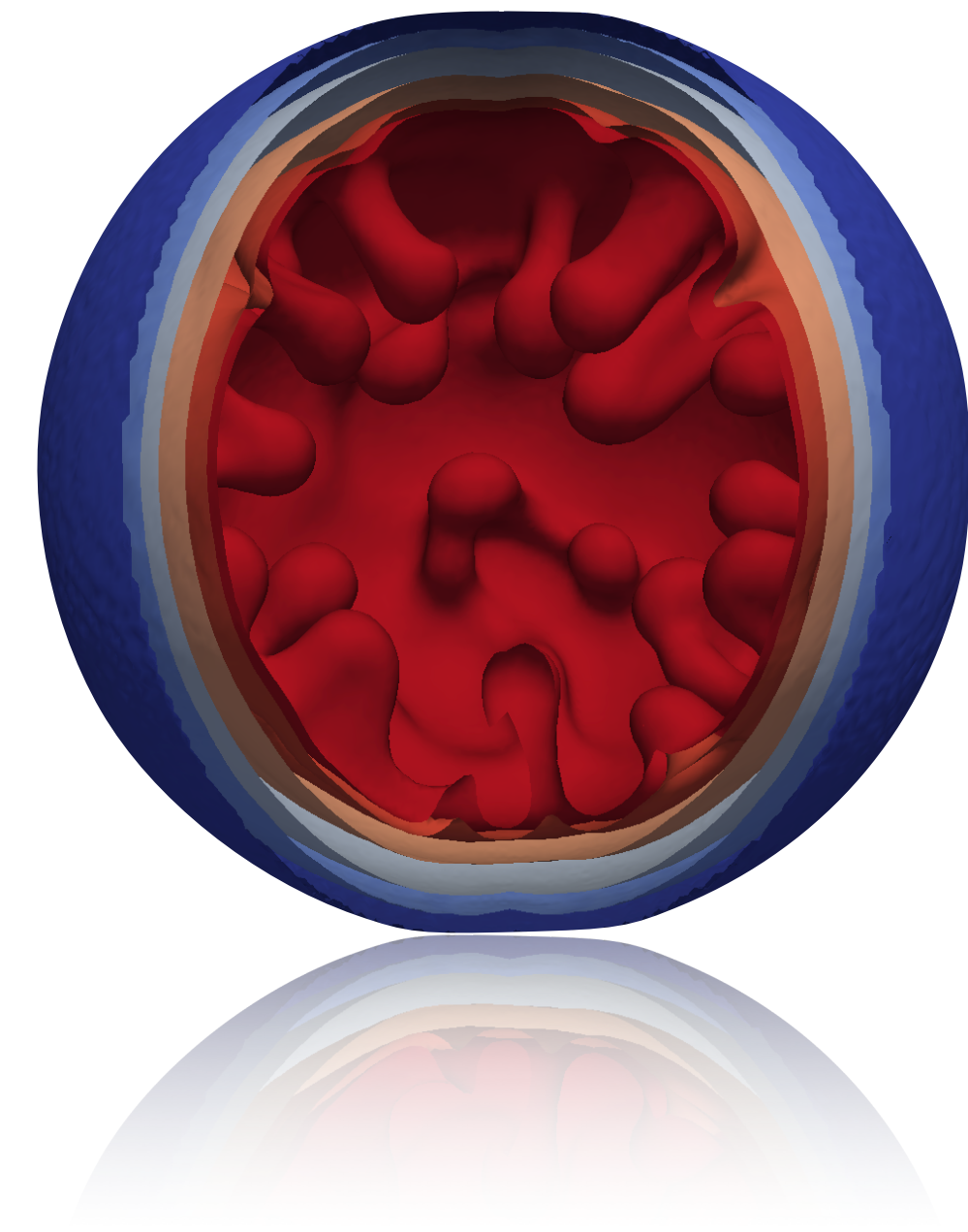


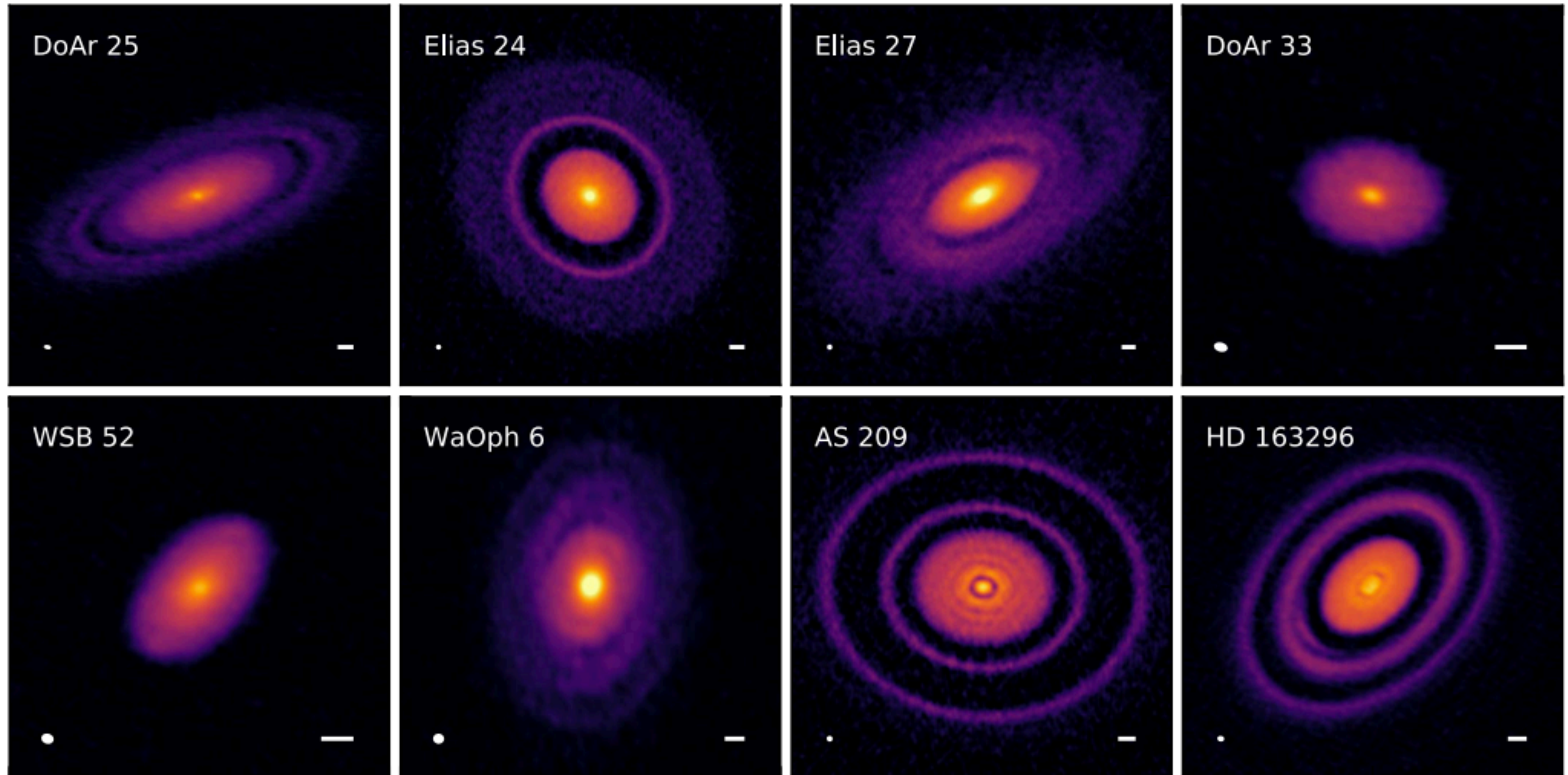
# Earliest compositional bifurcation of planetary building blocks

Tim Lichtenberg

Joanna Drażkowska (LMU Munich)  
Maria Schönbachler (ETH Zurich)  
Gregor Golabek (BGI Bayreuth)  
Thomas Hands (U Zurich)



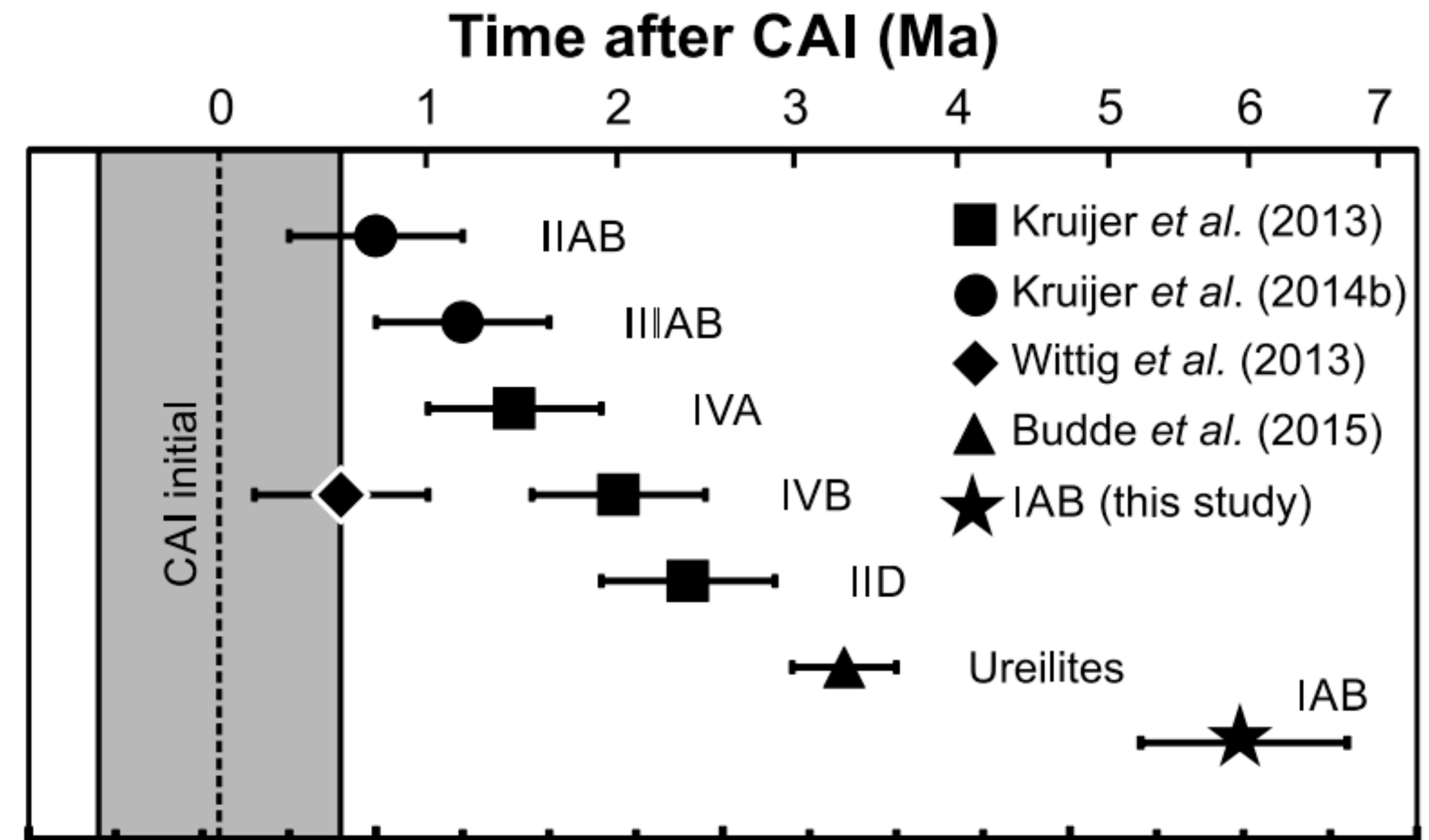
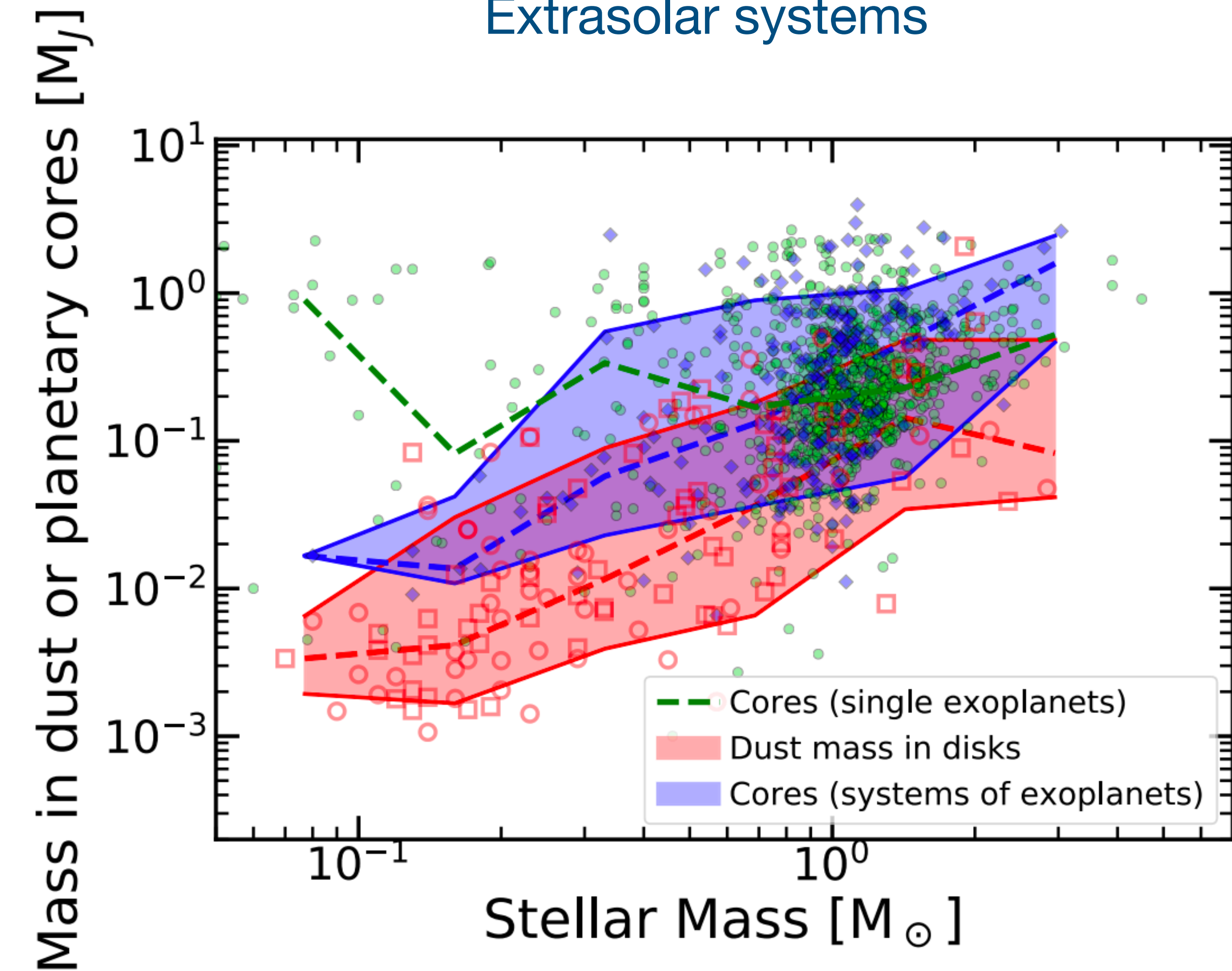
# Substructure in disks



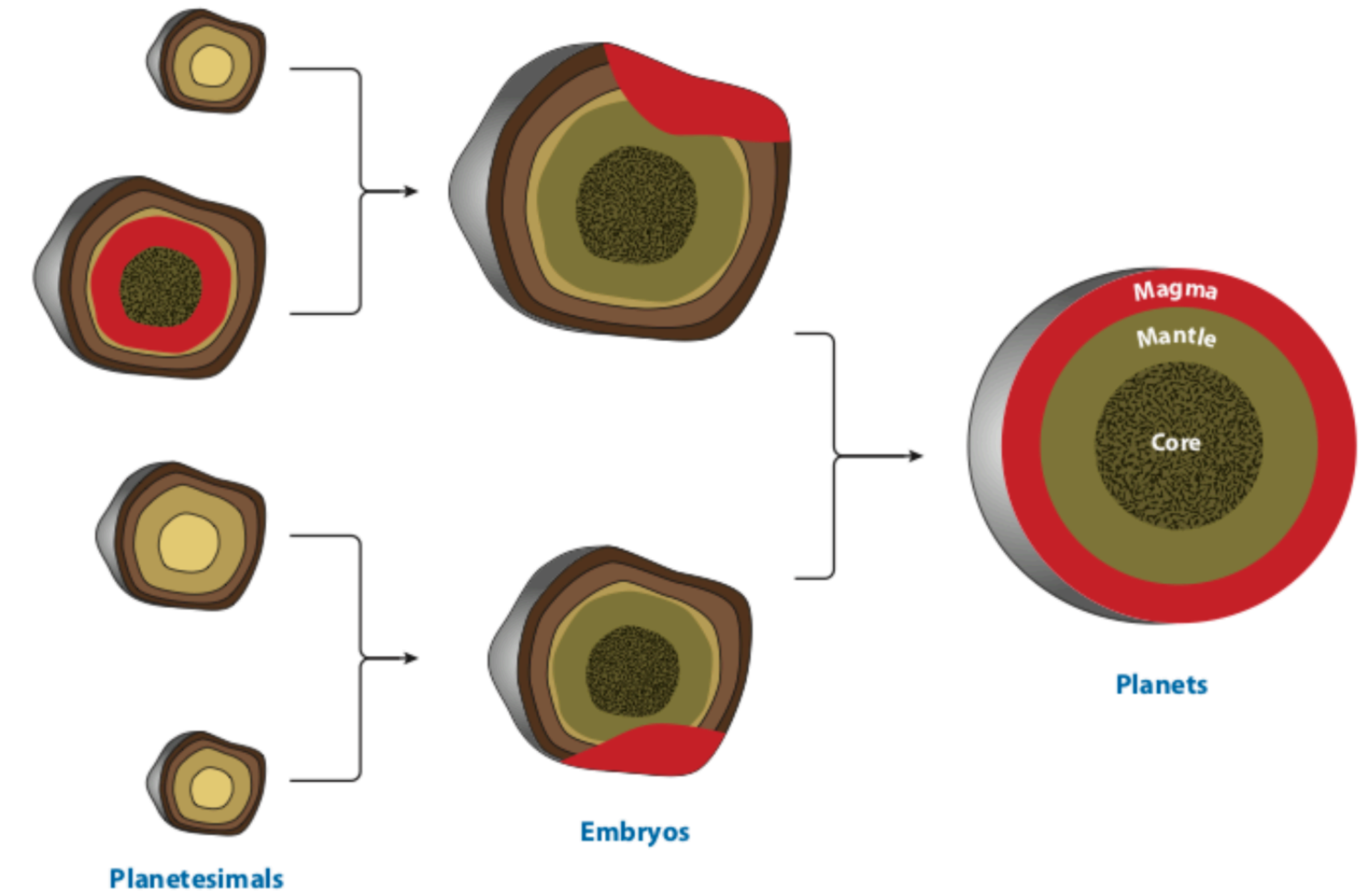
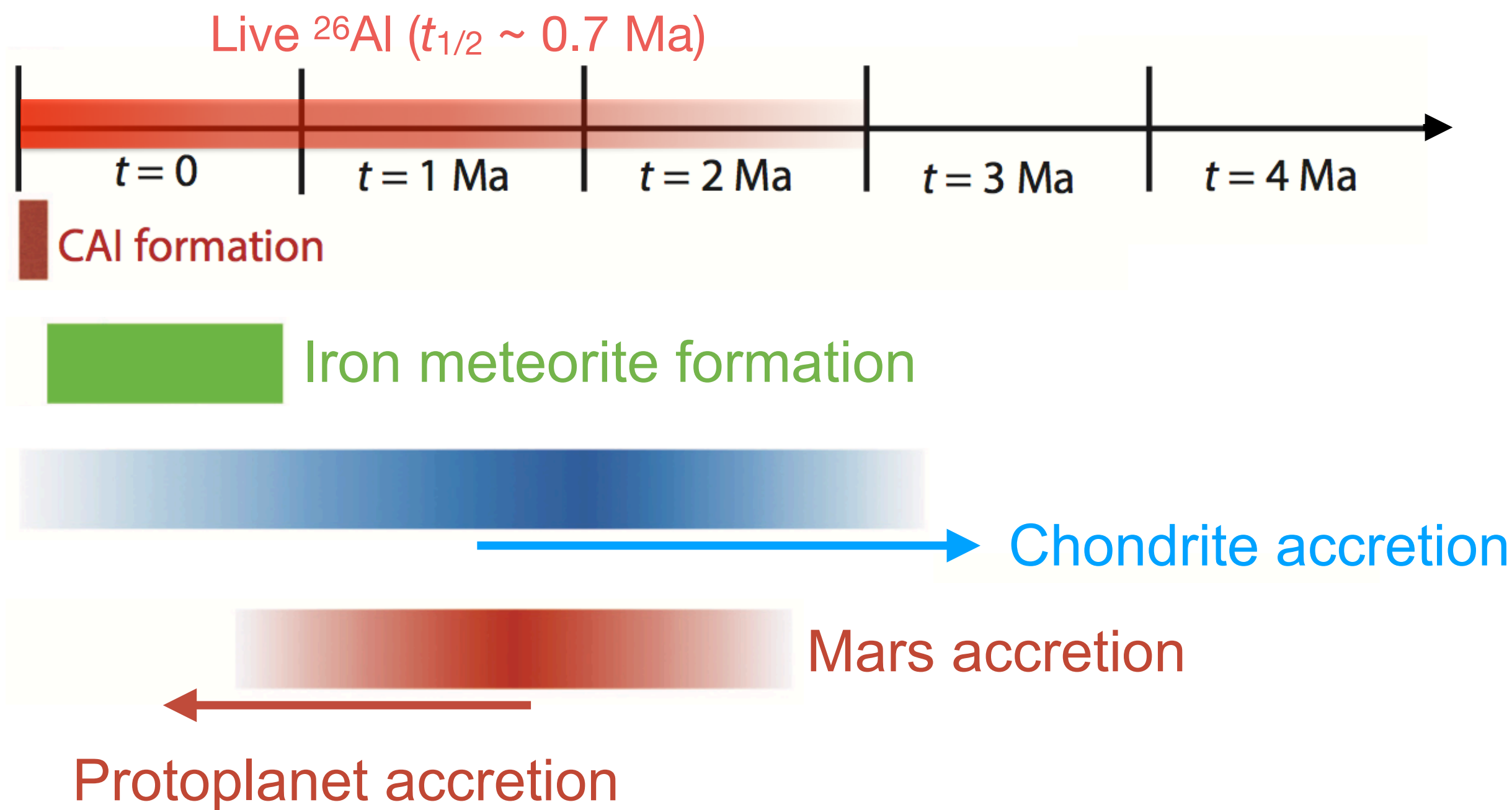
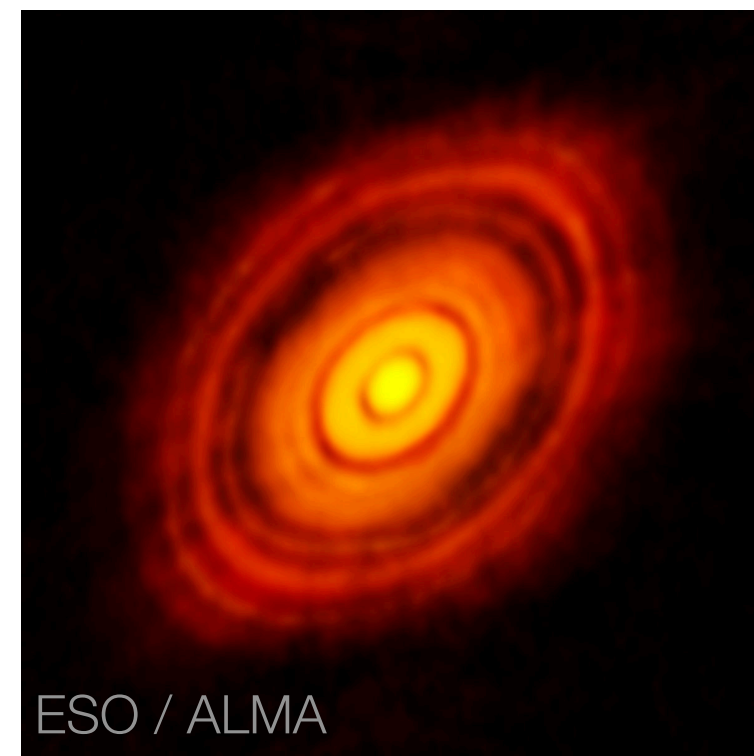
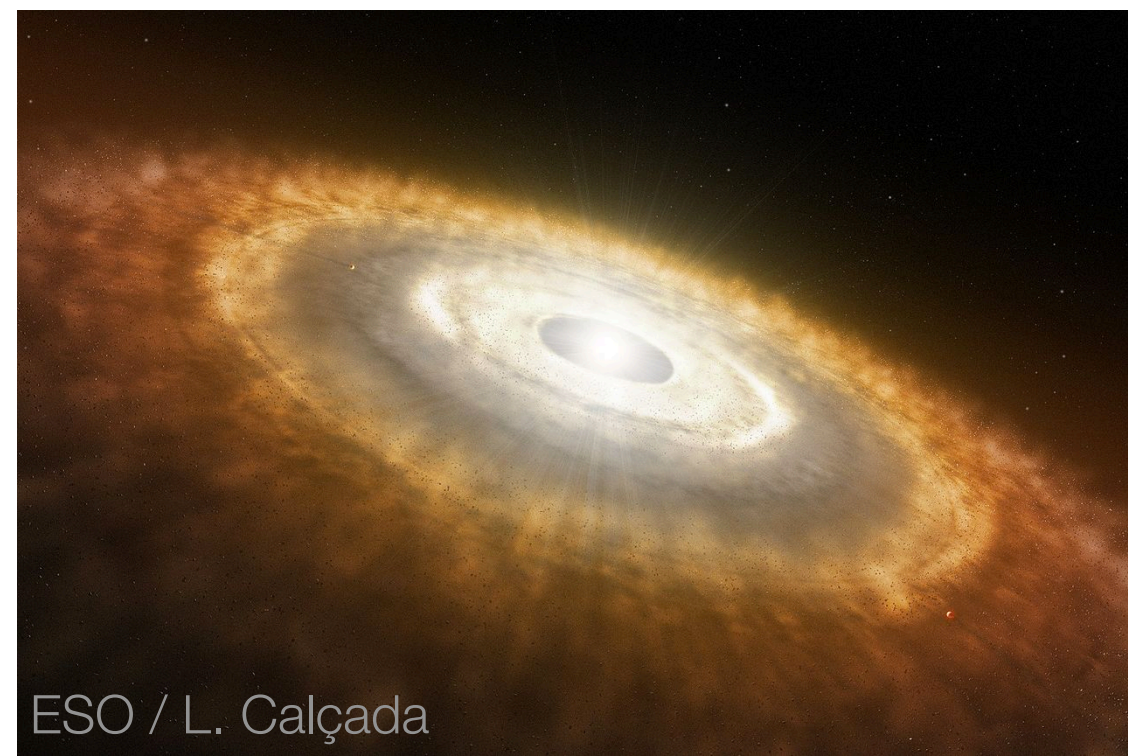
# Rapid onset of planet accretion

Extrasolar systems

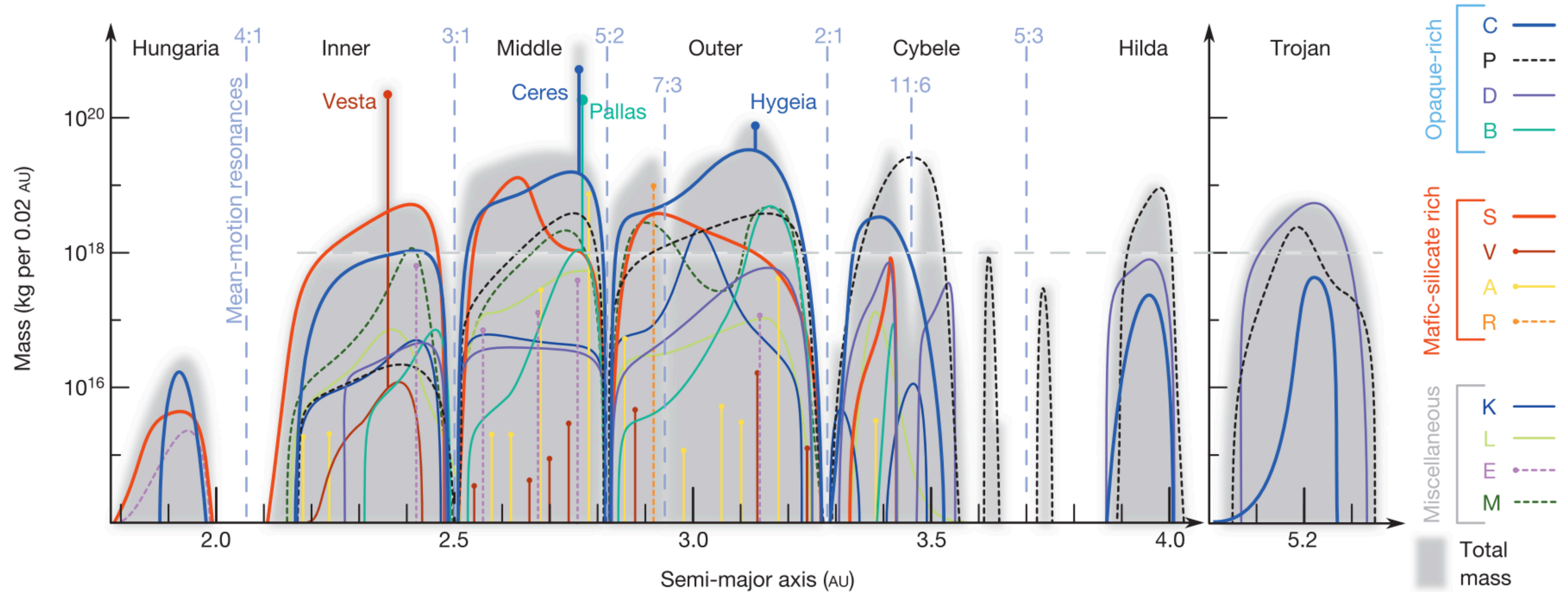
Solar System



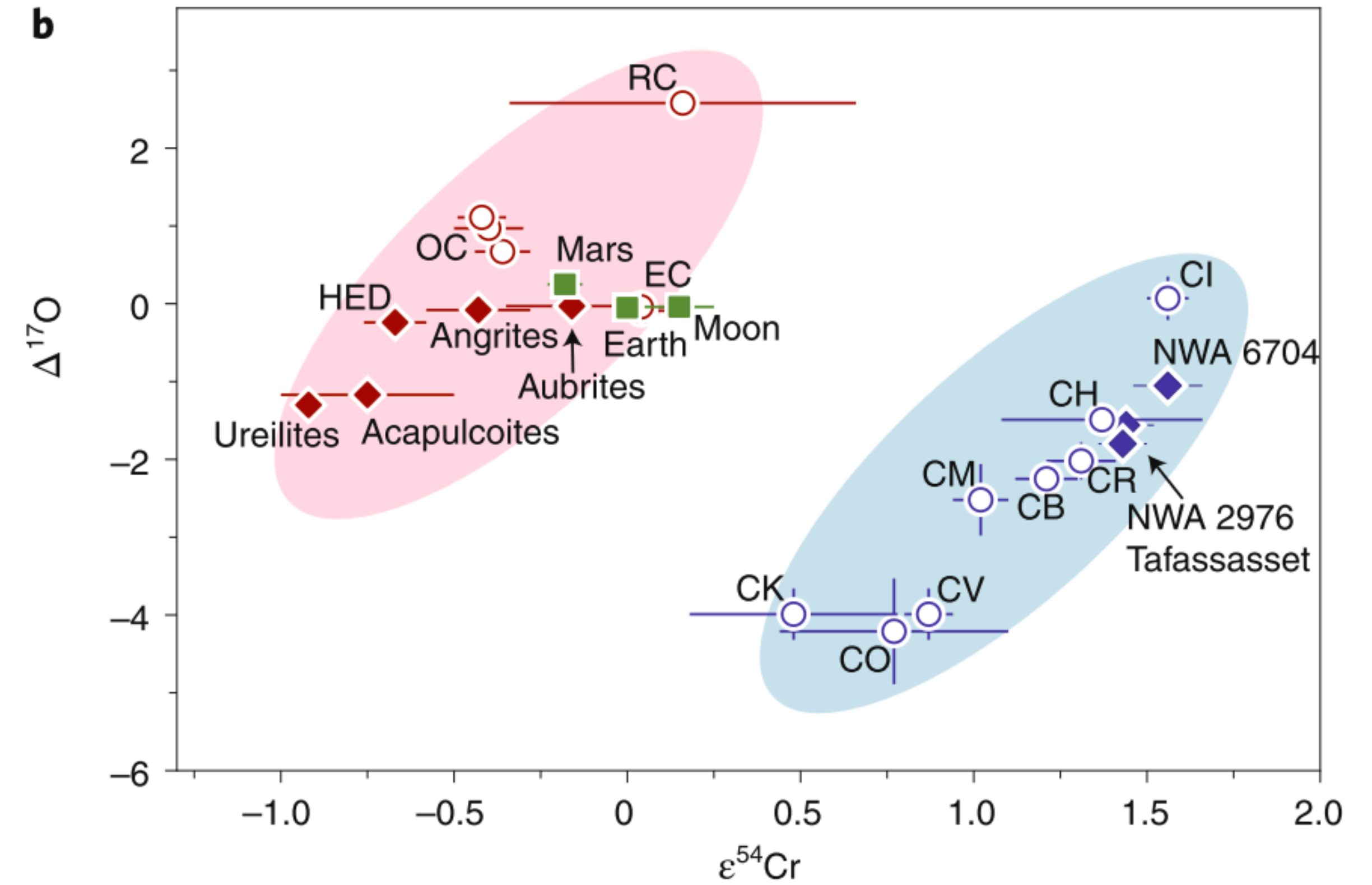
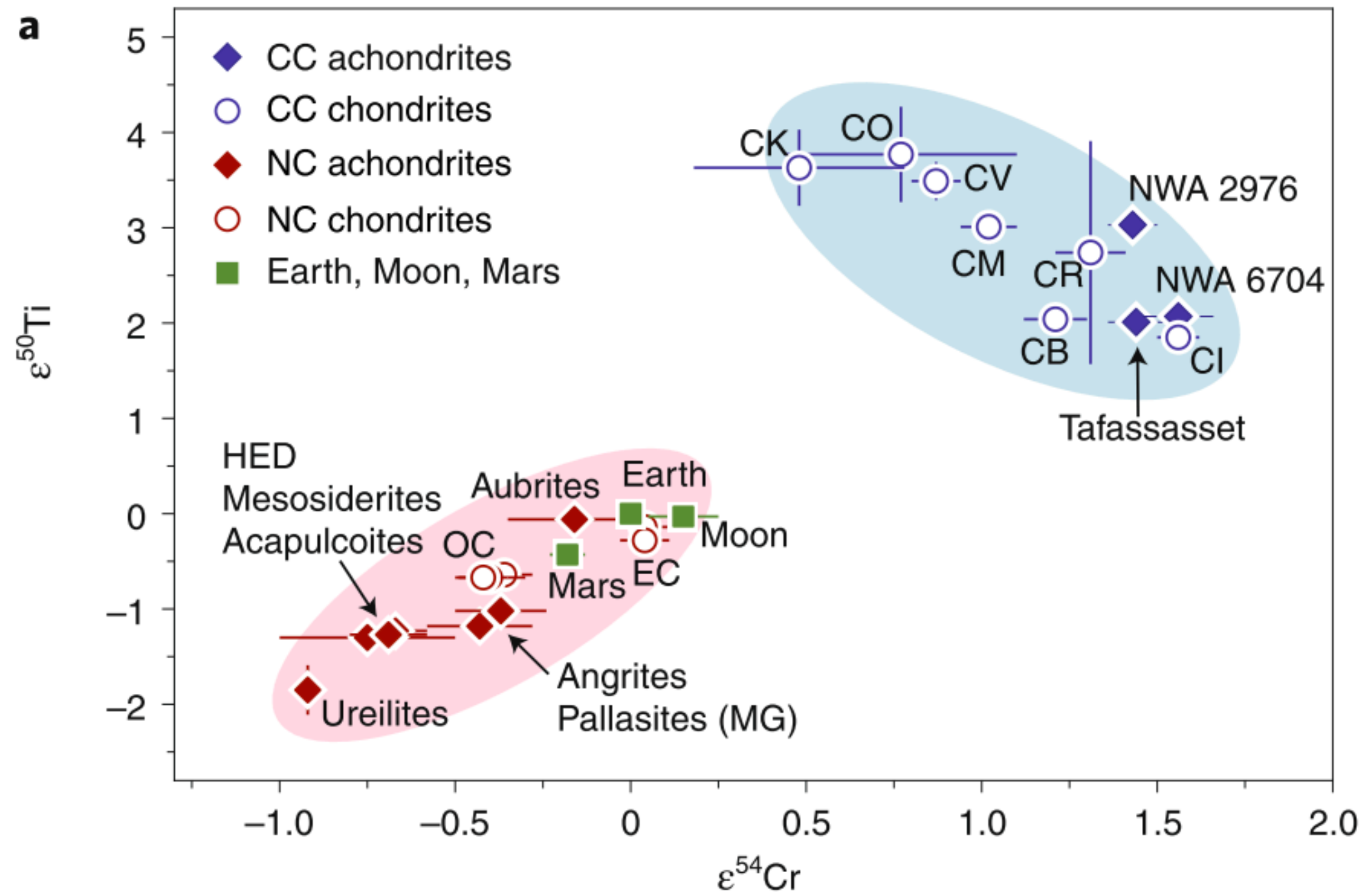
# Geophysical evolution during accretion



