Outflows and disks formation in massive dense core collapse

Benoît Commerçon
Centre de Recherche Astrophysique de Lyon
Matthias González (AIM CEA Saclay)
Neil Vaytet (NBI Copenhagen), **Jacques Masson** (CRAL Lyon)

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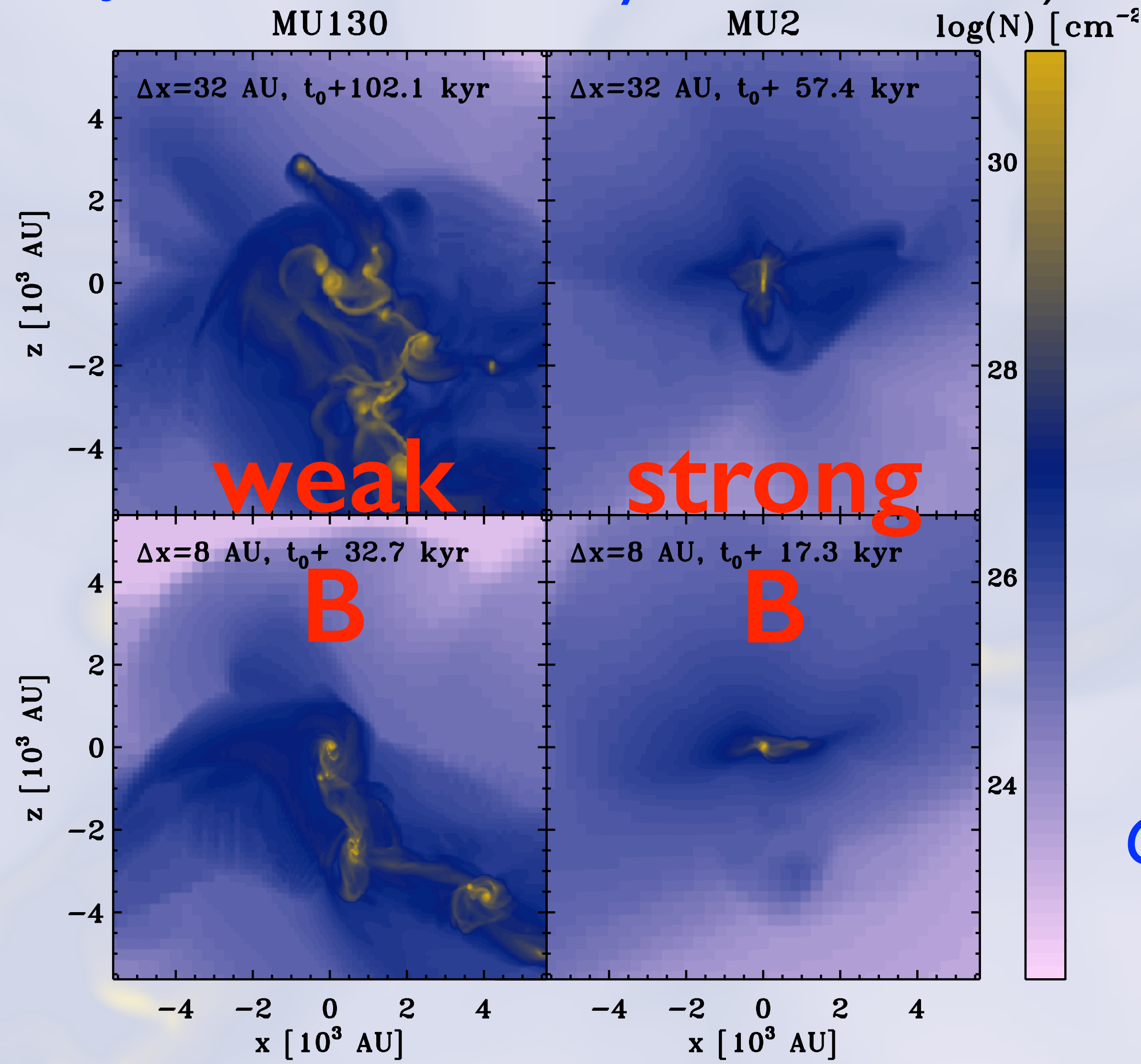
Formation of massive stars in magnetised cores

- ✓ Consider **isolated massive core,** threaded by **regular** magnetic fields
- ✓ Interplay between **magnetic braking and radiative feedback reduces** efficiently **fragmentation** (*Commerçon et al. 2011a, Myers et al. 2013*)



Commerçon et al. (2011a)

- ✓ *Choice of slowly rotating cores to focus on the star-disk-outflow system formation, without strong fragmentation*

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. 2011b, 2014, González et al. 2015*). In this work, just **grey**
- ✓ **Sink particles** using clump finder algorithm (*Bleuler & Teyssier 2014*)

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

Gravitational

Radiative

Lorentz

Ambipolar EMF

$$E_{\mathrm{AD}} = \frac{1}{\gamma_{\mathrm{AD}} \rho_{\mathrm{i}} \rho} [(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}$$

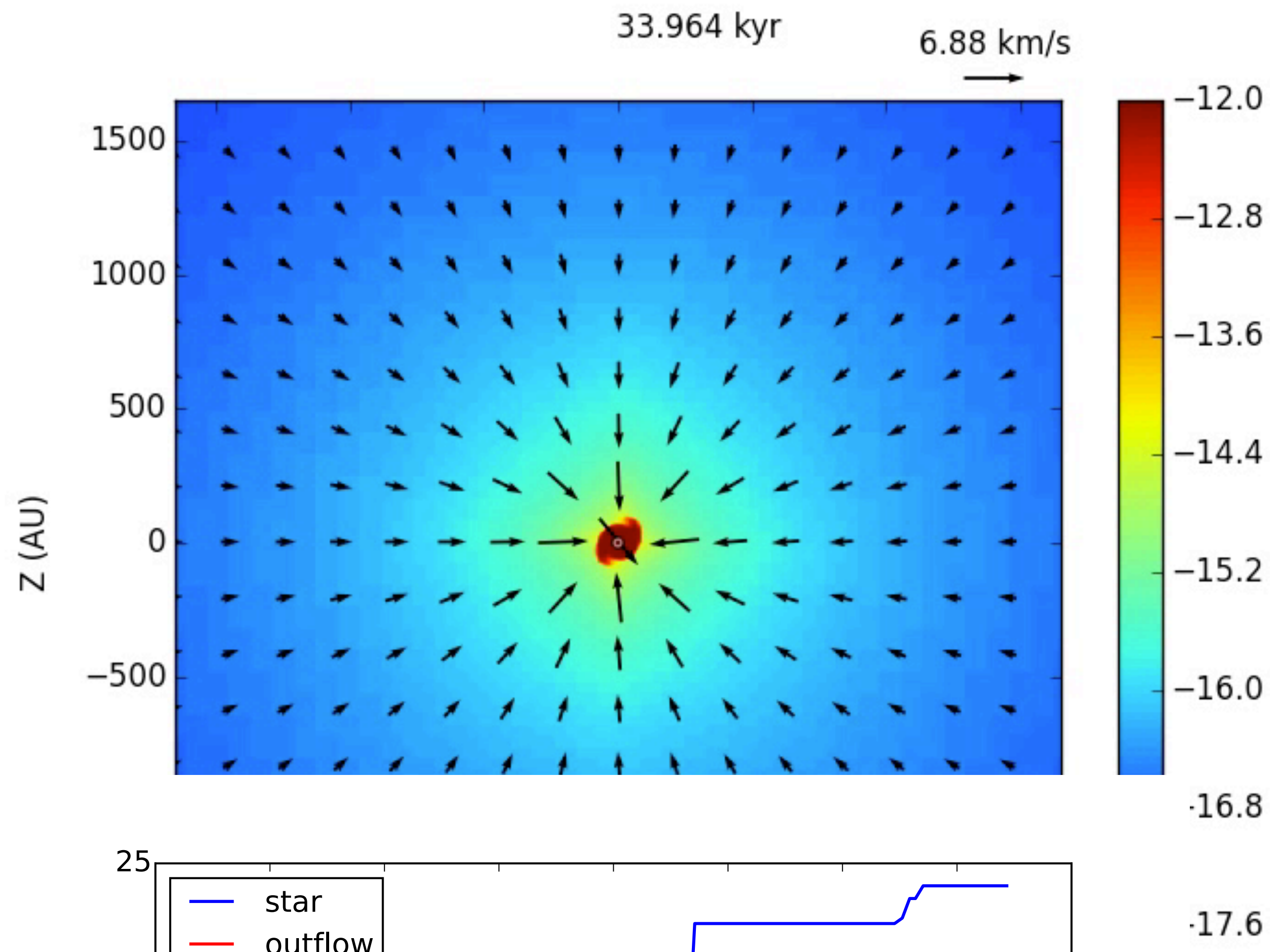
Initial conditions and protostellar evolution

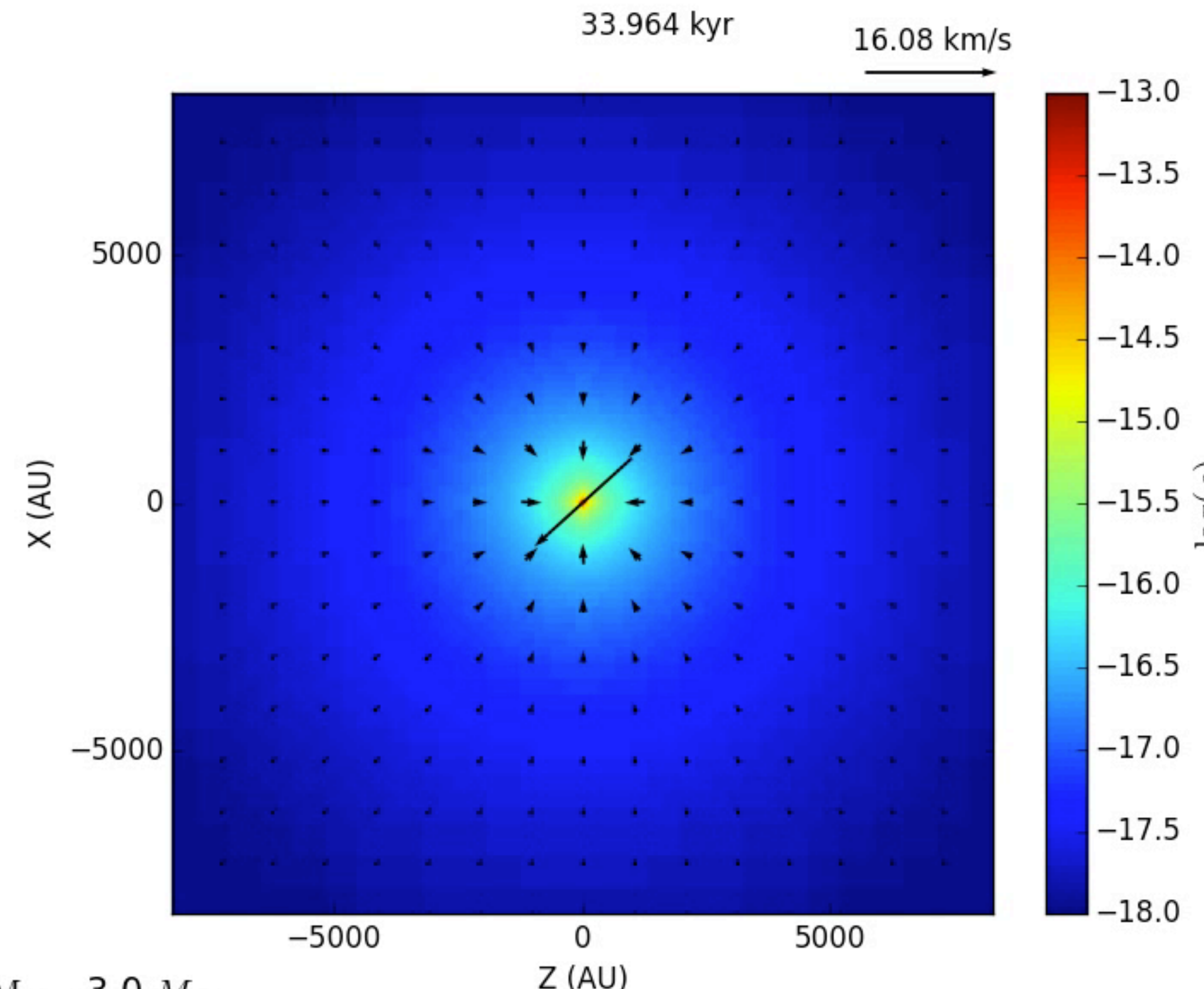
- ✓ 100 $M_\odot$; $\rho \propto R^{-2}$ (n_c=2x10^6 cm^{-3}); T = 20 K ; R_0 = 0.2 pc
- ✓ Solid body rotation Ω=3x10^{-15} Hz (r_d~650 AU)
- ✓ Uniform magnetic field (μ_{uni}=2,5,∞) (B=170, 68, 0 μG), aligned with rotation axis (x-axis)
- ✓ Refinement: 10 cells/Jeans length

