THE MINIMUM MASS SOLAR NEBULA: A 3 MILLION YEAR-OLD DISK.

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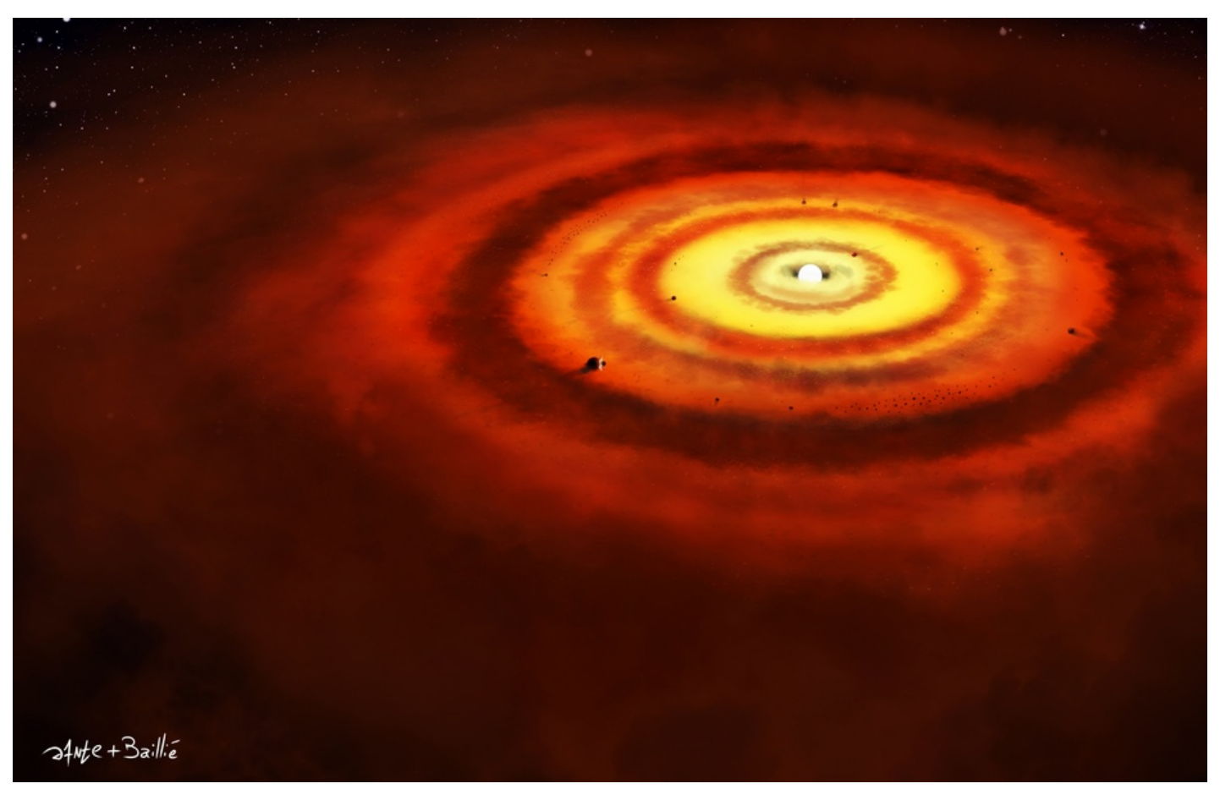
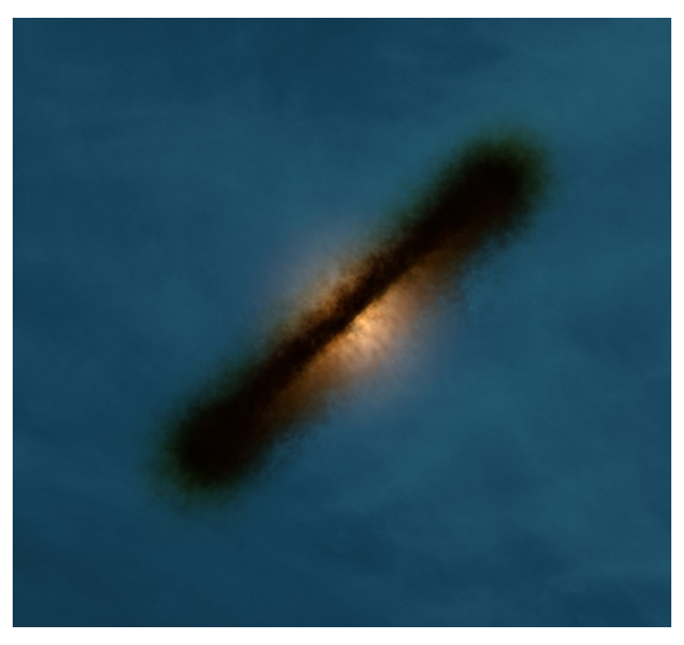


