Phase change process in embedded planet's envelope

2022/6/10

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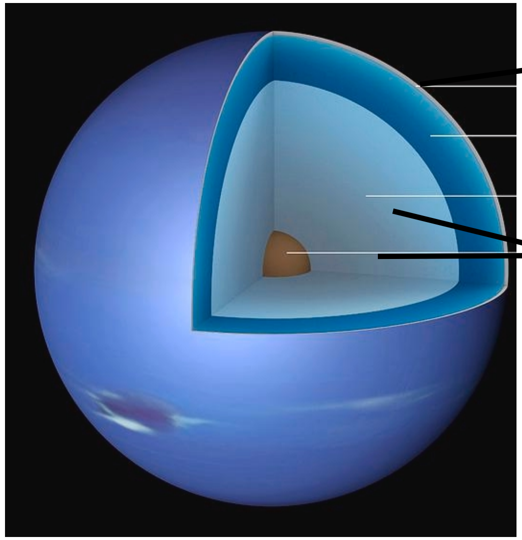
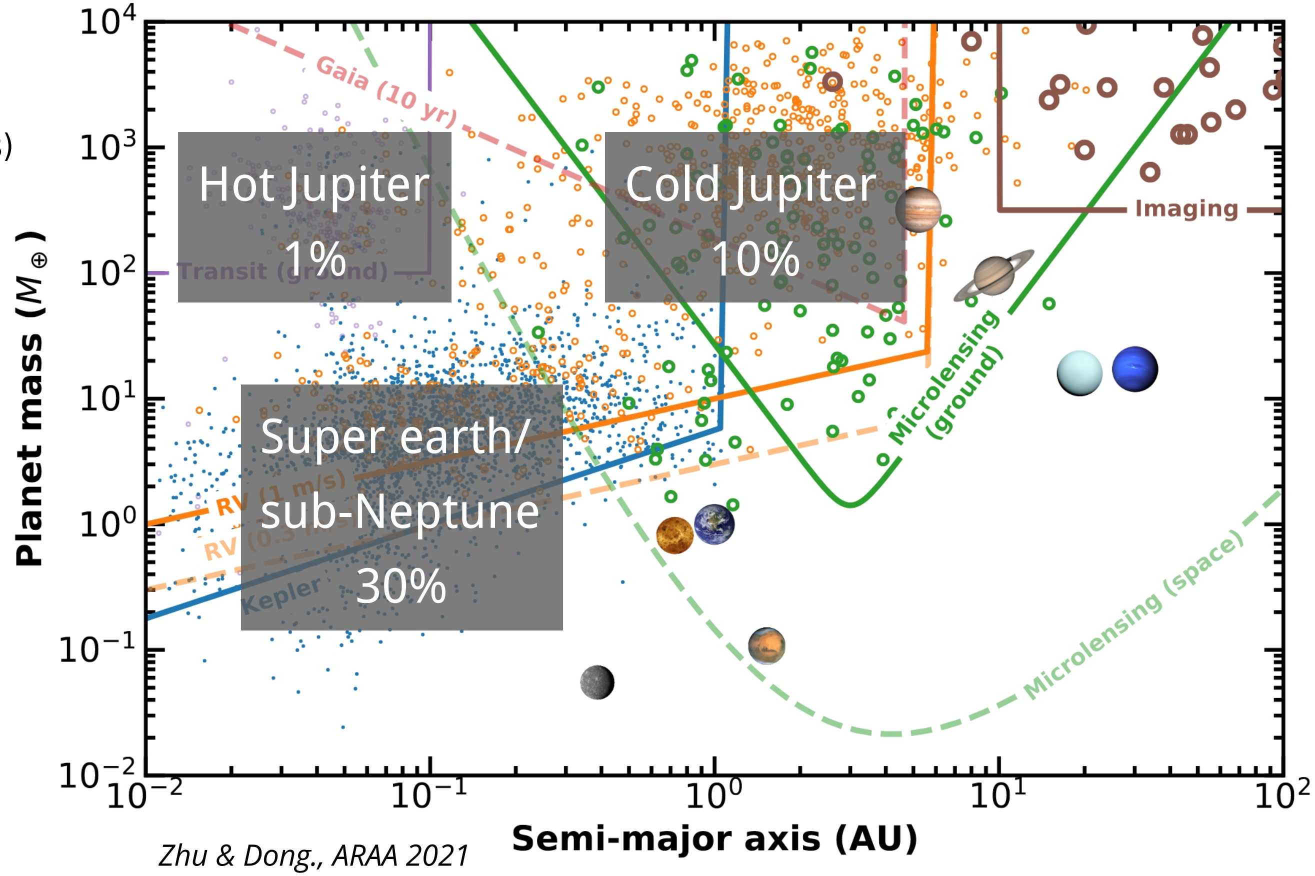
IAS Planet group meeting, Tsinghua University

Planets with Envelope



fineartamerica.com

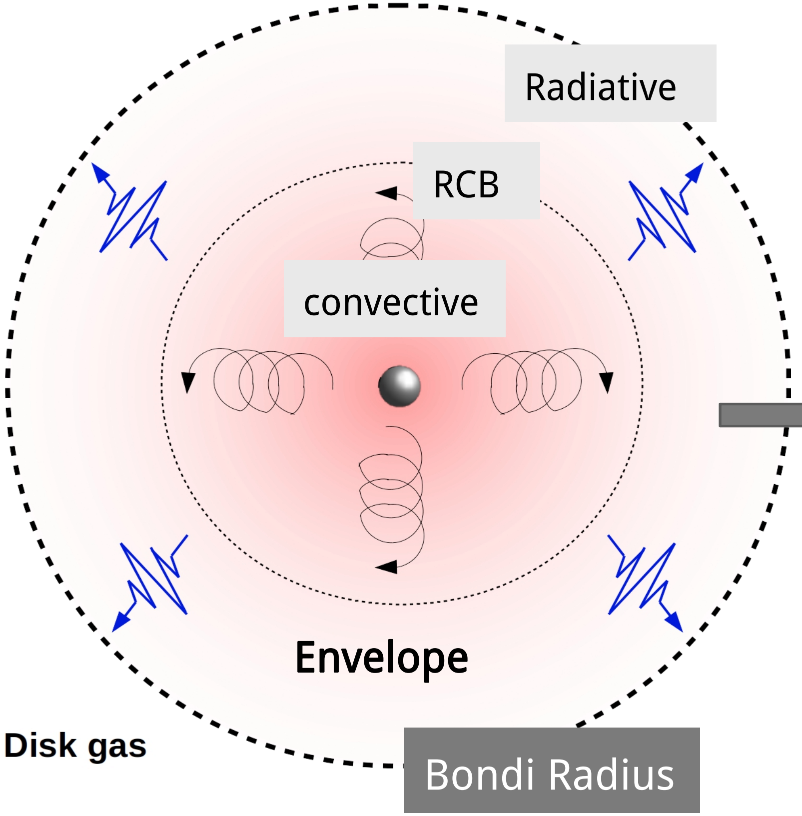
Neptune structure



Zhu & Dong., ARAA 2021

A majority of sub-Neptunes, how do they obtain their envelope?

1D envelope structure model



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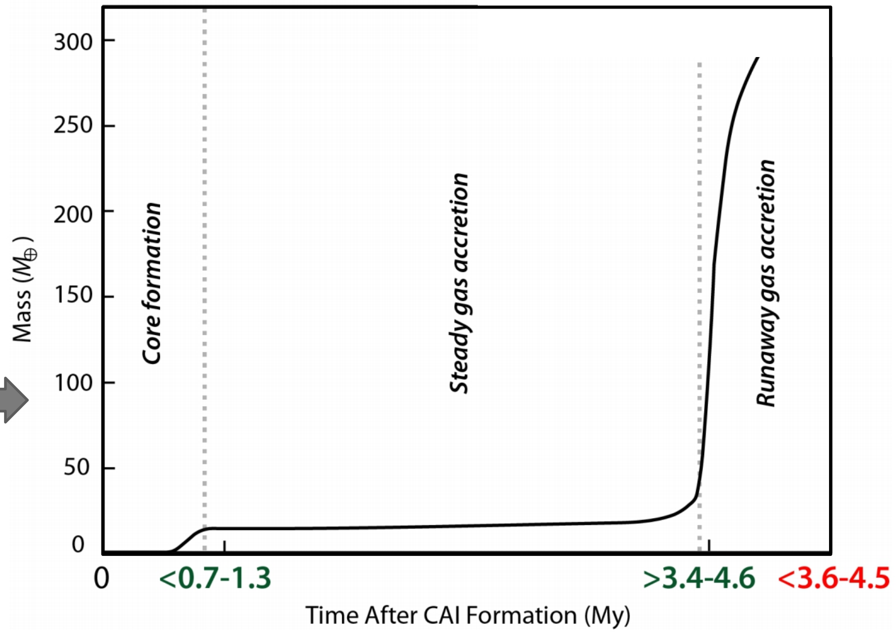
Classical 1D model

