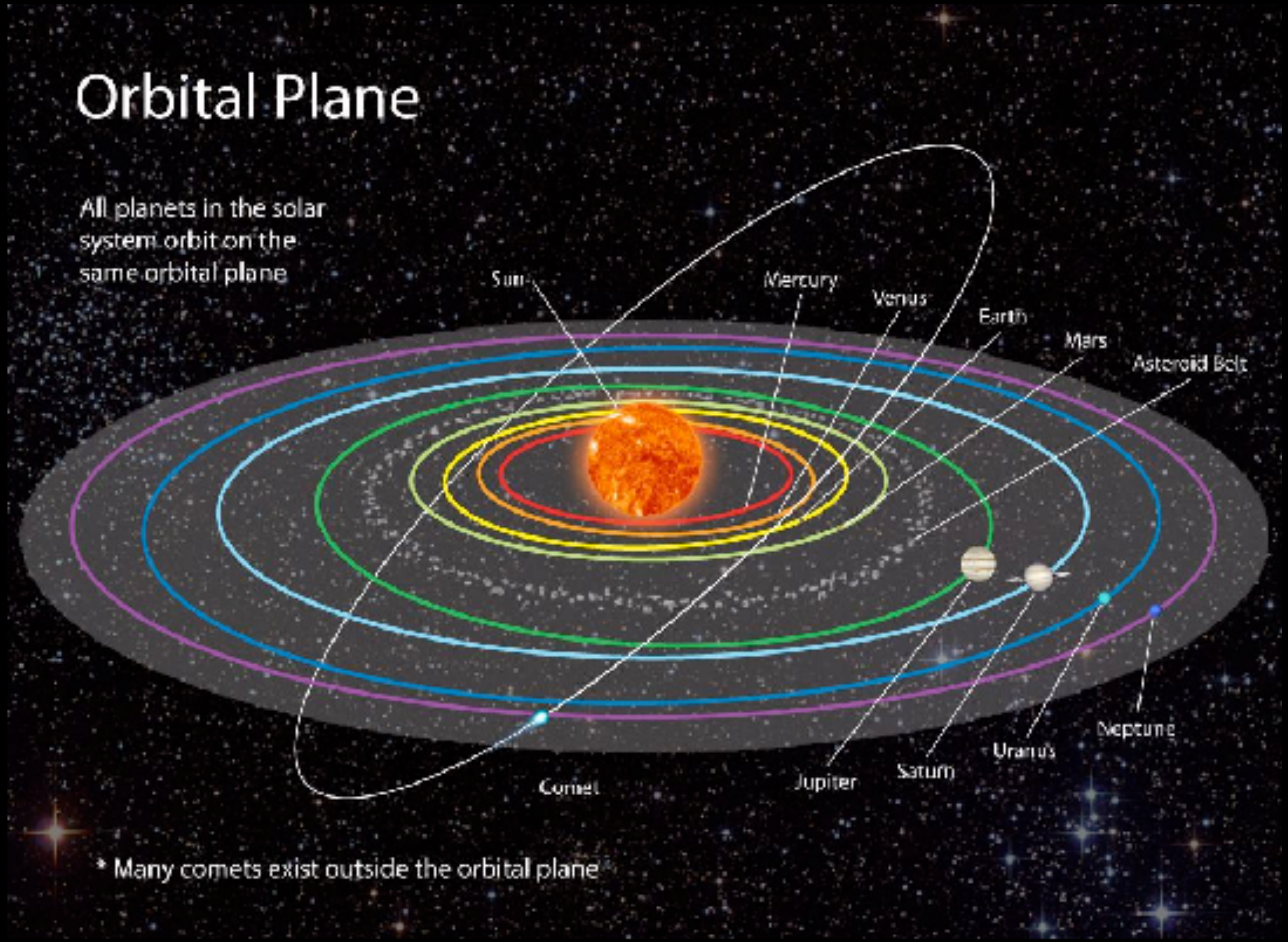
rock/iron, trace volatiles

mostly H/He with denser cores

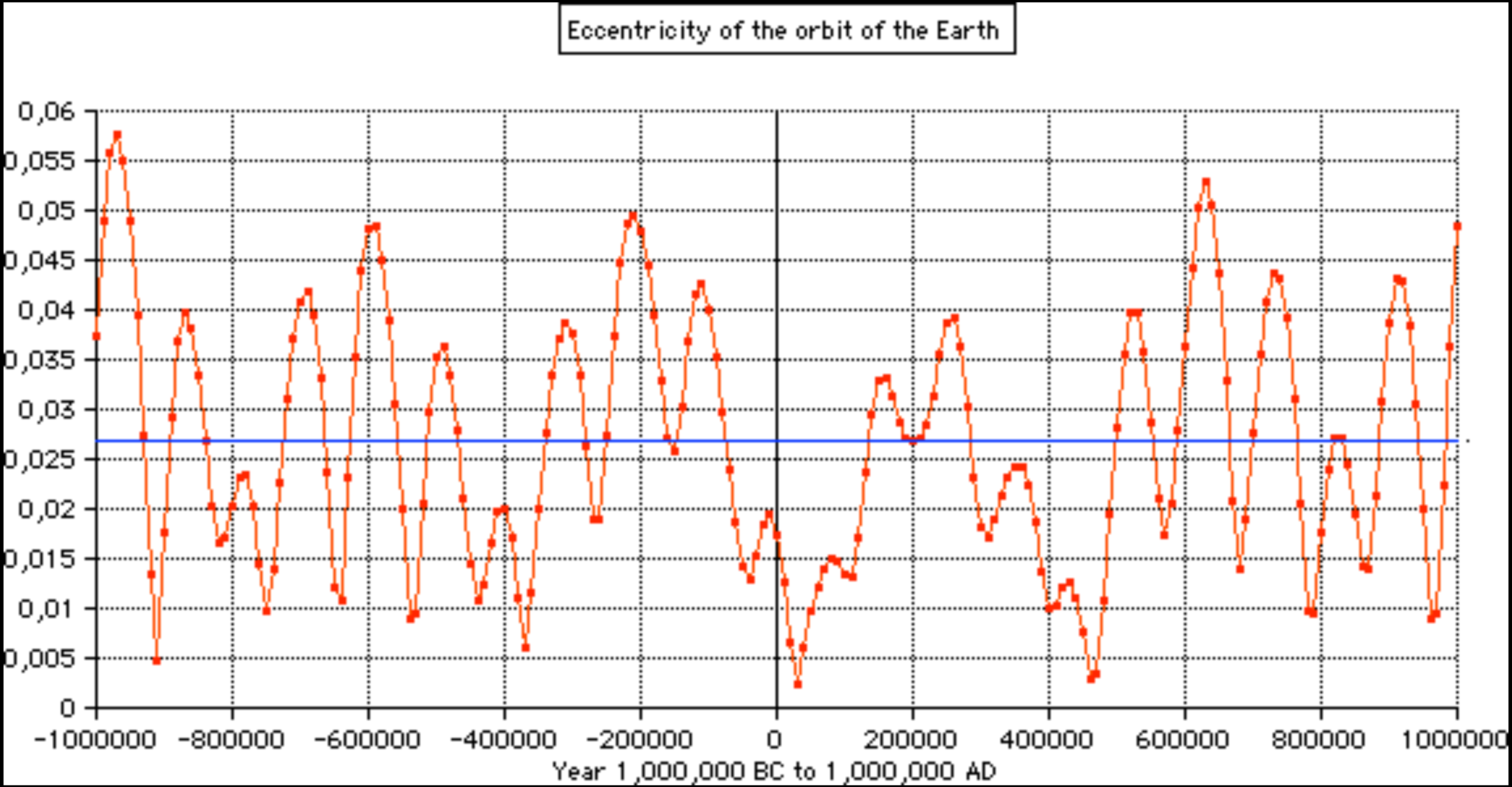
combination of
rock+ice+gas

Planetary orbits

- low eccentricities (e~0.05 for Jup/Sat, terrestrial planets)
- low inclinations (<few degrees)

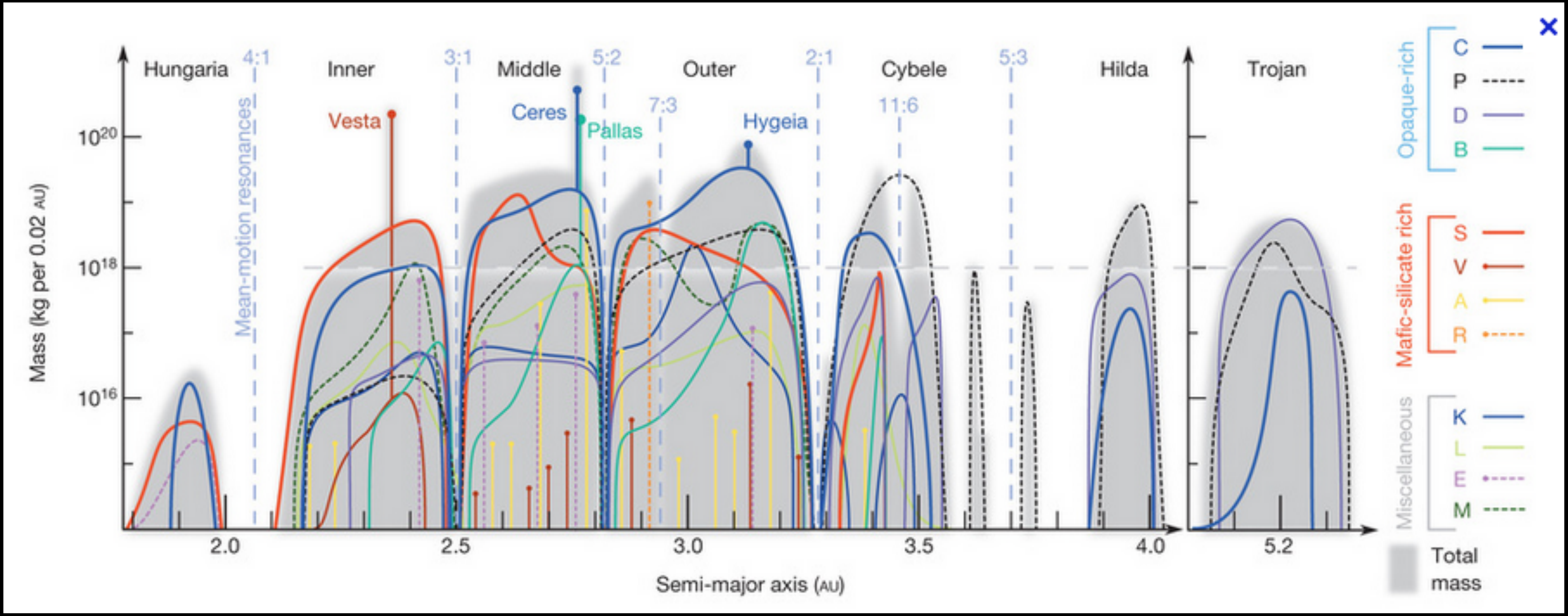


Planetary orbits not fixed in time



(link to climate via Milankovitch cycles)

Asteroid belt

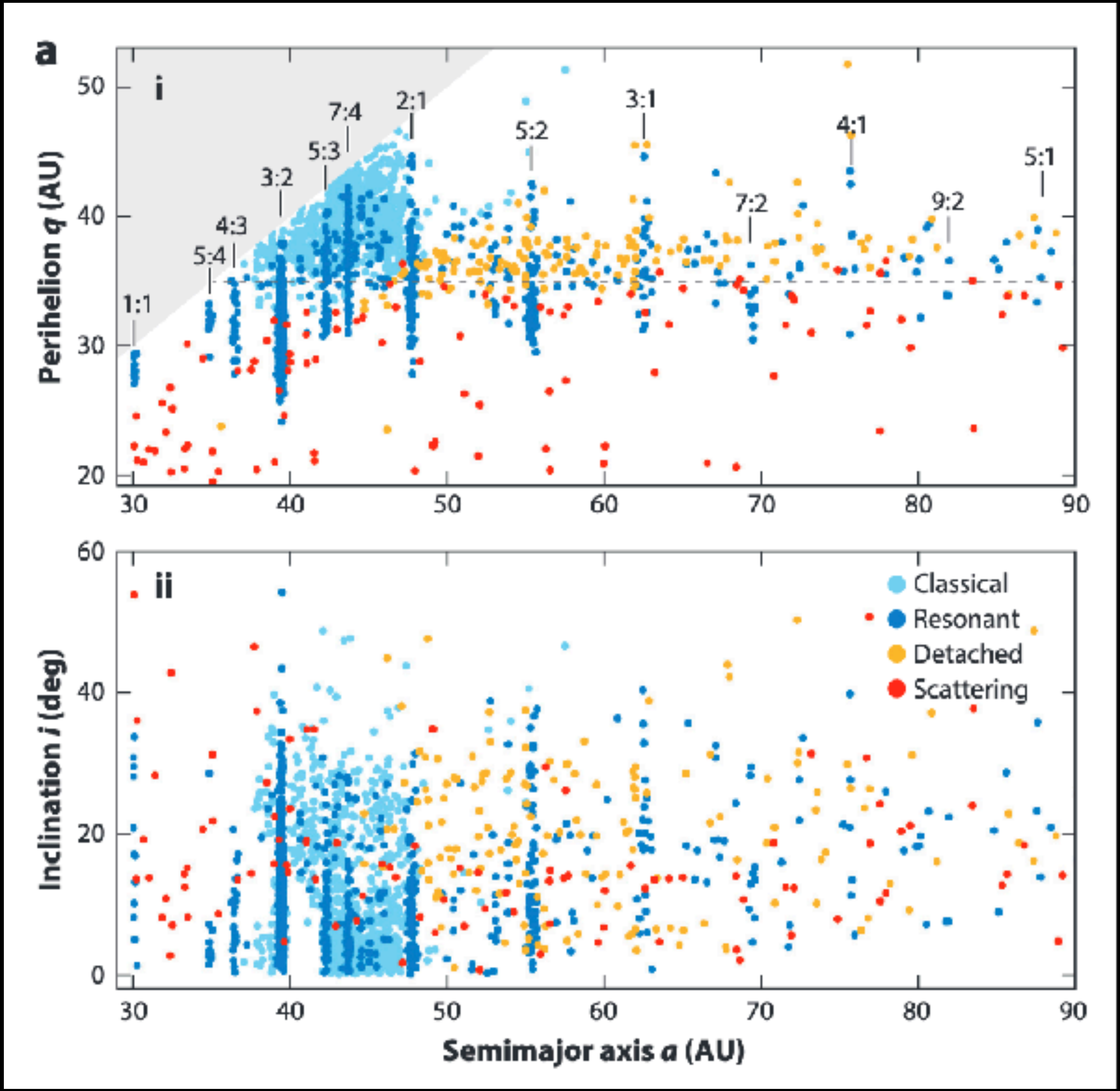


Demeo & Carry 2014

- Total mass ~ 5 x 10^{-4} M_{Earth}
- Diversity in composition
  - Rough inner (S-type)/outer (C-type) dichotomy

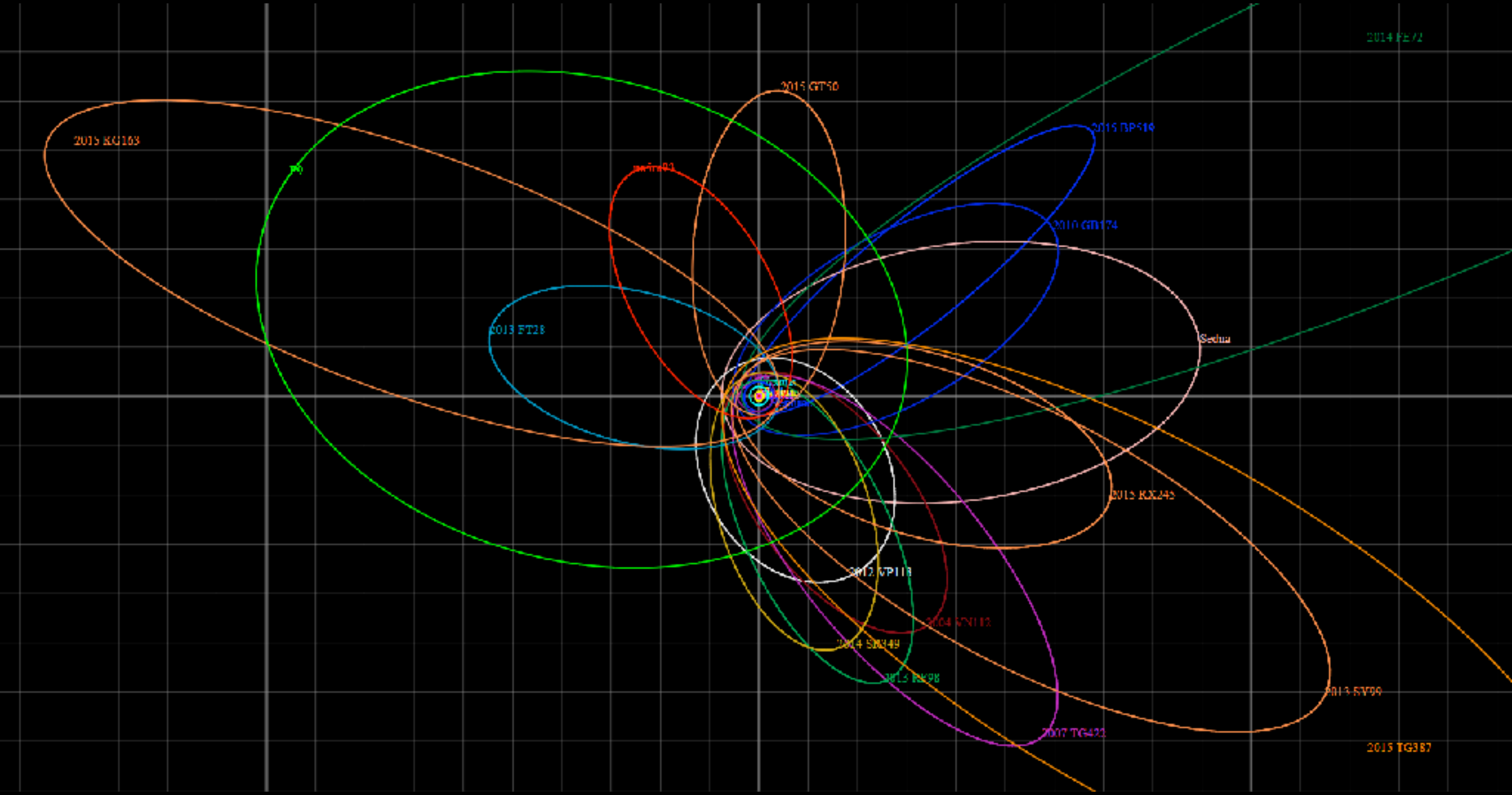
Kuiper belt

- Total mass ~ 0.1 M_{Earth}
- Variety of dynamical classes

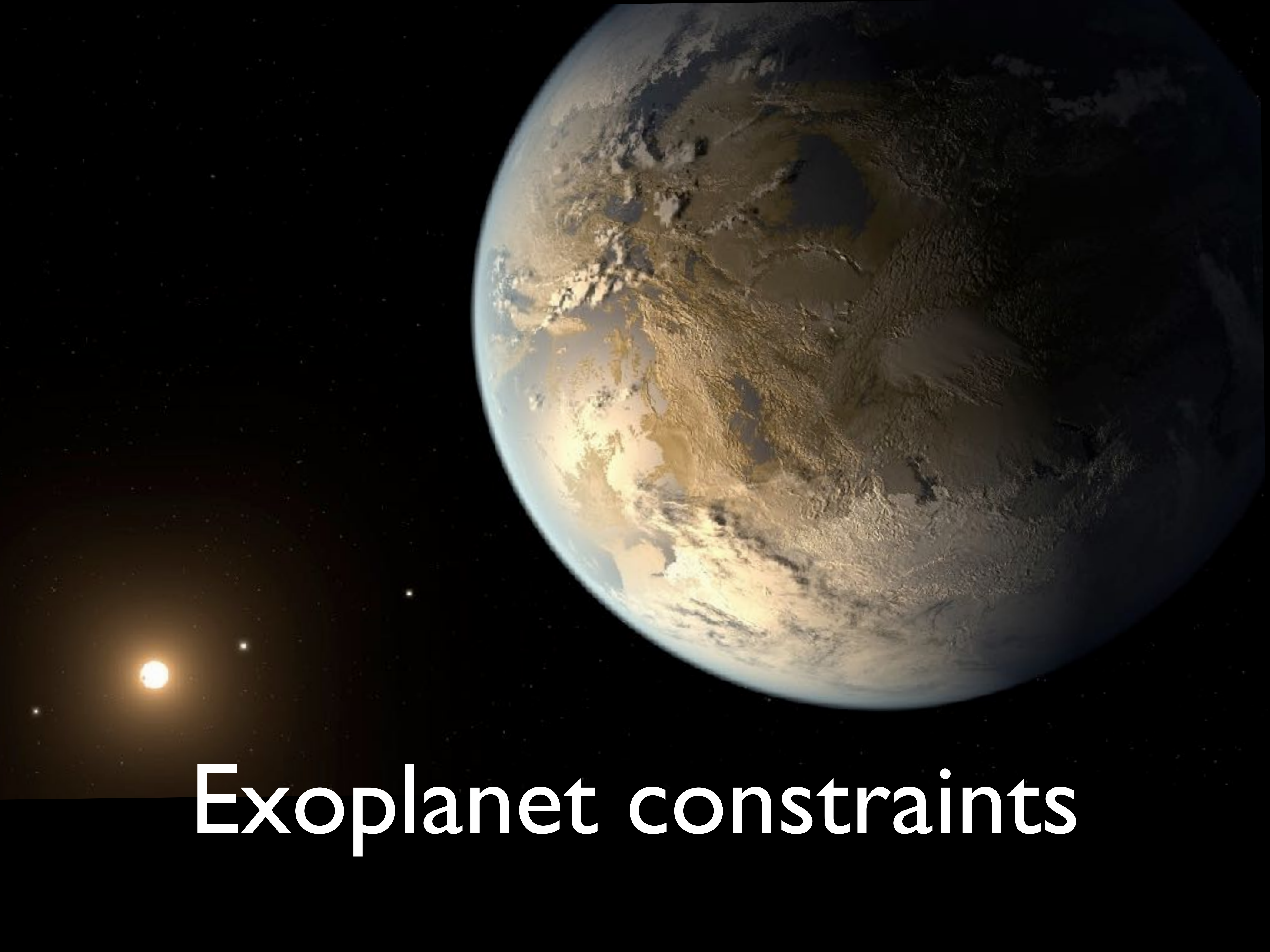


Gladman & Volk (2021)

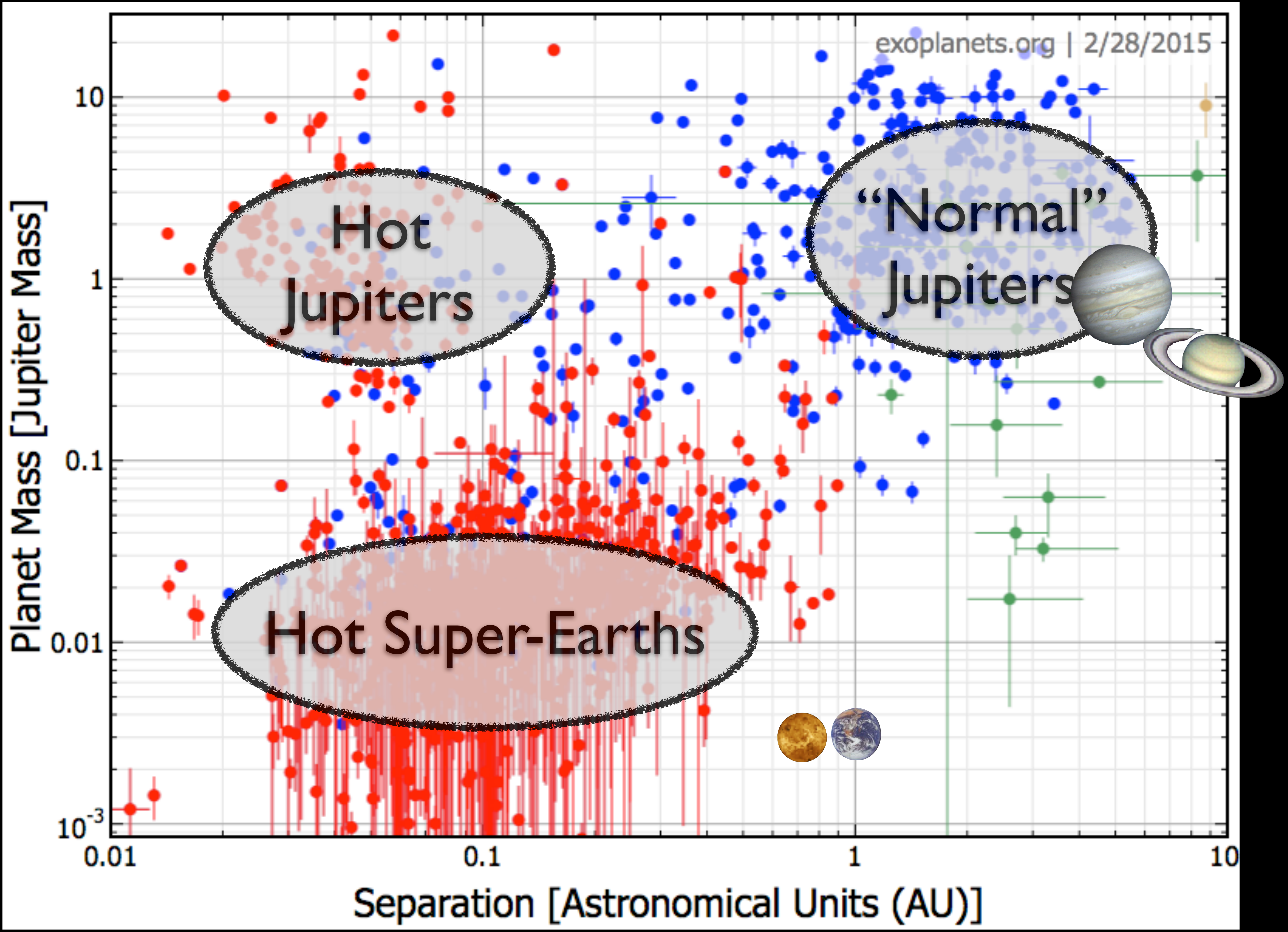
Evidence for "Planet Nine"?



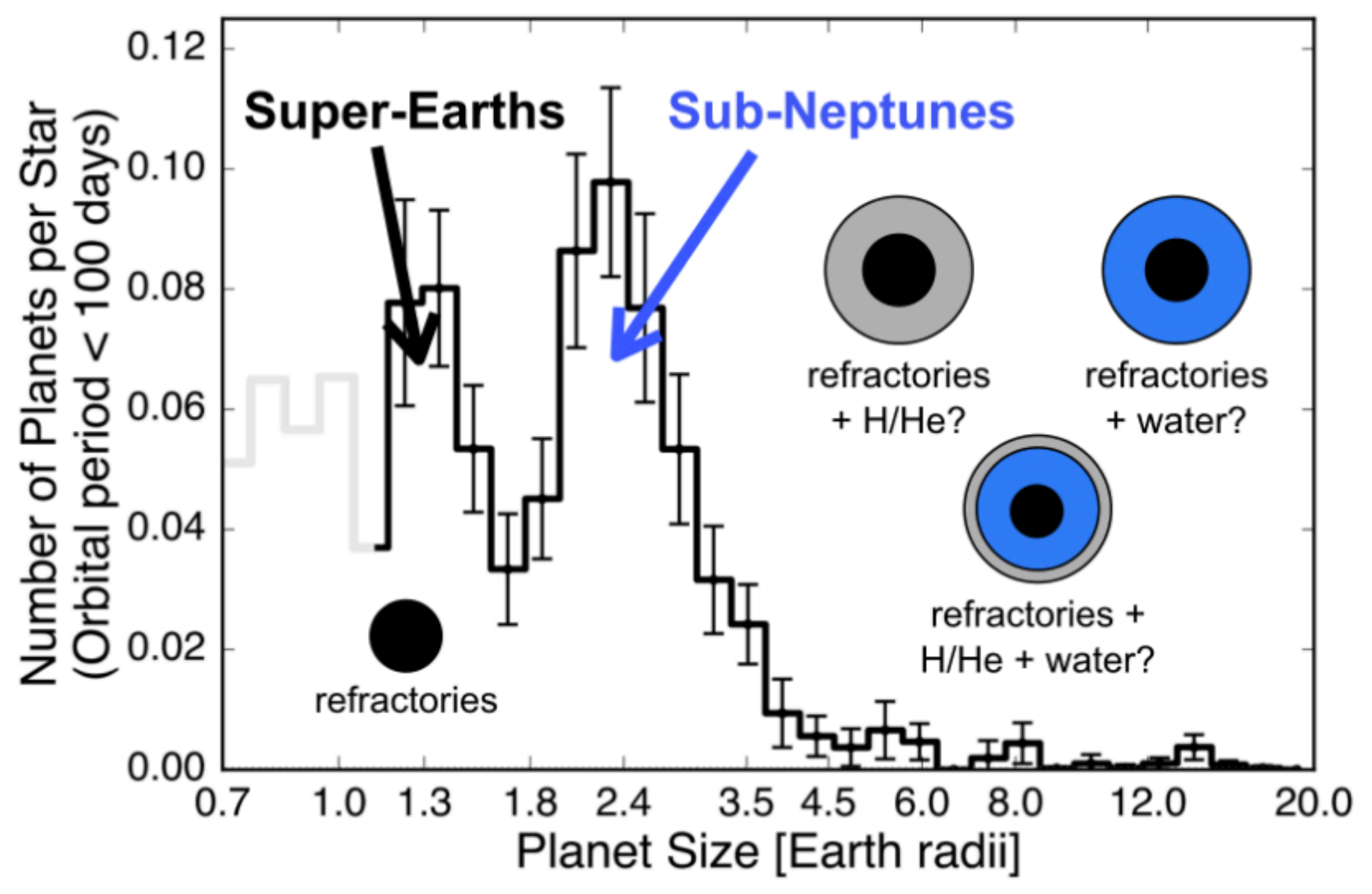
Batygin & Brown (2016); Brown & Batygin (2016); Batygin et al (2019), …



Exoplanet constraints

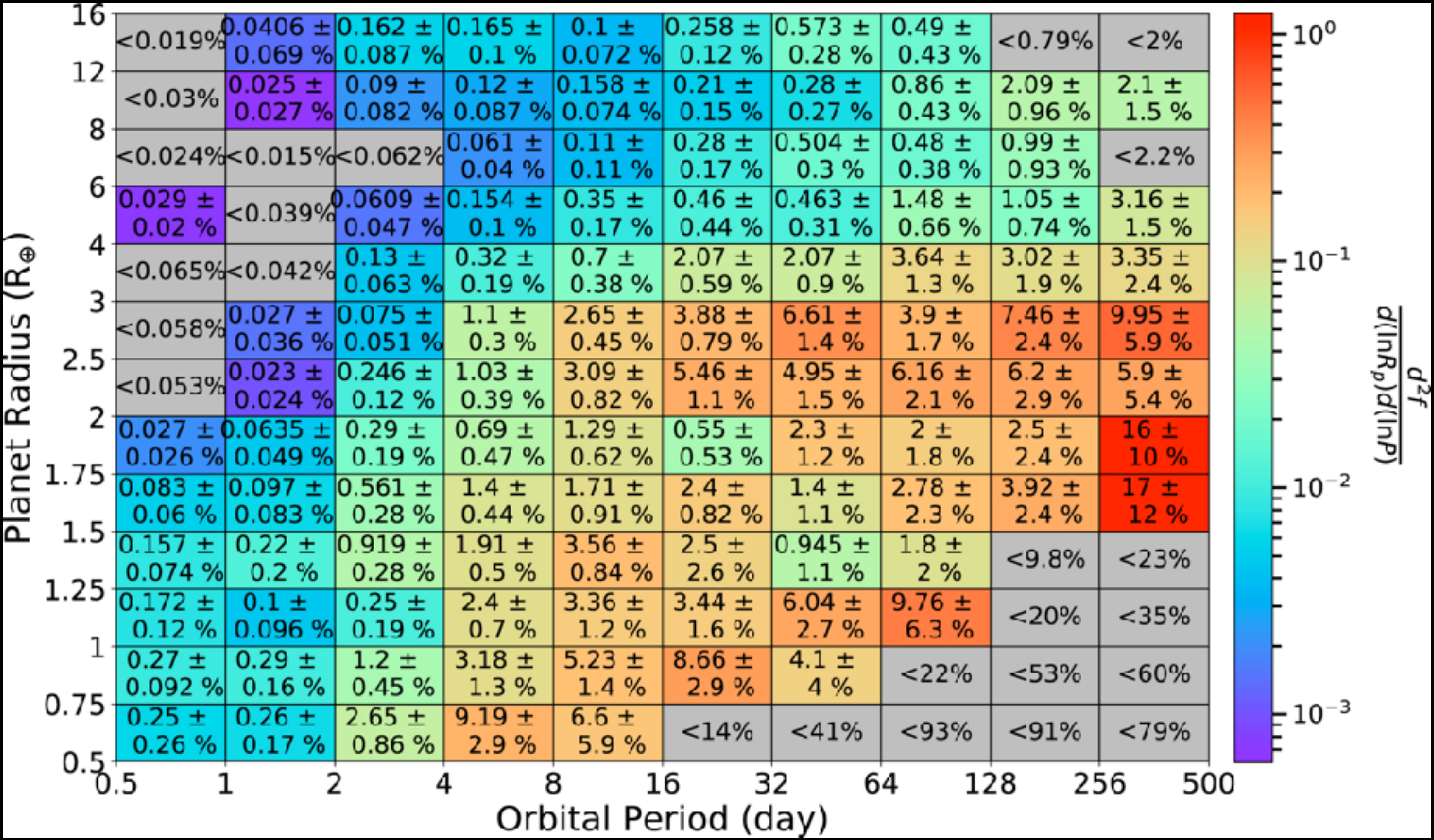

exoplanets.org | 2/28/2015
Hot Jupiters
"Normal" Jupiters
Hot Super-Earths
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^-3
0.01
0.1
1
10
Separation [Astronomical Units (AU)]

Exoplanet size distribution



Cloutier (2024)
after Fulton et al (2017); Fulton & Petigura (2018); van Eylen et al (2018), …

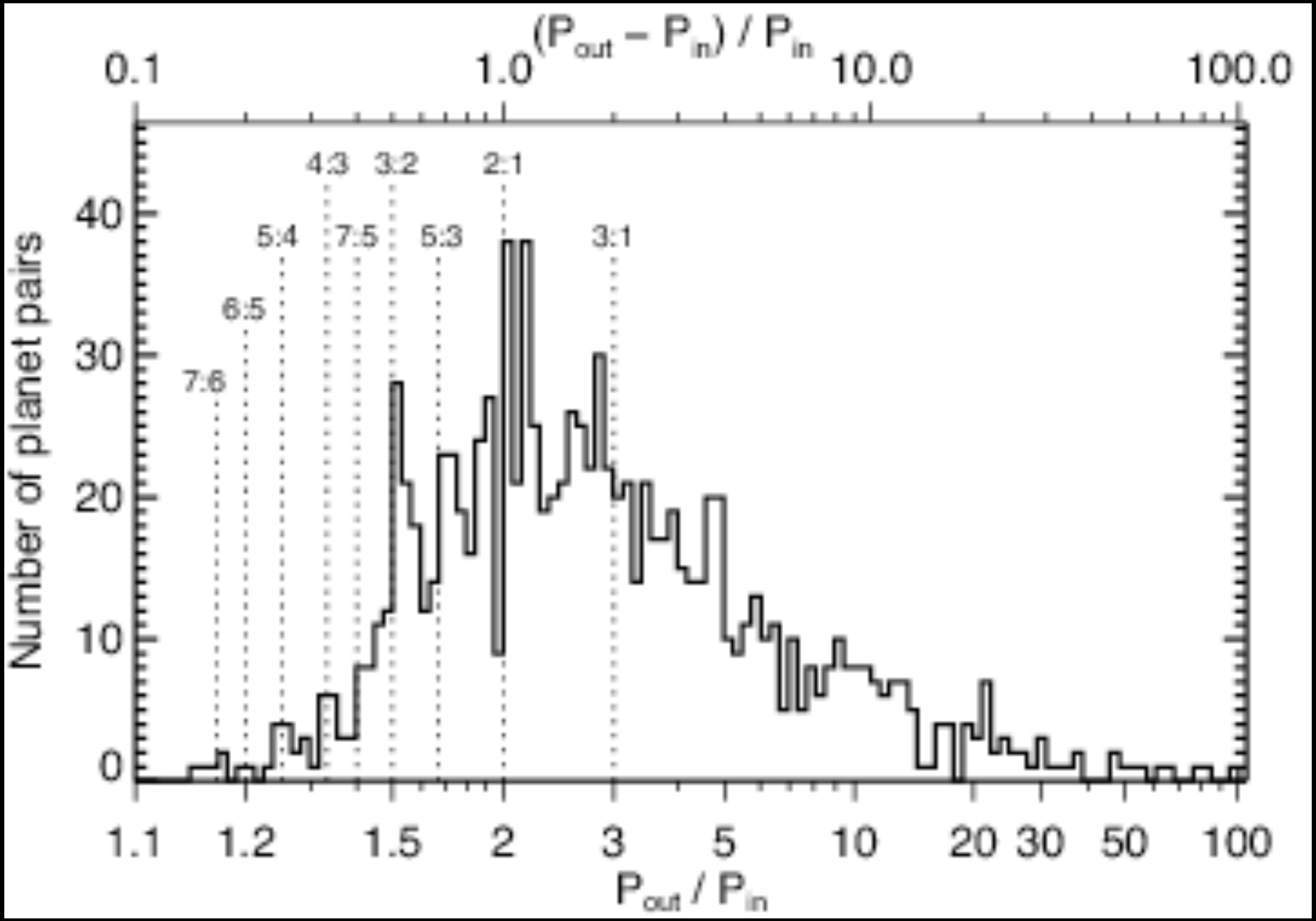
Exoplanet occurrence rate



<0.019%	0.0406 ± 0.069 %	0.162 ± 0.087 %	0.165 ± 0.1 %	0.1 ± 0.072 %	0.258 ± 0.12 %	0.573 ± 0.28 %	0.49 ± 0.43 %	<0.79%	<2%
<0.03%	0.025 ± 0.027 %	0.09 ± 0.082 %	0.12 ± 0.087 %	0.158 ± 0.074 %	0.21 ± 0.15 %	0.28 ± 0.27 %	0.86 ± 0.43 %	2.09 ± 0.96 %	2.1 ± 1.5 %
<0.024%	<0.015%	<0.062%	0.061 ± 0.04 %	0.11 ± 0.11 %	0.28 ± 0.17 %	0.504 ± 0.3 %	0.48 ± 0.38 %	0.99 ± 0.93 %	<2.2%
0.029 ± 0.02 %	<0.039%	0.0609 ± 0.047 %	0.154 ± 0.1 %	0.35 ± 0.17 %	0.46 ± 0.44 %	0.463 ± 0.31 %	1.48 ± 0.66 %	1.05 ± 0.74 %	3.16 ± 1.5 %
<0.065%	<0.042%	0.13 ± 0.063 %	0.32 ± 0.19 %	0.7 ± 0.38 %	2.07 ± 0.59 %	2.07 ± 0.9 %	3.64 ± 1.3 %	3.02 ± 1.9 %	3.35 ± 2.4 %
<0.058%	0.027 ± 0.036 %	0.075 ± 0.051 %	1.1 ± 0.3 %	2.65 ± 0.45 %	3.88 ± 0.79 %	6.61 ± 1.4 %	3.9 ± 1.7 %	7.46 ± 2.4 %	9.95 ± 5.9 %
<0.053%	0.023 ± 0.024 %	0.246 ± 0.12 %	1.03 ± 0.39 %	3.09 ± 0.82 %	5.46 ± 1.1 %	4.95 ± 1.5 %	6.16 ± 2.1 %	6.2 ± 2.9 %	5.9 ± 5.4 %
0.027 ± 0.026 %	0.0635 ± 0.049 %	0.29 ± 0.19 %	0.69 ± 0.47 %	1.29 ± 0.62 %	0.55 ± 0.53 %	2.3 ± 1.2 %	2 ± 1.8 %	2.5 ± 2.4 %	16 ± 10 %
0.083 ± 0.06 %	0.097 ± 0.083 %	0.561 ± 0.28 %	1.4 ± 0.44 %	1.71 ± 0.91 %	2.4 ± 0.82 %	1.4 ± 1.1 %	2.78 ± 2.3 %	3.92 ± 2.4 %	17 ± 12 %
0.157 ± 0.074 %	0.22 ± 0.2 %	0.919 ± 0.28 %	1.91 ± 0.5 %	3.56 ± 0.84 %	2.5 ± 2.6 %	0.945 ± 1.1 %	1.8 ± 2 %	<9.8%	<23%
0.172 ± 0.12 %	0.1 ± 0.096 %	0.25 ± 0.19 %	2.4 ± 0.7 %	3.36 ± 1.2 %	3.44 ± 1.6 %	6.04 ± 2.7 %	9.76 ± 6.3 %	<20%	<35%
0.27 ± 0.092 %	0.29 ± 0.16 %	1.2 ± 0.45 %	3.18 ± 1.3 %	5.23 ± 1.4 %	8.66 ± 2.9 %	4.1 ± 4 %	<22%	<53%	<60%
0.25 ± 0.26 %	0.26 ± 0.17 %	2.65 ± 0.86 %	9.19 ± 2.9 %	6.6 ± 5.9 %	<14%	<41%	<93%	<91%	<79%

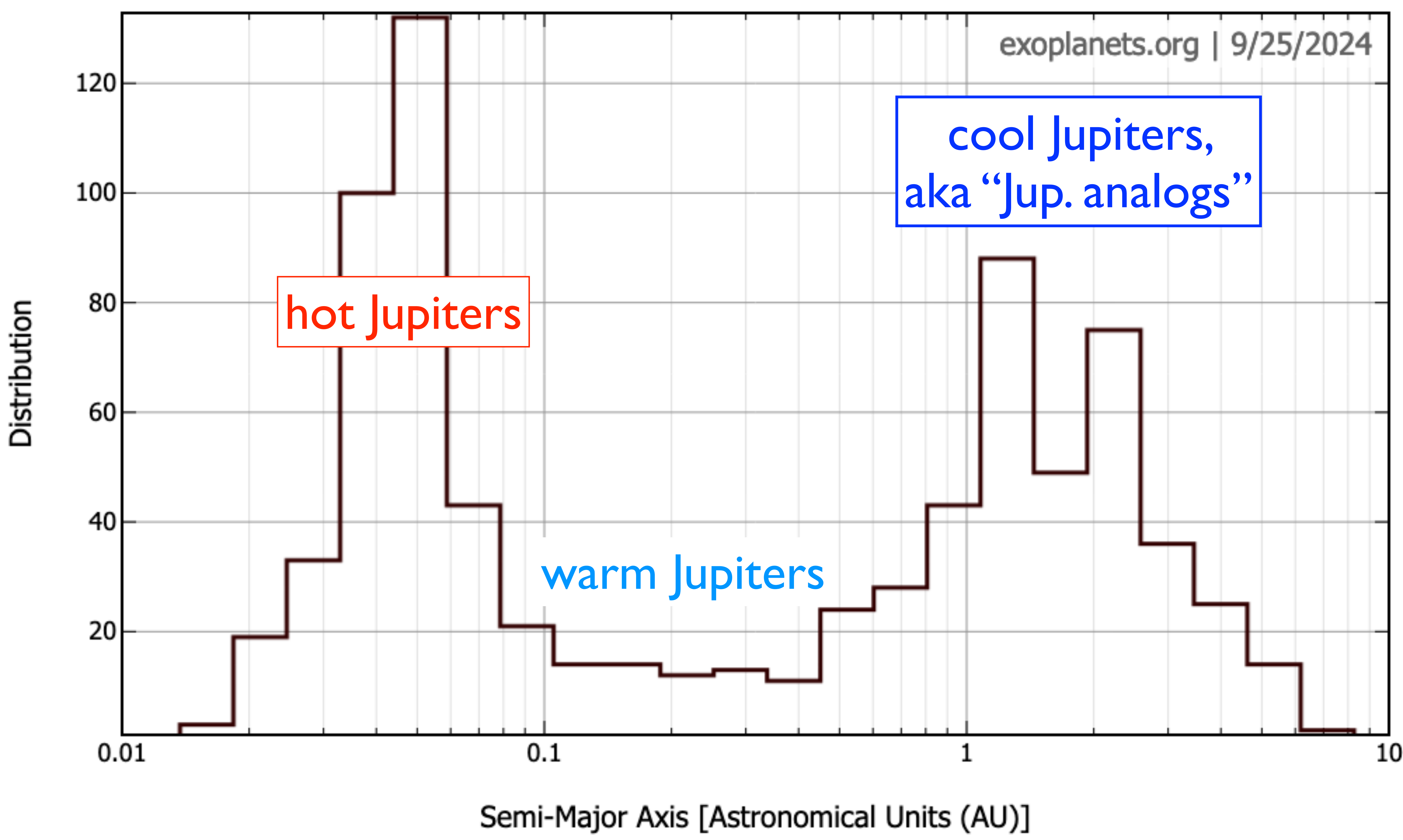
Hsu et al (2019)

Period Ratio distribution



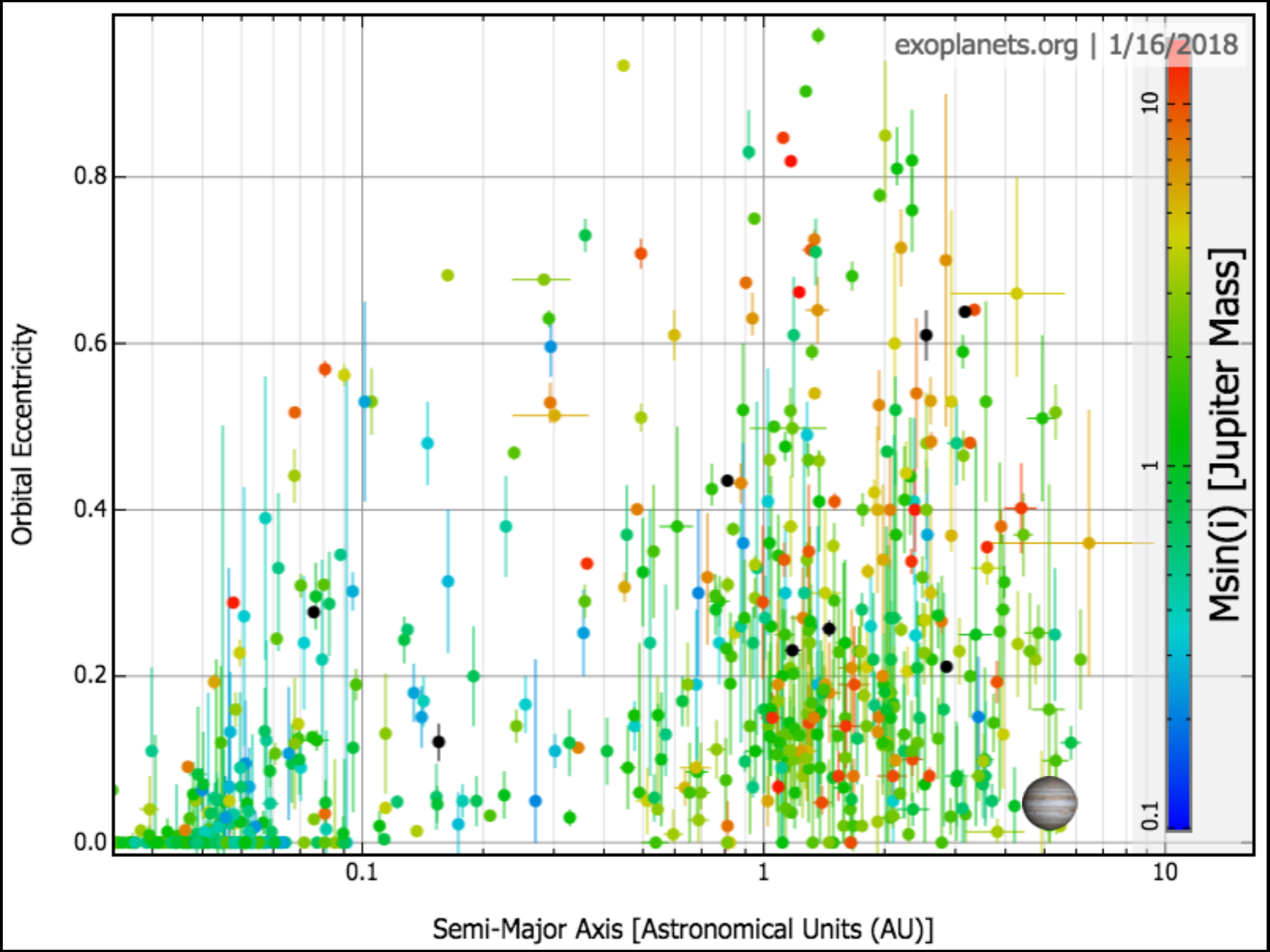
Winn & Fabrycky 2015

Radial distribution of gas giants



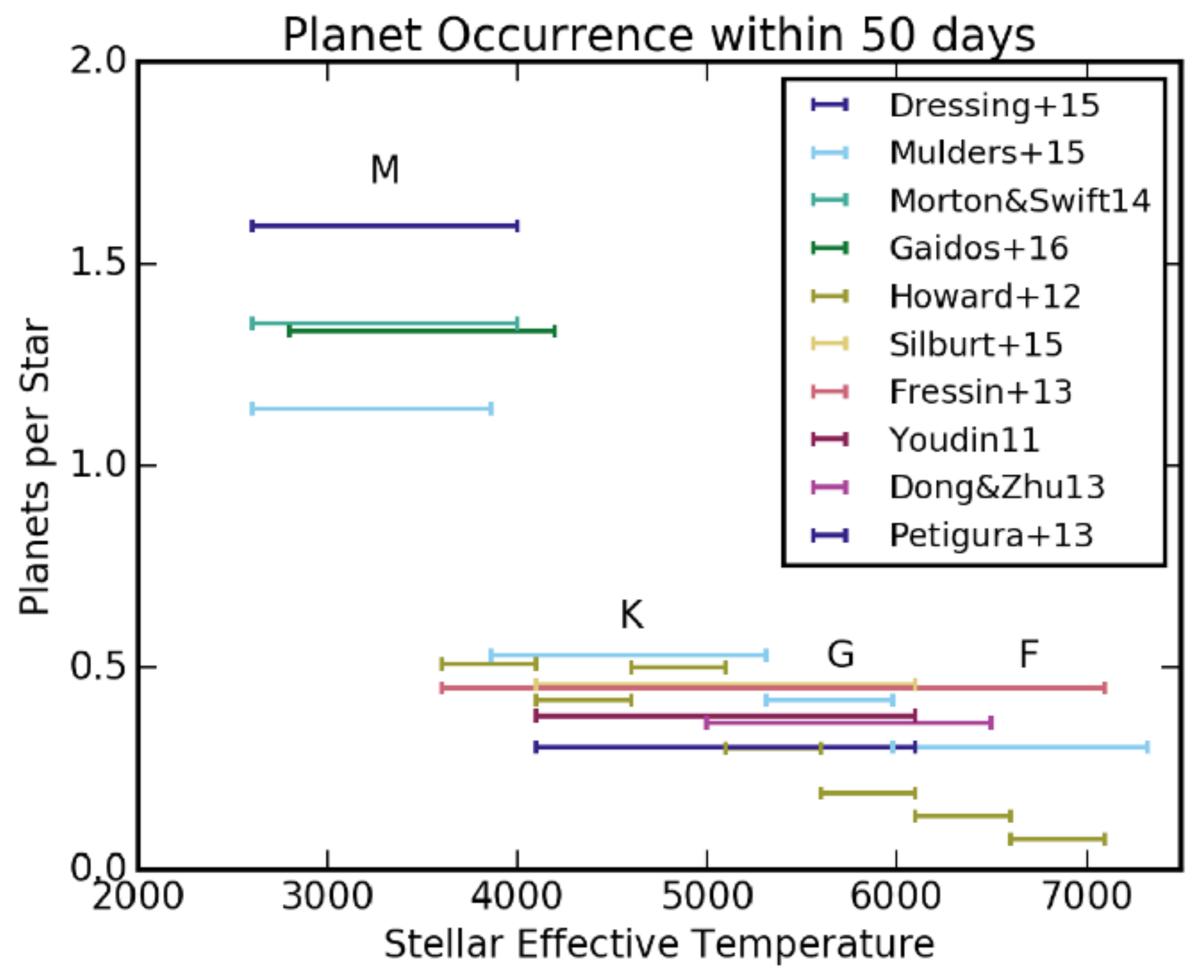
RV planets only, with M sin i > 0.1 M_{Jup}

Eccentricity distribution (giants)



Wright et al 2011

Low-mass stars have more close-in planets

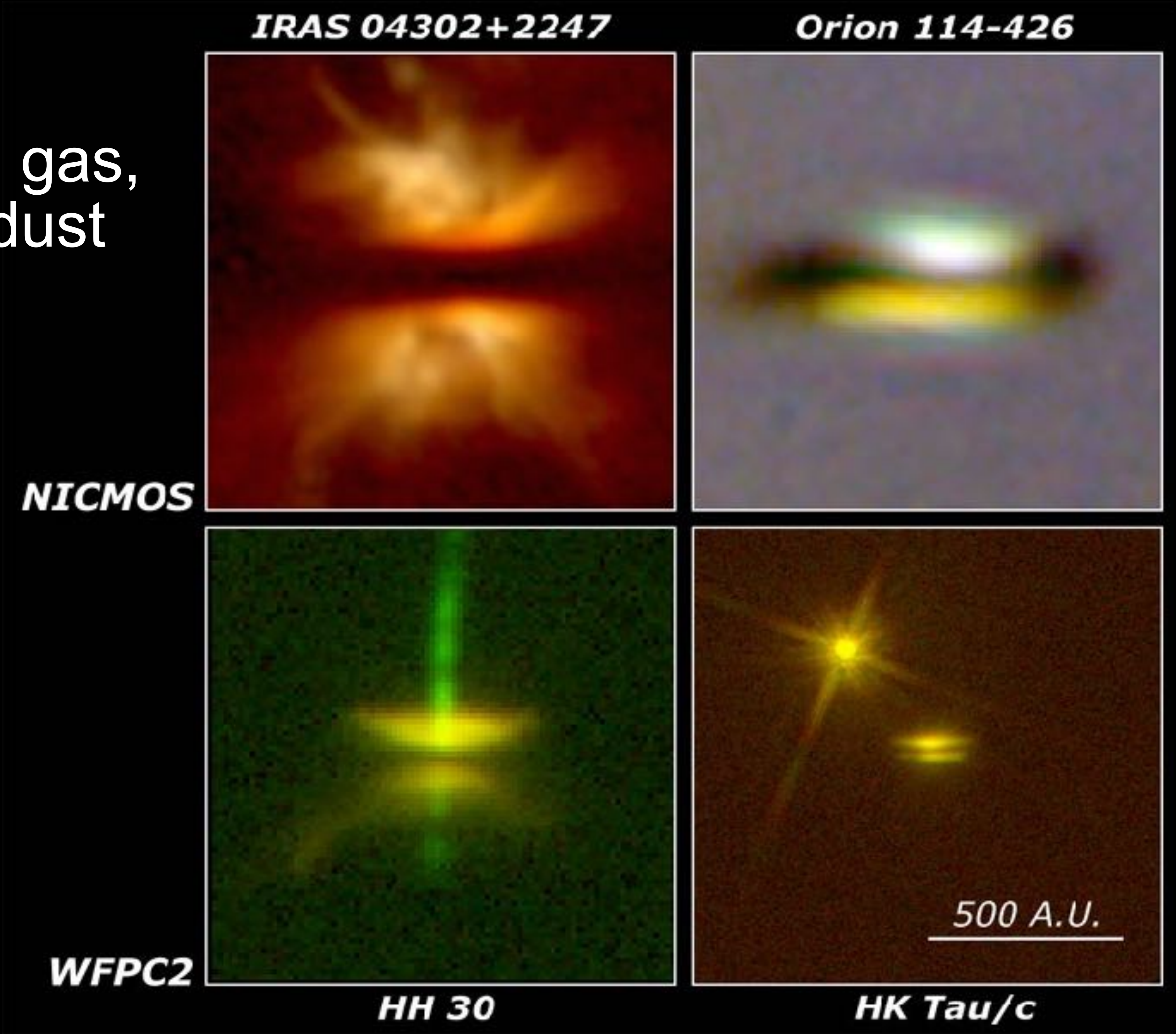


Mulders (2018)

Protoplanetary disks

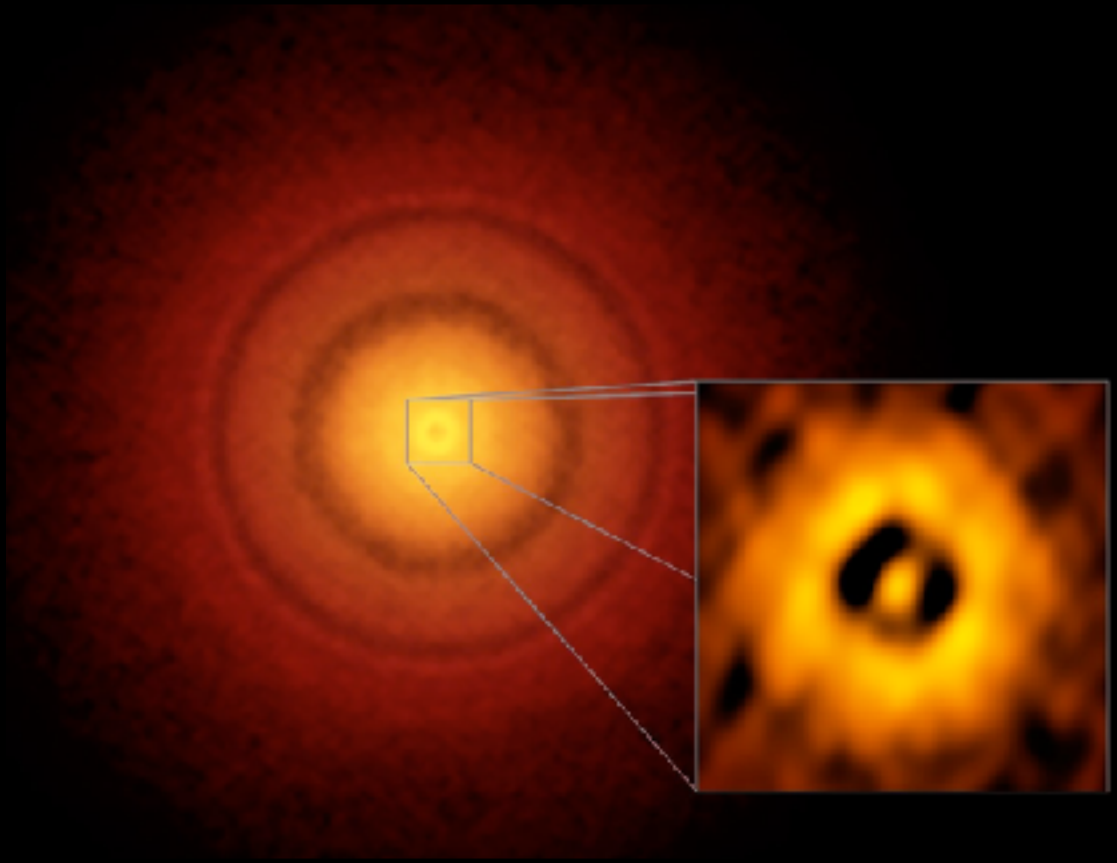
Disks around young stars: Hubble

- 99% gas, 1% dust



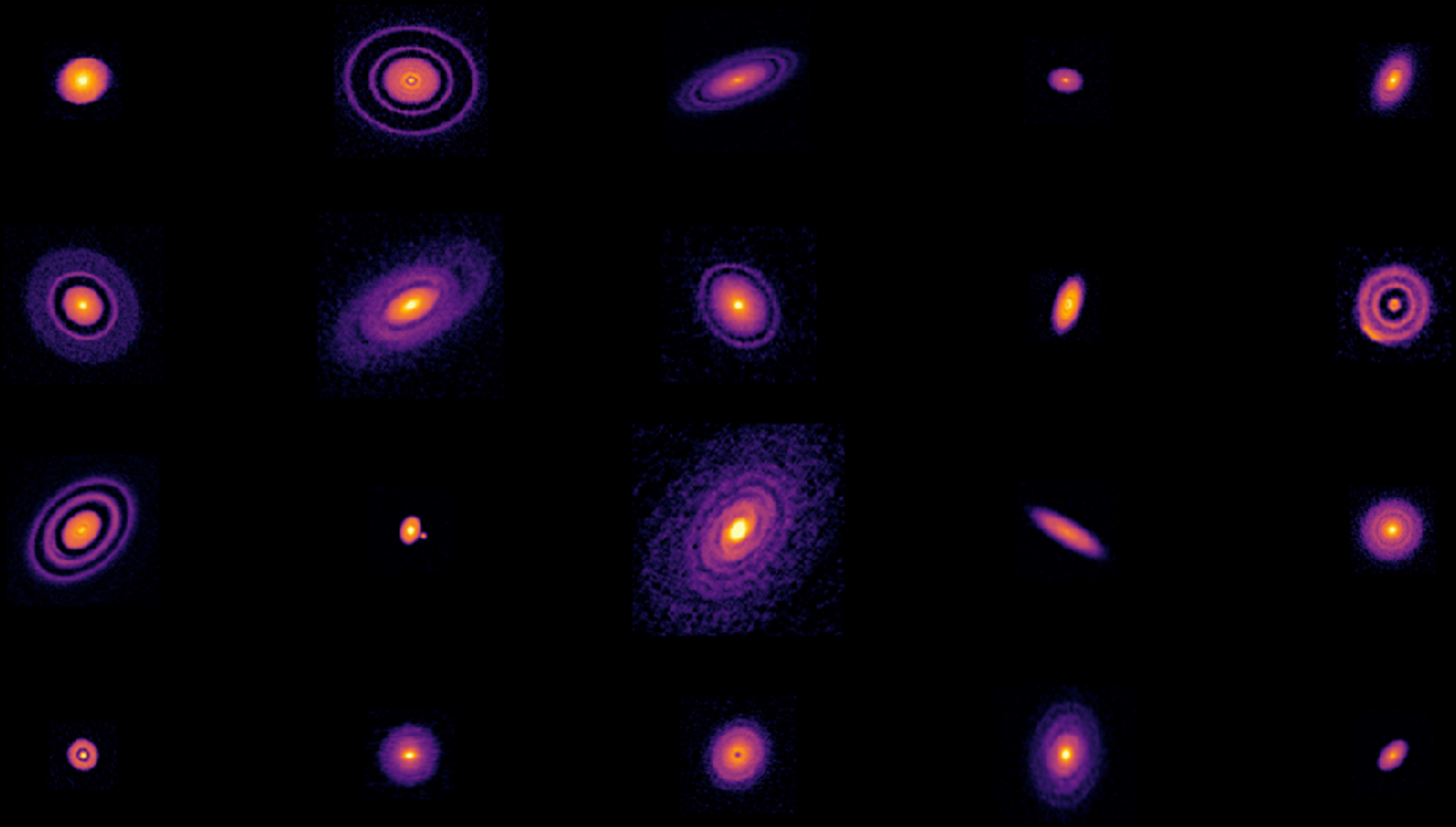
ALMA Images of young disks

ALMA Partnership 2015



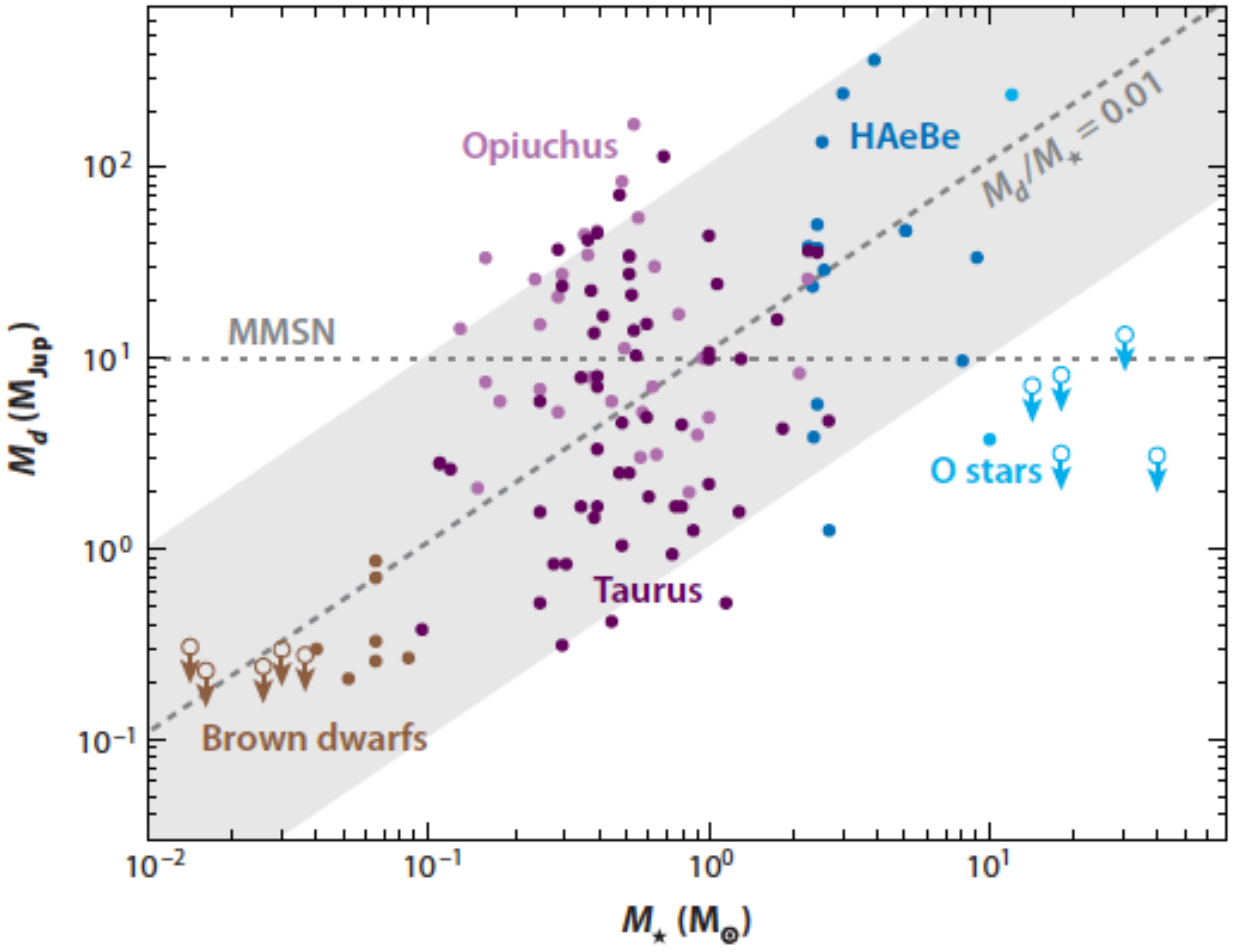
Andrews et al (2016)

DSHARP disks (ALMA)



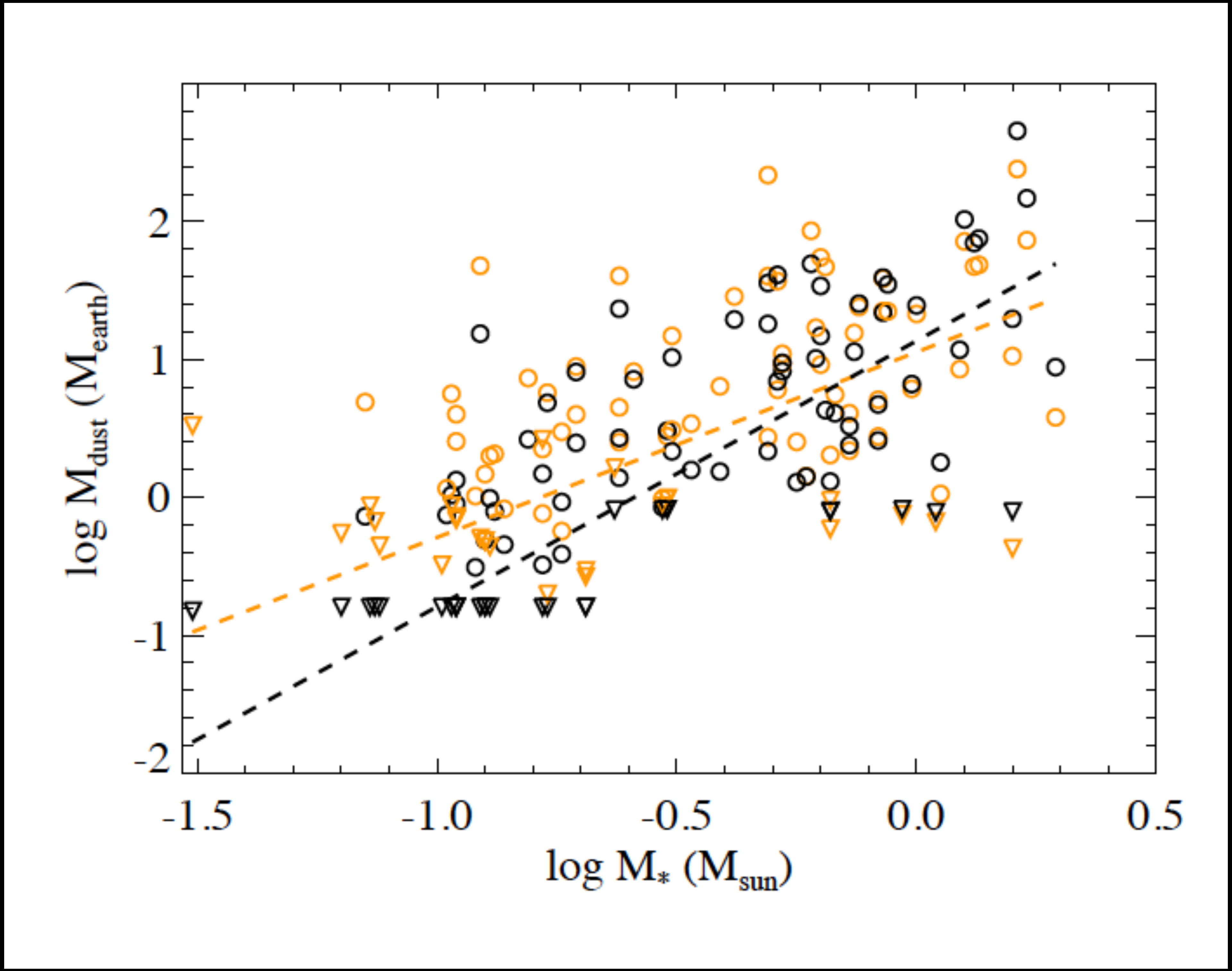
Andrews et al (2018)

Disk masses



Williams & Cieza 2011

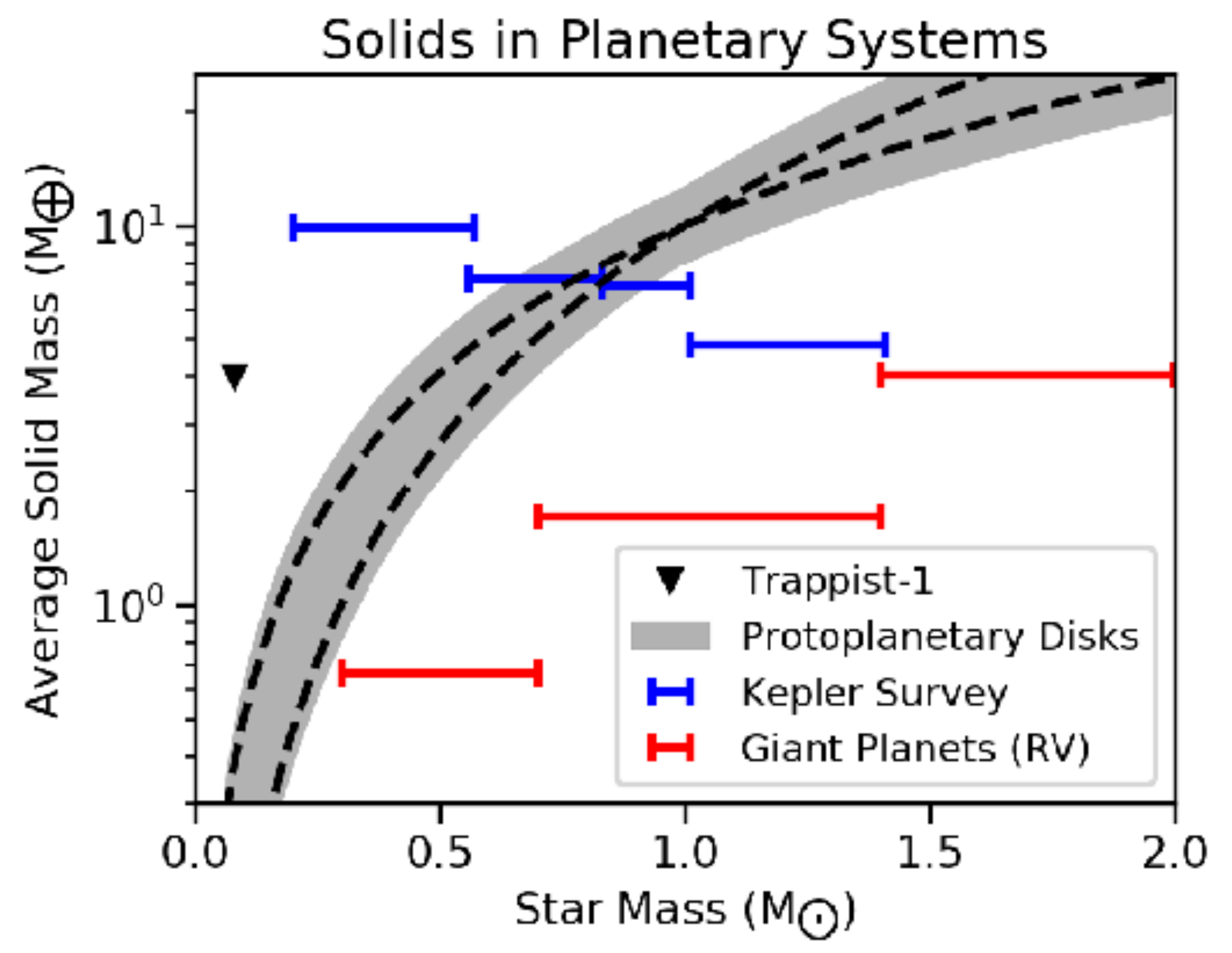
Mdisk-Mstar correlation ($Md \sim Mst^{1.6}$) — but lots of scatter



Pascucci et al (2016)

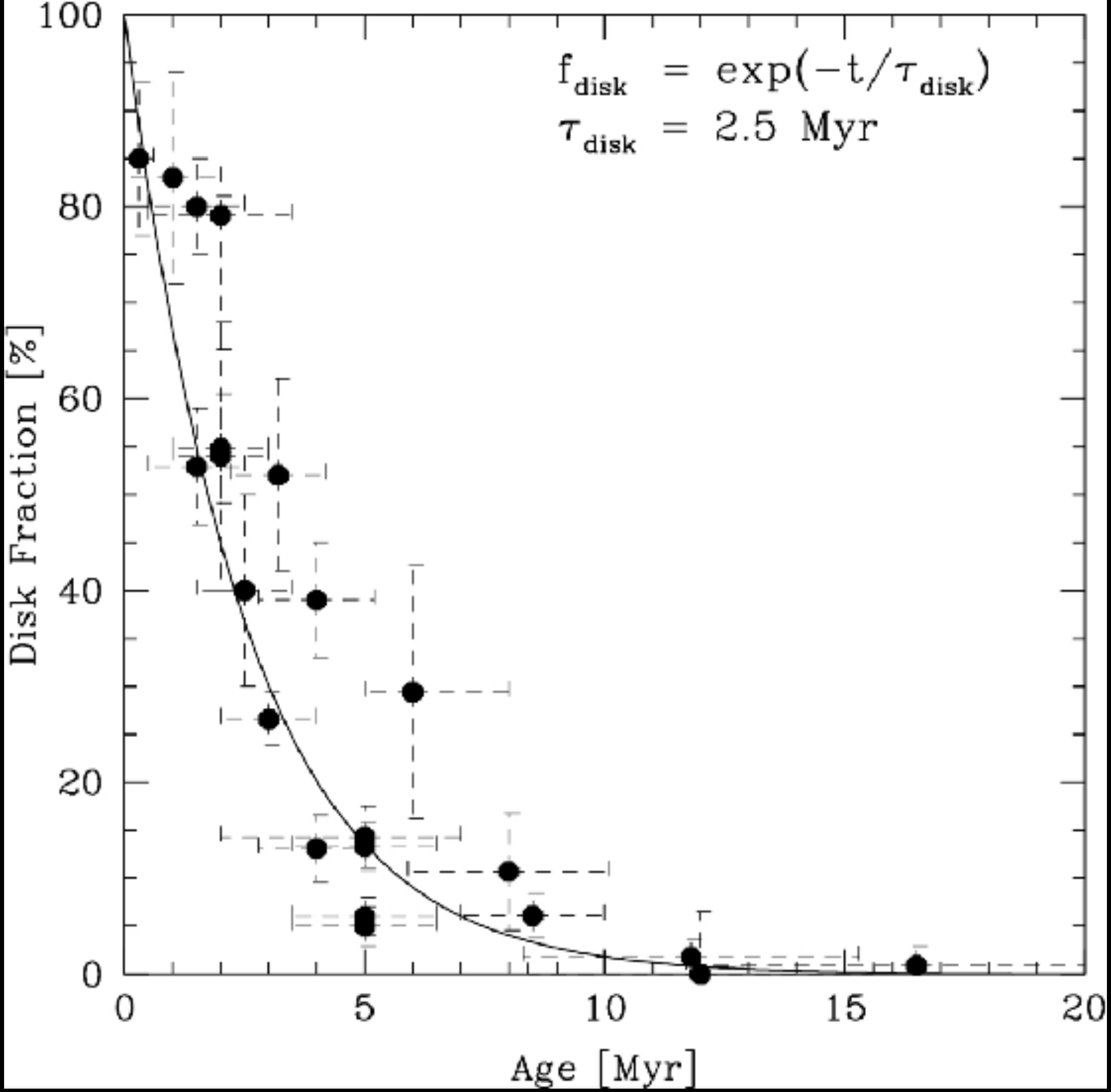
Are disk masses underestimated?

