Magnetic Braking Catastrophe in disk formation

Elisabete M. de Gouveia Dal Pino

IAG-University of São Paulo

MFU III– Poland, August 2011

Collaborators

Reinaldo Santos-Lima (IAG-USP)

Marcia R. M. Leão (IAG-USP)

Grzegorz Kowal (IAG-USP)

Diego-Falceta-Gonçalves (EACH-USP)

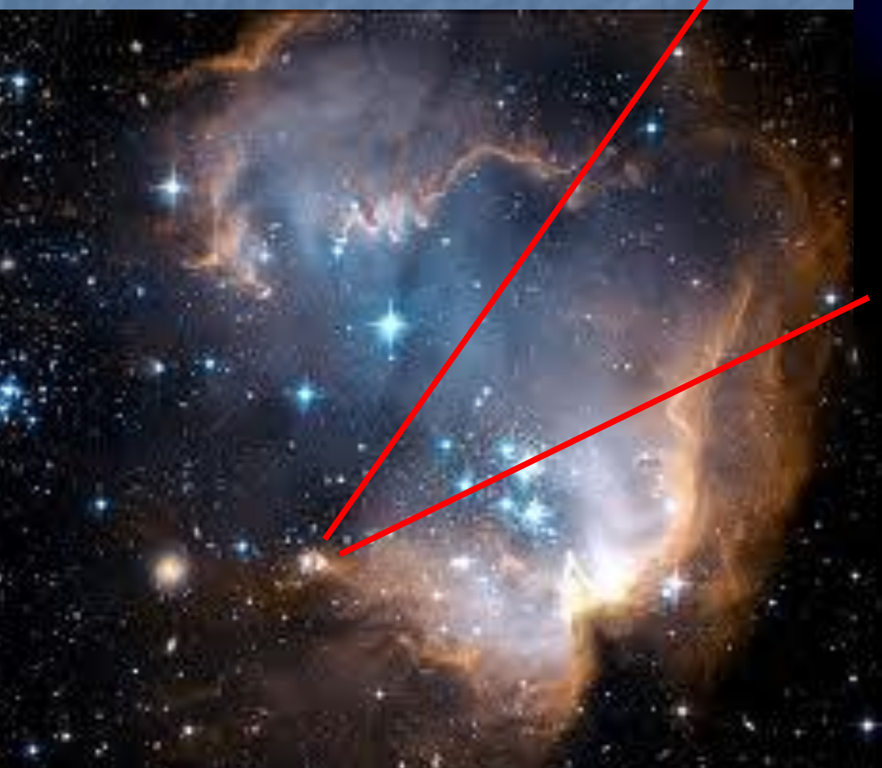
Alex Lazarian (U. Wisconsin)

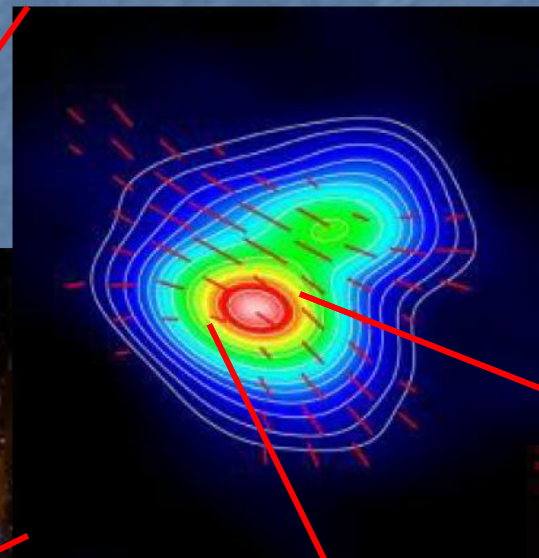
OUTLINE

- ✓**magnetic braking problem** in disk formation
- ✓**Proposed mechanisms:** ambipolar diffusion, Hall effect, Ohmic-resistivity
- ✓**Possible solution: flux transport by turbulent reconnection**

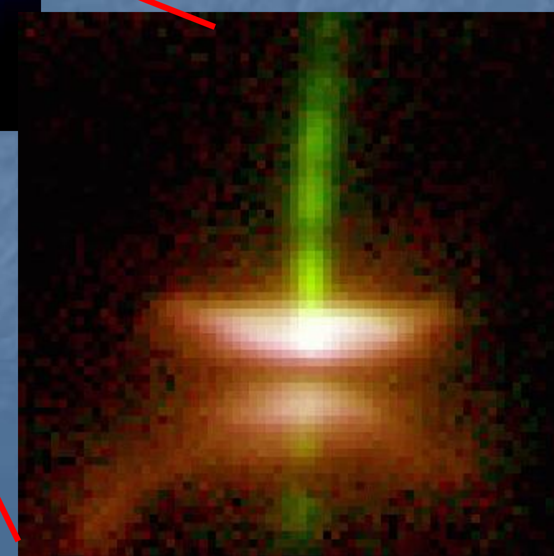
Star Formation not well understood in neither scale

