Non-ideal MHD consequences for the first Larson core

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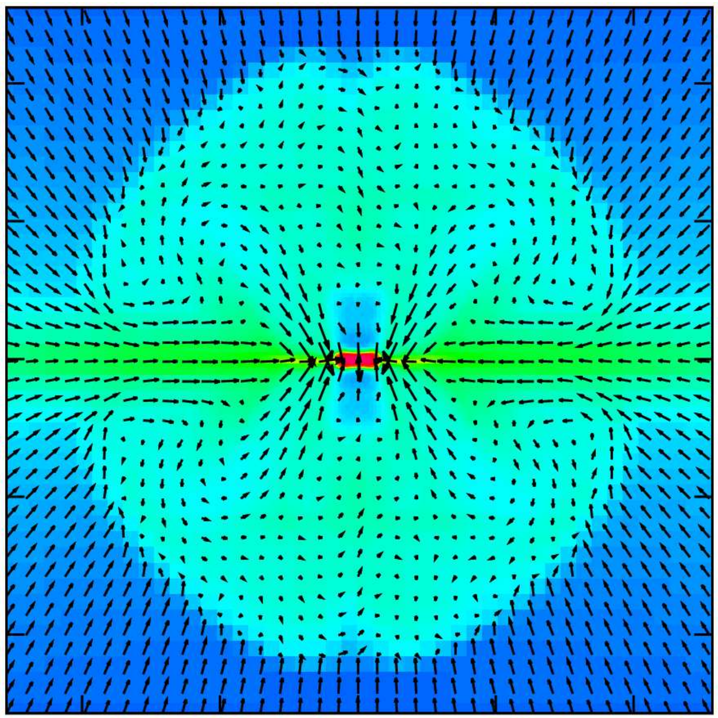
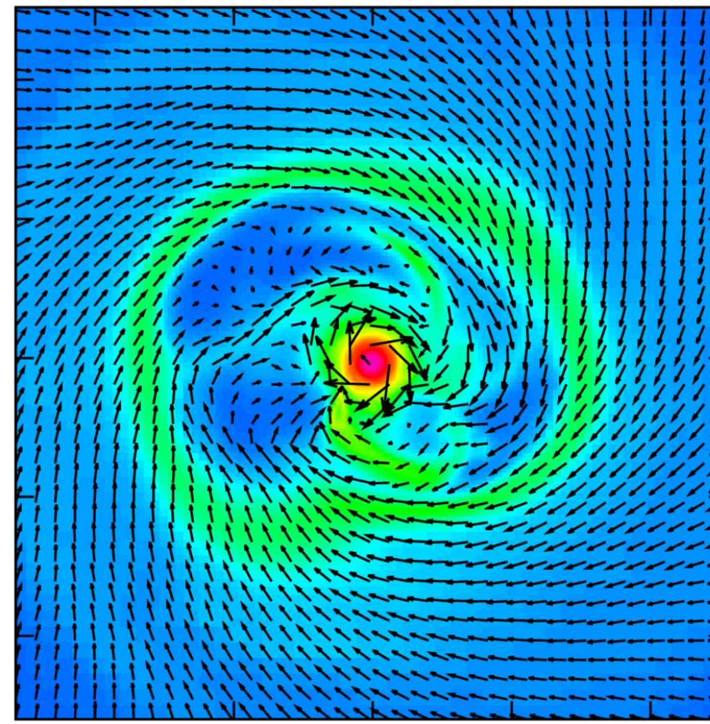
We study the consequences of ambipolar diffusion for the first Larson core and its surroundings, namely the disk and the outflow. We show that the decoupling of neutral matters and magnetic fields due to ambipolar diffusion has strong consequences in the magnetic field topology and therefore on angular momentum repartition and the following properties of the disk (velocity field, beta plasma, aspect ratio)

Subject :	:	oral
Topics	:	Astrophysics

Non-ideal magnetohydrodynamics in low mass star formation





Jacques Masson

Coworkers: Gilles Chabrier, Patrick Hennebelle, Benoit Commerçon, Neil Vaytet

The Plan

- I.General Context
  - The physics
  - Why bother ?
- II.Studying star formation
  - A.In a computer...
  - B.A better physics for a better understanding
- III.Numerical simulations : from micro- to macro-physics
  - C.First Larson core
  - D.Disks

What are we cooking?

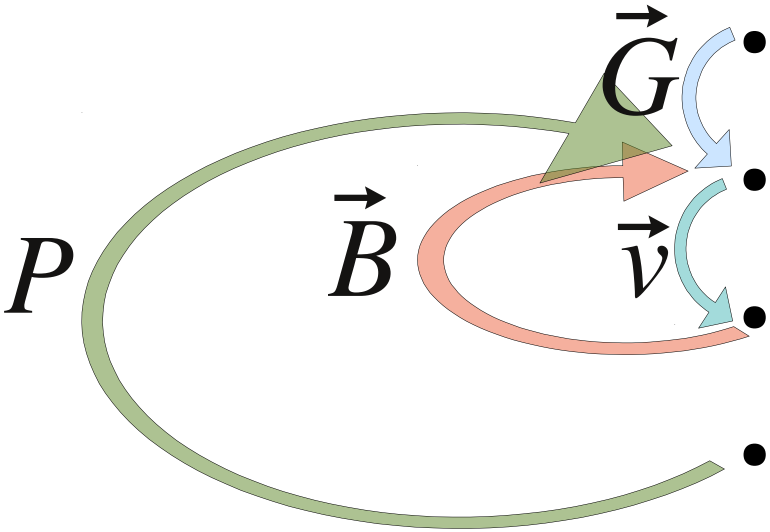
- Gravity
- Hydrodynamics
- Magnetic fields
- Transfer + EOS
- Chemistry + grains

It sounds delicious!

- Gravity
- Hydrodynamics
- Magnetic fields
- Transfer + EOS
- Chemistry + grains

- Poisson equation
- Euler equation
- Induction equation
- Energie equation
- Chemical network

Stirr, stirr, stirr...



- Poisson equation
- Euler equation
- Induction equation
- Energie equation
- Chemical network

N coupled chemical species...

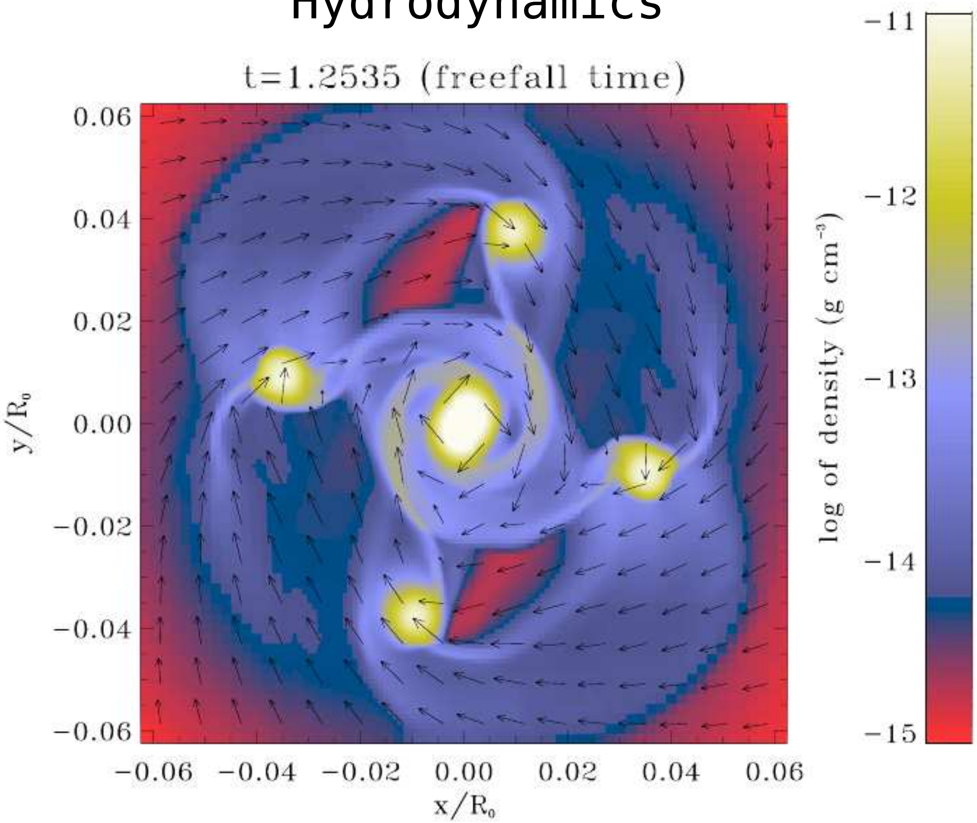
This is interesting...

- Fragmentation
- Disks formation
- Outflows and jets
- Angular momentum
- Magnetic flux

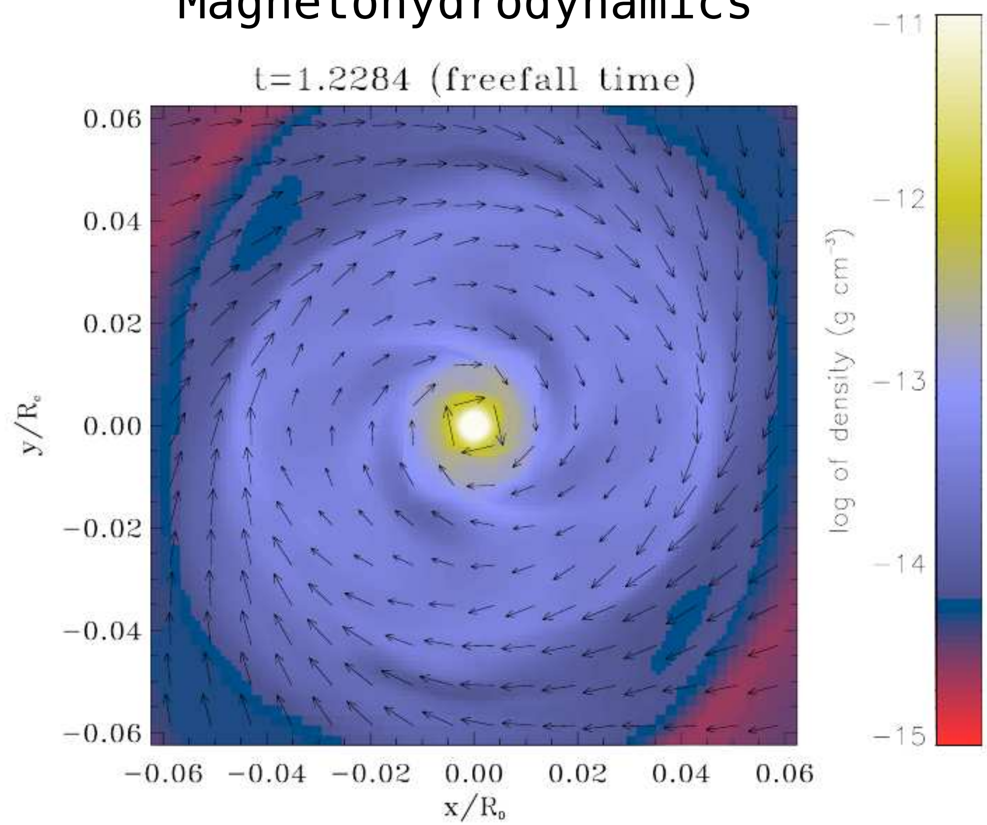
Conservation laws

- Angular momentum ωr^2
- Magnetic flux $\phi_B \propto B r^2$

Hydrodynamics



Magnetohydrodynamics

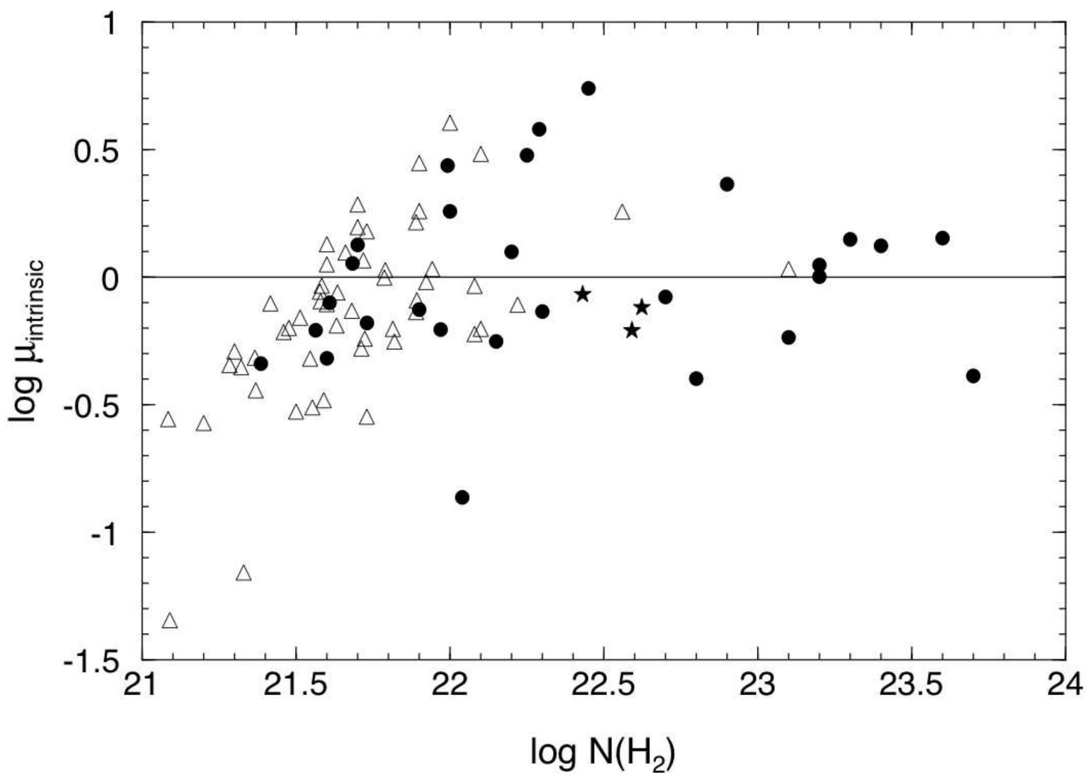


Hennebelle & Teyssier (2008)

Magnetic fields everywhere

$$\rho \frac{D\boldsymbol{v}}{Dt} = -\boldsymbol{\nabla}\left(P + \boxed{\frac{B^2}{2\mu_0}}\right) - \rho \boldsymbol{\nabla}\Phi + \boxed{\left(\frac{\boldsymbol{B}}{\mu_0}\cdot\boldsymbol{\nabla}\right)\boldsymbol{B}}$$

(Heiles et Crutcher 2005)



- Close to the critical value

$$M_{\text{crit}} = M_{\text{Jeans}} + M_{\text{mag}}$$

- Parameter:

$$\mu = \frac{\left(\frac{M}{\Phi}\right)}{\left(\frac{M}{\Phi}\right)_{crit}}$$

- B-field must decouple from neutral matter

Non-ideal MHD

- Taking into account collisions between charged and neutral particules, the magnetic field lines can decouple from the neutral matter.

$$Zen_i(\mathbf{E} + \mathbf{v_i} \times \mathbf{B}) - \rho_i \sum_{j=e,n} \nu_{ij}(\mathbf{v_i} - \mathbf{v_j}) = 0$$

$$-en_e(\mathbf{E} + \mathbf{v_e} \times \mathbf{B}) - \rho_e \sum_{j=i,n} \nu_{ej}(\mathbf{v_e} - \mathbf{v_j}) = 0$$

with $\nu_{\mathbf{kj}} = \rho_j \gamma_{kj} = \rho_j < \sigma v >_{kj} (m_j + m_k)^{-1}$

$$\mathbf{E} + \Big[\mathbf{v} + (\mathbf{v_e} - \mathbf{v_i}) + (\mathbf{v_i} - \mathbf{v})\Big] \times \mathbf{B} + \frac{n_n m_e < \sigma_{en} v_e >}{e}\Big[(\mathbf{v_e} - \mathbf{v_i}) + (\mathbf{v_i} - \mathbf{v})\Big] = 0$$

Thus, with : $\gamma_{\mathrm{AD}} = \frac{<\sigma_{in} v_i>}{(m_i + m_n)}$ and $\sigma = \frac{n_e e^2}{n_n m_e <\sigma_{en} v_e>}$

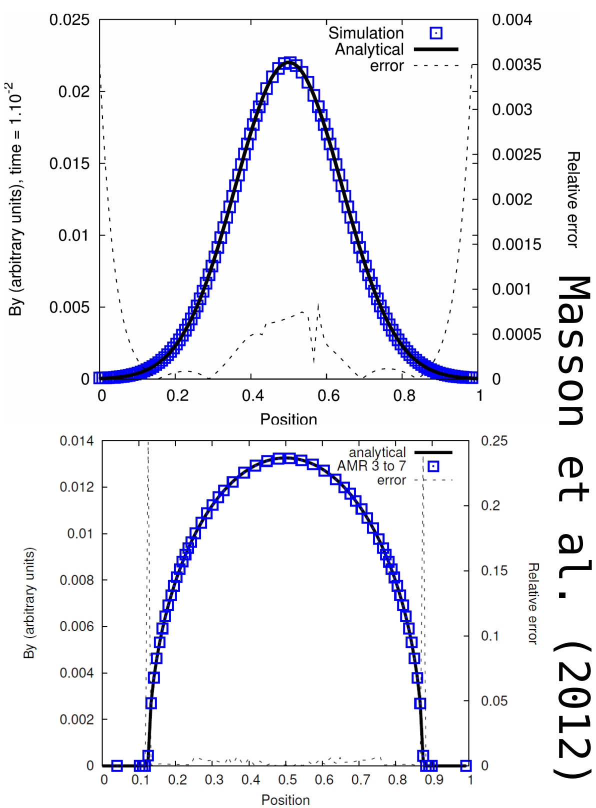
$$\partial_t \mathbf{B} = \nabla \times \Big[\mathbf{v_n} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{en_e} + \frac{\big[(\nabla \times \mathbf{B}) \times \mathbf{B}\big] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_i} - \frac{\mathbf{J}}{\sigma}\Big]$$

Non-ideal MHD

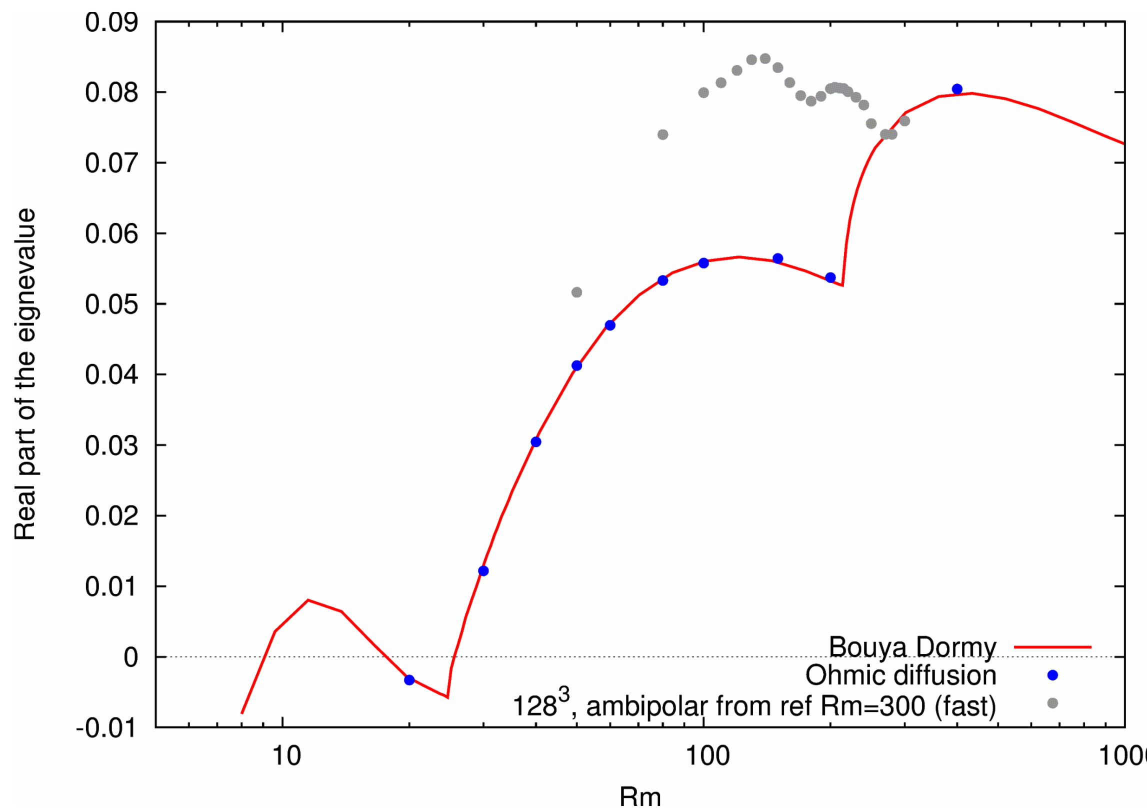
$$\partial_t \mathbf{B} = \nabla \times \left[\mathbf{v_n} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{e n_e} + \frac{[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_i} - \frac{\mathbf{J}}{\sigma} \right]$$

Induction | Hall | Ambipolar | Ohm

- Ohmique and ambipolar diffusion: true diffusion ?



Masson et al. (2012)



Masson et al. (in prep)

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A. Non-ideal MHD in RAMSES

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho\,(\mathbf{v}.\nabla)\mathbf{v} + \nabla P - \mathbf{F}_L = 0$$

$$\frac{\partial E_{tot}}{\partial t} + \nabla.((E_{tot} + P_{tot})\mathbf{v} - (\mathbf{v}.\mathbf{B})\mathbf{B} - \mathbf{E}_{AD} \times \mathbf{B}) = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times \mathbf{E}_{AD} = 0$$

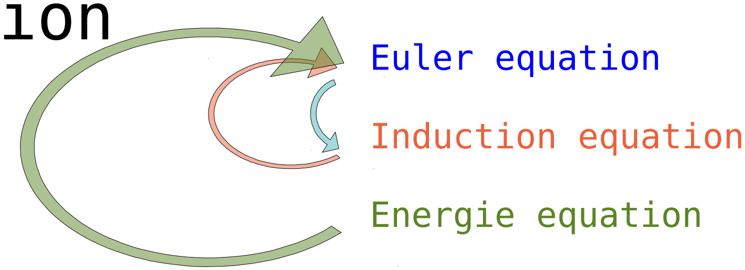
with $$E_{tot} = \rho\epsilon + \frac{1}{2}\rho v^2 + \frac{1}{2}B^2$$

$$\mathbf{F}_L = (\nabla \times \mathbf{B}) \times \mathbf{B}$$

$$\mathbf{E}_{AD} = (\mathbf{v}_i - \mathbf{v}_n) \times \mathbf{B} = \frac{1}{\gamma_{AD}\rho_i\rho}\mathbf{F}_L \times \mathbf{B}$$

60 pages in Masson et al. (2012)

- Tests for the induction equation
- Tests for oblique shock (45°)
- Tests for Alfvén waves



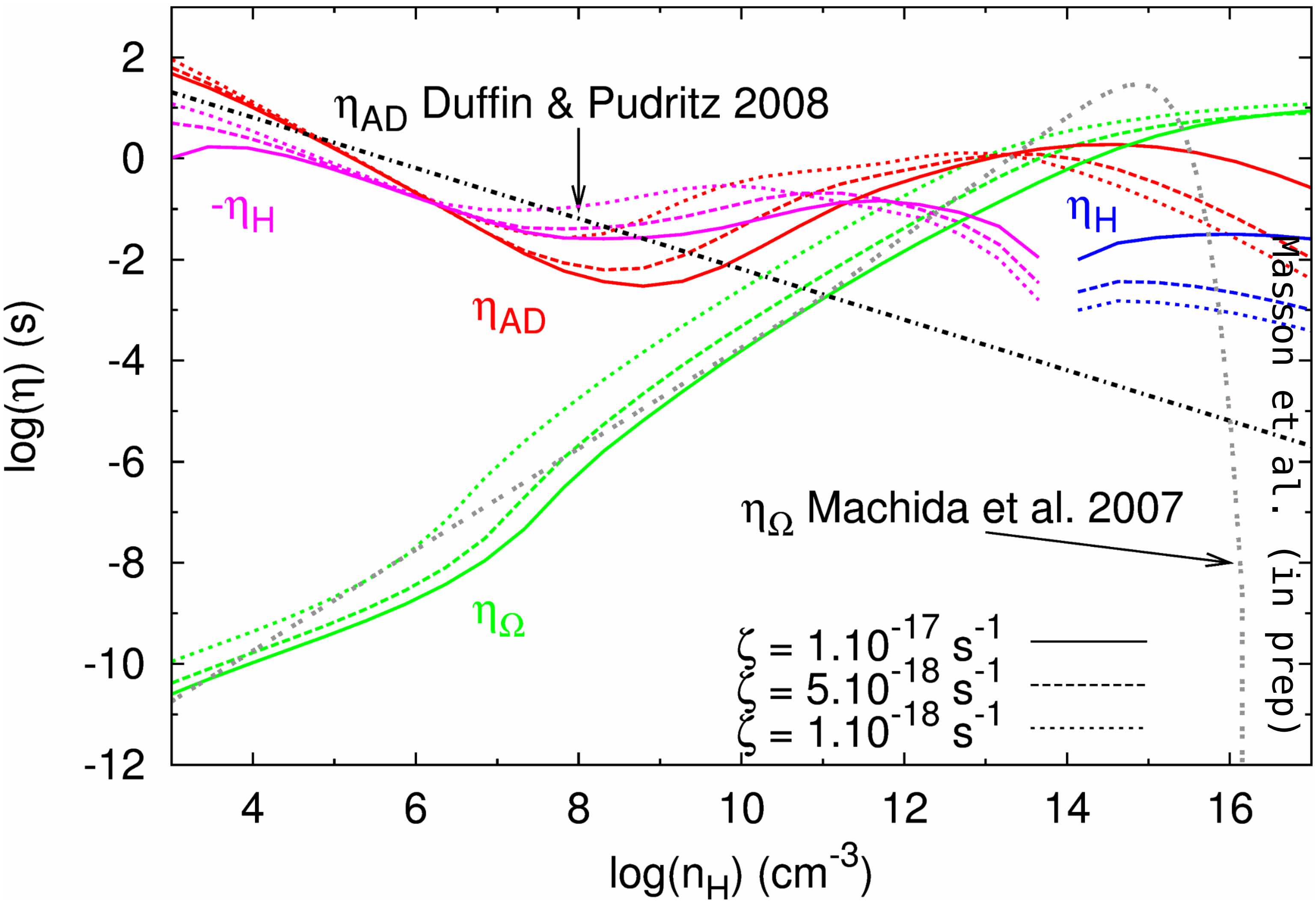
B.Microphysics

- $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\mathbf{v} \times \mathbf{B} - \eta_\Omega (\nabla \times \mathbf{B}) - \eta_H \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} - \eta_{AD} \frac{\mathbf{B}}{B} \times \left\{ (\nabla \times \mathbf{B}) \times \frac{\mathbf{B}}{B} \right\} \right]$$

- Physics and chemistry « under the carpet »
  - Dust grains, shape, properties...
  - Non-equilibrium chemical network
  - Temperature and density dependency

$$\left\{ \begin{array}{l} \ldots \\ \frac{dx_i}{\tilde{d}t} = \sum_{j=1}^{N} \left[\alpha_{ij} x_j + \frac{n_H}{2\zeta} \sum_{k=1}^{N} \beta_{ijk} x_j x_k - \frac{n_H}{\zeta} \gamma_{ij} x_j x_i \right] \\ \ldots \end{array} \right.$$

