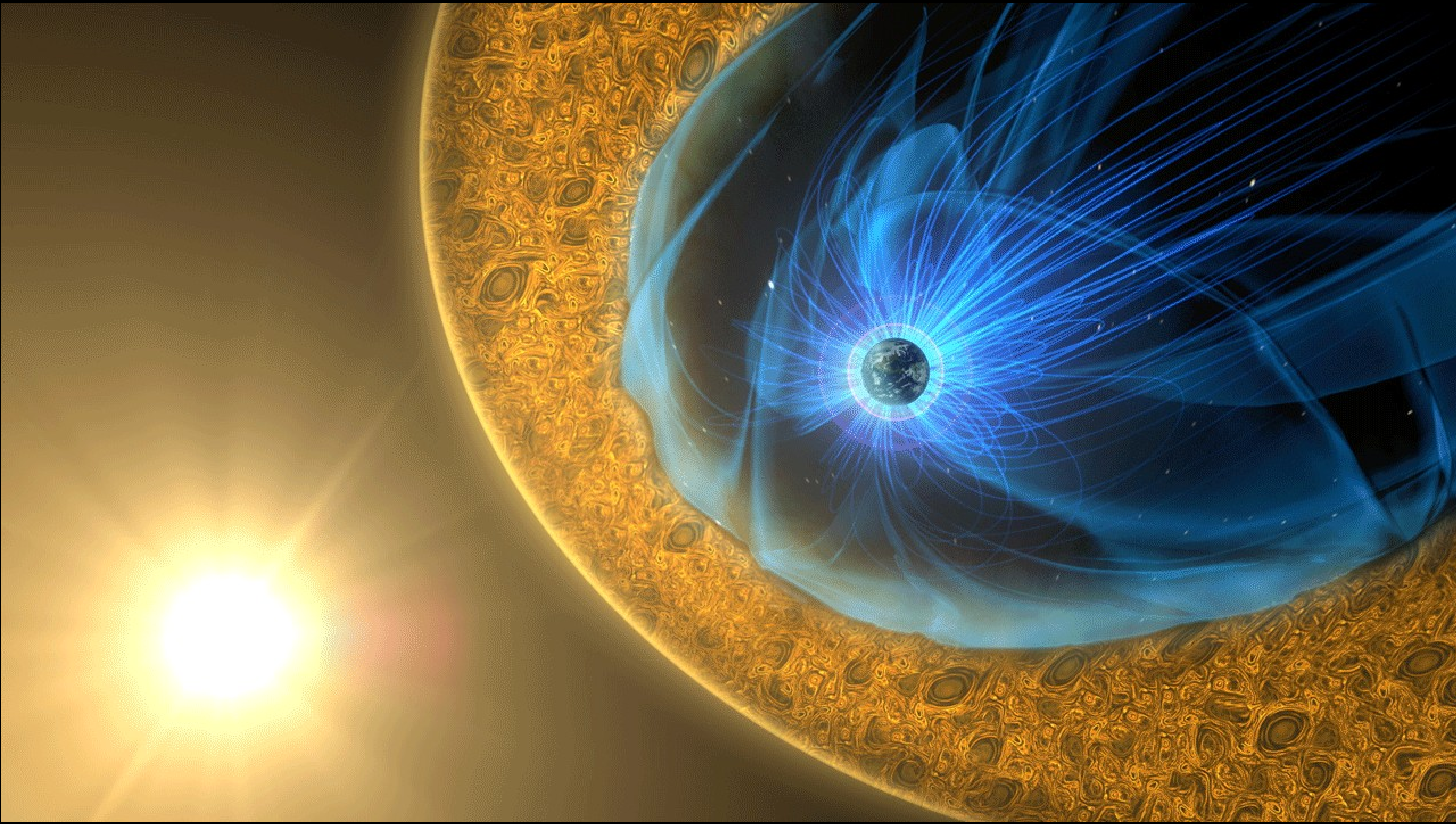
OBSERVATÓRIO DE SÃO PAULO
SANCTI PAVLI CÆLVM AGER MEVS

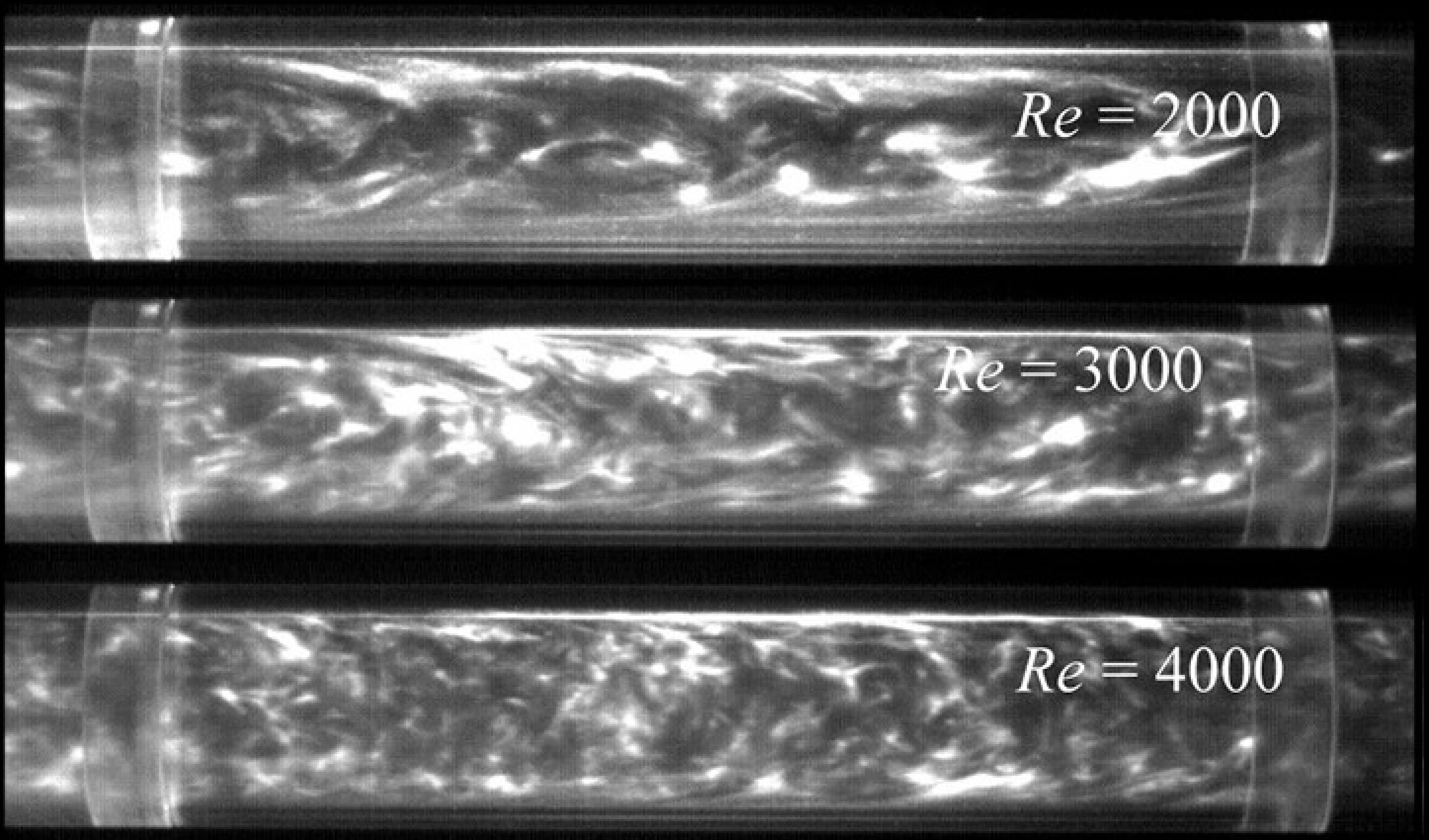
Turbulência em Meios Astrofísicos

Reinaldo Santos-Lima – IAG/USP

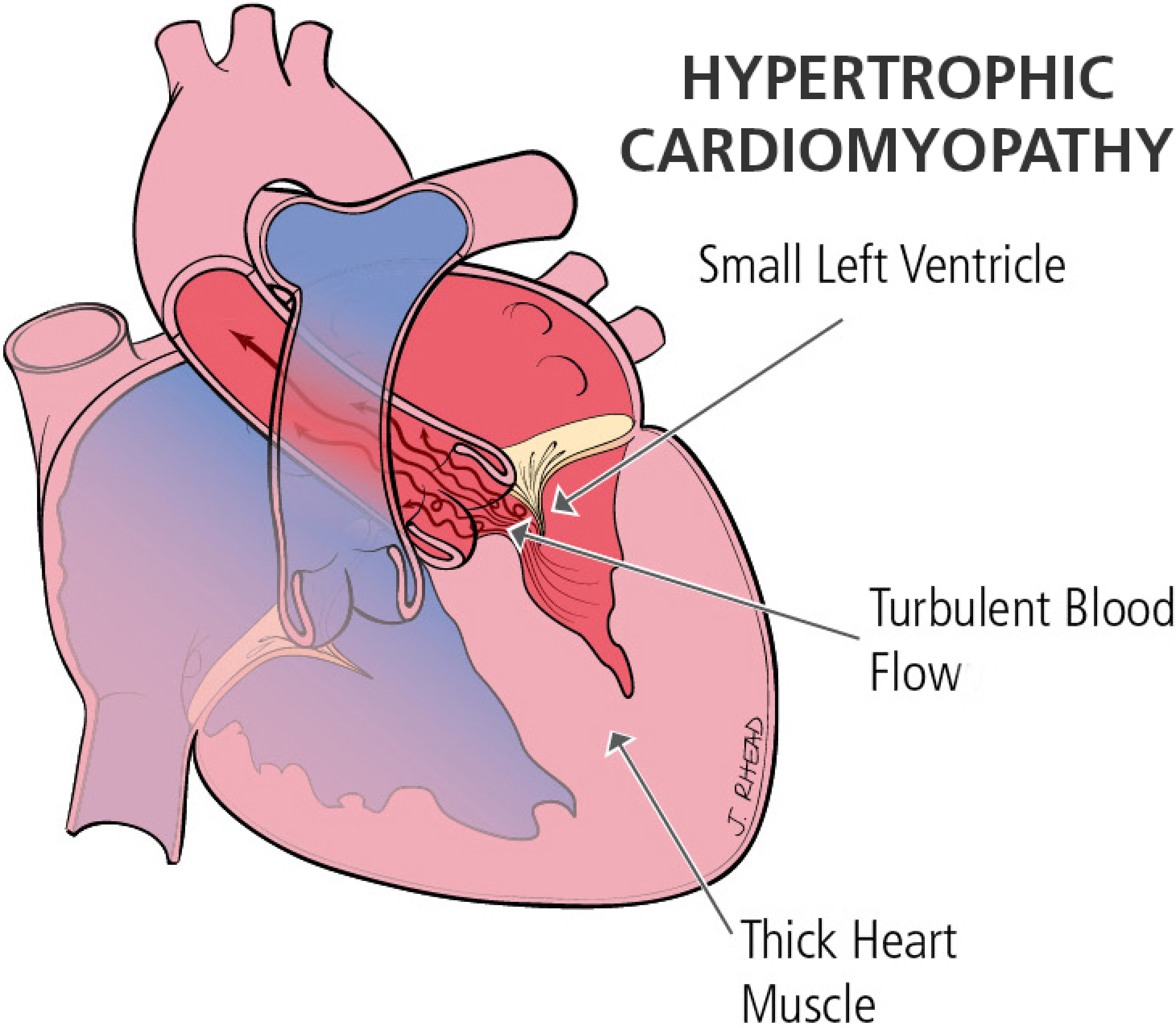
