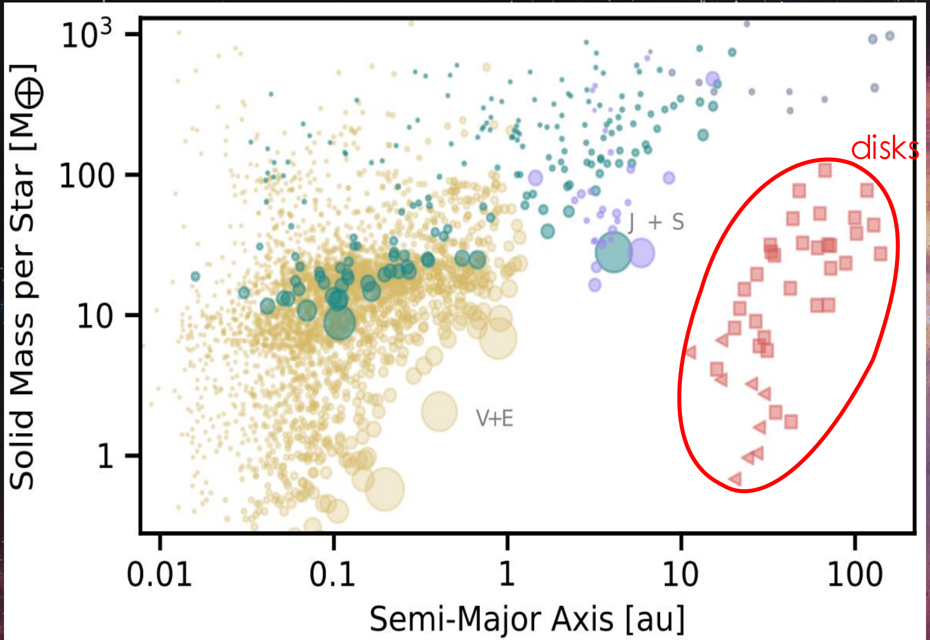
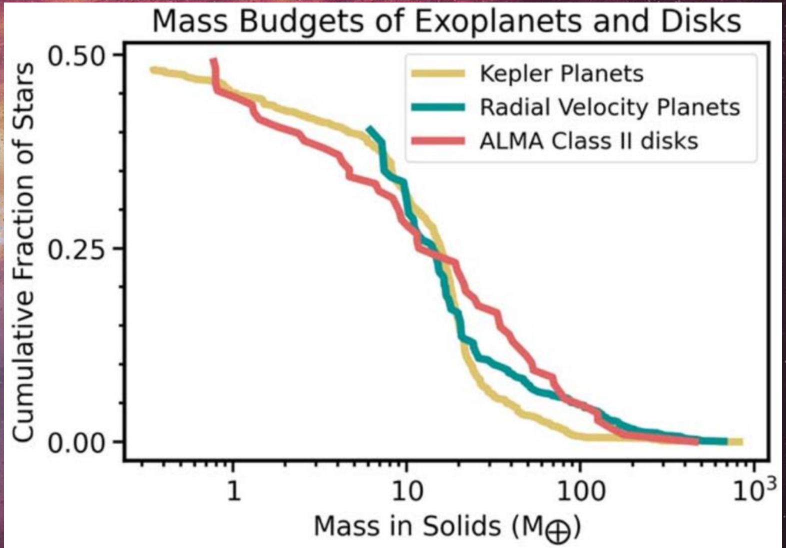
Sofia Savvidou

A giant solution to the mass budget problem of planet formation

PoPSF, Heidelberg, June 2026

The mass budget problem





Exoplanet masses measure equal or higher than disk masses!

Greaves&Rice2010,Najita&Kenyon2014,Mulders+2015,2018,Manara+2018

How do we measure dust/disk masses

- flux-to-mass Hildebrand (1983) conversion:

ASSUMPTIONS

optically thin emmission

unknown chemical abundances or grain structure

$$M = \frac{D^2 F_\nu}{\kappa_\nu B_\nu(T_{\rm dust})}$$

most of the solid mass in mm-sized grains

constant (average) opacity & temperature

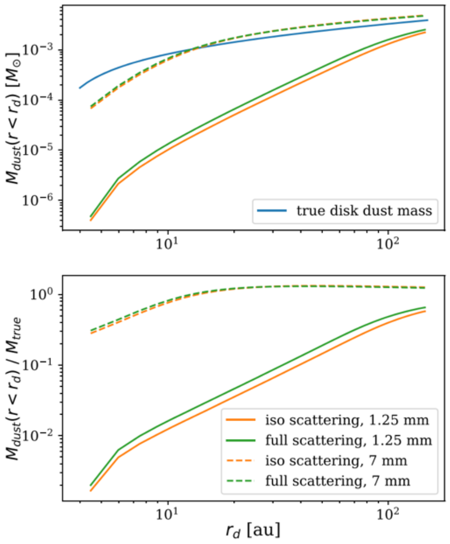
- constant dust-to-gas ratio assumed to be 1% or 1.5%

- gas masses are usually even harder to obtain (e.g. Bergin & Williams 2017, Bergin+ 2013, Trapman 2017, 2025, Calahan+ 2021)

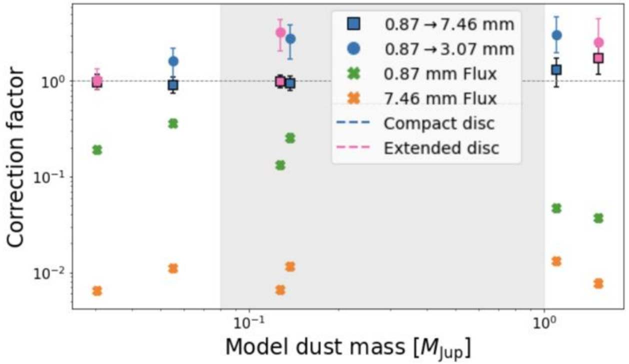
reviews: Miotello+2022, Manara+2022 PPVII chapters

Solutions

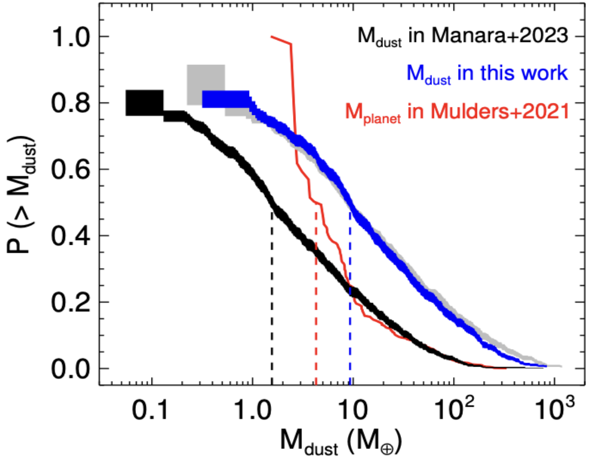
- **Optical depth / dust opacity corrections**



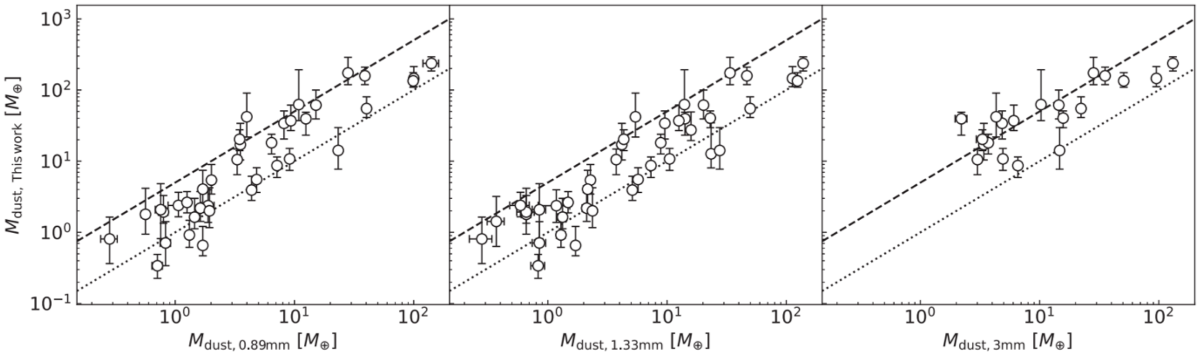
Zhu+ 2019 (dust scattering)



Viscardi+ 2025 (SED multi-wavelength)



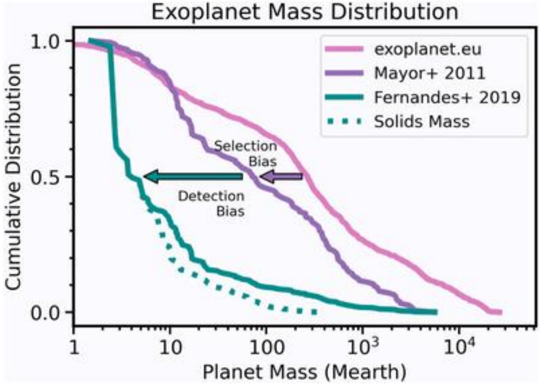
Liu+ 2024 (porous opacities)