Disk masses appear too small to explain the masses in observed planetary systems



Mulders (2018)

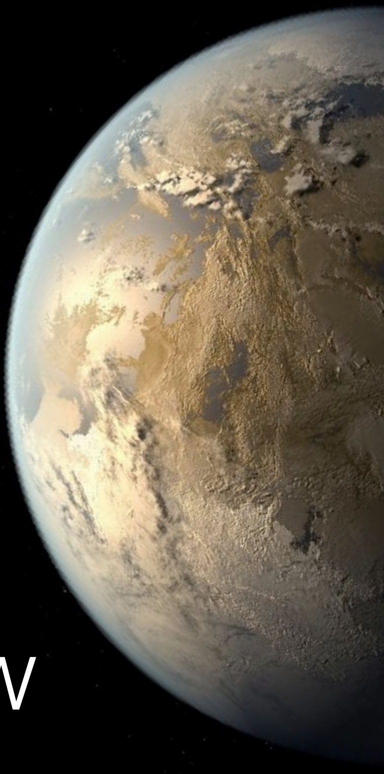
Gas disks (inferred from hot dust) dissipate on a few Myr timescale

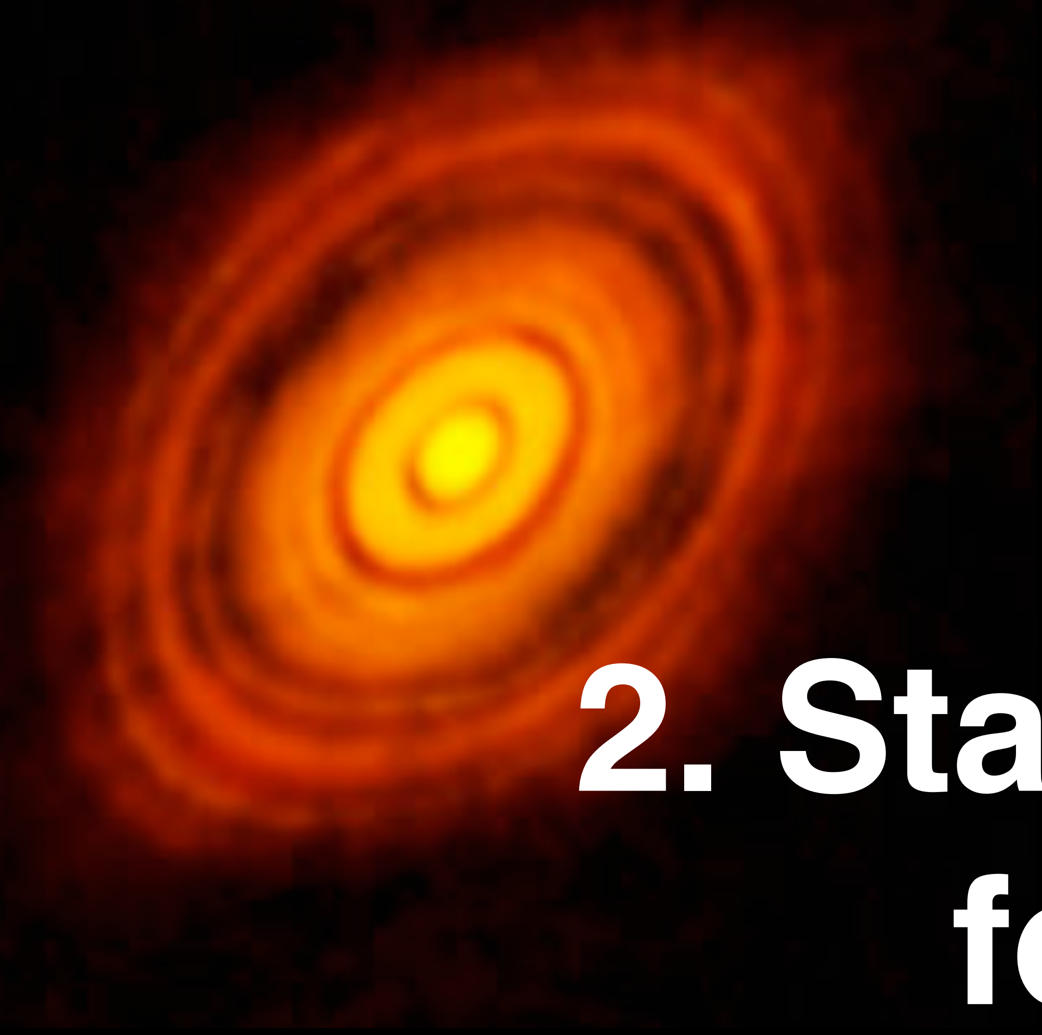


Mamajek 2009

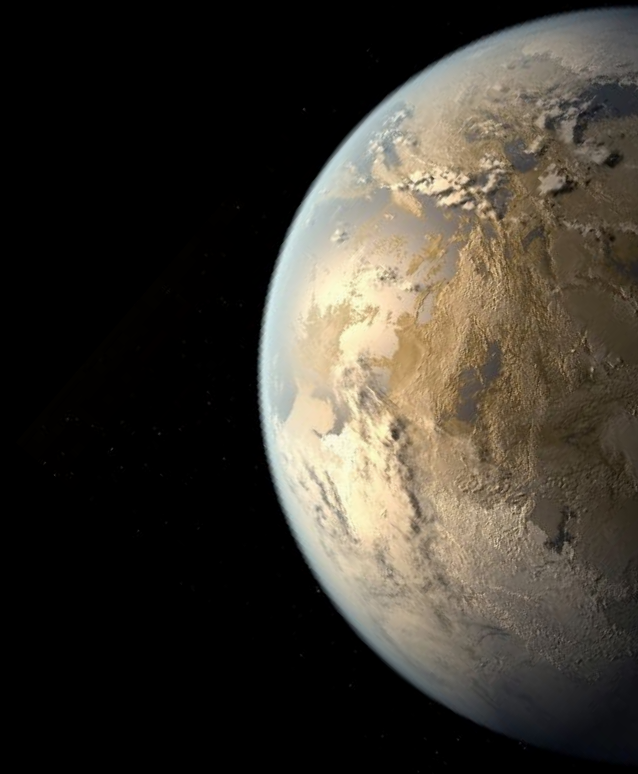
Observational constraints: summary

- Huge diversity of planetary systems
    - Solar System unusual at ~1% level
    - “Super-Earths” very common
- The window for most planet formation: the few million year lifetime of gaseous disks





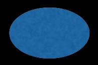
2. Stages of planet formation



- planetesimal formation
- pebble/planetesimal accretion
- orbital migration
- giant impacts
- gas accretion
- giant planet scattering

Planet formation: the cast of characters

pebbles:
~1mm-10cm

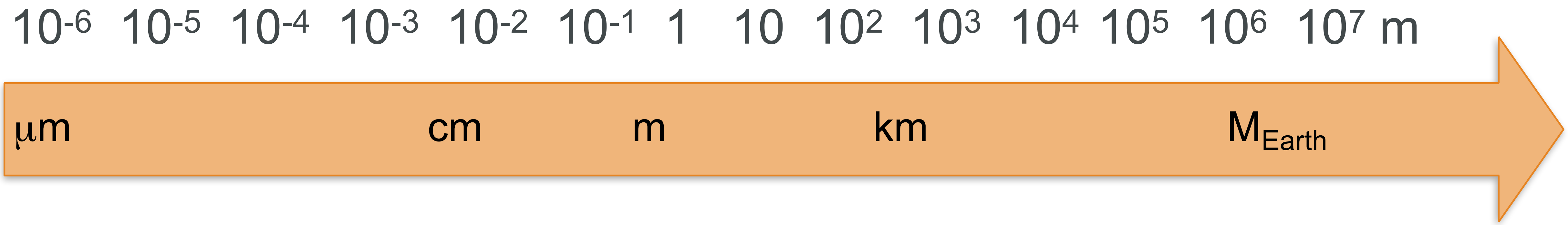


planetesimals:
~10-1000km

terrestrial planetary embryos (=protoplanets):
~Moon-sized or larger

giant planet "cores" or "embryos":
~Earth-sized or larger

Physics of growth between μm and 10^4 km

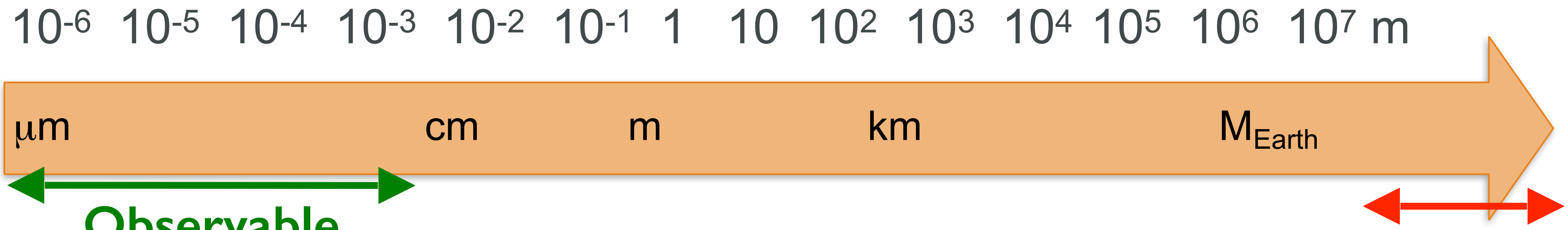


10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

μm cm m km M_{Earth}

Slide credit: P. Armitage

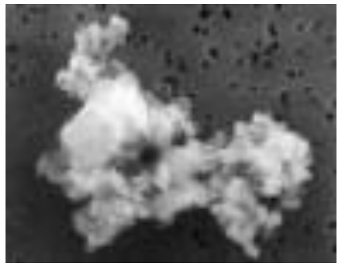
Physics of growth between μm and 10^4 km



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

μm cm m km M_{Earth}

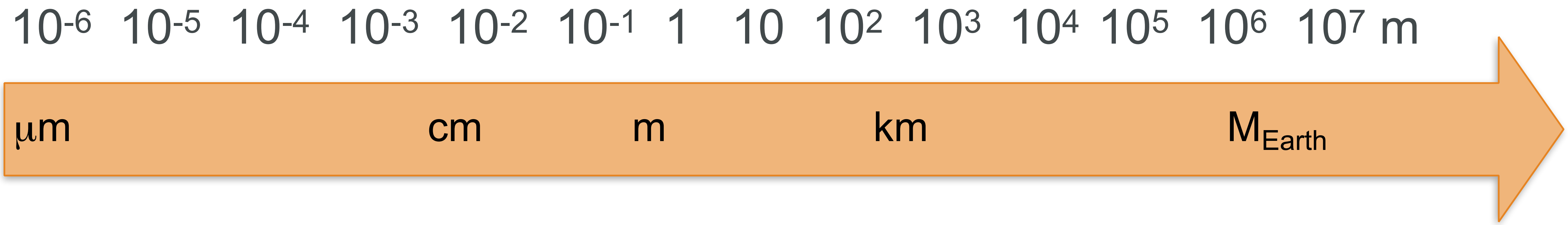
Observable
in visual, infrared
and (sub-)mm



Observable
by transits, RV

Slide credit: P. Armitage

Physics of growth between μm and 10^4 km

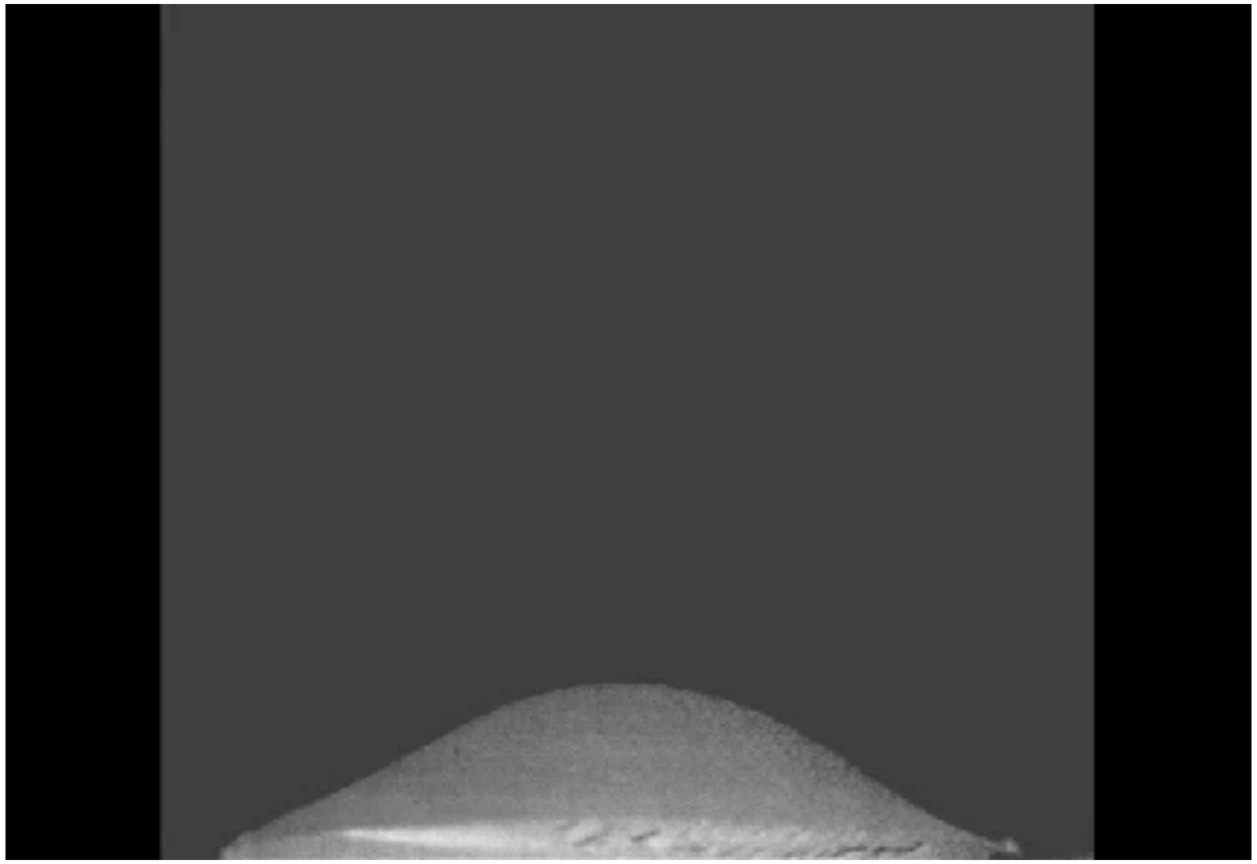


10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

μm cm m km M_{Earth}

Collisions lead
to growth (silicates)

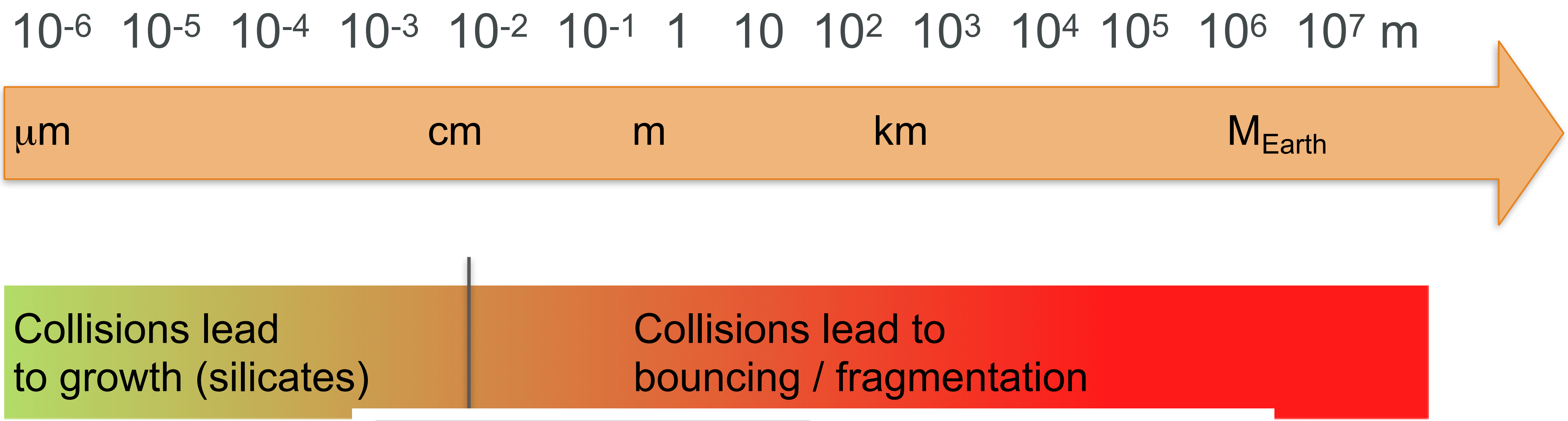
Collisions lead to
bouncing / fragmentation



Blum & Wurm (2008)

Slide credit: P. Armitage

Physics of growth between μm and 10^4 km



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

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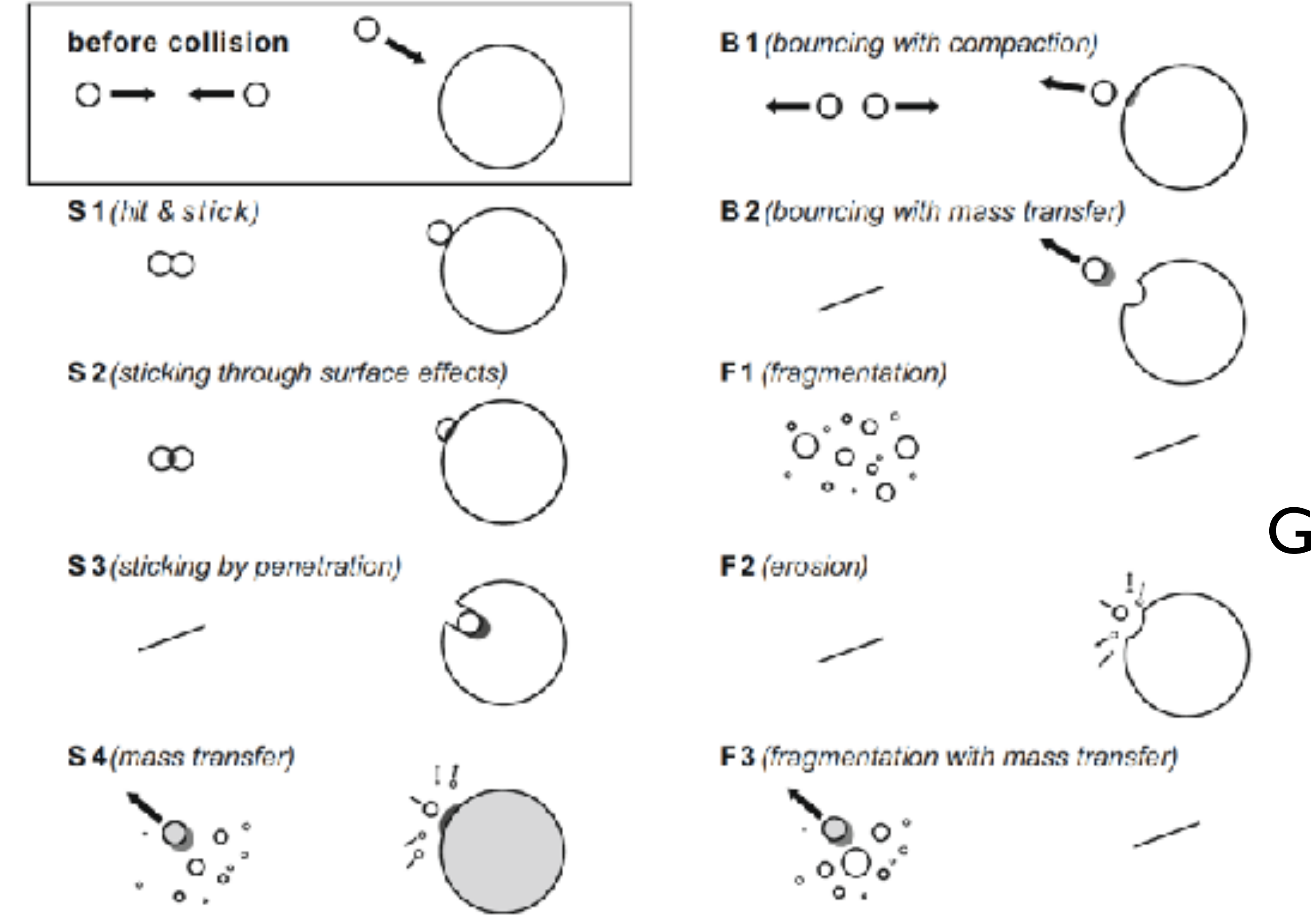
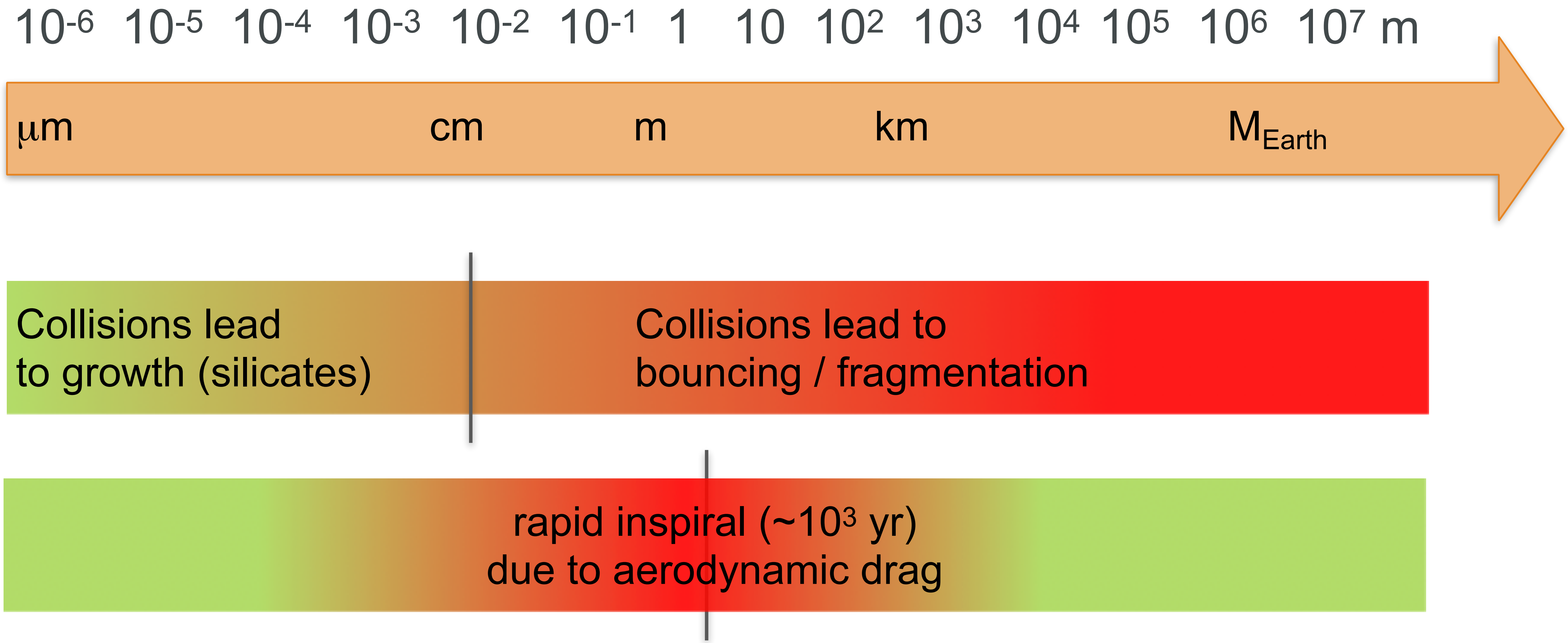


Guttler et al (2010)

Slide credit: P. Armitage

Physics of growth between μm and 10^4 km



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

μm cm m km M_{Earth}

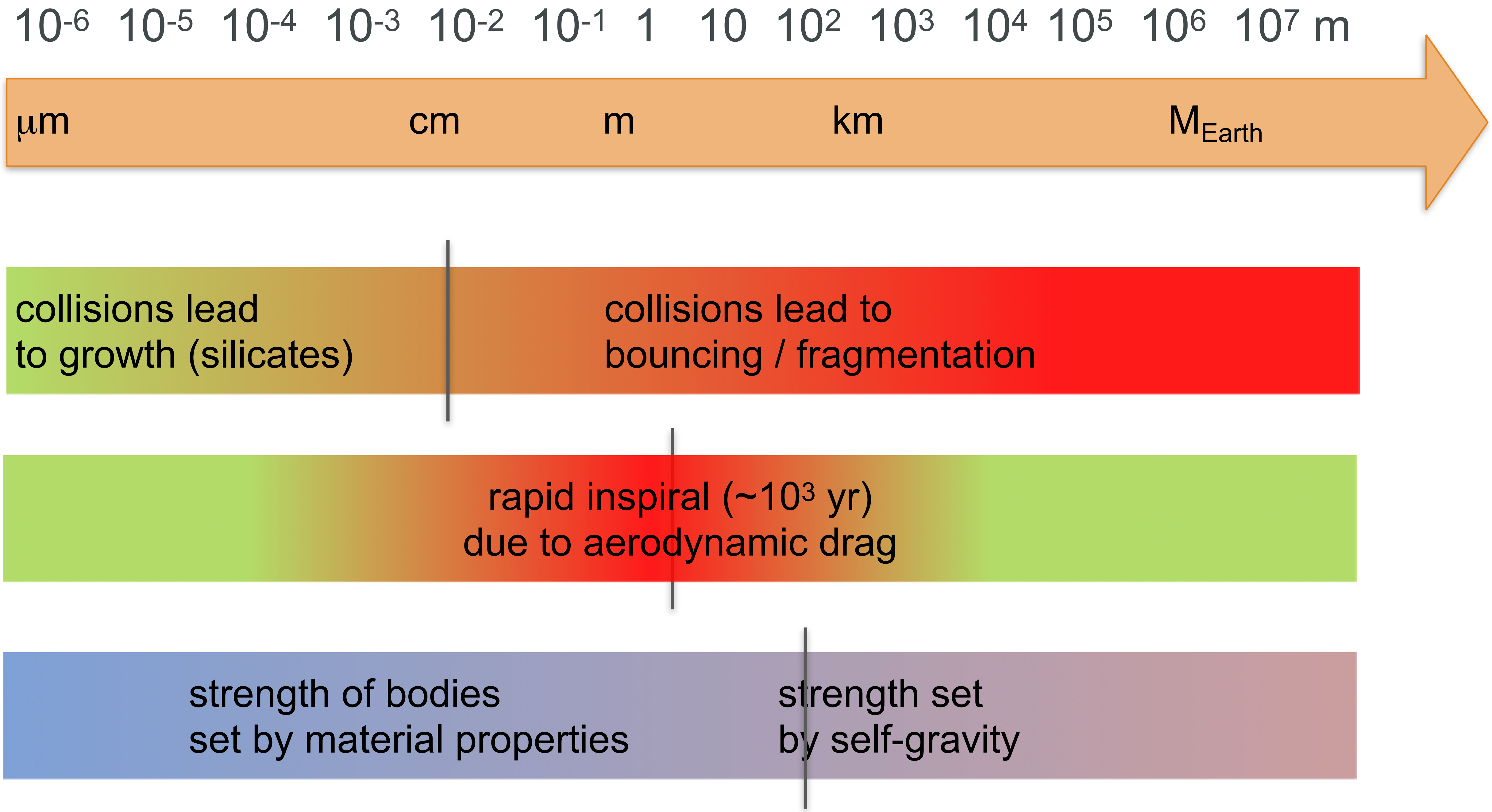
Collisions lead
to growth (silicates)

Collisions lead to
bouncing / fragmentation

rapid inspiral (~10^3 yr)
due to aerodynamic drag

Slide credit: P. Armitage

Physics of growth between μm and 10^4 km



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} m

μm cm m km M_{Earth}

collisions lead
to growth (silicates)

collisions lead to
bouncing / fragmentation

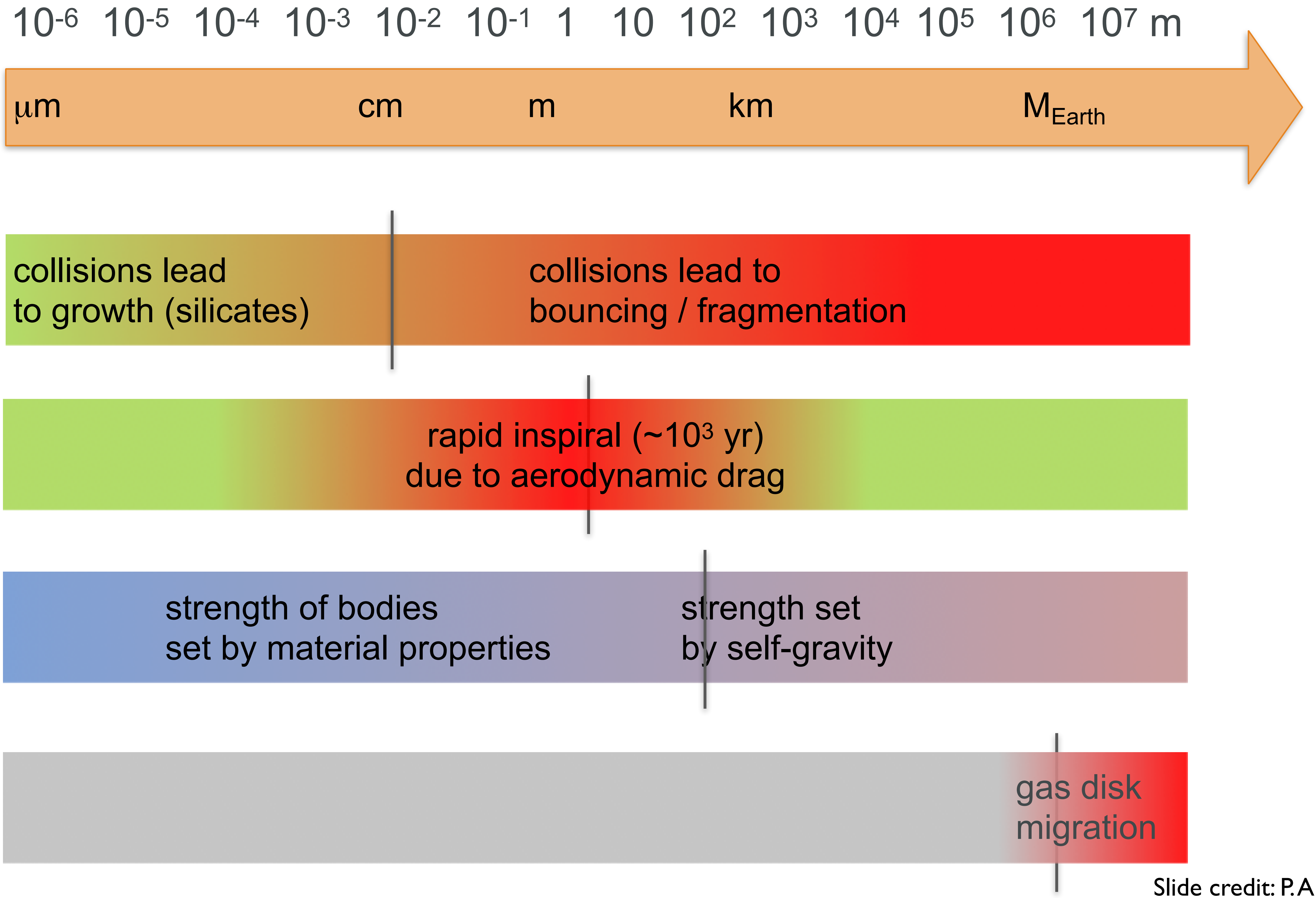
rapid inspiral (~10^3 yr)
due to aerodynamic drag

strength of bodies
set by material properties

strength set
by self-gravity

Slide credit: P. Armitage

Physics of growth between μm and 10^4 km



10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5 10^6 10^7 m

μm cm m km M_{Earth}

collisions lead to growth (silicates)

collisions lead to bouncing / fragmentation

rapid inspiral (~10^3 yr) due to aerodynamic drag

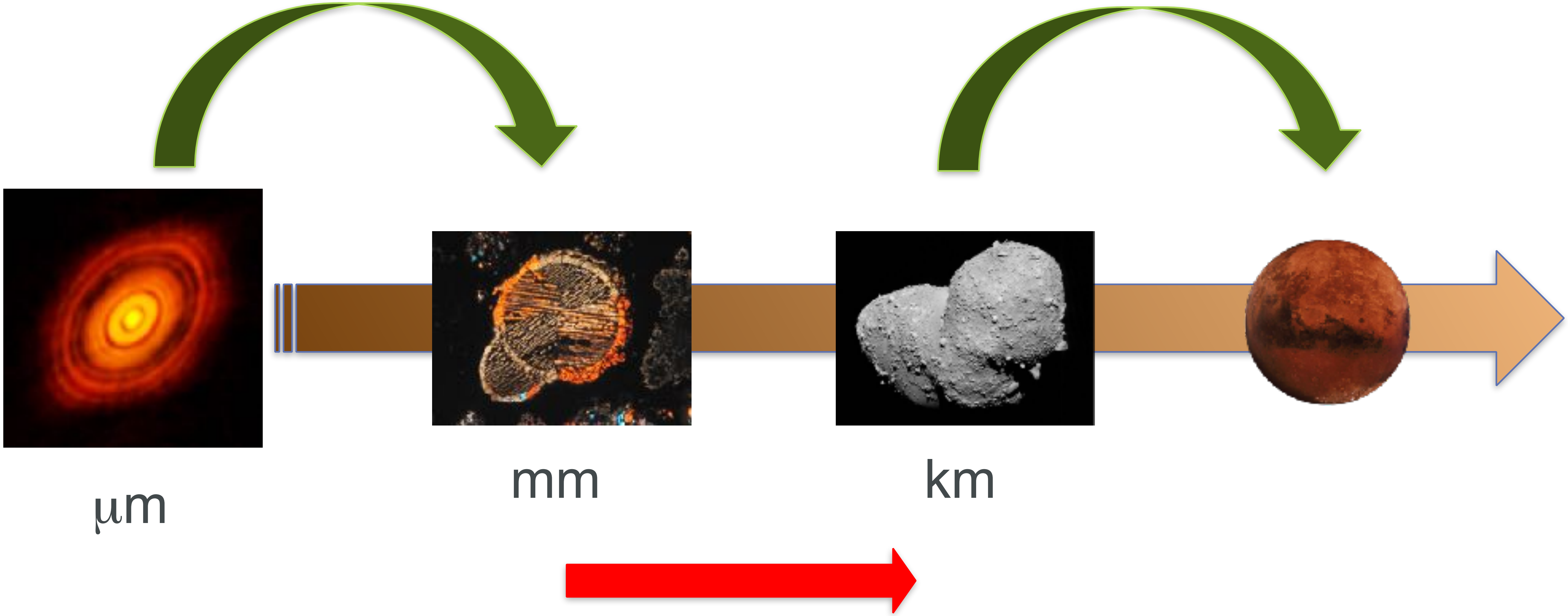
strength of bodies set by material properties

strength set by self-gravity

gas disk migration

Slide credit: P. Armitage

Forming the first planetesimals



aerodynamic &
material forces

gravity

μm

mm

km

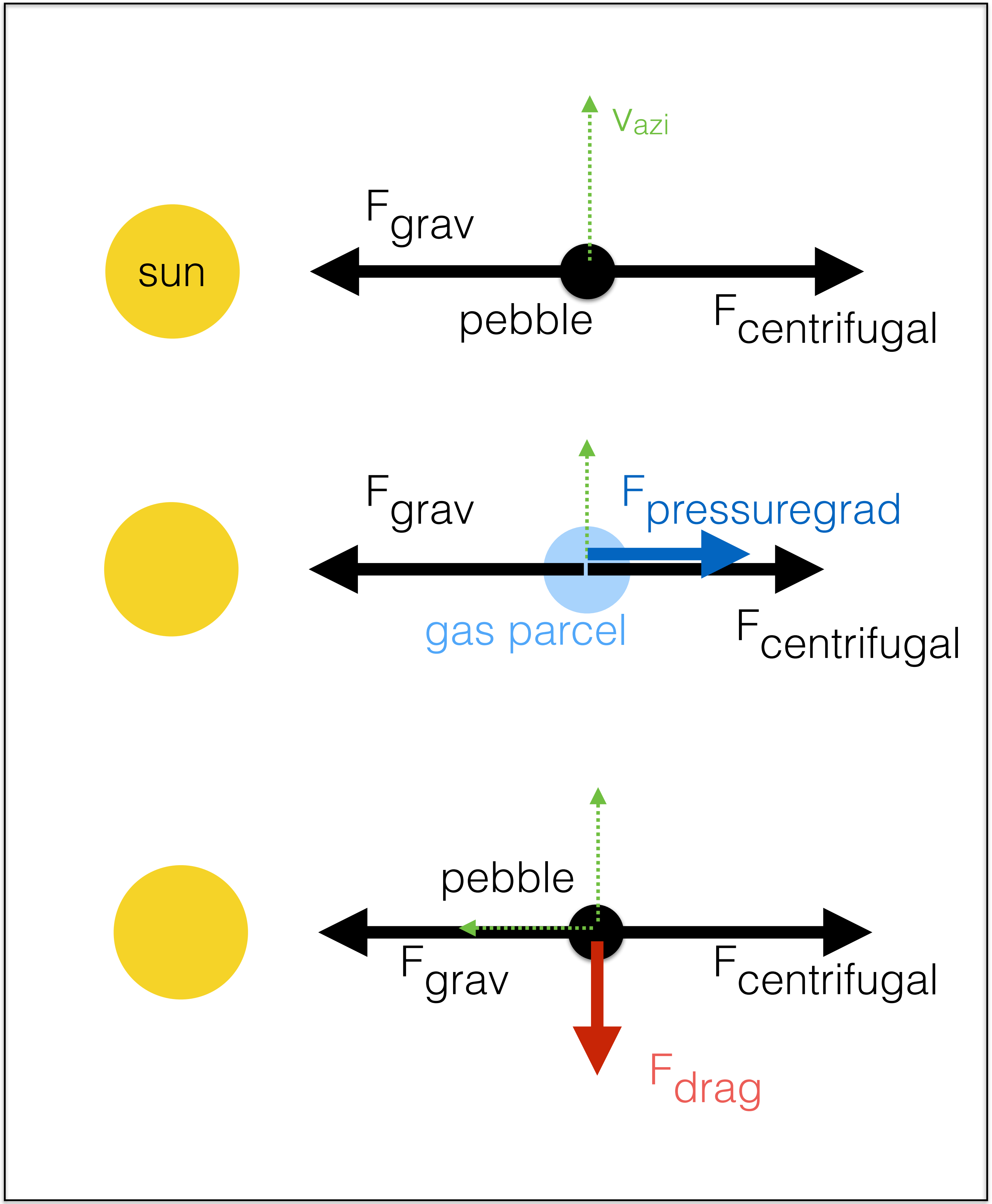
planetesimal formation

Slide credit: P. Armitage

(ii) Particle drift

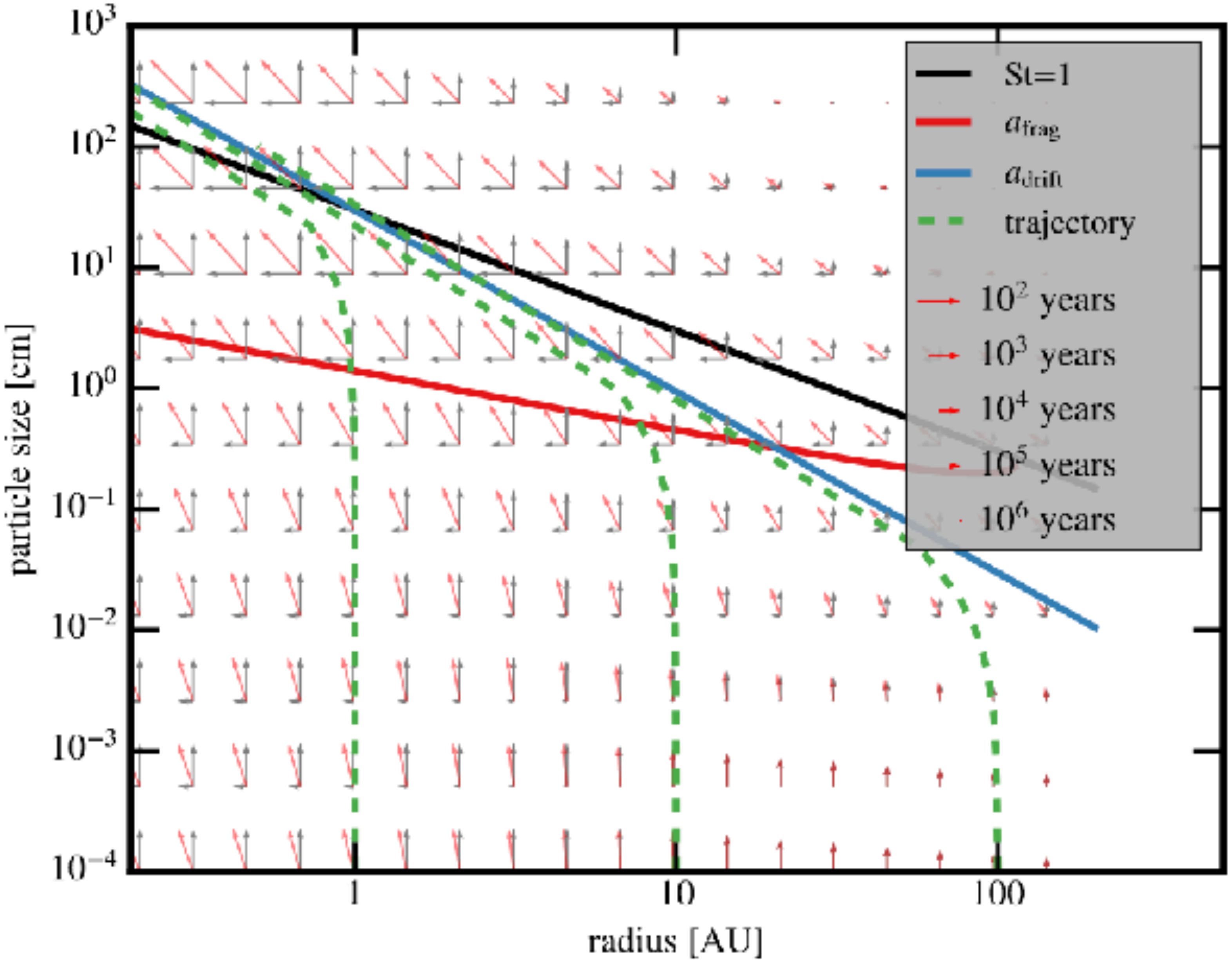
- pressure support on the gas reduces the orbital velocity of the gas
- particles feel a headwind
- gas drag forces the particles to drift inwards

$$\boxed{a_{\mathrm{drag}} = -\frac{v_{\mathrm{p}} - u_{\mathrm{g}}}{t_{\mathrm{f}}}}$$



Slide credit: M. Lambrechts

Growth and inward drift of dust



Birnstiel et al (2016)

The Stokes number

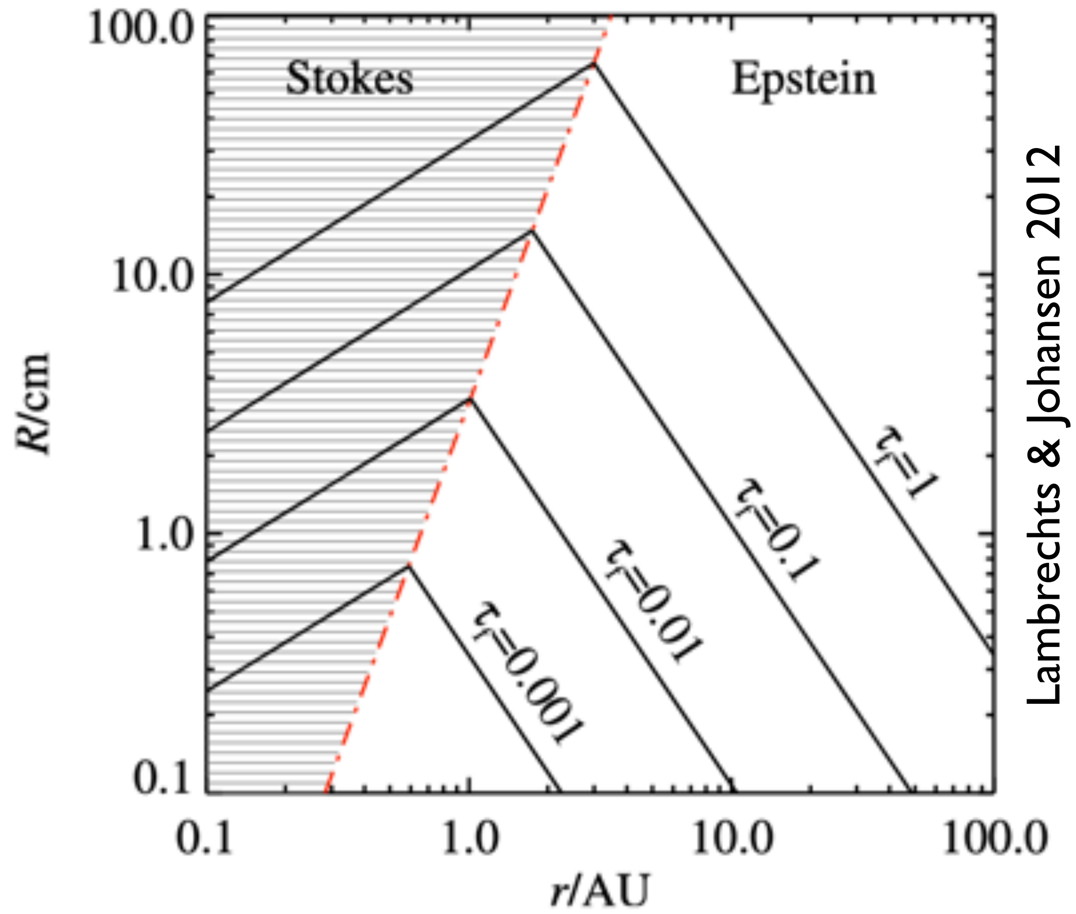
- Stokes number = the stopping time (due to gas drag) / the orbital timescale

dust monomer size

dust monomer density

$$\mathrm{St} = \frac{a\,\rho_{\mathrm{s}}}{\Sigma_{\mathrm{g}}}\,\frac{\pi}{2}$$

gas disk surface density



Lambrechts & Johansen 2012

Fastest drifting particle (“pebbles”) are where St=1

(“St = one”), or “stones” — Aurelien Crida

Streaming instability$^{\text{simplified}}$

Youdin and Goodman, 2005, Johansen et al 2007, Bai and Stone, 2010, Kowalik et al 2013, Yang and Johansen 2016, Lambrechts et al, 2016

Slide credit: M. Lambrechts

Streaming instability^{simplified}

Youdin and Goodman, 2005, Johansen et al 2007, Bai and Stone, 2010, Kowalik et al 2013, Yang and Johansen 2016, Lambrechts et al, 2016

Slide credit: M. Lambrechts

Streaming instability$^{\text{simplified}}$

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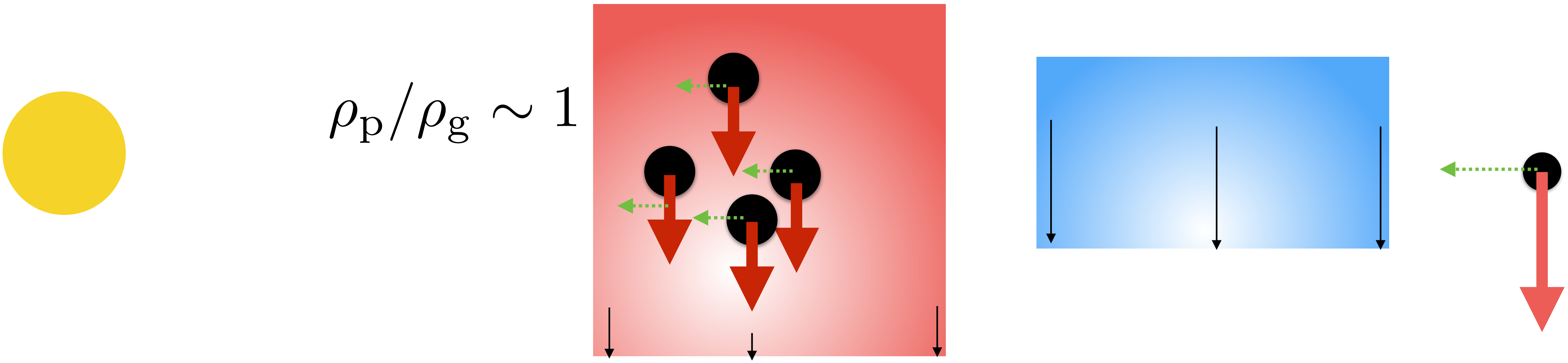
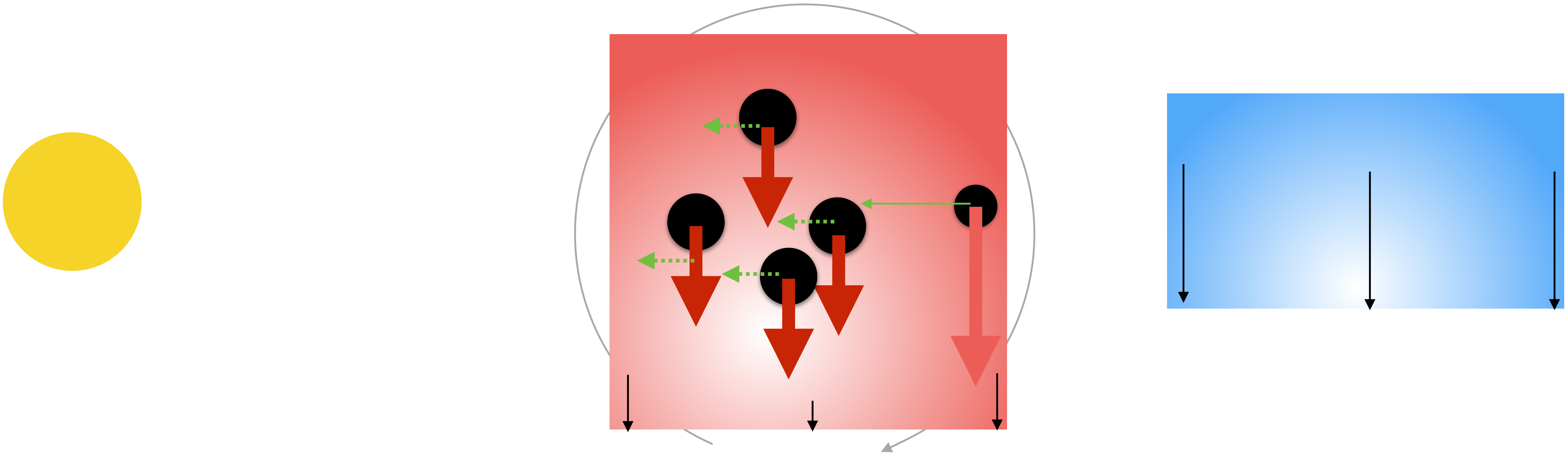


$\rho_\mathrm{p}/\rho_\mathrm{g} \sim 1$

Slide credit: M. Lambrechts

Streaming instability$^{\text{simplified}}$

Youdin and Goodman, 2005, Johansen et al 2007, Bai and Stone, 2010, Kowalik et al 2013, Yang and Johansen 2016, Lambrechts et al, 2016



Slide credit: M. Lambrechts

- **Streaming instability** leads to local clustering
- gravitational collapse of overdensities to km+ scale planetesimals

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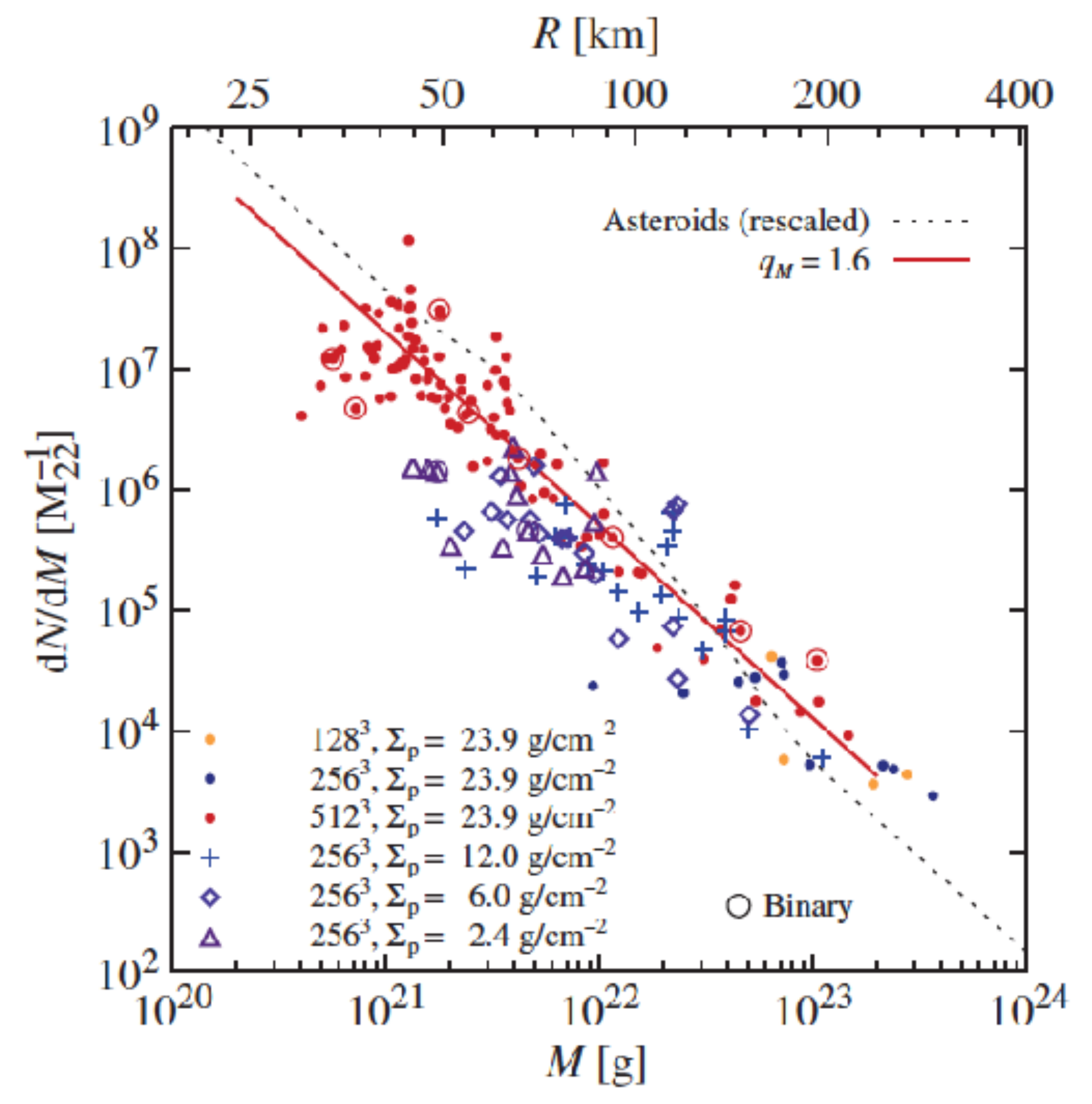
SCIENCES

Simulations: Jake Simon, Zhaohuan Zhu

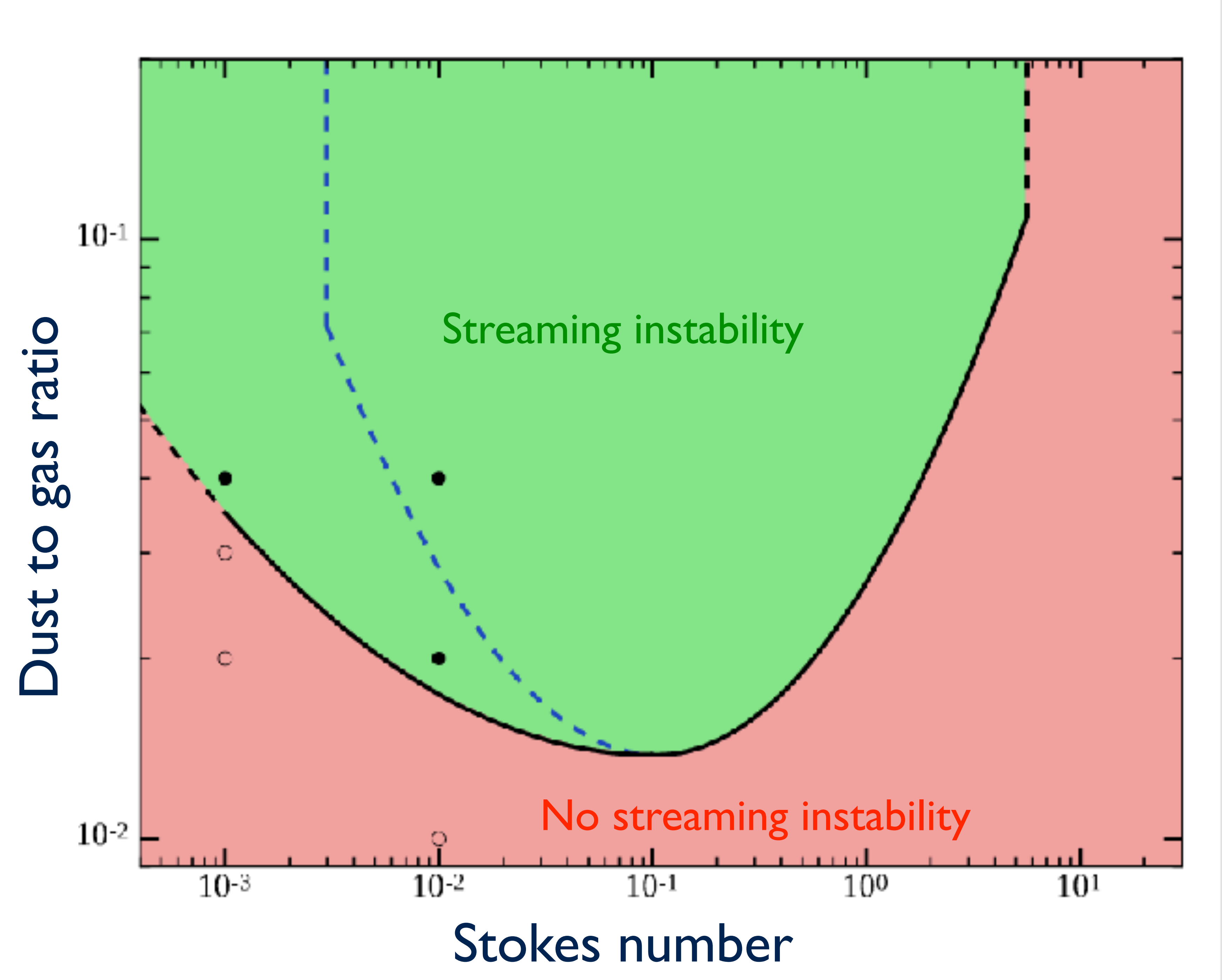
Streaming Instability

- Forms planetesimals up to R~300km
- Characteristic birth size distribution similar to asteroids



