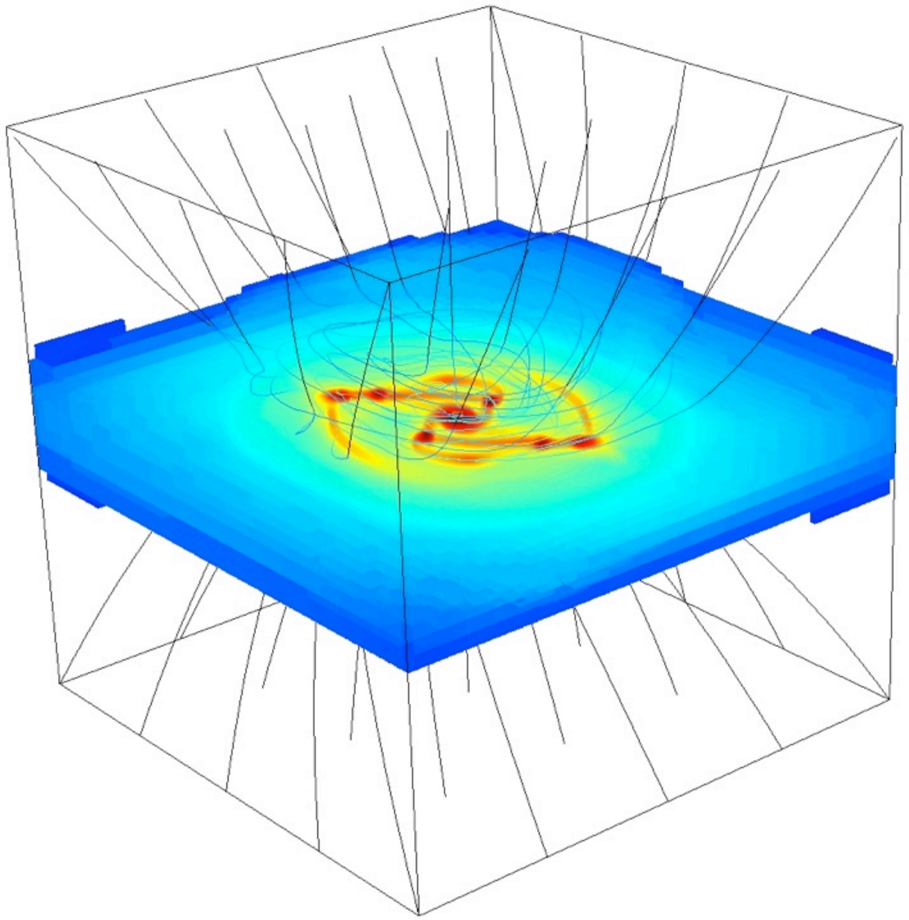
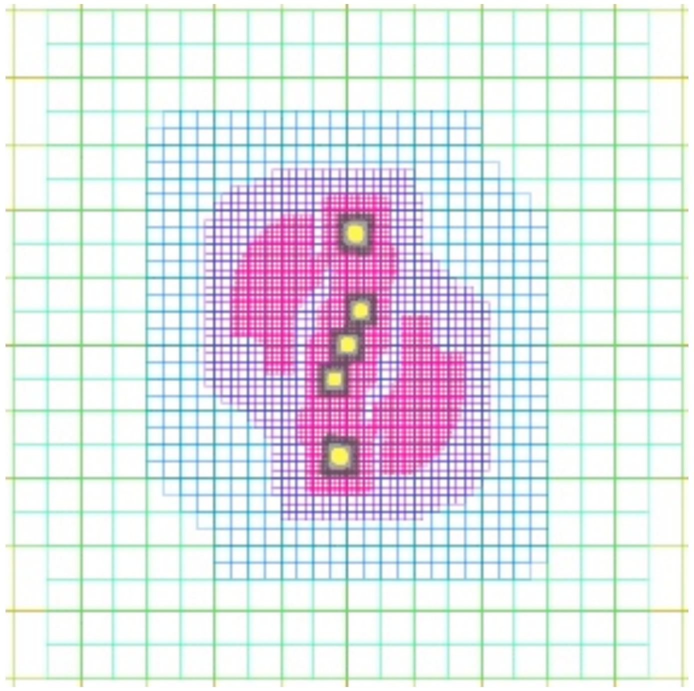


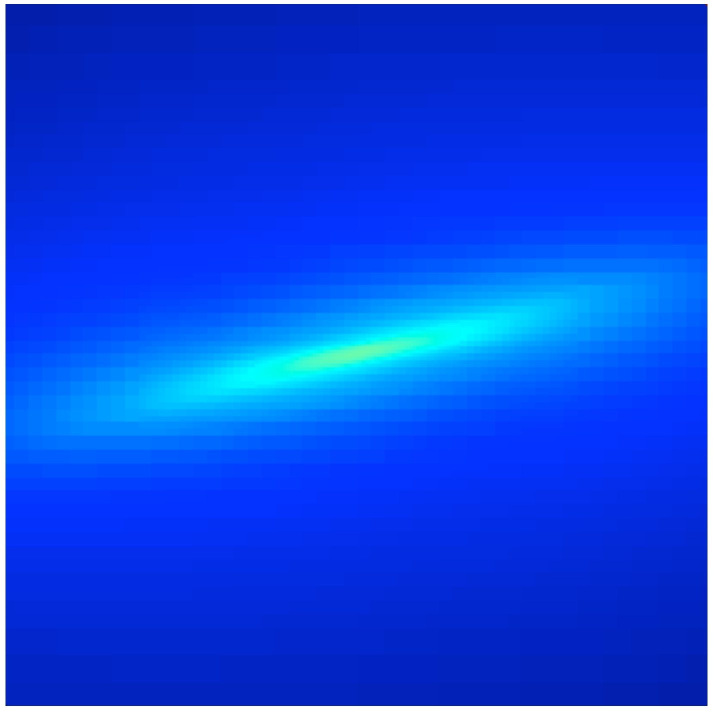
Early stages of protostellar collapse



Commerçon Benoît

Max Planck Institute for Astronomy

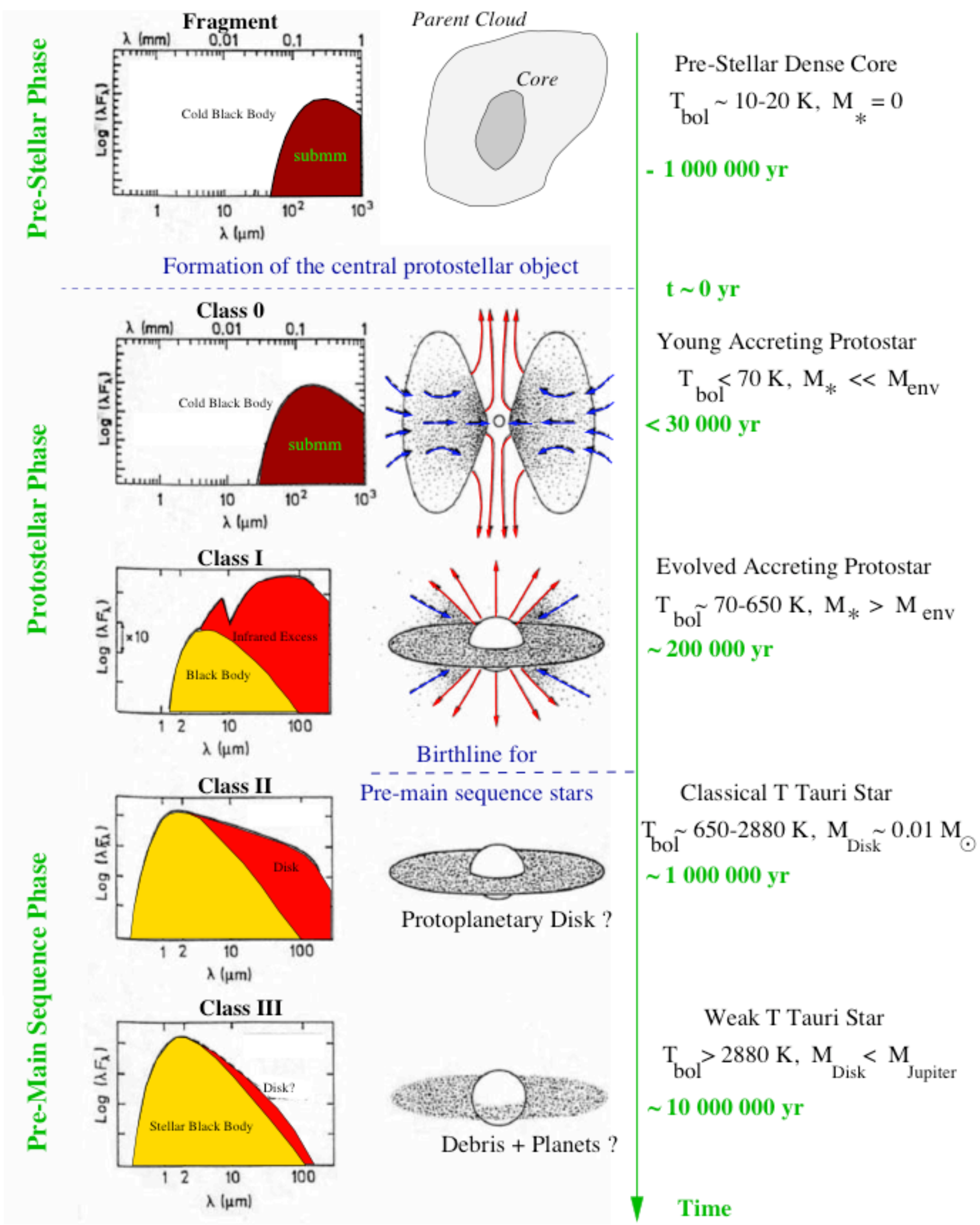
Collaborators**: Patrick Hennebelle, François Levrier* *(LRA/ENS Paris)*, ***Gilles Chabrier *(CRAL/ENS Lyon)*, ***Edouard Audit, Romain Teyssier*** *(SAp/CEA Saclay)* ***Ralf Launhardt, Kees Dullemond, Thomas Henning*** *(MPIA Heidelberg)*



Outlines

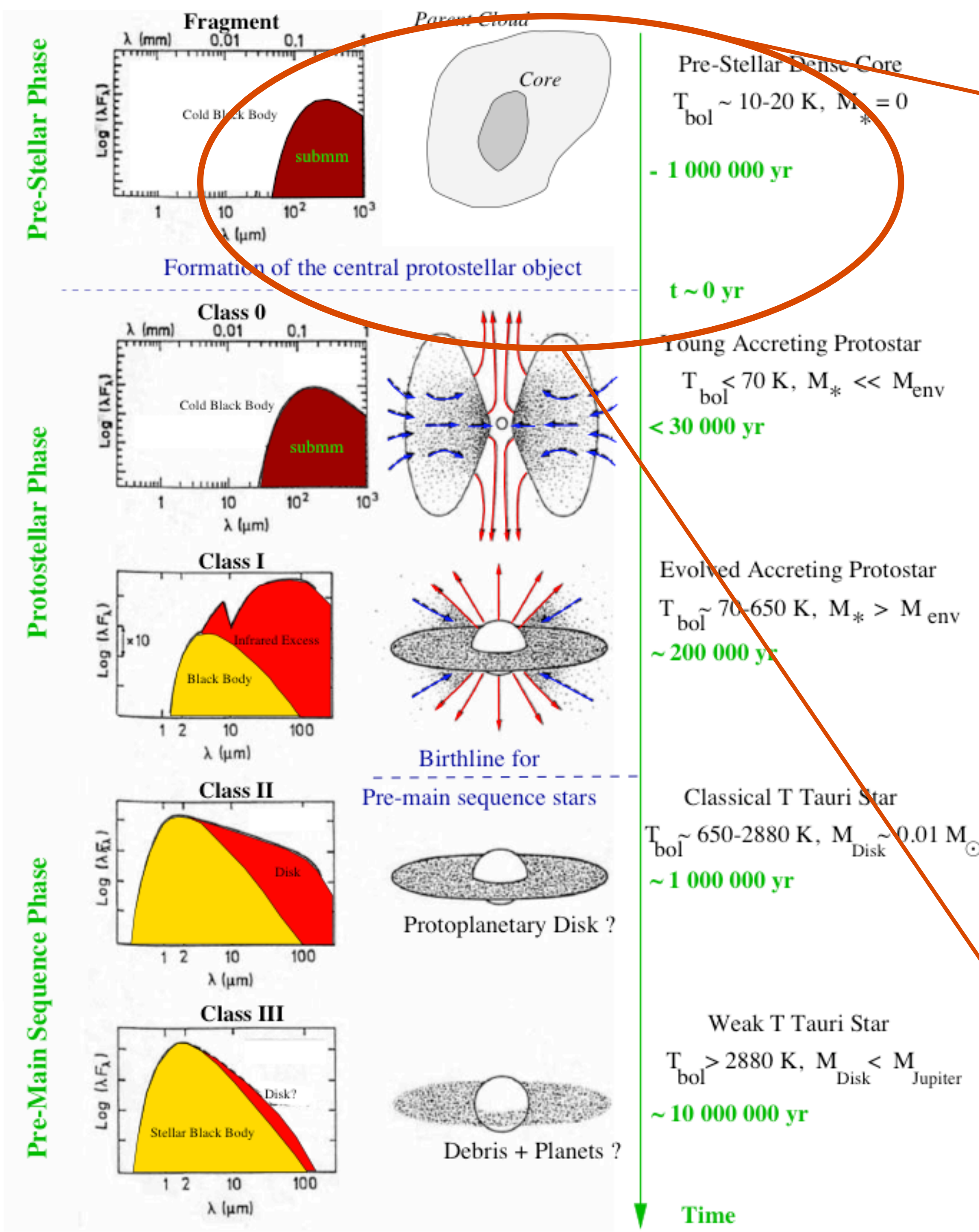
1. **Introduction**
2. **Method**
   - Radiation-magneto-hydrodynamics (RMHD) solver
3. **Low mass star formation calculations**
   - RMHD calculations: the fragmentation crisis
4. **Towards synthetic observations**
   - First steps: SED and ALMA dust emission maps