Abstract

Most planetary formation simulations rely on simple protoplanetary disk models evolved from the usual, though inaccurate, Minimum Mass Solar Nebula. Here, we suggest a new consistent way of building a protoplanetary disk from the collapse of the molecular cloud: both the central star and the disk are fed by the collapse and grow jointly. We then model the star physical characteristics based on pre-calculated stellar evolution models. After the collapse, when the cloud initial gas reservoir is empty, the further evolution of the disk and star is mainly driven by the disk viscous spreading, leading to radial structures in the disk: temperature plateaux at the sublimation lines of the dust species and shadowed regions that are not irradiated by the star. These irregularities in the disk surface mass density or midplane temperature may help trap planetary embryos at these locations, eventually selecting the composition of the planet cores. In addition, we redefine the disk timeline and describe the stages that lead to the MMSN model.



R. Hurt (NASA/JPL-Caltech/IPAC)

Problematic

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

Cloud & star model

We interpolate the stellar physical properties from tables of pre-calculated stellar evolutions (Piau et al., 2002, 2011, Marques et al., 2013).

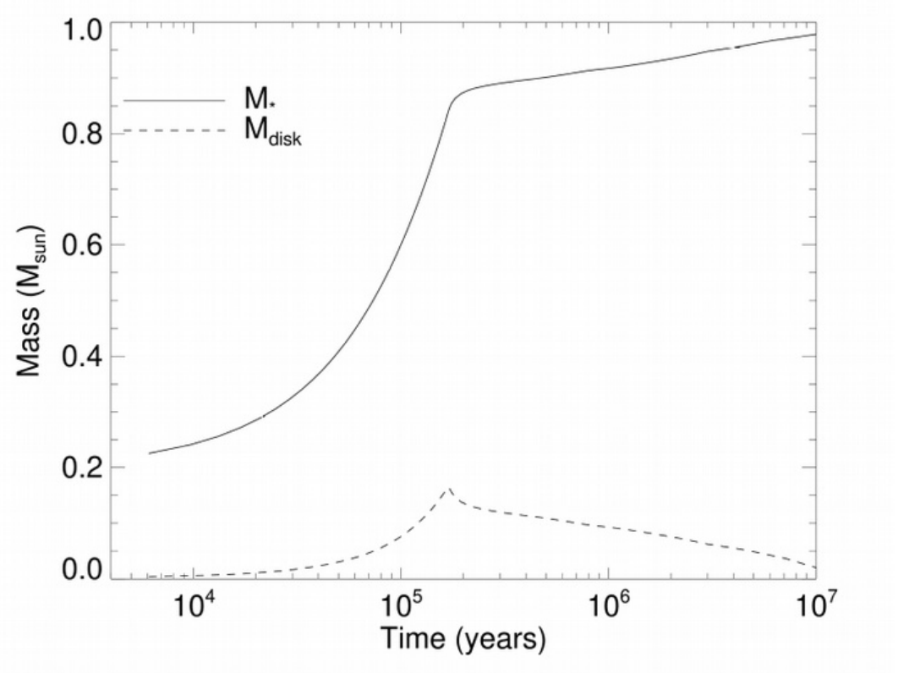


Figure 1 : Star and disk mass evolution.

The disk gains mass from the molecular cloud.
The star gains mass from the molecular cloud and accretion by the disk viscous spreading.

