Pebble accretion near the snowline

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w/ input from
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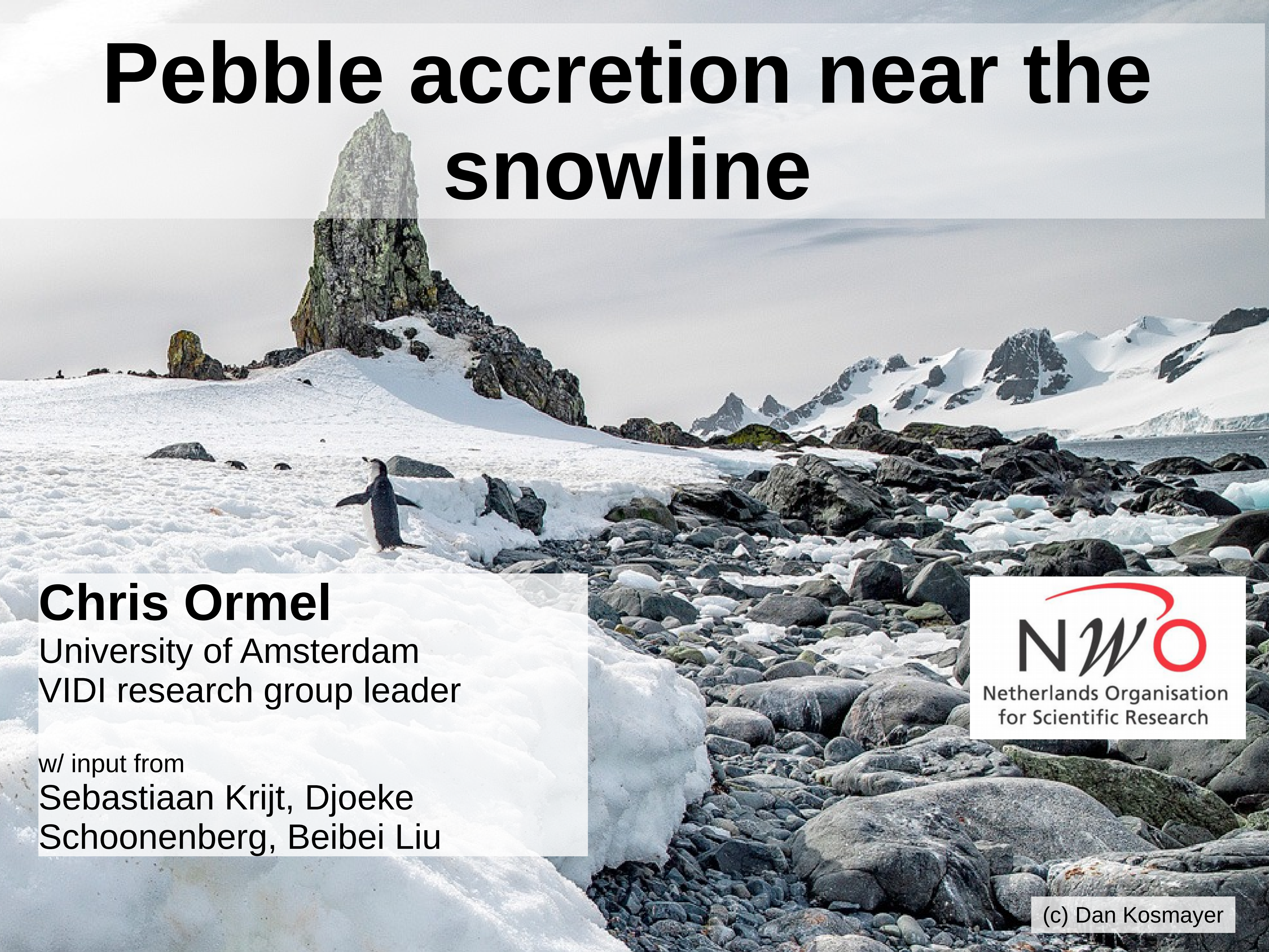
Netherlands Organisation for Scientific Research



(c) Dan Kosmayer

Key questions/contents

- Which are planet's building blocks

  kilometer size **planetesimals** or small **pebbles**?
  Planetesimals form at H_2O iceline

- Conditions for Pebble Accretion

  P.A. relies on planetesimals as "seeds"

- Pebble accretion efficiency

  Dependence on position, stellar mass; effects of H_2O iceline

- Implications to planets

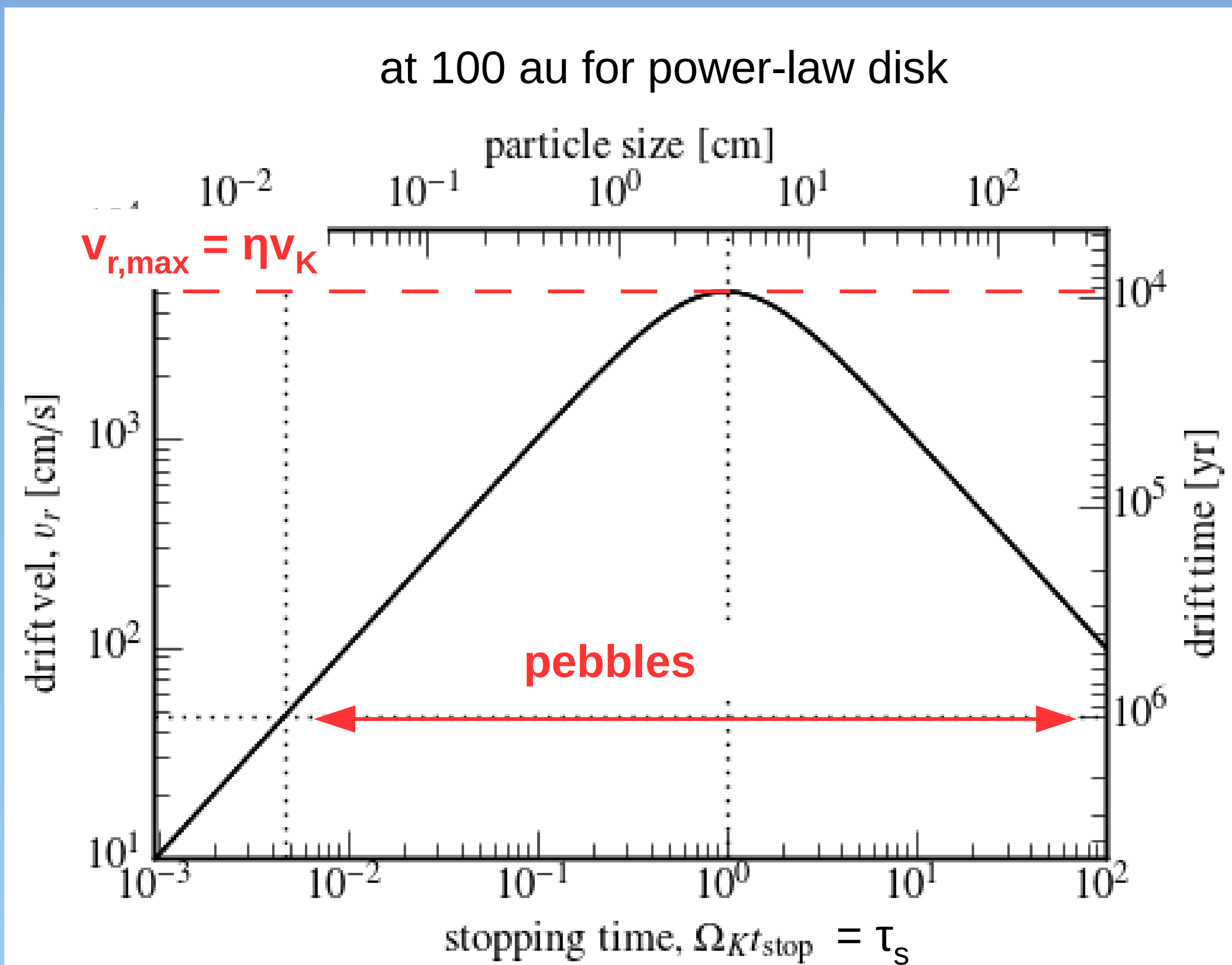
  Planet formation solar system vs. low mass stars

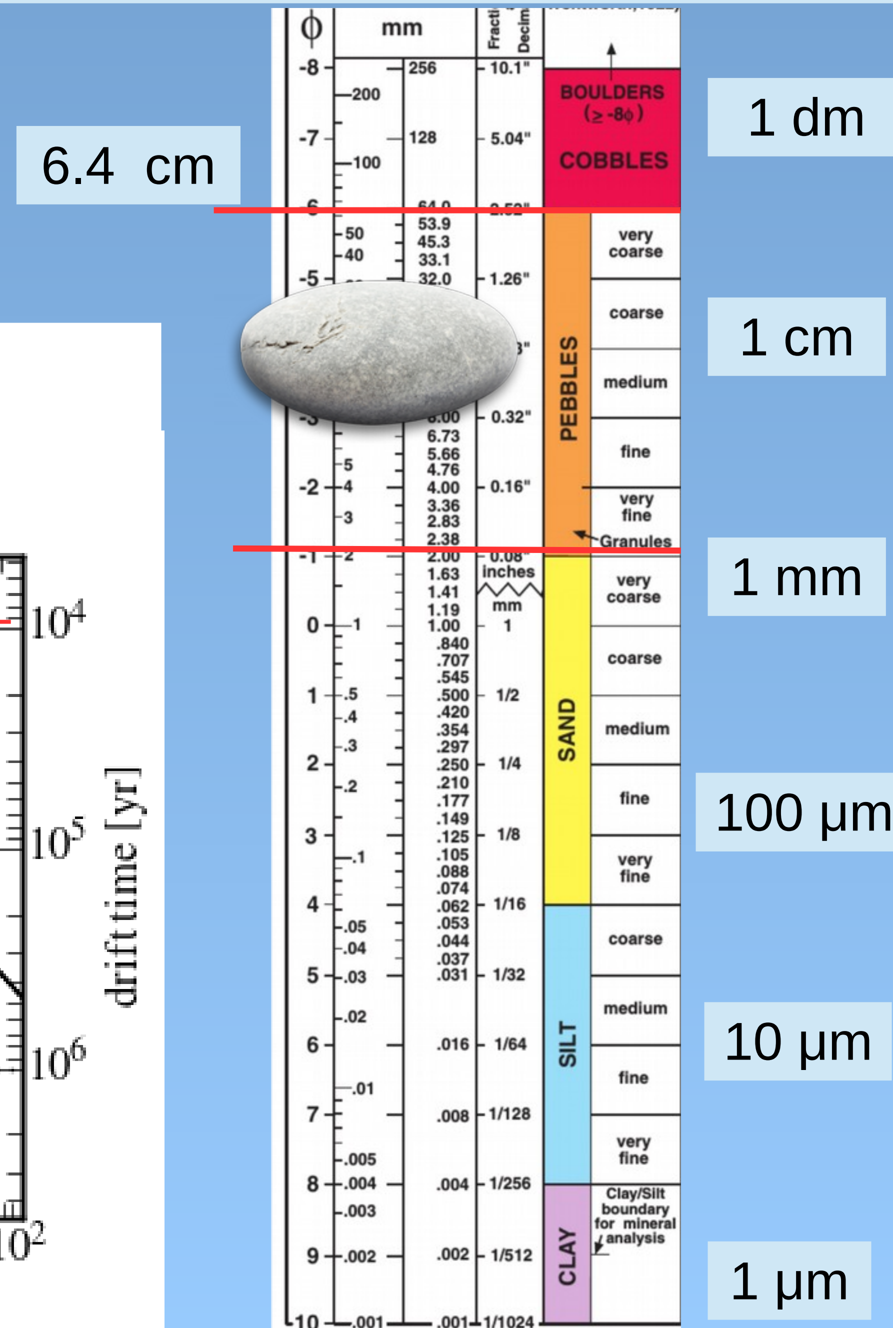
  Effects of P.A. on composition planets (rocky vs icy)

Pebble definition

Geologist: *particles 2 mm < d < 6.4 cm*

Astrophysical: *particles that drift*





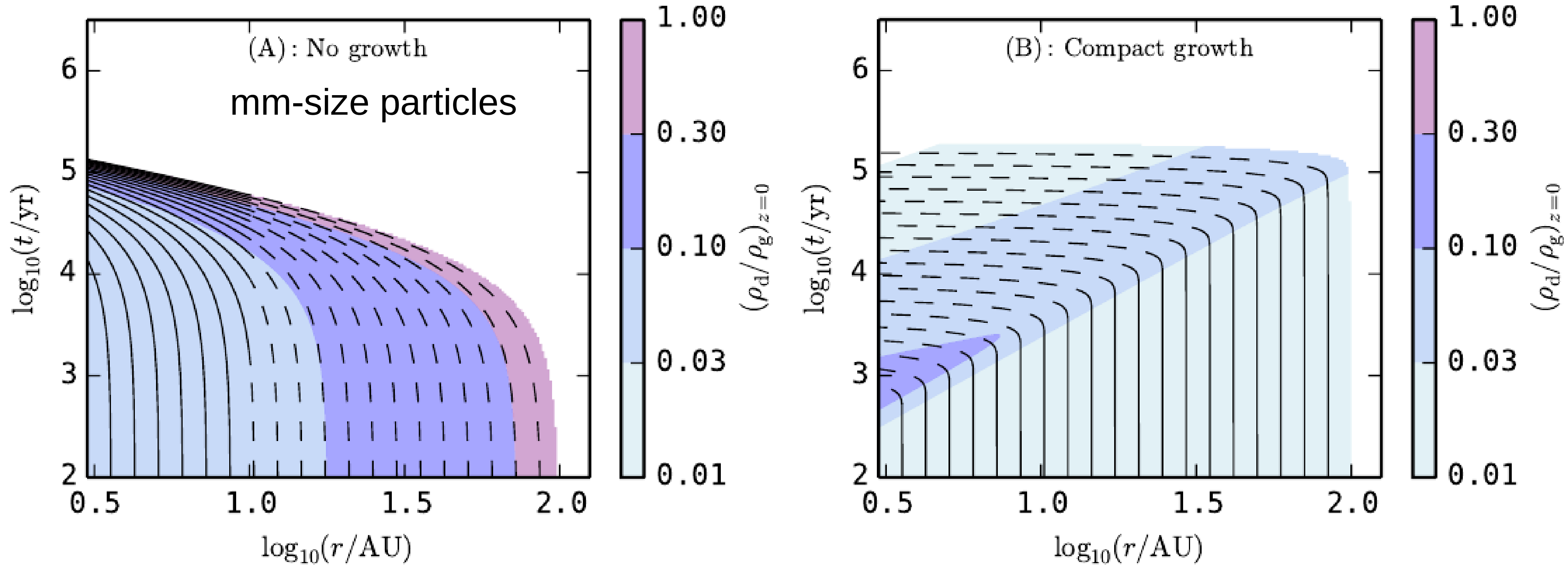
A pebble disk

HL-tau
ALMA collaboration

A pebble disk

Disks evolve inside out

Krijt et al. (2016)