Star formation evolutionary sequence



André 2002

Star formation evolutionary sequence



André 2002

Prestellar dense core collapse

First collapse

Isothermal

First Larson core

Adiabatic

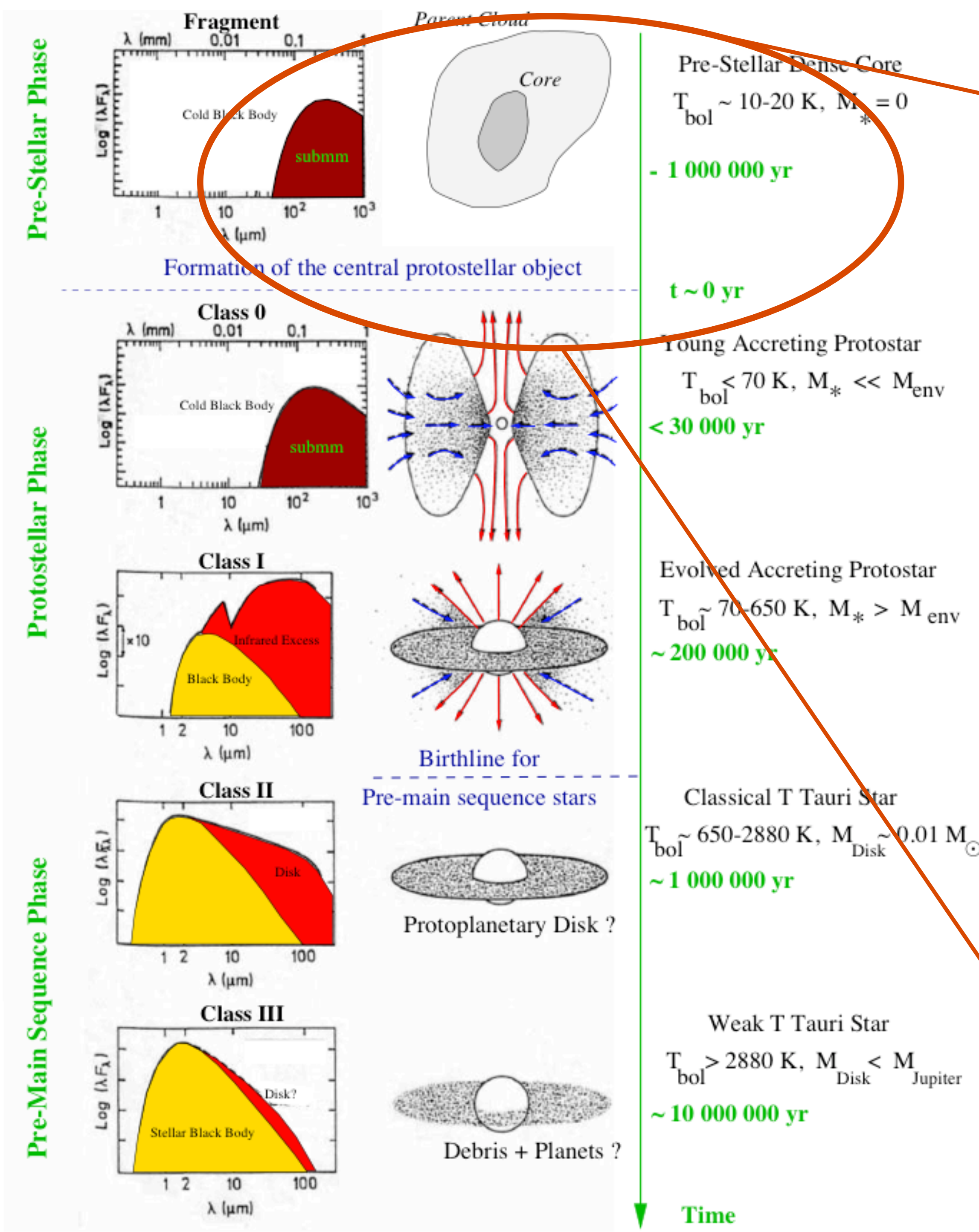
H_2 dissociation

Second collapse

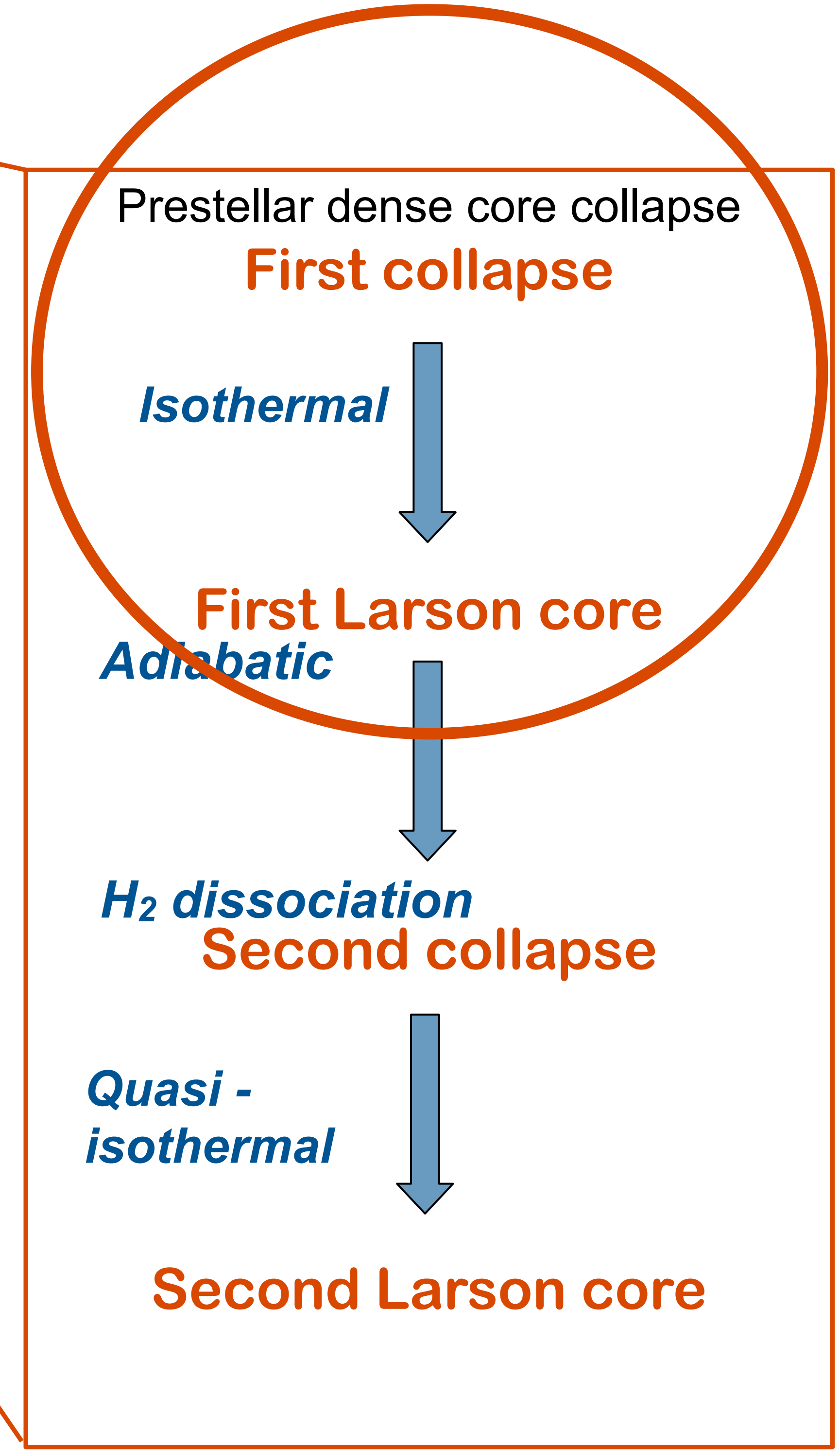
Quasi - isothermal

Second Larson core

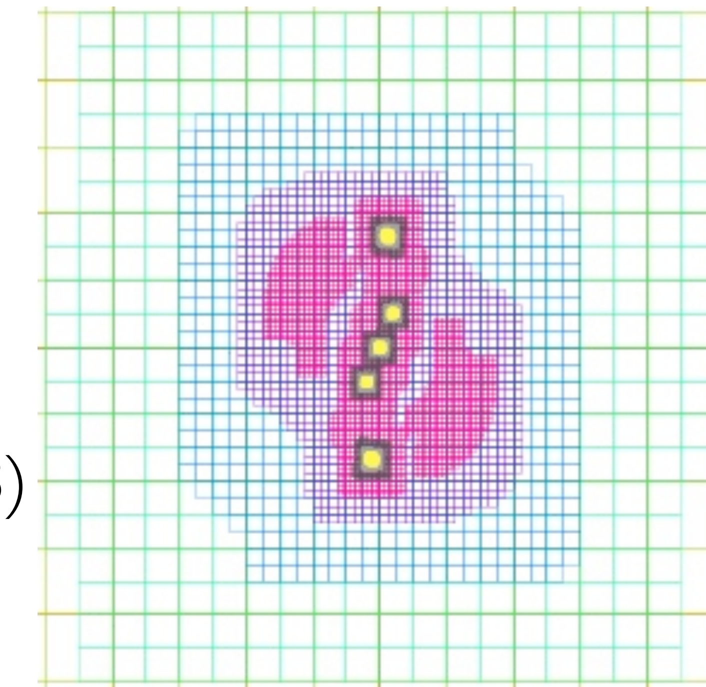
Star formation evolutionary sequence

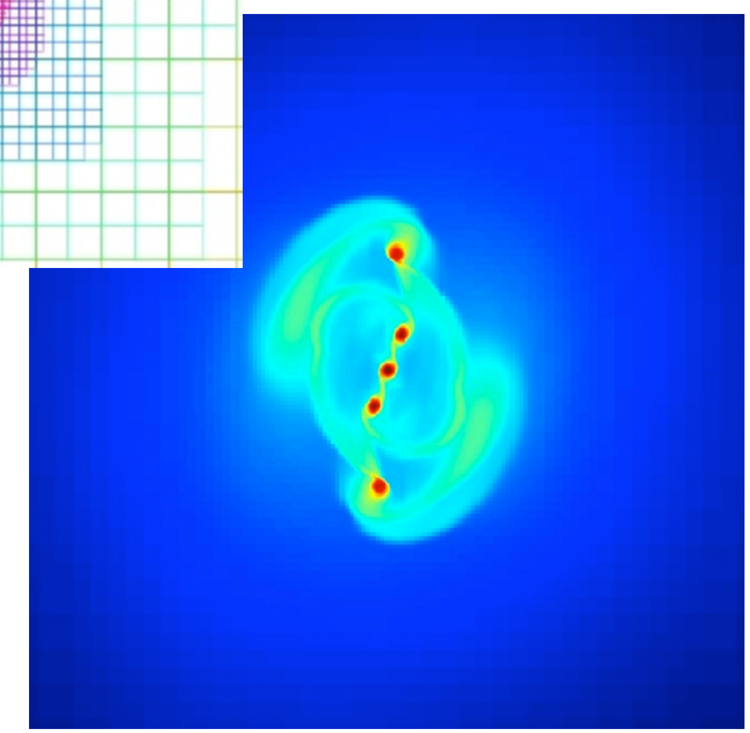


André 2002



RMHD with Flux Limited Diffusion in RAMSES





- ✓ **RAMSES code** *(Teyssier 2002)*
  - AMR code, 2nd order Godunov scheme
  - *Ideal* MHD solver (Fromang et al. 2006)
  - Jeans length refinement criterion for SF (Truelove et al. 1998, Commerçon et al. 2008)

