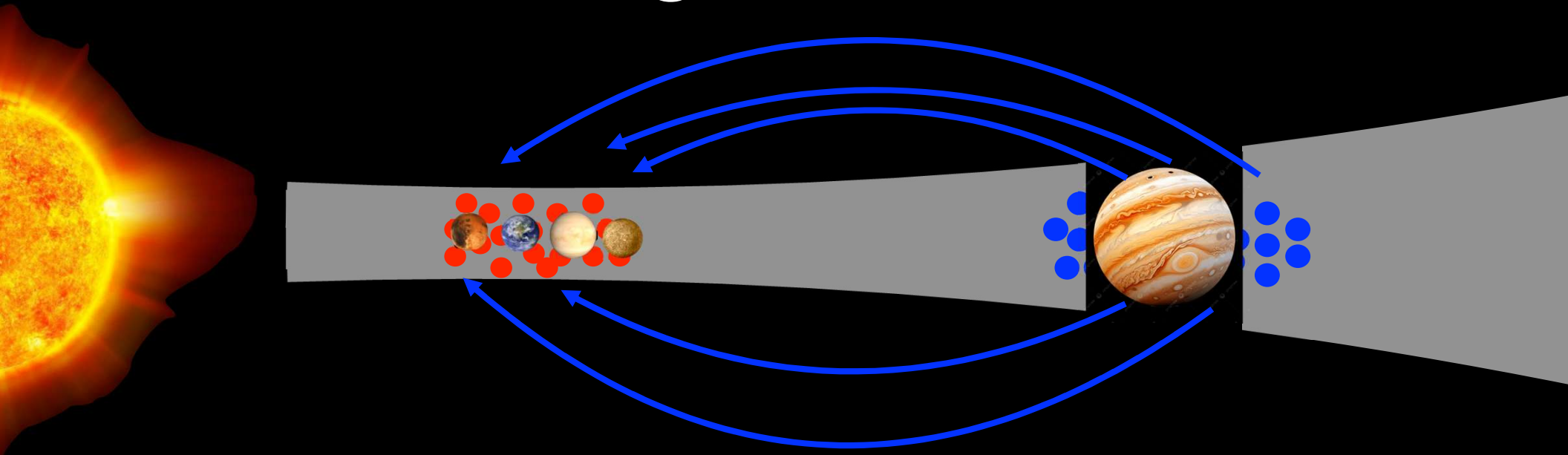


Water delivery to inner rocky planets driven by outer giants



Sean Raymond

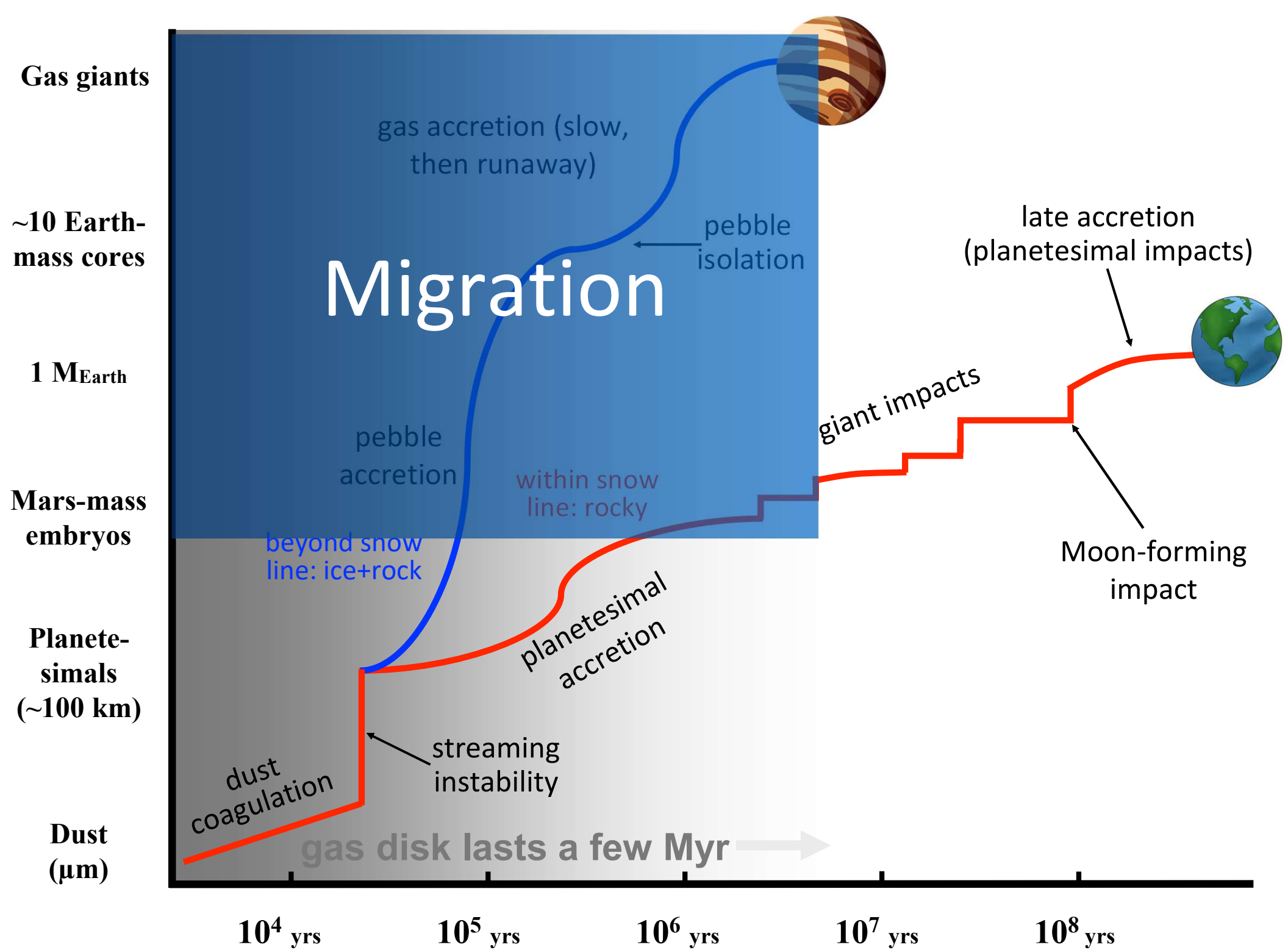
Laboratoire d'Astrophysique de Bordeaux, CNRS (France)

planetplanet.net

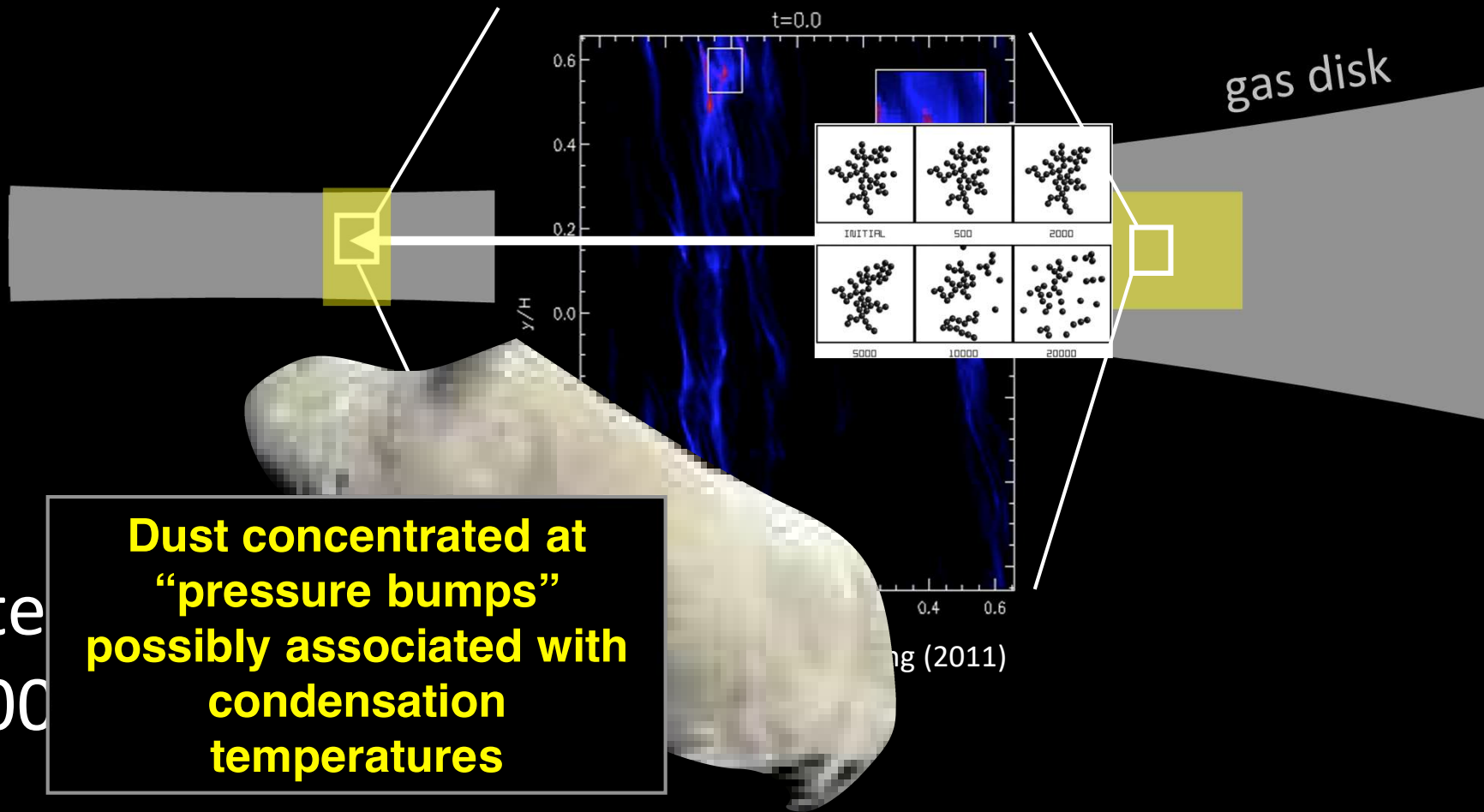
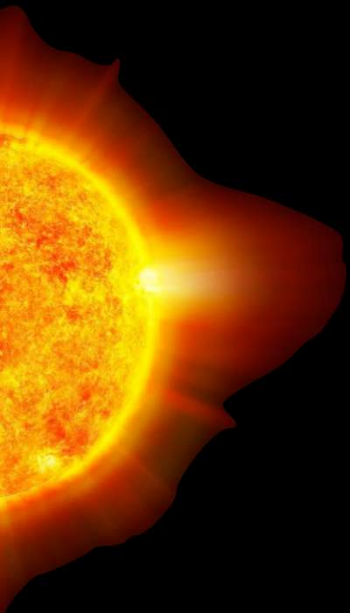
with Tom Quinn, Jonathan Lunine, Avi Mandell, Steinn Sigurdsson, Dave O'Brien, Alessandro Morbidelli, Nate Kaib, Emeline Bolmont, Phil Armitage, Andre Izidoro, Bertram Bitsch, Seth Jacobson, Karen Meech

Key idea

- Planetesimals form in rings
- Water delivery = water from outer ring toward inner ring
- Giant planets are almost universally BAD for water delivery, except in certain special cases.



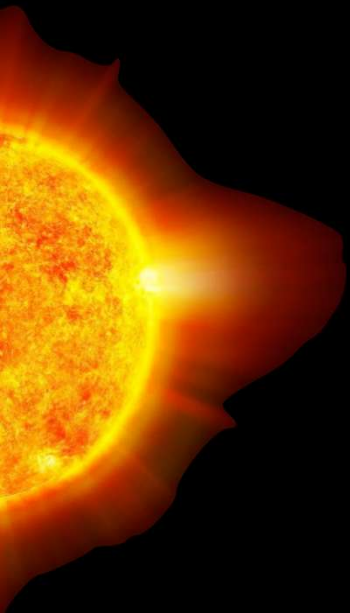
Planetesimal formation



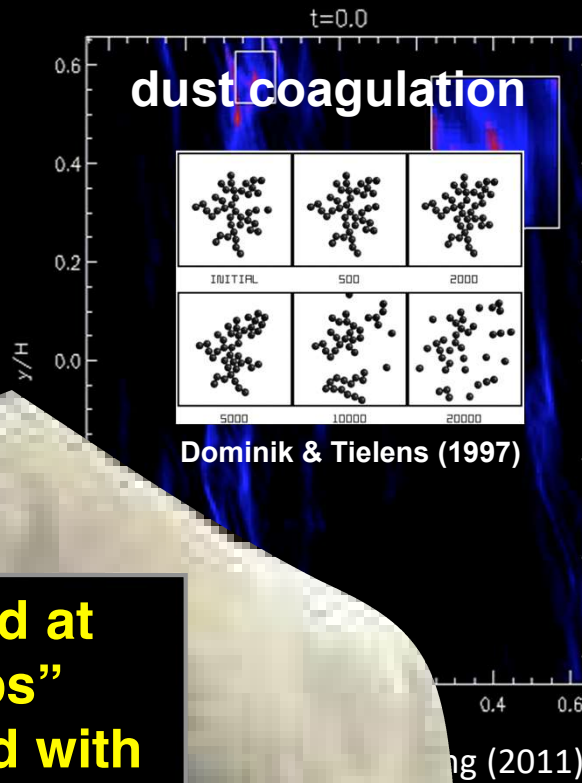
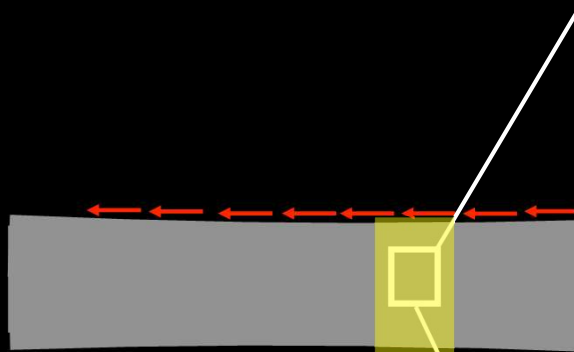
Planete
~100

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

Planetesimal formation



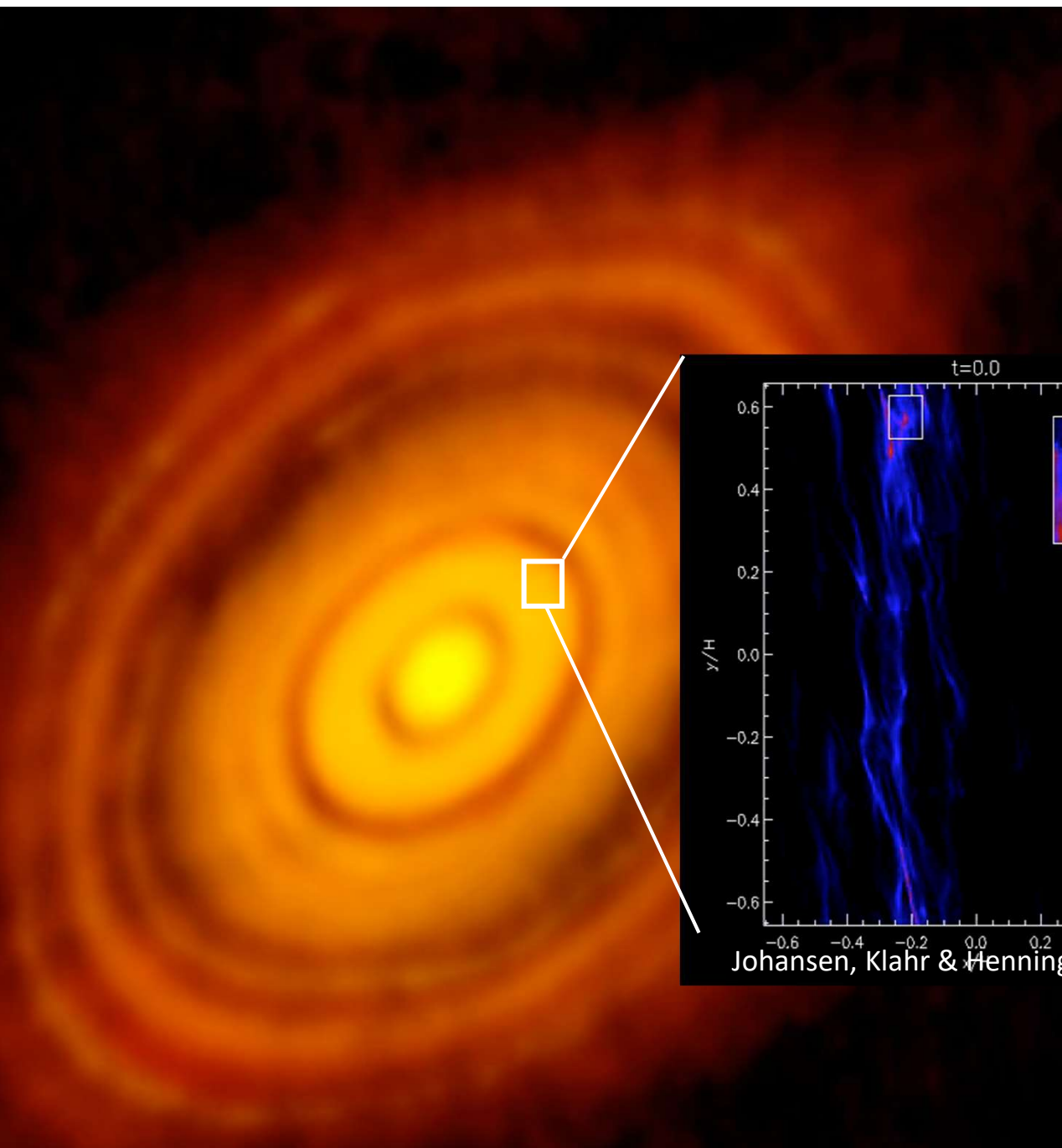
Planet
~100



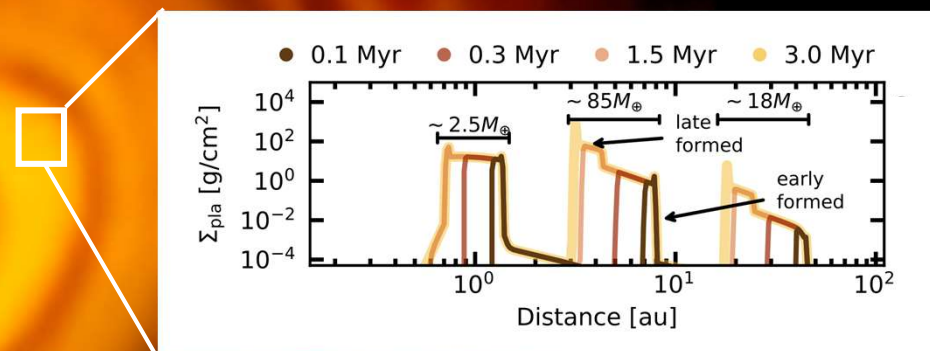
inward-drifting pebbles
gas disk



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



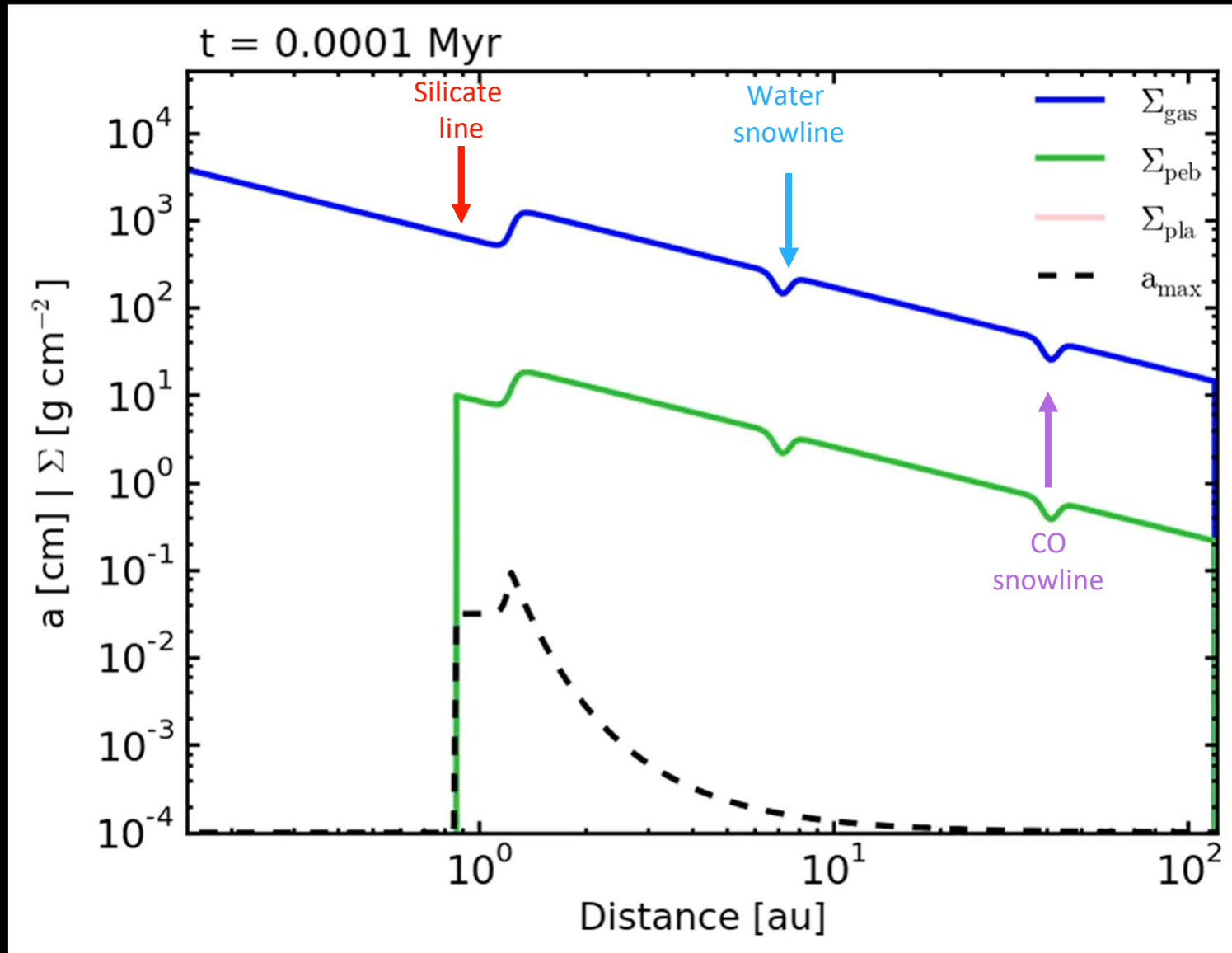
HL Tau's disk
(ALMA Partnership et al 2015)