B. Microphysics: macro-changes



- Conductivity

$$\sigma_{\parallel} = \sum_s \sigma_s$$

$$\sigma_{\perp} = \sum_s \frac{\sigma_s}{1+(\omega_s \tau_{sn})^2}$$

$$\sigma_H = -\sum_s \frac{\sigma_s \omega_s \tau_s n}{1+(\omega_s \tau_{sn})^2}$$

with

$$\sigma_s = \frac{n_s q_s^2 \tau_{sn}}{m_s}$$

$$w_s = \frac{q_s B}{m_s c}$$

$$\tau_{sn} = \frac{1}{a_{sH_e}} \frac{m_s + m_{H_2}}{m_{H_2}} \frac{1}{n_{H_2} < \sigma_{coll} w >_{sH_2}}$$

ζ : Ionisation rate

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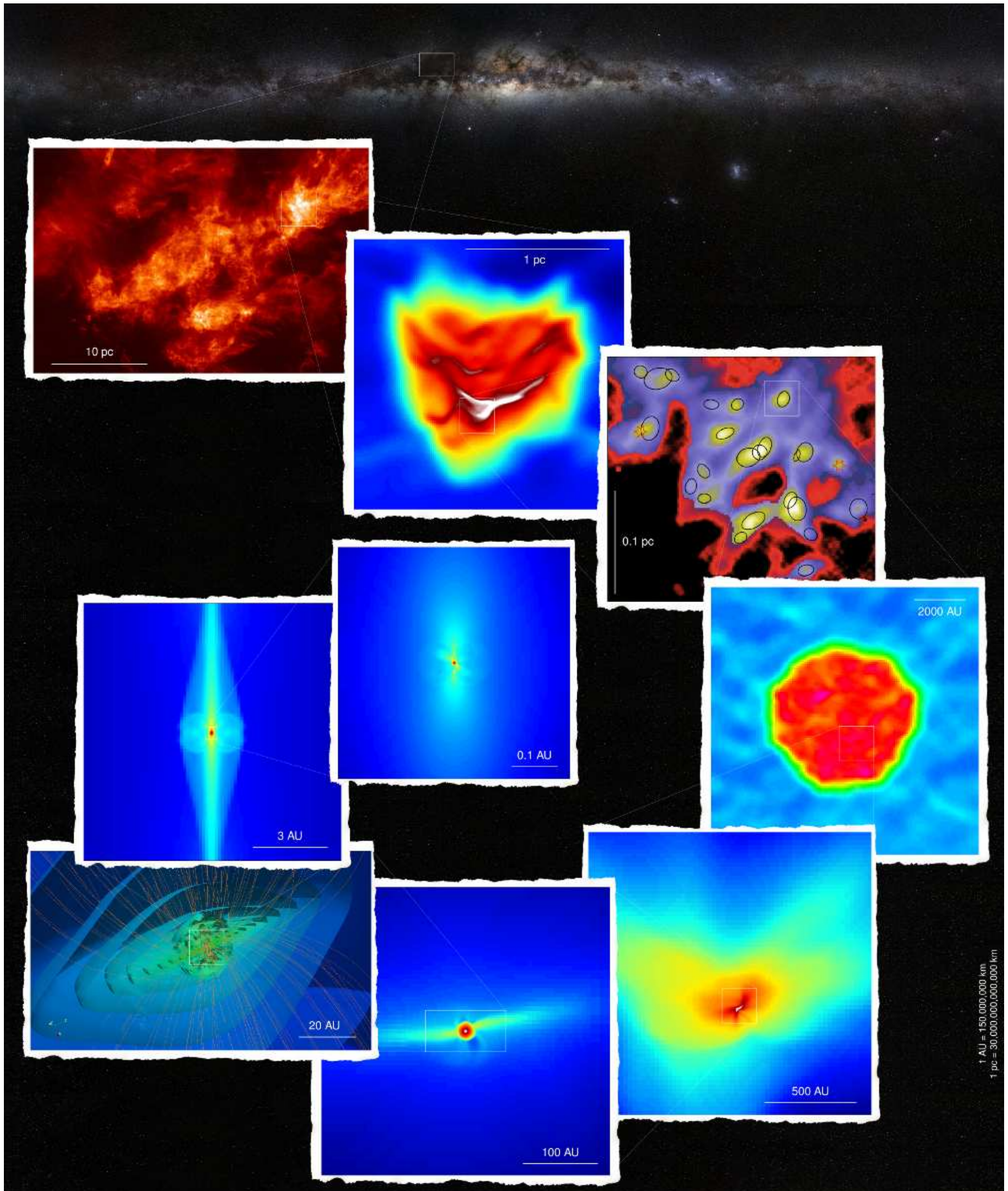
Starting block



Vaytet et al. (2013)

- Dense core

$$\rho = 10^{-18}\,\mathrm{g.cm}^{-3} \qquad M = 1\,M_{\odot}$$

- Thermal support

$$M > M_{\mathrm{crit}}$$

- Turbulent support (or solid-body rotation)

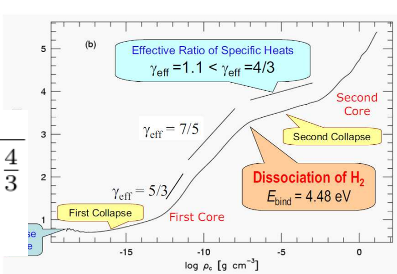
$$\omega \neq 0$$

- Magnetic field

$$\mu = \frac{(\frac{M}{\Phi})}{(\frac{M}{\Phi})_{crit}}$$

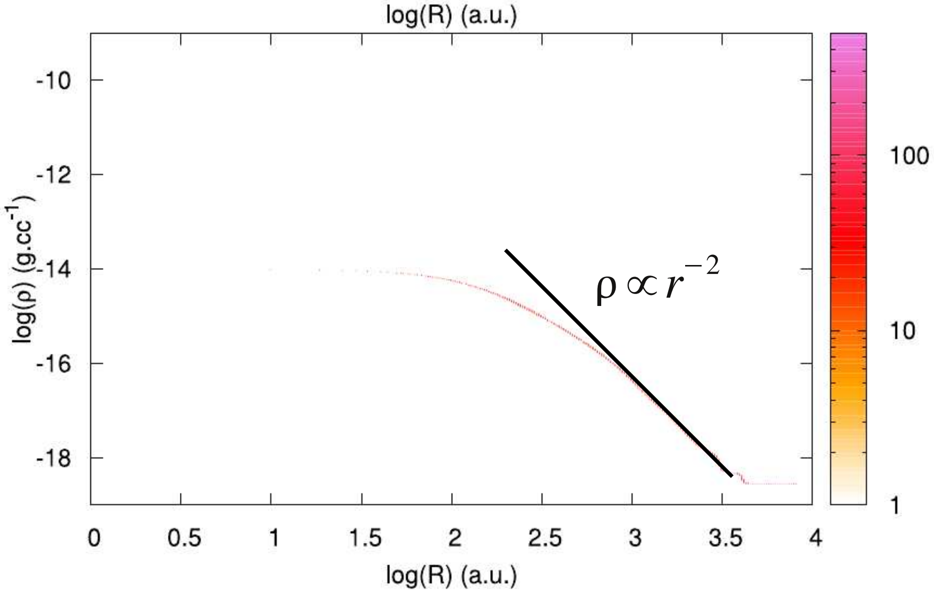
- Barotropic equation of state

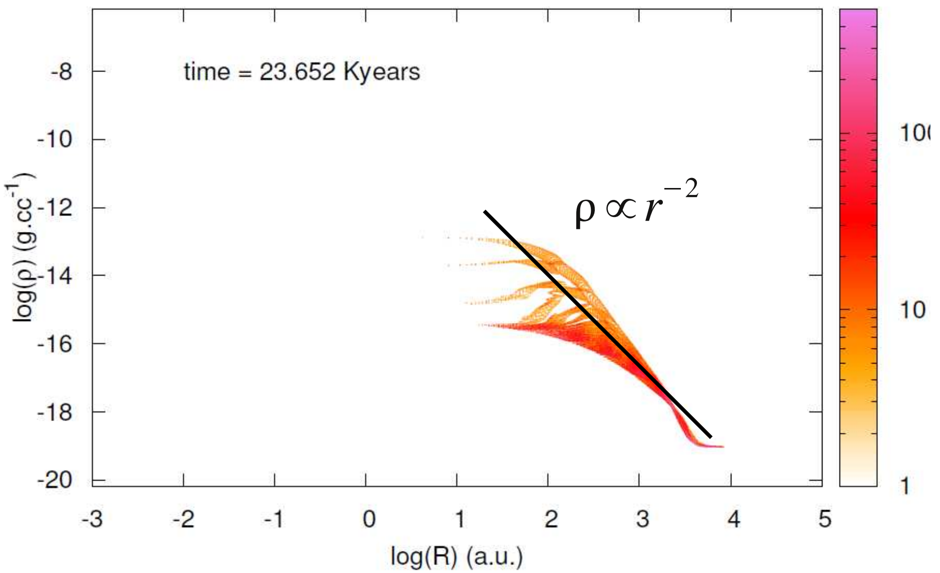
$$\frac{P}{\rho} = c_s^2 \sqrt{1 + \left(\frac{n_H}{10^{-13}\,\mathrm{g.cm}^{-3}}\right)^{\frac{4}{3}}}$$

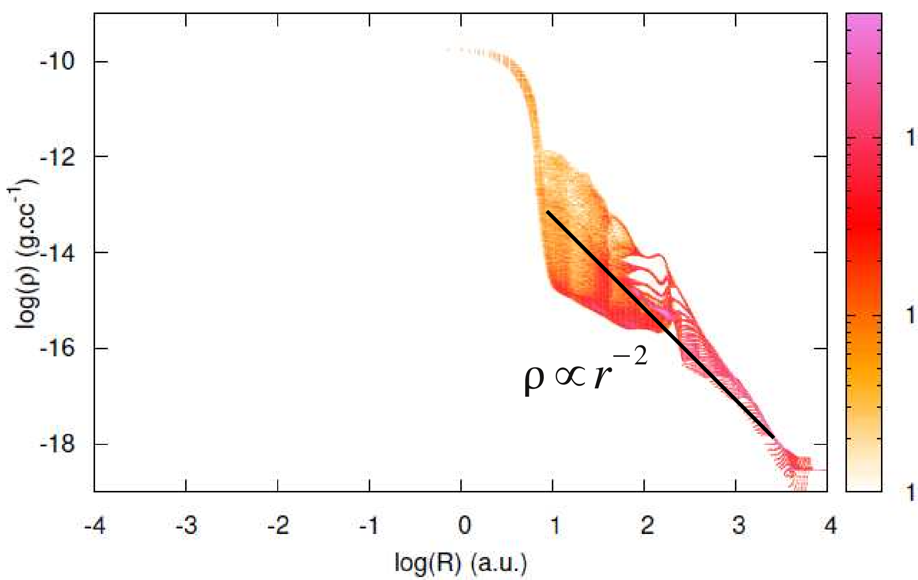


C. First core formation and structures

- Color: number of cells

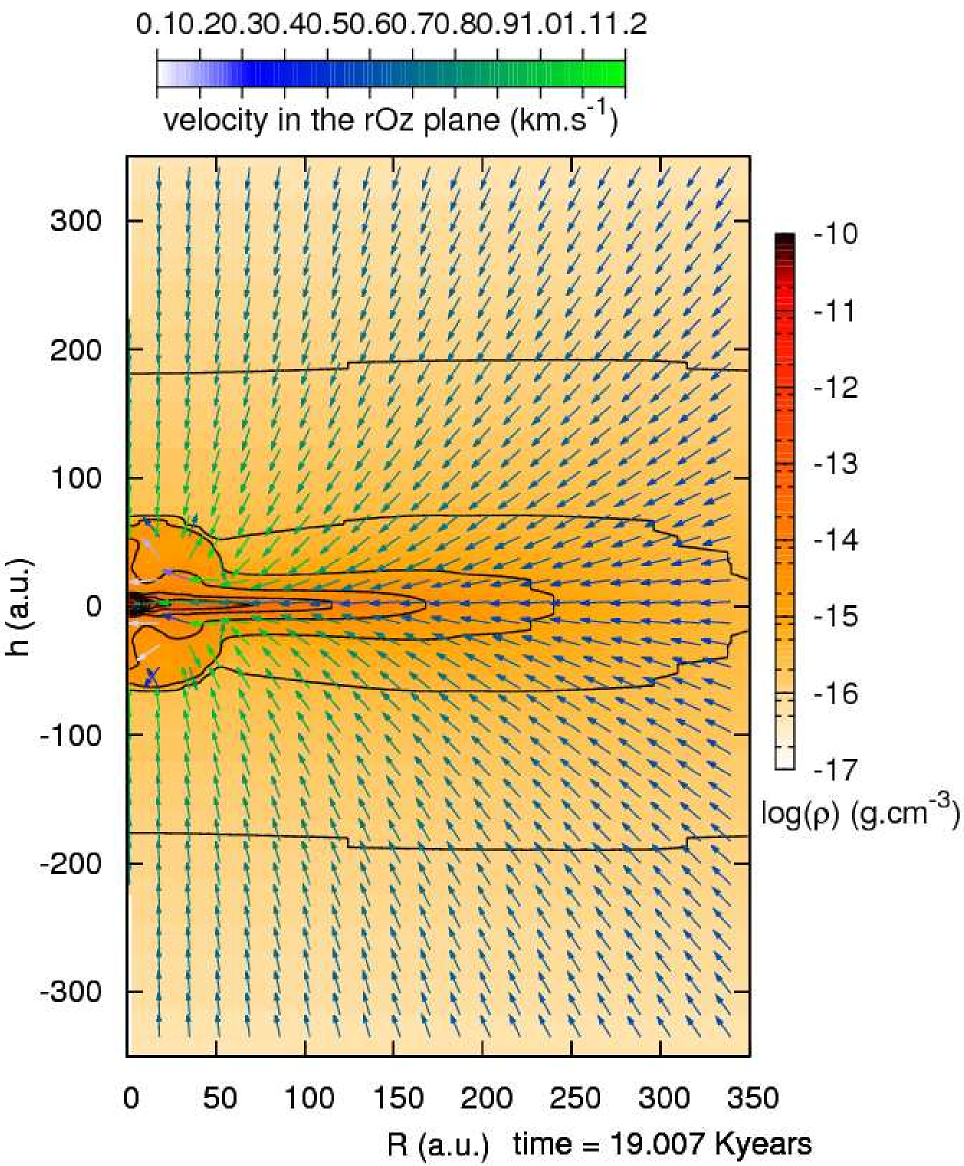


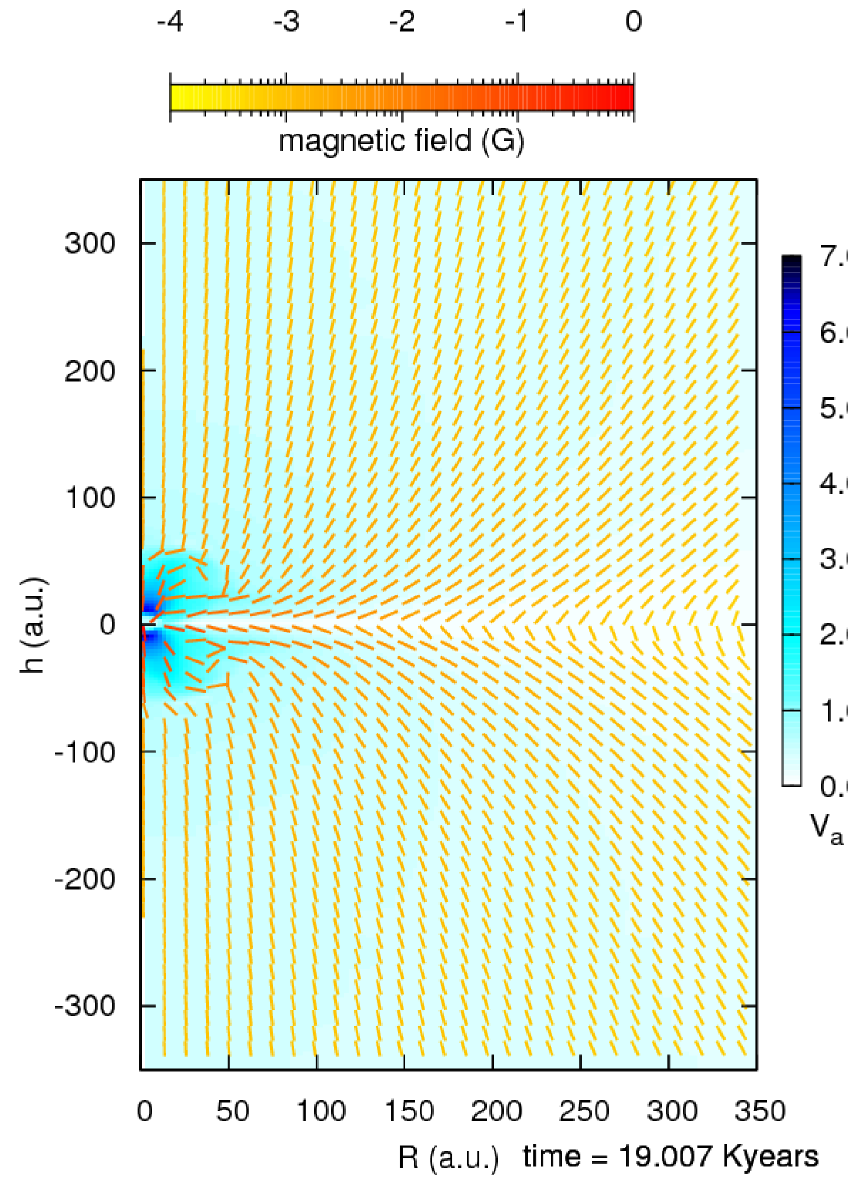




Masson et al. (in prep)

C. First core formation and structures



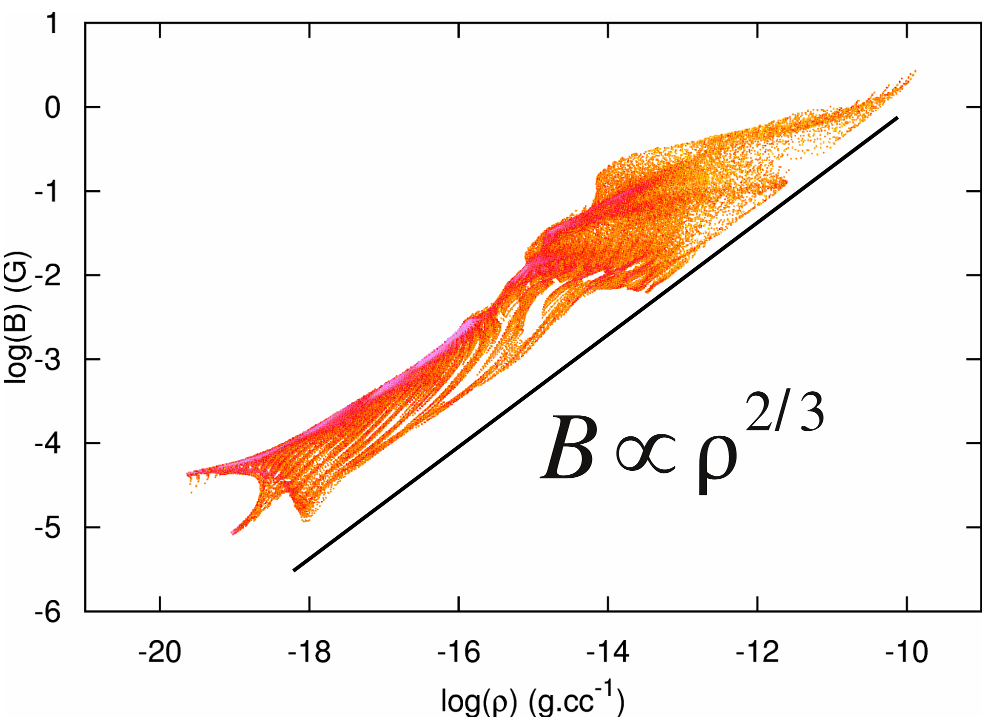


Masson et al. (in prep)

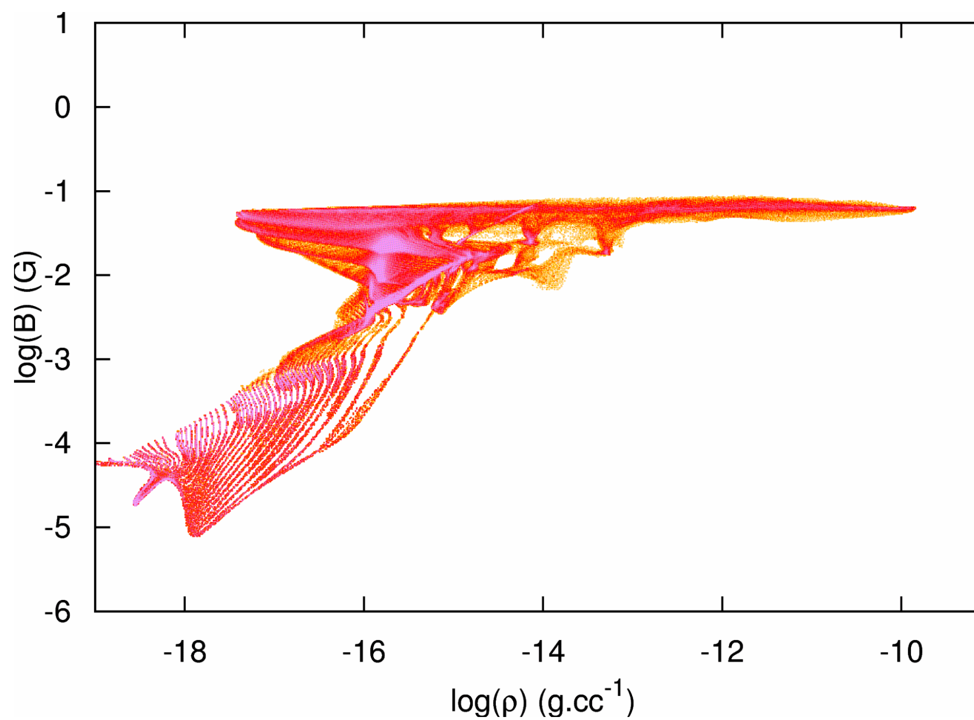
C. Magnetic fields at last !

- About the magnetic flux freezing...

No turbulence $\mu = 5$



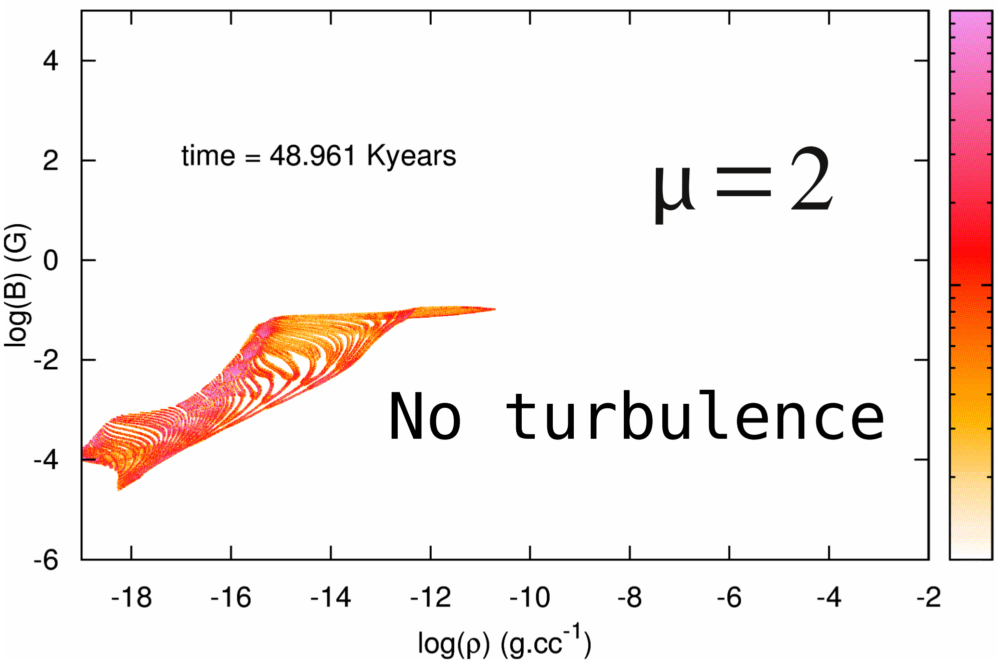
Ideal MHD: IMHD

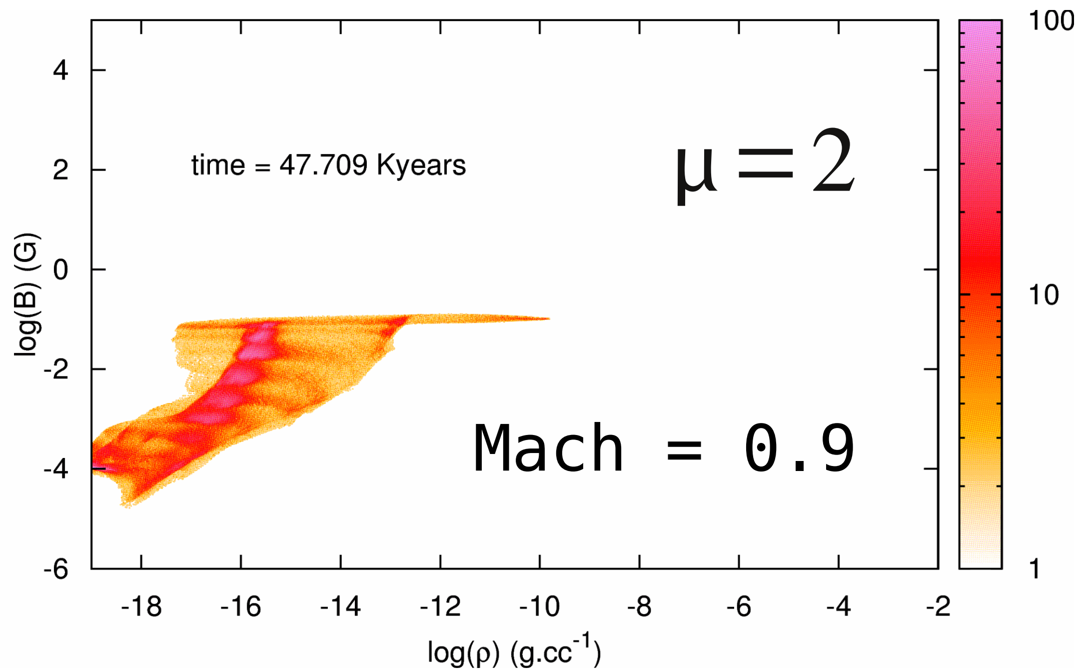


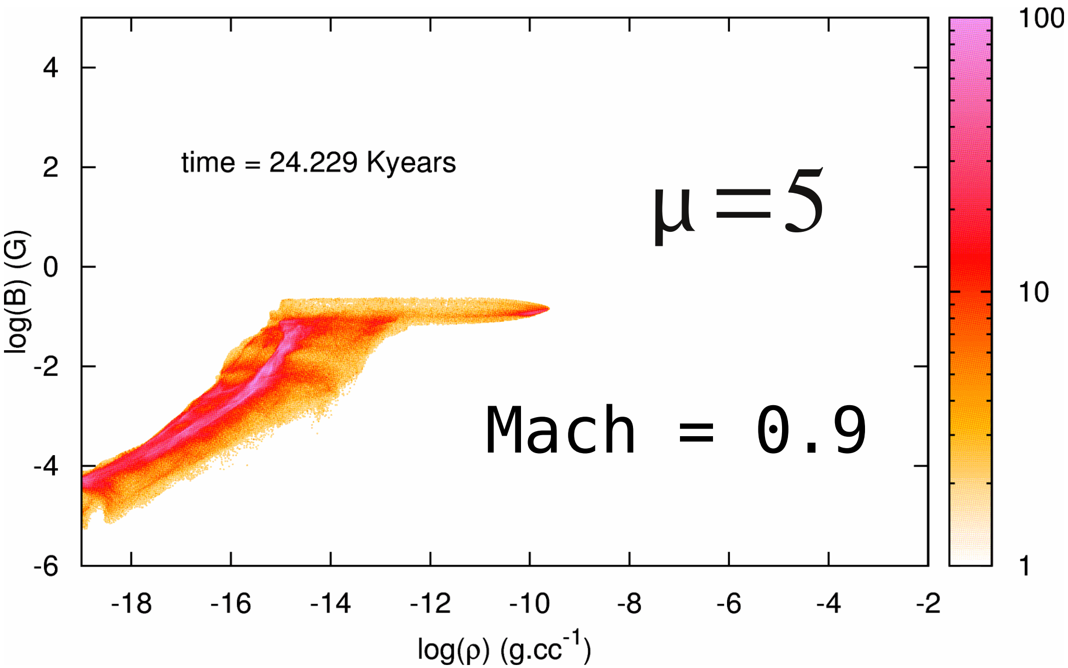
Masson et al. (in prep)

