Star formation: protostellar collapse

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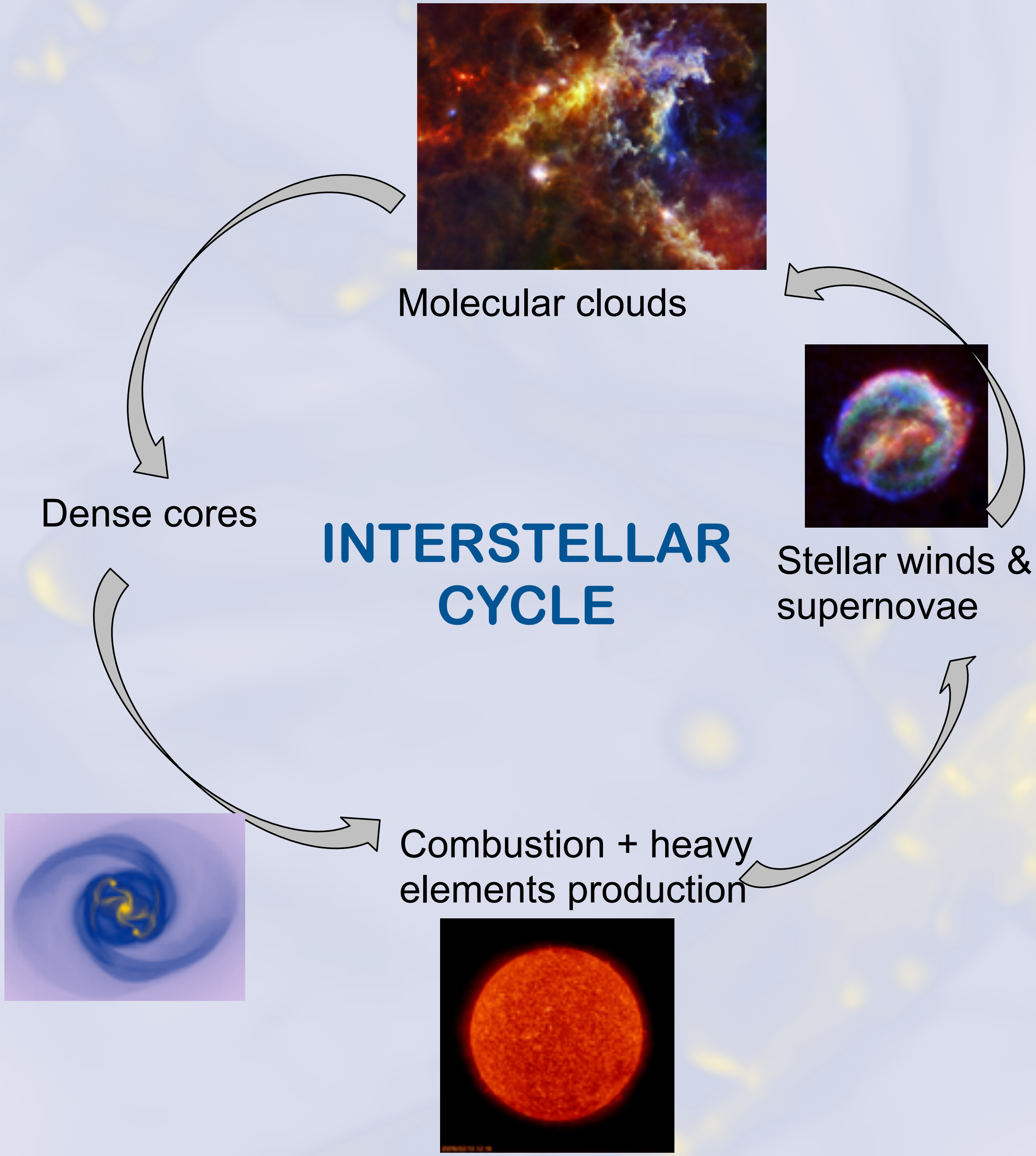
N. Vaytet (NBI Copenhagen), R. Teyssier (Zurich)

Outline

1. **Introduction**
2. **Methods**
    - AMR vs. SPH
3. **Low mass dense core collapse**
    - RHD and RMHD collapse
    - Disk formation and fragmentation crisis
    - Synthetic observations
4. **Massive dense cores collapse**
    - Early fragmentation inhibition
    - Disk & outflow formation

Why is star formation so important?



INTERSTELLAR CYCLE

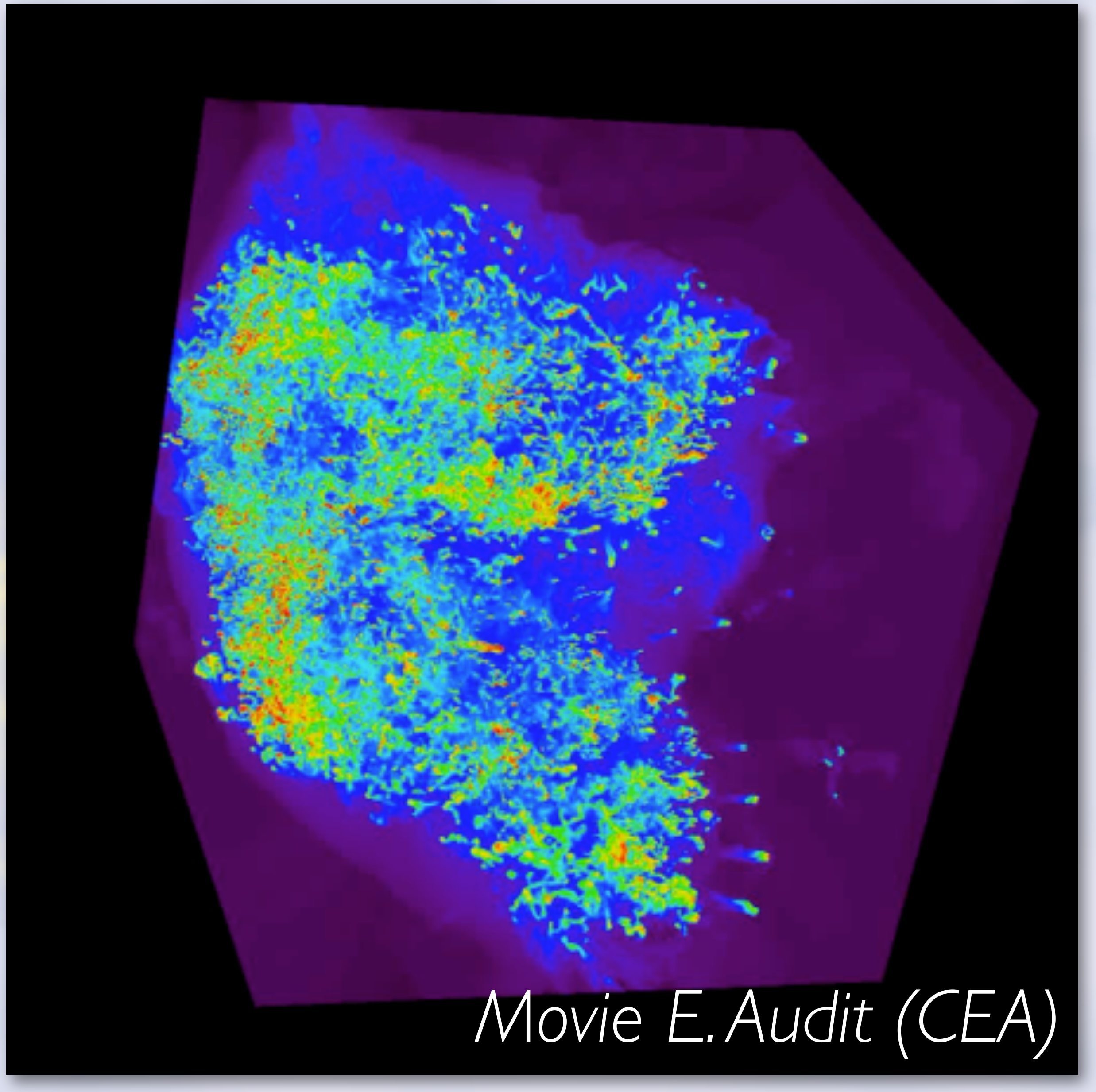
Molecular clouds

Dense cores

Combustion + heavy elements production

Stellar winds & supernovae

Turbulent molecular cloud



Movie E. Audit (CEA)

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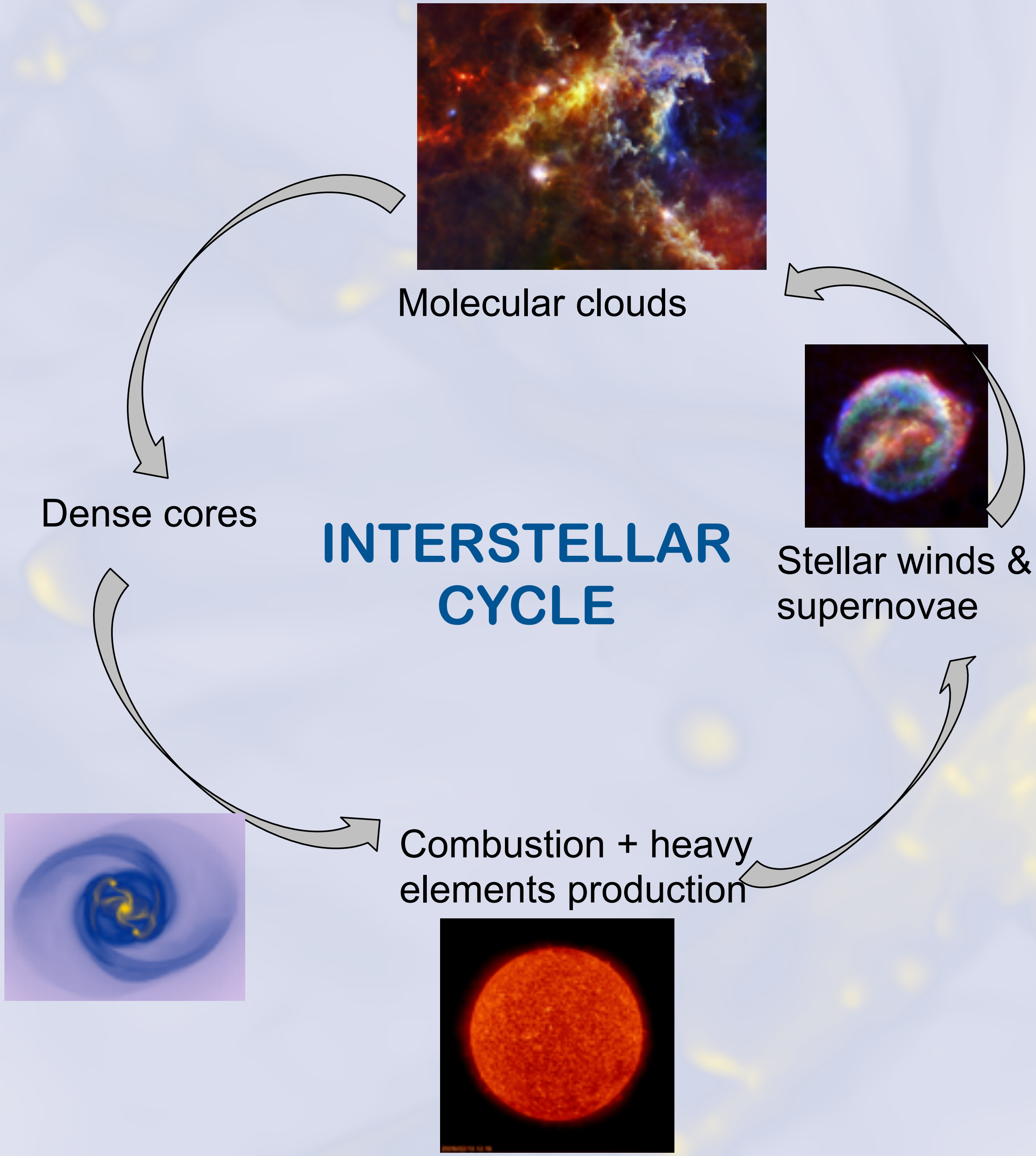

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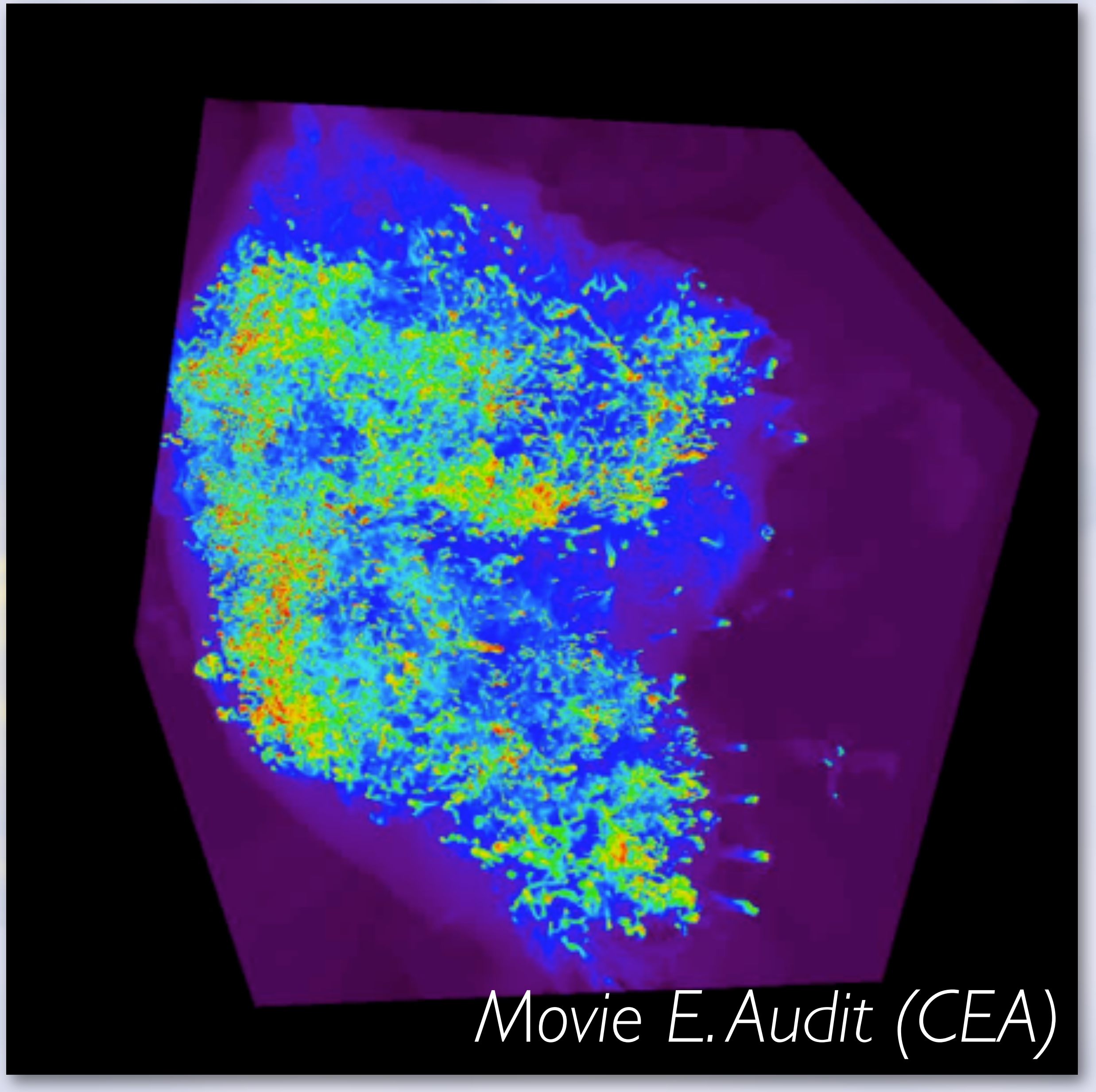

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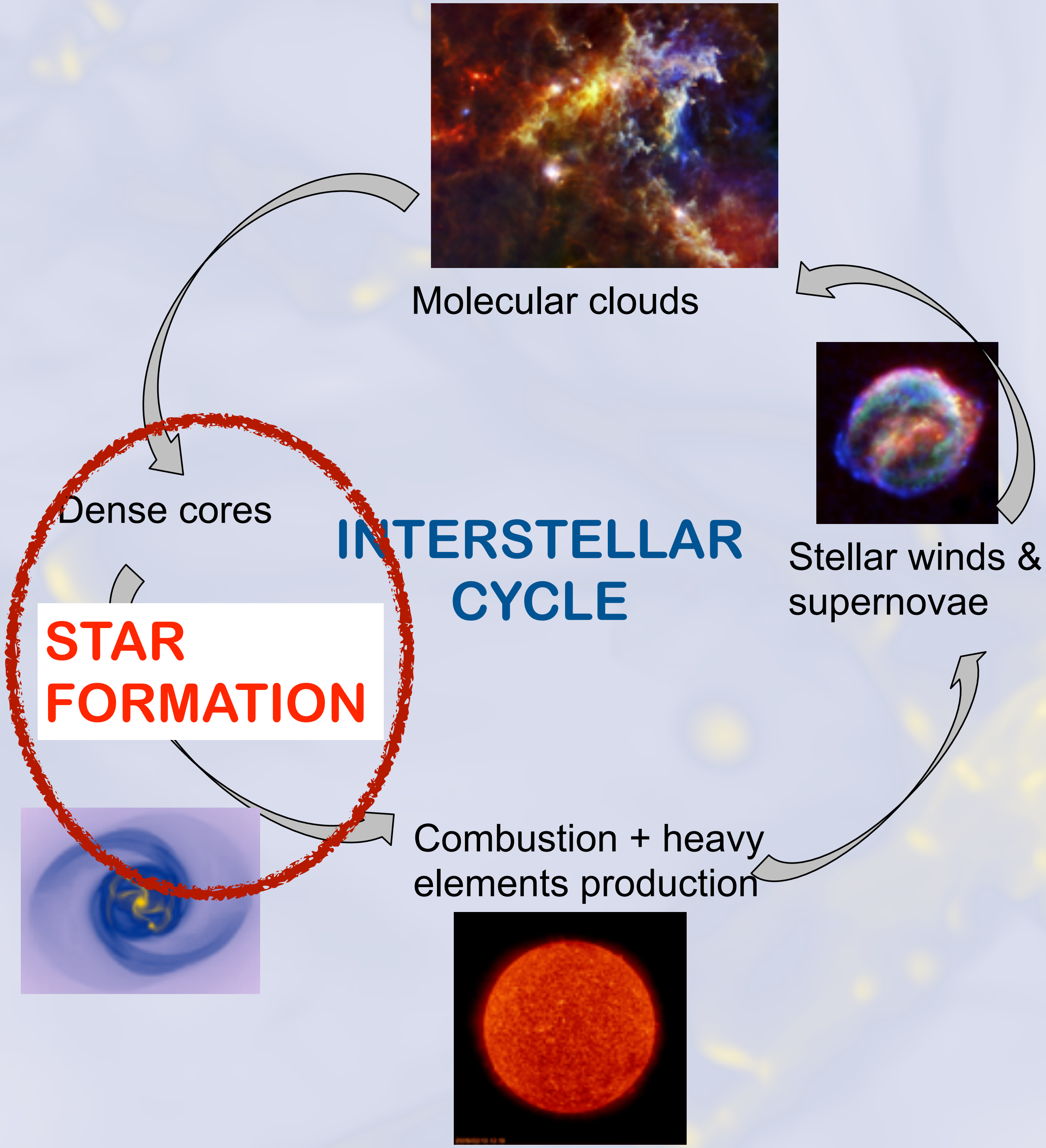

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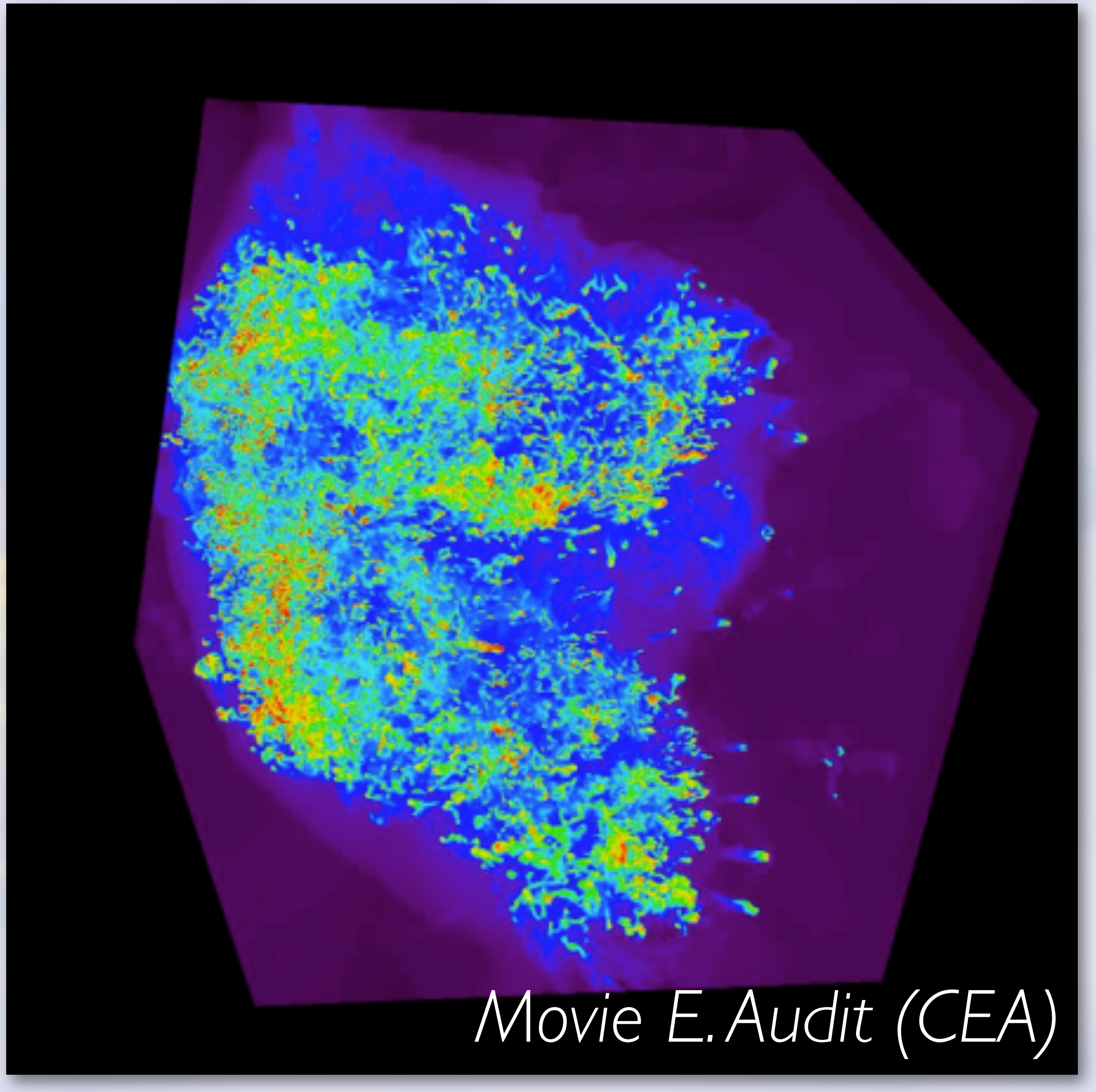

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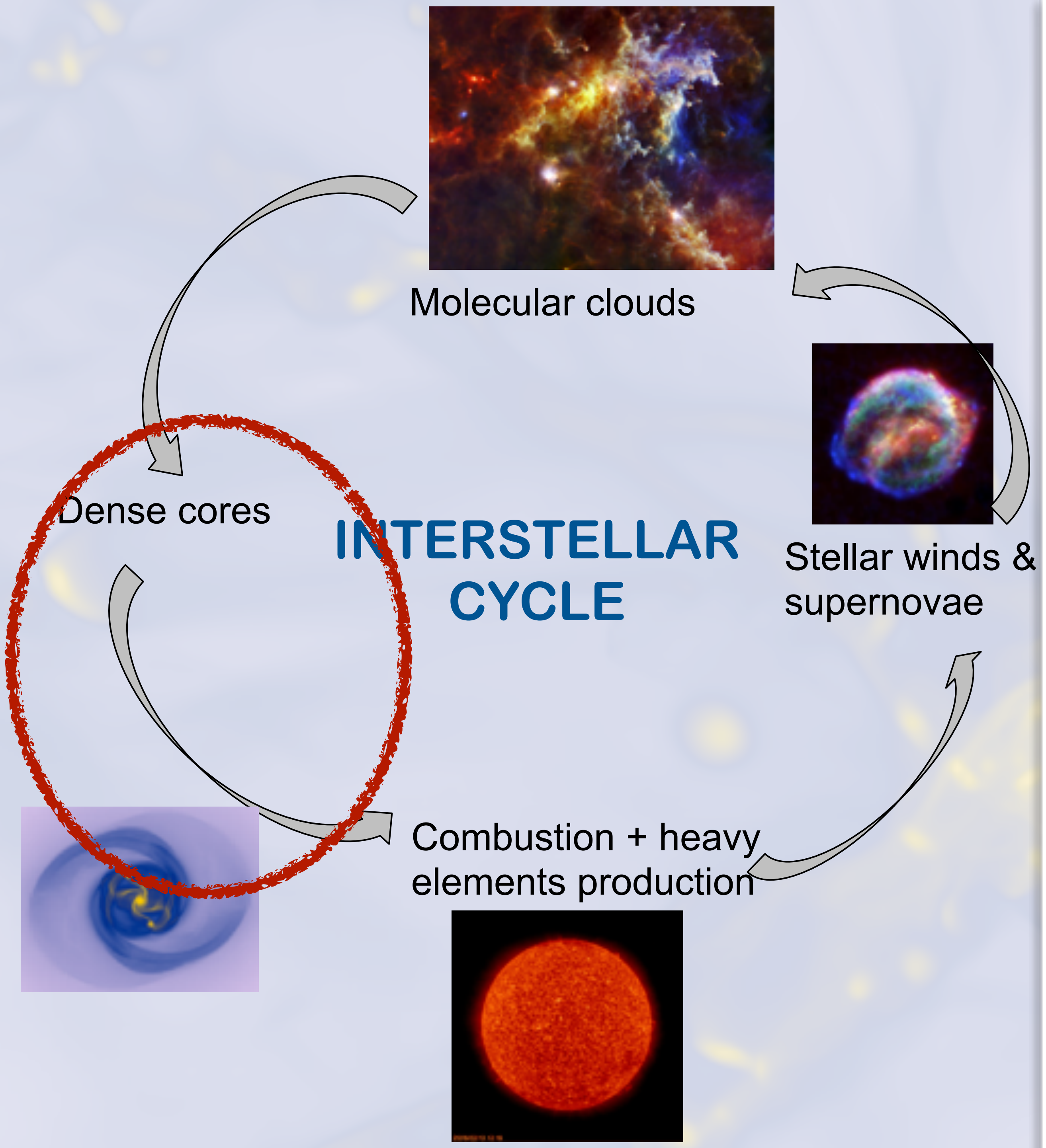

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INTERSTELLAR CYCLE

✓ Very few pbs in astrophysics without link to stars

✓ From large to small scales

- interstellar cycle
- galaxy formation and evolution
- planet formation/life

✓ A lot of **open questions**, e.g. :

- angular momentum/magnetic flux
- disk formation
- fragmentation, multiplicity, IMF, CMF
- star/brown dwarf/planet formation
- massive star formation

✶ Motivation for instrumentation, e.g., **JWST, ALMA** & **HERSCHEL** <=> **THEORETICAL** support

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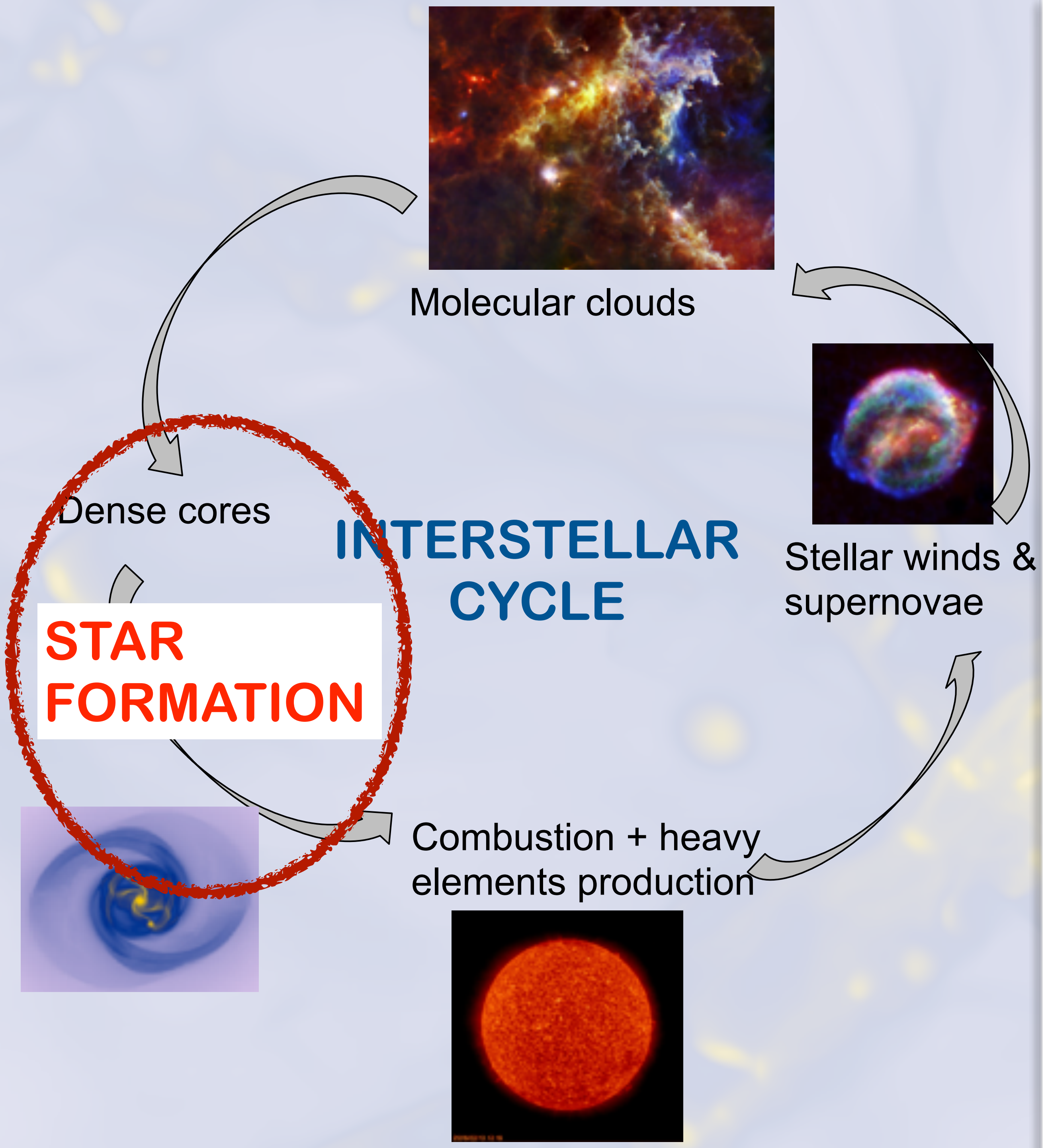

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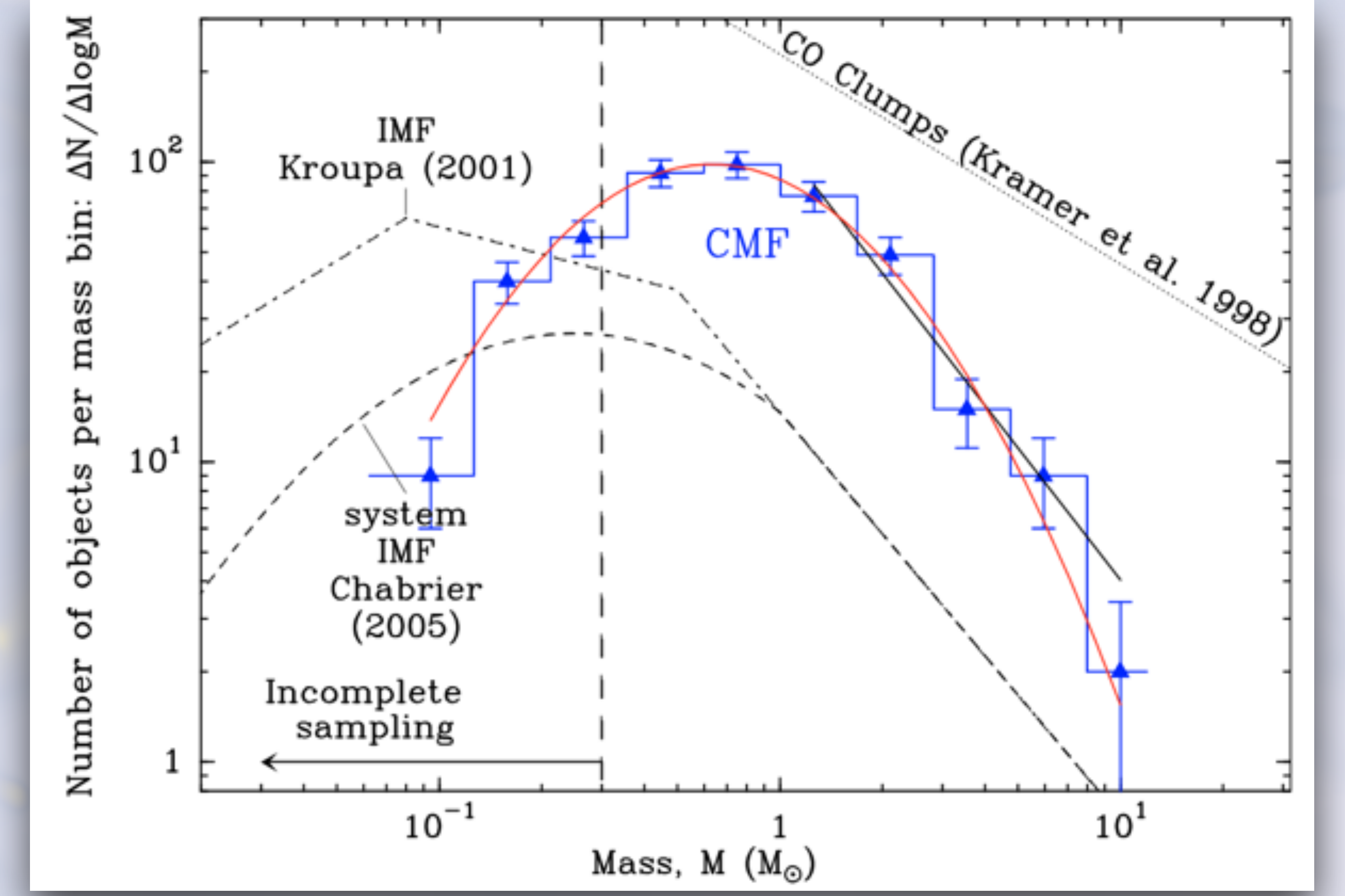
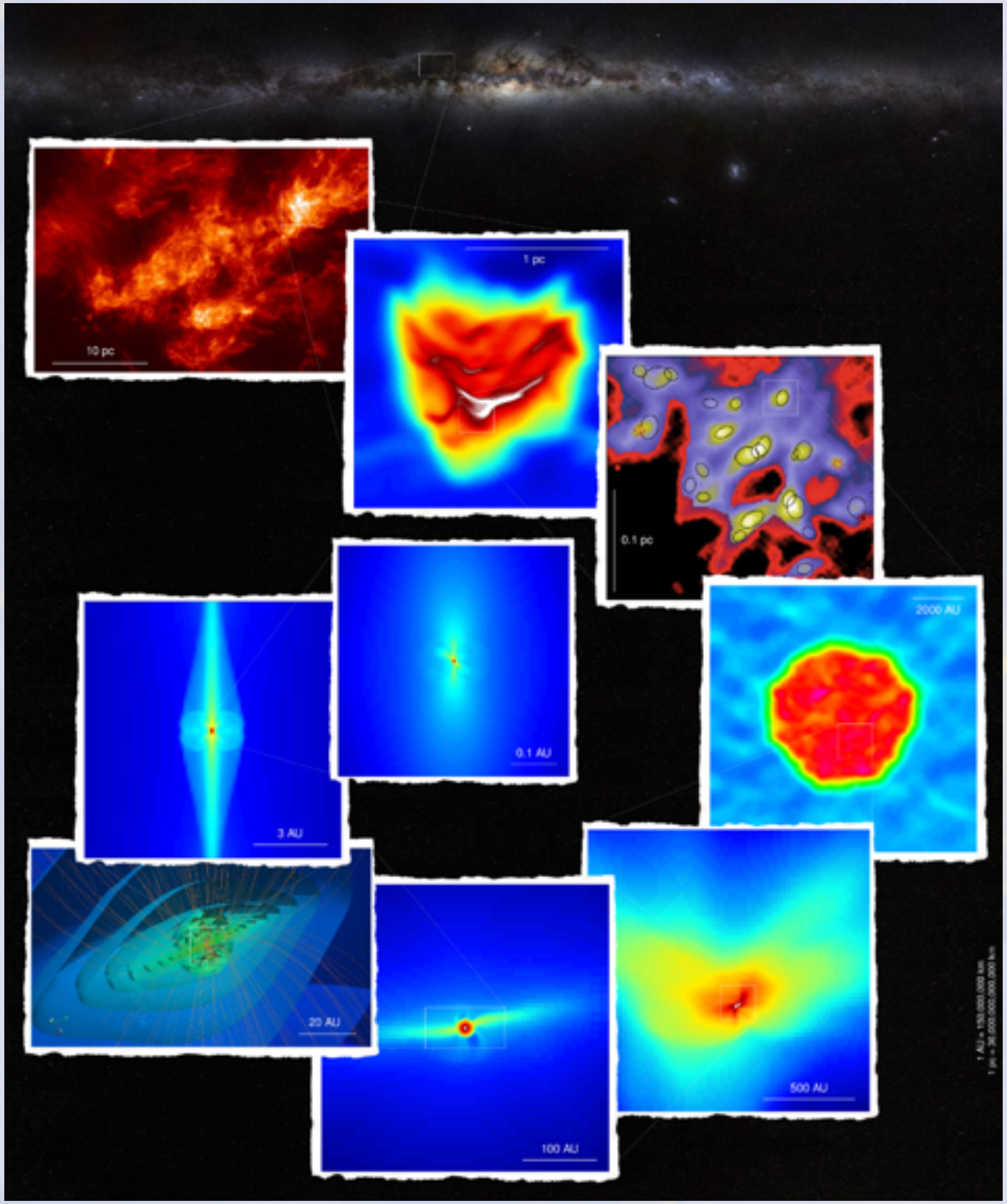
Dense core formation

- At the sonic scale for the majority
- Dense core are the progenitors of stars
- 1-1 relation between core mass function and initial stellar mass function?

Konyves et al. (2010)
HERSCHEL Observations



Star formation: building blocks & challenge



Vaytet et al. (2013)

- from parsec scale (10^{18} cm) to stellar radius (10^{10} cm)

- density: from 1 cm^{-3} to 10^{24} cm^{-3}

- temperature: 10 K -10^6 K

- ionisation depends on density and temperature… (*ideal vs non-ideal MHD*)

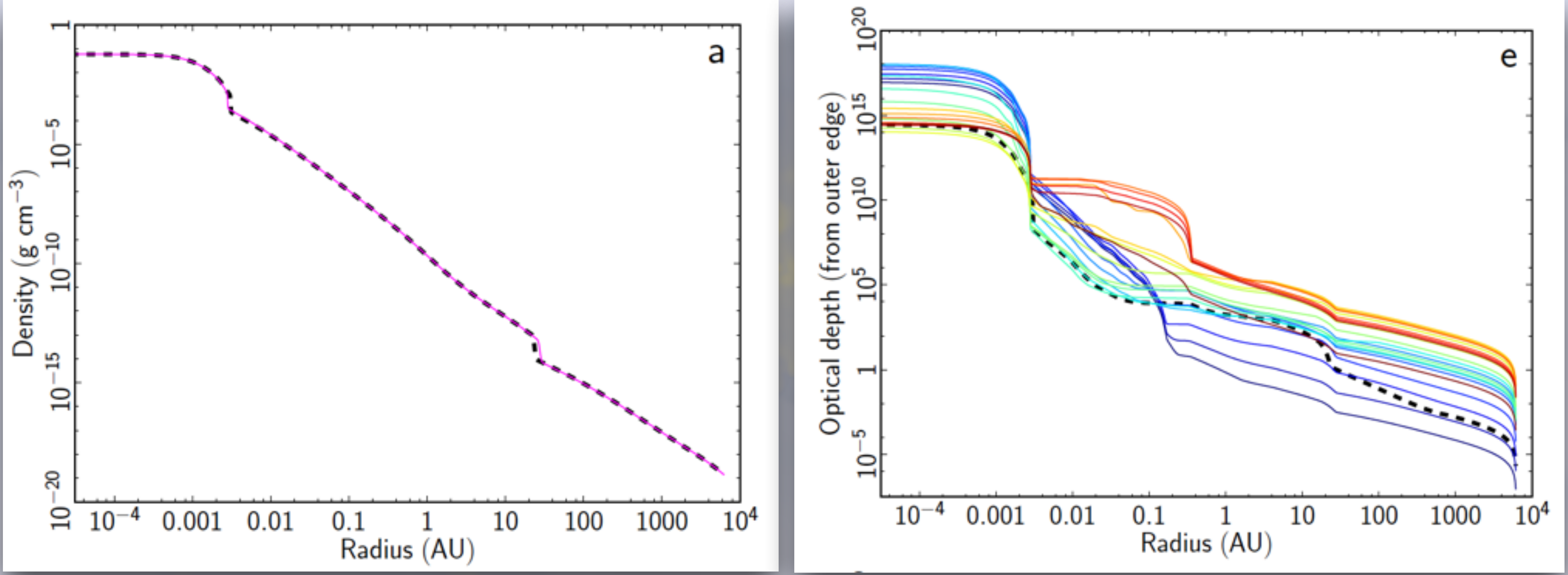
- chemistry, dust grain evolution (*H_2 formation, growth, evaporation*)

- initial conditions for stellar evolution (*entropy level, magnetic field flux/geometry, angular momentum*)

Star formation: the challenge

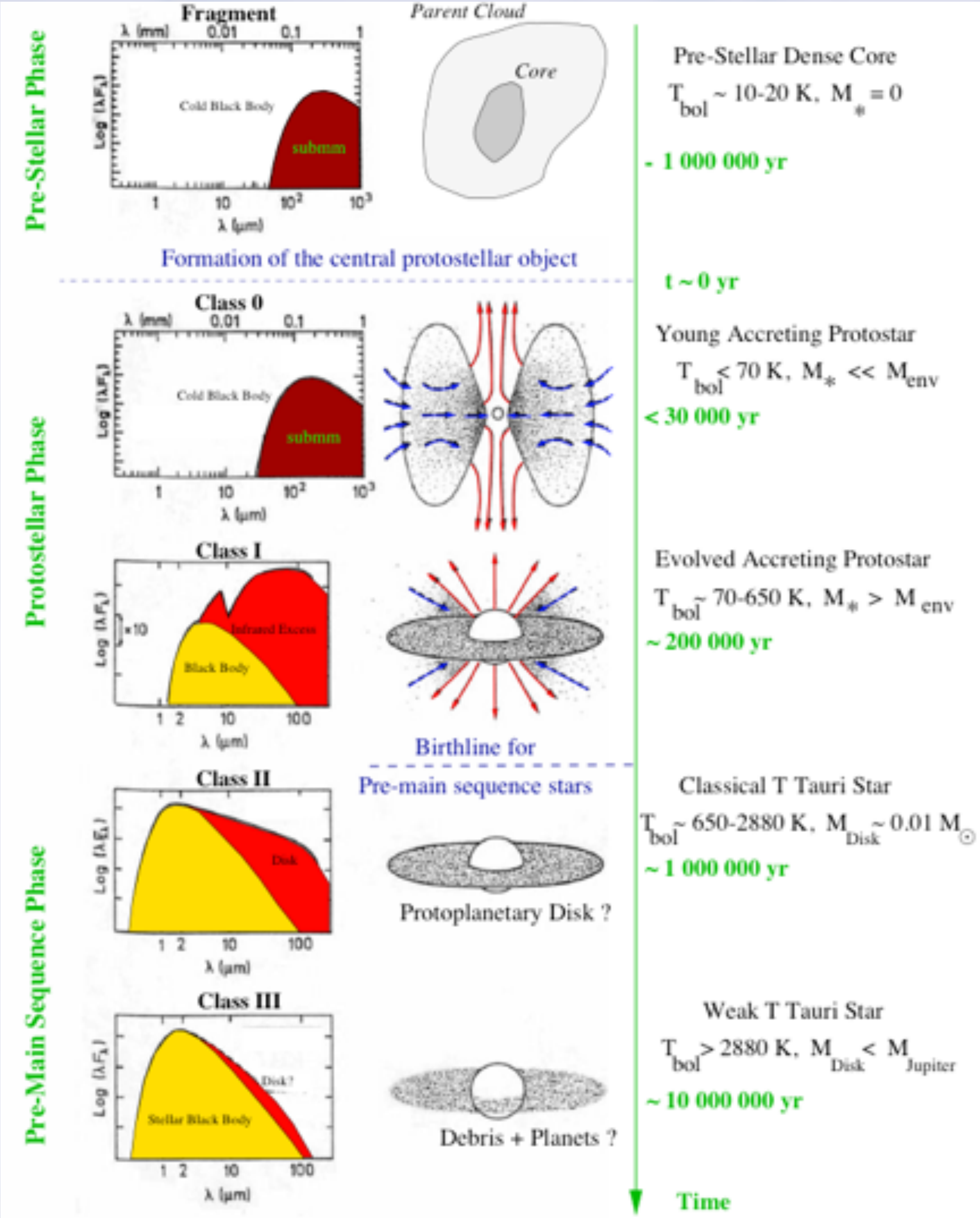
✓ Follow the dynamics over a wide range of physical scales:

- time scales: free-fall time (~$10^{4,5}$ yr) to second
- spatial scales: parsec to stellar radius
- physical scales: density ranges form 1 cm^{-3} to 10^{24} cm^{-3}



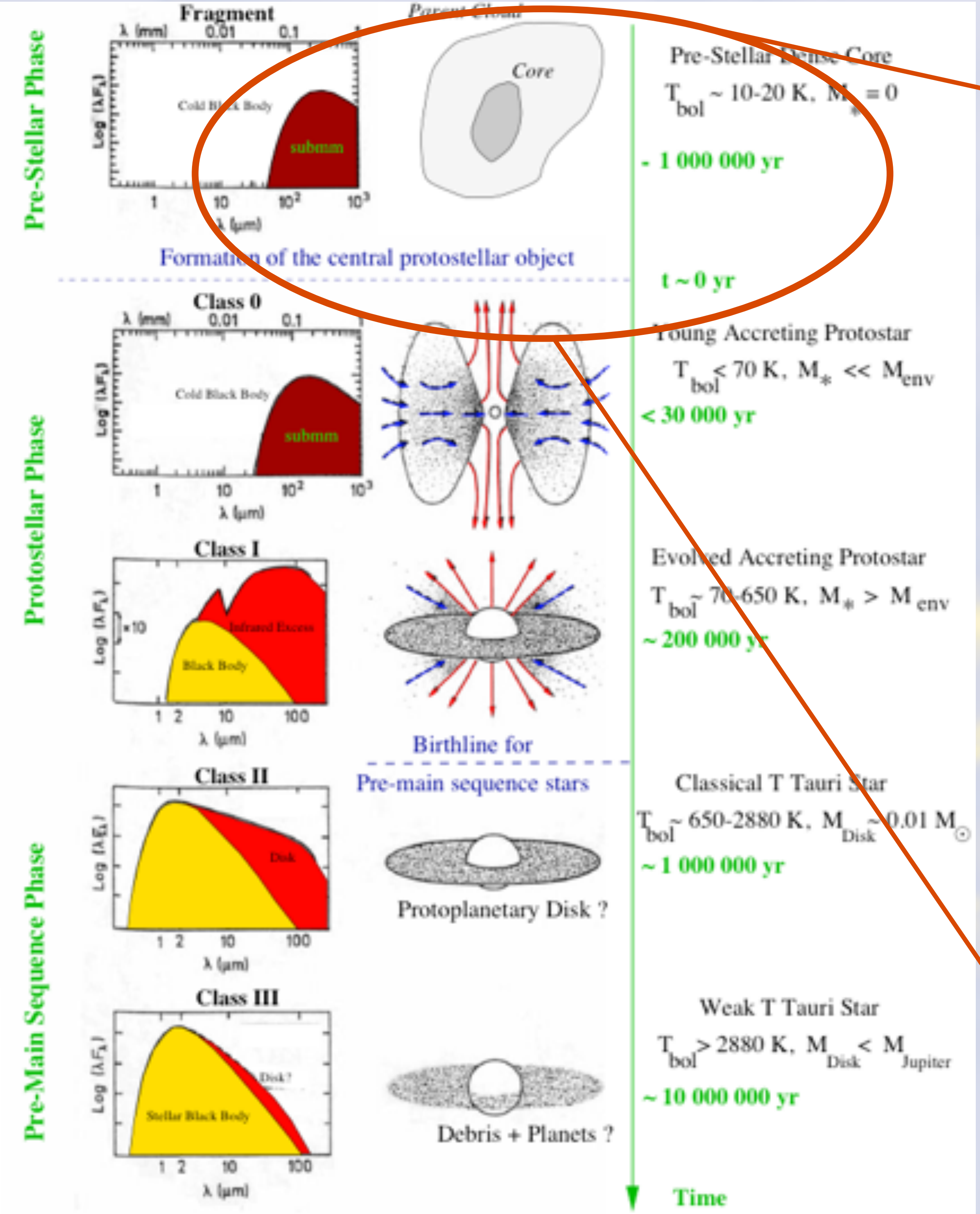
Vaytet et al. (2013)