BOUNDARY
Envelope is in Pressure balance with disk

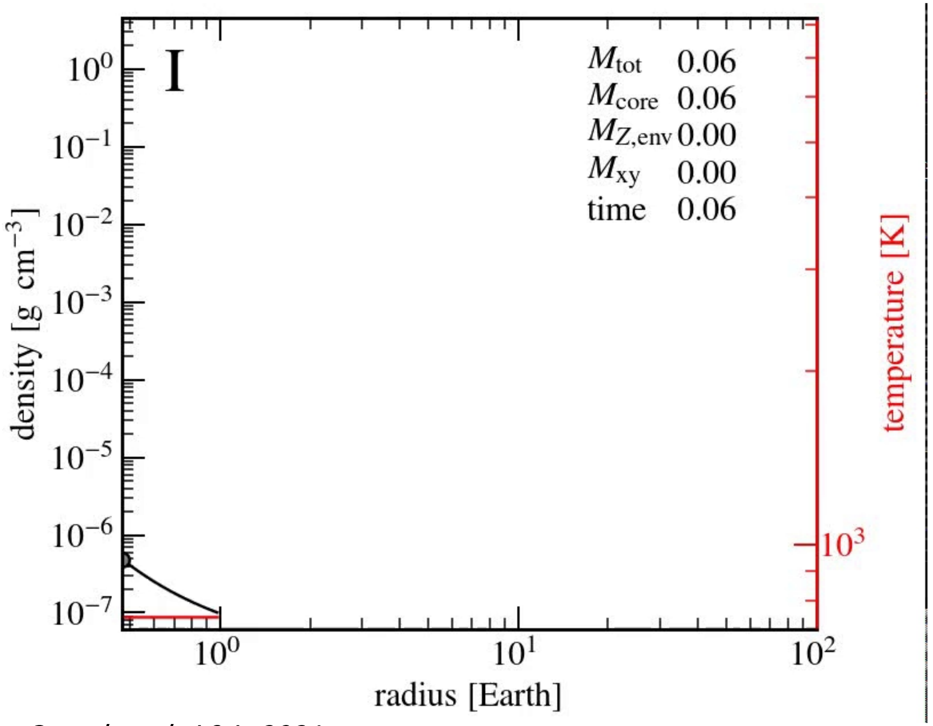
EQUATIONS
Hydro-static balance,
Mass conservation,
Luminosity equations
Equation of state....



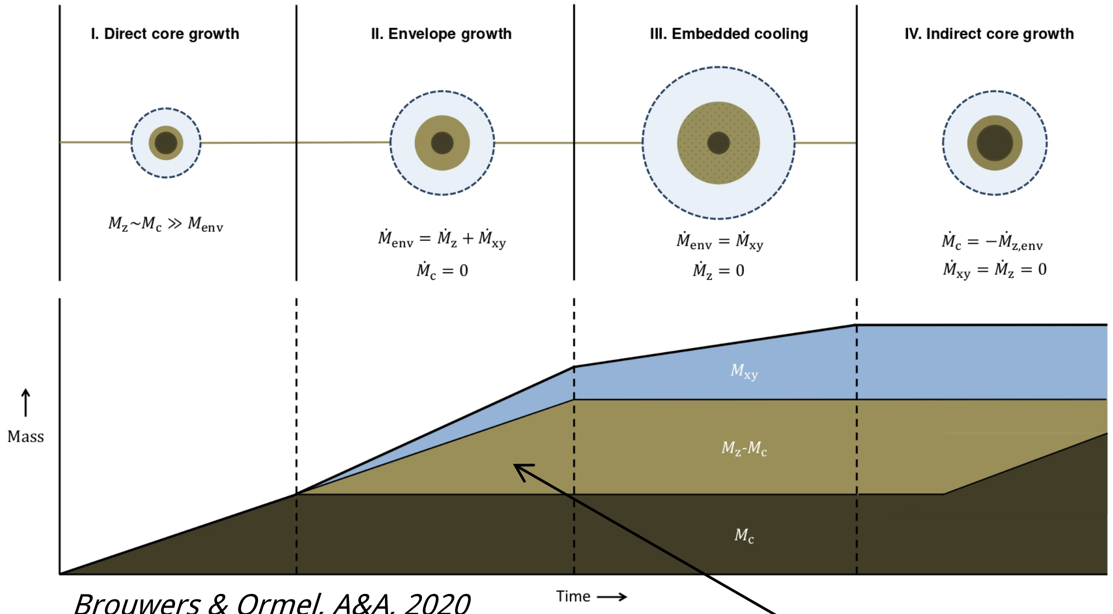
Weiss++, 49th LPSC 2018 Formation stages for Jupiter

One important result: planet will fall into runaway gas accretion once core mass reach 5~20 $M_\oplus$

