3D numerical calculations and synthetic observations of magnetized dense core collapse and fragmentation

Commerçon Benoît

LERMA/LRA - ENS Paris - CNES & ANR fellowships

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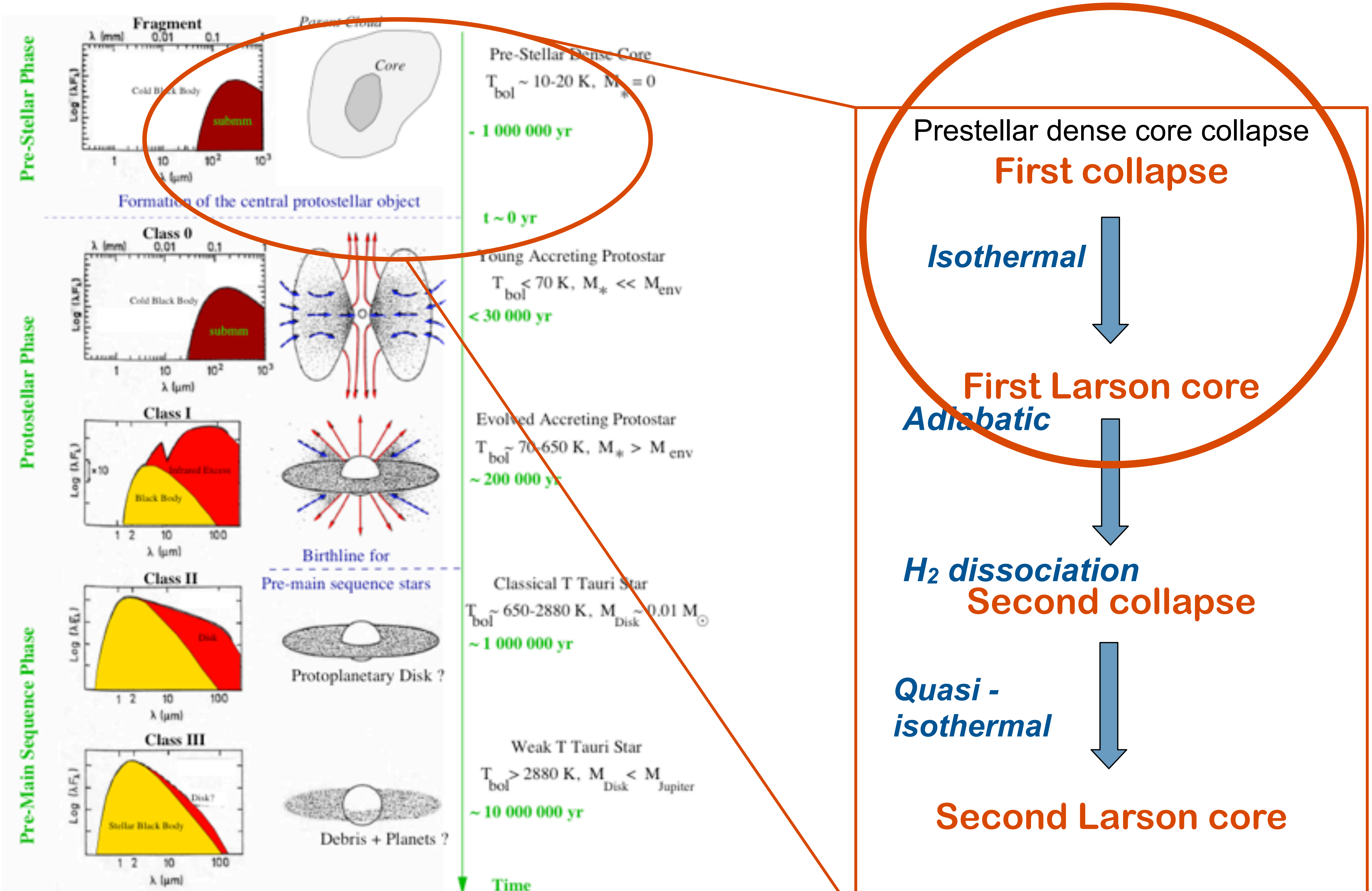
cnes

AGENCE NATIONALE DE LA RECHERCHE ANR

Outline

1. **Introduction & Methods**
2. **Low-mass star formation: synthetic observations of first Larson cores**
   - The fragmentation crisis & disk formation issue
   - SED and dust emission maps
   - ALMA predictions
3. **Massive dense cores collapse**
   - Early fragmentation inhibition
   - ALMA predictions
4. **Conclusion**