~10 pc, $10^2 - 10^3$ cm^{-3}





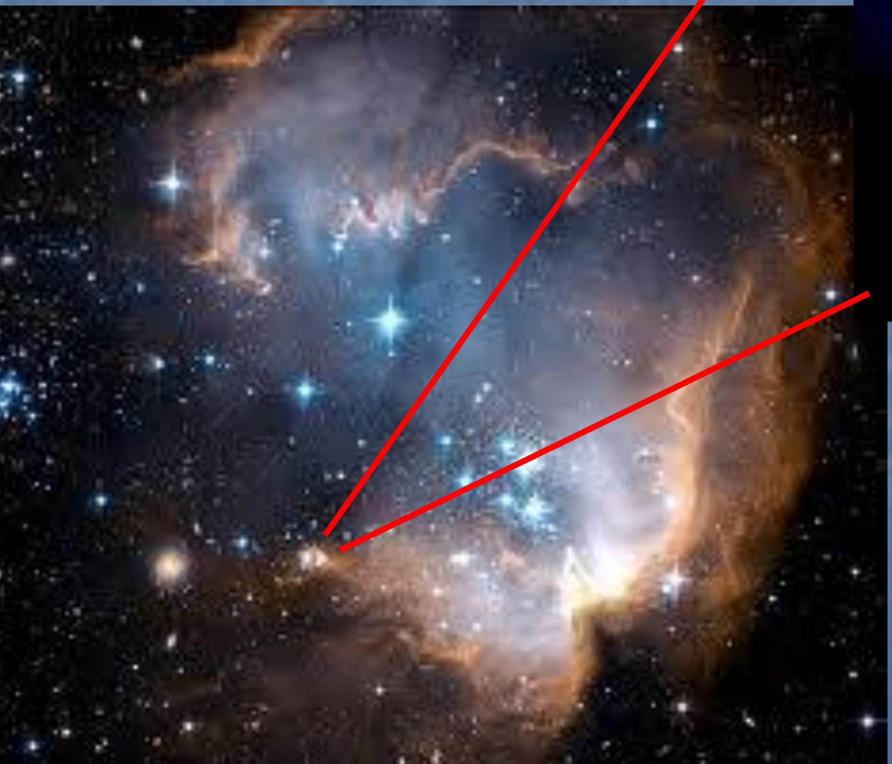
~100 AU

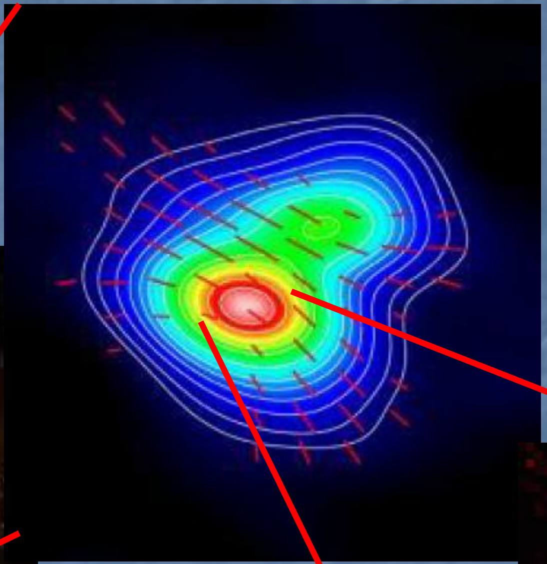


< 1pc,
10^4–10^6 cm^{-3}
~10 micro-G

Star Formation not well understood in neither scale

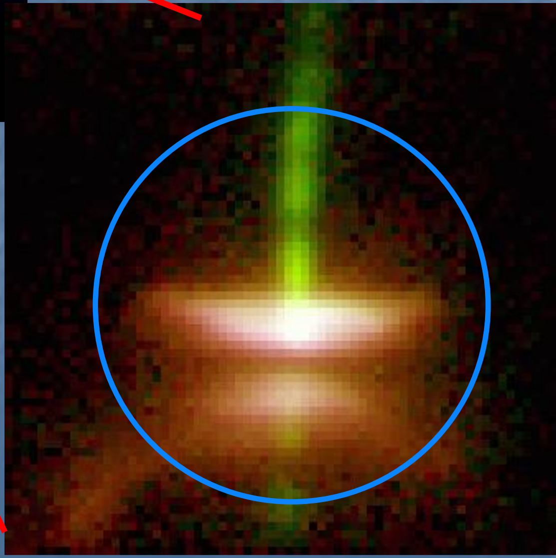
~10 pc, $10^2 – 10^3$ cm^{-3}





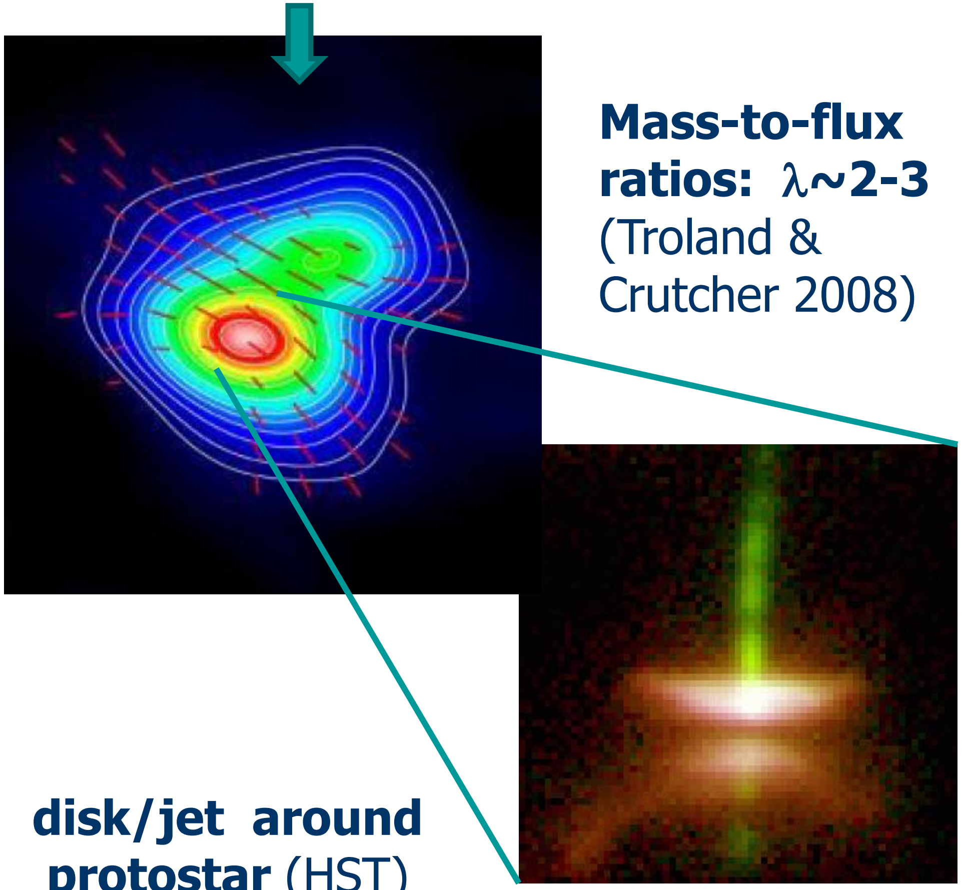
< 1pc,
$10^4–10^6$ cm^{-3}
~10 micro-G

~100 AU



@ 100 AU scales: evidence of rotationally supported disks

Collapsing cloud core

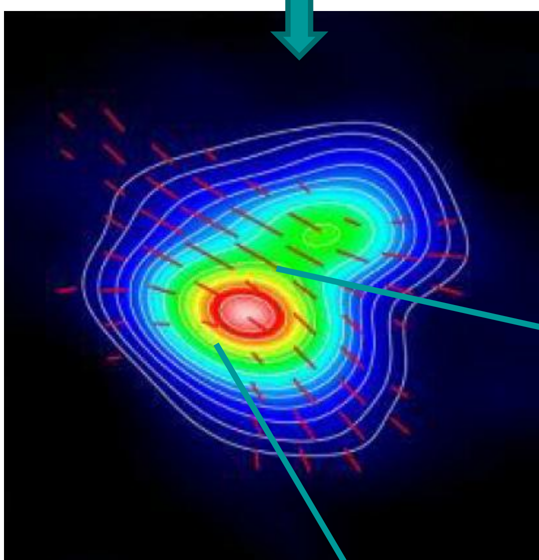


Mass-to-flux ratios: λ~2-3 (Troland & Crutcher 2008)

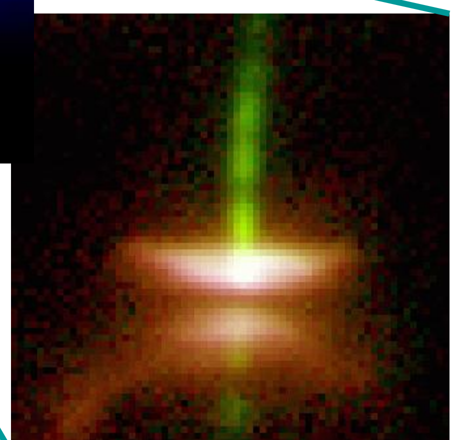
disk/jet around protostar (HST)

@ 100 AU scales: evidence of rotationally supported disks

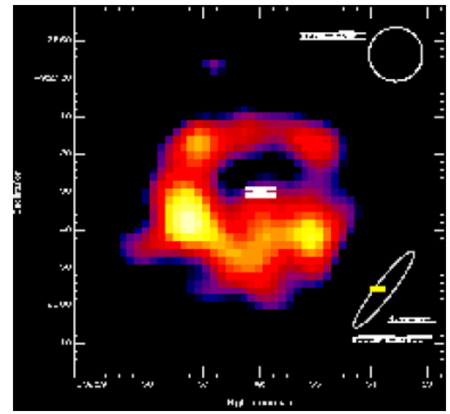
Collapsing cloud core



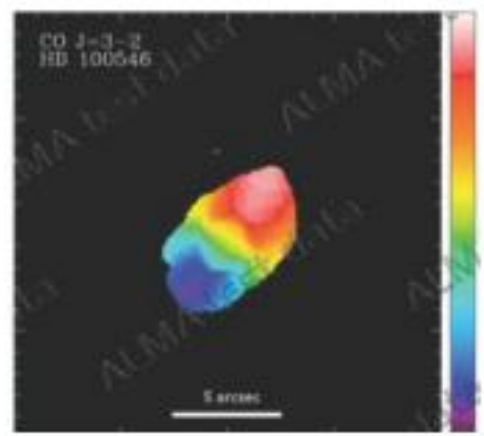
Mass-to-flux ratios: λ~2-3
(Troland & Crutcher 2008)



disk/jet around protostar (HST)



SCUBA
(200μm - 1mm)



ALMA CO (3-2)

rotating disks around protostars -> colors probe rotation

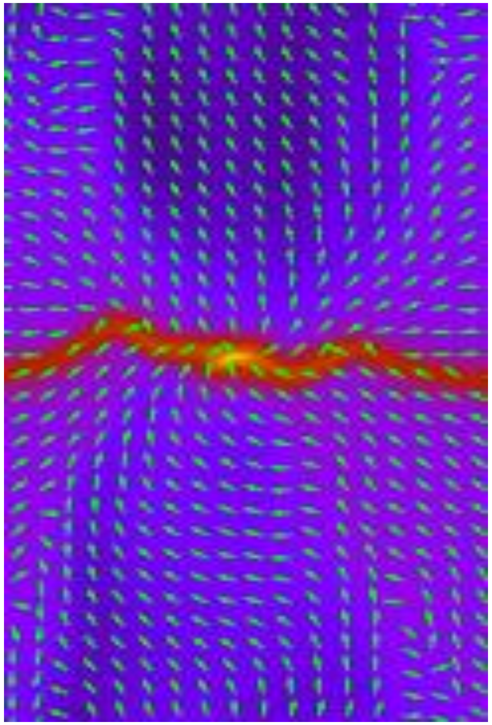
@100 AU scales: formation of rotationally supported disks?

BUT 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):

⬇

magnetic braking



3D Ideal MHD simulation: fails to form Keplerian disk around protostar

(Santos-Lima, de Gouveia Dal Pino, Lazarian 2011)

Magnetic Braking Problem?

