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Turbulent transport of astrophysical magnetic fields

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SÃO PAULO RESEARCH FOUNDATION

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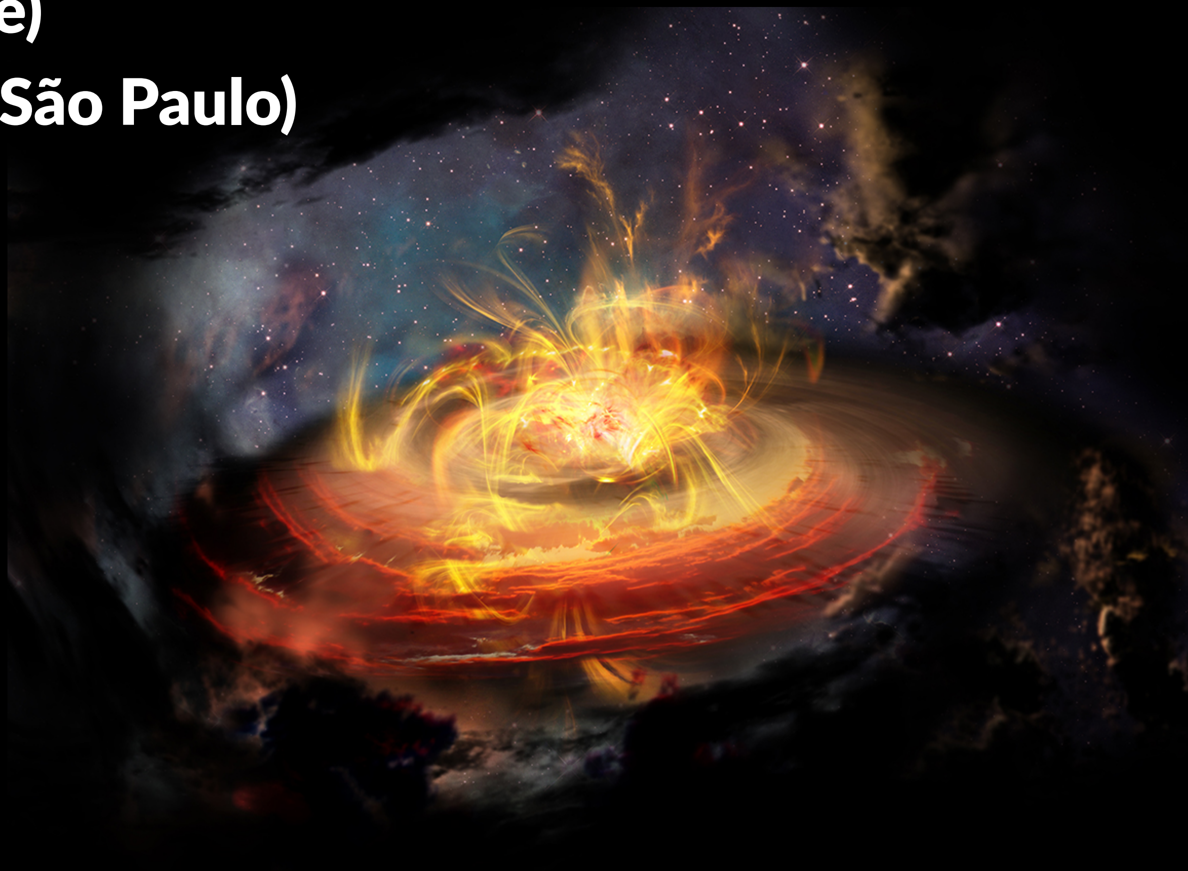
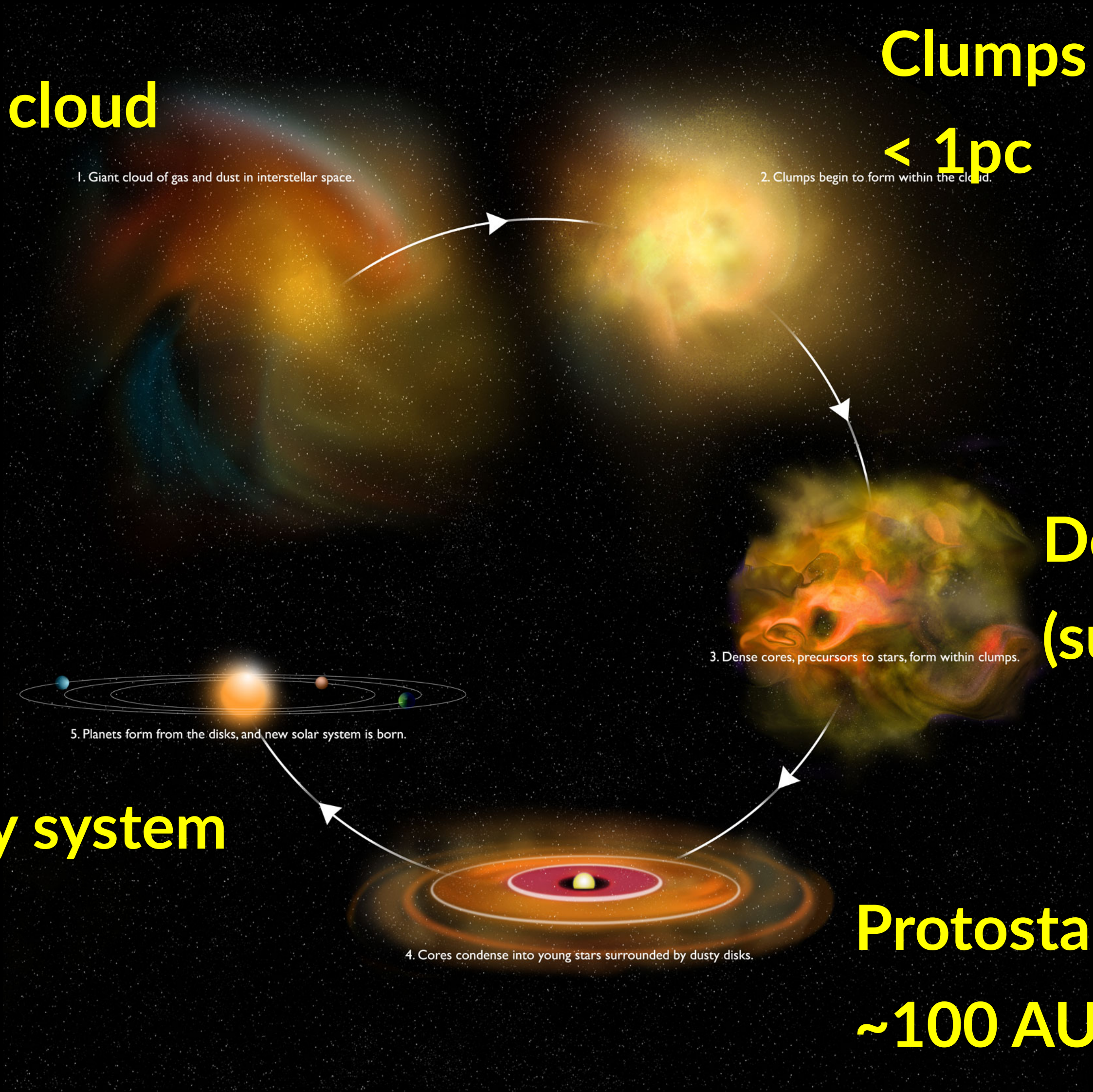


