Building the Minimum Mass Solar Nebula

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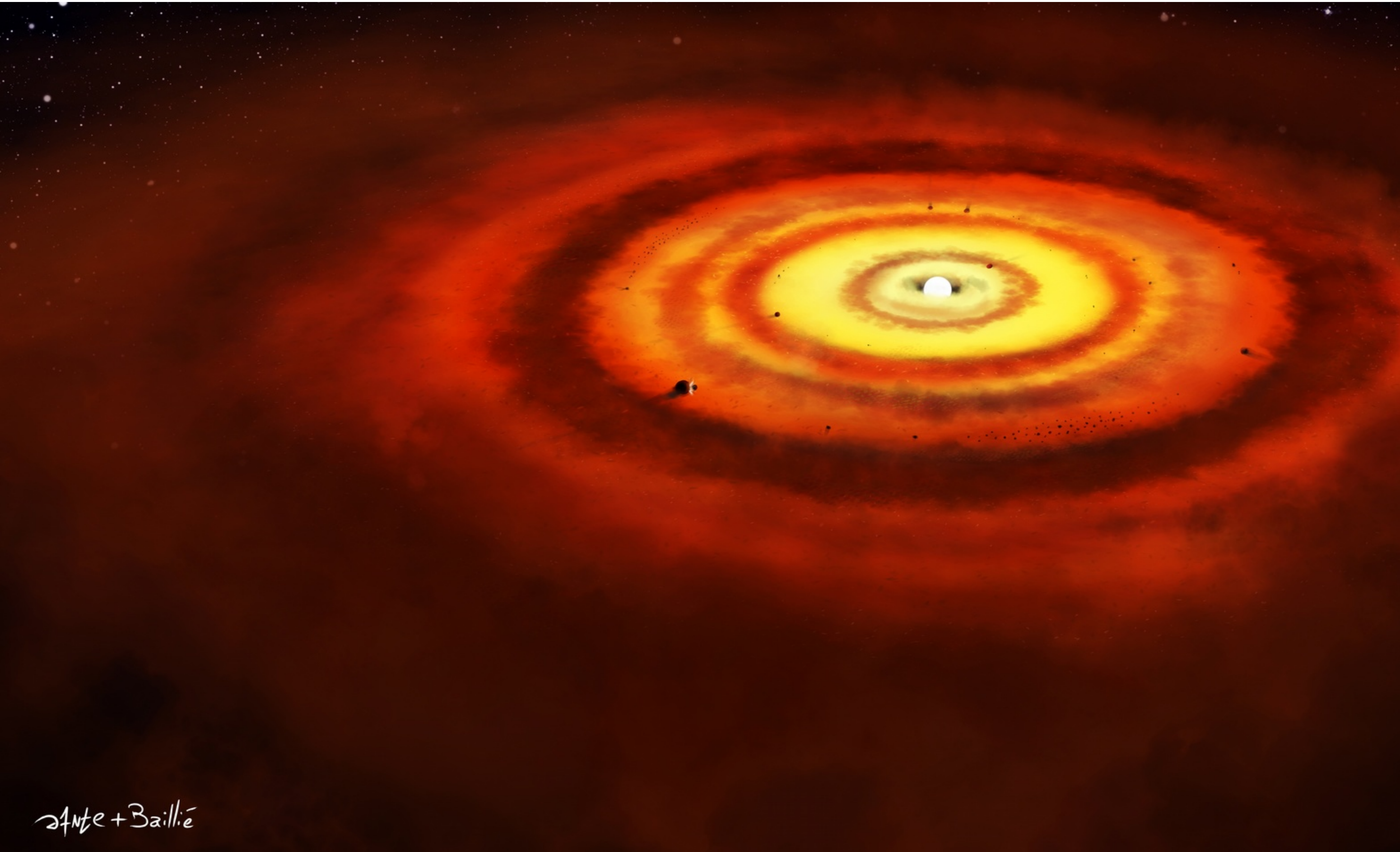
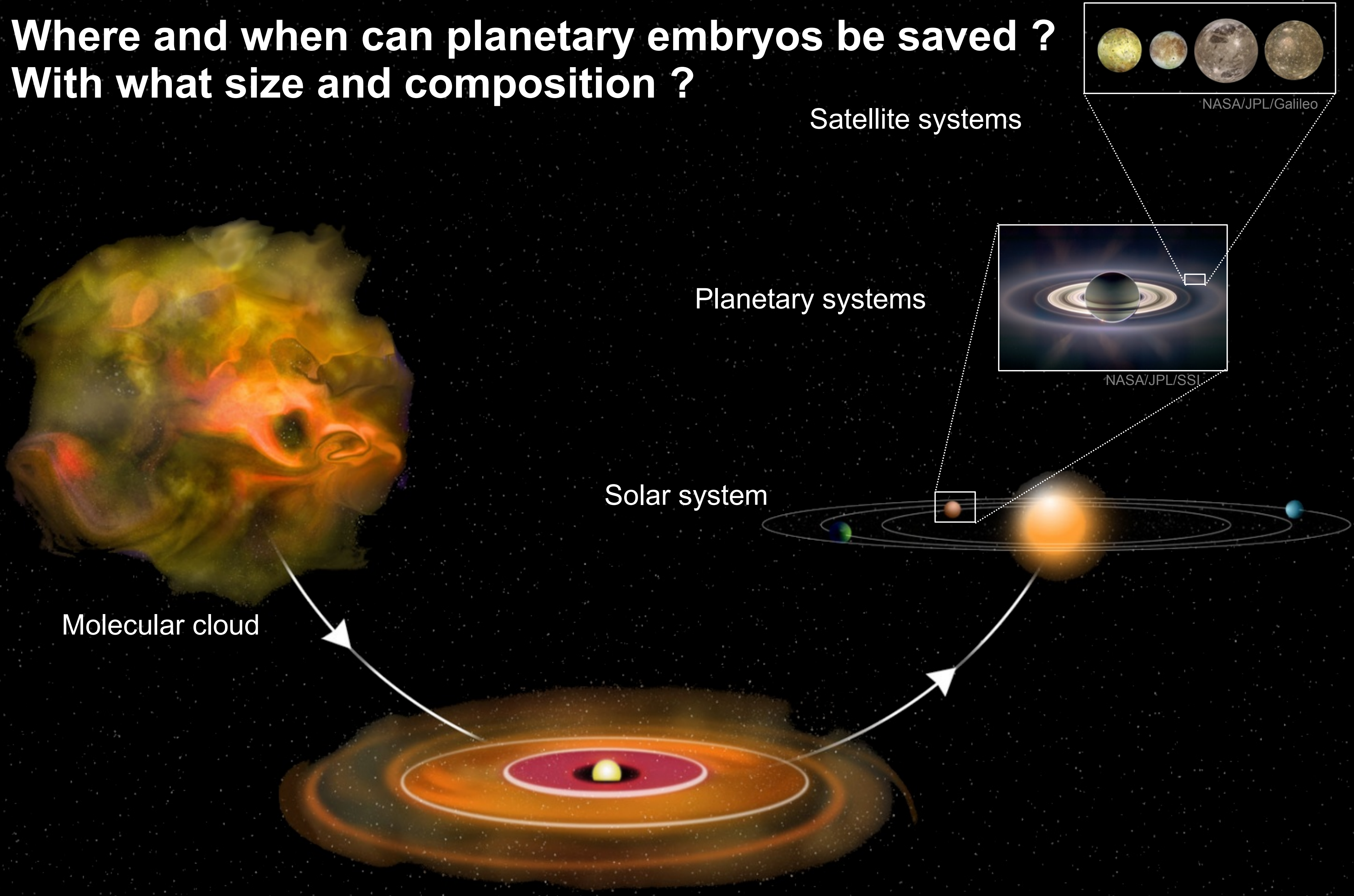


Where and when can planetary embryos be saved ? With what size and composition ?