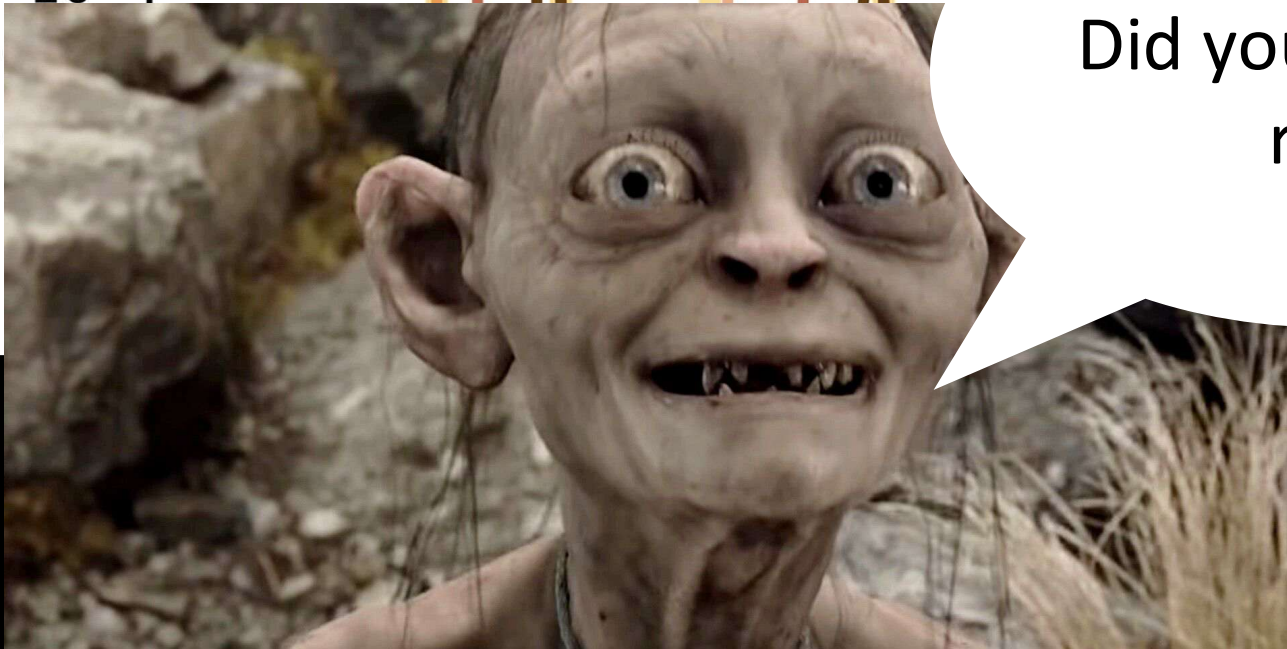
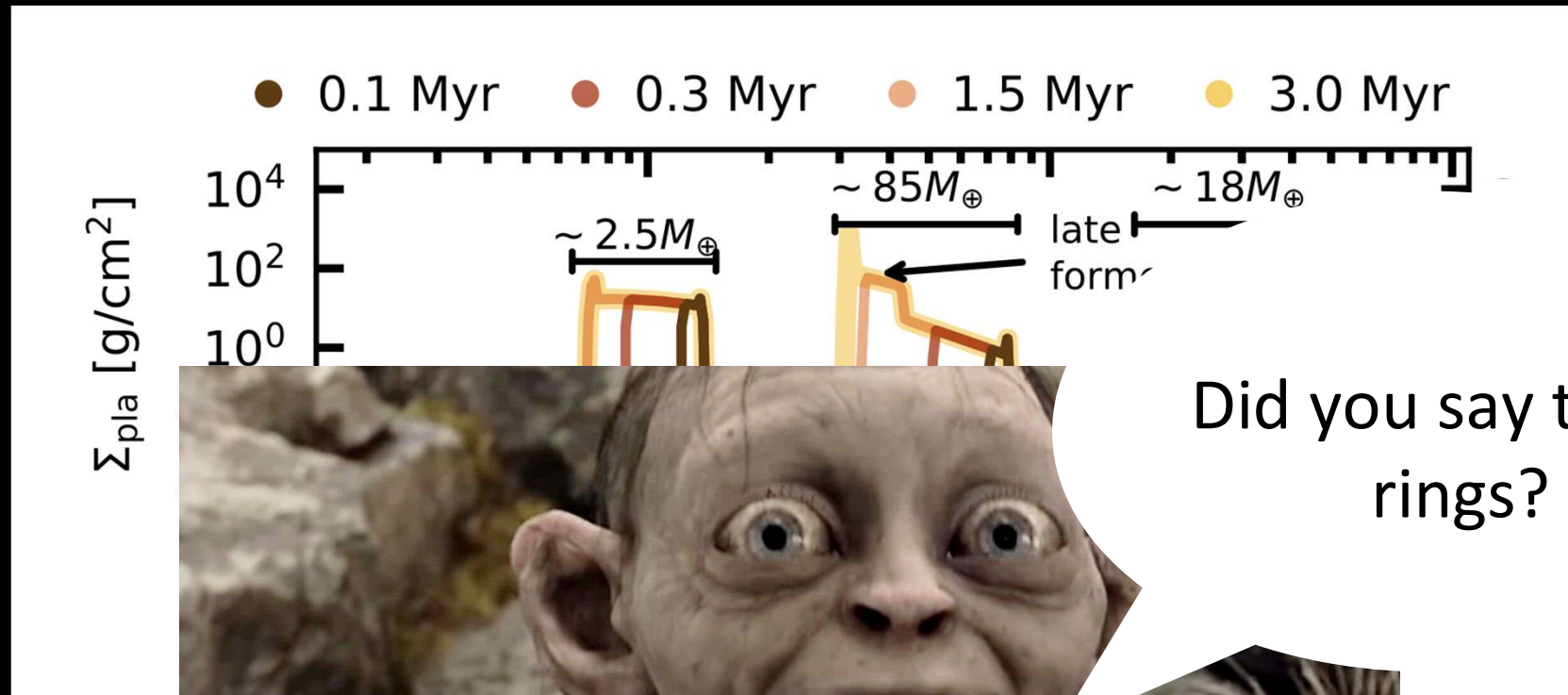
Izidoro et al (2022)

HL Tau's disk
 (ALMA Partnership et al 2015)

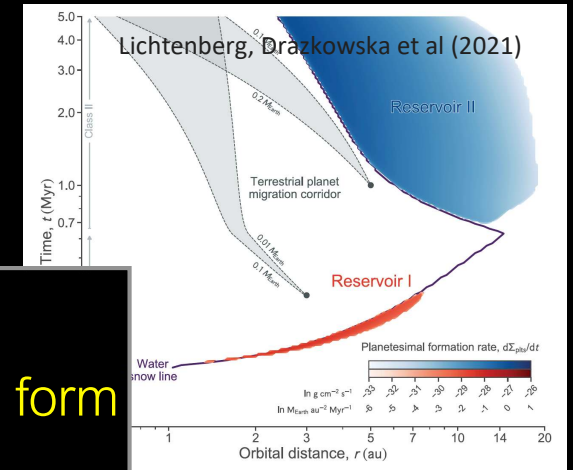
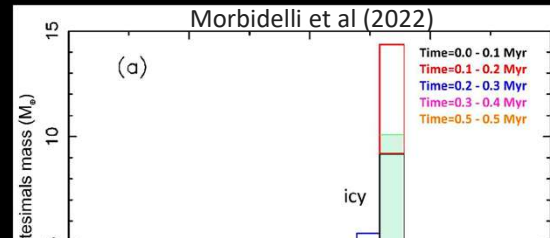
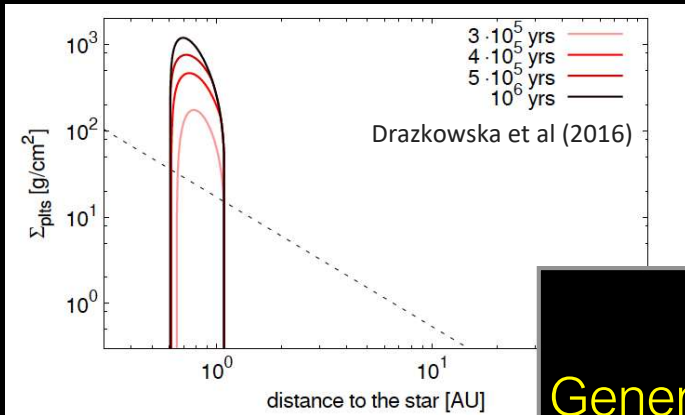
A model with dust coagulation/drift and three “pressure bumps”



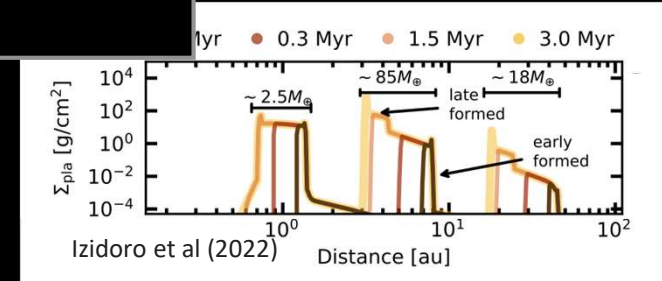
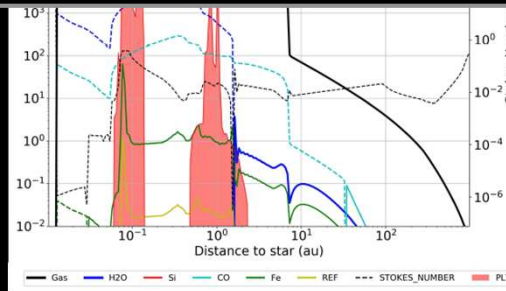
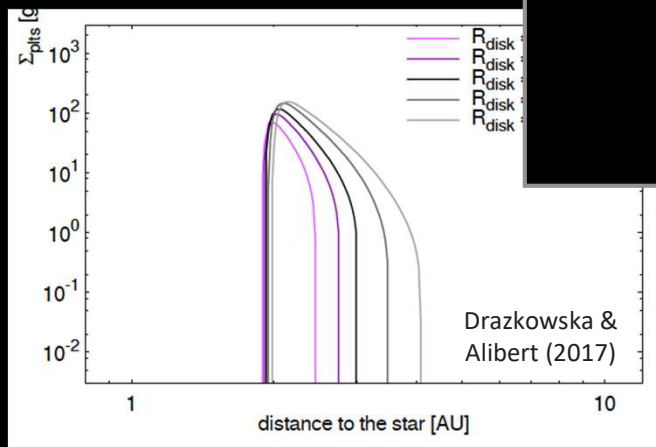
Three rings of planetesimals



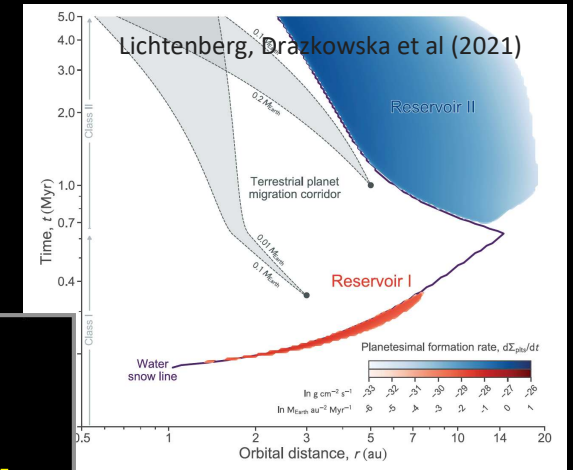
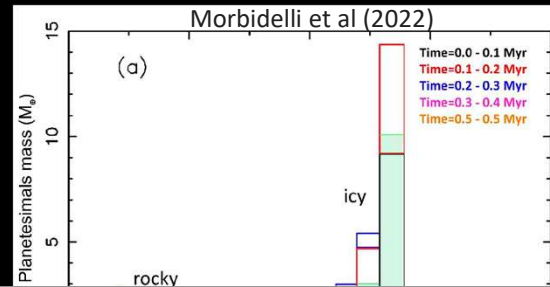
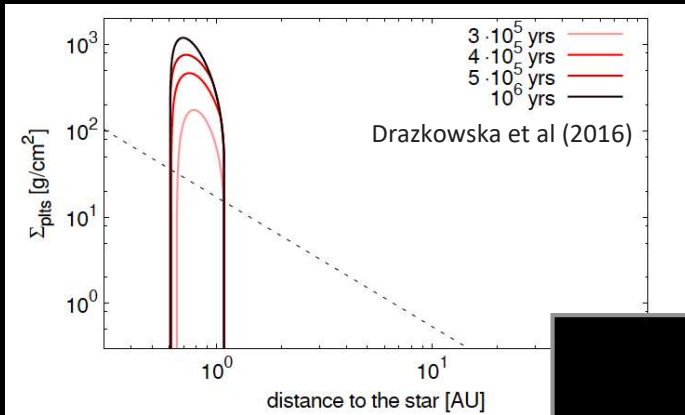
Planetesimal formation models: dust growth/drift with disk evolution



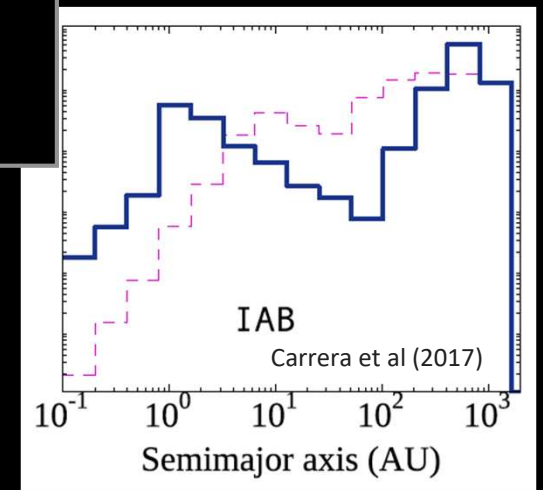
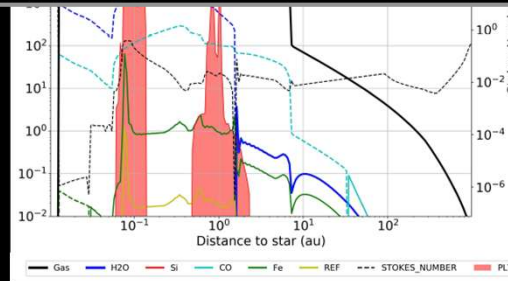
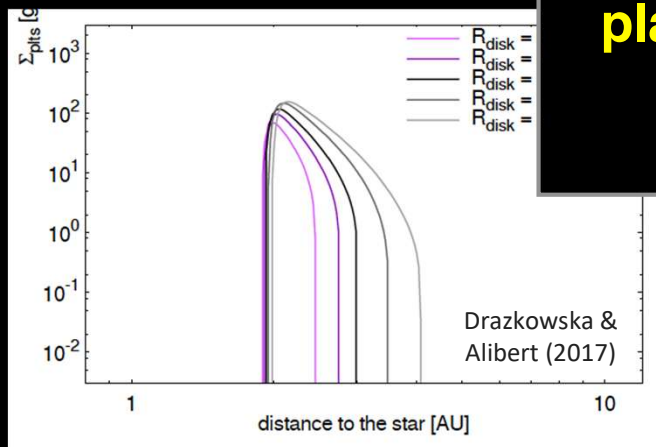
General agreement that planetesimals form in **rings** with likely connection to **condensation lines**



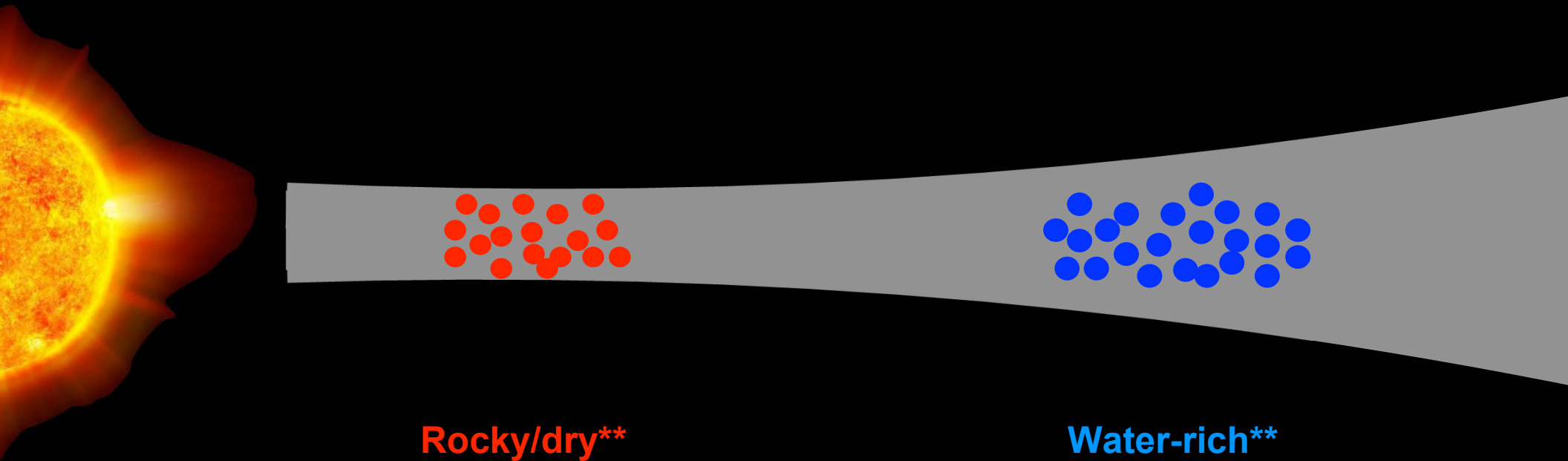
Planetesimal formation models: dust growth/drift with disk evolution



