Collapse of magnetized dense cores

Is there a fragmentation crisis ?

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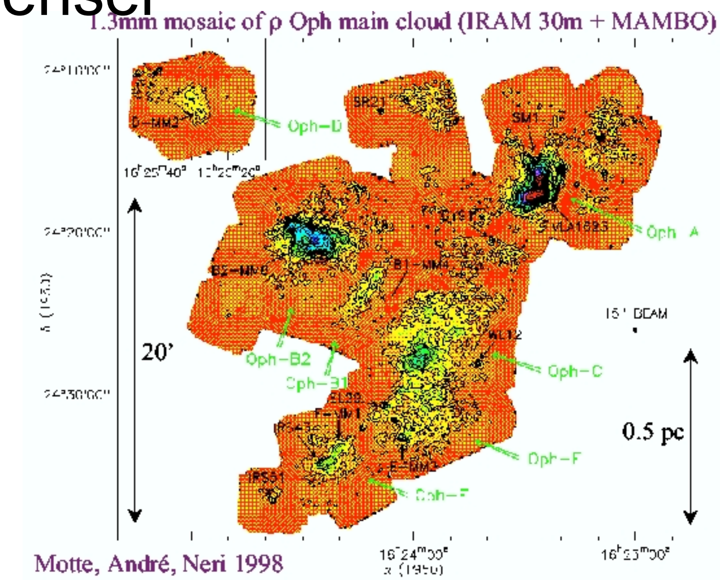
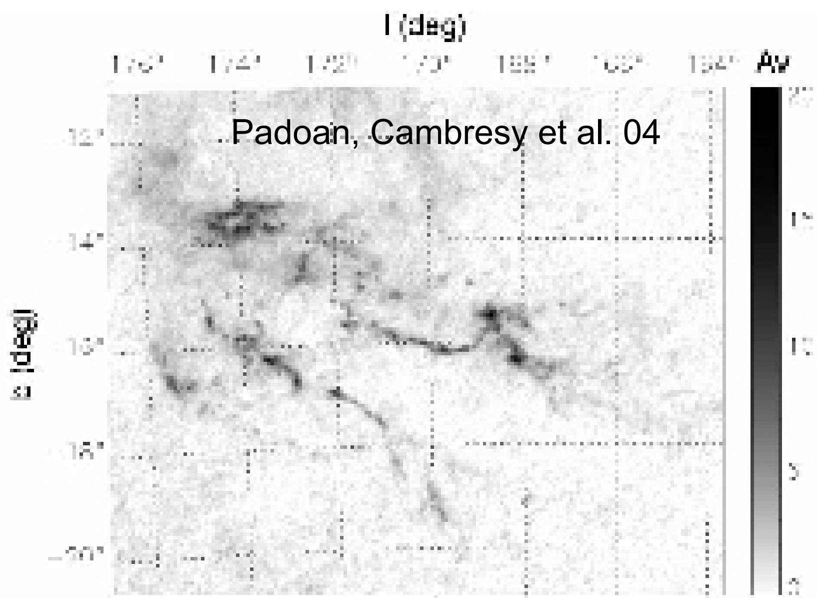
Molecular clouds and Dense cores

molecular clouds (10^4-10^5 Ms) contain dense core (0.1-10 Ms) roughly 10-100 times denser

ρ Oph molecular
cloud seen at 1.3 mm
with the Iram 30m telescope
Several dense cores can be seen

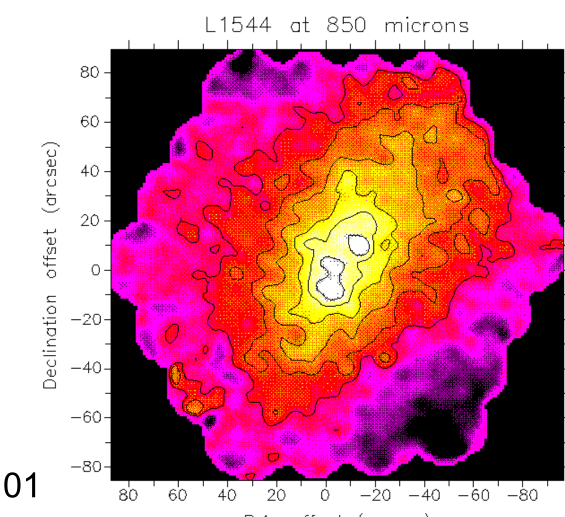


Taurus molecular cloud
seen in infrared extinction
(total mass about 10^4 Ms)



L1544 dense core (belonging to Taurus)
Seen at 1.3 mm (dust emission)
total mass is about 2 solar mass

Molecular clouds are often (not always) filamentary.



Ward-Thompson et al. 01

Studying the collapse is fundamental to:

-understand the formation of centrifugally supported disks

-understand how binaries form

A significant fraction of stars are binaries
(e.g. Duquenoy & Major 1991) although maybe not the case
for low mass stars (Lada 2006)

-understand the launching of outflows

-understand the formation of the protostar itself

Numerical experiment

Solve the ideal MHD self-gravitating fluid equations

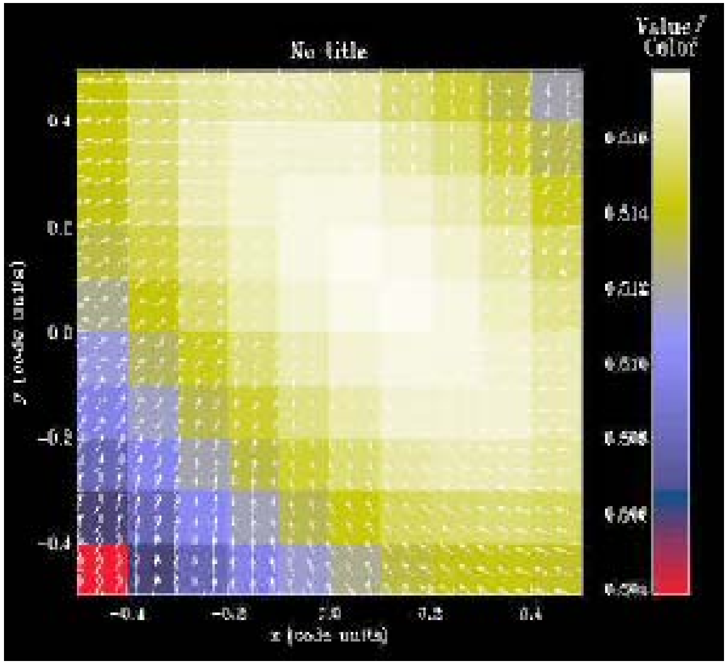
Initial conditions (as simple as possible…):

- -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

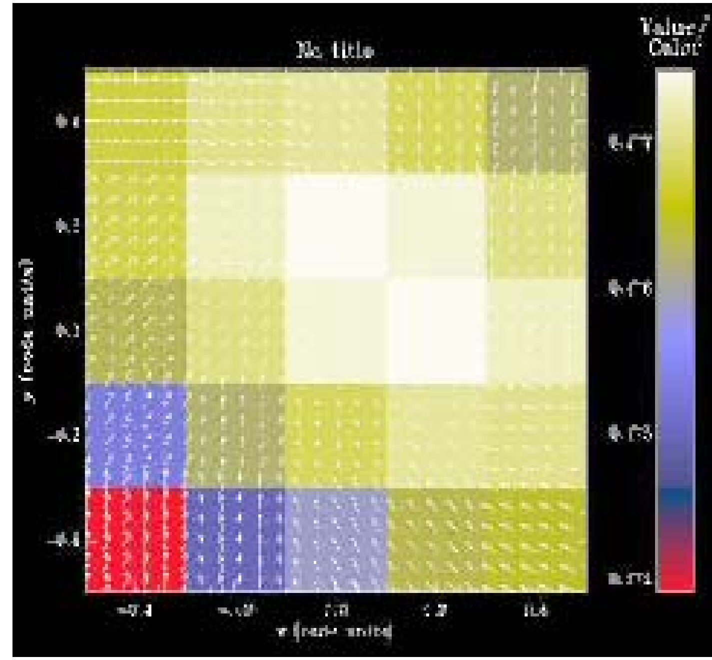
Adaptive Mesh Reffinement MHD code RAMSES
(insure div B =0), 9 levels of AMR, 10 cells per Jeans length
Roe solver

RAMSES HYDRO: Teyssier 2002
RAMSES MHD: Fromang, Hennebelle, Teyssier 2006
(available on line: ANR MAGNET)

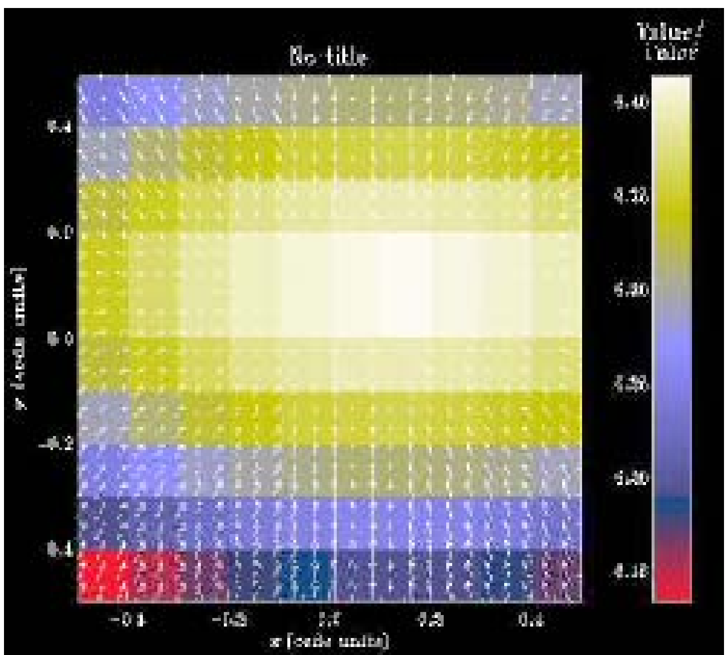
XY
hydro



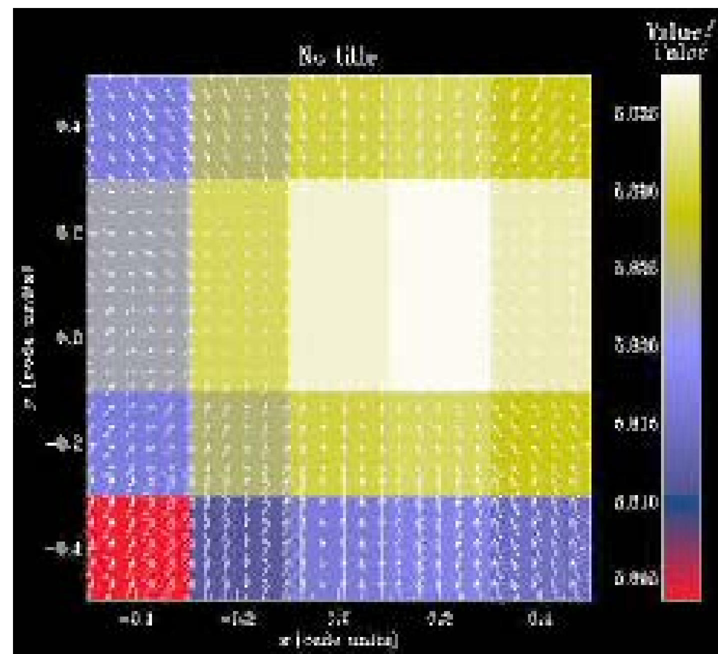
XY
MHD
μ=2



XZ
hydro



XZ
MHD
μ=2



Magnetic field seems to play a crucial role.
Let us have a closer look….