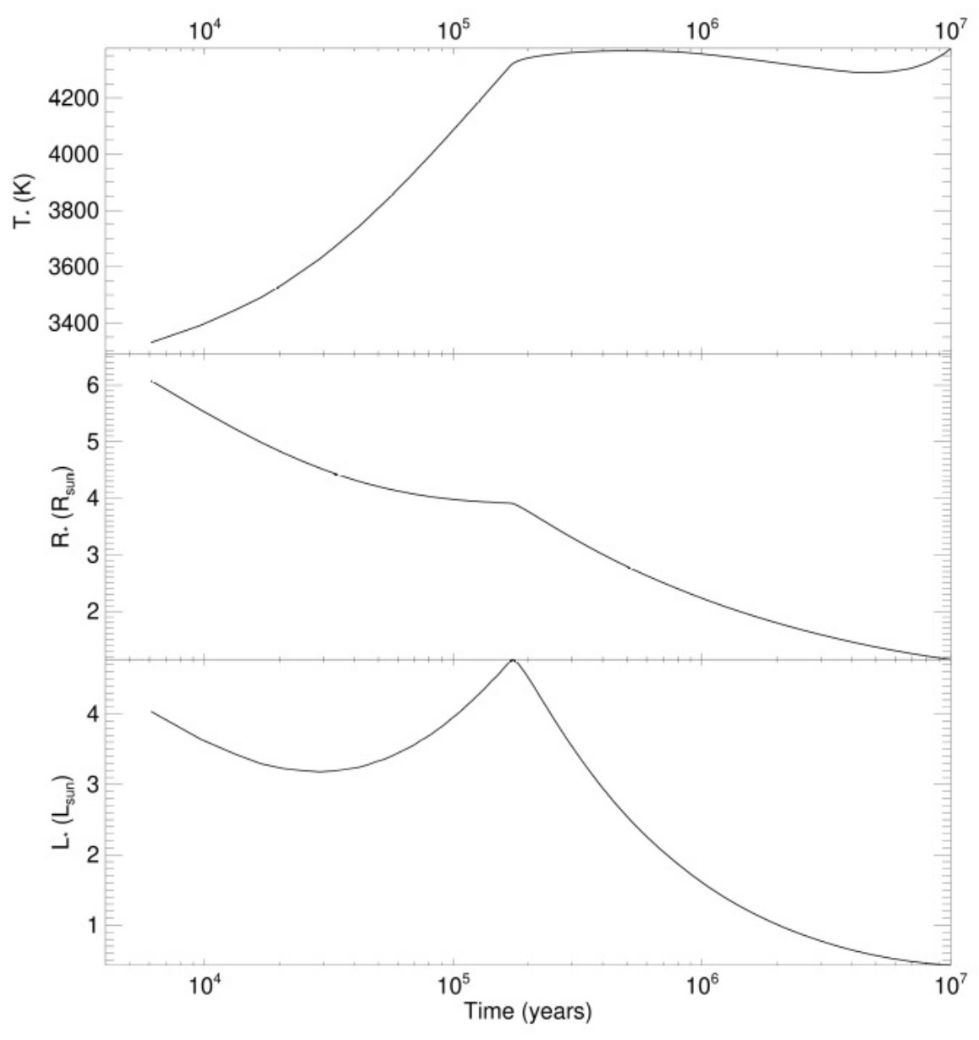


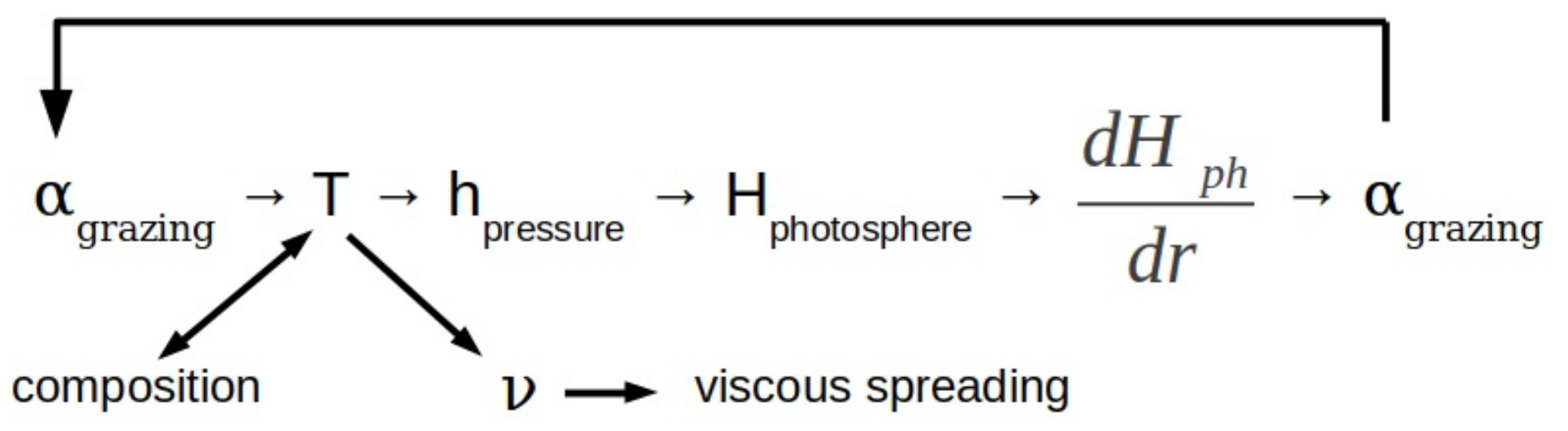
Figure 2 :
Stellar temperature, radius and luminosity evolution.

Disk model

1D + 1D numerical viscous spreading (Lynden-Bell, 1974) hydrodynamical code from Baillié et al., 2014, 2015, 2016 :

Elements	Condensation / Sublimation Temperature
Water ice	160 K
Volatile organics	275 K
Refractory organics	425 K
Troilite FeS	680 K
Olivine, pyroxene ([Fe,Mg] silicates)	1500 K

- **heating : irradiation + viscous + cloud + radiative cooling + disk self-shadowing**
- **coupling dynamics ⇄ thermodynamics (ν_{turb})**
- **coupling temperature ⇄ geometry (α_{gr})**
- **coupling temperature ⇄ composition (opacity)**



