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l'Observatoire de Paris

Magnetic braking and its effects during protostellar collapse

When Magnetic Field leads to Catastrophe and Crisis

Patrick Hennebelle

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Why *must* we understand collapse ?

Major astrophysical questions

⇒**Determine the initial conditions of the protostars**:
-entropy
-angular momentum (*the angular momentum problem*)
-magnetic field (*the magnetic flux problem*)

⇒**Binary and multiple system formation**

⇒**Disk formation: Planet formation and migration**

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

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Zoom into the central part of a collapse calculation (1 solar mass slowly rotating core)

(Allen et al. 03, Machida et al. 05, Banerjee & Pudritz 06, Price & Bate 07, Hennebelle & Fromang 08)

300 AU

XY
hydro

XY
MHD
μ=2

⊙ B, ω

XZ hydro

XZ
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↑ B, ω

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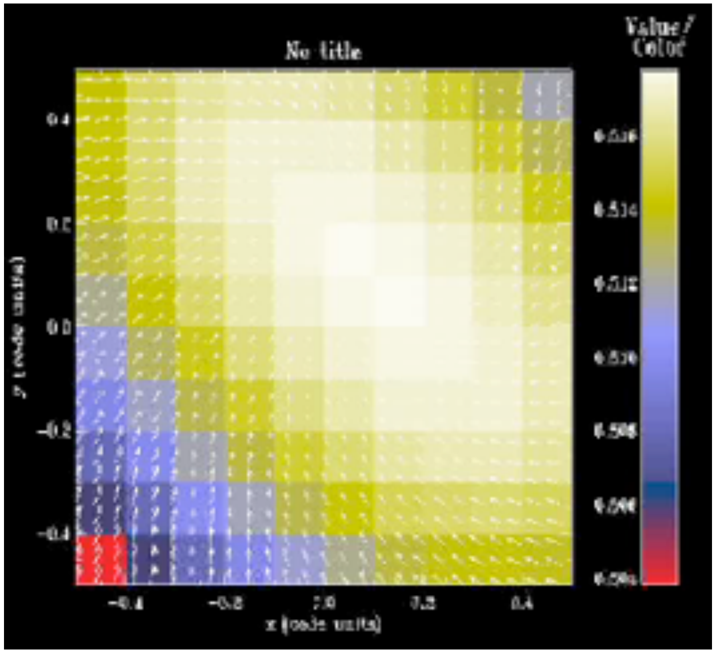
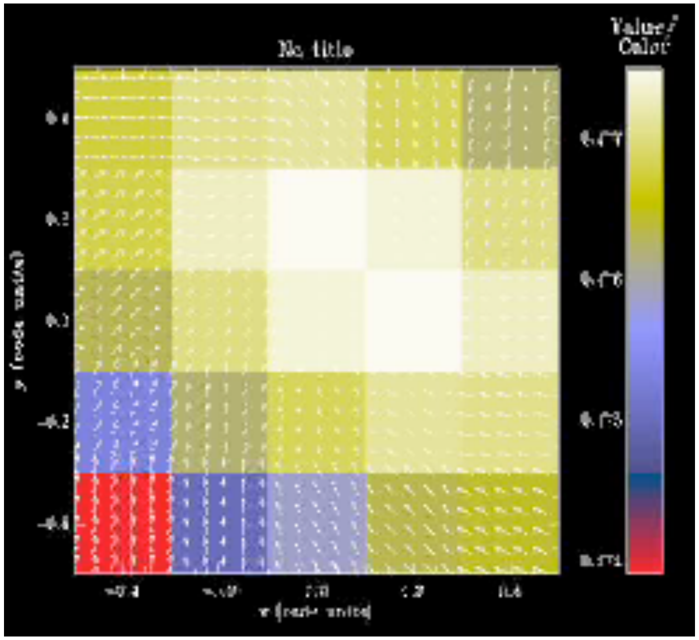
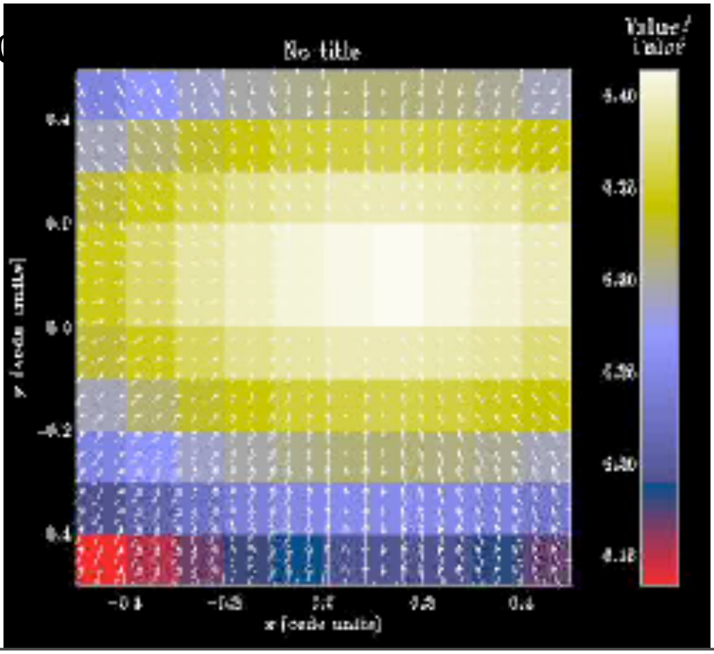


XY
MHD
μ=2



B, ω

XZ hydro



XZ
MHD
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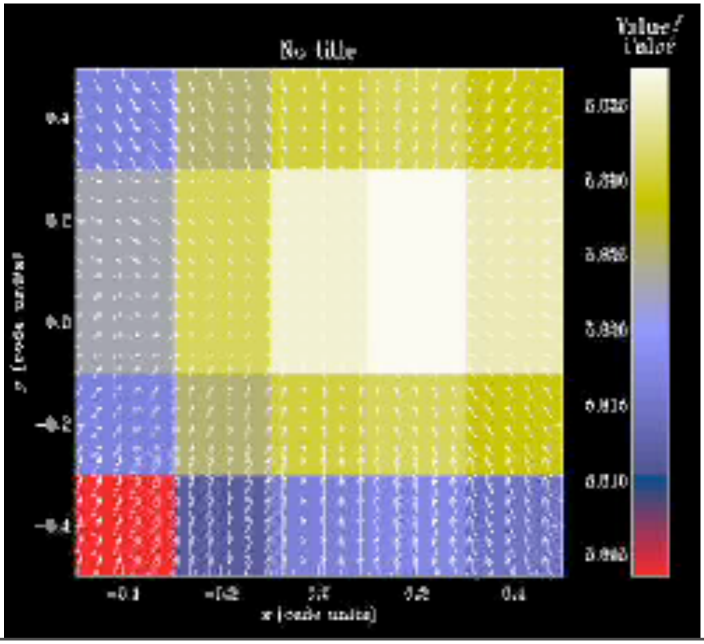

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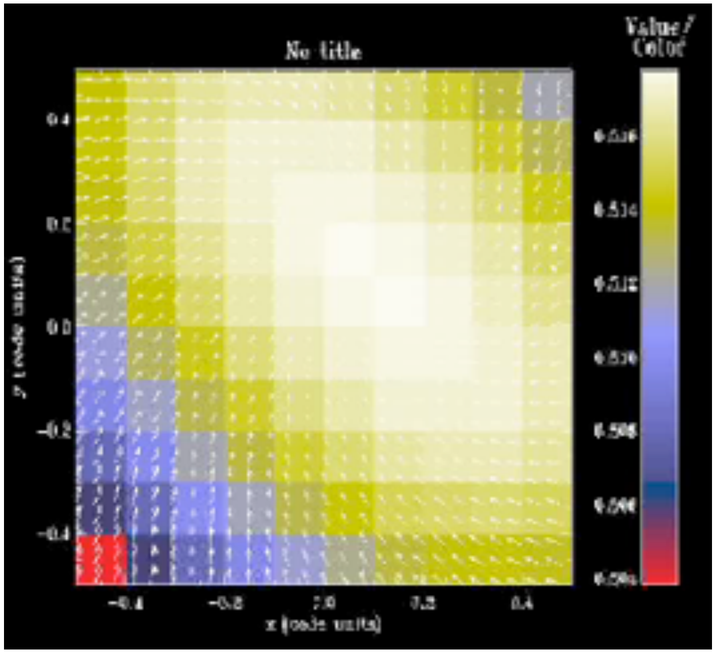

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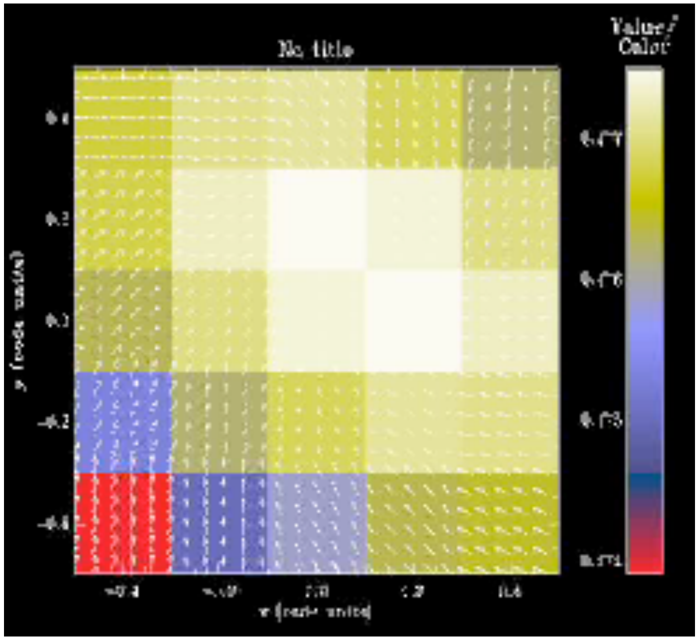

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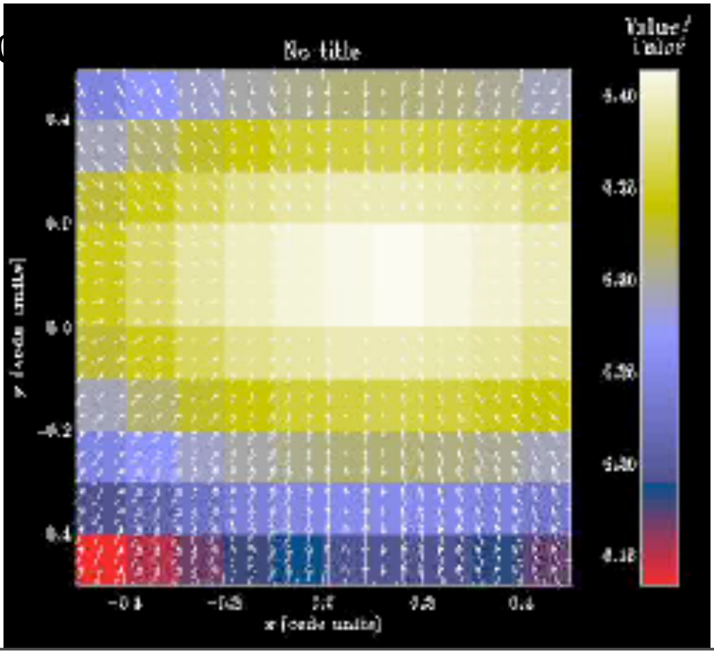
XZ hydr



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MHD
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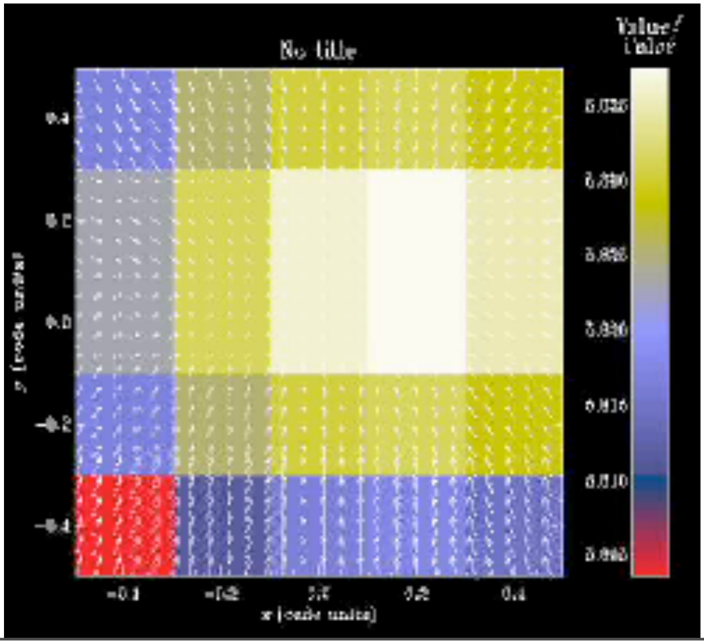

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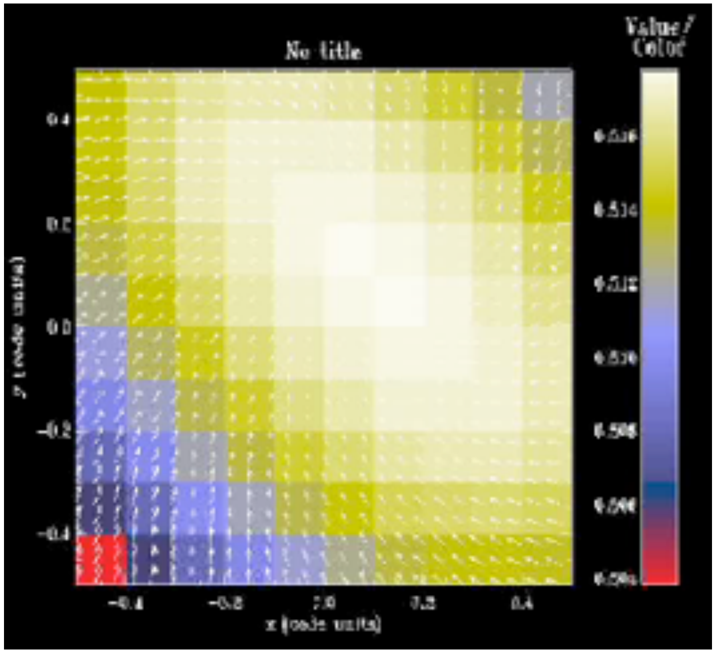

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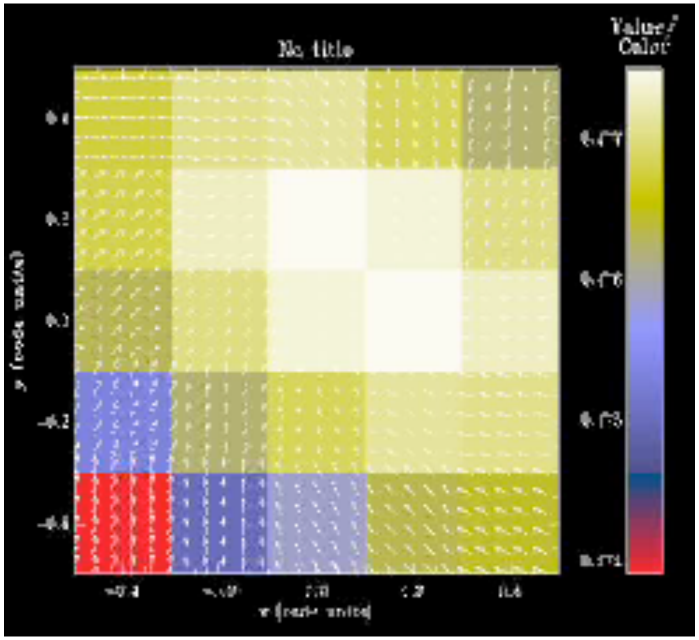

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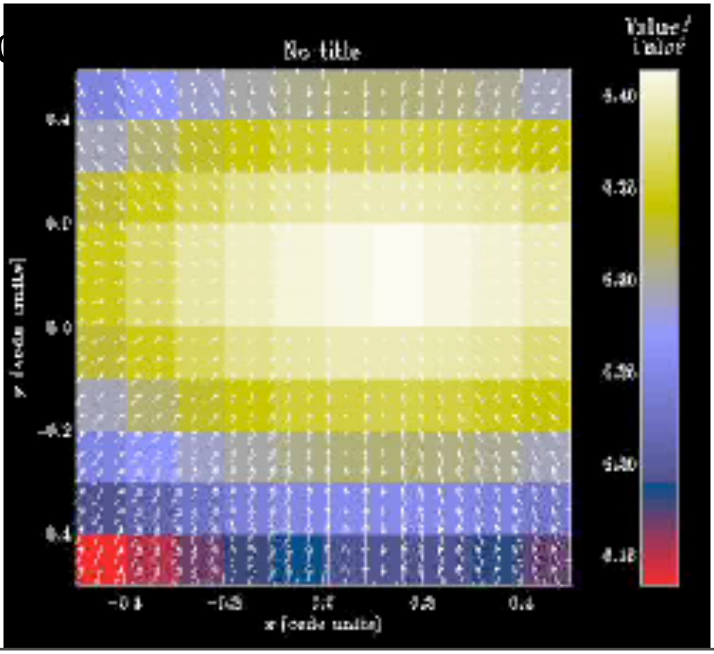

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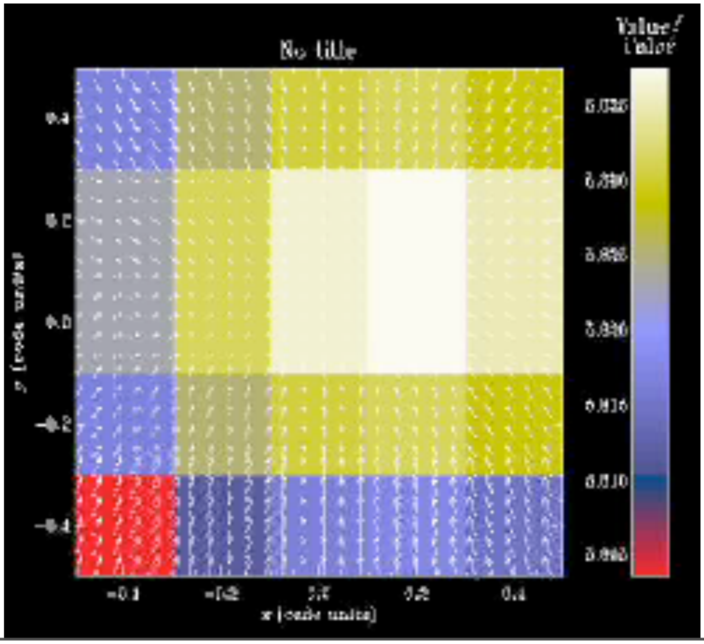

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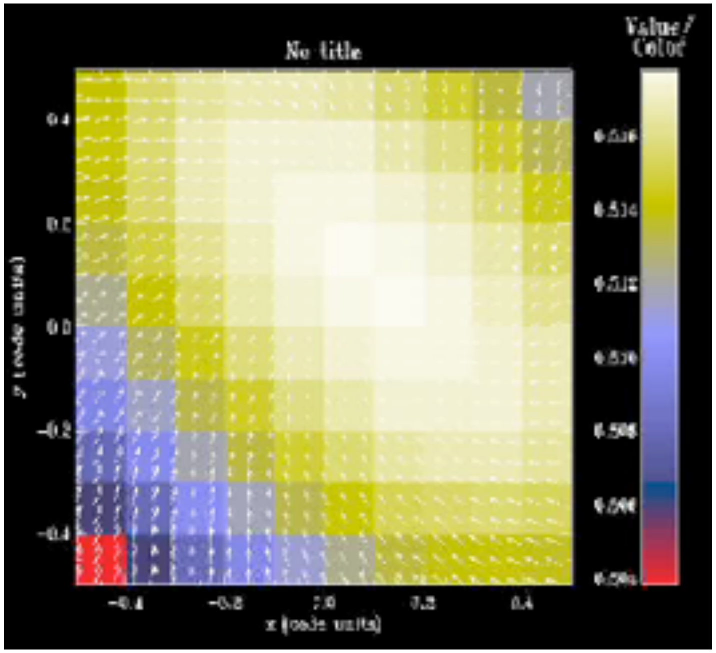

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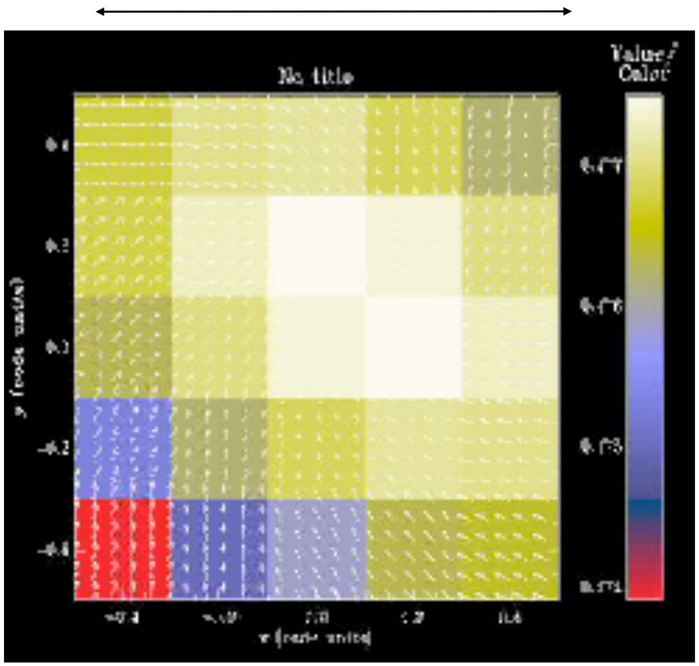

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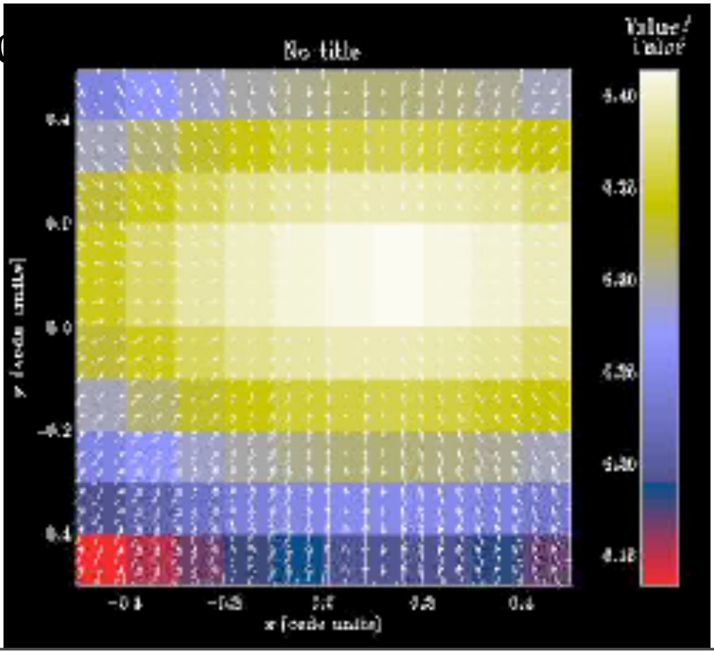

B, ω

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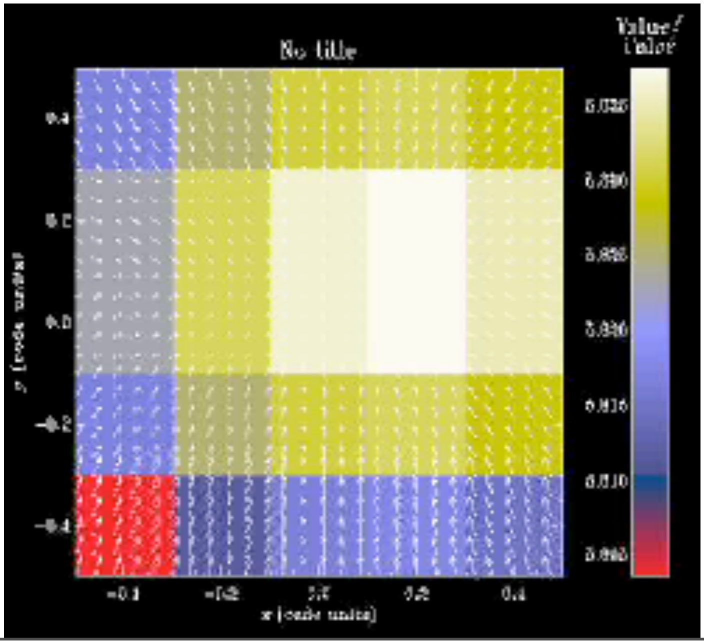
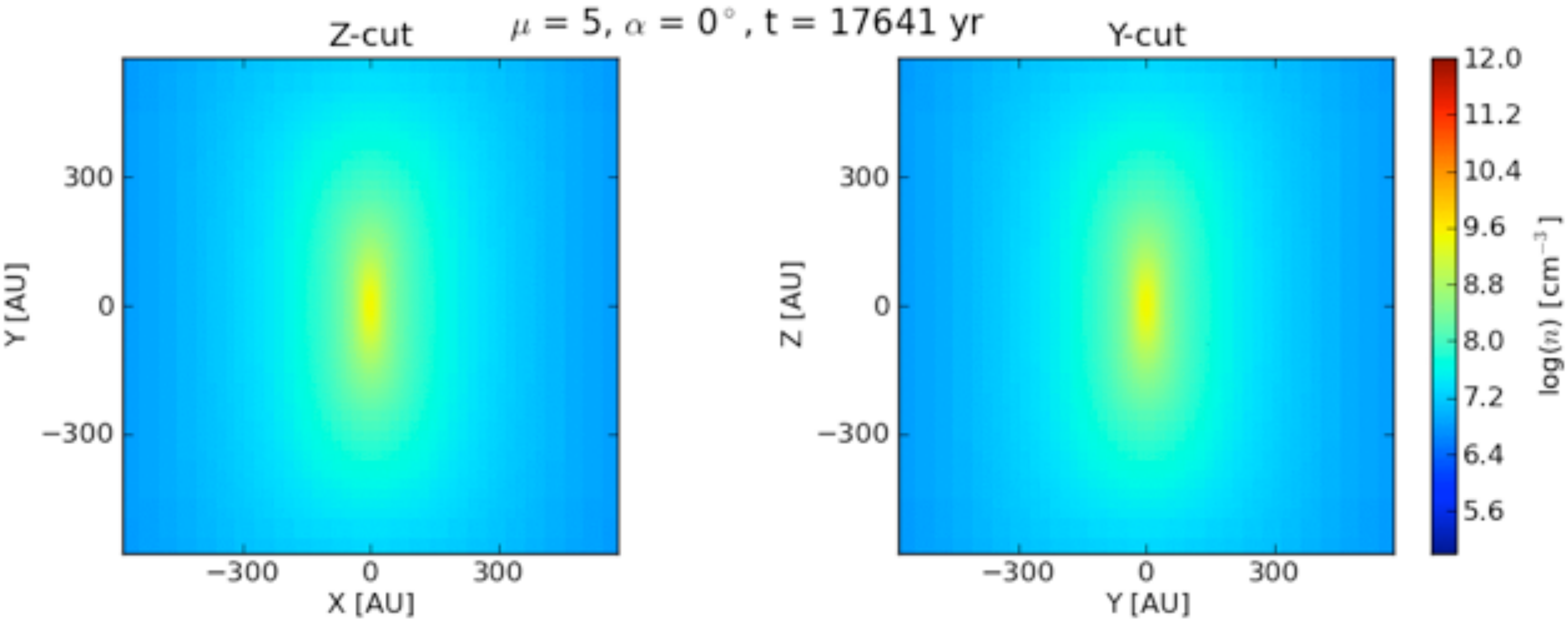
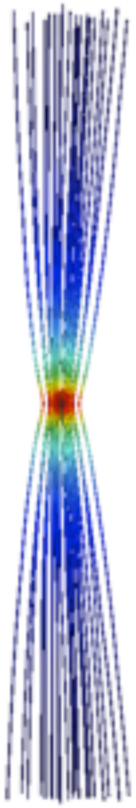
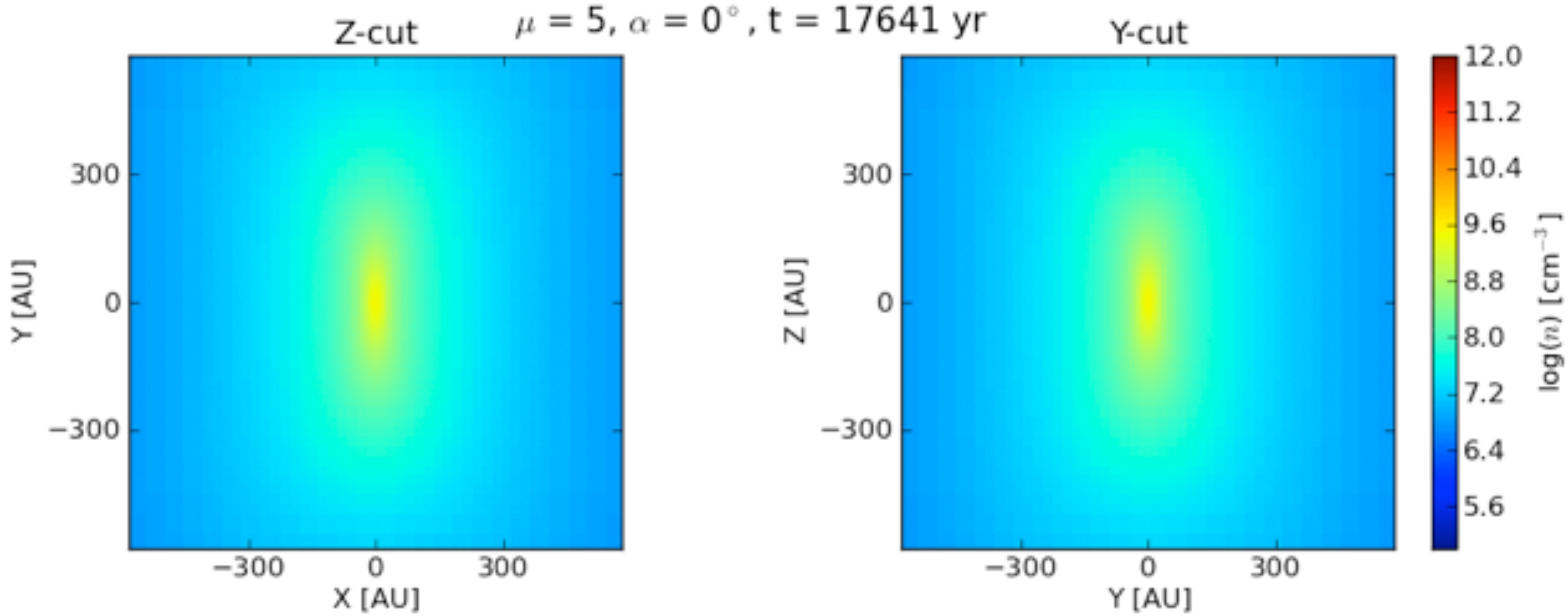