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

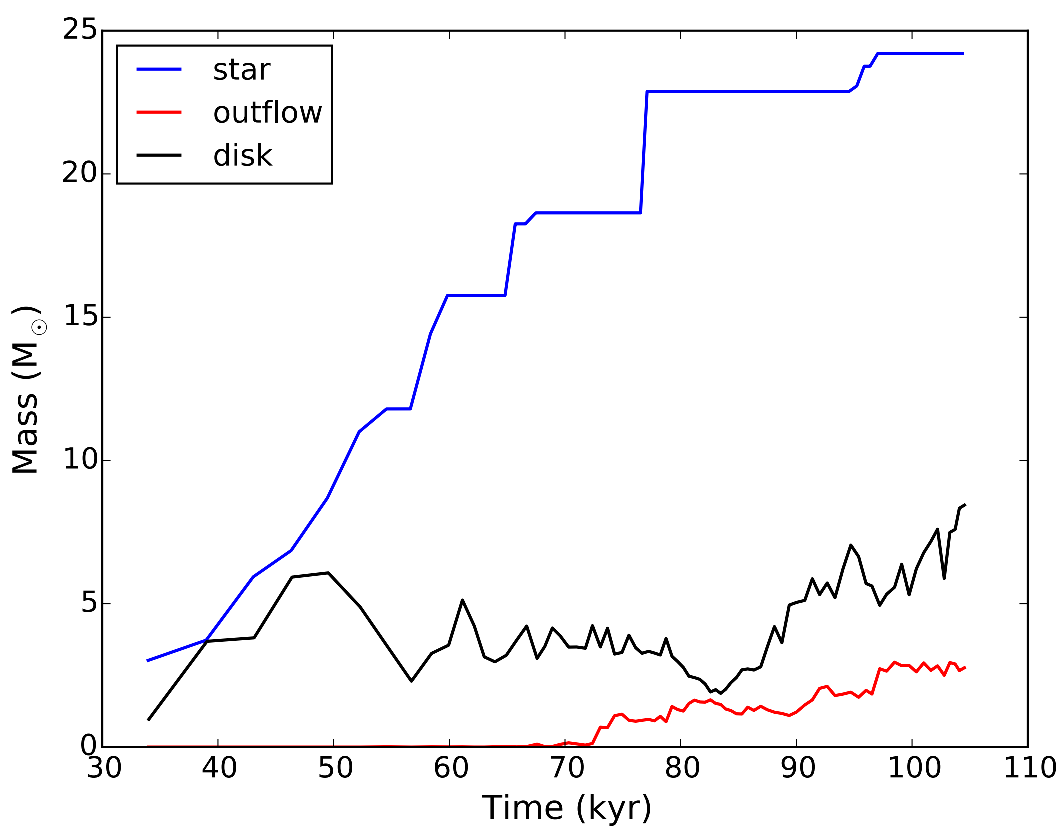
- ✓ 4 models: Hydro, Ideal MHD μ=2, ambipolar diffusion μ=2 and μ=5

Hydro collapse



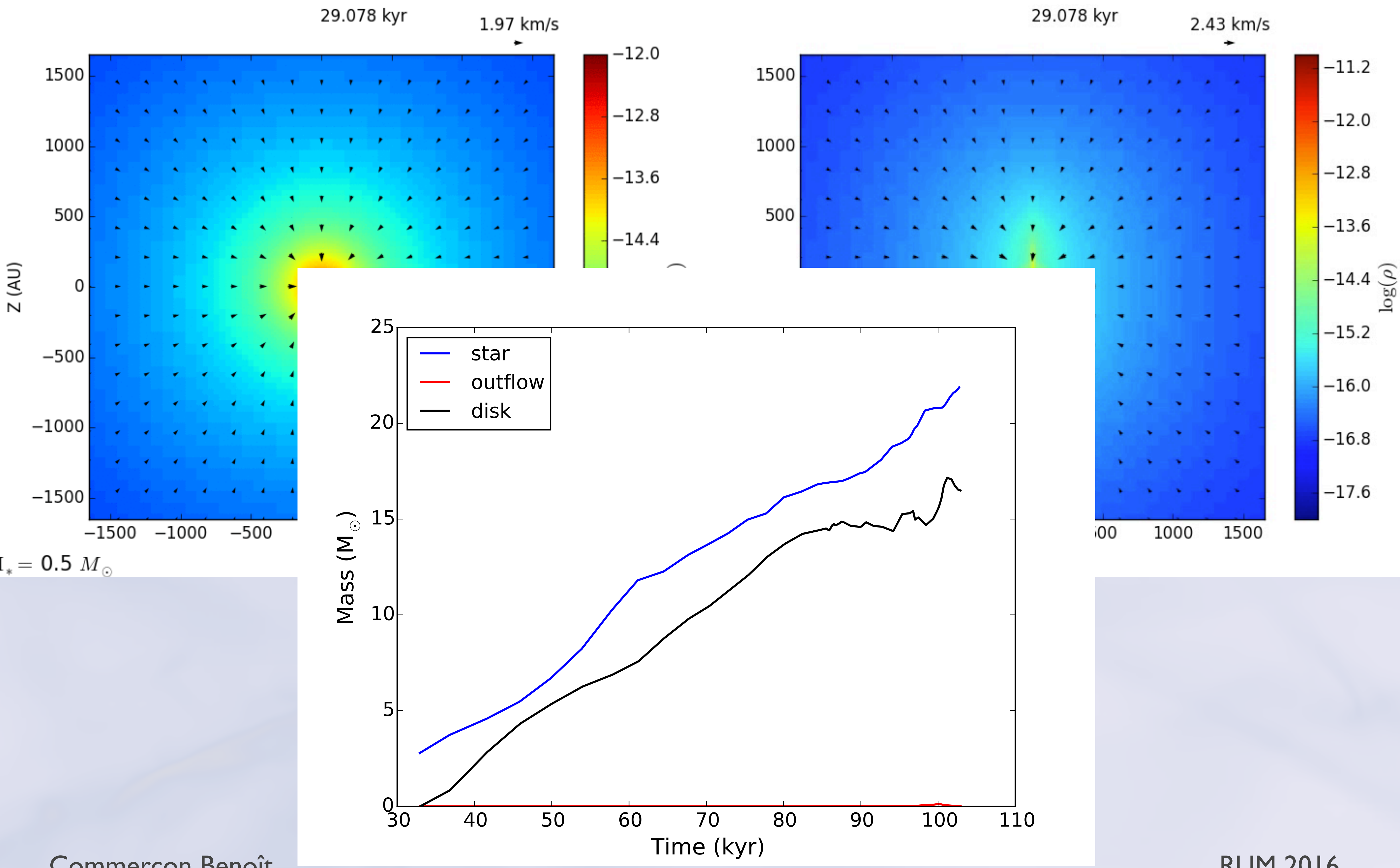


$M_* = 3.0\ M_\odot$



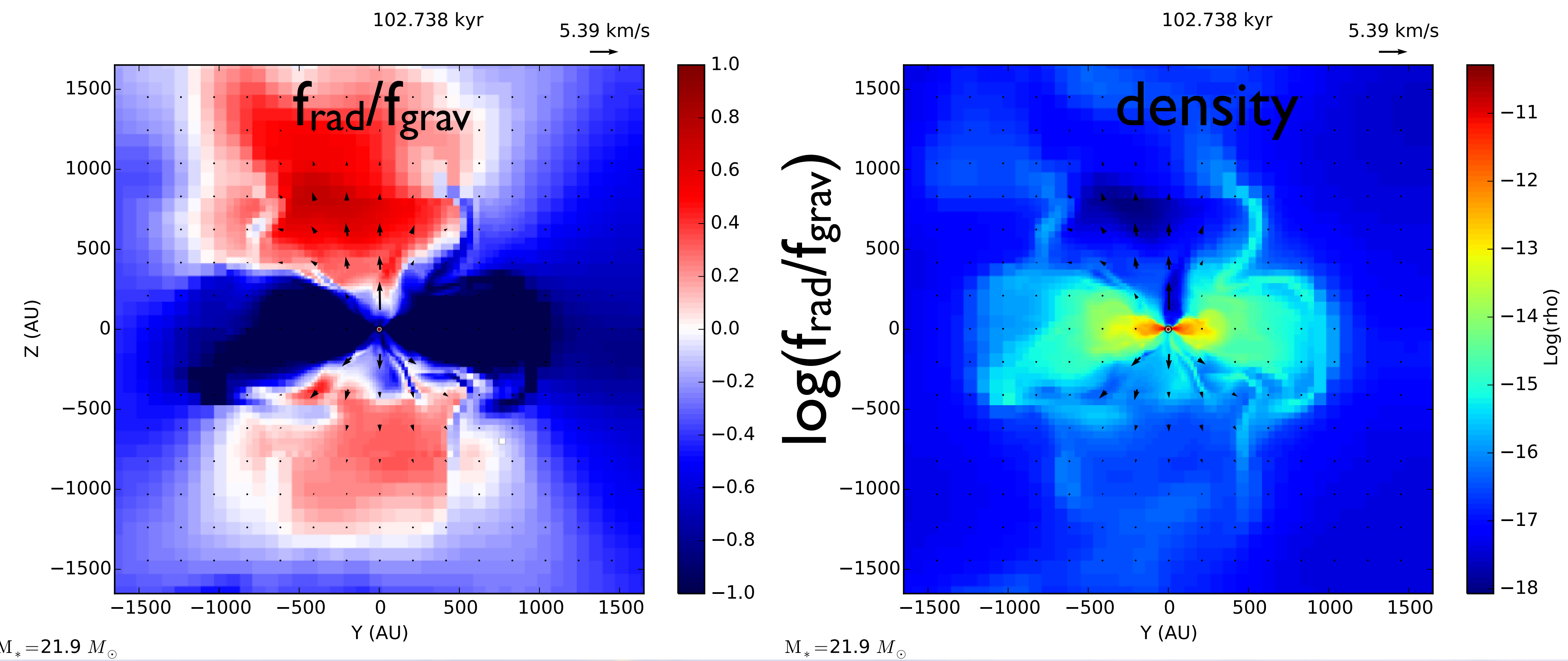
- ✓ Formation of a large disk: R~1000 AU
- ✓ Binary system: 24 and 13 $M_\odot$
- ✓ Radiative outflow/bubble (1500 AU)