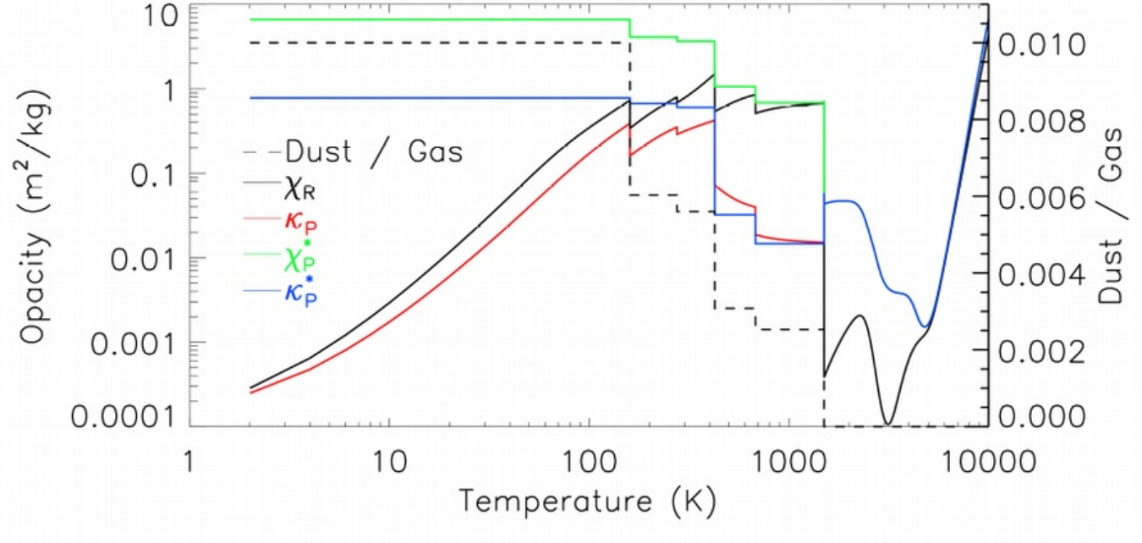


Figure 3 : Opacity variations with local temperature (from Semenov et al., 2003)

Disk structure and evolution

- The disk grows for **170 kyr** before emptying on the star by viscous spreading
- It gets hotter until the end of the collapse phase and then cools down
- Sublimation lines migrate as the disk evolves

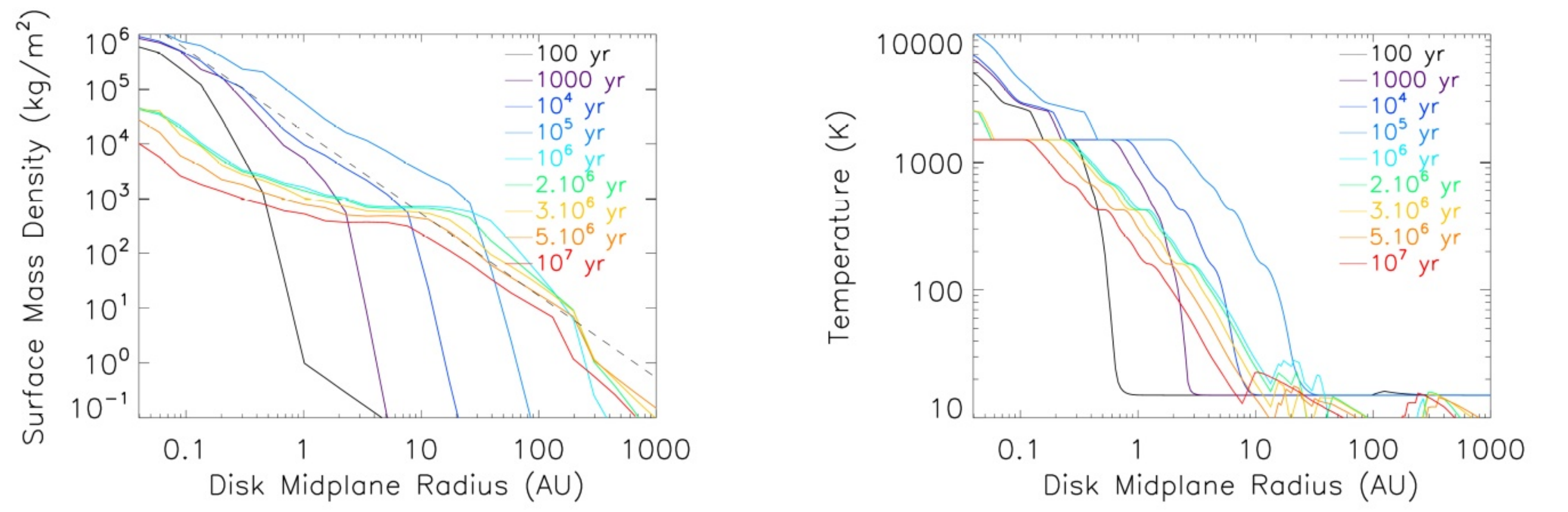


Figure 4 : Evolution of the surface-mass density and temperature radial profiles for disk fed by collapse of the molecular cloud.

