Massive star formation
collapse, fragmentation
outflows and disks

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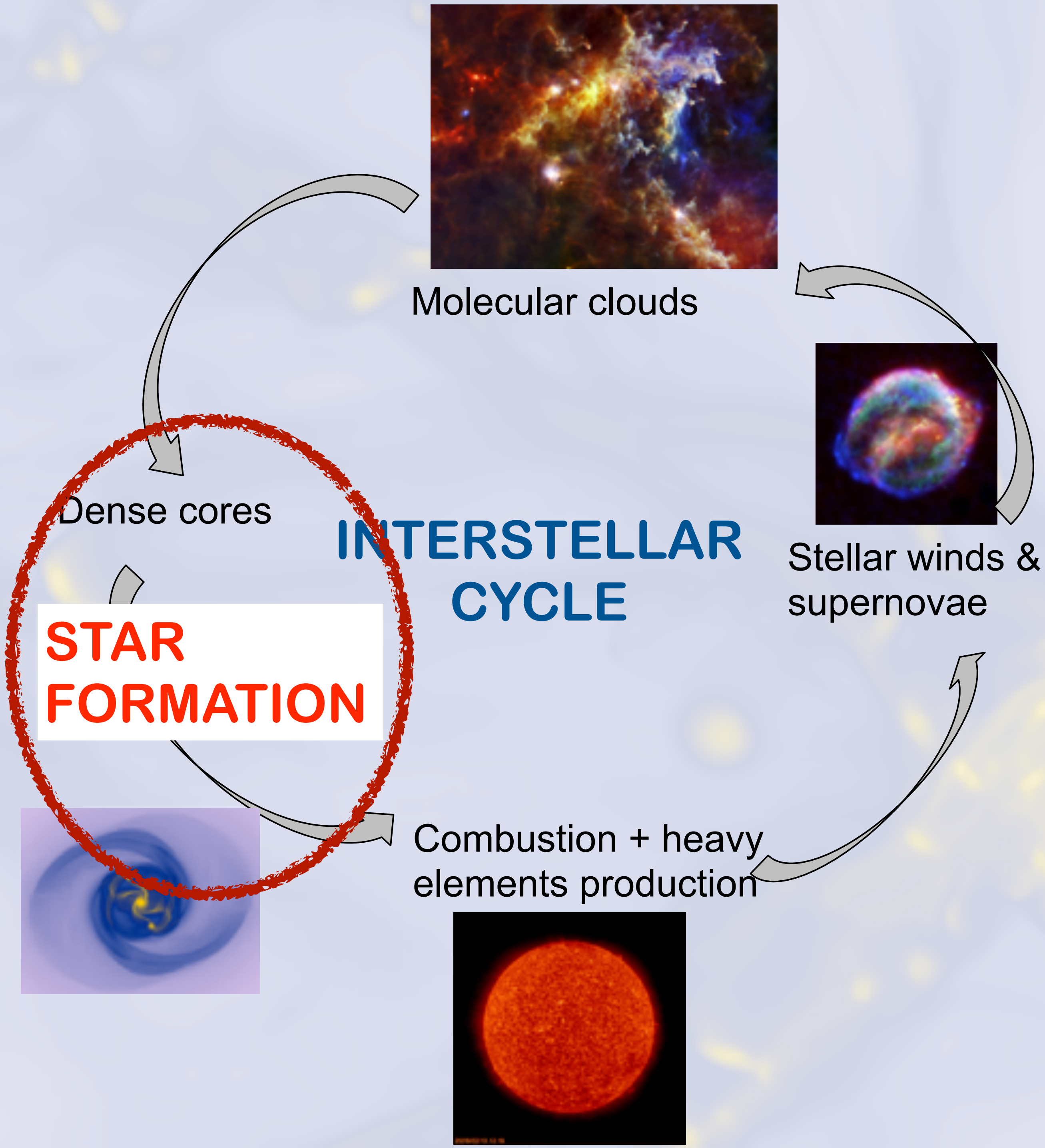
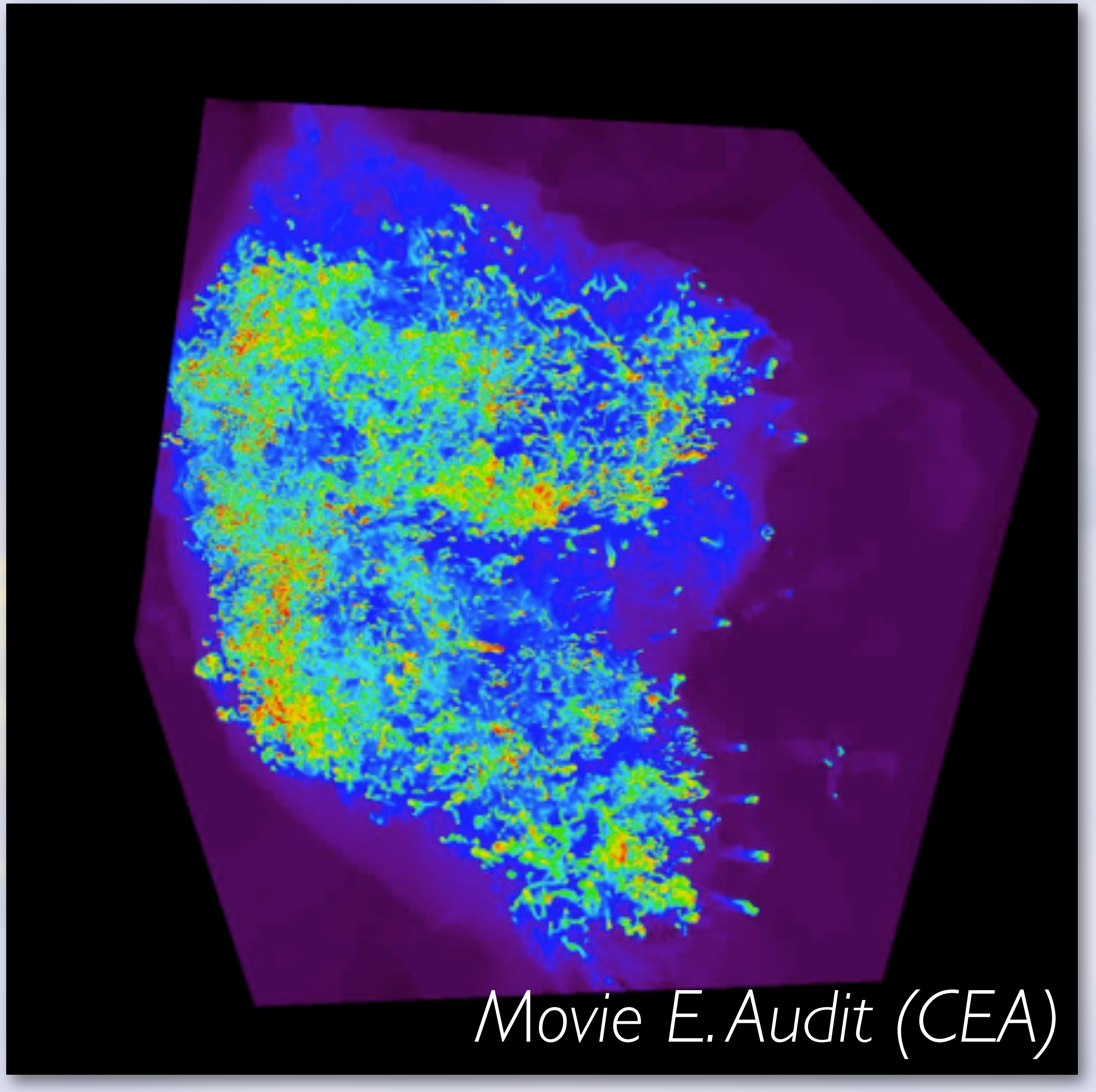
Outline

1. **Introduction**
2. **Methods**
3. **Massive dense cores collapse**
   - Early fragmentation inhibition
   - Disk & outflow formation

Why is star formation so important?



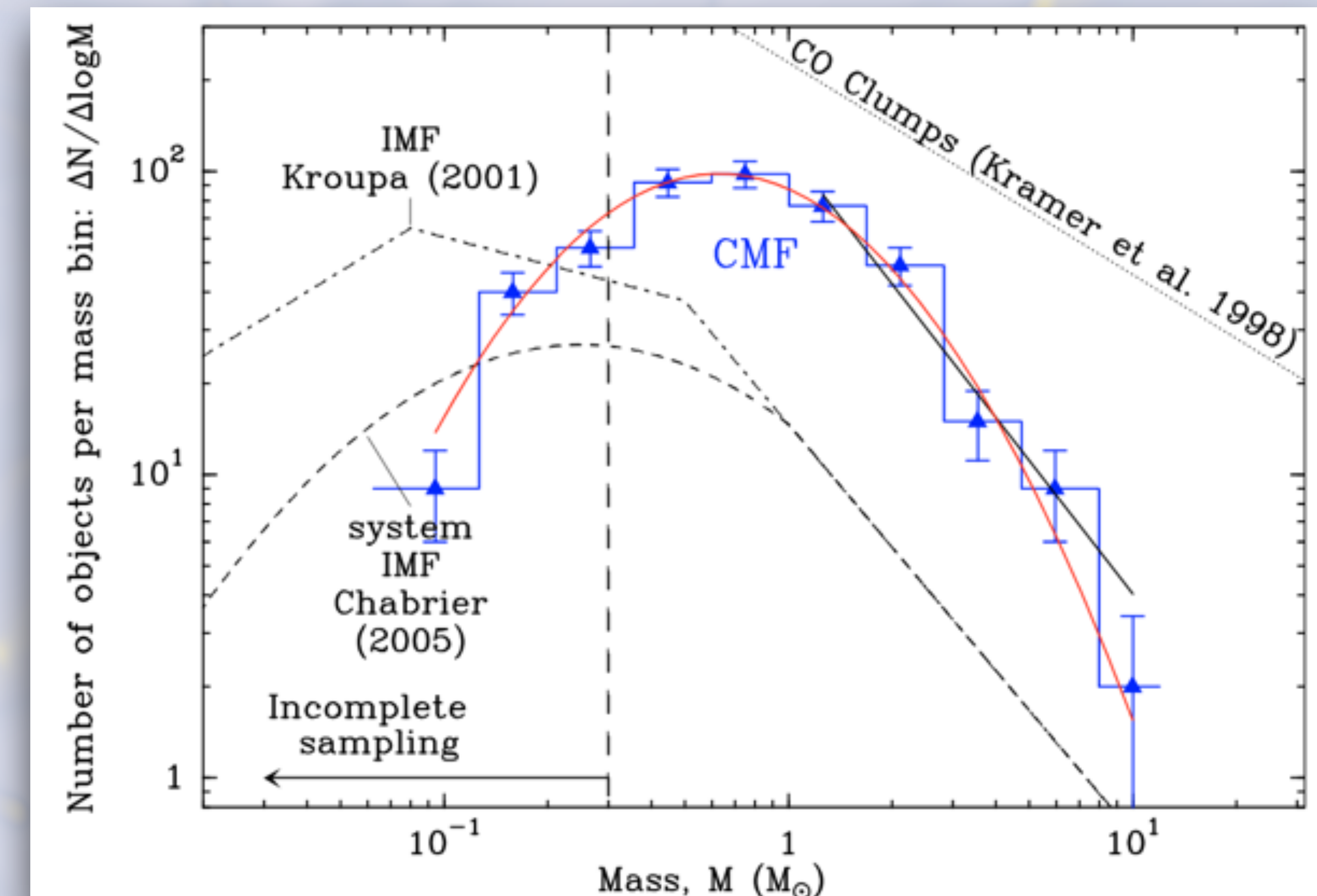
Turbulent molecular cloud



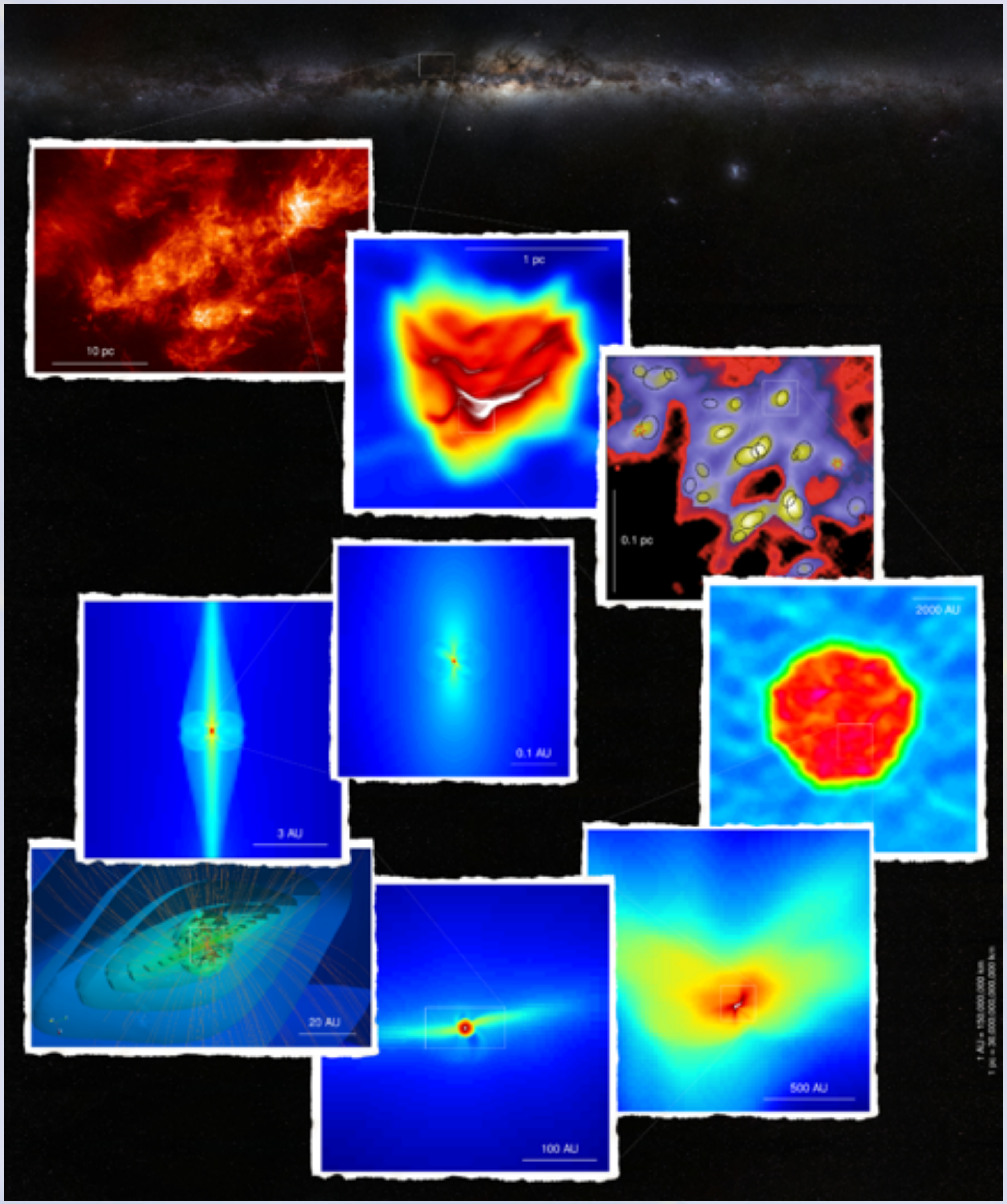
Dense core formation

- 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*)

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

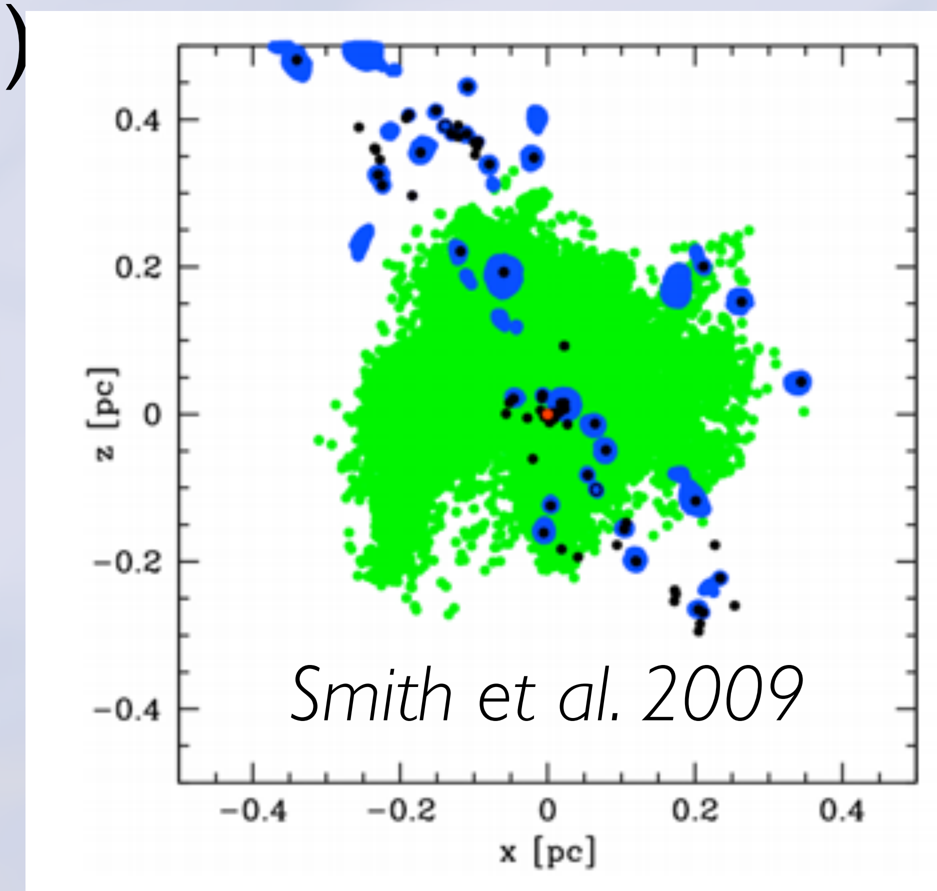
Lorentz force

High mass star formation scenarii

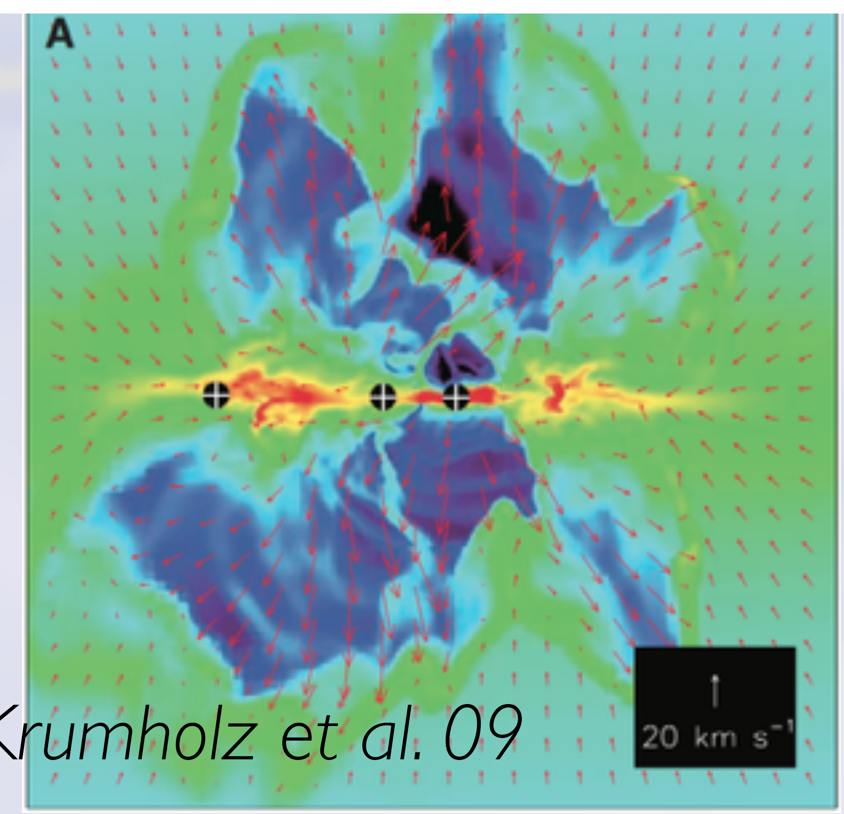
- **Competitive accretion (Bate, Bonnell et al.)**
  - Massive prestellar core does not exist
  - Star clusters and massive stars form simultaneously (*Smith et al. 2009*)