No growth: pileups
radial velocity drecreases inward

cf. Youdin & Shu (2002); Youdin & Chiang (2004)

Growth + drift
No strong pileups!

cf. Birnstiel et al. (2012); Okuzumi et al. (2012); Lambrechts & Johansen 2014; Sato et al. (2016)

Need special conditions

Planetesimal formation near iceline

Planetesimal formation at iceline
By streaming instability once ρ_{solid}/ρ_{gas} >~ 1

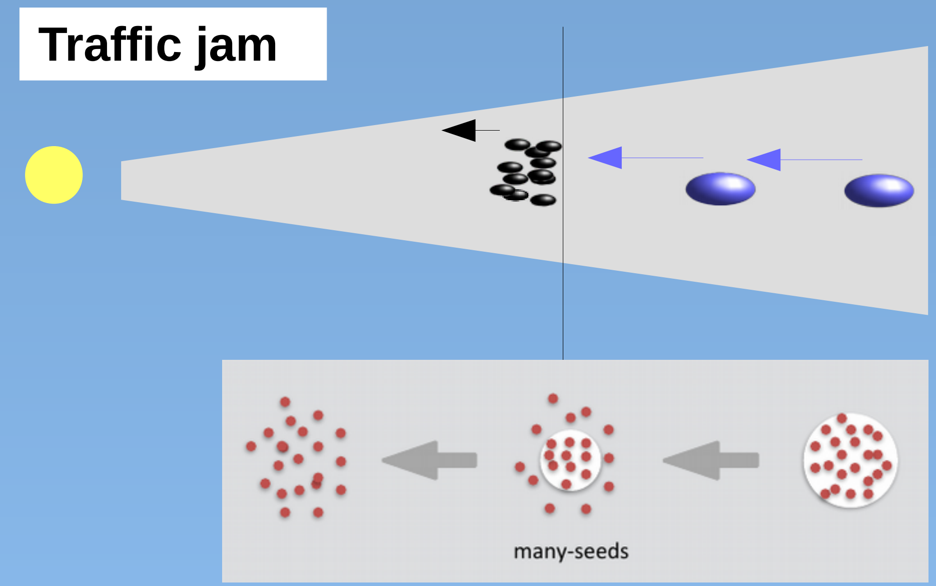
traffic jam effect
Ida & Guillot (2016)

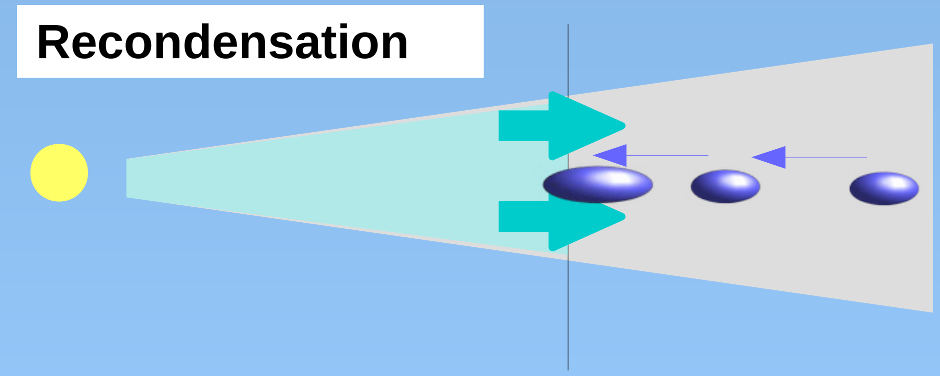
Diffusion & **recondensation** of H_2O
– Stevenson & Lunine (1988)
– Ros & Johansen (2013)
– Schoonenberg & Ormel (2017)

To summarize:

"Planetesimals form *first* at H_2O iceline"

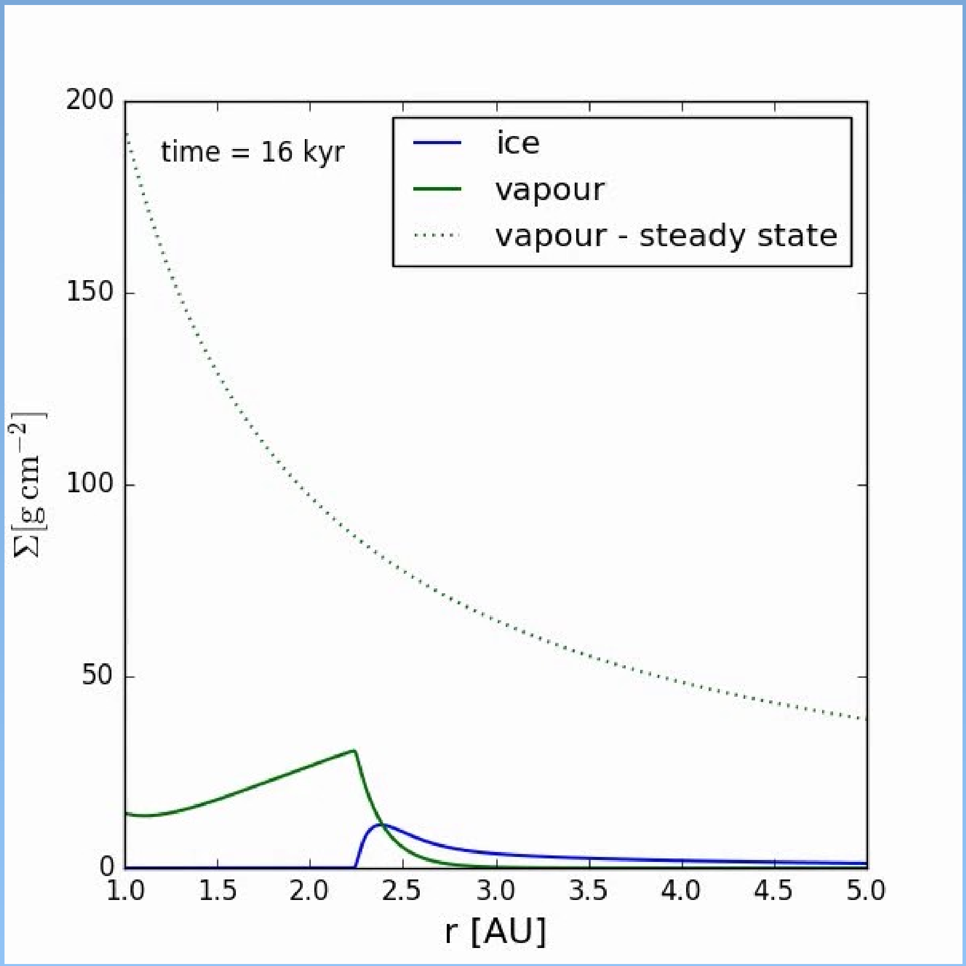
Drazkowska & Alibert (2017)





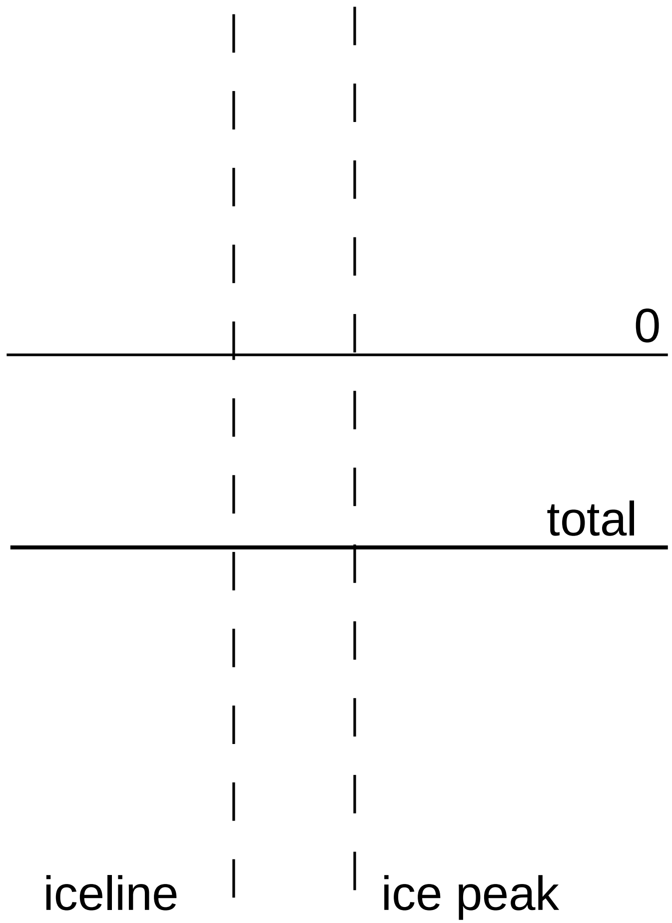
H_2O Iceline

Schoonenberg & Ormel (2017)



Schoonenberg & Ormel (2017)

$$\text{Mass flux} = \Sigma v + \Sigma_{\text{gas}} D_i \nabla \left(\frac{\Sigma_i}{\Sigma_{\text{gas}}} \right)$$