-disk formation

-outflows

-fragmentation

-influence of stronger pertubations

-comparison with observations

-towards more realistic initial conditions : a massive core

Density and velocity profiles in the equatorial plane

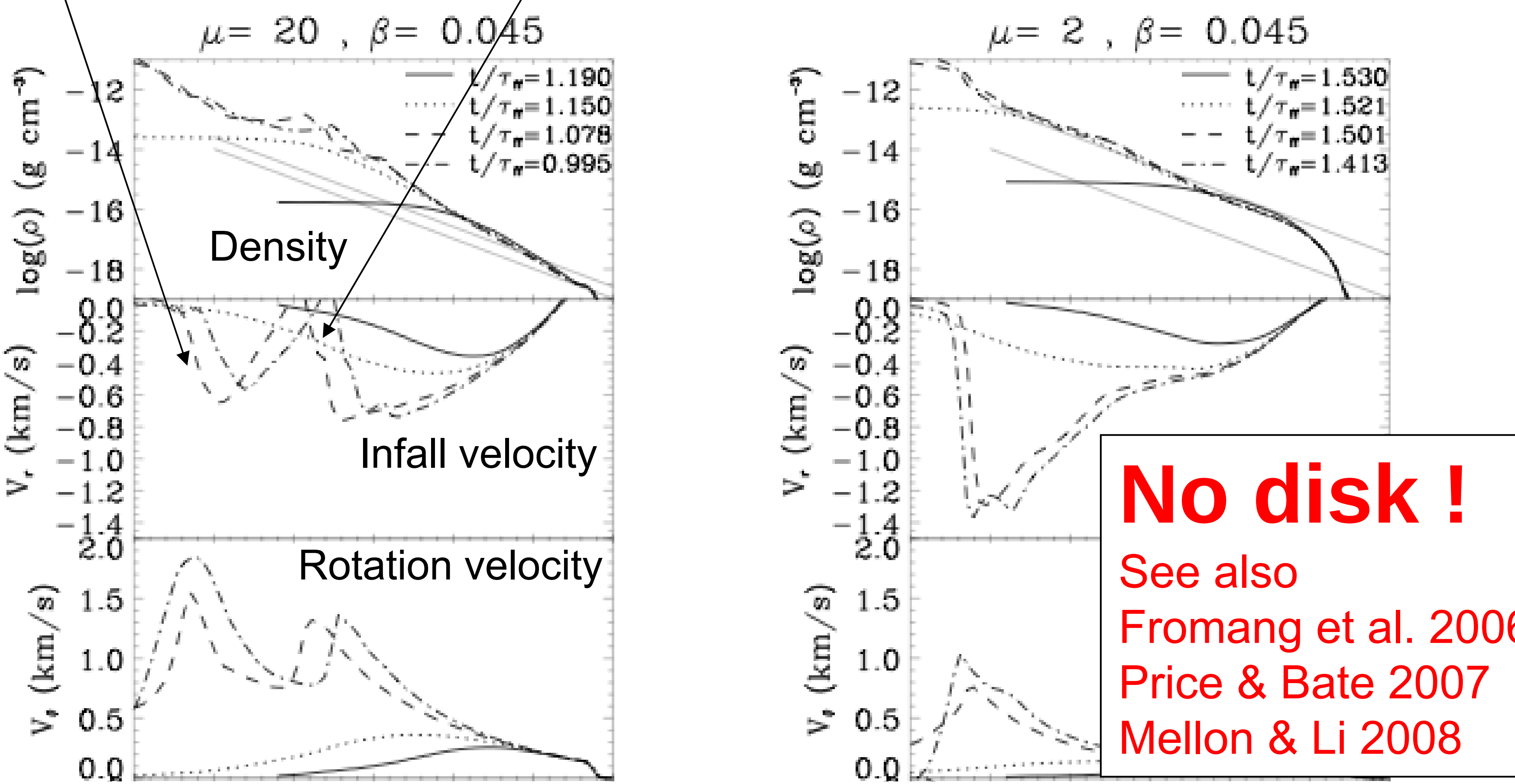
Distribution and evolution of angular momentum

2 fiducial cases:
μ=20 weakly magnetized cloud
μ=2 highly magnetized (still supercritical) cloud

Density, rotation and infall velocity profiles

Thermally supported core

Centrifugally supported disk



No disk !

See also
Fromang et al. 2006
Price & Bate 2007
Mellon & Li 2008

Hennebelle & Fromang 2008

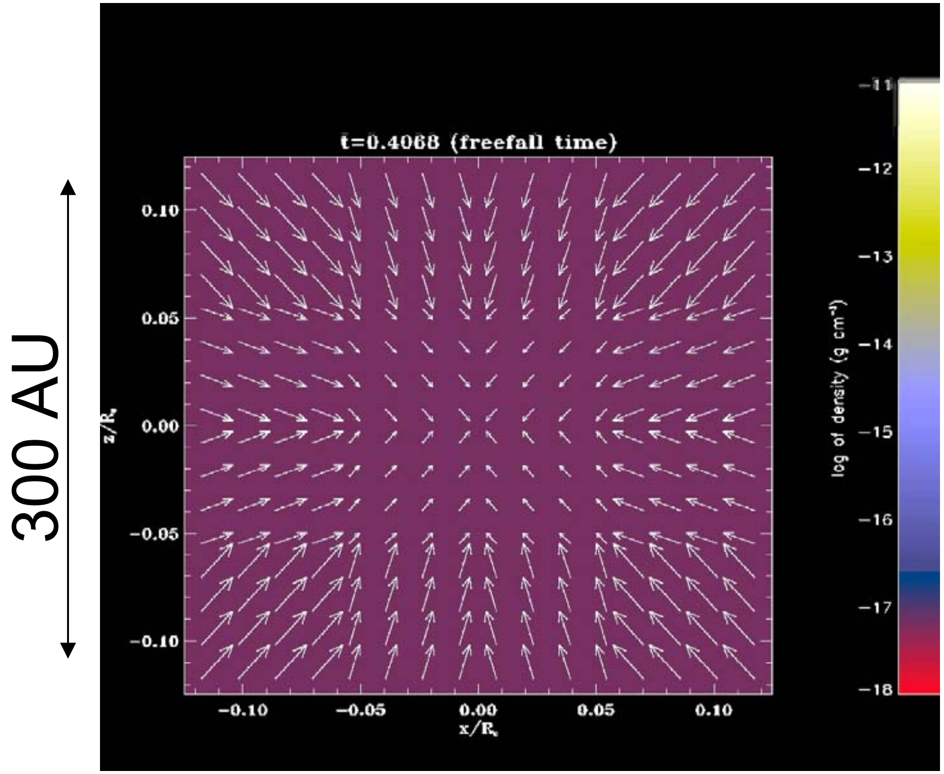
Density and velocity Profiles
in the XZ plane

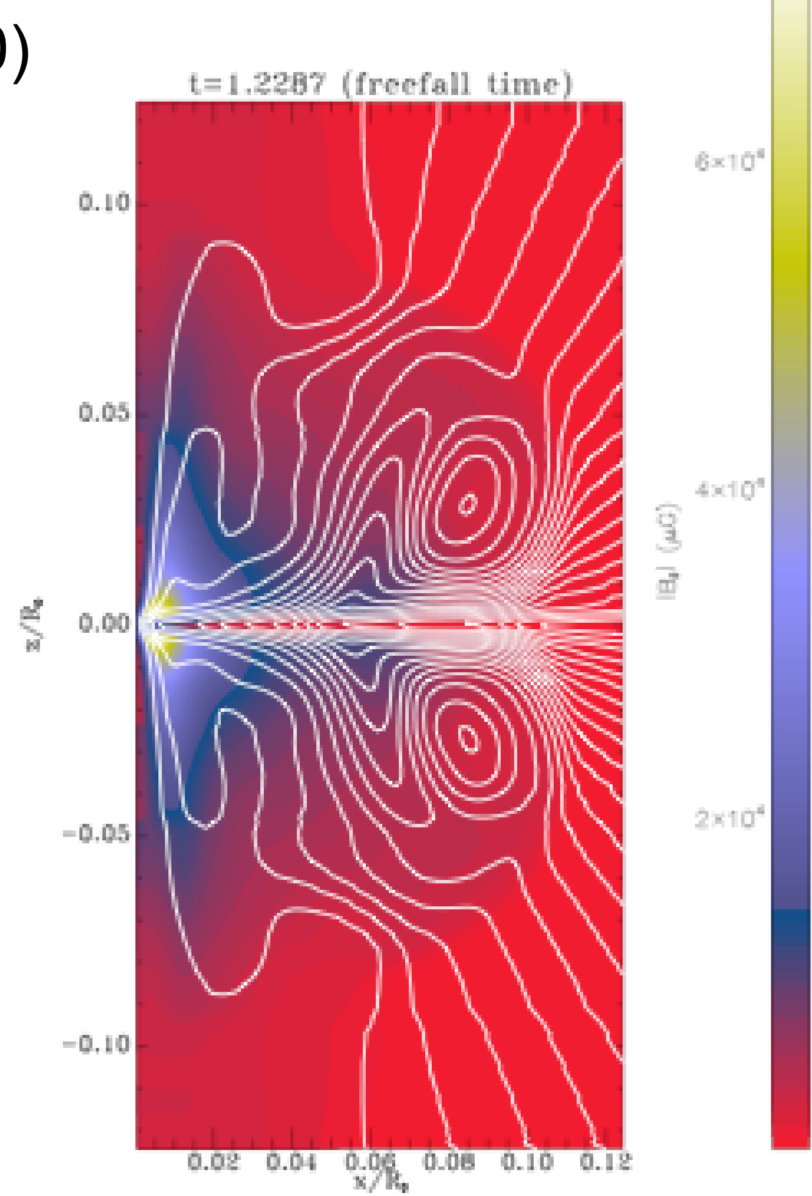
Outflows

Remember:

2 fiducial cases
μ=20 weakly magnetized cloud
μ=2 highly magnetized (still supercritical) cloud

Weak magnetic field (μ=20)



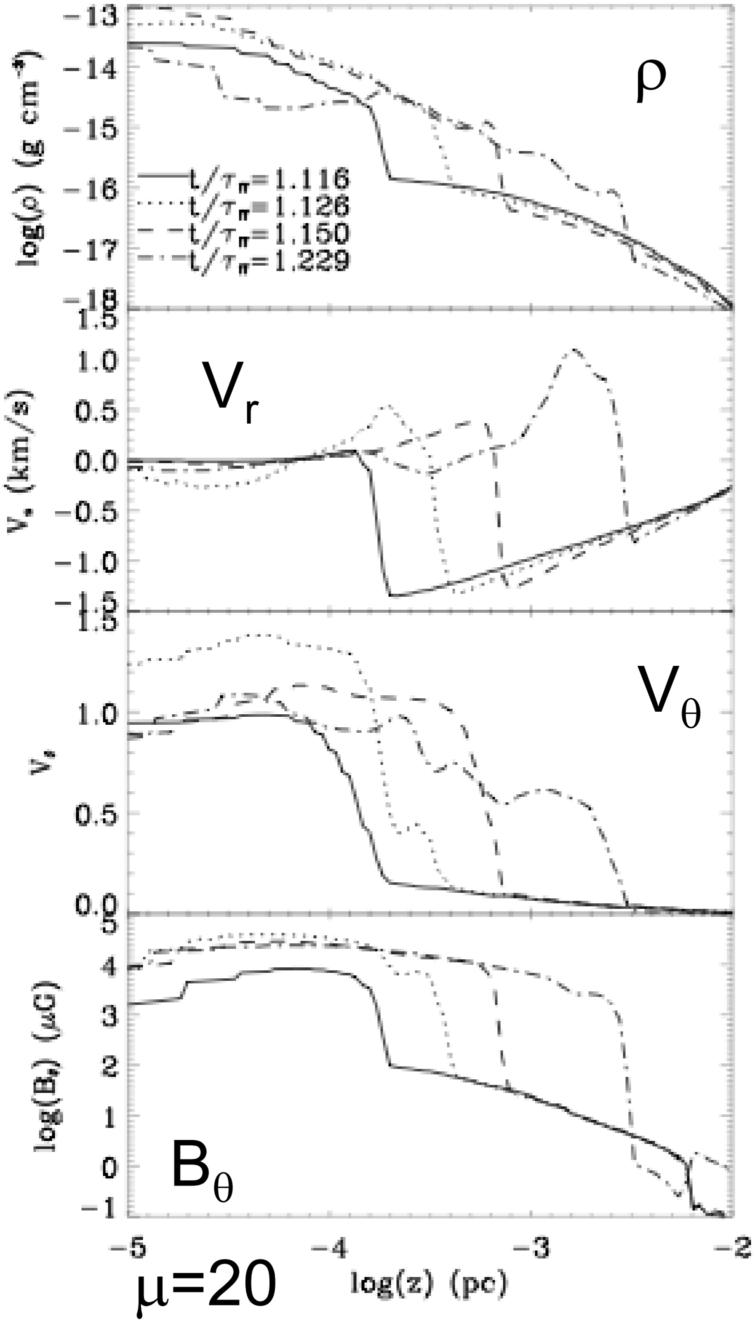


Disk formation expansion along the Z-axis around the whole structure

Hennebelle & Fromang 200

(see also Machida et al. 2005, Banerjee & Pudritz 2006, Mellon & Li 2008)

Quantitative estimates



The expansion is associated to a strong increase of B toroidal

Suggest: the magnetic pressure $\propto B_\theta^{\,2}$ is triggering the expansion (magnetic tower like)

Ram pressure=magnetic pressure

$$\rho_{\inf} V_{\inf}^{\;2} \approx B_\theta^{\;2} / 8\pi$$

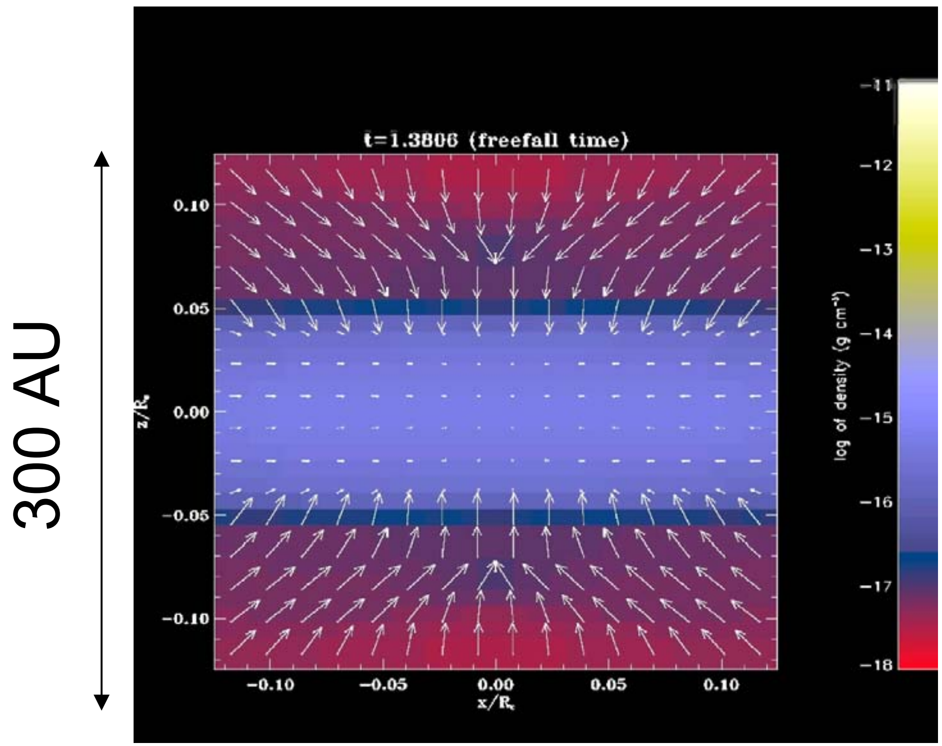
Generation of toroidal B

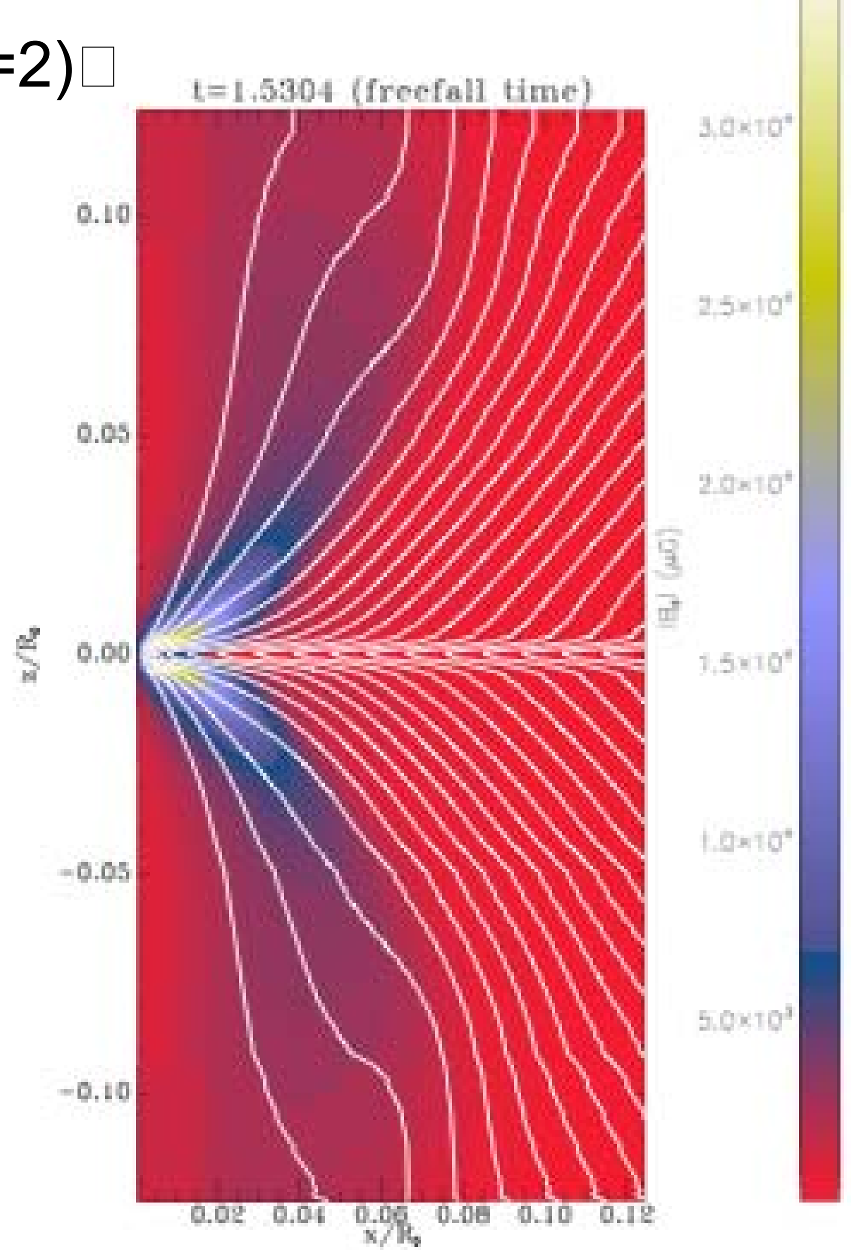
$$\int B_\theta dz \approx B_\theta l \approx B_z V_\theta t$$

=> $V_{tower} = \dfrac{B_z}{\sqrt{8\pi\rho_{\inf}}} \dfrac{V_\theta}{V_{\inf}}$

Quantitative agreement ~25%

Strong magnetic field (μ=2)