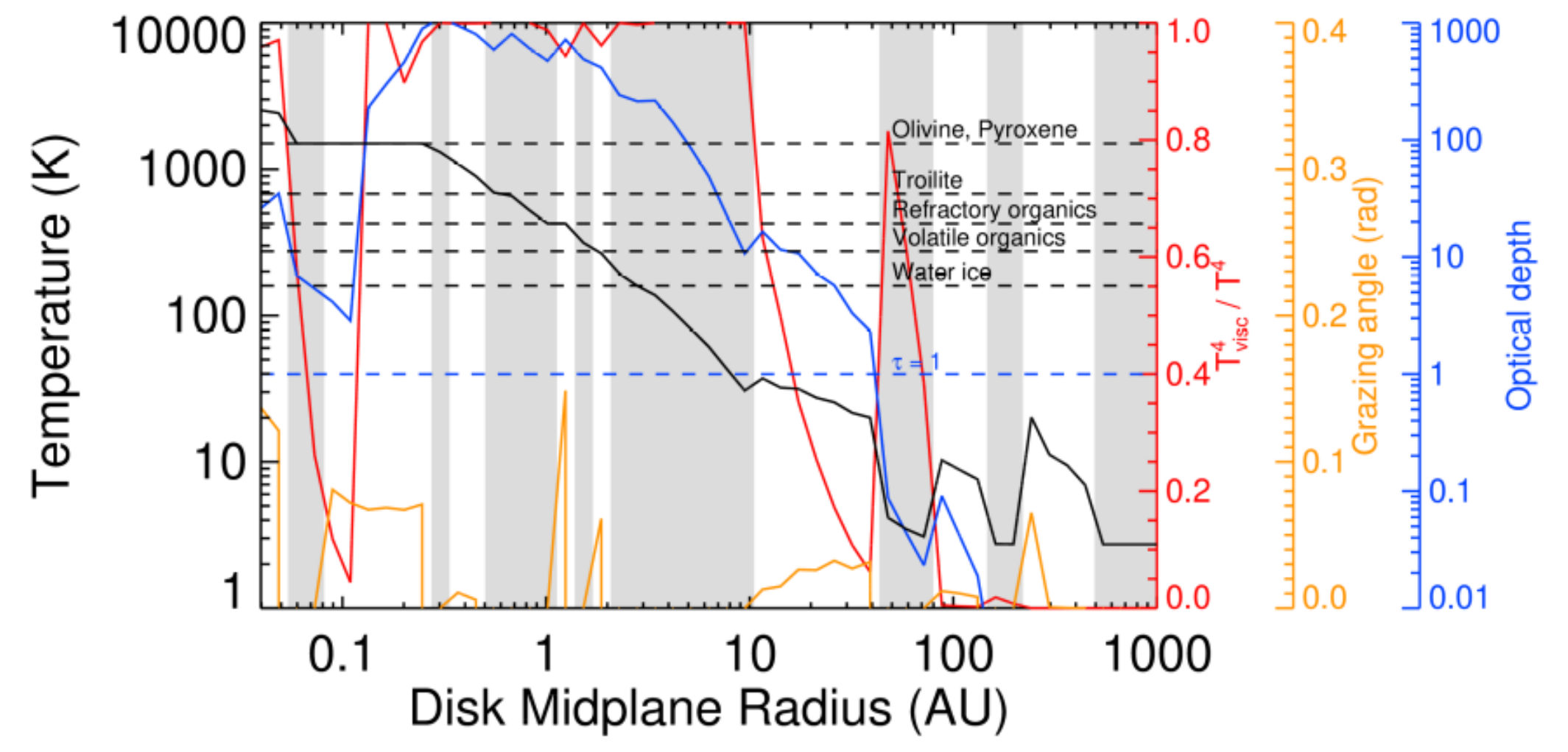


Figure 5 : Mid-plane temperature radial profile after 1 Myr. Shadowed regions in gray. The ratio of the viscous heating contribution over the total heating is presented in red, the grazing angle profile in yellow and the optical depth profile in blue.