Star formation evolutionary sequence



André 2002

Star formation evolutionary sequence



André 2002

Prestellar dense core collapse

First collapse

Isothermal ↓ *$10^{4,5}$ yr*

First Larson core

Adiabatic ↓ *a few 10^3 yr*

H_2 dissociation

Second collapse

Quasi - isothermal ↓ *10^2 yr*

Second Larson core

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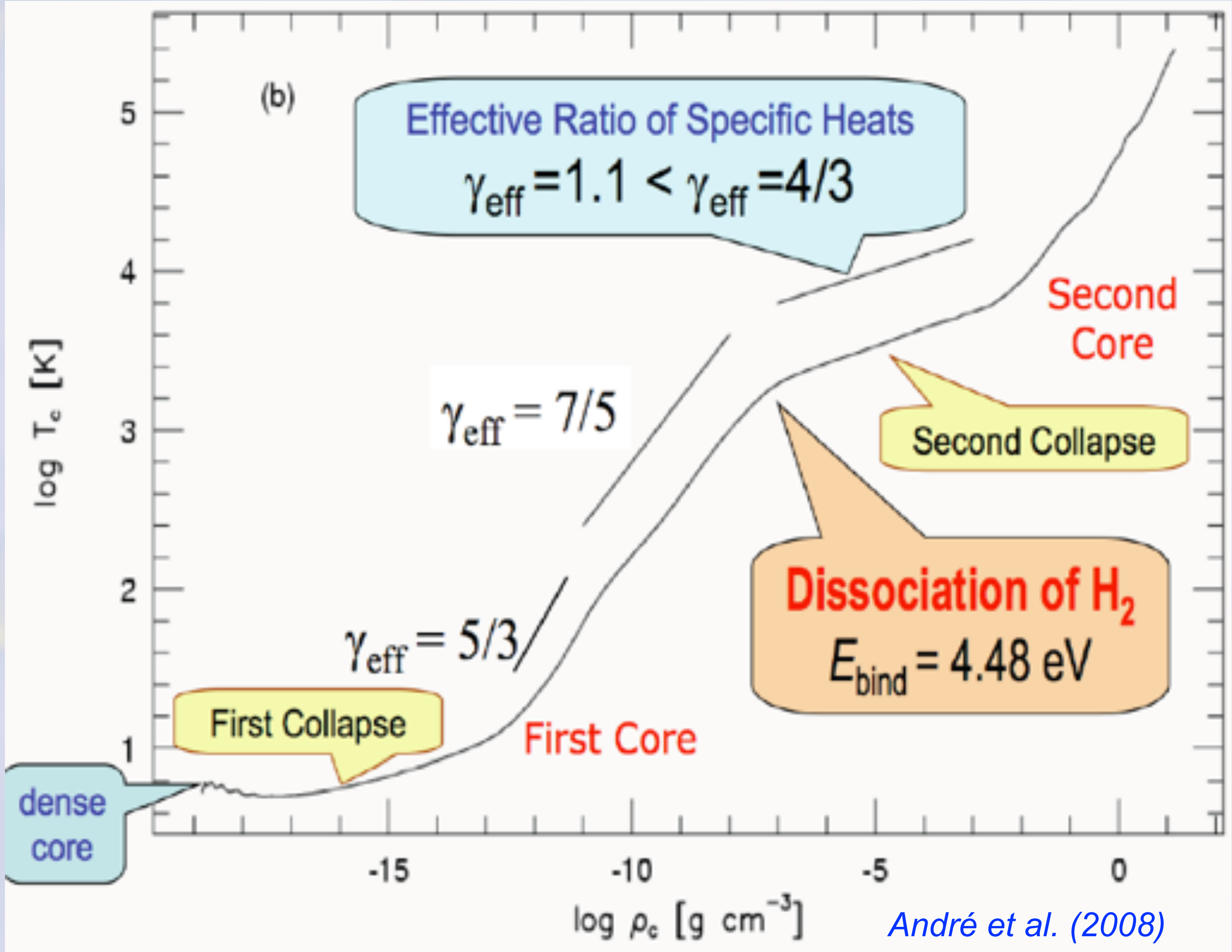

André et al. (2008)

$$M_{\rm Jeans} \propto \rho^{\frac{3}{2}n-2}$$

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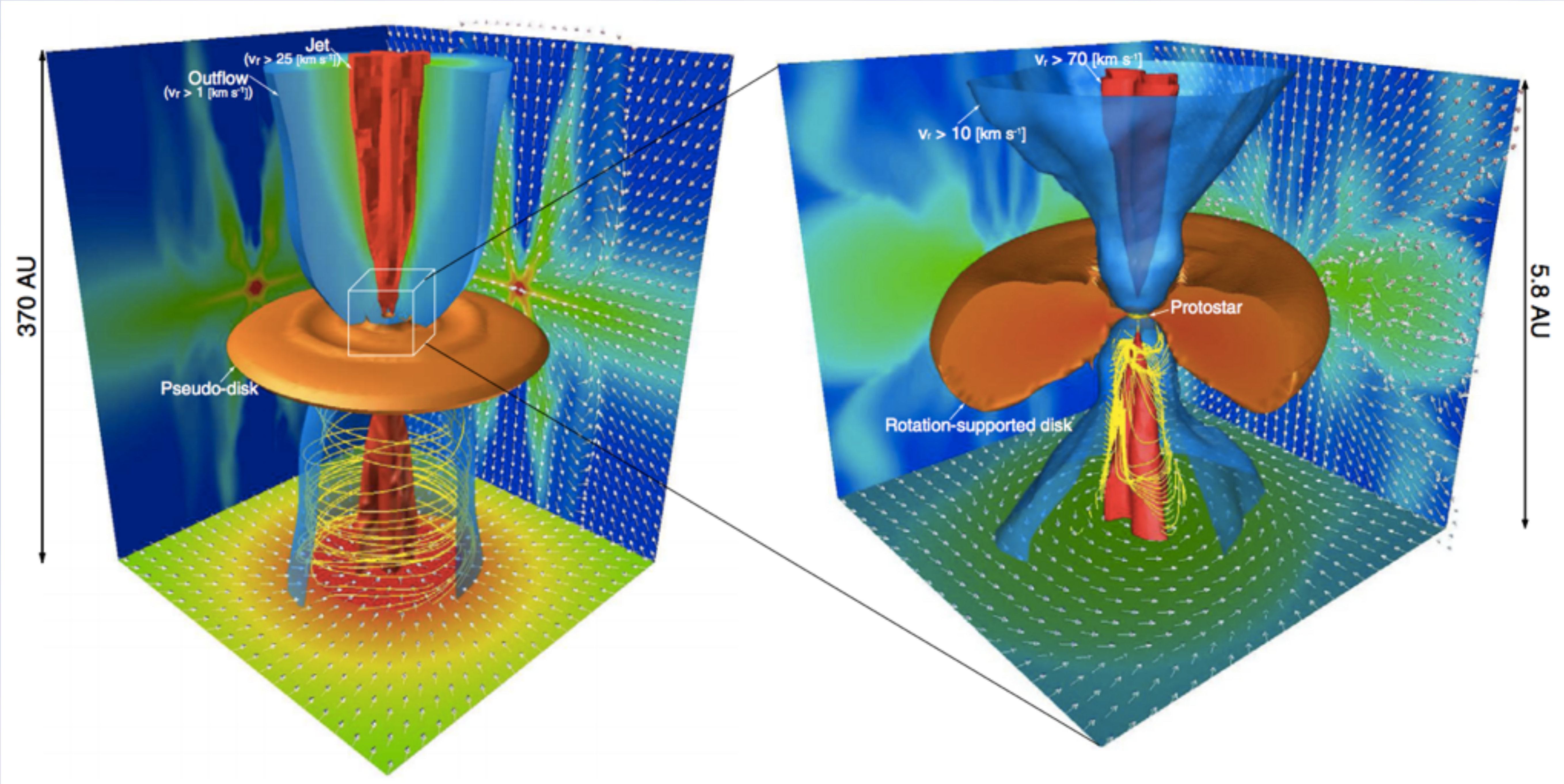
Protostellar core



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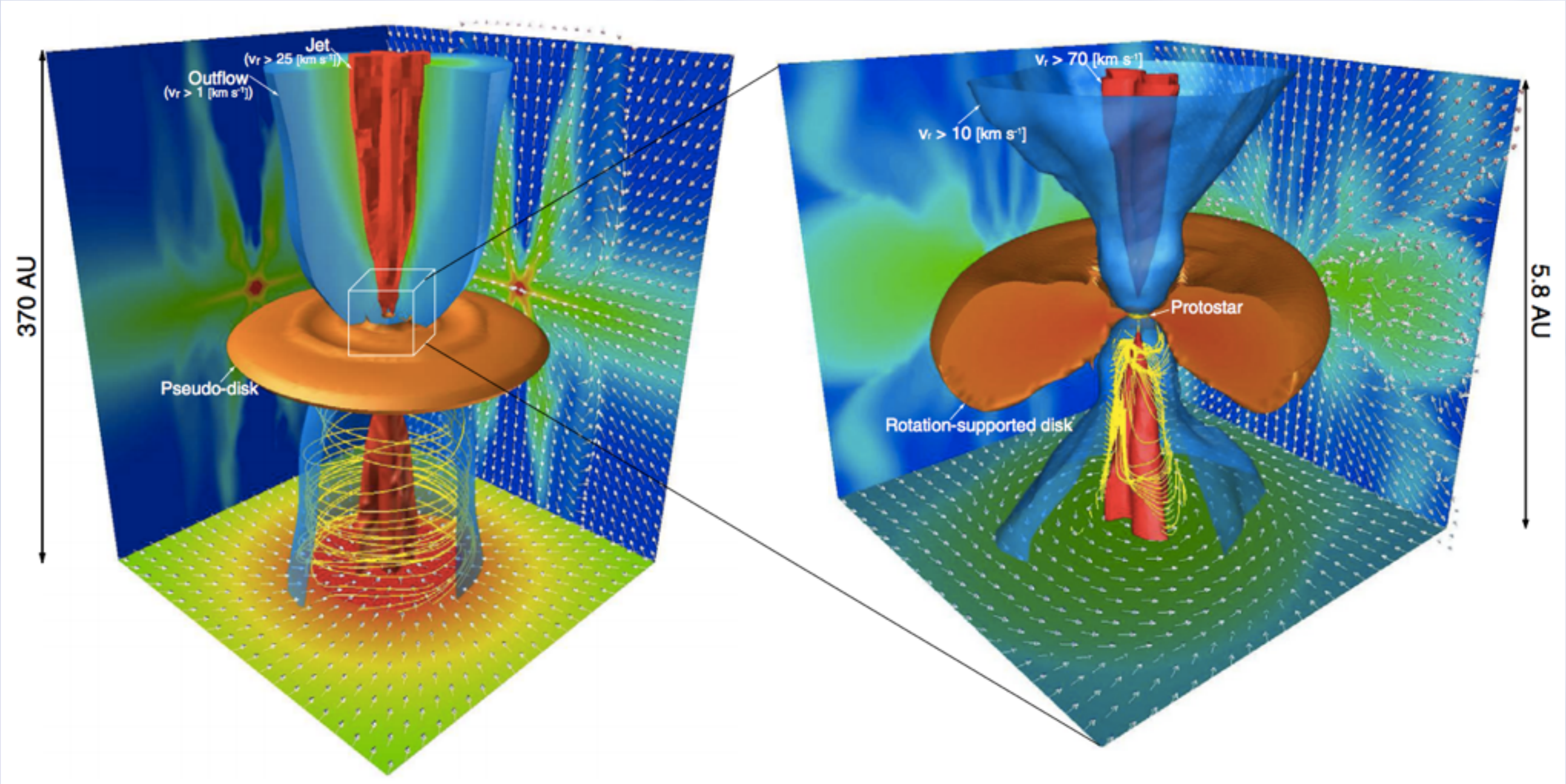
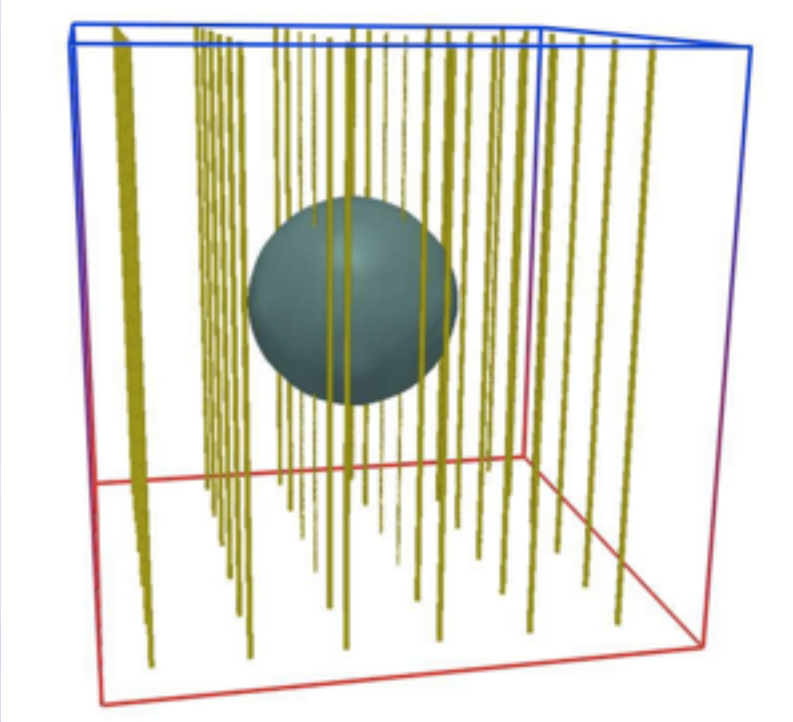


Machida et al.

Numerical experiments

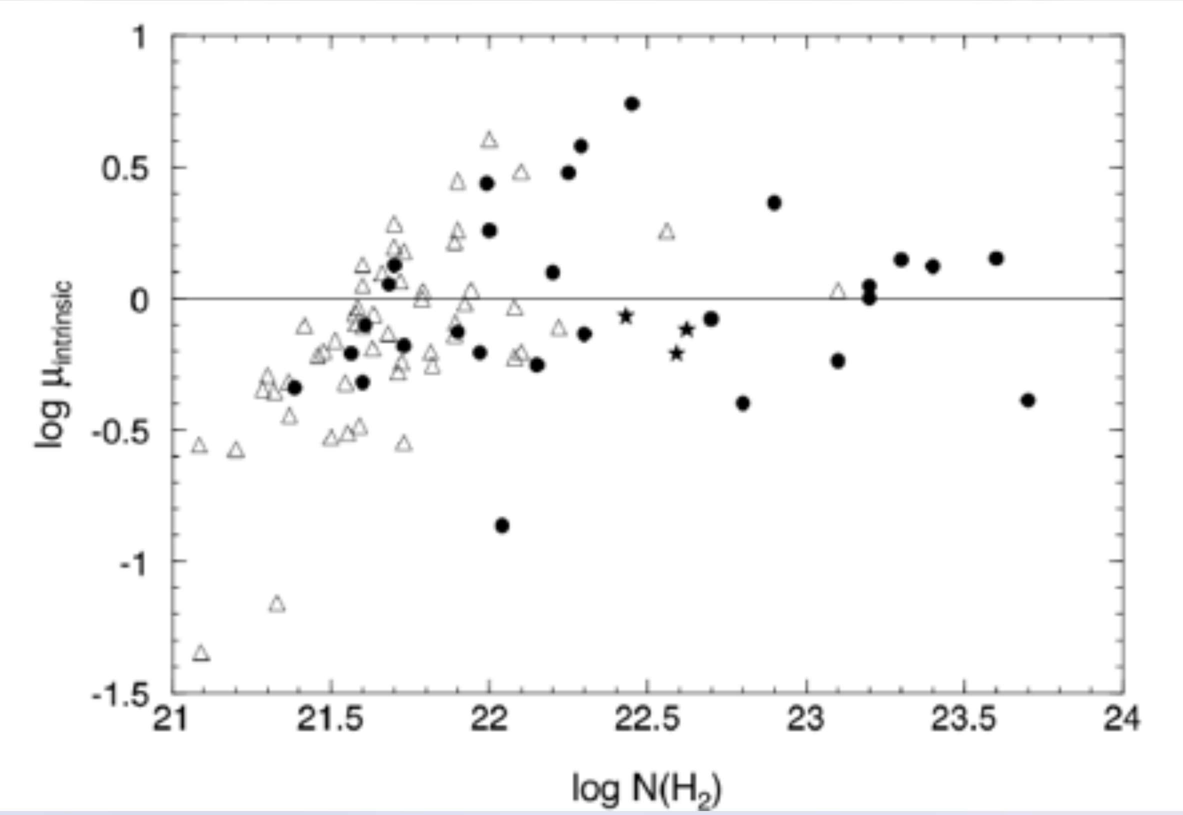


Typical initial conditions:

- $1\ M_\odot$ isolated dense core
- uniform / BE-like density profile
- uniform temperature (10 K, $\alpha = E_{th}/E_{grav}$)
- solid body / differential rotation ($\beta = E_{rot}/E_{grav}$)
- m=2 density perturbation / turbulent velocity field
- organised magnetic field

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

Refinement criterion solely based on the Jeans length



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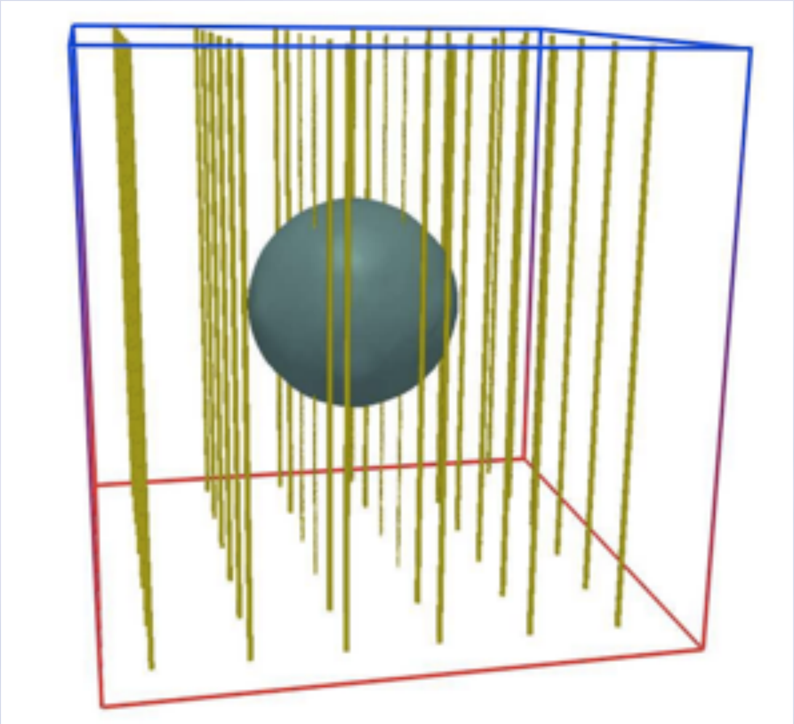

Banerjee & Pudritz (2006)

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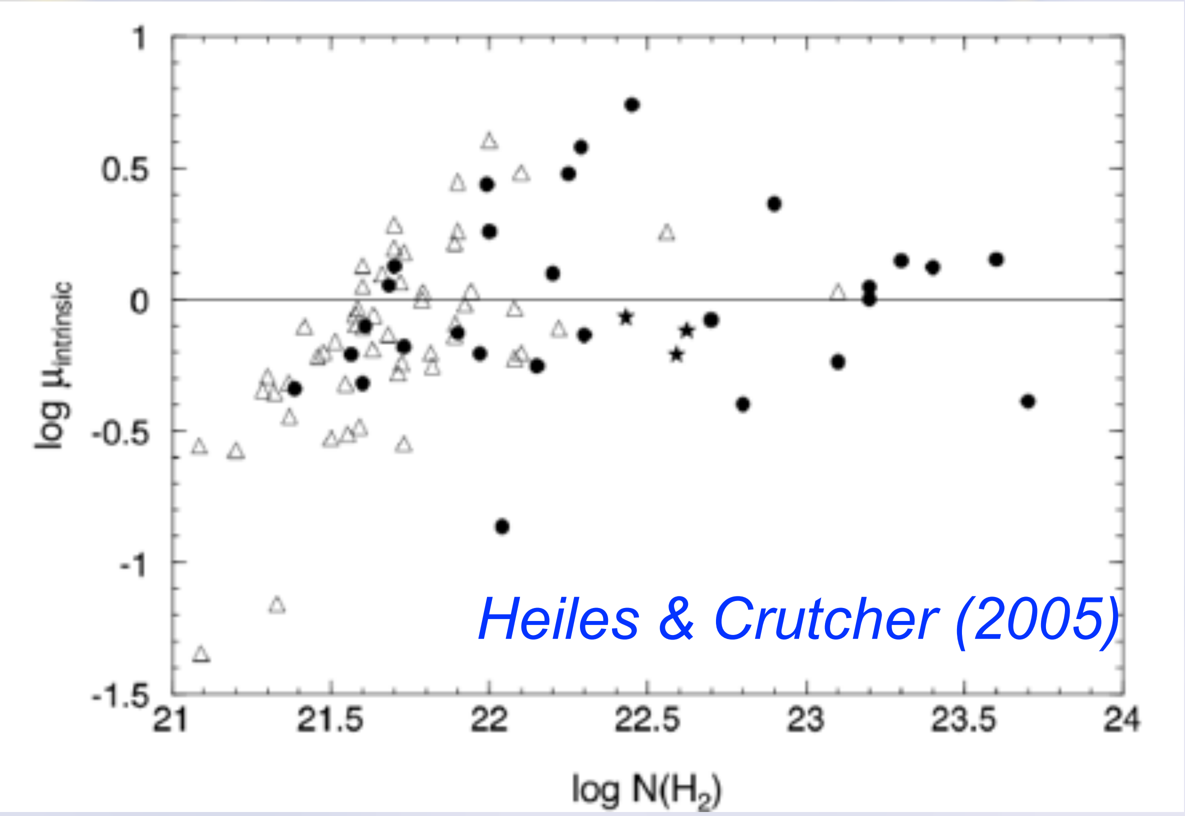

Heiles & Crutcher (2005)

Effect of magnetic fields and rotation

Consider a cloud of initial radius R, mass M and temperature T

Thermal support

- E_{th}/E_{grav} decreases when R decreases

$$\frac{E_{\rm th}}{E_{\rm grav}} = \frac{3M/m_p kT}{2GM^2/R} \propto R$$

Centrifugal support

- Angular momentum conservation
- E_{rot}/E_{grav} increases when R decreases

$$j = R_0^2\omega_0 = R^2\omega(t)$$

$$\frac{E_{\rm rot}}{E_{\rm grav}} = \frac{MR^2\omega^2}{GM^2/R} \propto \frac{1}{R}$$

Magnetic support

- Magnetic flux conservation
- E_{mag}/E_{grav} is constant when R decreases

$$\phi \propto BR^2$$

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

$$\frac{E_{\rm mag}}{E_{\rm grav}} = \frac{B^2R^3}{GM^2/R} \propto \left(\frac{\phi}{M}\right)^2$$

Effect of magnetic fields and rotation

Consequences:

Centrifugal forces become dominant

- flattening of the envelope
- formation of a centrifugally supported disk

Magnetic forces stay comparable to gravity

- flattening of the envelope
- NO formation if a supported structure
- formation of a pseudo-disk (Galli & Shu 1993)

Magnetic fields brakes the cloud

- transfer angular momentum from the inner part to the envelop

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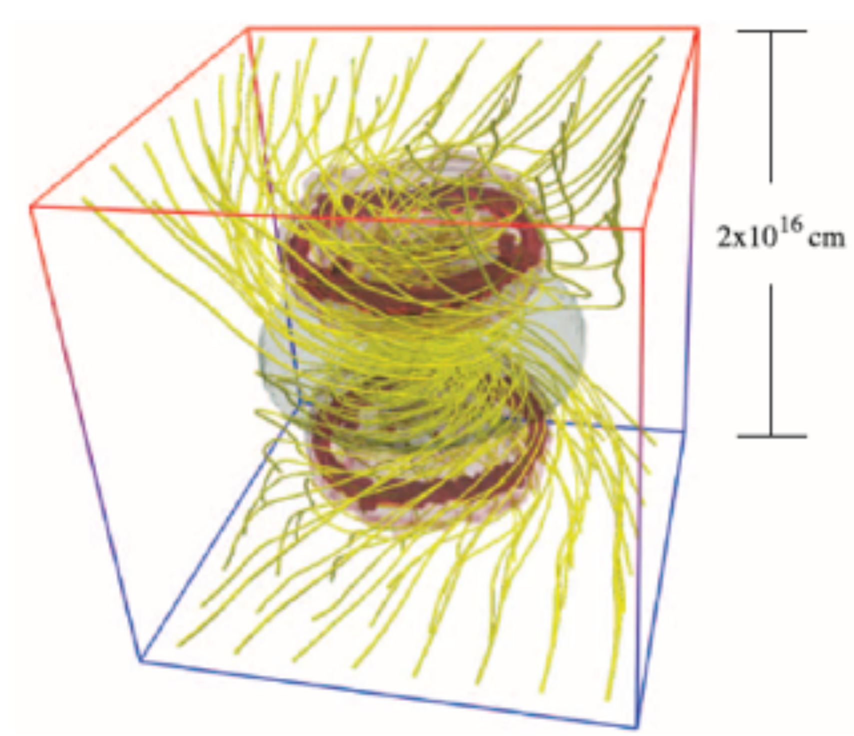
Numerics for star formation

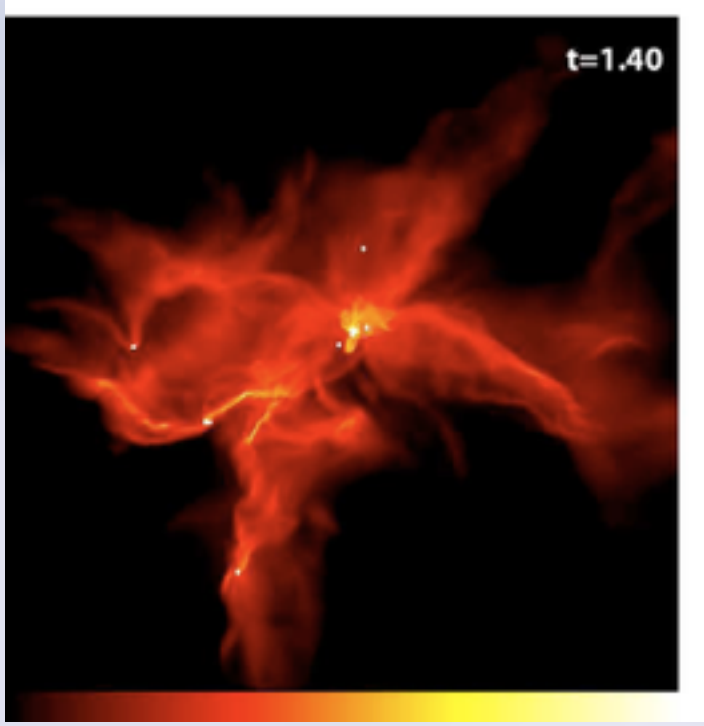
★ 2 numerical methods :

- **Grid based code (AMR)** : RAMSES code (*Teyssier 2002, Fromang et al. 2006, Commerçon et al. 2011a*), ORION code (*Krumholz et al.*) FLASH code (*Banerjee, Seifried et al.*), etc…
  - ➡ **Advantages :**
    - ✓ accuracy
    - ✓ shocks
    - ✓ refinement criteria
  - ➡ **Disadvantages :**
    - ✓ (headhach)
    - ✓ Eulerian



Banerjee & Pudritz 06

- **Lagrangian - SPH** : e.g. Bate & Price (RHD & MHD), Stamatellos et al. 2008 (RHD), etc…
  - ➡ **Advantages :**
    - ✓ Lagrangian
    - ✓ naturally adaptive
    - ✓ (simpler)
  - ➡ **Disadvantages :**
    - ✓ low density = low resolution
    - ✓ noise, dissipative
    - ✓ young



Bate et al. 02,03,08

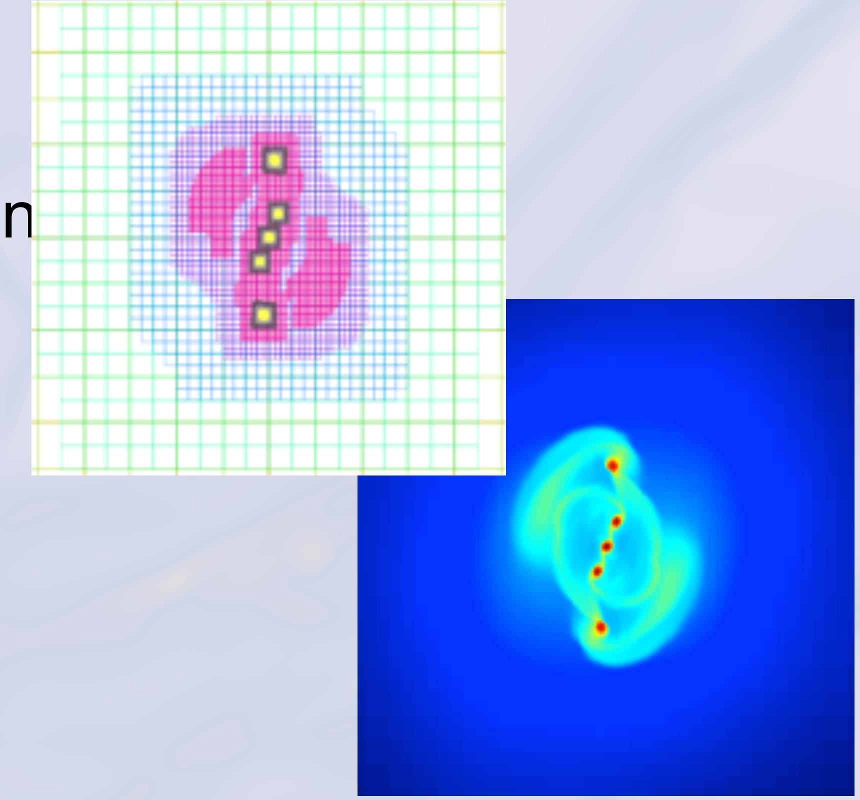
Numerical resolution criteria for SF

★ Gravitational instability ➔ **Jeans** length

AMR : Refinement criteria N_J as a function of the local Jean

$N_J \, . \, \Delta x < \lambda_{Jeans}$

- ↪ Truelove et al. 1997: $N_J \geq 4$
- ↪ Dynamical criterion



Numerical resolution criteria for SF

★ Gravitational instability ➔ **Jeans** length $\lambda_J = c_s\sqrt{\frac{\pi}{G\rho_0\gamma}}$

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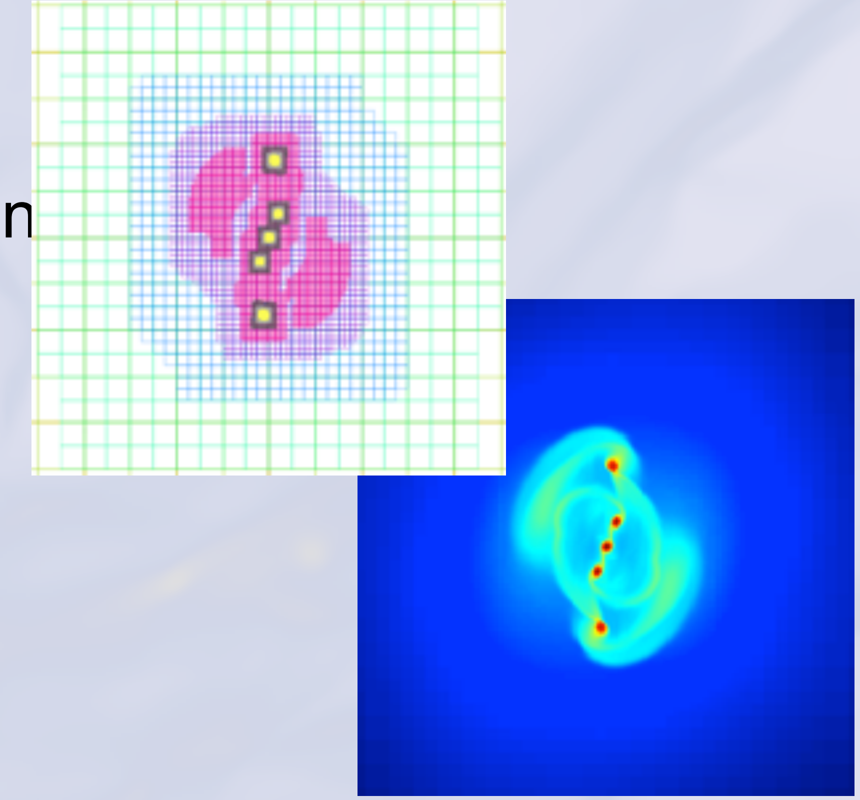

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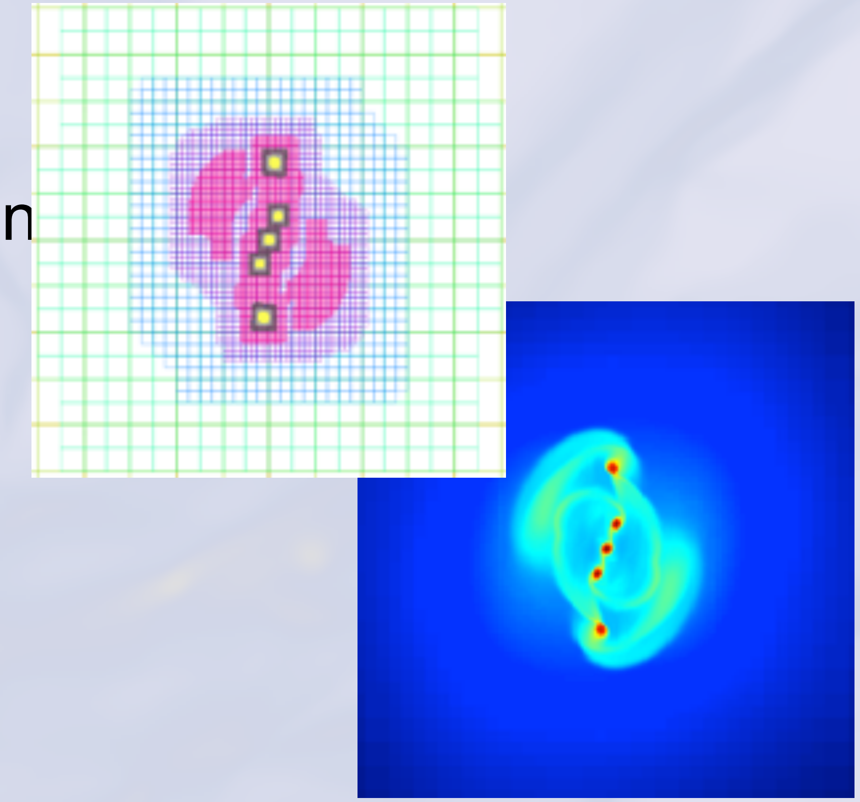

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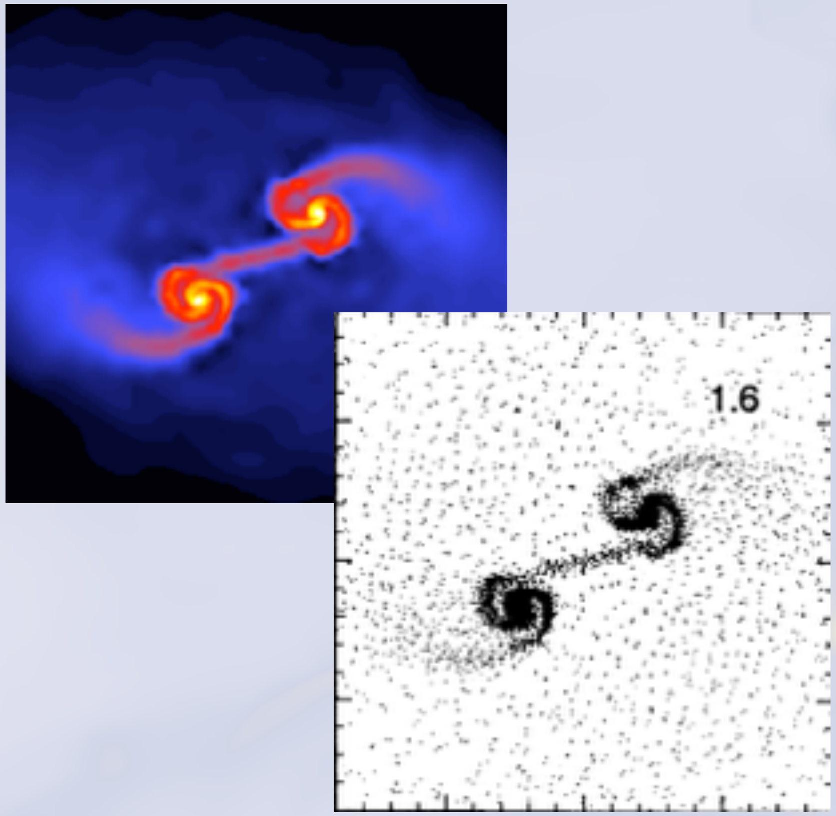
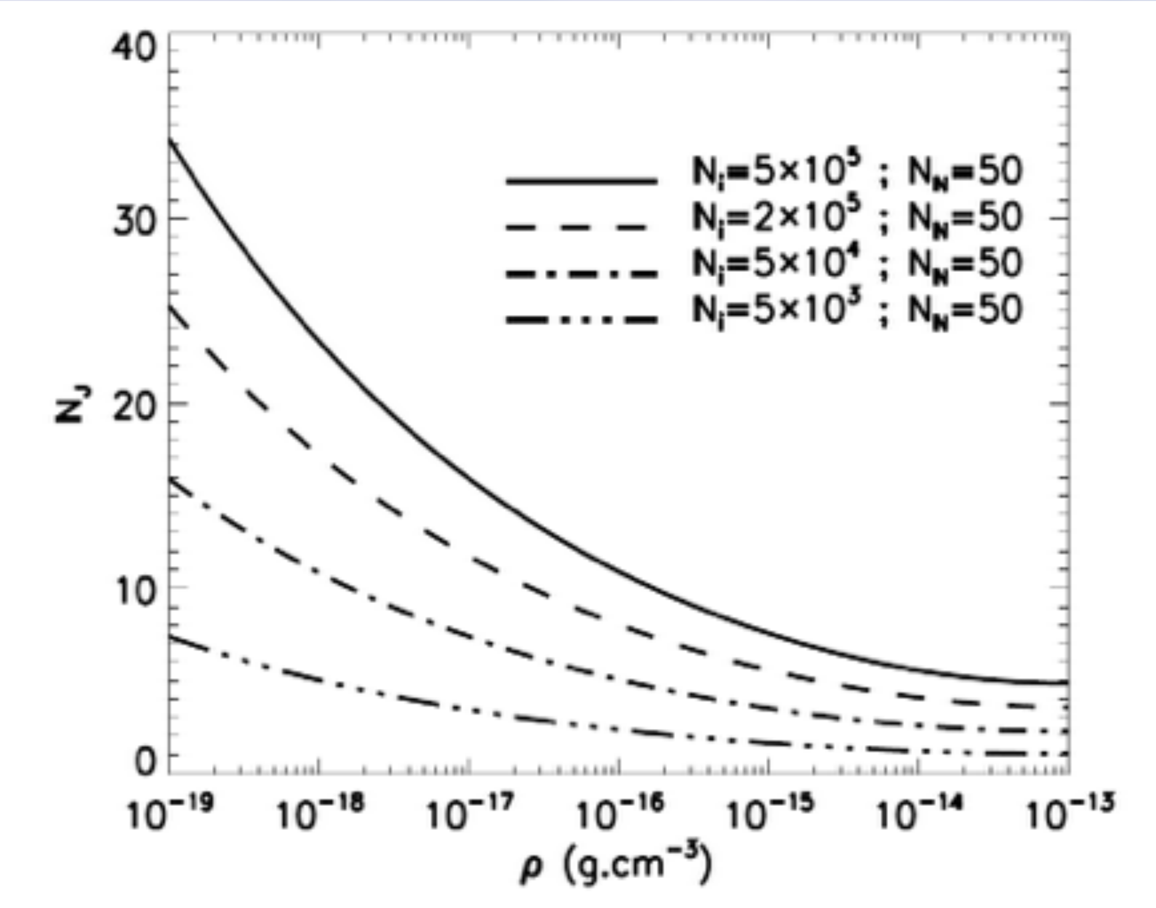


SPH : Total mass of the system particle + 2 N_N (M_{res}) should always be < than the local Jeans mass M_{Jeans} (Bate & Burkert 1997) ➔ static criterion

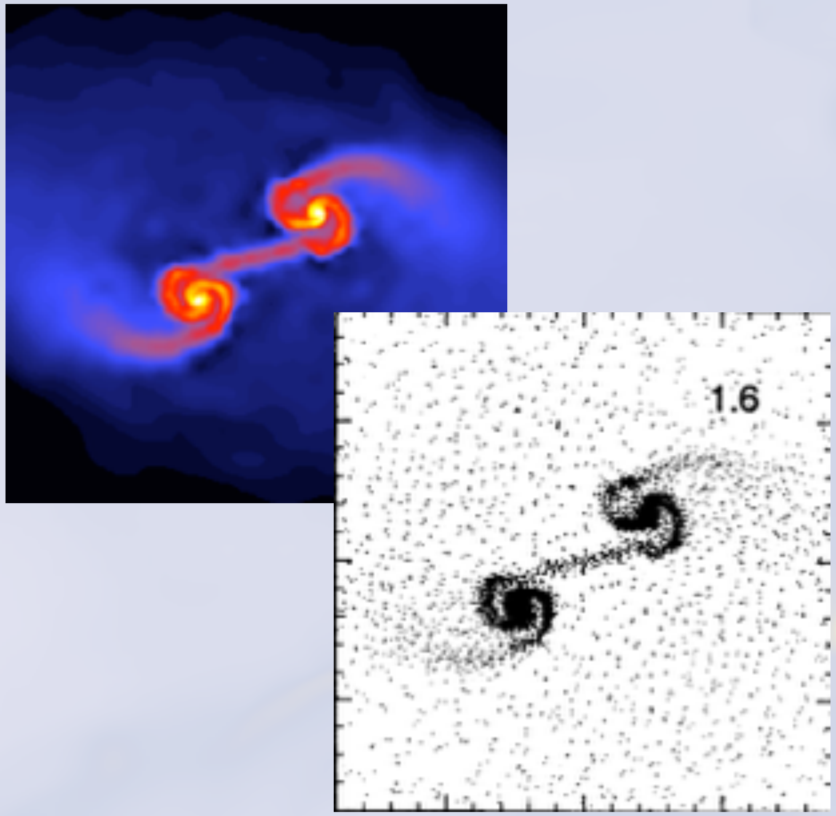
↪ 2 parameters : N_p number of particles

N_N number of neighbors

Numerical resolution criteria for SF



AMR vs. SPH resolution: $N_J^3 = M_{Jeans}/M_{res}$



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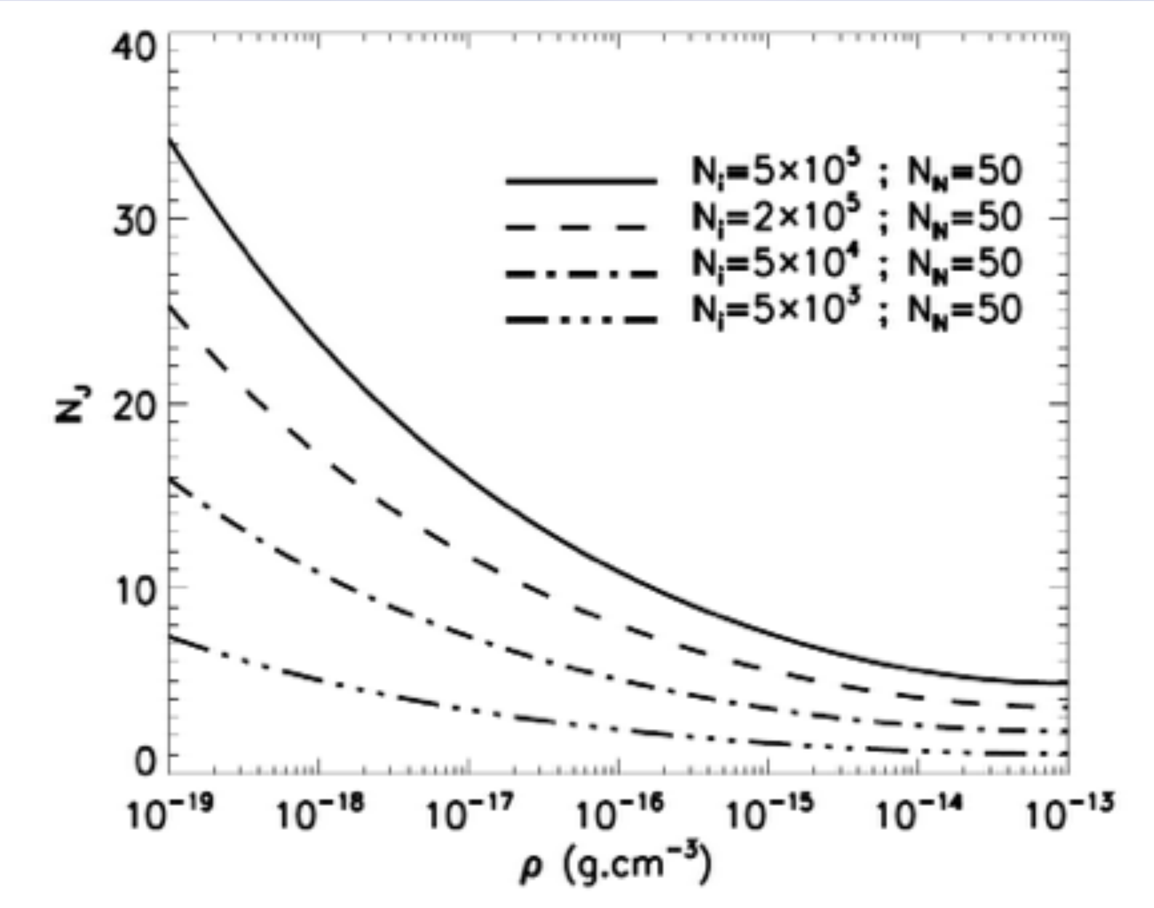


AMR vs. SPH resolution: $N_J^3 = M_{Jeans}/M_{res}$

★ Debate on the accuracy of both methods:

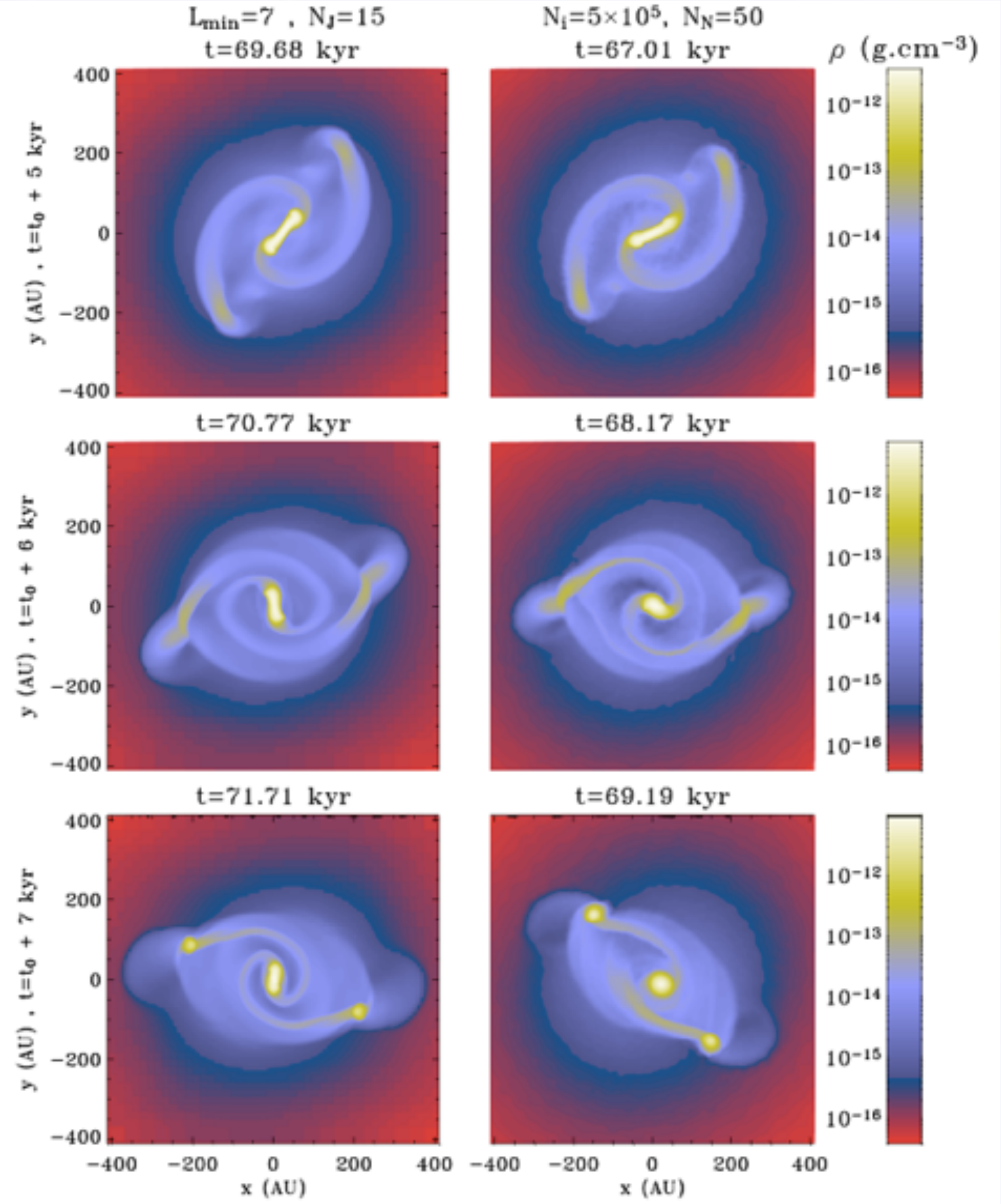
=> Are these methods appropriate for star formation?

