Synthetic populations of protoplanetary disks

CaSToRC HPC National Competence Center Seminar Series

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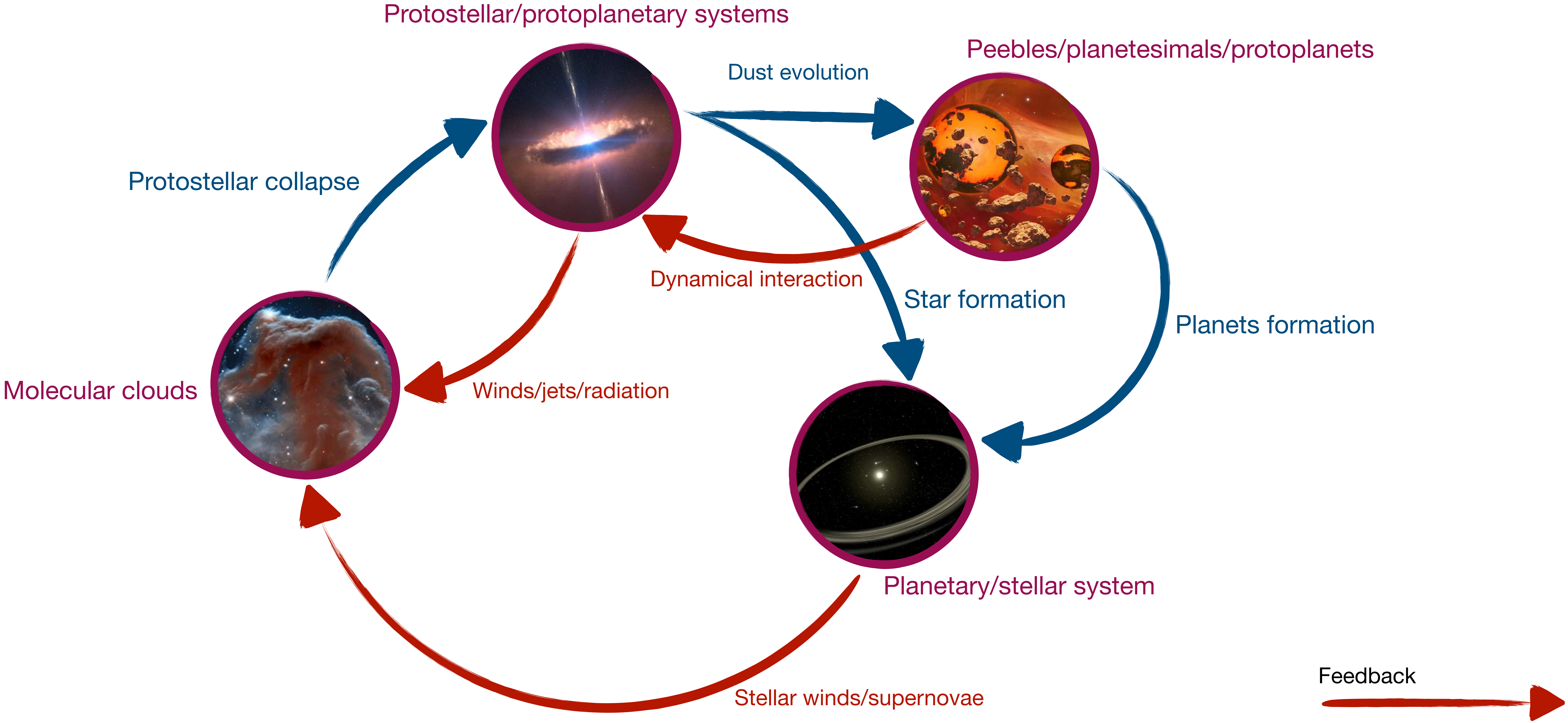
Ugo Lebreuilly 26/04/2022

Introduction The interstellar cycle



Protostellar/protoplanetary systems

Dust evolution

Peebles/planetesimals/protoplanets

Protostellar collapse

Dynamical interaction

Star formation

Planets formation

Molecular clouds

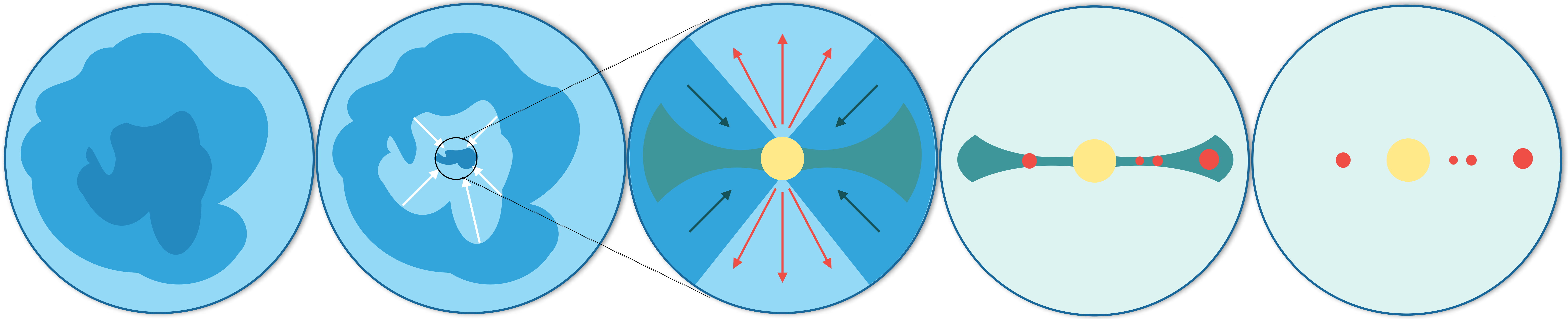
Winds/jets/radiation

Planetary/stellar system

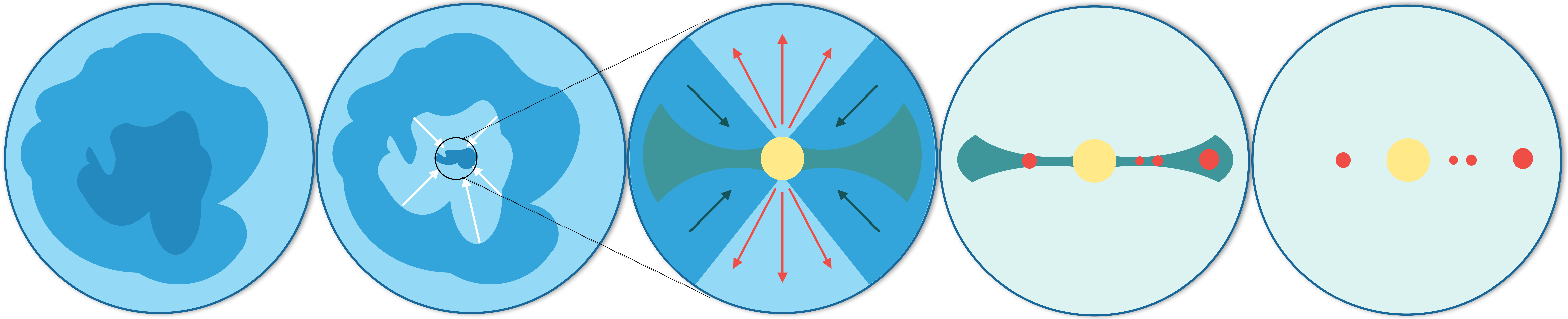
Stellar winds/supernovae

Feedback

Introduction The protostellar collapses



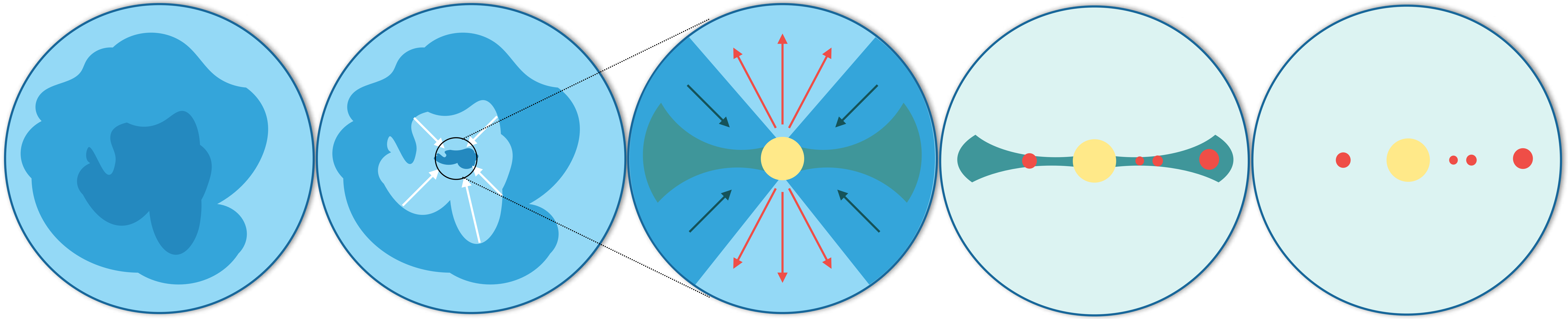
Introduction The protostellar collapses



Jeans mass (Jeans 1902)

$$M_{\text{core}} \geq \left(\frac{5k_{\text{B}}T_{\text{g}}}{\mu_{\text{g}}m_{\text{H}}\mathscr{G}}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{-1/2}$$

