Simulations des phases précoces de formation stellaire de faible et haute masse

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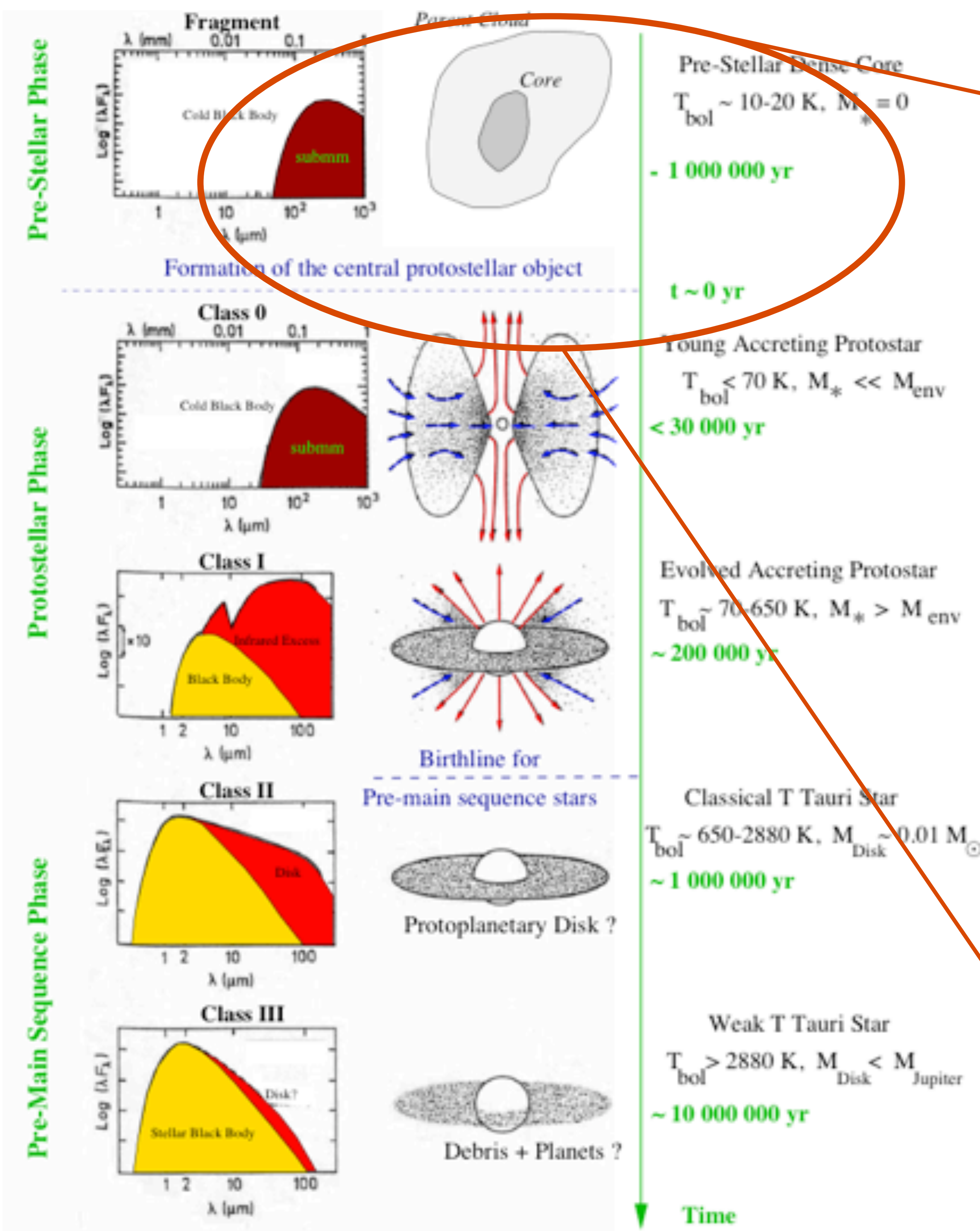
AGENCE NATIONALE DE LA RECHERCHE ANR

Outline

1. **Introduction & Methods**
2. **Low-mass stars**
   - fragmentation, disk formation
   - second collapse
   - synthetic observations
3. **Massive dense cores**
   - fragmentation inhibition by magnetic field and radiative transfer
   - observations (comparison, predictions)
4. **Conclusion and perspectives**

Empirical evolutionary sequence



André 2002

Prestellar dense core collapse

First collapse

Isothermal

First Larson core

Adiabatic

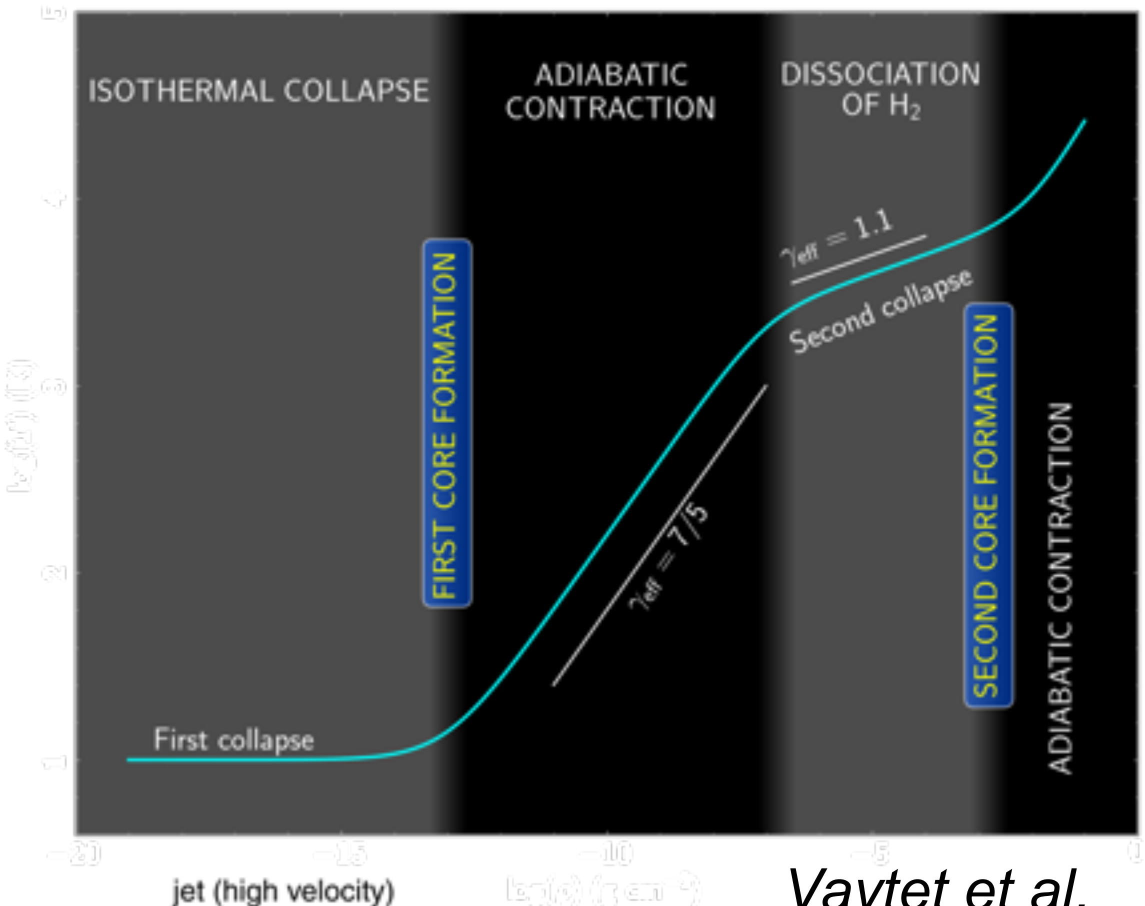
H_2 dissociation

Second collapse

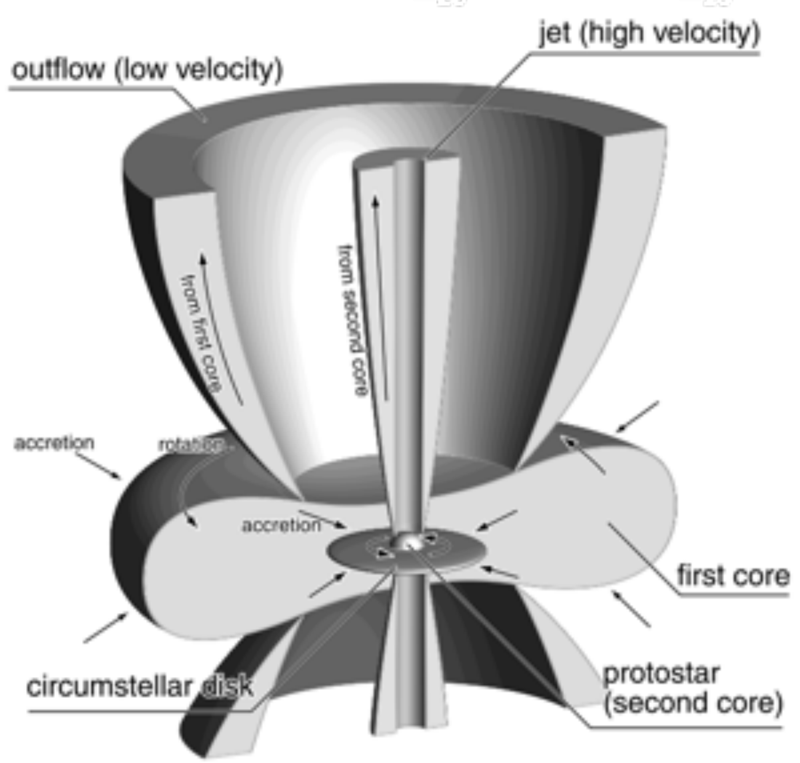
Quasi - isothermal

Second Larson core

Empirical evolutionary sequence



Vaytet et al.