General agreement that planetesimal formation is linked with condensation lines



Planetesimals form in rings

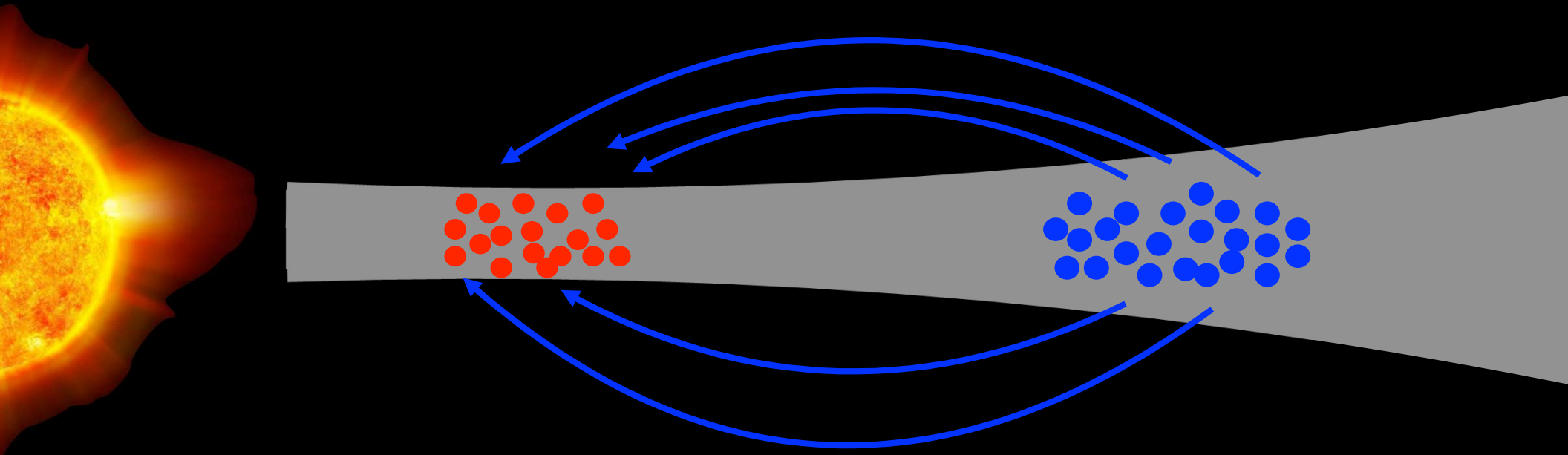


**Enstatite chondrites contain similar water concentration to Earth (Piani et al 2020)

**There is a wide range in water contents of carbonaceous chondrites (e.g., Alexander et al 2012)

Planetesimals form in rings

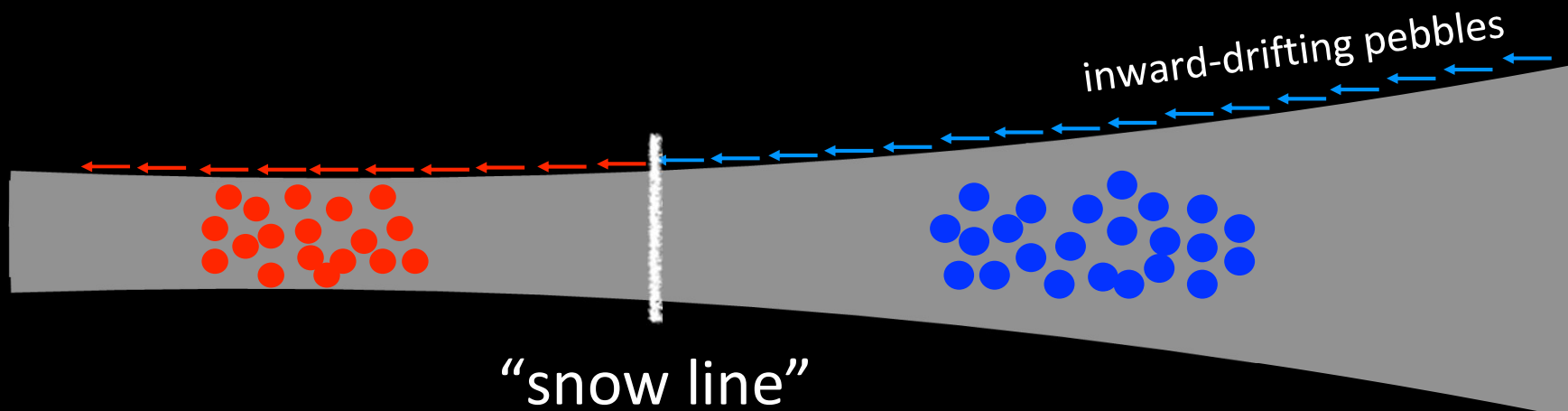
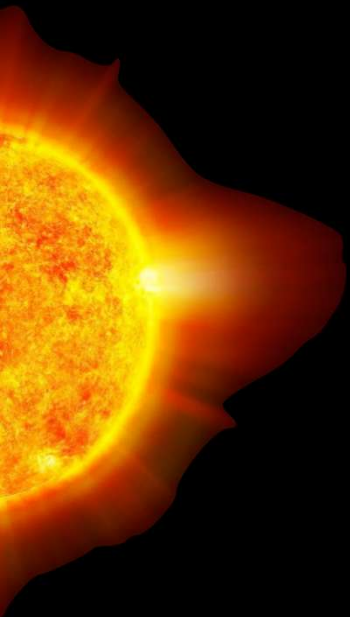
“Water delivery” = transfer of material from outer planetesimal ring to inner planets**



****Water delivery does not need to be in the form of planetesimals**

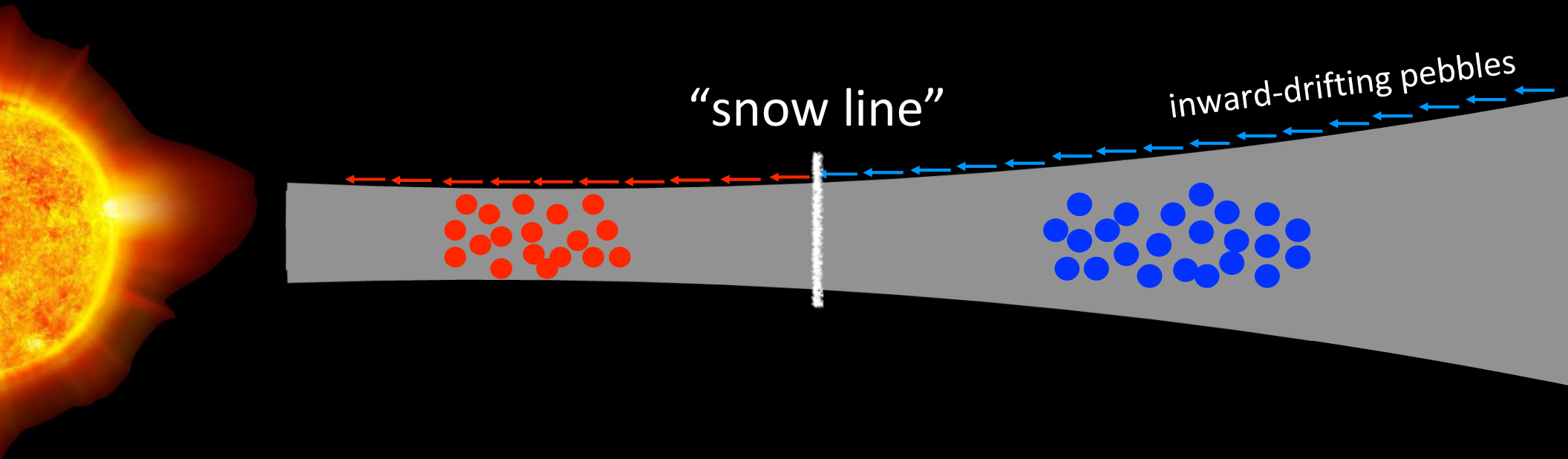
Can pebbles deliver water?

Not to planets interior to the snow line**



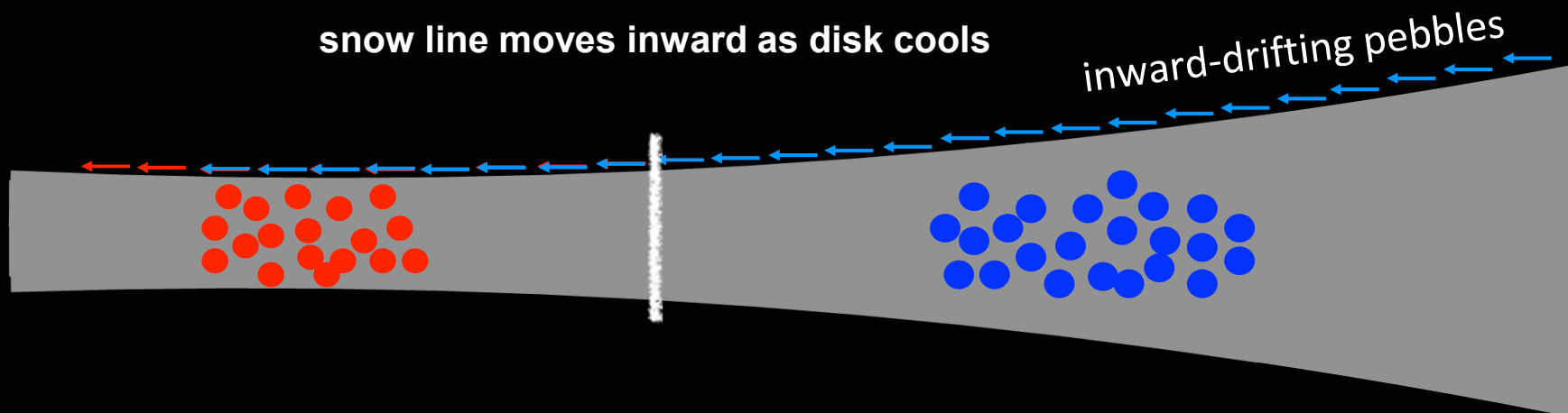
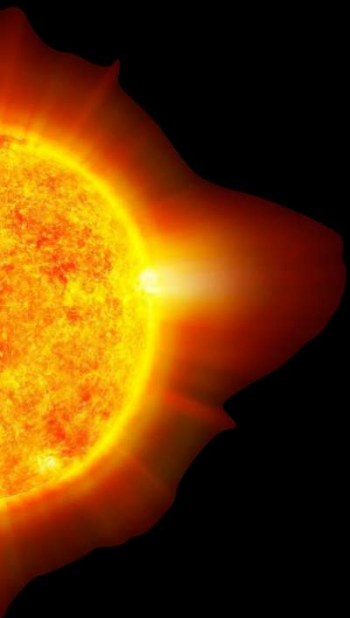
**of course, the snow line moves, and we'll come back to that later...

Can pebbles deliver water?



Not to planets interior to the snow line**

Can pebbles deliver water?



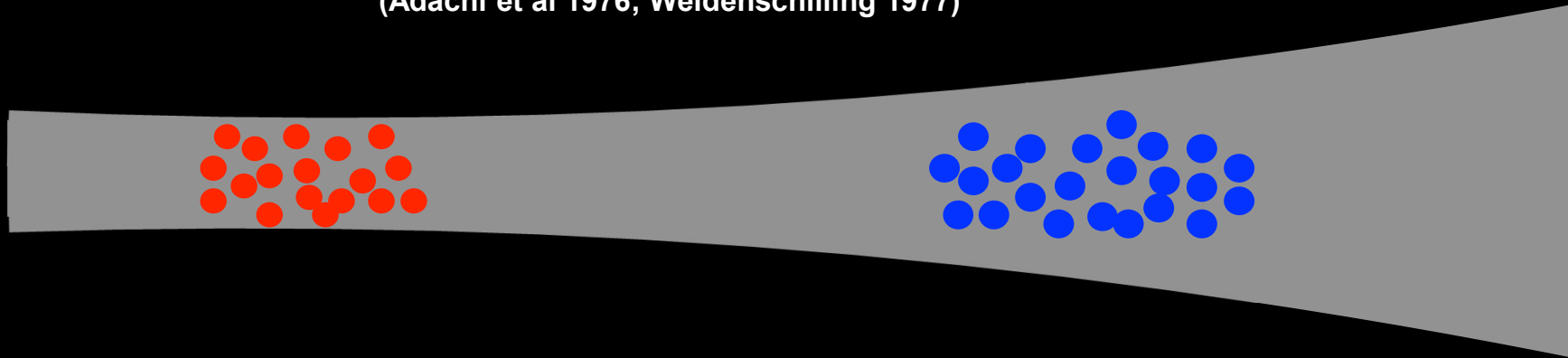
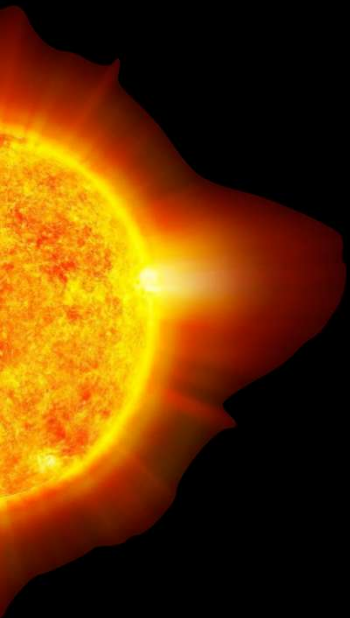
Pebbles can deliver water if there is a sufficient pebble flux and the snow line moves far enough inward

(e.g., Sato et al 2016; Bitsch et al 2019; Ida et al 2020; Izidoro et al 2021)

Can planetesimals deliver water?

Aerodynamic drag causes inward drift

(Adachi et al 1976; Weidenschilling 1977)

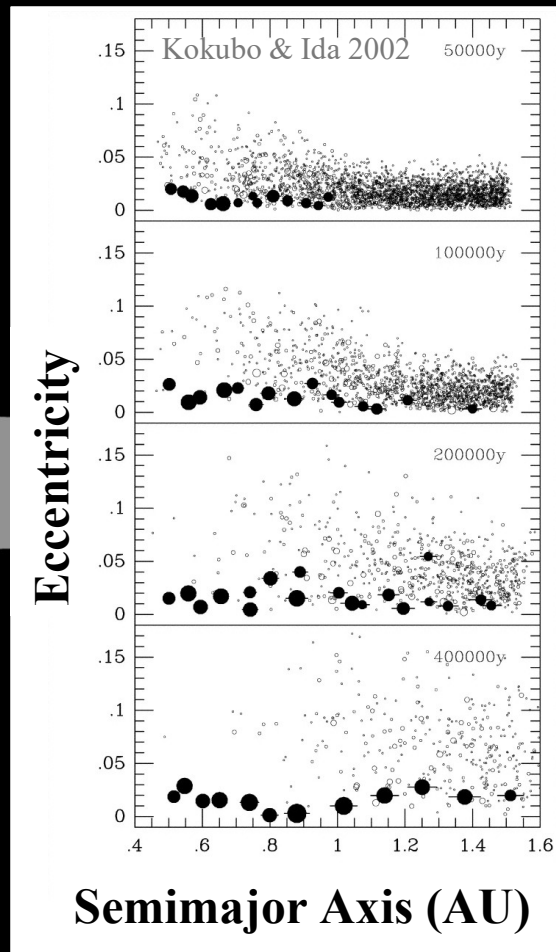


~100 m to 1km-scale planetesimals can deliver water**

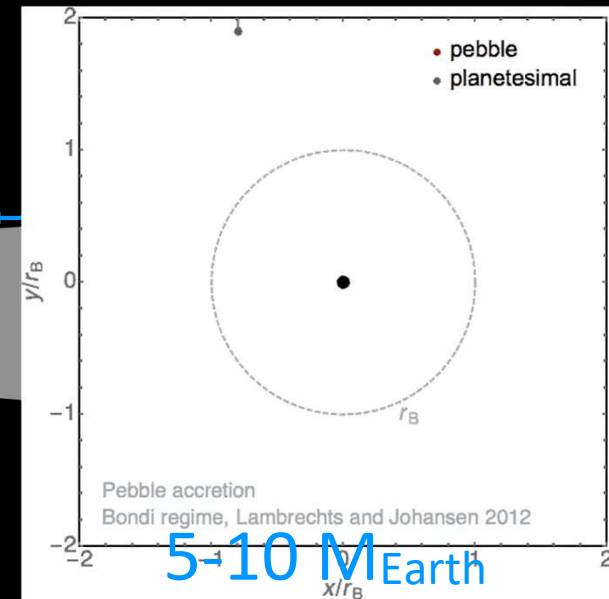
****Mass budget probably low; not well-studied**

Growth of planetary embryos

planetesimal accretion



pebble accretion



'cores'

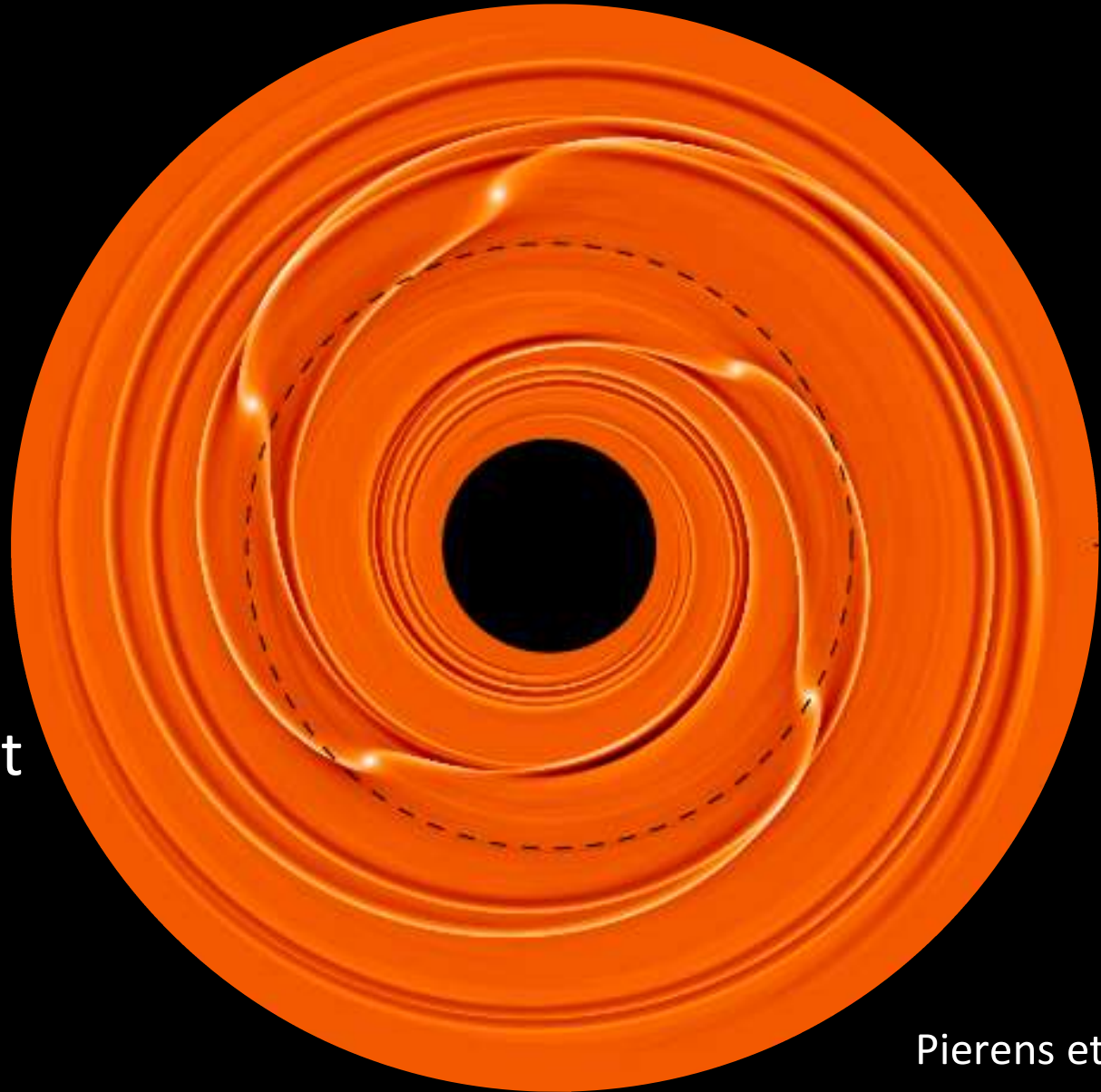
Pebble accretion dominates past the snowline,
planetesimal accretion closer-in**

(Lambrechts et al 2014; Morbidelli et al 2015; Ormel 2017; Izidoro et al 2022; Yap & Batygin 2024, ...)

