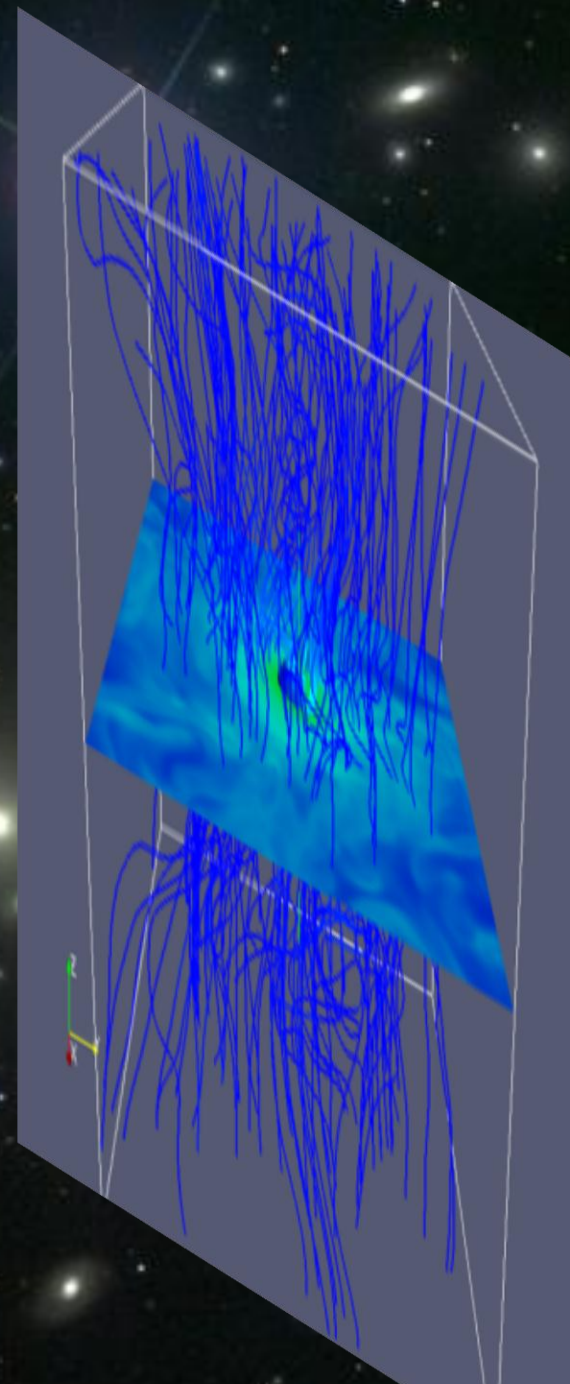
Star formation and reconnection diffusion of magnetic flux: a new paradigm from pc to AU scales



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MFU IV, Playa del Carmen, February 2013

Collaborators

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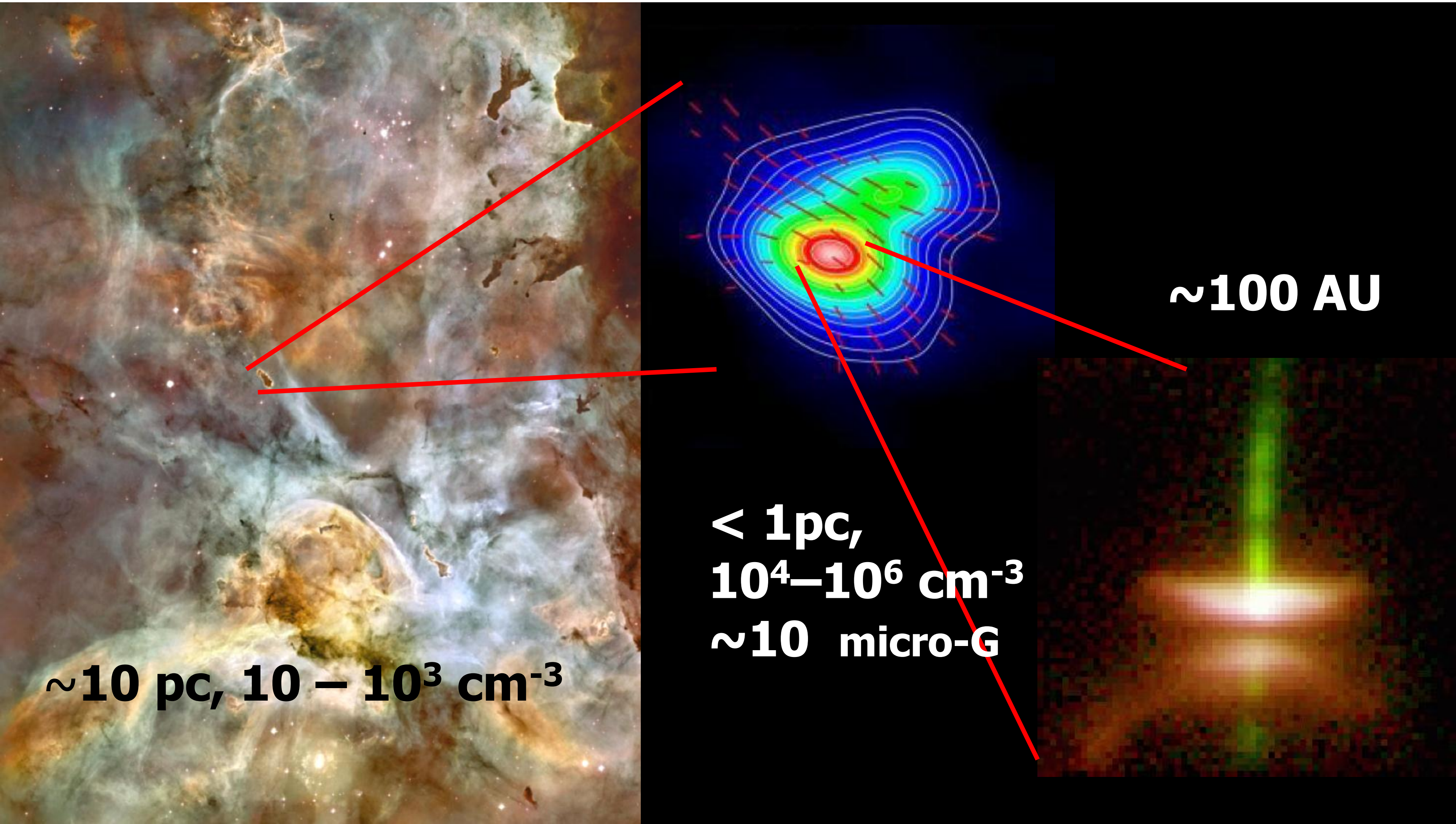
Star Formation not well understood in neither scale



Star Formation connected with turbulence

MHD turbulence super and transonic, and trans-Alfvenic (e.g. Vazquez-Semadeni et al.):

→ important for ISM structure & **star formation**

A crucial problem:
magnetic flux in young stars (TTauri) << magnetic flux of cloud progenitor

How is **magnetic field removed from a cloud** to allow its collapse??

Magnetic Flux Problem

Mechanism usually invoked to remove the magnetic flux excess:

Ambipolar diffusion (AD) of neutral gas through charged magnetized gas:

→ **has been challenged** by observations (Crutcher et al. 2008) and numerical simulations (Shu et al. 2006; Krasnopolsky et al. 2010, 2011; Li et al. 2011, Hennebelle et al);
(also McKee´s and Crutcher´s talks)

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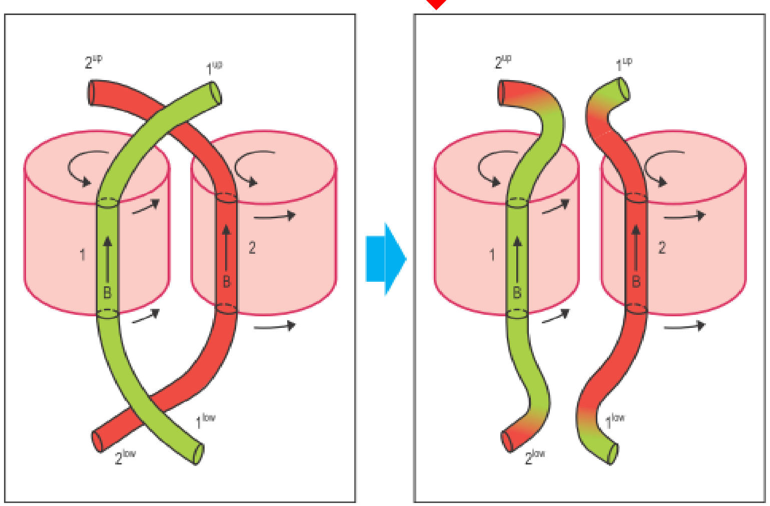
MHD turbulent diffusion: new scenario

In presence of turbulence: field lines reconnect fast (LV99) and magnetic flux transport becomes efficient (Lazarian 2005; tested by Santos-Lima et al. 2010, 2012, 2013; de Gouveia Dal Pino, et al 2012; Leao et al. 2012)

