Magnetic Fields in the Universe III

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Diffusion of magnetic fields in molecular clouds by turbulent reconnection

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Turbulence and structures in the ISM

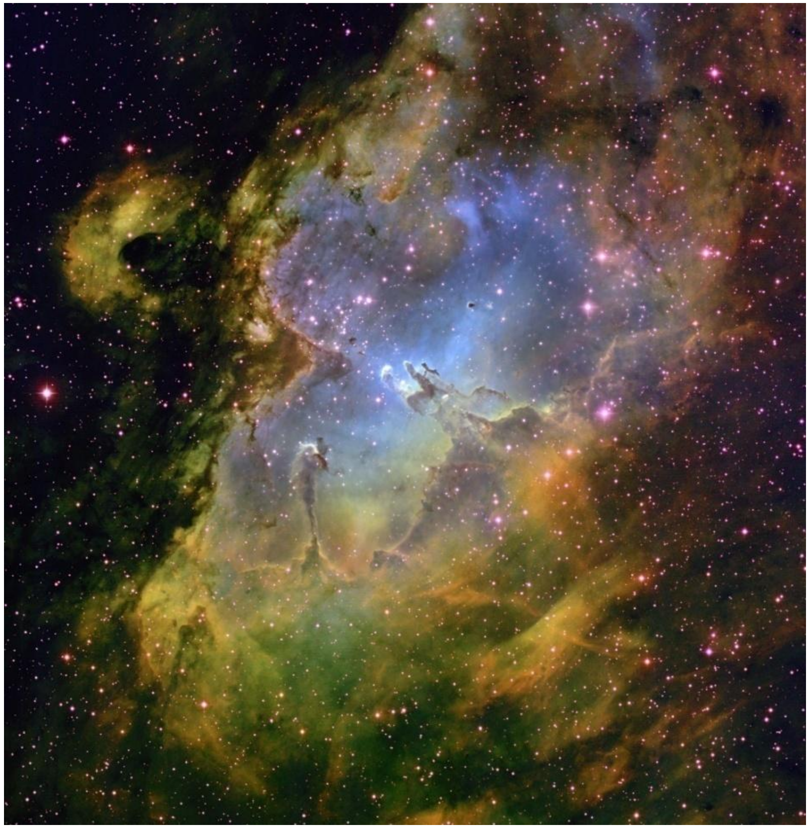
- From ~10pc to < 1pc
- 10^1 - 10^3 cm^{-3} to 10^4 - 10^6 cm^{-3}

- MHD turbulence is important for ISM structure and star formation
- Main mechanism: SNe shocks (Leão et al 2009); spiral waves, etc.

Credit: NASA, ESA, N. Smith (U. California, Berkeley) et al., and The Hubble Heritage Team (STScI/AURA)

Star Formation

Credit: T. A. Rector & B. A. Wolpa, NOAO, AURA



- If the gravitational forces dominate over all other resistive and dispersive forces $\Longrightarrow$ star formation.
- But we have a problem $\Longrightarrow$ **How is magnetic field diffused outward to allow cloud collapse?**

Goal: Study the role of turbulent reconnection in magnetic field removal from a collapsing molecular cloud to outside in order to ease star formation

Magnetic flux problem

Ideal MHD → B correlated with ρ
Observations → correlation is **weak**

Diffusive mechanisms usually invoked:

- **Ambipolar diffusion (AD)** (e.g. Heitch et al. 2004)
- Hyper resistivity: nature? (Shu et al. 2006)

➢ **AD may dominate late stages of collapse (although debatable – de Gouveia Dal Pino´s talk)**

➢ **Early stages?** (Shu et al. 2006, and papers by Crutcher and Mouschovias)

Magnetic flux problem

Ideal MHD → B correlated with ρ
Observations → correlation is **weak**

Alternative Mechanism:

Turbulent reconnection diffusion $\Longrightarrow$ in the presence of turbulence, reconnection is fast (Lazarian & Vishniac 1999) $\Longrightarrow$ magnetic field diffusion by reconnection is fast.

(de Gouveia Dal Pino's talk)

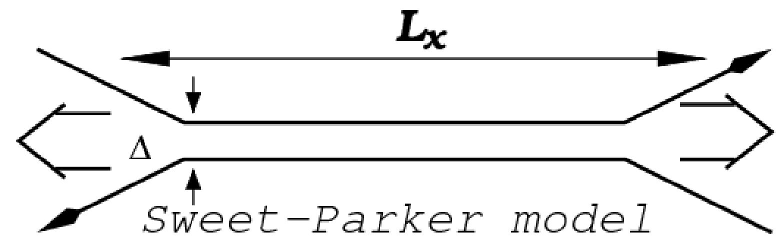
Turbulent reconnection

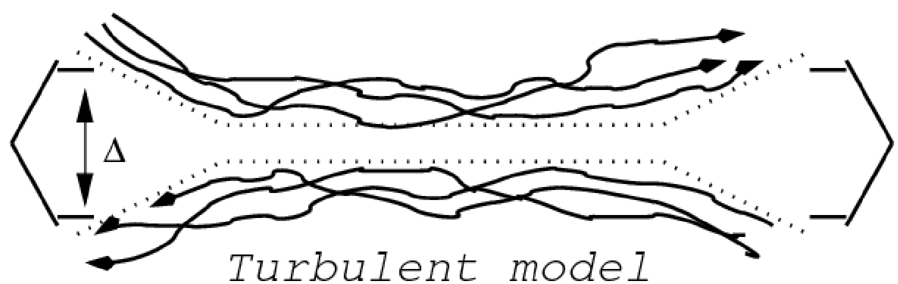
Lazarian & Vishniac (1999) fast reconnection model

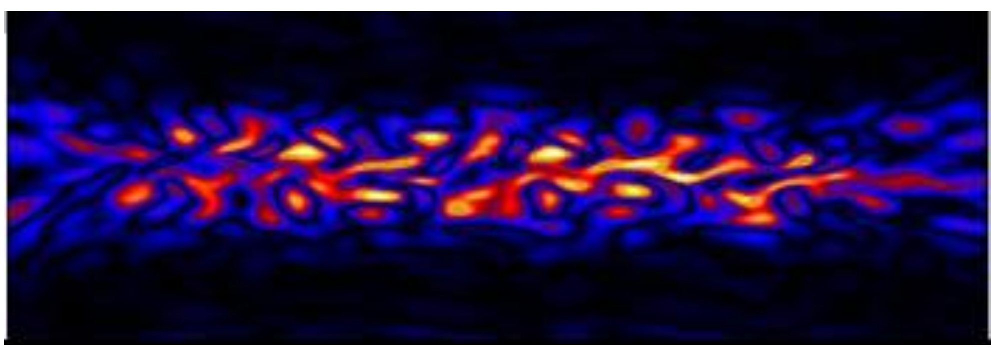
B dissipates on a small scale $\lambda_{||}$: many simultaneous reconnections events

Recently tested in numerical simulations (Kowal et al. 2009)

B is not frozen in a turbulent medium (Eyink, Lazarian, Vishniac 2011)