=> Are they converging?

☞ Identical initial conditions (uniform density & temperature sphere in solid body rotation, Boss & Bodenheimer test)

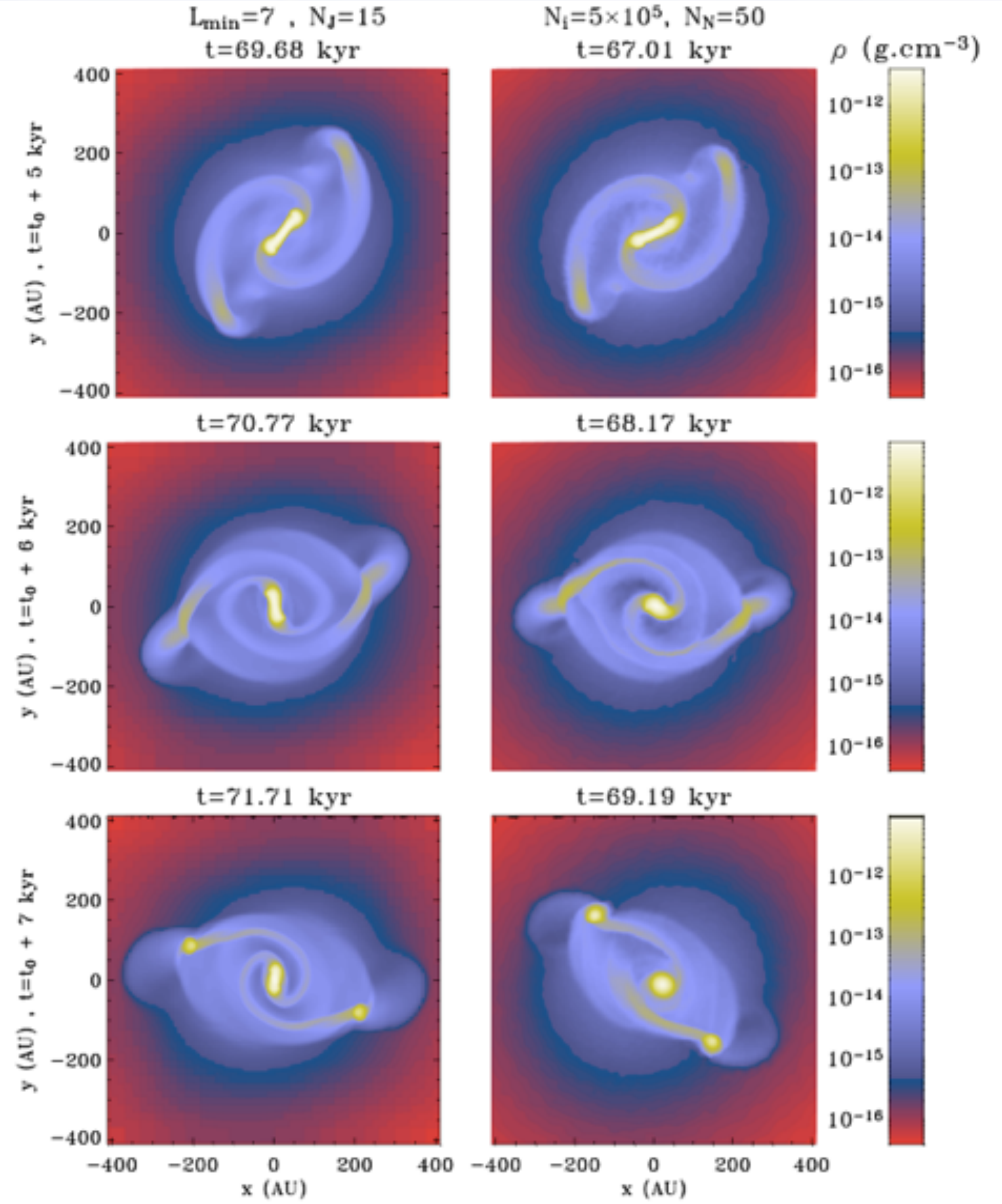
☞ Same equations (Euler equation: mass, momentum and total energy + barotropic closure relation)

AMR vs. SPH: Convergence



Commerçon et al. 2008

AMR vs. SPH: Convergence



AMR: 64^3 (L_{min}=6) ; ***N_J=15*** !

SPH: N_p=5x10^5 ; N_N=50

i.e. ~ **5300** particles/Jeans mass !

- CONVERGENCE!

Commerçon et al. 2008

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Radiation-magneto-hydrodynamics in RAMSES

- ✓ **Adaptive-mesh-refinement** code **RAMSES** (*Teyssier 2002*)
- ✓ **Non-ideal MHD** solver using Constrained Transport (*Teyssier et al. 2006, Fromang et al. 2006, Masson et al. 2012,2016*). In this work, just **ambipolar diffusion** with resistivity from equilibrium gas-grain chemistry (*Marchand et al. 2016*)
- ✓ **Multifrequency Radiation-HD** solver using the Flux Limited Diffusion approximation (*Commerçon et al. 2011, 2014, González et al. 2015*). In this work, just **grey**
- ✓ **Sink particles** using clump finder algorithm (*Bleuler & Teyssier 2014*)
- ✓ Gas-grain opacities from *Semenov et al. (2003)*

$$\begin{aligned}
\partial_t \rho &+ \nabla \cdot [\rho \mathbf{u}] &&= 0 \\
\partial_t \rho \mathbf{u} &+ \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I}] &&= -\rho \nabla \Phi - \lambda \nabla E_\mathrm{r} + (\nabla \times \mathbf{B}) \times \mathbf{B} \\
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\partial_t E_\mathrm{r} &+ \nabla \cdot [\mathbf{u} E_\mathrm{r}] &&= -\mathbb{P}_\mathrm{r} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) + \kappa_\mathrm{P} \rho c (a_\mathrm{R} T^4 - E_\mathrm{r}) \\
\partial_t B &- \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times E_\mathrm{AD} &&= 0
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Gravitational

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\partial_t \rho\mathbf{u} &+ \nabla\cdot[\rho\mathbf{u}\otimes\mathbf{u} + P\mathbb{I}] &&= -\rho\nabla\Phi - \lambda\nabla E_\mathrm{r} + (\nabla\times\mathbf{B})\times\mathbf{B}\\
\partial_t E_\mathrm{T} &+ \nabla\cdot[\mathbf{u}\,(E_\mathrm{T}+P_\mathrm{T}) - \mathbf{B}(\mathbf{B}\cdot\mathbf{u}) - E_\mathrm{AD}\times\mathbf{B}] &&= -\rho\mathbf{u}\cdot\nabla\Phi - \mathbb{P}_\mathrm{r}\nabla:\mathbf{u} - \lambda\mathbf{u}\nabla E_\mathrm{r} + \nabla\cdot\left(\frac{c\lambda}{\rho\kappa_\mathrm{R}}\nabla E_\mathrm{r}\right)\\
\partial_t E_\mathrm{r} &+ \nabla\cdot[\mathbf{u}E_\mathrm{r}] &&= -\mathbb{P}_\mathrm{r}\nabla:\mathbf{u} + \nabla\cdot\left(\frac{c\lambda}{\rho\kappa_\mathrm{R}}\nabla E_\mathrm{r}\right) + \kappa_\mathrm{P}\rho c(a_\mathrm{R}T^4 - E_\mathrm{r})\\
\partial_t B &- \nabla\times(\mathbf{u}\times\mathbf{B}) - \nabla\times E_\mathrm{AD} &&= 0
\end{aligned}$$

Gravitational **Radiative**

Radiation-magneto-hydrodynamics in RAMSES

- ✓ **Adaptive-mesh-refinement** code **RAMSES** (*Teyssier 2002*)
- ✓ **Non-ideal MHD** solver using Constrained Transport (*Teyssier et al. 2006, Fromang et al. 2006, Masson et al. 2012,2016*). In this work, just **ambipolar diffusion** with resistivity from equilibrium gas-grain chemistry (*Marchand et al. 2016*)
- ✓ **Multifrequency Radiation-HD** solver using the Flux Limited Diffusion approximation (*Commerçon et al. 2011, 2014, González et al. 2015*). In this work, just **grey**
- ✓ **Sink particles** using clump finder algorithm (*Bleuler & Teyssier 2014*)
- ✓ Gas-grain opacities from *Semenov et al. (2003)*

$$
\begin{aligned}
\partial_t \rho &+ \nabla \cdot [\rho \mathbf{u}] &&= 0 \\
\partial_t \rho \mathbf{u} &+ \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I}] &&= -\rho \nabla \Phi - \lambda \nabla E_\mathrm{r} + (\nabla \times \mathbf{B}) \times \mathbf{B} \\
\partial_t E_\mathrm{T} &+ \nabla \cdot [\mathbf{u}\,(E_\mathrm{T} + P_\mathrm{T}) - \mathbf{B}(\mathbf{B} \cdot \mathbf{u}) - E_\mathrm{AD} \times \mathbf{B}] &&= -\rho \mathbf{u} \cdot \nabla \Phi - \mathbb{P}_\mathrm{r} \nabla : \mathbf{u} - \lambda \mathbf{u} \nabla E_\mathrm{r} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) \\
\partial_t E_\mathrm{r} &+ \nabla \cdot [\mathbf{u} E_\mathrm{r}] &&= -\mathbb{P}_\mathrm{r} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) + \kappa_\mathrm{P} \rho c (a_\mathrm{R} T^4 - E_\mathrm{r}) \\
\partial_t B &- \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times E_\mathrm{AD} &&= 0
\end{aligned}
$$

Gravitational

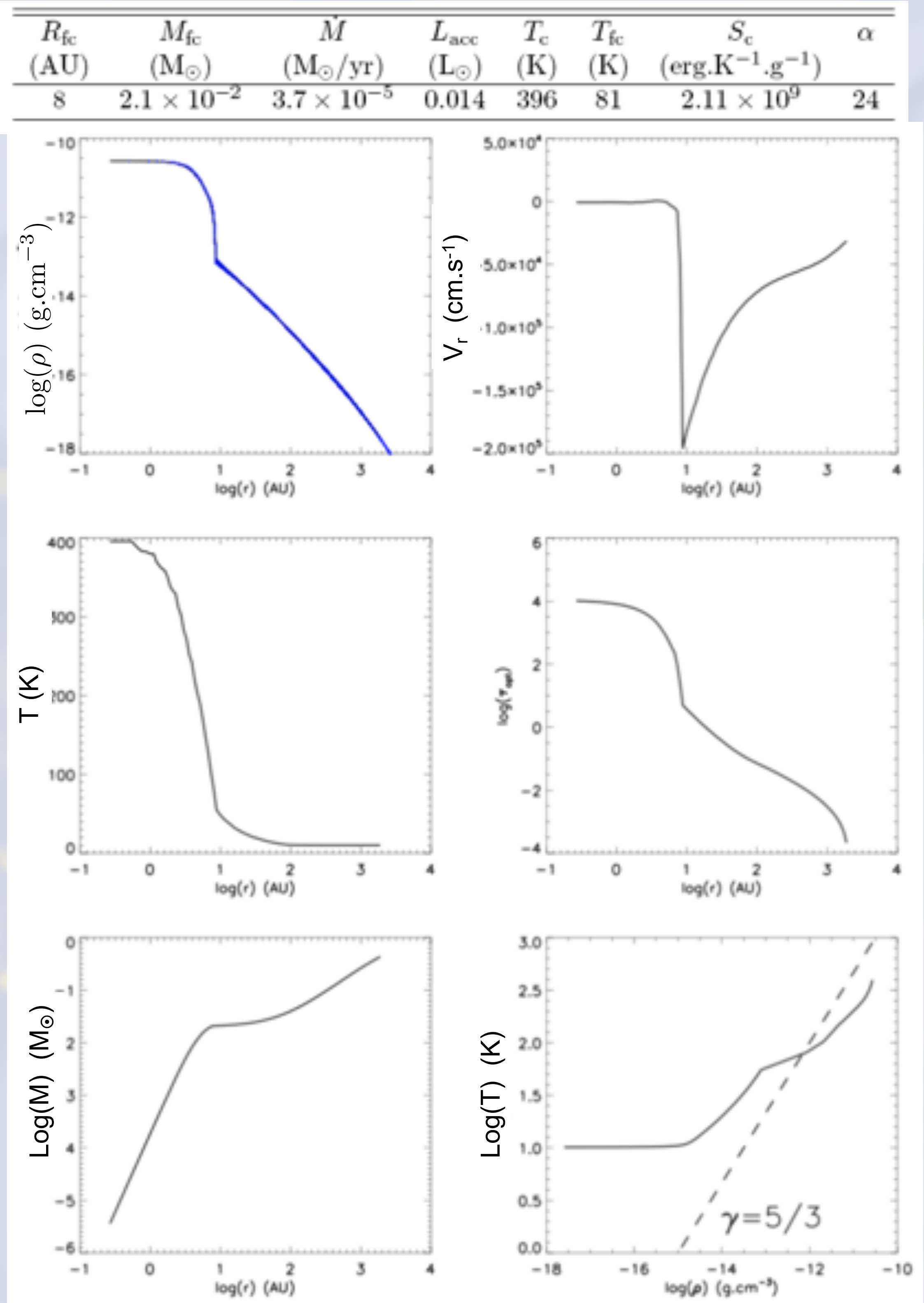
Radiative

Lorentz force

Spherical collapse

$\alpha = 0.50 = E_{th}/E_{grav}$

- ✓ spherical symmetry conserved
- ✓ 1st core properties similar to Masunaga et al. (1999)
- ✓ accretion shock: supercritical radiative shock, i.e ***all*** the incident ***kinetic energy*** is ***radiated*** away (*Commerçon et al. 2011b*)



R_{fc} (AU)	M_{fc} ($M_\odot$)	$\dot{M}$ ($M_\odot$/yr)	L_{acc} ($L_\odot$)	T_c (K)	T_{fc} (K)	S_c (erg.K^{-1}.g^{-1})	α
8	2.1×10^{-2}	3.7×10^{-5}	0.014	396	81	2.11×10^9	24

Commerçon et al. 2011a

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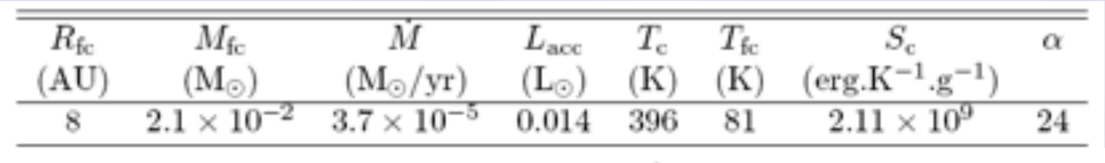

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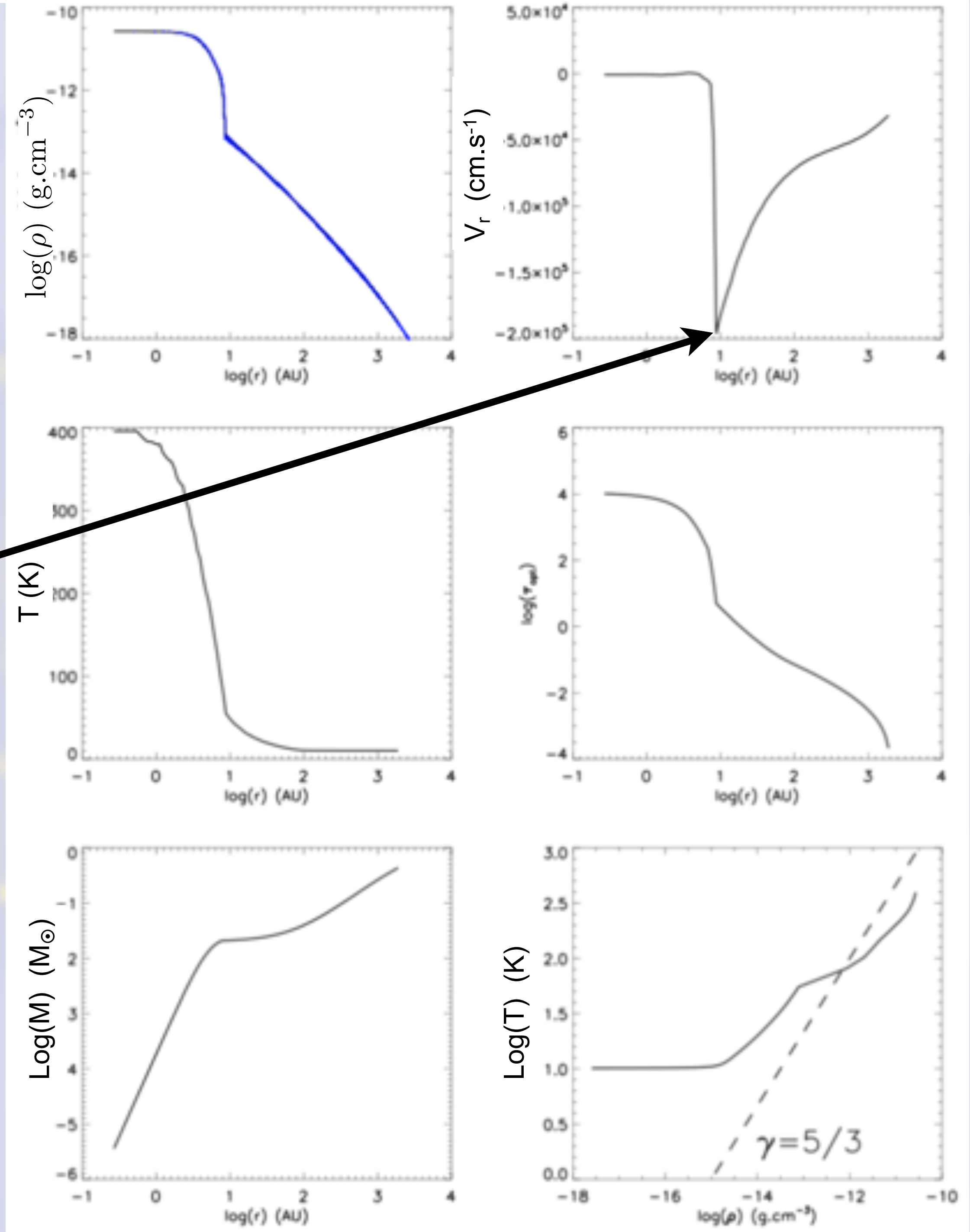


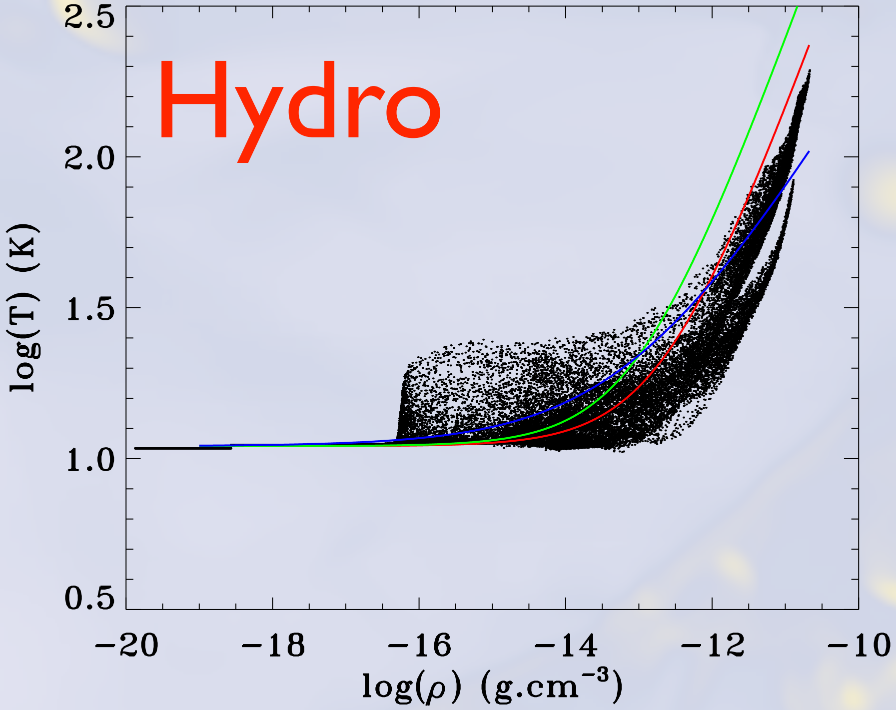
Commerçon et al. 2011a

1 M⊙ dense core collapse: Hydro

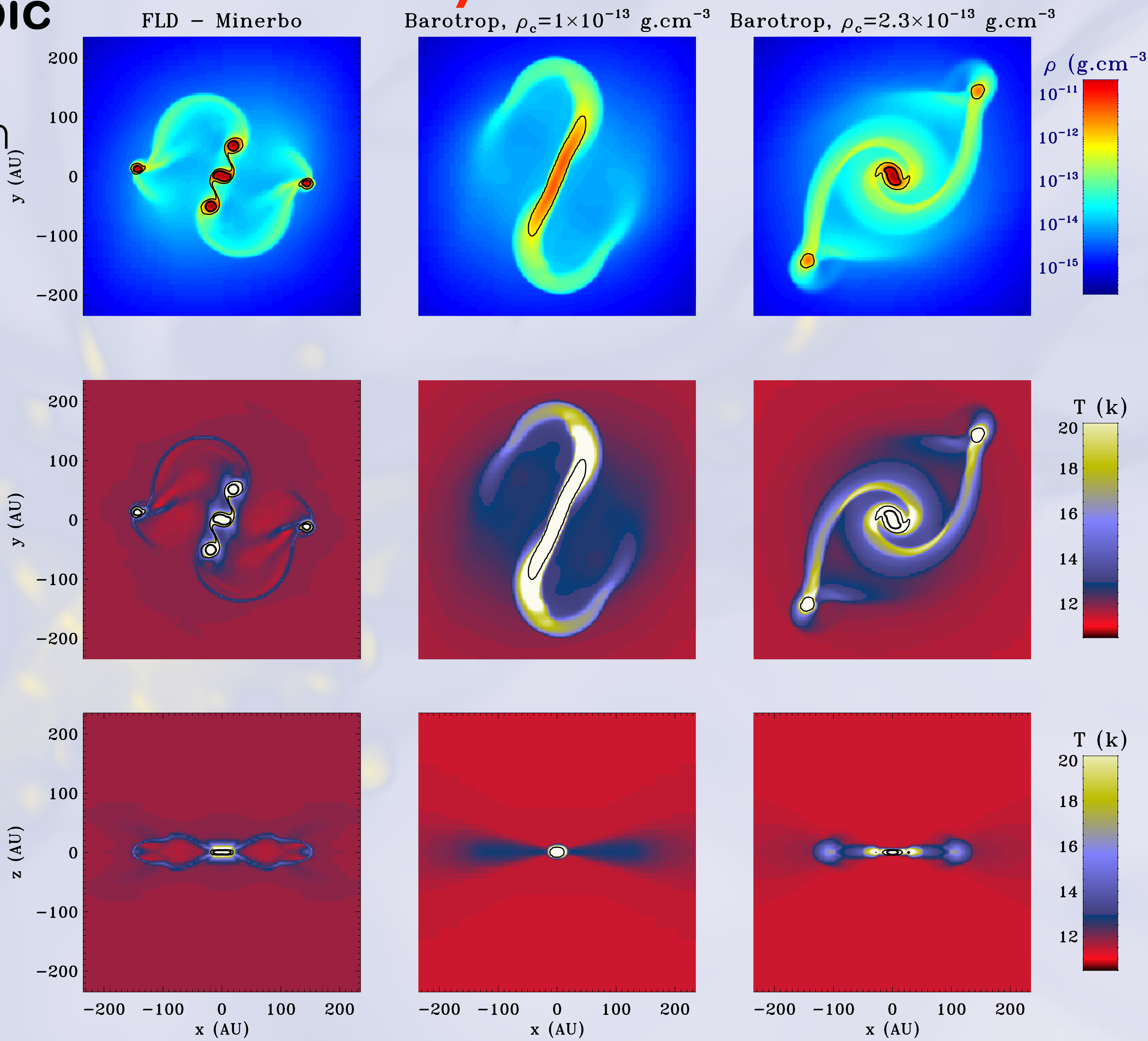
Comparison to the barotropic case

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

==> lower Jeans mass



Hydro



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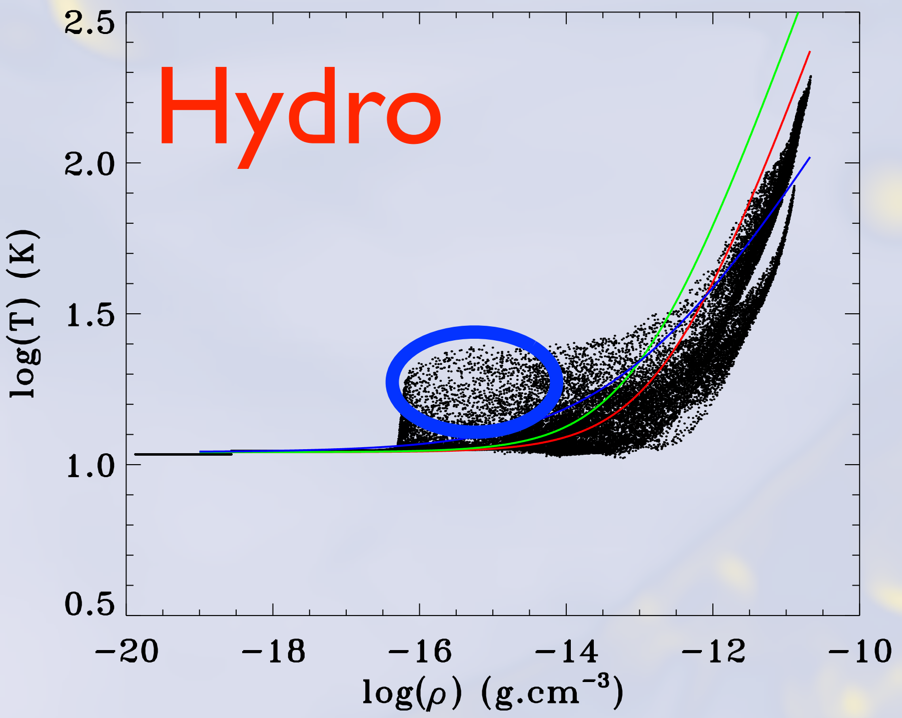
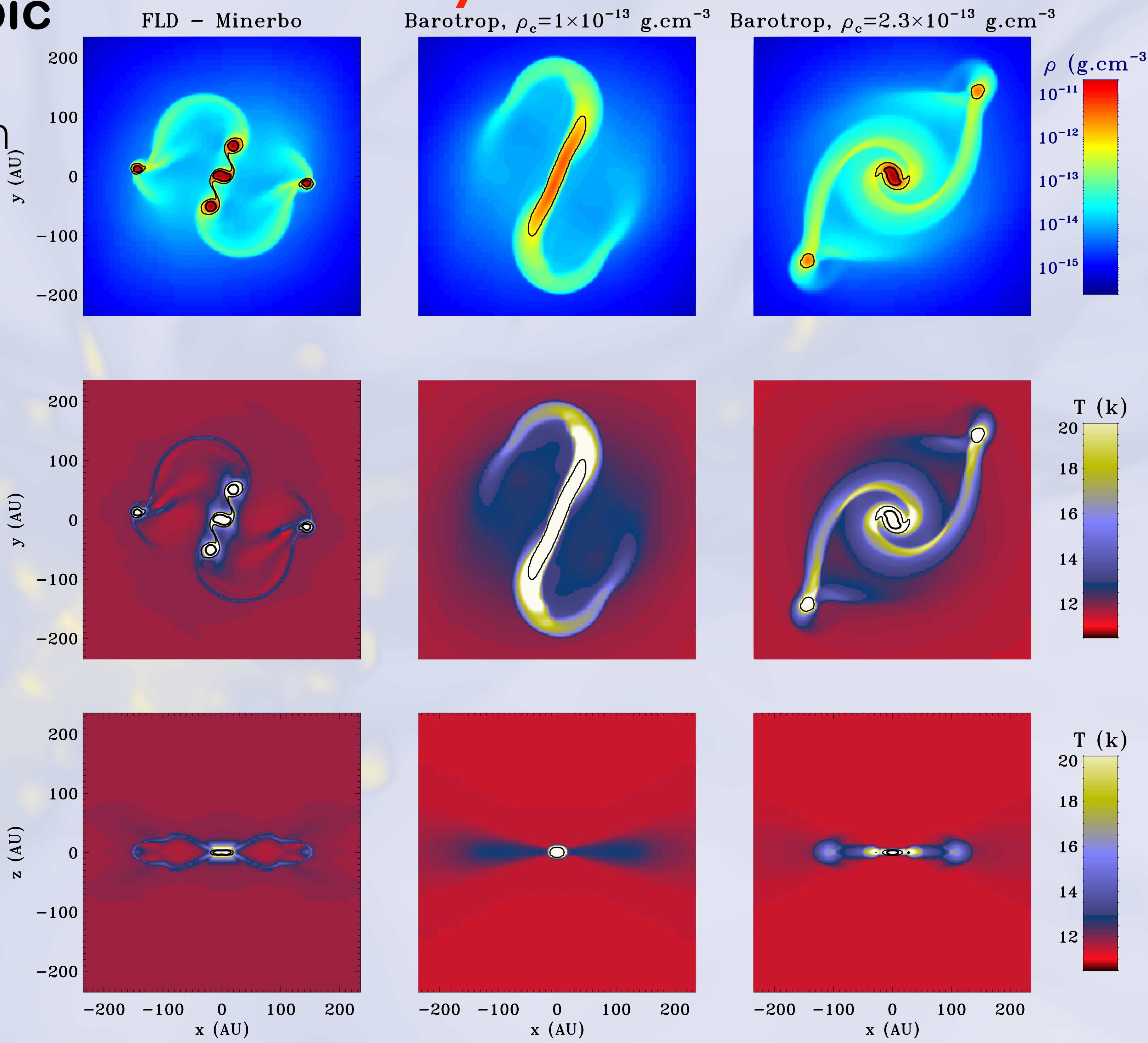


Hydro



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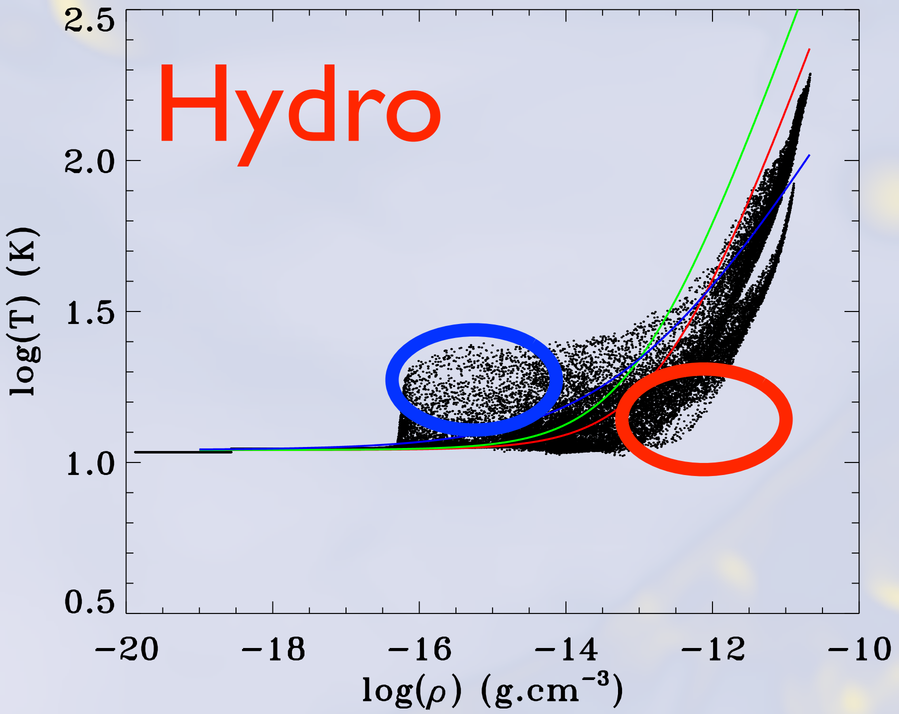
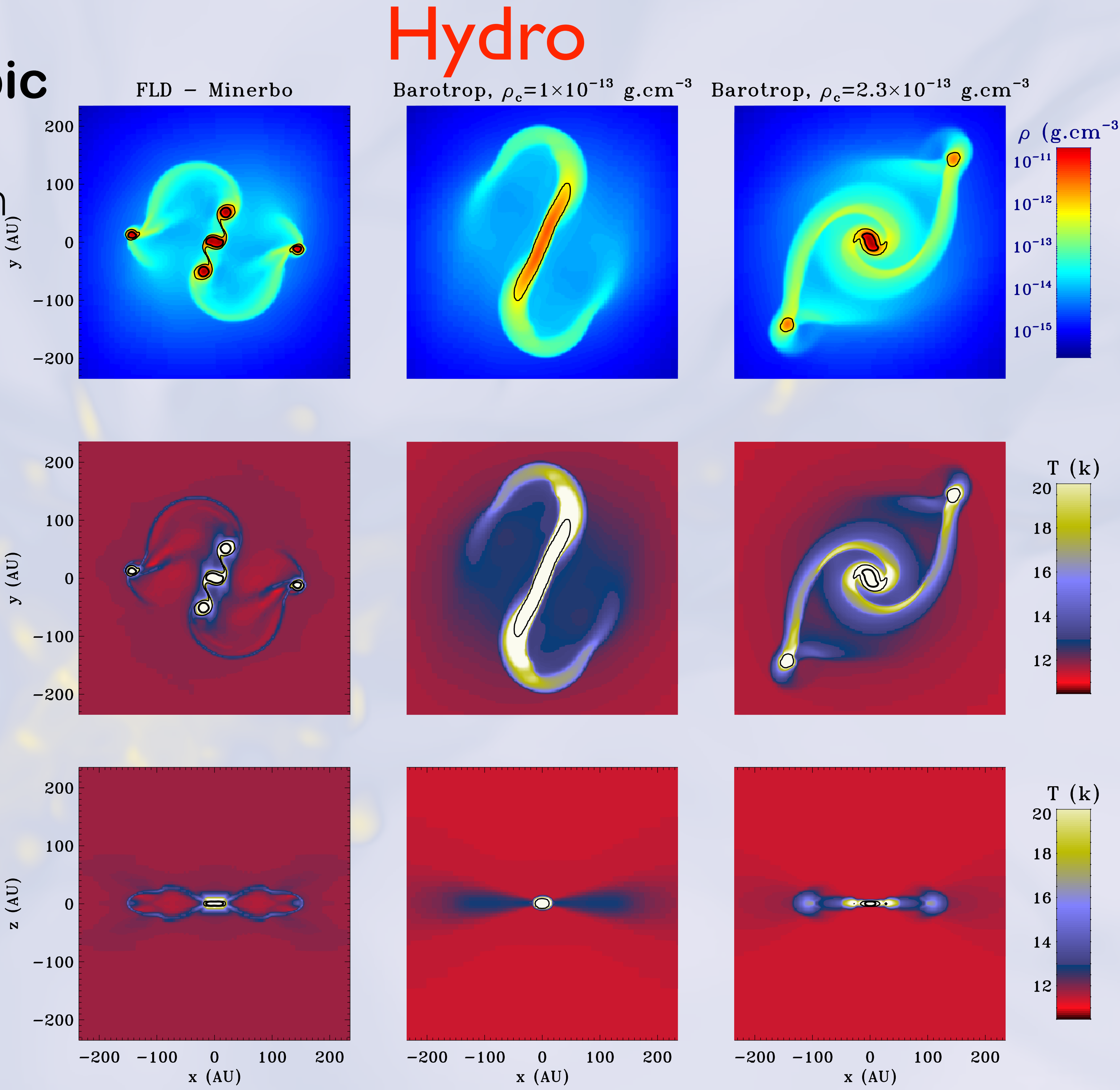
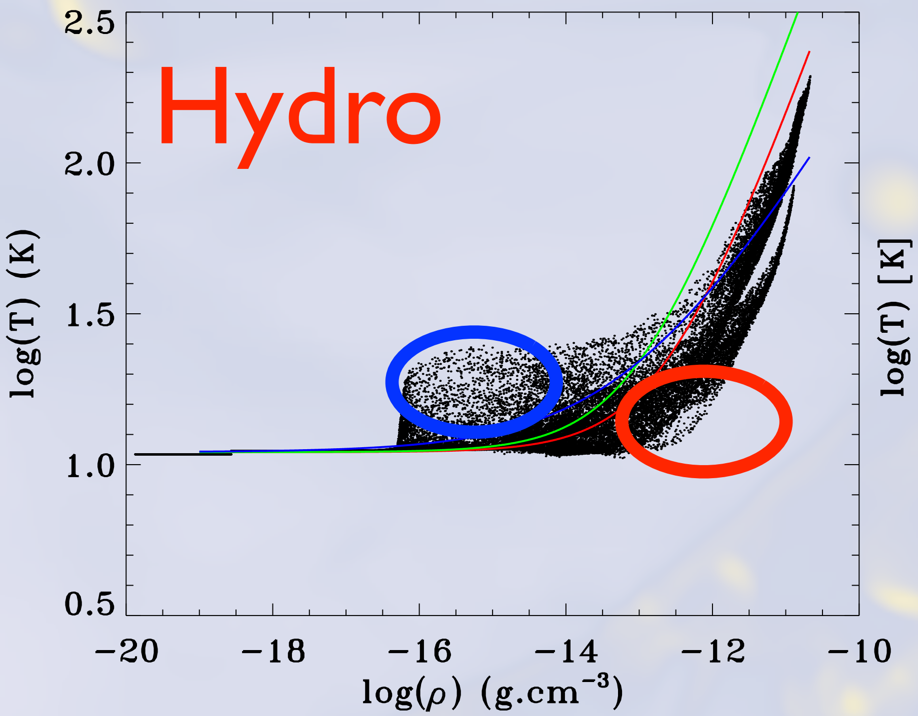


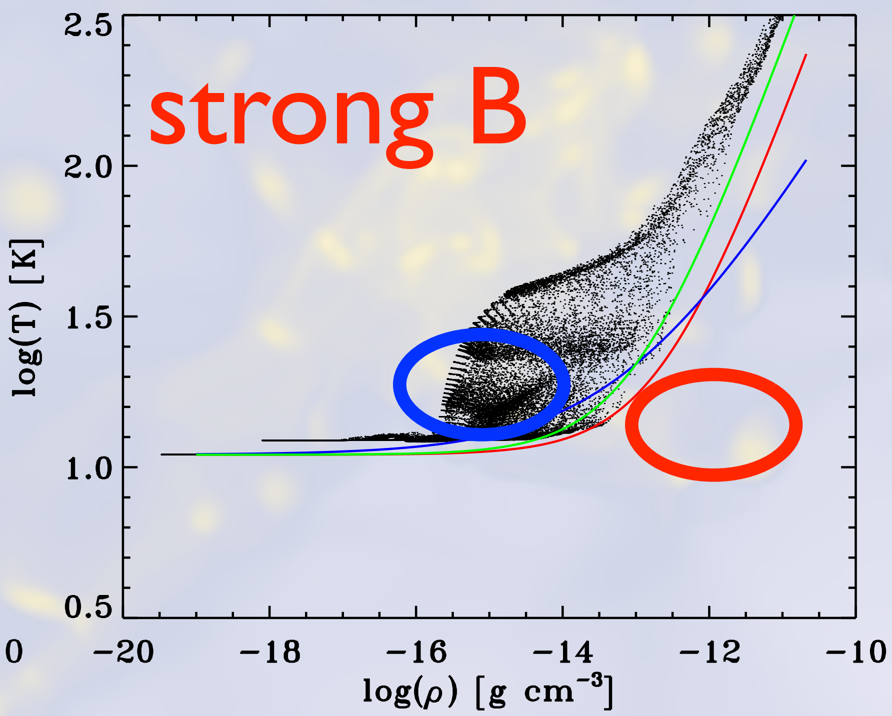


1 M⊙ dense core collapse: Hydro vs. μ =5

Comparison to the barotropic case

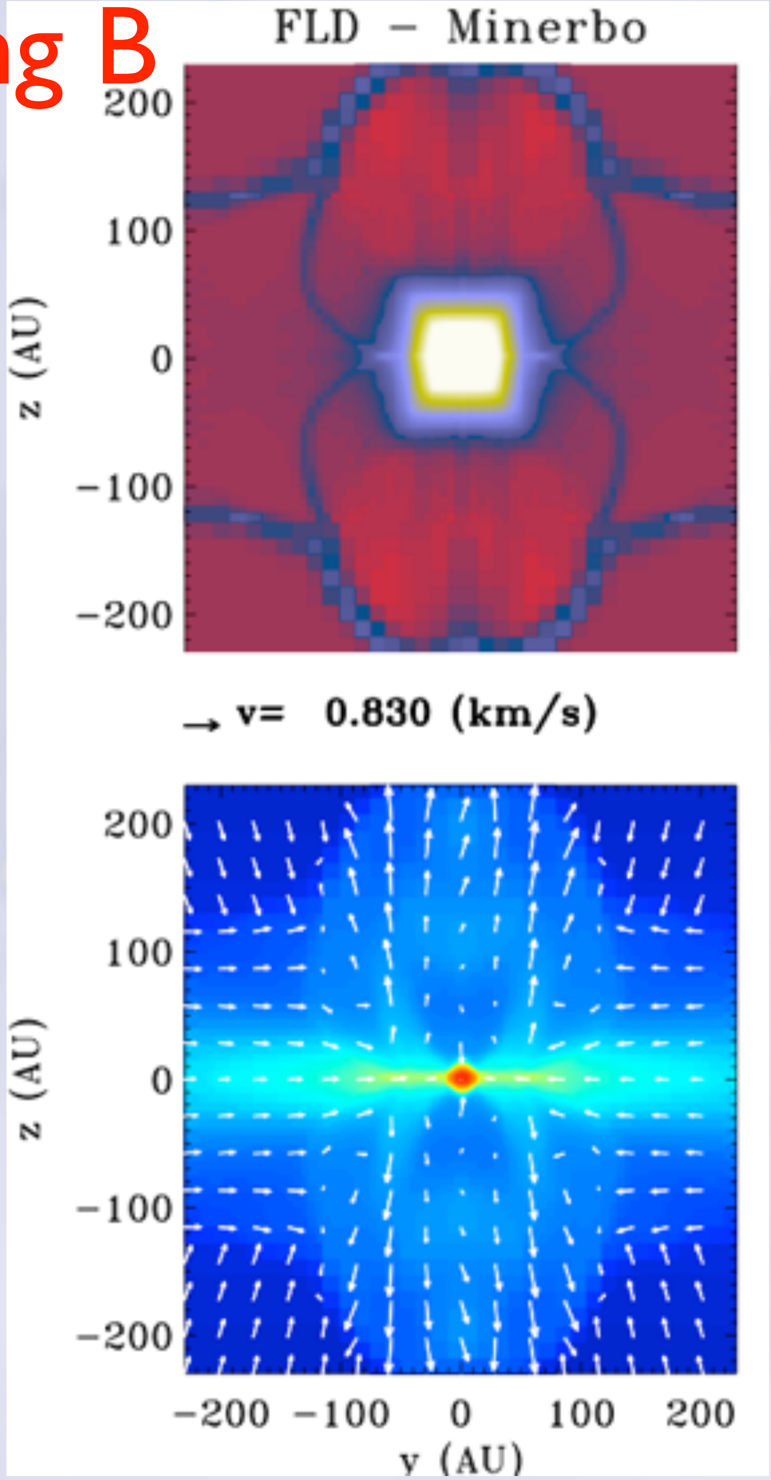
- **Hydro case**: more fragmentation
- **RMHD**: **magnetic** braking <=> radiative feedback (L_{acc})





Commerçon et al. 2010, A&AL

strong B



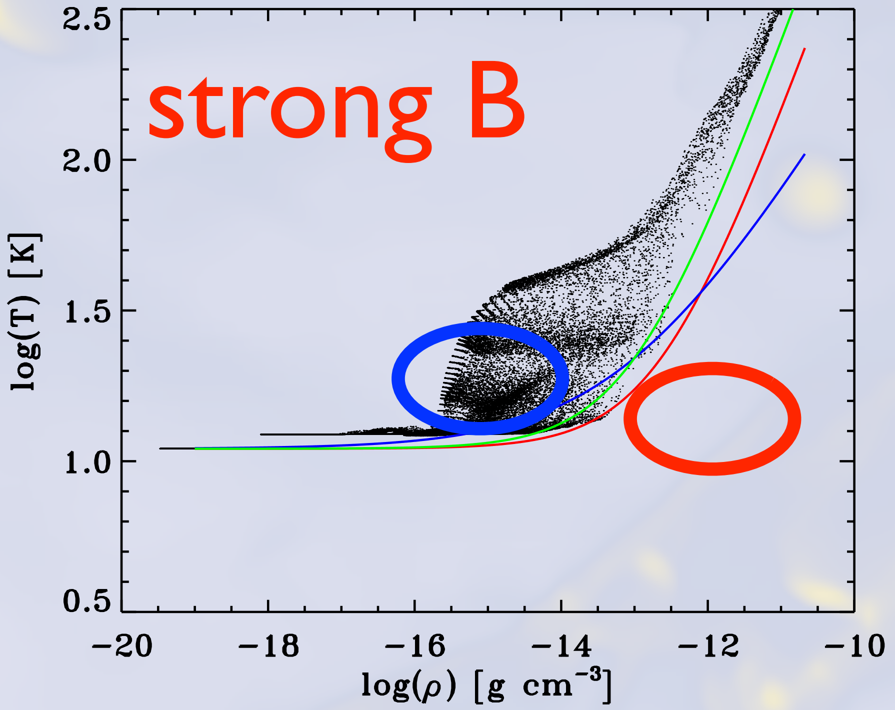
1 $M_\odot$ dense core collapse: FLD vs. barotrop