μ = 5, α = 0°, t = 17641 yr
Z-cut
Y-cut
300
0
−300
Y [AU]
−300
0
300
X [AU]
300
0
−300
Z [AU]
−300
0
300
Y [AU]
12.0
11.2
10.4
9.6
8.8
8.0
7.2
6.4
5.6
log(n) [cm^{-3}]




μ = 5, α = 0°, t = 17641 yr
Z-cut
Y [AU]
300
0
−300
−300
0
300
X [AU]
Y-cut
Z [AU]
300
0
−300
−300
0
300
Y [AU]
12.0
11.2
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8.8
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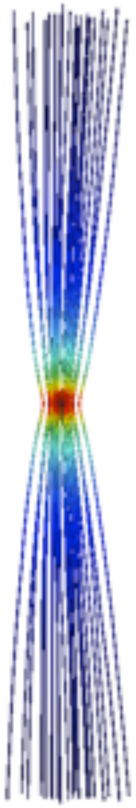
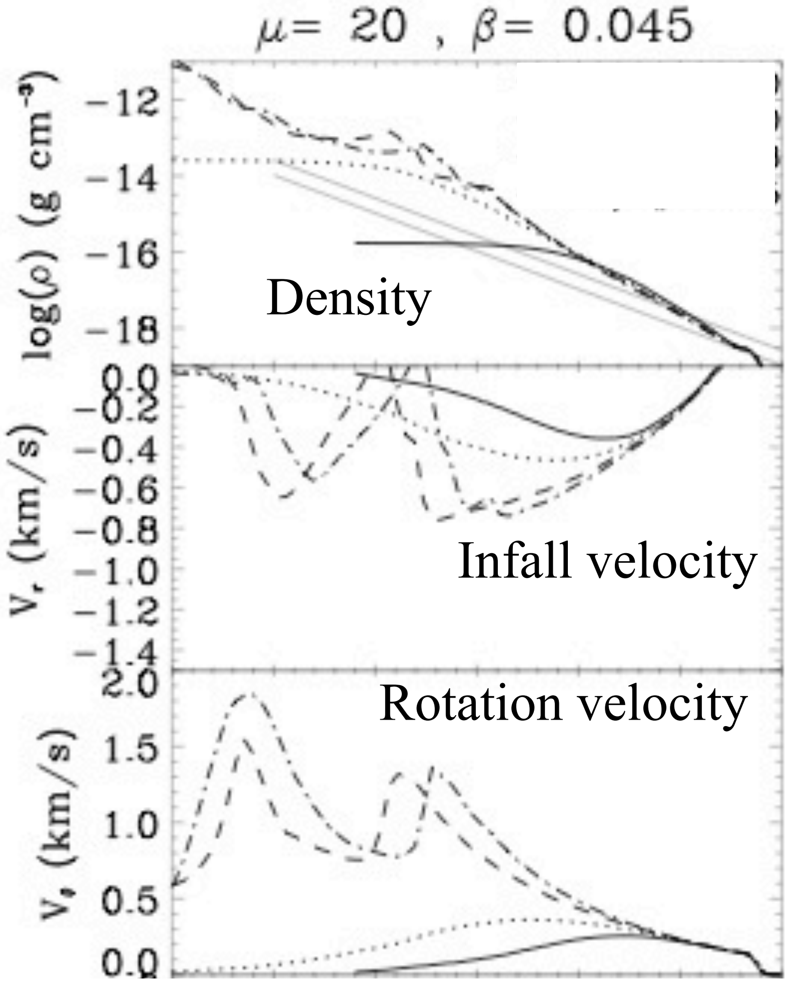
6.4
5.6
log(n) [cm^{-3}]



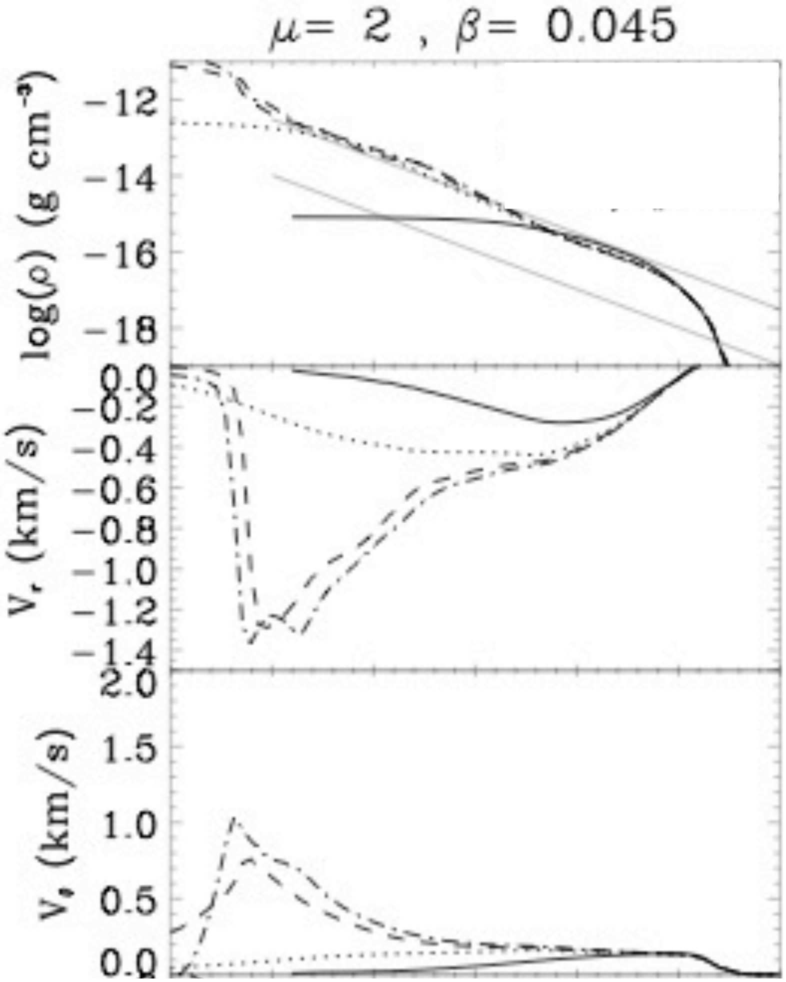
Density, rotation and infall velocity profiles



Density

Infall velocity

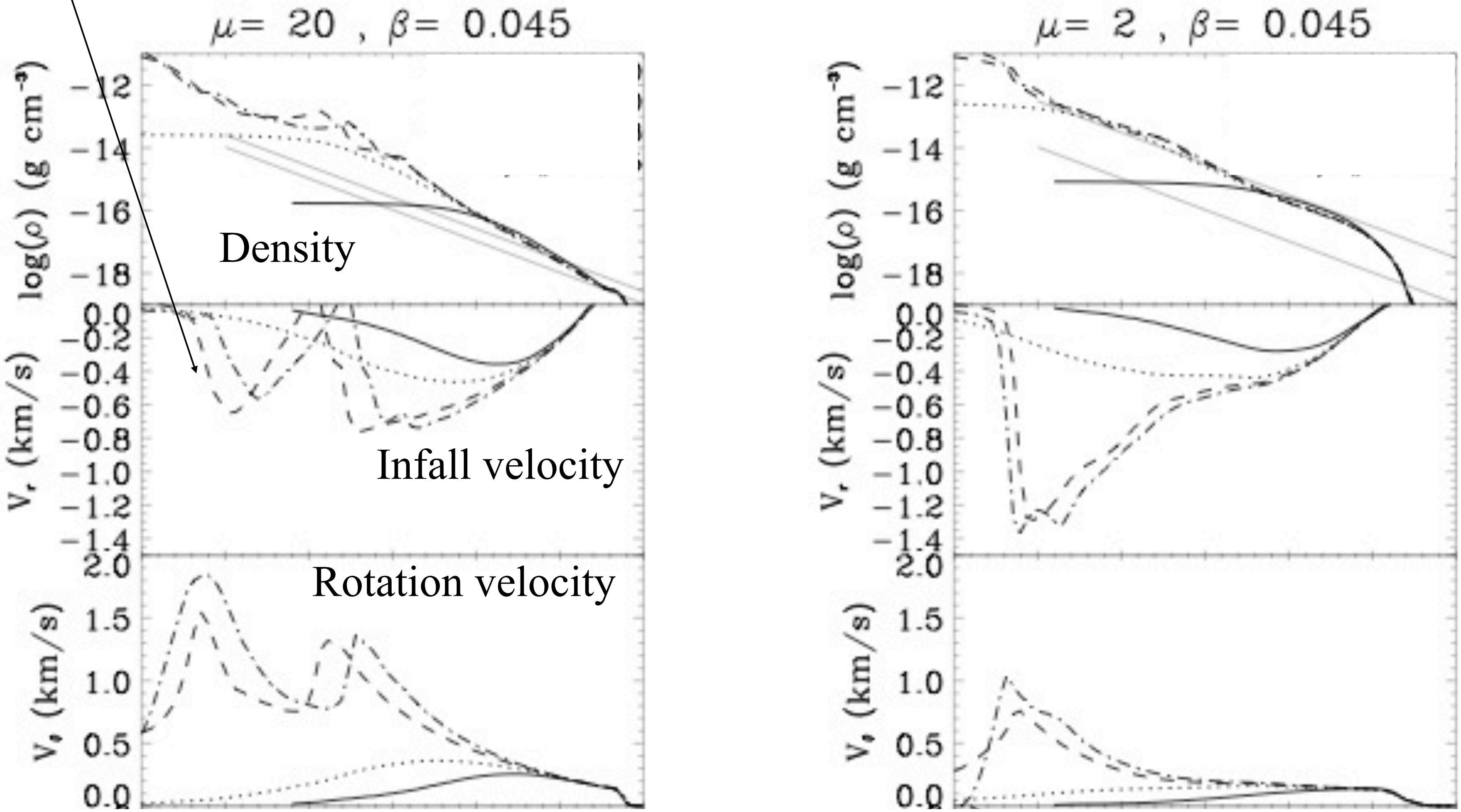
Rotation velocity



Hennebelle & Fromang 2008

Density, rotation and infall velocity profiles

Thermally supported core



Density

Infall velocity

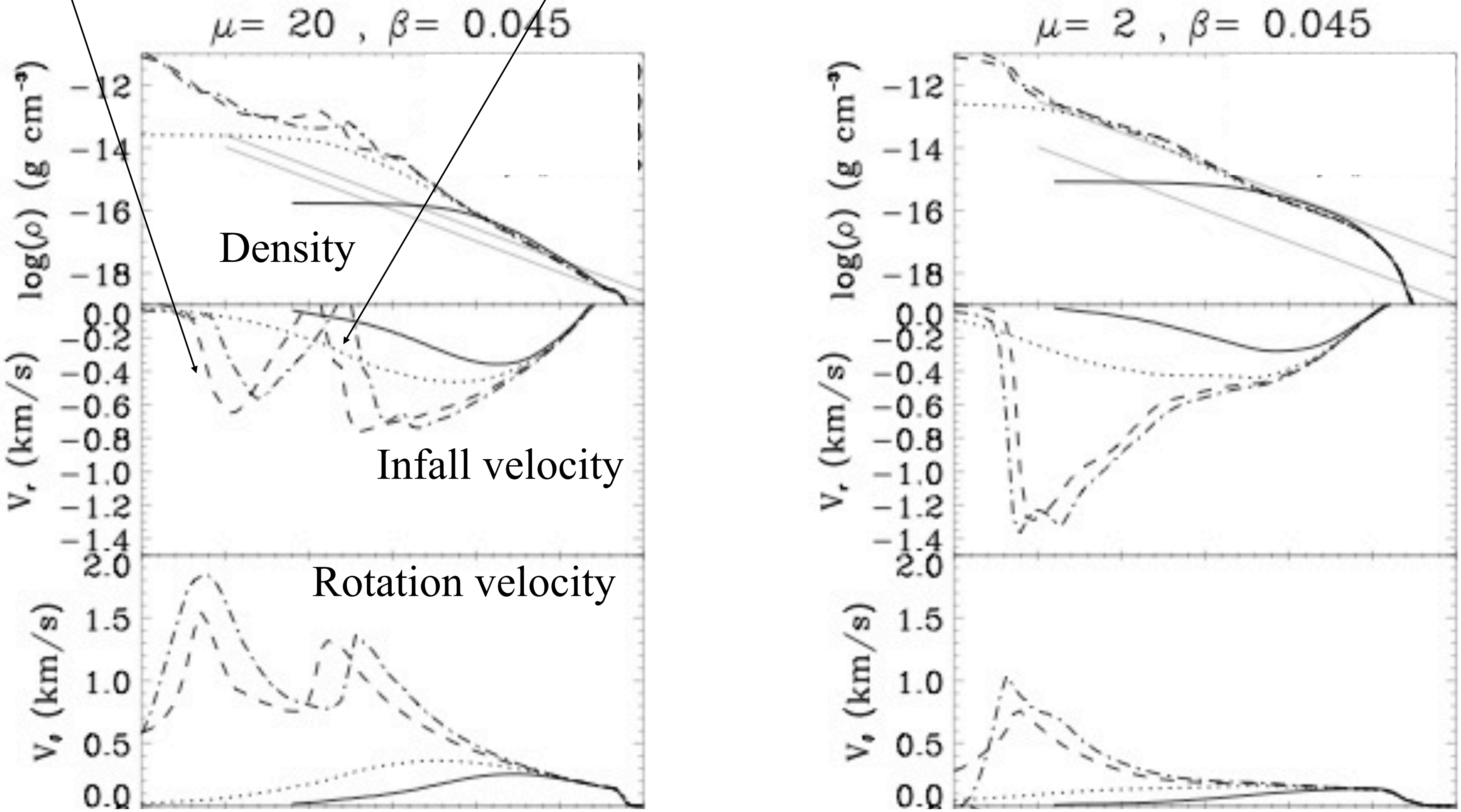
Rotation velocity

Hennebelle & Fromang 2008

Density, rotation and infall velocity profiles

Thermally supported core

Centrifugally supported disk



Density

Infall velocity

Rotation velocity

Hennebelle & Fromang 2008

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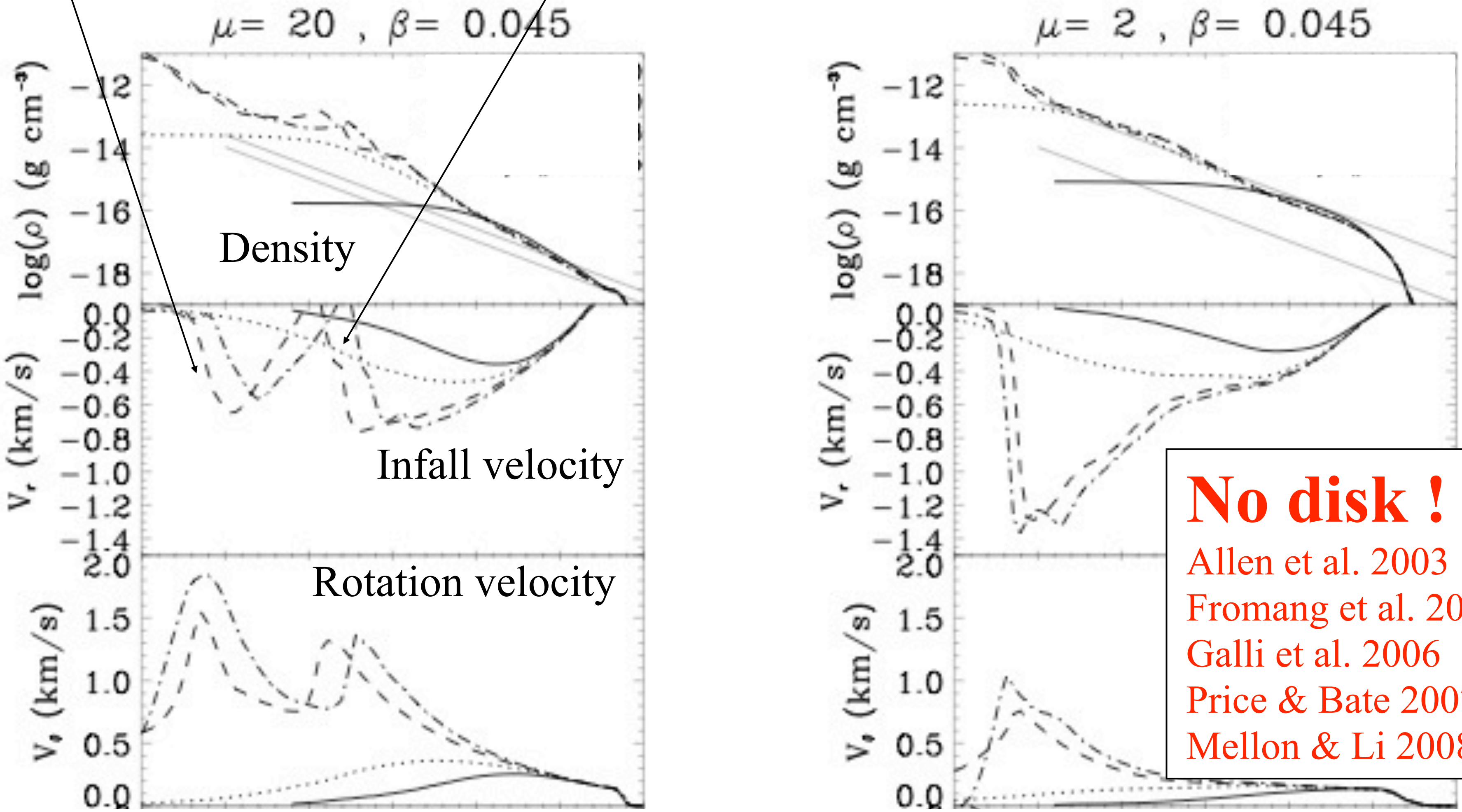


Density

Infall velocity

Rotation velocity

No disk !

Allen et al. 2003

Fromang et al. 2006

Galli et al. 2006

Price & Bate 2007

Mellon & Li 2008

Hennebelle & Fromang 2008

Can we understand this result by simple considerations ?

$$\left.\begin{aligned}\frac{\rho V_\theta}{\tau_{br}} &\propto B_z \frac{B_\theta}{4\pi h} \\ \frac{B_\theta}{\tau_{br}} &\propto B_z \frac{V_\theta}{h}\end{aligned}\right\} \Rightarrow \tau_{br} \approx \frac{\sqrt{4\pi h^2 \rho}}{B_z}$$

$$\tau_{rot} \approx \frac{2\pi\, r_d}{V_\theta},$$

$$\frac{\tau_{br}}{\tau_{rot}} \approx \frac{V_\theta \sqrt{4\pi h^2 \rho}}{2\pi\, r_d B_z}$$

$$V_\theta \approx \left(\frac{GM_d}{r_d}\right)^{1/2}, M_d \approx \pi r_d{}^2 z\rho \Rightarrow V_\theta \approx \left(G\pi\rho r_d z\right)^{1/2}$$

$$\Rightarrow \frac{\tau_{br}}{\tau_{rot}} \approx \left(\frac{z}{r_d}\right)^{1/2} \frac{G^{1/2}\rho}{B_z} \approx \left(\frac{z}{r_d}\right)^{1/2} \frac{\mu_{eff}}{(2\pi)^{1/2}}$$

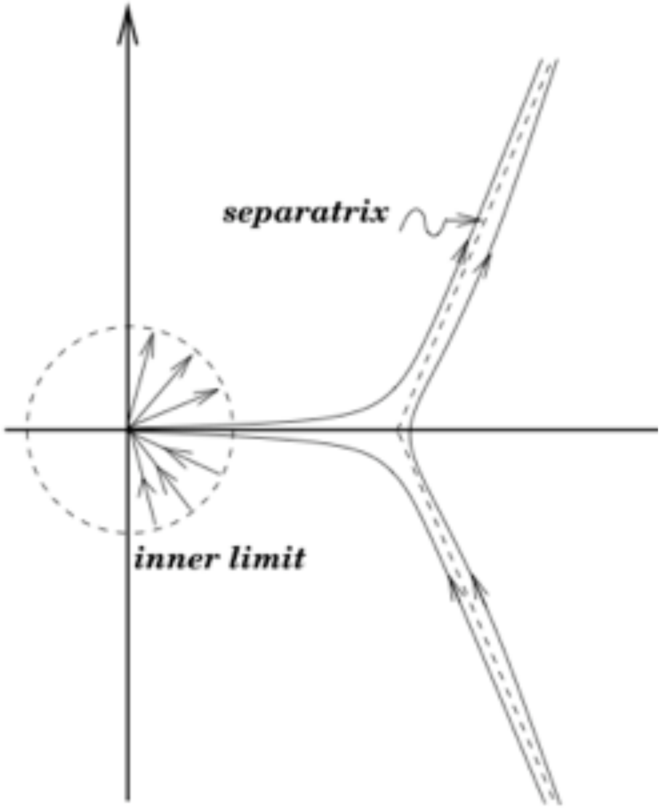
z/r_d is easily < 10 while $\mu_{eff} < \mu$ (as only a fraction of the column density has contracted)

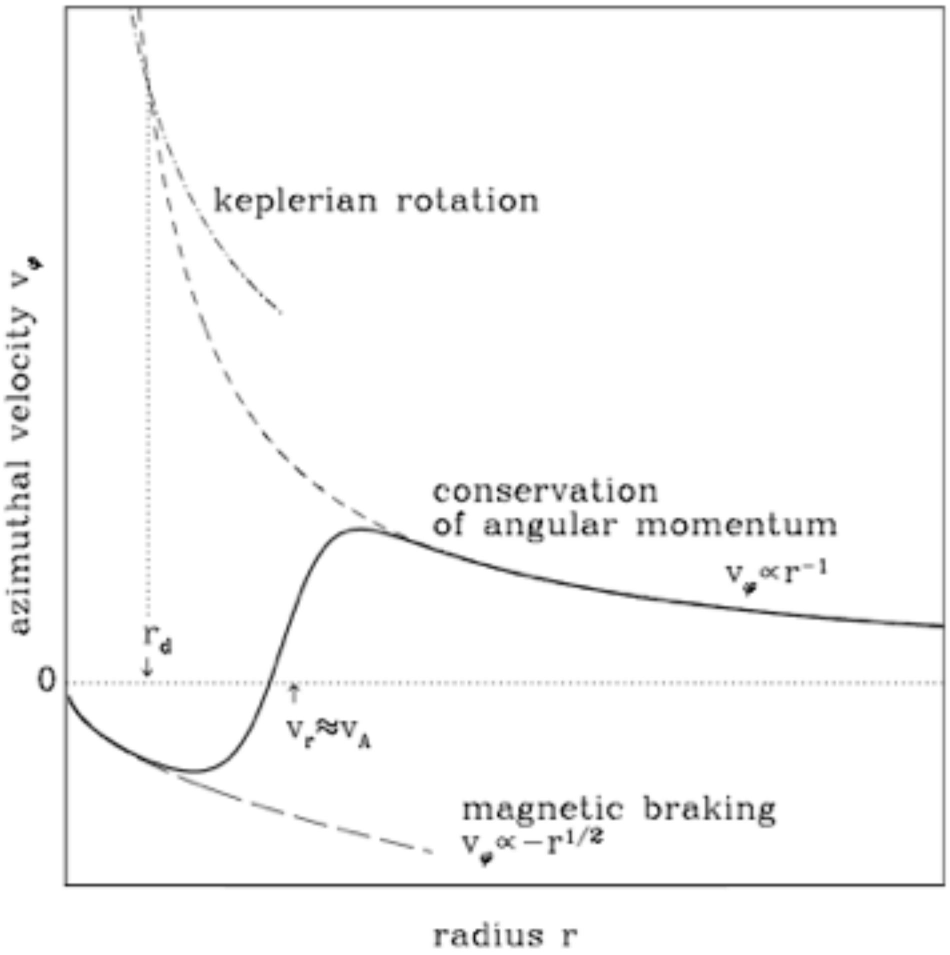
Thus a value of μ~5-10 seems entirely reasonable.

Can we understand this result by less simple considerations ?

Galli et al. 2006

Galli et al. study magnetized self-similar solutions and infer their asymptotic behavior. They show that because the field lines are strongly stretched by gravitational collapse, the field is strongly amplified and the braking very efficient.