Polluted Envelope from pebble evaporation



Ormel et al, A&A, 2021



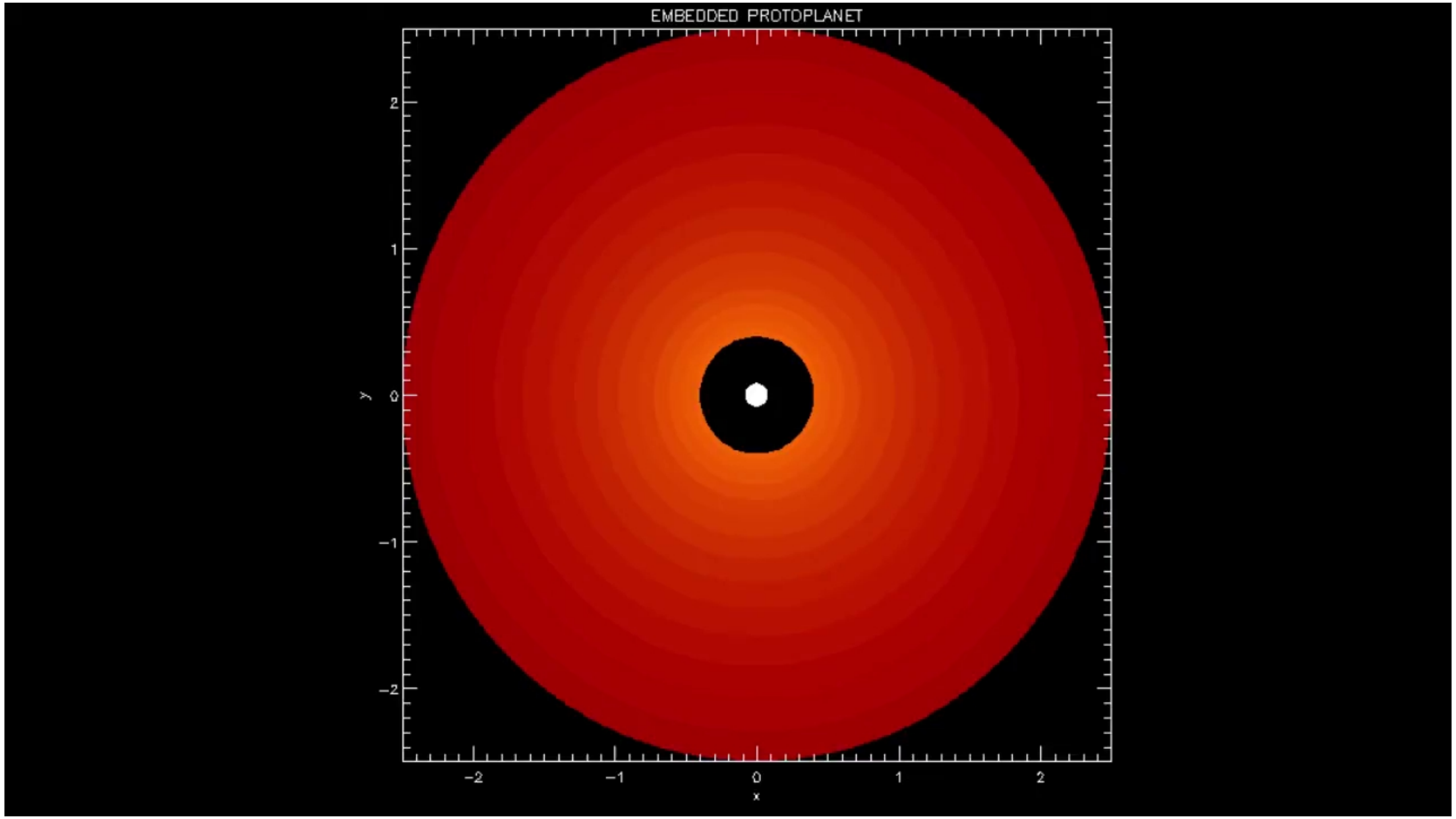
Brouwers & Ormel, A&A, 2020

mean molecular weight higher

Brouwers+ 2019,2020,2021
Ormel+ 2021
Venturini+ 2016

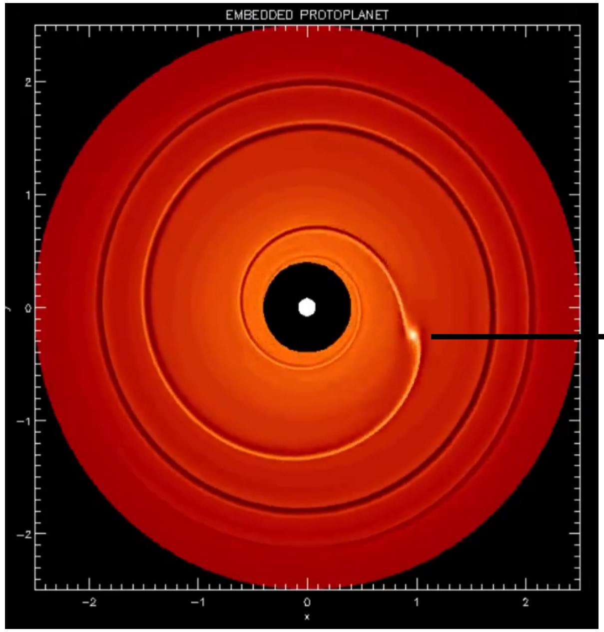
Even **easier** to get runaway accretion, where are the sub-Neptunes come from ?