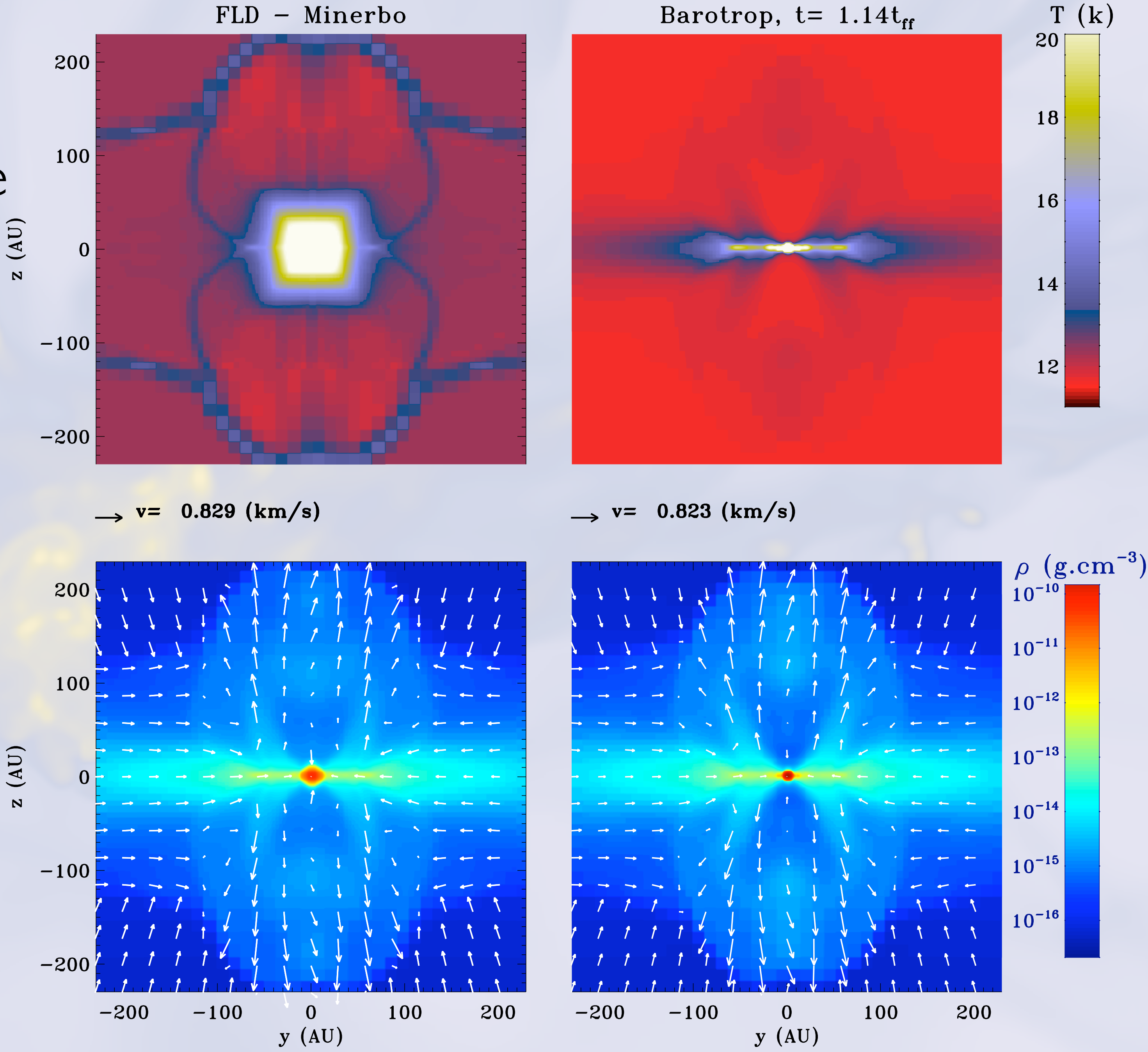
Comparison to the barotropic case

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

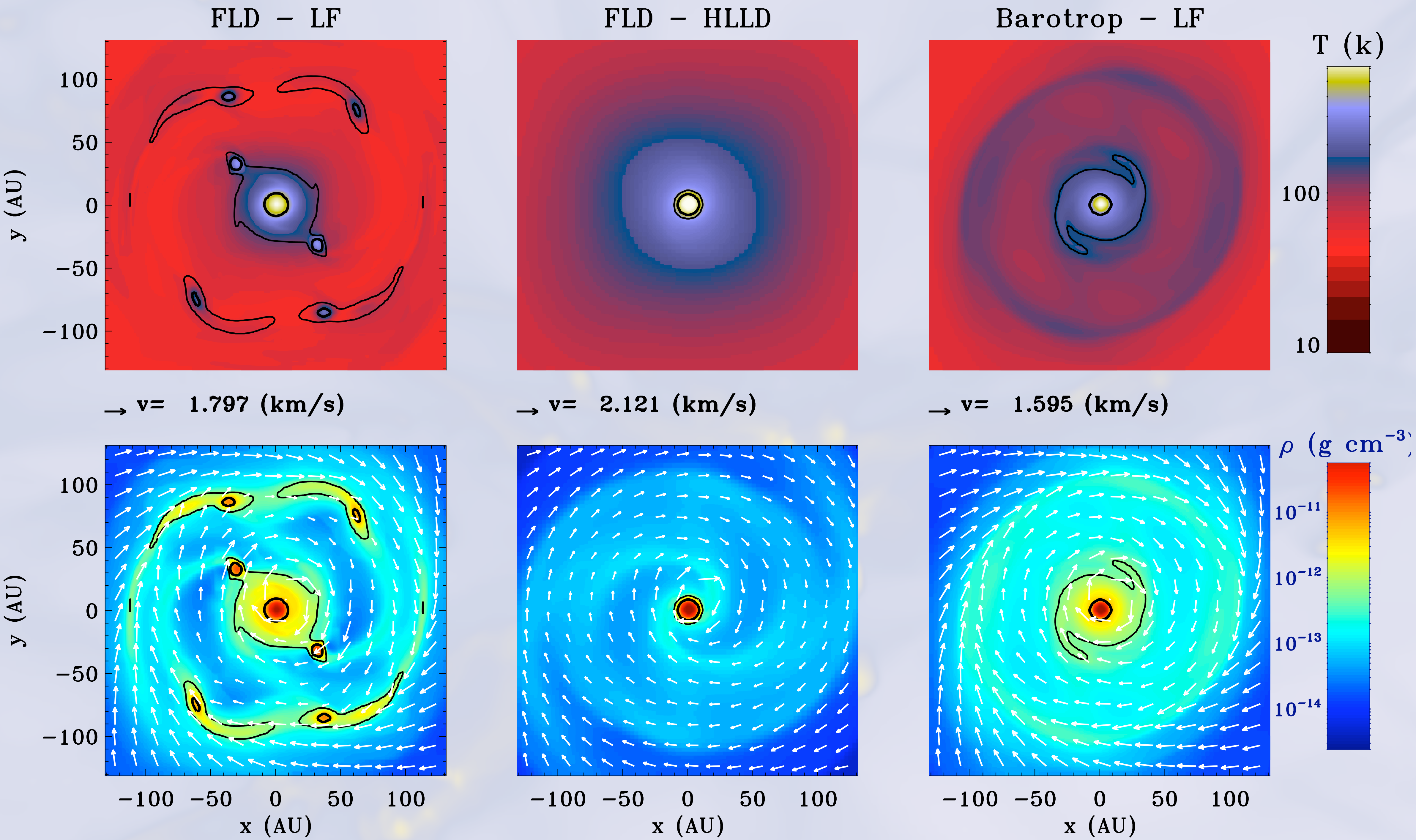
<=> **observations**

Commerçon et al. 2010, A&AL





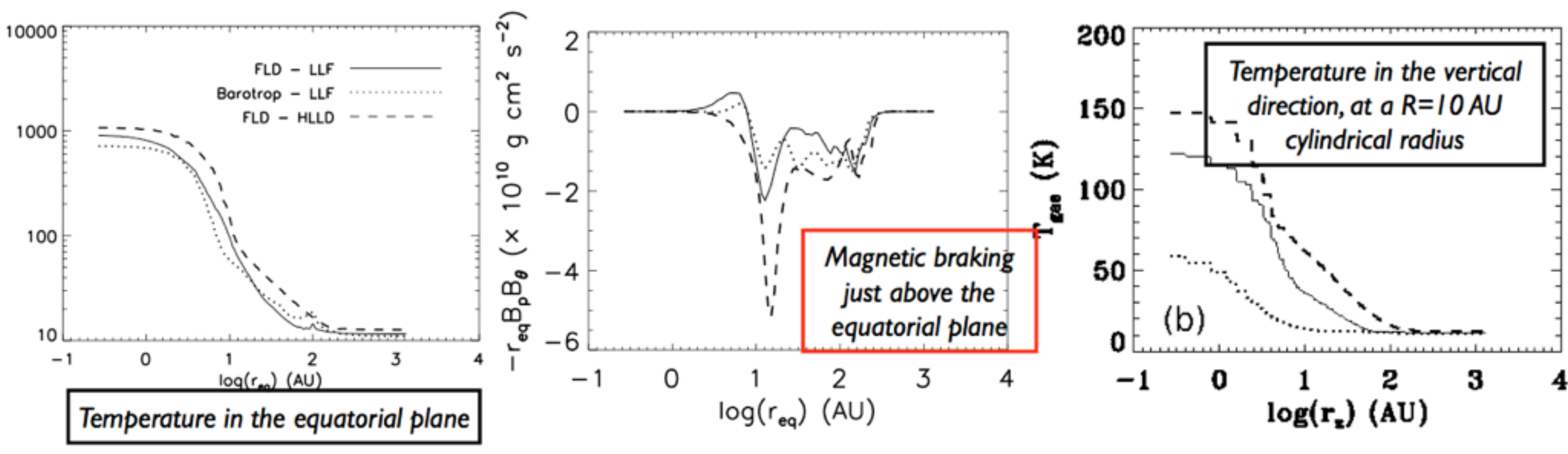
Intermediate case, μ =20 - Numerical issue



Commerçon et al. 2010, A&AL

Intermediate case, μ =20 - Numerical issue

Commerçon et al. 2010, A&AL



- ✓Diffusivity of the solver => 2 effects that favor fragmentation:
  - ➡ inefficient magnetic braking
  - ➡ more massive disk
- ✓ Radiative feedback depends on the magnetic braking: $L_{acc} \propto V_{inf}^3$ (supercritical radiative shock)!

Influence of the magnetization

MU=5
Strong B

MU=20
Weak B

Hydro
B=0

equatorial
plane

yz - plane

Influence of the magnetization

MU=5
Strong B

MU=20
Weak B

Hydro
B=0

equatorial plane

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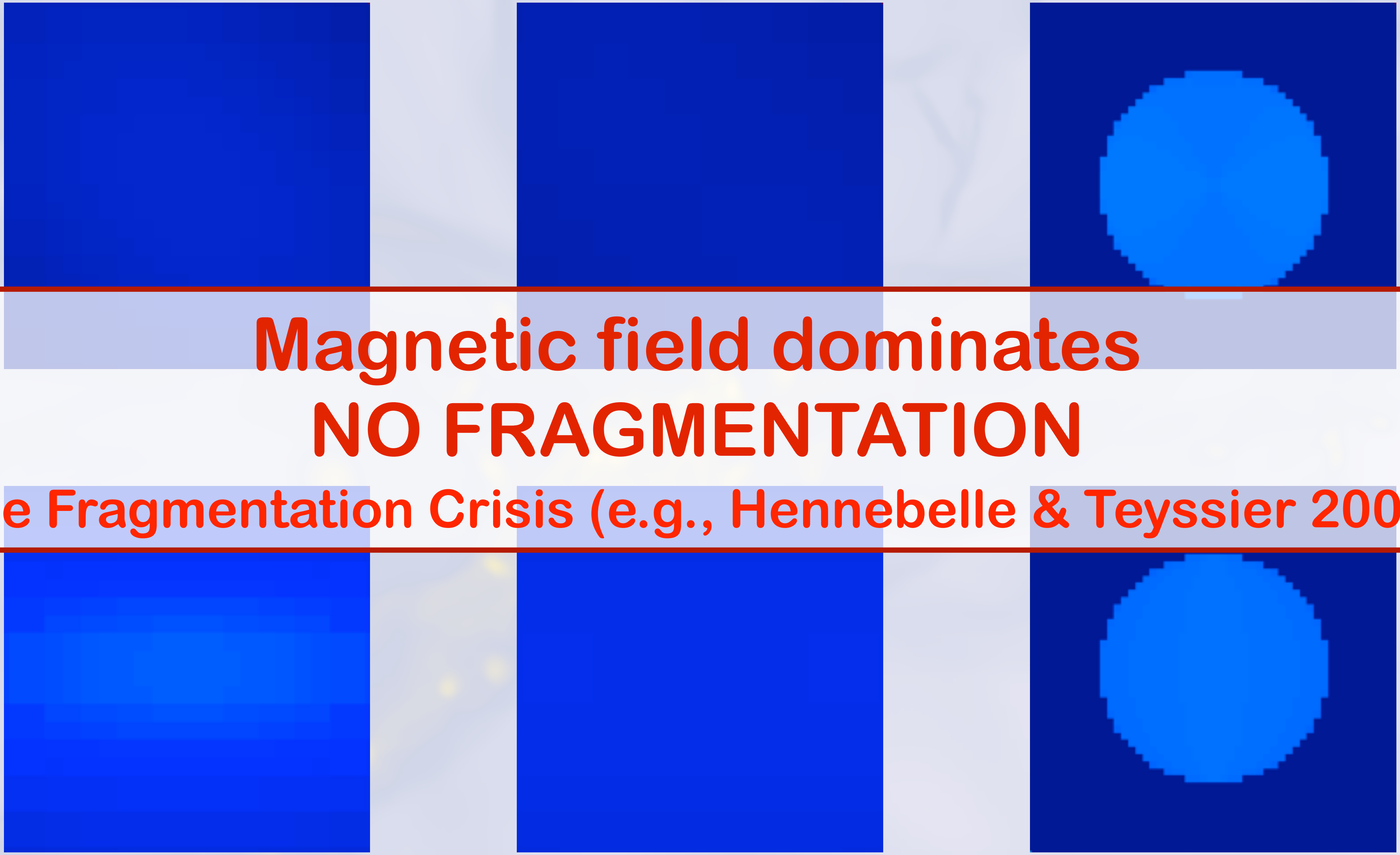
Influence of the magnetization



Magnetic field dominates

NO FRAGMENTATION

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

Disk formation in magnetised cores

- ✓ **Late formation**
  - ➢ end of class 0, $M_{env} << M_{env,0}$ (e.g., *Machida & Hosokawa 2013*)

- ✓ **Misalignment**
  - ➢ no reason for the rotation axis and the magnetic field to be aligned (e.g., *Hull et al. 2013*)
  - ➢ reduces magnetic braking efficiency (e.g. *Hennebelle & Ciardi 2009, Joos et al. 2012, Li et al. 2013*)

- ✓ **Turbulent diffusion**
  - ➢ reconnection events fast with Ohmic diffusion only, collective effect at larger scale (e.g. *Santos Lima et al. 2012, Joos et al. 2013, Seifried et al. 2013*)

- ✓ **Non-ideal MHD**
  - ➢ Ohm dissipation (*Tomida et al. 2013, 2015, Machida et al.*)
  - ➢ Hall effect (*Krasnopolsky et al. 2011, Tsukamoto et al. 2015, Wurster et al. 2016*)
  - ➢ ambipolar diffusion (*Tsukamoto et al. 2015, Masson et al. 2016, Wurster et al. 2016*)

Non ideal MHD

$$
\begin{aligned}
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \Bigg[& \mathbf{v}_{\mathrm{n}} \times \mathbf{B} \\
& - \eta_{\Omega} (\nabla \times \mathbf{B}) \\
& - \eta_{\mathrm{H}} \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{\|\mathbf{B}\|} \right\} \\
& - \eta_{\mathrm{AD}} \frac{\mathbf{B}}{\|\mathbf{B}\|} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{\|\mathbf{B}\|} \right\} \Bigg]
\end{aligned}
$$

Non-ideal effects:

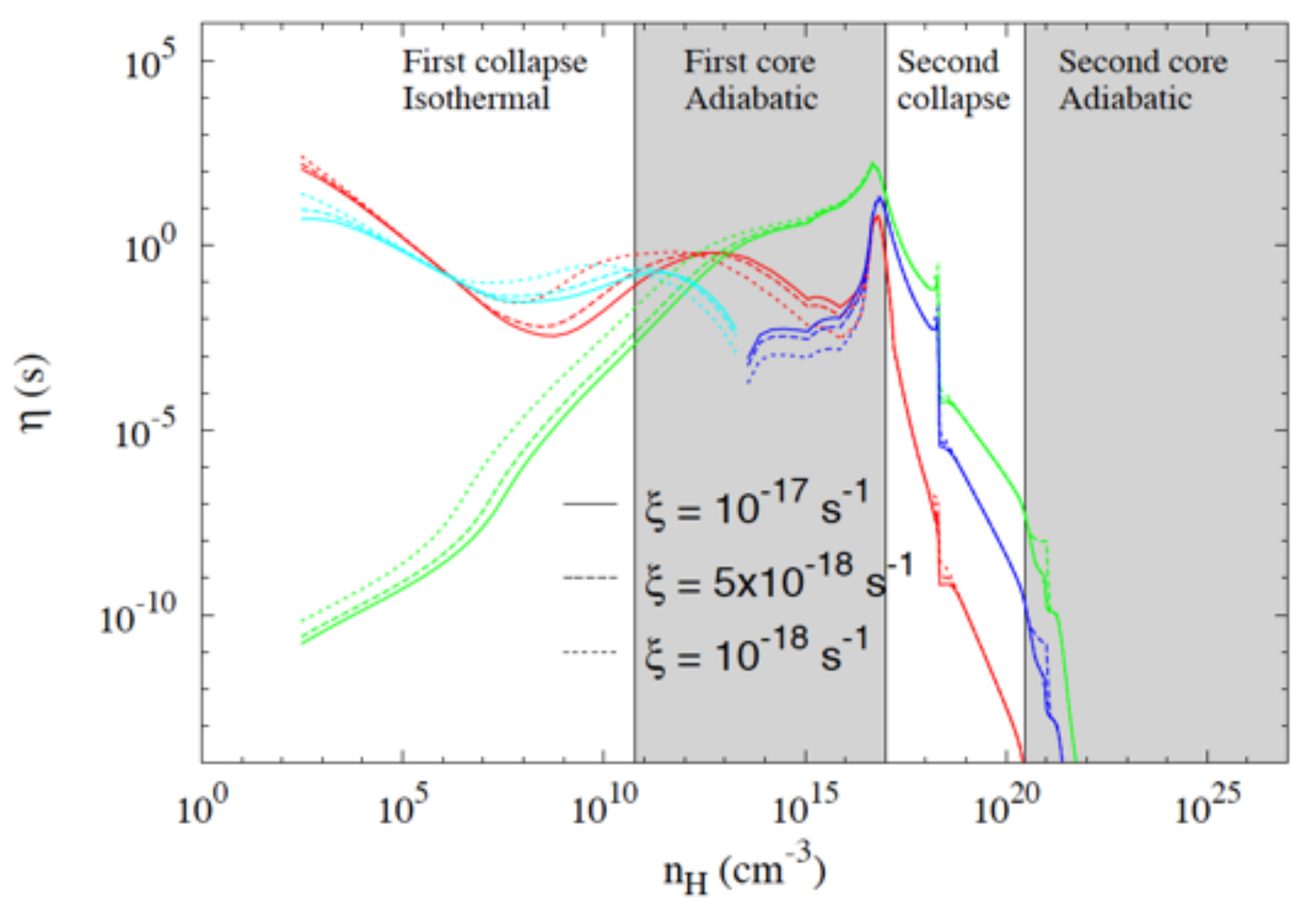
- rearrangement of magnetic field lines
- reconnection
- magnetic flux diffusion
- … needs gas-grain chemistry

Non ideal MHD

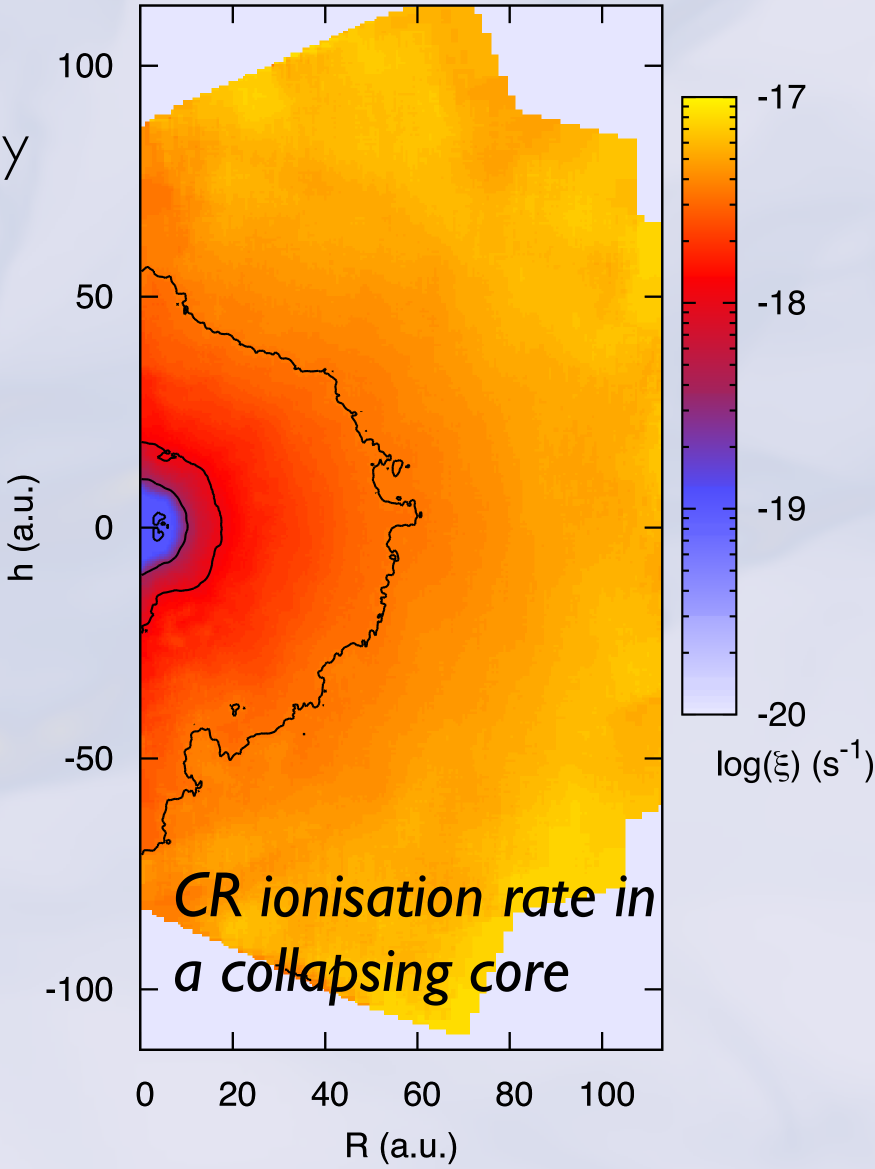
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \Bigg[\mathbf{v}_{\rm n} \times \mathbf{B} - \eta_{\Omega}(\nabla \times \mathbf{B}) - \eta_{\rm H} \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{||\mathbf{B}||} \right\} - \eta_{\rm AD} \frac{\mathbf{B}}{||\mathbf{B}||} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{||\mathbf{B}||} \right\} \Bigg]$$

Non-ideal effects:

- rearrangement of magnetic field lines
- reconnection
- magnetic flux diffusion
- … needs gas-grain chemistry



Marchand et al. (2016)



CR ionisation rate in a collapsing core

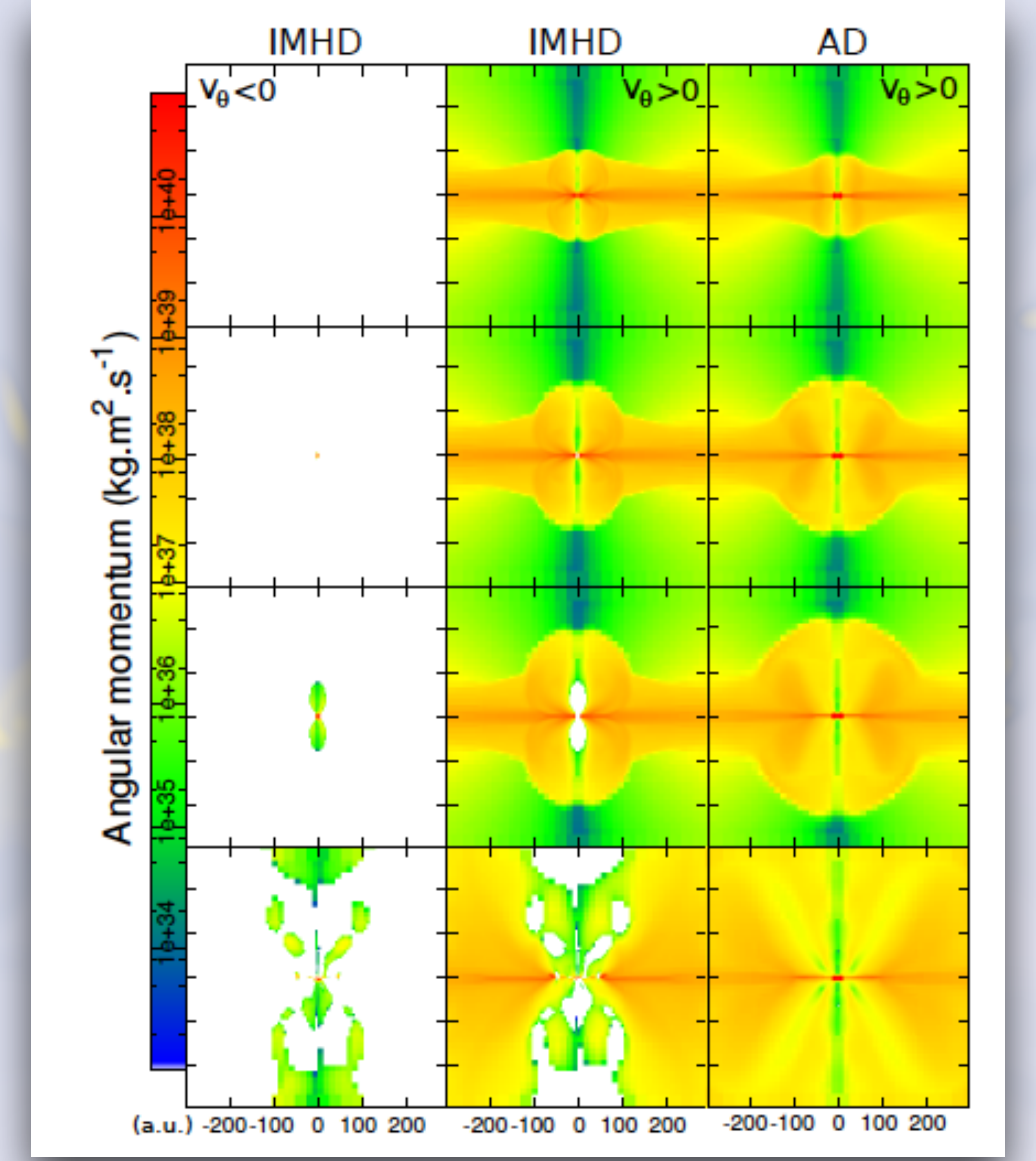
1/ **Grain evaporation** is the *most* important effect

2/ Needs at least 20 bins in dust grain size distribution to converge…

Influence of non-ideal MHD

Rotation and interchange instability

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



Masson et al. (2016)

Influence of non-ideal MHD

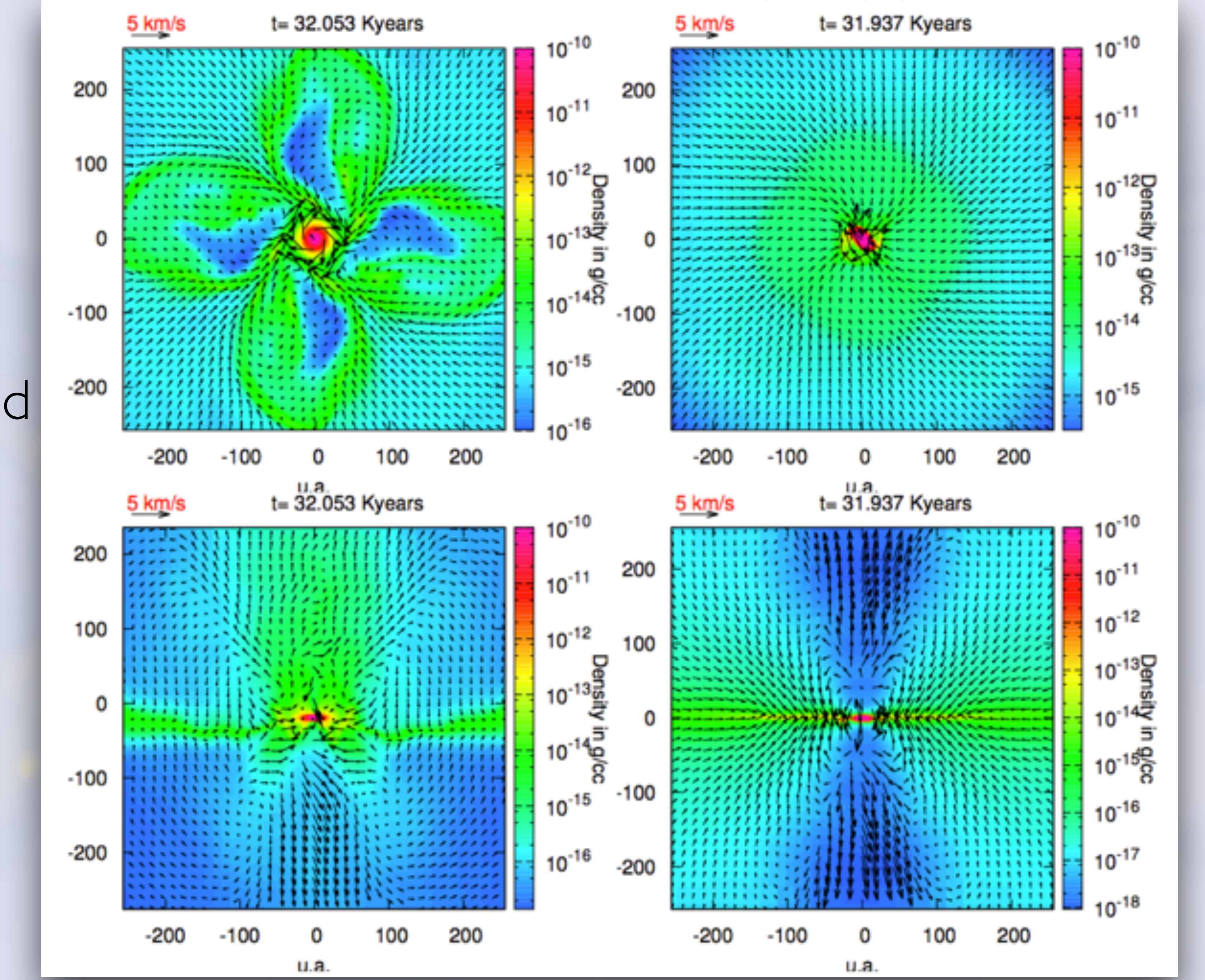
Rotation and interchange instability

- reduce magnetic braking (suppress counter-rotation found in ideal MHD)
- reduce development of interchange instability

- changes at the first core scale
- diffusion is *controlled*

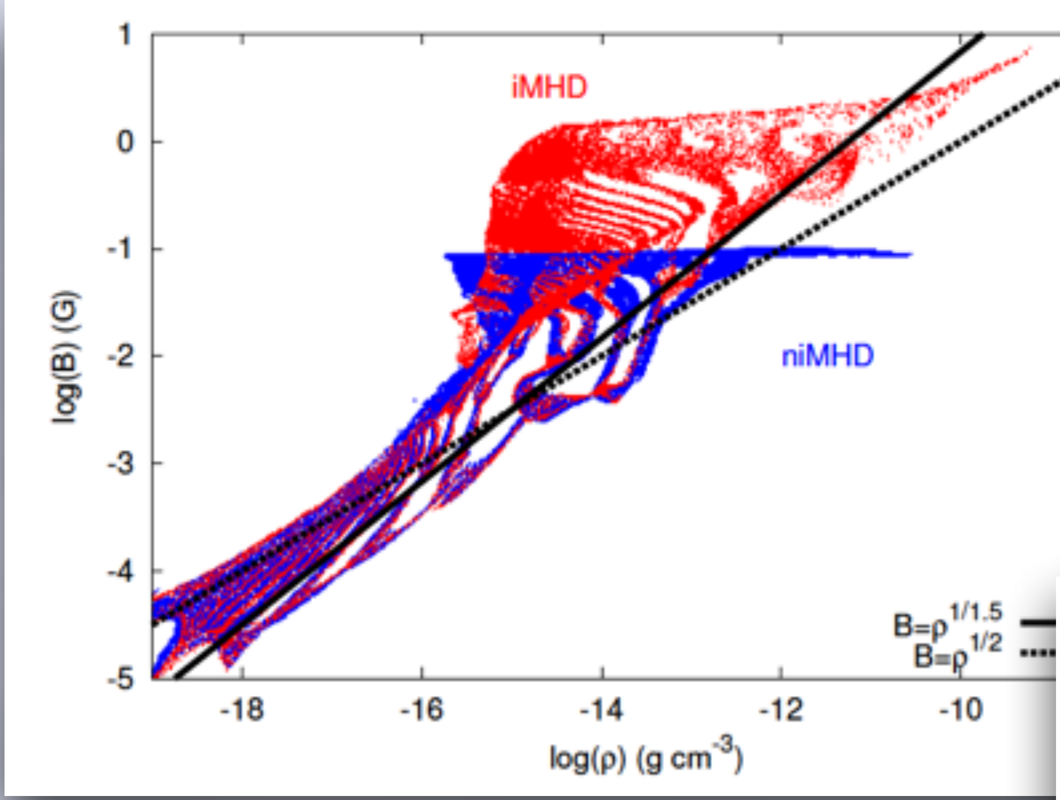
Ideal

Ambipolar diffusion



J. Masson PhD

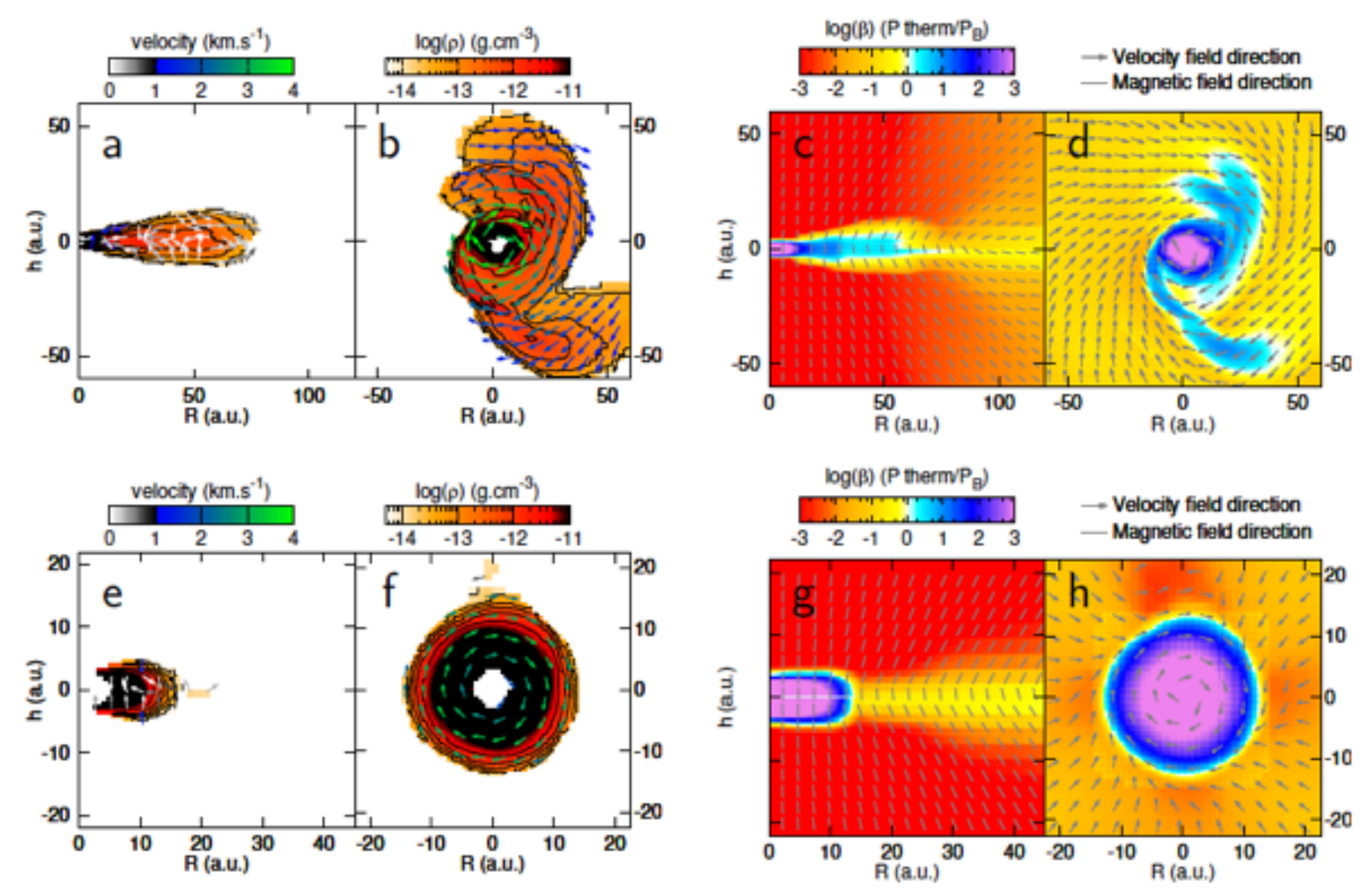
Misalignment & ambipolar diffusion



- formation of a **plateau** at B~0.1G
- **reorganisation** of magnetic field lines (essentially **poloidal**)

=> **reduced magnetic braking**

- mass and radius of first core do not change
- **weaker outflows** compared to ideal MHD

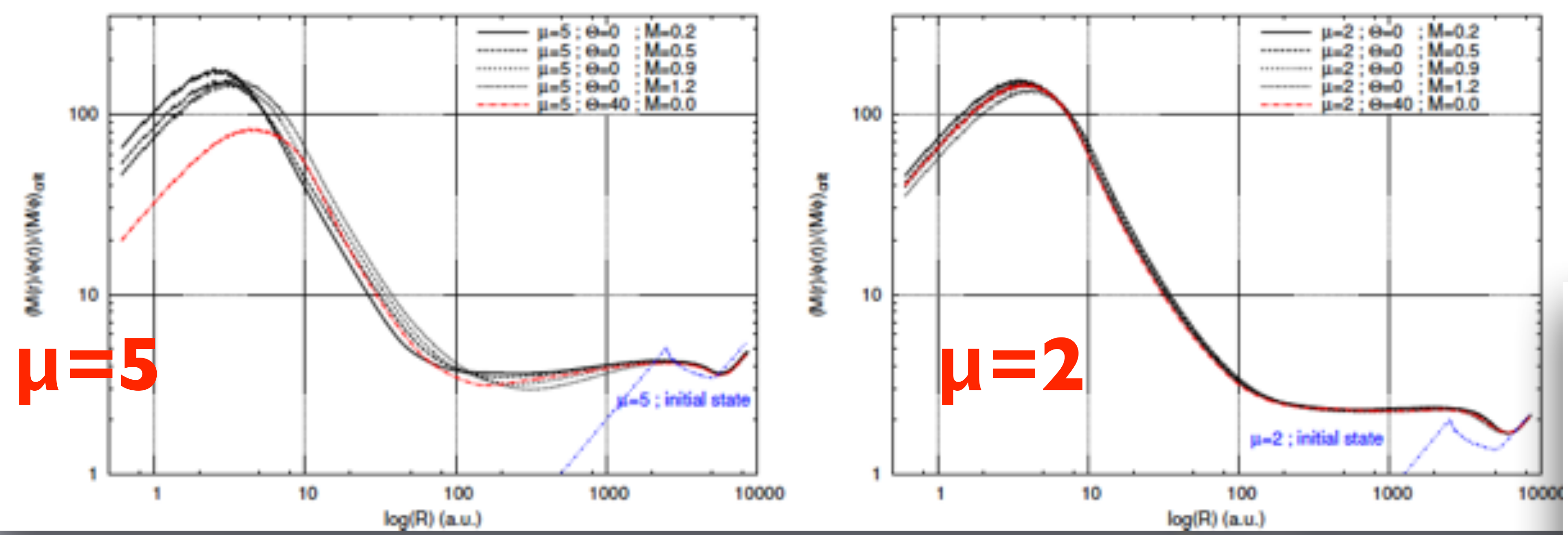


- Rotationally supported disk formation (**R ~ 50 AU**) - consistent with obs.
- disk size **depends** on misalignment
- **P_{therm}/P_{mag}>1** within disks
- **poloidal** magnetic field

=> initial conditions for protoplanetary disks studies

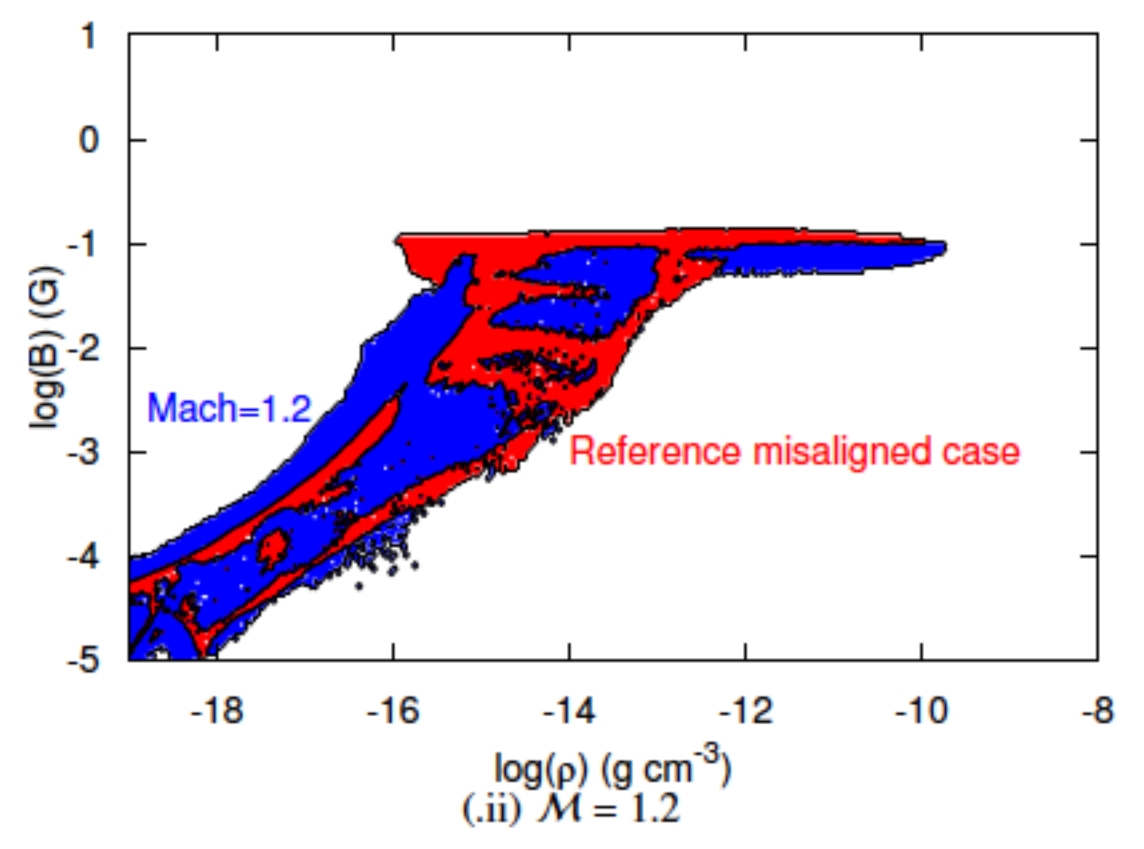
Masson et al. 2016

Turbulence & ambipolar diffusion

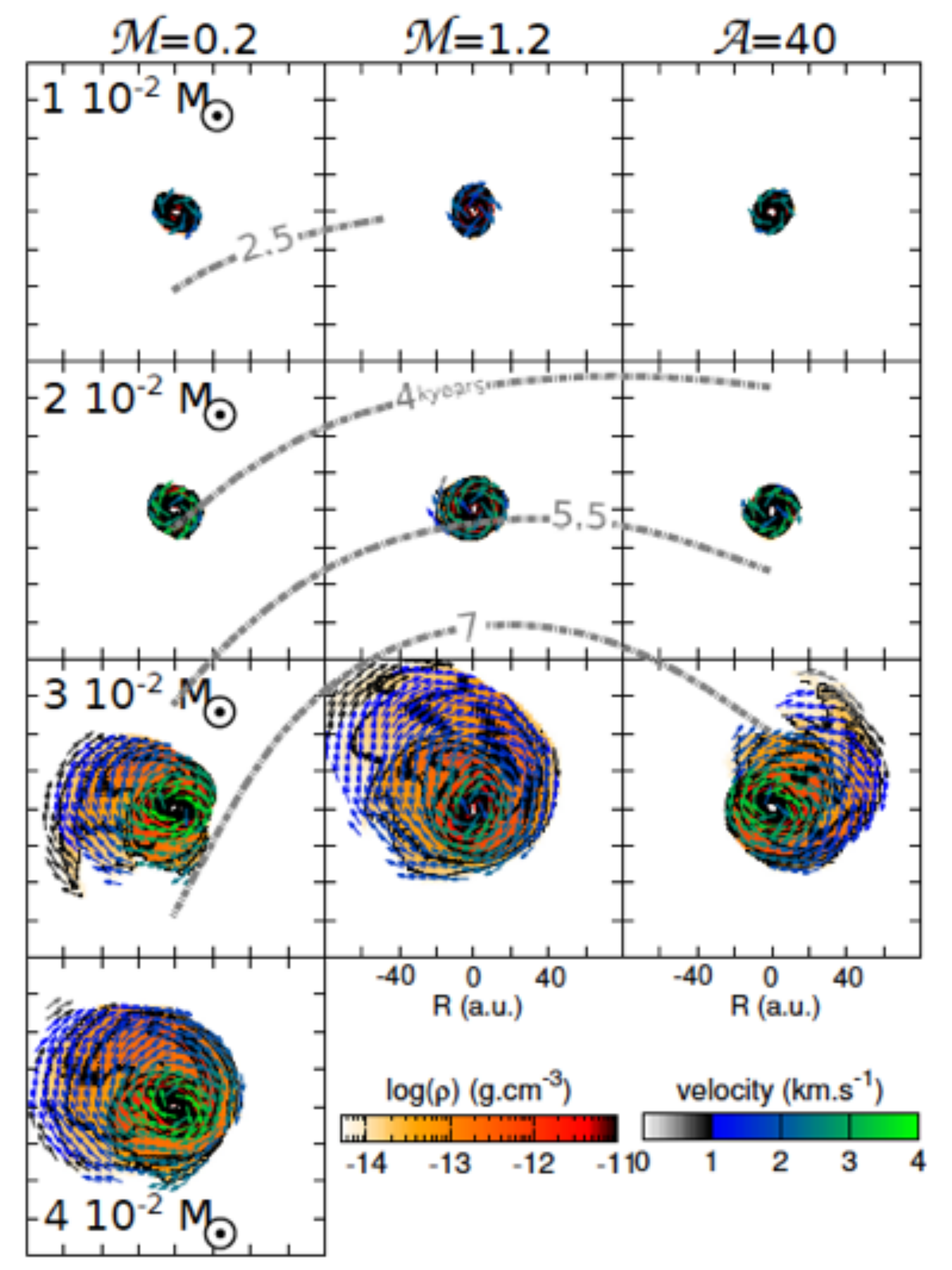


- disk size **does not depend** on turbulence level

=> combination between turbulent diffusion and ambipolar diffusion?

