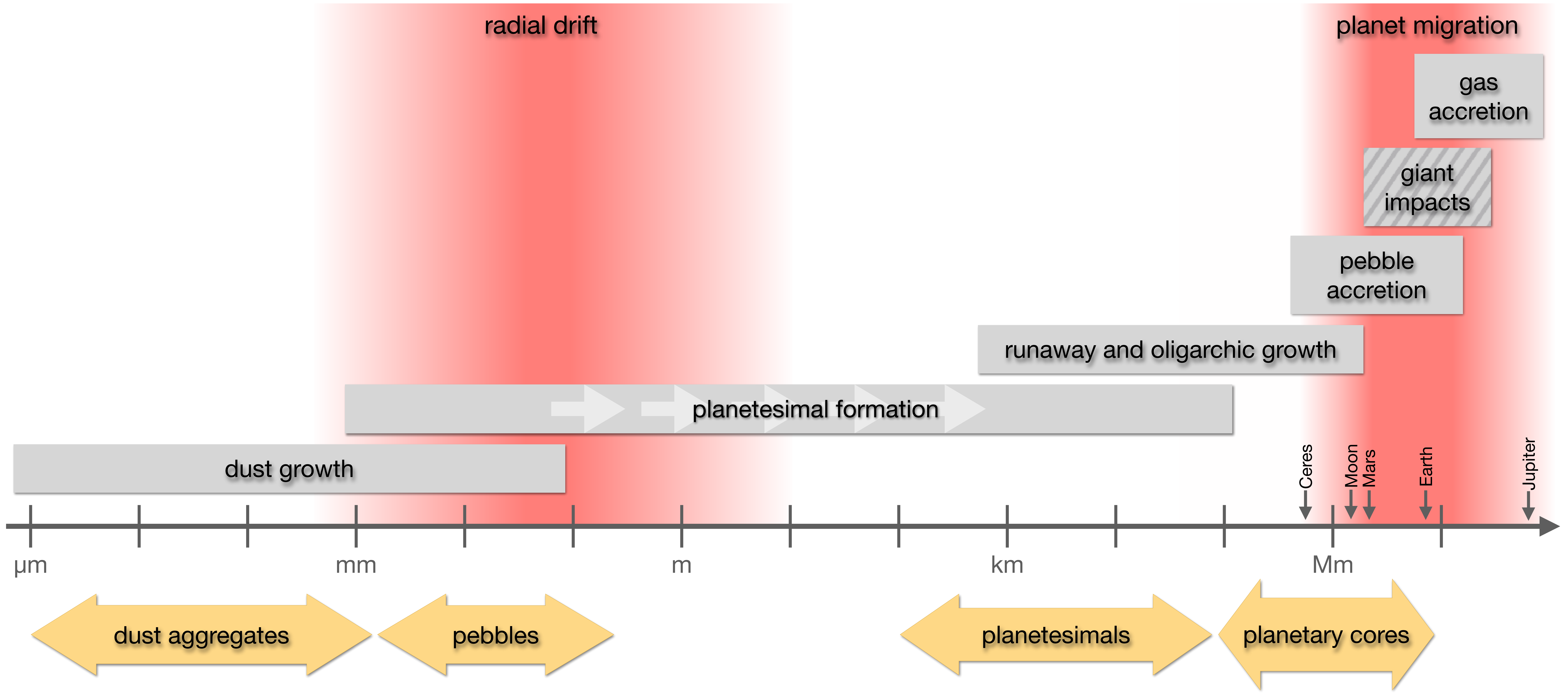
FROM DUST GROWTH TO PLANET FORMATION

Joanna Drążkowska

MIAPP, Garching, 25.10.2021

image Credit: Alan Brandon/Nature

OVERVIEW OF THE PLANET-FORMING PROCESSES



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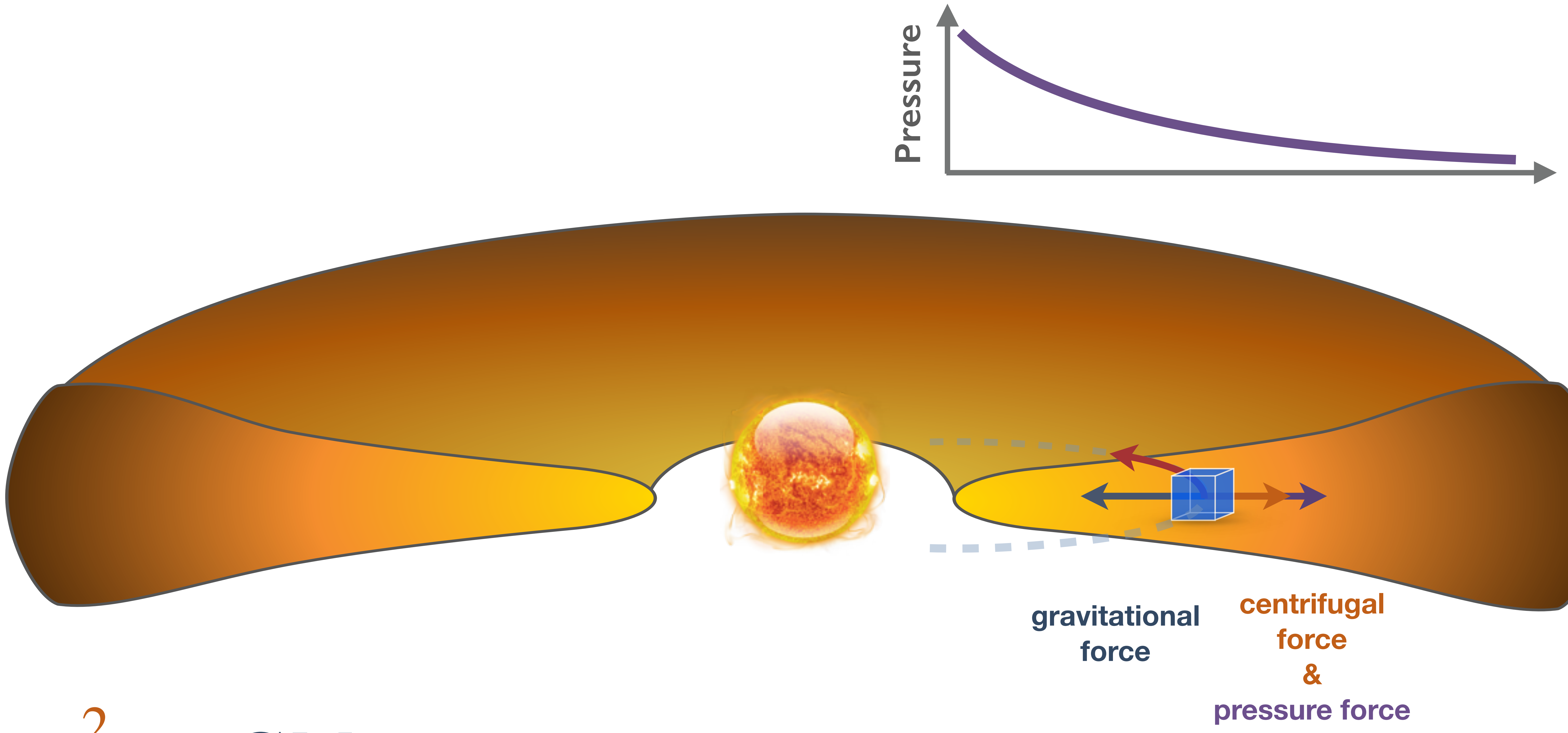
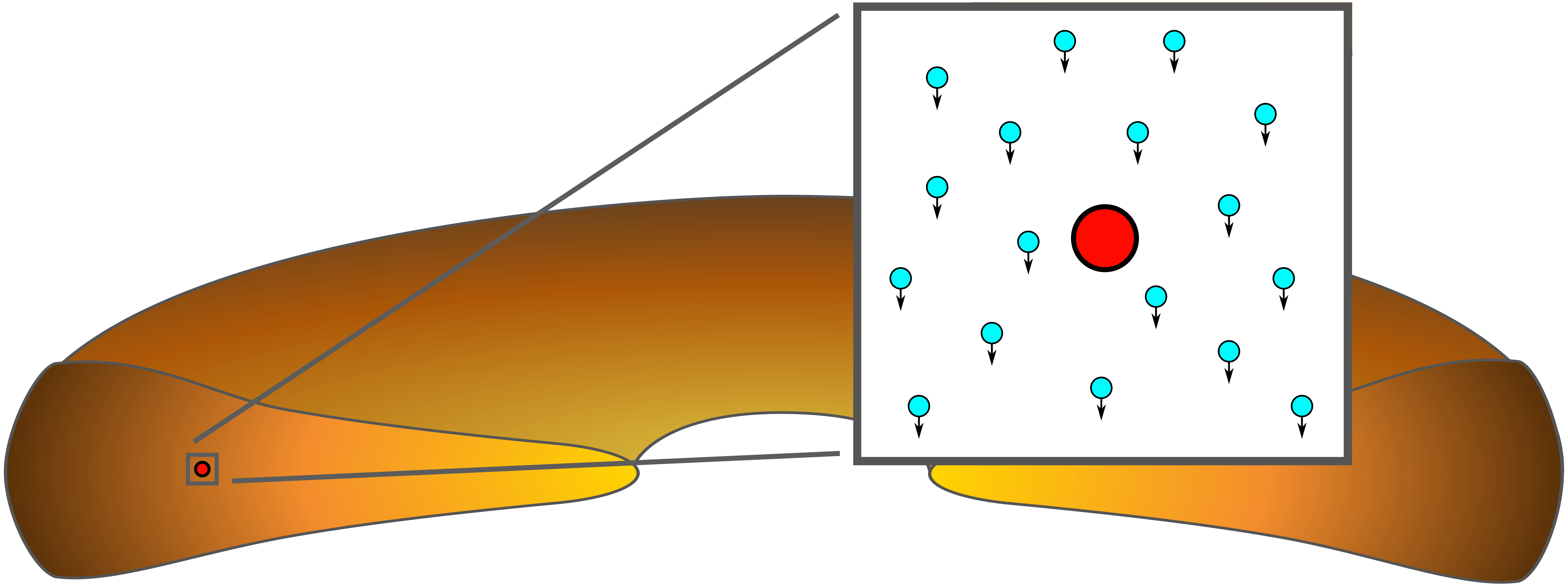
CIRCUMSTELLAR DISK 1.0.1.



$$\frac{v_\phi^2}{r} = \frac{GM_\star}{r^2} + \frac{1}{\rho}\frac{dP}{dr} \longrightarrow v_\phi \approx v_K \cdot \left(1 - \eta\right)$$

Gas rotation is typically ~0.5% slower than Keplerian

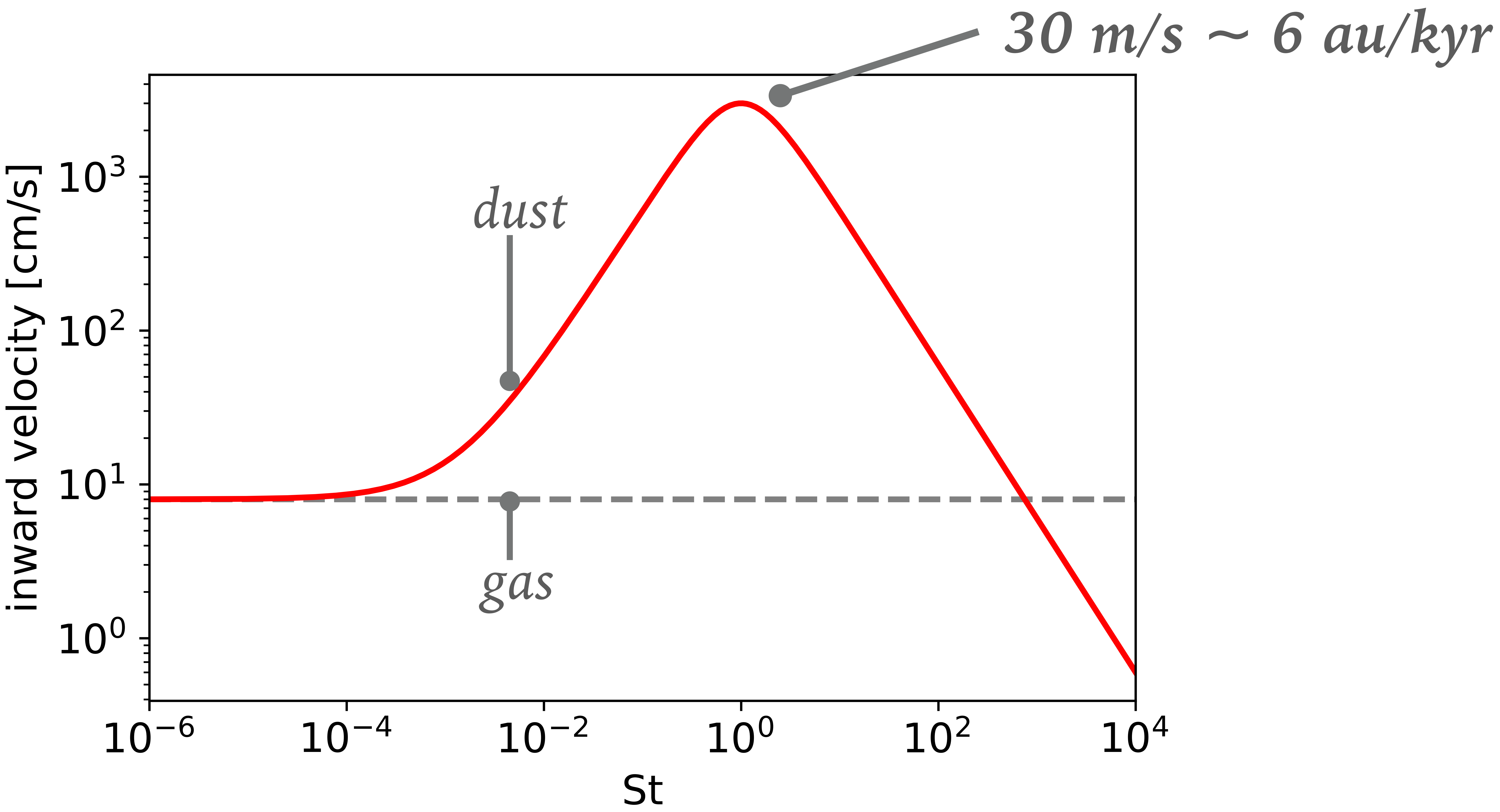
DUST IS COUPLED TO THE GAS



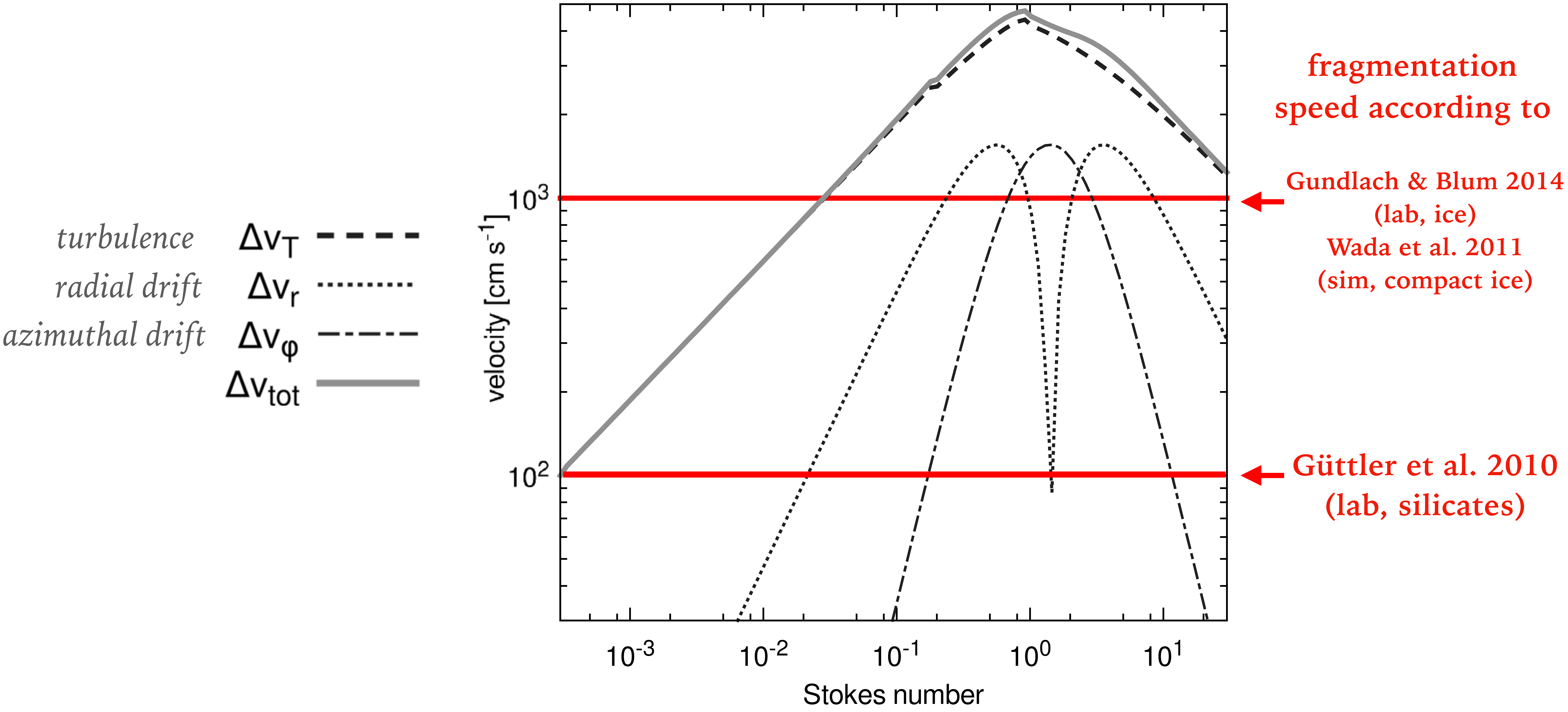
The strength of the gas-dust coupling is parametrised with the Stokes number