MHD + ambipolar diffusion: AD

C.Stress tests



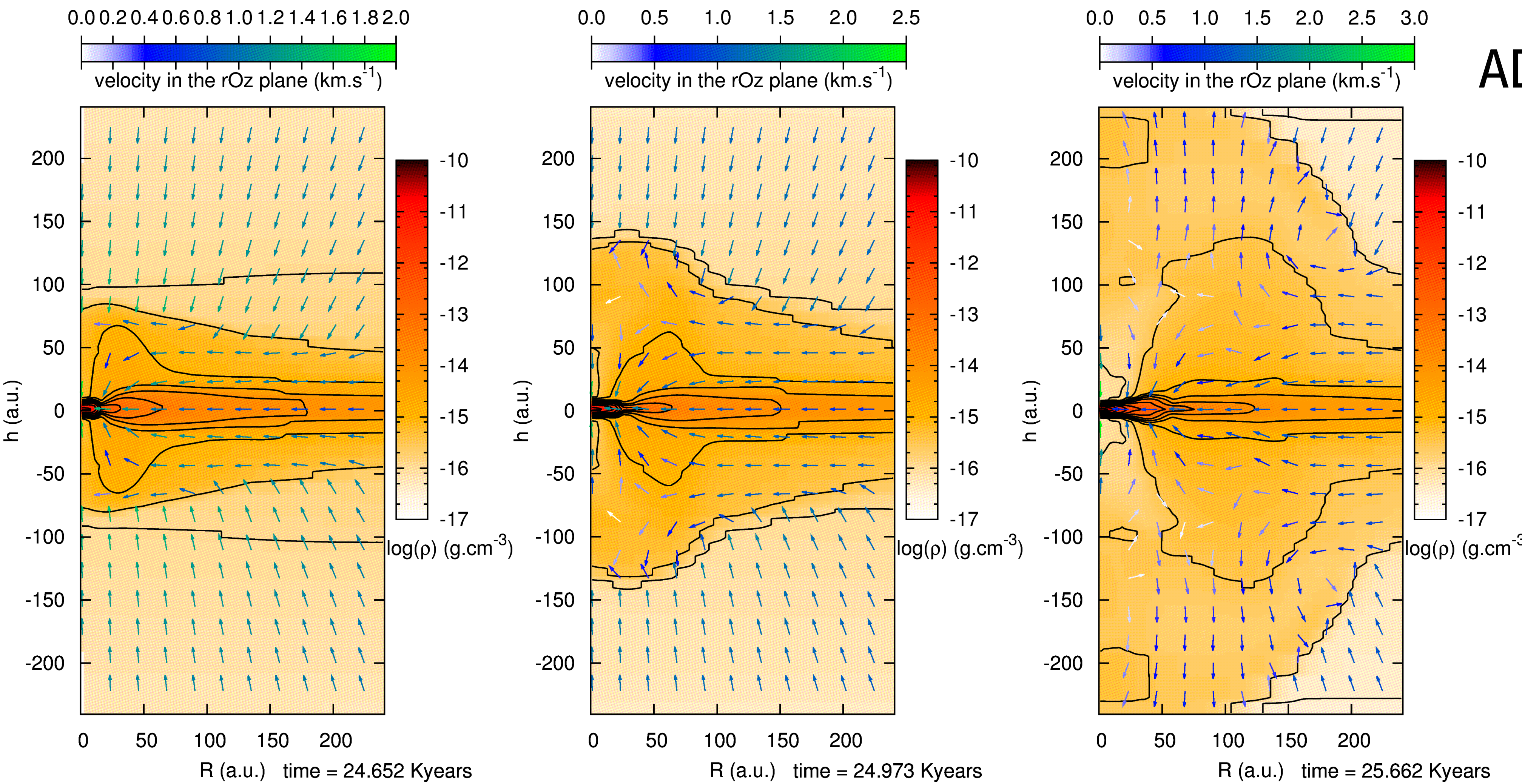




- Independant of initial magnetic field strength
- Self-consistent chemistry

C.Density

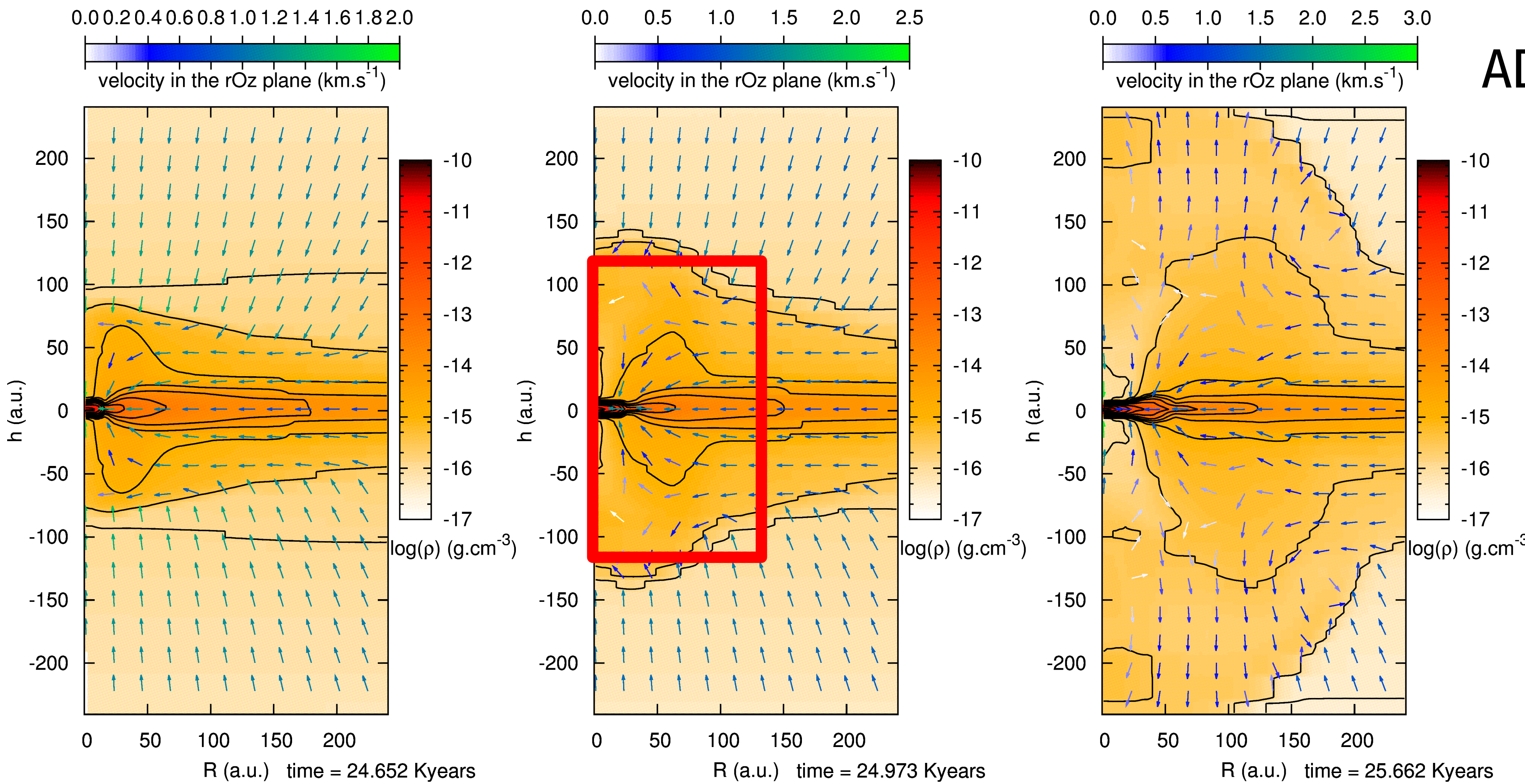
- Rotation, Mach=0, $\mu=5$



Masson et al. (in prep)

C.Density

- Rotation, Mach=0, $\mu=5$

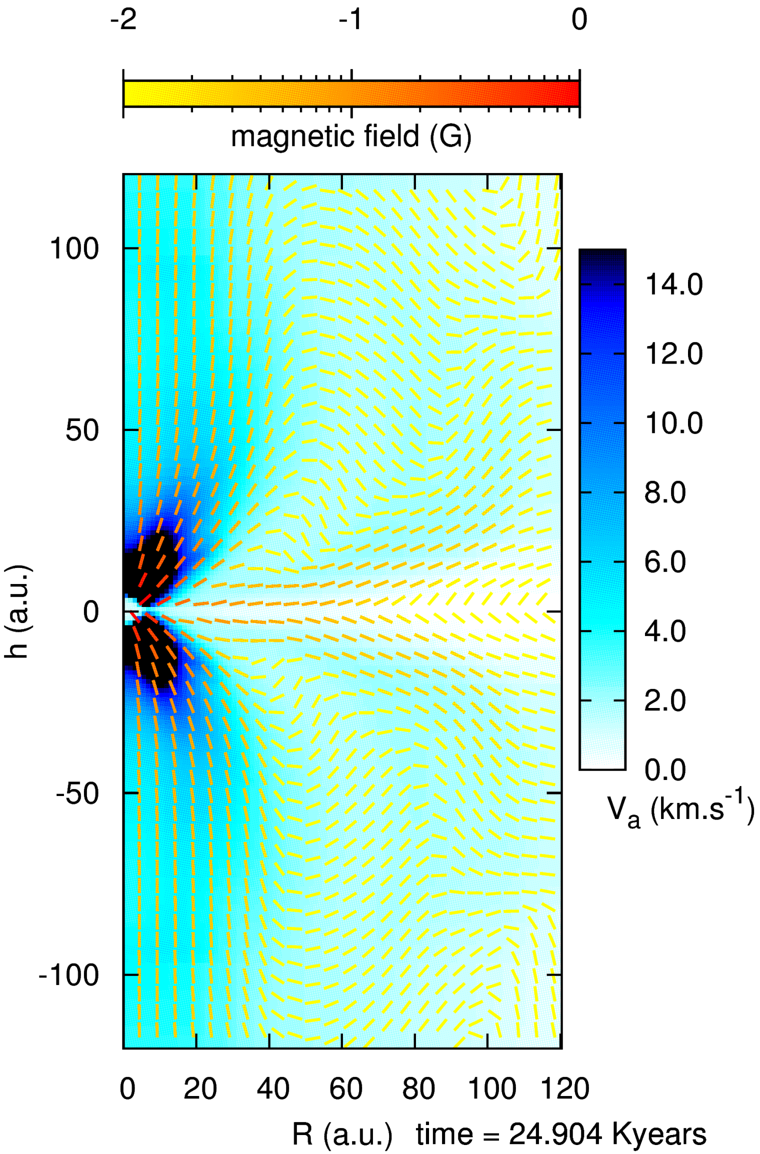


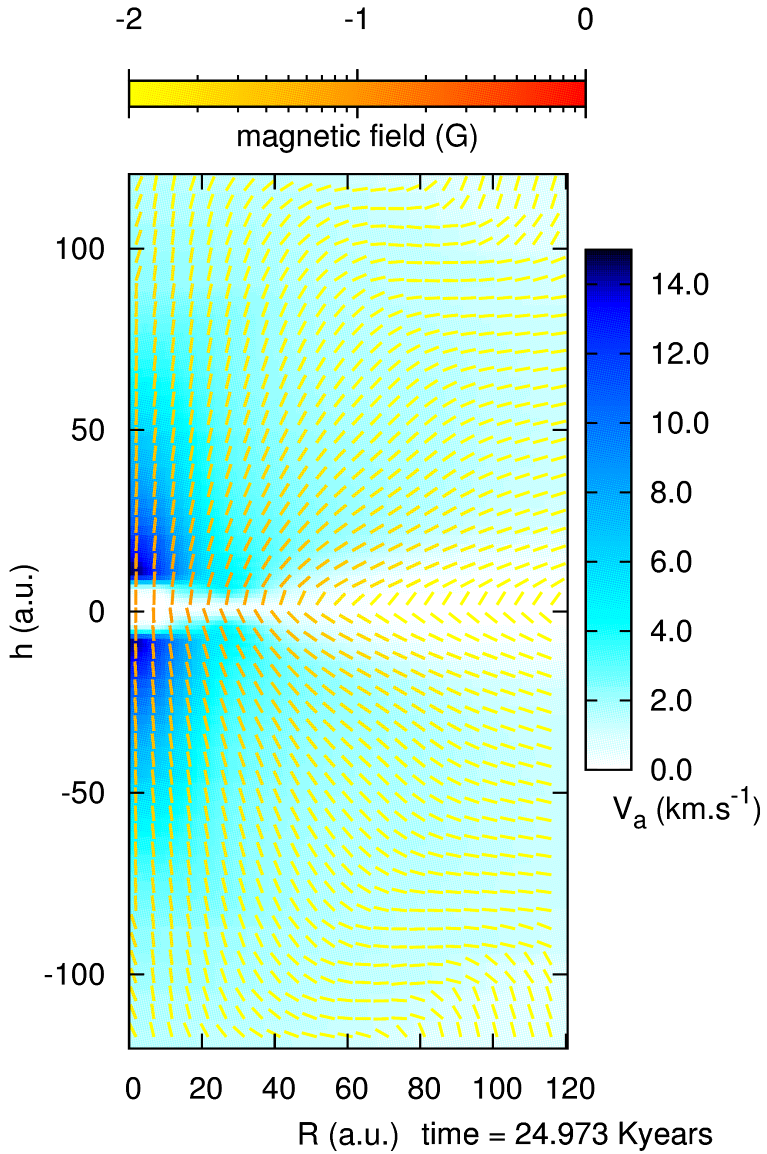
Masson et al. (in prep)

C.B

- Rotation, Mach=0, $\mu=5$

IMHD



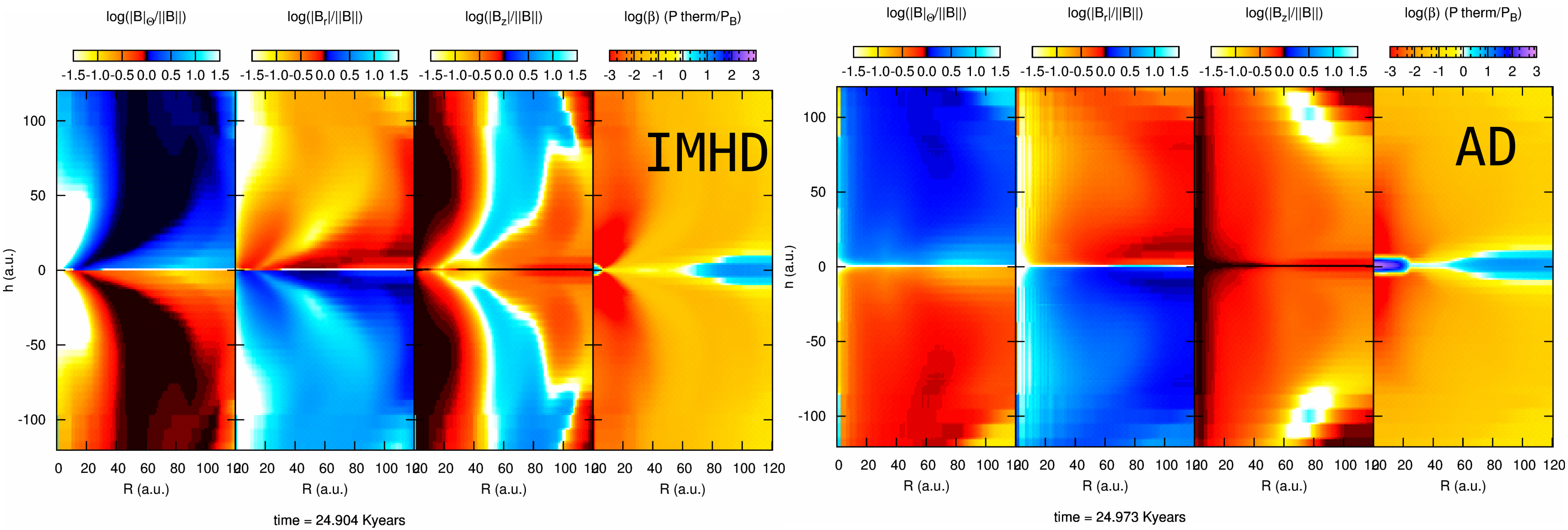


AD

Masson et al. (in prep)

C. A magnetized environment

- Rotation, Mach=0, $\mu=5$



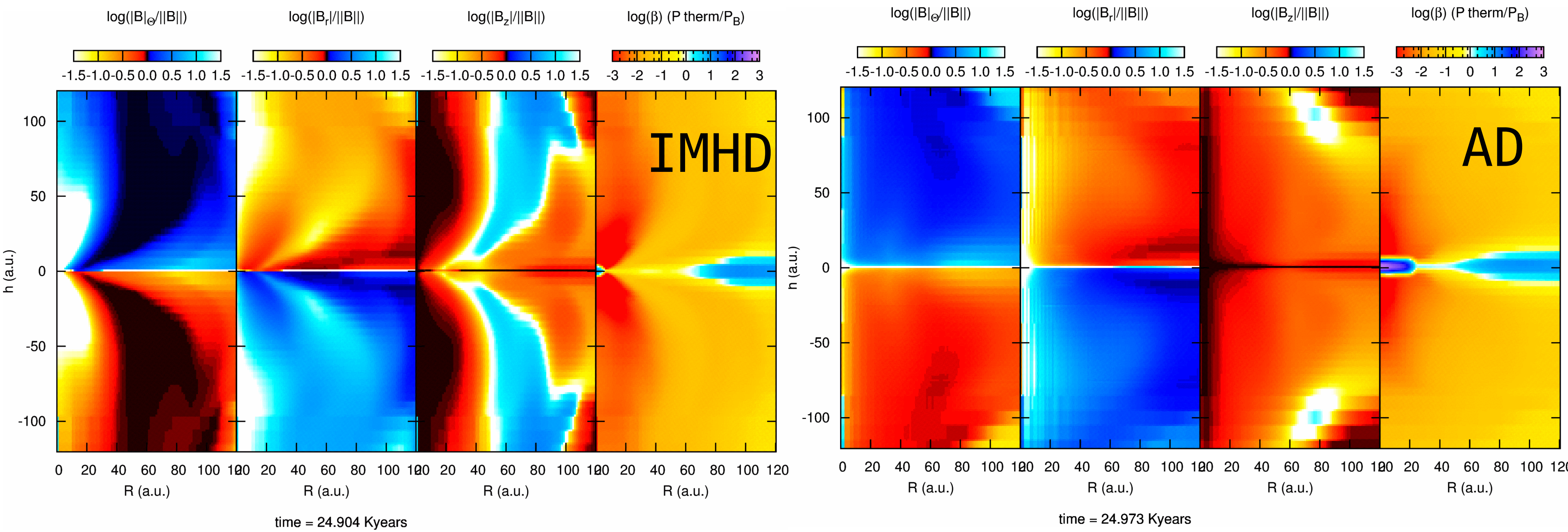
Masson et al. (in prep)

Color scale is in log and accounts for both positive and negative numbers. We plot the ratio of a given component of the field over the norm of the field:

- Black is 100 % and dark blue/red is strong ; White = weak

C. A magnetized environment

- Rotation, Mach=0, $\mu=5$



Masson et al. (in prep)

Time evolution ?

Color scale is in log and accounts for both positive and negative numbers. We plot the ratio of a given component of the field over the norm of the field:

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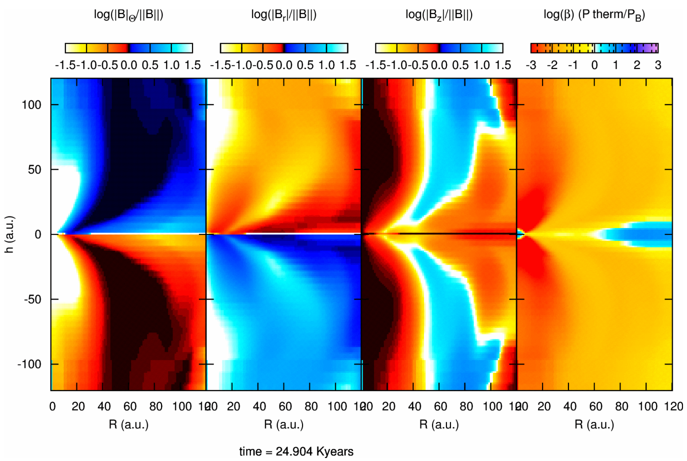
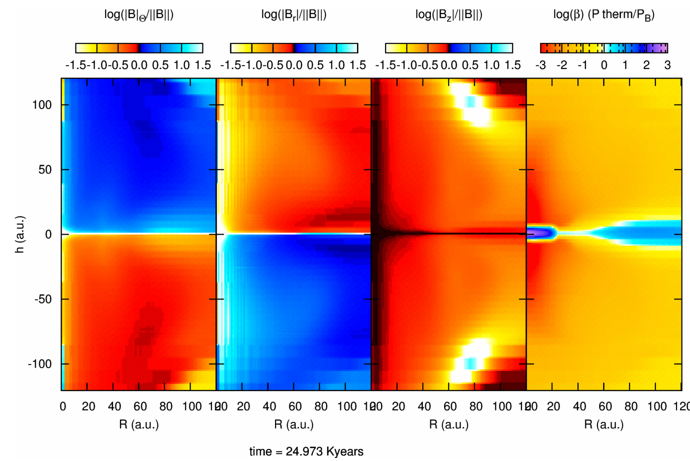
C.A magnetized environment

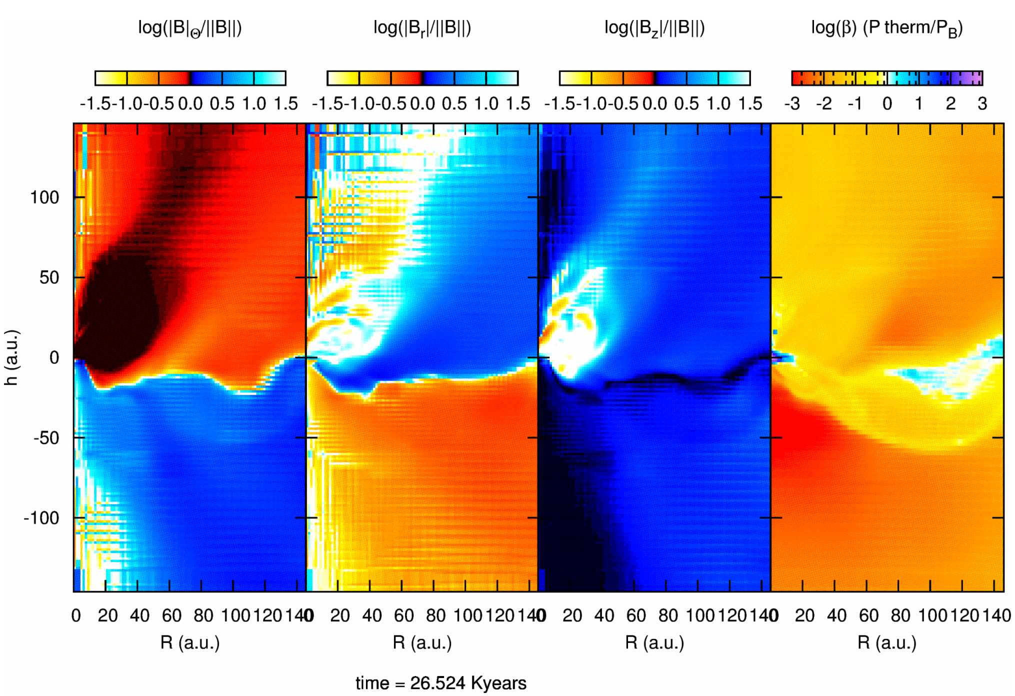
- Rotation, Mach=0, $\mu=5$

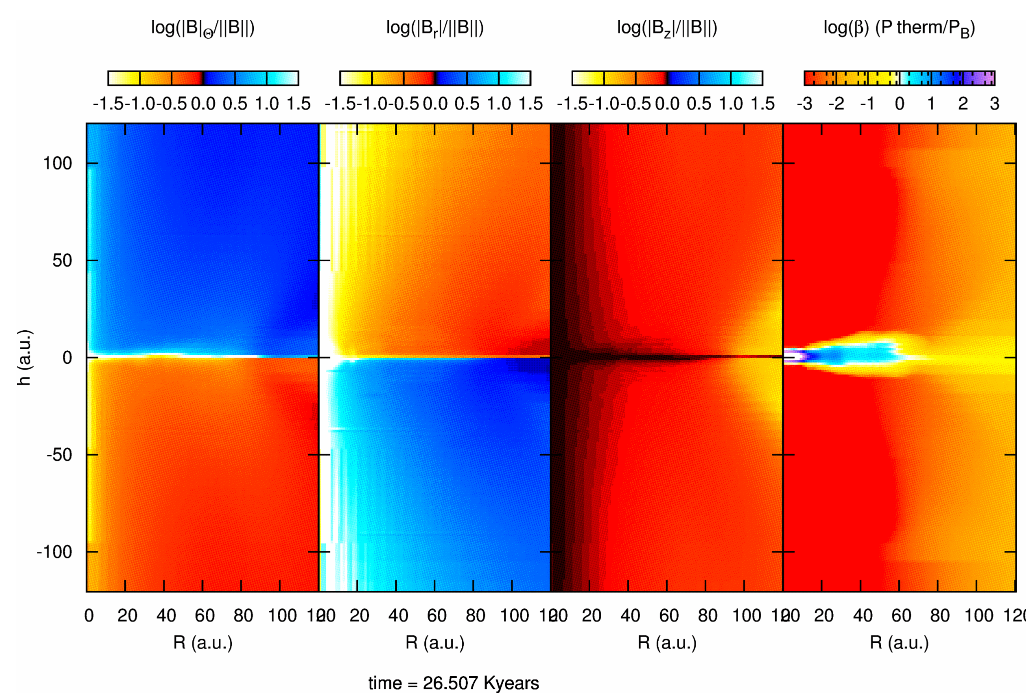


IMHD



AD

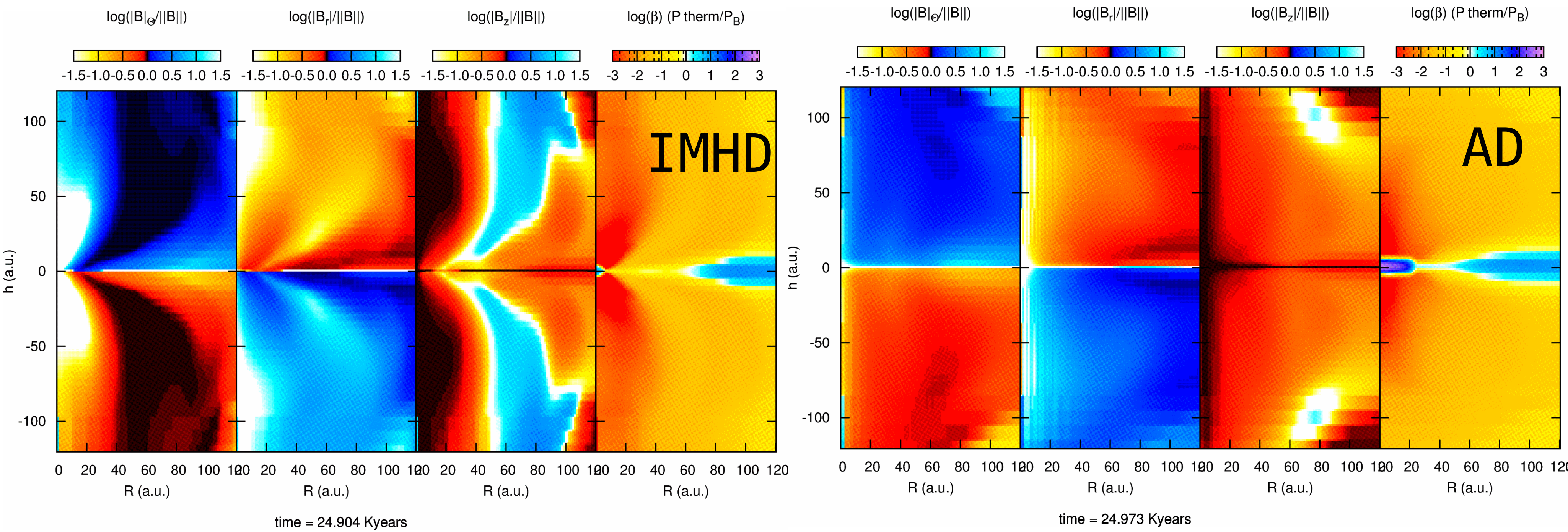




Masson et al. (in prep)

C. A magnetized environment

- Rotation, Mach=0, $\mu=5$



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Masson et al. (in prep)

Breaking of the symmetry, toroidal support, split monopole or complex (turbulent-like) geometry of the field.