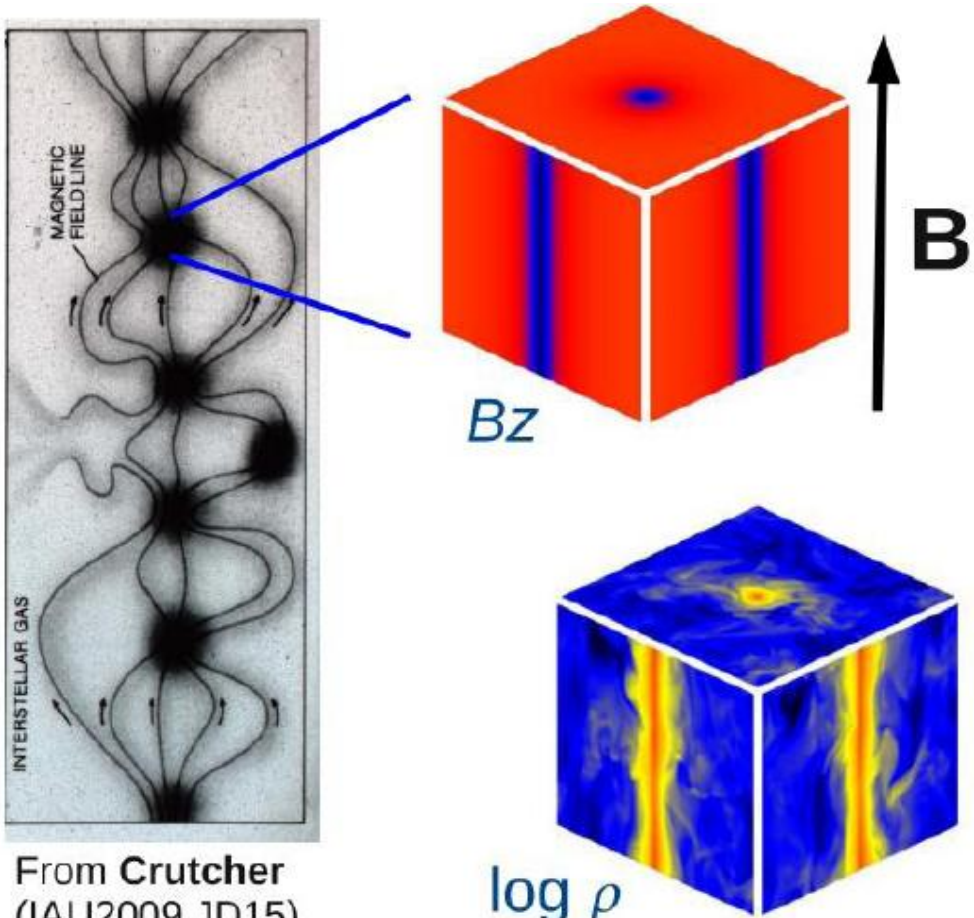






Formation of collapsing clouds due to turbulent reconnection flux transport:

Cylindrical Symmetry

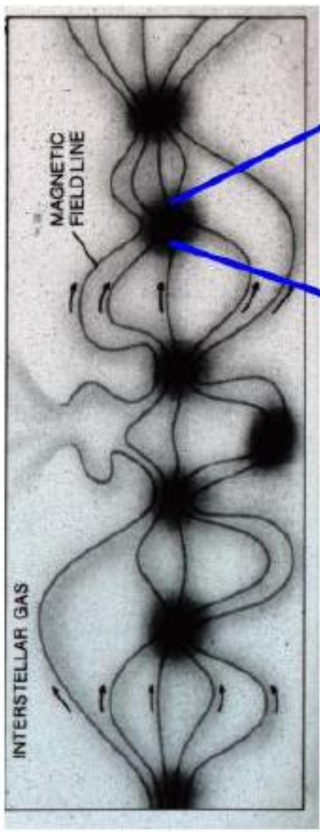


From **Crutcher** (IAU2009 JD15)

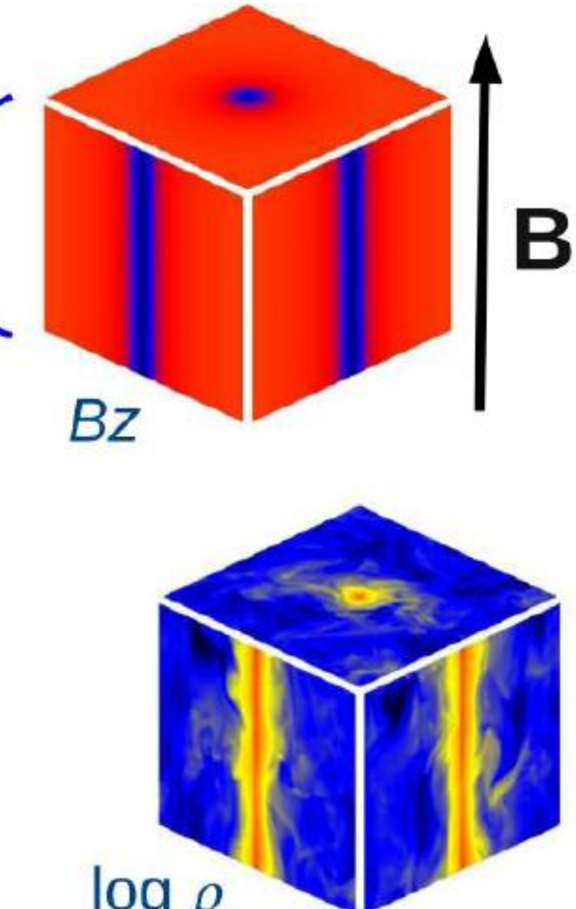
- Cylindrical symmetry
- Without self-gravity
- Dimensionless simulations
- One fluid model
- Periodic boundaries
- Starting in and out of equilibrium

Santos-Lima et al, ApJ, 2010

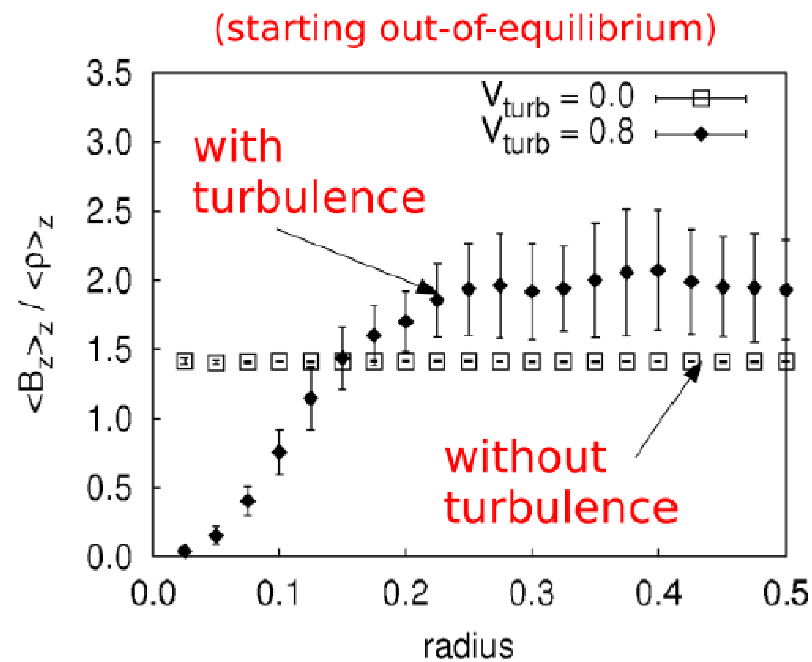
Formation of collapsing clouds due to turbulent reconnection flux transport:
Cylindrical Symmetry