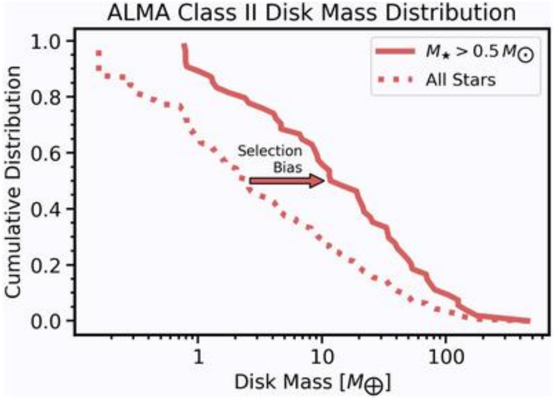


Xin+ 2023 (optically thick at 3 mm)

Solutions

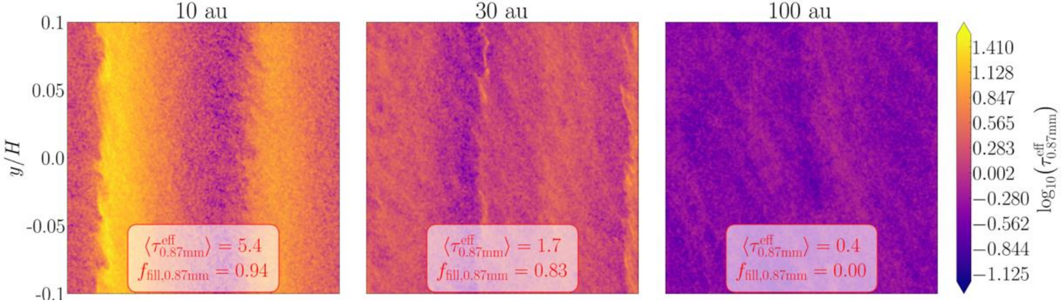
- **Observational bias correction**





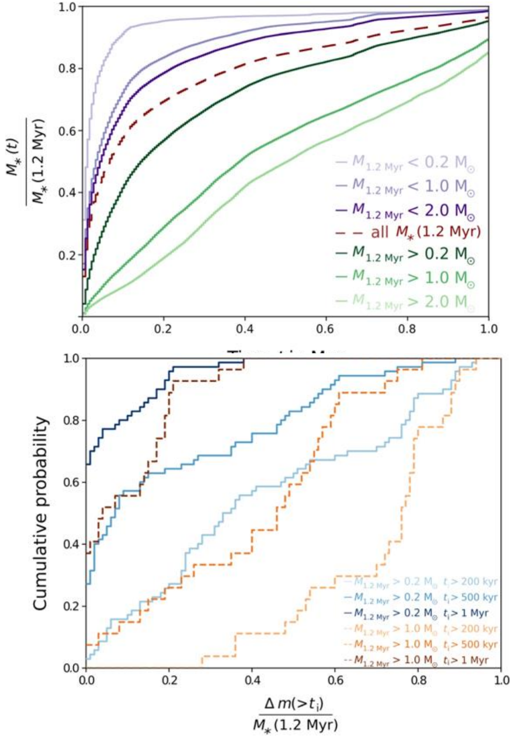
Mulders+ 2021 (discrepancy disappears for solar-mass stars when survey biases are corrected)

- **Streaming instability hiding mass**



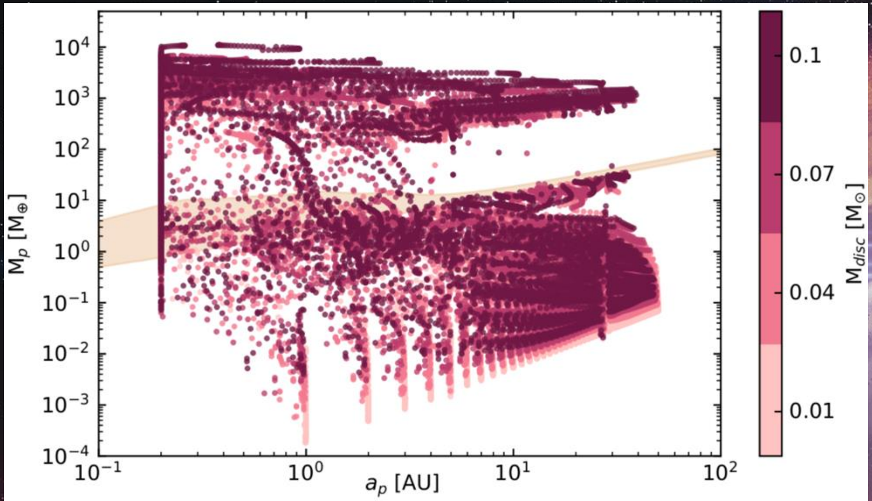
Godines+ 2026 (factors 2–7 from clumping)

- **Late infall / replenishment**



Kuffmeier+ 2023

Same sample as the one Bert discussed

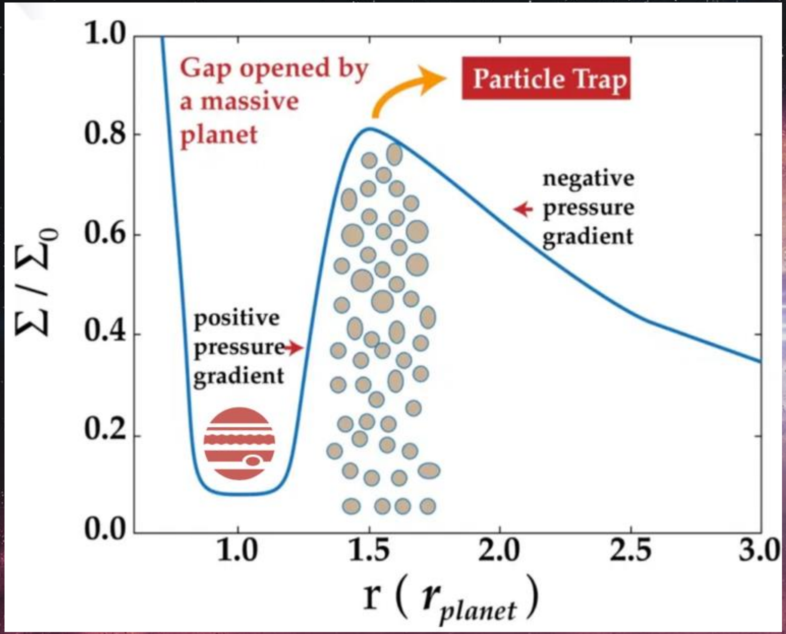


Parameter	Values	
M_0 [$M_\odot$]	0.01, 0.04, 0.07, **0.1**	initial disc mass
R_0 [$R_\odot$]	50, 100, 150, **200**	initial disc radius
α	**0.0001**, 0.0005, 0.001	α-viscosity parameter
t_0 [Myr]	**0.1**, 0.5, 0.9, 1.3	starting time of embryo
$\alpha_{p,0}$ [AU]	1-50 every 1	initial position of embryo
u_{frag} [m/s]	1, 4, 7, **10**	fragmentation velocity
f_{DG}	0.01, **0.015**, 0.03	dust-to-gas ratio

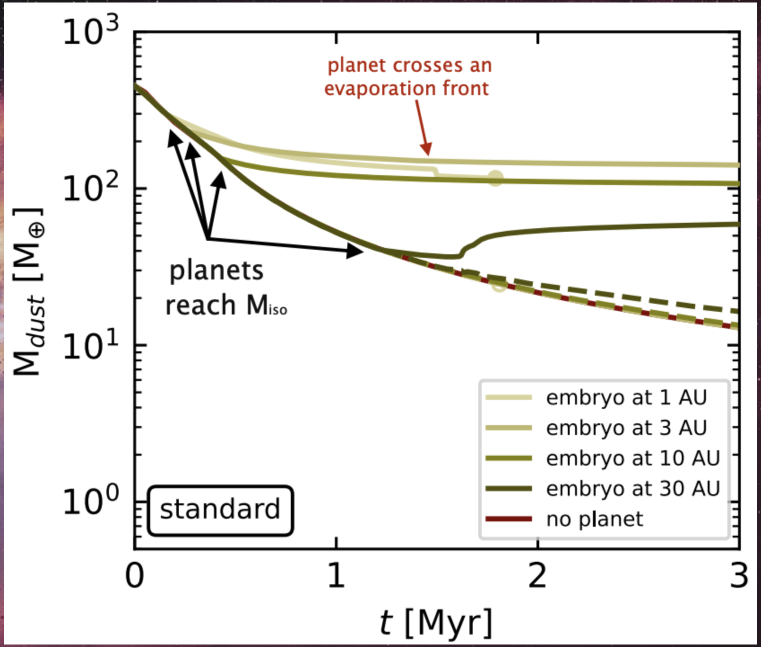
Savvidou & Bitsch 2023

- Parameter study of (giant) planet formation in relation to the initial conditions
- We can also follow-up on the dust evolution

How does the dust mass evolve?