Symmetry conserved, high beta, disks.

D.Disks, criteria

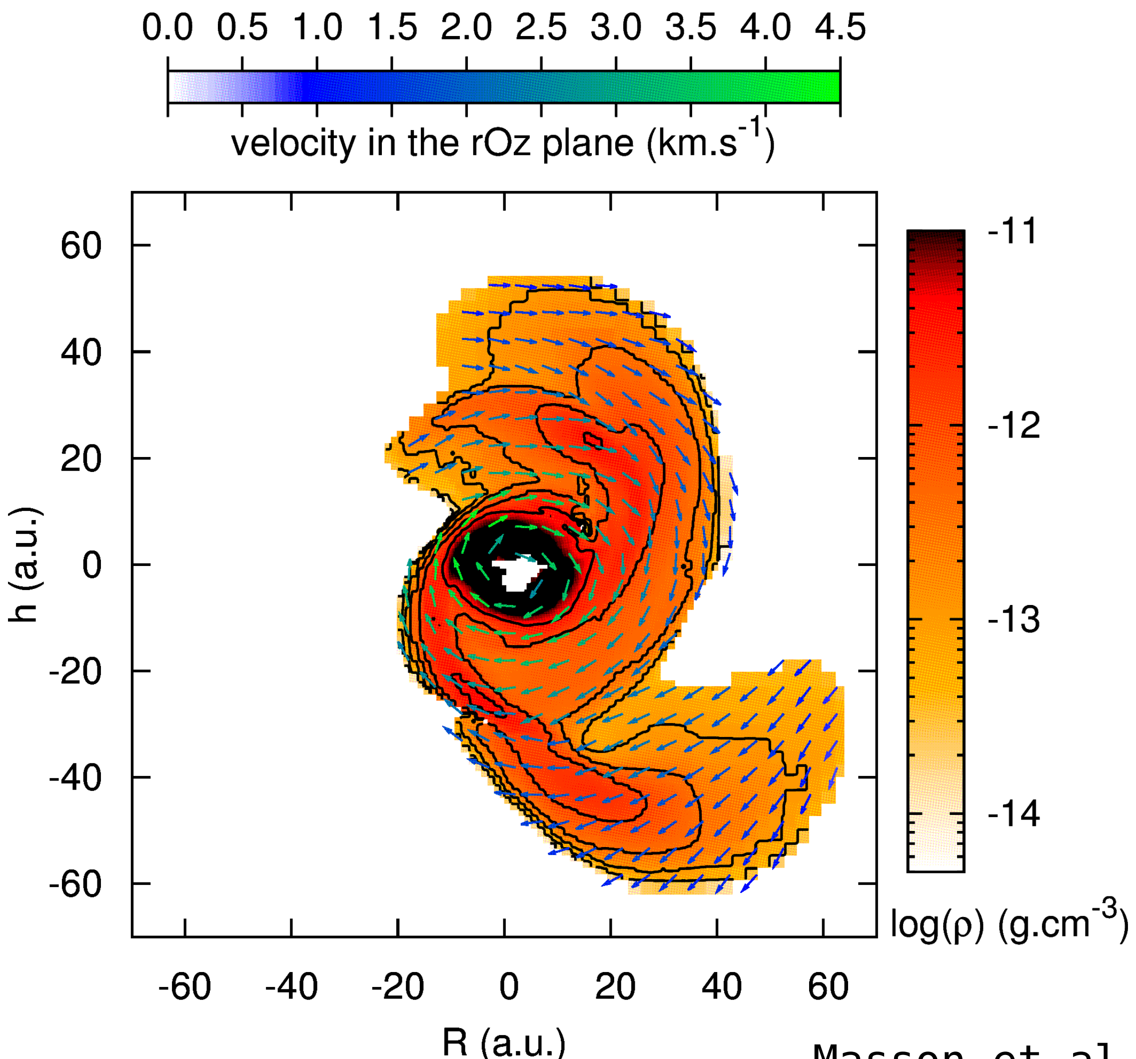
- Criteria for the disk

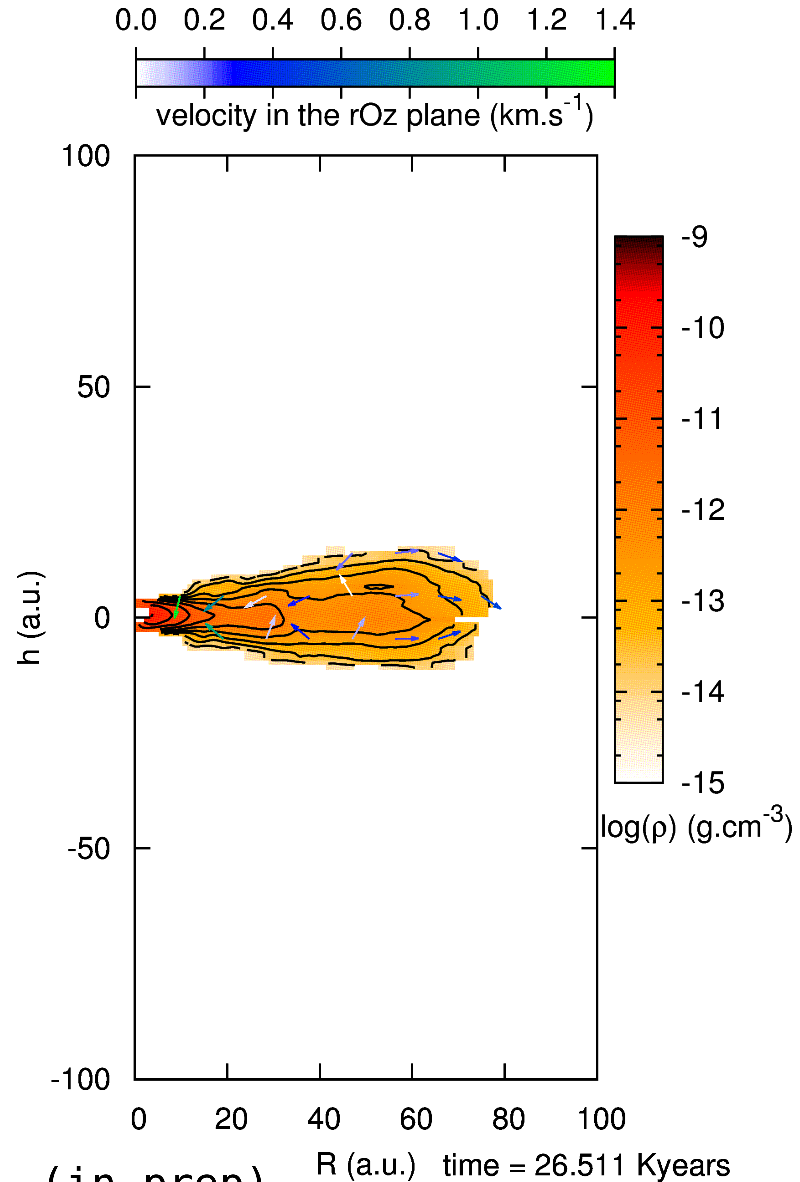
$$v_\theta > f\ v_r$$
$$v_\theta > f\ v_z$$
$$\rho\ v_\theta^2/2 > f\ P$$
$$\rho > 10^9\,\mathrm{cm}^{-3}$$

Joos et al. (2012)

D. Consequences for the disk?

- Rotation, Mach=0, $\mu=5$

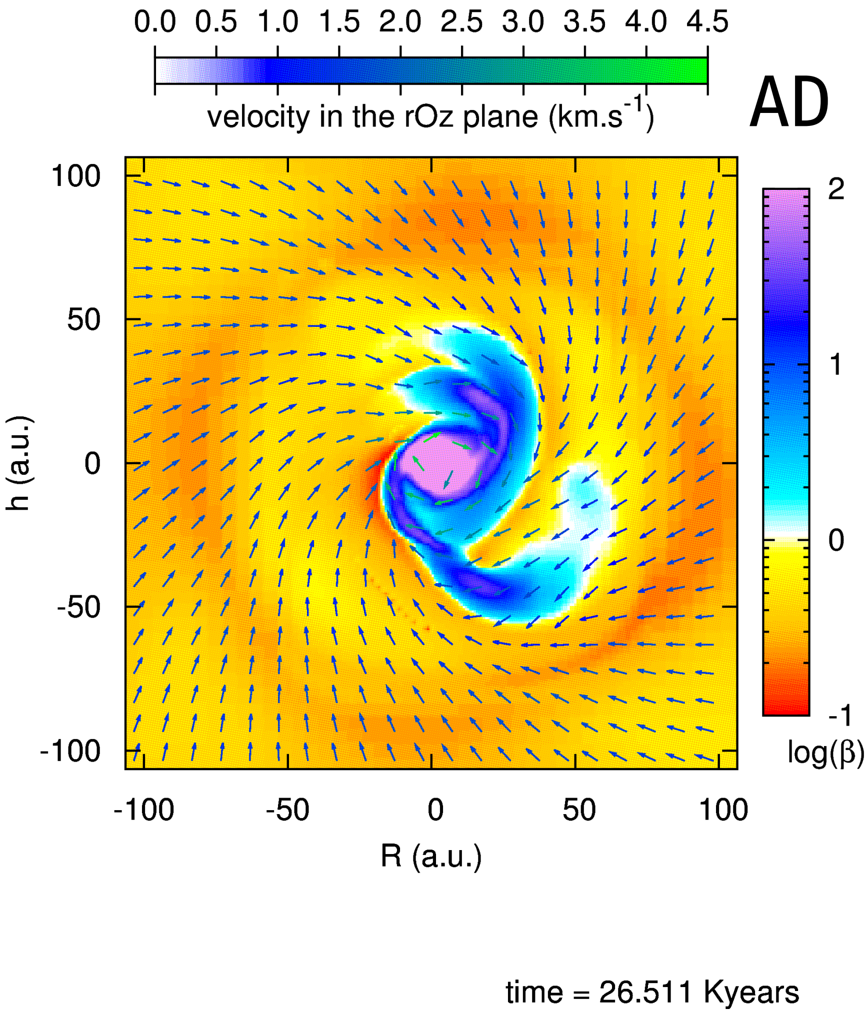


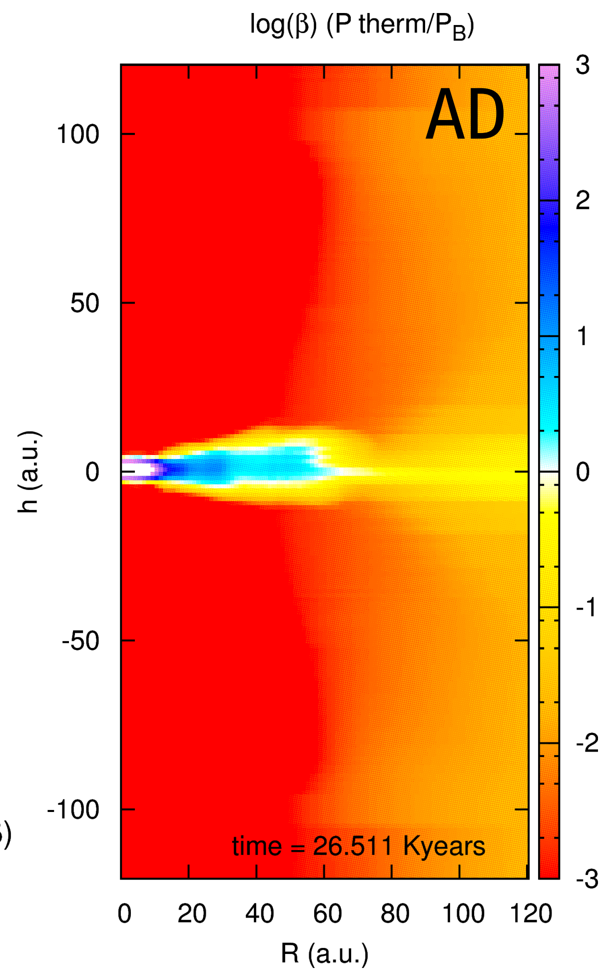


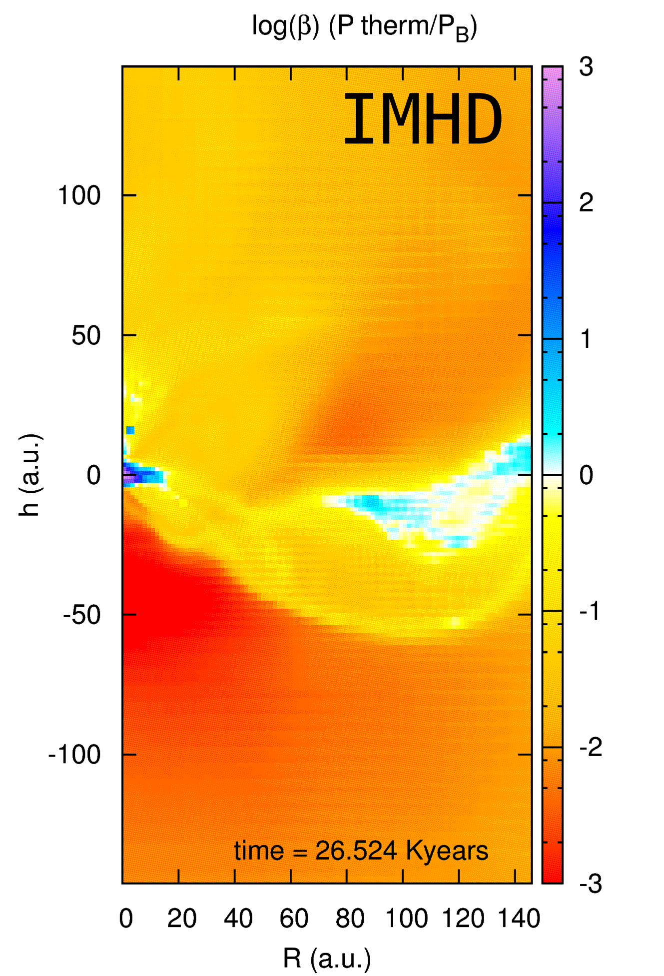
Masson et al. (in prep)

D. Consequences for the disk (beta)?

- Rotation, Mach=0, $\mu = 5$



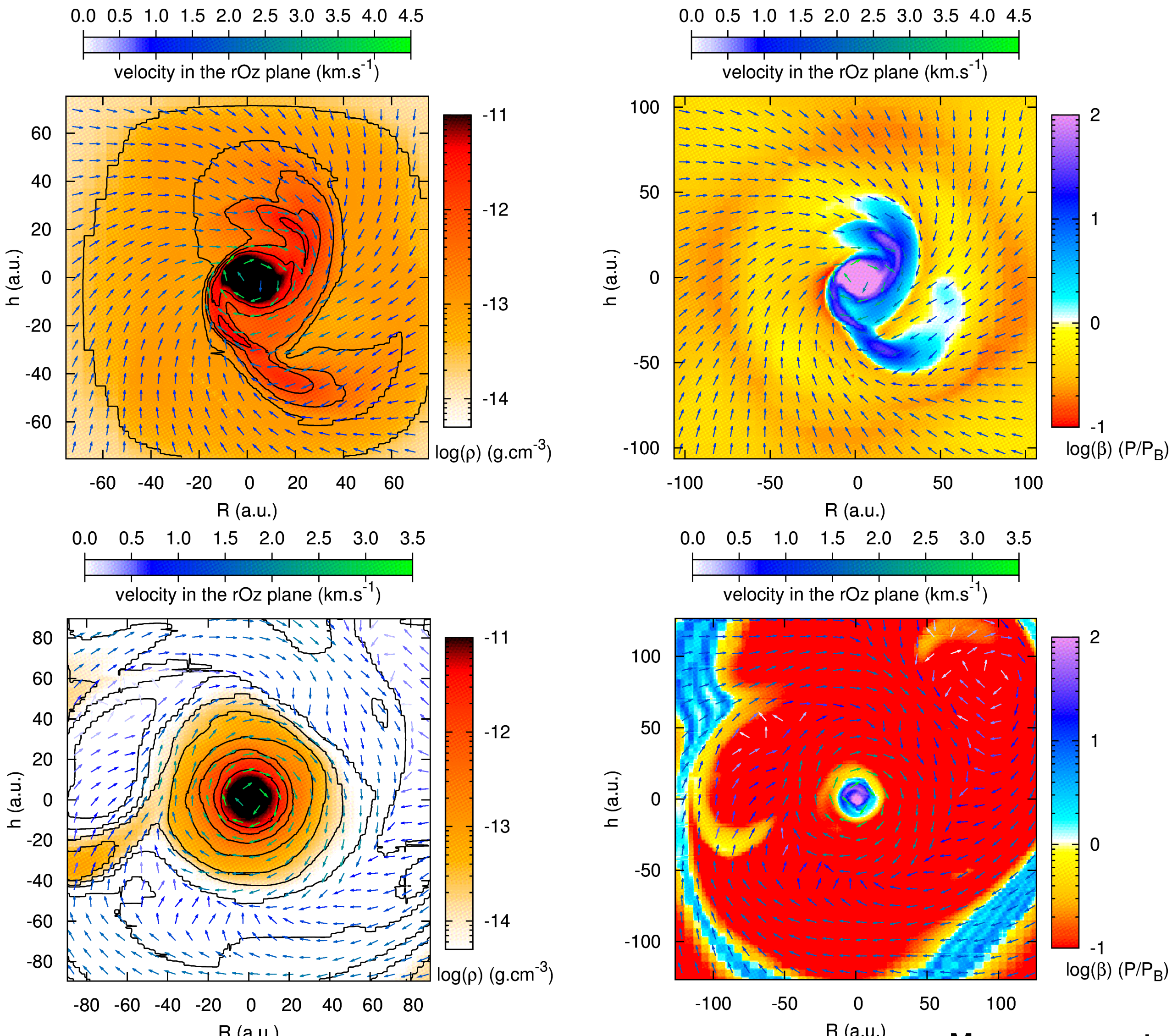




Masson et al. (in prep)

D. Consequences for the disk (beta)?

- Rotation, Mach=0, $\mu=5$



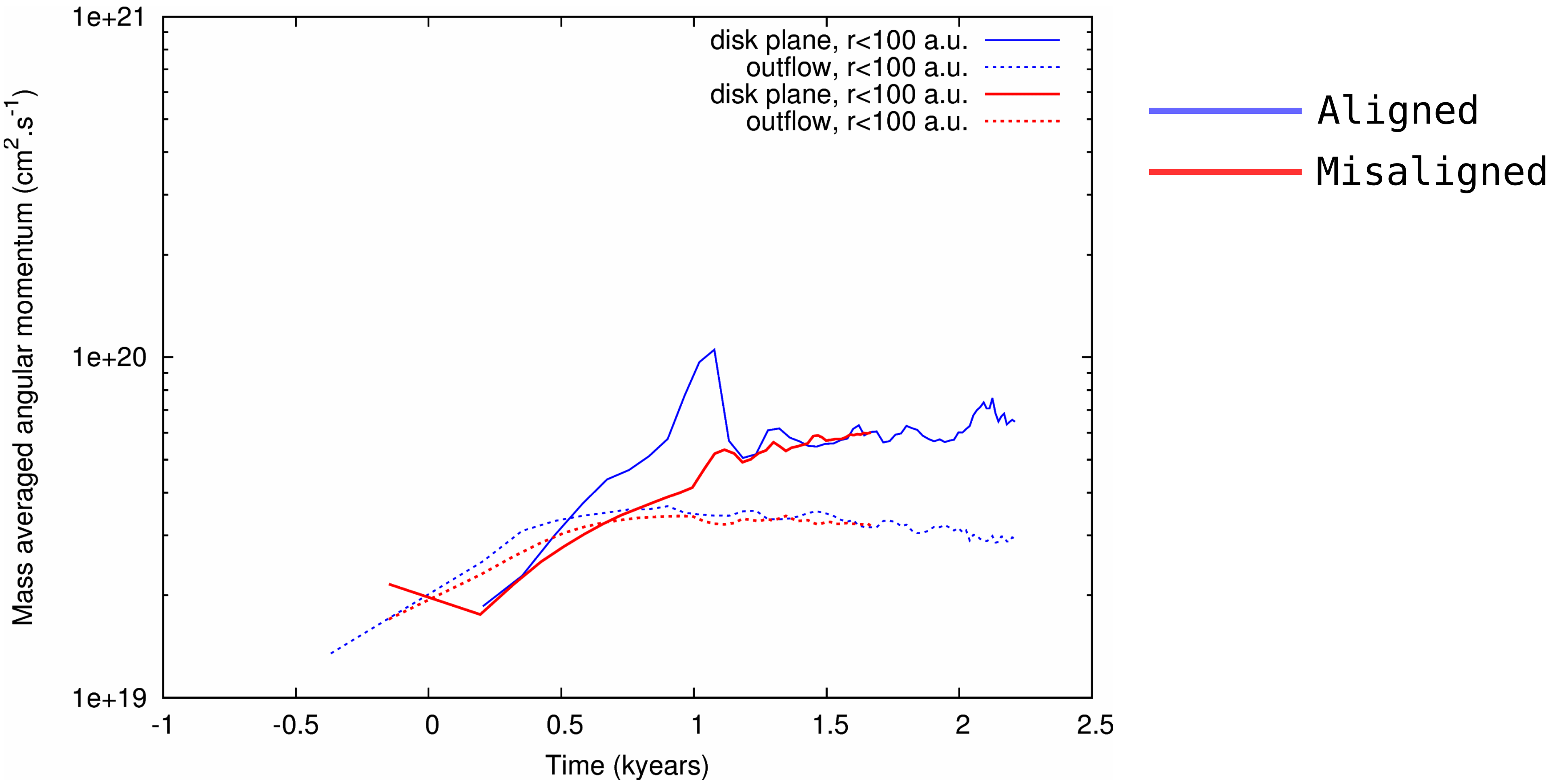
AD

IMHD

Masson et al. (in prep)

D. Consequences for the disk (angular momentum)?

- Rotation, Mach=0, $\mu=5$



Masson et al. (in prep)

D.Consequences for the disk (angular momentum)?