Star formation evolutionary sequence

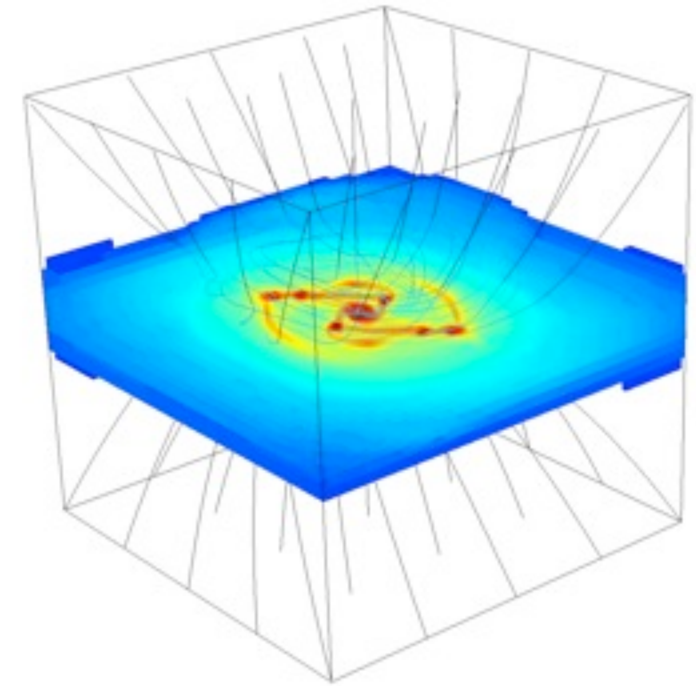


André 2002

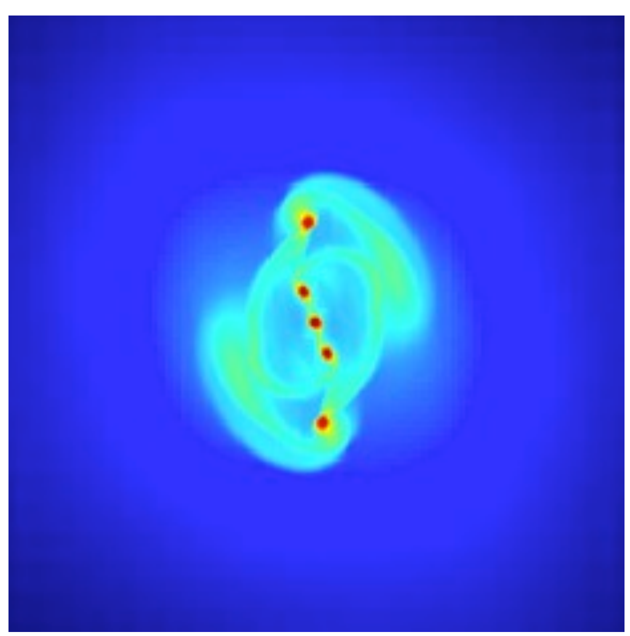
RMHD with Flux Limited Diffusion in RAMSES

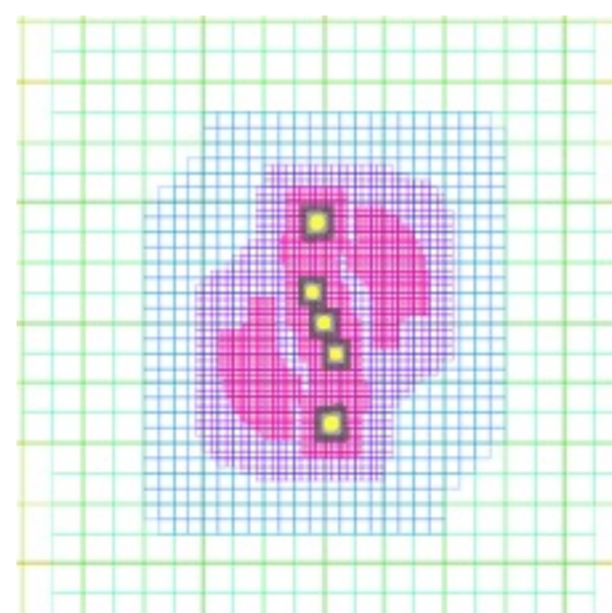
✓ **RAMSES code** *(Teyssier 2002)*

- AMR code, 2nd order Godunov scheme
- Ideal MHD solver (*Fromang et al. 2006*)
- RHD solver with the Flux Limited Diffusion (*Commerçon et al. 2011b*)
- Self-gravity
- Jeans length refinement criteria (>10 pts/λ_J)



Density





Grid

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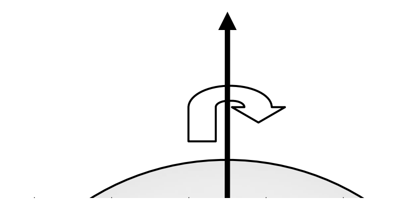
Initial conditions (numerical experiment)

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

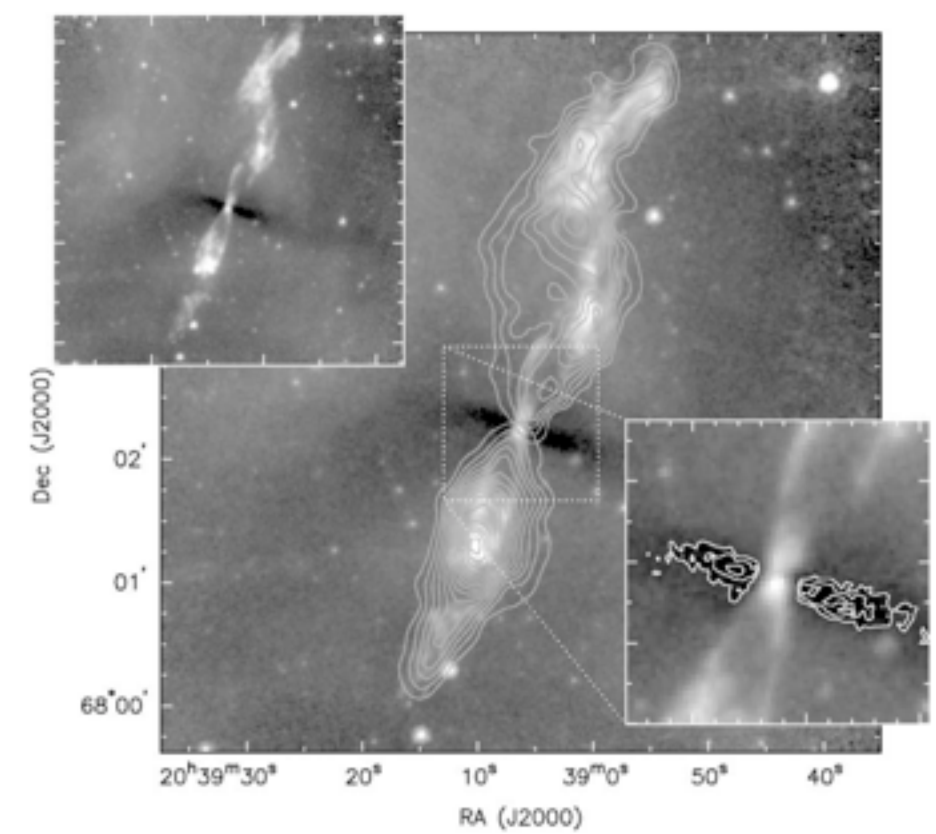


★ **Radiative transfer:** efficient cooling (*Attwood et al. 09*) and heating (*Krumholz et al. 09, Bate 09*).
Grey opacities from Semenov et al. 03.