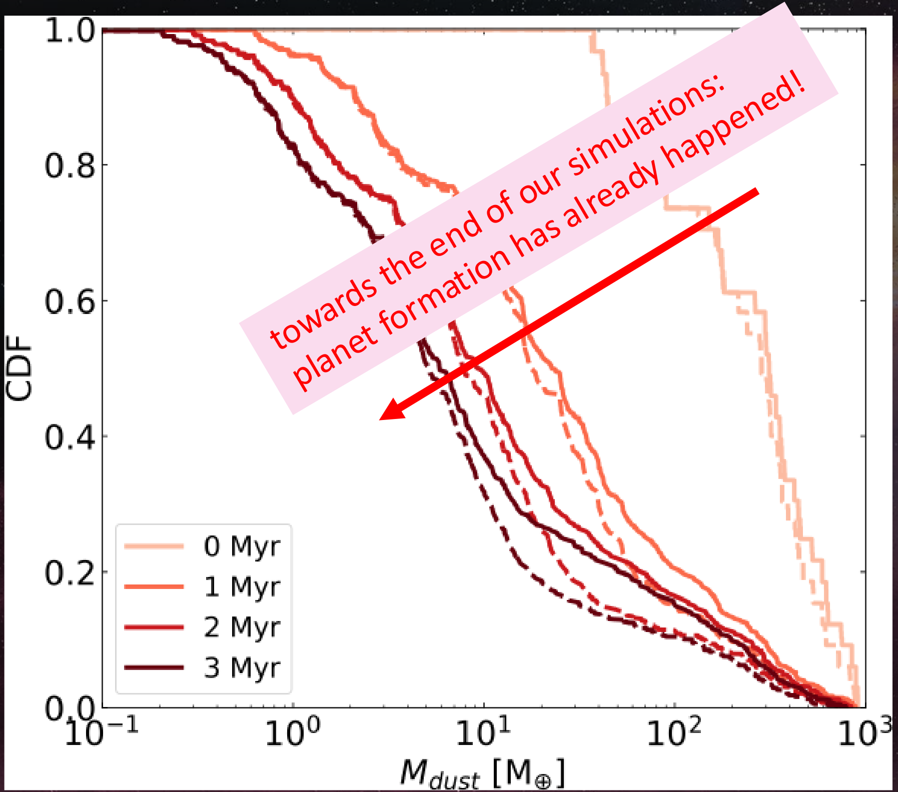
Pinilla 2025



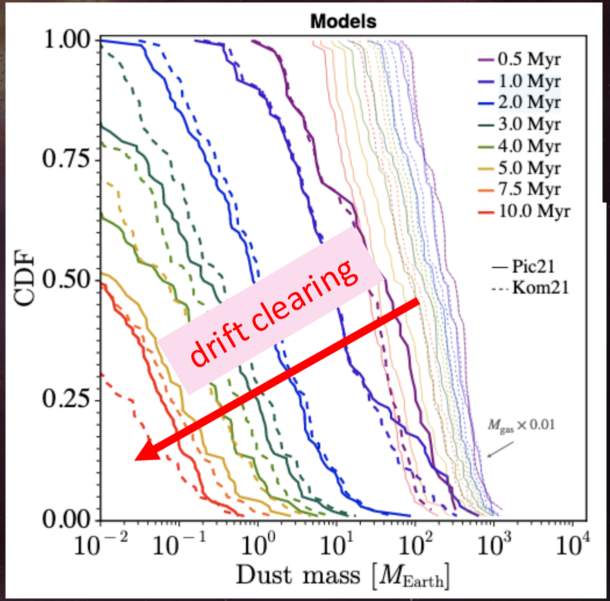
Savvidou & Bitsch 2023

Optically thin dust assumption leads to underestimated masses if a giant has formed in the disk!
(similarly for other dust traps)

Total vs optically thin dust mass



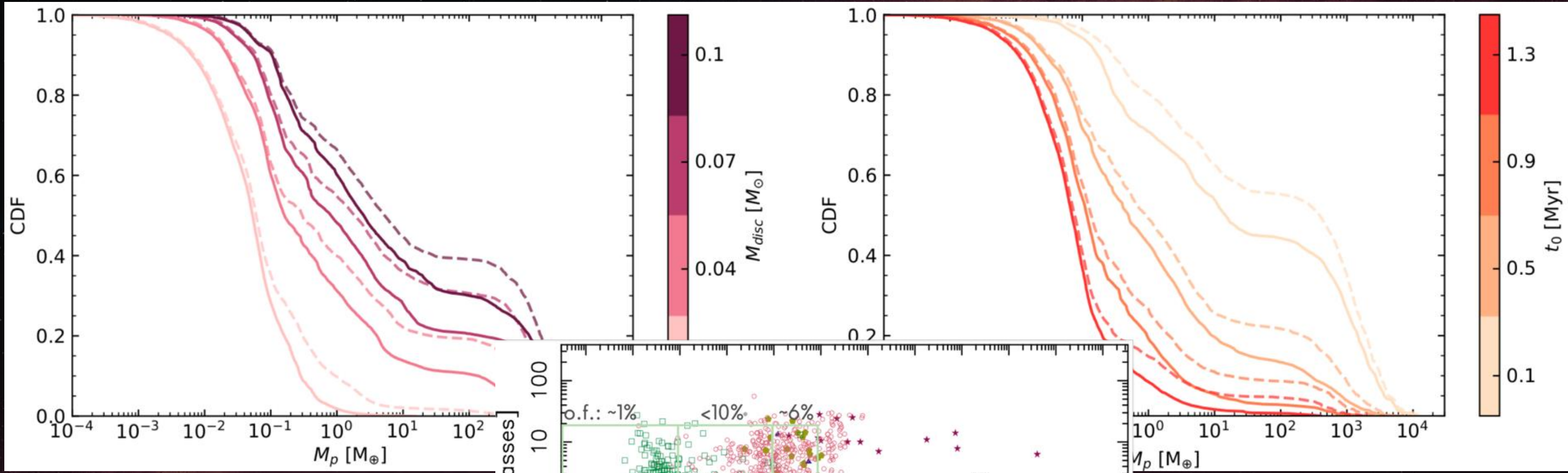
Savvidou & Bitsch 2024



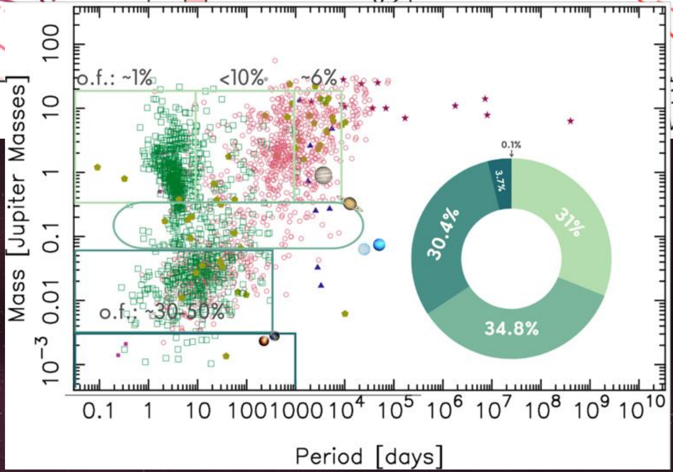
Drążkowska+2022 PPVII chapter

Appelgren et al. 2023

Initial disk conditions dictate probability of giant planet formation



Savvidou & Bitsch 2023



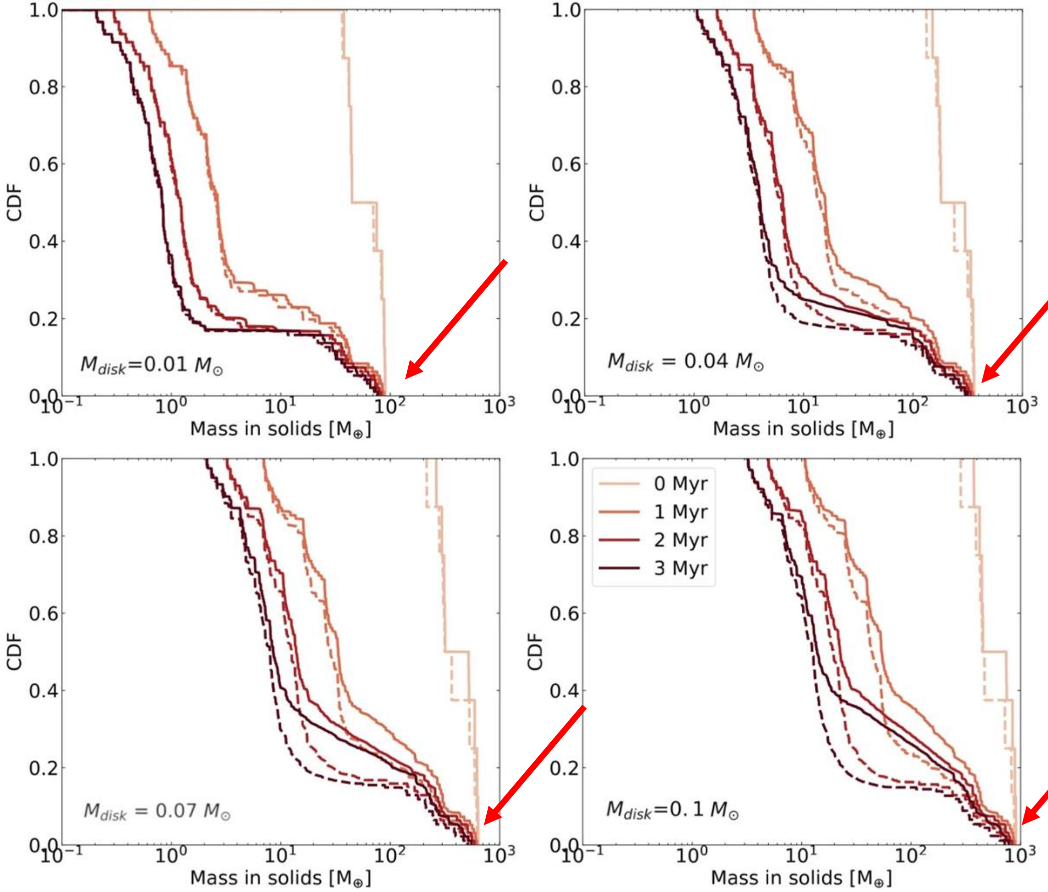
Comparison of giant exoplanet occurrence rates and structured disks supports this as well

