Collapse of magnetized dense cores

Is there a fragmentation crisis ?

Patrick Hennebelle

(ENS-Observatoire de Paris-KITP)

Collaborators:

Sébastien Fromang, Romain Teyssier,

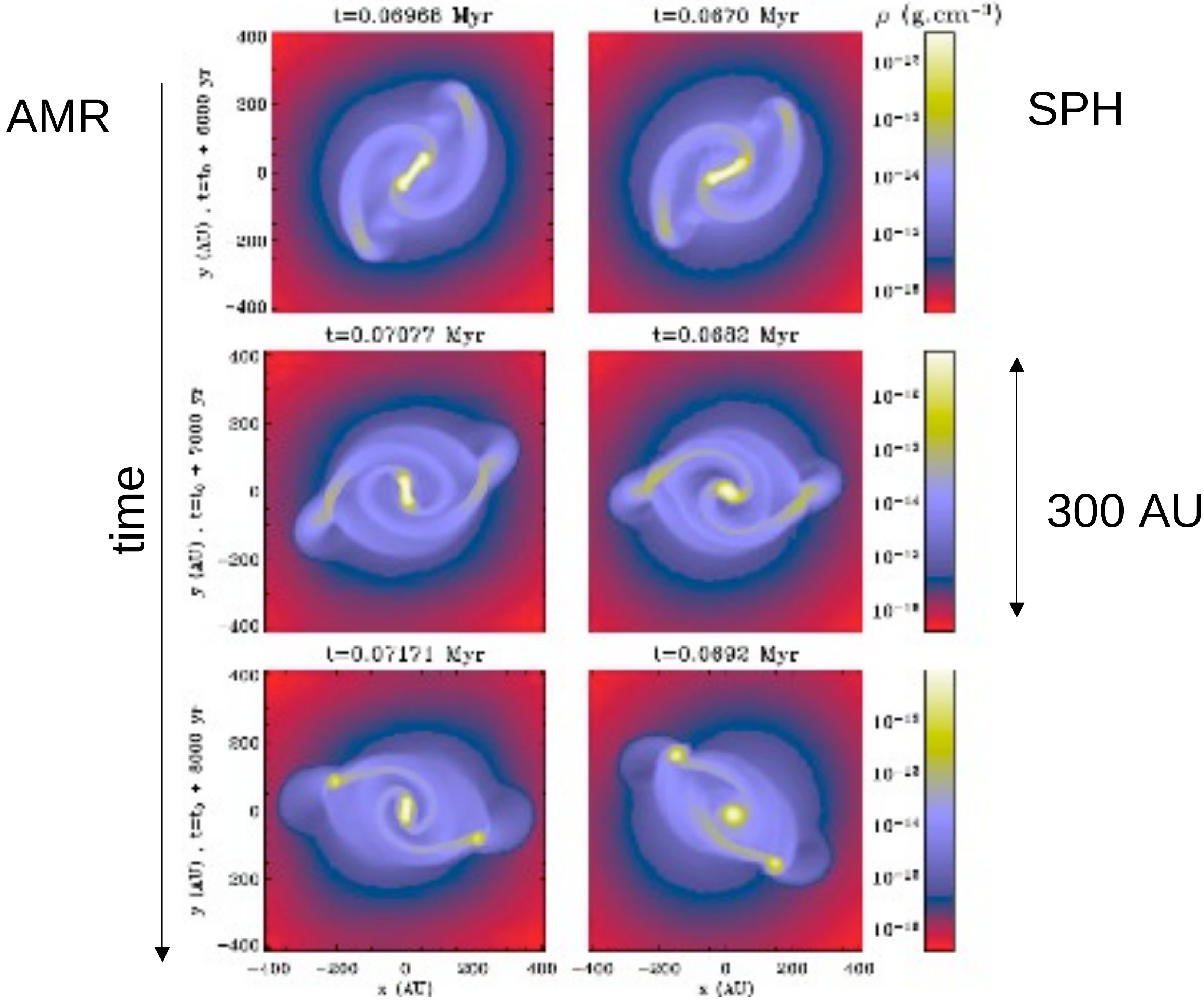
Benoît Commerçon, Philippe André

-A significant fraction of stars are binaries
(e.g. Duquenoy & Major 1991) although maybe not the case for low mass stars (Lada 200)

-Original ideas like fission of a star or capture do not work

-"Standard scenario": formation of a big massive disk which fragments into few objects
(review Bodenheimer et al. 2000, PPIV)

Rotation or turbulence necessary to produce fragmentation are compatible with observations
(rotational or turbulent energy few percents of the gravitational energy)



Commerçon et al. 08

But magnetic fields are observed….

Typically one infers μ=1-4 (geometry issue)
Crutcher et al. 1999, 2004

What are the effects of the magnetic field ?

-Magnetic support

-Magnetic braking

-….

Magnetic support:

(Mestel 1965, 1966, Strittmatter 1966, Nakano 1981, Mouschovias 1977, Shu et al. 1987)

Consider a cloud of mass M, radius R, treated by B

Flux conservation: $\phi \propto BR^2$

magnetic / gravitational energy:

$$\frac{B^2R^3}{M^2/R} \propto (\phi/M)^2$$

Independent of R, B *dilute* Gravity

$$(\phi/M)_{crit} = \sqrt{G}/0.13$$

Estimation of the critical mass to flux ratio:
(Similar to Egrav=Emag but based on Virial theorem)

mass-to-flux larger than the critical value : **cloud is supercritical**
mass-to-flux smaller than the critical value : **cloud is subcritical**
(If the cloud is subcritical, it is stable for any external pressure !)