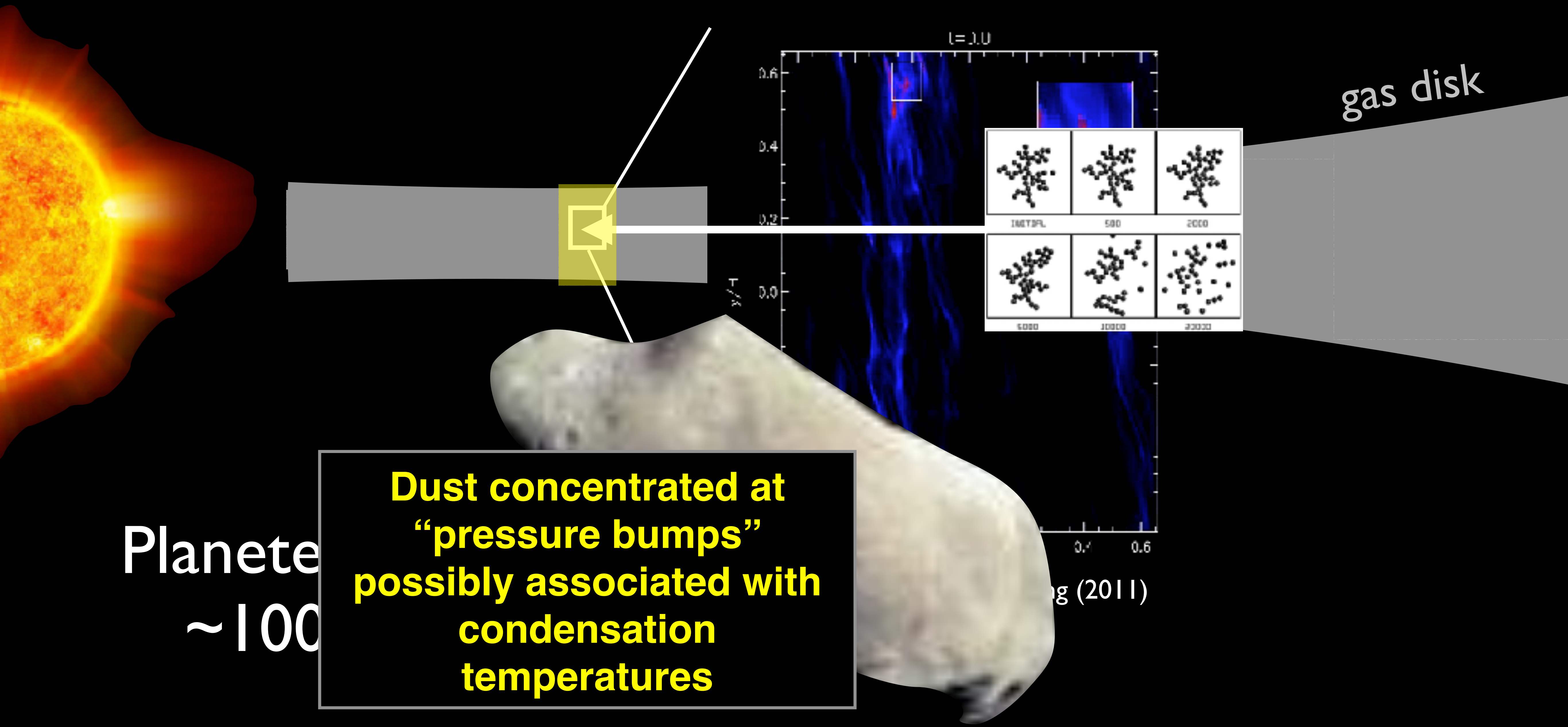
Johansen et al (2015); also Simon et al (2016)

The streaming instability requires an enhancement in the dust-to-gas ratio



Yang et al (2017)

Planetesimal formation models: dust growth/drift with disk evolution



g (2011)

Planete

~100

Dust concentrated at “pressure bumps” possibly associated with condensation temperatures

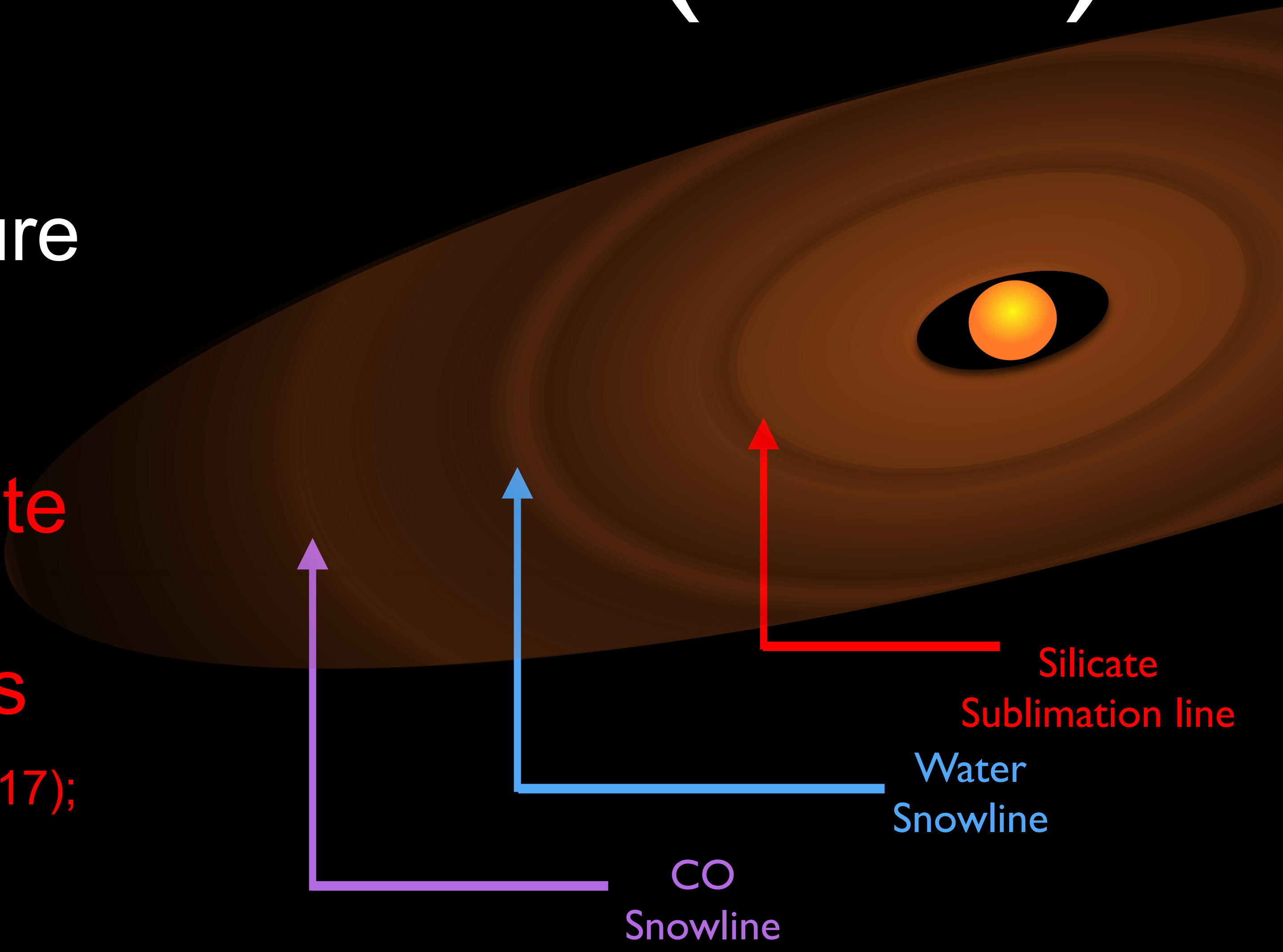
Model of Izidoro et al (2022)

Planetesimal formation in a gaseous disk assuming pressure bumps (traps)

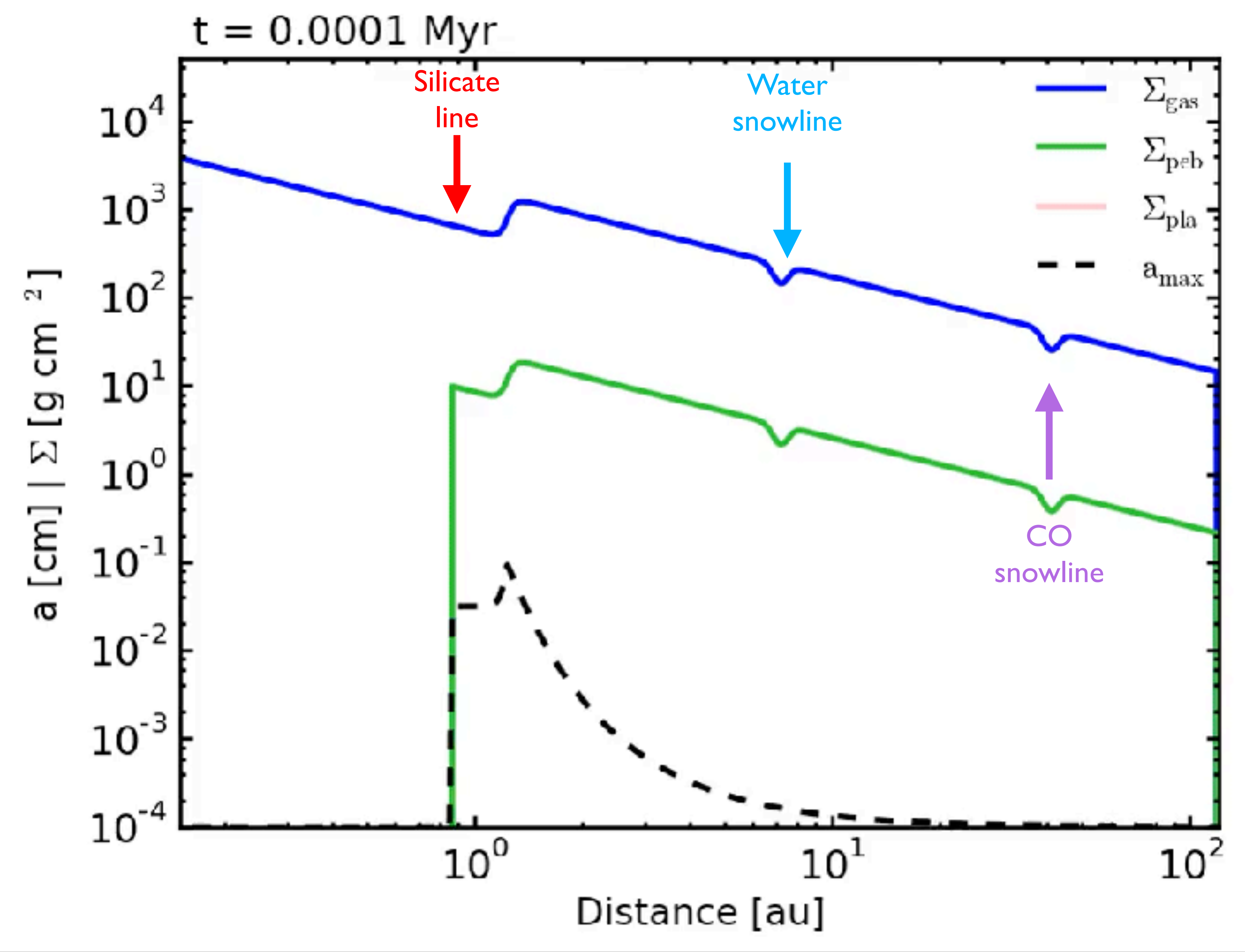
1) at T~1400 K, near the silicate sublimation line due to thermal ionization of the gas disk (Desch & Turner 2015; Flock et al 2017);

2) at T~170 K, the water snowline (Muller et al 2021, Charnoz et al 2021);

3) at T~30 K, the CO-snowline (Qi et al 13, Flock et al 2015, Vanthoff et al 2017, Bosman & Banzatti 2019, Vericel & Gonzalez 20)

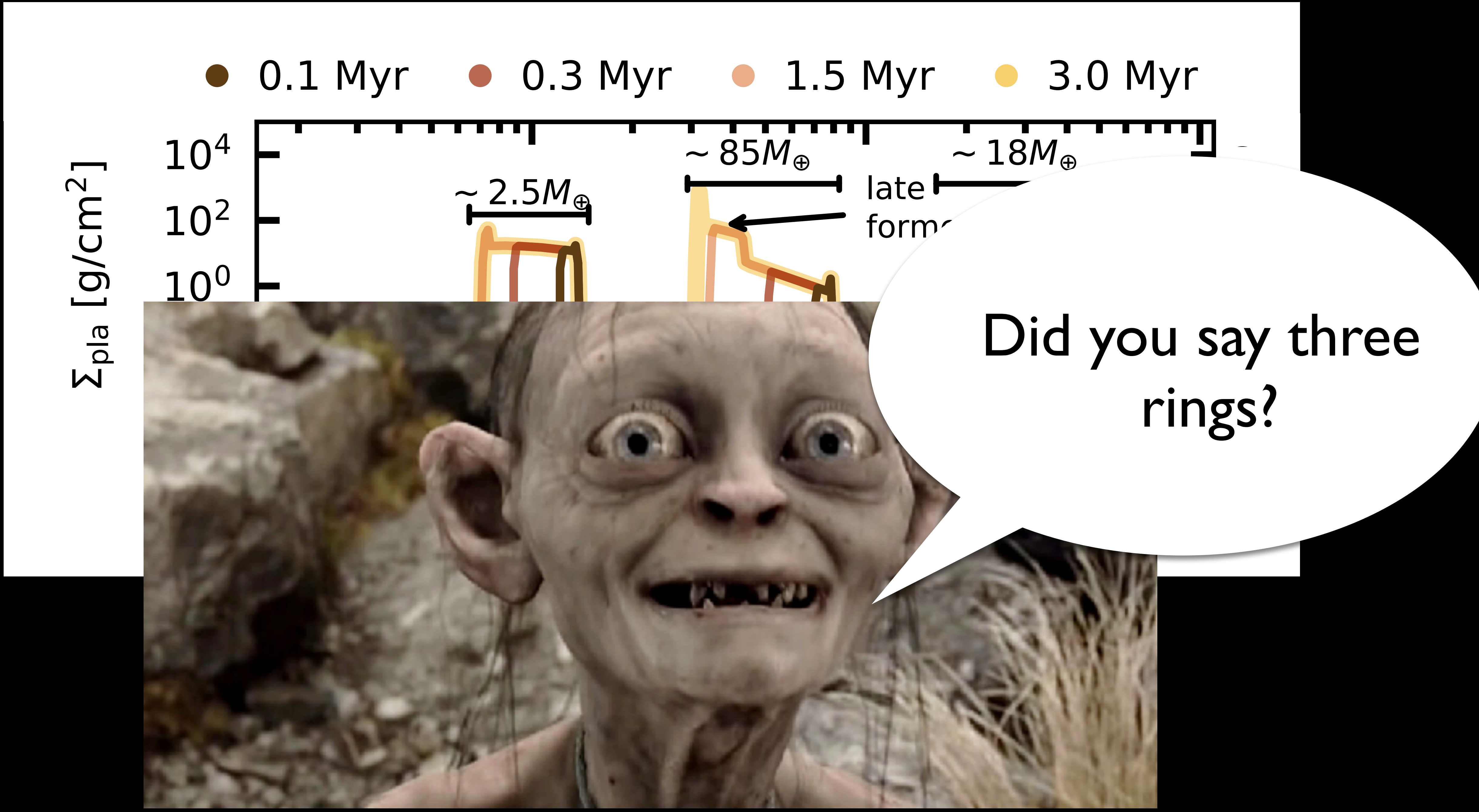


A model with dust coagulation/drift and three "pressure bumps"



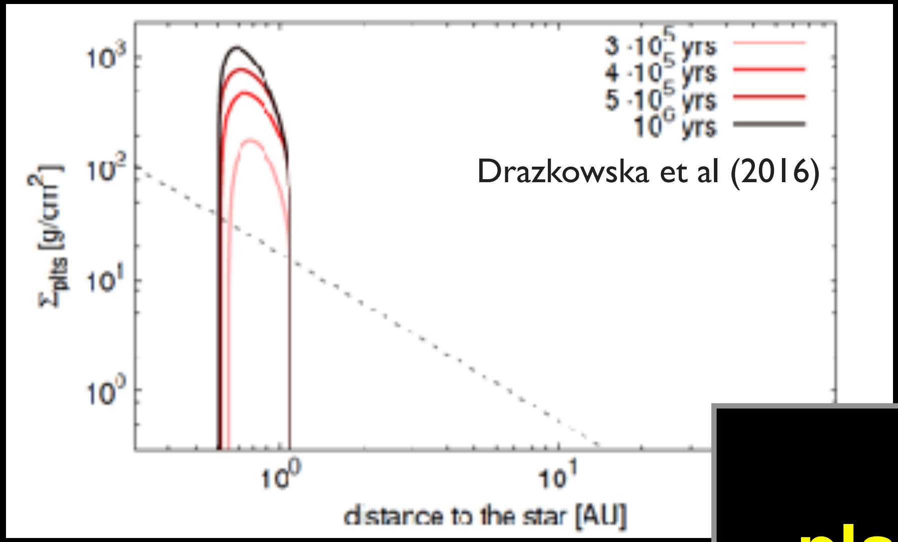
Izidoro et al (2022)

Three rings of planetesimals

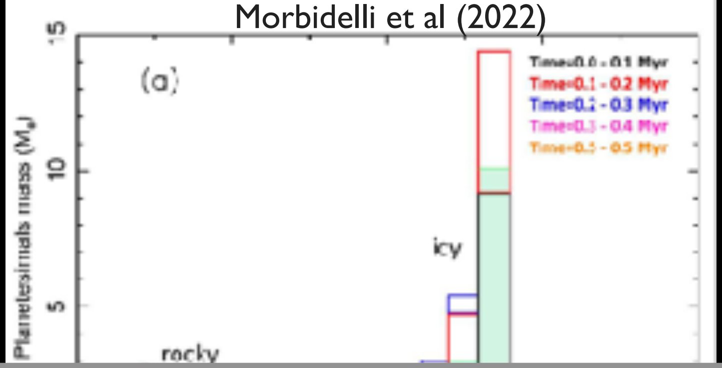


Izidoro et al (2022)

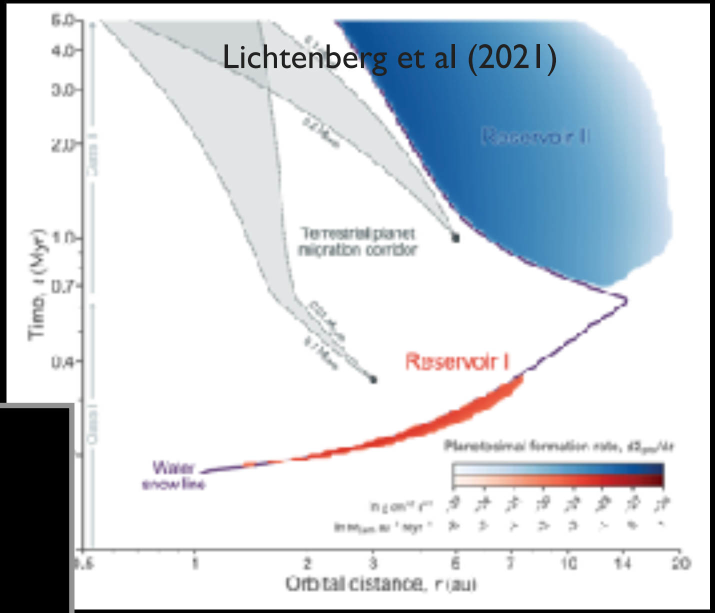
Planetesimal formation models: dust growth/drift with disk evolution



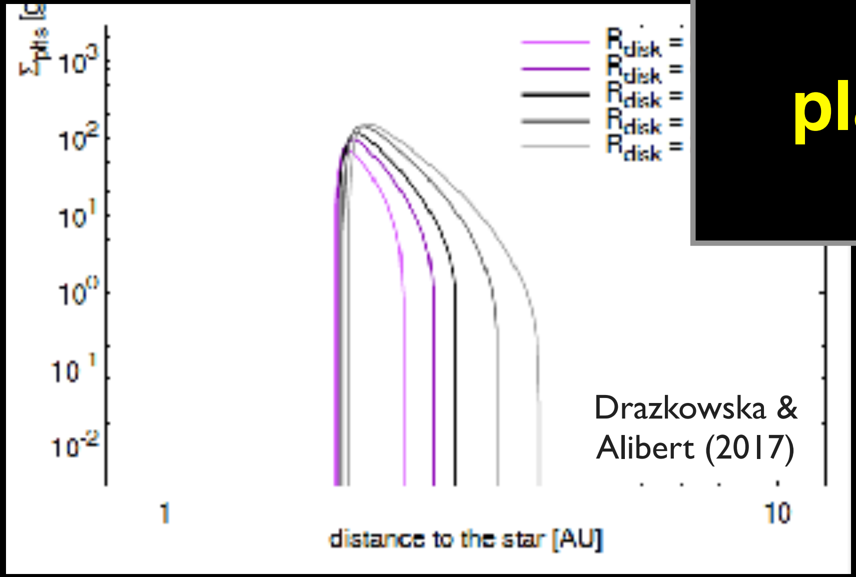
Drazkowska et al (2016)



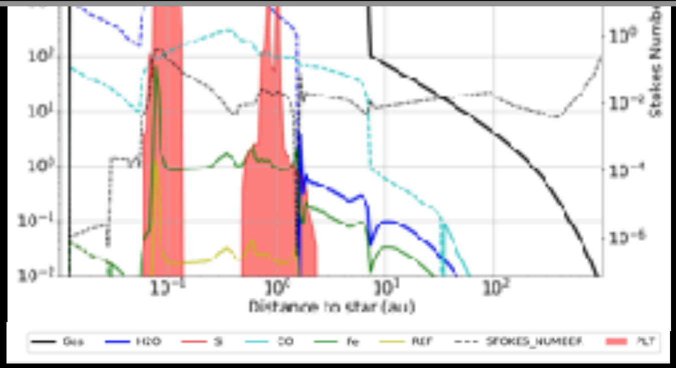
Morbidelli et al (2022)

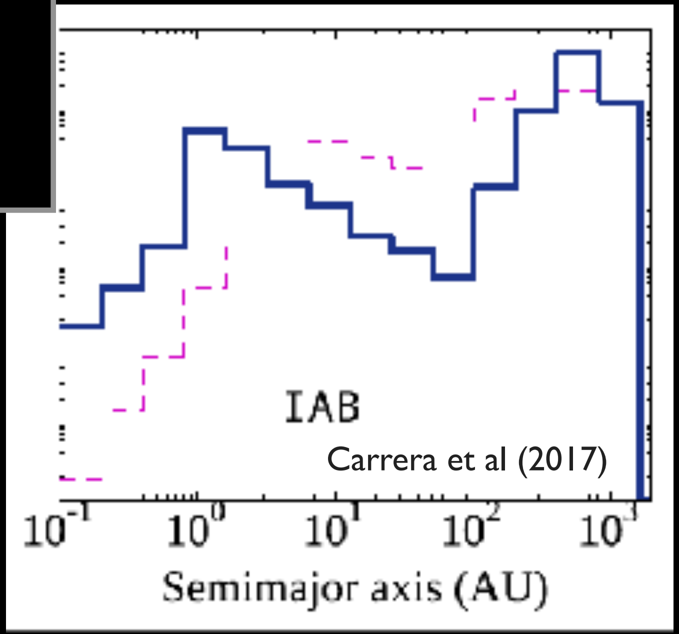


Lichtenberg et al (2021)



Drazkowska & Alibert (2017)





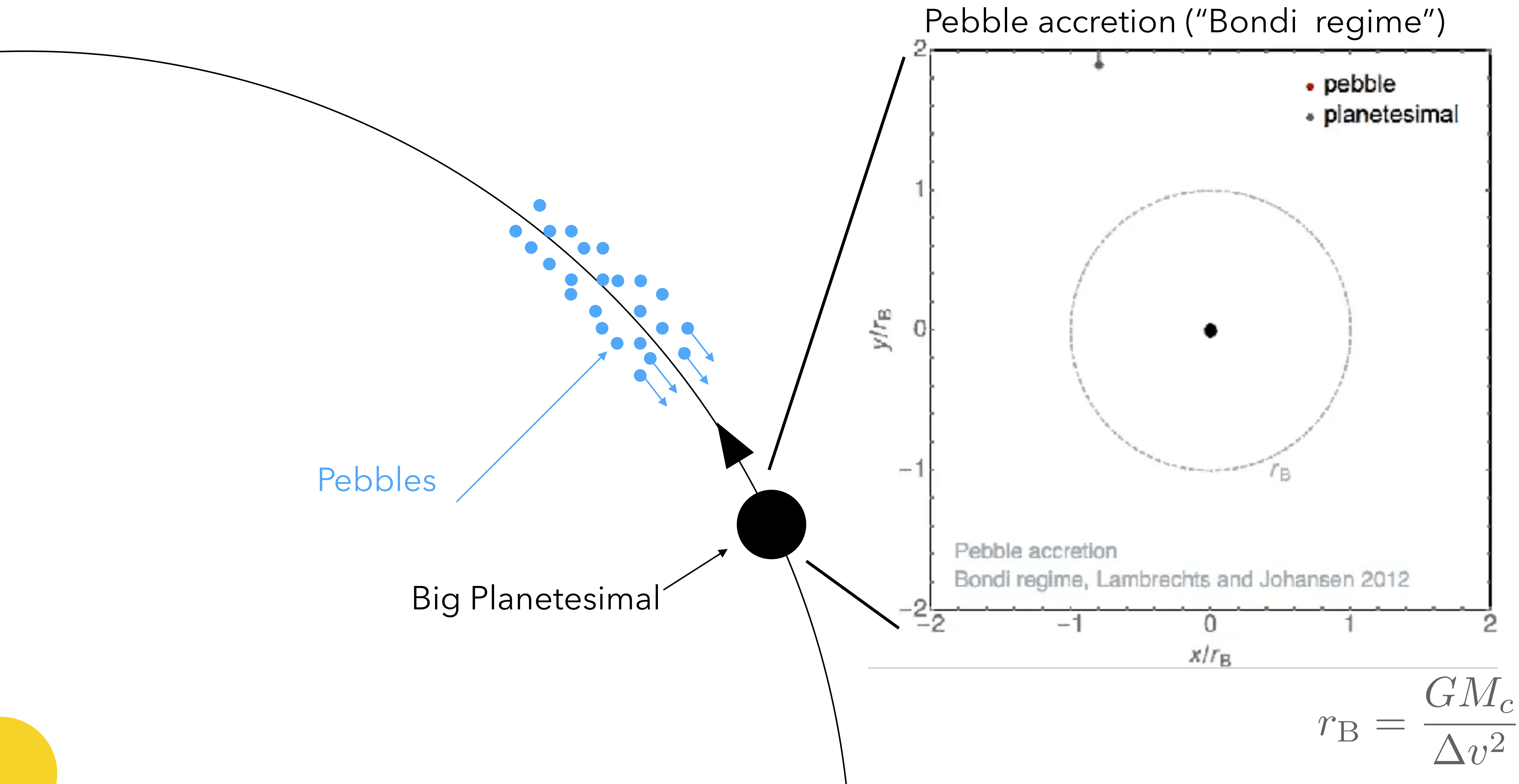
Carrera et al (2017)

General agreement that planetesimal formation is linked with condensation lines: planetesimals probably form in rings, not disks

Slide credit: M. Lambrechts

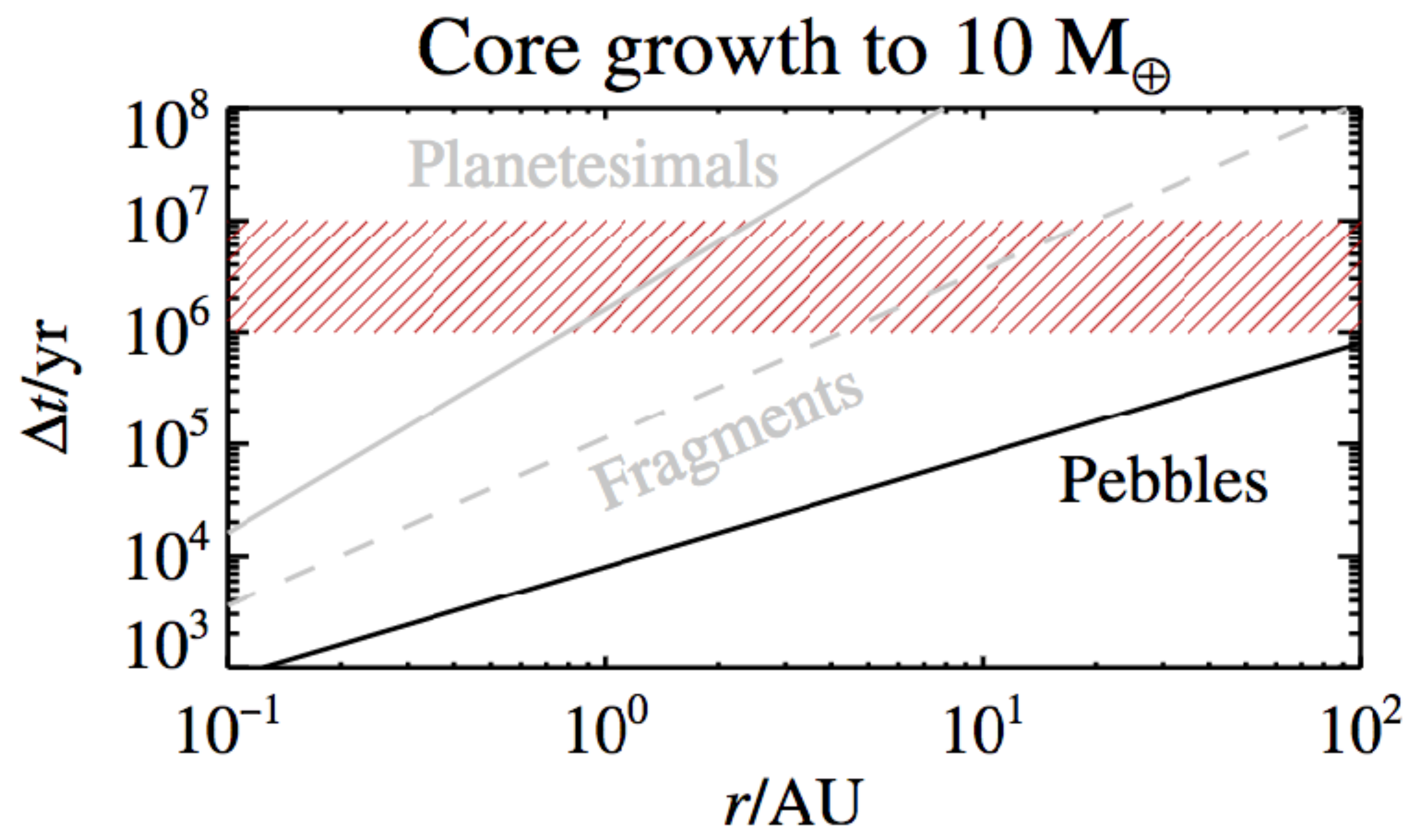
Pebble accretion

Lambrechts & Johansen, 2012



$$r_{\mathrm{B}} = \frac{GM_c}{\Delta v^2}$$

Pebble accretion is key for forming giant planet cores

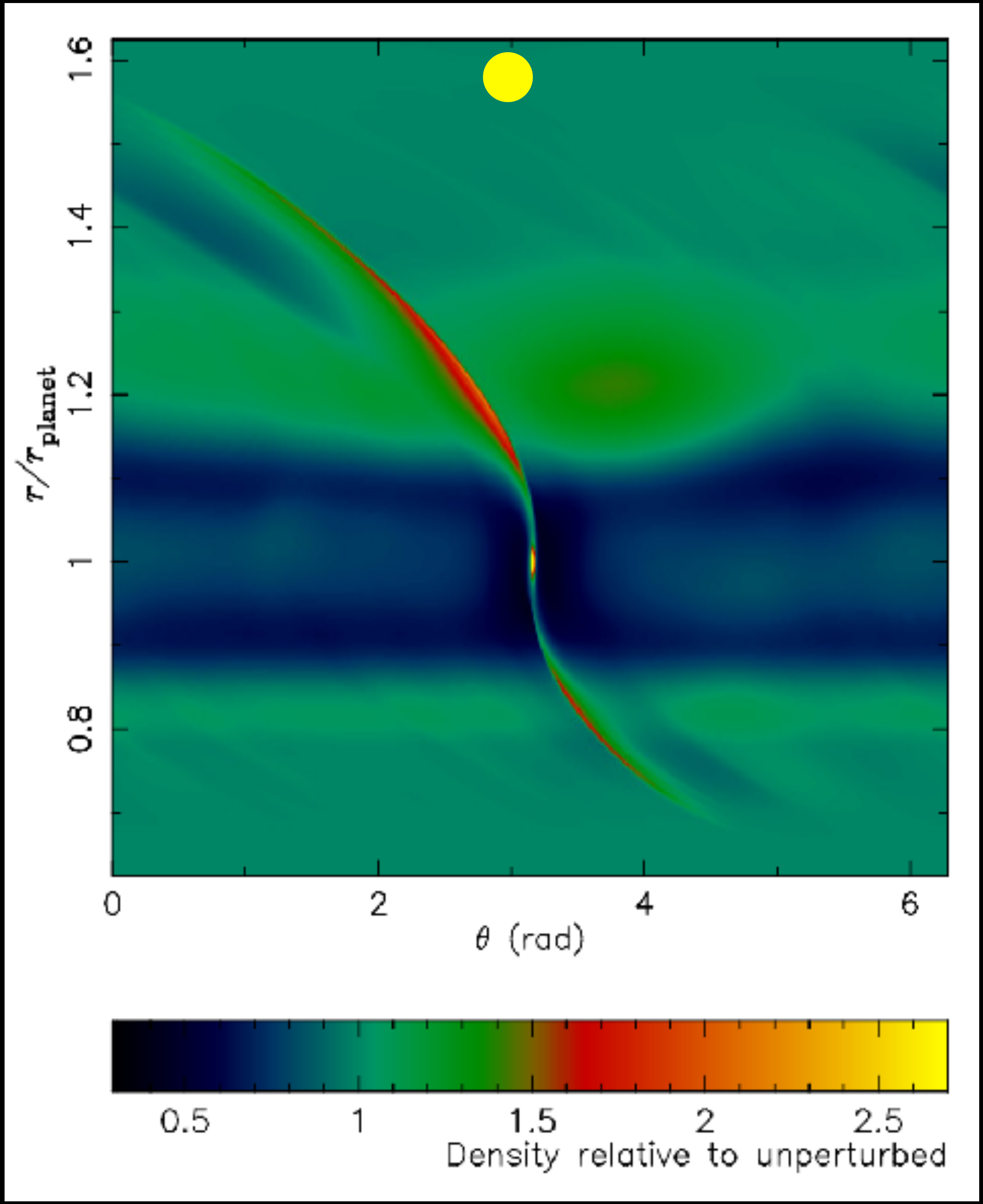


Lambrechts & Johansen (2012)

Pebble accretion is self-limiting

Above "pebble isolation mass", a planet creates an exterior pressure bump that traps pebbles

(~20 M_E for typical disk at Jup's orbit)

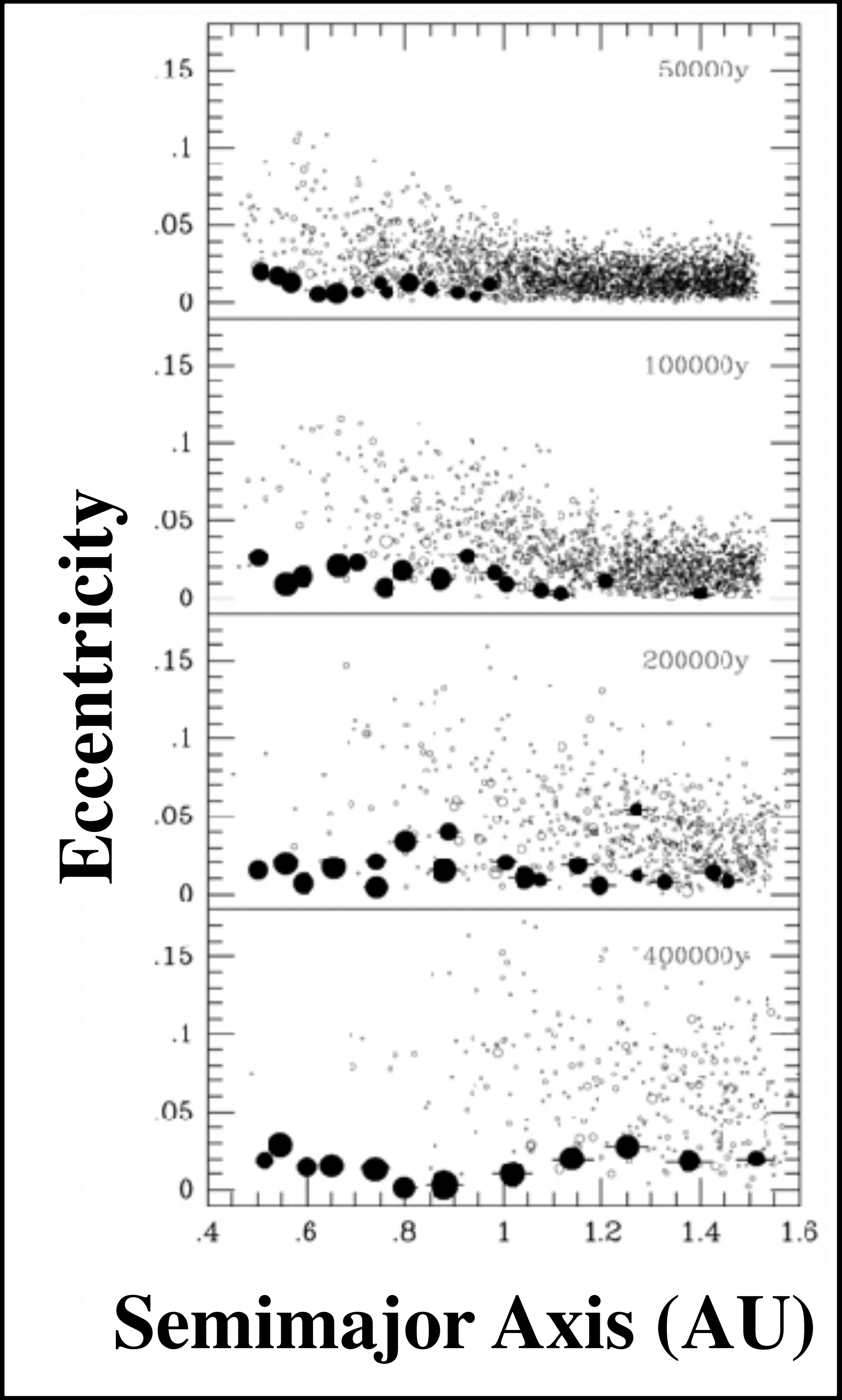


Lambrechts et al (2014); also Bitsch et al (2018)

Planetesimal accretion

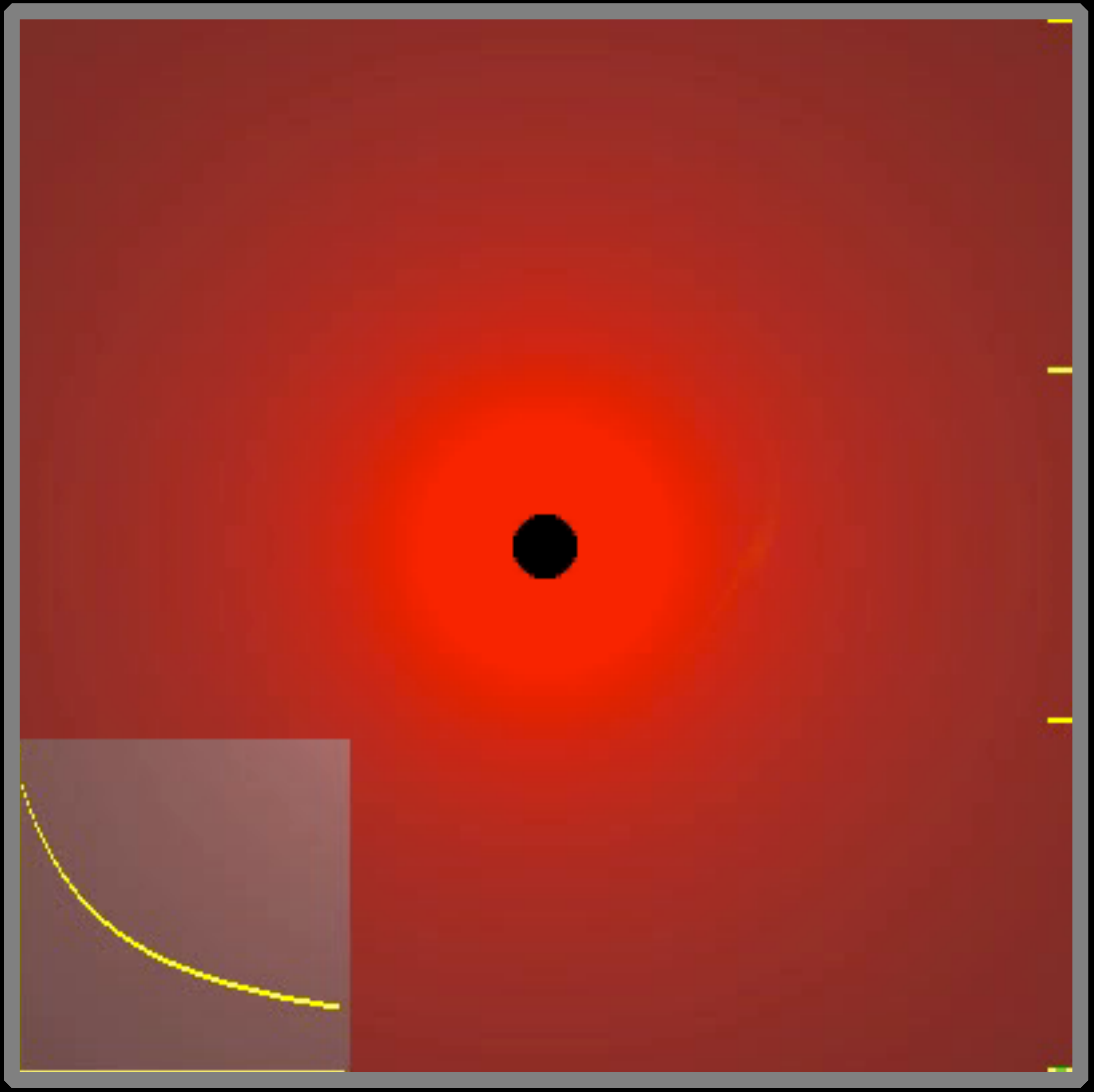
(dominates in terrestrial planet region)

- Runaway growth: big embryos get bigger faster by eating planetesimals



Kokubo & Ida 2002

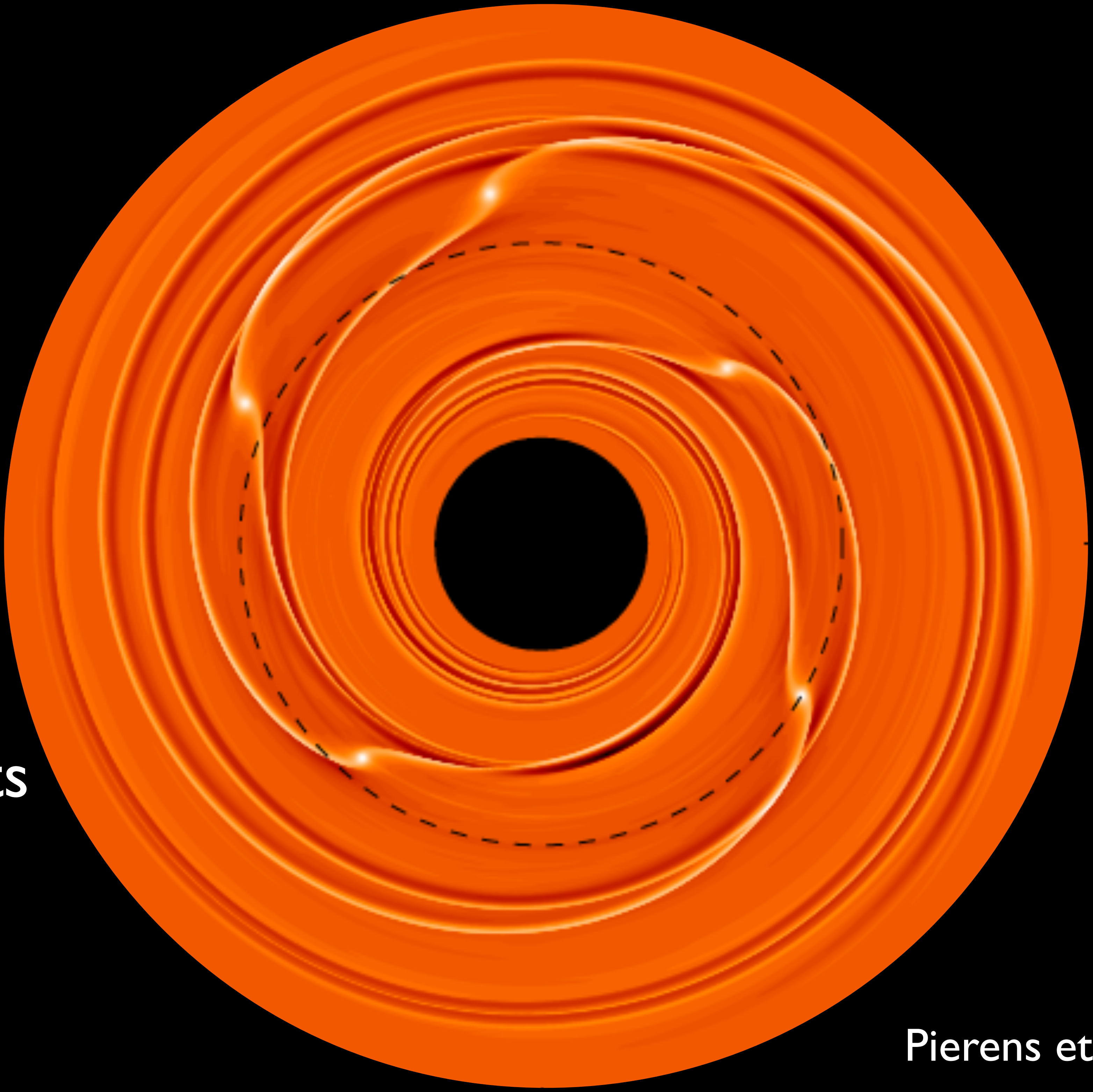
Gravitational planet-disk interaction: orbital migration



P. Armitage

Type I migration

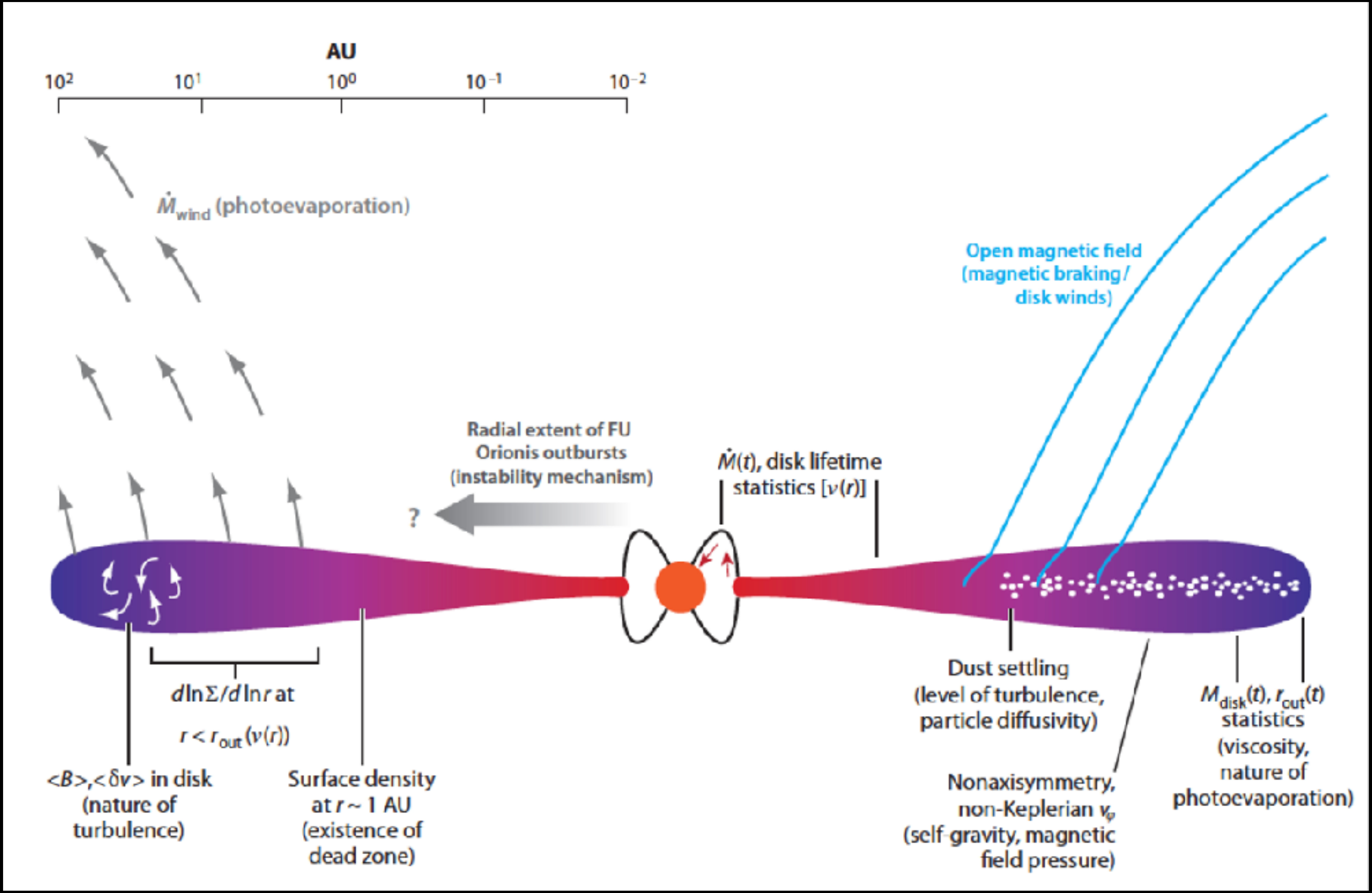
Matters for
Mp >~ MEarth



More massive planets
migrate faster

Pierens et al (2013)

Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Baruteau et al 2014; Kley & Nelson 2014



Armitage 2011

Migration stops at the inner edge of the disk

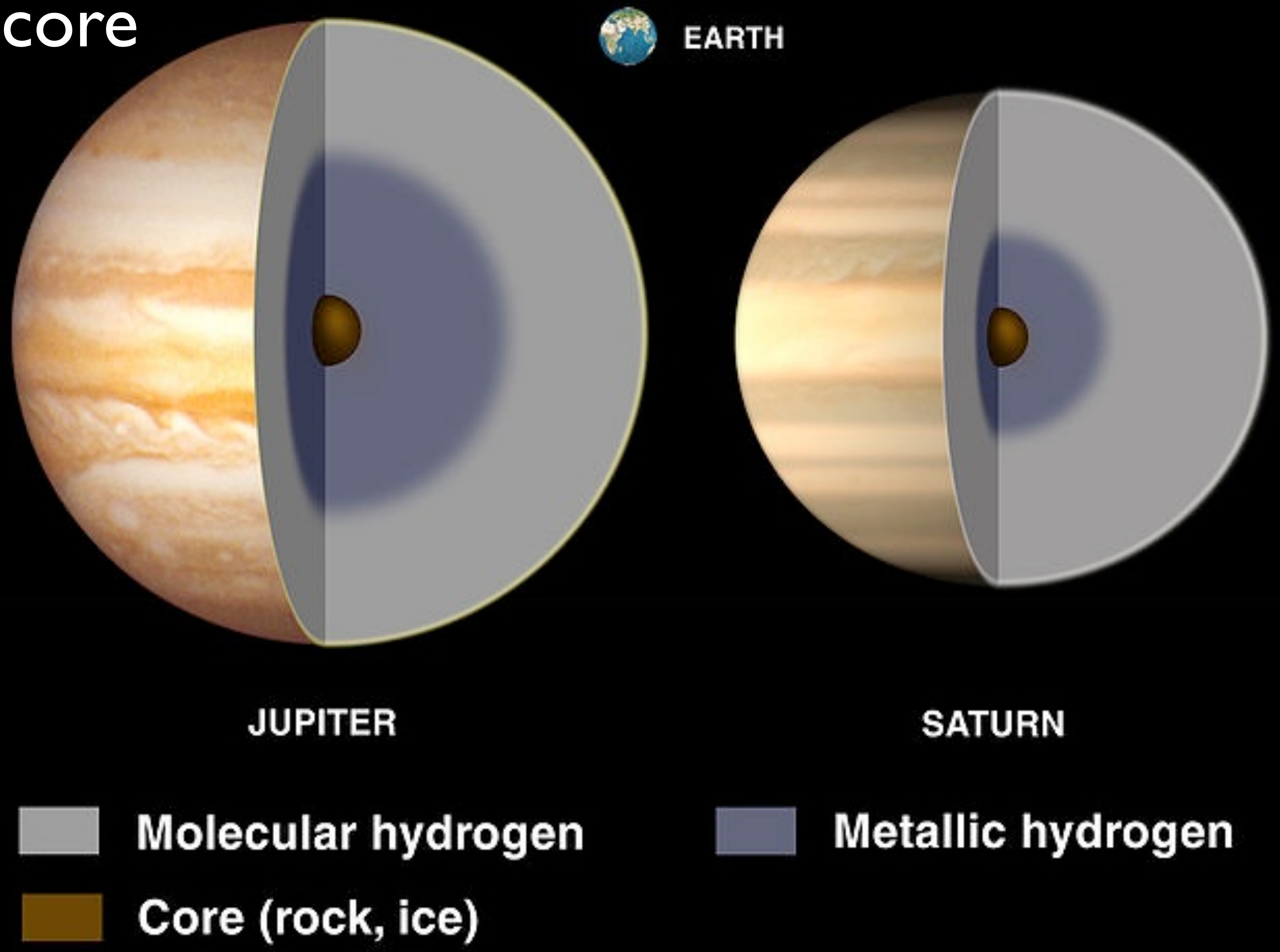
Masset et al (2006)

also Romanova & Lovelace (2006); Flock et al (2017)

Core accretion

growth of a large
solid core

gas accretion

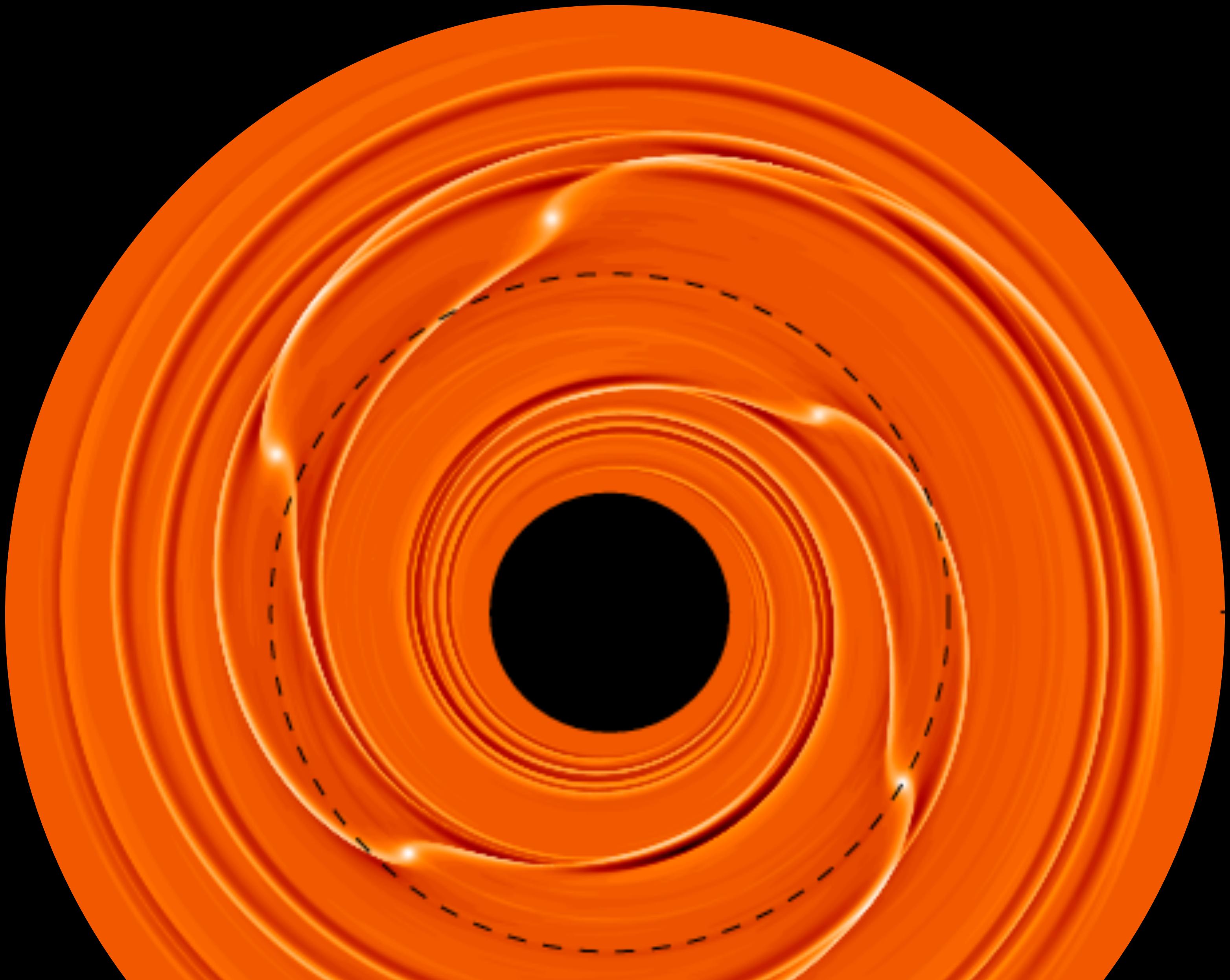


Core migration accretion

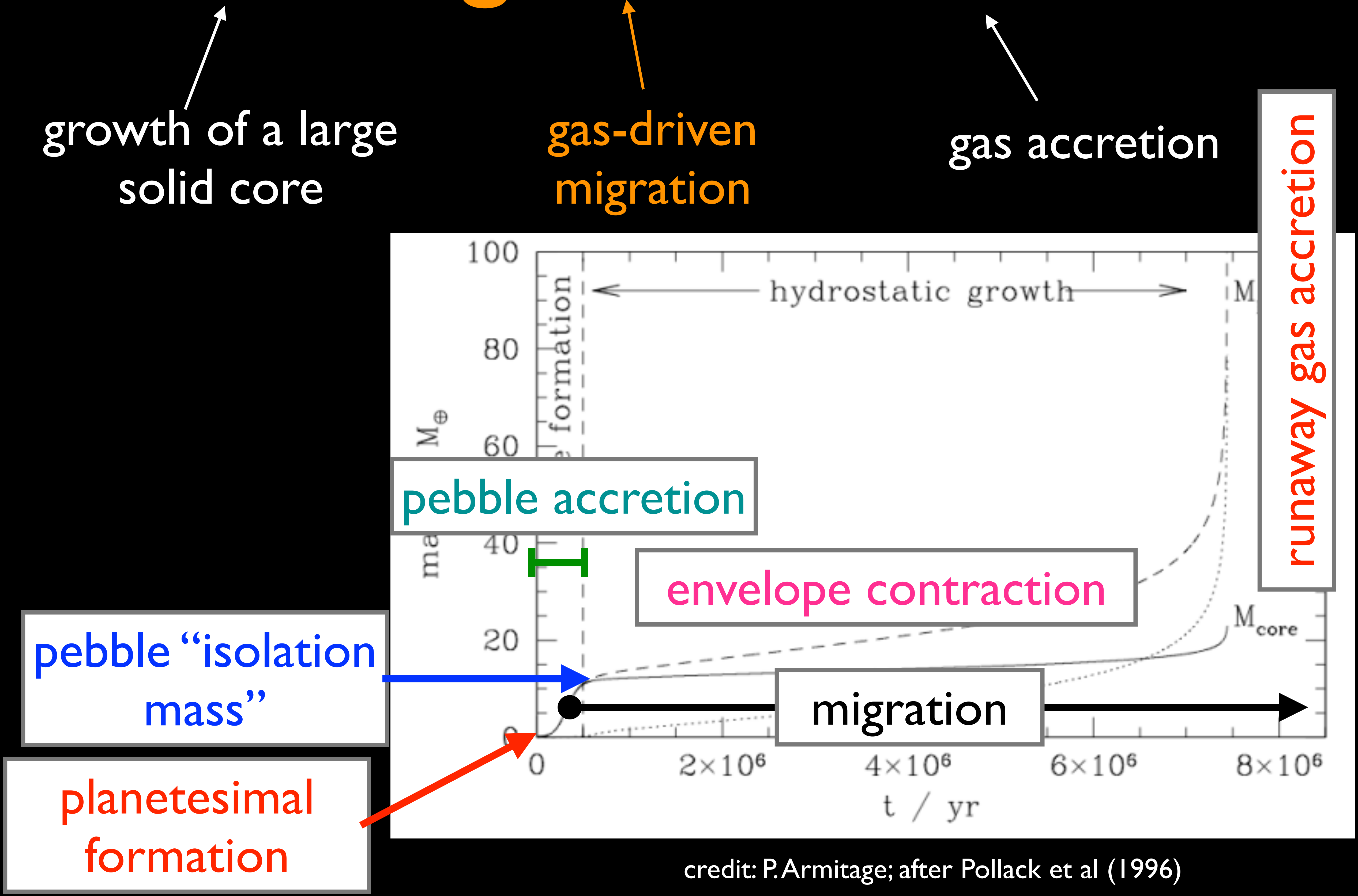
growth of a large
solid core

gas-driven
migration

gas accretion



Core migration accretion



growth of a large solid core

gas-driven migration

gas accretion

runaway gas accretion

pebble accretion

envelope contraction

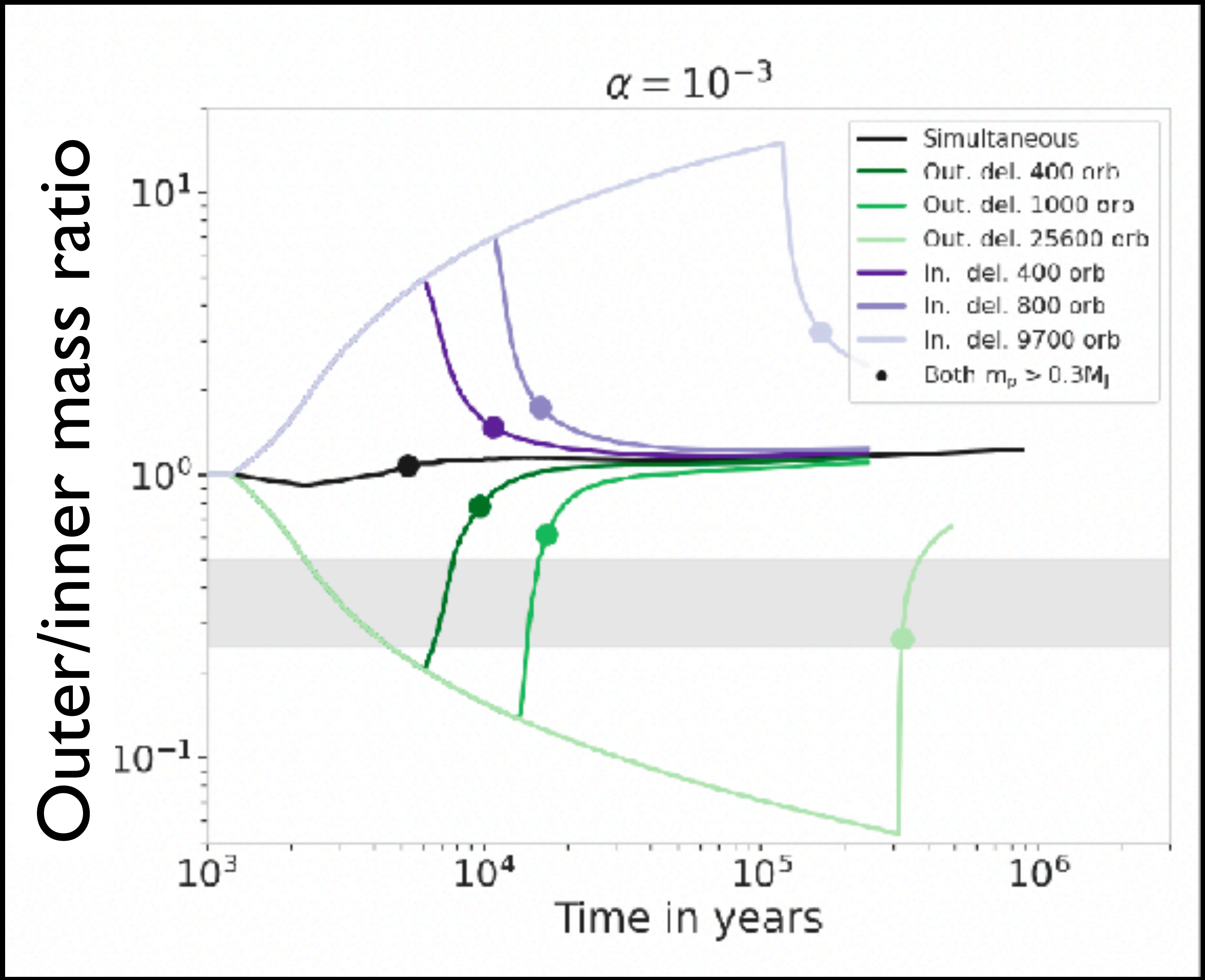
pebble "isolation mass"

migration

planetesimal formation

credit: P. Armitage; after Pollack et al (1996)

