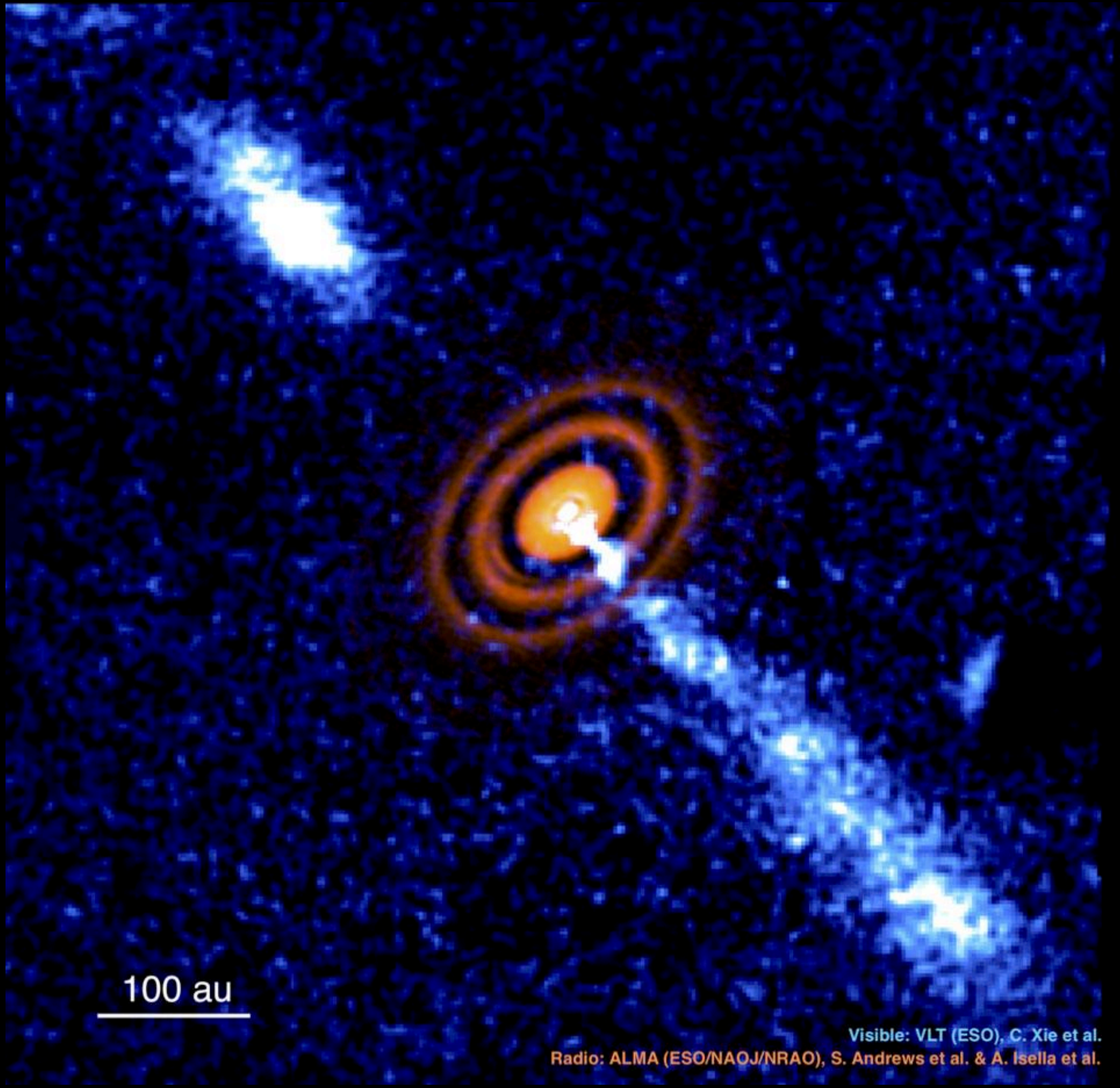
Planet formation & stellar compositions



Visible: VLT (ESO), C. Xie et al.
Radio: ALMA (ESO/NAOJ/NRAO), S. Andrews et al. & A. Isella et al.

Tristan Guillot (Obs. Côte d’Azur, Nice)
w/ thx to Masanobu Kunitomo, Gaël Buldgen, Shigeru Ida, Alessandro Morbidelli

Solar System Formation: Astrophysical background

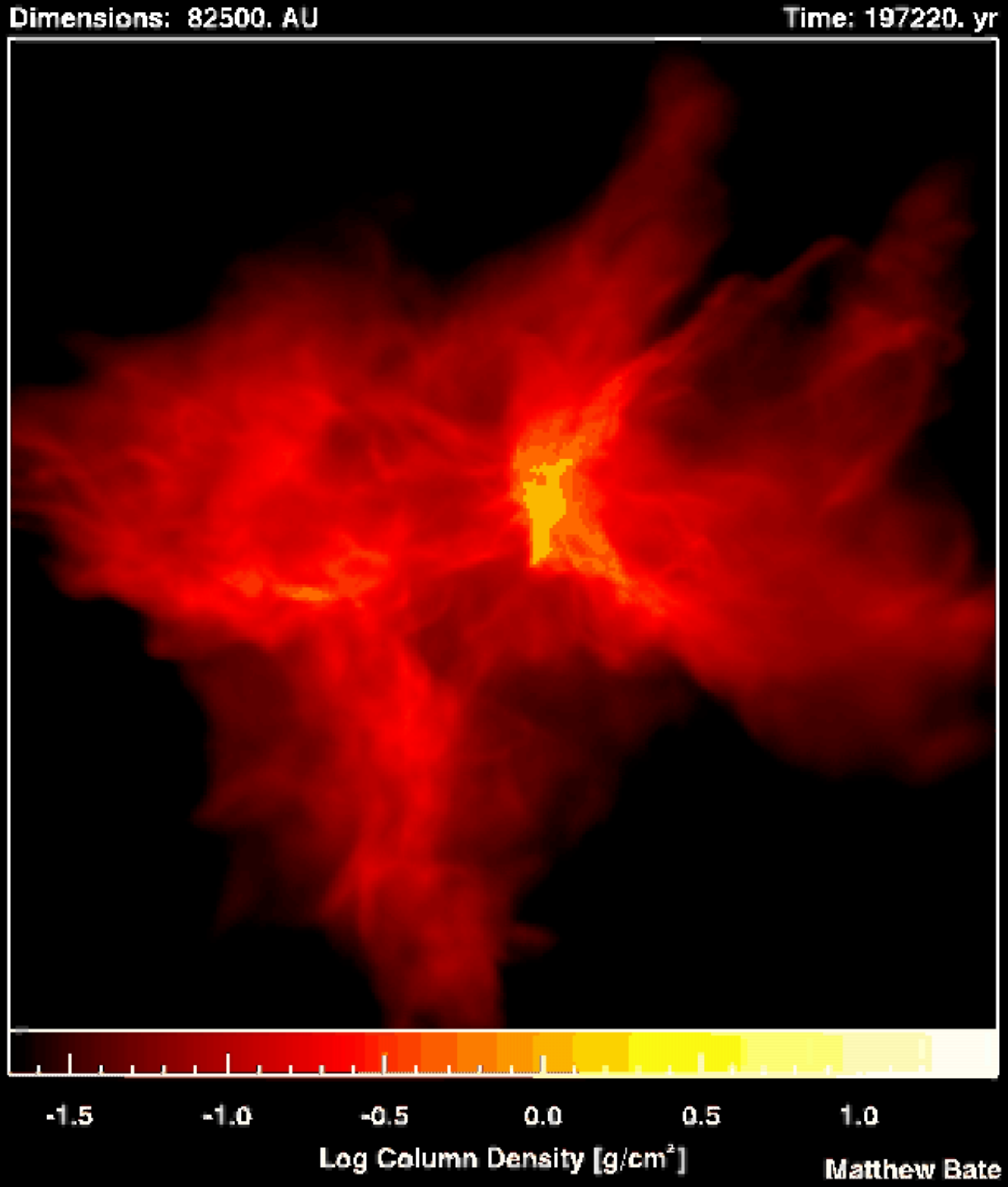
- 1 Ma

A molecular cloud core collapses

50 Ma

Earth-Moon system

Solar System Formation: Astrophysical background

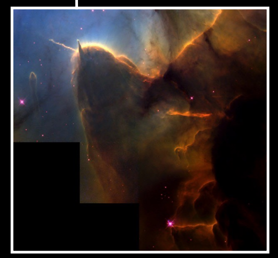


Solar System Formation: Astrophysical background

0 Ma

The protosun and the
protosolar disk form

50 Ma



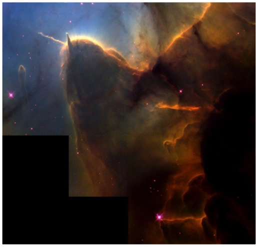
Solar System Formation: Astrophysical background