$$\mathrm{St} = \frac{t_{\mathrm{stop}}}{t_{\mathrm{orb}}}$$

RADIAL DRIFT – CONSEQUENCE OF THE DUST-GAS COUPLING



COLLISION SPEEDS



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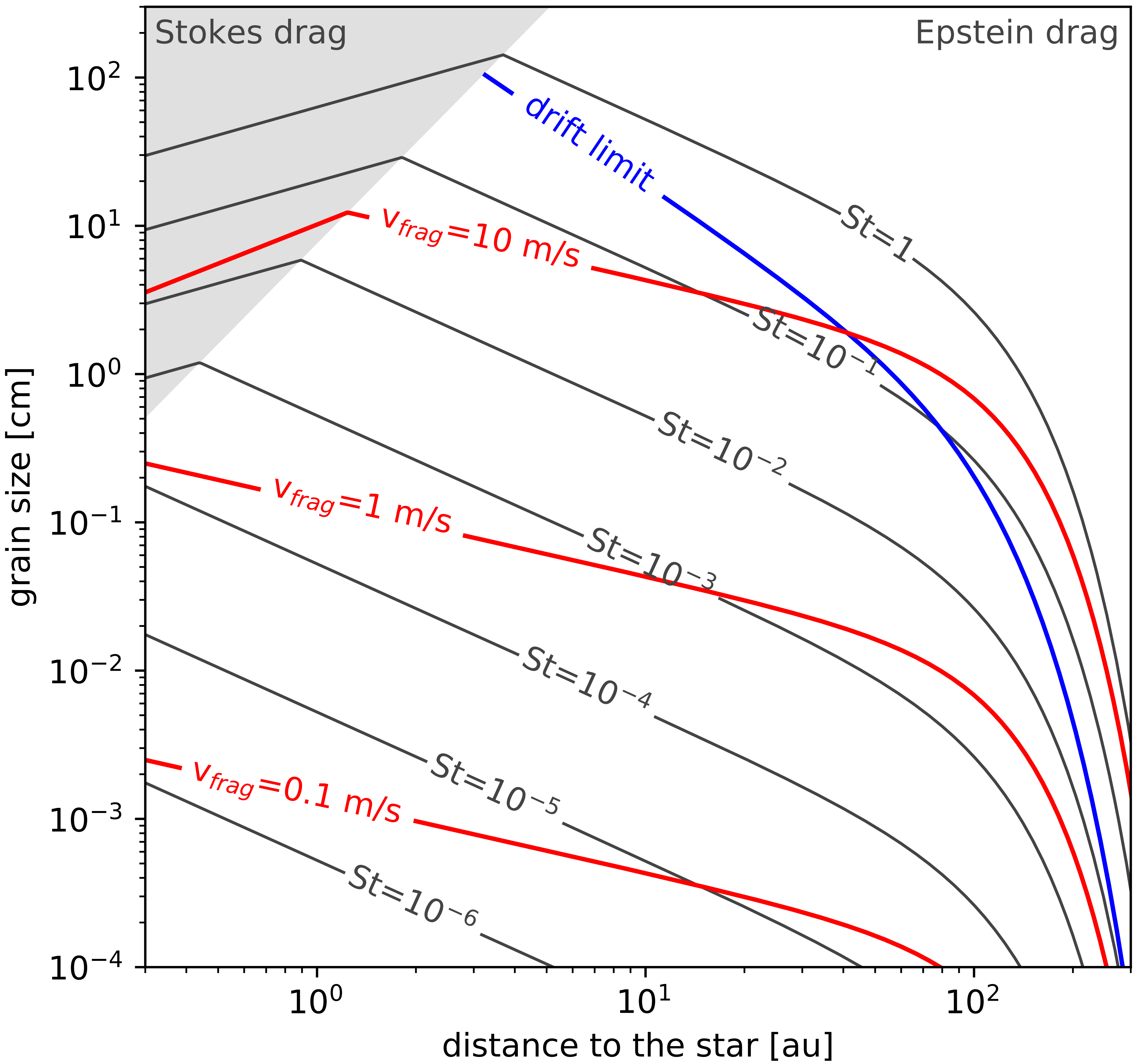
GROWTH BARRIERS



Dust growth is restricted by **radial drift** when the drift timescale is shorter than the growth timescale and by **fragmentation** when the collision speed exceeds a threshold value v_{frag}.

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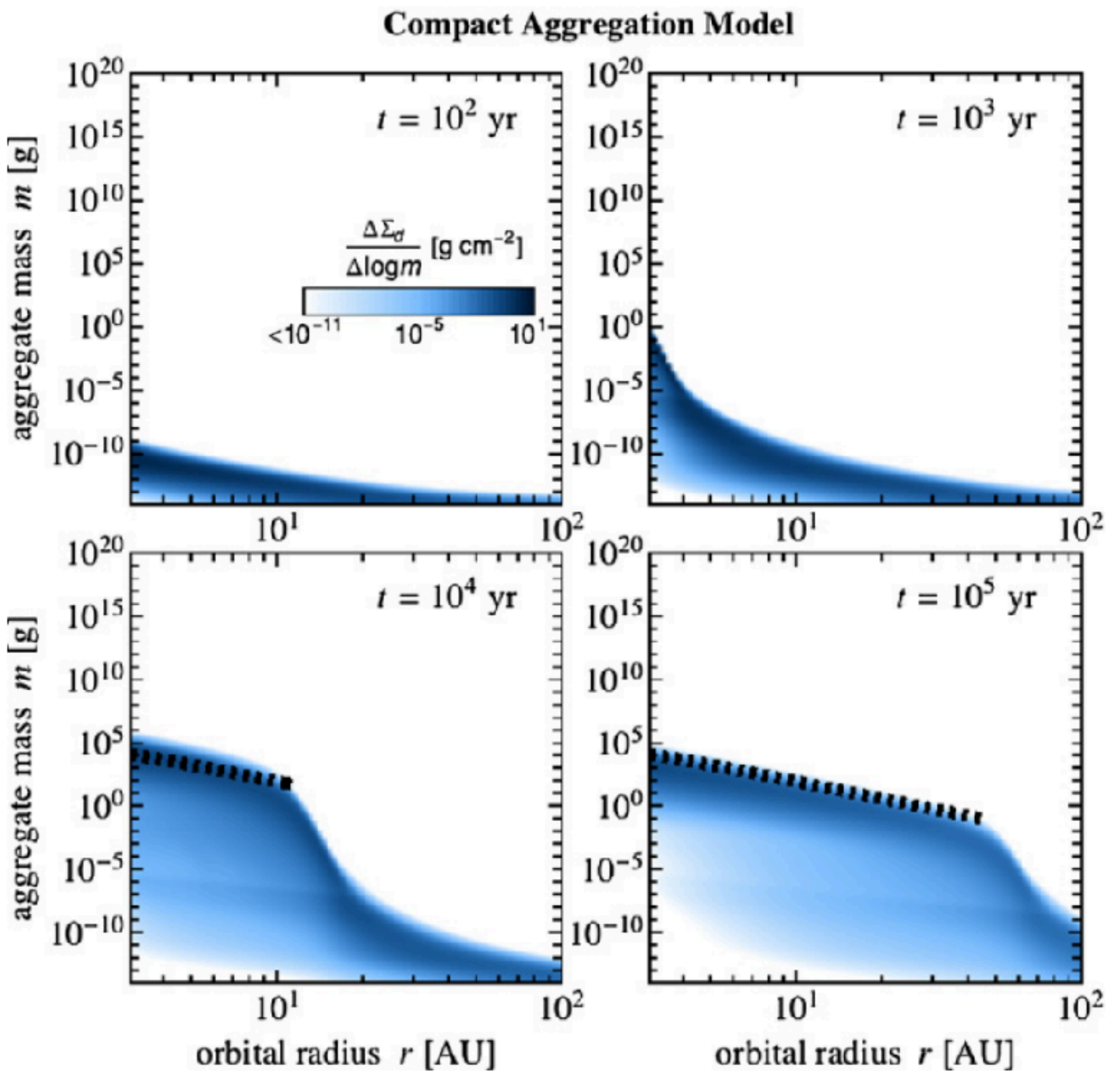
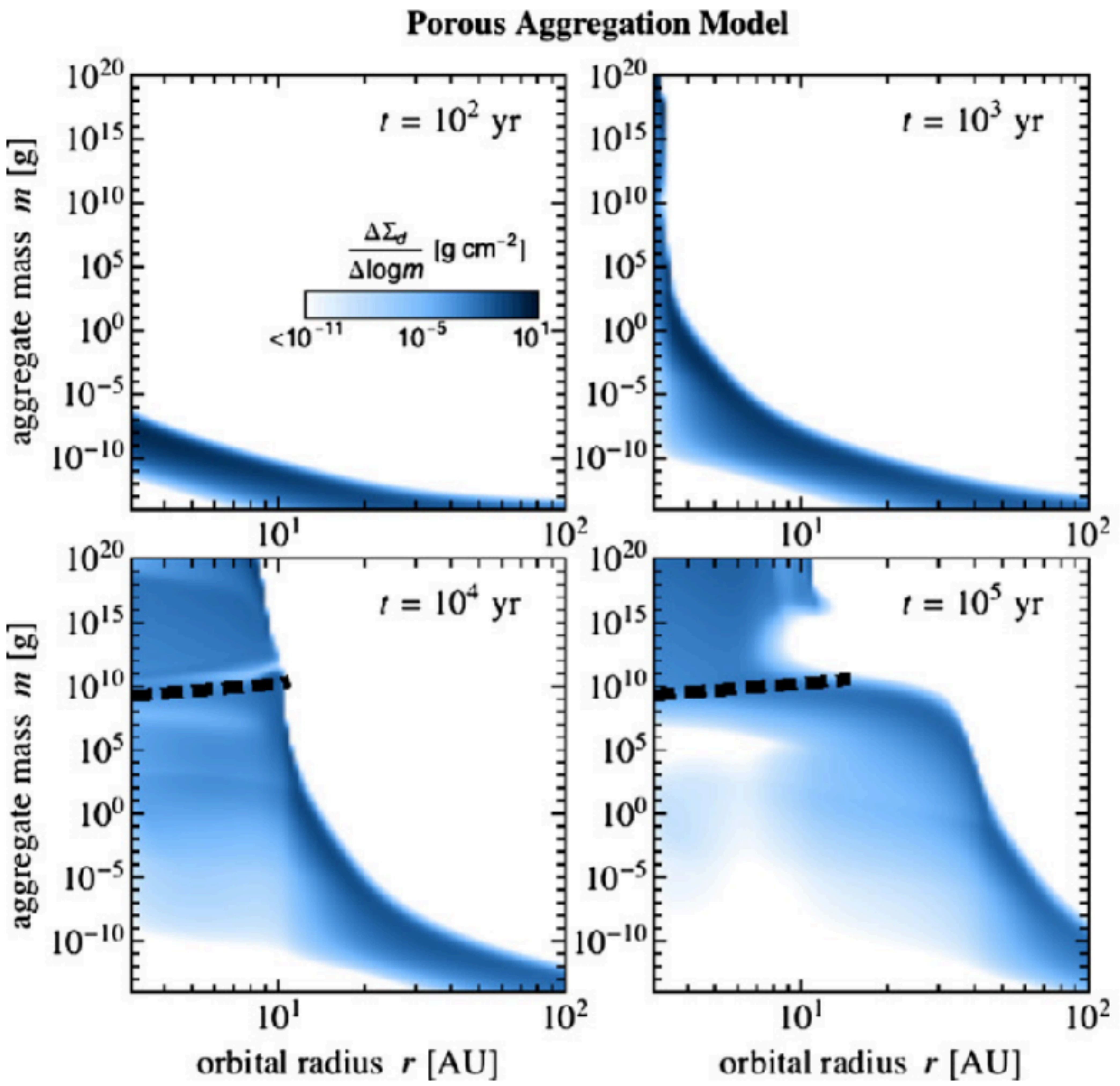
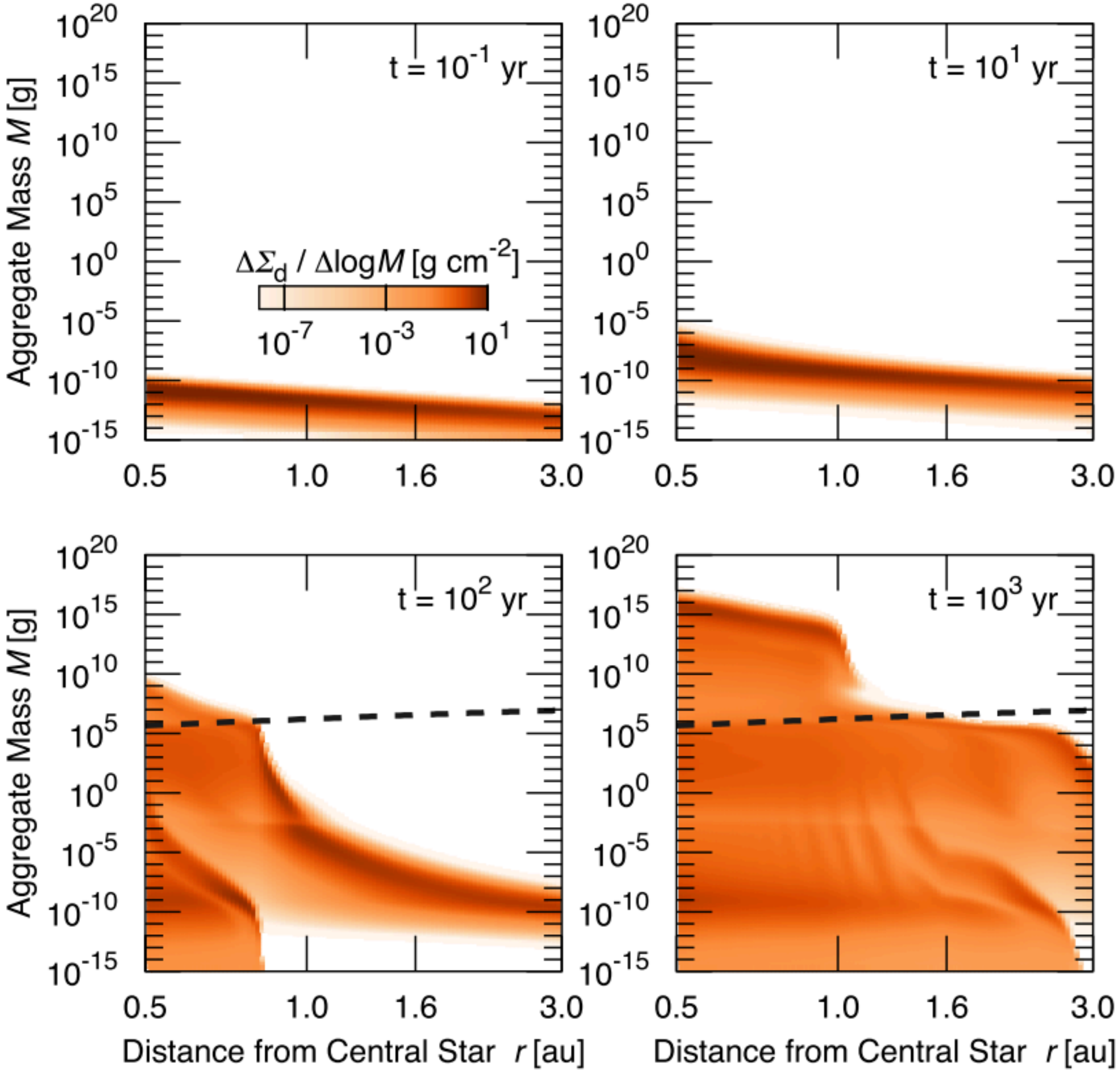
DIRECT GROWTH MAY BE POSSIBLE IN THE STOKES DRAG REGIME

Okuzumi et al. 2012; however, Schräpler, Blum, et al. 2017 showed that including erosion stops the growth.