Orbital migration

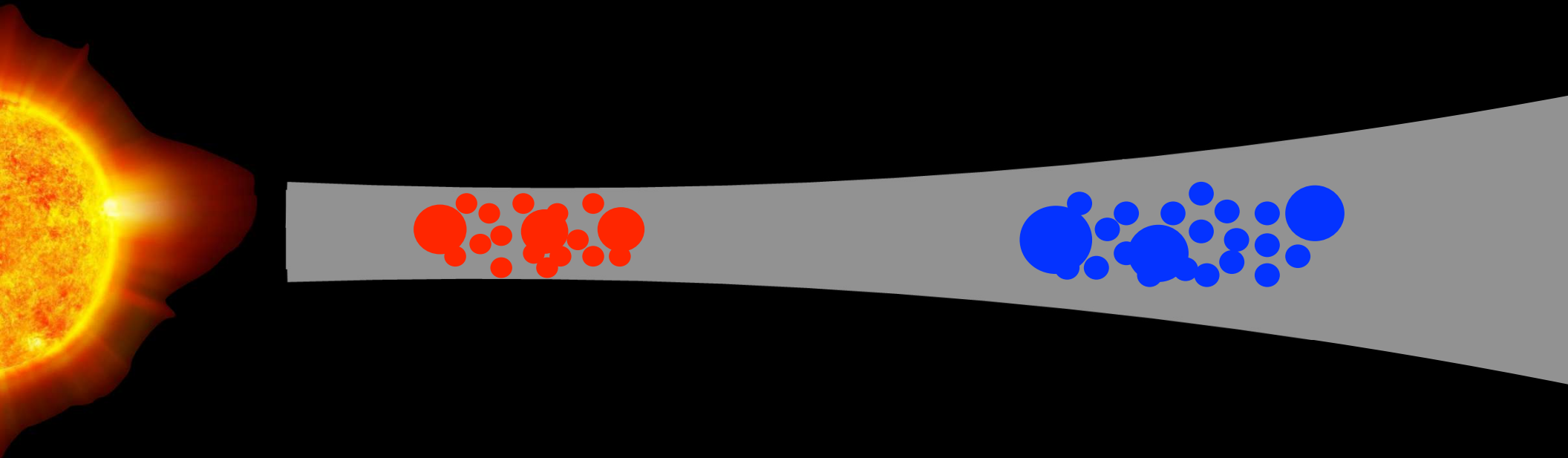
Matters for
 $M_p > \sim M_{\text{Earth}}$

More massive planet
 \Rightarrow faster migration



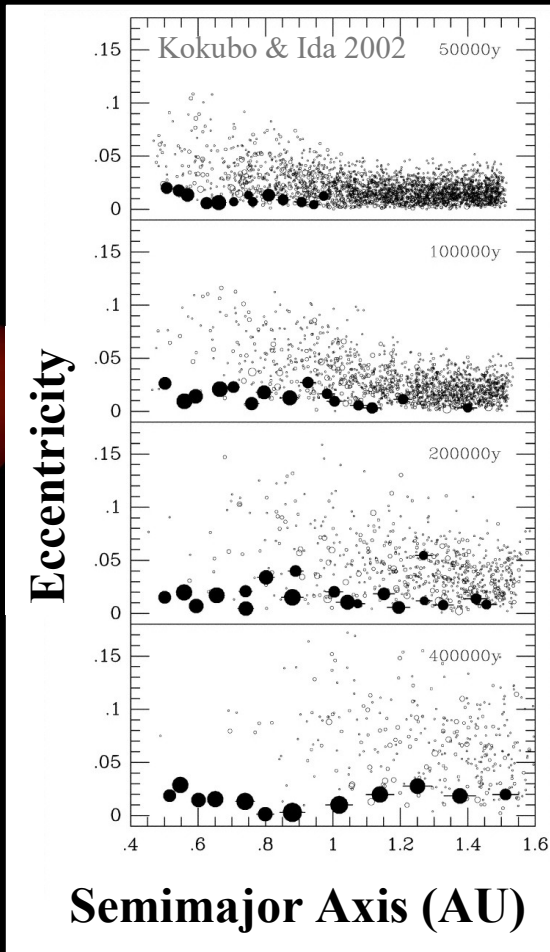
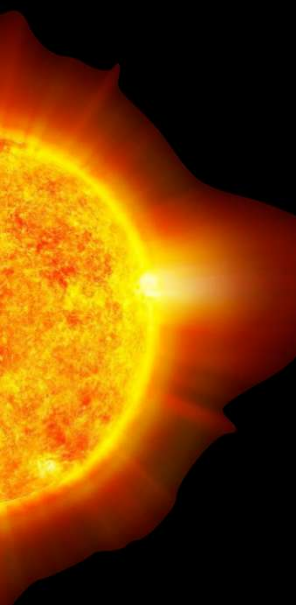
Pierens et al (2013)

Migrating icy embryos can deliver water

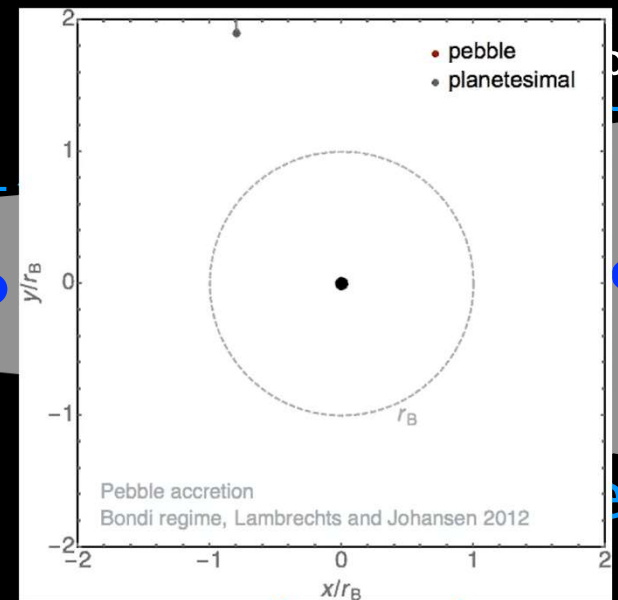
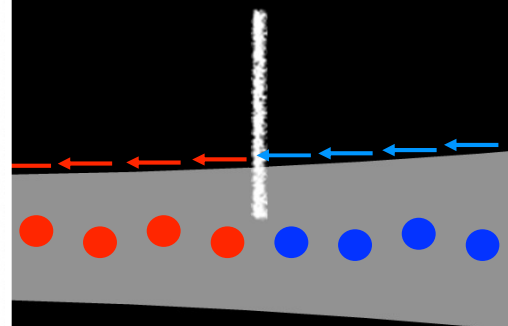


(e.g. Kuchner 2003, Raymond et al 2008, Ogihara et al 2009, Bitsch et al 2019; Izidoro et al 2021)

Planetary simulations



“snow line”



pebbles

planetesimal accretion

planetesimal accretion closer-in

dominates past the snowline,

pebble accretion

(Lambrechts et al 2014; Morbidelli et al 2015; Ormel 2017; Izidoro et al 2022; Yap & Batygin 2024, ...)

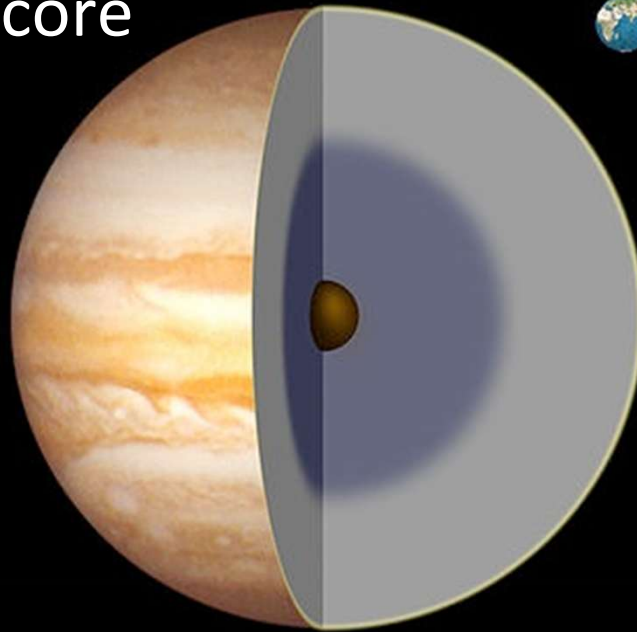
Gas giants



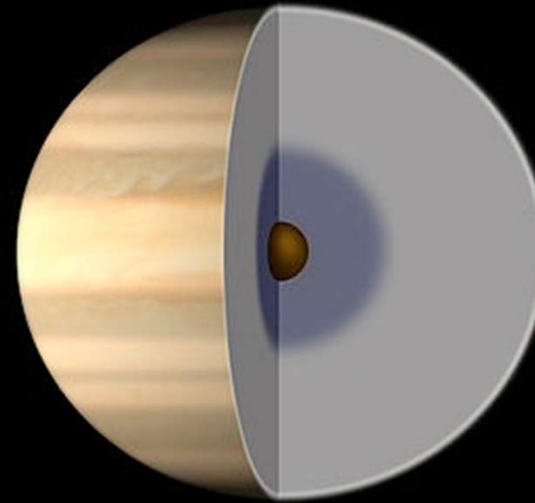
Core accretion

growth of a large
solid core

gas accretion



JUPITER



SATURN

■ Molecular hydrogen

■ Metallic hydrogen

■ Core (rock, ice)

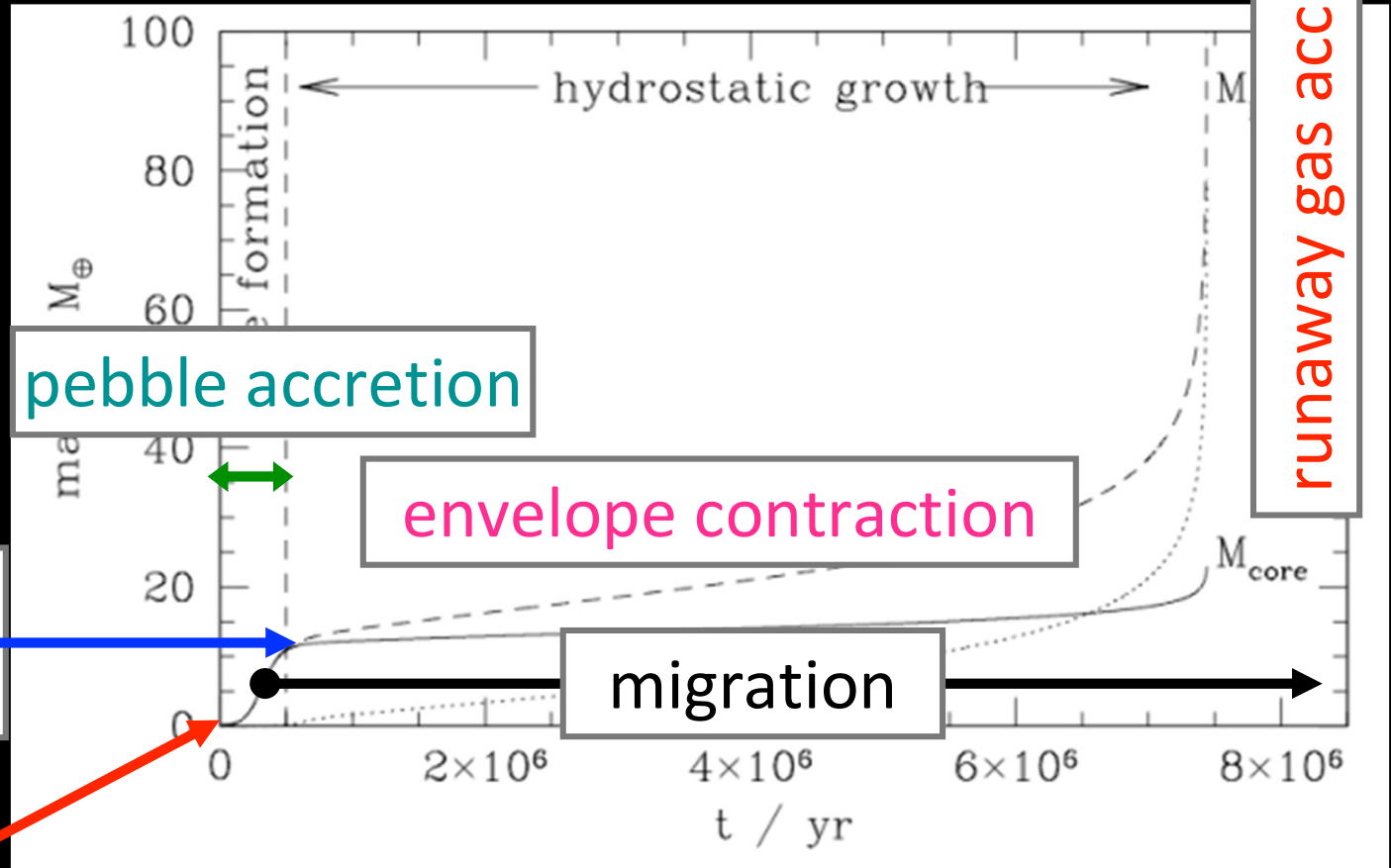
Core migration accretion

growth of a large solid core

gas-driven migration

gas accretion

runaway gas accretion



pebble accretion

envelope contraction

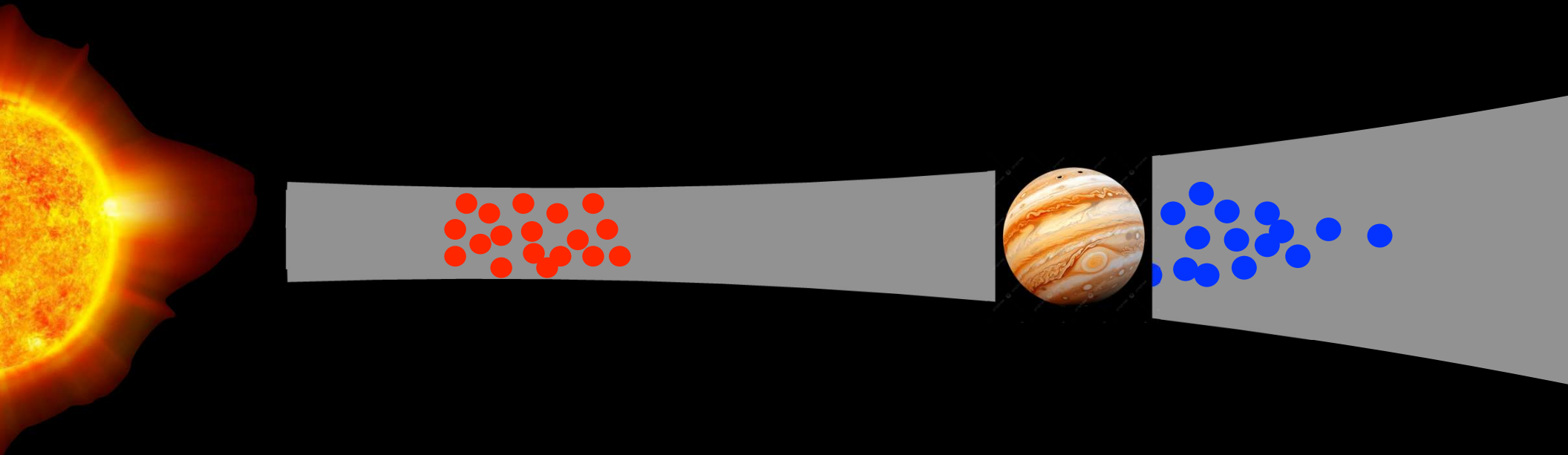
migration

pebble "isolation mass"

planetesimal formation

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

Gas giants usually grow from outer ring



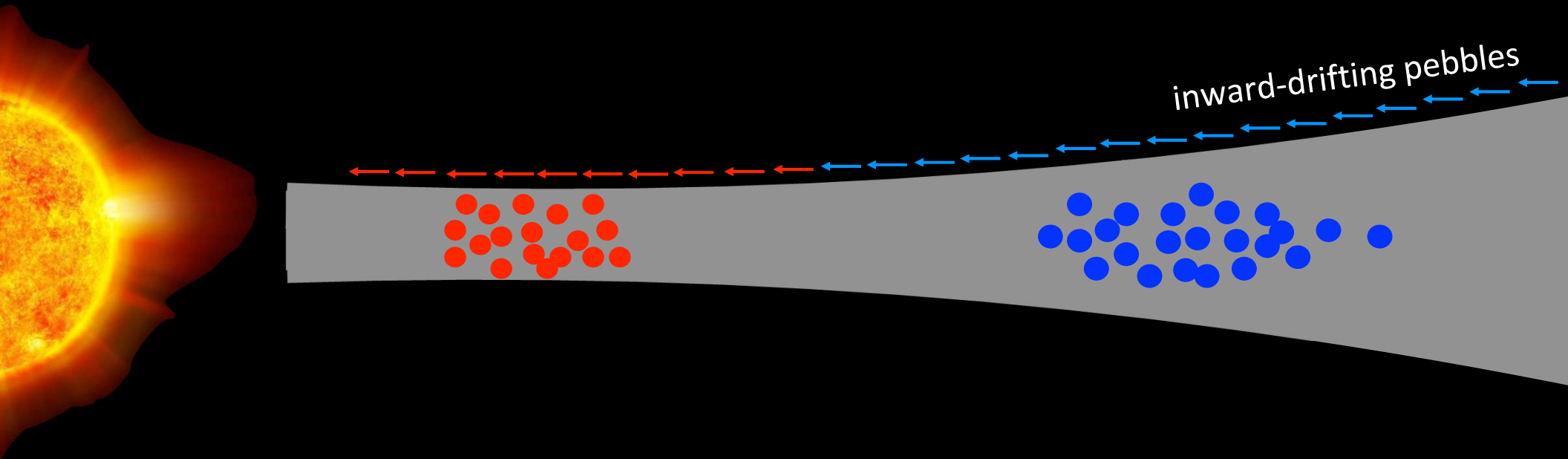
Why?