H_2O Iceline

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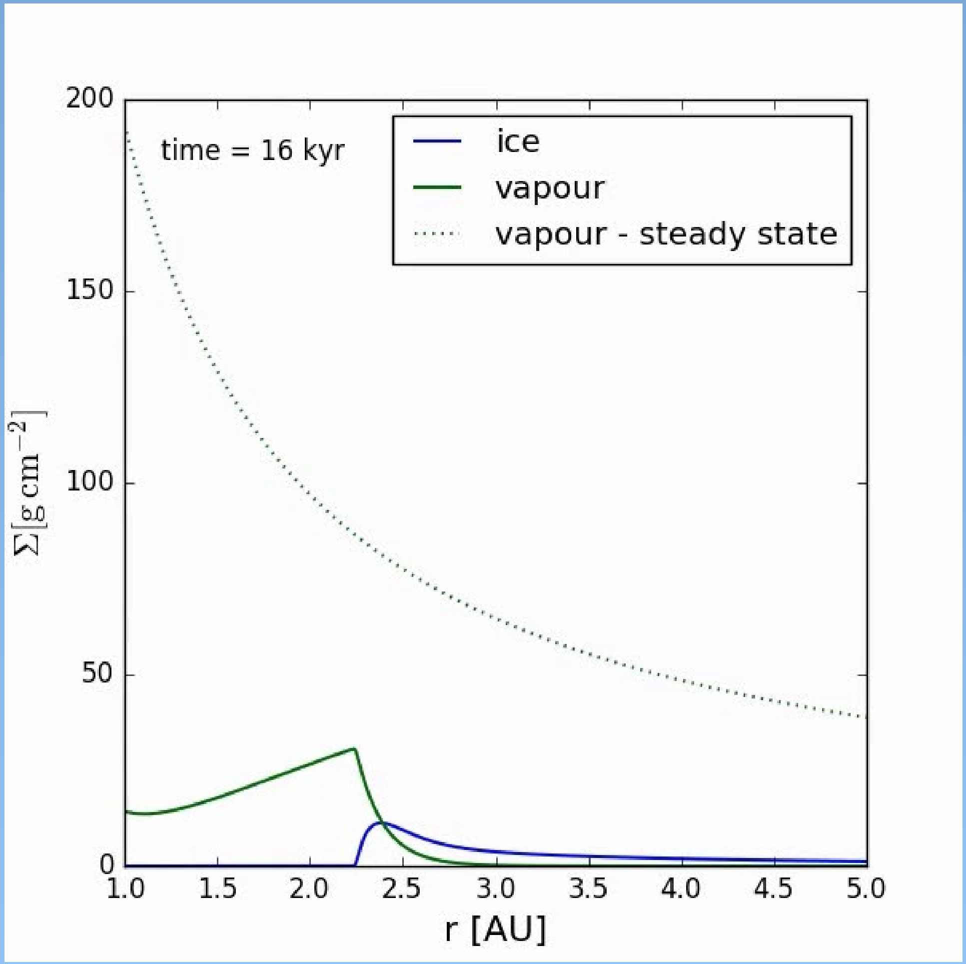
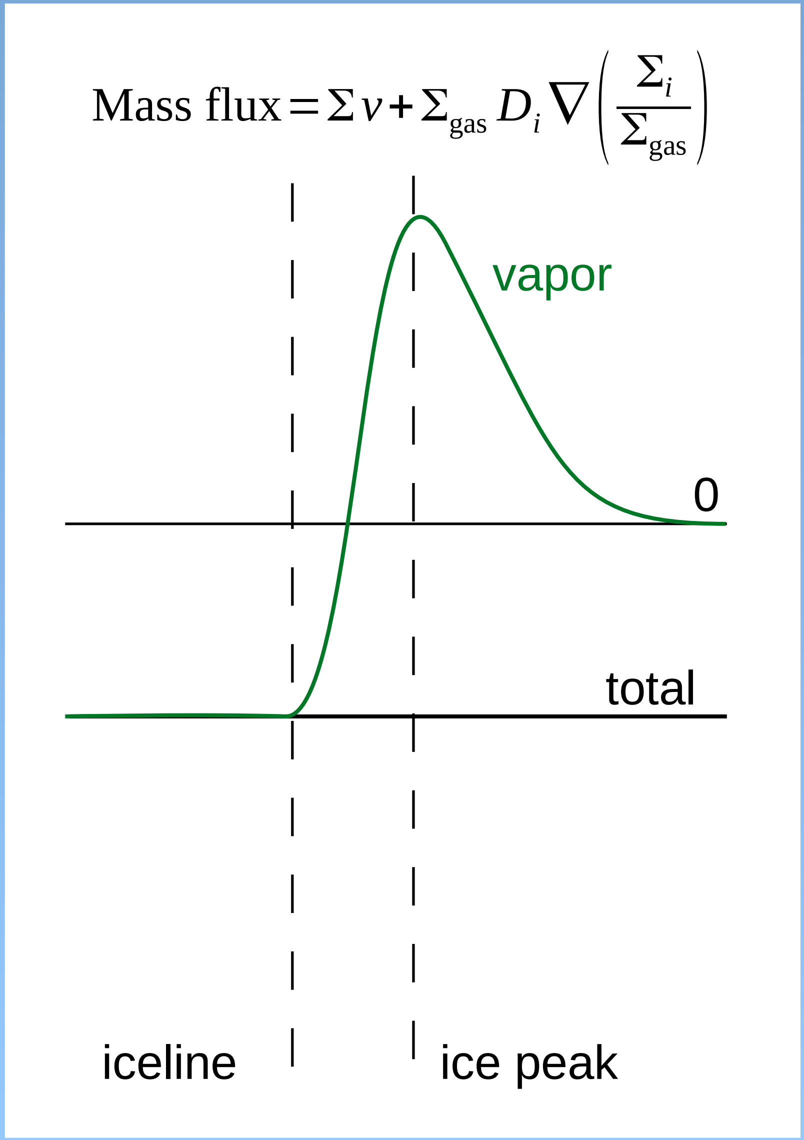
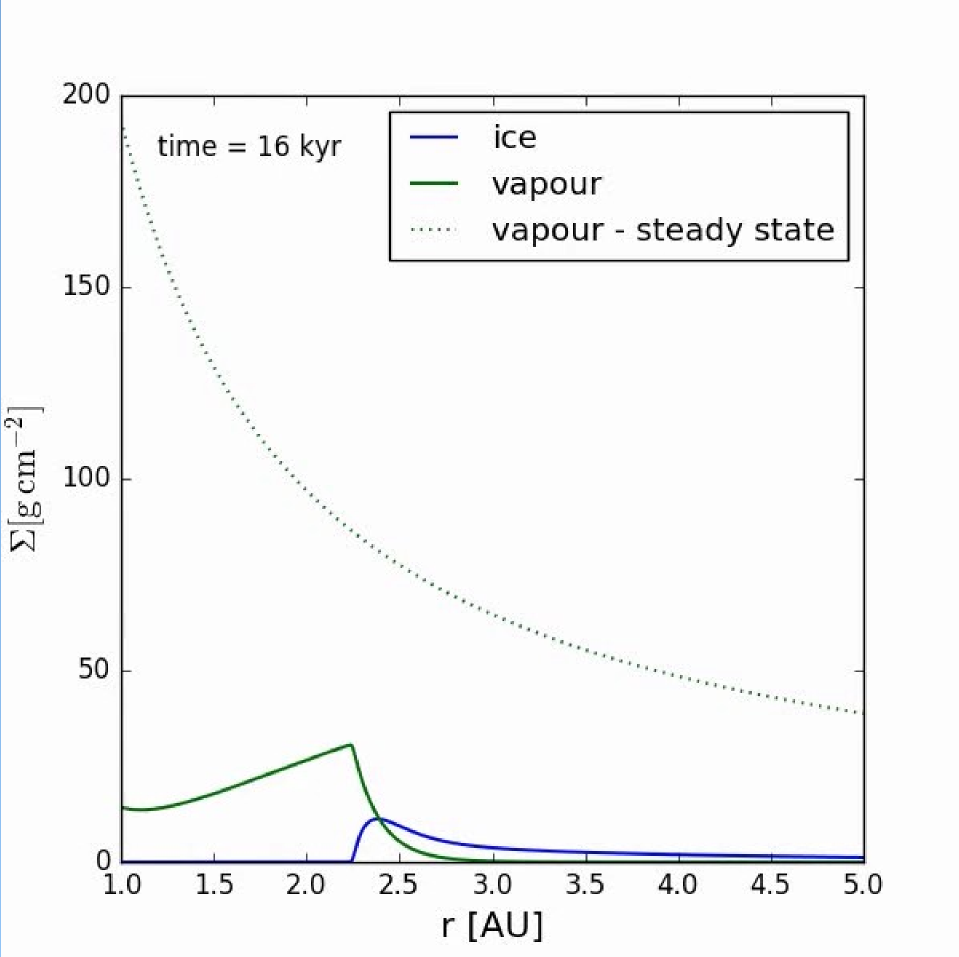


Schoonenberg & Ormel (2017)

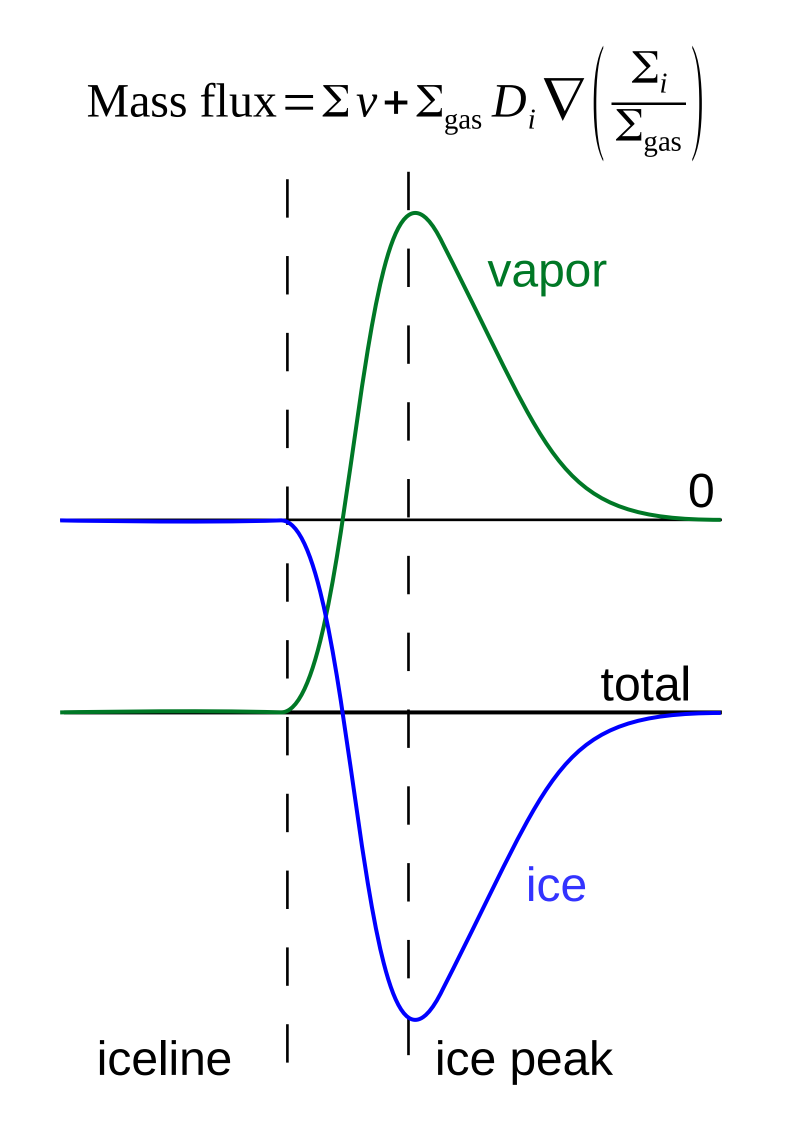


H_2O Iceline

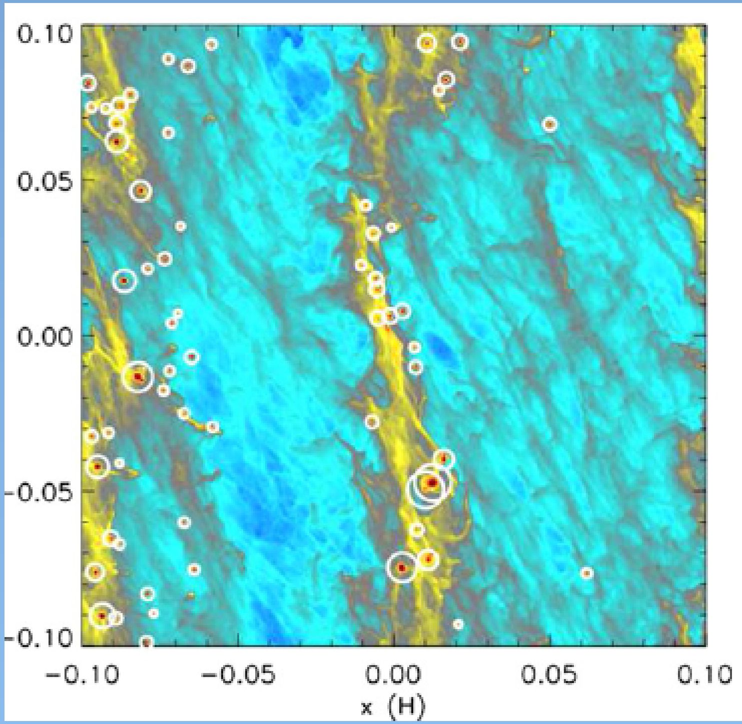
Schoonenberg & Ormel (2017)

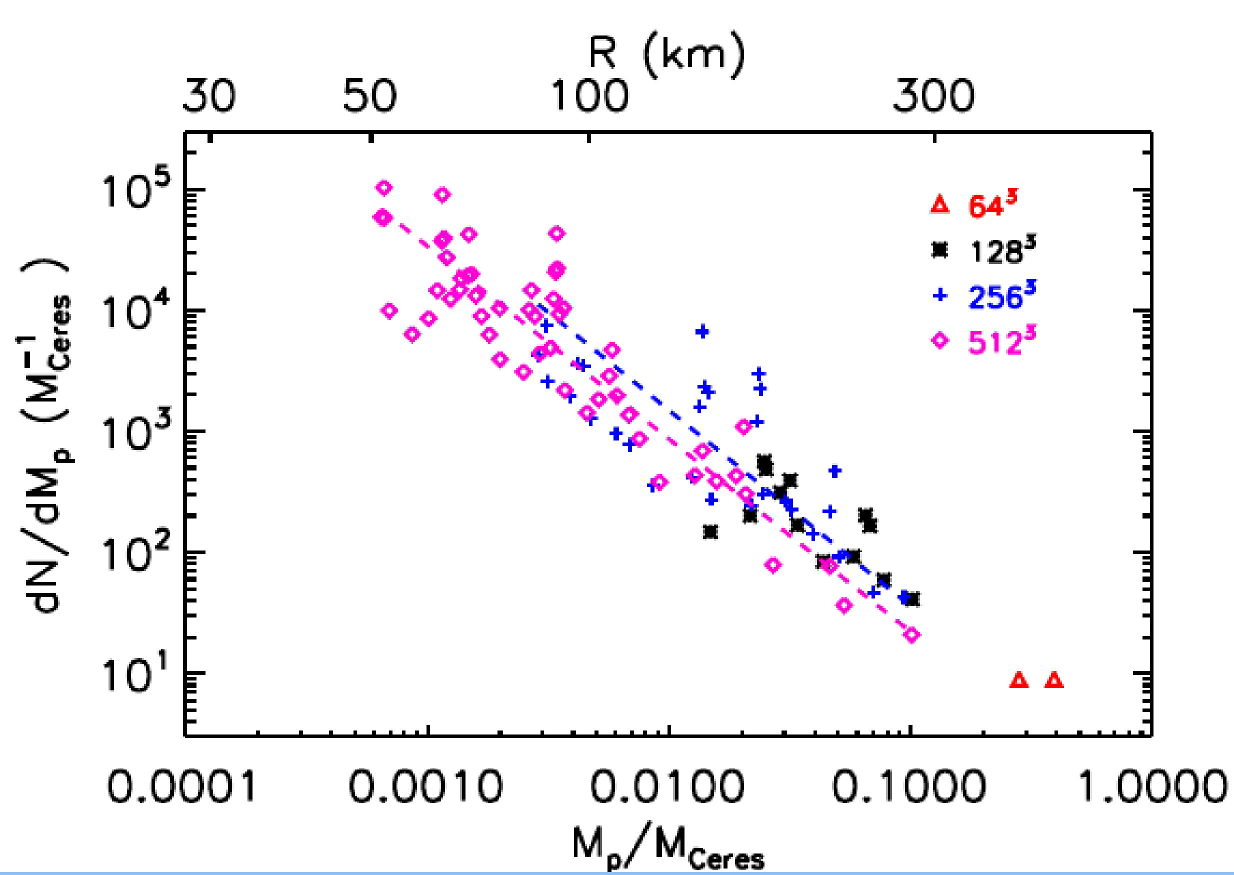


Schoonenberg & Ormel (2017)