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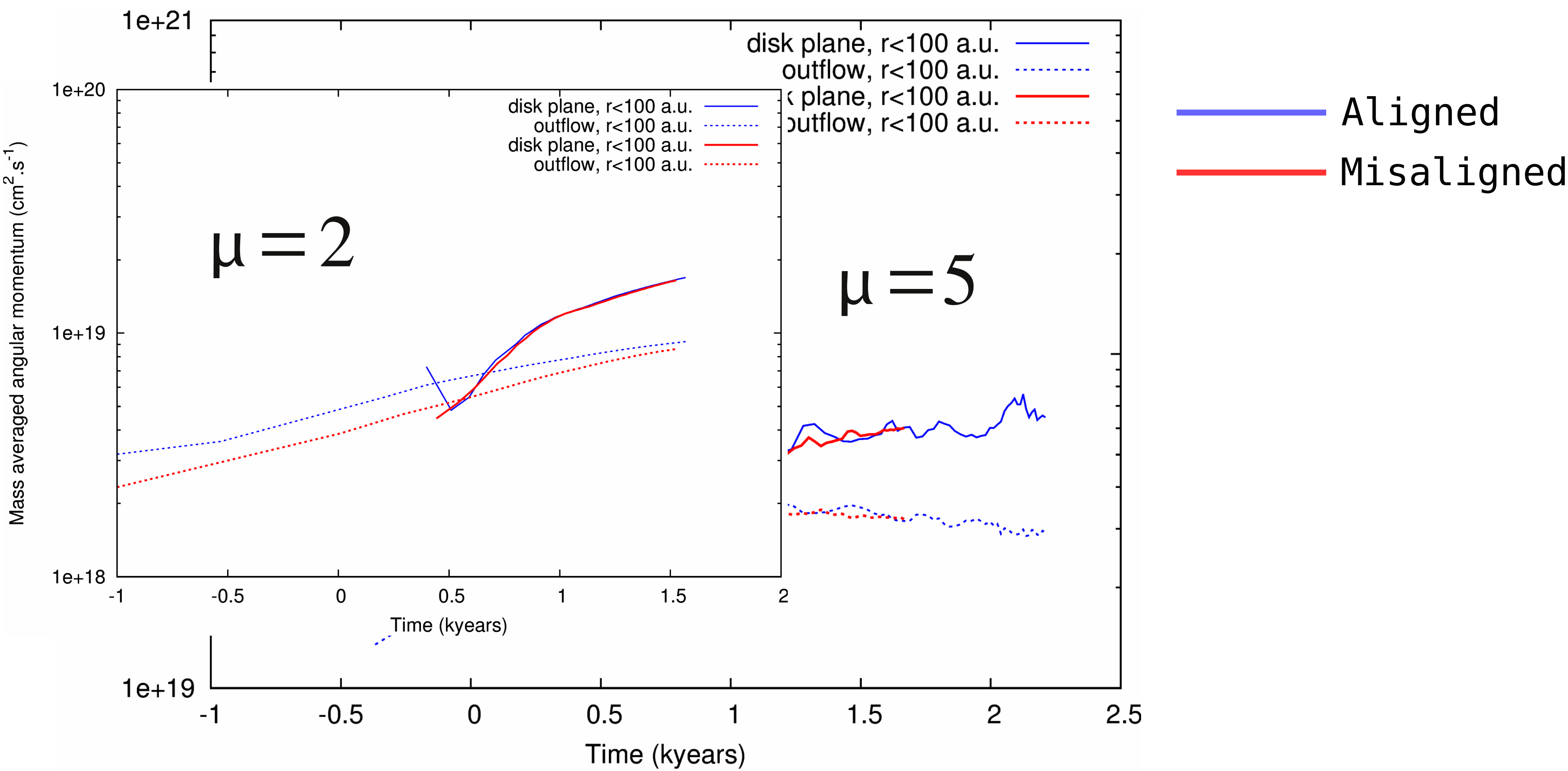

Masson et al. (in prep)

D. Consequences for the disk (disk mass)?

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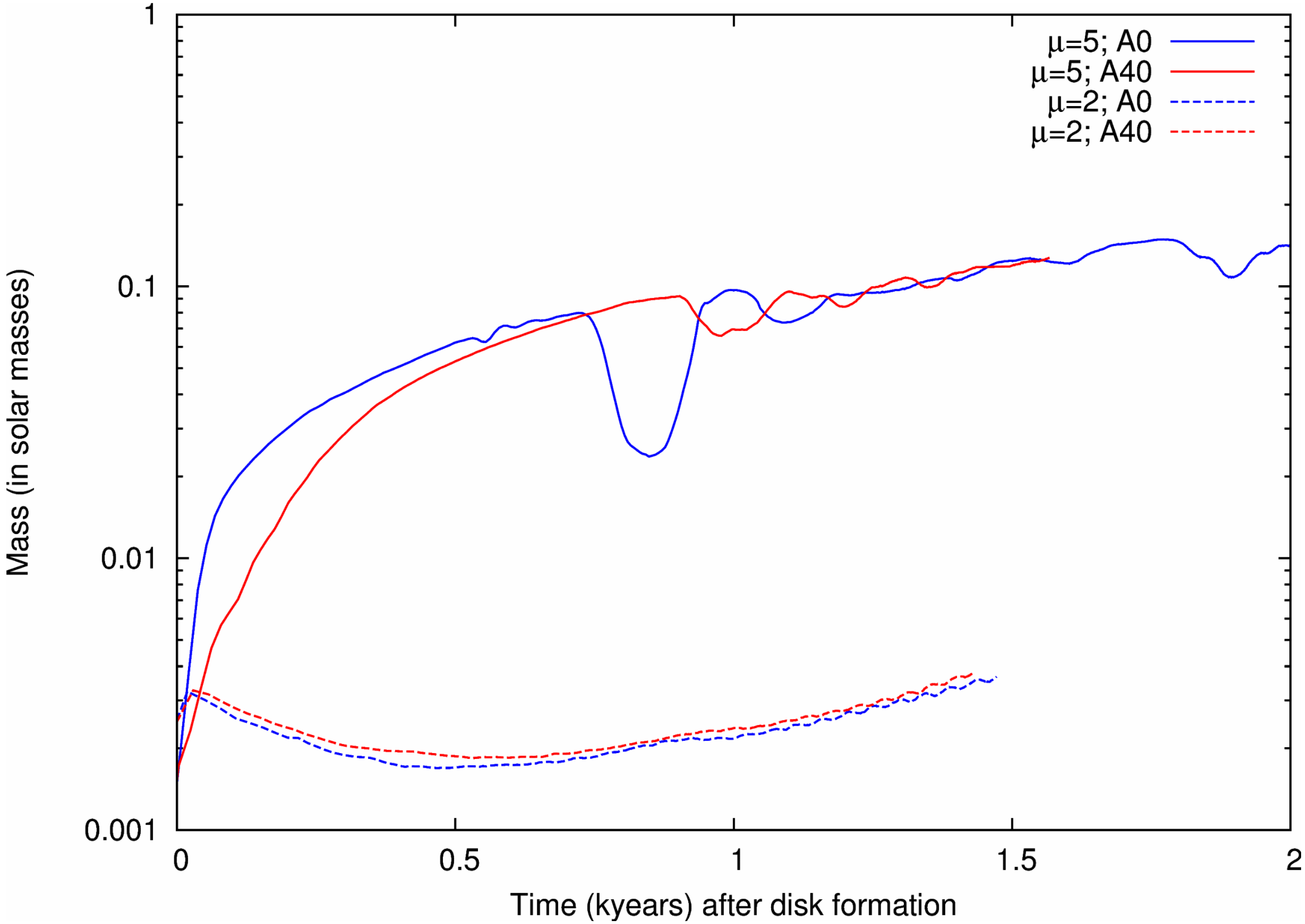


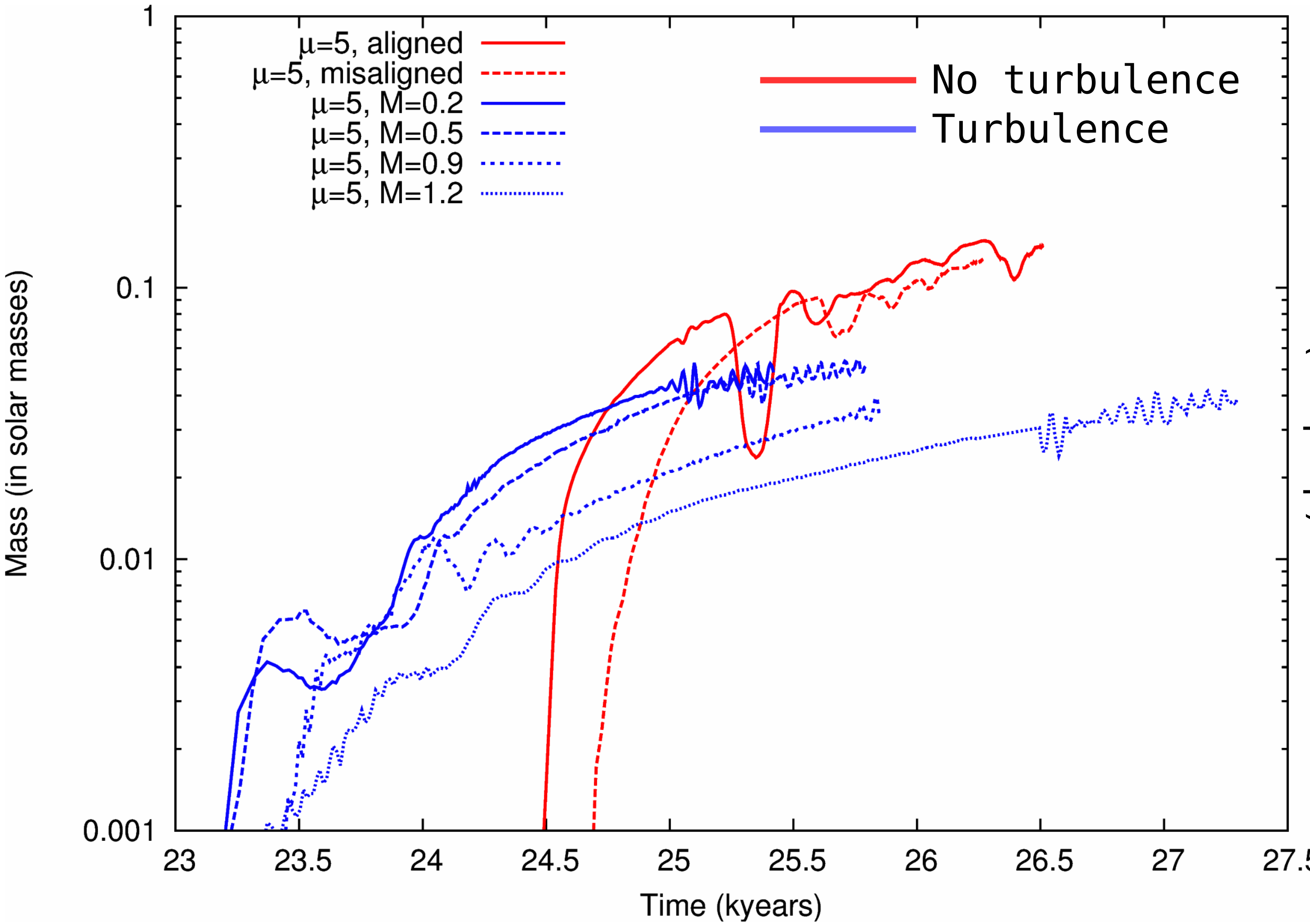
Aligned

Misaligned

Convergence:
Disk mass
Angular momentum
(and resolution)

Masson et al. (in prep)

D. What happens in a non-peculiar case?



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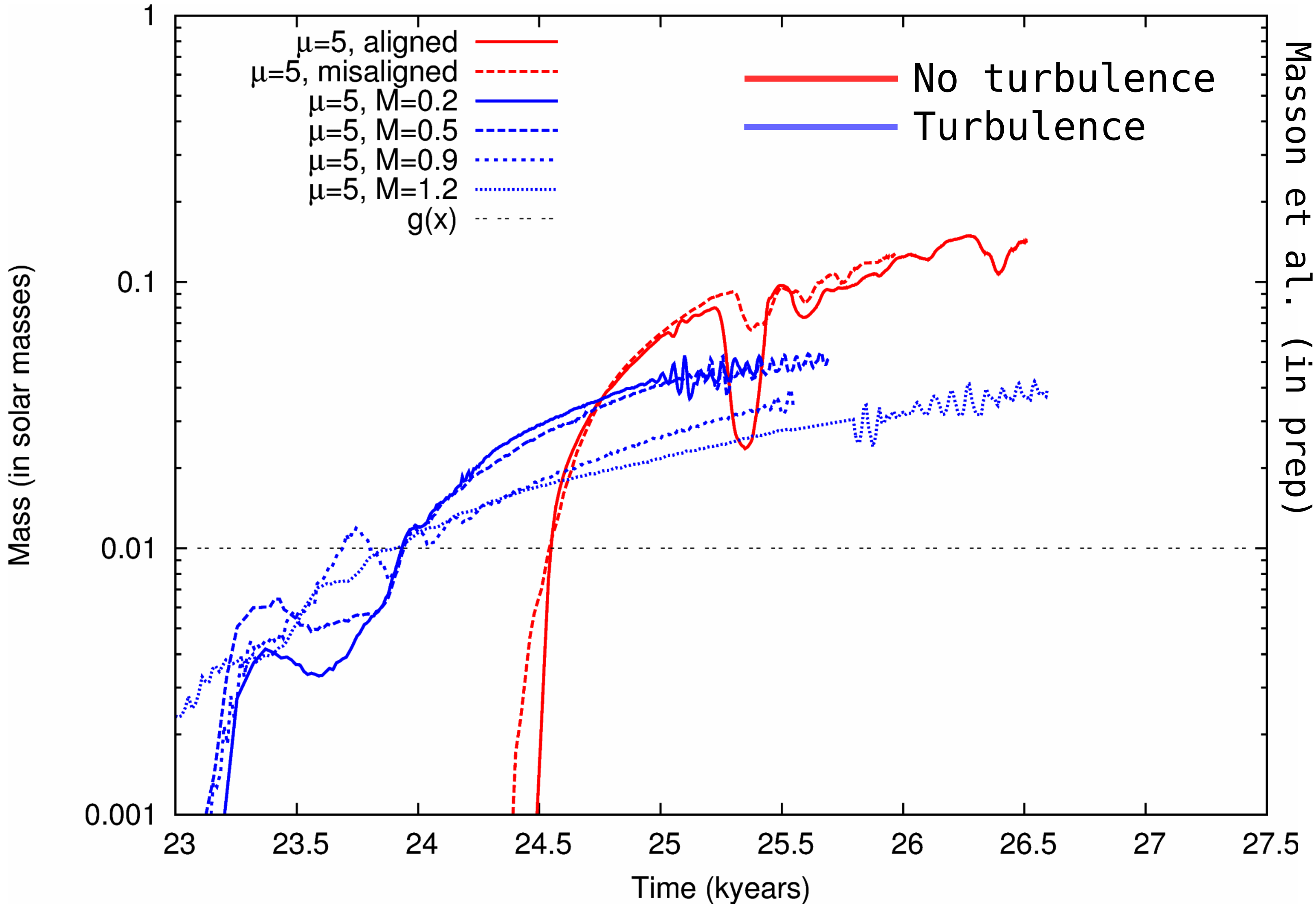
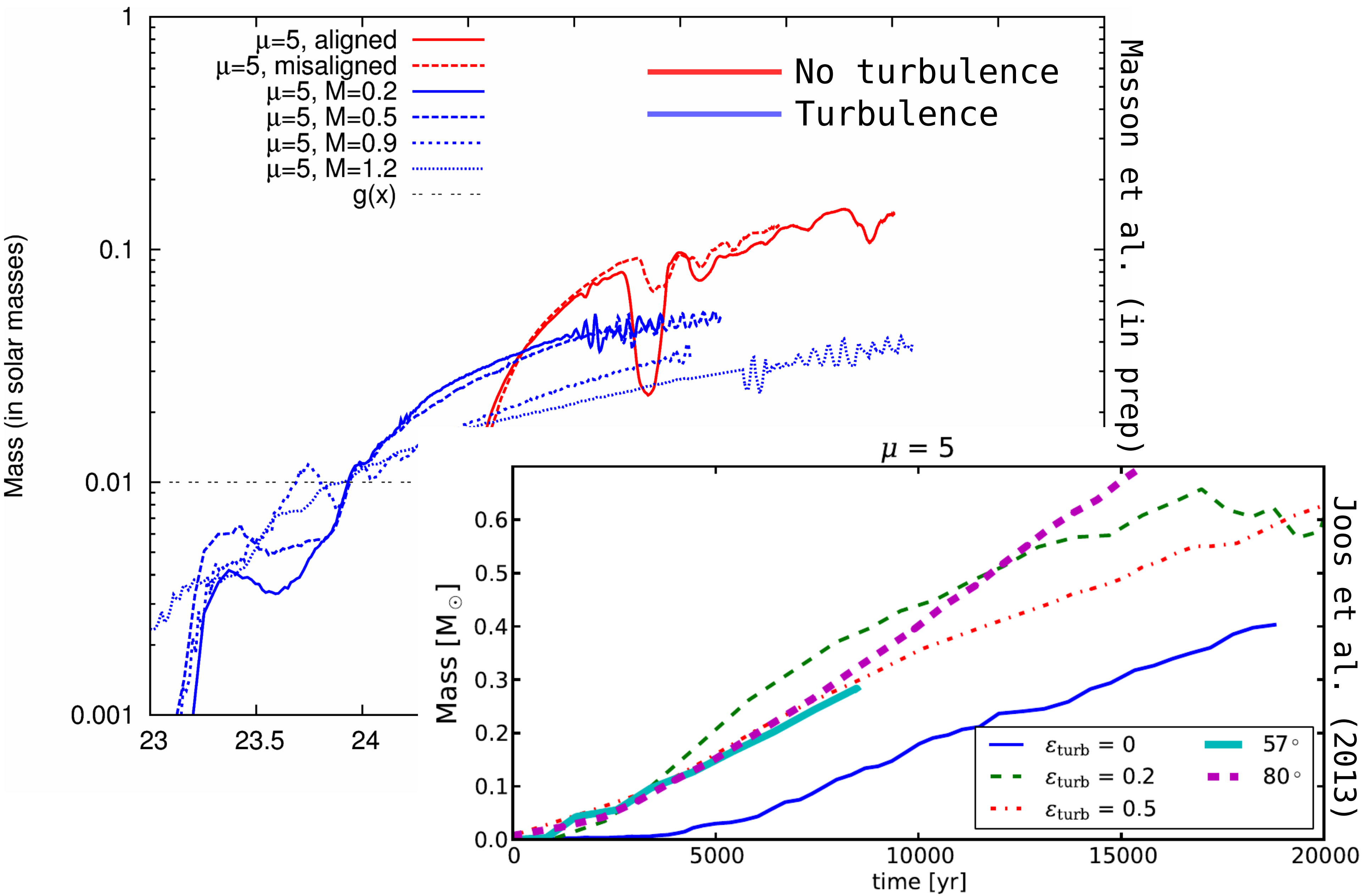


D. What happens in a non-peculiar case?



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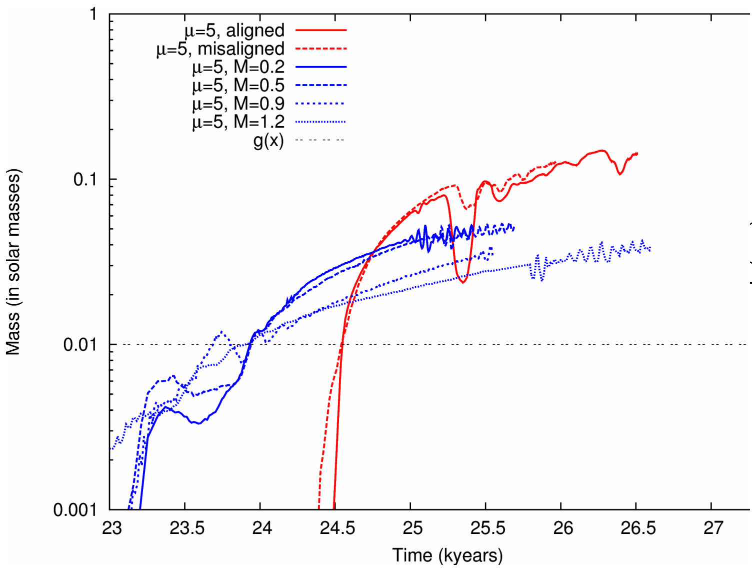
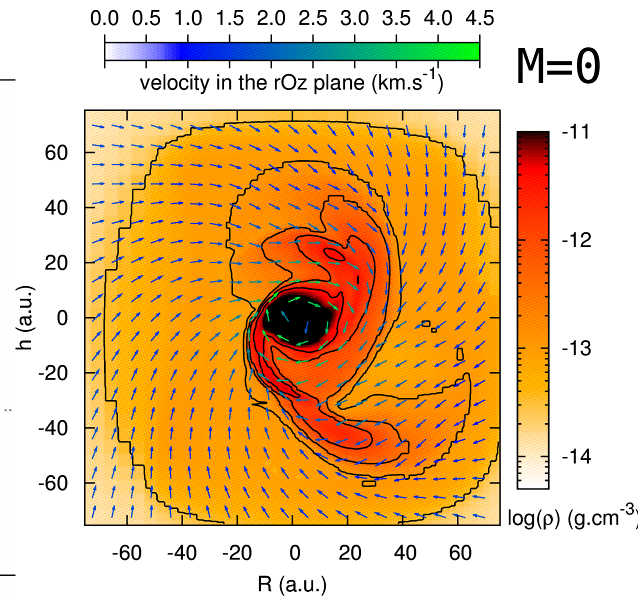
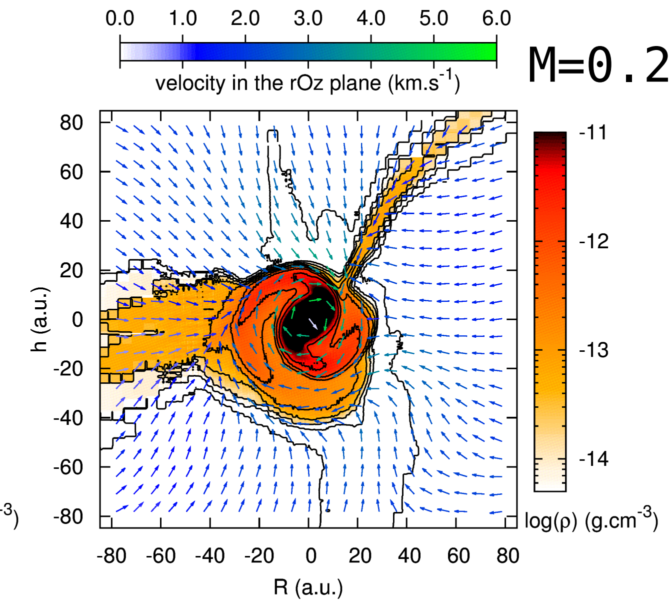
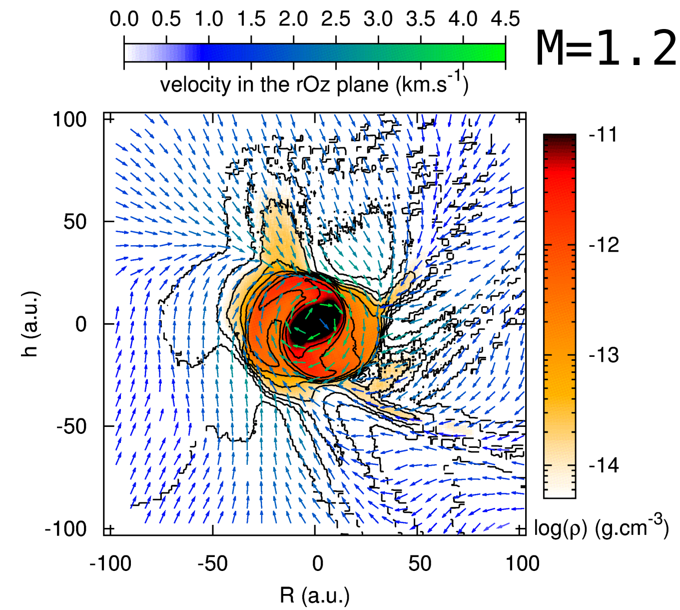






time = 26.507 Kyears



Masson et al. (in prep)

- Low amount of turbulence enough to change the picture
- The shape and properties (e.g. beta plasma) of the disk are not very dependant on the amount of turbulence
- Interaction between turbulent field and ambipolar diffusion?

Thank you for your attention!

A.B. Implementation of ambipolar diffusion in RAMSES

C.D. First collapse and disks

- Structural differences (density, magnetic field) due to ambipolar diffusion
- Appearance of a diffusion plateau resilient to small perturbations in the initial conditions
- Formation and growth of Keplerian disks around the first Larson core
- Study of the combined action of turbulence and ambipolar diffusion
- Hihghlights of limits of first Larson core studies

Thank you for your attention!

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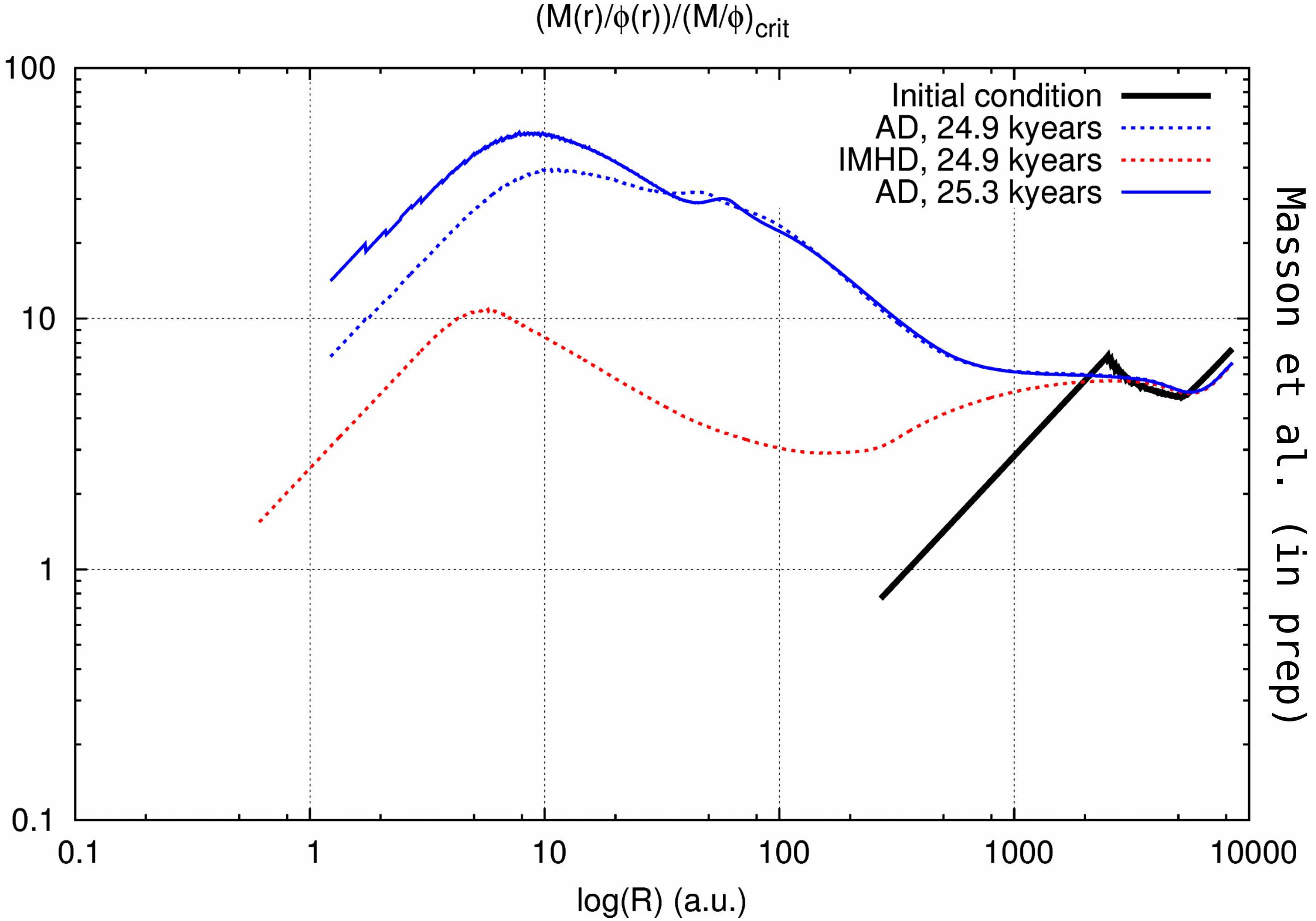
E. To go further…

- Second collapse with RMHD and Ohmic dissipation (see next talk too!)
- Hall effect