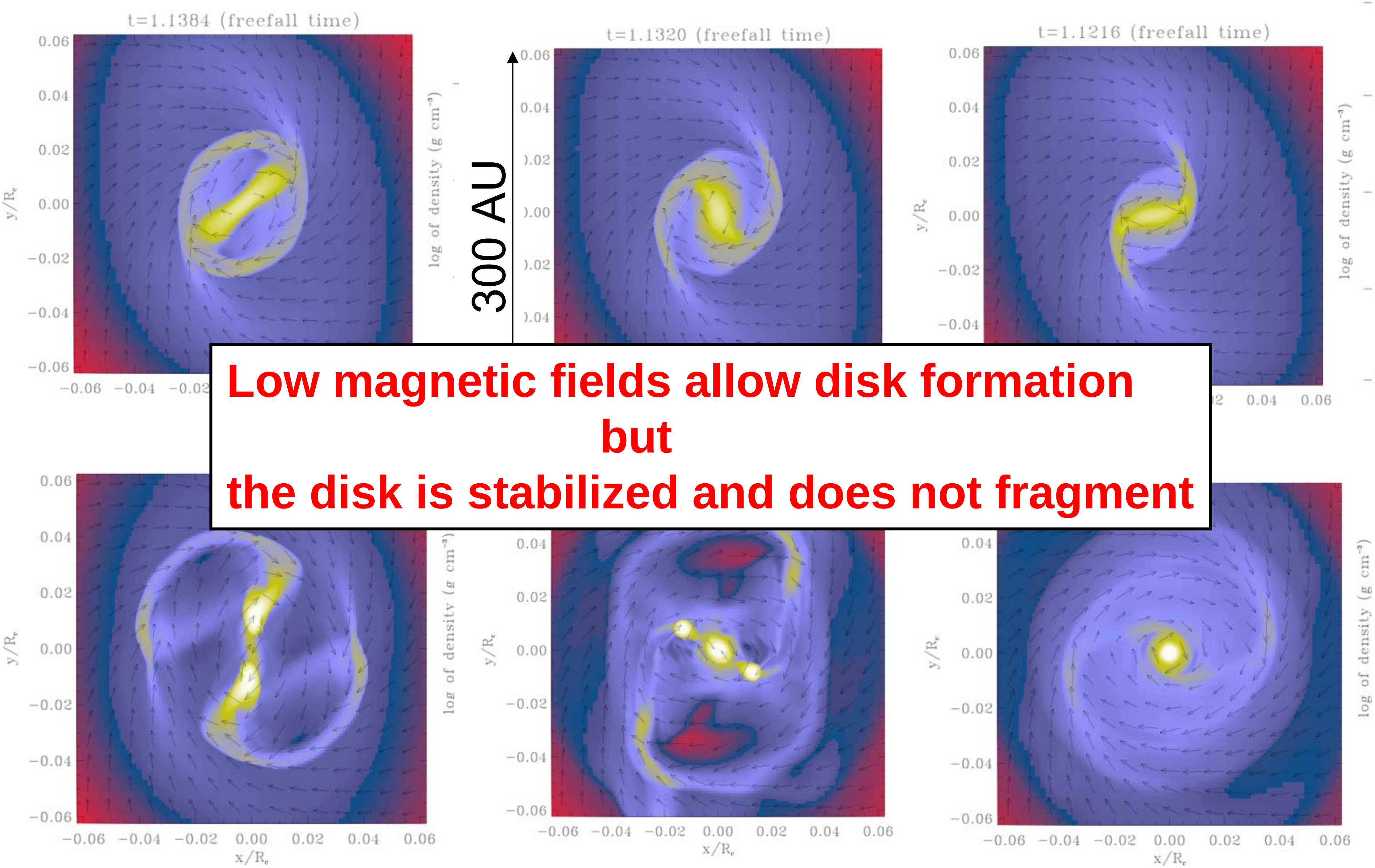


Remember: -No centrifugally supported disk
(instead magnetized pseudo-disk)
-Only first collapse is treated

Fragmentation

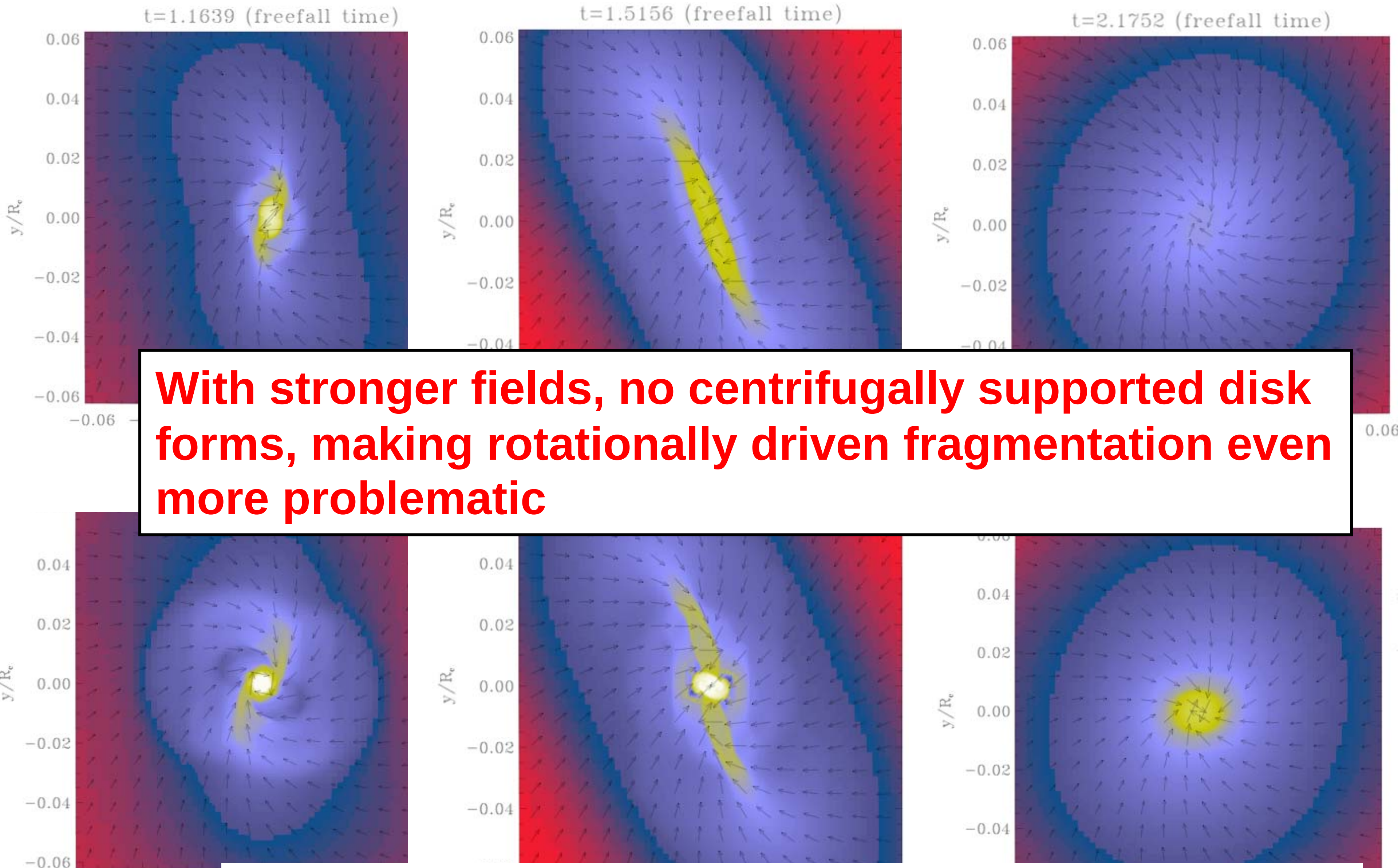
Formation of multiple systems

m=2 perturbations of amplitude 10% is initially setup by hand 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) μ=5 μ=2 μ=1.25



With stronger fields, no centrifugally supported disk forms, 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:

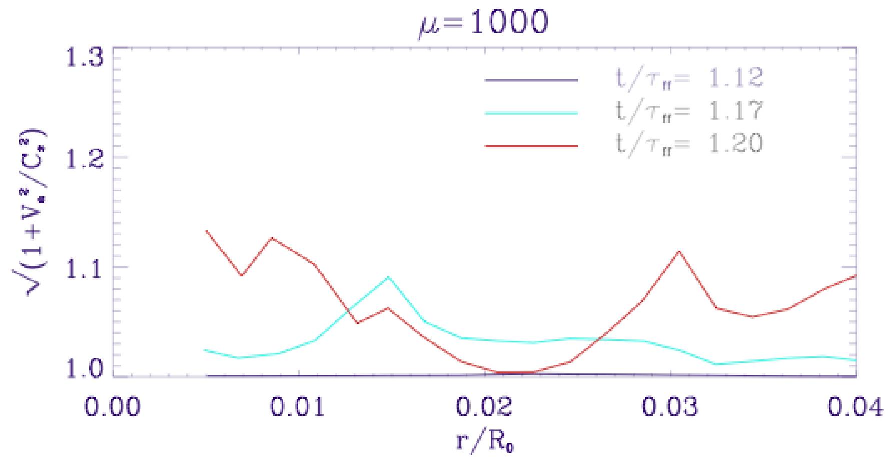
$$\omega^4 - \left[4\Omega^2 - 2\pi G\Sigma_0|k| + k^2\left(c^2 + \frac{B^2}{4\pi\rho}\right)\right]\omega^2 + \frac{(k^2c^2 - 2\pi G\Sigma_0|k|)(\mathbf{k},\mathbf{B})^2}{4\pi\rho} = 0 \quad (1)$$

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

But destabilizing contribution of the magnetic tension
$\Rightarrow$Configuration unstable

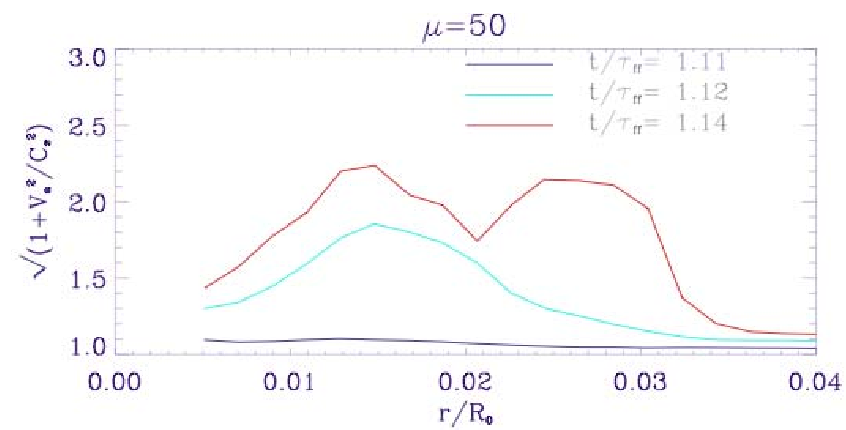
However, in a differentially rotating system (like a disk in Keplerian rotation), a toroidal magnetic field is quickly generated and the first effect becomes dominant.
(Elmegreen 1987, Gammie 1996)