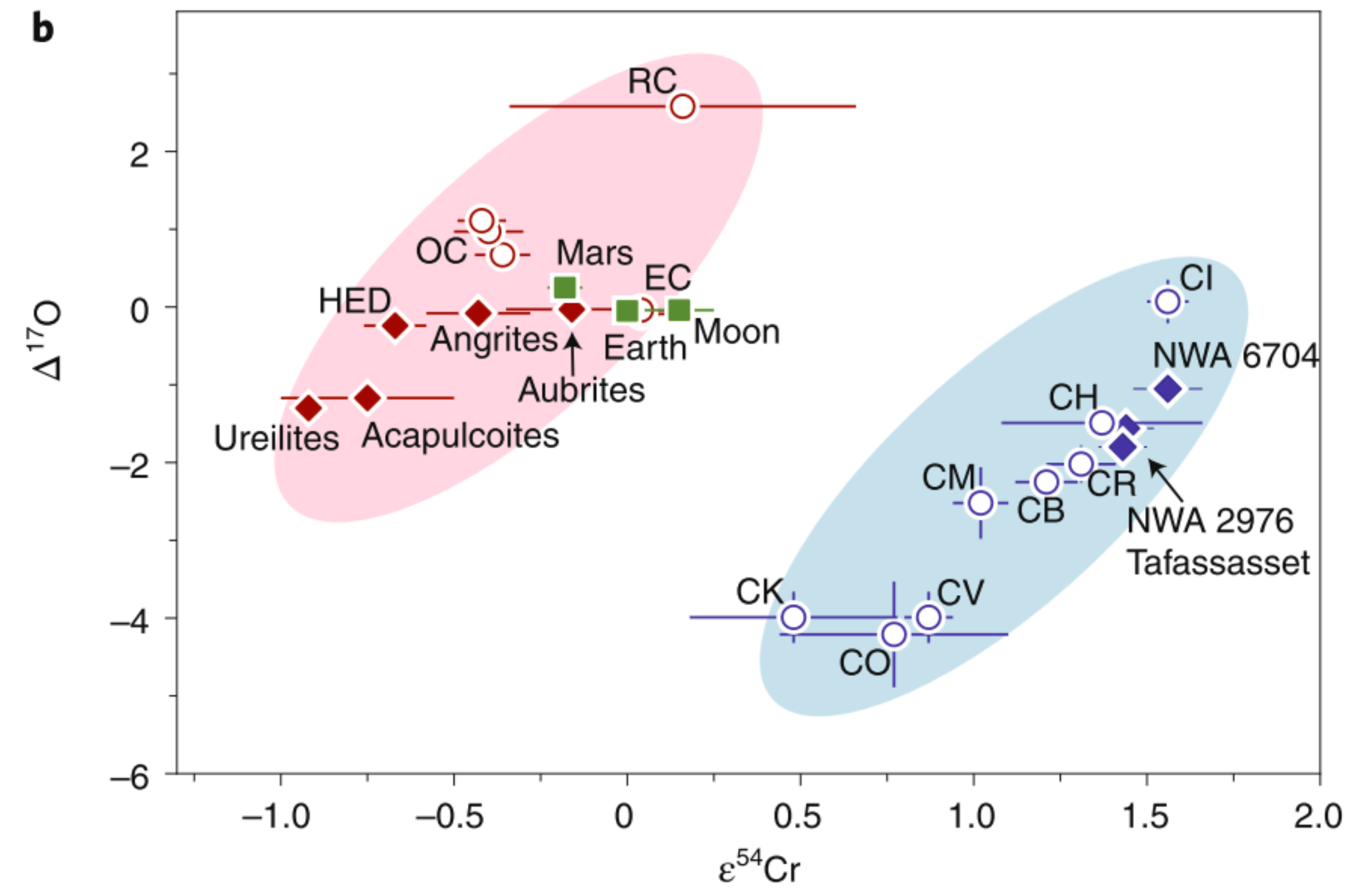
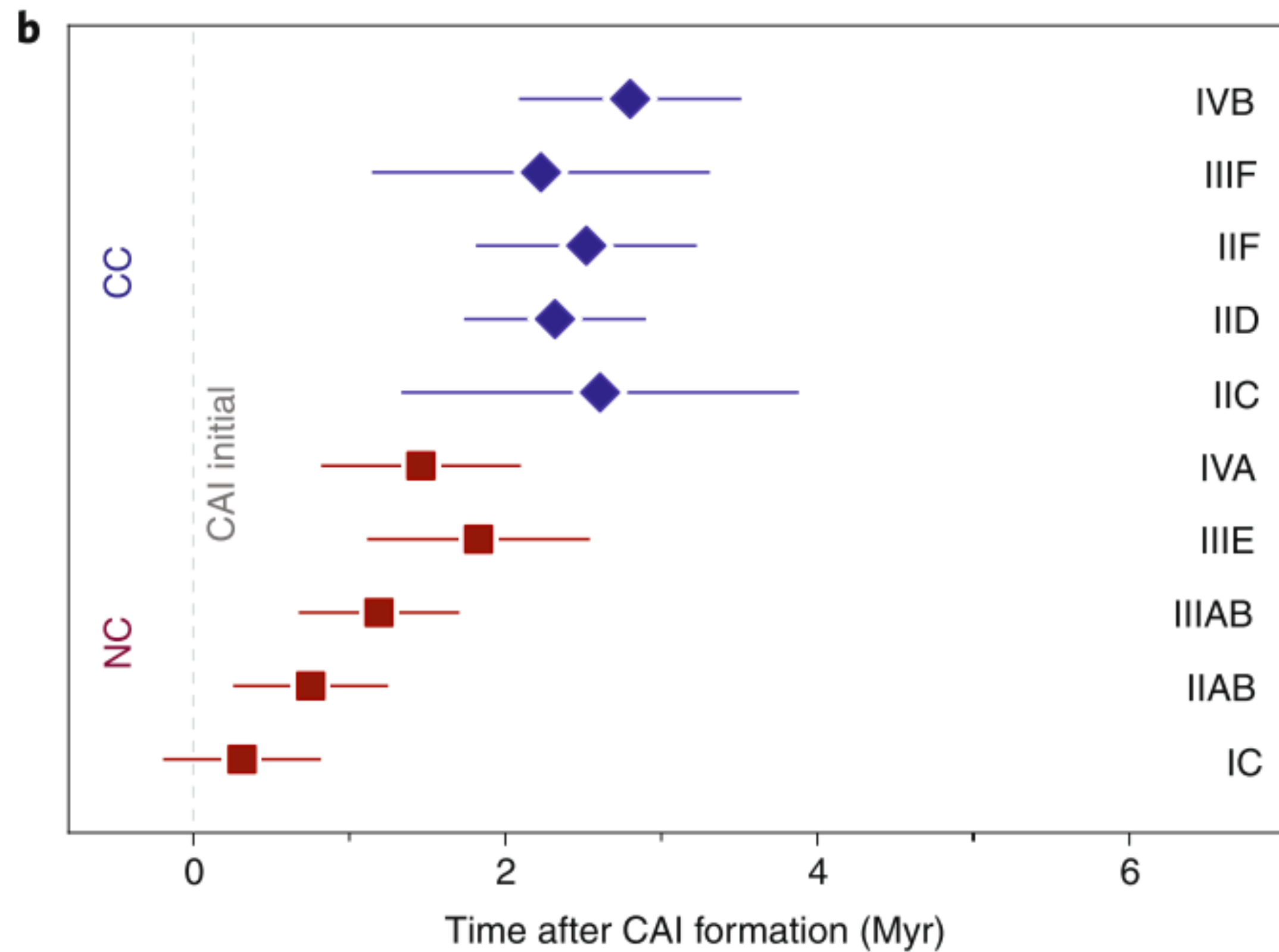
# Asteroid belt substructure



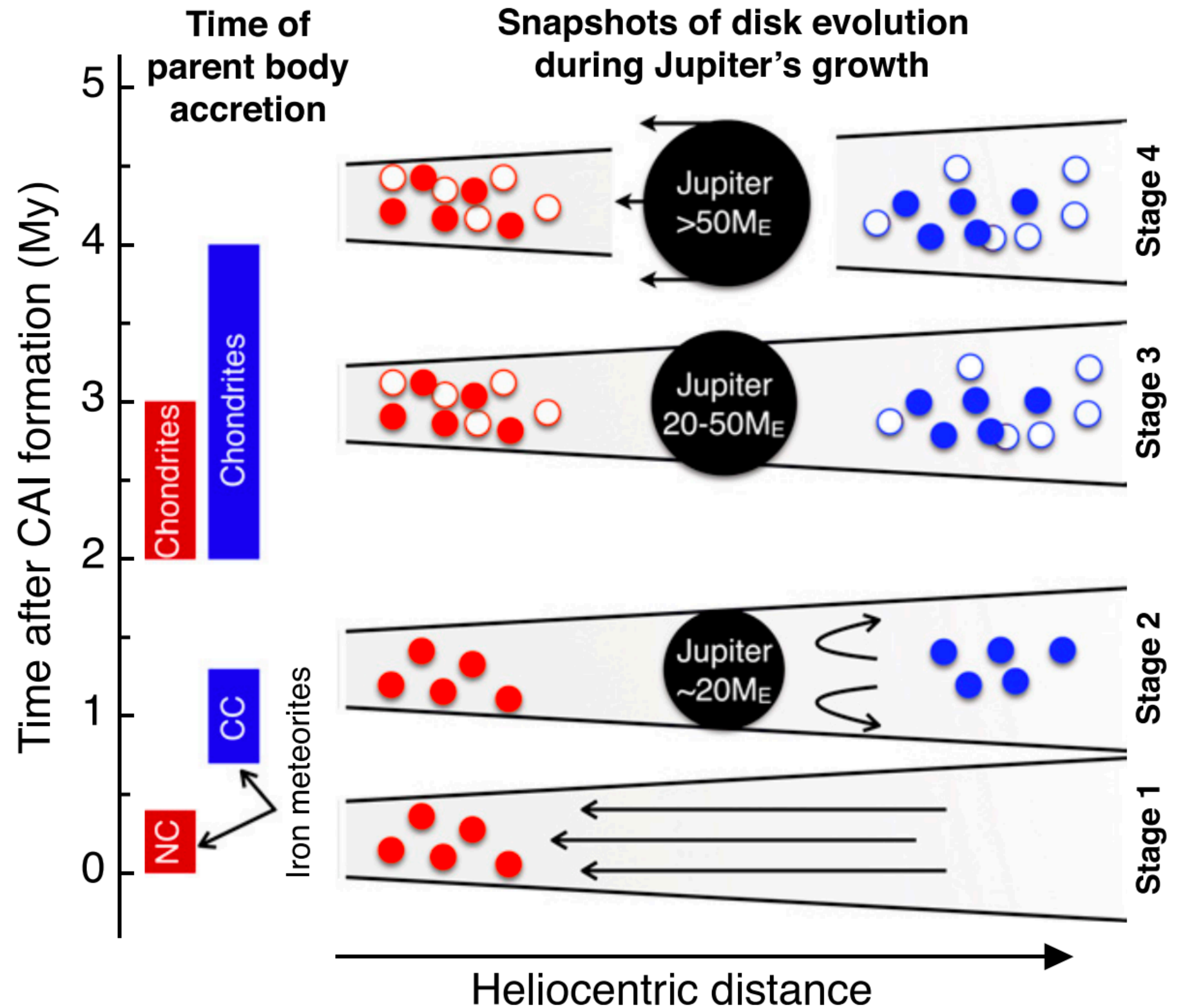
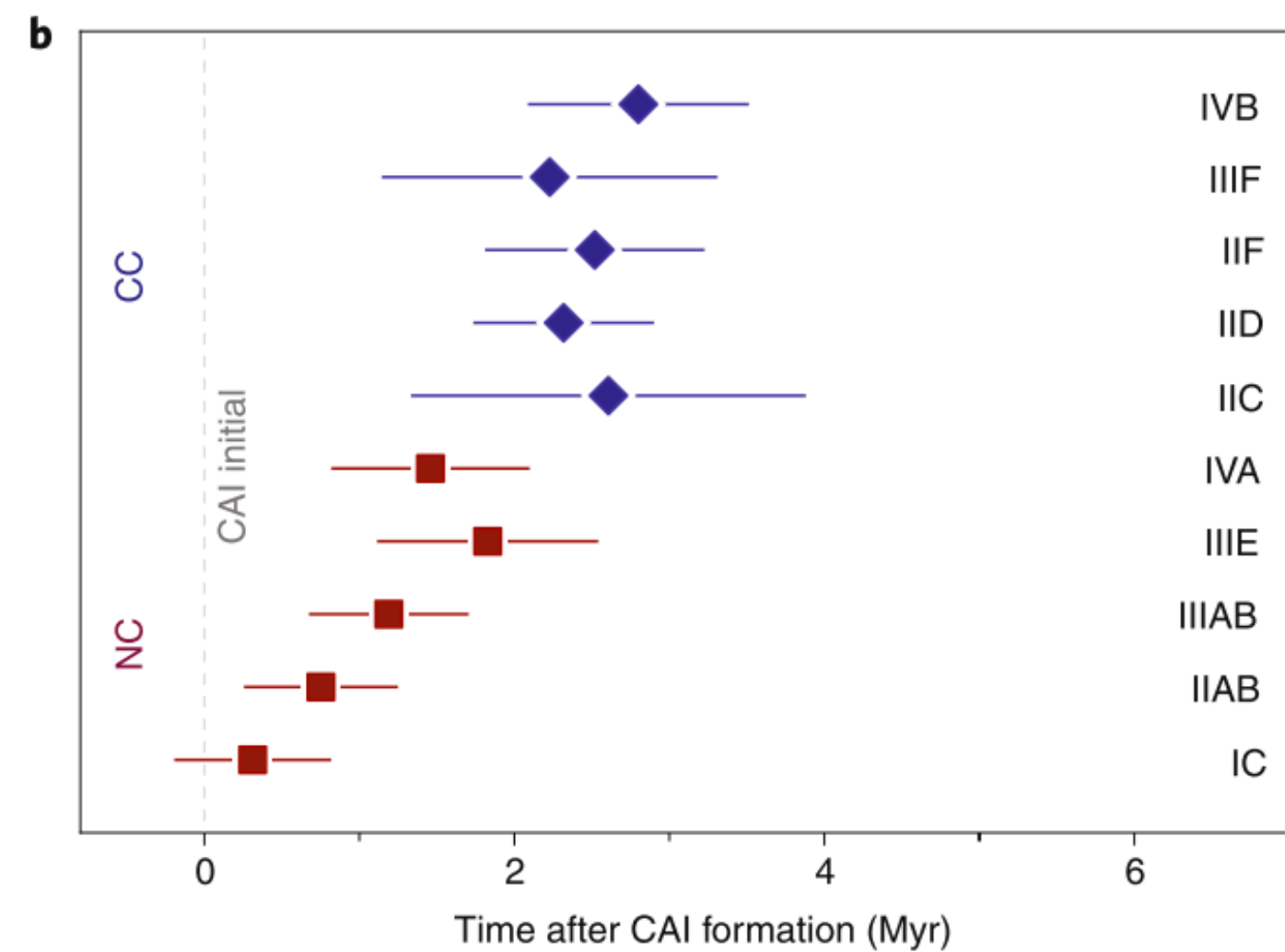
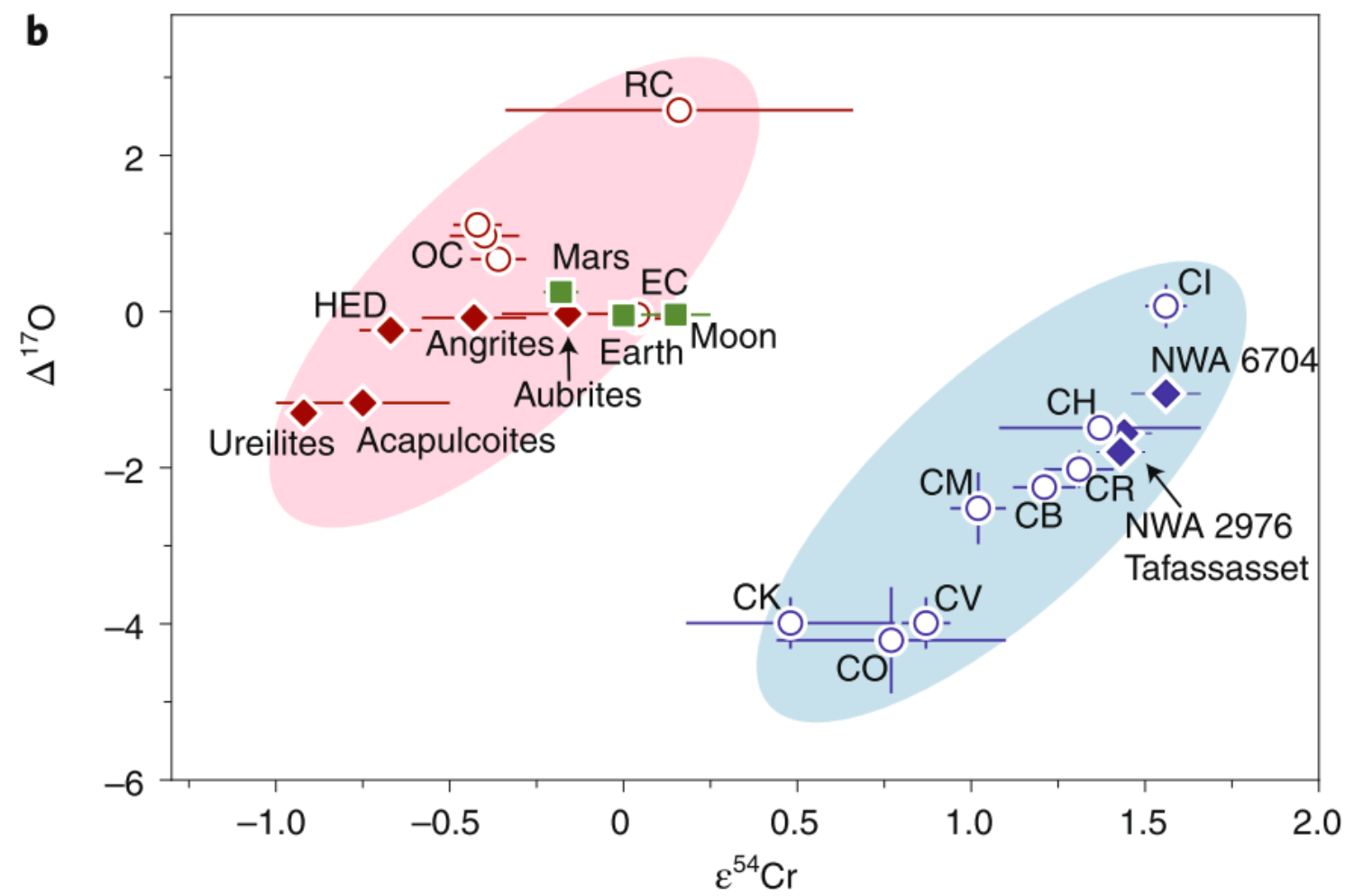
# Dichotomous nucleosynthetic anomalies



# Isotope dichotomy

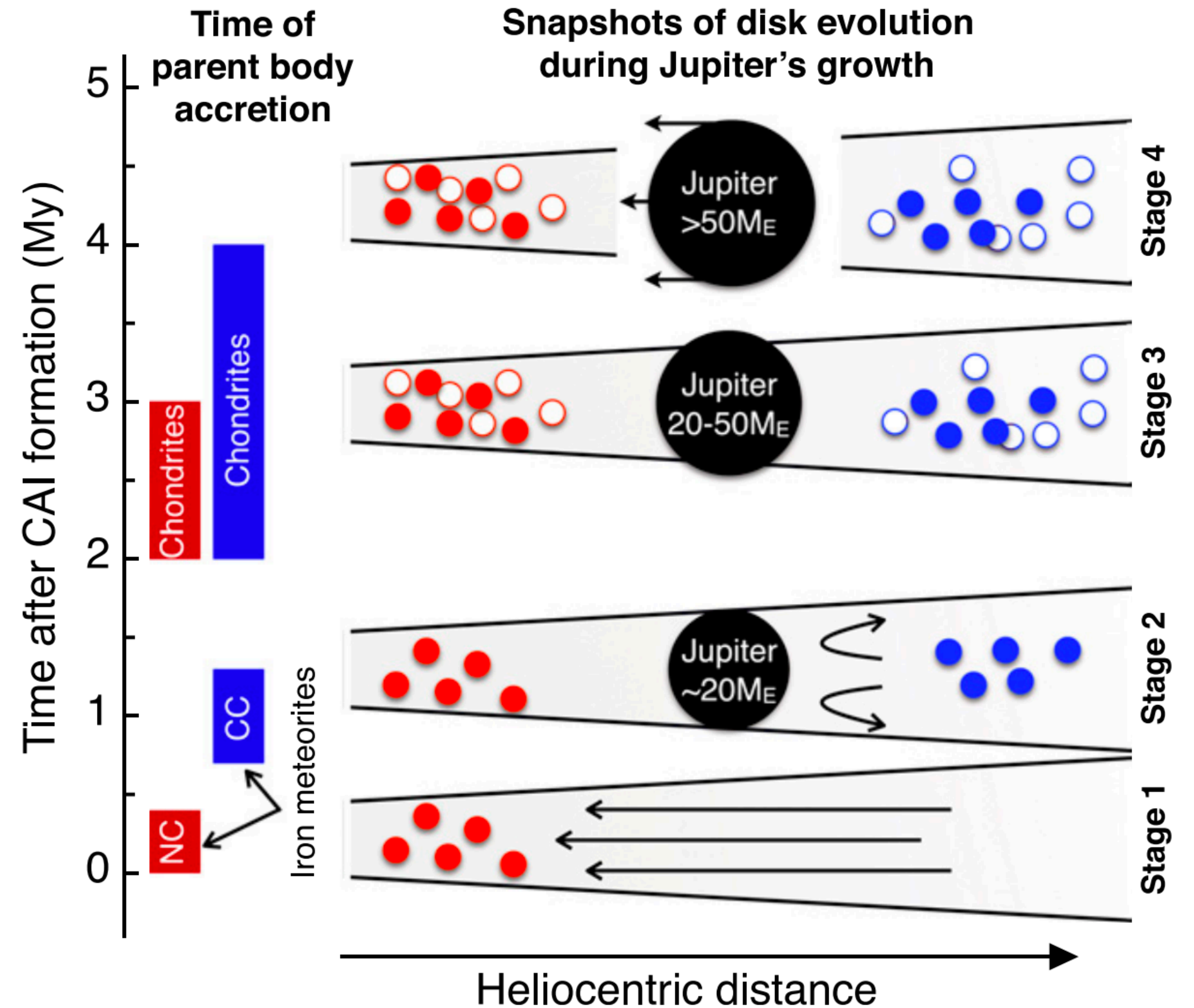
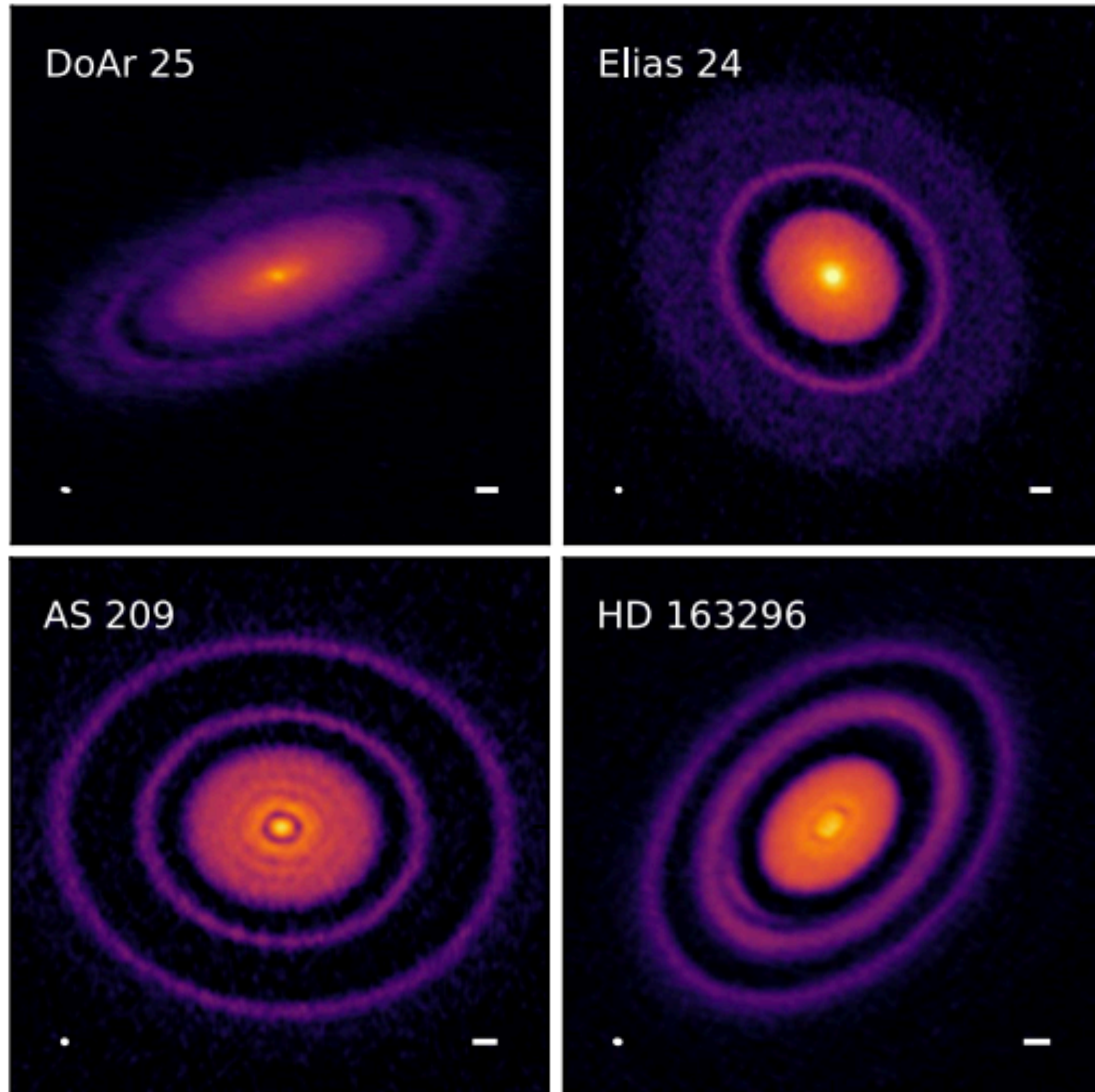


# Spatial & temporal fragmentation

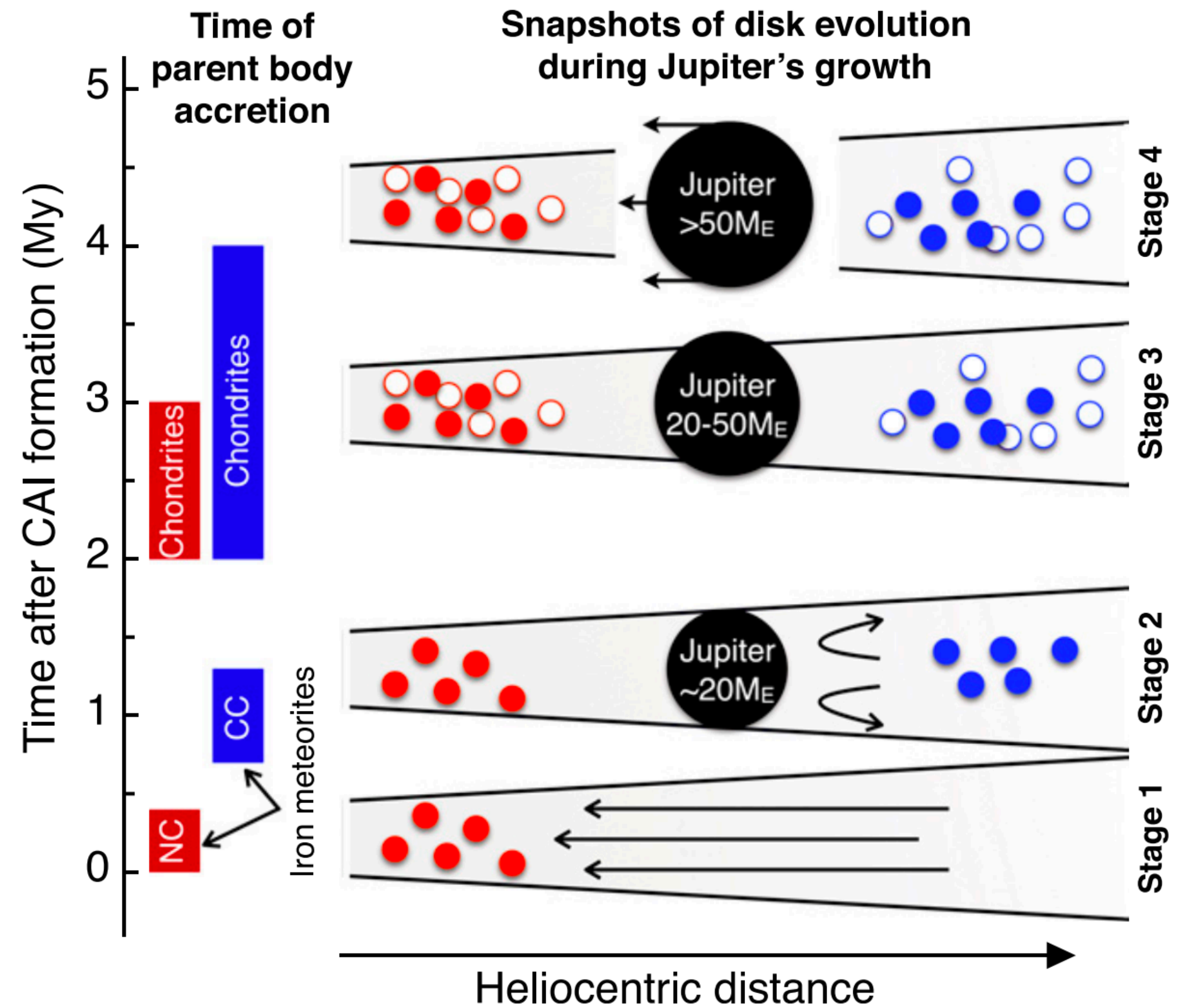
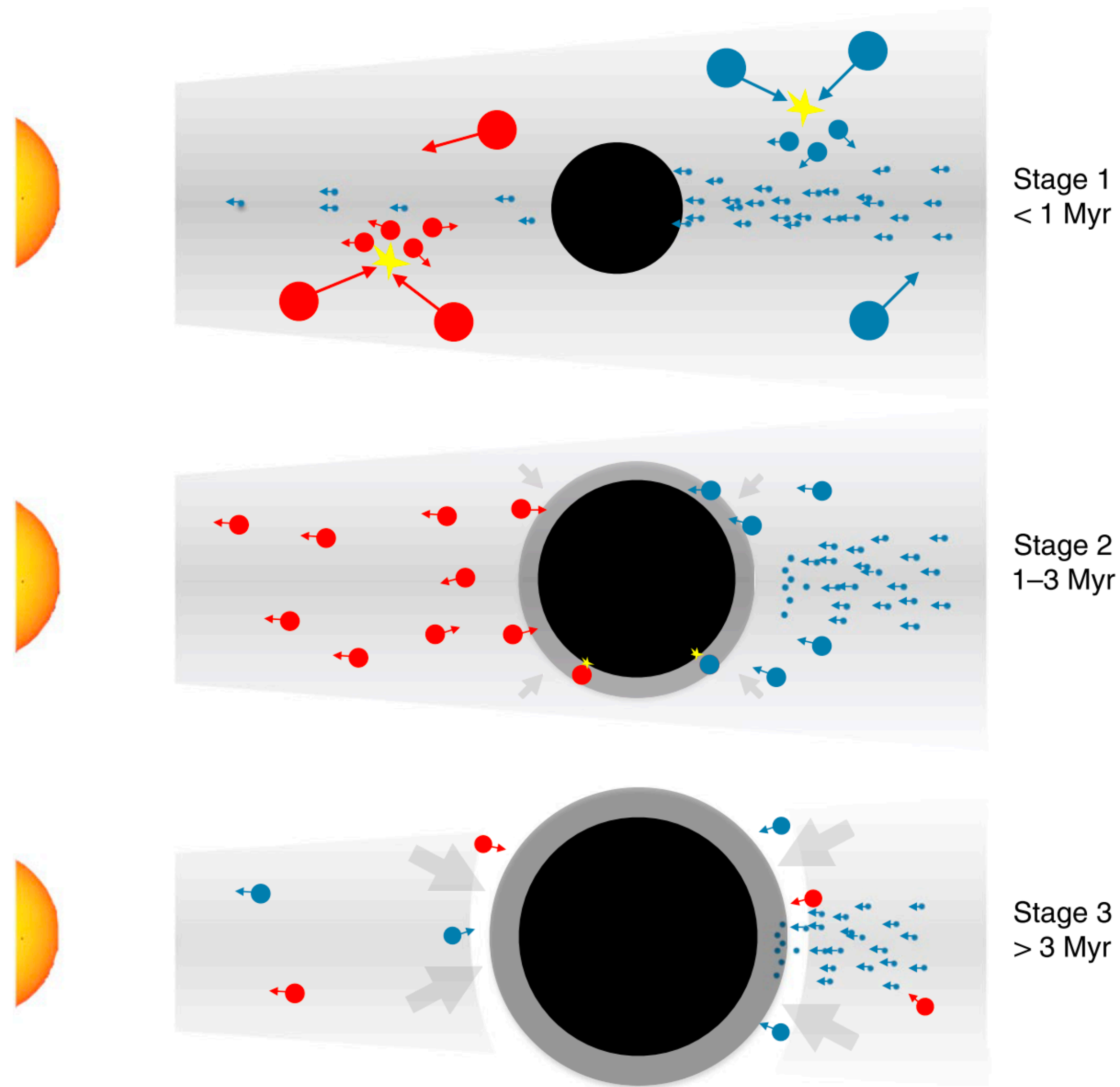