★ **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 $\mu \sim 2\text{-}5$)



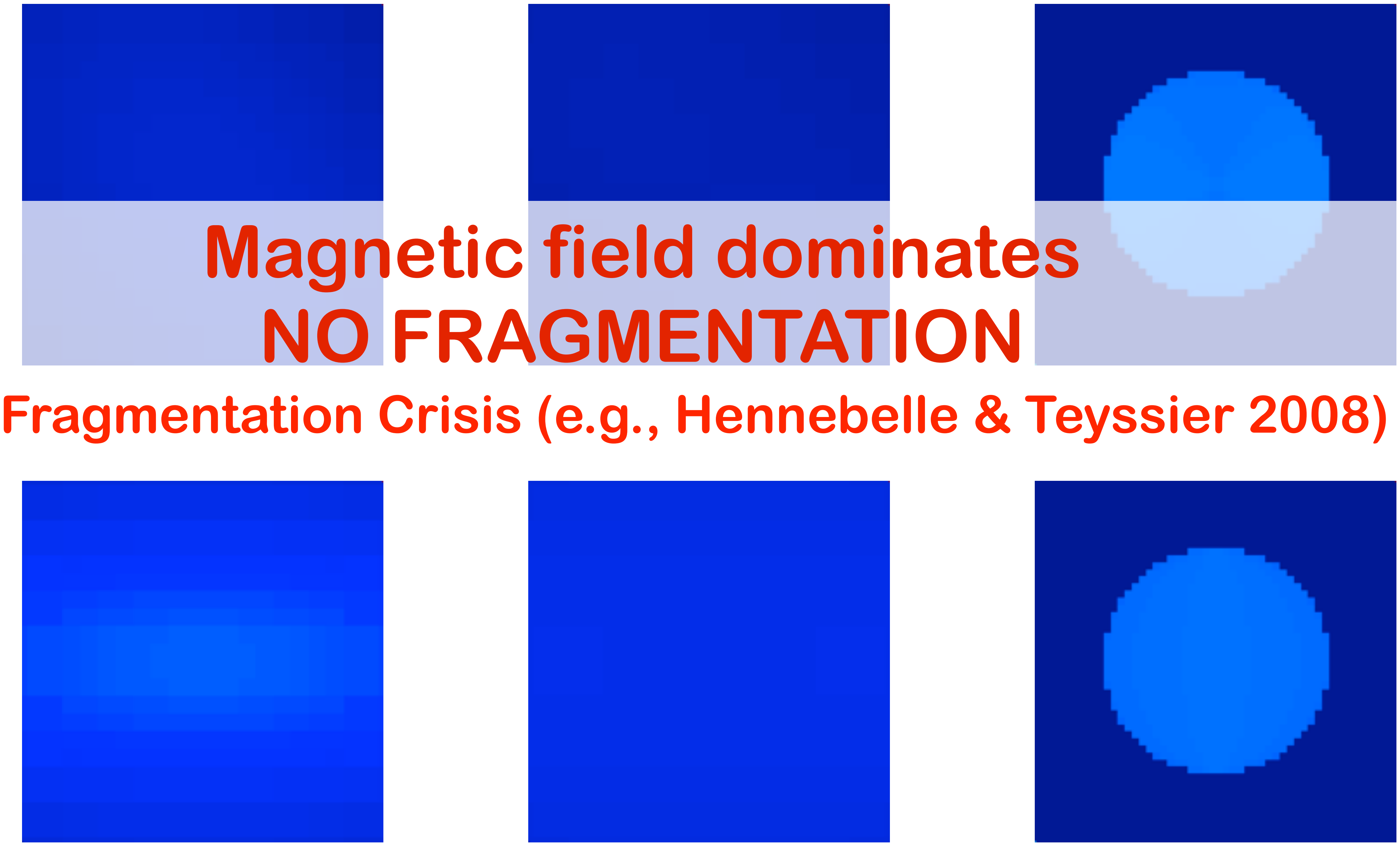
Looney et al. 2007

Influence of the magnetization

MU=5 Strong B | **MU=20 Weak B** | **Hydro B=0**

equatorial plane

yz - plane



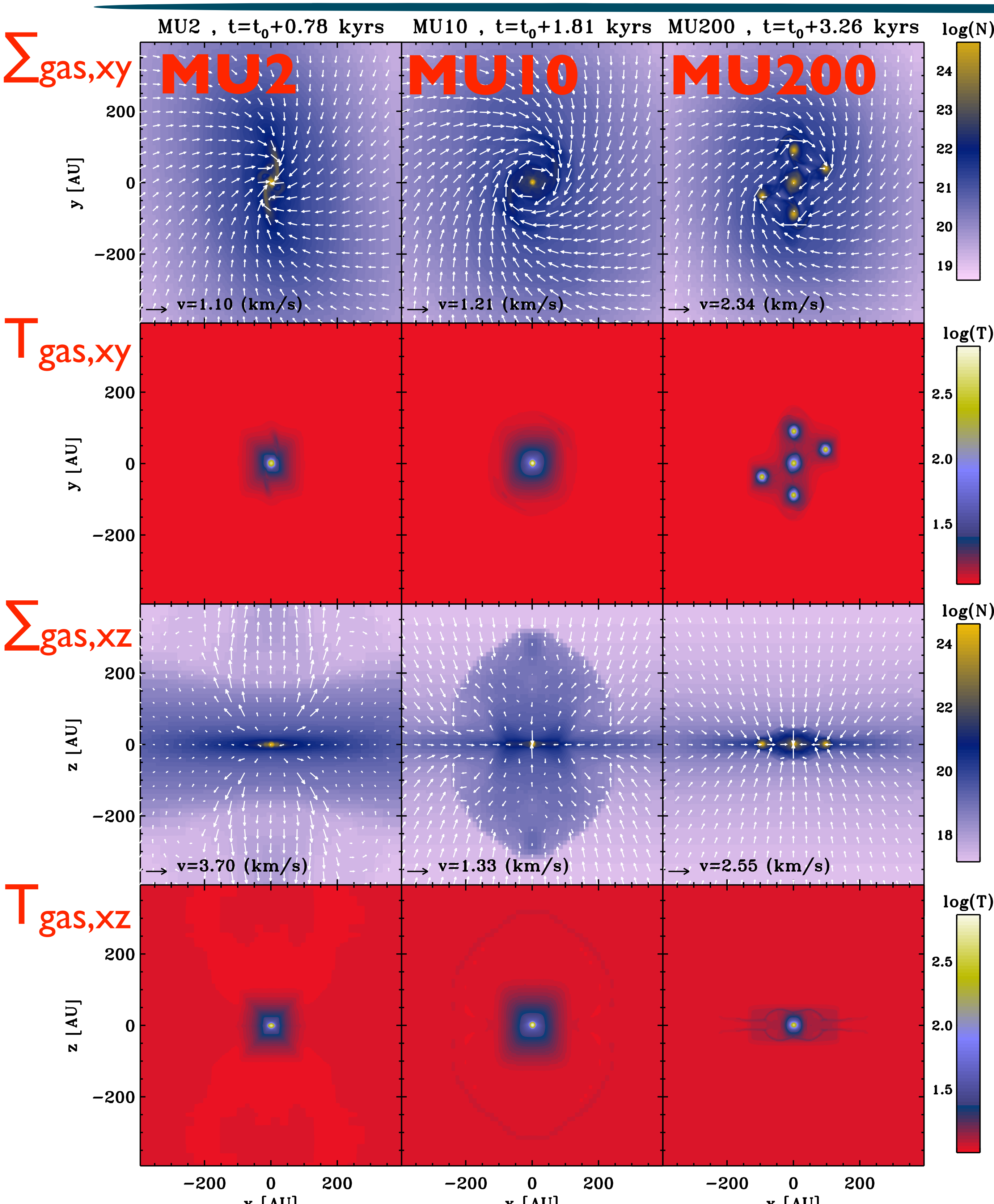
Magnetic field dominates
NO FRAGMENTATION