C.A different mu(r) to face

- Rotation, Mach=0, $\mu=5$



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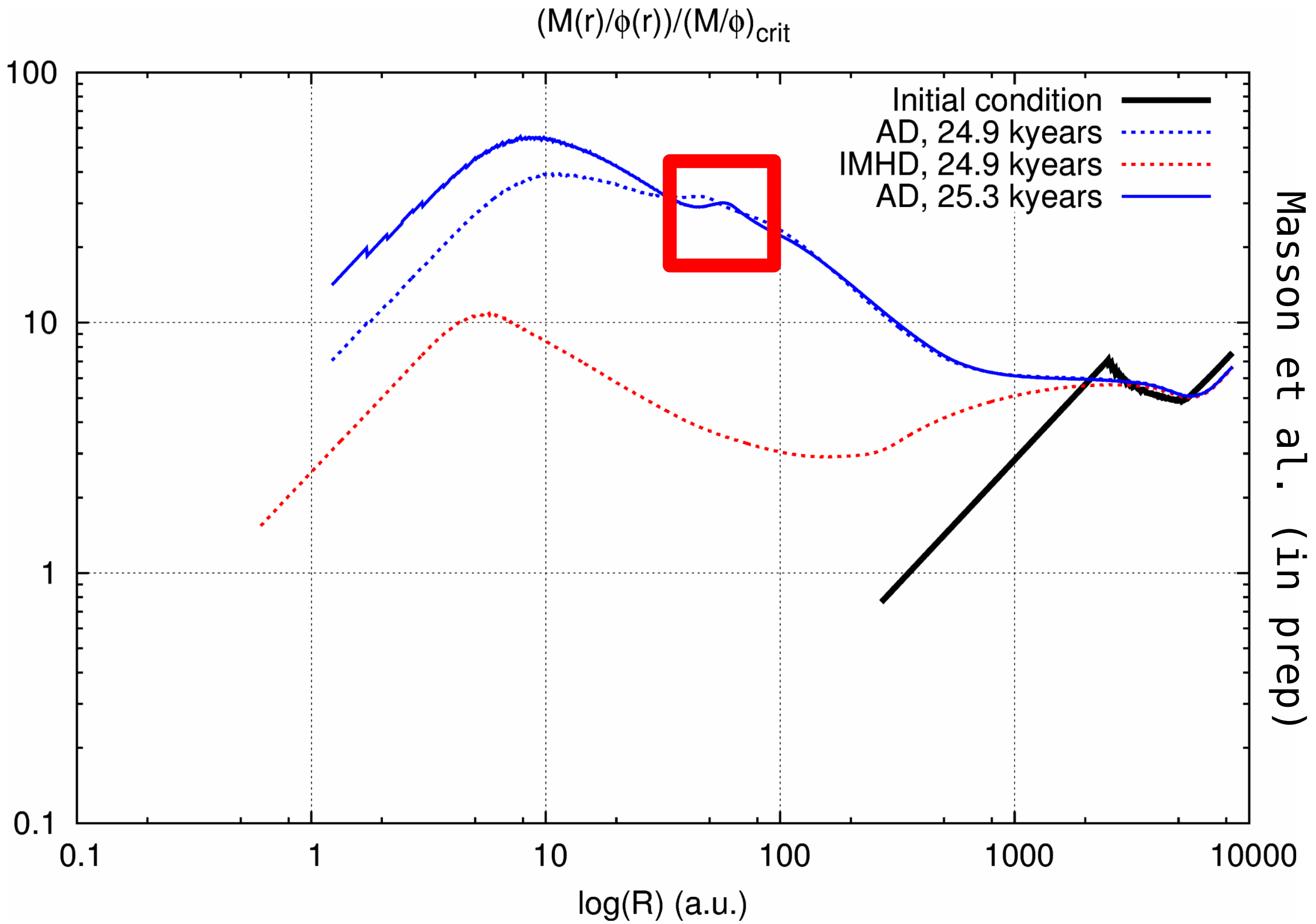
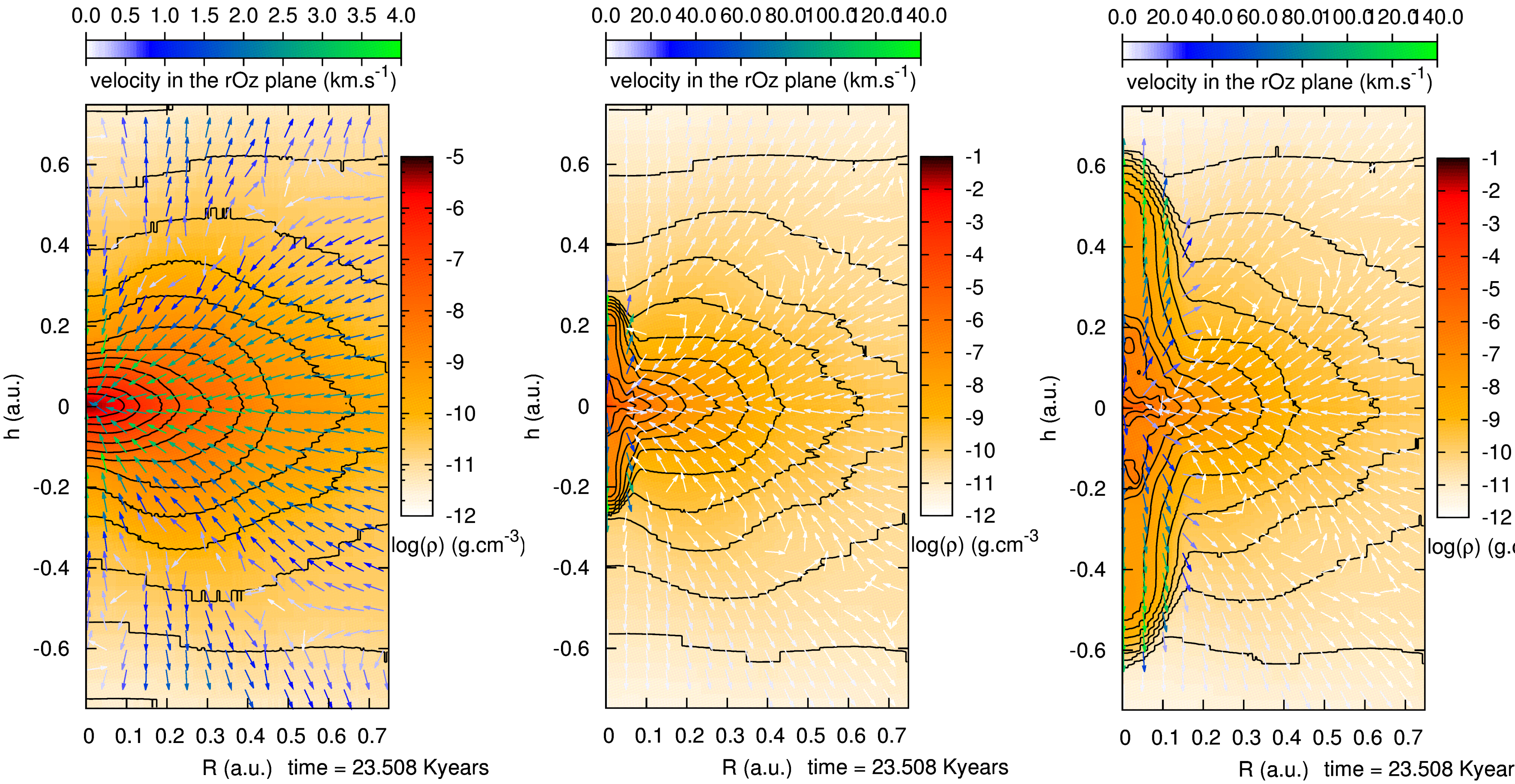


D. Second collapse: thermo-magnetic jet



Masson et al. (in prep)

Ideal MHD, barotropic equation

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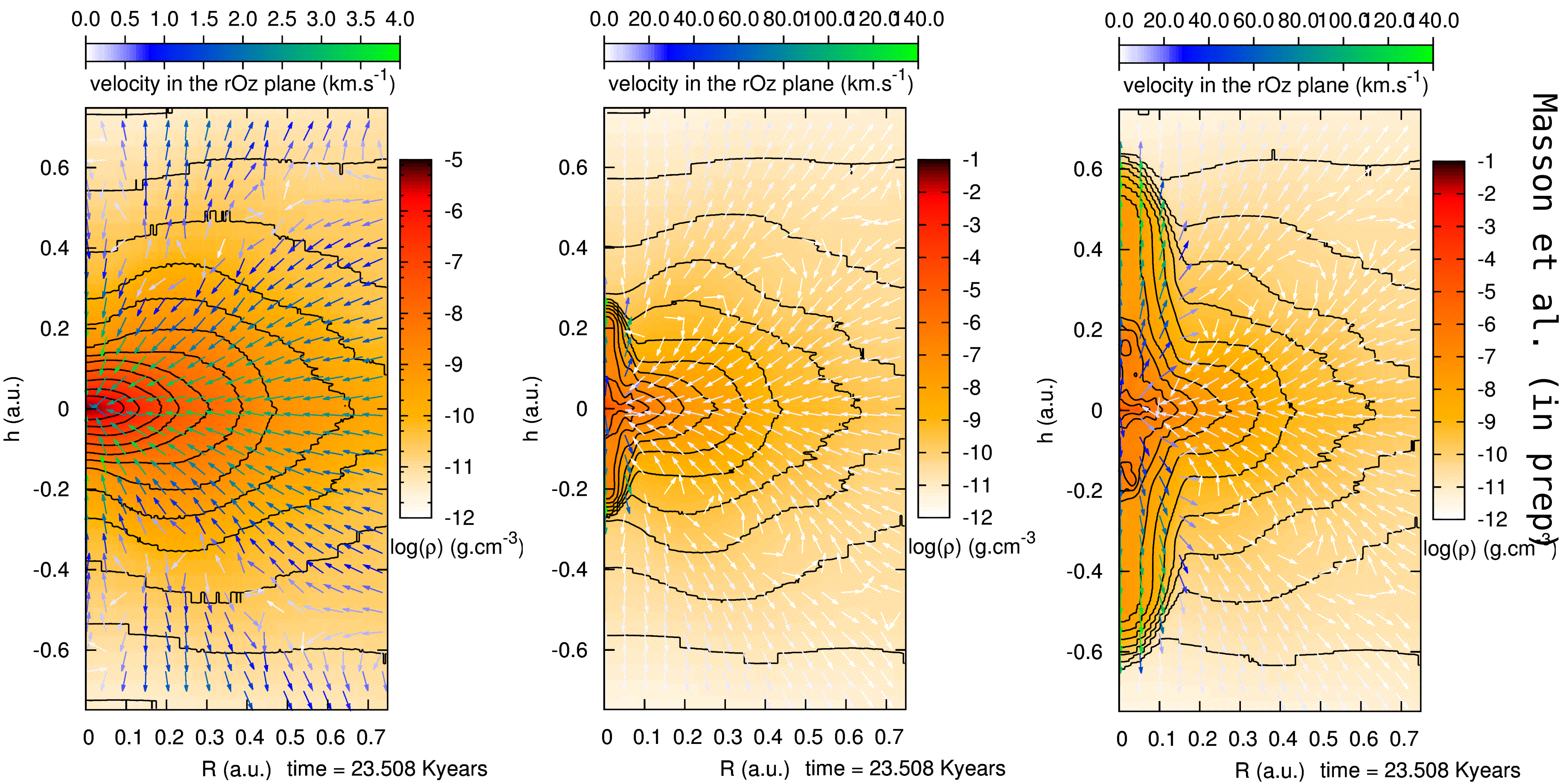
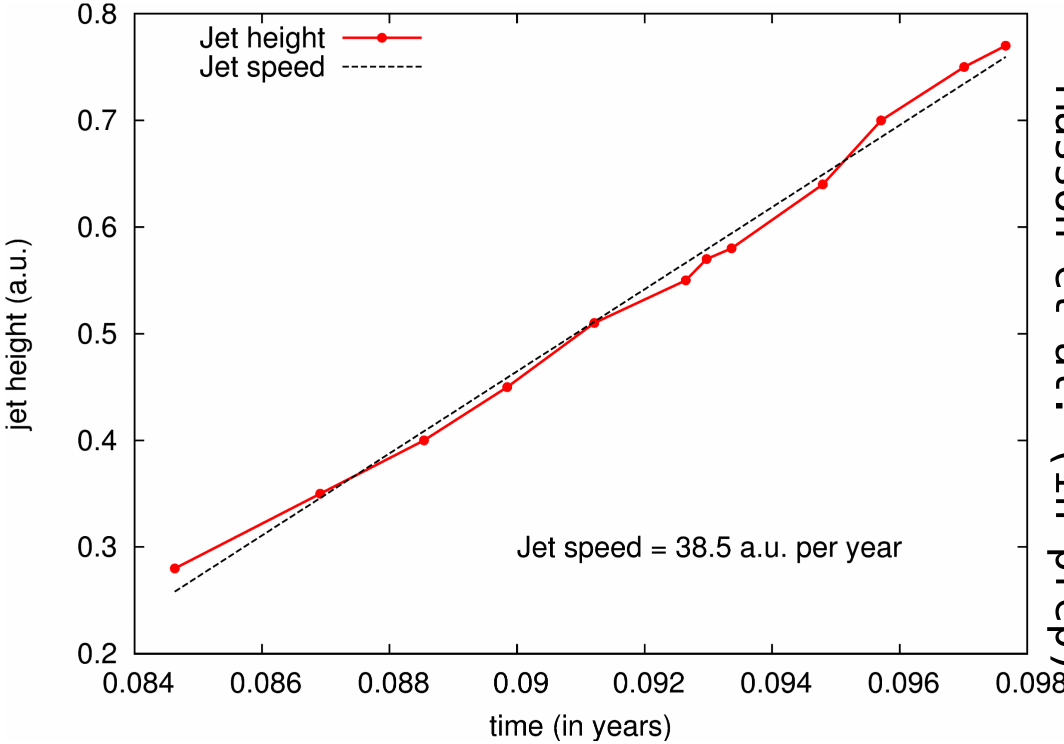


Masson et al. (in prep)

Ideal MHD, barotropic equation

Matter of time ?

D. Second collapse: thermo-magnetic jet

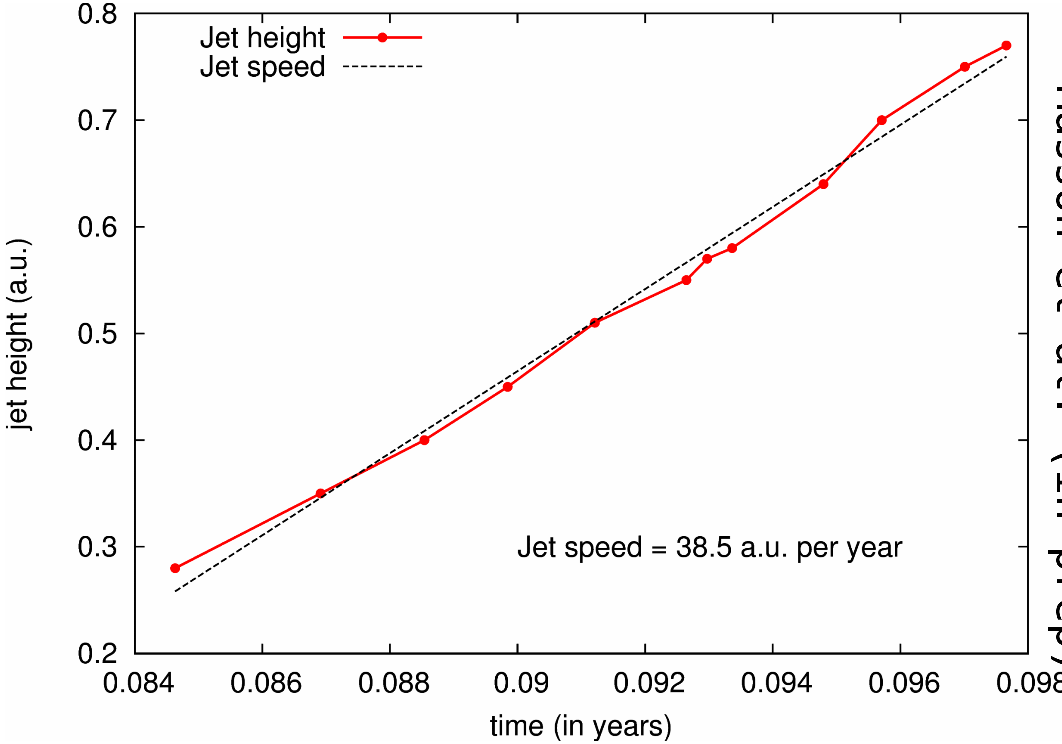


Masson et al. (in prep)

Jet E.T.A. at the frontier of the first core: 1 year.

Ideal MHD, barotropic equation

D. Second collapse and beyond



Masson et al. (in prep)

Jet E.T.A. at the frontier of the first core: 1 year.

Ideal MHD, barotropic equation

- Limits ?

- Radiative transfer feedback ?
- Slow down of the jet ?
- Ohmic dissipation ?
- Ambipolar diffusion?

- Simulations running (walking…) !

Conclusions (I)

A.B. Implémentation des termes ambipolaire et Ohmique dans RAMSES

- Formulation adaptée à l'étude des effondrements de coeurs denses, sans approximation par un opérateur de Laplace
- Validation par de nombreux tests (induction pure et couplage magnétohydrodynamique)
- Mise en évidence de différences importantes quant à l'expression vectorielle de la diffusion ambipolaire sur le problème fondamental de la dynamo cinématique
- Code d'évolution chimique versatile

Conclusions (II)

C. Premier effondrement

- Mise en évidence de différences structurelles (densité, champ magnétique) associées à la diffusion ambipolaire
- Étude de la formation et croissance des disques Kepleriens autour du premier coeur de Larson
- Étude de l'action combinée de la turbulence et de la diffusion ambipolaire
- Mise en évidence de limites de l'étude du premier effondrement via une équation barotropique, pour la MHD idéale et non idéale

Conclusions (III)

D. Second effondrement

- Implémentation d'une équation d'état réaliste (dissociation du dihydrogène, couplages non linéaires) adaptée à l'étude du second effondrement et second coeur de Larson
- Modification de l'implémentation du transfert radiatif dans RAMSES (Commerçon et al. 2010) pour simuler le second effondrement
- Mise en évidence de possibles conséquences importantes sur le premier coeur (jet collimaté)
- Simulations en cours de calcul pour décrire les deux phases d'effondrement de manière cohérente

Perspectives

- Premier effondrement
  - Étude du rôle de la diffusion ambipolaire dans la diffusion de la turbulence
  - Étude détaillée de la structure du champ magnétique dans les disques (MRI, interactions disque-étoile)
- Second effondrement
  - Atteindre le second effondrement en MHD non idéale et avec le tranfert radiatif
  - Étudier l'impact du second effondrement sur l'évolution à long terme à l'échelle du premier coeur
  - Fragmentation, formation des binaires, jets, etc...

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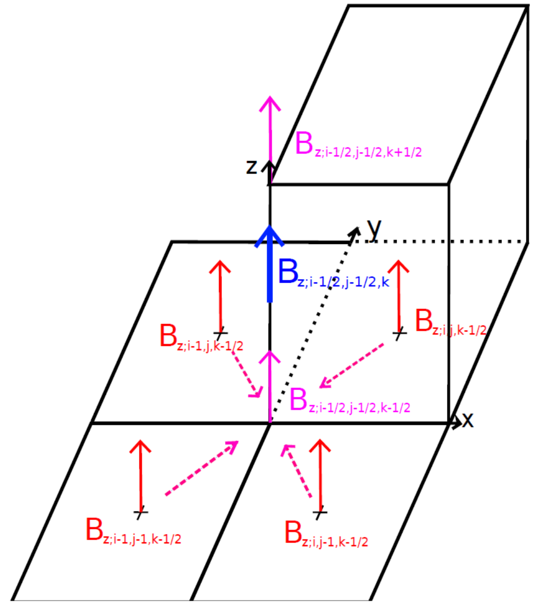
Thank you for your attention !

MHD non idéale dans RAMSES



- Exprimer le champ magnétique au bons endroits

- Optimiser les calculs pour les différents termes non idéaux

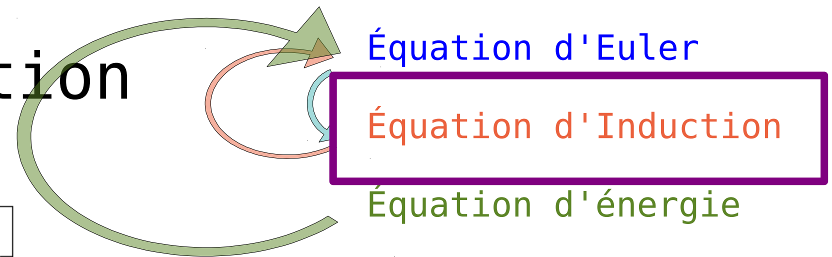
$$\partial_t \mathbf{B} = \nabla \times \left[\mathbf{v_n} \times \mathbf{B} - \frac{\mathbf{J} \times \mathbf{B}}{e n_e} + \frac{[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}}{\gamma_{\mathrm{AD}} \rho \rho_i} - \frac{\mathbf{J}}{\sigma} \right]$$

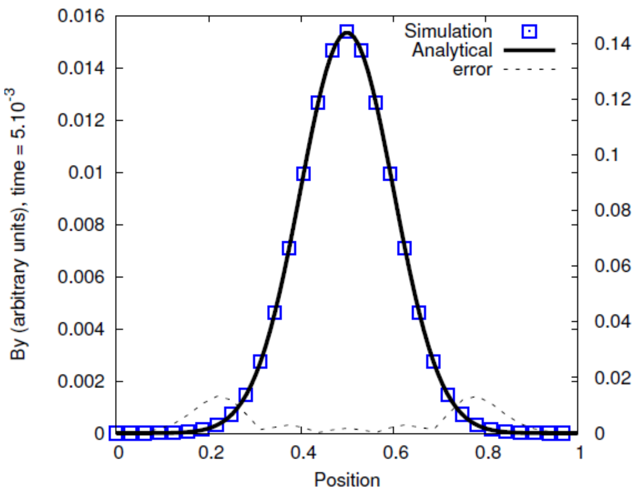
- Correctement décrire le chauffage

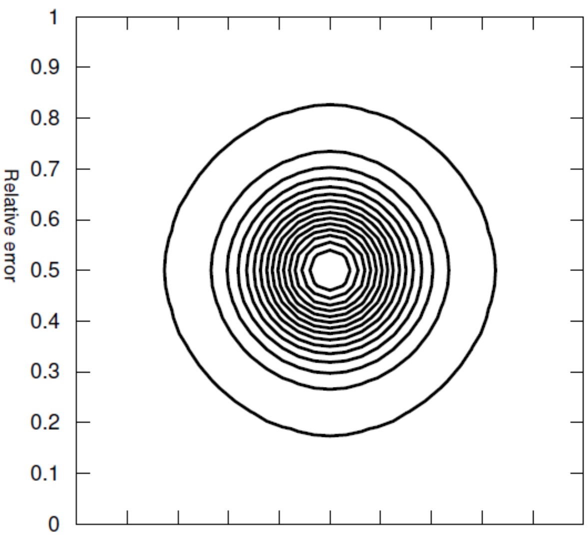
$$\rho T \frac{ds}{dt} = \frac{\|(\nabla \times \mathbf{B}) \times \mathbf{B}\|^2}{\gamma_{AD} \rho \rho_i}$$

MHD non idéale dans RAMSES

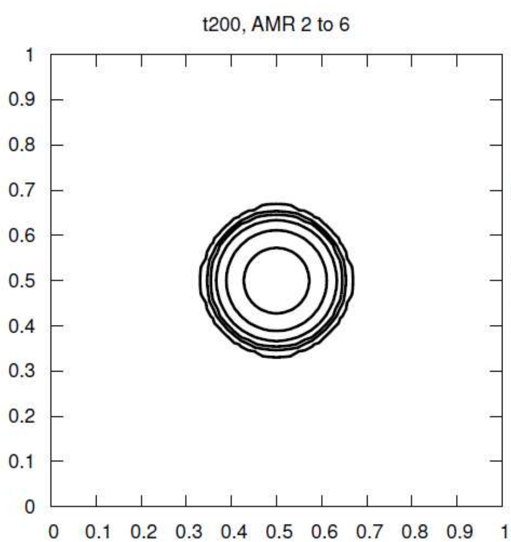
- Tests de l'équation d'induction

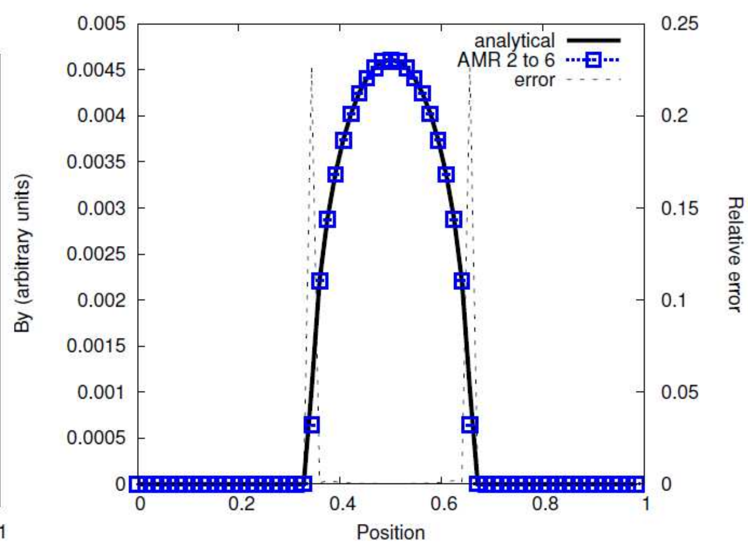






Diffusion Ohmique

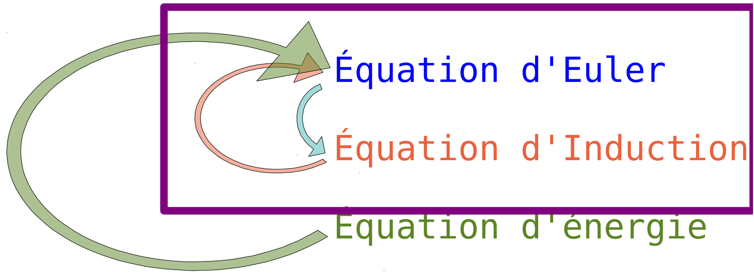


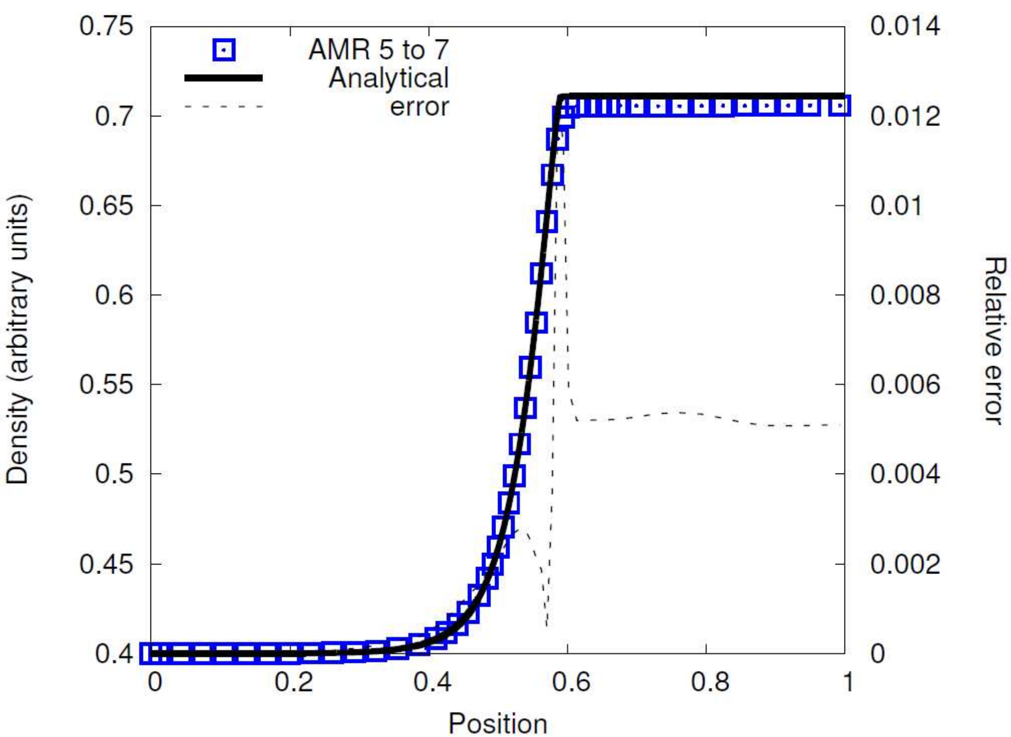


Diffusion ambipolaire

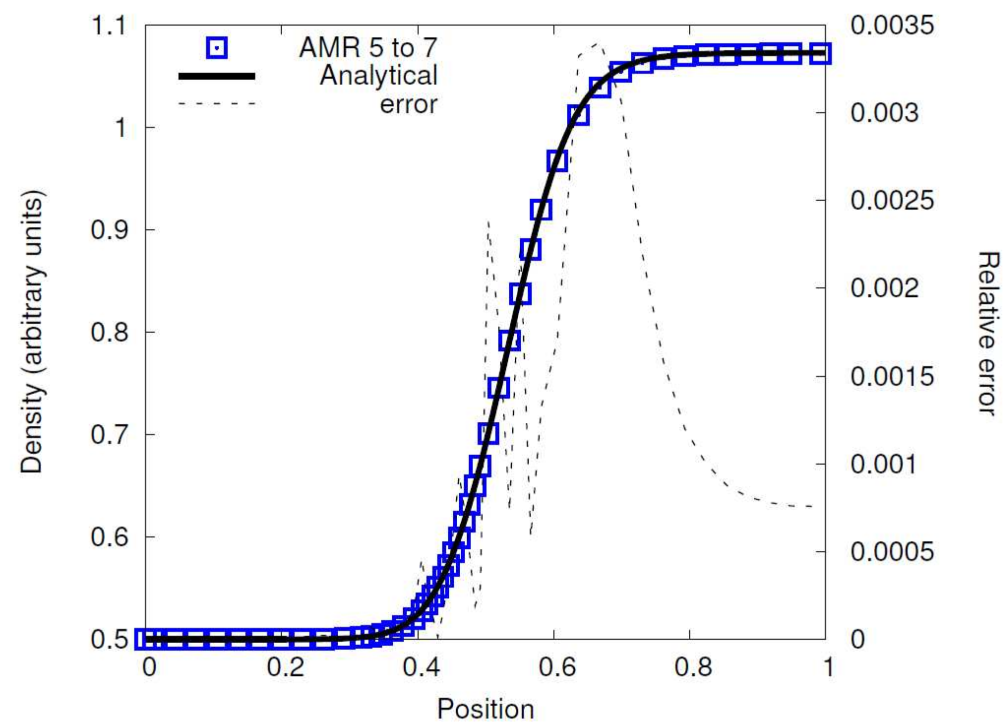
MHD non idéale dans RAMSES

- Tests pour des chocs obliques (45°)