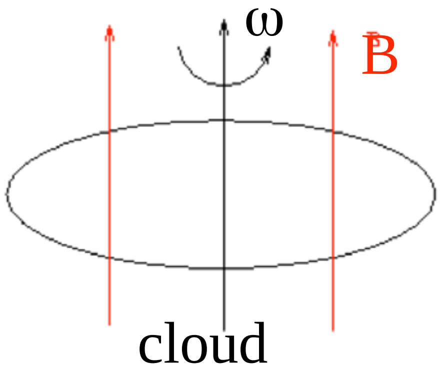
μ= mass-to-flux over critical mass-to-flux ratio

Magnetic braking:

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

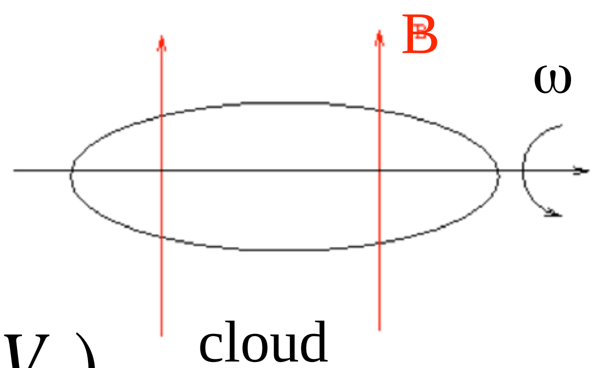
rotation generates torsional Alfvén waves which carry angular momentum outwards

<u>Typical time:</u> 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:

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



magnetic field orthogonal to the axis:

$$\tau_{perp} \approx ((1 + \rho_{core} / \rho_{env})^{1/2} - 1) \times (R_{core} / 2V_a)$$

Since $\rho_{core} / \rho_{env} >> 1$, the braking is more efficient perpendicularly to the rotation axis

Initial conditions (as simple as possible…):

-uniform density sphere

-solid body rotation

-uniform magnetic field parallel to the rotation axis

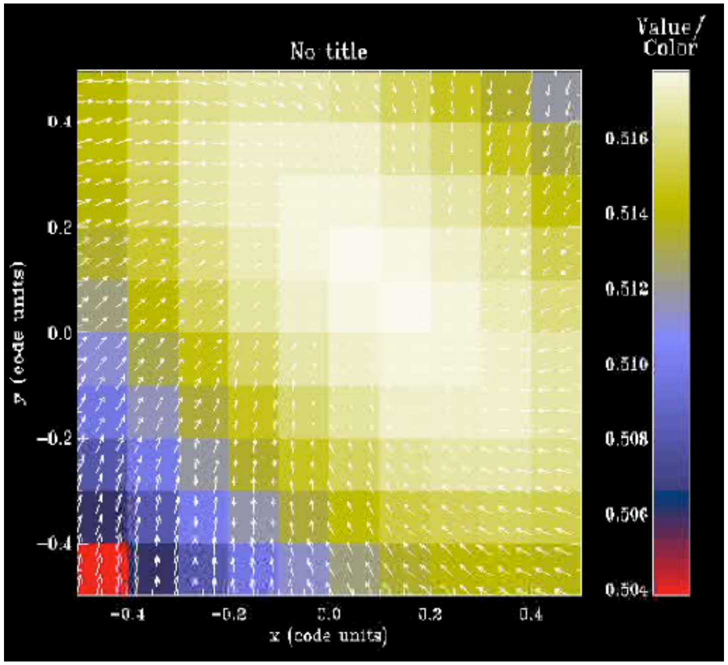
-add an m=2 perturbation in density and magnetic field of amplitude 0.1 (weak)

-barotropic equation of state

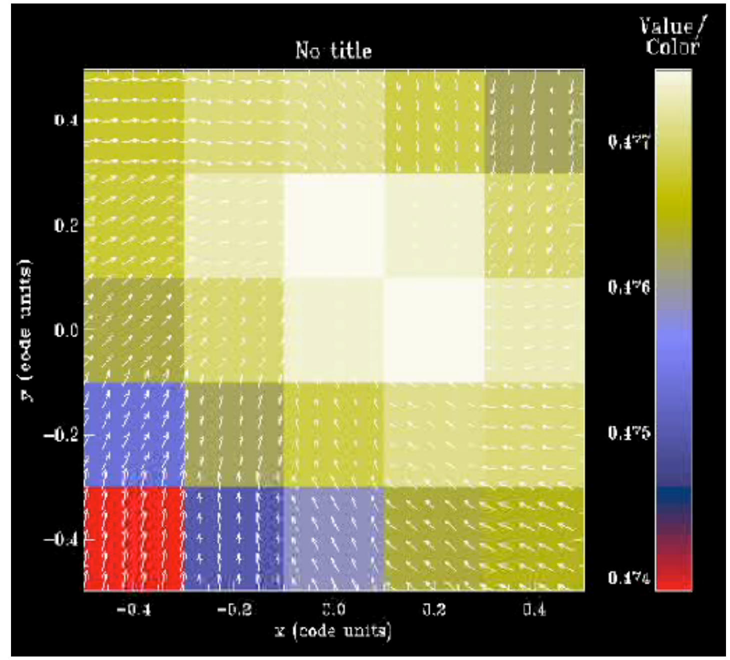
AMR MHD code RAMSES (insure div B =0)
9 levels of AMR, 10 cells per Jeans length
Roe solver