To solve it: need to remove B-field

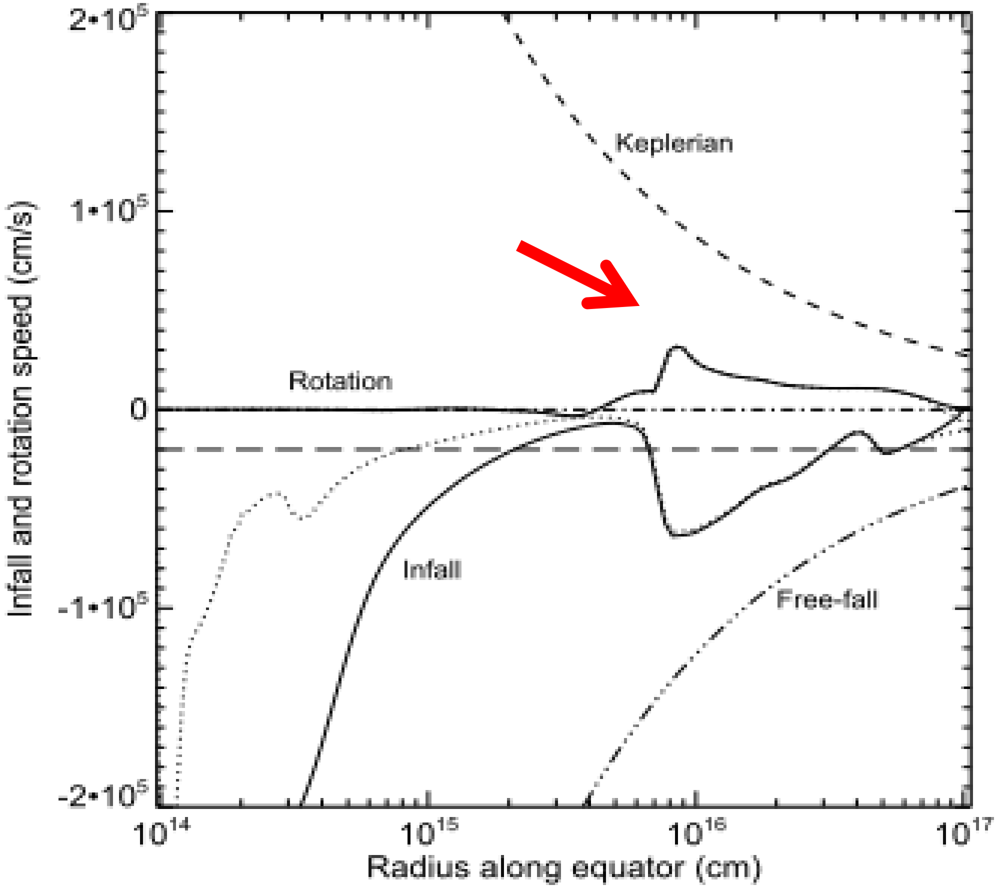
Diffusive mechanisms usually invoked:

- **Ambipolar diffusion (AD)** (Mestel & Spitzer 1956; Muschovias 1979; Heitch et al. 2004)
- **Hall effect** (Krasnopolsky et al. 2011, Li et al. 2011)
- **Ohmic-resistivity (classic or enhanced)** (Shu et al. 2006;Krasnopolsky et al. 2010; Machida et al. 2010, 2011)

Ambipolar Diffusion not sufficient?

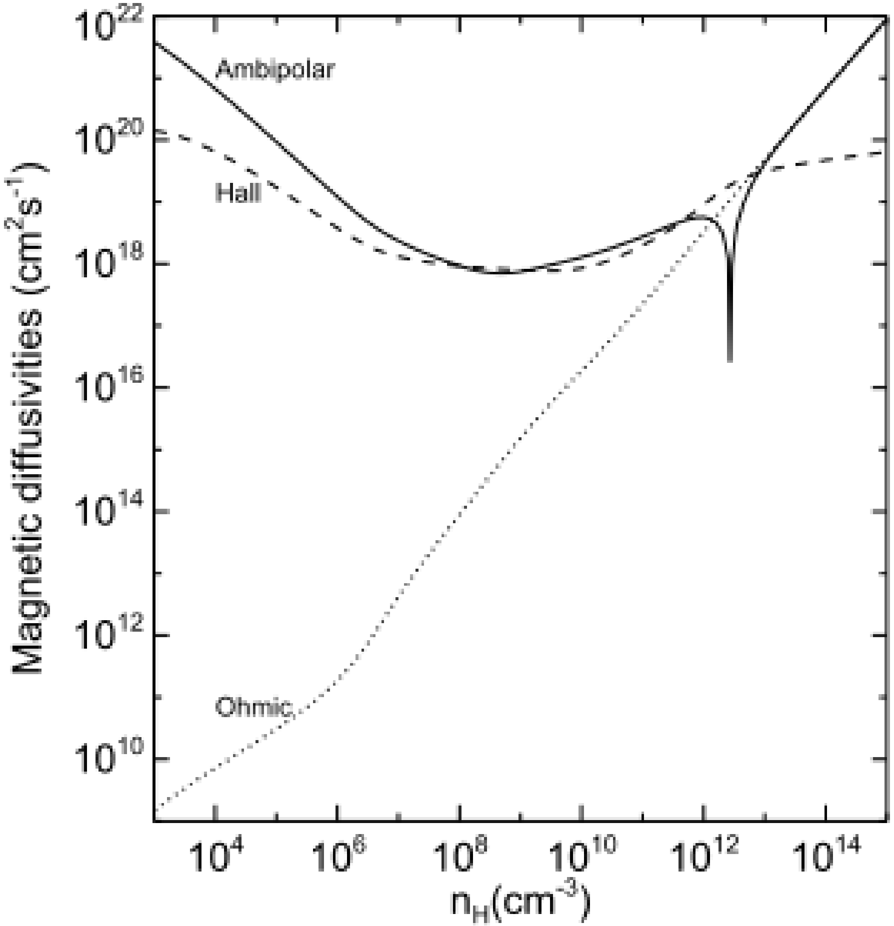
- **AD: NOT sufficient to remove flux and stop magnetic braking**
  (Mellon & Li 2009, Krasnopolsky & Konigl 2002)

- **AD ENHANCES braking**:
  allows the magnetic flux to pile up in a small circumstellar region -> where braking efficiency increases (Li+2011)



2D MHD simulation with AD
(Li, Krasnopolsky, Shang 2011)

Realisitic Hall Effect not efficient?



Li, Krasnopolsky, Shang 2011

- **Hall effect -> torque:** can spin up material close to central object (even when the core is initially non-rotating) (Krasnopolsky+2011)

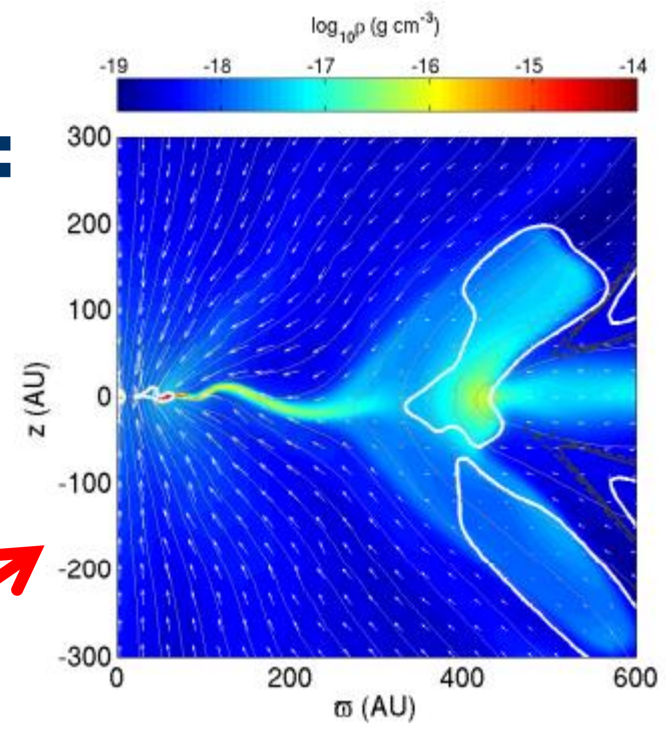
- **BUT:** spun-up material remains **too sub-Keplerian to form rotationally supported disk** (Li+2011)

Ohmic Resistivity not efficient?

- **Classical Ohmic resistivity:**

$$\eta = 1.7 \times 10^{17} \left(\frac{\rho}{10^{-13}\,\mathrm{g\,cm^{-3}}} \right) \; (\mathrm{cm^2\,s^{-1}})$$

Also fails to form rotationally supported disk



2D MHD simulation with Ohmic resistivity
(Krasnopolsky et al. 2010)

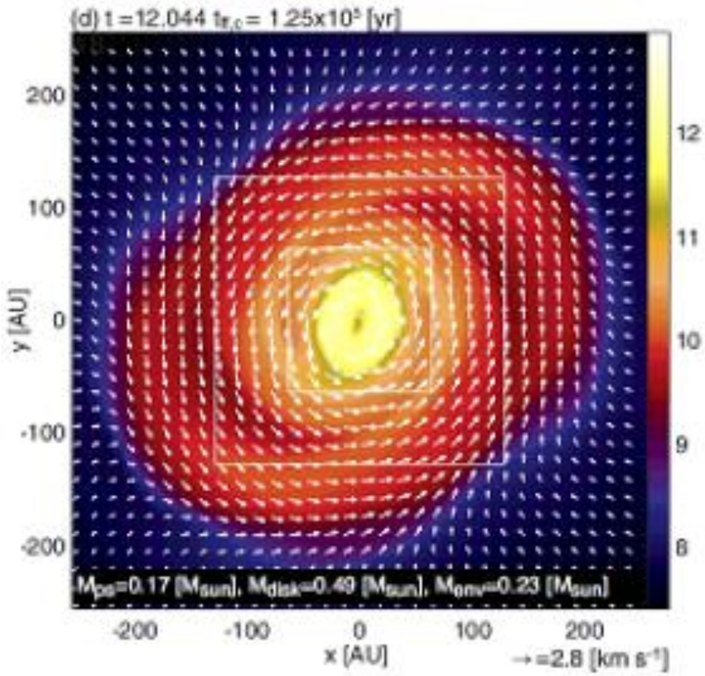
Controverse on Ohmic resistivity?