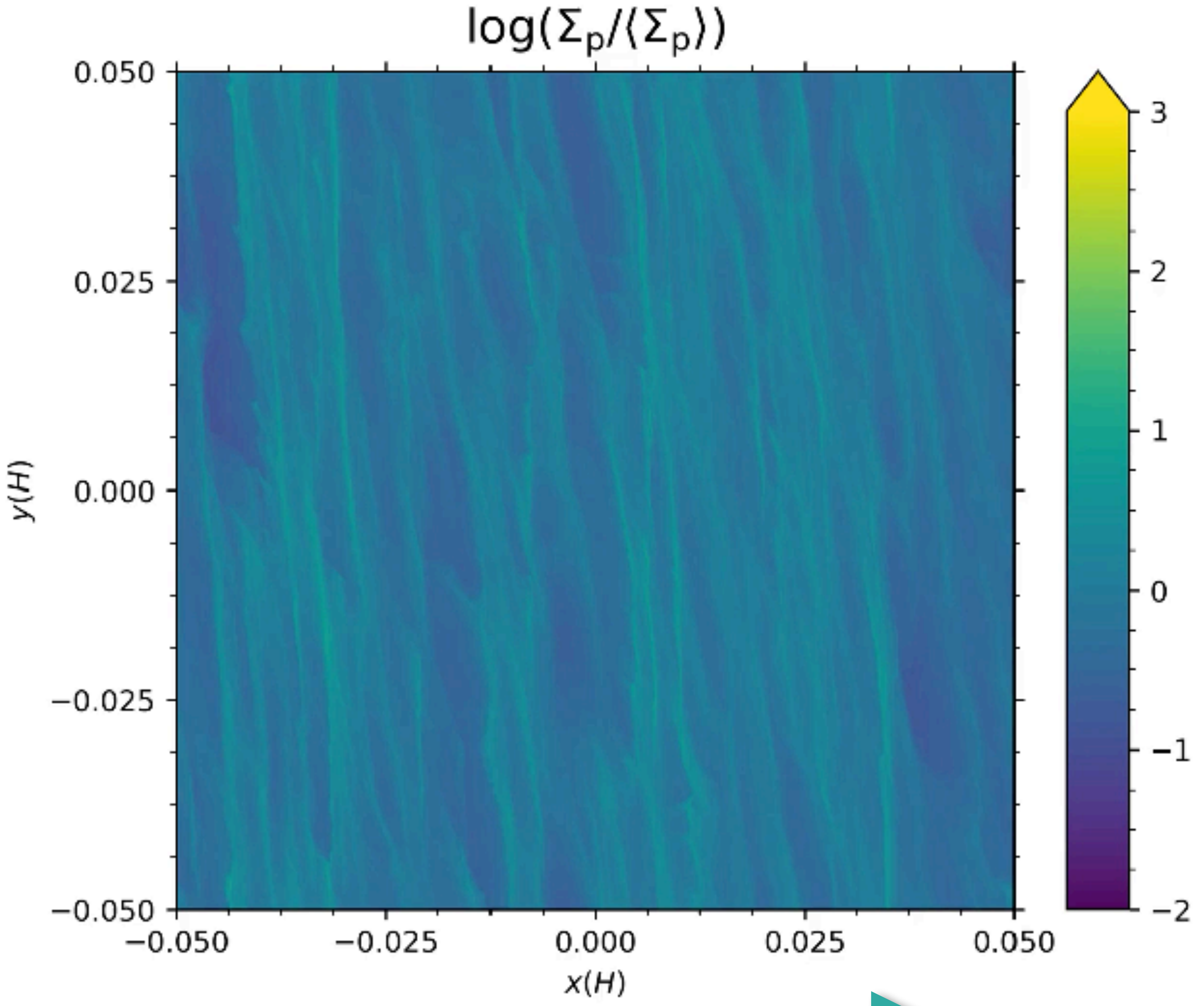


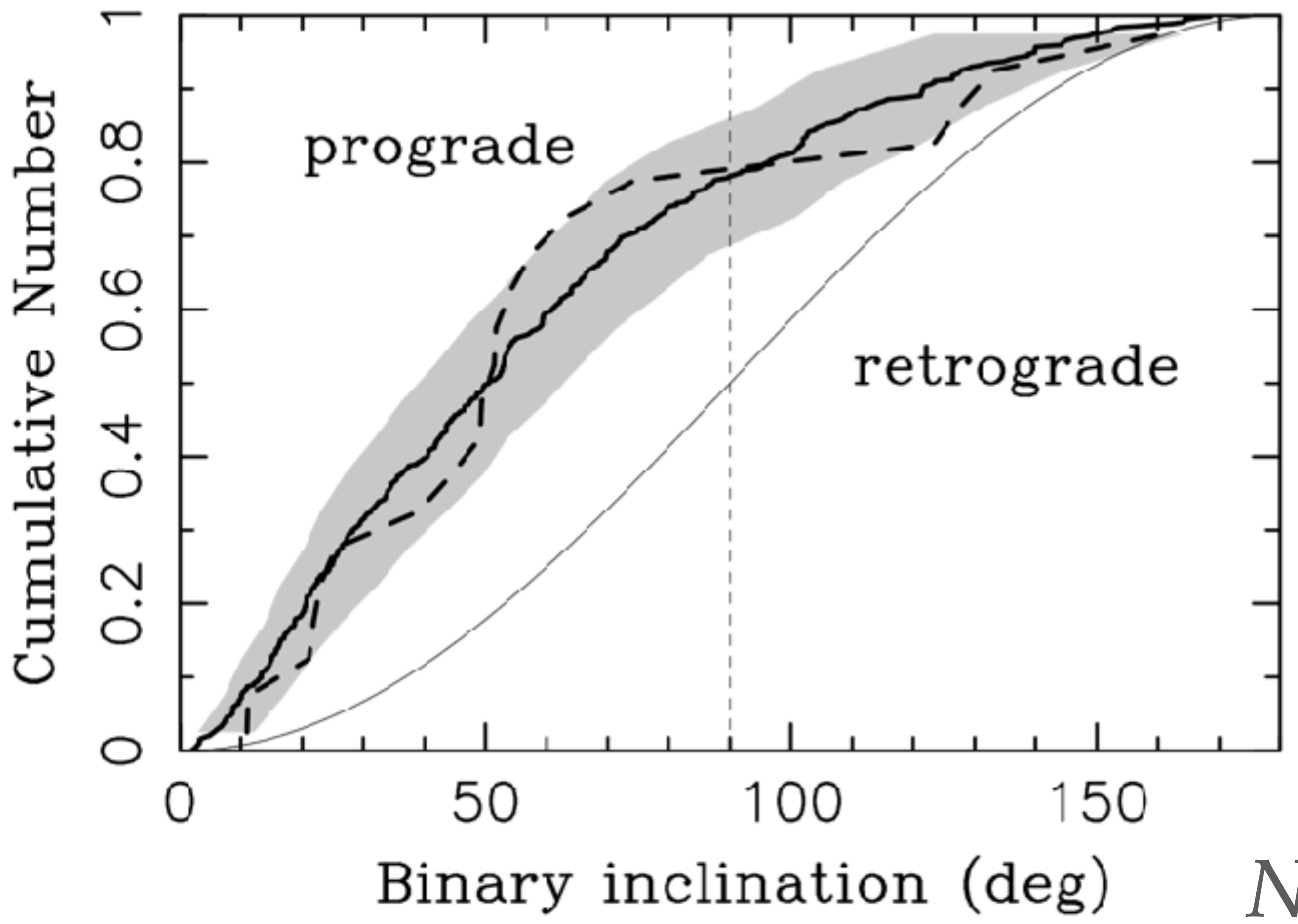
DIRECT GROWTH MAY BE POSSIBLE IN THE STOKES DRAG REGIME

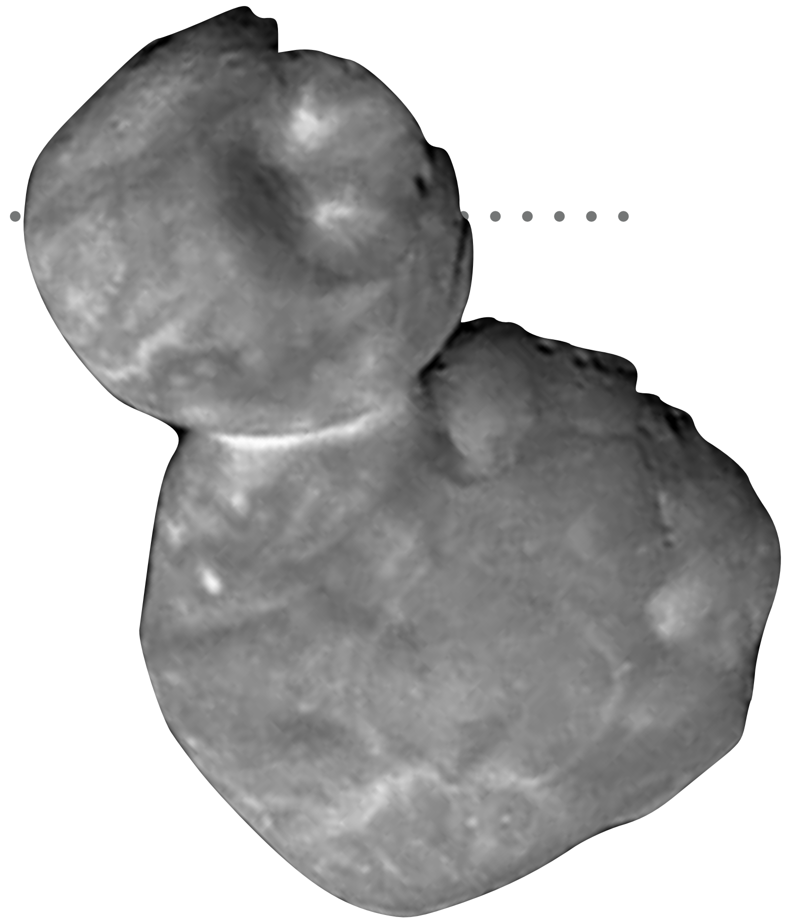


Homma et al. 2019: breakthrough the fragmentation barrier is possible thanks to sticky organic mantles.

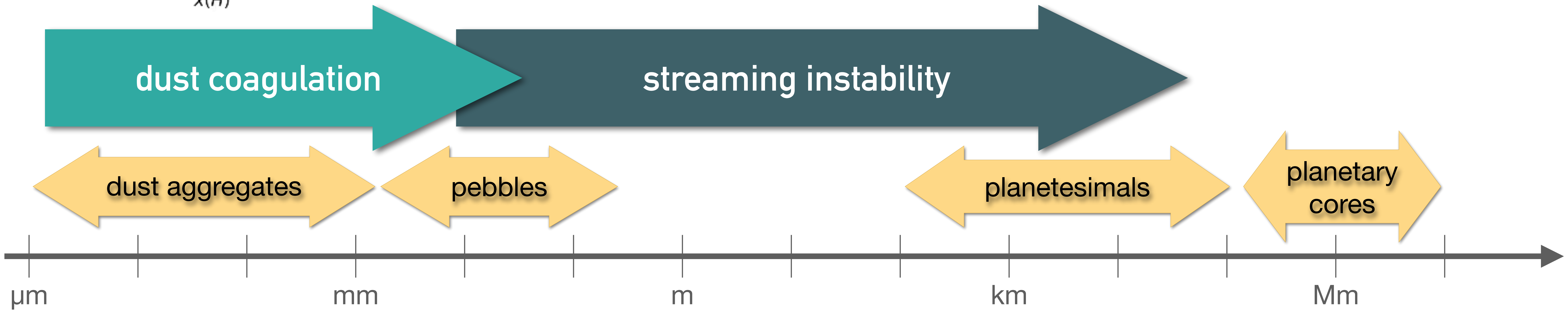
PLANETESIMAL FORMATION BY THE STREAMING INSTABILITY





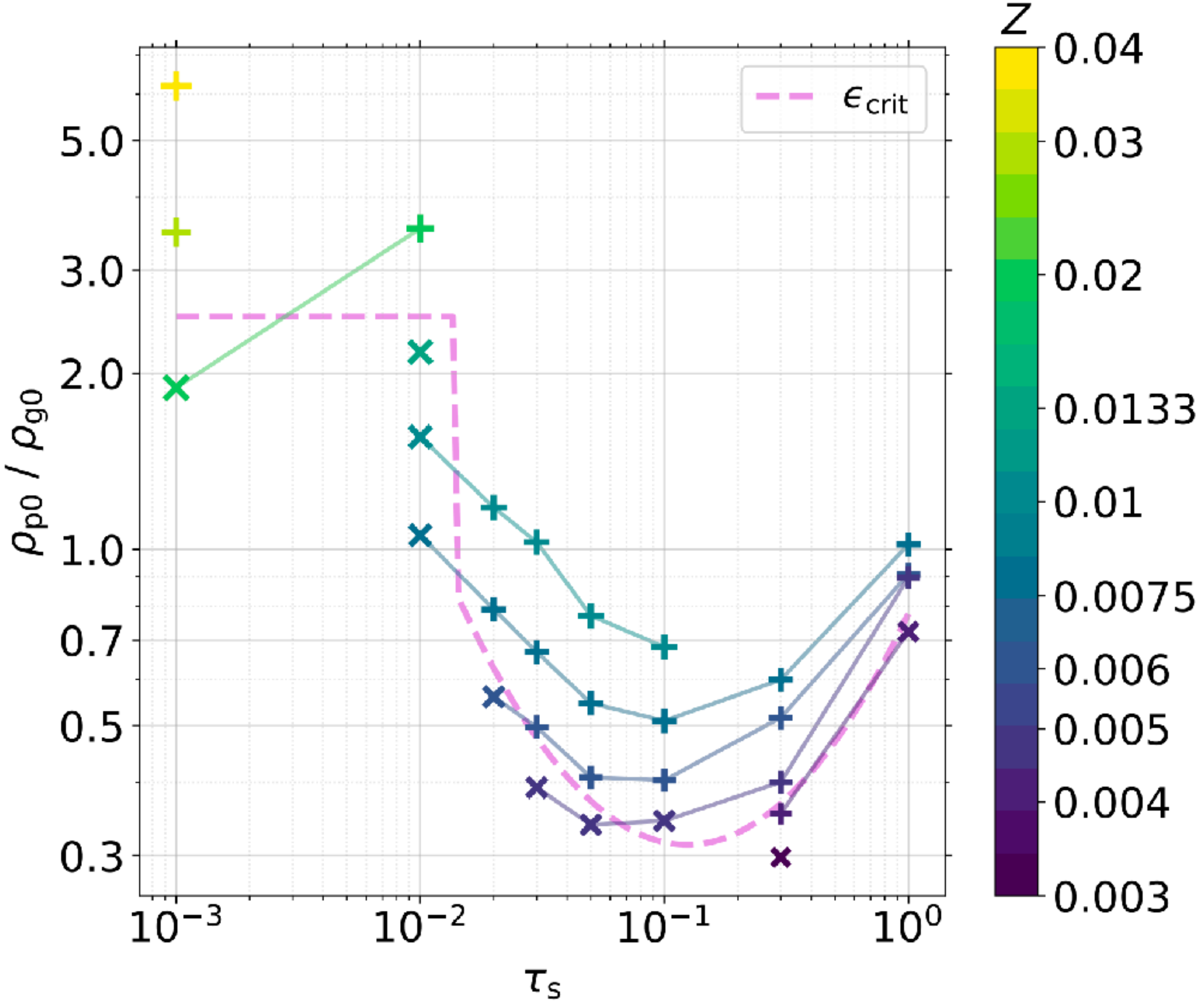


Nesvorný et al. 2019

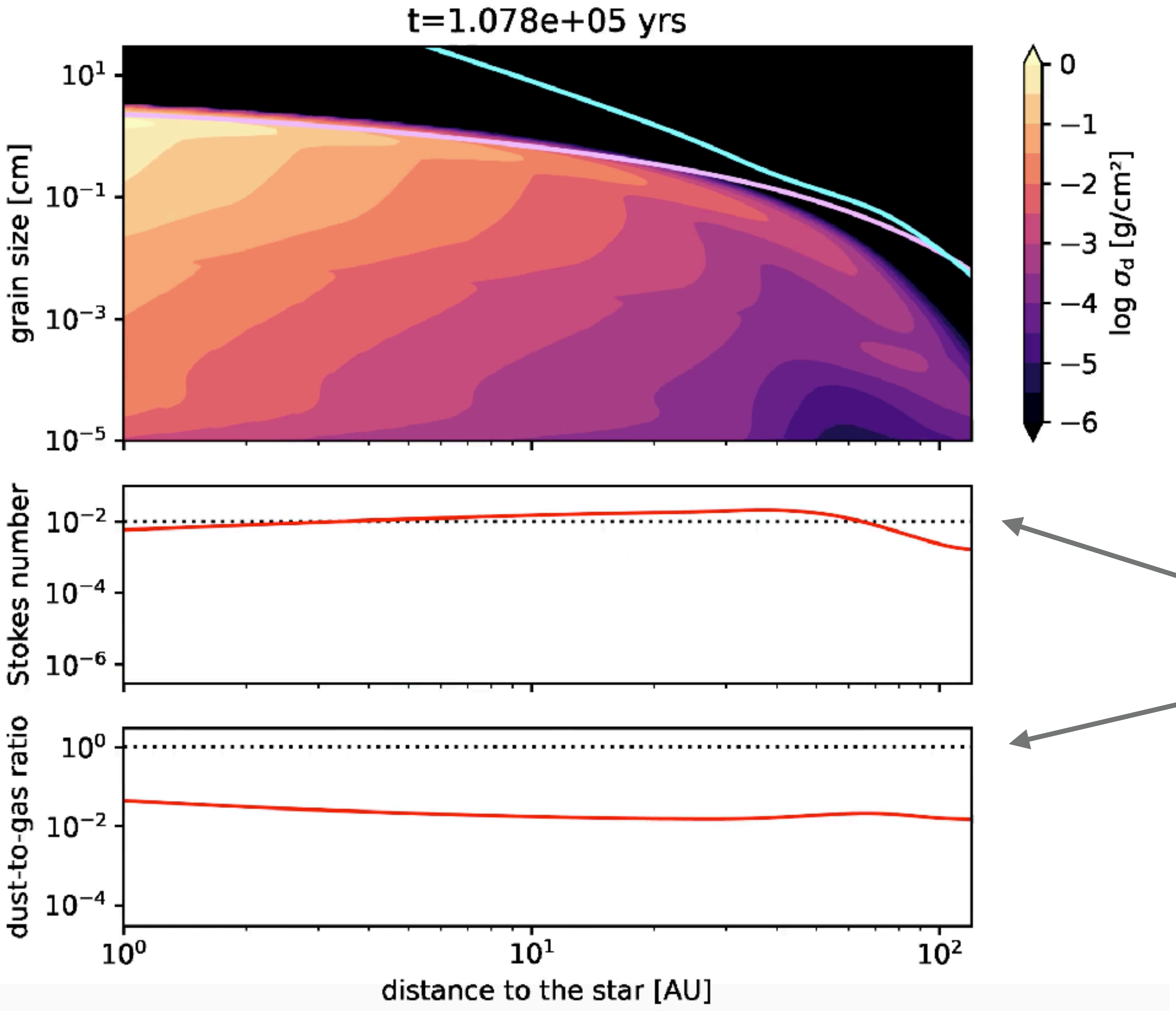


STREAMING INSTABILITY REQUIRES DUST-TO-GAS RATIO ENHANCEMENT

planetesimal formation threshold
Li & Youdin (2021)



HOW TO TRIGGER PLANETESIMAL FORMATION?