S. Andrews, L. Cieza, A. Isella, A. Kataoka, B. Saxton (NRAO/AUI/NSF), and ALMA (ESO/NAOJ/NRAO)

Motivation: star formation

Bill Saxton, NRAO/AUI/NSF



Star formation phases

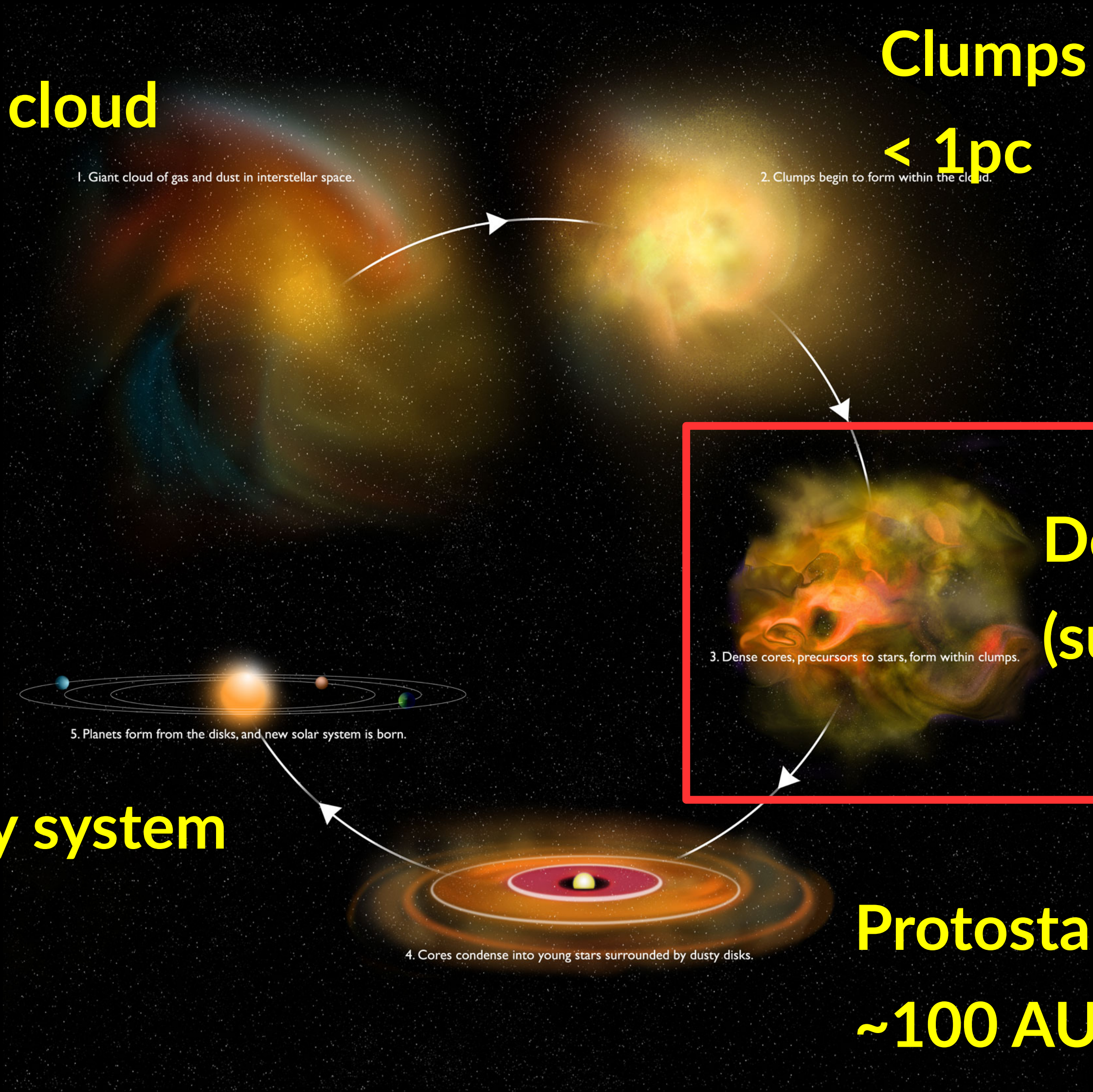
Bill Saxton, NRAO/AUI/NSF

Giant molecular cloud

~10pc

Clumps

< 1pc



Dense cores

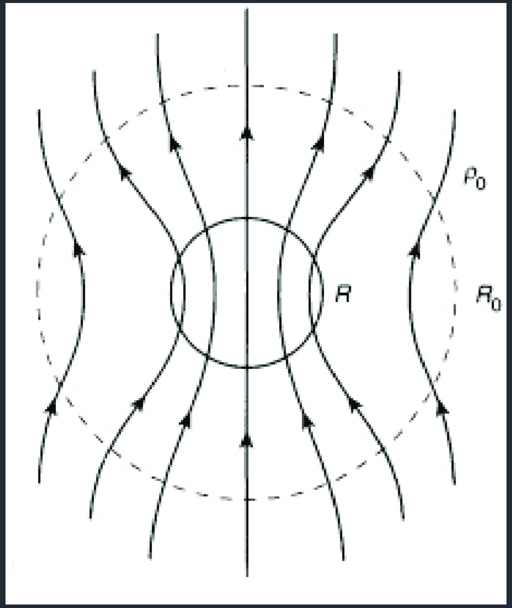
(sub/super-critical)

Young planetary system

Protostar + Keplerian disk

~100 AU

Magnetic flux problem



Star-forming environment: relatively low electrical resistivity

⇒ magnetic diffusion required by observations ~ 10^3 times the Ohmic diffusion *(Shu et al. 2006)*

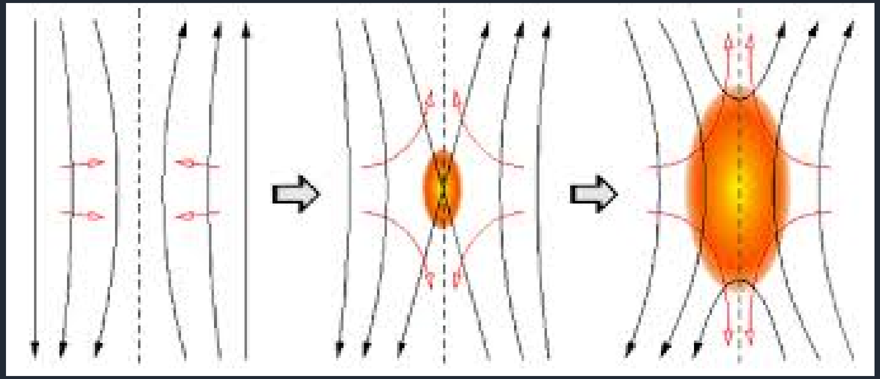
Ambipolar Diffusion (AD)

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \nabla \times \left\{ \frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c \gamma_{in} \rho \rho_i} \right\}$$

Efficiency has been challenged by observations *(Lazarian, Esquivel & Crutcher 2012)* **and theory** *(Shu et al. 2006)*

Diffusion by turbulent reconnection

- Turbulence boosts **magnetic field reconnection** rate *[see talk by G. Kowal]*
  ⇒ efficient the transport of tube fluxes



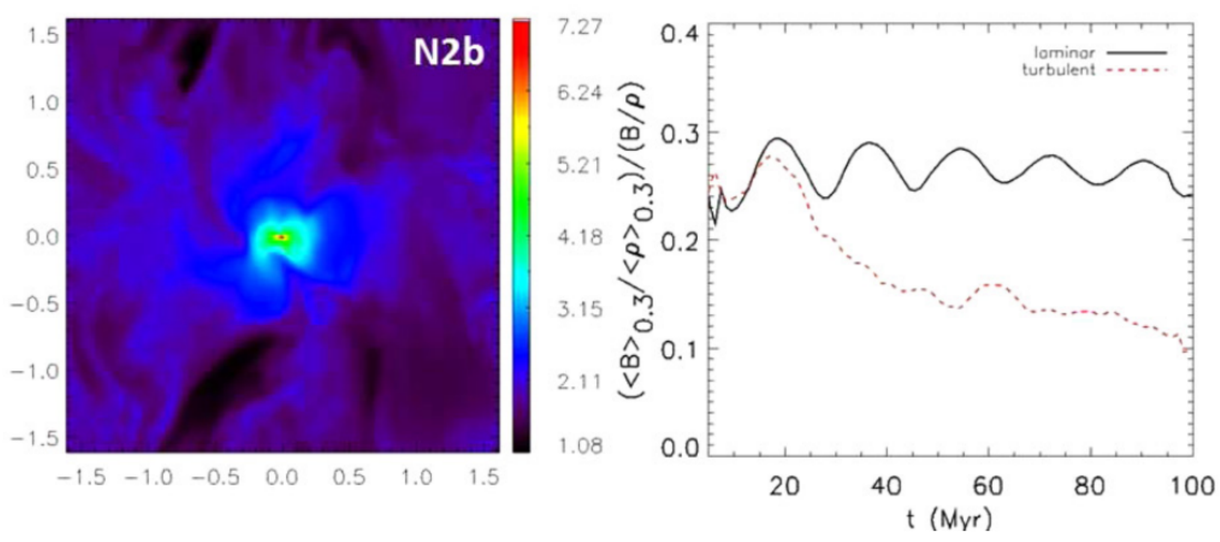
- **Violation of the frozen-in** condition: magnetic field diffusion **independent** of the medium resistivity

Theoretical prediction for the Reconnection Diffusion (RD) coefficient:
(Lazarian 2005)

$$D_{\mathbf{B}} = \ell v_\ell \times \min\left\{1, \left(\frac{v_\ell}{v_A}\right)^3\right\}$$

Can RD solve the magnetic flux problem?

- **Yes! demonstrated in:** *Santos-Lima et al. (2010), Leão et al. (2013)*
- RD can turn **sub-critical** cores into **supercritical** ones *(Leão et al. 2013)*
- RD can explain the observed mass-flux ratio relation between cloud core and envelope *(Crutcher et al. 2011; Leão et al. 2013)*

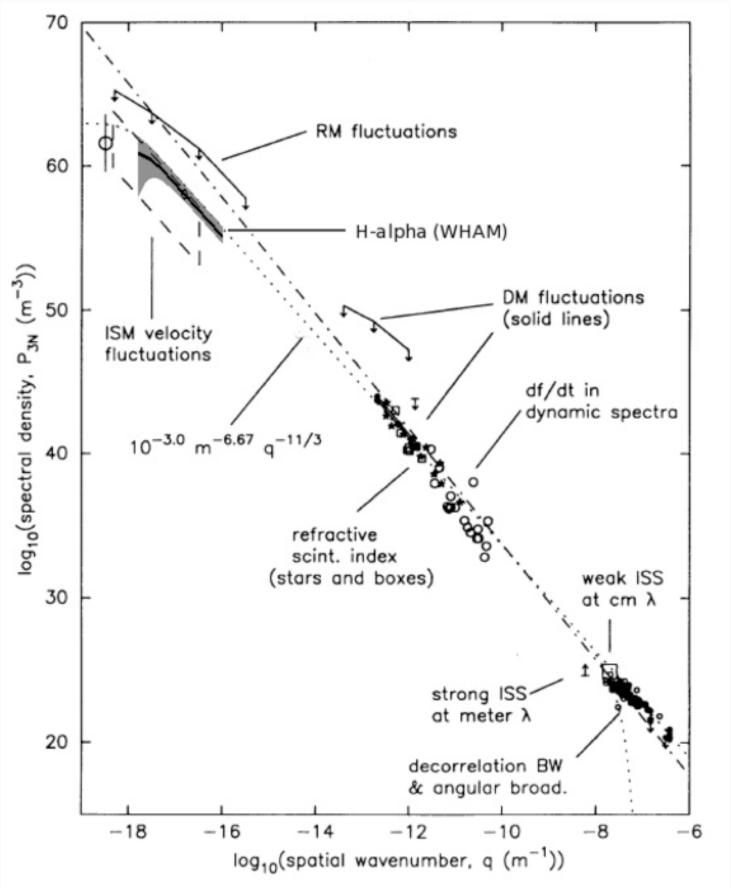


$t = 100$ Myr, $\beta = 3.0$, $n = 90$ cm^{-3},
$Mpot = 41 M_{\odot}$, $R_{cloud} = 3$ pc, $R_{core} = 0.1$ pc

(Leão et al. 2013)

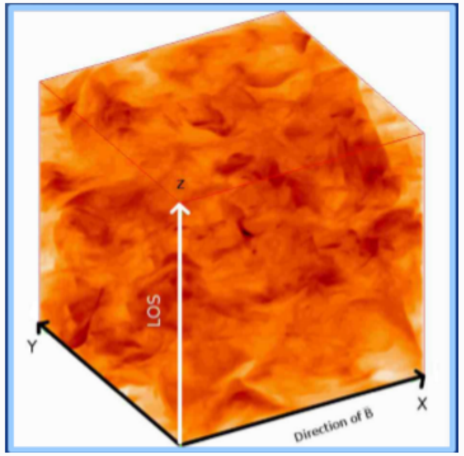
Why do we need turbulence?

The *big power-law in the Sky*



Chepurnov & Lazarian (2010)

- ISM turbulence is MHD turbulence
- Scales ranging from AUs to kpc
- Sources: Supernova, galactic arms, outflows, etc.
- Phases of the ISM: different MHD turbulence regime.