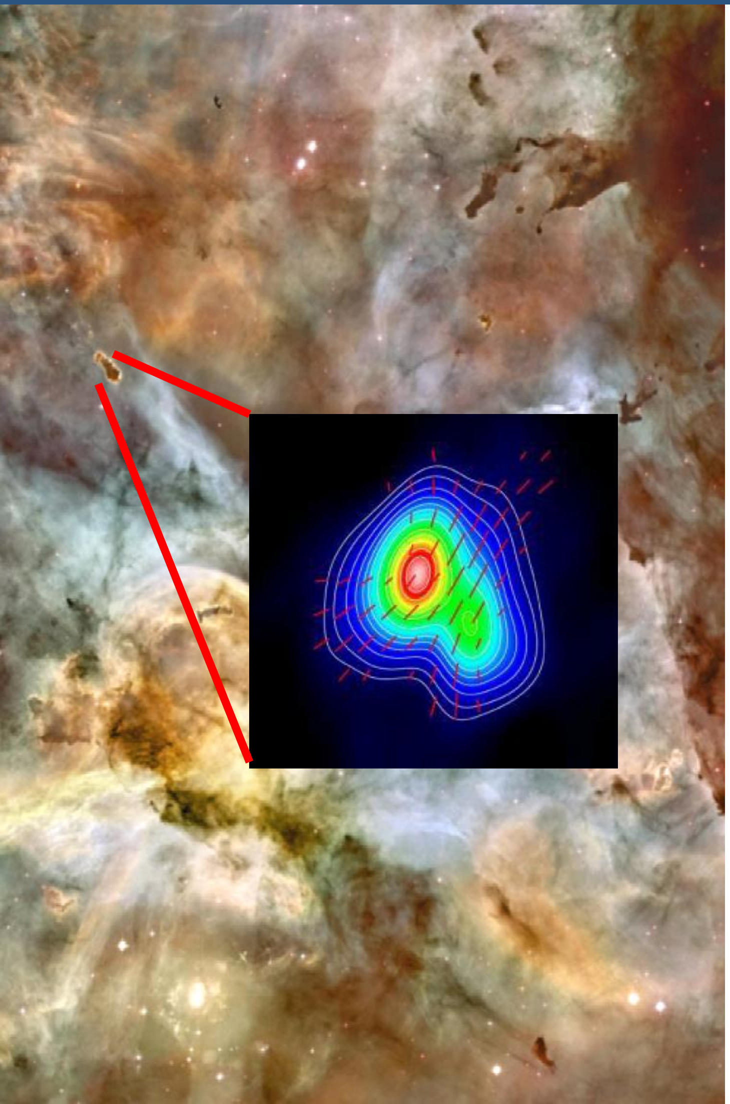


$$\eta_t \sim l_{\rm inj} v_{\rm turb} \qquad \text{if } v_{\rm turb} \geq v_A$$

$$\eta_t \sim l_{\rm inj} v_{\rm turb} \left(\frac{v_{\rm turb}}{v_A}\right)^3 \qquad \text{if } v_{\rm turb} < v_A$$

Lazarian 2005, 2012
Santos-Lima et al. 2010
Eyink et al. 2011

Reconnection Diffusion in clouds



Embedded magnetic flux should be partially removed from denser to less dense regions by **turbulent magnetic reconnection diffusion**

⬇

Allow cloud clump collapse!

Testing reconnection diffusion in gravitating clouds: 3D MHD simulations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = -c_s^2 \nabla \rho + (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Psi + \mathbf{f}$$

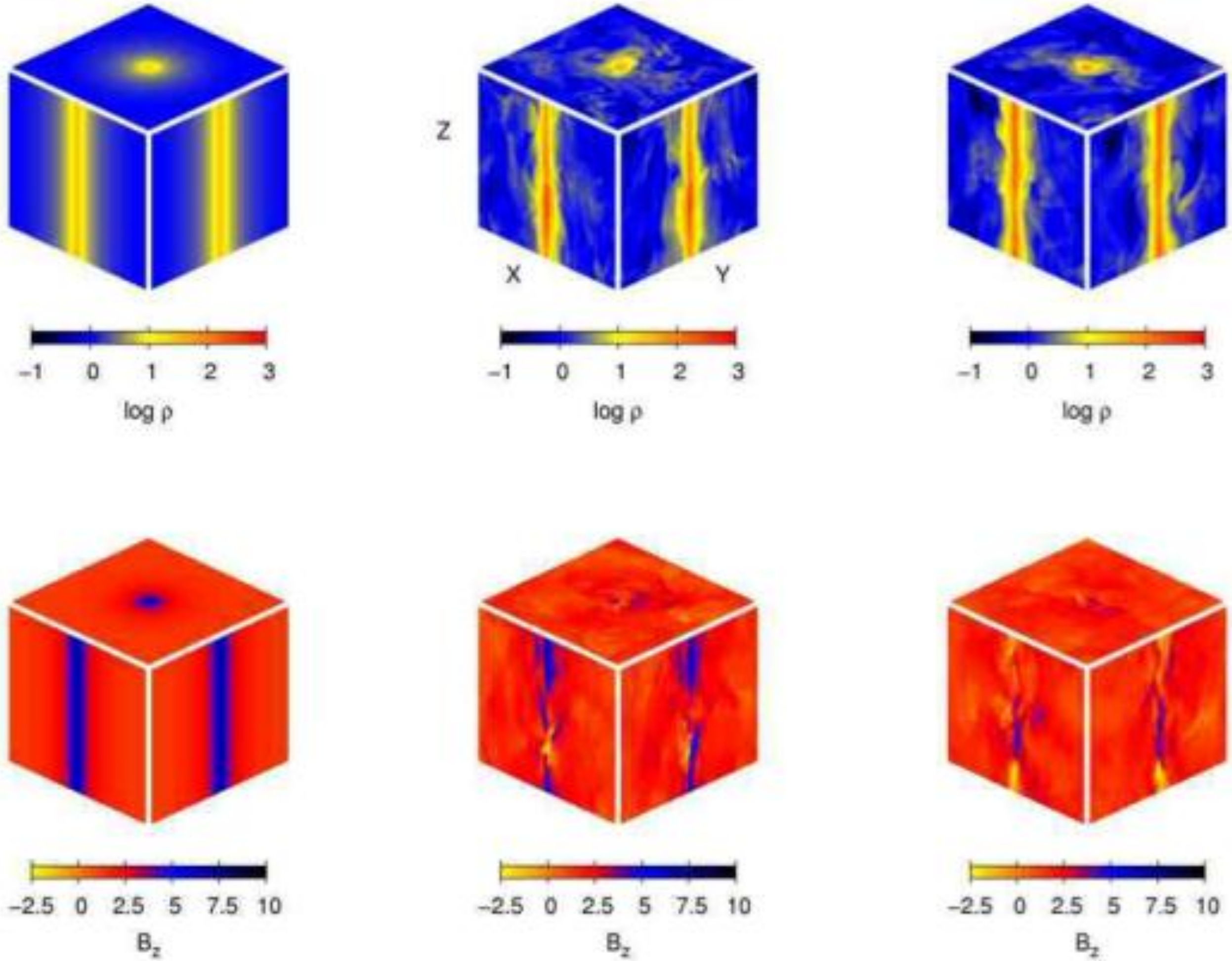
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta_{\mathrm{Ohm}} \nabla^2 \mathbf{B}$$

- 2^{nd} order shock capturing Godunov scheme with HLL solver (Kowal et al. 2007, Santos-Lima et al. 2010)

- f: isotropic, non-helical, solenoidal, delta correlated in time random force term (responsible for injection of turbulence)

- $\eta_{Ohm} = 0$

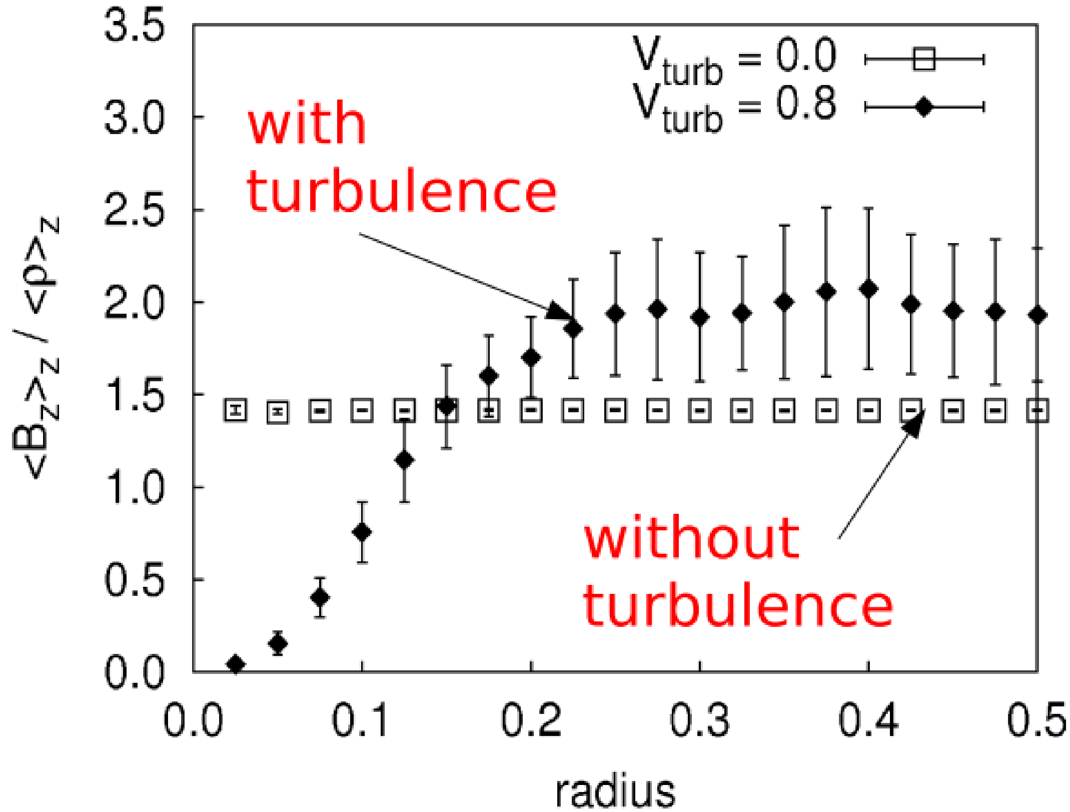
Magnetic Field diffusion in gravitating clouds: 3D MHD simulaitons