- **Machida et al. (2010; 2011):**

  rotationally supported disk w/ Ohmic resistivity!

- **HOW? different initial setup**
  (>10 x denser, 10 x slower rotation in cloud central regions)

Process SLOW: ~10^5 yr and forms massive disk: ~0.5 M_S



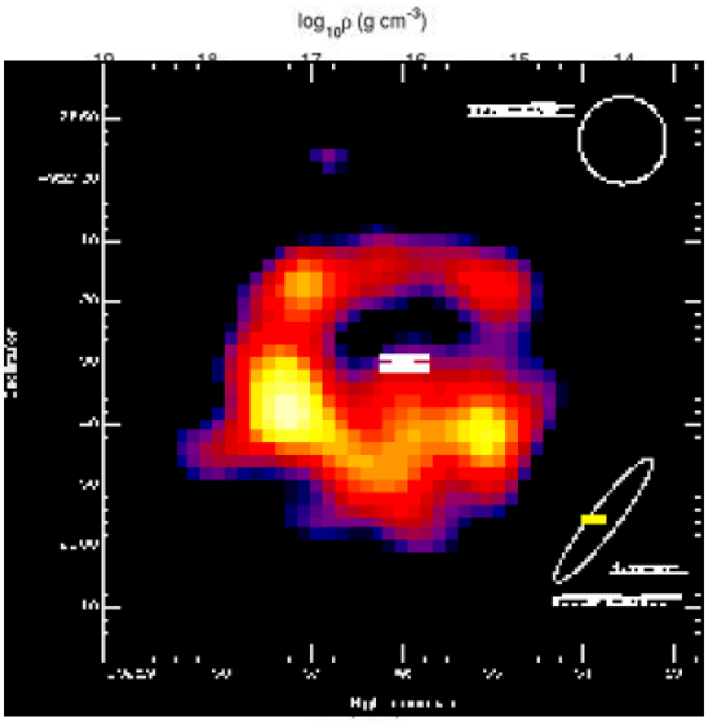
3D MHD simulations with Ohmic resistivity
(Machida, Inutsuka, Matsumoto 2011)

New faster mechanism to remove magnetic flux

To enable formation of 100 AU Keplerian proto-stellar disk:

↓

Magnetic flux removal by Turbulent Reconnection diffusion



Disk around protostar
(SCUBA)

New scenario

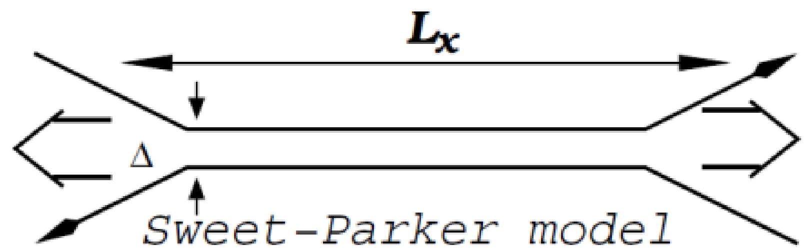
Diffusion through turbulent reconnection.

Due to turbulence: field lines reconnect, changing their topology and then magnetic flux escapes from denser regions.

➔ *Lazarian (2005), Santos-Lima et al. (2010)*

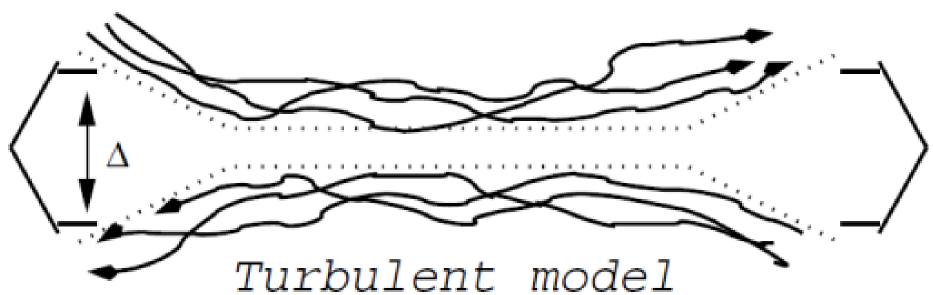
Underlying physics

Turbulent reconnection:



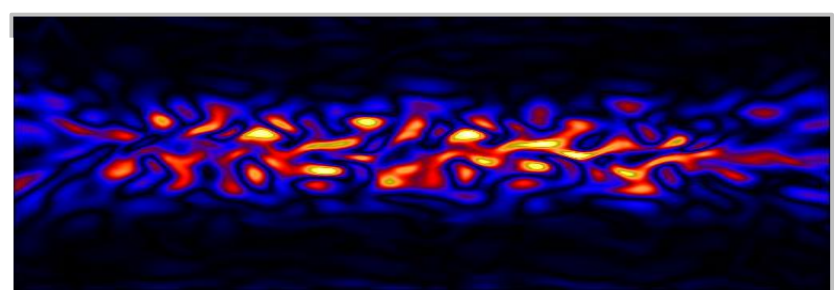
↓

- Lazarian & Vishniac (1999) fast reconnection model



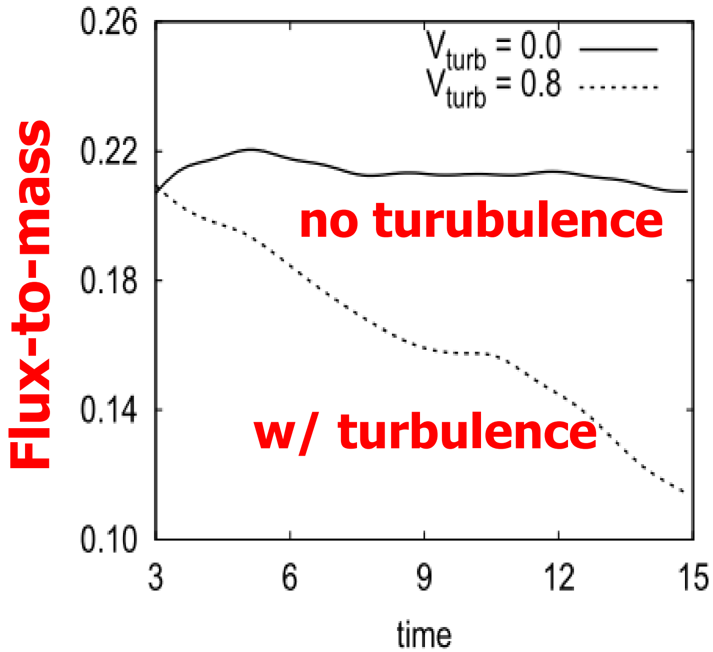
B dissipates on a small scale $\lambda_{||}$: many simultaneous reconnection events