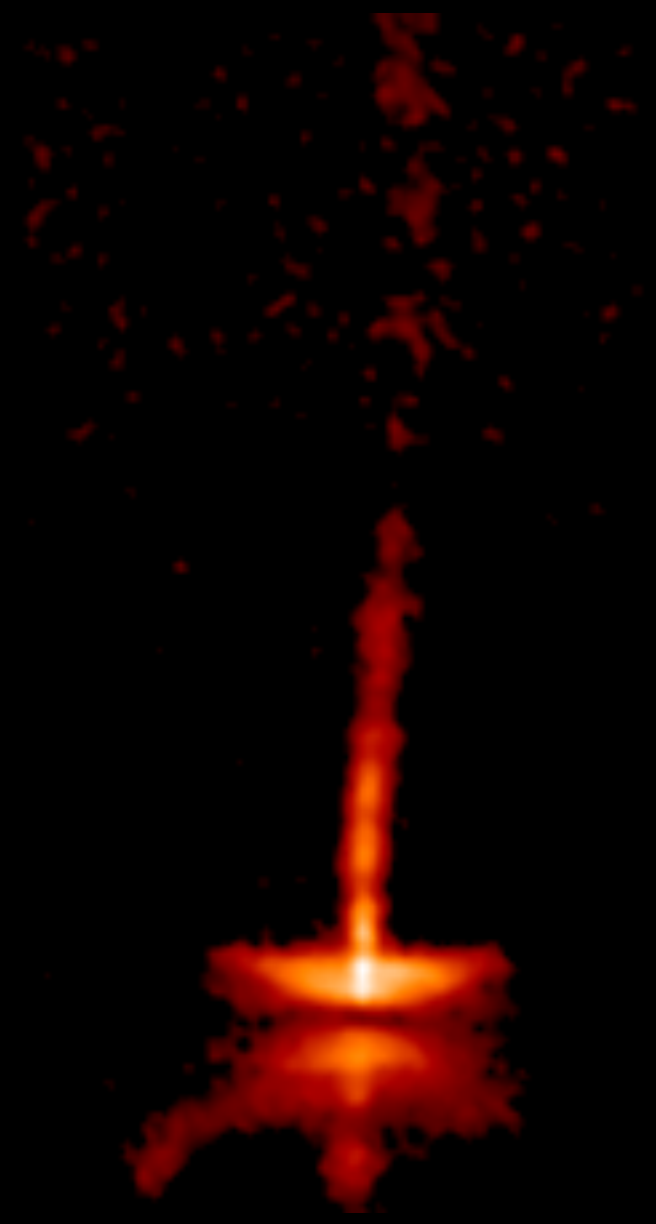
0 Ma

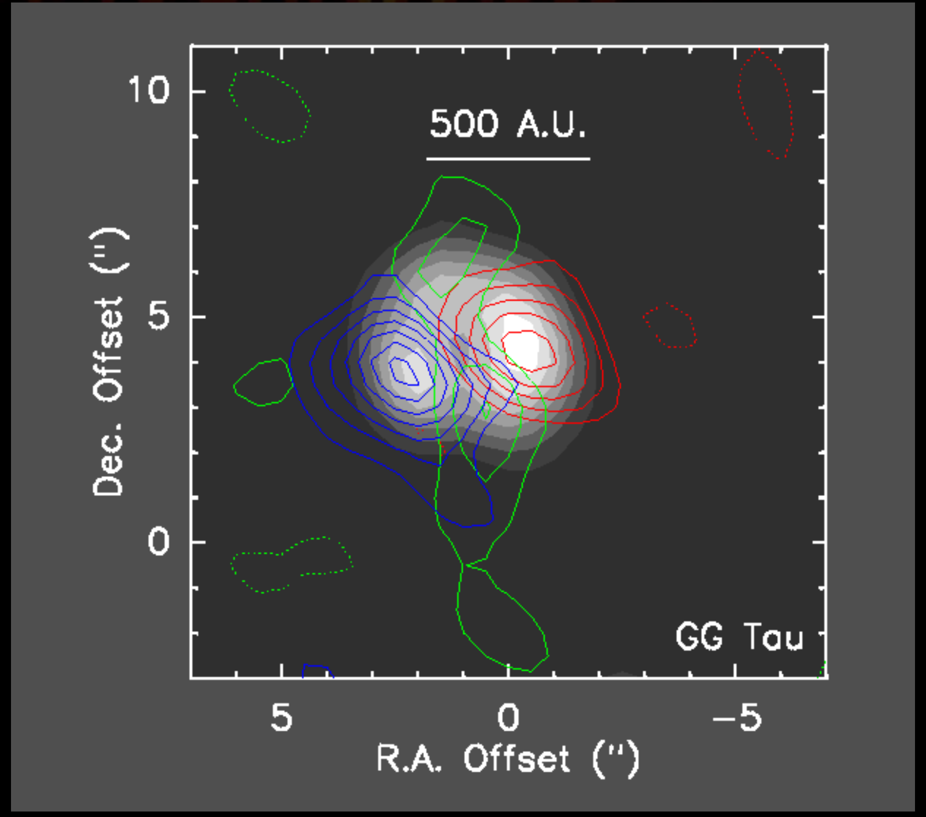
gas disk
phase

~5 Ma

50 Ma







Solar System Formation: Astrophysical background

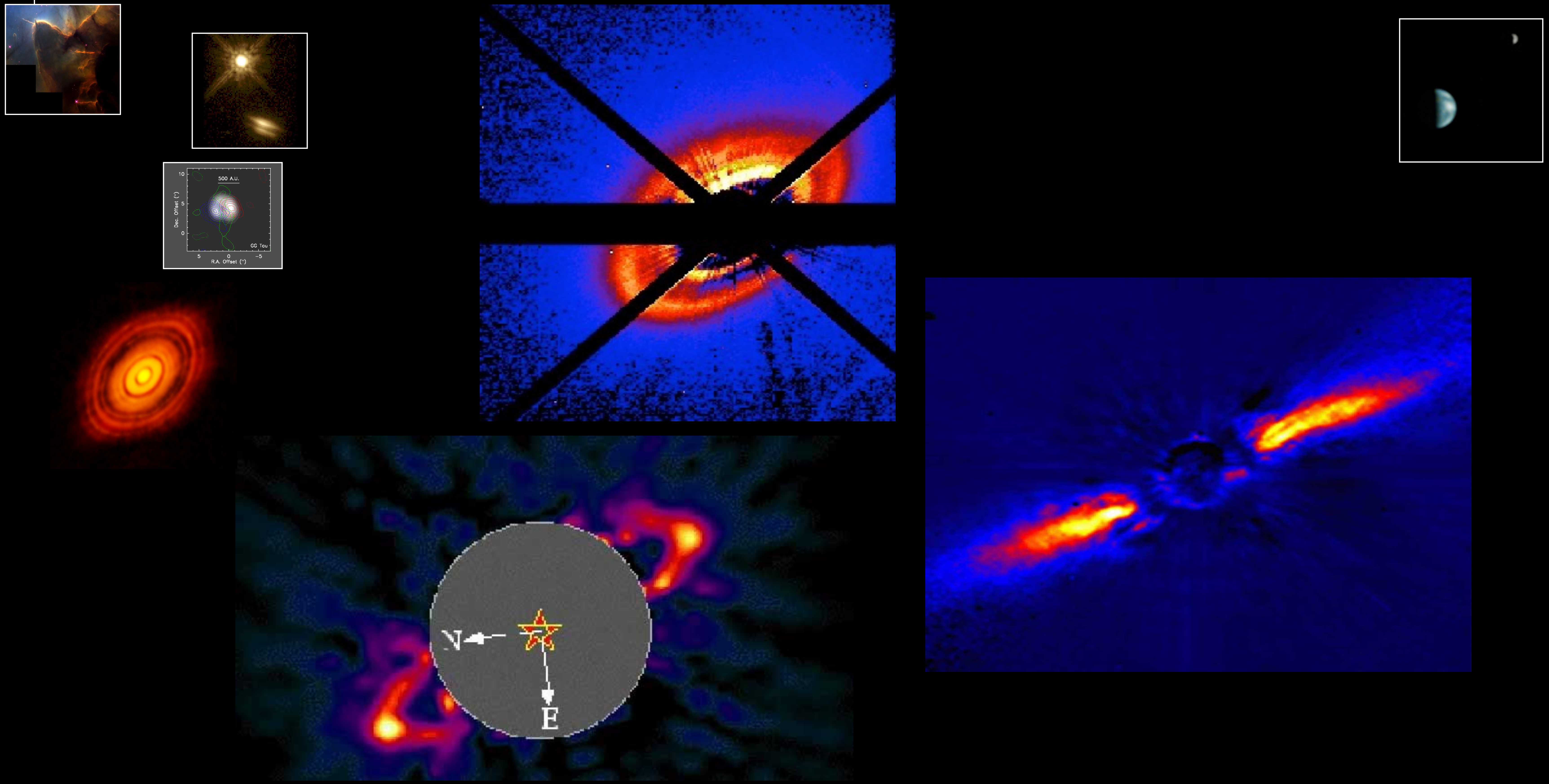
0 Ma

gas disk
phase

~5 Ma

debris disk
phase

50 Ma



Solar System Formation: Astrophysical background

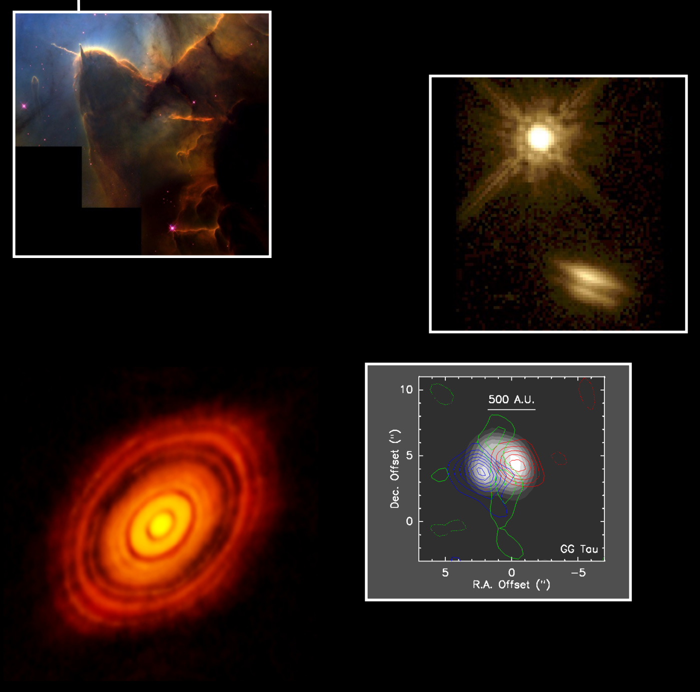
0 Ma

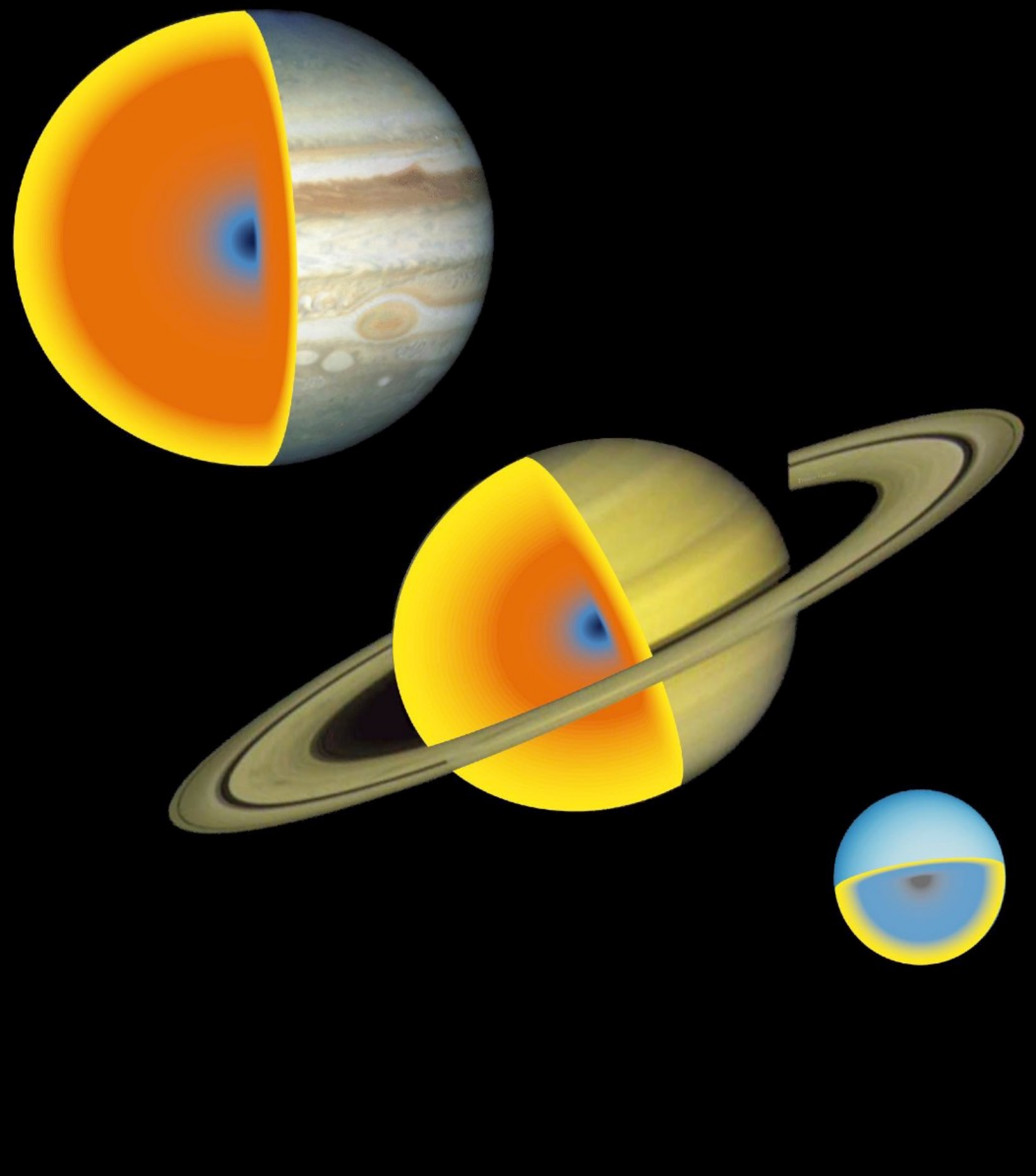
gas disk phase

~5 Ma

debris disk phase

50 Ma



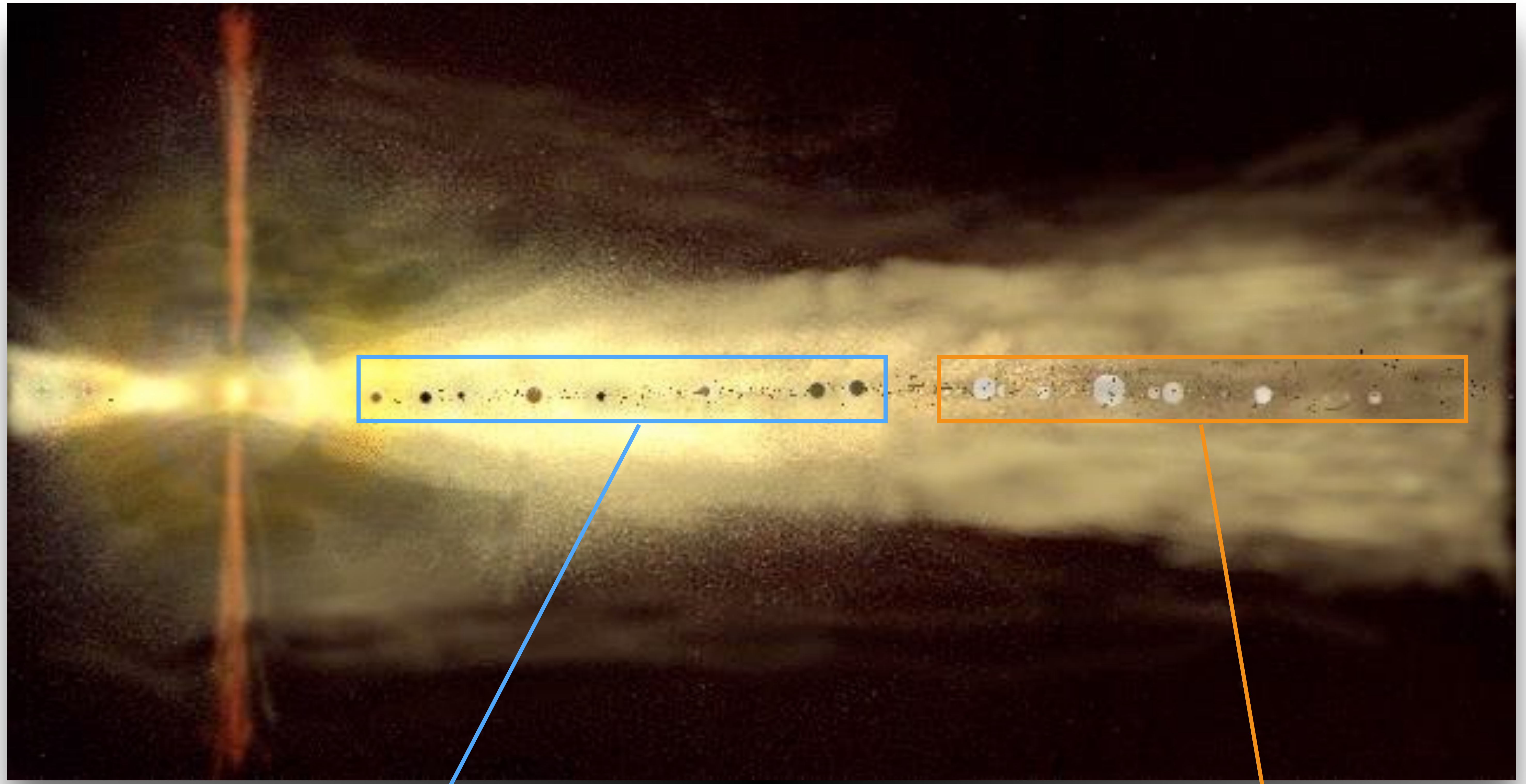


Giant planets form

Planet formation: Classical picture

- A circumstellar disk form from the collapse of a molecular cloud core and spreads viscously (e.g., Shakura & Sunyaev 1973, Lynden-Bell & Pringle 1974, Shu 1977)
  - The collapse of the cloud takes ~10^5 yrs, disk spreading takes 10^6 to 10^8 yrs.
- Planetesimals (1-10km) form rapidly (e.g., Weidenschilling 1980)
  - Settling to the mid-plane + gravitational instabilities lead to a formation of planetesimals in 10^4 to 10^5 yrs.
- Runaway growth: (Greenberg et al. 1978; Wetherill & Steward 1989; Ida & Makino 1992)
  - Gravitational focusing means that large embryos grow at the expense of small ones
  - This phase ends when relative velocities become too large, i.e., for masses around a Ceres mass, and in ~10^5 yrs
- Oligarchic growth (Kokubo & Ida 1998, Thommes et al. 2003)
  - Slower growth of oligarchs by accretion of smaller embryos.
  - This phase ends when the mass in small planetesimals has become too small to damp the eccentricities of large embryos. This occurs for masses between moon mass at 1 au and up to 10 M_{Earth} at 10 au, on timescales of ~10^5 yrs to several 10^6 yrs.

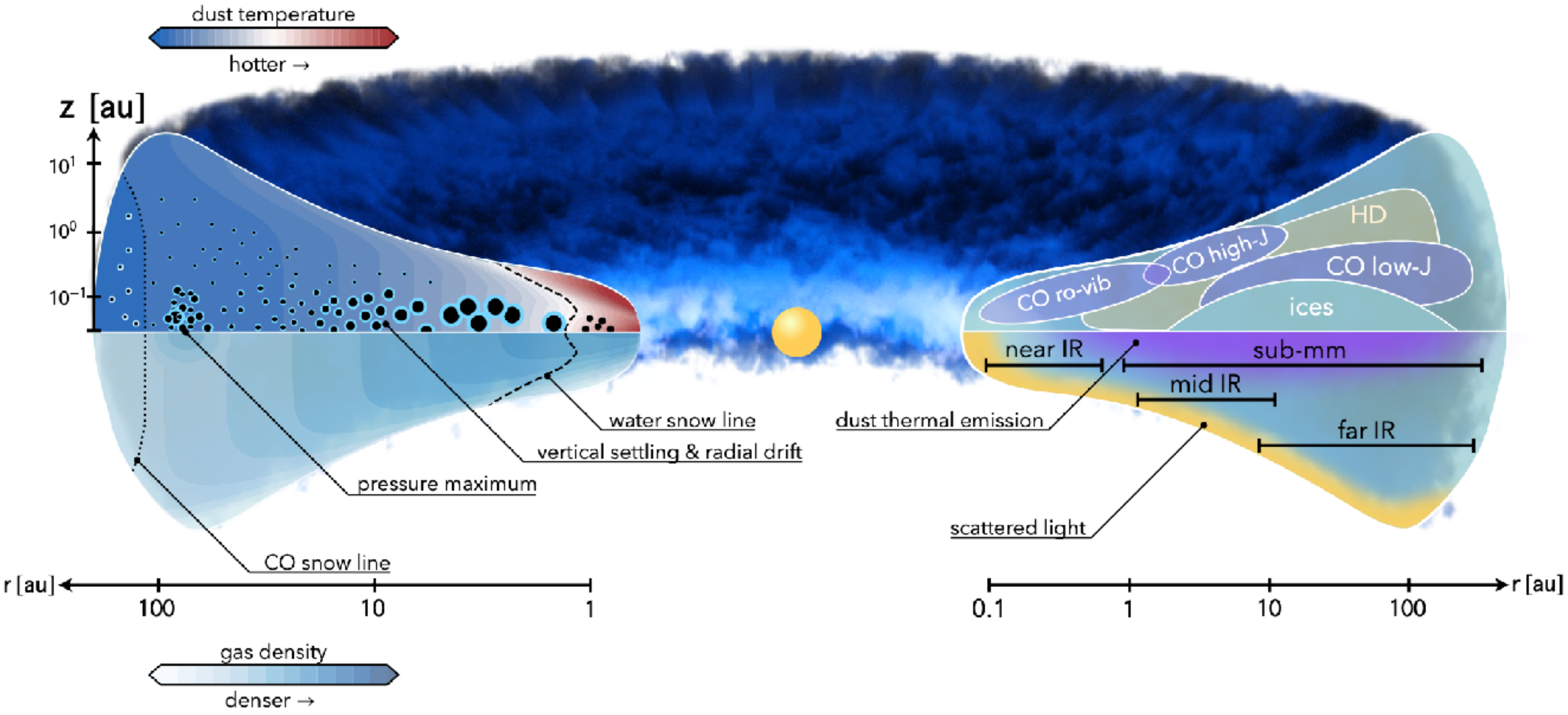
Standard picture: after the oligarchs



Terrestrial planet region:
growth by giant impacts

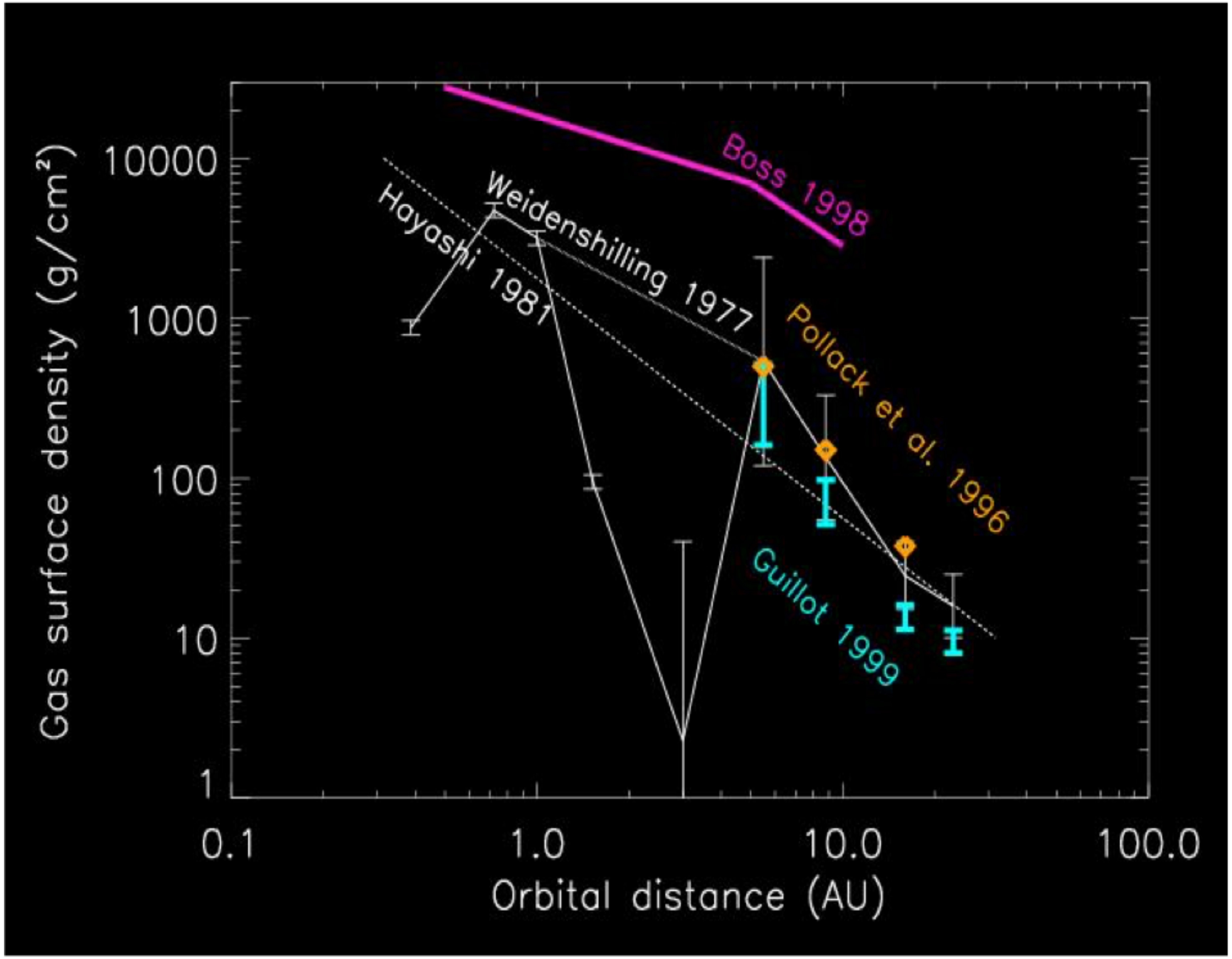
Giant planet region:
growth by gas accretion