iMHD collapse, $\mu = 2$



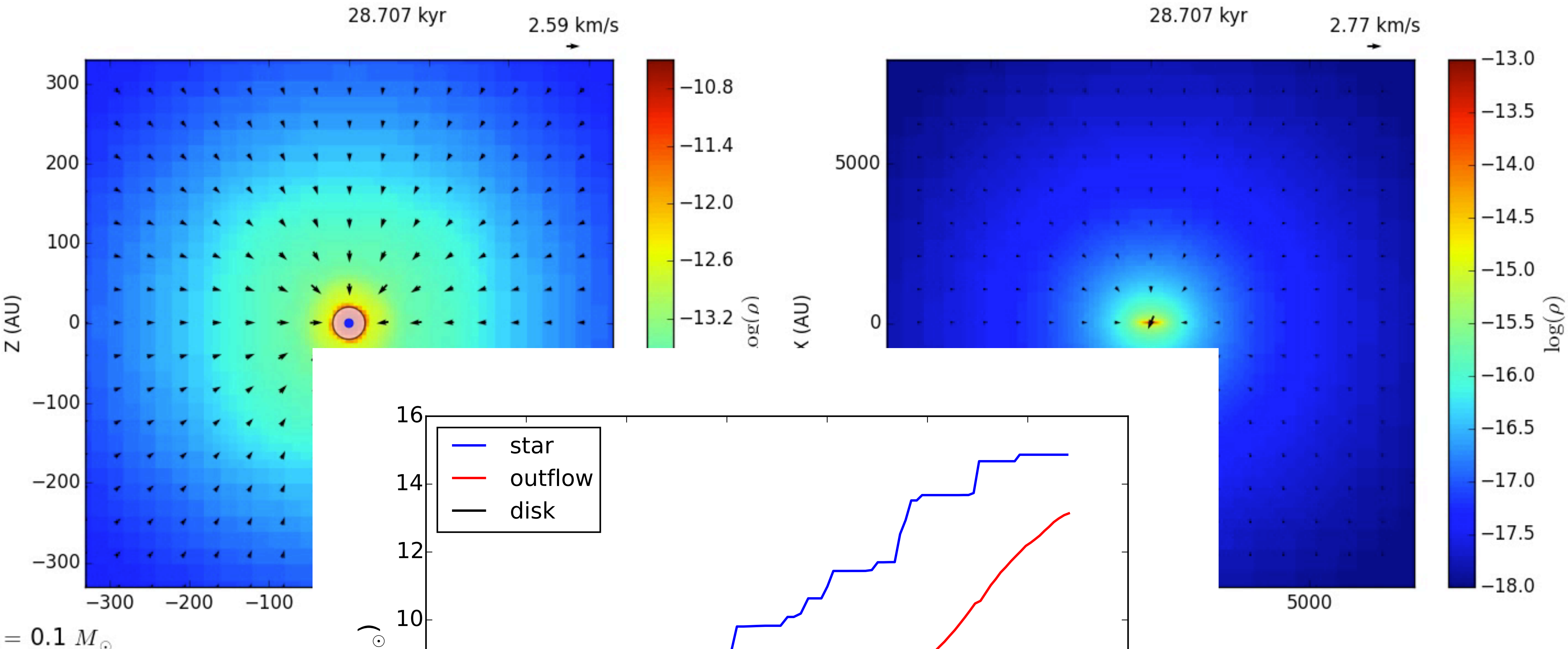
$M_* = 0.5\ M_\odot$

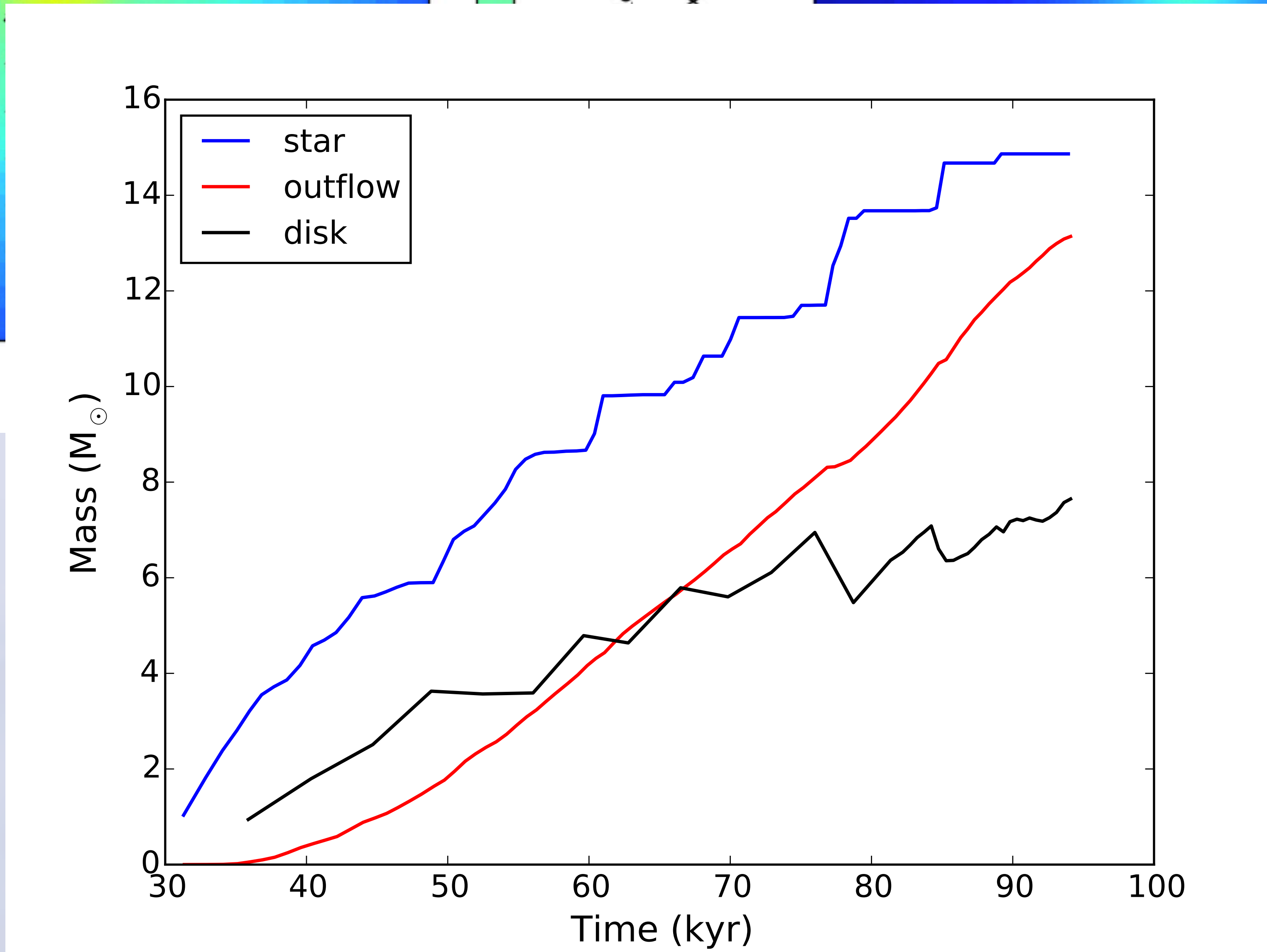
Hydro & iMHD: origin of the outflow



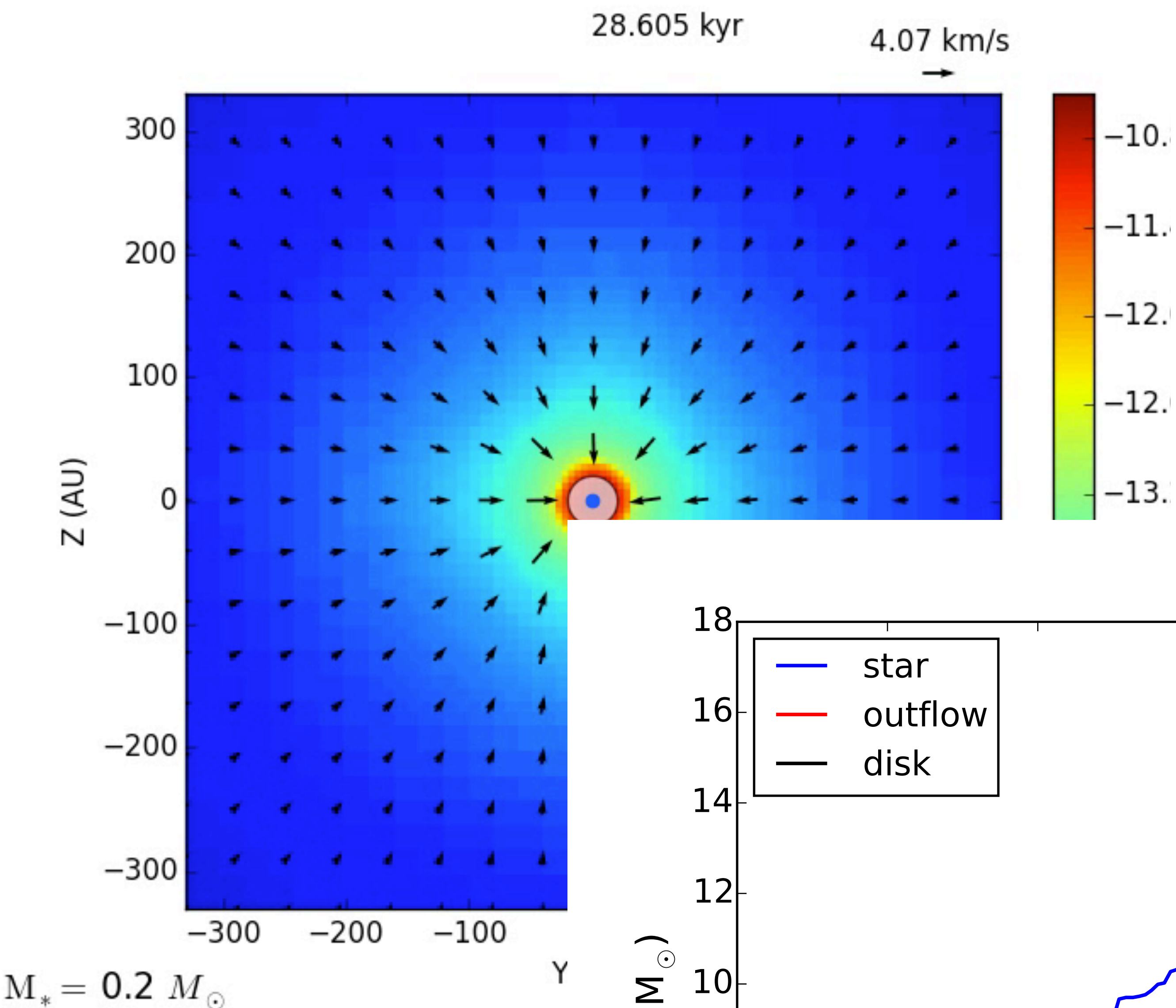
- Outflow has a radiative origin
- Magnetic fields disorganised by magnetic flux expulsion (interchange instability, e.g., *Masson et al. 2016*)