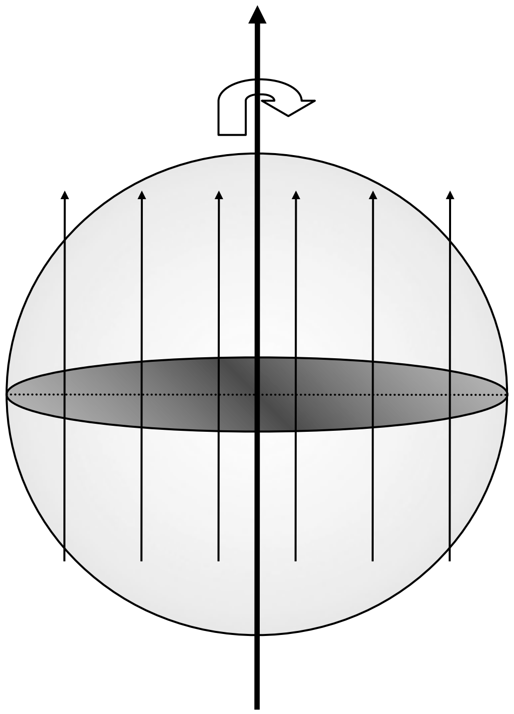
- ✓ **RHD** solver in the *comoving* frame using the grey **F**lux **L**imited **D**iffusion approximation (Commerçon et al. 2011a):

$$
\left\{
\begin{array}{llll}
\partial_t \rho & + & \nabla [\rho \mathbf{u}] & = 0 \\
\partial_t \rho \mathbf{u} & + & \nabla [\rho \mathbf{u} \otimes \mathbf{u} + (P + 1/3 E_\mathrm{r}) \mathbb{I}] & = -(\lambda - 1/3) \nabla E_\mathrm{r} \\
\partial_t E_\mathrm{T} & + & \nabla [\mathbf{u} (E_\mathrm{T} + P + 1/3 E_\mathrm{r})] & = -(\lambda - 1/3) \nabla (\mathbf{u} E_\mathrm{r}) + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) \\
\partial_t E_\mathrm{r} & + & \nabla [\mathbf{u} E_\mathrm{r}] & = -\mathbb{P}_\mathrm{r} : \nabla \mathbf{u} + \kappa_\mathrm{P} \rho c (a_\mathrm{R} T^4 - E_\mathrm{r}) + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right)
\end{array}
\right.
$$

Riemann solver - explicit | Corrective terms - explicit | Coupling + Diffusion - implicit

Initial conditions (numerical experiment)

1 $M_\odot$ **isolated dense core:** uniform density and temperature (10 K, $\alpha = E_{th}/E_{grav}$), solid body rotation ($\beta = E_{rot}/E_{grav}$), m=2 density perturbation (amplitude A=10%)
==> Small-scale fragmentation



★ **Radiative transfer:** efficient cooling (Attwood et al.09) and heating (Krumholz et al. 09, Bate 09).
Grey opacities from Semenov et al. 03.

★ **Ideal MHD <==> flux freezing:** $\varphi \propto BR^2$
Magnetic field lines are twisted and compressed:

==> **Outflow** (e.g. Machida et al., Banerjee & Pudritz 06, Hennebelle & Fromang 08, Mellon & Li 2008)

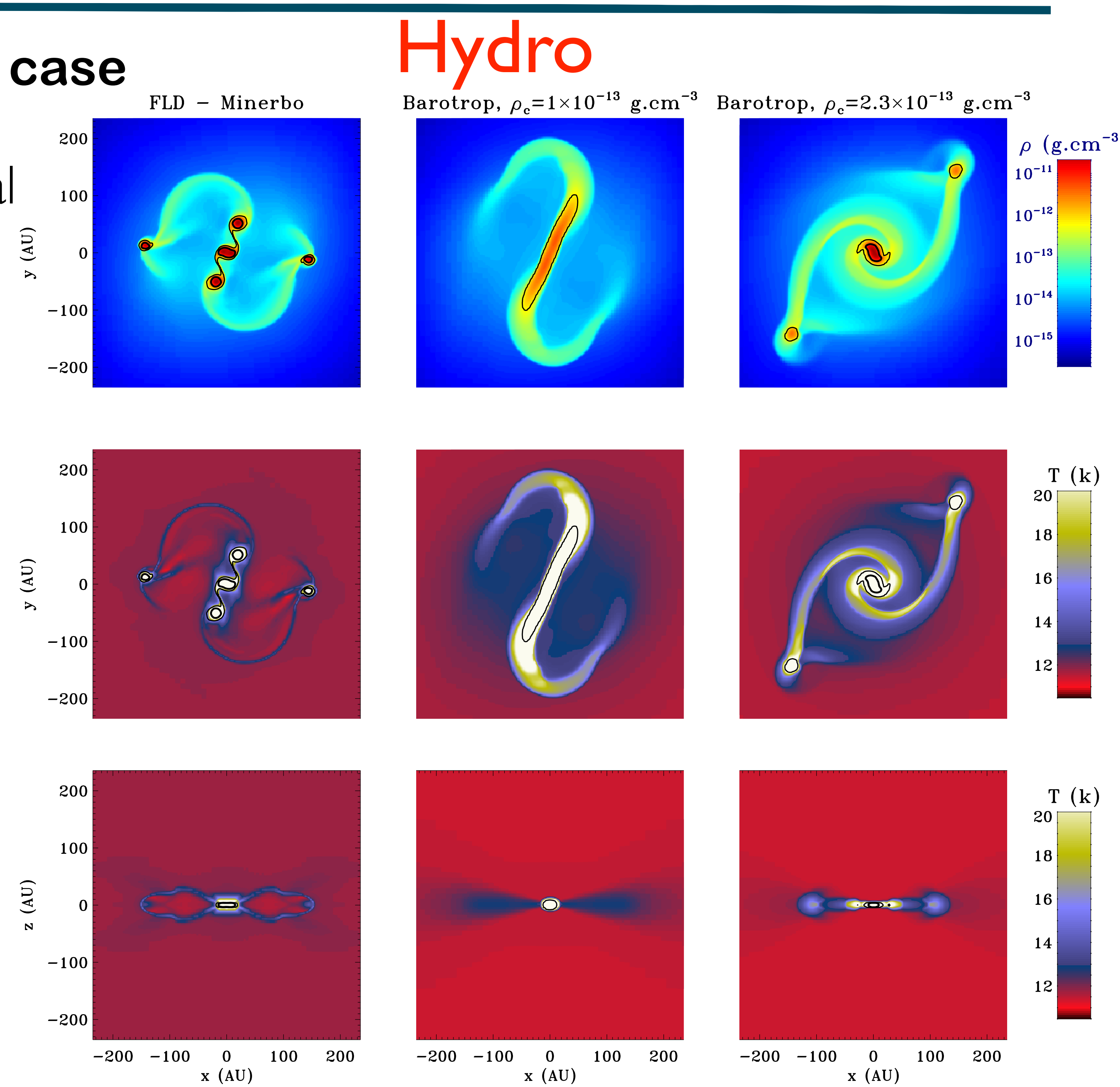
$\mu = (\varphi/M)_{crit} / (\varphi/M)$ (observations $\mu \sim 2\text{-}5$)

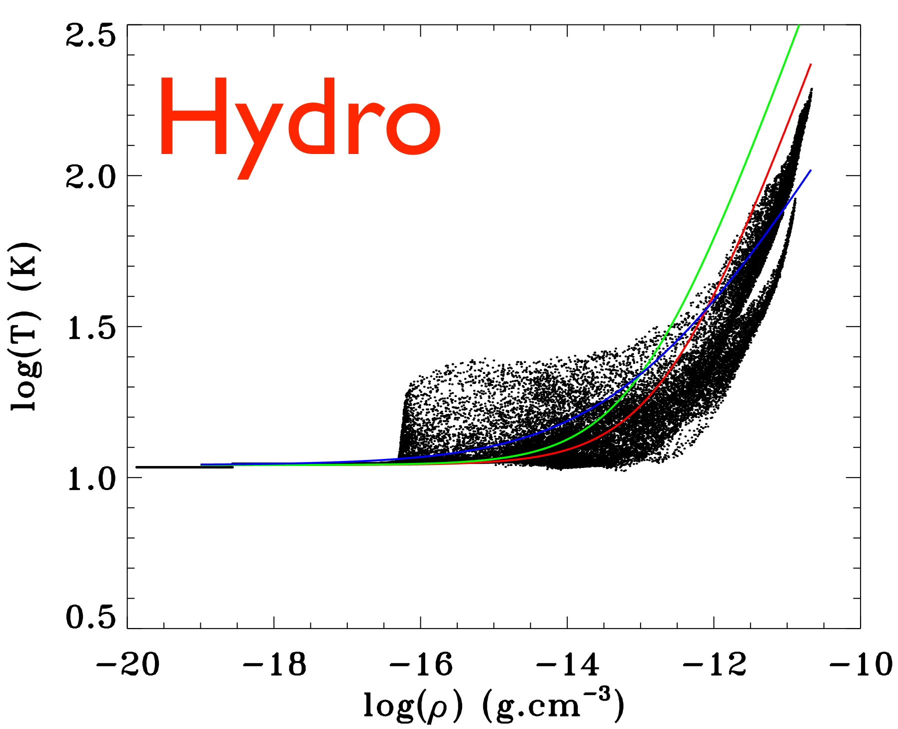
1 M⊙ dense core collapse: Hydro

Comparison to the barotropic case

- **Hydro case**: more fragmentation
- gas cools efficiently in the vertical direction

==> lower Jeans mass





1 M☉ dense core collapse: Hydro

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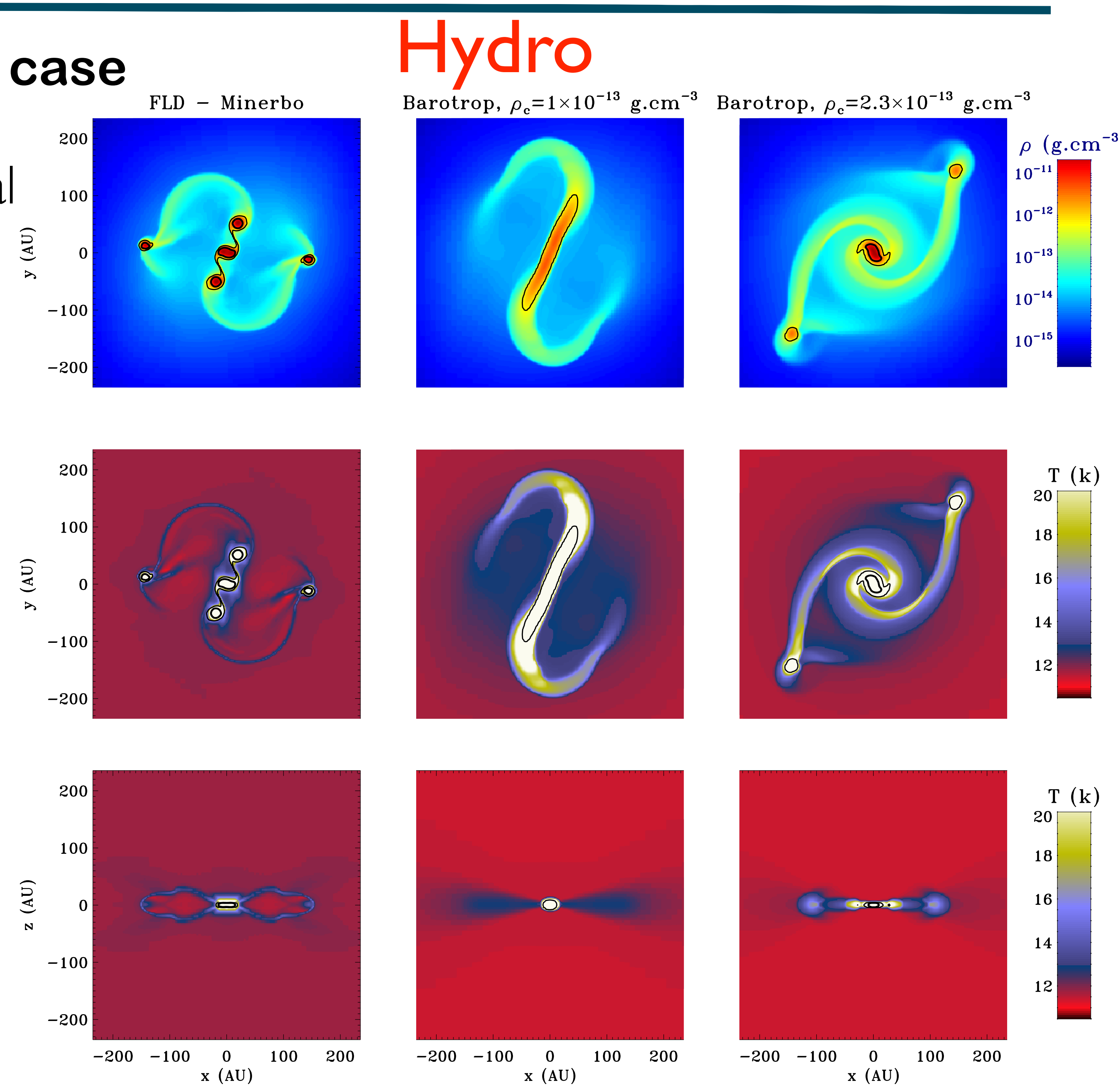