RAMSES HYDRO: Teyssier 2002
RAMSES MHD: Fromang, Hennebelle, Teyssier 2006

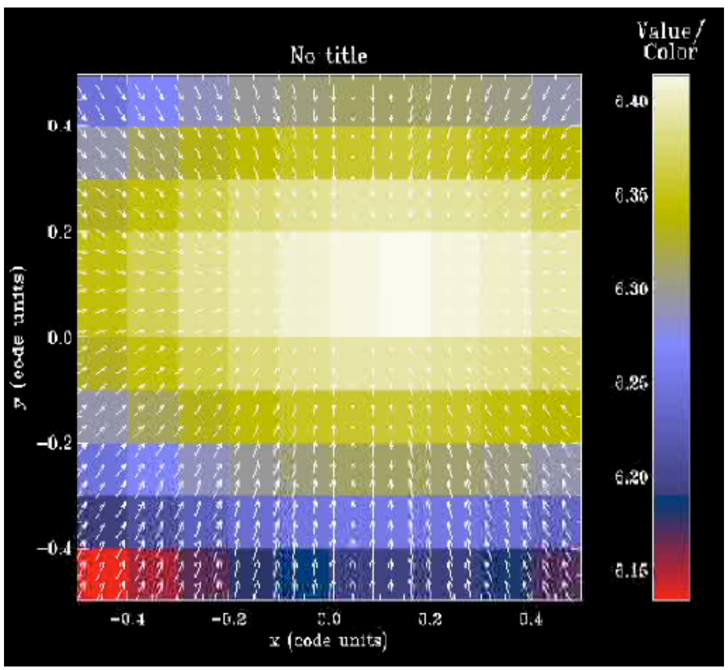
XY
hydro



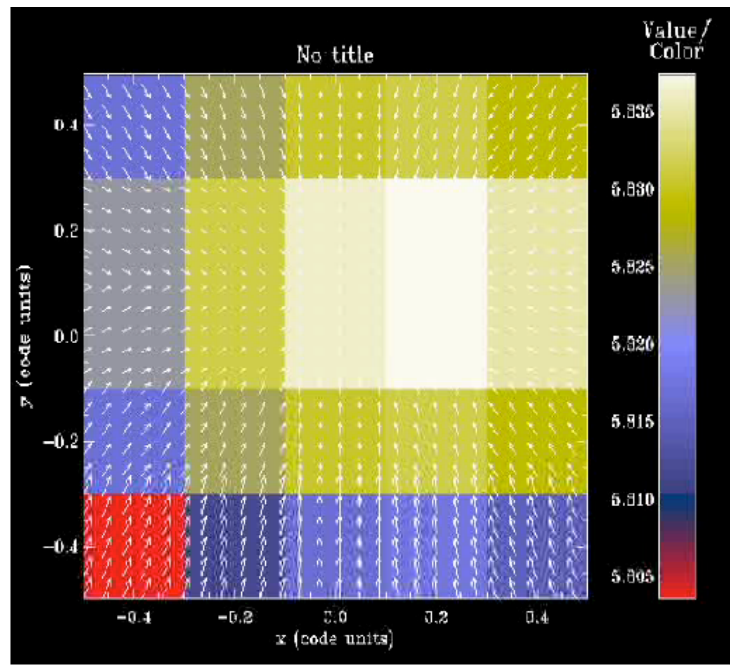
XY
MHD
μ=2



XZ
hydro



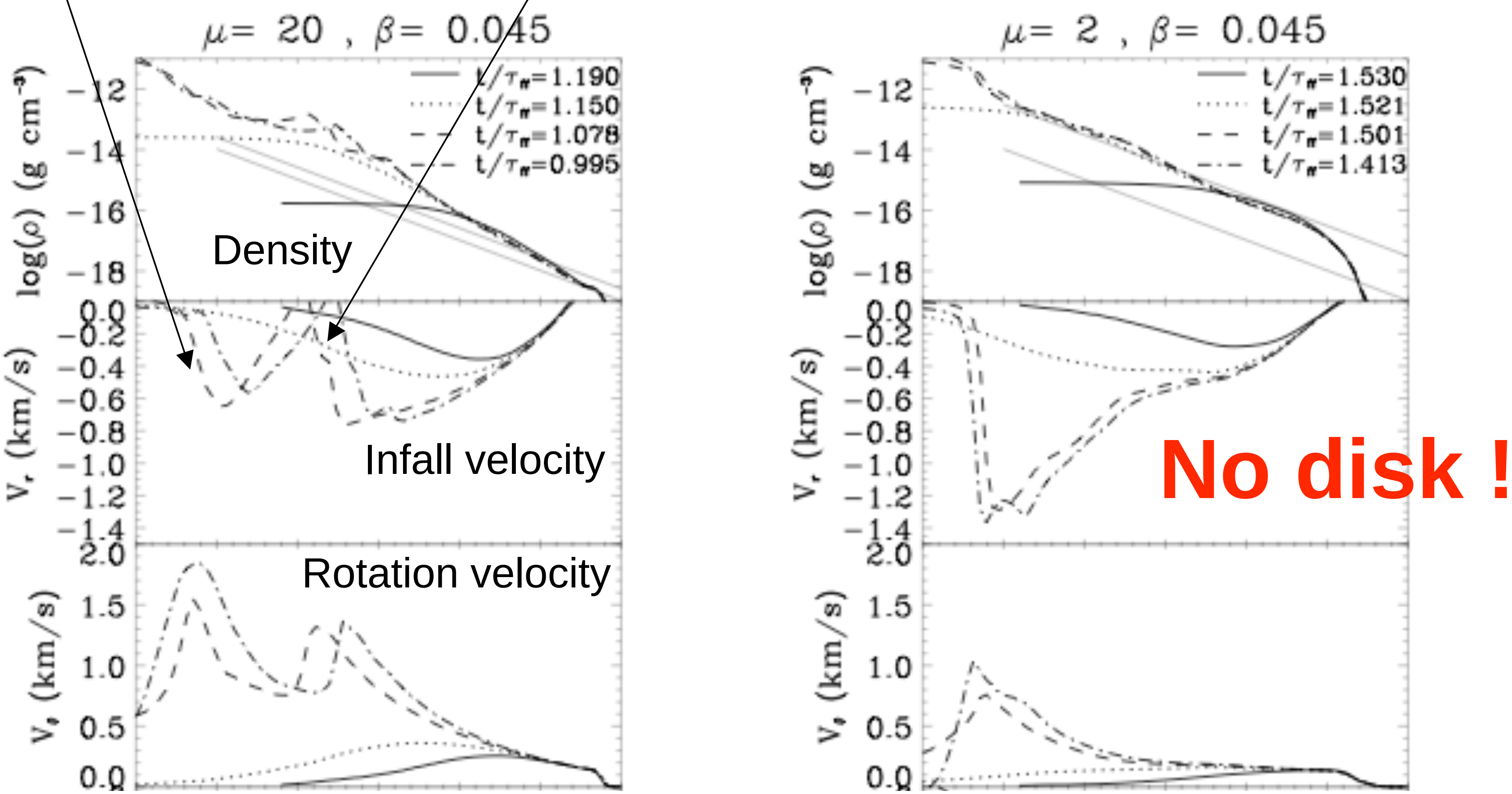
XZ
MHD
μ=2



Magnetic field seems to play a crucial role.
Let us have a closest look
(note do not consider outflow further in the talk).