Two planets growing in the same disk tend to end up at ~the same mass

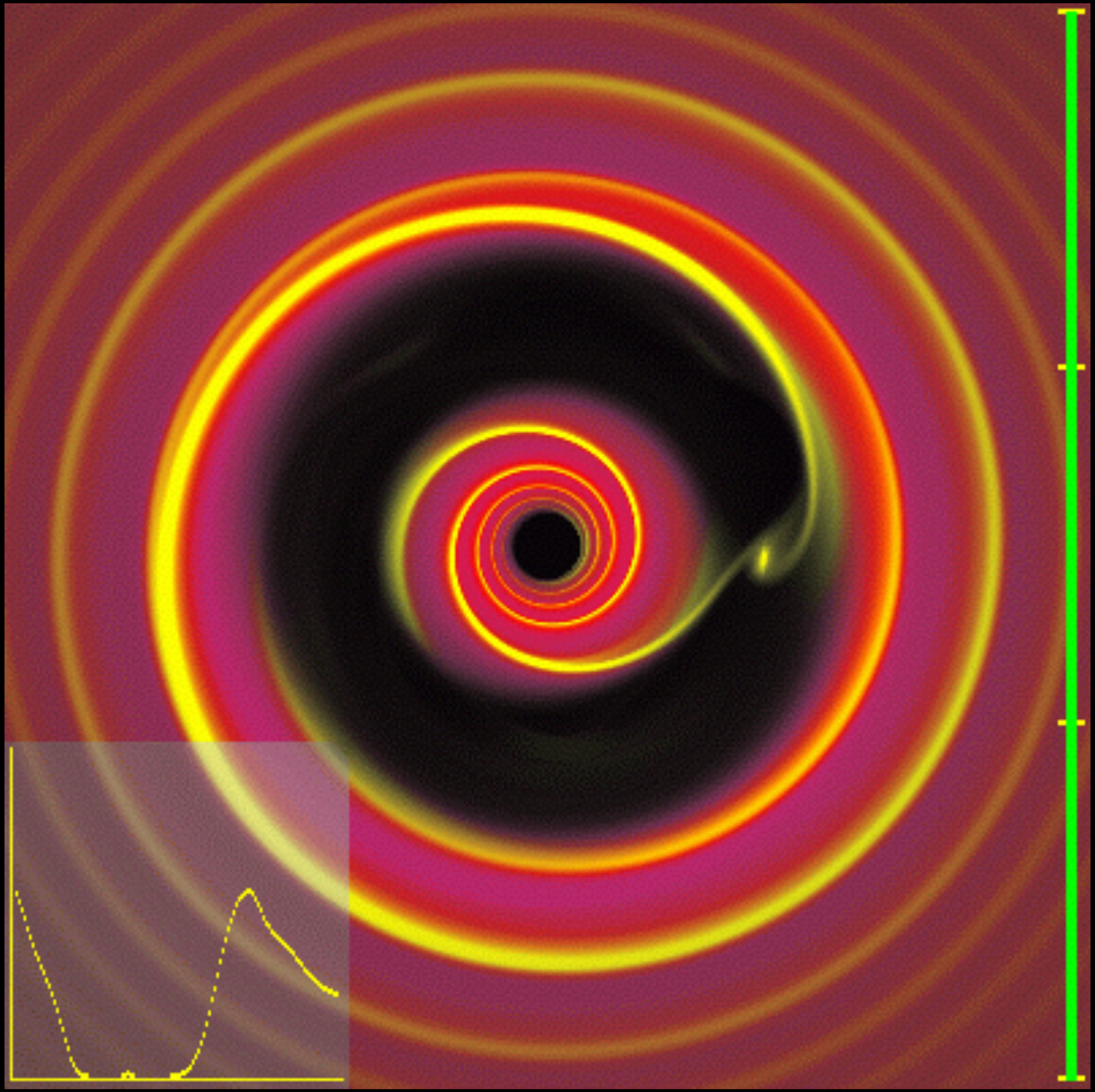


Jup/Sat mass ratio

Bergez-Casalou et al 2022

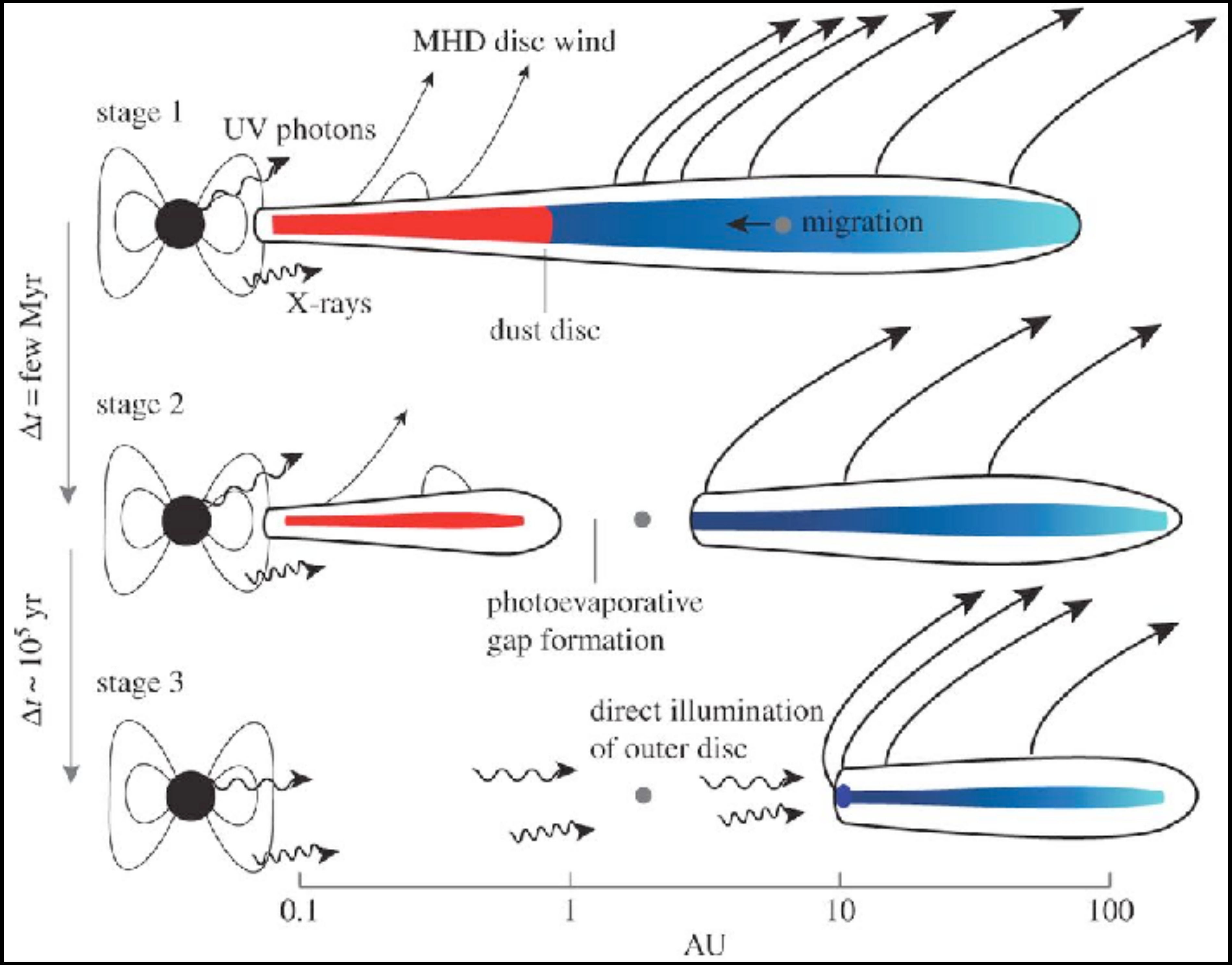
Type 2 migration

- Carve gap in disk
- Migration almost always inward
- Special cases: 2+ planets can migrate outward (e.g., Grand Tack model)



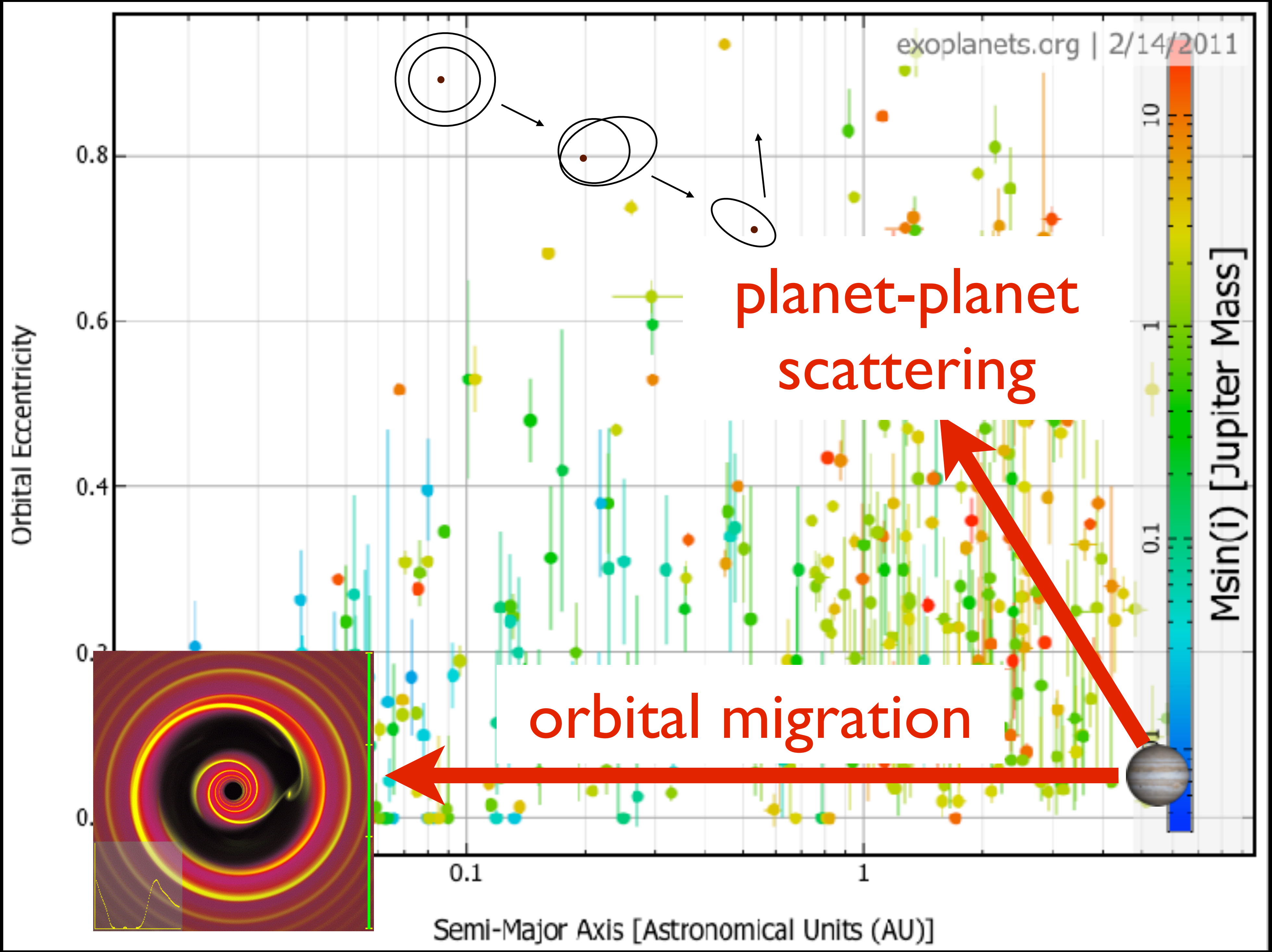
P. Armitage

Inside-out photo-evaporation of gaseous disk



Armitage (2010)

Giant exoplanets



planet-planet scattering

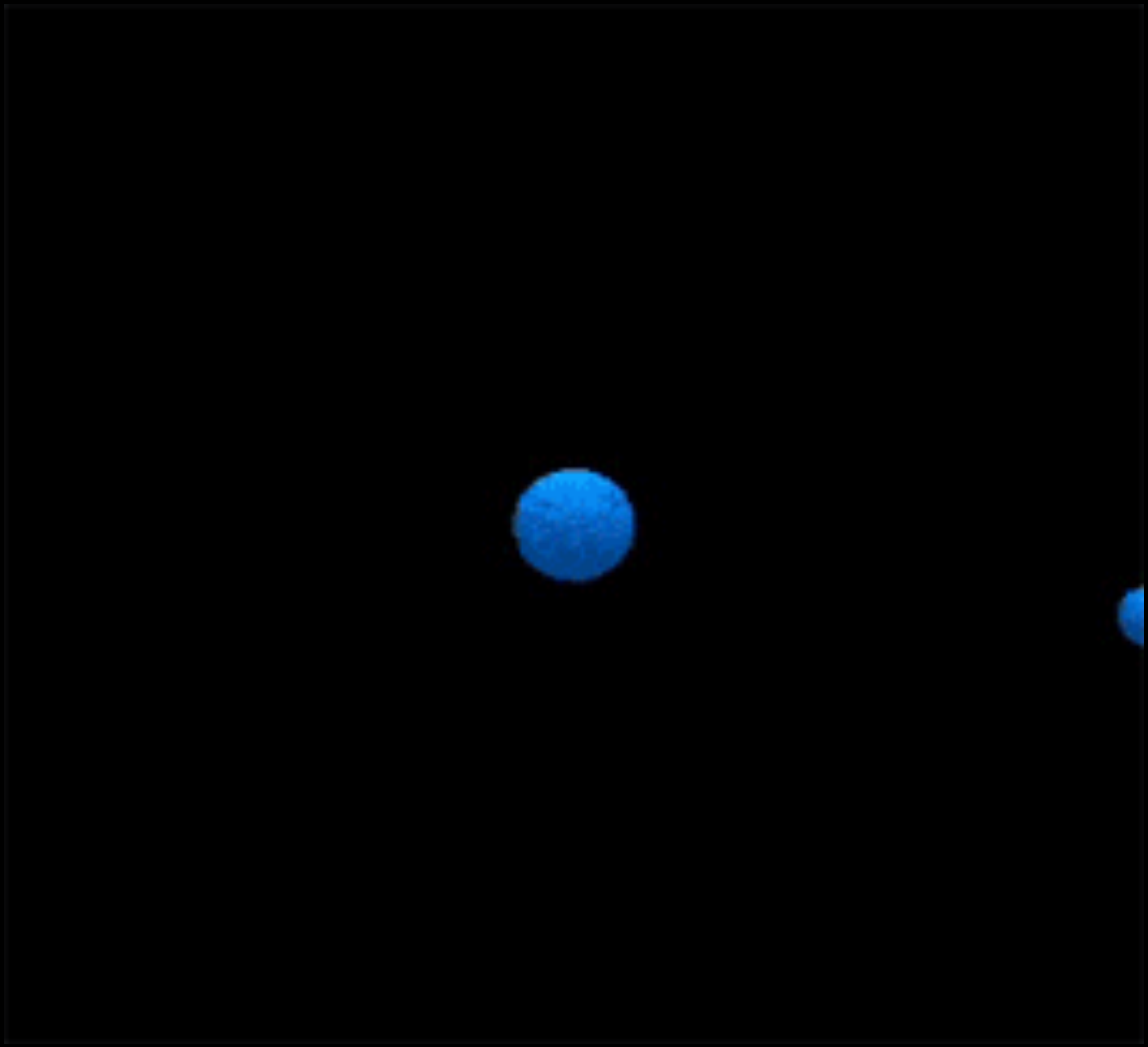
orbital migration

Wright et al 2011

Planet-planet scattering

Credit: Eric Ford

Giant impacts between embryos

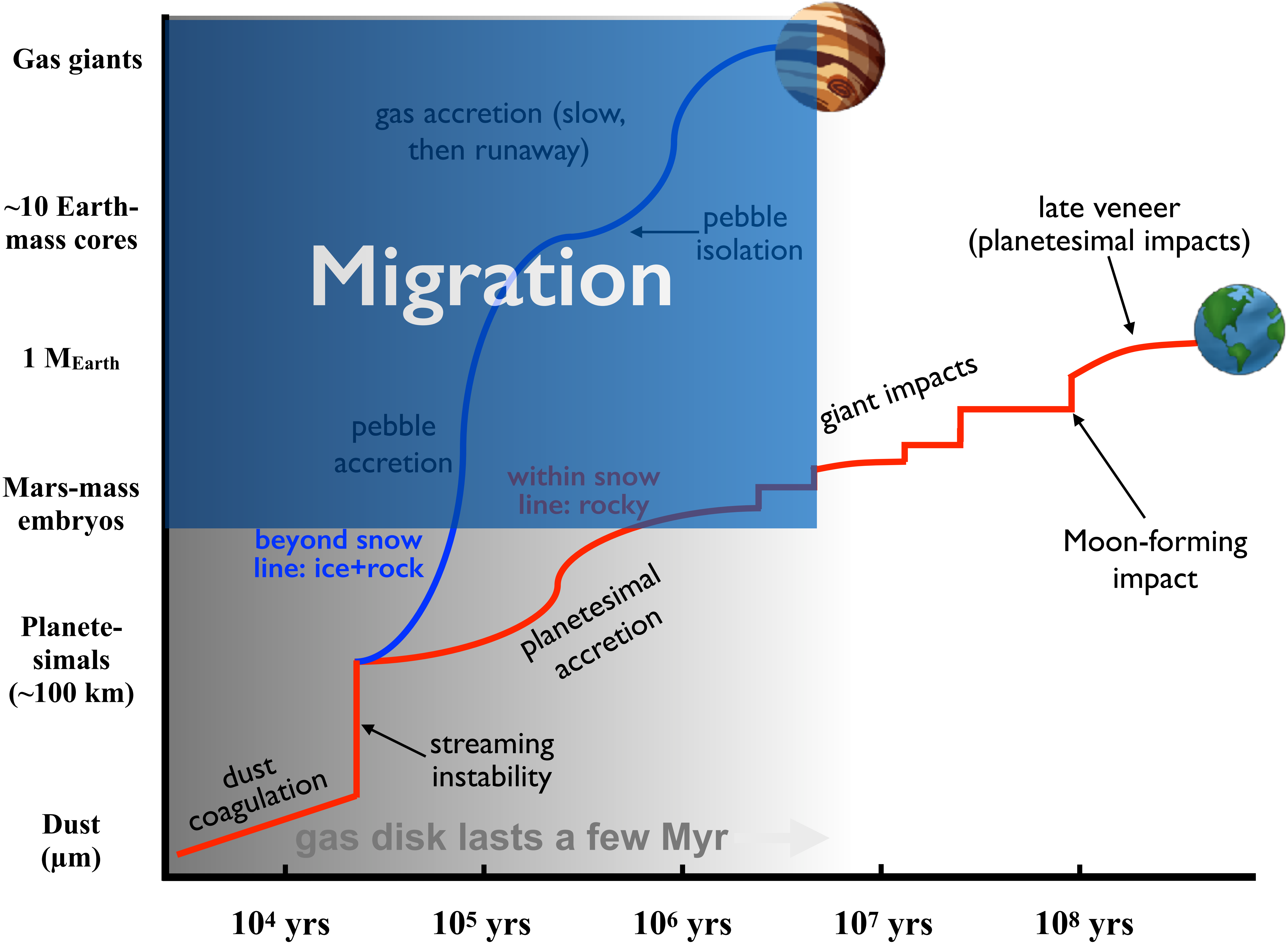


credit: Agnor & Asphaug

Final planetesimal impacts: “late accretion/veneer”

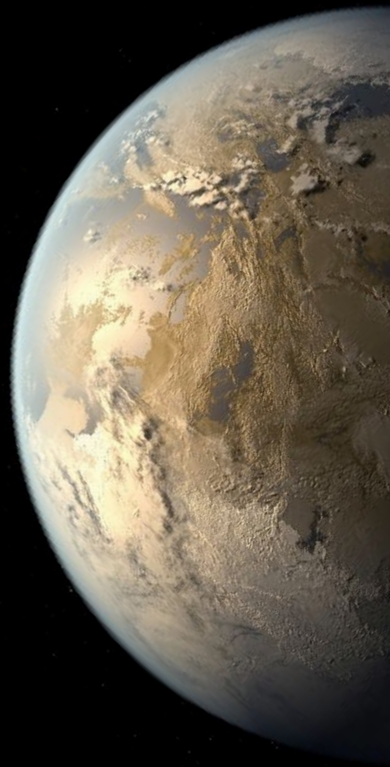
Estimate: ~0.5% of Earth’s mass accreted from planetesimals after Moon-forming impact

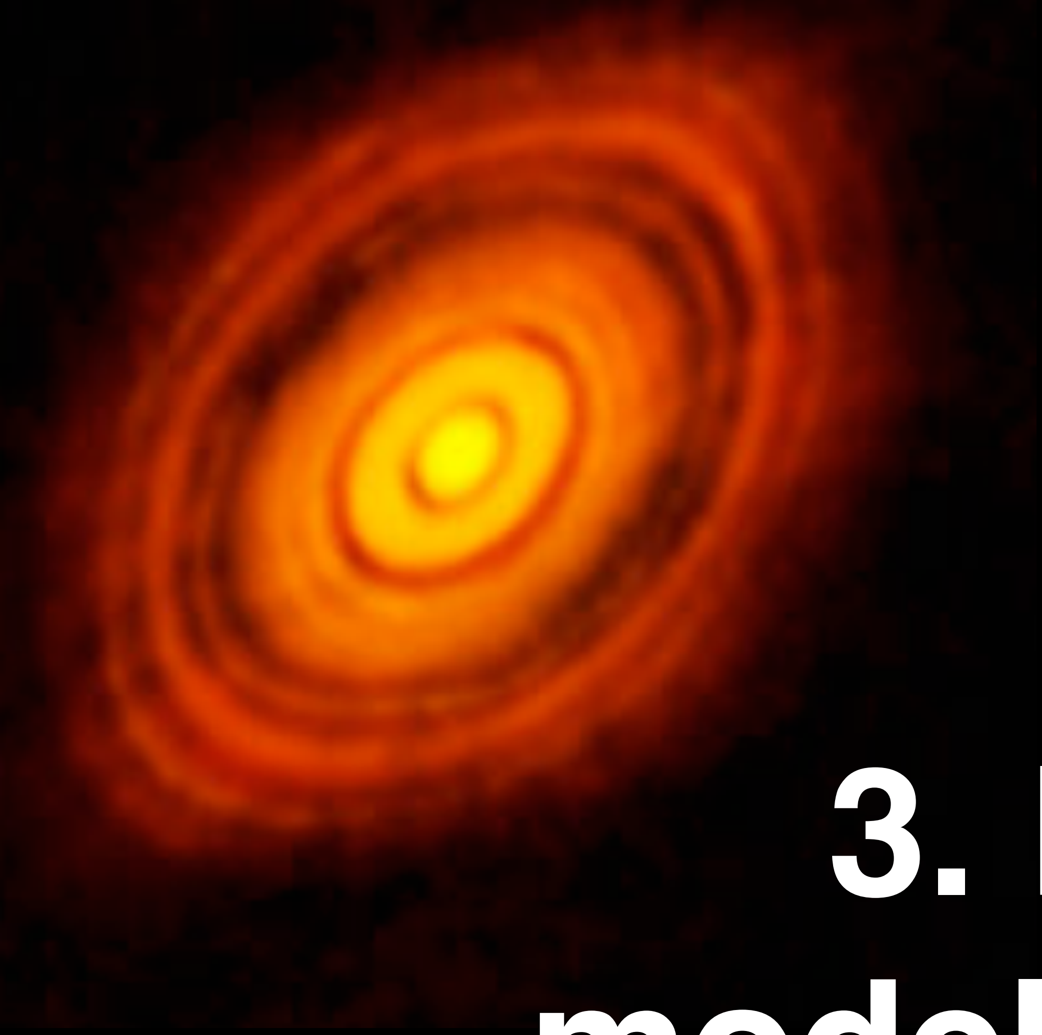
(Day et al 2007; Walker 2009)


Gas giants
~10 Earth-mass cores
1 MEarth
Mars-mass embryos
Planetesimals (~100 km)
Dust (µm)
gas accretion (slow, then runaway)
pebble isolation
Migration
pebble accretion
within snow line: rocky
beyond snow line: ice+rock
planetesimal accretion
streaming instability
dust coagulation
gas disk lasts a few Myr
giant impacts
late veneer (planetesimal impacts)
Moon-forming impact
10^4 yrs
10^5 yrs
10^6 yrs
10^7 yrs
10^8 yrs

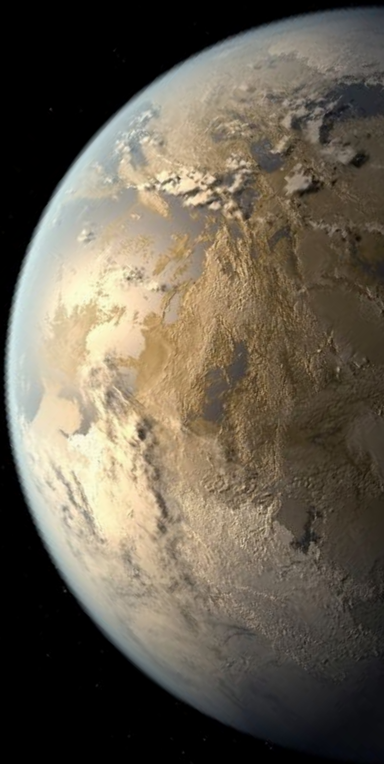
Summary: Stages of planet formation

- planetesimal formation
- pebble/planetesimal accretion
- orbital migration
- giant impacts
- gas accretion
- giant planet scattering

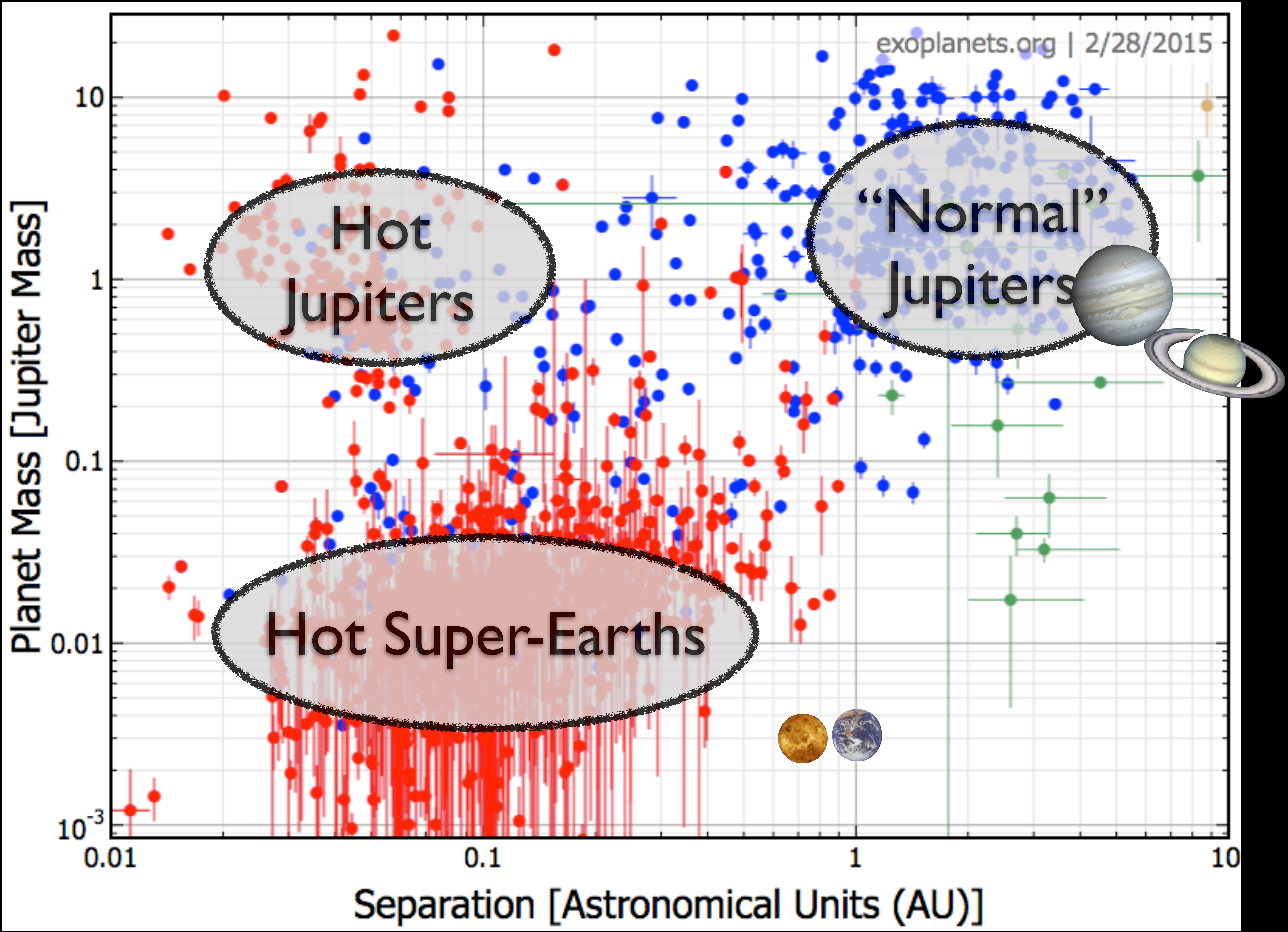


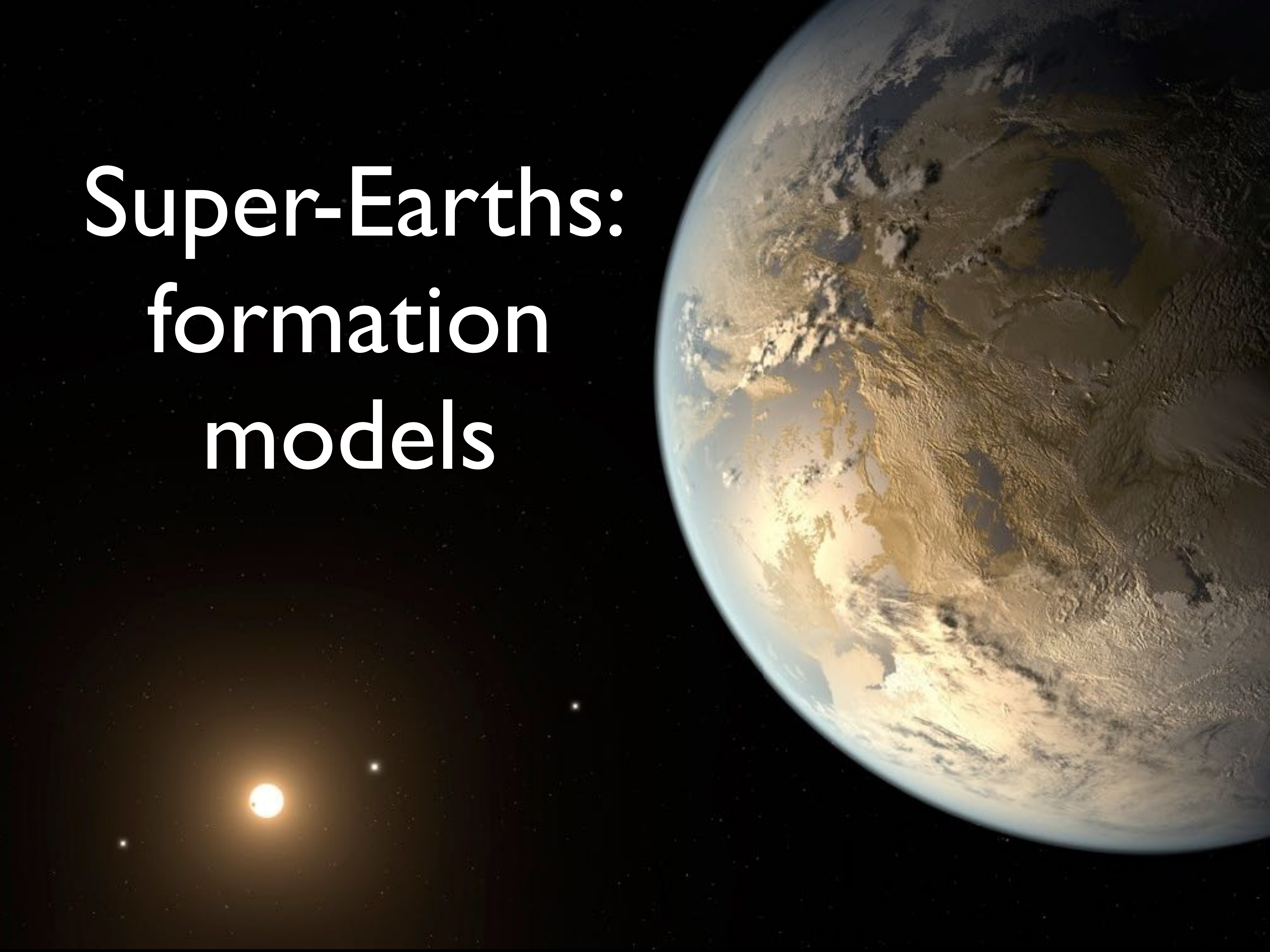


3. Formation models: exoplanets



- Close-in “super-Earths”
- Gas giants


exoplanets.org | 2/28/2015
Hot Jupiters
"Normal" Jupiters
Hot Super-Earths
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
Separation [Astronomical Units (AU)]



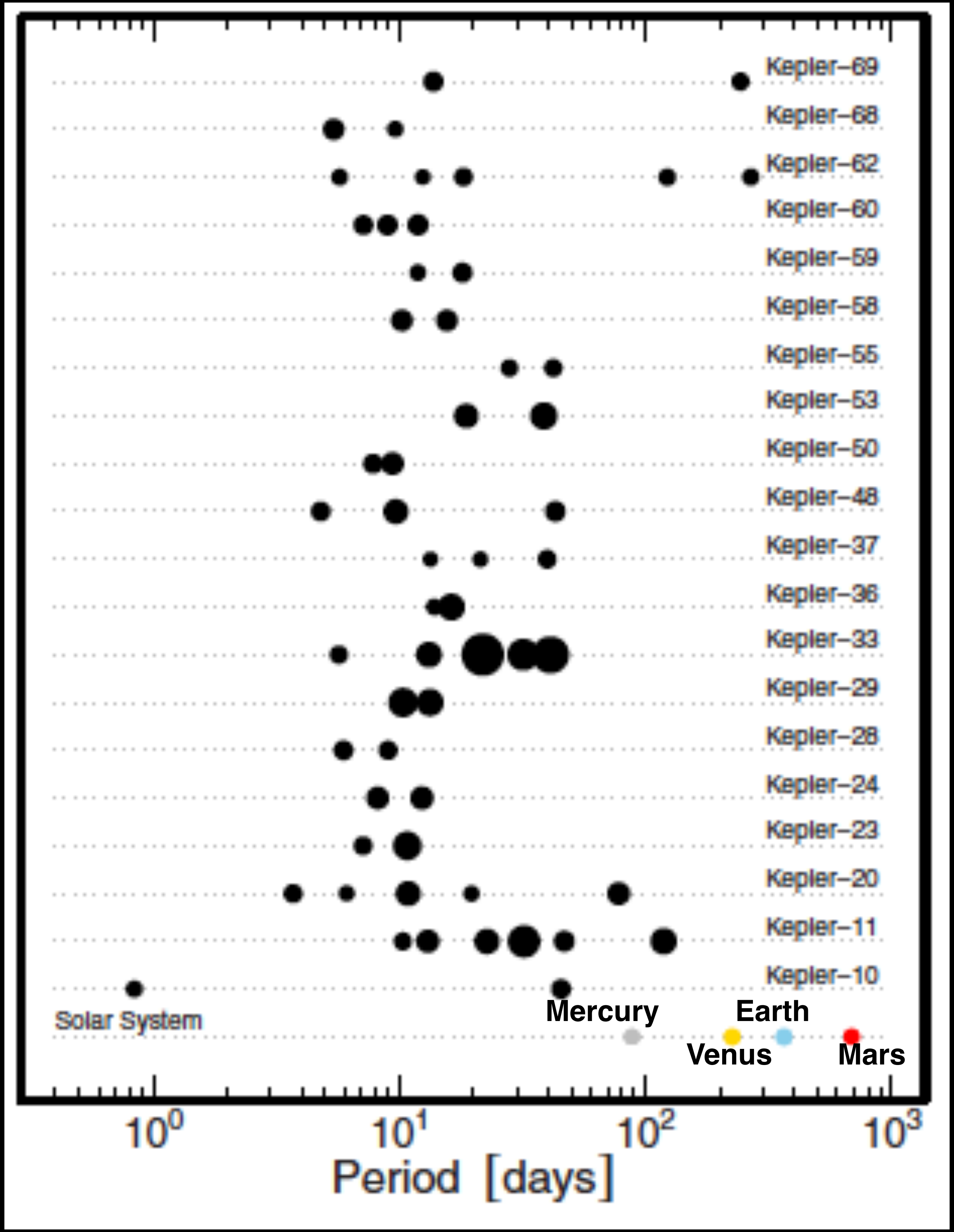
Super-Earths: formation models

Super-Earths and the Solar System

Occurrence rate:

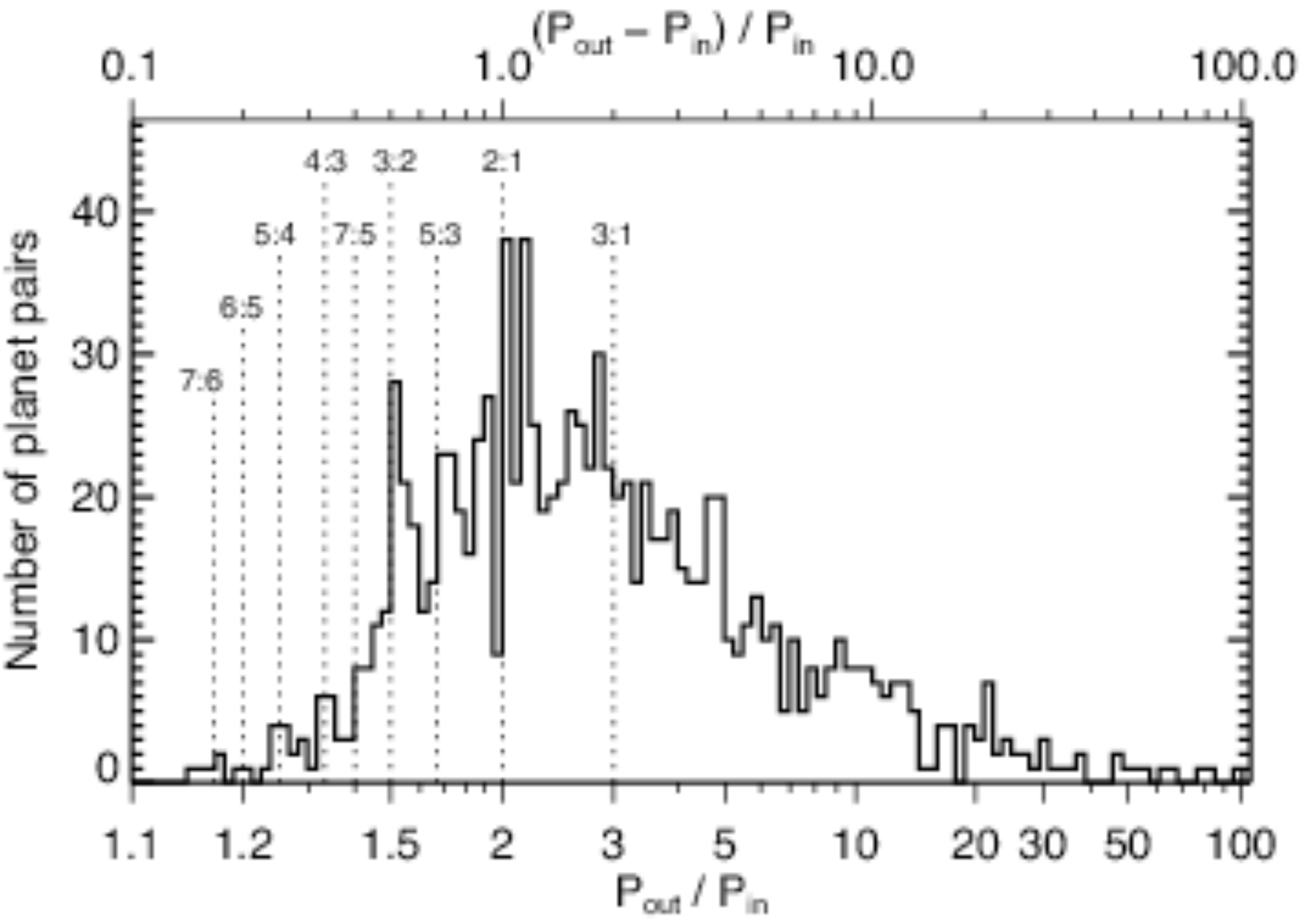
~50%

(Mayor et al 2011; Howard et al 2012; Fressin et al 2013, Mulders et al 2018; many more)



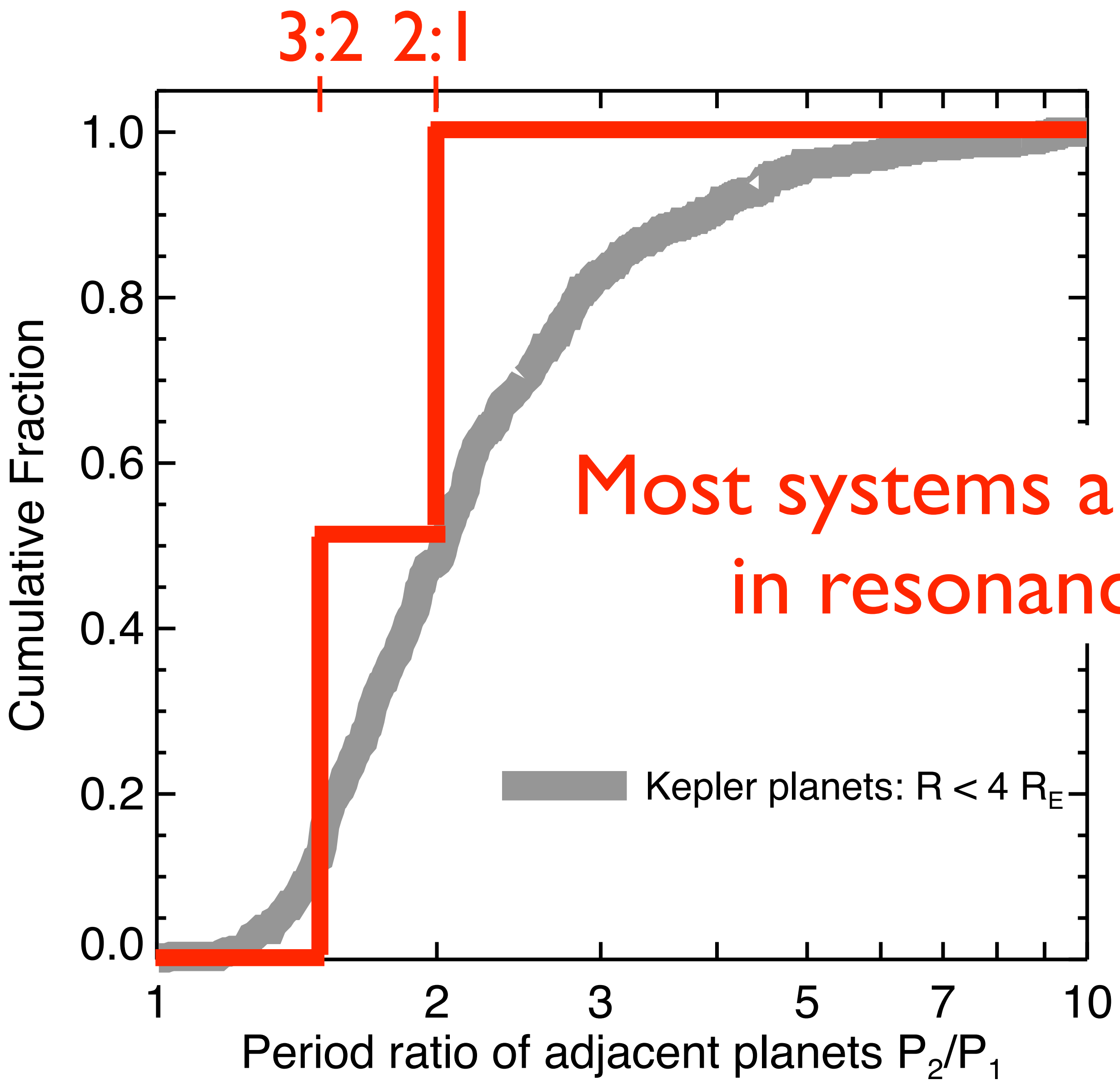
Schlaufman (2014); Kepler data from Batalha et al (2013) and Rowe et al (2014)

Period Ratio distribution



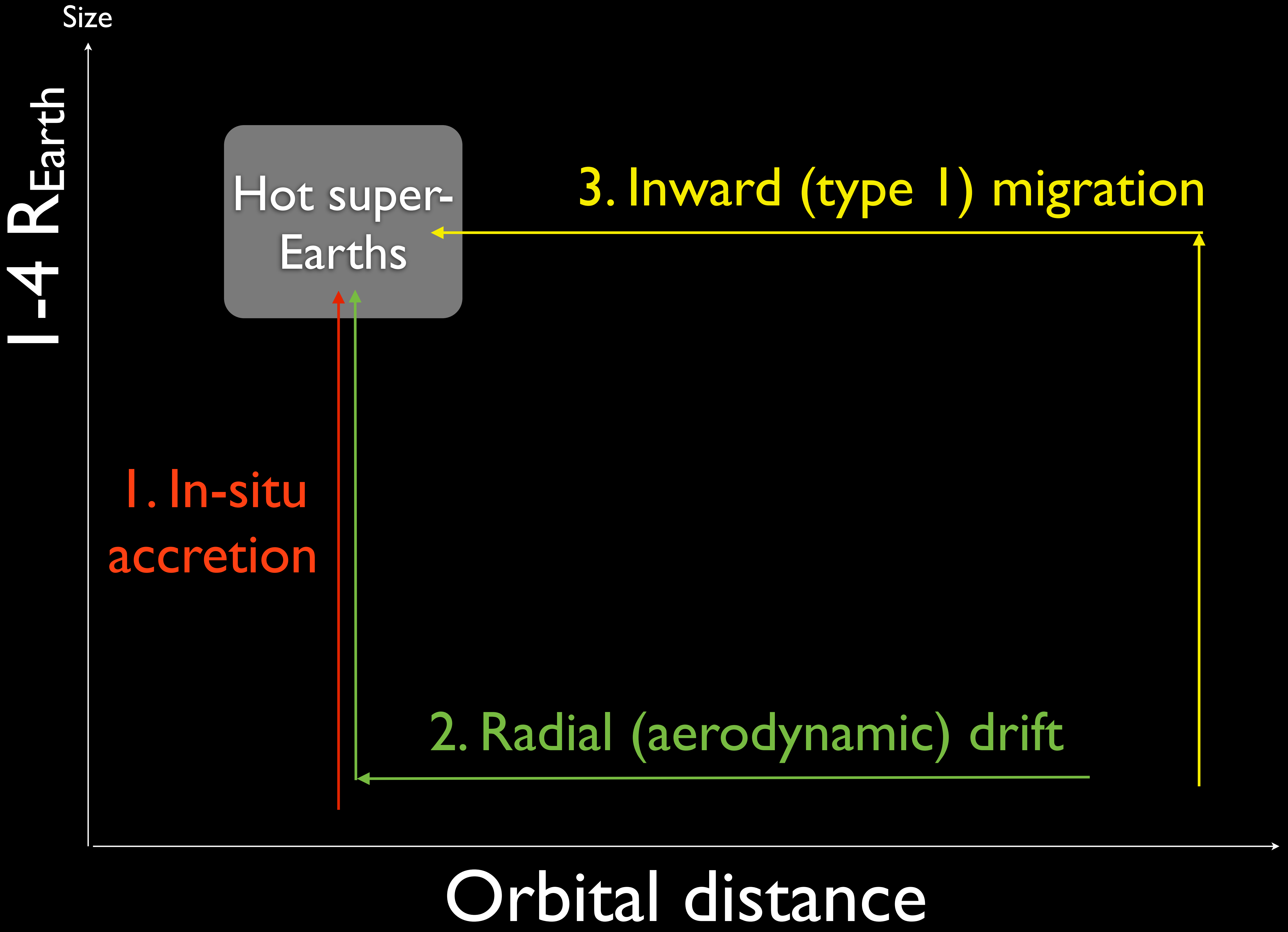
Winn & Fabrycky 2015

Period ratio distribution



Most systems are not in resonance

Lissauer et al (2011); Fabrycky et al (2014)



Size

1-4 R_{Earth}

Hot super-Earths

3. Inward (type 1) migration

1. In-situ accretion

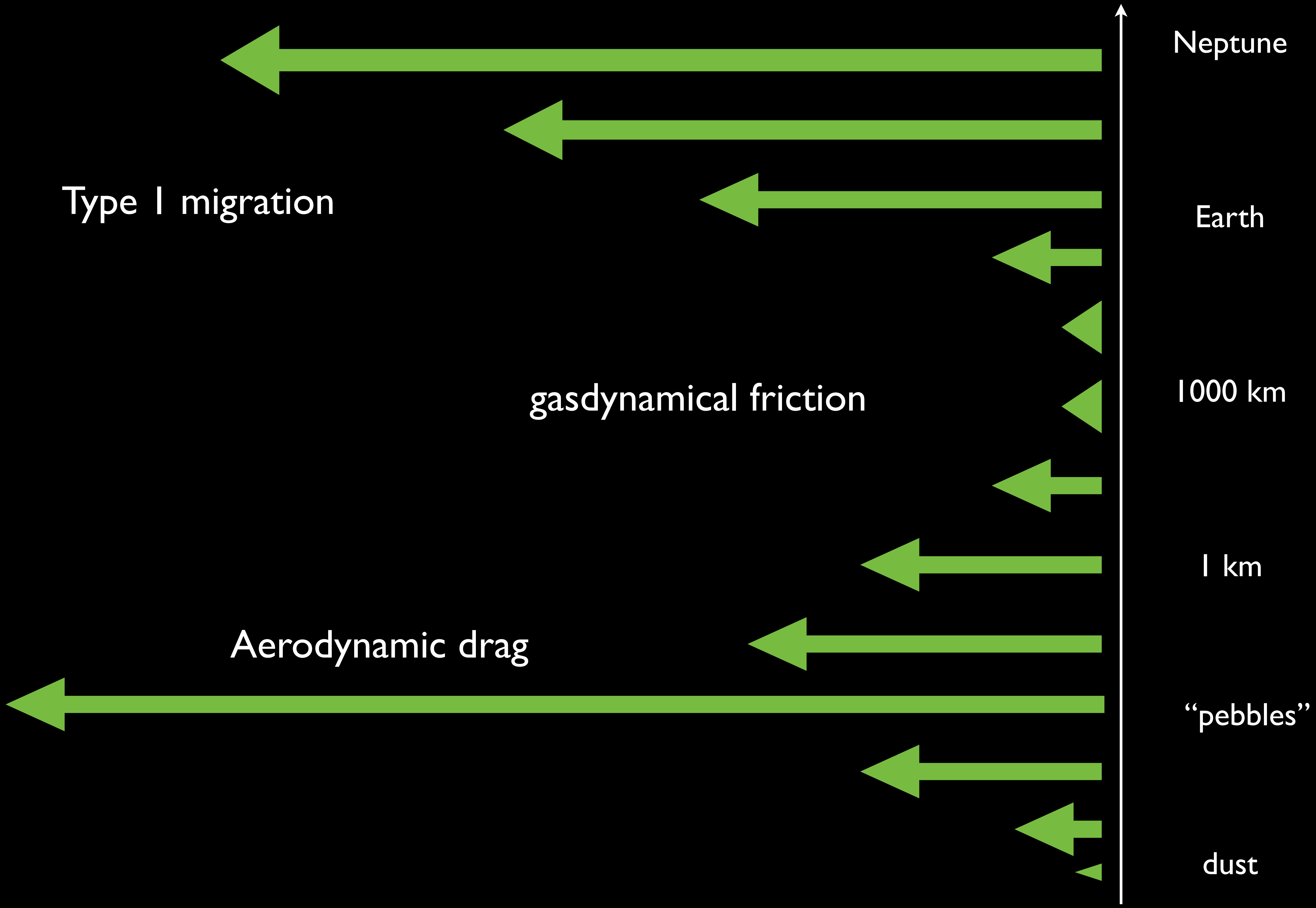
2. Radial (aerodynamic) drift

Orbital distance

Terquem & Papaloizou (2007), McNeil & Nelson (2010), Rogers et al (2011), Swift et al (2013), Cossou et al (2014), Ogihara et al (2015), **Izidoro et al (2017)**

Raymond et al (2008), Chiang & Laughlin (2013)

Gaseous disk causes orbital decay

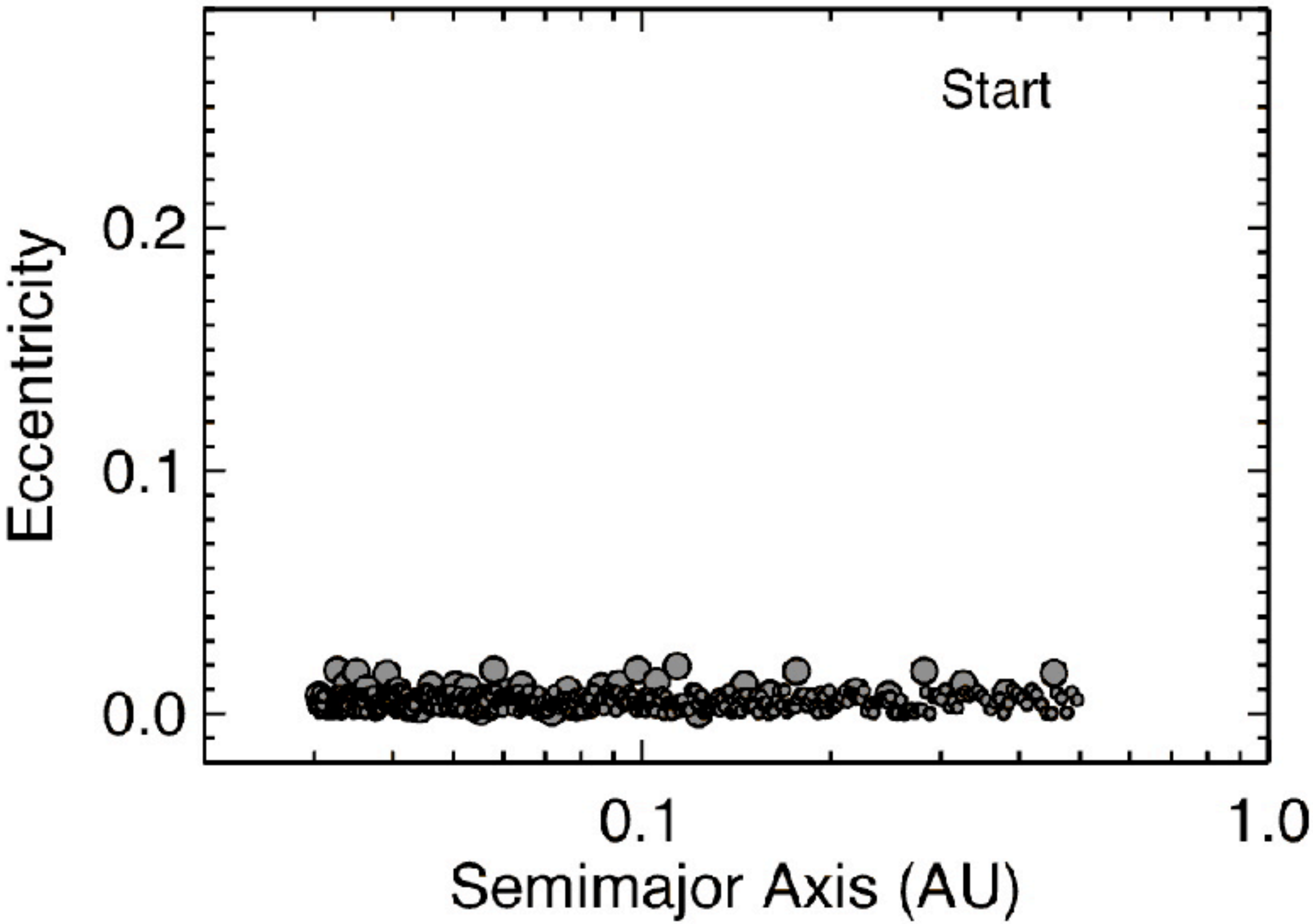


Type 1 migration

gasdynamical friction

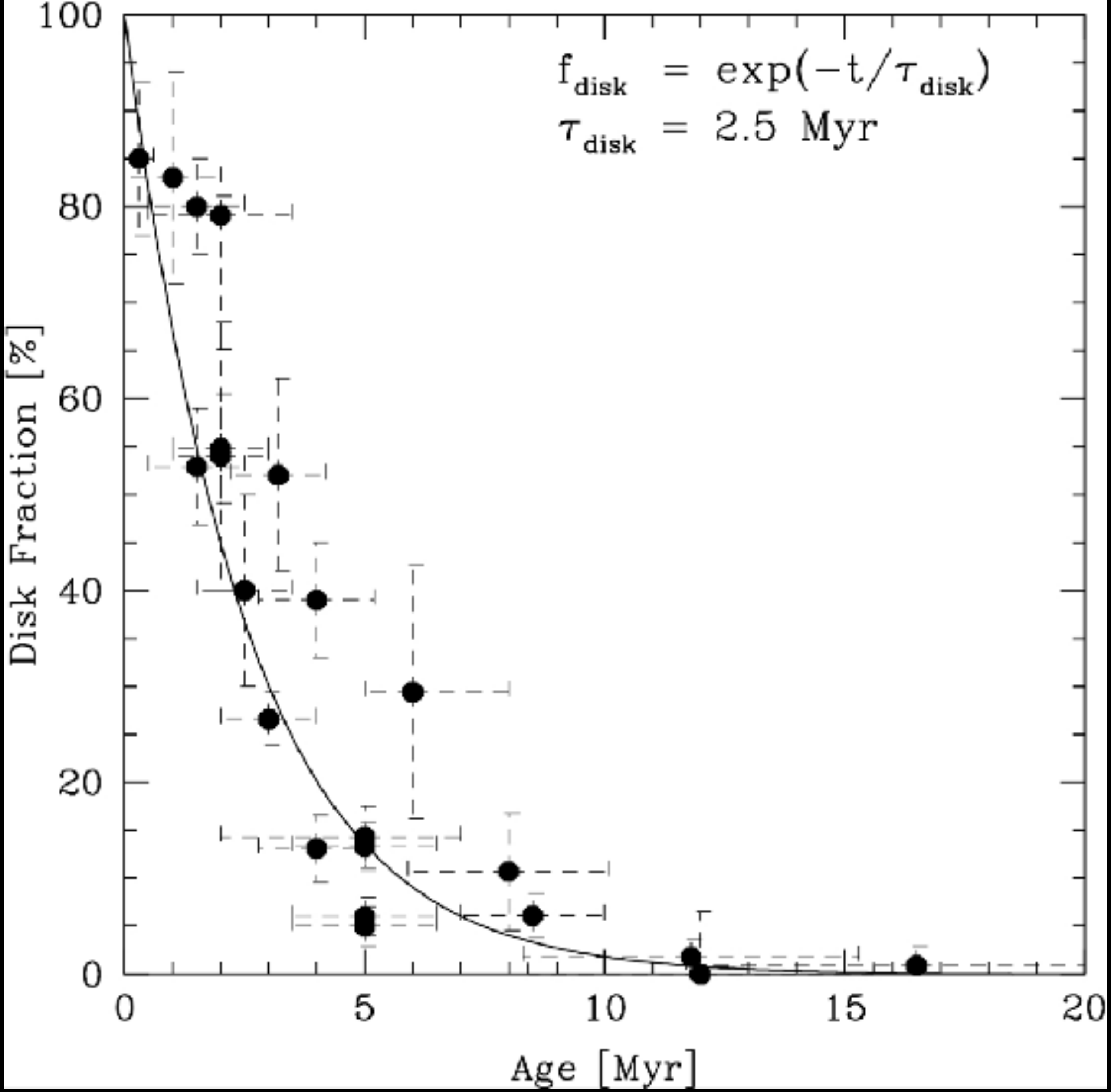
Aerodynamic drag

Growth timescales are very short



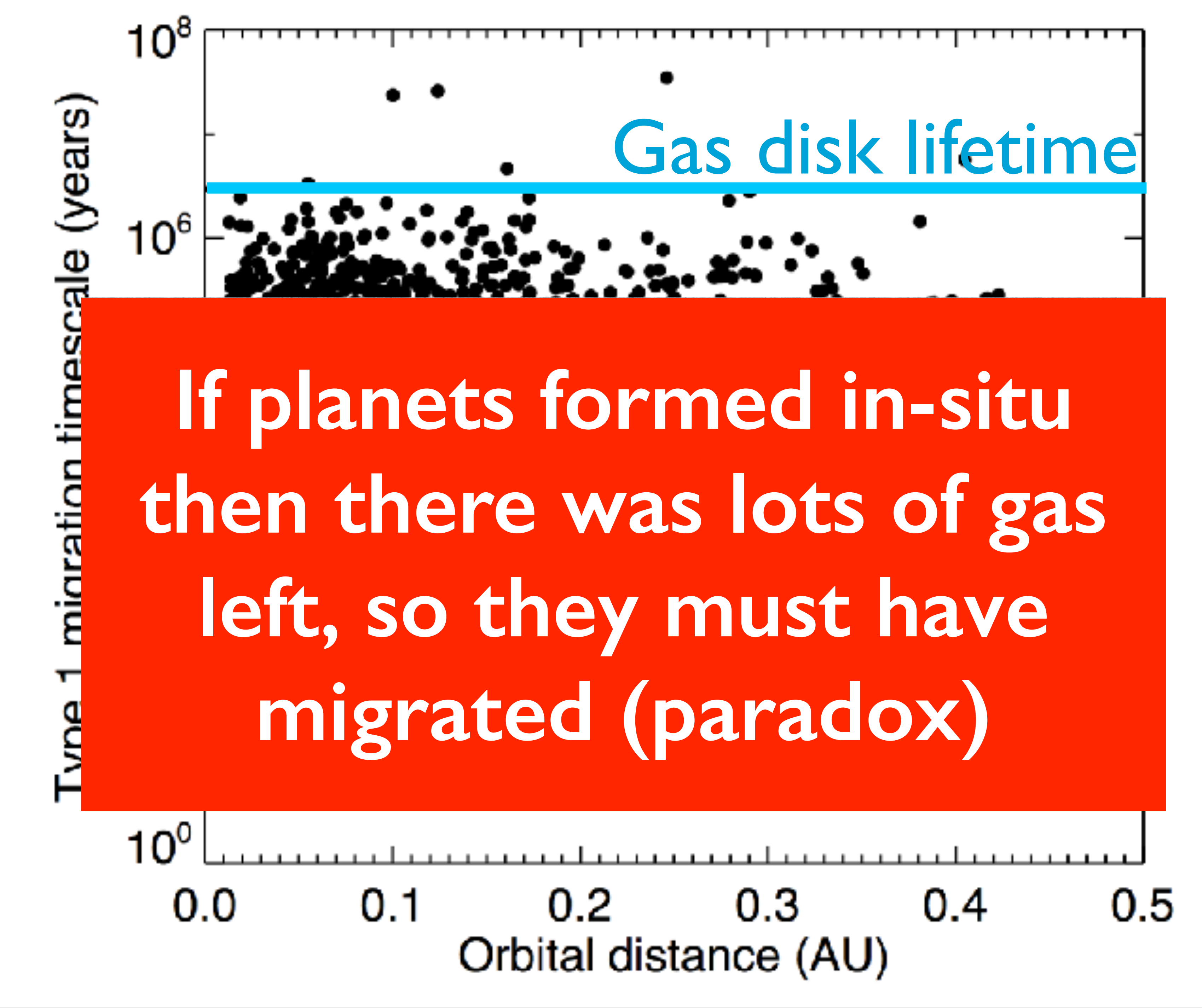
Bolmont et al 2014

Gas disks (inferred from hot dust) dissipate on a few Myr timescale



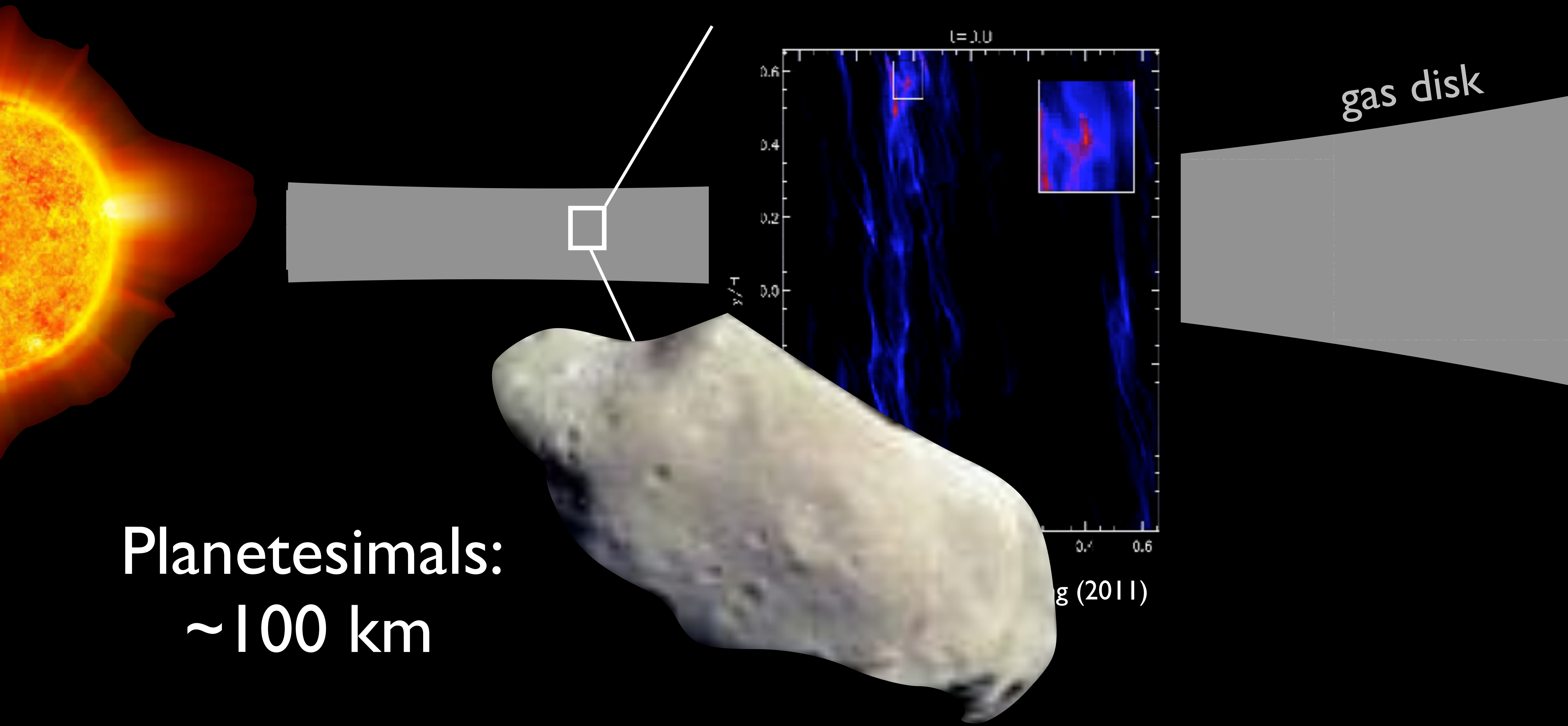
Mamajek 2009

Migration timescales are very short: "in-situ" accretion is impossible



If planets formed in-situ then there was lots of gas left, so they must have migrated (paradox)

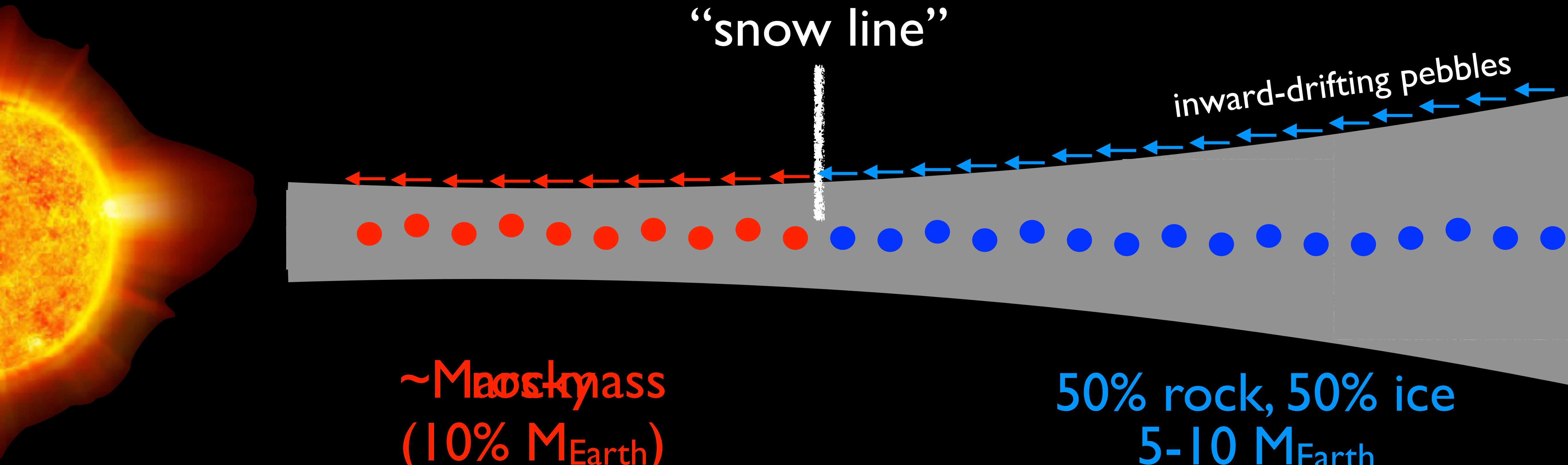
See Inamdar & Schlichting 2015, Schlichting 2014; Ogihara et al 2015; Grishin & Perets 2015