Van der Marel and Mulders (2021)

e.g. Hsu et al., 2020; Mulders et al., 2018; Fulton et al., 2021; Rosenthal et al., 2021; Drążkowska et al., 2023

“Hidden” mass scales with initial disk mass

Savvidou 2026

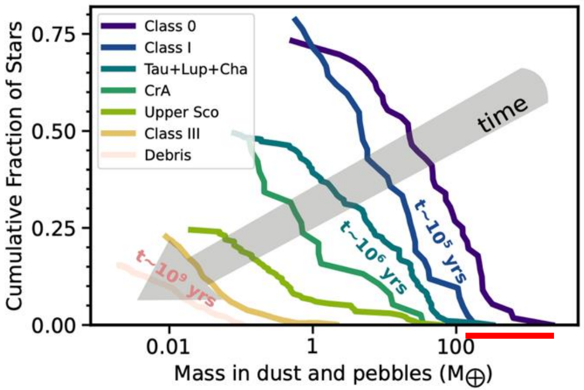


Maximum mass:

- too low for low mass disks (1% $M_\odot$)
- too high for high mass disks (10% $M_\odot$)

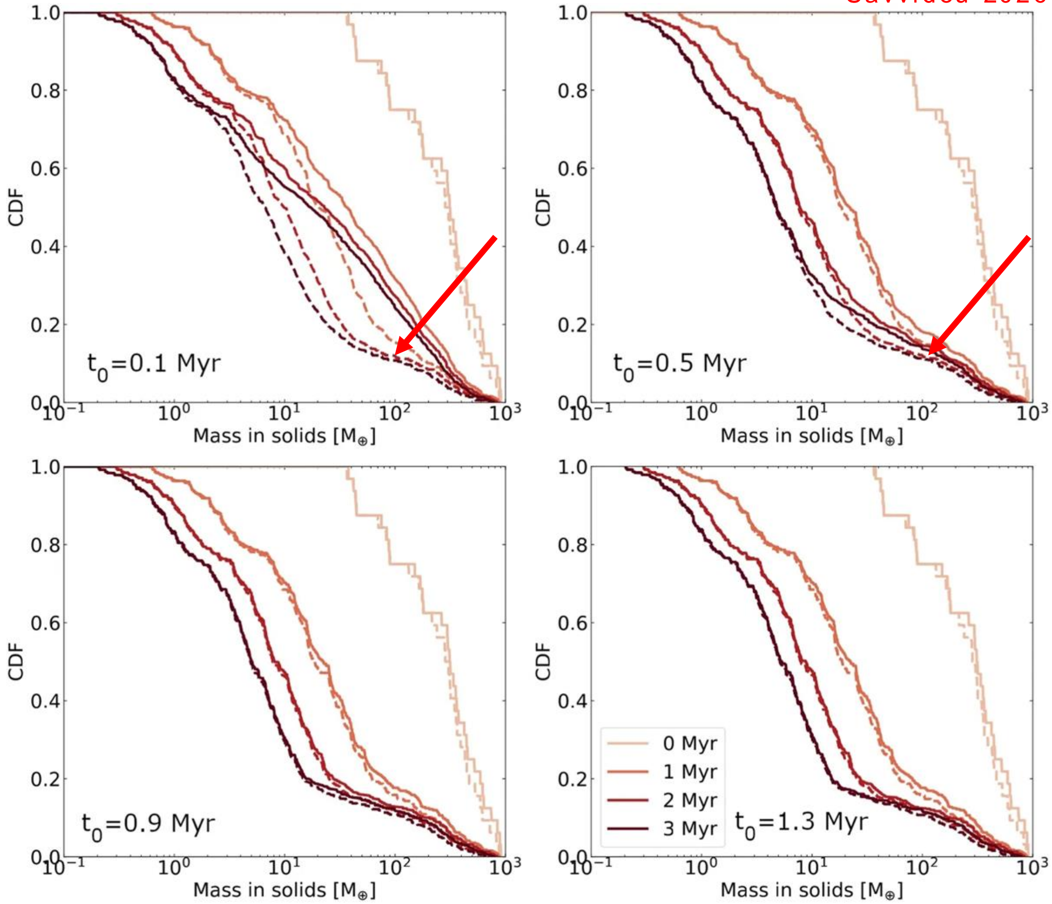
Best match to observed disks: **M_{disk} ~ 4-7% $M_\odot$**

+disks with M_{disk}=7% $M_\odot$ **produced ~20% of giants**



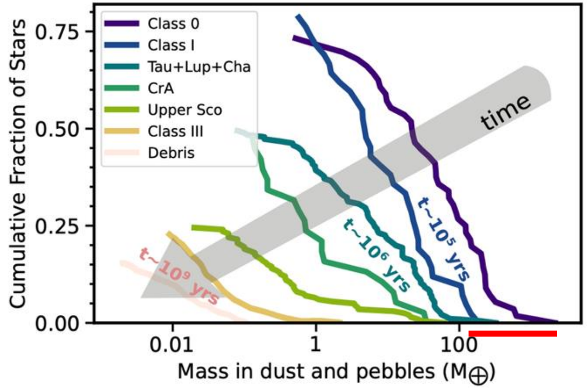
“Hidden mass” scales with embryo injection time

Savvidou 2026



Growth from embryos at t_0 ~ 0.5 Myr produces an appropriate number of giants

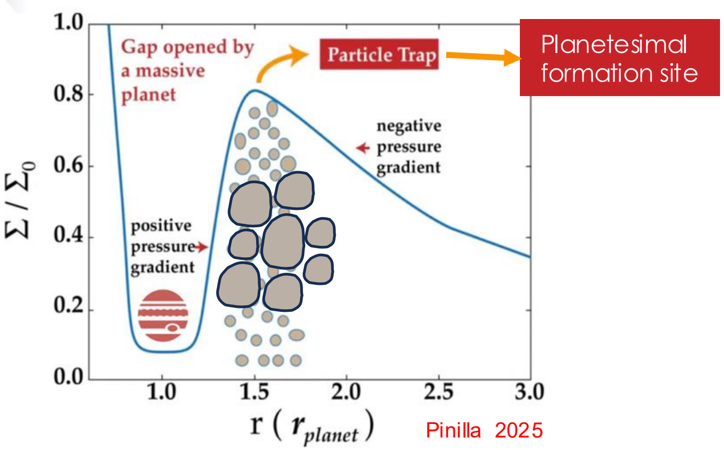
Even the optically thin dust mass remains high at 3 Myr (~10% disks with M_{dust}>100M_E)



What about (late stage) planetesimals?