1. **Much more (solid) mass past snow line** (e.g., Armitage 2011)
2. **Pebble accretion more efficient past snow line** (e.g., Morbidelli et al 2015)
3. **Giant exoplanets typically found past 1 au** (e.g., Butler et al 2006)

Effect of an outer giant on water delivery



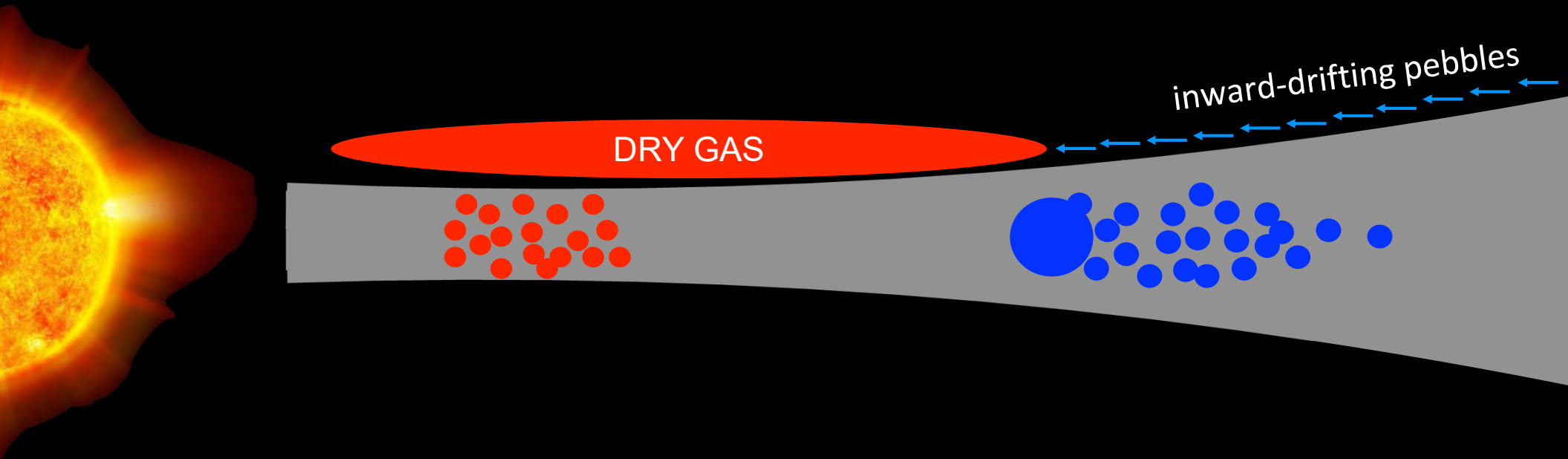
Gas giant cores block drifting pebbles



“Pebble isolation” : pebble flux blocked

(Lambrechts et al 2014; Morbidelli et al 2015; Bitsch et al 2018)

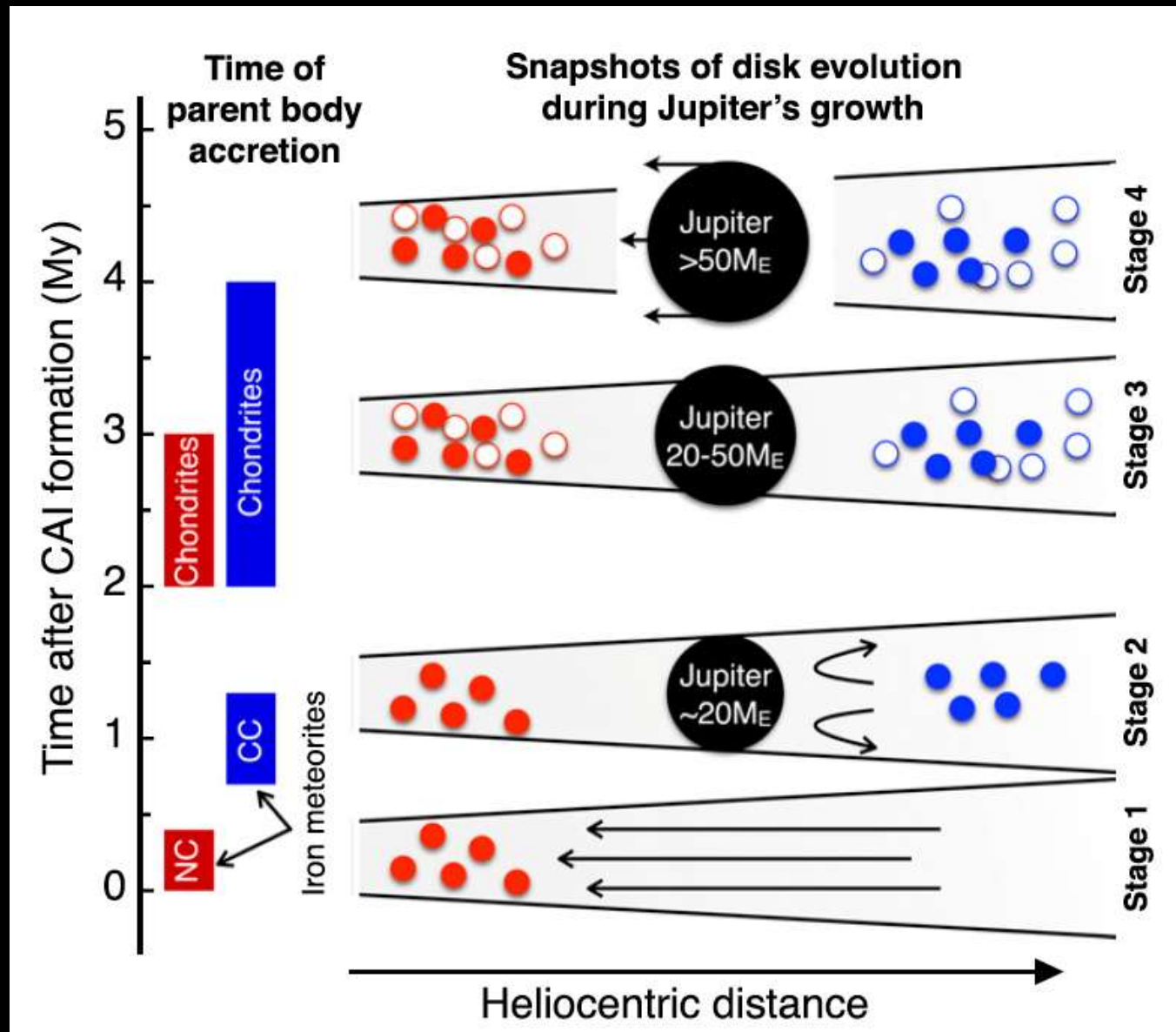
Gas giant cores block drifting pebbles



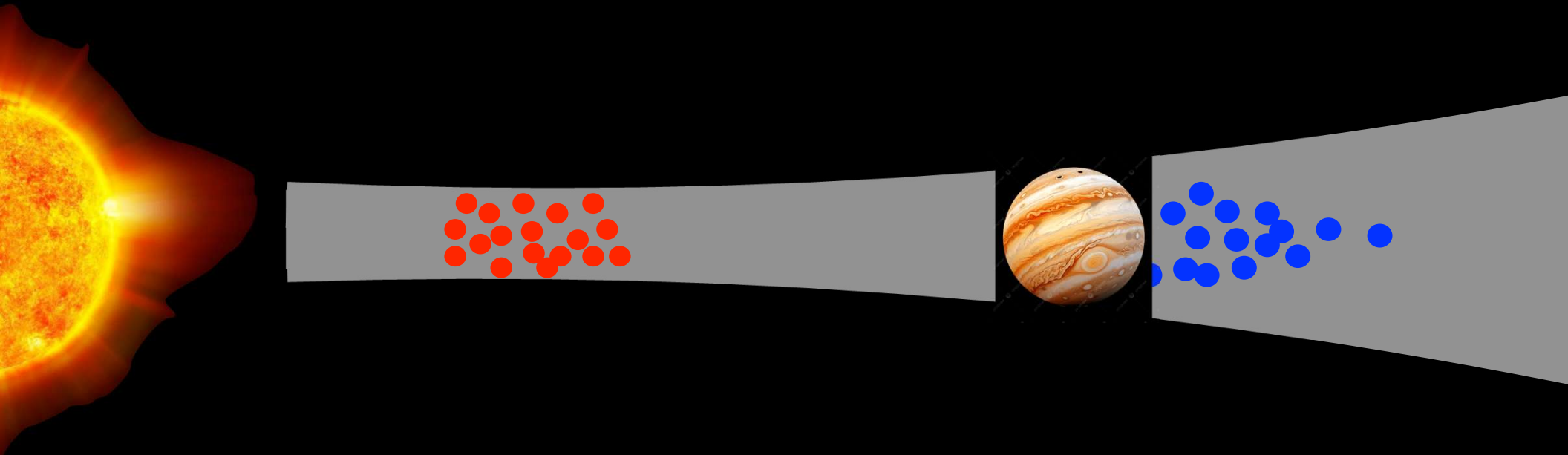
Gas interior is wet if $r_{\text{core}} < \text{snowline}$, dry if $r_{\text{core}} > \text{snowline}$

(Bitsch et al 2021)

Meteorite isotopes and ages hint at Jupiter blocking pebbles



Gas giants (often) block migration of ice giants



Jupiter and Saturn blocked inward migration of icy embryos, which grew into ice giants**

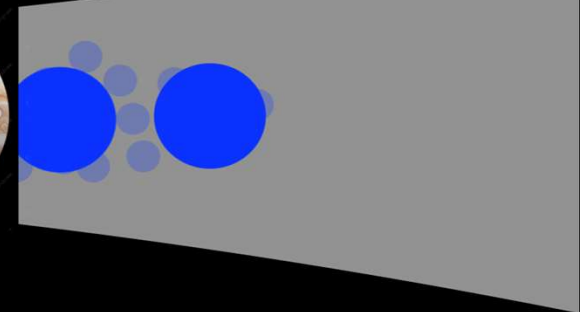
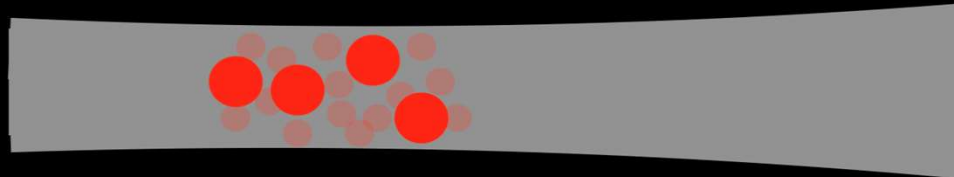
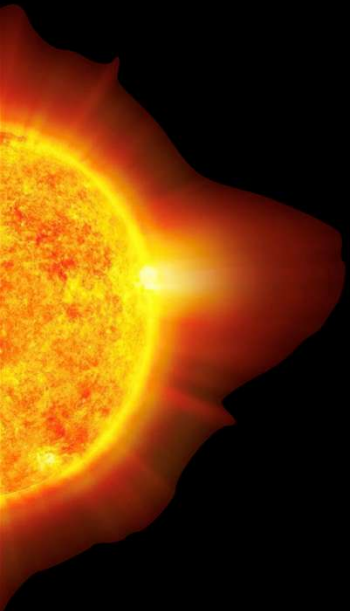
(Izidoro et al 2015 a,b)

**** (Gas giants can only block the migration of more distant cores)**

Izidoro et al (2015) prediction: anti-correlation between super-Earths, outer giants

But observations find a positive correlation at high metallicity, otherwise no correlation

(e.g., Barbato et al 2018, Bryan et al 2019, Rosenthal et al 2024, Bonomo et al 2025).

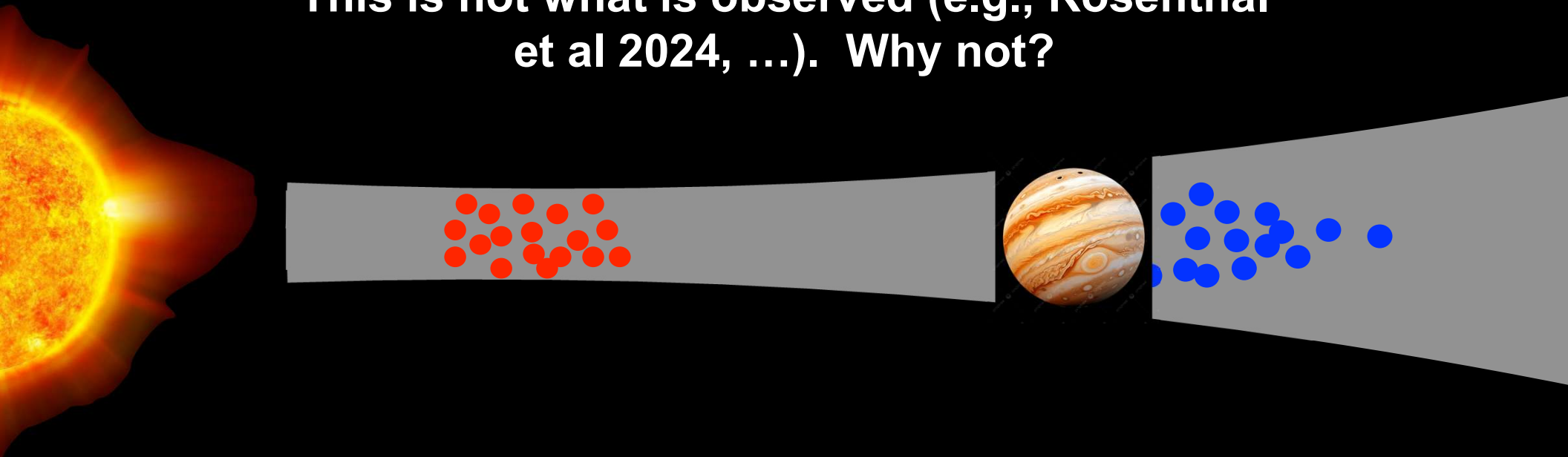


Why?

- It is often not the innermost icy core that becomes the gas giant (?)
- “Jumpers” are more common than expected (?)
- Gas giants and super-Earths formation are both a function of solid disk mass (?)
- Inner/outer planetesimal disk properties are not connected (?)

Izidoro et al (2015) prediction: anti-correlation between super-Earths, outer giants

This is not what is observed (e.g., Rosenthal et al 2024, ...). Why not?

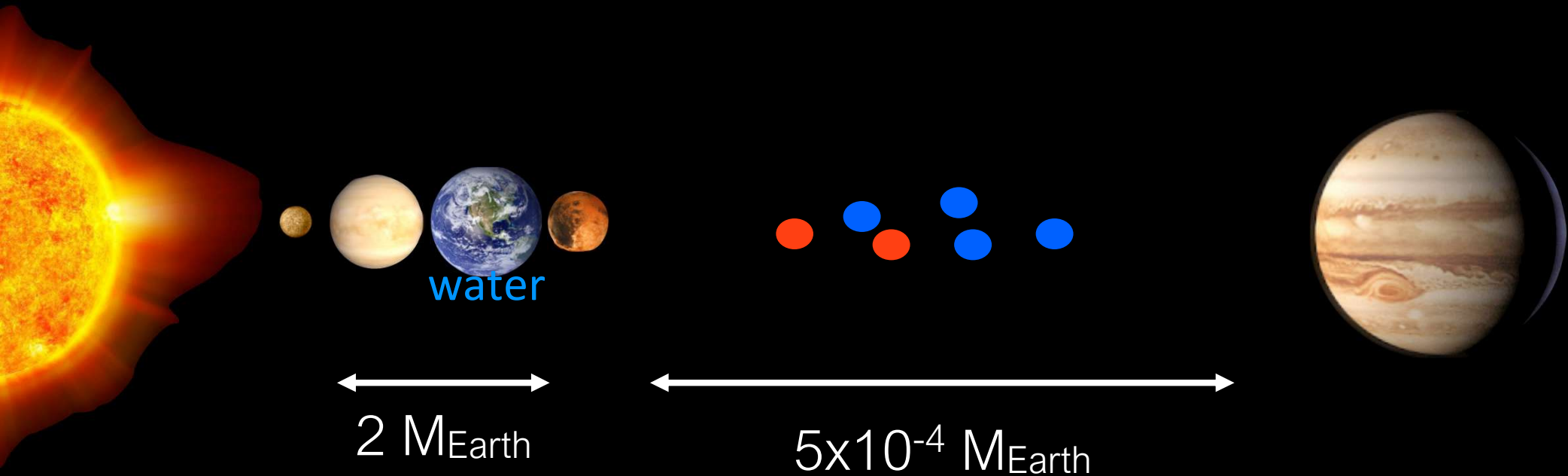


- It is often not the innermost icy core that becomes the gas giant
- “Jumpers” are more common than expected
- Gas giants and super-Earths formation are both a function of total disk mass

The Solar System and giant exoplanets

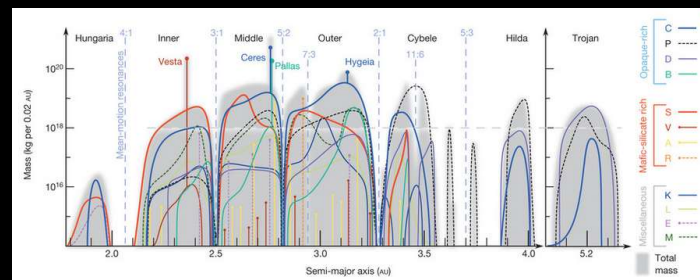
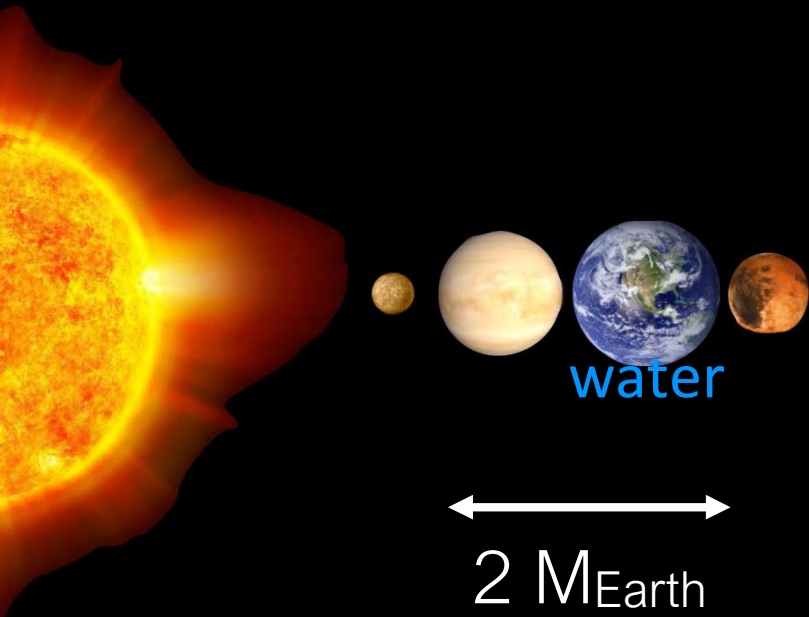


The (inner) Solar System



The (inner) Solar System

Demeo &
Carry 2014

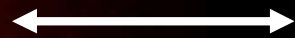


$5 \times 10^{-4} M_{\text{Earth}}$



The (inner) Solar System

Demeo &
Carry 2014

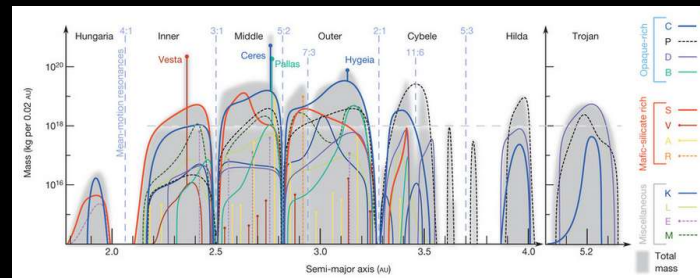


$2 M_{\text{Earth}}$

Number, masses

Orbits

Growth timescales,
compositions,
isotopic ratios



$5 \times 10^{-4} M_{\text{Earth}}$

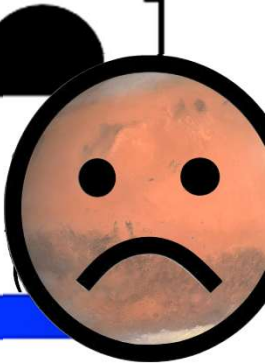
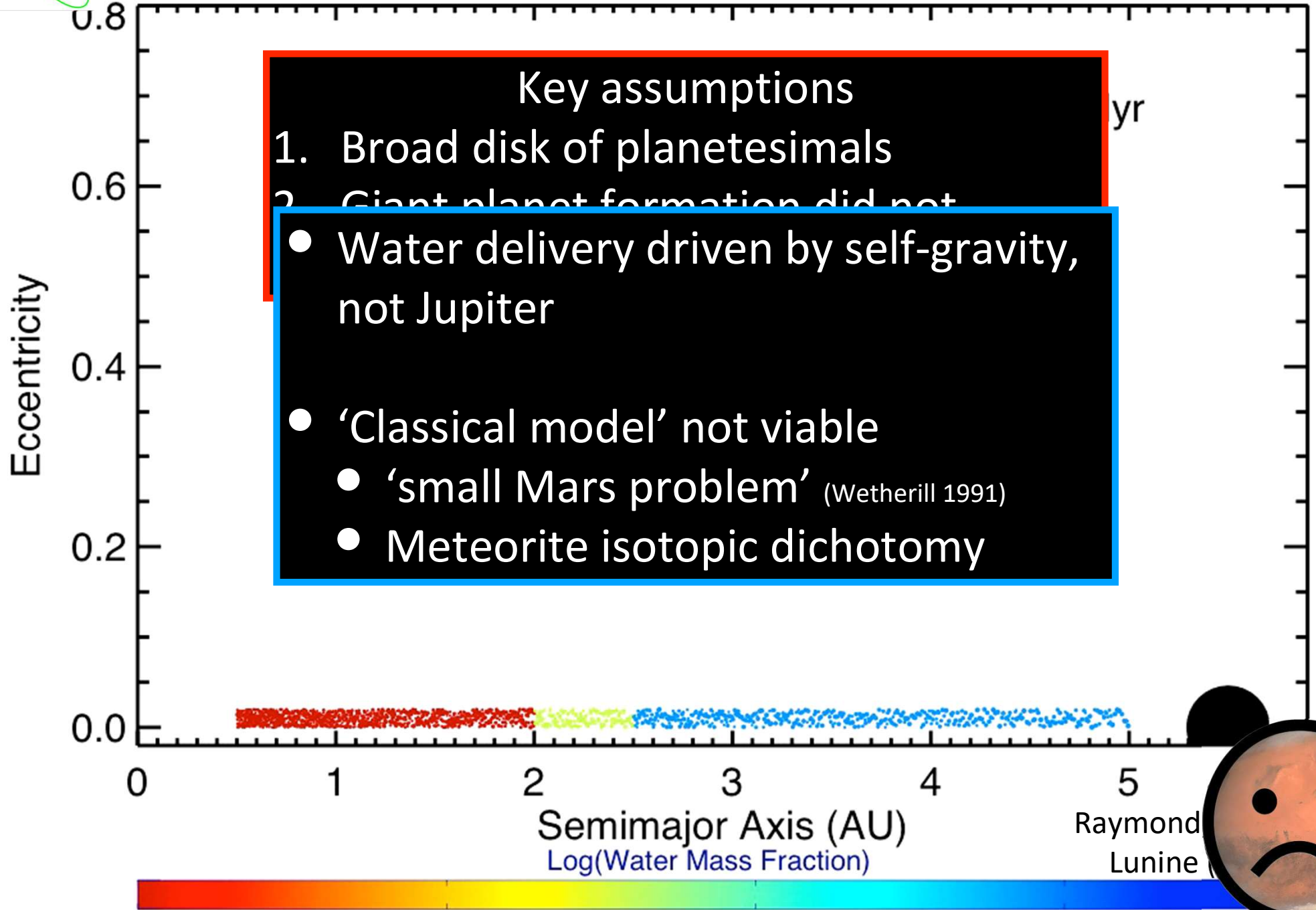
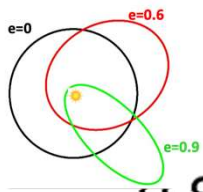
Total mass