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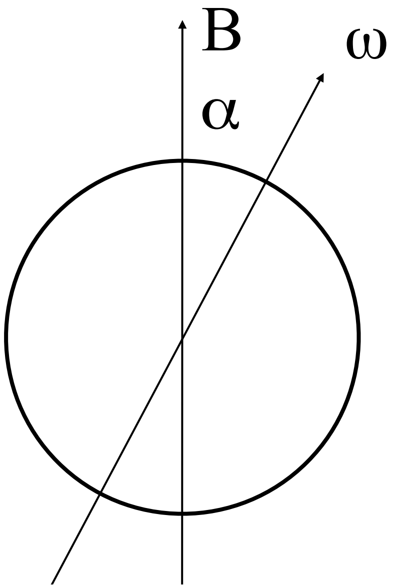
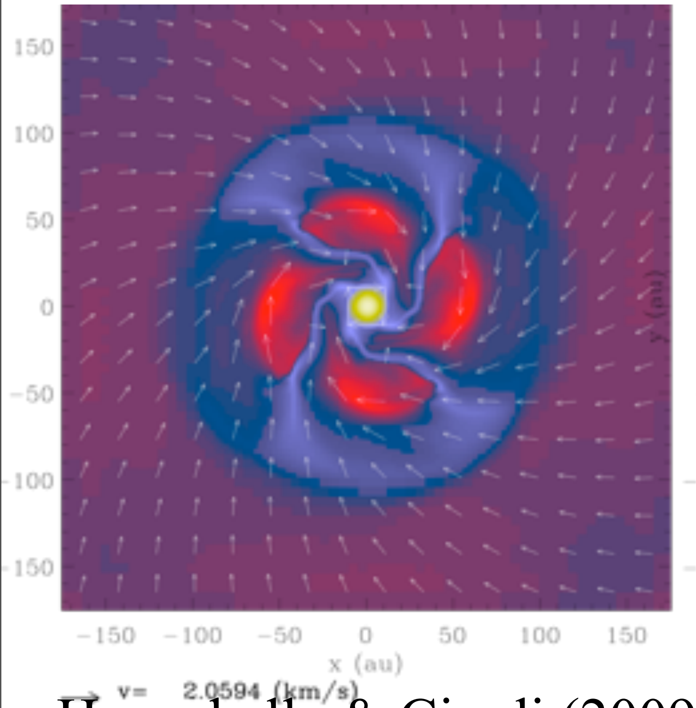
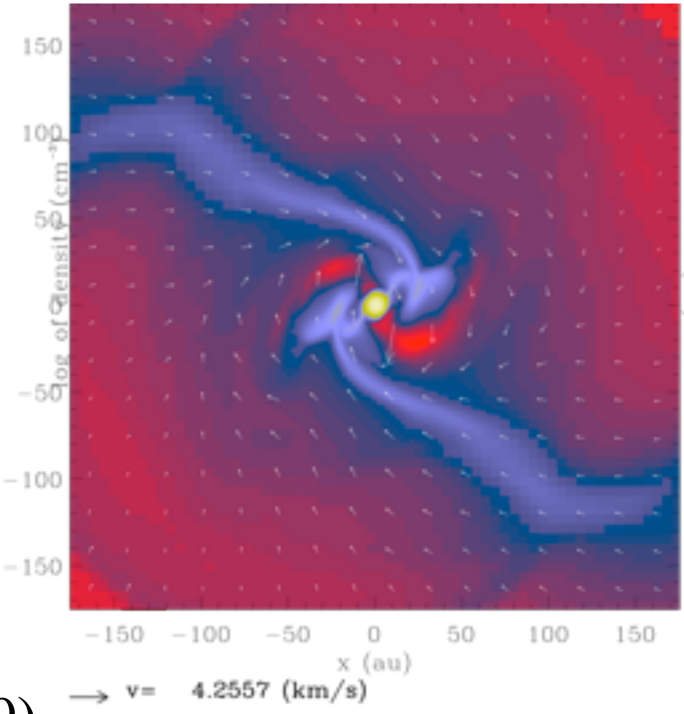
Can different magnetic configurations modify magnetic braking ?



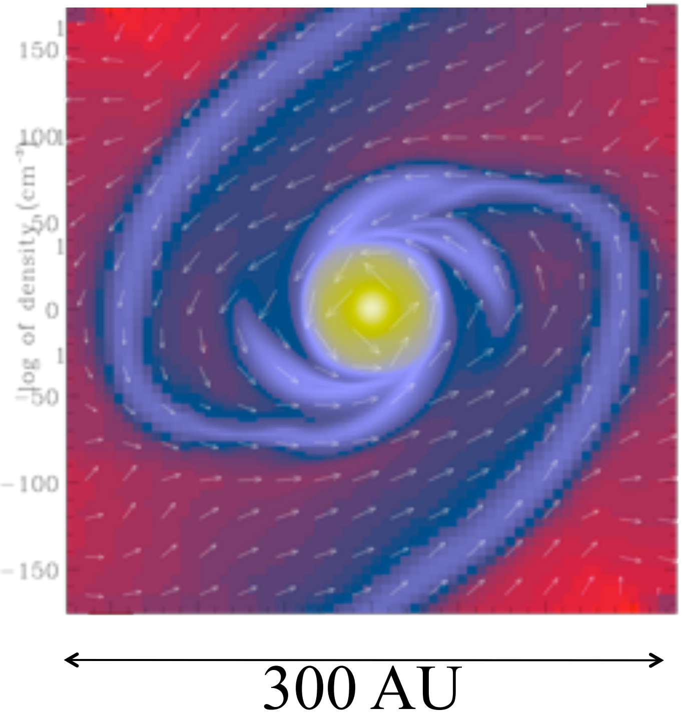
μ=5,α=0°



μ=5,α=20°



μ=5,α=90°

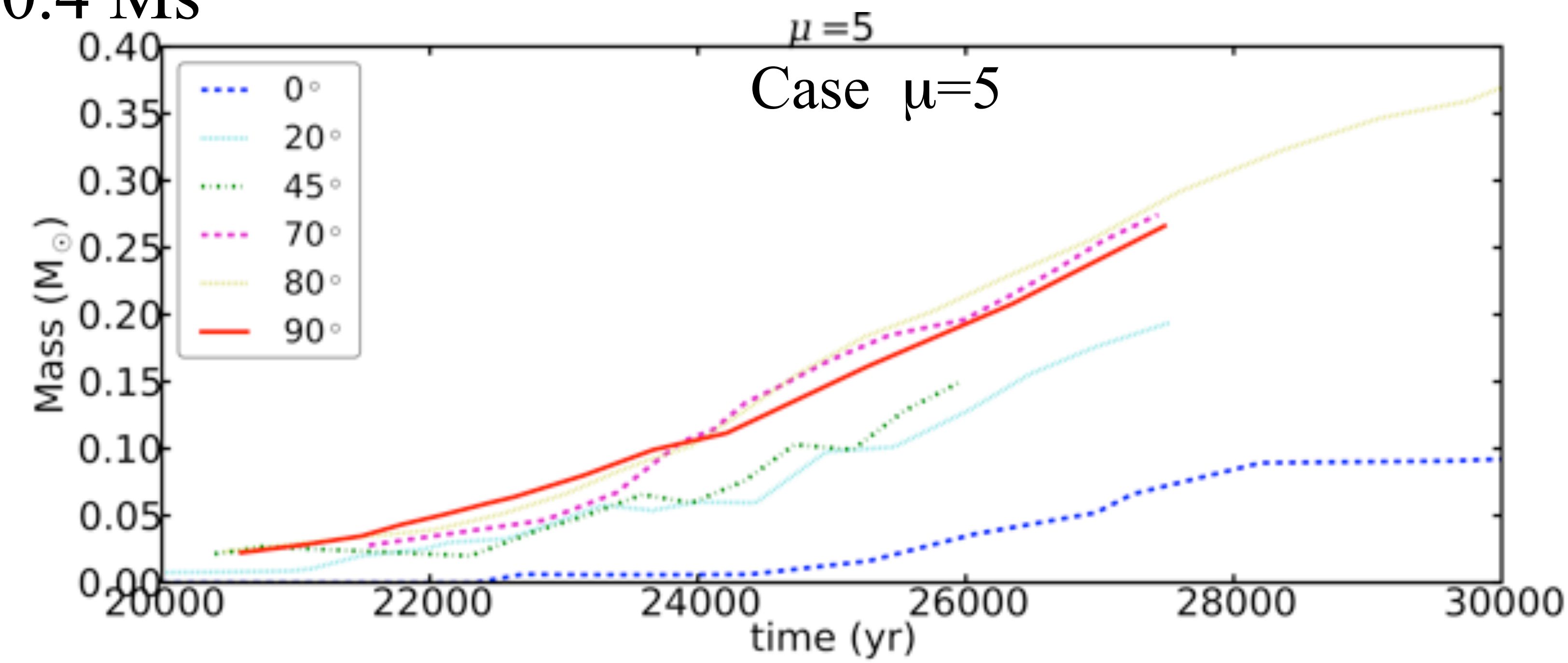


Hennebelle & Ciardi (2009)

Joos et al. 2012

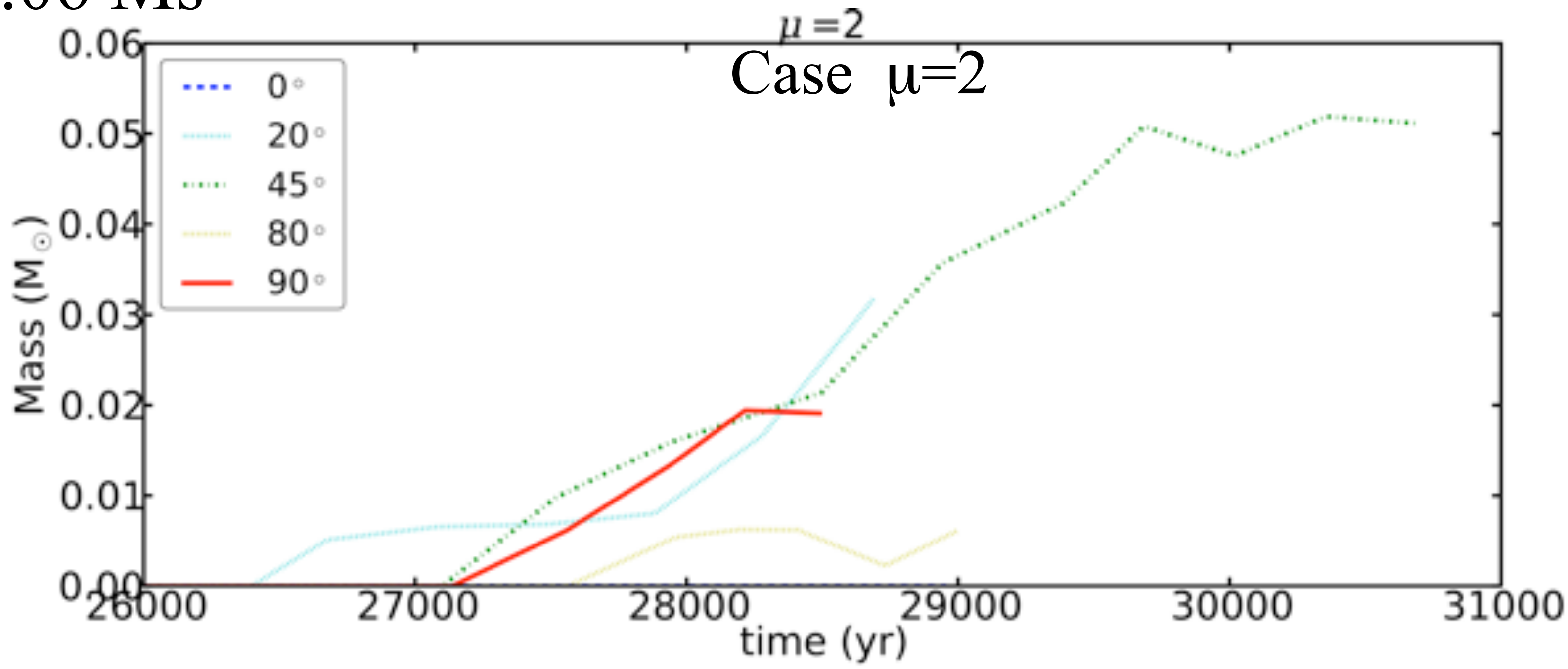
Disk mass vs time

0.4 Ms



Case μ=5

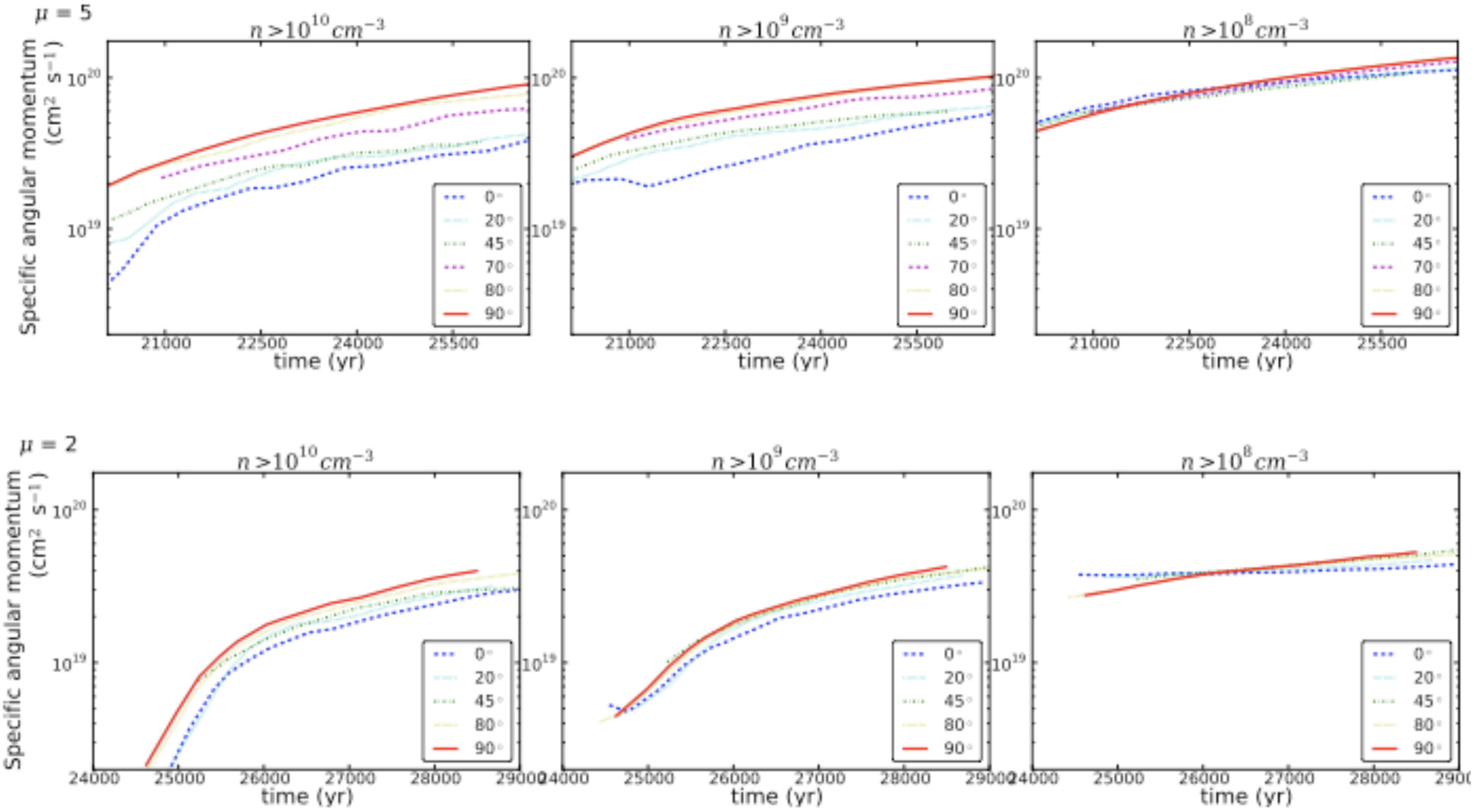
0.06 Ms



Case μ=2

Joos et al. 2012

Specific angular momentum above various density thresholds

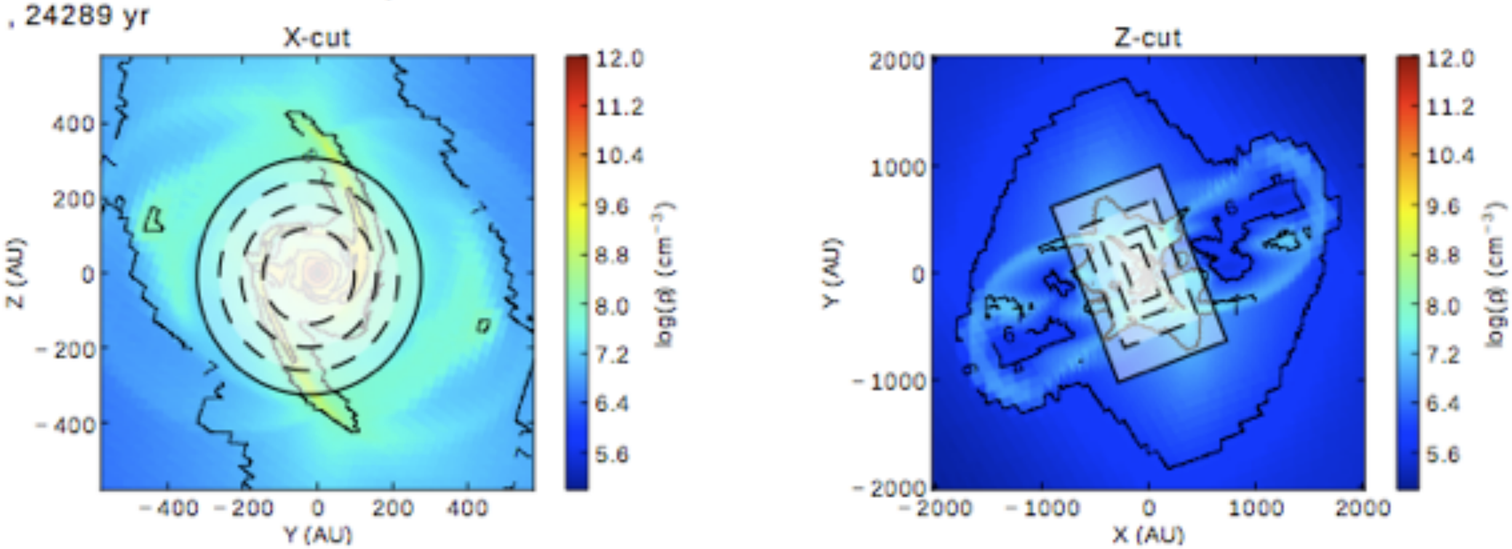


Joos et al. 2012

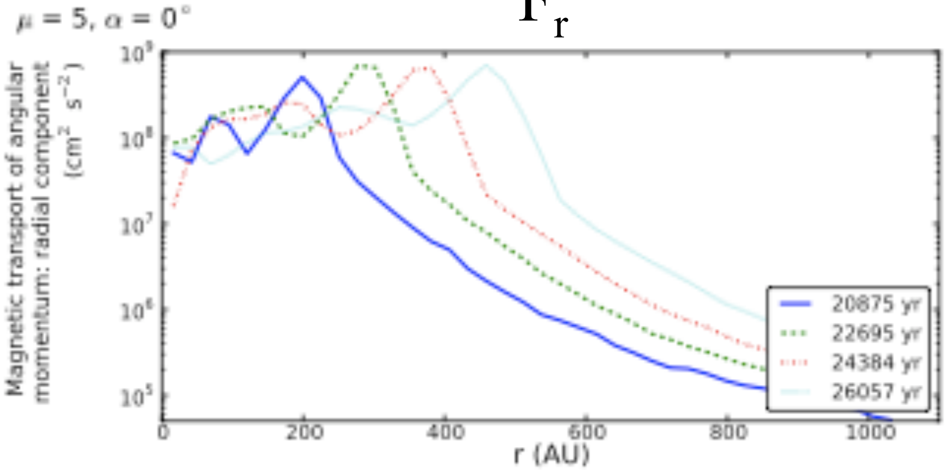
$$F_v^B(R) = \left| \int_0^{2\pi} \int_0^R r \frac{B_\phi(r,\phi,\pm h(r)/2) B_z(r,\phi,\pm h(r)/2)}{4\pi} r \mathrm{d}r \mathrm{d}\phi \right|$$

and

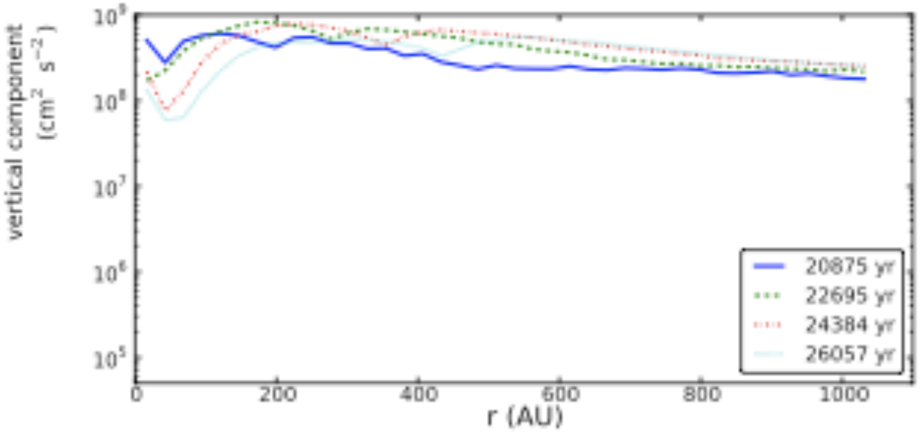
$$F_r^B(R) = \left| \int_0^{2\pi} \int_{-h(R)/2}^{h(R)/2} R \frac{B_\phi(R,\phi,z) B_r(R,\phi,z)}{4\pi} R \mathrm{d}z \mathrm{d}\phi \right|,$$



F_r



F_v

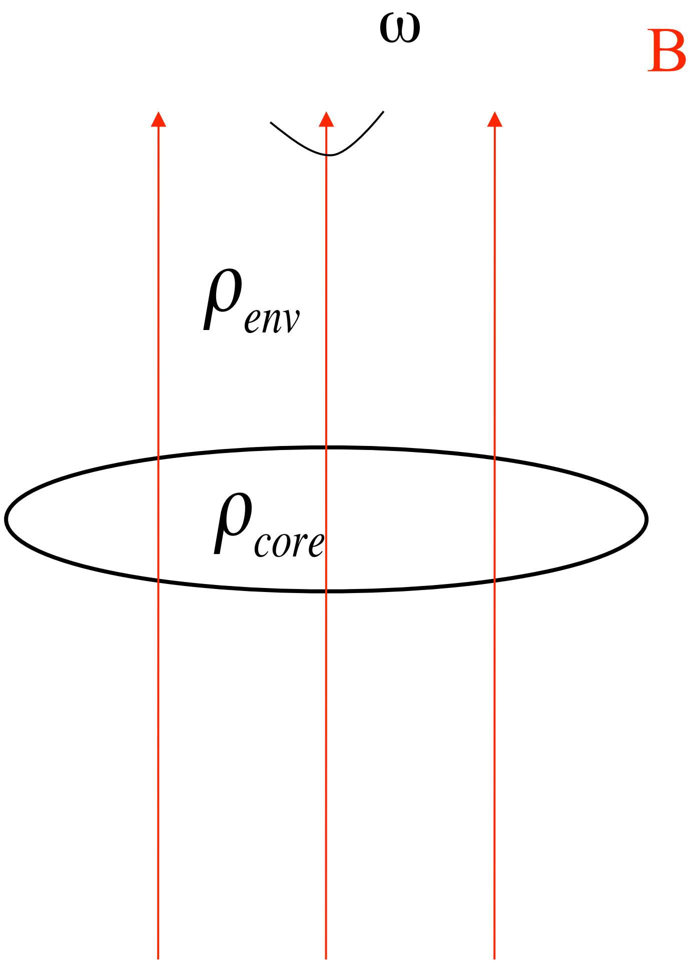


Magnetic braking

(Gillis et al. 74,79, Mouschovias & Paleologou 79,80, Basu & Mouschovias 95, Shu et al. 87)

rotation generates torsional Alfvén waves which carry angular momentum outwards

Typical time: AW propagate far enough so that the external medium receives angular momentum comparable to the cloud initial angular momentum



Magnetic field parallel to the rotation axis:

$$\rho_{core} Z_{core} \approx \rho_{env} \tau_{para} V_a$$

$$\Rightarrow \tau_{para} \approx (\rho_{core}/\rho_{env}) \times (Z_{core}/V_a)$$

$$\approx \frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}}$$

since $M = 2\pi Z_{core} R^2 \rho_{core}$ and $\phi = \pi R^2 B$

In the aligned configuration, the magnetic braking can be much more efficient if the field lines are fanning out (Mouschovias 1991)

$$M_{core} J_{core} \approx M_{env} J_{env}$$

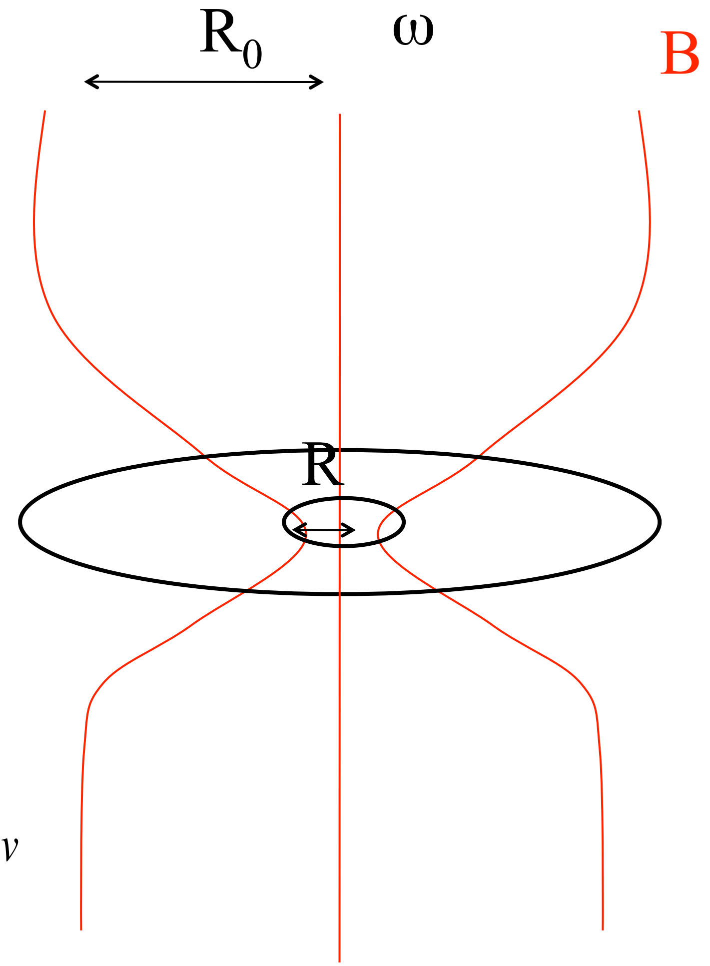
$$\pi\rho_{core} Z_{core} R_{core}{}^{4} \omega_{core} \approx \pi\rho_{env} \tau_{para} V_{a} R_{env}{}^{4} \omega_{env}$$

$$\Rightarrow \tau_{para} \approx \frac{\rho_{core}}{\rho_{env}} \frac{Z_{core}}{V_a} \frac{R_{core}{}^{4}}{R_{env}{}^{4}} \frac{\omega_{core}}{\omega_{env}}$$

$$\approx \frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}} \frac{R_{core}{}^{2}}{R_{env}{}^{2}}$$

since $M = 2\pi Z_{core} R_{core}{}^{2} \rho_{core}$ and $\phi = \pi R_{env}{}^{2} B_{env}$