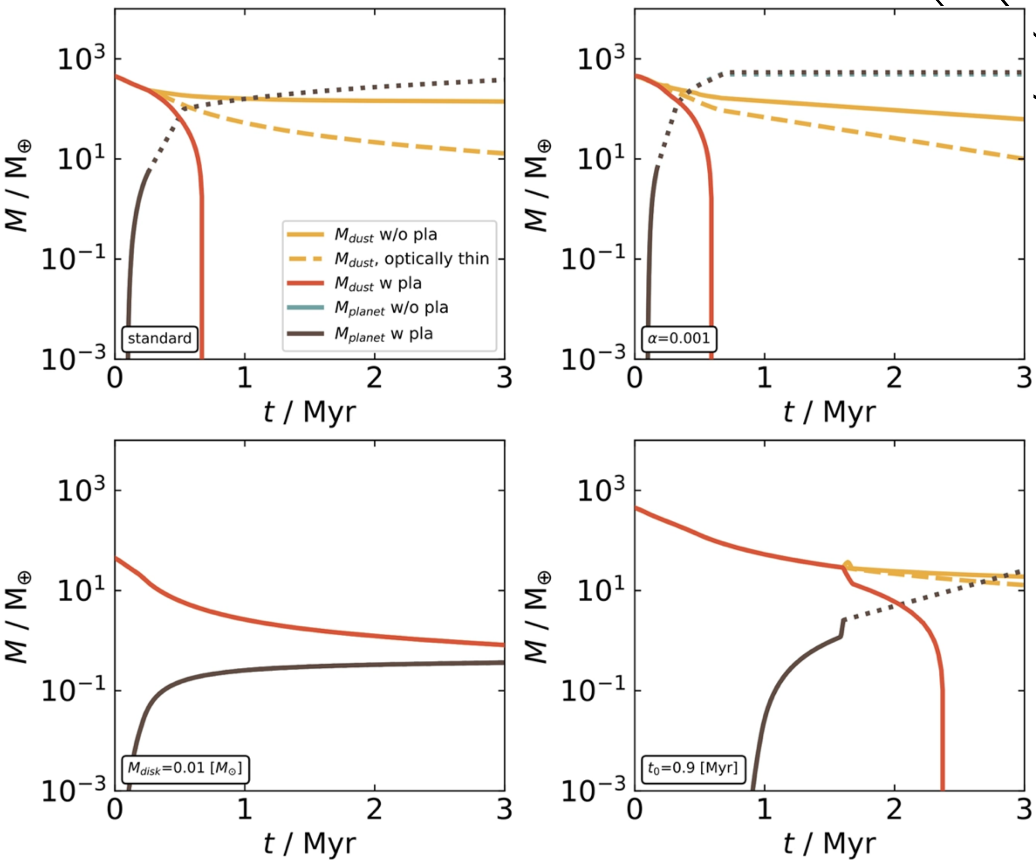
Under fruitful conditions a significant amount of dust mass can get converted to planetesimals

(e.g. Johansen et al., 2014; Eriksson et al., 2020; Carrera et al. 2021; Voelkel et al., 2022; Andama et al., 2024, Johansen & Lyra 2026)



Pinilla 2025

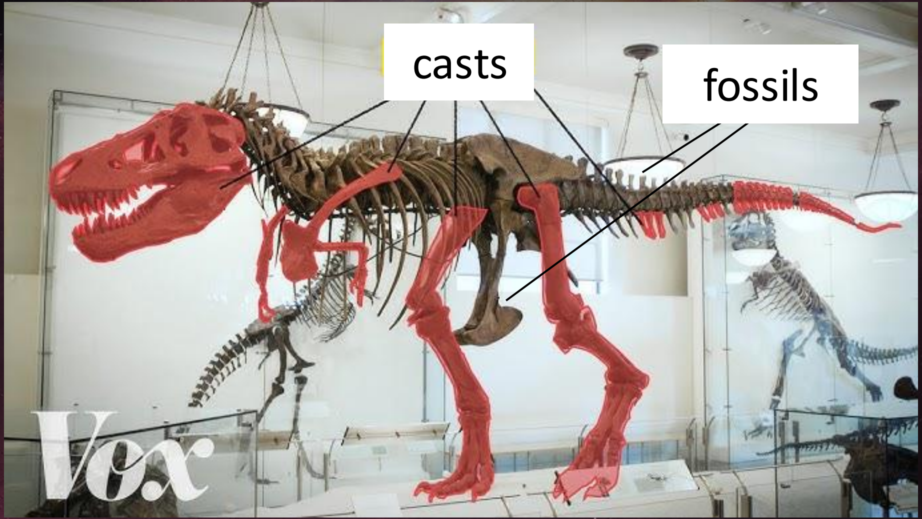
Savvidou 2026



Conversion to larger bodies could naturally lead to very low evolved disk masses

Conclusion:

The disk mass budget problem is highlighting our shortcoming in reconciling our theoretical understanding with the observational data more than it is an issue with the standard framework of planet formation.



Thank you!

Conclusion:

The disk mass budget problem is highlighting our shortcoming in reconciling our theoretical understanding with the observational data more than it is an issue with the standard framework of planet formation.

- Not all disks can be/need to be initially heavy to successfully form planets
  - not all disks have to form giant planets and/or multiple planets and
  - even intermediate disk masses can form giant planets efficiently
- Observed disks are a mixture of initial conditions, evolutionary stages and processes they have gone through but on a population level we should expect that some dust mass is still unaccounted for
- Low disk masses of evolved systems can be an natural outcome: drift, accretion, planetesimal and planet formation, winds/PE
  - Planet formation is not necessarily threatened (it's a matter of timescales and efficiency)

There is more, wait for it...!

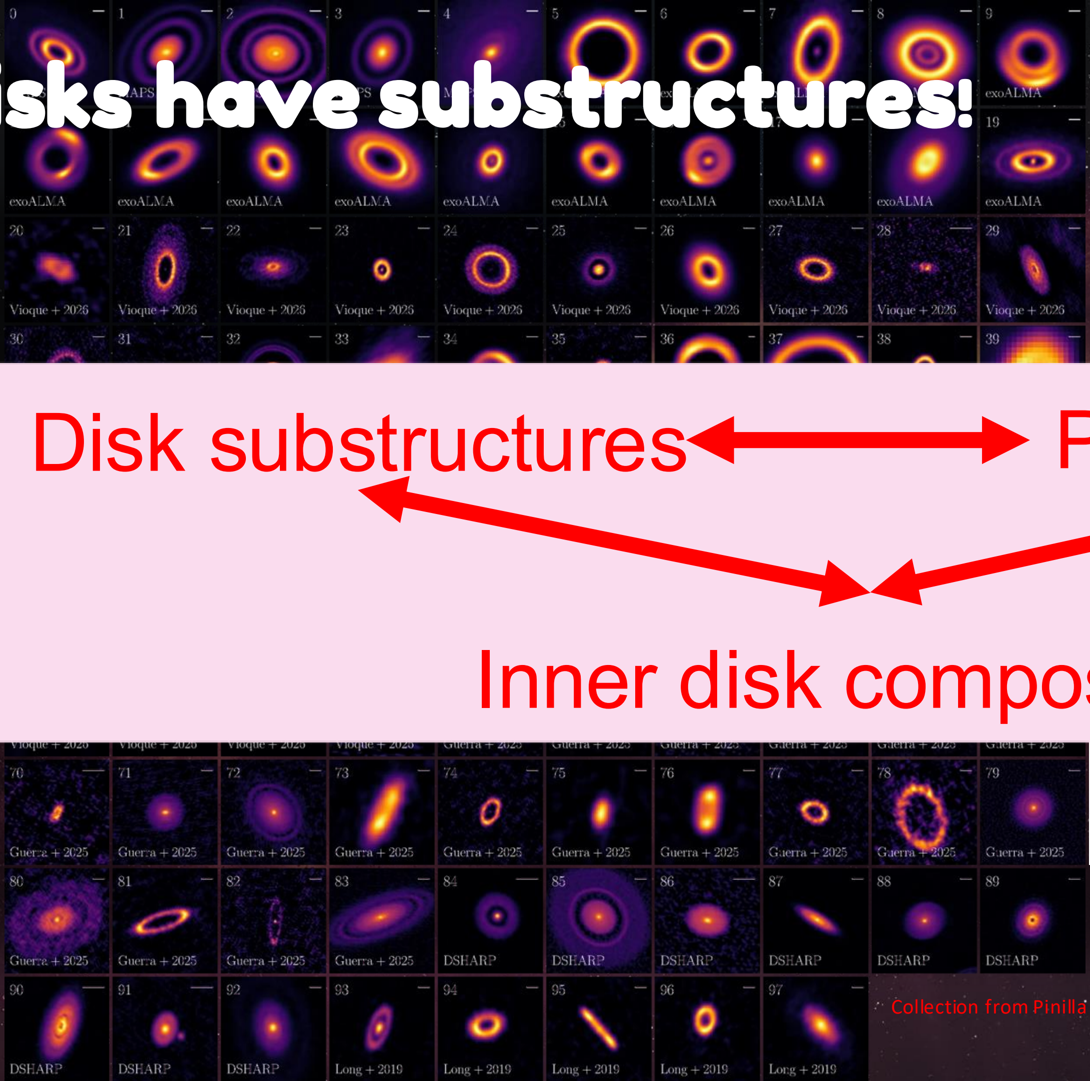
Sofia Savvidou

Mind the gap!:

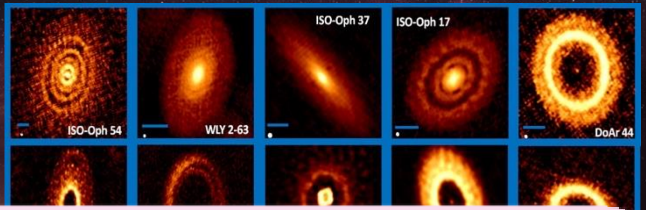
Is the inner disk composition regulated by the disk and stellar properties or the existence of substructures?

PoPSF, Heidelberg, June 2026

Disks have substructures!