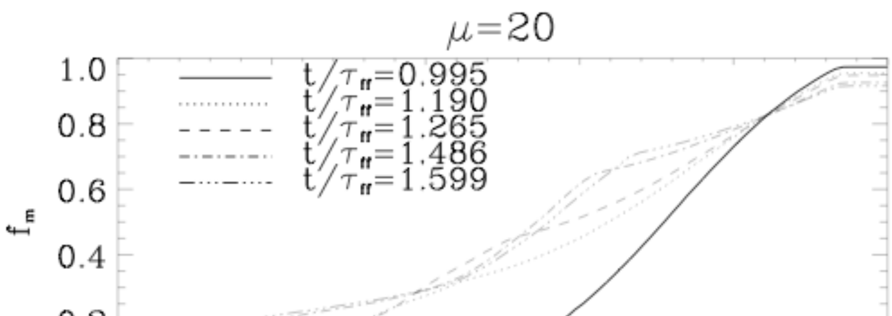
Thermally supported core

Centrifugally supported disk

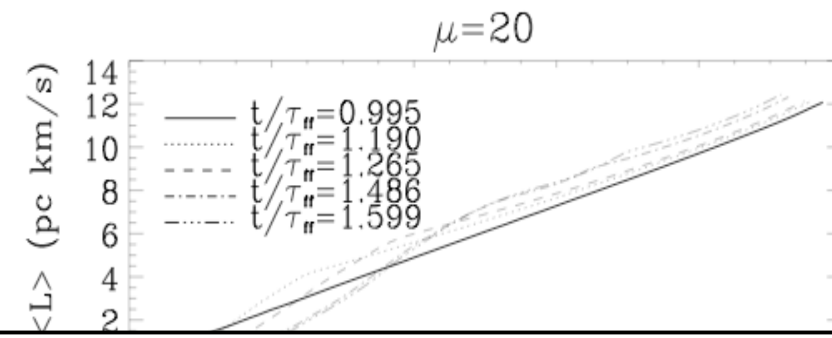


Hennebelle & Fromang 2008

Distribution of mass as a Function of cylindrical radius



Distribution of specific angular momentum as a function of mass