Planet-disk interaction



Kley & Nelson., ARAA 2012

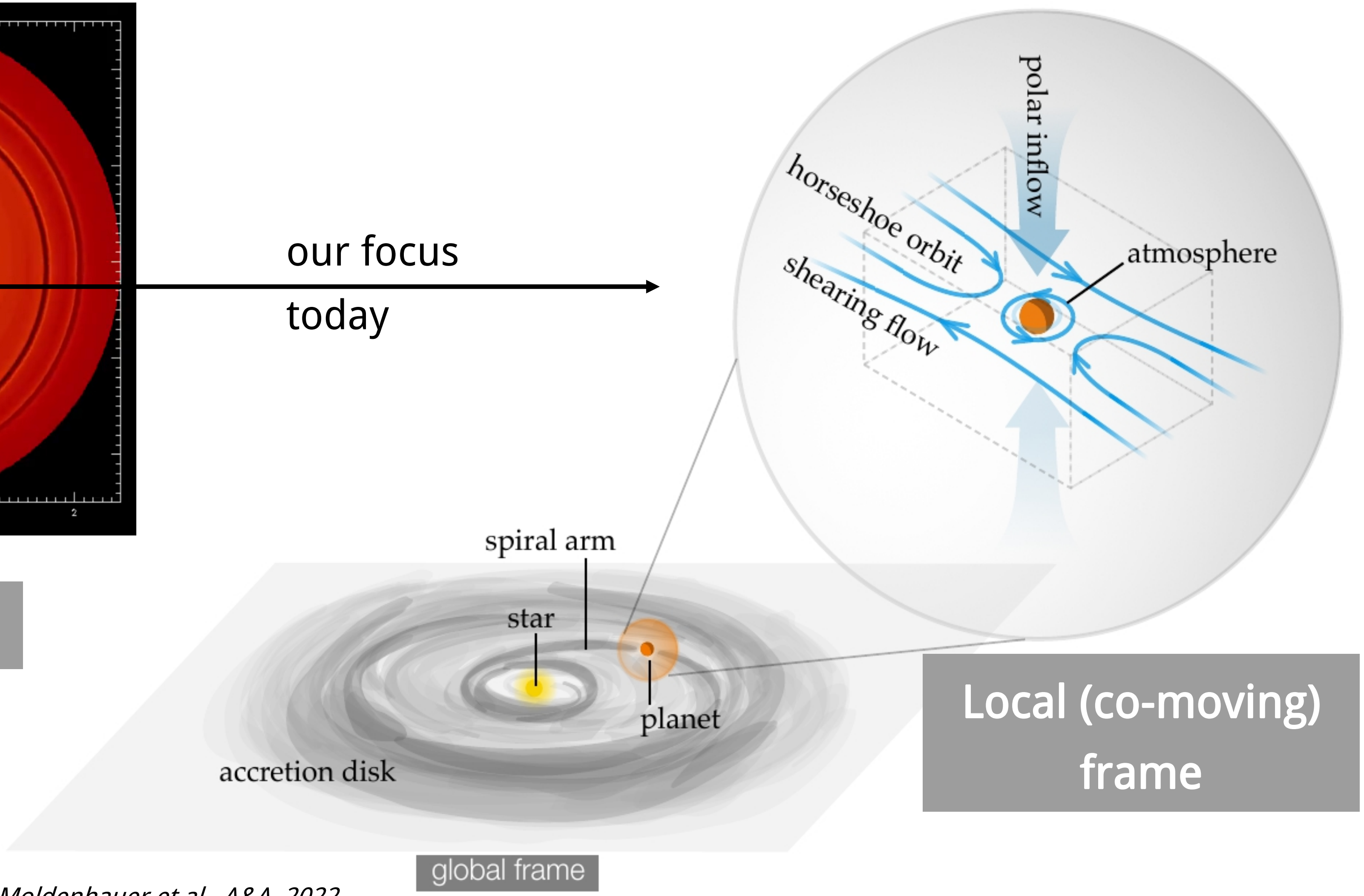
Local shearing flow



Kley & Nelson., ARAA 2012

Global frame

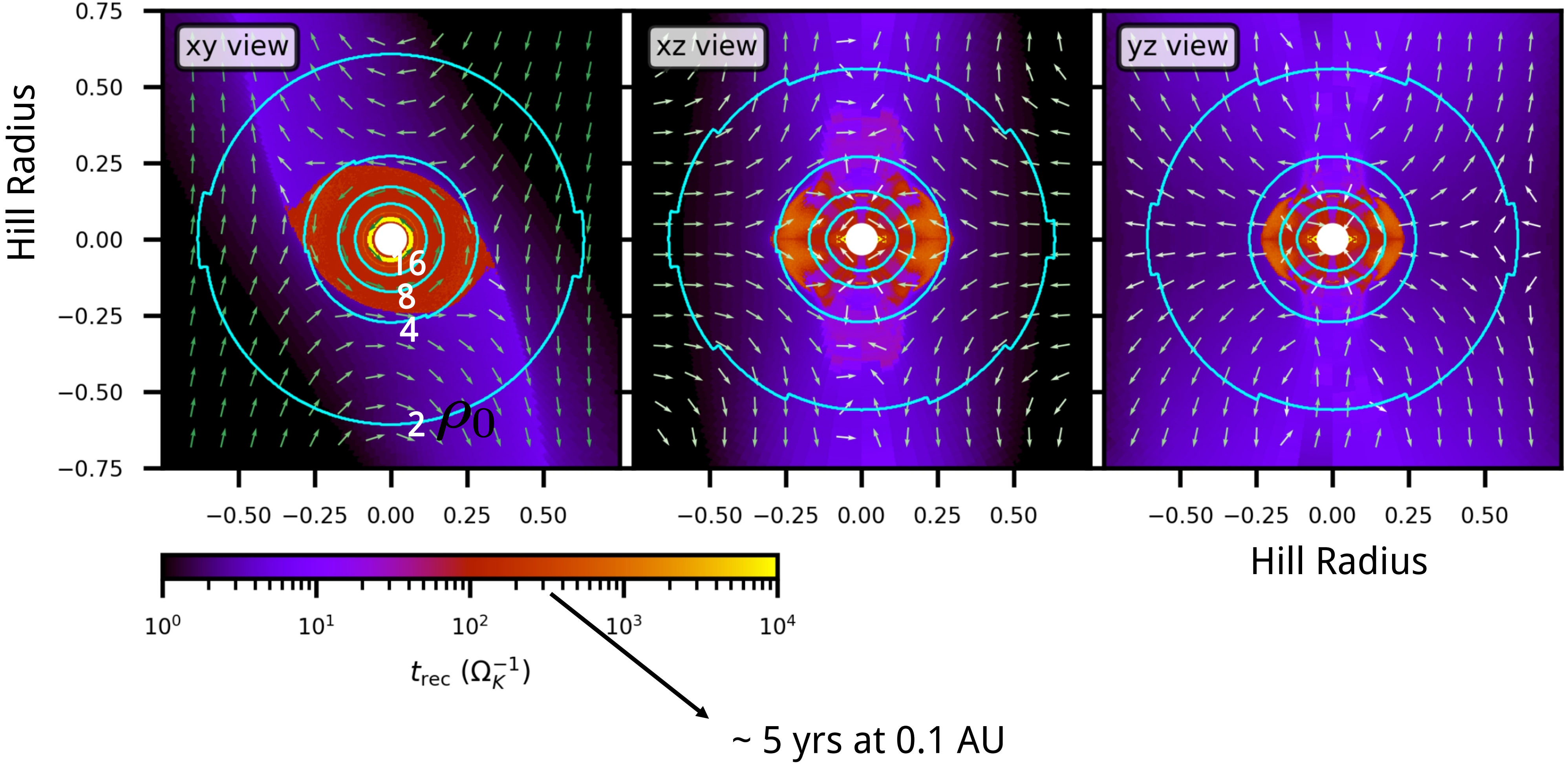
our focus
today



Local (co-moving) frame

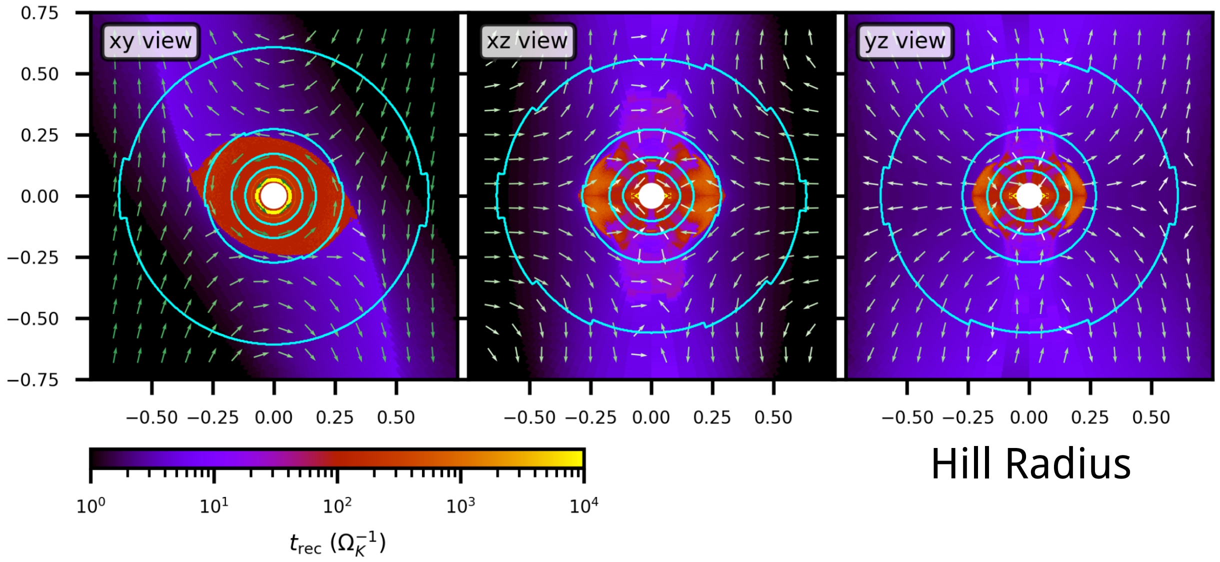
Moldenhauer et al., A&A, 2022

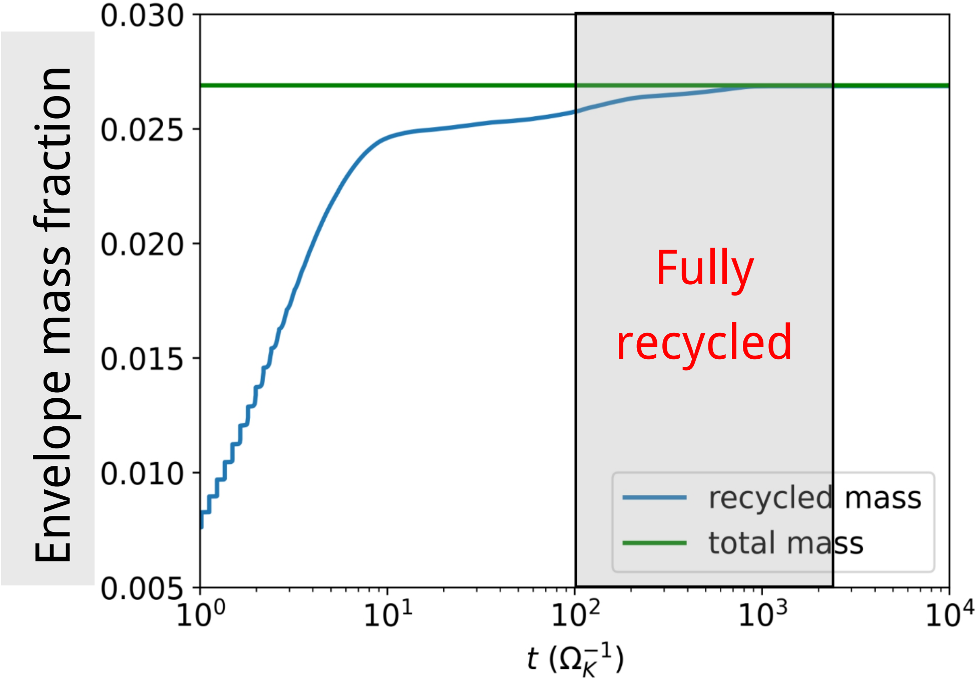
Envelope recycling



Moldenhauer et al., ApJL, 2021

Envelope recycling



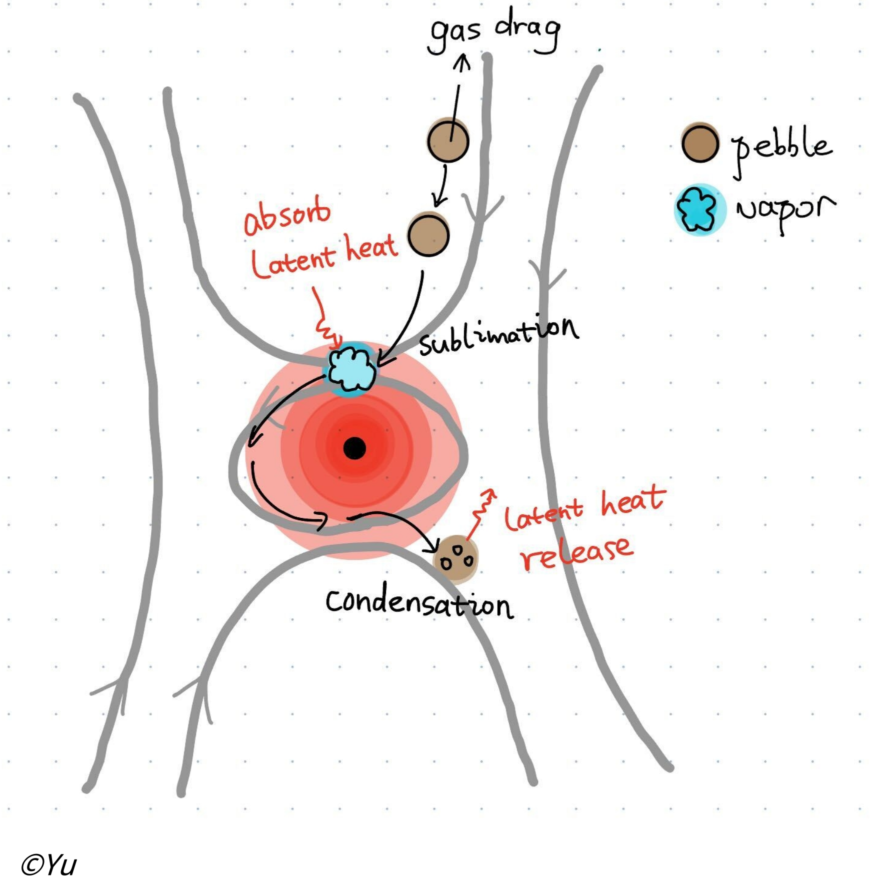


Fully recycled for pure H/He gas seen in 3D RHD simulations.