- Most of the **inner disk is self-shadowed** (up to the heat transition barrier)
- Sharp edge and positive temperature gradient at the heat transition barrier
- **Enlarged snow and sublimation zones at the temperature plateaux**

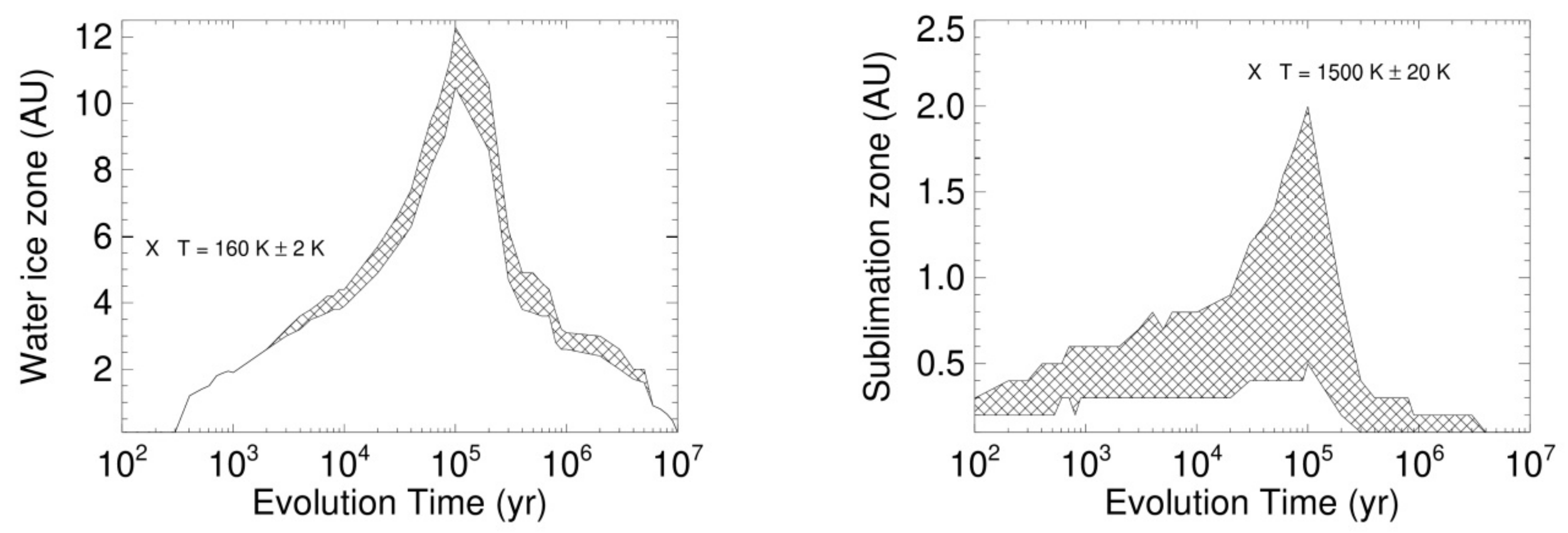


Figure 6 : Time evolution of the snow region and silicates sublimation zone.

Sublimation lines and therefore traps migrate outward at first and inward after the end of the collapse phase

Planetary migration maps

Torques are very sensitive to Σ and T gradients.

Disk formed by collapse of the molecular cloud.