NASA/JPL/Galileo

Satellite systems

Planetary systems

NASA/JPL/SSI

Solar system

Molecular cloud

Protoplanetary disk

Problematic

- **Planetary embryos tend to fall onto their host star in < 10^5 years**

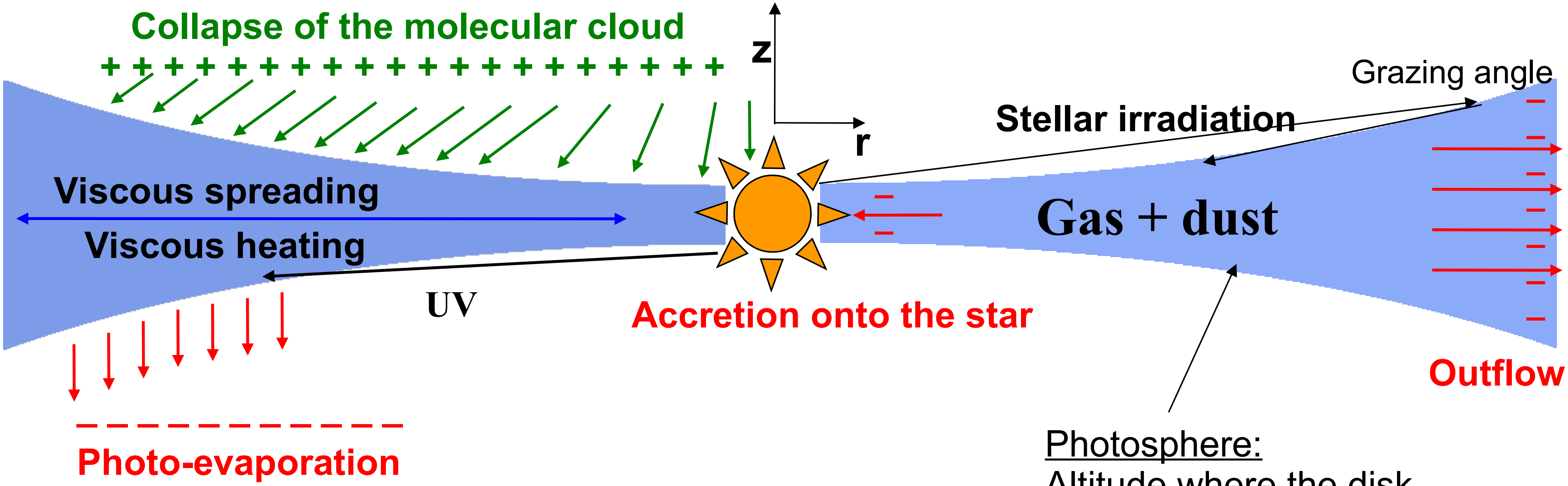
→ Need to trap them to save them !

- Traps are strongly correlated with **density and temperature anomalies** (shadowed regions, sublimation lines…)
- They **evolve** in time as the disk spreads viscously

But the viscous evolution is strongly depending on the initial disk profile (MMSN) : need to reconsider the initial condition

→ building the disk (and the star) from the collapse of the molecular cloud

Toward a self-consistent disk

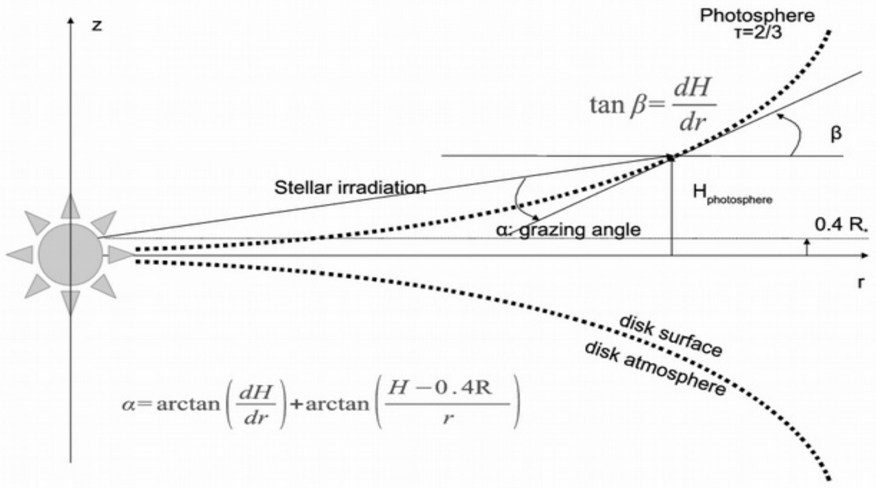


Photosphere:
Altitude where the disk becomes optically thin

Disk ~ a few % mass of the star
99 % gas (H, He) + 1 % µm dust (Si, Fe, Mg, O, …)

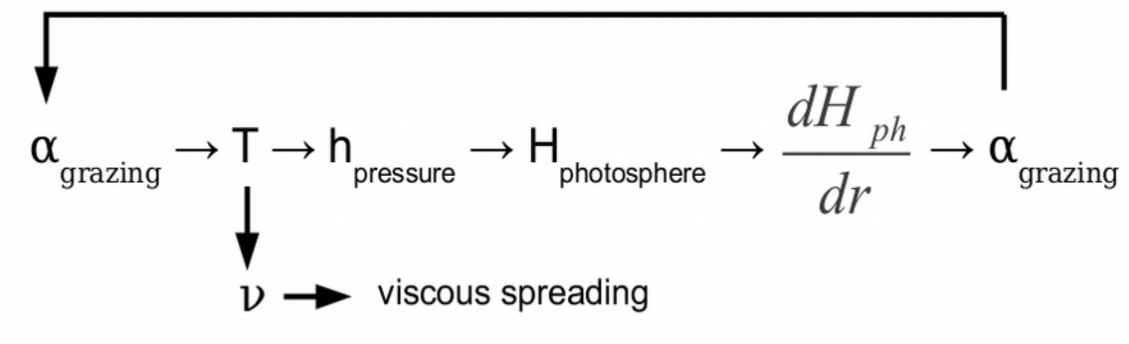
Keplerian shear + magnetic field → MRI → turbulence → viscosity
α disk : turbulent viscosity (Shakura & Sunyaev, 1973)

Local thermodynamics



Baillié & Charnoz, 2014

Iterative procedure to solve the heat budget



Heating implicit equation :

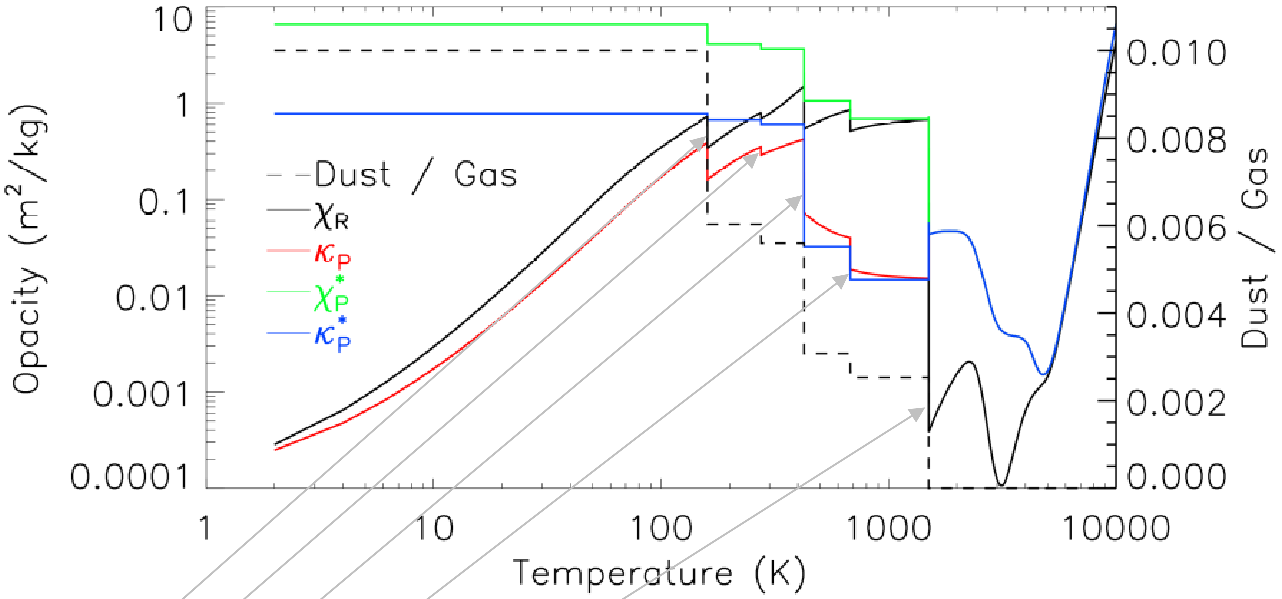
- Stellar irradiation
- Viscous heating
- Cloud + Radiative cooling
- Disk self-shadowing

Self-consistent process to determine T, $h_{pressure}$, $\alpha_{grazing\ angle}$, $H_{photosphere}$ …