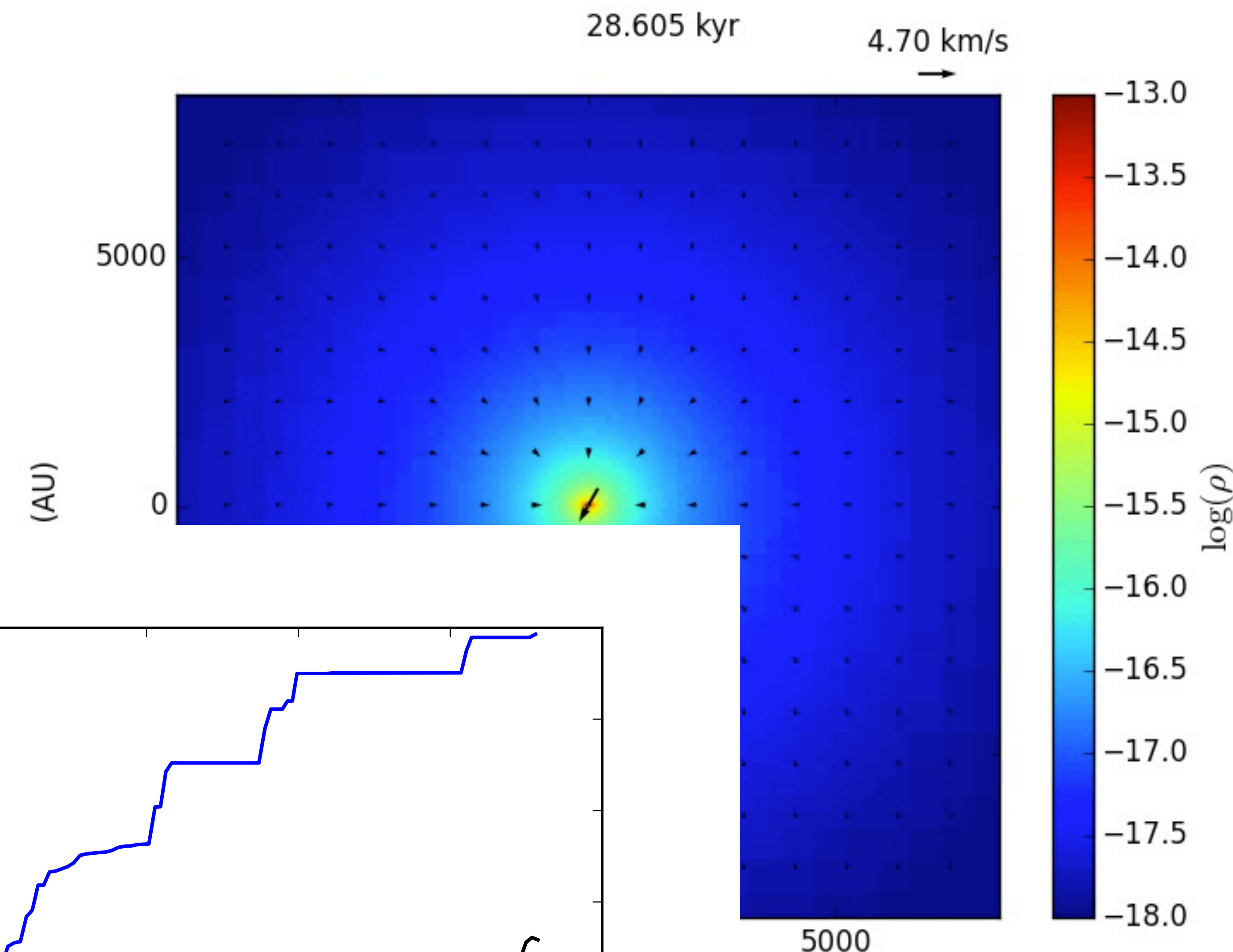
Ambipolar diffusion, μ =2

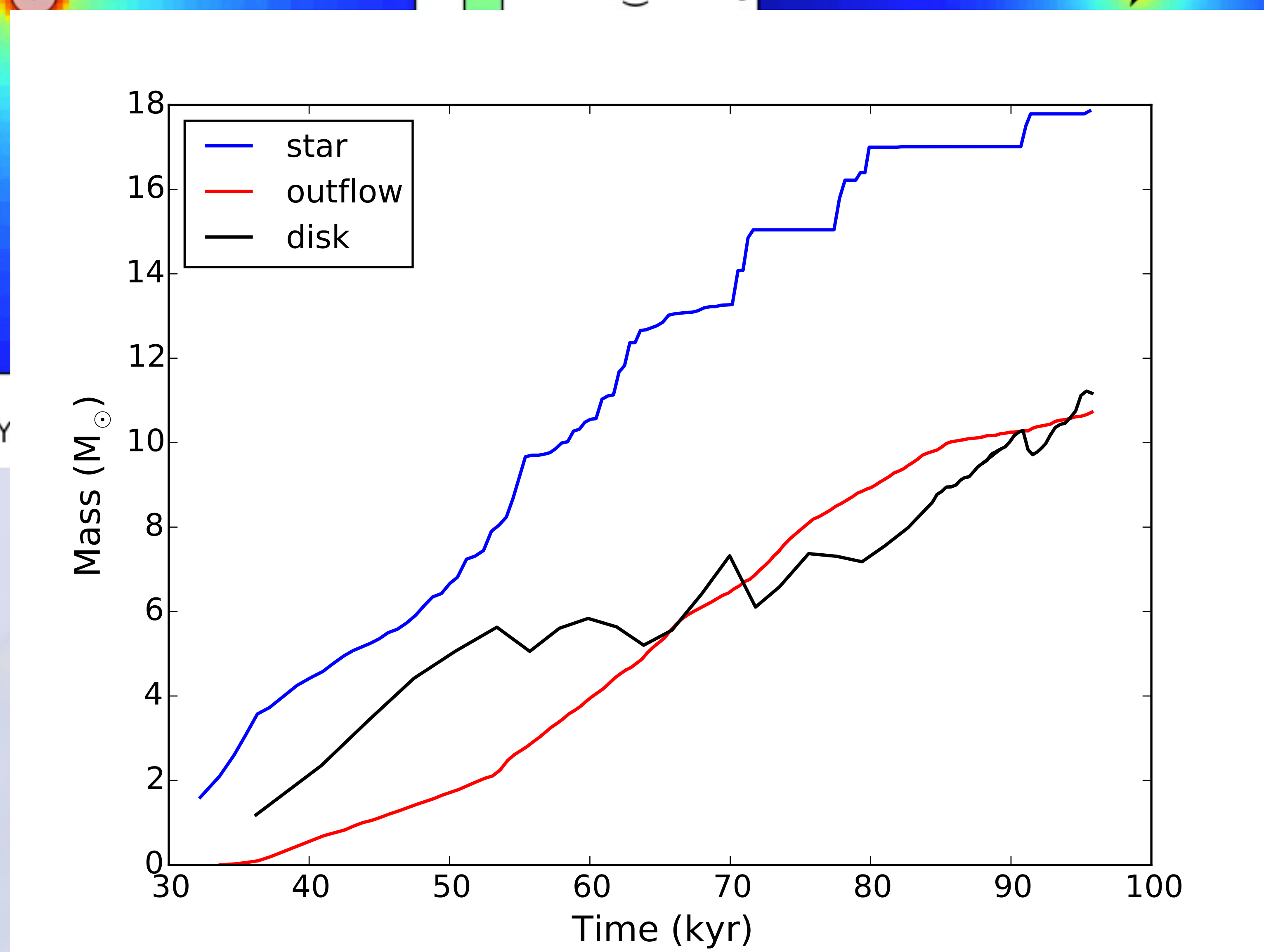




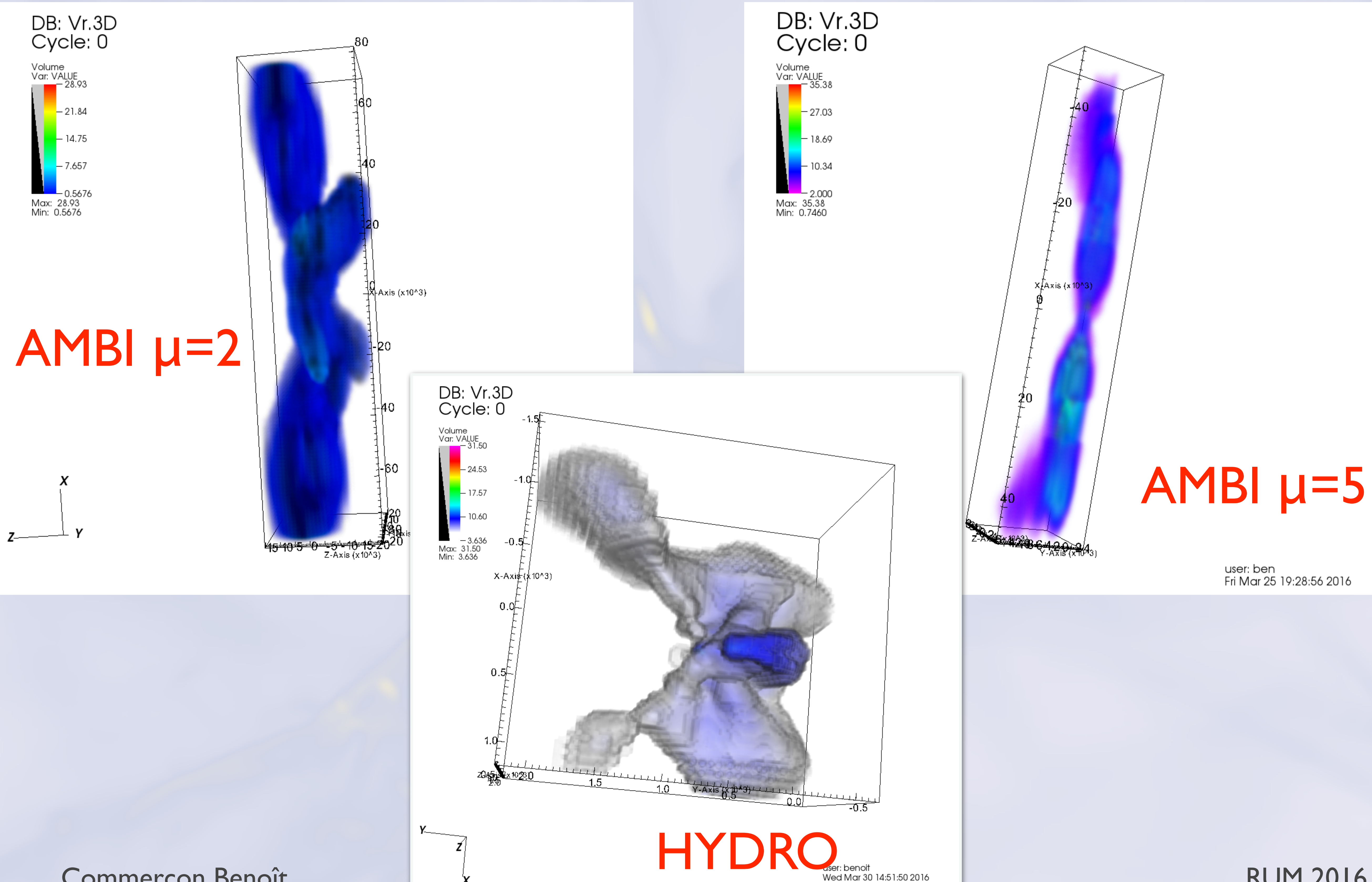
Ambipolar diffusion, $\mu = 5$



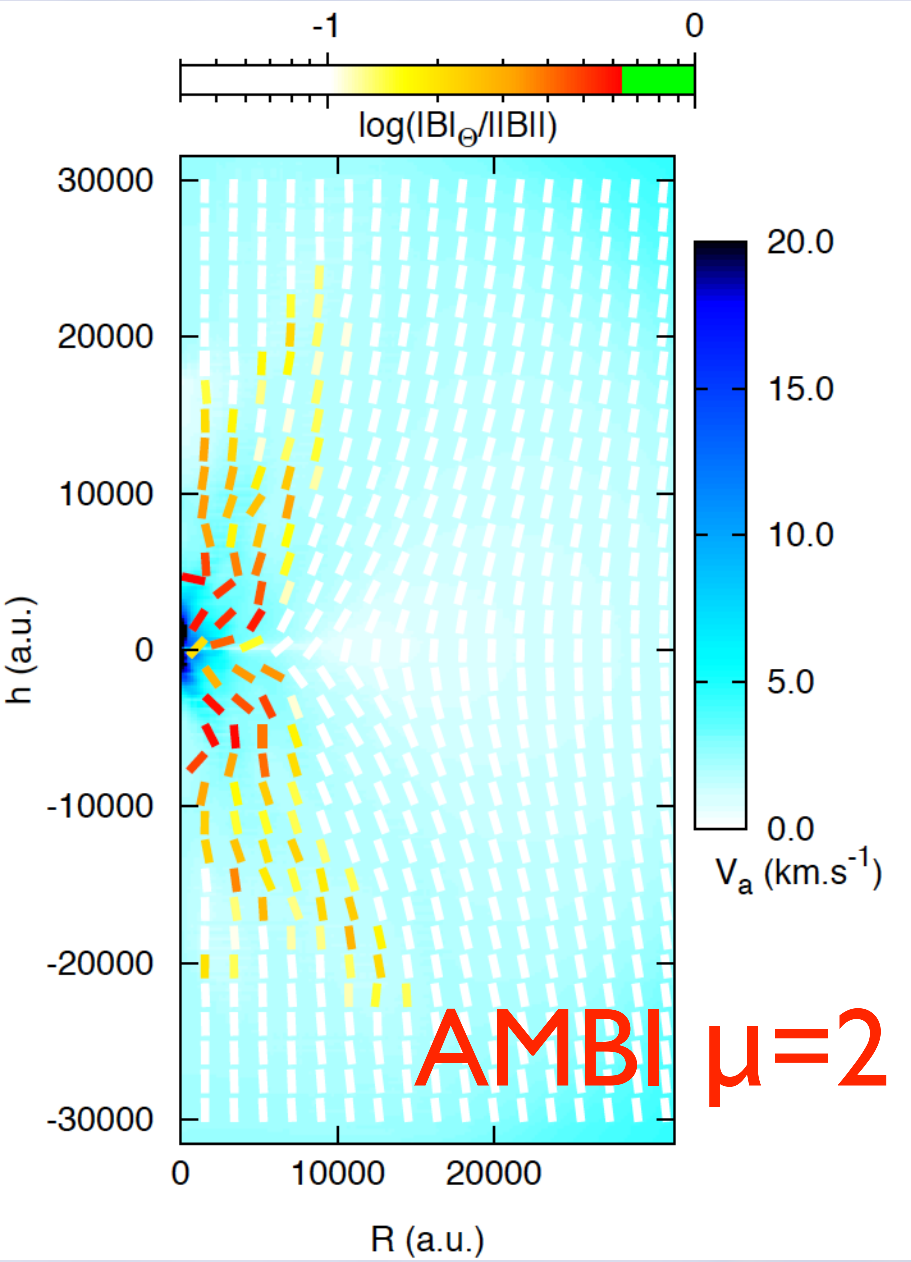




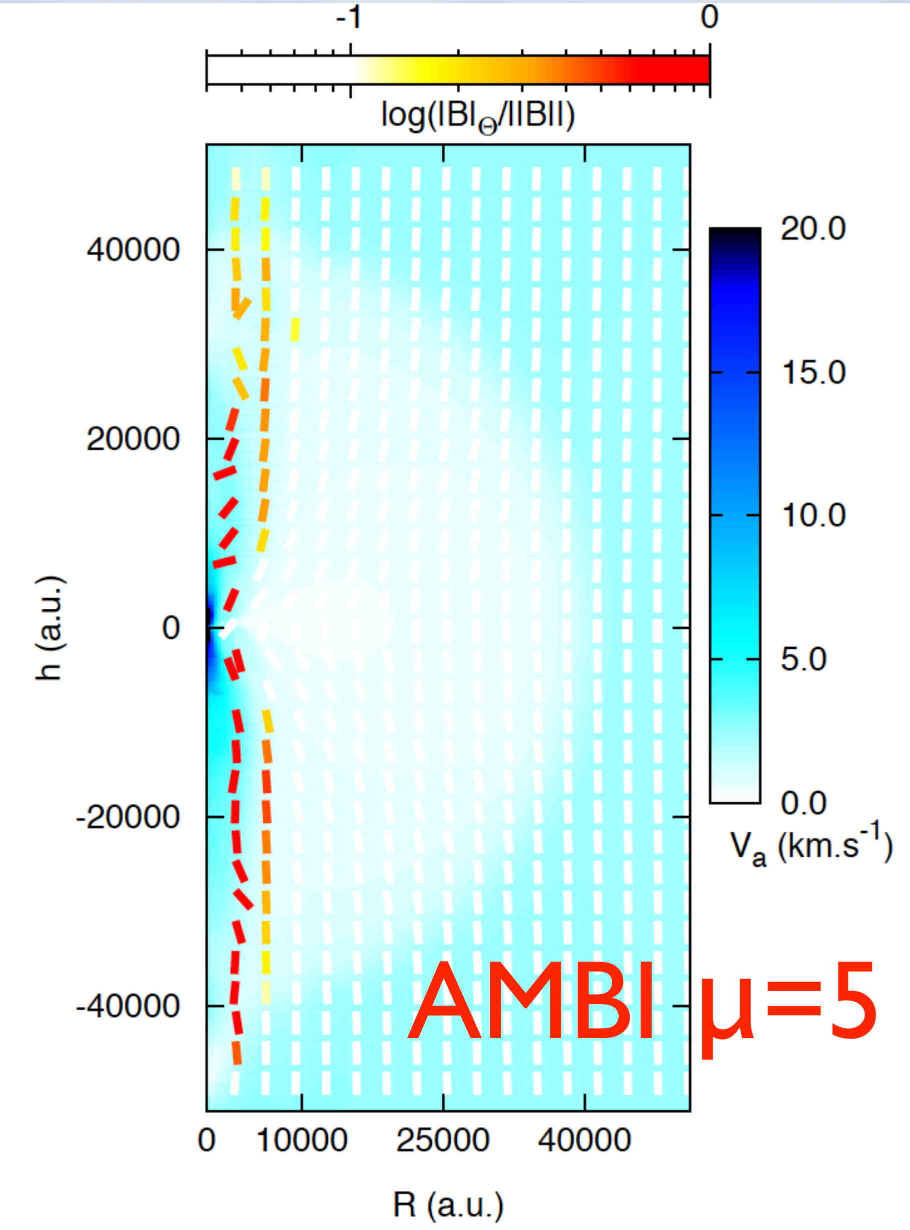
Outflow morphology

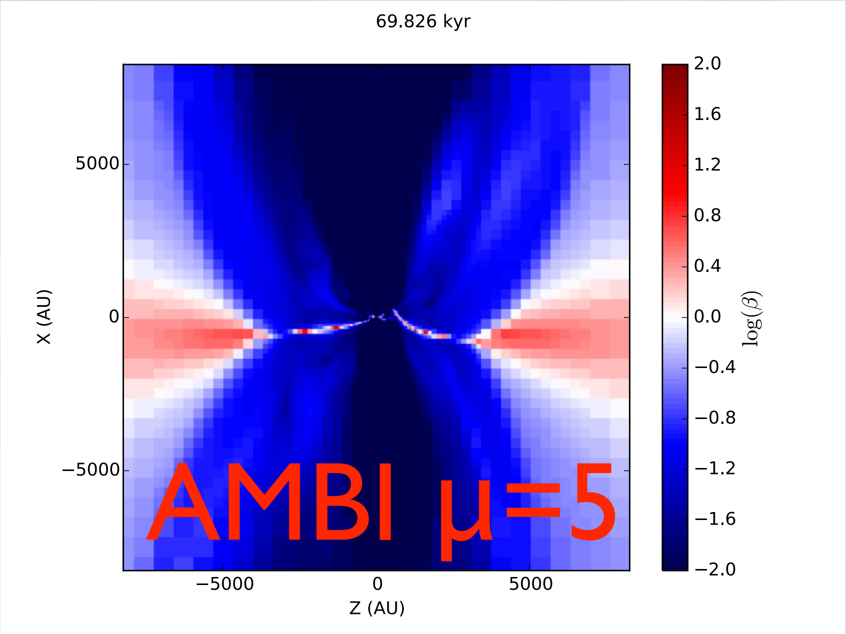