S/C dichotomy

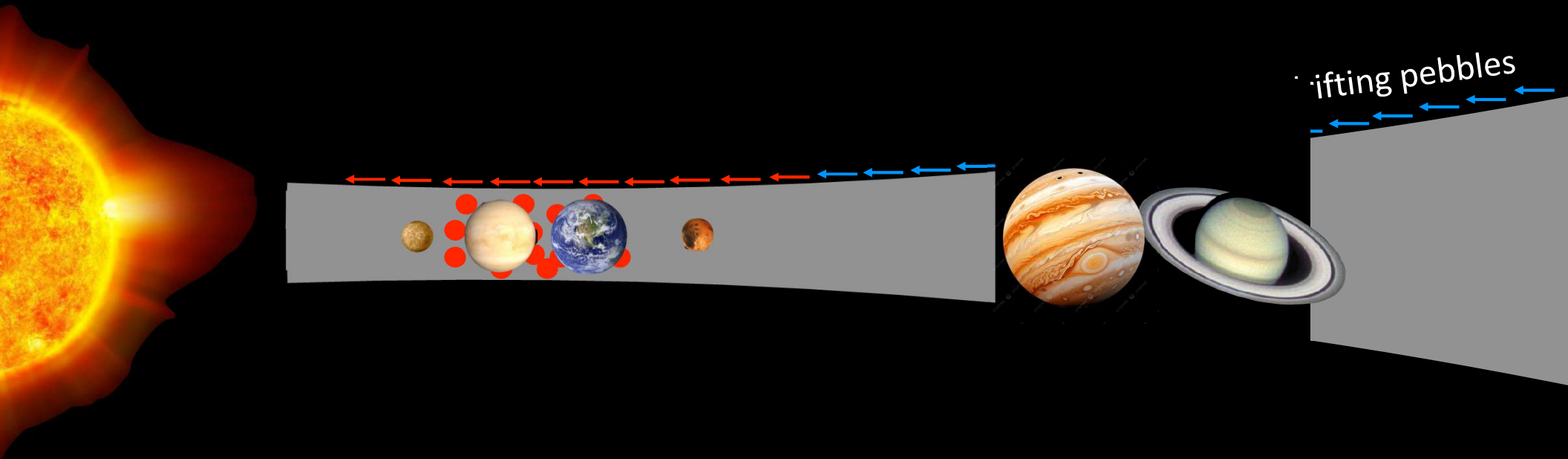
Orbital distribution



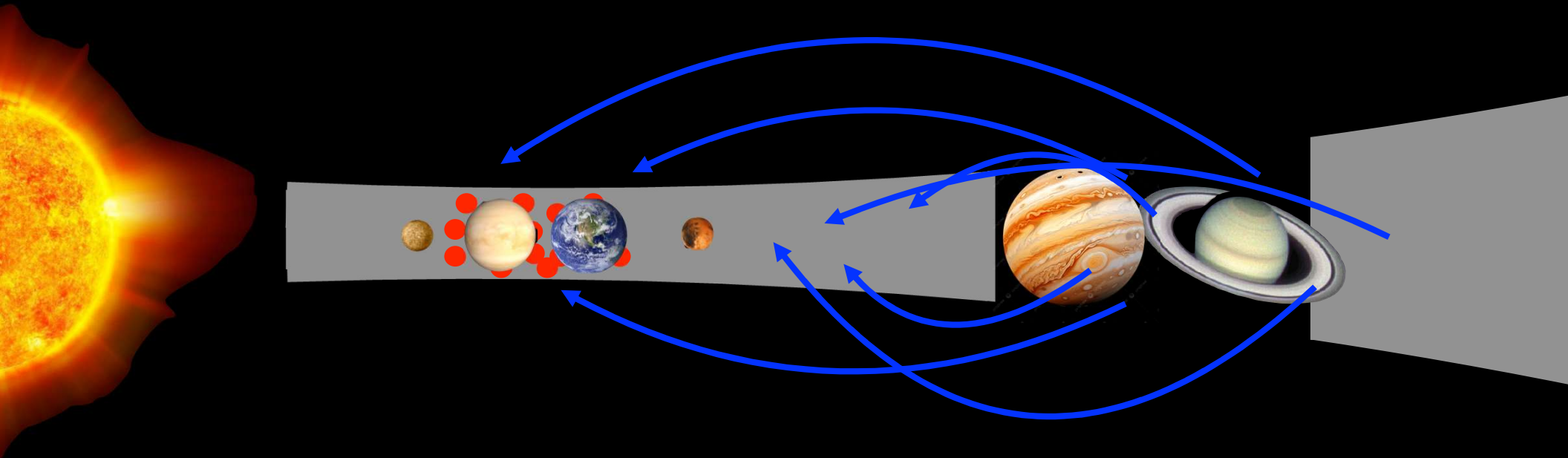
The “classical model”



The Solar System (no migration)

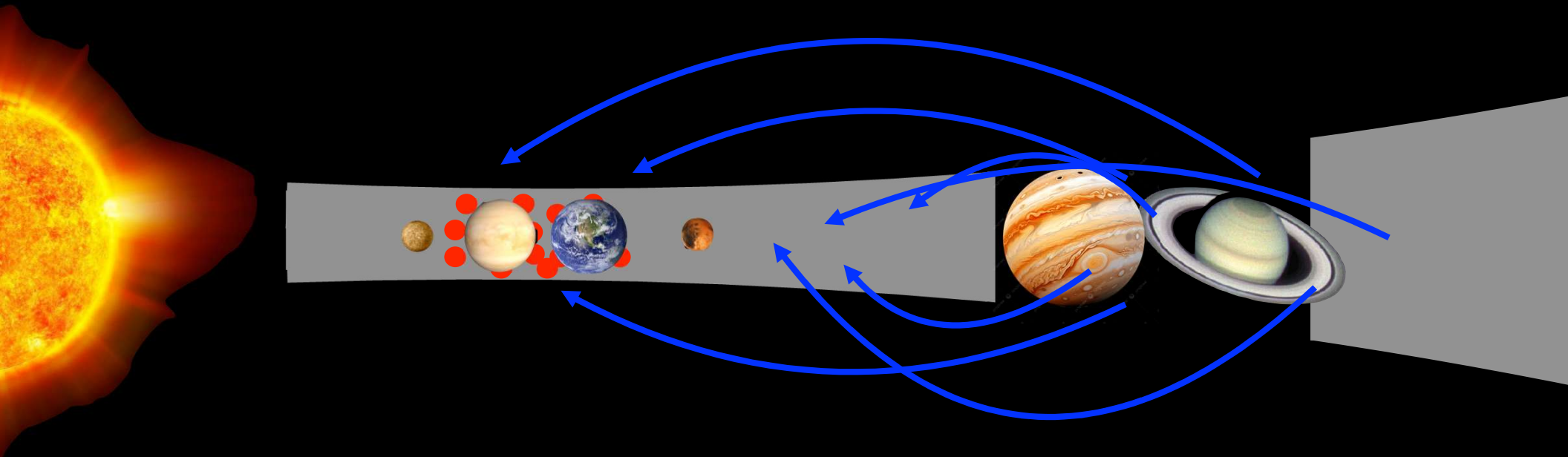


The Solar System (no migration)



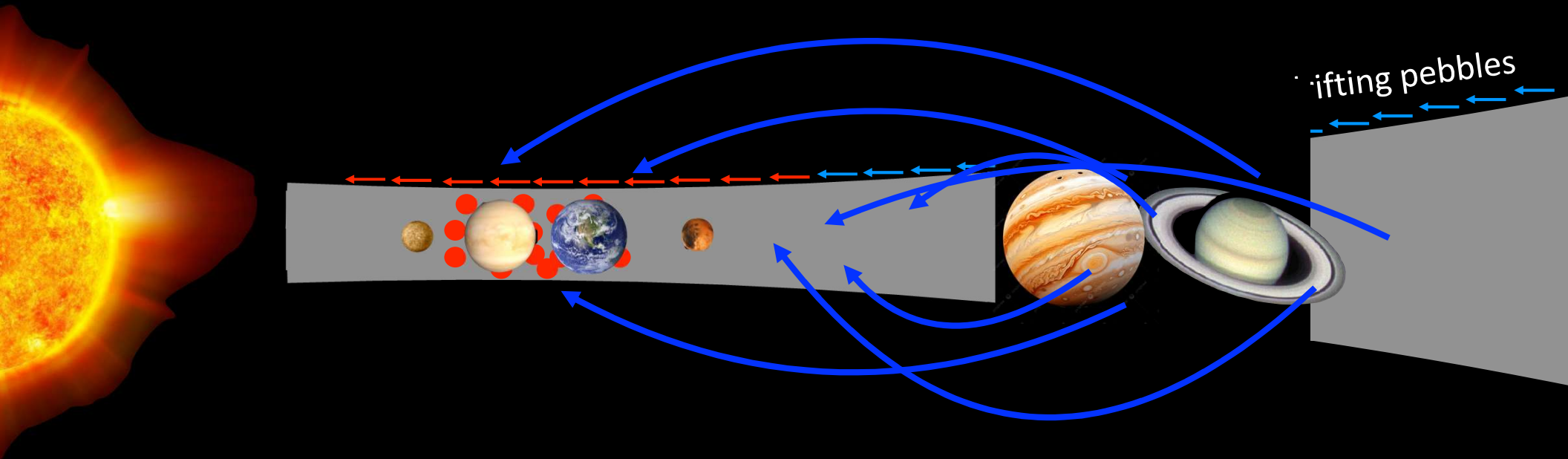
C-type asteroids implanted during giant planet growth
(Raymond & Izidoro 2017)

The Solar System (no migration)

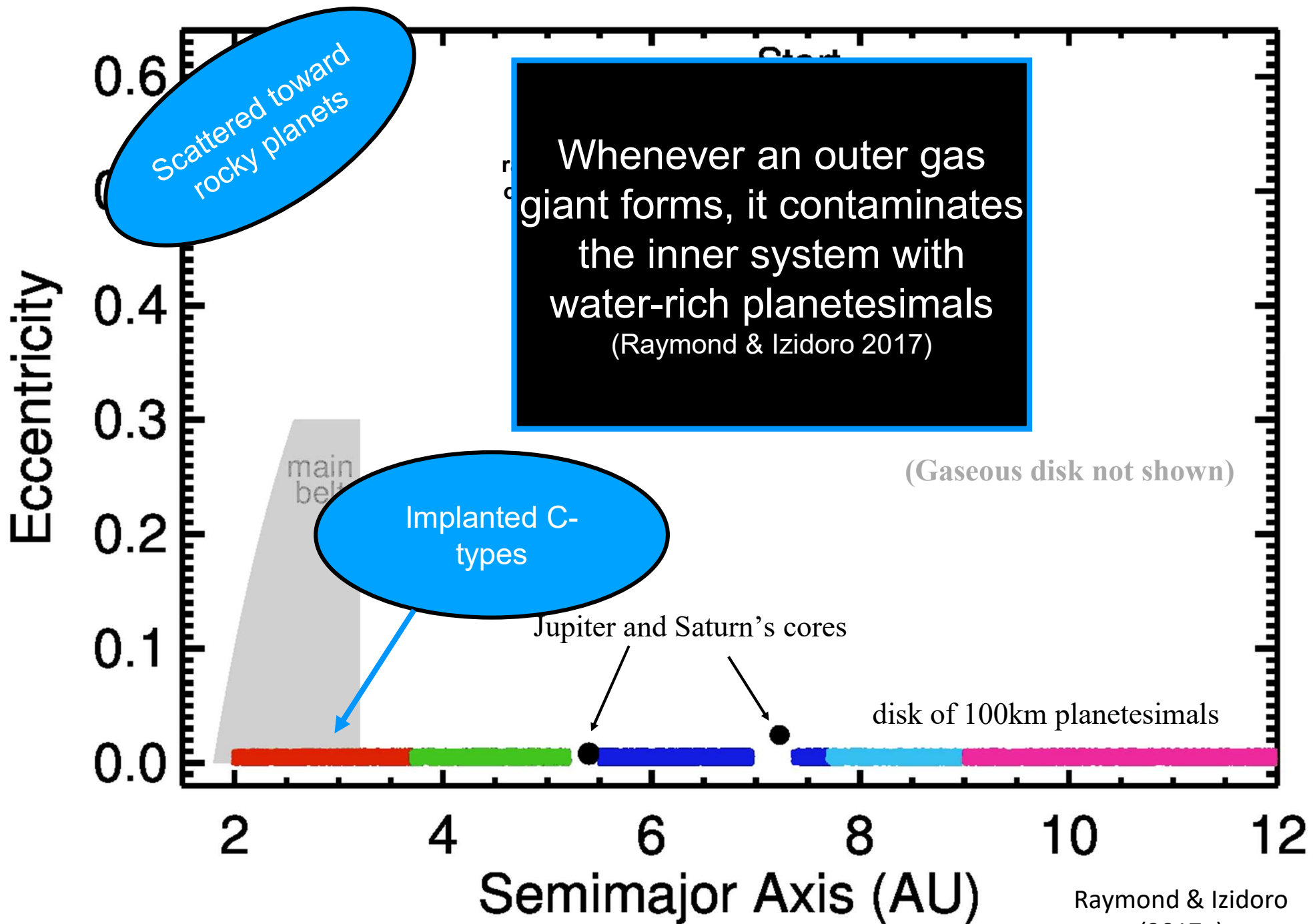


C-type asteroids implanted during giant planet growth
(Raymond & Izidoro 2017)

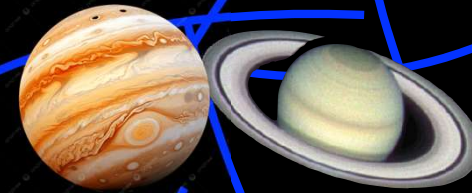
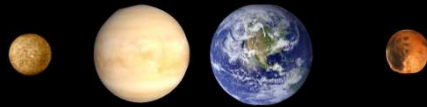
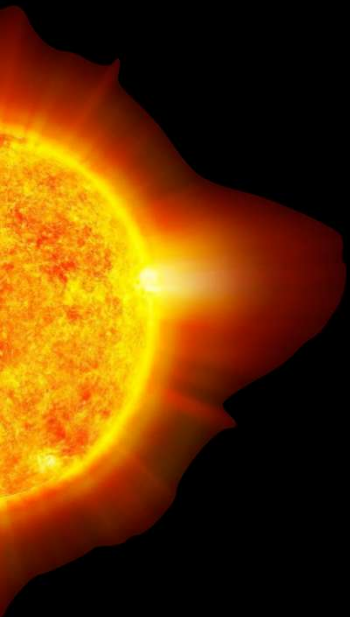
The Solar System (no migration)



C-type asteroids implanted during giant planet growth
(Raymond & Izidoro 2017)



Water delivery from planetesimal scattering inefficient after gas disk dispersal

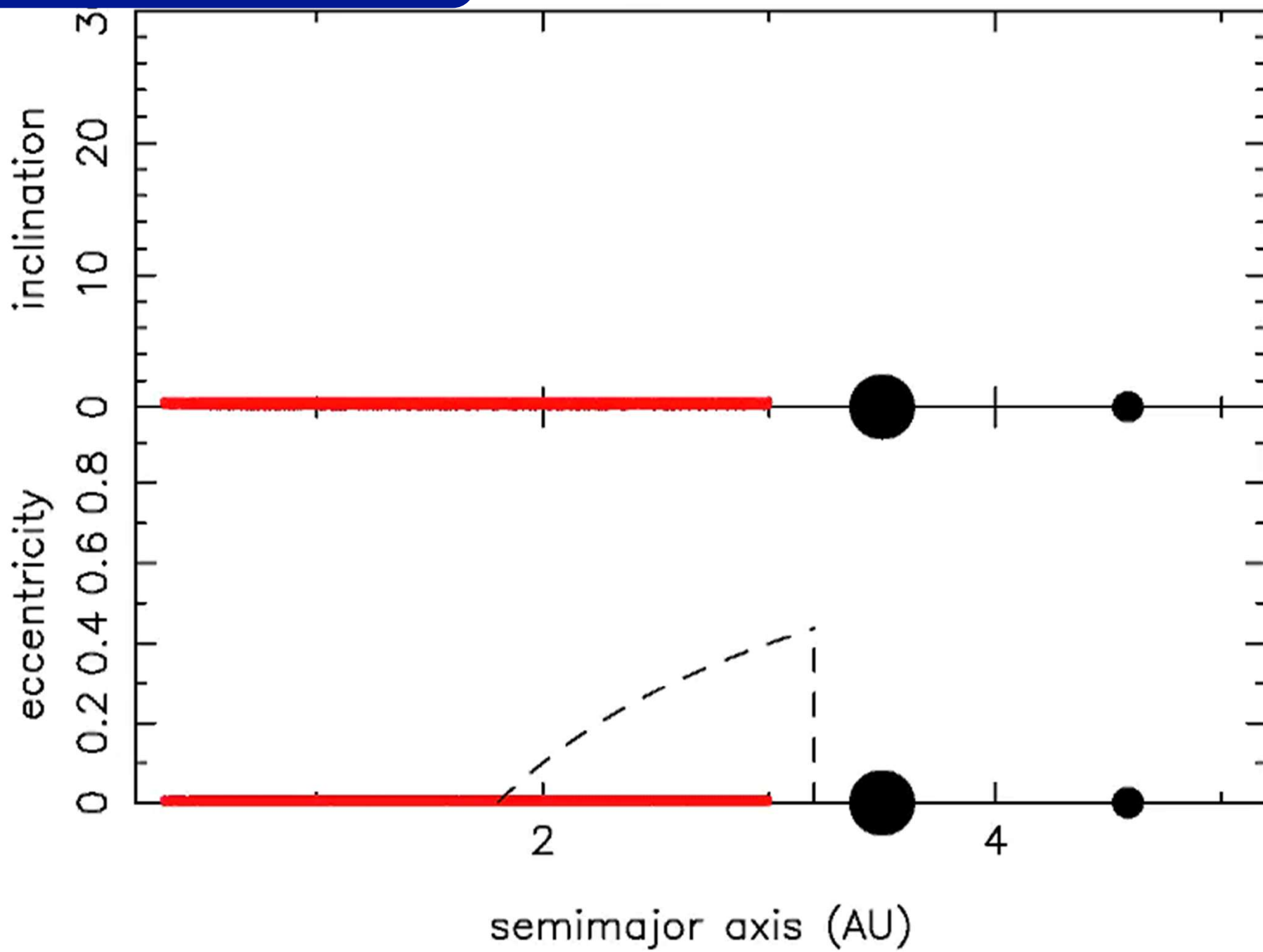


**With no gas for drag, Jupiter ejects almost all planetesimals
=> minimal water delivery****

****this is why comets are only a very minor source of Earth's water
(e.g., Morbidelli et al 2000)**

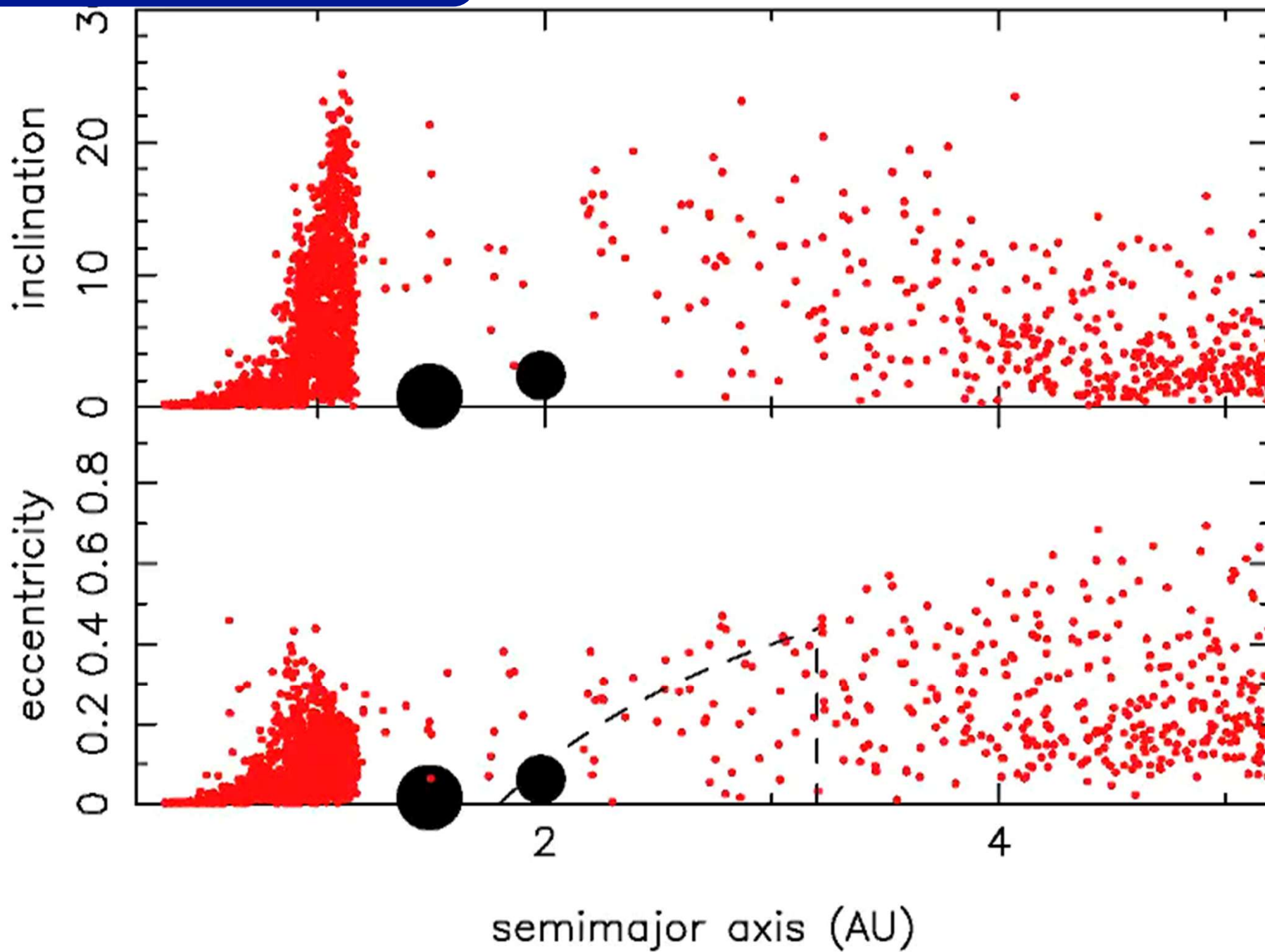
The Grand Tack model
(Walsh et al 2011)