Burkhart et al. 2009

Why does turbulence appear?

$$\frac{\partial \mathbf{v}}{\partial t} + \underbrace{\mathbf{v} \cdot \nabla \mathbf{v}}_{\text{advection}} = -\frac{\nabla P}{\rho} + \underbrace{\nu \nabla^2 \mathbf{v}}_{\text{viscosity}}$$

Turbulent flows: $\mathrm{Re} \sim \frac{\text{advection}}{\text{viscosity}} \sim \frac{\ell v}{\nu} \gg 1$

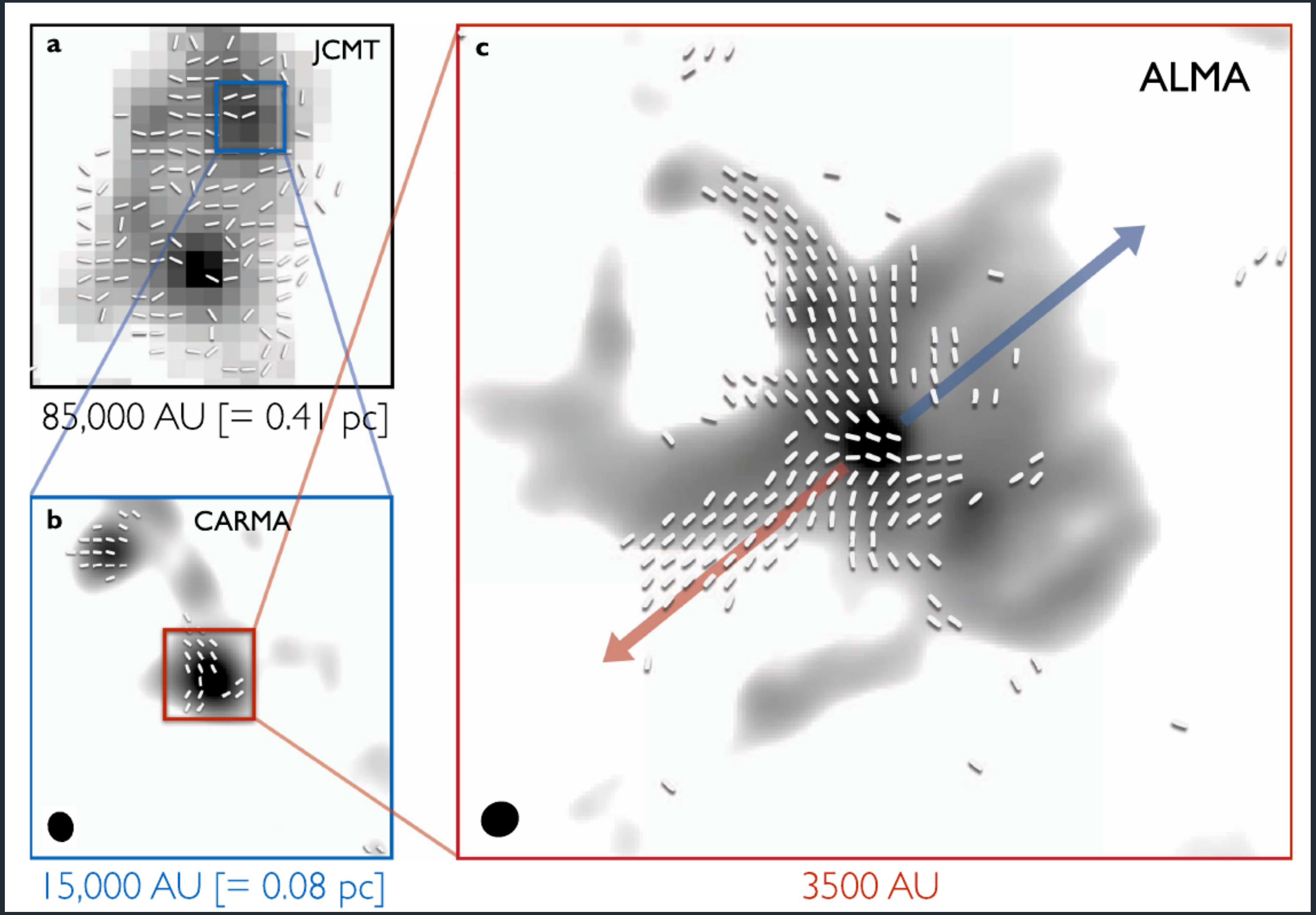
- Sun's convection zone: **Re ~ 10^{13}**
- Protostellar disks: **Re ~ 10^{9}**
- Insterstellar medium: **Re ~ 10^{7}**
- Intracluster medium of galaxies: **Re ~ 10^{2}**

MHD turbulence presence during star formation

Protostellar source Ser-emb 8

Data consistent with **trans-** or **super-Alfvénic** turbulence in the host cloud

Hull et al. (2017)



Star formation phases

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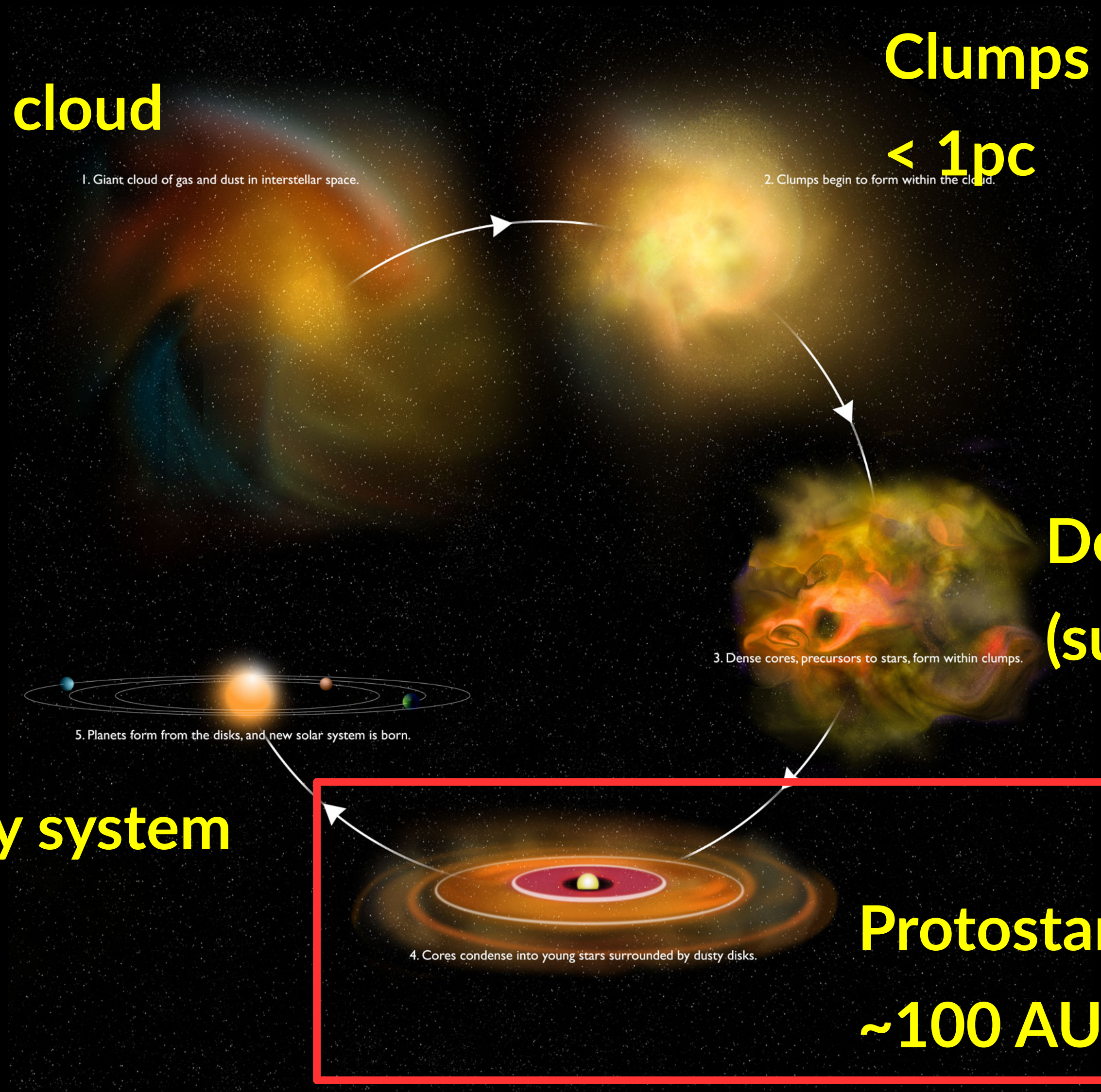


Dense cores

(sub/super-critical)