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

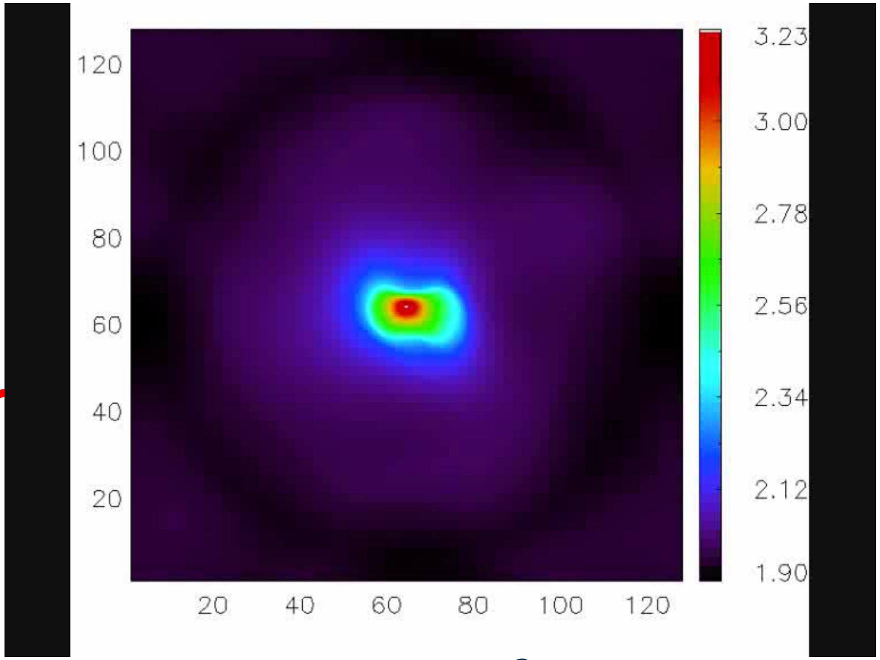


MF removal by turbulent reconnection from COLLAPSING CLOUDS

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



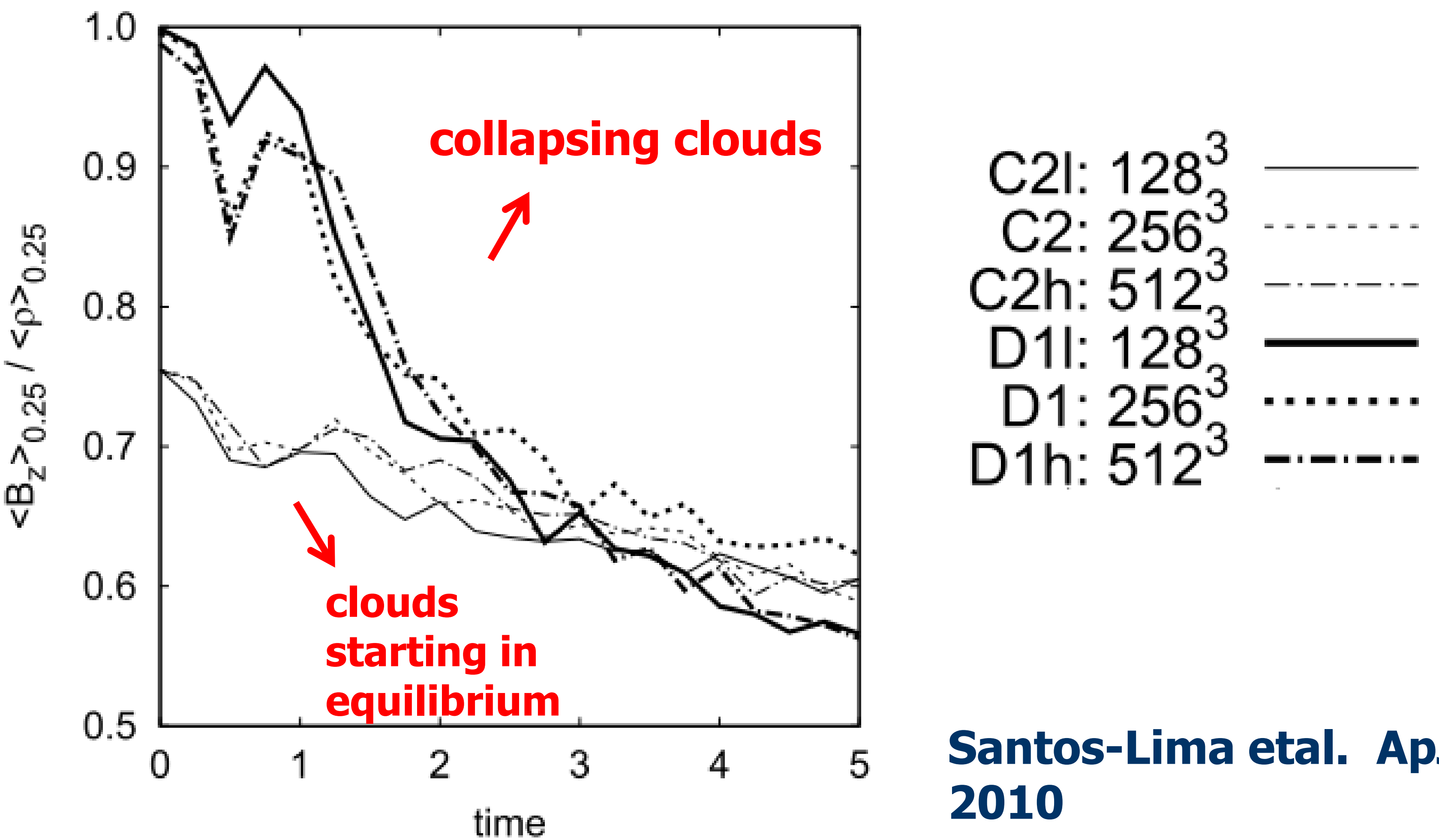
core formation



β=3, n=100 cm^{-3} t_f=95 Myr

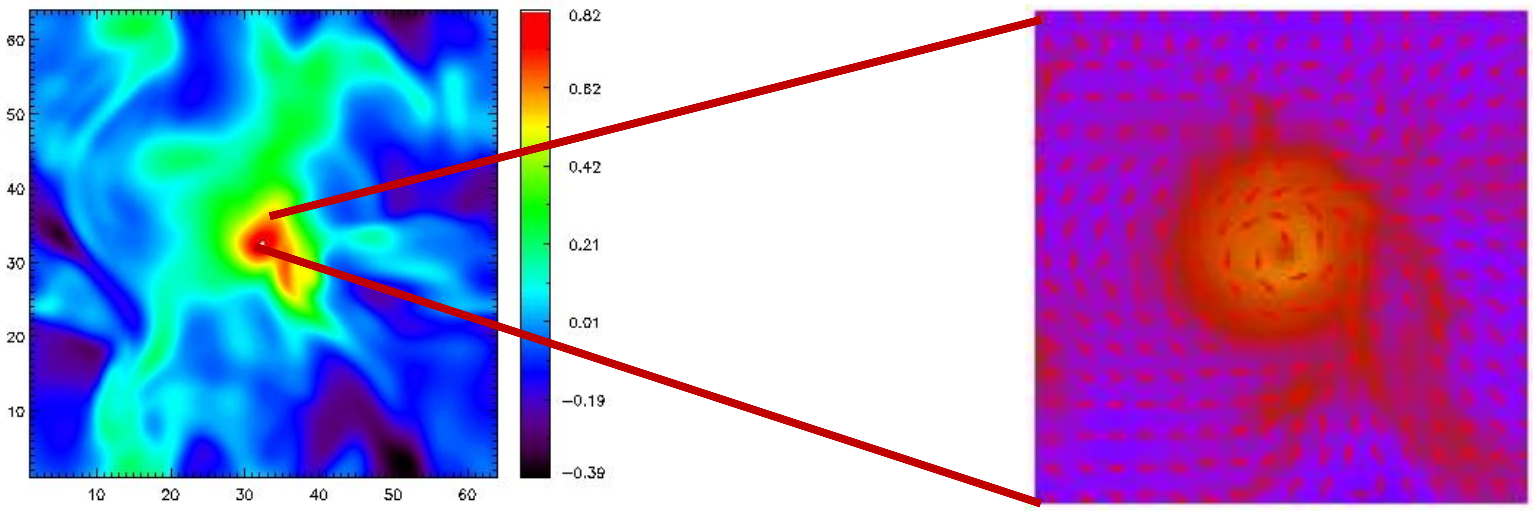
(Santos-Lima et al. 2010; see also Leão´s talk)

Effects of numerical resolution on the reconnection diffusion



Santos-Lima etal. ApJ 2010

Rotationally Supported Disk formation due to turbulent reconnection diffusion



3D MHD simulations of disk formation

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

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

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

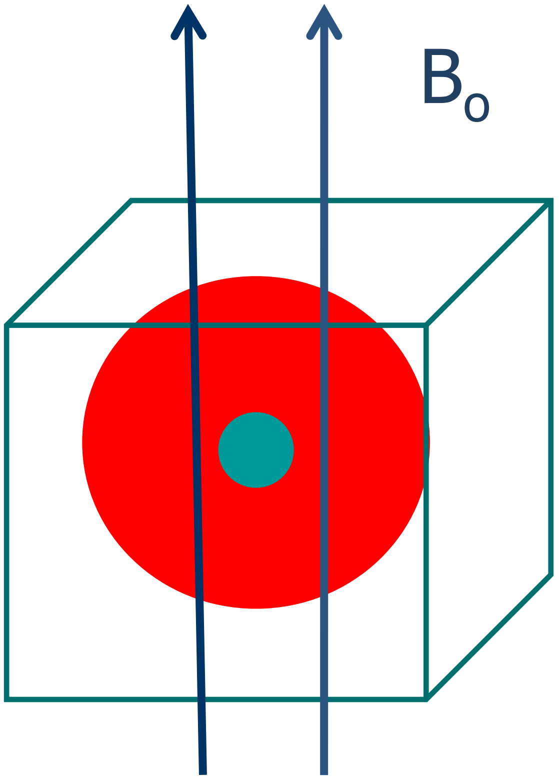
- 2^{nd} order shock capturing Godunov scheme with HLL solver (Kowal et al. 2007)

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

- $\eta_{Ohm} = 0$

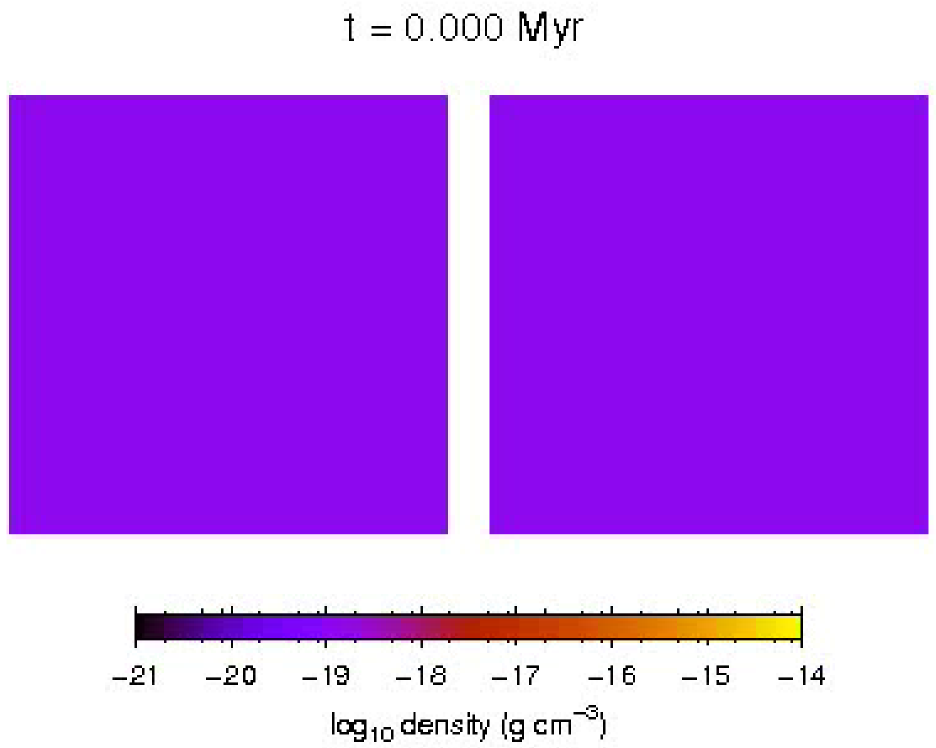
3D MHD simulations of disk formation: setup