Outflow collimation

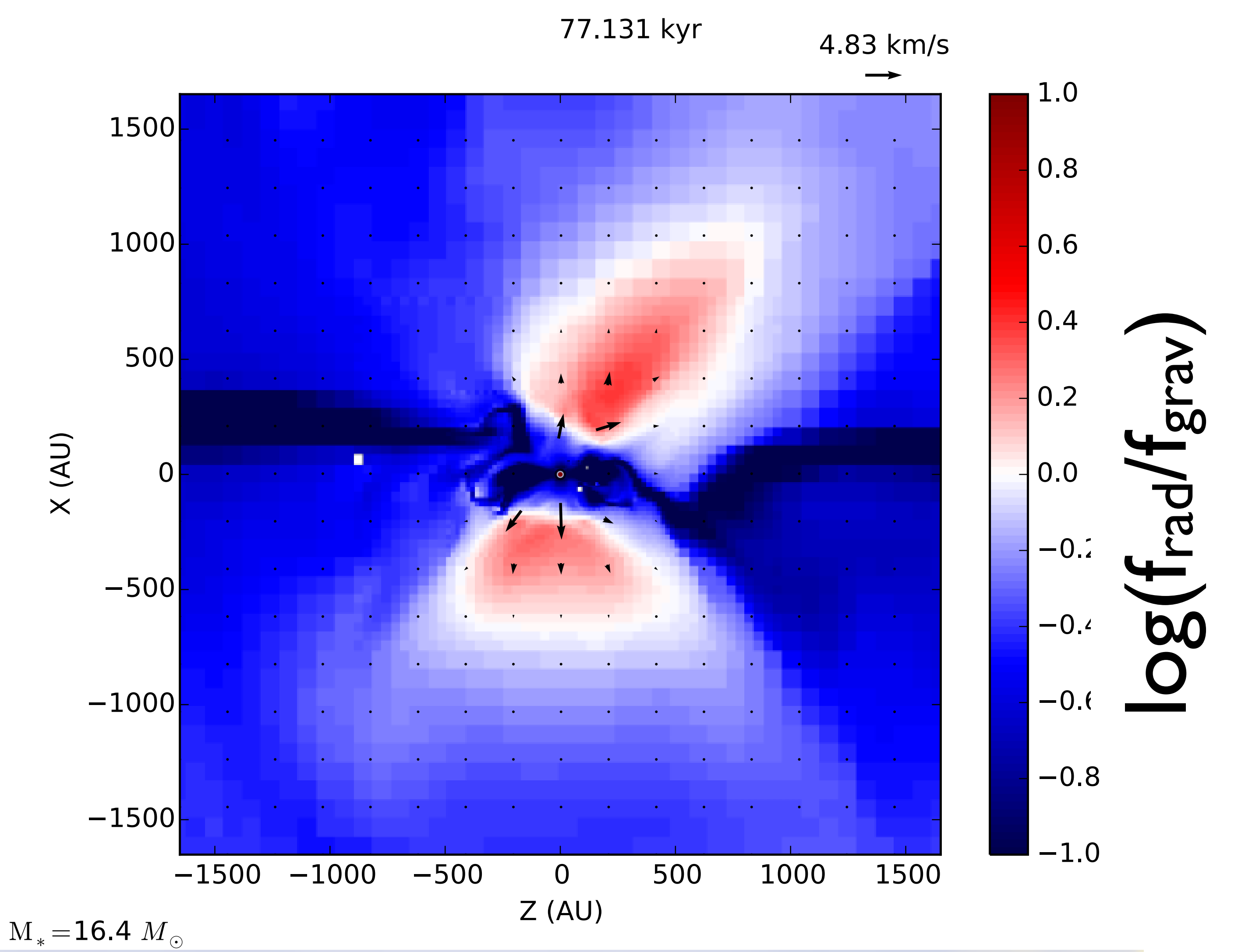


- ✓ outflow collimated by toroidal B-field
- ✓ outflow extends up to 80 000 AU when $M_\star=15M_\odot$, $V_{out,max}=40$ km/s
- ✓ outflow is strongly magnetized

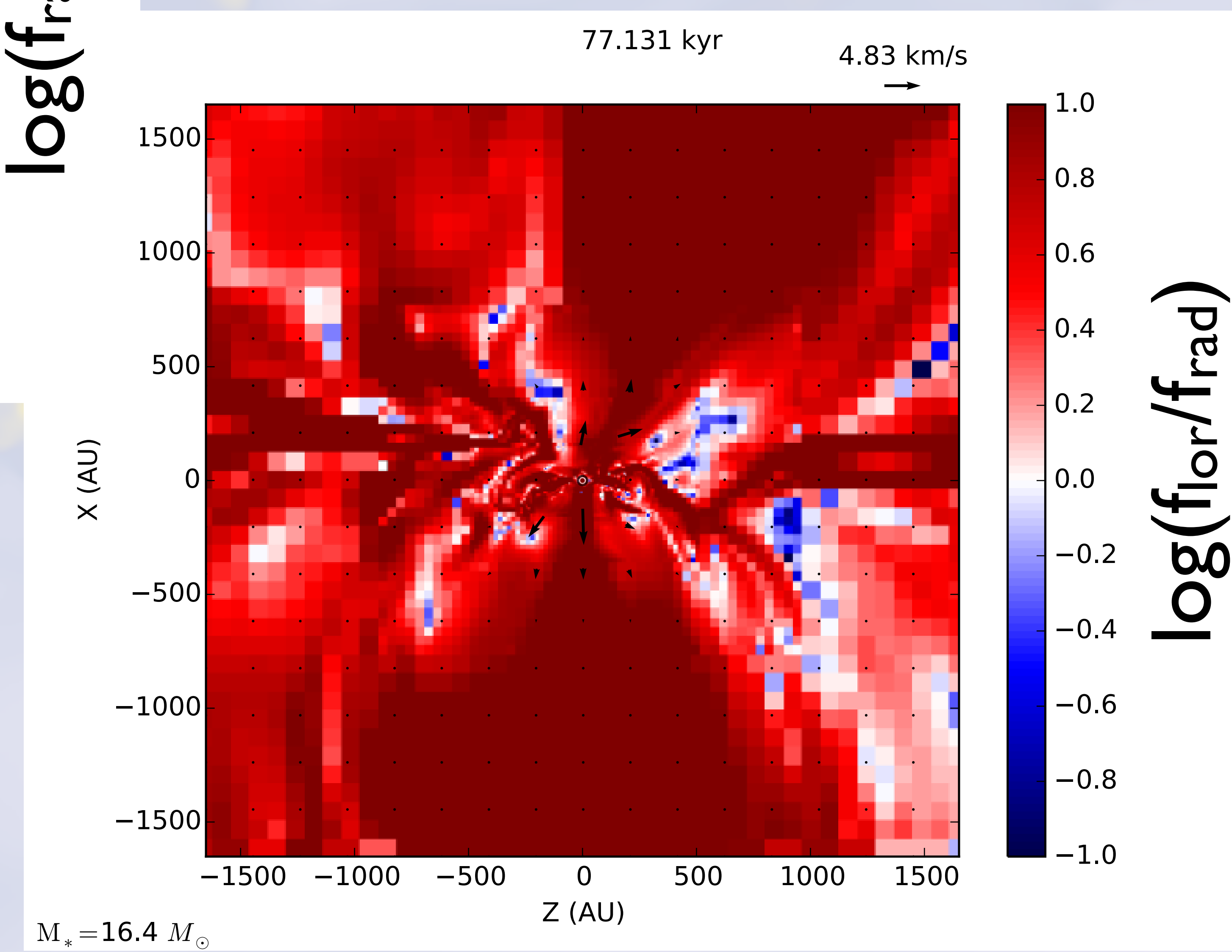




Is radiative feedback important?