Hot gas in the disk continuously **refresh the envelope!**

Moldenhauer et al., ApJL, 2021

This work



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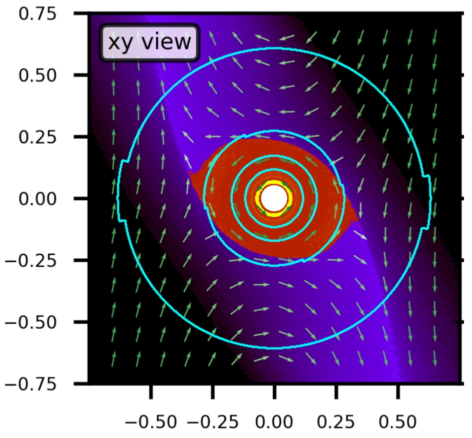

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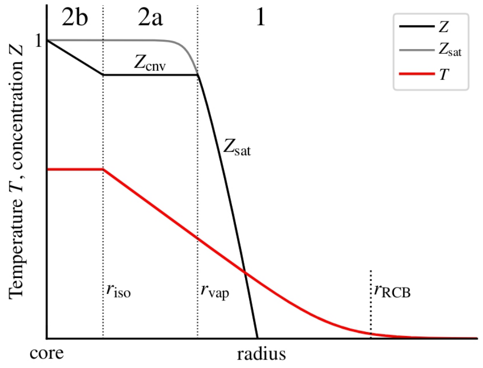
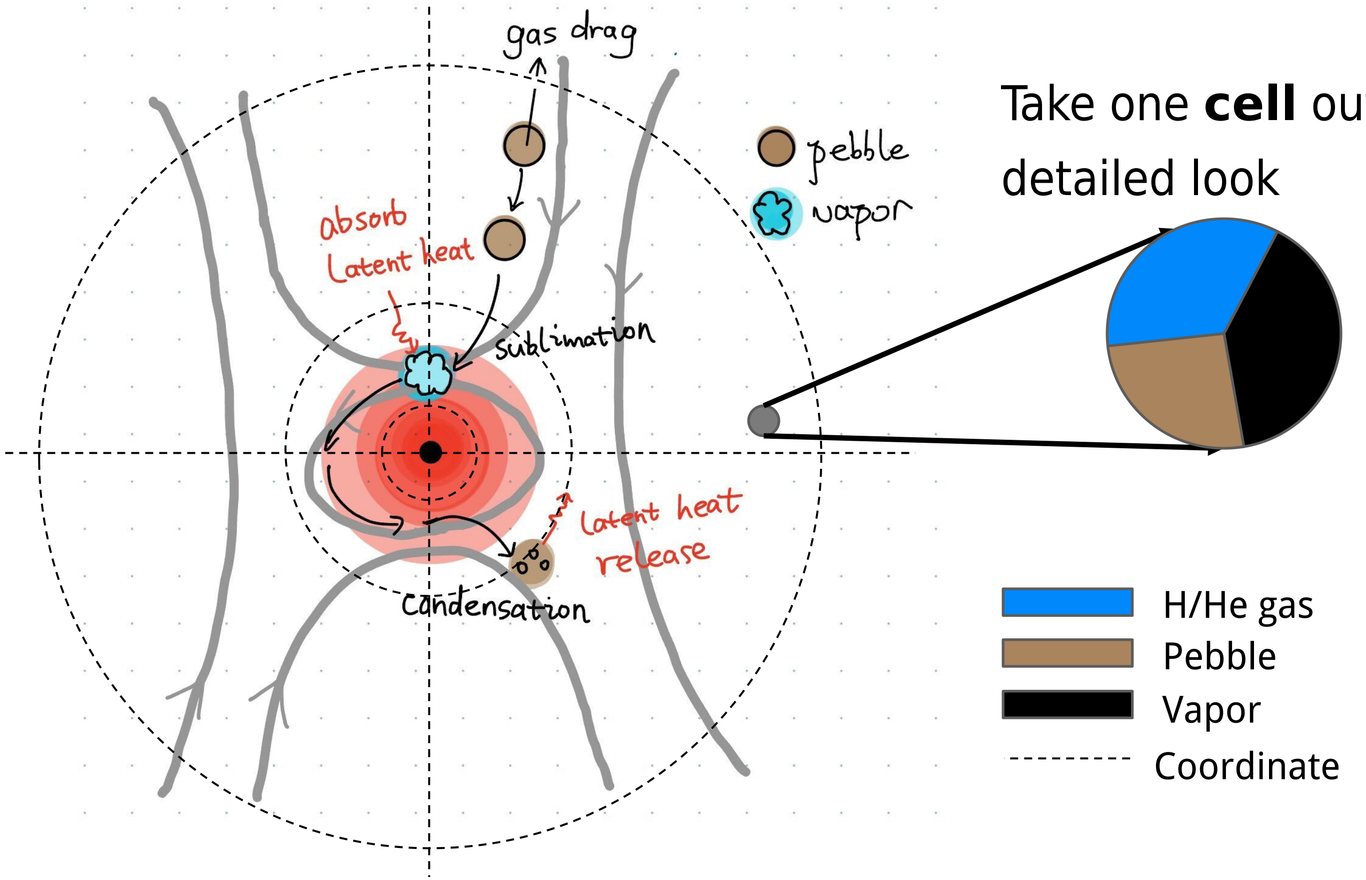


How is recycling mechanism affected by pebble evaporation?

- Is the entire envelope fully recycled, can it prevent runaway gas accretion?
- What are the implications for compositions of planets, like (super) earth's dry water content e.g.

Model set-up: Hydrodynamic



Fluid Species		
fluid	description	stopping time
H/He	*feel pressure*	
Vapor	*feel pressure*	
Pebble	Ice, Silicate etc. Pressureless	$\tau_{pebble} = any$

Numerical tool:

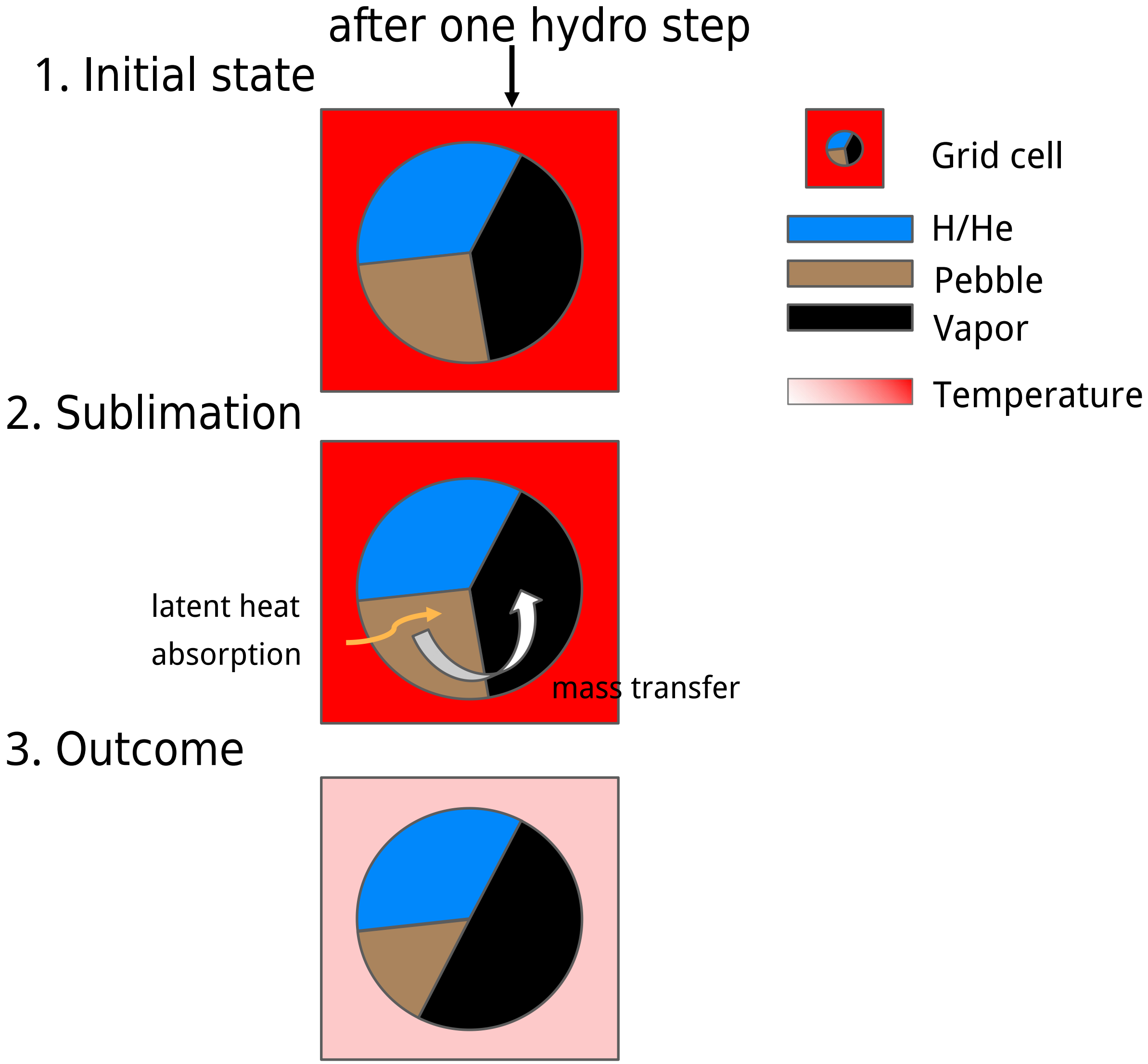
Athena++ Multi-Fluid Dust module

Huang & Bai, ApJS accepted.

https://arxiv.org/abs/2206.01023

- Local frame, 2D Polar coordinate, Radially logarithmic spacing.
- Planet (2-3$M_{\oplus}$) is put at 5 AU with following a MMSN disk profile. All units are normalized to local (at 5 AU) scale height, sound speed and orbital frequency.