Introduction The protostellar collapses

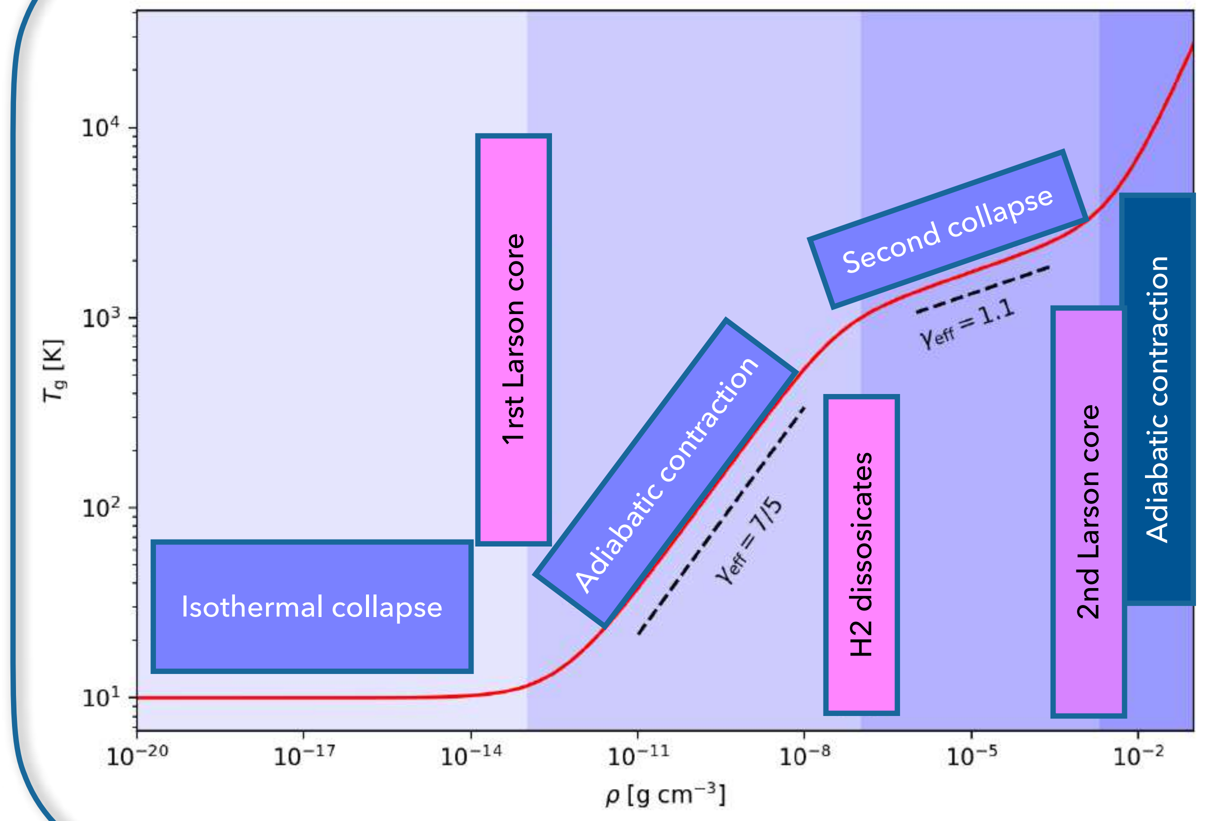


Free-fall timescale

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32\mathcal{G}\rho_0}}$$

10 000 - 100 000 yrs

See Larson 1969



0 → 100 000 yrs

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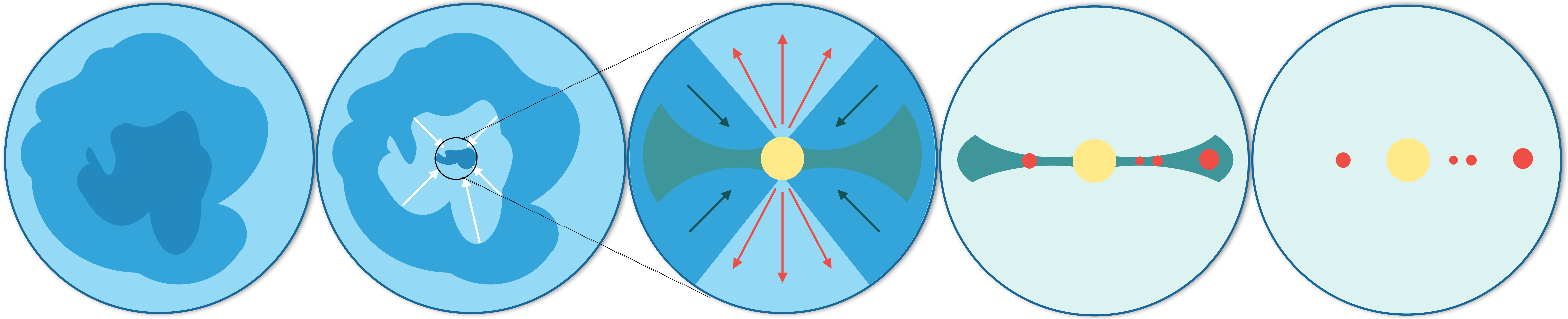


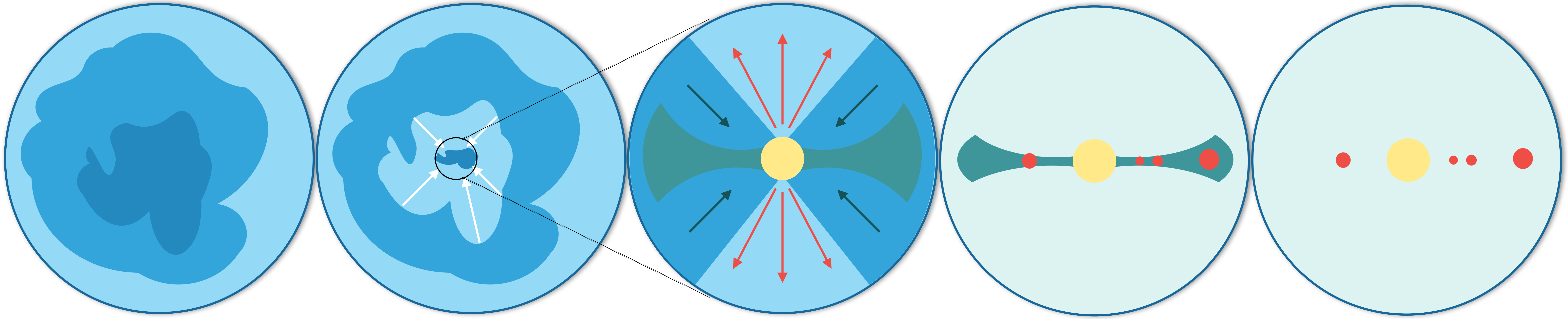
Accretion + Ejection

Protoplanetary disk

Matter ejected at the poles (winds and jets)

10 000 - 100 000 yrs

Introduction The protostellar collapses



Protoplanetary disks

Quasi keplerian Gaz + dust

Planet formation by coagulation and fragmentation of dust grains

Later evaporation of the disk (winds? Photo-evaporation)

1 000 000 - 50 000 000 yrs

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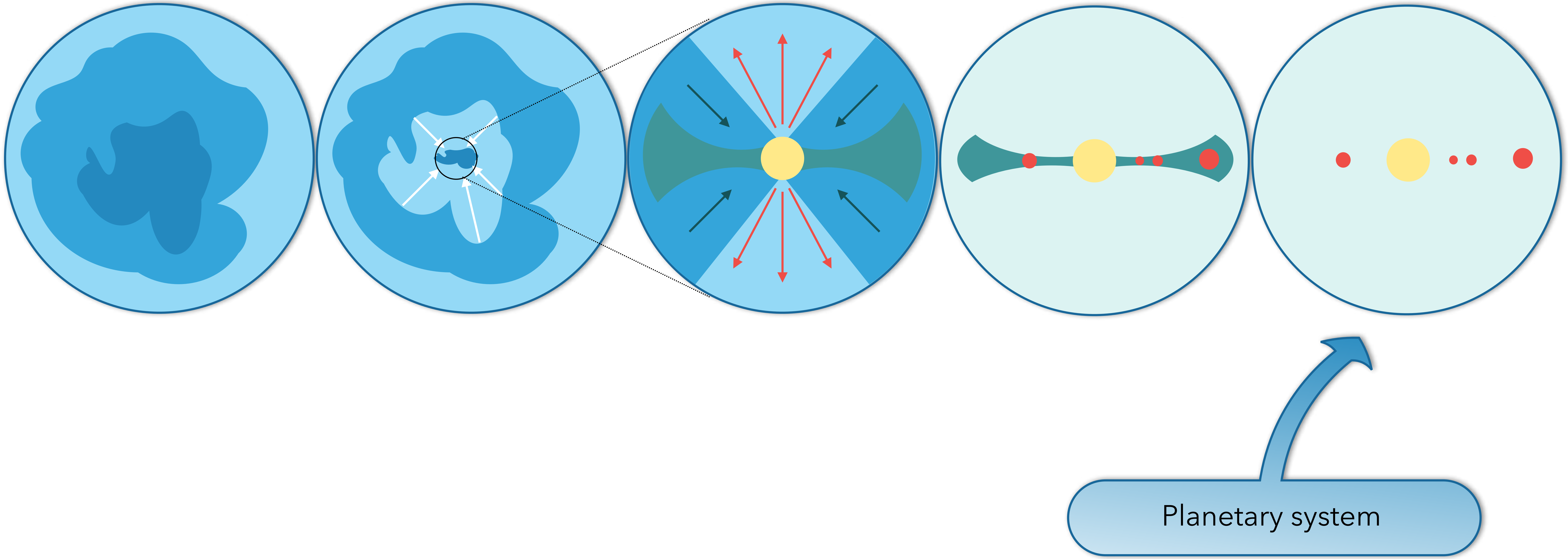
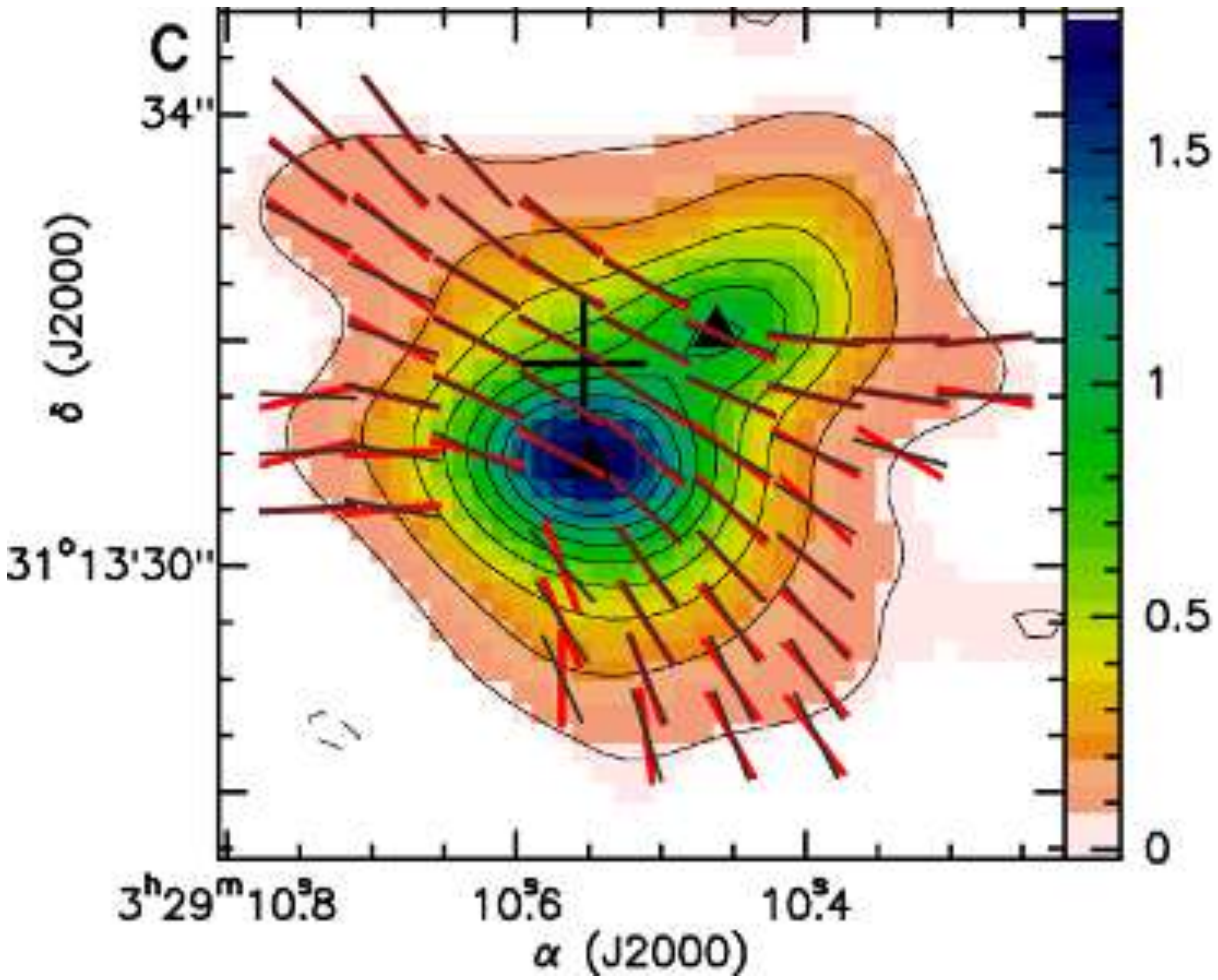