Planetesimals:
~100 km

Planetesimals

Planetary embryos



rocky

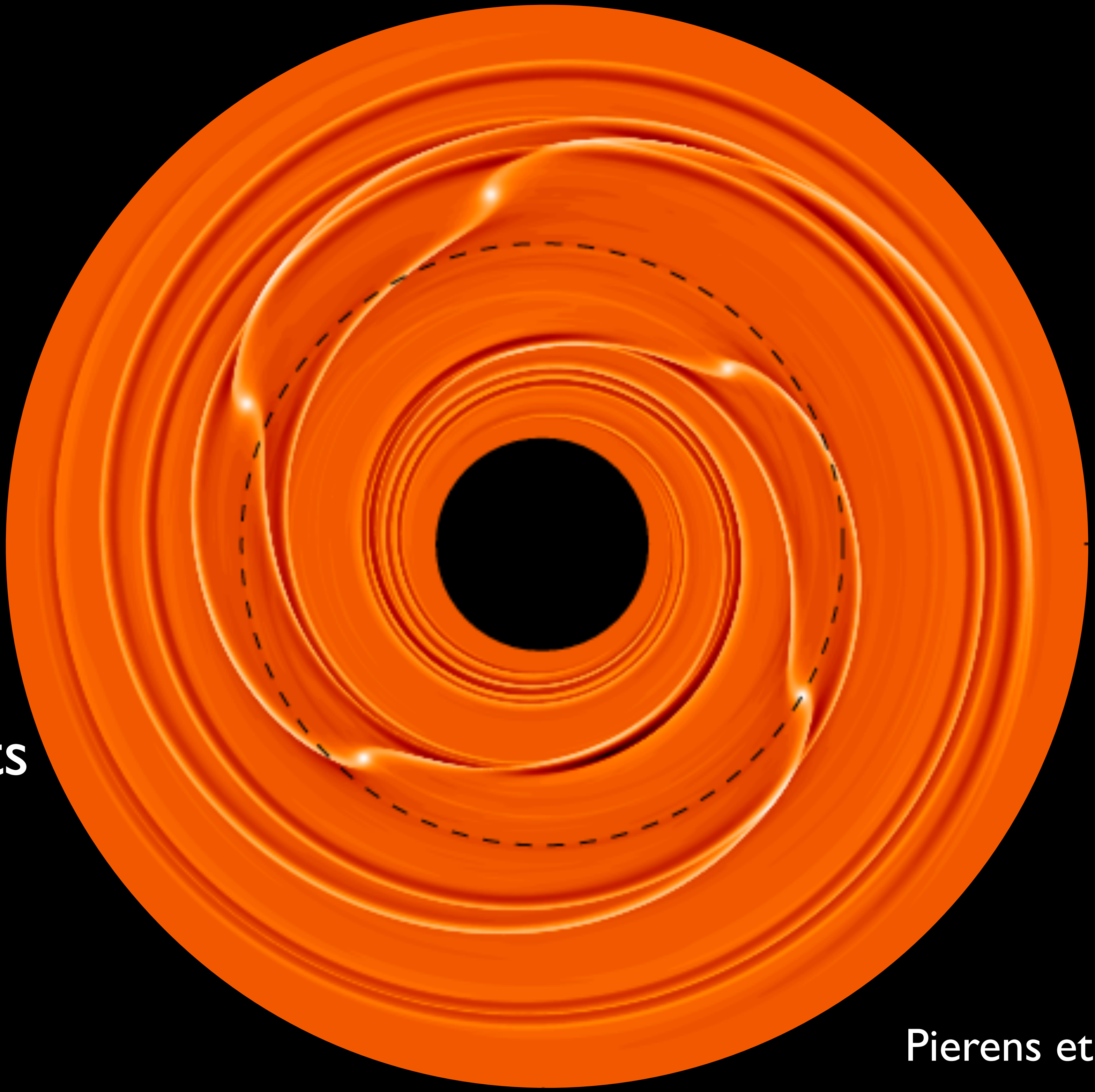
~Mars-mass
(10% M_{Earth})

50% rock, 50% ice
5-10 M_{Earth}

Pebble accretion is far more efficient past the snowline
(Lambrechts et al 2014; Morbidelli et al 2015; Ormel 2017)

All roads lead to migration…

Orbital migration



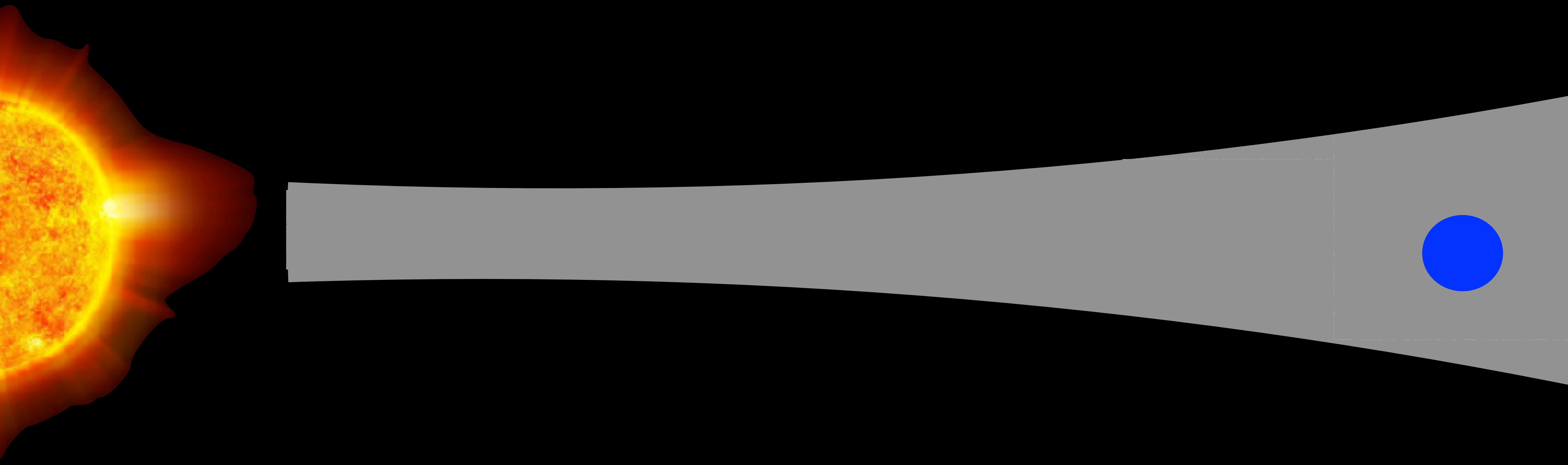
Pierens et al (2013)

Matters for
Mp >~ MEarth

More massive planets
migrate faster

Golreich & Tremaine 1980; Ward 1986, 1997; Kley & Crida 2008; Paardekooper et al 2010, 2011; Pierens et al 2013; Lega et al 2014; Bitsch et al 2014; Kley & Nelson 2014

Migrating planets are trapped at the inner edge of the disk



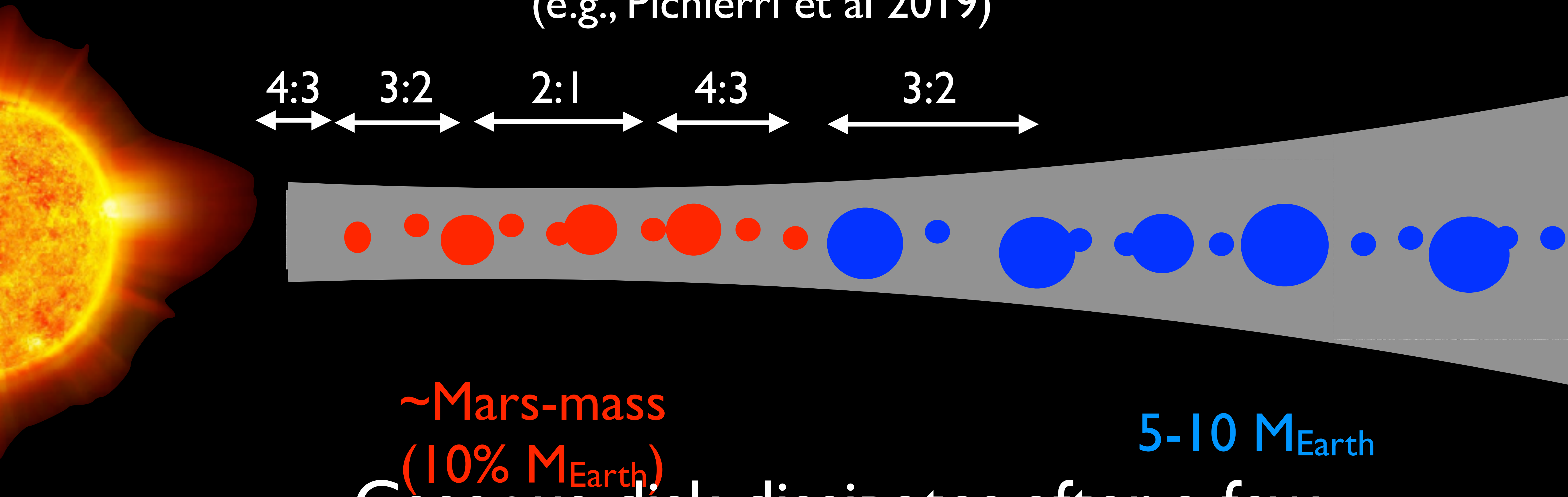
Masset et al (2006); Romanova & Lovelace (2006)

Planetary embryos

Resonant chain

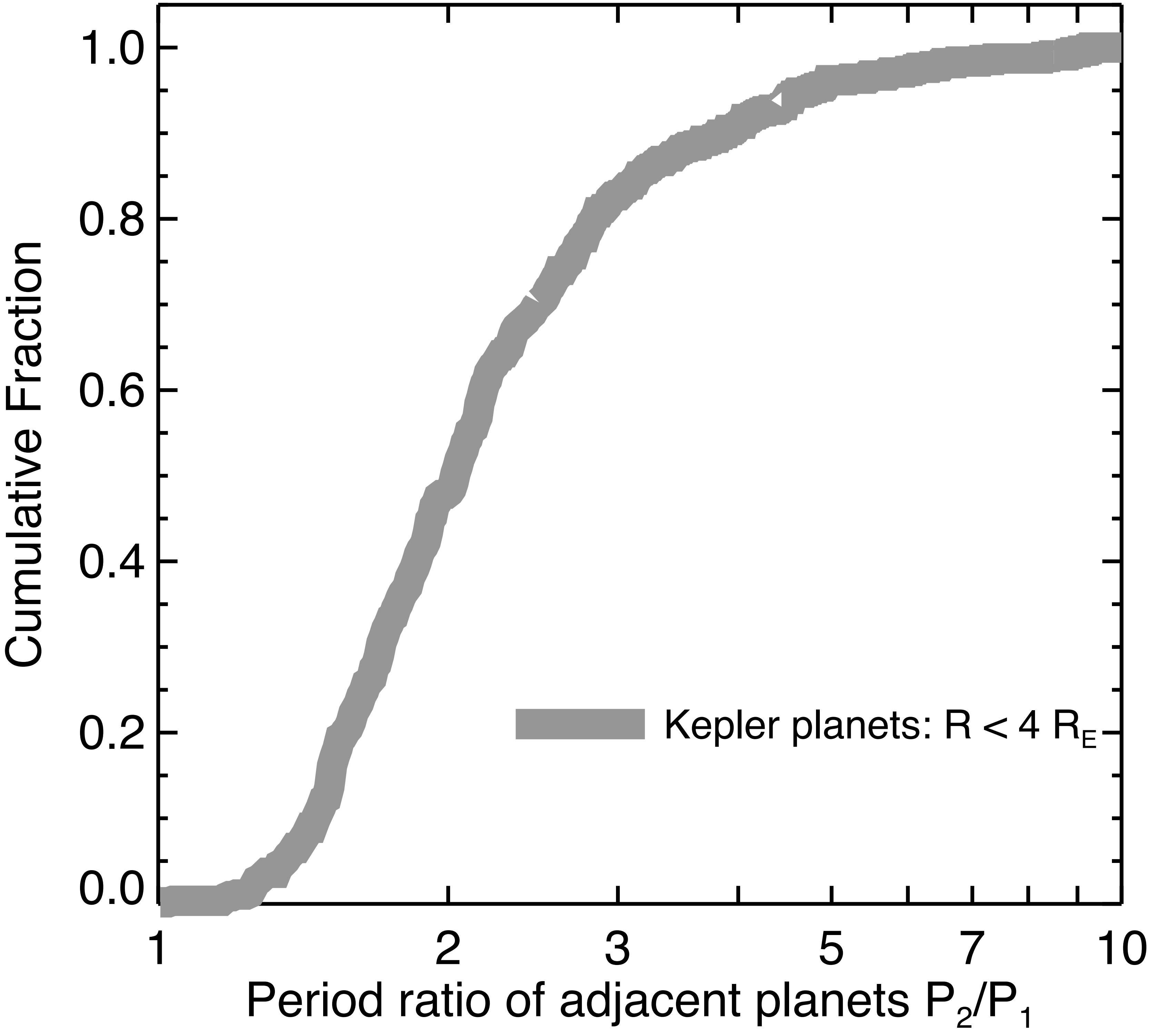
Instability spreads planets out and destroys resonances

(e.g., Pichierri et al 2019)

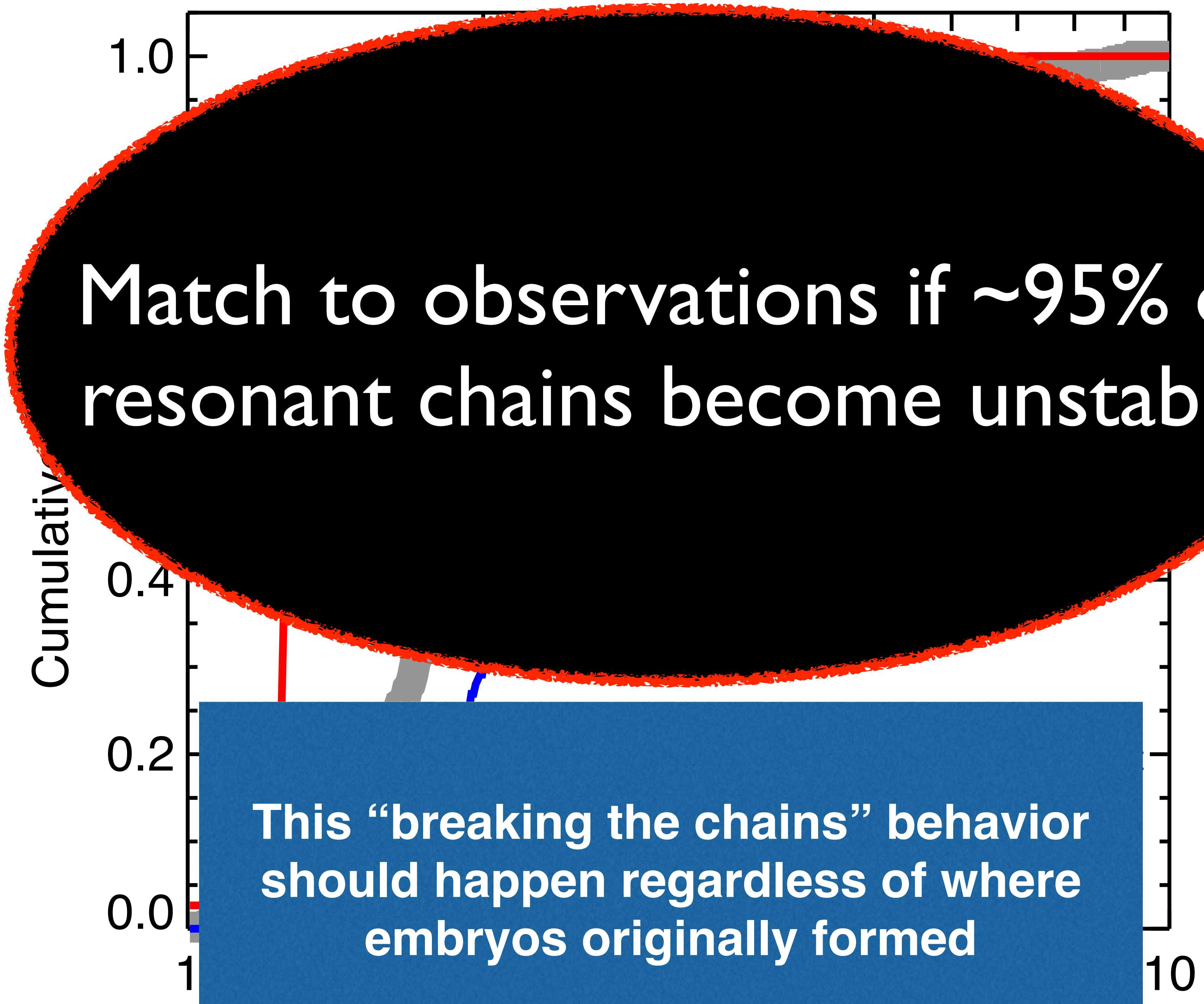


Gaseous disk dissipates after a few million years

The period ratio distribution



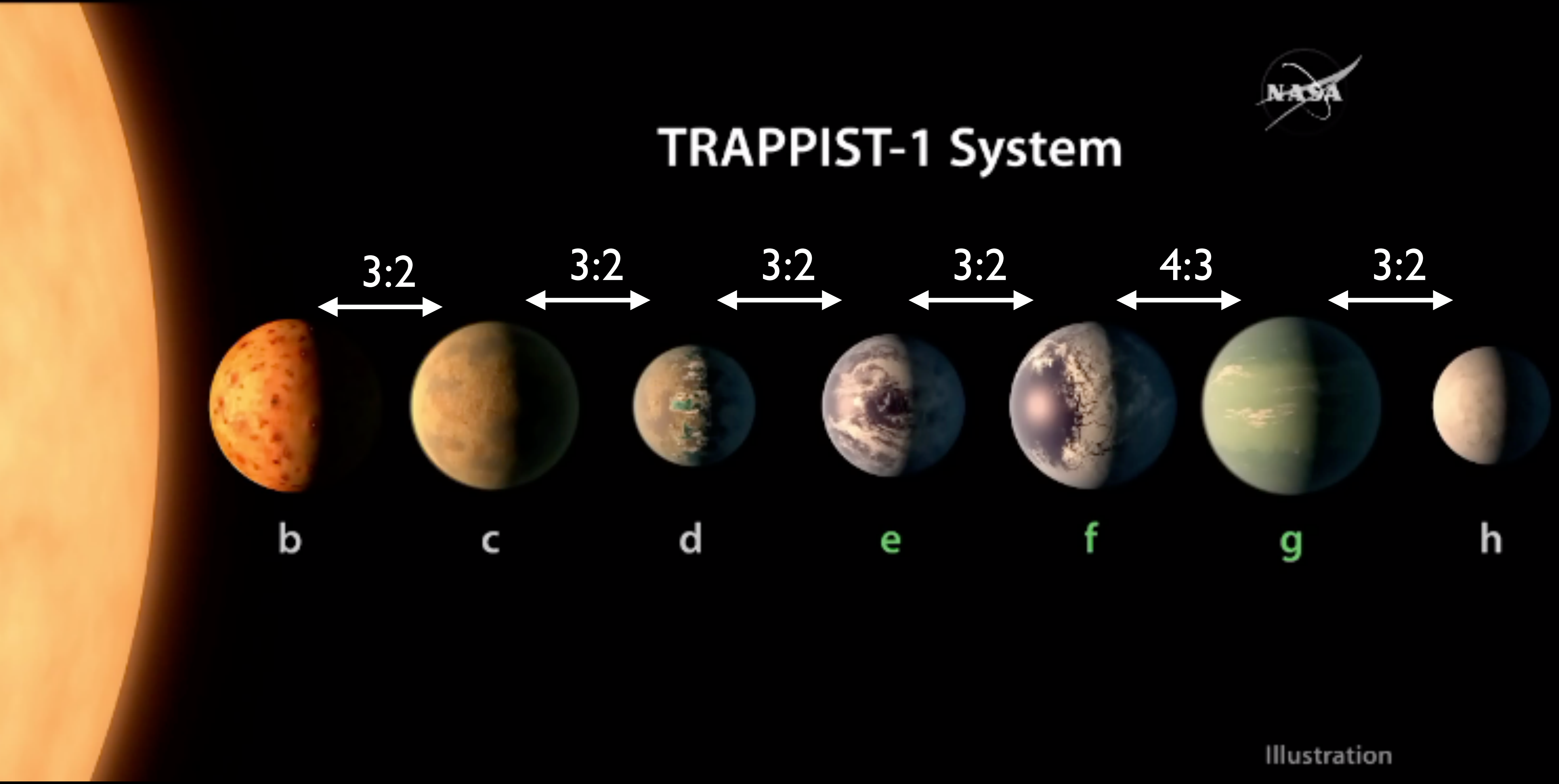
The period ratio distribution



Match to observations if ~95% of resonant chains become unstable

This "breaking the chains" behavior should happen regardless of where embryos originally formed

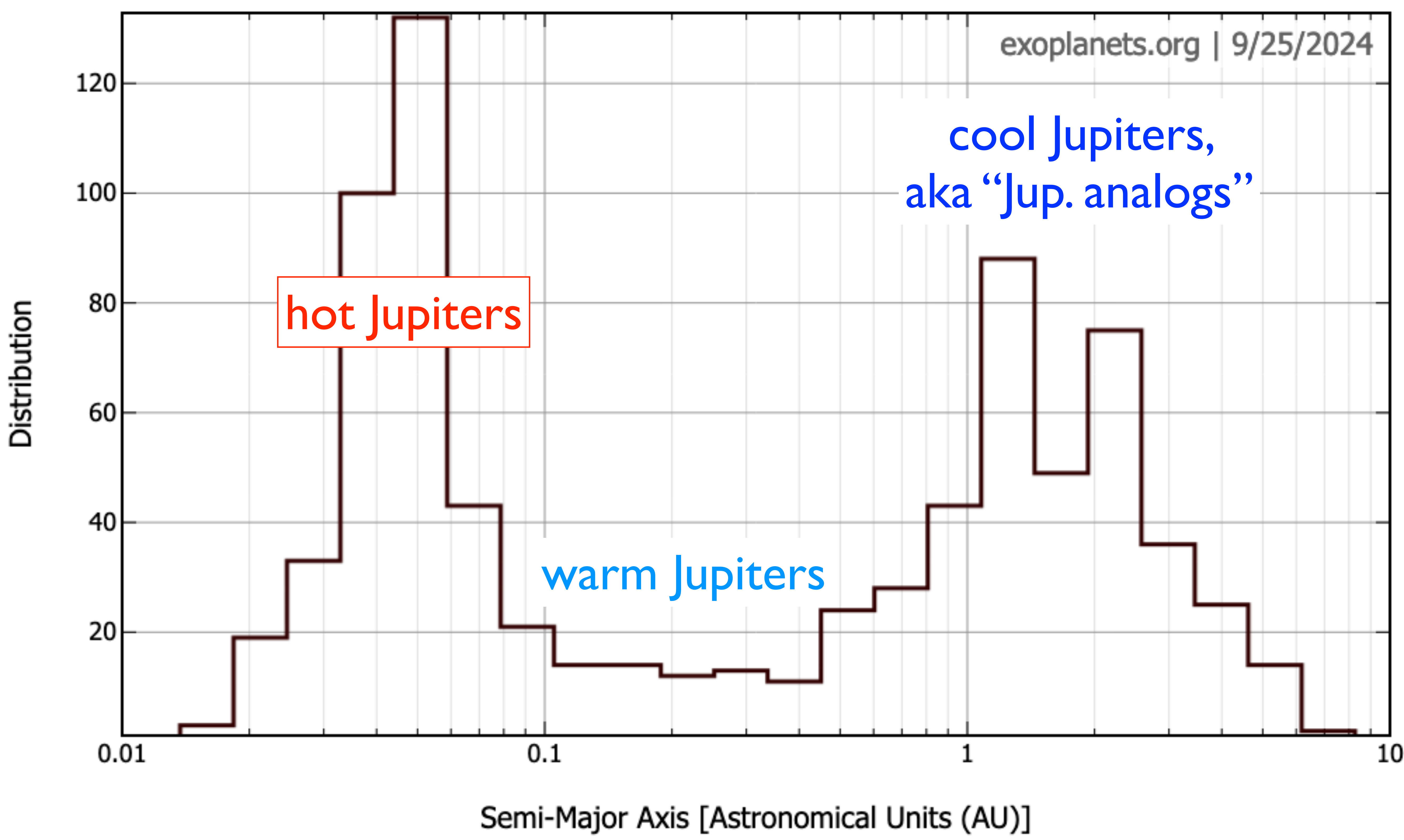
Izidoro et al (2017, 2021); Goldberg & Batygin (2022)



(Gillon et al 2017, Luger et al 2017)

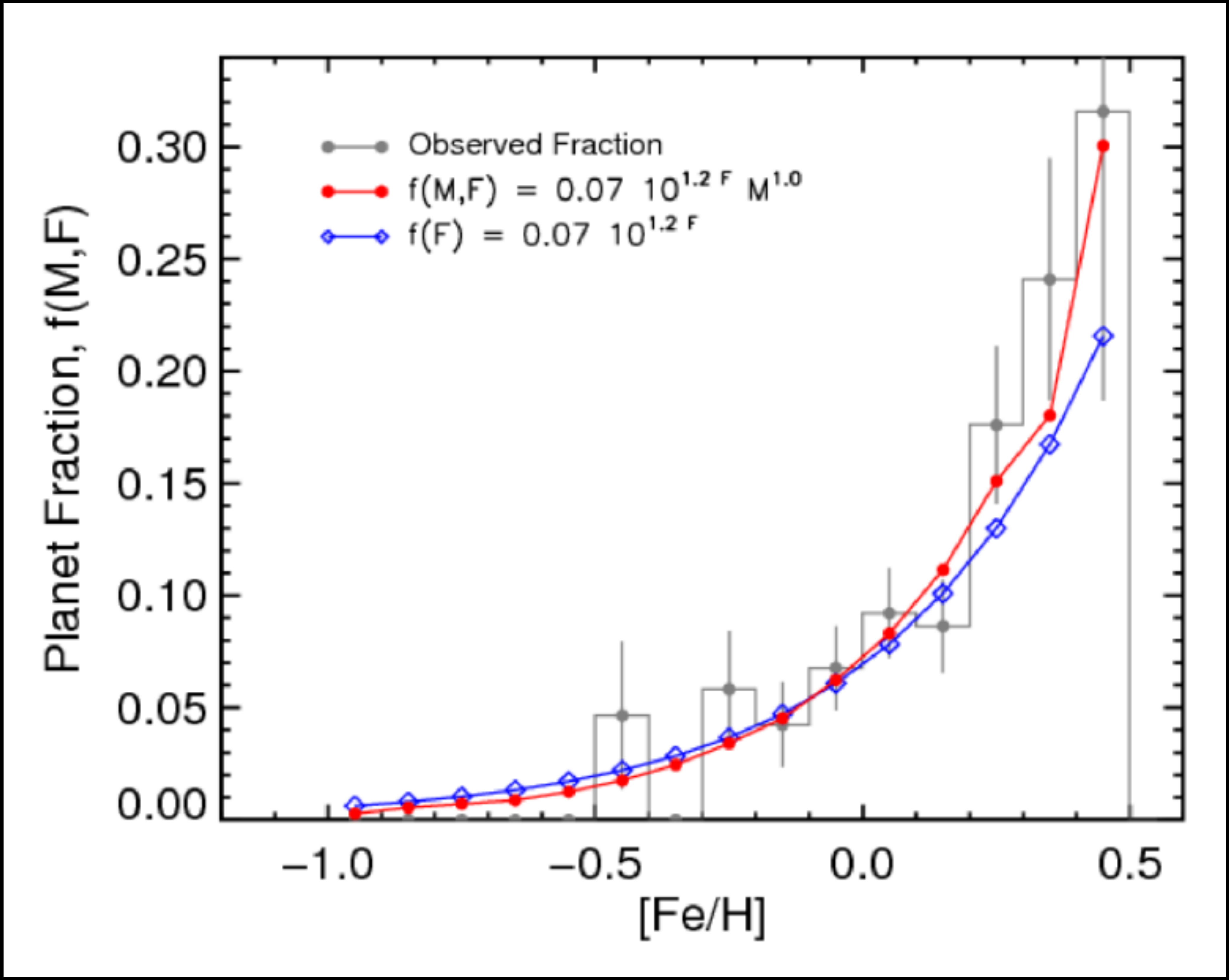
Giant (exo)planets

Radial distribution of gas giants



RV planets only, with $M \sin i > 0.1\ M_{Jup}$

Giant planet-metallicity correlation



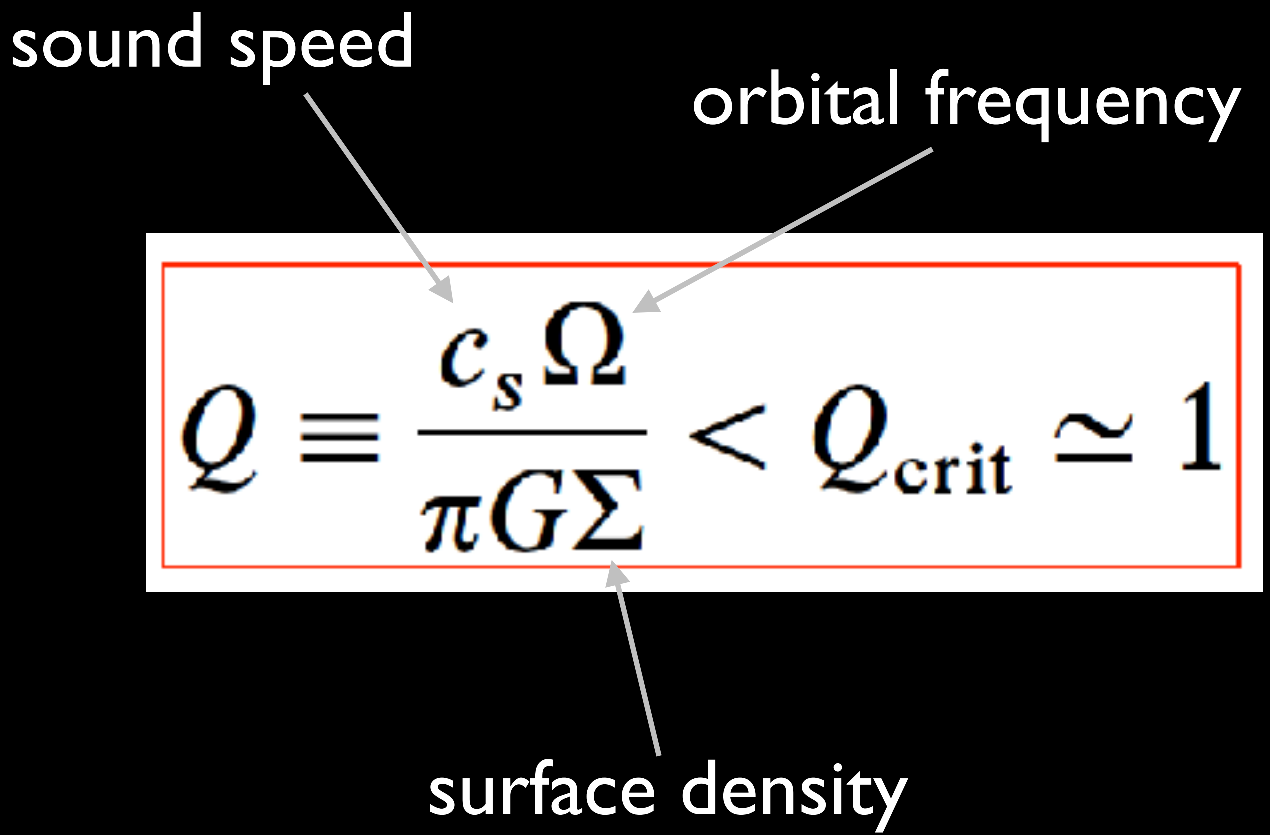
Johnson et al (2010); also Gonzalez (1997); Santos et al (2003); Fischer & Valenti (2005)

Formation models for giant planets

- Disk instability
- Core accretion

Disk instability

- Requires a region in the disk to be Toomre unstable



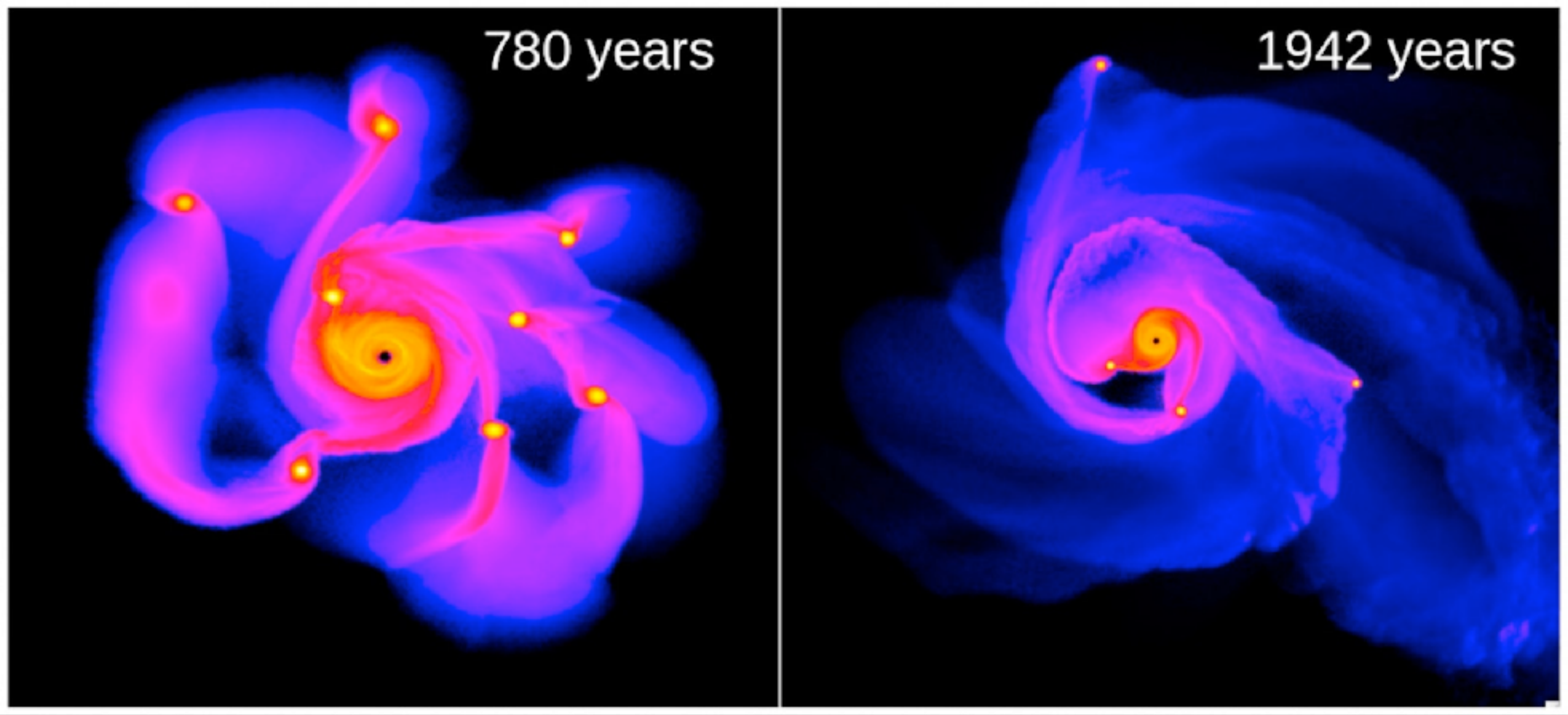
sound speed

orbital frequency

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\mathrm{crit}} \simeq 1$$

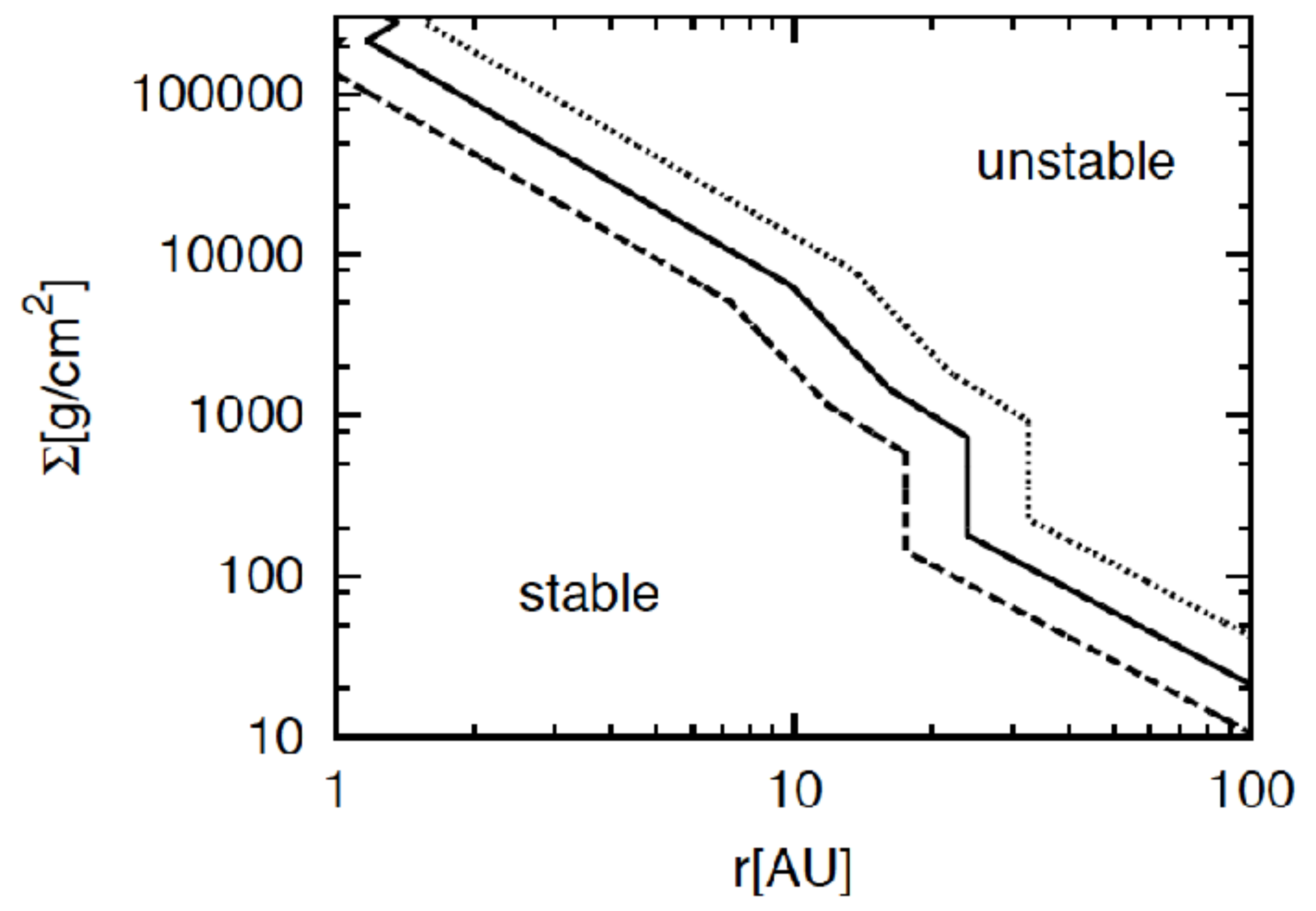
surface density

Disk instability



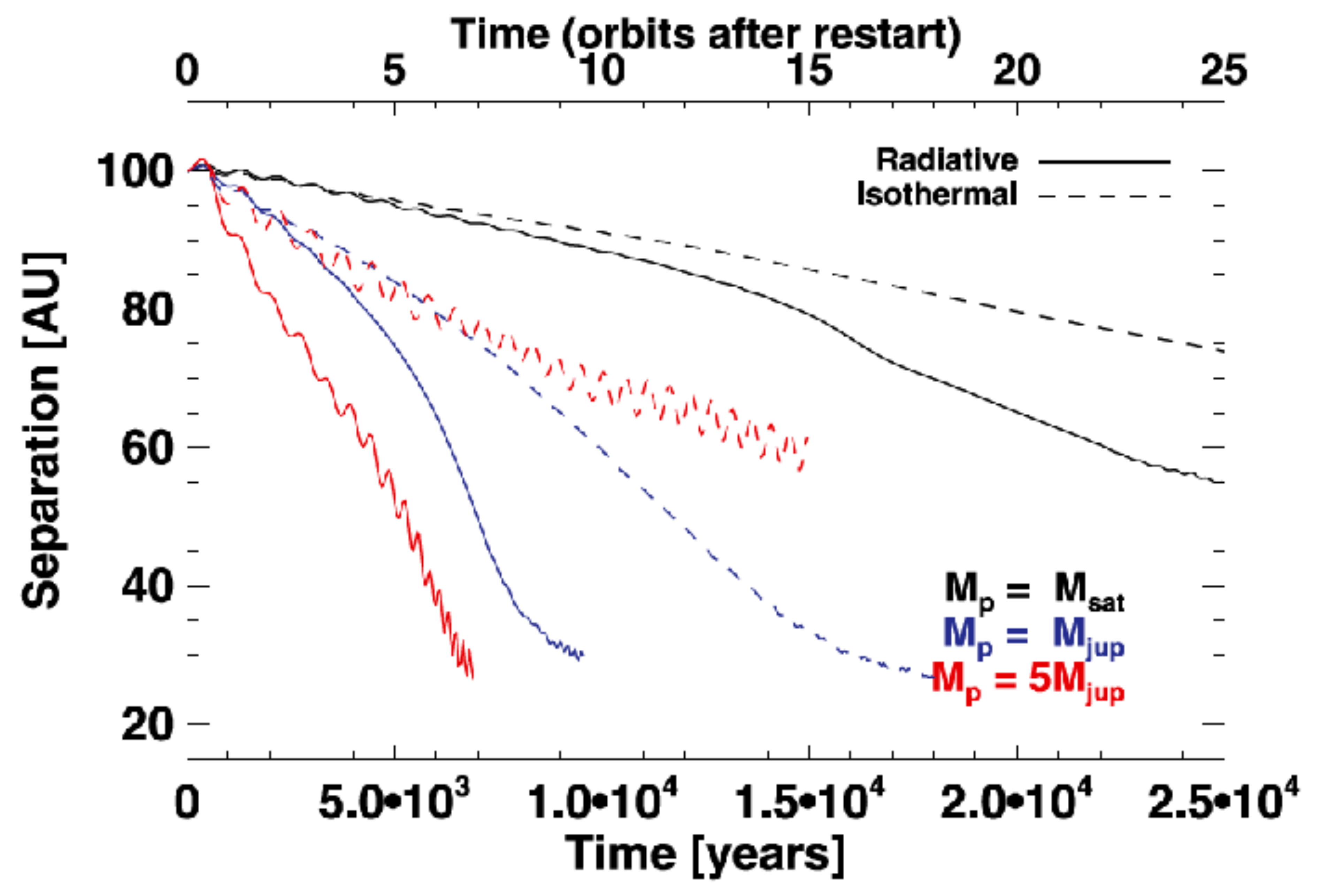
Mayer & Quinn (2016)

Gravitational instability: only important for massive wide-orbit planets



Kimura & Tsuribe (2012)

Clumps formed by disk instability migrate inward rapidly

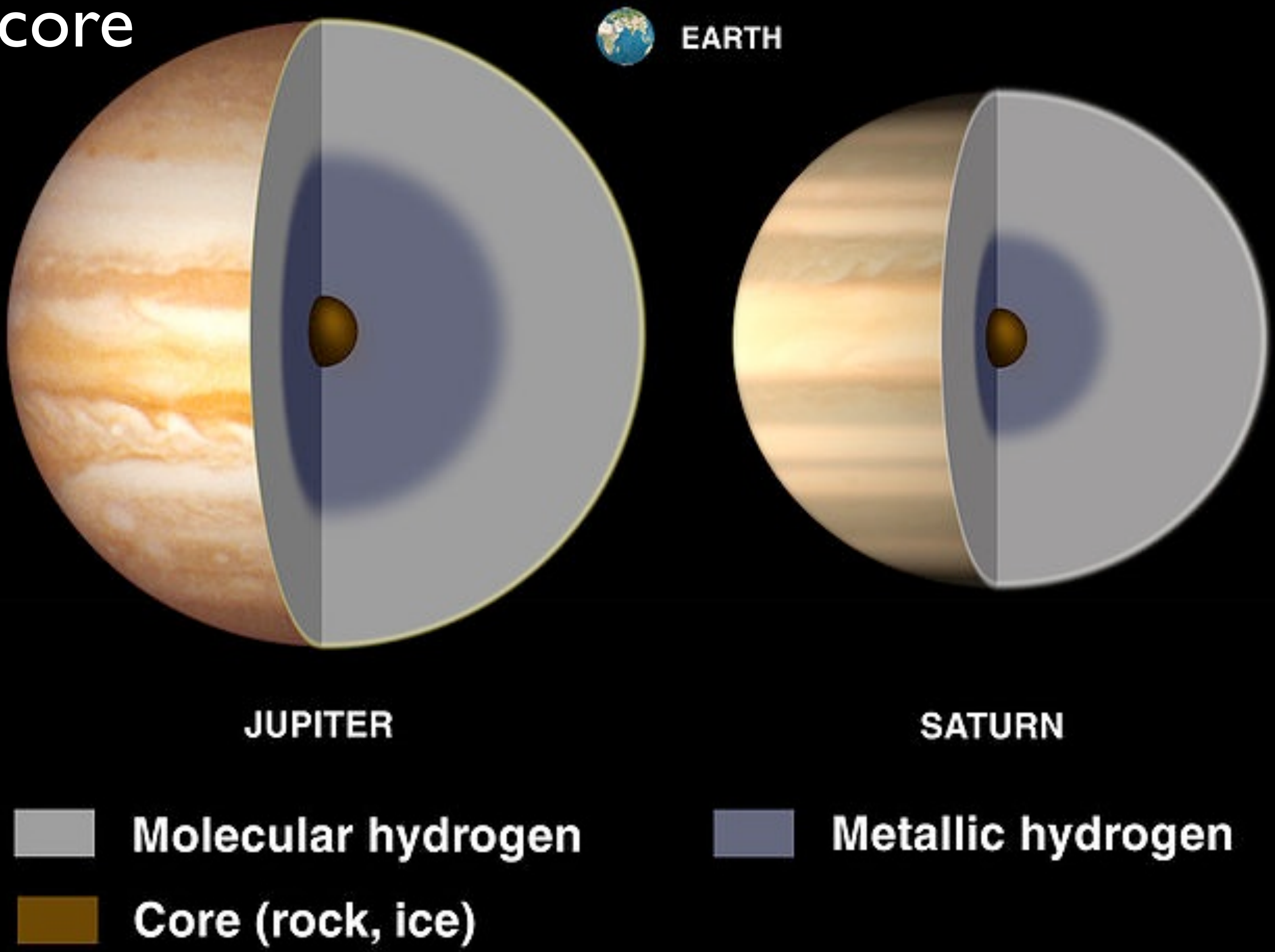


Baruteau et al (2012);
“tidal downsizing hypothesis” by Nayakshin (2010)

Core accretion

growth of a large solid core

gas accretion

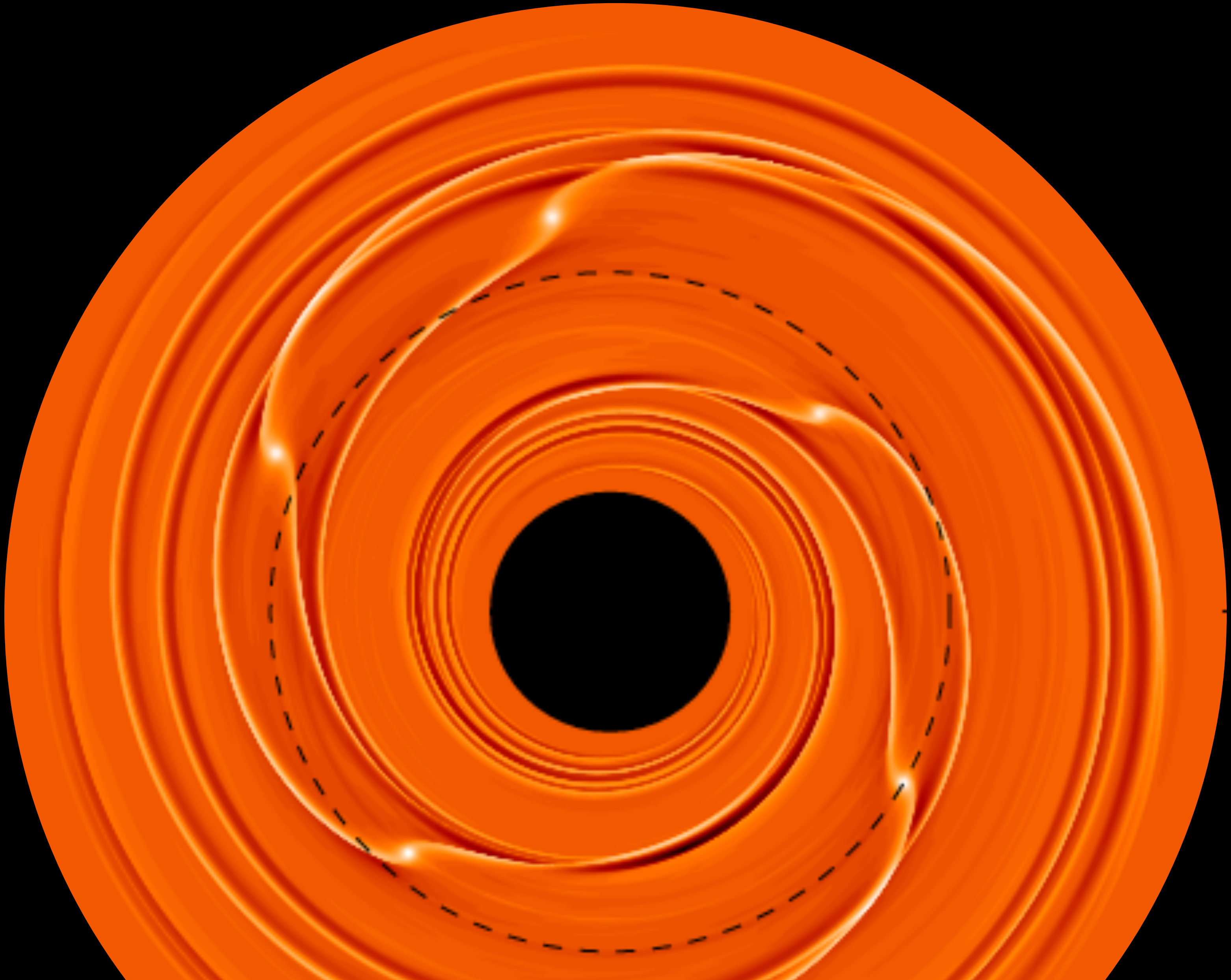


Core migration accretion

growth of a large
solid core

gas-driven
migration

gas accretion

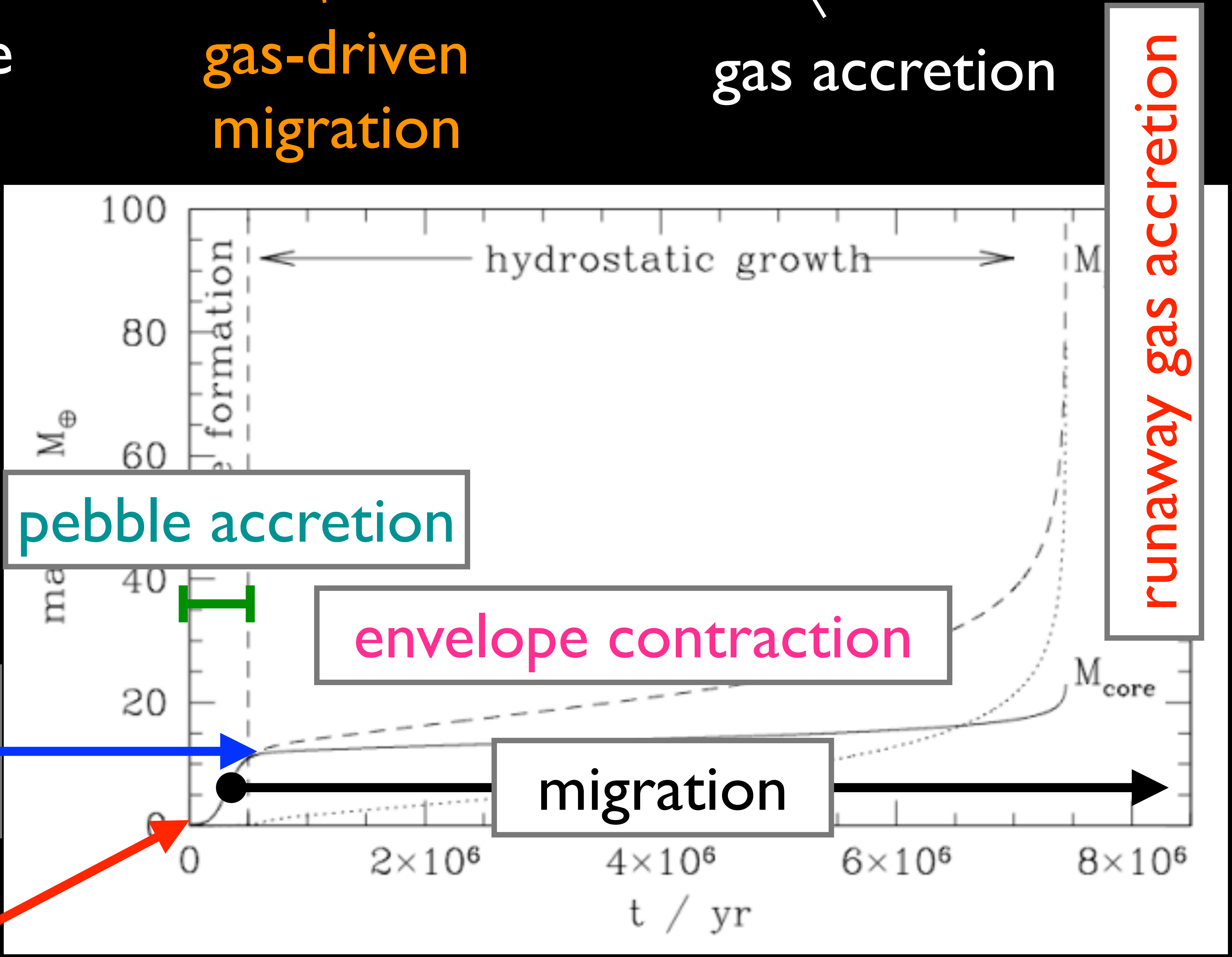


Core **migration** accretion

growth of a large solid core

gas-driven migration

gas accretion



runaway gas accretion

pebble accretion

envelope contraction

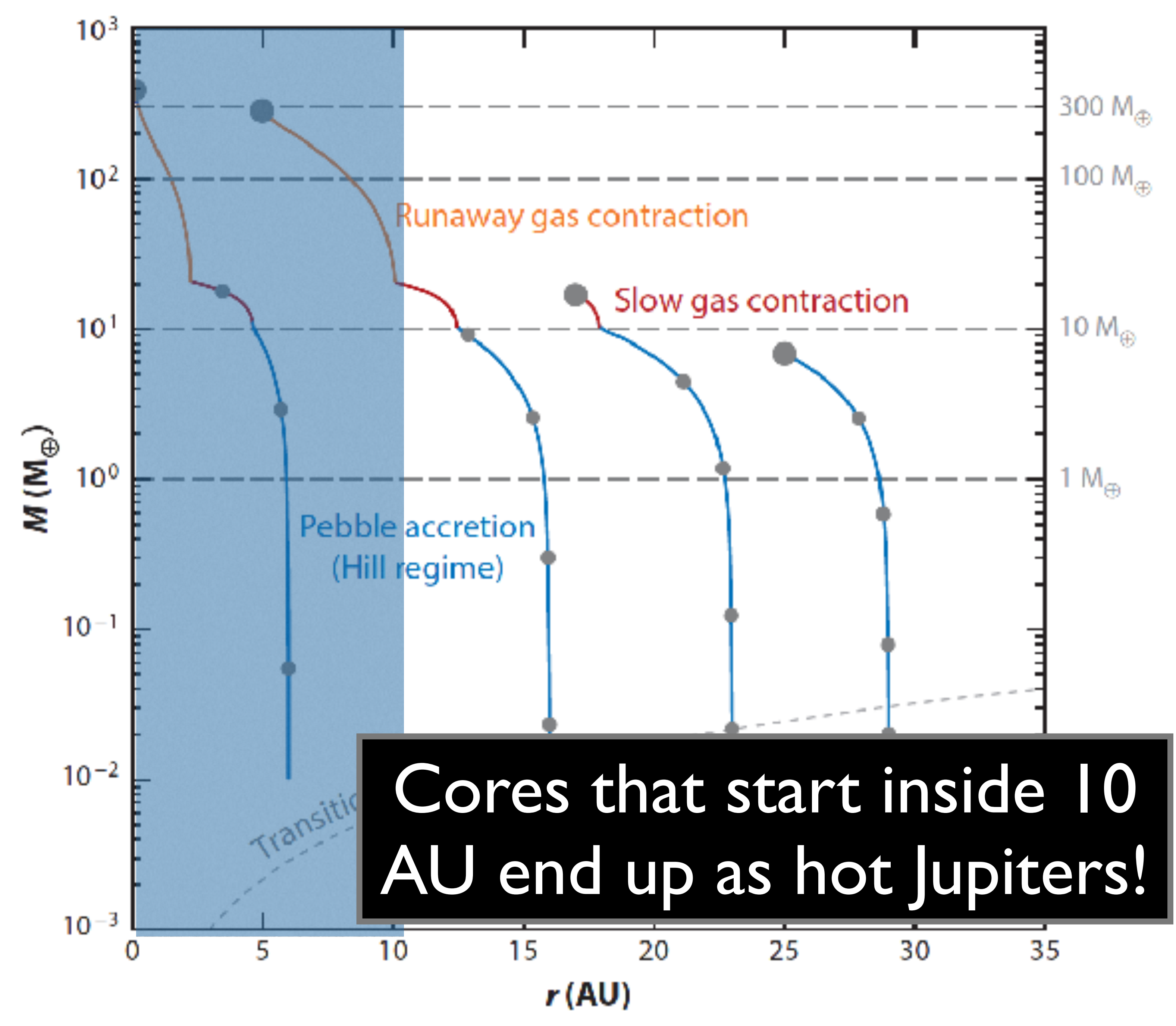
pebble "isolation mass"

migration

planetesimal formation

credit: P. Armitage; after Pollack et al (1996)

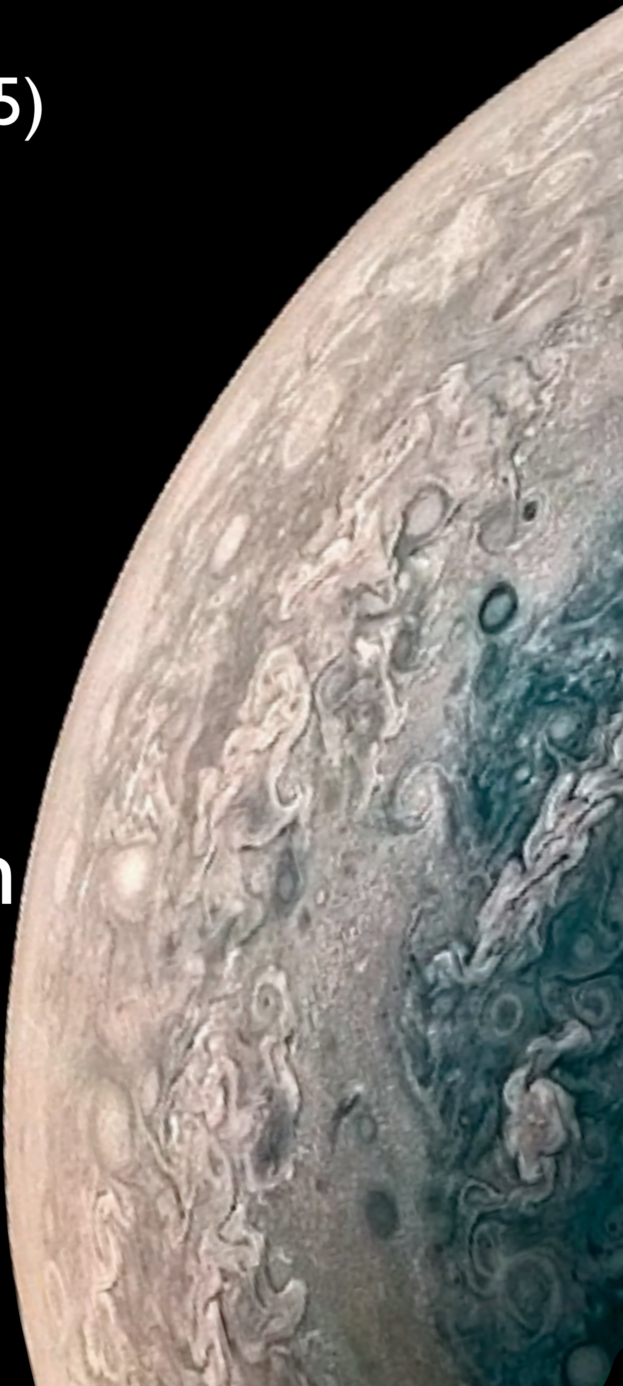
Growth/migration tracks with pebble accretion



Cores that start inside 10 AU end up as hot Jupiters!

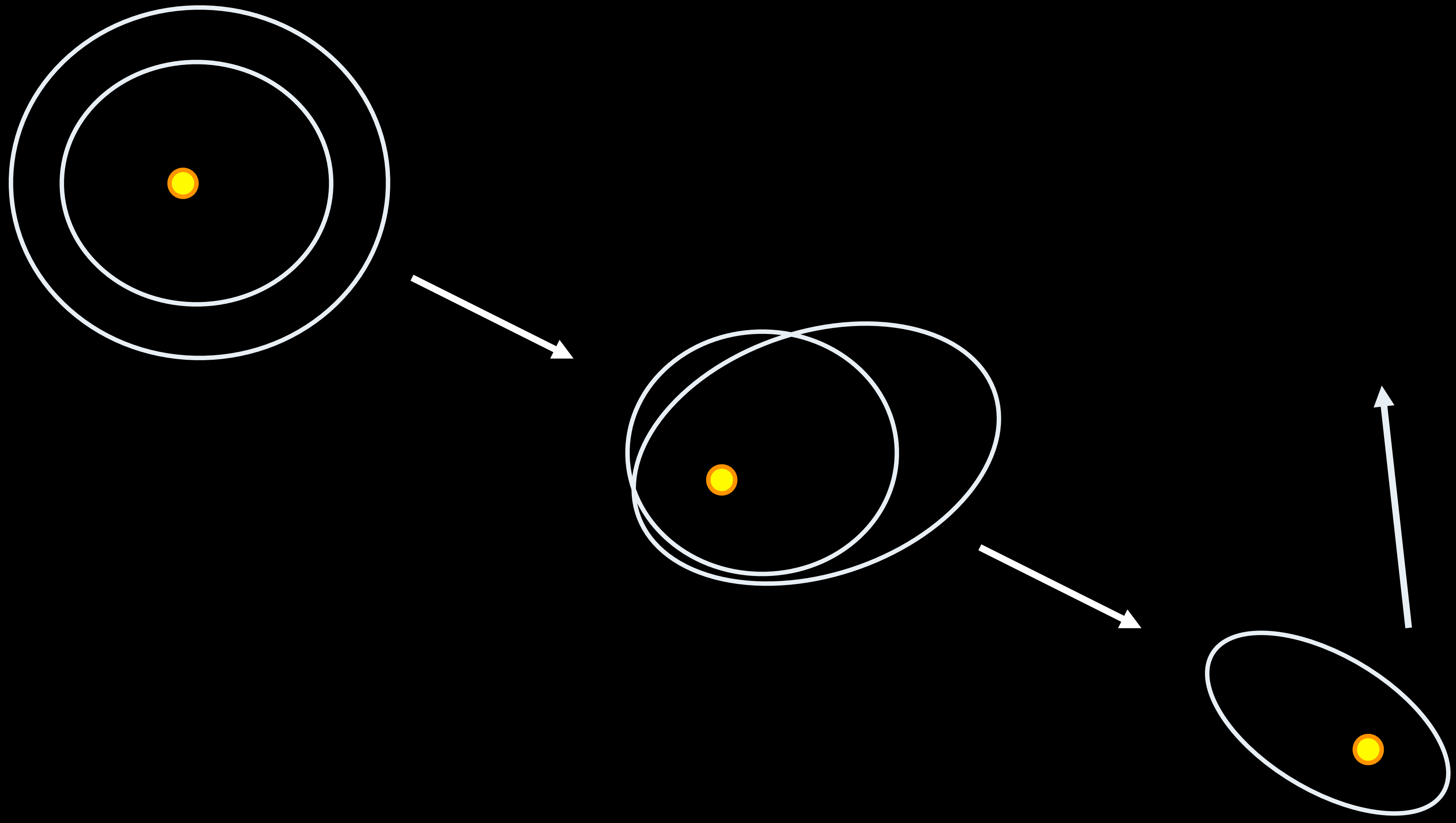
Johansen & Lambrechts (2017); after Bitsch et al (2015)

How did Jupiter end up at 5 AU?