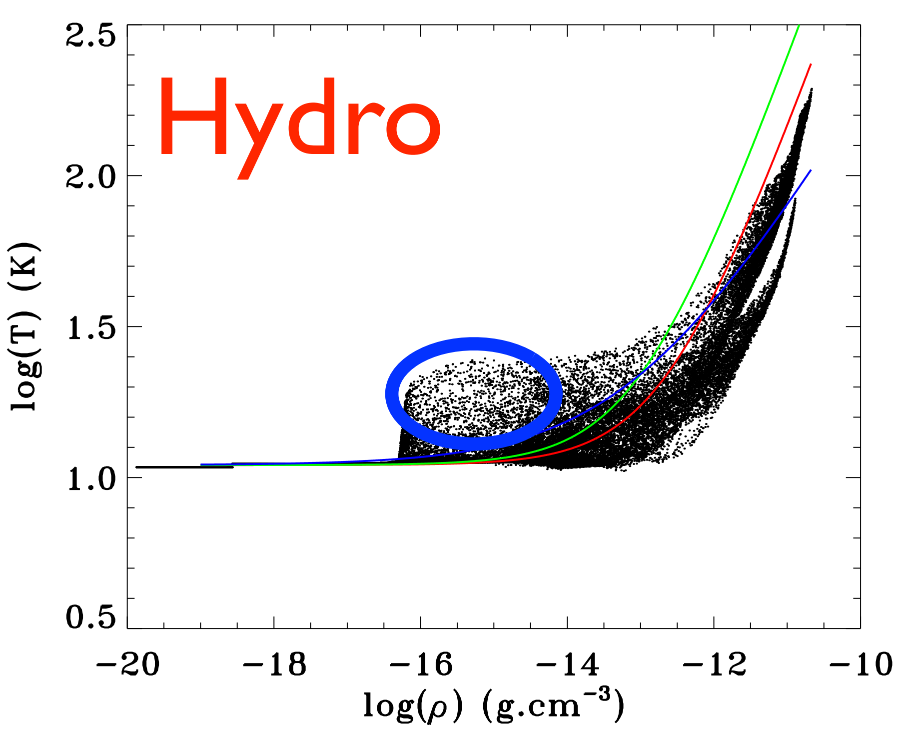

1 M☉ dense core collapse: Hydro

Comparison to the barotropic case

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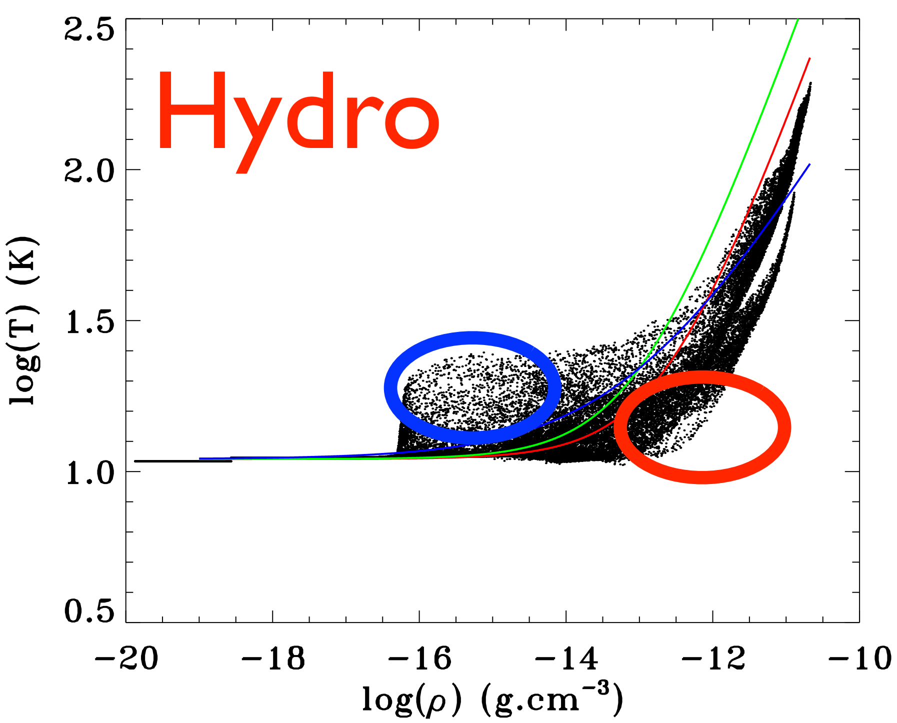
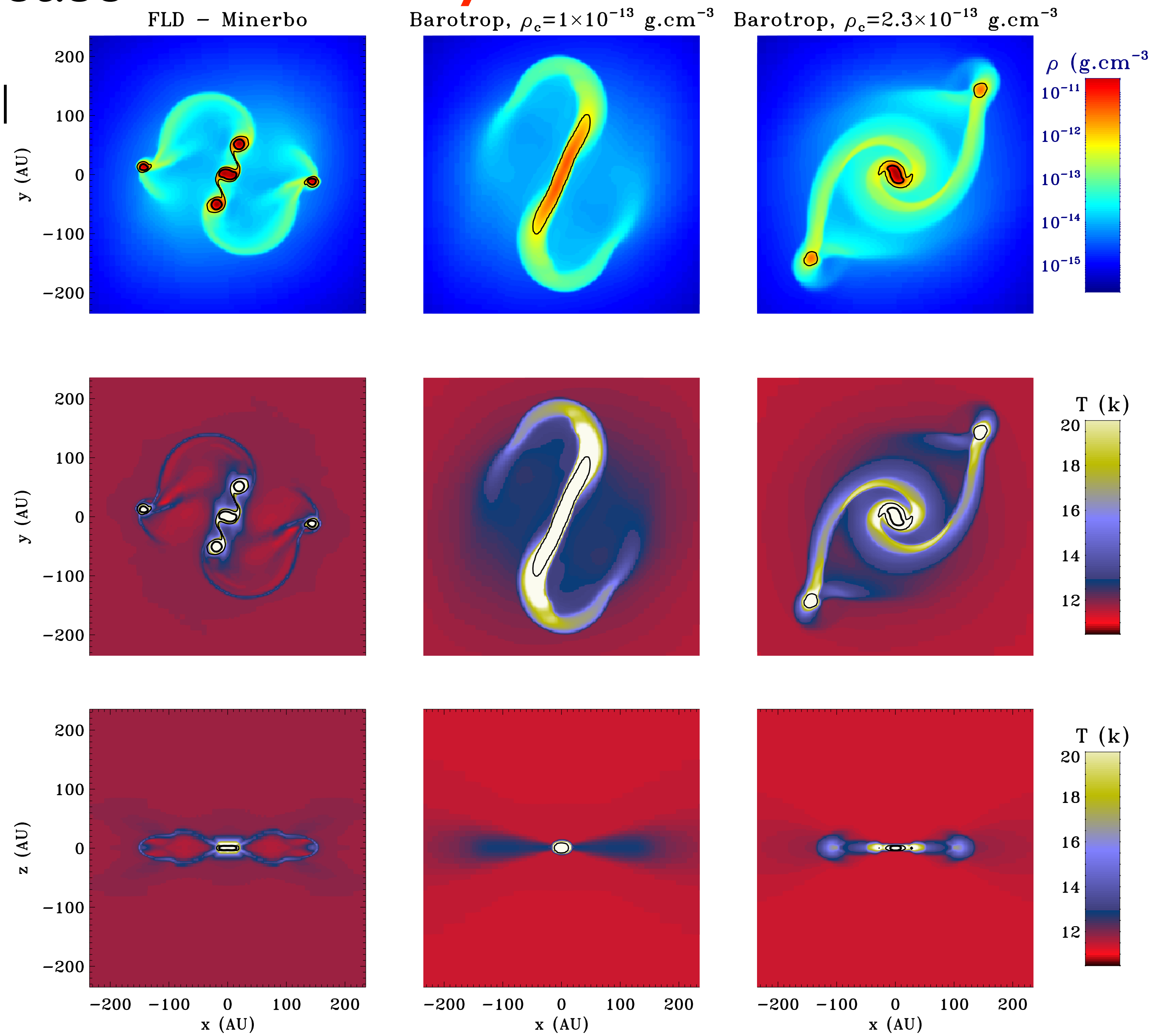