Planetary system

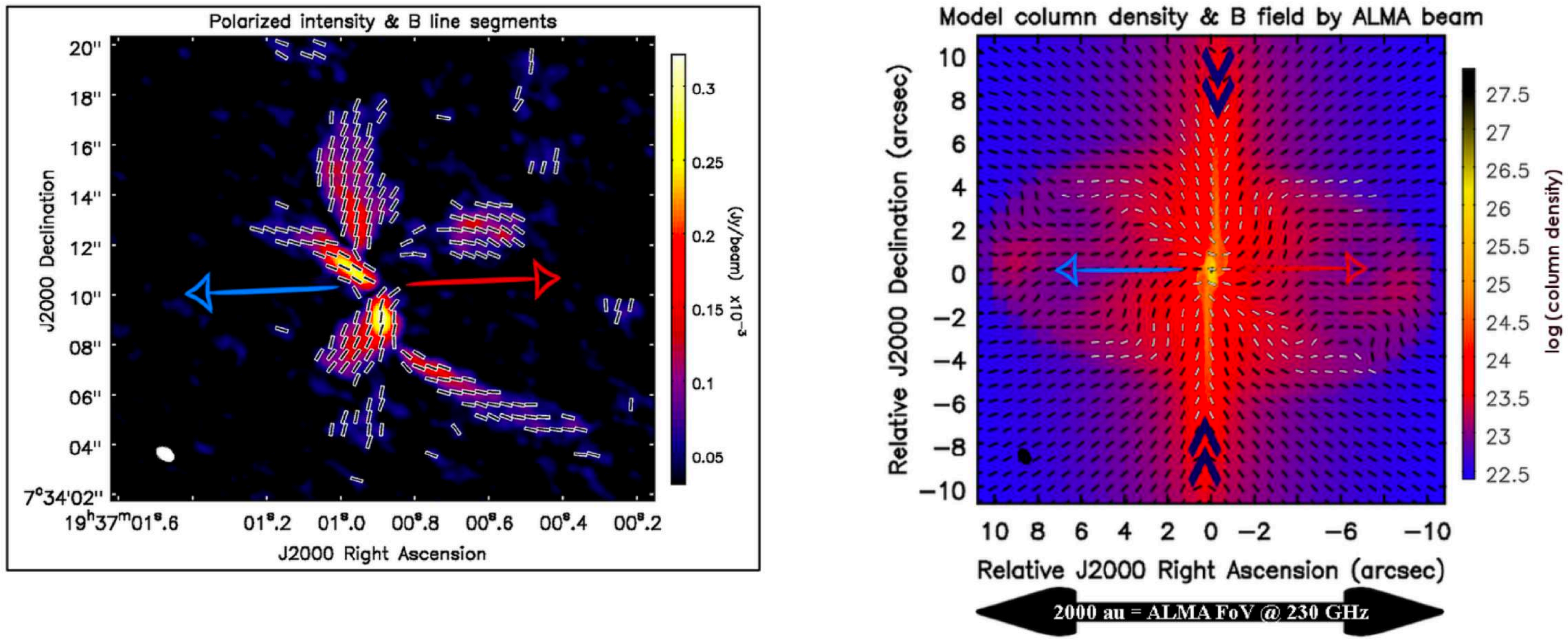
Introduction Magnetic fields

Hourglass magnetic field



NGC 1333 IRAS 4A (Girart et al., 2006)

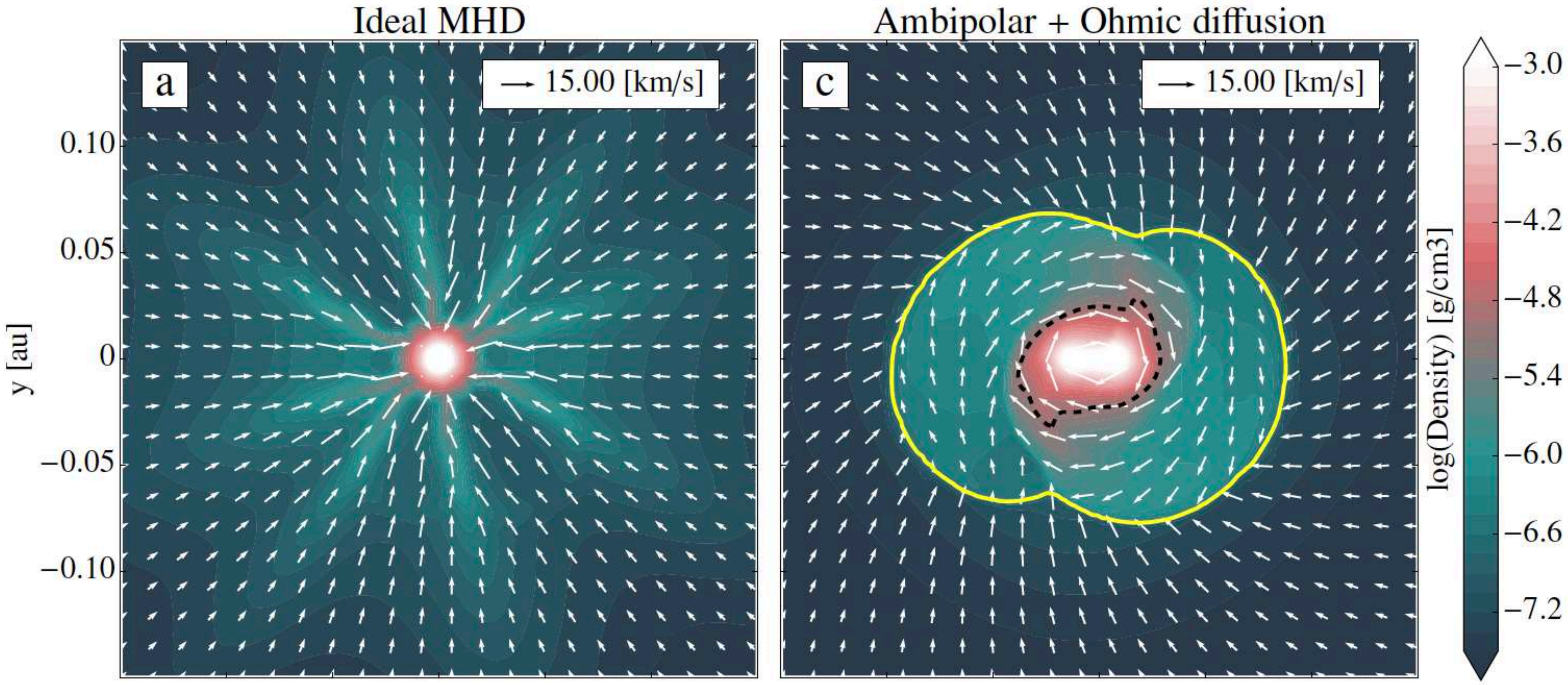
Magnetically regulated collapse



Protostar B335 (Maury et al., 2018)

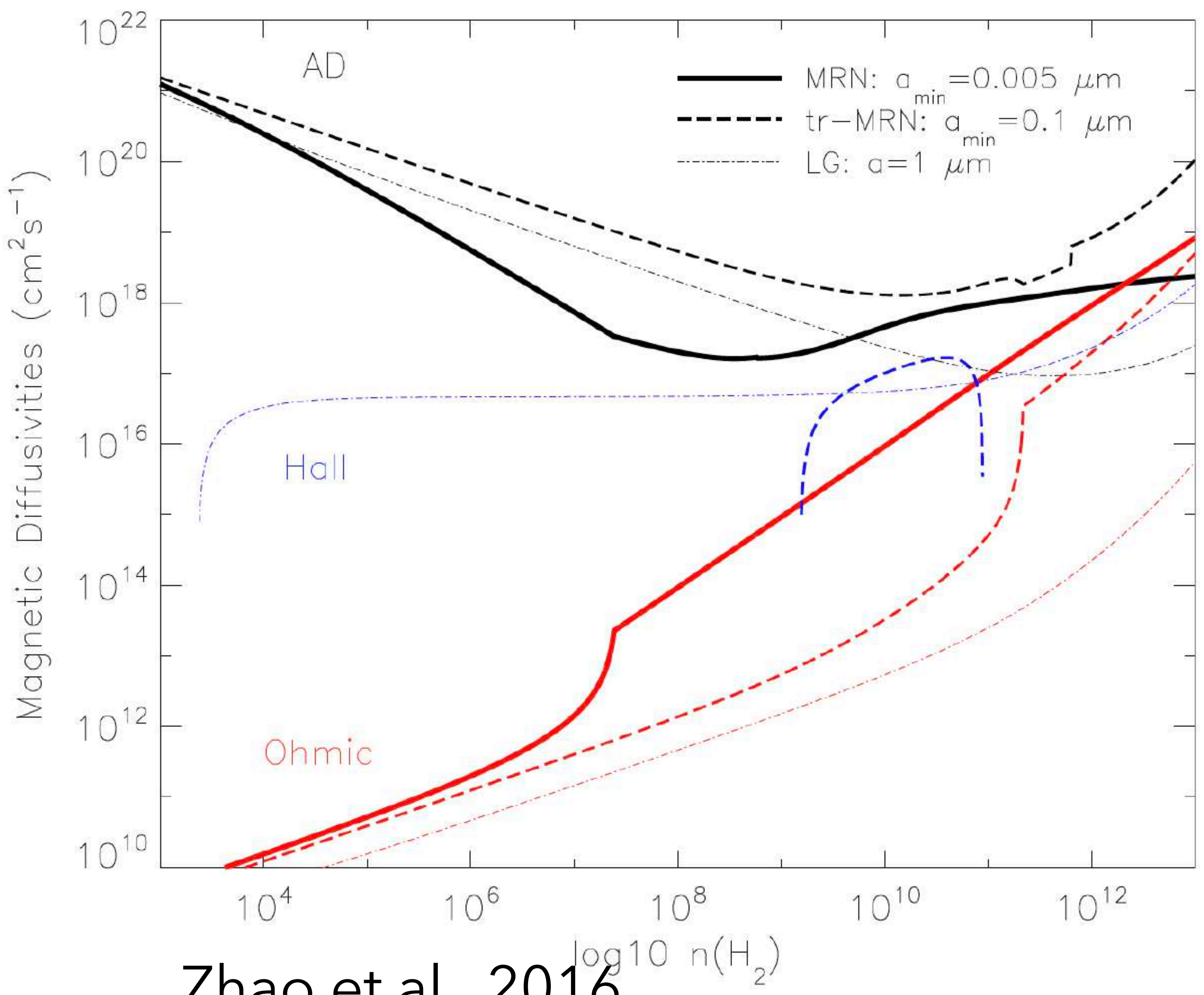
Introduction Magnetic fields

Ideal vs non-ideal MHD



Vaytet et al., 2018

Magnetic diffusivities (resistivities)



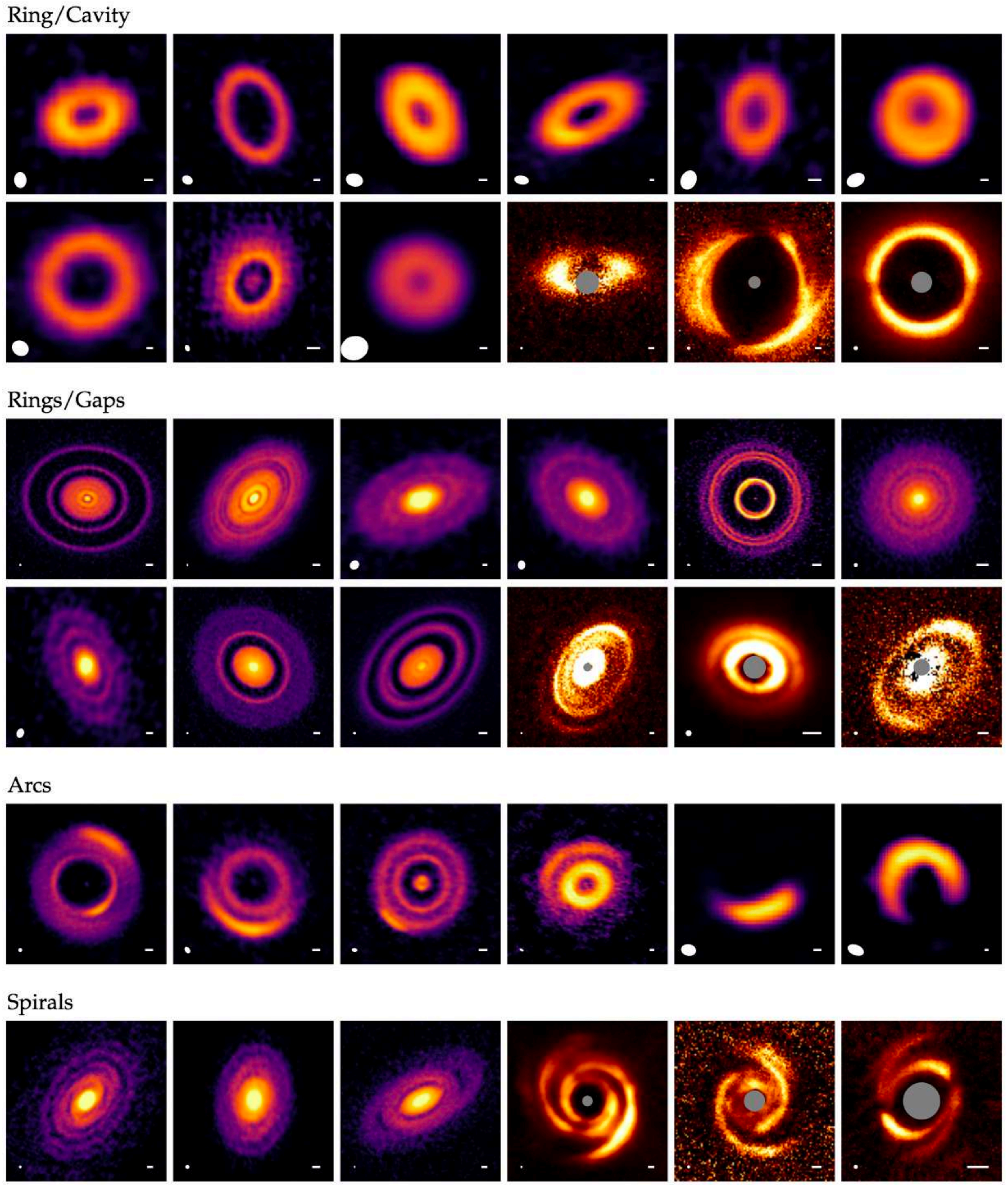
Zhao et al., 2016

Introduction Stars do not form alone !