Planetesimal IMF

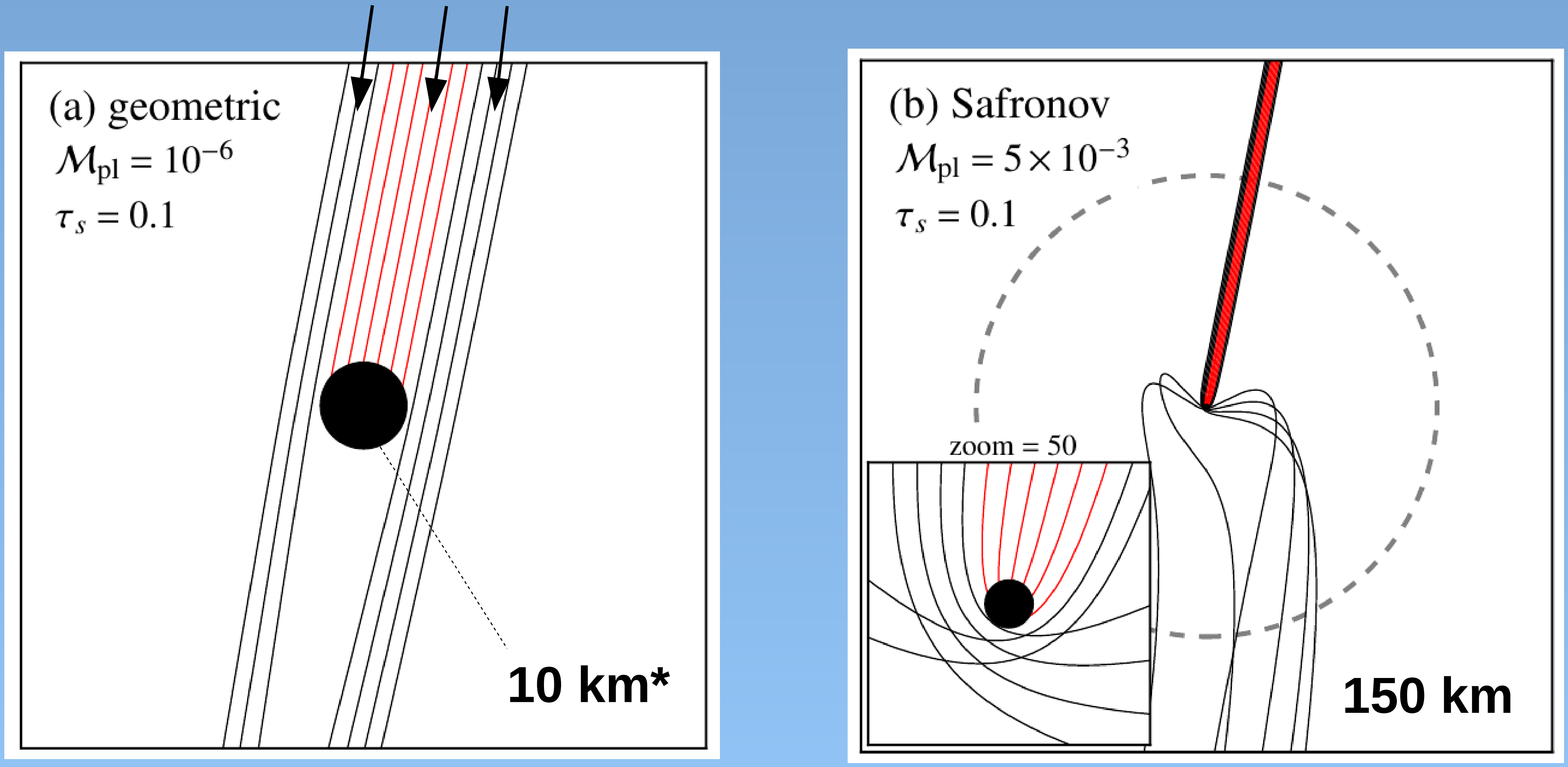




Johansen et al. (2015)
Simon et al. (2016)
Schaefer et al. (2017)

Is ~100 km sufficient for pebble accretion?

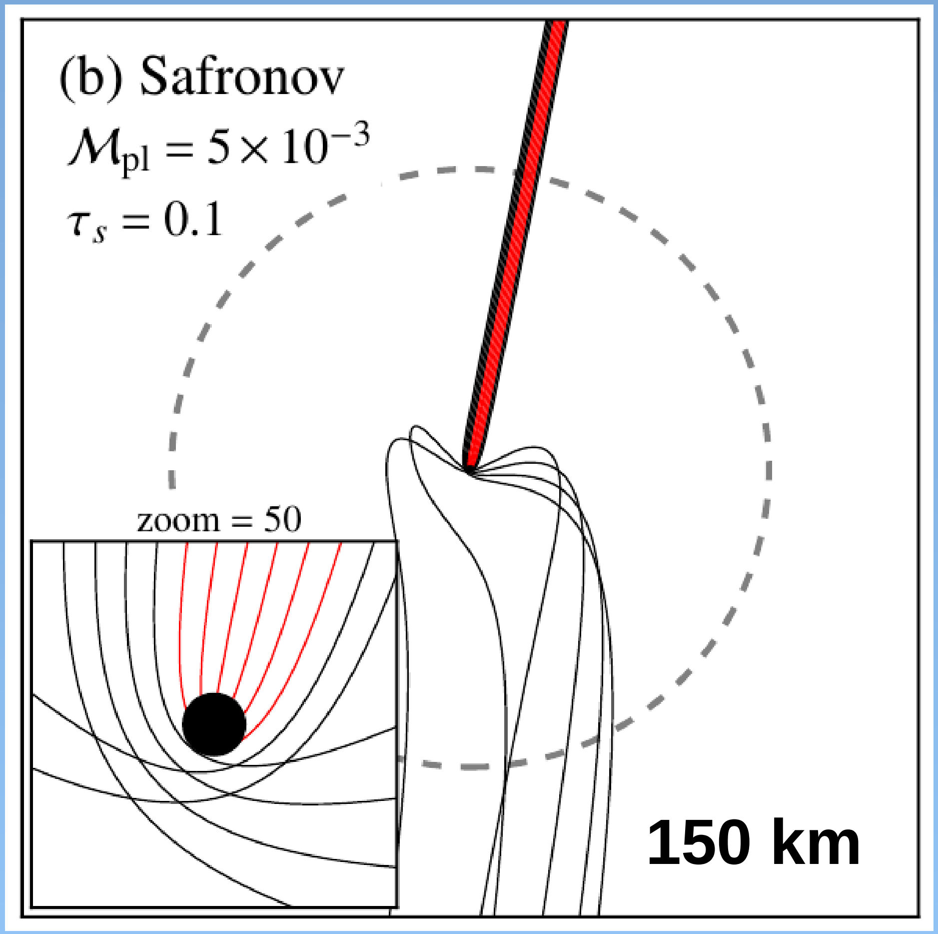
No pebble accretion



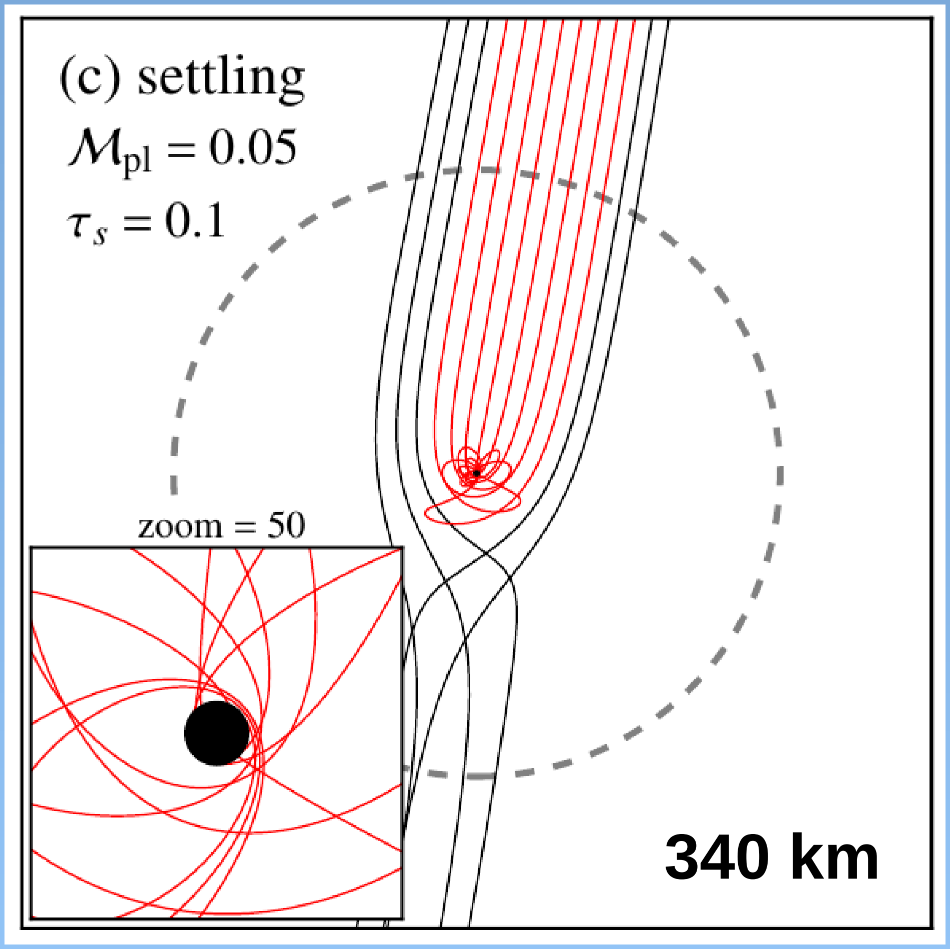
* 1 au, solar-mass star, disk headwind 50 m sec^{-1}

Ormel (2017)

Onset pebble accretion

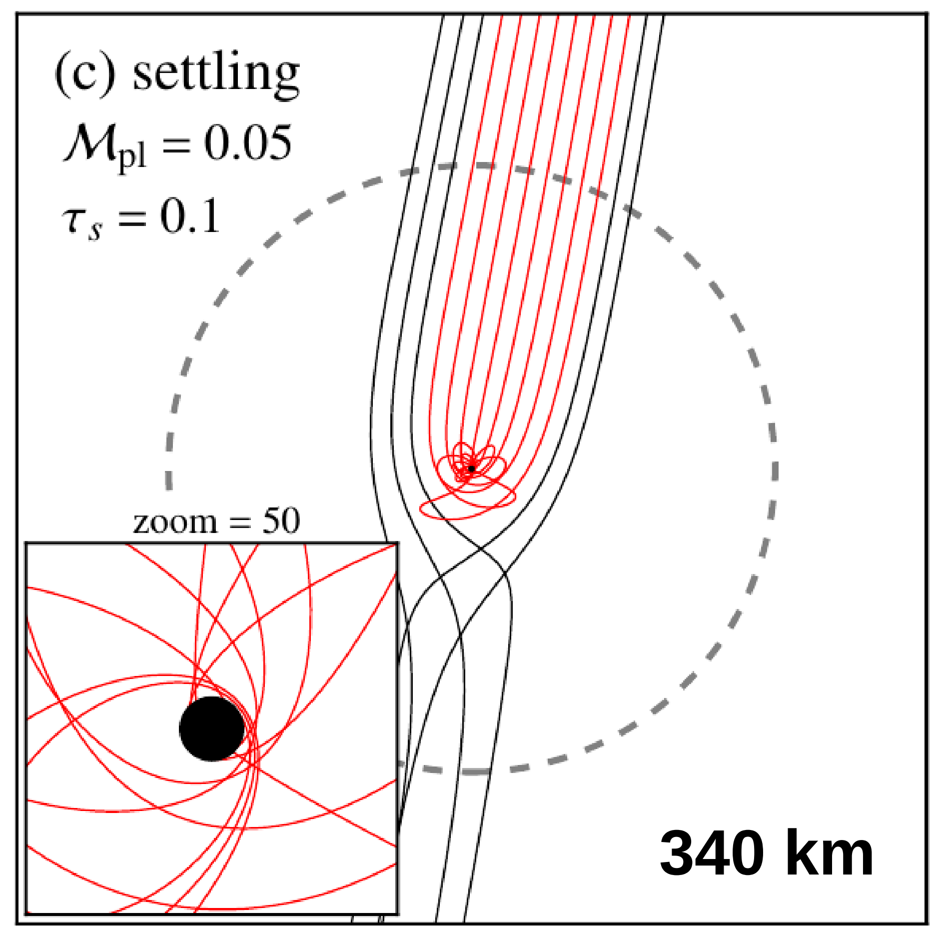


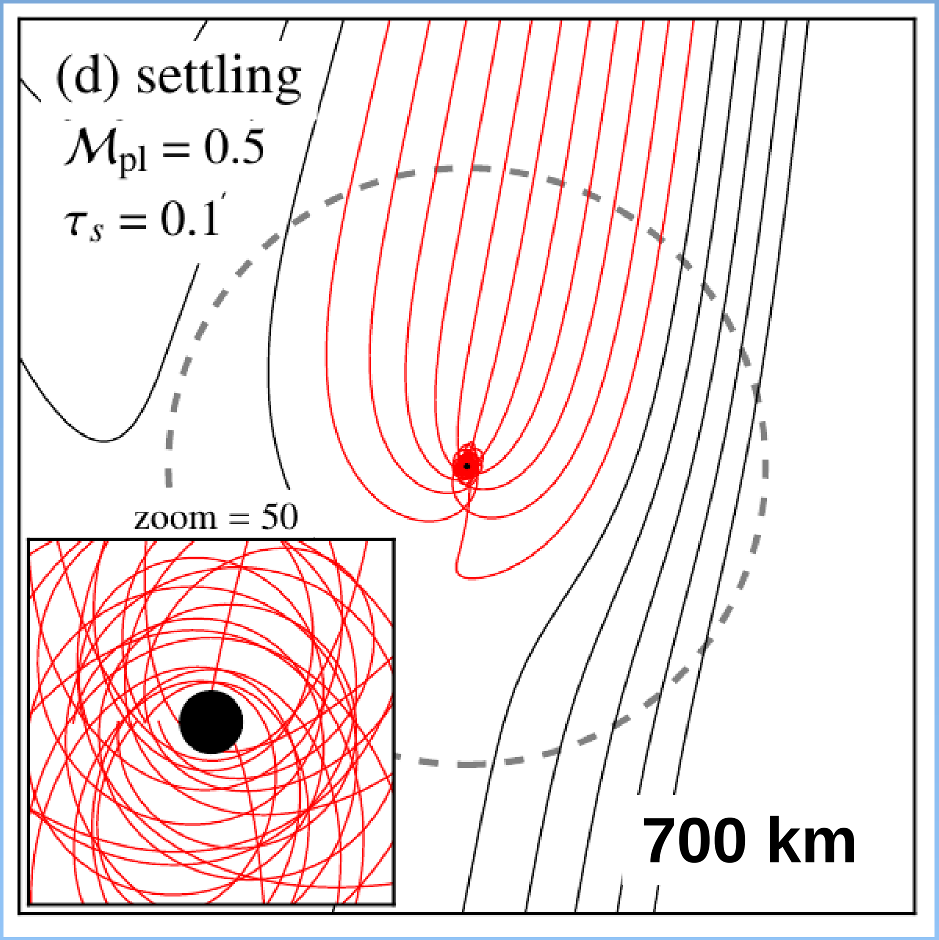
No Pebble accretion



Pebble accretion

Onset pebble accretion





Ormel (2017)