- drift barrier

- fragmentation barrier

SI threshold

github.com/stammler/dustpy

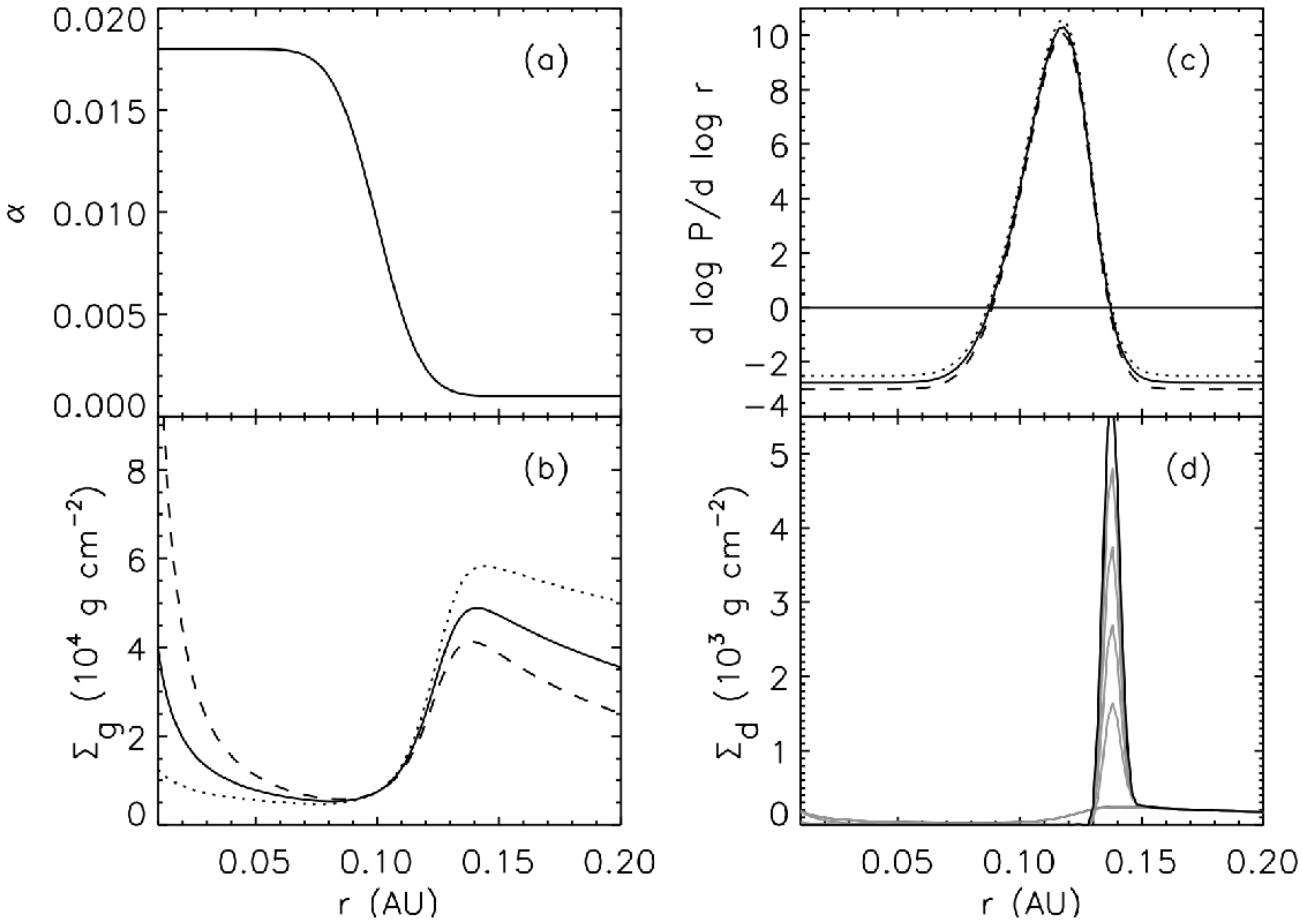
WATER SNOW LINE AS A PRIVILEGED LOCATION FOR PLANET FORMATION

associated pressure bump:
Kretke & Lin 2007
Brauer et al. 2008
Guilera et al. 2020
Charnoz et al. 2021
…

cold finger effect:
Stevenson & Lunine 1988
Cuzzi & Zahnle 2004
Ros & Johansen 2013
Ros et al. 2019
…

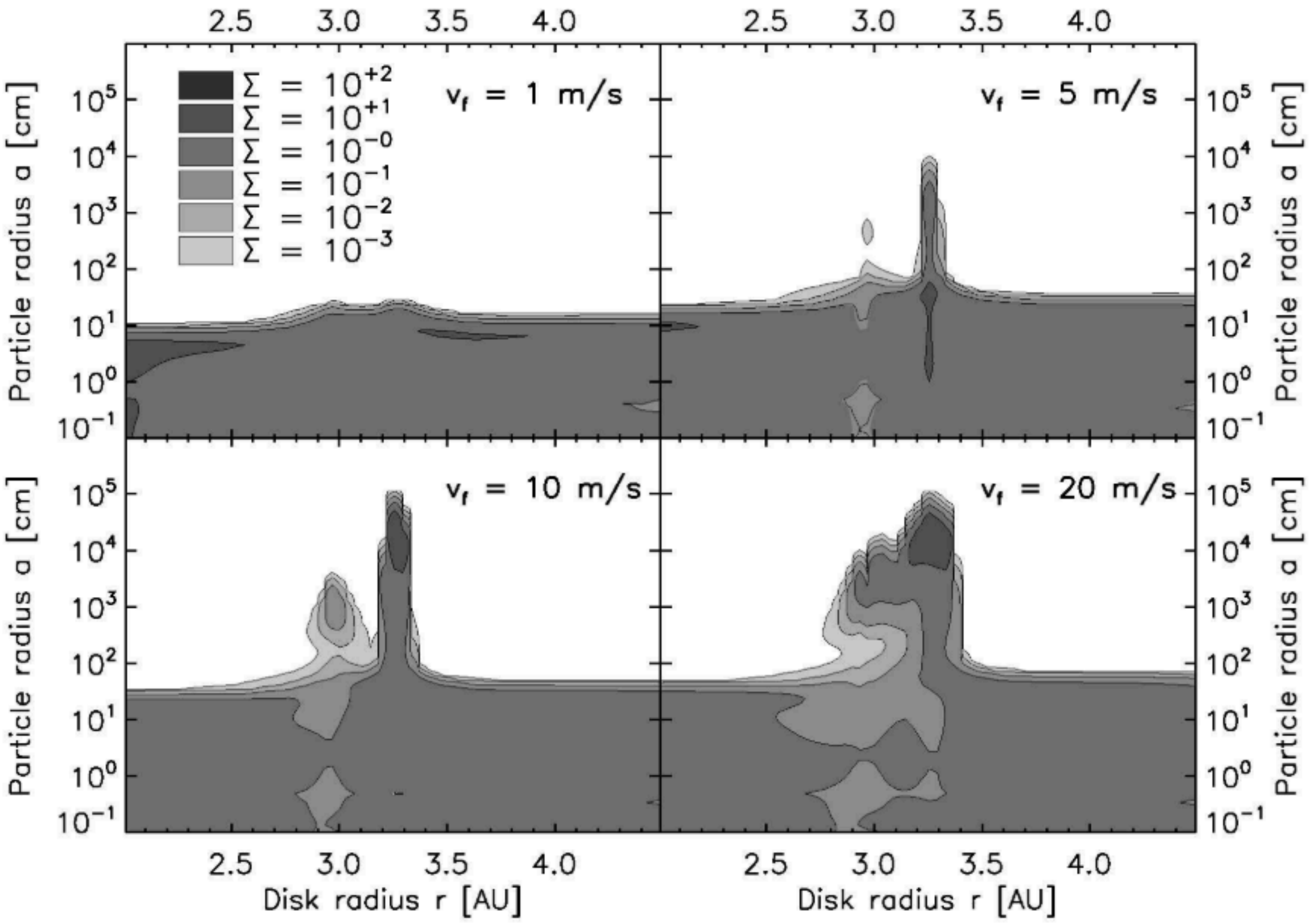
traffic jam / pile-up:
Birnstiel et al. 2010
Ida & Guillot 2016
Schoonenberg & Ormel 2017
Hyodo et al. 2021
…