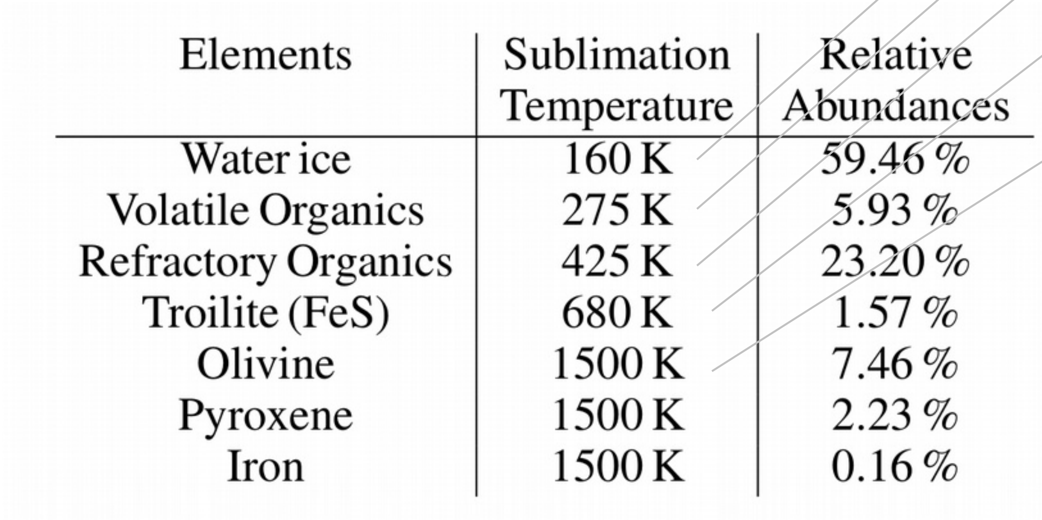
Temperature-dependent dust opacities

The temperature affects the disk composition.

Opacities drop when the disk major components sublimate.

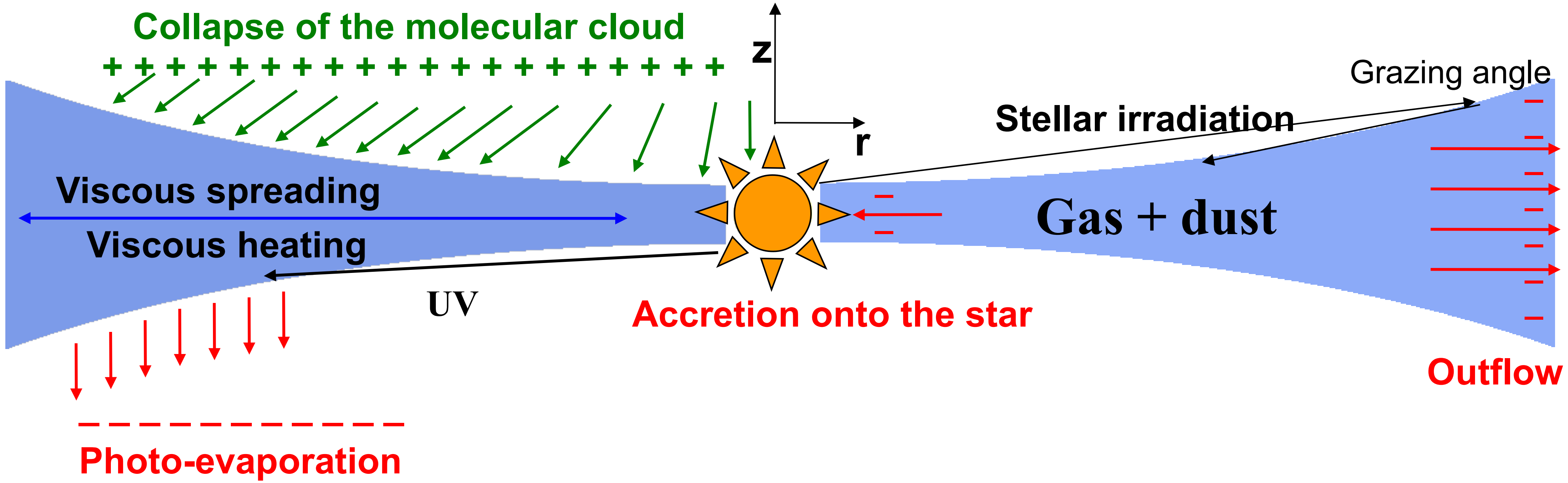


From Semenov et al., 2003



Elements	Sublimation Temperature	Relative Abundances
Water ice	160 K	59.46 %
Volatile Organics	275 K	5.93 %
Refractory Organics	425 K	23.20 %
Troilite (FeS)	680 K	1.57 %
Olivine	1500 K	7.46 %
Pyroxene	1500 K	2.23 %
Iron	1500 K	0.16 %

Toward a self-consistent disk



Disk evolution includes (Baillié et al., 2014, 2015, 2016) :

- Coupling between **dynamics** and **thermodynamics** : viscosity
- Coupling between **temperature** and **geometry** : radiative heating
- Coupling between **temperature** and **composition**: opacity model

Long-term evolution: 1D+1D-hydrodynamical code

(azimuthal sym + vertical isothermal density distribution)

Building the disk consistently with the young star

Infall mass accretion rate (cloud star+disk): $\dot{M}_{\rm cd} = 0.975 \frac{c_s^3}{G}$ where $r < R_c(t)$:

$$R_c(t) = 10.5 \left(\frac{\omega_{\rm cd}}{10^{-14}\,{\rm s}^{-1}}\right)^2 \left(\frac{T_{\rm cd}}{15\,{\rm K}}\right)^{-4} \left(\frac{M(t)}{1\,M_\odot}\right)^3 \,{\rm AU}$$

Mass and angular momentum conservation:

$$\frac{\partial \Sigma(r,t)}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(\sqrt{r}\,\frac{\partial}{\partial r}\left(\nu\Sigma\sqrt{r}\right)\right) + S(r,t) + S_2(r,t)$$

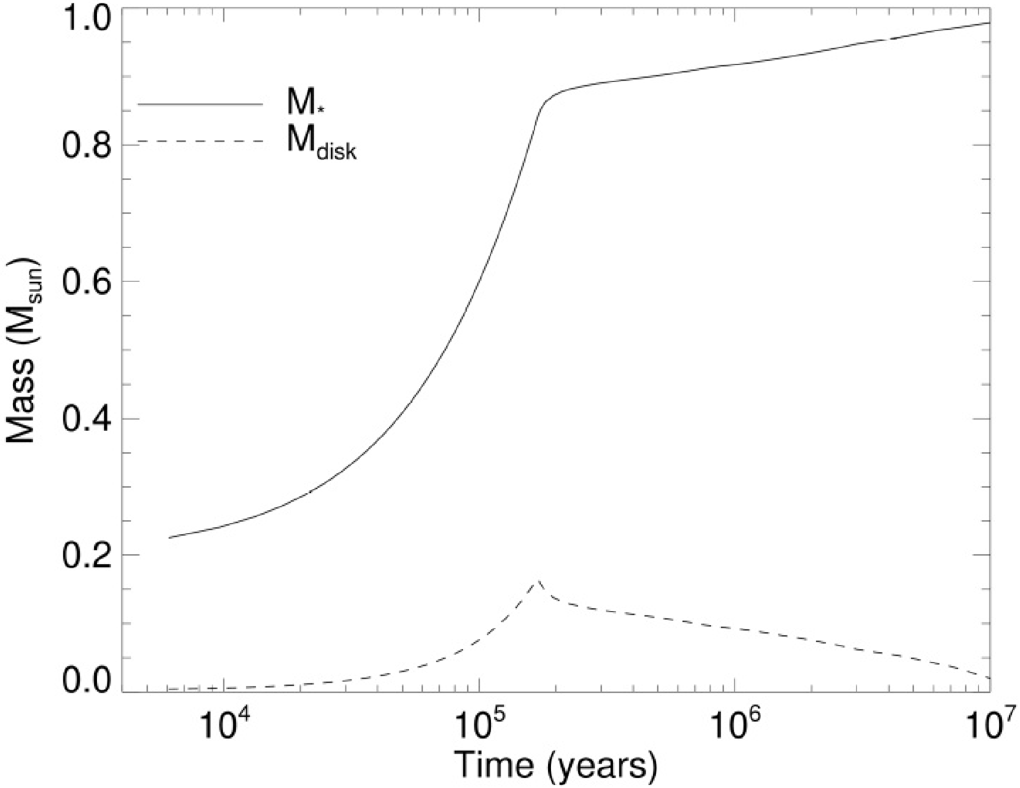
where

$$S(r < R_c(t), t) = \frac{\dot{M}_{\rm cd}}{8\pi R_c^2}\left(\frac{r}{R_c}\right)^{-3/2}\left[1 - \left(\frac{r}{R_c}\right)^{1/2}\right]^{-1/2}$$

is a source term that accounts for the infall of the molecular cloud gas onto the disk at radius r, and

$$S_2(r,t) = \frac{1}{r}\frac{\partial}{\partial r}\left(r^2\,\Sigma(r,t)\,\frac{\dot{M}_*}{M_*}\right)$$

is a source term that accounts for the varying stellar mass.