Smooth and turbulent flow

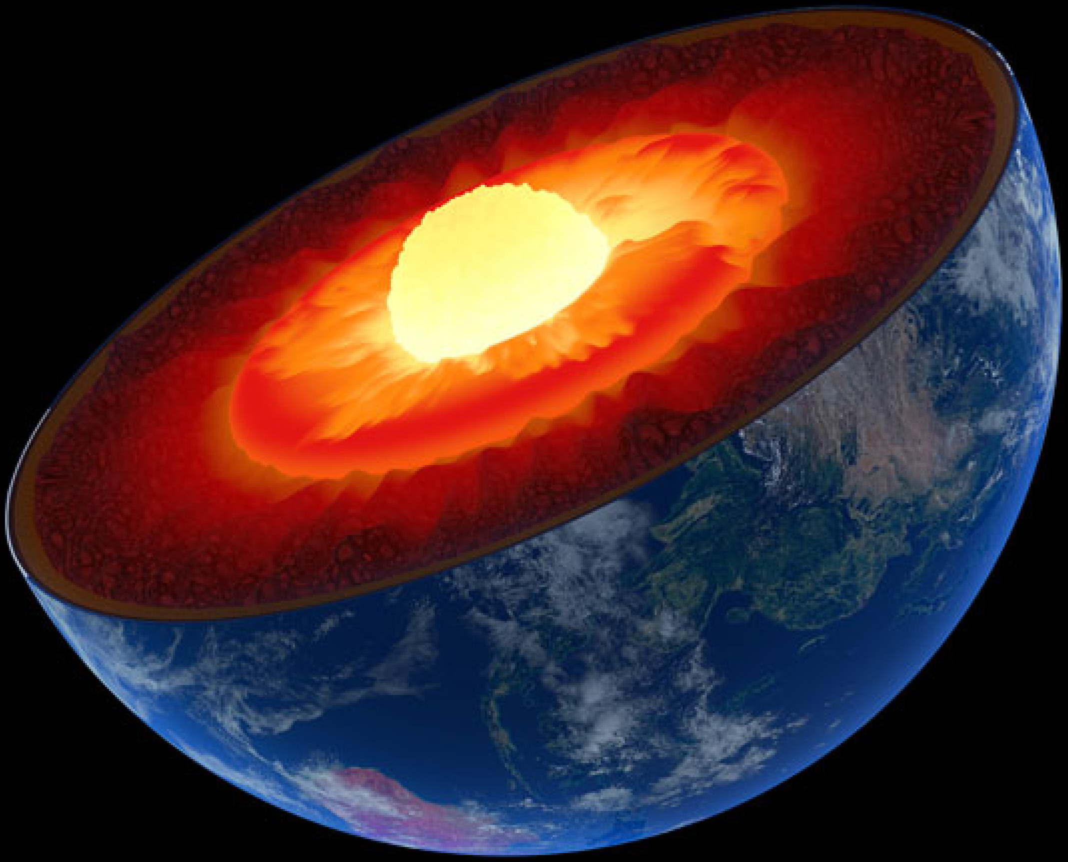
Exemplos de turbulência na natureza




Re = 2000
Re = 3000
Re = 4000

HYPERTROPHIC CARDIOMYOPATHY





1. ***Por que a turbulência se desenvolve?***

2. ***Como compreendemos a turbulência?***