From Crutcher (IAU2009 JD15)



- Reduction of the flux-to-mass ratio in the central region
- Gas inflow into central region



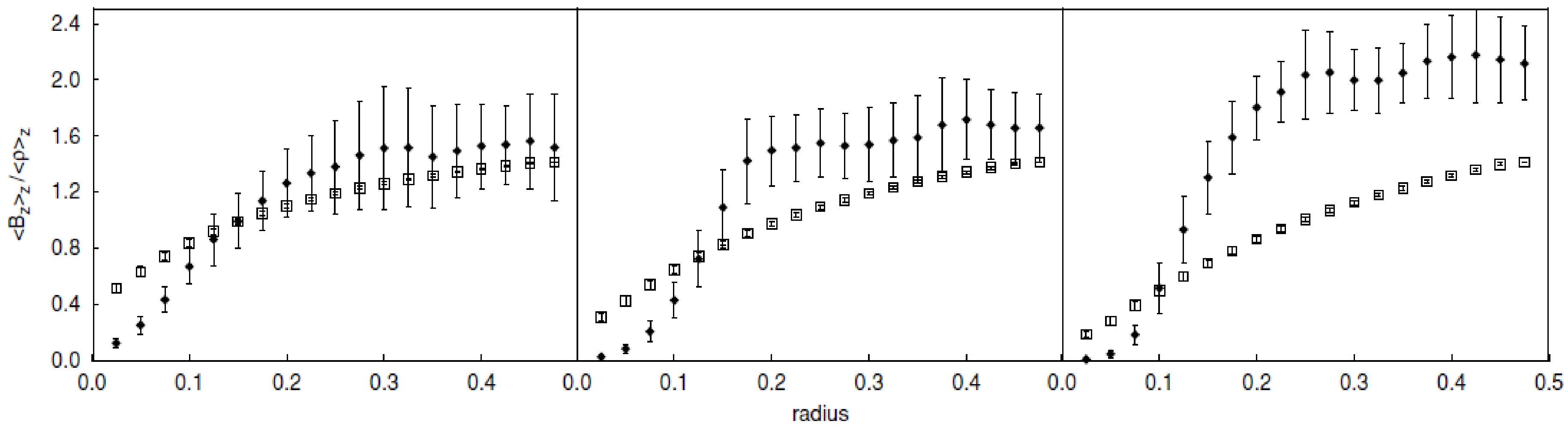
Santos-Lima et al, ApJ, 2010

Dependence with the external potential

Starting out-of-equilibrium

$\beta = 1.0$

A=0.6 A=0.9 A=1.2

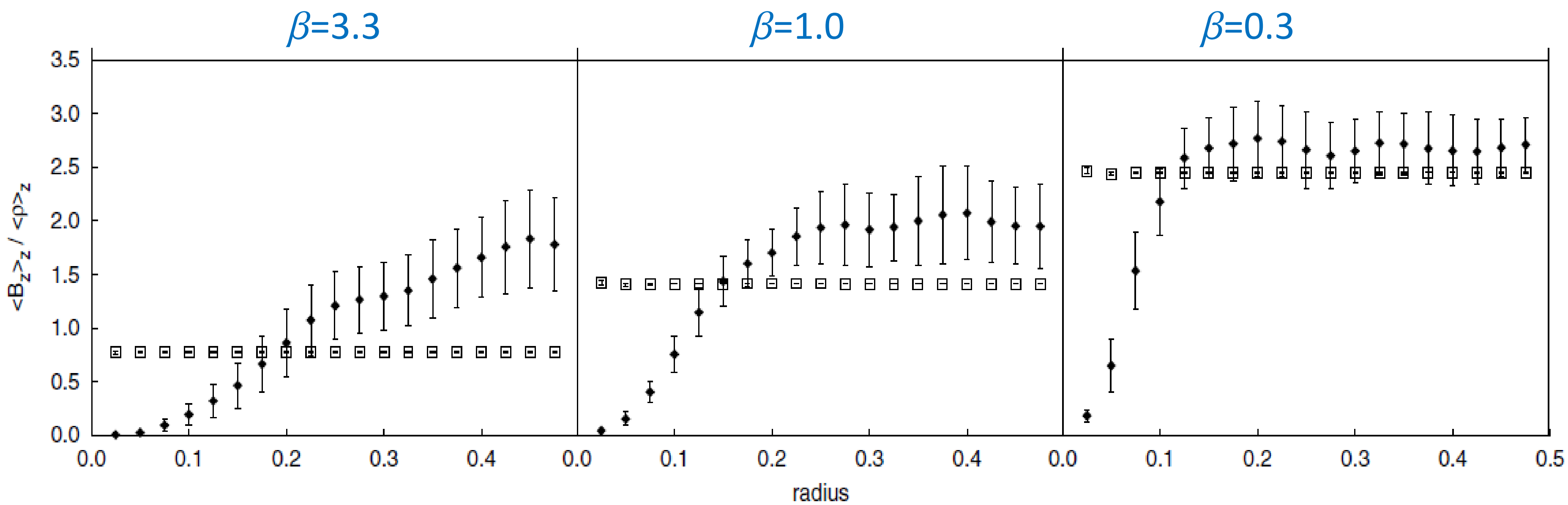


Higher external potential ⟶ higher the transport of magnetic field to the outer, less dense regions of the cloud

Dependence with β

Starting at equilibrium

A = 0.9



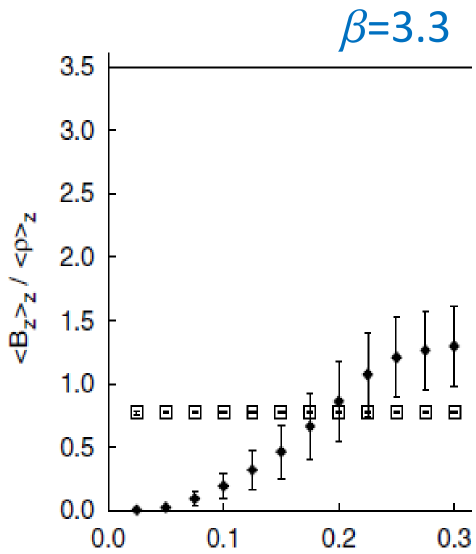
Lower $\beta \longrightarrow$ the higher the transport of magnetic field to the outskirts of the cloud