Santos-Lima et al. ApJ, 2010

Magnetic field diffusion in gravitating clouds: 3D simulations

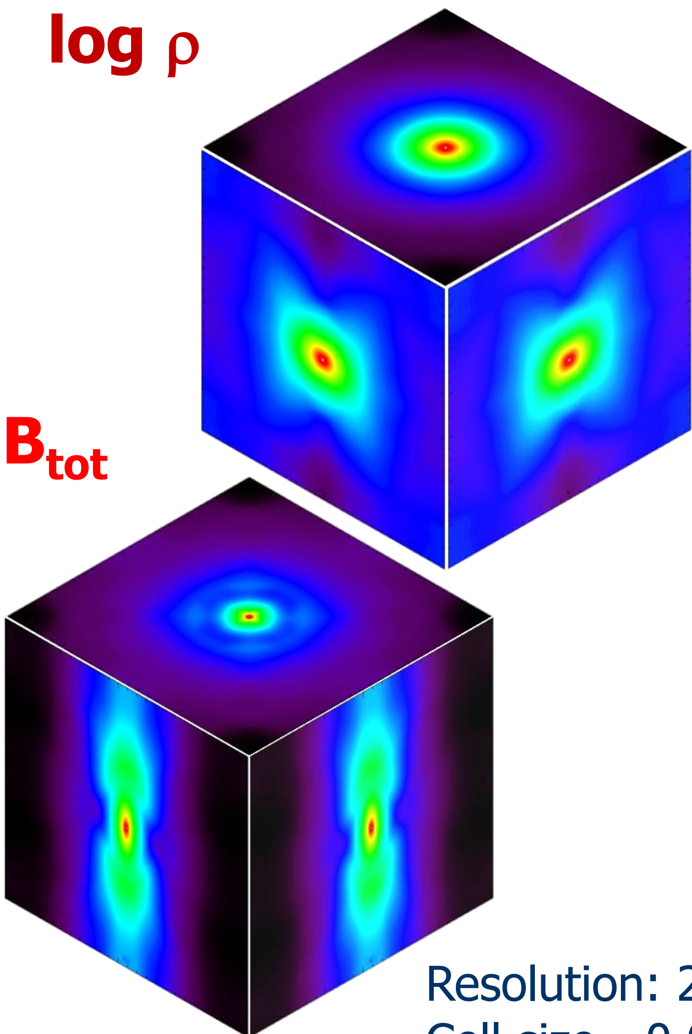
(starting out-of-equilibrium)



- Removal of magnetic flux from the central regions (strong-gravity);
- Gas inflow into the central region;
- **Reduction of the flux-to-mass ratio in the central region.**

(Santos-Lima et al., ApJ, 2010)

Formation of supercritical cores by turbulent reconnection flux transport

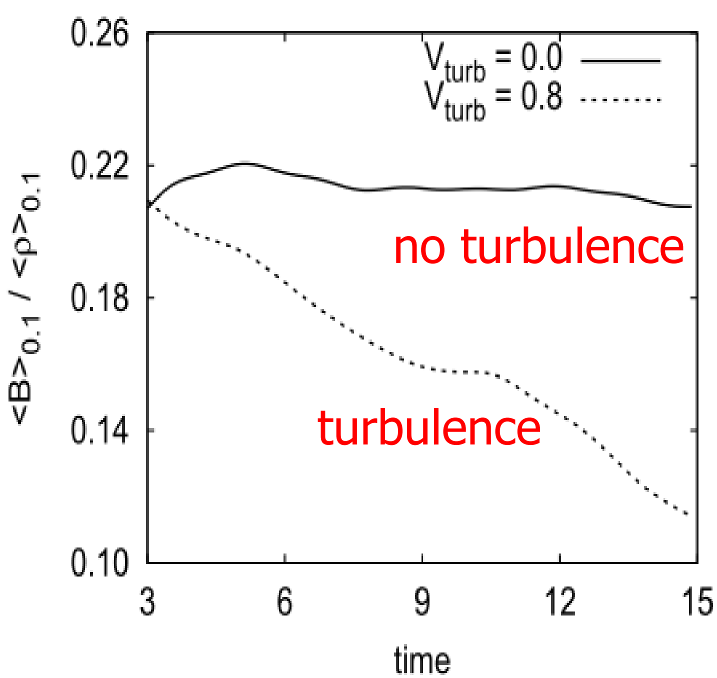


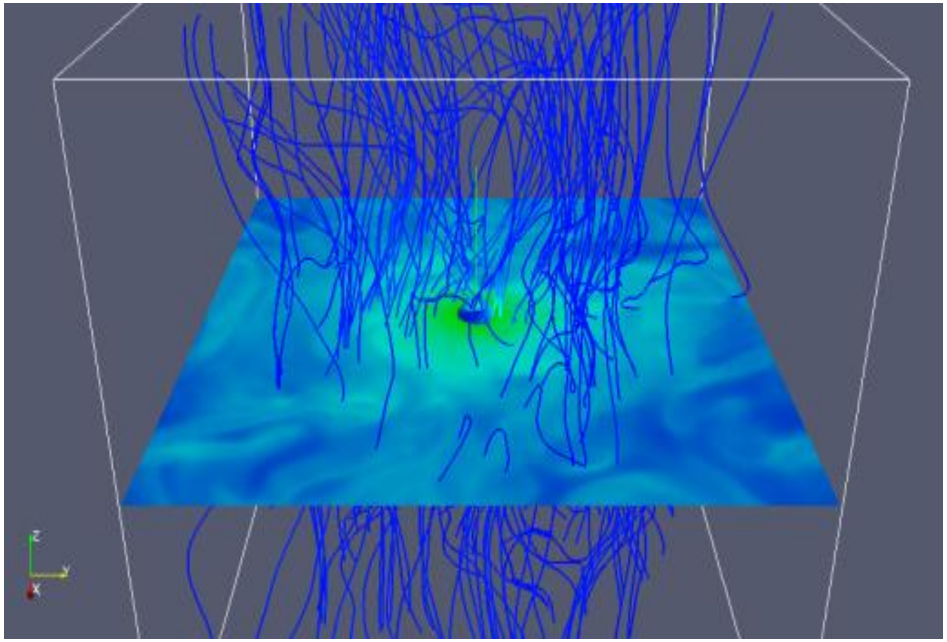
Resolution: 256^3
Cell size= 0.0126 pc

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

Self-Gravitating collapsing clouds

Self-gravitating gas + central spherical potential (~1/r²)