Hydro



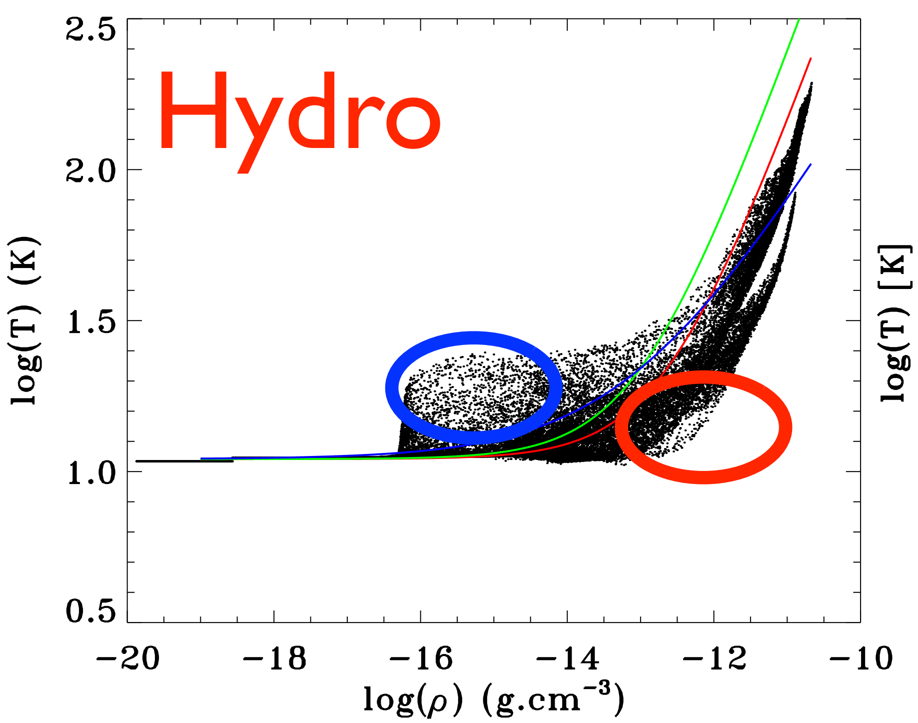
1 M⊙ dense core collapse: Hydro vs. μ=5

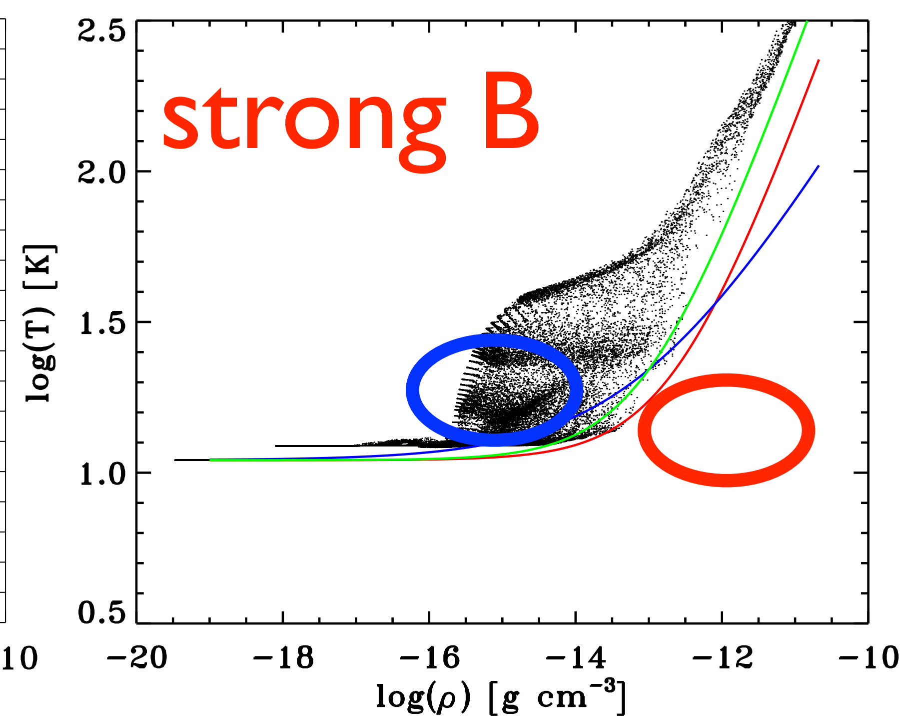
Comparison to the barotropic case

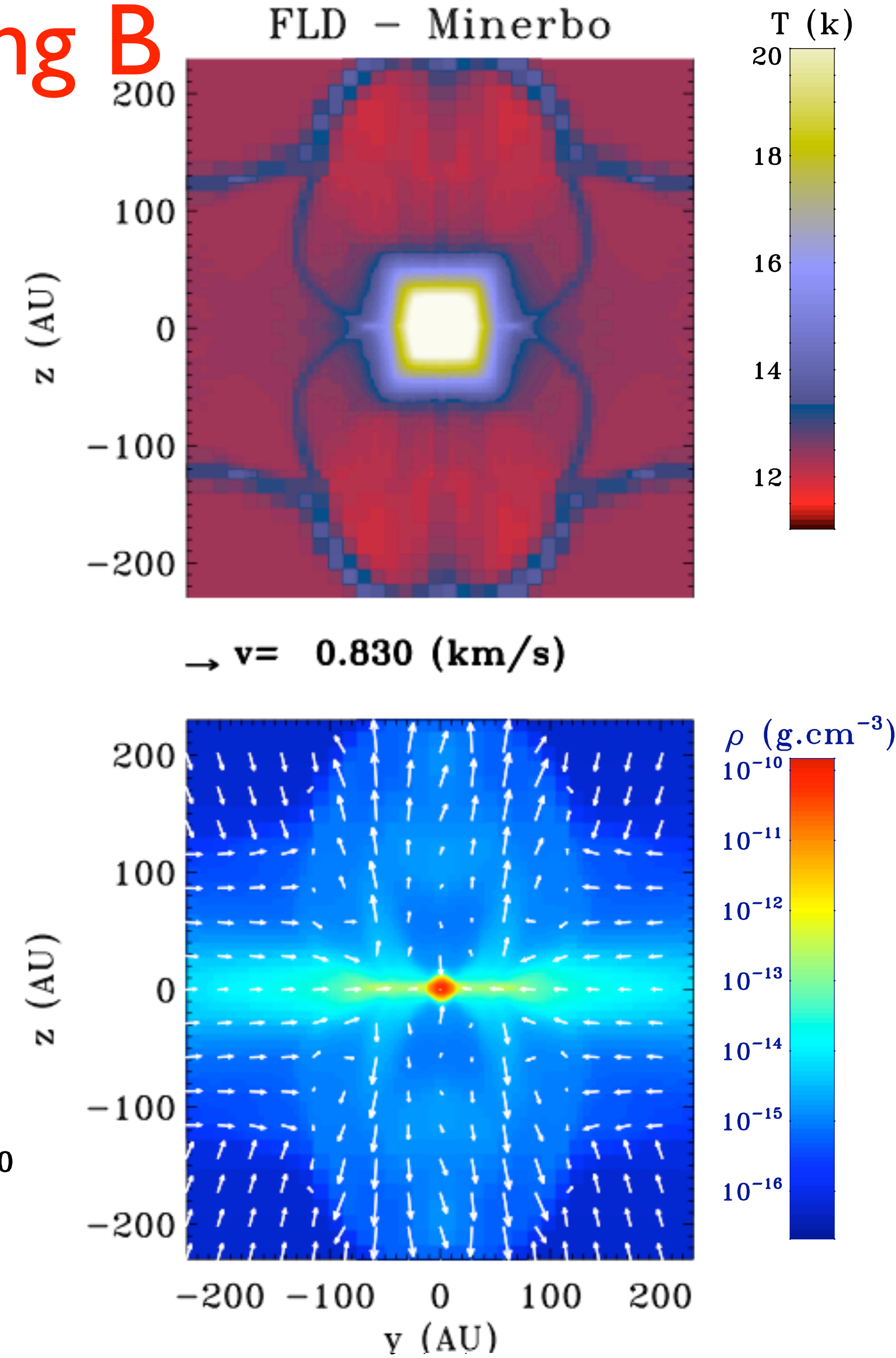
- **Hydro case**: more fragmentation
- **RMHD**: **magnetic** braking <=> radiative feedback (L_{acc})

Commerçon et al. 2010, A&AL

strong B







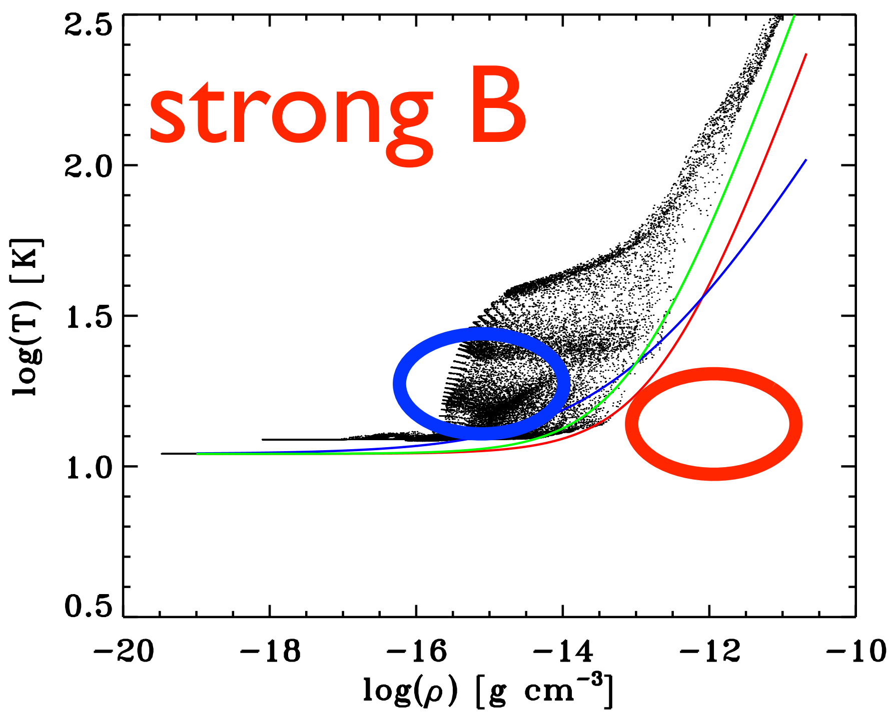
1 $M_\odot$ dense core collapse: Hydro vs. μ=5

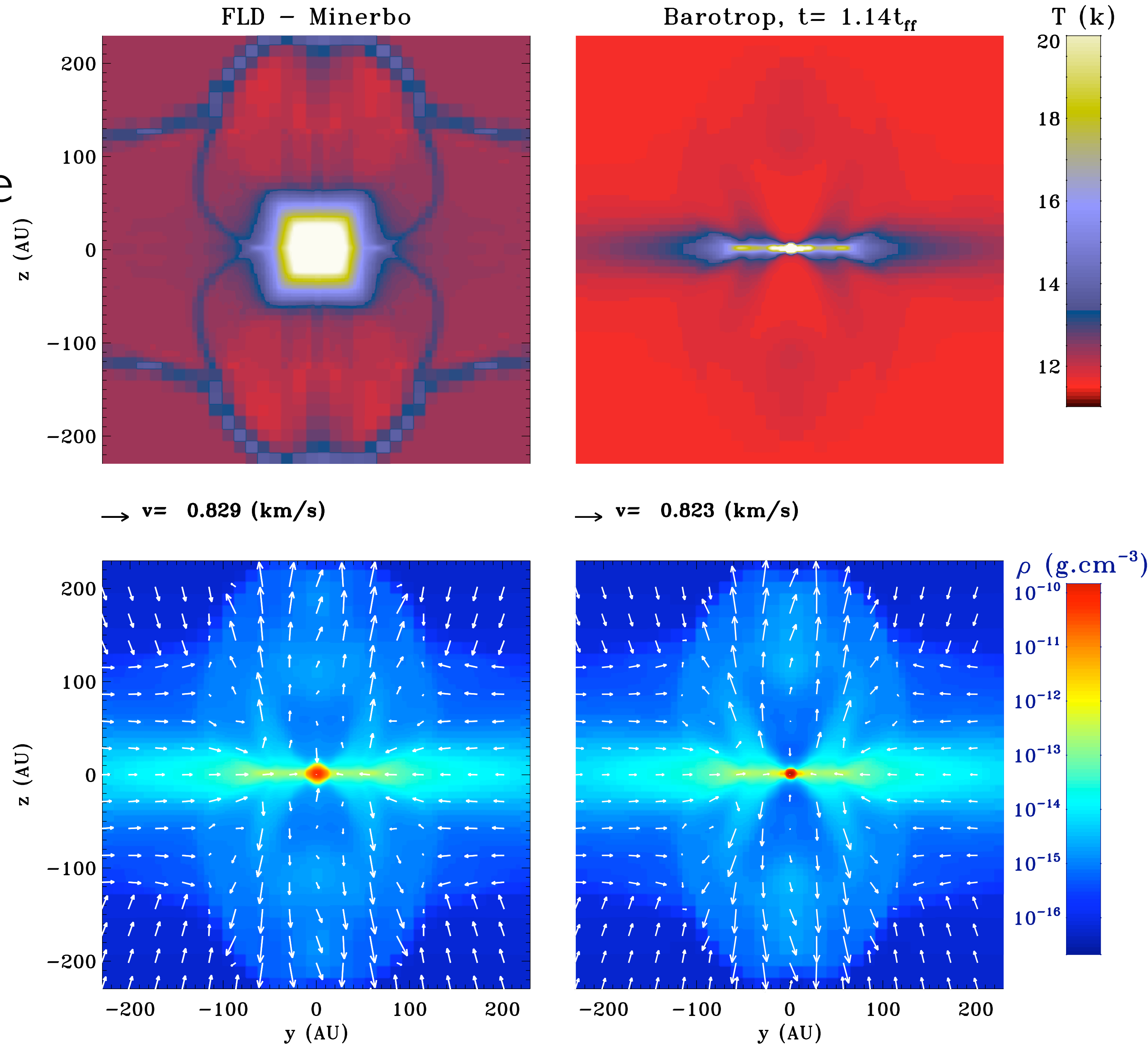
Comparison to the barotropic case

Commerçon et al. 2010, A&AL

- **Hydro case**: more fragmentation
- **RMHD**: **magnetic** braking <=> radiative feedback (L_{acc})
- Significant differences in the temperature distribution