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



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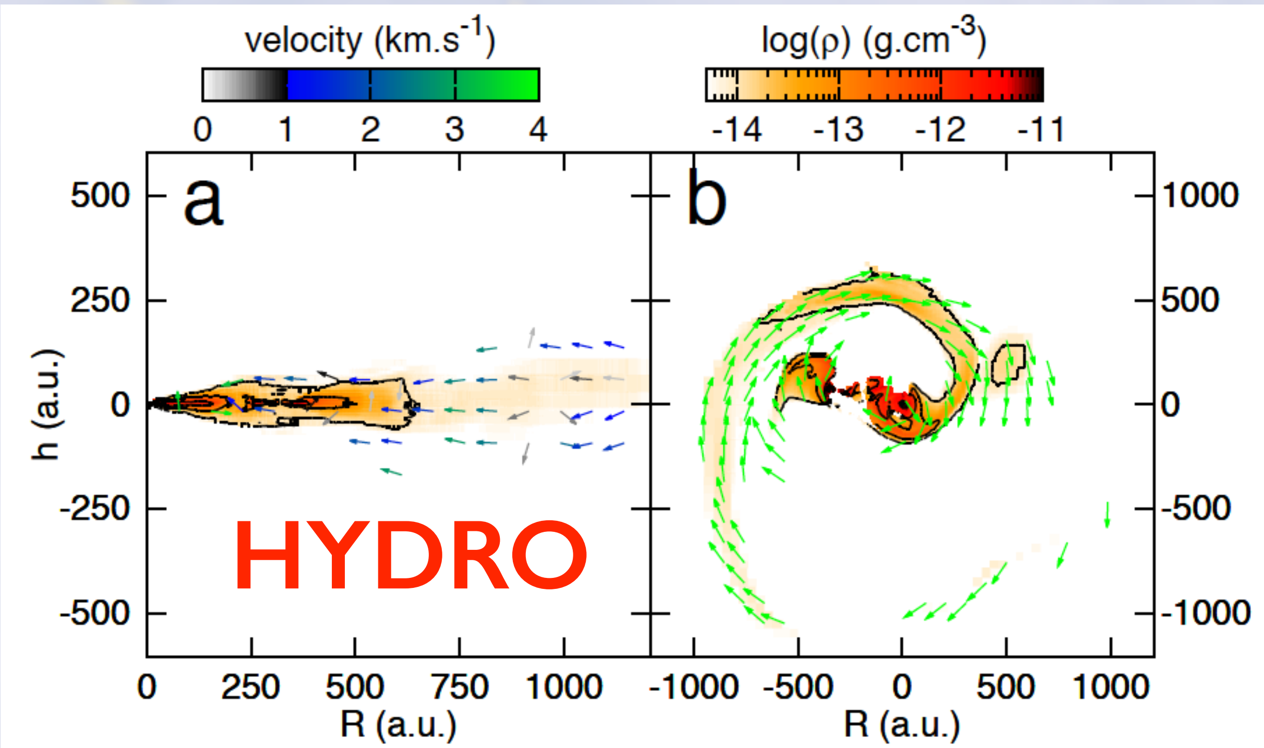
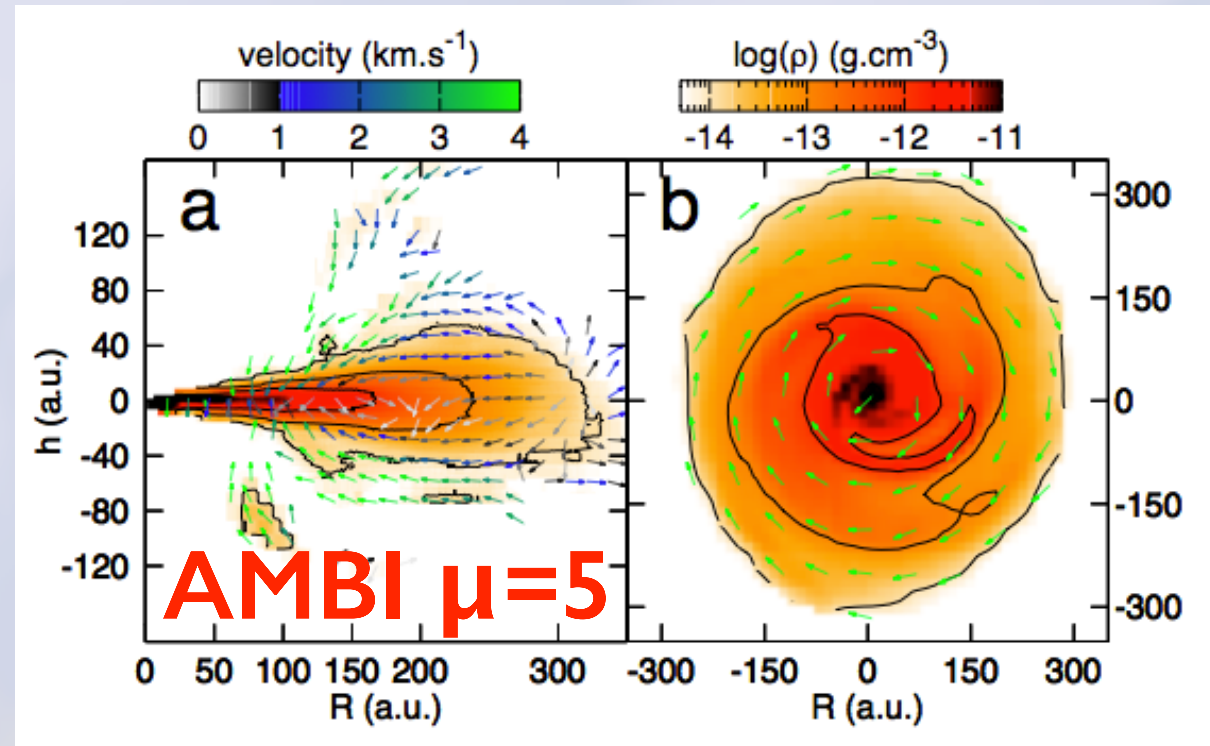
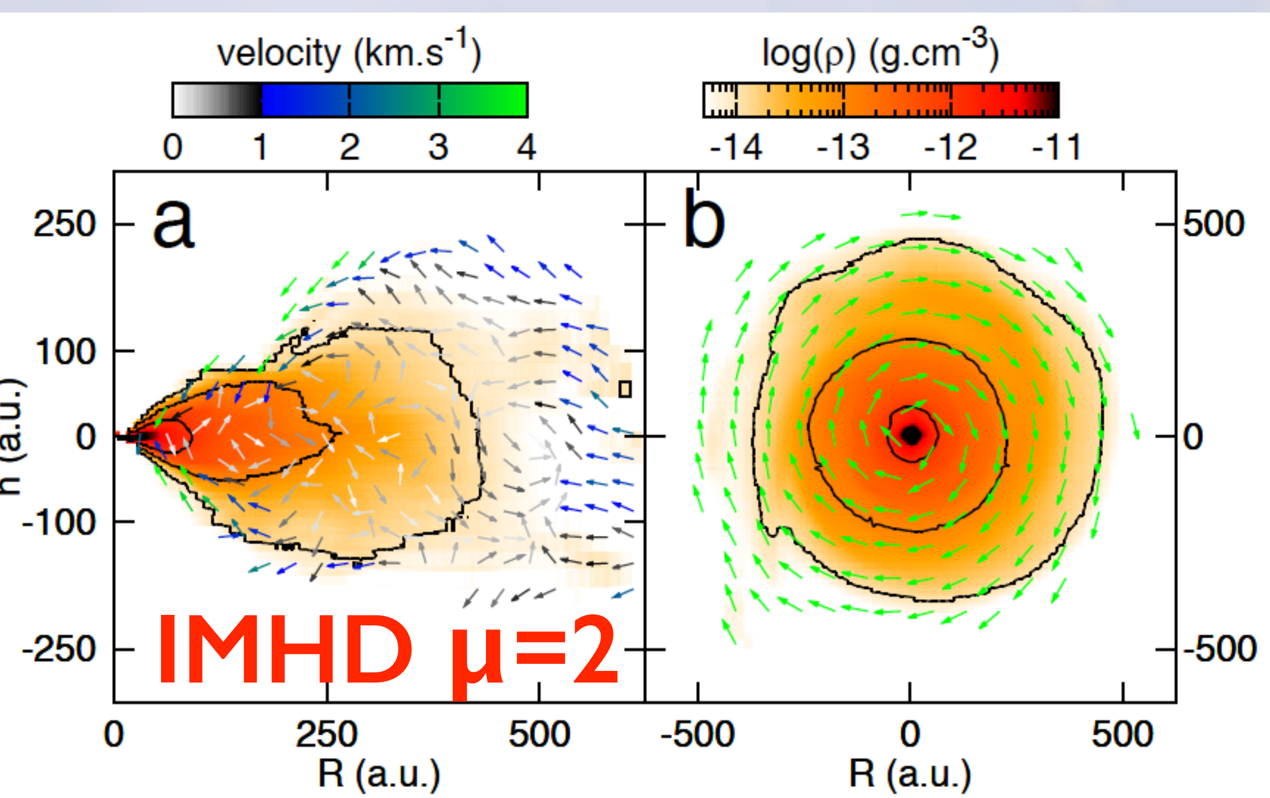
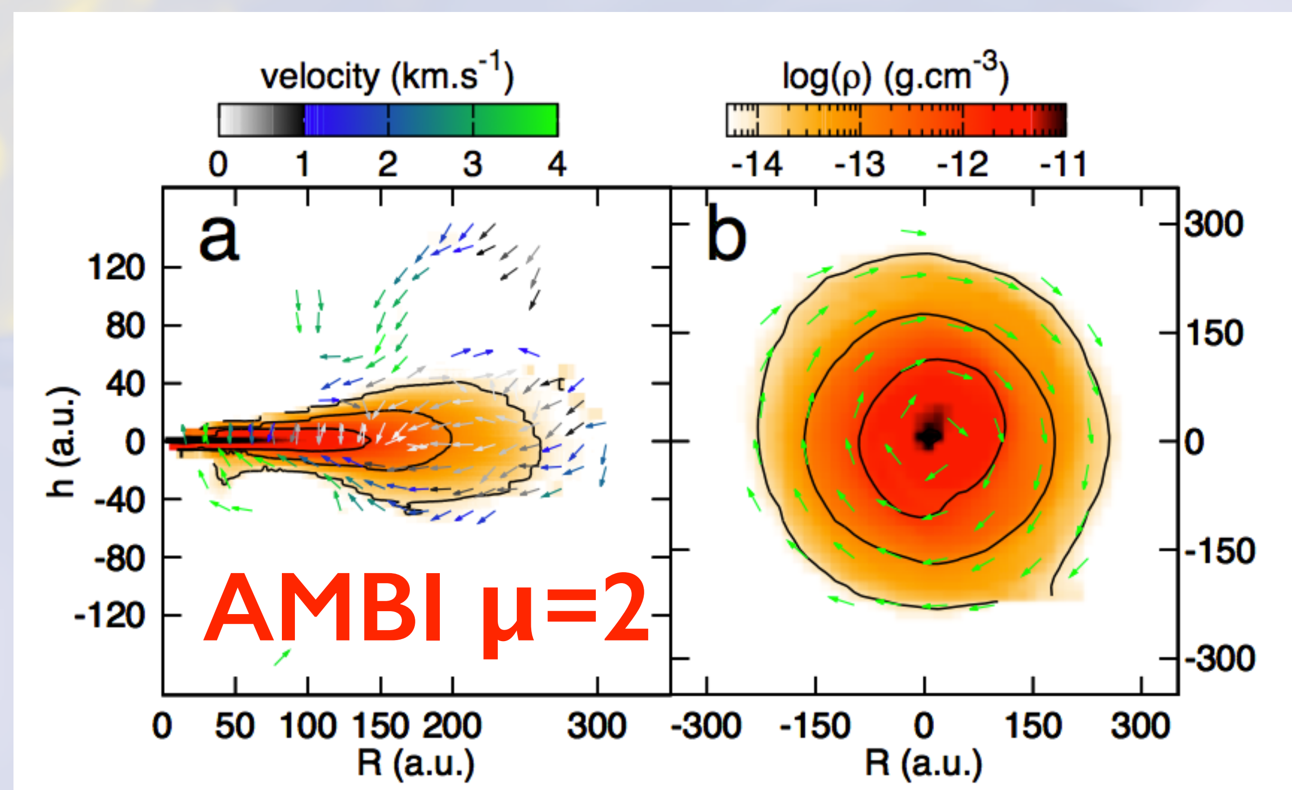
Discs properties