Machida et al. (2010)

Prestellar dense core collapse

First collapse

Isothermal

First Larson core

Adiabatic

H_2 dissociation

Second collapse

Quasi - isothermal

Second Larson core

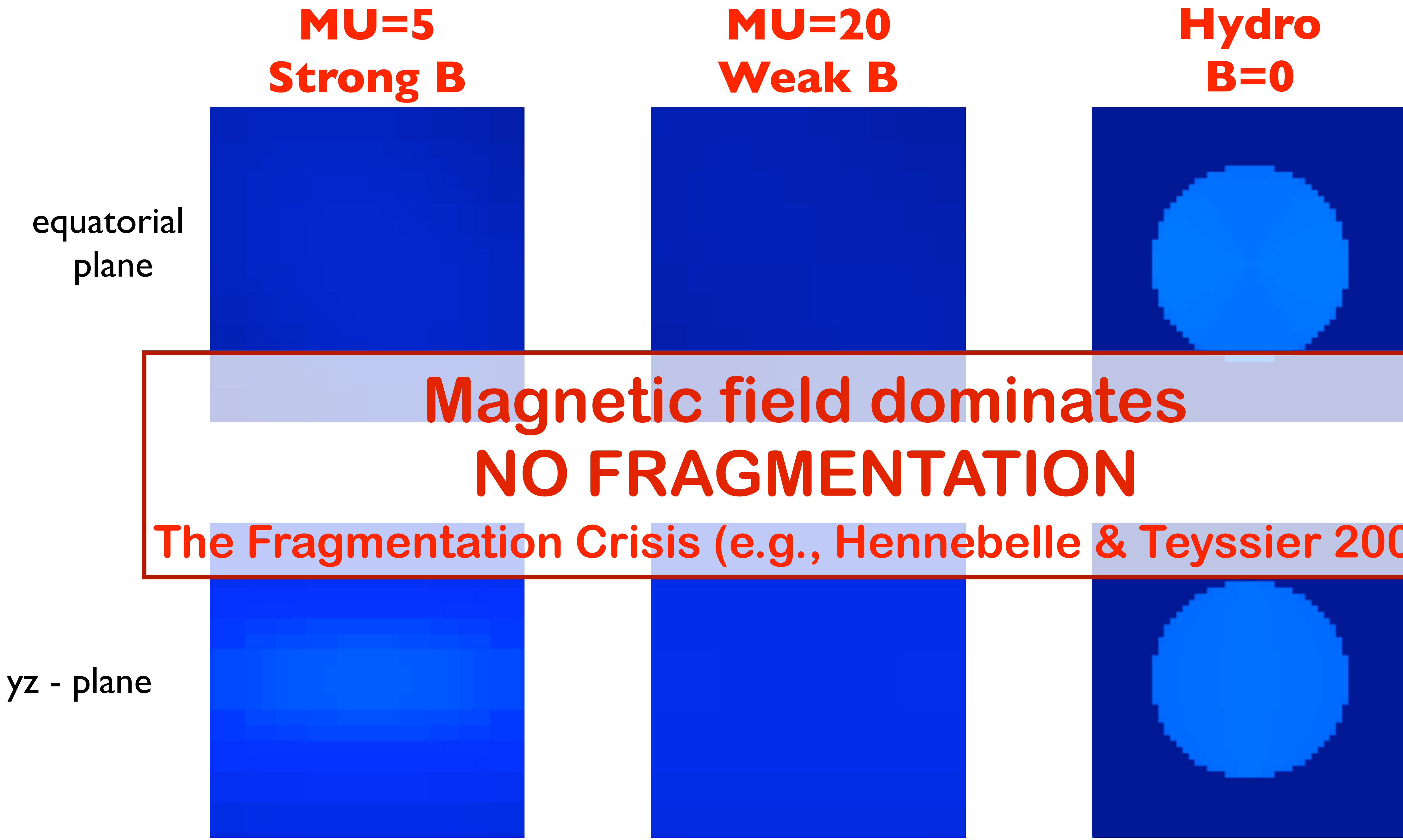
Study collapse, why?

- link between CMF and IMF, i.e., between the ISM and the stellar system, SFE
- disk formation - link to planet formation
- multiplicity:
  - ✓ when/how is it set?
  - ✓ linked to the disk formation issue
- Some of the big problems:
  - ✓ fragmentation, disk formation
  - ✓ massive star formation
  - ✓ angular momentum/magnetic flux

2010 - State of the art

- ideal MHD + barotropic EOS commonly used
- first 3D calculations with radiative transfer (grey FLD) and ideal MHD
- first collapse and first Larson core formation and evolution

Influence of the magnetization



Magnetic field dominates

NO FRAGMENTATION

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

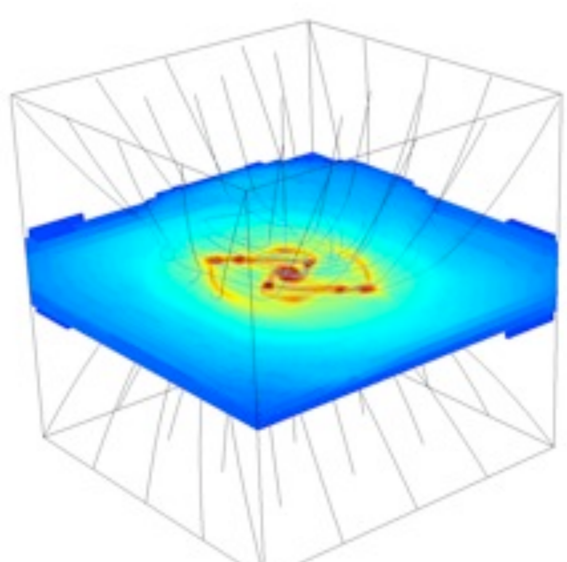
Tool developments

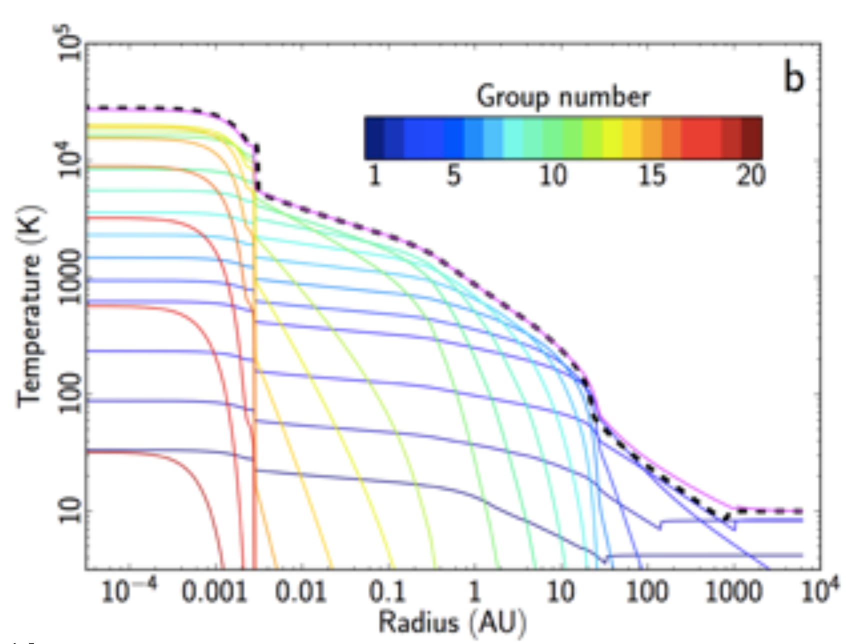
- **non-ideal MHD** in the AMR code RAMSES (*Teyssier 2002*): ambipolar diffusion, Ohmic dissipation (*Masson et al. 2012*)

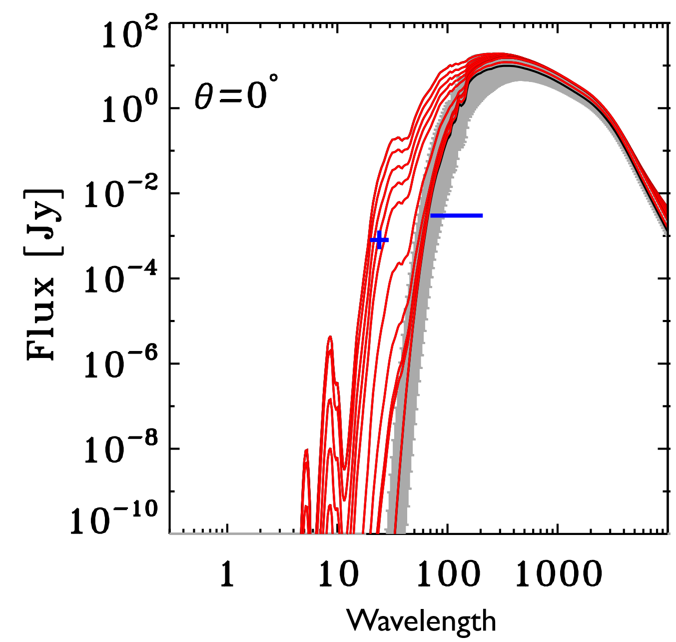
- **multigroup FLD** in 1D spherical code and in RAMSES (*Vaytet et al. 2012,2013, González et al. in prep*)

- new method for implicit schemes on AMR grids (*Commerçon et al. 2014*). Factor >5 faster for FLD + can be applied for non ideal MHD