Standard picture: a disk interior



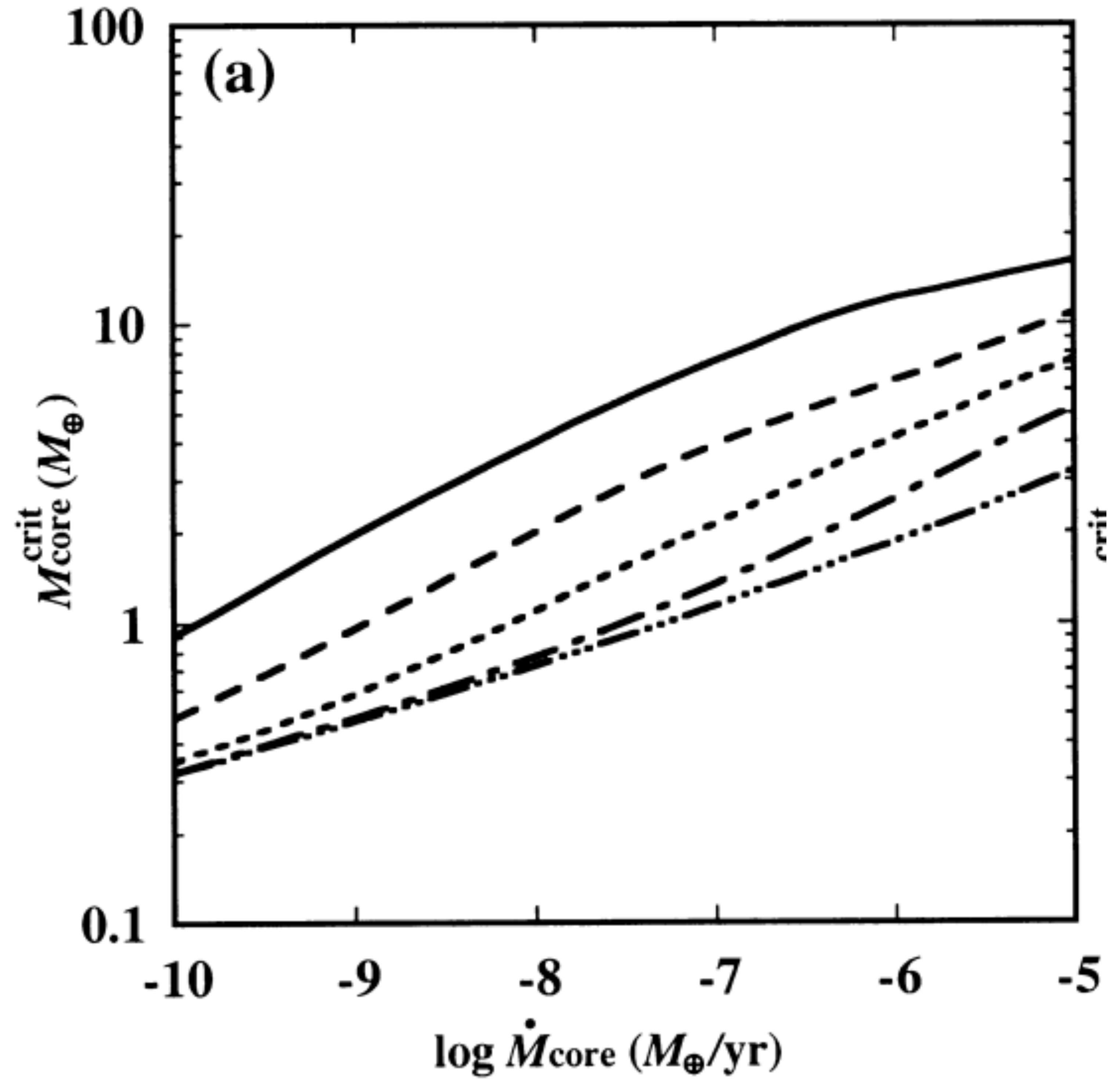
A. Miotello et al., PPVII chap. 14

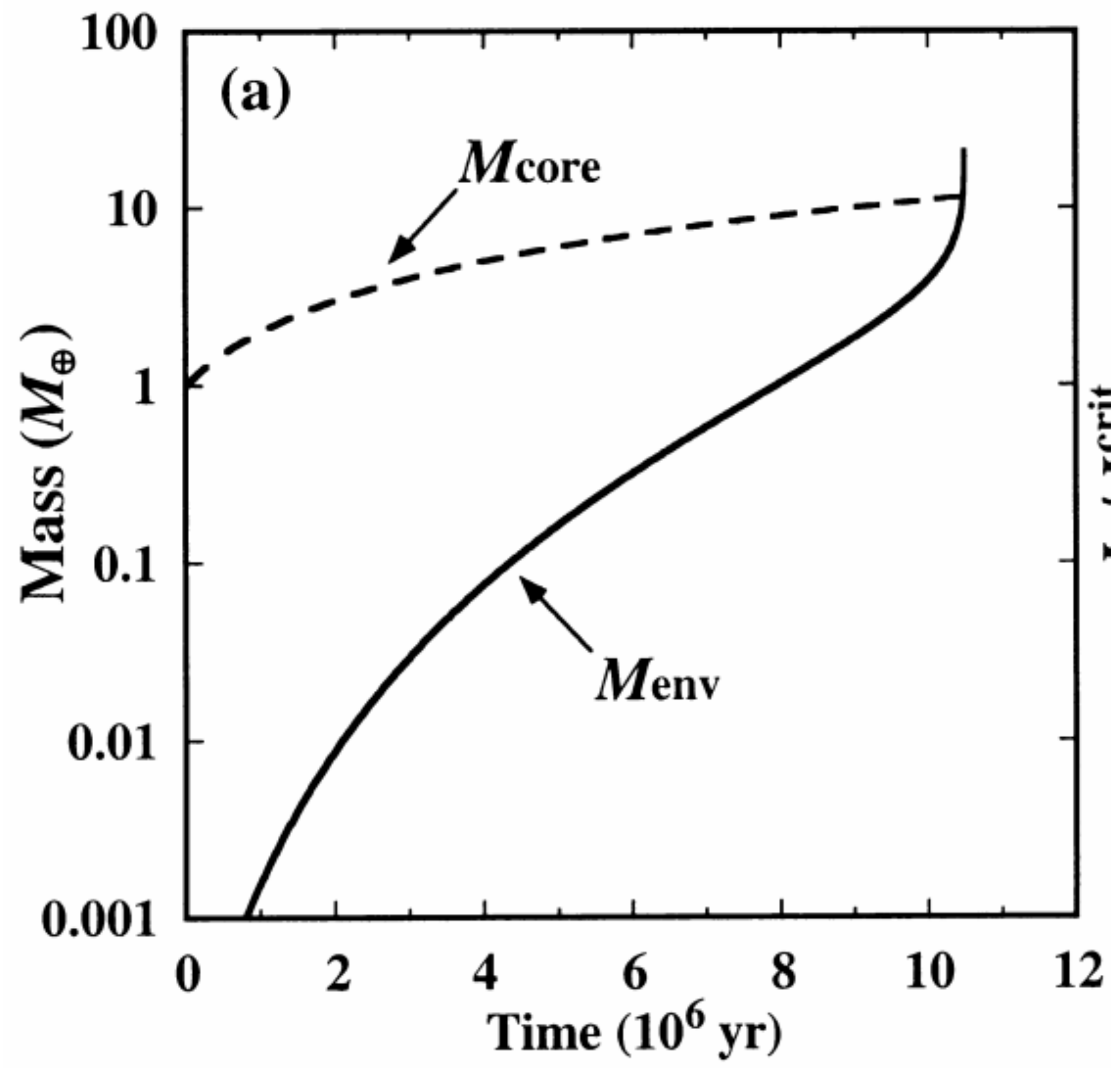
Standard picture: the MMSN



Standard picture: forming the giants

- A growing core cannot be in equilibrium with the disk gas surrounding it after it reaches a certain critical mass (Mizuno 1980, see also Stevenson 1981)



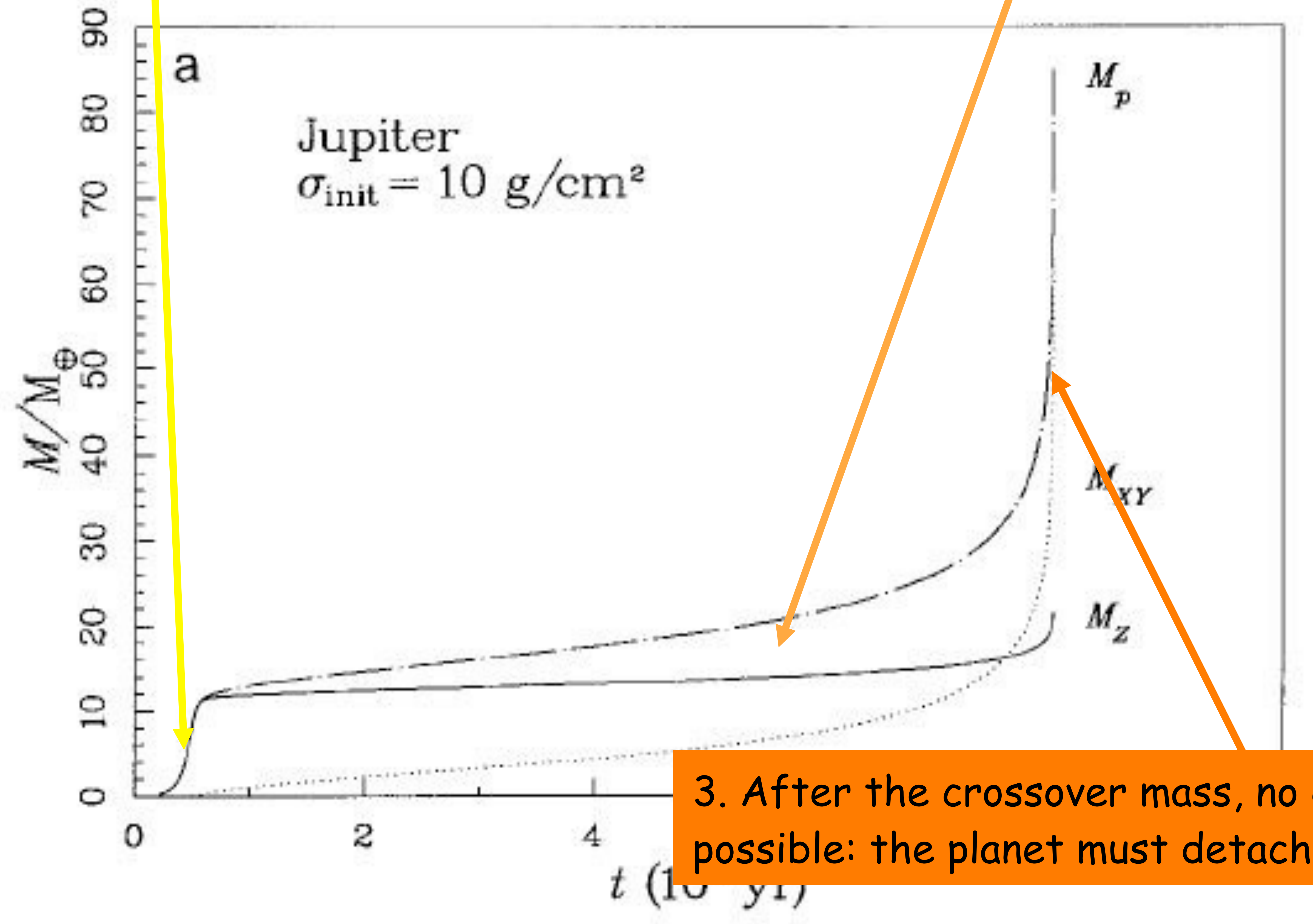


Ikoma et al. (2000)

Standard picture: The accretion phase

1. A core forms by oligarchic growth

2. The envelope grows by cooling + planetesimal accretion

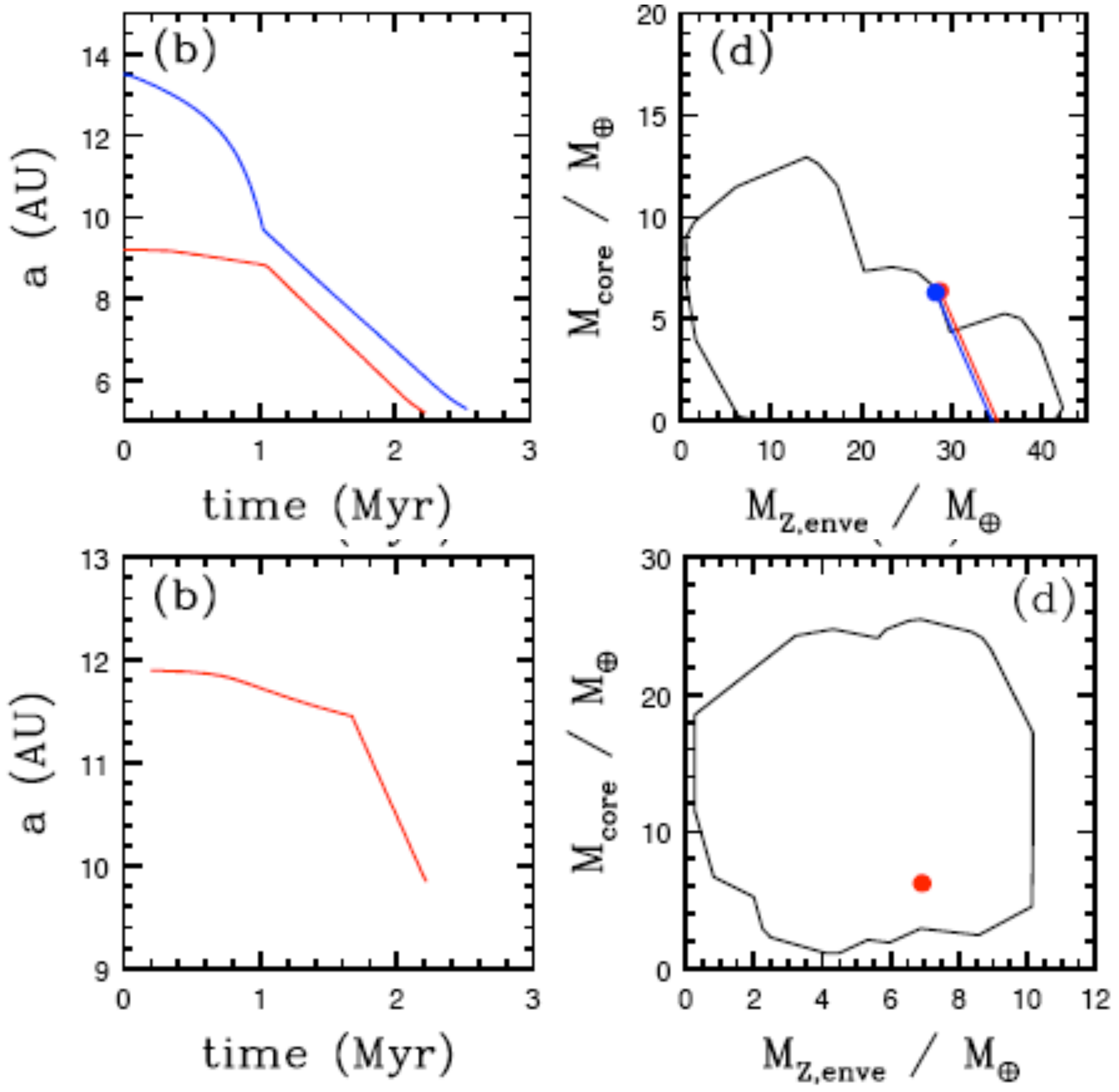


3. After the crossover mass, no equilibrium is possible: the planet must detach from the disk.

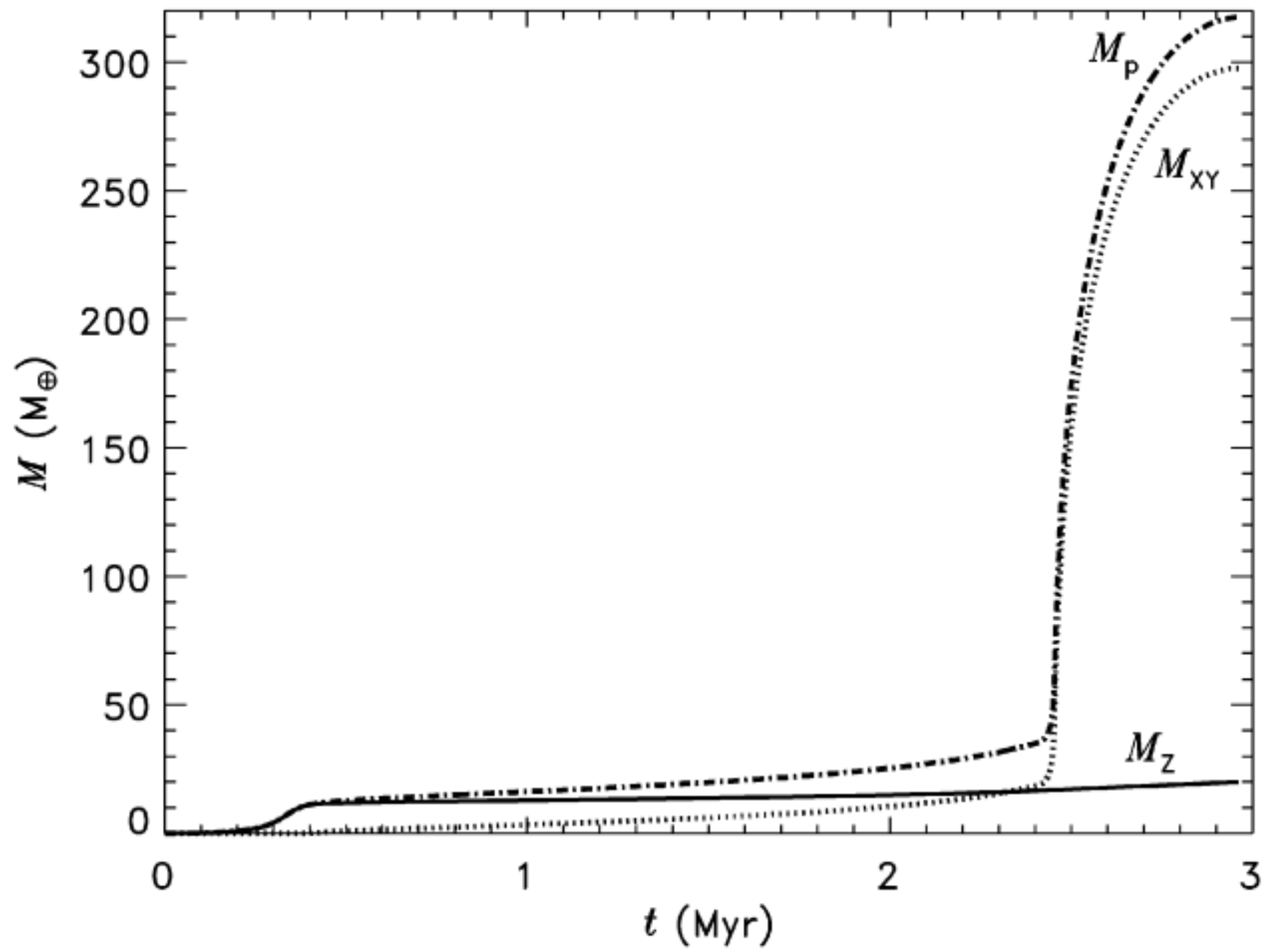
Pollack et al. (1996)

Standard picture: envelope enrichment

- All 4 giant planets have atmospheres enriched in C/H over the solar value
- This may be explained by the capture of planetesimals during the rapid growth phase of the envelope (Alibert et al. 2005, Lissauer et al. 2009)
- Core erosion may also play a role (Guillot et al. 2004; See also Wilson & Militzer 2011, 2012)
- Planetesimal accretion after the completion of the planet growth is very small (Matter et al. 2009)



Alibert et al. (2005)

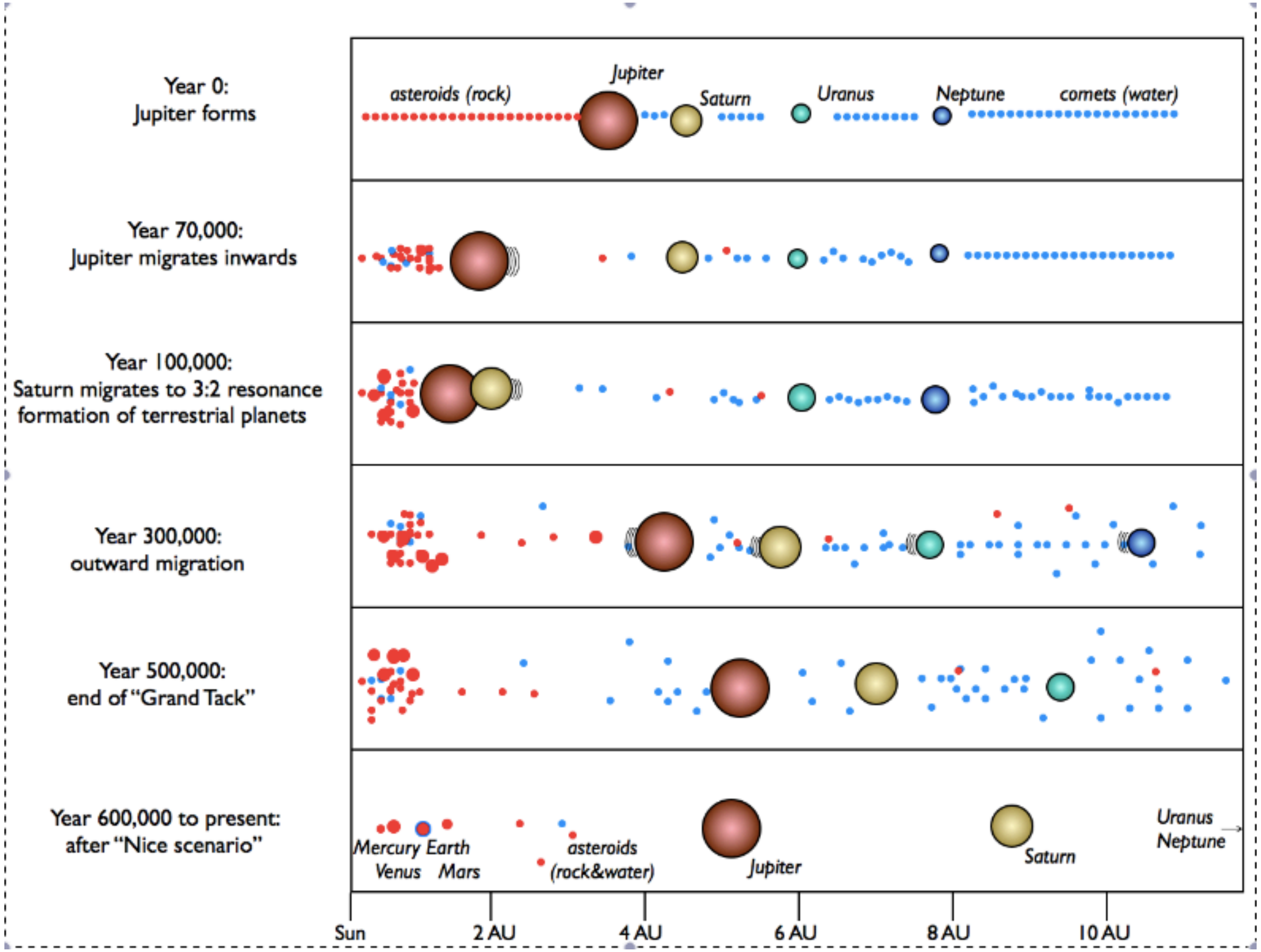


Lissauer et al. (2009)

Beyond the standard picture

- Planetesimals do not form easily
  - Solids cannot form a small-enough mid-plane for gravitational instabilities in the dust to form planetesimals directly (Dubrulle et al. 1995)
  - Grain growth is suppressed at the bouncing barrier to sizes ~10cm (Zsom et al. 2011)
- Giant planets take too much time to form
  - In realistic simulations, giant planets cores clear gaps which prevent growth to critical mass before the disk dissipates on ~Ma timescales (Levison, Thommes & Duncan 2010)
- Grains & planets migrate