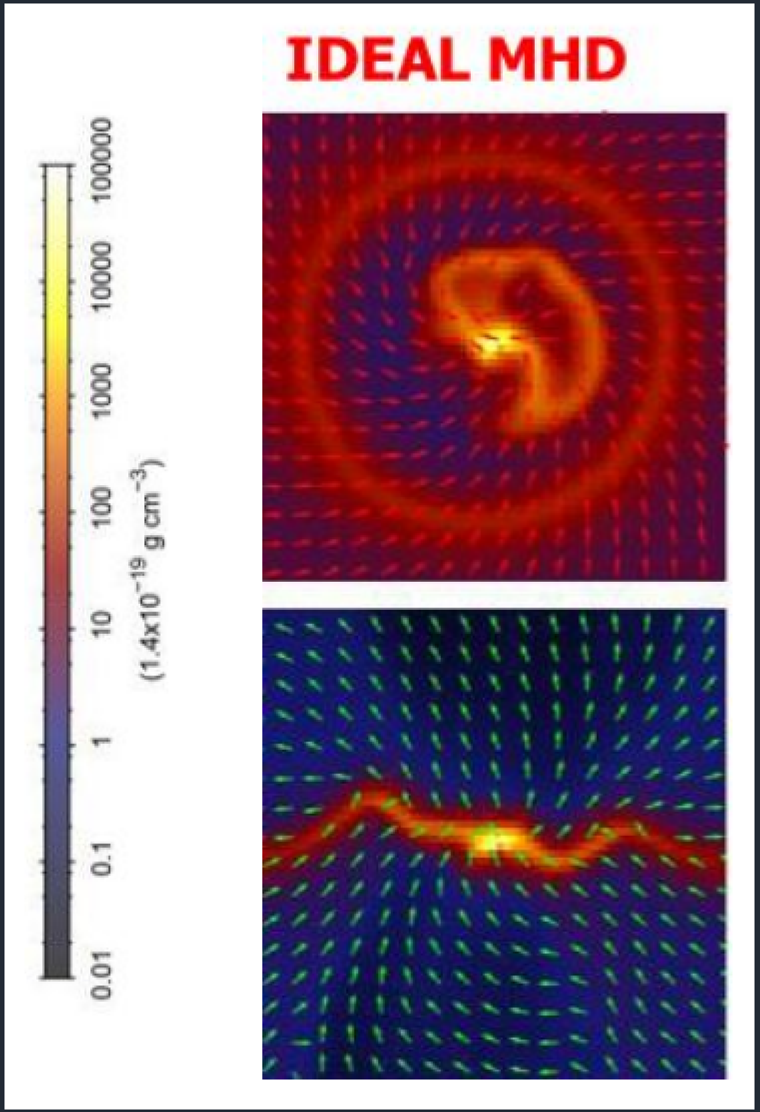
Young planetary system

Protostar + Keplerian disk

~100 AU

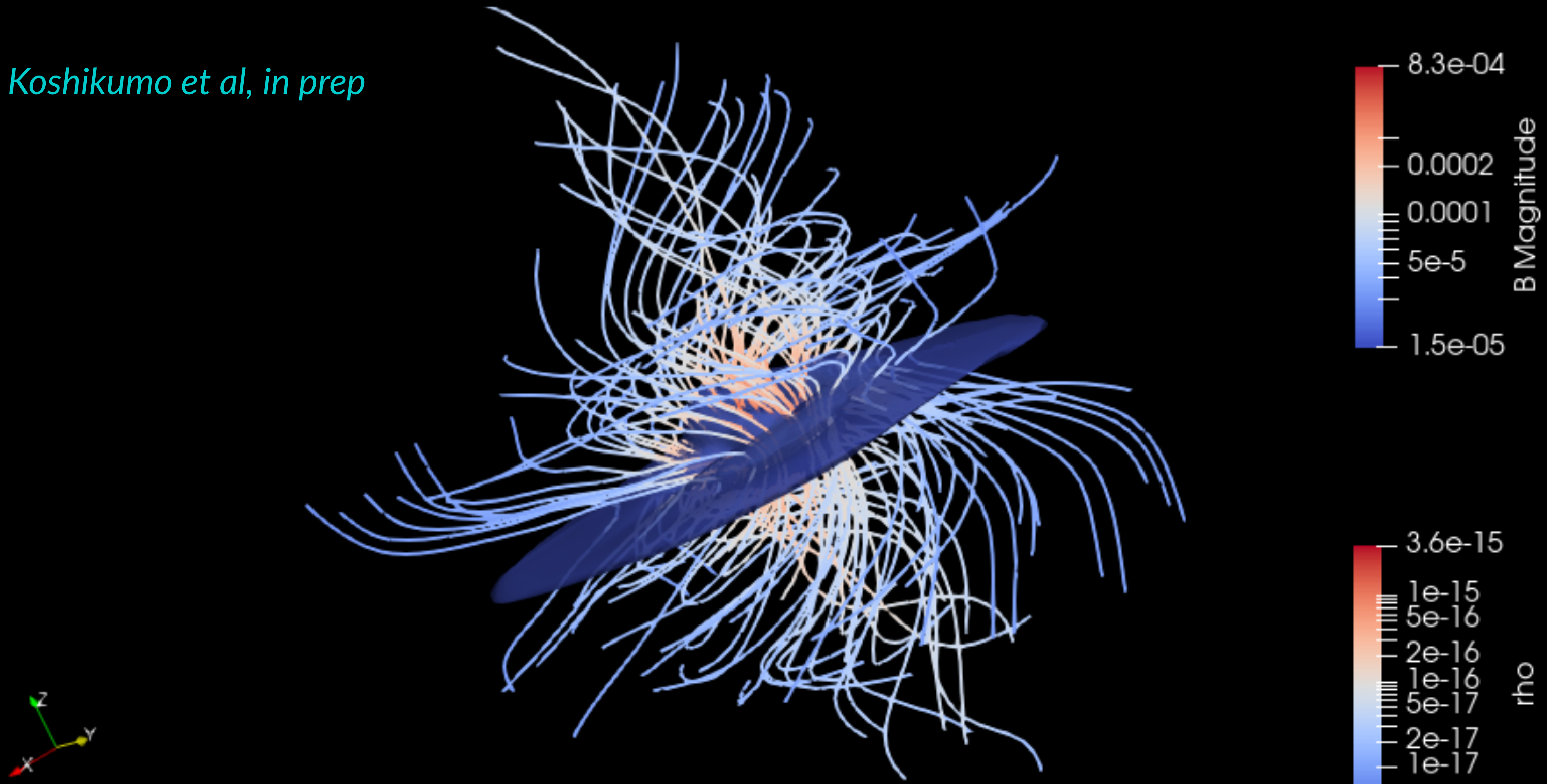
Magnetic braking catastrophe

- **Ideal MHD theory →** formation of rotationally supported disks is suppressed
- Magnetic fields mediate extraction of angular momentum from the disk, **preventing** the formation of a **Keplerian disk** *(Allen et al. 2003; Galli et al. 2006; Krasnopolsky 2010; Li et al. 2011; Santos-Lima et al. 2012; González-Casanova et al. 2015; Lam et al. 2019; ...)*

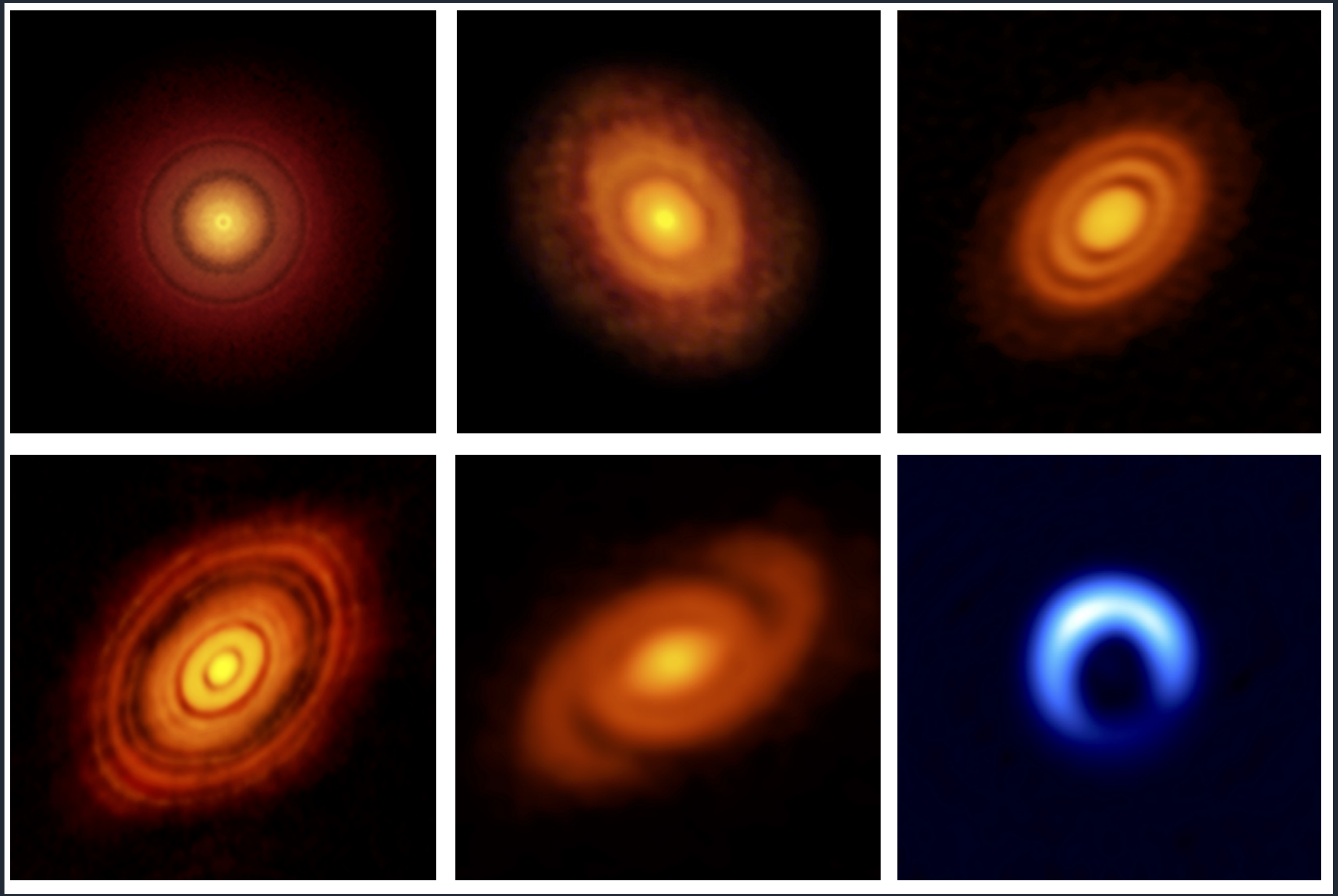


Santos-Lima, de Gouveia Dal Pino & Lazarian (2012)