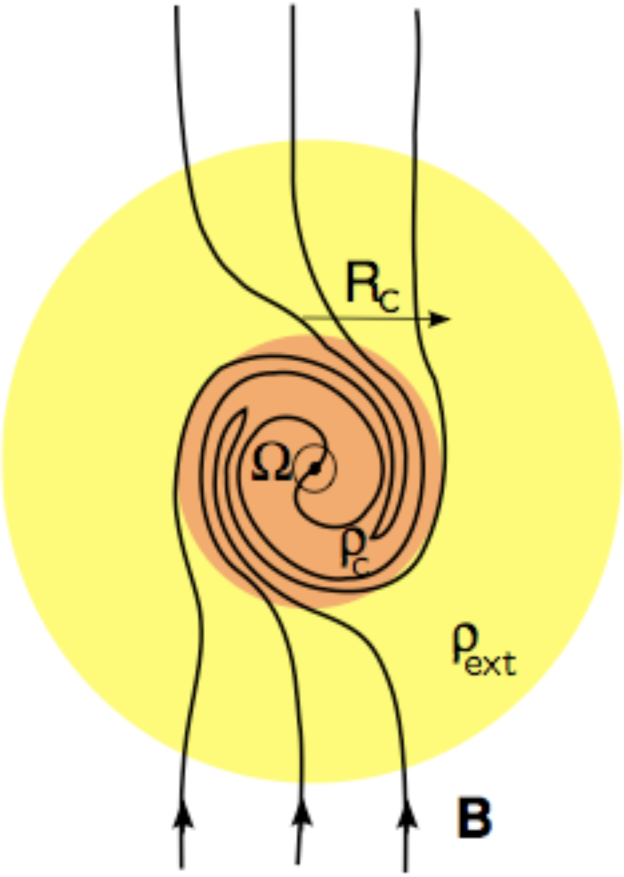
and assuming corotation $\omega_{core} \approx \omega_{env}$



Thus, the magnetic braking is more efficient when field lines are fanning out

Magnetic braking in the perpendicular case

The geometry of the field lines is complex. It is traditionally assumed that Bα1/R (Mouschovias 1991)



$$\pi\rho_{core} Z_{core} R_{core}^{4} \approx \pi\rho_{env} Z_{core}\left(R_{perp}^{4} - R_{core}^{4}\right)$$

$$\Rightarrow \tau_{perp} \approx \int_{R_{core}}^{R_{perp}} \frac{dR}{V_a} = \frac{R_c}{2V_a(R_c)}\left(\sqrt{1+\rho_{core}/\rho_{env}} - 1\right)$$

$$\approx \frac{M}{\phi} \times 2\sqrt{\frac{\pi}{\rho_{core}}}$$

since $M = 2\pi Z_{core} R^2 \rho_{core}$ and $\phi = \pi R^2 B$

Comparison between timescales

(Joos et al. 2012)

$$\frac{\tau_{perp}}{\tau_{para}} \approx \frac{\frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{core}}}}{\frac{M}{\phi} \times \sqrt{\frac{\pi}{\rho_{env}}}\left(\frac{R_{core}}{R_0}\right)^2} \approx \sqrt{\frac{\rho_{env}}{\rho_{core}}} \times \left(\frac{R_{core}}{R_0}\right)^{-2}$$

When the field lines are aligned:
=> the braking is more efficient in the perpendicular case

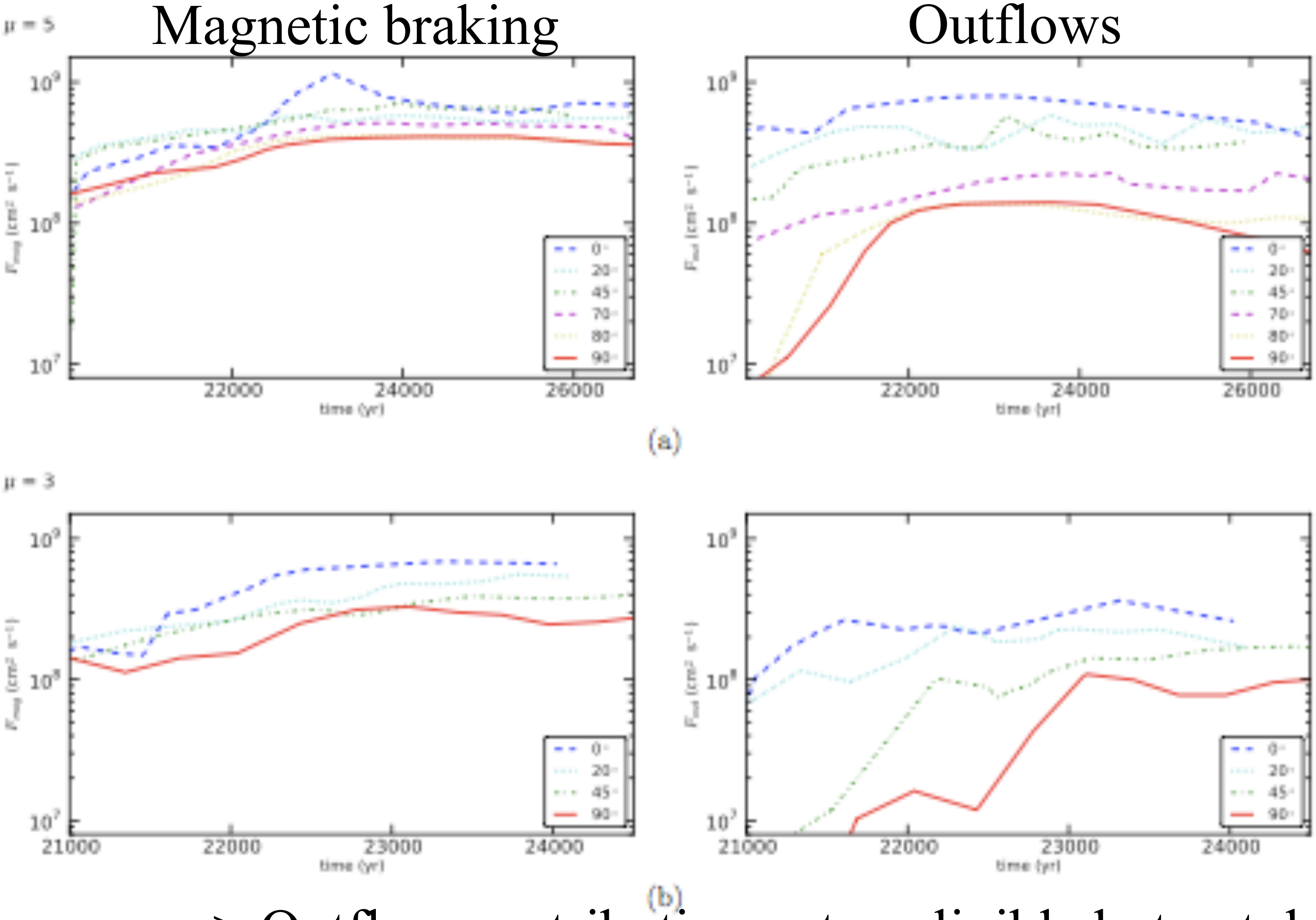
$$\frac{\tau_{perp}}{\tau_{para}} \approx \sqrt{\frac{\rho_{env}}{\rho_{core}}}$$

When the field lines are fanning out, assuming $\rho \propto R^{-2}$
=> the braking is more efficient in the aligned case

$$\frac{\tau_{perp}}{\tau_{para}} \approx \sqrt{\frac{\rho_{core}}{\rho_{env}}}$$

Contribution of braking due to outflows

Comparison between the mean flux of angular momentum due to magnetic braking and outflow at 150 AU above equatorial plane



Magnetic braking

Outflows

Joos et al. 2012

=> Outflow contribution not negligible but not dominant

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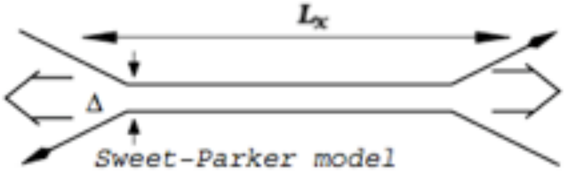
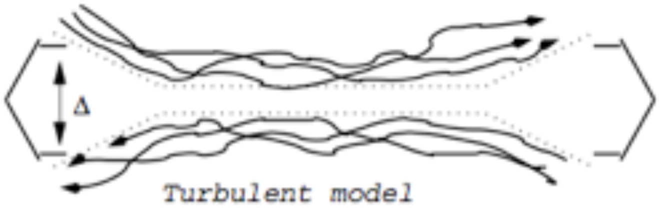
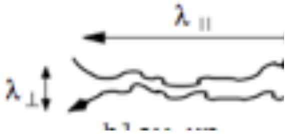
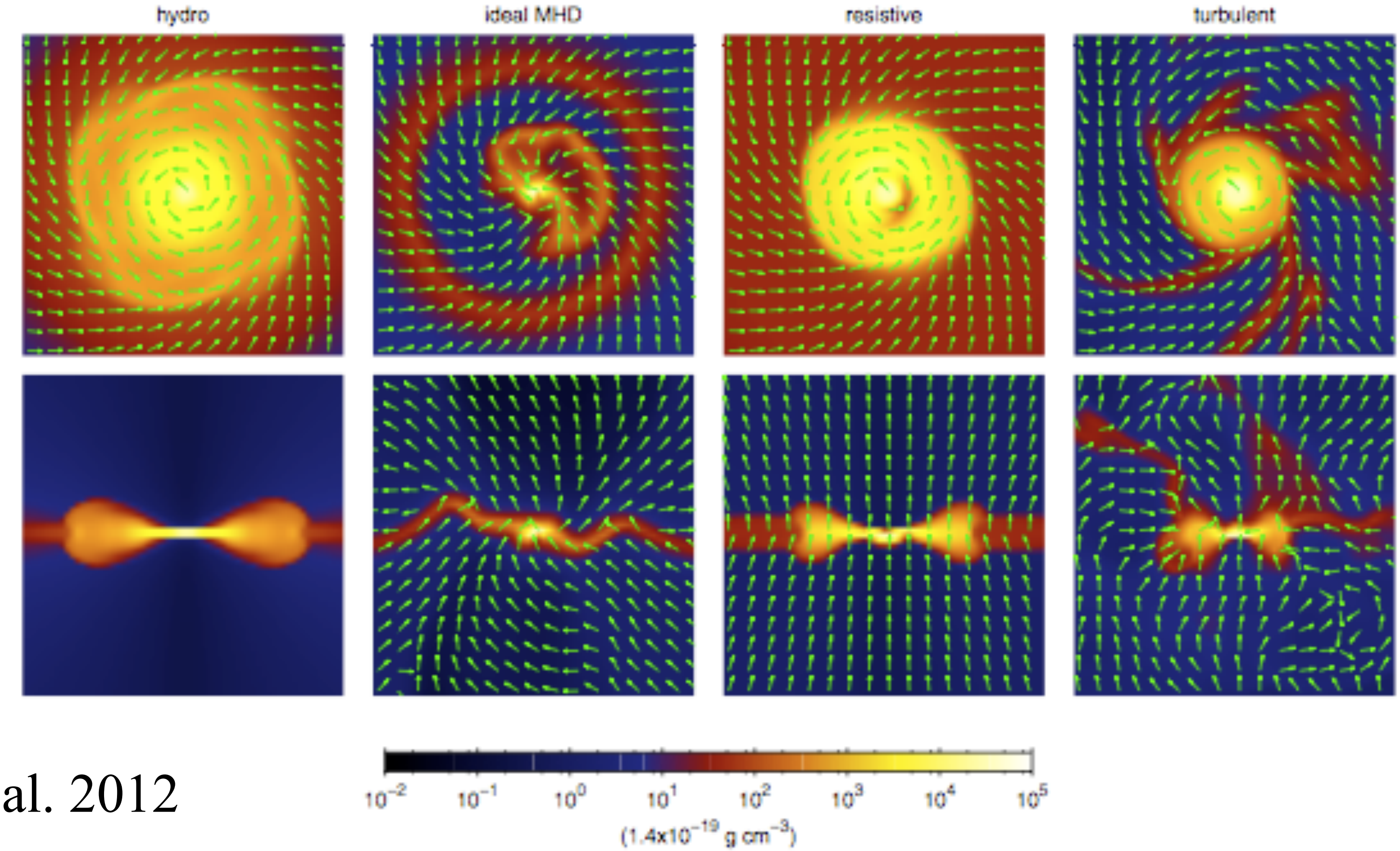
Another limitation:
Impact of turbulence diffusion/reconnection

(Seifried et al. 2011, Santos-Lima et al. 2012)



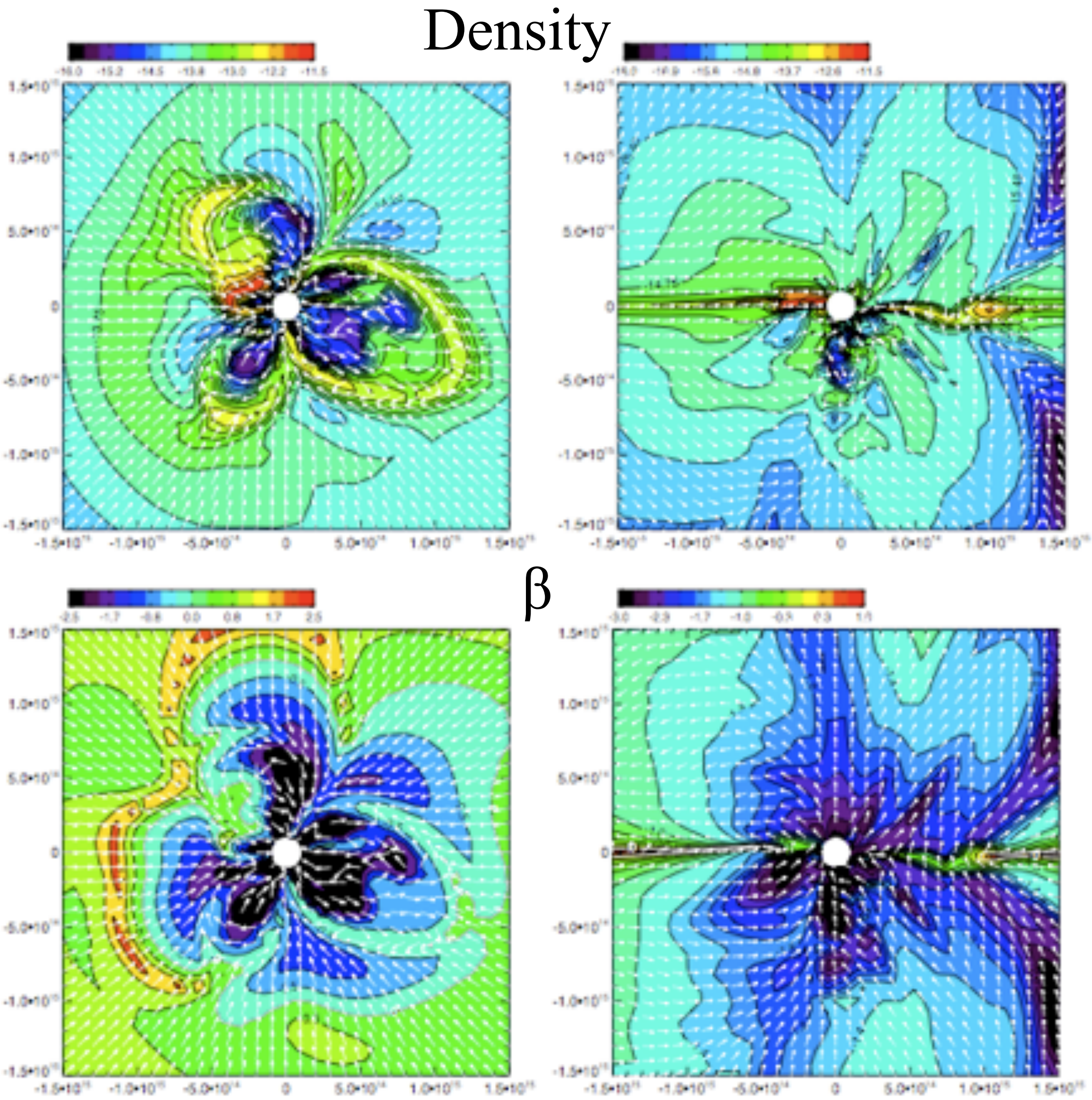




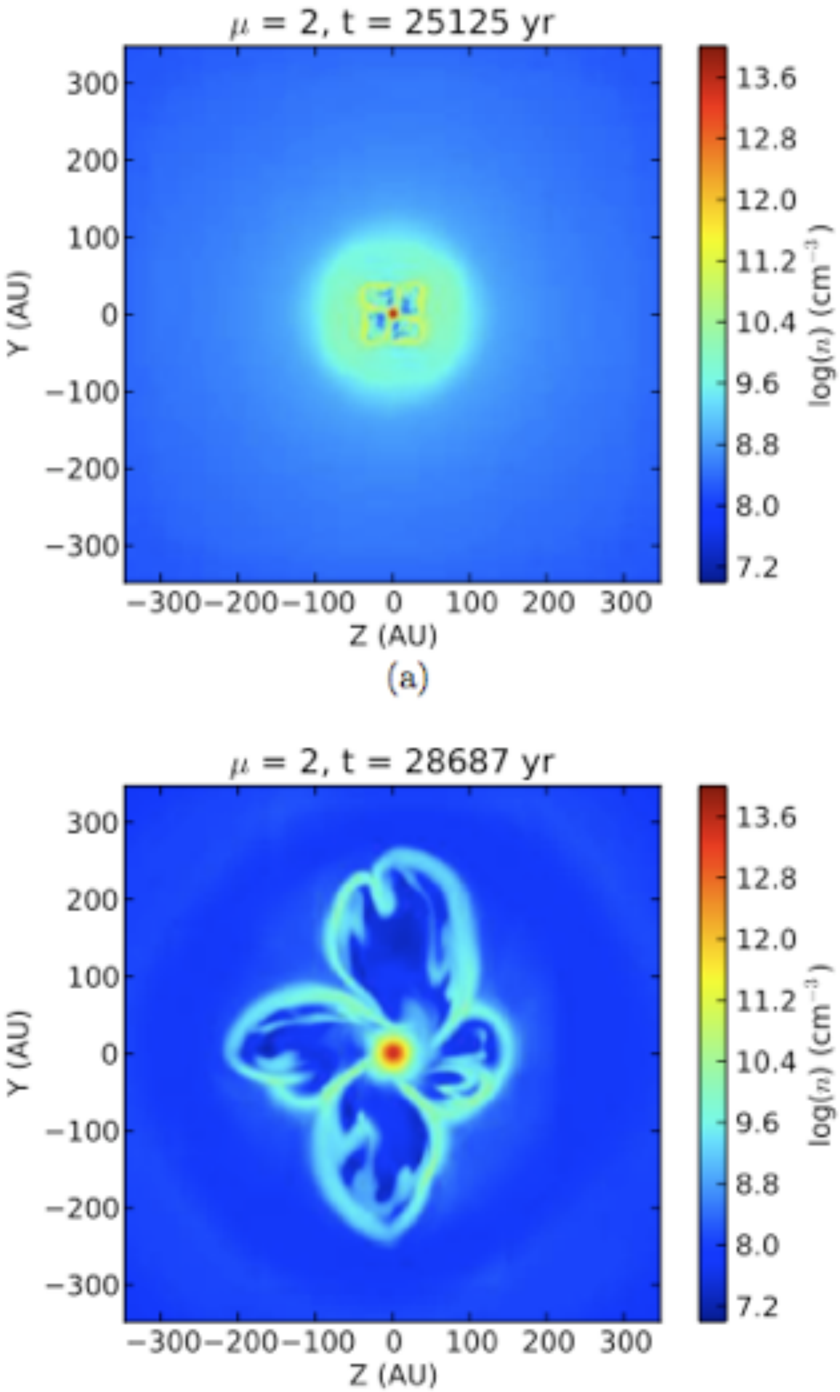


Santos-Lima et al. 2012

Spontaneous symmetry breaking: the interchange instability



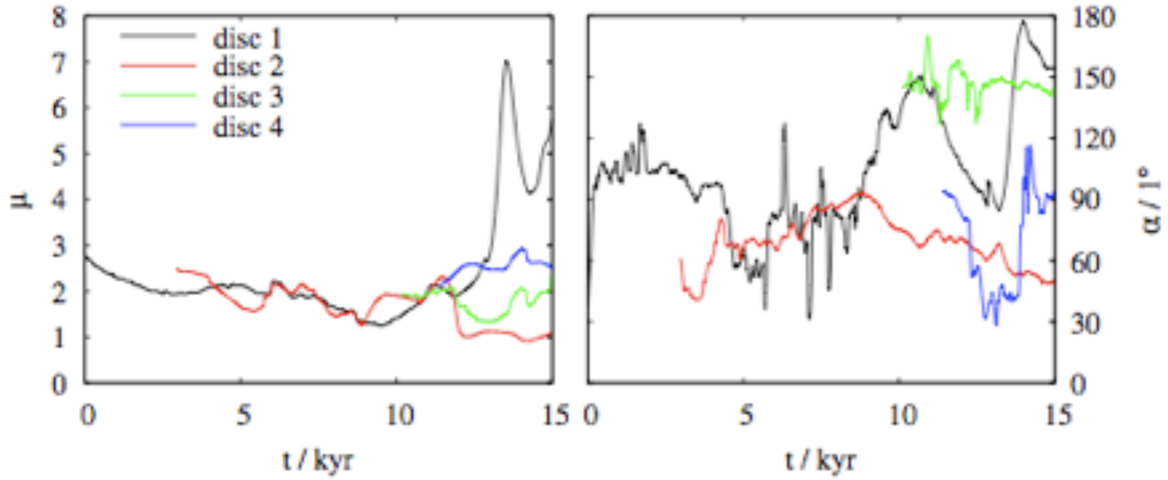
Krasnopolsky et al. 2012



Joos et al. 2012

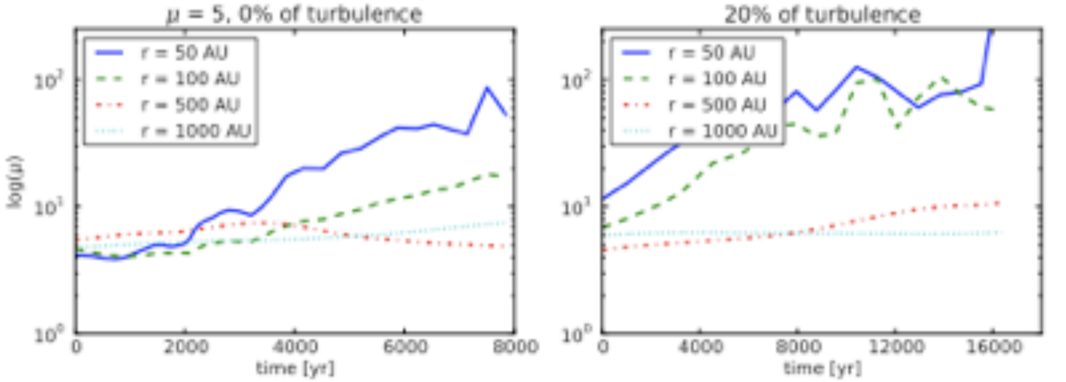
Mass to flux ratio as a function of time for various initial magnetisation and level or turbulence

At 500 AU



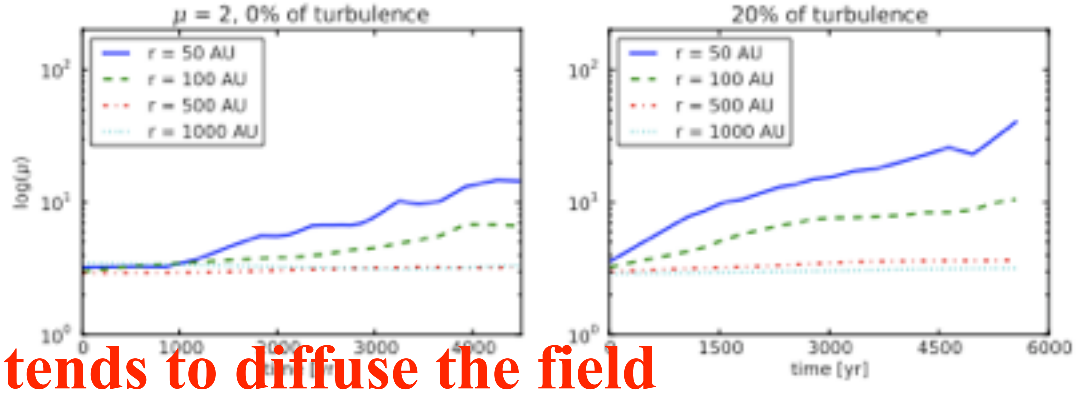
Seifried et al. 2012

μ



(b)

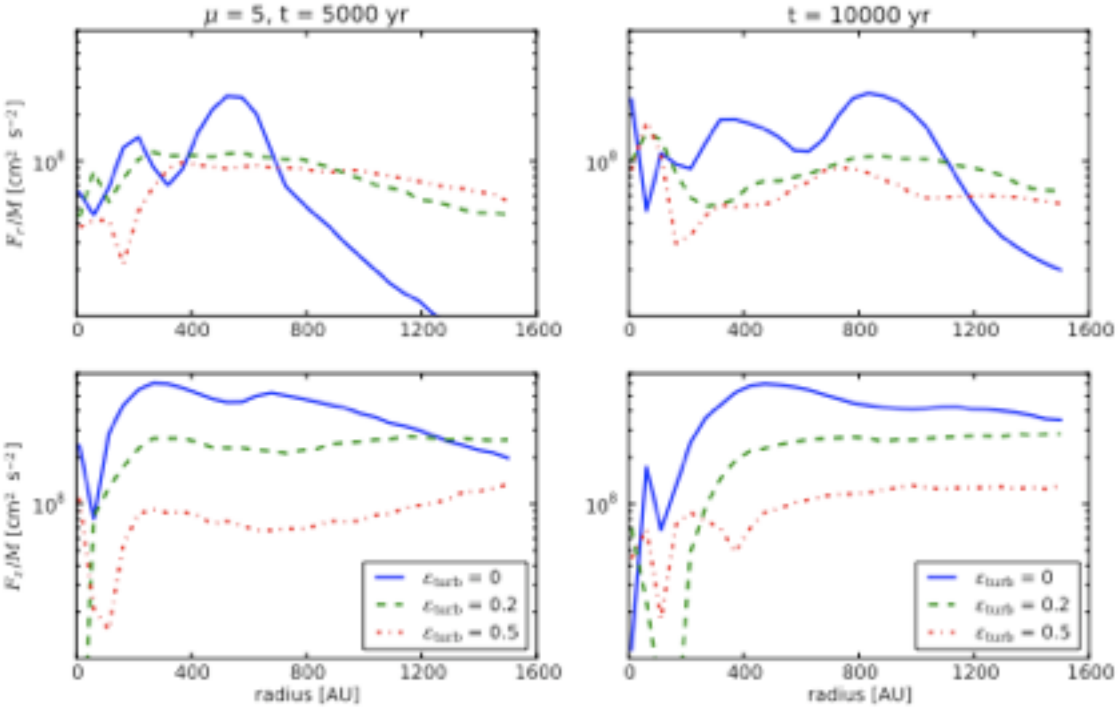
μ



Joos et al. 2013

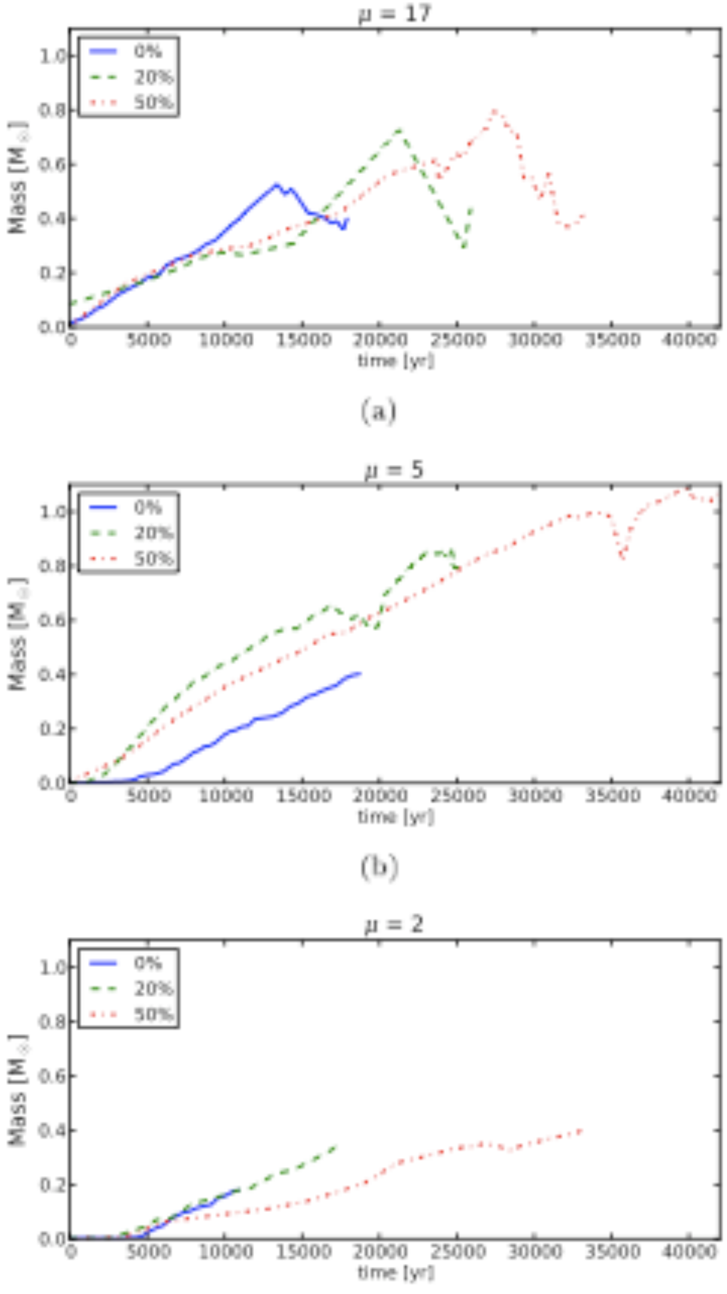
=> Turbulence tends to diffuse the field