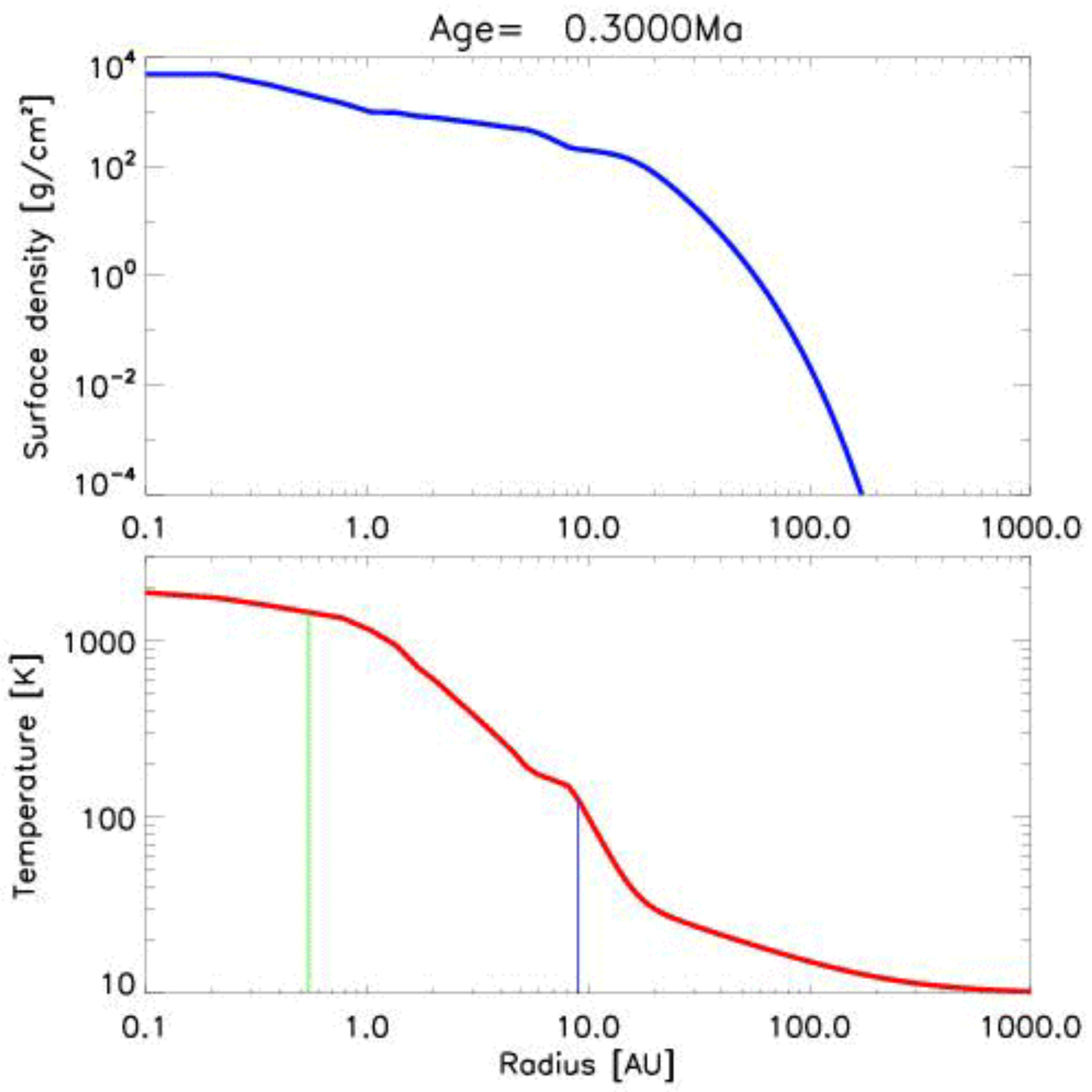
Beyond the standard picture



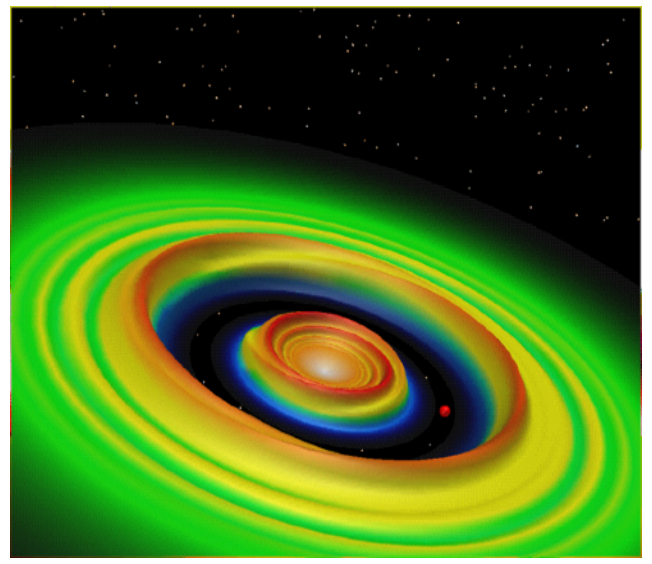
Walsh et al. (2011)

Evolving disks

- Disks are not static
  - Collapse of molecular cloud core ~10^5 yrs
  - Evolution of the disks ~a few 10^6 yrs.
- Giant planet formation requires:
  - The formation of solid planetesimals and cores
  - Accretion of the disk gas
- Once formed, planets migrate

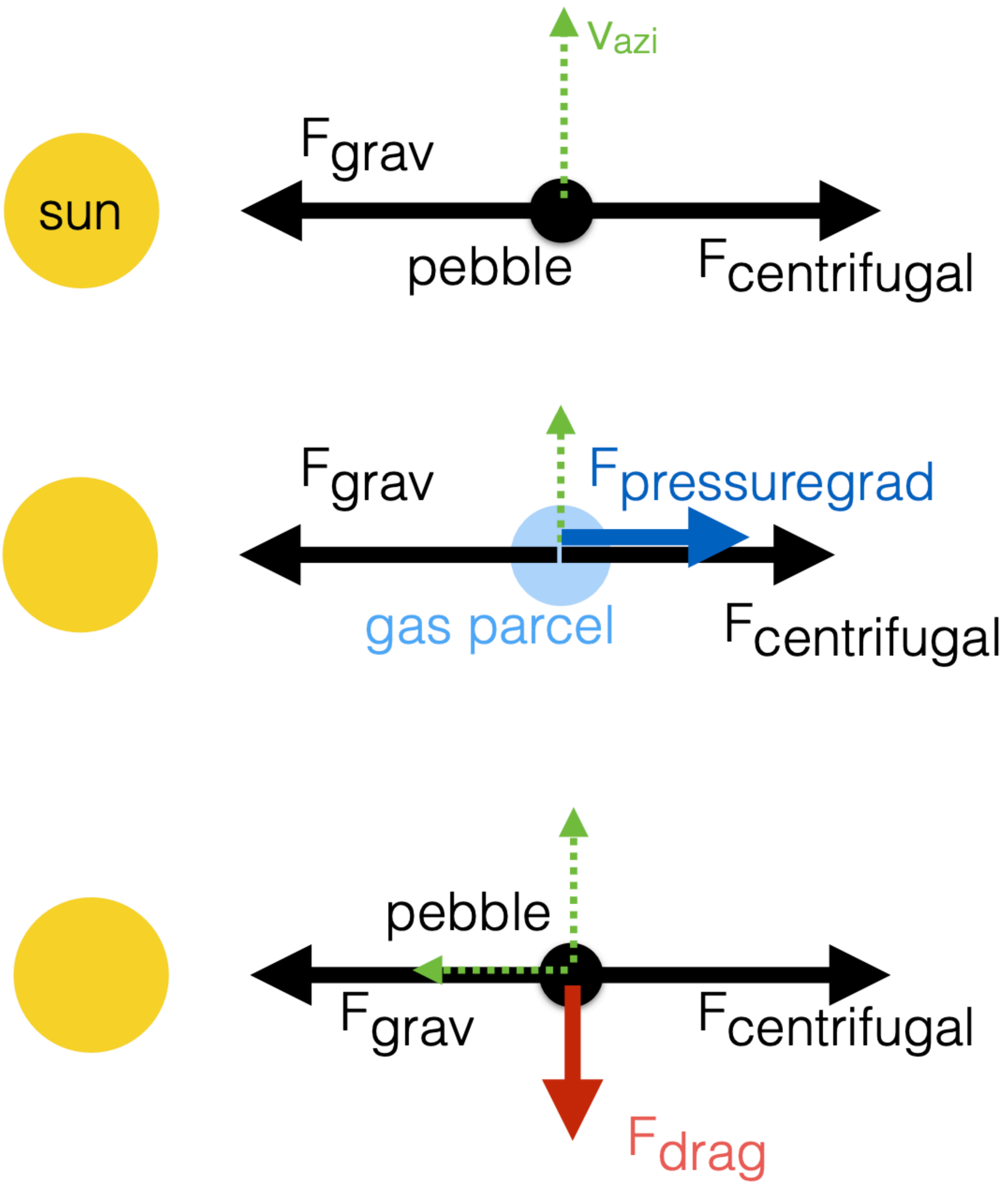


Hueso & Guillot (2005)

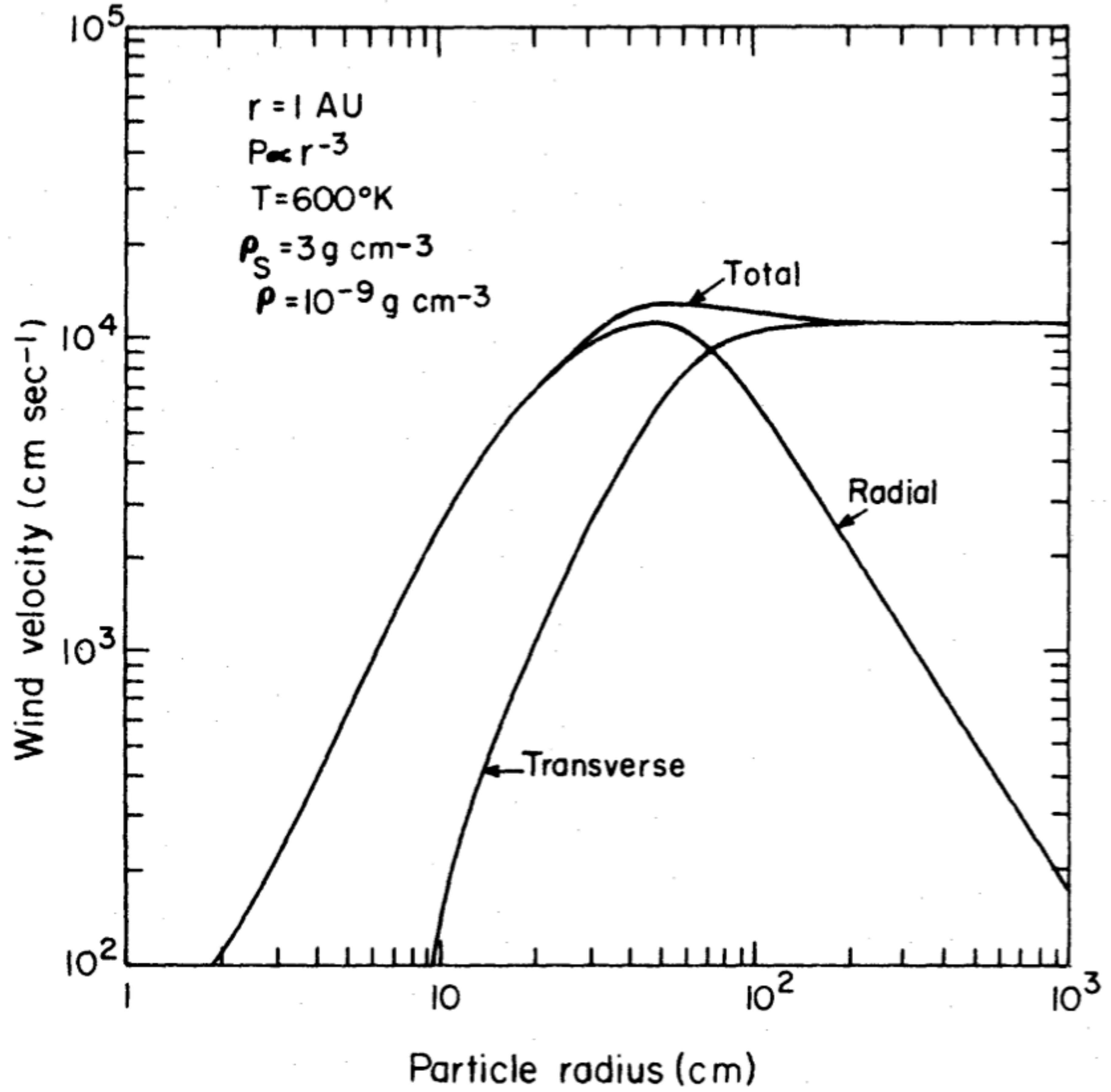


Dobbs-Dixon et al. (2006)

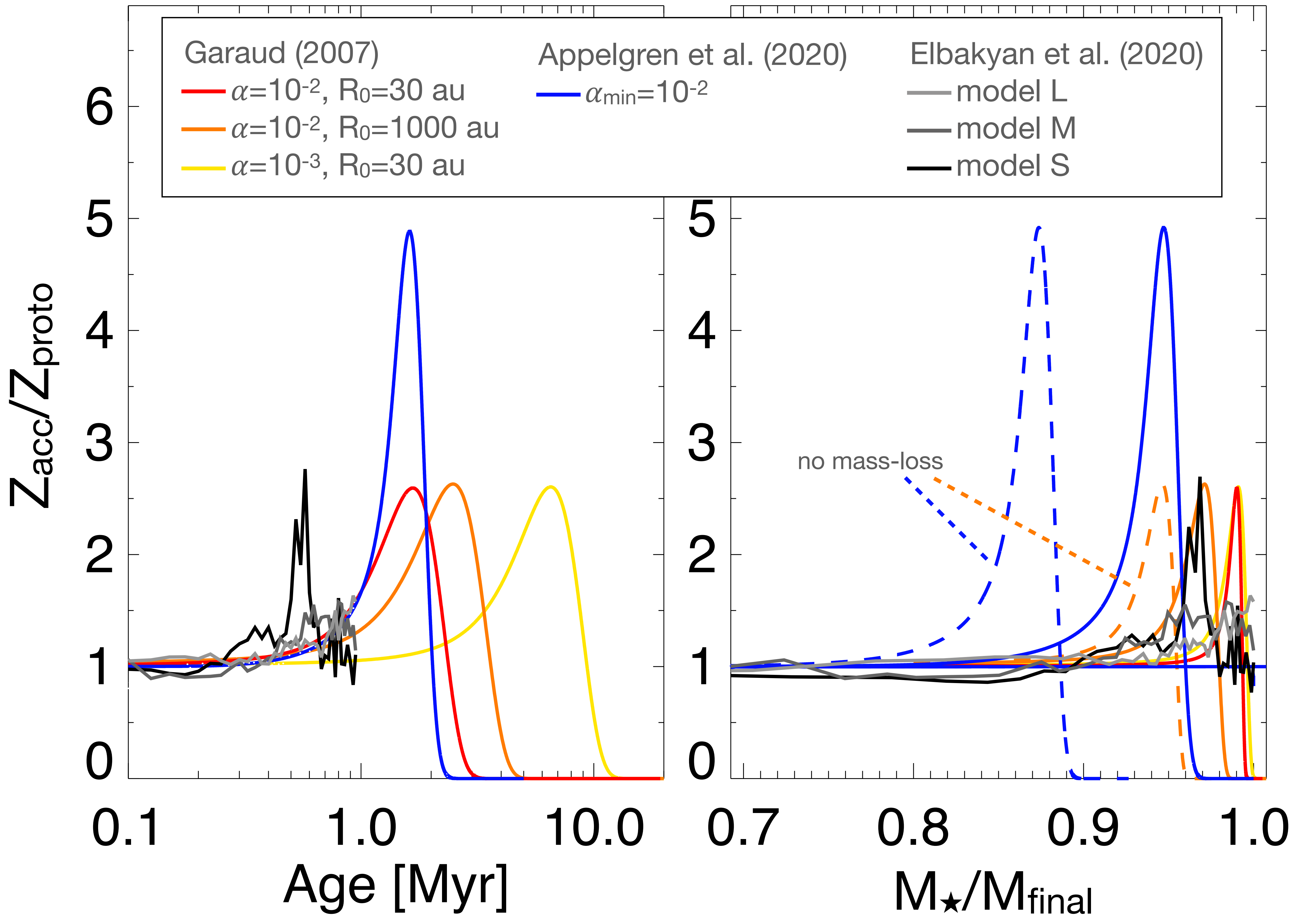
Solids in peril



Aeronamic drag (Weidenschilling 1977)



Pebble wave(s)



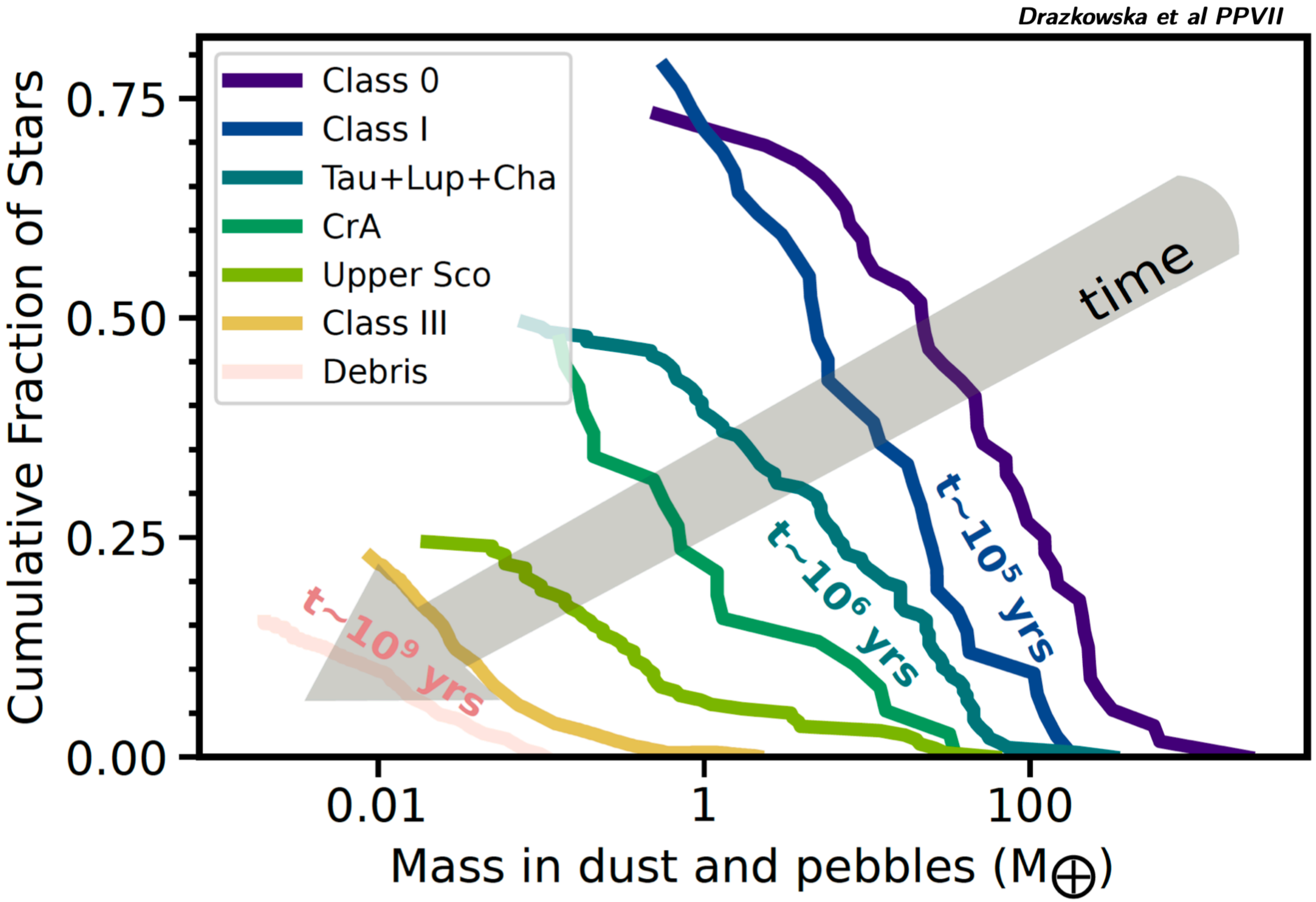
Kunitomo & Guillot (2021)