Growth of the toroidal magnetic field within the disk

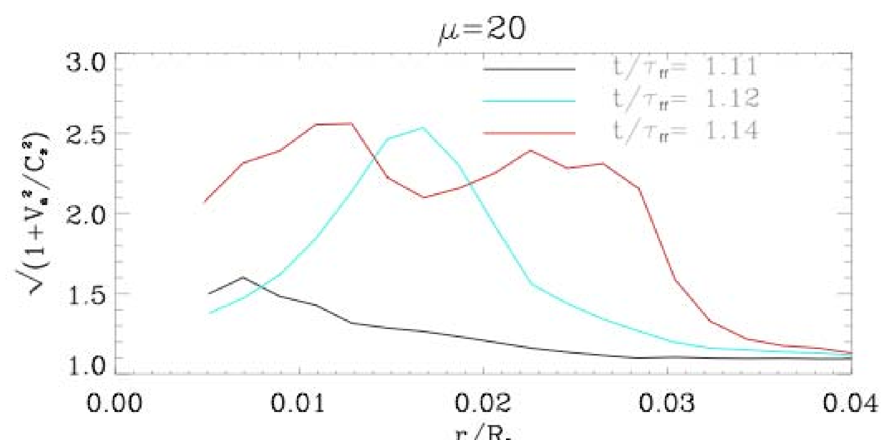


Importance of V_a/C_s

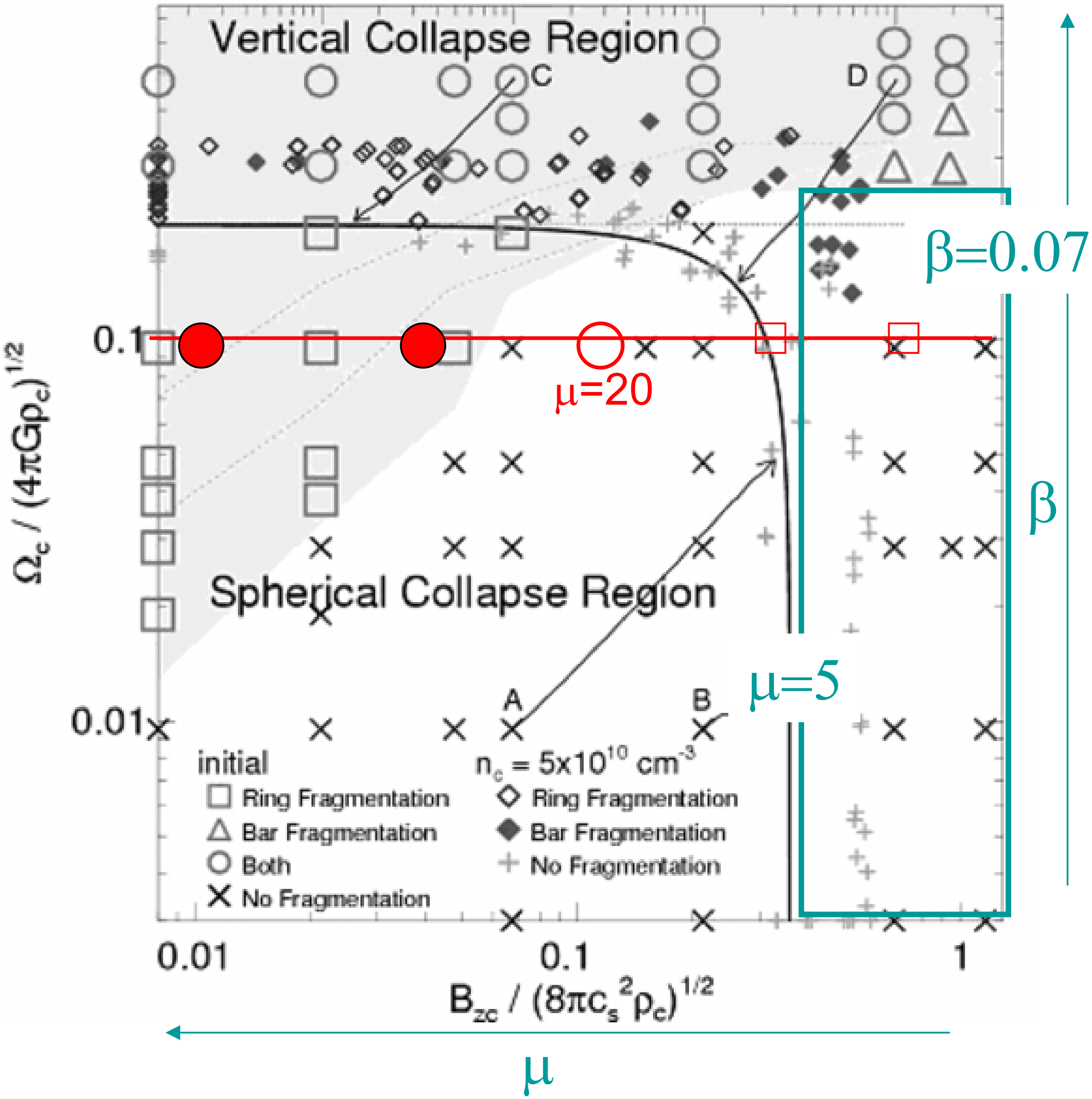
for various μ and various times



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



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)

This work

(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

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

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

But we need to fragment….

(remember…a large fraction of stars are binaries)

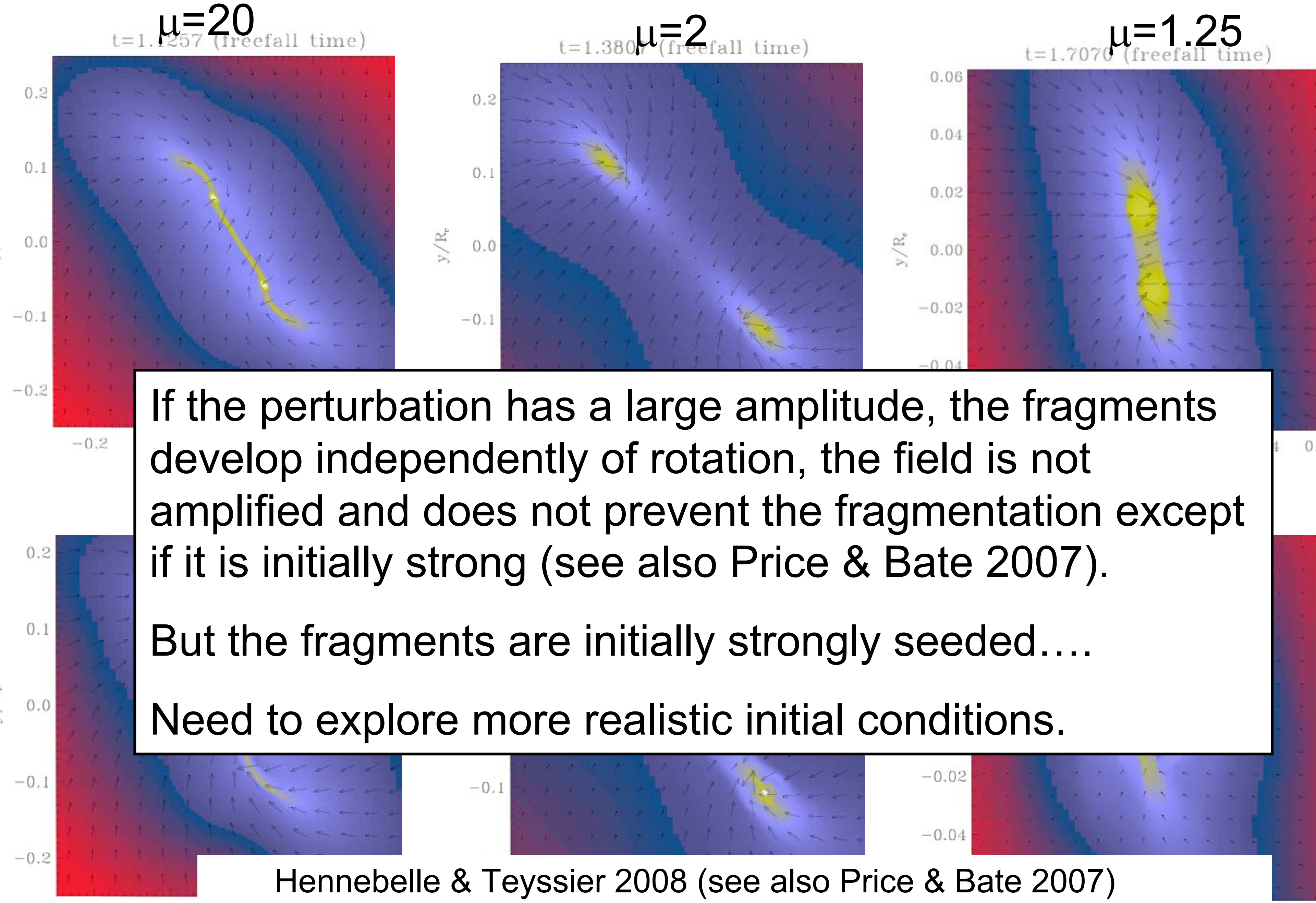
How to resolve the conumdrum ?

-Effect of larger perturbation amplitudes

-Ambipolar diffusion

-Fragmentation during the second collapse
(second collapse: H_2 dissociation at T>2000 K
dissociation energy compensate pdV work => isothermal collapse)
(Machida et al. 2007)

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



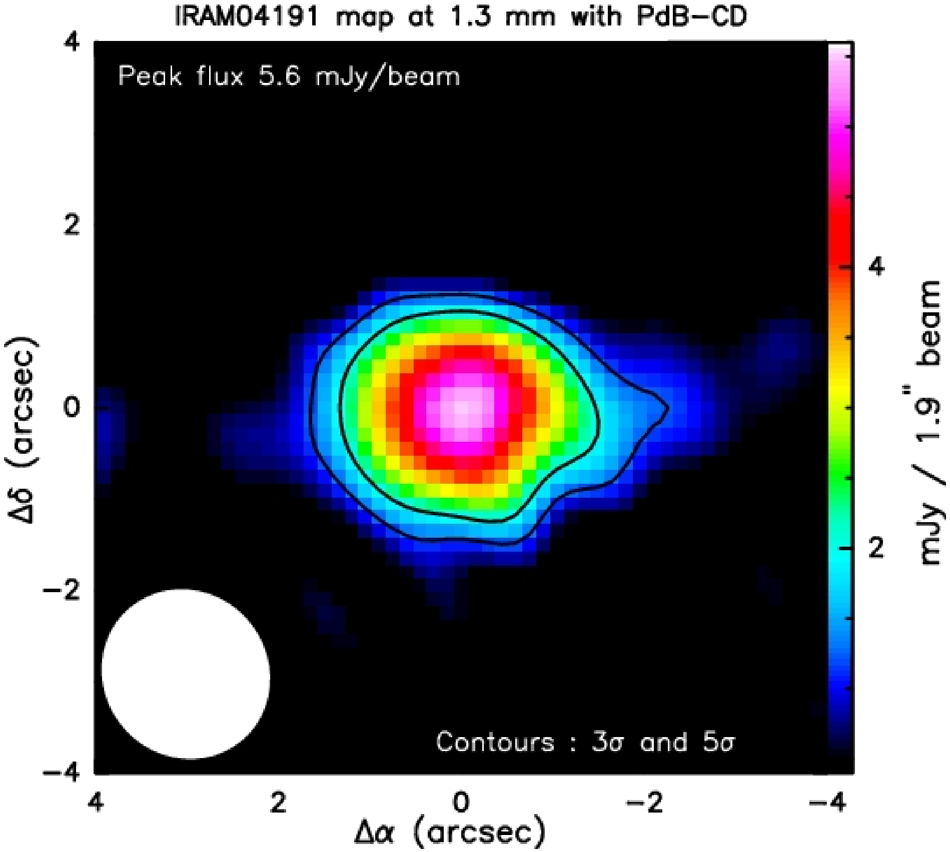
If the perturbation has a large amplitude, the fragments develop independently of rotation, the field is not amplified and does not prevent the fragmentation except if it is initially strong (see also Price & Bate 2007).