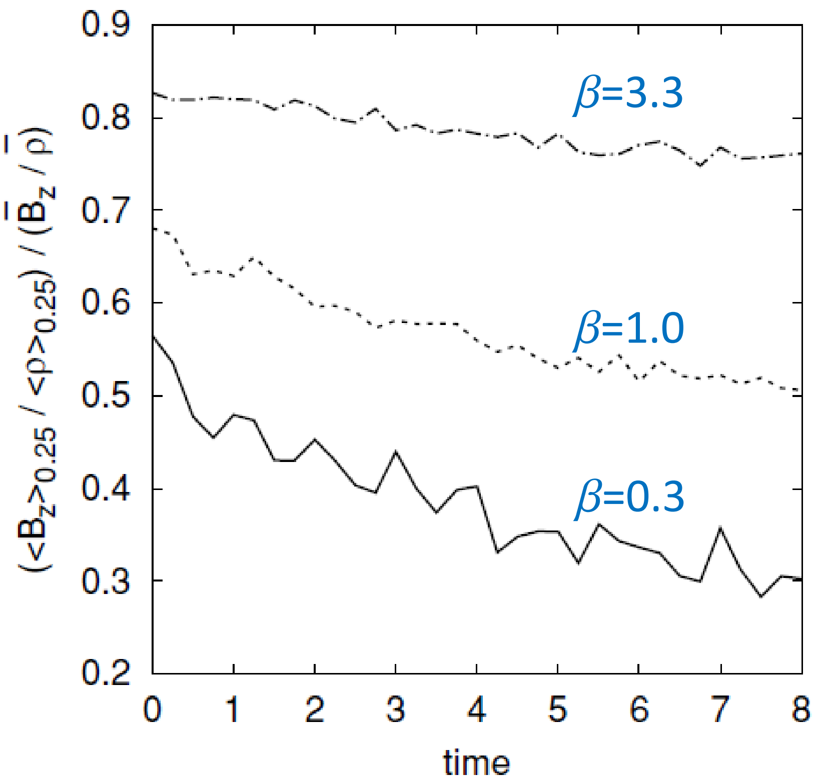
$$\beta = \frac{p_{th}}{p_M} = \frac{8\pi\rho_c c_s^2}{B_c^2}$$

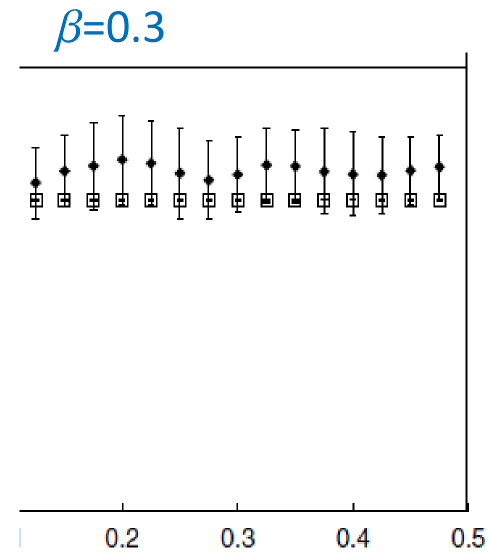
Dependence with β

Starting at equilibrium

A = 0.9





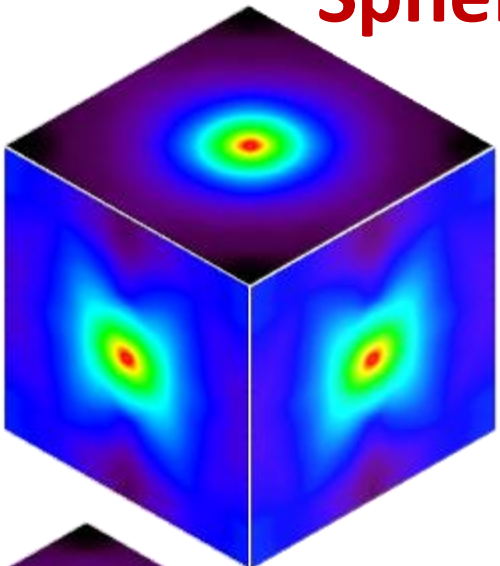


Lower β– ıetic field
to the ou

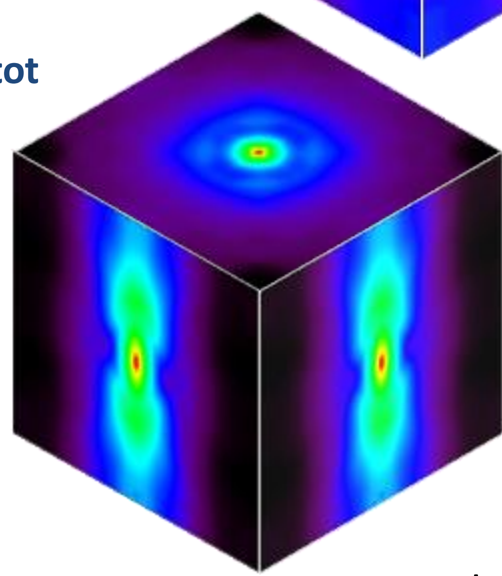
$$\beta = \frac{p_{th}}{p_M} = \frac{8\pi\rho_c c_s^2}{B_c^2}$$

More realistic cloud modeling:
Spherical Symmetry, Self-Gravity

log ρ



B_{tot}

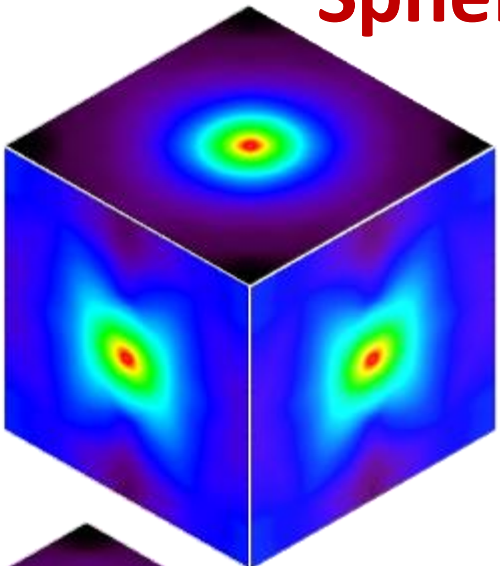


Resolution: 256^3
Cell size= 0.0126 pc

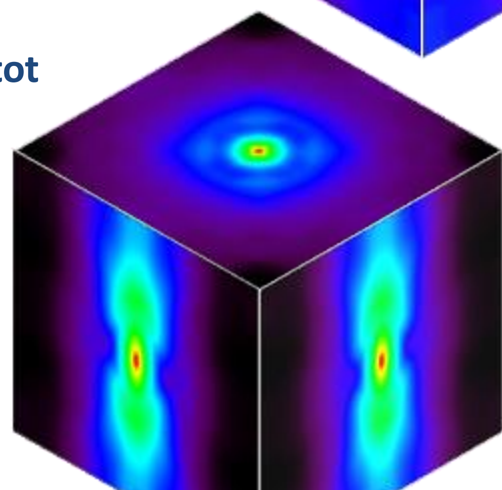
- **Self-gravitating gas**
- **Spherical central potential ($\sim 1/r^2$)**
- One fluid model
- Periodic boundary conditions
- Isothermal eq. of state
- Starting out-of-equilibrium
- Injection of subsonic and trans-Alfvenic turbulence
- Subcritical clouds