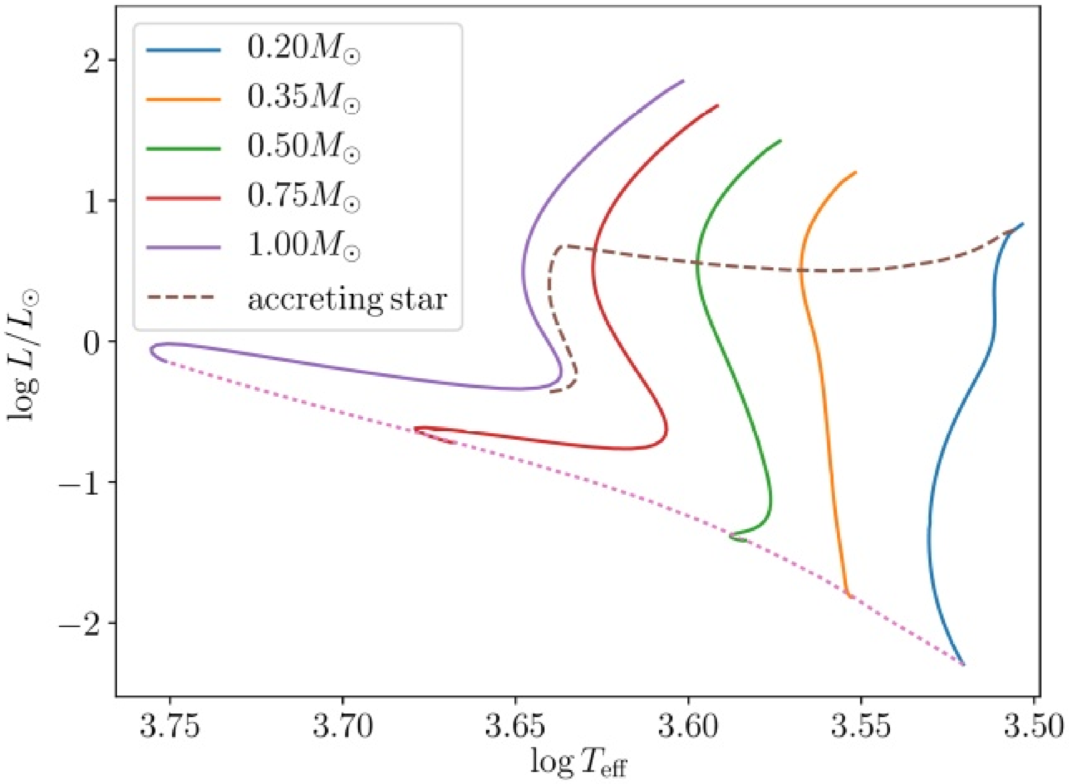


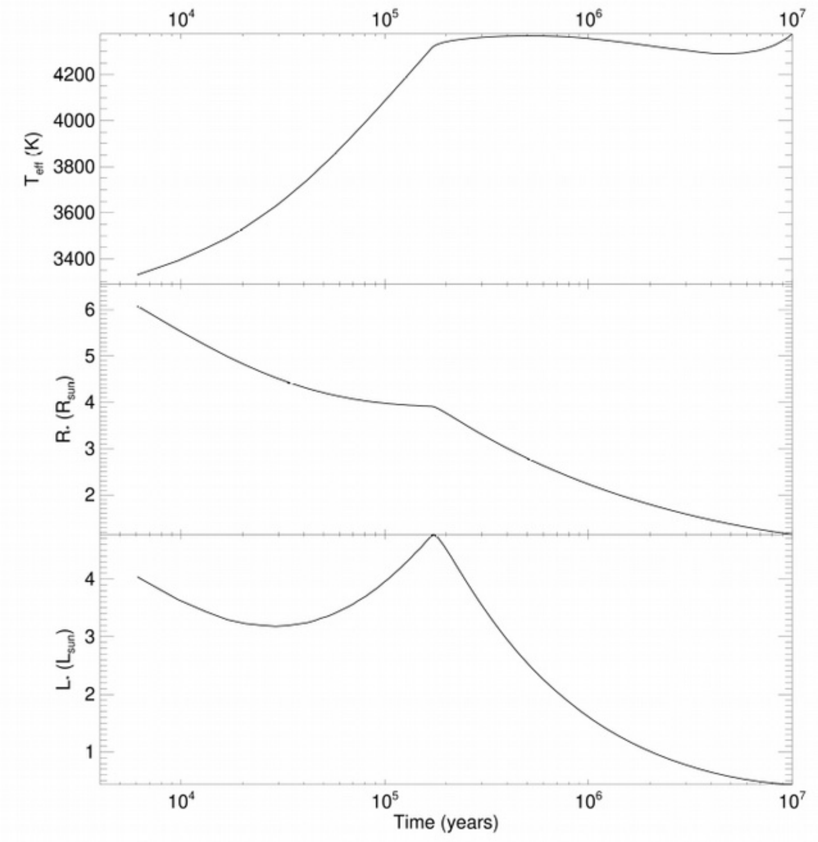
Baillié et al., 2019

The disk reaches 0.19 M* at the end of the collapse (after 170 kyr).

Building the disk consistently with the young star

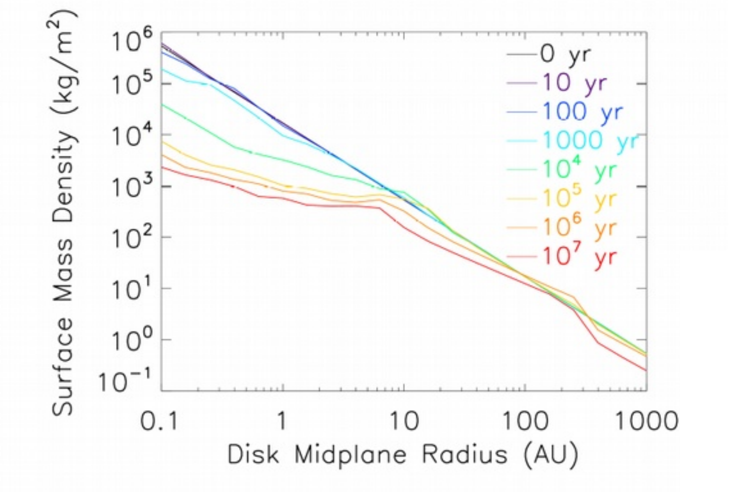
The star temperature, radius and luminosity are interpolated over **pre-calculated stellar evolutions**, based on the simulated mass accretion rate from the viscous evolution.