T= 0.000 ky



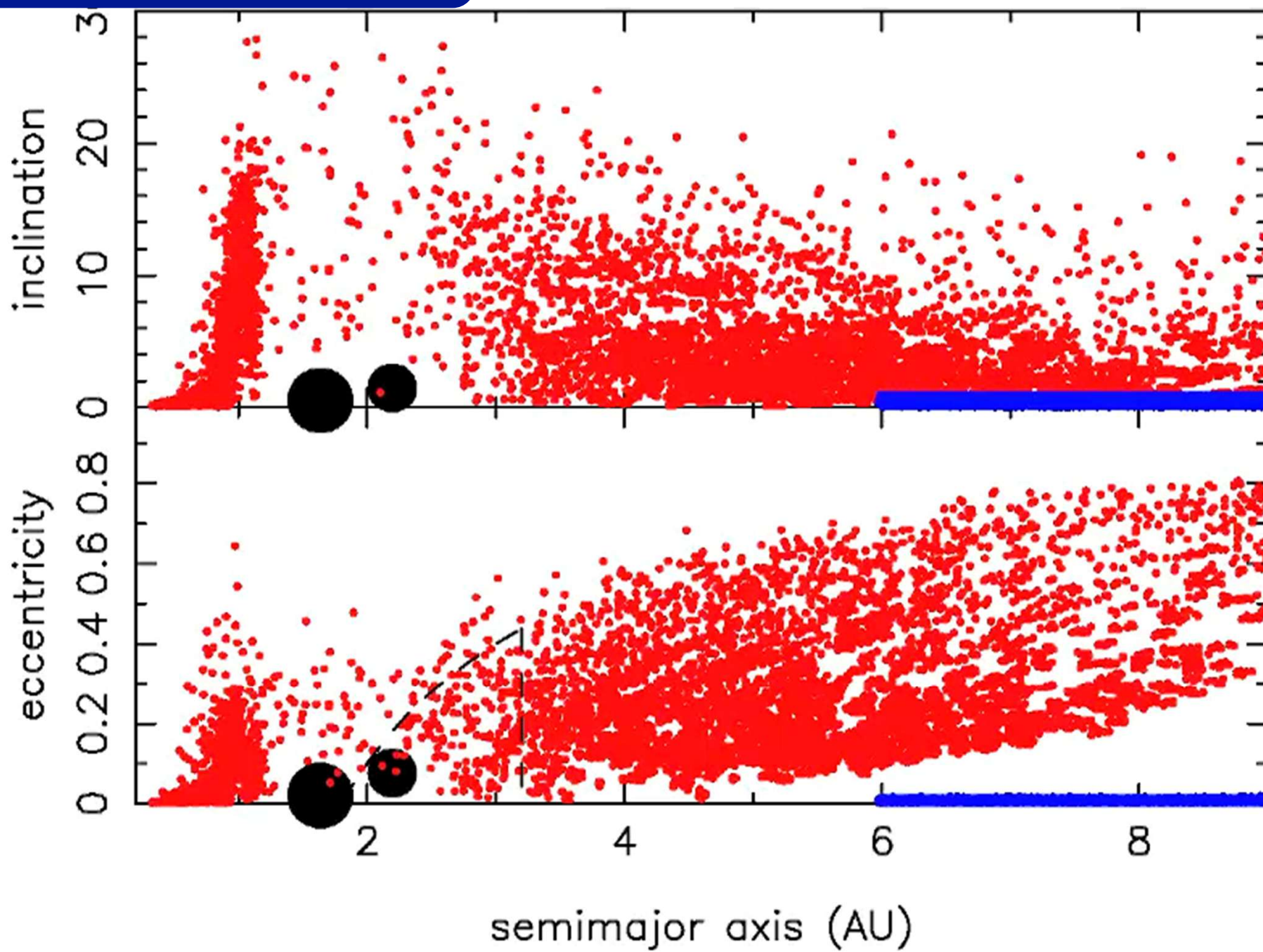
The Grand Tack model
(Walsh et al 2011)

$T = 100.000 \text{ ky}$



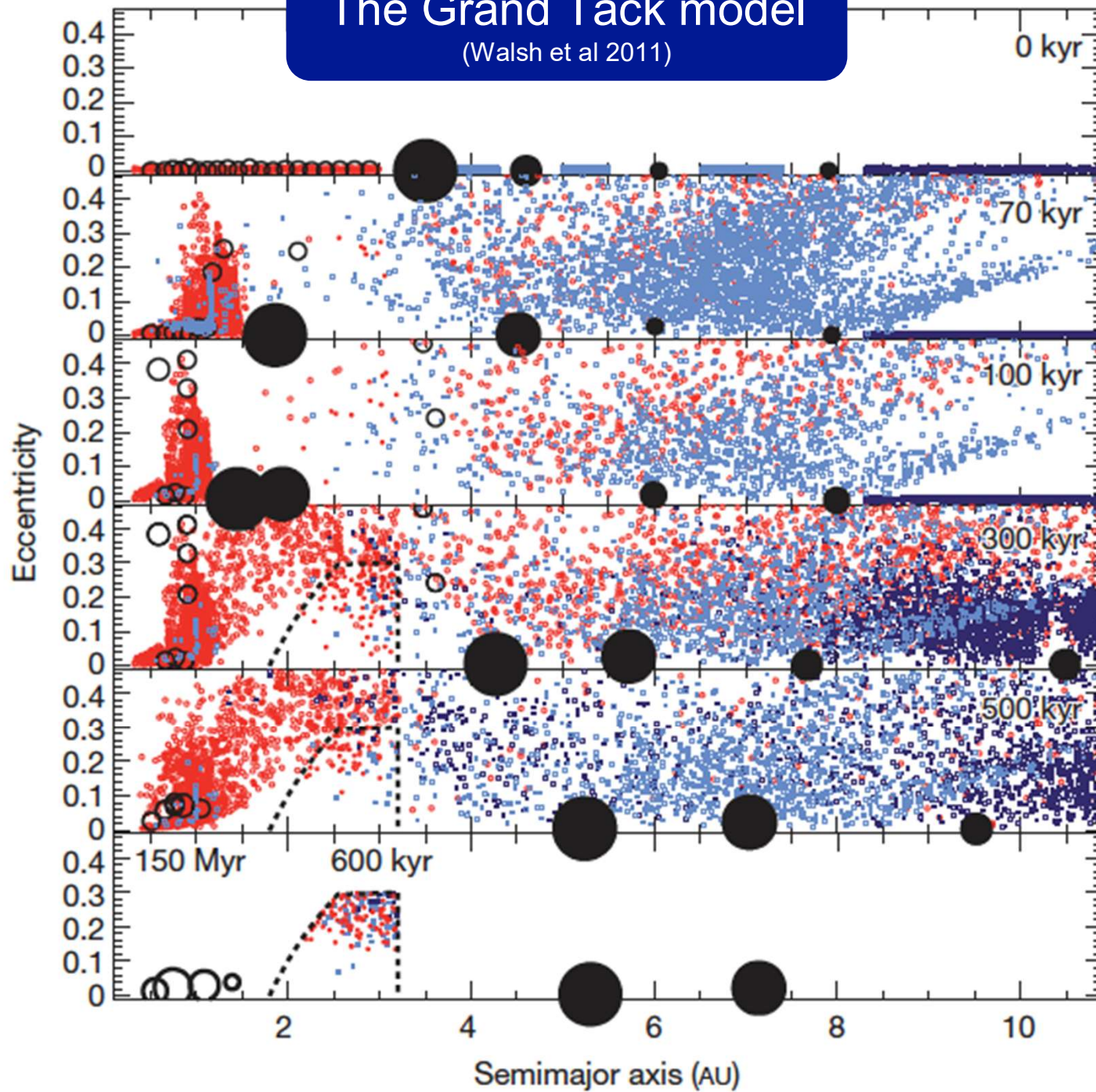
The Grand Tack model
(Walsh et al 2011)

$T = 110,000$ ky

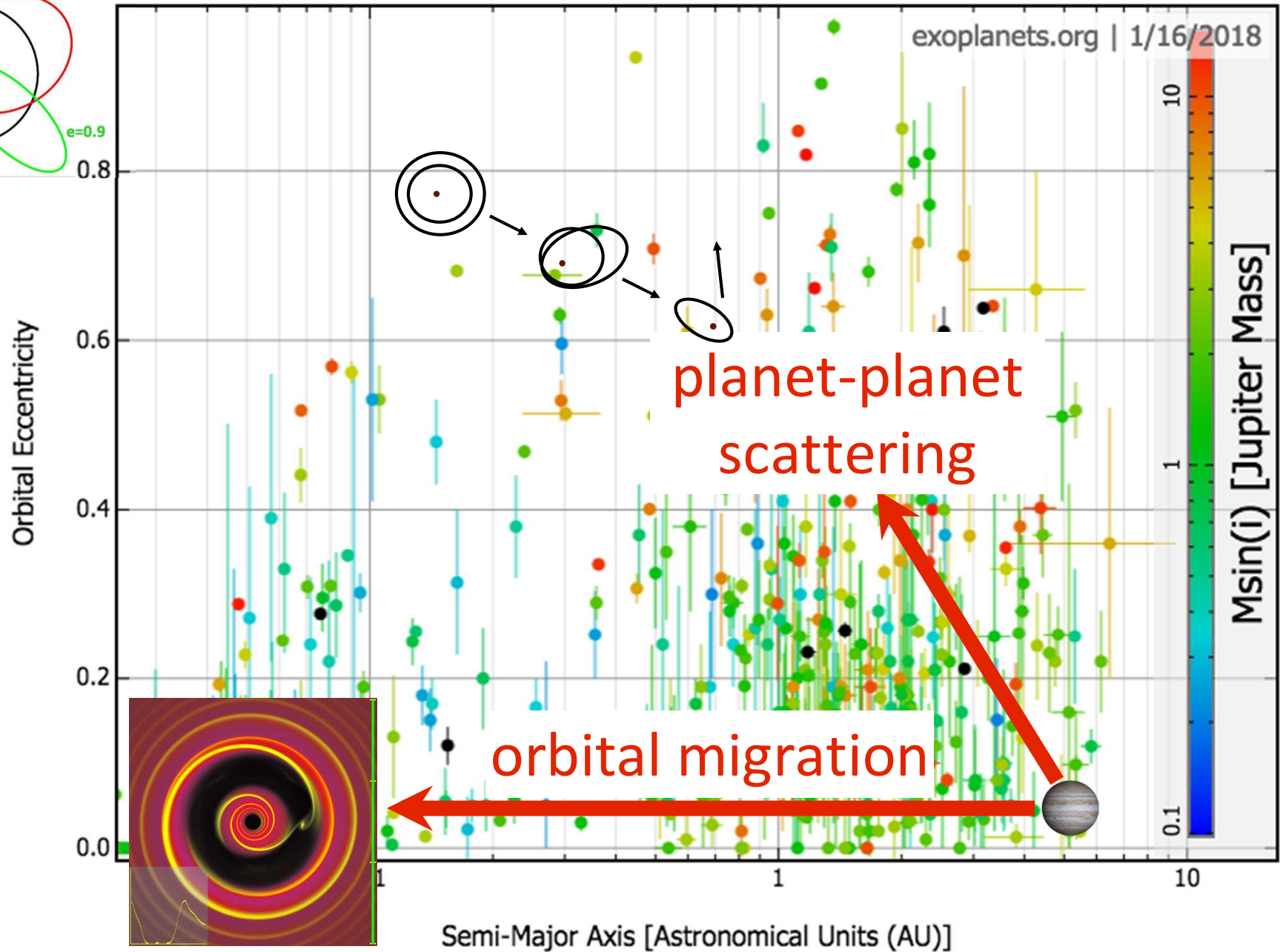
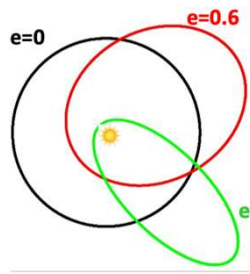


The Grand Tack model

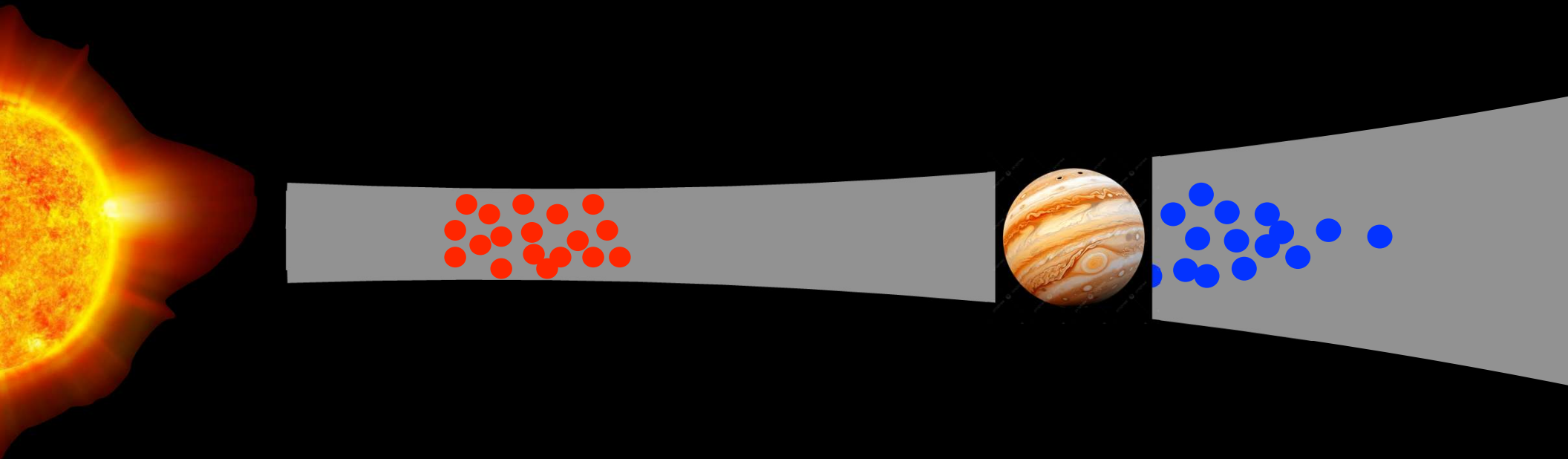
(Walsh et al 2011)