Koshikumo et al, in prep

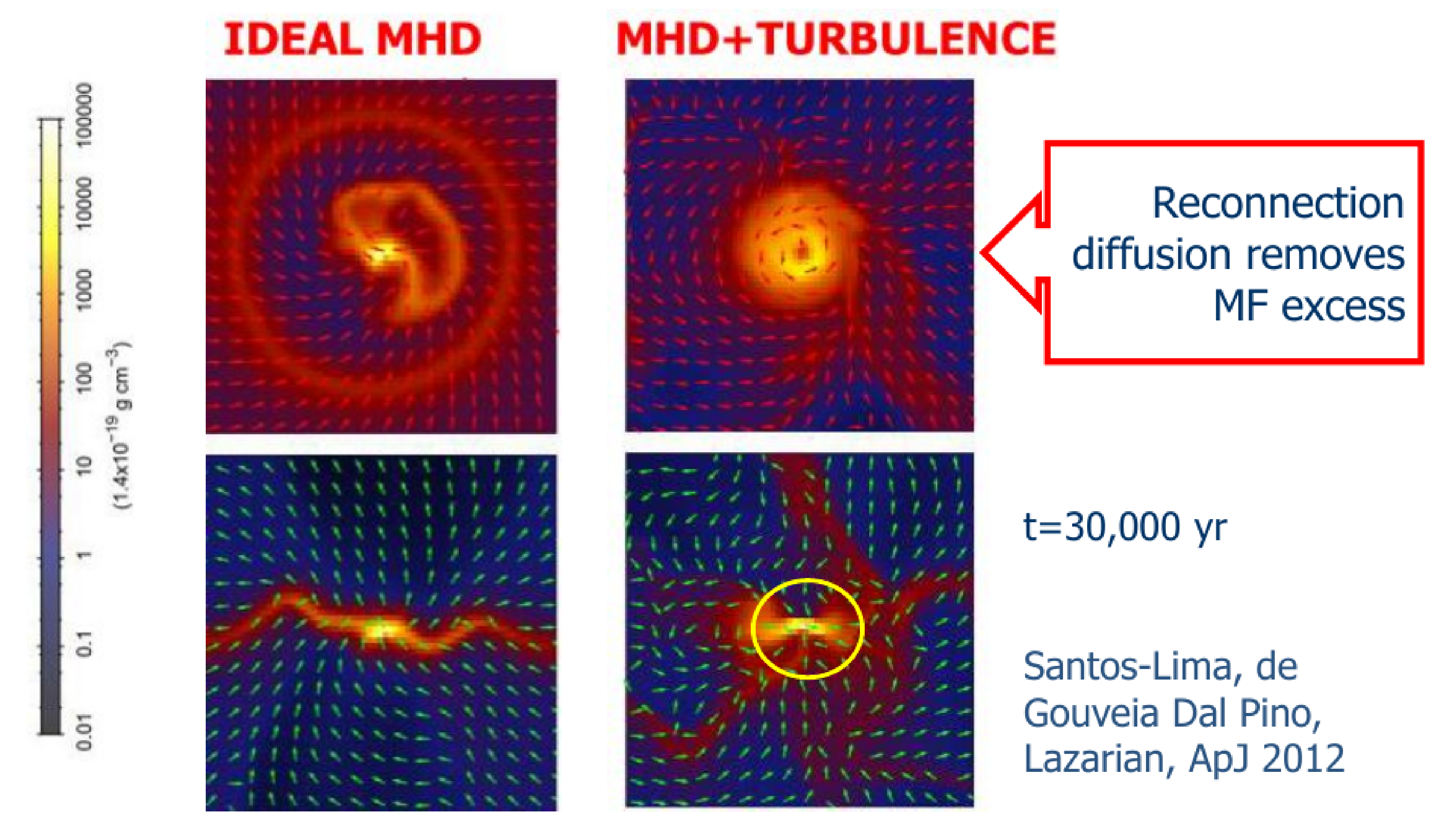


But we do observe protoplanetary disks!



[S. Andrews, L. Cieza, A. Isella, A. Kataoka, B. Saxton (NRAO/AUI/NSF), and ALMA (ESO/NAOJ/NRAO)]

Can RD allow the formation of Keplerian protostellar disks?



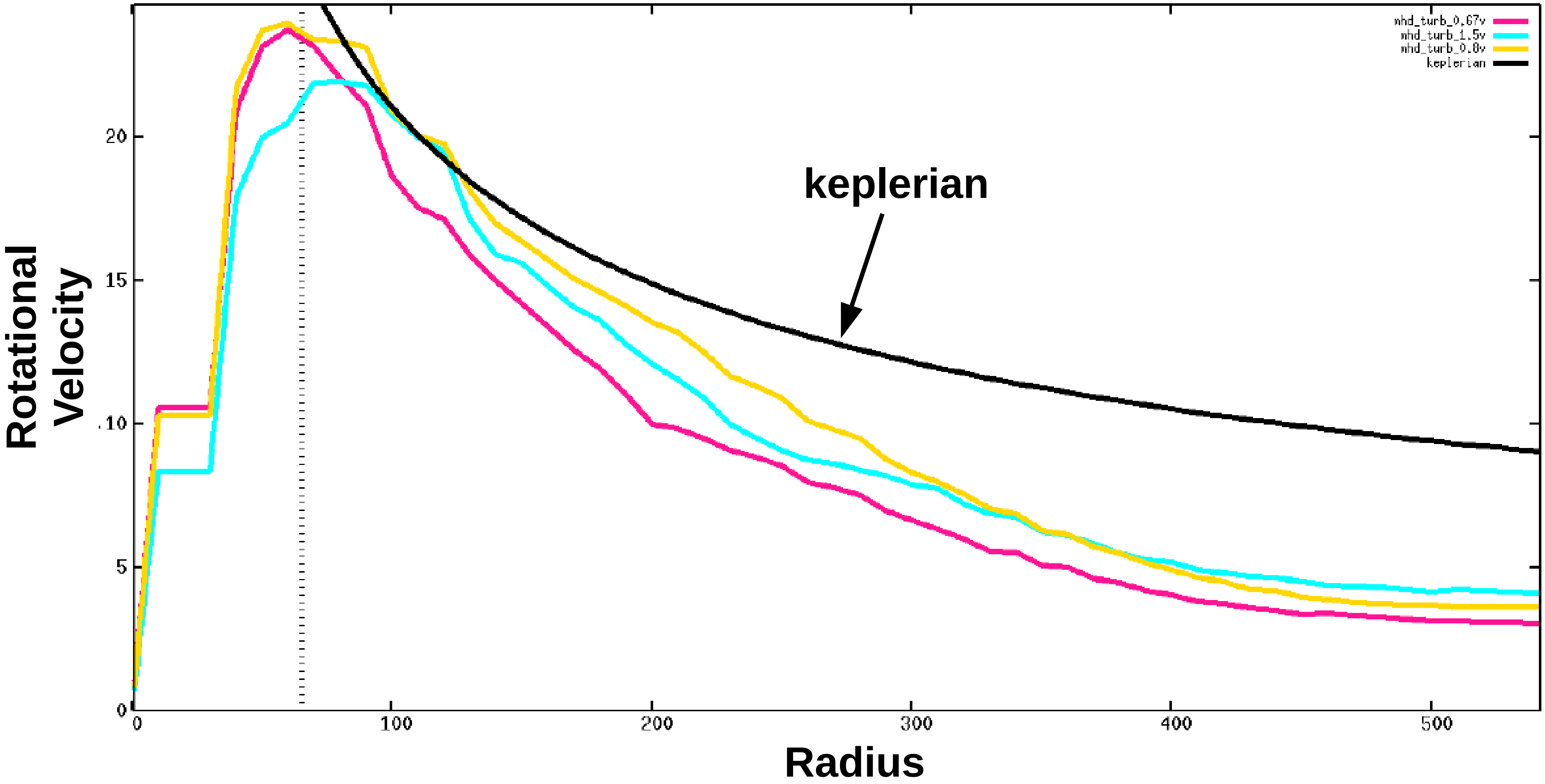
Which mechanism does allow disk formation?

- **AD, Ohmic resistivity or RD?** Comparison depends on the quantitative knowledge of the transport rate due to each one

- Quantitative tests of the RD was still missing

- The study described in the following supports the predictions of the RD theory and allows a **more careful** interpretation of the RD in numerical simulations

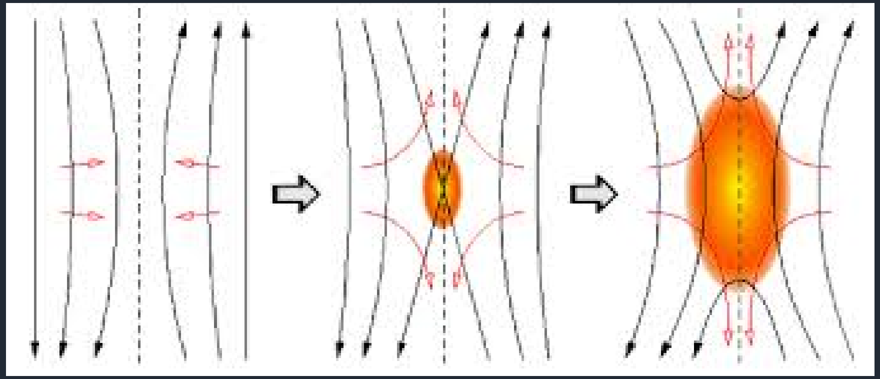
Disk formation at different levels of turbulence



Koshikumo et al, in prep

Back to the RD theory: missing quantitative test

- Turbulence boosts **magnetic field reconnection** rate *[see talk by G. Kowal]*
  ⇒ efficient the transport of tube fluxes



- **Violation of the frozen-in** condition: magnetic field diffusion **independent** of the medium resistivity

Theoretical prediction to be tested:

$$D_{\mathbf{B}} = \ell v_\ell \times \min\left\{1, \left(\frac{v_\ell}{v_A}\right)^3\right\}$$