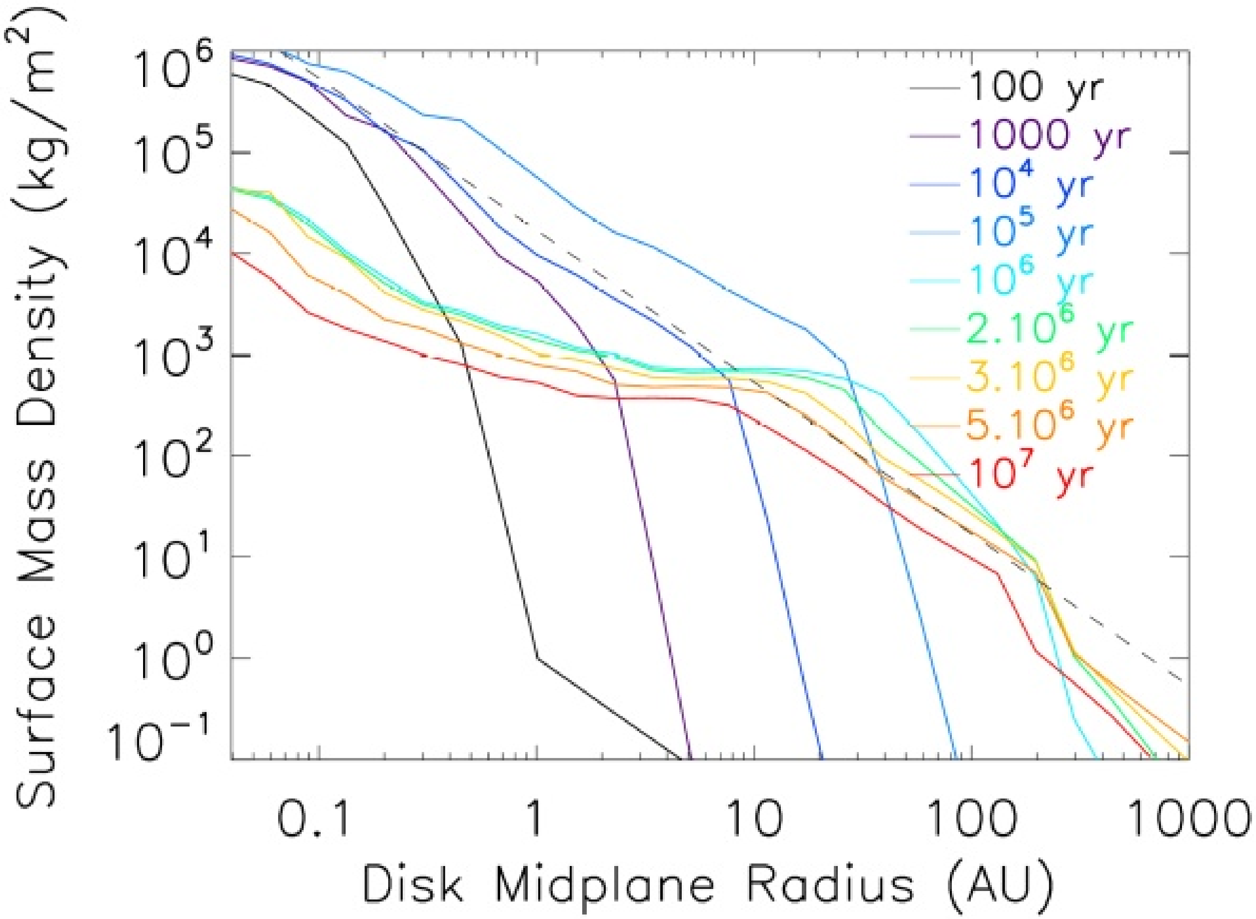
Adapted from Marques et al., 2013

Surface-mass density evolution

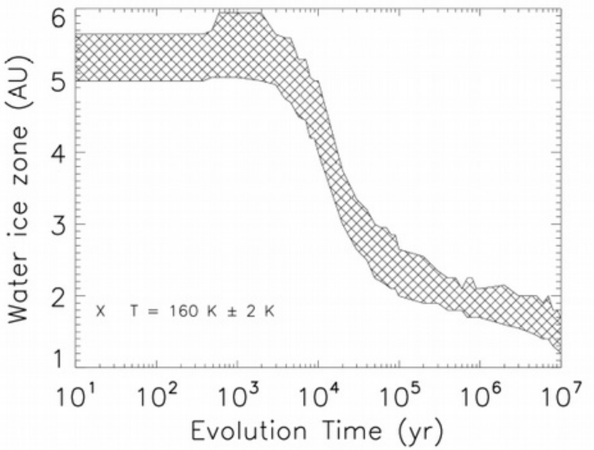


MMSN evolution
(Baillié et al., 2016)

The disk extends to 50 AU after 100 kyr.
Denser inner disk after 1 Myr (stronger dM/dt).
Asymptotic trend : Σ α r $^{-1}$ (consistent with observations).

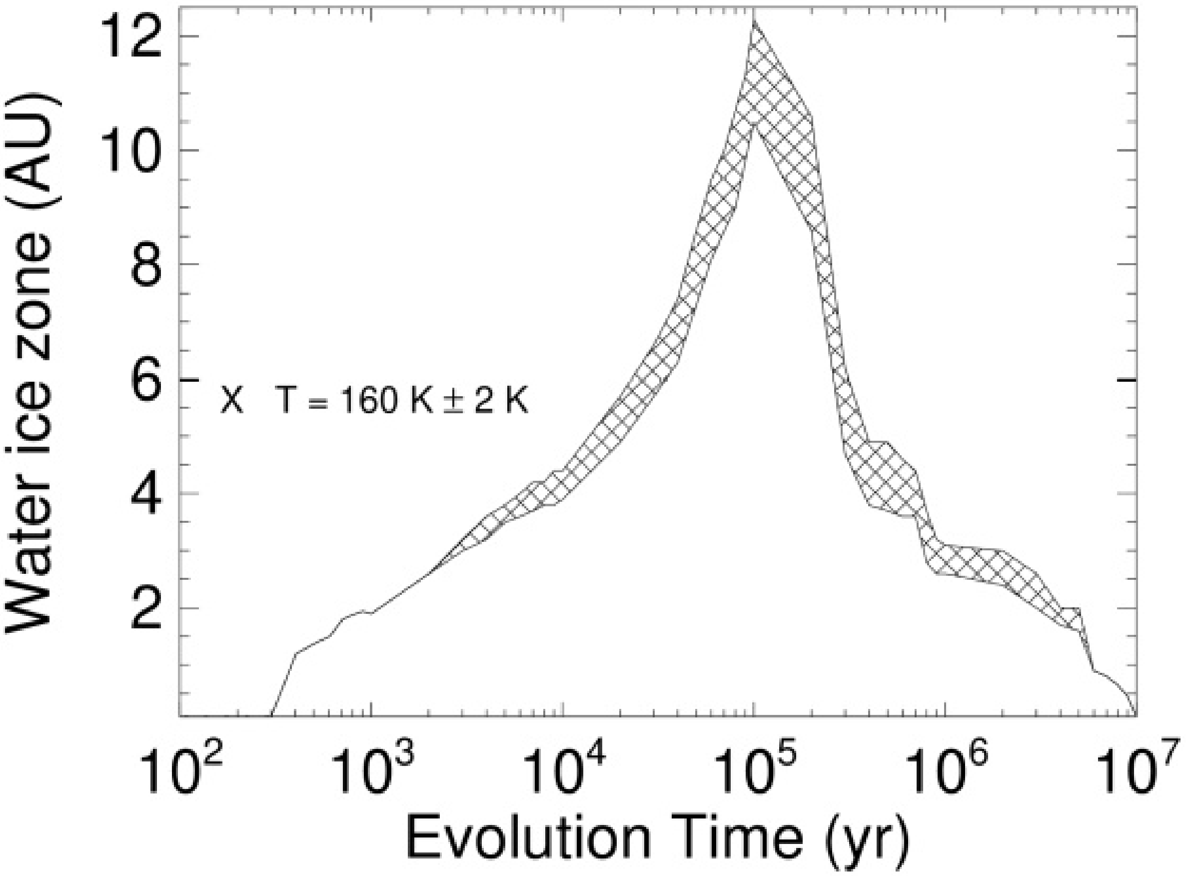


Snowline evolution

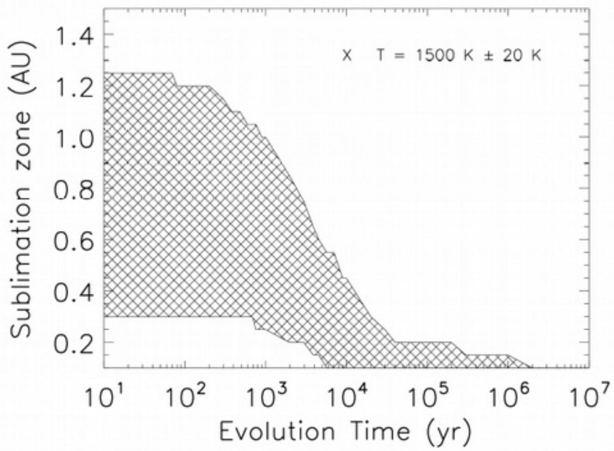


MMSN evolution
(Baillié et al., 2016)

After 100 kyr, the snowline migrates inward from 12 AU to 2 AU.