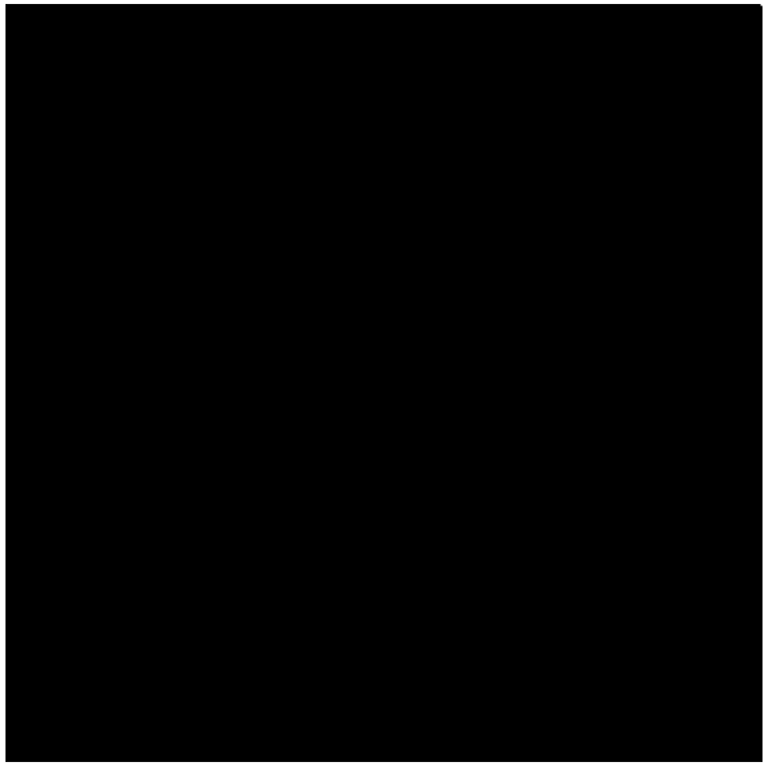
<=> **observations**



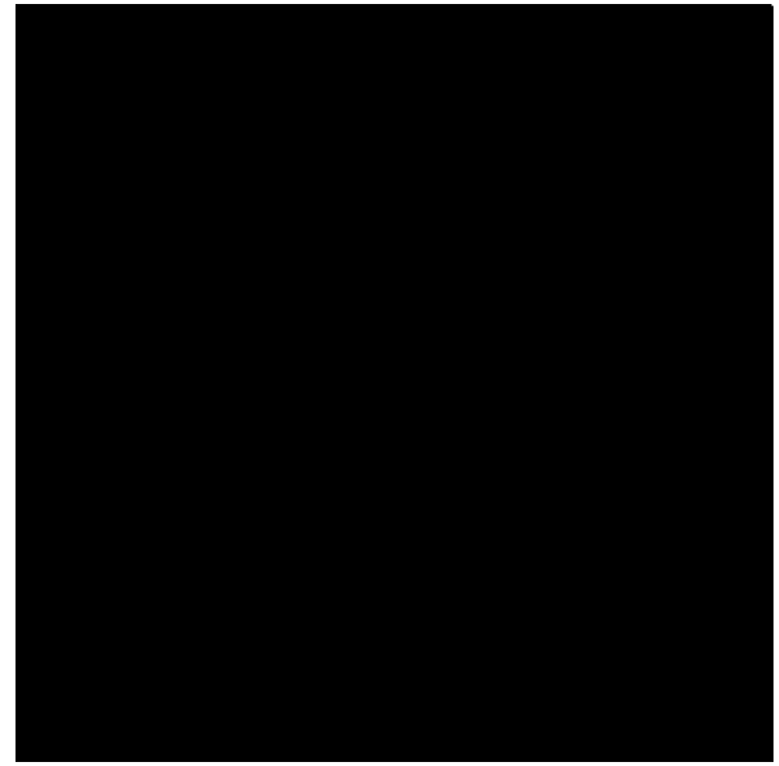


Moderate magnetized case, 1 $M_\odot$, μ=5, RMHD

Temperature

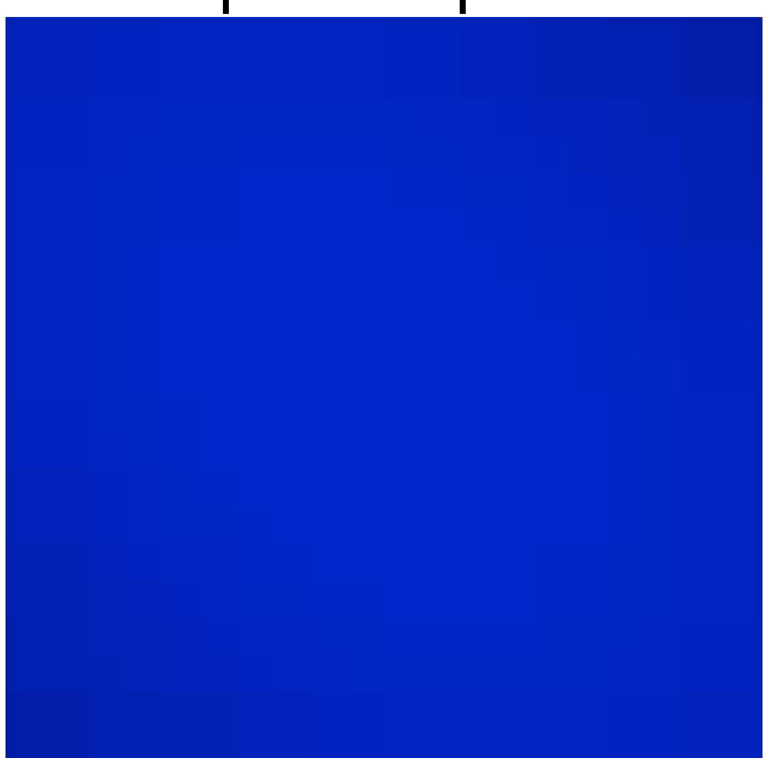


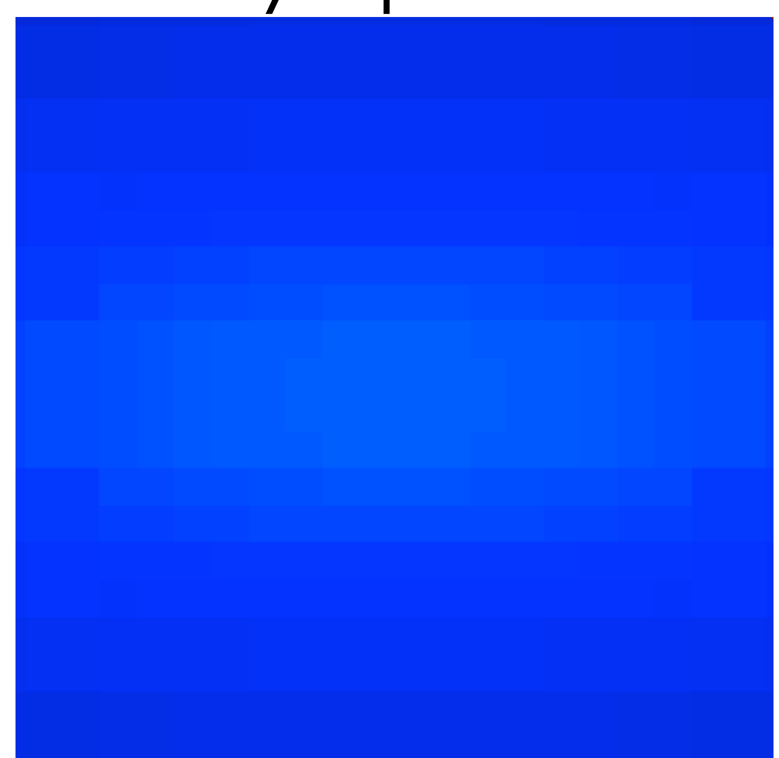
equatorial plane



yz - plane

Density

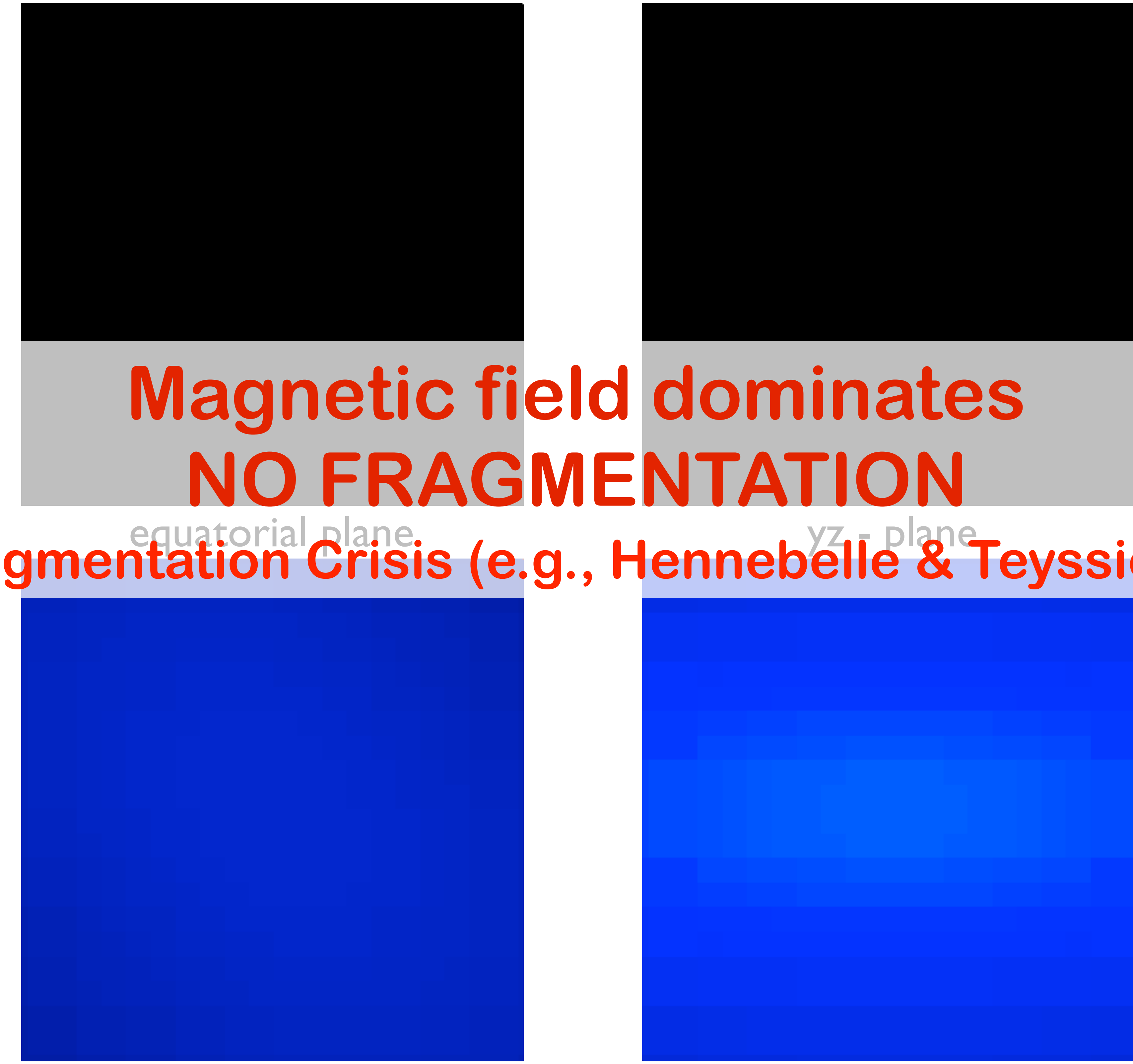




Moderate magnetized case, 1 $M_\odot$, μ=5, RMHD

Temperature

Density



Magnetic field dominates
NO FRAGMENTATION

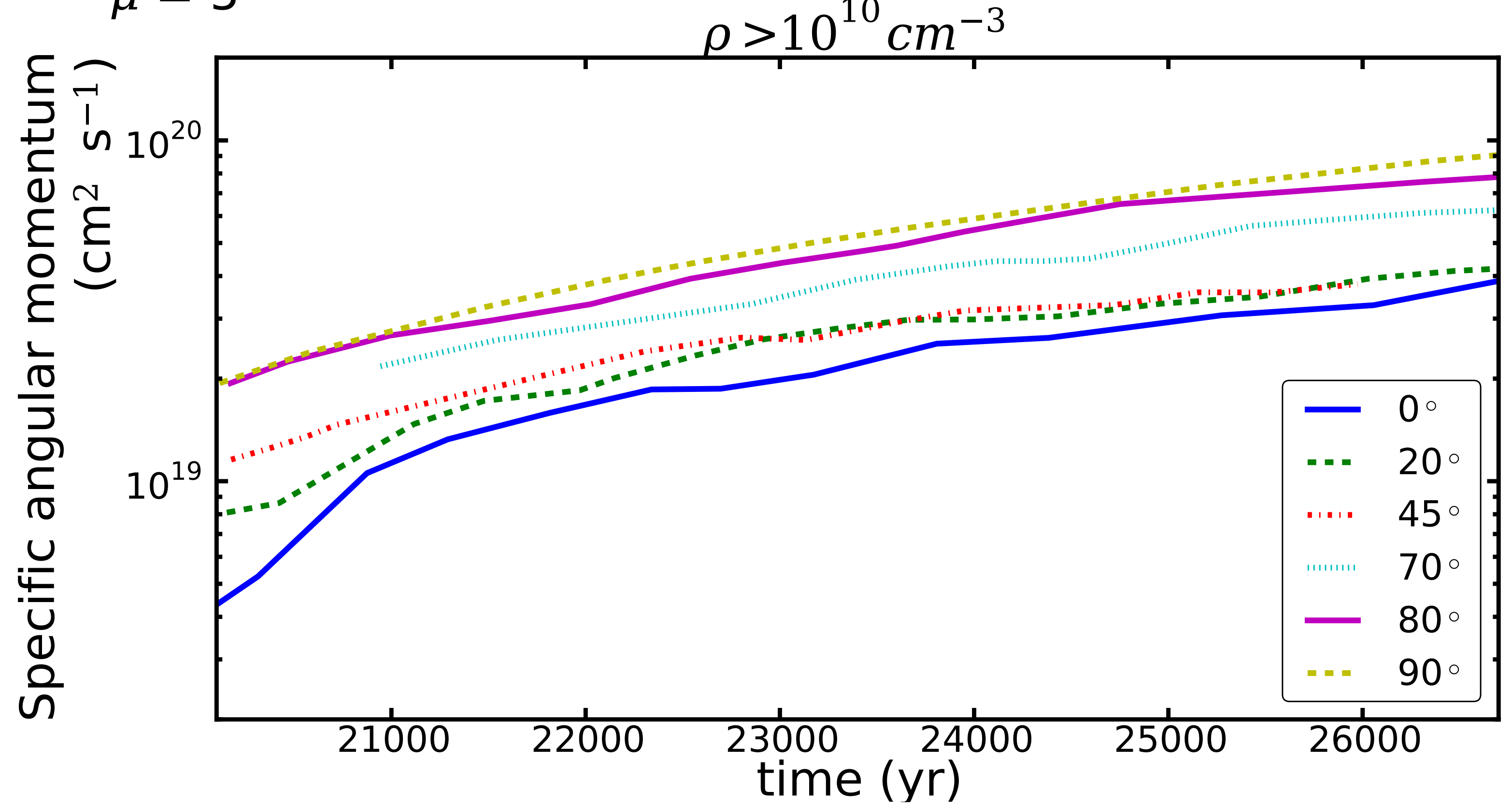
The Fragmentation Crisis (e.g., Hennebelle & Teyssier 2008)

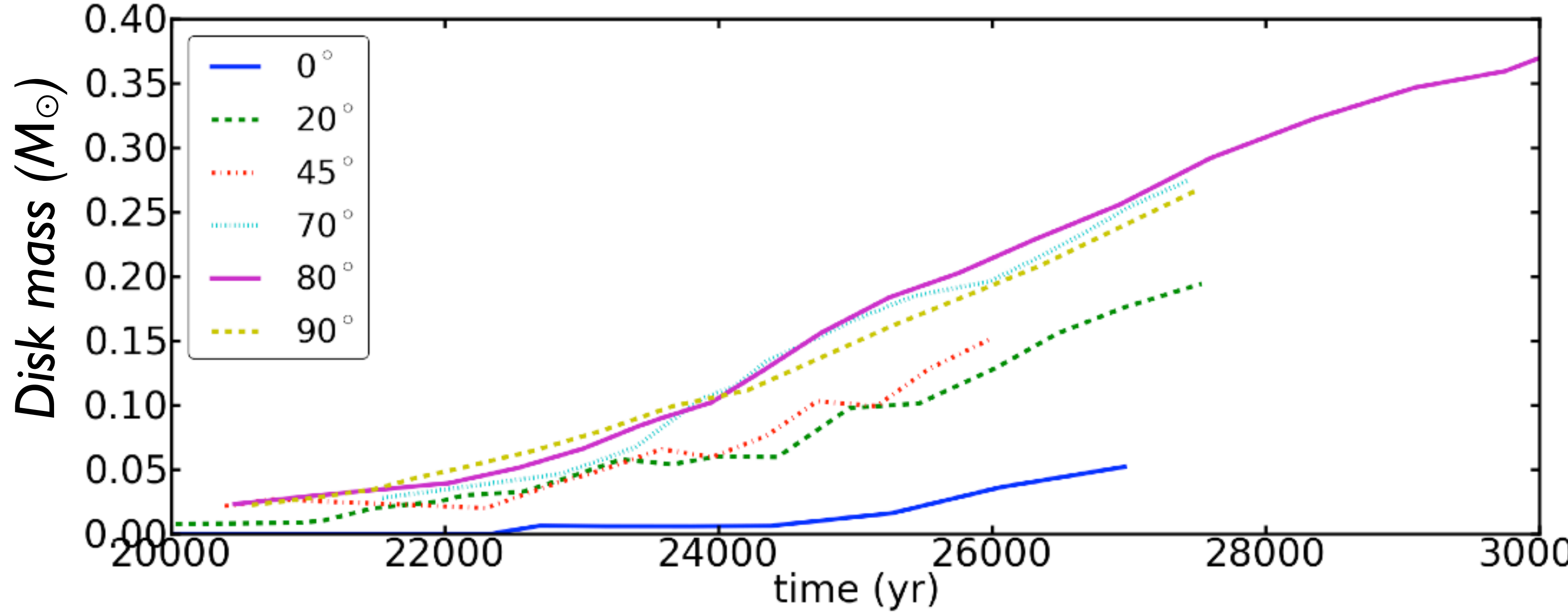
Solve the fragmentation crisis

- Non-ideal MHD
- Large scale fluctuations
- **Angle B/rotation axis**
  (Hennebelle & Ciardi 2009)

  See Marc JOOS Poster (barotropic EOS)

$\mu = 5$





Joos et al. in prep.