β=3, n=100 cm^{-3}, M= 41 M$_{sun}$, r=3pc

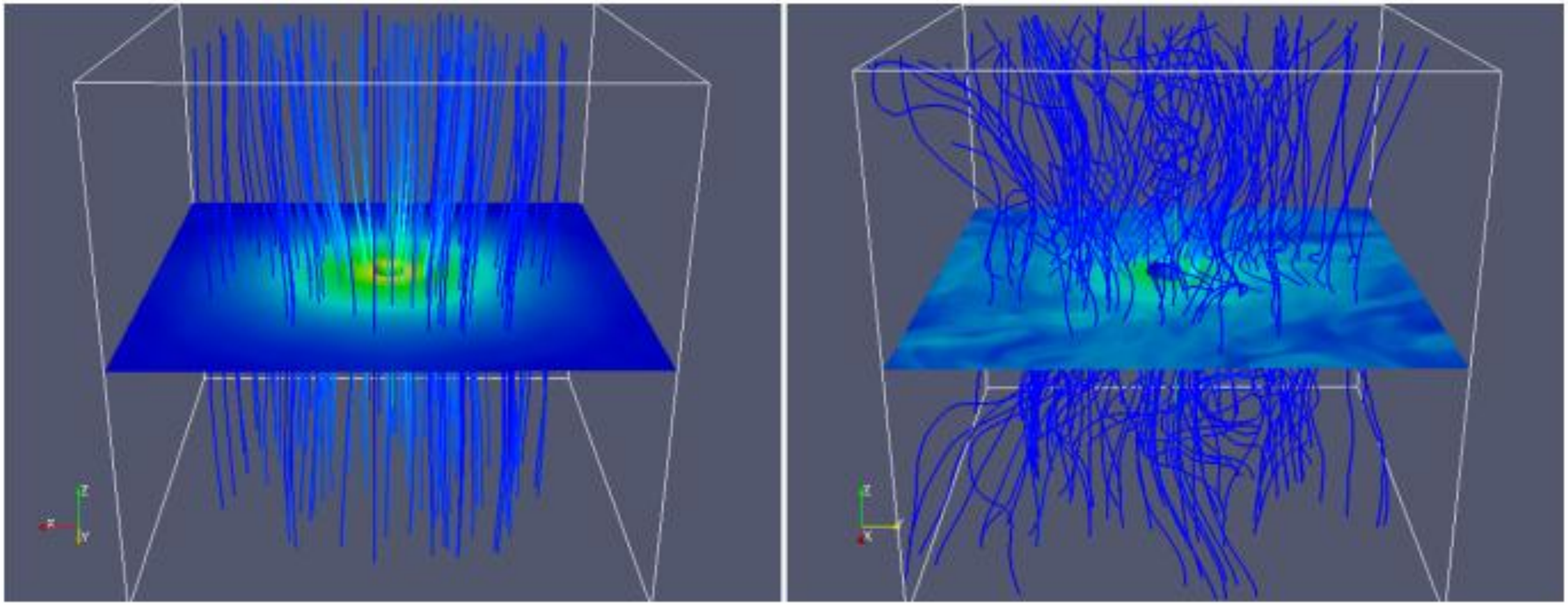
t=100 Myr

Leão, de GDP, Santos-Lima, Lazarian, Kowal 2012

Self-Gravitating colapsing clouds

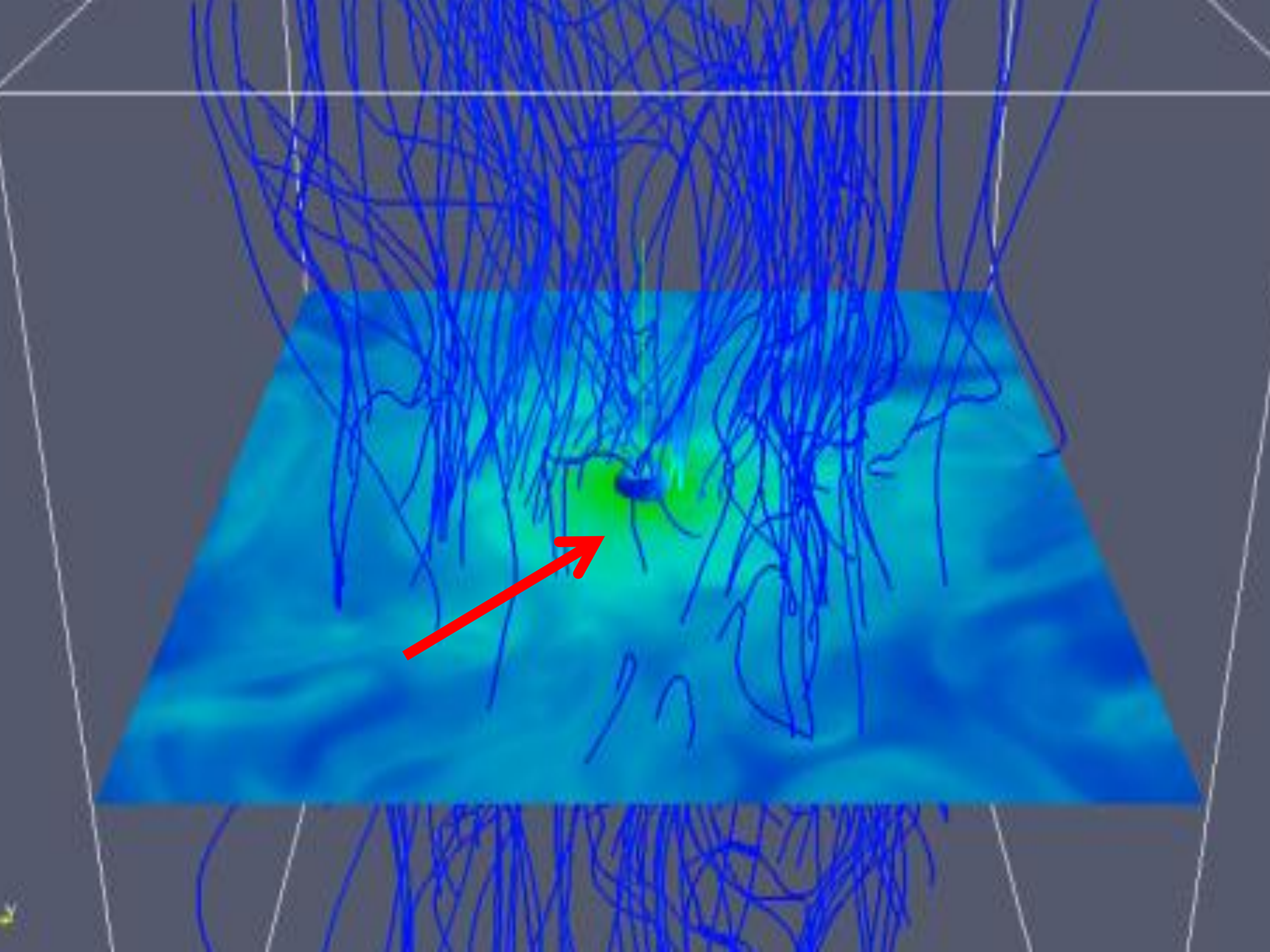
Self-gravitating gas + central spherical potential (~1/r²)