(Giant) exoplanets

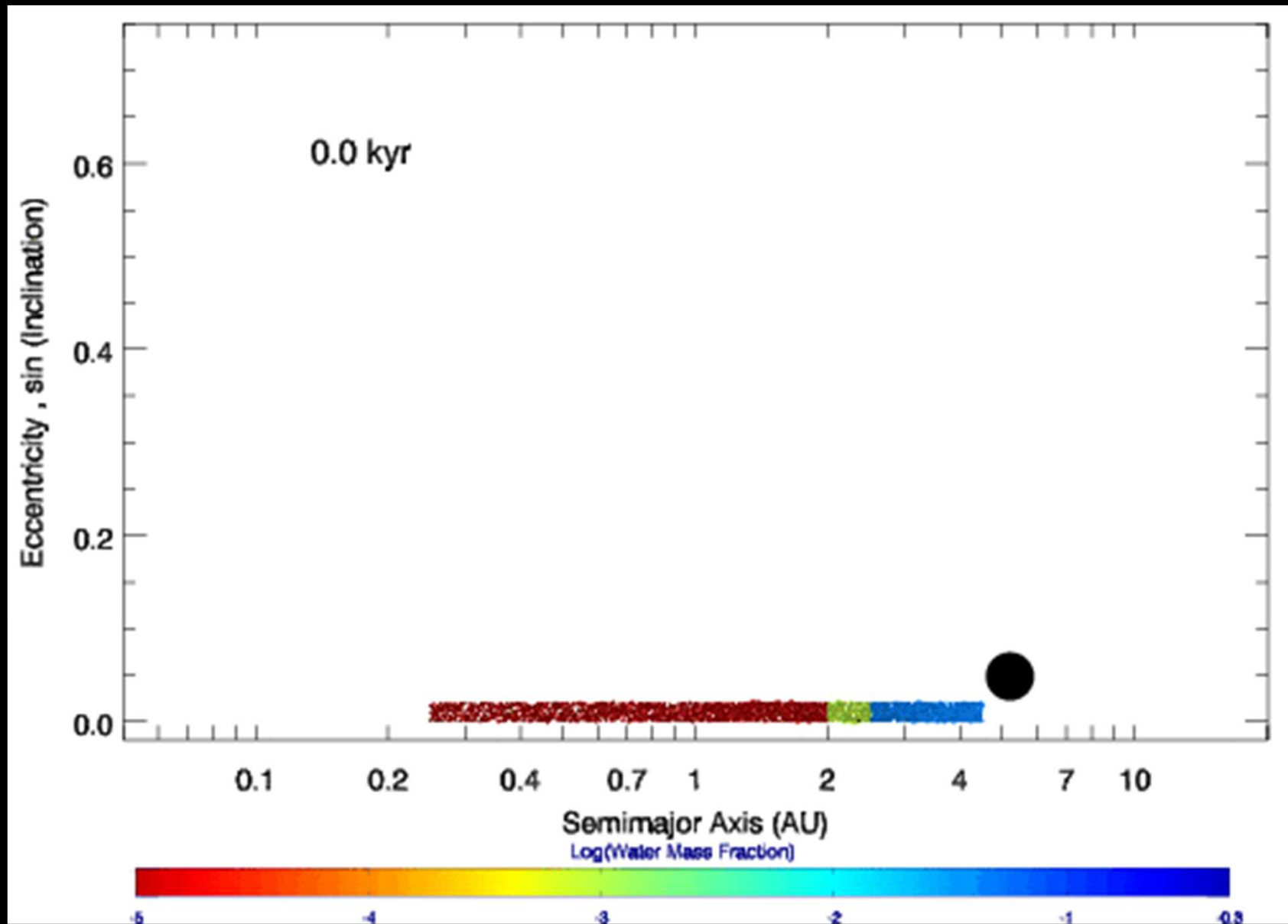


Gas giants can migrate inward

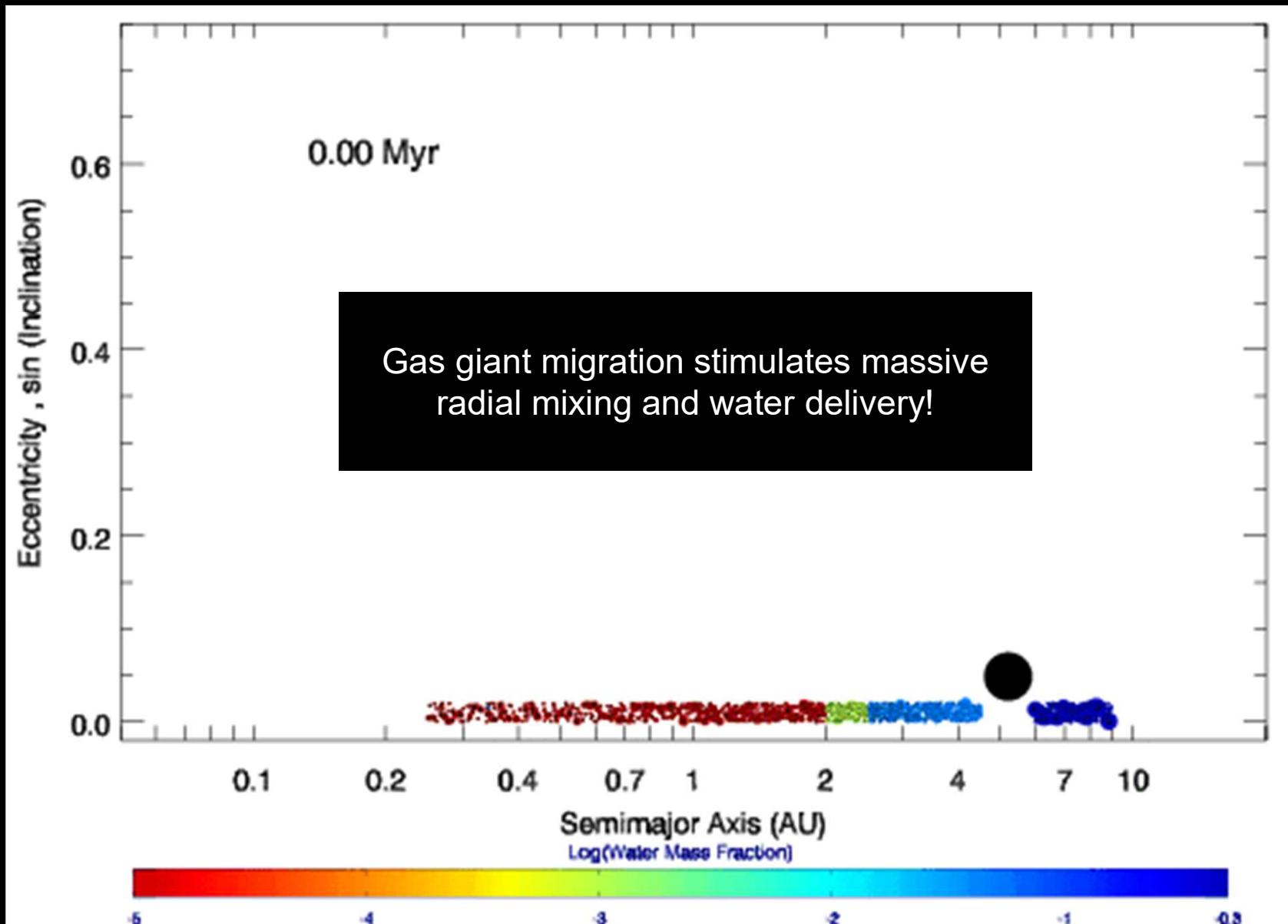


Disk migration as possible source of hot Jupiters
(e.g. Lin et al 1996)

A gas giant migrating through a rocky disk



A gas giant migrating through a rocky disk

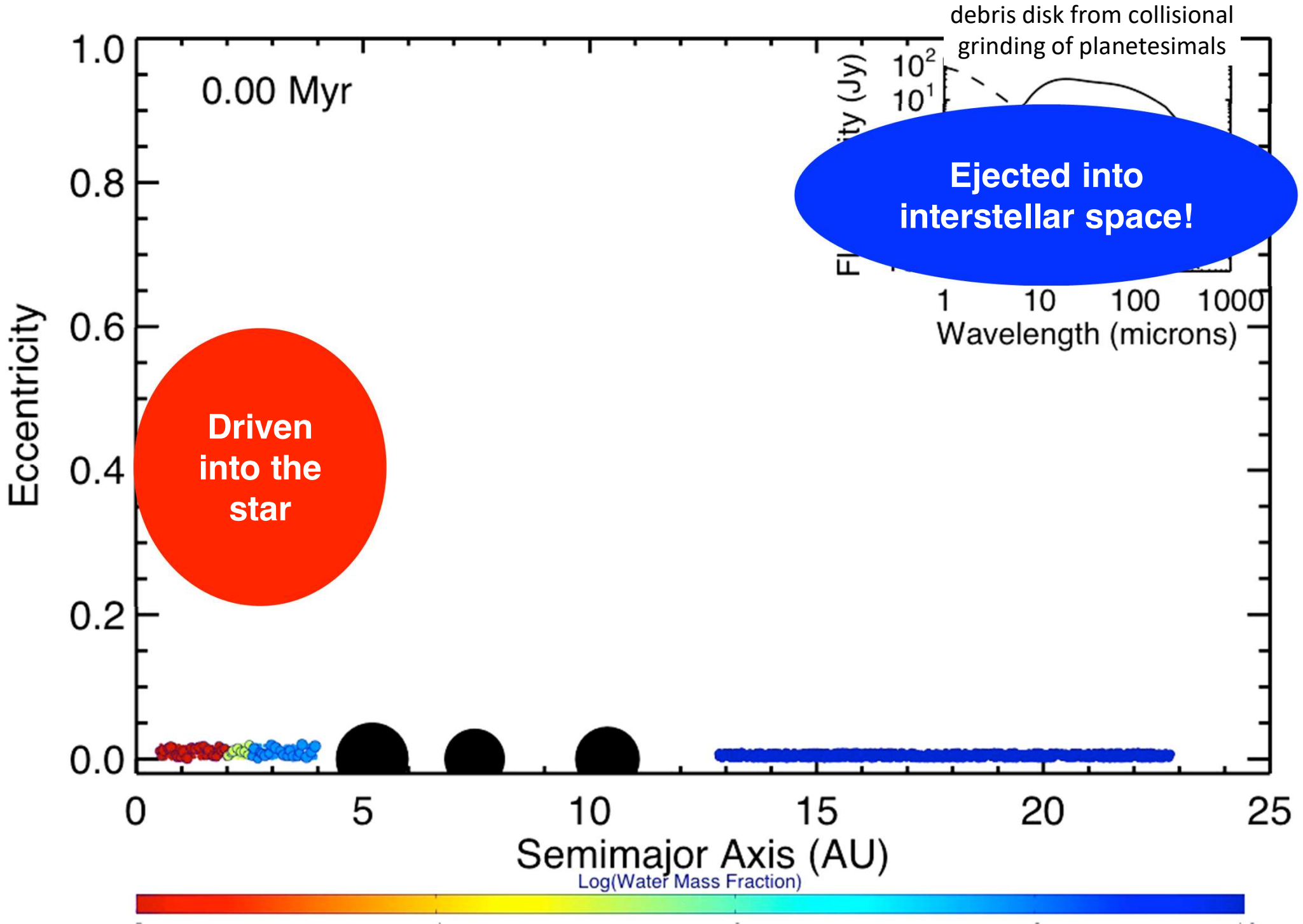




Planet-planet scattering



Simulation Time: 00.0 years



Raymond et al (2012)

Effect of an outer giant on water delivery

- Pebble drift: **blocked**
- Inward-migrating cores: **blocked**
- Planetesimal scattering: **made possible**
- Giant planet migration: **massive radial mixing**
- Dynamical instability: **rocky planet destruction!**

Put together, outer giants have a **mostly negative** impact on water delivery

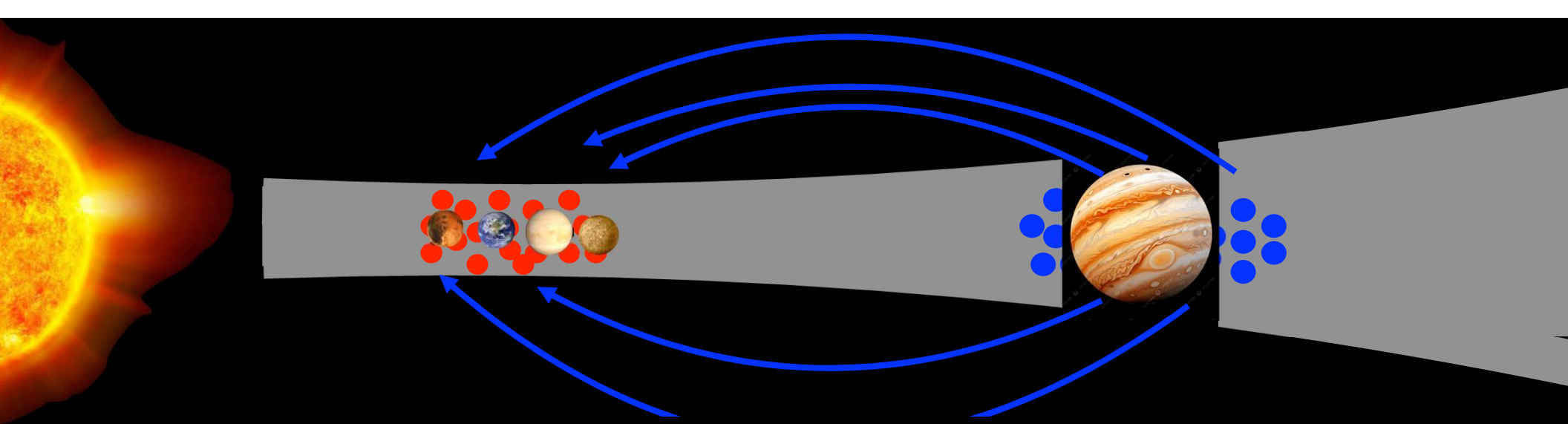


Should rocky planets be drier or wetter with an outer giant?

(e.g., as inferred from bulk densities)

- If **drier**: gas giants form fast and block inward mass flux
- If **wetter**: timing of giant planet formation unimportant. Lots of mass = lots of radial mixing.
- If **no difference**: inner/outer planetesimal rings less coupled than generally thought

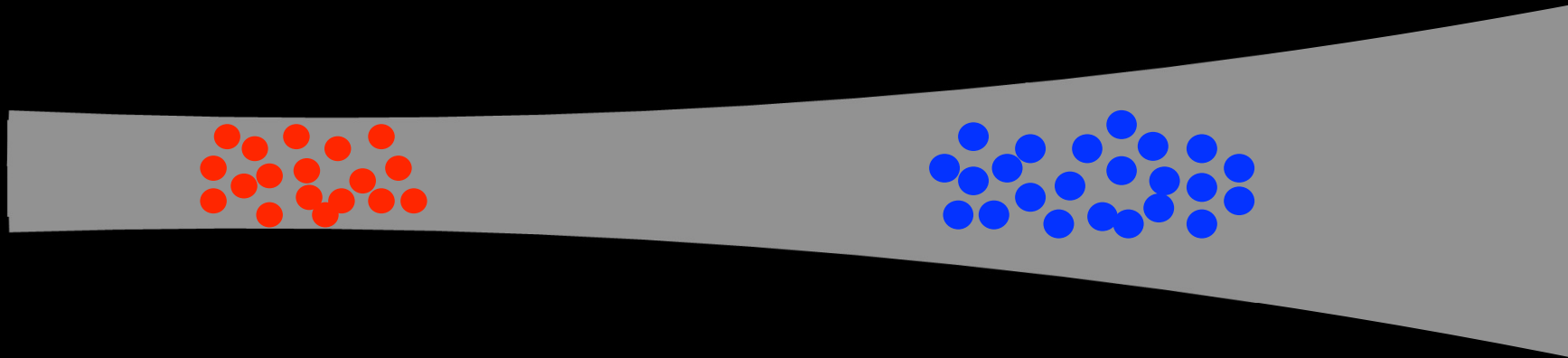
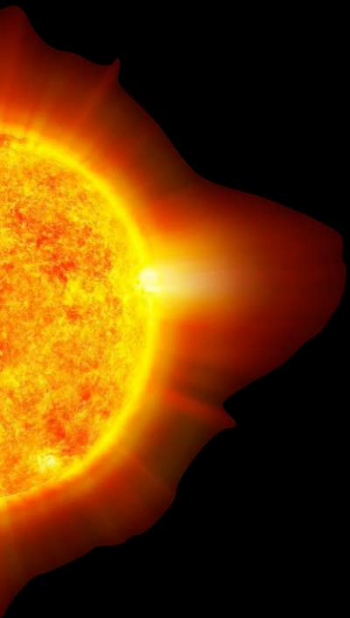




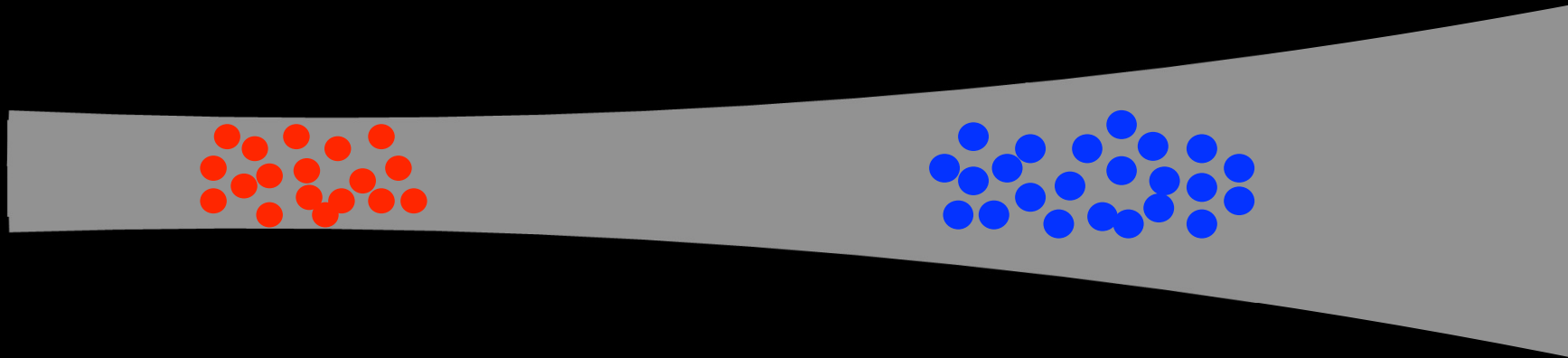
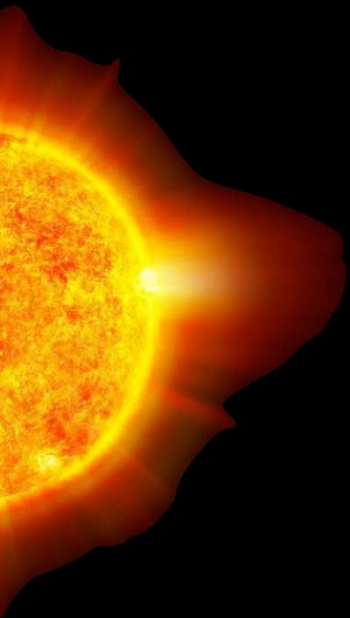
Some relevant papers

- **Exotic Earths: Forming Habitable Worlds with Giant Planet Migration — Raymond, Mandell & Sigurdsson (2006)**
- **Fossilized condensation lines in the Solar System protoplanetary disk — Morbidelli et al (2016)**
- **Origin of water in the inner Solar System: Planetesimals scattered inward during Jupiter and Saturn's rapid gas accretion — Raymond & Izidoro (2017)**
- **Rocky super-Earths or waterworlds: the interplay of planet migration, pebble accretion, and disc evolution — Bitsch et al (2019)**
- planetplanet.net — **the Solar System's story**

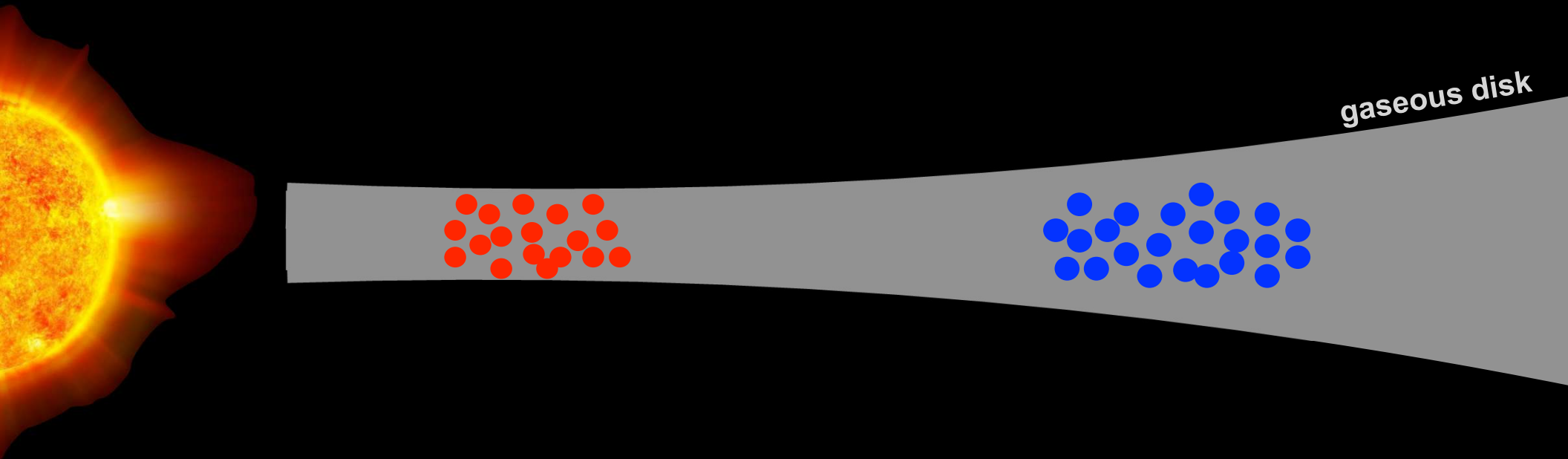
The Solar System (simple)



The Solar System (simple)

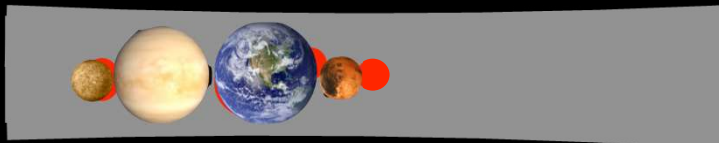
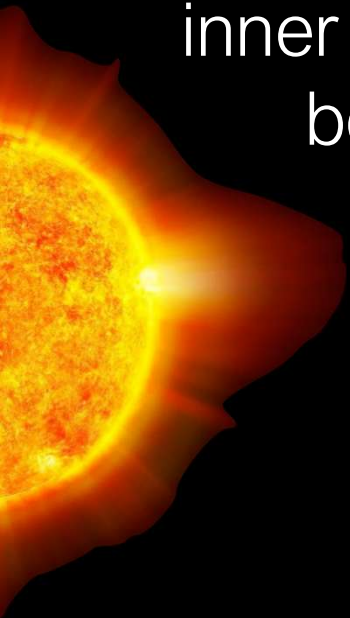


Planetesimals form in rings



Planetesimals and planetary embryos

The gas disk dissipates after a few million years
inner planets' growth perturbed,
bombarded with comets



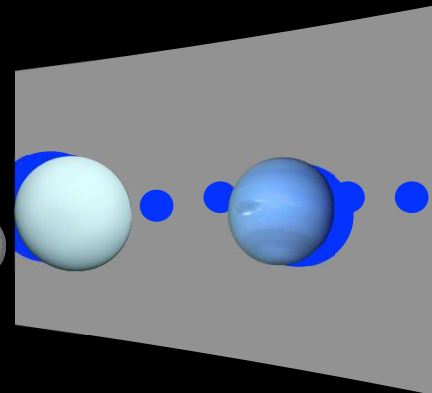
giant impacts



Jupiter



Saturn



Dynamical instability among
giant planets