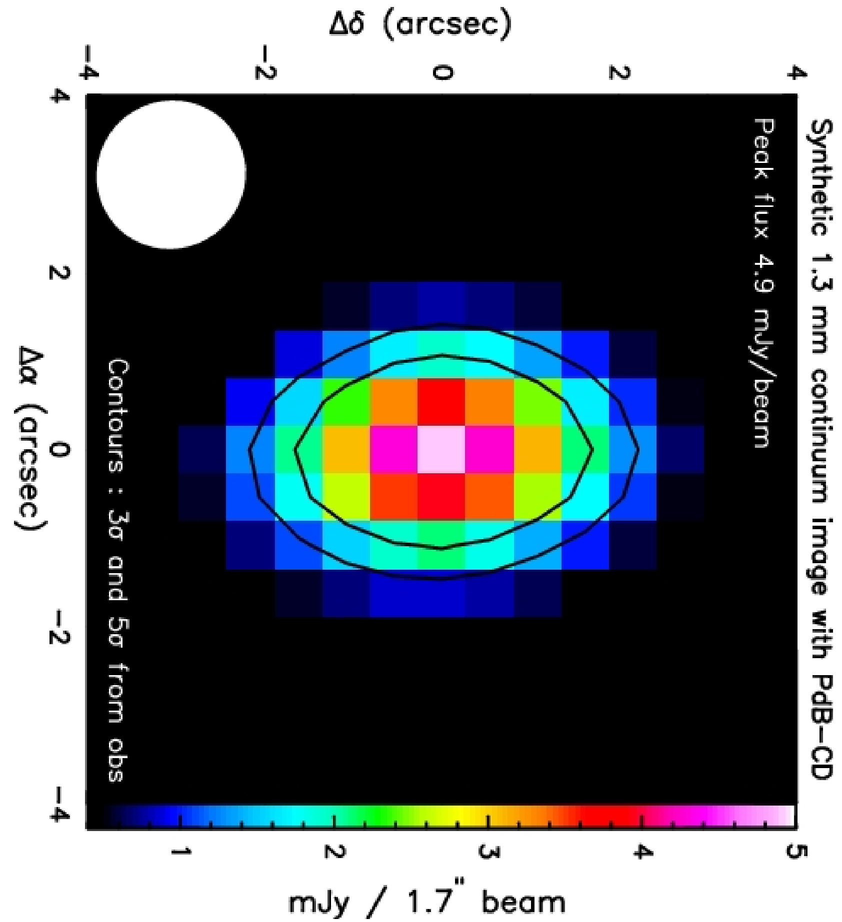
But the fragments are initially strongly seeded….

Need to explore more realistic initial conditions.

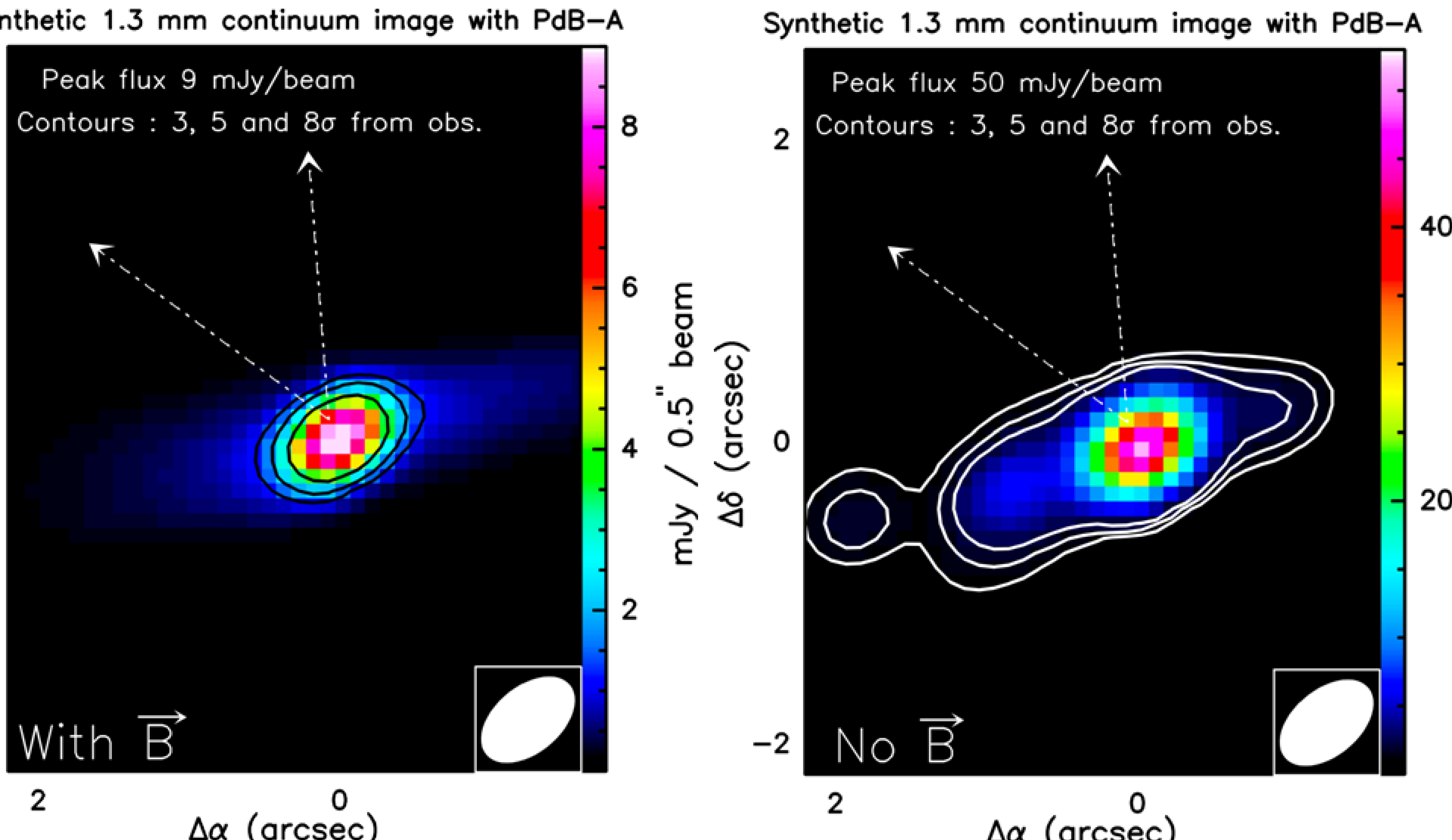
Hennebelle & Teyssier 2008 (see also Price & Bate 2007)

Comparison between model and data for IRAM04191





Maury et al. In prep



nthetic 1.3 mm continuum image with PdB-A
Peak flux 9 mJy/beam
Contours : 3, 5 and 8σ from obs.
With B
mJy / 0.5" beam
Δα (arcsec)
Synthetic 1.3 mm continuum image with PdB-A
Peak flux 50 mJy/beam
Contours : 3, 5 and 8σ from obs.
No B
Δδ (arcsec)
Δα (arcsec)

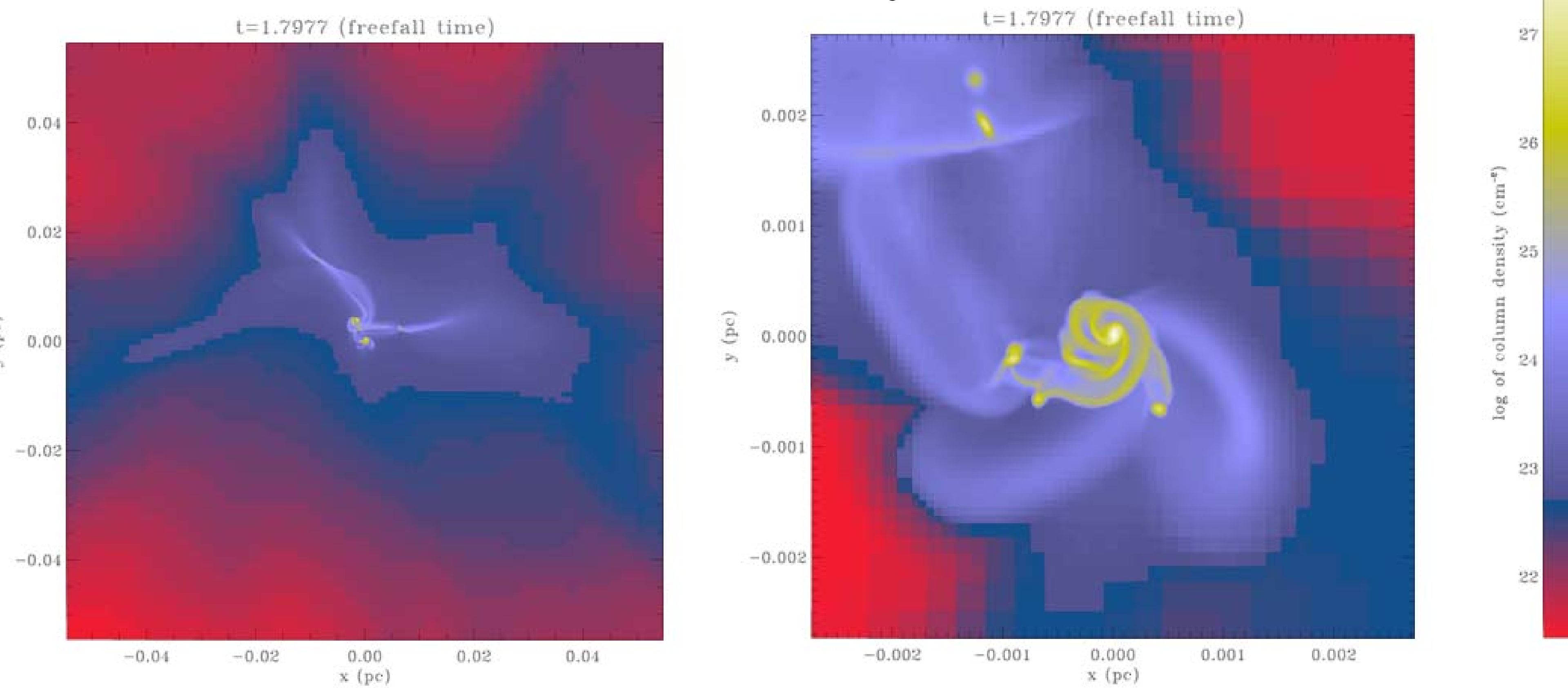
Toward less idealized/ more realistic initial conditions