- **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



Smith et al. 2009



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

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

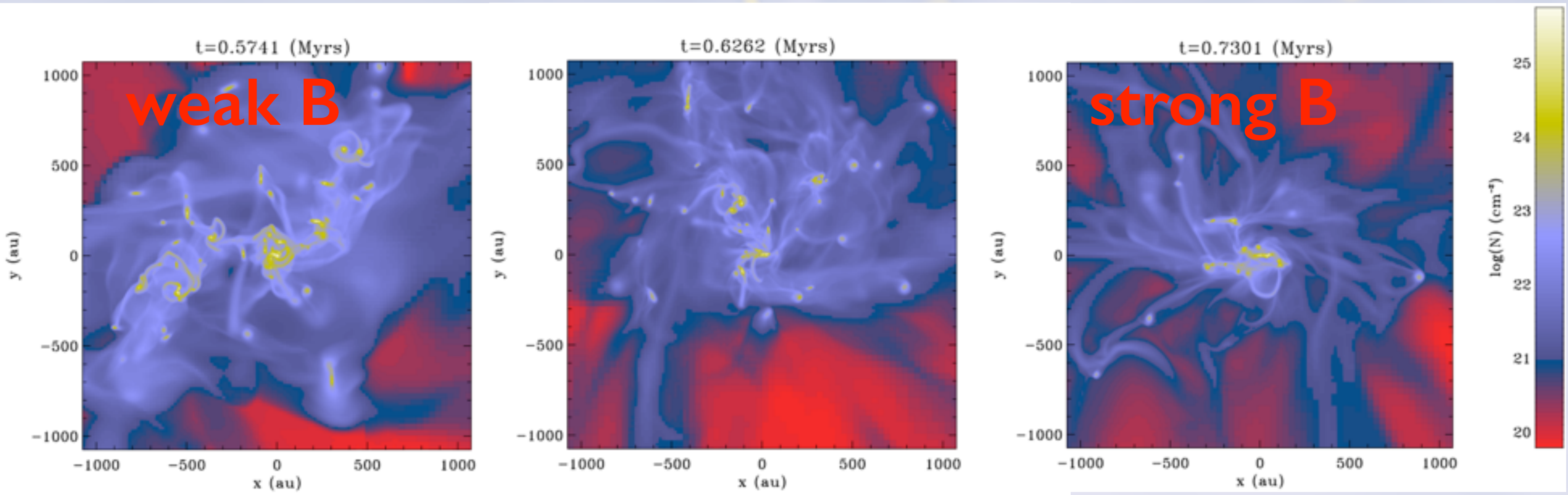
$$\rho_c = 1.4 \times 10^{-20} \ \mathrm{g\,cm^{-3}}$$

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

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

100 M⊙ turbulent dense core collapse

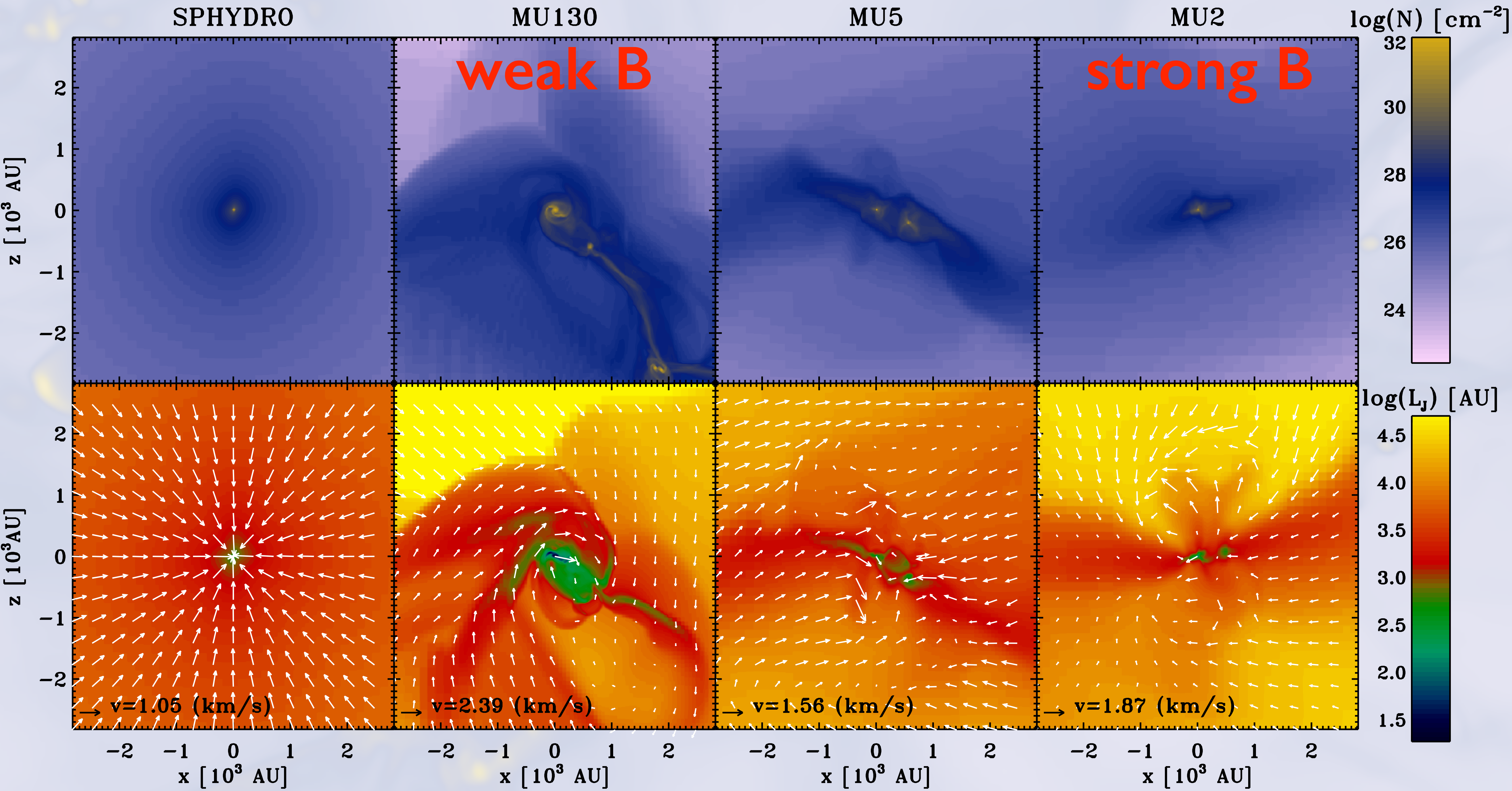
High-mass star formation: 100 M⊙ magnetized, turbulent and dense core w. FLD (follow-up of Hennebelle et al. 2011 barotropic study)

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

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

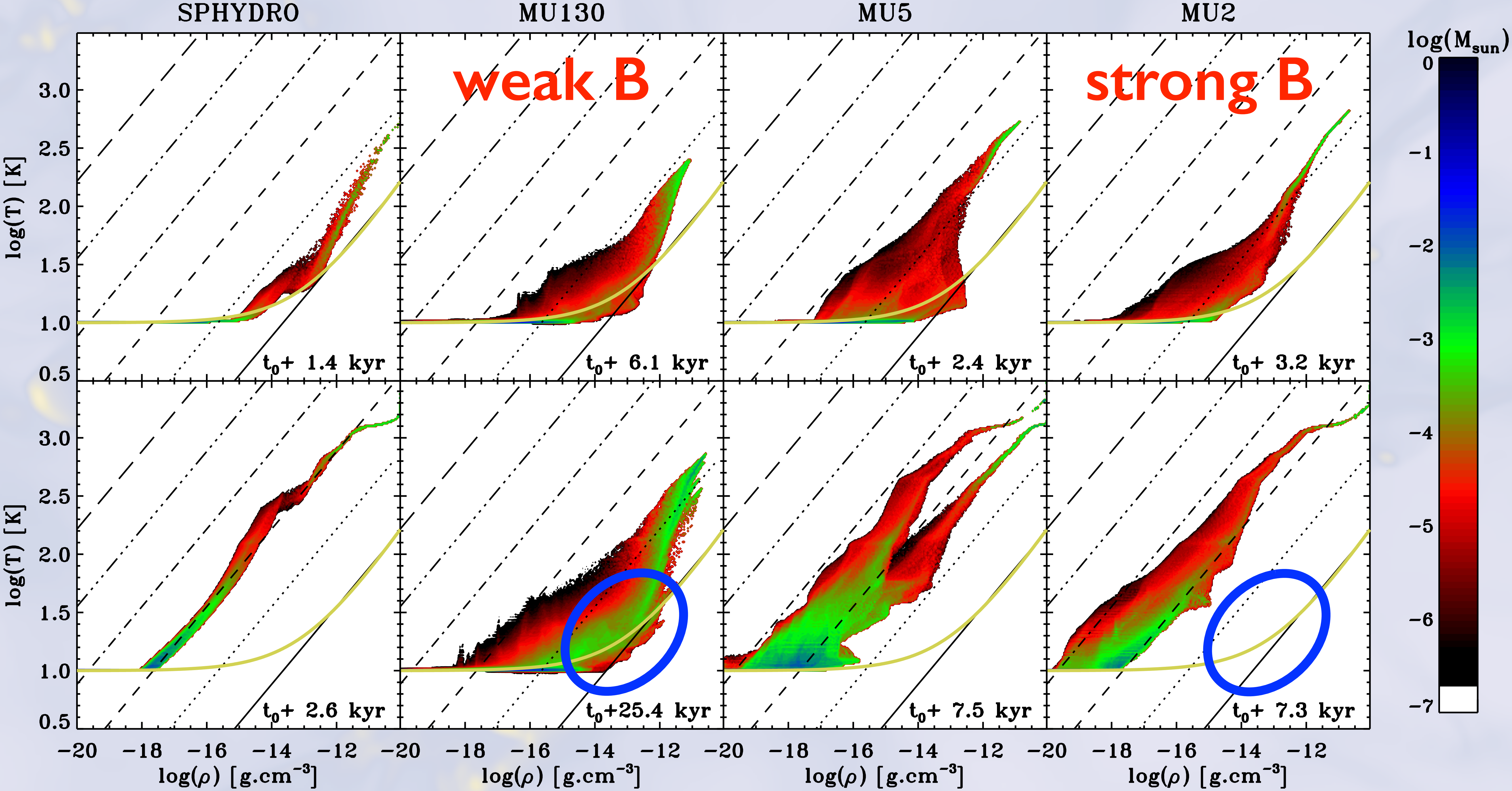
Commerçon, Hennebelle & Henning, ApJL 2011

100 M⊙ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

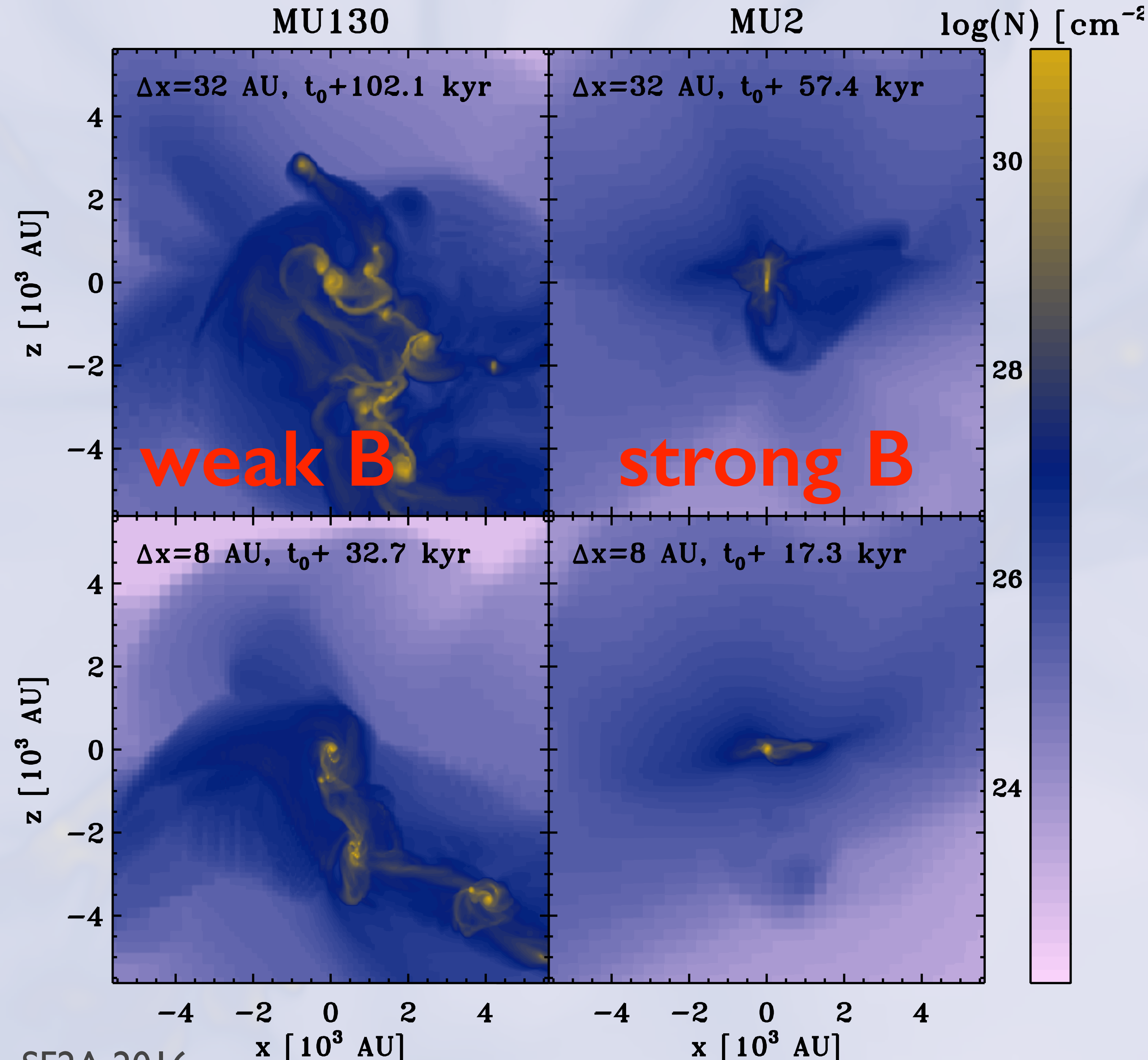
100 M⊙ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

100 M⊙ turbulent dense core collapse

✓ Trend confirmed with lower resolution runs:

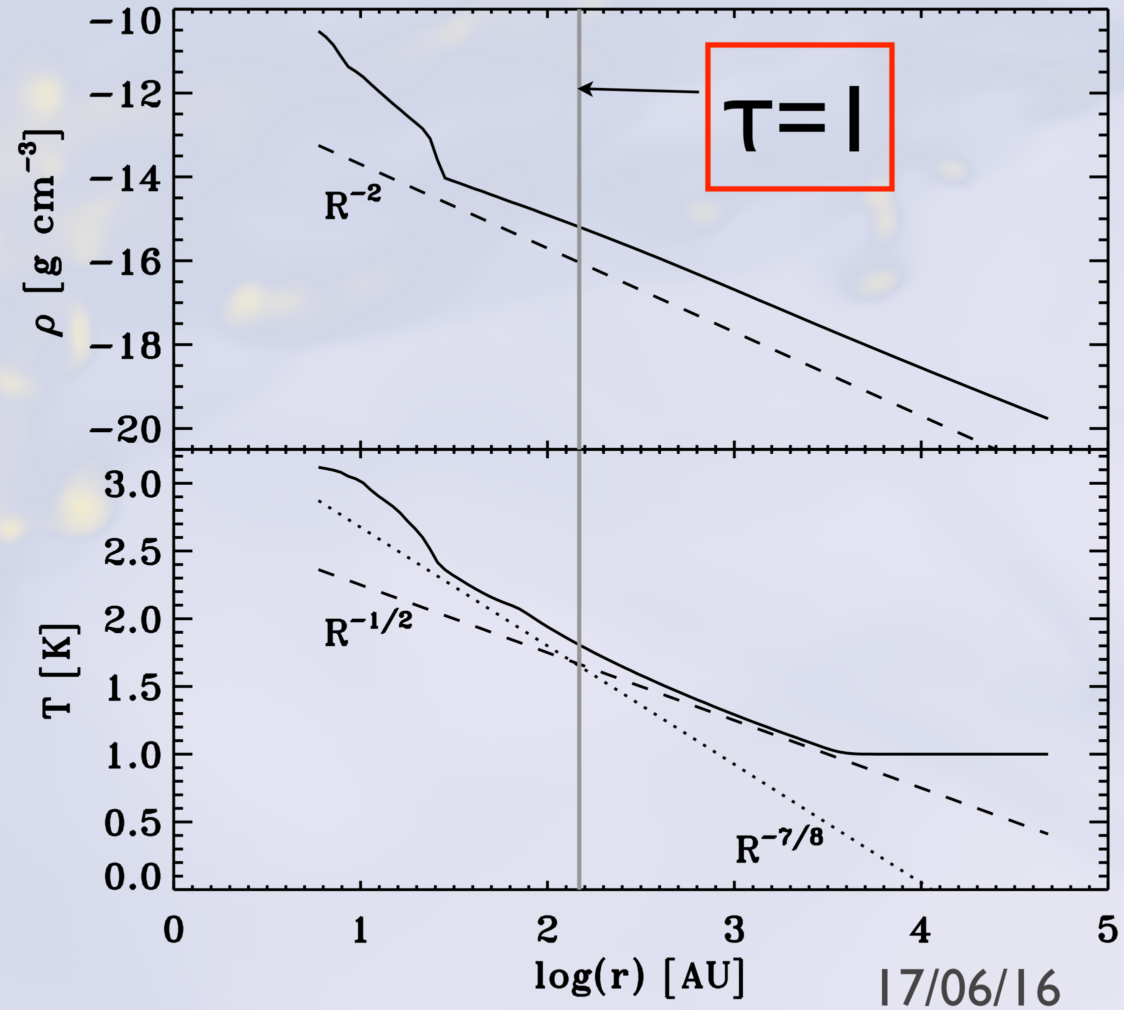


What's different?

☞ **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. 2011b)*



✓ Jeans stable mass ($M_\odot$):

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

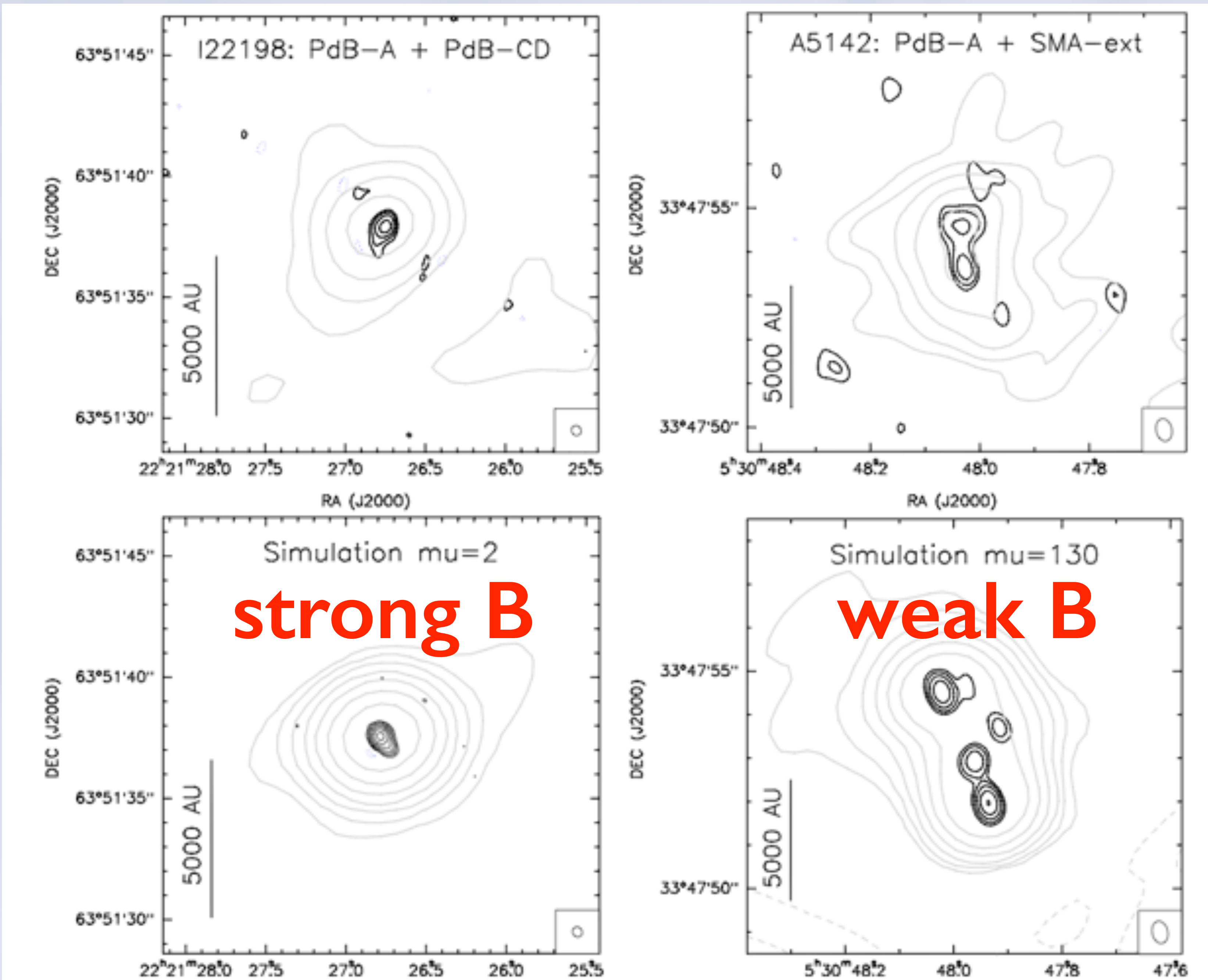
Towards massive star formation?