SNOW LINE: PRESSURE BUMP BECAUSE OF VISCOSITY TRANSITION



Kretke & Lin 2007

SNOW LINE: PRESSURE BUMP BECAUSE OF VISCOSITY TRANSITION



strong pressure bump

+

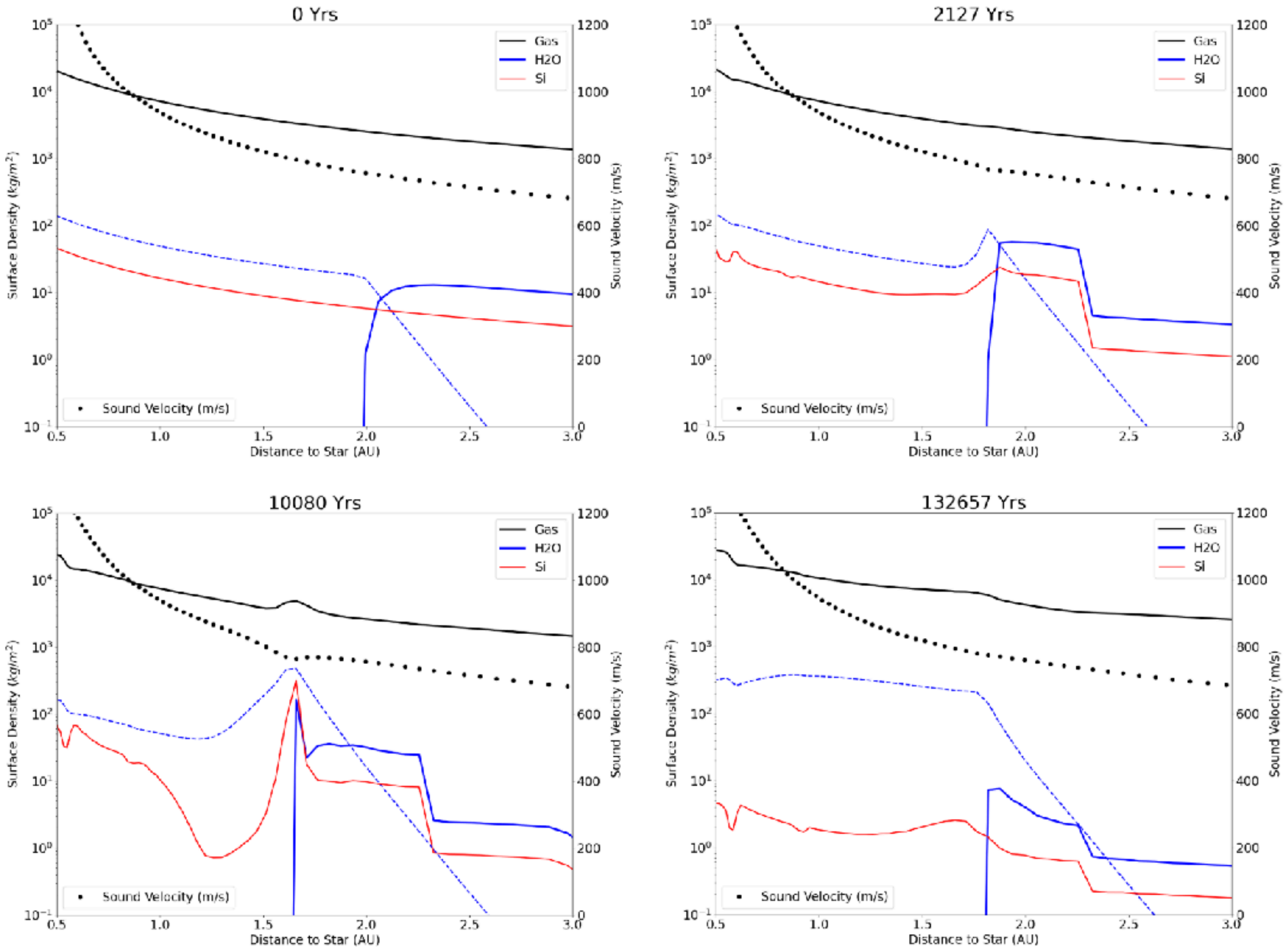
high fragmentation velocity

=

direct growth to planetesimals

Brauer et al. 2008

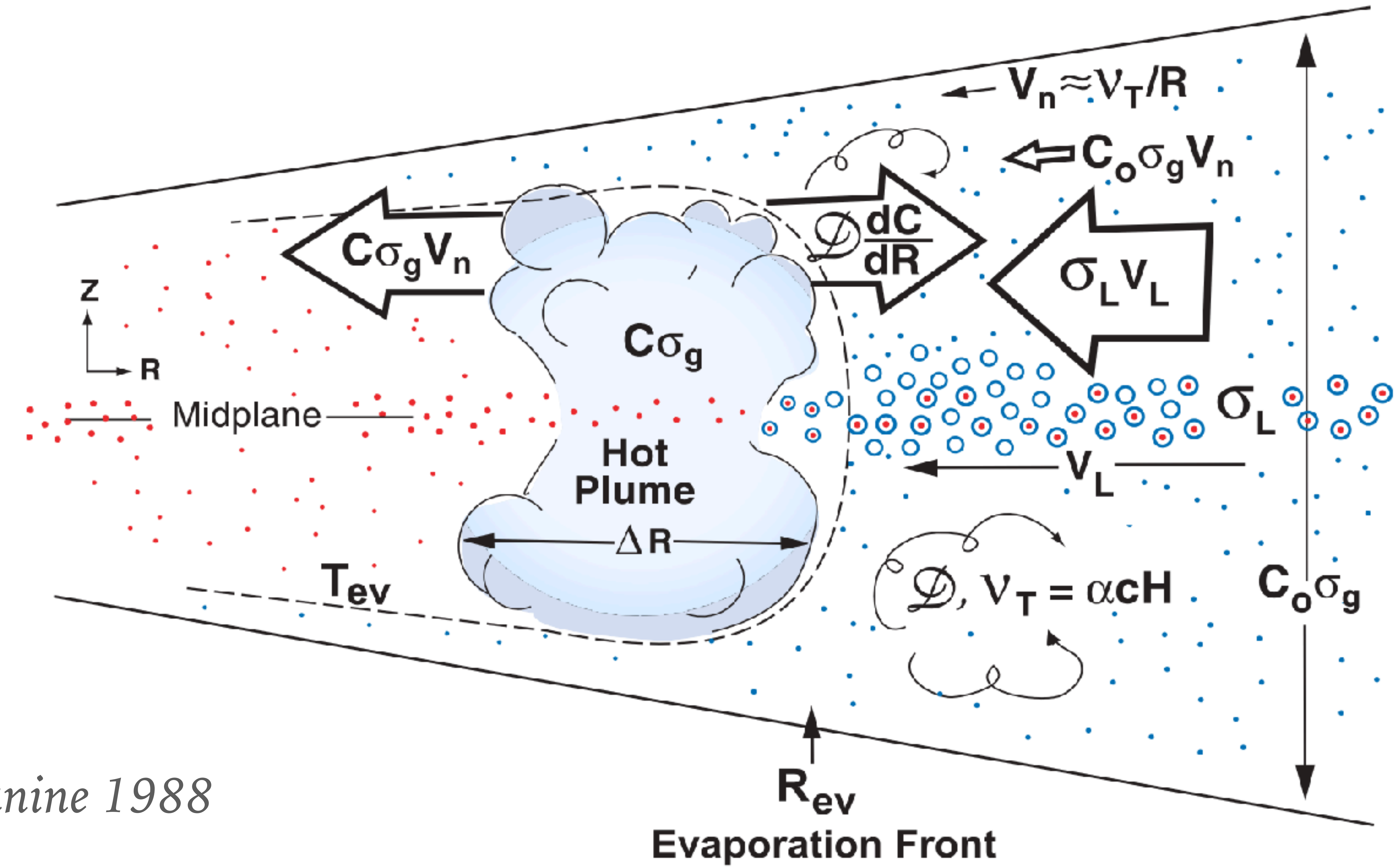
SNOW LINE: PRESSURE BUMP BECAUSE OF THE SOUND SPEED CHANGE



Charnoz et al. 2021

however: Gárate et al. 2019 finds the pressure bump only for Z ≥ 3%

SNOW LINE: THE COLD FINGER EFFECT



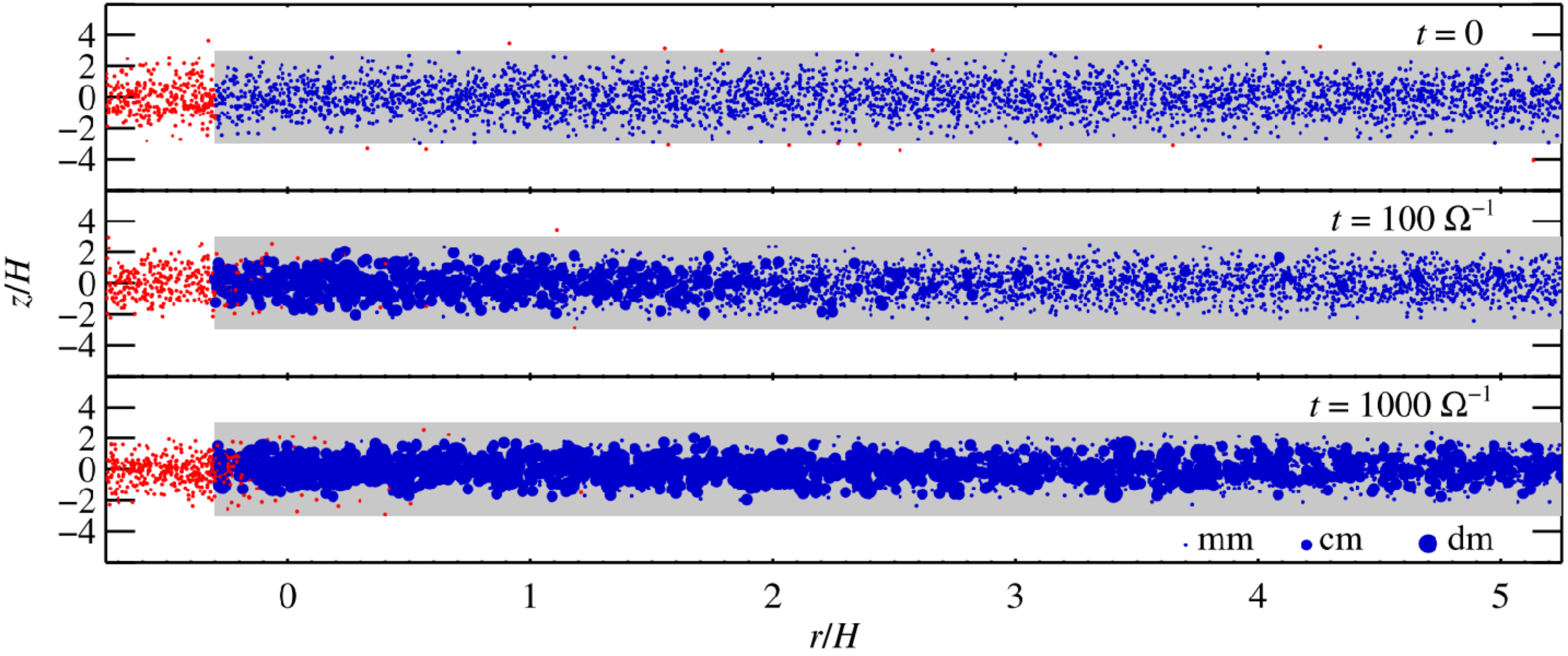
Cuzzi & Zahnle 2004

see also: Stevenson & Lunine 1988

SNOW LINE: THE COLD FINGER EFFECT

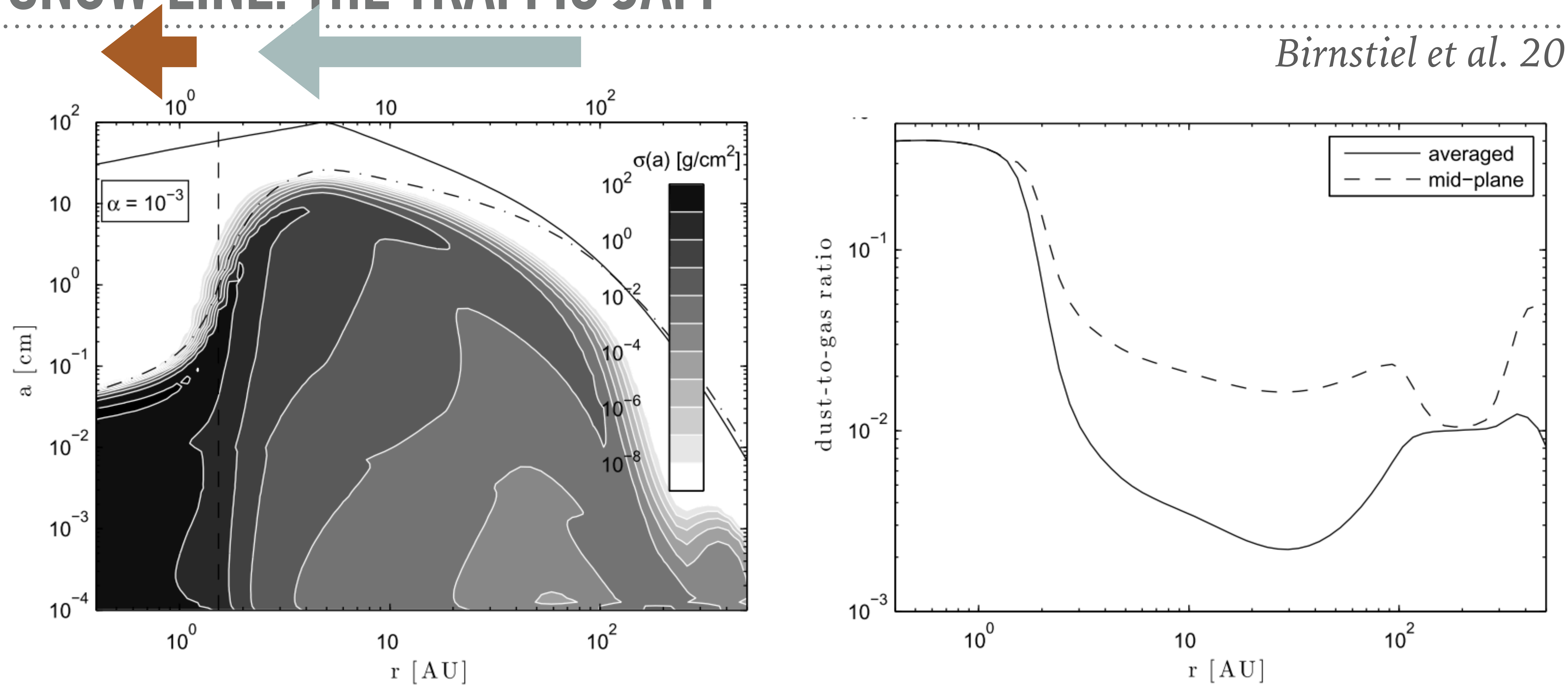
Ros & Johansen 2013: pebble growth thanks to ice deposition outside of the snow line

BUT: no small grains, no fragmentation



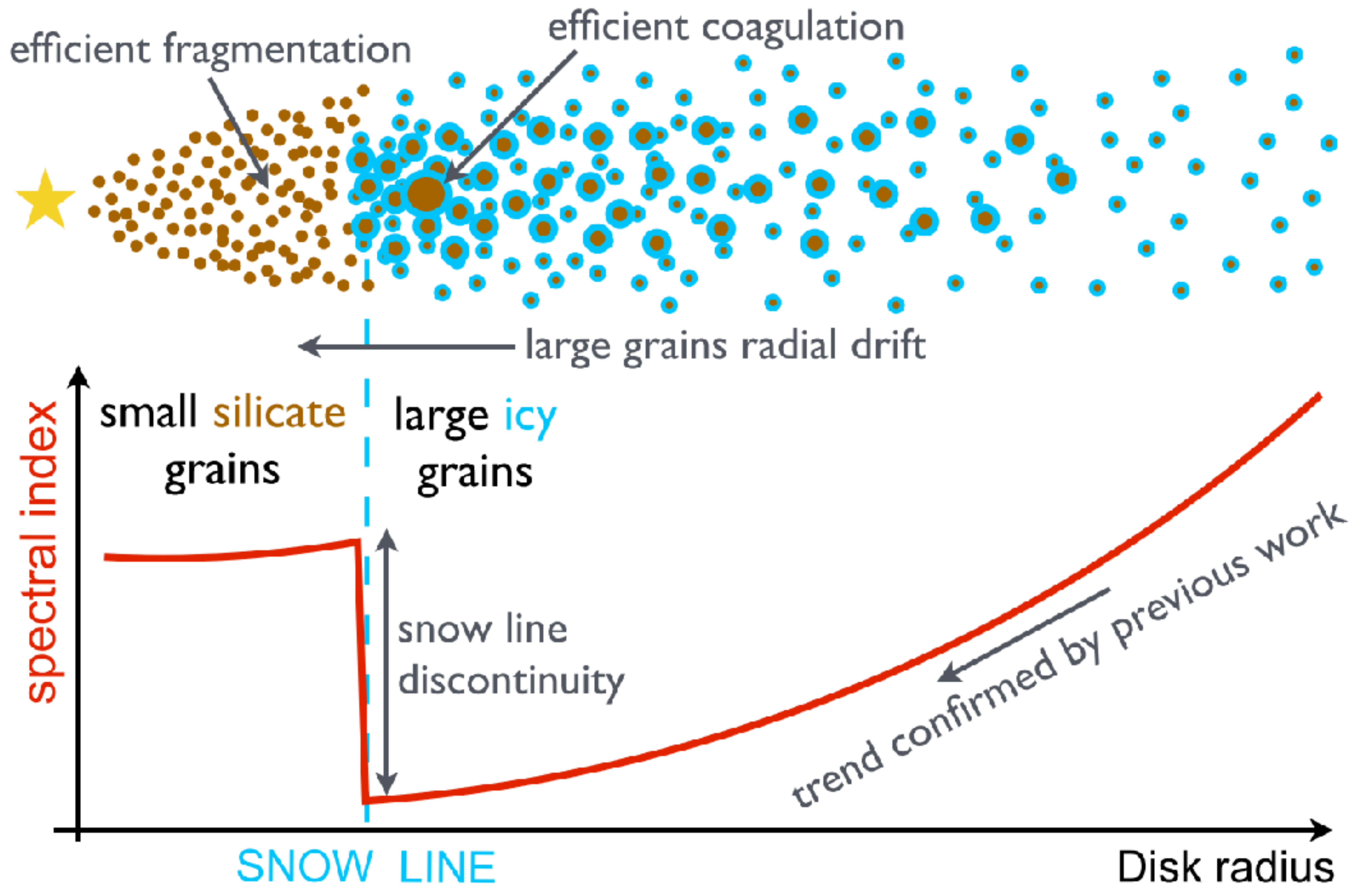
SNOW LINE: THE TRAFFIC JAM

Birnstiel et al. 2010



BUT the new laboratory experiments don't support this:
Gundlach et al. 2018, Musiolik & Wurm 2019, Steinpilz et al. 2019

SNOW LINE: THE TRAFFIC JAM



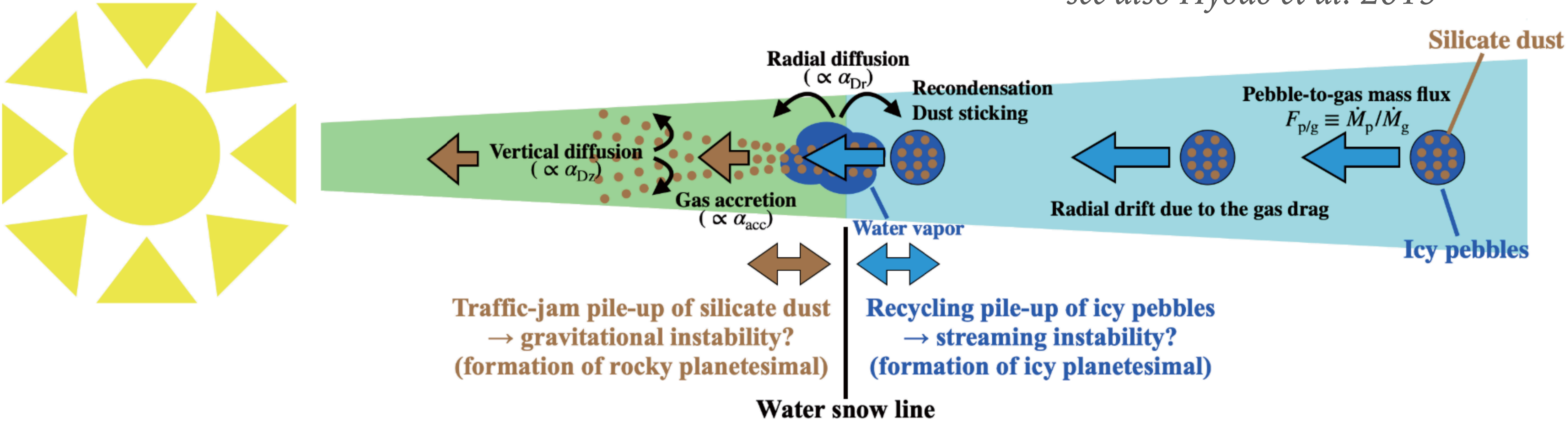
Banzatti et al. 2015

Cieza et al. 2016 reported that such a spectral index transition is seen at 42 au in the disk around the outbursting protostar V883 Ori

Schoonenberg, Okuzumi, & Ormel 2017 pointed out the timescale problem: building up the traffic jam takes >10⁴ yrs, much longer than the outburst duration

SNOW LINE: THE TRAFFIC JAM

figure from Hyodo et al. 2021
see also Hyodo et al. 2019



Guillot & Ida 2016
Ida et al. 2021

Schoonenberg & Ormel 2017
Drążkowska & Alibert 2017

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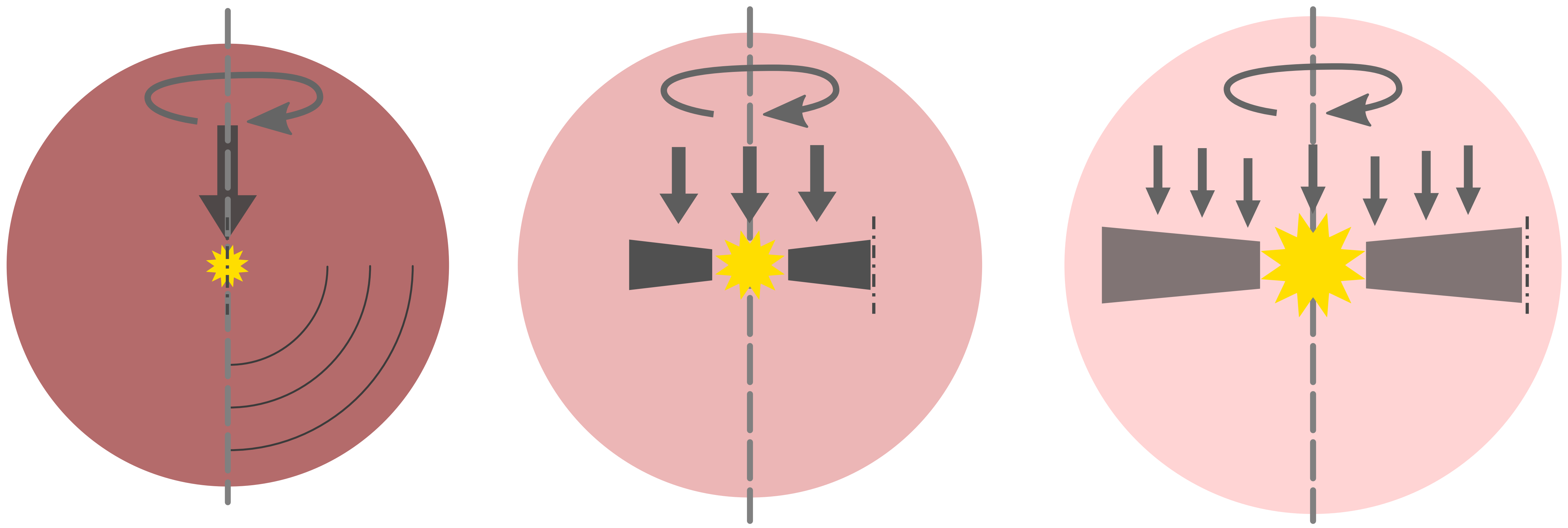
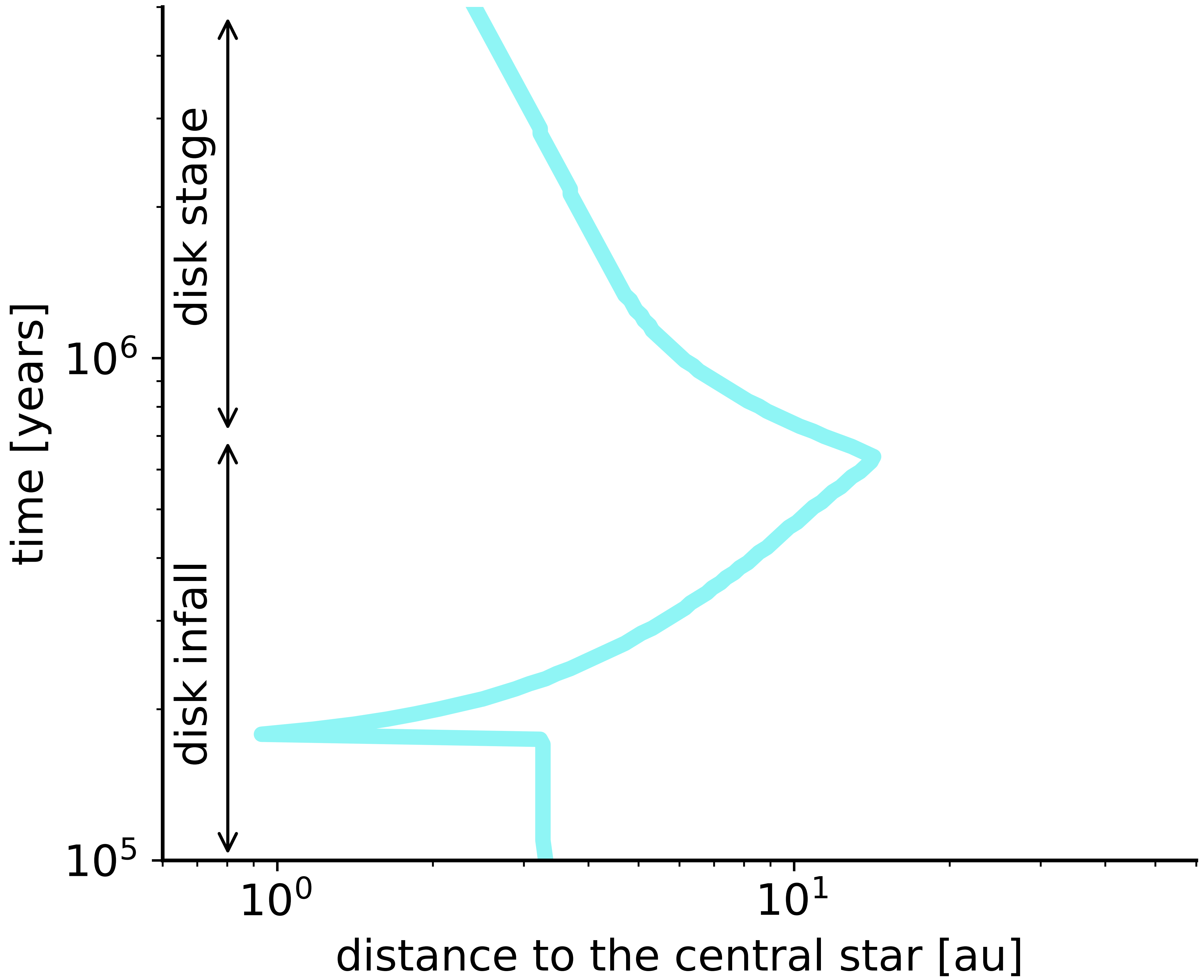
POSITION OF THE SNOW LINE DEPENDS ON THE DISK MODEL