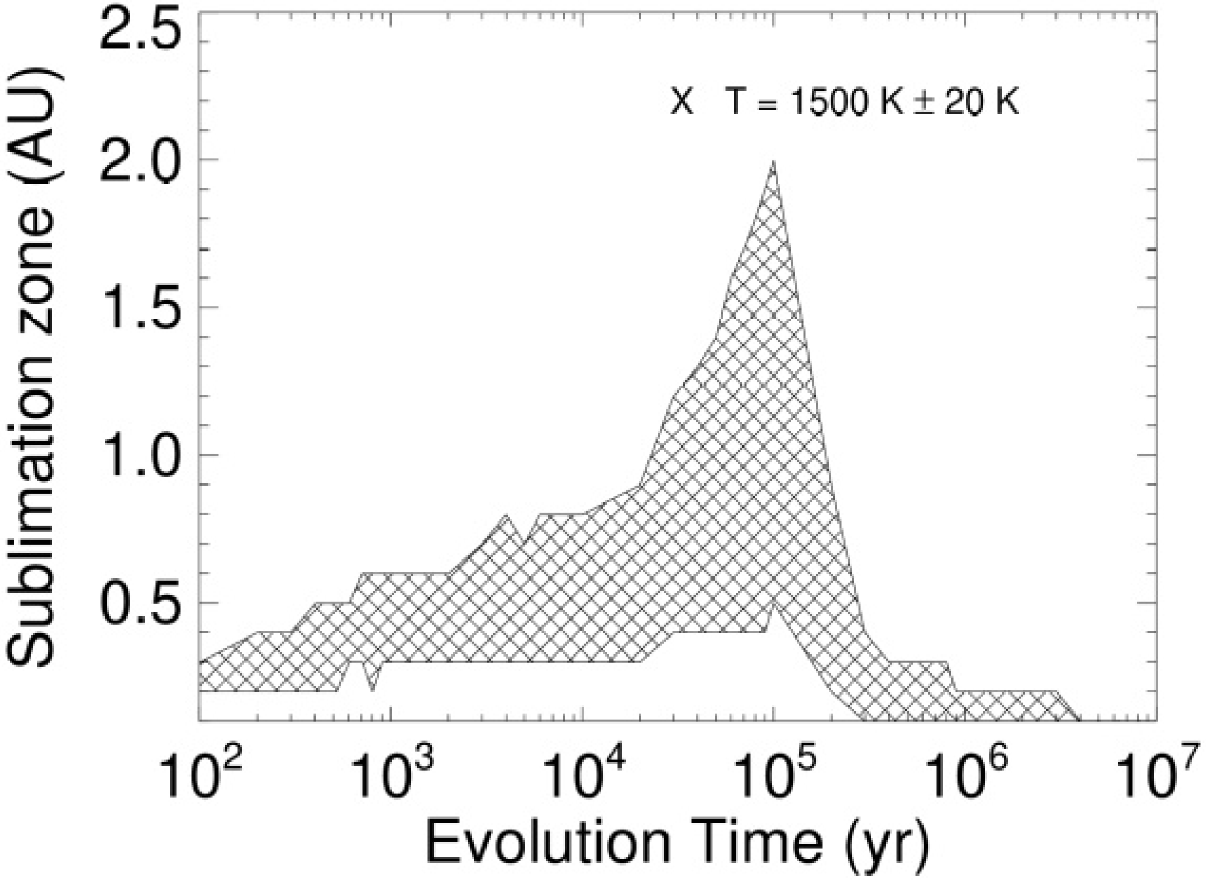


Silicate sublimation line evolution

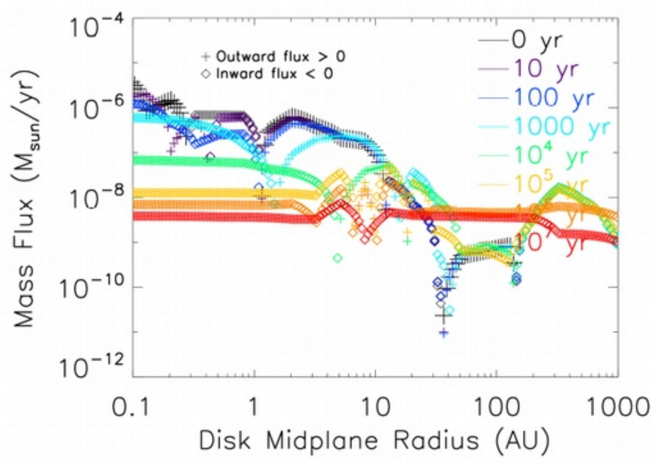


MMSN evolution
(Baillié et al., 2016)

Silicate line remains unchanged after 100 kyr.