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

Take Away I

- ✓ Magnetic field cannot be neglected (*e.g. Hennebelle & Teyssier 2008, Commerçon et al. 2010, Seifried et al. 2011, Joos et al. 2012*)
- ✓ Fragmentation crisis at the Class 0 stage for low-mass star formation - No massive and fragmenting disk
- ✓ Supported by observations (*e.g. Maury et al. 2010*)

Towards synthetic observations



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

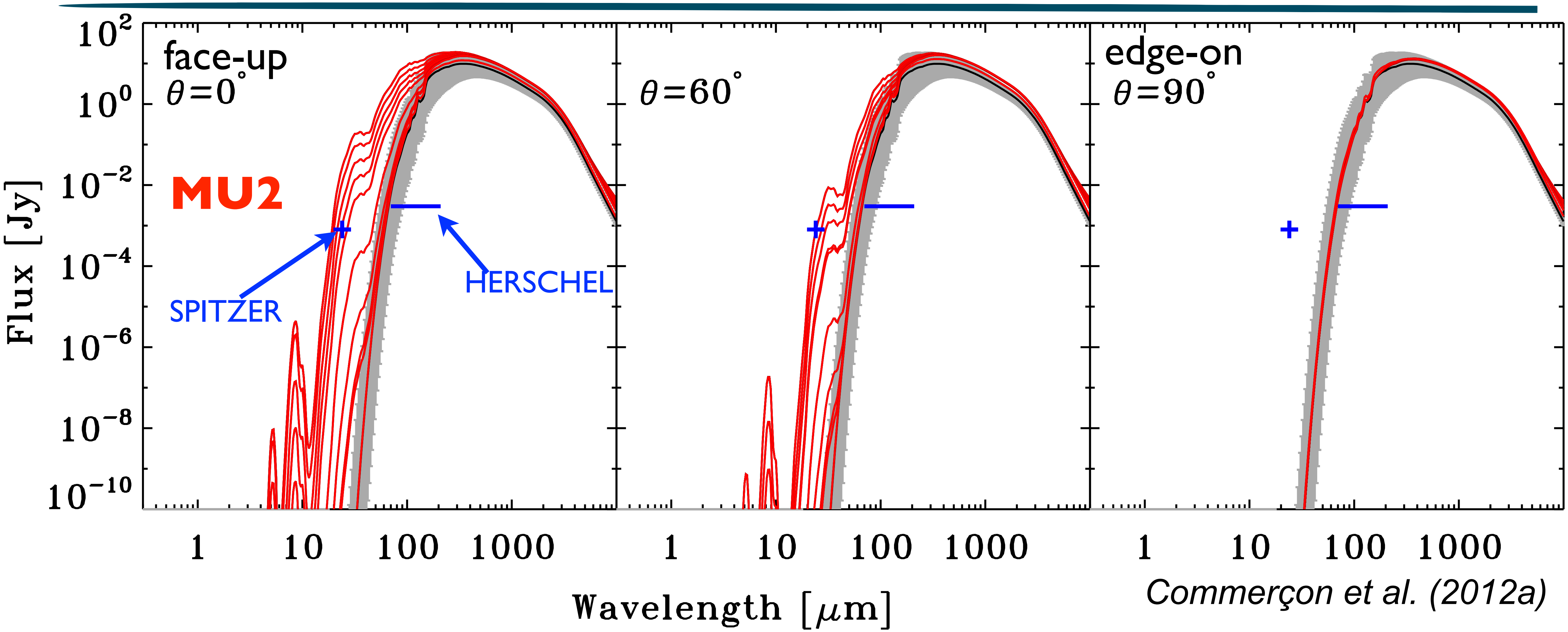
- First core lifetime:

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, Dullemond & Henning, A&A 2012a

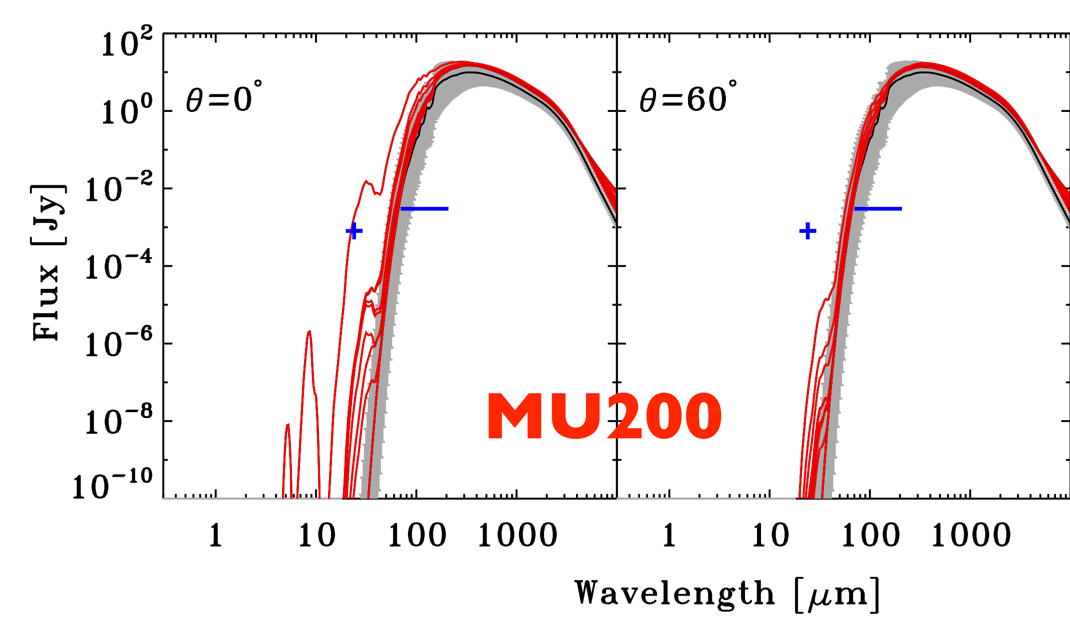
SED - Do we see a first core signature?