Mean flux along the pole and in the radial direction



⇒Turbulence reduces magnetic braking and disks tend to be bigger (for intermediate magnetic field)

Disk masses



(a)

(b)

(c)

Joos et al. 2013

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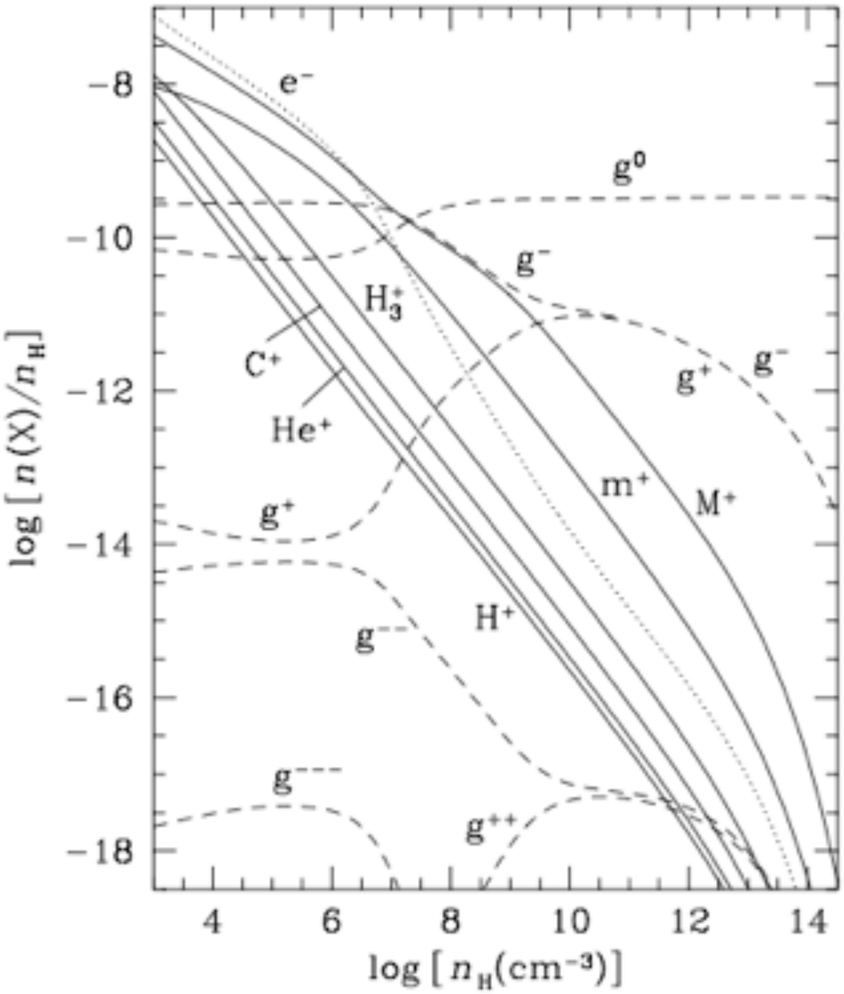
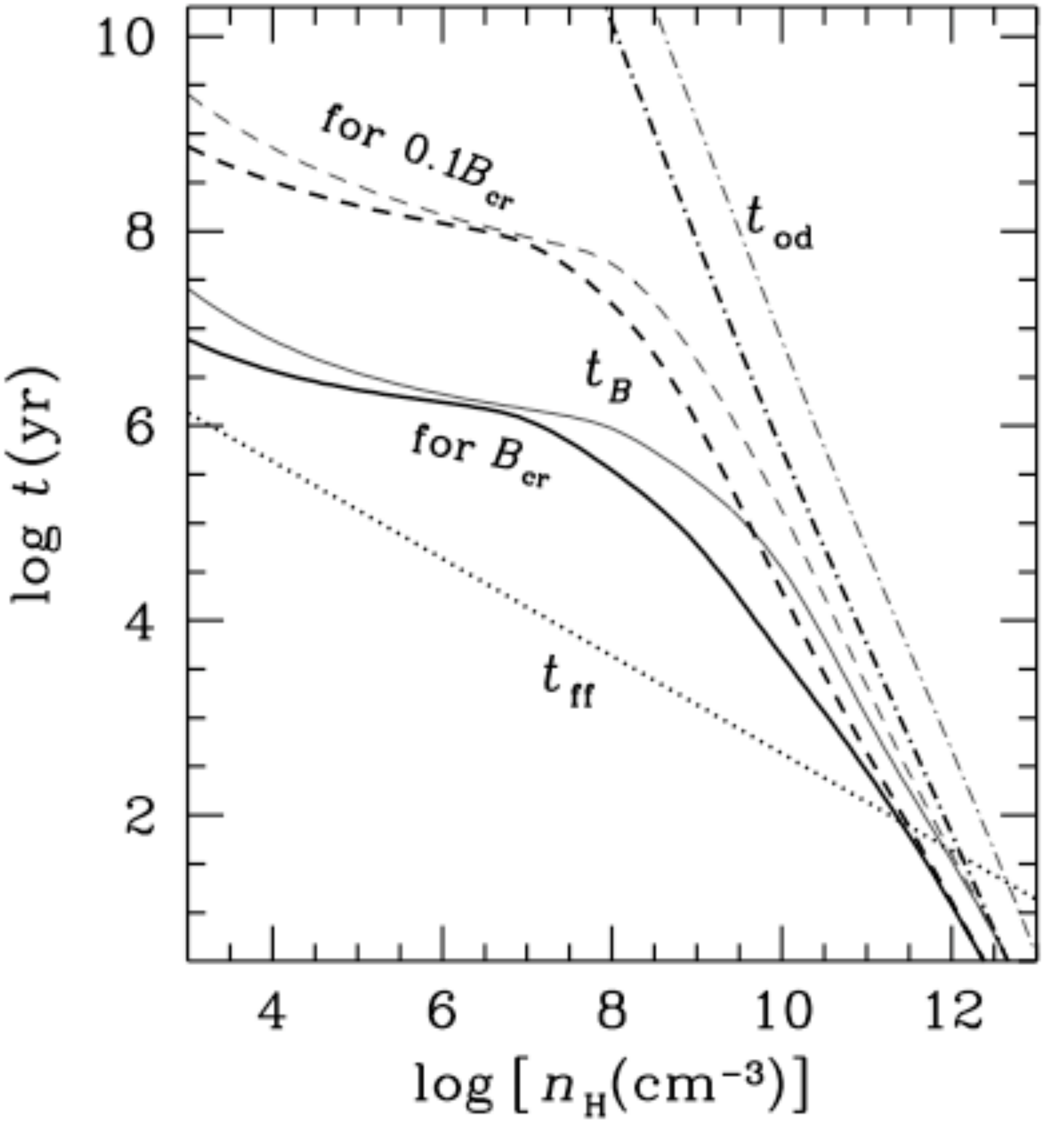
Detailed microphysics implying chemistry network

Abundances of species



Nakano et al. 2002

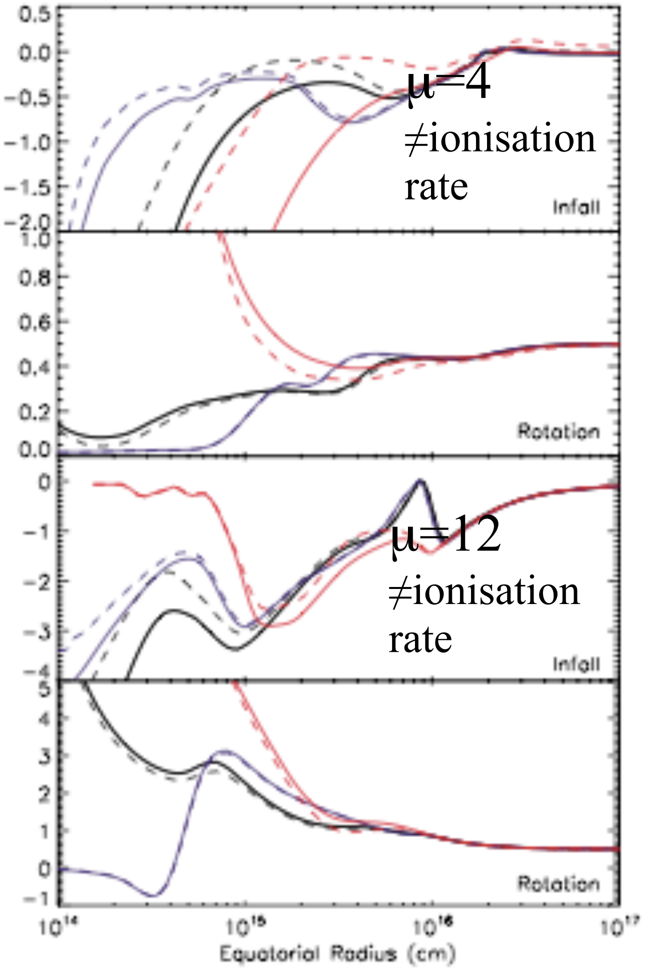
Diffusion time vs density



Can ambipolar diffusion modify this?

(Mellon & Li 2009, Duffin & Pudritz 2009)

Mellon & Li 09
Collapse with a.d.

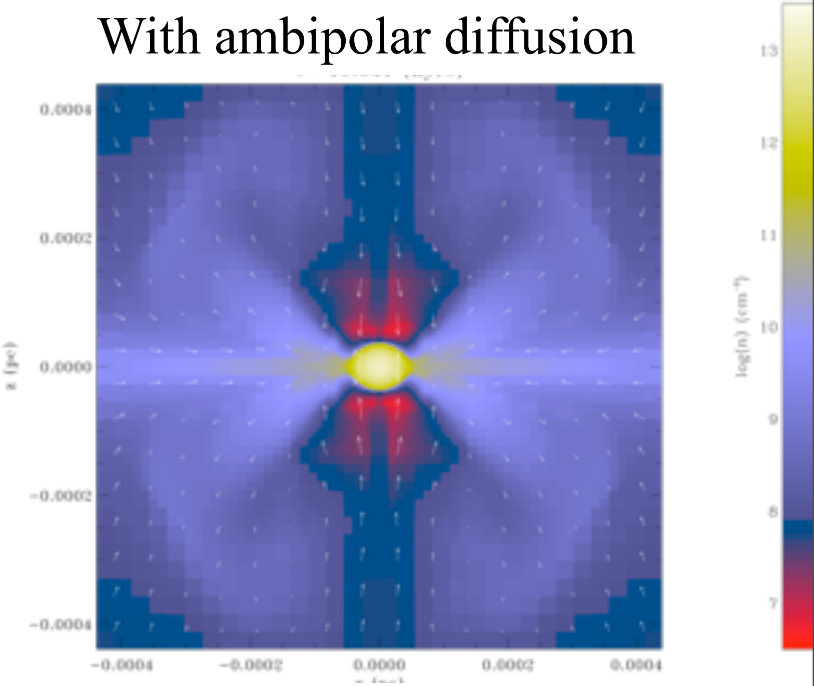


μ=4
≠ionisation
rate

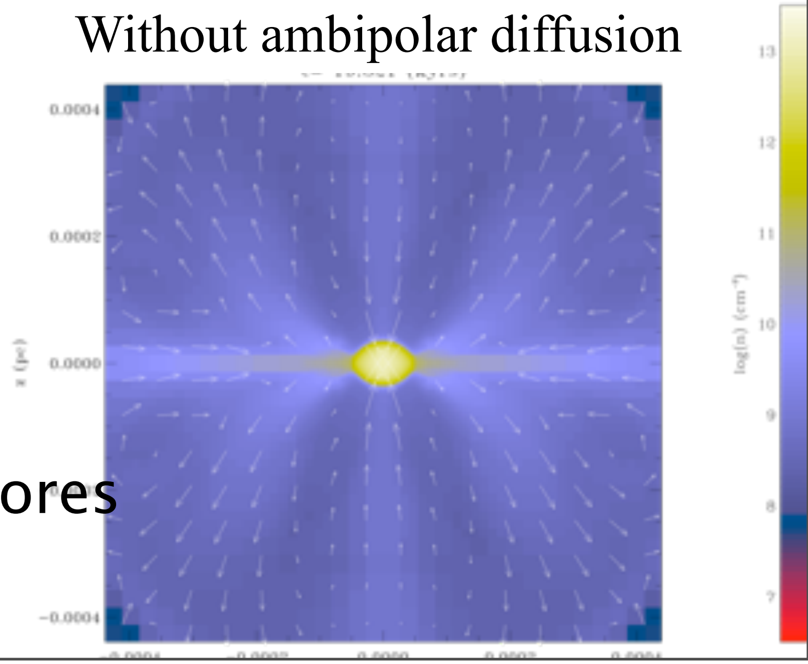
μ=12
≠ionisation
rate

Masson et al. in prep

With ambipolar diffusion



Without ambipolar diffusion

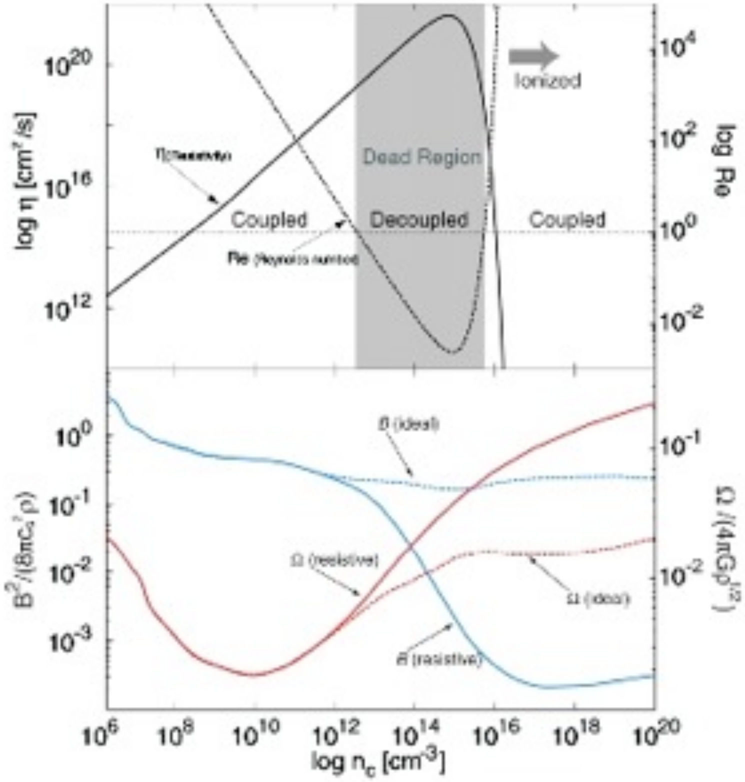


τ_{amb}/τ_{ff} = 8 for critical cores

τ_{amb} α B^2=>slow!

Impact of ohmic dissipation (a solution to the flux problem ?)

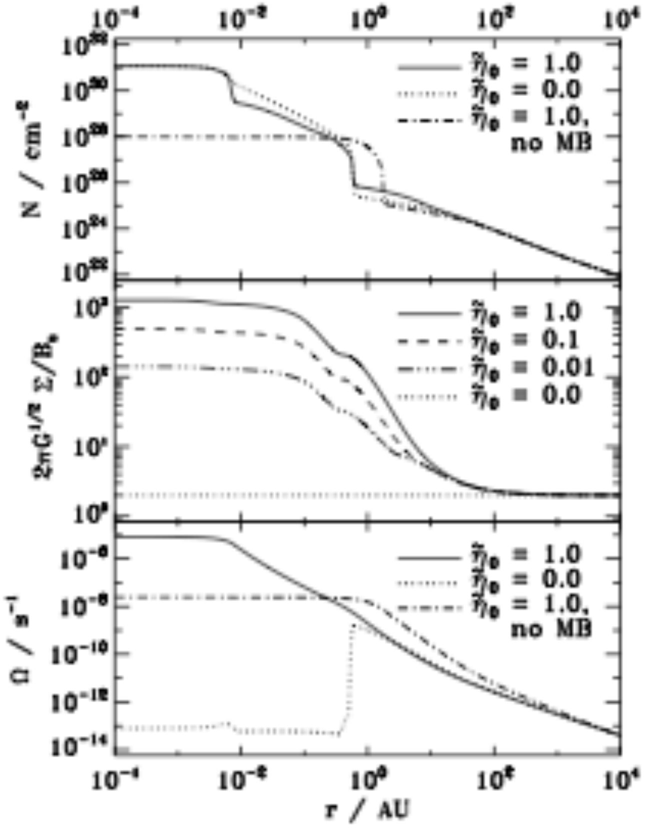
Machida et al. 2007



Interestingly: Desh and Mouschovias, Nakano et al. (2002) predicts that a lot of flux should be lost at densities larger than 10^{11} cm^{-3}(grains carry the charge).

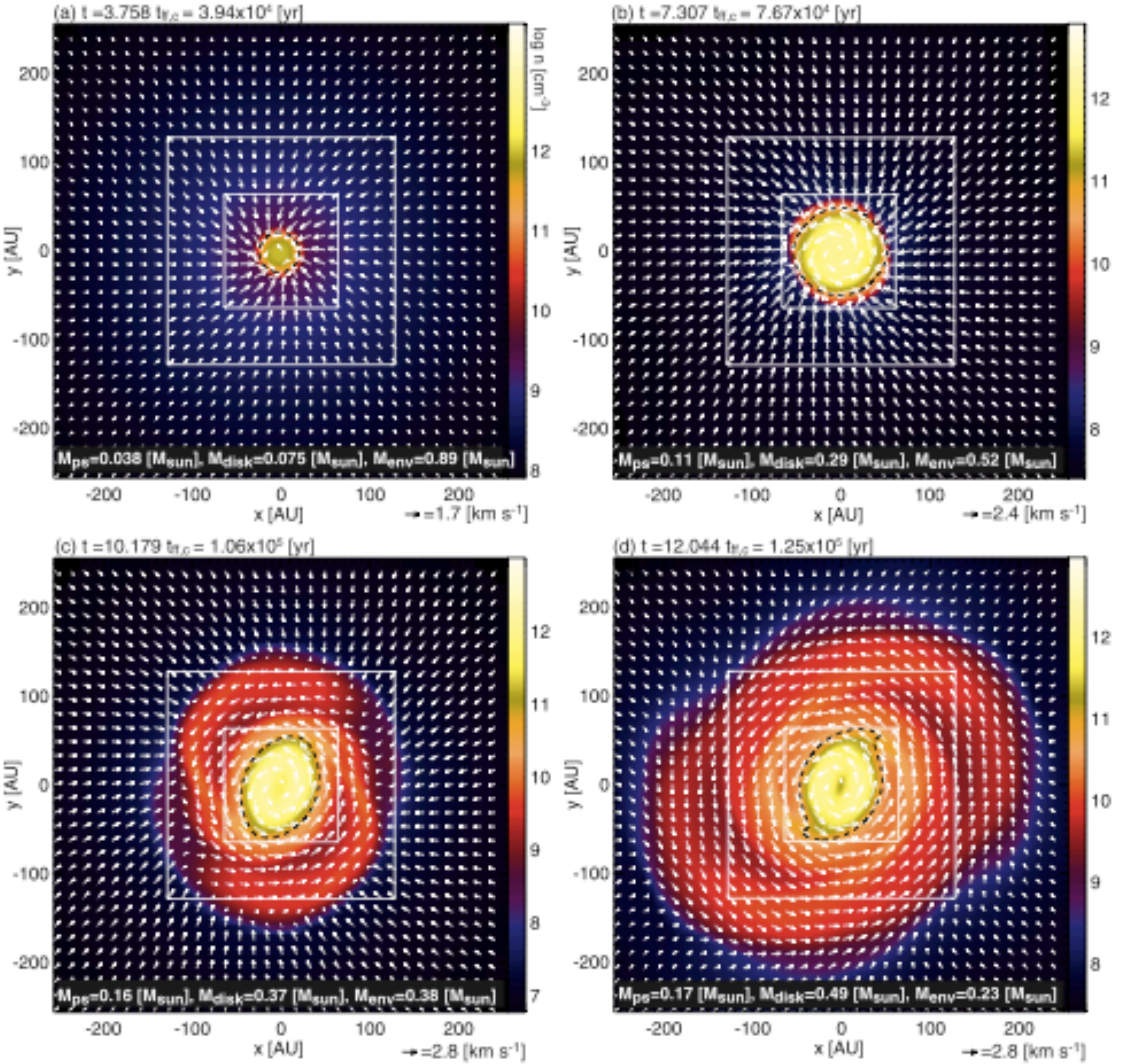
First calculation with resistive MHD
done by Machida et al. 2007
Characteristic scales of about 10-20 AU
⇒**Formation of compact disks**

Dapp & Basu recent work
(1D calculation)

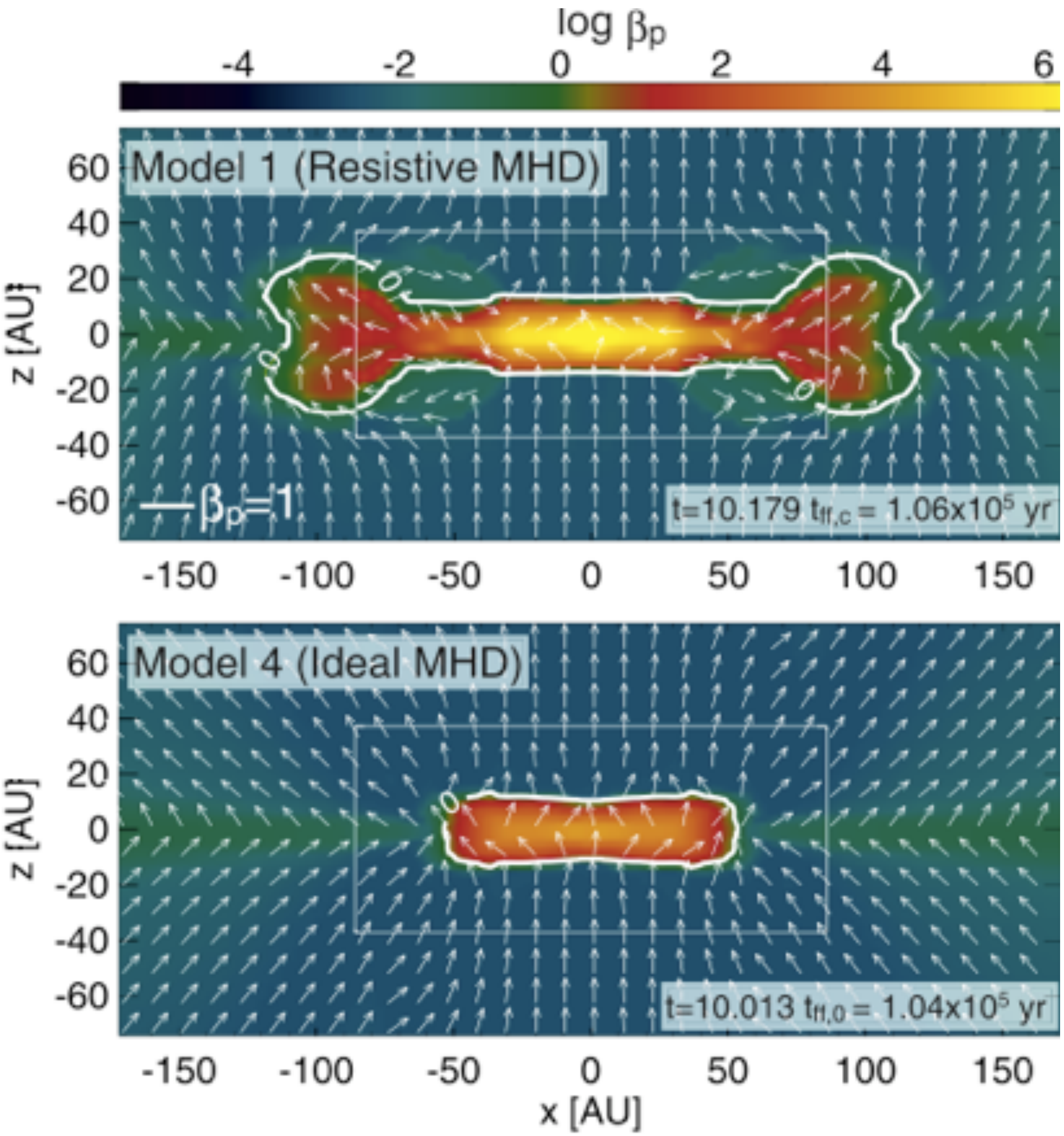


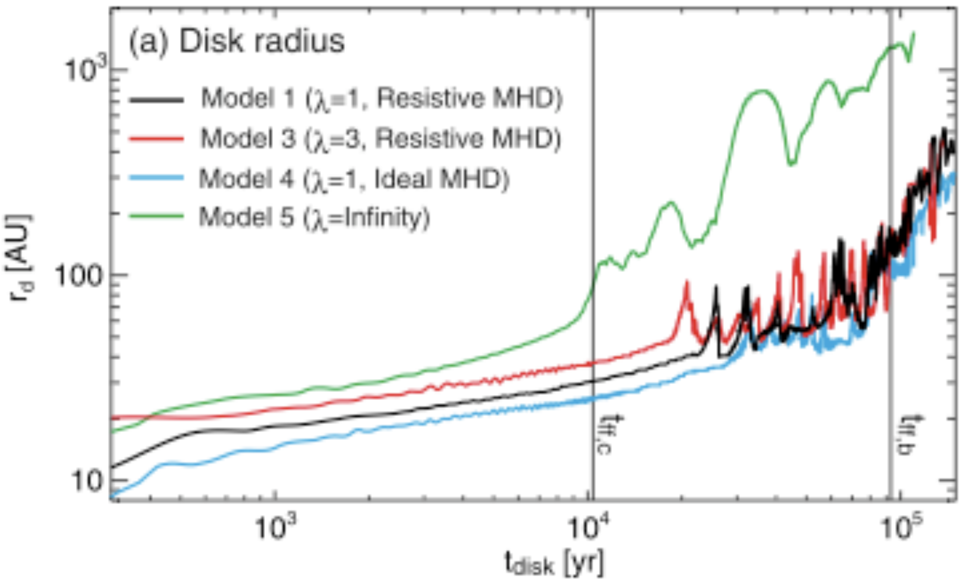
Resistive 3D simulations, aligned case (Machida et al. 2011)