- **interface** between RAMSES outputs and the 3D radiative transfer code RADMC-3D (*Dullemond, Heidelberg*)







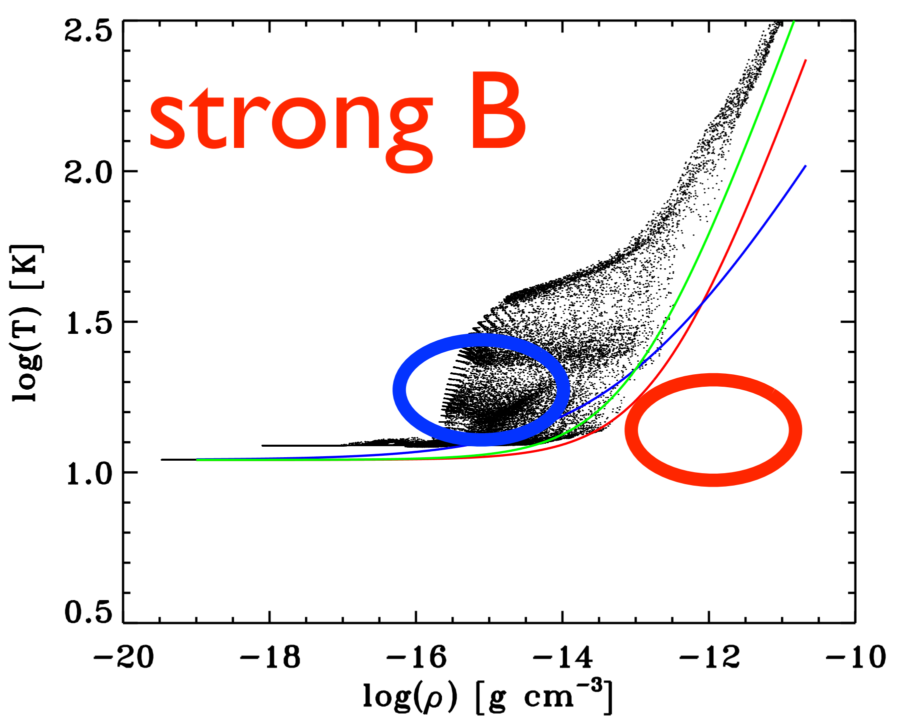
1 M☉ dense core collapse: FLD vs. barotrop