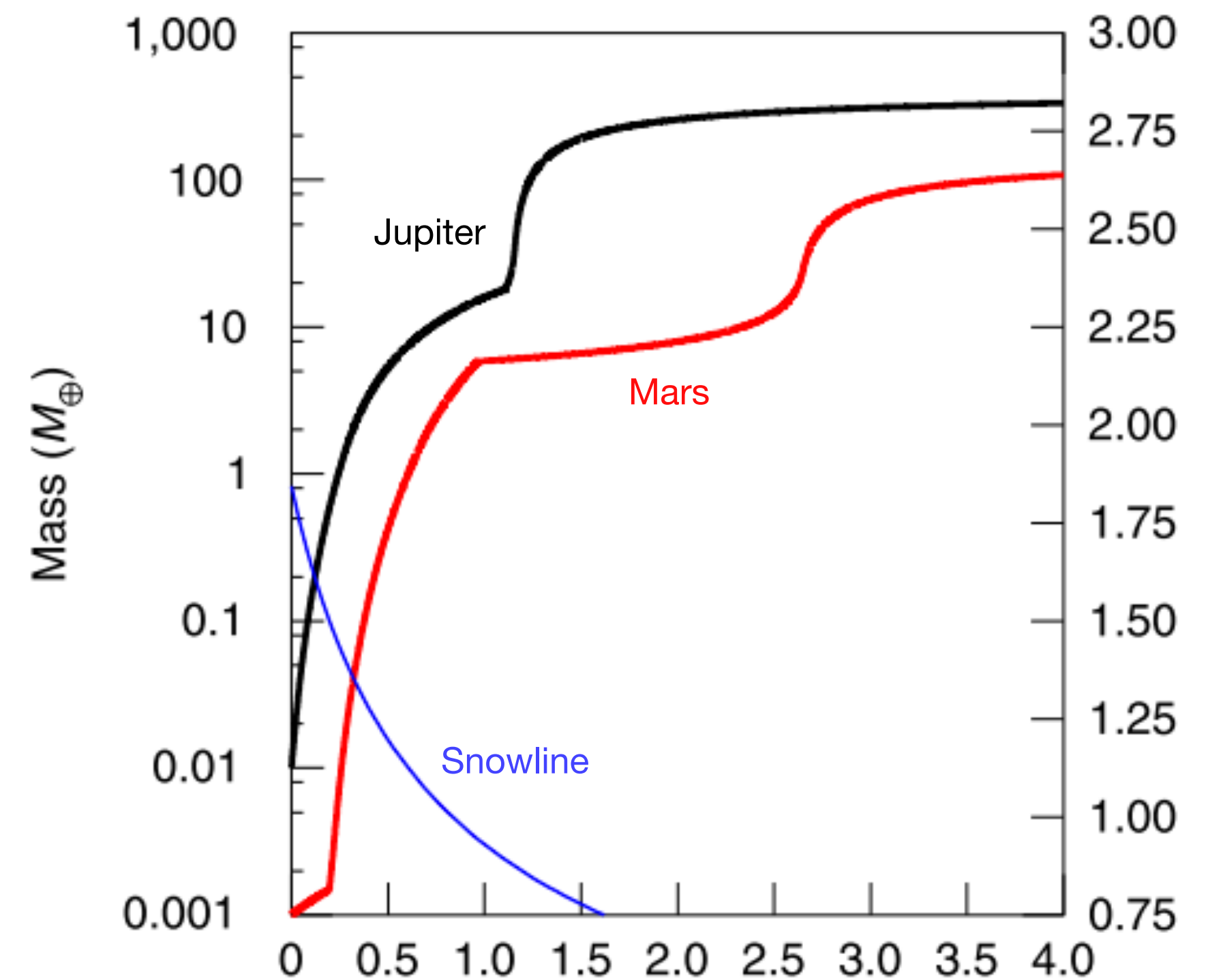
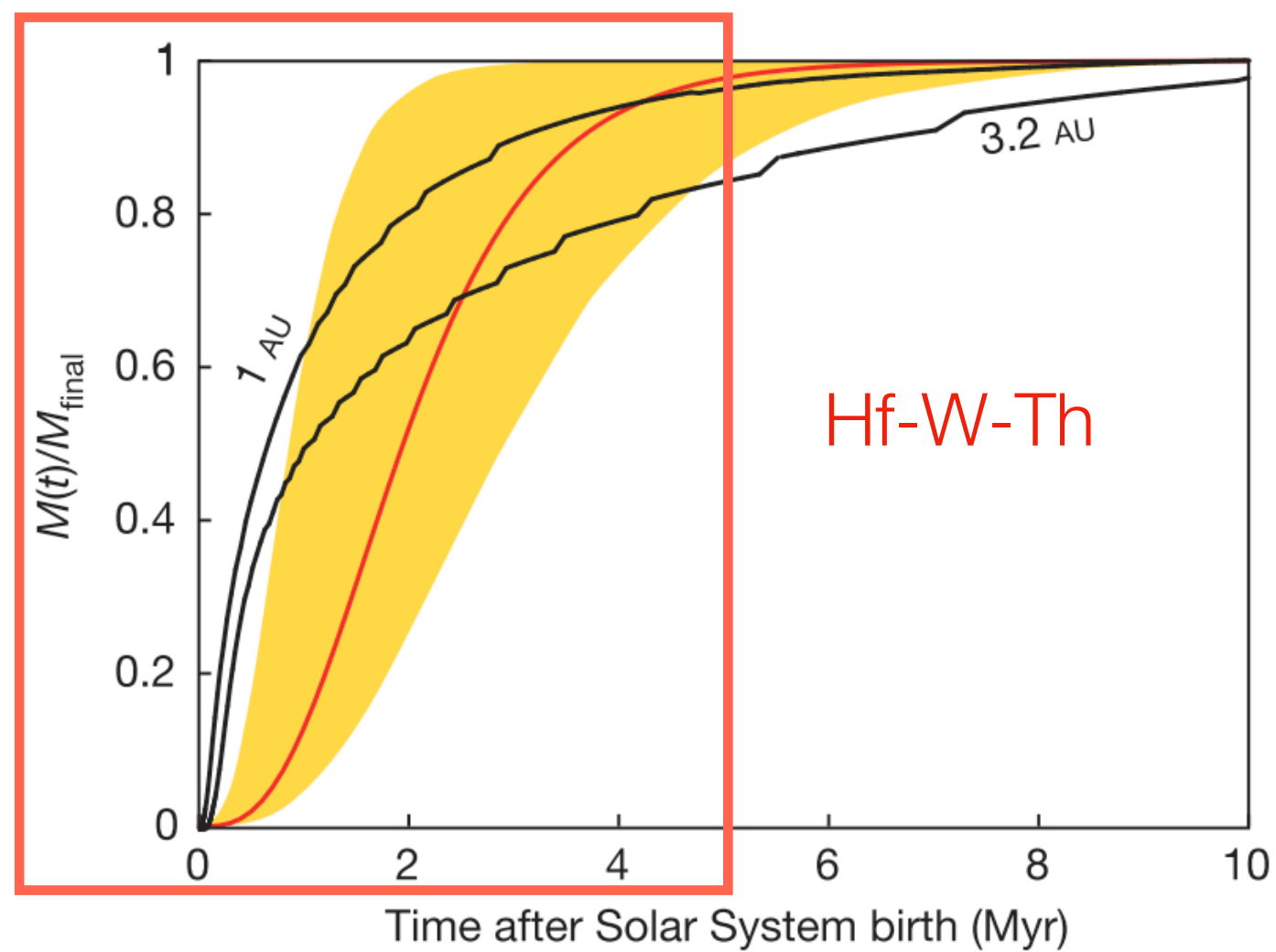
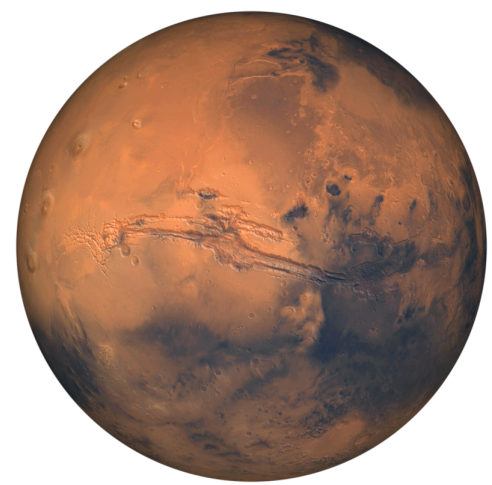
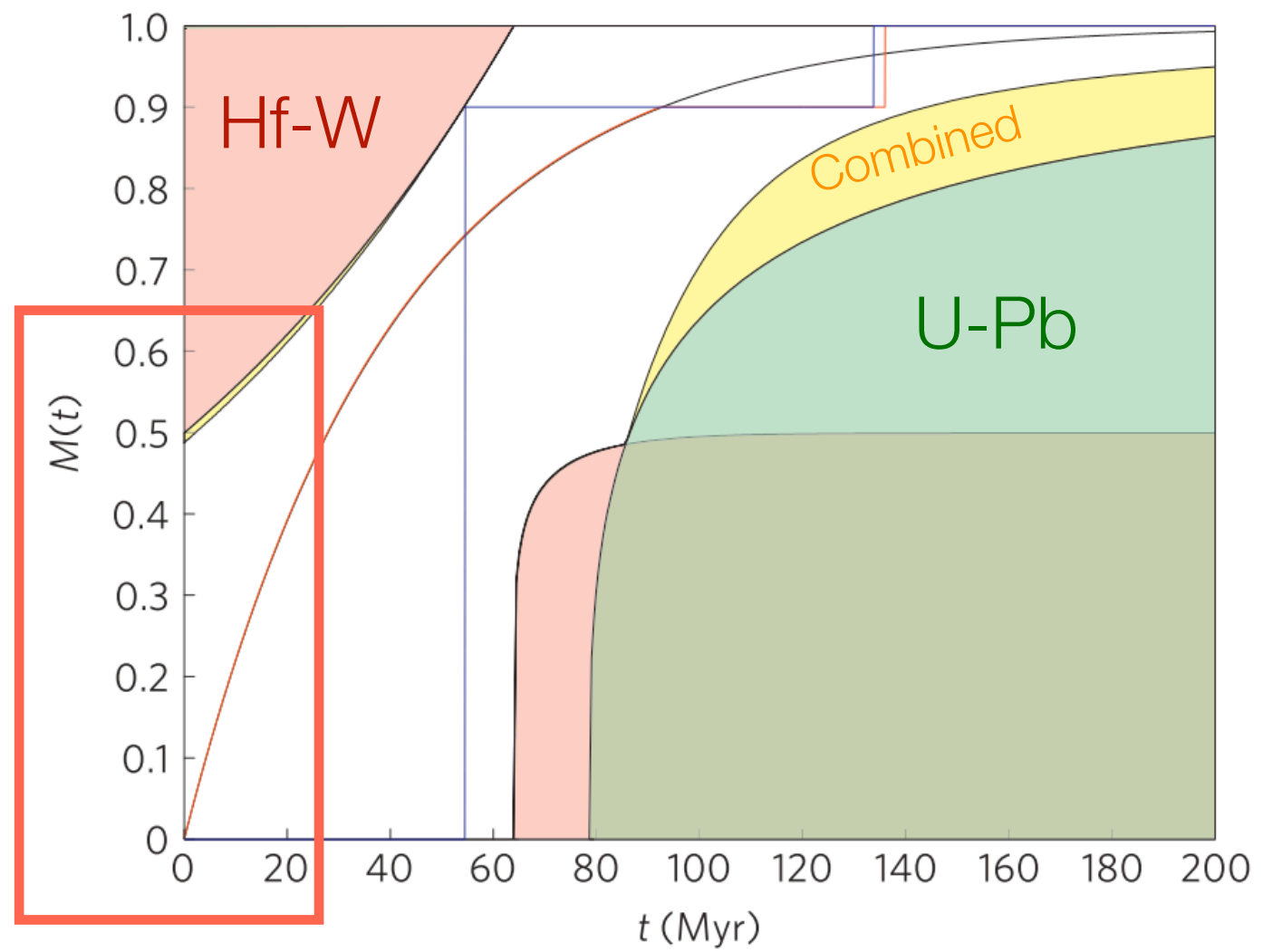
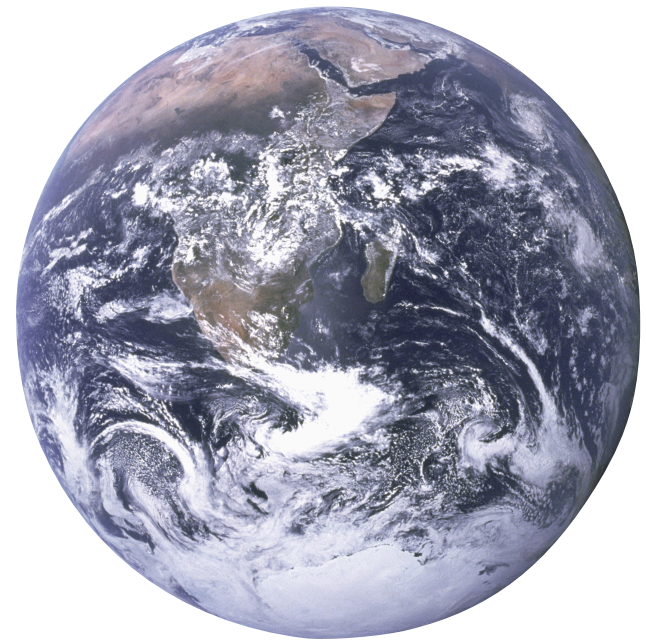
# Spatial & temporal fragmentation



# Rapid growth of Jupiter's core

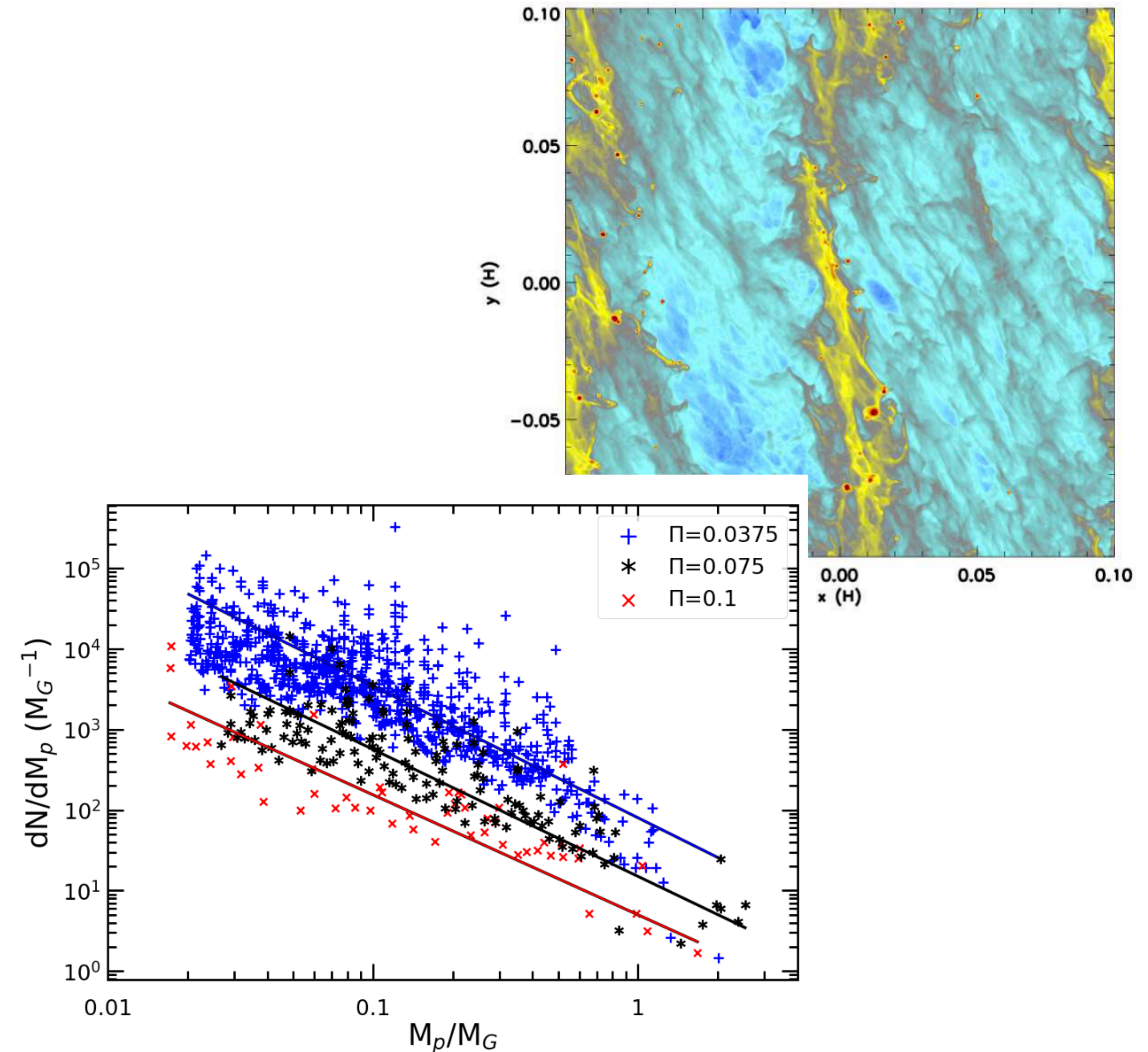


# But protracted growth for the inner planets?



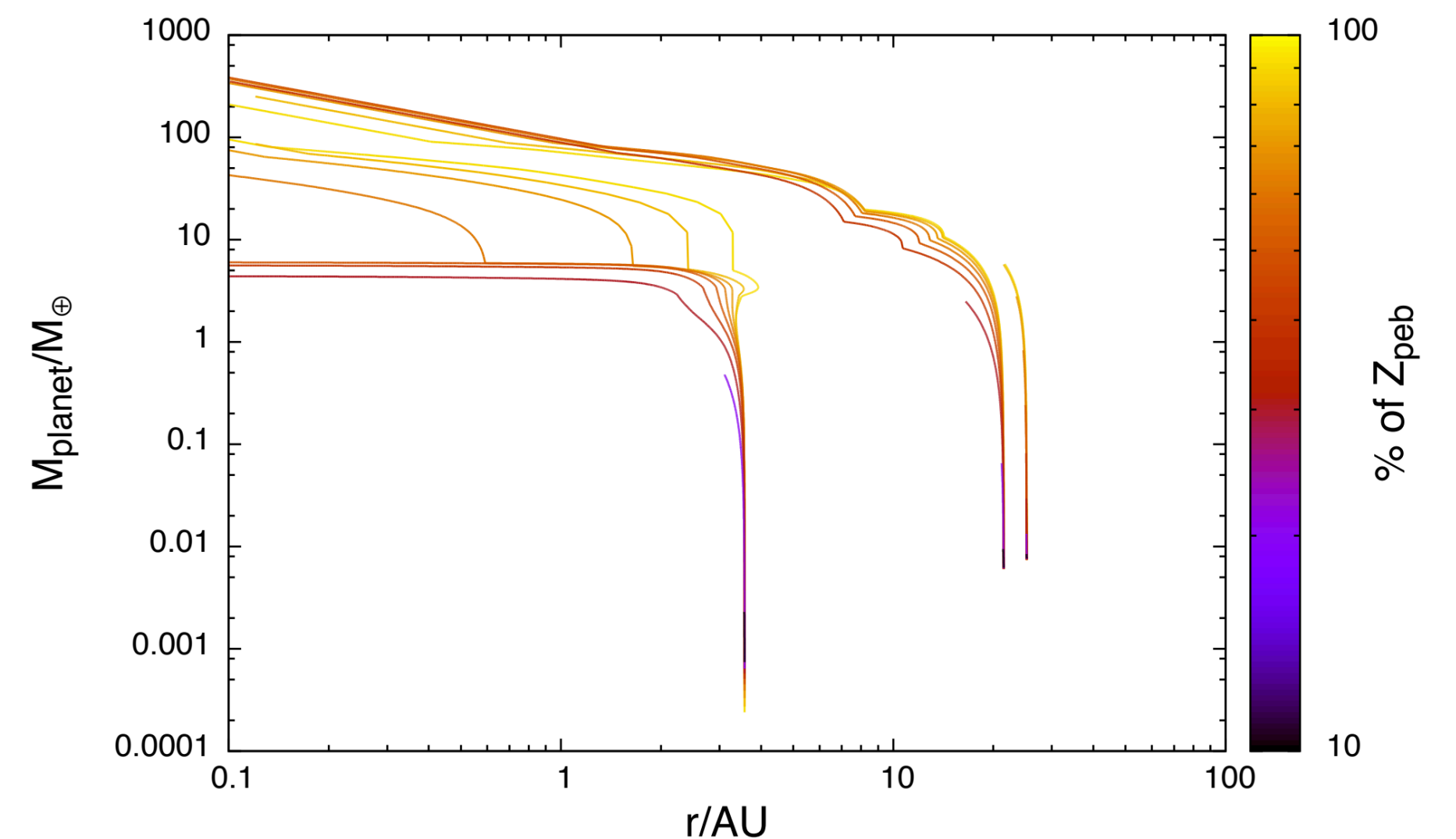
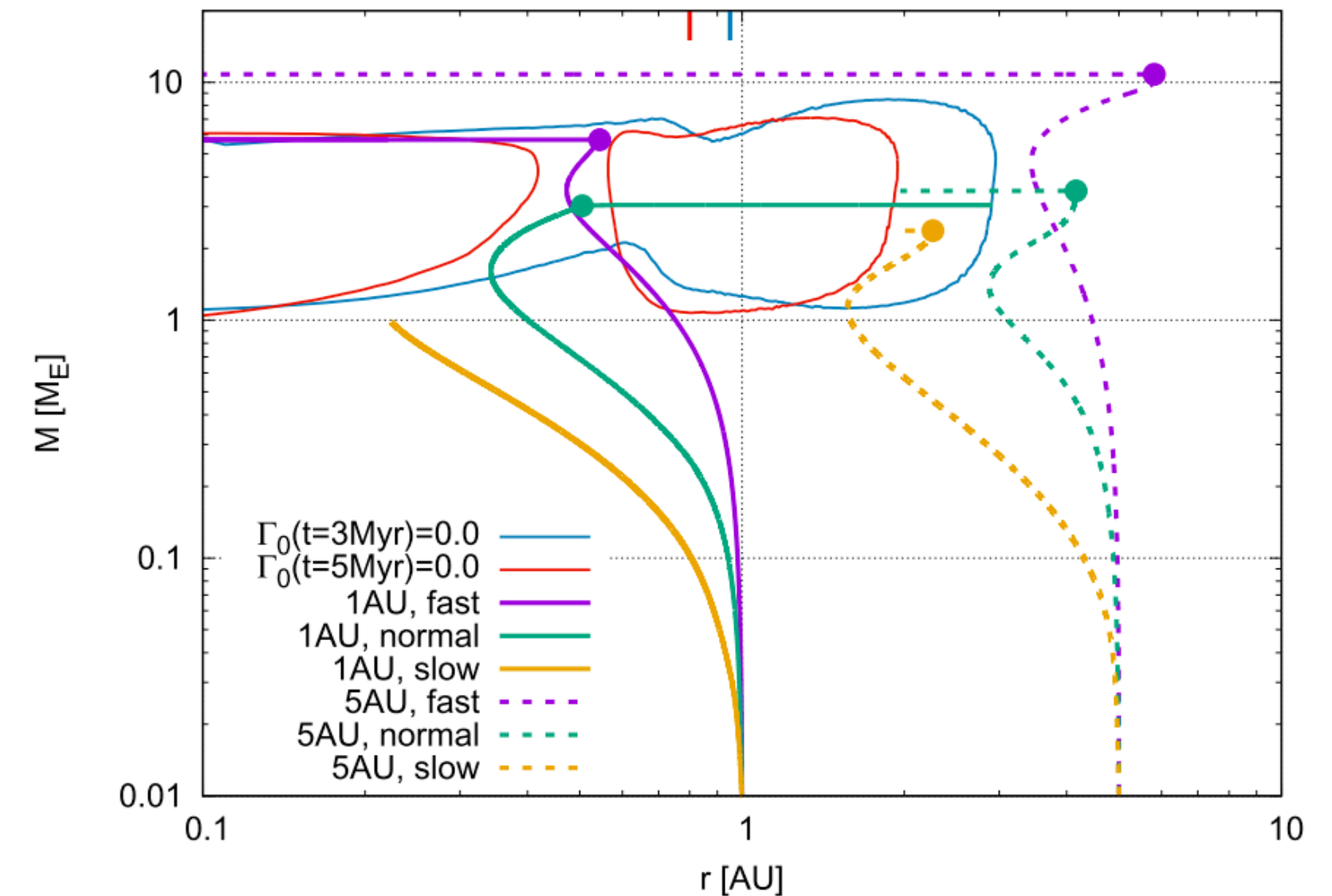
# Further challenges

- Hard to form a  $20 M_{\text{Earth}}$  planet in  $\approx 1$  Myr
  - ▶ Streaming instability (SI)  $\approx 10^5$ - $10^6$  yrs
  - ▶ SI-SFD tapered  $R_{\text{max}} \approx 300$  km
- Optimistic models of pebble accretion rapid ( $\approx 10^4$  yr): migration-constrained
- Jupiter is a porous ‘filter’
- Early-formed Jupiter scatters  $\gg M_{\text{ast.-belt}}$  into inner Solar System
  - ▶ Need Grand Tack; secondary dynamics
- Jupiter’s atmospheric composition
- Trojan swarm asymmetry



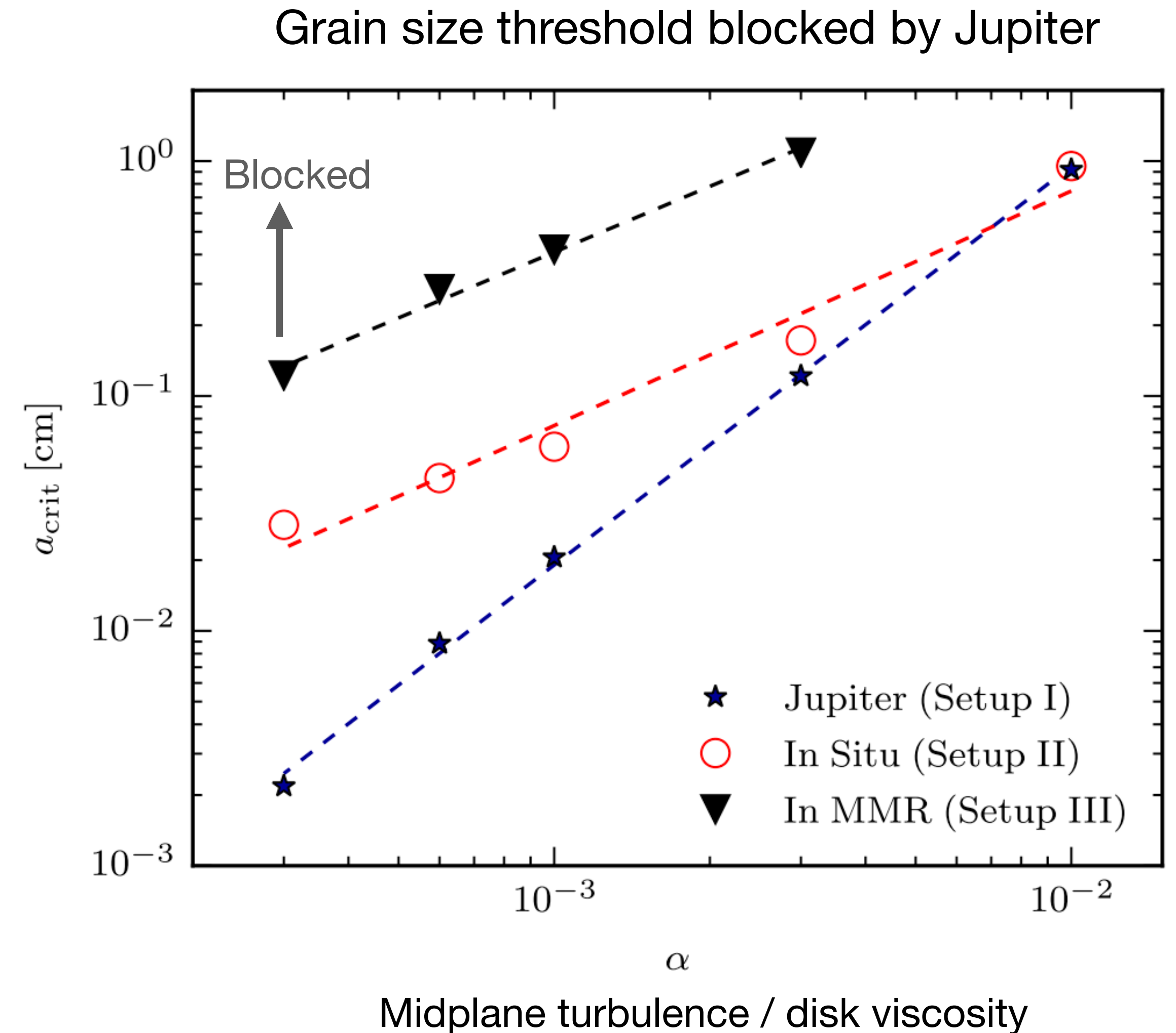
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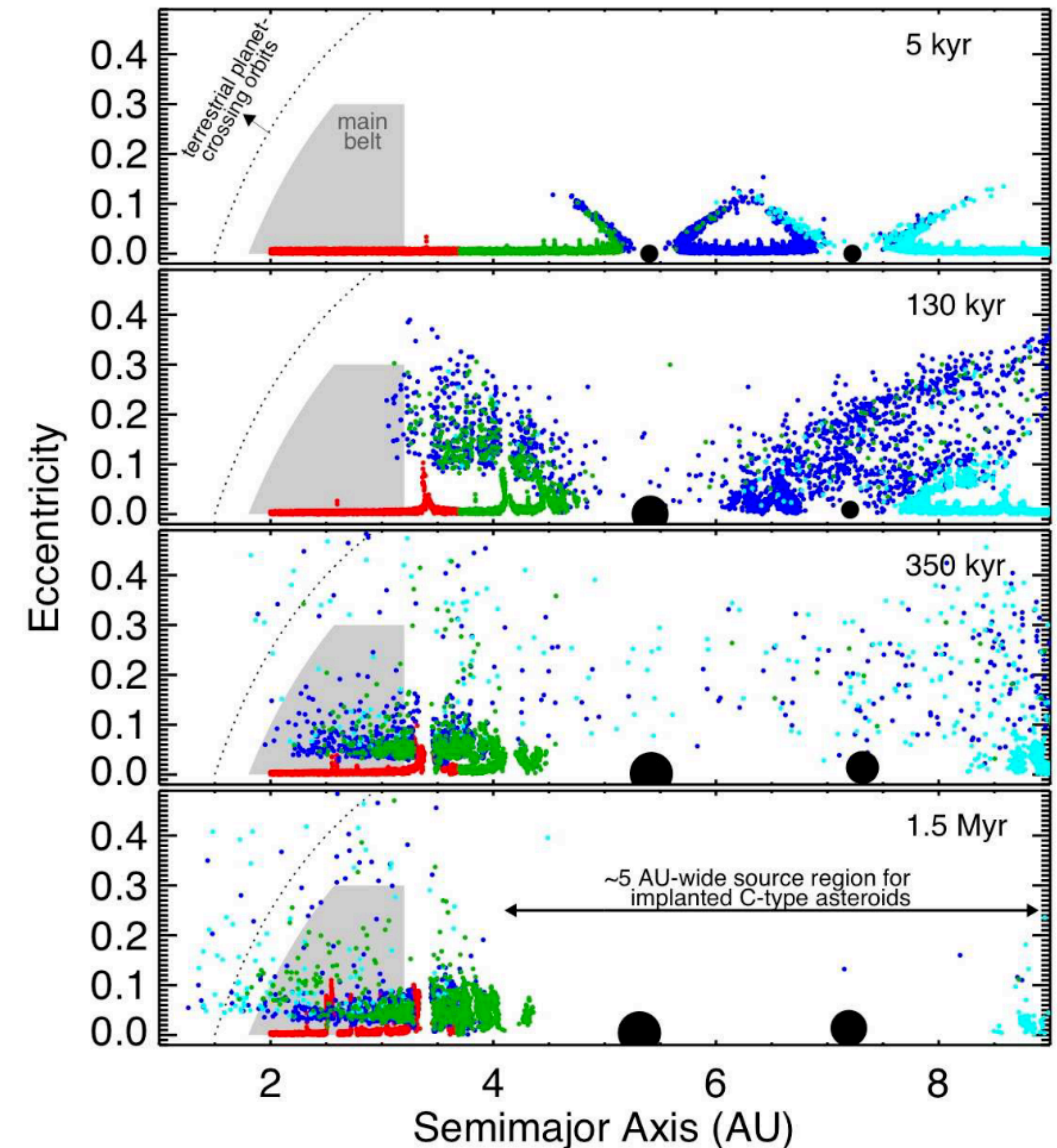
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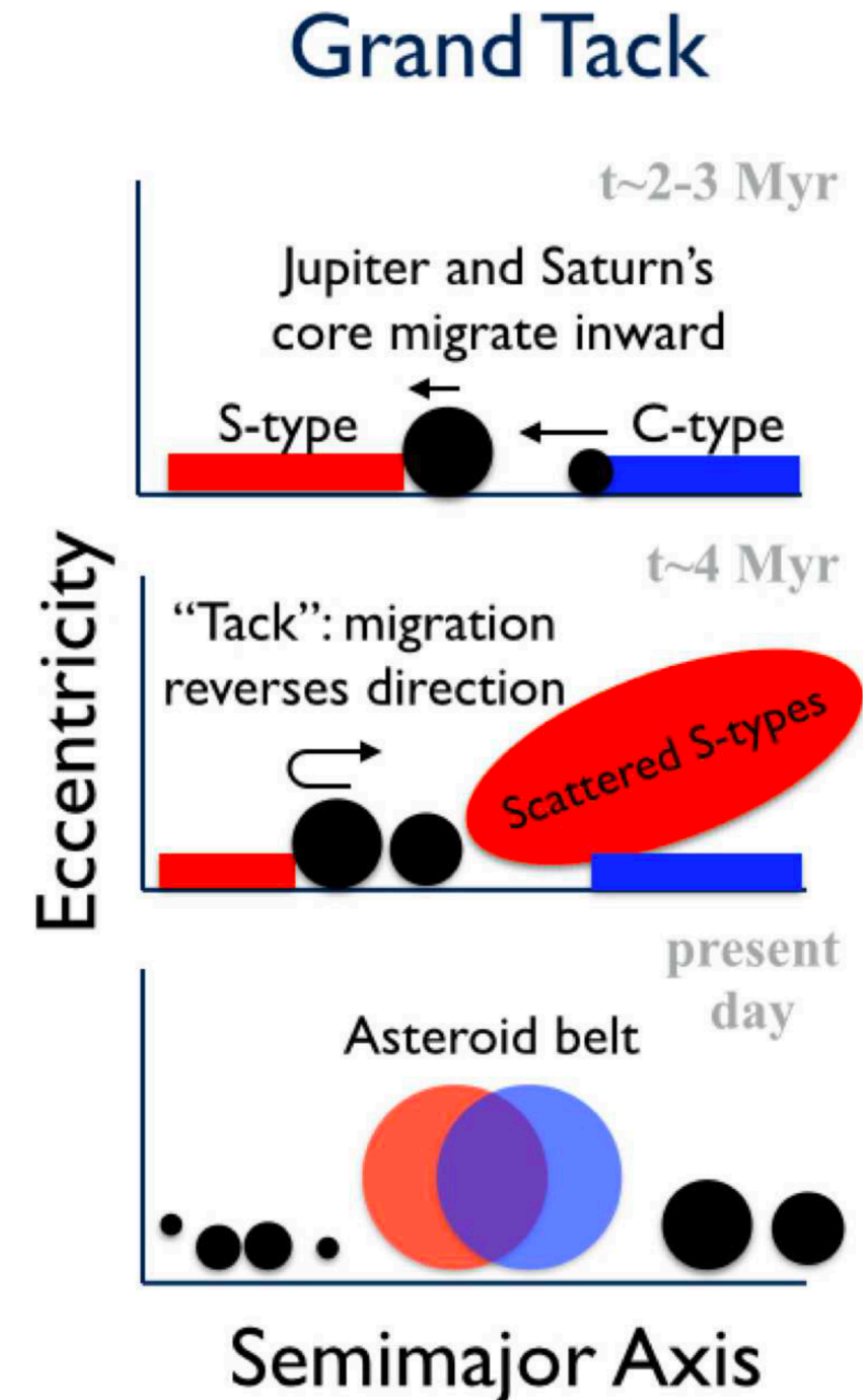
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# Further challenges