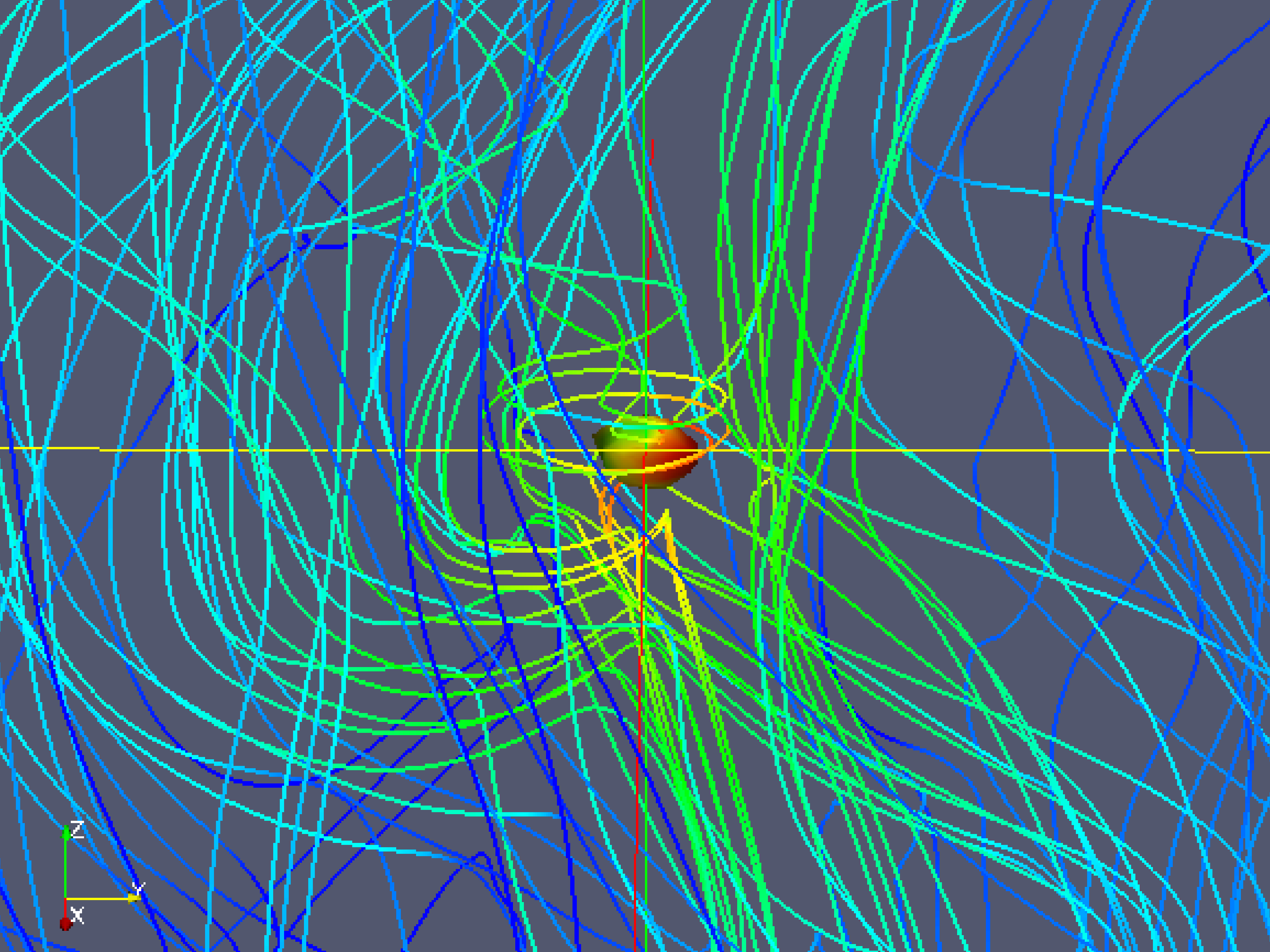
Non-turbulent | Turbulent



Subcritical core | **Supercritical core**

β=3, n=100 cm^{-3} t=100 Myr **Leão et al. 2013**

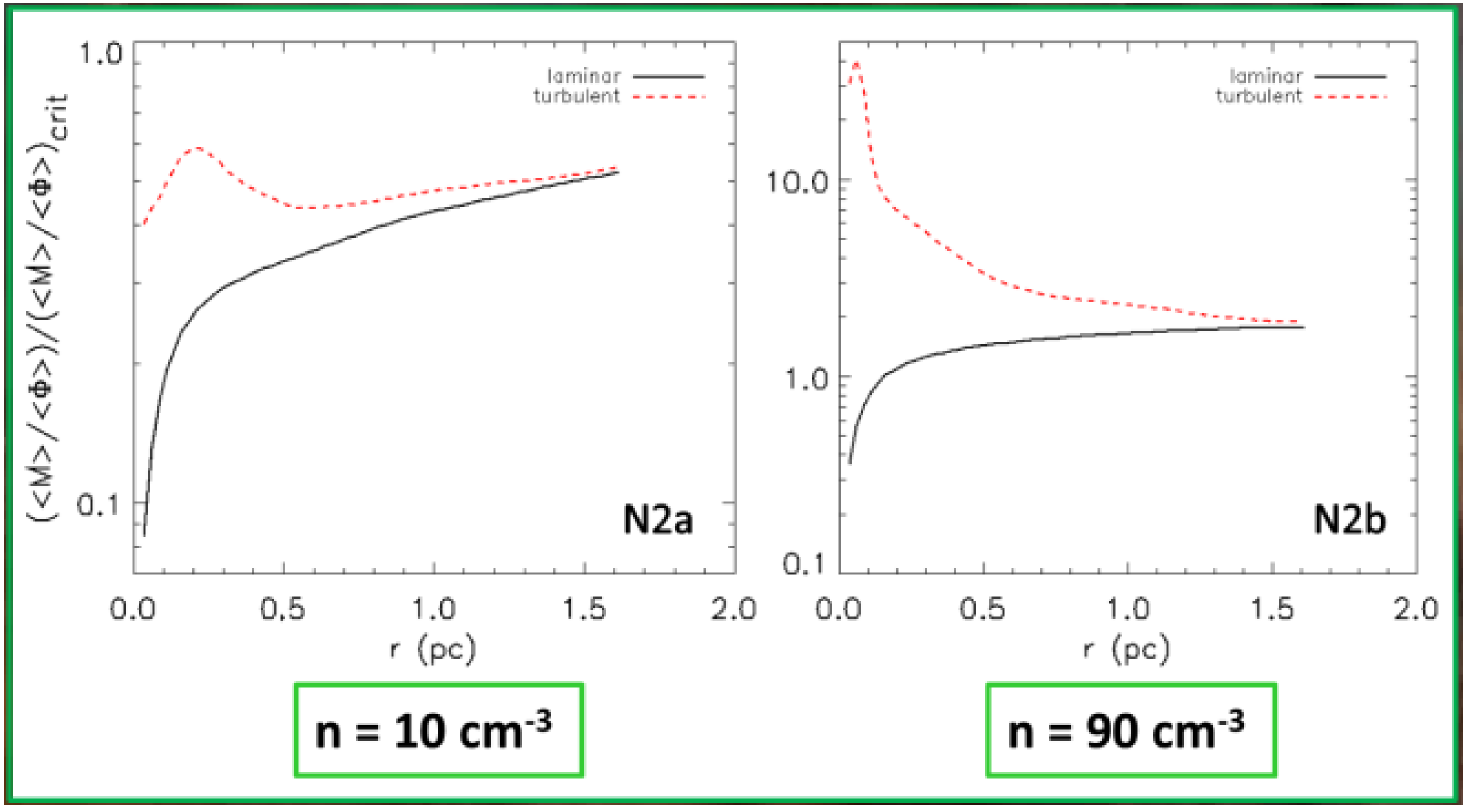




Z
Y
X

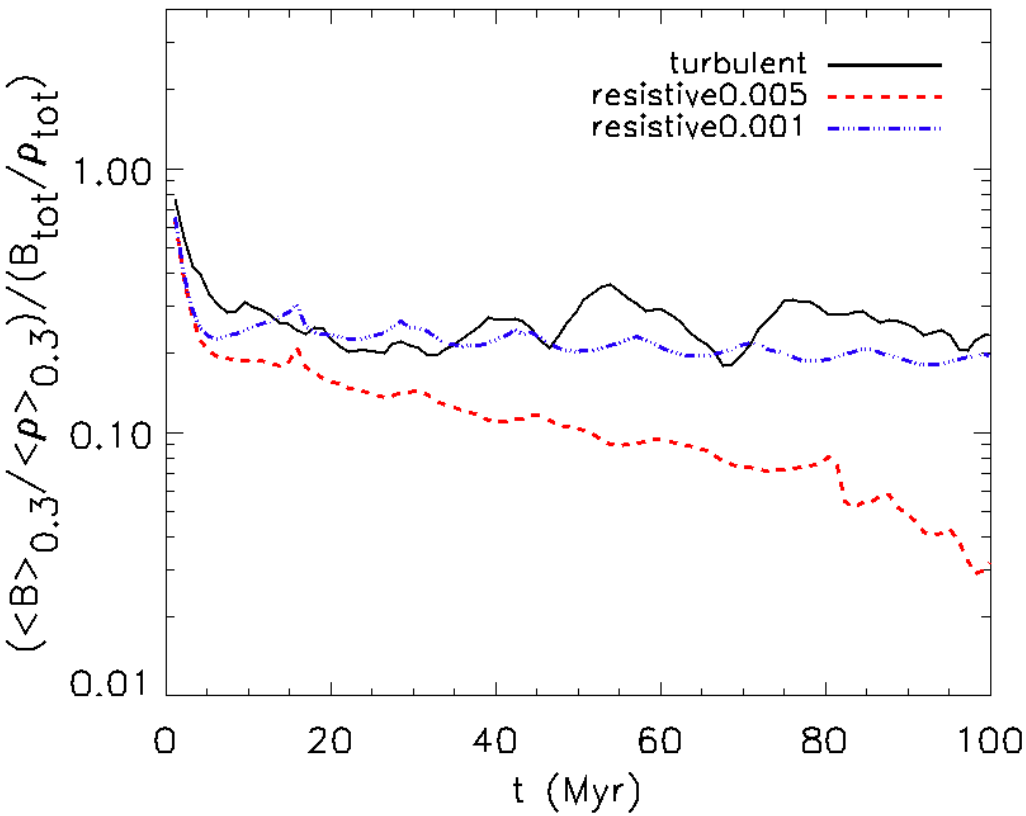
Self-Gravitating collapsing clouds

Larger self-gravity (density) the larger the magnetic transport



Leão et al. 2012

Resistivity Effects



To estimate the turbulent resistivity we perform models with strong resistivity.

$\eta_{turb} \sim 10^{20-22}$ cm²/s

Estimate:

$\eta_{ohm} \sim 10^{9}$ cm²/s

$\eta_{num} \sim 10^{19-20}$ cm²/s

$\eta_{AD} \sim 10^{15}$ cm²/s

Leão et al. 2012

Comparison with observations

Observed mass-to-magnetic flux ratio in cloud cores (Troland & Crutcher 2008; Crutcher et al. 2009, 2010;):

$$\mu_{crit} = 0.45 - 1.15$$

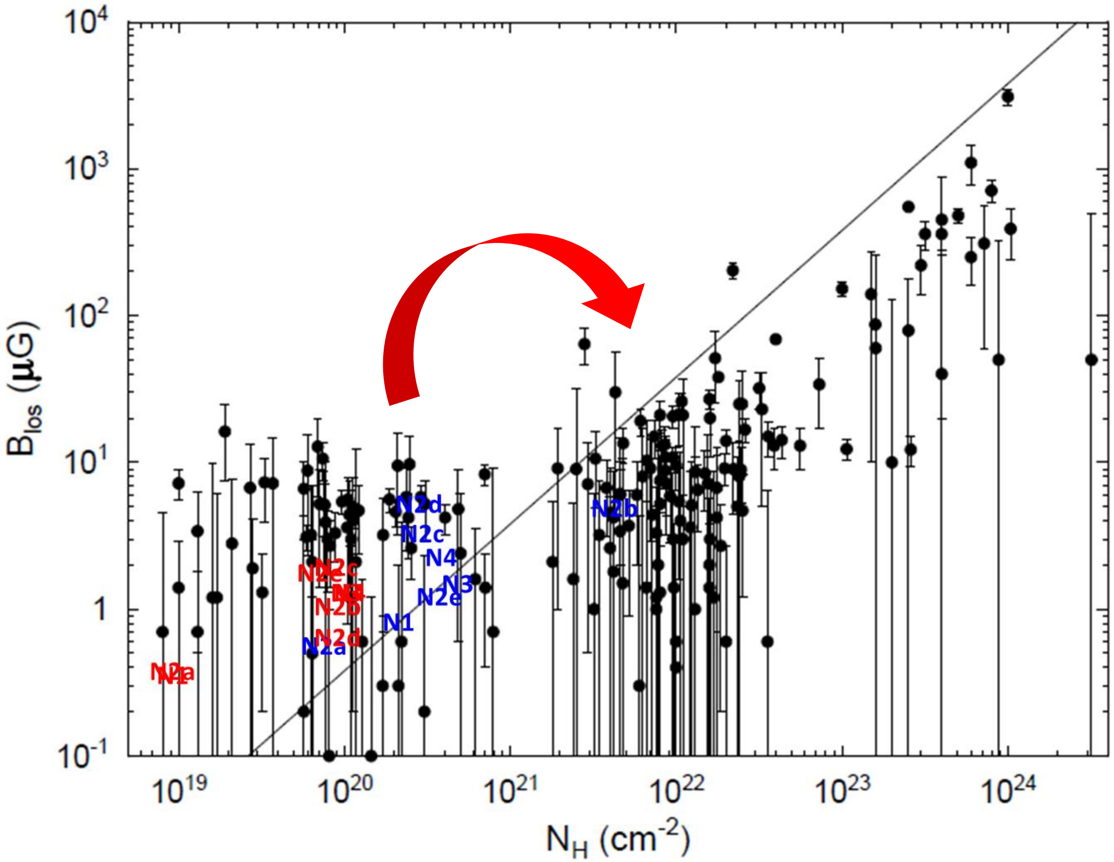
Cores built up in our models by turbulent reconnection diffusion

$$\mu_{crit} = 0.15 - 5.25$$

Our built up cores have mass-to-magnetic flux ratio between cloud core and envelope consistent with observations:

$$R' = (M_c/\Phi_c)/(M_{c+e}/\Phi_{c+e})$$ **<1**

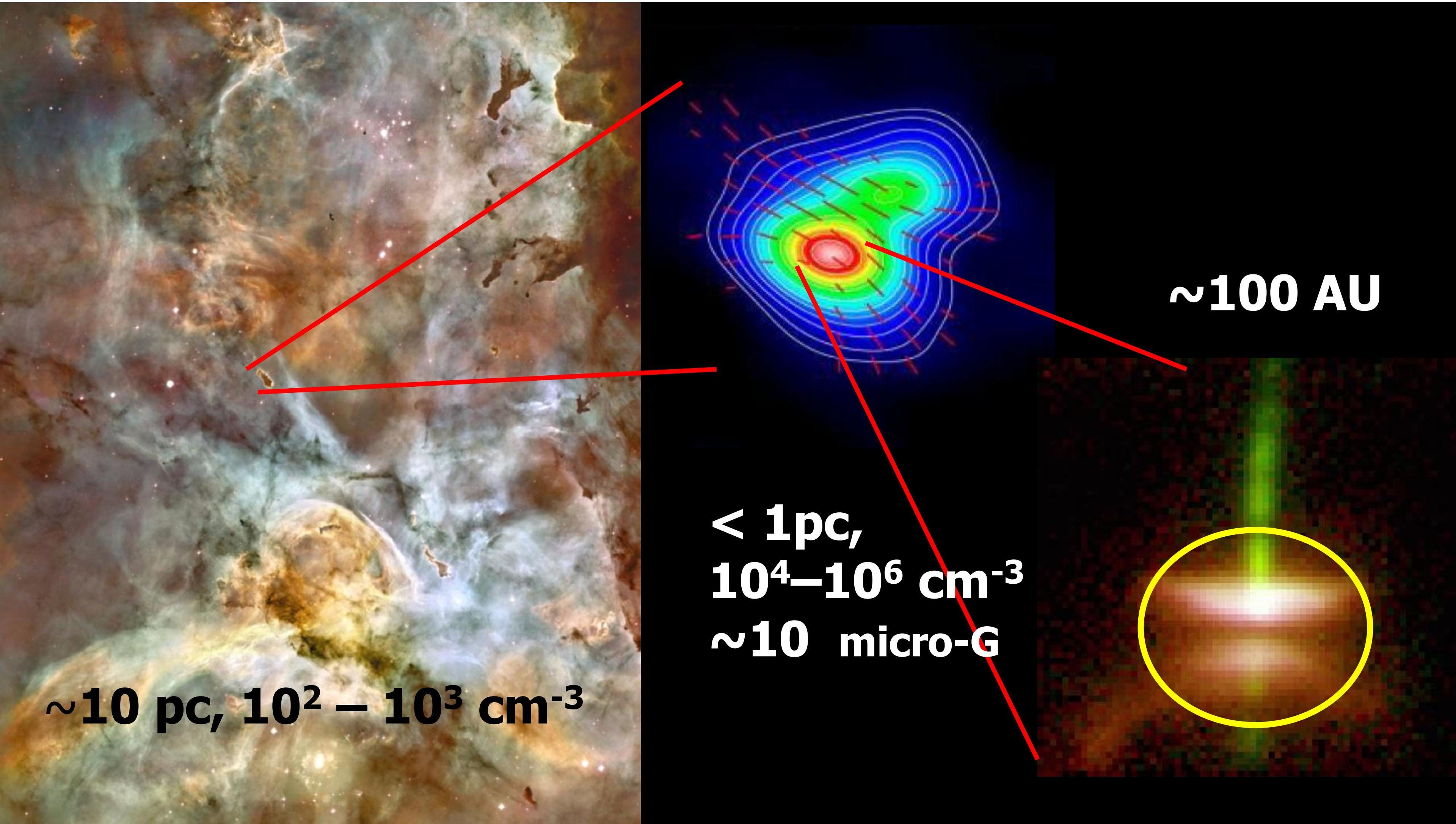
Comparison with observations



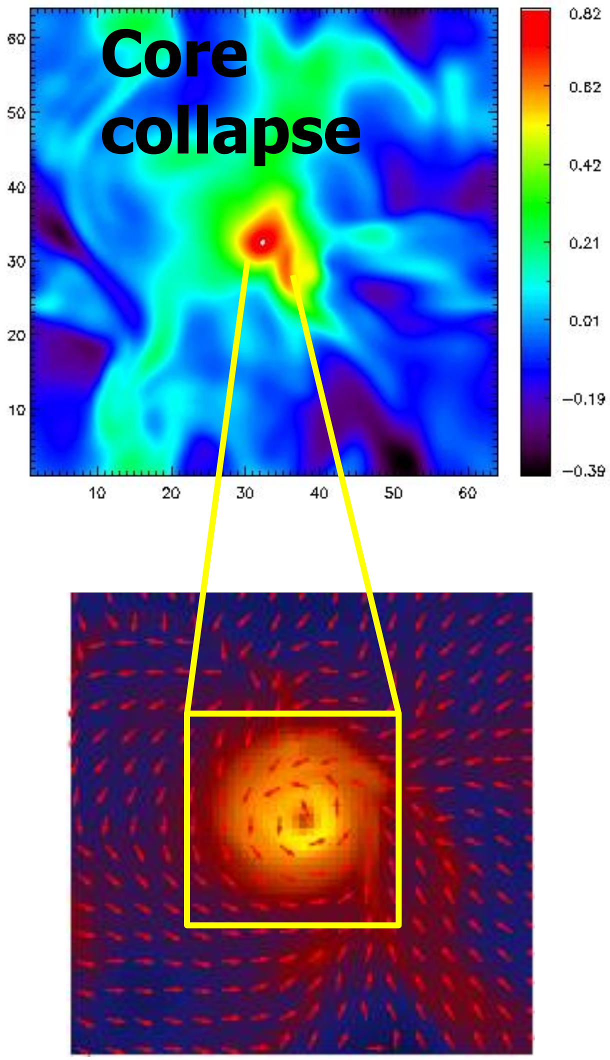
- Simulations versus observed cores by Crutcher et al. (2009, 2010)
- From 12 initially subcritical clumps -> 6 form critical/supercritical

HI, OH, and CN Zeeman measurements of the magnitude of B_{los} versus n_H in cloud clumps (from Crutcher et al. 2010).

@ 100 AU scales: evidence of rotationally supported disks



Supercritical core collapse -> rotationally supported disk?



?

Ideal MHD theory:

Magnetic fields of cloud cores suppress formation of rotationally supported disks (Allen et al. 2003; Galli et al. 2006; Li et al. 2011):

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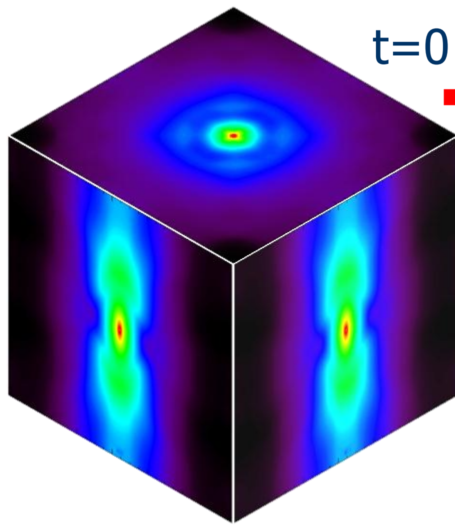
magnetic braking

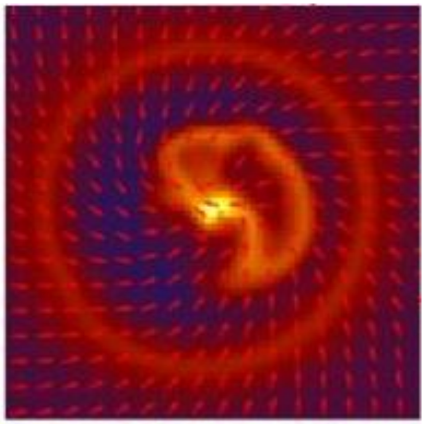
@100 AU scales: formation of rotationally supported disks?

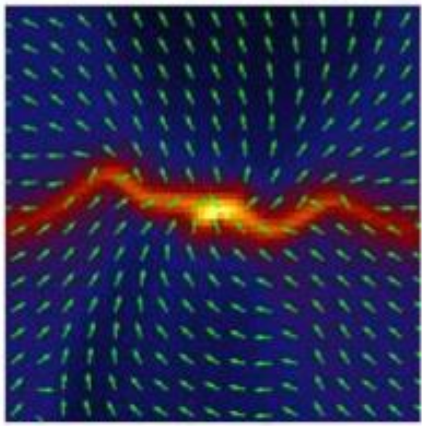
3D IDEAL MHD simulations:

Starting collapsing supercritical, rotating core



t=0



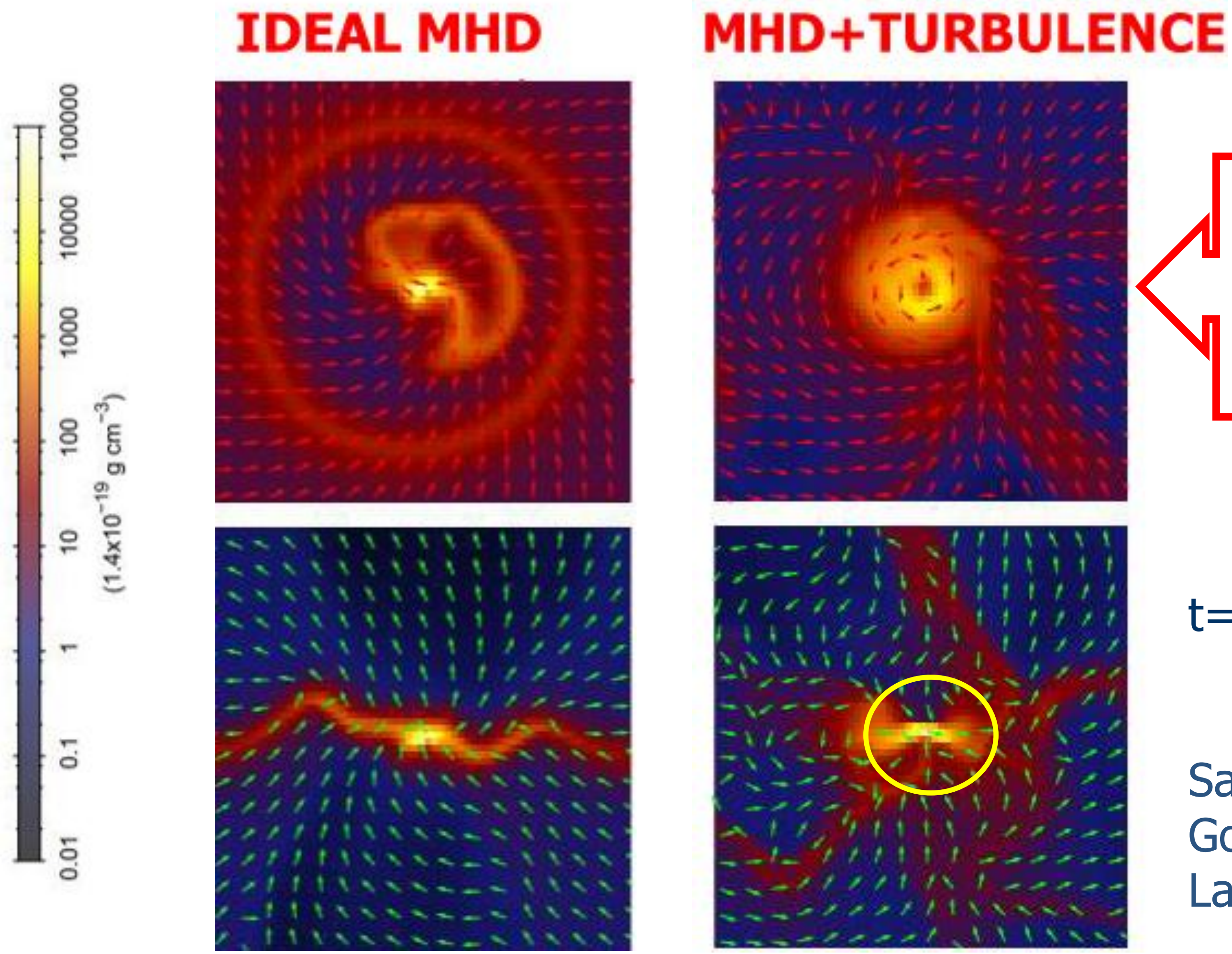


t = 30,000 yr

Fails to form Keplerian disk around protostar (Santos-Lima, deGDP, Lazarian ApJ 2012)