Direct numerical simulations: forced turbulence

- **The Pencil Code** *(Brandenburg et al.)*, 3D-MHD

$$\frac{D\ln\rho}{Dt} = -\nabla\cdot\mathbf{v},$$

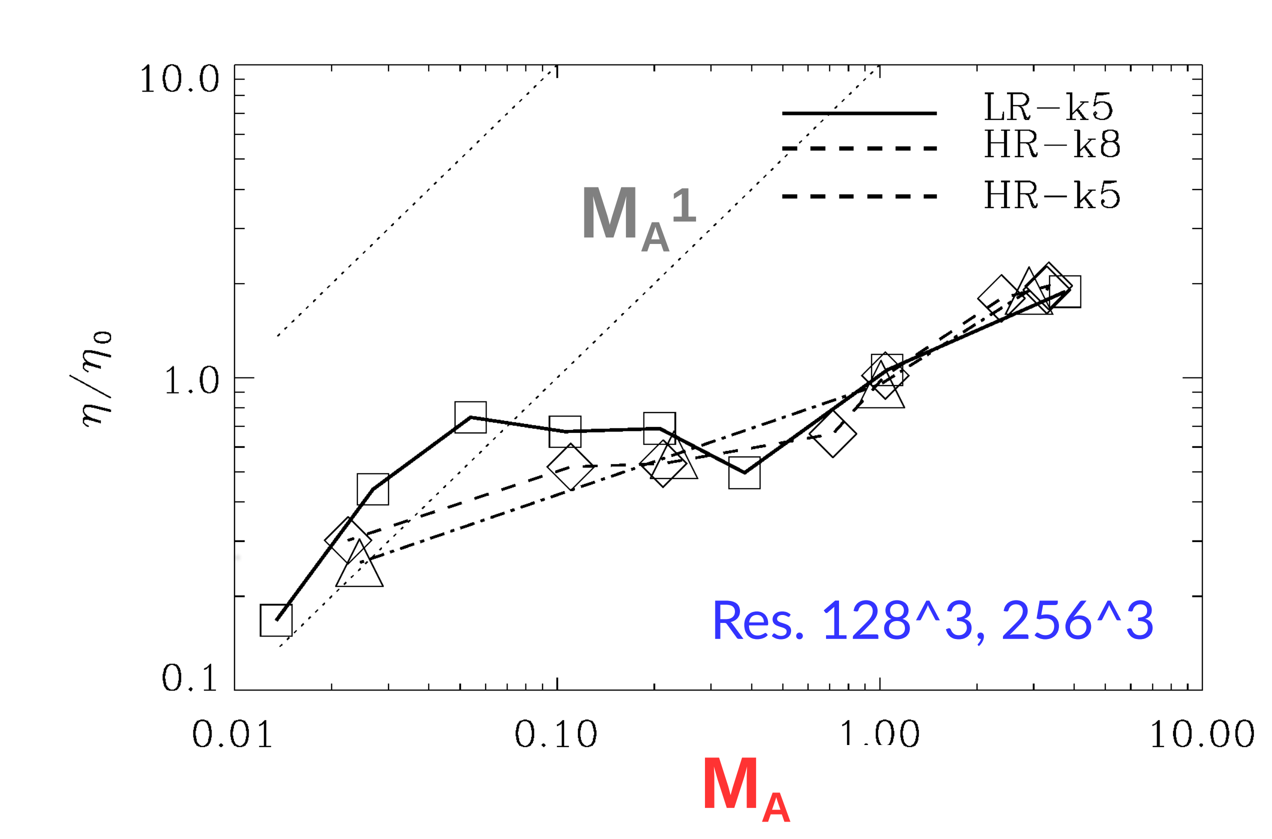
$$\frac{D\mathbf{v}}{Dt} = -c_s^2\nabla\ln\rho + \frac{1}{\rho}\mathbf{J}\times(\mathbf{B_0}+\mathbf{B}) + \nu_3\nabla^6\mathbf{v} + \mathbf{f},$$

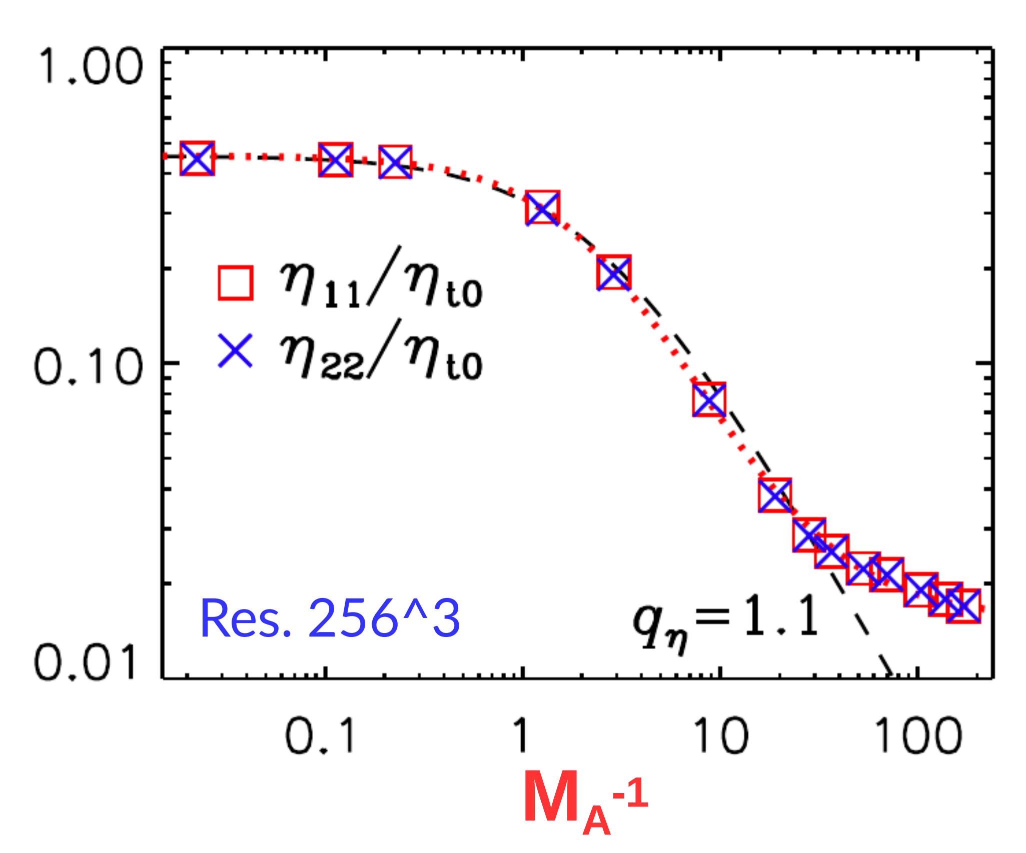
$$\frac{\partial\mathbf{A}}{\partial t} = \mathbf{v}\times(\mathbf{B_0}+\mathbf{B}) + \eta_3\nabla^6\mathbf{A},$$

- **Test Field method** *(Schrinner et al. 2005, 2007; Brandenburg et al. 2010)*
- Non-helical forcing, subsonic, **subAlfvenic**, uniform B_0, $k_{INJ}L$ = 3-5, $\nu_3 = \eta_3$

First results

Theoretical prediction: $D_{\mathbf{B}} = \ell v_\ell \times \min\left\{1, \left(\frac{v_\ell}{v_A}\right)^3\right\}$





$\eta \sim L_i V_i M_A^{0-1}$

Karak et al. (2014)

Deviations from the RD theory/LV99 hypotheses?

- Compressibility?

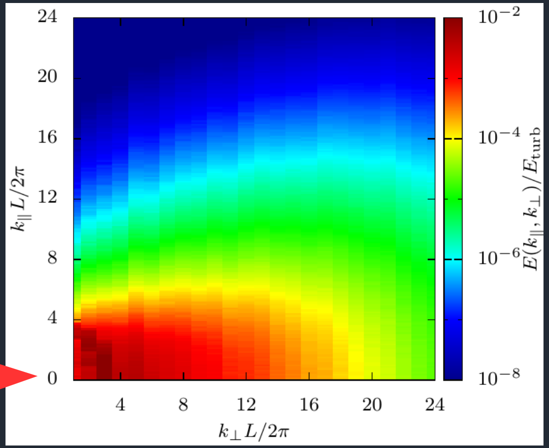
- Deviations of turbulence from the statistics of the **weak** regime?
  - Due to **finite box** size *(Nazarenko 2007)*
  - Due to the **forcing** used *(Perez & Boldyrev 2008; Bigot & Galtier 2011; Alexakis 2011; Meyrand et al. 2015)*

Direct numerical simulations of the RD:

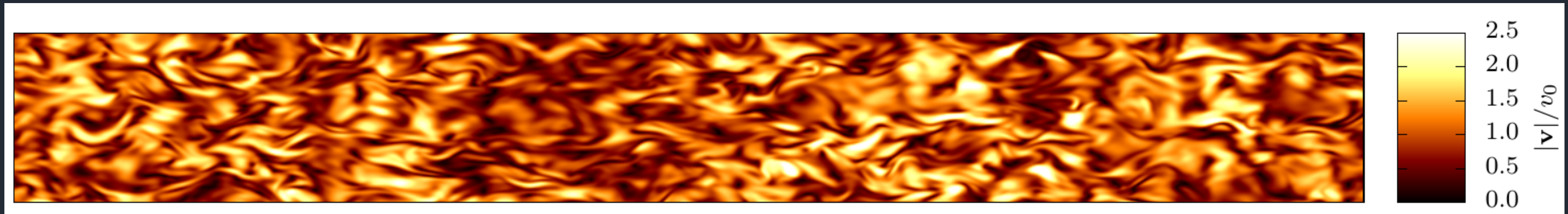
1. Forcing effects

Forcing distribution in K-space: 2D modes

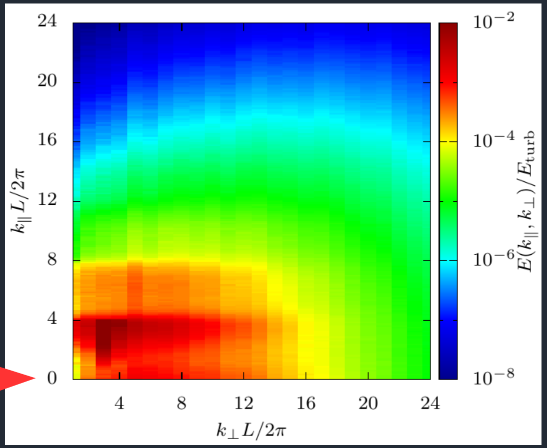
2D modes



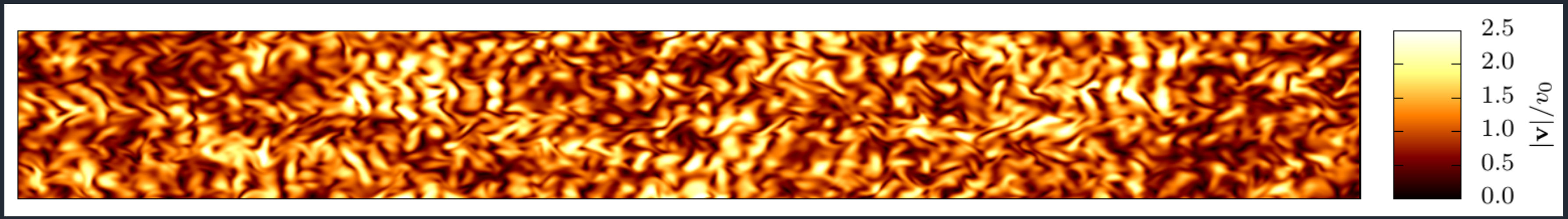
Amplitude independent of θ



2D modes

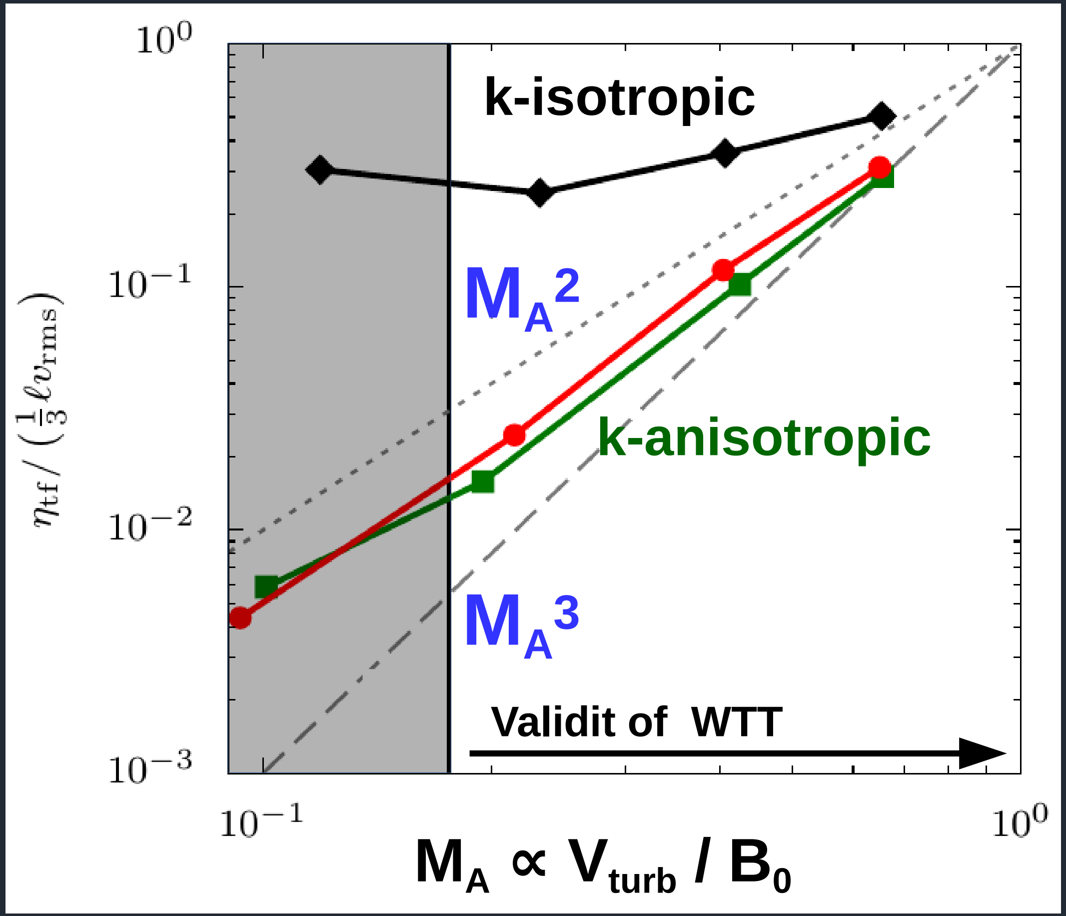


Amplitude $\propto (k_{\|})^2$

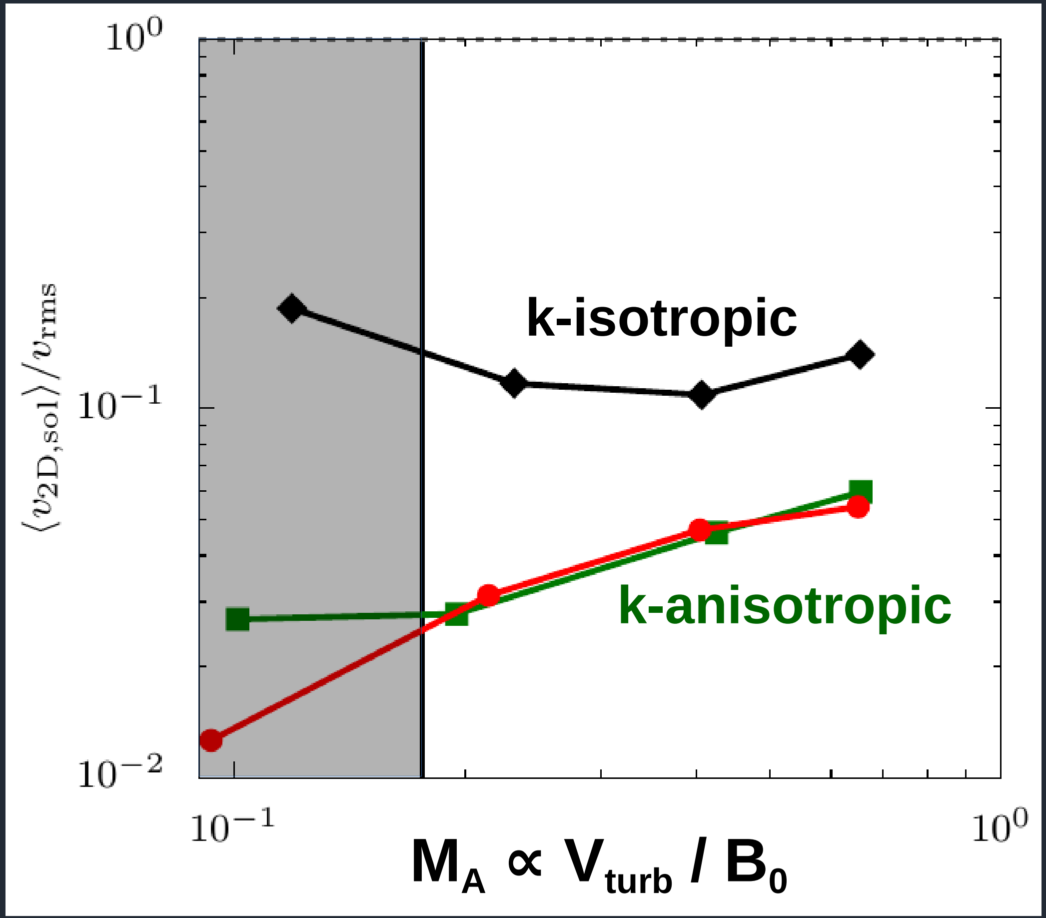


Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)

Turbulent diffusivity



2D solenoidal velocities



Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)

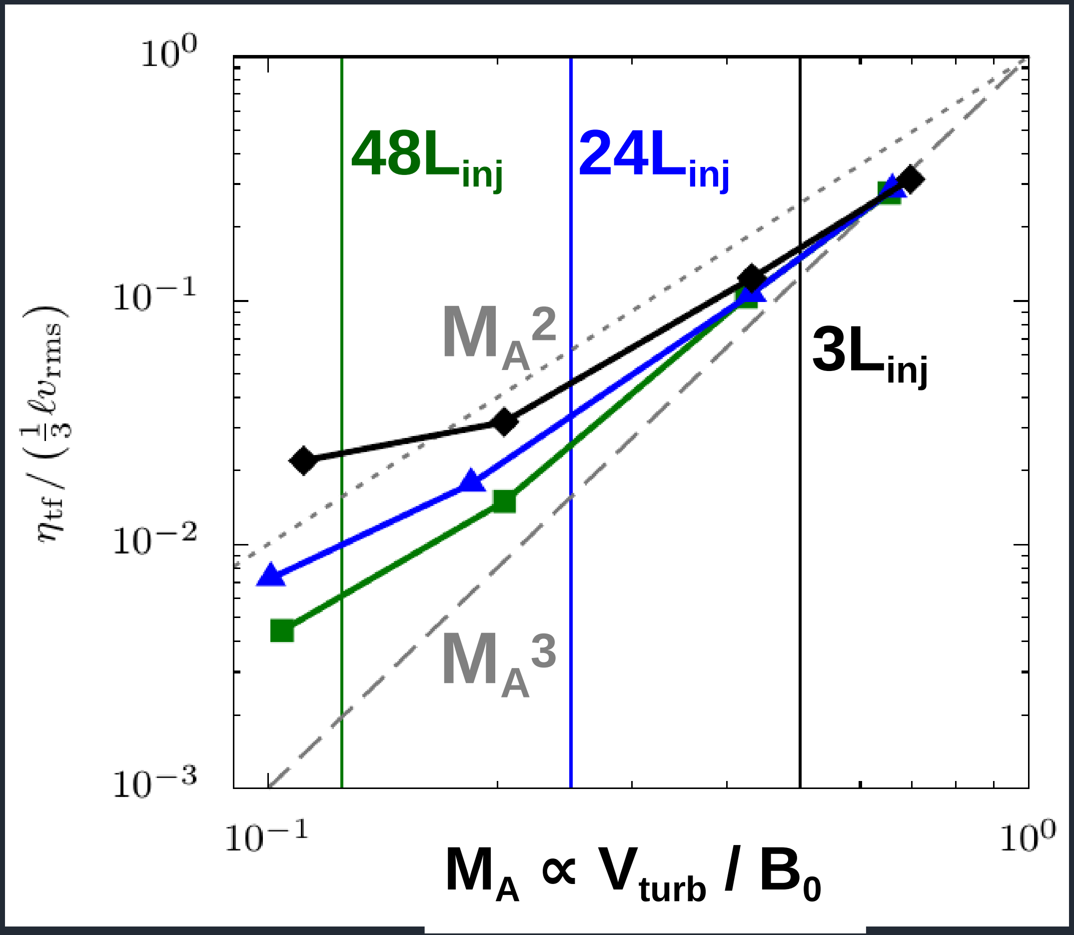
Direct numerical simulations of the RD:

1. Forcing effects

2. Finite domain size

Box length parallel to B

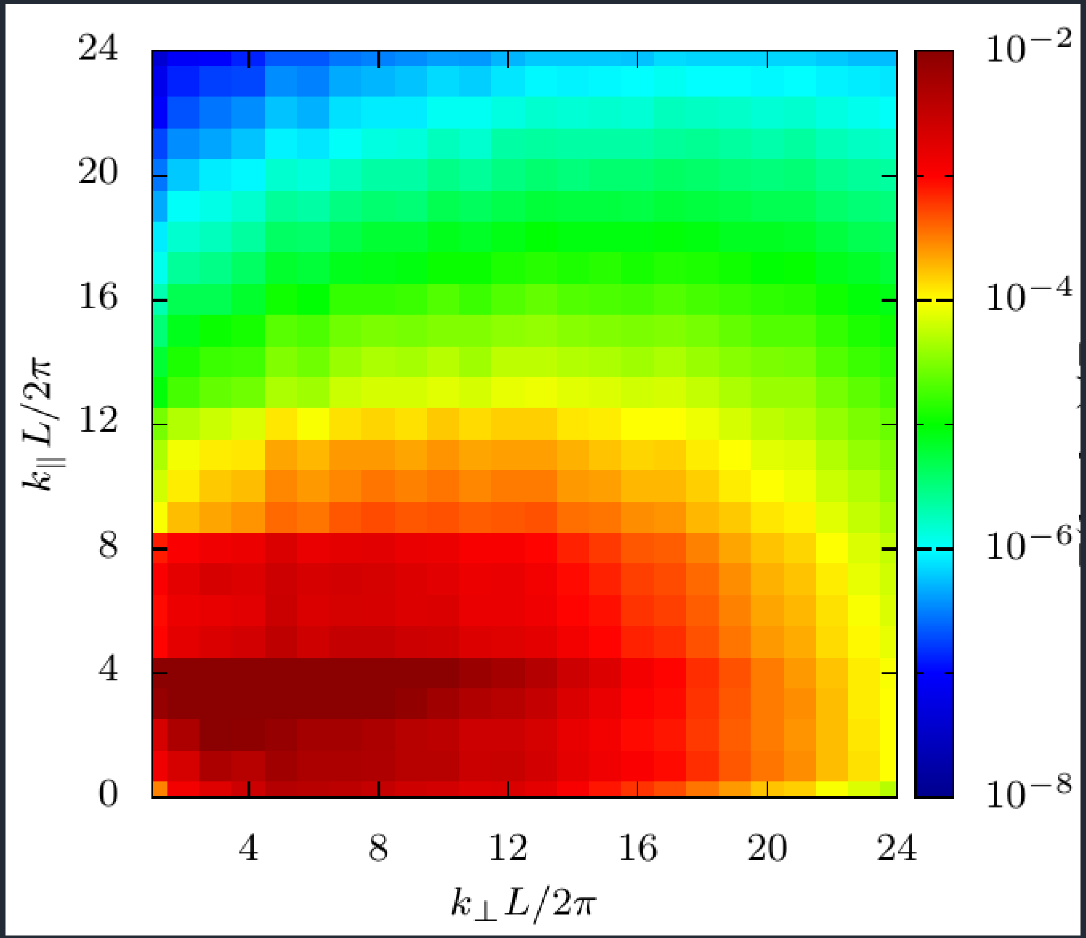
Turbulent diffusivity



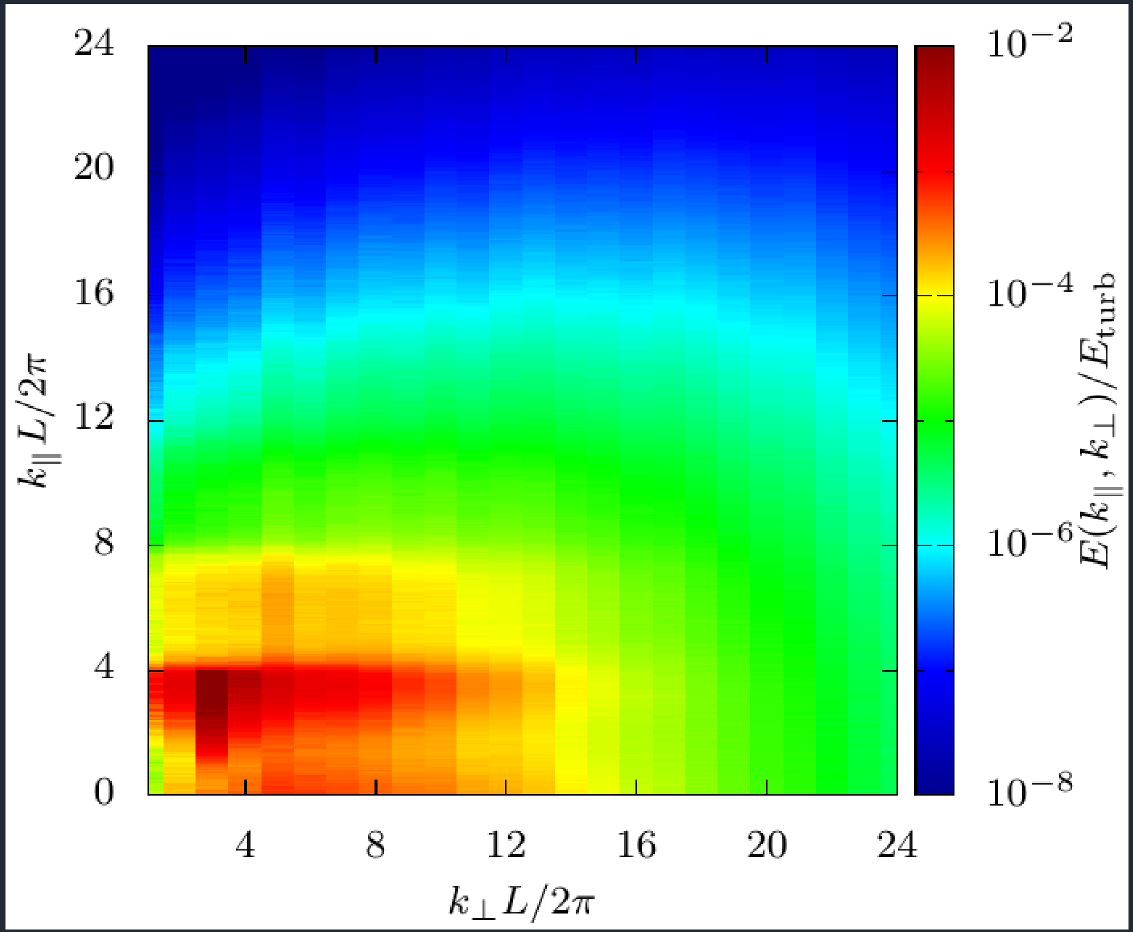
Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)

Turbulence Power Spectrum

$L_{||}$ = 3L_{inj}, Ma=0.4



$L_{||}$ = 48L_{inj}, Ma=0.4



Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)

Direct numerical simulations of the RD:

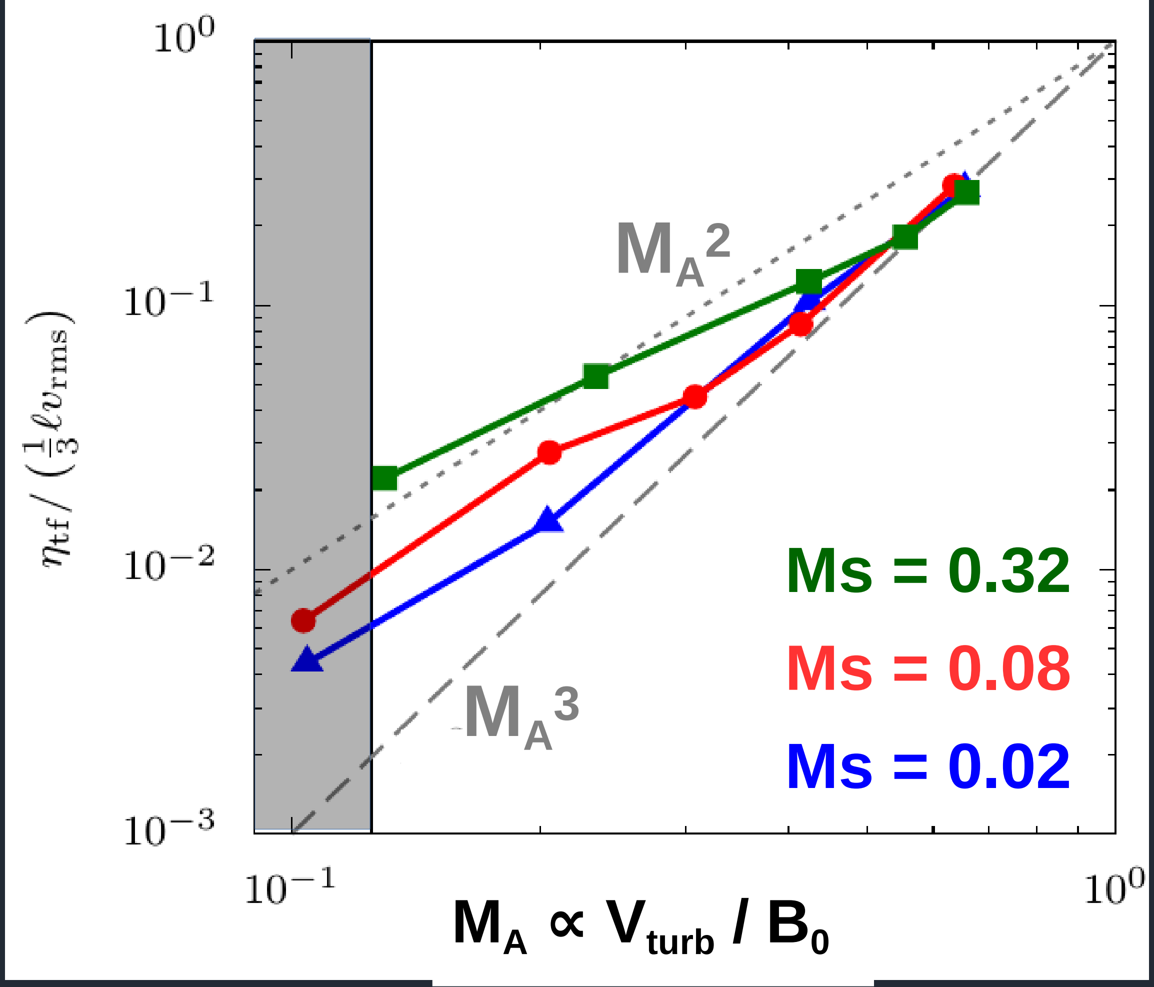
1. Forcing effects

2. Finite domain size

3. Compressibility

Turbulence with finite compressibility

Turbulent diffusivity



Santos-Lima, Guerrero, de Gouveia Dal Pino, Lazarian (2021)

Key points

1. Some star forming processes seem to require the **violation** of the frozen in condition. The **RD mechanism** appears as a natural solution, and the comparison of its efficiency with other mechanisms depends on the **quantitative** knowledge of the RD rates.

2. Our numerical simulations seem to be **consistent** with the RD diffusion theory prediction for the diffusivity when approaching the incompressible limit, and show an increased efficiency when turbulence is compressible.

3. The common choices for turbulence forcing in numerical studies introduce **artificial effects** that cause the diffusion coefficient to **deviate** from the RD theory in the regime of strong magnetic fields.