Model set-up: phase change process



We have added **sublimation/condensation to** Athena++ !

Basic idea of dealing phase change:

Energy & Mass conservation in a local cell.

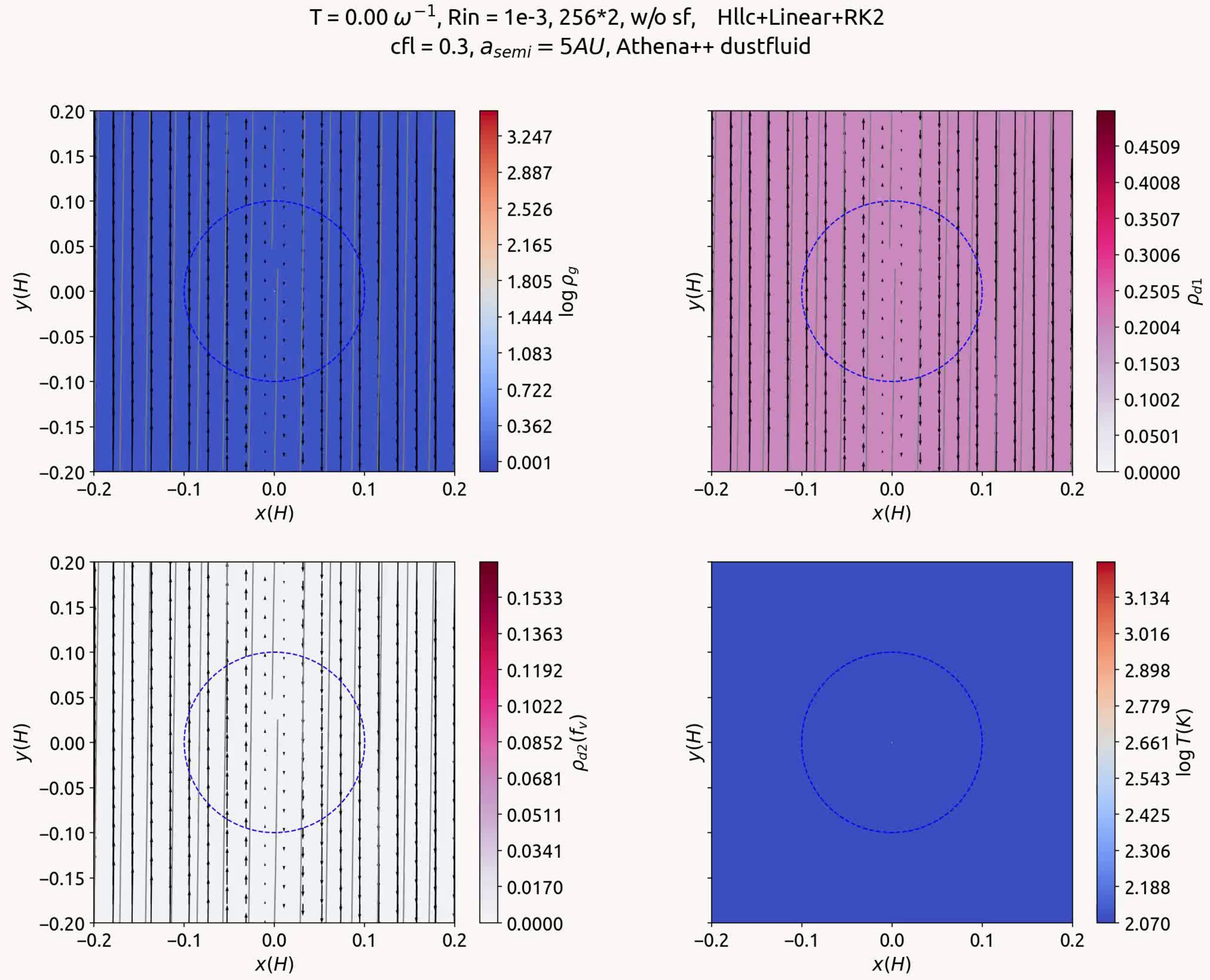
Cheng Li & Xi Chen, ApJS, 2019

$$\rho_{d,ini} = 0.2$$
$$\rho_{g,ini} = 1.0$$

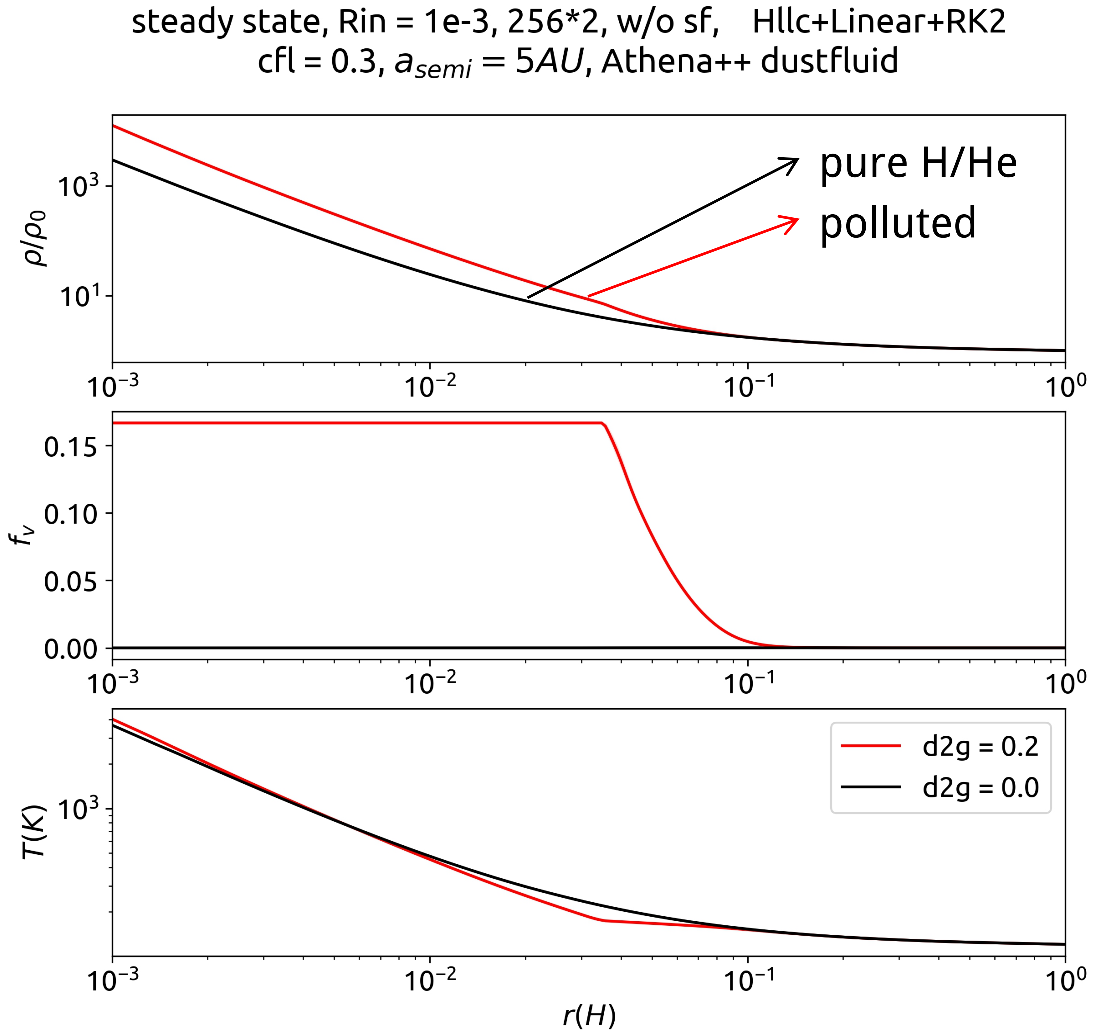
Results:

well-coupled Icy dust

(St = 0)