-> magnetic fields transport angular momentum to outside of the disk

Formation of Keplerian disk by turbulent reconnection MF removal



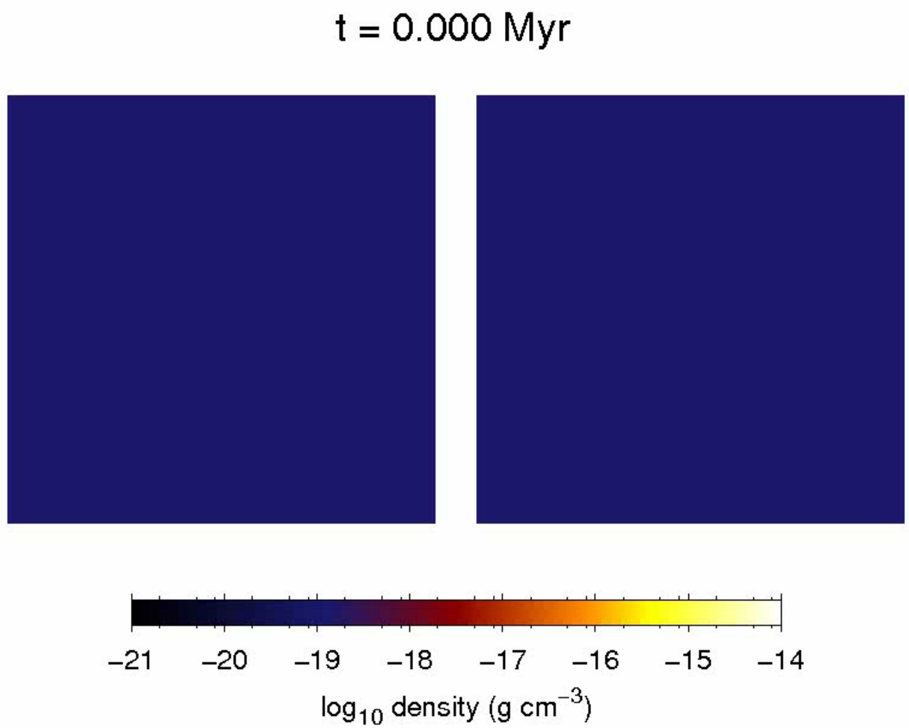
Reconnection diffusion removes MF excess

t=30,000 yr

Santos-Lima, de Gouveia Dal Pino, Lazarian, ApJ 2012

Formation of Keplerian disk due to turbulent reconnection MF removal

MHD + turbulence

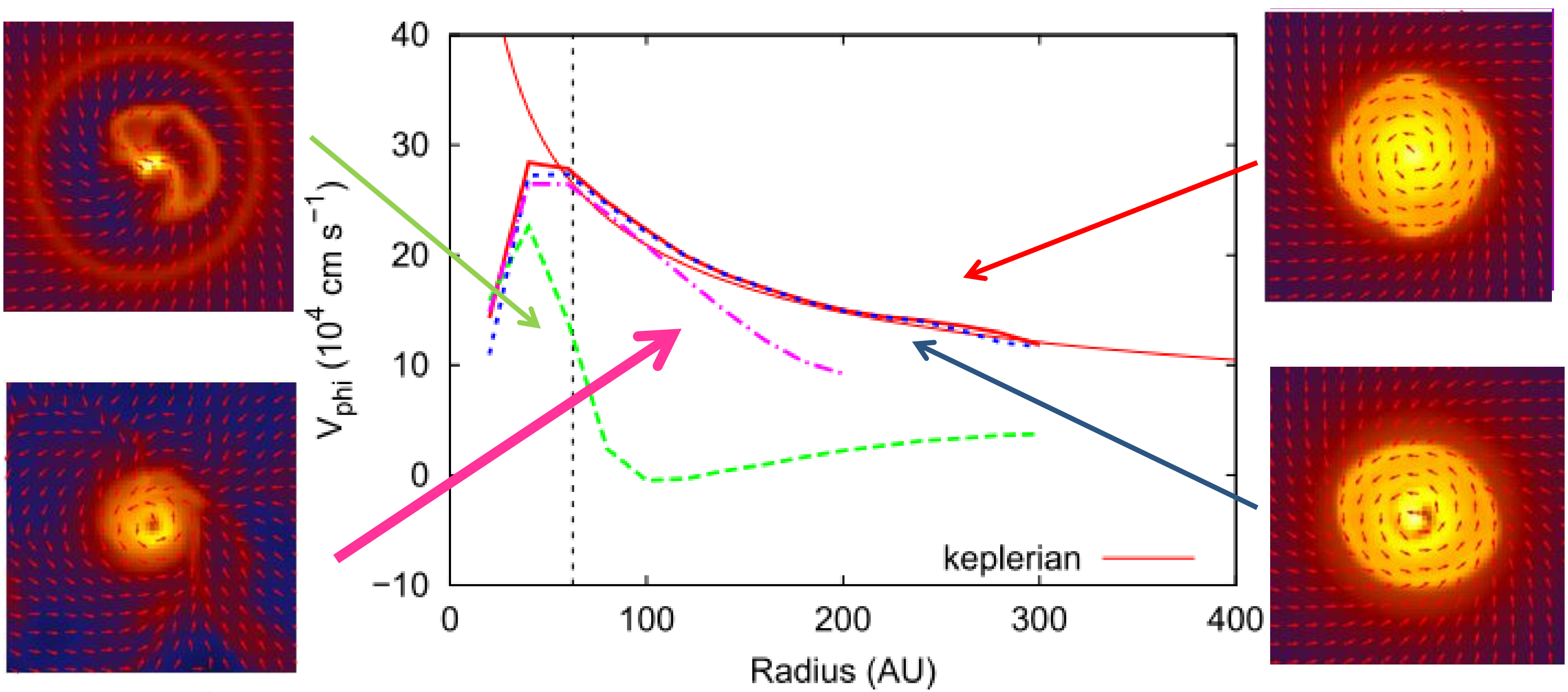


Santos-Lima, de Gouveia Dal Pino, Lazarian, ApJ 2012

Disk rotation velocity

IDEAL MHD

HYDRO



MHD + turbulence

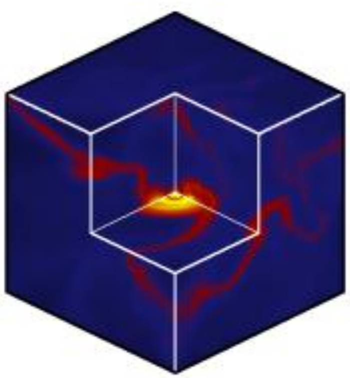
MHD SUPER-η

Santos-Lima, de Gouveia Dal Pino, Lazarian 2012, 2013

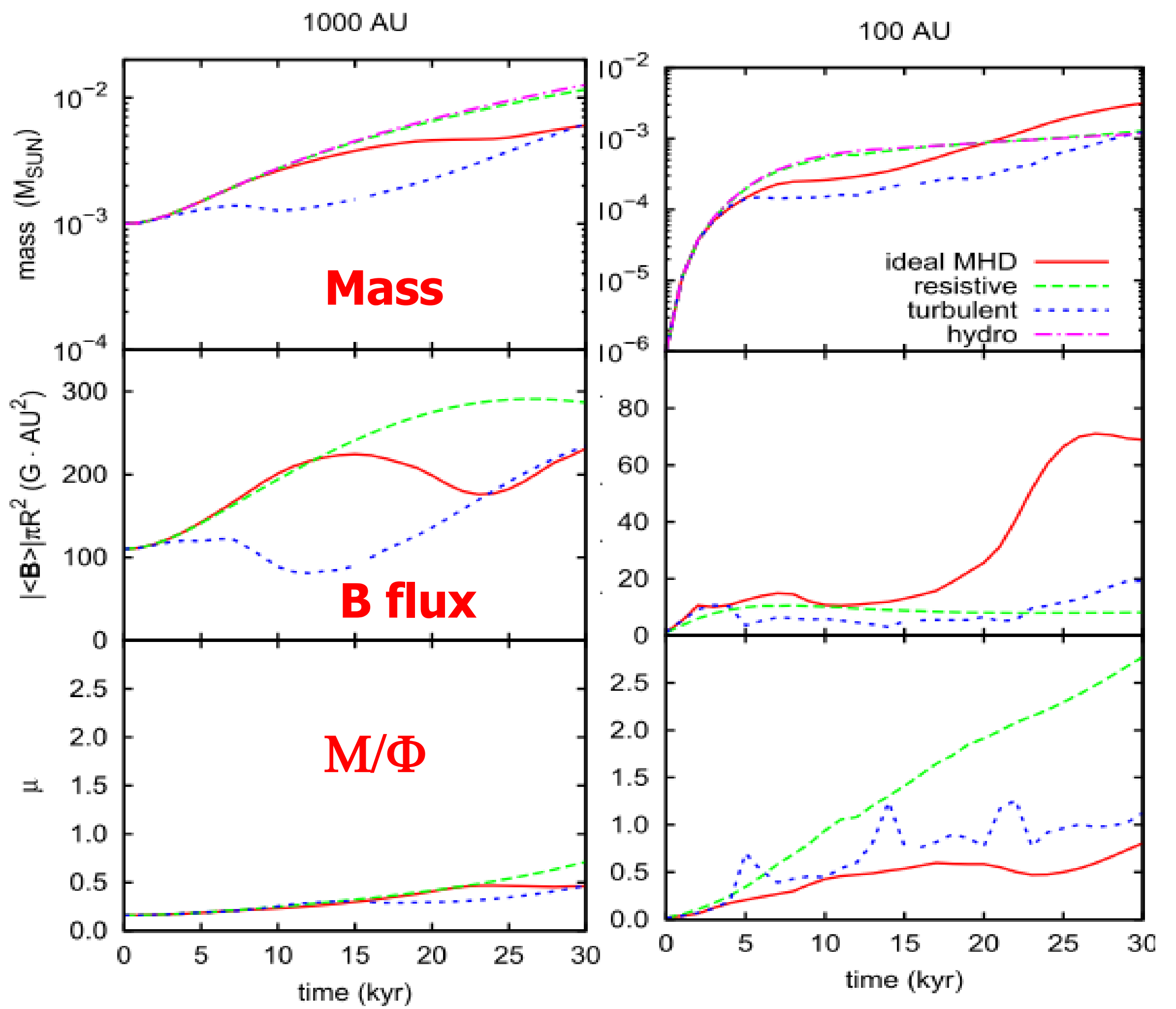
Is magnetic flux loss necessary to stop magnetic braking or not?