Onset of pebble accretion

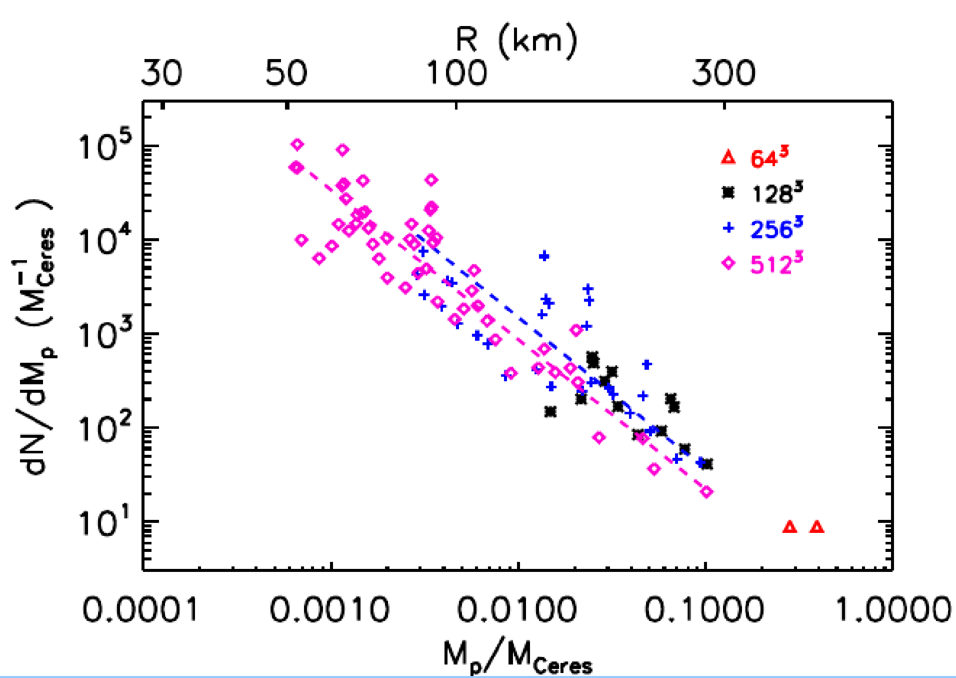
$$R_{\mathrm{P.A.}} \approx 220\ \mathrm{km} \left(\frac{v_{\mathrm{hw}}}{50\ \mathrm{m/sec}} \right) \left(\frac{r}{\mathrm{au}} \right)^{0.42} \left(\frac{\tau_s}{0.1} \right)^{0.28}$$

Visser & Ormel (2016)

Smaller in colder disks or in pressure bumps

Increases with disk orbital radius

Larger for larger pebbles



Planetesimal → pebble-accretion bodies
May need "classical" phase
e.g., planetesimal runaway growth
Levison et al. (2015)

Not all pebbles are accreted!

Efficiency = probability of accretion

In 2D limit

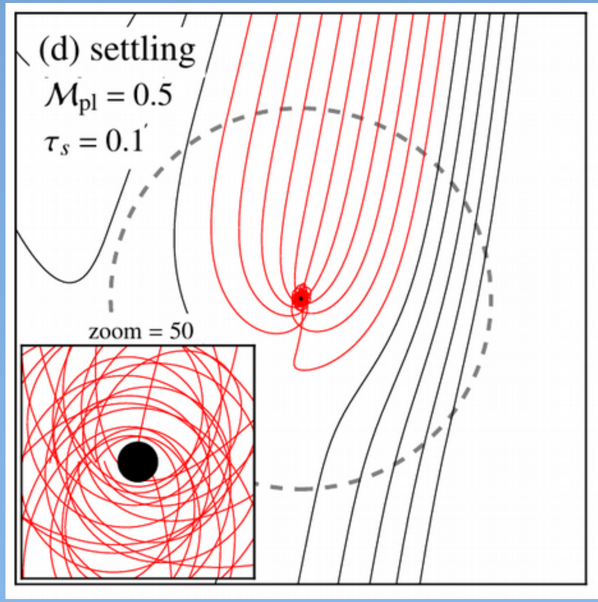
$$\epsilon_{2D} = \frac{0.31}{\eta} \left(\frac{M_p}{M_\star \tau_s} \frac{\Delta v}{v_K} \right)^{1/2}$$

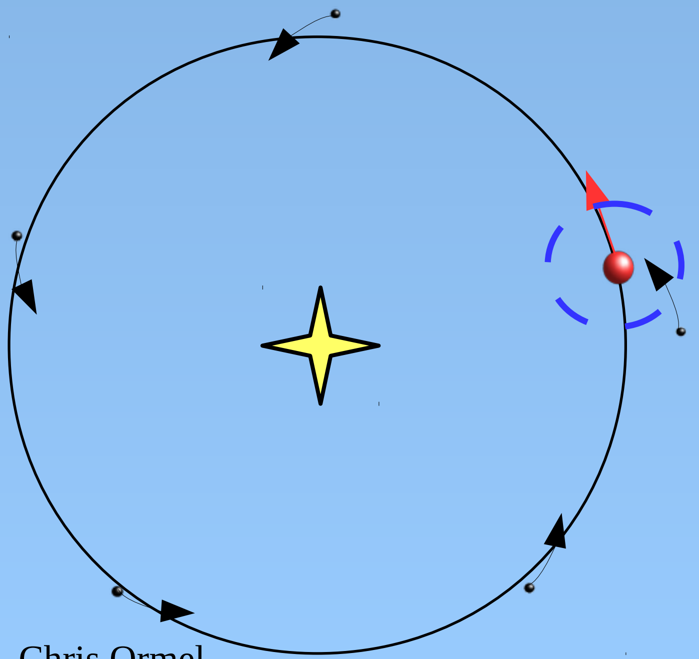
In 3D limit

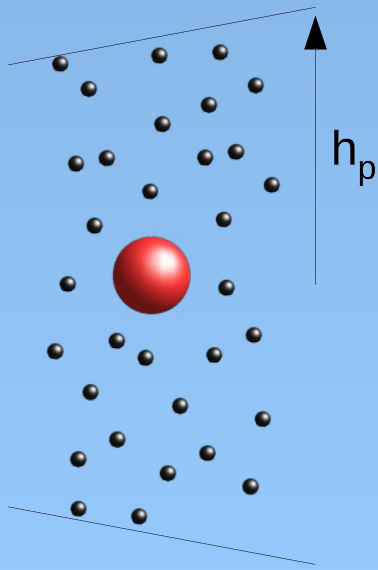
$$\epsilon_{P.A.} = 0.39 \frac{M_p}{M_\star} \frac{1}{\eta H_p / r}$$

Liu & Ormel, subm.

Expression consistent w/ literature but prefactors different



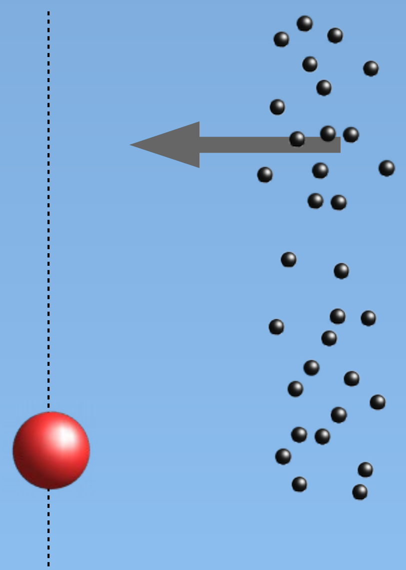




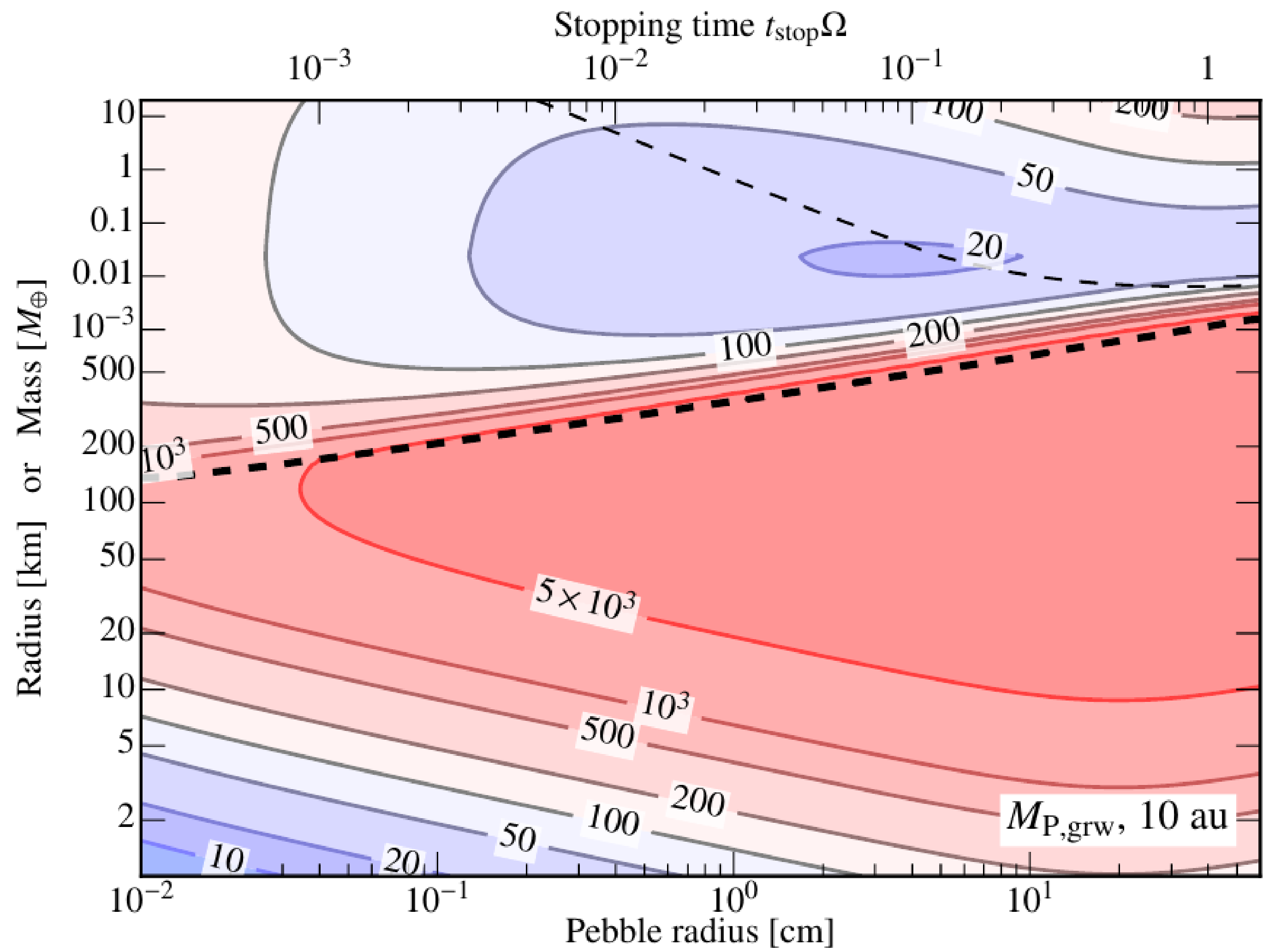
Pebble-doubling mass

(in Earth masses)

$m_{P,grw} = M_p/\varepsilon_{P.A.}$



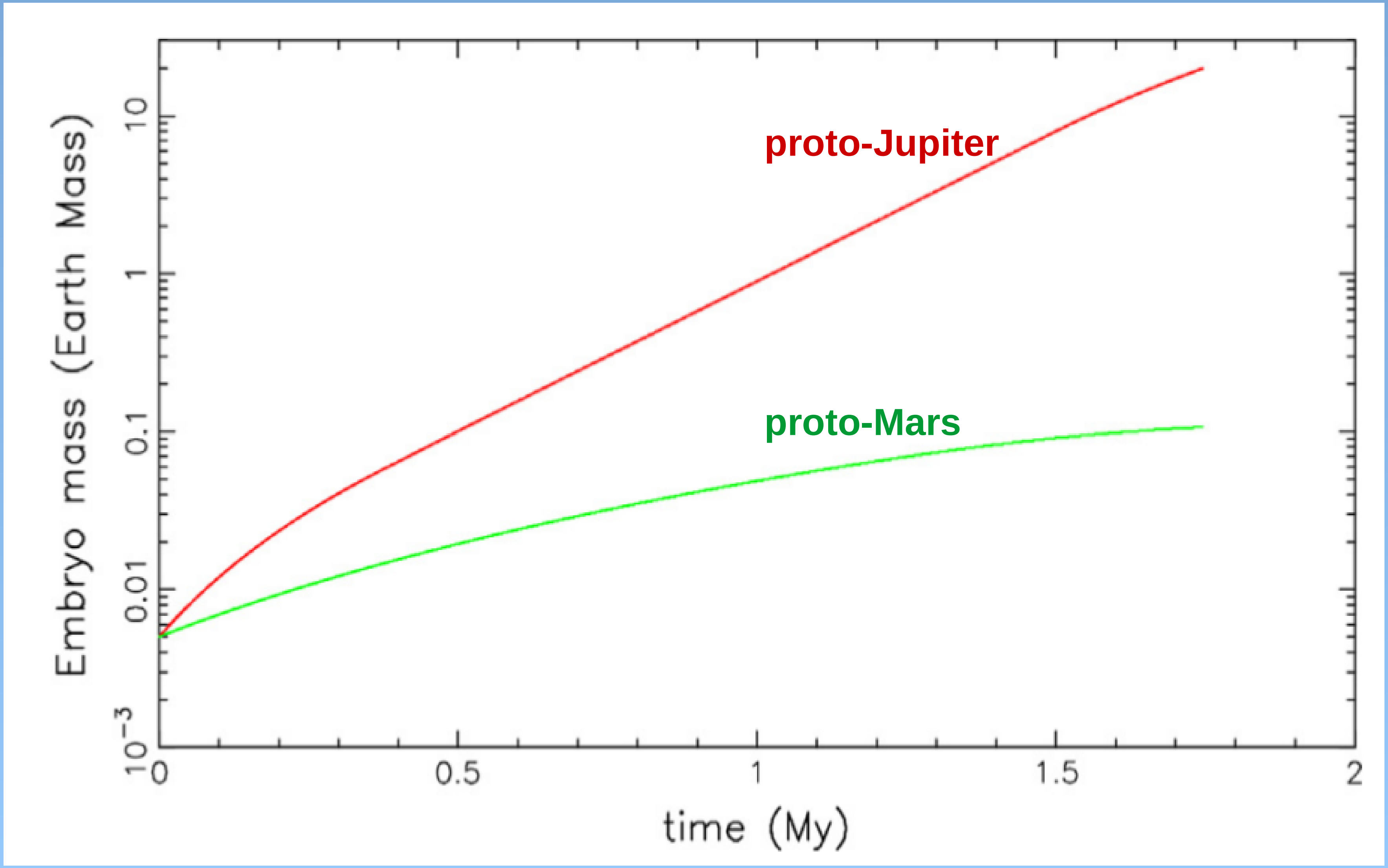
How many pebbles [Earth masses] needed to double the mass of the planet →



Ormel (2017), download here.