- ✓ **Low magnetic field:** fragmentation crisis, protostellar feedback would not help
  - ➡ similar to previous studies neglecting magnetic fields (competitive accretion), or having a too low resolution (*Peters et al. 2011*)
  - ★ Can magnetic field be neglecting?

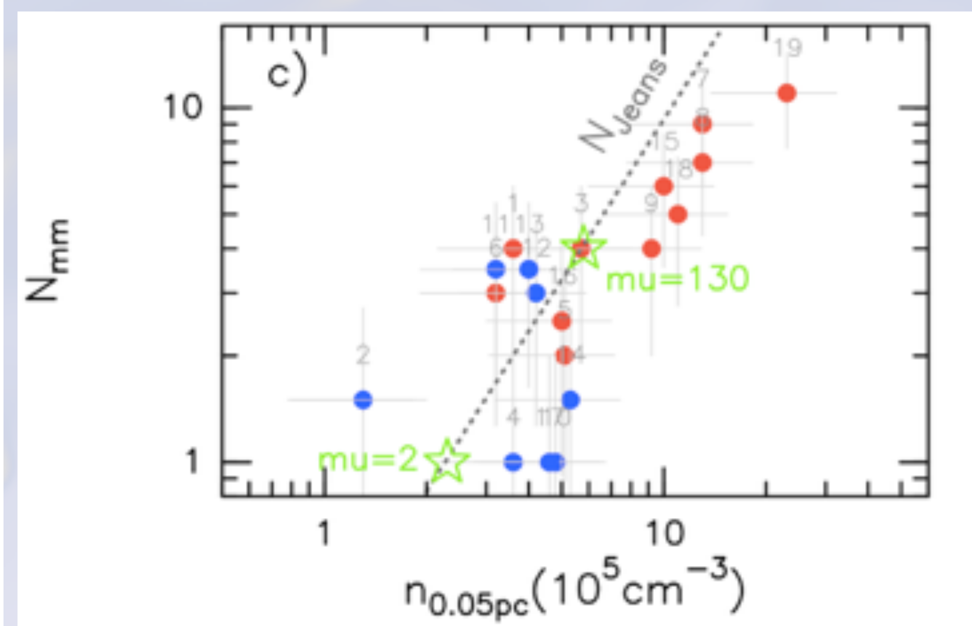
- ✓ **Intermediate magnetization:** 2 fragments arranged in a filamentary like structure. Secondary fragment not produced by disk fragmentation (*Krumholz et al.*).
  - ➡ **OB association** formation

- ✓ **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⊙ 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.



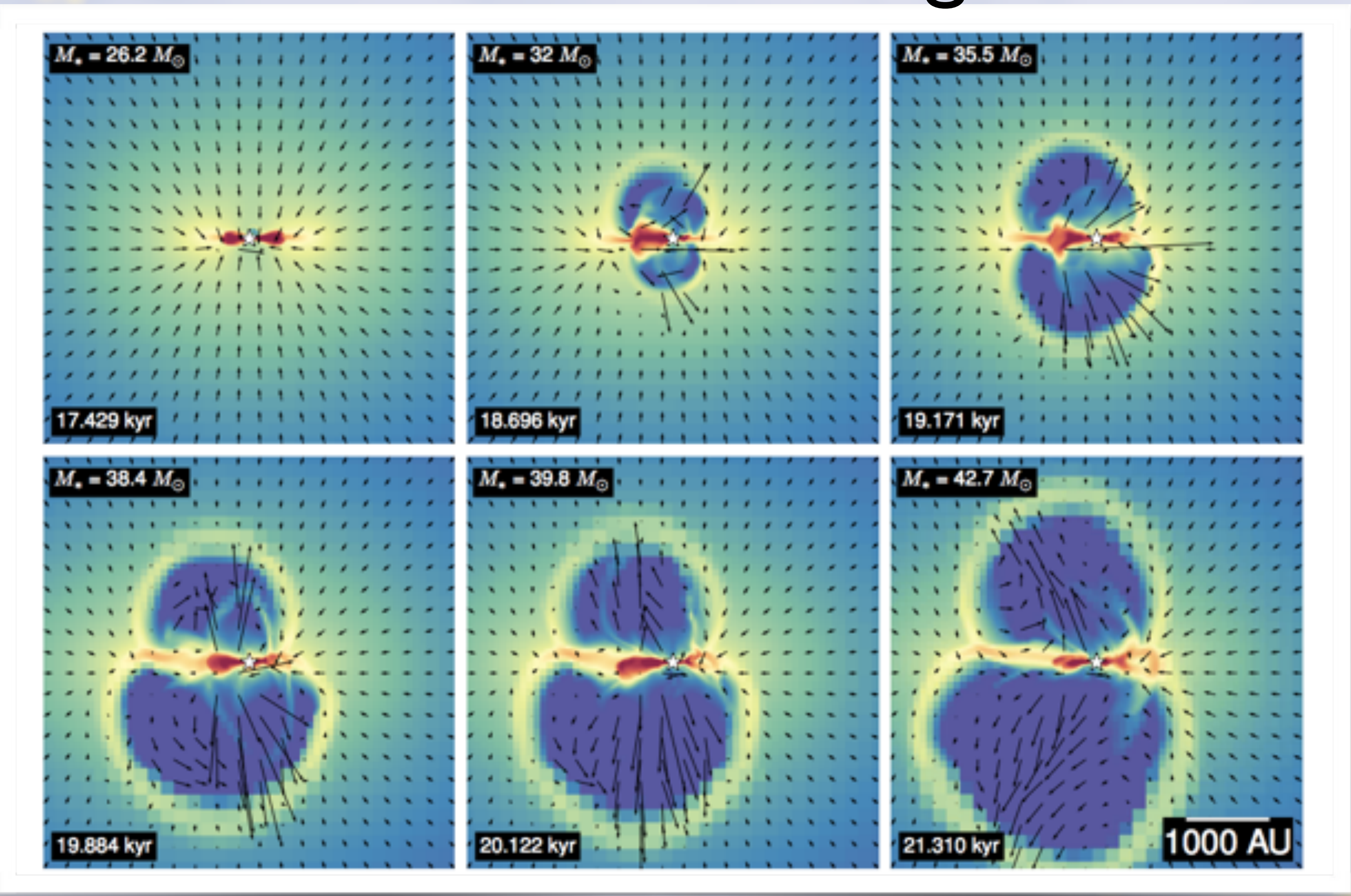
Palau et al., 2013 & 2014, ApJ

Take Away I

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

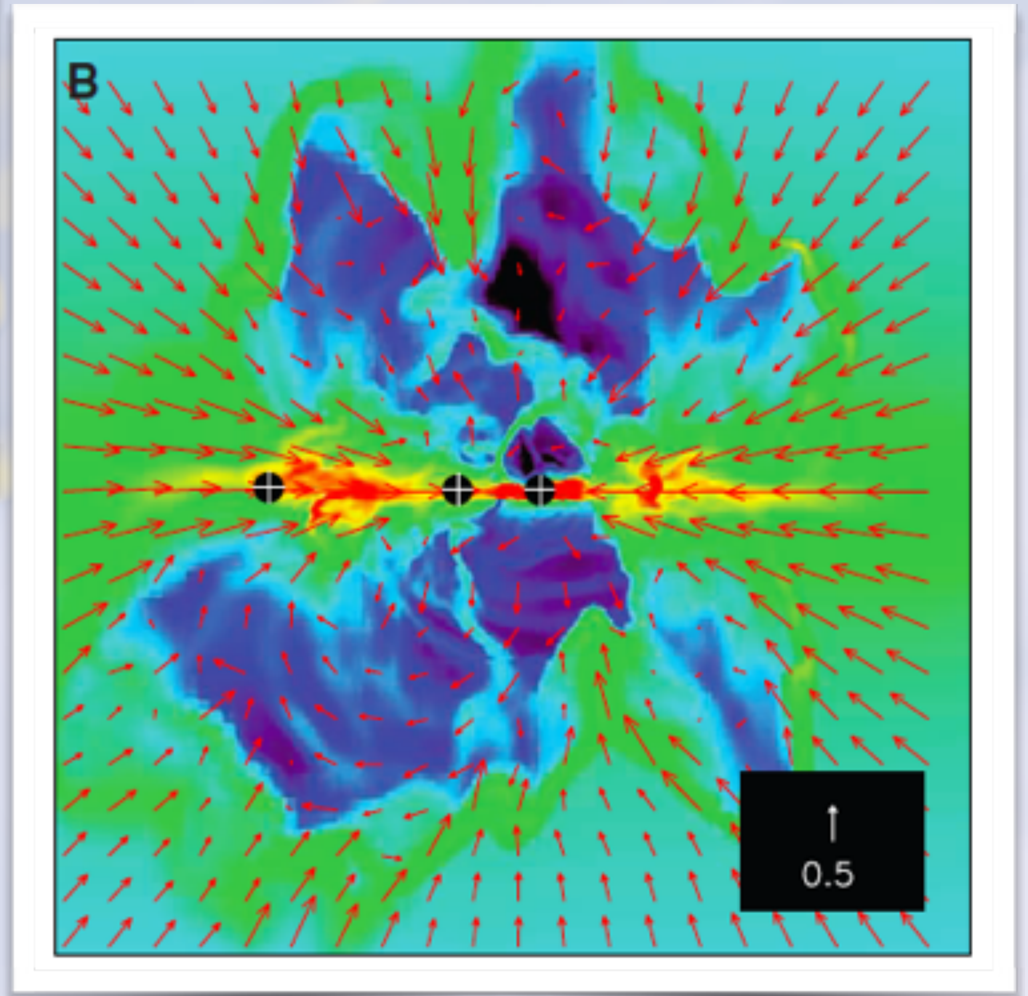
Formation of a massive star

Disc accretion - Flashlight effect



Klassen et al. (2016)

Radiative RT instability



Krumholz et al. (2009)

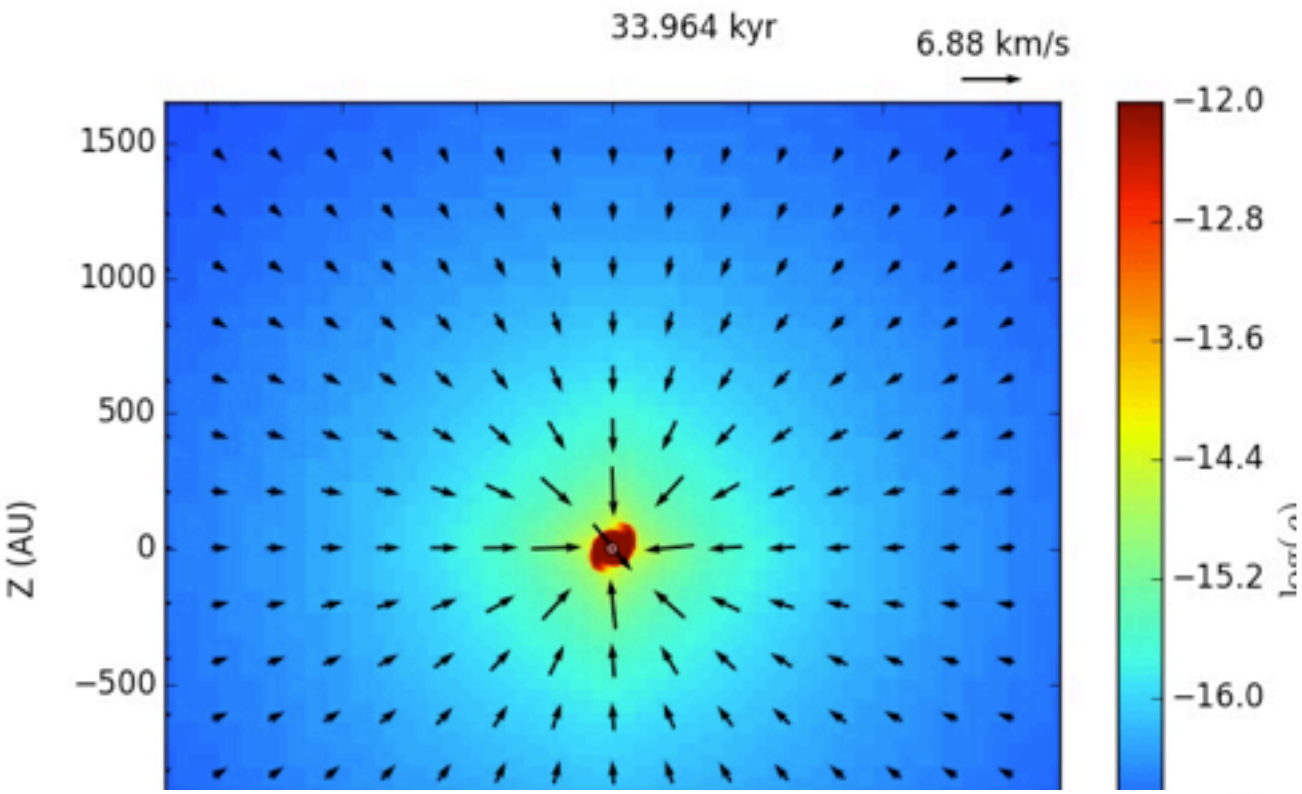
Initial conditions and stellar evolution

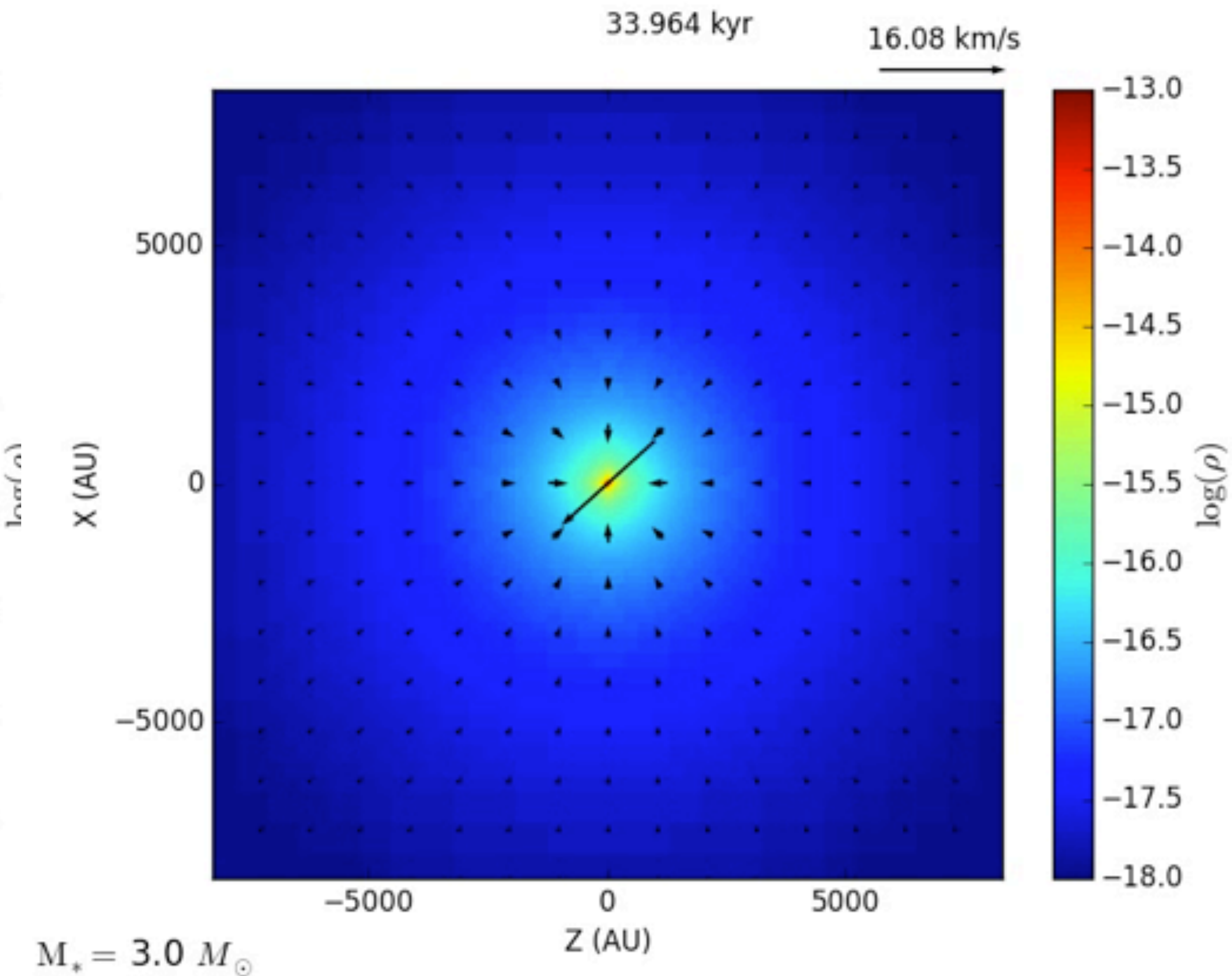
- ✓ 100 $M_\odot$; $\rho \propto R^{-2}$ ($\rho_c = 2\text{x}10^6$ cm^{-3}); T = 20 K ; R_0 = 0.2 pc
- ✓ Solid body rotation $\Omega = 3\text{x}10^{-15}$ Hz ($r_d \sim 650$ AU)
- ✓ Uniform magnetic field ($\mu_{uni} = 2, 5, \infty$) (B=170, 68, 0 μG), aligned with rotation axis (x-axis)
- ✓ at least 10 cells/Jeans length