Seifried et al. (2012) say:
NO

We say:
YES



Santos-Lima, de Gouveia Dal Pino, Lazarian, MNRAS 2013



B-Flux Transport in SF Summary

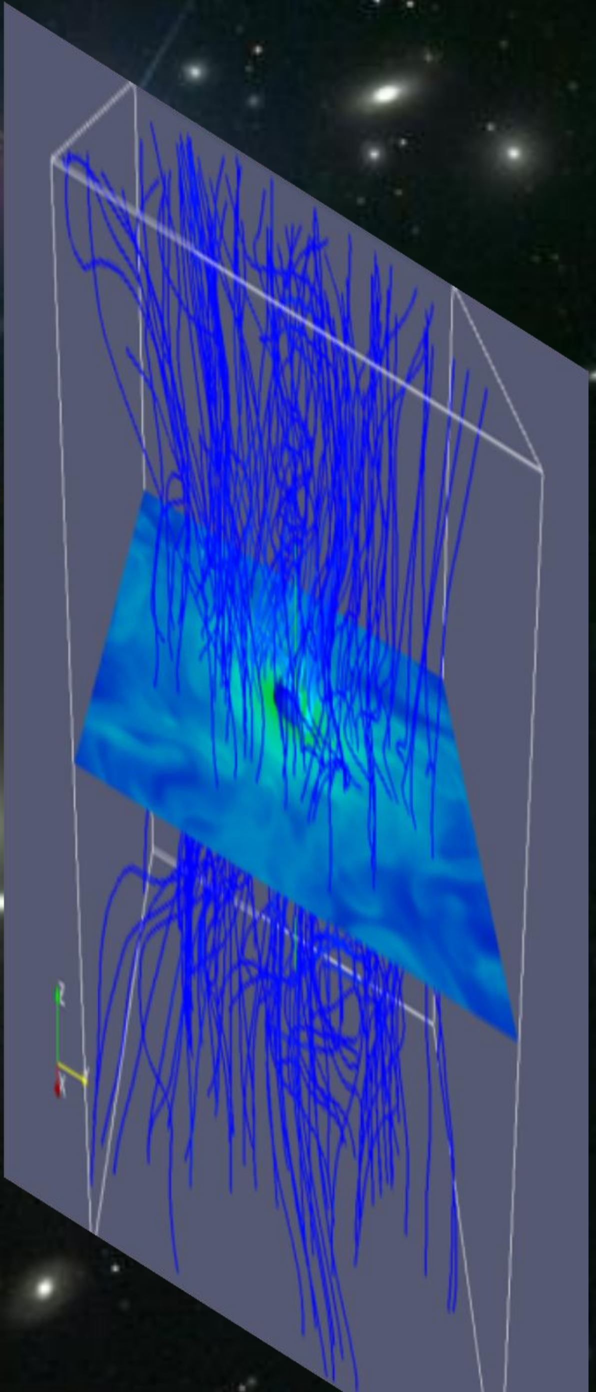
- B-flux removal from collapsing clouds and cores: successfully accomplished with **turbulent reconnection diffusion - TRD** (no need of AD)

- **TRD** can play essential role in the removal of B-flux in **different phases of star-formation** and make molecular clouds - subcritical -> supercritical

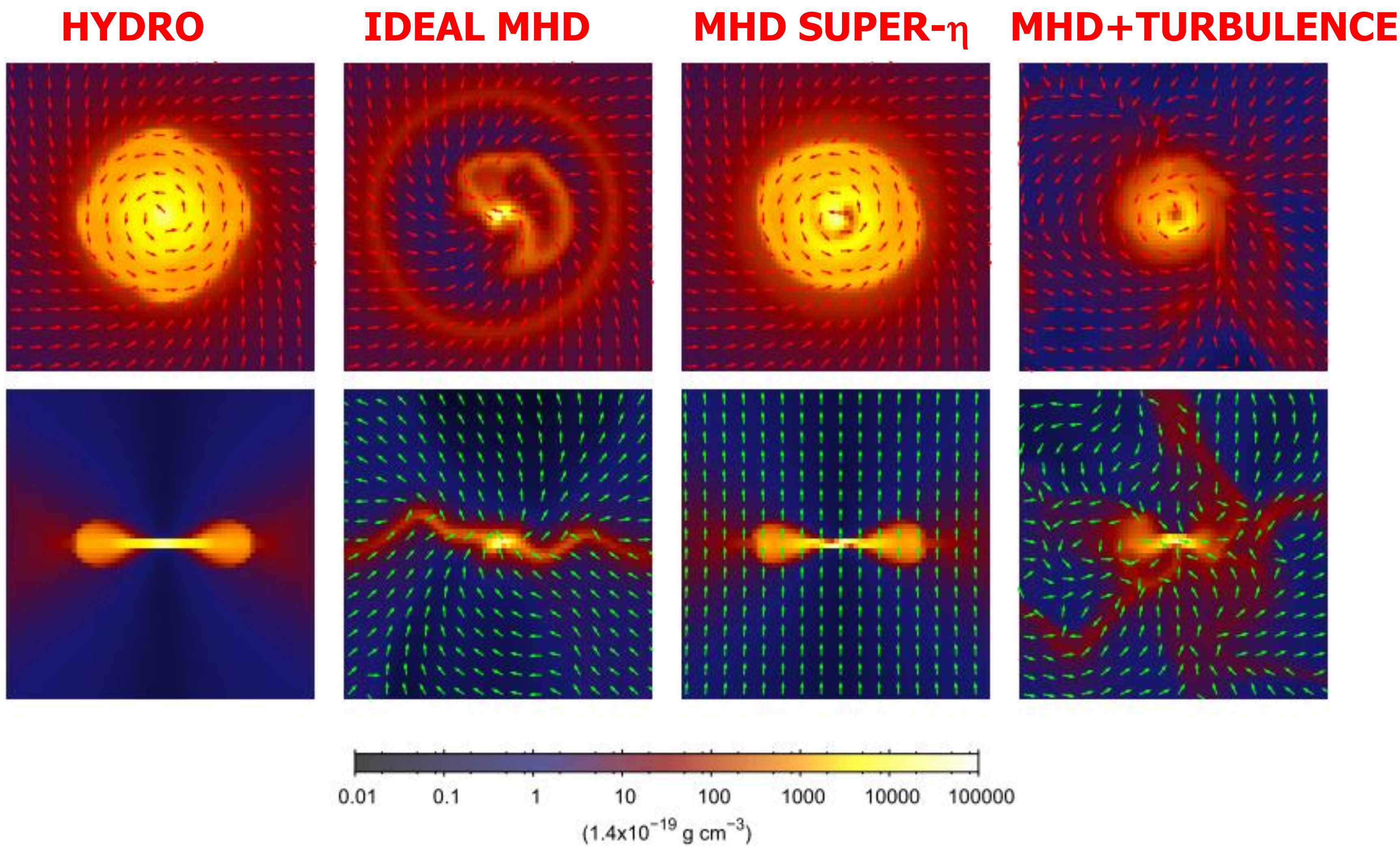
- In a large tested sample of clouds: **few develop** critical or supercritical cores, but with **R´<1** -> consistent with obs.

- **TRD** can transport B-flux excess and allow formation of **rotationally supported accretion disks**

Thank you

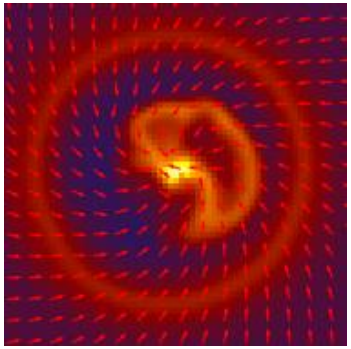


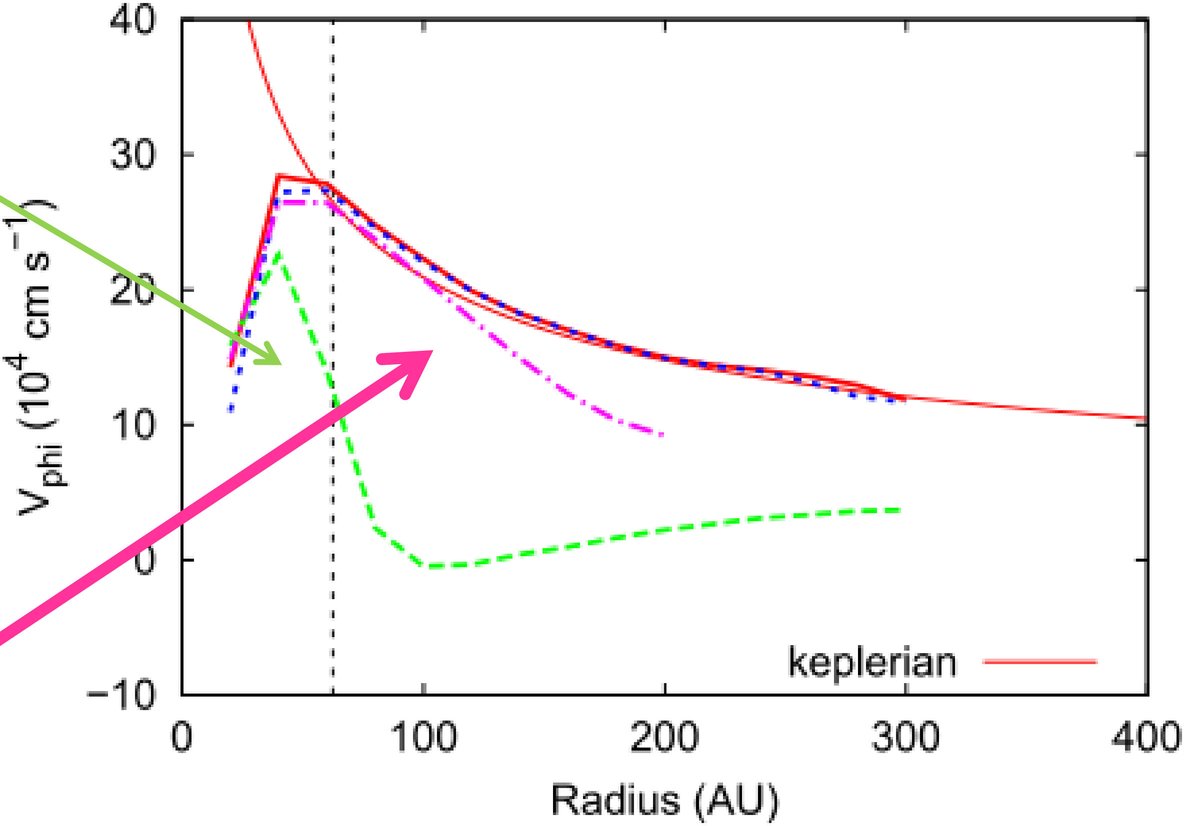
Formation of Keplerian disk by turbulent reconnection MF removal

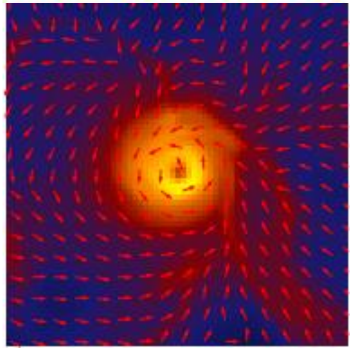


Disk rotation velocity

IDEAL MHD







MHD + turbulence

Santos-Lima, de Gouveia Dal Pino, Lazarian 2012