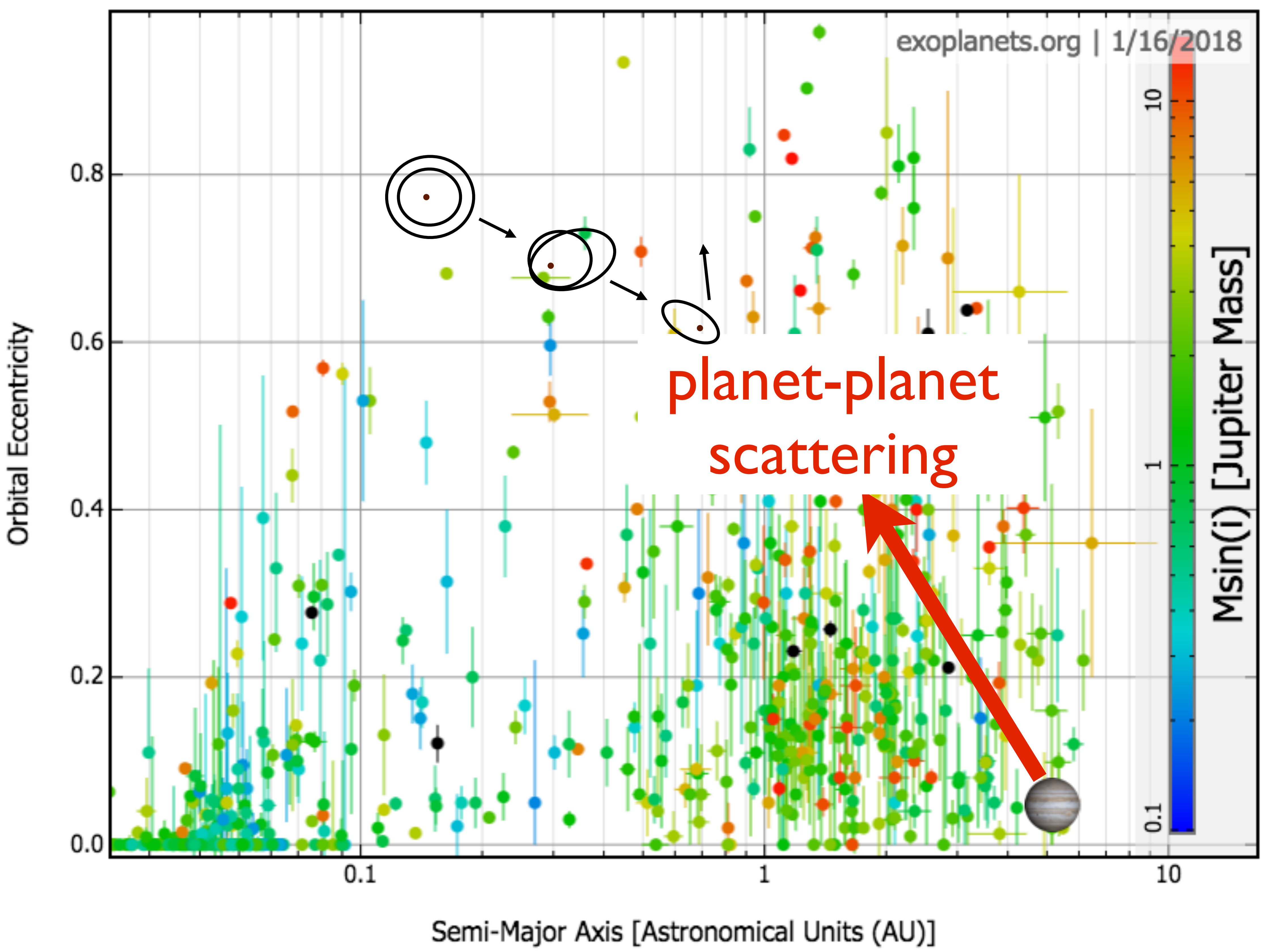


- Jupiter's core formed at 15-20 AU (Bitsch et al 2015)
- Very low viscosity disks: very slow type 2 migration (e.g., Bitsch et al 2019; Griveaud et al 2024)
- Inner disk evaporated away, planets could't migrate closer than ~1 AU (Alexander & Pascucci 2012)
- Saturn stopped or reversed Jupiter's migration (Masset & Snellgrove 2001; Grand Tack model)

The giant exoplanet eccentricity distribution: planet-planet scattering

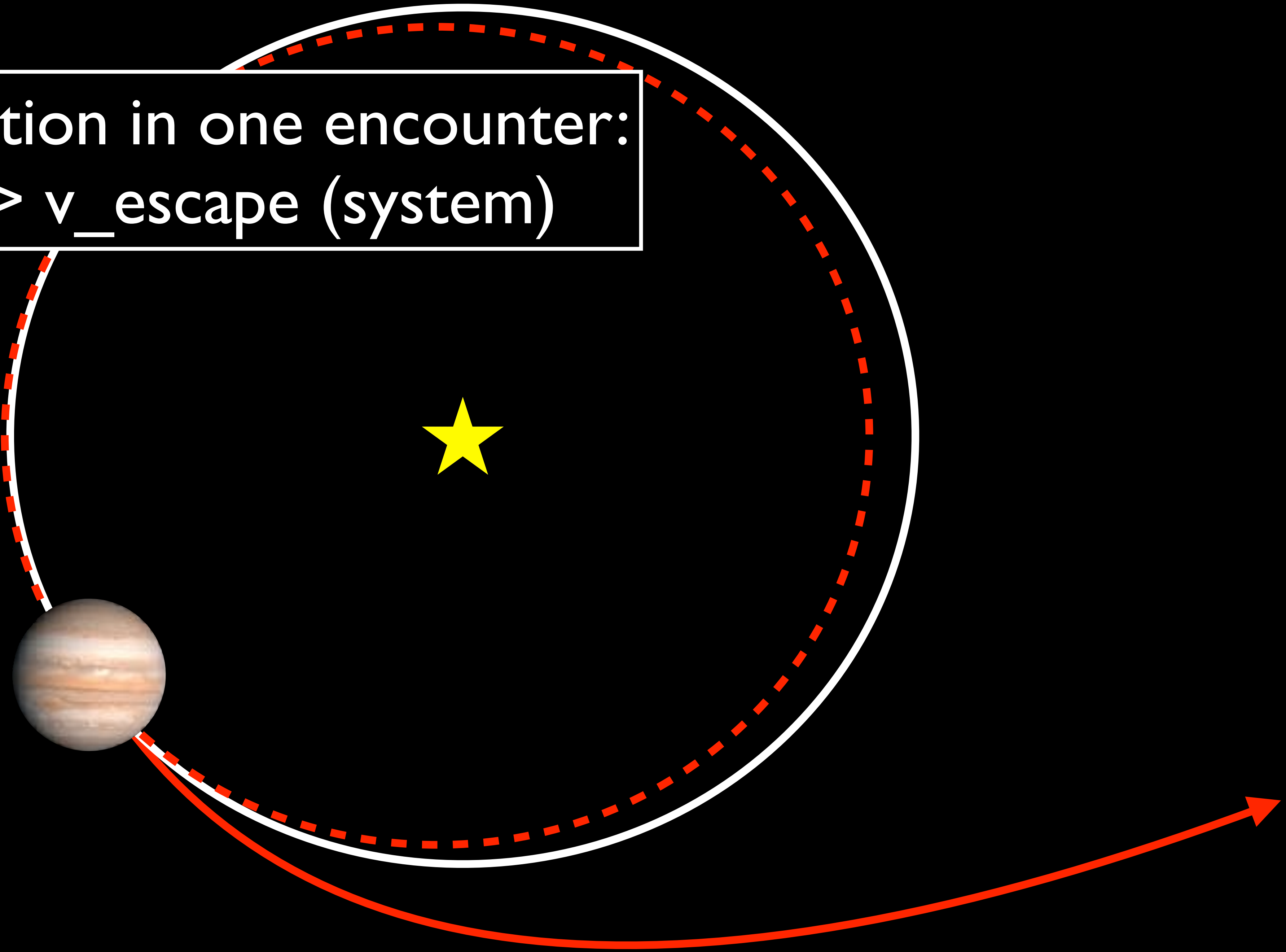


Giant exoplanets



planet-planet scattering

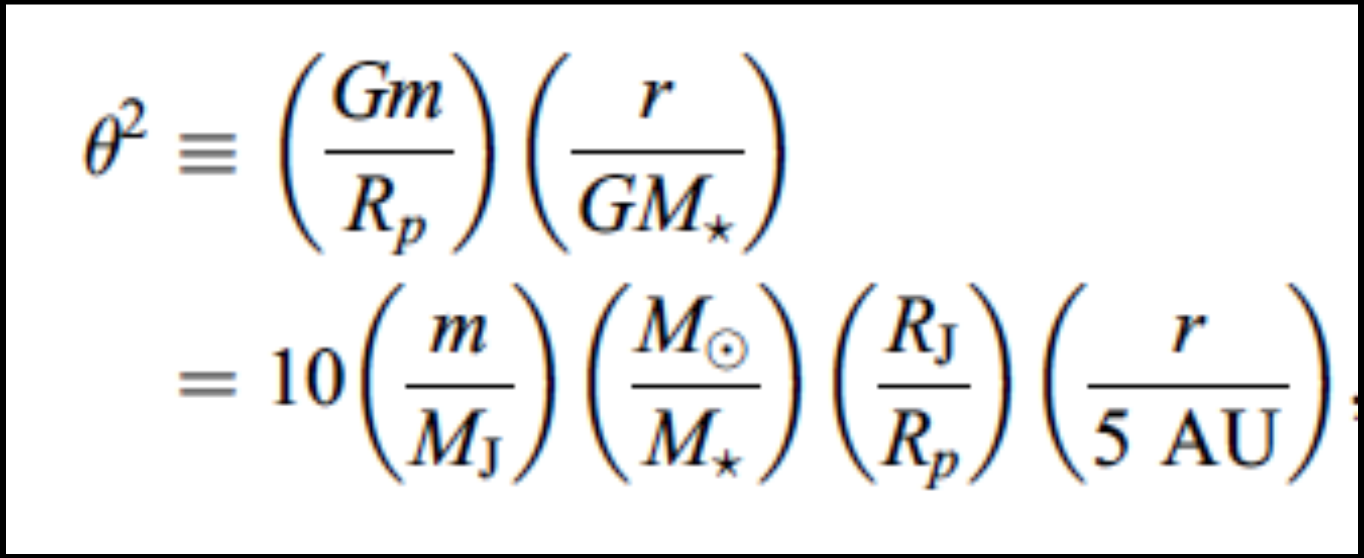
Scattering vs accretion



Requirement for ejection in one encounter:
v_escape (planet) > v_escape (system)

The "Safronov number": scattering vs accretion

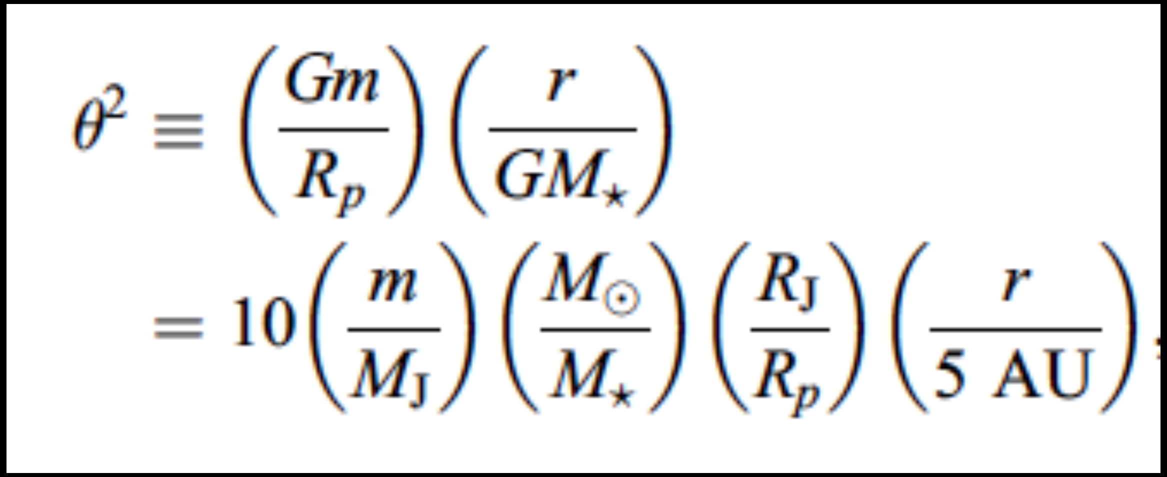
- Ratio of escape speed from planet's surface to escape speed from system at planet's orbital radius



$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right) = 10\left(\frac{m}{M_J}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_J}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right)$$

The “Safronov number”: scattering vs accretion

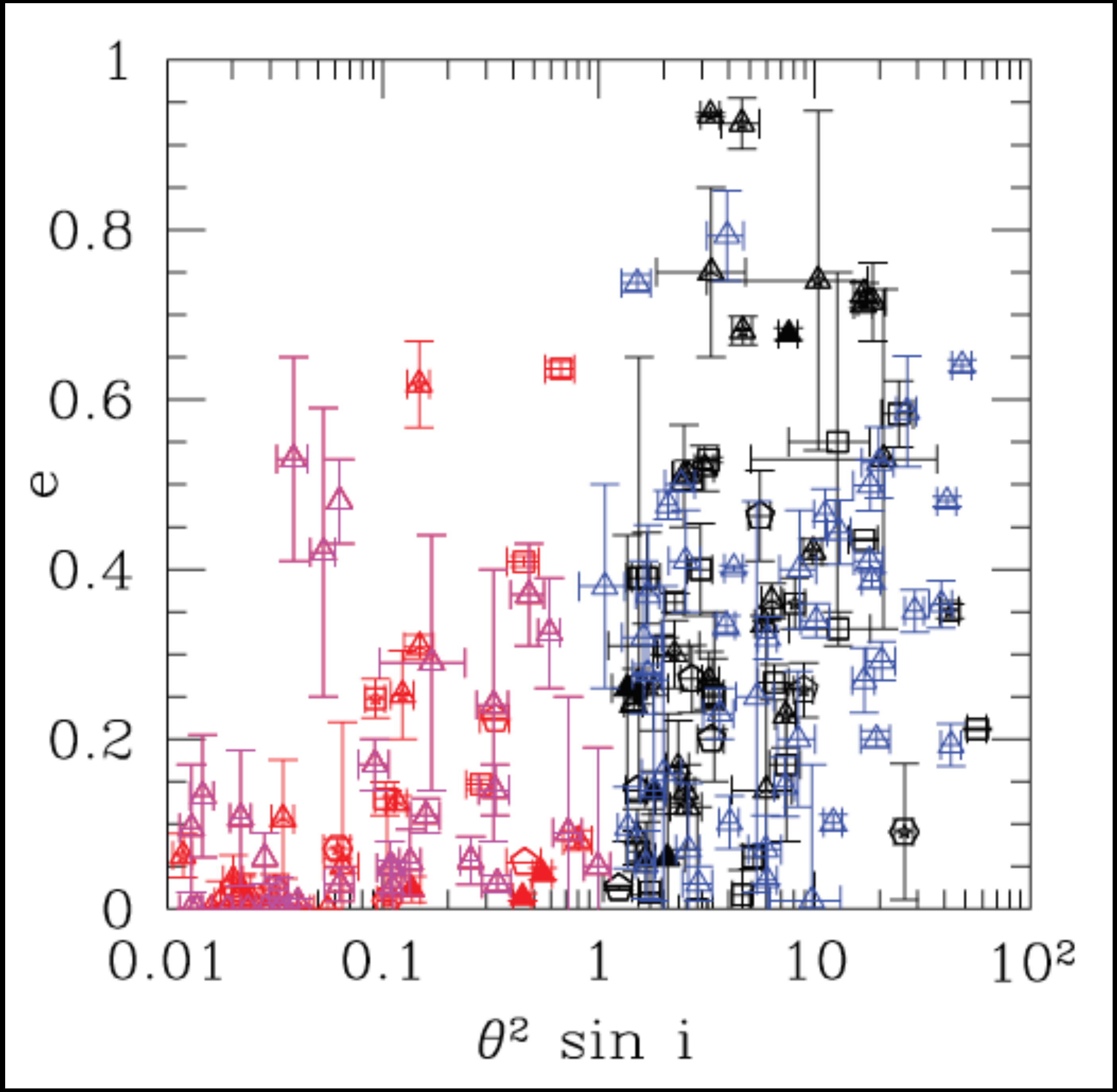
- Saf>1: high-mass or distant planets — **scattering**
- Saf<1: low-mass or close-in planets — **accretion**



$$\theta^2 \equiv \left(\frac{Gm}{R_p}\right)\left(\frac{r}{GM_\star}\right)$$

$$= 10\left(\frac{m}{M_\mathrm{J}}\right)\left(\frac{M_\odot}{M_\star}\right)\left(\frac{R_\mathrm{J}}{R_p}\right)\left(\frac{r}{5\ \mathrm{AU}}\right)$$

Giant planet eccentricities correlate with Safronov#



Ford & Rasio (2008)

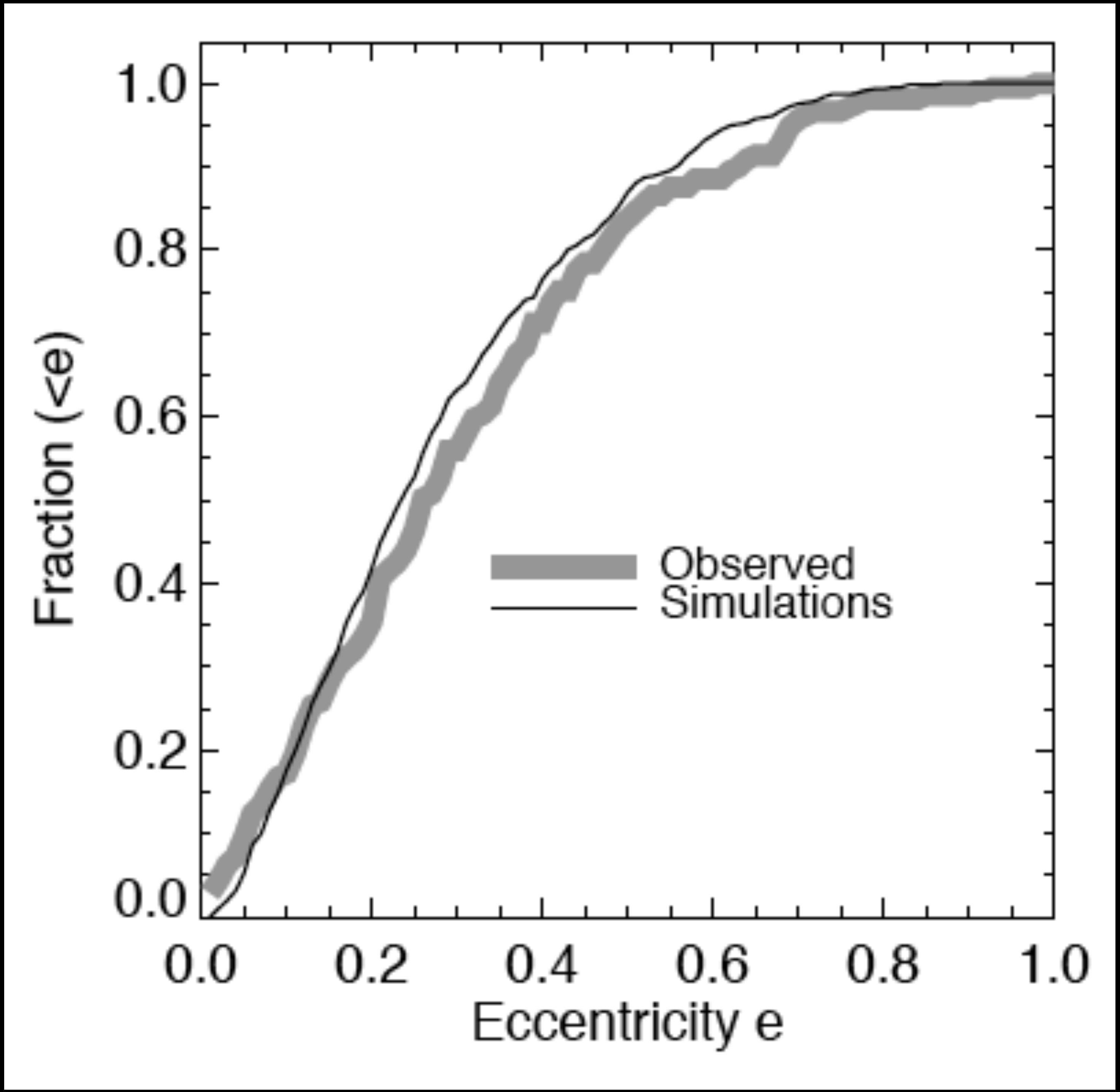
Planet-planet scattering

Credit: Eric Ford

Survivors of planet-planet scattering match the eccentricity distribution

To fit eccentricity distribution, 75-95% of giant exoplanet systems must be survivors of instability

(Juric & Tremaine 2008; Chatterjee et al 2008; Raymond et al 2010)

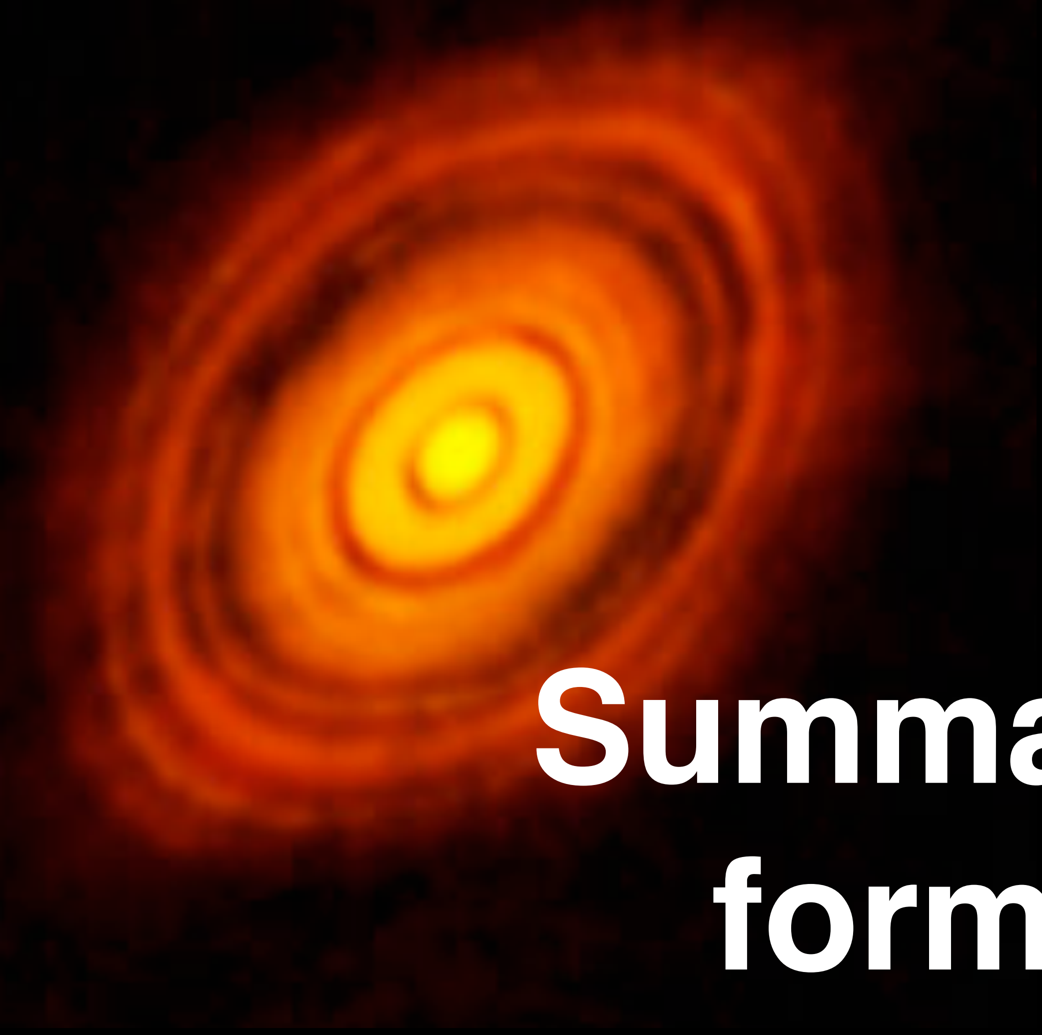


Raymond et al (2009)

Planet-planet scattering generates free-floating planets

Several hundred FFPs known to date (typically Jupiters)

[e.g., Mroz et al 2017, Kirkpatrick et al 2019, Miret-Roig et al 2022, Sumi et al 2023]



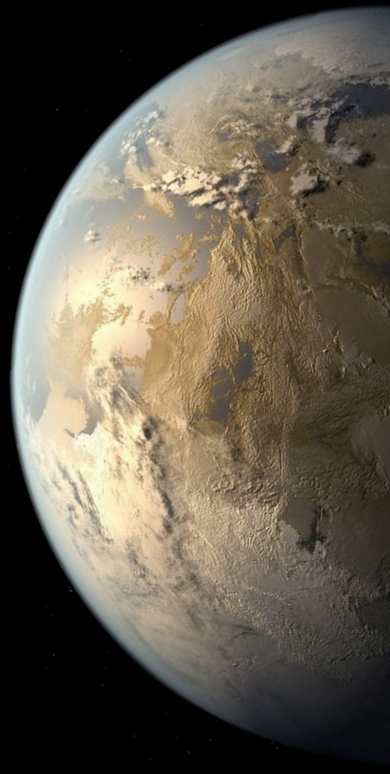
Summary of exoplanet formation models

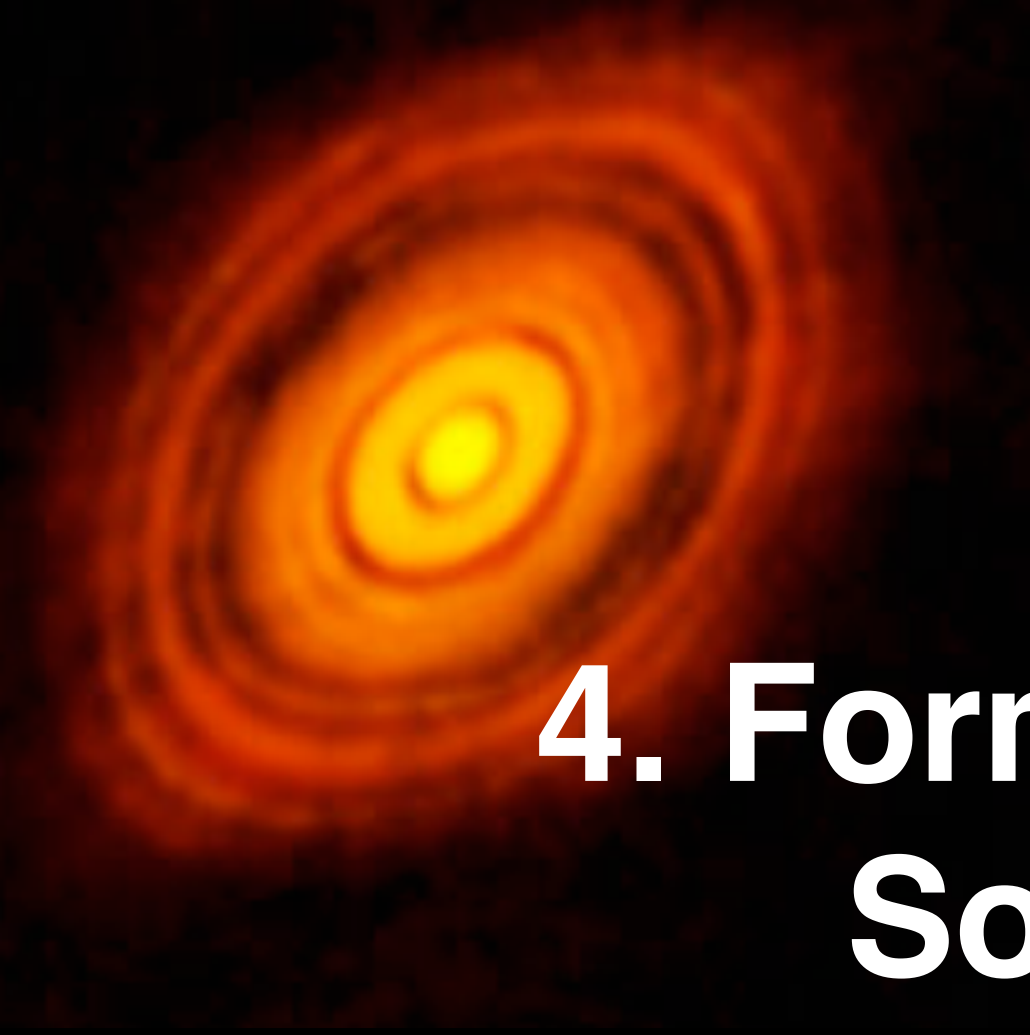
Close-in “super-Earths”

- In-situ growth impossible
- Migration then instability (“breaking the chains”)

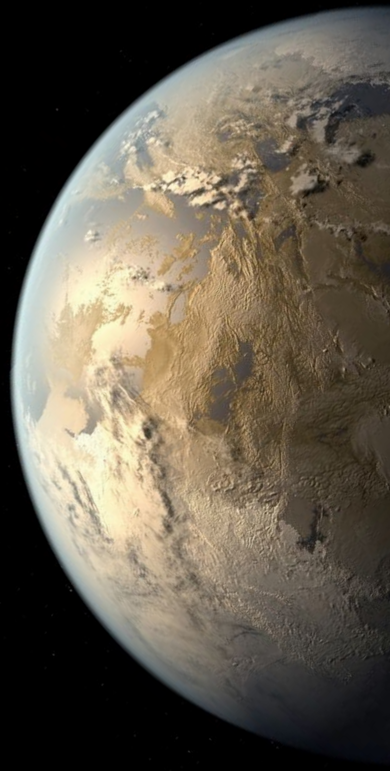
Gas giants

- Disk instability only for outer high-mass planets
- Core-migration-accretion
- Planet-planet scattering





4. Formation models: Solar System



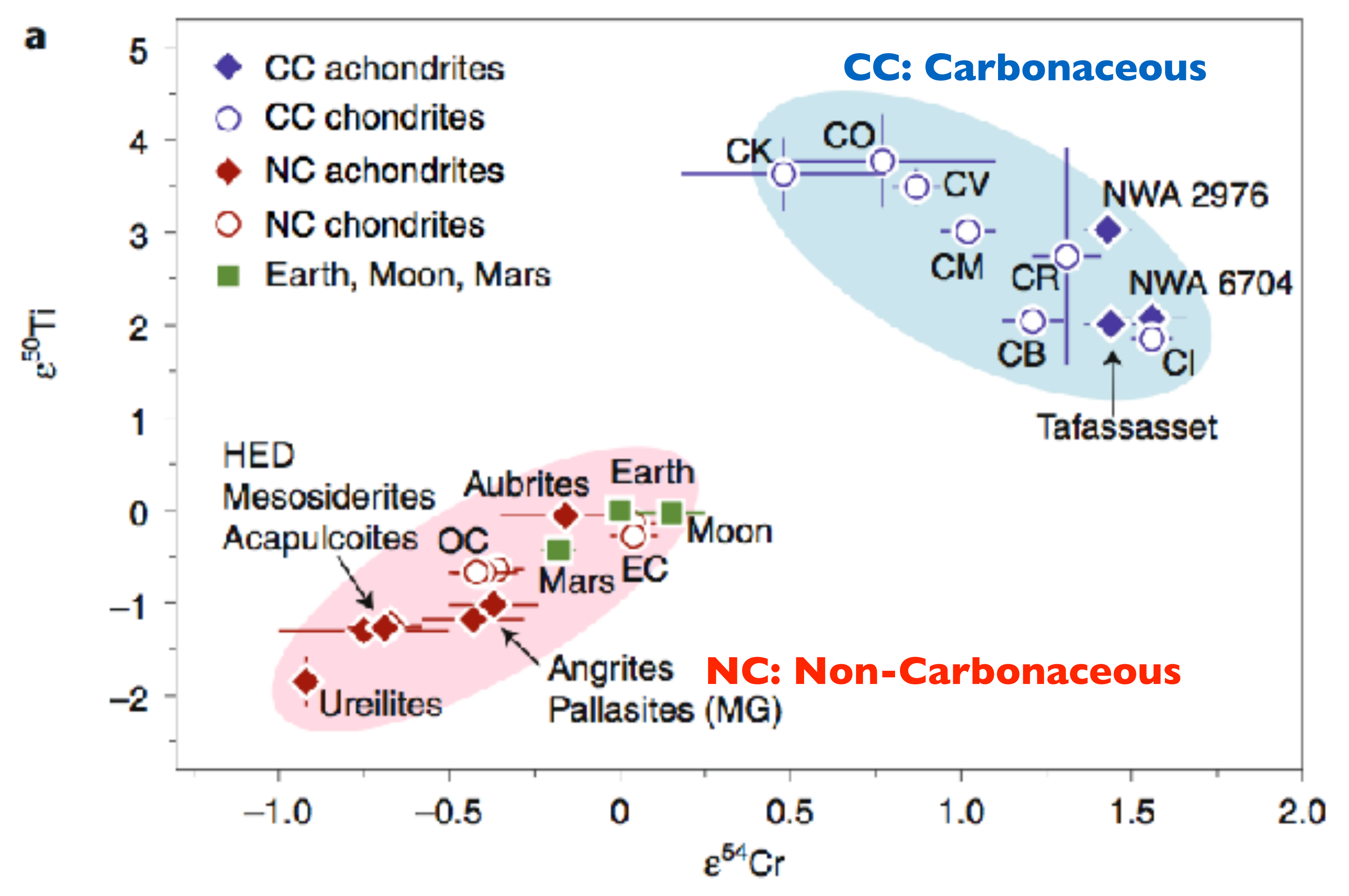
- Constraints + timeline
- The “Classical model”
- Alternate models
- Origin of water on Earth

A few key events in Solar System history that (almost) everyone agrees upon…

rough time order

1. Planetesimals formed
2. Planetary embryos formed
3. Gas giants formed (and migrated)
4. Giant planet instability
5. Moon-forming impact

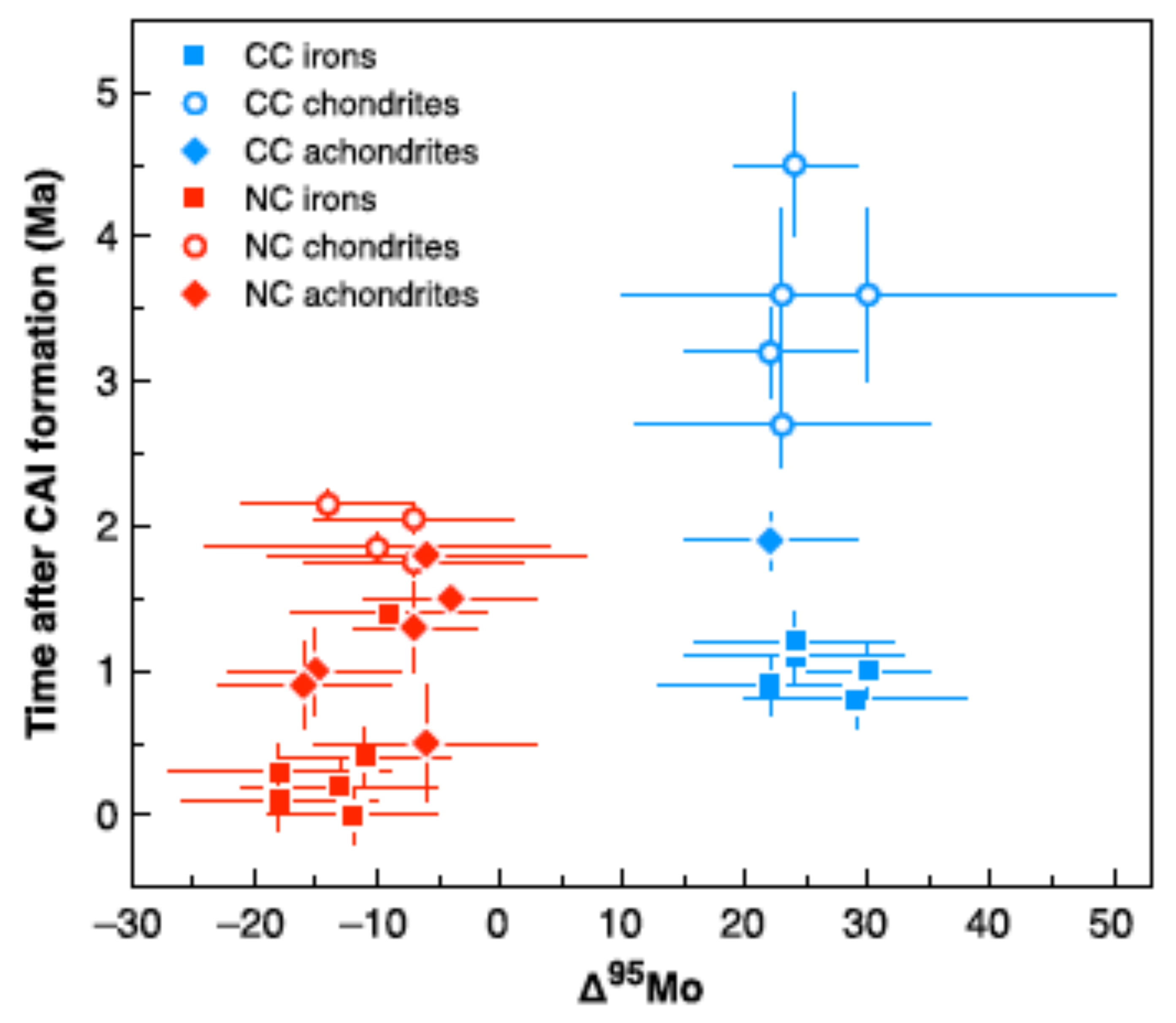
Key event 1: formation of two classes of planetesimals



Kruijer et al (2020)

Did they form at different times or in different places?

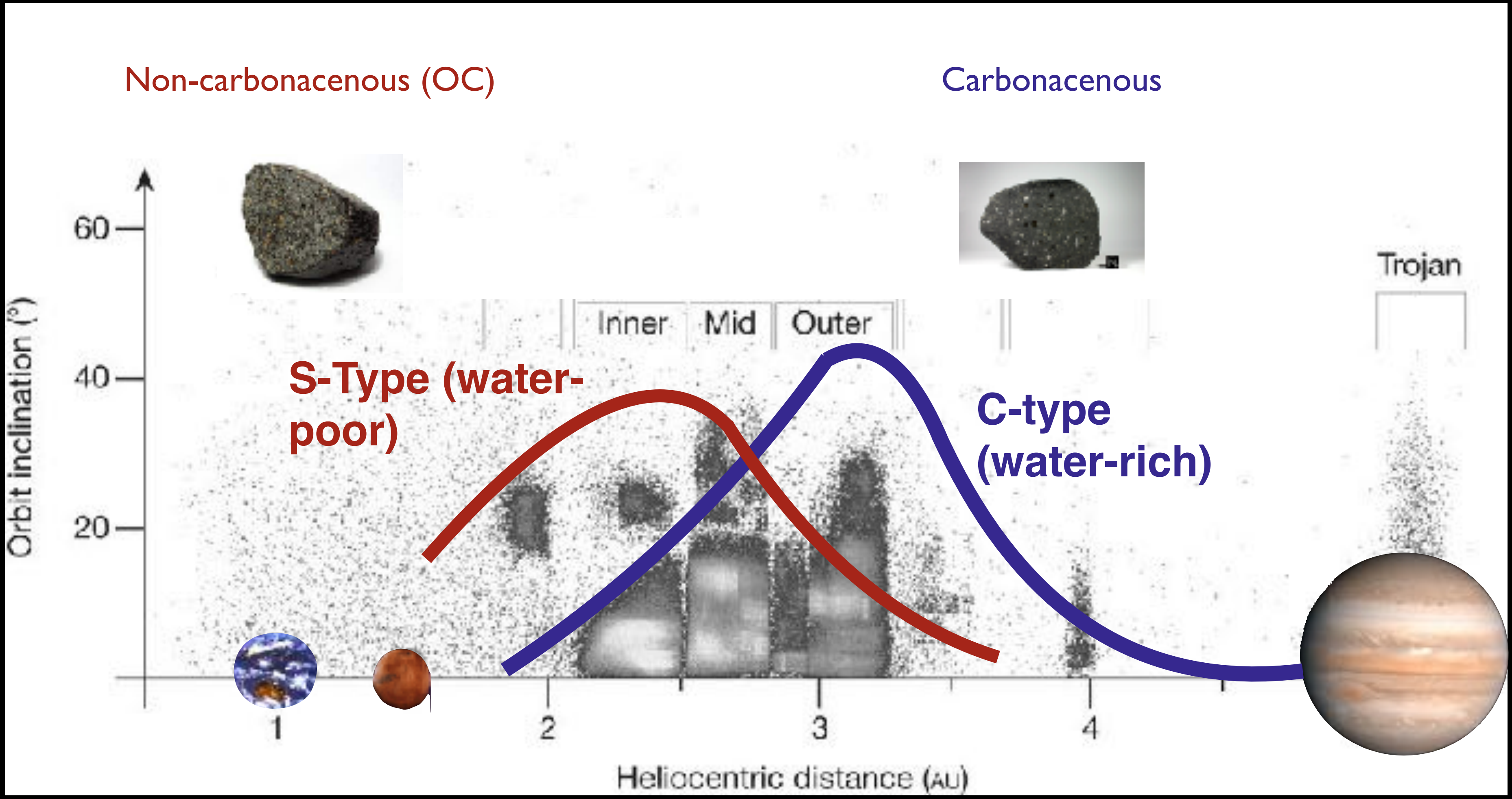
NC and CC planetesimals were forming at the same time



Kleine et al (2020)

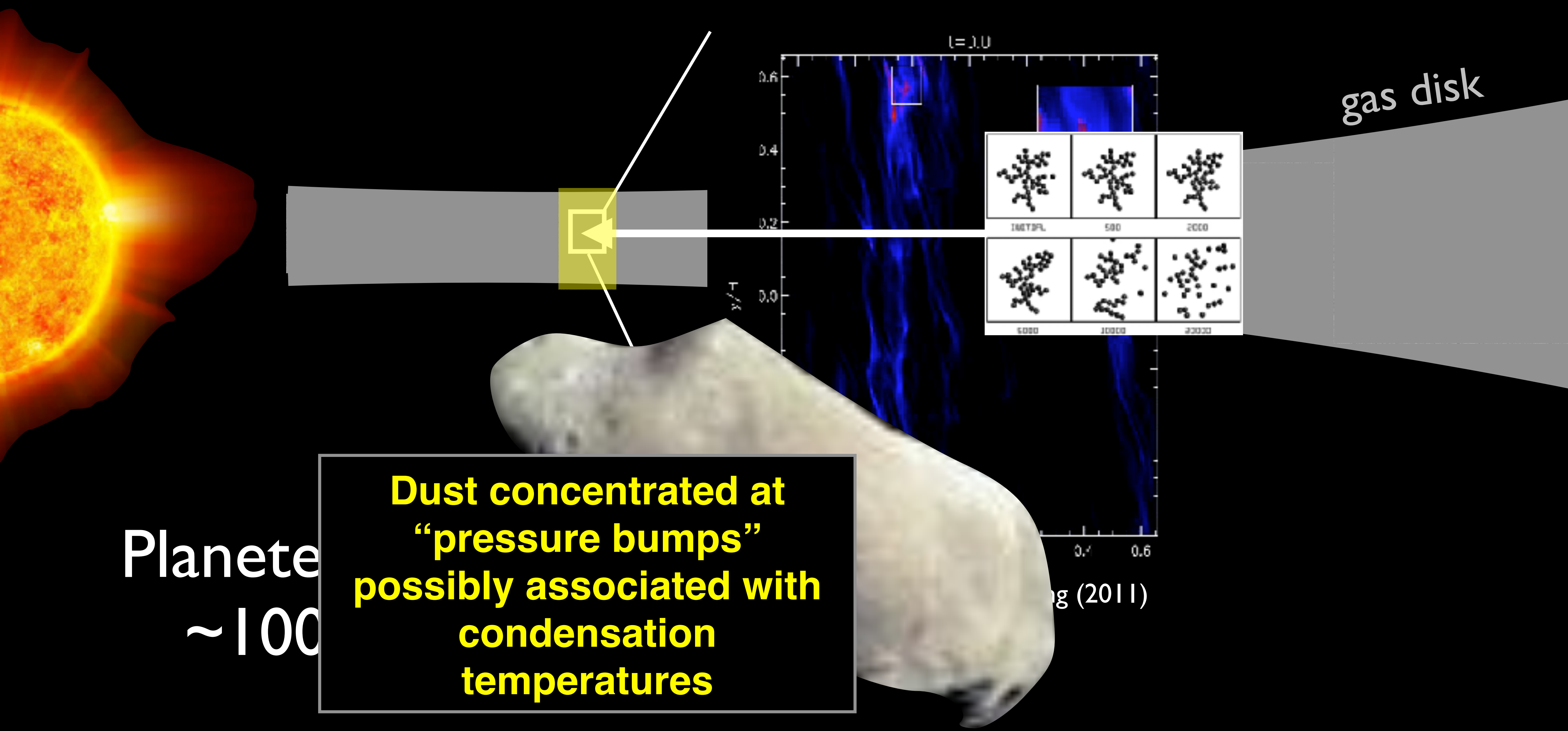
They formed in different places!

Surviving NC and CC planetesimals have overlapping orbits



Gradie & Tedesco 1982; Demeo & Carry 2014

Planetesimal formation models: dust growth/drift with disk evolution



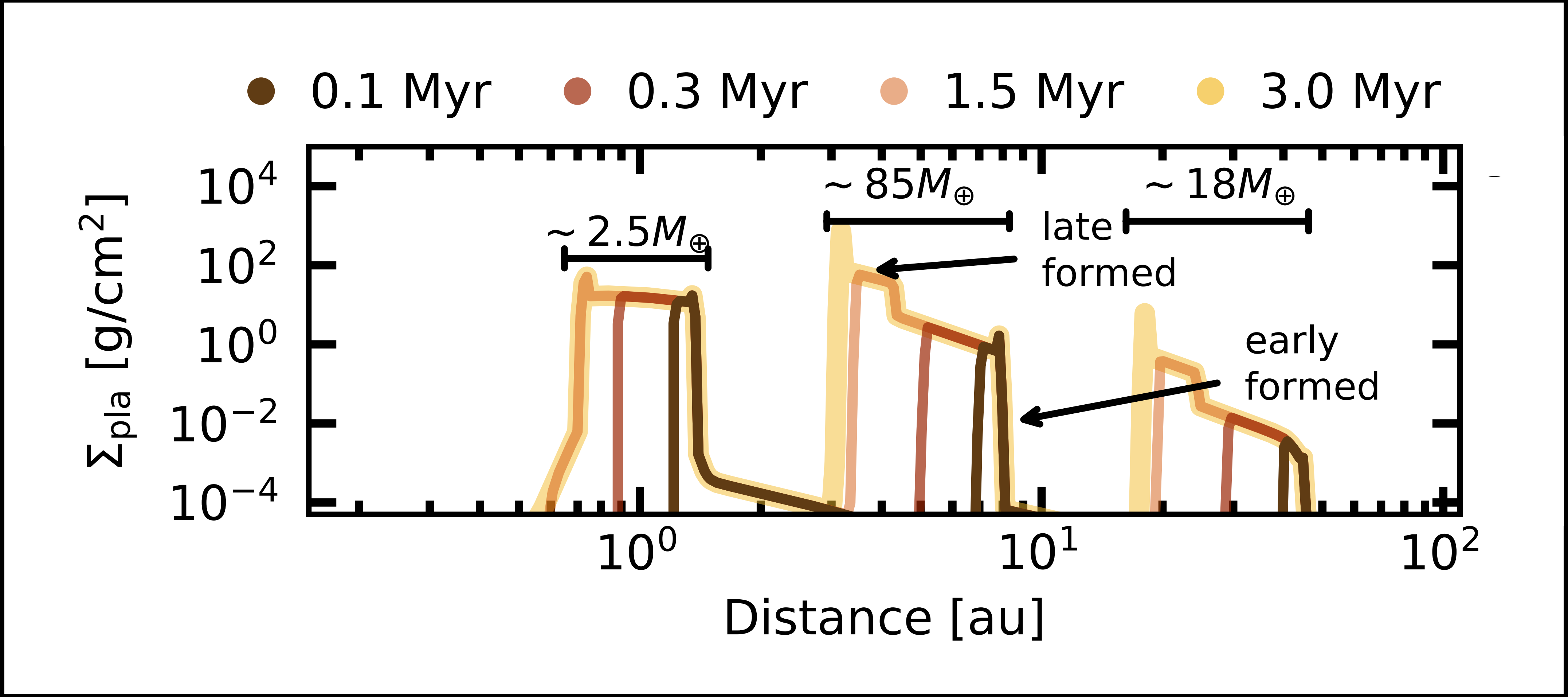
Dust concentrated at “pressure bumps” possibly associated with condensation temperatures

g (2011)

Planete

~100

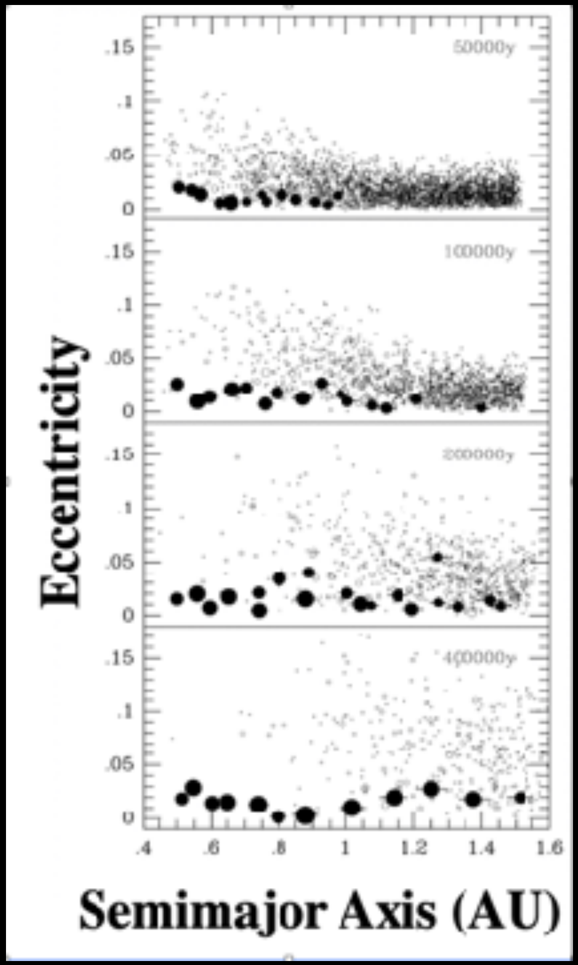
Three rings of planetesimals



Izidoro et al 2022

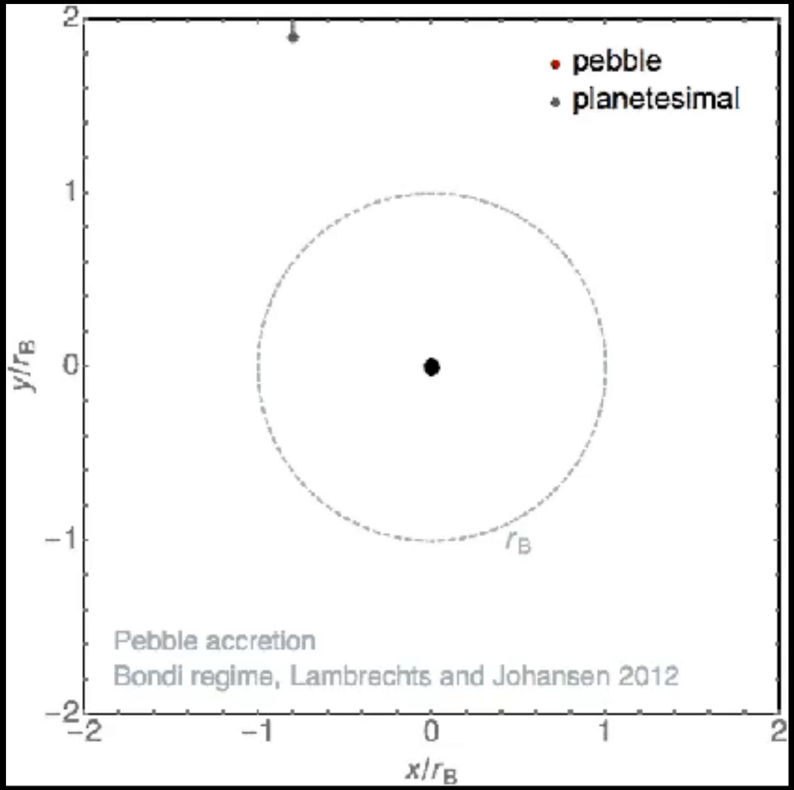
Key event 2: growth of *planetary embryos* and giant planet cores

inside snow line:
planetesimal accretion



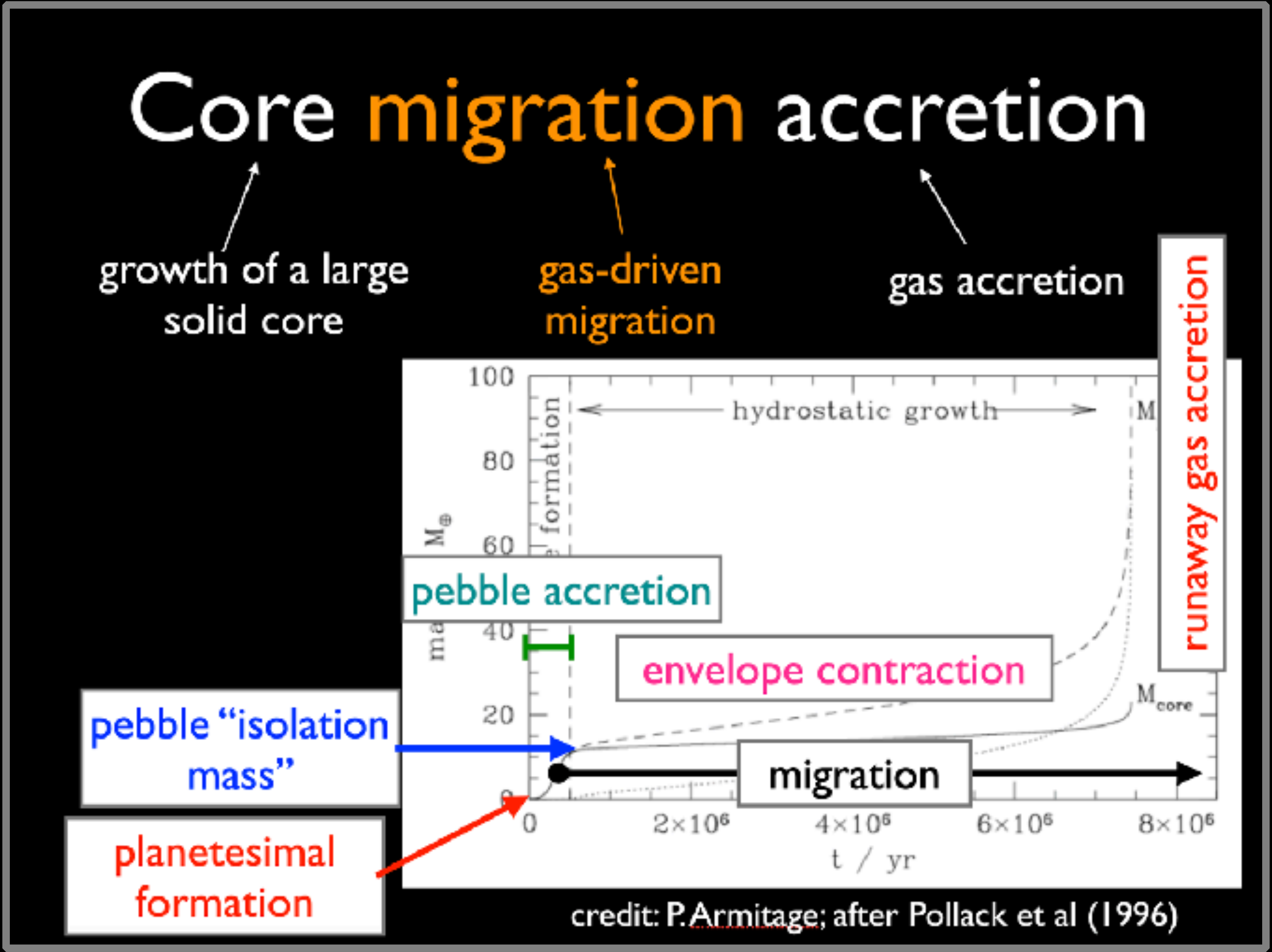
terrestrial planetary embryos:
~Mars-sized

beyond snow line:
pebble accretion



giant planet "cores":
~Earth-sized or larger

Key event 3: Growth of Jupiter and Saturn



Core migration accretion

growth of a large solid core

gas-driven migration

gas accretion

runaway gas accretion

pebble accretion

envelope contraction

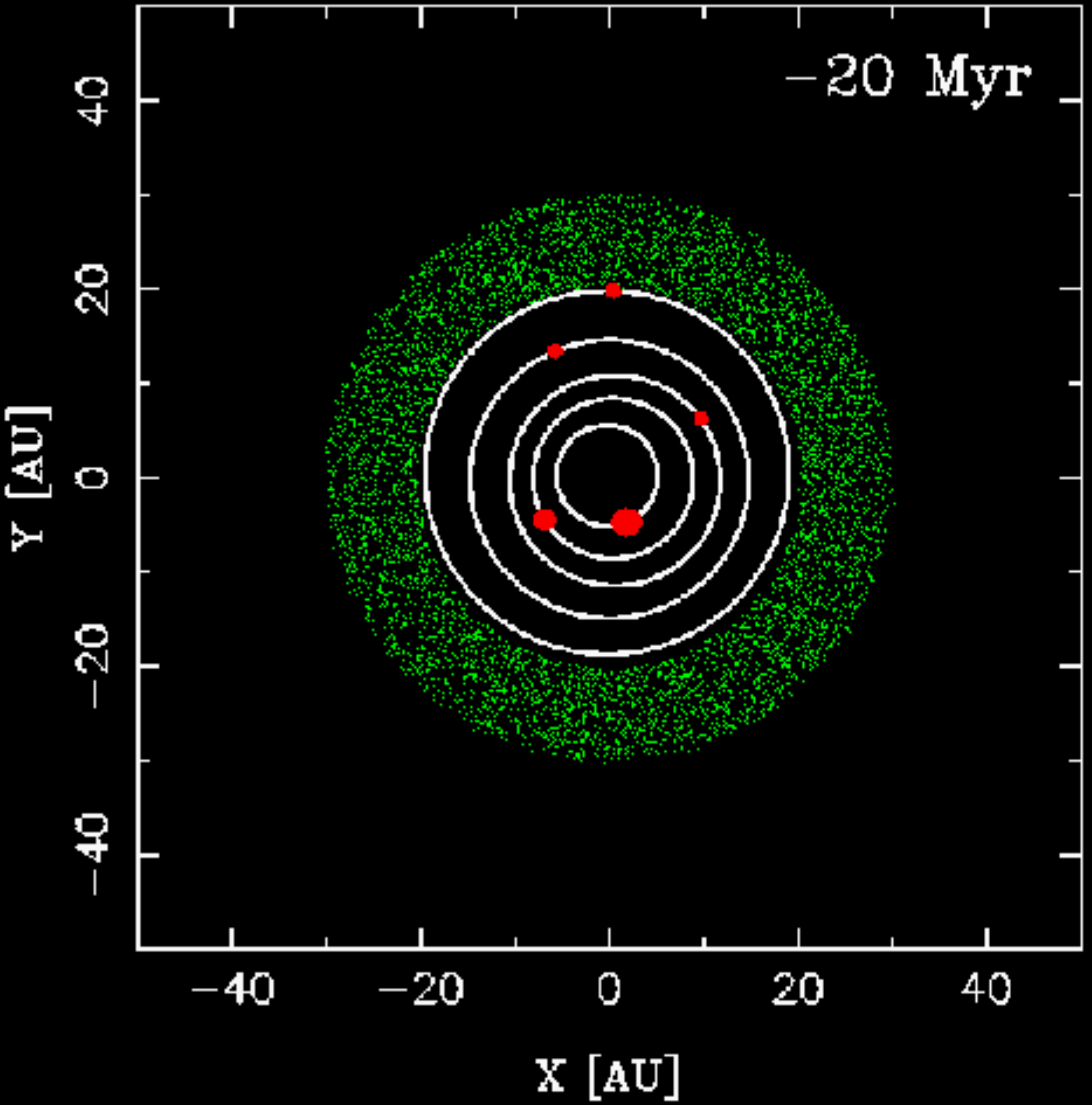
pebble "isolation mass"

migration

planetesimal formation

credit: P. Armitage; after Pollack et al (1996)

Key event 4: the giant planet (dynamical) instability

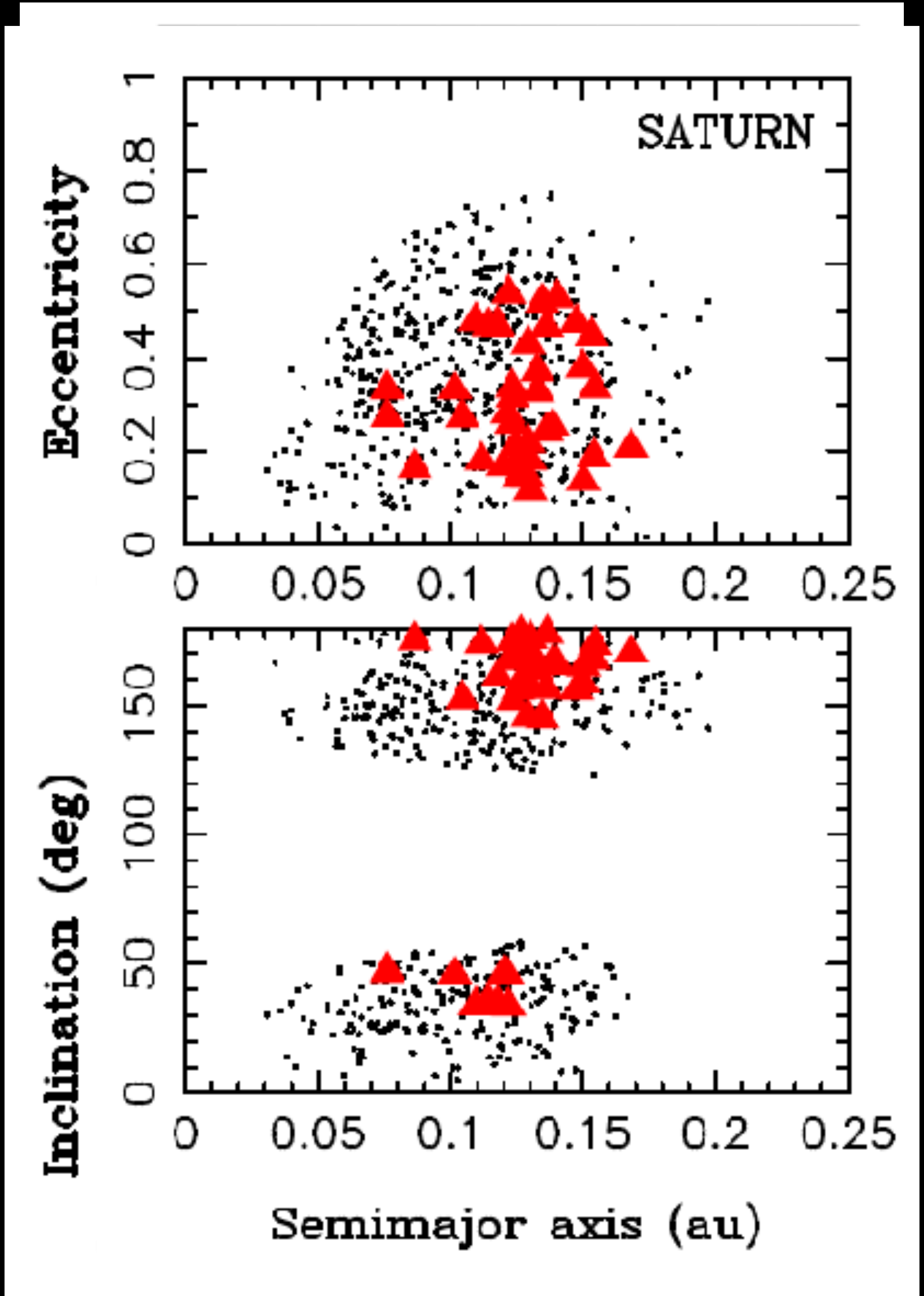


Nesvorny (2011)

also Tsiganis et al (2005), Morbidelli et al (2007), Batygin & Brown (2012), Clement et al (2021)…

The instability explains:

- Giant planets' orbits
- Inclinations of Jupiter's Trojan asteroids
- Capture of irregular satellites of the giant planets
- Orbital structure of the Kuiper belt

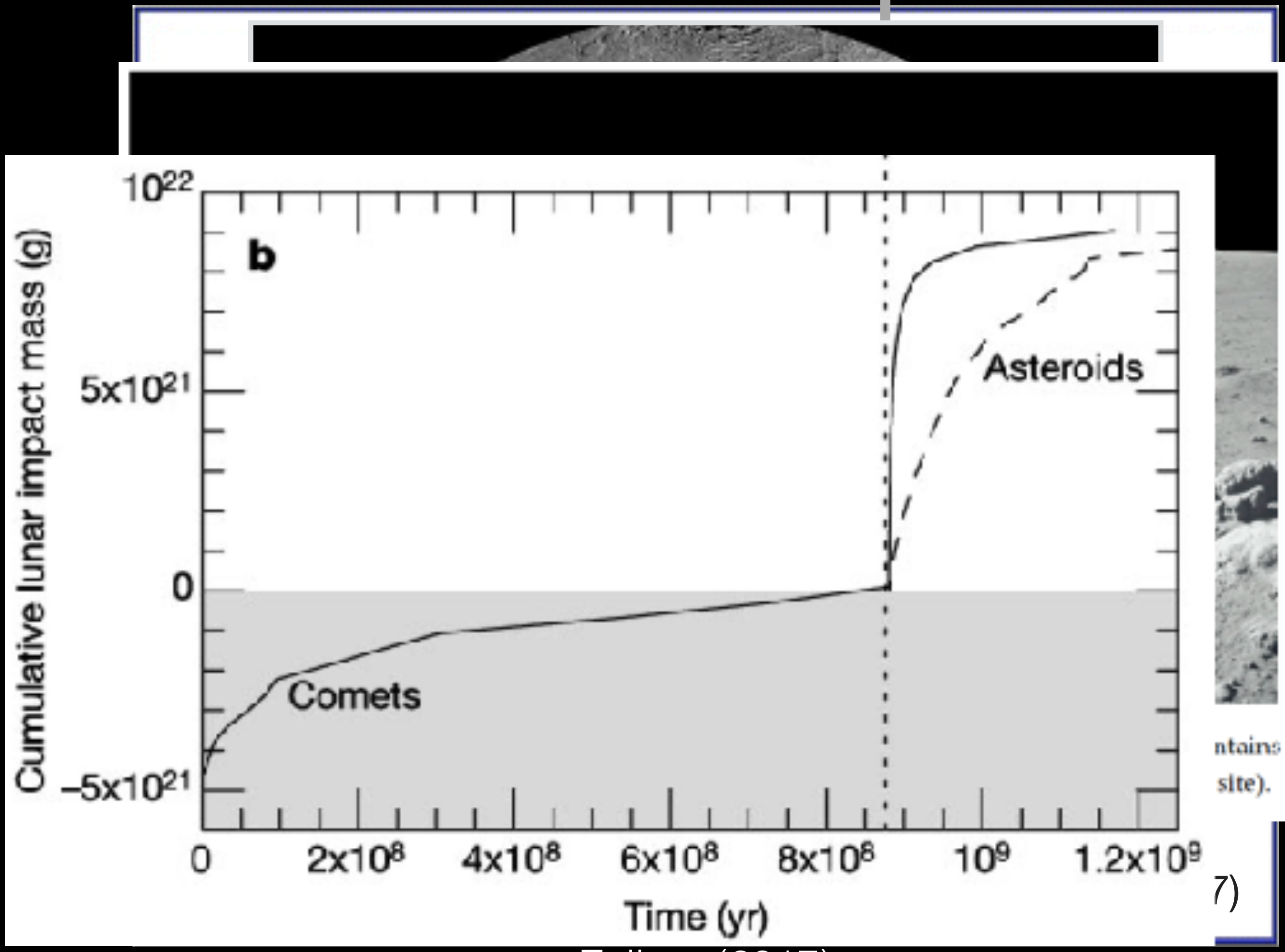


Nesvorny & Morbidelli (2012)

Nesvorny (2018)

When did the instability happen?