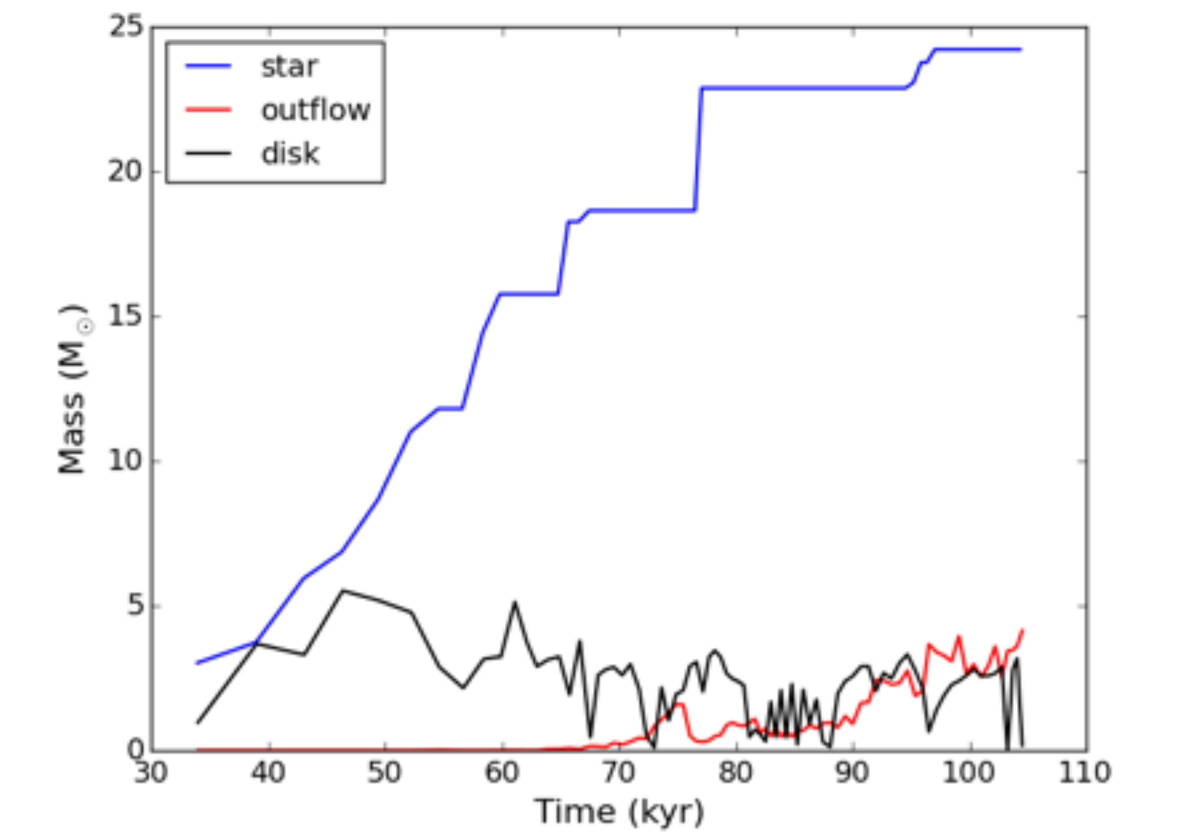
- ✓ Sink particles : $\rho_{thre} = 10^{10}$ cm^{-3} , $r_{sink} = \sim 20$ AU ($4\Delta x_{min}$)
- ✓ Protostellar feedback sources associated to the sink:
  - ★ internal luminosity given by Hosokawa et al. tracks (R. Kuiper), $L_{acc}=0$
  - ★ all the accreted mass goes in stellar content (most favorable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

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

Hydro collapse

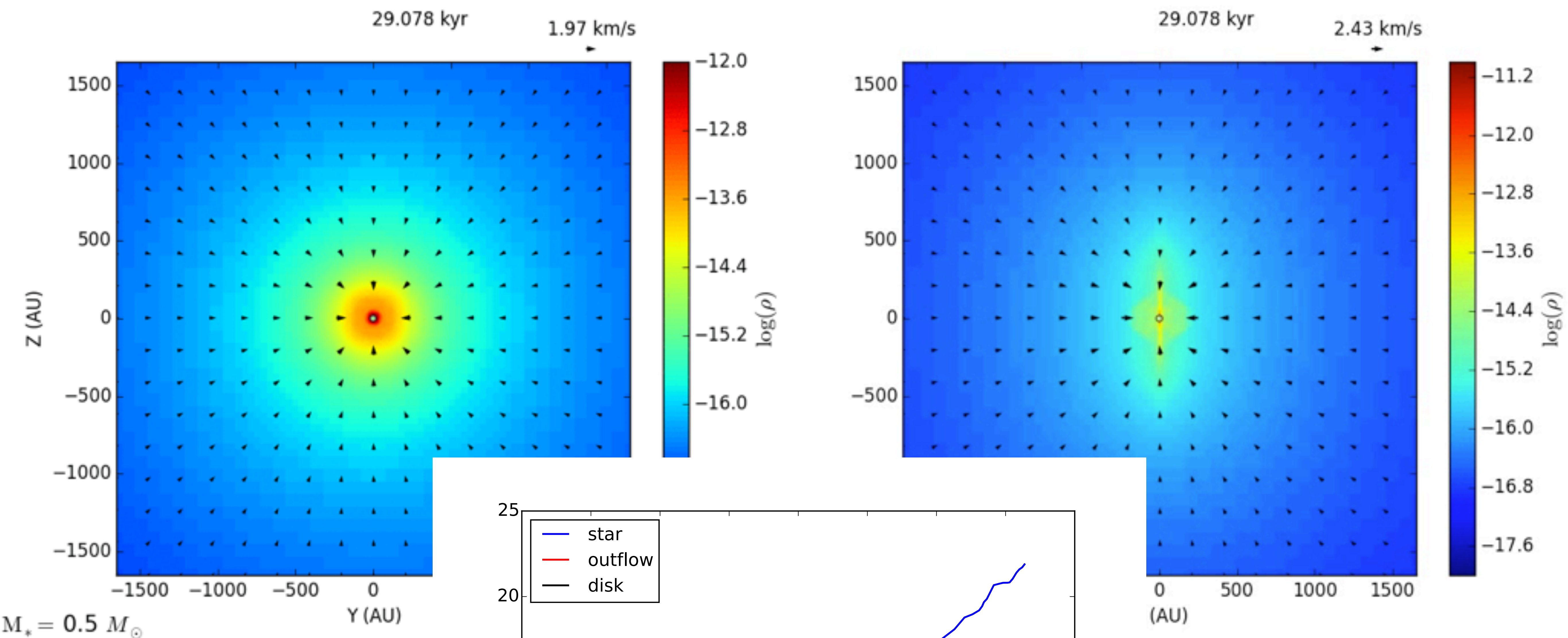


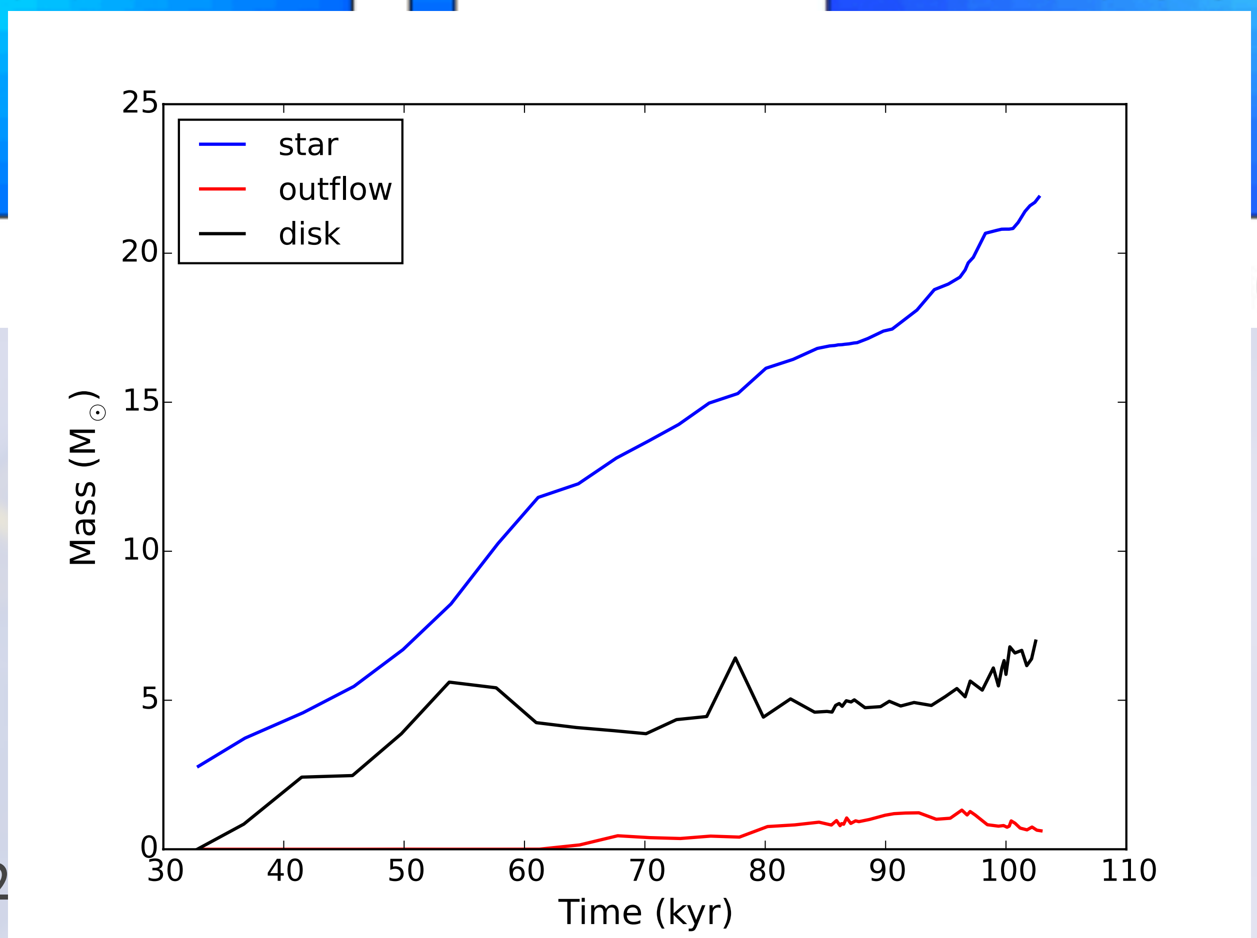




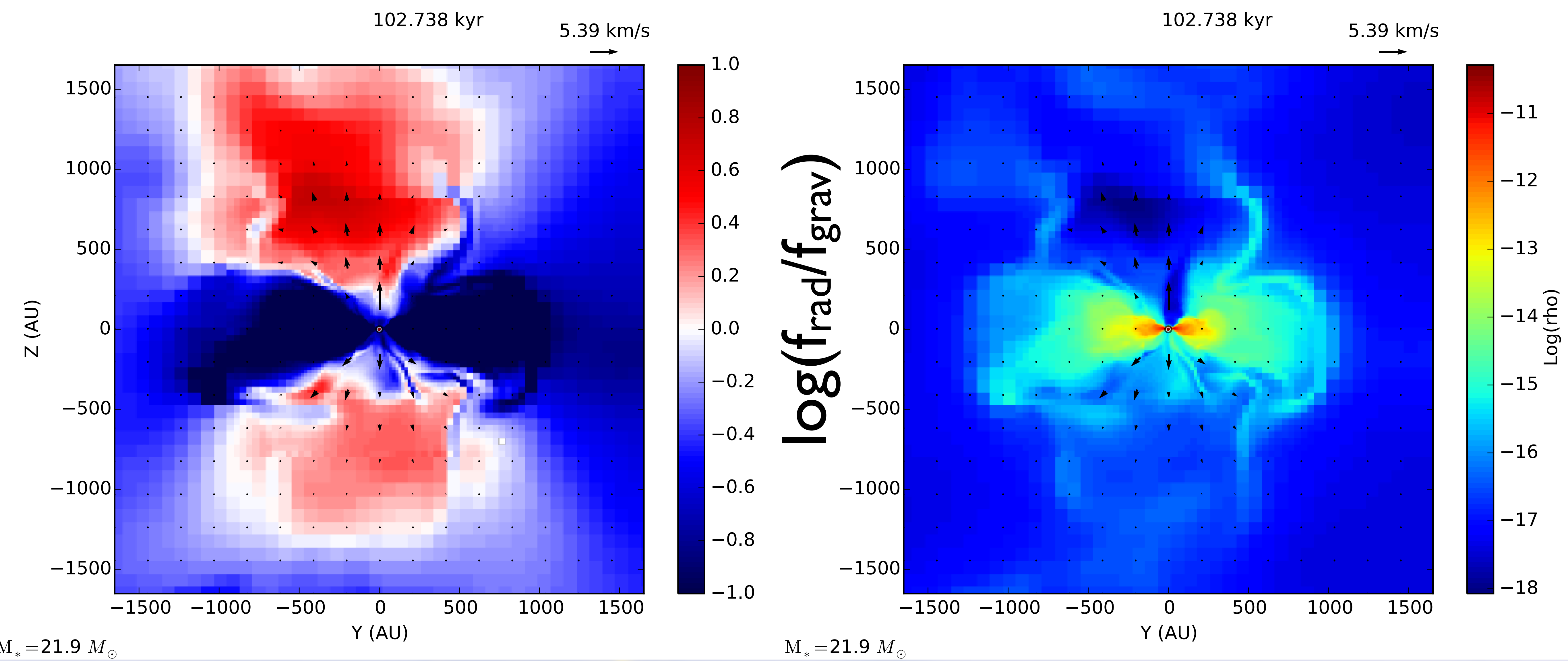
- ✓ Formation of a large disk: R~1000 AU
- ✓ Binary system: 24 and 13 $M_\odot$
- ✓ Radiative outflow/bubble (1500 AU)