More realistic cloud modeling:
Spherical Symmetry, Self-Gravity

log ρ



B_{tot}



- **Self-gravitating gas**
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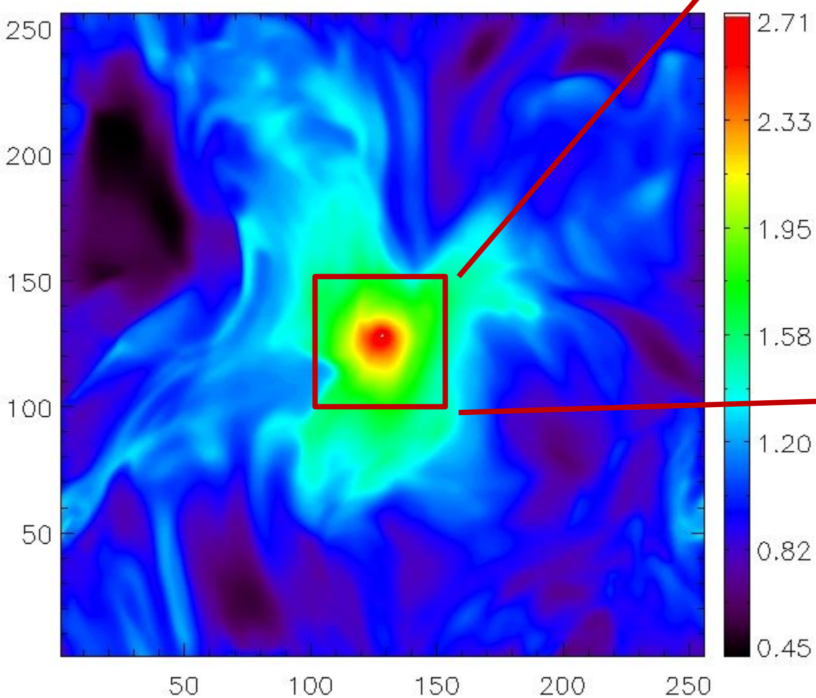
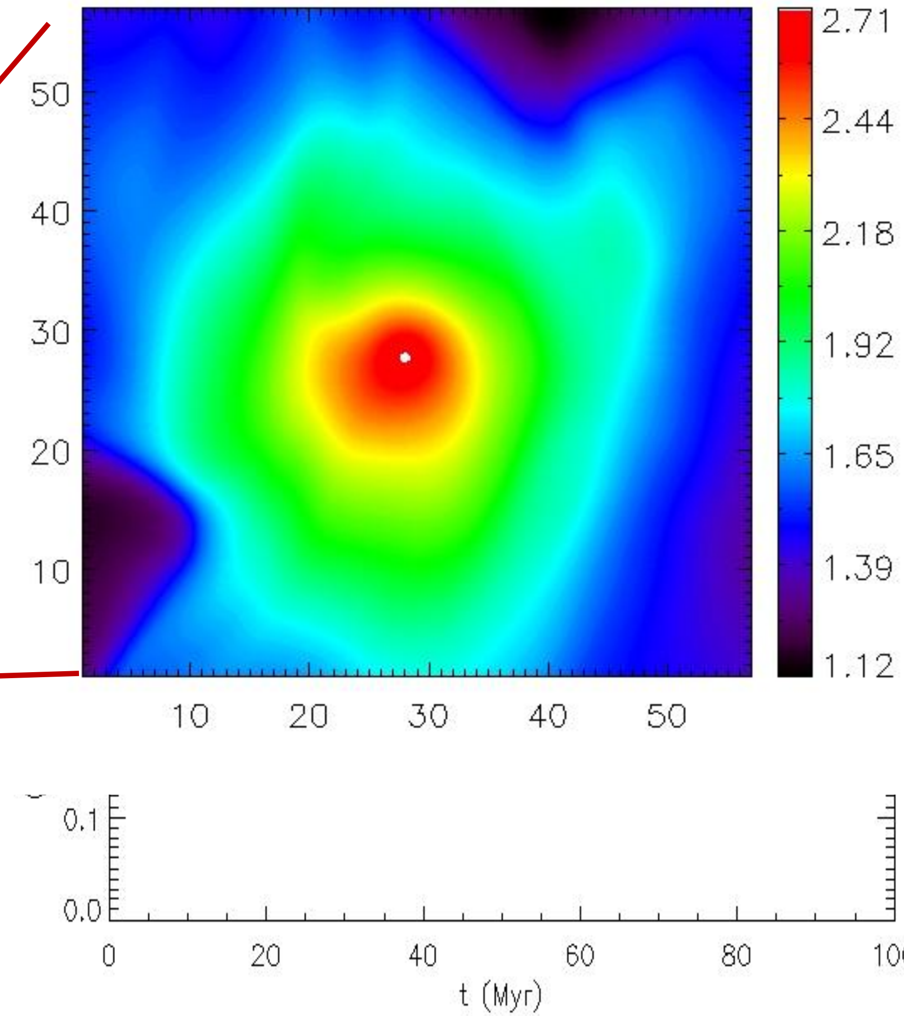
We want to study the diffusion of the magnetic fields by turbulent reconnection applied in the **early stages** of the cloud collapse.

Self-gravit

Self-gravitating gas + spher





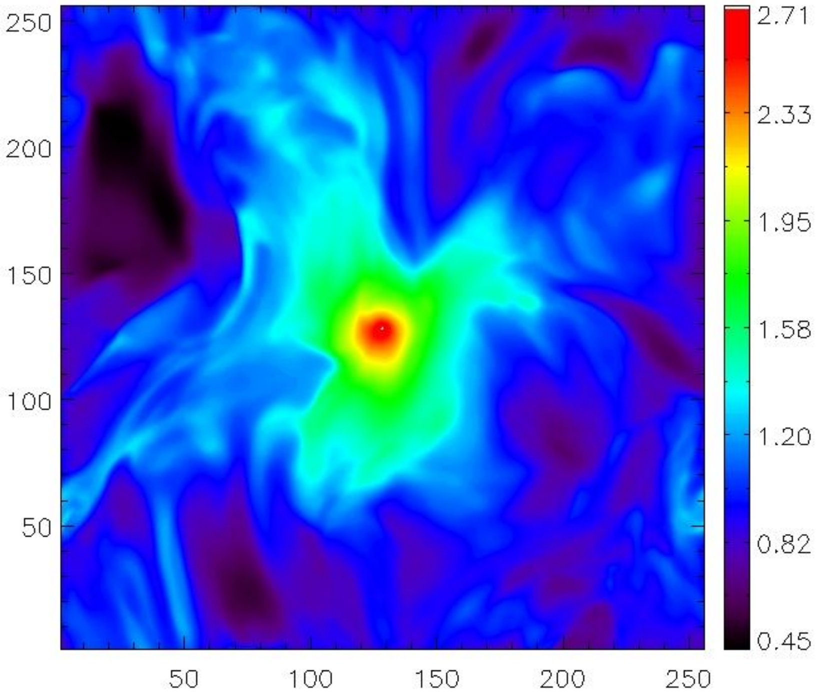
t = 100 Myr, β = 3.0, n =10 cm^{-3}, M$_{pot}$ $\sim$ 41 M$_{\odot}$, r$_{cloud}$ $\sim$ 3pc,