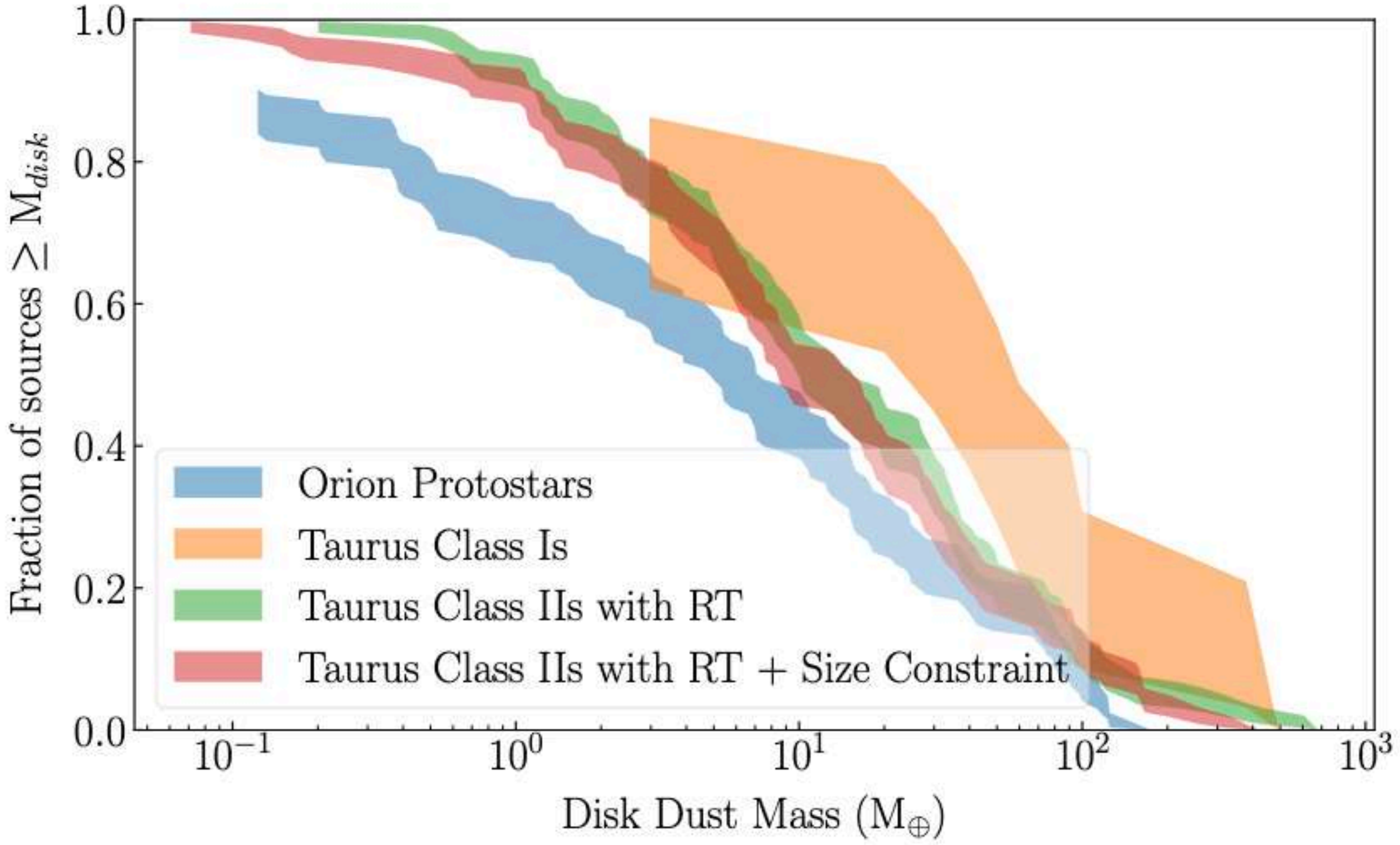
Perseus molecular cloud (Spitzer space telescope)

Stars form in protostellar clumps within massive molecular clouds
-> Spectrum of initial (local) conditions & spectrum of stars
-> Interactions between young stars/disks

Introduction Disks are very diverse !



DSHARP survey - Andrews et al., 2018



VANDAM survey - Sheehan et al., 2022

PRACE Synthetic populations of protoplanetary disks

Goals

1. To generate synthetic self-consistent populations of disks and constrain (statistically) the initial conditions of planet formation
2. To predict the internal structure (gas, temperature, magnetic field) of protoplanetary disks
3. To predict the dust content (in mass and size) of protoplanetary disks
4. To provide a physical interpretation of young disk observations

Methods

-Several clump collapse calculations with different initial conditions (magnetic field, Mach number, size, mass) and physical processes (non-ideal MHD, radiative feedback, dust)

-Rezooms on some specific disks to get the internal structure !

-Synthetic observations with radiative transfer code

Ressources

32.7 million CPU hours (so far 18.3 have been used) on the JUWELS cluster

-1 Run is about 3-4 million CPU hours on ~1000 CPUs.

See Lebreuilly et al., (2021) for a similar previous work

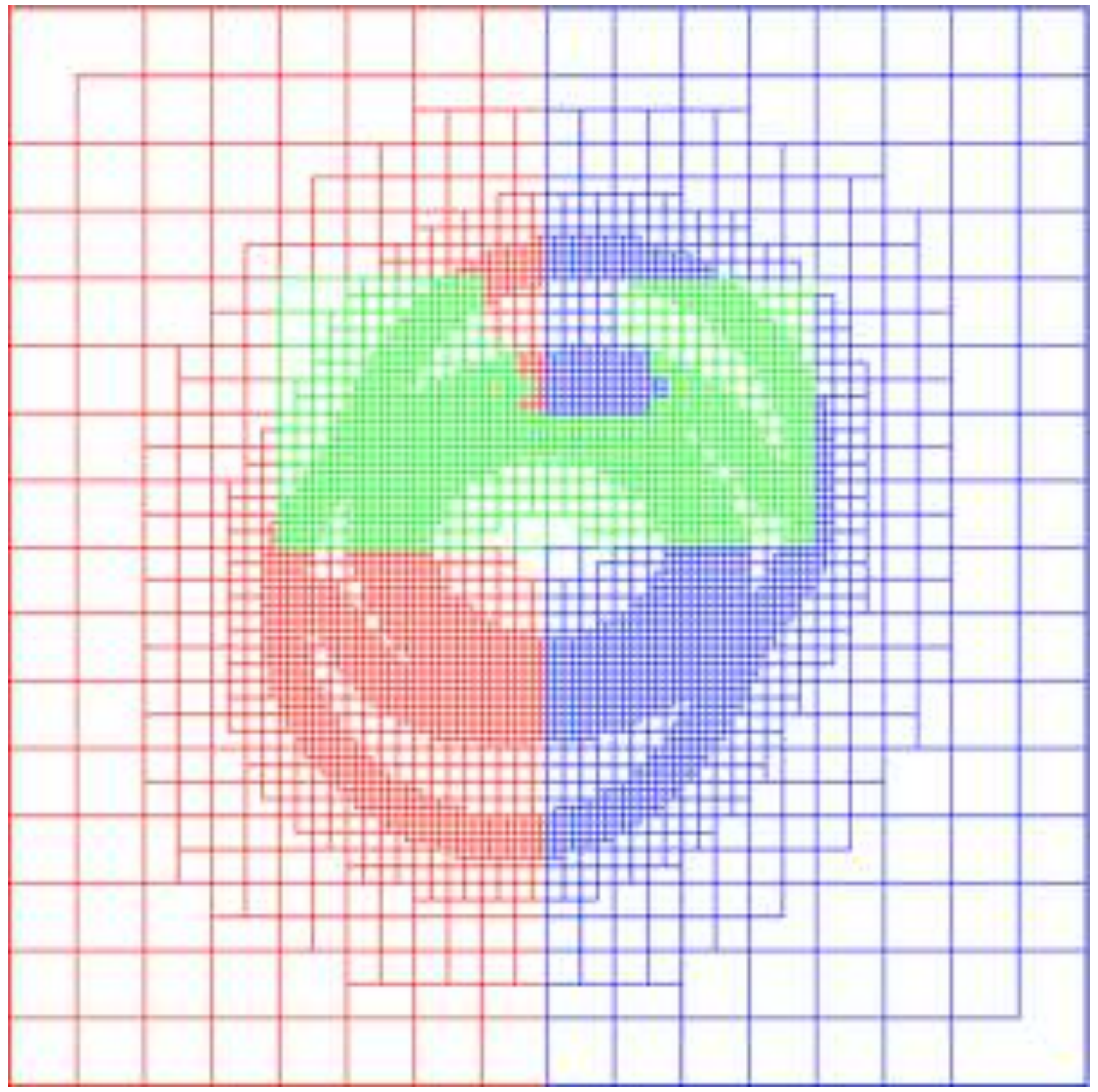
Model RAMSES code (Teyssier 2002)

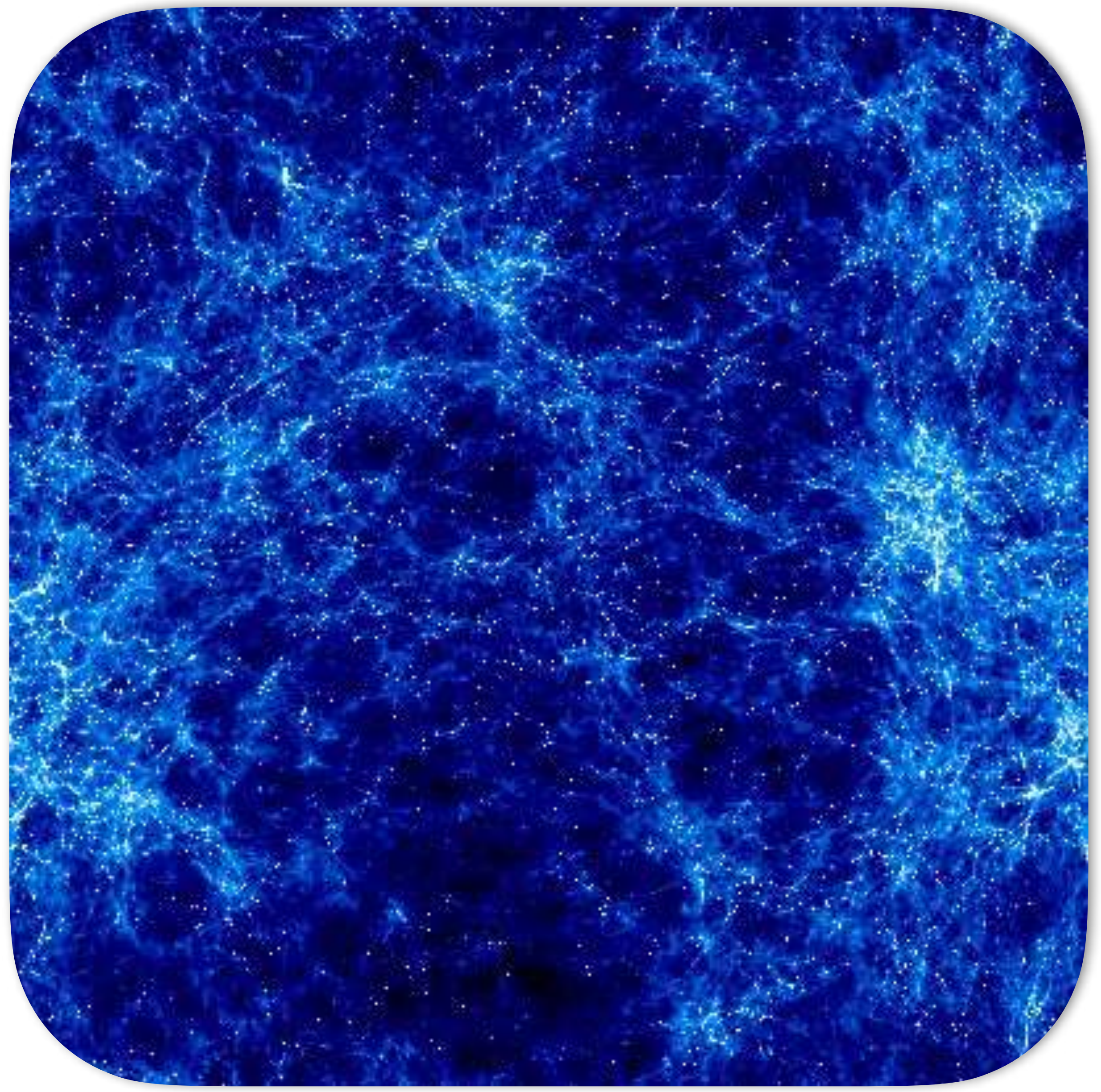
Eulerian code for radiative non-ideal MHD with self-gravity (and dust, see Lebreuilly et al., 2019)