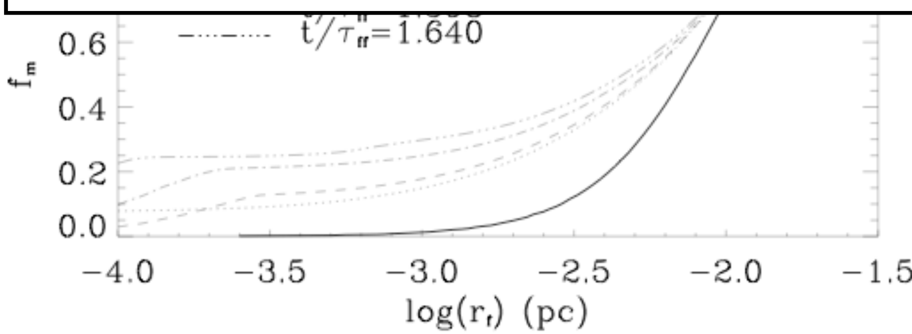


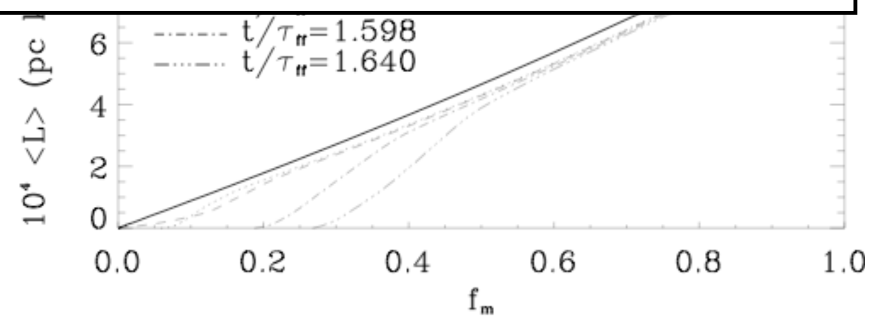
Implication

Distribution of angular momentum different because

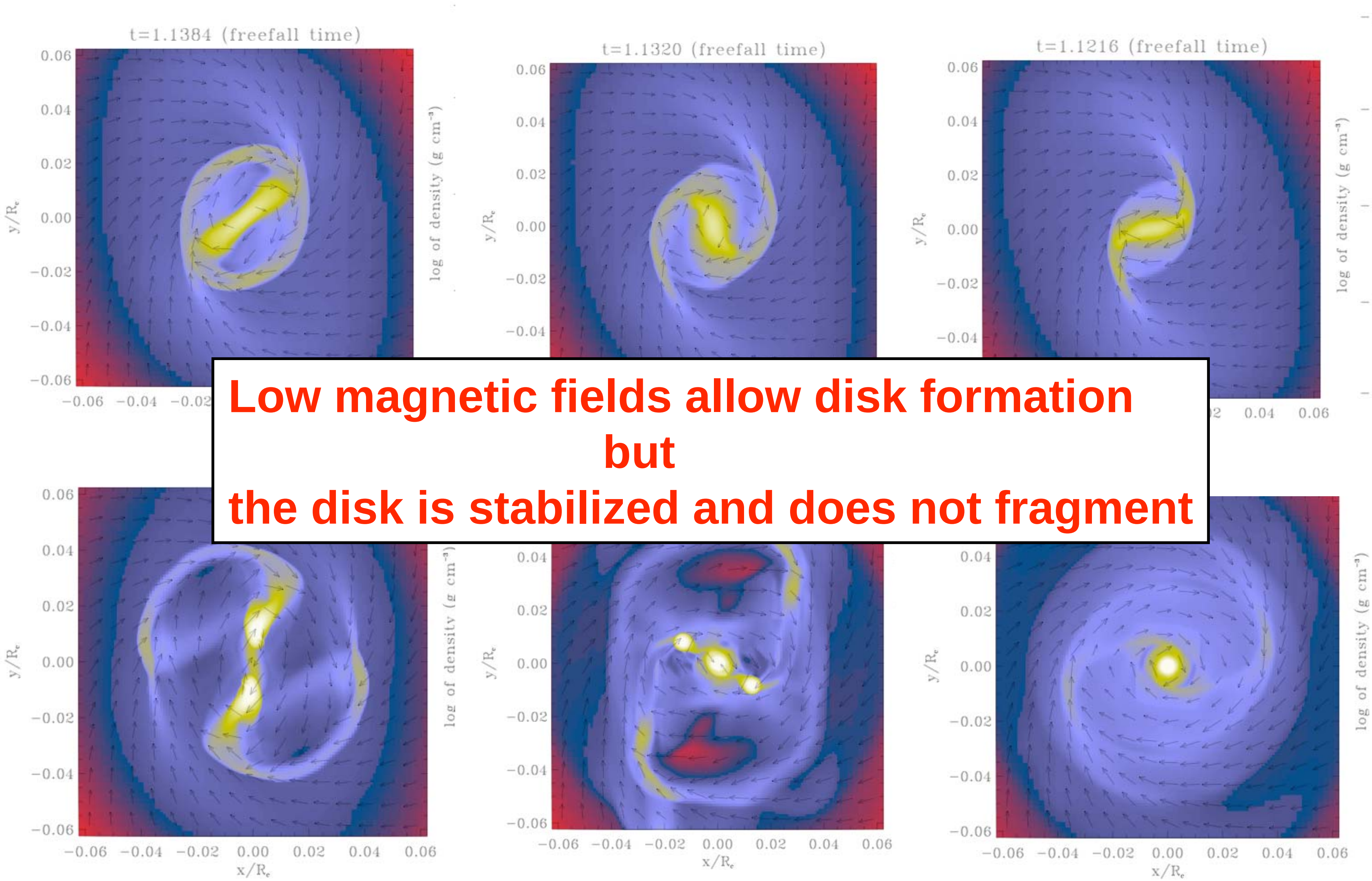
-collapse proceeds more spherically in weakly magnetized cases