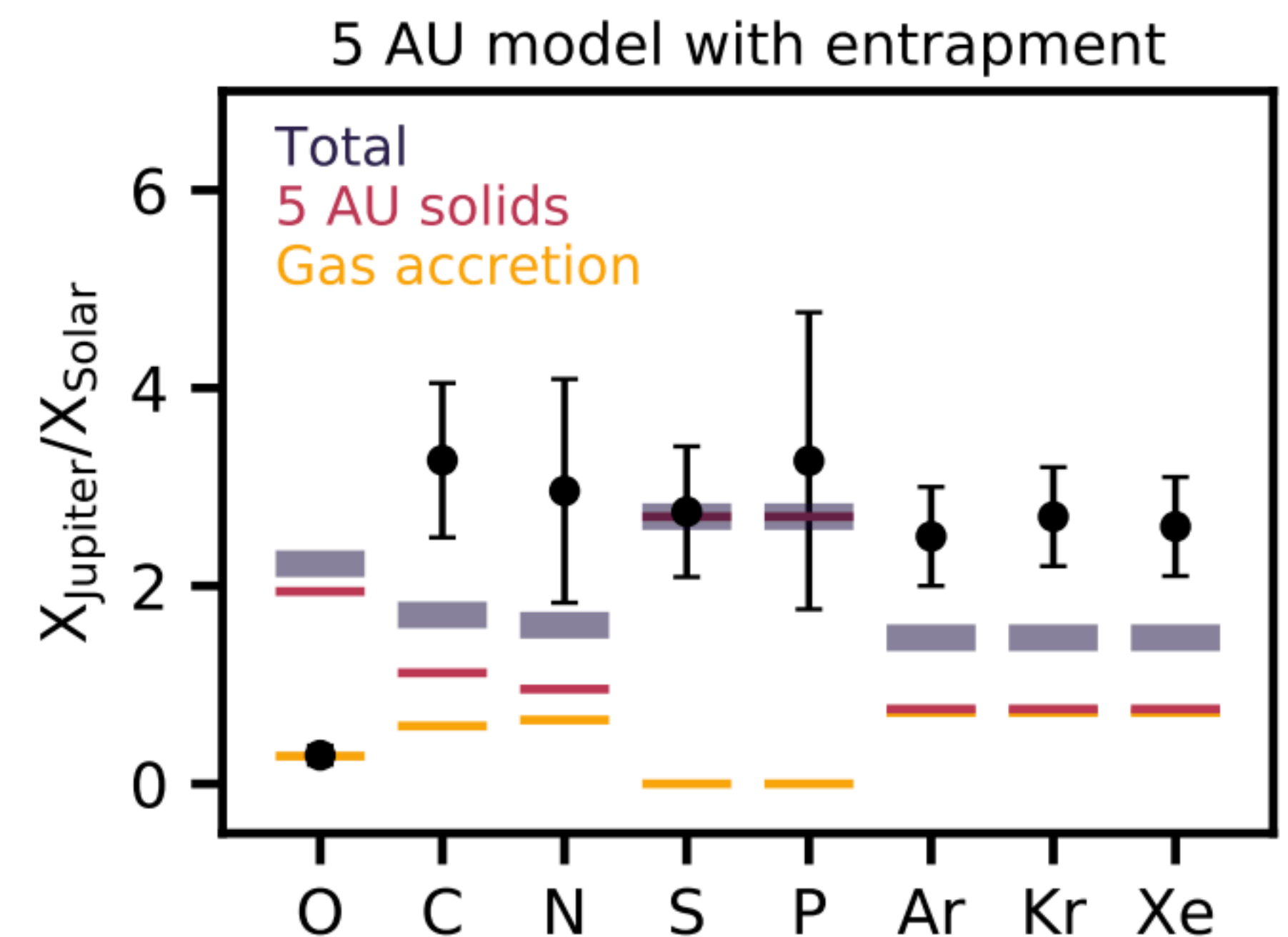
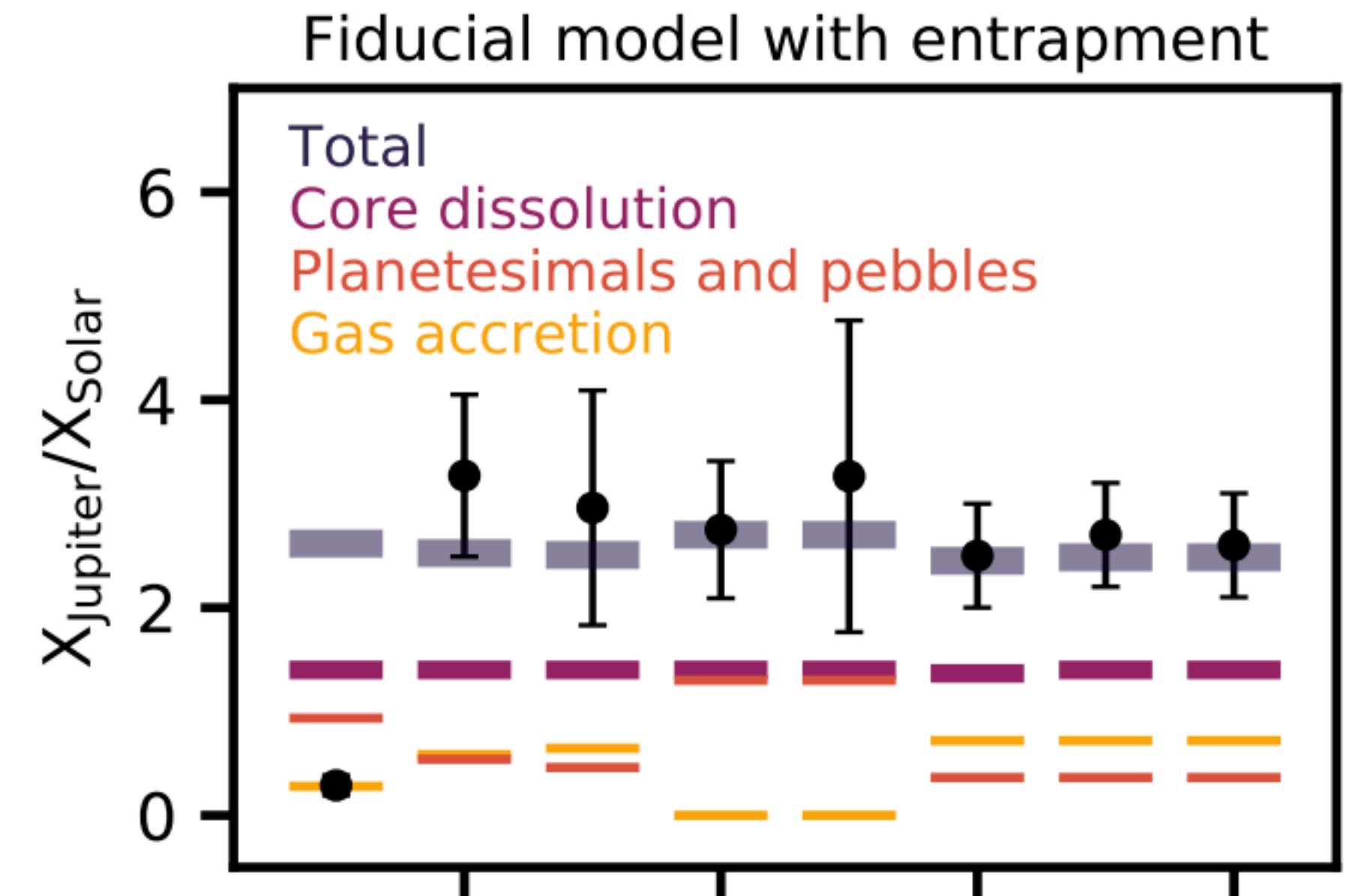
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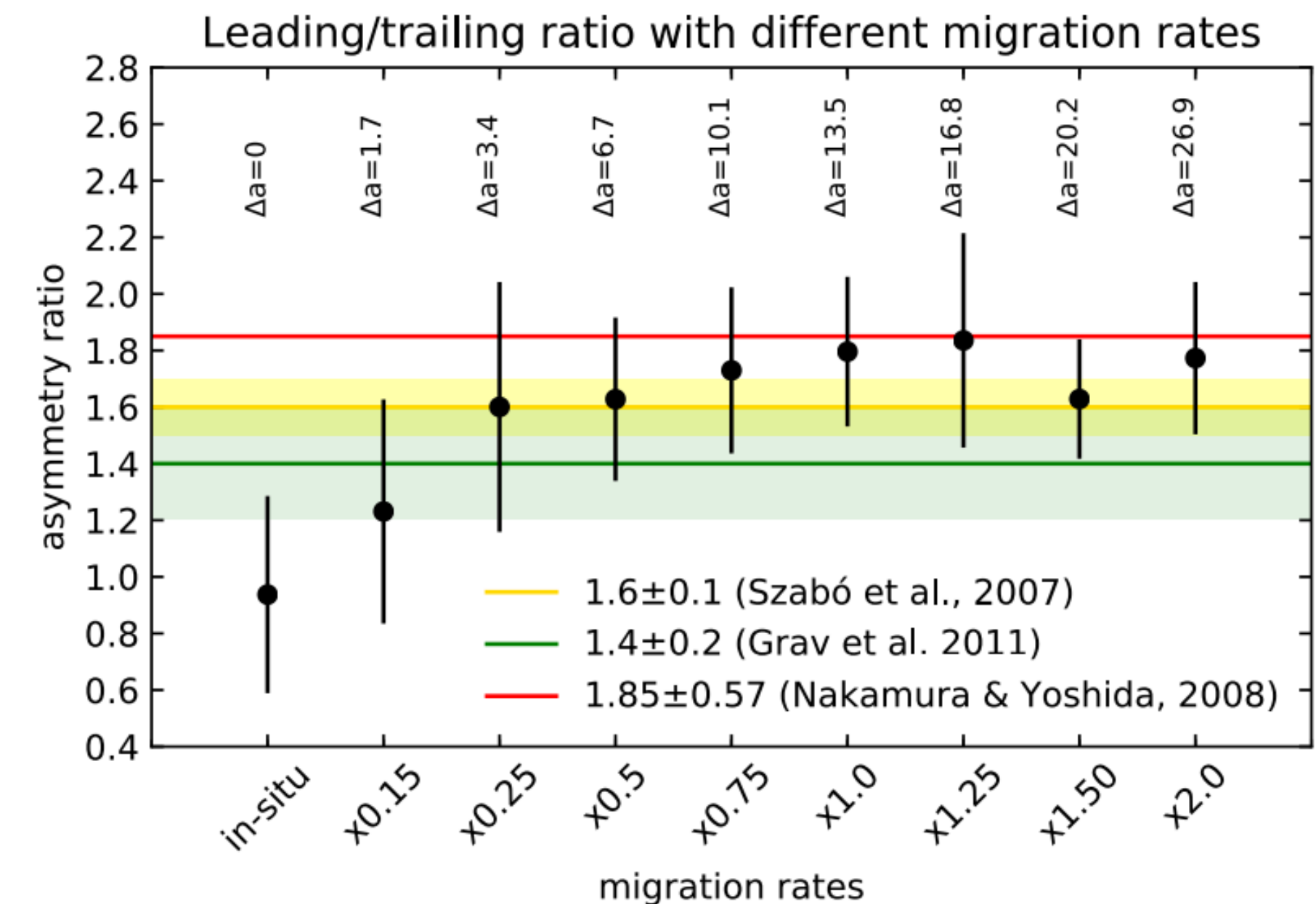
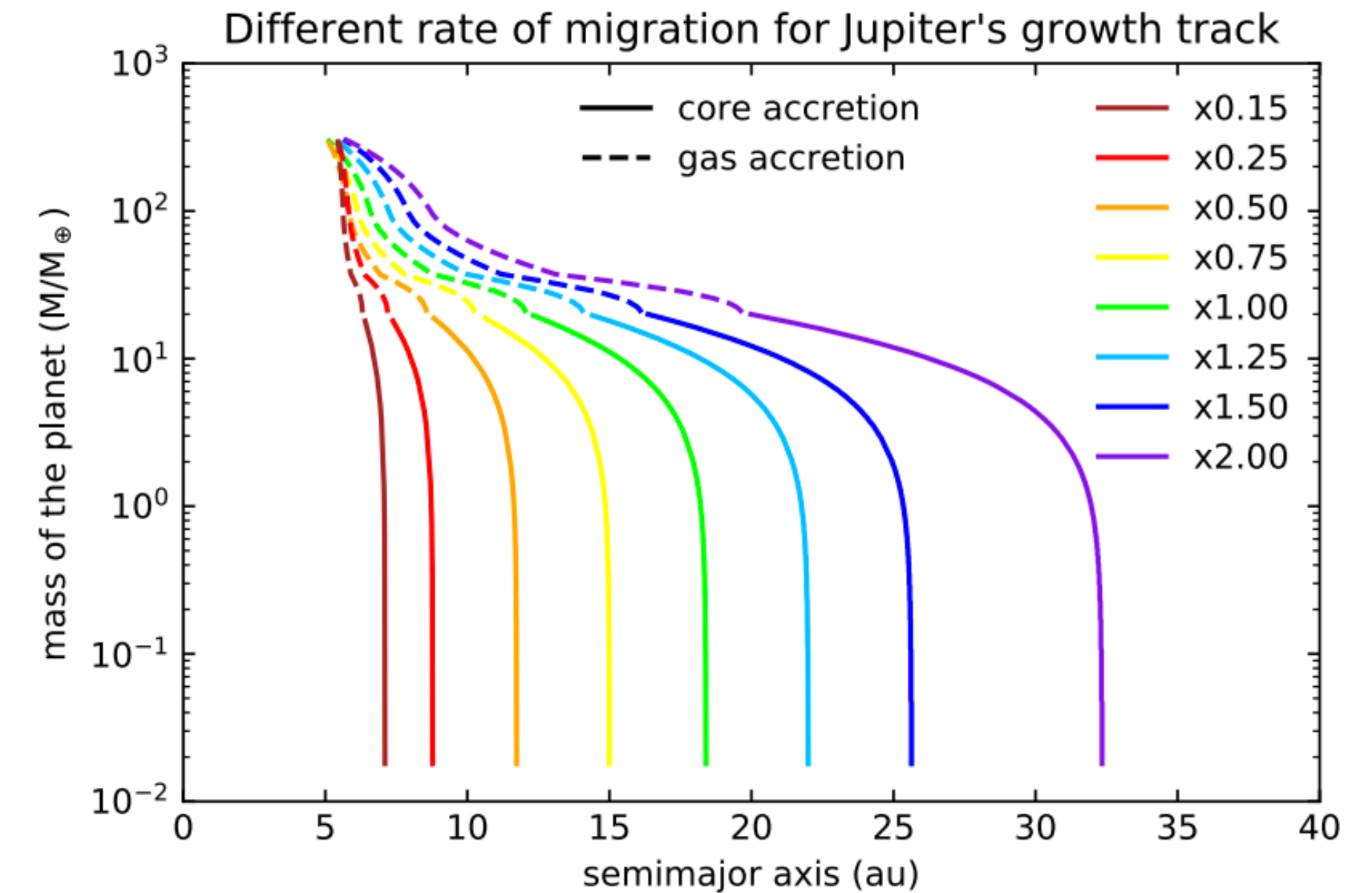
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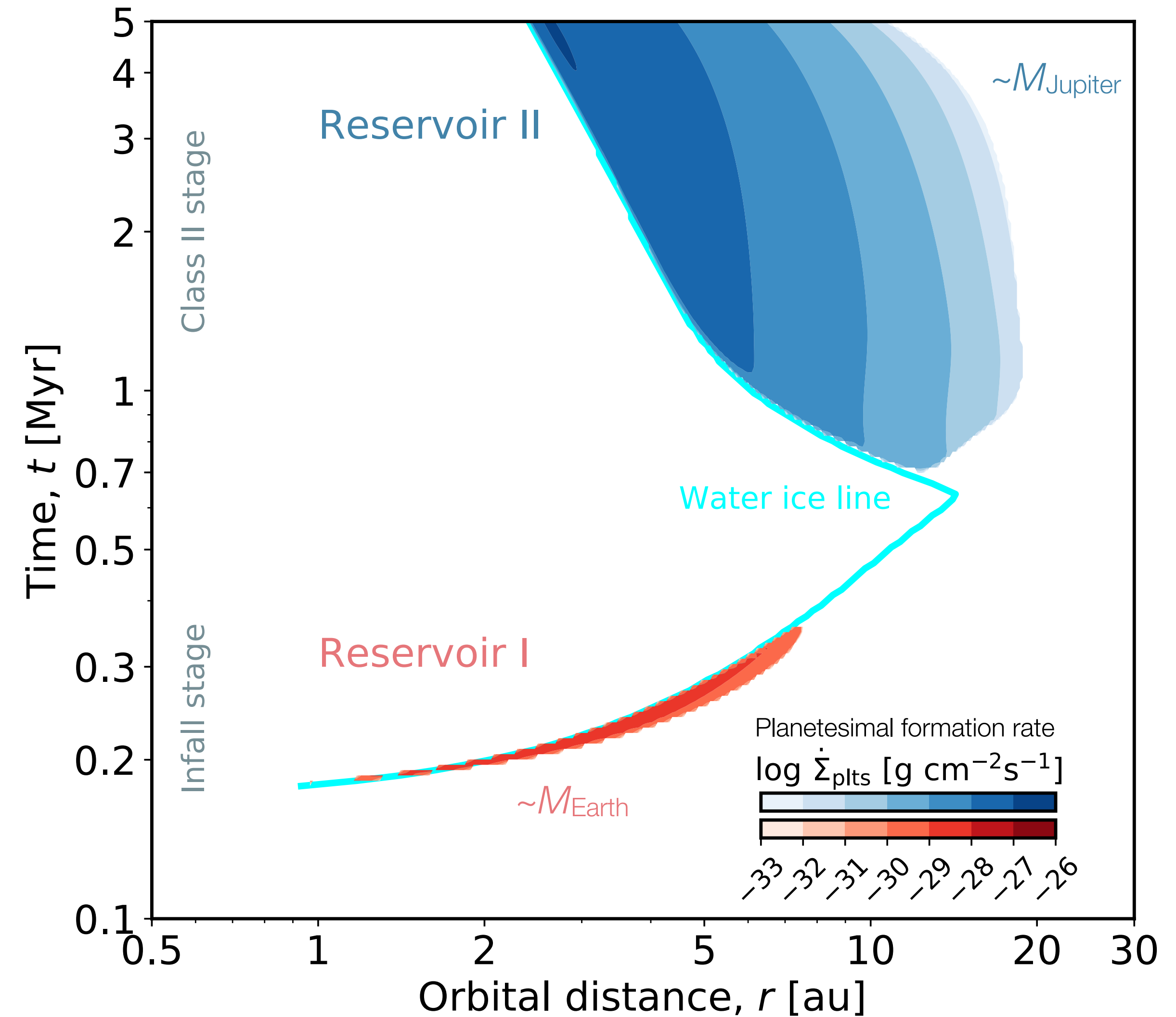
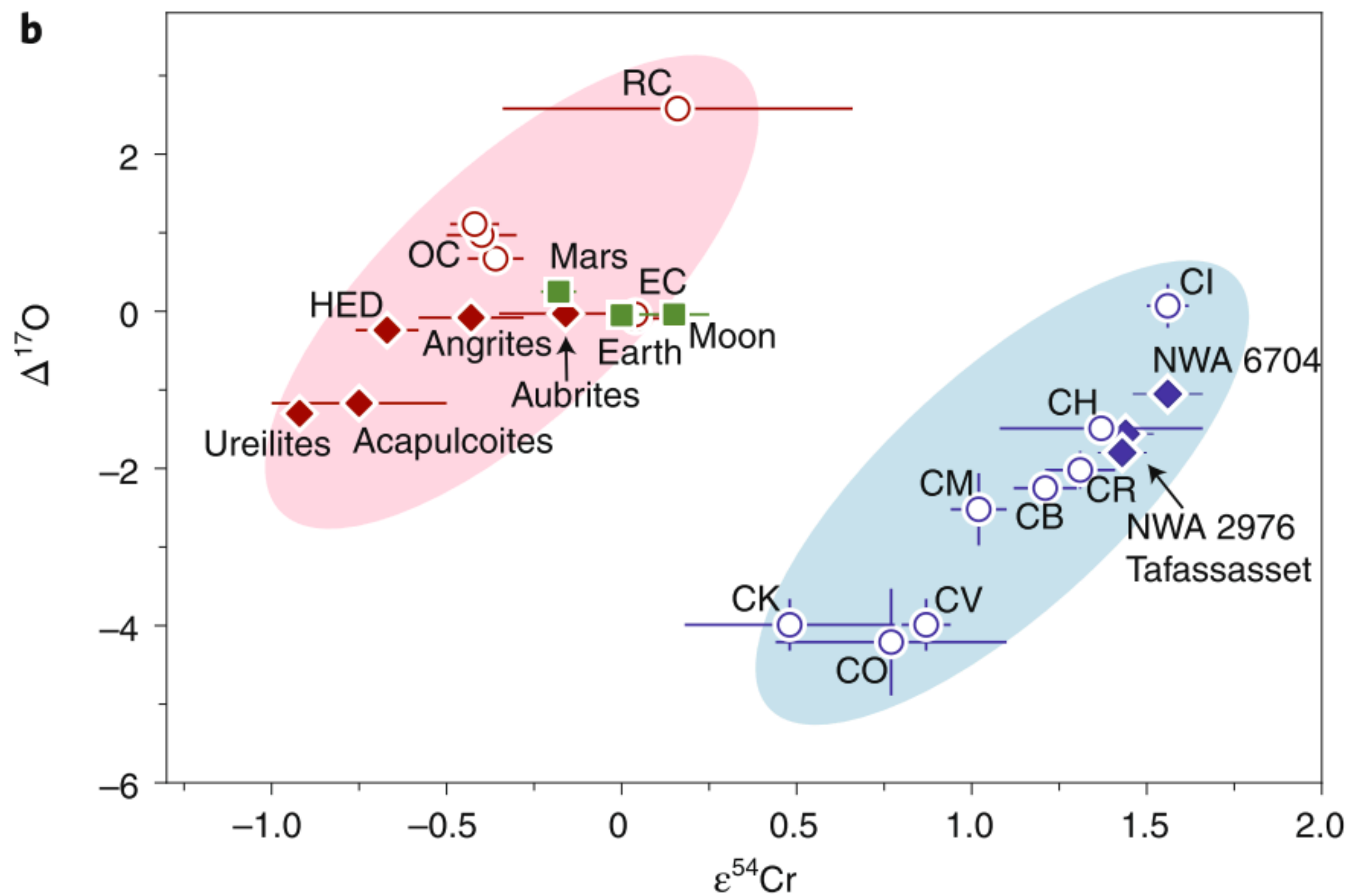
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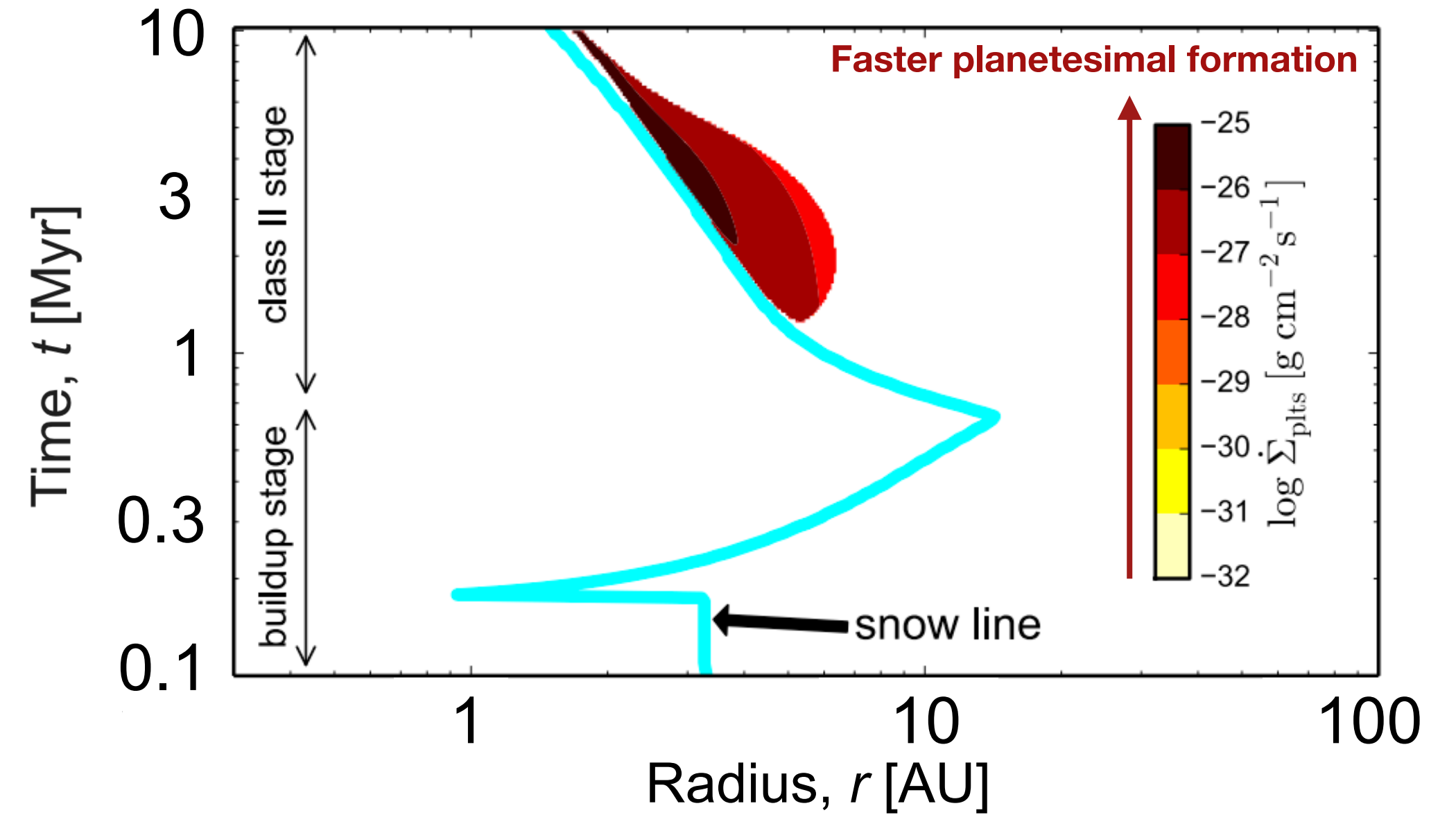
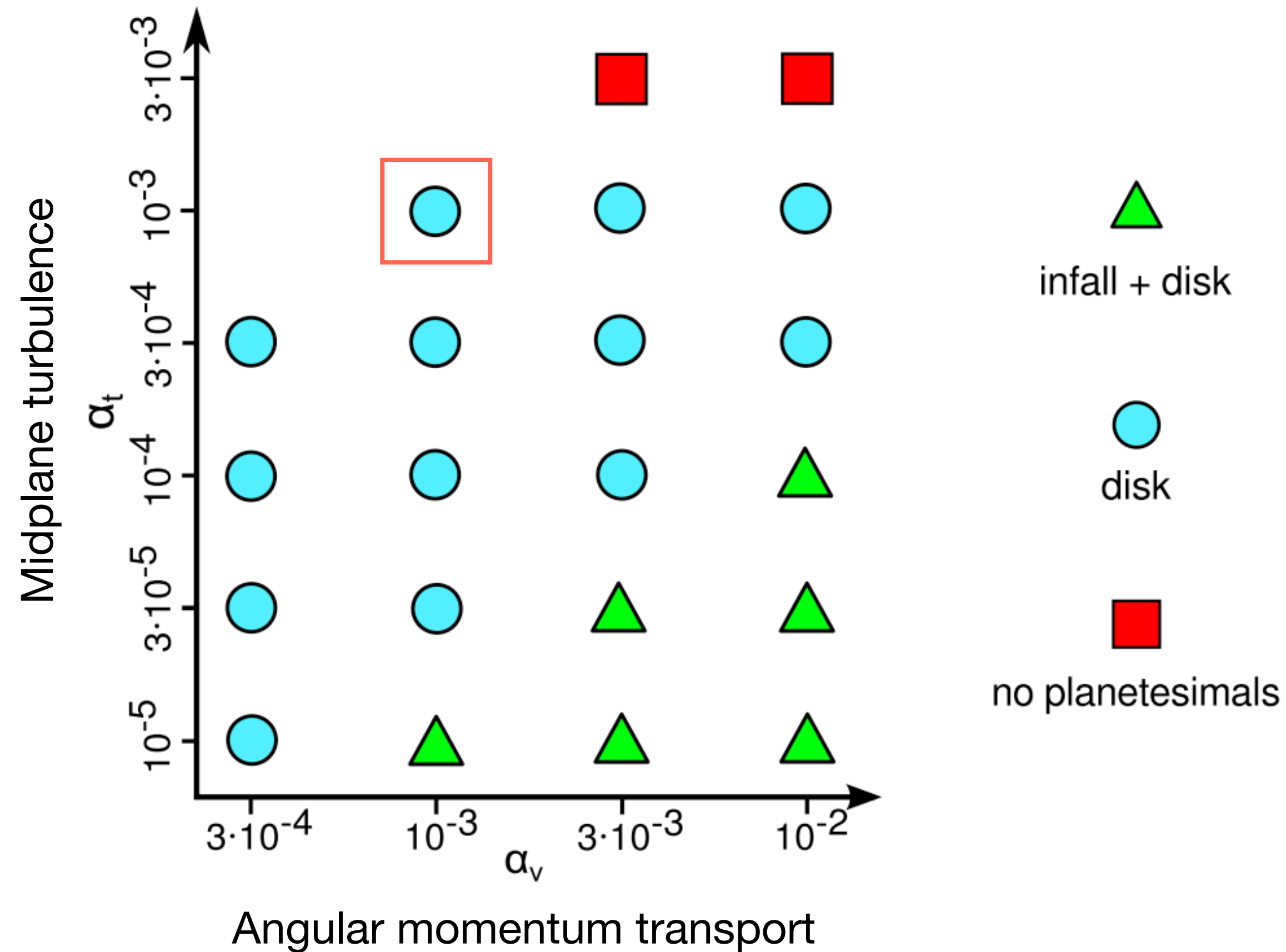


# Earliest compositional bifurcation of planetary building blocks

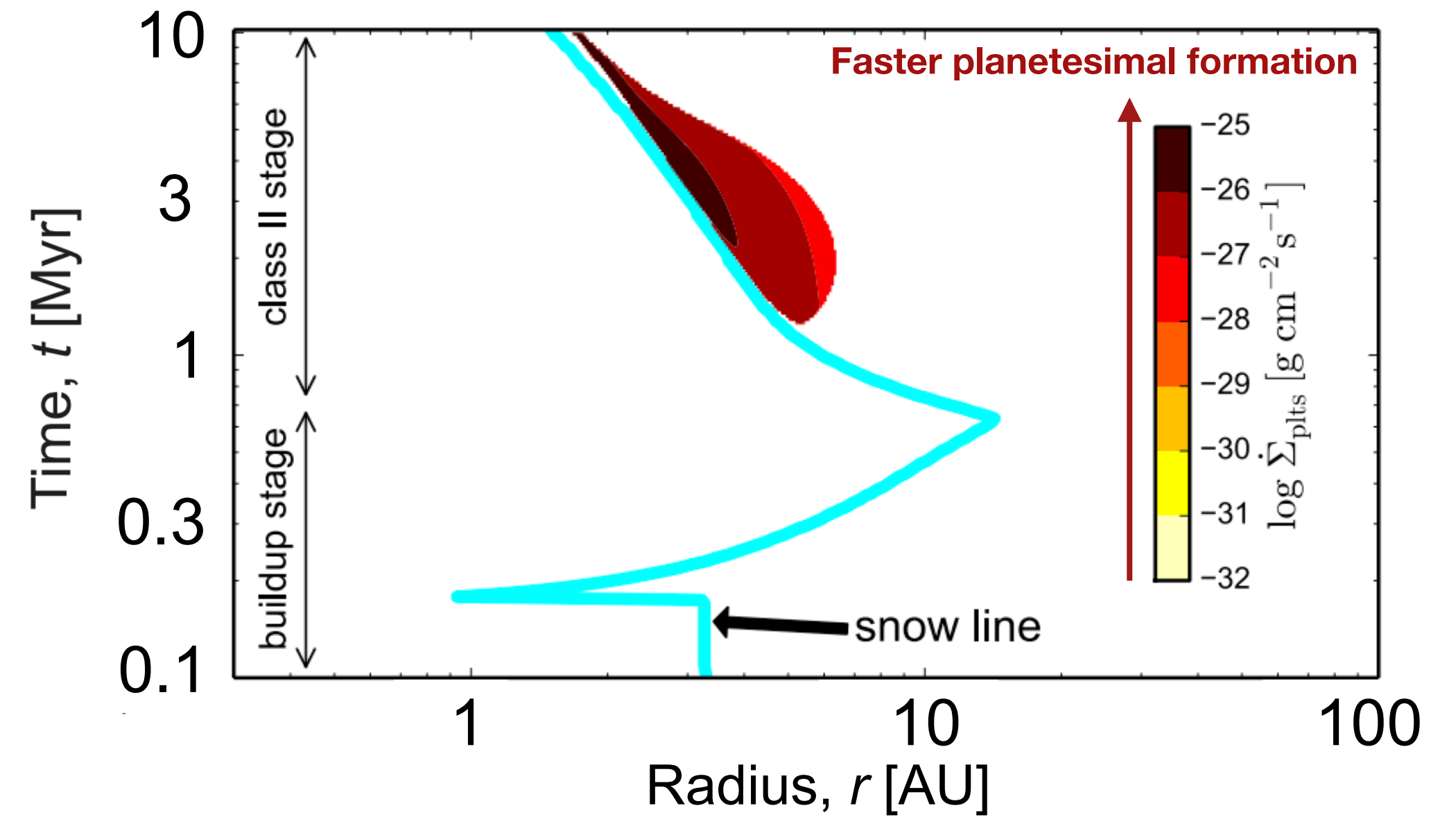
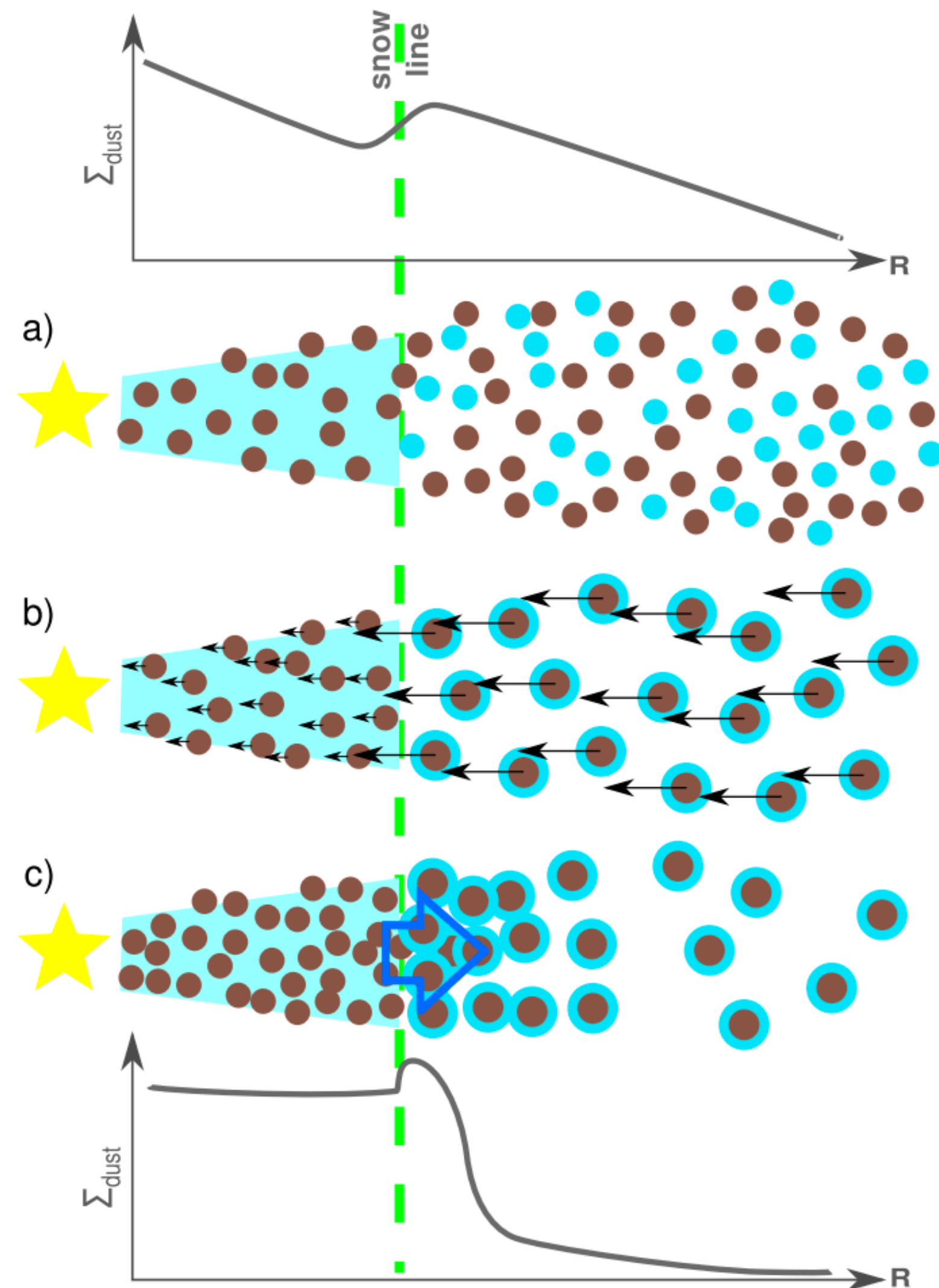
Lichtenberg, Drażkowska, Schönbächler, Golabek, Hands, in prep.