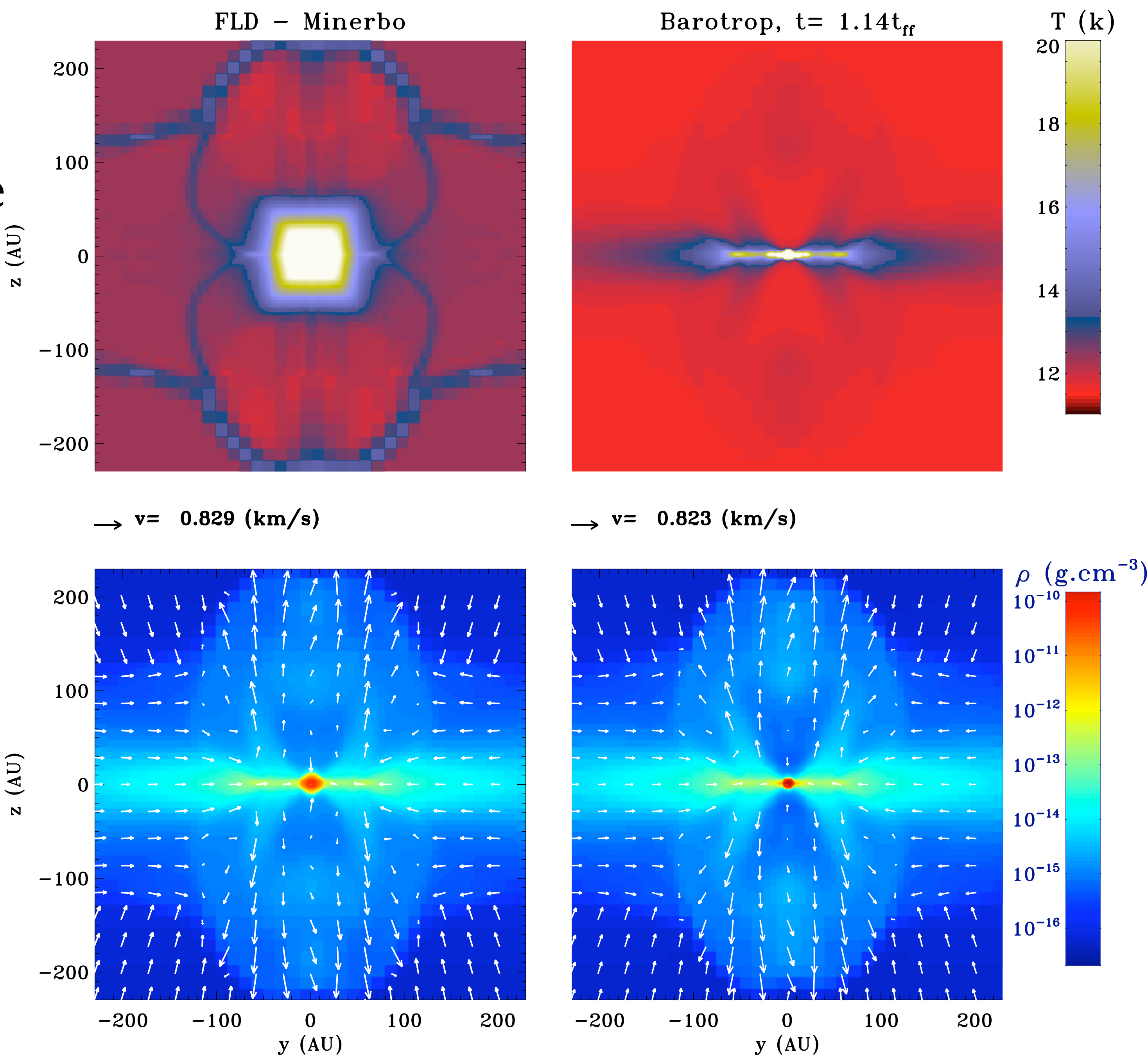
Comparison to the barotropic case

Commerçon et al. 2010, A&AL

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

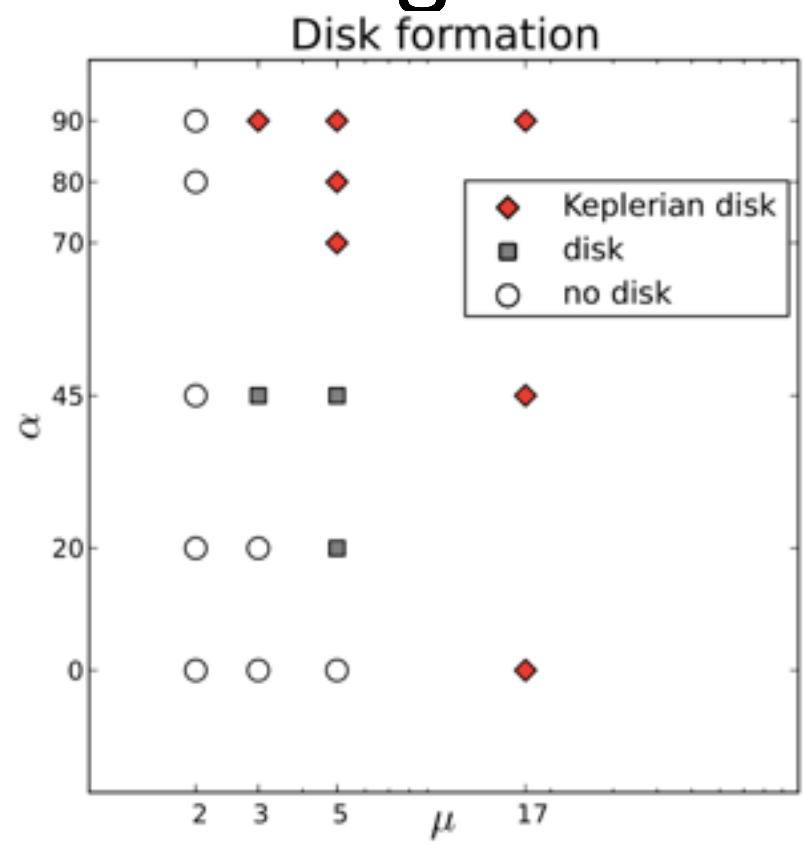
<=> **observations**



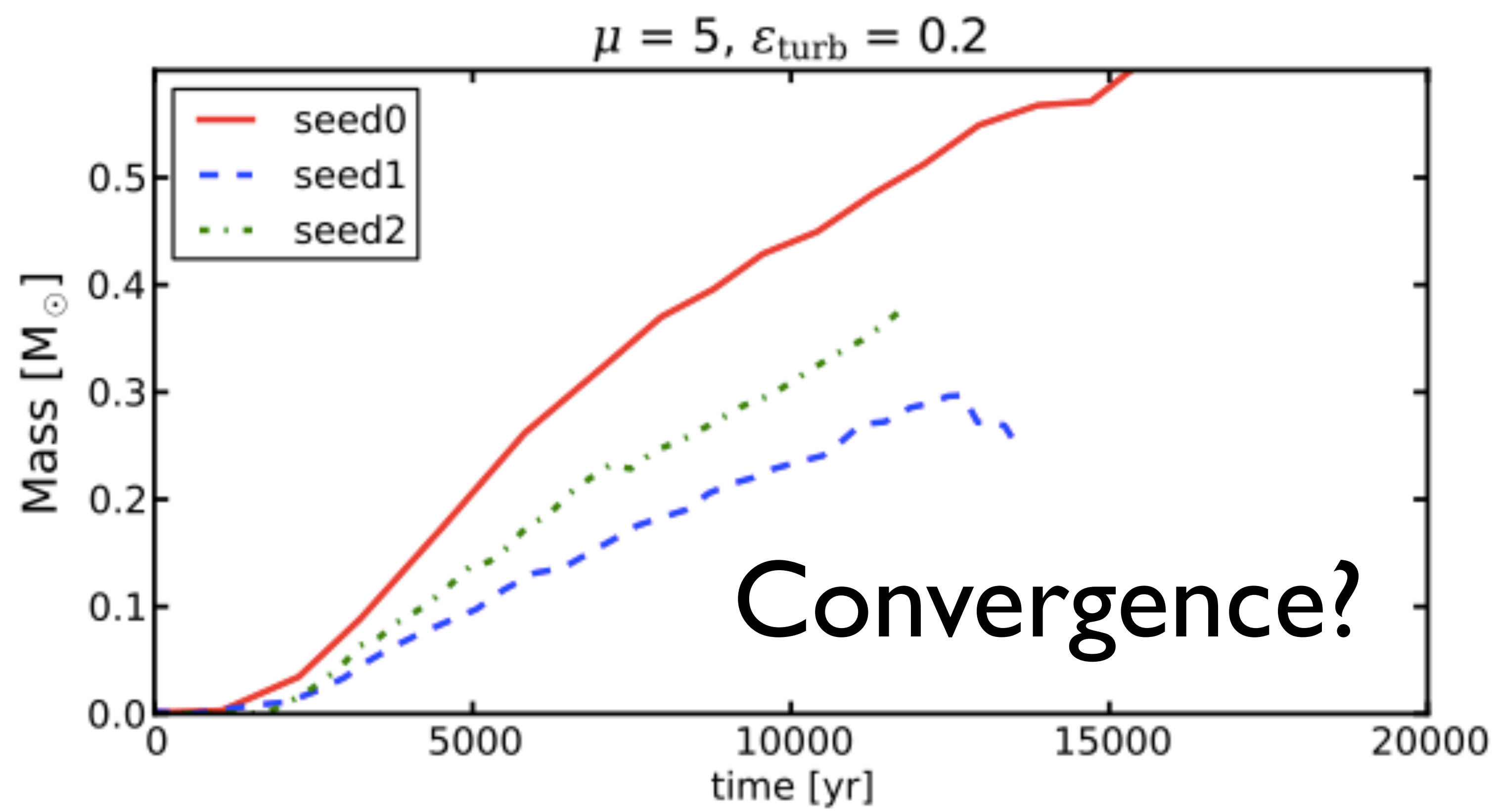


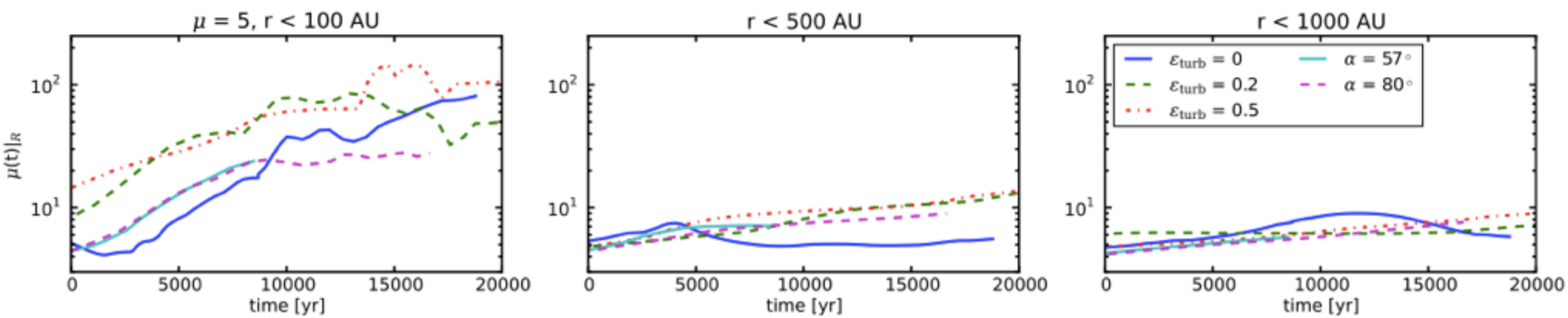
Influence of turbulence and misalignement

Misalignement



Turbulence





Joos et al. (2012, 2013)
Ciardi & Hennebelle (2011)

Influence of non-ideal MHD

Disk formation and interchange instability

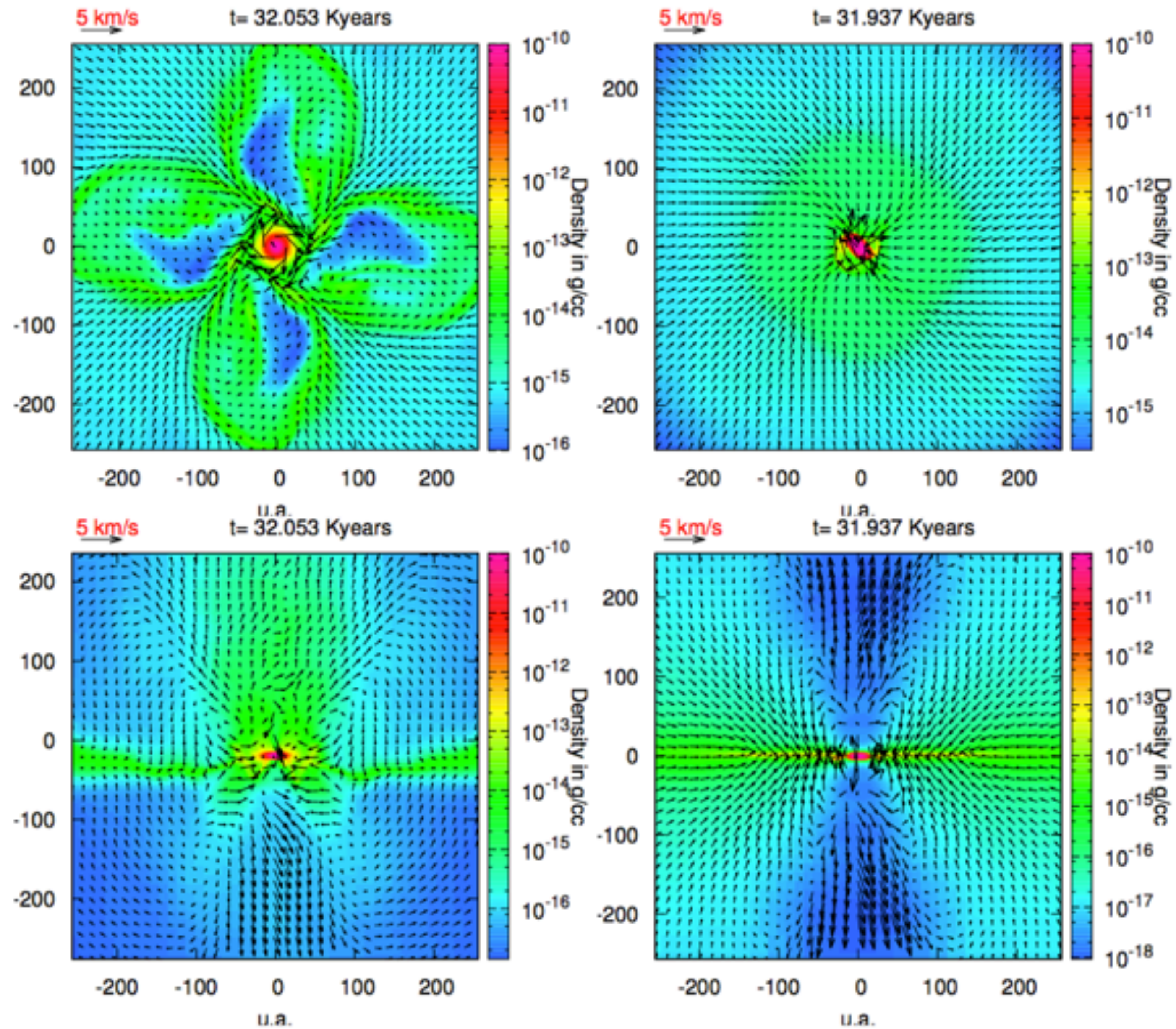
- reduce magnetic braking (suppress counter-rotation found in ideal MHD)

- similar qualitative results in the turbulent case

but

- magnetic pressure is greatly reduced in the disk with AD
- changes at the first core scale
- diffusion is *controlled*