-magnetic braking reduces the angular momentum in strong field cases





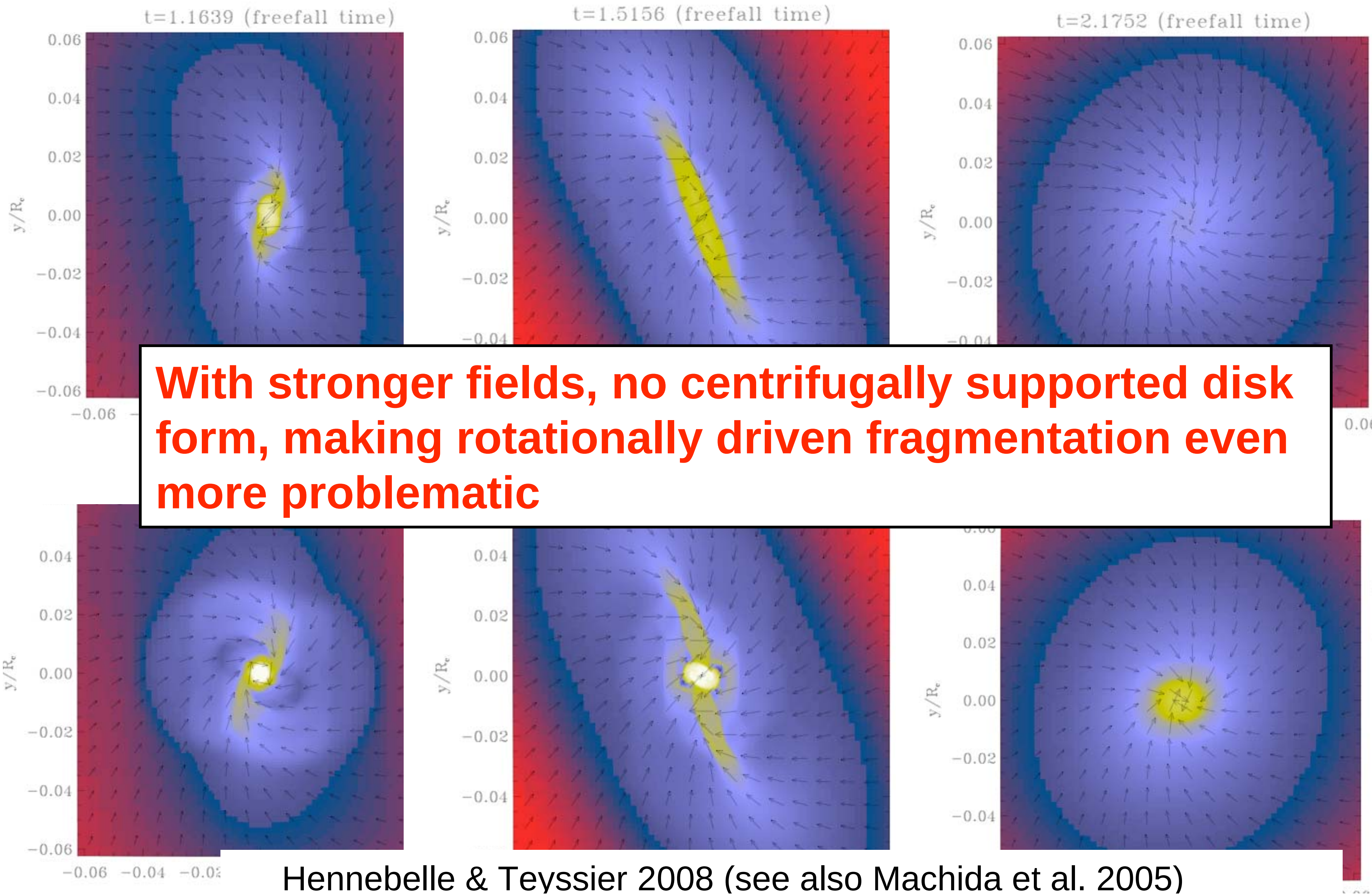
μ=1000 (hydro) μ=50 μ=20



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

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

$\mu=5$ $\mu=2$ $\mu=1.25$



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

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

Why magnetic field stabilizes the disk so efficiently ?

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

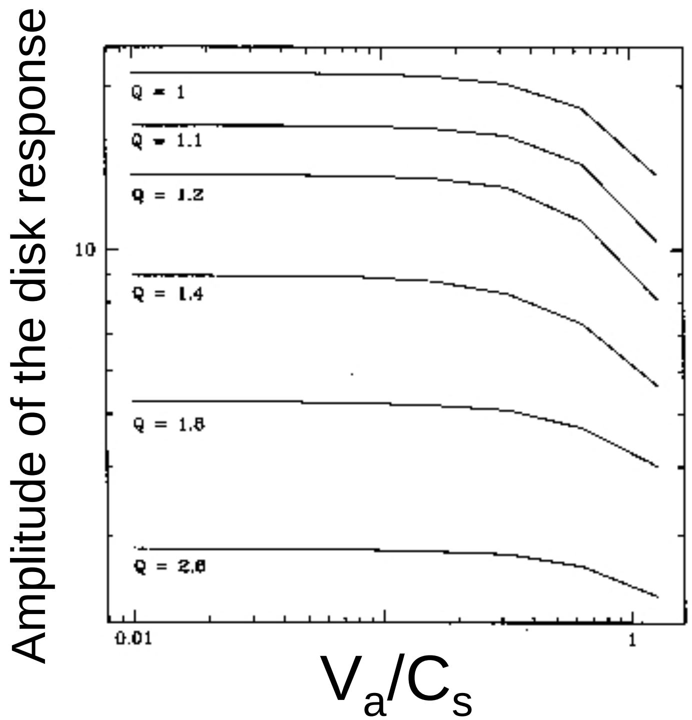
$$\omega^4 - \left[4\Omega^2 - 2\pi G\Sigma_0|k| + k^2\left(c^2 + \frac{B^2}{4\pi\rho}\right)\right]\omega^2 + \frac{(k^2c^2 - 2\pi G\Sigma_0|k|)(\mathbf{k}.\mathbf{B})^2}{4\pi\rho} = 0 \quad (1)$$

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 ?

Let us estimate the ratio of the time needed for the Alfven speed, to be comparable to the sound speed, over the fragmentation time

-Growth rate of B_θ, obtained from induction equation, assume Keplerian rotation for simplicity

-Characteristic time, τ_{mag}, obtained by requiring

$$B_\theta /(4 \pi \rho)^{1/2} = C_s$$

-Fragmentation time, τ_{frag}, assumed to be the rotation time

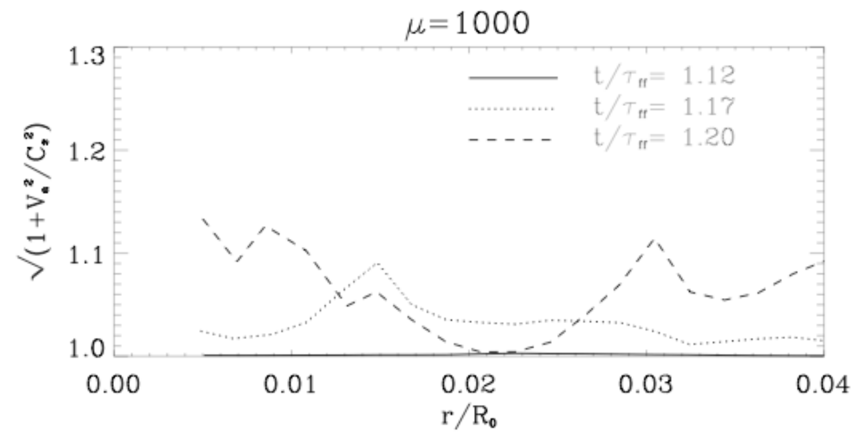
Criteria for disk stabilisation: $\tau_{mag} / \tau_{frag} = 1$