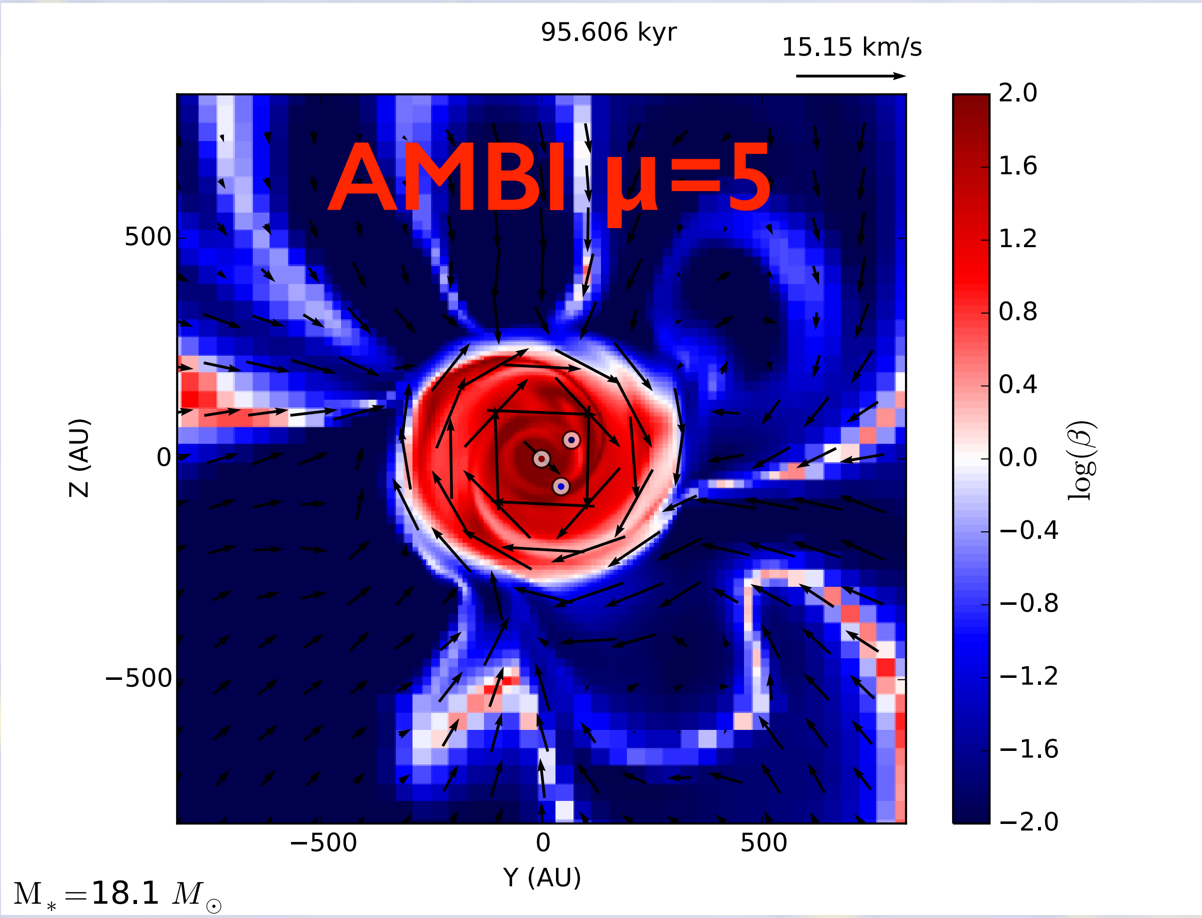


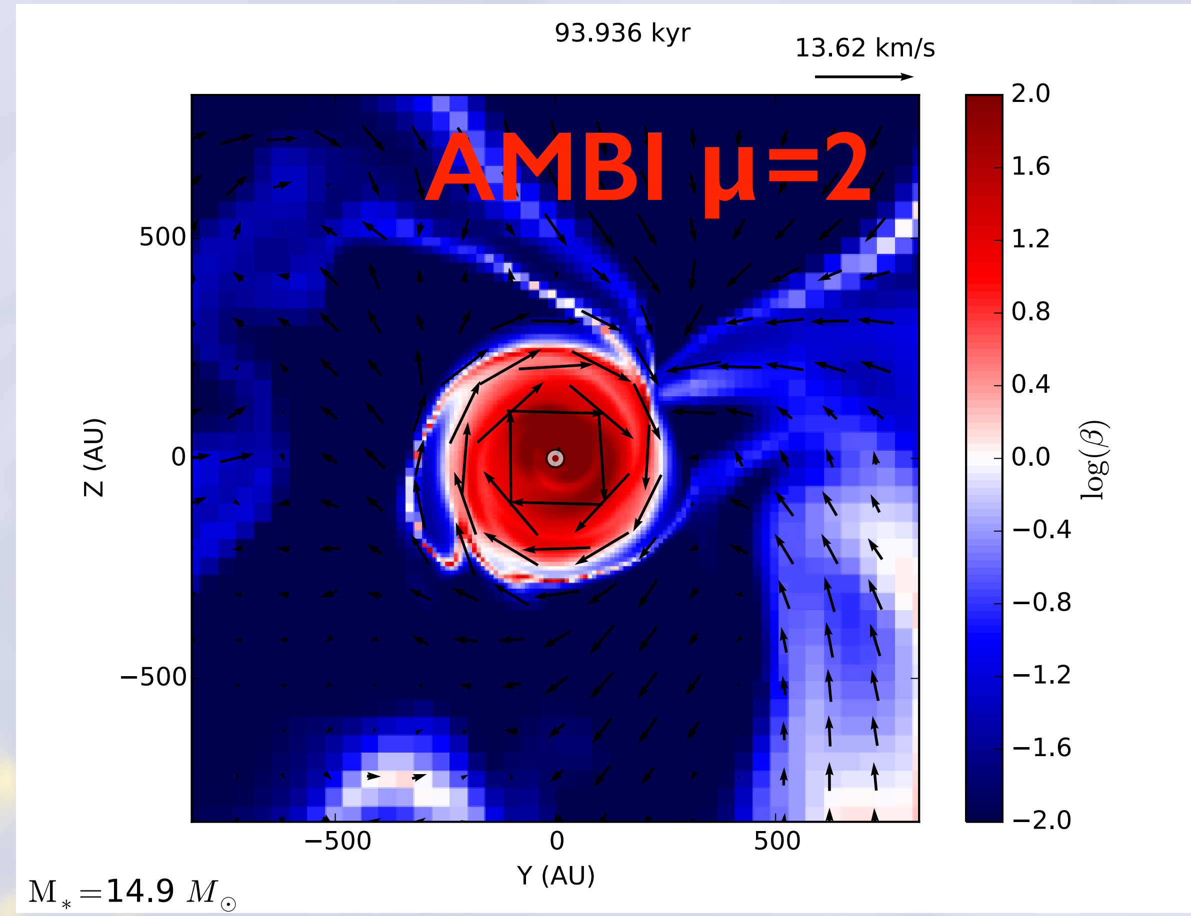


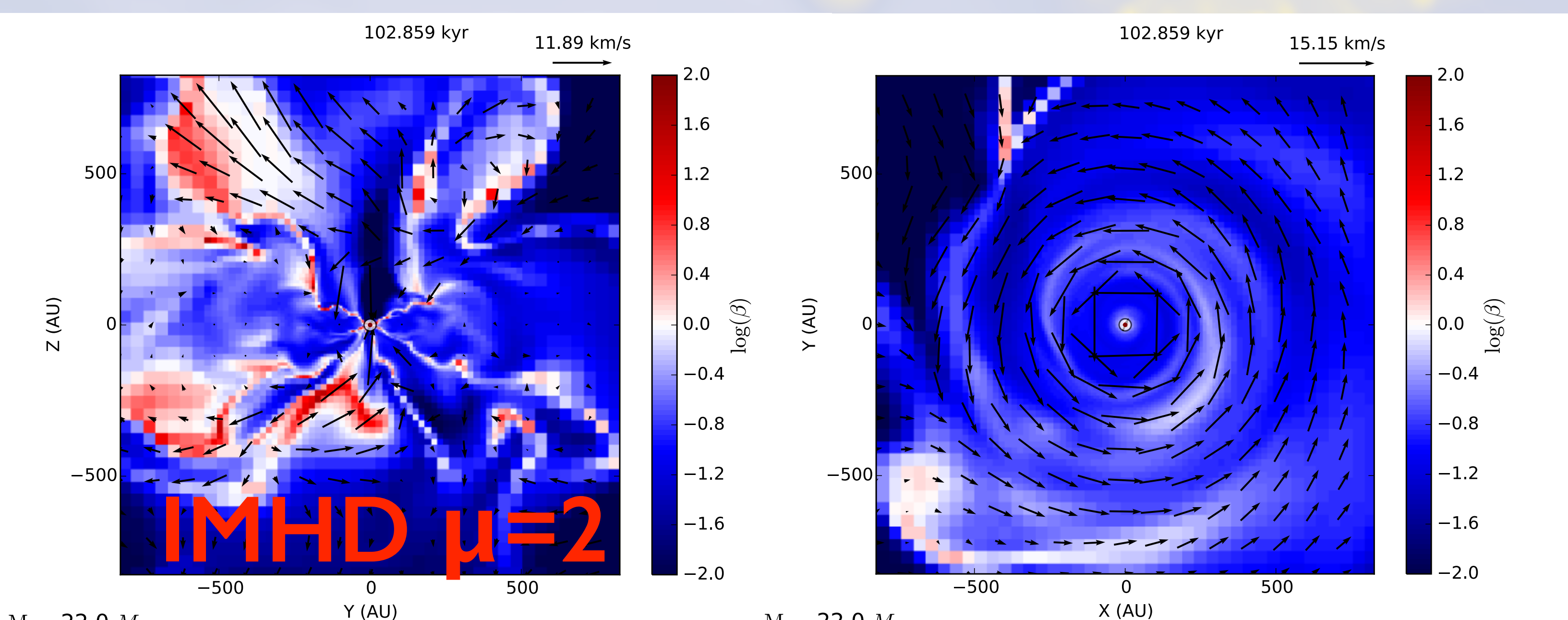




Discs properties

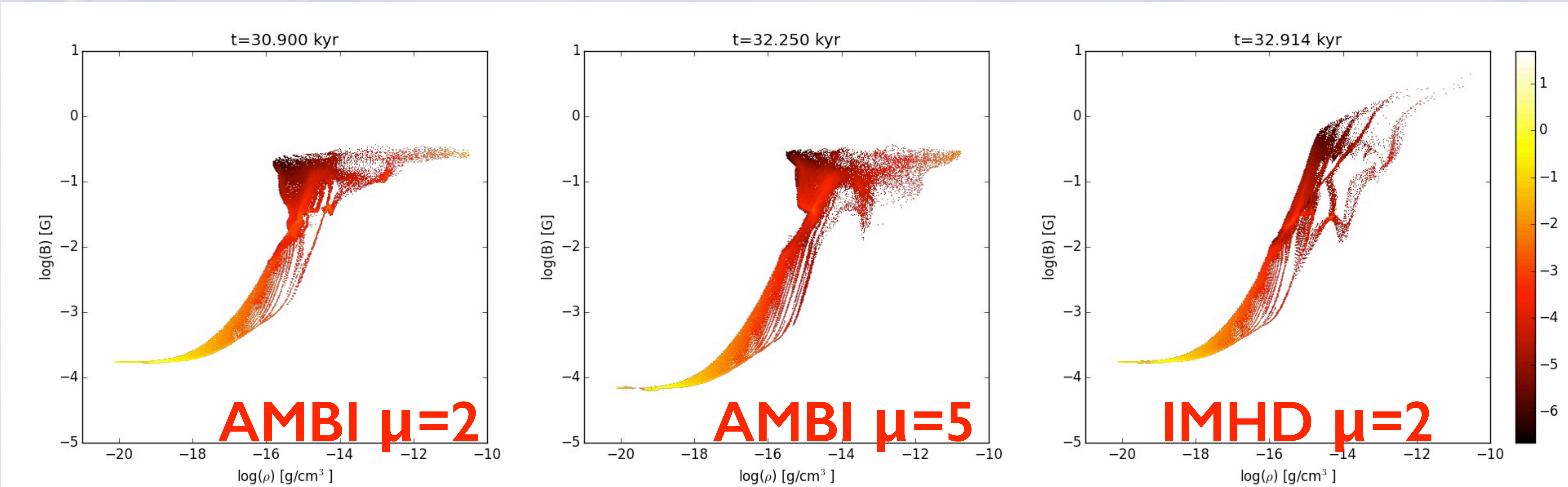






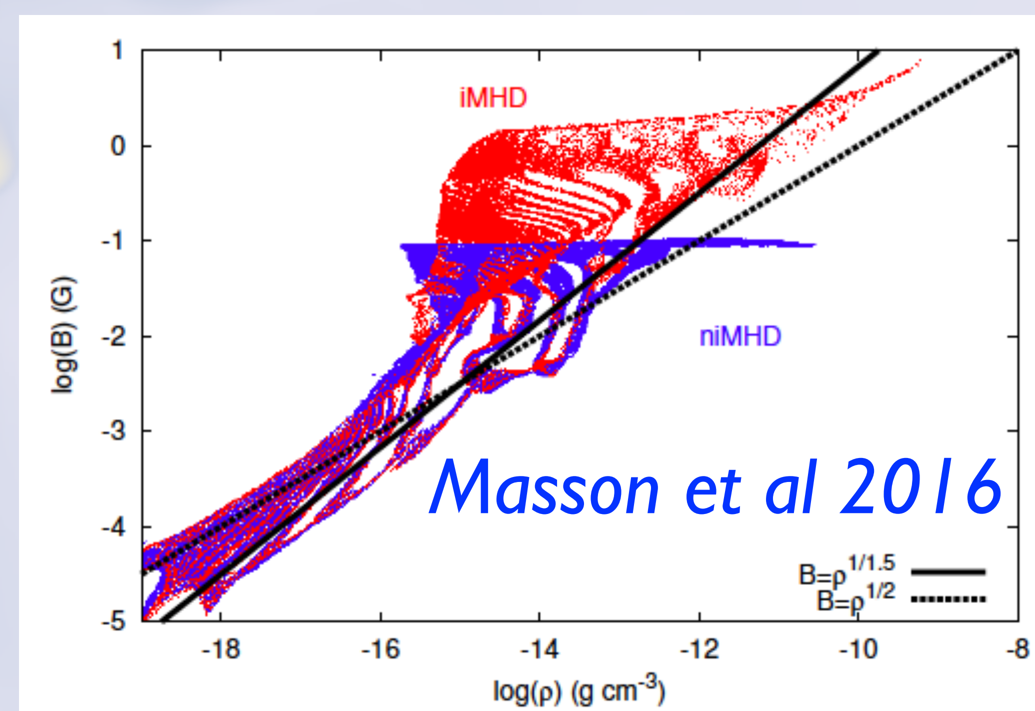
- ✓ discs are dominated by thermal pressure with AD (i.e. hydro discs)
- ✓ thick and magnetised disk with iMHD