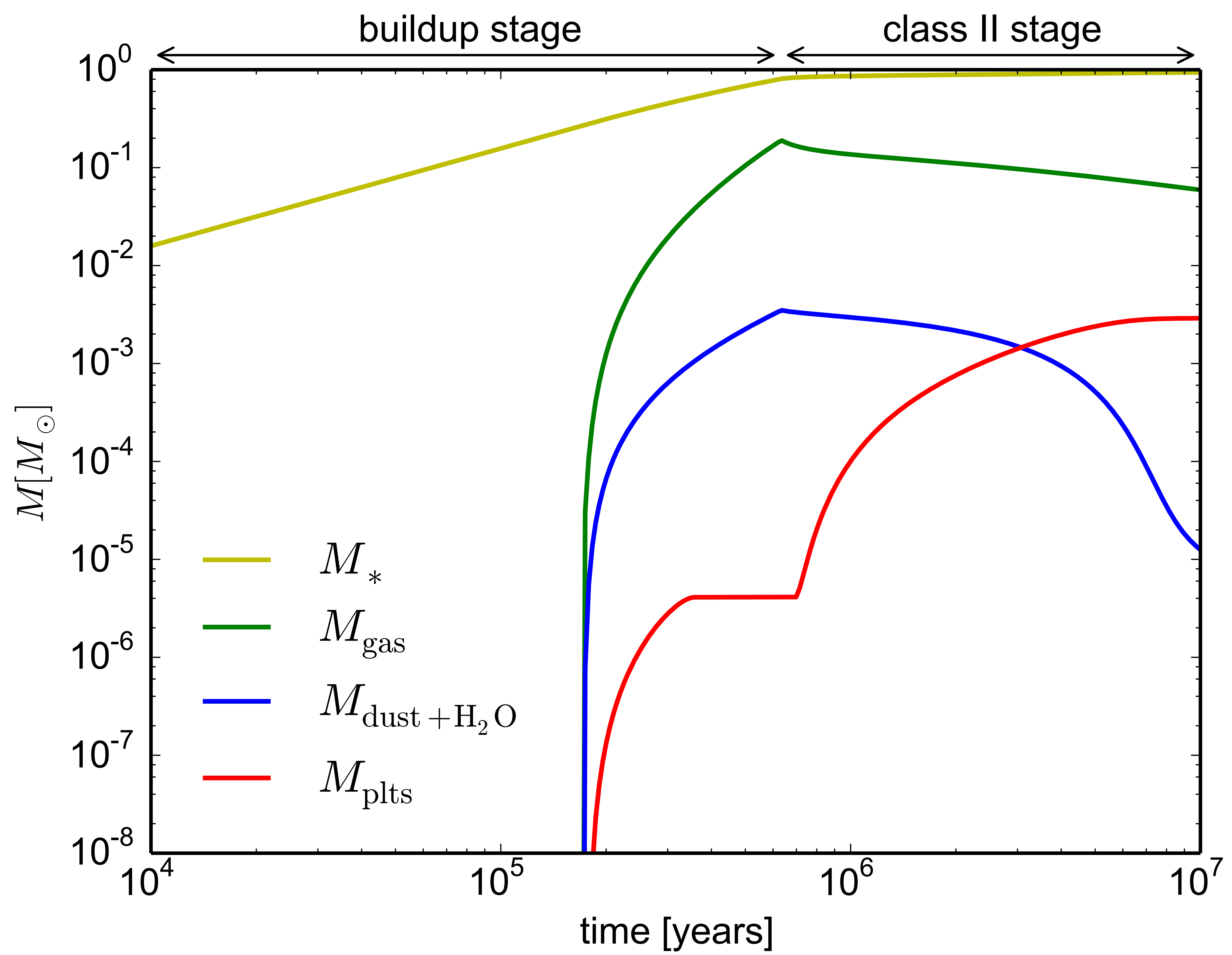
inside-out rotating infall model

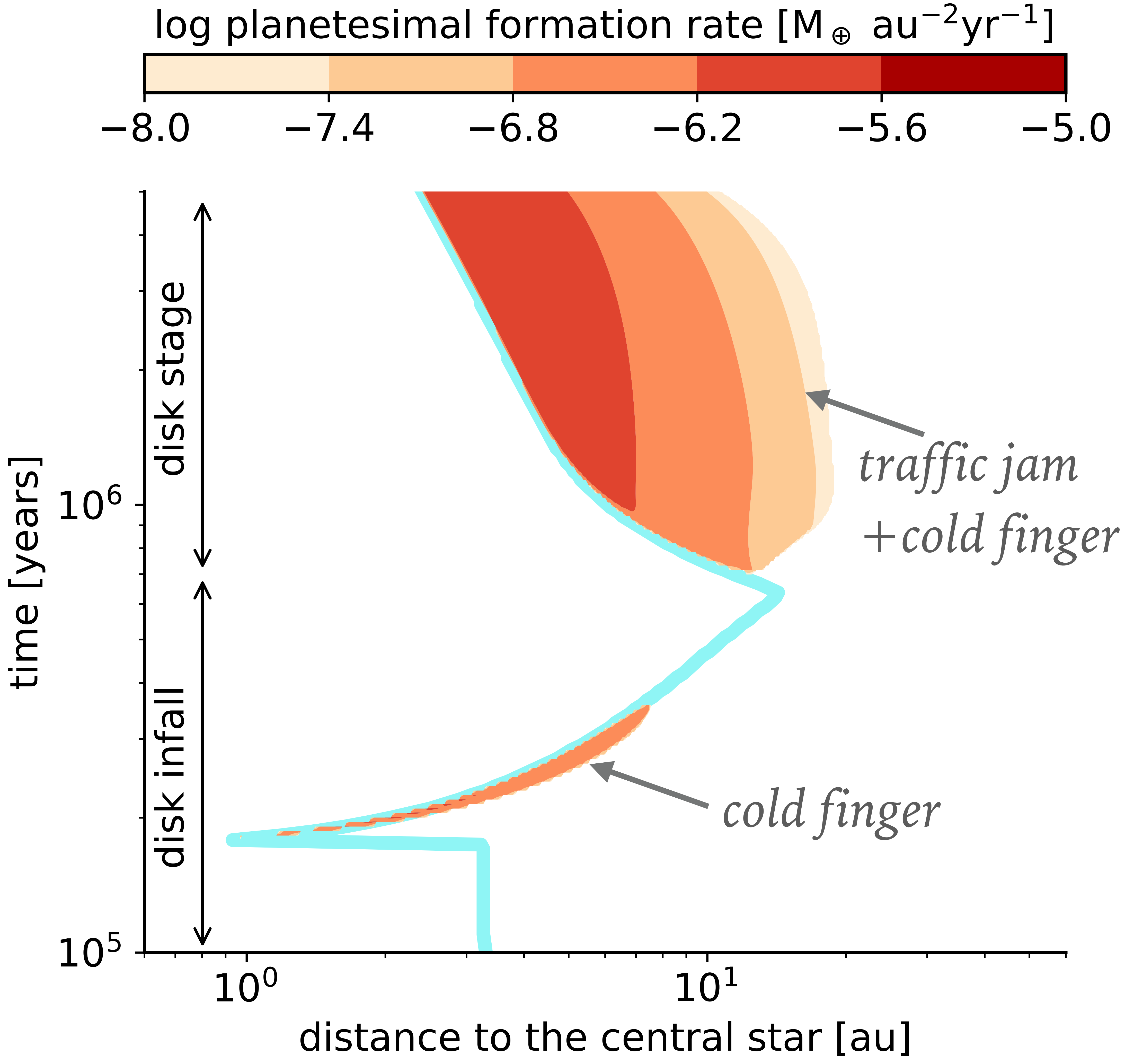
Shu (1977), Ulrich (1976), Hueso & Guillot (2005)



PLANETESIMAL FORMATION HAPPENS OVER THE DISK LIFETIME

Drążkowska & Dullemond (2018)





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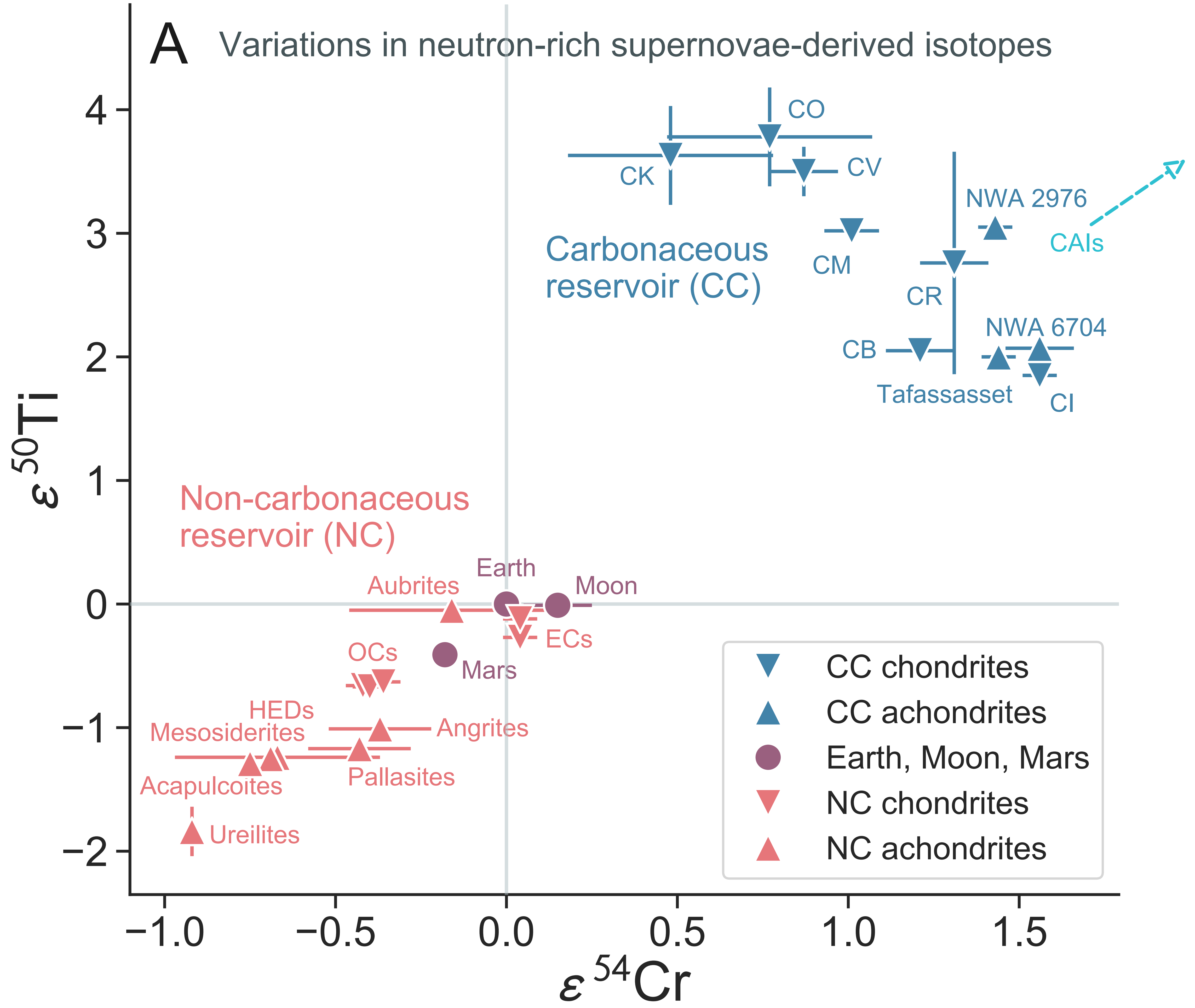
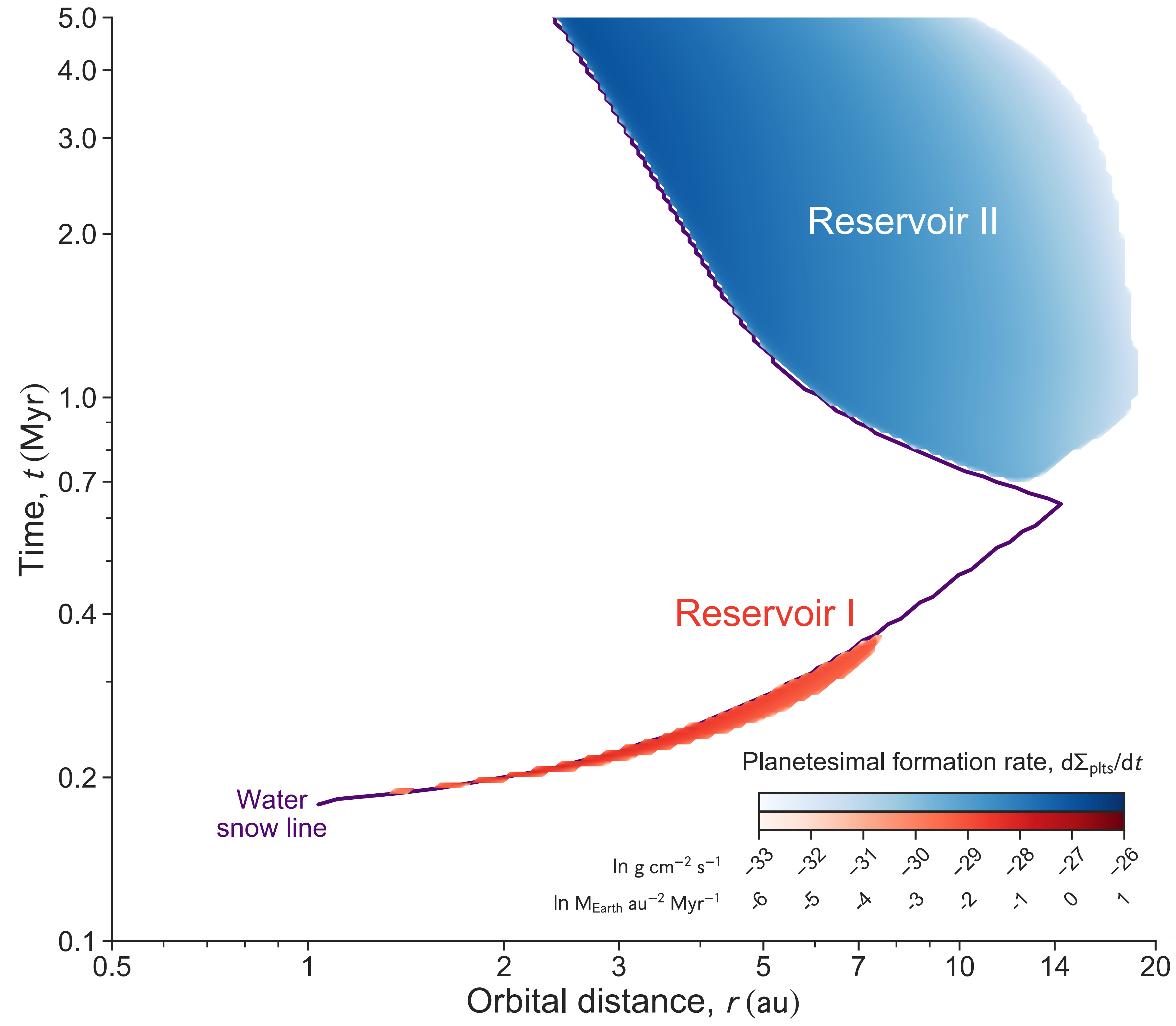
TWO BURSTS OF PLANETESIMALS → ISOTOPIC DICHOTOMY/GRADIENT

Lichtenberg, Drążkowska et al. (2021)





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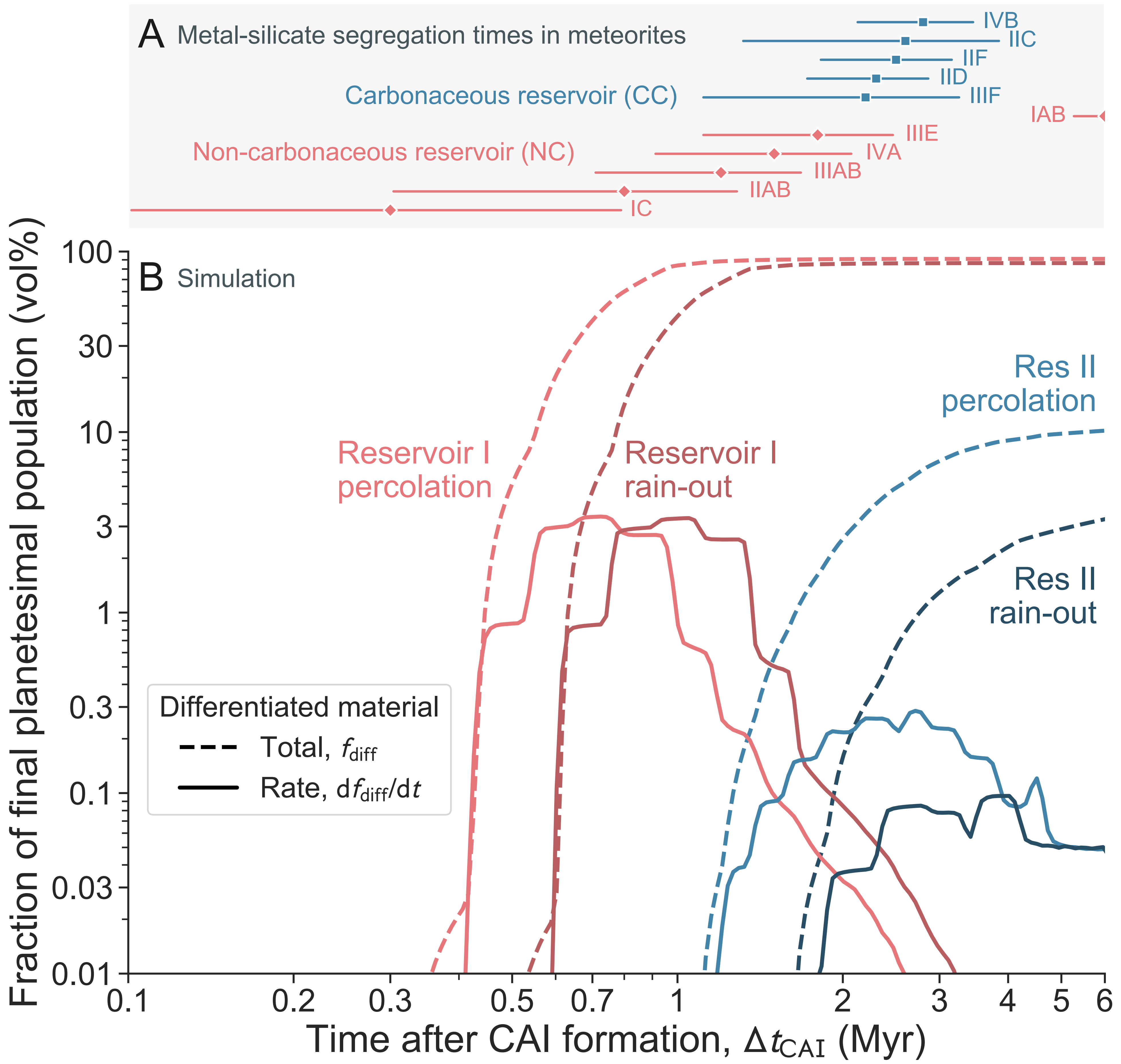
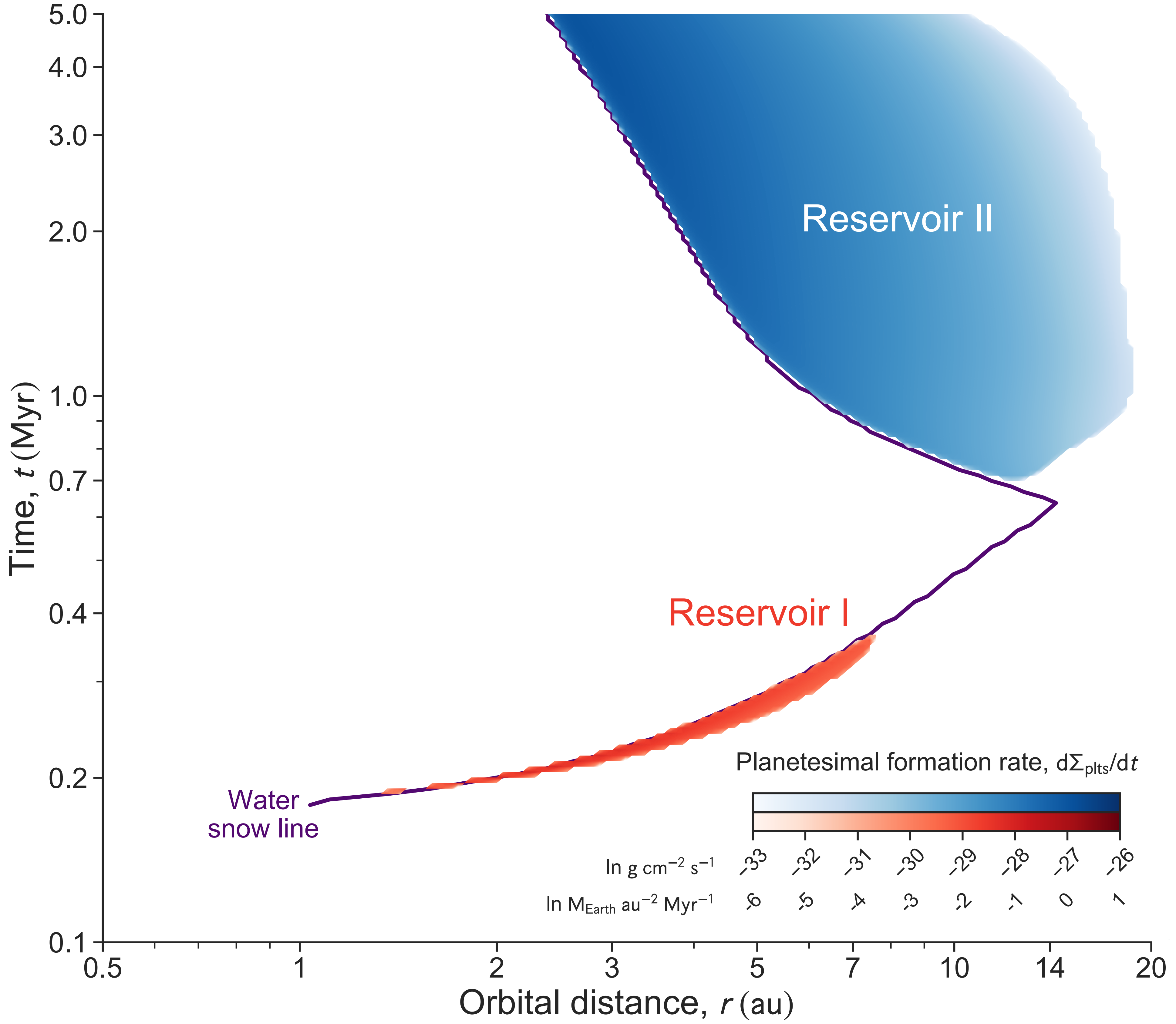
METEORITIC CONSTRAINTS: CORE FORMATION TIME

see Ted Bergin's talk

Lichtenberg, Drążkowska et al. (2021)