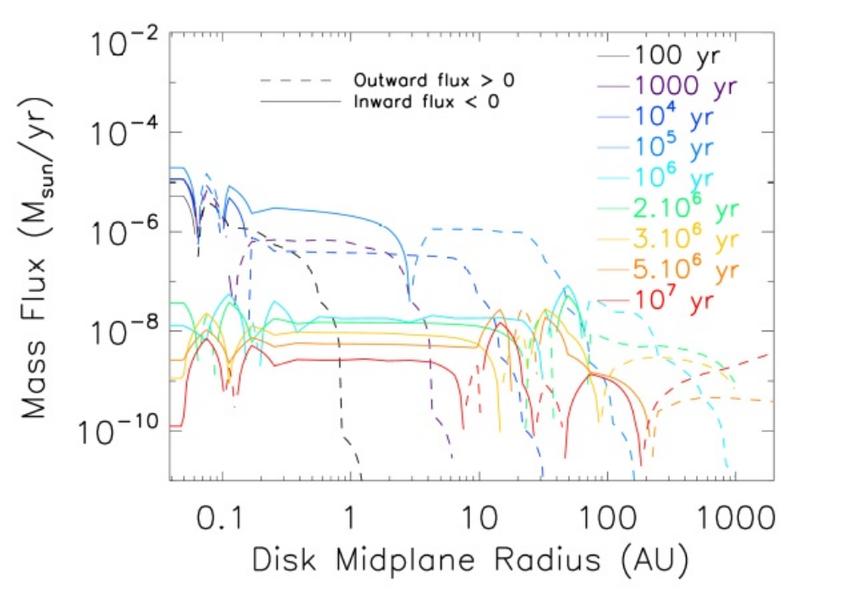
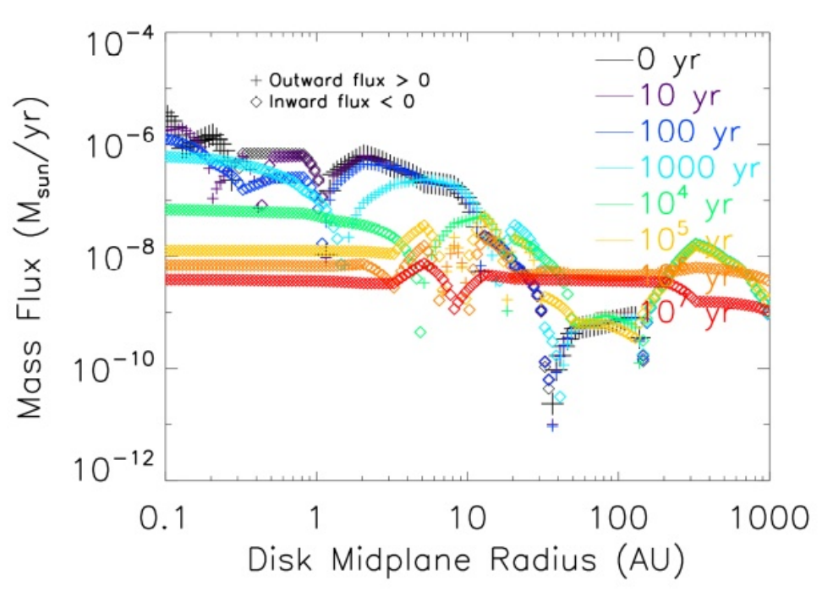
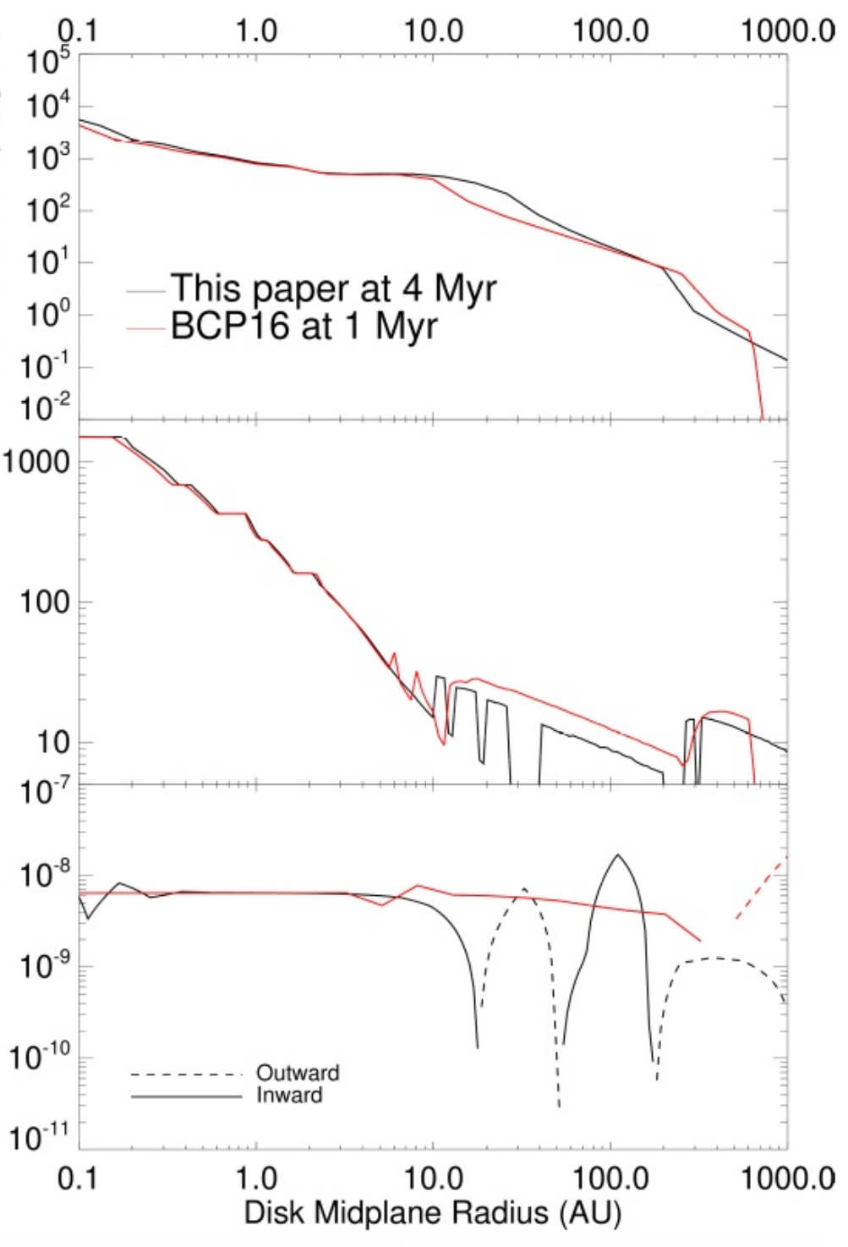


Figure 7 : Evolution of the mass flux profile.