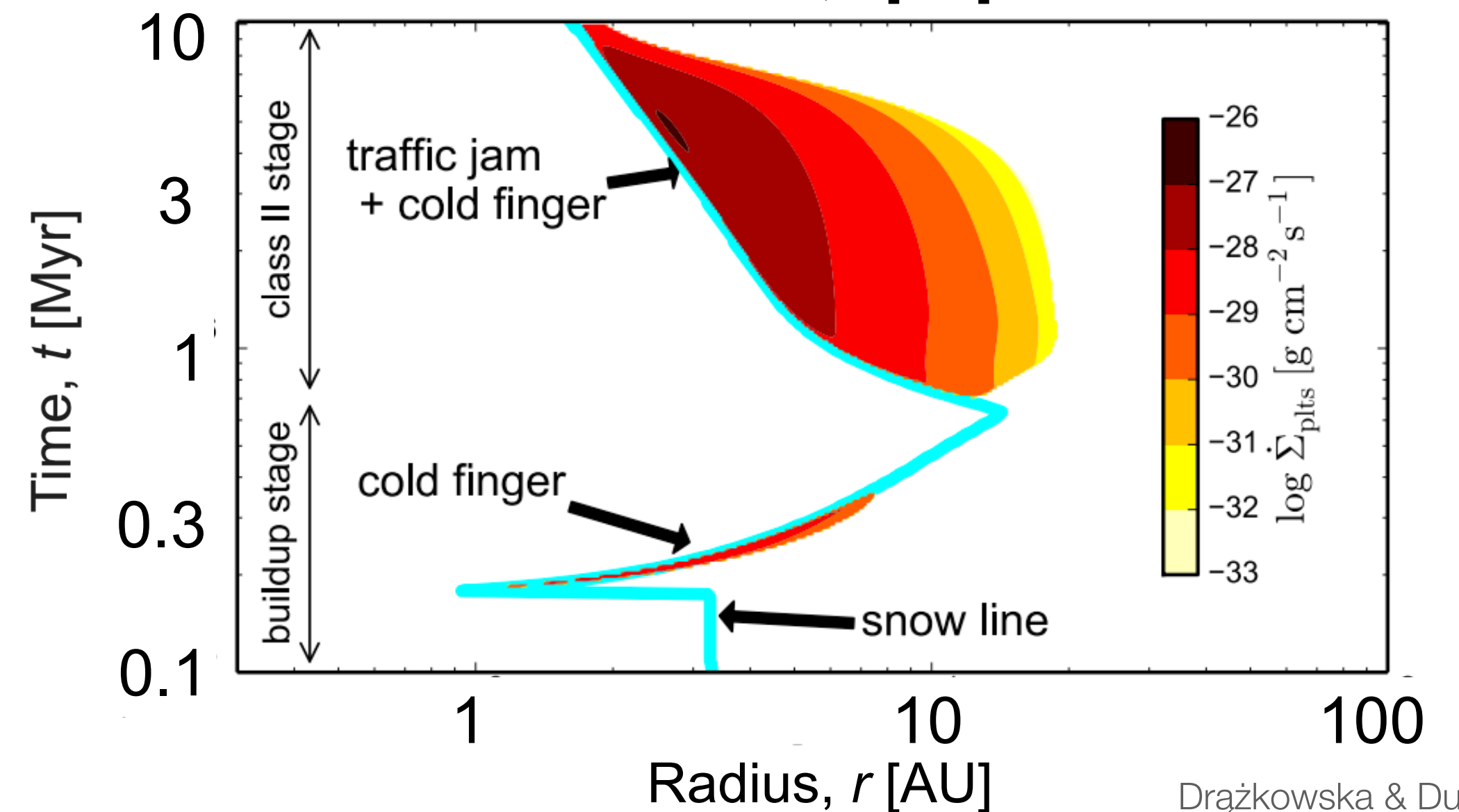
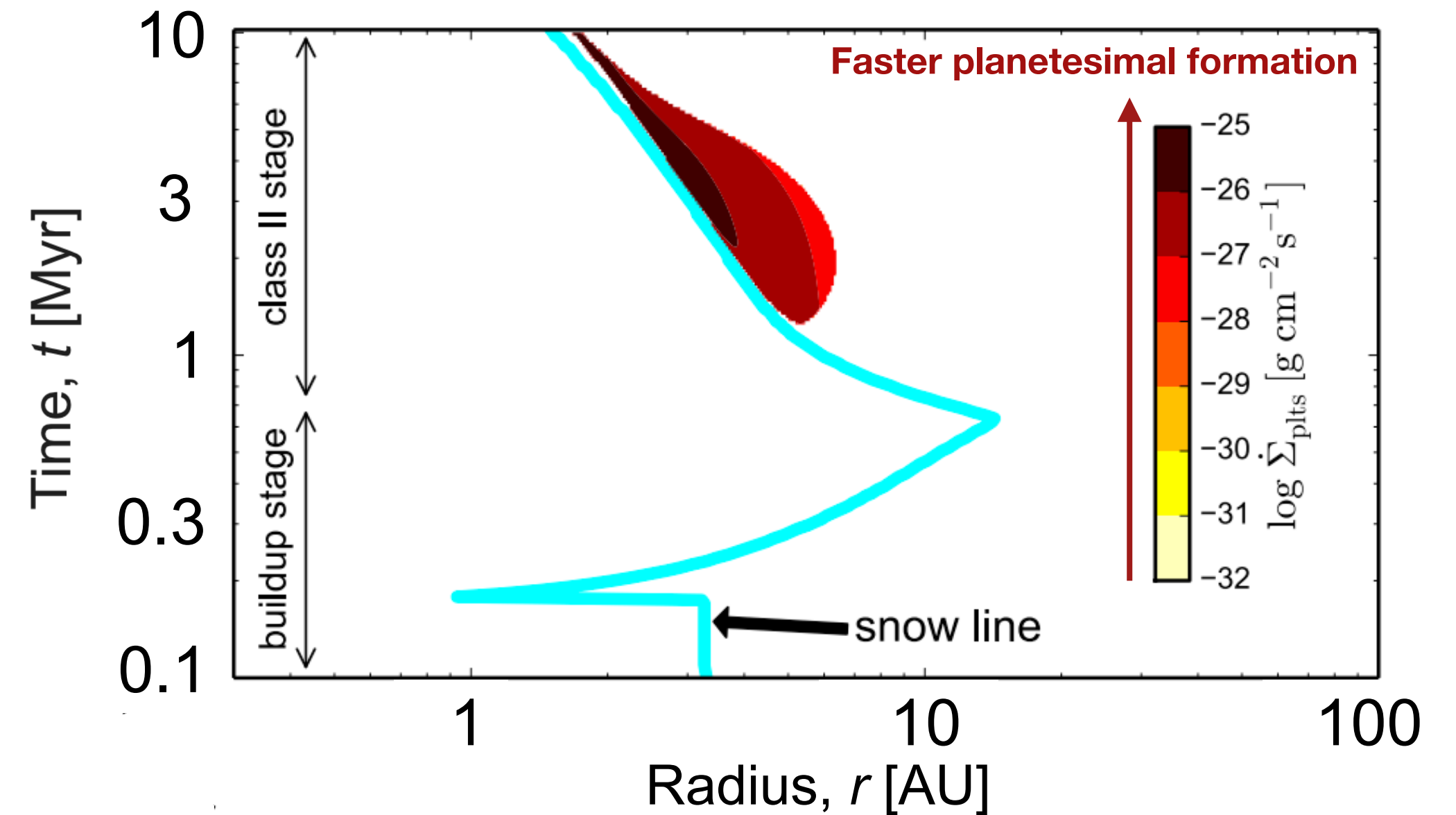
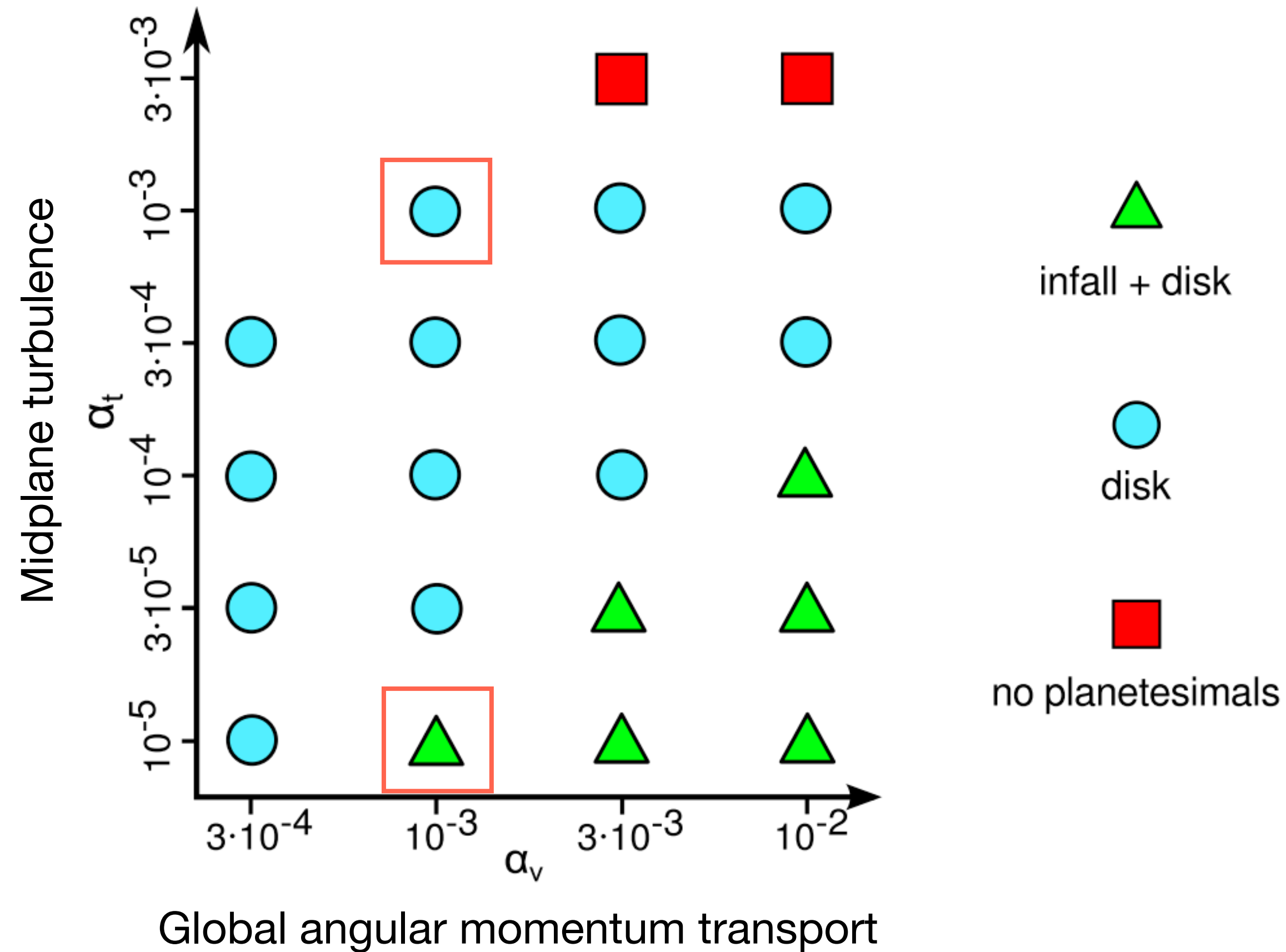
# Planetesimal formation in $\approx$ wind-driven disk



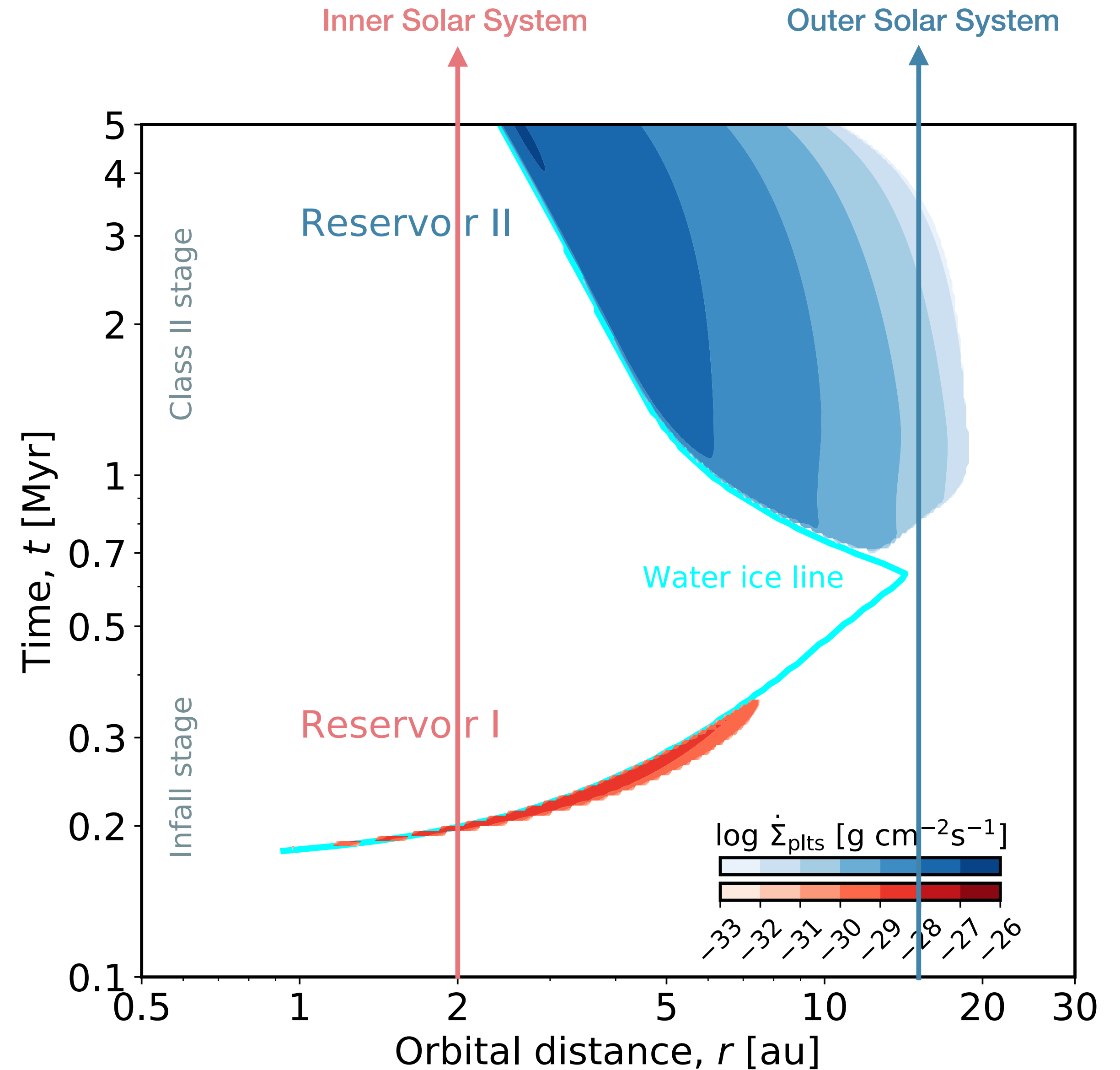
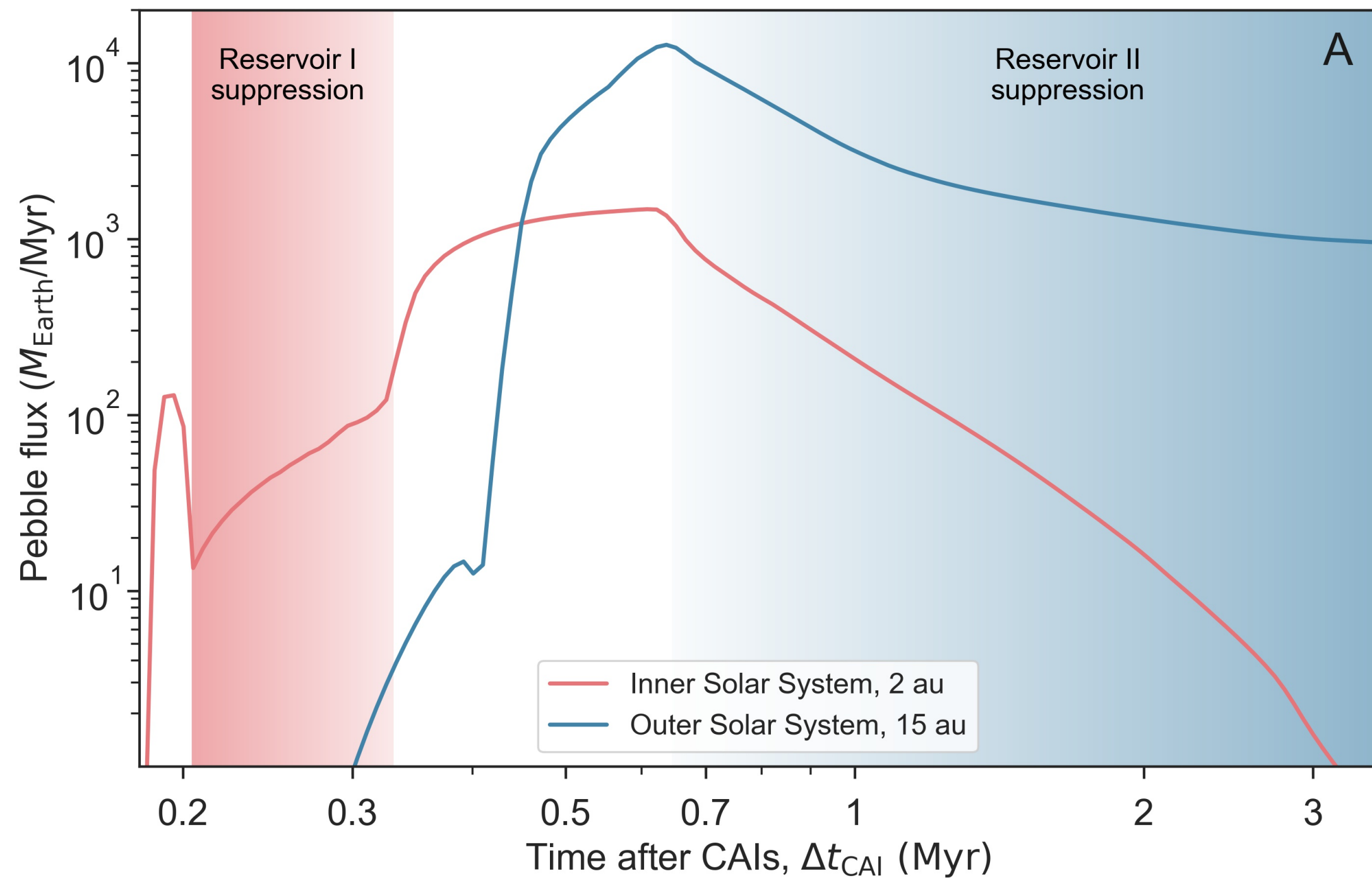
# Water vapour re-/condensation



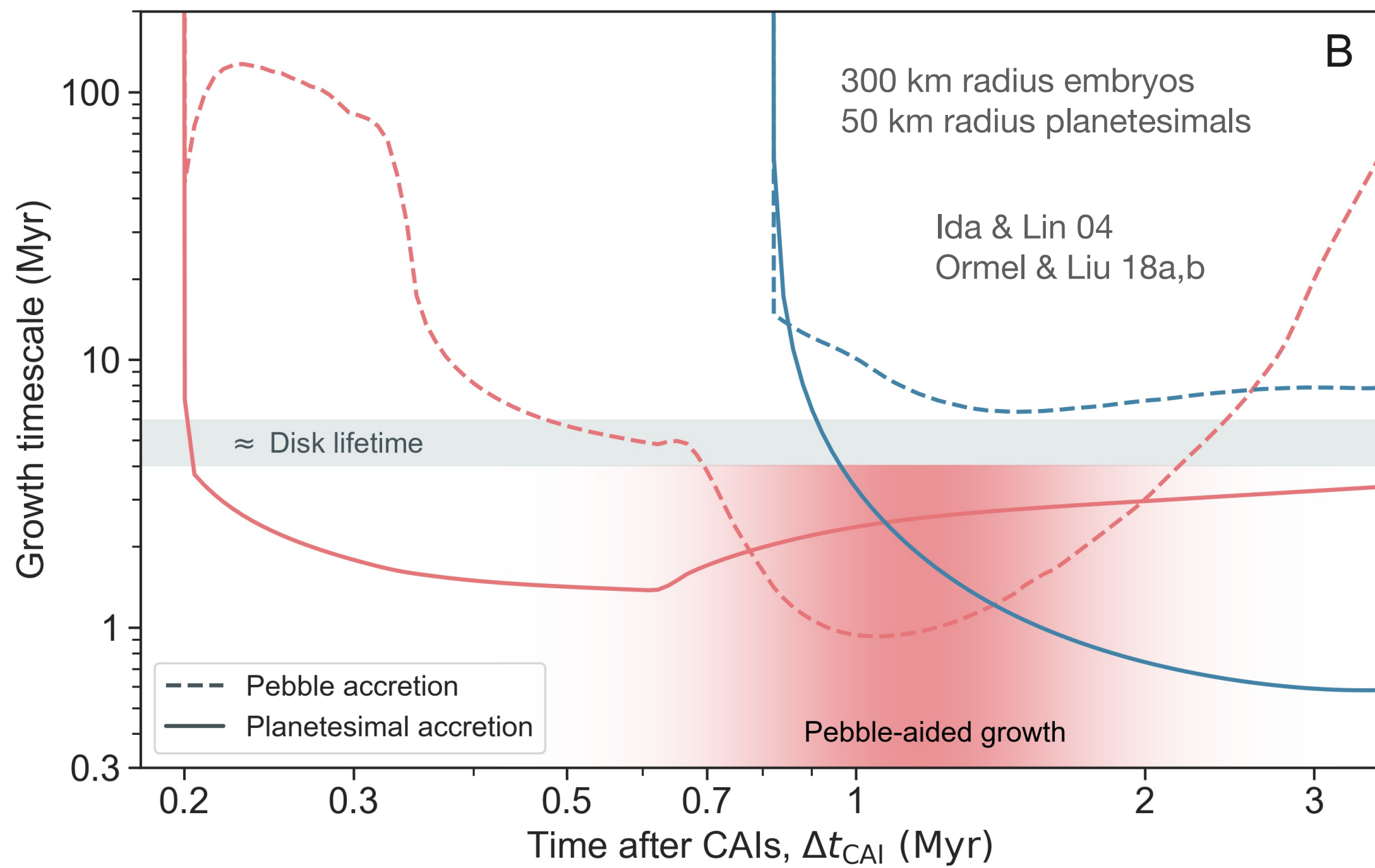
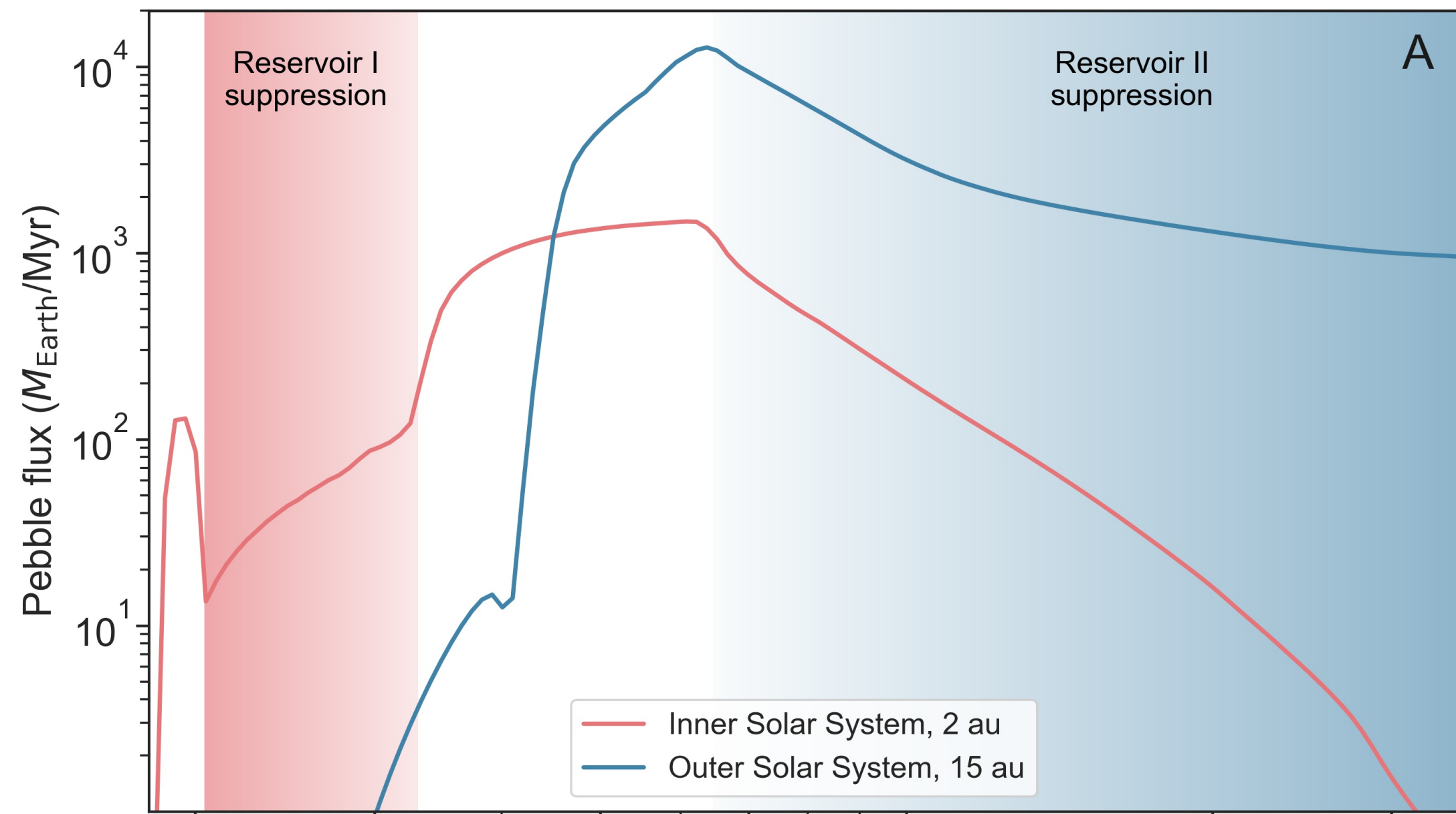
# Rapid accretion in midplane-quiescent disks



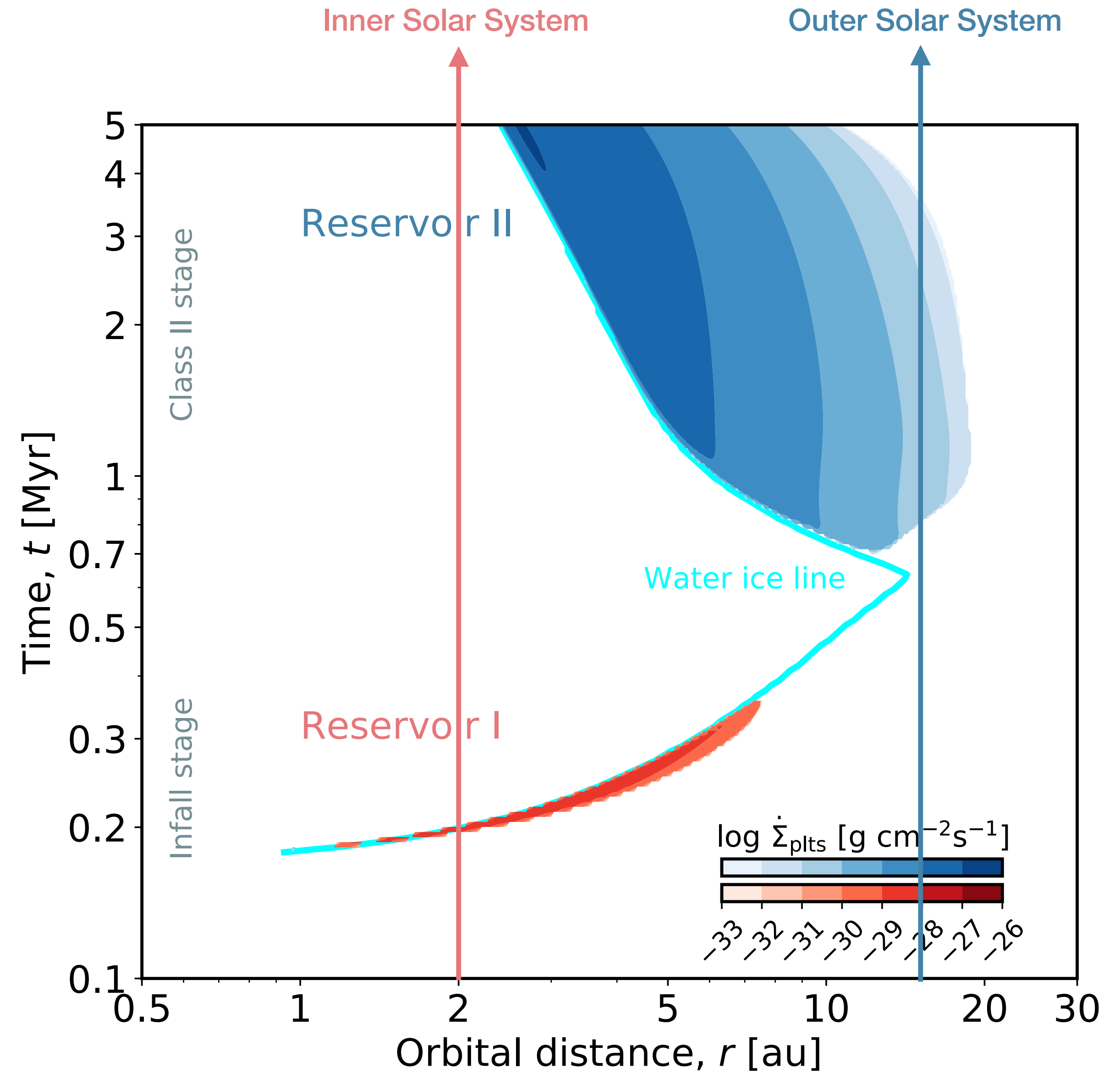
# Pebble suppression



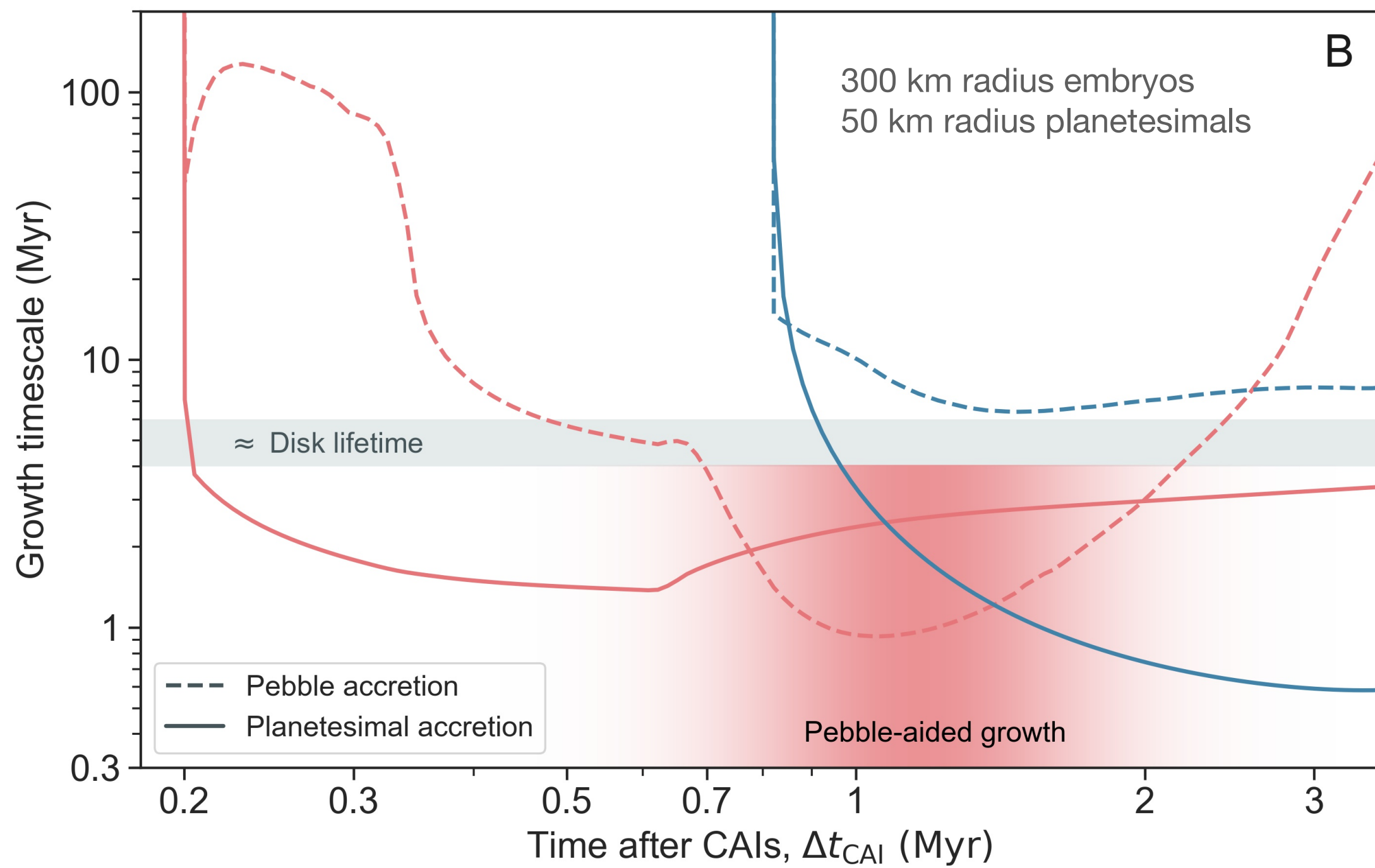
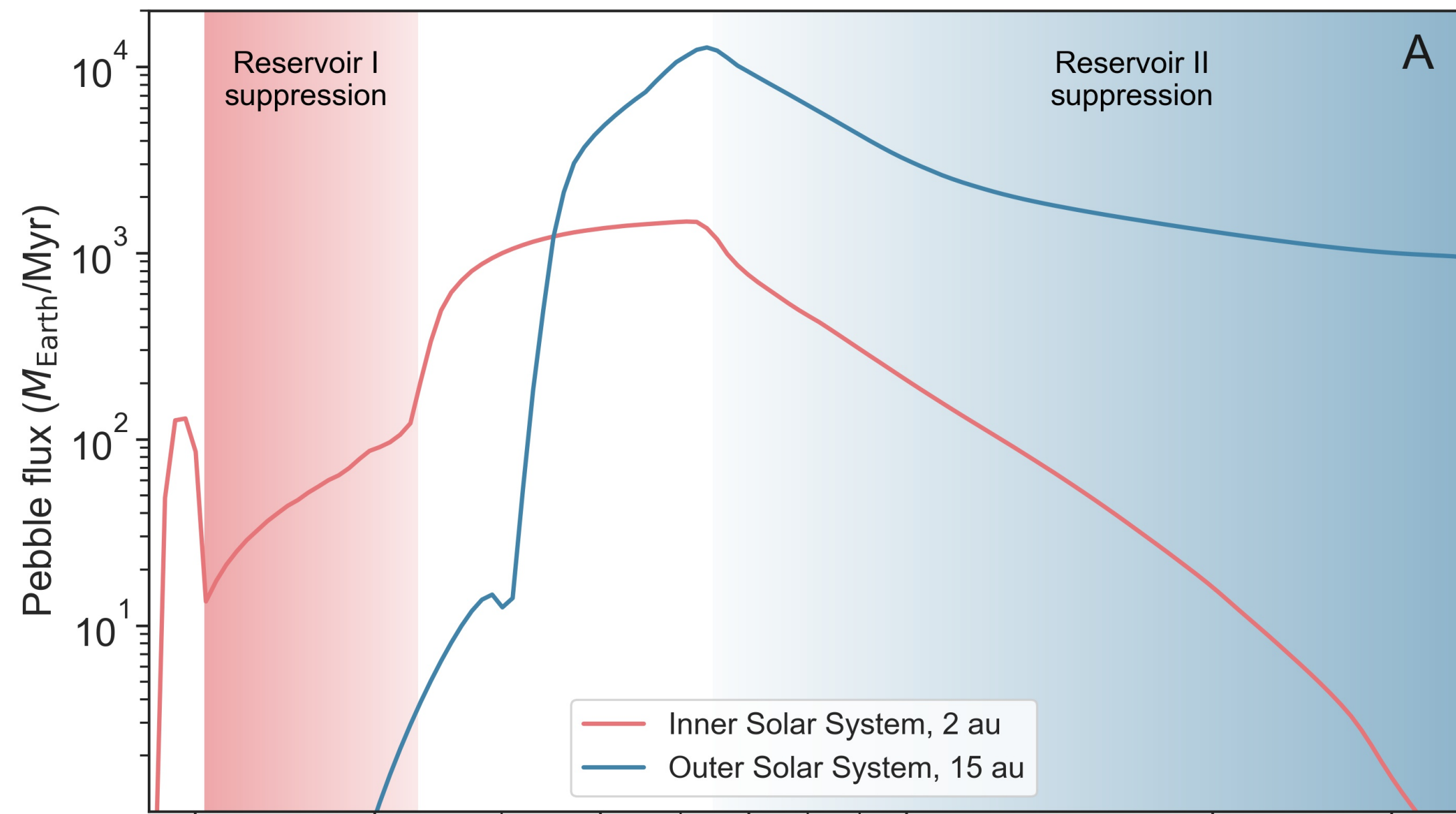
- Limits reservoir mixing
- Protracts inner embryo growth