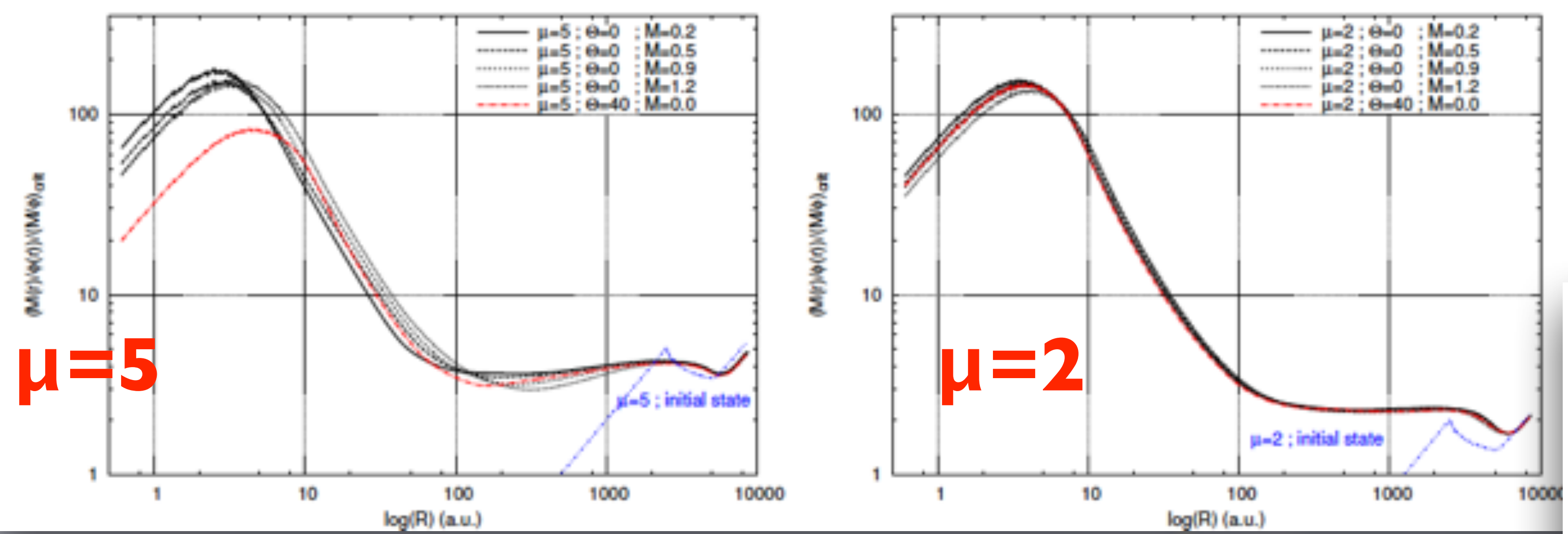


(.ii) $\mathcal{M} = 1.2$



Masson et al. in prep.

Turbulence & ambipolar diffusion



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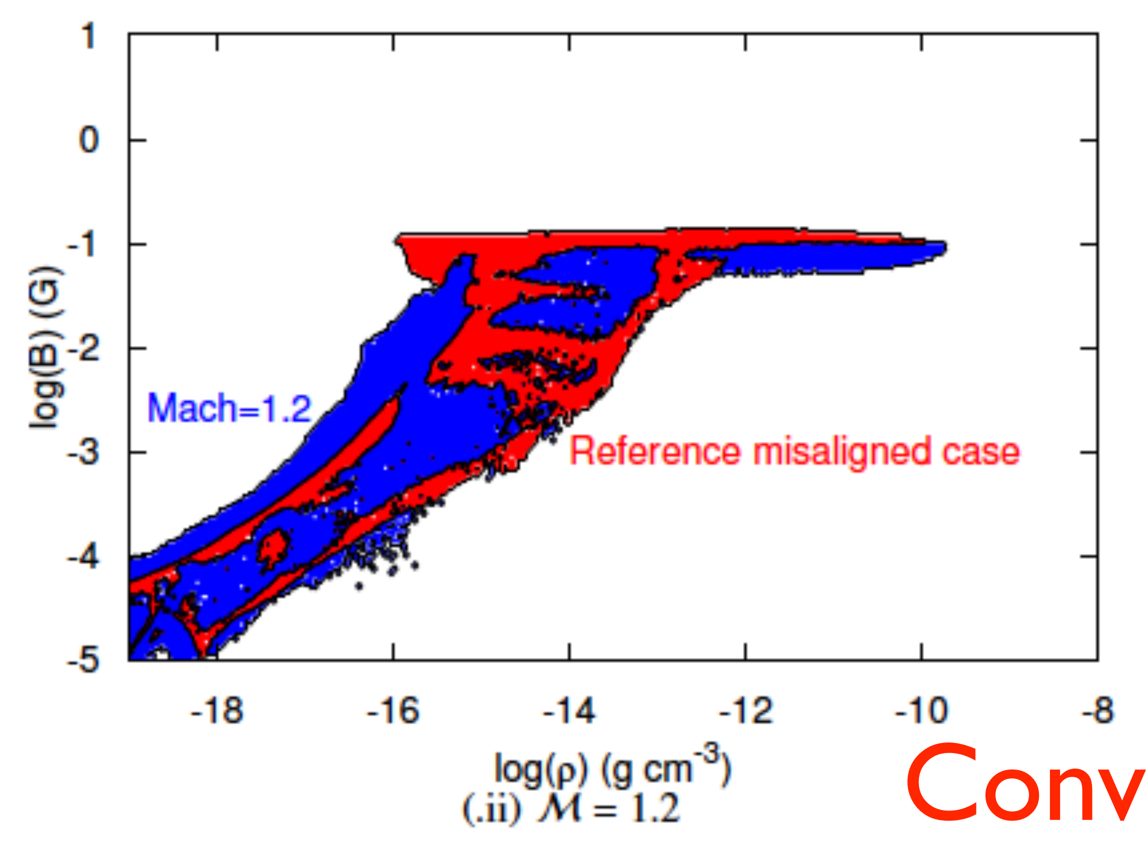

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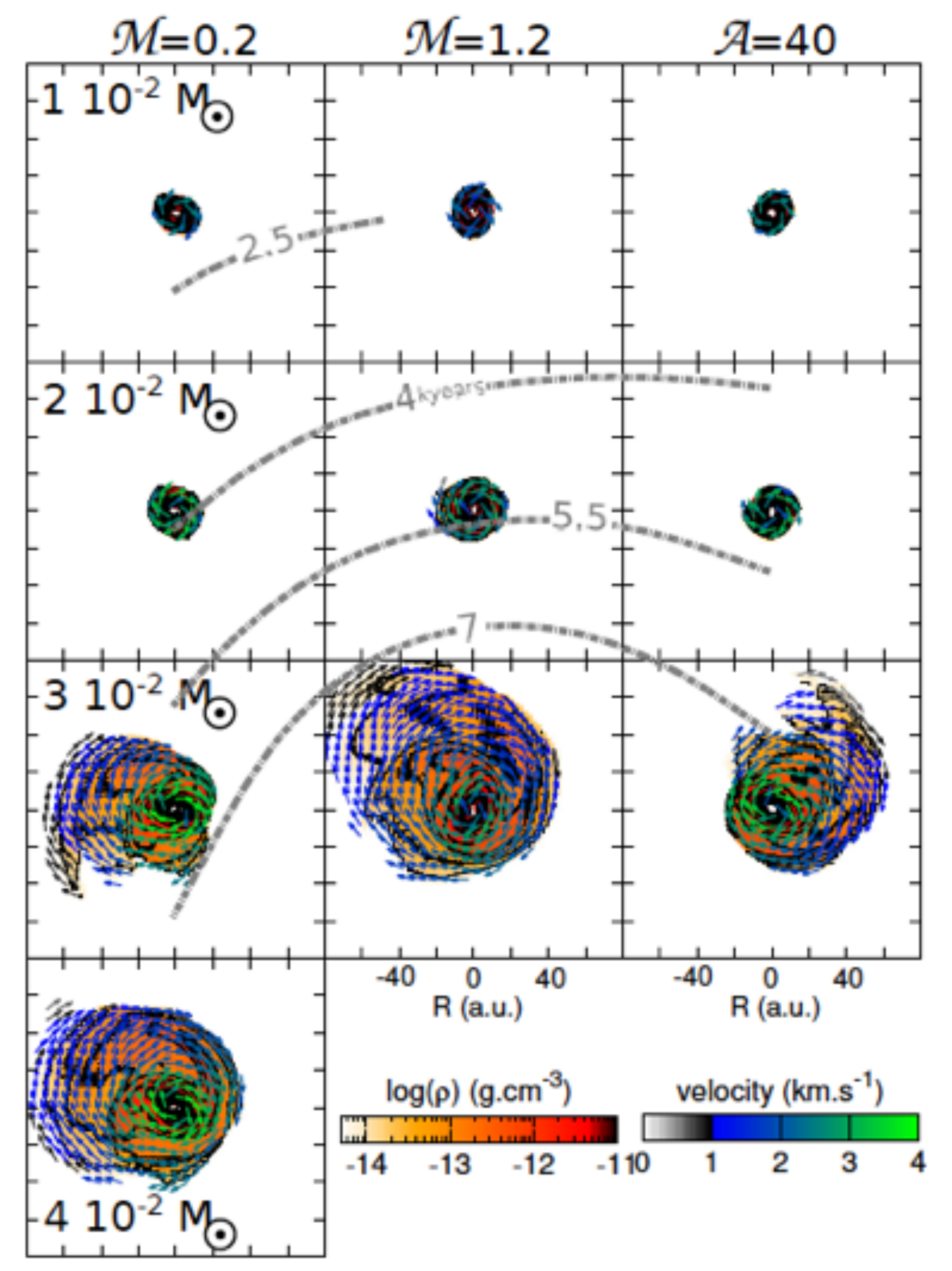
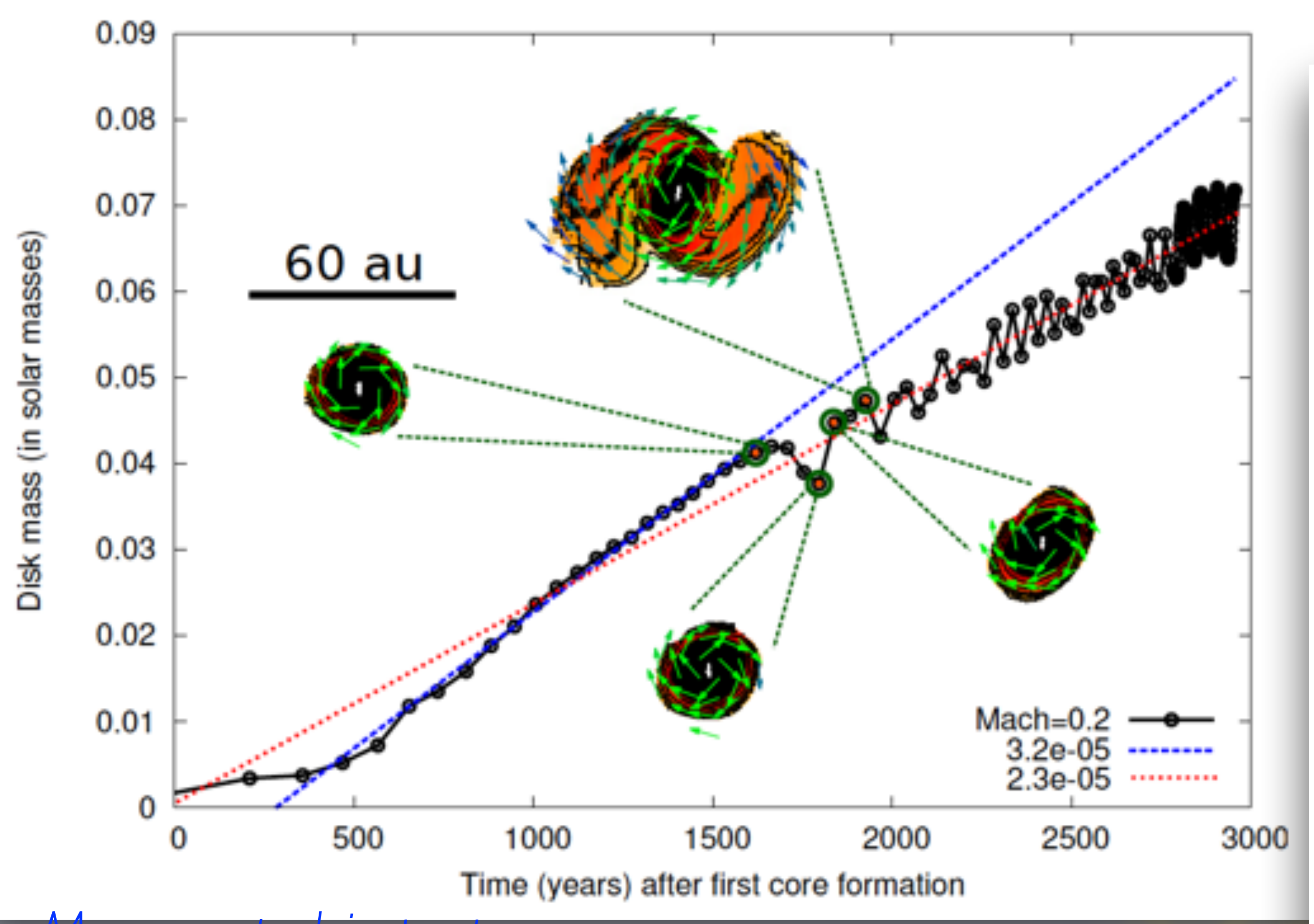
Convergence!

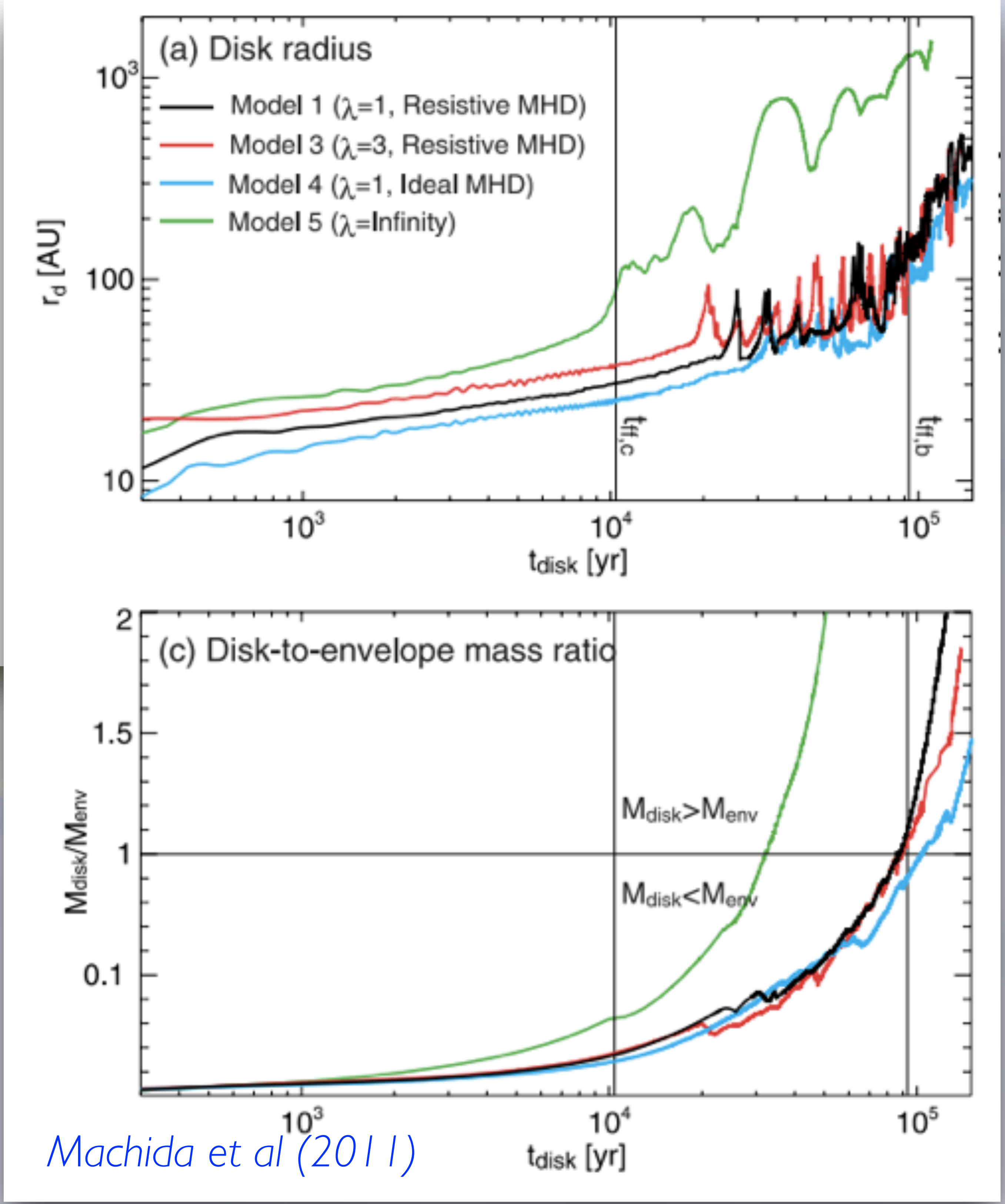


Masson et al. in prep.

Late evolution

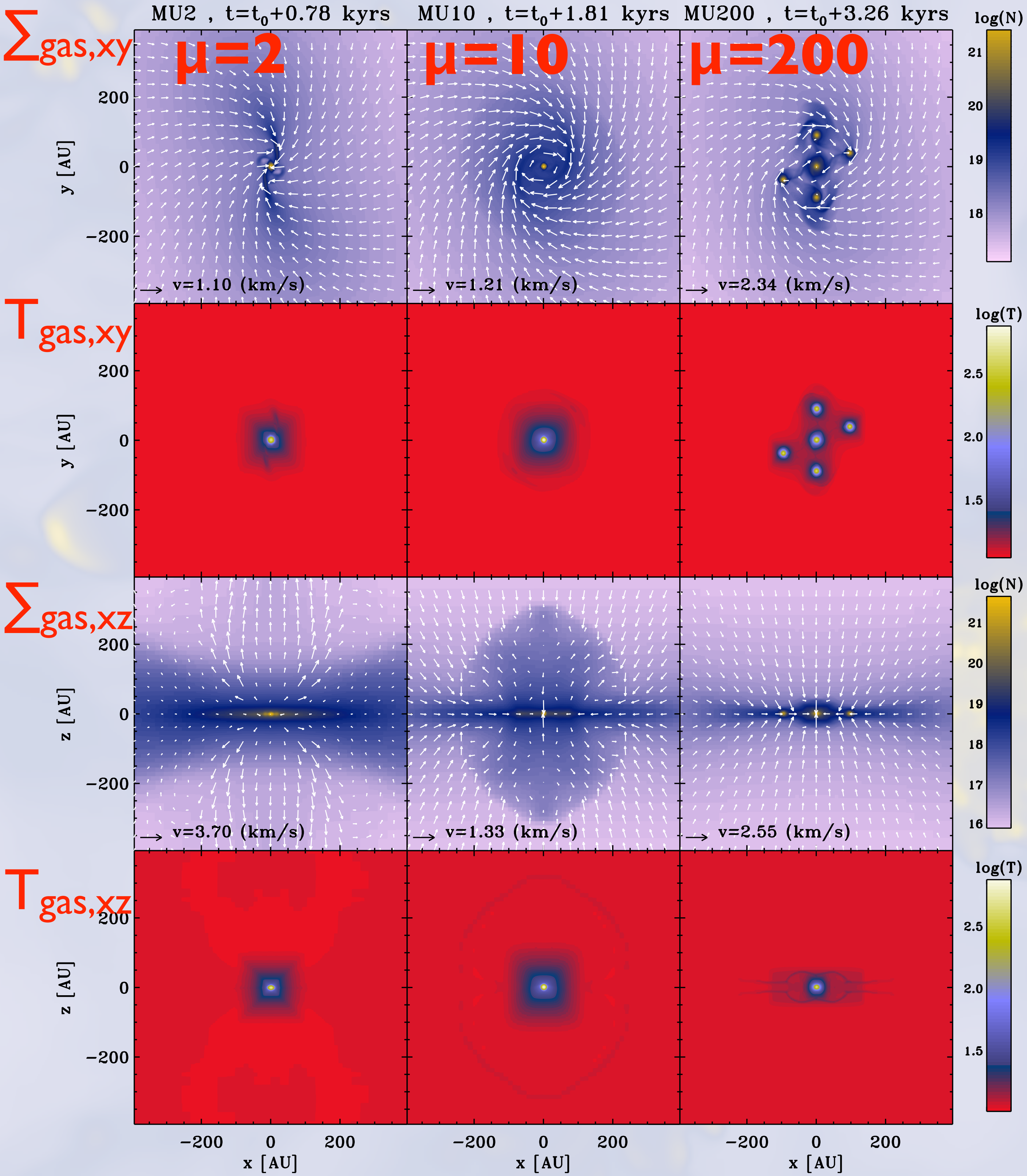


Masson et al. in prep.



Machida et al (2011)

Towards synthetic observations



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

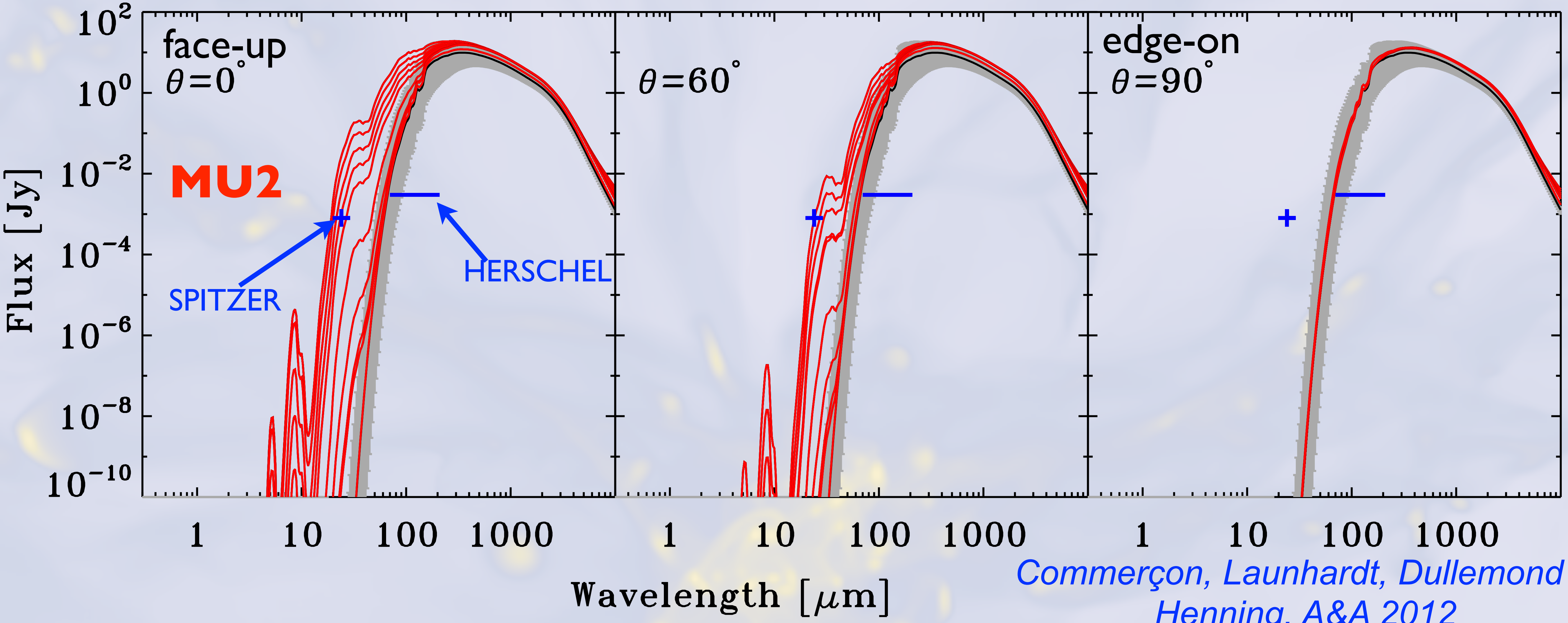
- First core lifetime:

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 2012

SED - Do we see a first core signature?



Commerçon, Launhardt, Dullemond &
Henning, A&A 2012

- *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

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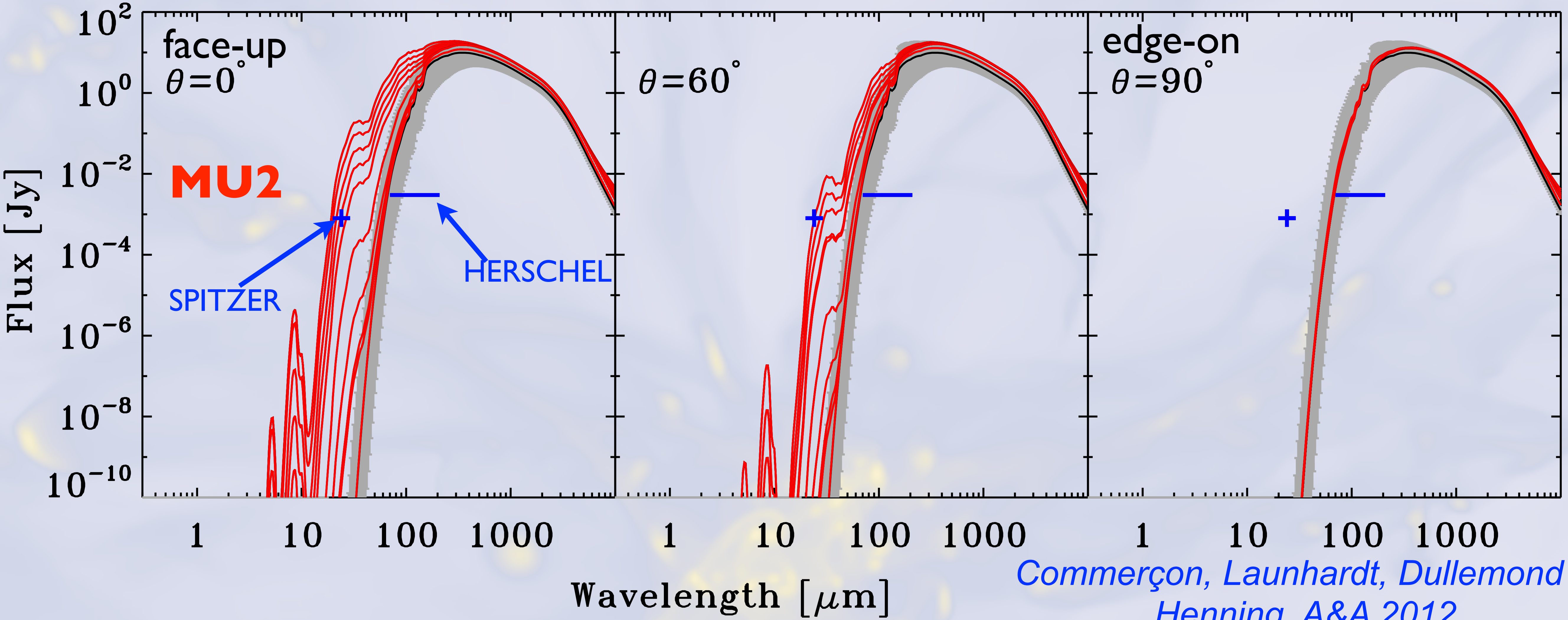

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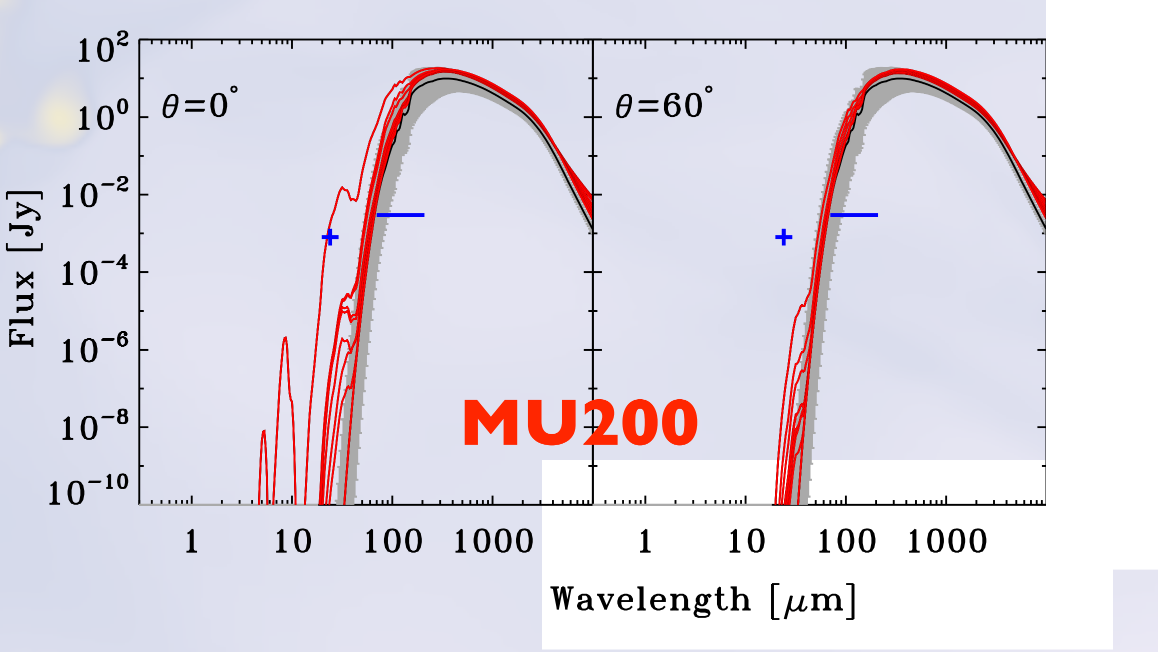
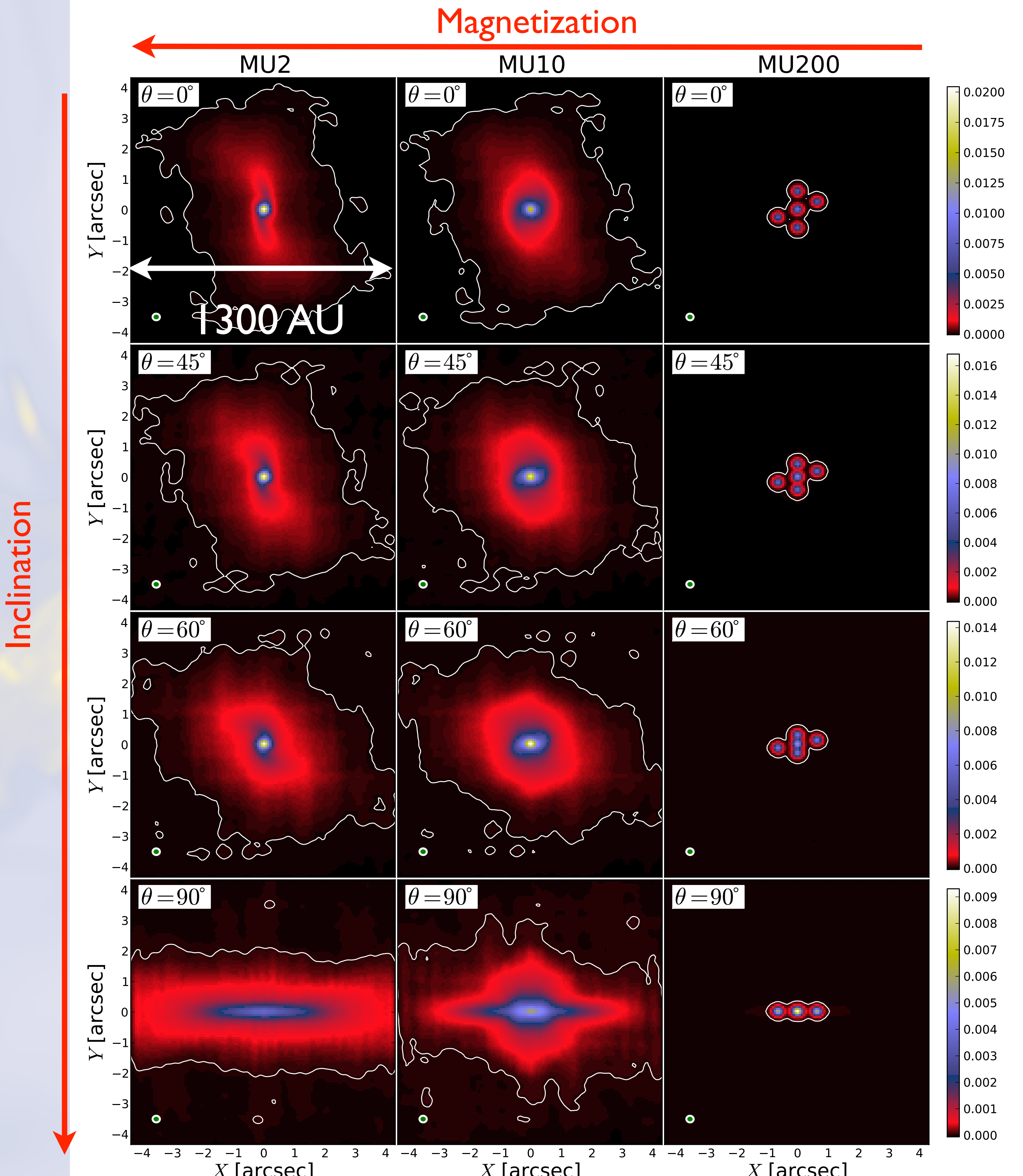


Synthetic ALMA dust emission maps



ALMA Band 3 Config 20 @150 pc

Commerçon, Levrier et al. A&A, 2012

Take Away I

- ✓ Fragmentation crisis at the Class 0 stage for low mass star formation - No massive, extended & fragmented disk

- ✓ Magnetic field cannot be neglected

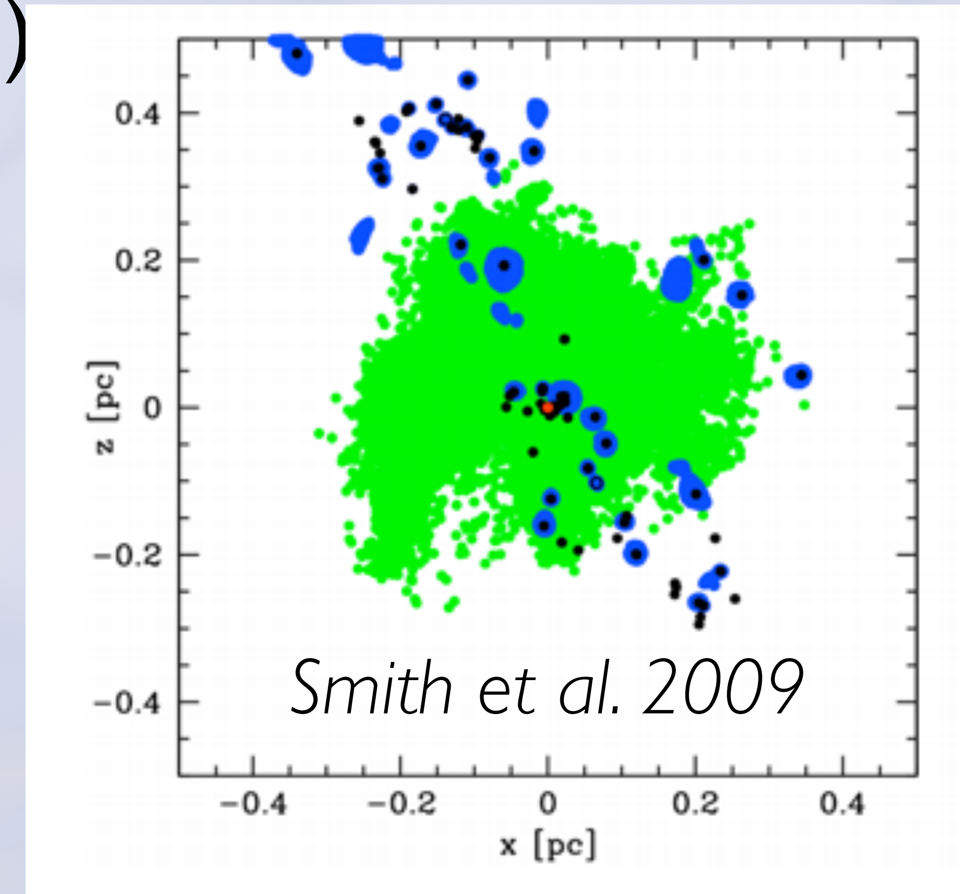
- ✓ Supported by observations, no large disks (*e.g. Maury et al. 2010*)

Outline

1. **Introduction**
2. **Methods**
   - AMR vs. SPH
3. **Low mass dense core collapse**
   - RHD and RMHD collapse
   - Disk formation and fragmentation crisis
   - Synthetic observations
4. **Massive dense cores collapse**
   - Early fragmentation inhibition
   - Disk & outflow formation

High mass star formation scenarii

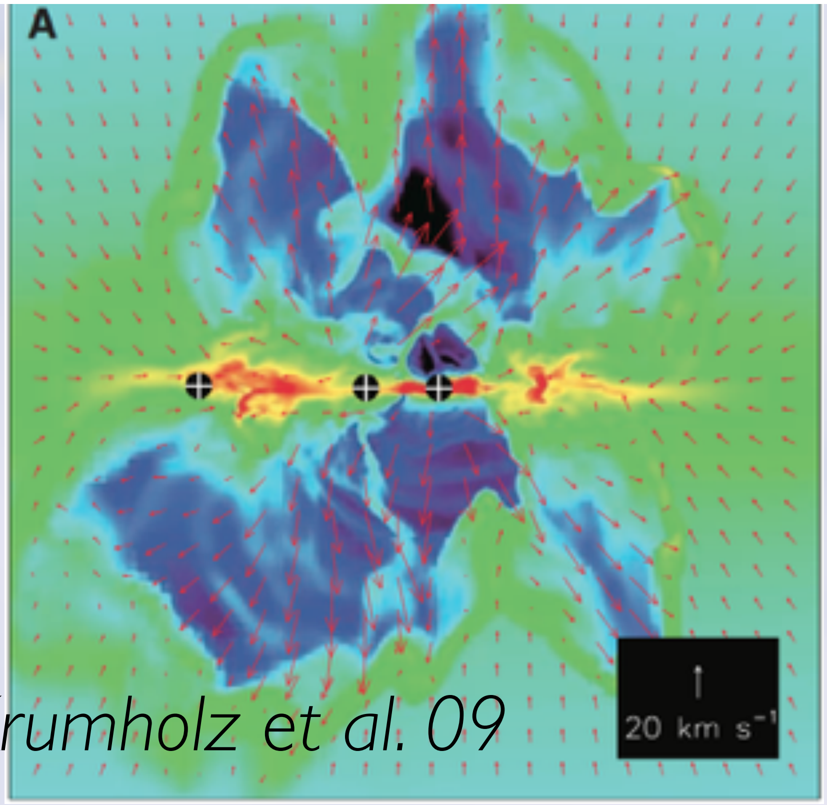
- **Competitive accretion (Bate, Bonnell et al.)**
  - Massive prestellar core does not exist
  - Star clusters and massive stars form simultaneously (*Smith et al. 2009*)



Smith et al. 2009

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

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



Krumholz et al. 09

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)

==> 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

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

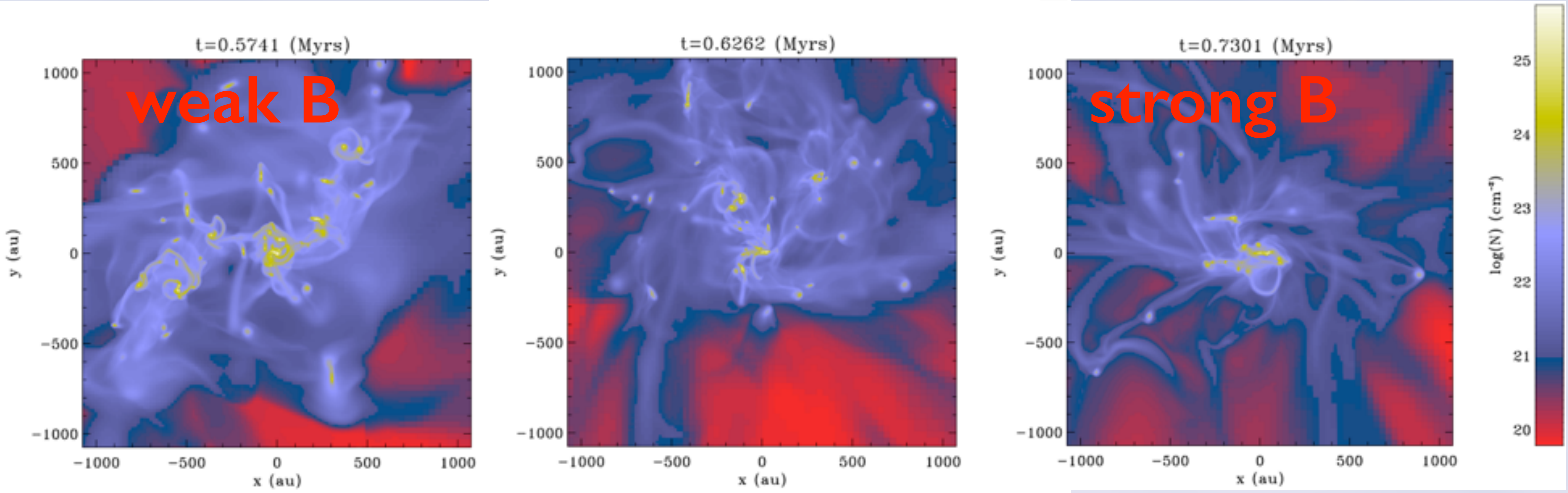
$$\rho_c = 1.4 \times 10^{-20}\ \mathrm{g\,cm^{-3}}$$

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

100 M⊙ turbulent dense core collapse

High-mass star formation: 100 M⊙ magnetized, turbulent and dense core w. FLD (follow-up of Hennebelle et al. 2011 barotropic study)

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



μ=120 μ=5 μ=2

Hennebelle et al. 2011

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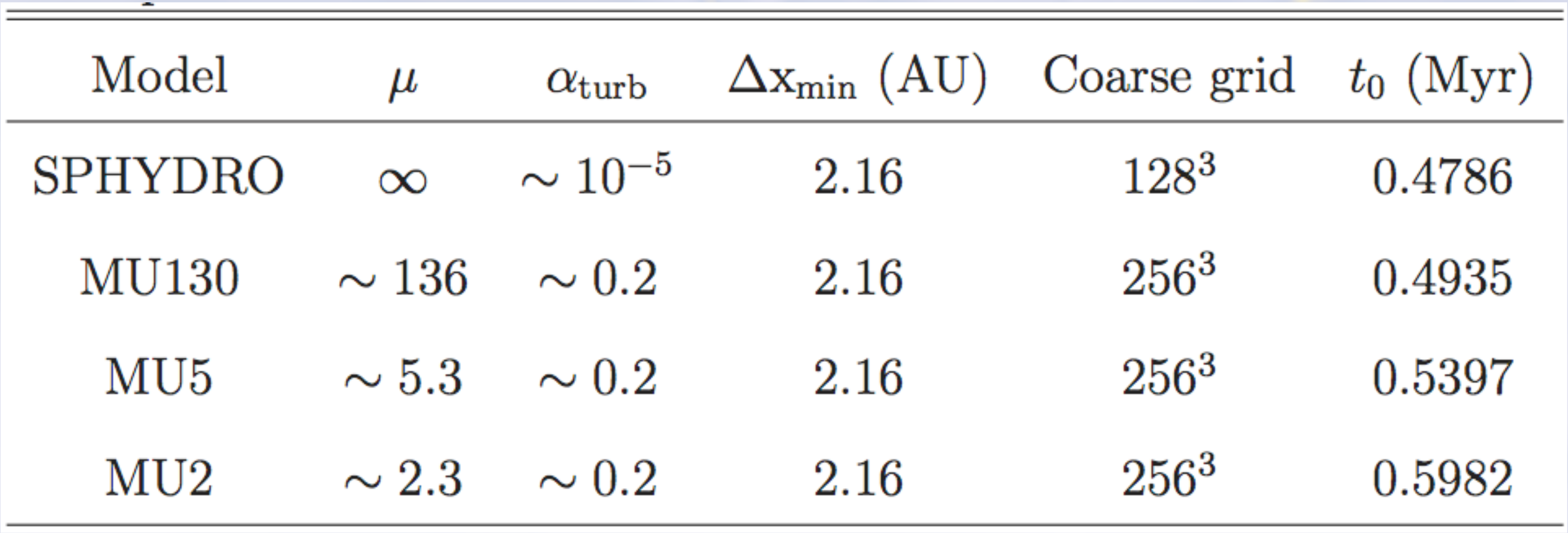
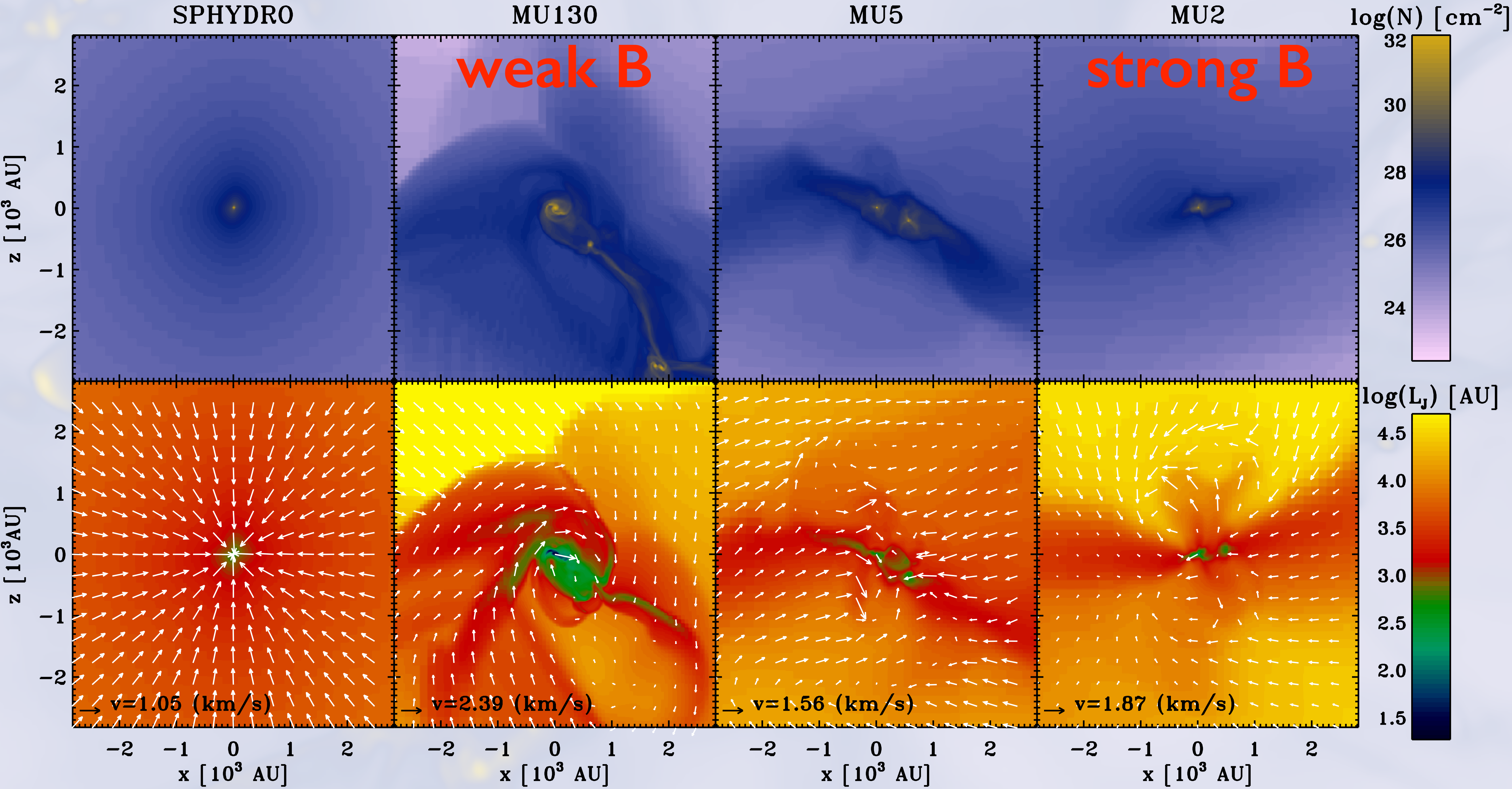