- “Terminal lunar cataclysm” likely sampling bias (Chapman et al 2007, Boehnke & Harrison 2016, Zellner 2017, Hartmann 2020)
- New analysis: instability earlier than ~100 Myr
  - Binary Jupiter Trojan (Nesvorny et al 2018)
  - Highly siderophile elements++ (Morbidelli et al 2018)
  - Reset ages in meteorite parent bodies (Mojzsis et al 2019



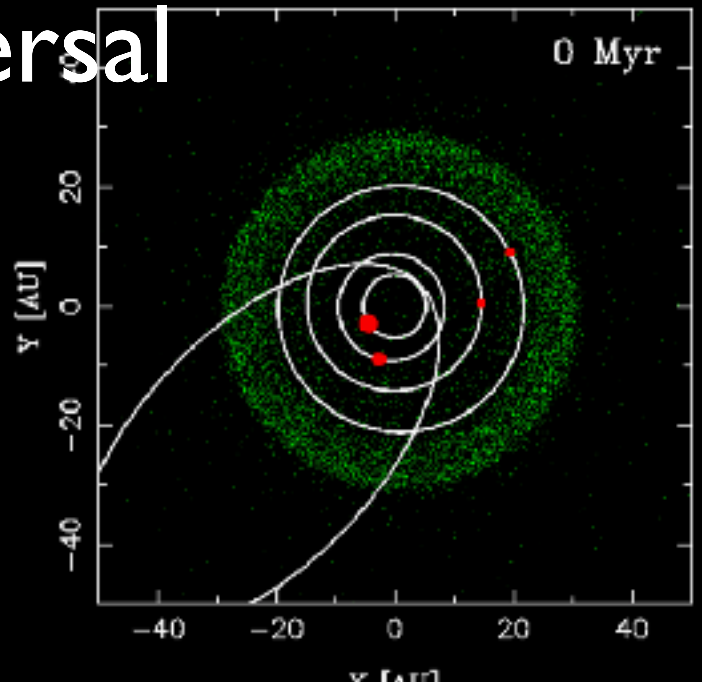
Original “Nice model” instability timing (Gomes et al 2005)

Zellner (2017)

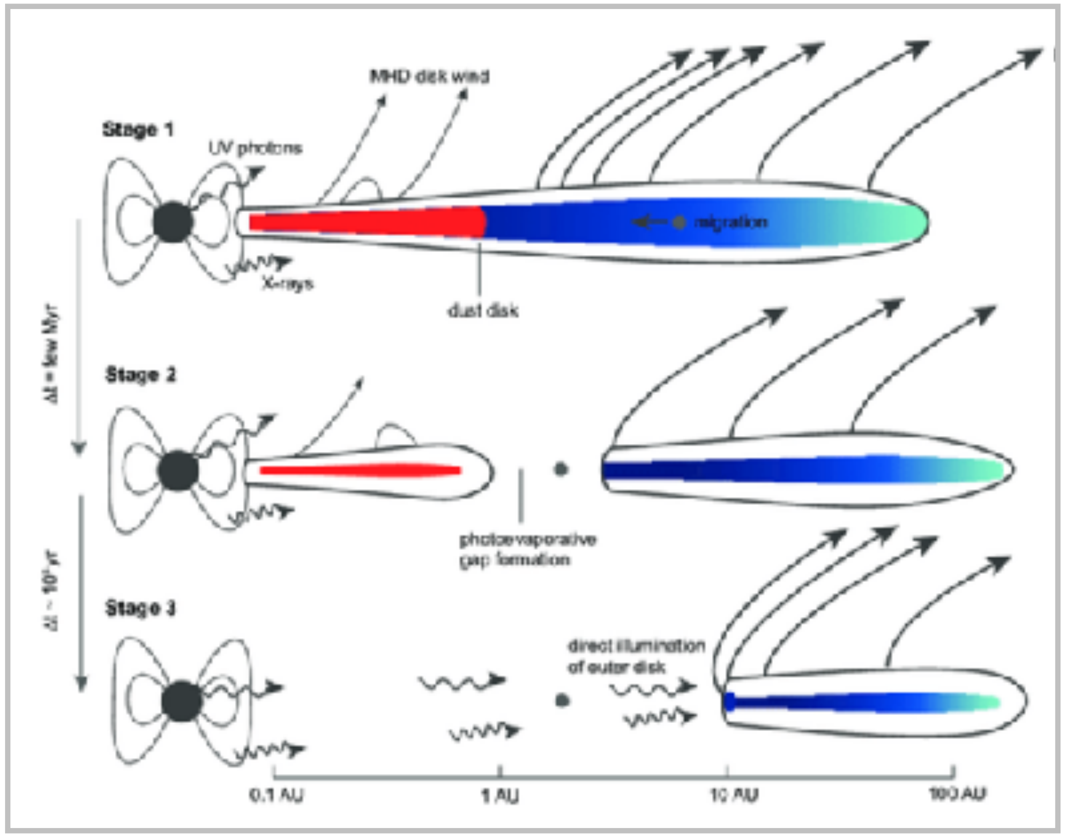
New results based on Pd-Ag isotopes and asteroid reset ages favor instability shortly after gas disk dispersal (Hunt et al 2022; Harper Edwards et al 2024)

Possible instability triggers

1. Gas disk-driven instability: instability happens at gas disk dispersal (Liu et al 2022)
2. Self-triggered instability: instability within few Myr of gas dispersal (Ribeiro de Sousa et al 2020)
3. Planet-planetesimal disk interactions: instability ~30-60 Myr after gas dispersal (Quarles & Kaib 2019; Ribeiro de Sousa 2020)

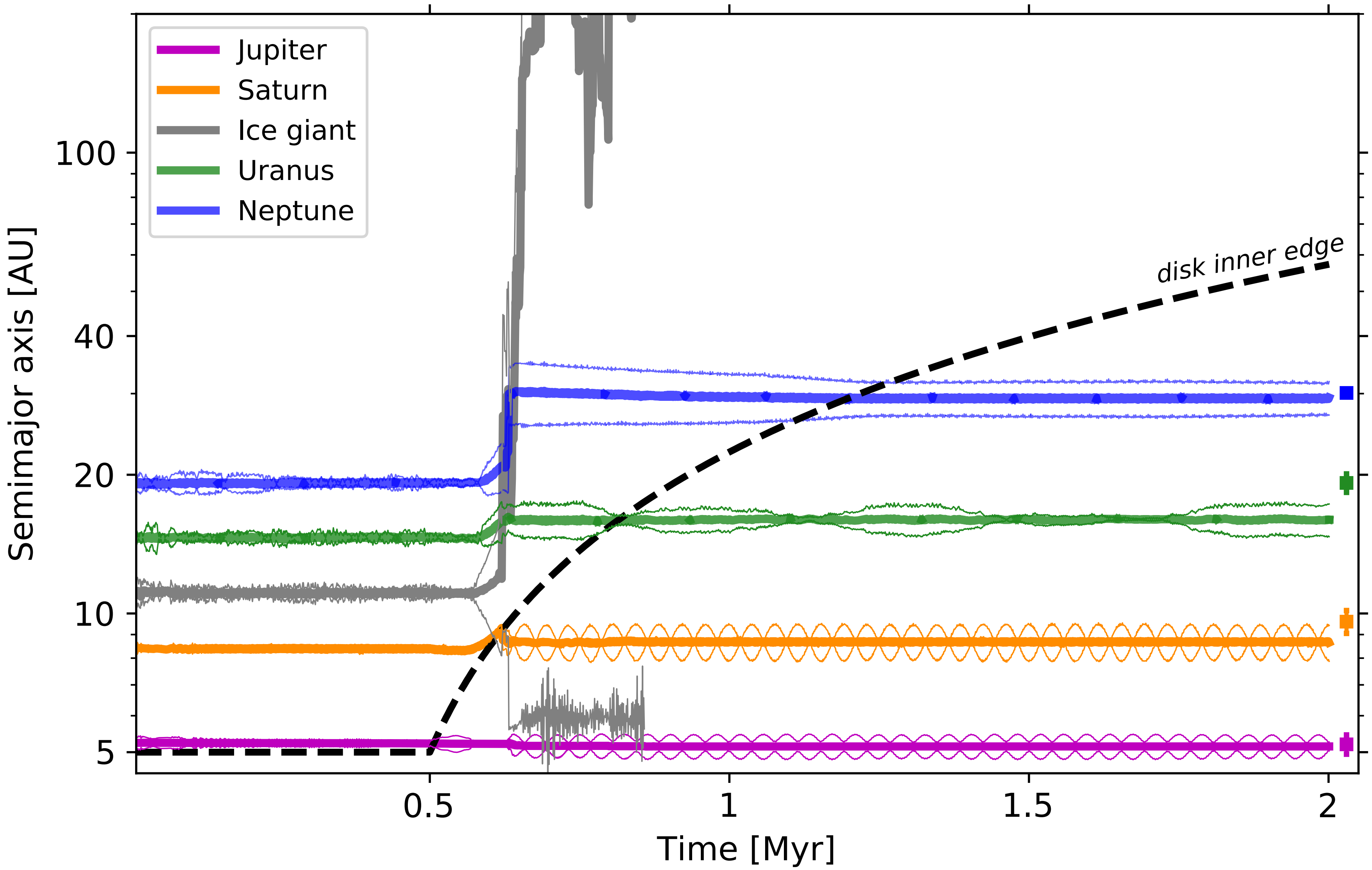


Possible instability trigger: inside-out photo-evaporation of gaseous disk



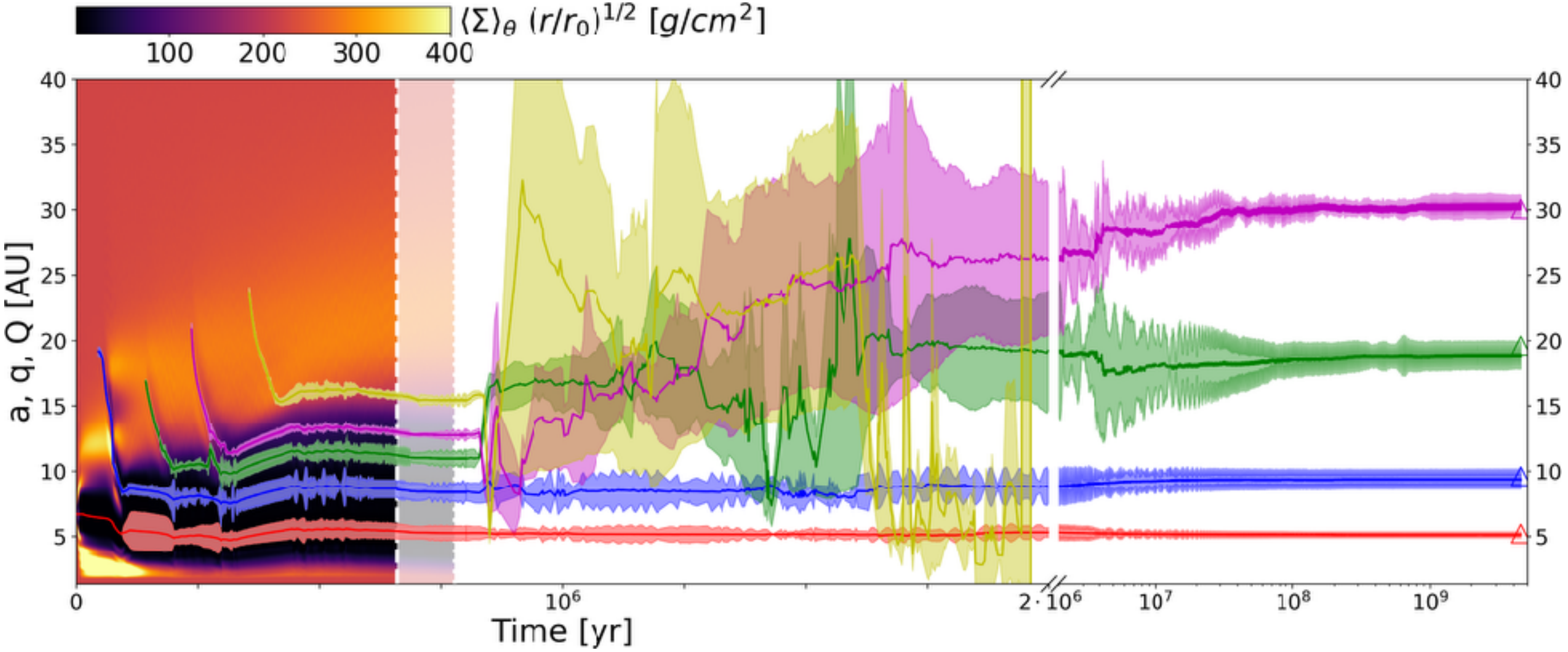
Ercolano & Pascucci (2017)

Giant planet instability driven by dispersal of gaseous disk



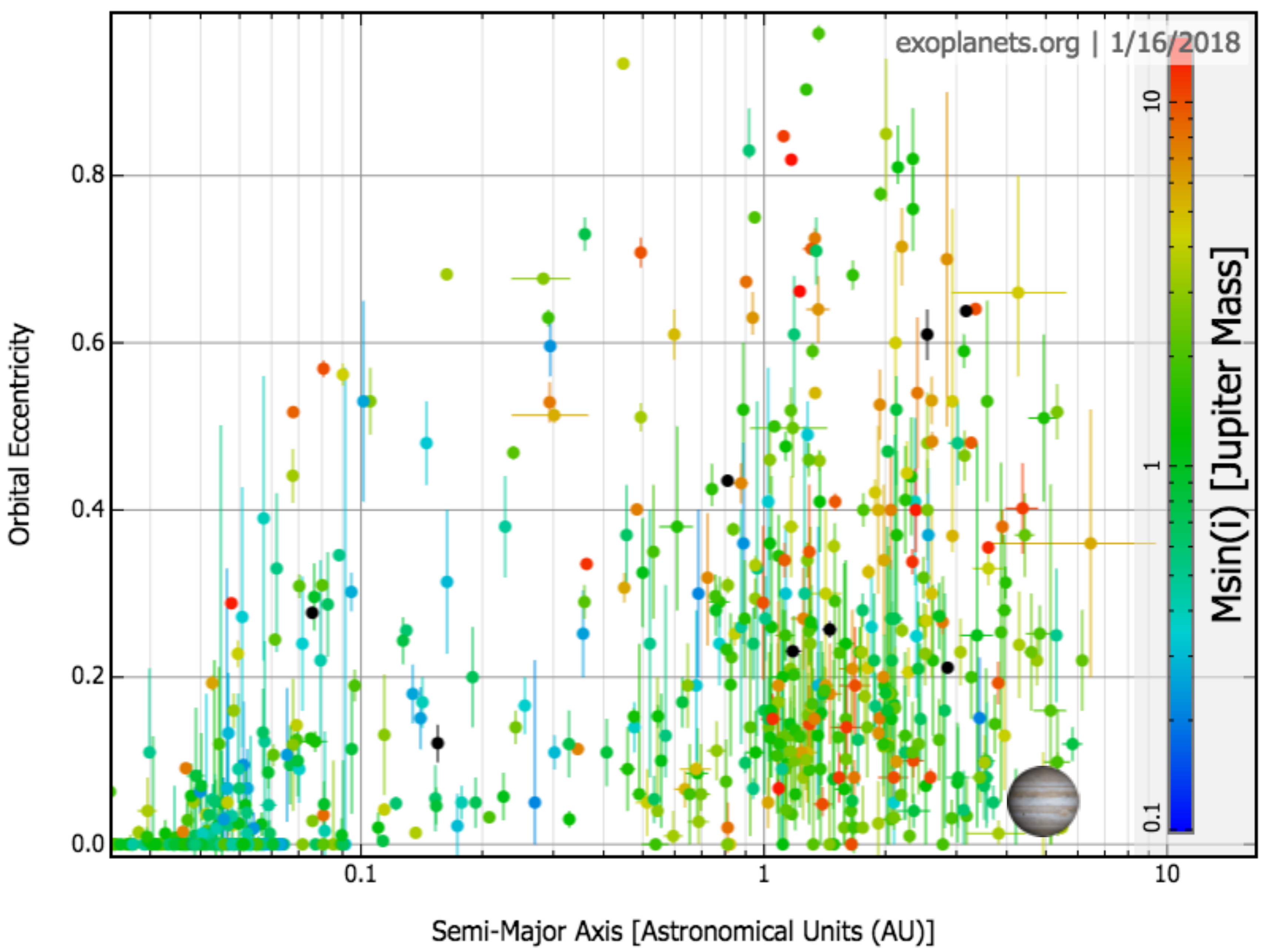
Liu et al (2022)

Another example: self-triggered instability after gas disk dispersal



Griveaud et al (2024)

Remember : the Solar System's dynamical instability was very gentle when compared with exoplanets



Wright et al 2011

Key event 5: the Moon-forming impact

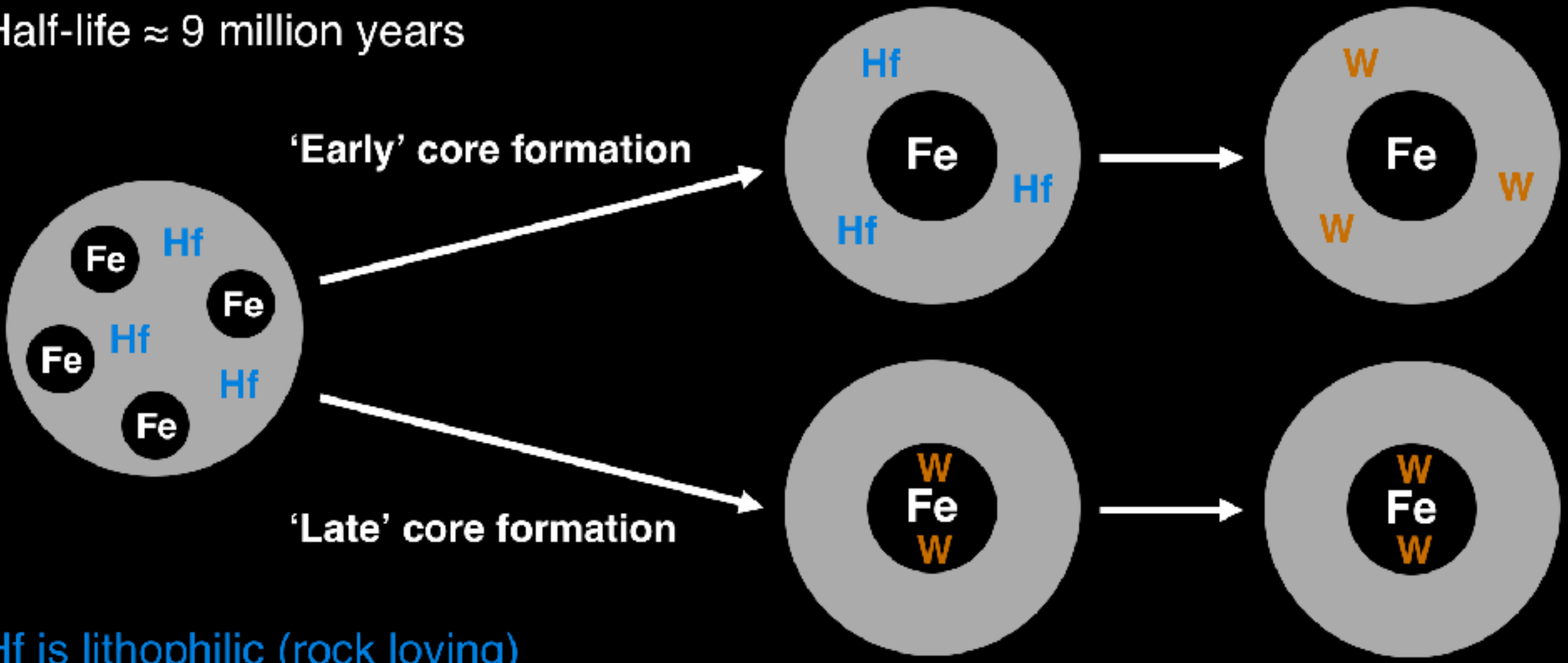
Thought to represent final embryo-embryo impact, at t~50-100 Myr (e.g. Kleine et al 2009)

Credit: Kegerreis et al (2022)

Hafnium — Tungsten Dating

$^{182}\mathrm{Hf} \rightarrow {}^{182}\mathrm{W}$

Half-life ≈ 9 million years



Hf is lithophilic (rock loving)

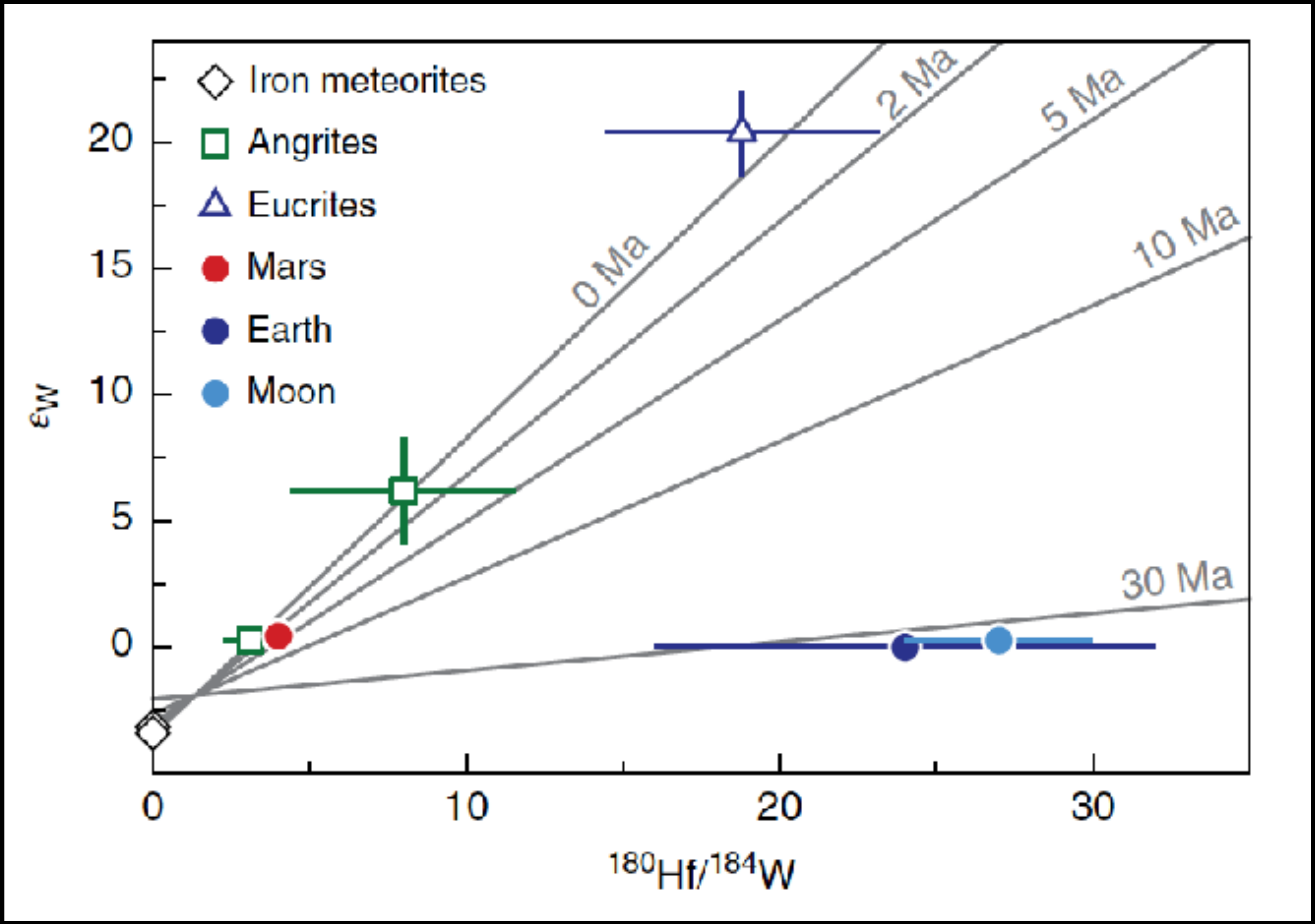
W is siderophilic (iron loving)

credit: viranga13 (Wikimedia commons)

Hf/W isotopes constrain Earth's core formation time (last giant impact)

Half-life of Hf decay = 8.9 Myr

$$\varepsilon_W = \left[\frac{\left({}^{182}\mathrm{W} / {}^{184}\mathrm{W} \right)_{\mathrm{sample}}}{\left({}^{182}\mathrm{W} / {}^{184}\mathrm{W} \right)_{\mathrm{standard}}} - 1 \right] \times 10^4$$

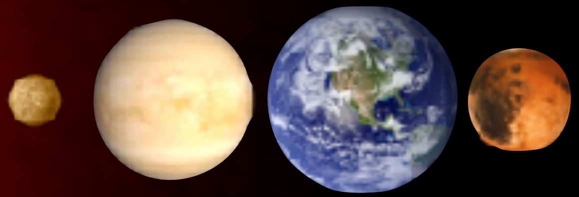


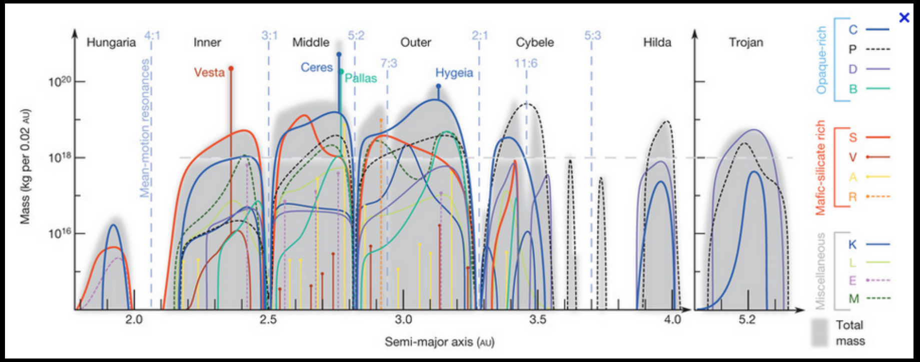
Nimmo & Kleine (2015)

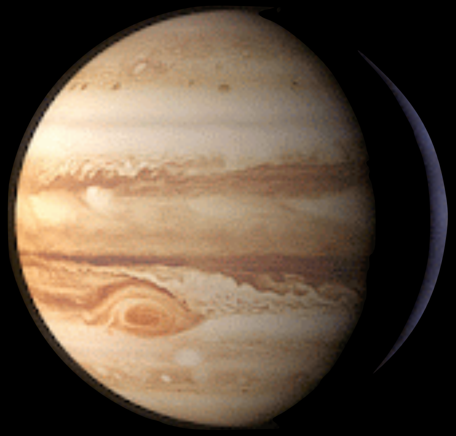
Terrestrial planet formation models

The goal: reproduce the (inner) Solar System

Demeo & Carry 2014







$2\ M_{Earth}$

Number, masses

Orbits

Growth timescales, compositions, **isotopic ratios**

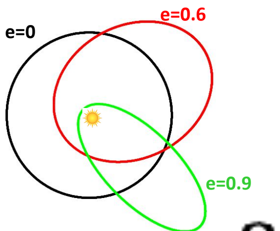
$5\times10^{-4}\ M_{Earth}$

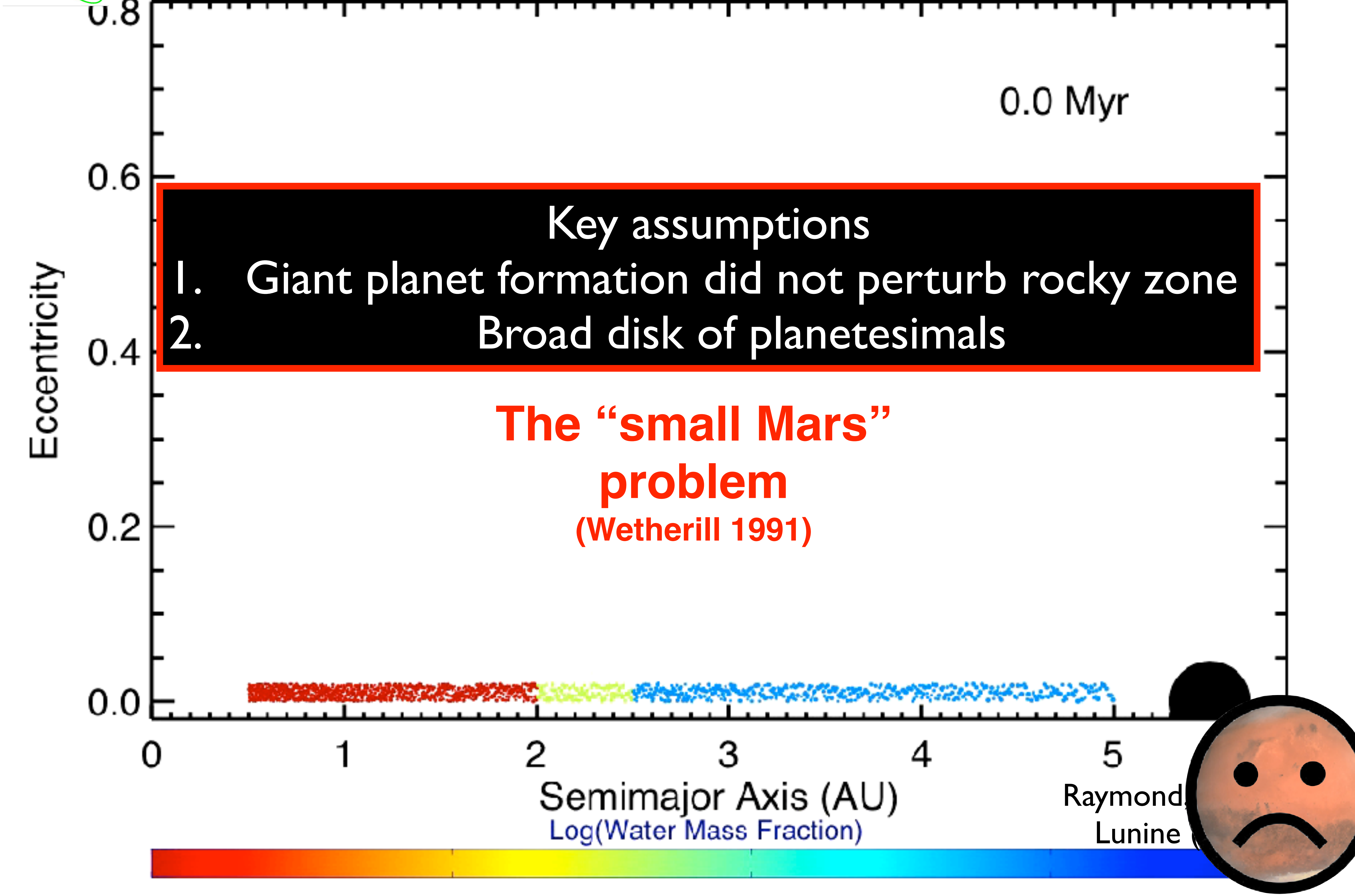
Total mass

S/C dichotomy

Orbital distribution

The “classical model”



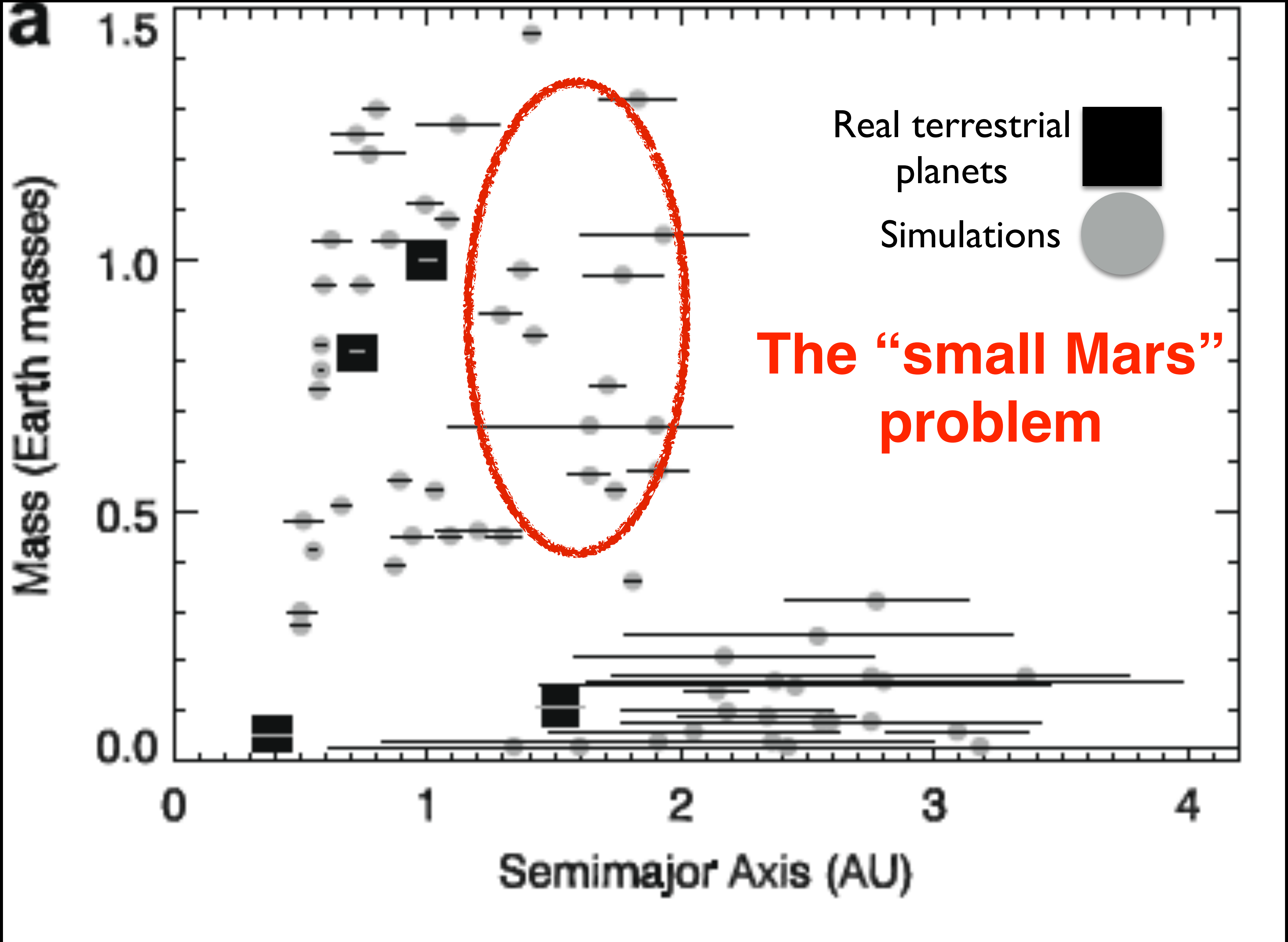


Key assumptions

1. Giant planet formation did not perturb rocky zone
2. Broad disk of planetesimals

The “small Mars” problem

(Wetherill 1991)



The “small Mars” problem

Raymond et al 2009

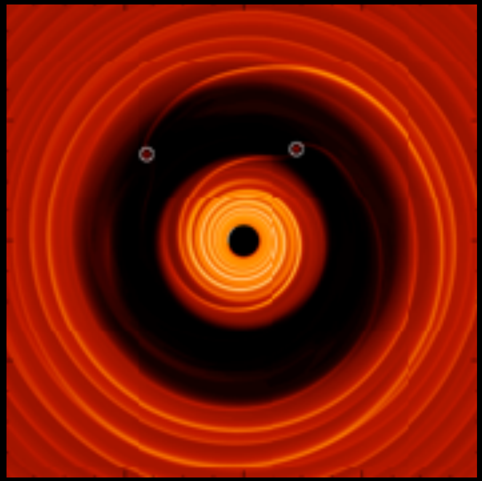
Wetherill 1991; Chambers 2001; O’Brien et al 2006; Raymond et al 2006, 2009, Morishima et al 2008, 2010; Nagasawa et al 2005, 2007; Thommes et al 2008; Fischer & Ciesla 2014; Izidoro et al 2014, 2015, Kaib & Cowan (2015), Woo et al (2020, 2021)

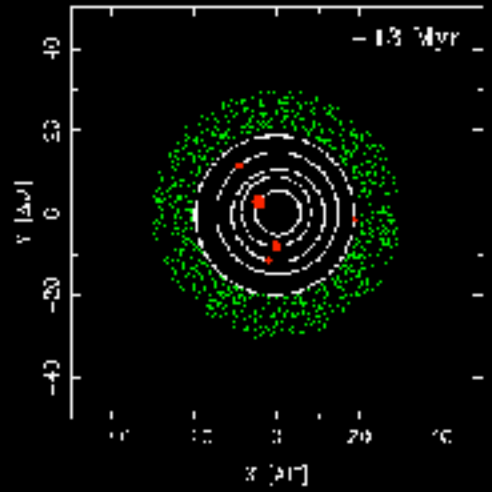
Possible solutions to the small Mars problem


“Empty asteroid belt”


Pebble-driven


Convergent migration


The “Grand Tack”

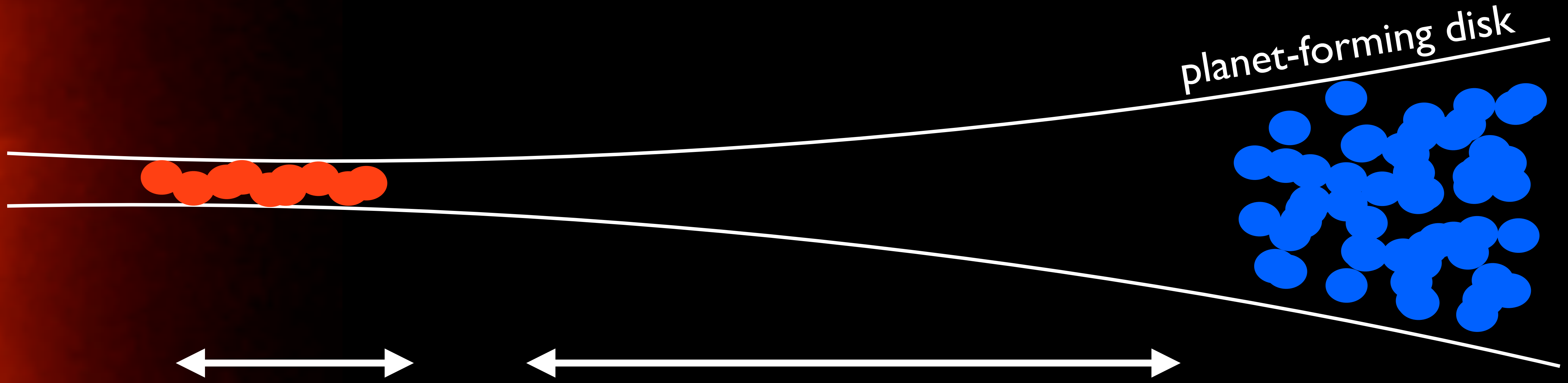


Early instability


Later dynamical sculpting

1. Empty asteroid belt

Assumption: few (if any) planetesimals formed in Mars region/asteroid belt

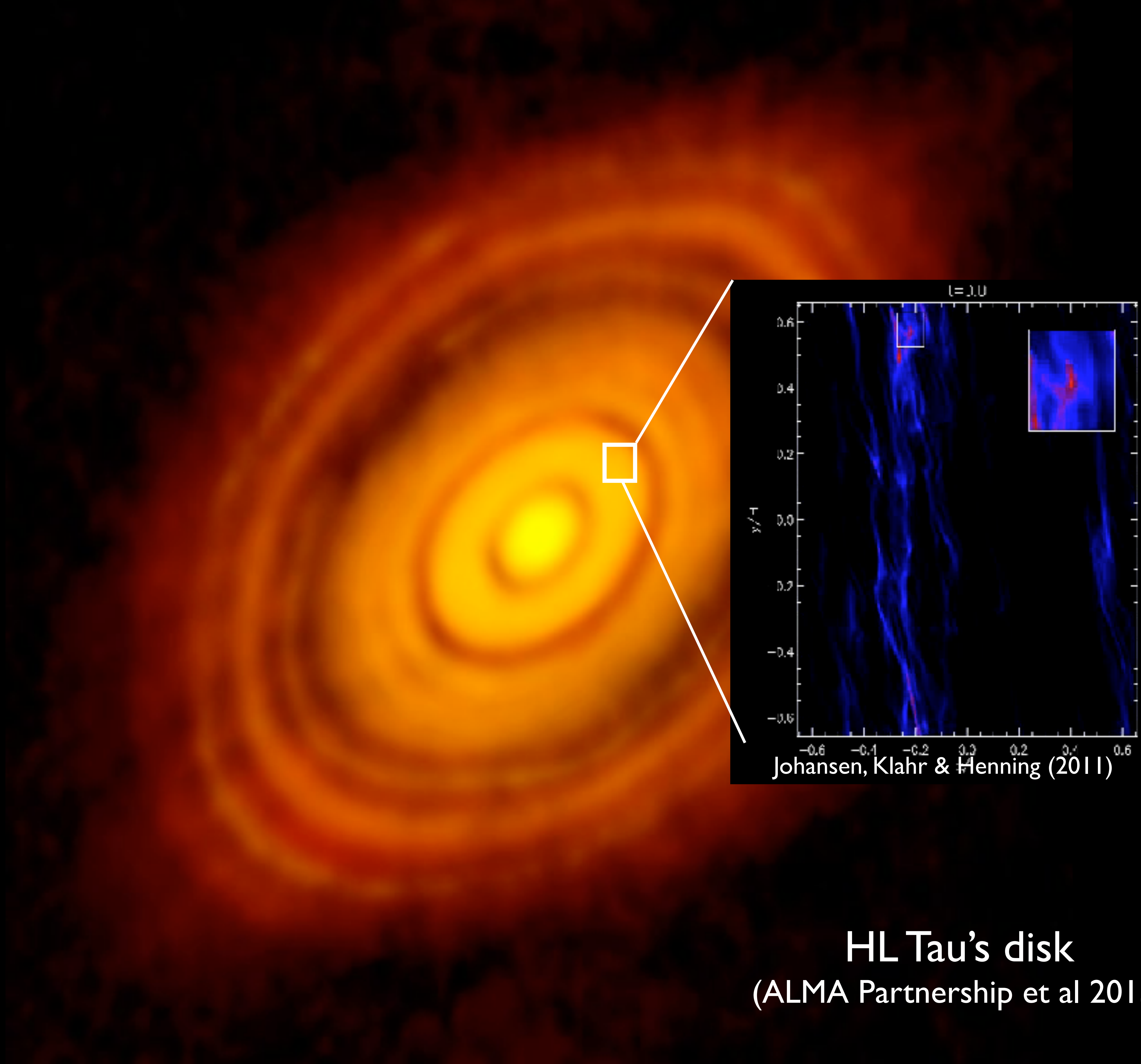


planet-forming disk

$2\ M_{Earth}$

No (or few) planetesimals

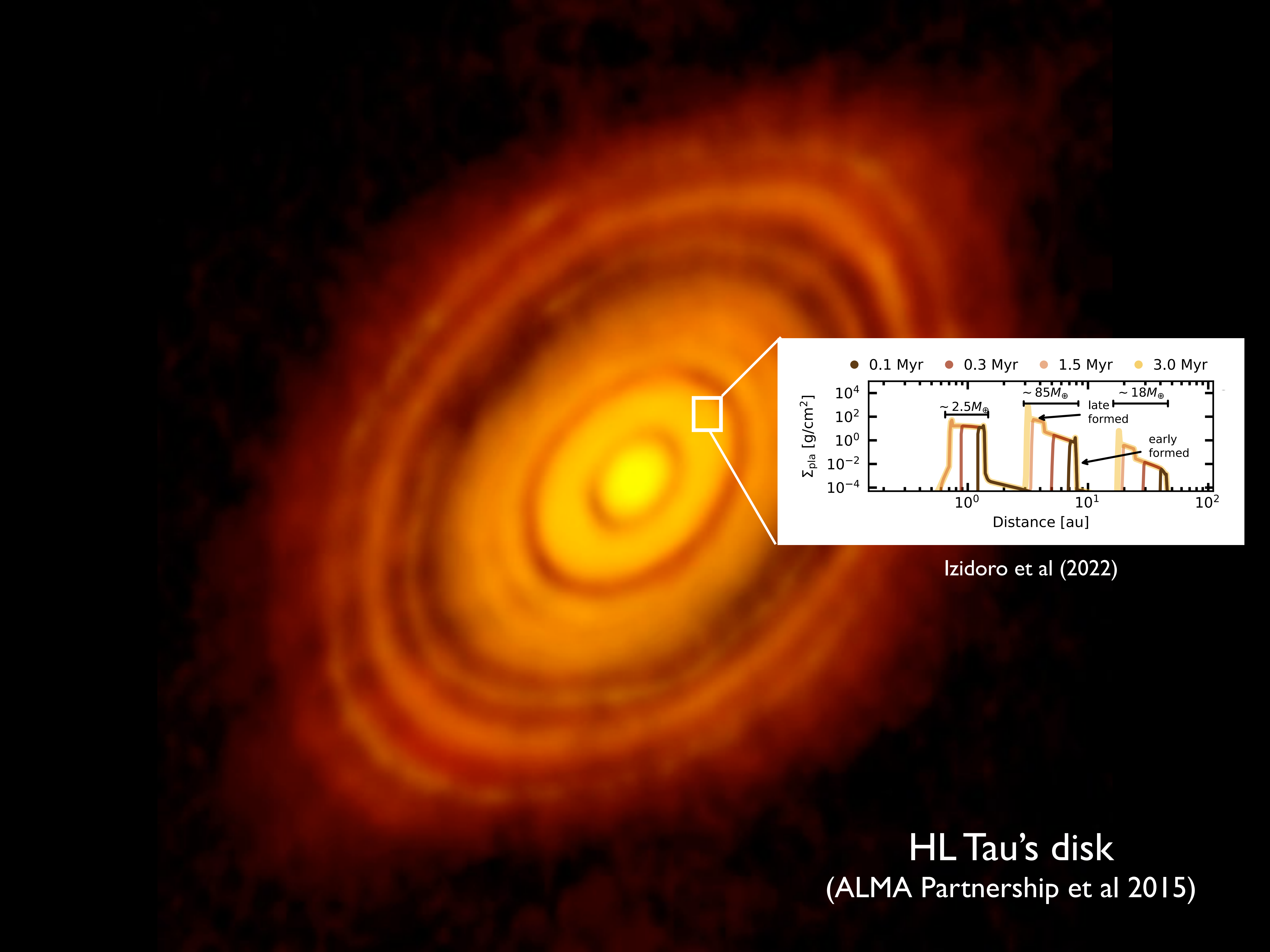
(Hansen 2009; Izidoro et al 2015; Kaib & Cowan 2015; Walsh & Levison 2016, 2019; Drazkowska et al 2016; Raymond & Izidoro 2017b)



Johansen, Klahr & Henning (2011)

HL Tau’s disk

(ALMA Partnership et al 2015)



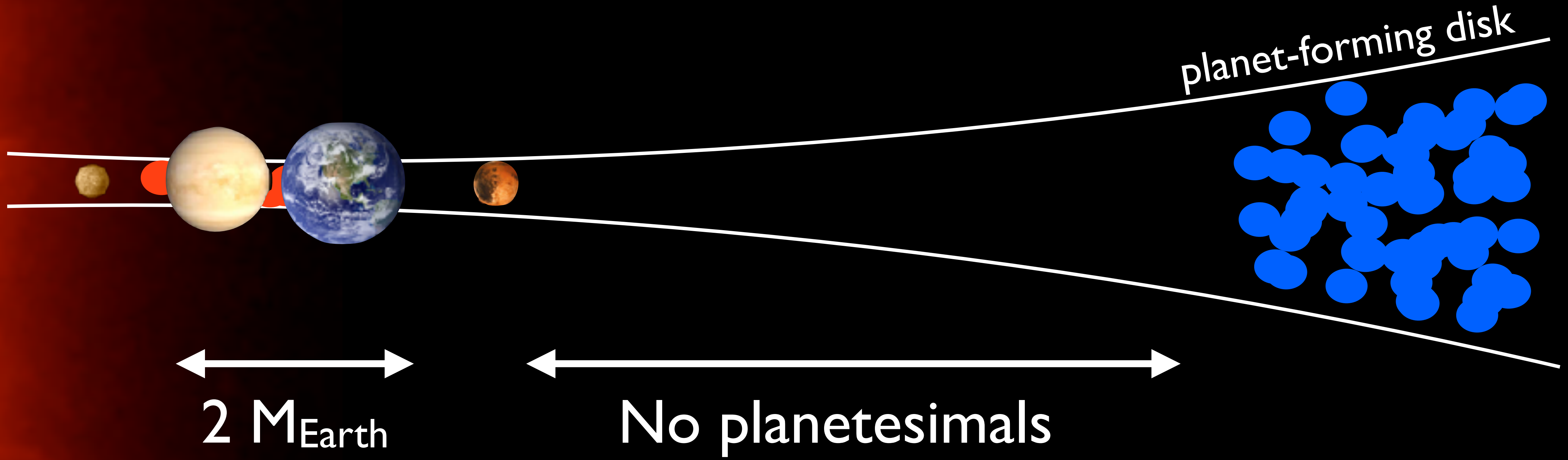
Izidoro et al (2022)

HL Tau's disk

(ALMA Partnership et al 2015)

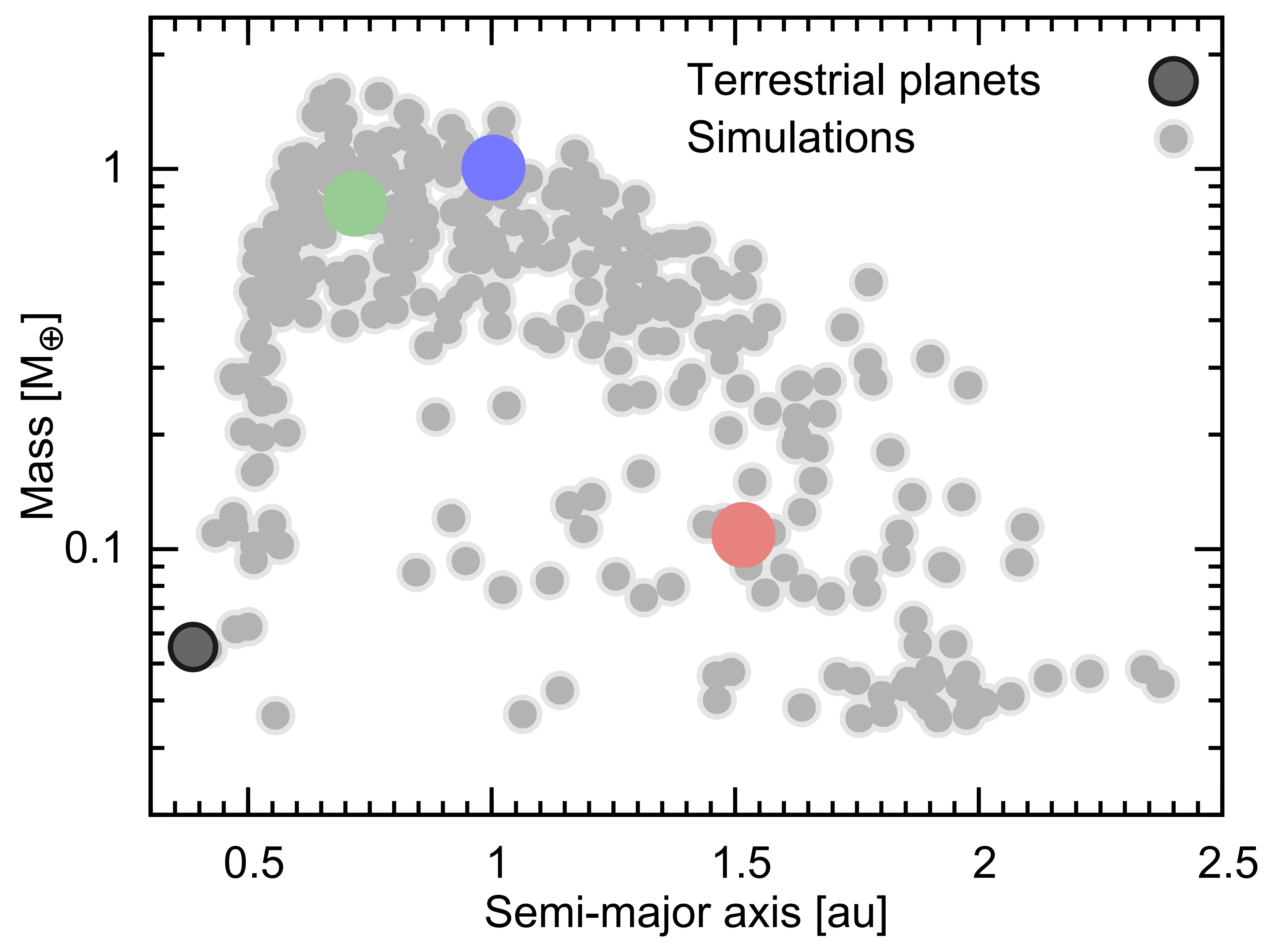
1. Empty asteroid belt

Assumption: few (if any) planetesimals formed in Mars region/asteroid belt

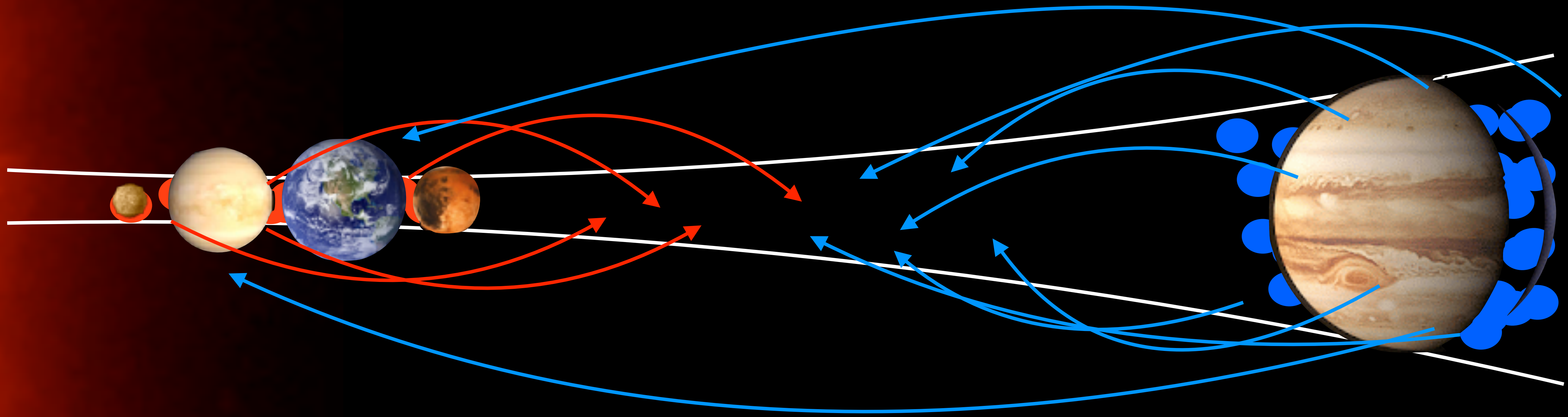


(Hansen 2009; Izidoro et al 2015; Kaib & Cowan 2015; Walsh & Levison 2016, 2019; Drazkowska et al 2016; Raymond & Izidoro 2017b)

1. Empty asteroid belt



Izidoro et al 2022



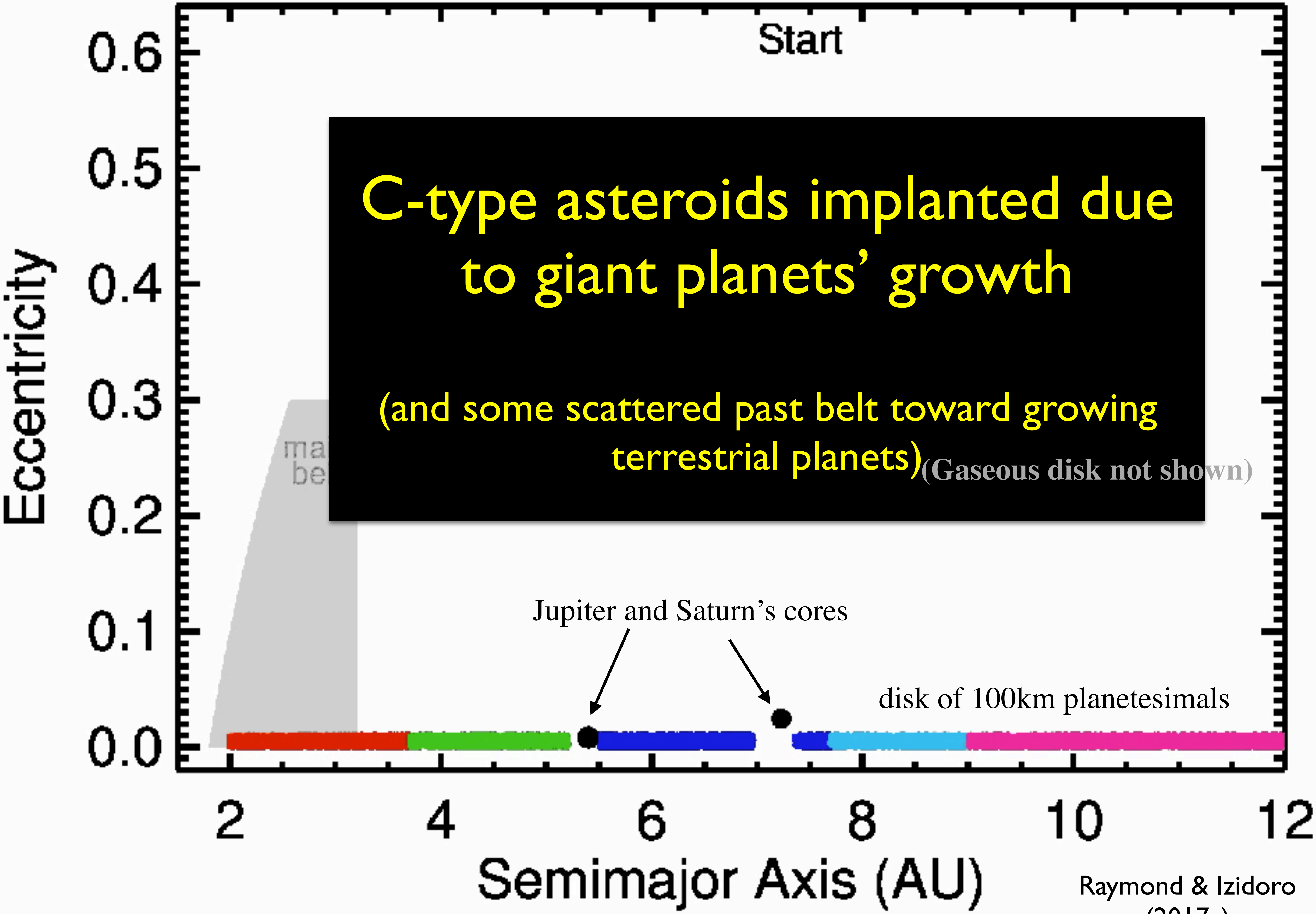
C-types and some of Earth's water
from giant planet region

NC asteroids (Vesta, Irons, S-types, …)
scattered out from terrestrial planet region

Raymond & Izidoro (2017a,b)

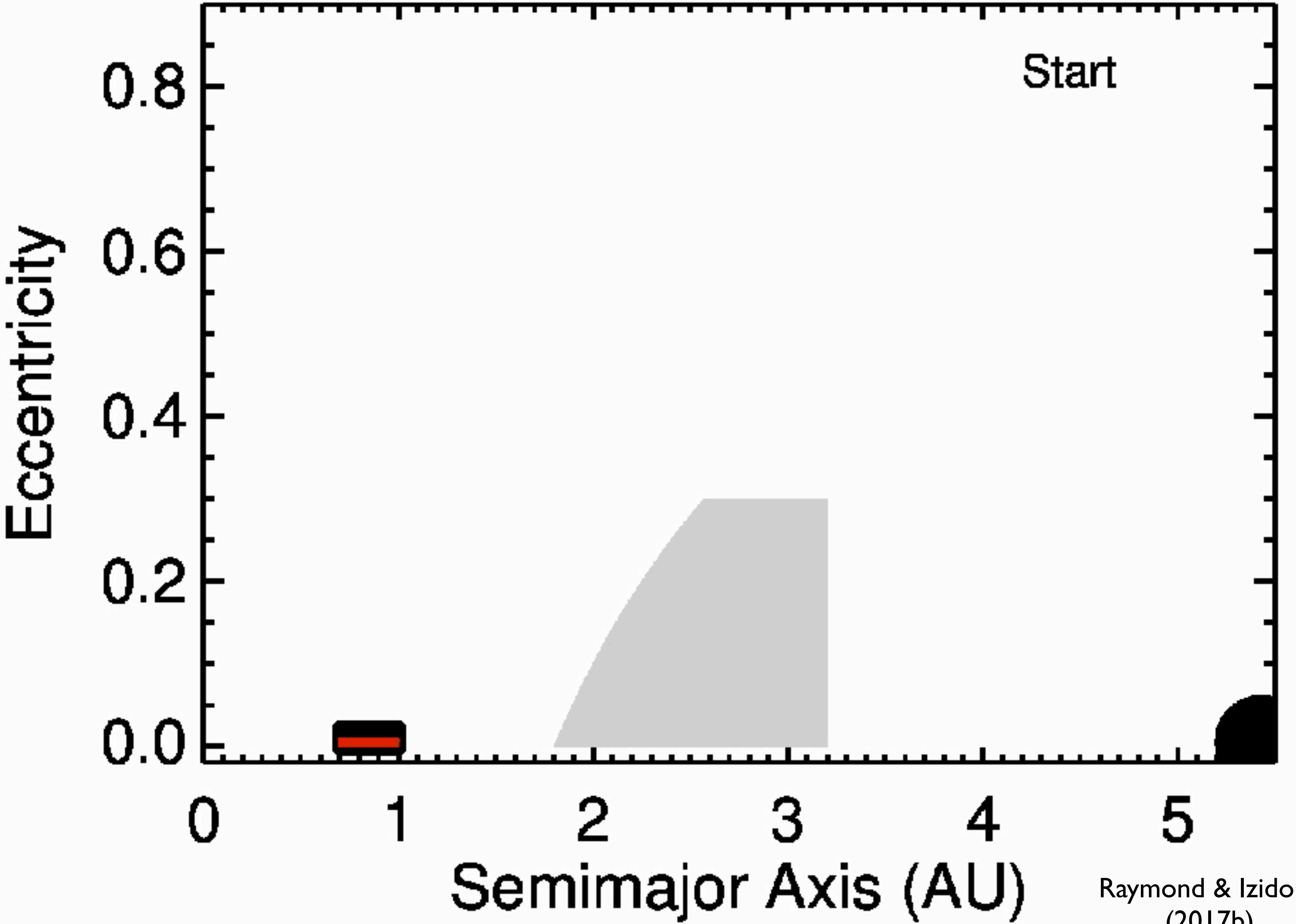
C-type asteroids implanted due to giant planets' growth

(and some scattered past belt toward growing terrestrial planets)



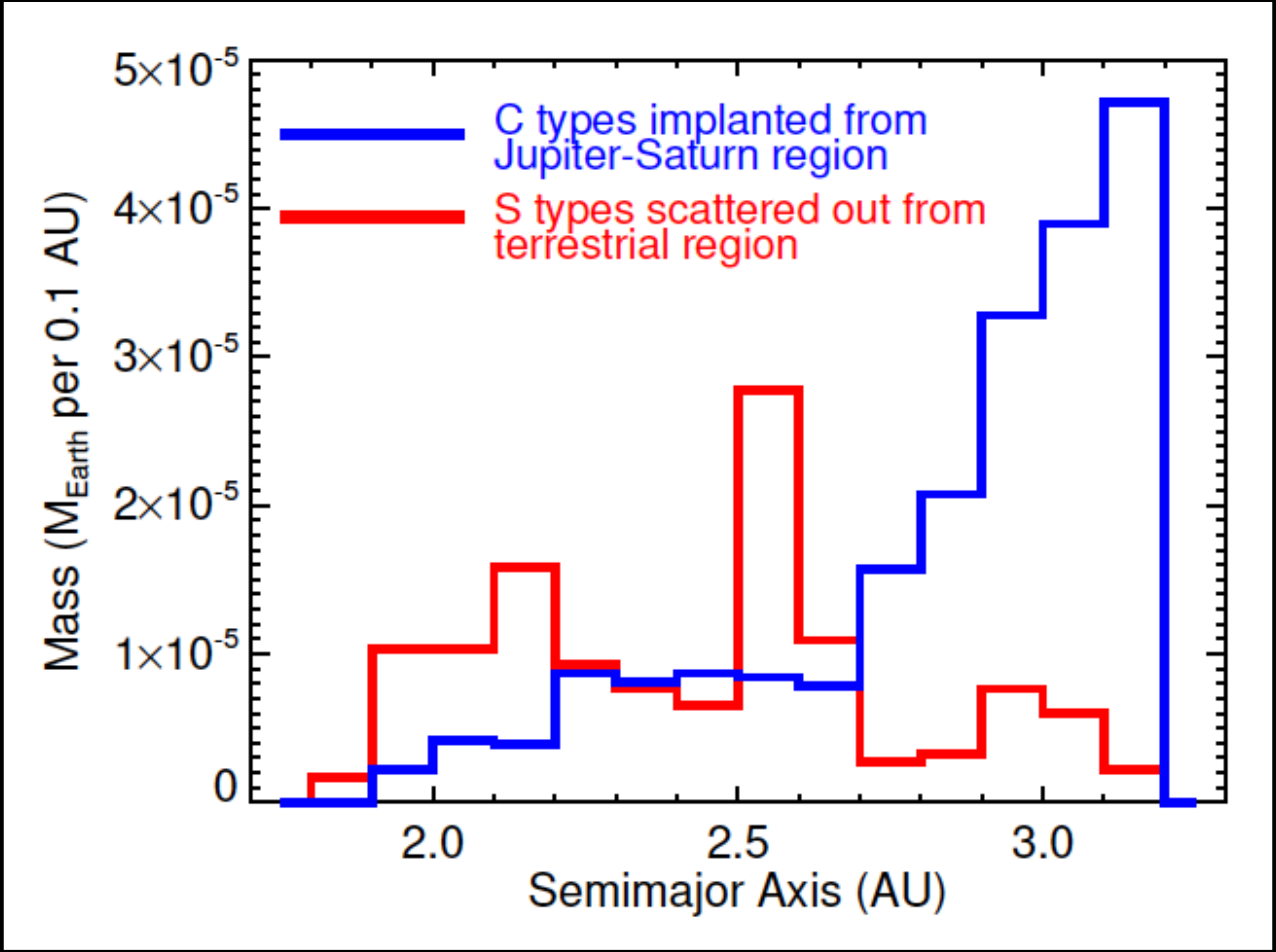
Raymond & Izidoro
(2017a)

50 simulations of terrestrial planet formation



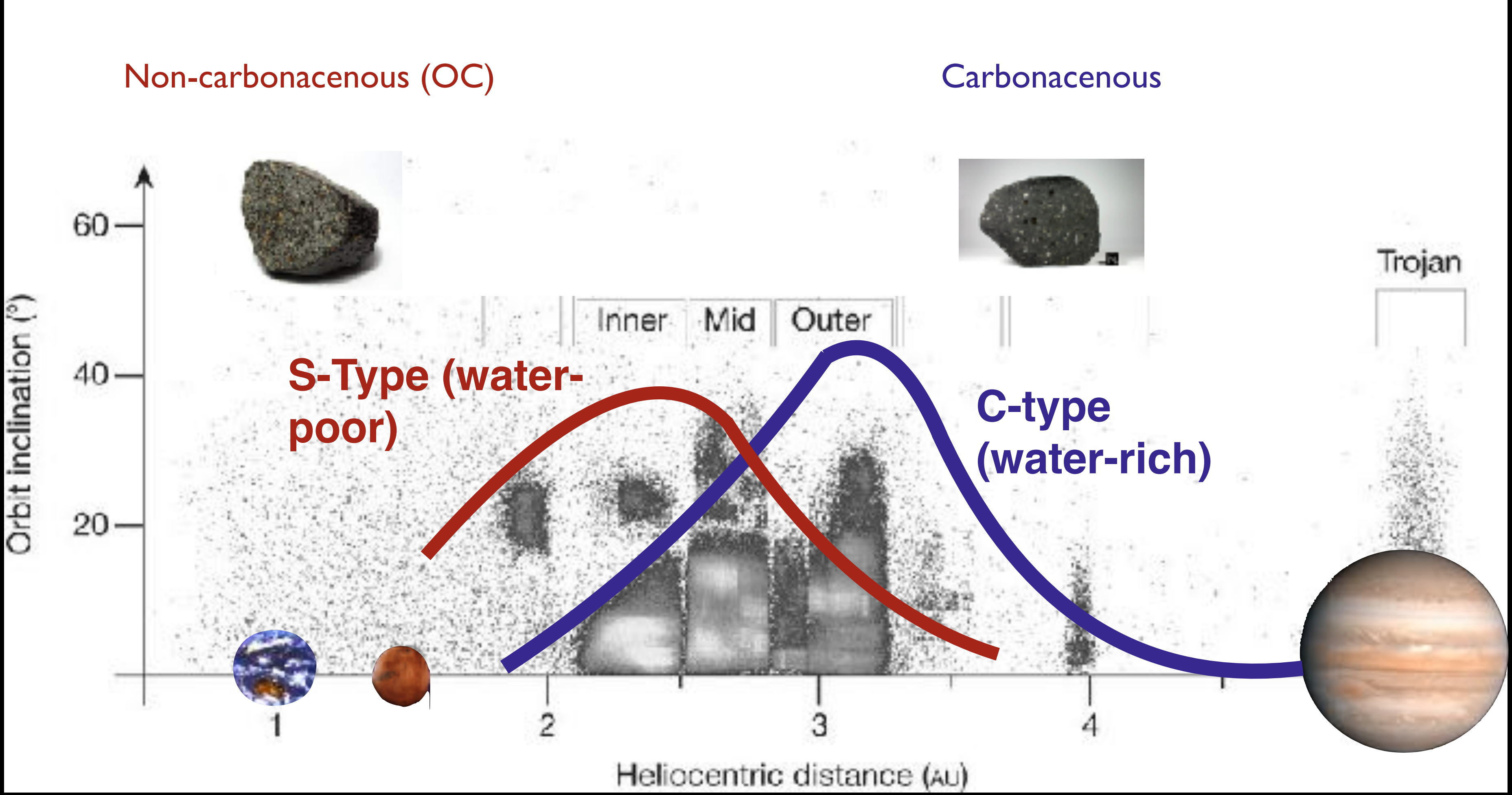
Raymond & Izidoro
(2017b)

100% implanted asteroid belt



Raymond & Izidoro (2017b)

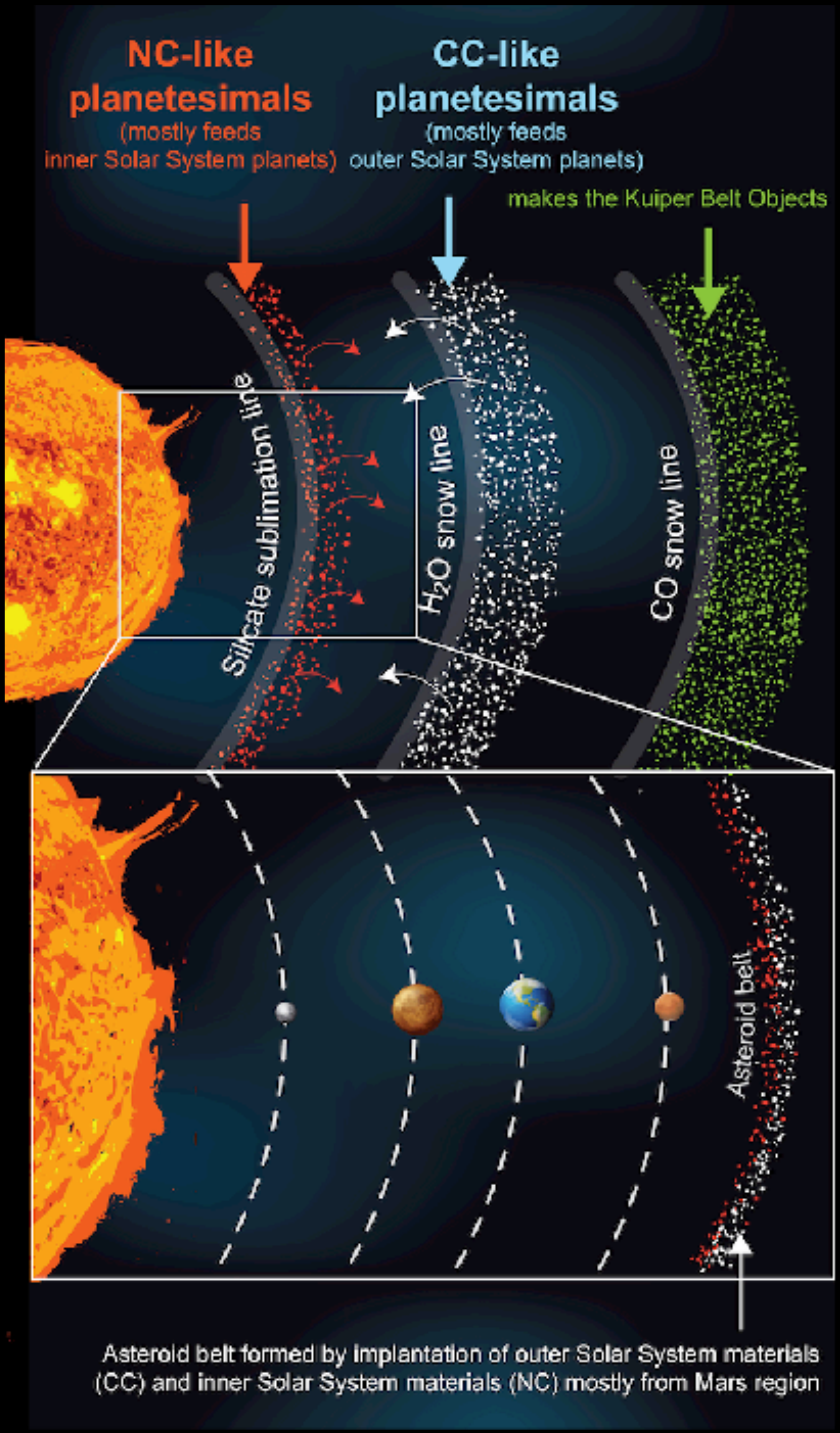
NC and CC planetesimals formed far apart but were brought together by the planets' growth