- The outer disk is an important reservoir of material
  - $\Sigma \propto r^{-1} \implies m(r) = \int 2\pi r \Sigma dr \propto r$
- Grains grow, pebbles form and drift
- This leads to an enrichment of the inner disk
- This enrichment is only temporary

A DECADE OF DATA

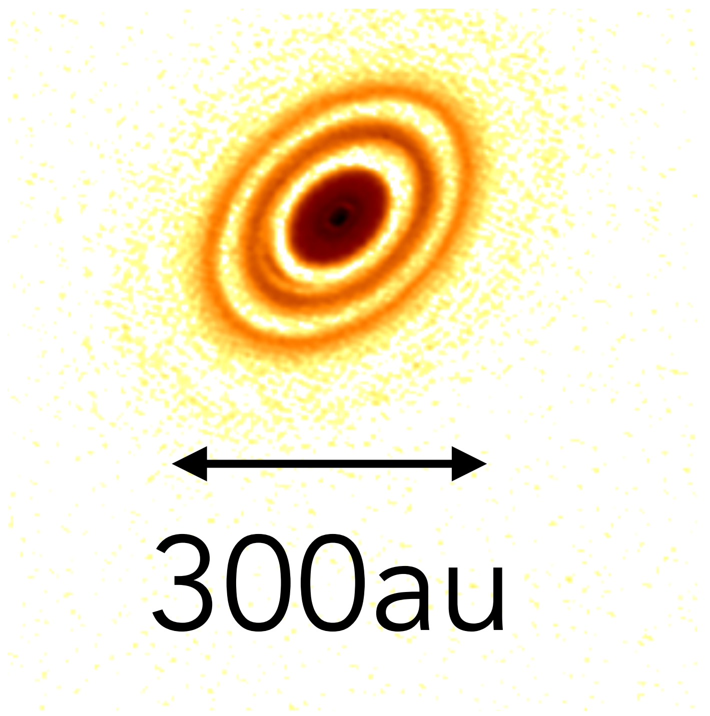
A. Miotello, PPVII chap. 14

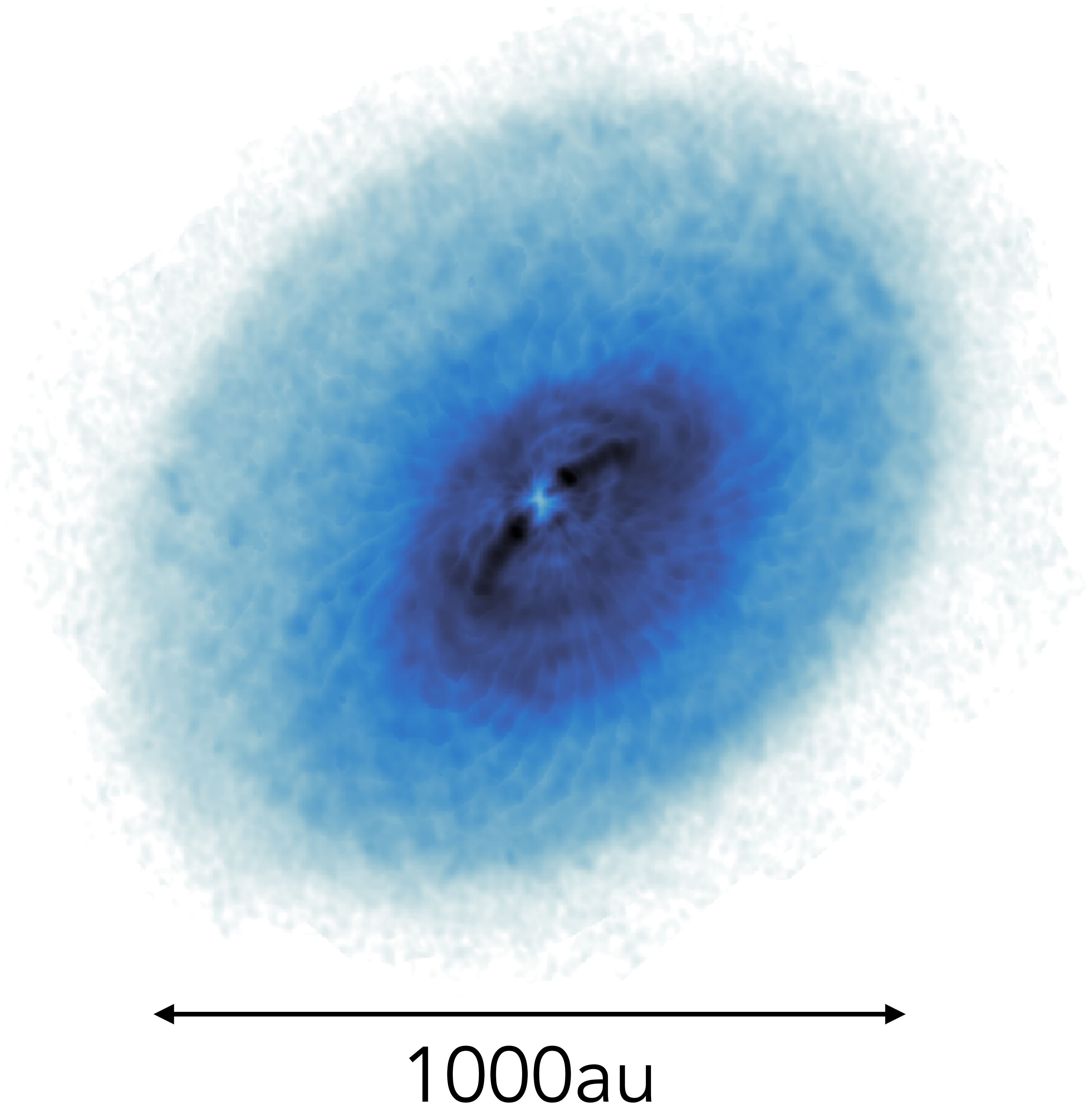
Observed dust depletion in protoplanetary disks



Drazkowska et al., PPVII chap. 18

Observed dust migration in protoplanetary disks



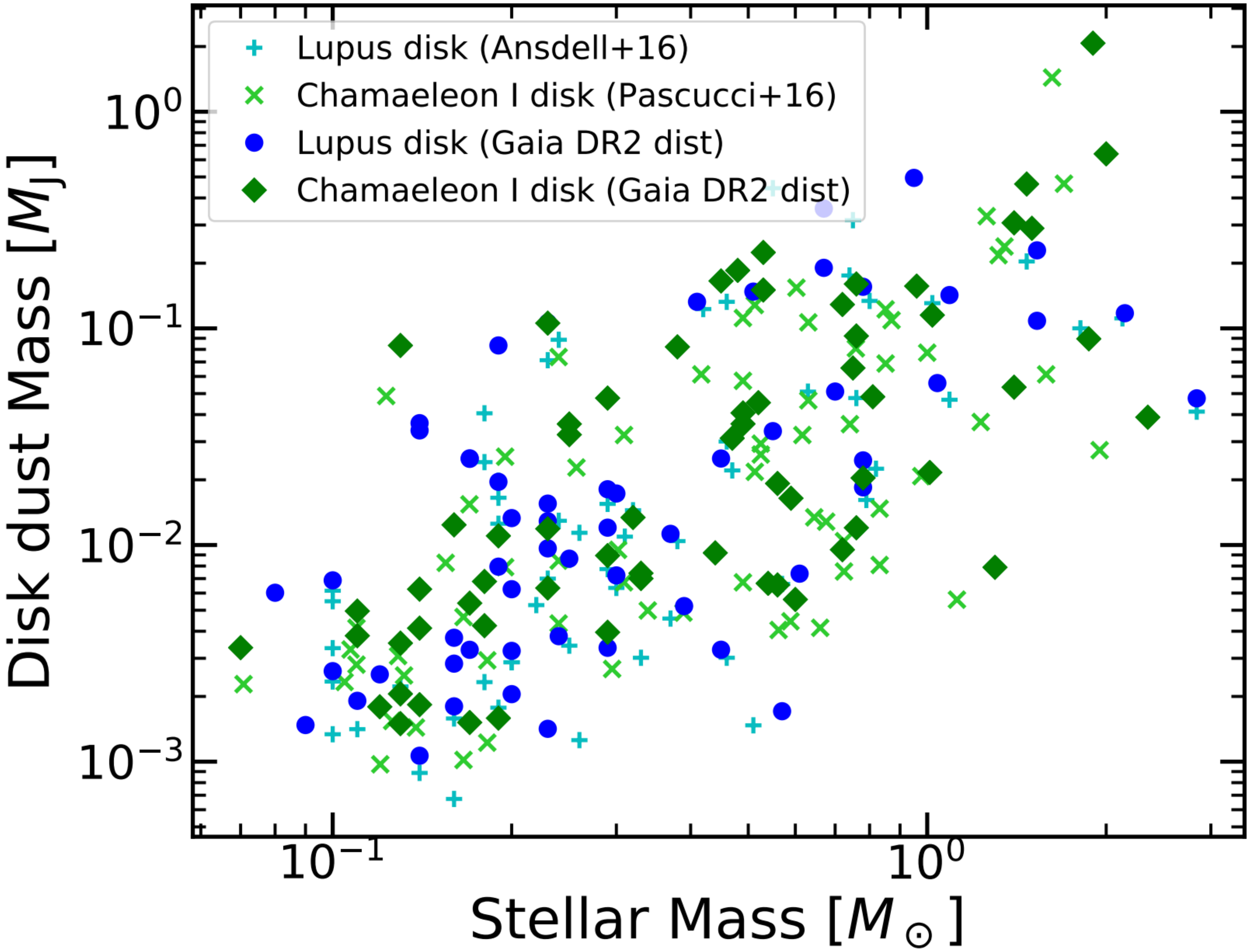


Dust disk at mm wavelengths
Data from Andrews+2018, Huang+2018, Isella+2018

Gas disk
Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

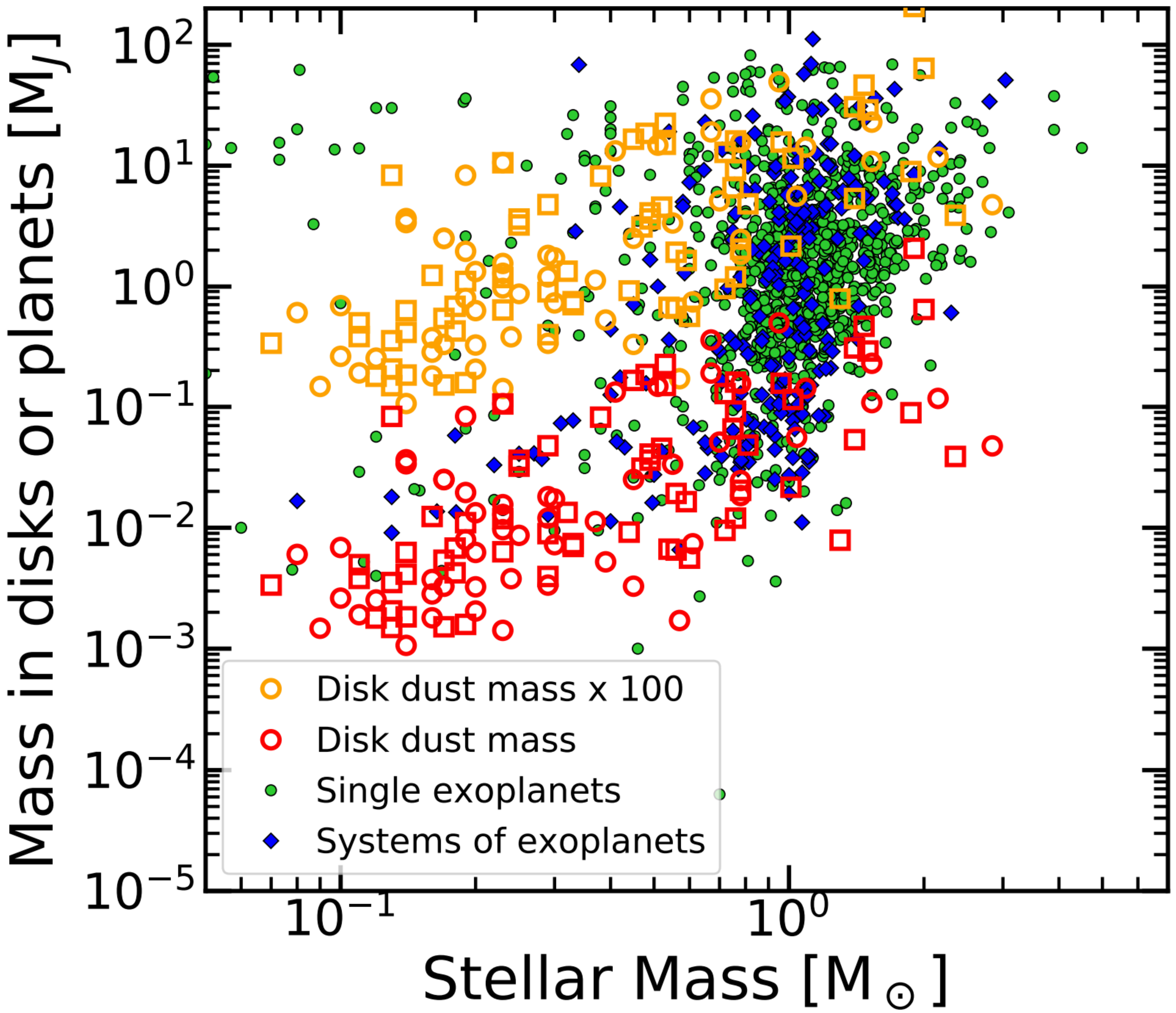
C. Pinte et al., PPVII chap. 18

Disk dust mass



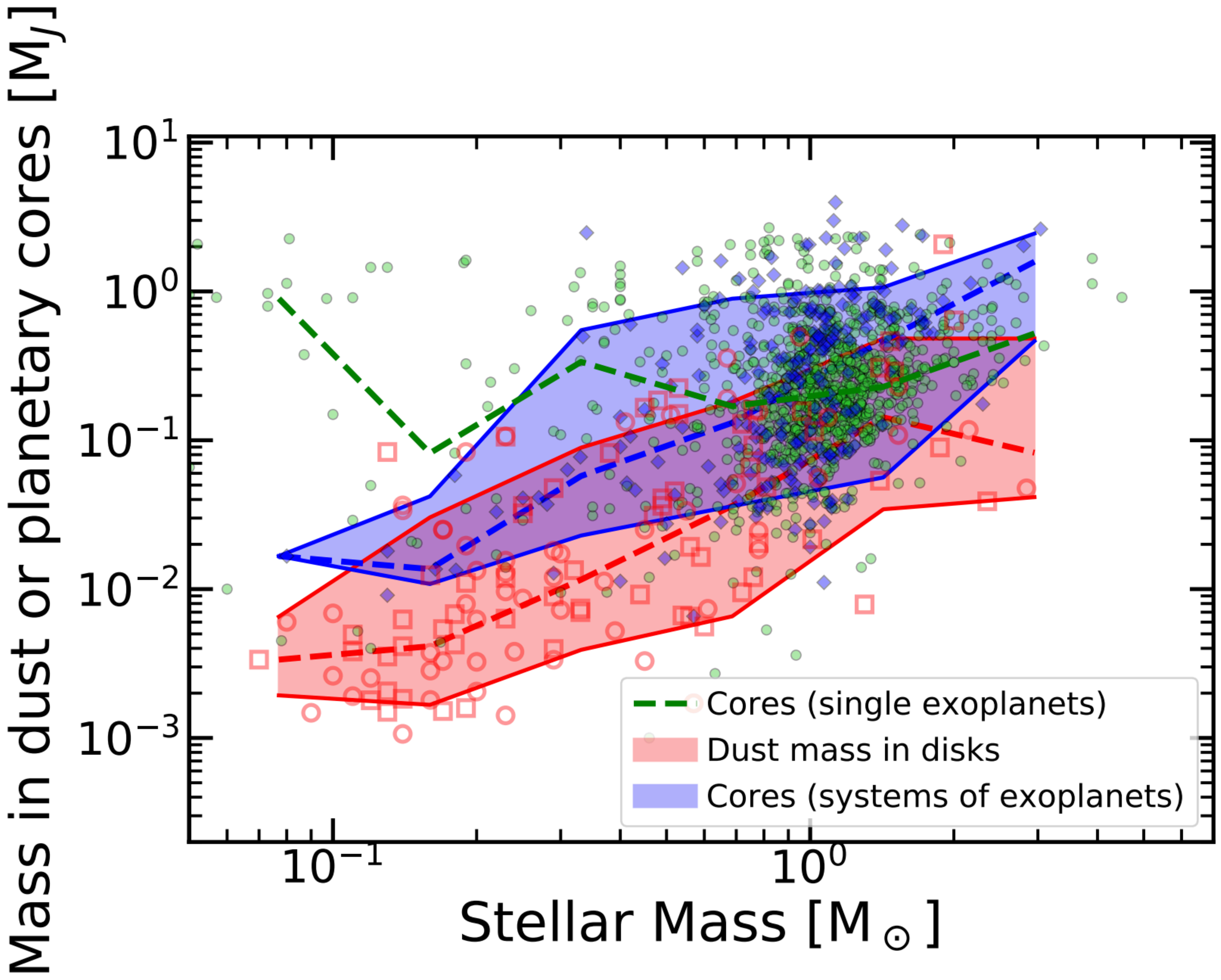
Manara, Morbidelli & Guillot (2018)

Disk dust masses vs. planetary masses



Manara, Morbidelli & Guillot (2018)

A lack of dust!

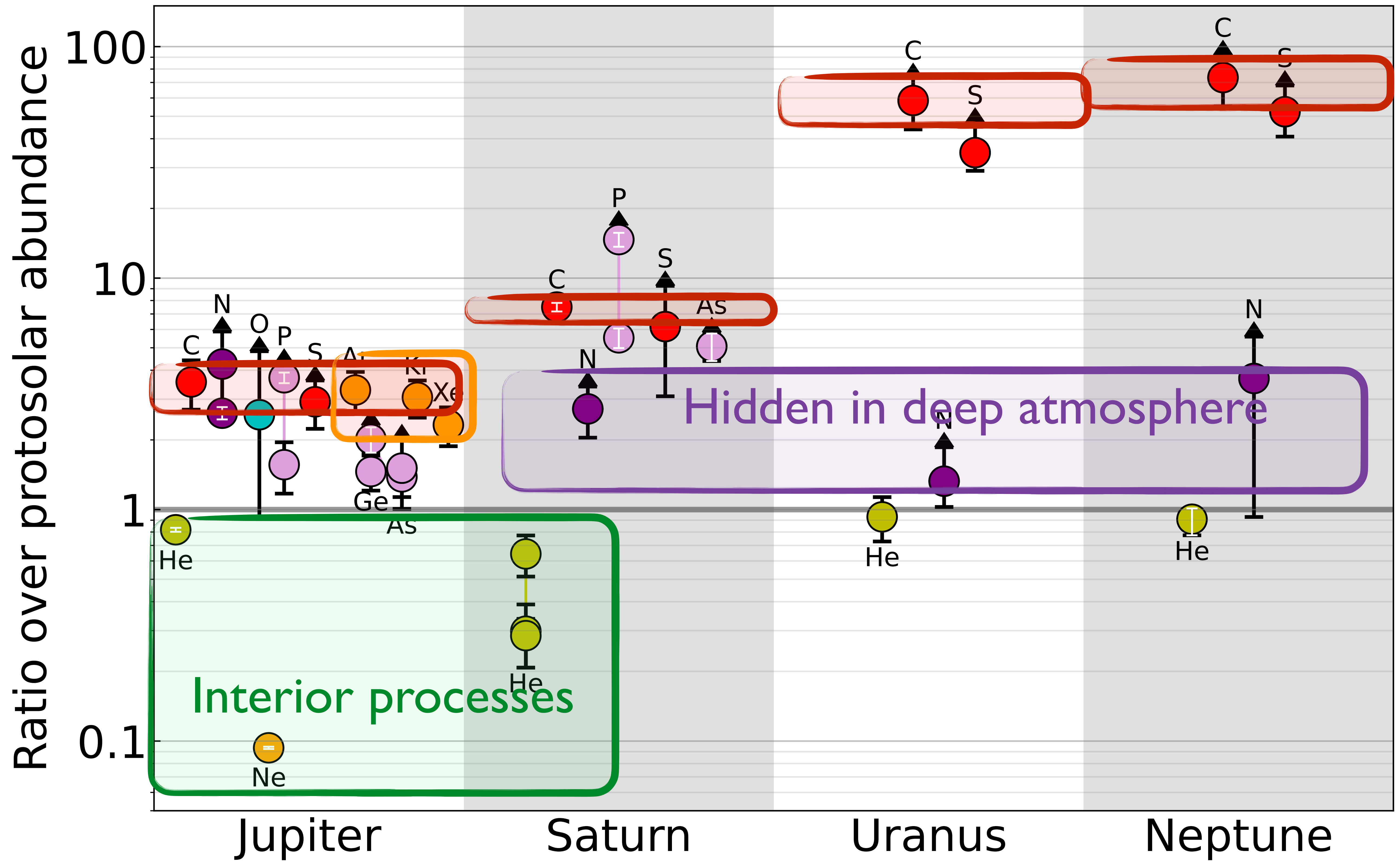


planets must form early!