Finite volume Godunov method

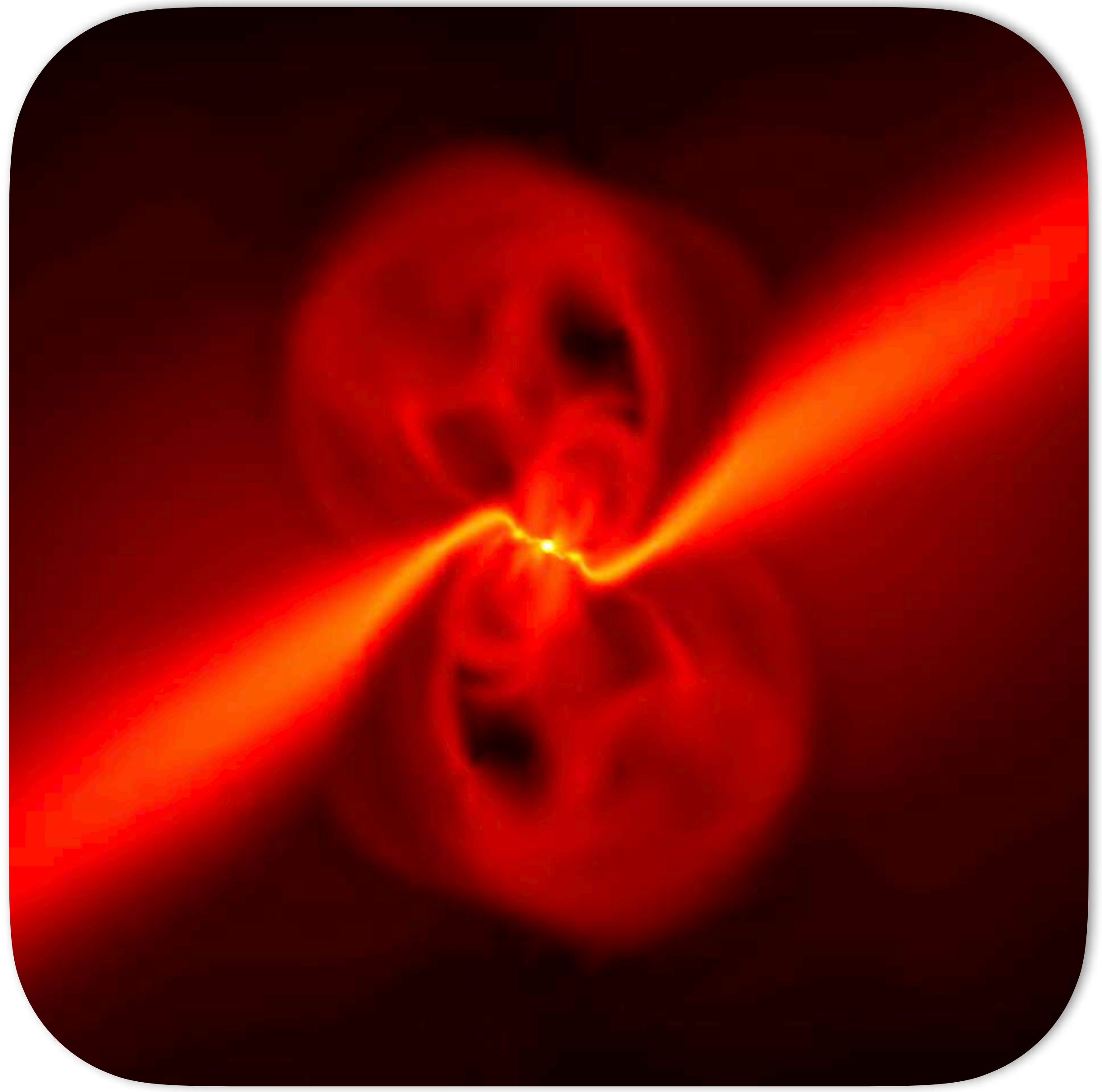
Adaptive mesh refinement grid

Extremely polyvalent code: used for cosmology, star formation, planet formation, galactic dynamics etc..





Cosmology (Horizon projets)
Credits: Romain Teyssier



Star formation
Ex : Lebreuilly et al., 2020 & 2021

Model Protostellar collapse of a massive clump

Collapse of turbulent massive clumps

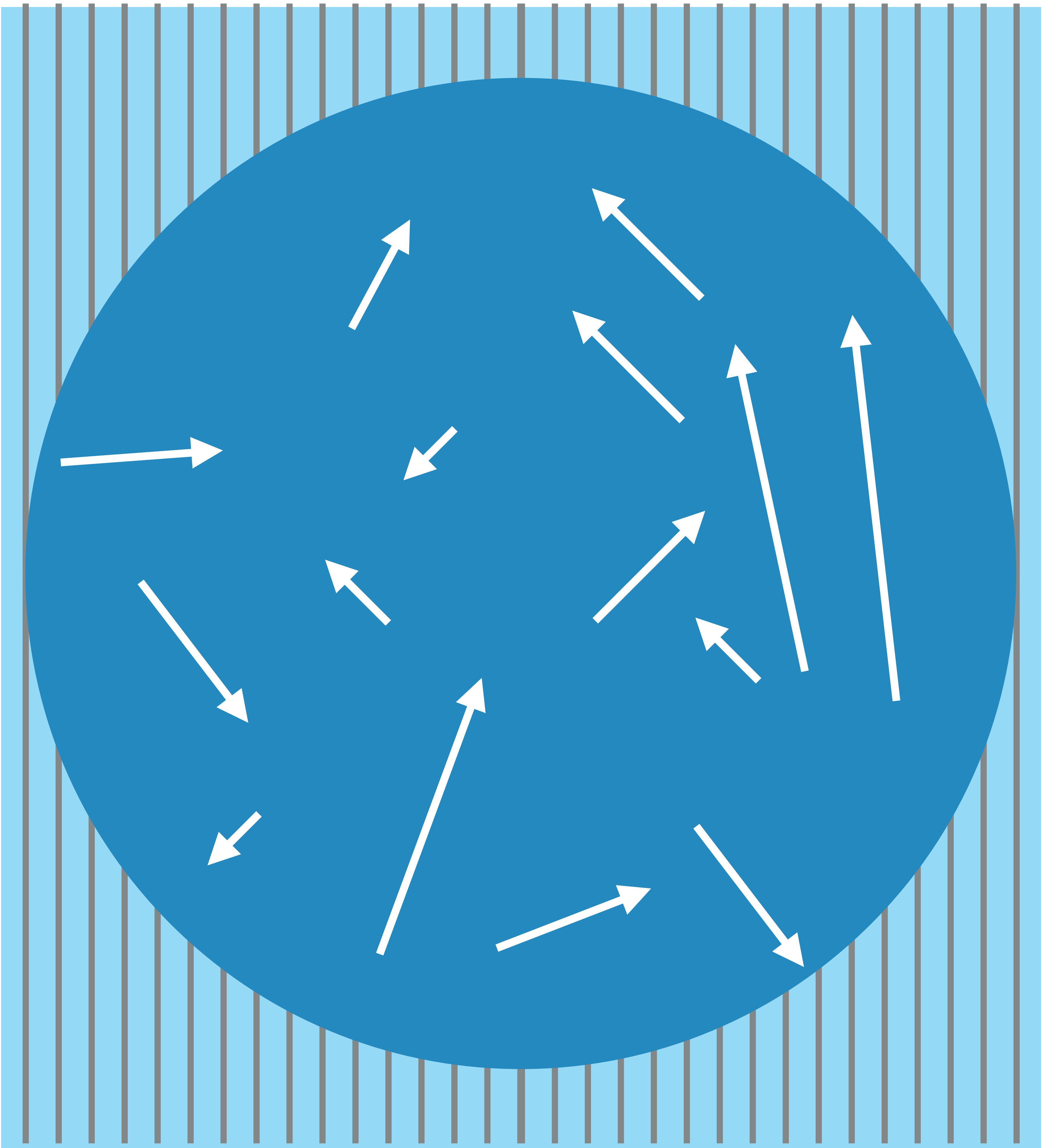
Uniform initial density (~$3 \times 10^{-19} \mathrm{g\ cm}^{-3}$), globally Jeans unstable

Supersonic velocity perturbation (Mach 7)