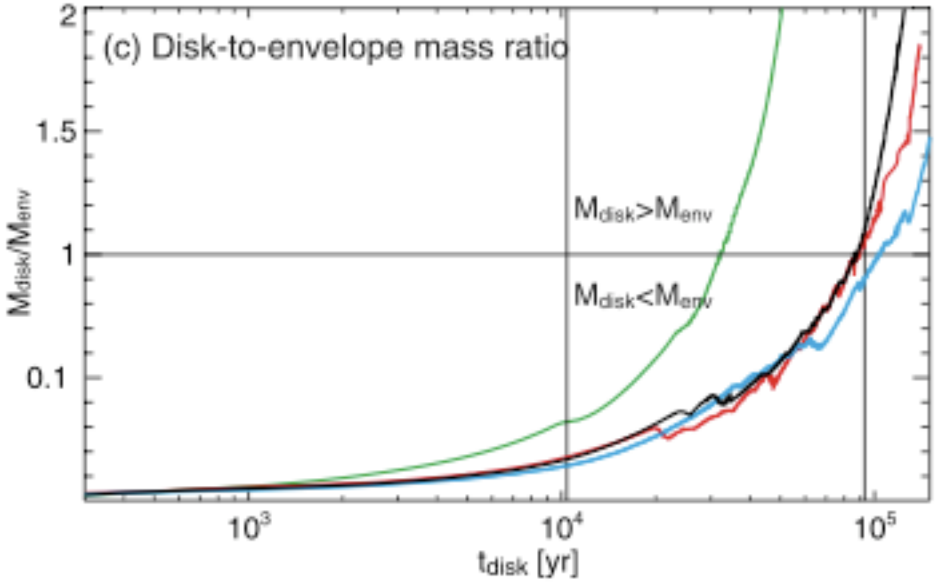
Growth of the disk



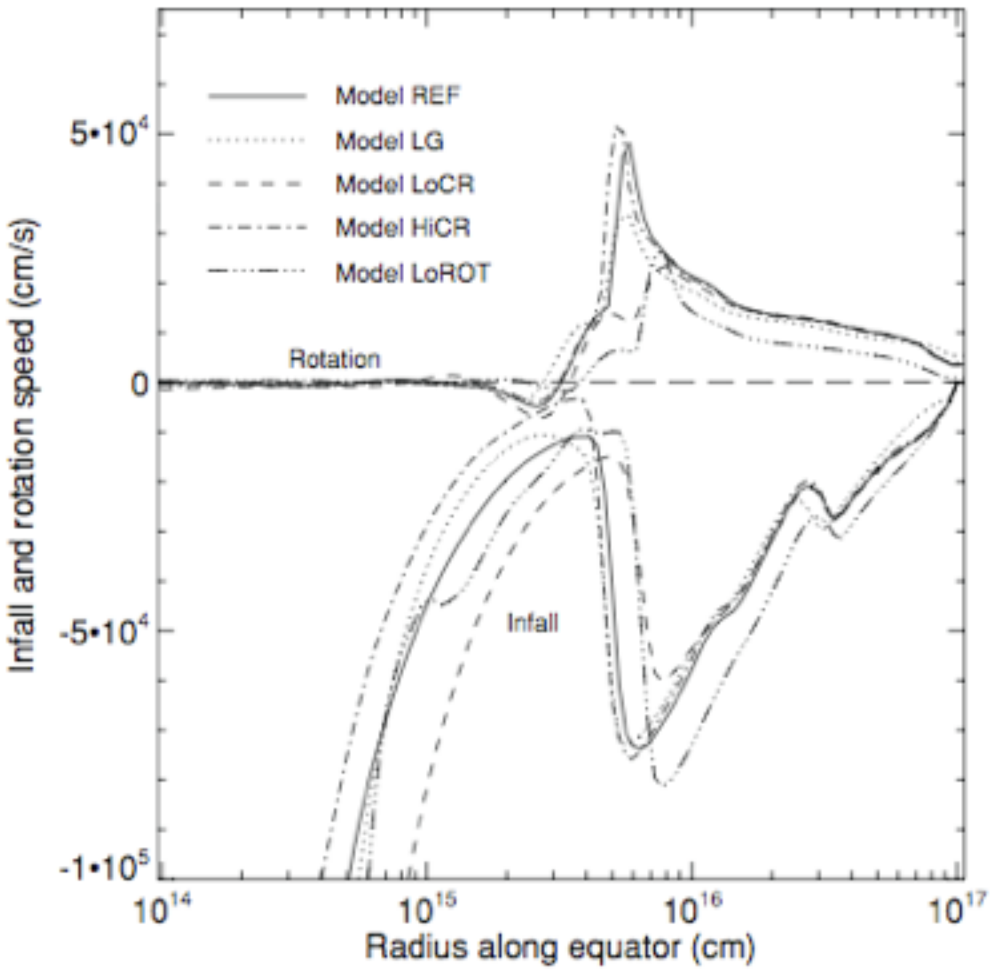
Resistive 3D simulations, aligned case (Machida et al. 2011)
Comparison between different models.







However, Li et al. 2011 performed a series of simulations taking into account ambipolar diffusion, Hall effect and Ohmic dissipation and find no disk at all…



Confused situation

Could be due to:

-Li et al. have a sink whose radius is 6AU

-Machida et al. perform 3D non-axisymmetric runs while Li et al. perform 2D runs. Possibly due to enhanced transport/flux lost in Machida et al. ?

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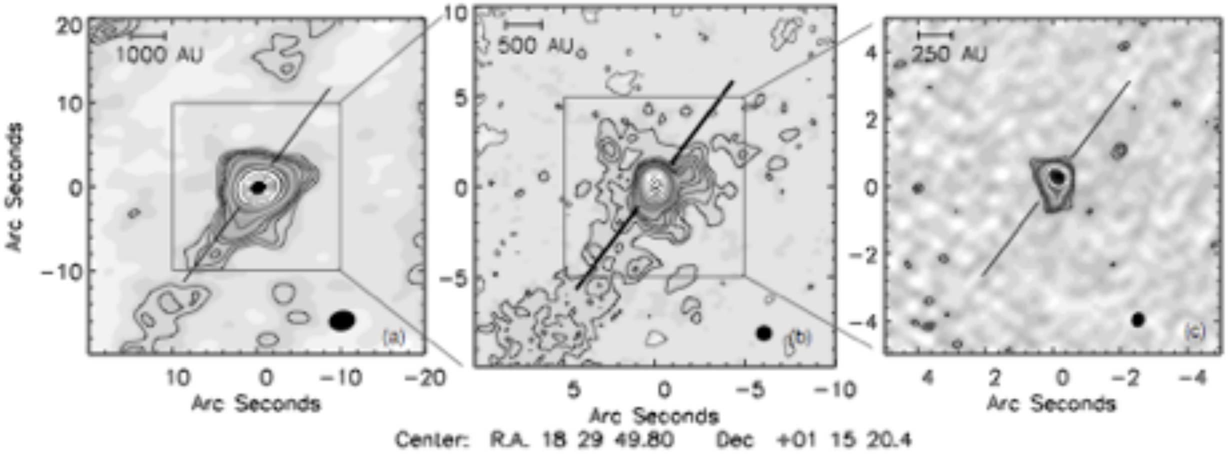
Are there disks at the class 0 stage ?

Difficult issue because strong emission from the envelope that must be removed.

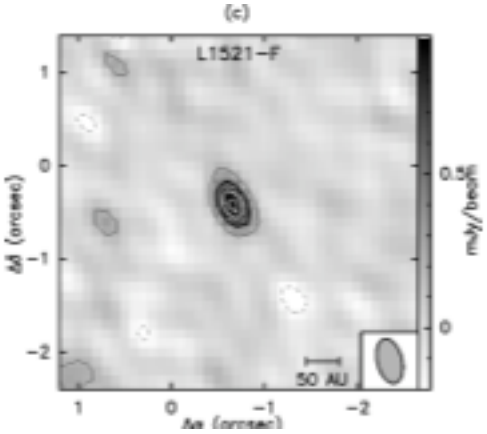
-Jorgensen et al. claim to infer disks from their modeling (disk is not resolved) but Brinch et al. (2009) do not see rotation in some of them

-Enoch et al. (2009) claim to resolve a 1 Ms disk in a 8 Ms source but conclusion depends on assumptions (density profile) for the envelope

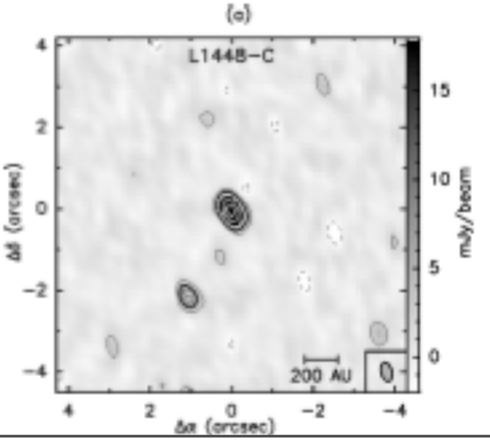


-Maury et al. [illegible] very little fragmentation at scales smaller than 500 AU

a source in Taurus



a source in Perseus



Comparison of the PdBI maps with MHD simulations

Hydrodynamical simulations produce too much extended (+ multiple) structures if compared to Maury et al. 2010 Observations.

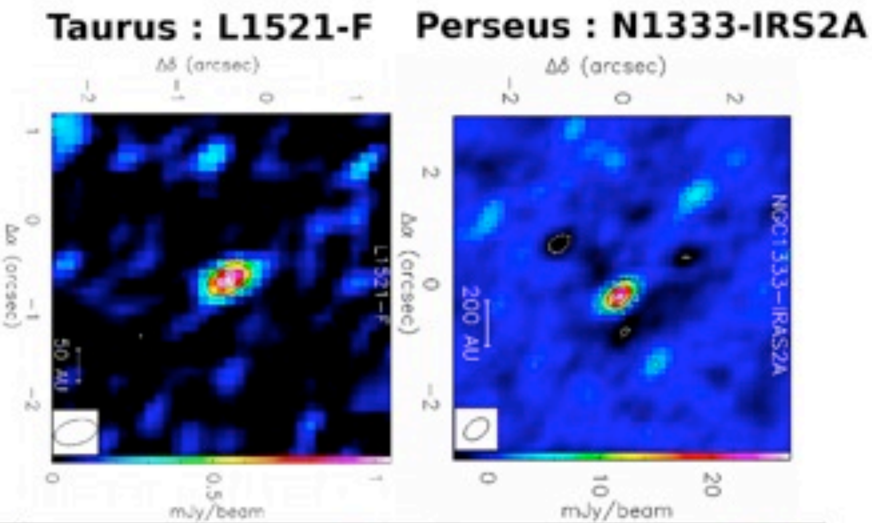
→ MHD simulations ?

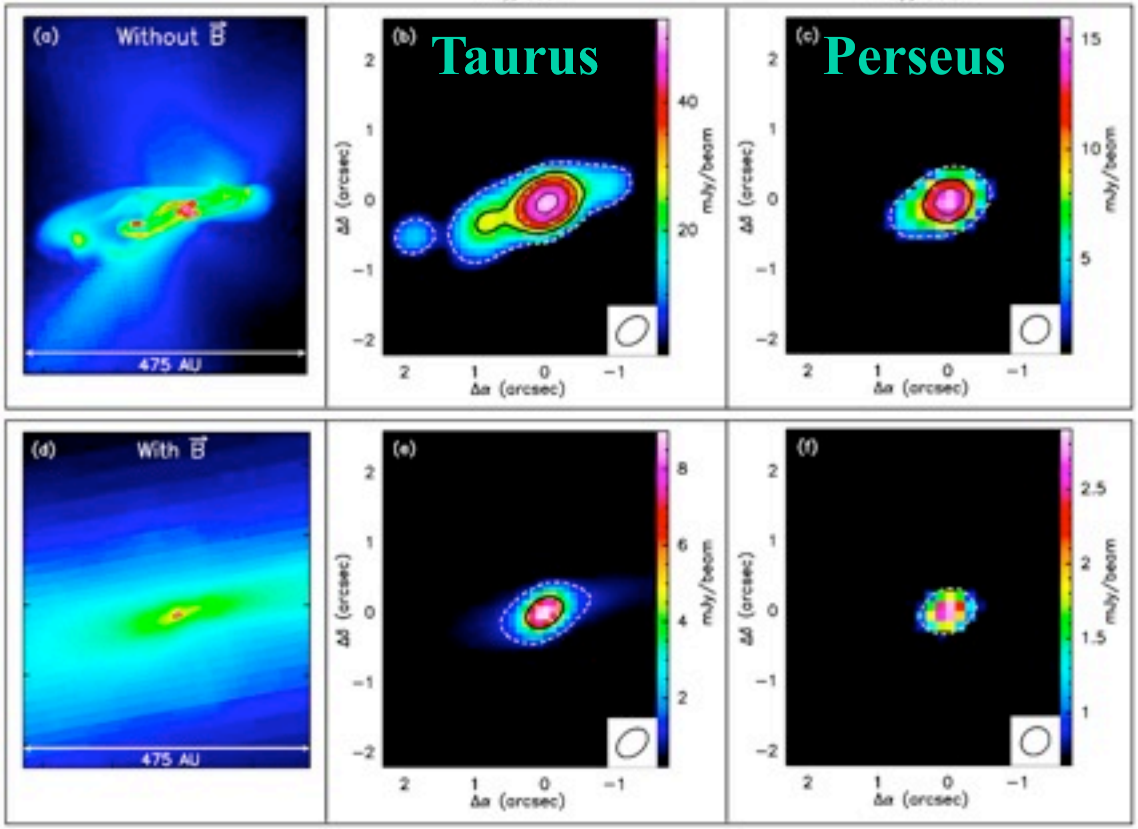
MHD simulations : produce PdB-A synthetic images with **typical FWHM ~ 0.2” - 0.6”**

Similar to Class 0 PdB-A sources observed !

↓

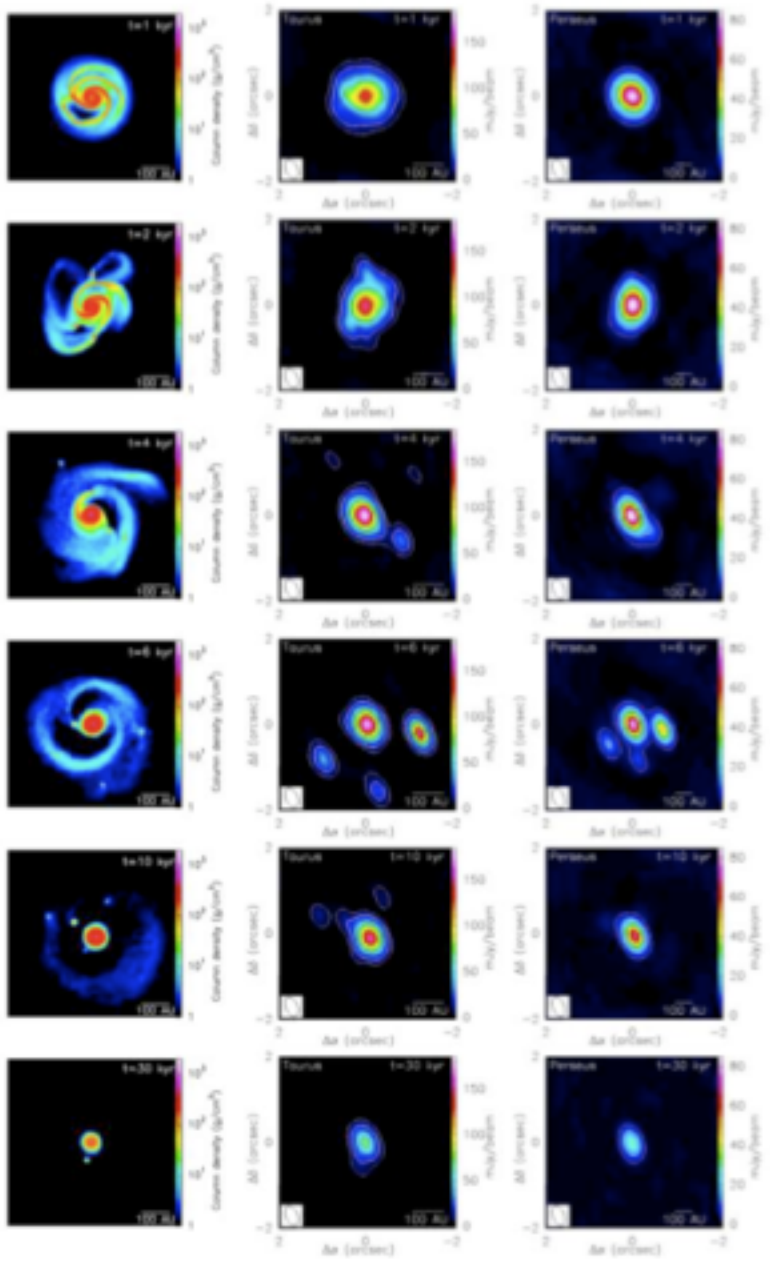
need B to produce compact, single PdB-A sources.





Maury et al. 2010

An alternative view: Stamatellos et al. (2010) propose that massive disks form and quickly fragment. Thus the chance to see them is weak.



Some conclusions regarding disk formation and braking:

-magnetic field modifies very significantly the early disk formation

-for intermediate magnetization, the geometry is important and braking is more efficient in the aligned case

-turbulence is reducing the braking because it diffuses the field and naturally generates non-aligned configuration, it helps forming disks

-non-ideal MHD may help but some debate remains. It seems reasonable that it should help forming small disk

-Unclear that there is a *problem* since very few observations of class 0 disks are available

-We need to get a distribution of inner structure and of initial conditions (field strength and configuration, rotation) before we can conclude whether the problem is understood

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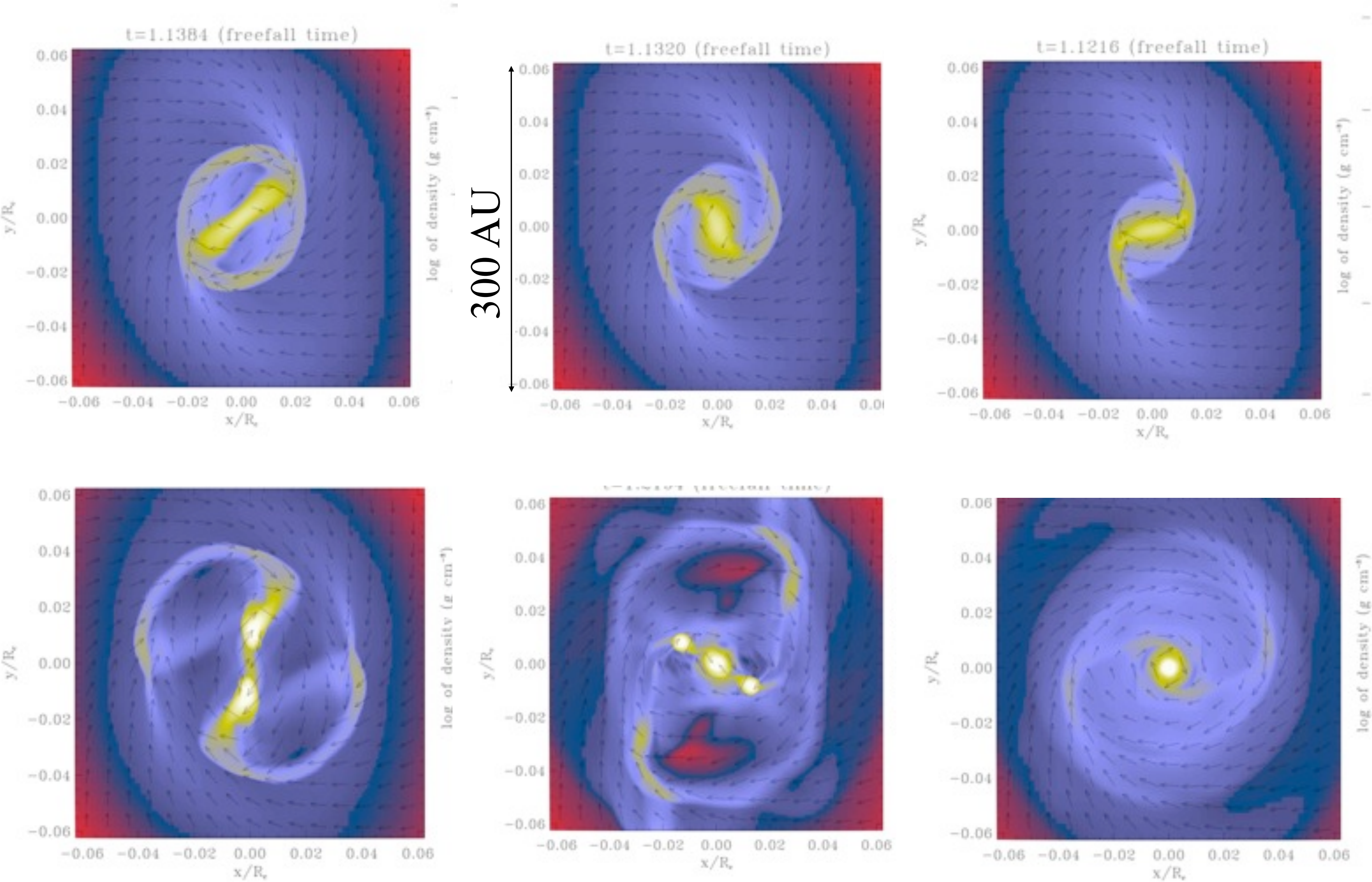
Influence of a weak magnetic field on the fragmentation

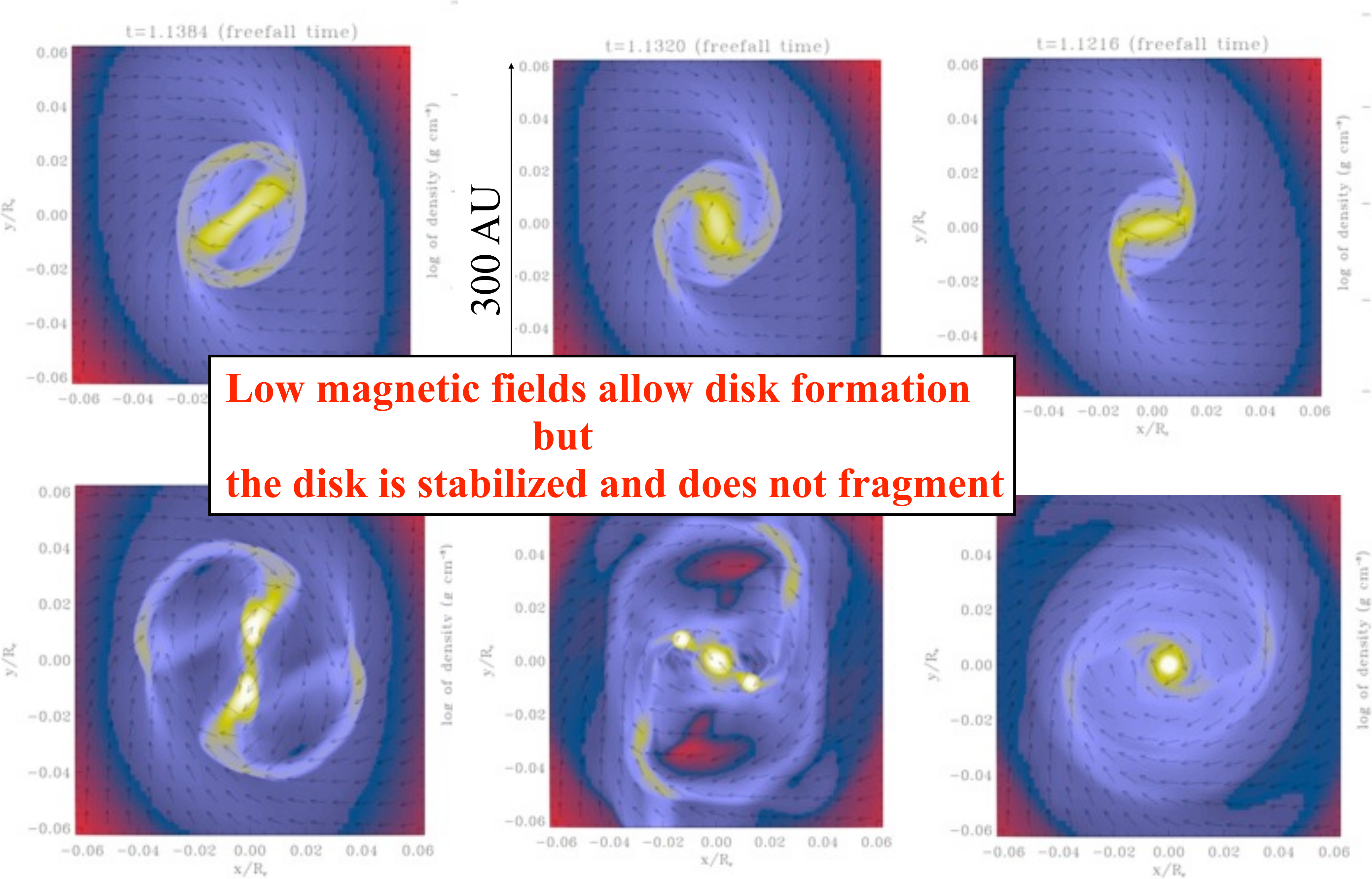
μ=1000 (hydro) μ=50 μ=20



Hennebelle & Teyssier 2008 (see also Machida et al. 2005)