iMHD collapse, $\mu = 2$



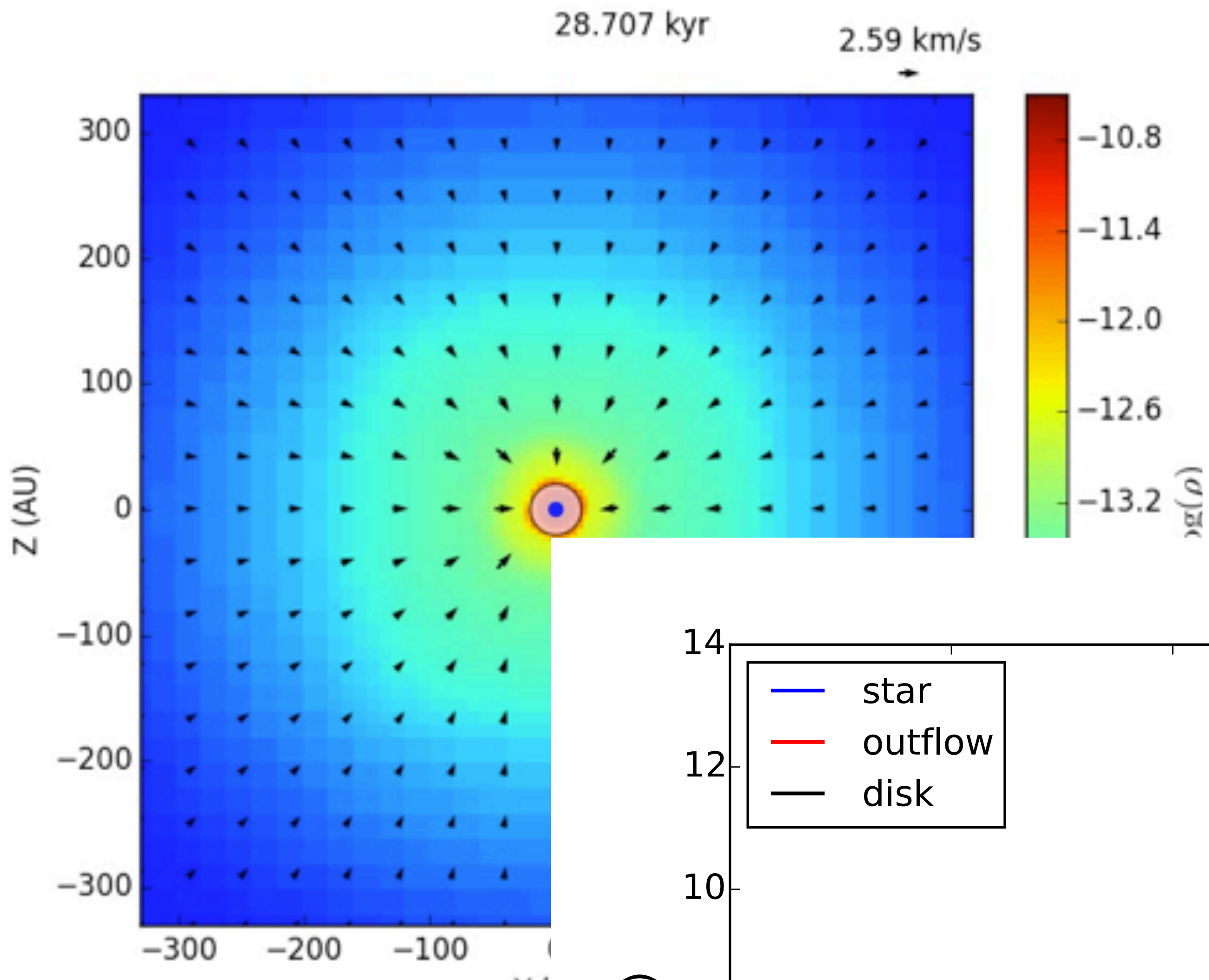


Hydro & iMHD: origin of the outflow

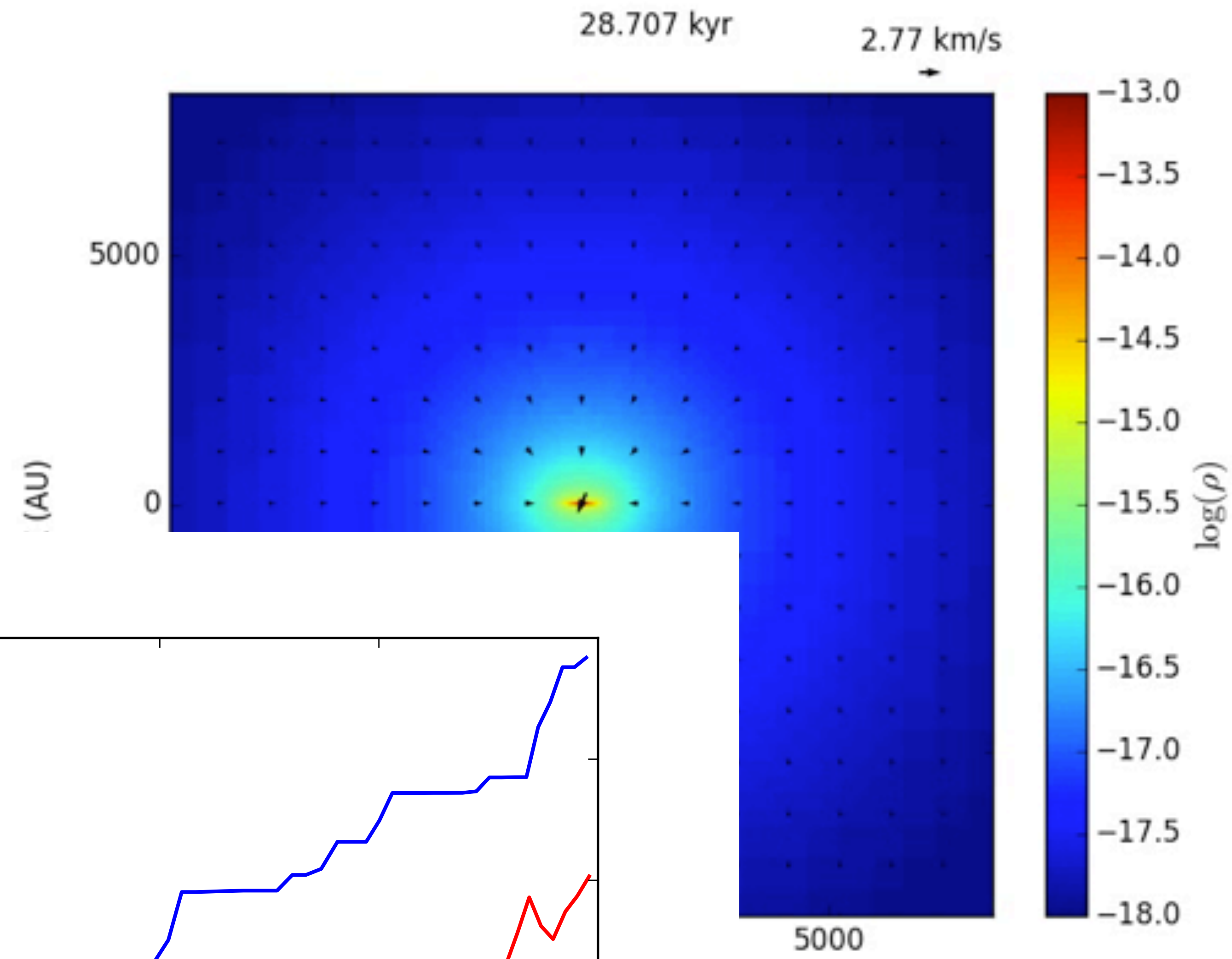


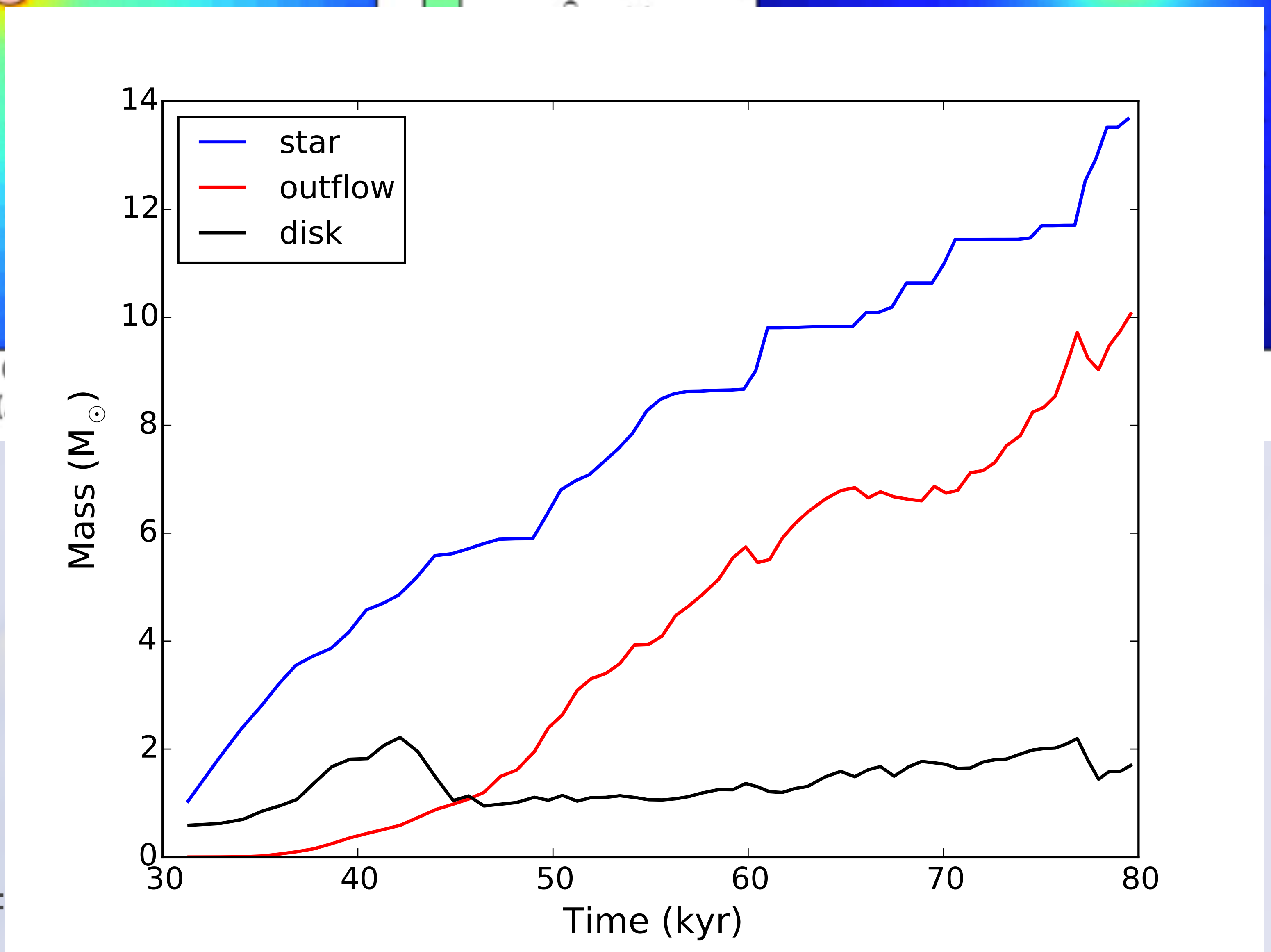
- Outflow has a radiative origin
- Magnetic fields disorganised by magnetic flux expulsion (interchange instability, e.g., *Masson et al. 2016*)