Commerçon et al. (2012a)

- *Objects at 150 pc, 3000 AU x 3000 AU region*
- *Prestellar core = initial conditions (black line)*
- Emission in the FIR => HERSCHEL, SPITZER
- But similar SEDs in the MU200 model, i.e. **with a disk**!

=> Issues in SED-fitting models for early Class 0?



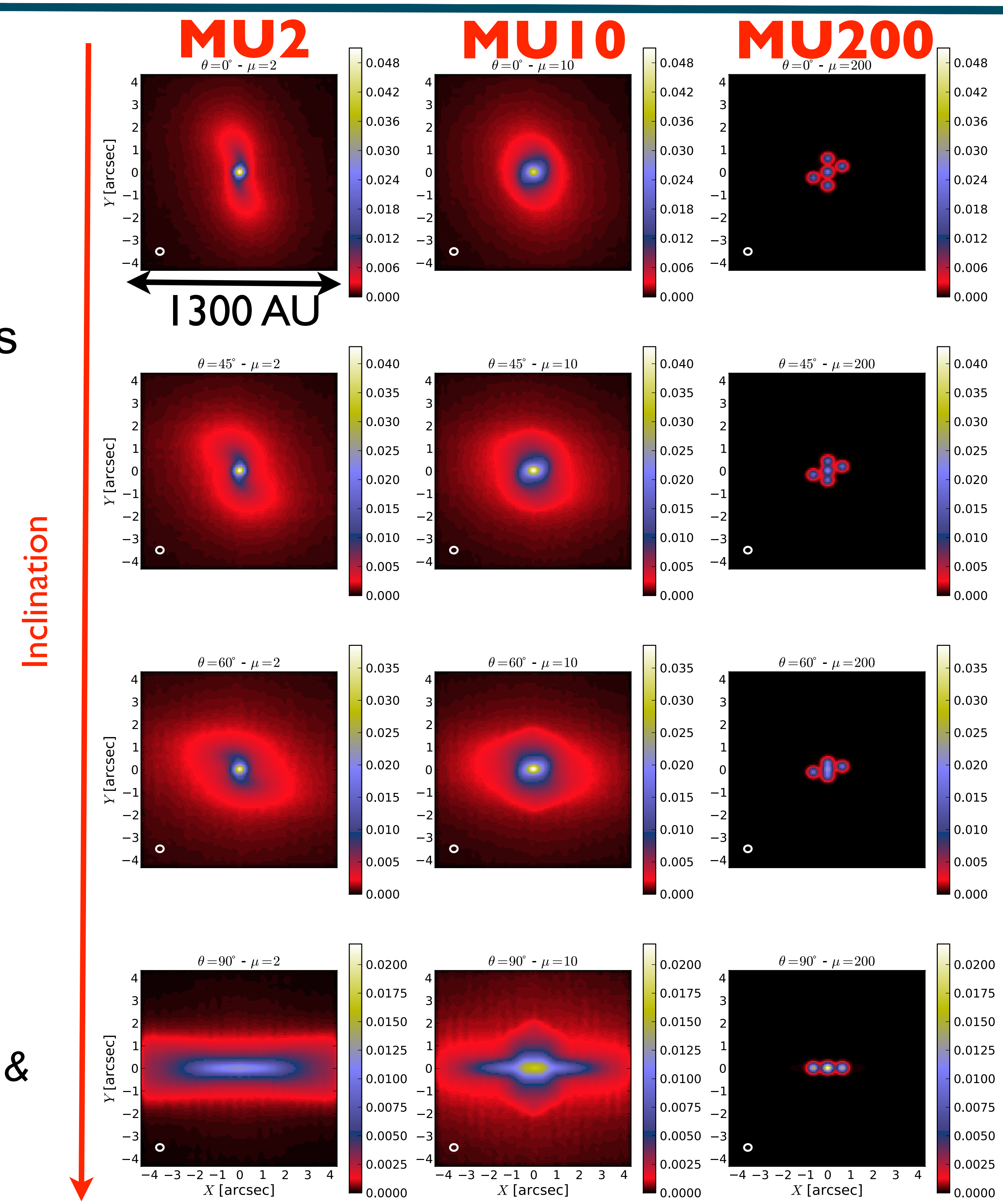
Help to select first core candidates & to distinguish starless cores and first cores

Synthetic ALMA dust emission maps

- GILDAS IRAM simulator

- Different bands and configurations tested

ALMA Band 4 Config 15 @150 pc



Commerçon, Levrier, Maury, Henning & Launhardt (2012b)

Take Away II

- ✓ First core candidates can be identified with compact emission at wavelength 20 μm< λ < 100 μm
- ✓ ALMA will give an answer to the fragmentation problem