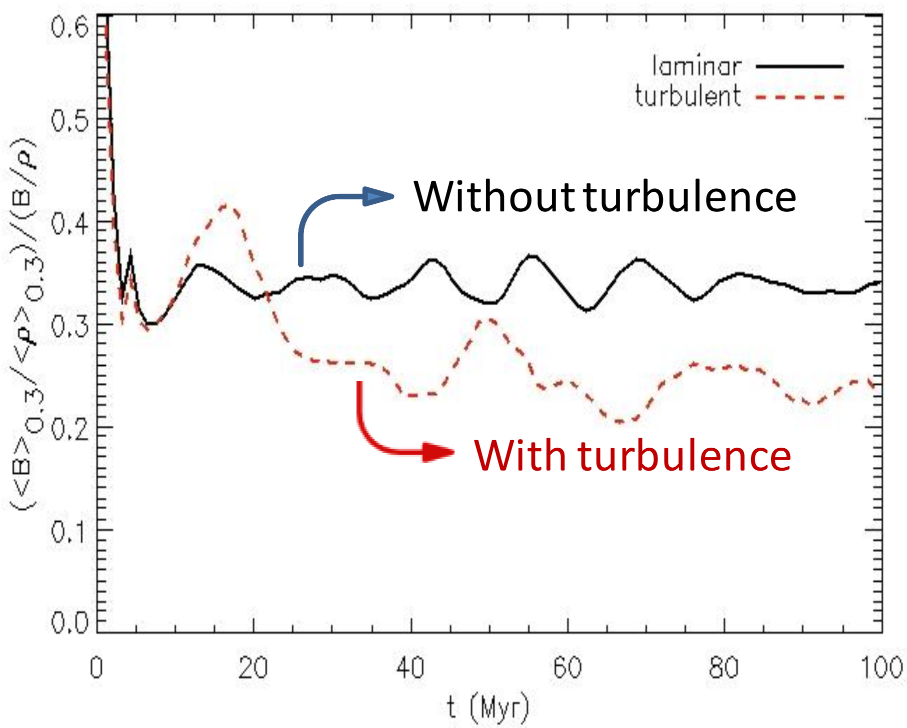
r$_{core}$~0.3pc

Leão et al. 2011 (in prep.)

Self-gravitating clouds

Self-gravitating gas + spherical central potential ($\sim 1/r^2$)





t = 100 Myr, β = 3.0, n =10 cm^{-3}, $M_{pot} \sim 41\ M_{\odot}$, $r_{cloud} \sim 3$pc,

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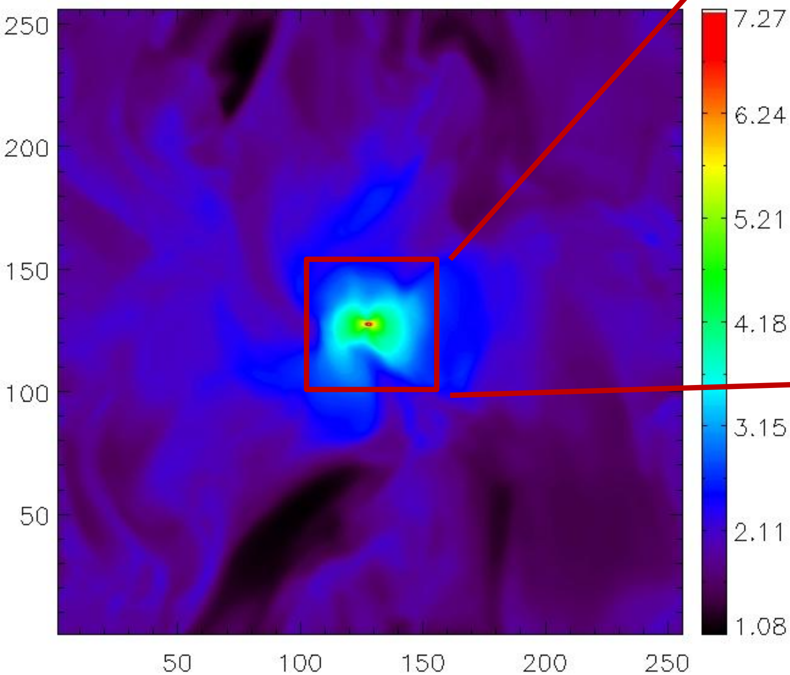
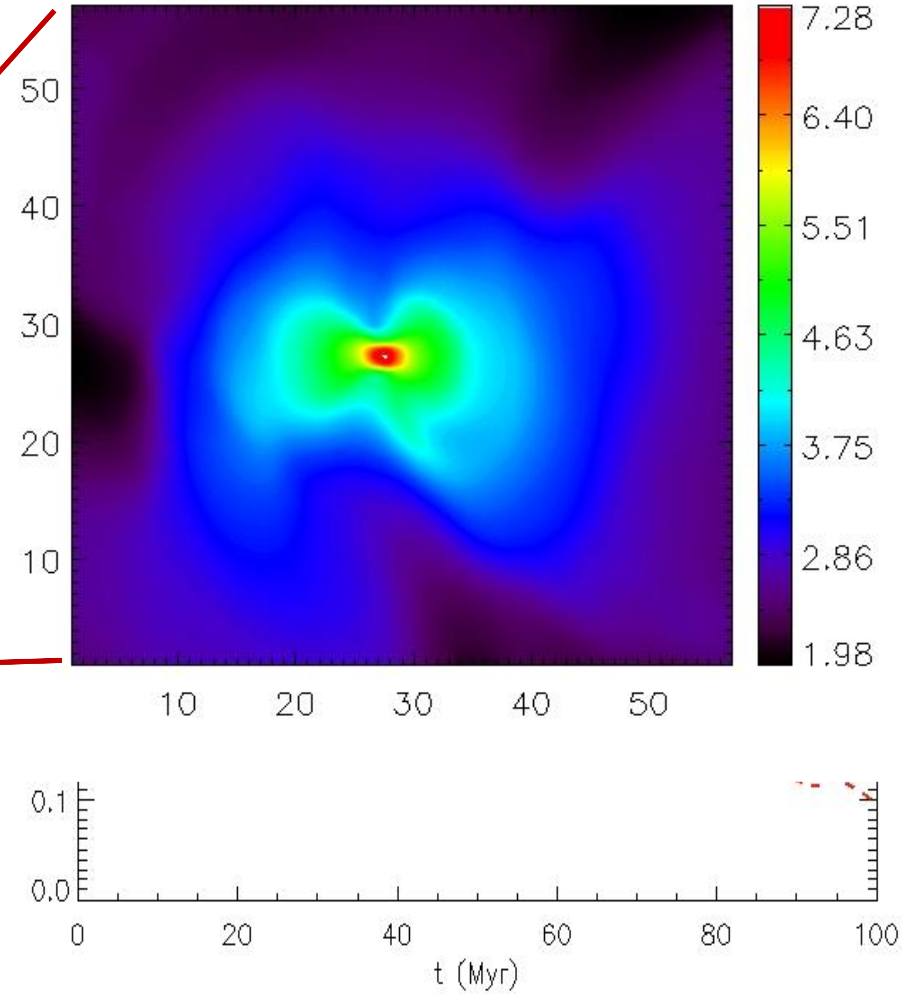
Self-gravita