Consider Bonnor-Ebert type spheres with turbulence

-density contrast between center and edge around 20
-turbulent field (with ramdom phases in the Fourier space) is setup initially (no forcing)

A 30 solar mass cloud
Near Virial equilibrium initially
Turbulence= gravity
No B

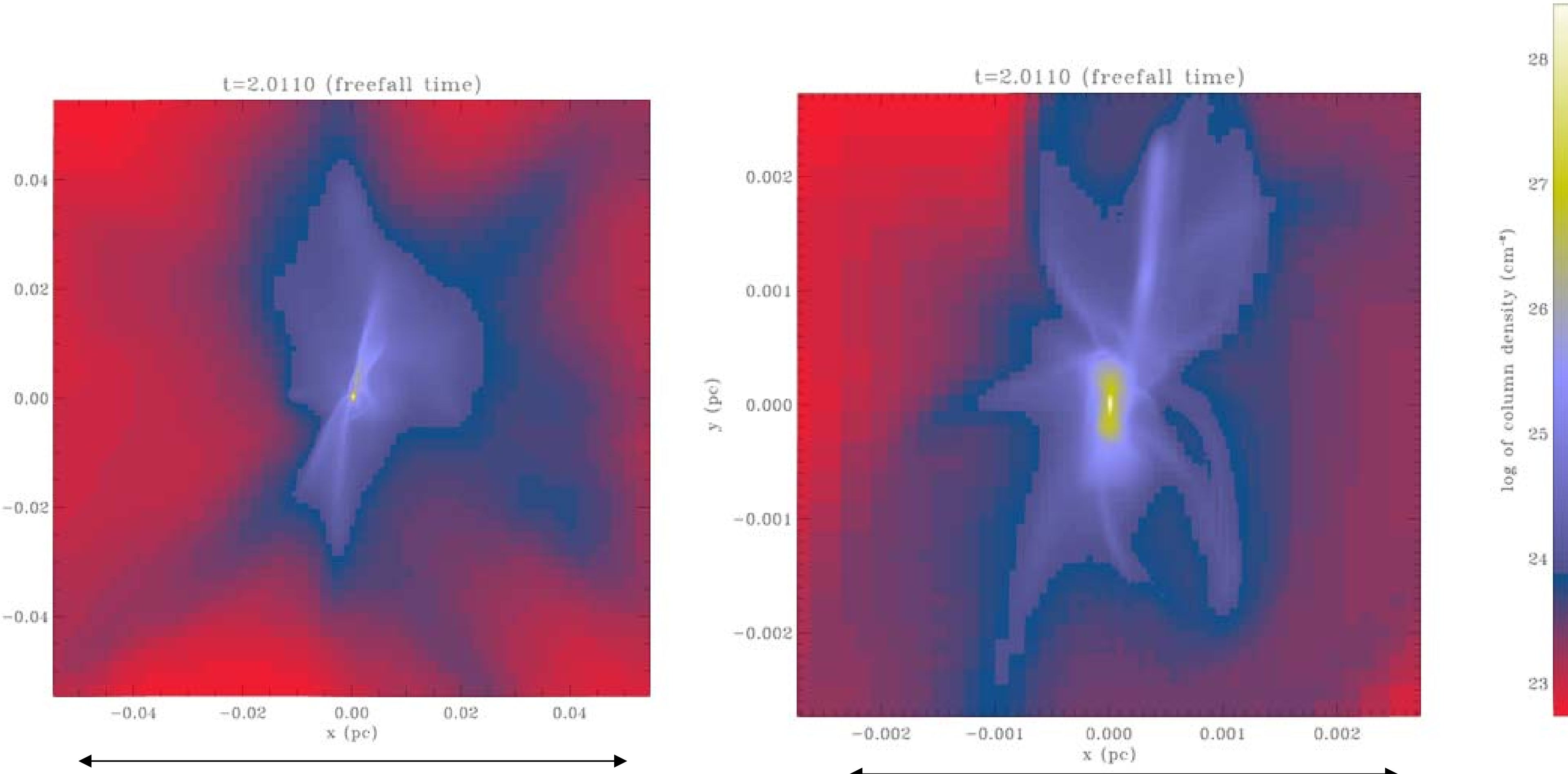
Column density



0.1 pc

0.005 pc

A 30 solar mass cloud
Near Virial equilibrium initially
Turbulence= gravity
Magnetic energy=thermal energy



0.1 pc

0.005 pc

CONCLUSIONS

Magnetic field has a deep impact on the collapse of dense cores (even for low magnetic intensities because B is amplified by differential motions)

Depending on the magnetic strength, it can:

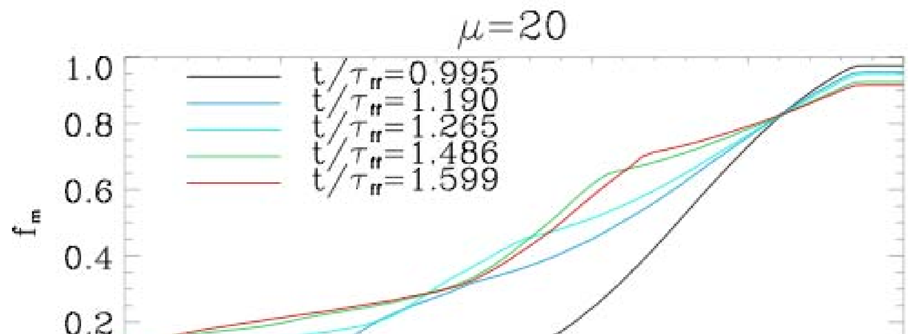
-supress the fragmentation of big disks
-remove the disk formation
-launch outflows (even without centrifugally supported disks)

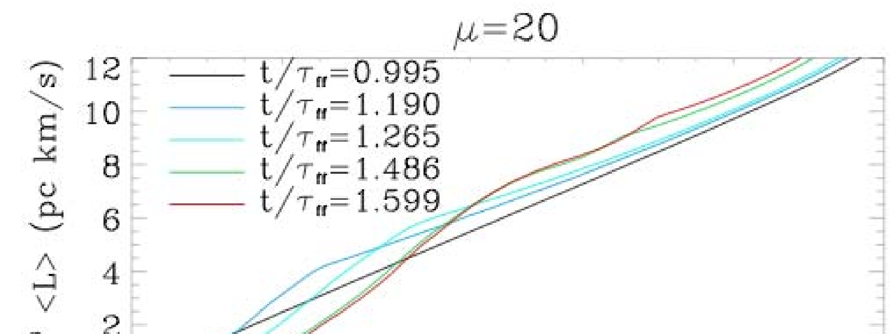
Fragmentation possible if initial perturbations are strong enough

Further studies must investigate further:
-how to generate sufficient perturbations (more realistic contexts)
-the second collapse with non-ideal MHD effects
-radiative transfer effect (Commercon’s talk)

Distribution of mass as a function of cylindrical radius

Distribution of specific angular momentum as a function of mass



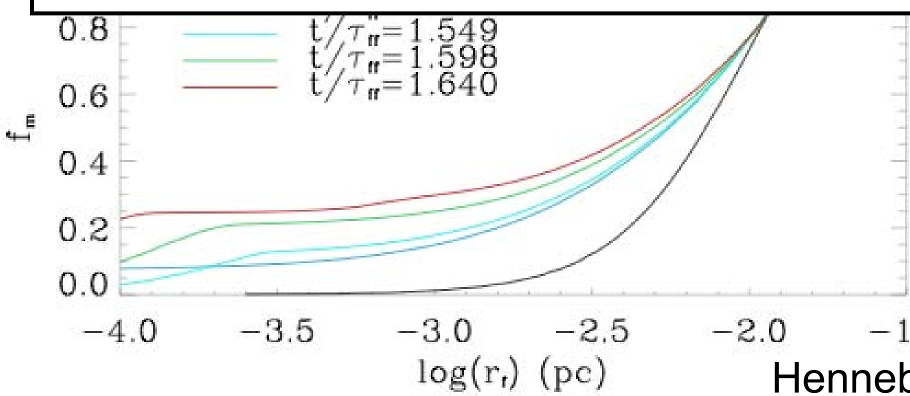


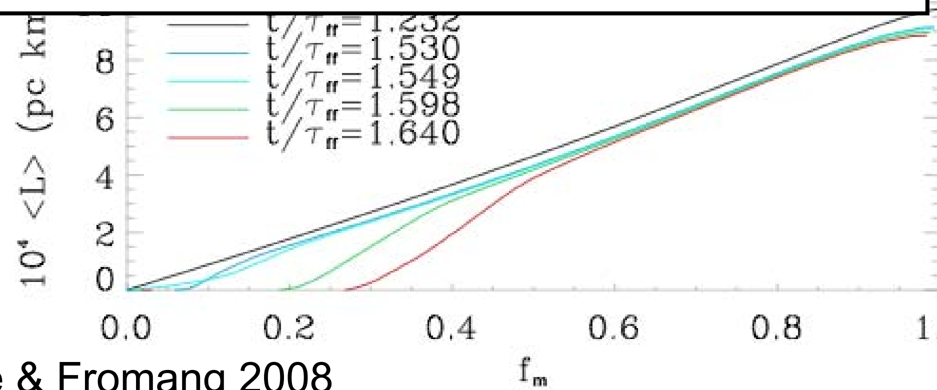
Implication

Distribution of angular momentum different because

-collapse proceeds more spherically in weakly magnetized cases

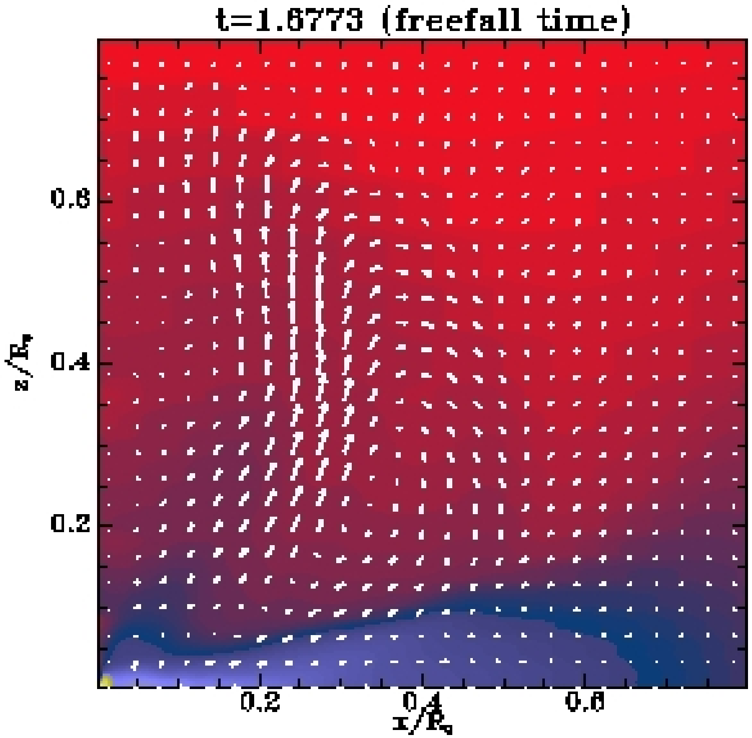
-magnetic braking reduces the angular momentum in strong field cases