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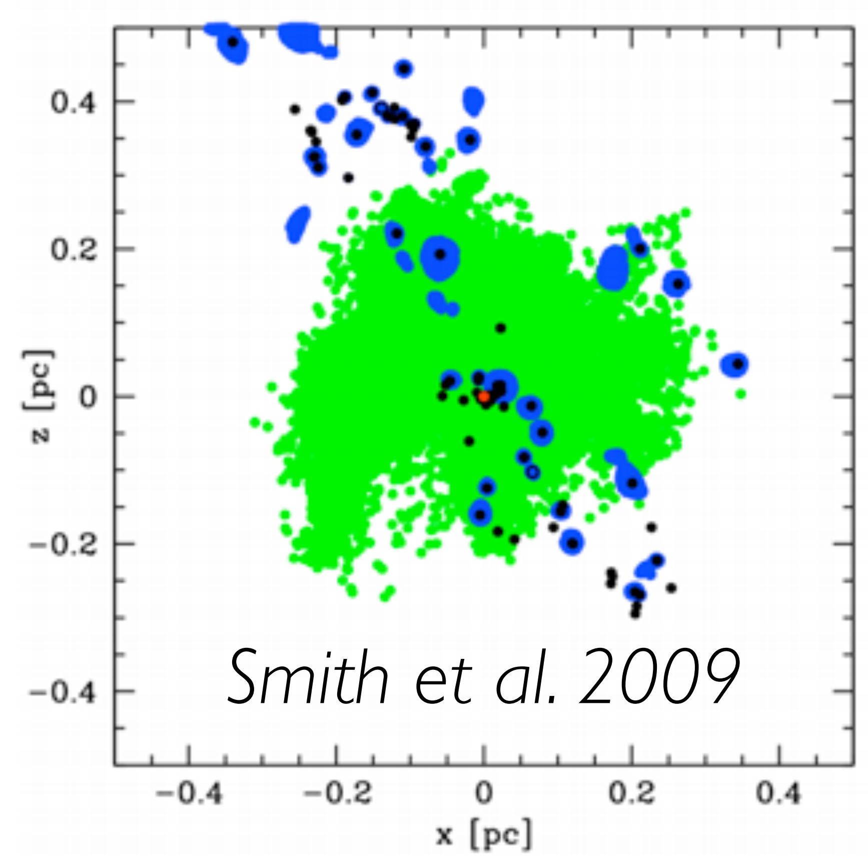
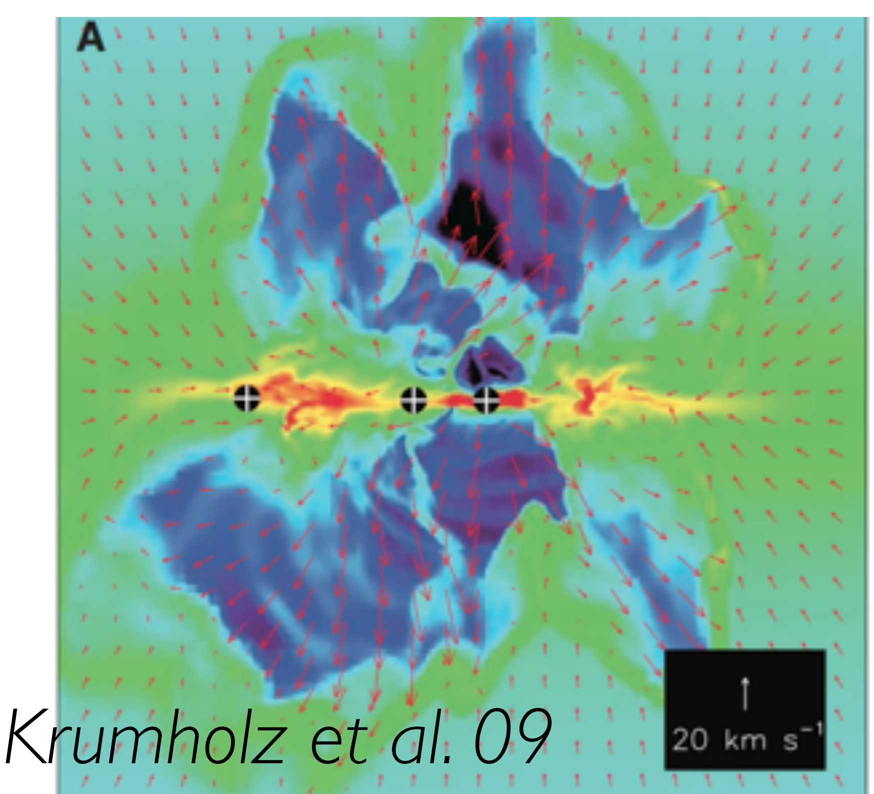
High mass star formation scenarii

- **Competitive accretion (Bate, Bonnell et al.)**
  - Massive prestellar core does not exist
  - Star clusters and massive stars form simultaneously (*Smith et al. 2009*)



- **Gravitational collapse (Krumholz et al.)**
  - Massive prestellar does exist
  - Fragmentation suppressed by protostellar feedback
  - Column density threshold $\Sigma=1$ g cm^{-2} (*Krumholz & McKee 2008*)



- **But... to date:**
  - Magnetic field neglected
  - More or less crude resolution
  - Initial fragmentation

100 $M_\odot$ turbulent dense core collapse

High-mass star formation: 100 $M_\odot$ magnetized, turbulent and dense core w. FLD (follow-up of *Hennebelle et al. 2011* barotropic study)

==> First full RMHD calculations

==> Influence of the magnetic field strength and radiative transfer on collapse, outflow launching and fragmentation

- T_0=10 K
- Kolmogorov initial power spectrum

$$P(k) \propto k^{-5/3}$$

- Flat profile

$$\rho(r) = \frac{\rho_c}{1 + (r/r_0)^2}$$

$$\rho_c = 1.4 \times 10^{-20} \ \mathrm{g\,cm^{-3}}$$

$$r_0 \sim 0.22 \ \mathrm{pc}$$

Favorable for initial fragmentation (e.g *Girichidis et al. 2011*)