Application I: solar system

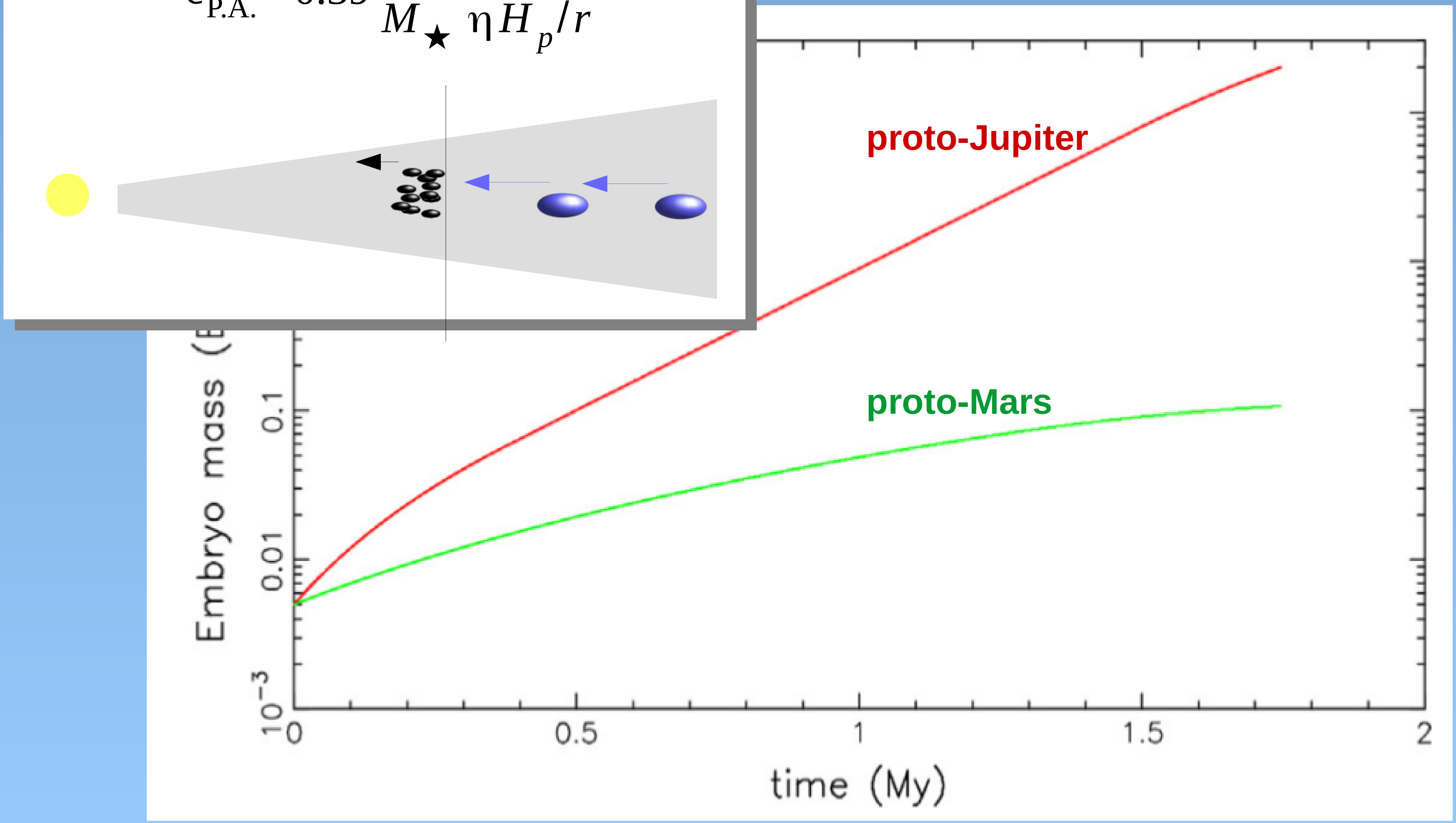
Morbidelli et al. 2015



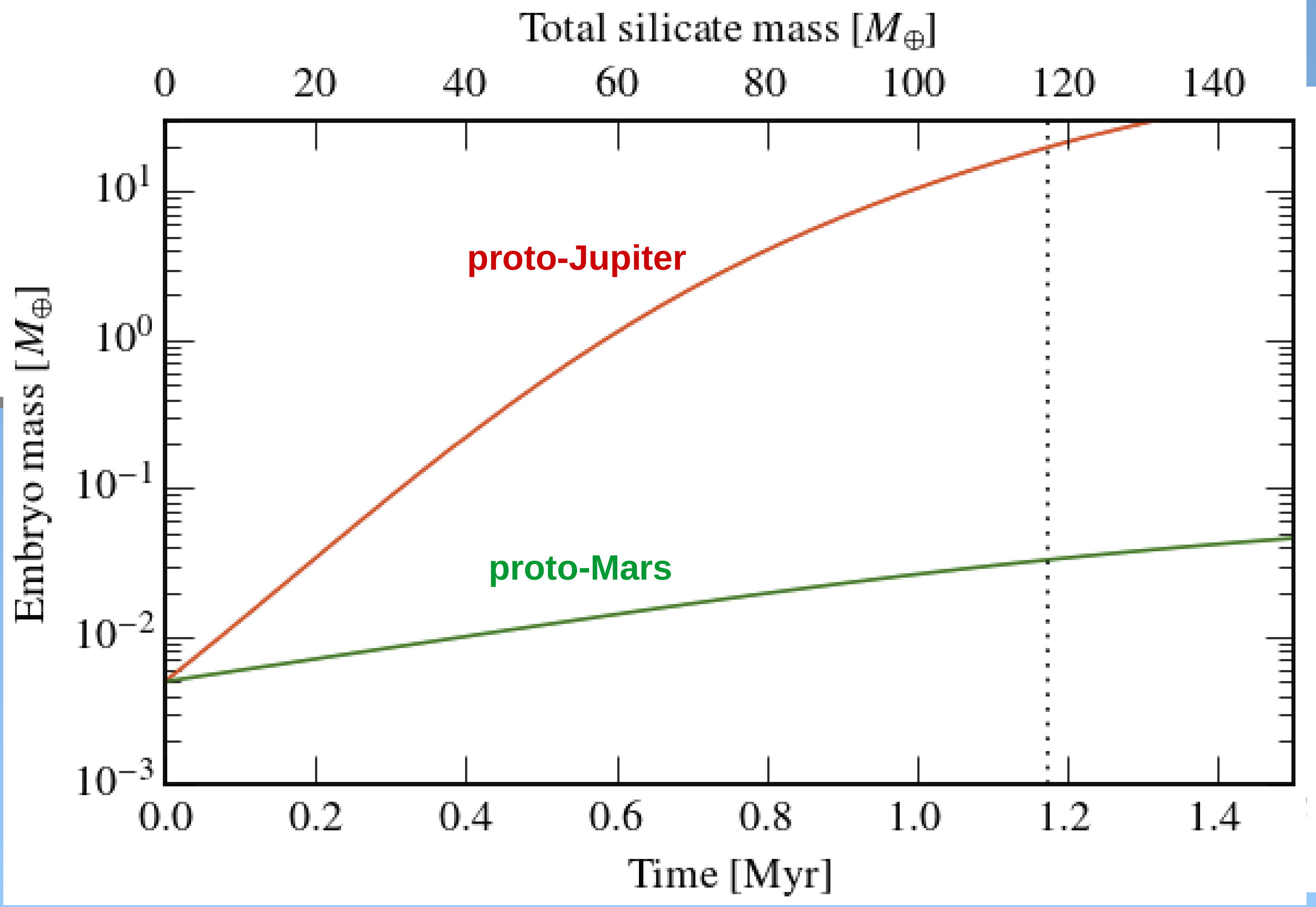
Application I: solar system

Morbidelli et al. 2015

$$\epsilon_{\mathrm{P.A.}} = 0.39 \frac{M_p}{M_\star} \frac{1}{\eta H_p / r}$$



Application I: solar system
Morbidelli et al. 2015



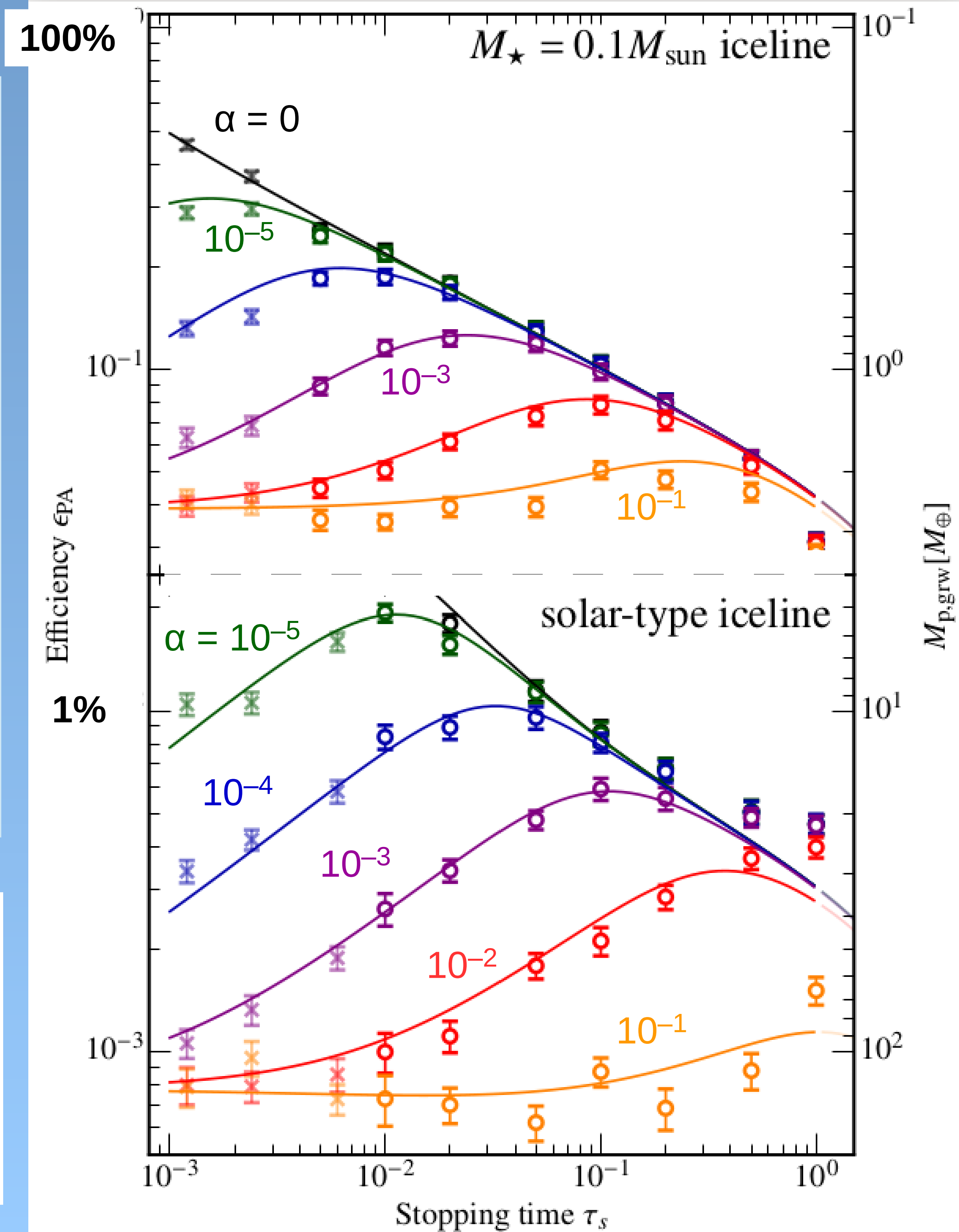
Application II:

Icelines around low-mass stars

Pebble accretion is *far more efficient* around low-mass stars b/c:

– further in
– Hill radii larger

$$\epsilon_{\mathrm{P.A.}} = \frac{0.39}{\eta} \frac{M_p}{M_\star} \frac{1}{H_p/r}$$