Collection from Pinilla 2025

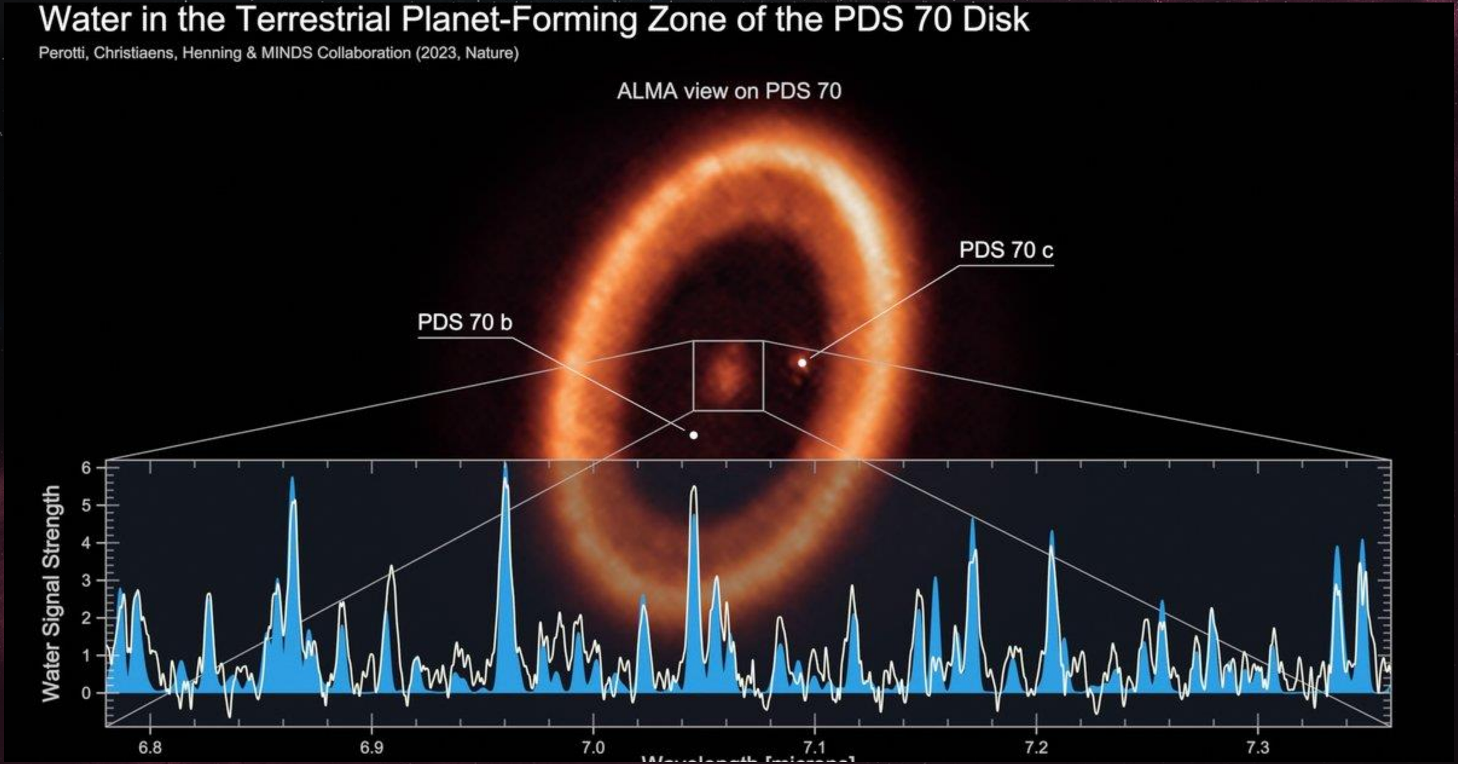


Garufi et al. 2017

Disk substructures ⟷ Planet formation

Inner disk composition

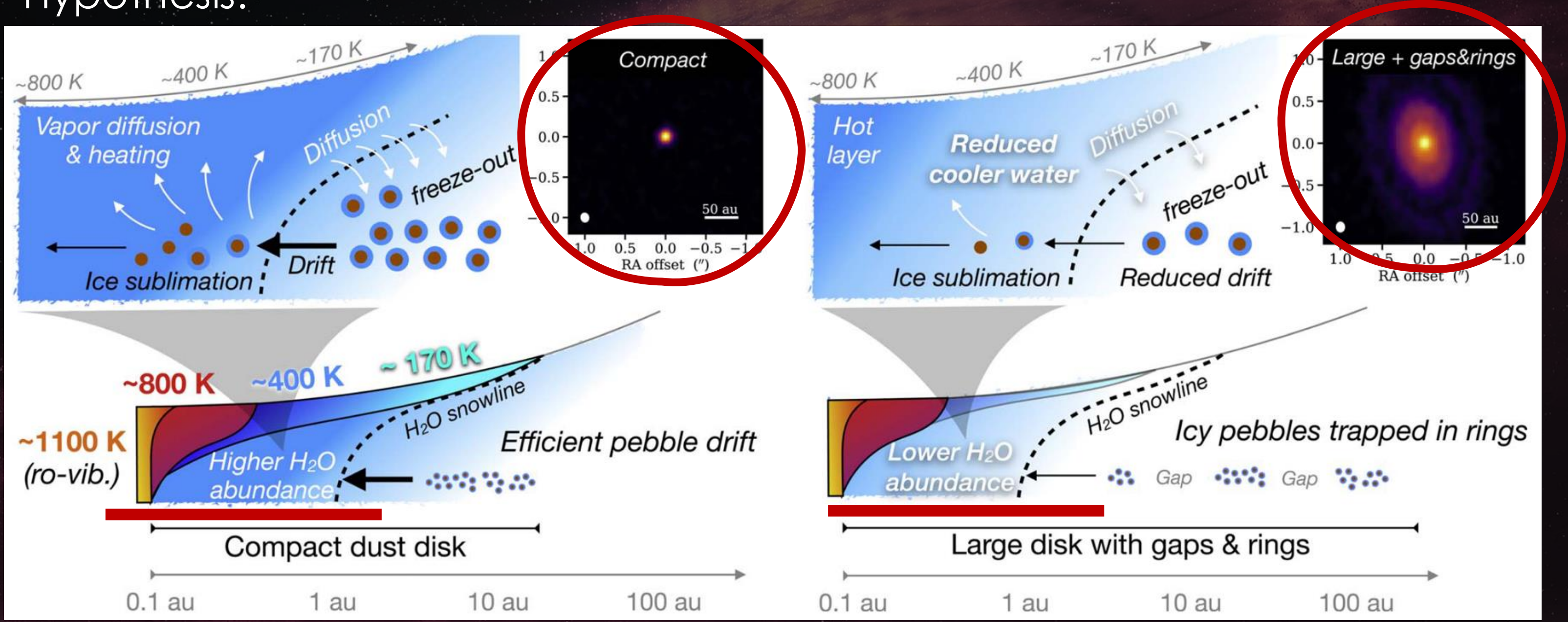
Inner disk composition!



JWST (MIRI/MRS) observations can reveal the inner disk composition

Is the inner disk composition determined by substructures or disk properties?

Hypothesis:

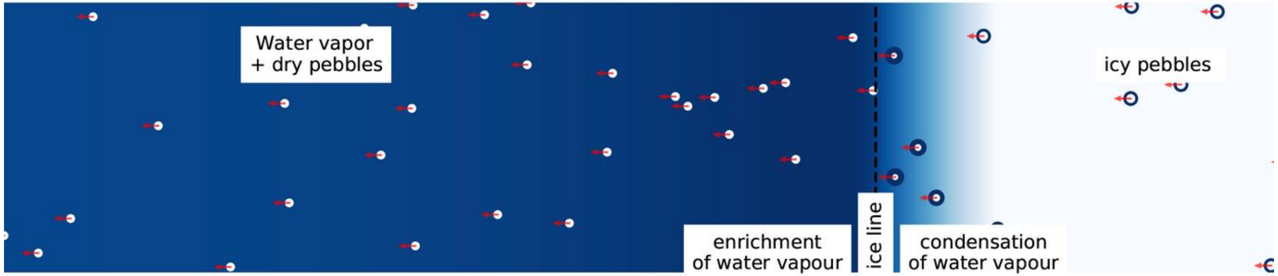


Banzatti+ 2023

Is it substructures or disk size?