Threaded by an initial uniform magnetic field

$$\mu = \left(\frac{M_0}{\phi}\right) / \left(\frac{M}{\phi}\right)_c$$

No initial rotation



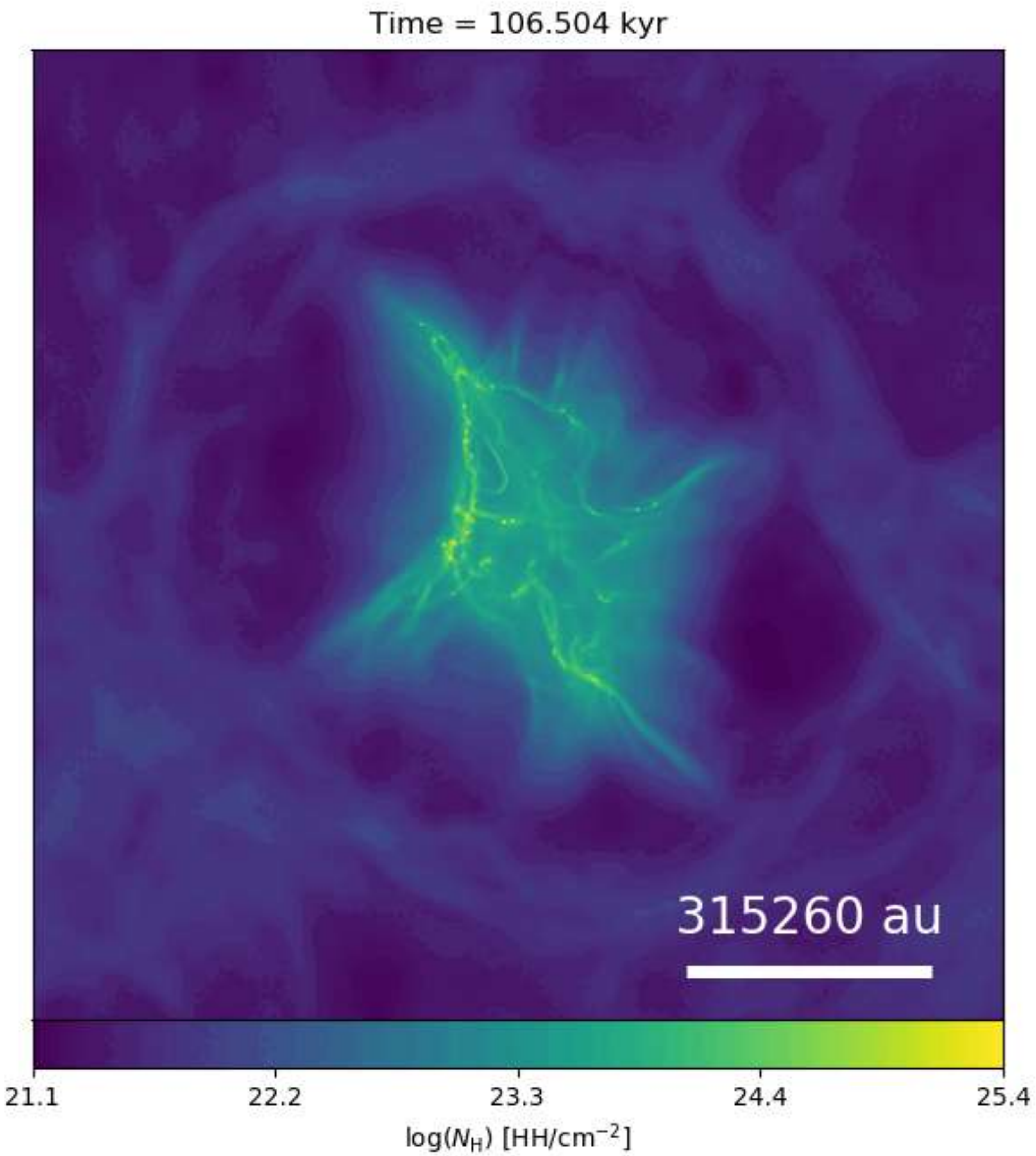
Boss & Bodenheimer setup (Boss & Bodenheimer 1979)

Model Protostellar collapse of a massive clump

-The grid is refined up to 1 astronomical unit (which is 5 orders of magnitude smaller than the whole clump !)

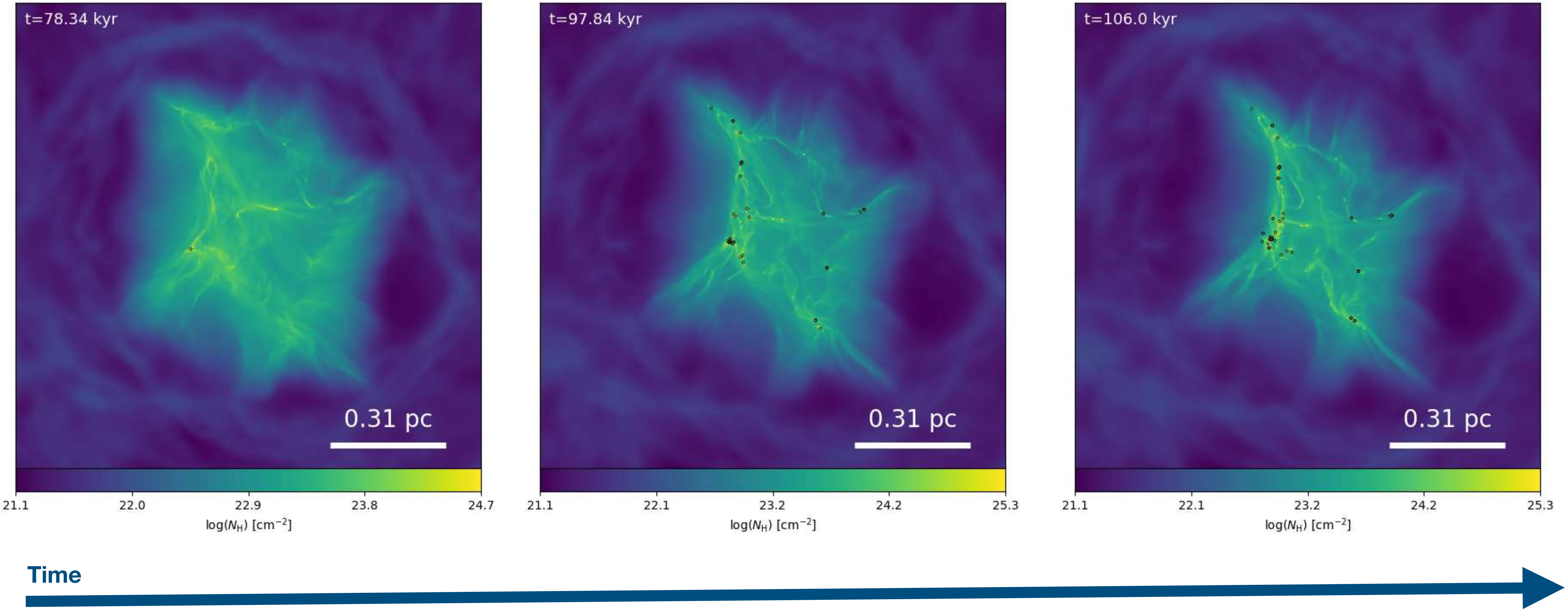
-Star are represented by sink particles and are formed above a density threshold

-Disk naturally form from angular momentum conservation around protostar and we form a population of disks (>30 and up to 100) for each calculation.

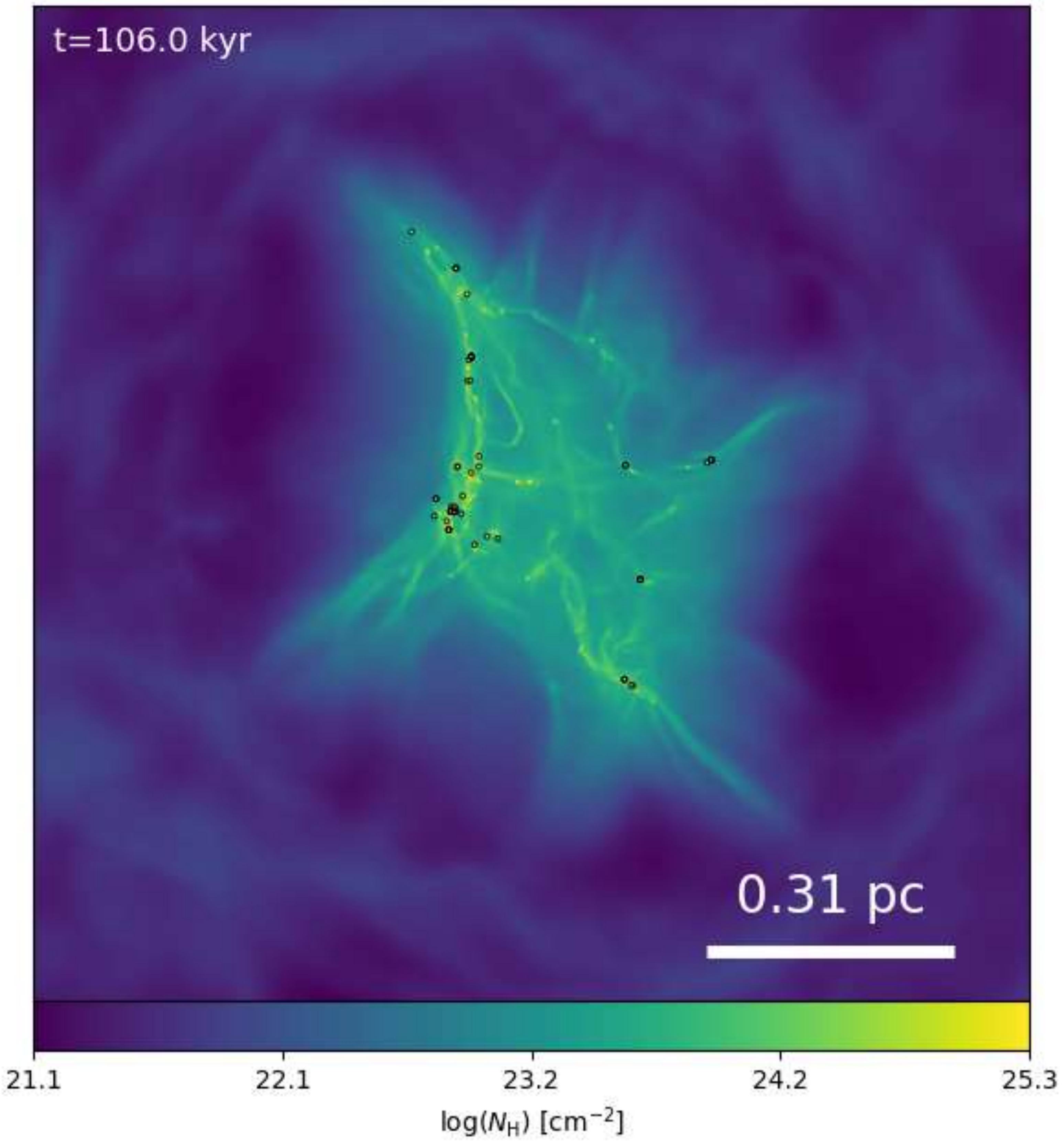


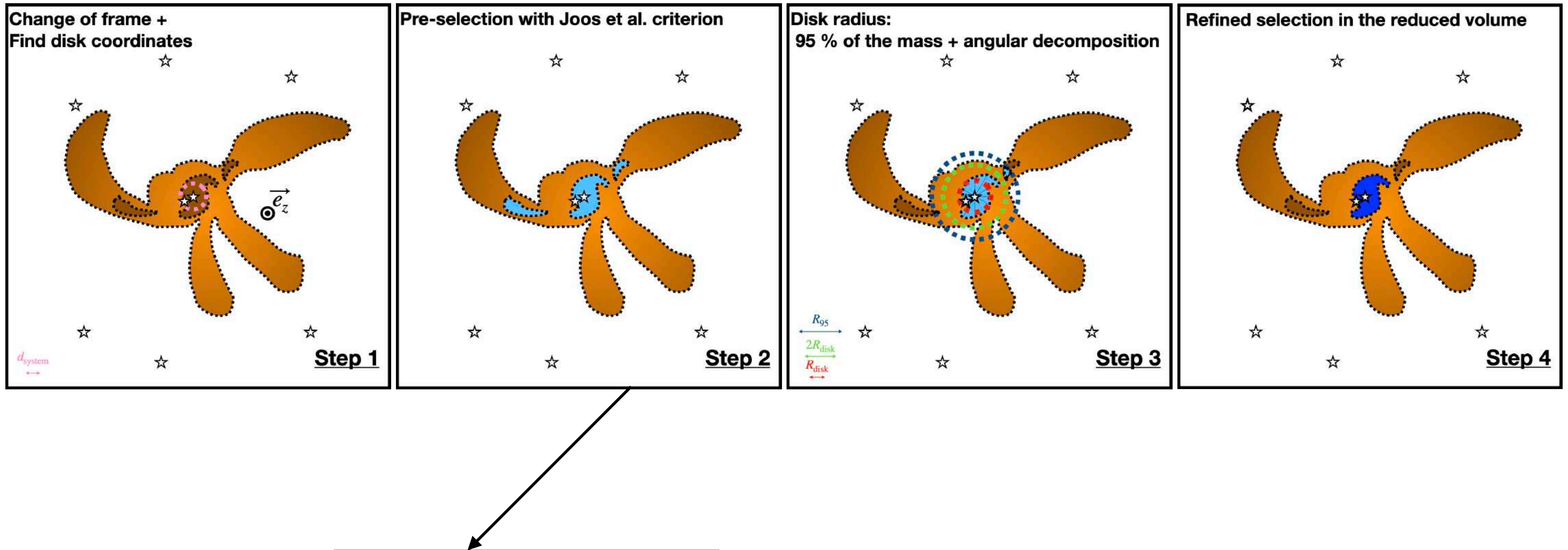
Results Fiducial run NMHD-F01

Run NMHD-F01 : Non ideal MHD run with a relatively strong magnetic field (mass-to-flux 10)