Model	μ	$\alpha_{\rm turb}$	$\Delta x_{\rm min}$ (AU)	Coarse grid	t_0 (Myr)
SPHYDRO	∞	$\sim 10^{-5}$	2.16	128^3	0.4786
MU130	~ 136	~ 0.2	2.16	256^3	0.4935
MU5	~ 5.3	~ 0.2	2.16	256^3	0.5397
MU2	~ 2.3	~ 0.2	2.16	256^3	0.5982

Commerçon, Hennebelle & Henning, ApJL 2011

100 M⊙ turbulent dense core collapse



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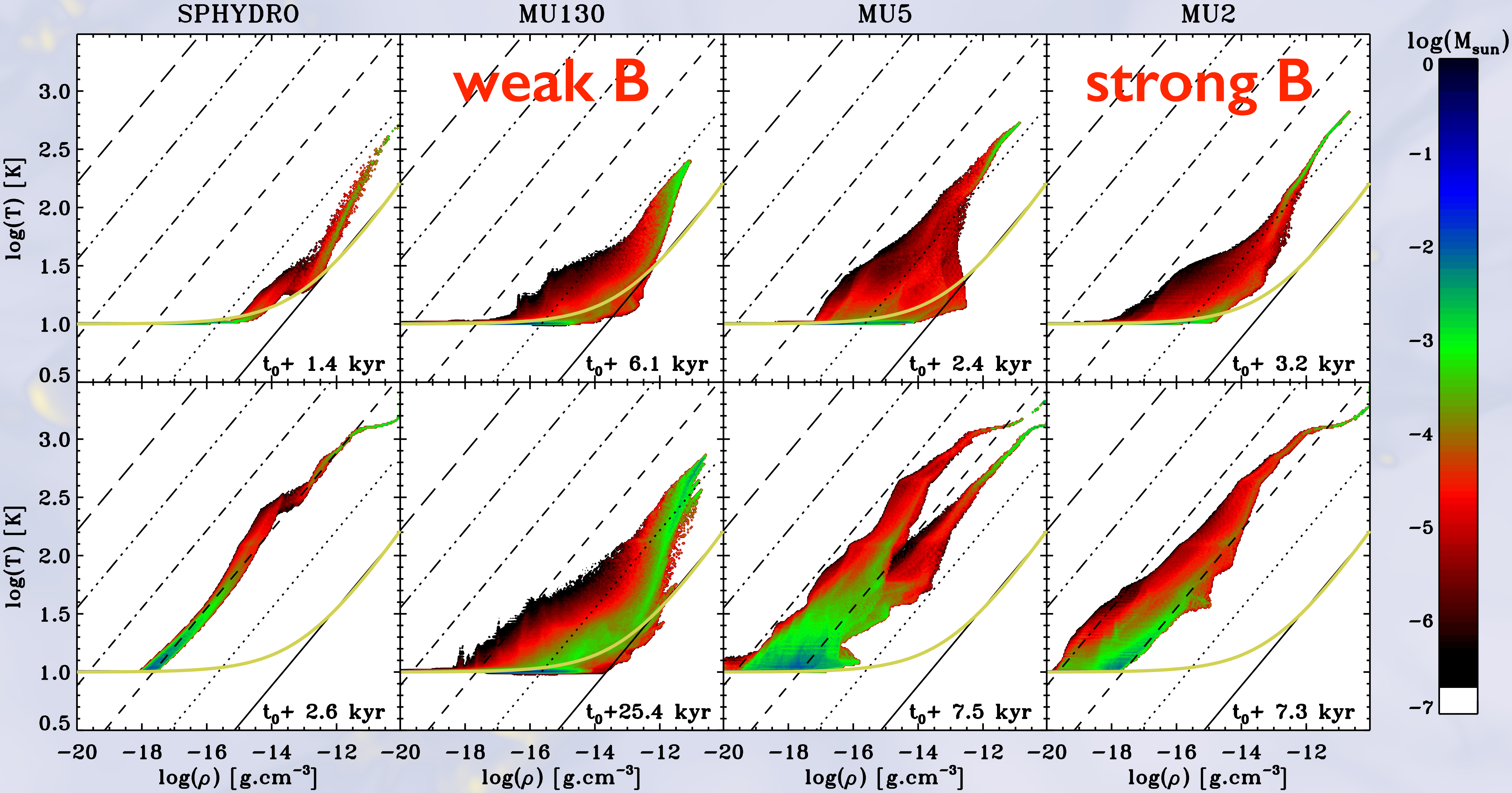

Commerçon, Hennebelle & Henning, ApJL 2011

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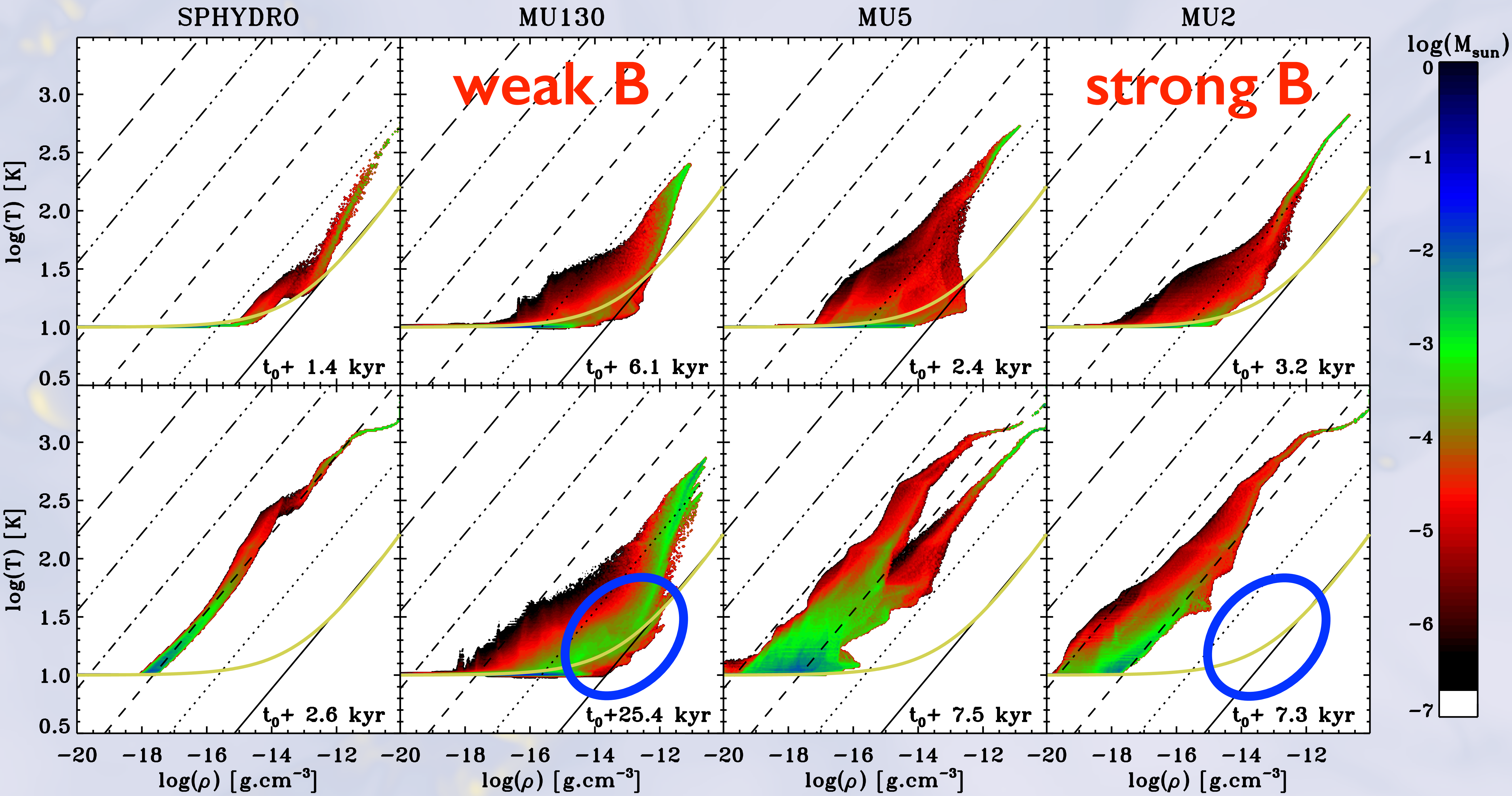
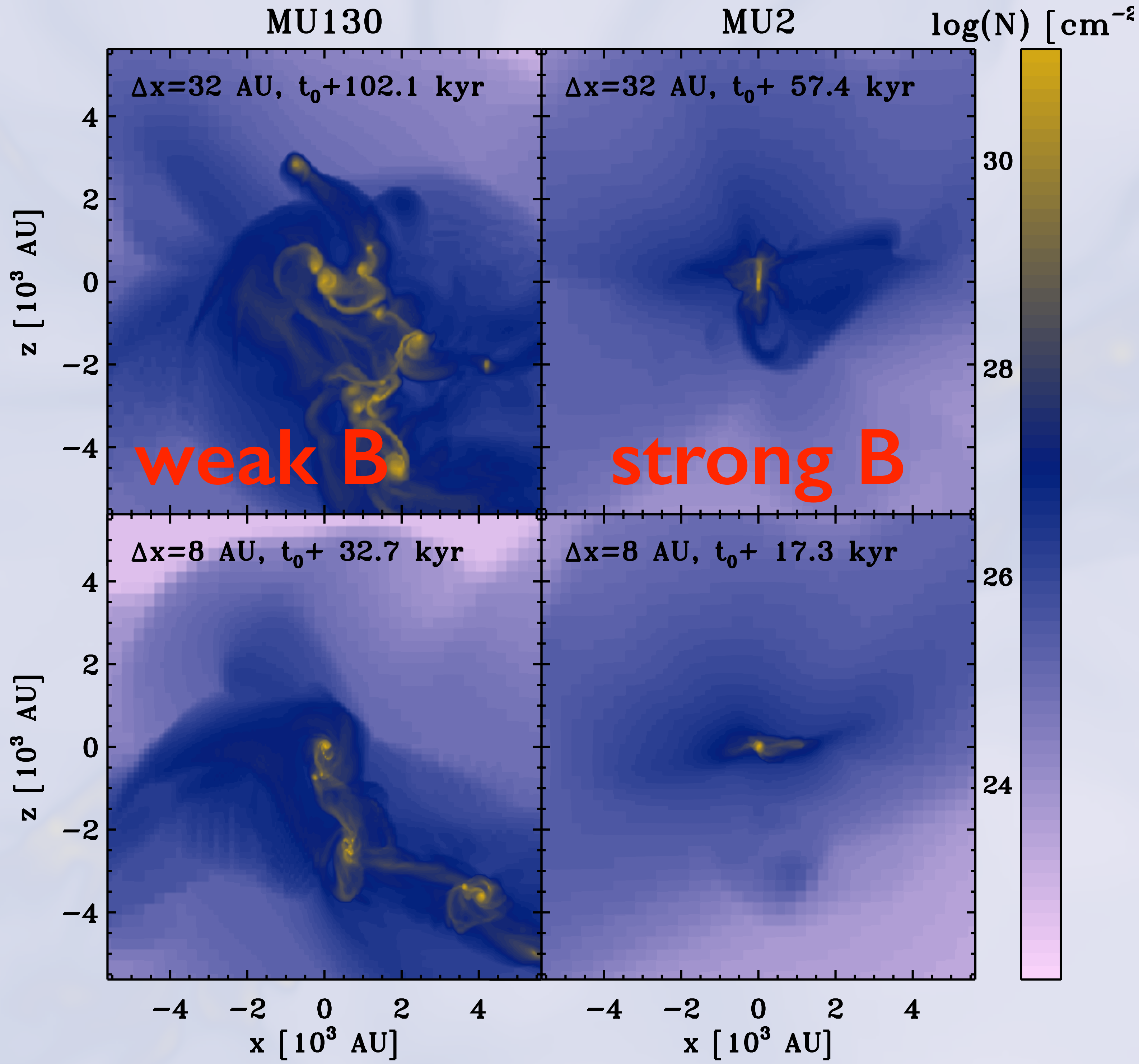


Commerçon, Hennebelle & Henning, ApJL 2011

100 M⊙ turbulent dense core collapse

- ✓ Trend confirmed with lower resolution runs:



What’s different?

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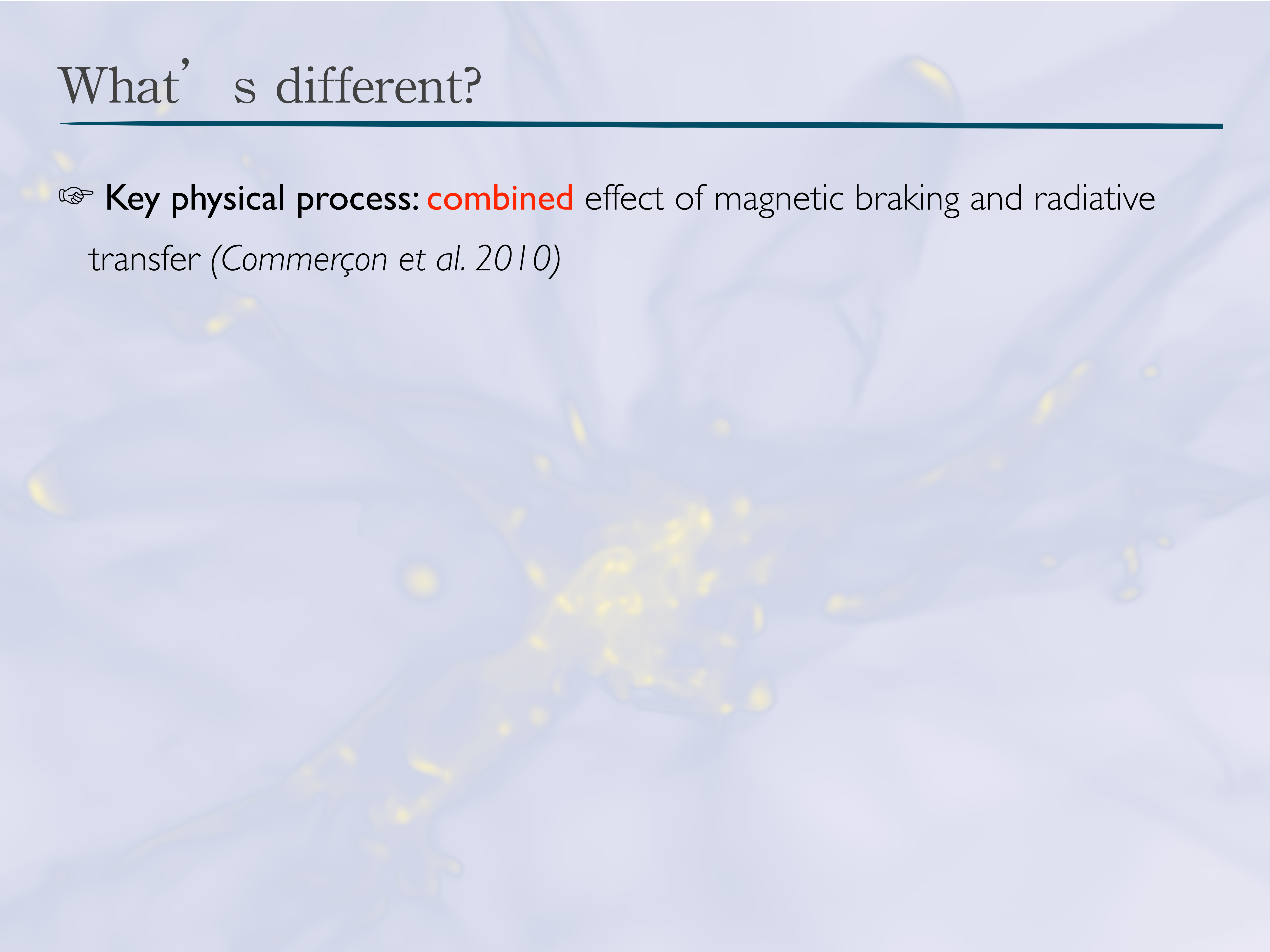

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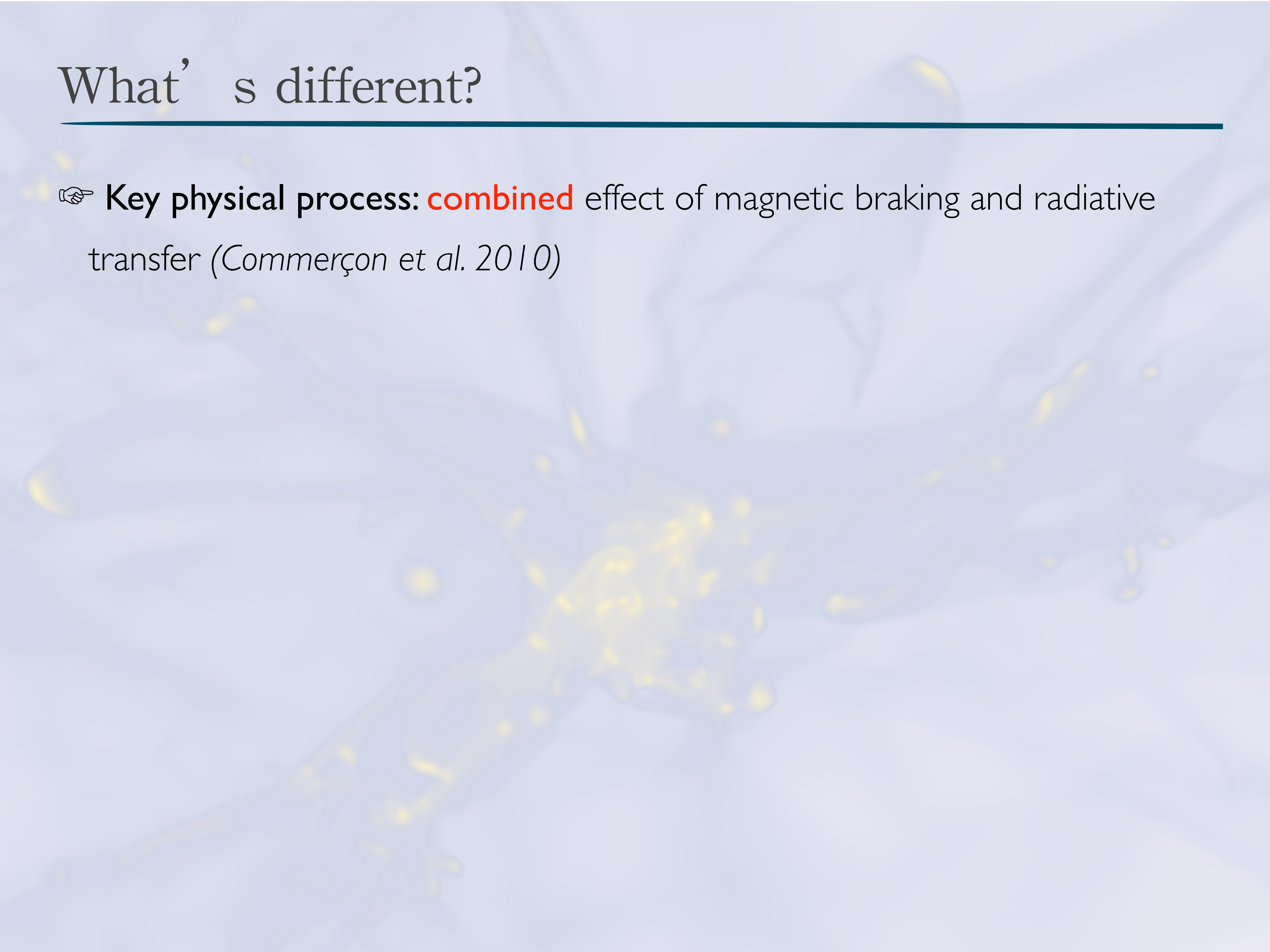

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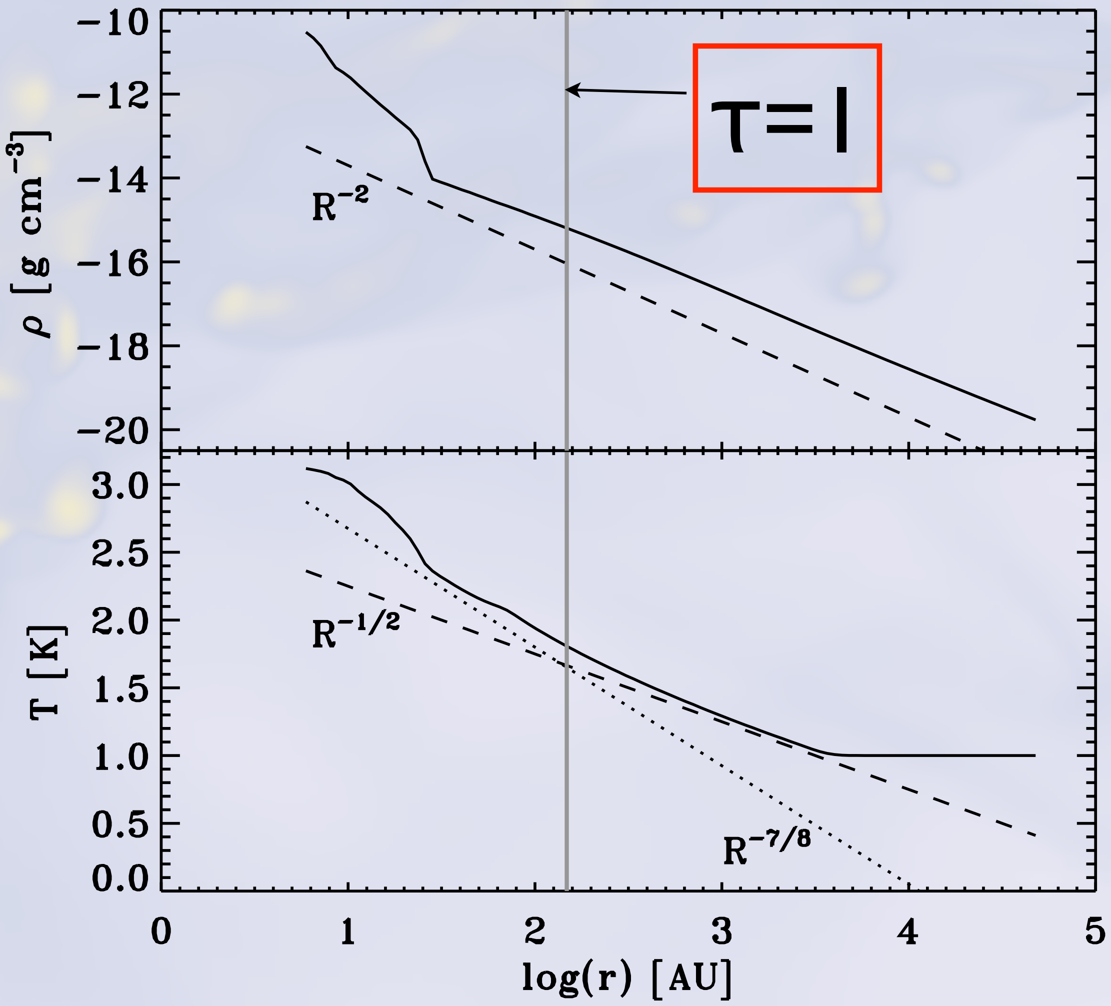


SPHYDRO	MU130	MU5	MU2
30	0,2	1,2	10

Towards massive star formation?

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

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

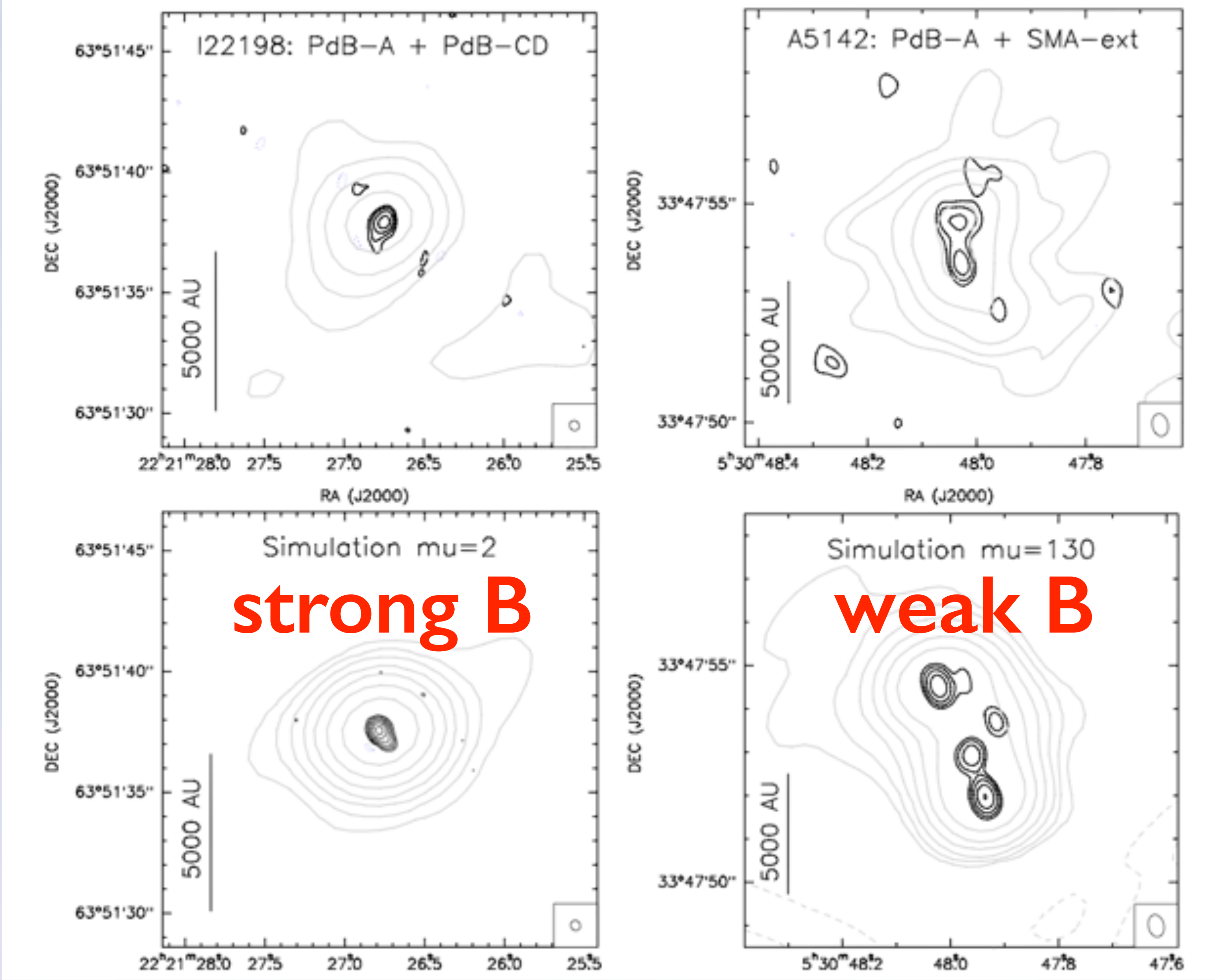
✓ **Intermediate magnetization:** 2 fragments arranged in a filamentary like structure. Secondary fragment not produced by disk fragmentation (*Krumholz et al.*).

- ➡ **OB association** formation

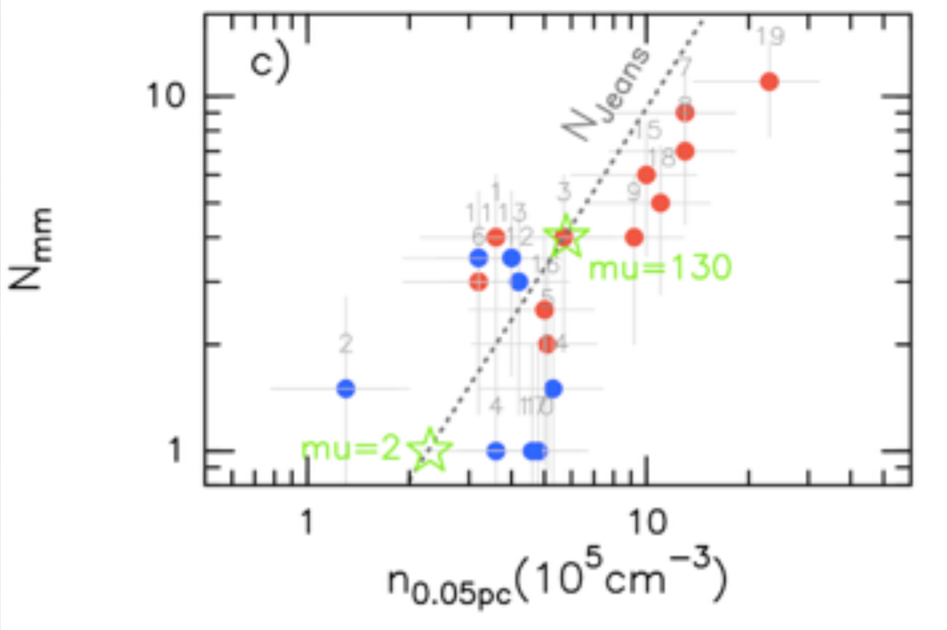
✓ **High magnetization:** 1 single fragment

- ➡ **Isolated** massive star formation (e.g. observations by *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

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.



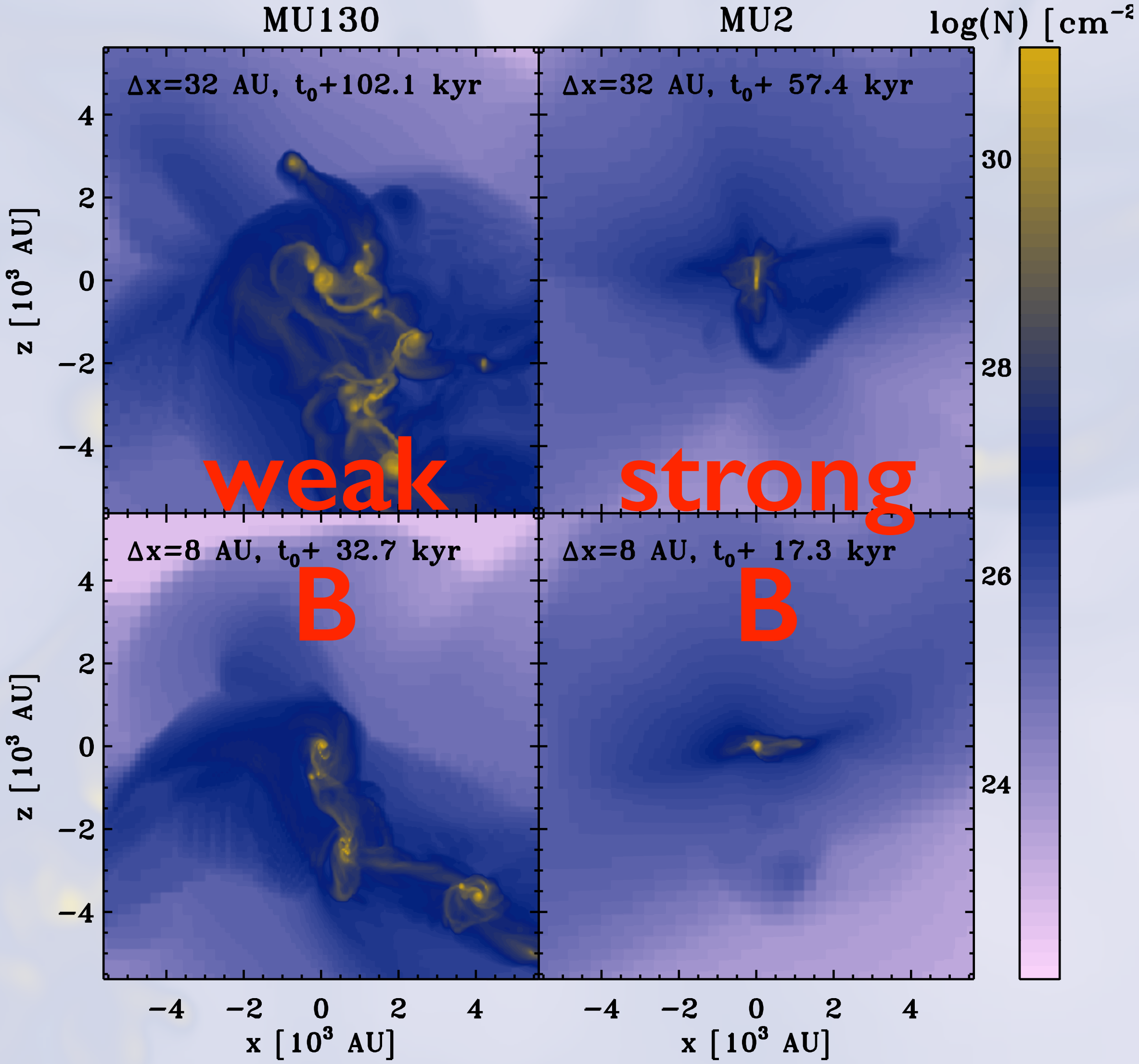
Palau et al., 2013 & 2014, ApJ

Take Away II

- Fragmentation can be inhibited in massive dense cores
- Highly magnetized massive dense cores => progenitors of high mass stars

Formation of massive stars in magnetised cores

- ✓ Focus on isolated massive core, threaded by regular magnetic fields
- ✓ Interplay between magnetic braking and radiative feedback reduces efficiently fragmentation (Commerçon et al. 2011, Myers et al. 2013)
- ✓ *Choice of slowly rotating cores to focus on the star-disk-outflow system formation, without strong fragmentation*



Commerçon et al. 2011

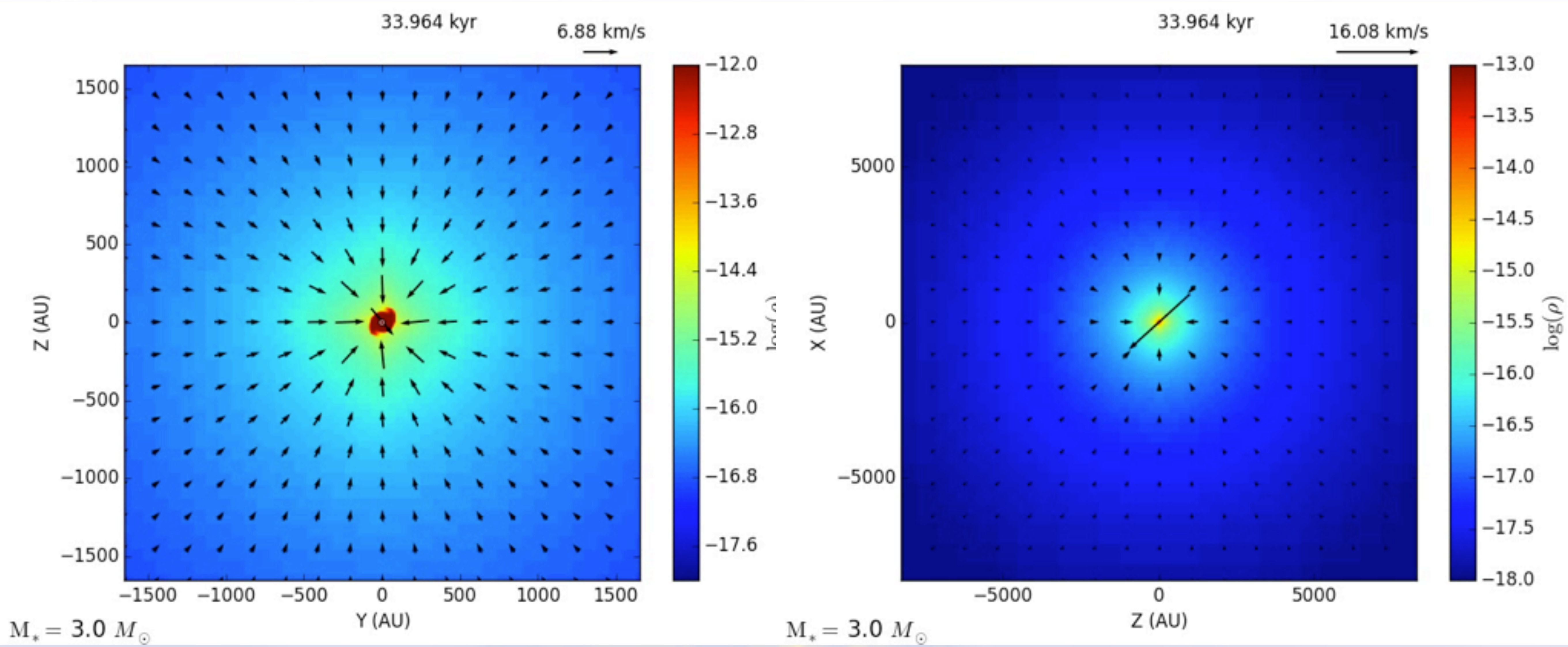
Initial conditions and stellar evolution

- ✓ 100 $M_\odot$; $\rho \propto R^{-2}$ ($\rho_c=2\mathrm{x}10^{6}$ cm^{-3}); T = 20 K ; R_0 = 0.2 pc
- ✓ Solid body rotation $\Omega=3\mathrm{x}10^{-15}$ Hz ($r_d\sim650$ AU)
- ✓ Uniform magnetic field ($\mu_{uni}=2,5,\infty$) (B=170, 68, 0 μG), aligned with rotation axis (x-axis)
- ✓ at least 10 cells/Jeans length

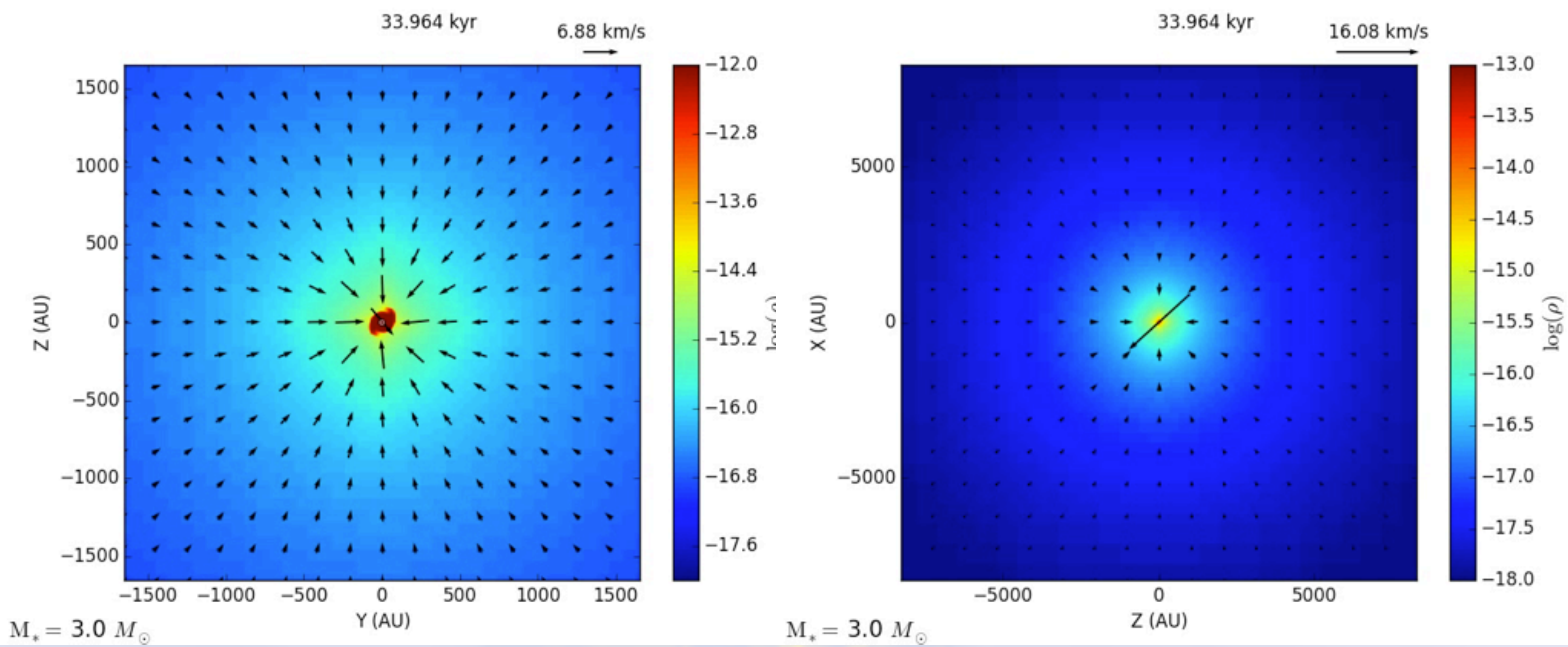
- ✓ Sink particles : $\rho_{thre}=10^{10}$ cm^{-3} , r_{sink}=~20 AU ($4\Delta x_{min}$)
- ✓ Protostellar feedback sources associated to the sink:
  - ★ internal luminosity given by Hosokawa et al. tracks (R. Kuiper), $L_{acc}=0$
  - ★ all the accreted mass goes in stellar content (most favorable case)
  - ★ NO sub-grid model for outflow

- ✓ 4 models: Hydro, IMHD μ=2, ambipolar diffusion μ=2 and μ=5

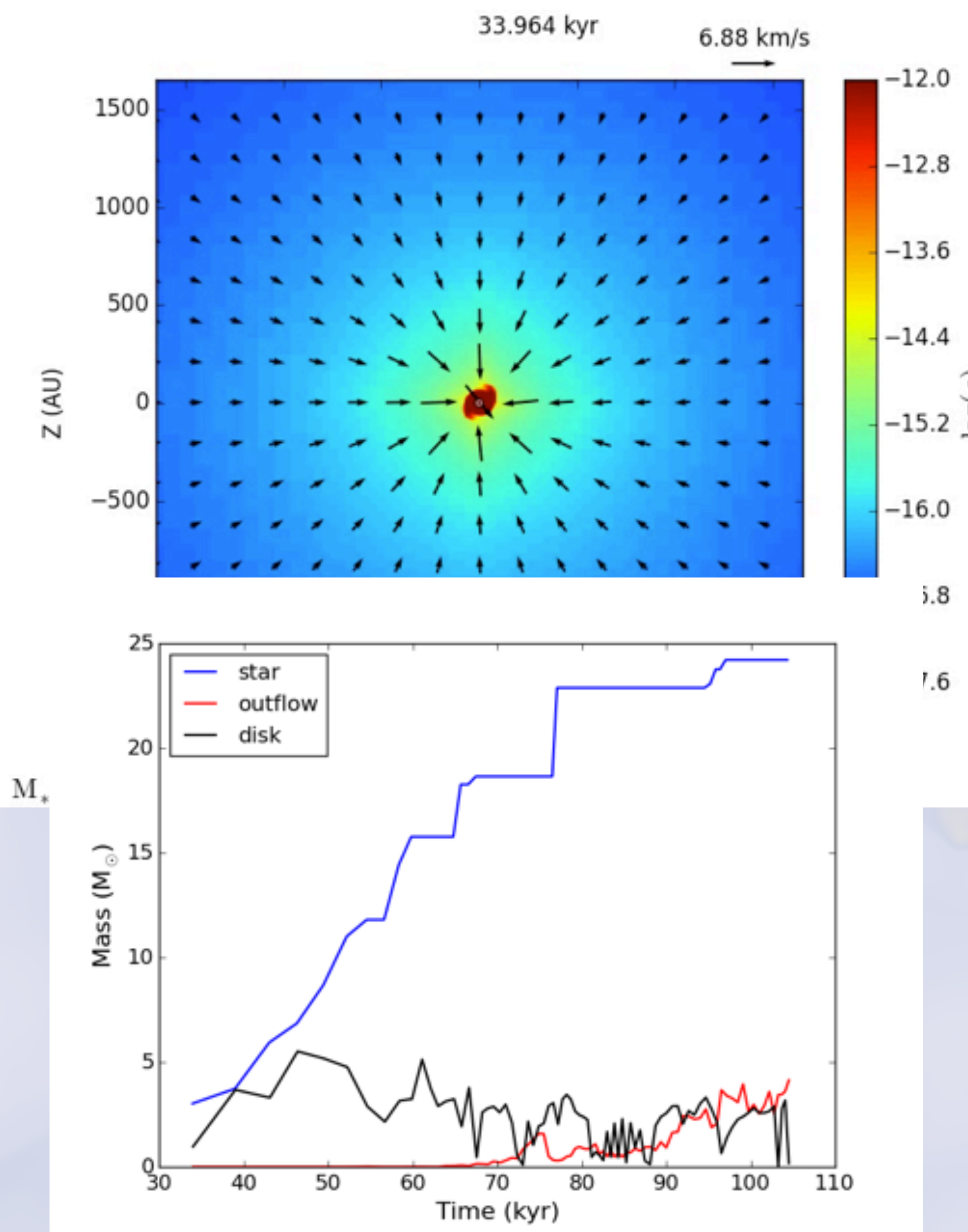
Hydro collapse

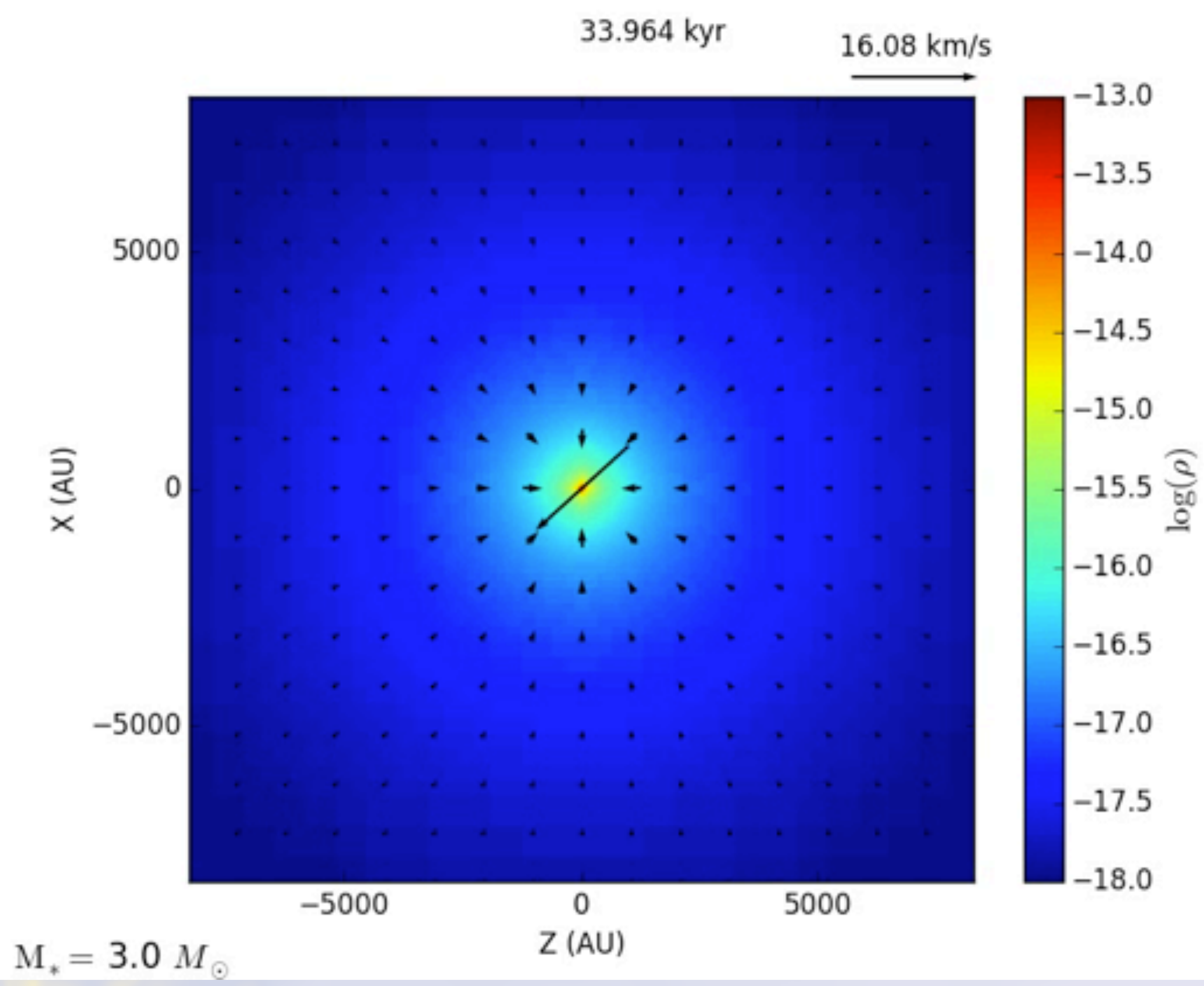


Hydro collapse



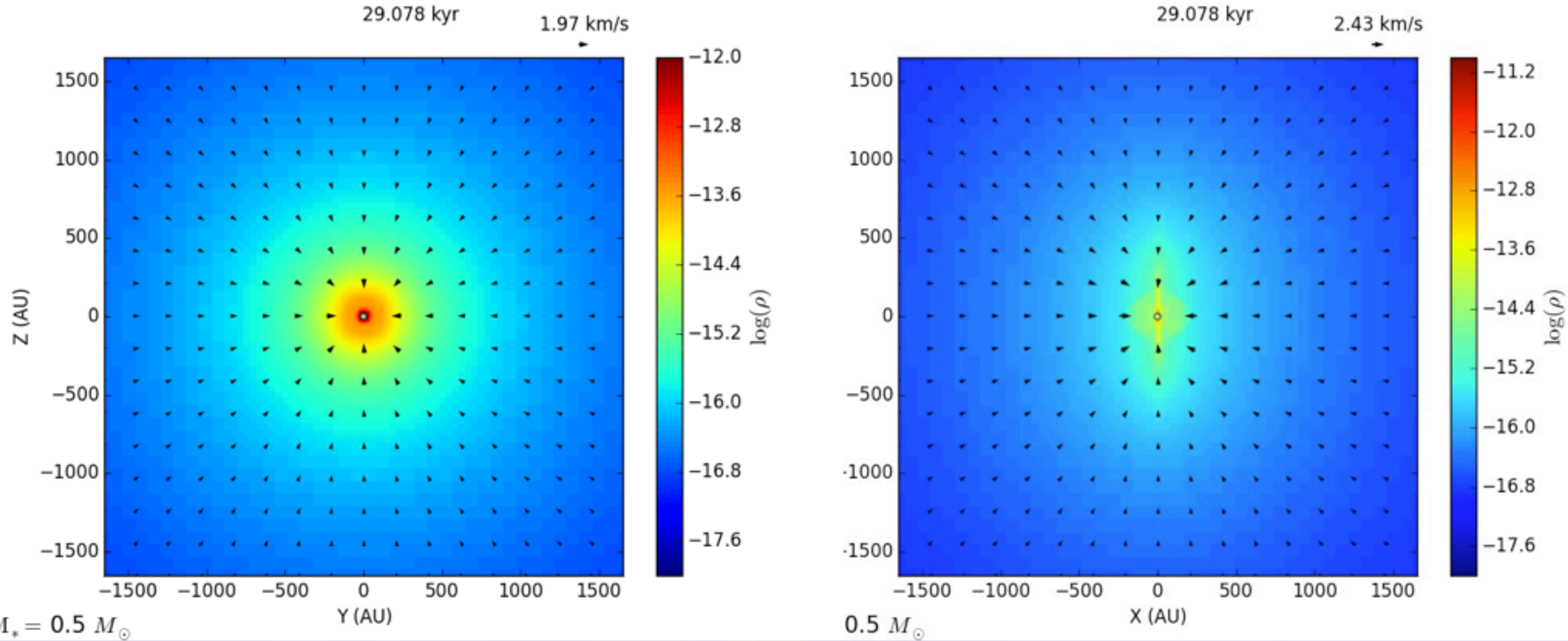
Hydro collapse





- ✓ Formation of a large disk: R~1000 AU
- ✓ Binary system: 24 and 13 M⊙
- ✓ Radiative outflow/bubble (1500 AU)