- Collapsing, rotating core (1 M_S)
- Around protostar – sink particle (0.5 M_S)
- initial density ~10^{-19} g/cm^3 (~10^5 cm^{-3})
- Initial magnetic field B_o= 35 μG
- initial rotation: $v_\Phi = c_s \tanh(R/R_c)$
- Initial sound speed c_s=0.2 km/s
- initial mass-to-flux ratio: λ~3
- open boundaries
- injection of supersonic, sub-Alfvenic turbulence



- resolution: 384x384x256 (cell size=15.6 AU)

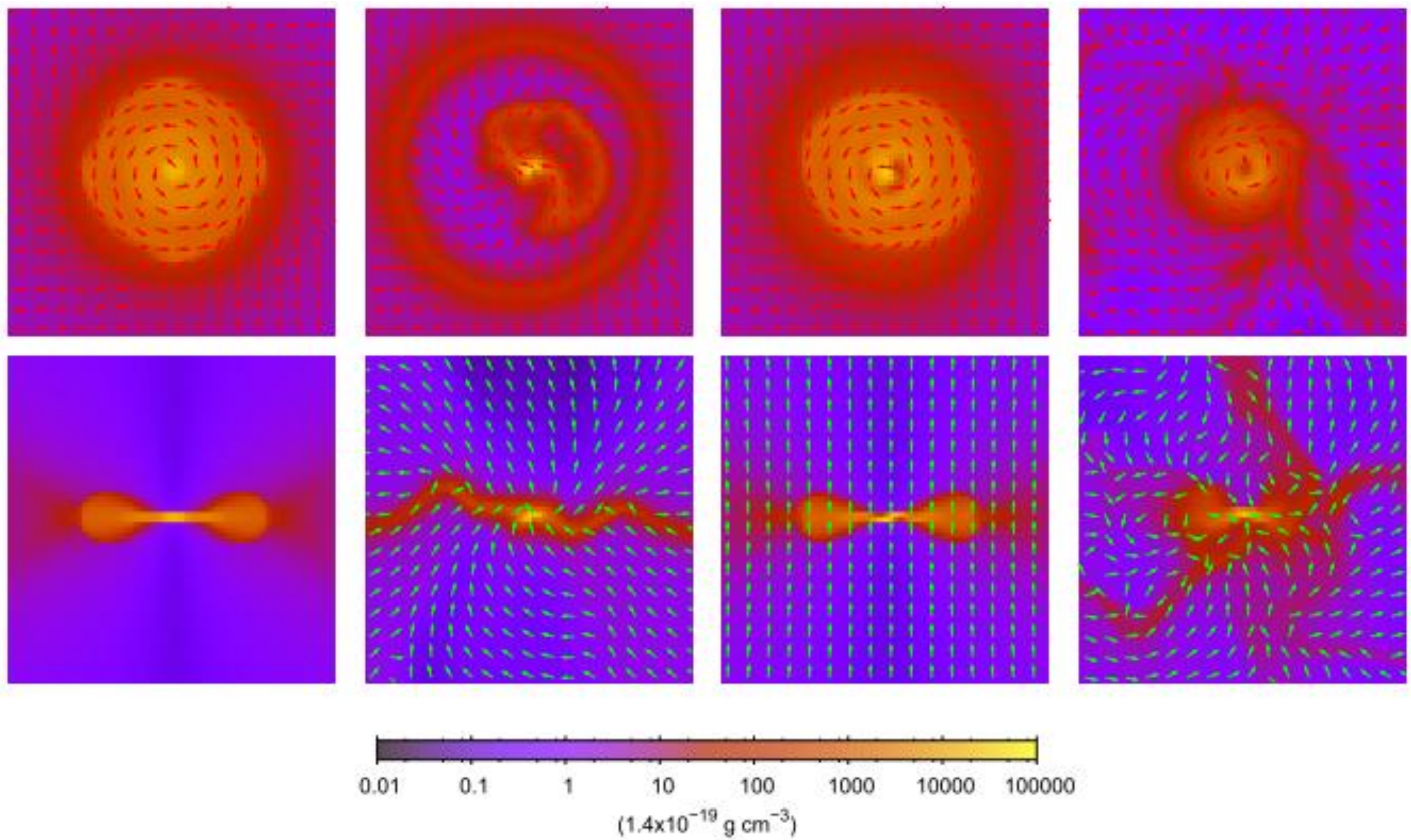
Formation of Keplerian disk due to turbulent reconnection MF removal



Santos-Lima, de Gouveia Dal Pino, Lazarian 2011

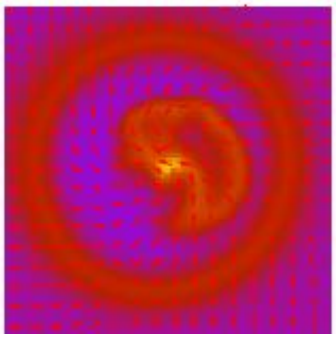
Formation of Keplerian disk by turbulent reconnection MF removal