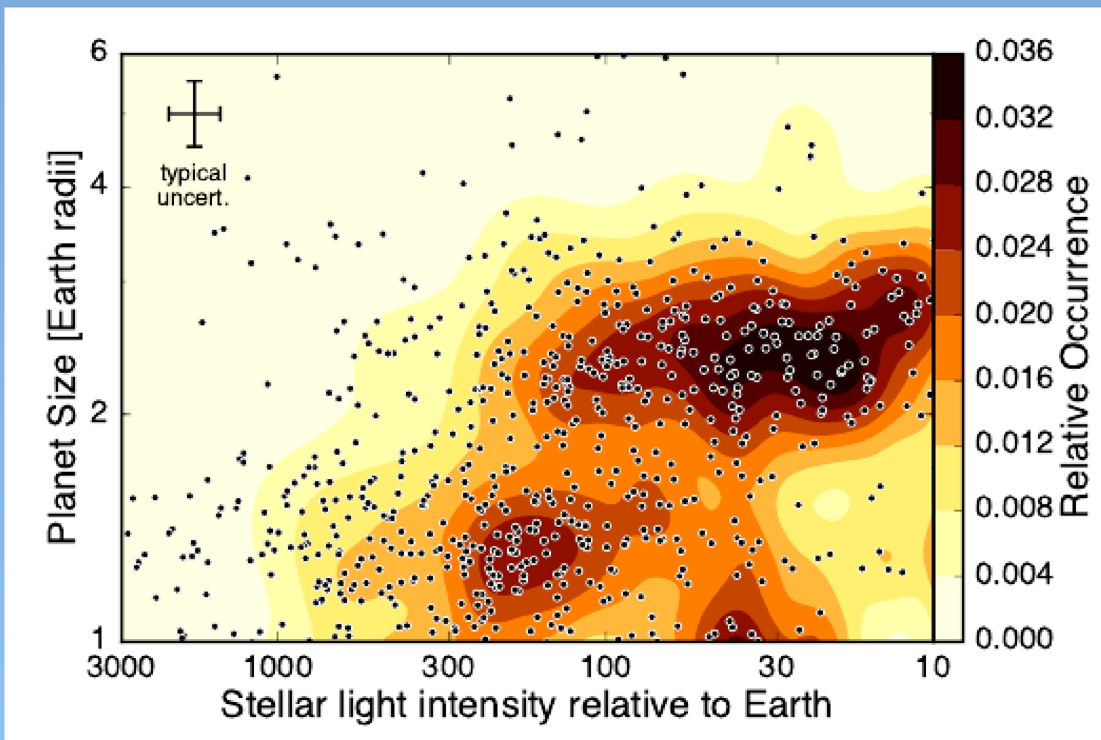


Efficiency and pebble doubling mass for a 0.1 M_{Earth} mass →
[Ormel & Liu, in prep.]

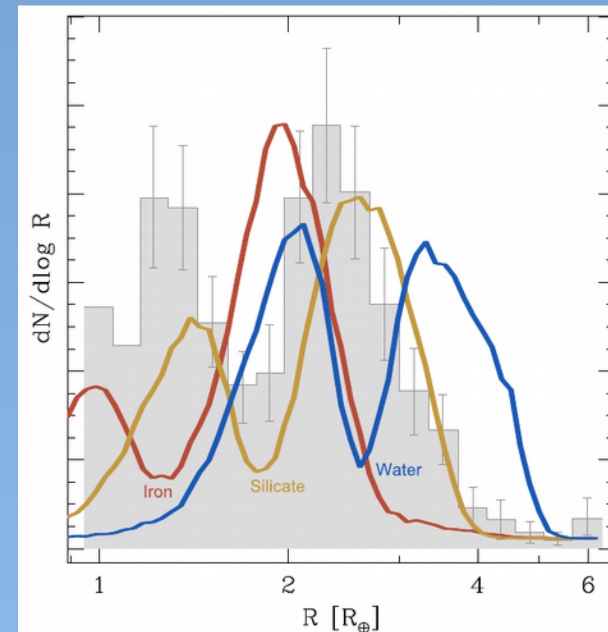
* solar-type star: h=0.05; η=0.003
* M-star: h=0.03; η = 0.001

Composition of planets

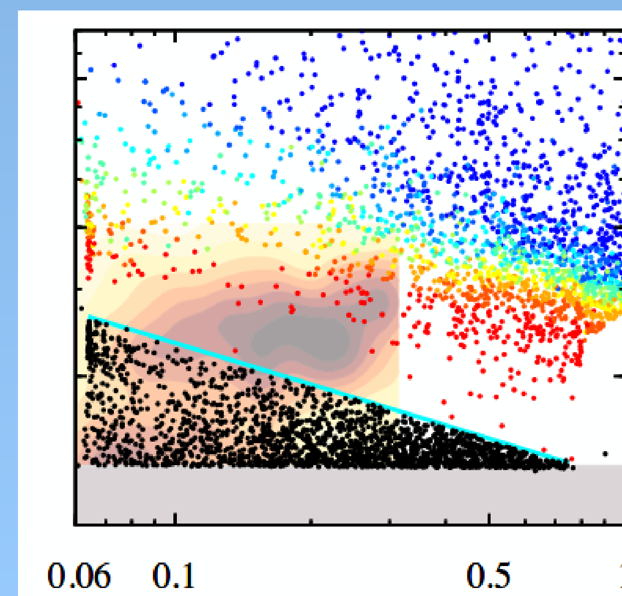
How to keep them rocky?



Fulton et al. (2017)



Owen & Wu (2017)



Jin & Mordasini

1. Formation, then migration

Rock after ice
– start icy at snowline
– migrate interior to snowline
– accrete silicate pebbles afterwards
– end up w/ rocky composition

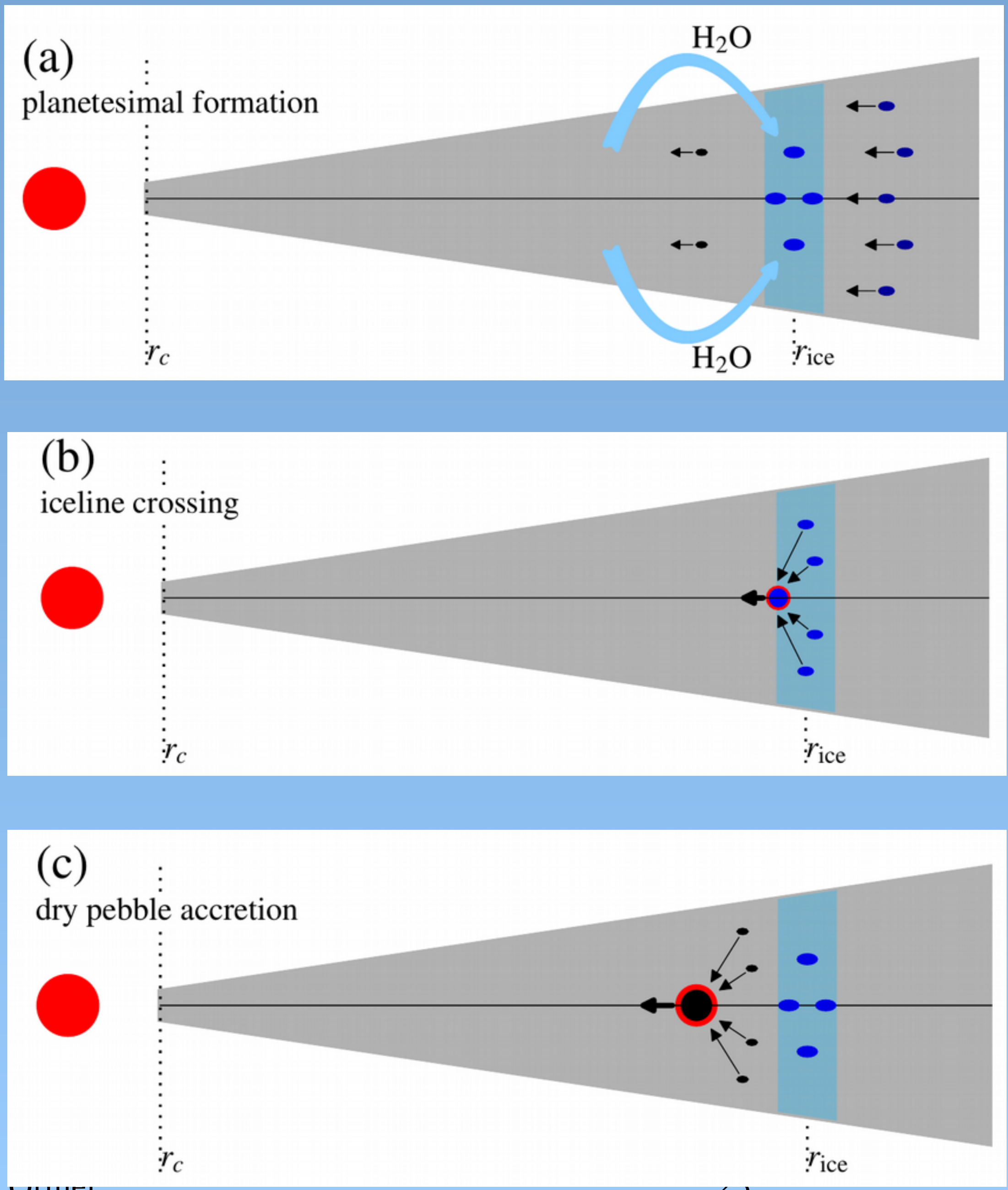
Scenario works esp. for low-mass stars

Make similar planets
similar size planets in system indicative of formation at single location?
Weiss et al. (2017)

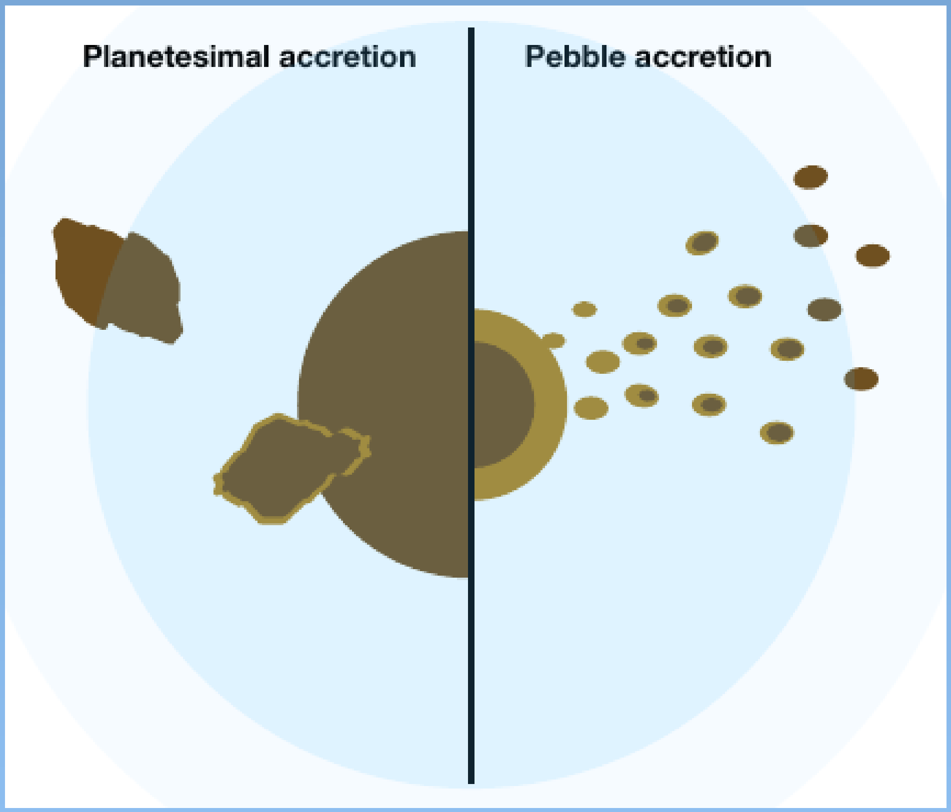
cf. “inside-out” planet formation models
Chatterjee & Tan (2014, 2015); Hu et al. (2017)

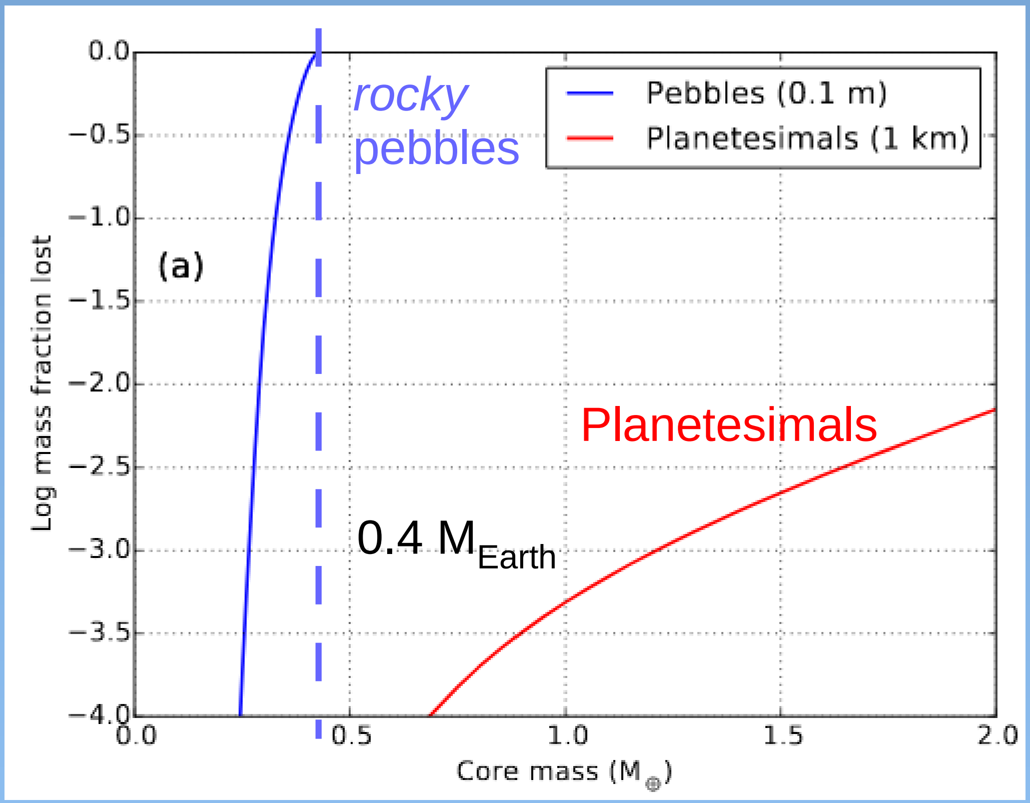
Scenario for formation of TRAPPIST-1 system →