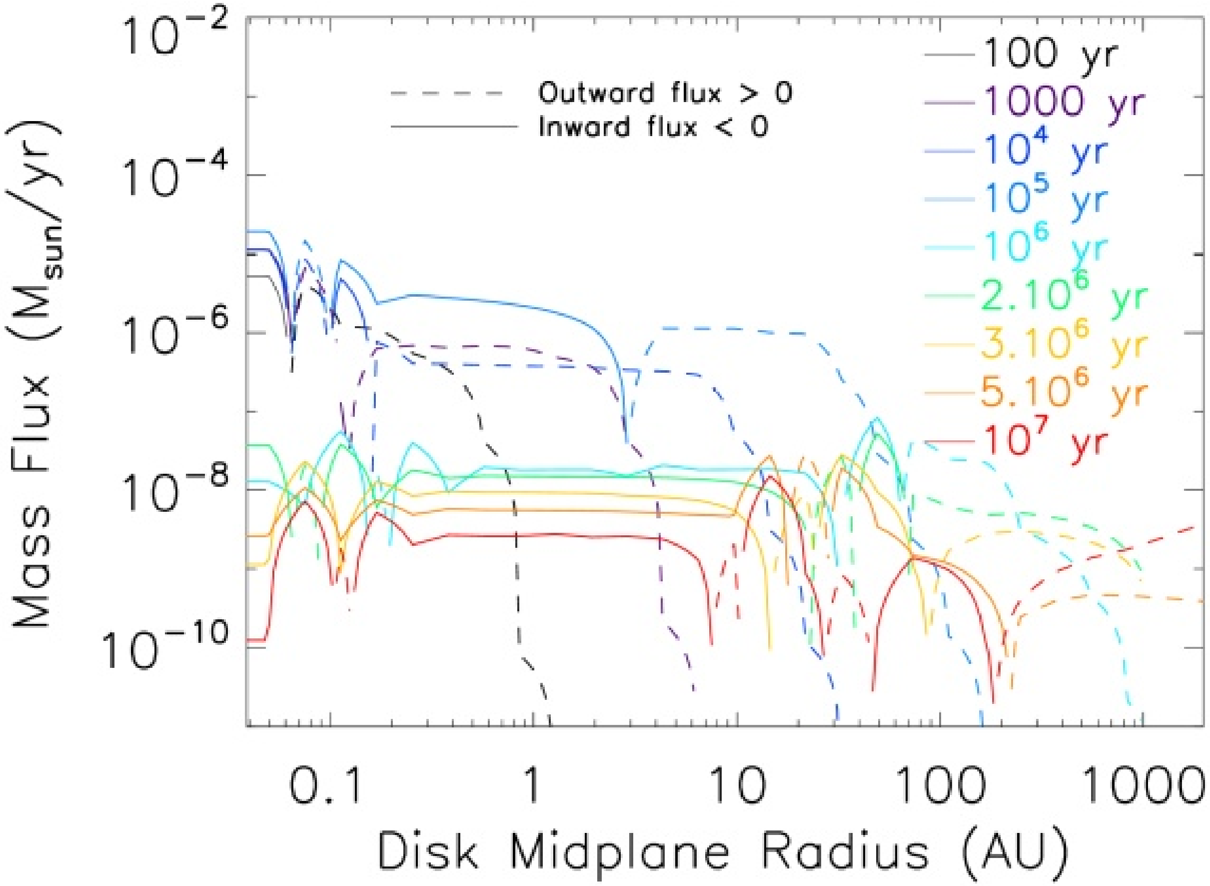


Equivalent timeline

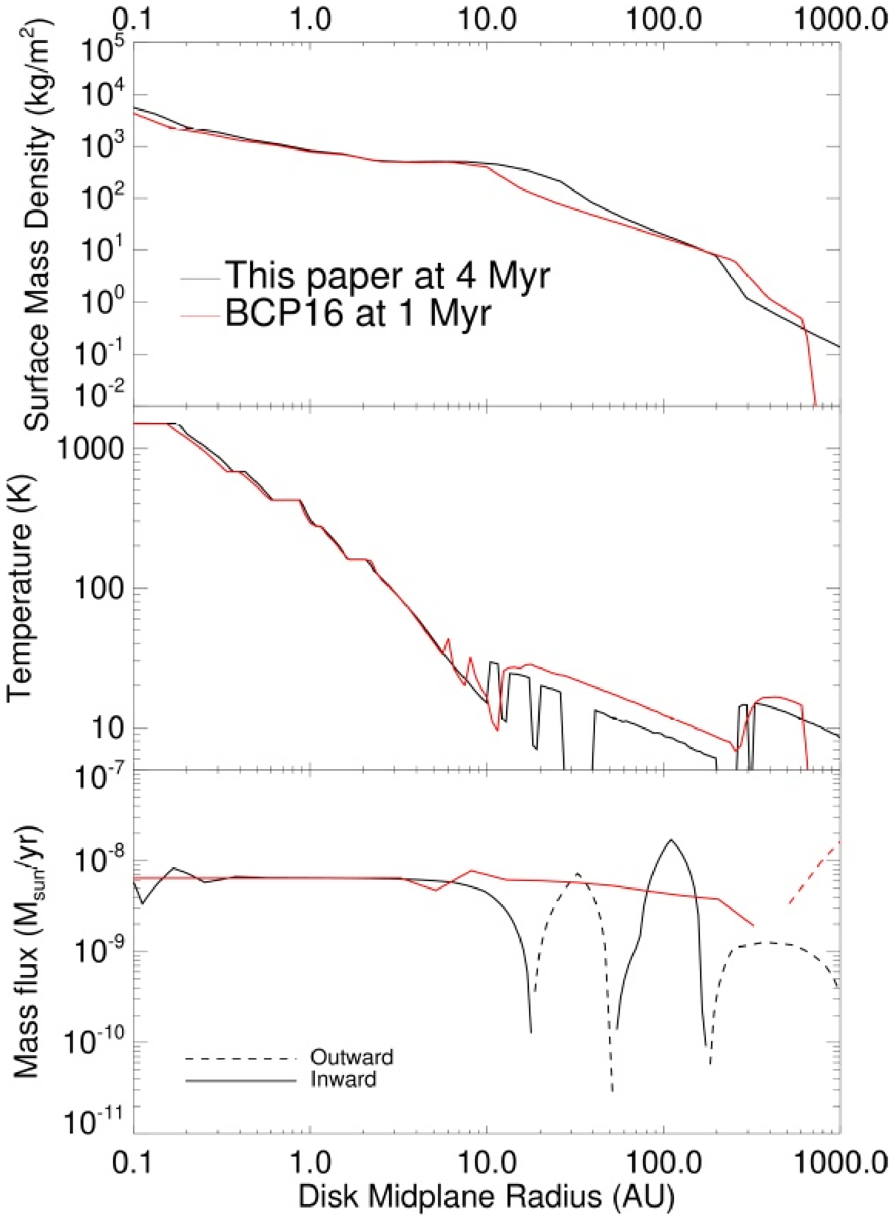


MMSN evolution
(Baillié et al., 2016)

Disk age defined by
its mass accretion rate



Equivalent timeline



Equivalent accretion rates:

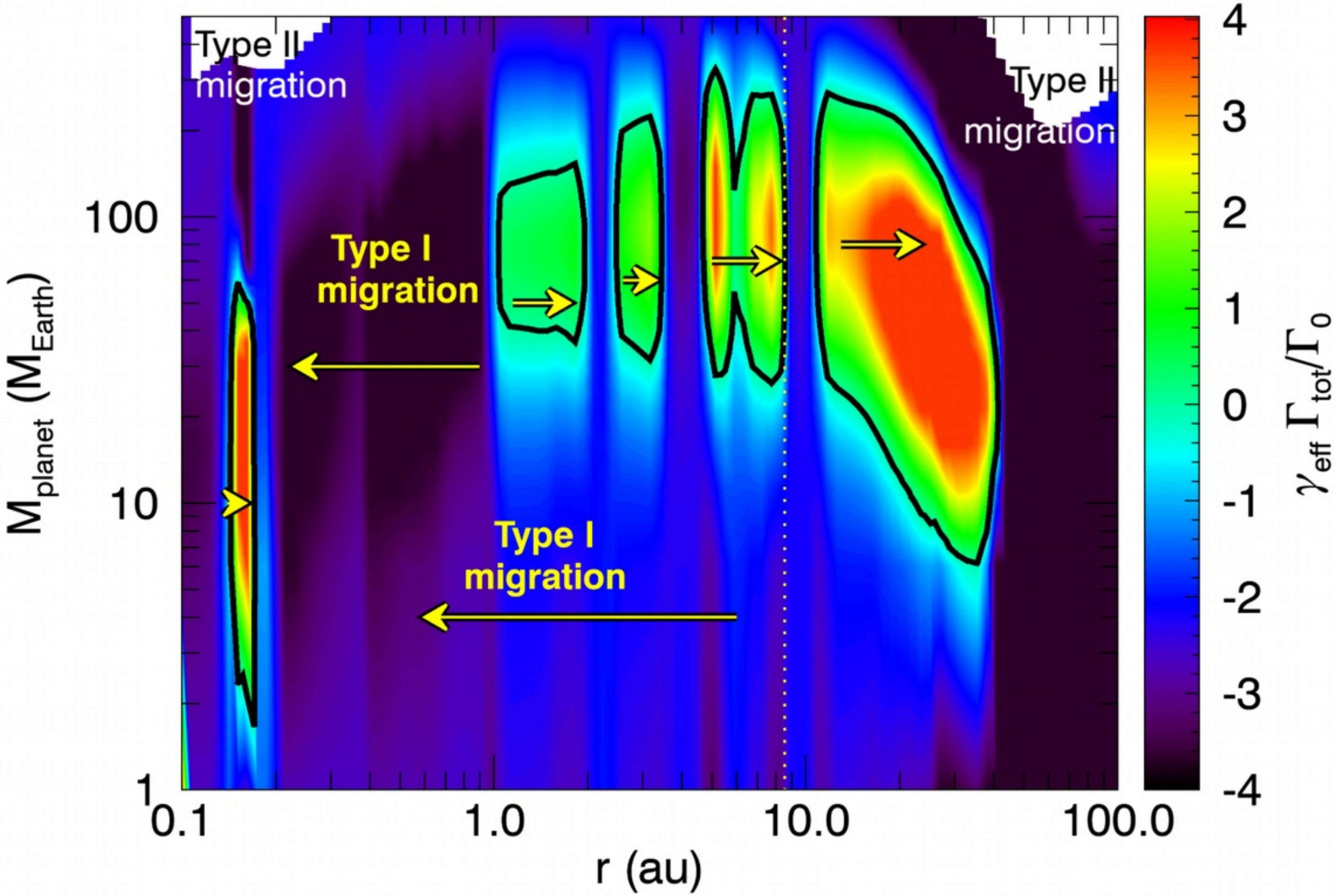
MMSN (Baillié2016)	Collapse-formed disk (Baillié2019)
10 kyr	500 kyr
100 kyr	3 Myr
1 Myr	4 Myr
5 Myr	7 Myr

Planet traps after 200 kyr

Temperature and density bumps may counter type I migration : outward migration generate **planet traps**.