Self-gravitating gas + spher





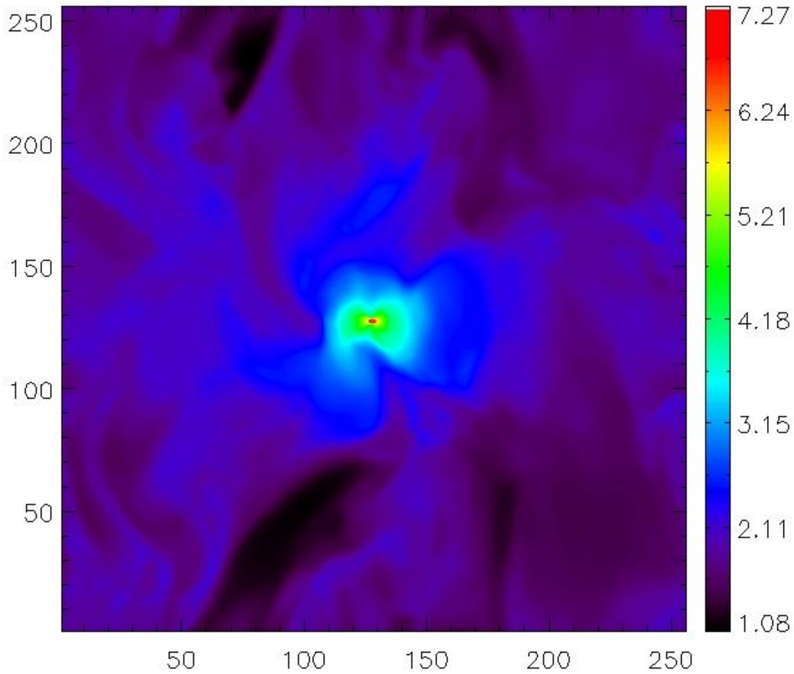
t = 100 Myr, β = 3.0, n =90 cm^{-3}, M_{pot} ~ 41 $M_{\odot}$, r_{cloud} ~ 3pc,

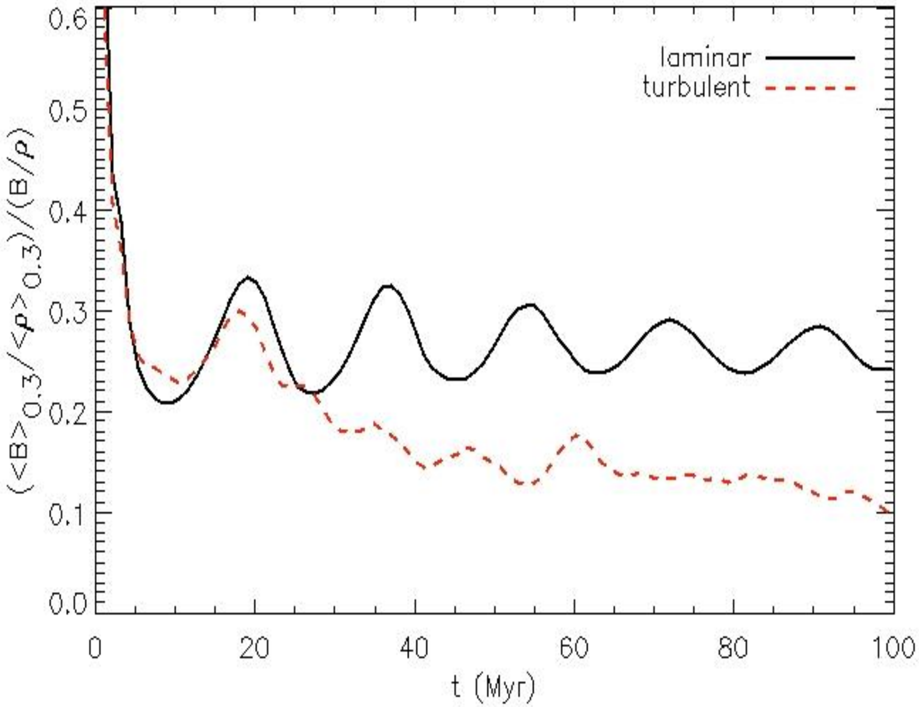
r_{core}~0.1pc

Leão et al. 2011 (in prep.)

Self-gravitating clouds

Self-gravitating gas + spherical central potential ($\sim 1/r^2$)





t = 100 Myr, β = 3.0, n =90 cm^{-3}, $M_{pot} \sim 41\ M_{\odot}$, $r_{cloud} \sim 3pc$,

$\mathbf{r_{core} \sim 0.1pc}$

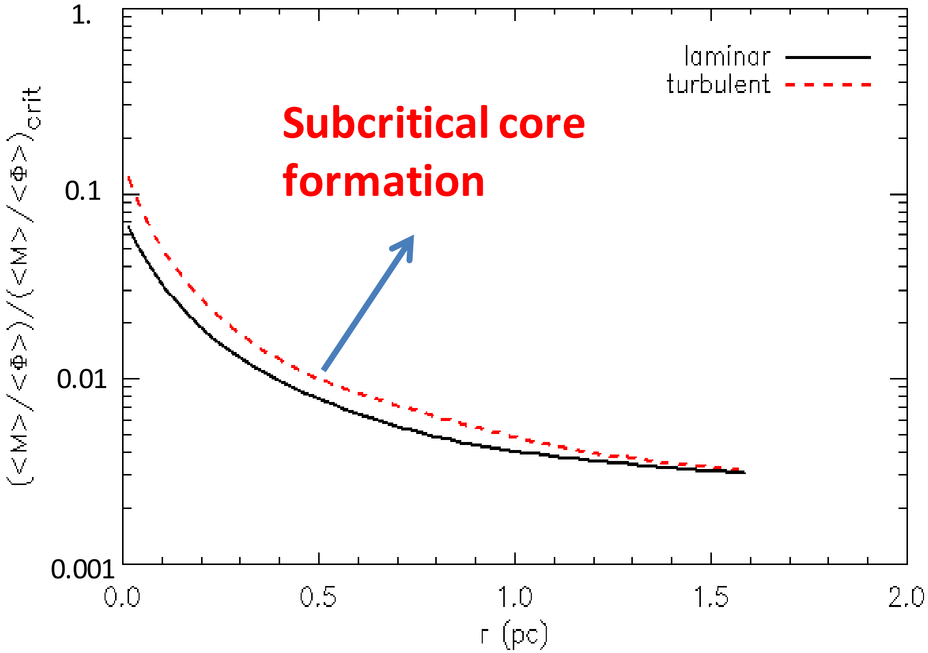
Leão et al. 2011 (in prep.)