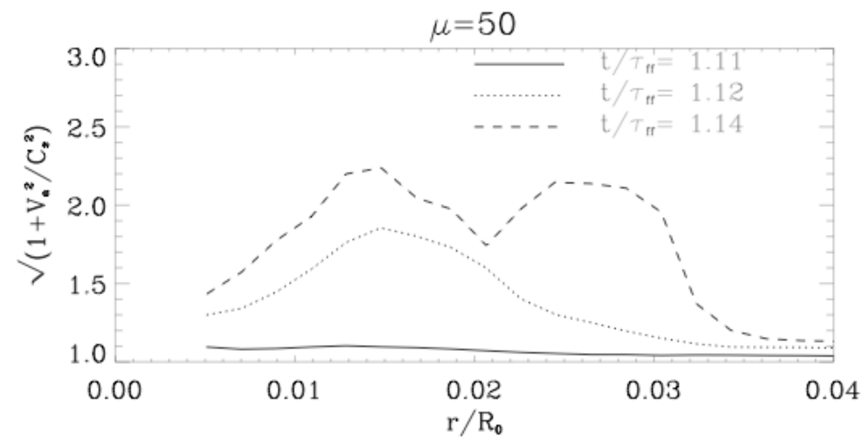
This leads, to a critical μ, $\mu < 15 / \alpha = 40$ in the present case

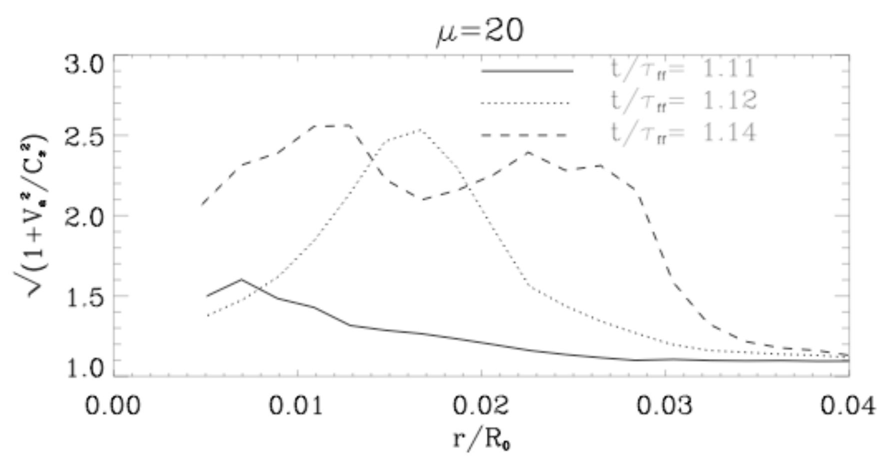
Importance of V_a/C_s

for various μ and various times

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







But we need to fragment….

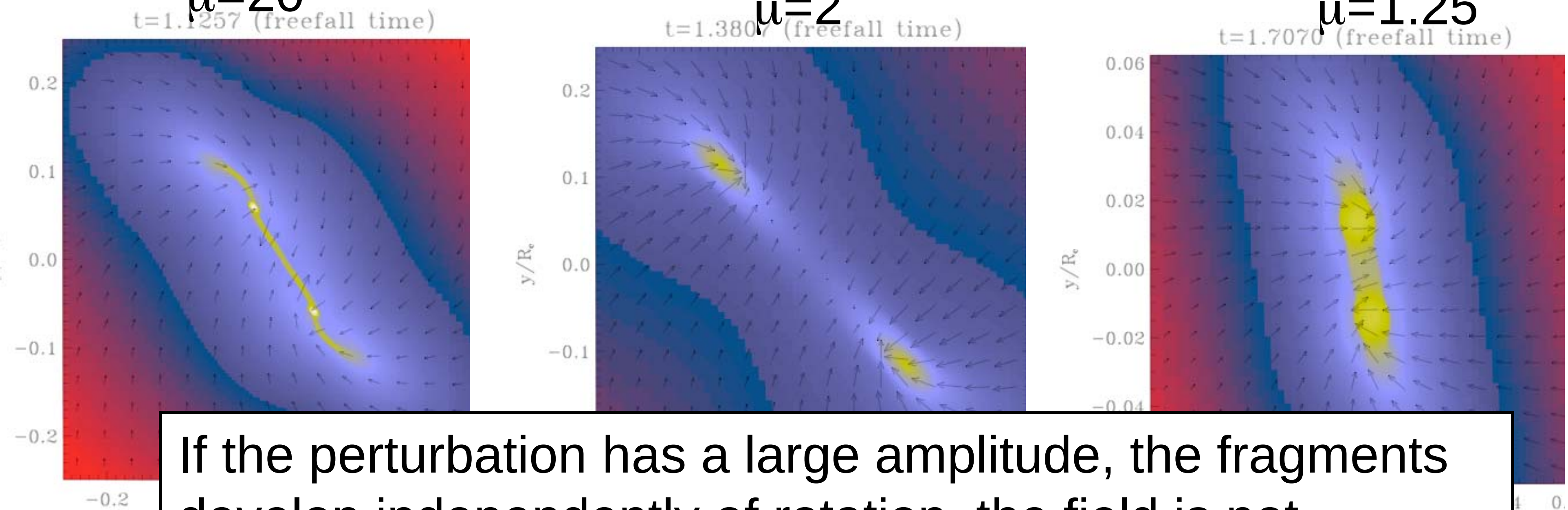
How to resolve the cocumdrum ?