chemcomp: 1+1D code

Schneider & Bitsch 2021a



The gap depth,

$0 < f_{gap} <= 1$

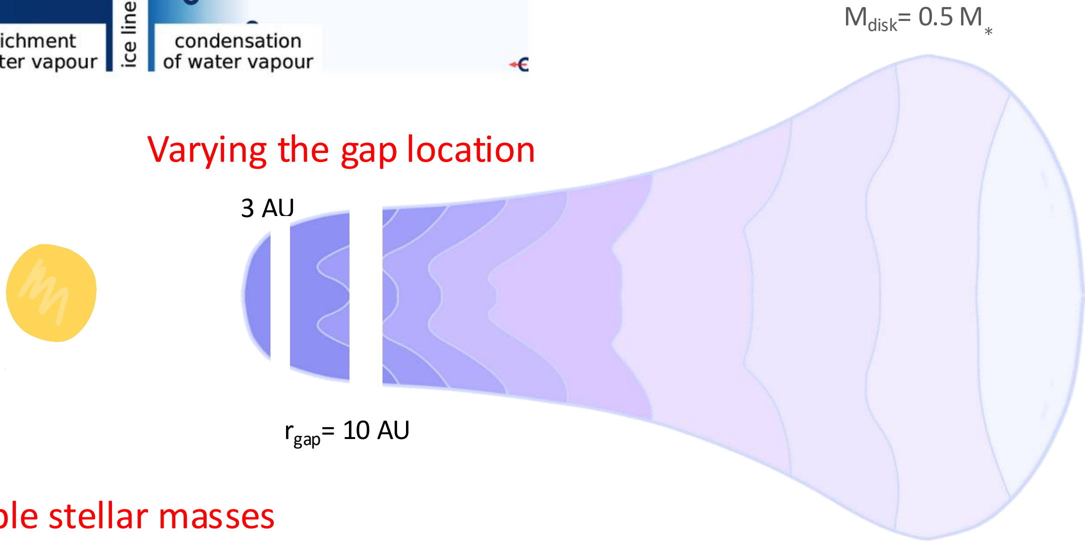
the gap timing!,

$t_{gap} = 0 – 0.5$ Myr

disk viscosity

$a = 10^{-4}, 3 \times 10^{-4}, 10^{-3}$

Varying the gap location



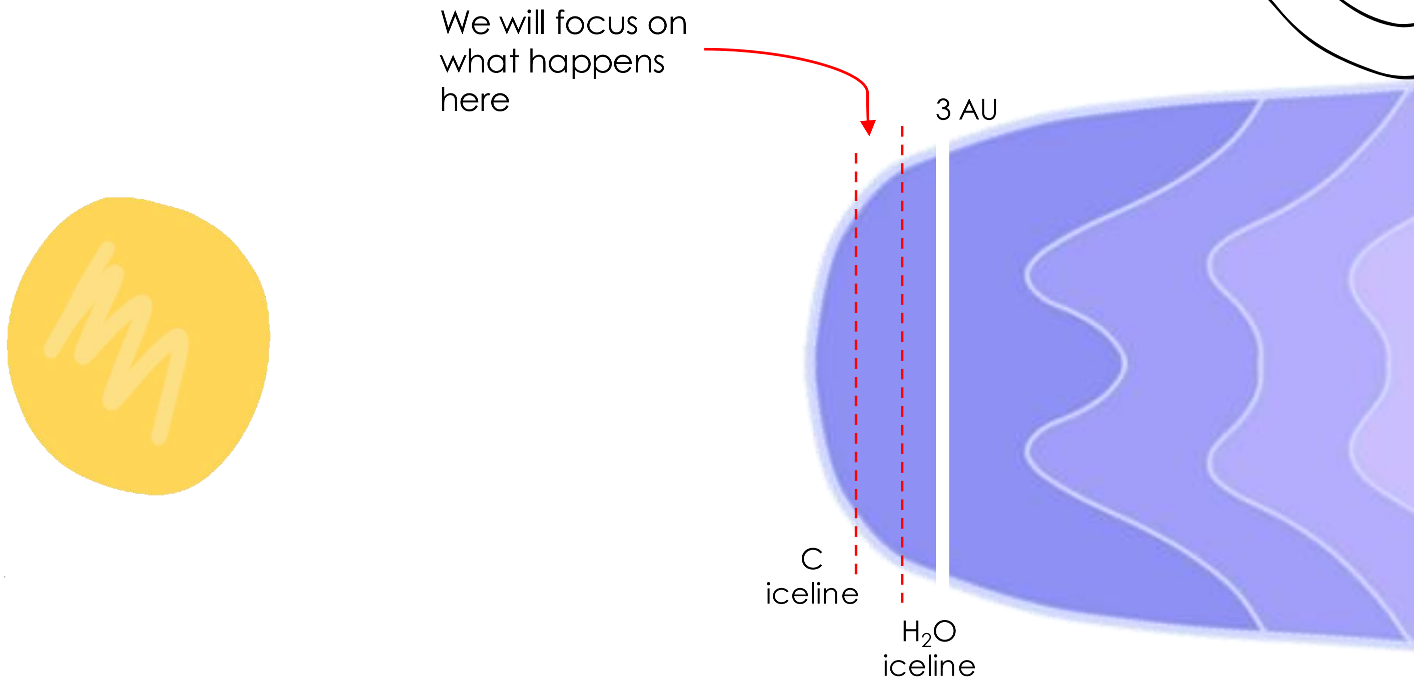
+ disk size!

$R_{disk} = 20\text{-}150$ AU

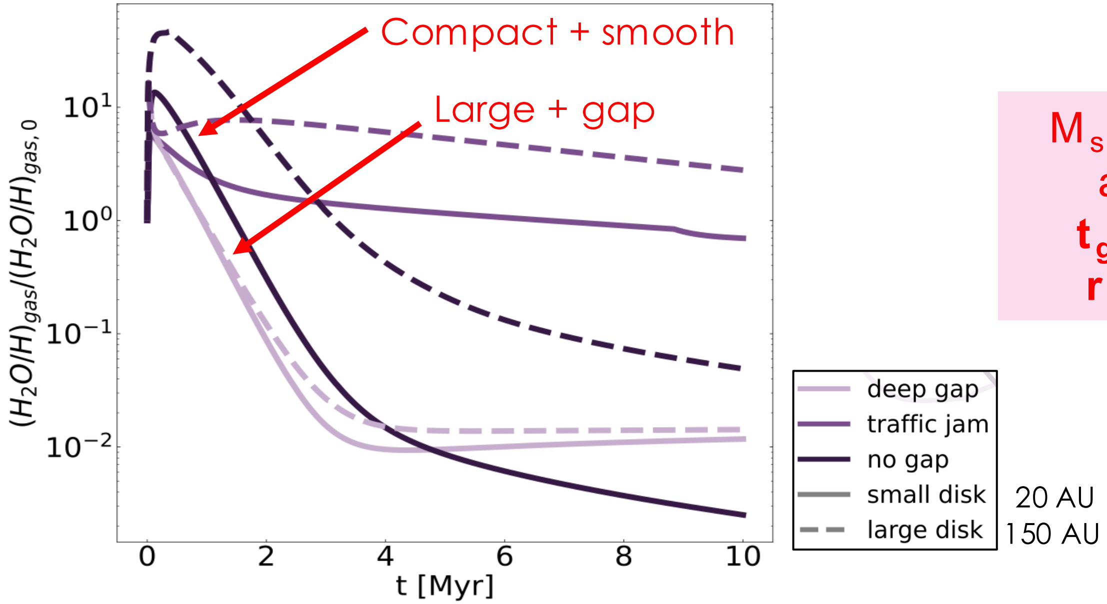
+ multiple stellar masses

$M_{star} = 0.1, 0.4, 0.7, 1, 1.3\ M_\odot$

Is it substructures or disk size?



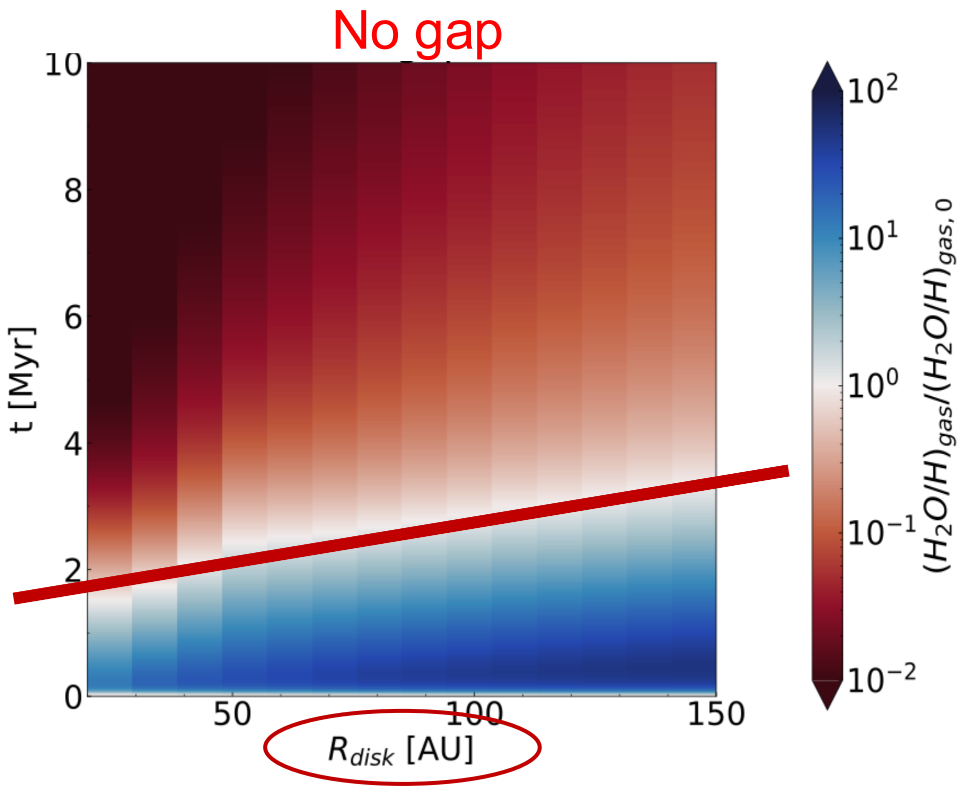
Water abundance fraction over time for different regimes & radii