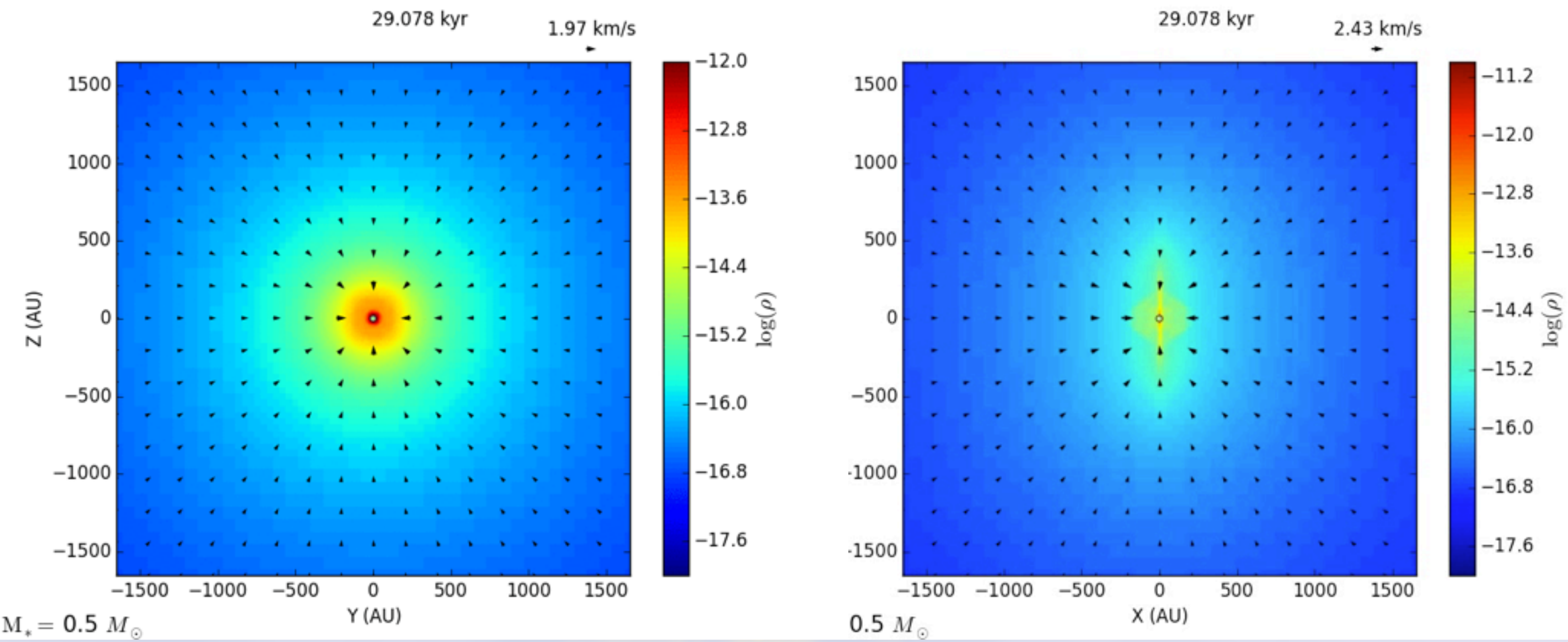
iMHD collapse, $\mu = 2$



$M_* = 0.5\ M_\odot$

$0.5\ M_\odot$

iMHD collapse, $\mu = 2$



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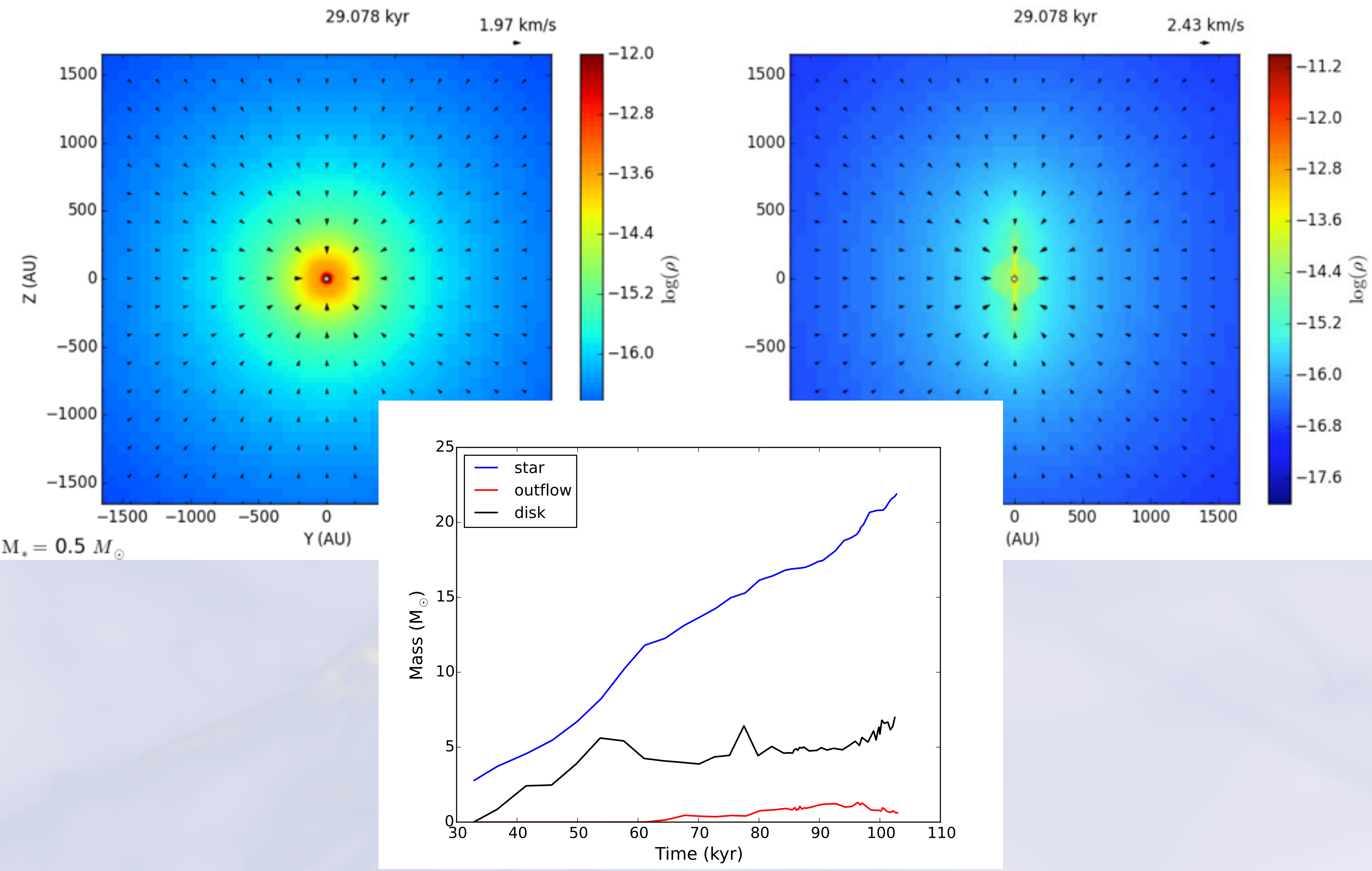
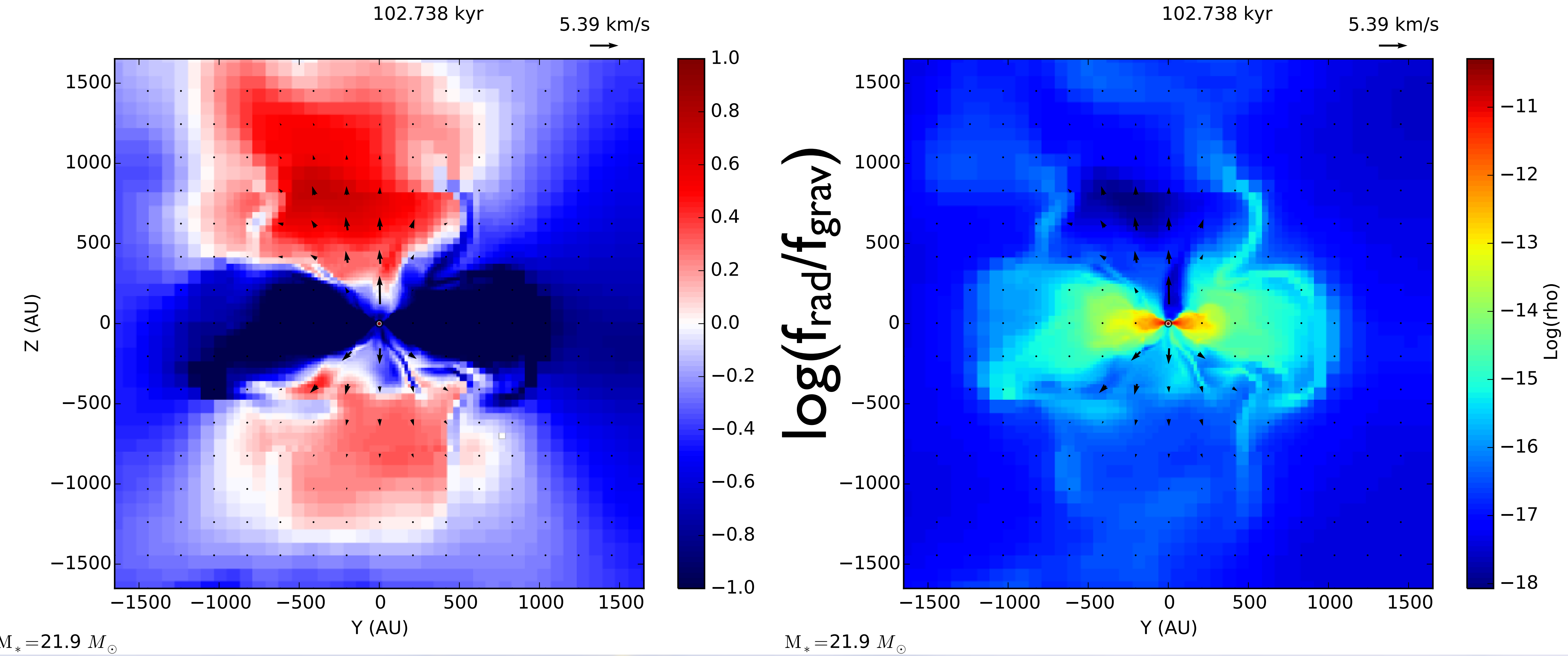
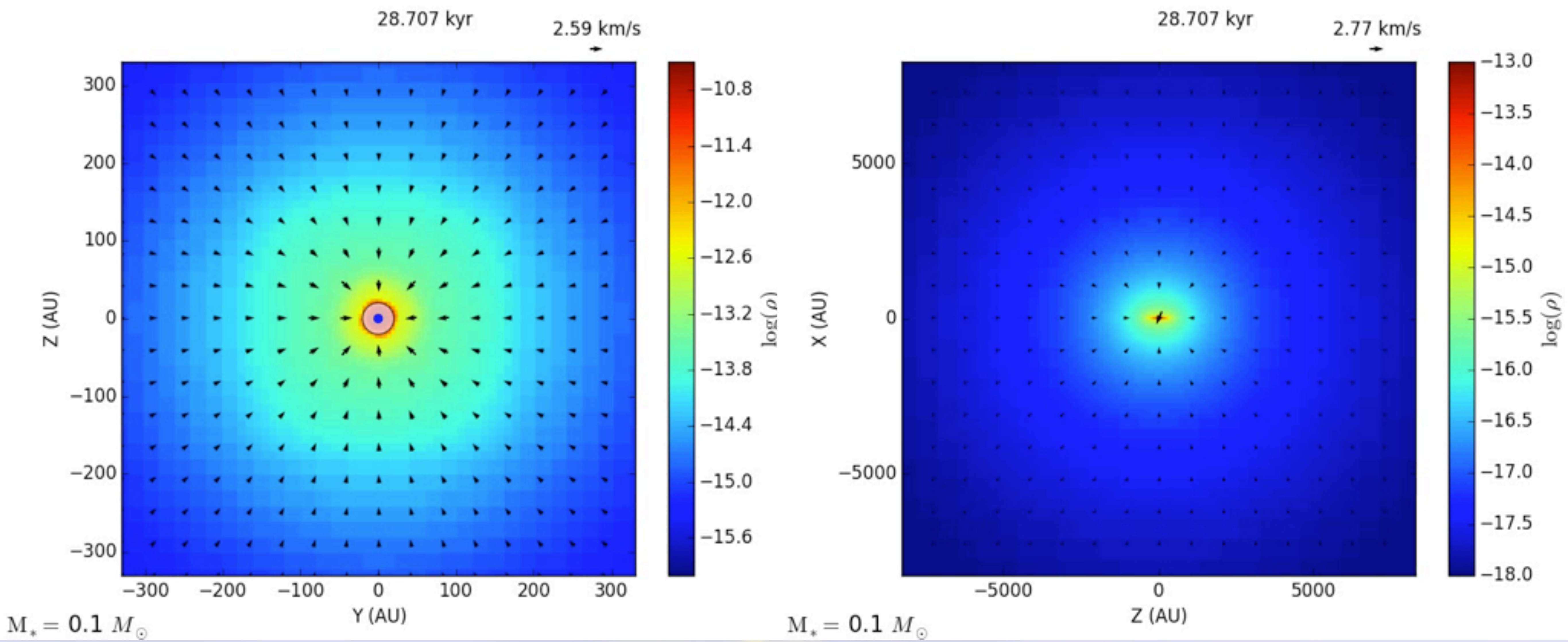


Hydro & iMHD: origin of the outflow



- Outflow has a radiative origin
- Magnetic fields disorganised by magnetic flux expulsion (interchange instability, e.g., *Masson et al. 2016*)

Ambipolar diffusion, $\mu = 2$



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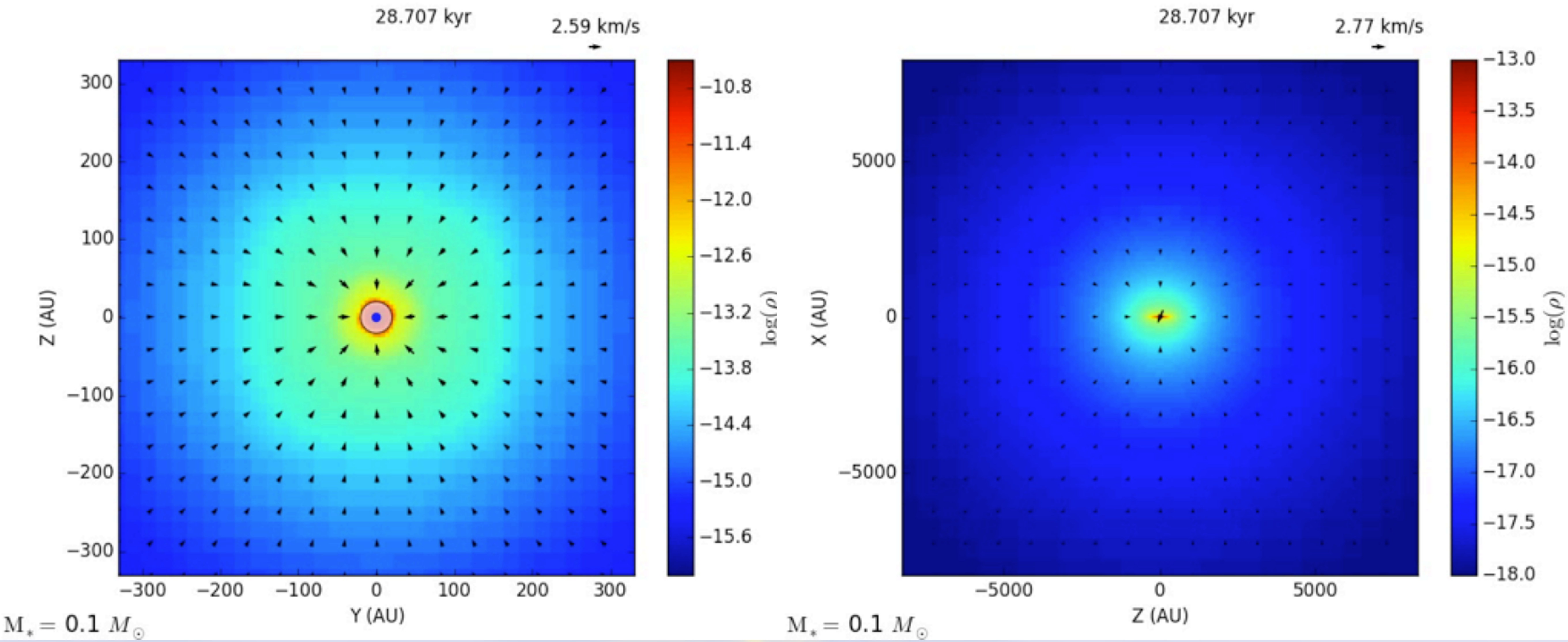

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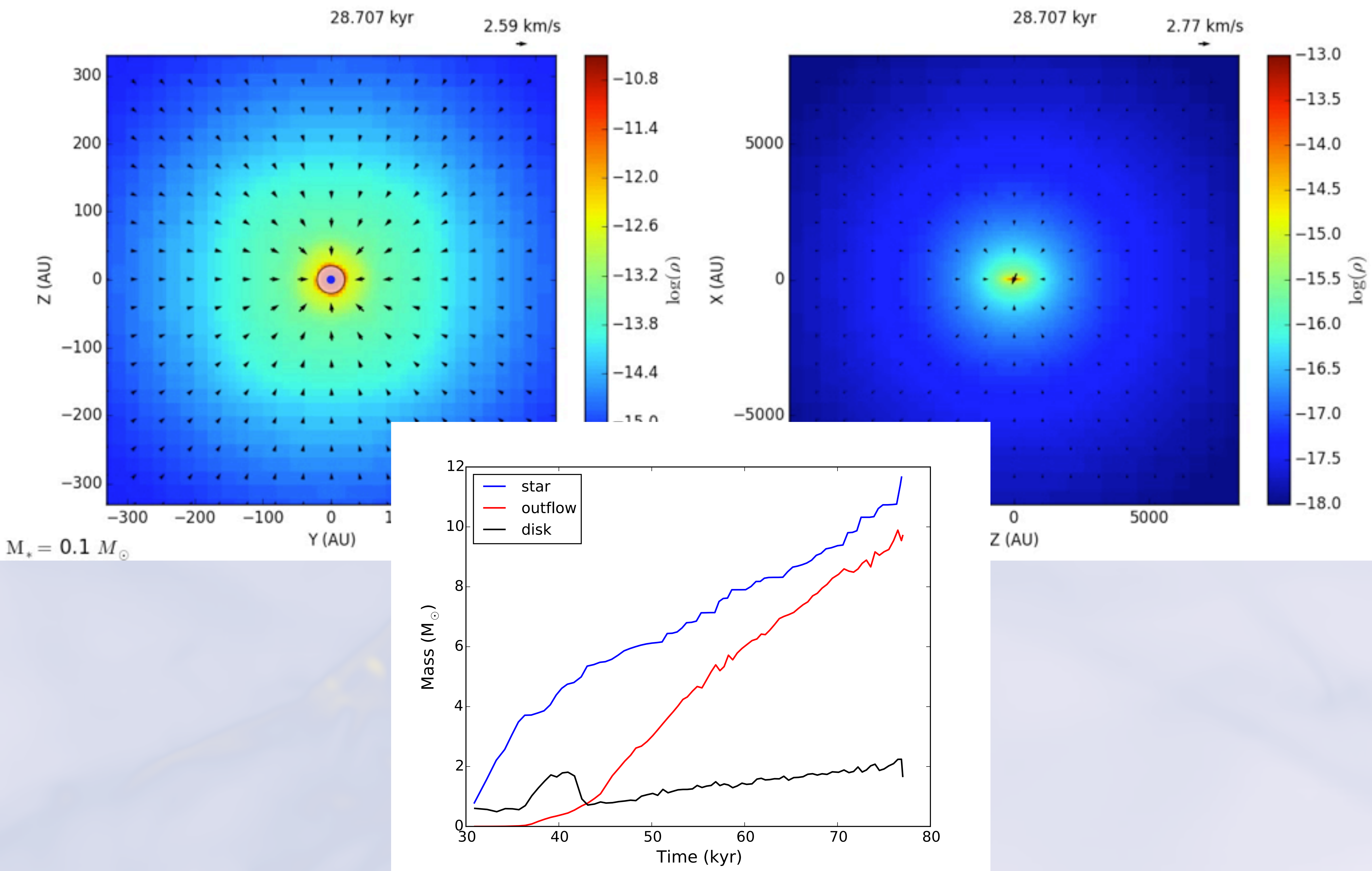
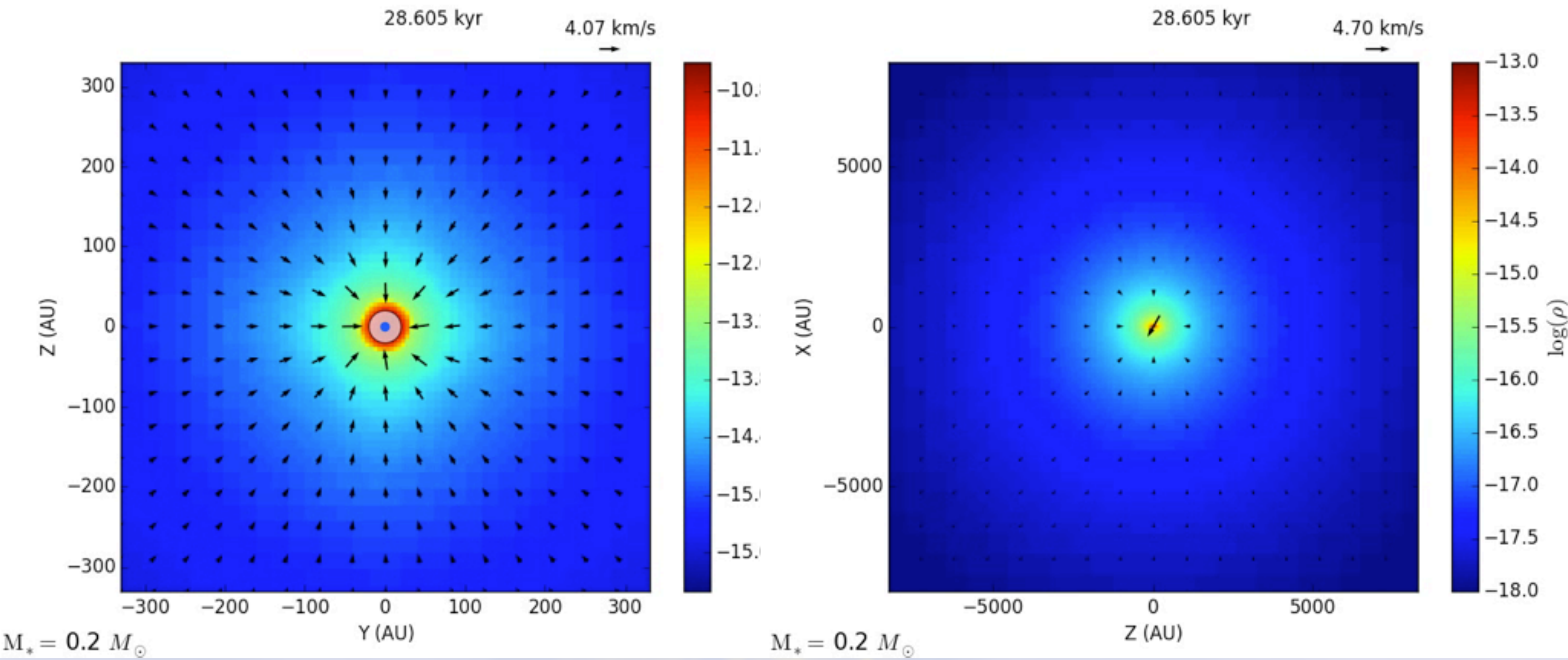
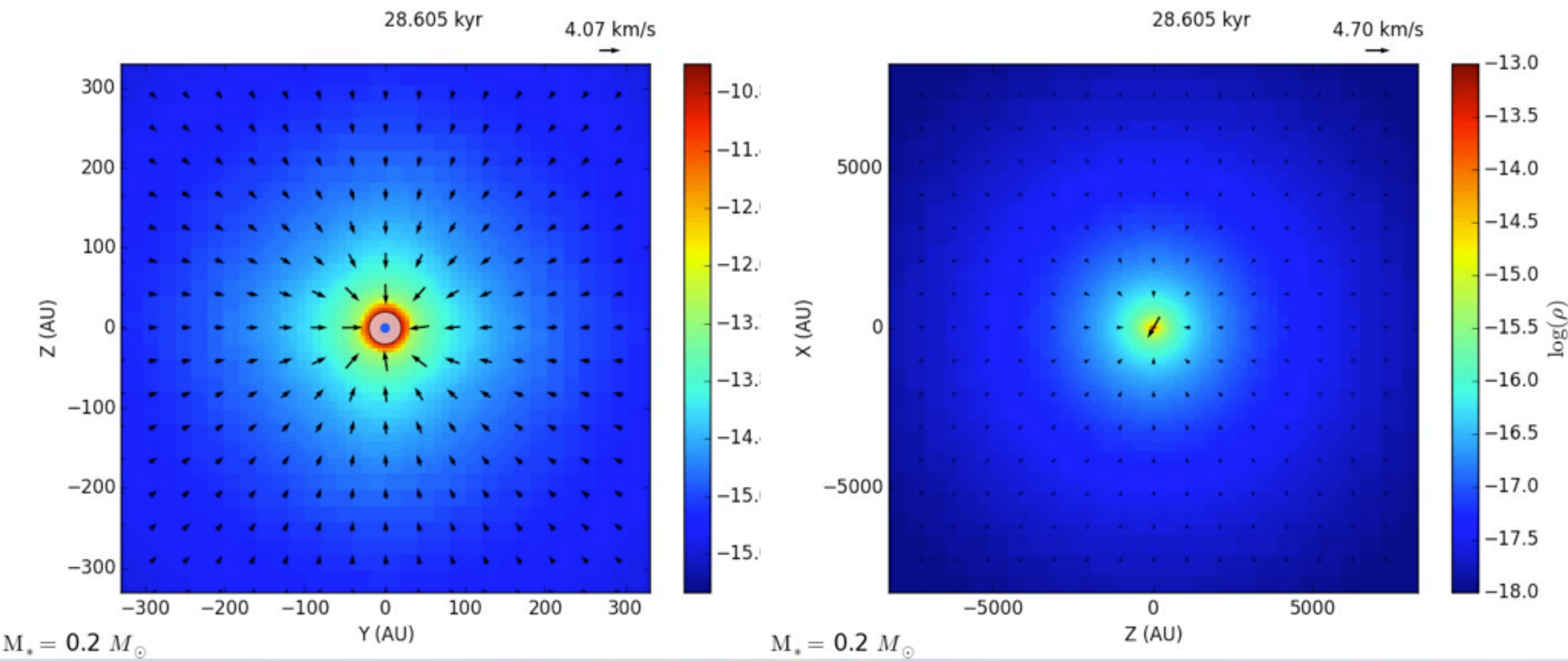