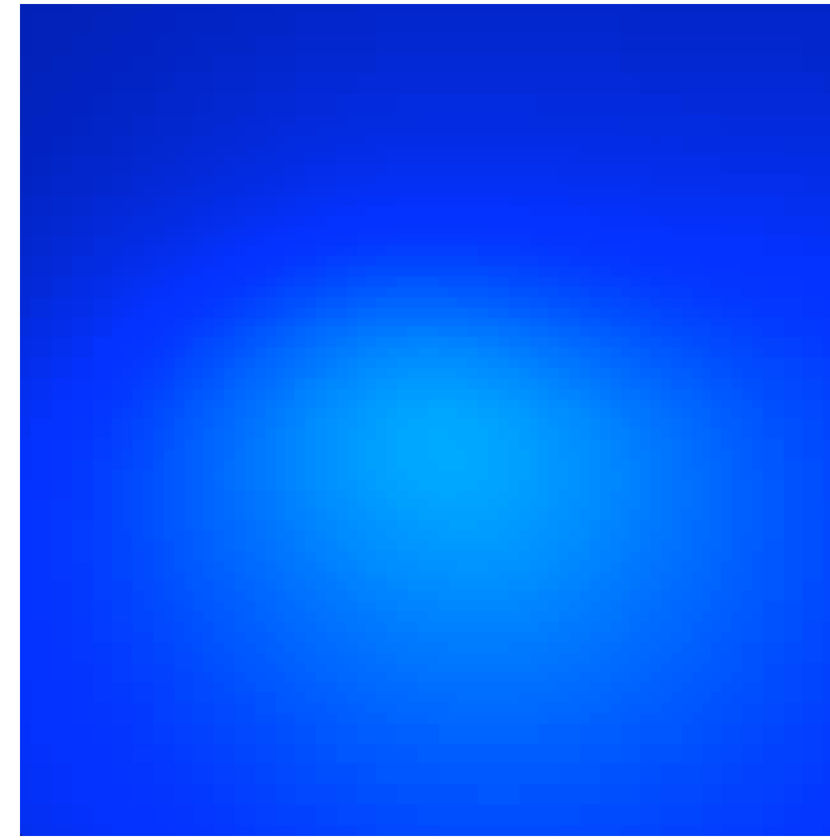
Solve the fragmentation crisis

RMHD case

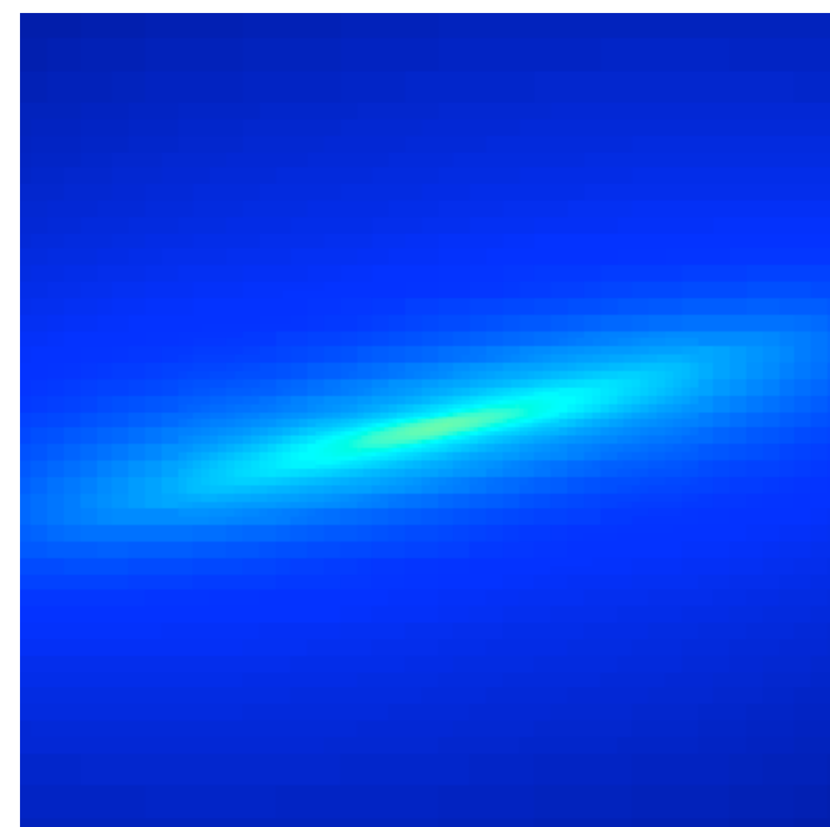
- Non-ideal MHD
- Large scale fluctuations
- **Angle B/rotation axis** (Hennebelle & Ciardi 2009, Commercon et al. in prep)
    - Formation of a disk
    - but no fragmentation up to $\mu=20$...

See Marc JOOS Poster

xy-plane

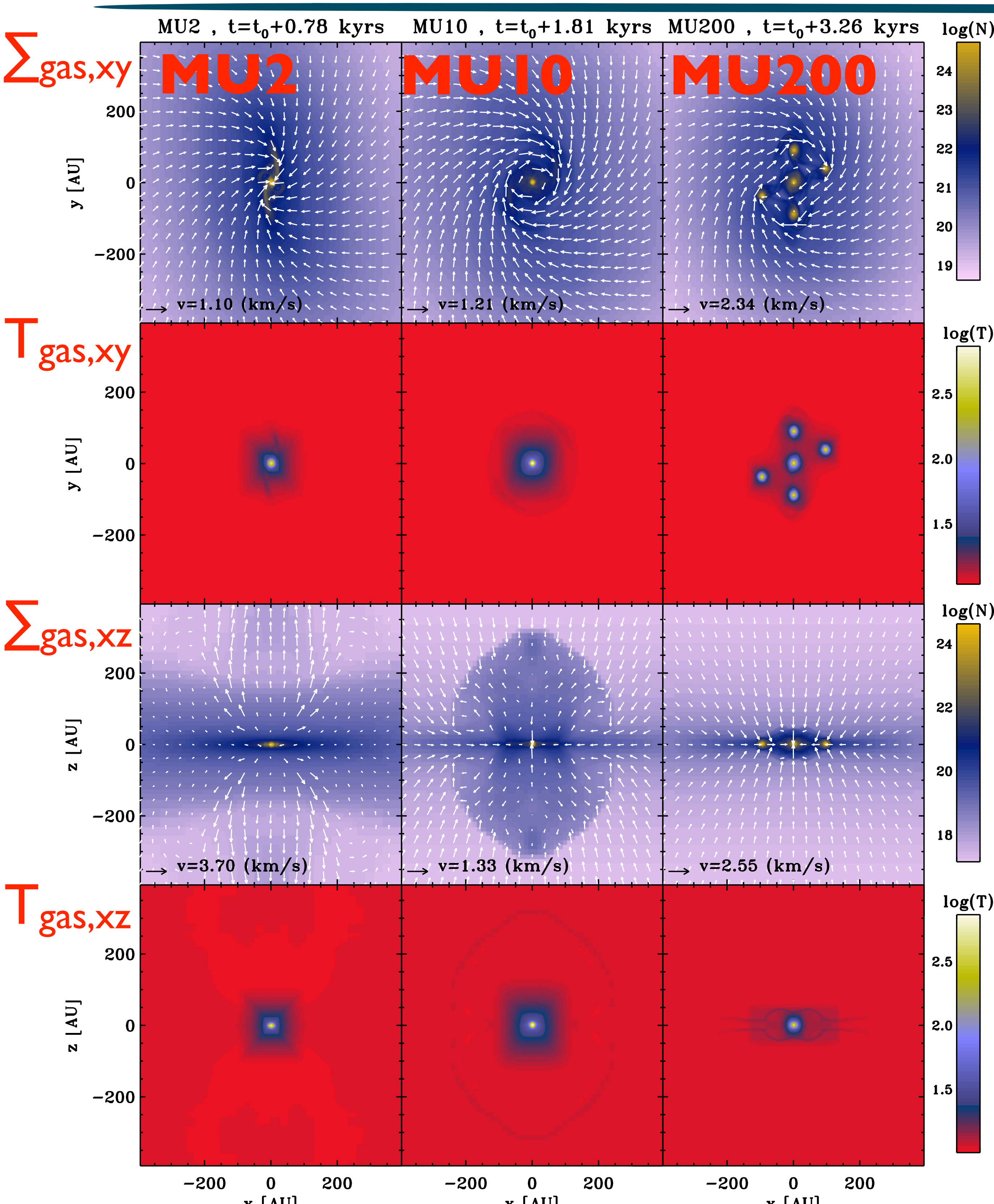


yz-plane



$\alpha=0.37$, $\beta=0.045$, $m=2$, $A=0.1$, $\mu=5$, $\theta=45^{\circ}$

Towards synthetic observations



- 3 representative cases
  - *MU2*: pseudo-disk + outflow
  - *MU10*: disk + pseudo-disk + outflow
  - *MU200*: disk + fragmentation

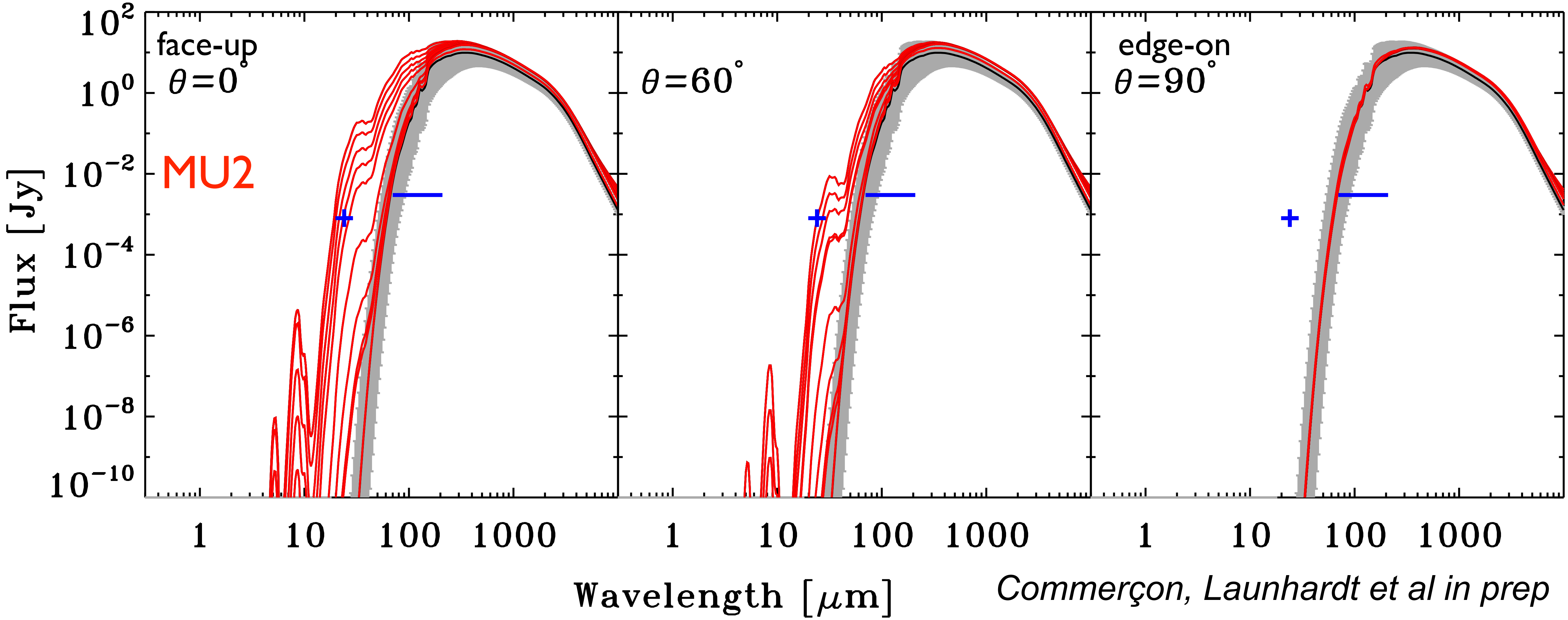
- First core lifetime:

MU2	*MU10*	*MU200*
1.2 kyr	3 kyr	> 4 kyr

- Images & SED computed with the radiative transfer code **RADMC-3D**, developed by C. Dullemond (ITA Heidelberg)
- $T_{dust} = T_{gas}$ (given by the RMHD calculations)

Commerçon, Launhardt et al in prep

SED - Do we see a first core signature?