Ideal | **Ambipolar diffusion**



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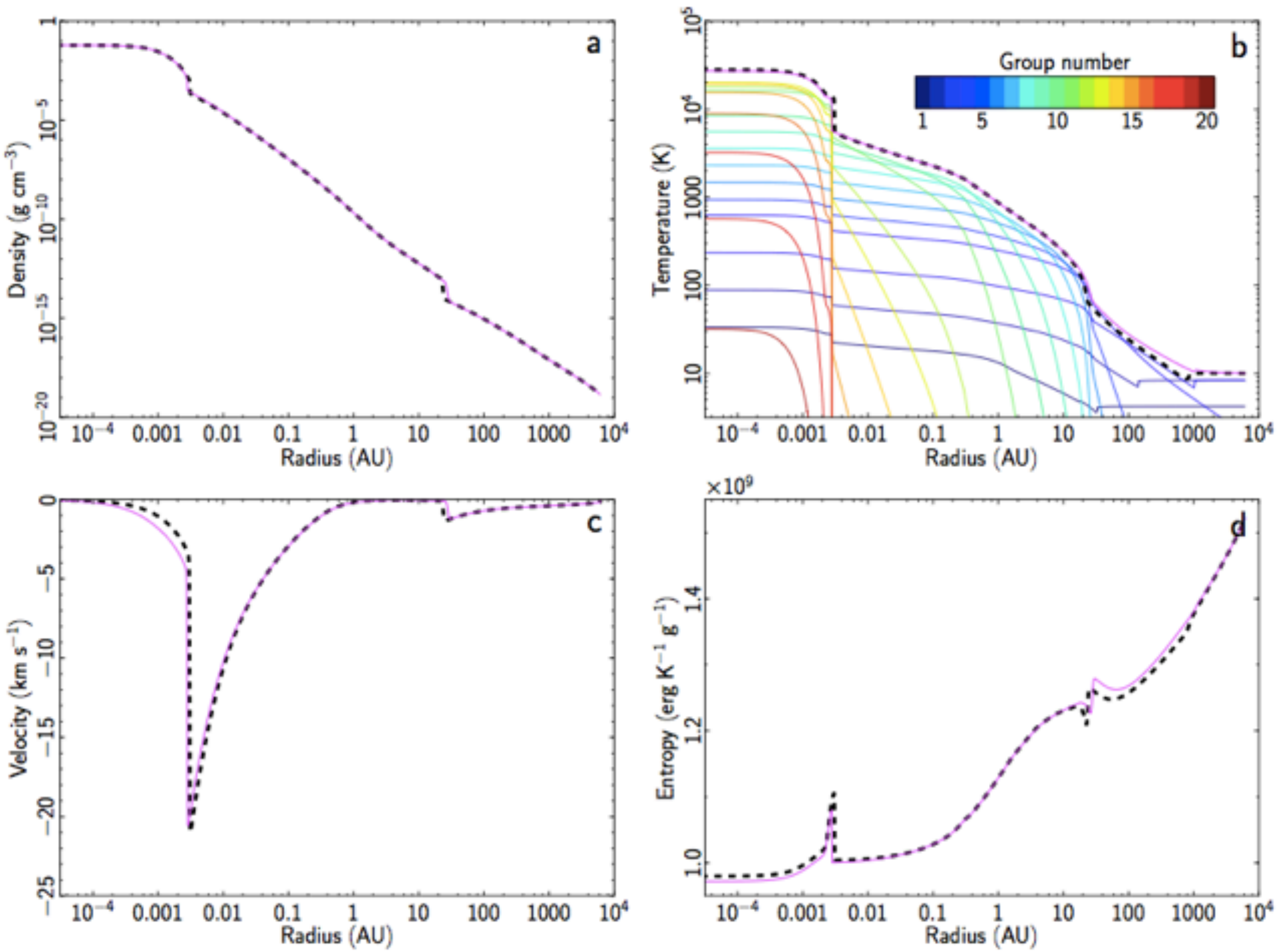
Second collapse



Vaytet et al. (2012,2013)

- grey RT does well in 1D spherical geometry

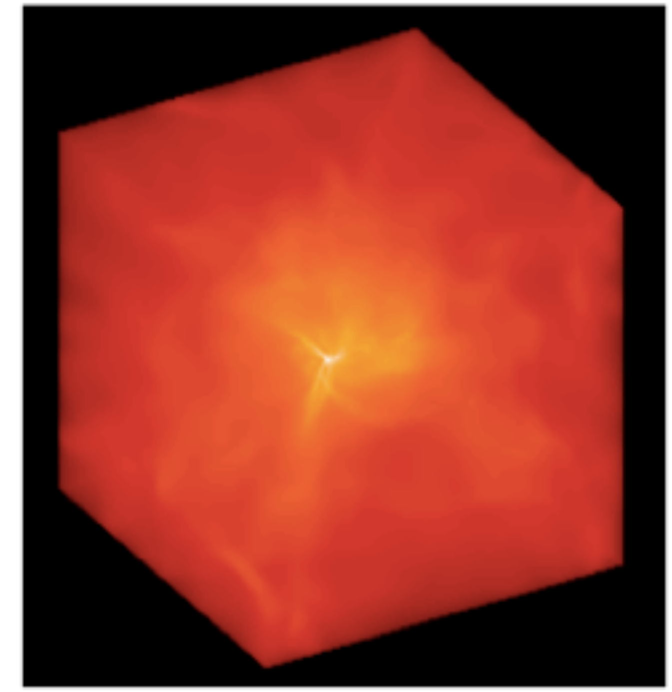
- second core accretion shock is sub-critical at the beginning (*all* is transferred to the protostar!)

- 3D is running in RAMSES. Stay tuned!

Synthetic observations

3D radiative transfer

interface with the 3D radiative transfer code RADMC-3D (*Dullemond*, ITA-Heidelberg, Germany) to postprocess the RAMSES calculations.



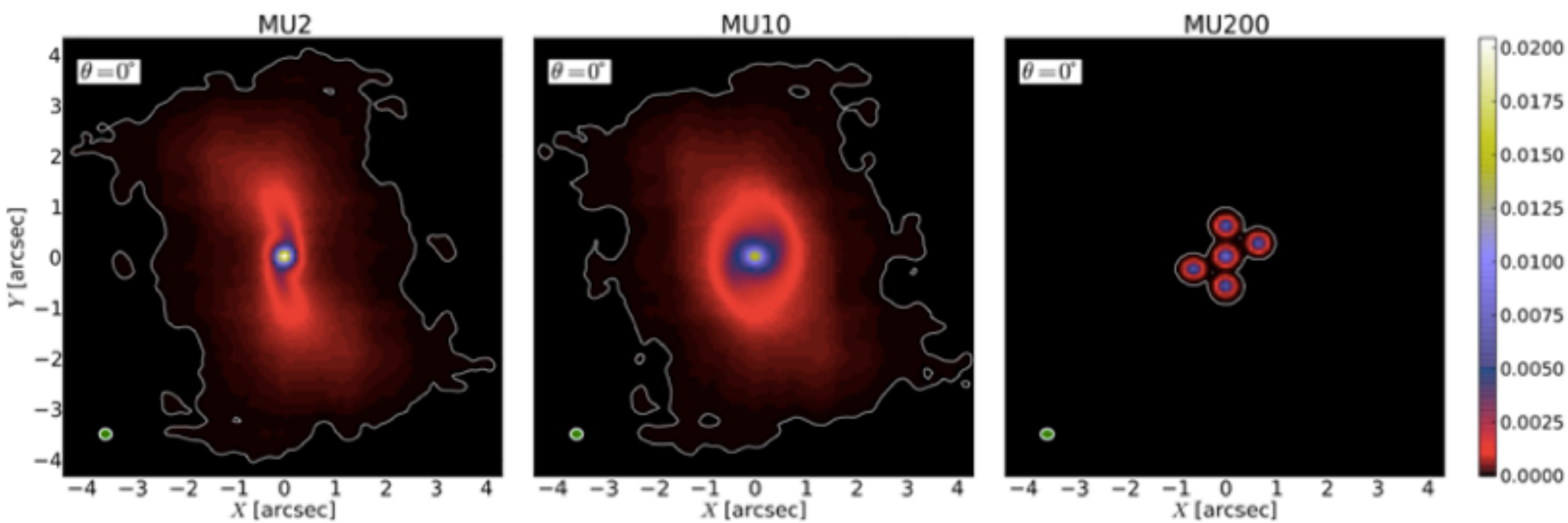
★ RADMC-3D features:

- dust continuum emission
- line emission

★RADMC-3D outputs:

- dust emission maps
- spectral energy distribution
- line emission maps/profiles

ALMA PREDICTIONS



Commerçon et al. (2012b)

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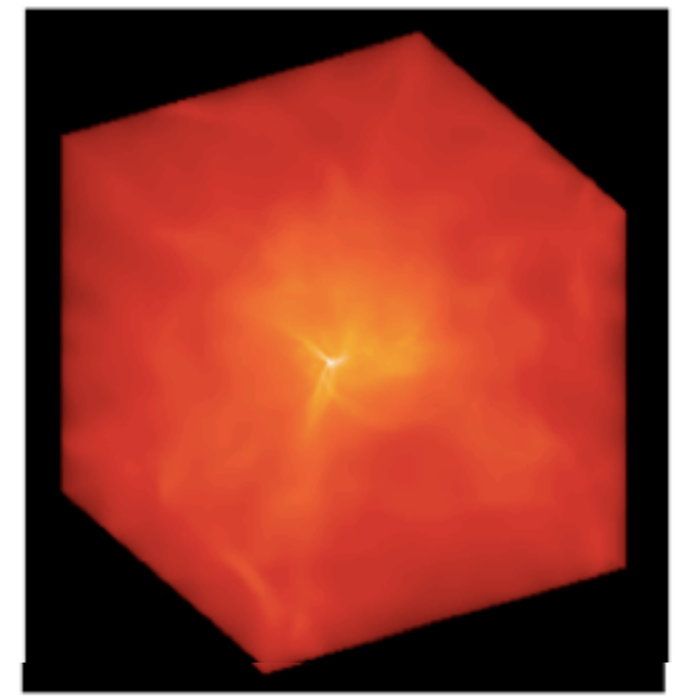