HYDRO | **IDEAL MHD** | **$\eta=10^3 \eta_o$** | **MHD+TURBULENCE**

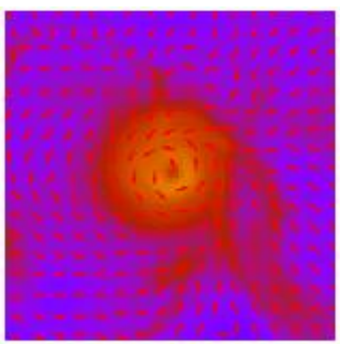


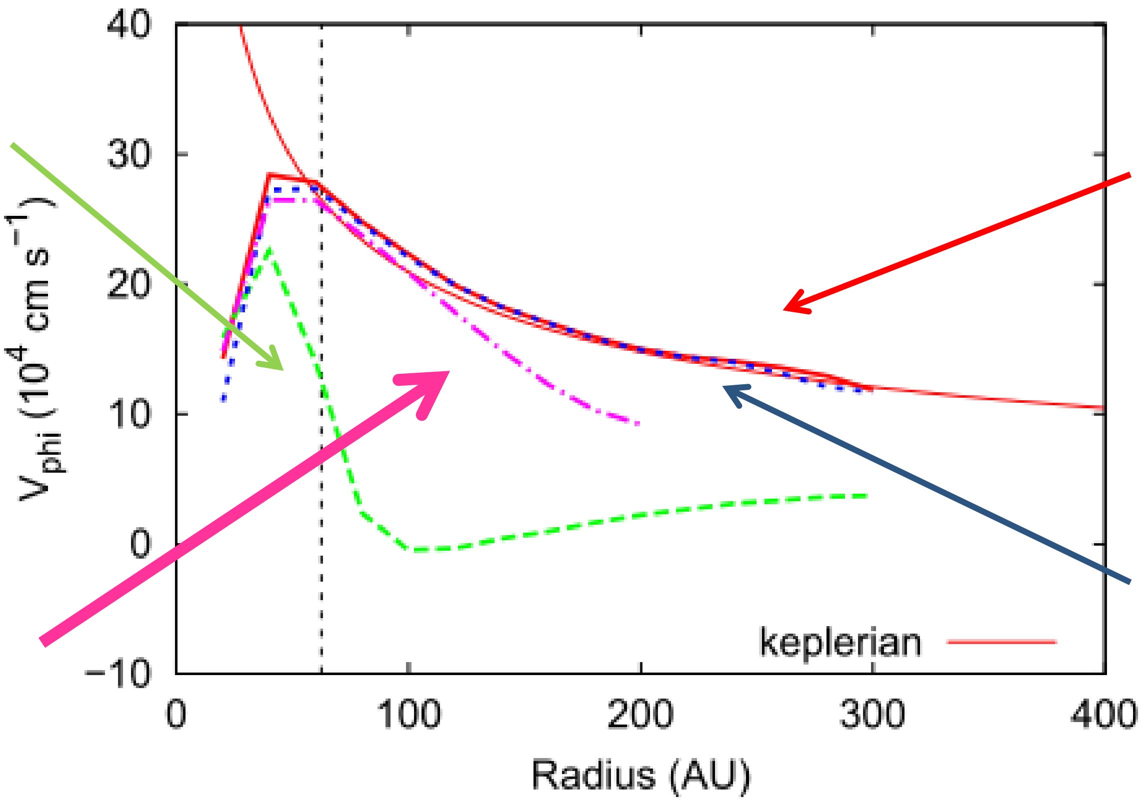
Disk rotation velocity

IDEAL MHD

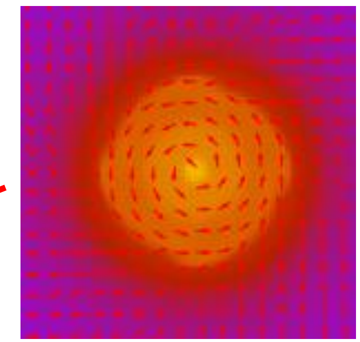


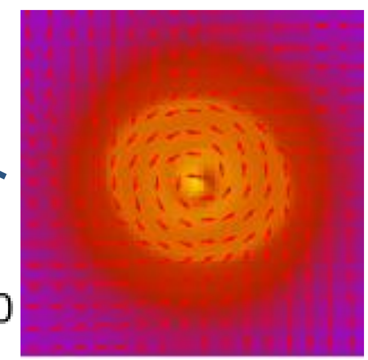
MHD + turbulence





HYDRO



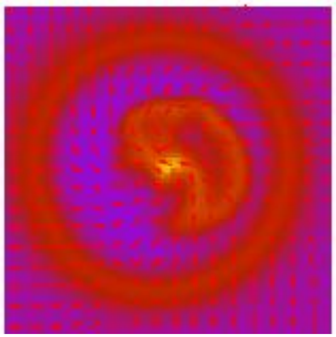


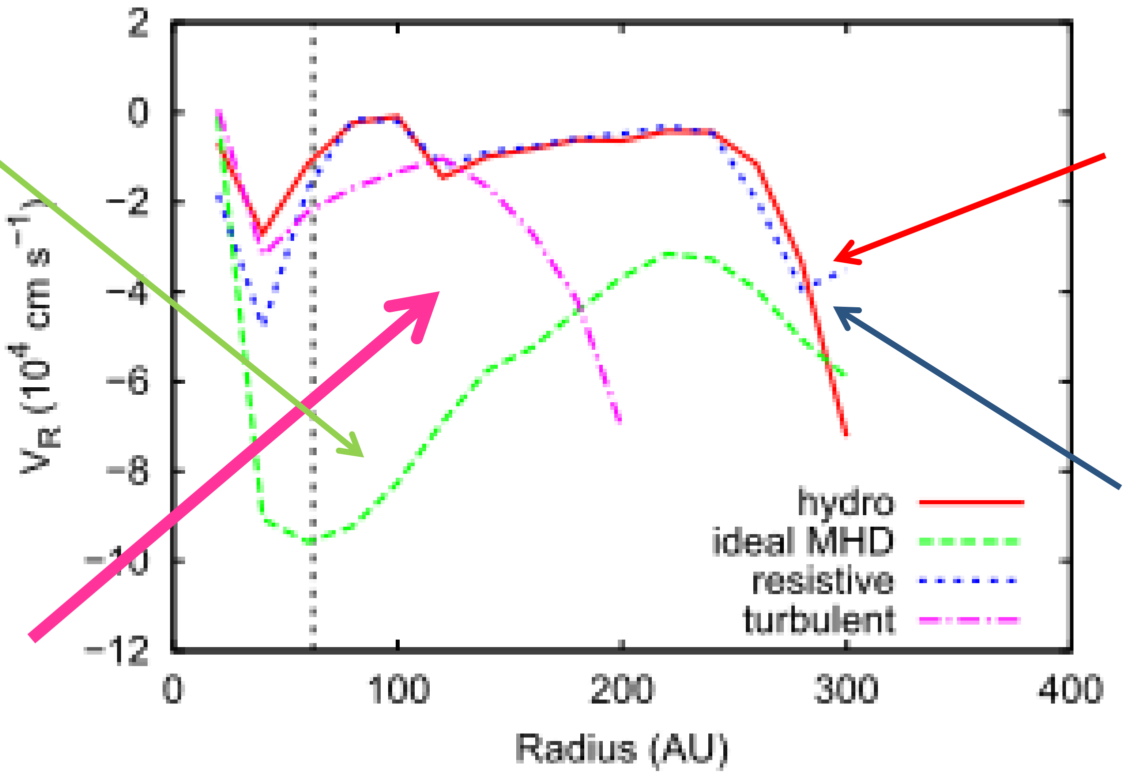
MHD SUPER-η

Santos-Lima, de Gouveia Dal Pino, Lazarian 2011

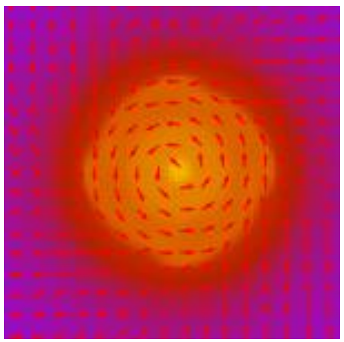
Disk infall velocity

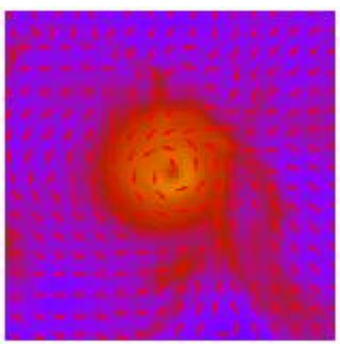
IDEAL MHD



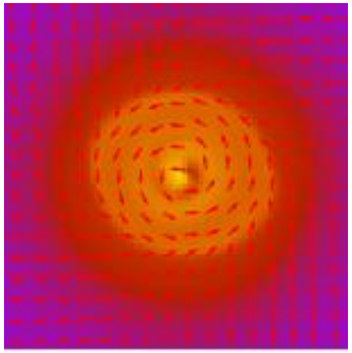


HYDRO





MHD + turbulence

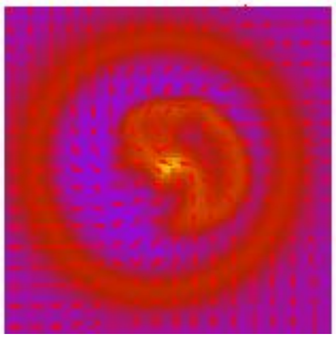


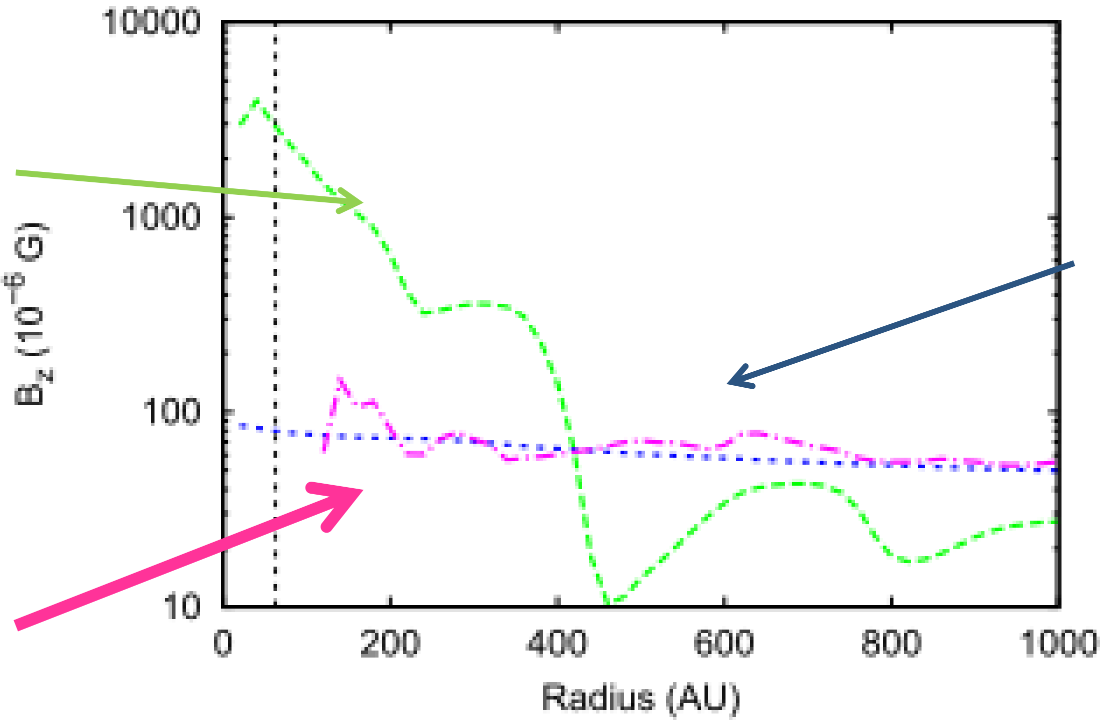
MHD SUPER-η

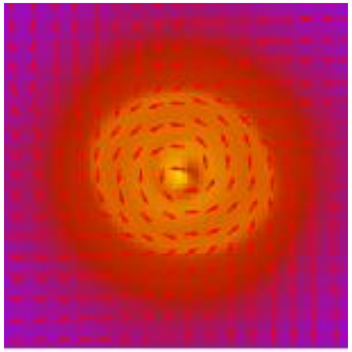
Santos-Lima, de Gouveia Dal Pino, Lazarian 2011