$M_* = 0.1\ M_\odot$

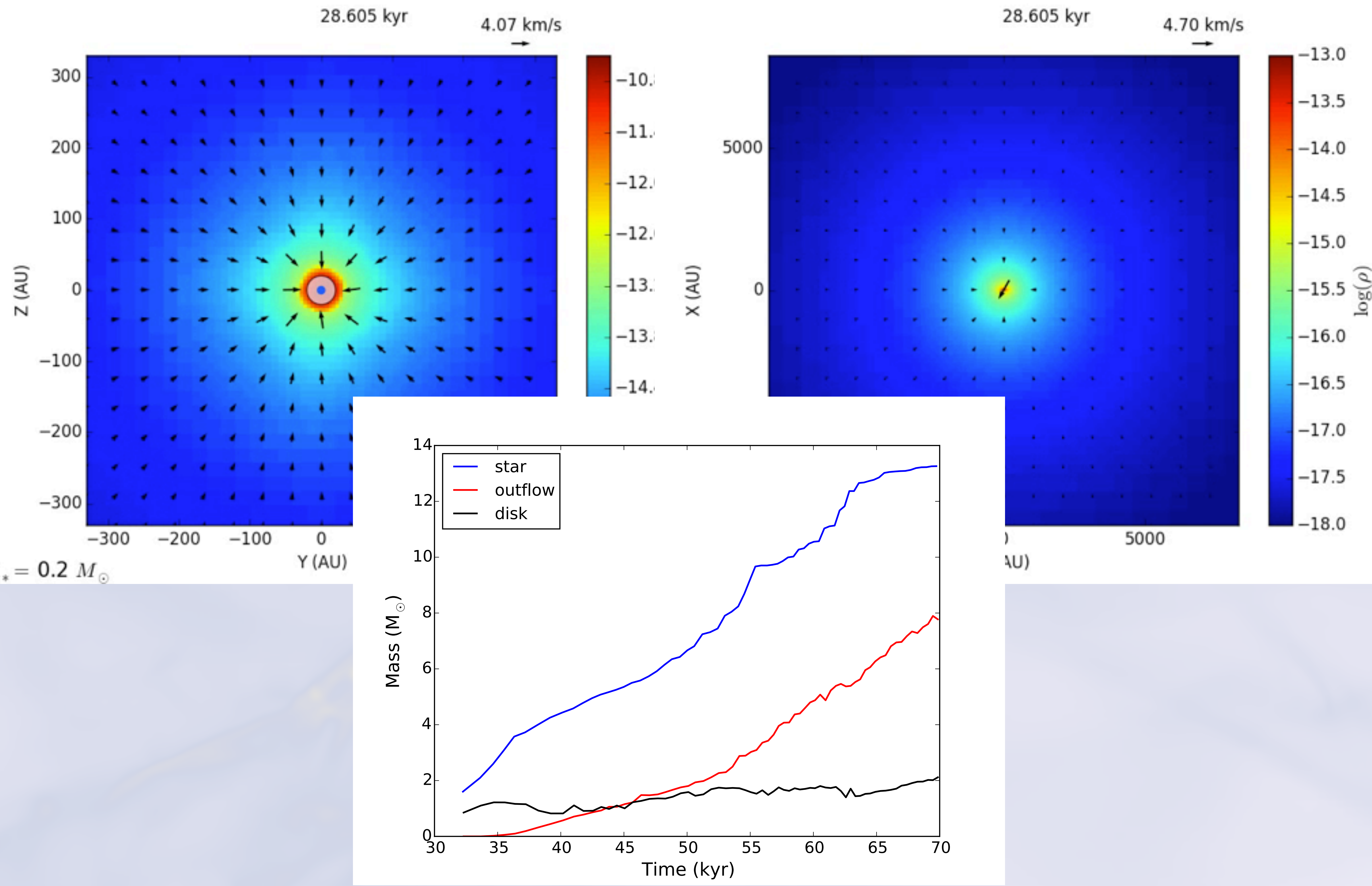
Ambipolar diffusion, μ =5



Ambipolar diffusion, $\mu = 5$

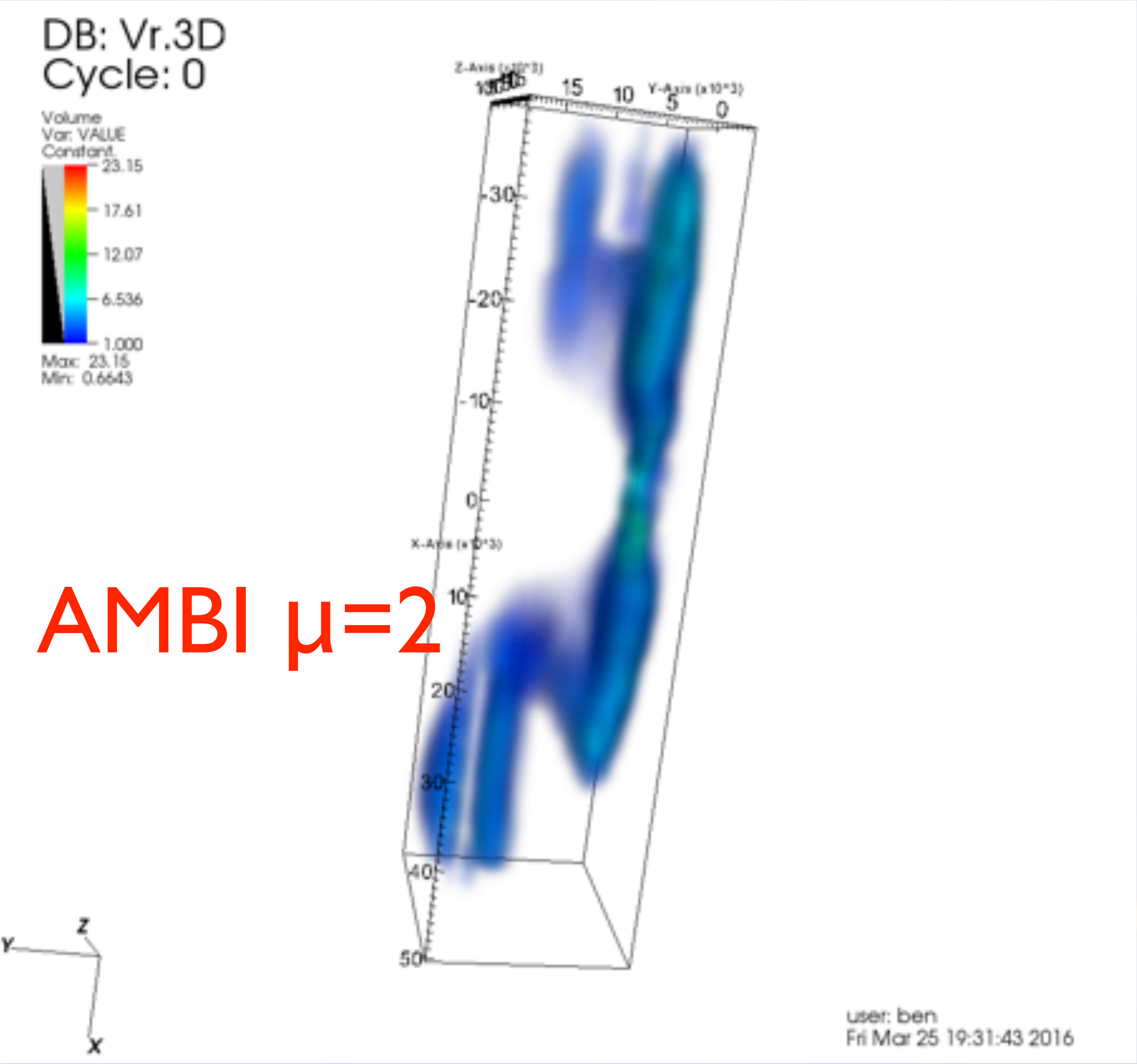


Ambipolar diffusion, μ =5

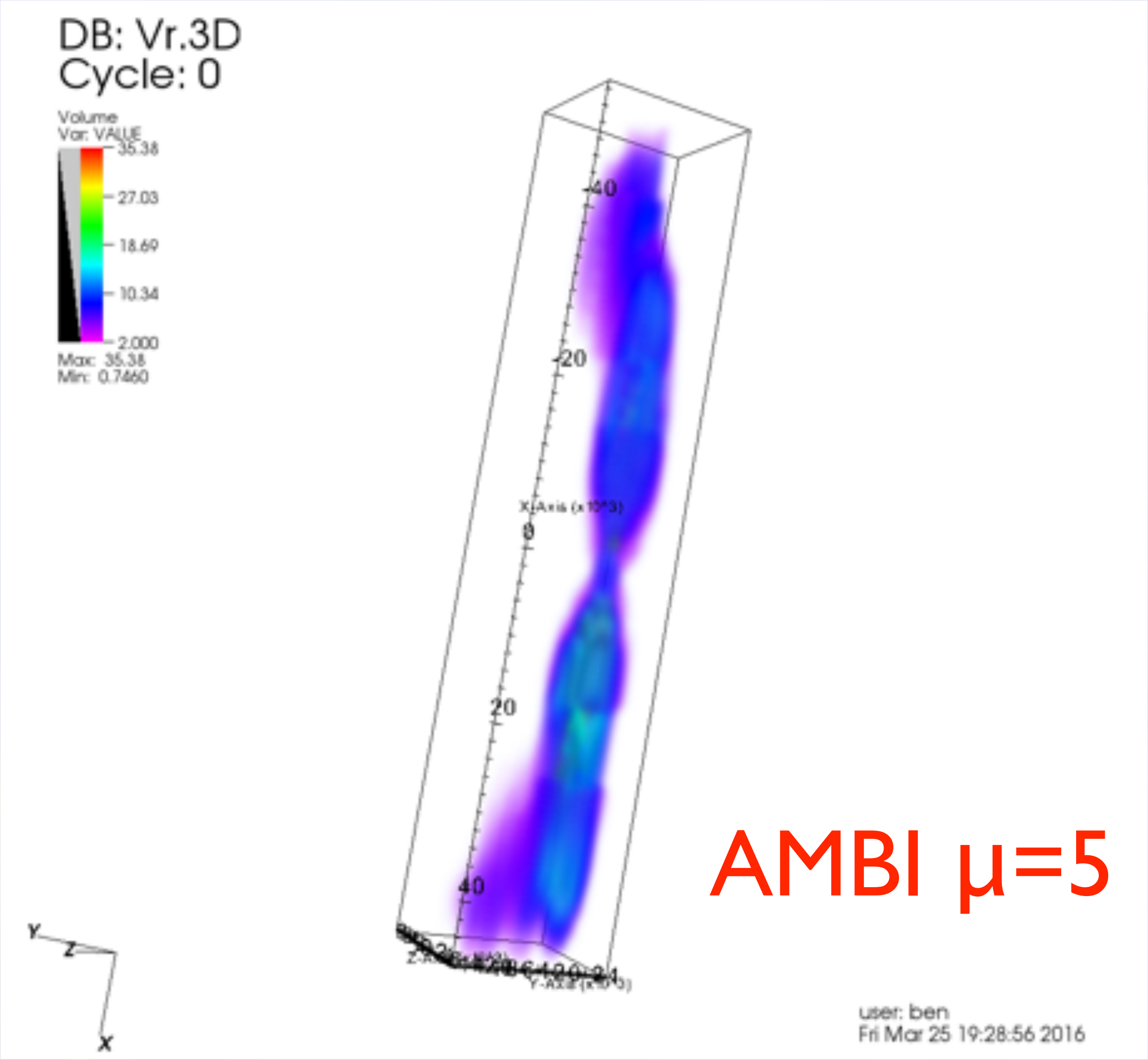


$M_* = 0.2\ M_\odot$

Outflow morphology

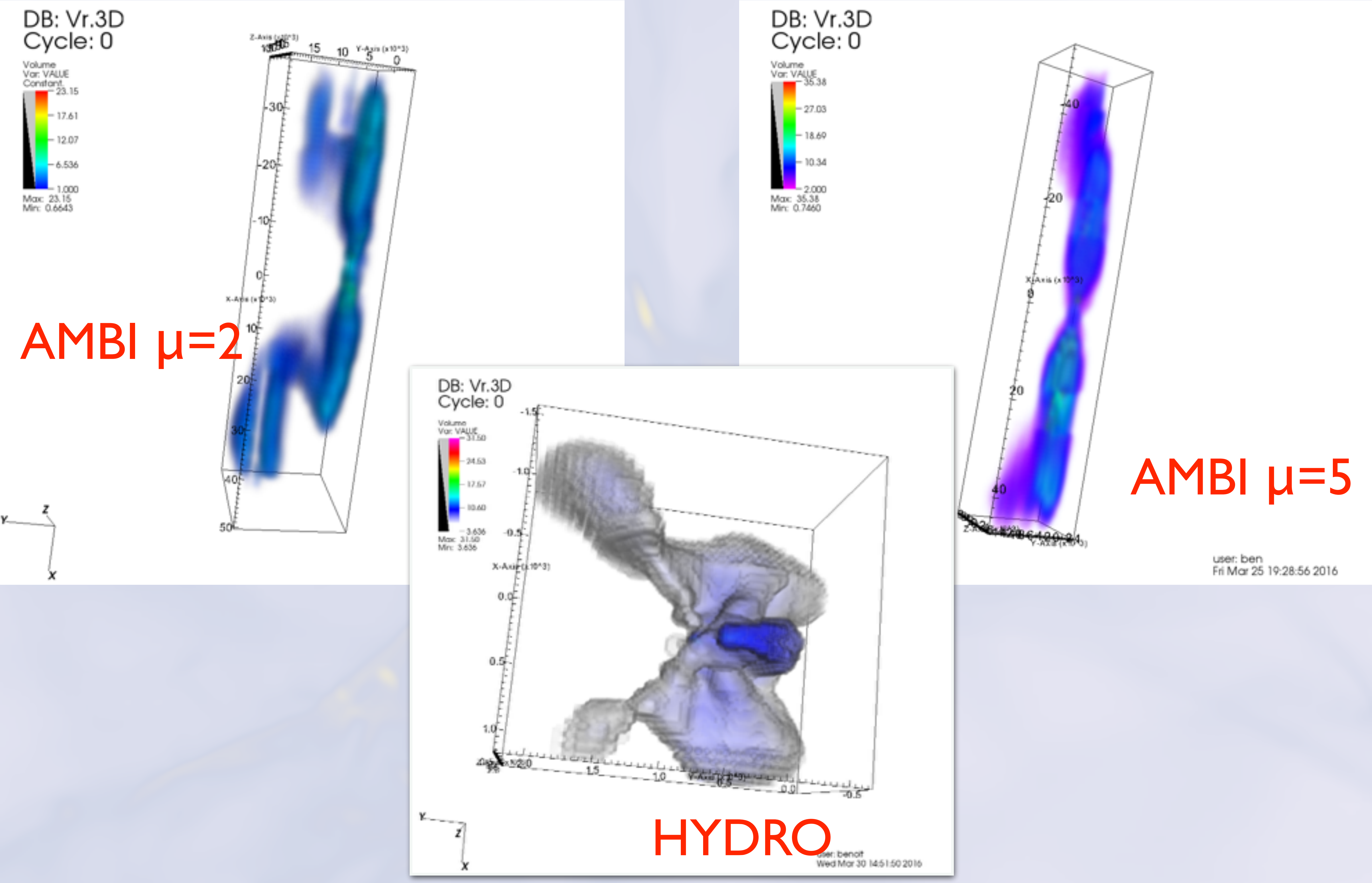


AMBI μ=2



AMBI μ=5

Outflow morphology



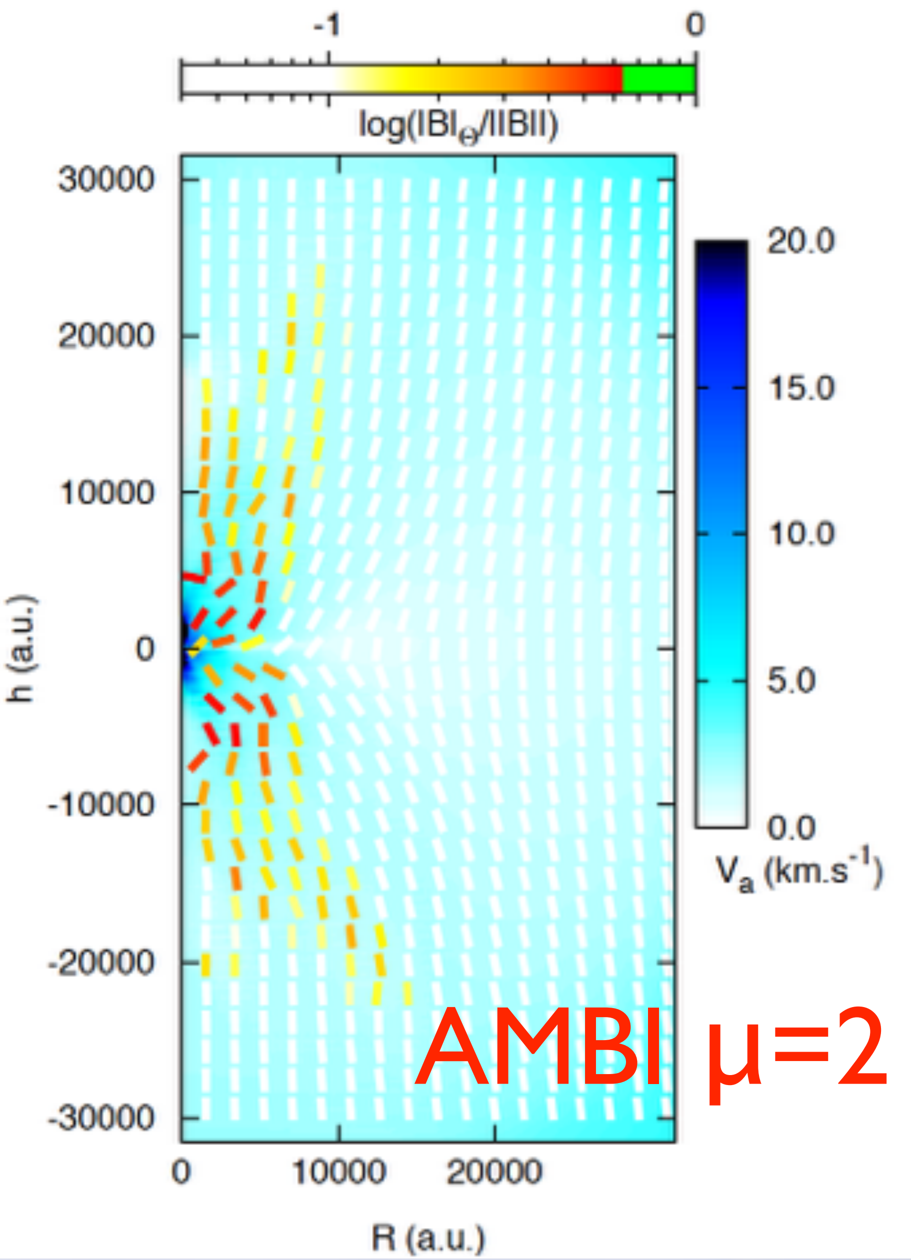
AMBI μ=2

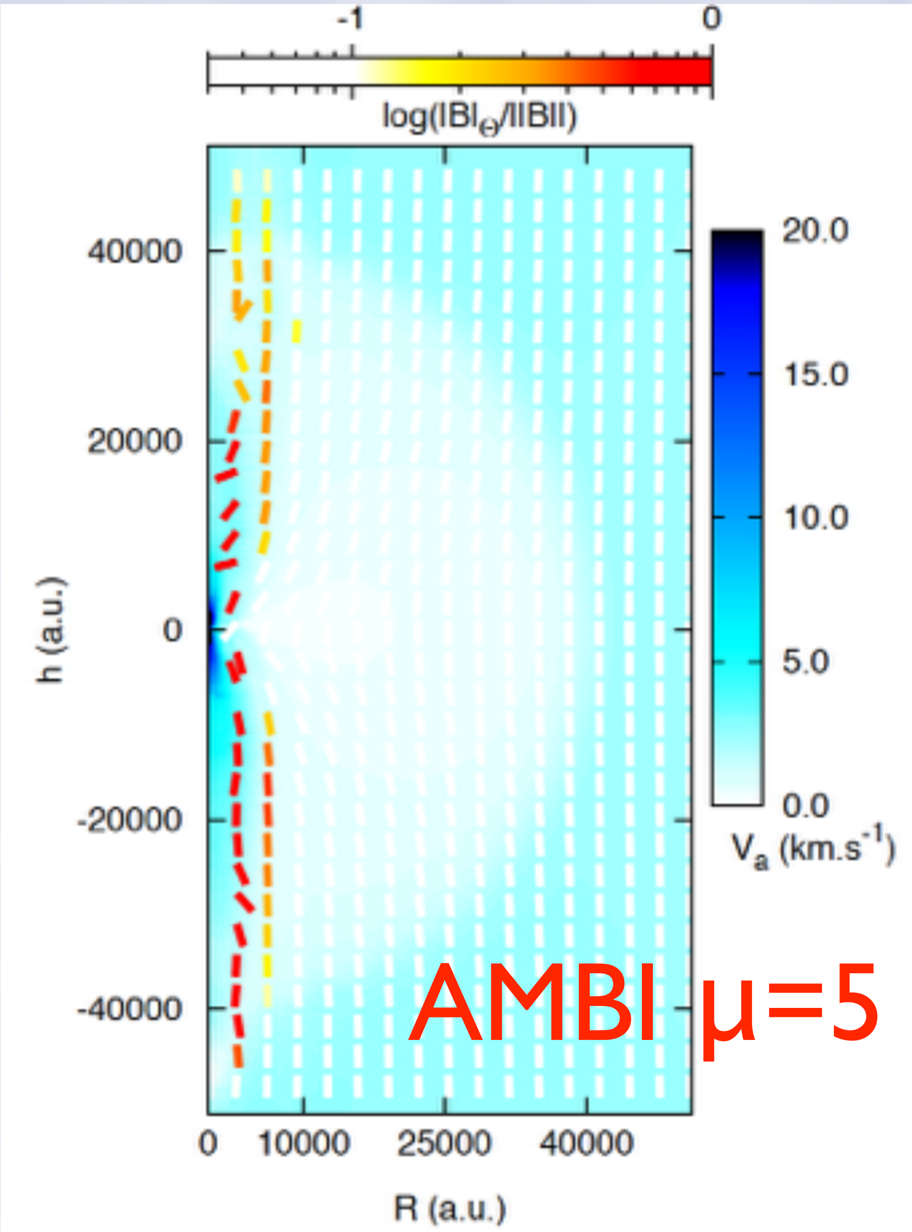
HYDRO

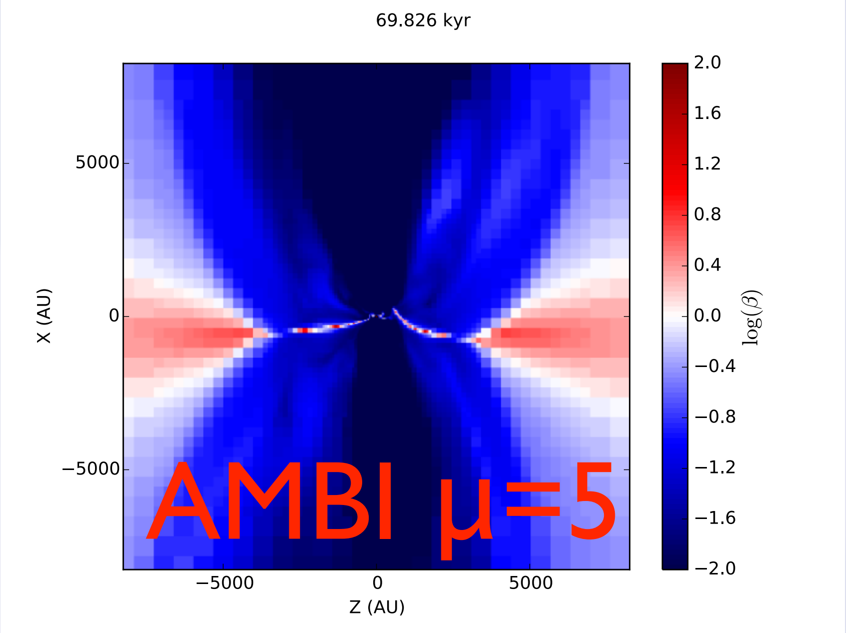
AMBI μ=5

Outflow collimation

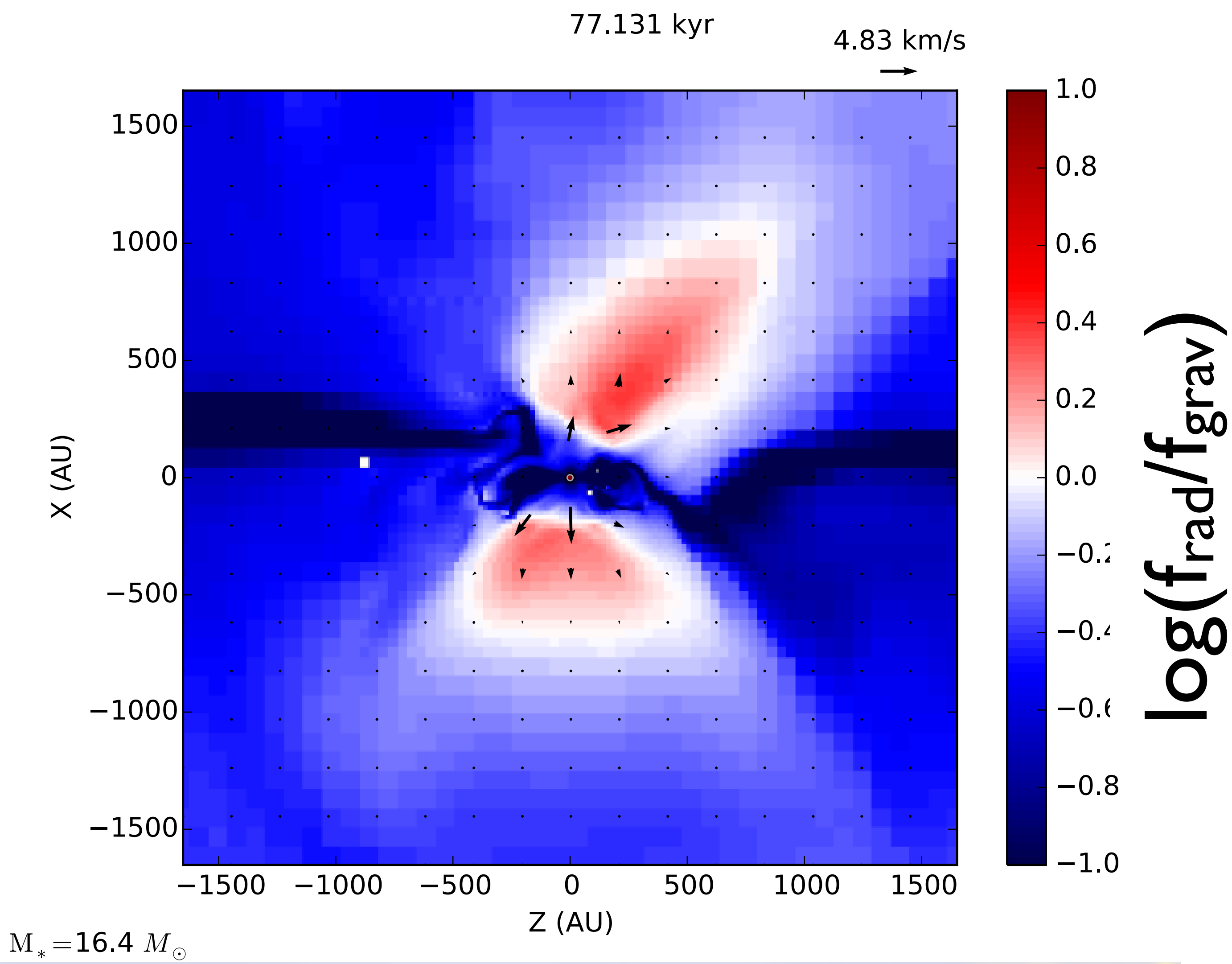
- ✓ outflow collimated by toroidal B-field
- ✓ outflow extends up to 50 000 AU when $M_\star=12M_\odot$,$V_{out,max}=40$ km/s
- ✓ outflow is strongly magnetized



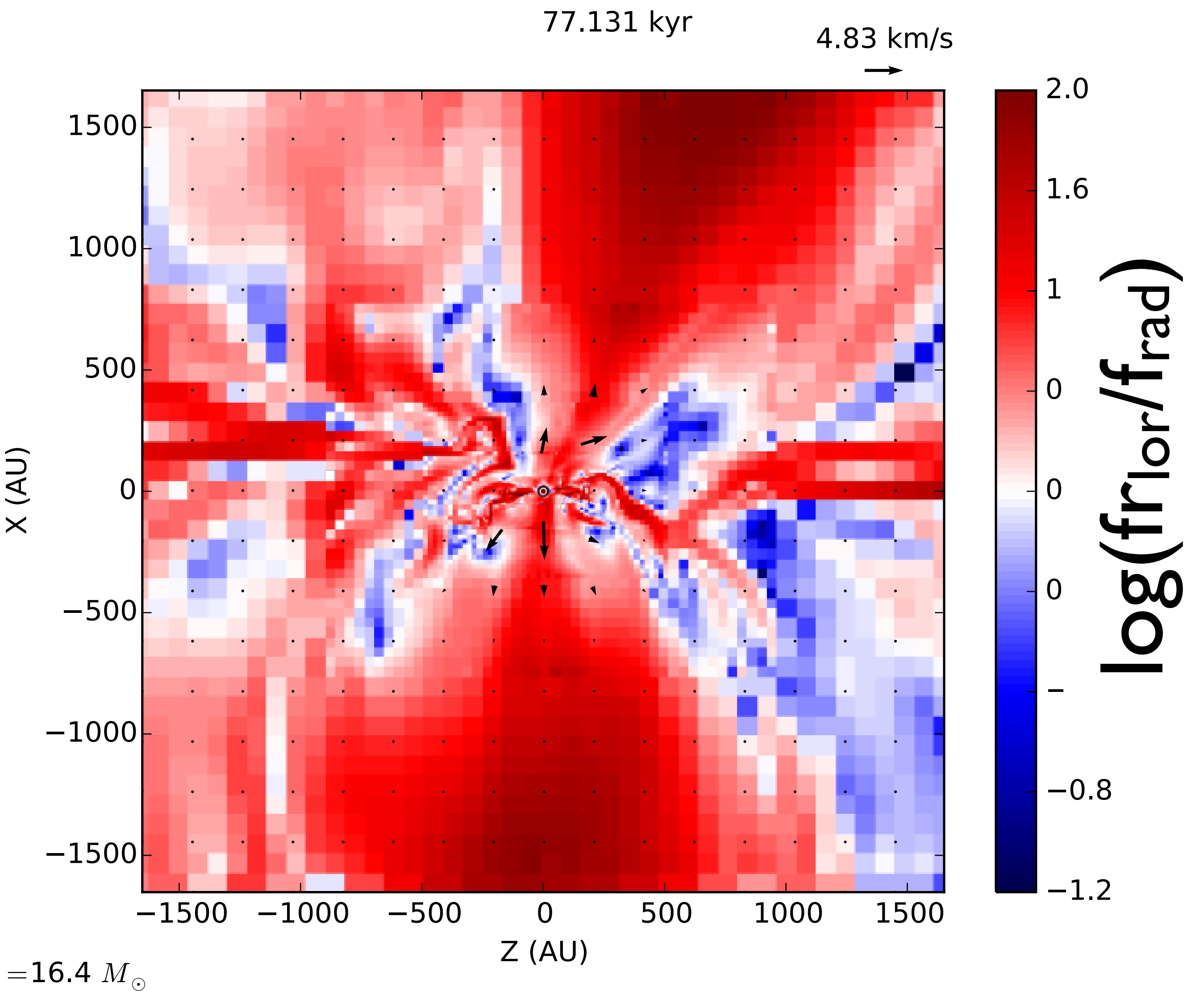




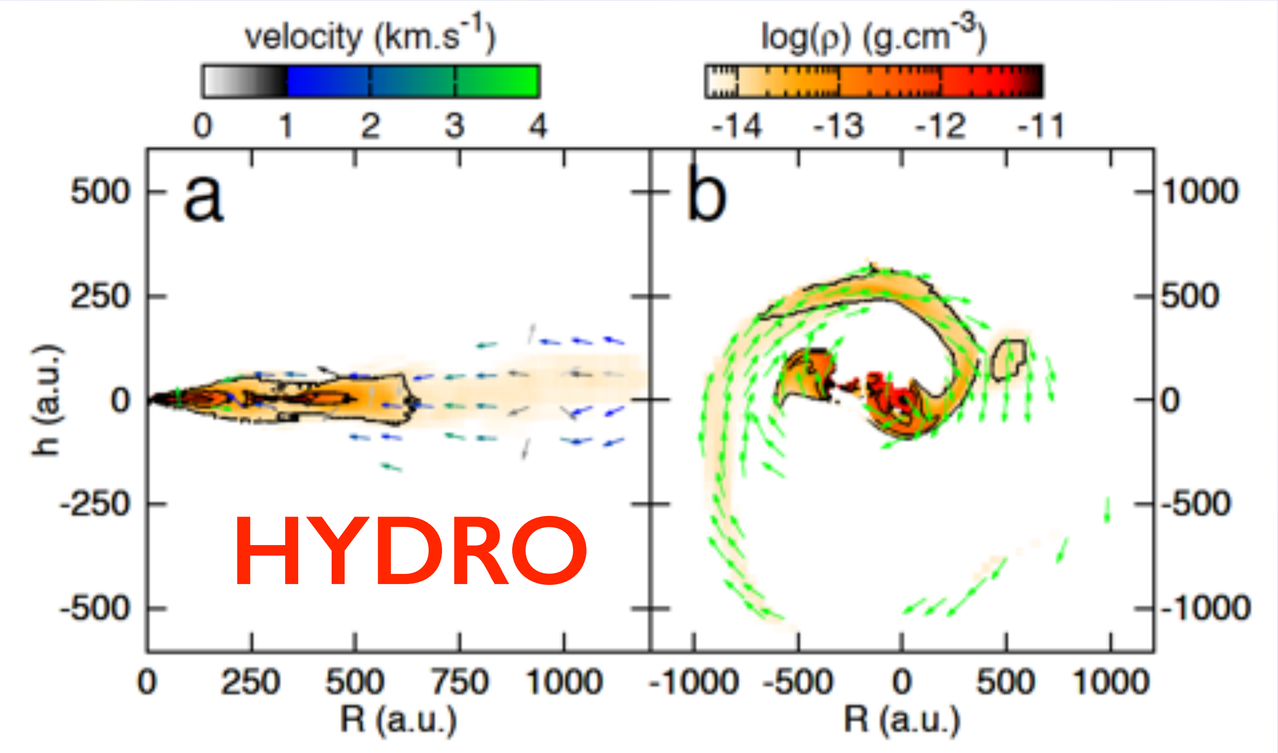
Is radiative feedback important?

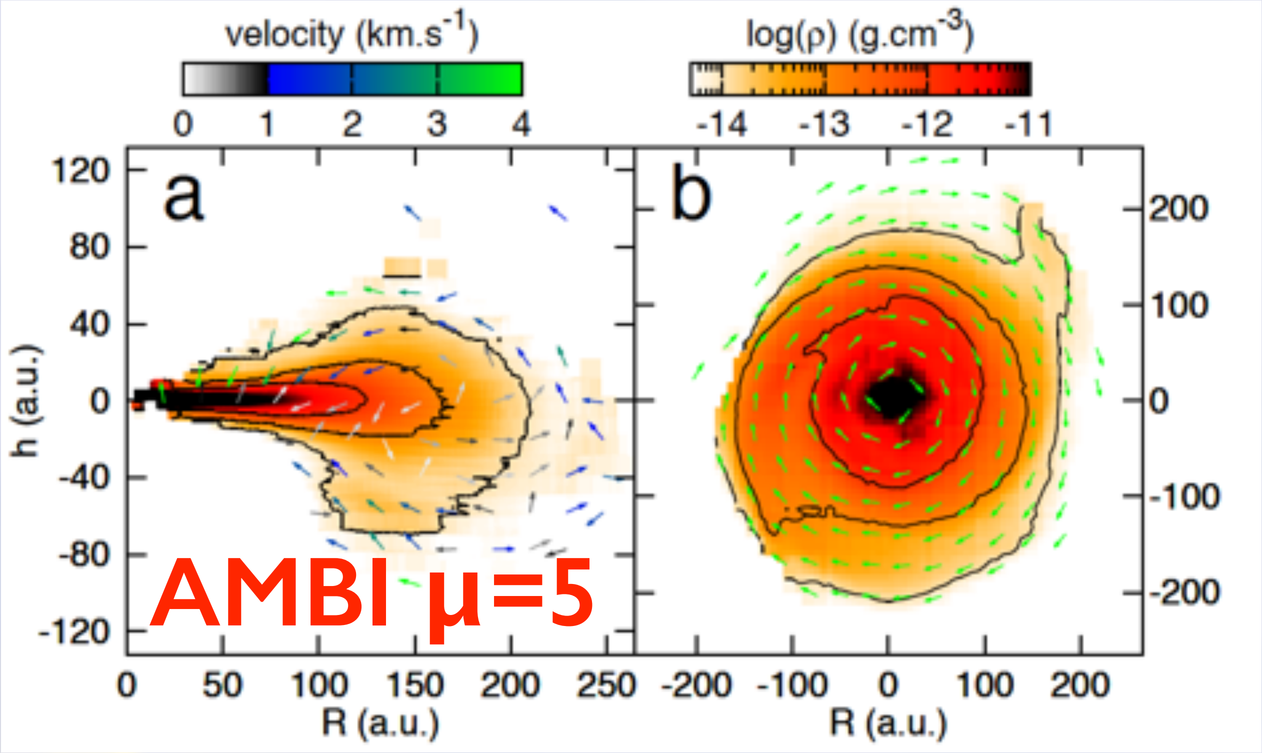


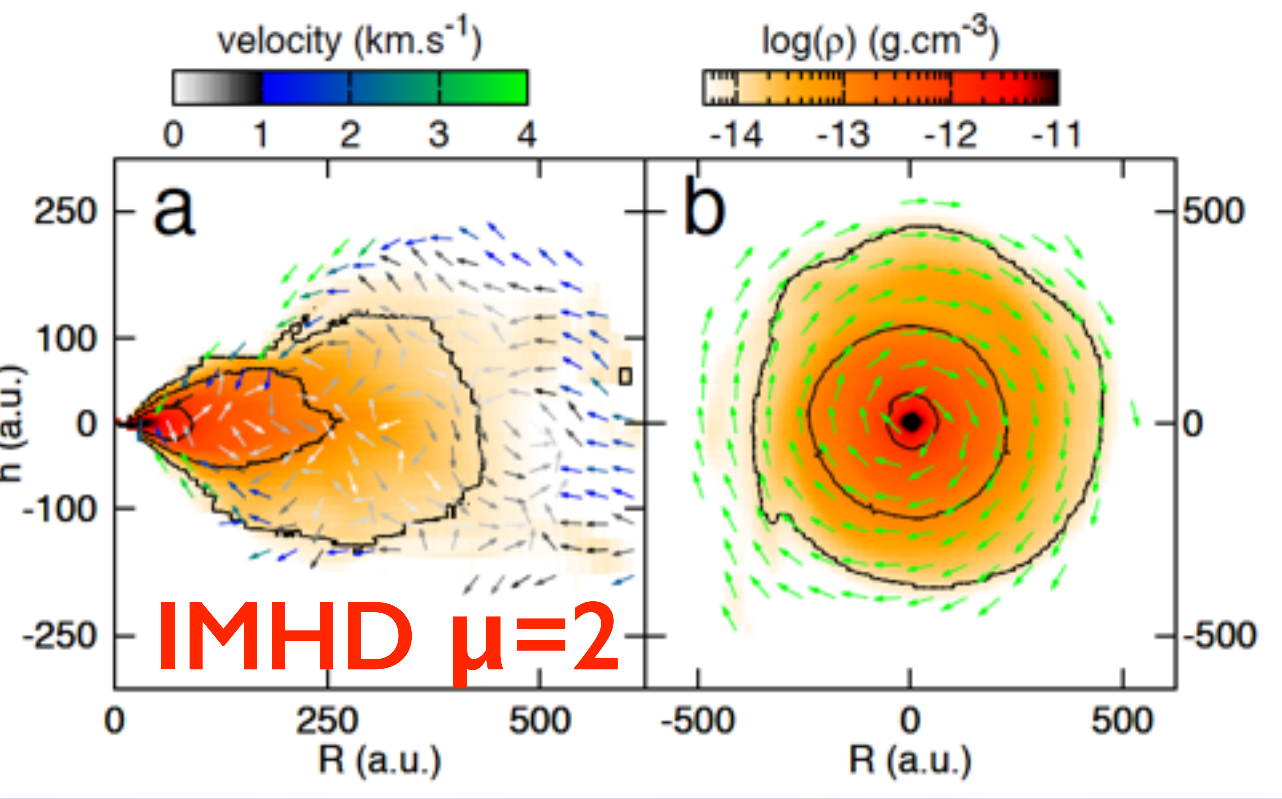
✓ radiative force contributes to the outflow, but does not dominate over the Lorentz force

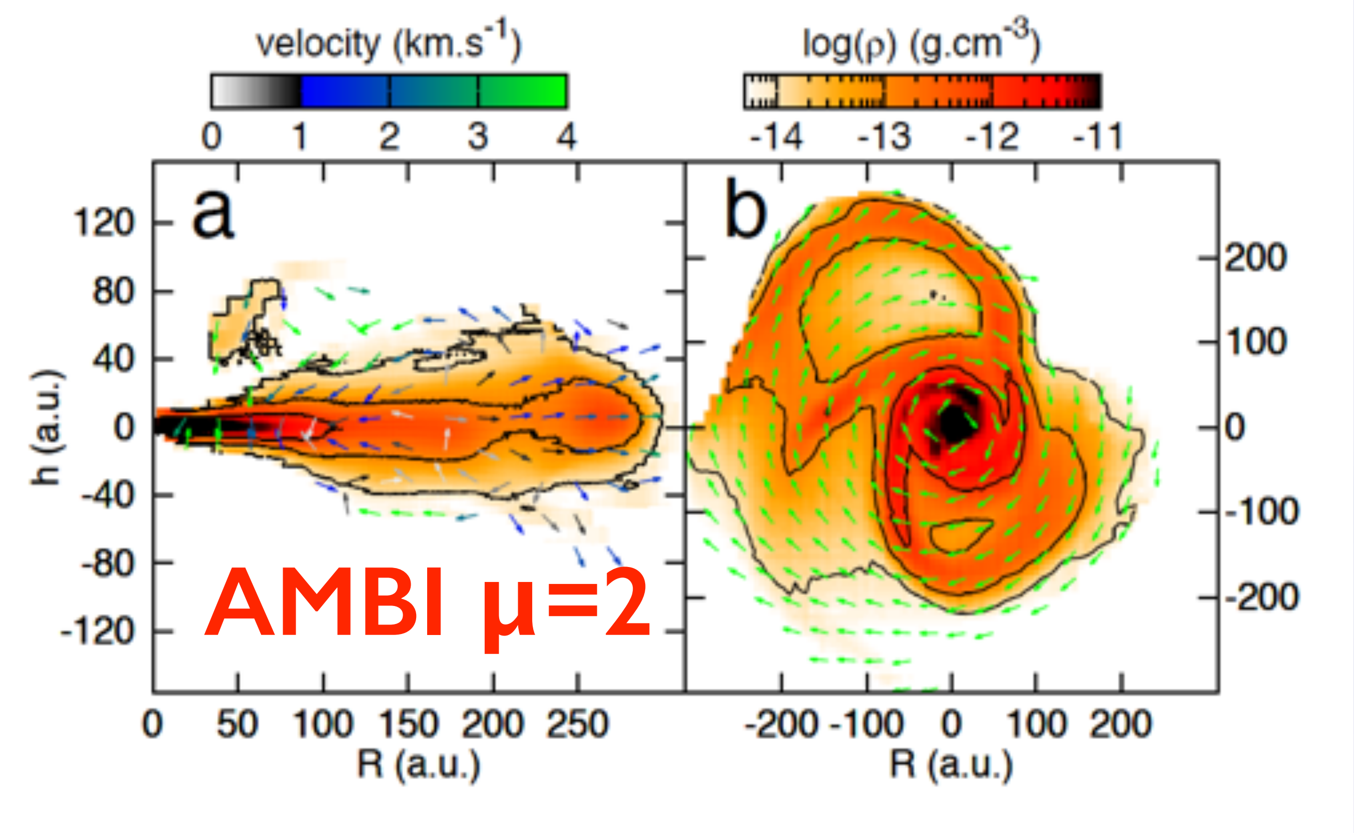


Discs properties









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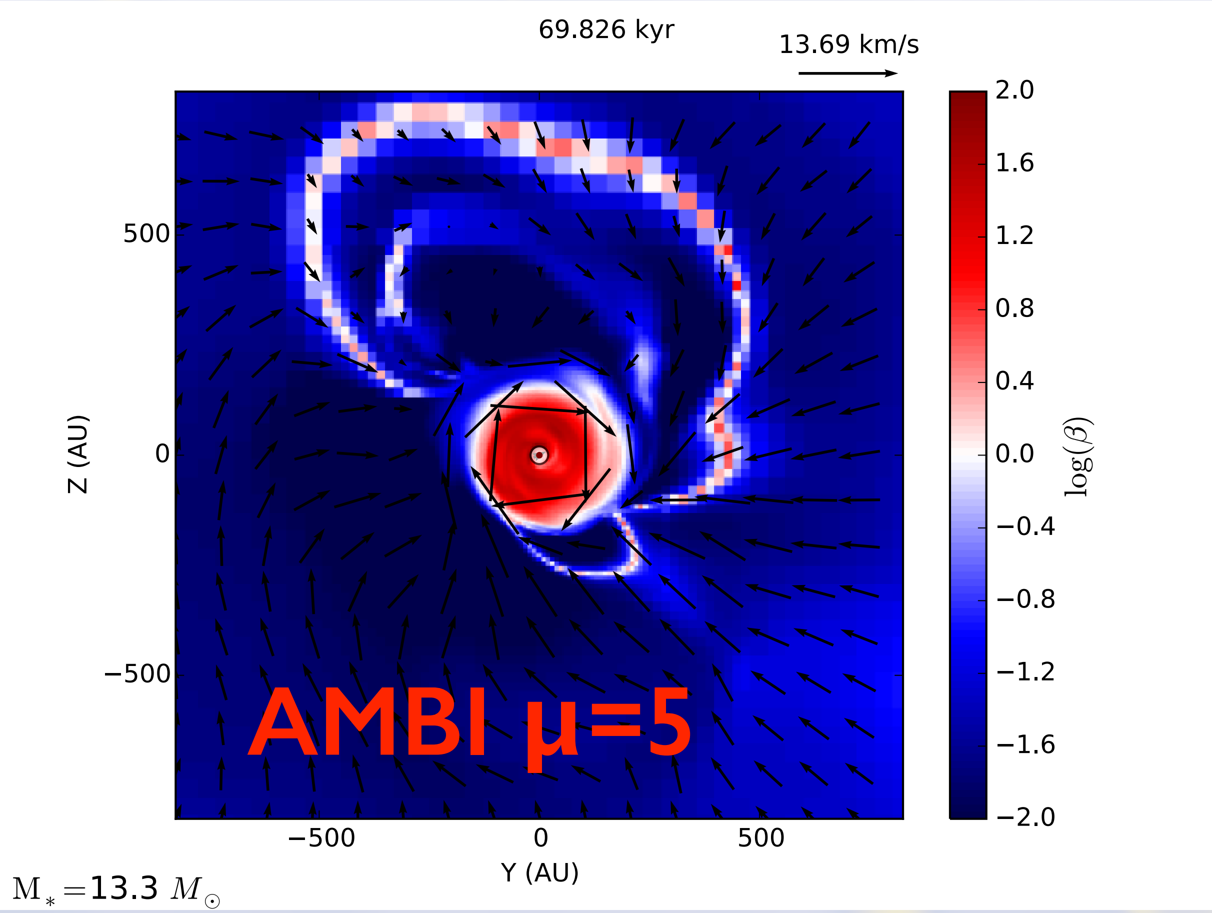
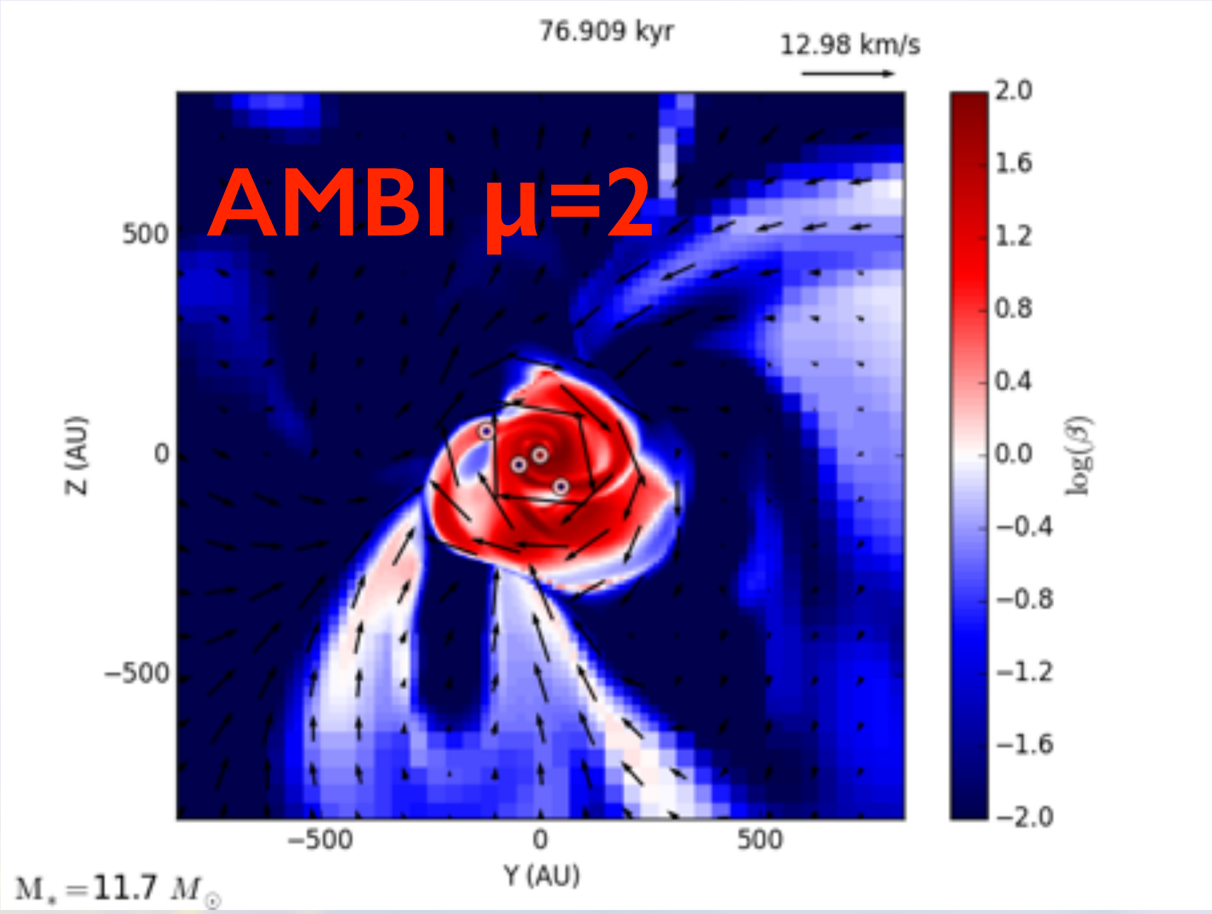
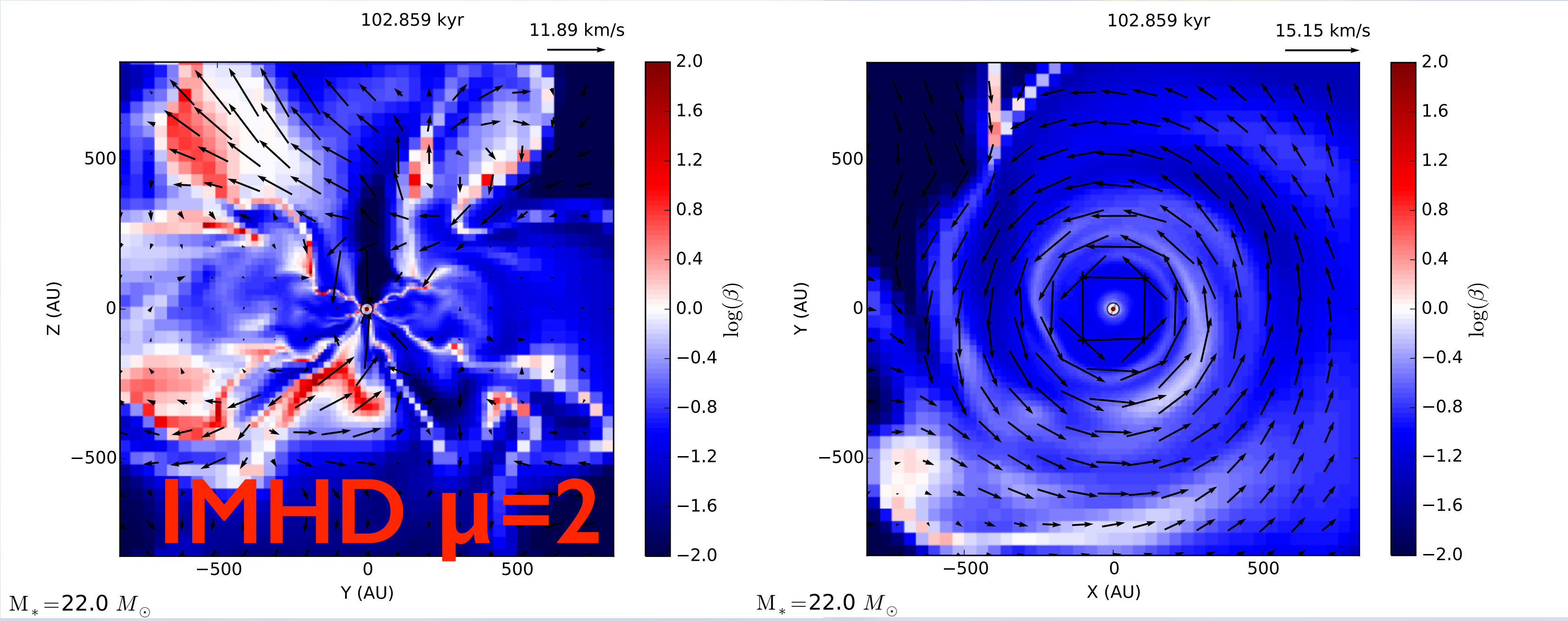
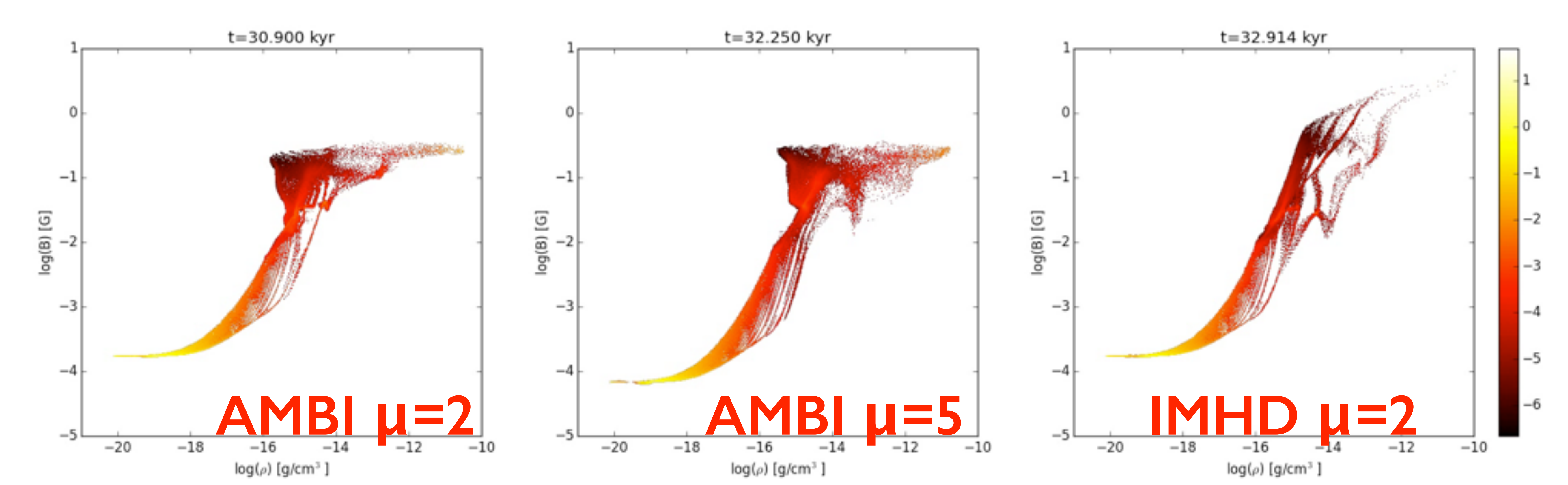






- ✓ discs are dominated by thermal pressure with AD (i.e. hydro discs)
- ✓ thick and magnetised disk with iMHD

Magnetisation



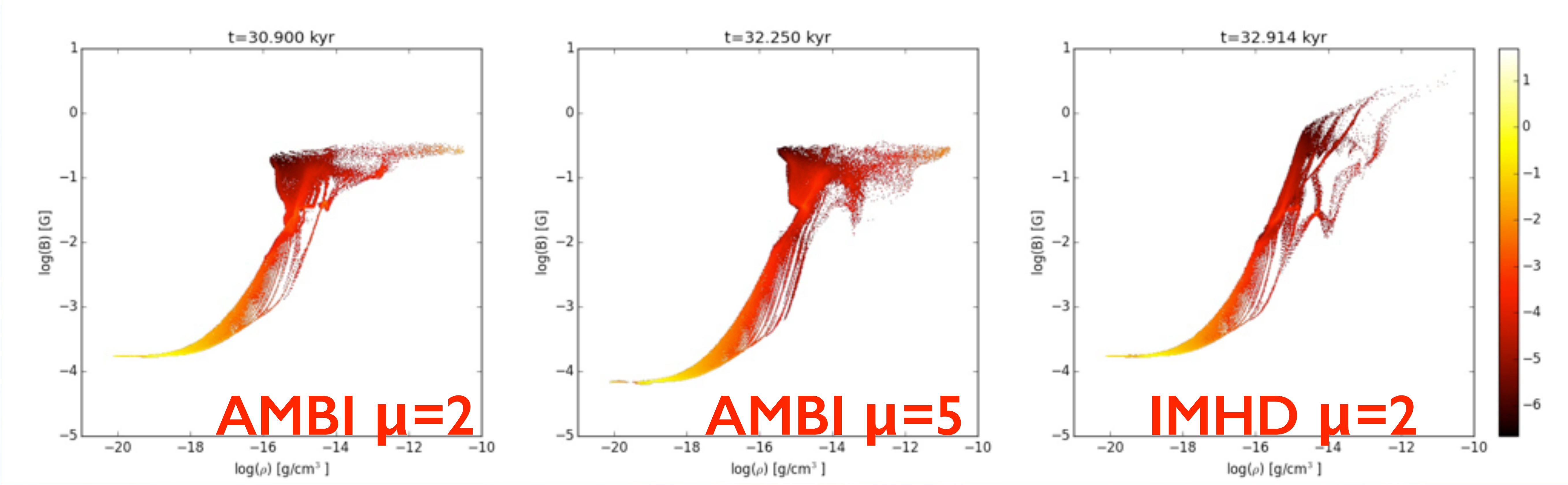
AMBI μ=2

AMBI μ=5

IMHD μ=2

- ✓ Bmax reduced by > 1 order of magnitude by AD
- ✓ plateau @ B<1G
- ✓ similar to results found in low mass star formation

Magnetisation



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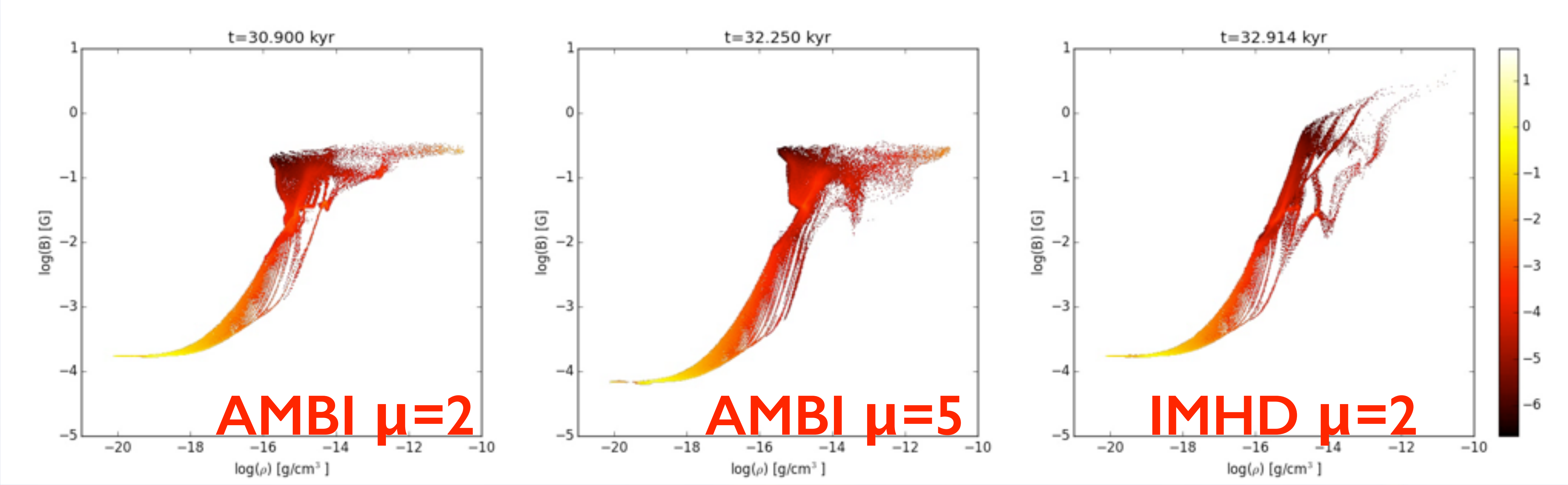

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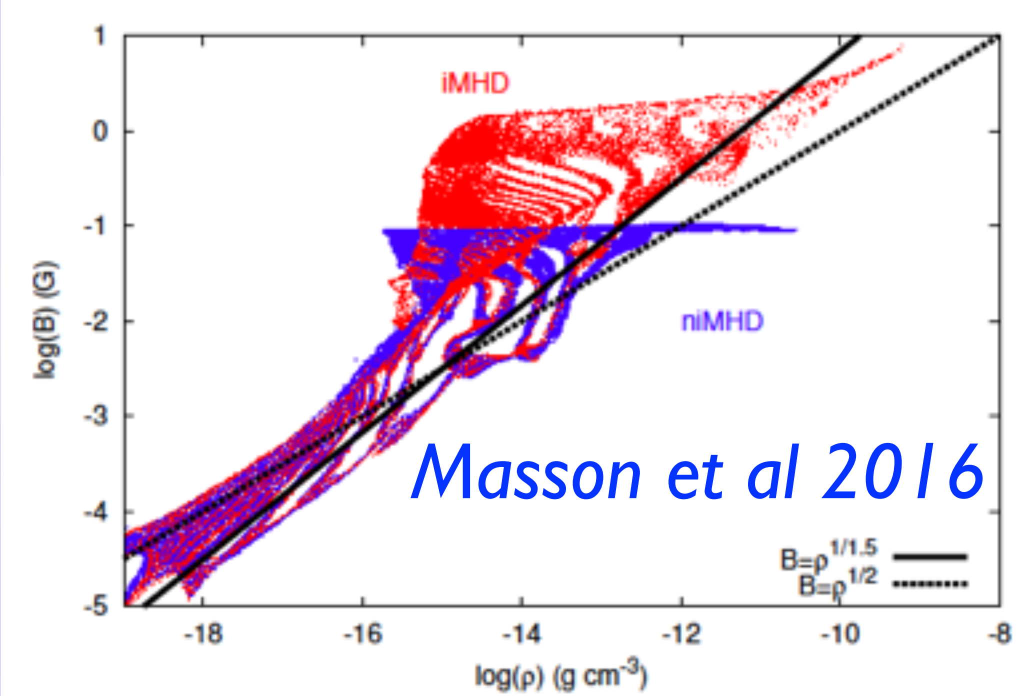

Masson et al 2016

Take away III

- ☑ Outflow is primarily of magnetic origin
- ☑ Magnetic outflow extends up to 50 000 AU in massive cores
- ☑ Radiative force does not overtake with $M_\star<15\ M_\odot$, but contributes to acceleration
- ☑ No large disk - R<500 AU
- ☑ observational diagnostics
- ☑ ideal MHD and hydro models have strong limitations wrt
  1. outflow launching
  2. disk properties (as well as for low-mass star formation…)
  3. angular momentum transport

THANK YOU