Ambipolar diffusion, $\mu = 2$

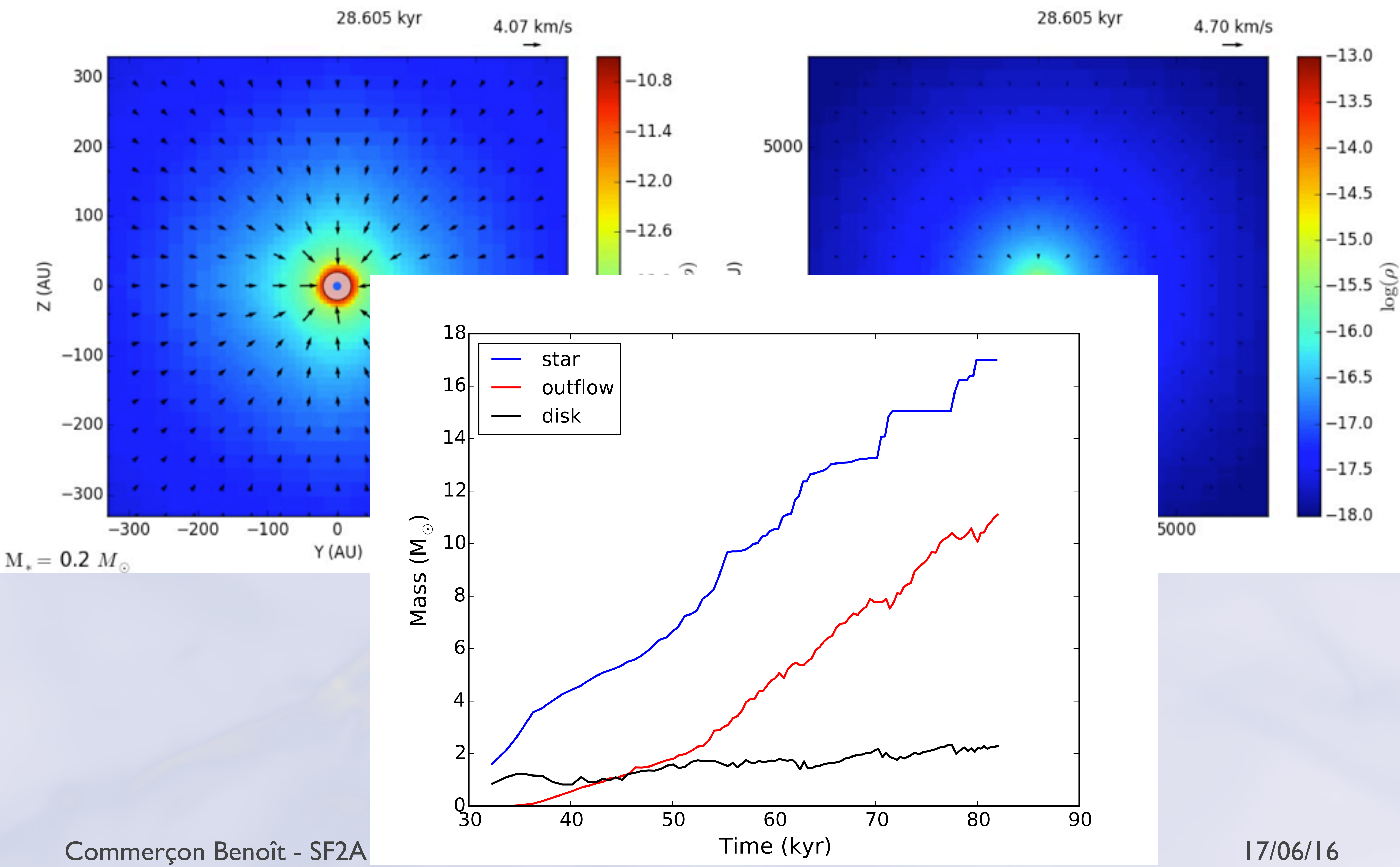


$M_* = 0.1\ M_\odot$

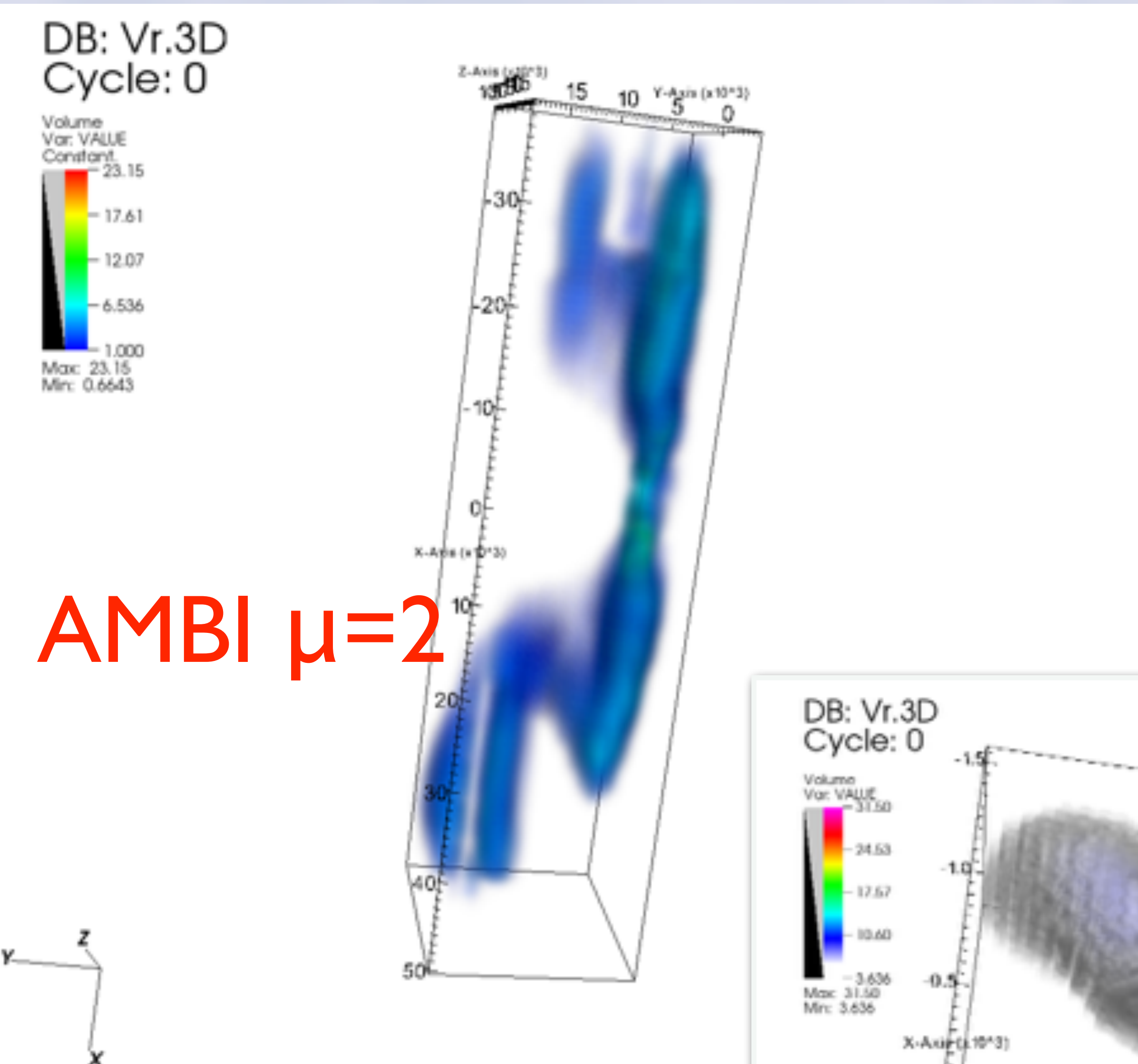


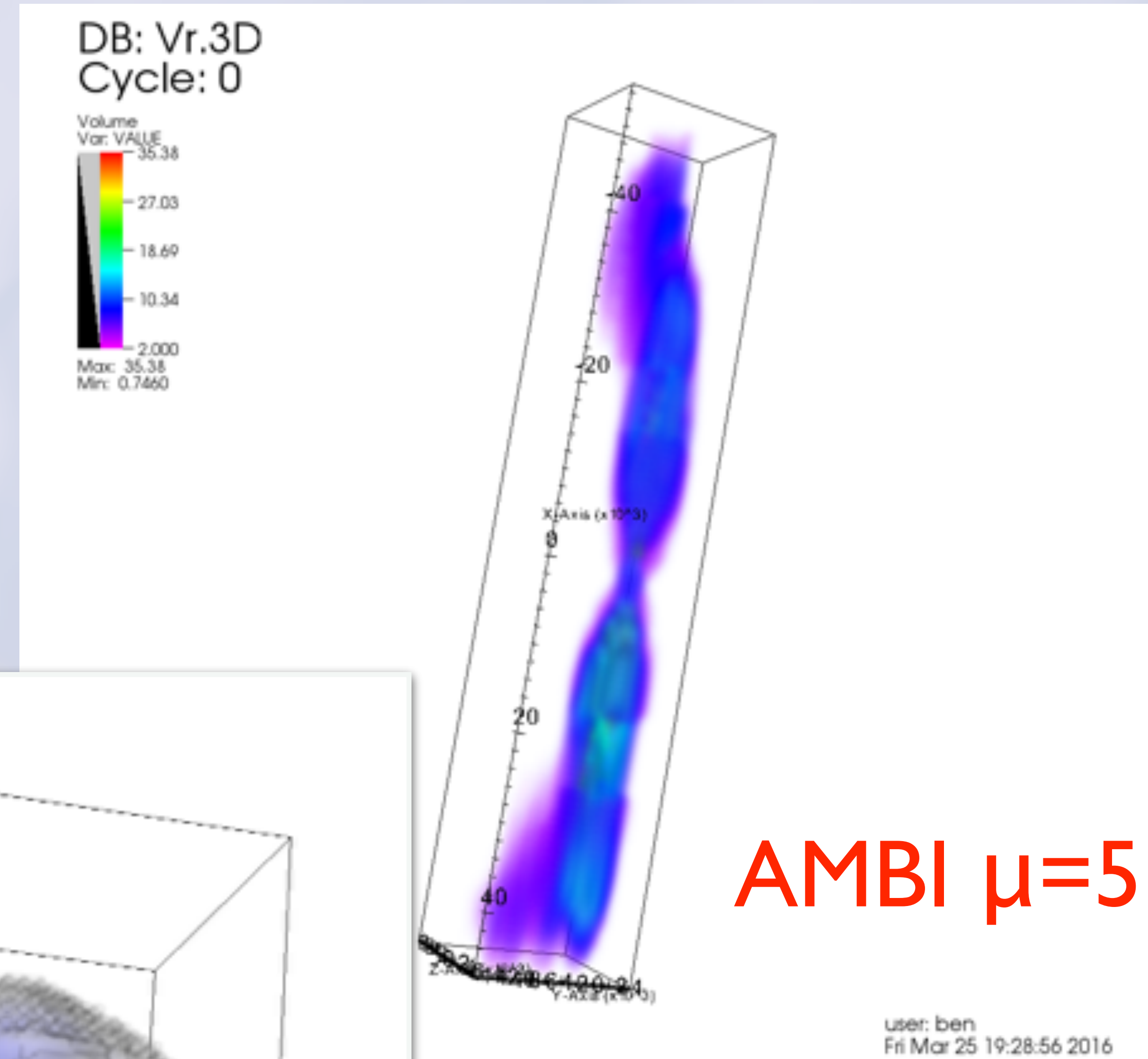


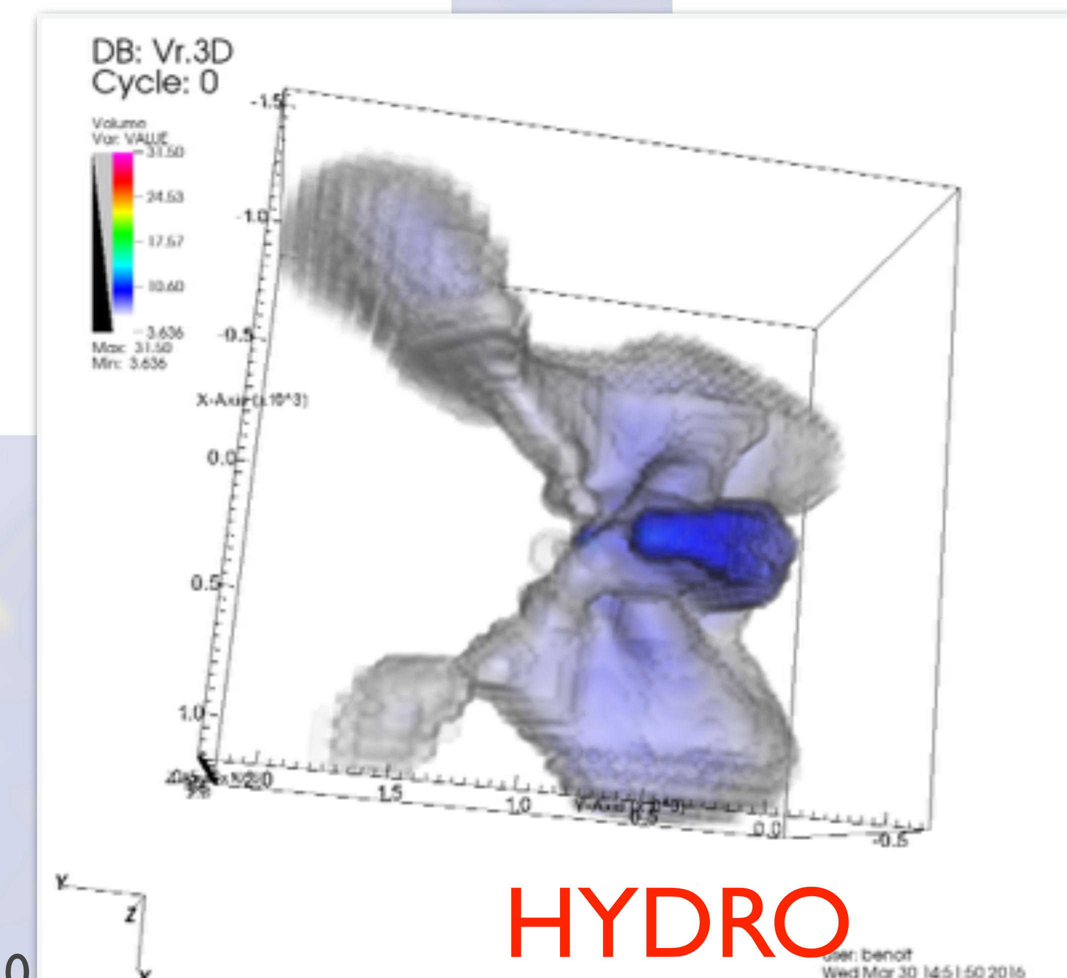
Ambipolar diffusion, μ =5



Outflow morphology

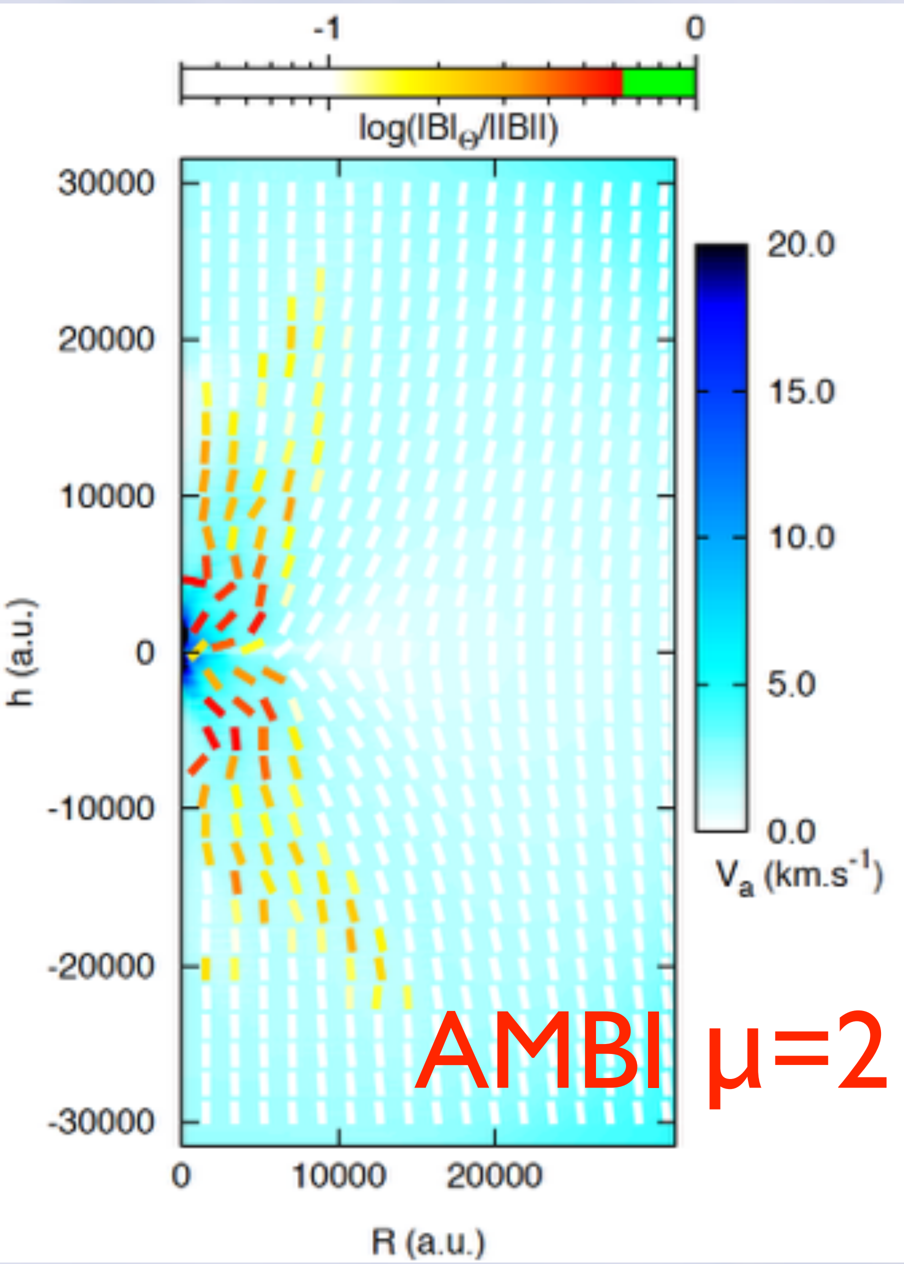


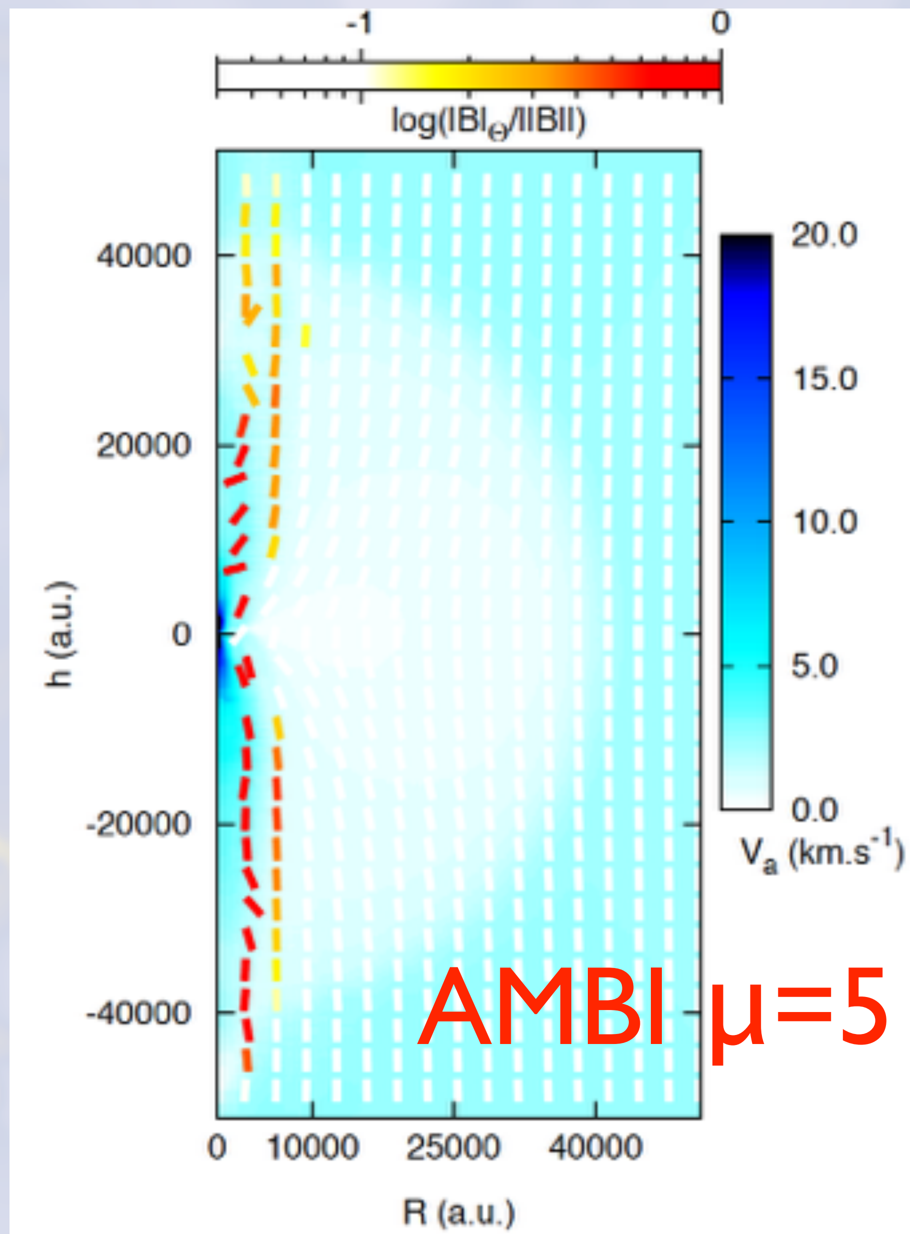


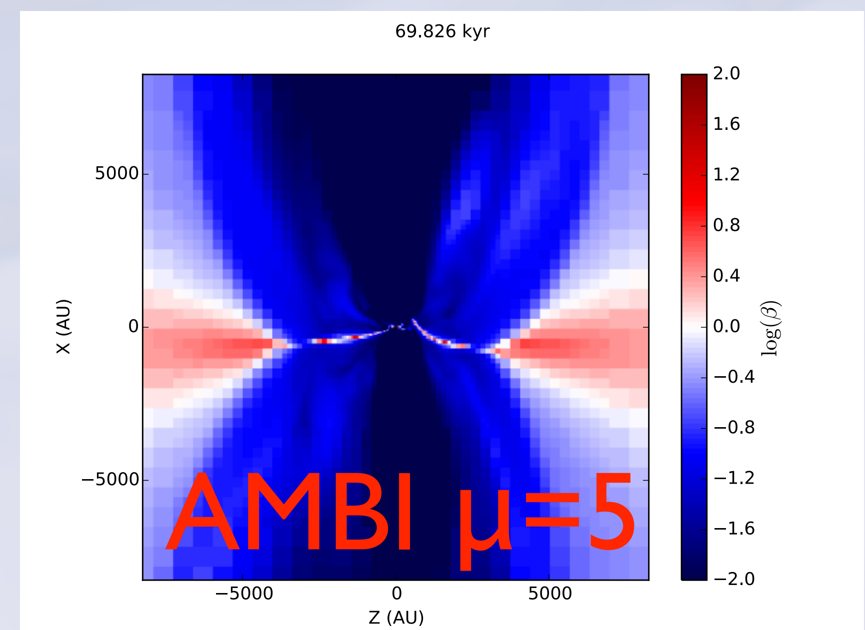


Outflow collimation

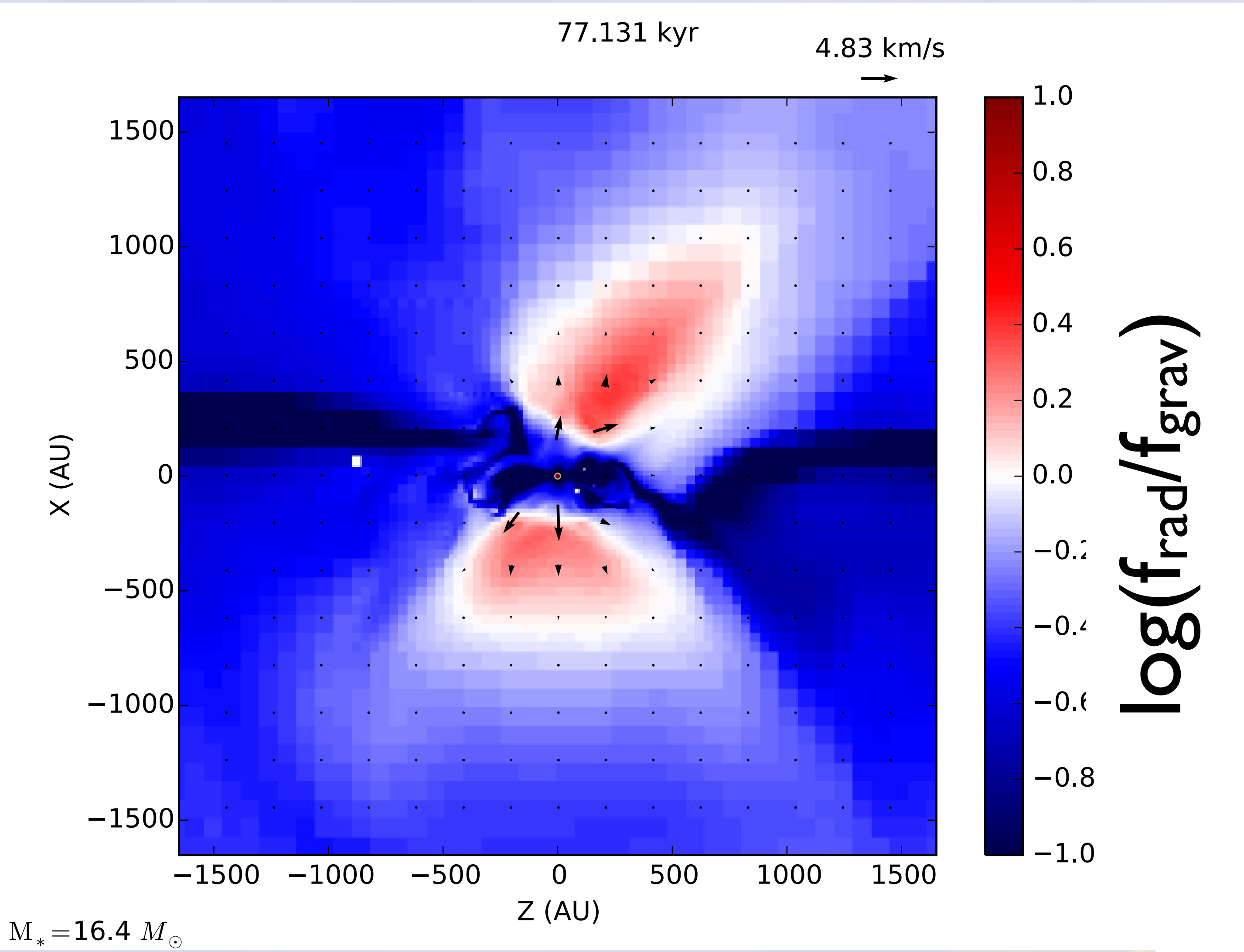
- ✓ outflow collimated by toroidal B-field
- ✓ outflow extends up to 50 000 AU when $M_\star$=12$M_\odot$,$V_{out,max}$=40 km/s
- ✓ outflow is strongly magnetized



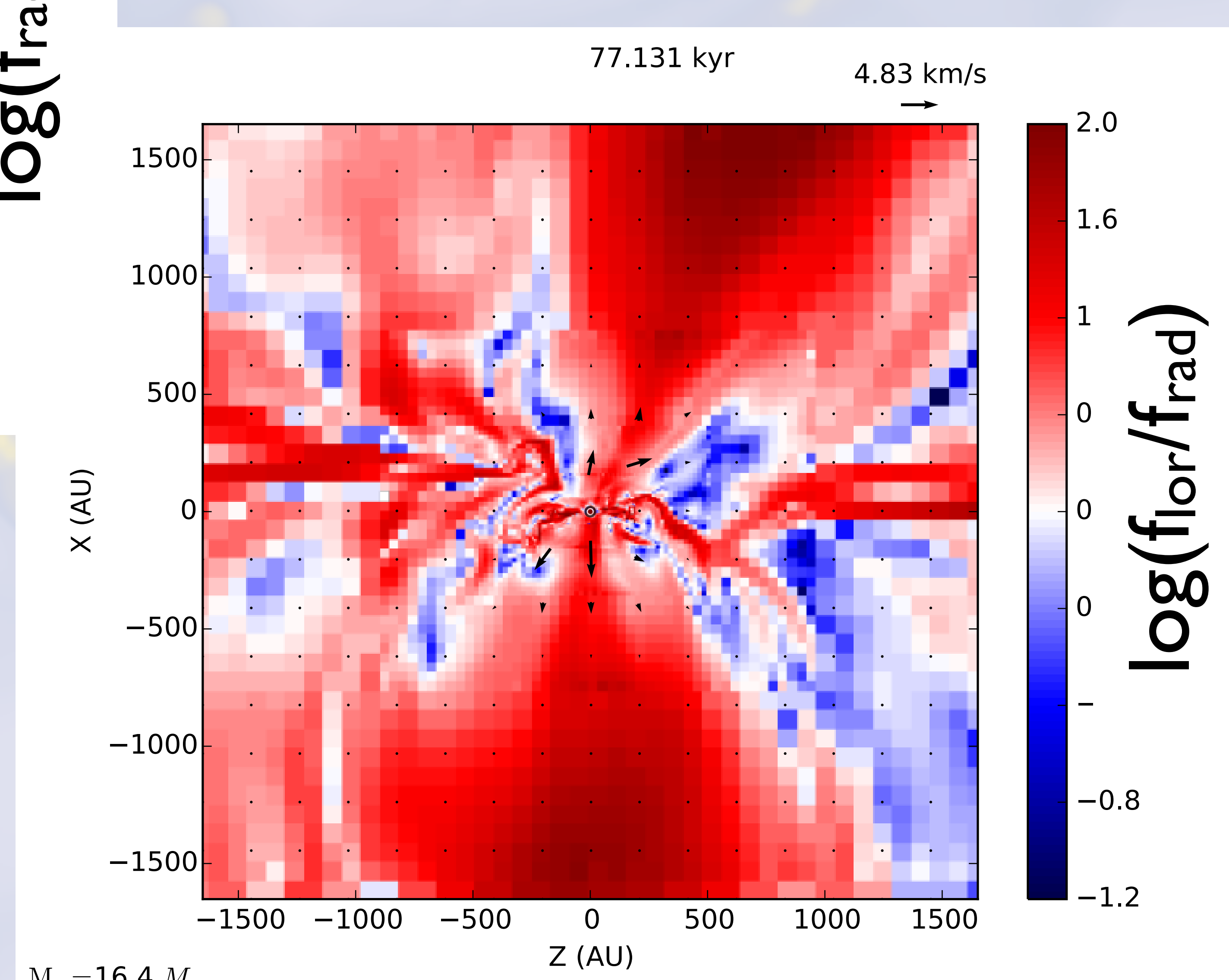




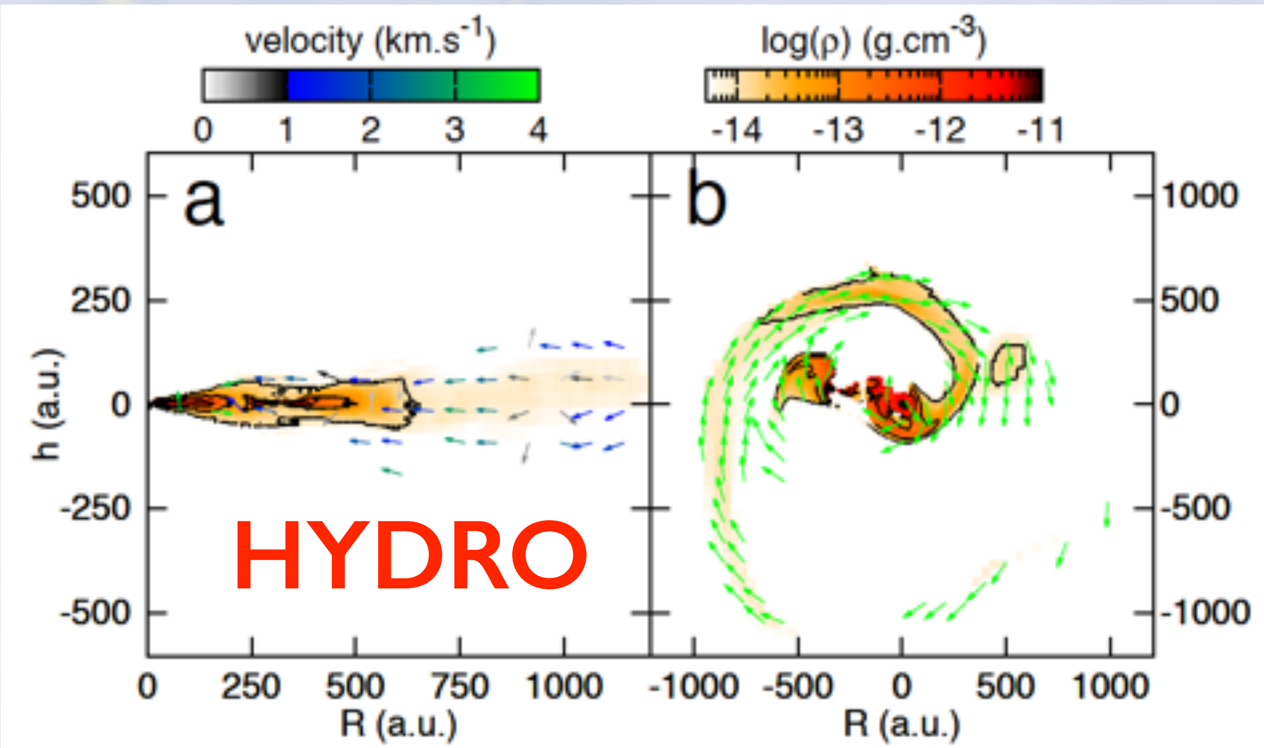
Is radiative feedback important?