100 $M_\odot$ turbulent dense core collapse

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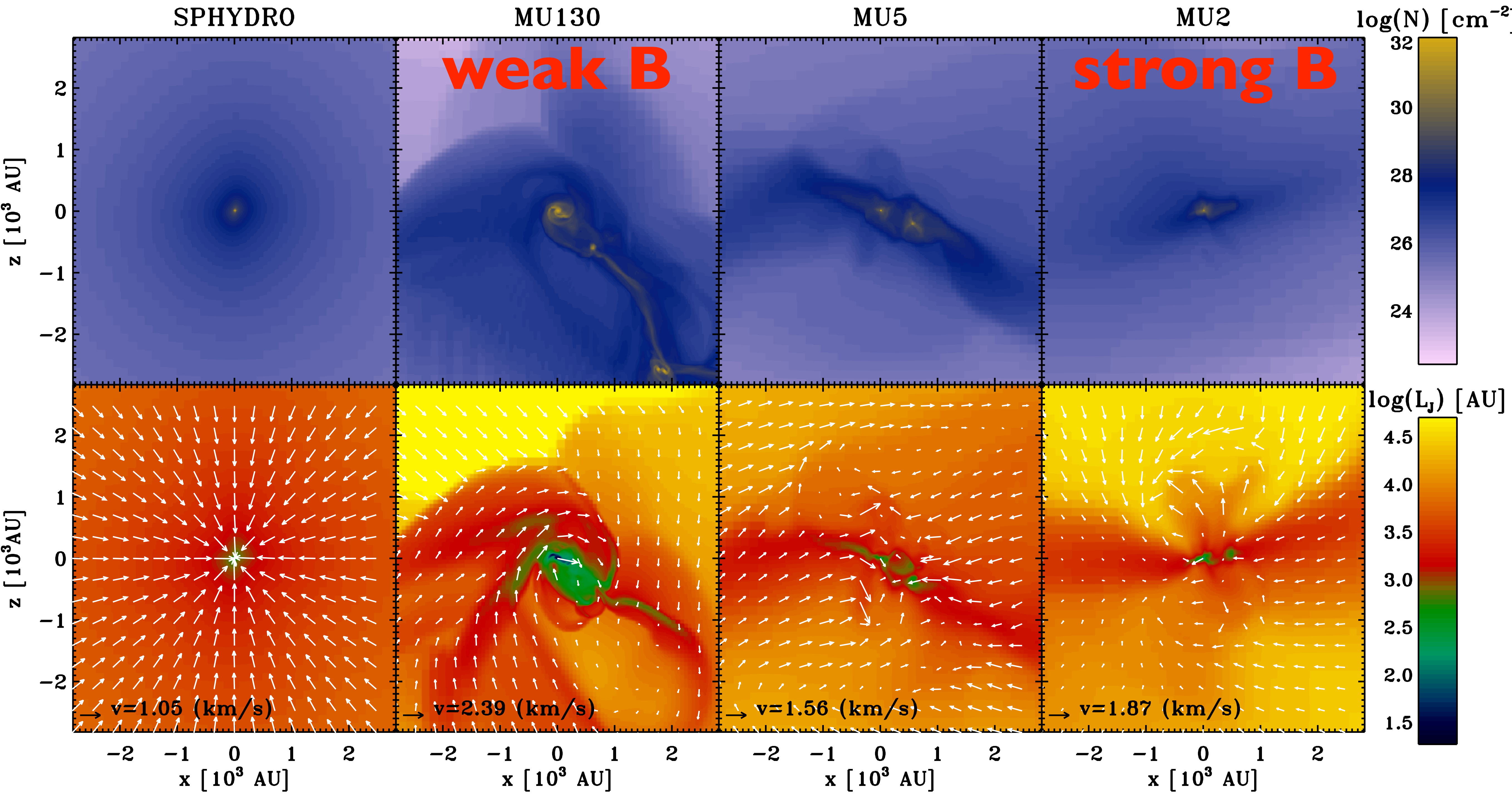
Model	μ	$\alpha_{\rm turb}$	$\Delta x_{\rm min}$ (AU)	Coarse grid	t_0 (Myr)
SPHYDRO	∞	$\sim 10^{-5}$	2.16	128^3	0.4786
MU130	~ 136	~ 0.2	2.16	256^3	0.4935
MU5	~ 5.3	~ 0.2	2.16	256^3	0.5397
MU2	~ 2.3	~ 0.2	2.16	256^3	0.5982

Commerçon, Hennebelle & Henning, ApJL 2011

100 $M_\odot$ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

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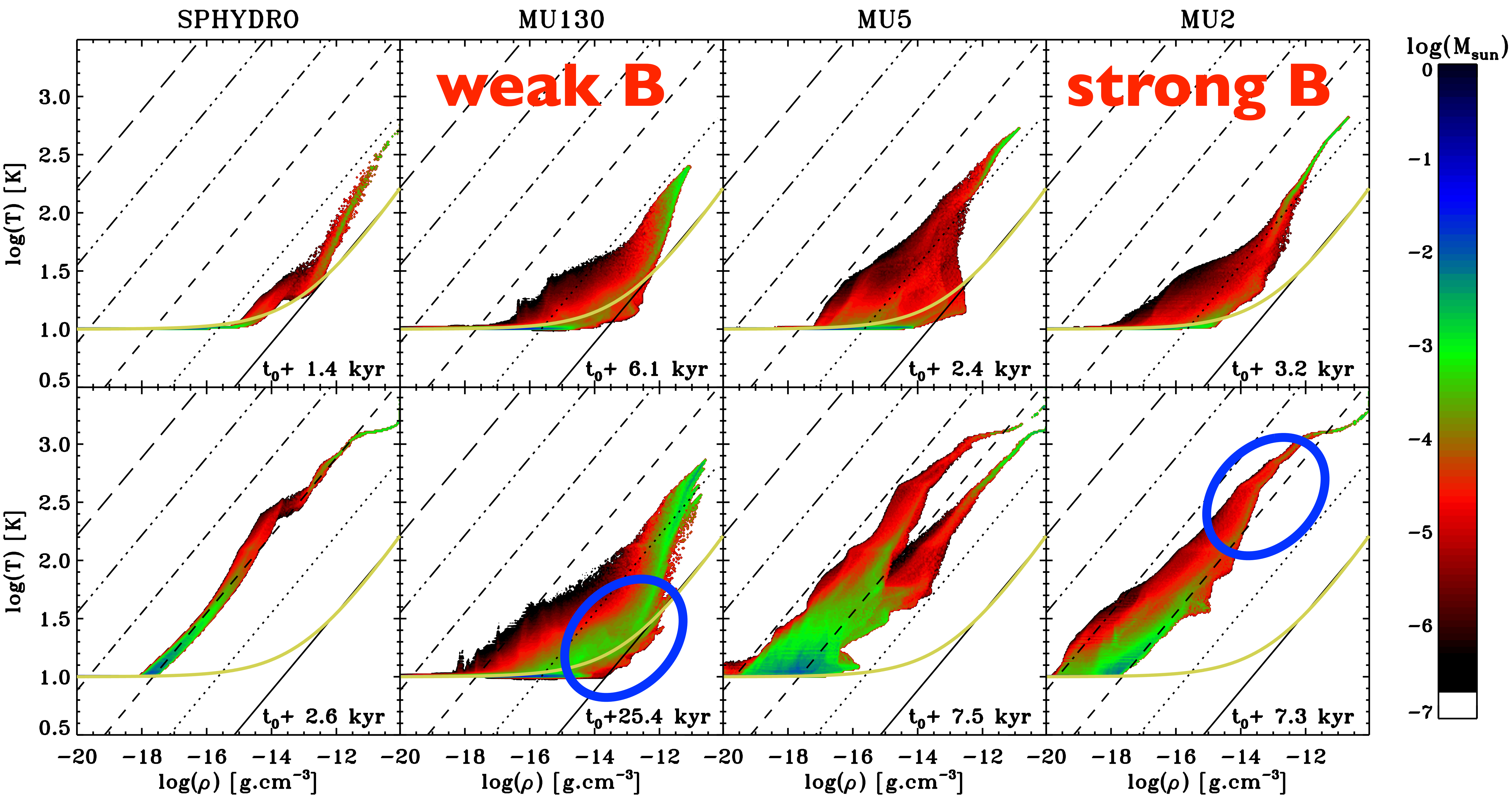


Commerçon, Hennebelle & Henning, ApJL 2011

What's different?