-Effect of larger perturbation amplitudes

-Ambipolar diffusion

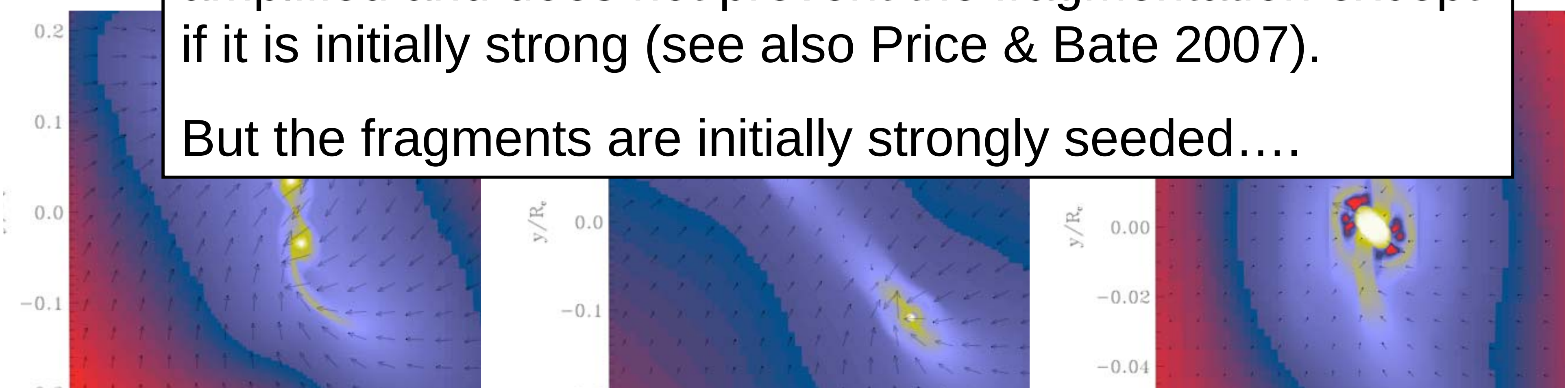
-Fragmentation during the second collapse

Let us consider an m=2 perturbation with an amplitude of 50%



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….

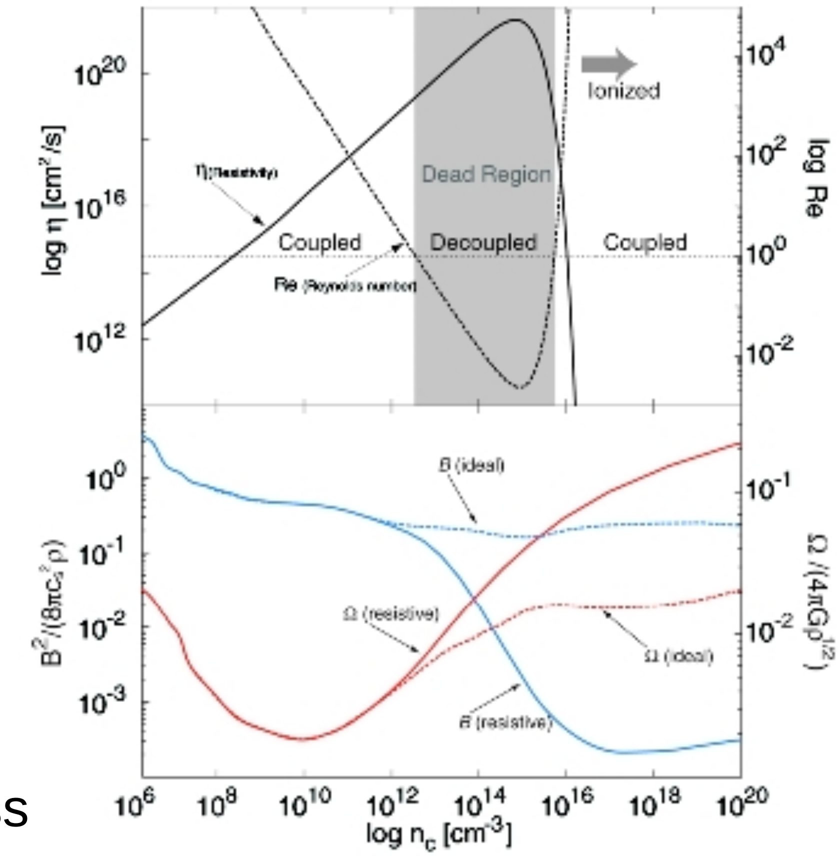


Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

Fragmentation during the second collapse ?

Originally investigated by Bonnell & Bate (1994) to explain the formation of tide binaries.

Interestingly: Nakano et al. (2002) predicts that a lot of flux should be lost At densities larger than 10^{11} cm^{-3}.
First calculations with resistive MHD done by Machida et al. 2007



Most of the flux is lost and therefore fragmentation is certainly possible.

Banerjee & Pudritz (2006) report The formation of a tide binary formed during the second collapse (despite ideal mhd)

Problem: form only tide binary which have to accrete most of their mass

CONCLUSIONS

Magnetic field has a deep impact on the collapse of dense cores

Depending on the magnetic strength, it can:

-supress the fragmentation of big disks

-remove the disk formation

-launch outflows

Fragmentation possible if initial perturbations are strong enough

Further studies must investigate:
-how likely they are going to occur
-the second collapse with non-ideal MHD effects