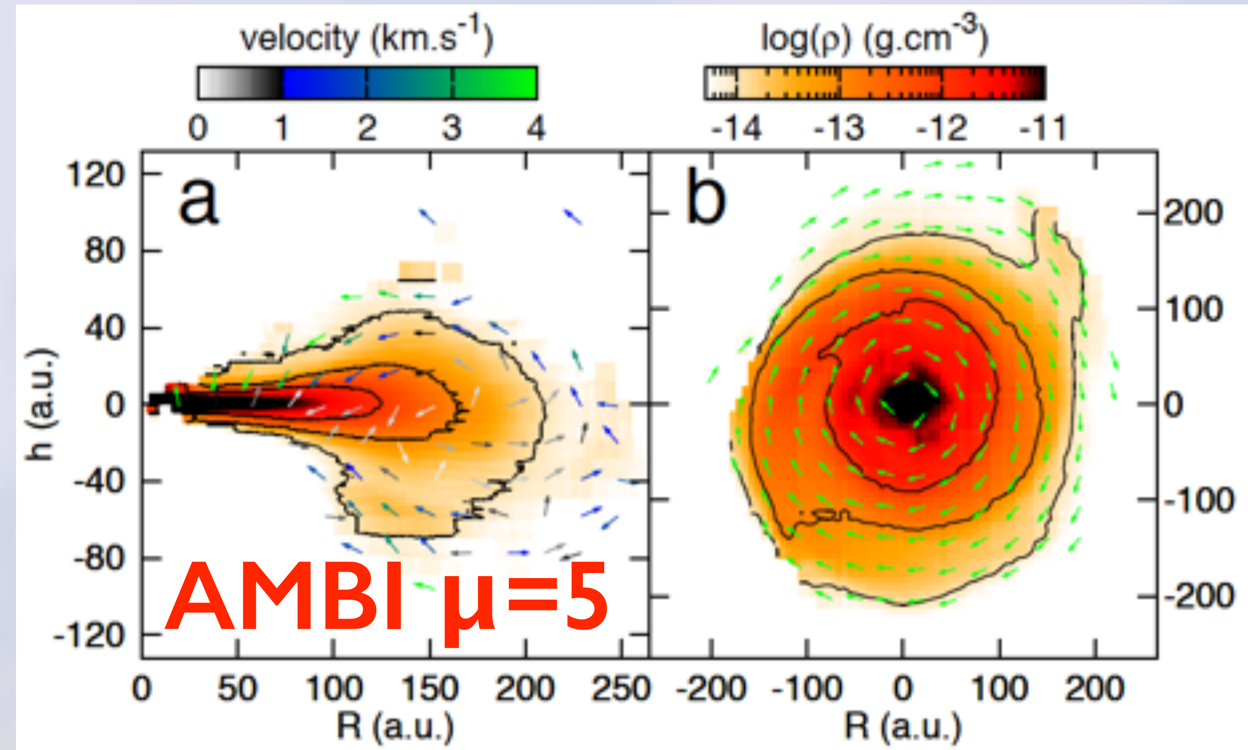


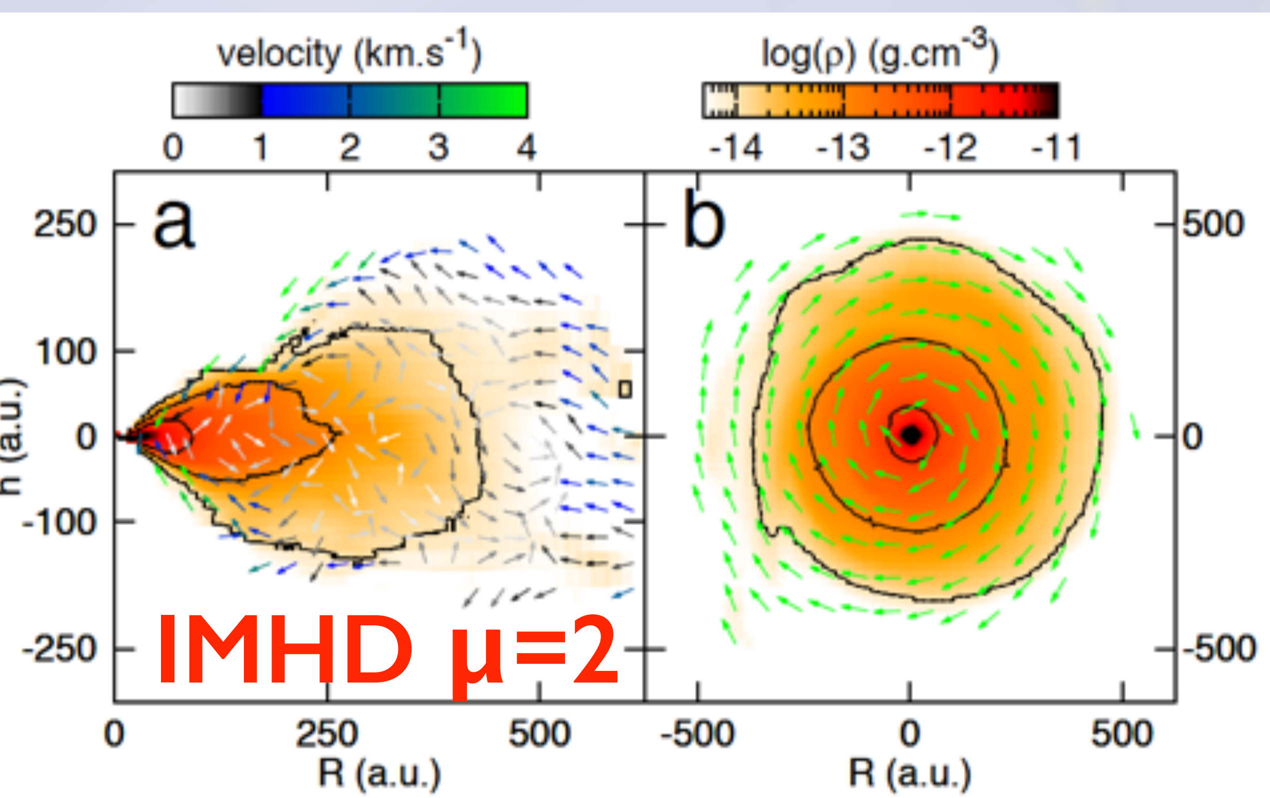
✓ radiative force contributes to the outflow, but does not dominate over the Lorentz force

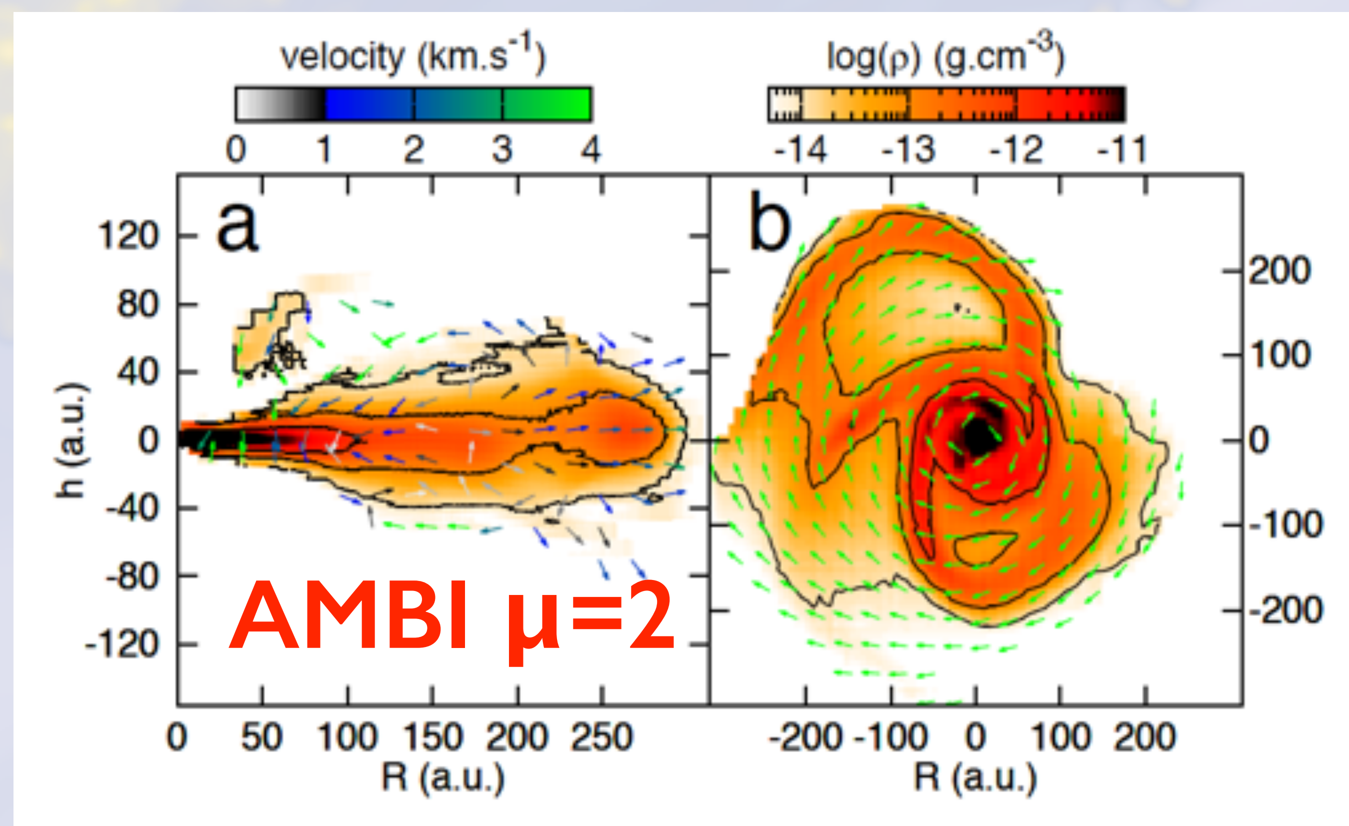


Discs properties

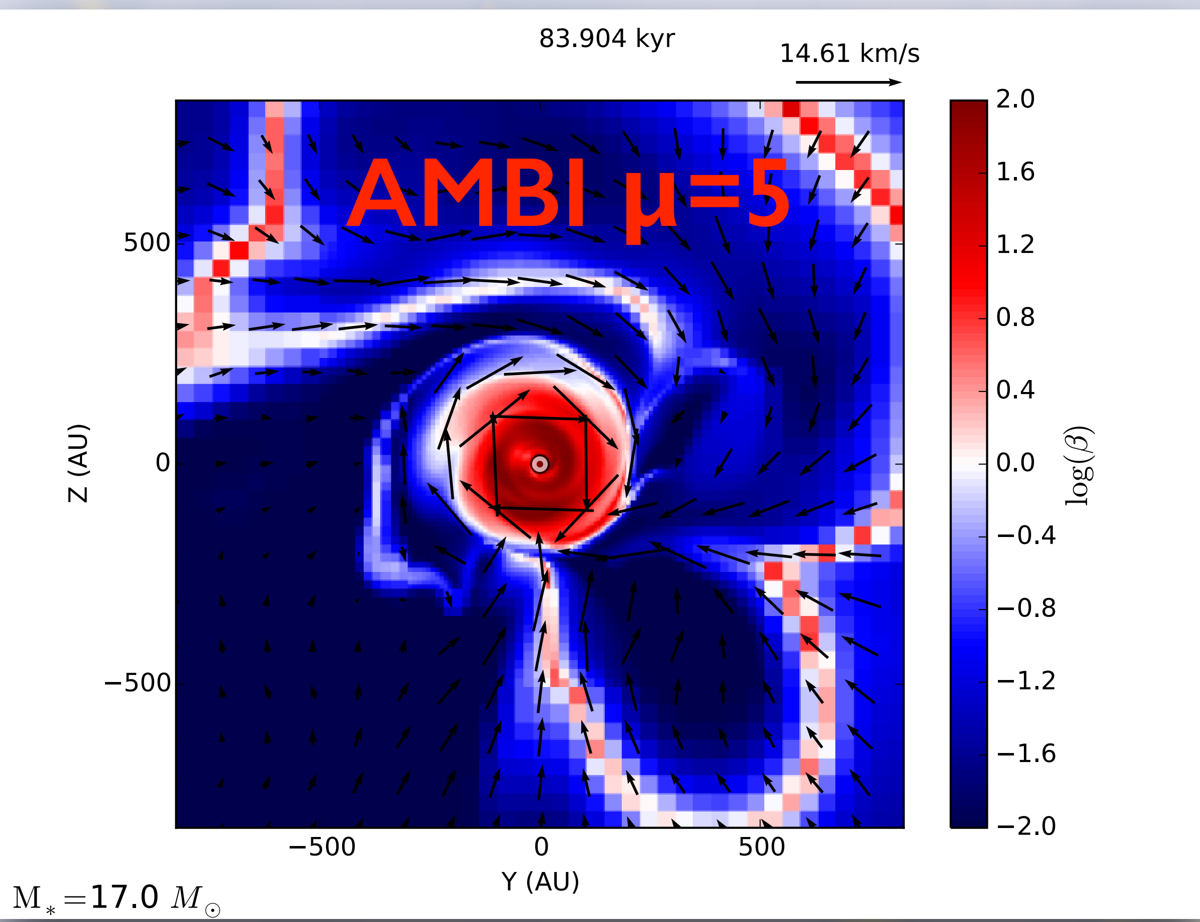


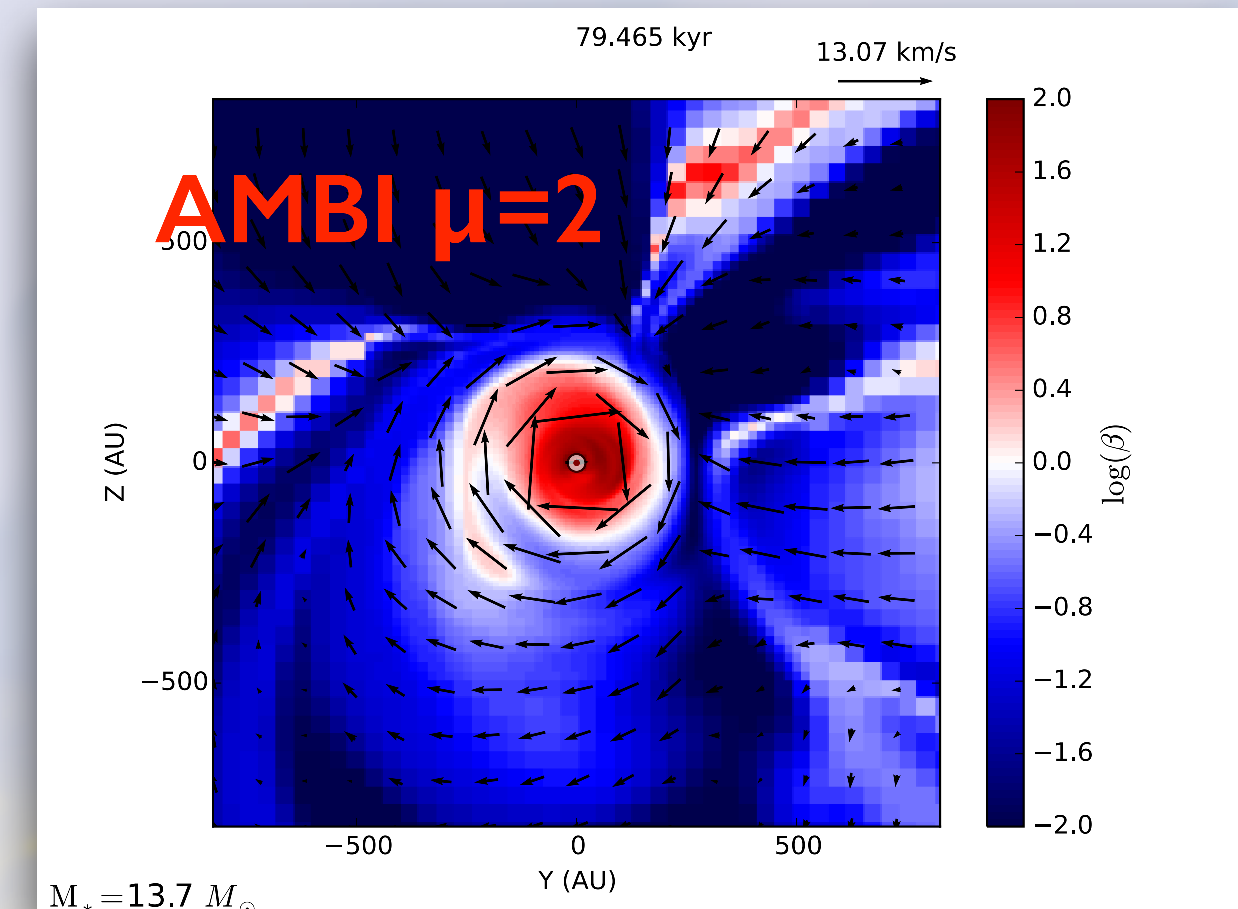


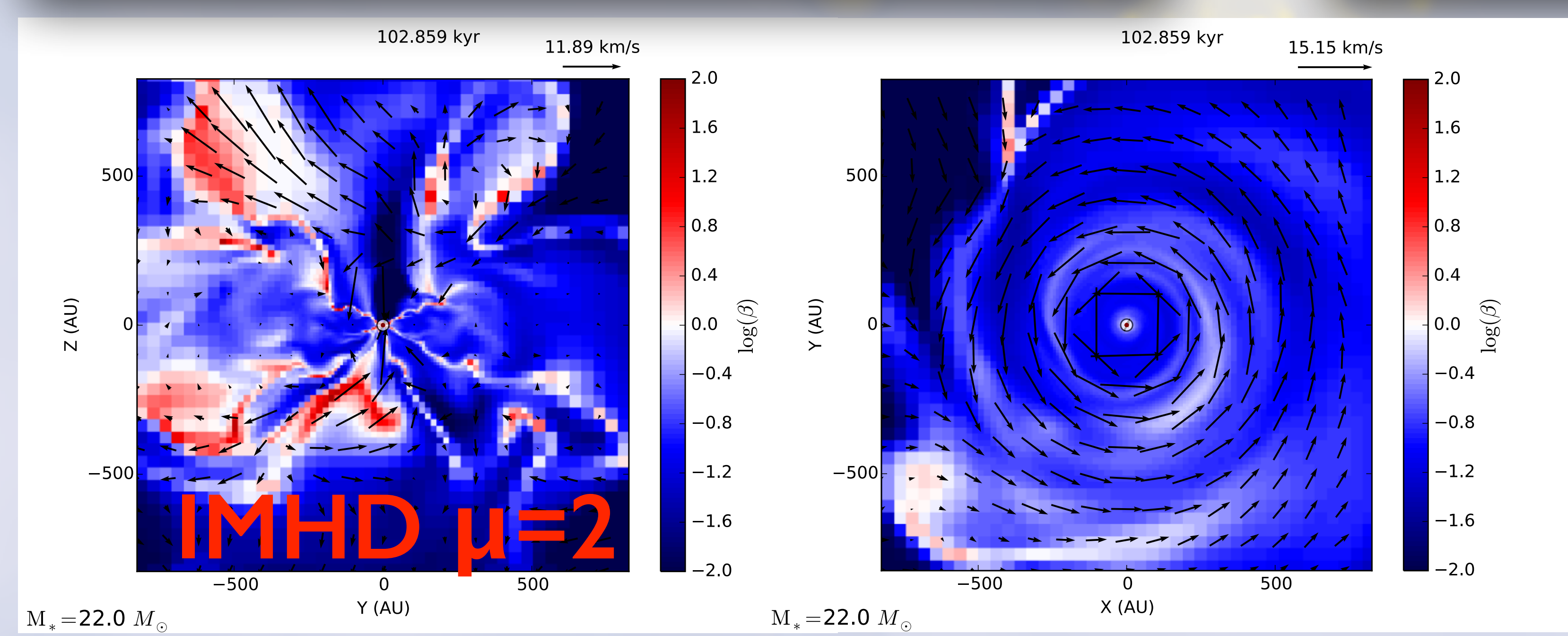




Discs properties

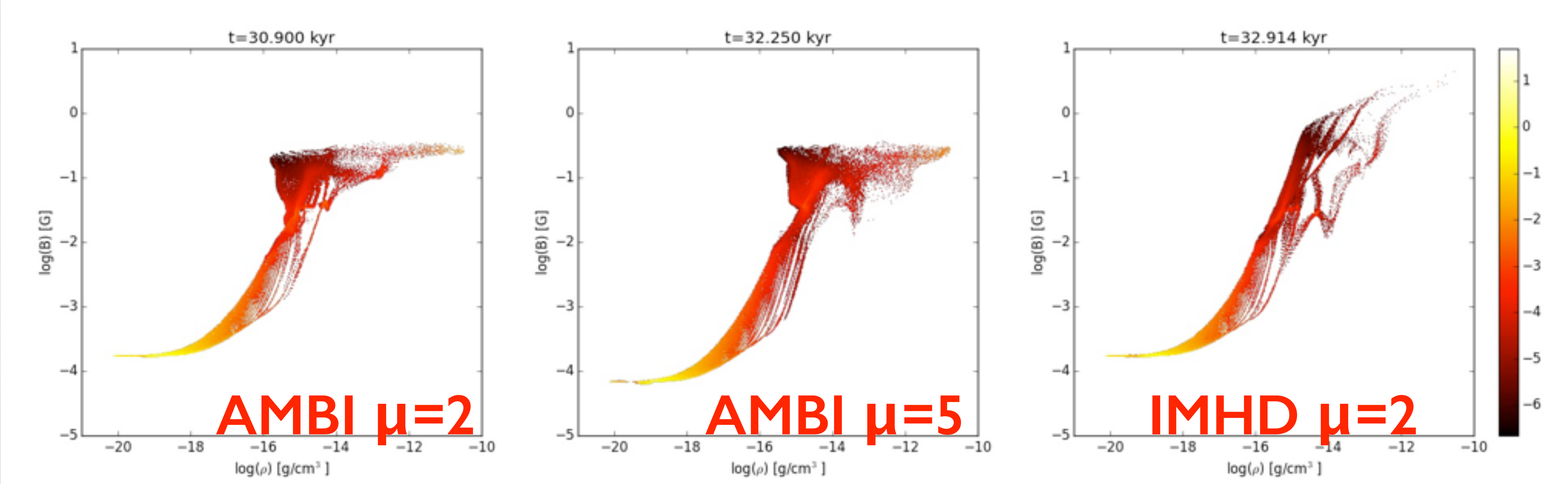






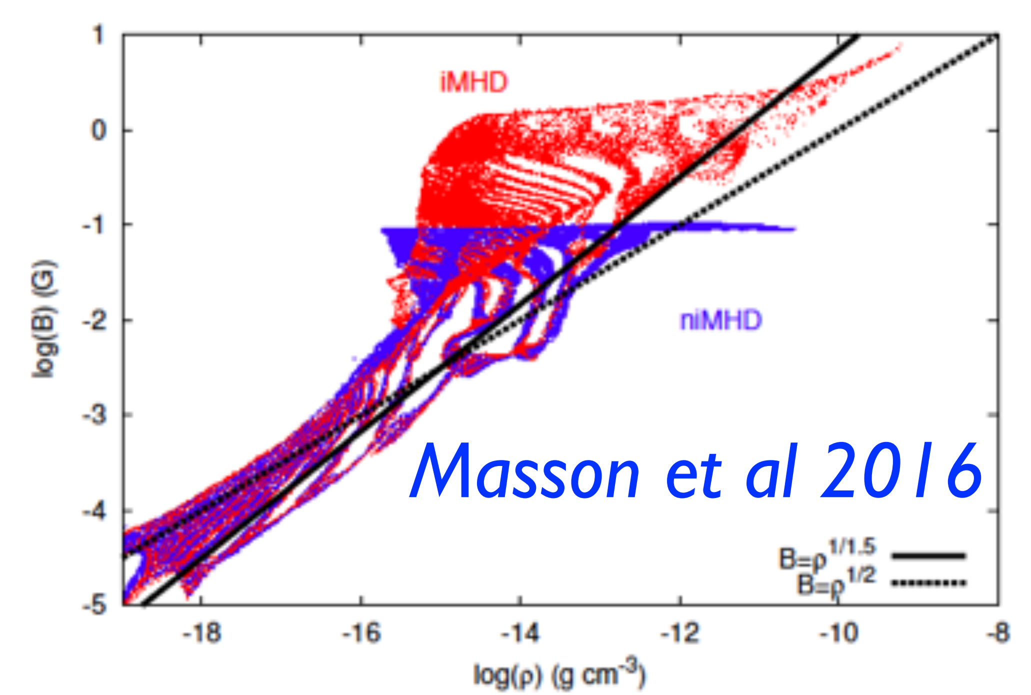
- ✓ discs are dominated by thermal pressure with AD (i.e. hydro discs)
- ✓ thick and magnetised disk with iMHD