Magnetisation



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

low mass star formation



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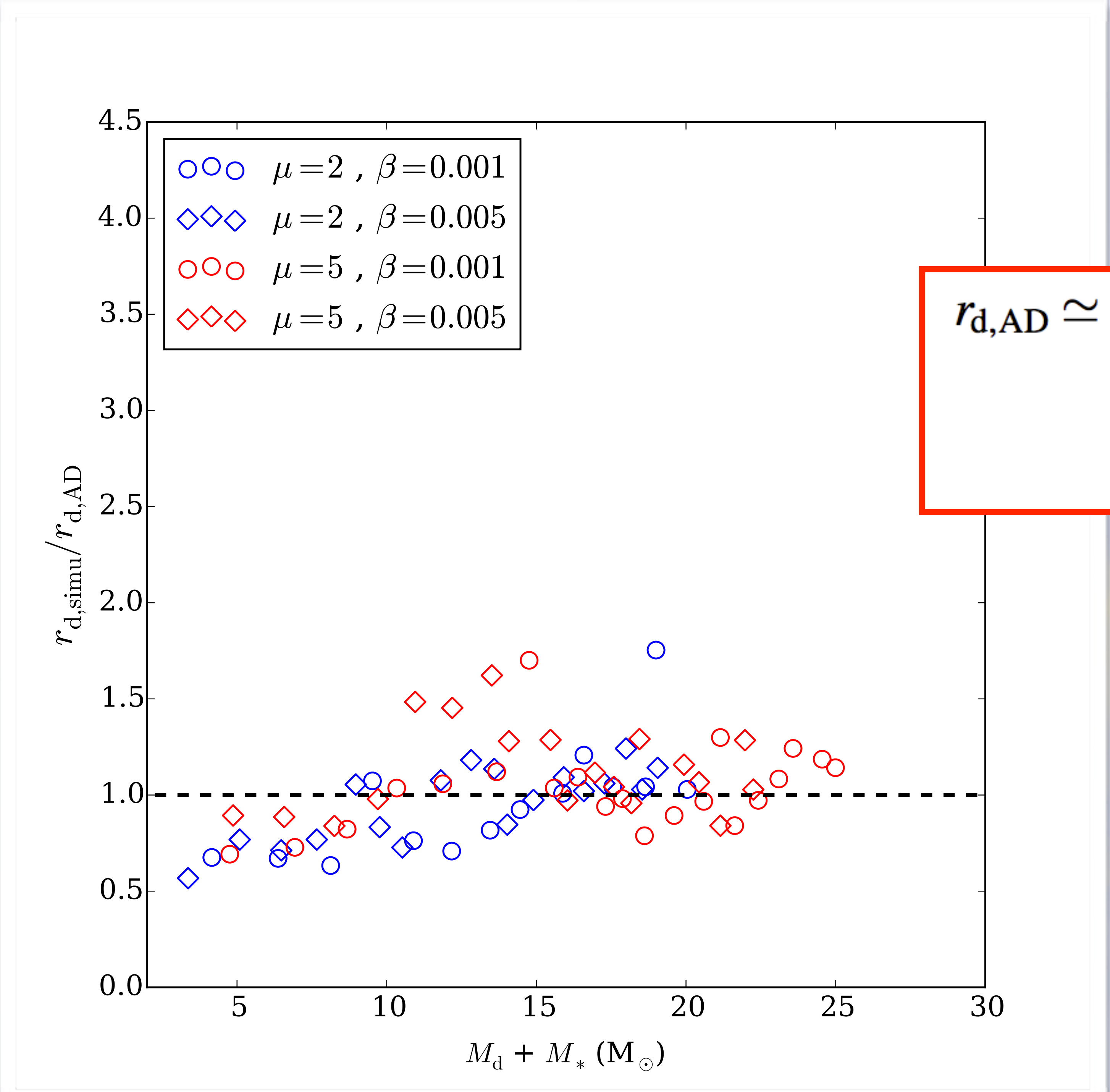
Disc size regulation by ambipolar diffusion



$$r_{\rm d,AD} \simeq 18\ {\rm au} \times \delta^{2/9} \left(\frac{\eta_{\rm AD}}{0.1\ {\rm s}}\right)^{2/9} \left(\frac{B_z}{0.1\ {\rm G}}\right)^{-4/9} \left(\frac{M_{\rm d} + M_*}{0.1\ M_\odot}\right)^{1/3}$$

- ✓ disc radius regulated by ambipolar diffusion
- ✓ Weak dependance on the mass
- ✓ Works for low mass star as well!

Hennebelle, Commerçon, Chabrier & Marchand, ApJL in press

Conclusion

- ☑ Outflow is primarily of magnetic origin
- ☑ Magnetic outflow extends up to 80 000 AU
- ☑ Radiative force does not overtake with $M_\star$<15 $M_\odot$, but contributes to acceleration
- ☑ Rayleigh Taylor instability not relevant

- ☑ No large disk - R<500 AU
- ☑ ideal MHD and hydro models have strong limitations wrt
  1. outflow launching
  2. disk properties (as well as for low-mass star formation… see Masson et al. 2016)
  3. angular momentum transport
- ☑ Next: couple to a better irradiation scheme (M1?)

Astrosim school


Ecole numerique pour l'astrop
https://astrosim.sciencesconf.org/?forward-action=index&forward-controller=index&lang=en

Astrosim : Ecole numérique pour l'astrophysique

26 juin - 7 juillet 2017, Lyon, France

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- Planning
- Practical informations
- Registration
- List of Participants

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OBJECTIVES OF THE SCHOOL

Numercal simulations are playing a key role in many areas of modern sciences including astrophysics as well as in the industry. It is not unavoidable and is complementary of observations and theory. Without numerical simulations our understanding of astrophysical systems would be significantly less than what it is today.

However, performing numerical simulations for astrophysics requieres a large ensemble of specific skills in several different areas. First there are generic aspects common to many simulations such as massively parallel calculations, numerical methods of applied mathematics and algorithms as well as analyis of large volumes of data. Second several programs called codes have been developed by groups of developers during the last decades to treat various astrophysical problems. Running and developing these codes is a necessity for advanced researchers as well as PhD students, however this represents sometimes such an effort and an expertize that a specific training is needed.

The goal of the school will be to present several codes that are playing a key role in today astrophysics. Both theorical aspects regarding the methods used and the practical ones, that is to say how to use the codes will be descrived. In particular practical sessions will be organised during the afternoons.

PROGRAM AND SPEAKERS

The organisation of the school will be as follows:

-2 theoretical lectures will be given every morning during which practical

SCIENTIFIC ORGANISING COMMITTEE

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Benoît Commerçon

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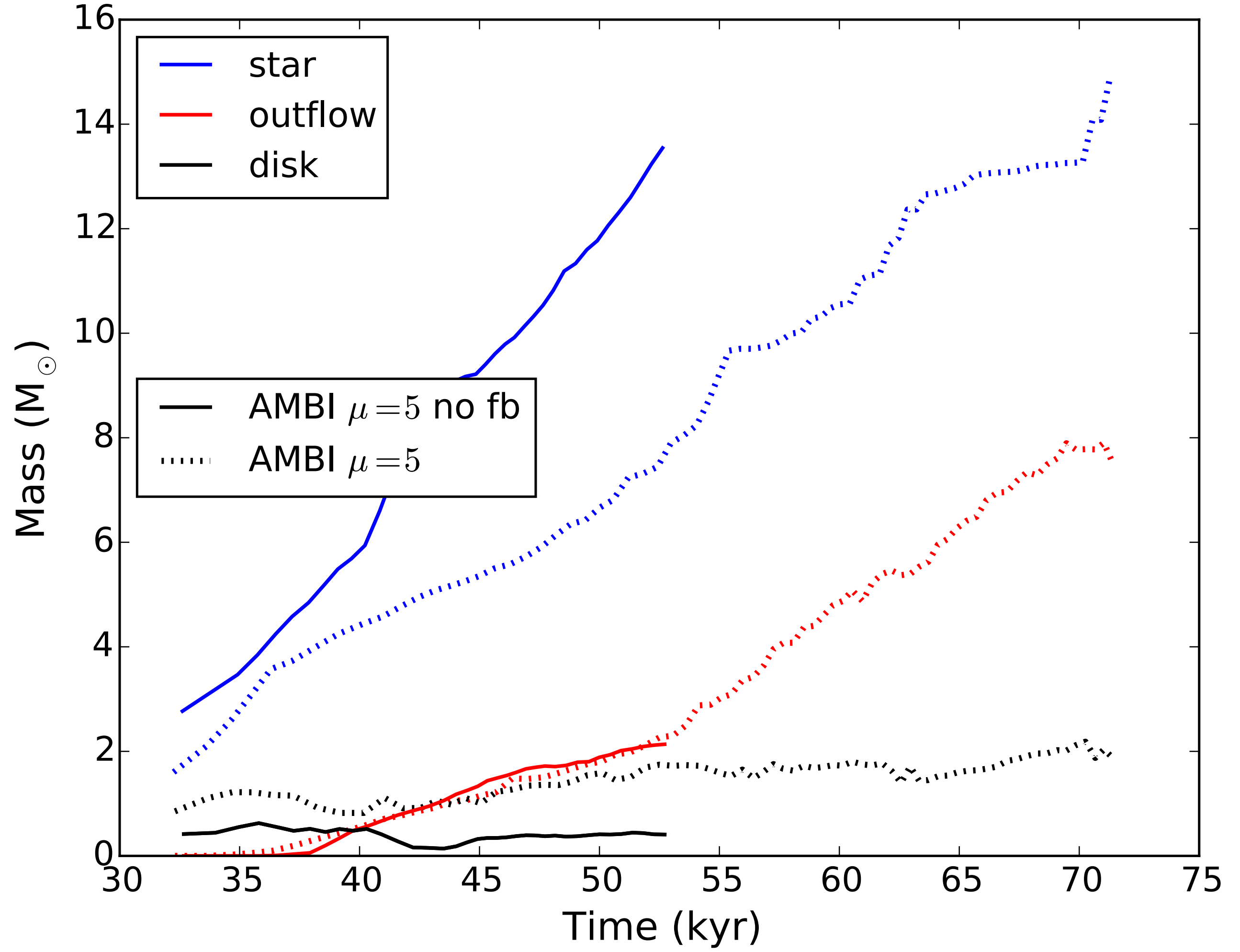
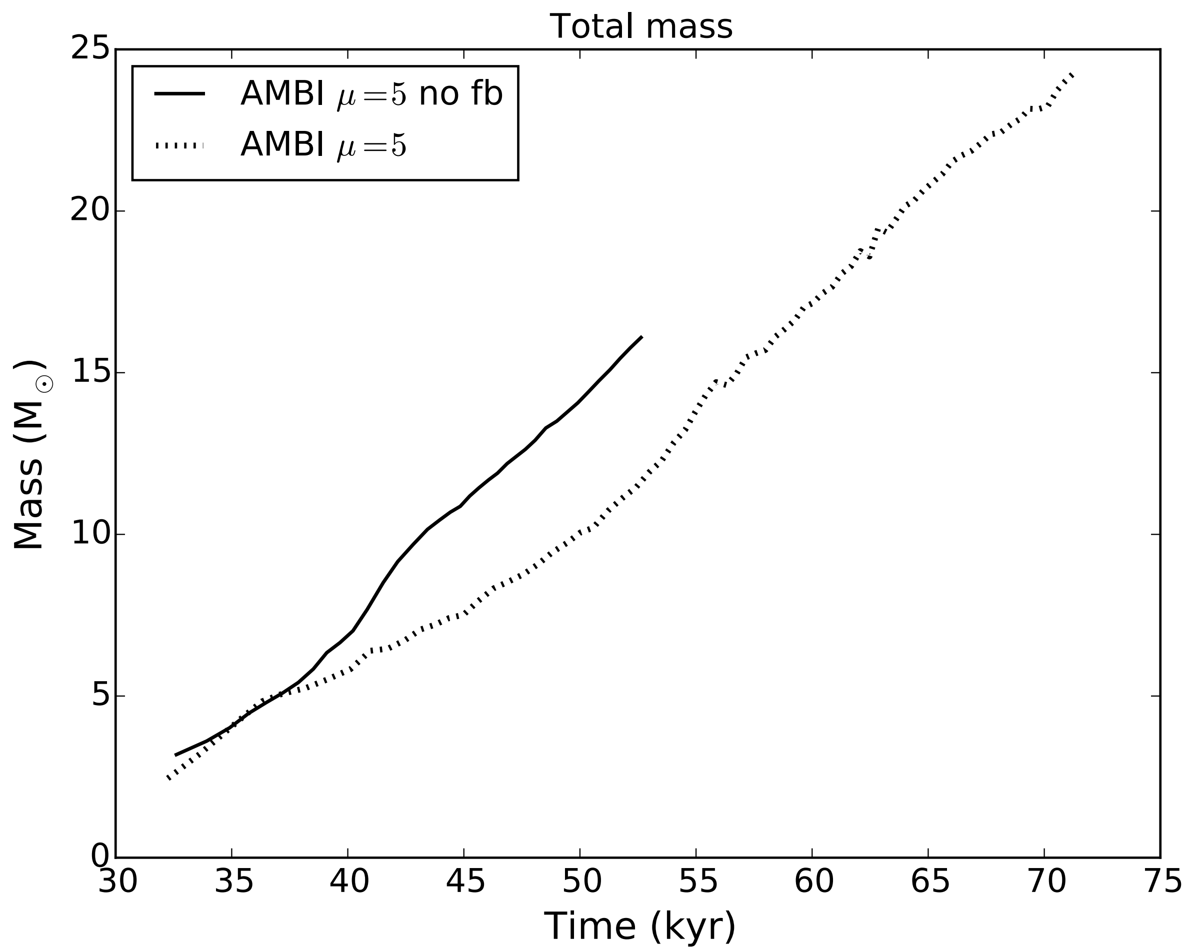
THANK YOU

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?