Manara, Morbidelli & Guillot (2018)

Abundances: Solar System Giant Planets

Atmosphere

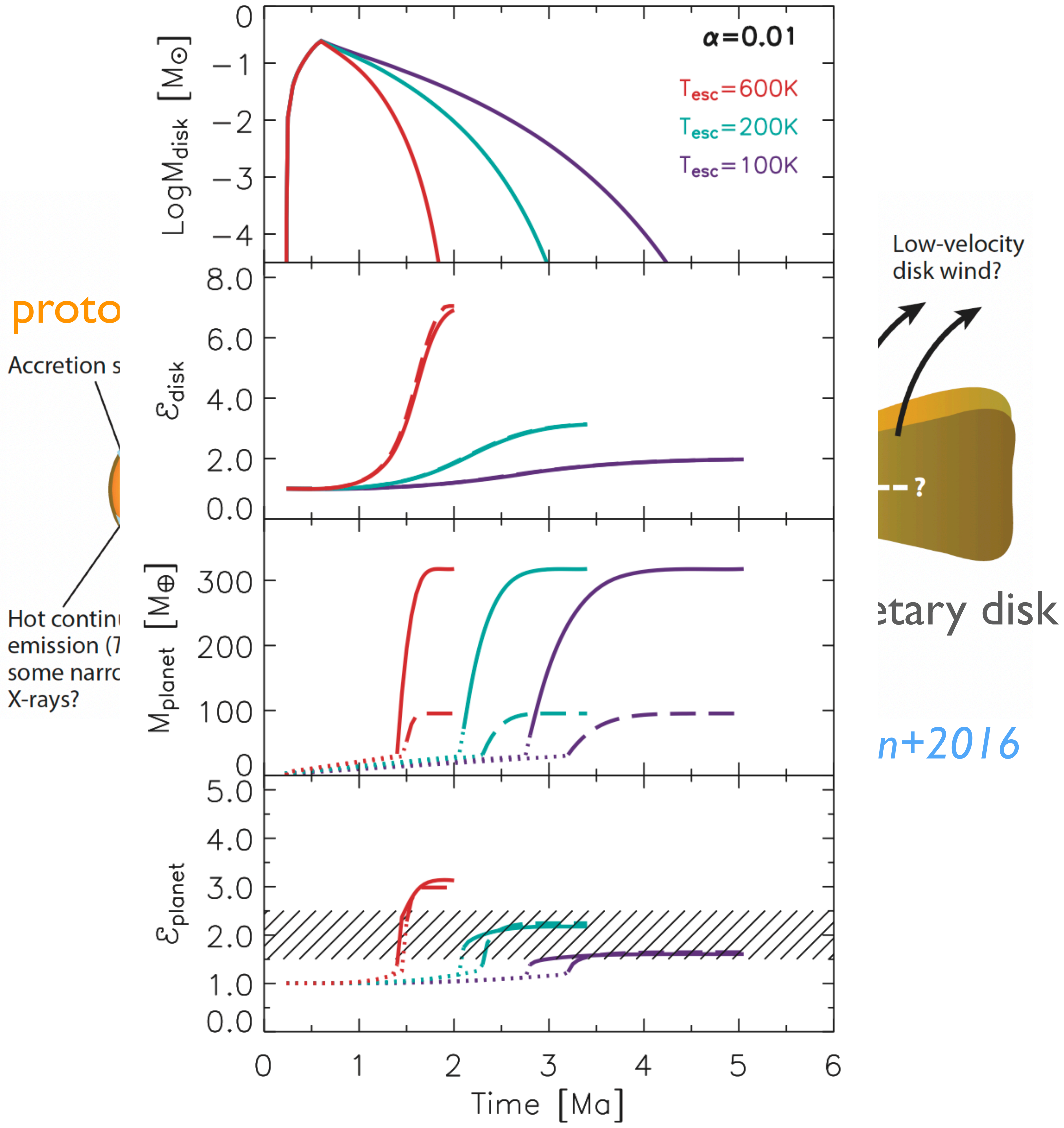


Guillot et al. PPVII

Bulk (from interior models)

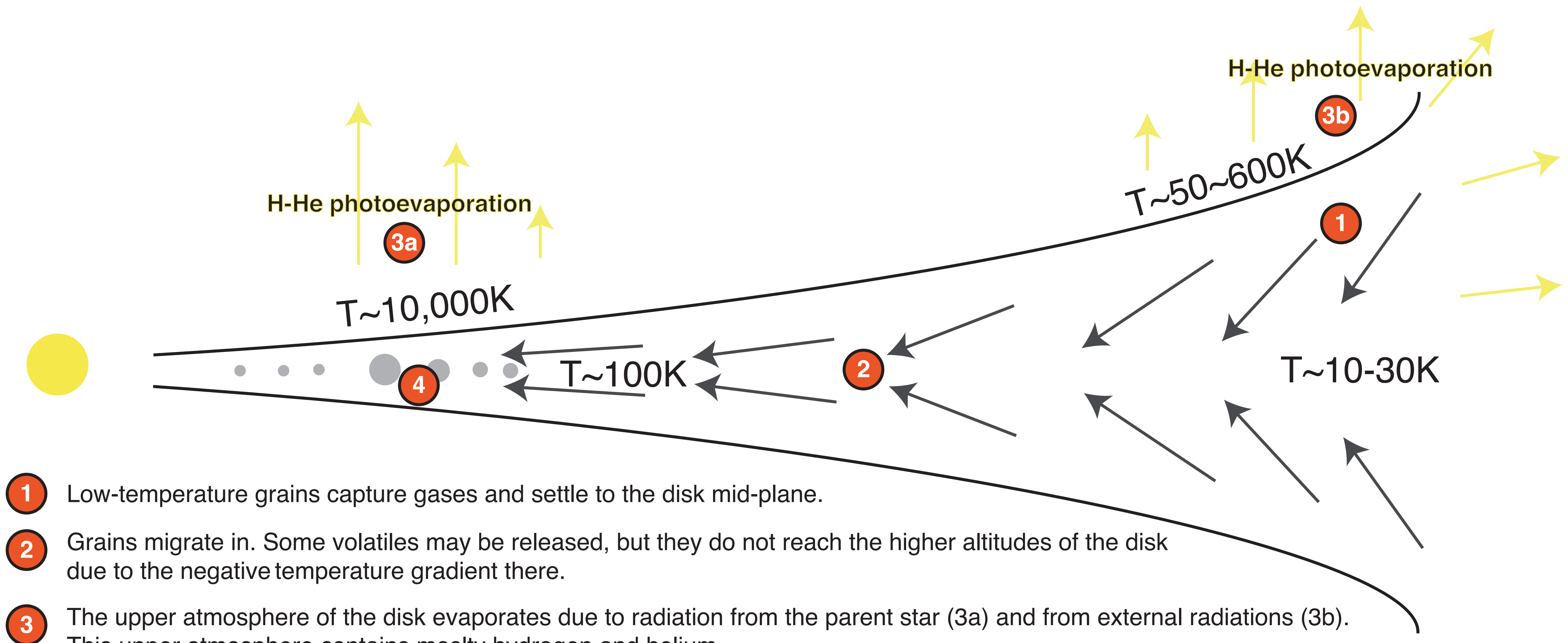
- Jupiter: 3-9 x solar
  - 15 to 40 $M_\oplus$
    - Debras+Chabrier2019, Miguel+2022, Militzer+2022, Howard+2023.
- Saturn: 11-13 x solar
  - 16-18 $M_\oplus$
    - Mankovich+Fuller2021
- Uranus & Neptune
  - Only 1-4 $M_\oplus$ in hydrogen & helium
- Tension between interior models & atmospheric abundance constraints

Importance of disk winds and photoevaporation



- Photoevaporation/winds are not fractionating *locally*
  - $m_{crit}/m_H = 1 + \dfrac{kT\dot{\Sigma}_{evap}}{bgX_H m_H^2} \approx 3000$ to 10^6
- However photoevaporation is taking place high/far in the disk
  - these zones are depleted in grains
- This must lead to a *global* fractionation, i.e., a progressive enrichment of the disk
  - It can account for Jupiter's enrichment in noble gases.
  - It also would account for the $^{14}N/^{15}N$ ratio
    - Guillot & Hueso (2006)

Predicting giant planets compositions



① Low-temperature grains capture gases and settle to the disk mid-plane.

② Grains migrate in. Some volatiles may be released, but they do not reach the higher altitudes of the disk due to the negative temperature gradient there.

③ The upper atmosphere of the disk evaporates due to radiation from the parent star (3a) and from external radiations (3b). This upper atmosphere contains moslty hydrogen and helium.

④ Giant protoplanets gradually capture a disk gas which is enriched in non-hydrogen-helium species.

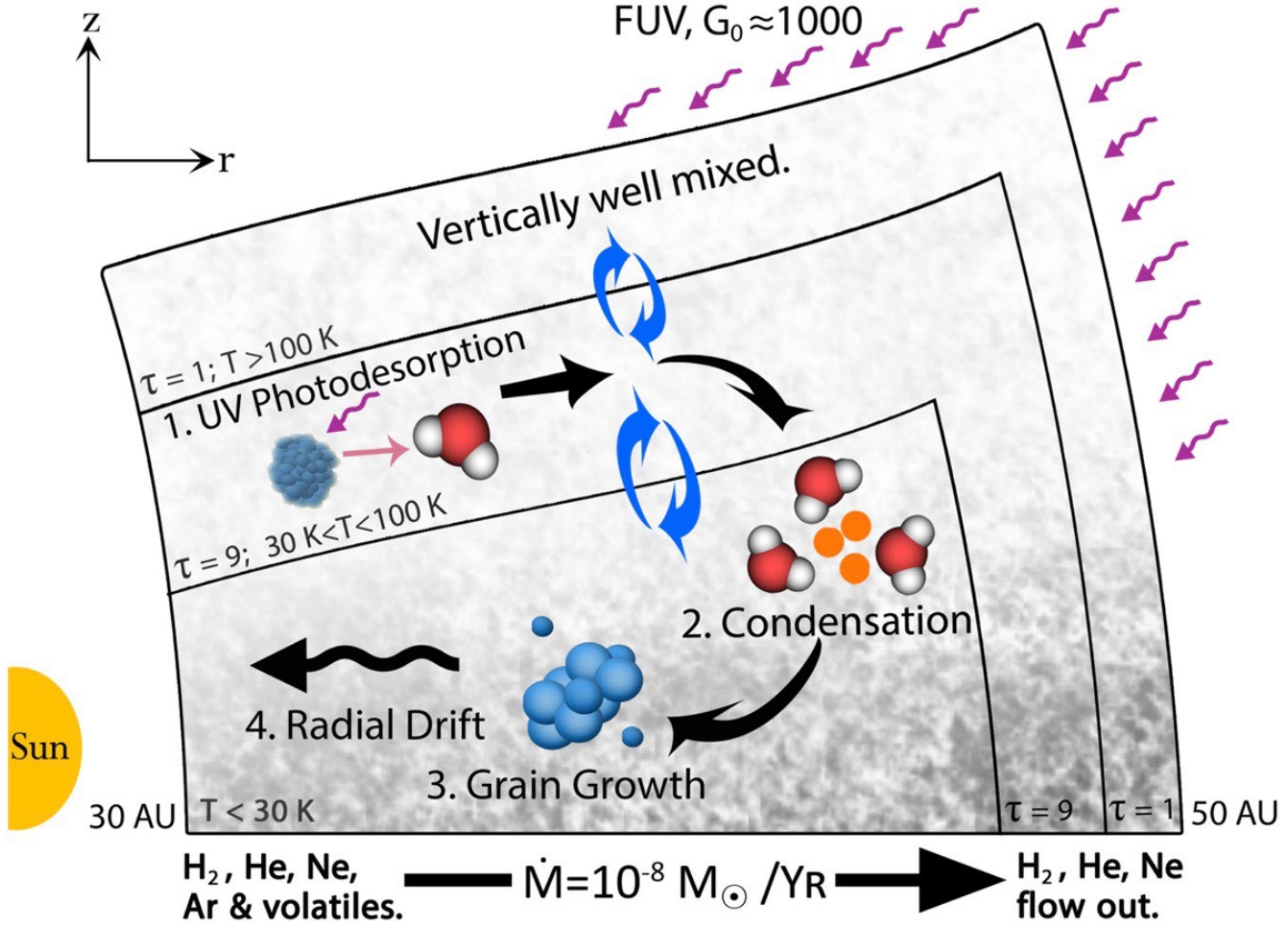
- Initial accretion phase
  - buried too deep inside the planet
    - Except in massive giant planets?
- Accretion of solid & gas combined
  - Need to include the evolution of the composition of the disk with time
- Ending the gas supply is also key!

Guillot & Hueso (MNRAS, 2006)
Atreya et al., Saturn book (2018)
see also Monga & Desch (2015)

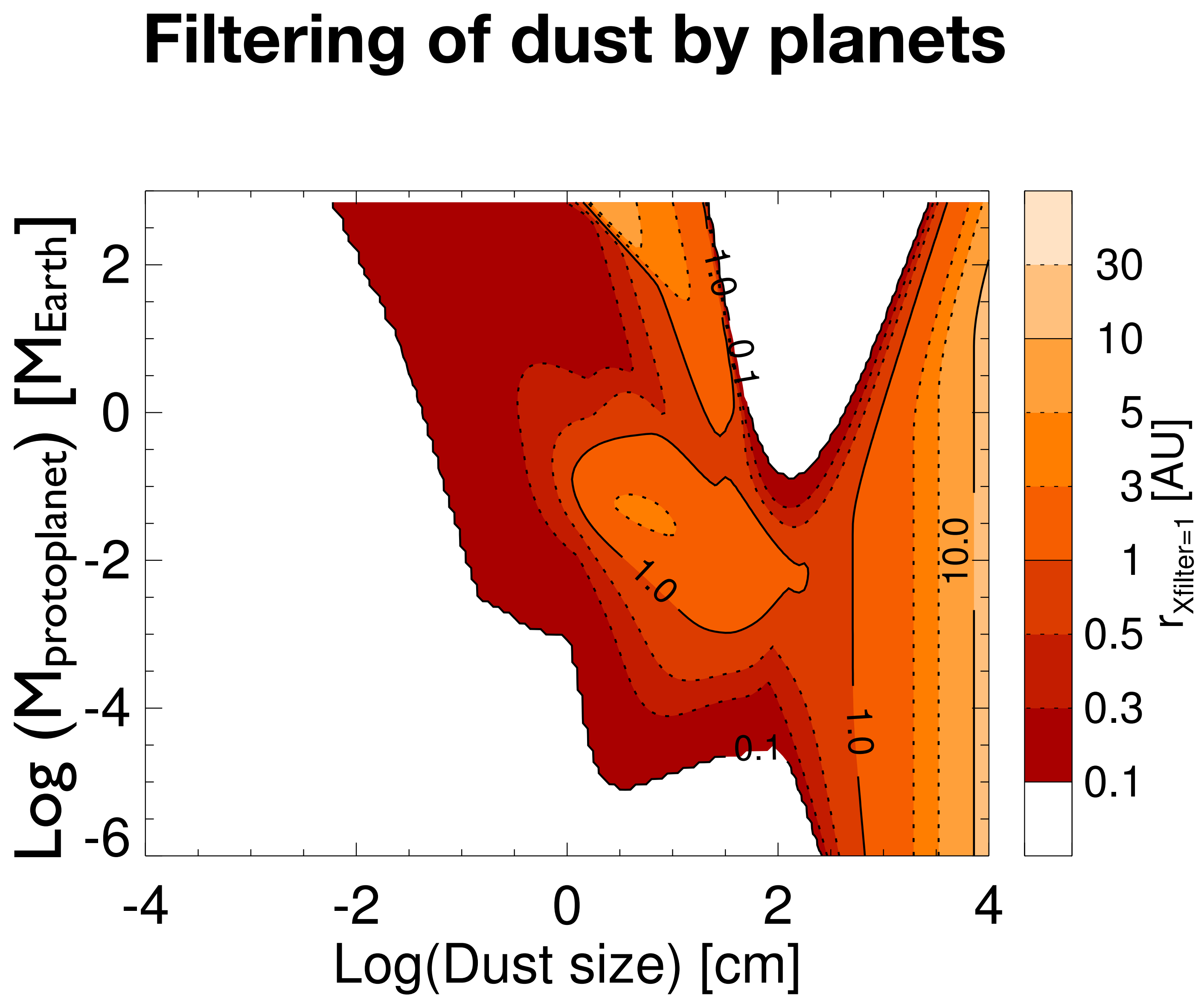
Explaining the enrichment in noble gases

- Guillot & Hueso (2006):
  - Enriching Jupiter in noble gases through planetesimal accretion is unlikely
  - Demonstration that noble gases enrichments are naturally explained through their trapping by grains in the outer disk combined to the progressive photoevaporation of the protosolar disk

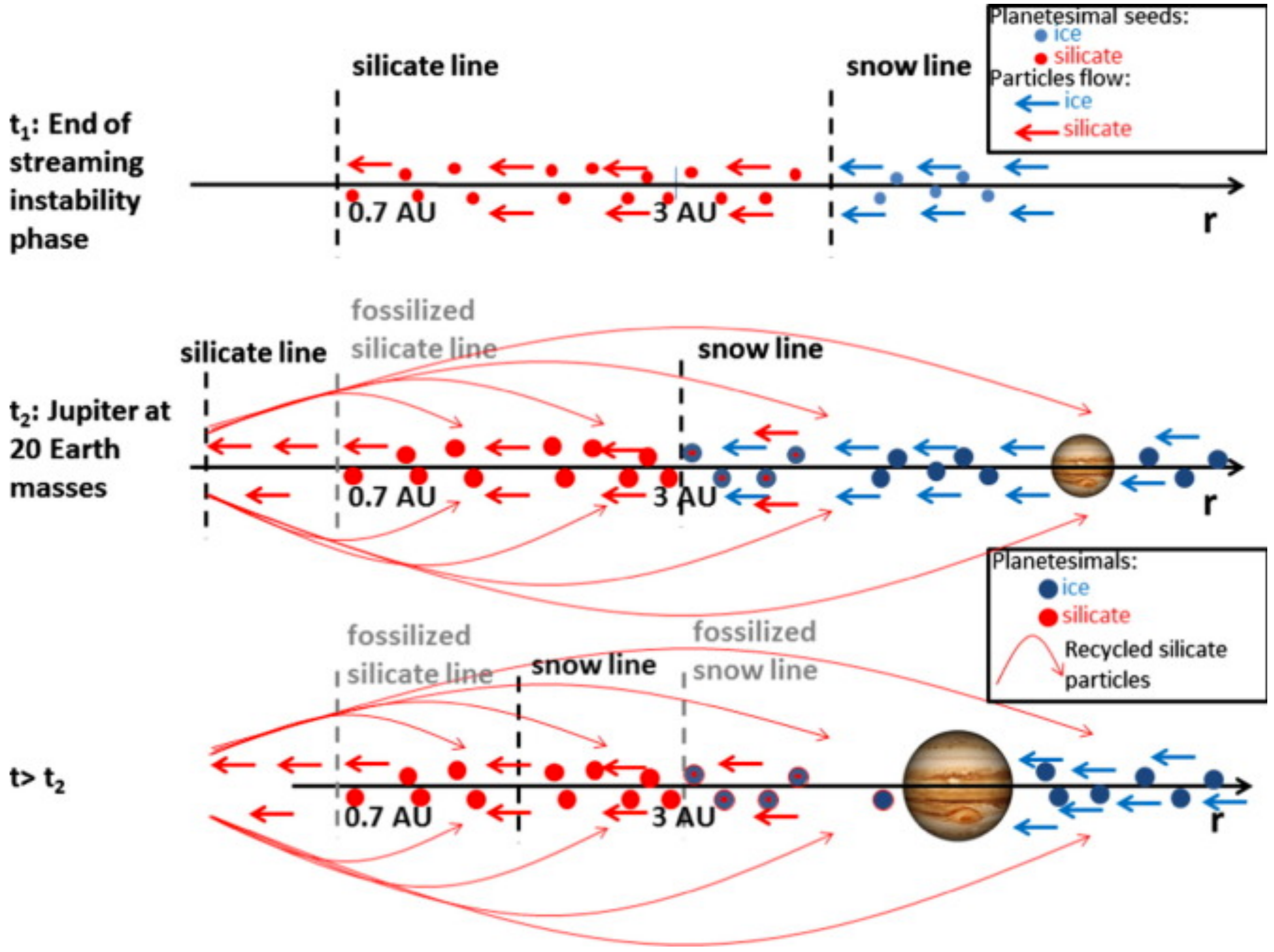
- Monga & Desch (2015)
  - Show that UV absorption in the outer disk is necessary to trap noble gases onto grains
  - Find that the enrichment mechanism is more efficient than GH2006 by not accounting for the possibility of grain removal in photo evaporative regions
    - The observed enrichment may be reached when only ~70% of the disk has been photo evaporated (rather than 98% for GH2006)
  - Confirms & extends the work of GH2006