Diffusion Ohmique



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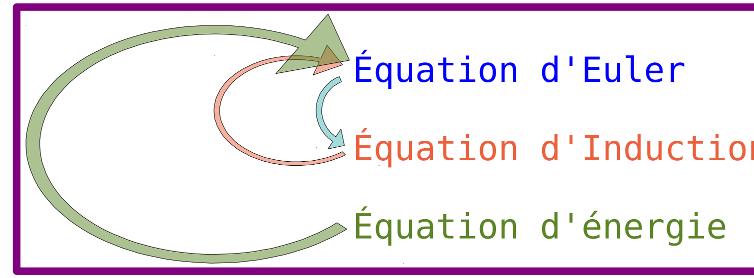
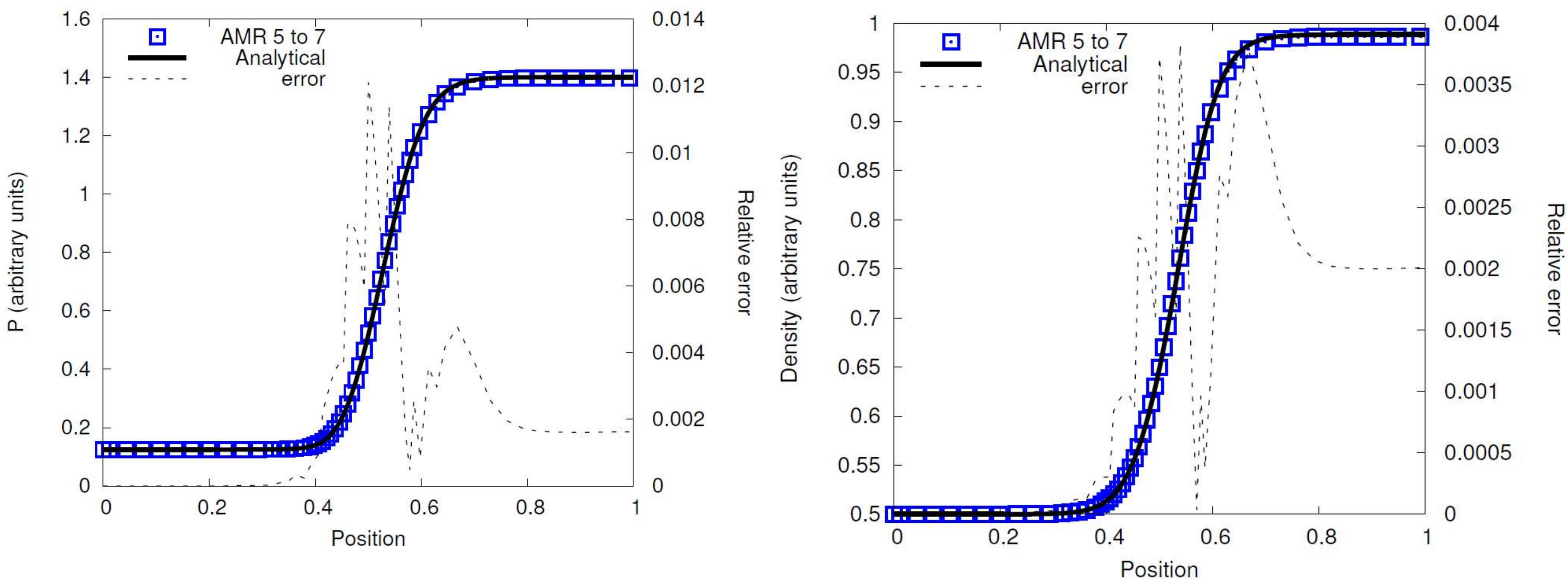
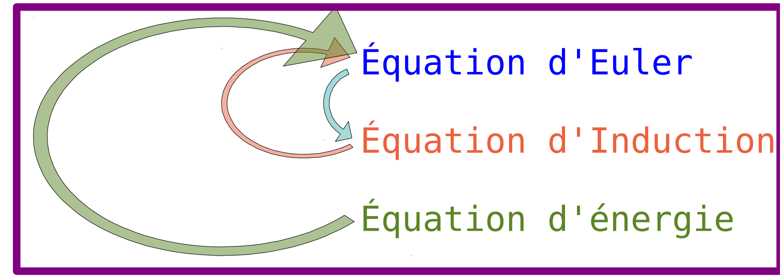




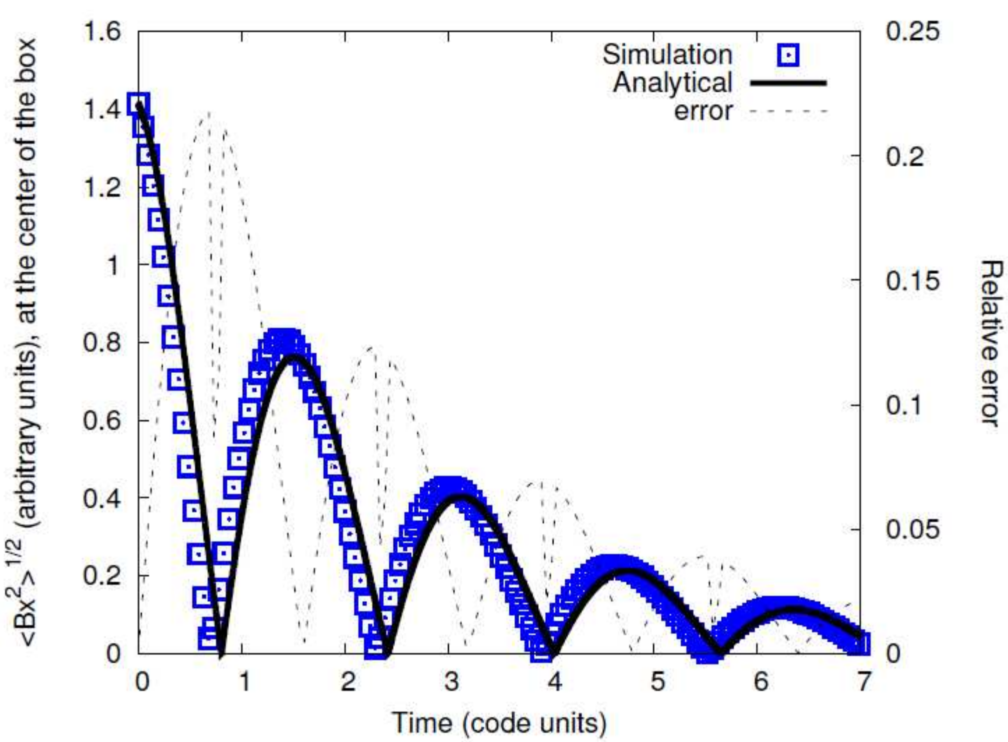
Diffusion ambipolaire

MHD non idéale dans RAMSES

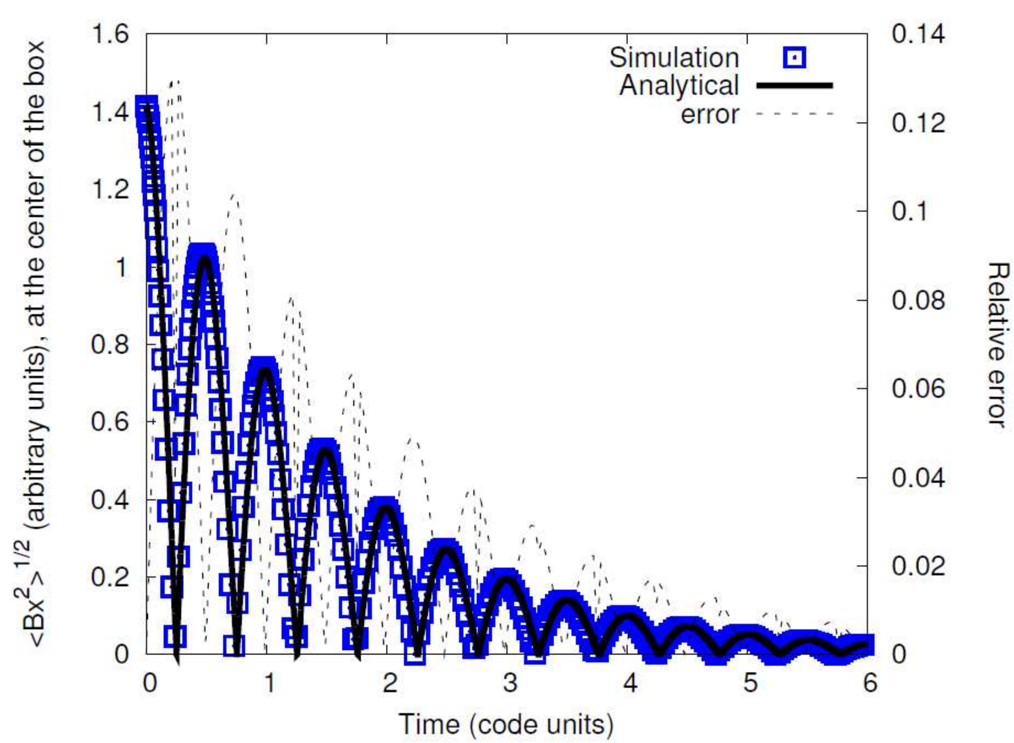
- Tests pour des ondes d'Alfvén



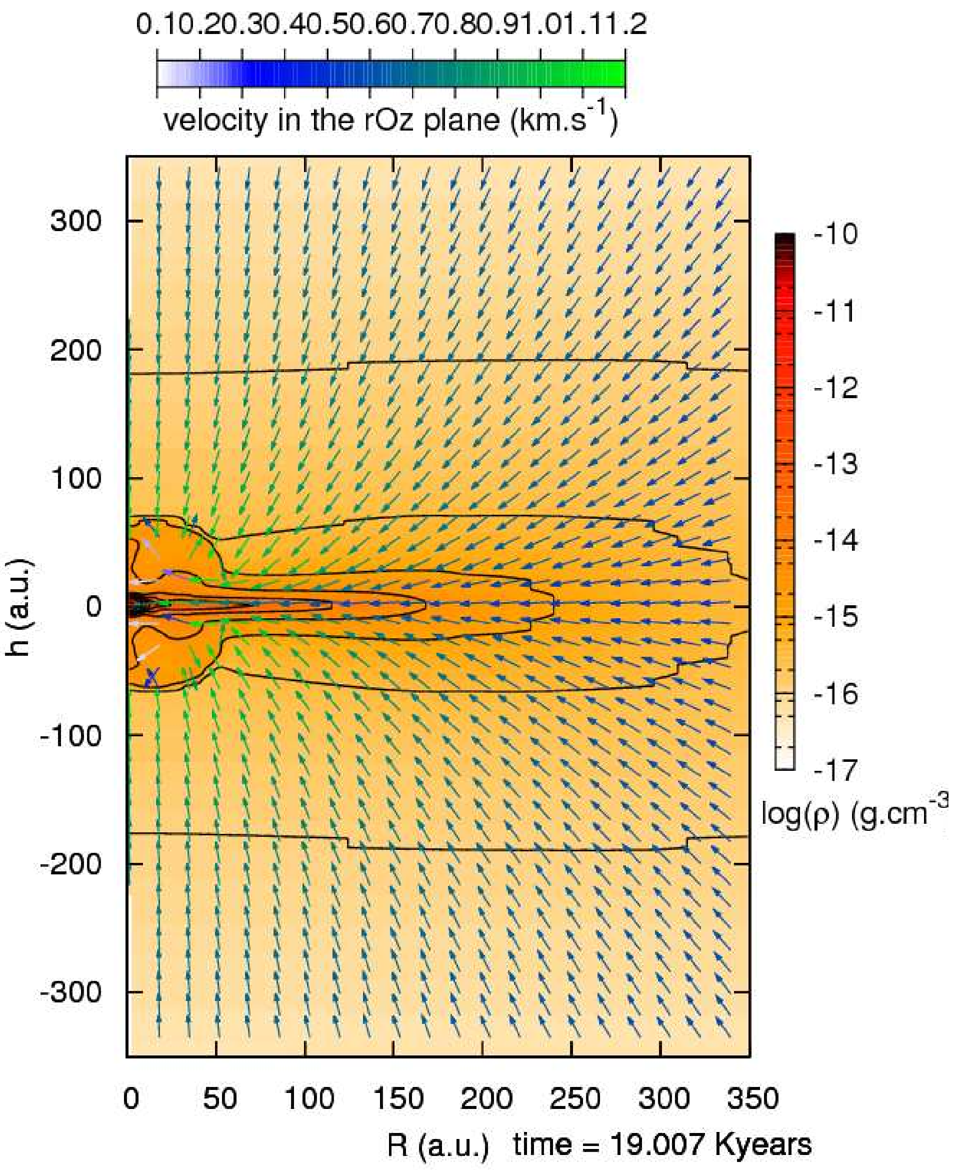
Diffusion Ohmique

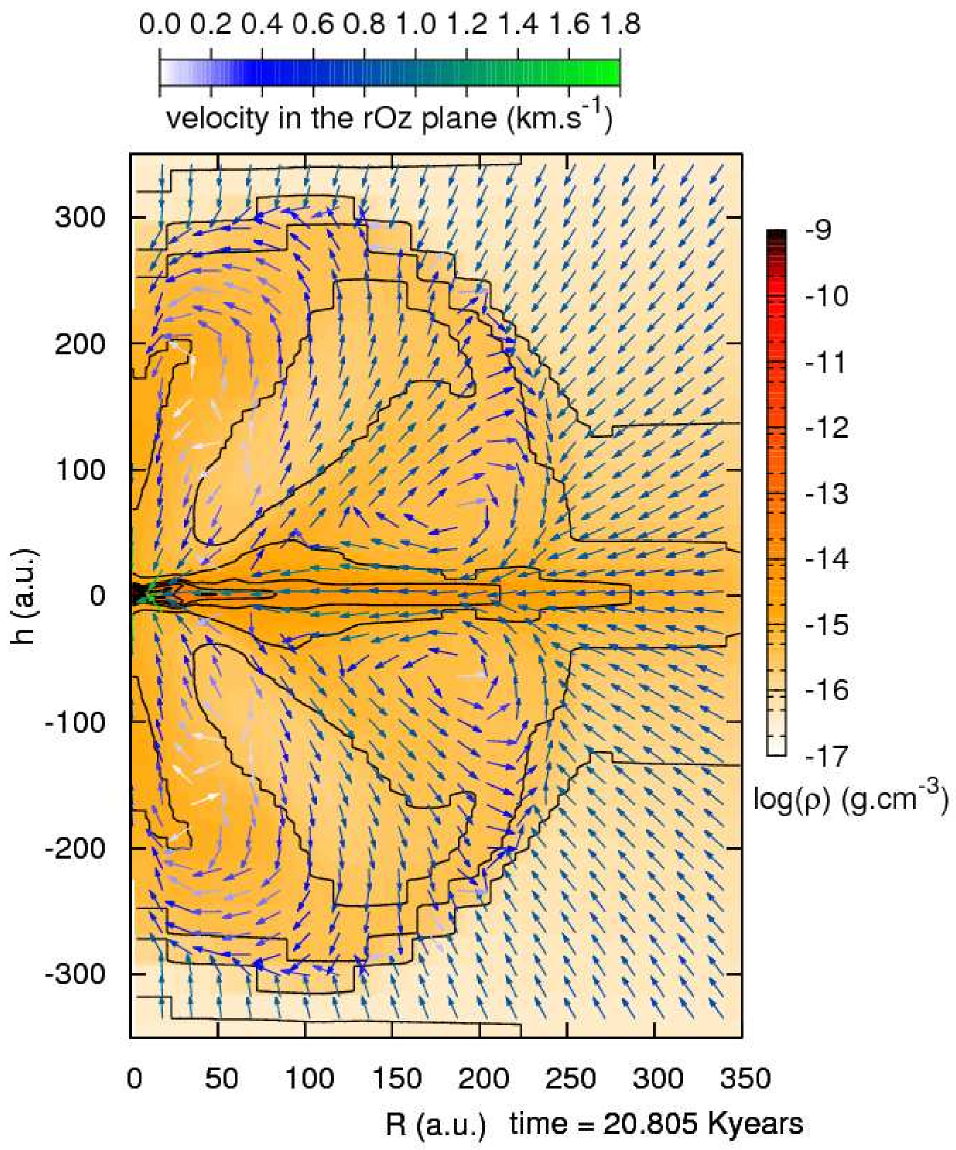


Diffusion ambipolaire

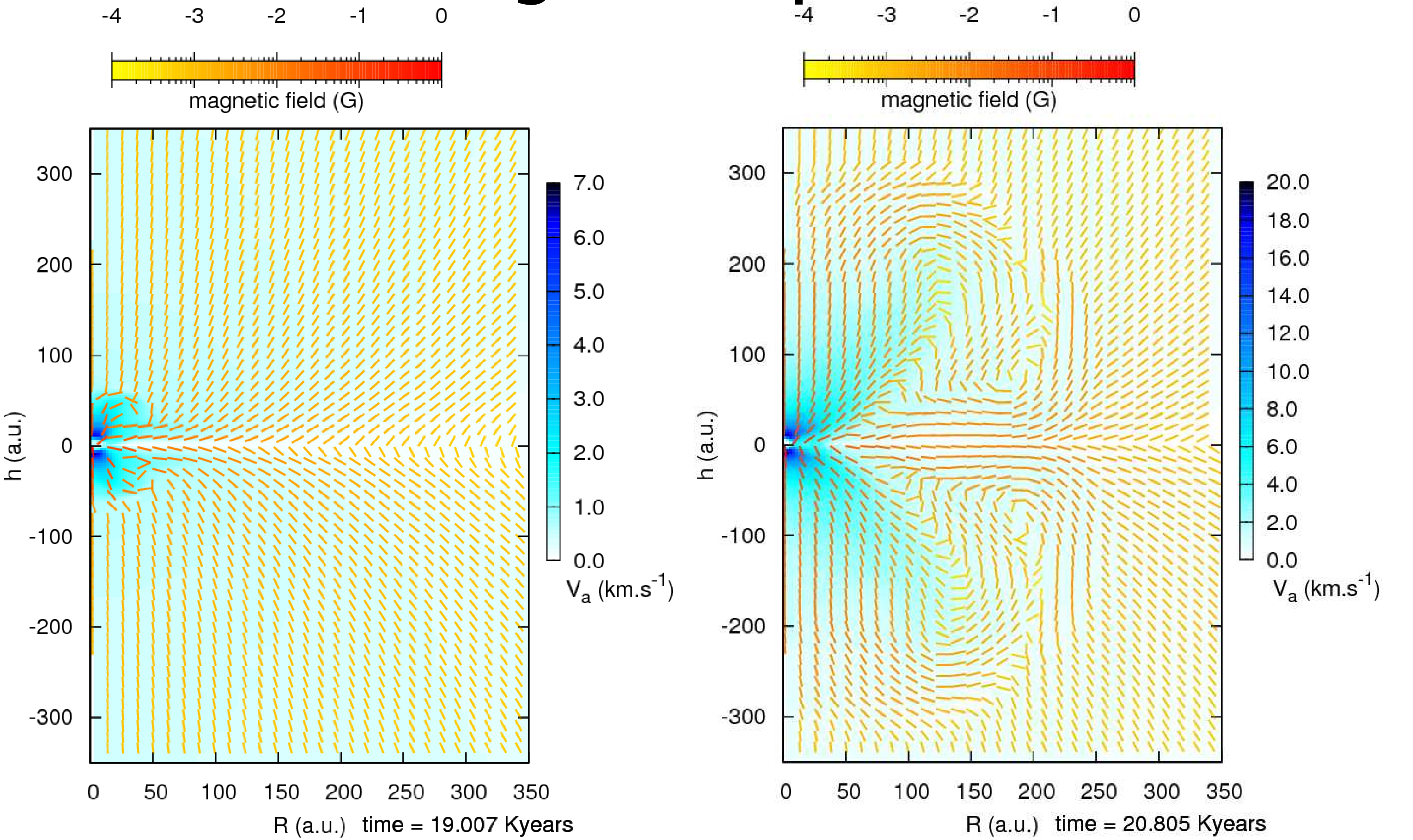


Formation du premier coeur et structures : densité





Formation du premier coeur et structures : champ magnétique



Disques et fragmentation

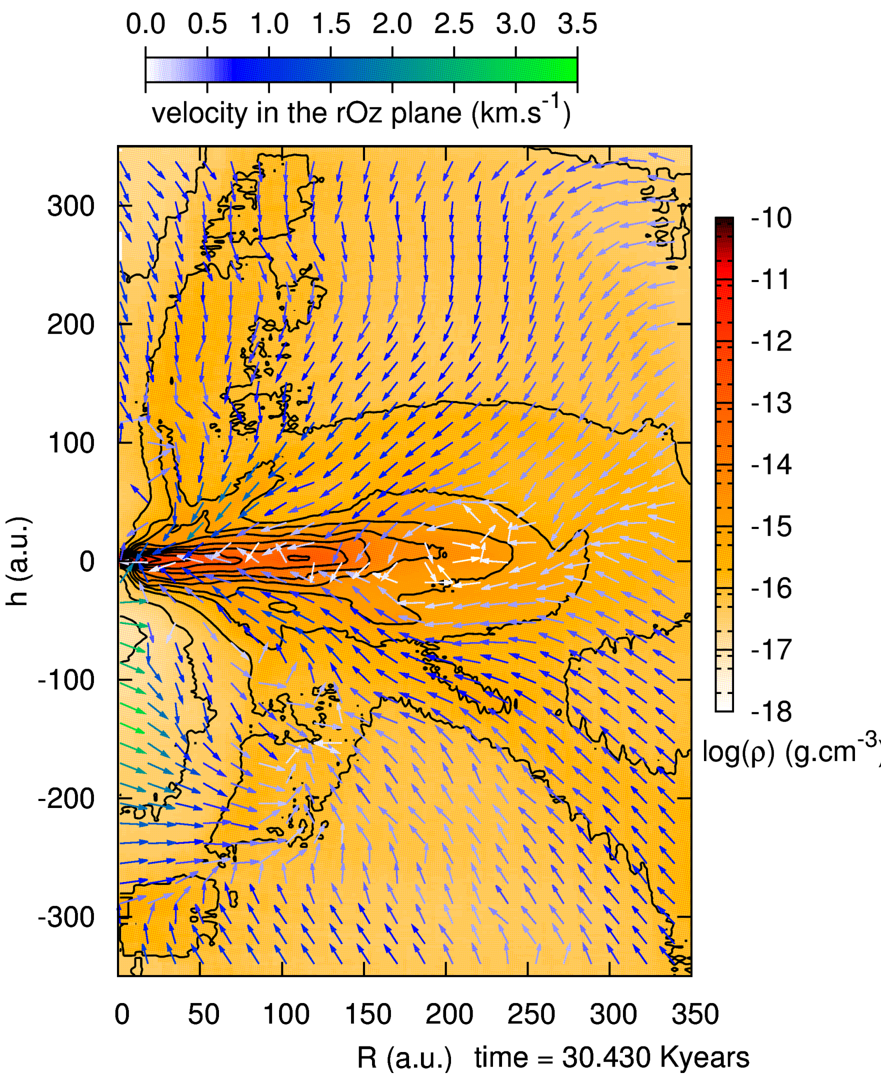
- Turbulence, $\mu=5$

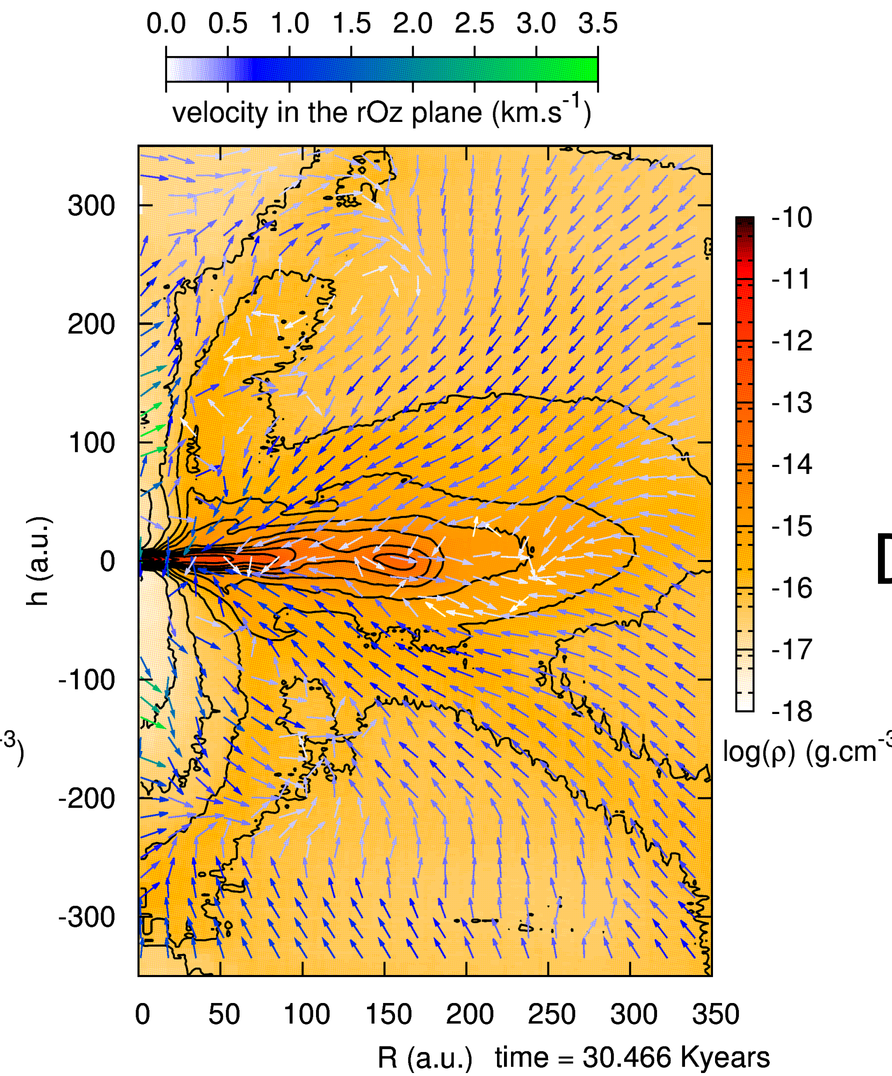
setup	Mach< 1		Mach> 1	
MHD case	Ideal	AD	Ideal	AD
disk ?	flat (9)	flat (10)	flat (8)	flat (13)
M_{disk} ($M_\odot$)	0.10	0.10	0.08	0.093
R_{disk} (a.u.)	200	200	240	300
$P_{magnetic}/\rho\frac{v_\theta^2}{2}$	10^{-2} & 1	10^{-3} & 1	10^{-2} & 5	10^{-4} & 0.5
outflow delay (10^3 years)	15	8	no	10
$\mathbf{J}_{\text{specific}}^{\mathbf{r=100}\text{ a.u.}}$ (10^{20} cm^2.s^{-1})	1.0	1.0	1.0	1.0
$\mu(r=100$ a.u.)	15	20	20	20
first core formation (10^3 years)	19.4	19.0	20.0	20.0
$R_{\text{first core}}$ (a.u.)	8.5 & 11.1	9 & 13	8.9 & 9	8.9 & 8.9
$M_{\text{first core}}$ ($\times 10^{-2}$ a.u.)	4.8	2.9	3.3	2.6
$\mu(r=10$ a.u.) (r in a.u.)	20 (5)	20 (8)	11 (7)	30 (6)
$P_{magnetic}$ (dyn.cm^{-1})	1.6×10^{-2}	1.1×10^{-3}	2.0×10^{-2}	1.1×10^{-3}