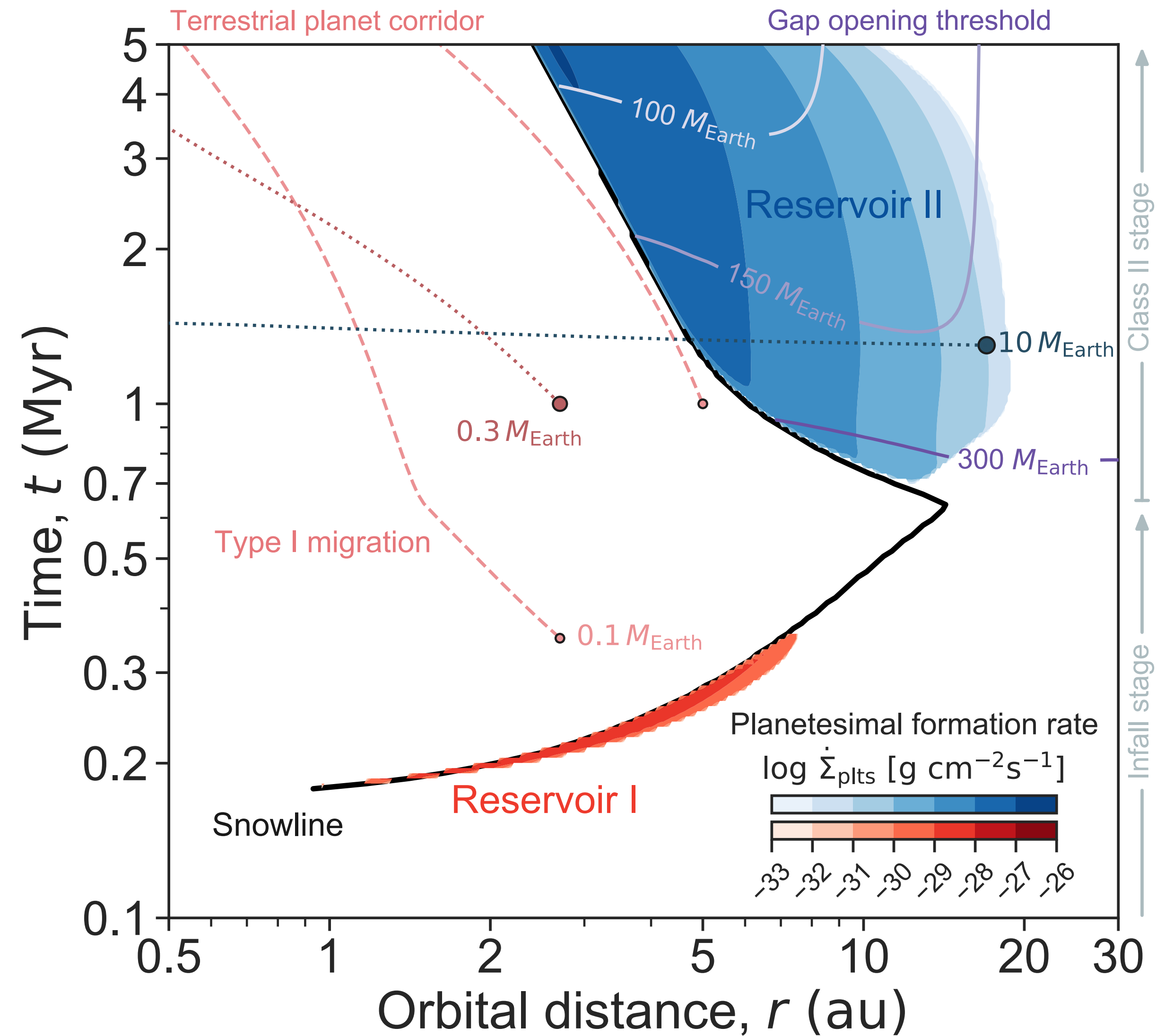
# Dominant growth mode



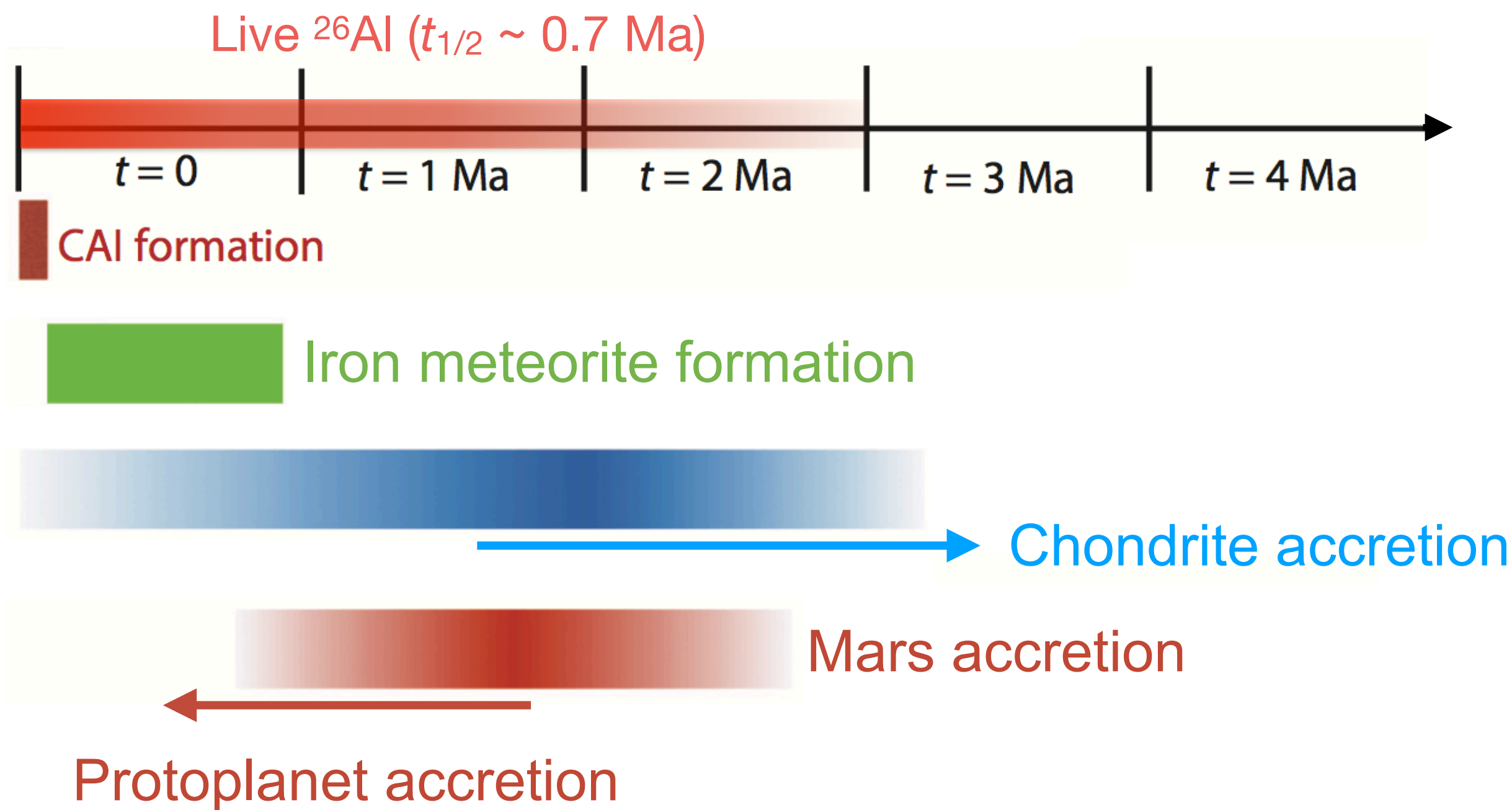
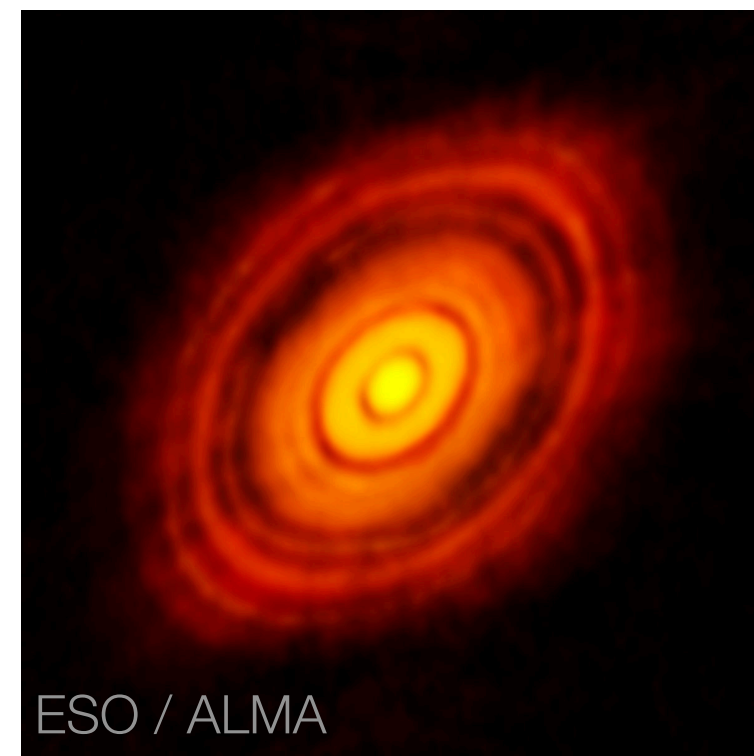
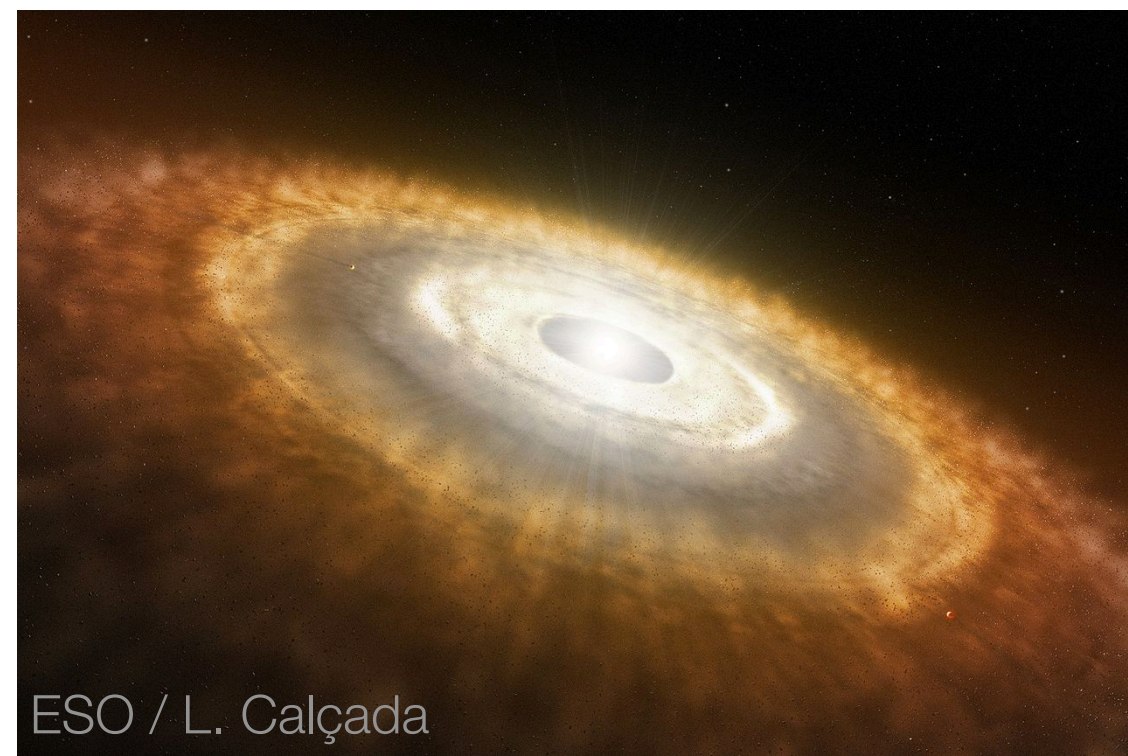




# Dominant growth mode

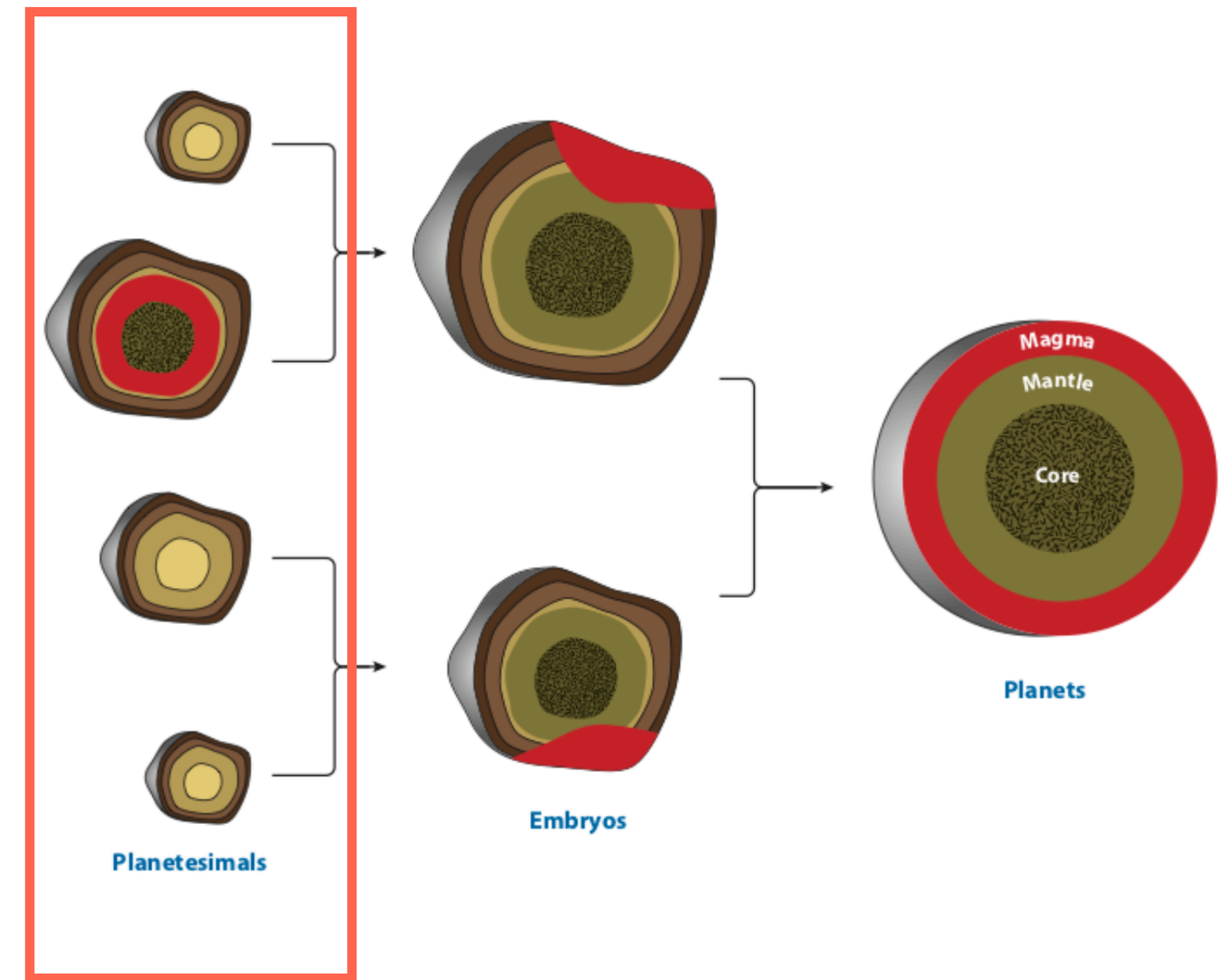


# Geophysical evolution during **early** accretion

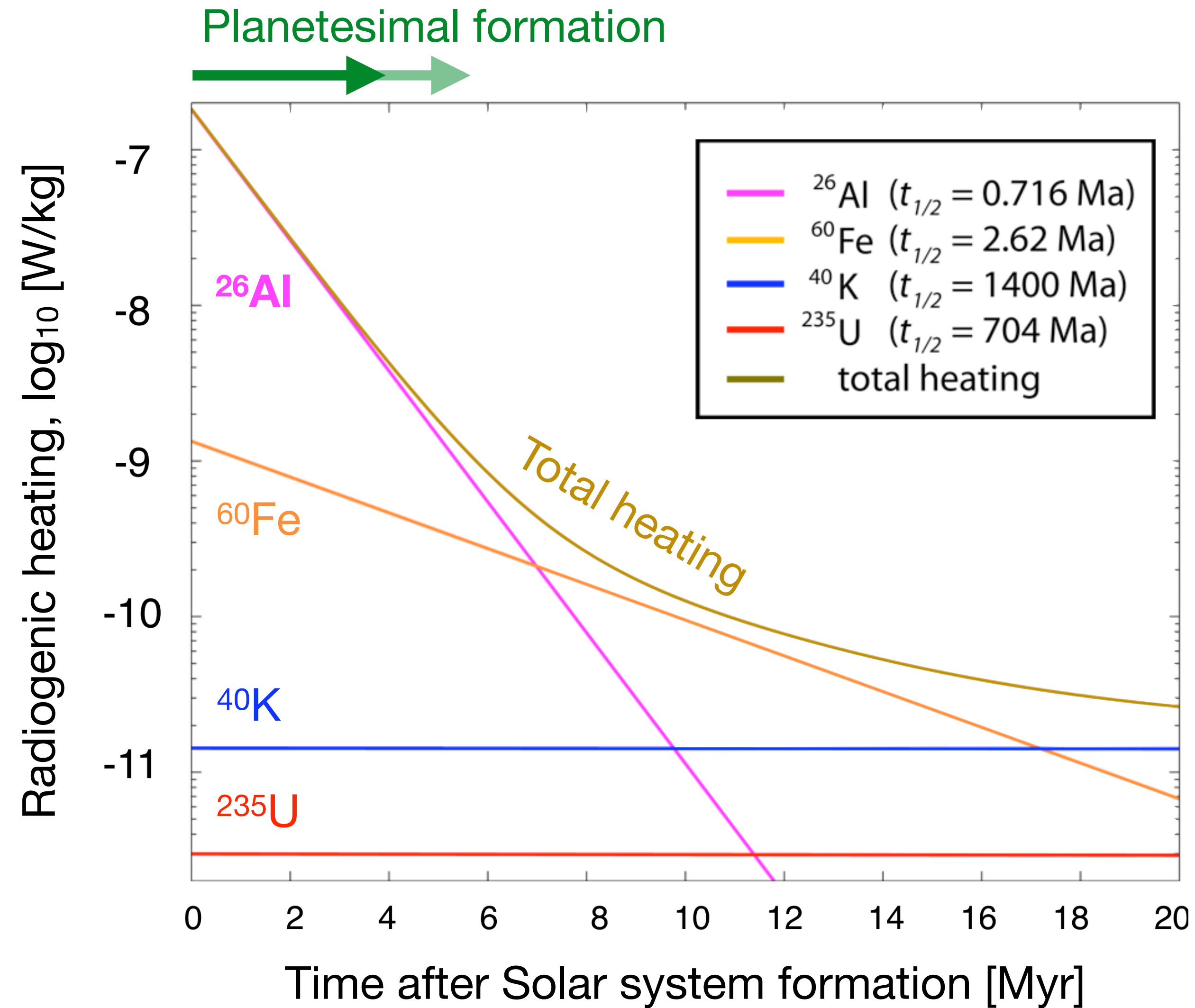


$^{26}\text{Al}$  dominated

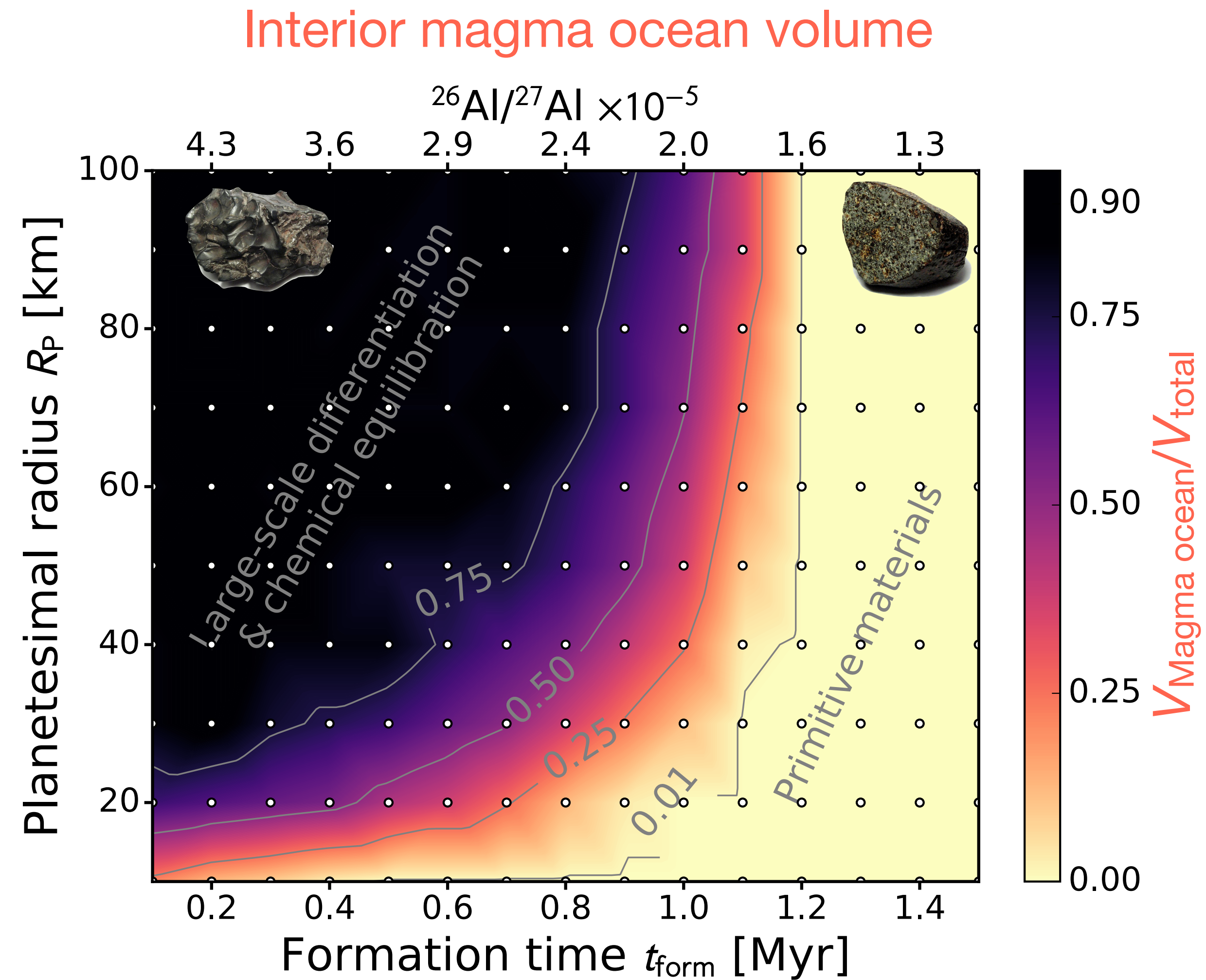
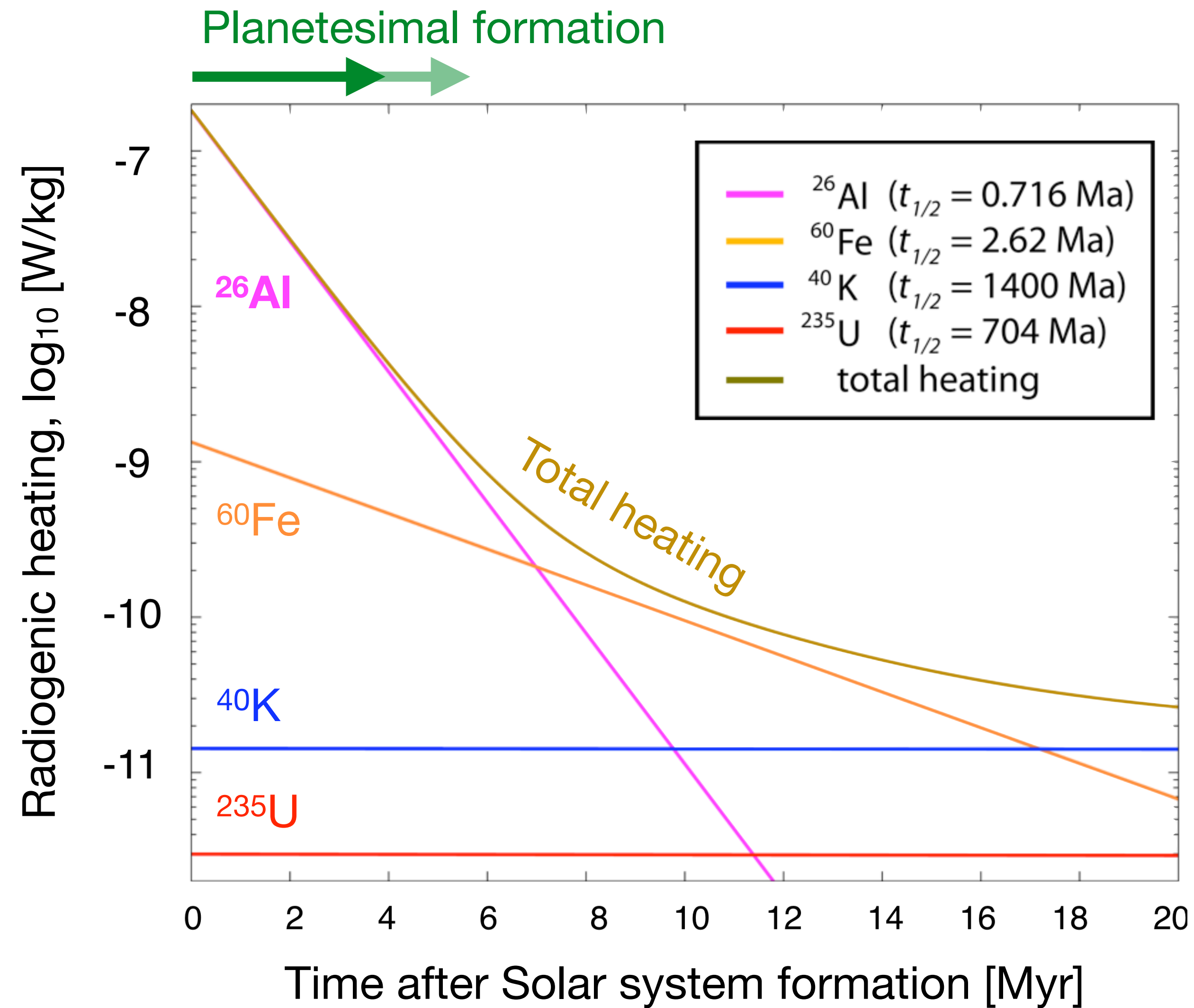
Accretion-energy dominated



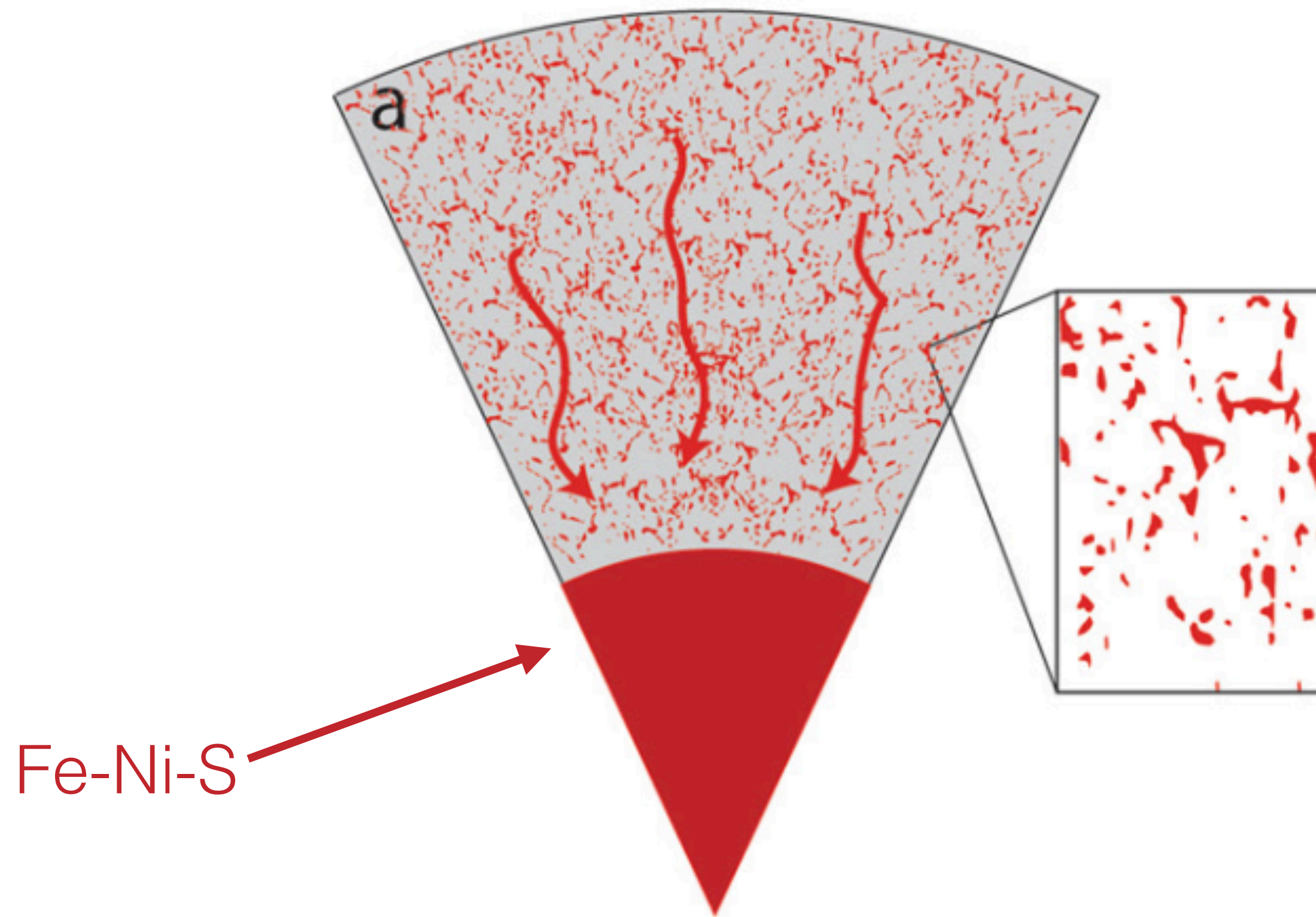
# Radiogenic heating drives thermal evolution