Gradie & Tedesco 1982; Demeo & Carry 2014

Empty asteroid belt

- Inner ring = terrestrial planets
- Middle ring = giant planet cores
- Outer ring = primordial Kuiper belt

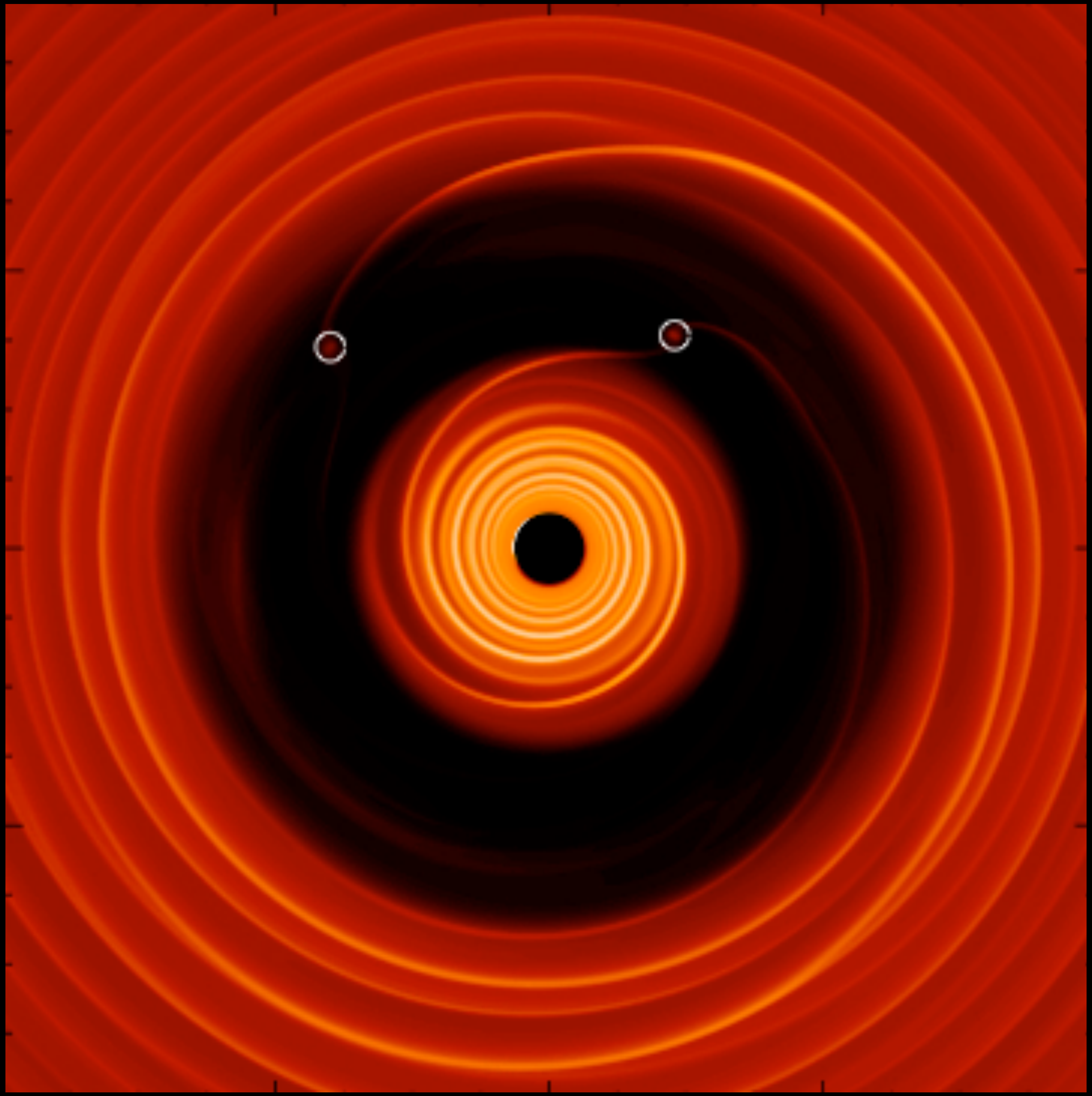


Asteroid belt formed by implantation of outer Solar System materials (CC) and inner Solar System materials (NC) mostly from Mars region

image from Izidoro et al (2022), but representative of lots of models (e.g., Morbidelli et al 2022)

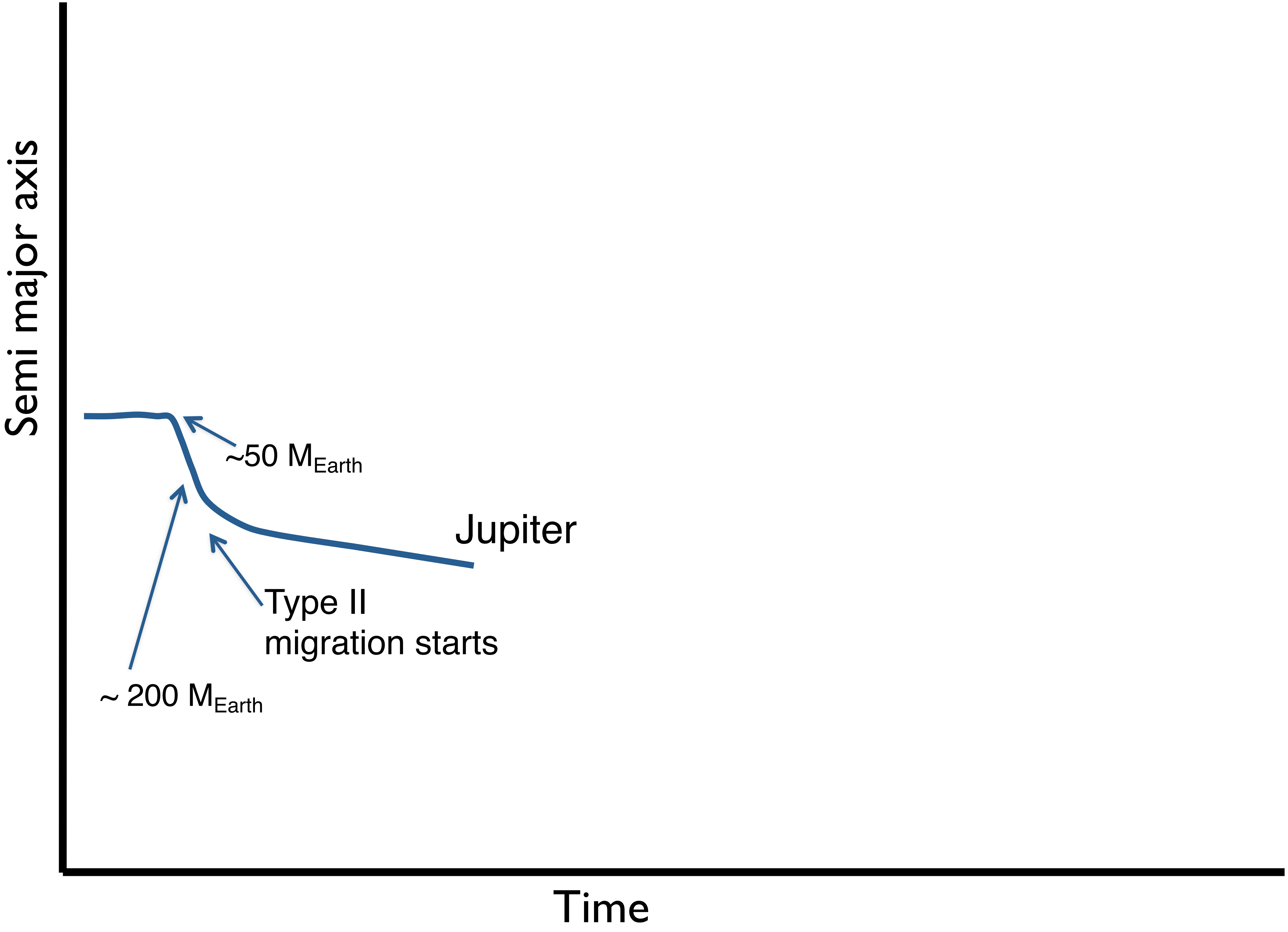
2. The Grand Tack

(Walsh et al 2011)

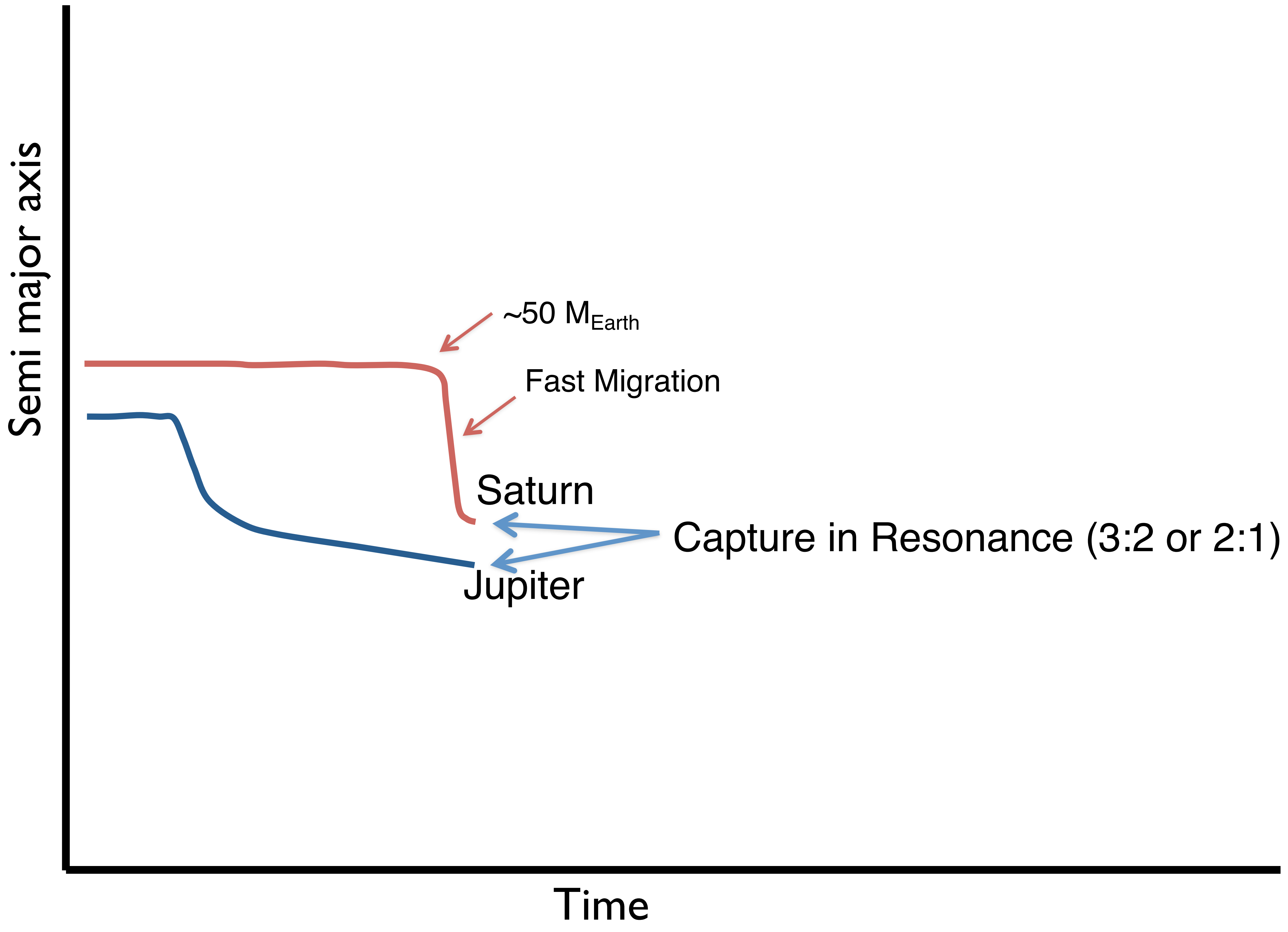


Pierens & Raymond
(2011)

Jupiter in the gaseous disk

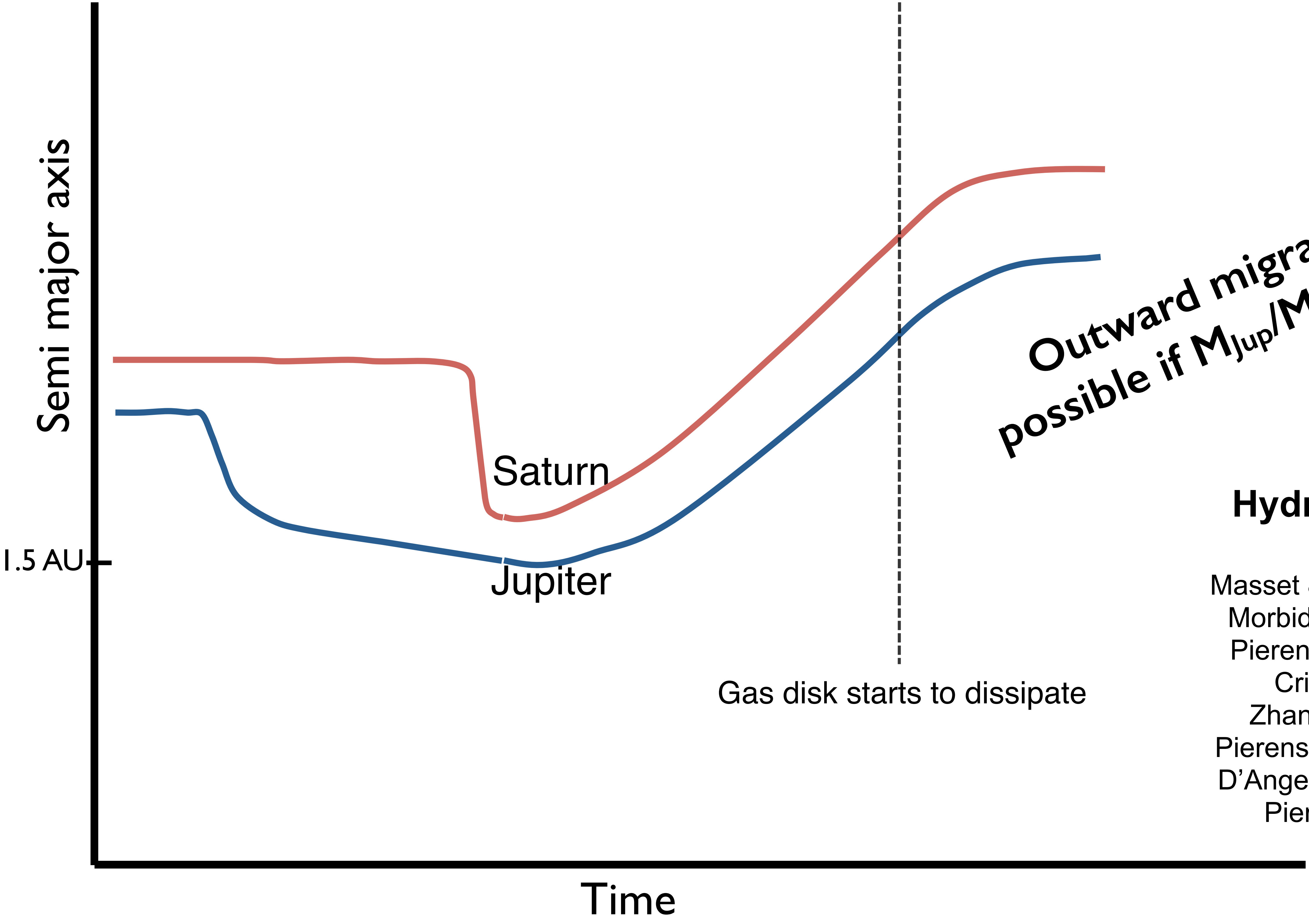


Jupiter and Saturn in the gaseous disk



The Grand Tack model

(Walsh et al 2011)

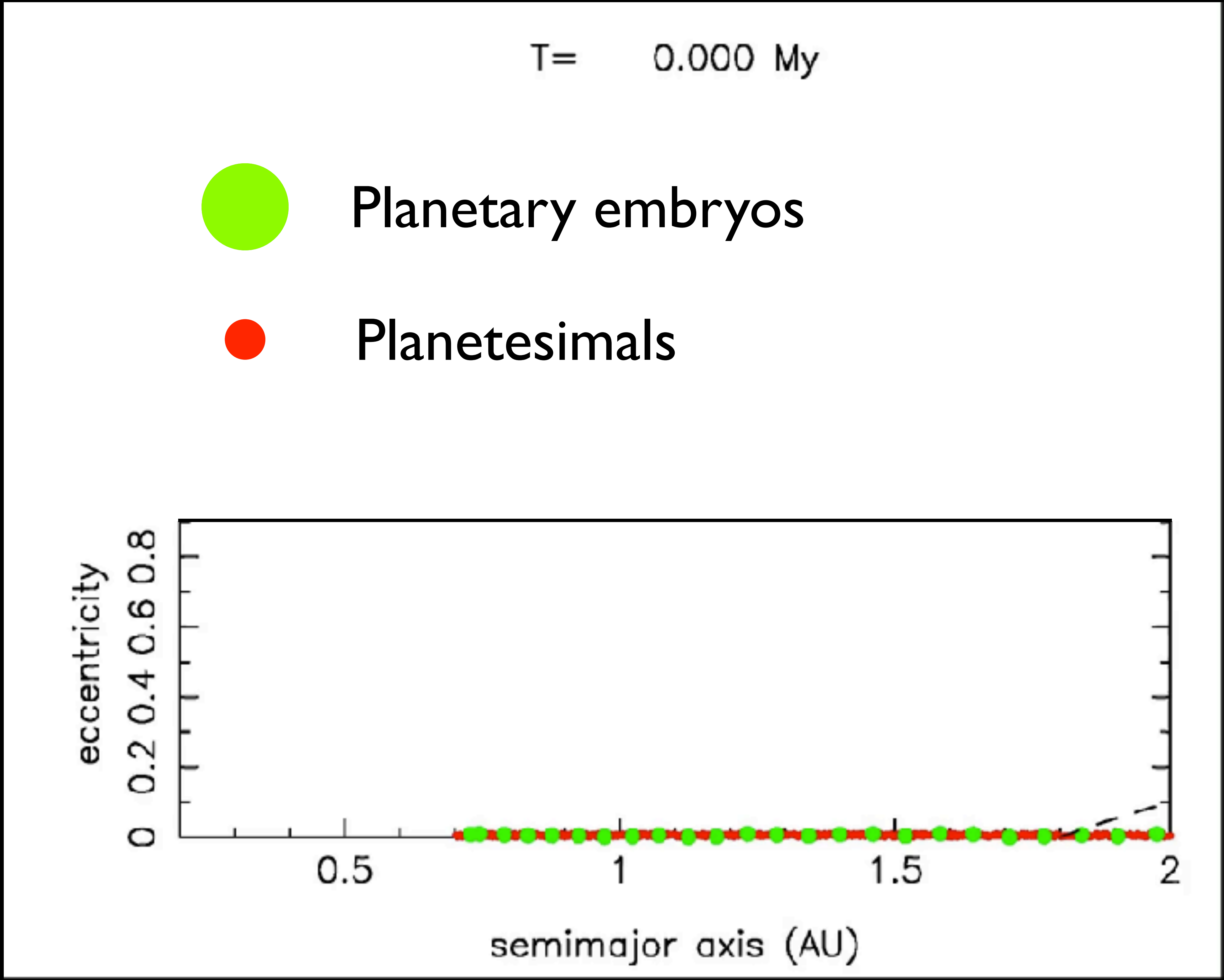


Outward migration possible if M_{Jup}/M_{Sat} = 2-4

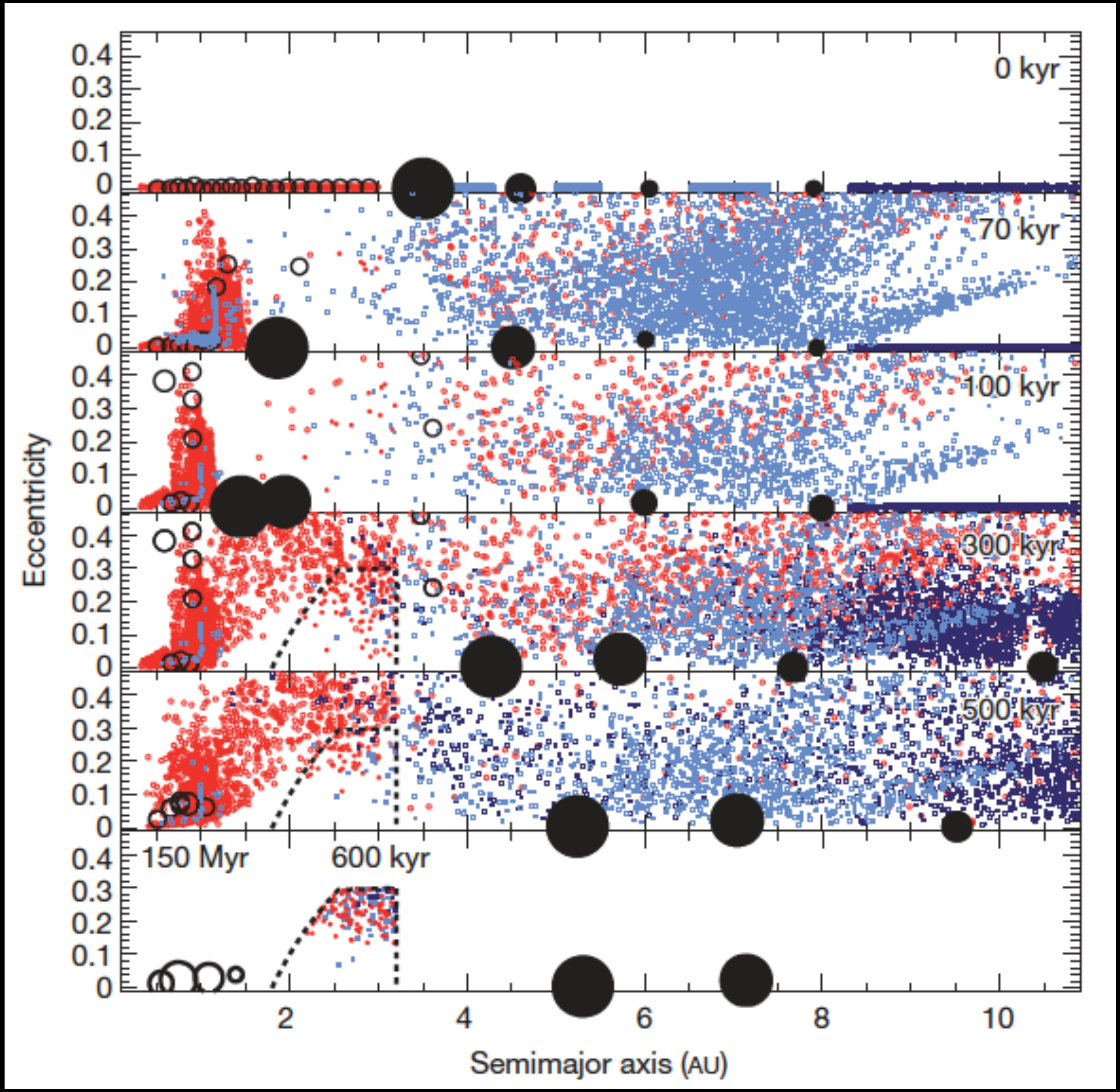
Hydrodynamical studies

Masset & Snellgrove 2001;
Morbidelli & Crida 2007;
Pierens & Nelson 2008;
Crida et al 2009;
Zhang & Zhou 2010;
Pierens & Raymond 2011;
D'Angelo & Marzari 2012;
Pierens et al 2014

The Grand Tack model

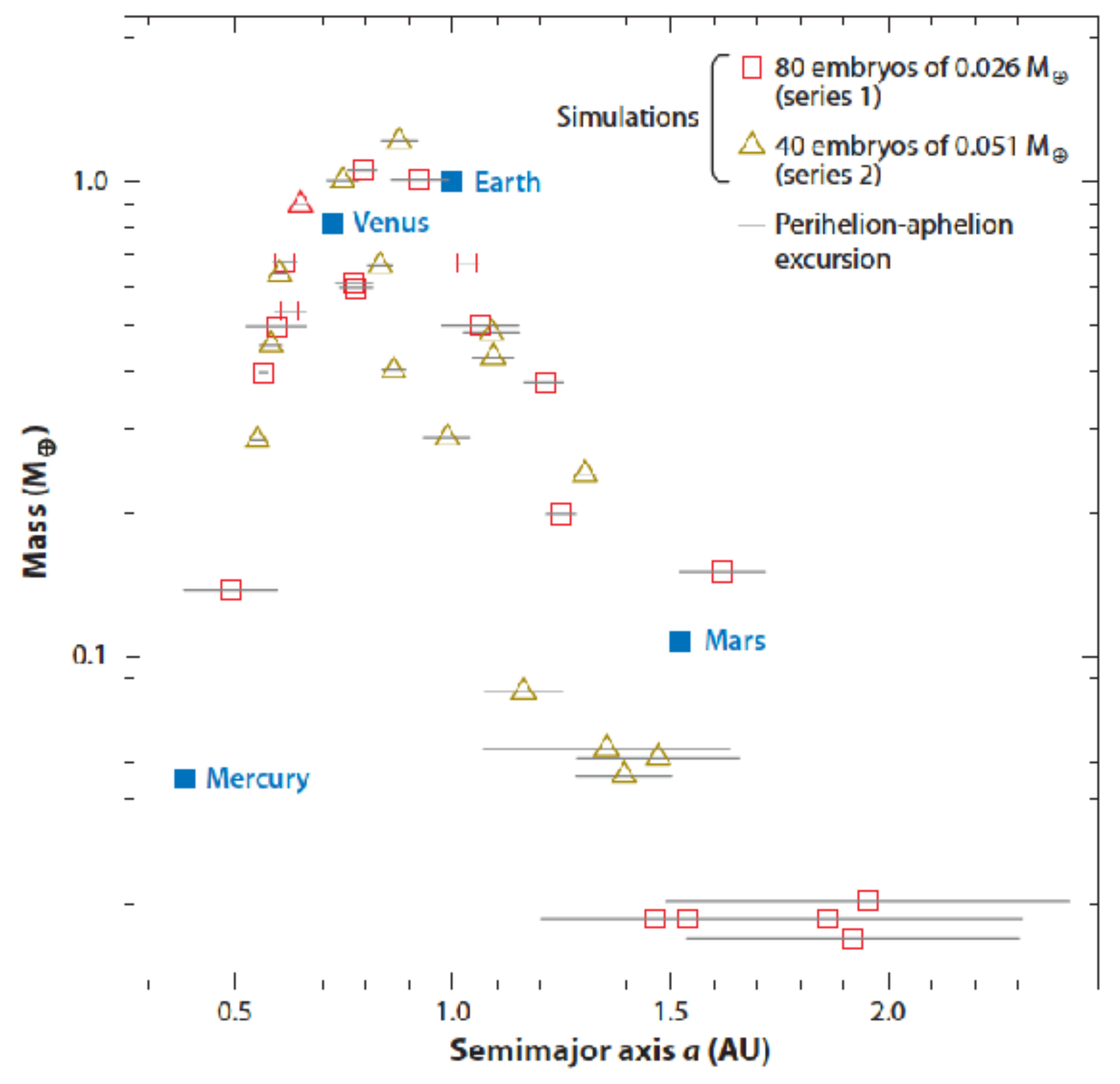


The Grand Tack



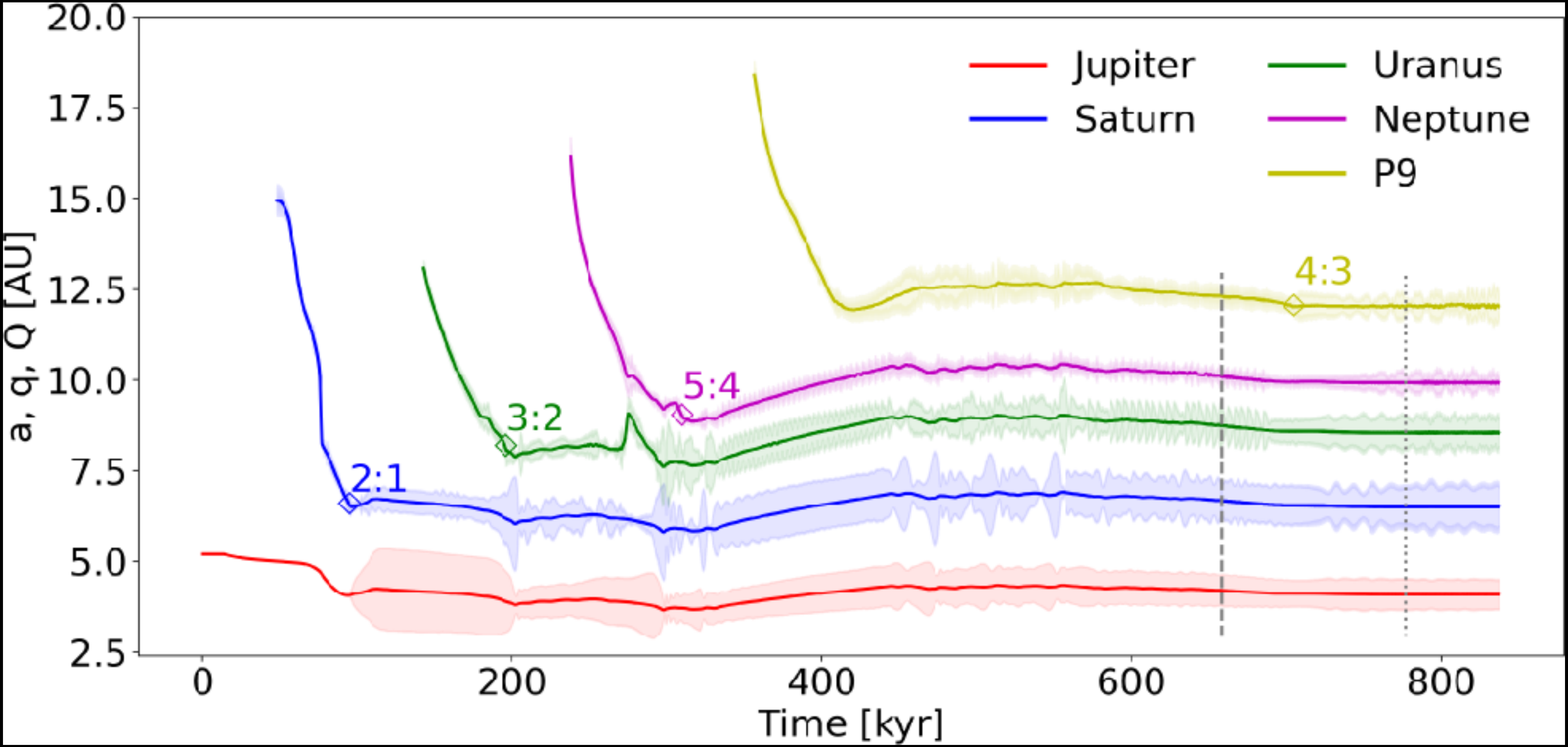
Walsh et al 2011

Grand Tack terrestrial planets



Morbidelli et al (2012)

Can Jup and Sat really migrate outward? (maybe not)

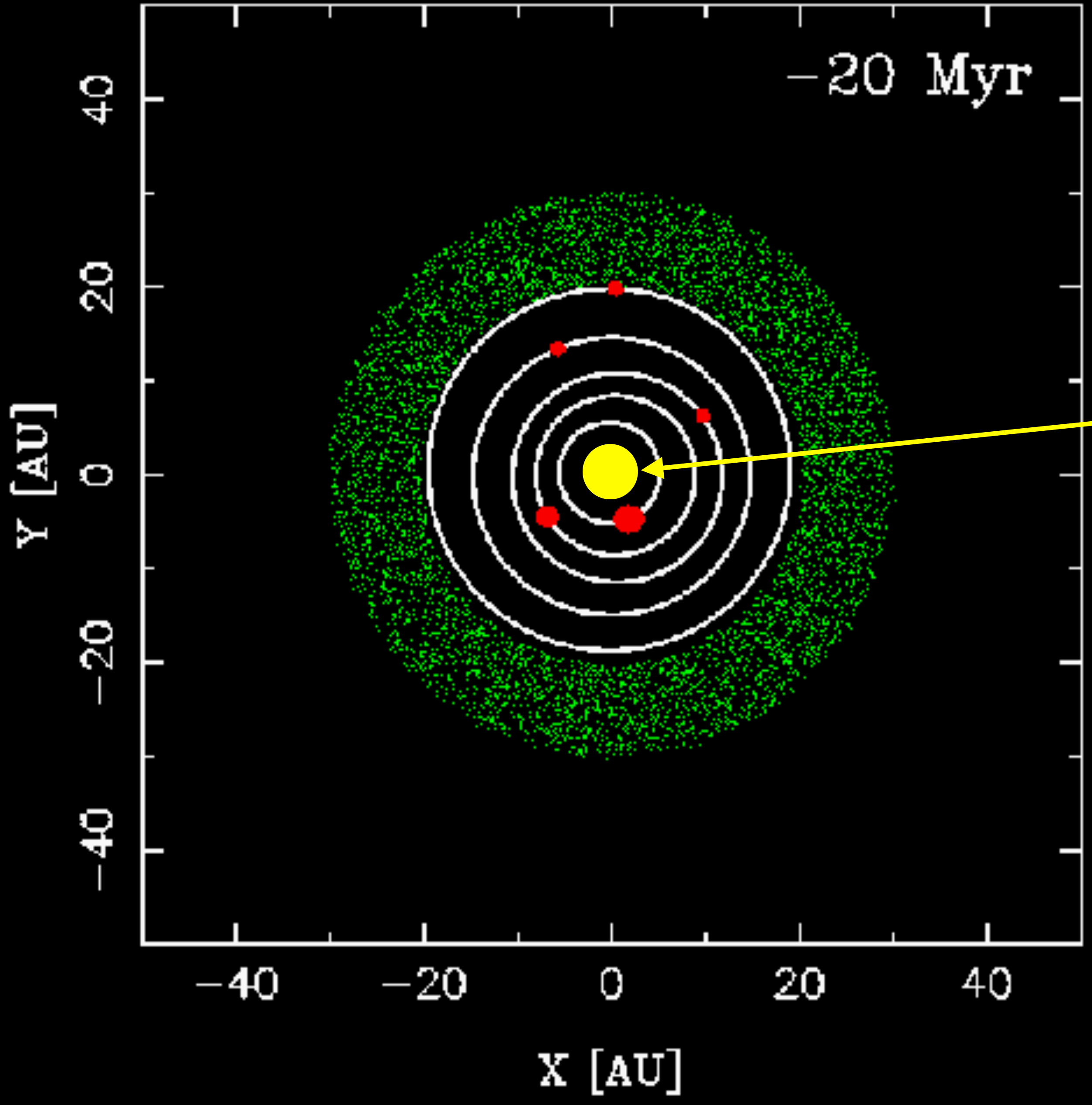


(assumption: very low-viscosity disk)

Griveaud et al (2024)

What if the giant planet instability happened early?

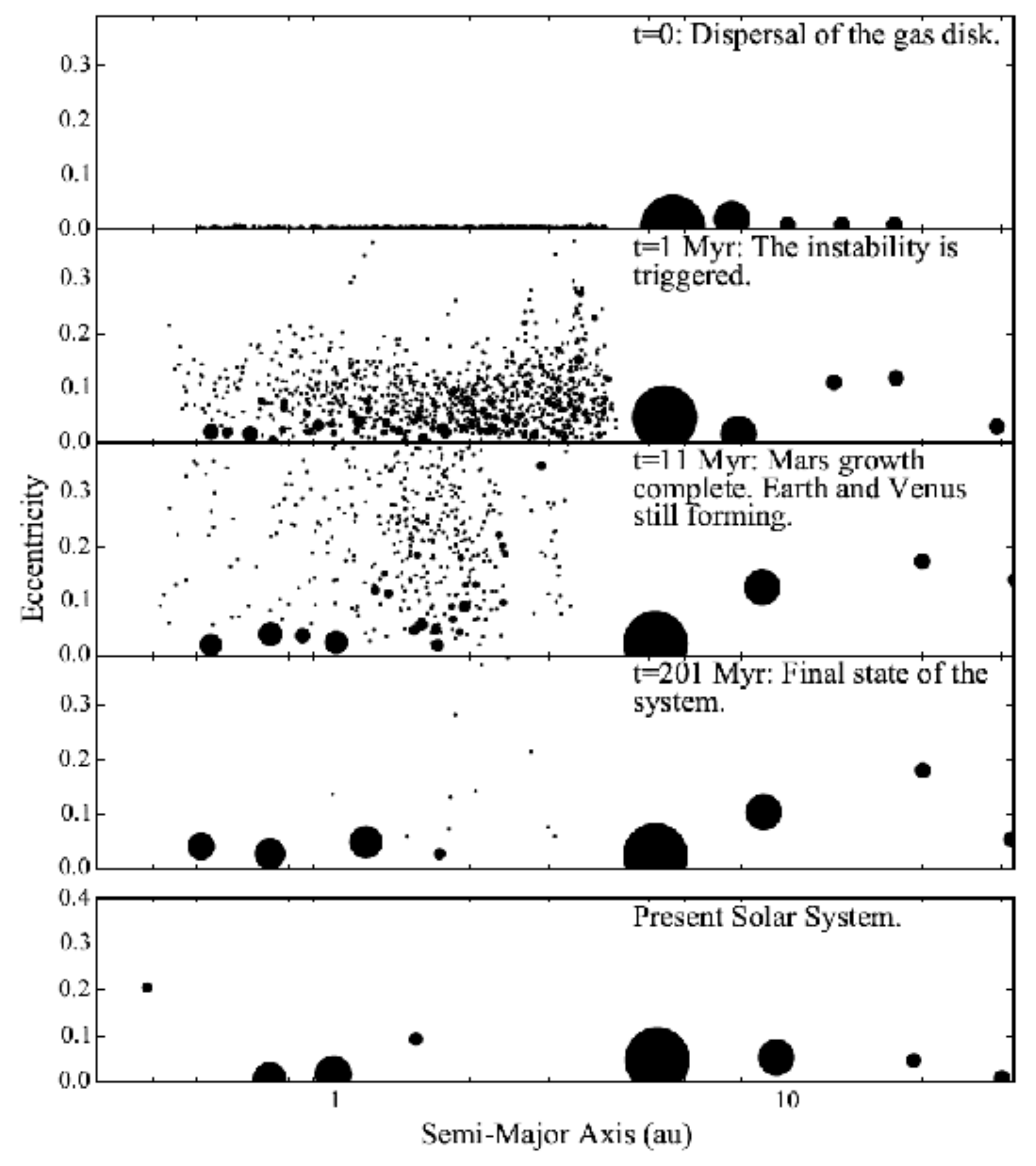
(true for instability triggers 1 and 2)



terrestrial planet region

Nesvorny (2011)

The Early Instability model

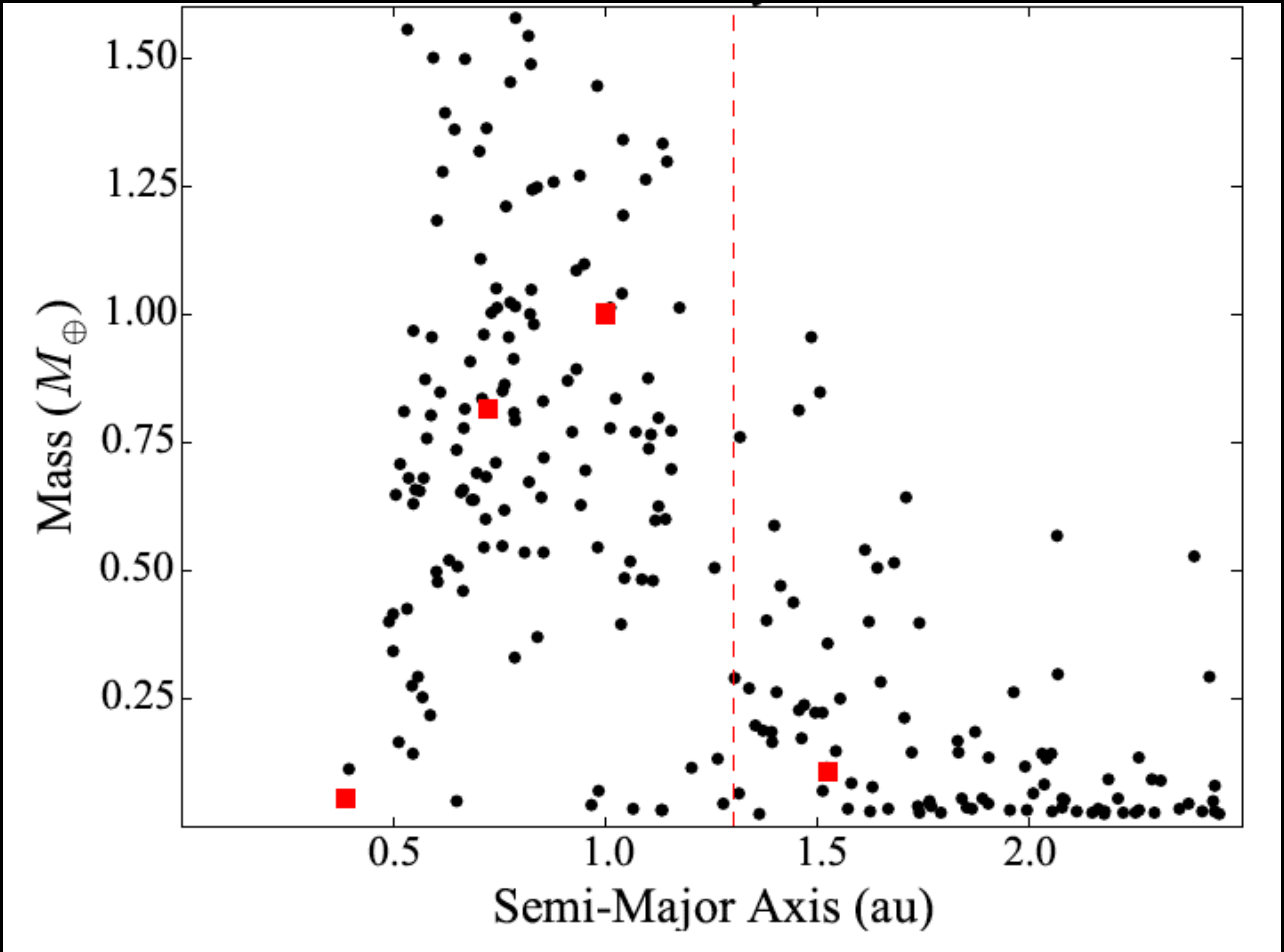


Clement et al

(2018, 2019, 2021)

(also Nesvorny et al 2021; Joiret et al 2023, 2024)

Early instability terrestrial planets



Clement et al (2018, 2019, 2021, 2023)

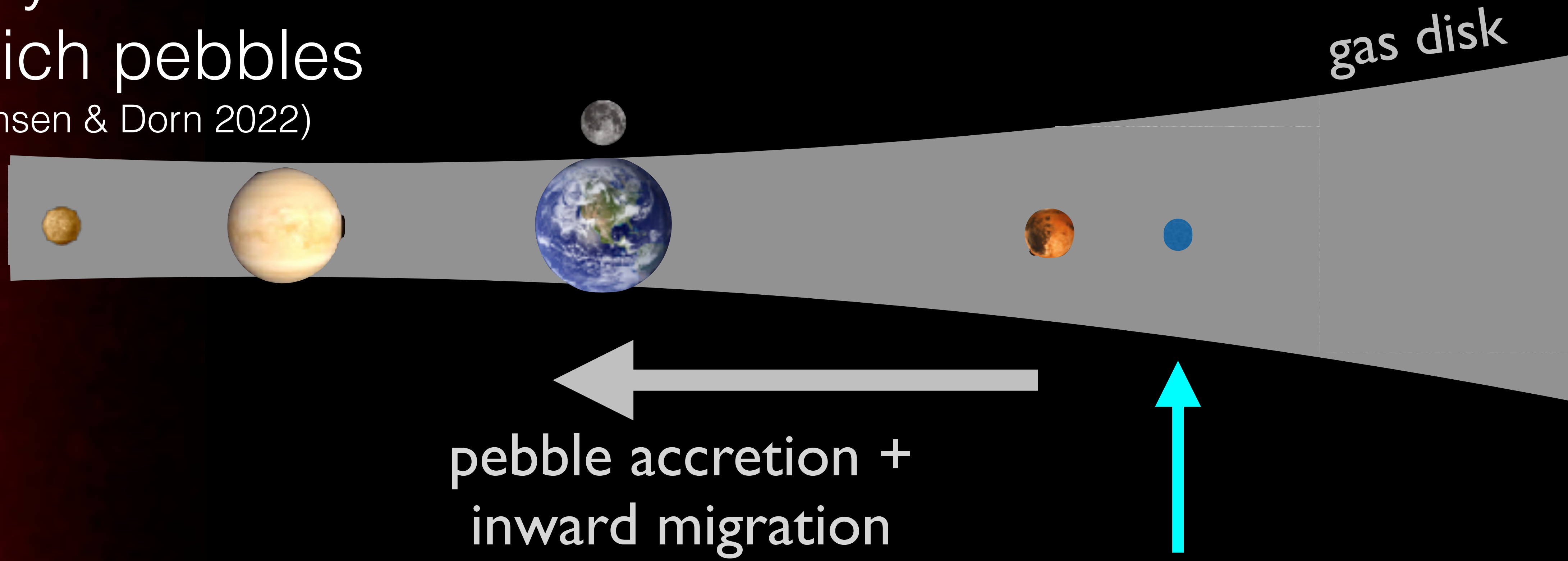
4. Pebble-accretion scenario

(Johansen et al 2021)

Assumption: large planetesimals only form in preferred location

Late giant impact forms the Moon

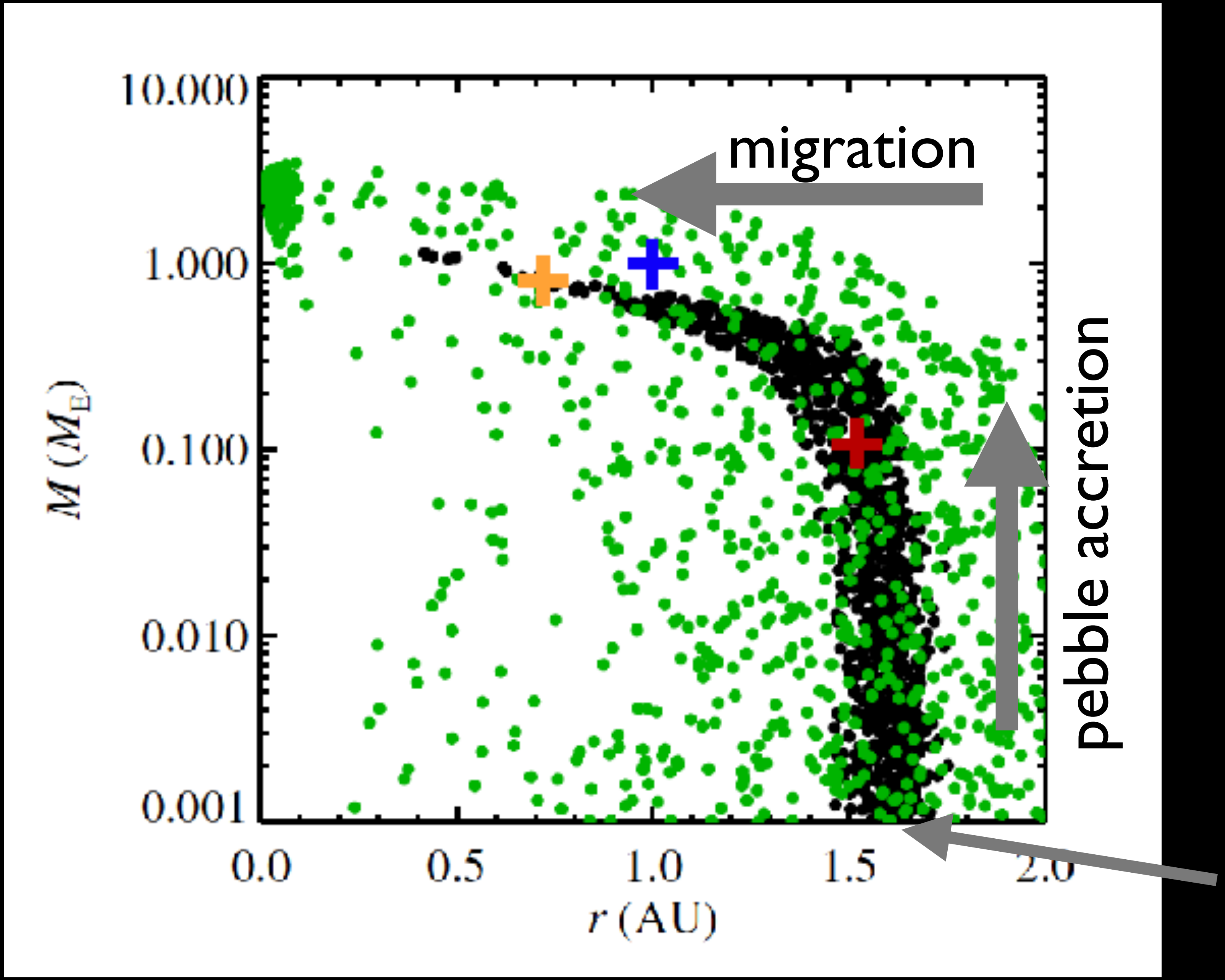
Mercury forms from iron-rich pebbles
(Johansen & Dorn 2022)



The Sun's gaseous disk dissipates after a few million years

Pebble-accretion scenario

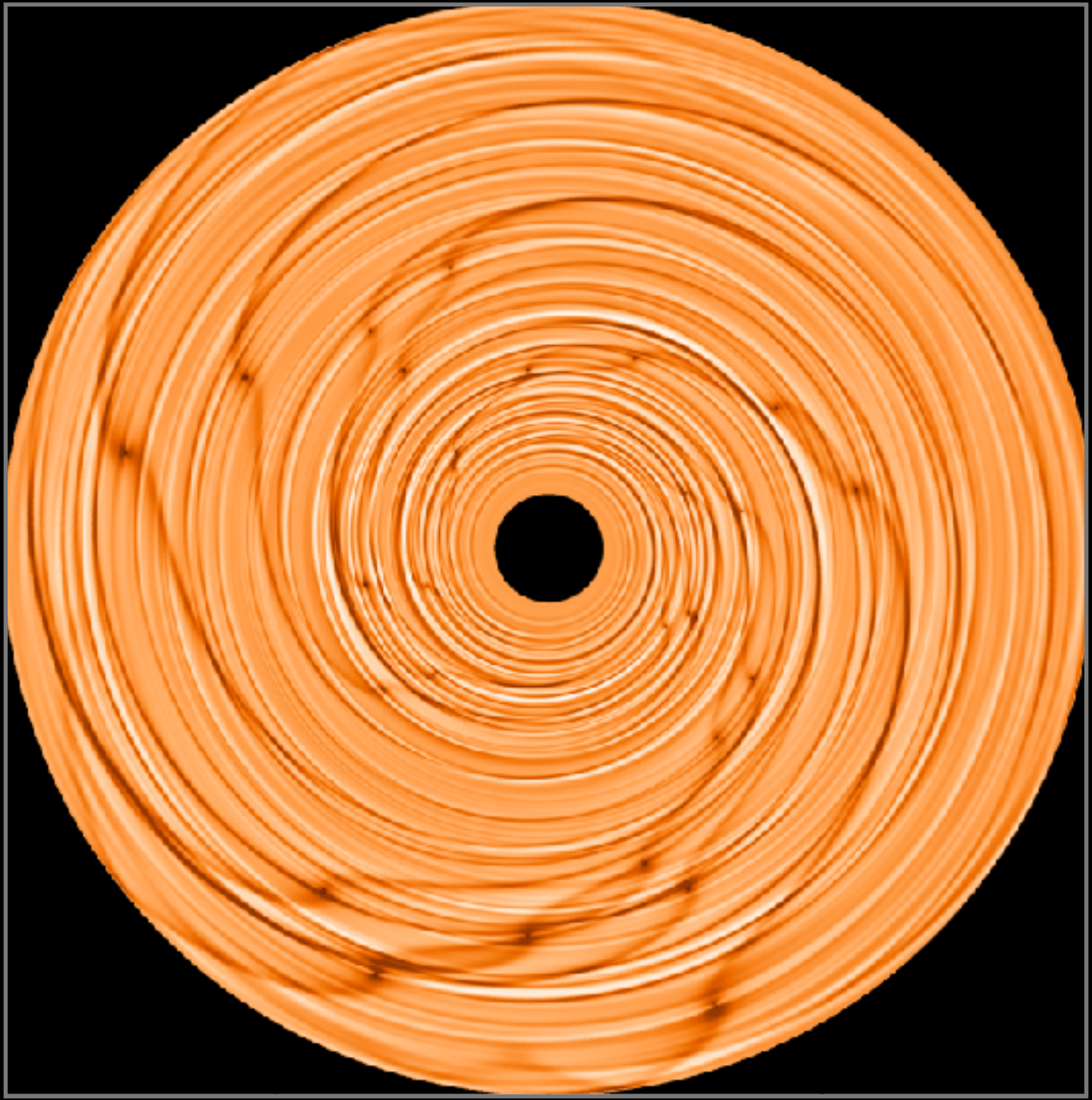
Key assumption: large planetesimals only form in preferred location



Johansen et al (2021)

green = wide planetesimal ring,
black = narrow

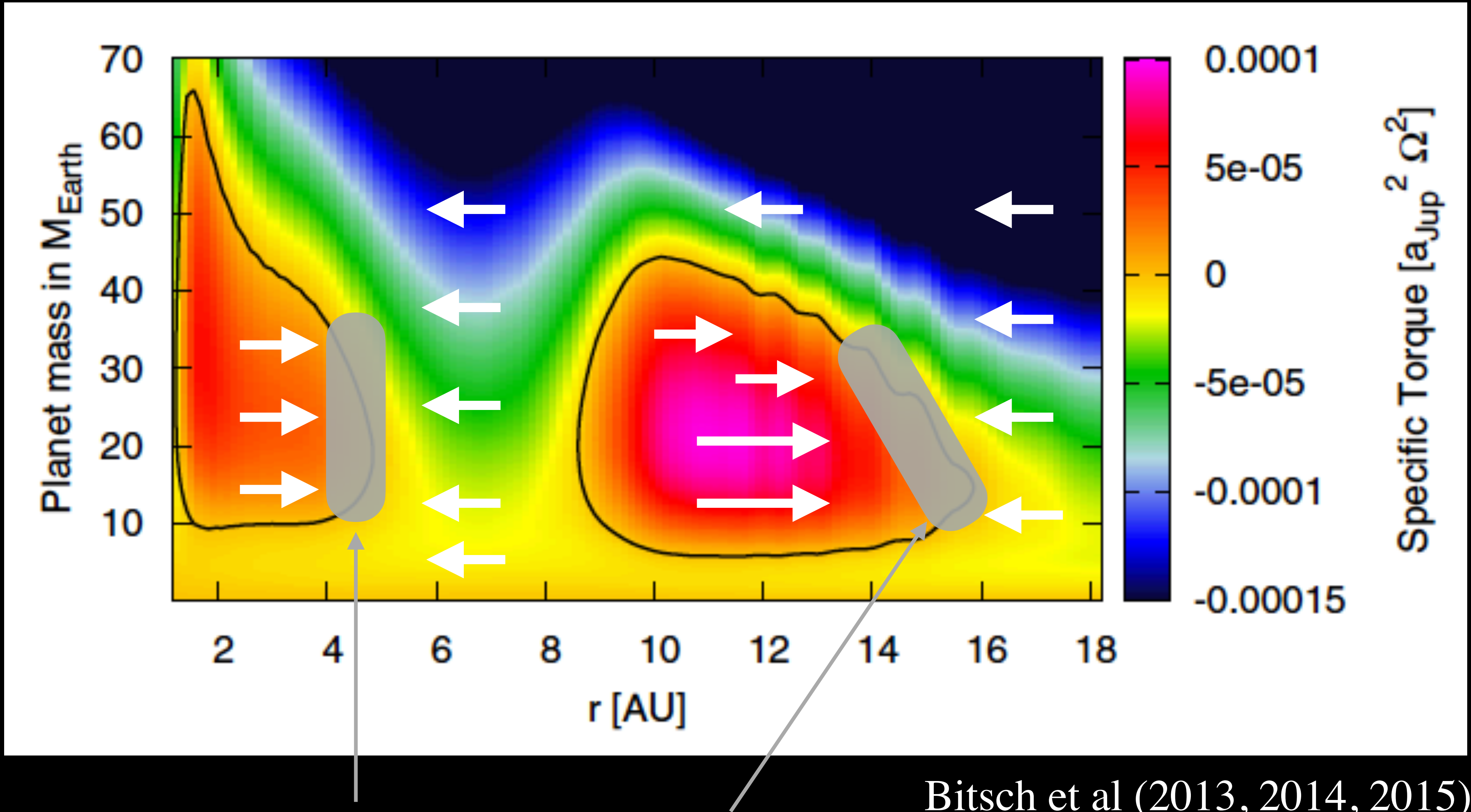
5. Convergent migration of planetary embryos



Broz et al (2021)

A migration "map"

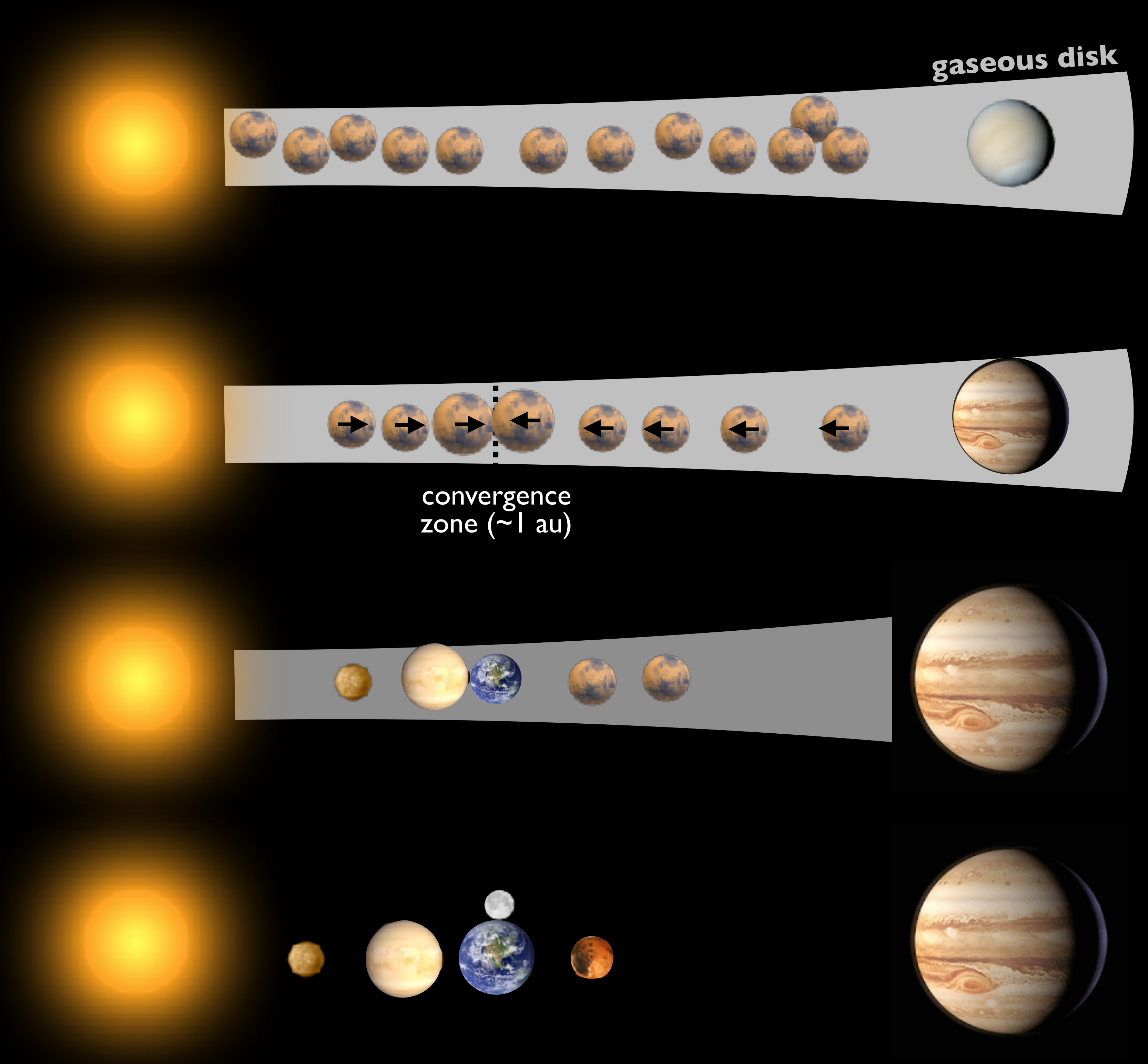
(for a specified disk model)



Bitsch et al (2013, 2014, 2015)

Convergence zones

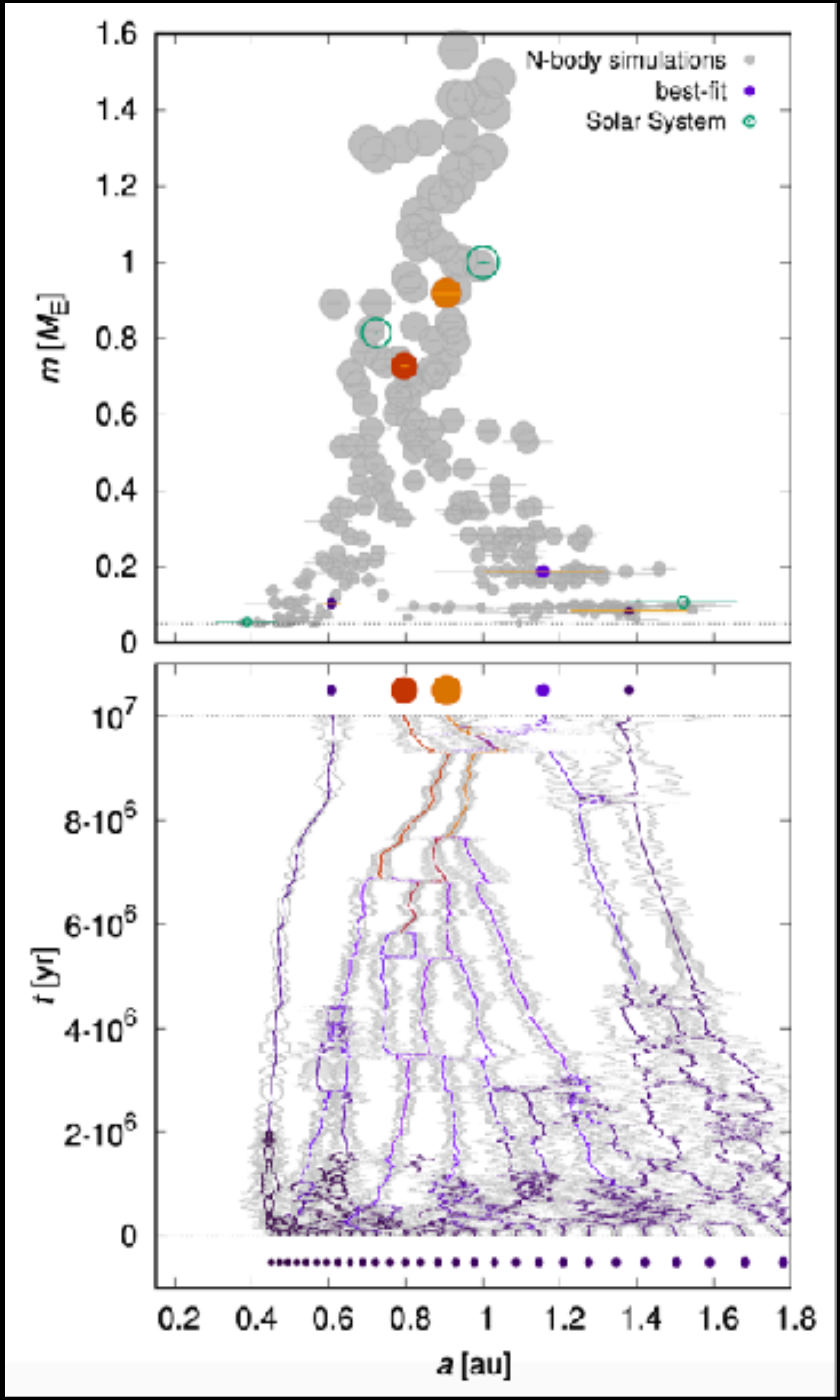
Convergent migration model



Broz et al (2021)

(image from news & views by Raymond 2021)

Convergent migration model



Broz et al (2021)

Possible solutions to the small Mars problem

Is a narrow annulus of planetesimals realistic?

"Empty asteroid belt"

How efficient is pebble accretion in terrestrial zone?

Pebble-driven

Are convergent migration zones common?

Convergent migration

Does outward migration work with gas accetion?

The "Grand Tack"

When did the instability really happen?

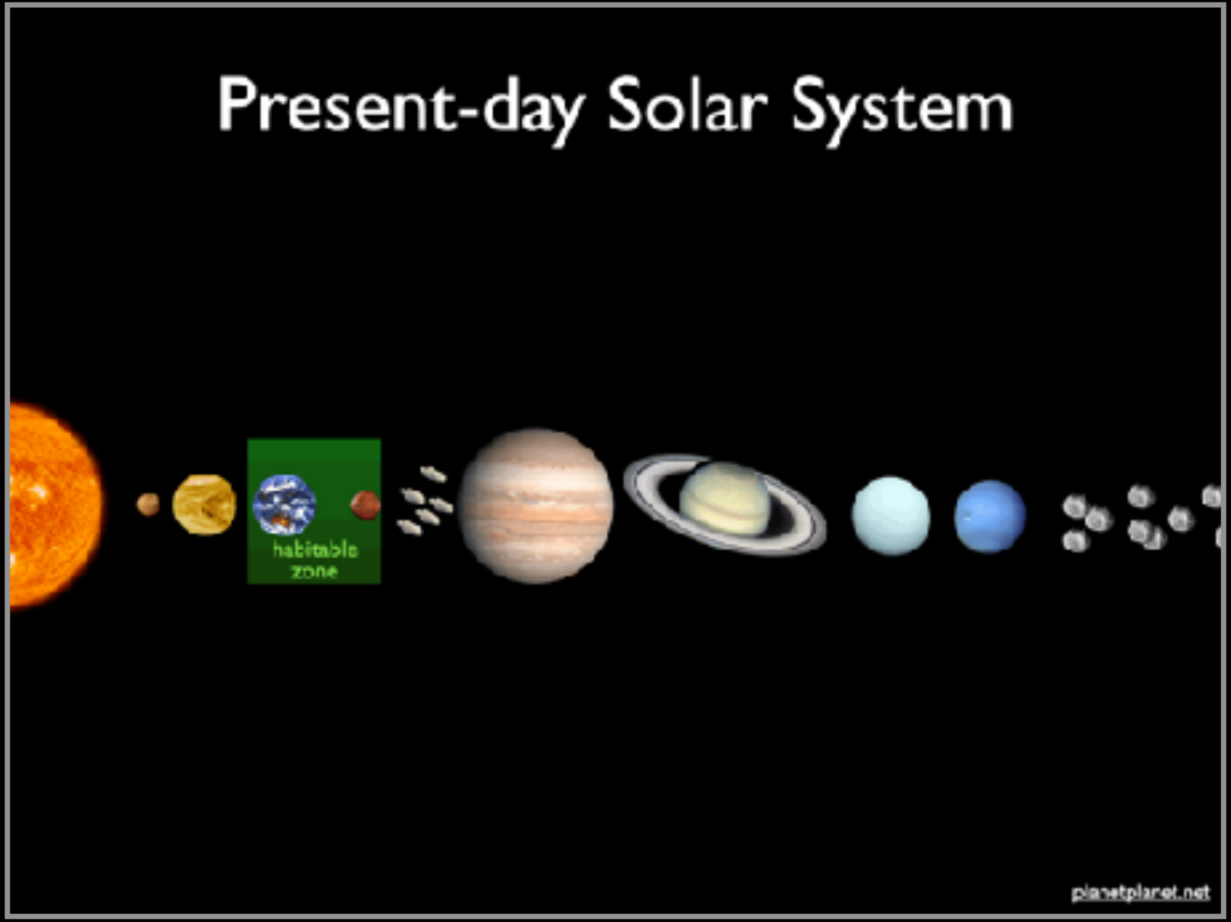
Early instability

Later dynamical sculpting

Additional resources

- *Planet Formation: key processes and global models* Raymond & Morbidelli 2022 (*arxiv:2002.05756*)

- The Solar System’s Story (planetplanet.net)



Present-day Solar System

(from “The end of the Solar System”)