Jupiter and Saturn as barriers to the pebble inflow


Filtering of dust by planets

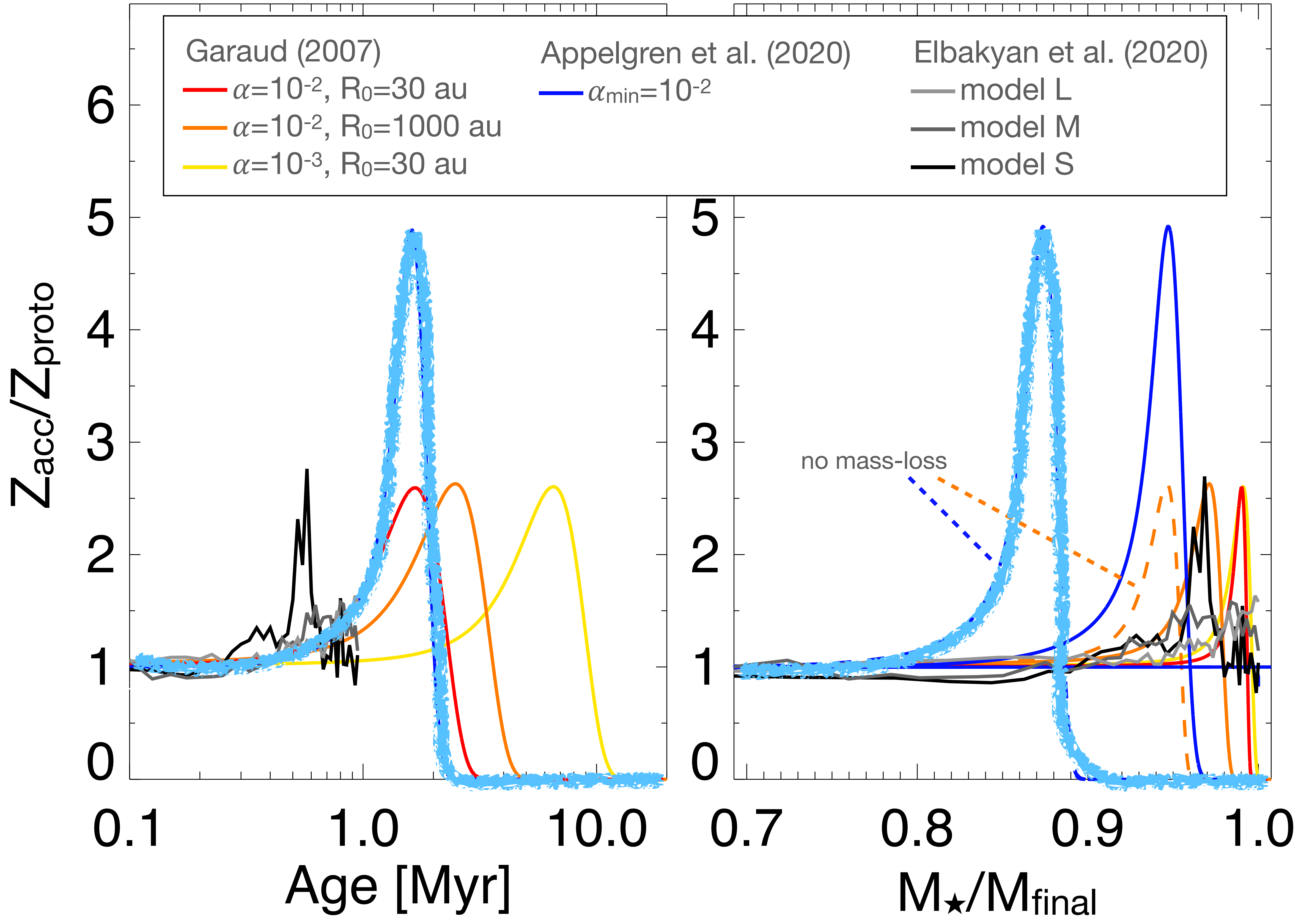
Guillot et al. (2014)



Morbidelli et al. (2016)

Depending on planet location w.r.t. ice lines, the composition of material inside of the planet is affected differently

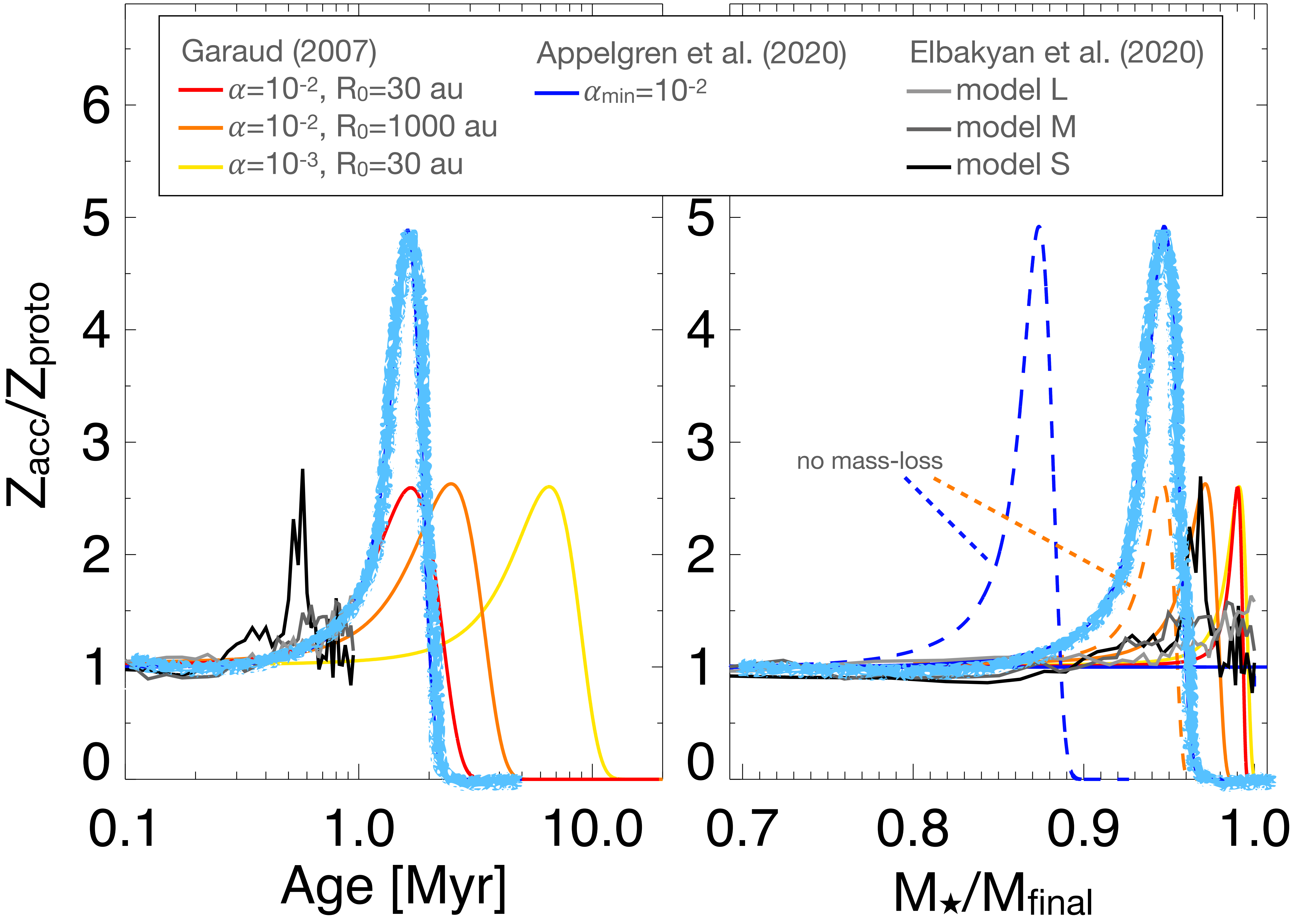
Pebble wave



w/o photoevaporation
w/o planets

Kunitomo & Guillot (2021)

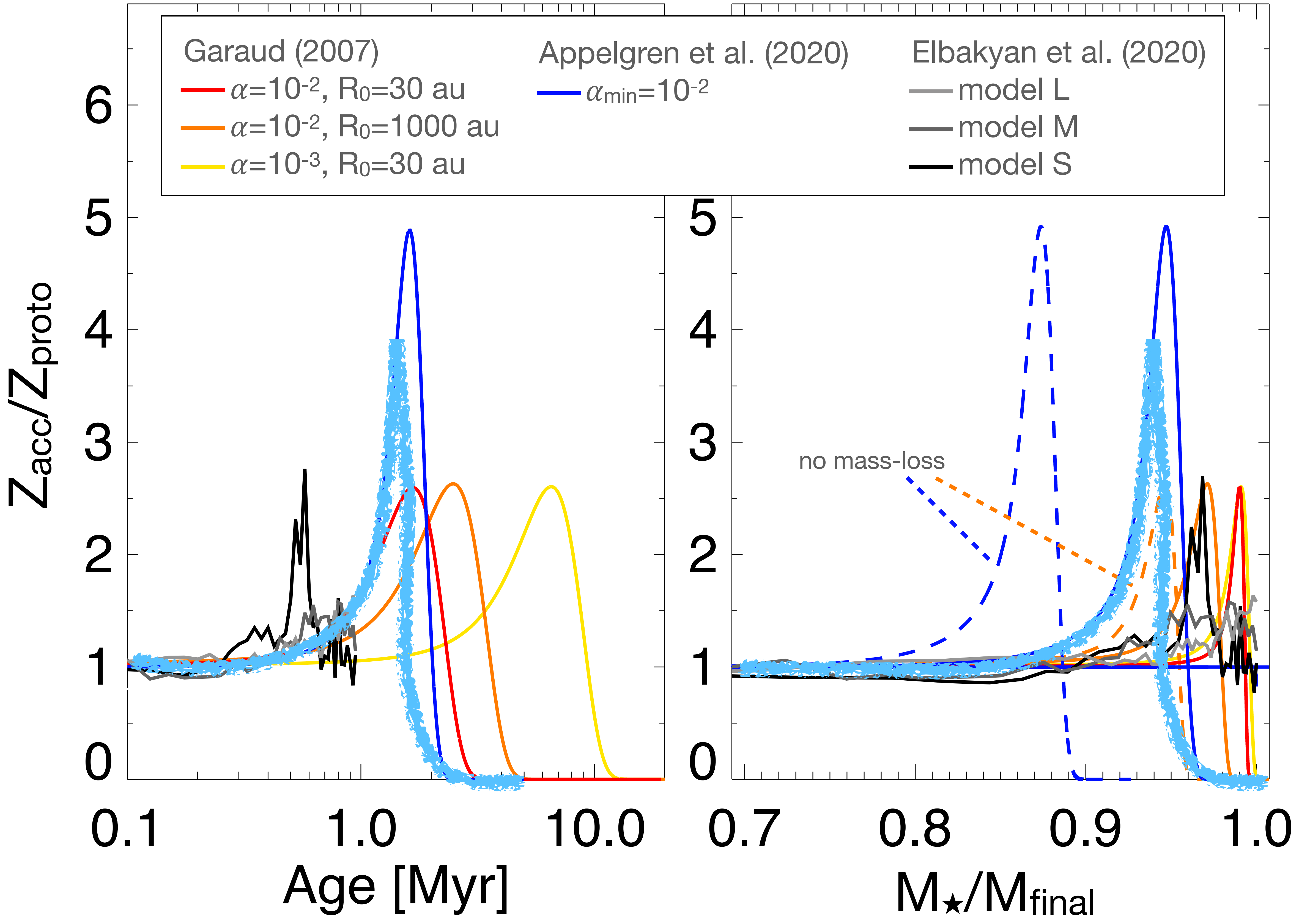
Pebble wave



w/ photoevaporation
w/o planets

Kunitomo & Guillot (2021)

Pebble wave

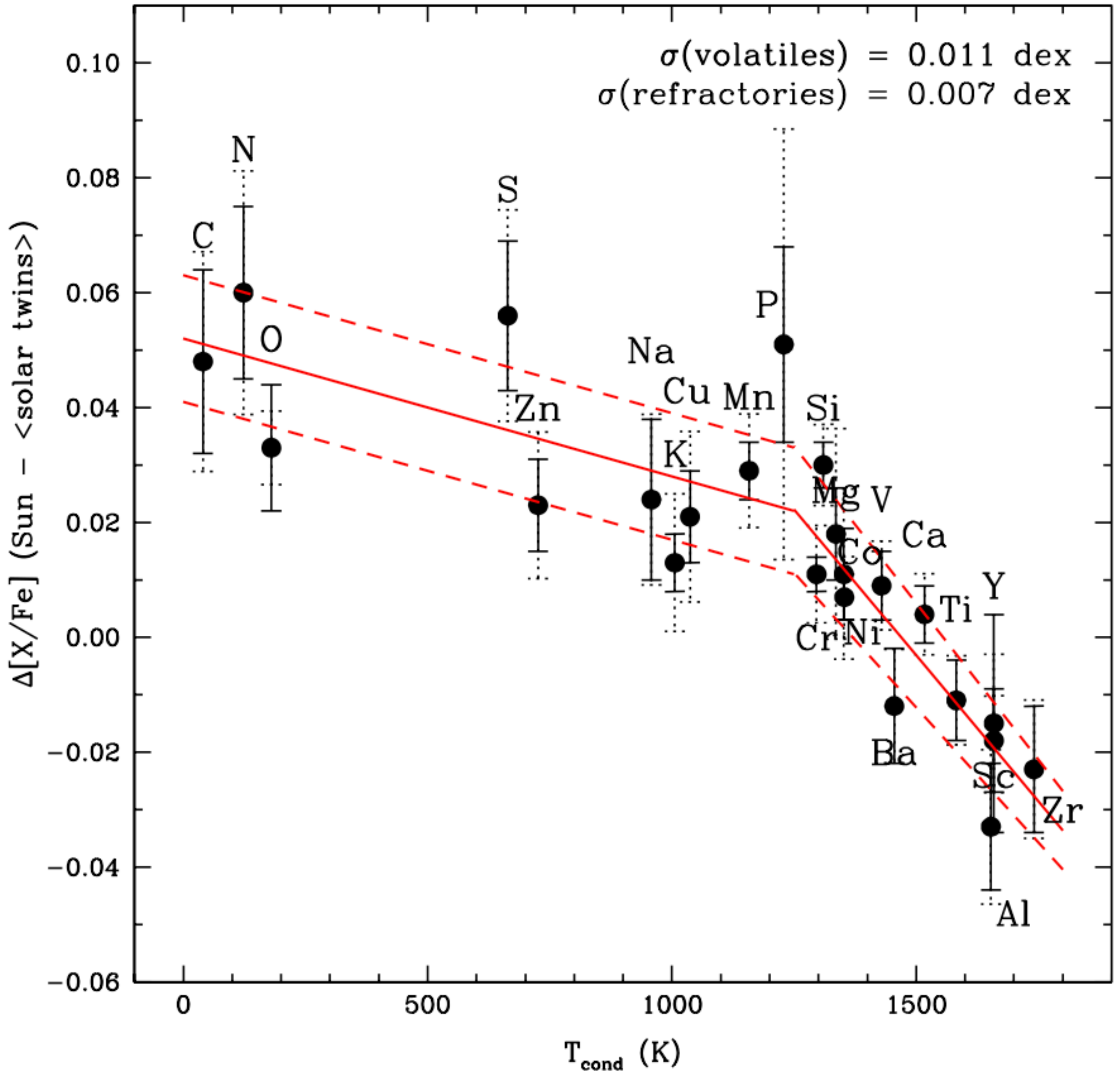


w/ photoevaporation
w/ planets

Kunitomo & Guillot (2021)

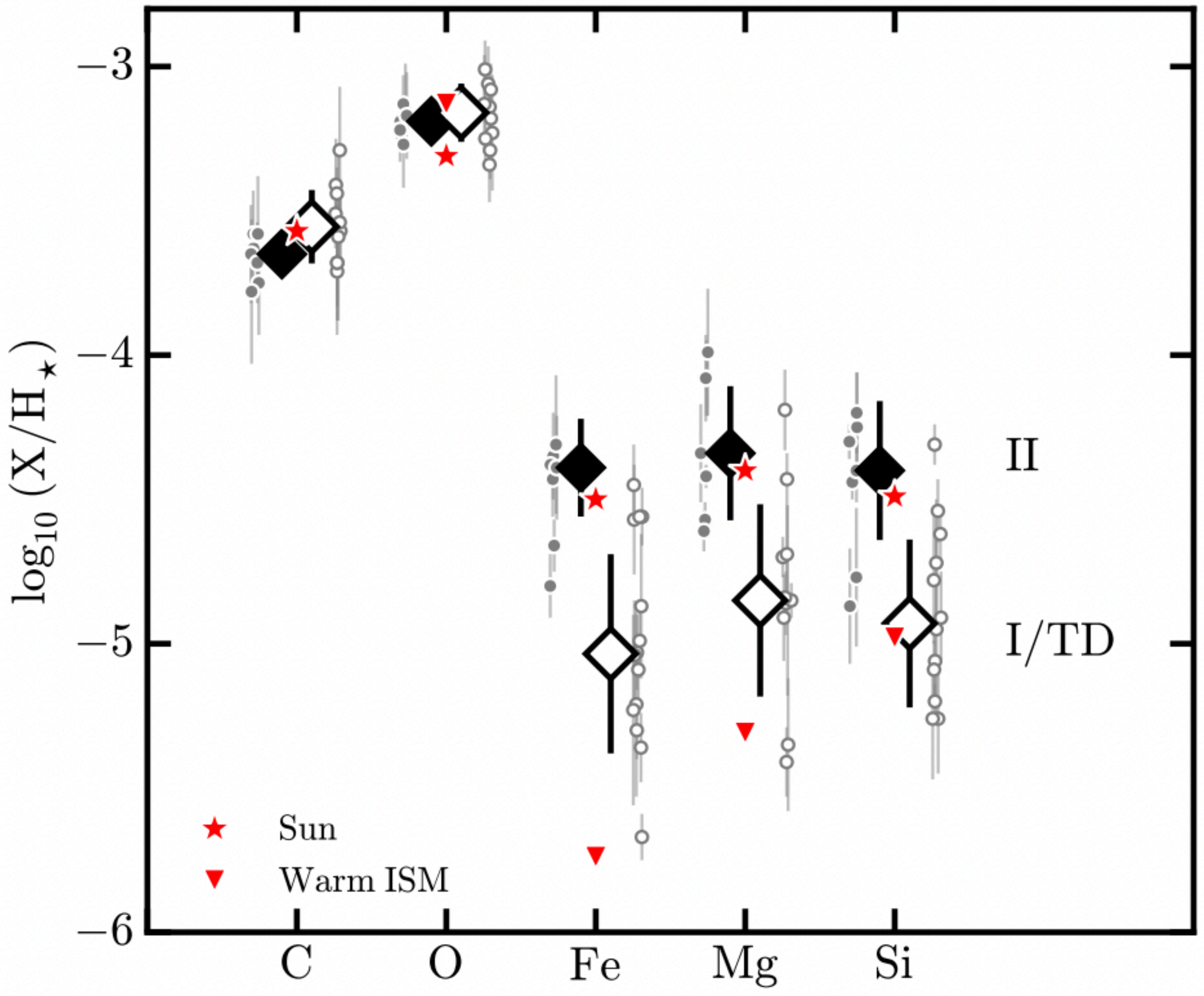
Consequences for the star: observations

Our Sun compared to solar twins



Melendez et al. (2009)