# Planetesimal interior evolution

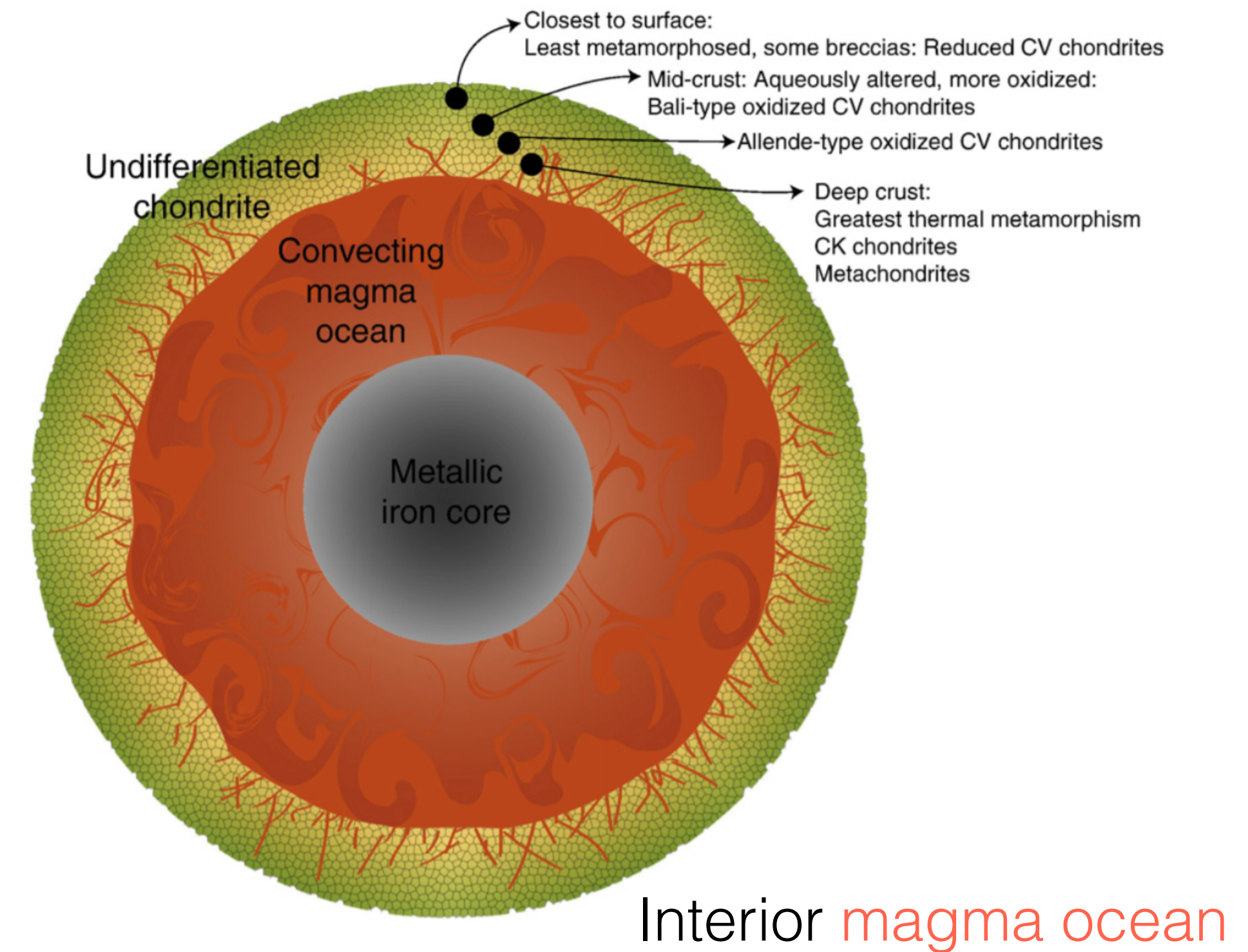


# Chemical differentiation of planetesimals



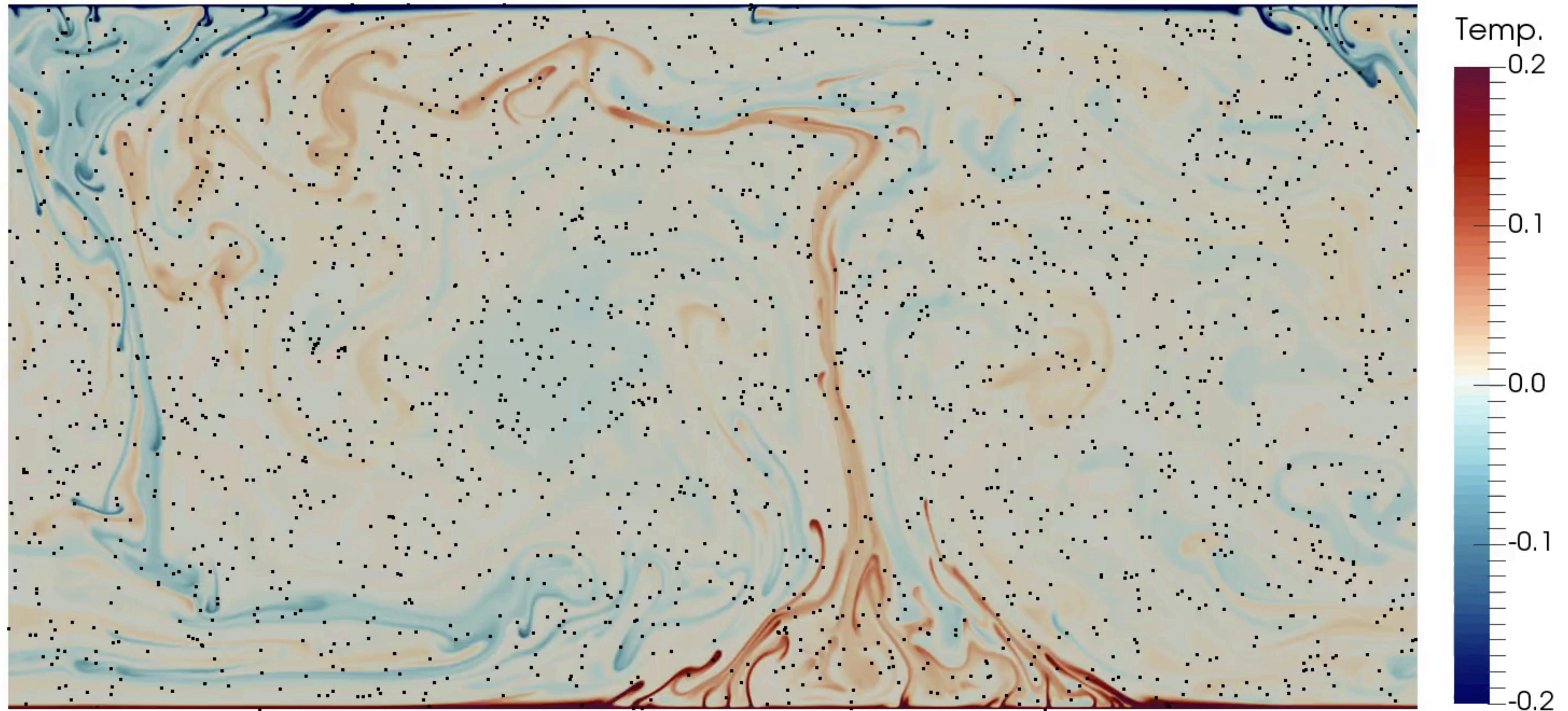
Fe-Ni-S

Fe-Ni-S percolation  
*1<sup>st</sup> stage core formation*



Fe-Ni rain-out  
*2<sup>nd</sup> stage core formation*

# Chemical differentiation of planetesimals



Time: 0 My

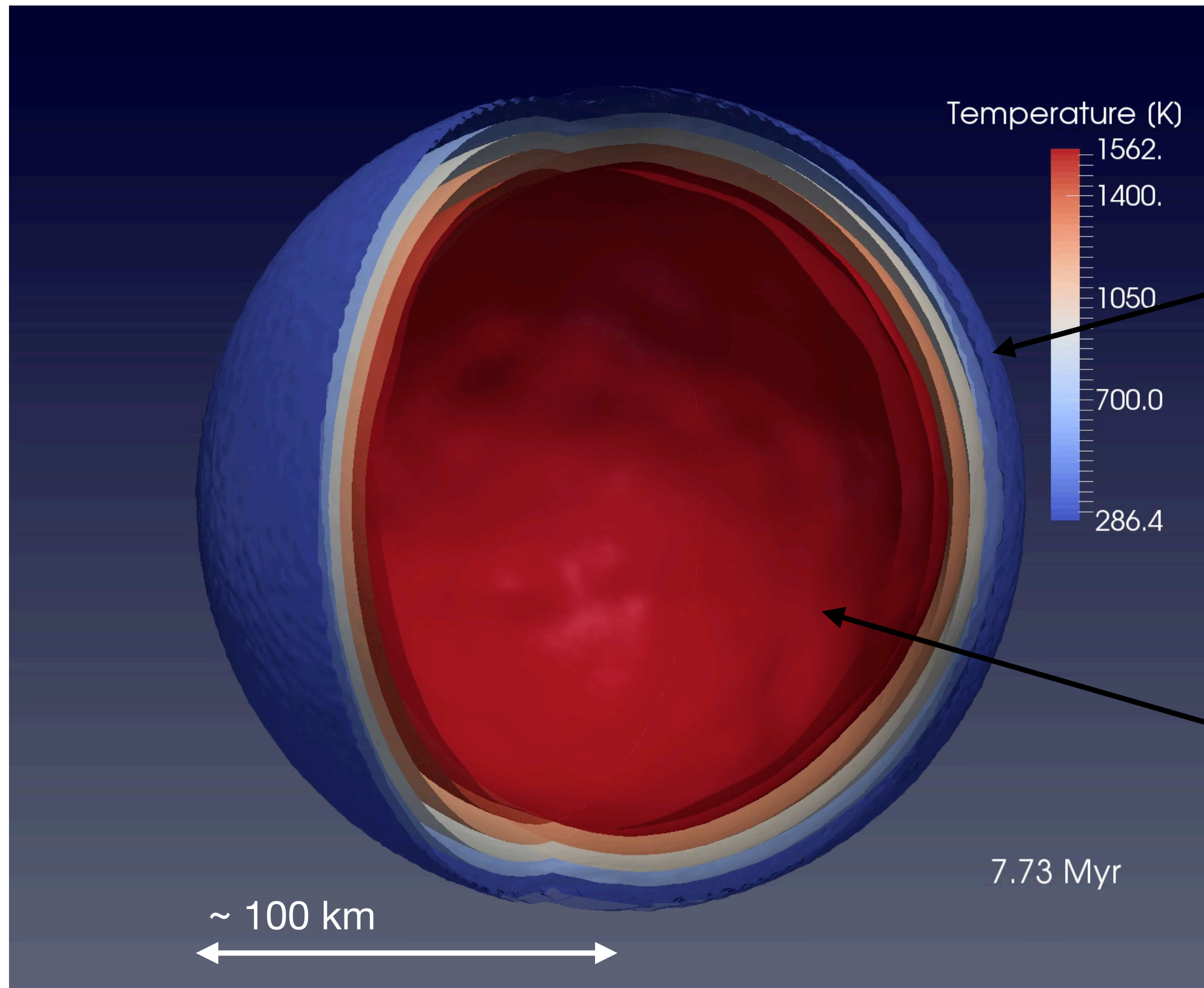
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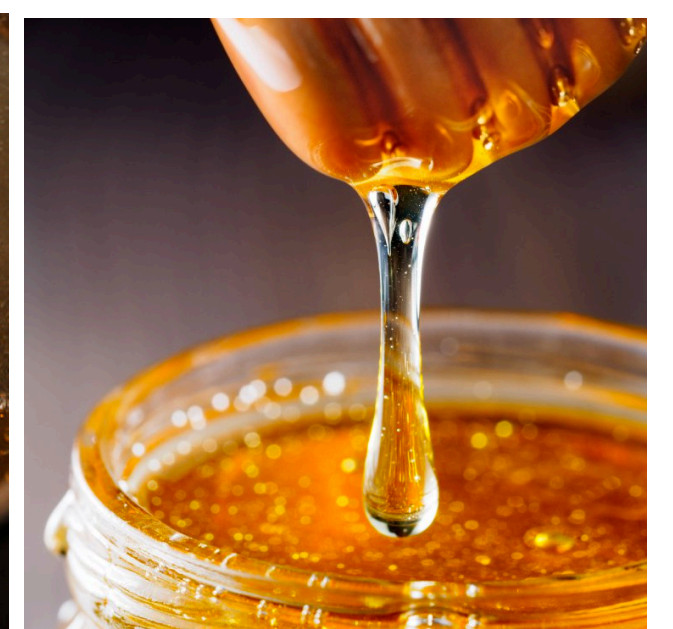
Interior magma ocean

'Rock' viscosity  $\sim 10^{-2} - 10^1$  Pa s

# Chemical differentiation of planetesimals



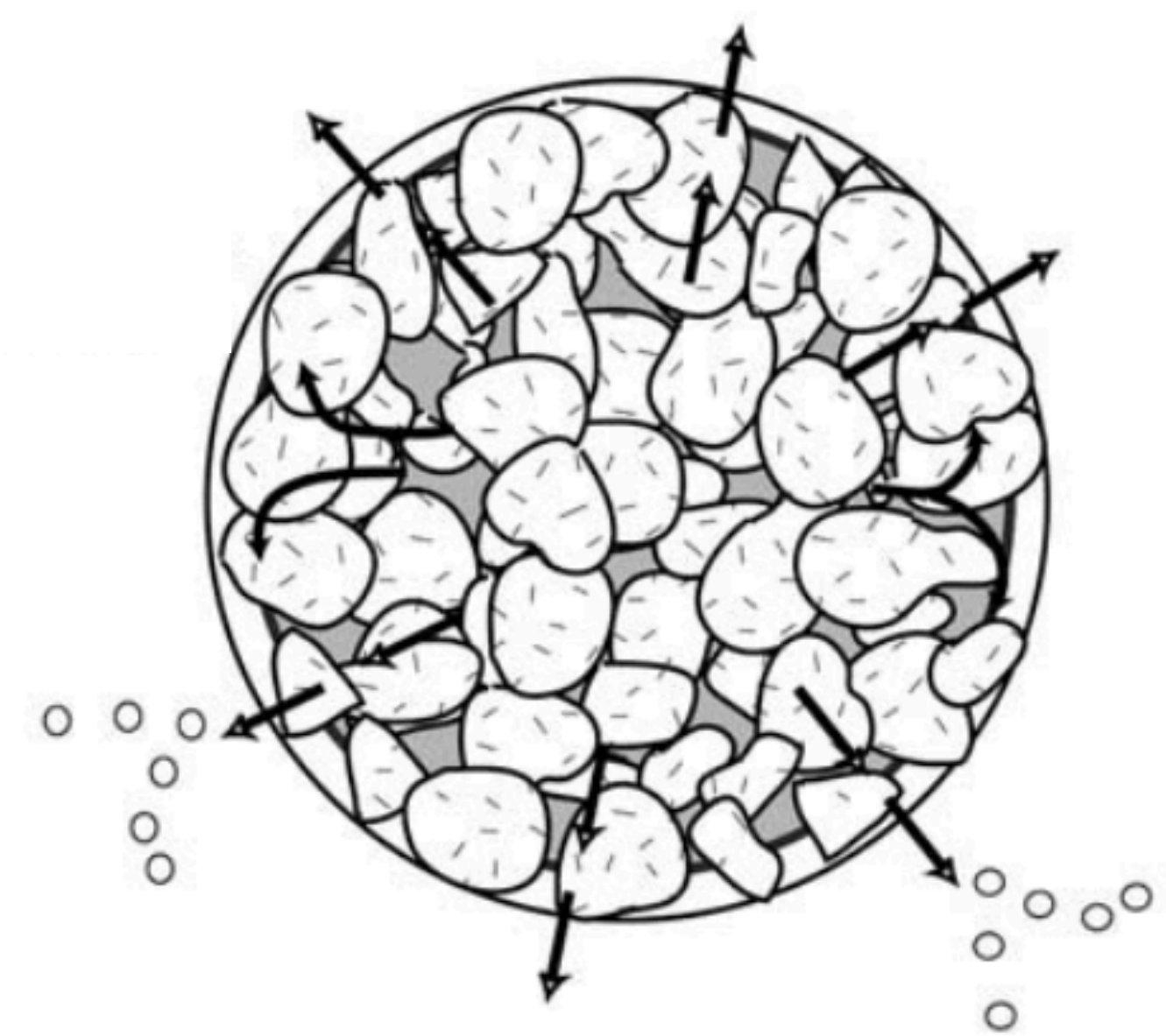
Rock viscosity  
 $\sim 10^{20}$  Pa s



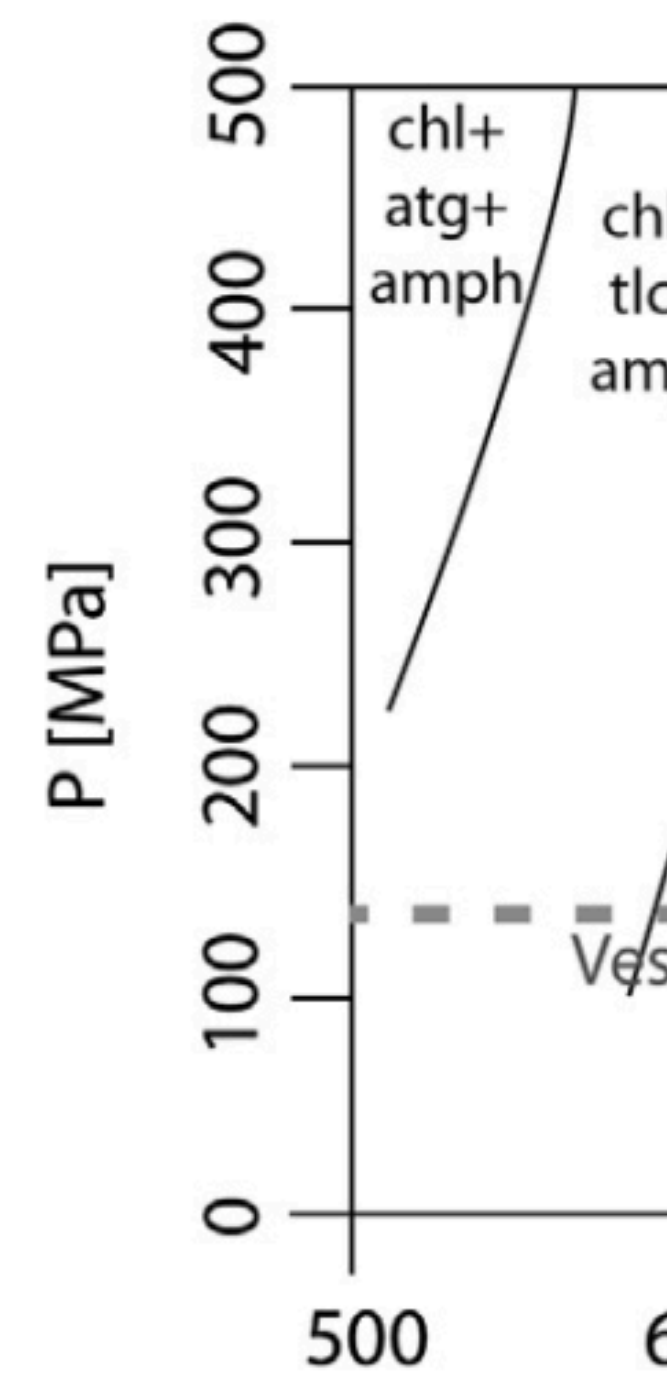
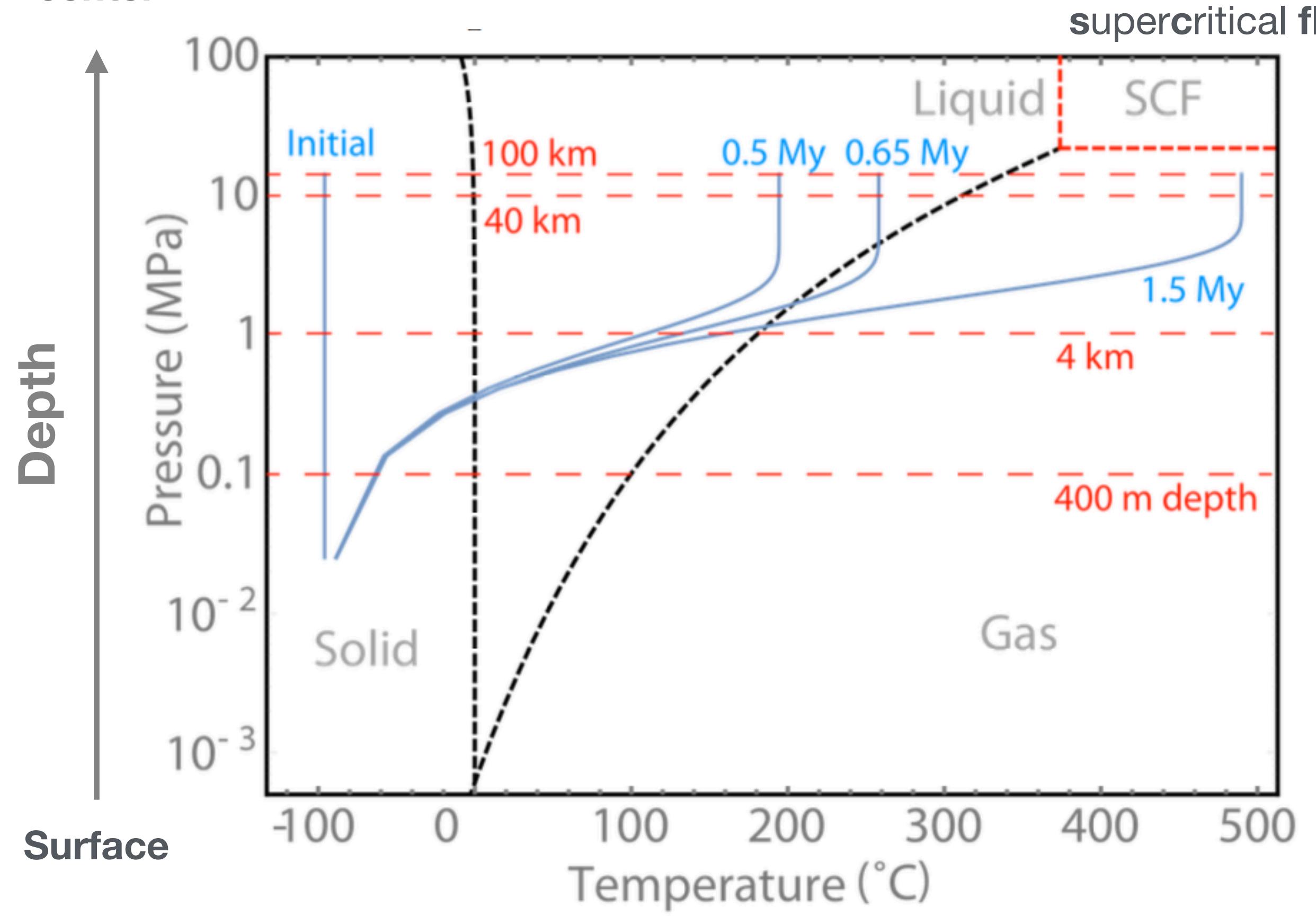
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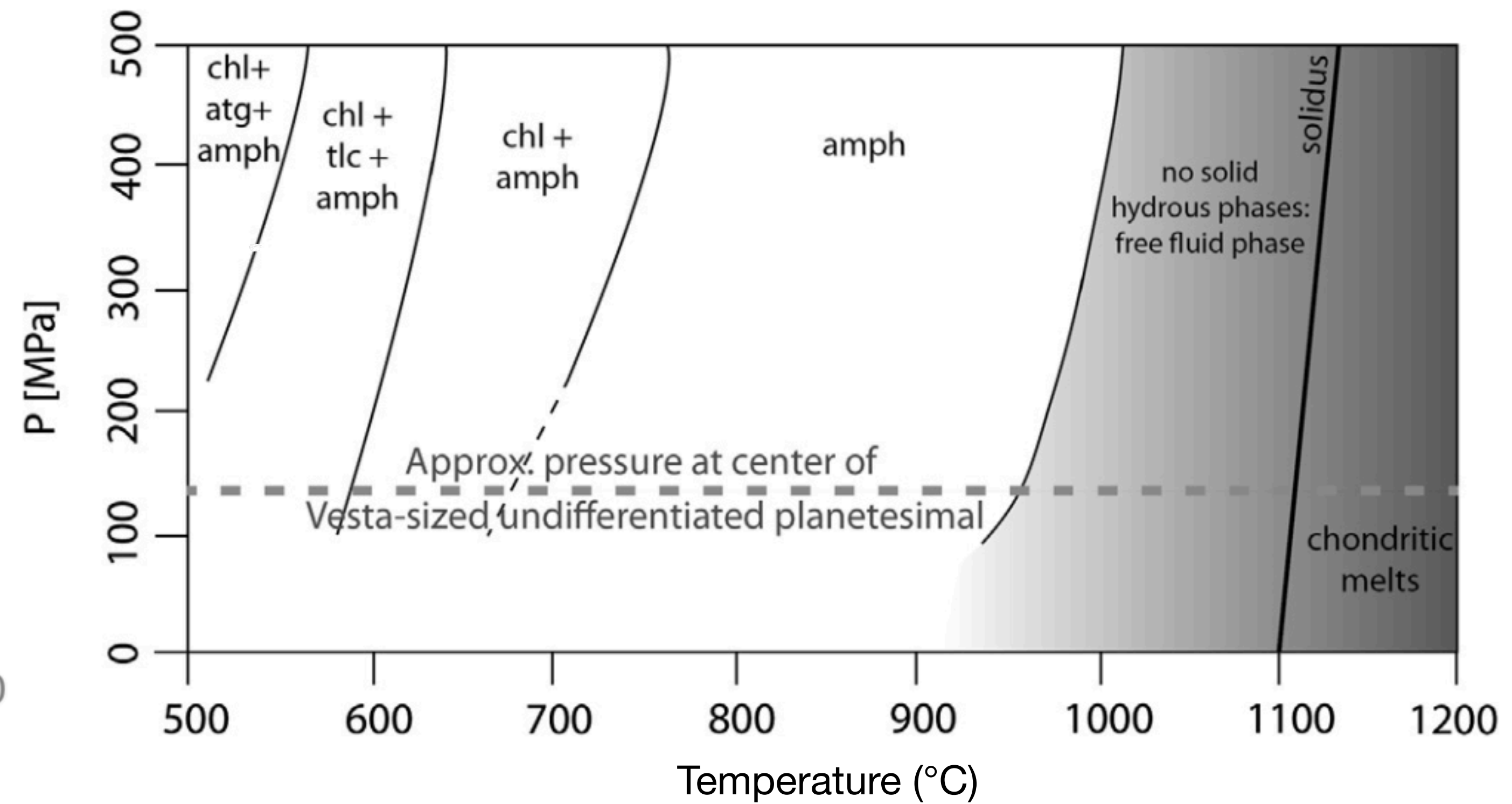
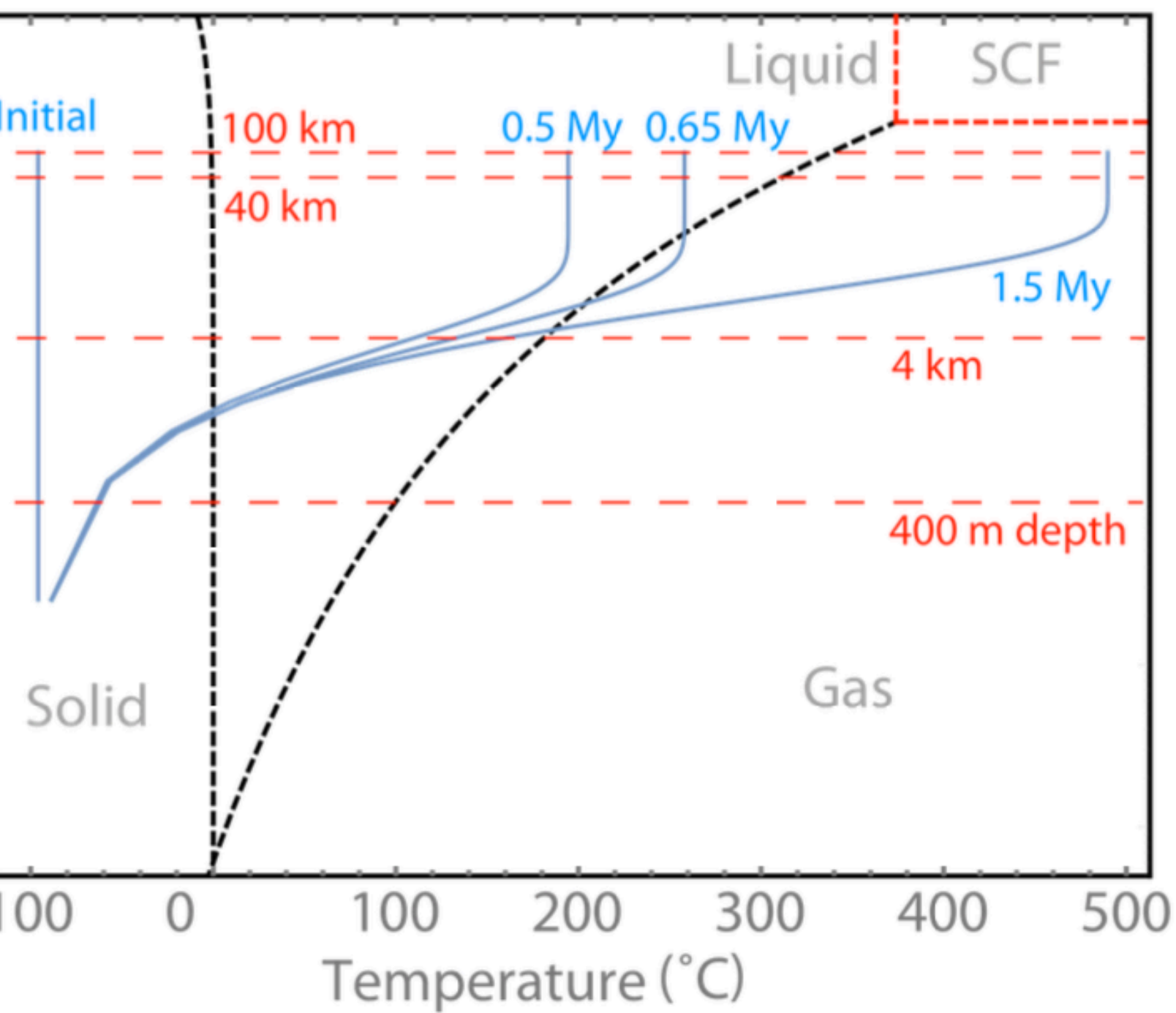
# Planetesimal 'hydrology'



Planetesimal center

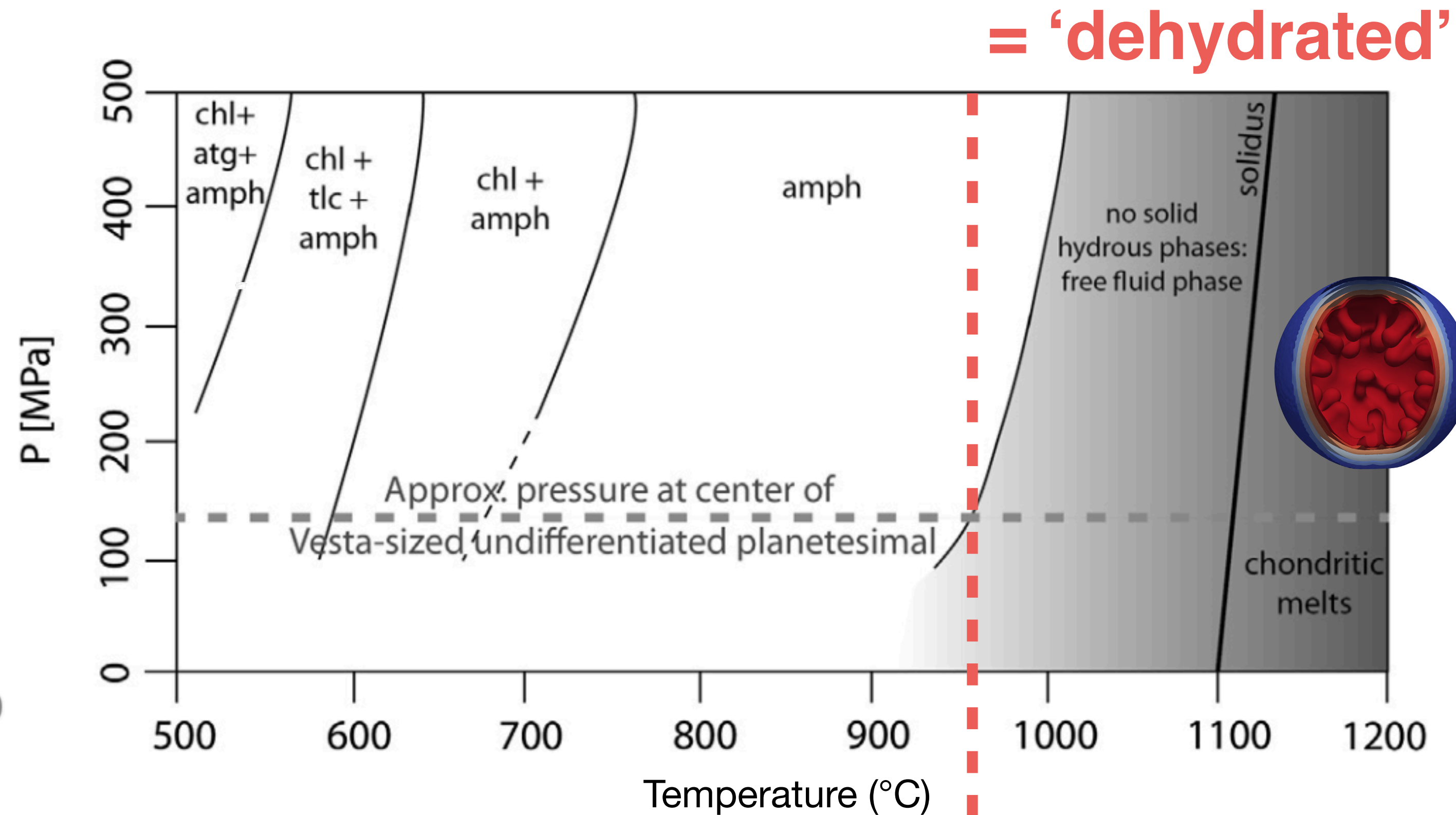
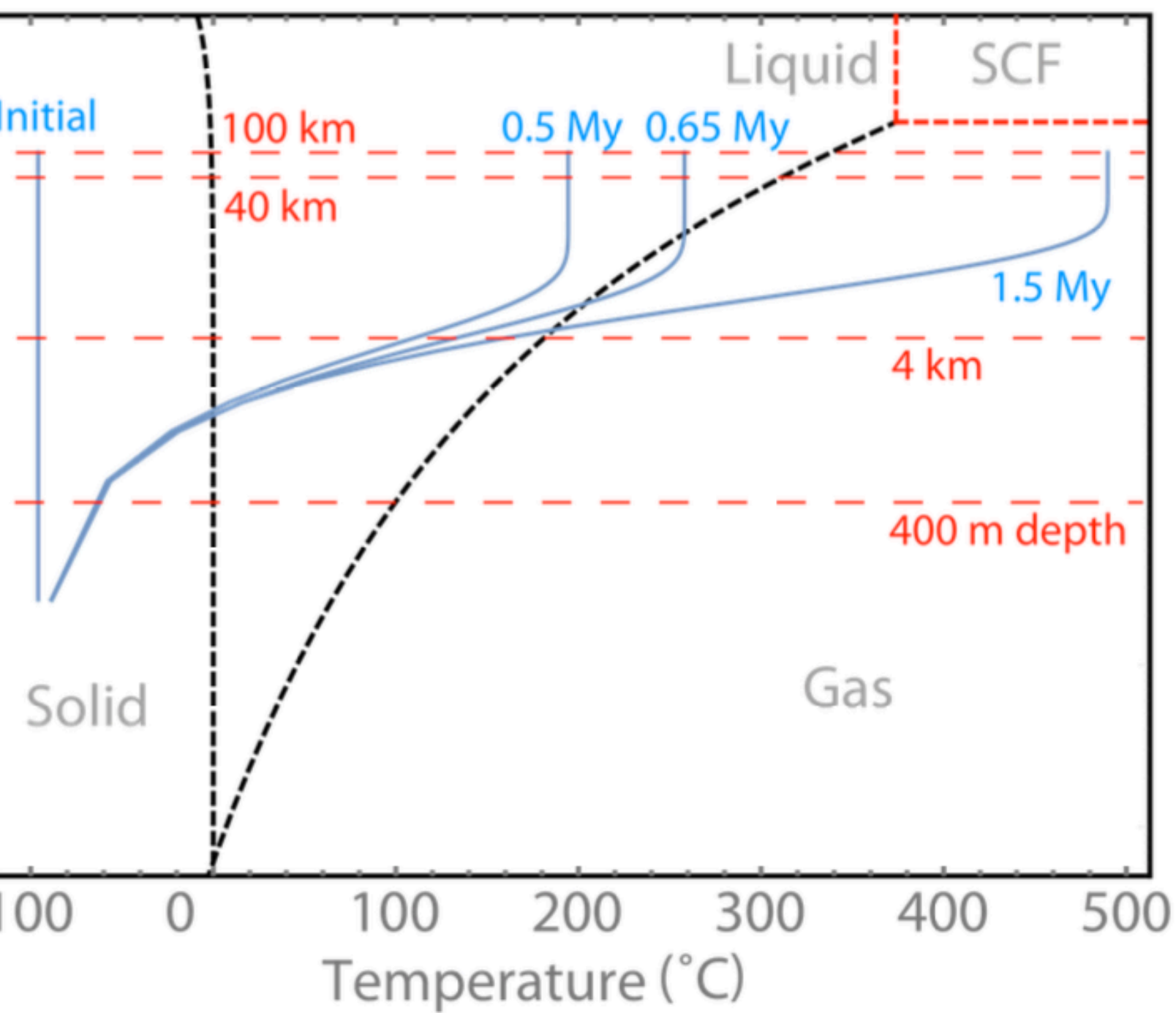


# Planetesimal 'hydrology'



$^{26}\text{Al}$  heating

# Planetesimal 'hydrology'



= 'dehydrated'

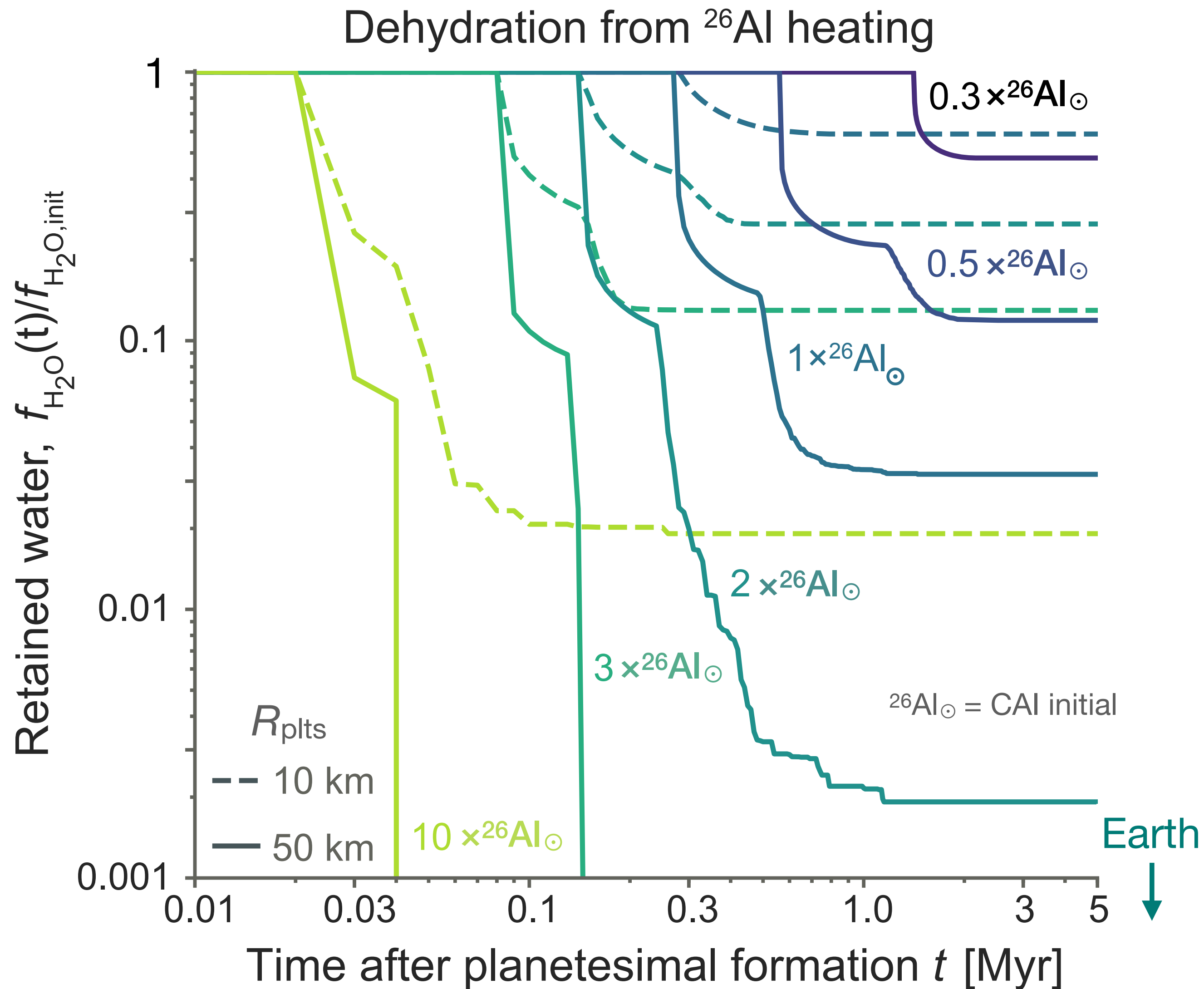
<sup>26</sup>Al-heating

'wet'