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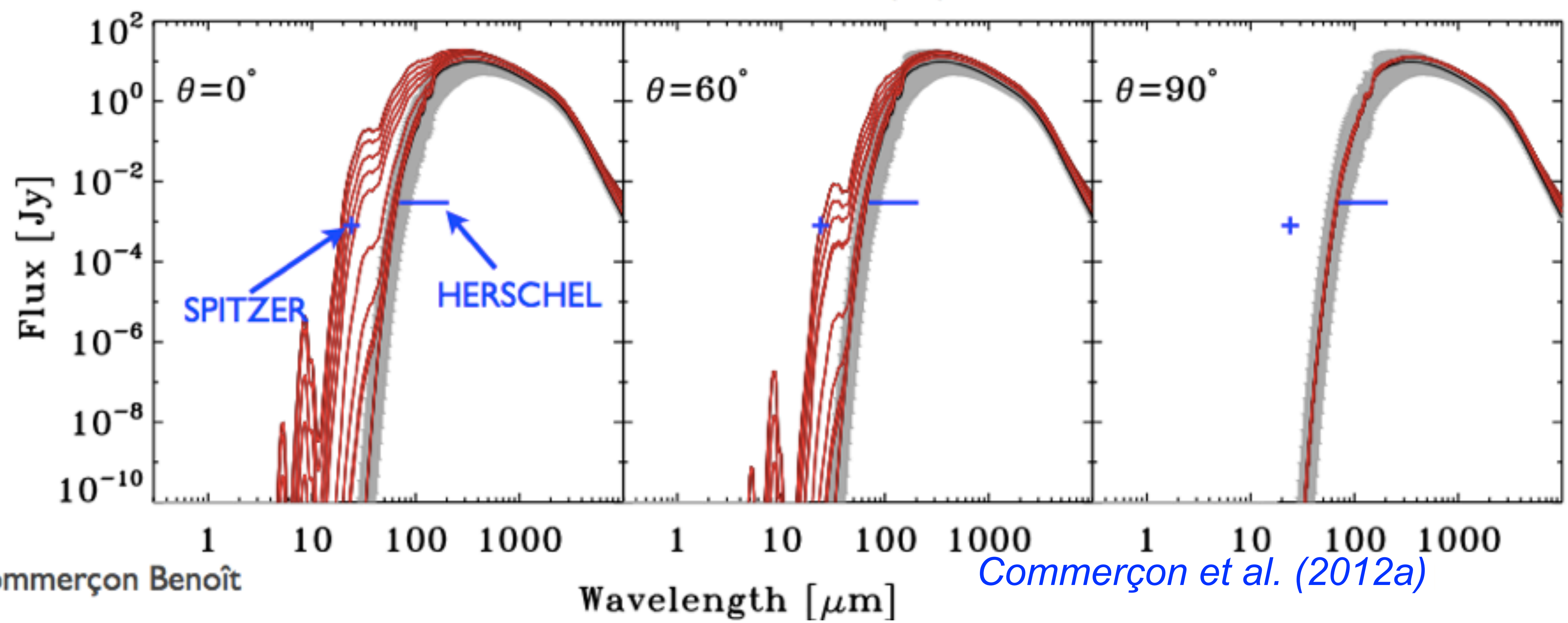
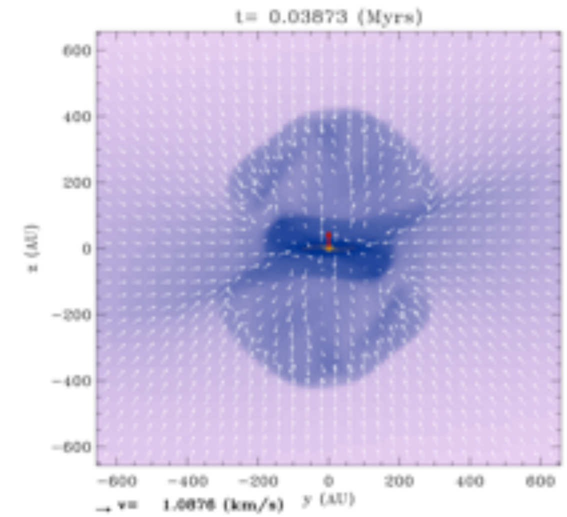


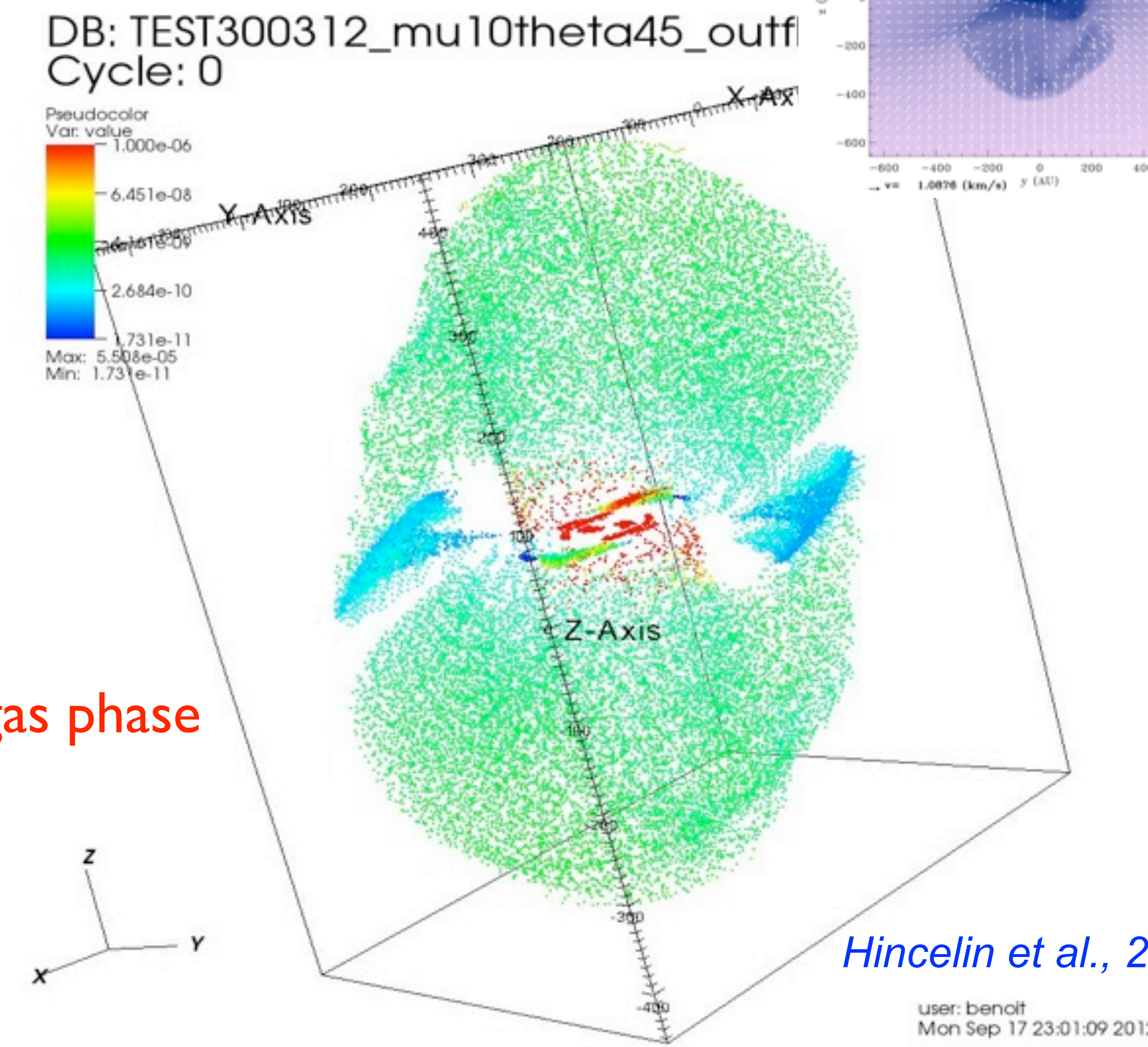
Commerçon et al. (2012a)

Chemical composition

- 10^6 tracer particles & store position, temperature & density
- Compute the chemistry using the Bordeaux **NAUTILUS** gas-grain chemistry code (655 species, >6000 reactions)
- 50 000 CPU hours for chemistry