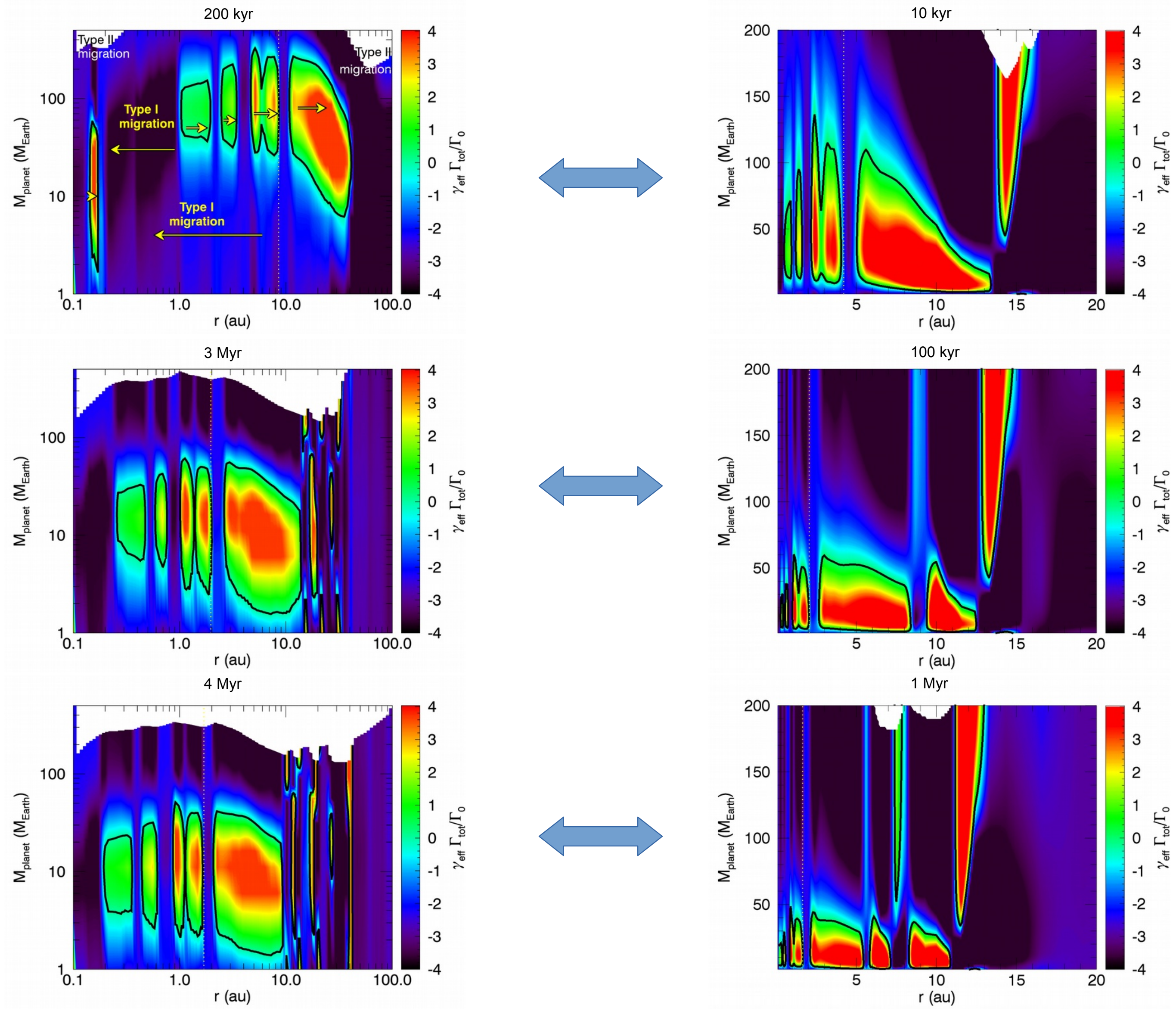


Disk evolved from an initial MMSN.



Assuming that **disks of similar ages have similar mass accretion rates**, we can rescale the MMSN timeline to fit the timeline of the disk formation by collapse.

The evolution from the disk formation to an MMSN-like stage seems to require about 2-3 Myr. Though the MMSN evolves faster, **disks of similar mass accretion rates will present similar planet traps and deserts at the sublimation lines and heat transitions**



Disk evolved from an initial MMSN.

Figure 8 : Migration maps showing the direction and intensity of the migration of planetary embryos wrt location and mass.

Super-Earths can get trapped very early in the inner disk.

Conclusions

- **The disk forms in 170 kyr and reaches an MMSN-like stage in 2-3 Myr**
- **Planet traps follow the sublimation lines → « trapped migration »**
- **Modeling the disk formation by the cloud collapse allows to understand the multiple trapping possibilities in the first million years of planet formation**

Perspectives

- Photoevaporation
- Planetary growth, multiple-planet interactions
- Variable turbulent viscosity, deadzones
- Separate treatment of gas and dust flux

https://perso.imcce.fr/kevin-baillie/migrationmap_movie.html

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