Commerçon, Launhardt et al in prep

- MU2 model at @ 150 pc, 3000 AU x 3000 AU region
- Prestellar core = initial conditions (black line)
- Strong in the FIR => HERSCHEL, SPITZER?

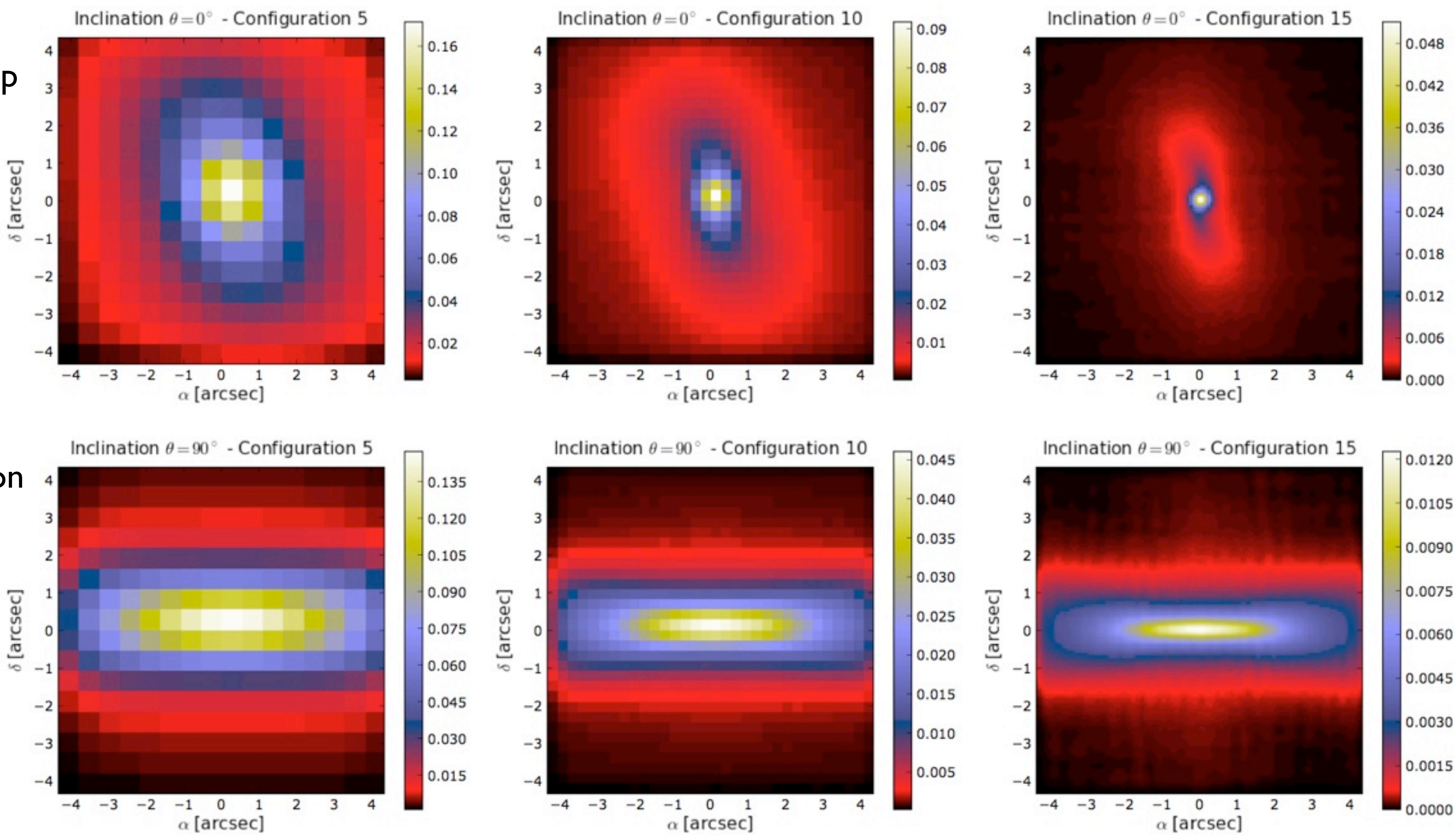
=> Help to select first core candidates

Synthetic ALMA dust emission maps

Brightness I in Jy/beam - $\mu = 2$ - Band 4   λ ~ 2 mm, @ 150 pc

face-up

edge-on



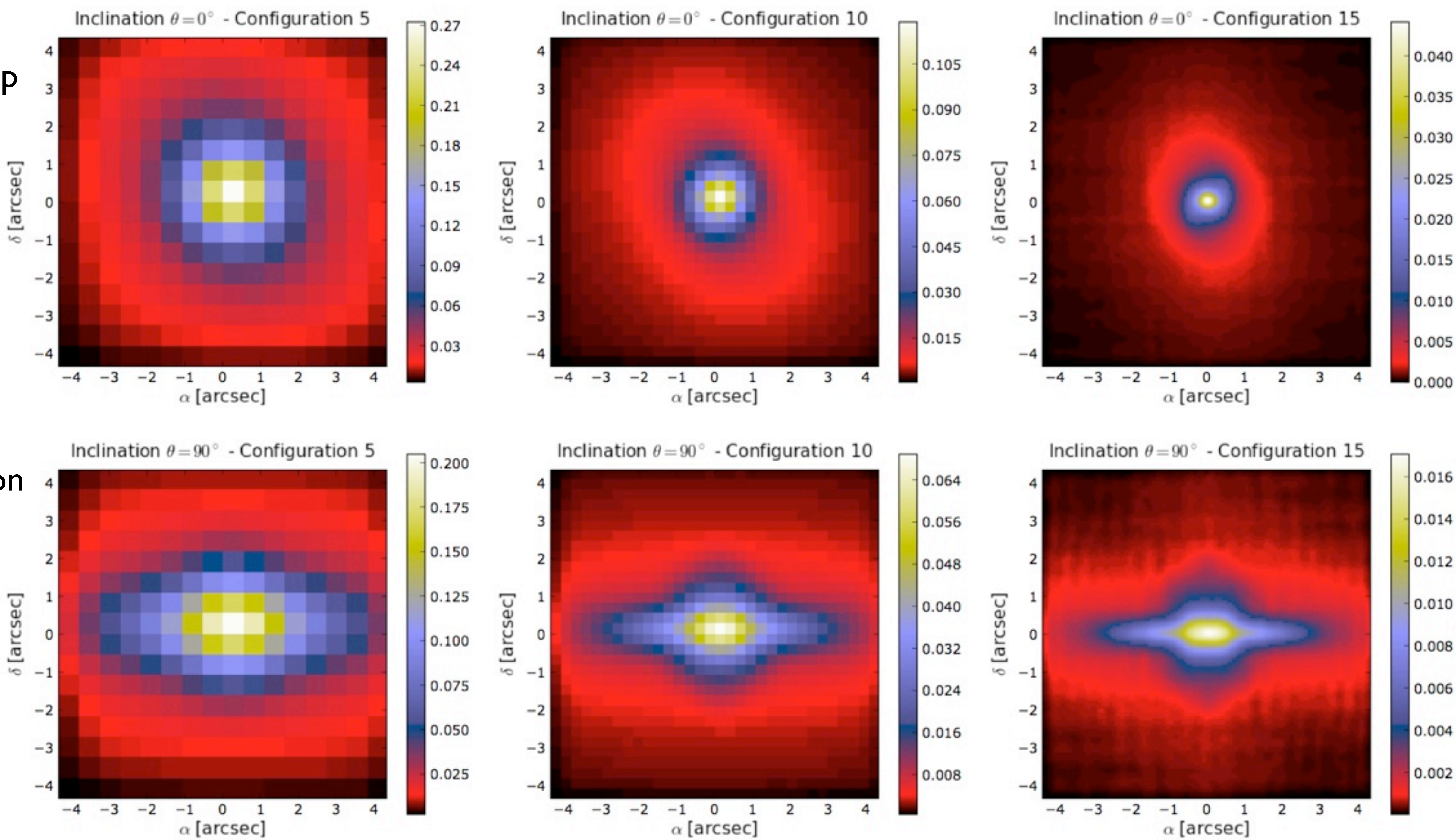
Commerçon, Levrier et al in prep

Synthetic ALMA dust emission maps

Brightness I in Jy/beam - $\mu=10$ - Band 4 λ ~ 2 mm, @ 150 pc

face-up

edge-on



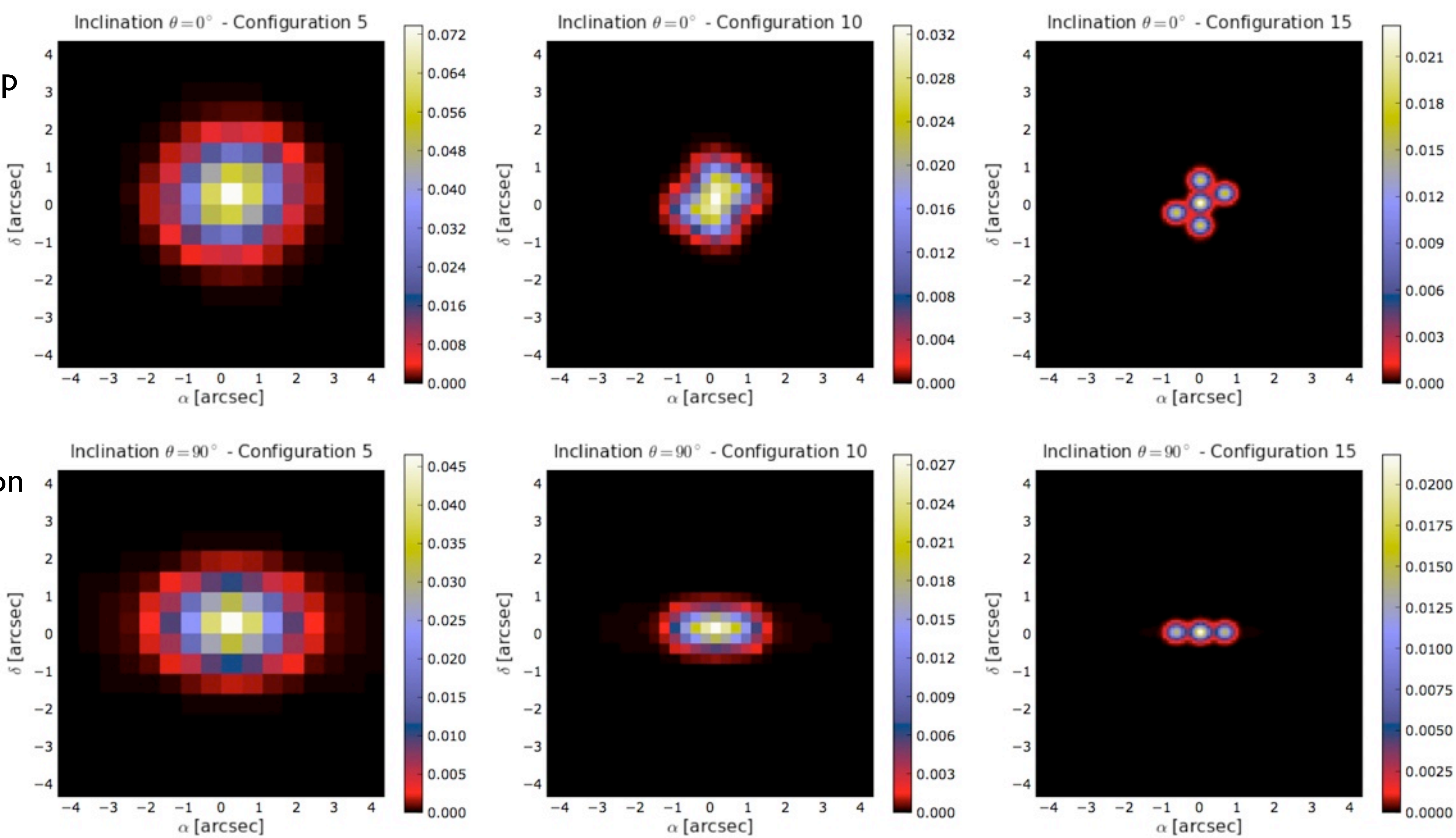
Commerçon, Levrier et al in prep

Synthetic ALMA dust emission maps

Brightness I in Jy/beam - $\mu = 200$ - Band 4 λ ~ 2 mm, @ 150 pc

face-up

edge-on



Commerçon, Levrier et al in prep

Conclusion & prospects

- ☑ **First** full RMHDs calculations with **AMR** of dense core collapse at small scales (*Commerçon et al. 2010)*
- ☑ Magnetic field **inhibits** small-scale fragmentation
- ☑ Magnetic braking **favors** radiative feedback (*Commerçon et al. 2010, 2011b*)
- ☑ First core lifetime decreases with magnetization
- ☑ First core selection with SED
- ☑ ALMA prediction: answer to the fragmentation crisis?

- ★ Effect of the angle rotational axis/magnetic field with RMHD
- ★ Influence of the initial mass (0.01 to 10 $M_{\odot}$)
- ★ Chemistry + molecular line emission.

THANK YOU