=> Access to the 3D abundances within the collapsing dense cores





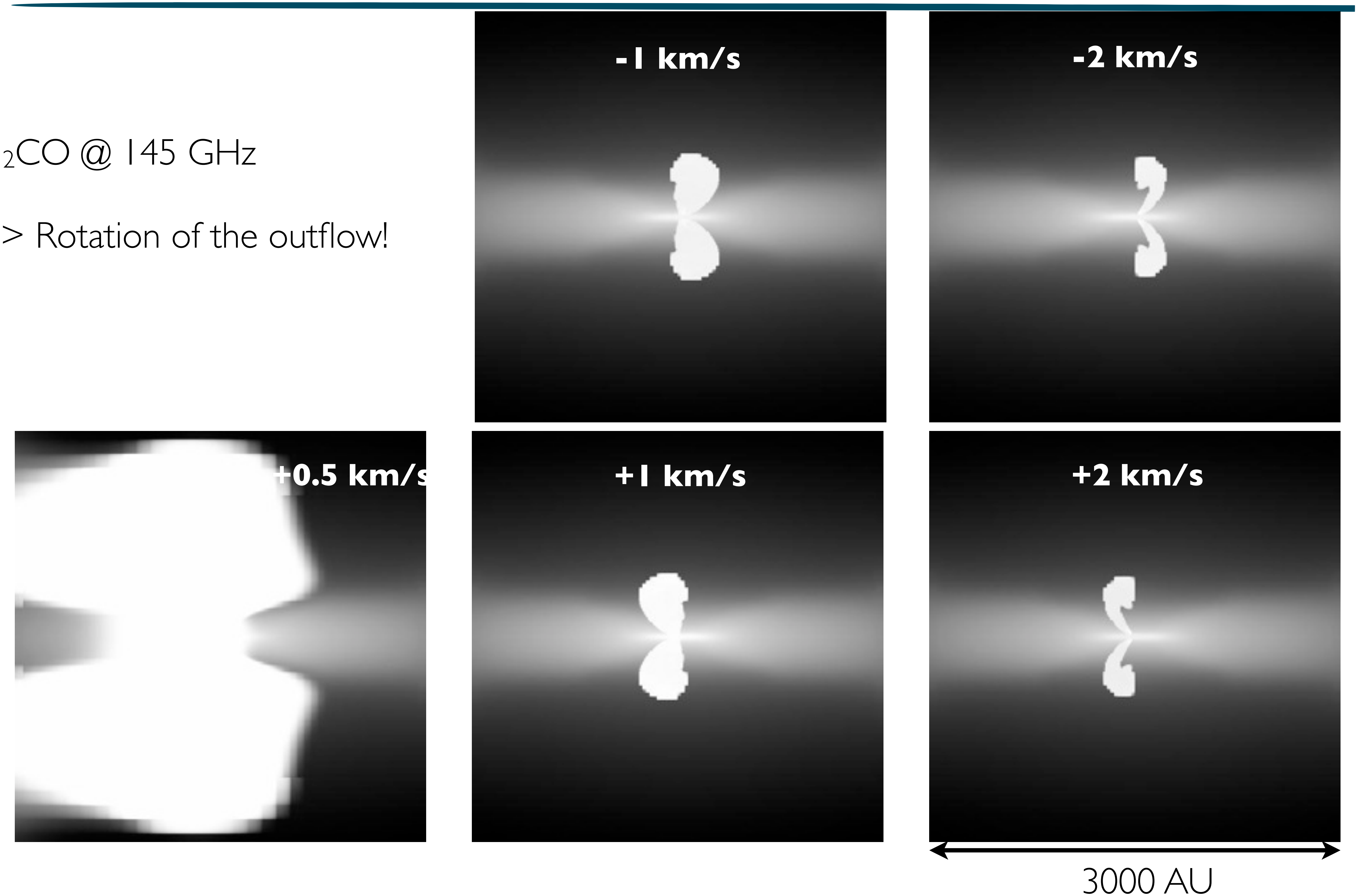
CO abundance in the gas phase

Hincelin et al., 2013

Line emission (under progress)

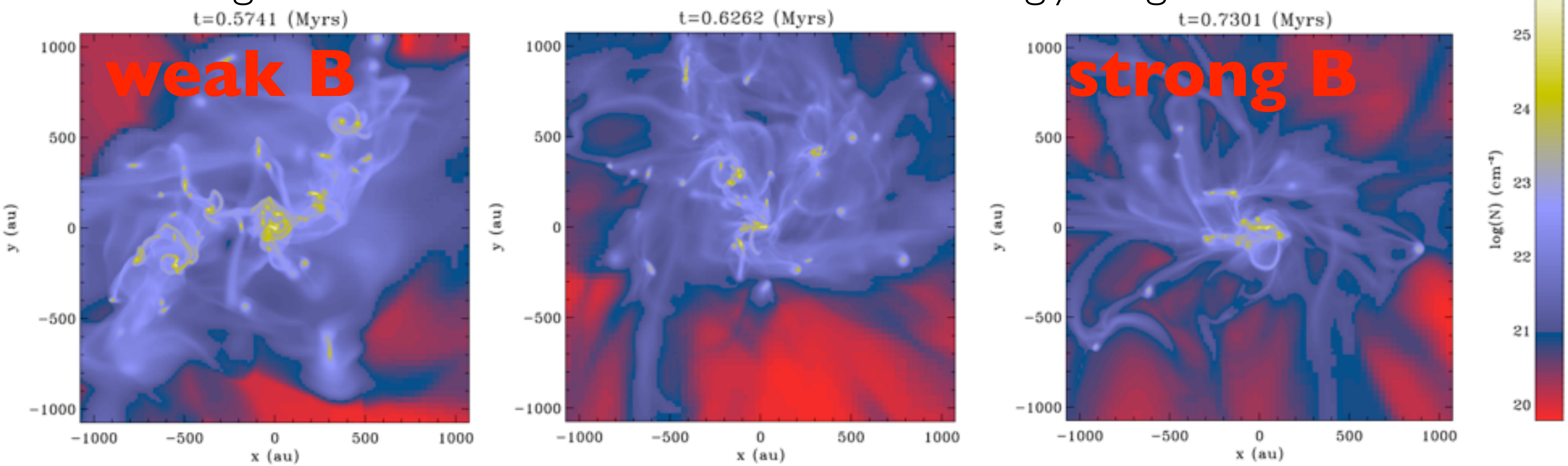
H_2CO @ 145 GHz

=> Rotation of the outflow!



100 $M_\odot$ turbulent dense core collapse

✓ Magnetic fields alone reduced fragmentation by a factor ~2
✓ Fragmentation zone is less extended in strongly magnetized cores

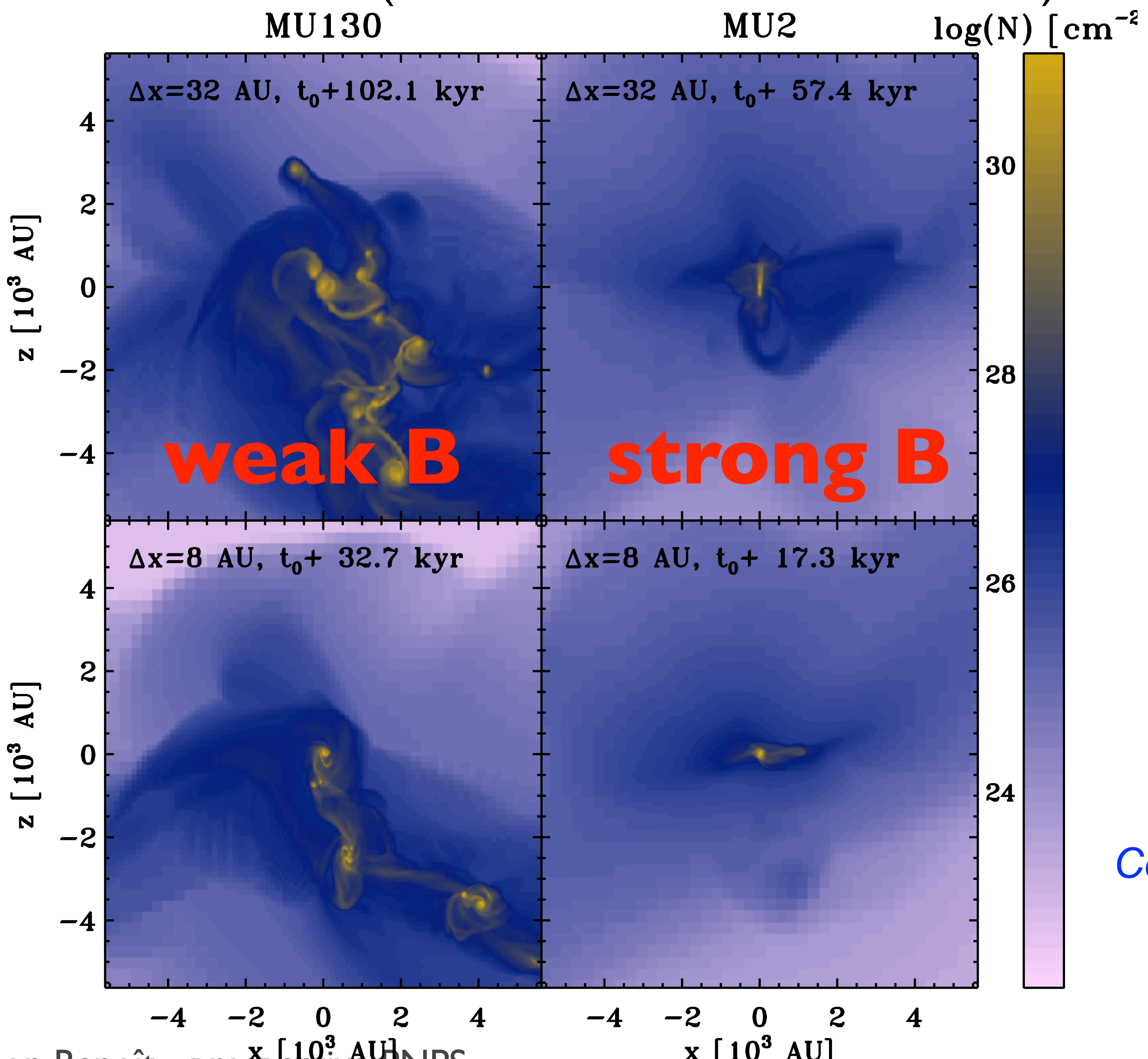


μ=120 μ=5 μ=2

Hennebelle et al. (2011)