Disques et fragmentation

- Turbulence, $\mu = 5$

IMHD

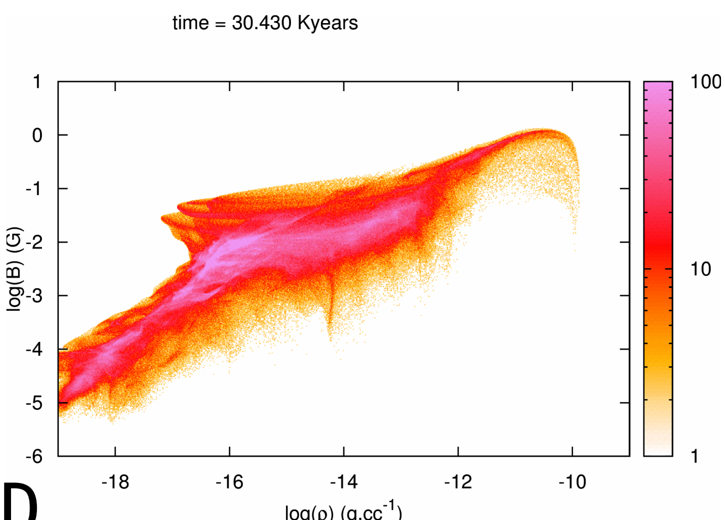


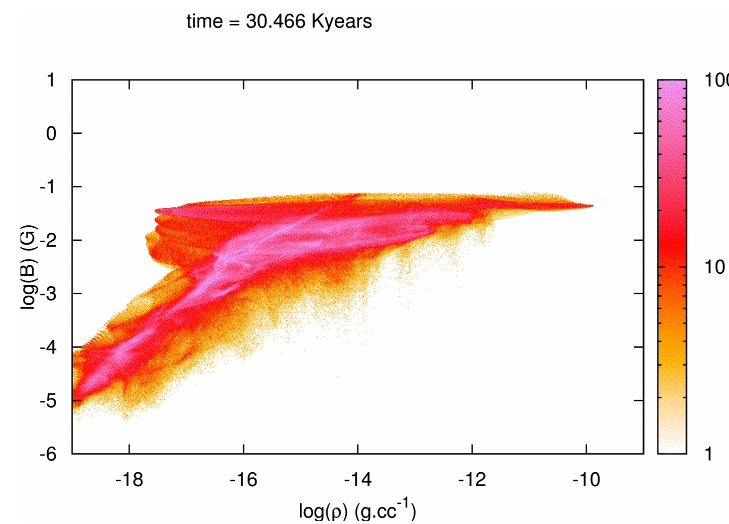


DA

Disques et fragmentation

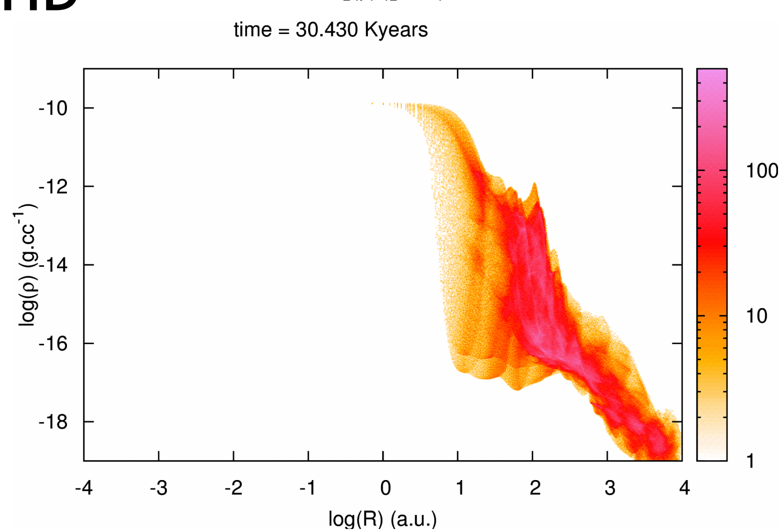
- Turbulence, $\mu=5$

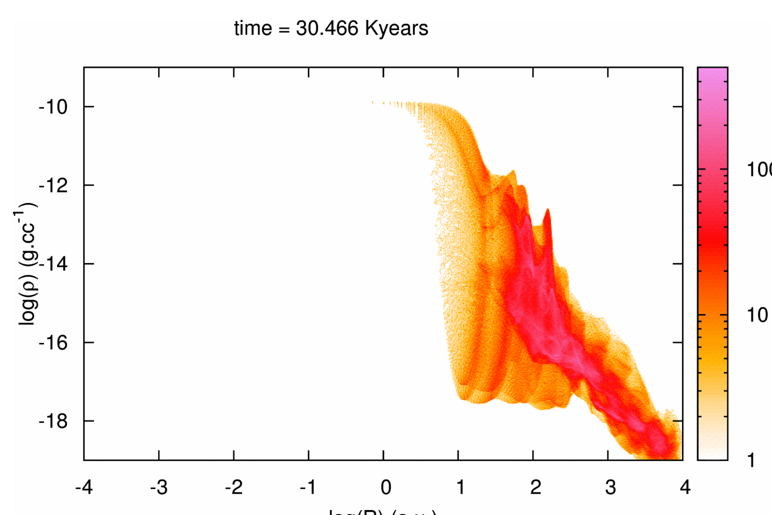




IMHD

DA





Disques et fragmentation

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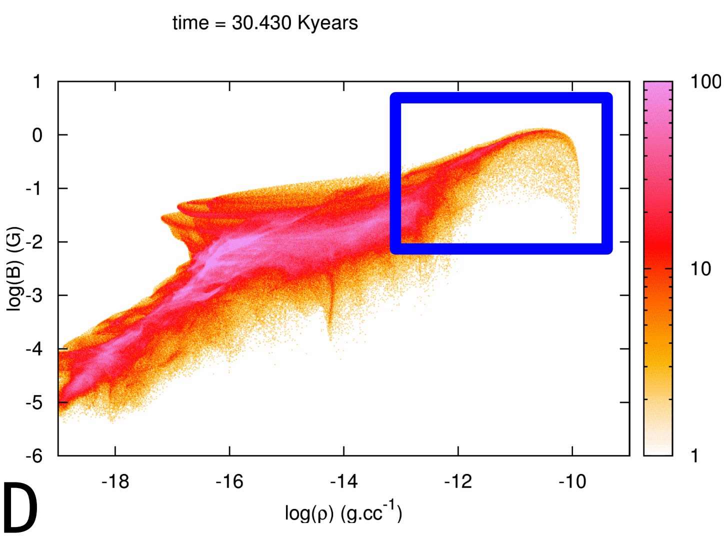

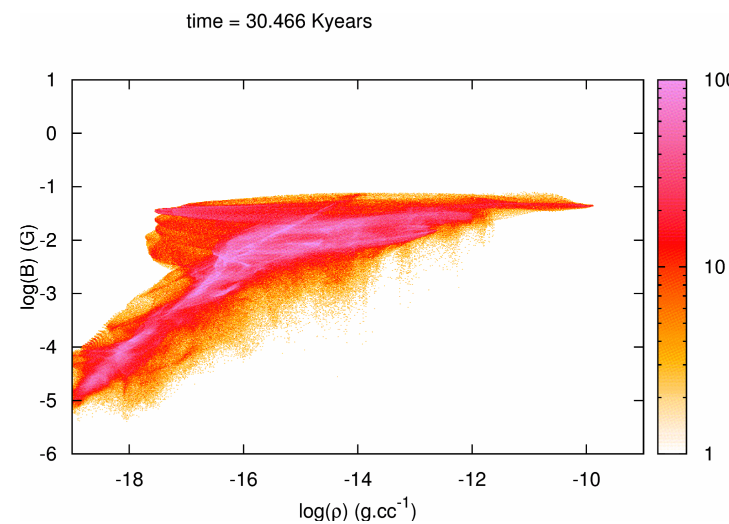

IMHD

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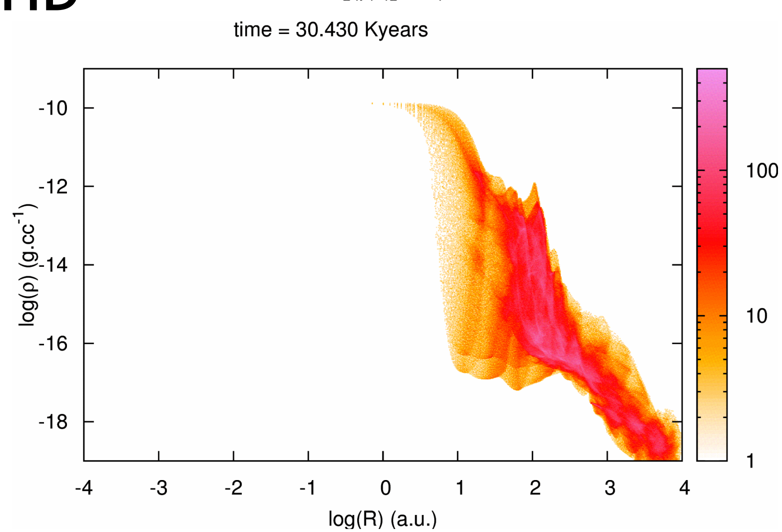
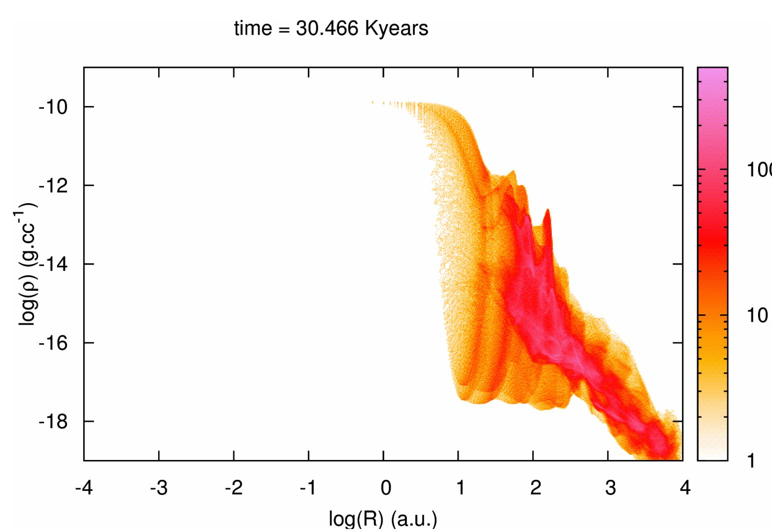
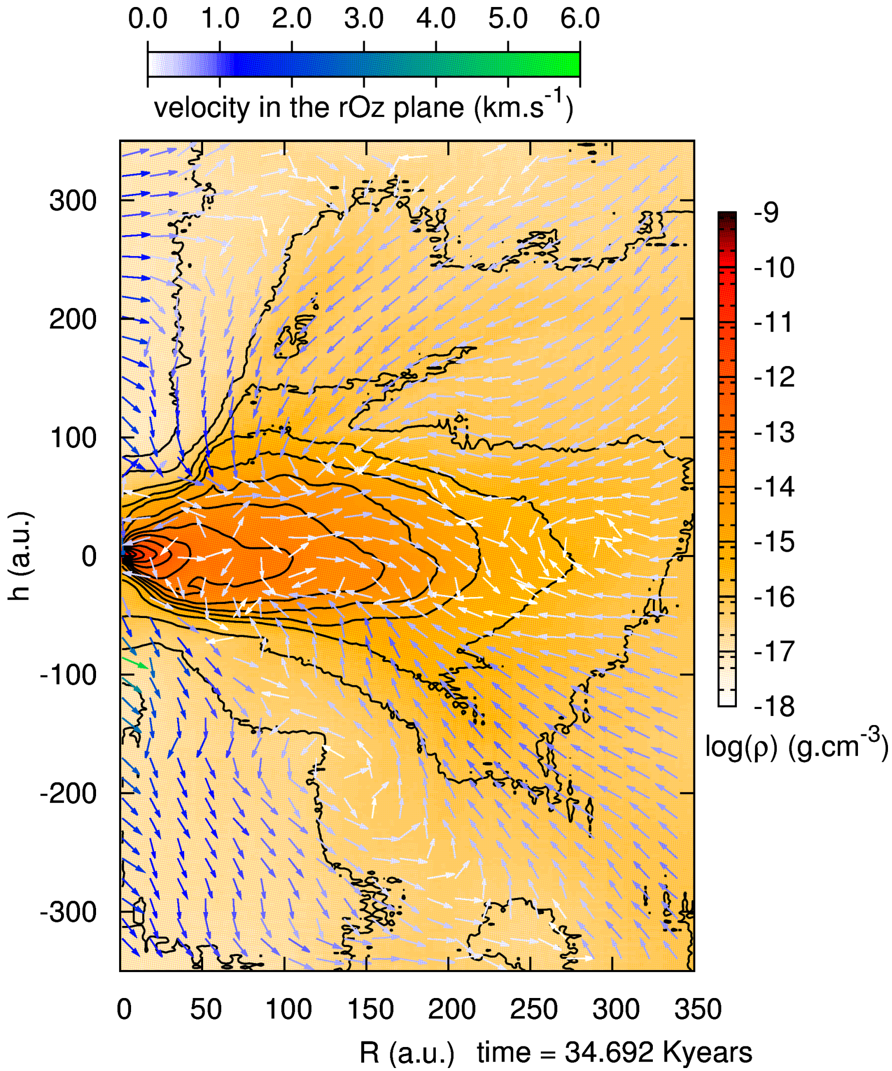




Disques et fragmentation

- Turbulence, μ=5



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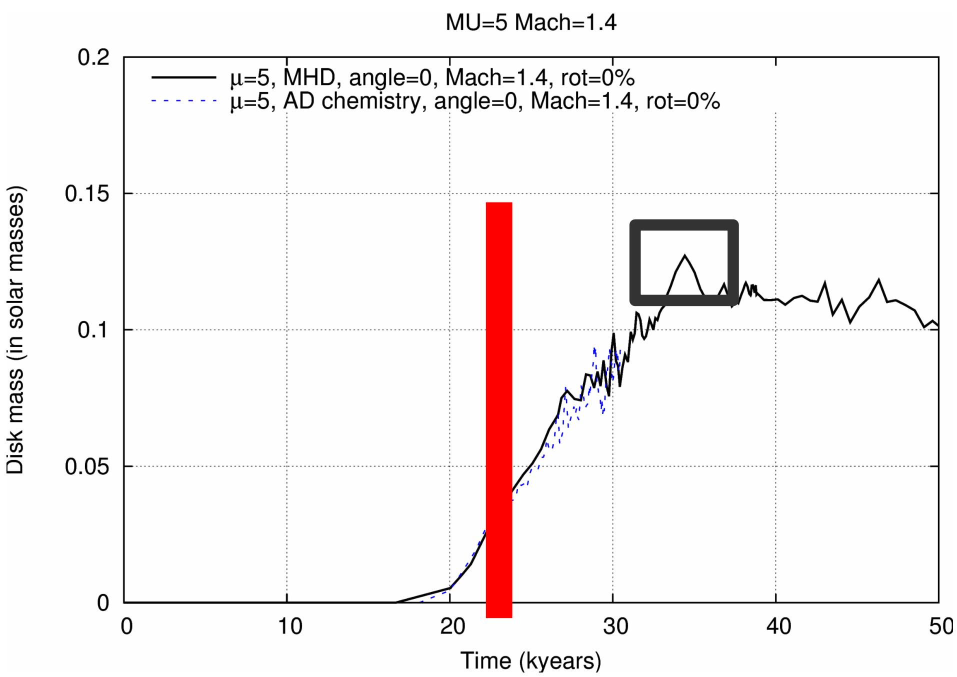
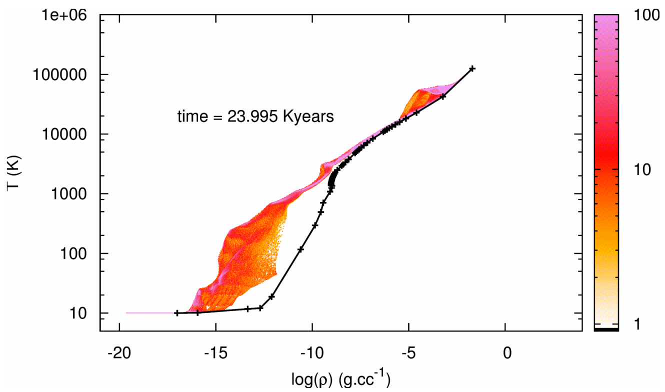


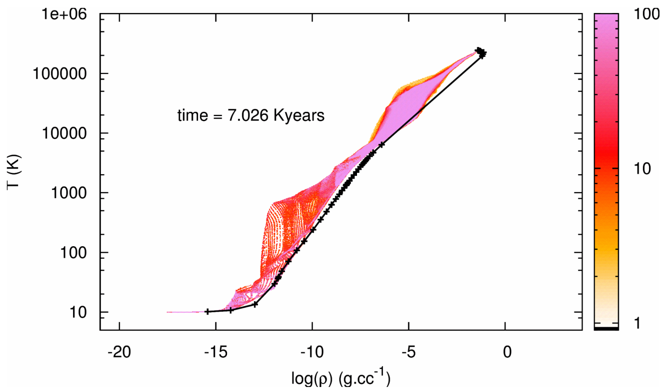
Question de temps ?

- Second effondrement, jets...

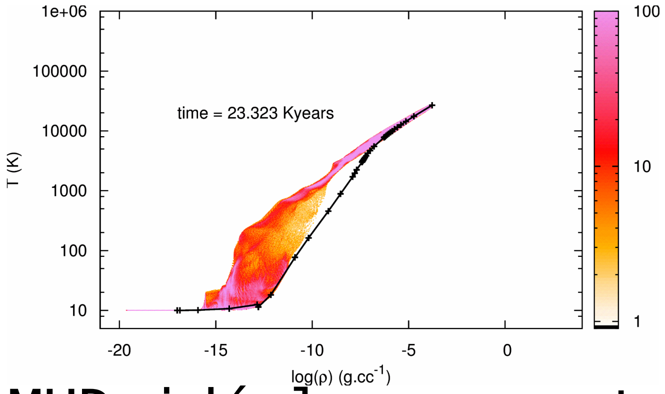
Second effondrement : transfert radiatif



L_Jeans8+isoJeans(300K)



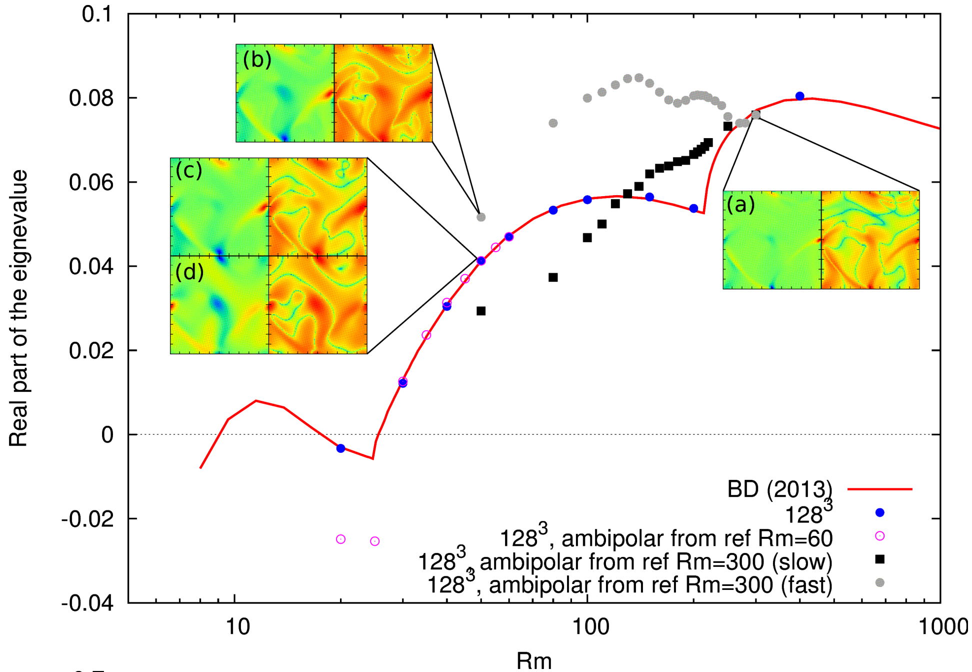
L_Jeans8+isoJeans(10K)

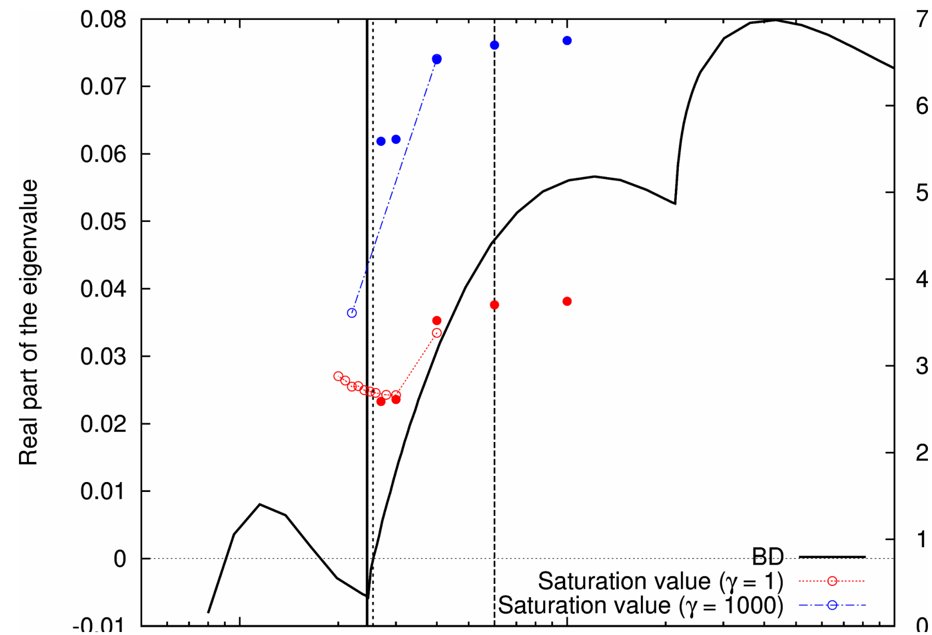


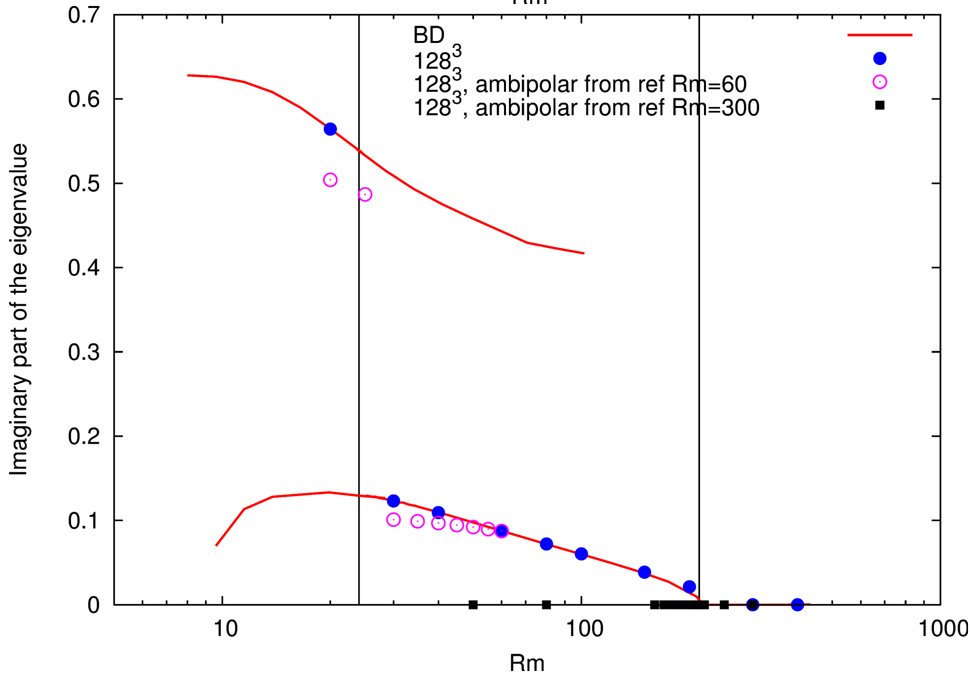
L_Jeans16+isoJeans(300K)

MHD idéale, avec transfert et équation d'état

ABC dynamo using AD







- Topological differences
- Non-linear bifurcation