Results Extracting the disks





$$v_\phi > 2v_r$$

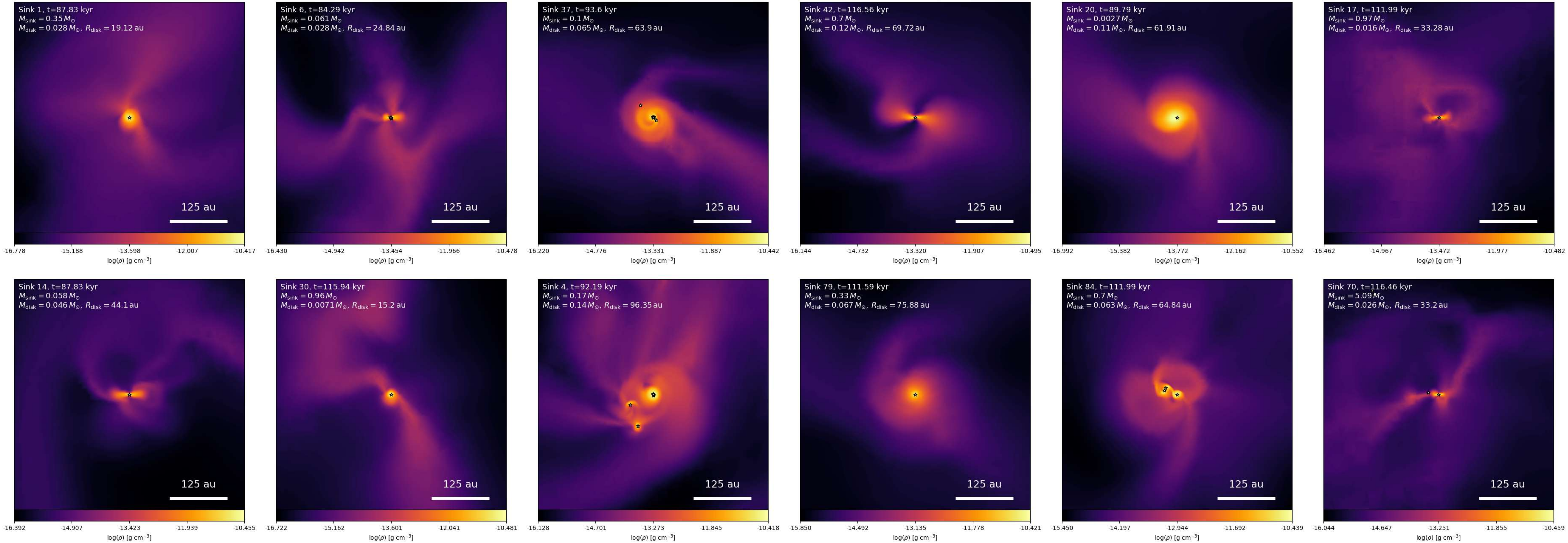
$$v_\phi > 2v_z$$

$$\frac{1}{2}\rho v_\phi^2 > 2P_{\rm th}$$

$$n > n_{\rm thre} = 10^9\ {\rm cm}^{-3}$$

Joos et al., 2012

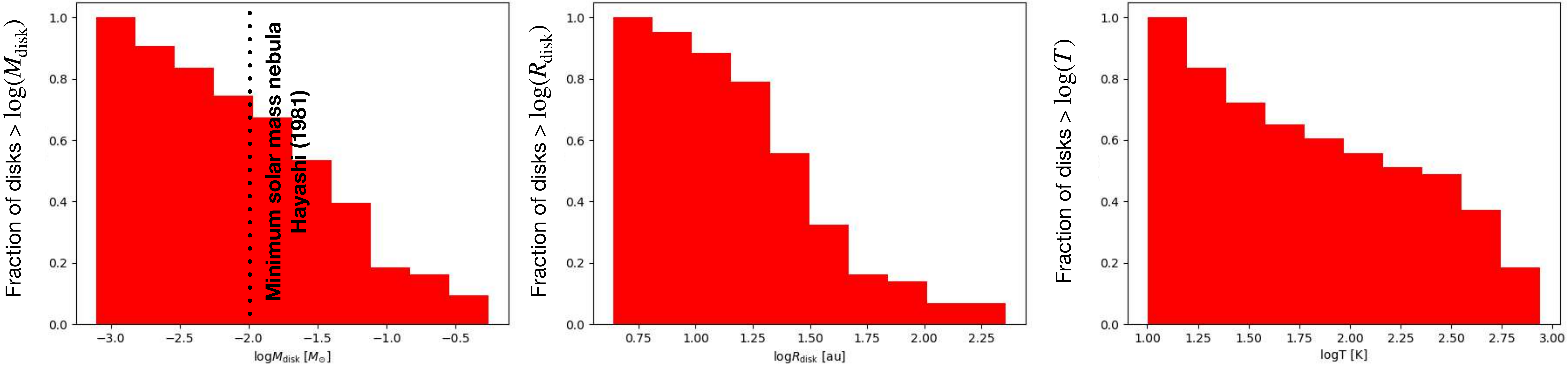
Results Extracting the disks



Commonly observed features:

Spirals, non axi-symmetric streamers, multiple systems, flybys

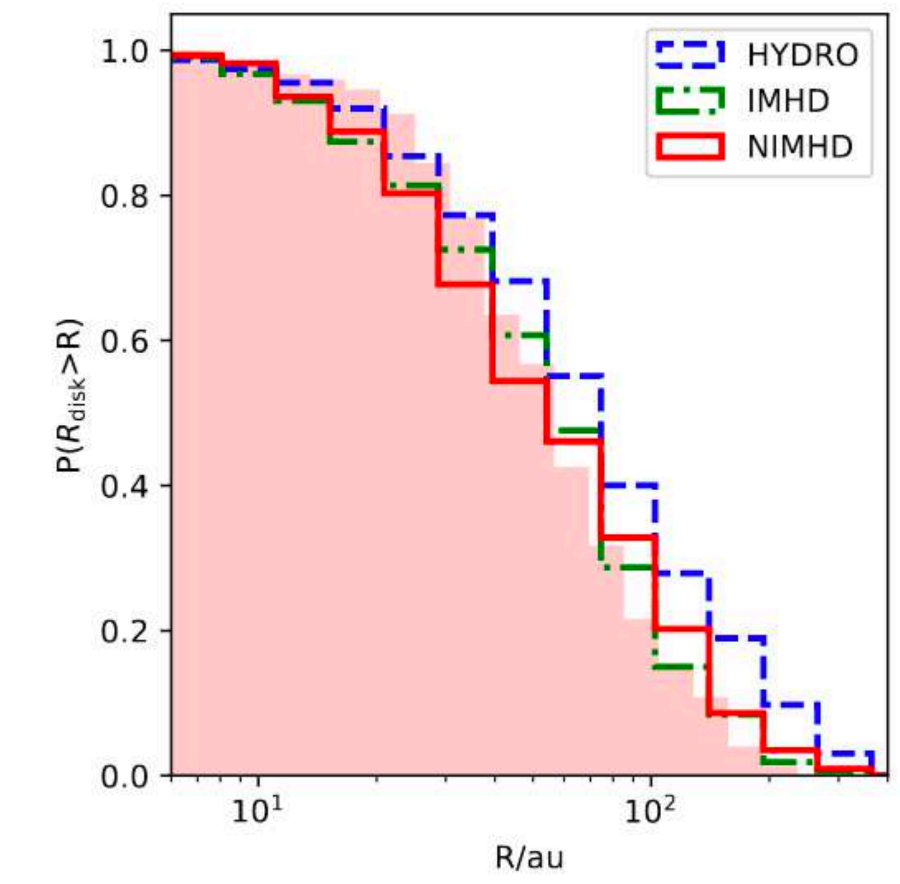
Results Disk populations



Our disks are

- Massive (enough to form planets) which suggest early formation
- Compact (as are observed ones!) because of magnetic braking
- Hot (half of them >100 K), the temperature is controlled by the radiation from the central star

But how these properties depend on the initial cloud and physics included ?