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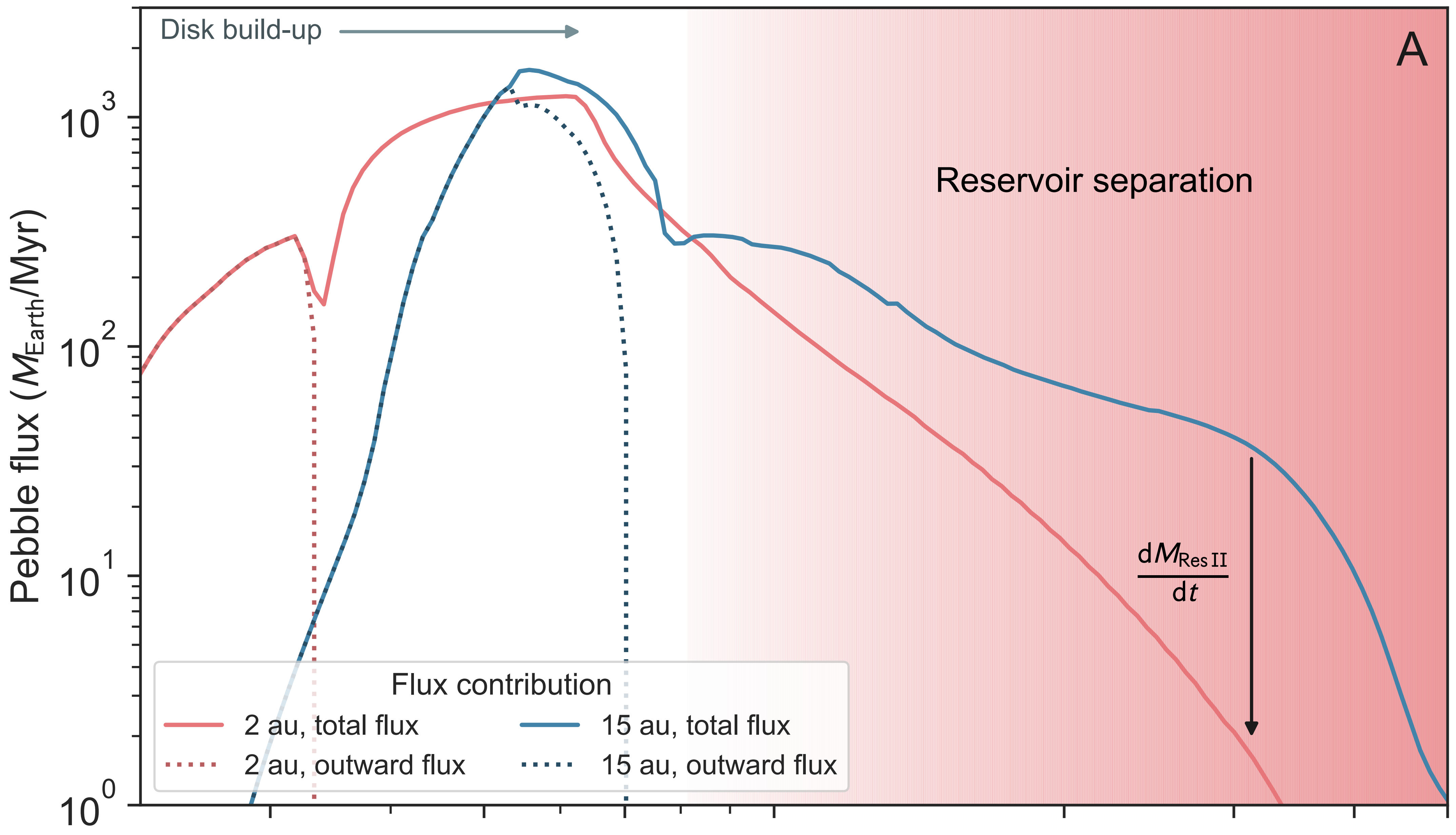
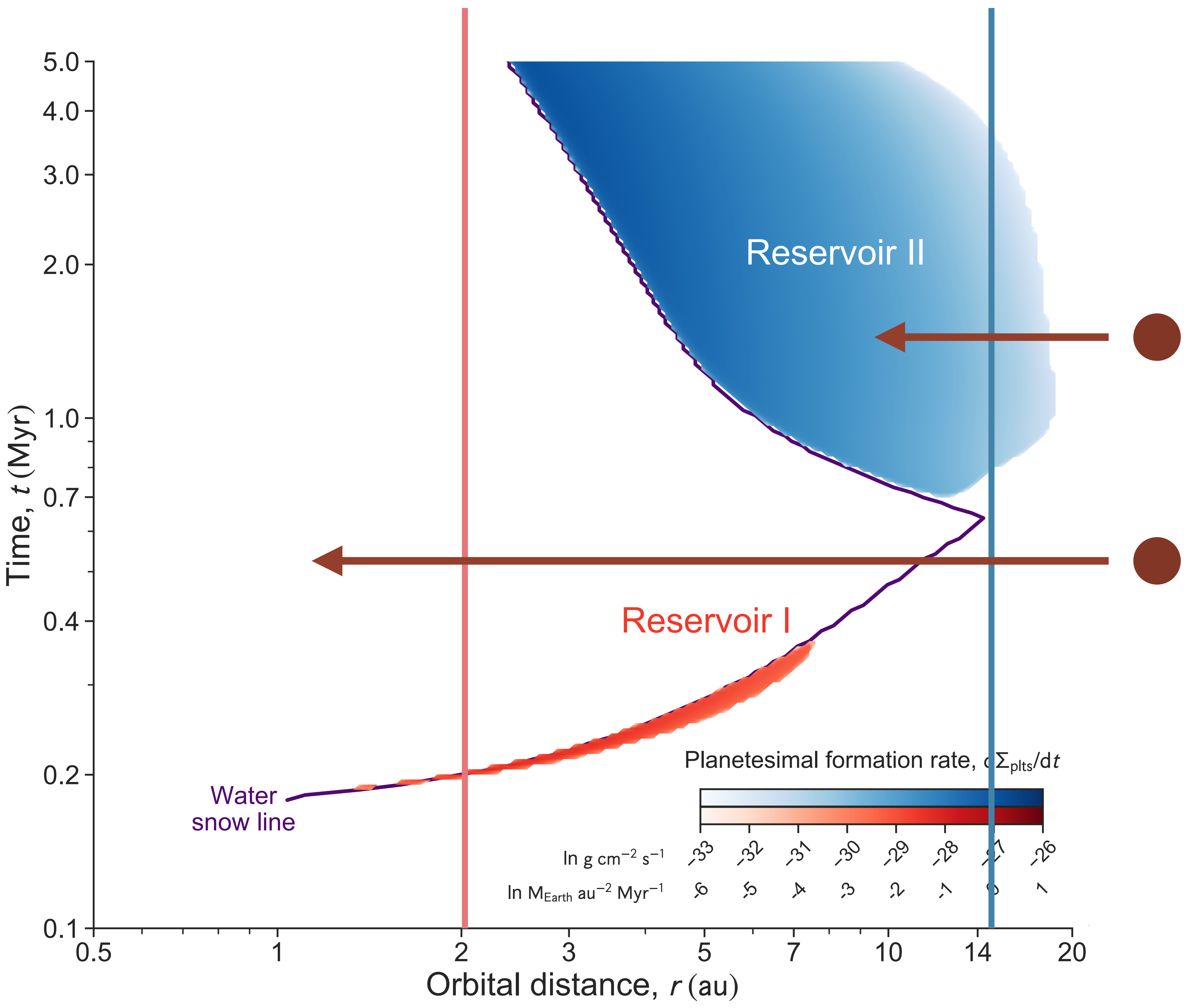
PEBBLES THAT FORM RES II PLANETESIMALS DON'T PASS THE SNOW LINE

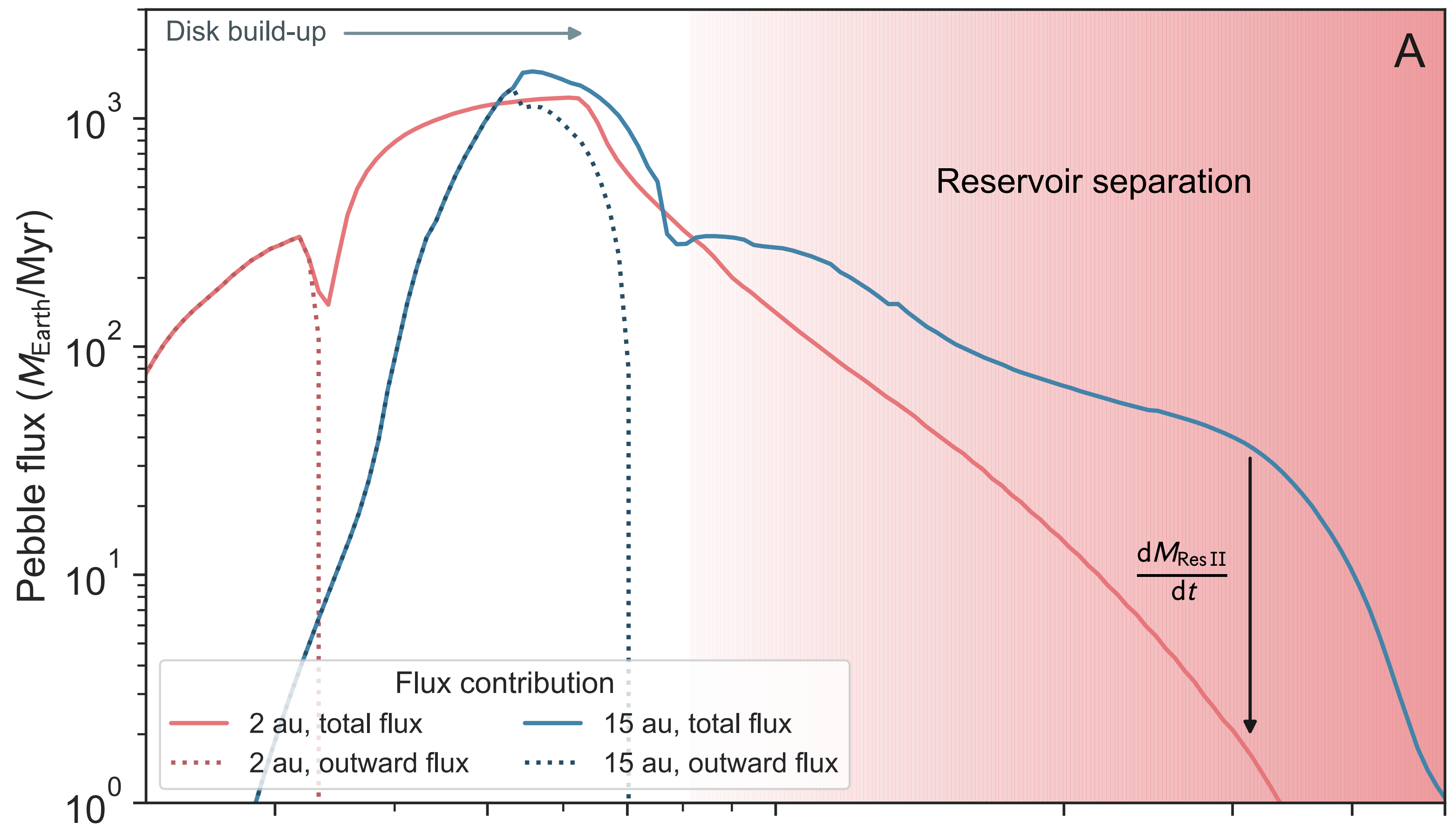
Lichtenberg, Drążkowska et al. (2021)

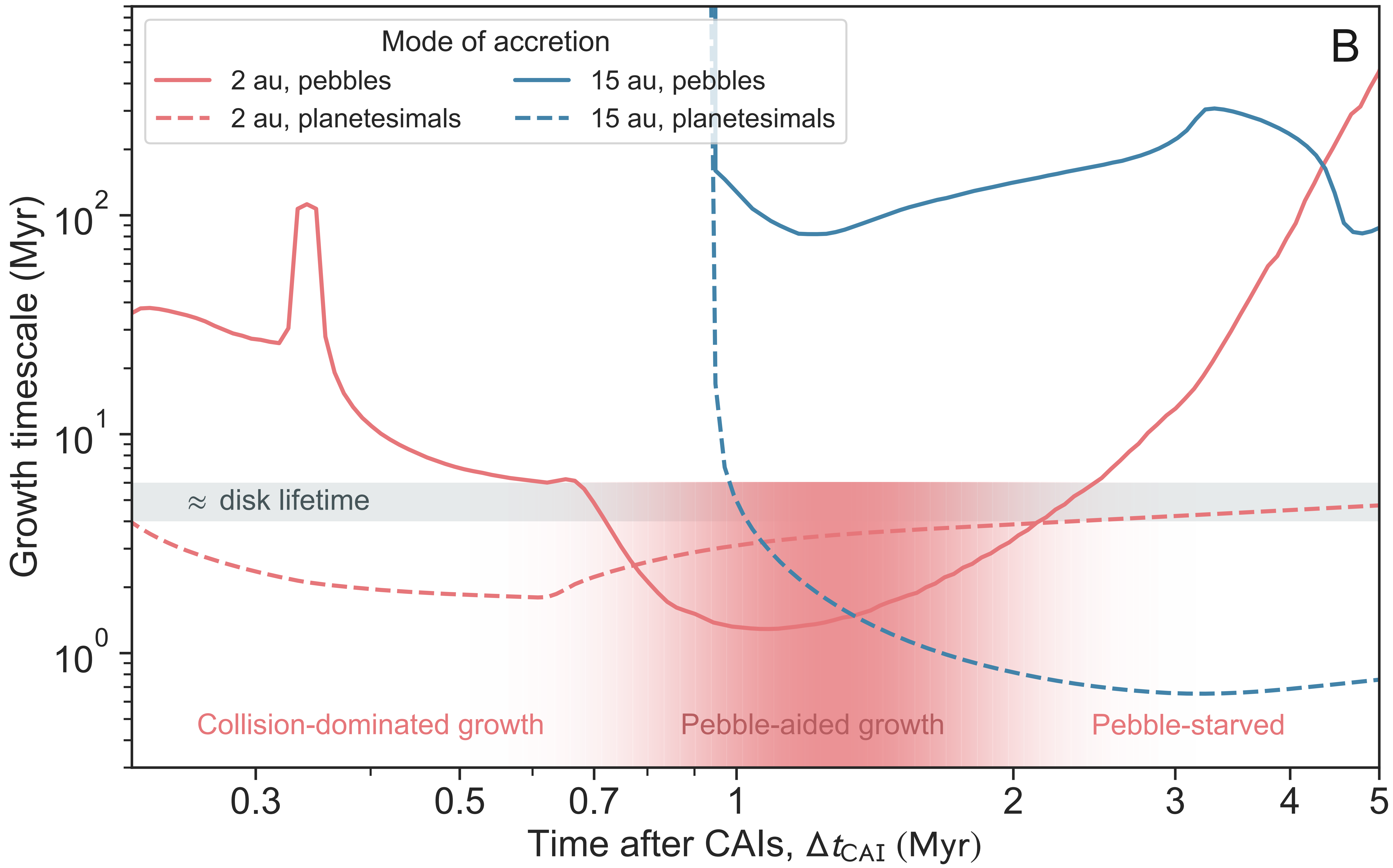




THE DOMINANT MODE OF PLANETARY GROWTH

Lichtenberg, Drążkowska et al. (2021)