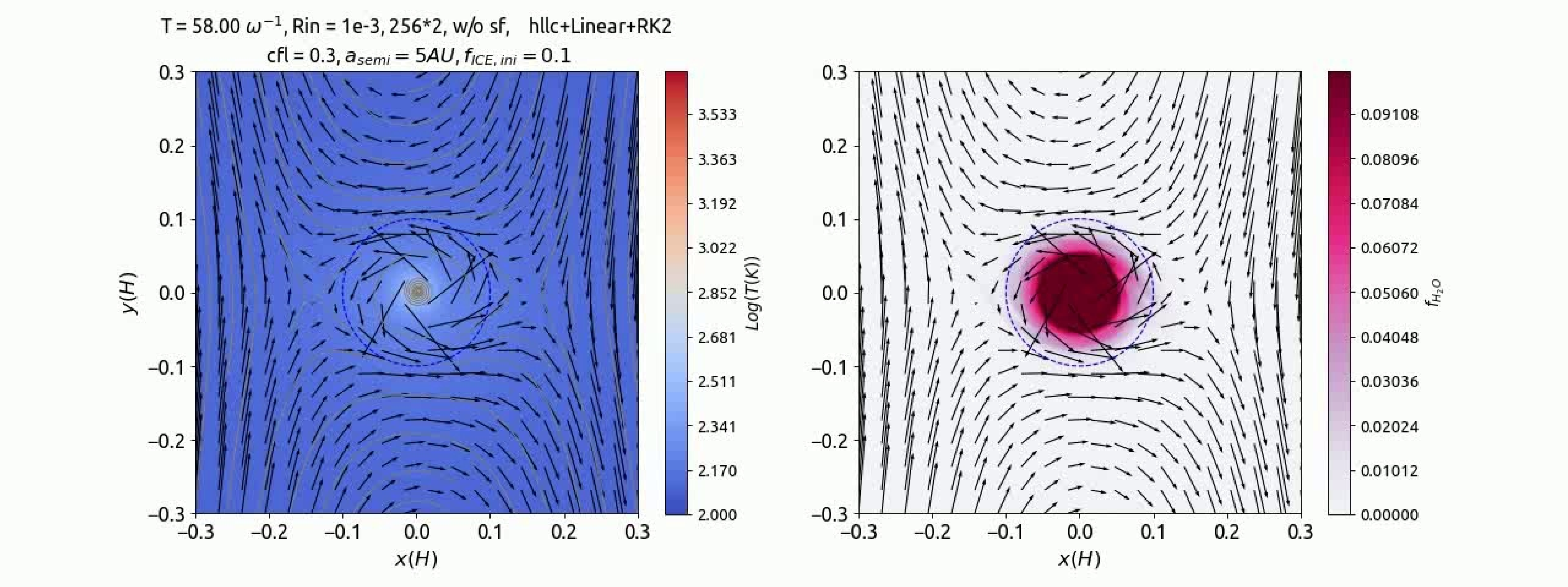
Results: Well-coupled Icy dusts



Gas density increase since vapor injects in.

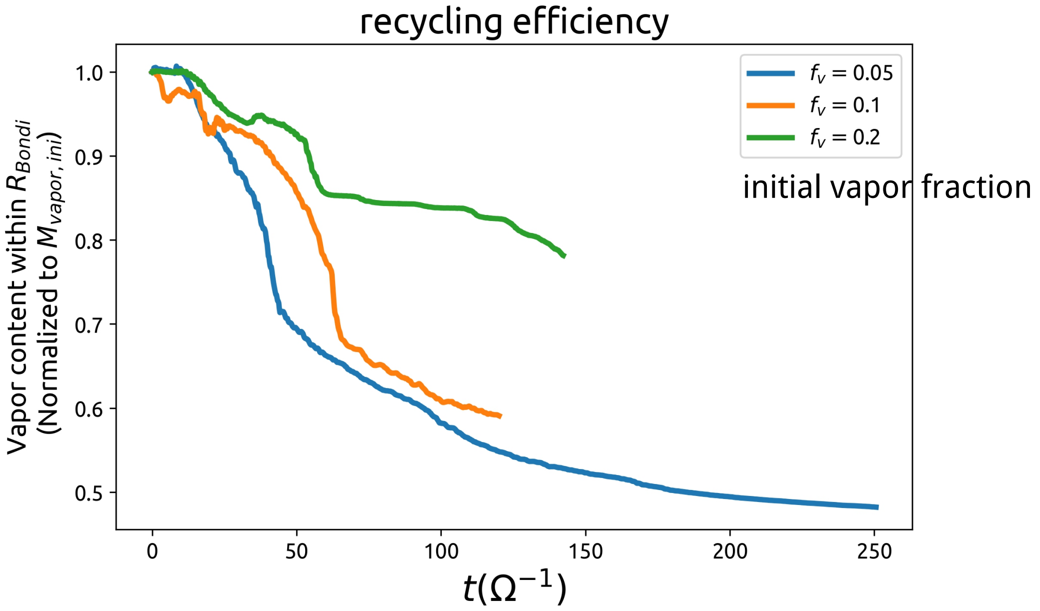
Vapor fraction reach ~ 17% and go flat for the inner region (Well -coupled dusts).

Flatter temperature profile at sublimation region because of latent heat absorption.



Recycling efficiency:
Let fresh H/He in

More difficult to recycle vapors out for higher vapor fraction.