☞ **Key physical process:** combined effect of magnetic braking and radiative transfer *(Commerçon et al. 2010)*

✓ **Magnetic braking:** magnetization ↗ accretion rate ↗

✓ **Accretion shock** on the 1st hydrostatic core: all the infall kinetic energy radiated away *(Commerçon et al. 2011a)*

✓ Jeans stable mass ($M_\odot$):

SPHYDRO	MU130	MU5	MU2
30	0.2	1.2	10

Towards massive star formation?

✓ **Low magnetic field:** fragmentation crisis, protostellar feedback would not help

➡ similar to previous studies neglecting magnetic field (competitive accretion), or having a too low resolution (*Peters et al. 2011*)

★ Can magnetic field be neglecting?

✓ **Intermediate magnetization:** 2 fragments arranged in a filamentary like structure. Secondary fragment not produced by disk fragmentation (*Krumholz et al.*).

➡ **OB association** formation

✓ **High magnetization:** 1 single fragment

➡ **Isolated** massive star formation (e.g. observations by *Bontemps et al., Girart et al., Bestenlehner et al. & Bressert et al.*)

➡ Further evolution by disk accretion (e.g. *Kuiper et al. 2010*)

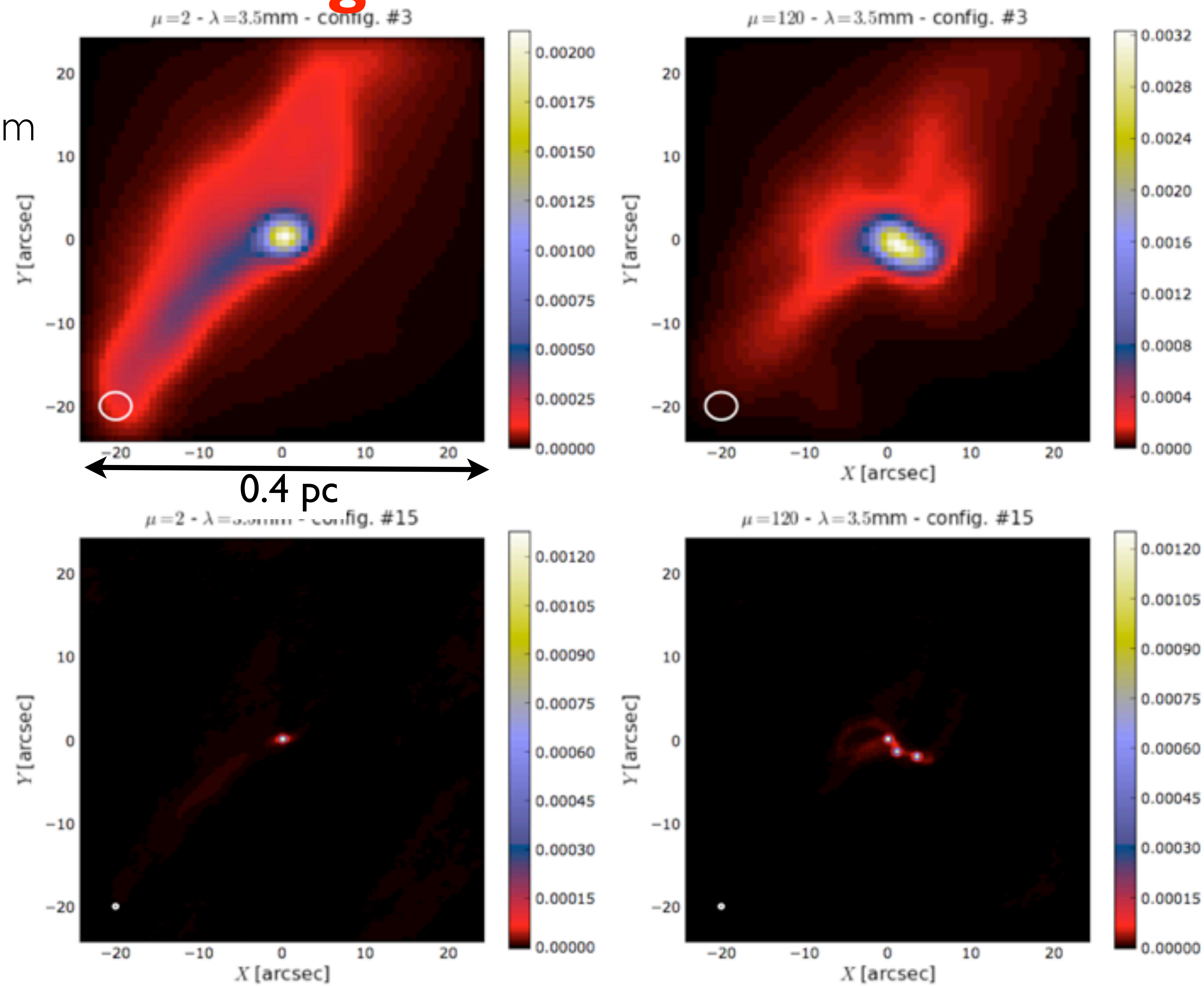
★ Need longer time integration, sink particles

ALMA predictions: dust emission @ 3.5 mm

Actual resolution: 3'' @ 3.5 mm
(e.g. Bontemps et al. 2010)

ALMA maps, config. 15

strong B **weak B**



Take Away III

✓ Massive dense cores do not fragment

✓ Highly magnetized massive dense cores => progenitors of high mass stars

Conclusion & prospects

- ☑ **R**adiation-**M**agneto-**H**ydro**d**ynamic solver with **AMR**
- ☑ **First** full RMHDs calculations of dense core collapse and outflow at small scales (*Commerçon et al. 2010, 2011c)*
- ☑ Magnetic field **inhibits** small-scale fragmentation, “even” with radiative transfer. Magnetic braking **favors** radiative feedback
- ☑ SEDs <=> First core **candidates**
- ☑ Early **fragmentation inhibition** for collapsing massive dense cores
- ☑ **Magnetized massive** dense cores = good **candidates** for massive star formation

THANK YOU