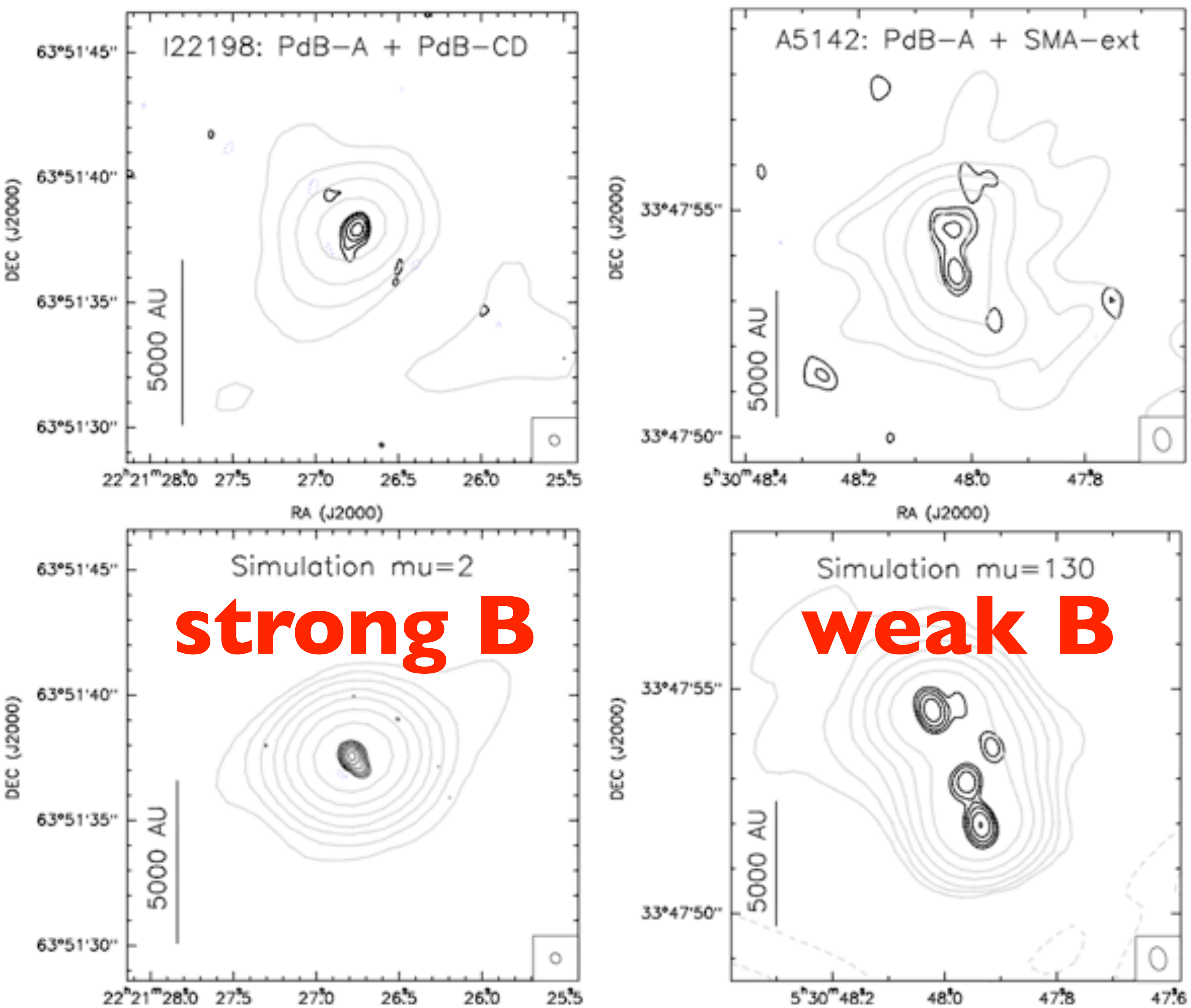
100 $M_\odot$ turbulent dense core collapse

- ✓ Early fragmentation suppressed with magnetic fields (large scale) & radiative transfer (small scales < a few 100 AU)

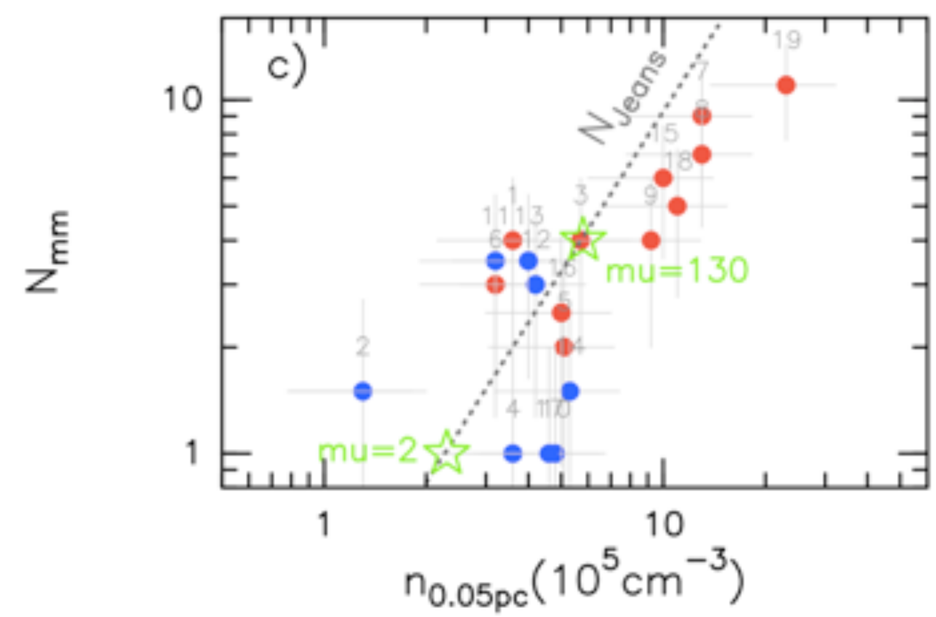


Commerçon, Hennebelle & Henning, 2011, ApJL

100 $M_\odot$ turbulent dense core collapse



- Simulations reproduce remarkably well observations, but... for both the strong and weak magnetized cases.
- find only one correlation for the number of mm-clumps versus the density at 0.05 pc, i.e., the denser the more fragmented.

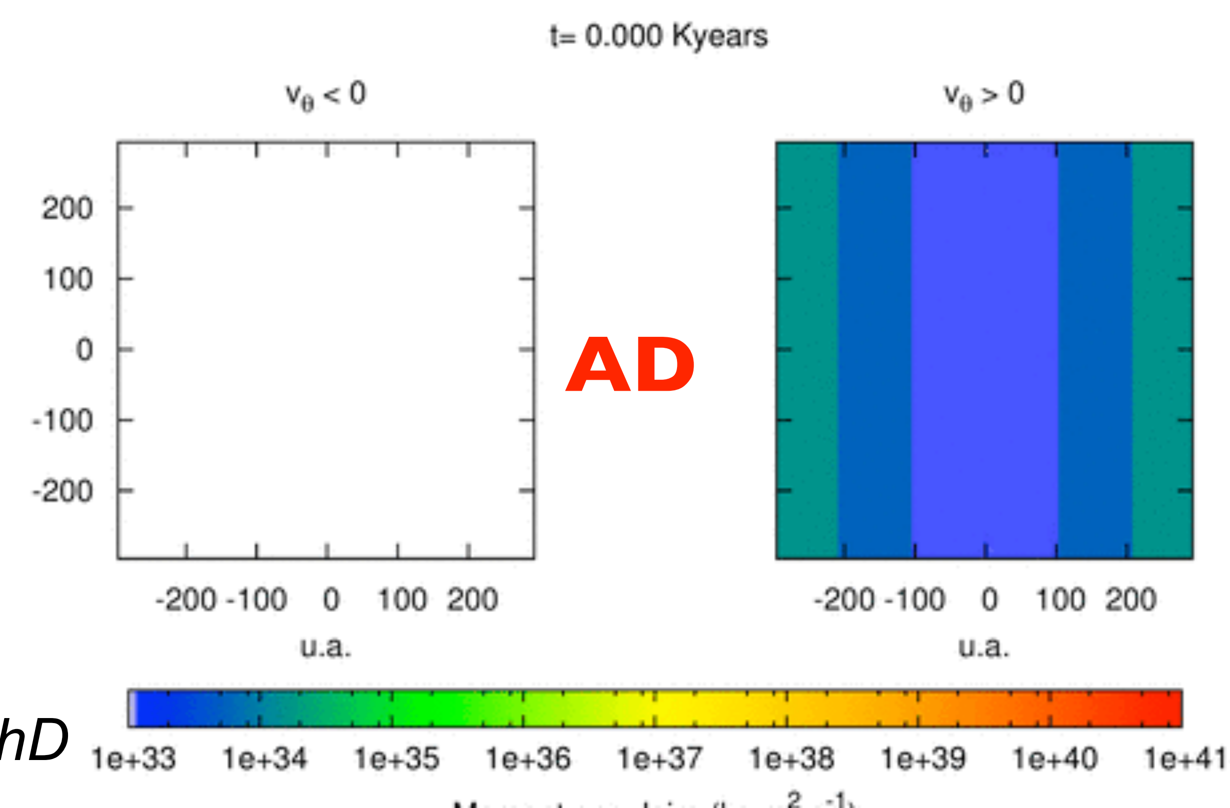


Palau et al., 2013 & 2014, ApJ

Take Away for SF

- ✓ Magnetic field and radiative transfer cannot be neglected
- ✓ Strong interplay between magnetic braking and radiative feedback
- ✓ Disk can form but do not fragment
- ✓ Ideal MHD has strong limitation on the horizon of predictability

Ideal



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Conclusions & perspectives

- ➡ Powerful tools with a lot of physics: non ideal MHD, radiative transfer and chemistry
- ➡ Direct comparison between observations and 3D models (tracer particles)
- ➡ What next?
  - ★ initial conditions
  - ★ more statistics, IMF
  - ★ second collapse in 3D
  - ★ coupling chemistry (MHD, cooling/heating), cosmic ray
- ➡ Link to planet formation via disk formation issue and chemistry

THANK YOU