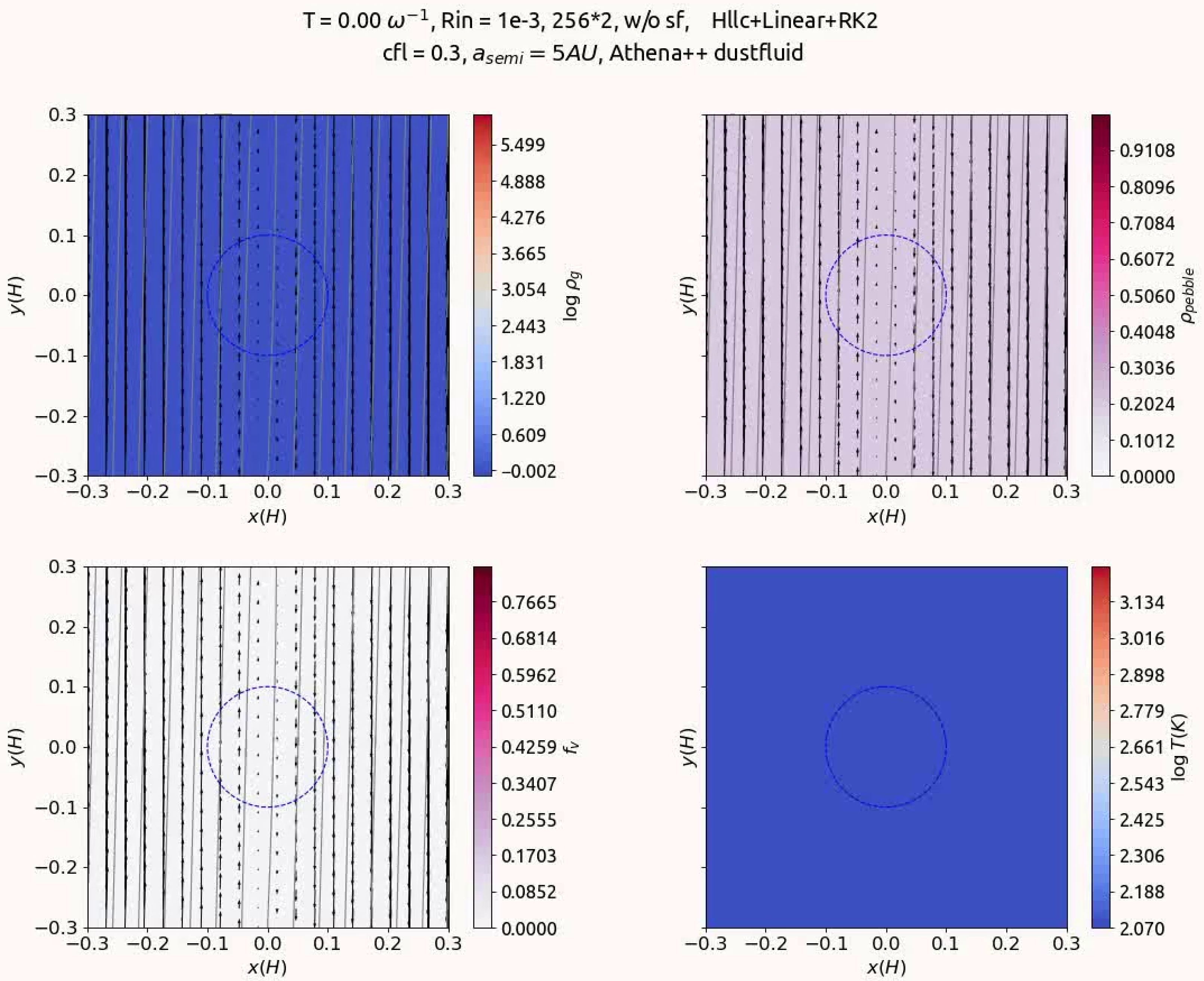


$\rho_{d,ini} = 0.2$

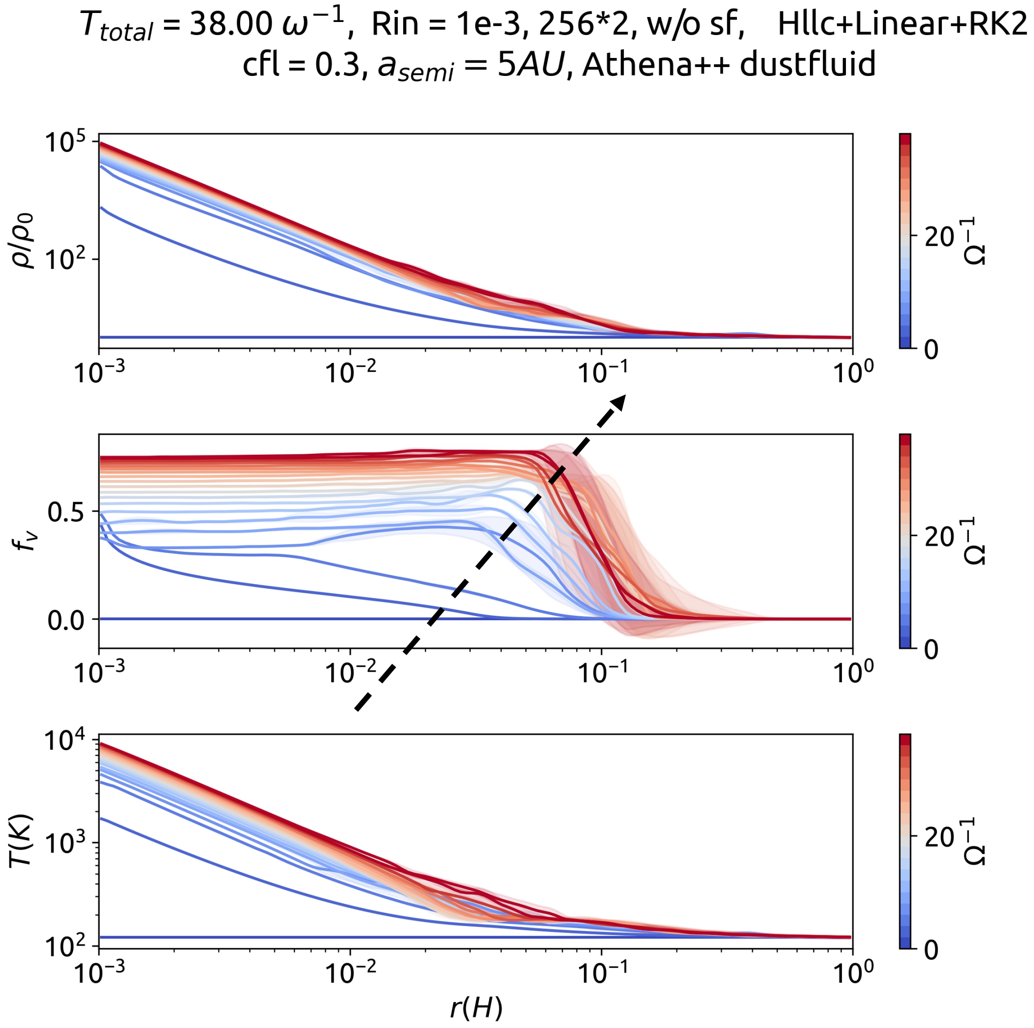
$\rho_{g,ini} = 1.0$

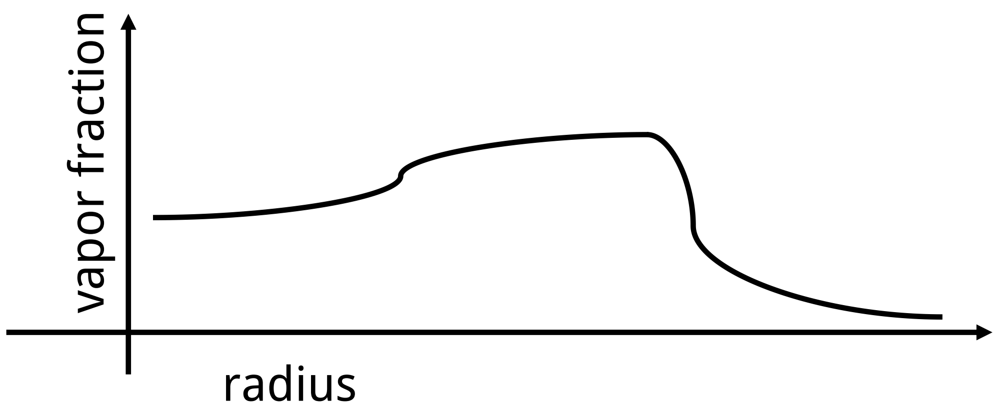
Results:

Pebbles with St = 0.05



Results: Pebbles with St =0.05





Vapor **piles up** at phase change region
-> Trigger Rayleigh–Taylor,
Kelvin–Helmholtz instabilities?

Will the **turbulence mixing** help deliver water to inner region of super earths' envelope?

Summary

- We modified Athena++ multi-fluid dust module to account for phase changes.
- We find steady state for well-coupled dusts, while St=0.05 pebbles trigger instabilities. The recycling slows down for higher vapor fraction case.

Next steps

- Quantify effects on recycling efficiency, investigate pebbles with different properties (St, mean molecular weight etc.).
- Conduct 3D simulations.

Back-up slides: Tricks in dealing vapor fraction

fluid module			
fluid	description	stopping time	label
ρ_g	*He/H + vapor*		fluid*
$\rho_{d,dust}$	dust particle	$\tau_{d,dust} = any$	dustfluid*1
$\rho_{d,f_{vapor}}$	tracer particle to represent vapor fraction only	$\tau_{d,f_{vapor}} = 0$	dustfluid2

*: fluid: feel pressure; dustfluid: pressureless

Athena + dustfluid module workflow

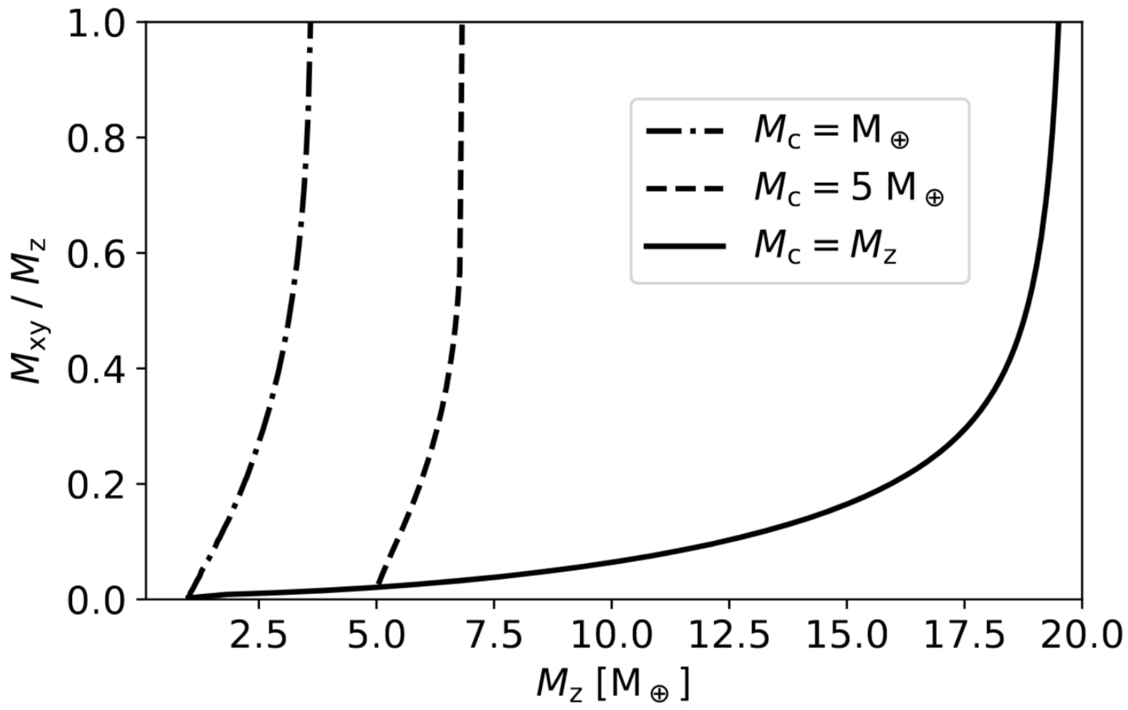


Fig. 6. Evolution of three planets in phase II with our default parameters (see Table 1) at 0.1 AU. The solid curve indicates the classical case, where the core grows indefinitely and the envelope is metal-free. In the dash-dotted and dashed lines, the growth of the core is limited to $M_\oplus$ and 5 $M_\oplus$, respectively. Accretion of nebular gas accelerates when the envelope becomes polluted. This leads to a smaller mass in metals at the onset of runaway accretion.

Brouwers & Ormel, A&A, 2020