Disk magnetic field distribution

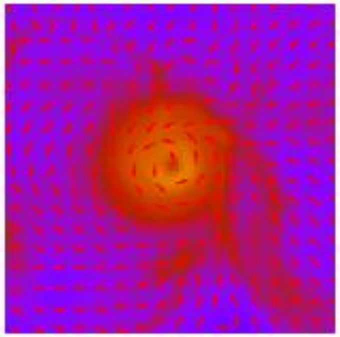
IDEAL MHD







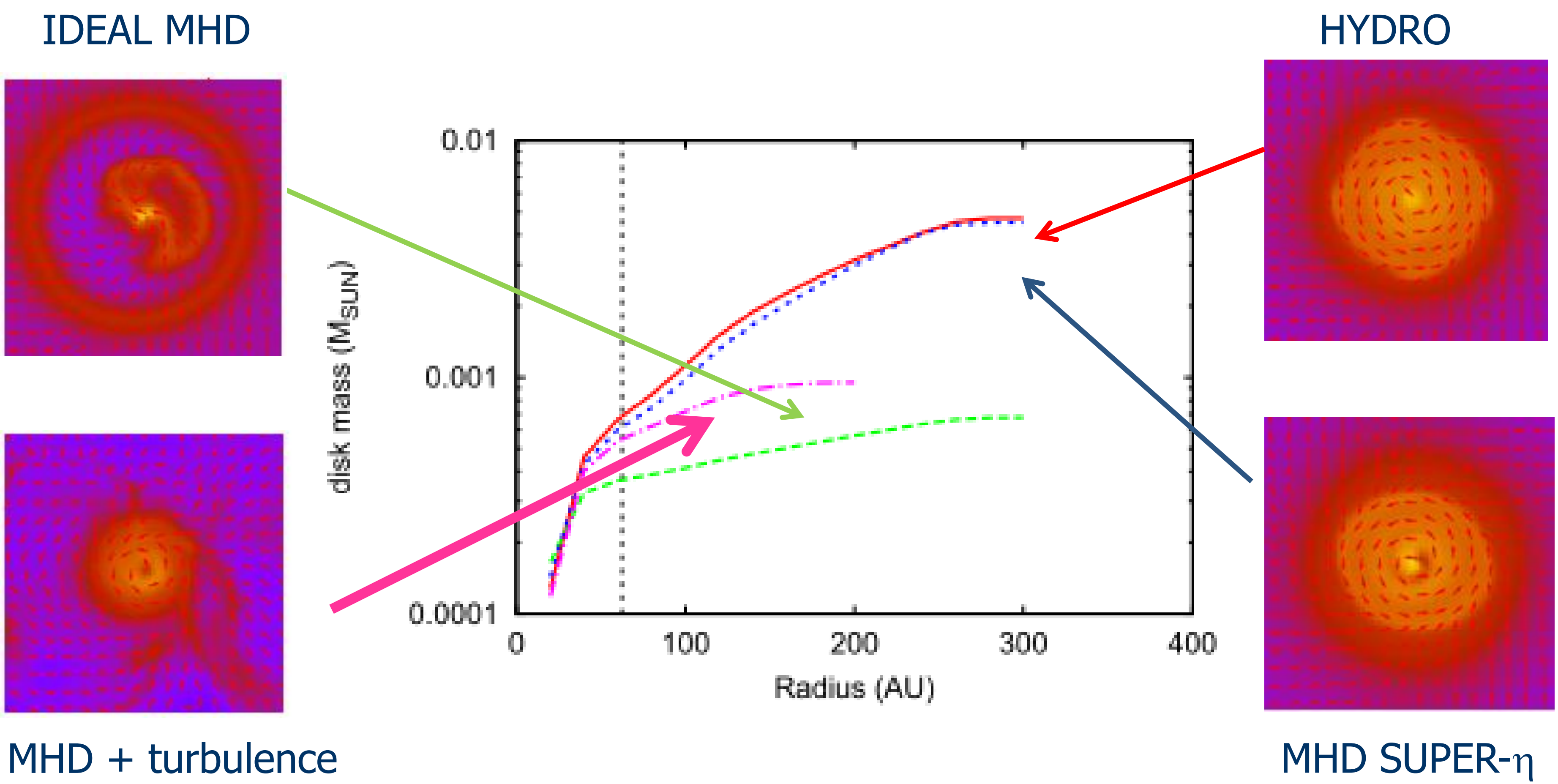
MHD SUPER-η



MHD + turbulence

Santos-Lima, de Gouveia Dal Pino, Lazarian 2011

Disk mass



Santos-Lima, de Gouveia Dal Pino, Lazarian 2011

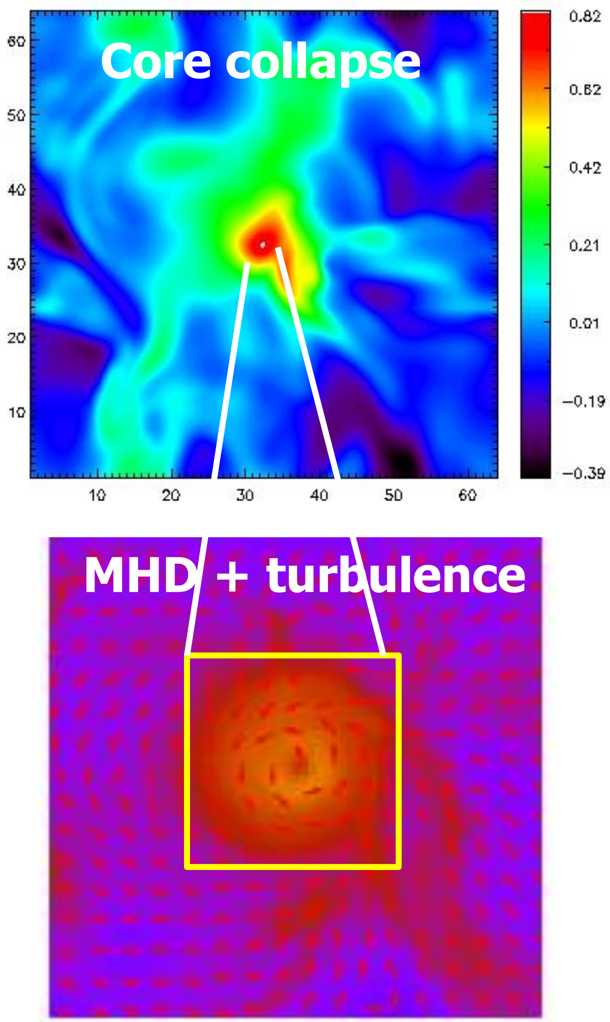
B-Flux Transport Summary

- **AD, Hall effect, Ohmic-resistivity: NOT sufficient** to suppress magnetic braking and allow Keplerian disk formation (in ~10^4yr)

- **Turbulent reconnection can solve the magnetic braking catastrophe:** transport B-flux excess from collapsing core allow formation of **rotationally supported accretion disks 100 AU** (Santos-Lima et al. 2011)

- **B-flux removal from collapsing clouds**: also successfully accomplished with **turbulent reconnection** (Santos-Lima et al. 2010; also Leao´s talk)

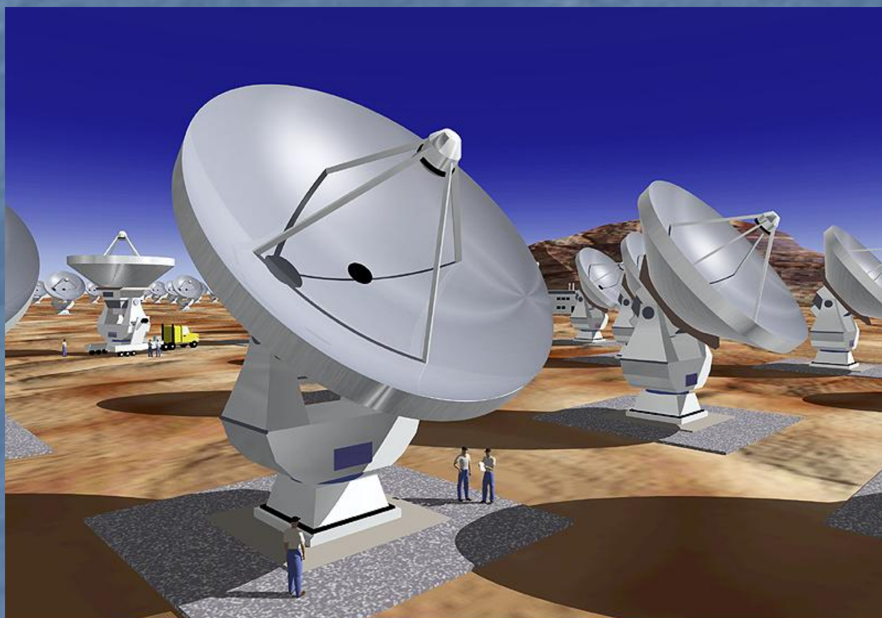
B-Flux Transport Summary



- **Turbulent reconnection** can play important role in the removal of B-flux in **different phases of star-formation: from collapsing clouds to disks**

LLAMA – Long Latin American Millimetric Array

ALMA


ESO PR Photo 24a/99 (8 June 1999) Artist's Impression of ALMA (Atacama Large Millimetre Array) © European Southern Observatory

+

LLAMA

- **Cold structures in Universe**
- **Star formation**
- **Accretion disks**

VLBI: milli-arcsec resolution

THANK YOU !