Influence of a weak magnetic field on the fragmentation

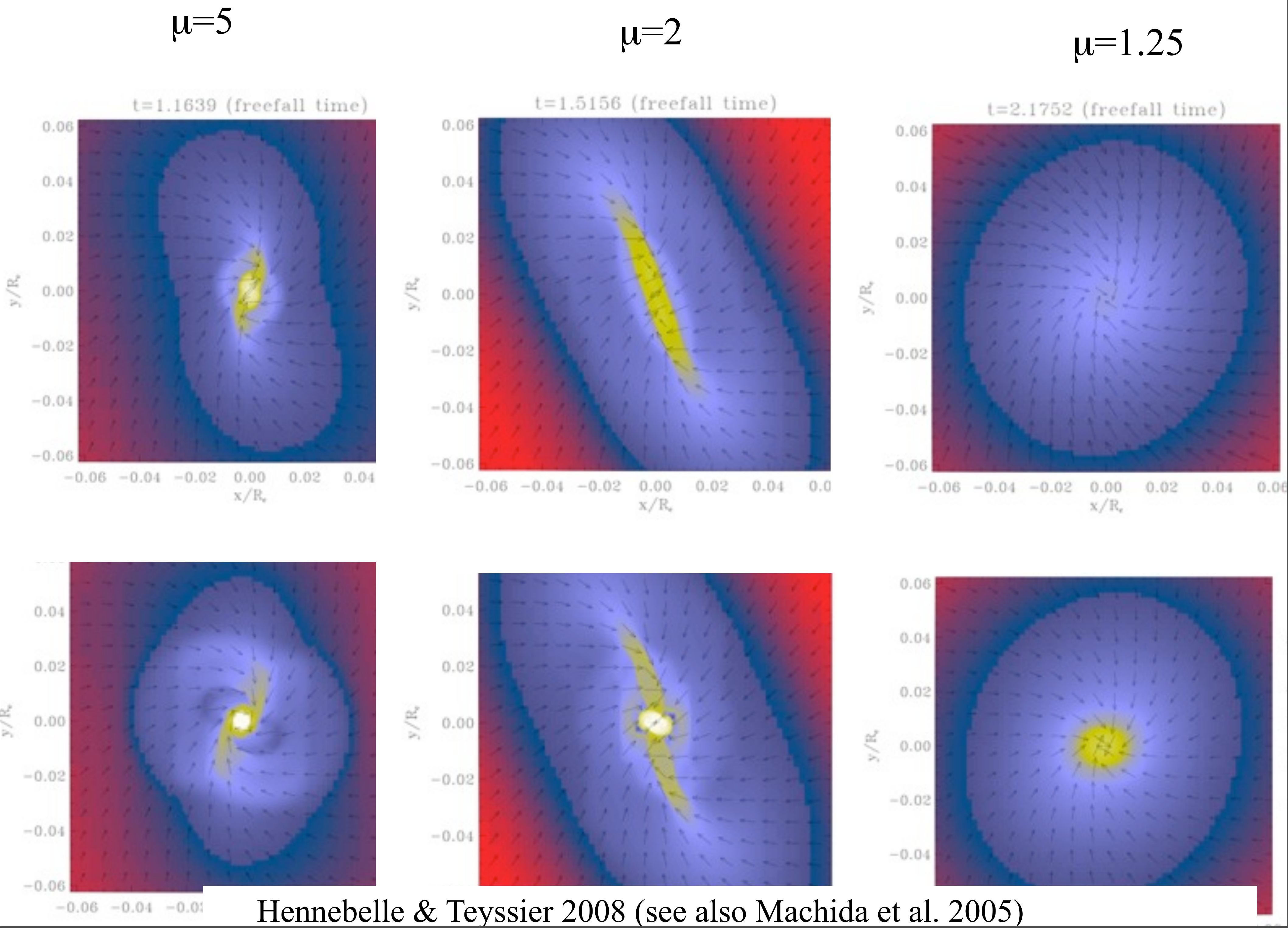
μ=1000 (hydro) μ=50 μ=20



Low magnetic fields allow disk formation
but
the disk is stabilized and does not fragment

Hennebelle & Teyssier 2008 (see also Machida et al. 2005)

For smaller μ, magnetic braking removes the disk



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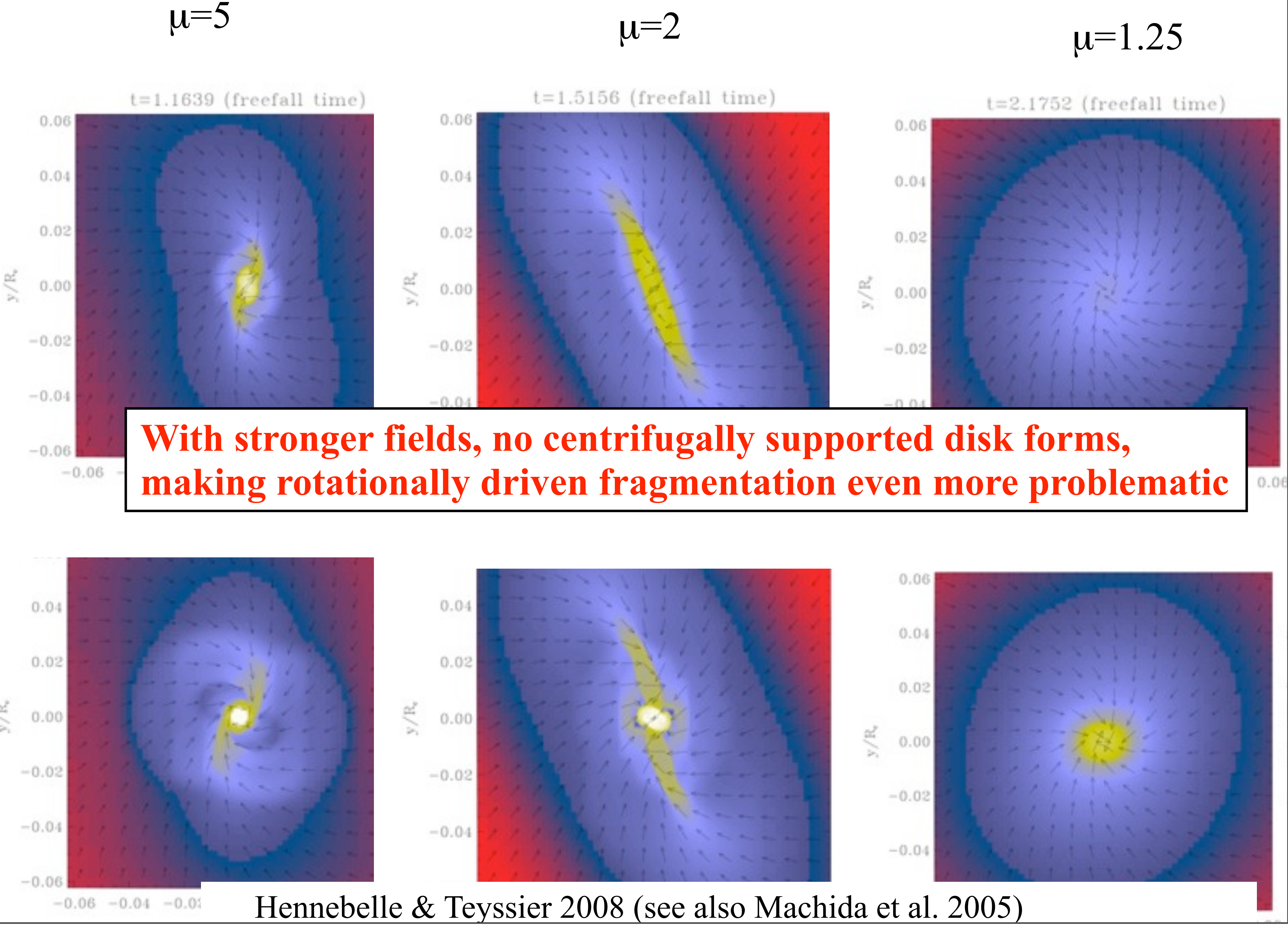
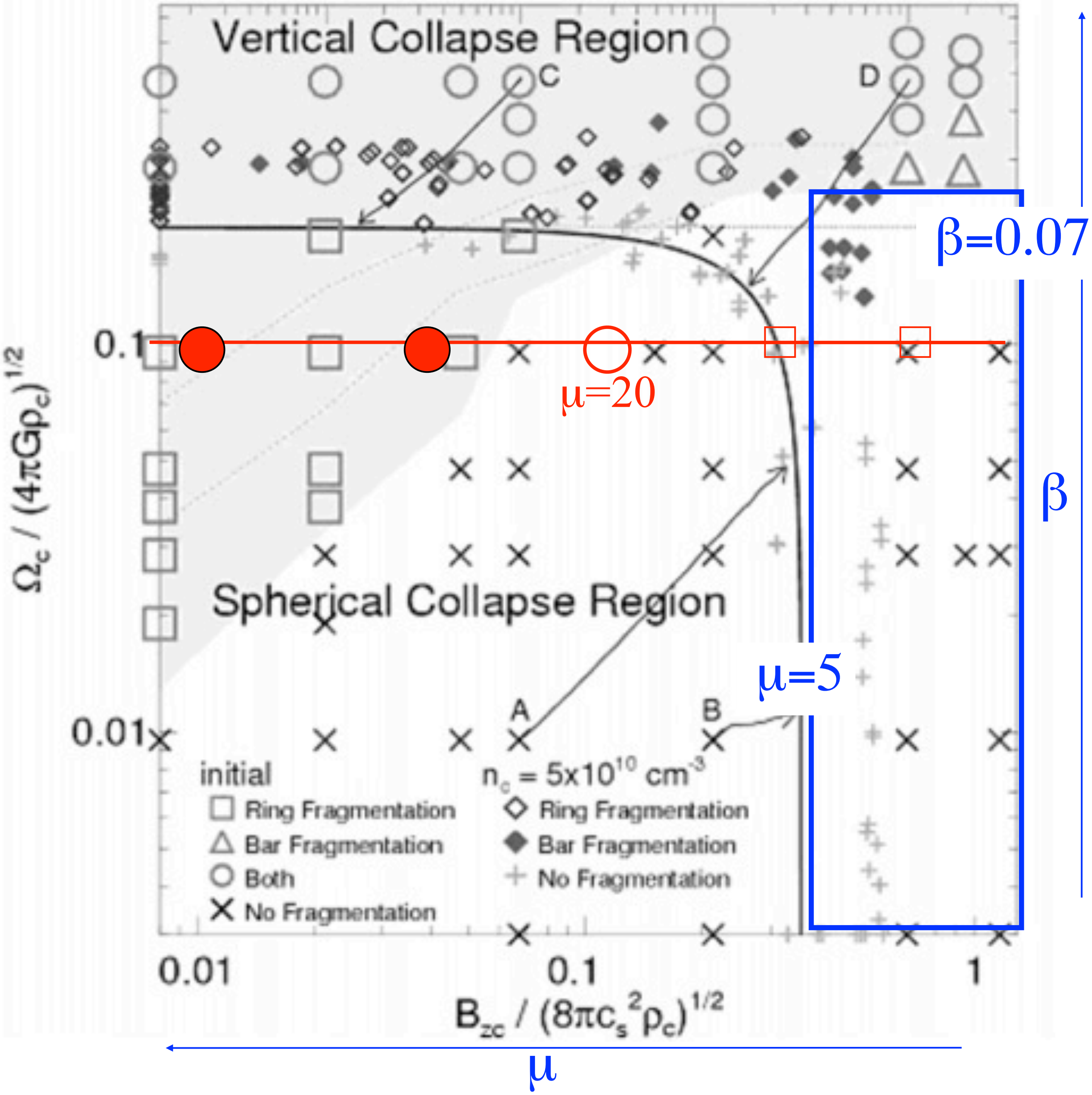


With stronger fields, no centrifugally supported disk forms, making rotationally driven fragmentation even more problematic

Hennebelle & Teyssier 2008 (see also Machida et al. 2005)

Fragmentation: results of Machida et al. 2005



Observations
(Crutcher 2004,
Goodman et al. 1993,
Caselli et al. 2002)

μ<5 (may be <2)
β<0.07
(β=0.02, typical)

Hennebelle & Teyssier 2008
amplitude of perturbation: 0.1
μ: 1000-1.25
corrected β about 0.01
(uncorrected β =0.045)

□ No class-0 disk
○ Class-0 disk no fragmentation
● Fragmentation

$$\Omega_c/(4\pi G\rho_c)^{1/2} = \sqrt{\beta}, \quad \beta = E_{rot}/E_{grav}$$

$$B_{zc}/(8\pi C_s{}^2\rho_c) \approx \sqrt{3}/(\sqrt{\alpha}\mu), \quad \alpha = E_{therm}/E_{grav}, \mu = (M/\phi)/(M/\phi)_{crit}$$

Why magnetic field stabilizes the disk so efficiently ?

Consider a uniformly rotating, self-gravitating, magnetized layer. Lynden-Bell (1966) obtained the dispersion relation:

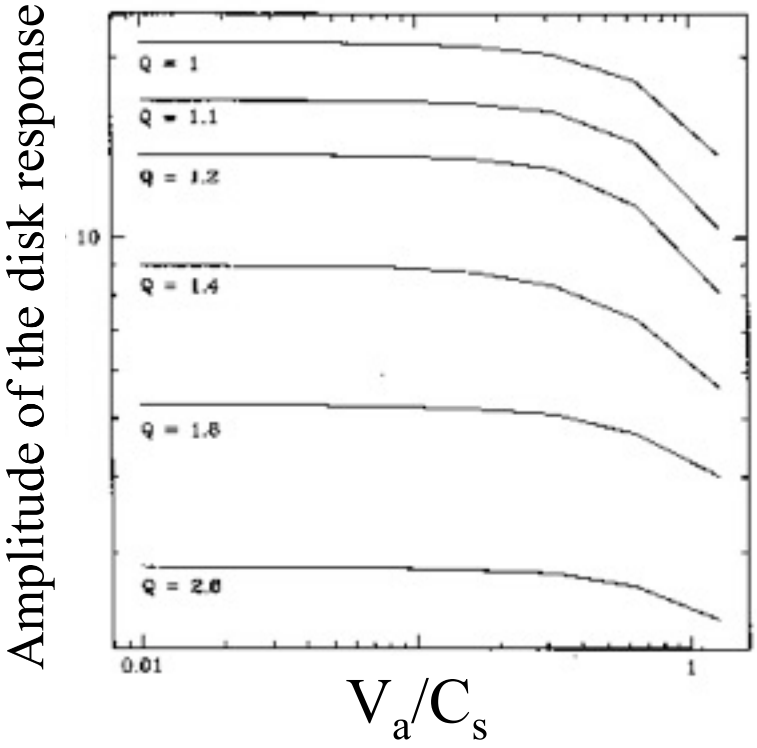
$$\omega^4 - \left[4\Omega^2 - 2\pi G\Sigma_0|k| + k^2\left(c^2 + \frac{B^2}{4\pi\rho}\right)\right]\omega^2 + \frac{(k^2c^2 - 2\pi G\Sigma_0|k|)(\mathbf{k}.\mathbf{B})^2}{4\pi\rho} = 0 \tag{1}$$

It entails a modified sound speed due to the magnetic pressure forces => stabilizing effect.

But destabilizing contribution of the magnetic tension
⇒Configuration unstable

However, in a differentially rotating system (like a disk in Keplerian rotation), a toroidal magnetic field is quickly generated and the first effect becomes dominant.
(Elmegreen 1987, Gammie 1996)

Amplitude of the disk response for various Q, in presence of shear

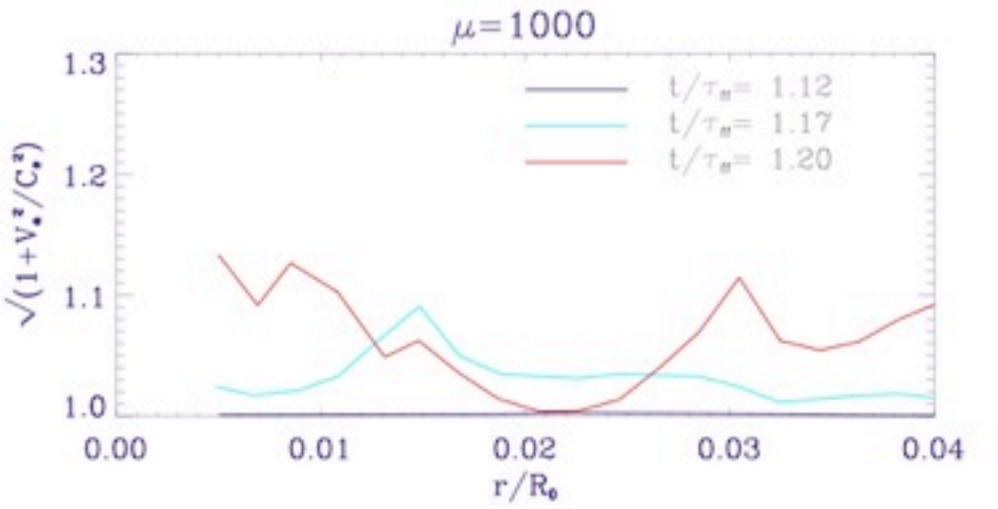


Gammie 1996

When the Alfven speed within the disk is comparable to the sound speed, the response to a perturbation is much weaker.

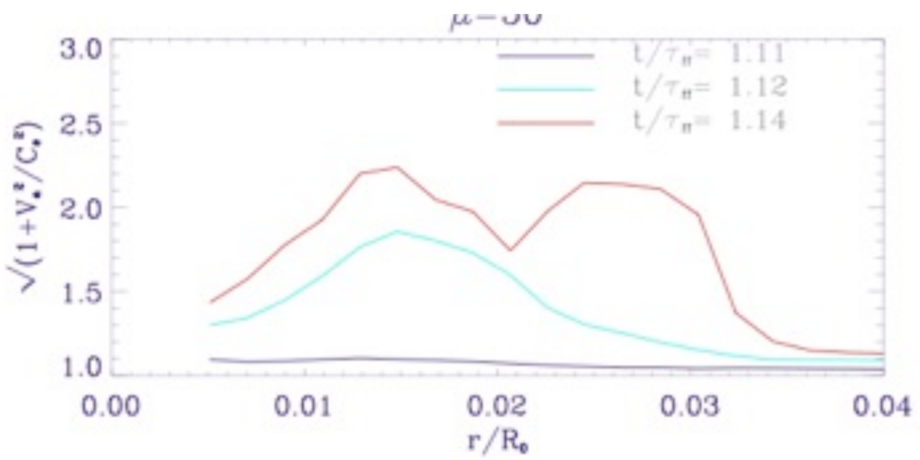
Can we use this criteria to understand more quantitatively
the numerical results ?

Growth of the toroidal magnetic field within the disk

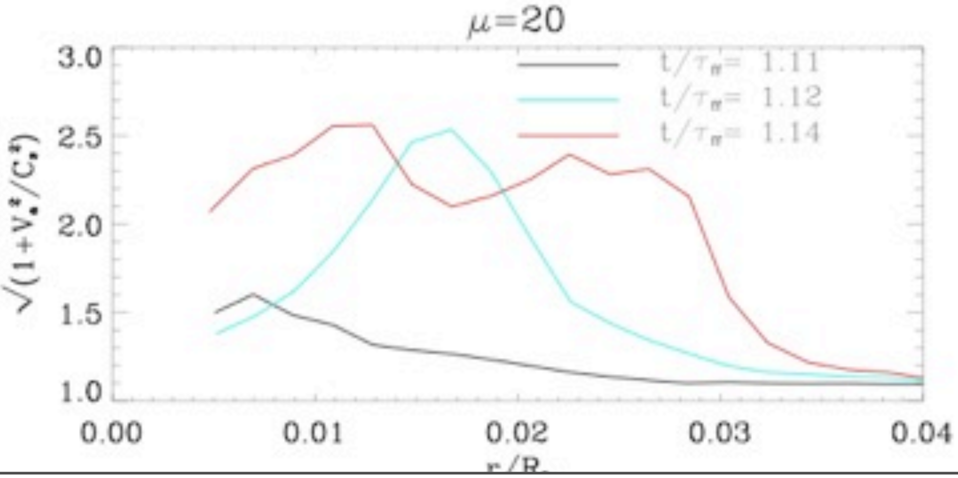


Importance of V_a/C_s

for various μ and various times



=>Compatible with the assumption that the toroidal field, stabilizes the disk.



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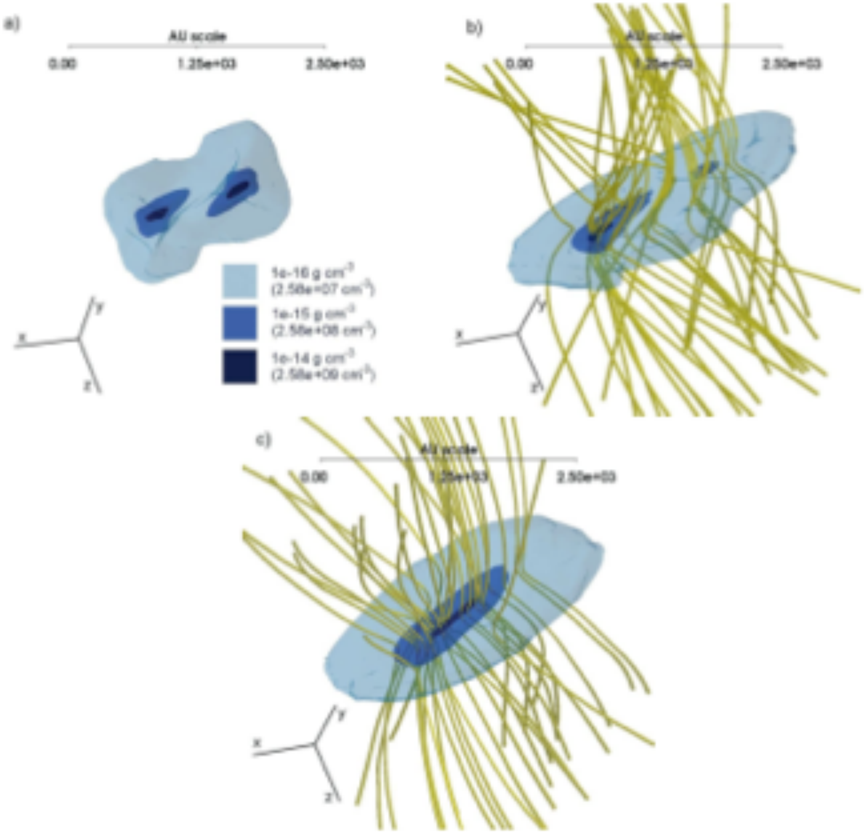
Influence of non-ideal MHD

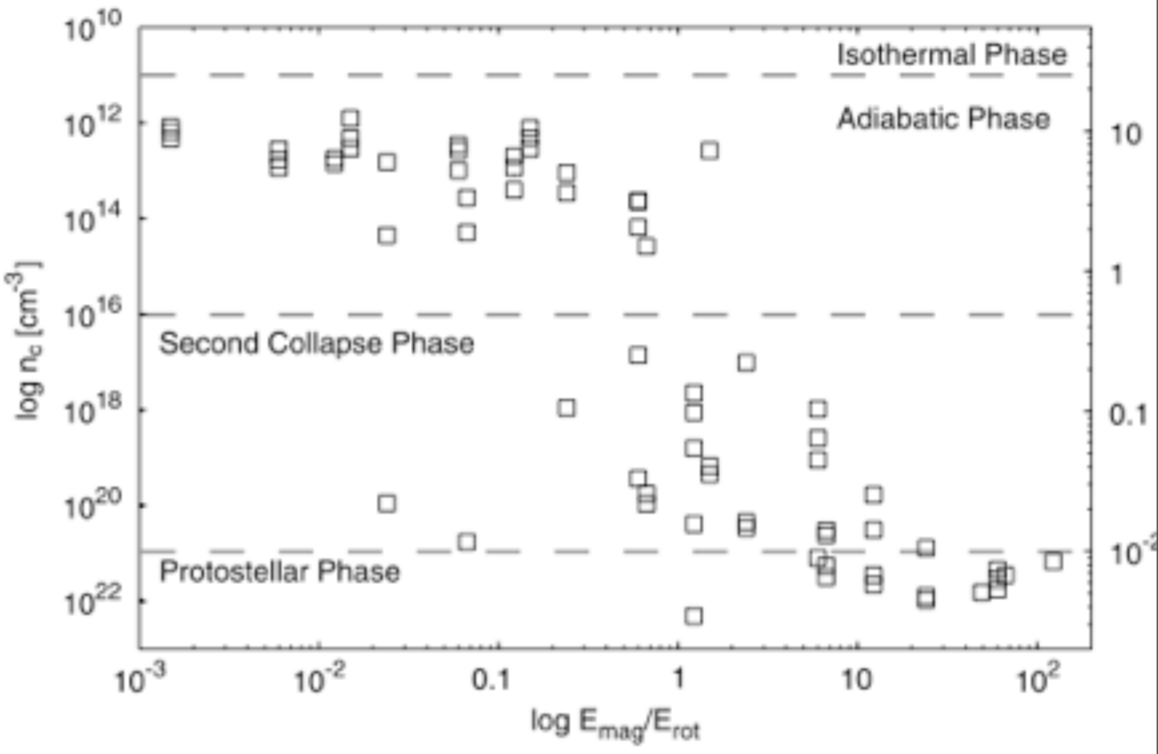
Ambipolar diffusion

Duffin & Pudritz 09
A fastly rotating model



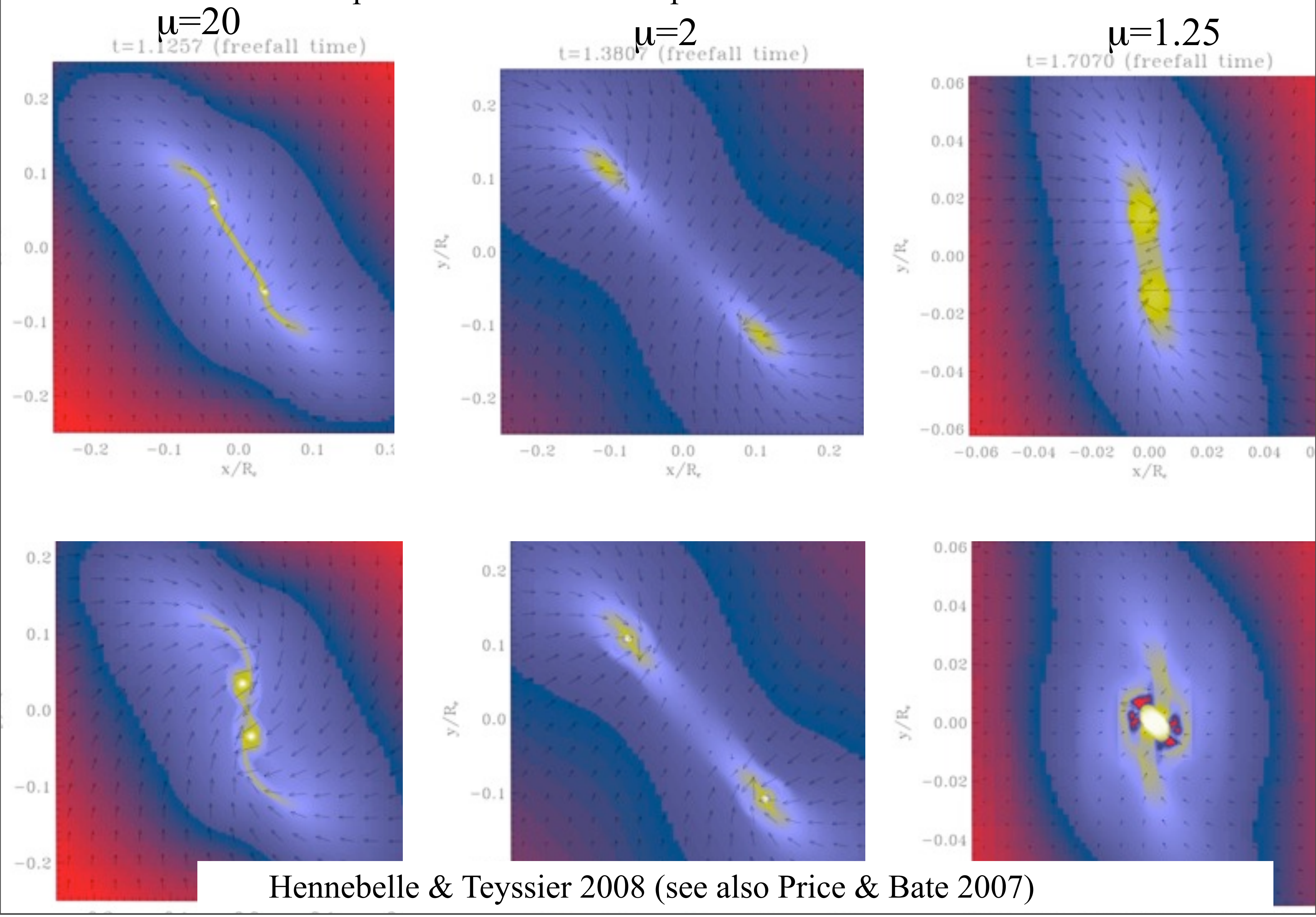
Ohmic dissipation

Machida + 08
147 simulations treating 2nd collapse
102 simulations fragment
Simulations with realistic initial conditions fragment only during the second collapse