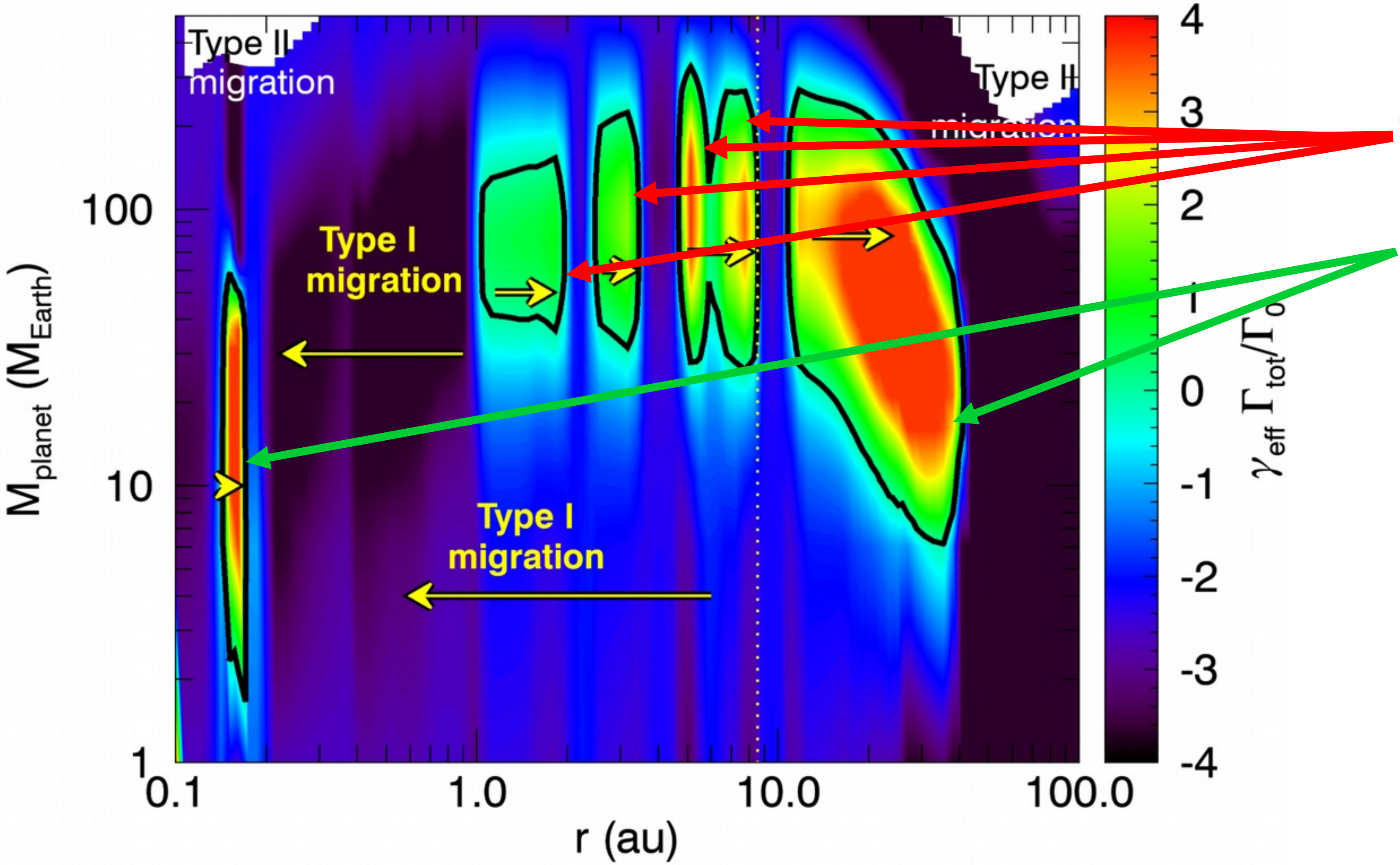
→ save planetary embryos

→ favor accumulation and growth



Planet traps after 200 kyr

Super-Earths / Neptunes trapping inner to the snowline.
+ Giant planets at the snowlines.
Early gap is unlikely to open as super-massive planets are probably not formed yet.



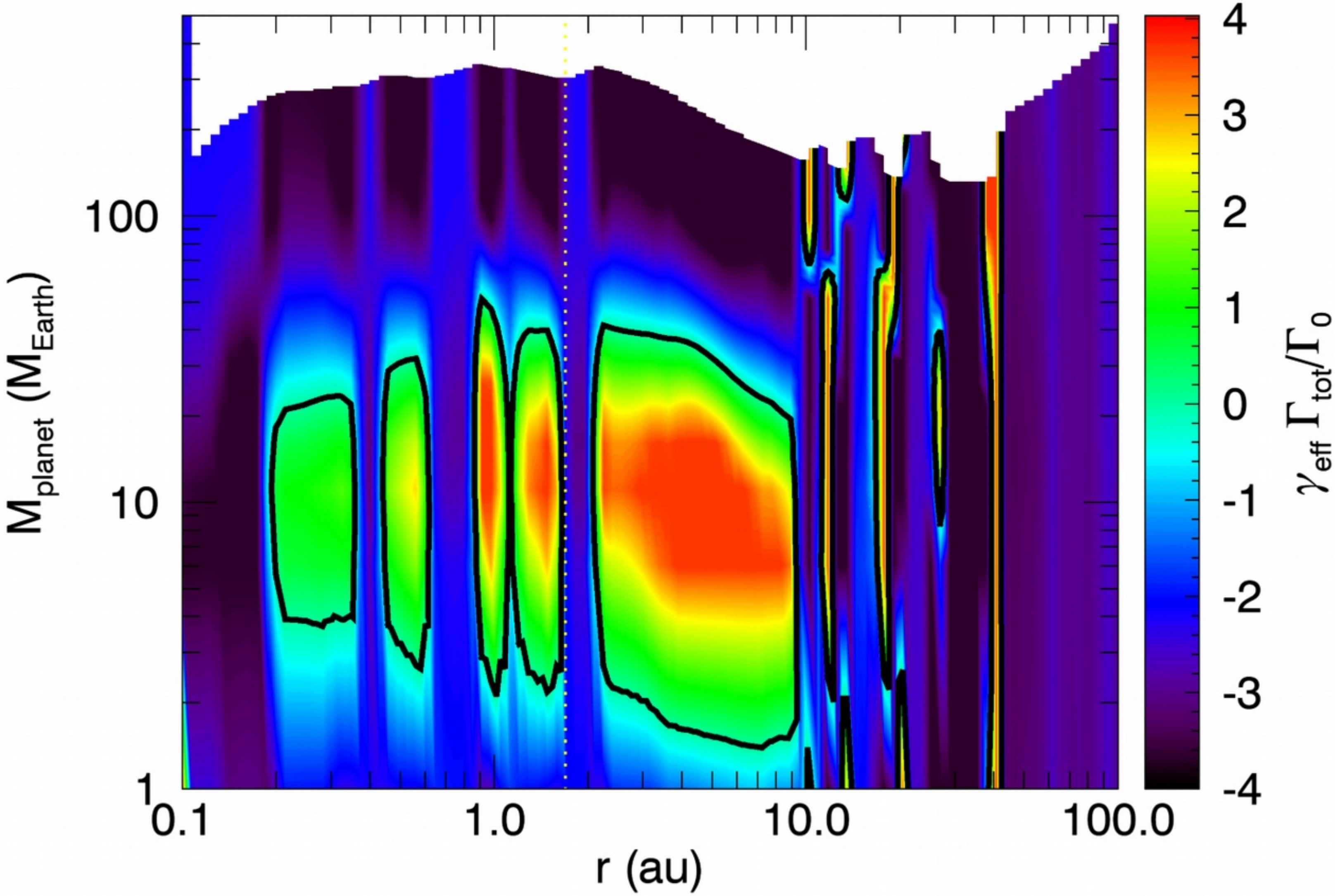
“Iceline” planet traps

“Heat barrier” planet traps

Early trapping possible beyond 40 AUs.

Planet traps after 4 Myr

Multiple possibilities for **close-in Super-Earths**.
Harder to save massive planets that did not open a gap yet.
Trapped-migration may preserve embryos in the long term.



Take-away points

Disk structure :

- Density asymptotic trend is similar to the MMSN evolution
- **Early icelines are shifted outer** in the disk
- **MMSN is ~ 2 Myr older than a collapse-formed disk**

Impact on planetary migration :

- Super-Earths can get trapped early enough in the inner disk
- Cold giants may survive if they open a gap before 200 kyr
- Late close-in SE/Neptunes can get trapped and survive
- Planet trapping can happen much earlier than the MMSN phase

Increasing diversity of planets that may be saved in disks that are built from the collapse of the molecular cloud

Thank you for your attention.

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Work in progress

Evolution :

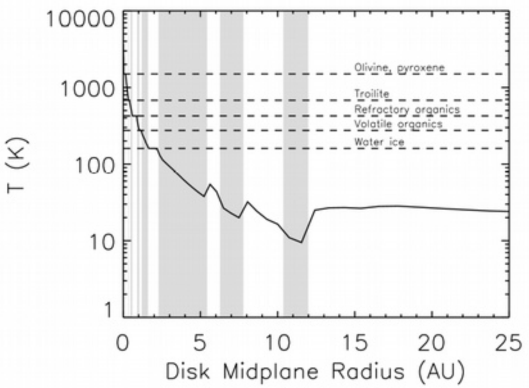
- **Earlier phases** than the MMSN are now accessible : growth
- **Photo-evaporation**
- Modeling other **young stars**

Structure :

- Inner structure : **dead-zones**, variable turbulence

Temperature profile after 1 Myr

Shadowed regions extend up to 10 AU.
Temperature plateaux are moved outer in the disk :
→ **water ice can be found around 3 AU.**



MMSN evolution
(Baillié et al., 2016)