Accreting Ae/Be Herbig stars (λ-Boo stars)

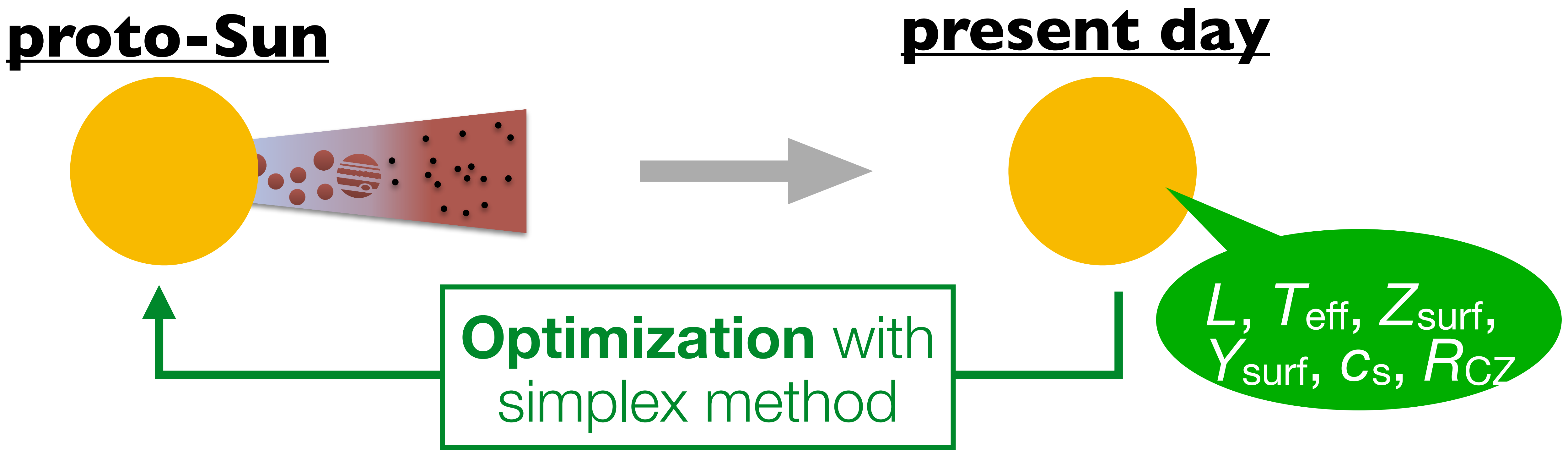


Kama et al. (2015)

⇒ Could be explained if the giant planets accreted much more rocks than ices (Kunitomo et al. 2018).

Evolution of our Sun w/ variable accretion

Kunitomo, Guillot & Buldgen (2022)
Kunitomo & Guillot (2021)

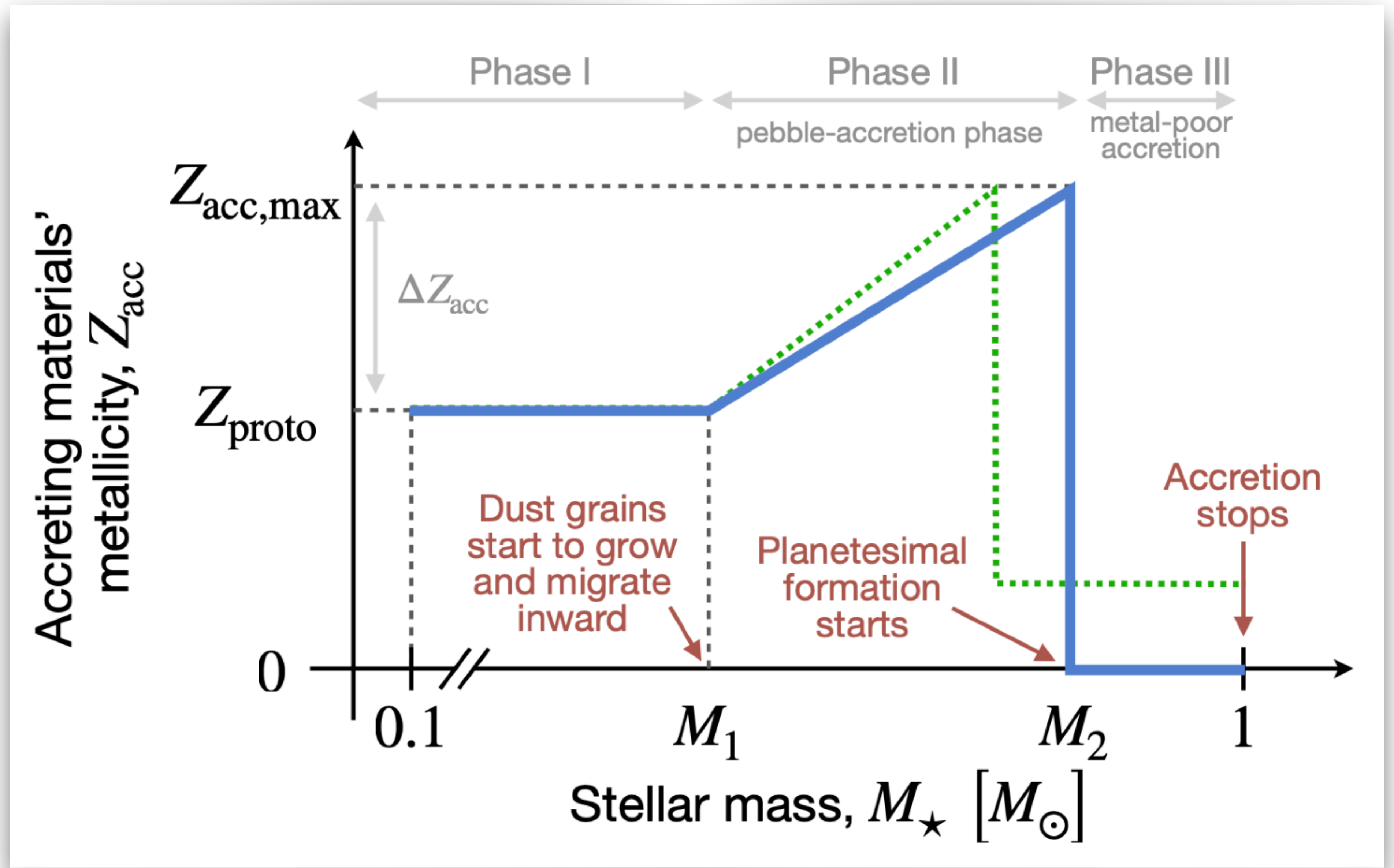


proto-Sun

present day

Optimization with simplex method

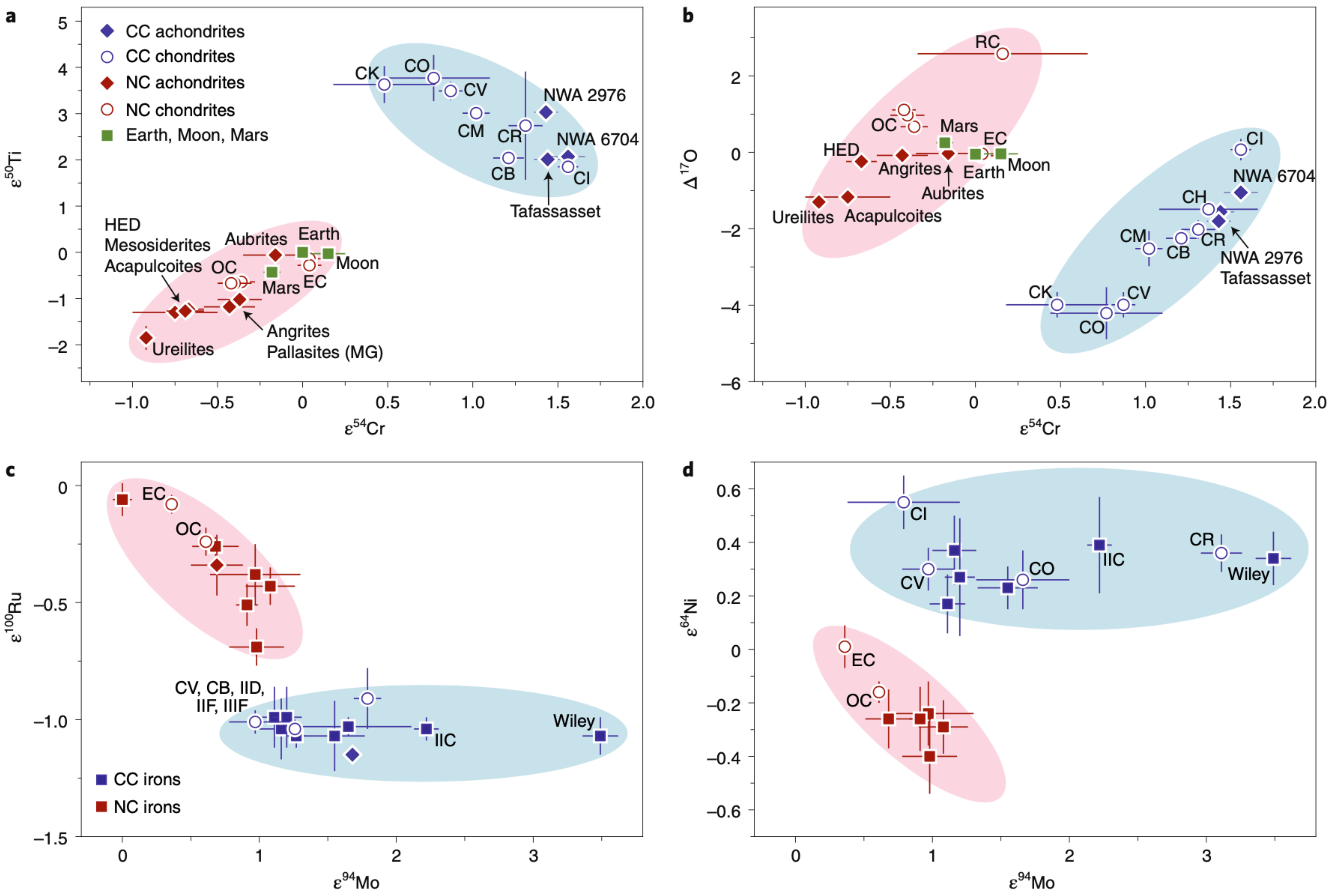
L, $T_{\rm eff}$, $Z_{\rm surf}$, $Y_{\rm surf}$, c_s, $R_{\rm CZ}$



- Evolution calculations using MESA
- Models are optimized to fit the present-day constraints
    - Spectroscopy
    - Seismology
    - Physical characteristics
- An opacity increase is used to fit the seismological constraints
    - Agrees with Fe-opacity lab measurements
- Accretion is taken into account
    - with or without variable accretion

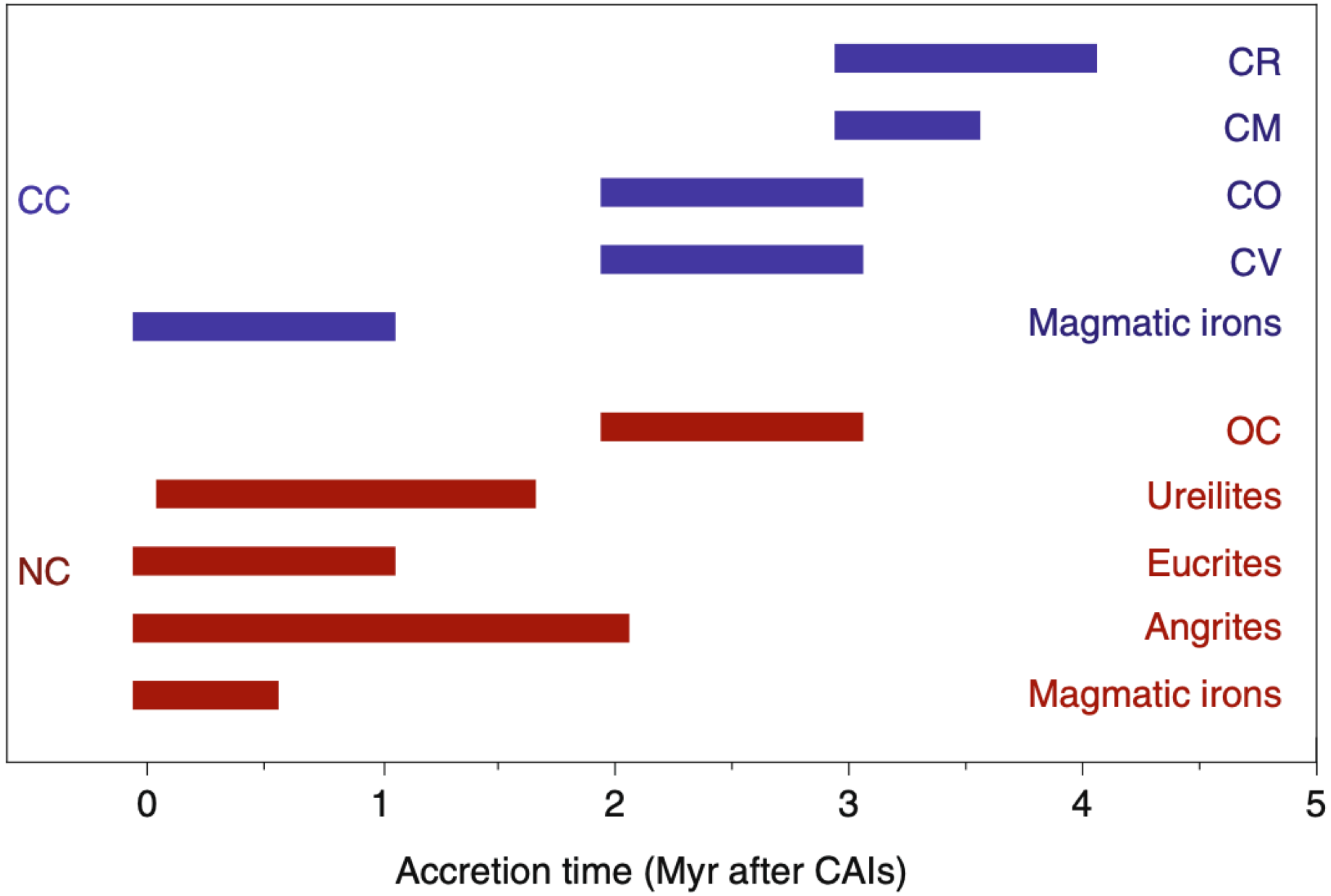
Time constraints from meteoritic data

- Isotopic dichotomy of the early solar system
  - Kruijer et al. (2020)



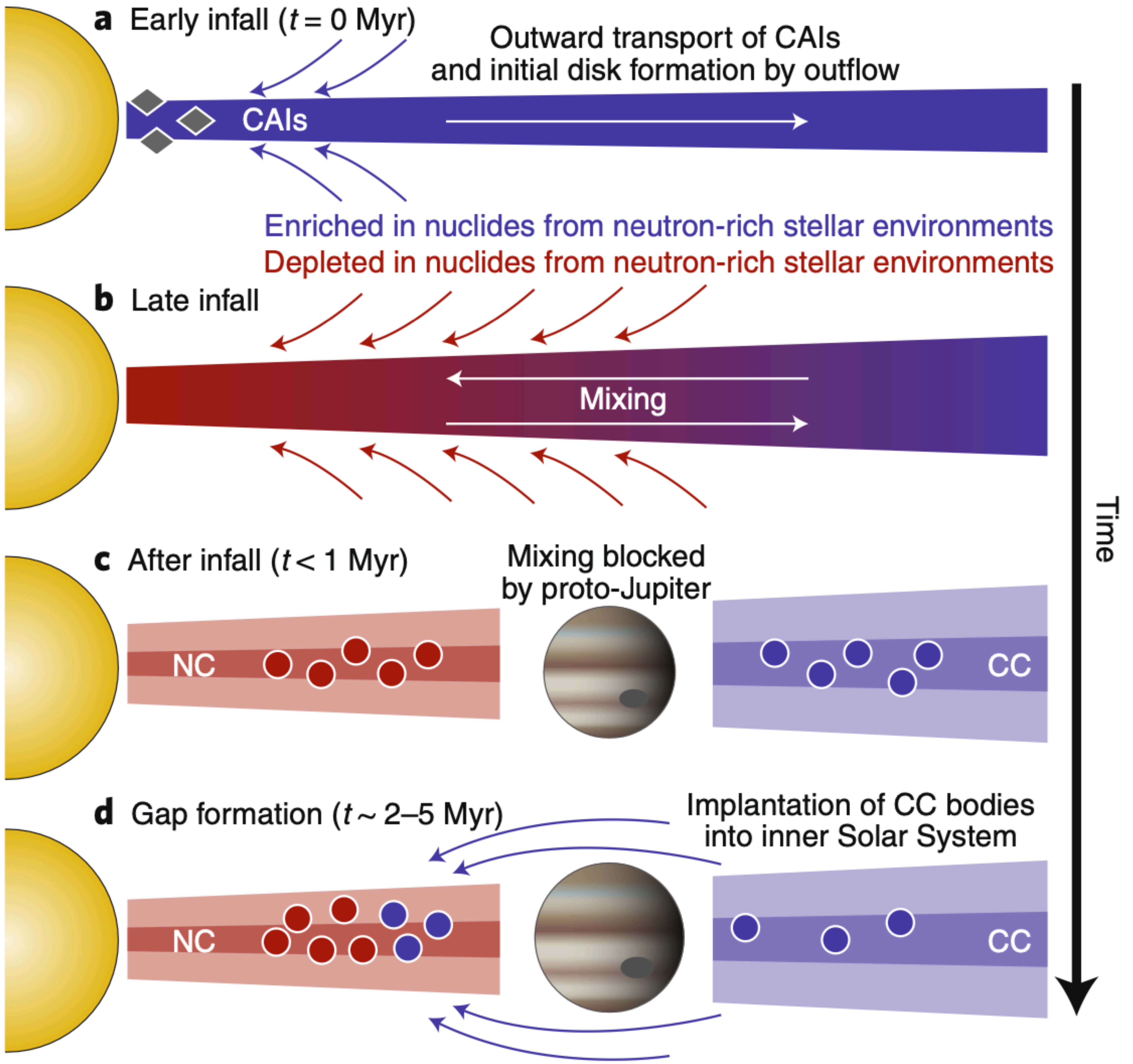
Time constraints from meteoritic data

- Isotopic dichotomy of the early solar system
  - Kruijer et al. (2020)
- This is also coupled to a dichotomy in the formation times



Time constraints from meteoritic data

- Isotopic dichotomy of the early solar system
  - Kruijer et al. (2020)
- This is also coupled to a dichotomy in the formation times
- Favors an early (<1Myr) formation of Jupiter's core, and a slow growth to Jupiter's final mass in ~5 Myr



Evolution of our Sun w/ variable accretion

Kunitomo, Guillot & Buldgen (2022)
Kunitomo & Guillot (2021)