Ormel et al. (2017)



2. Pebble evaporation in envelope

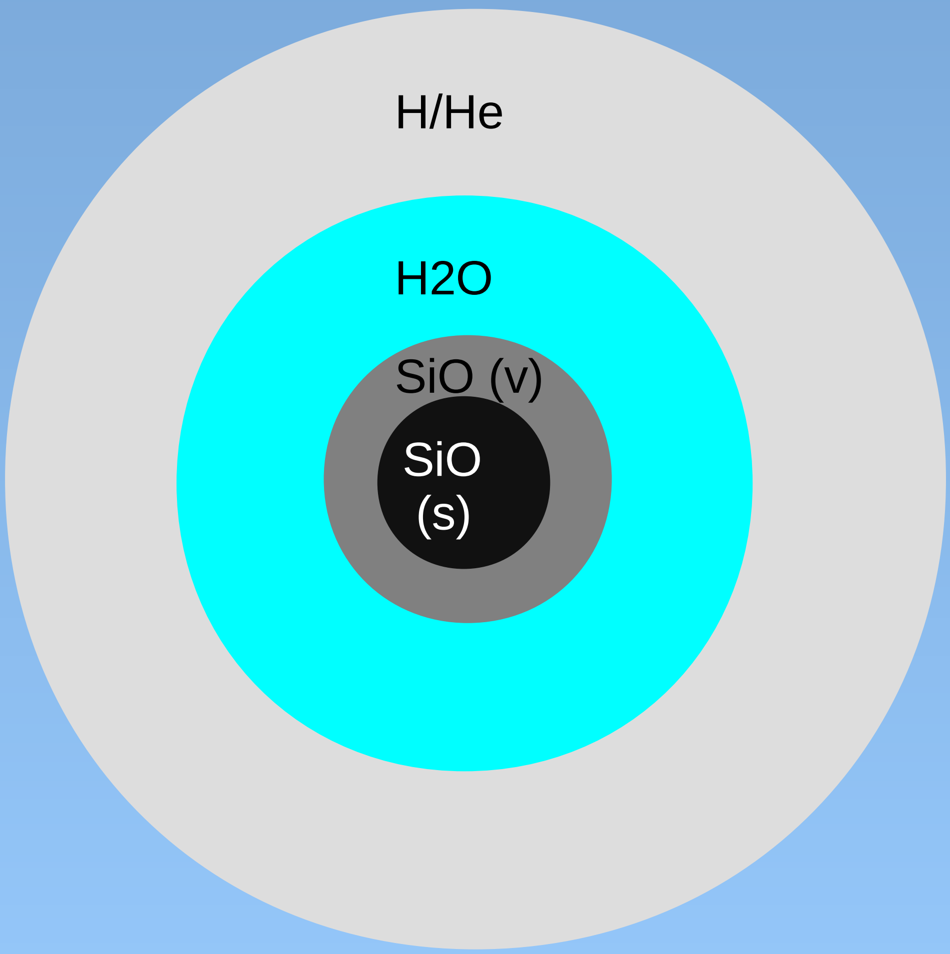




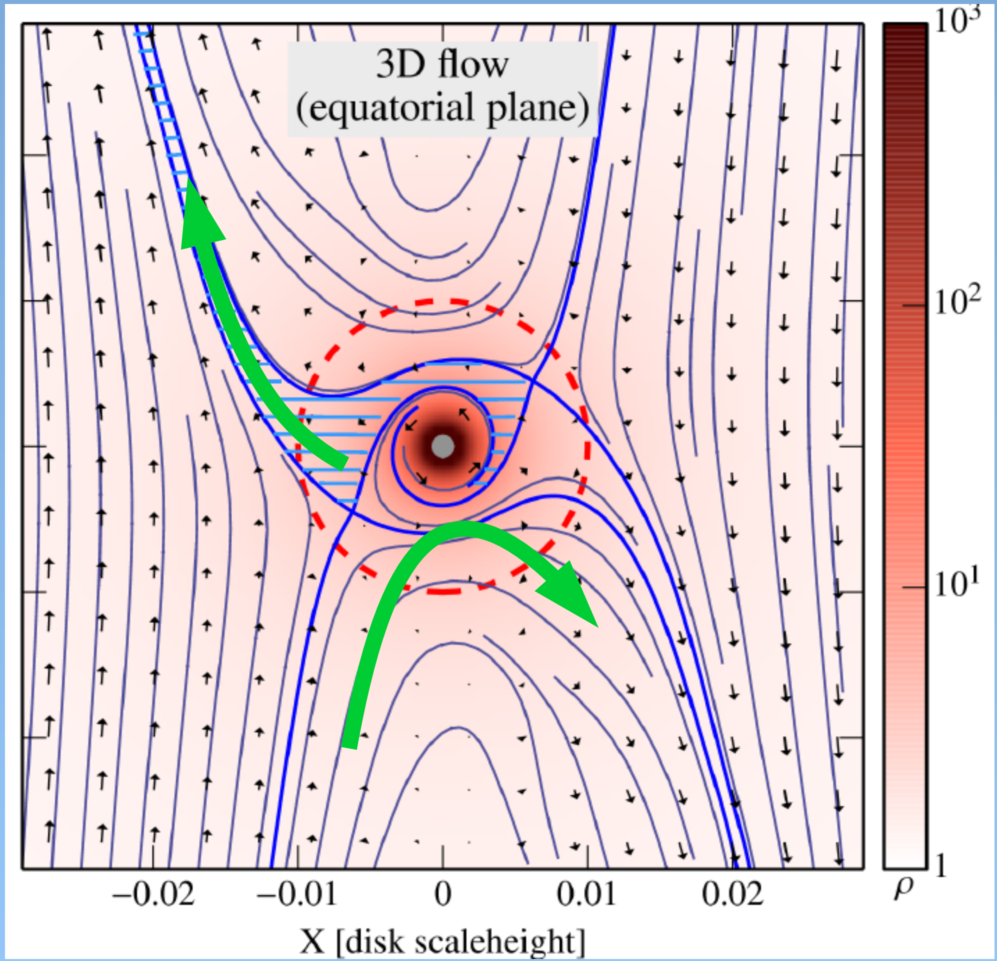
Brouwers, Vazan, Ormel (2017)

Evaporation + Recycling remove H_2O

1D structure

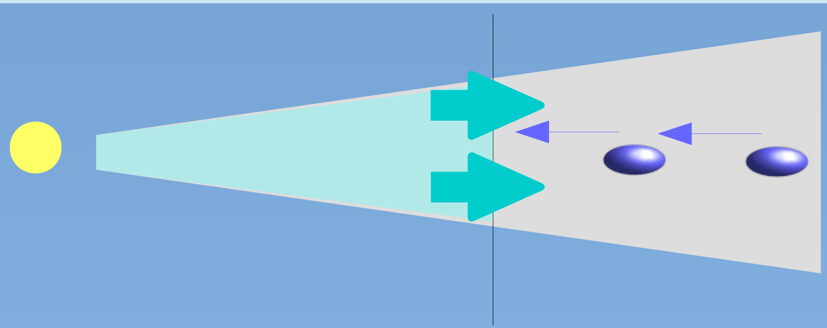


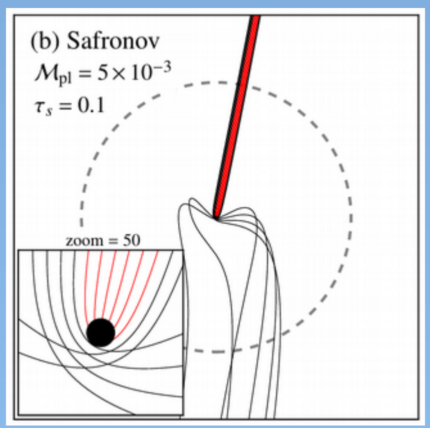
Recycling envelope ← → disk

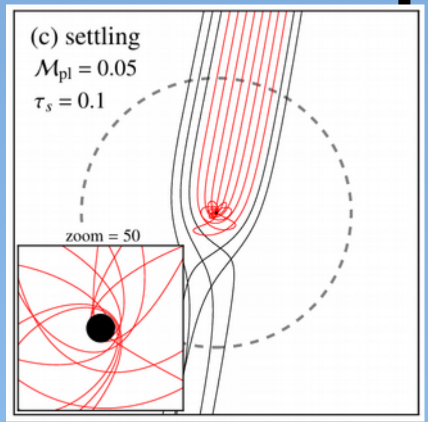


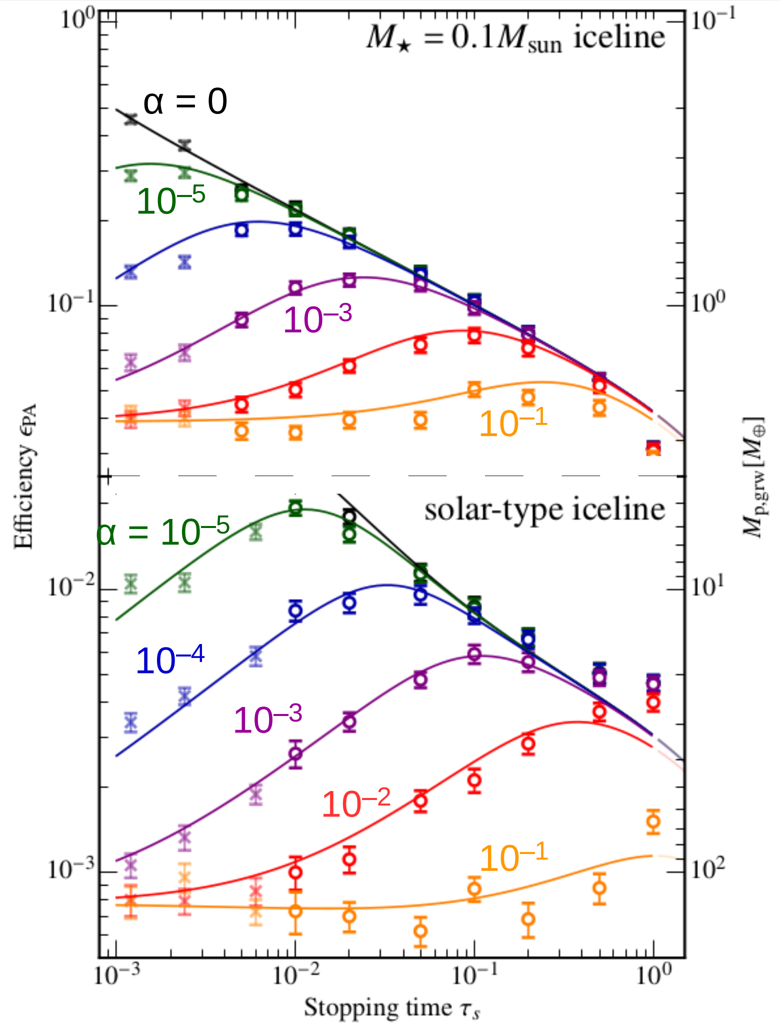
Ormel et al. (2015); Fung et al. (2015); Cimerman et al. (2017); Lambrechts & Lega (2017)

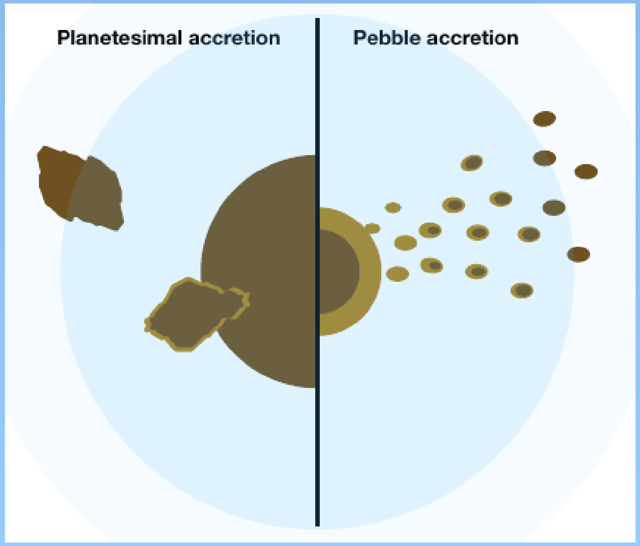
Summary

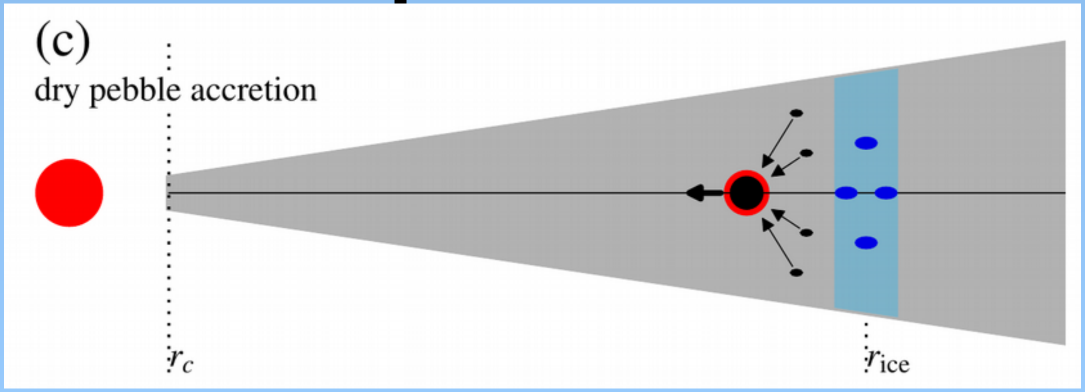



(b) Safronov
$M_{pl} = 5\times10^{-3}$
$\tau_s = 0.1$
zoom = 50


(c) settling
$M_{pl} = 0.05$
$\tau_s = 0.1$
zoom = 50


$M_\star = 0.1 M_{sun}$ iceline
α = 0
10^{-5}
10^{-3}
10^{-1}
solar-type iceline
α = 10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Efficiency ϵ_{PA}
$M_{p,grw} [M_\oplus]$
Stopping time τ_s


Planetesimal accretion
Pebble accretion


(c)
dry pebble accretion
r_c
r_{ice}