GROWTH TIMESCALES

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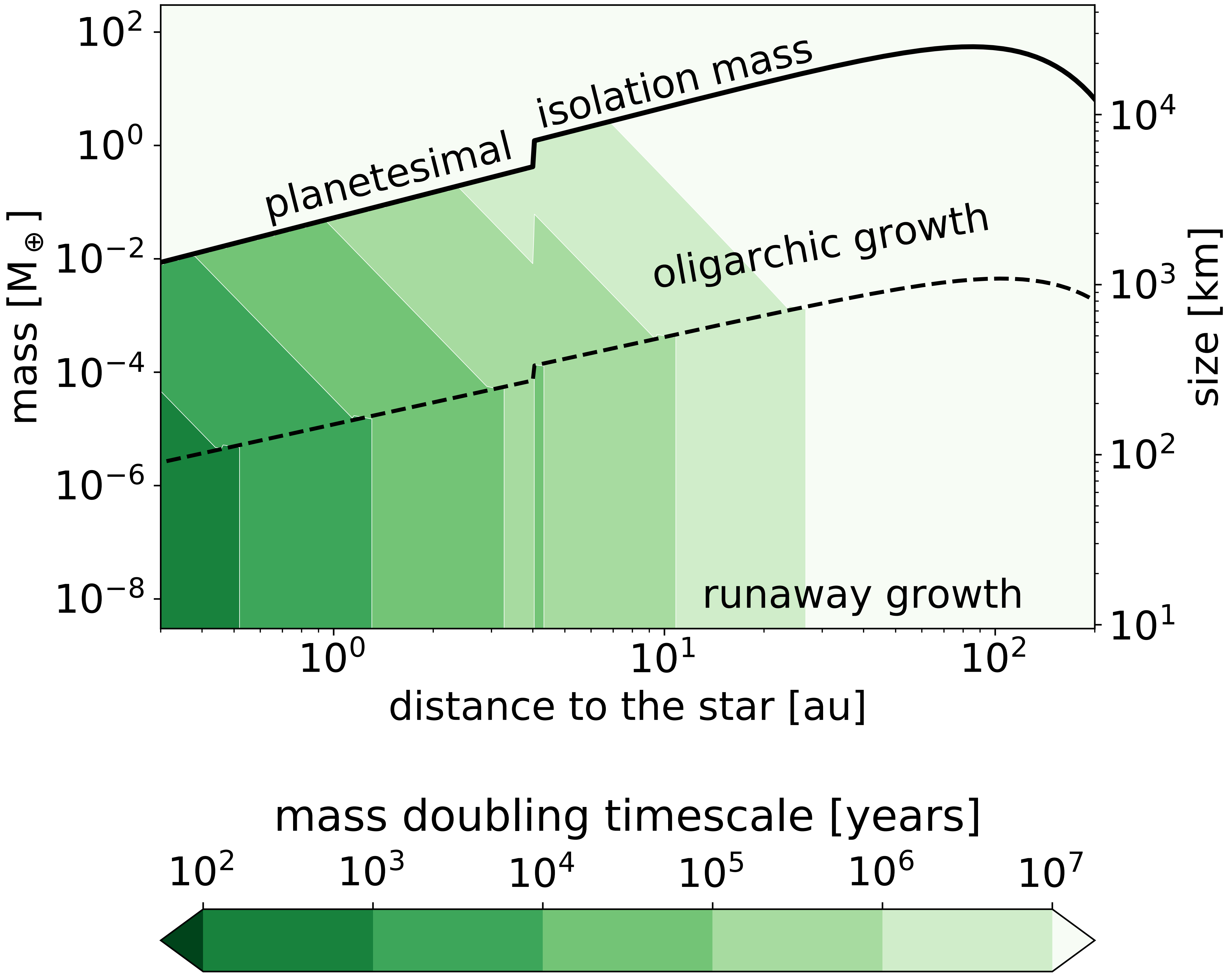
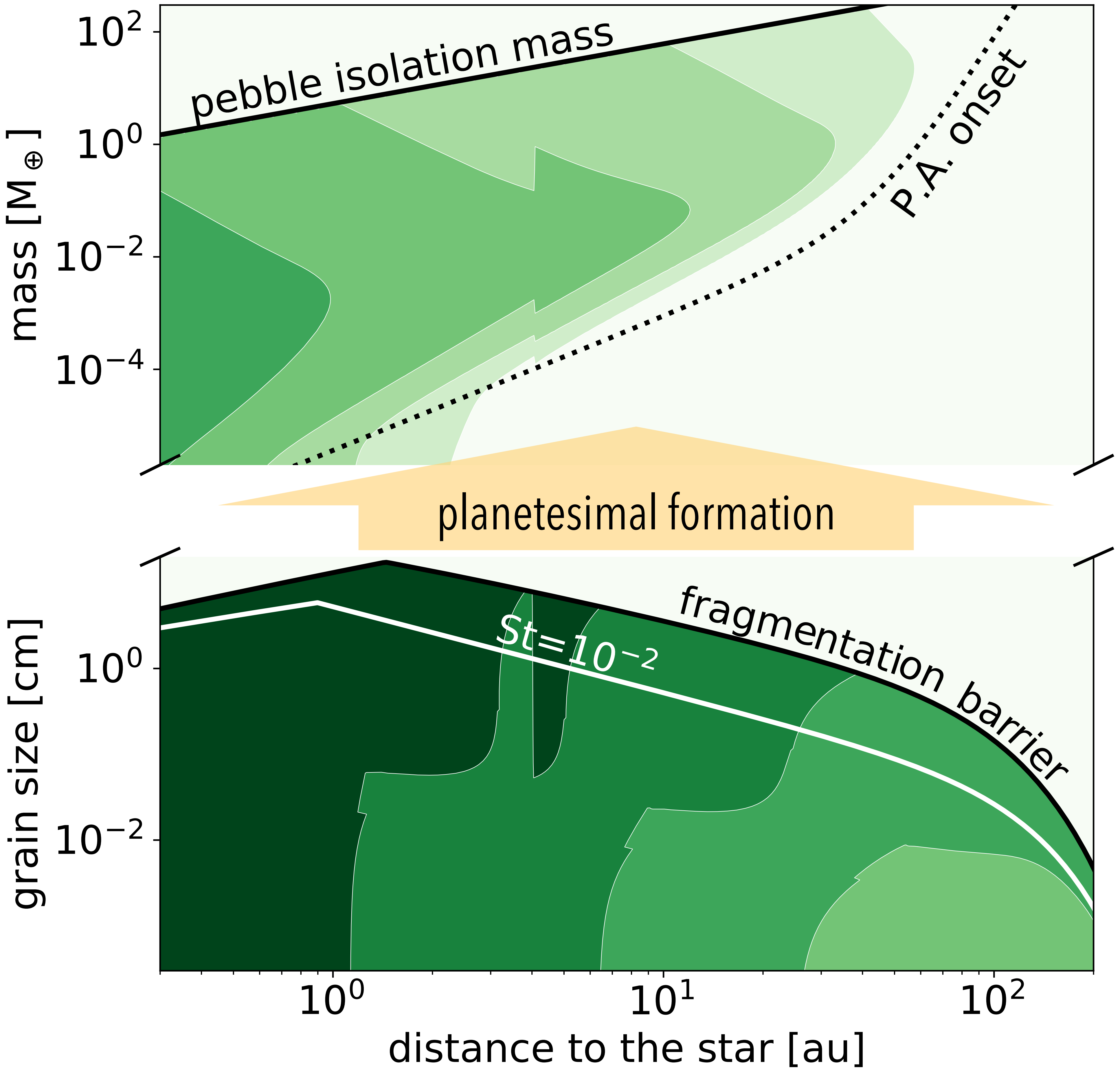
PLANETESIMAL ACCRETION



PEBBLE ACCRETION



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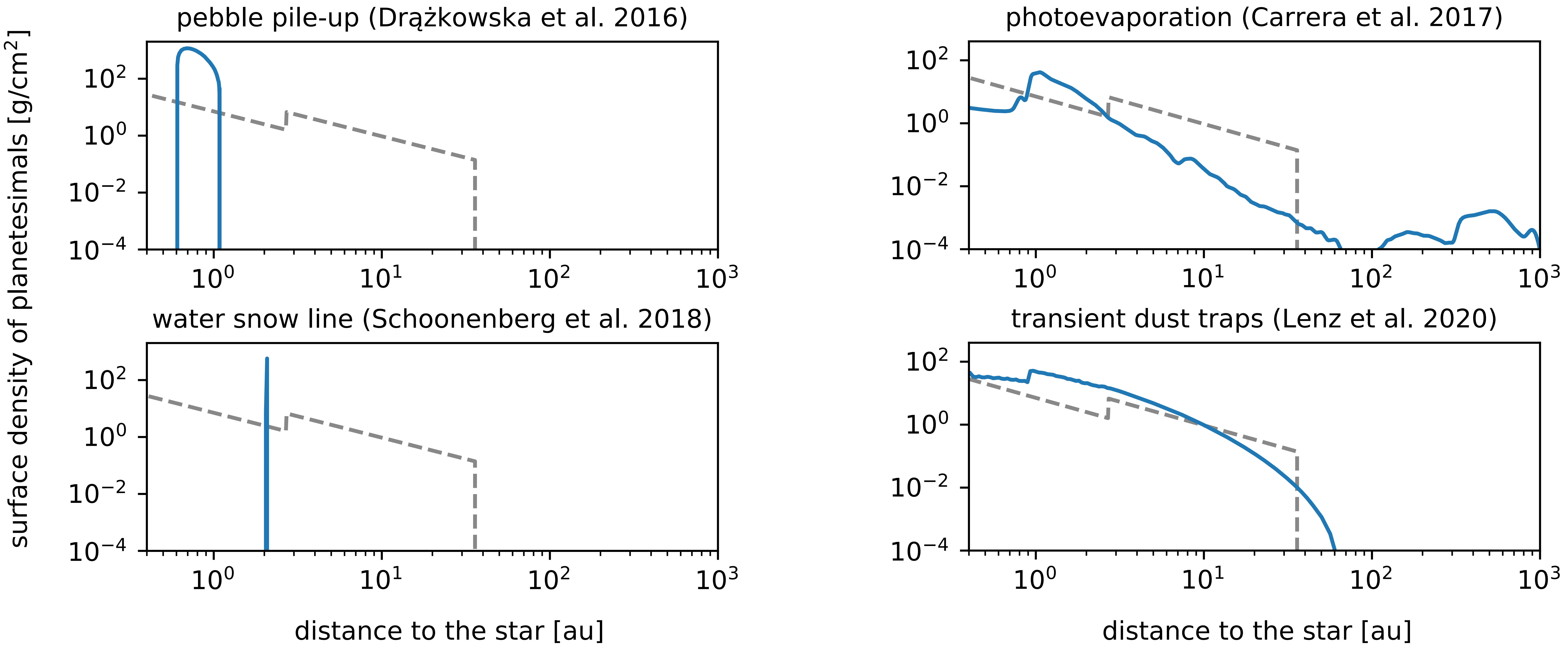
PLANETESIMAL FORMATION RESULTS DEPEND ON ASSUMPTIONS



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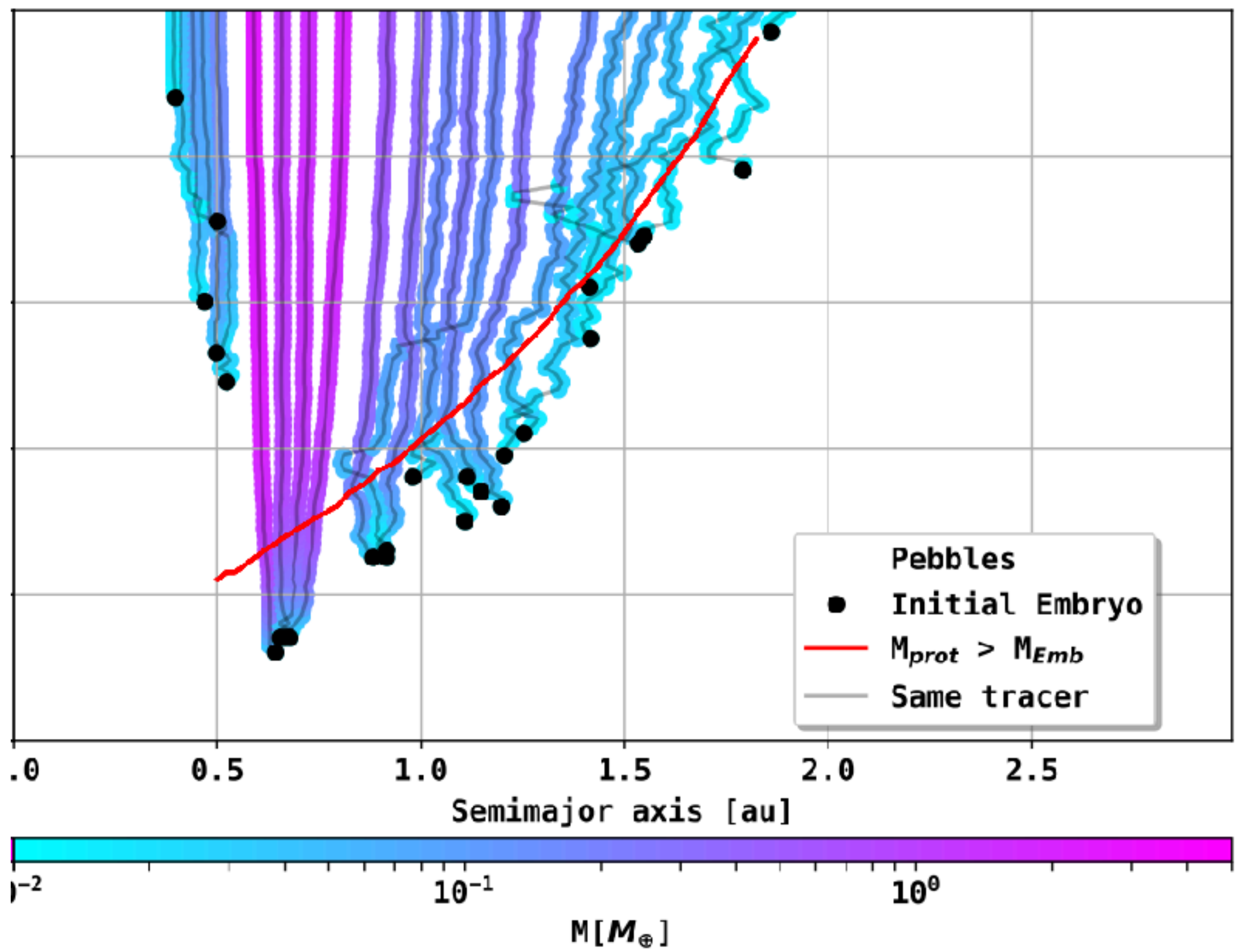
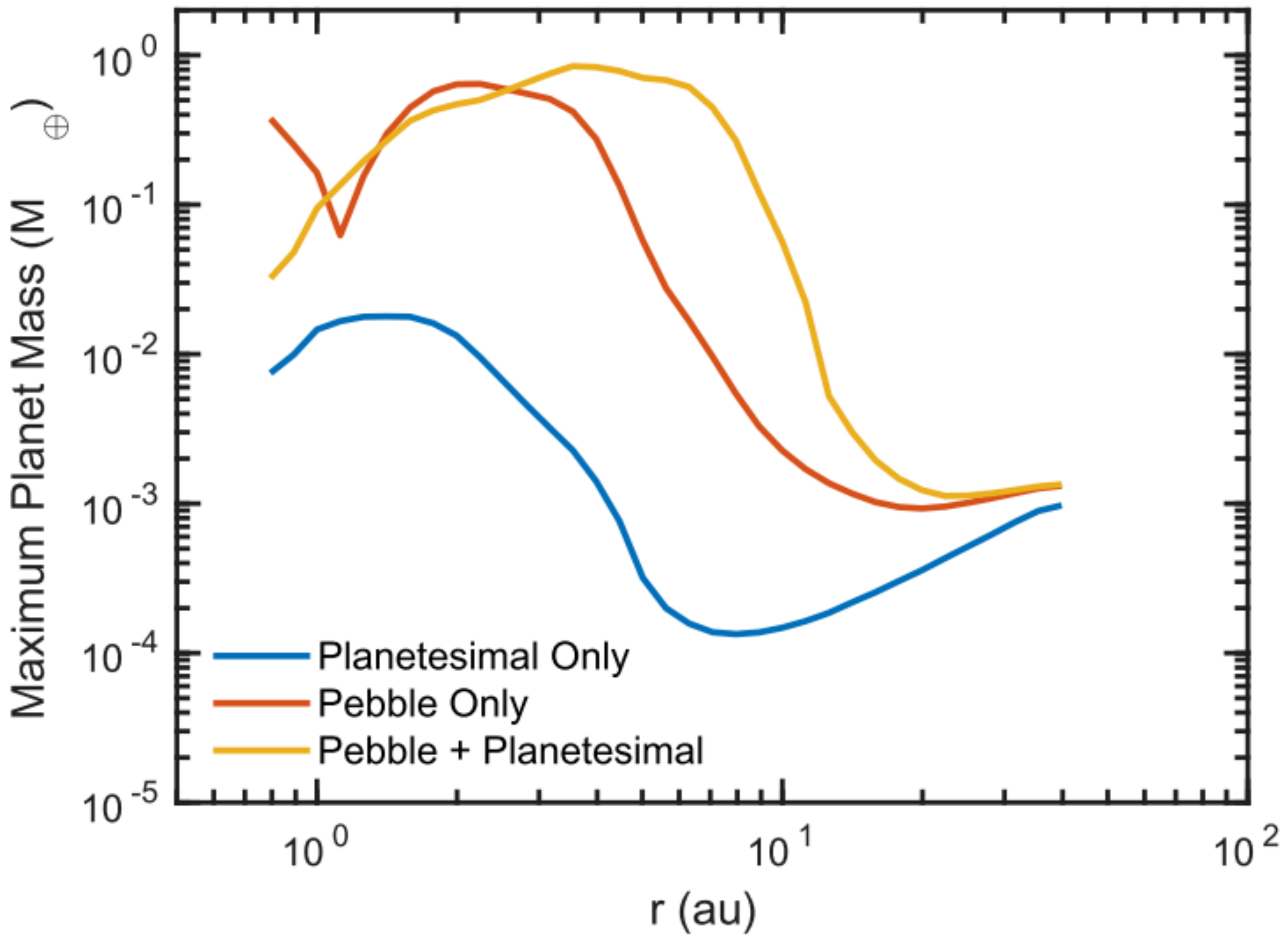
FORMING PLANETESIMALS EVERYWHERE DOESN'T TAKE YOU ANYWHERE

- Hubert Klahr



Voelkel et al. 2021



Coleman 2021

TAKE-AWAYS

- Water snow line is a good place to trigger early planetesimal formation.
- Planetesimals formation is spatially and temporarily fragmented.
- Planetesimal formation is not a single burst, in the Solar System they formed for several Myrs. We need models coupling dust evolution, planetesimal formation, and planetary growth.
- The dominant mode of planetary growth depends on the local availability of planetesimals and pebbles. Even within the same disk, it may vary with location and time.
- The pebbles that are used to form planetesimals cannot be used to grow planets by pebble accretion. Ongoing planetesimal formation reduces solids transport.