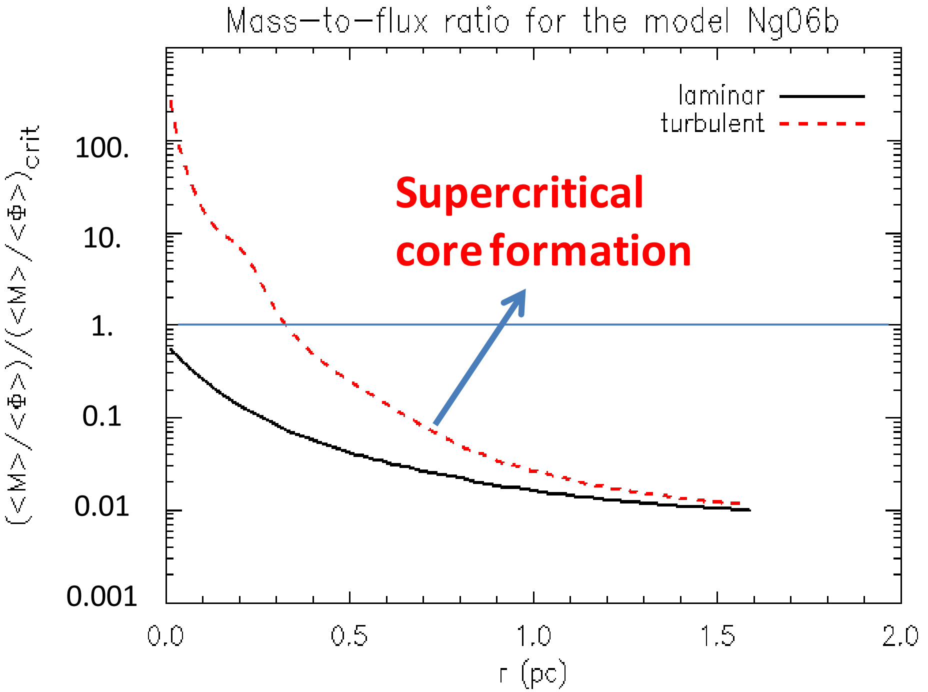
Self-gravity dependence

$\beta = 3.0$

Starting out of equilibrium

$M_{pot} \sim 41\ M_{\odot}$





n =10 cm^{-3}

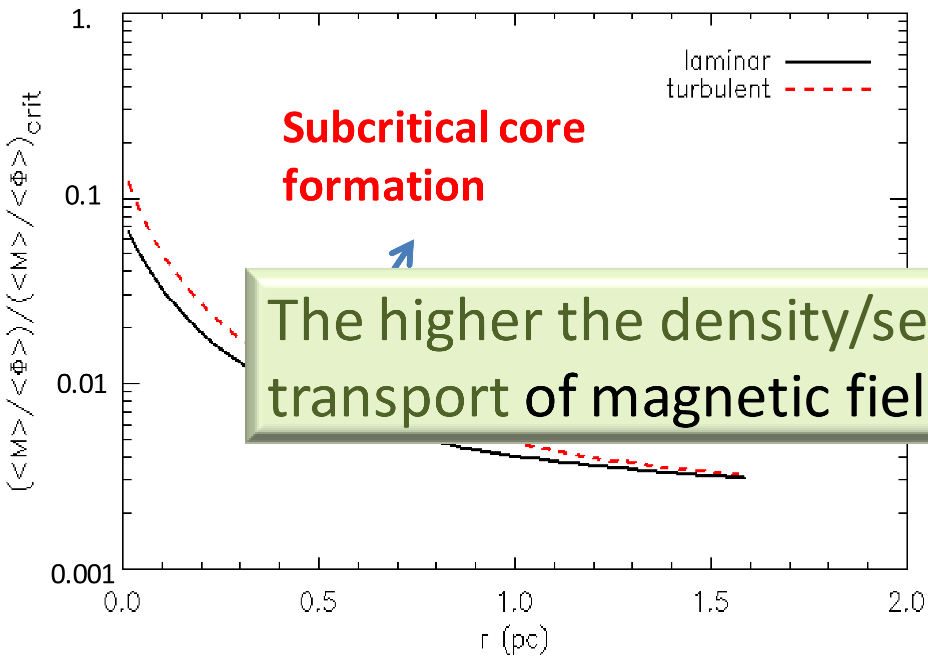
n =90 cm^{-3}

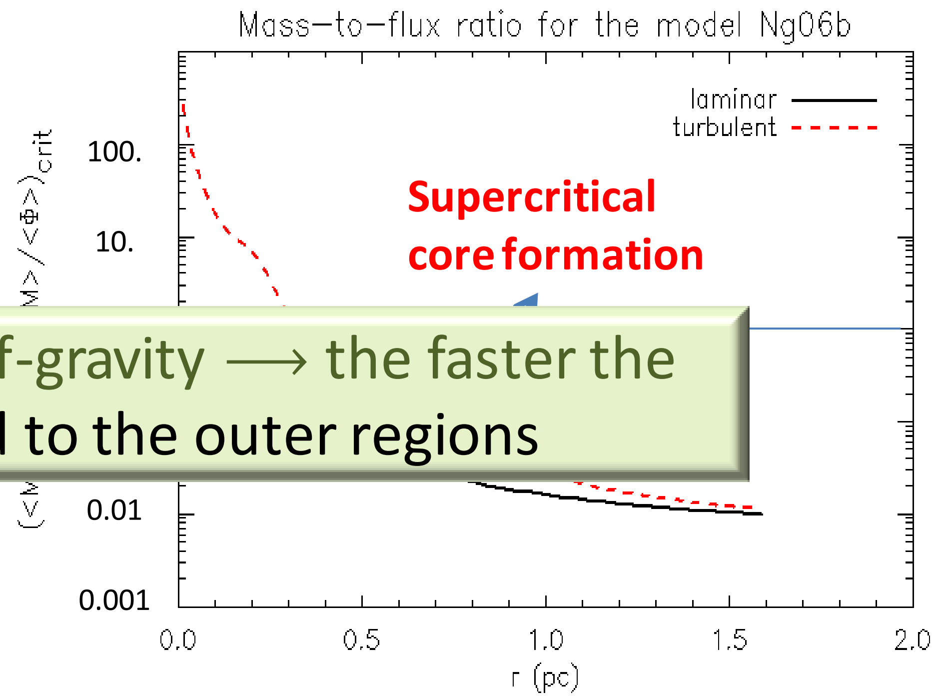
Self-gravity dependence

$\beta = 3.0$

Starting out of equilibrium

$M_{pot} \sim 41\ M_{\odot}$





The higher the density/self-gravity ⟶ the faster the transport of magnetic field to the outer regions

$n = 10\ cm^{-3}$

$n = 90\ cm^{-3}$

Summary

Turbulent reconnection diffusion effect on Star Formation

- The new setup with **spherical external gravitational potential and self-gravity** has confirmed the main results obtained by Santos-Lima et al. (2010) with cylindrical clouds.

- **Magnetic flux removal from collapsing clouds to form sub and supercritical cores**: successfully accomplished with **turbulent reconnection (no need of AD)**

Summary

- **Self-gravity** has an important effect as it facilitates the gas infall and therefore, the decoupling of the magnetic field that is more easily removed to the outer regions of the collapsing cloud
- The lower the **beta t**he more effective the diffusion of the magnetic field
- An increase in **self-gravity** is more important than an increase in **central external gravitational potential** in order to have magnetic flux transport
- Turbulence removes B-flux from collapsing, self-gravitating clouds **making them supercritical within a narrow range of densities ($10 < n < 100$ cm^{-3} for the M_{pot} ~$50M_{\odot}$)**