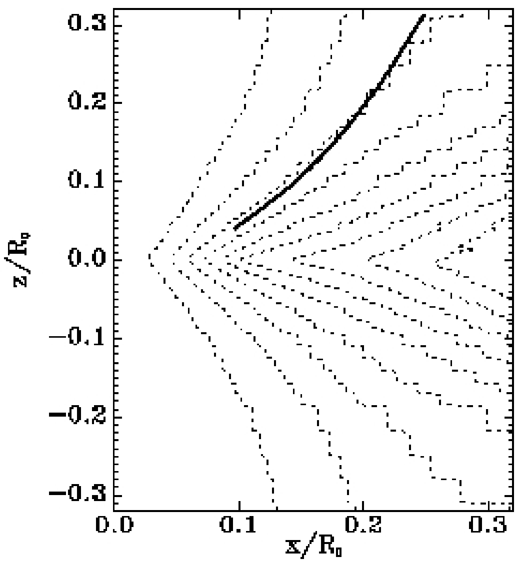




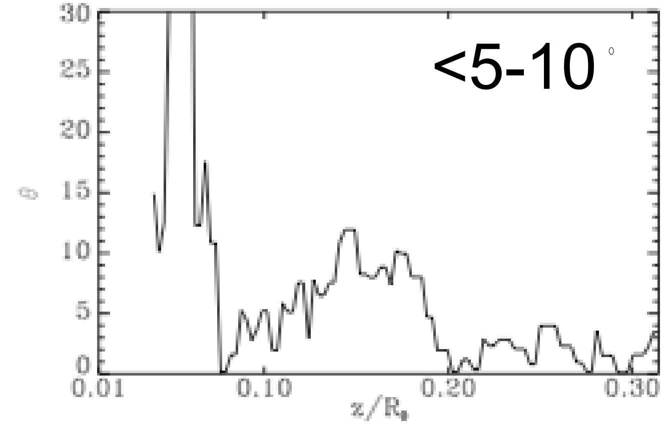
Hennebelle & Fromang 2008

Check 2 predictions of steady state models (Blanford & Payne 1981):

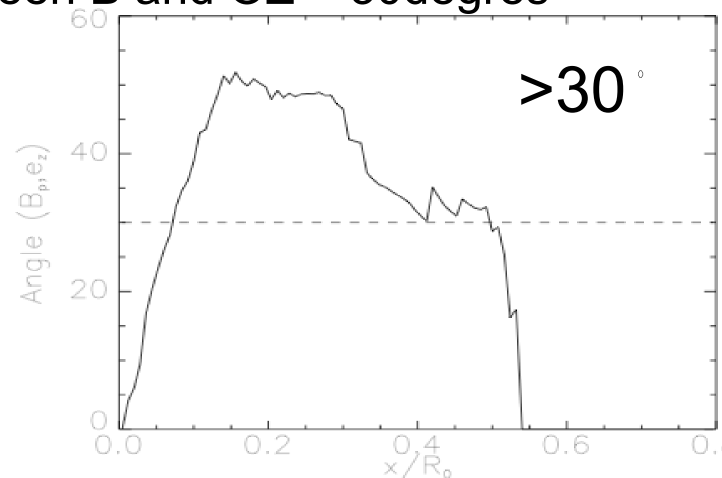




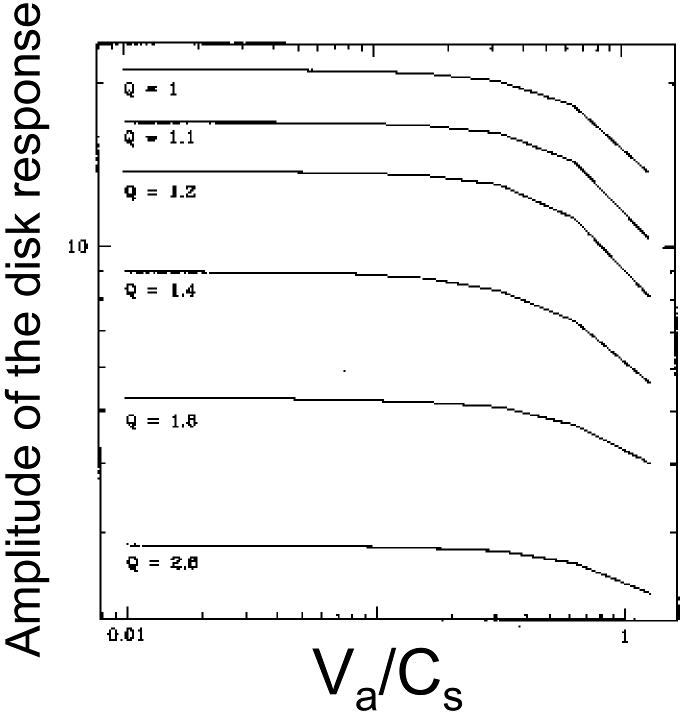
Angle between poloidal stream and field lines: 0



Angle between B and OZ > 30degres



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

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

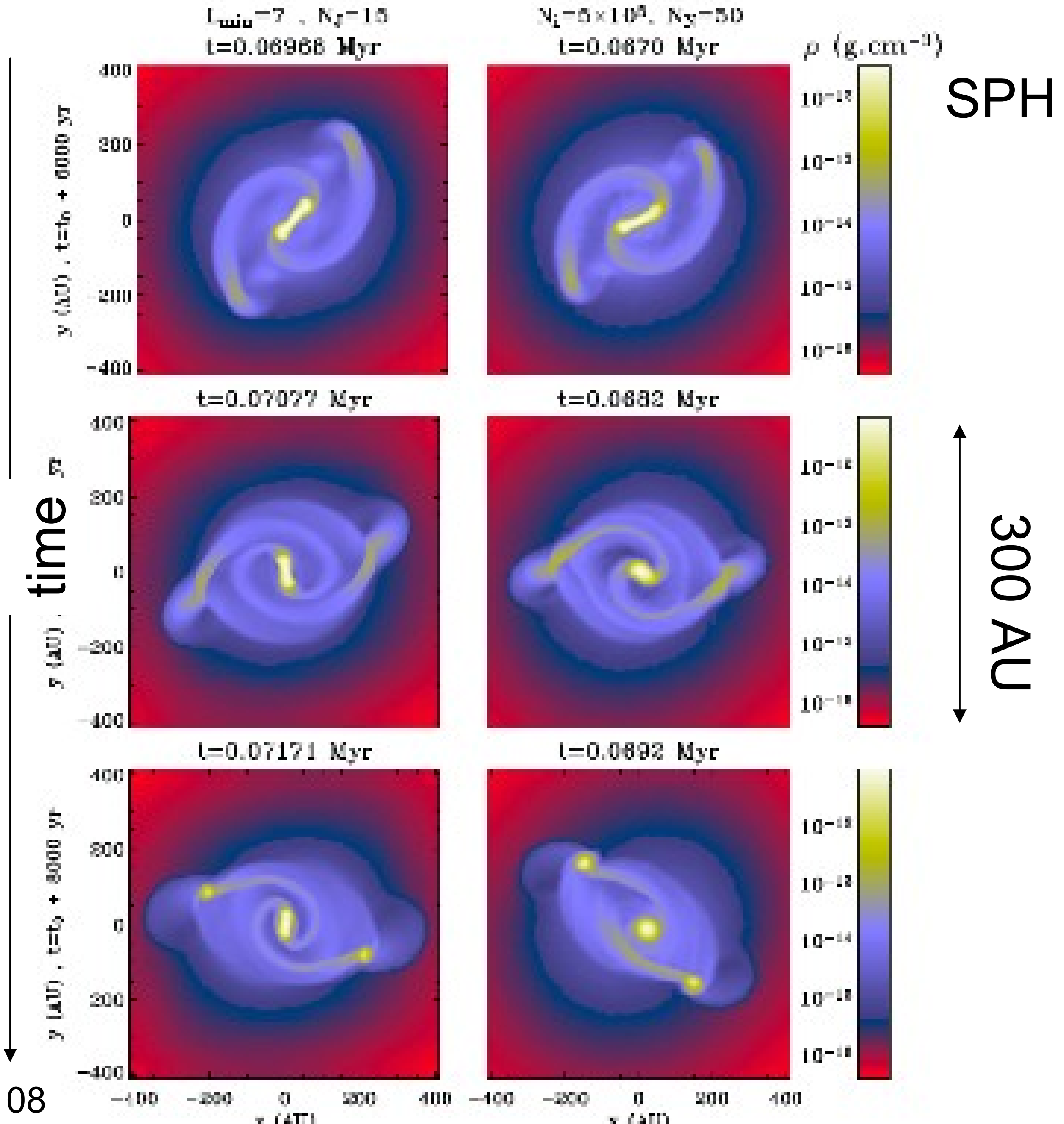
-Fragmentation time, τ_{frag}, assumed to be the rotation time

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

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

Standard fragmentation calculation (AMR and SPH)

AMR



-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)

Rotation or turbulence necessary to produce fragmentation are compatible with observations (rotational or turbulent energy few percents of the gravitational energy, Goodman et al. 1993)

Commerçon et al. 08

But magnetic fields are observed….

Typically one infers $\mu=(M/\phi)/(M/\phi)_c=1\text{-}4$
Crutcher et al. 1999, 2004

What are the effects of the magnetic field ?

-Magnetic support
(possible regulation of the star formation if the magnetic field
is sufficiently strong => Role of ambipolar diffusion.
In this talk only supercritical fields are considered)

-Magnetic braking

-….   (think twice before thinking to fully understand an mhd process)