Effets of initial density perturbations ?

m=2 perturbation with an amplitude of 50%



Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

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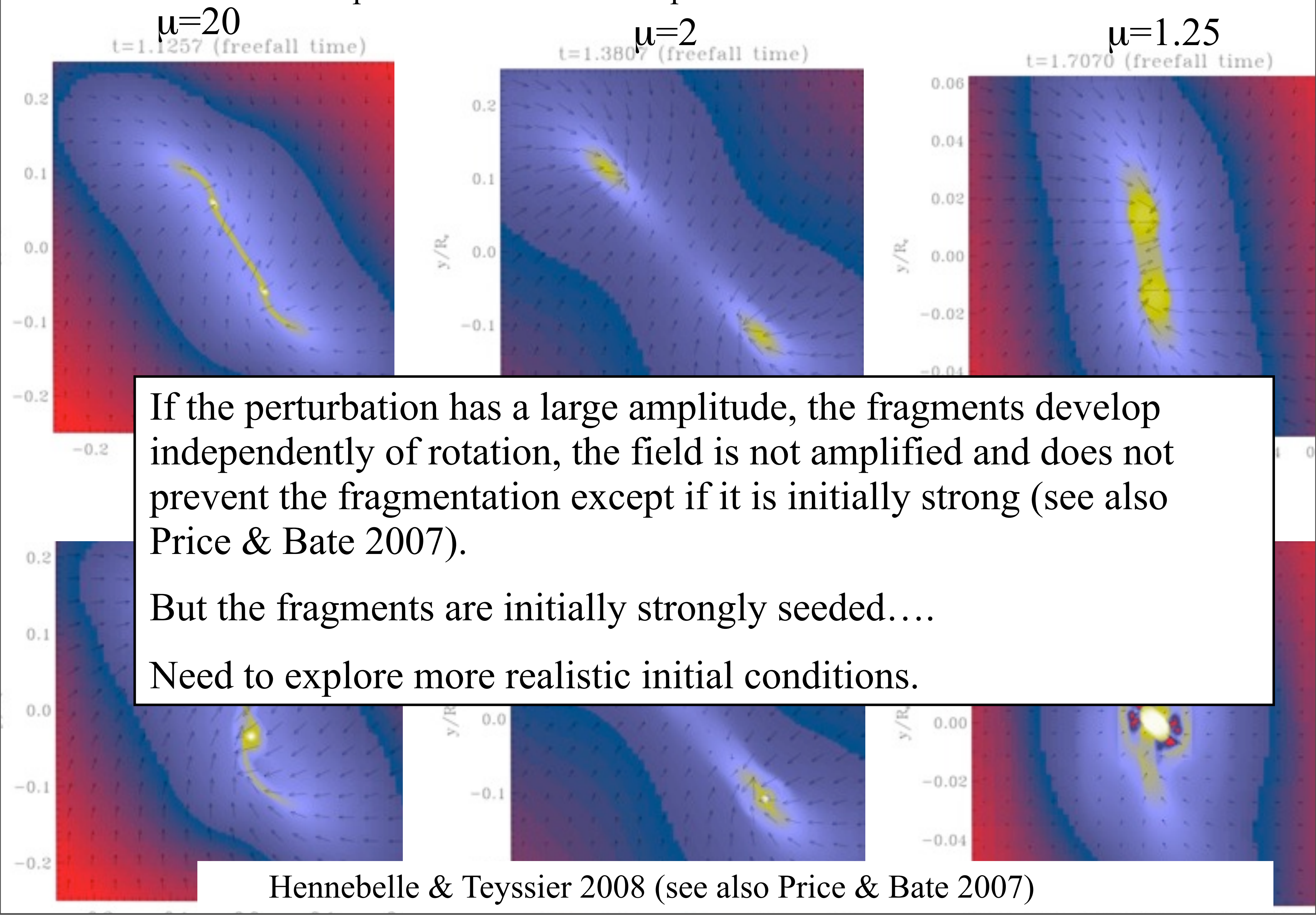

If the perturbation has a large amplitude, the fragments develop independently of rotation, the field is not amplified and does not prevent the fragmentation except if it is initially strong (see also Price & Bate 2007).

But the fragments are initially strongly seeded….

Need to explore more realistic initial conditions.

Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

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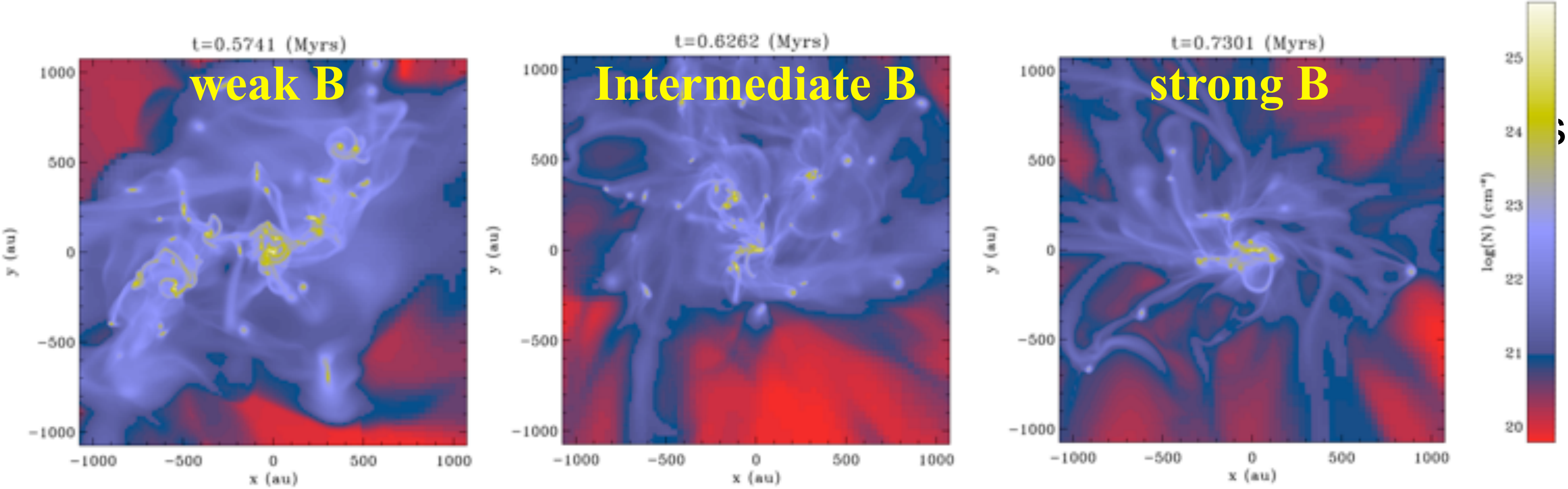
100 $M_\odot$ magnetized, turbulent and dense barotropic core

(other related works : Peters et al. 2010, Seifried et al. 2012)

Turbulence is initially seeded, Eturb/Egrav ~20%



μ=120 μ=5 μ=2

Hennebelle et al. 2011

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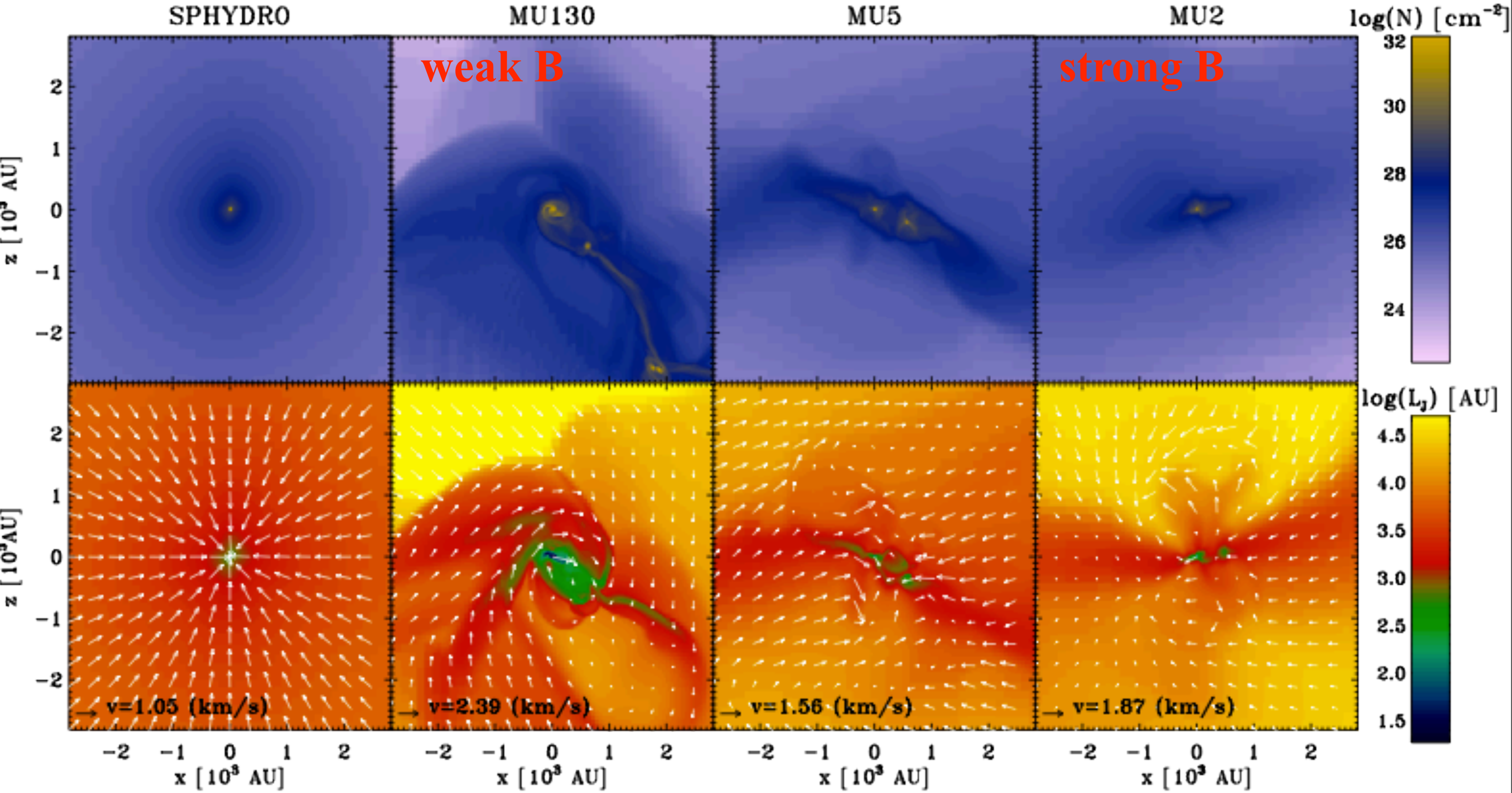
100 M$_\odot$ turbulent dense core collapse

Eturb/Egrav=20% initially

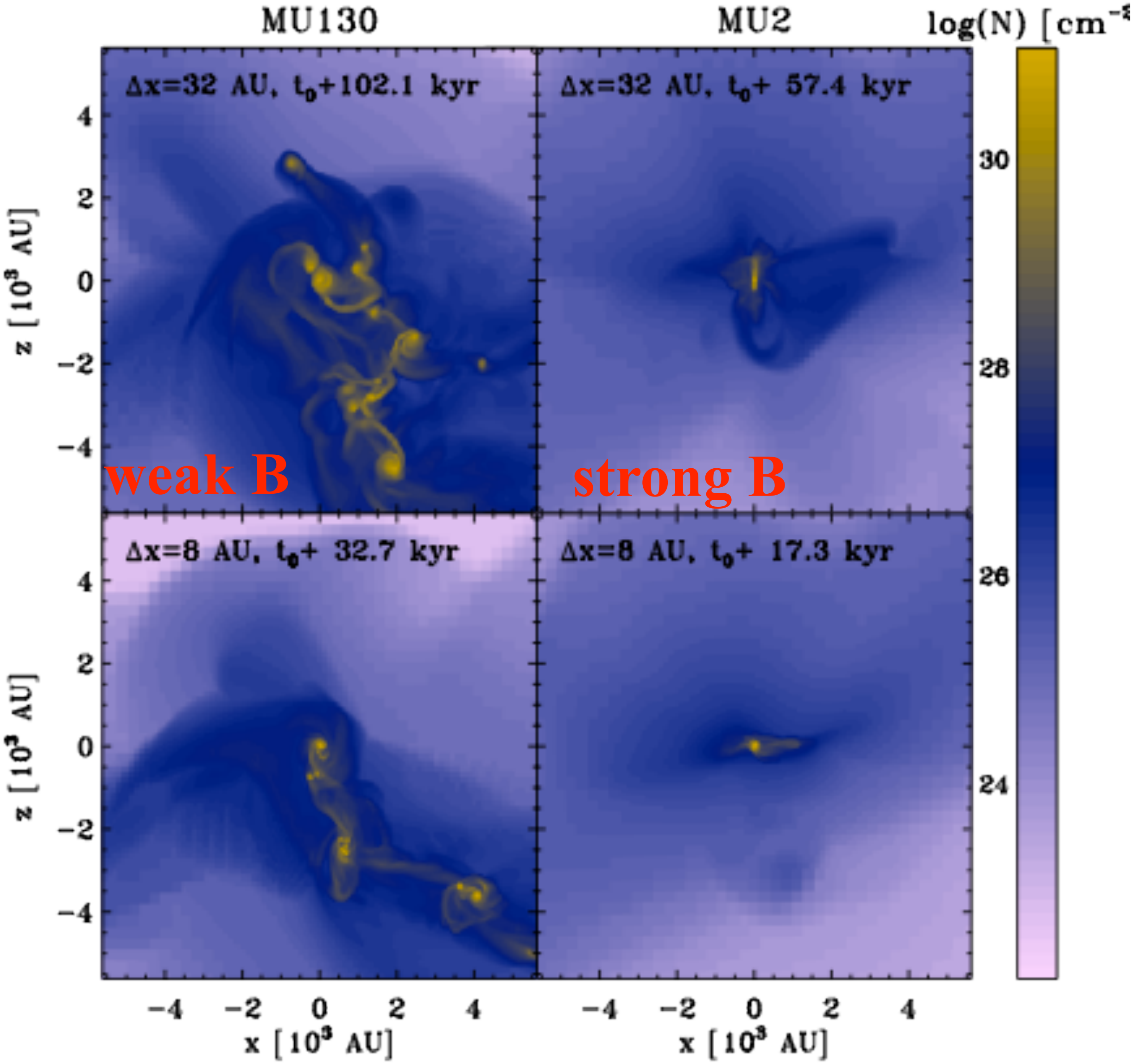


Commerçon, Hennebelle & Henning, ApJL 2011

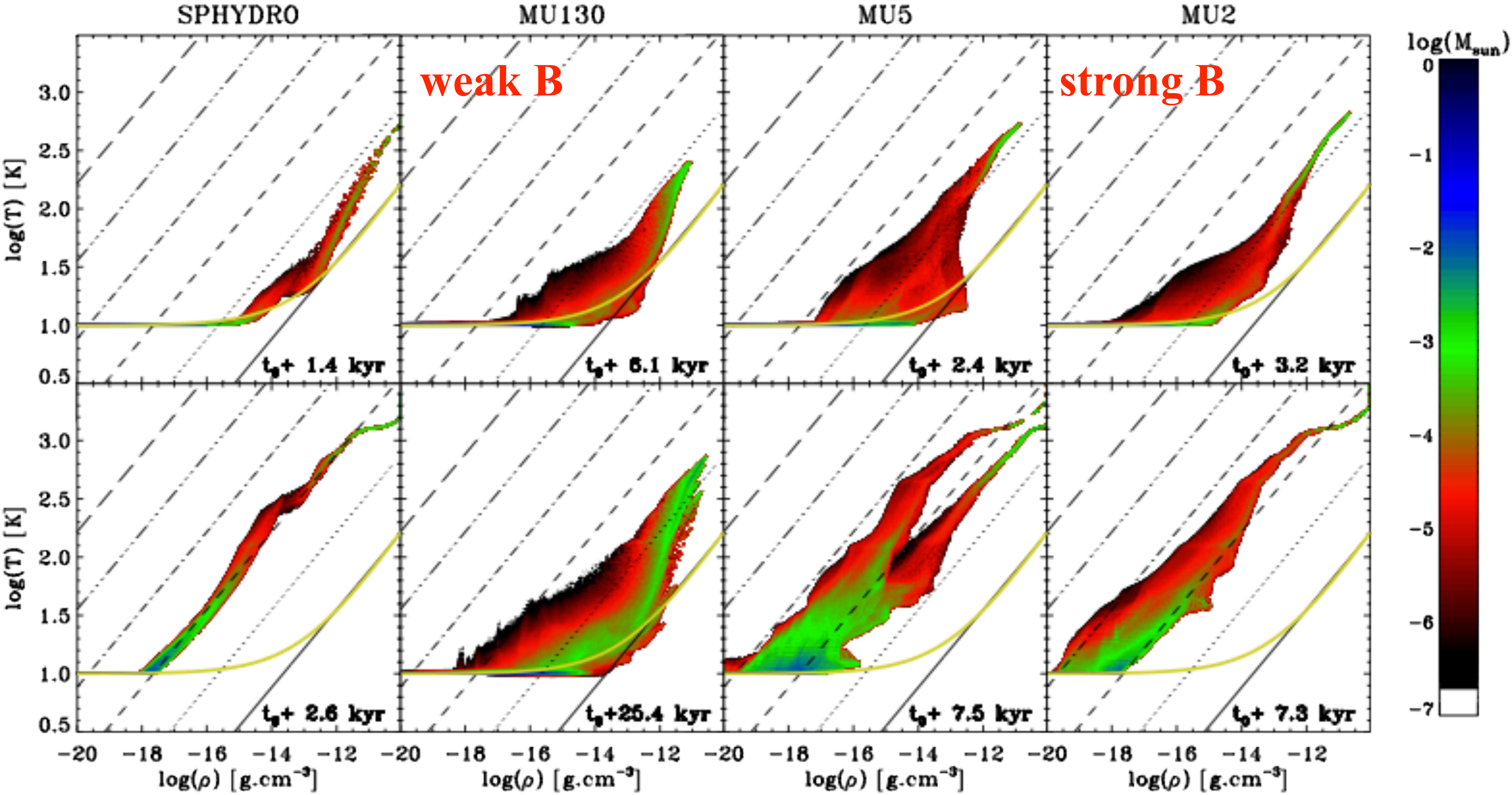
(see also Price & Bate 2009 at larger scales)

100 M⊙ turbulent dense core collapse

Trend confirmed with lower resolution runs:

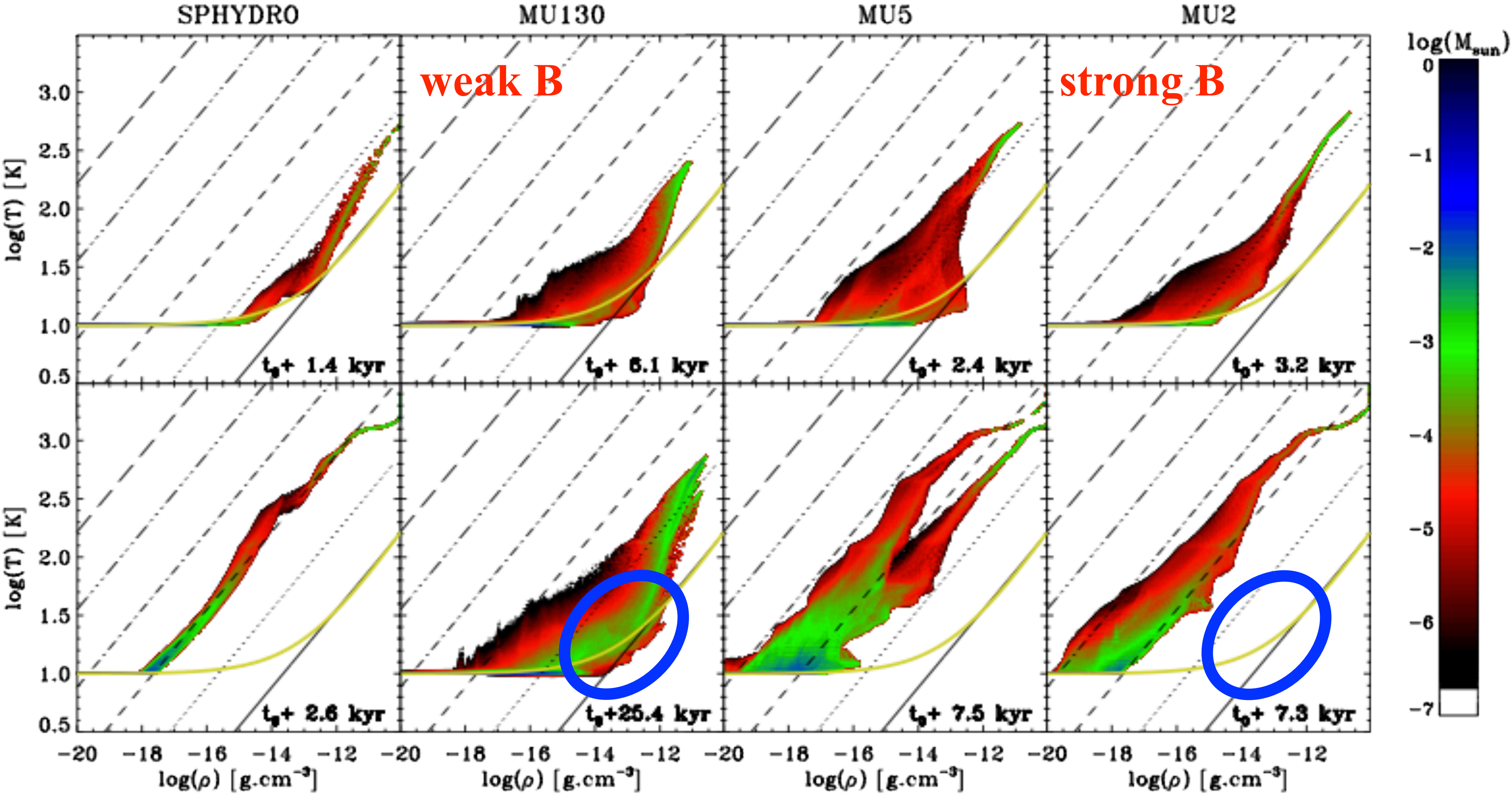


100 $M_\odot$ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

100 $M_\odot$ turbulent dense core collapse



Commerçon, Hennebelle & Henning, ApJL 2011

1) Catastrophic braking

1.1) The catastrophe…

1.2) Alleviating the catastrophe: magnetic configuration

1.3) Alleviating the catastrophe: impact of turbulence

1.4) Alleviating the catastrophe: non-ideal MHD ?

1.5) Is there a catastrophe or was there a catastrophe ?

2) Fragmentation crisis

2.1) A fragmentation "crisis" for low mass cores ?

2.2) How to solve it ?

2.3) Influence of B on high mass cores

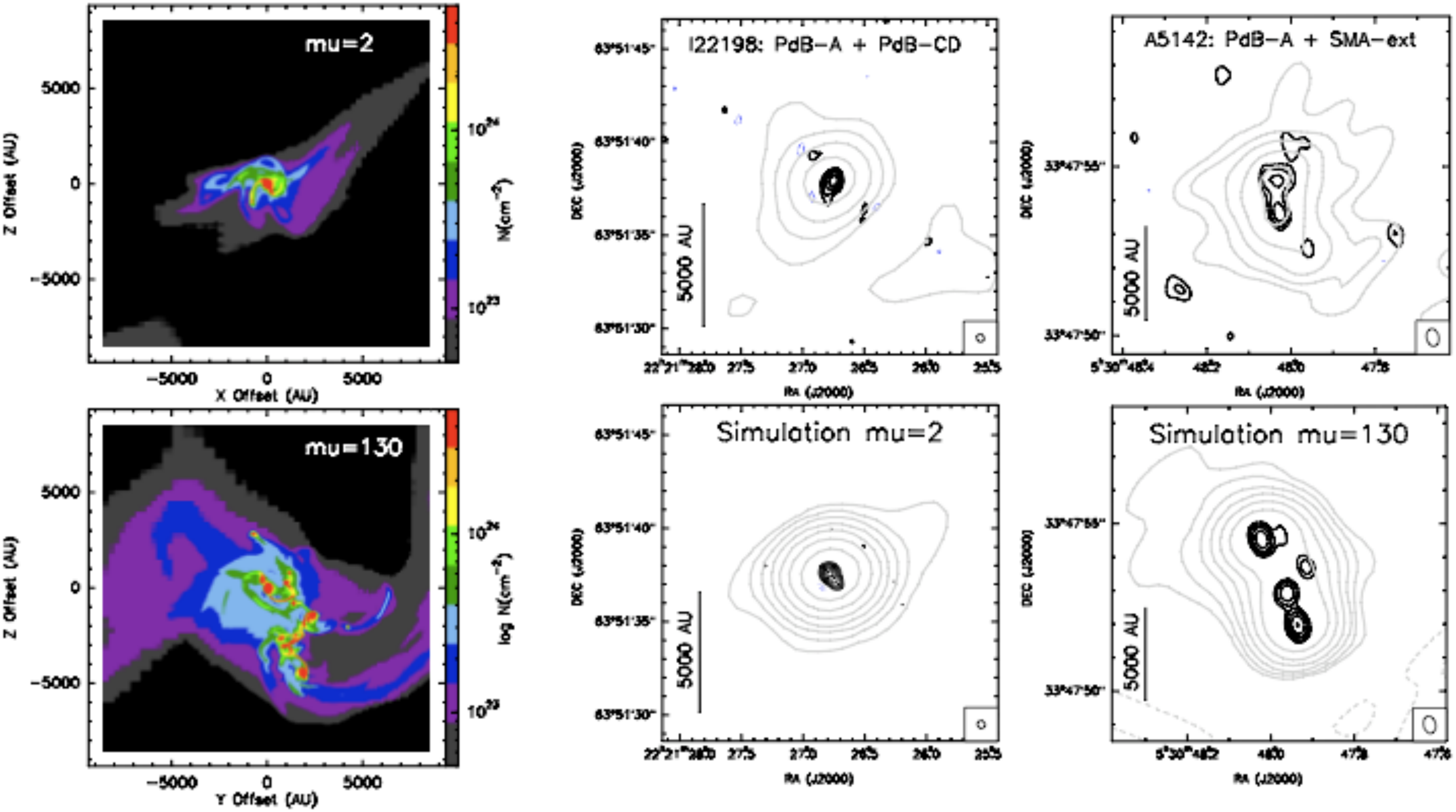
2.4) When magnetic field and radiative feedback collaborate

2.5) A crisis: really ?

Confrontation with real observations of massive class-0 cores

Palau et al. 2013

Some cores show sign of fragmentation some not. No obvious correlation with any observed parameters (mass, rotation…). Magnetic field ?



Conclusions regarding fragmentation

In low mass cores, the magnetic field has a huge impact on the fragmentation, especially “rotationally driven fragmentation”

-”large scale fragmentation” induced by initial large scale density perturbations is possible

-”small scale fragmentation” during second collapse is possible even when the field is strong

In high mass core, the magnetic field reduces but do not suppress fragmentation because the magnetic field is diffused out

The combination of magnetic field and radiative feedback leads to a very significant quenching of fragmentation. Route to form massive stars ?