$M_{star} = 0.7\ M_{\odot}$
$a = 3\text{x}10^{-4}$
$\mathbf{t_{gap} = 0\ Myr}$
$\mathbf{r_{gap} = 3\ AU}$

Savvidou et al. in prep

Water abundance fraction over time for different regimes & radii



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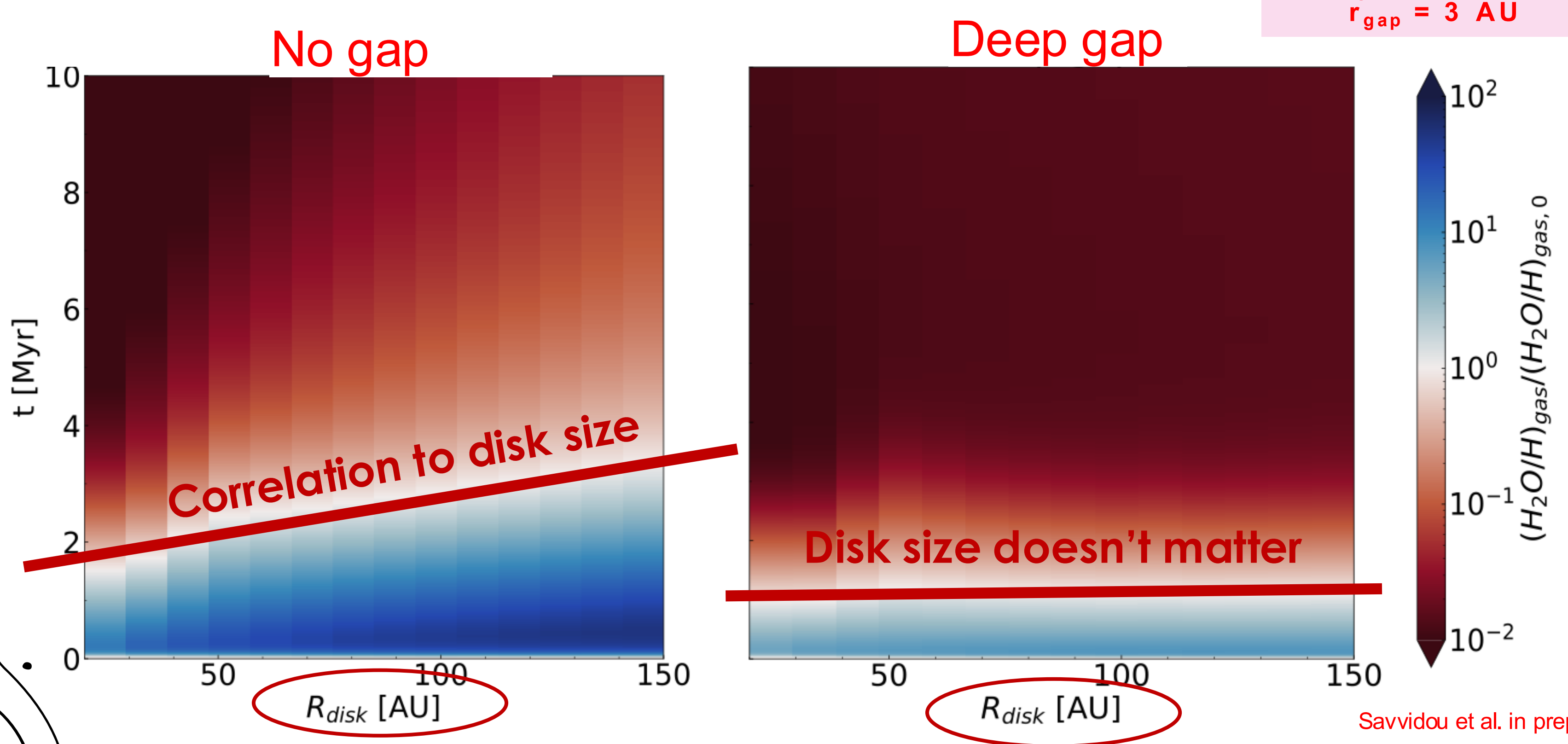

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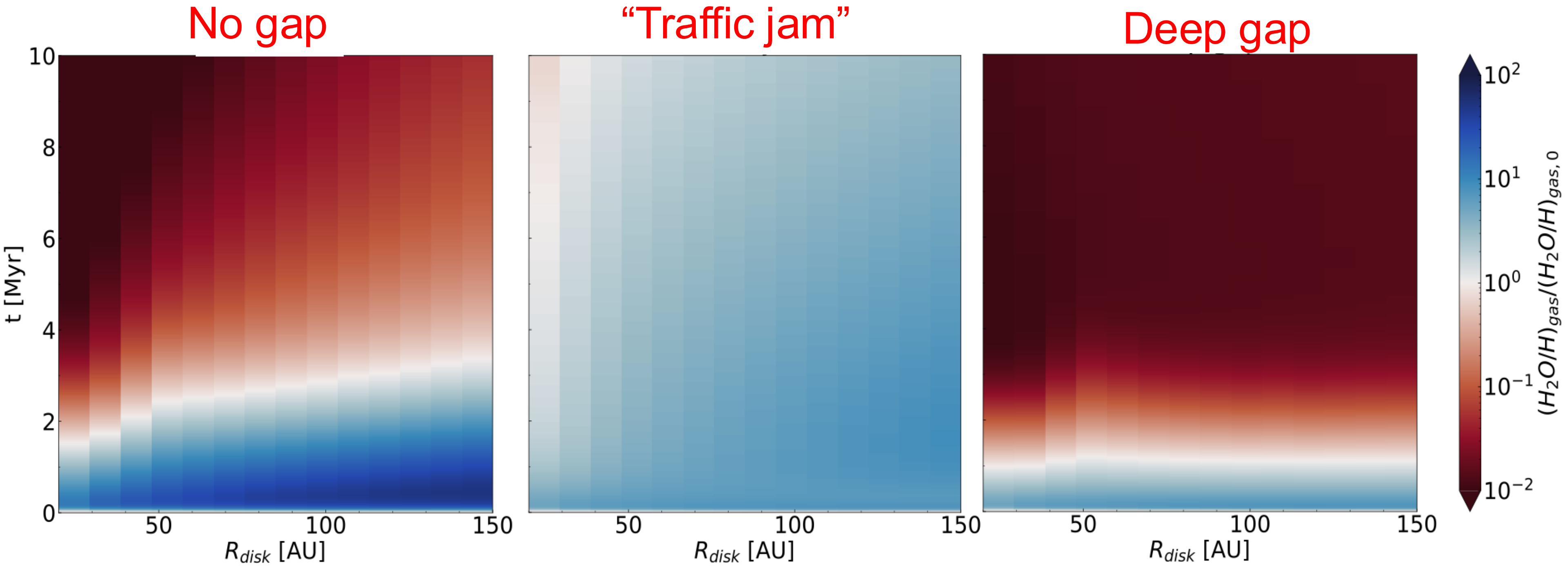


Savvidou et al. in prep

Conclusion:

Substructures dominate the regulation of the inner disk composition

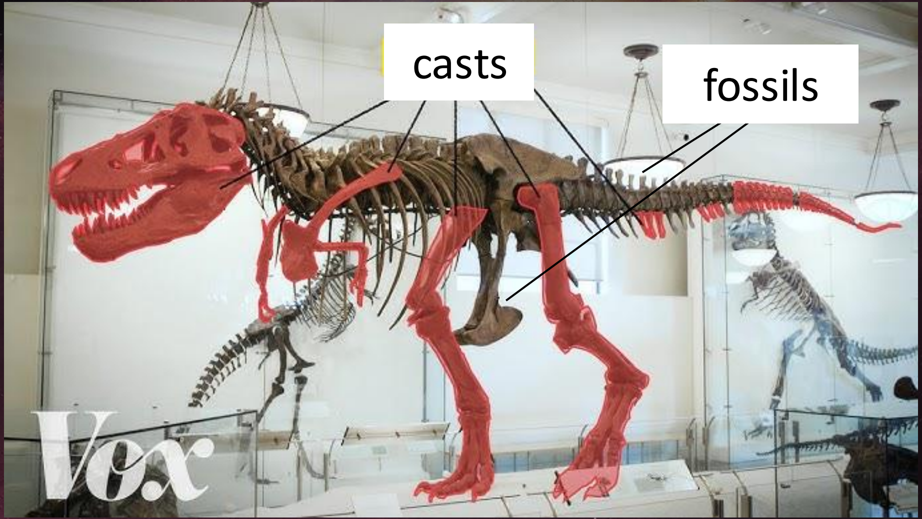
- Substructures "win" over the disk size (especially if they form early and are long-lasting)
- Is the inner and outer disk connected? Convince me they are not!
  (It's a discussion of timescales and filtration)
- More theoretical work is needed to robustly explain observations (see also Mah, **Savvidou** & Bitsch 2024, Kaalyan et al. 2023 and Mah et al. 2023)

Sofia Savvidou
PoPSF, Heidelberg, June 2026

Thank you!

Conclusion:

- We need more careful steps in our effort to link models to observations



Thank you!