Magnetisation



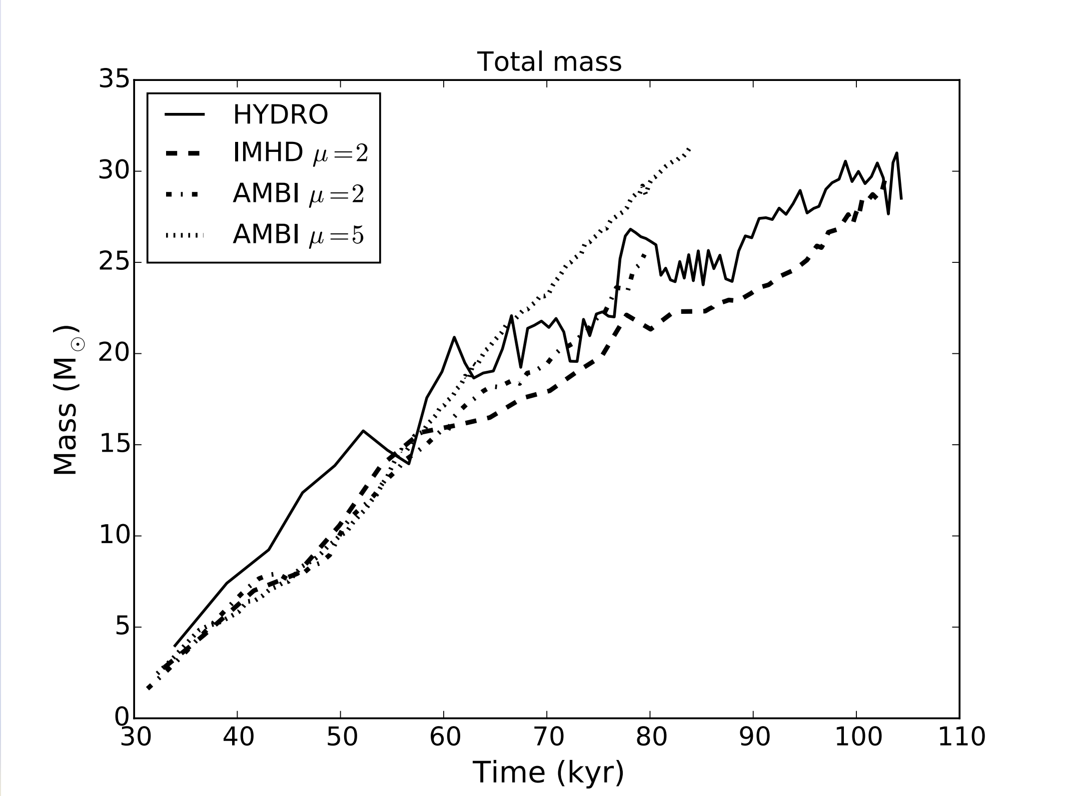
- ✓ Bmax reduced by > 1 order of magnitude by AD
- ✓ plateau @ B<1G
- ✓ similar to results found in

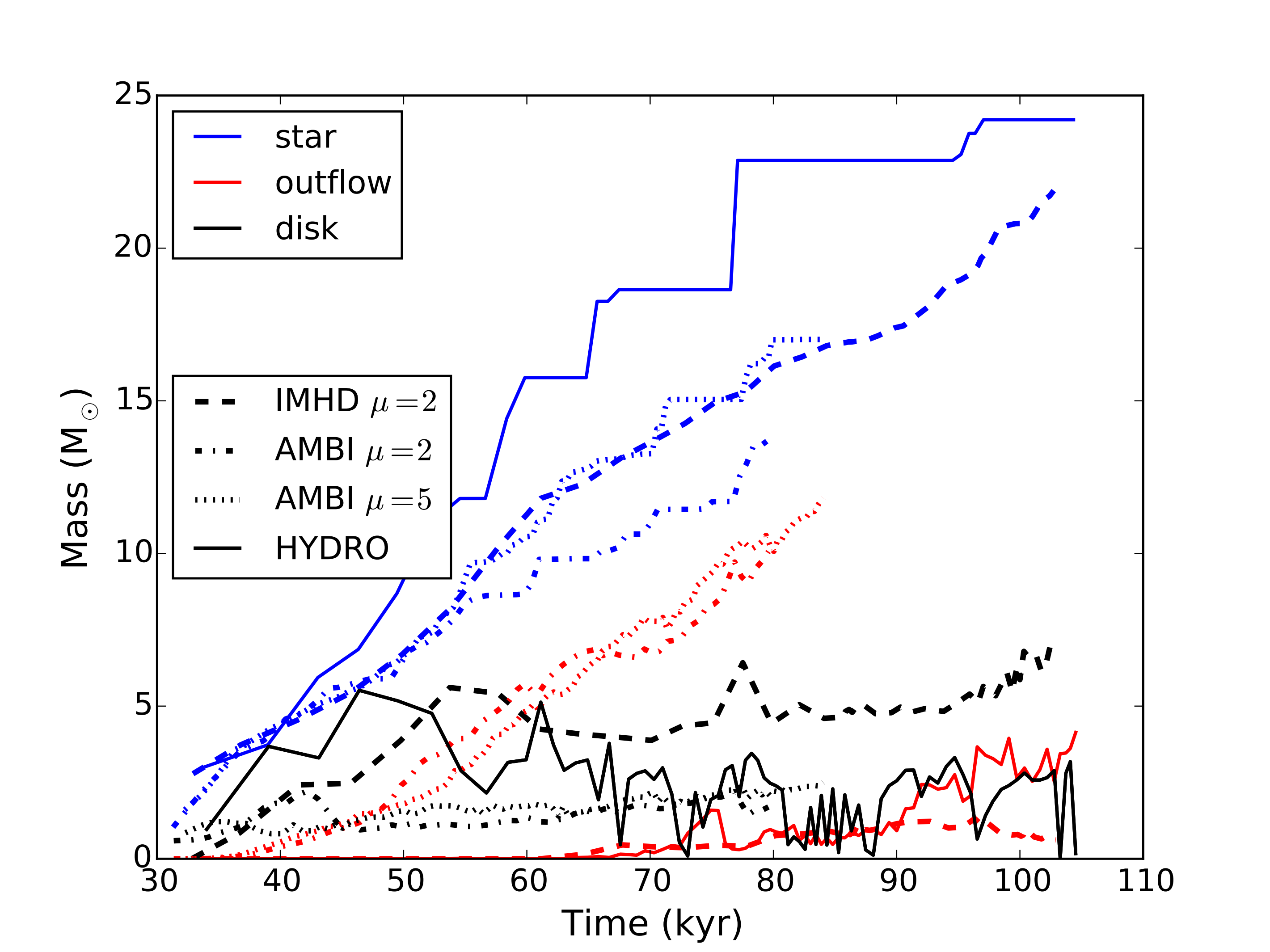
low mass star formation



Mass budget

	dM	dM	dM
HYDRO	3x10	5.9x10	fragmentation
IMHD	2.7x10	9x10	1x10
AMBI	2.6x10	2.1x10	2.3x10
AMBI	3.1x10	2x10	3.4x10



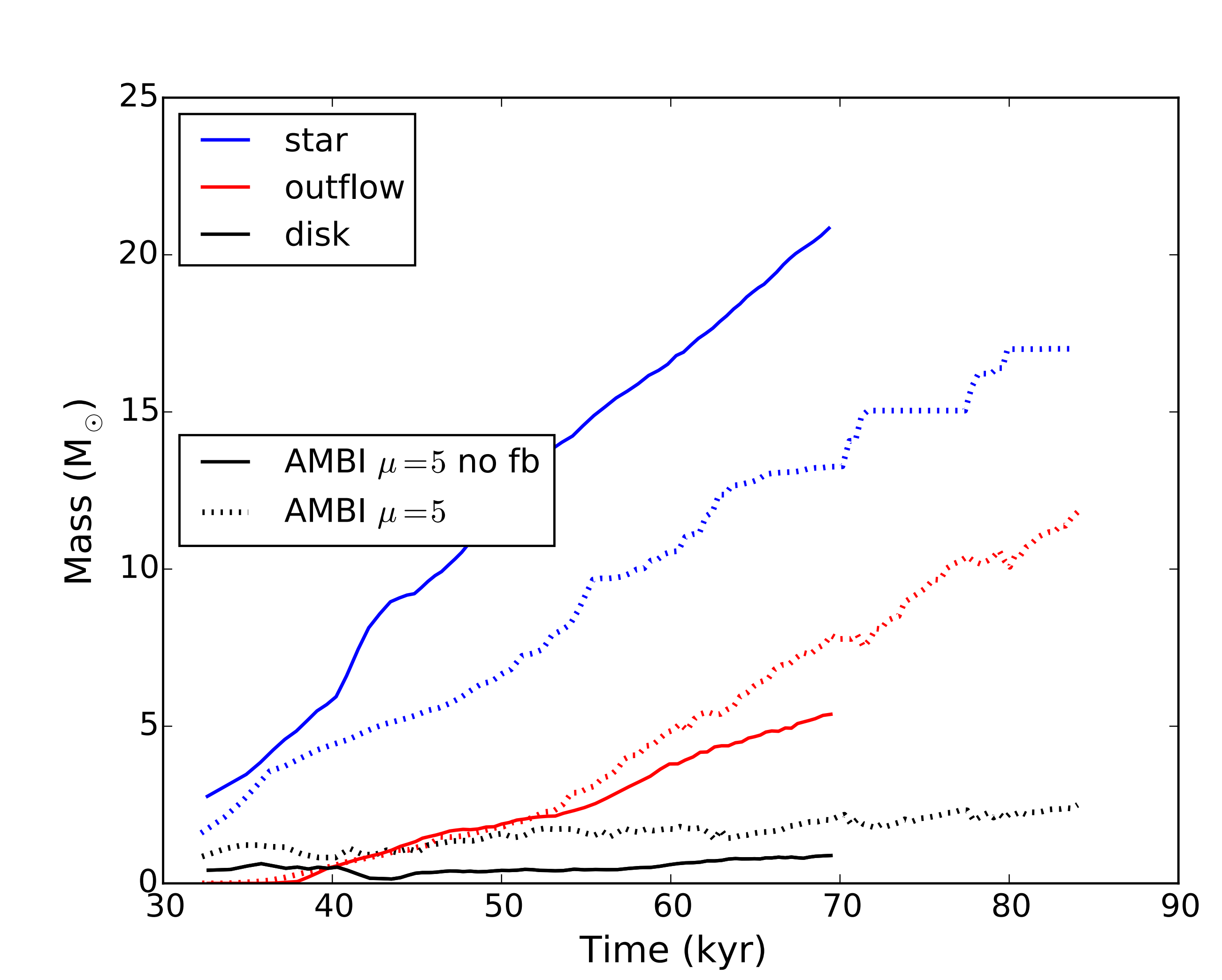


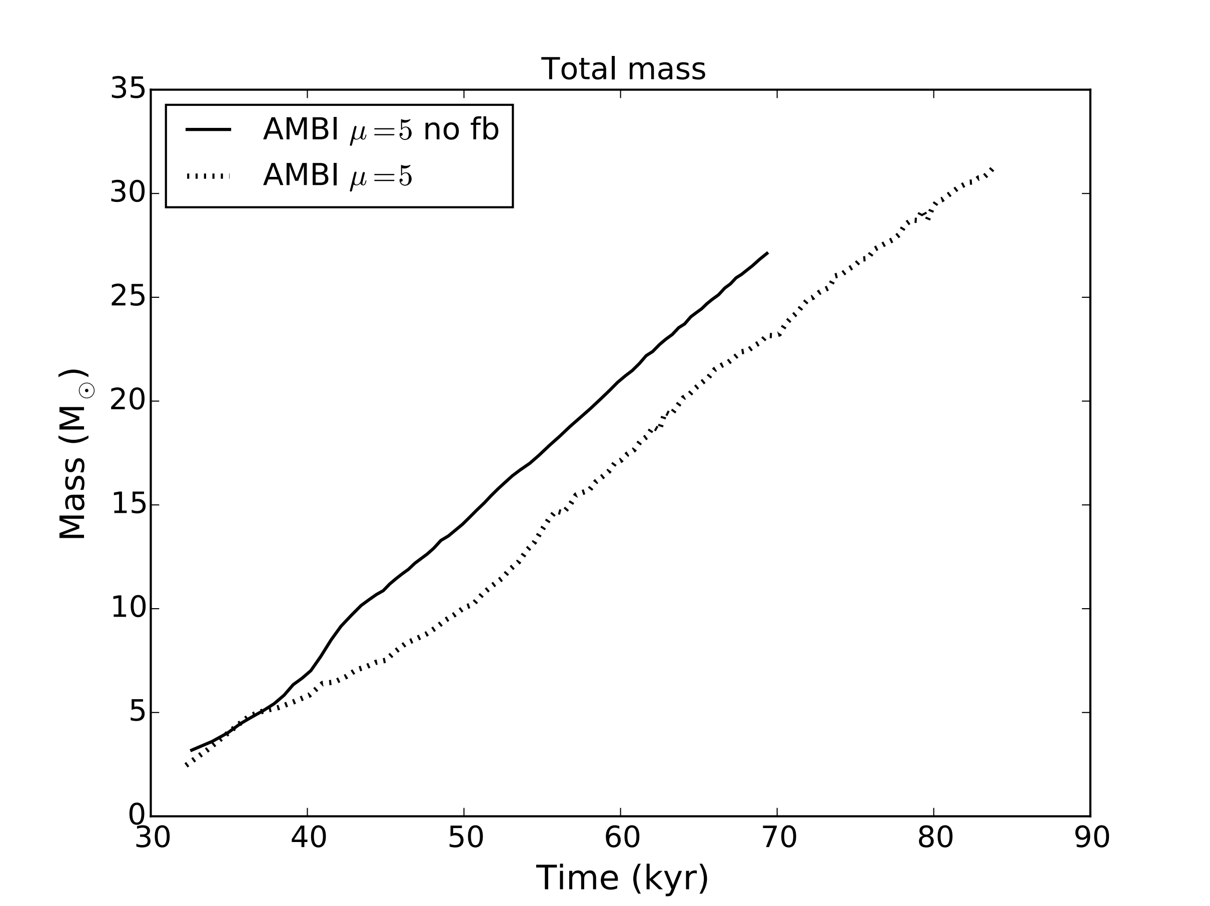
- Total mass similar in all models
- $\dot{M}_{acc} \sim \dot{M}_{out}$ w. ambipolar diffusion
- steady state w. AD

➡efficient angular momentum removal

Is radiative feedback important?

- Model AMBI μ=5 w/o feedback

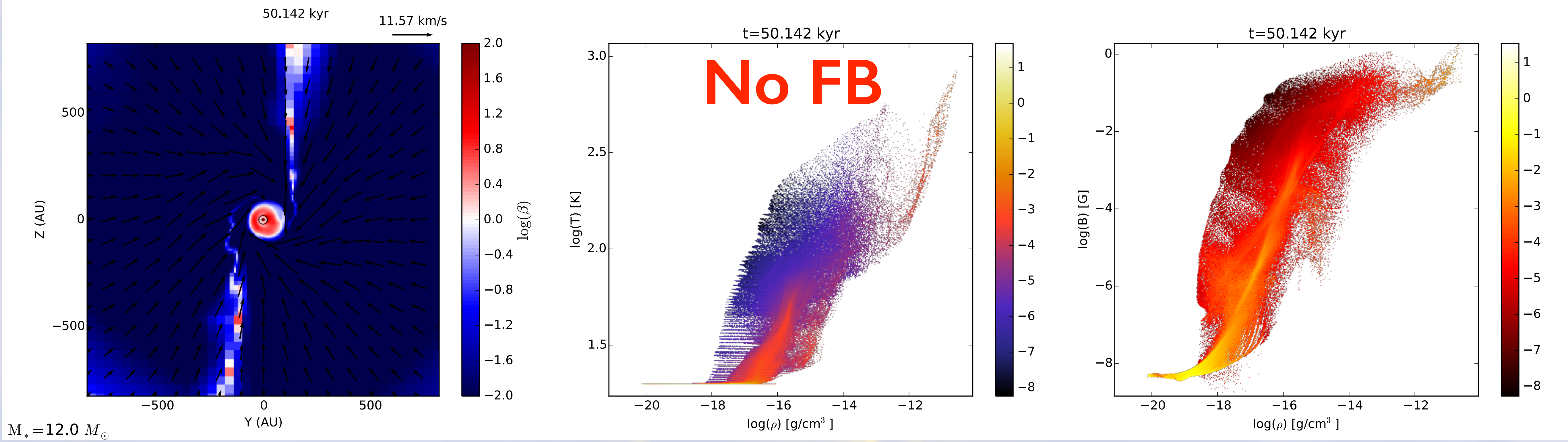


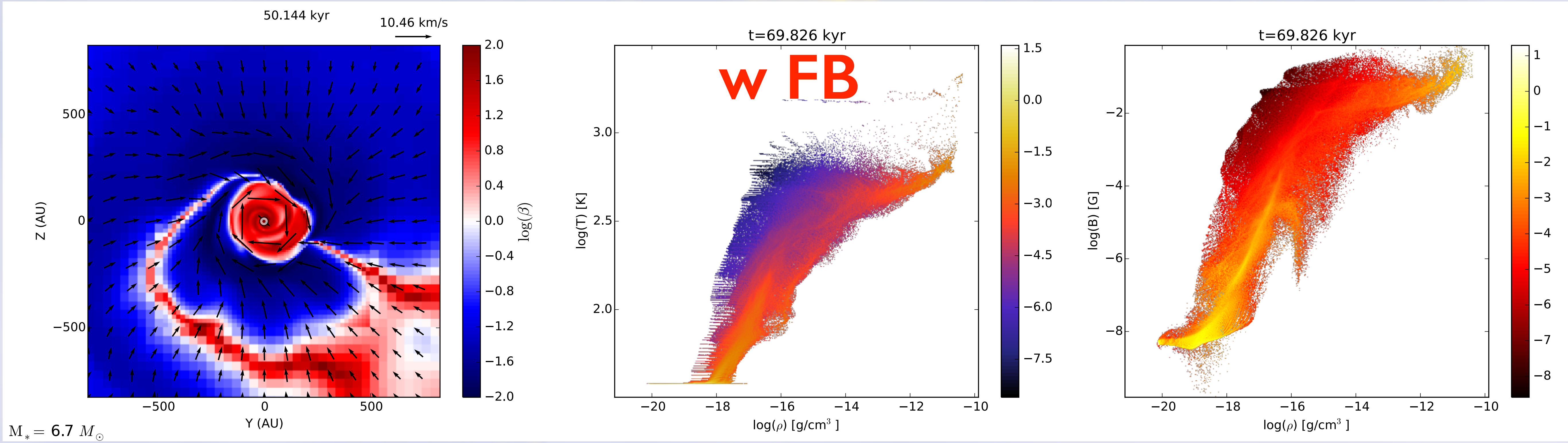


✓ significant differences in the stellar and disk mass, not in the outflow

➡ magnetic origin

Is radiative feedback important?





Take away II

- ☑ 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
- ☑ No radiative Rayleigh-Taylor instability
- ☑ 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