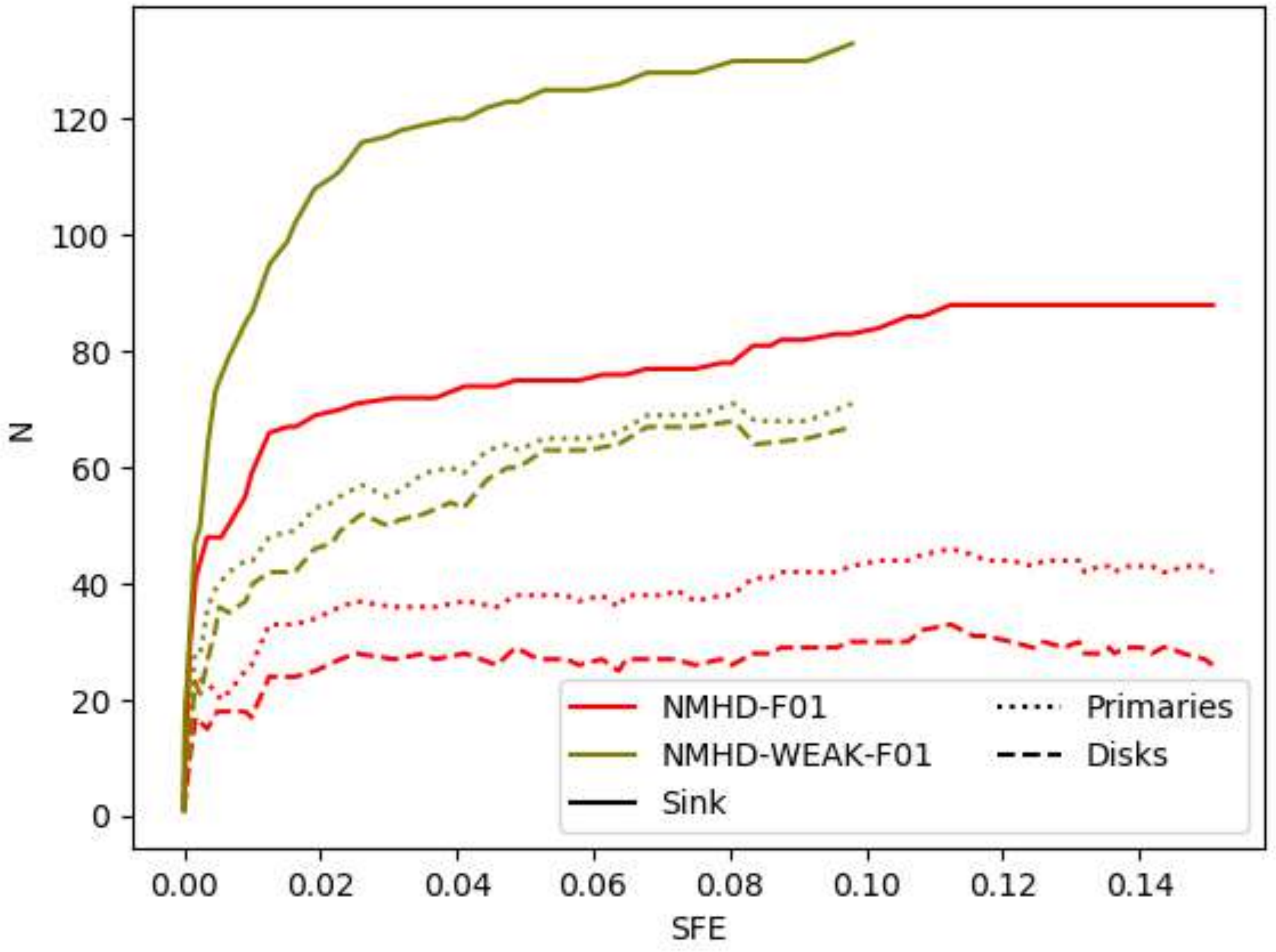


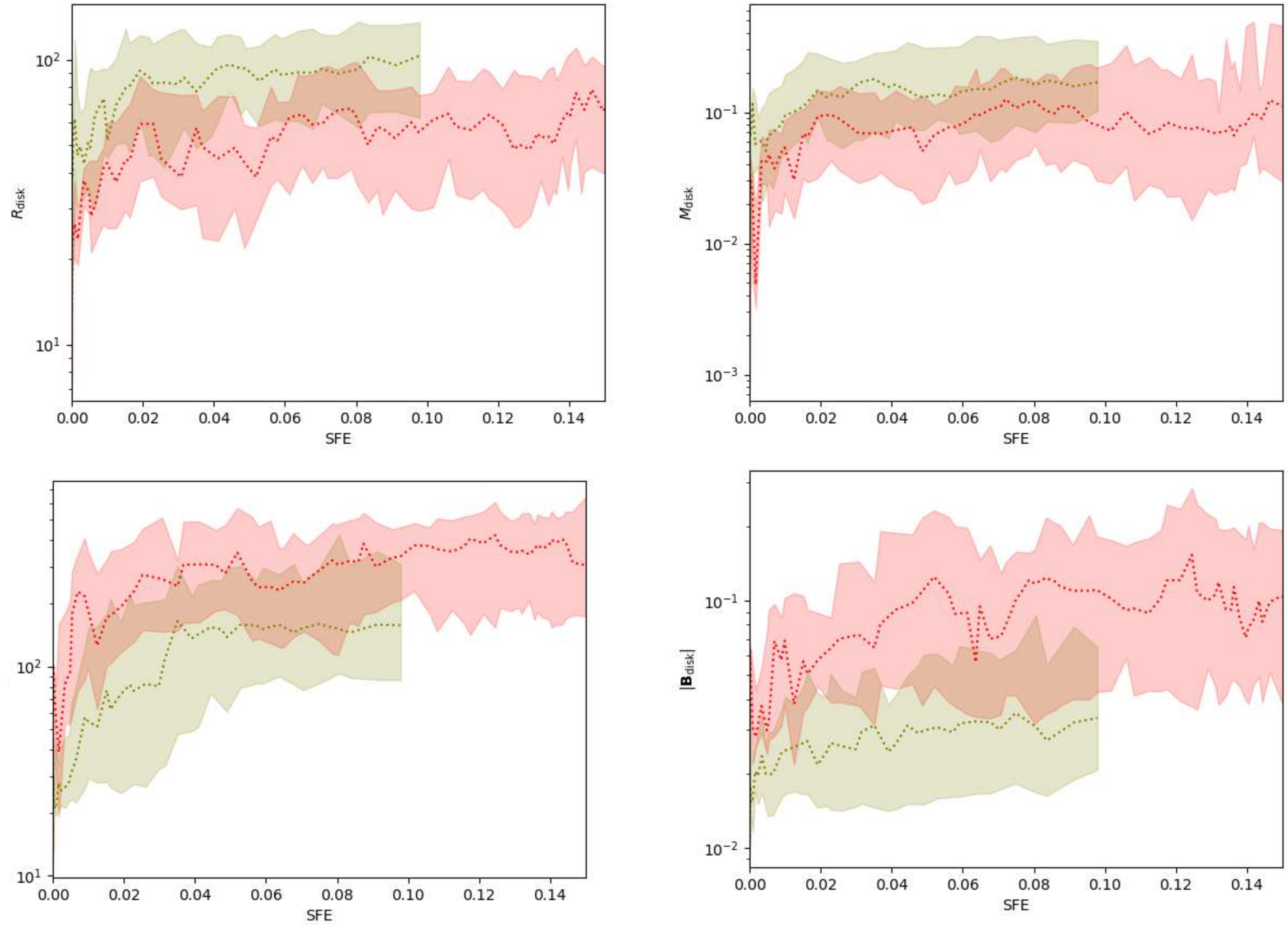
See Lebreuilly et al., (2021)

Results Impact of the magnetic field

Strong vs weak field

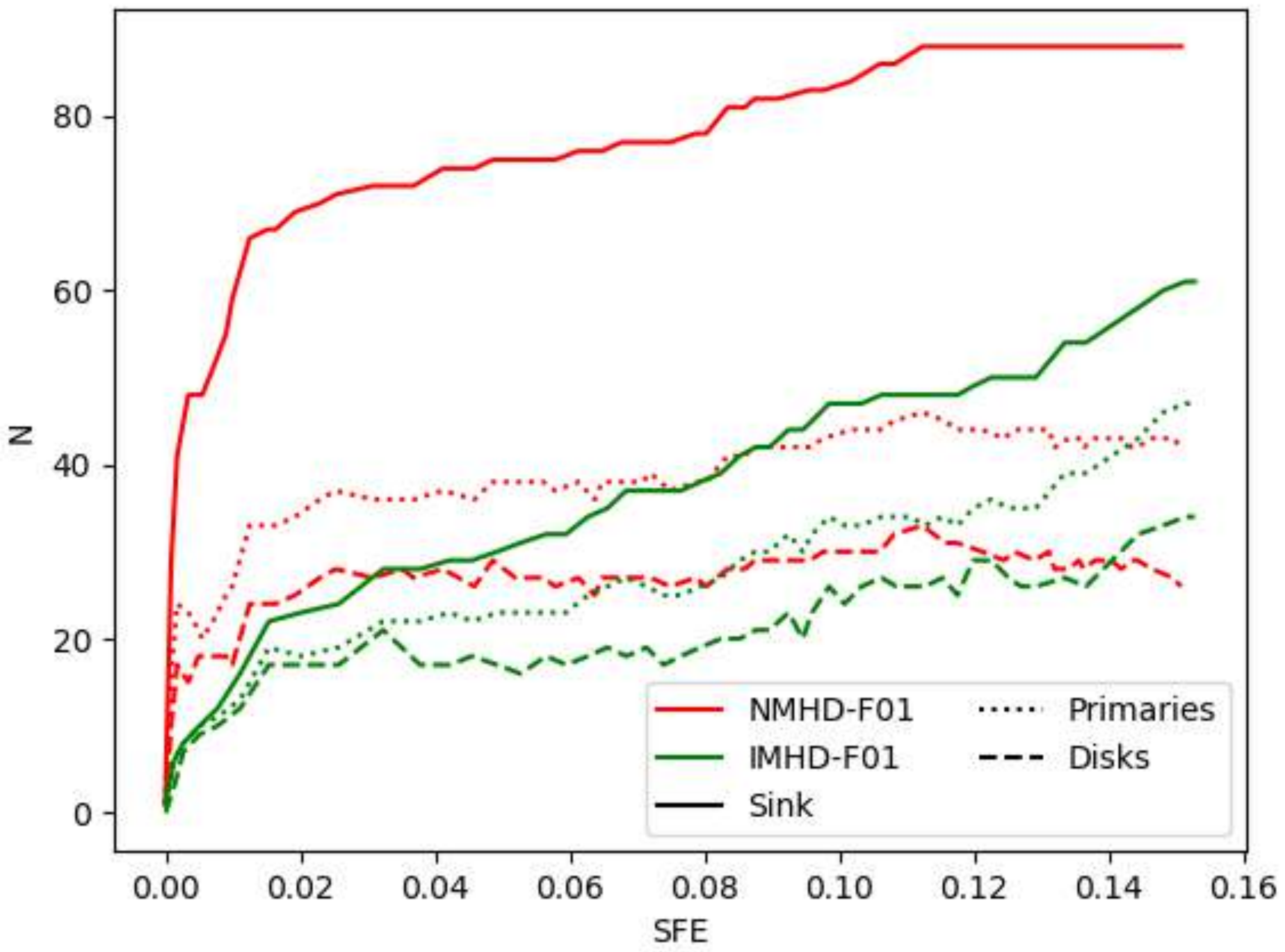
Weak field = Strong field / 5

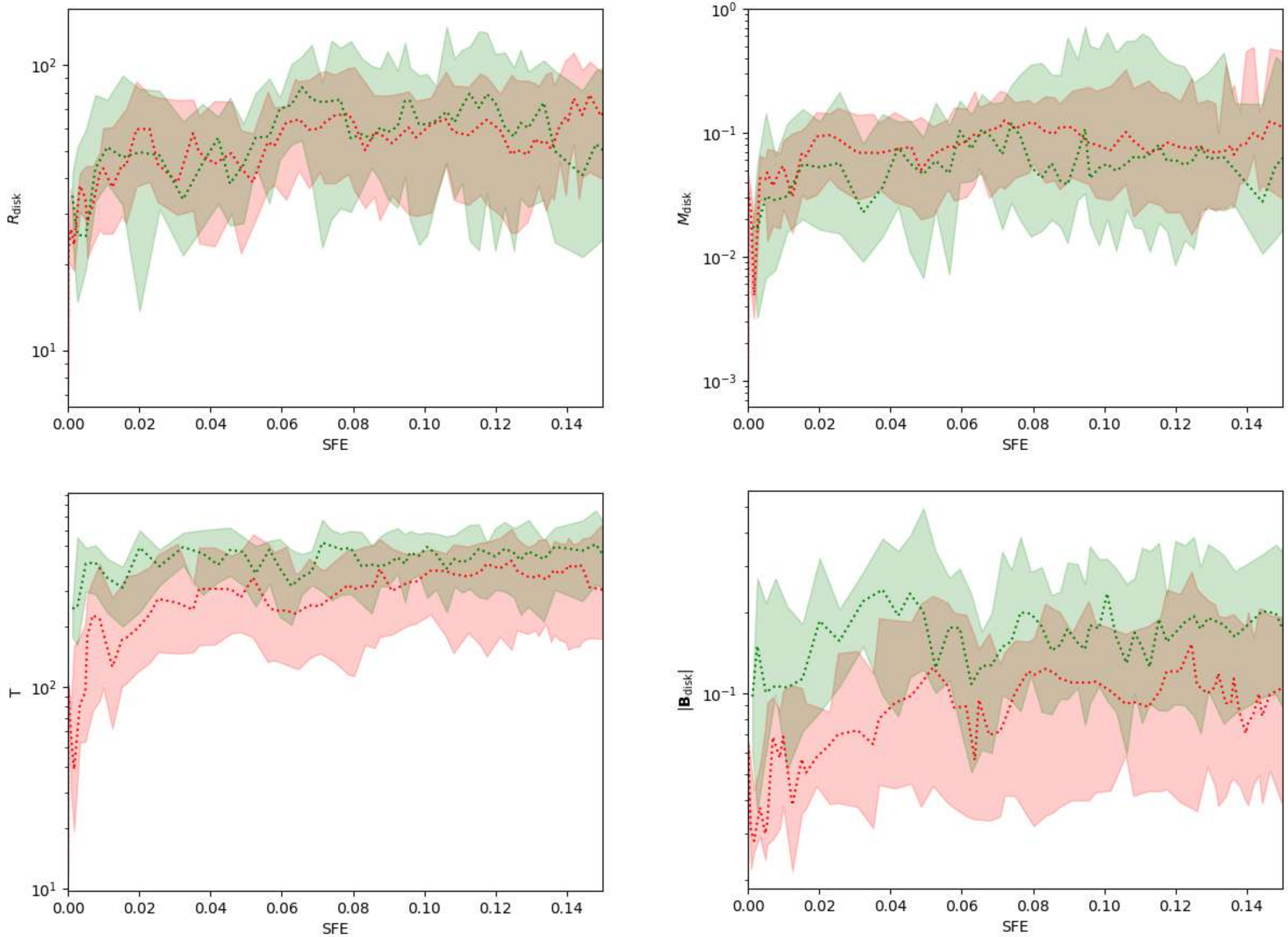




Results Impact of the magnetic field

Ideal MHD vs non ideal MHD





Conclusion

A. We are successfully forming “self-consistent” populations of protoplanetary disks

B. These populations are in good agreement with observed ones

C. Our disks are massive enough to form solar like planetary systems !
  - This suggests early planet formation

D. We investigated the impact of the magnetic field on the disk populations
  - Non-ideal MHD impacts significantly the stellar population, the magnetic field strength and the disk properties (with lower mass disks in particular)
  - Magnetic field strength as a very important impact on the disk population

E. We modelled dust for the first time
  - mm grains are formed
  - Grains are carried out in the outflows

Bonus Rezooms on specific disks