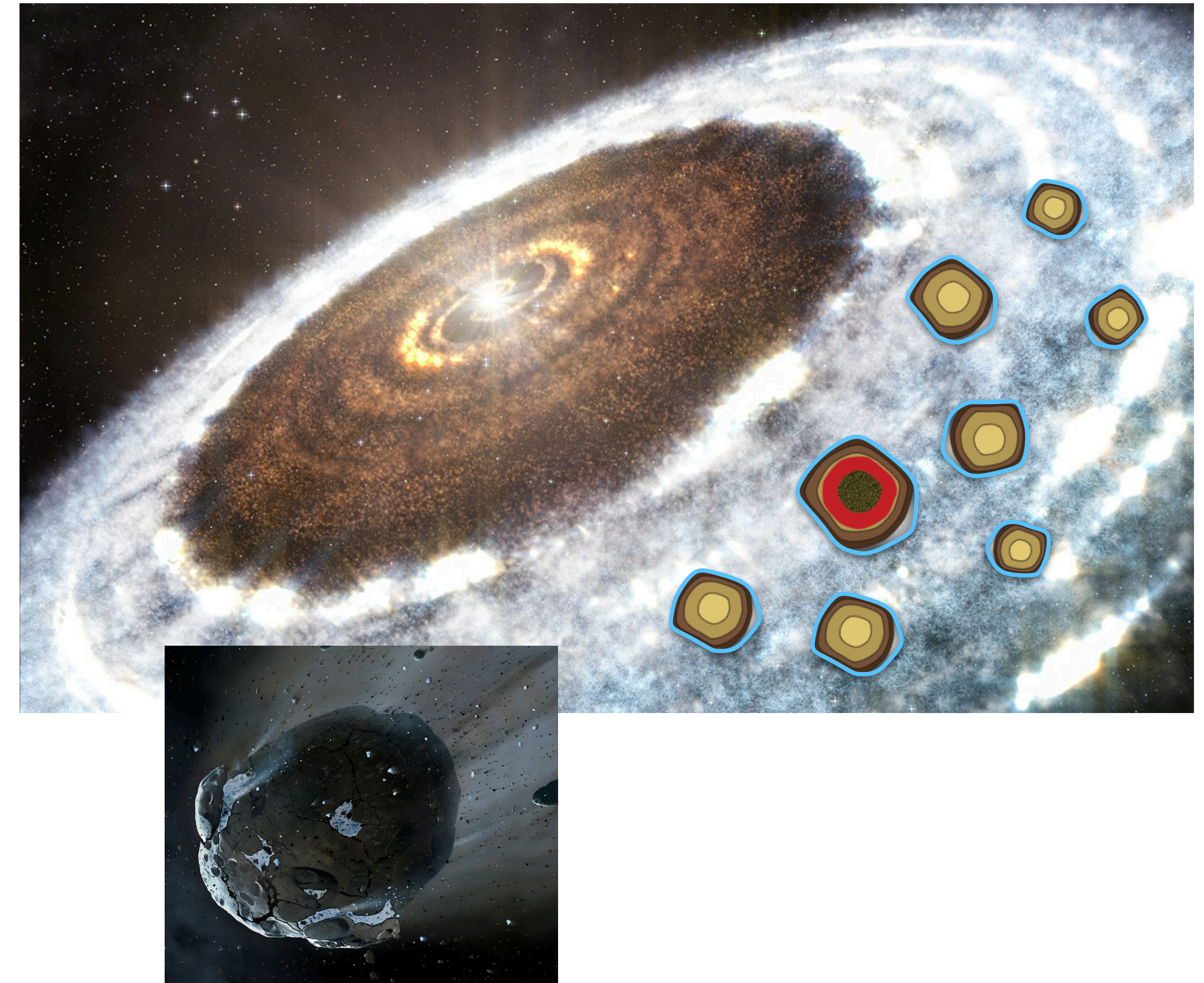
dry



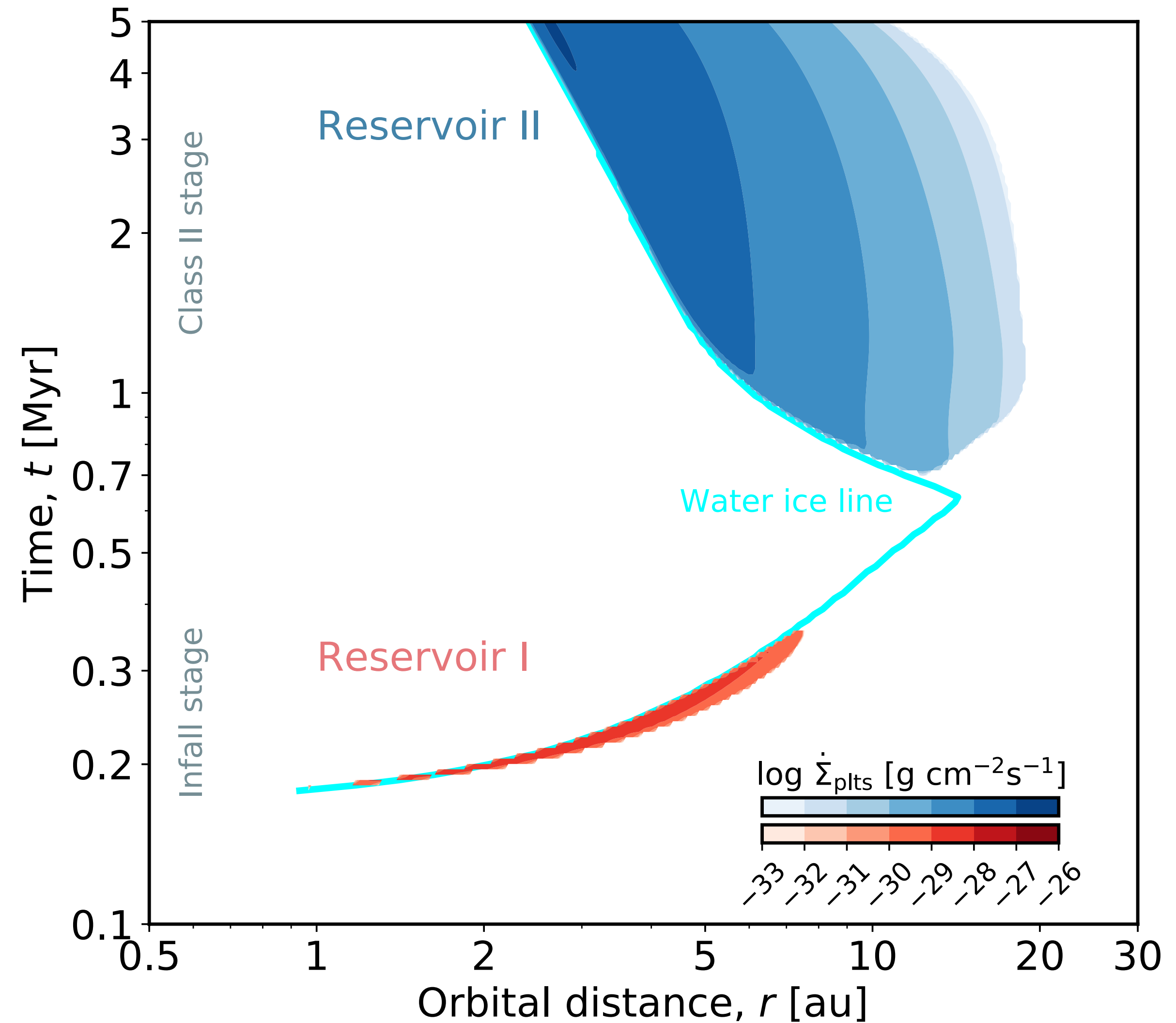
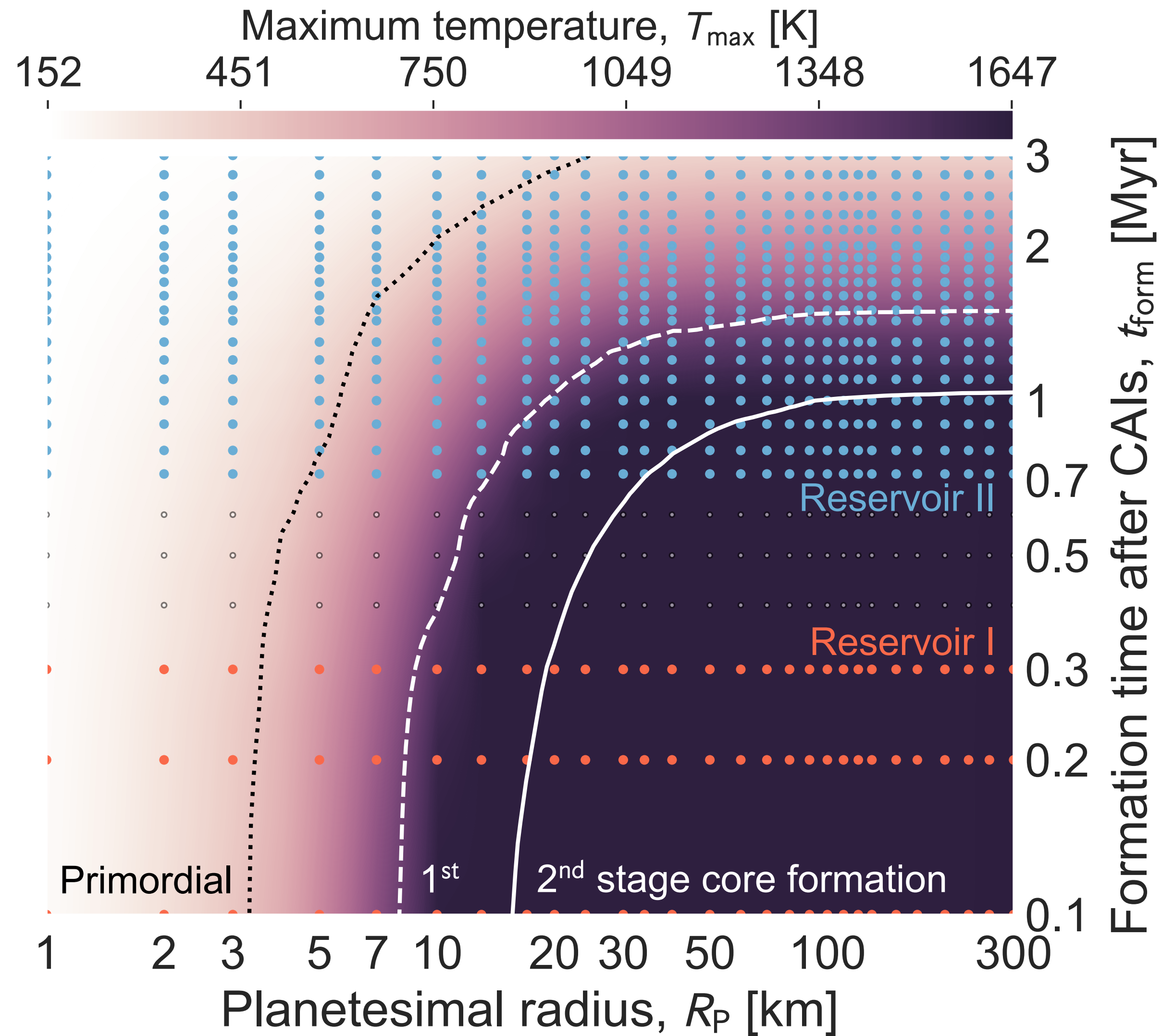
# Getting rid of the water: radiogenic heating



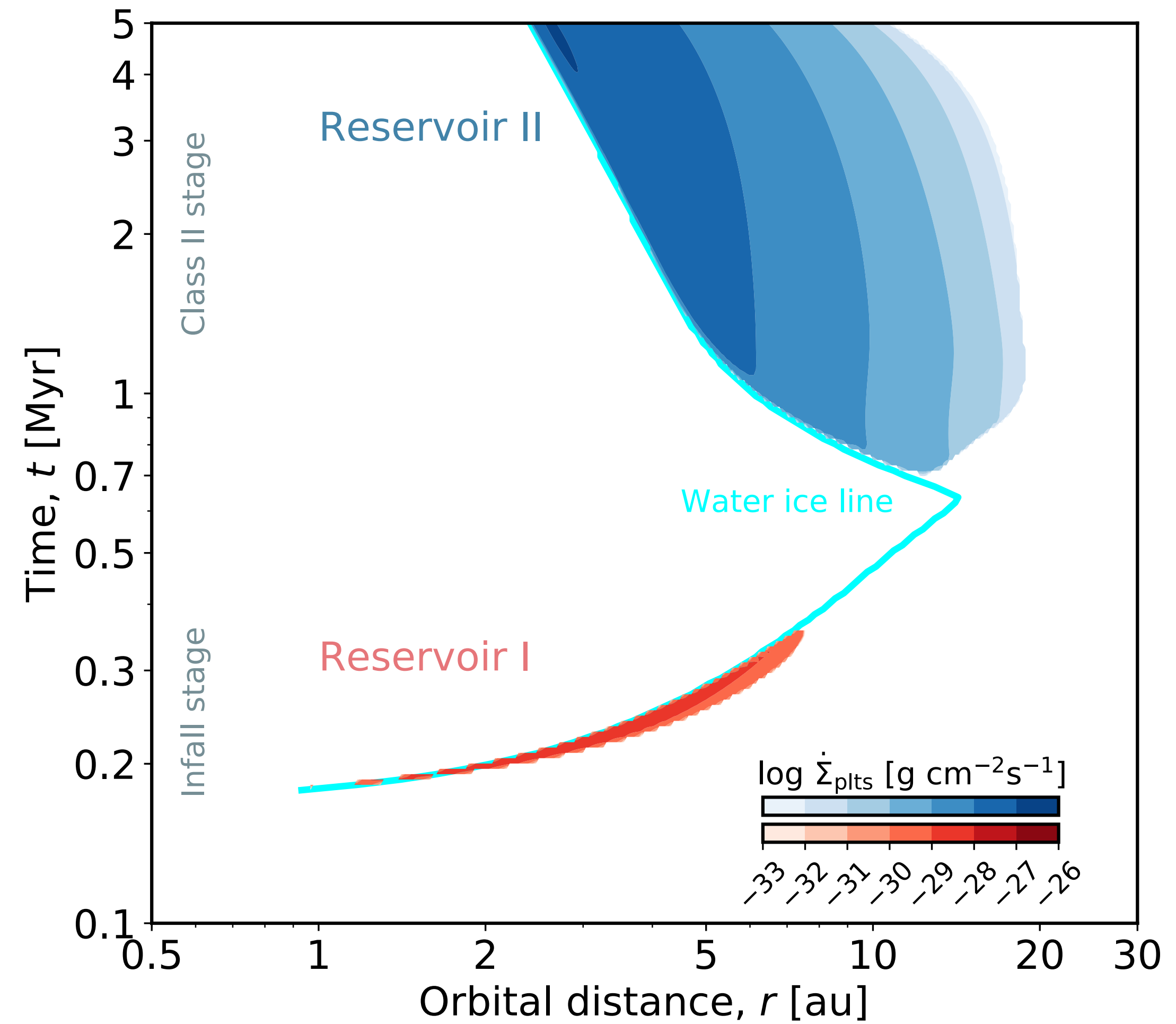
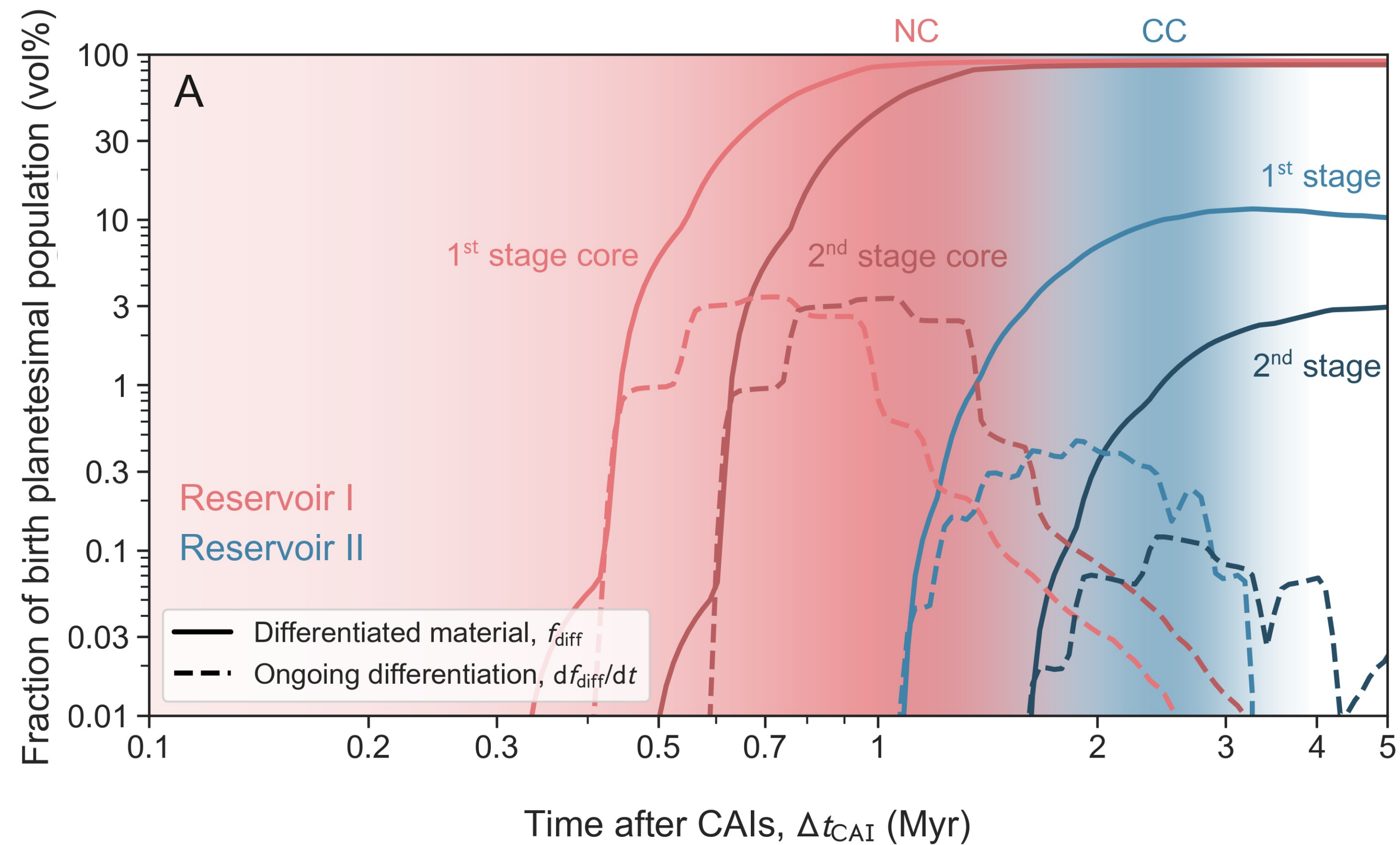
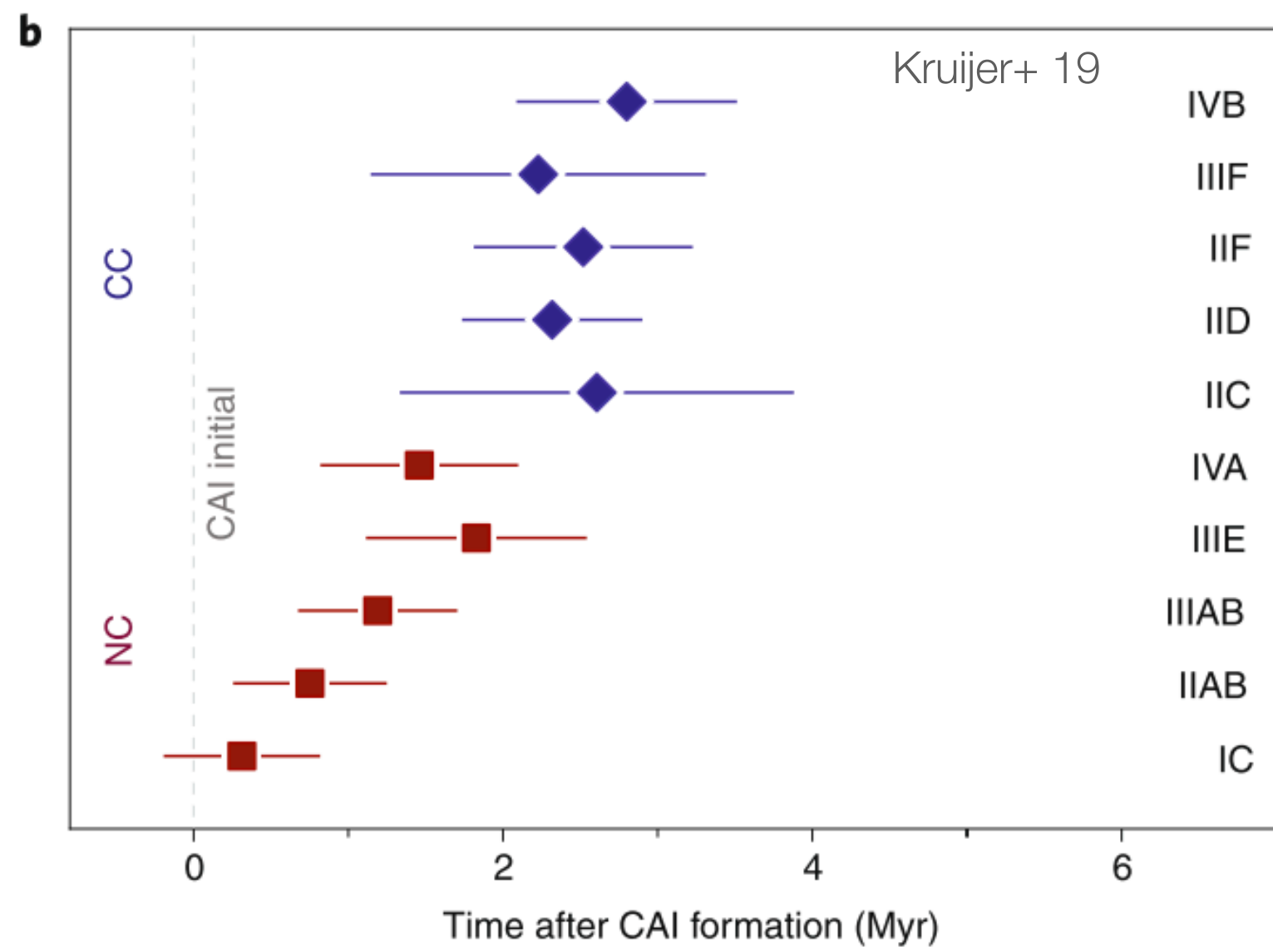
$^{26}\text{Al}$ -heated icy planetesimals forming planets



# Compositional bifurcation of reservoirs

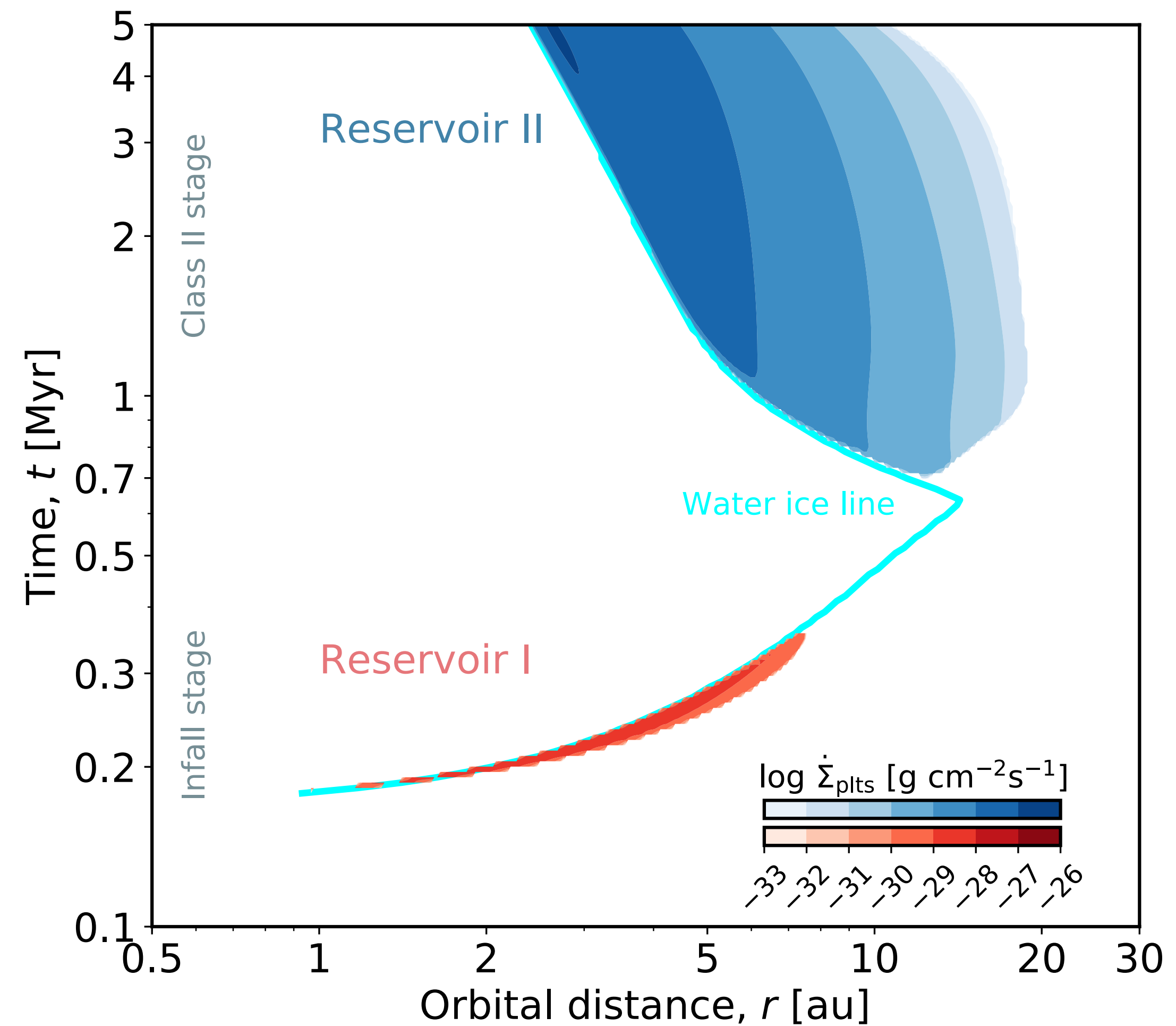
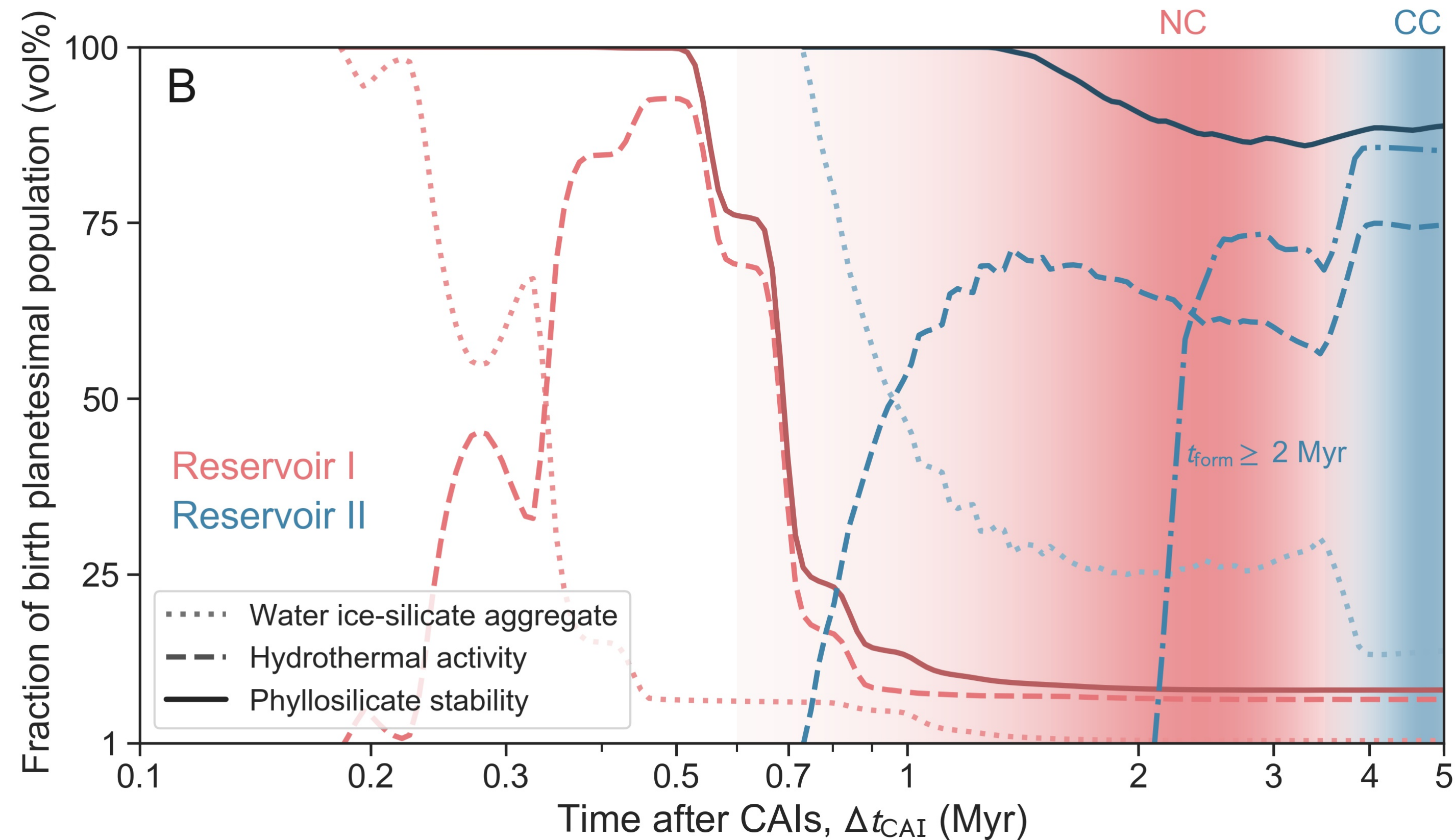
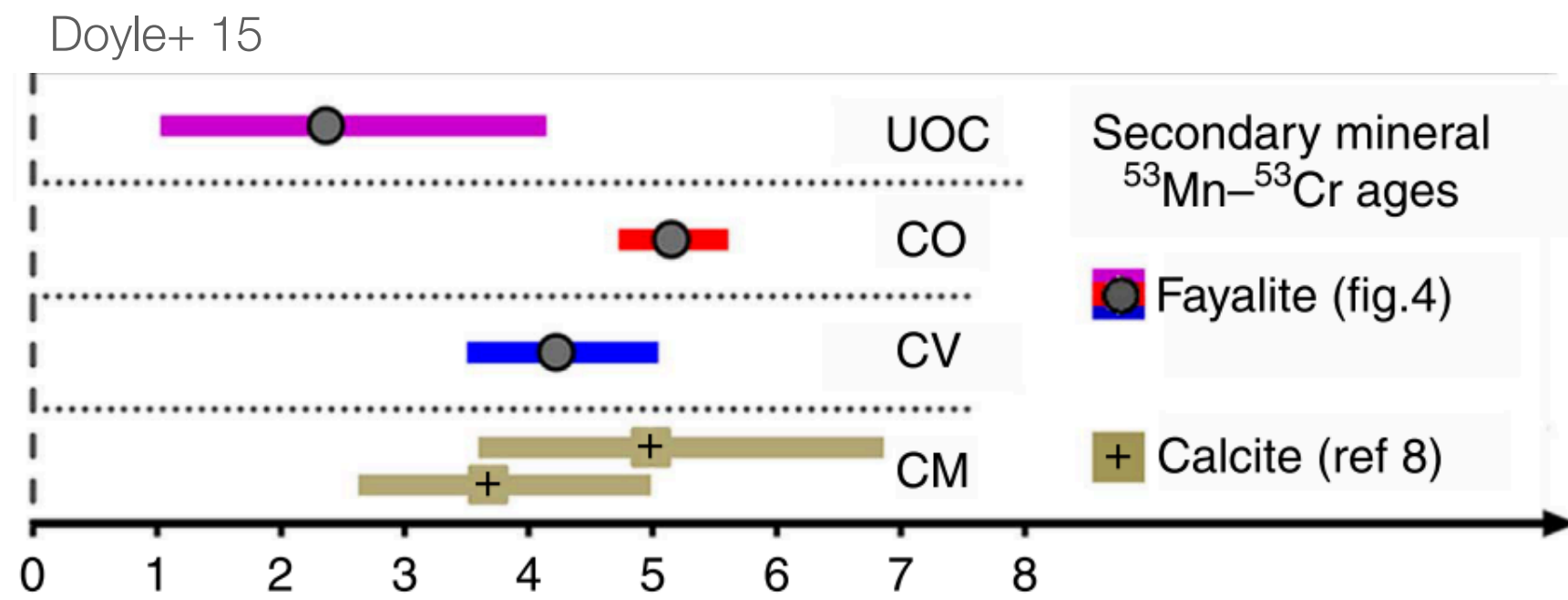


# Compositional chronology: Iron core formation

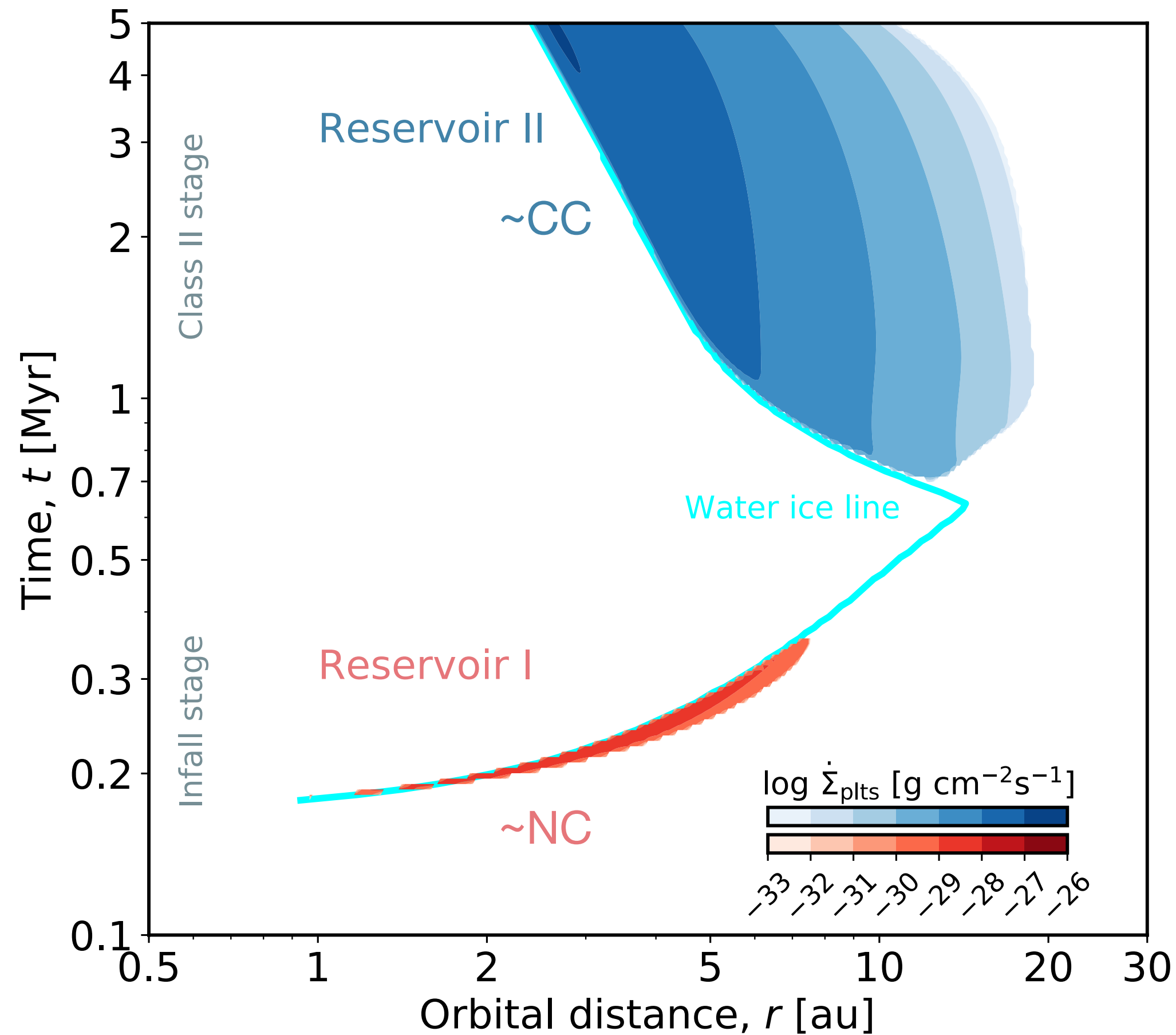


# Compositional chronology: Water loss & hydrothermal activity

Meteorite group	Reservoir	$\Delta t_{\text{CAI}} \pm 2\sigma$ (Myr)
OC	NC	$2.4^{+1.8}_{-1.3}$
CV	CC	$4.2^{+0.8}_{-0.7}$
CO	CC	$5.1^{+0.5}_{-0.4}$
CR	CC	$4.8 \pm 3.0$
CI	CC	$4.9 \pm 0.7$
CM	CC	$4.8^{+0.5}_{-0.4}$
Tagish Lake	CC	$4.7^{+1.3}_{-1.1}$
CC mean		$4.8 \pm 0.6$



# Earliest compositional bifurcation of planetary building blocks



- Model reproduces temporal, spatial, mass and compositional constraints of the early Solar System
  - ▶ Reduced need for secondary dynamics
  - ▶ Rocky planets seeded *before* giant planets
  - ▶ Absence of super-Earths in Solar System
- Heterogeneous water accretion to inner Solar System:
  - ▶ **Water-depleted**  $\rightarrow$  **dry**  $\rightarrow$  **water-rich**  
(Sarafian+ 17a,b; Peslier+ 17; Piani+ 17,18; McCubbin & Barnes 19)
  - ▶ Wet inner planetary systems?
  - ▶ Connects accretion sequence to potentially observable disk parameters