3. ***Quais são os efeitos da turbulência?***

1. Por que a turbulência se desenvolve?

2. Como compreendemos a turbulência?

3. Quais são os efeitos da turbulência?

Turbulent flows

$$\underbrace{\rho\,(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u})}_{\text{Acceleration}} = \underbrace{-\nabla p}_{\text{Pressure}} + \underbrace{\nu\,\triangle\,\vec{u}}_{\text{Viscosity}}$$

$$\mathbf{Re} = \frac{\mathbf{LU}}{\nu} \gg \mathbf{1}$$

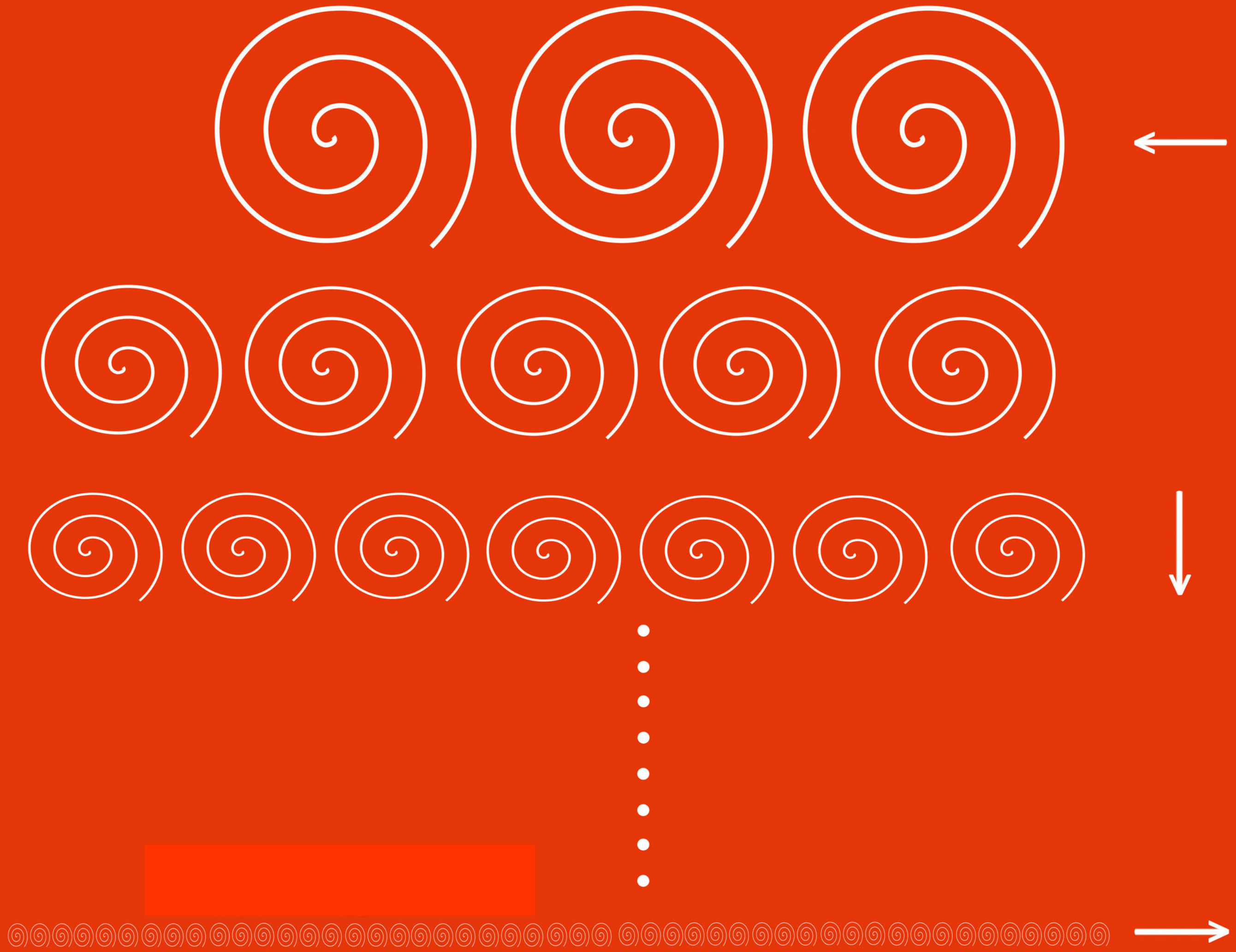
Astrophysical flows:

- Sun convection zone (upper part): $\mathbf{Re} \sim \mathbf{10^{13}}$
- Protostellar disks: $\mathbf{Re} \sim \mathbf{10^{9}}$
- Galaxies: $\mathbf{Re} \sim \mathbf{10^{7}}$
- Intracluster medium: $\mathbf{Re} \sim \mathbf{10^{2}}$

1. Por que a turbulência se desenvolve?

2. **Como compreendemos a turbulência?**

3. Quais são os efeitos da turbulência?

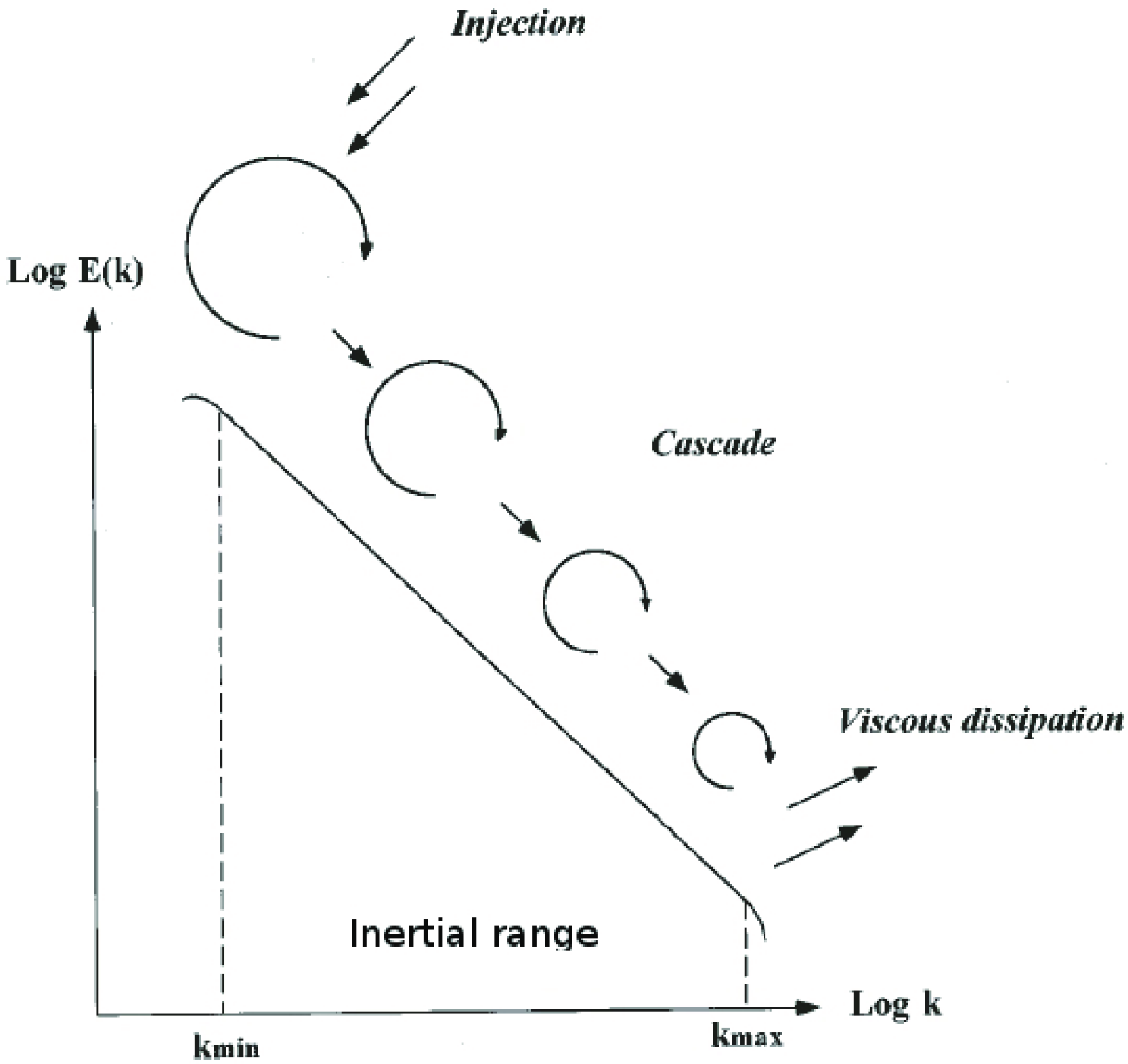


energy injection

energy cascade

energy dissipation

Energy cascade in turbulent flows



Kolmogorov (1941)

- isotropy
- universality
- locality

$$E(k) \propto k^{-5/3}$$

$$l_\nu = \left(\frac{\nu^3}{\epsilon}\right)^{1/4}$$

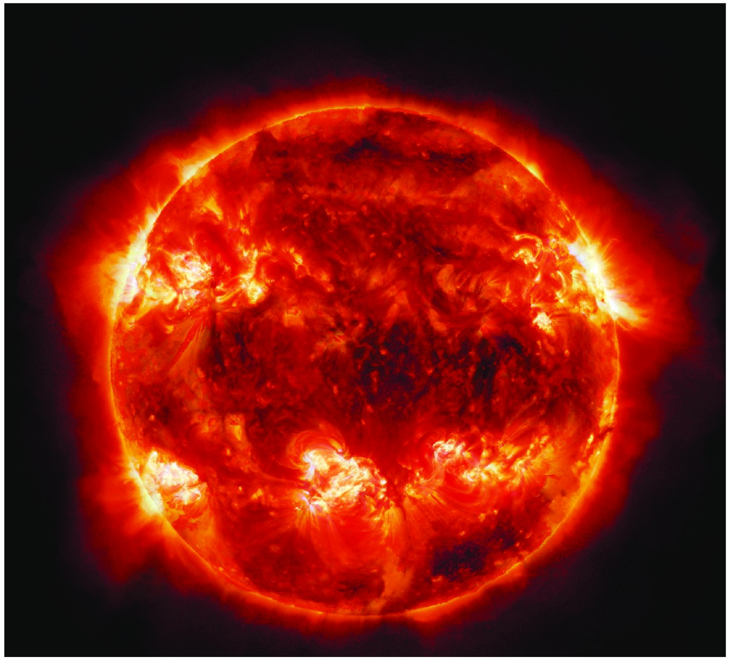
Turbulence in plasmas

Plasma: gas electrically conducting.

Constitutes more than 90% of the visible Universe! (Goedbloed 2004)

Magnetic fields and **turbulence** – ubiquitous in astrophysical plasmas:

- Stellar surfaces and interiors
- Molecular clouds
- Warm and hot phases of the interstellar medium (ISM)
- ISM of external galaxies
- Intracluster medium of galaxies (ICM)



Magnetohydrodynamic (MHD) description

Links the evolution of the macroscopic variables of a **magnetized conducting fluid** and **magnetic fields**, in mutual interaction.

Ideal MHD basic equations

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

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left\{ \left(e + p + \frac{B^2}{8\pi} \right) \mathbf{u} + \frac{1}{4\pi} (\mathbf{u} \cdot \mathbf{B}) \mathbf{B} \right\} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

1. Por que a turbulência se desenvolve?
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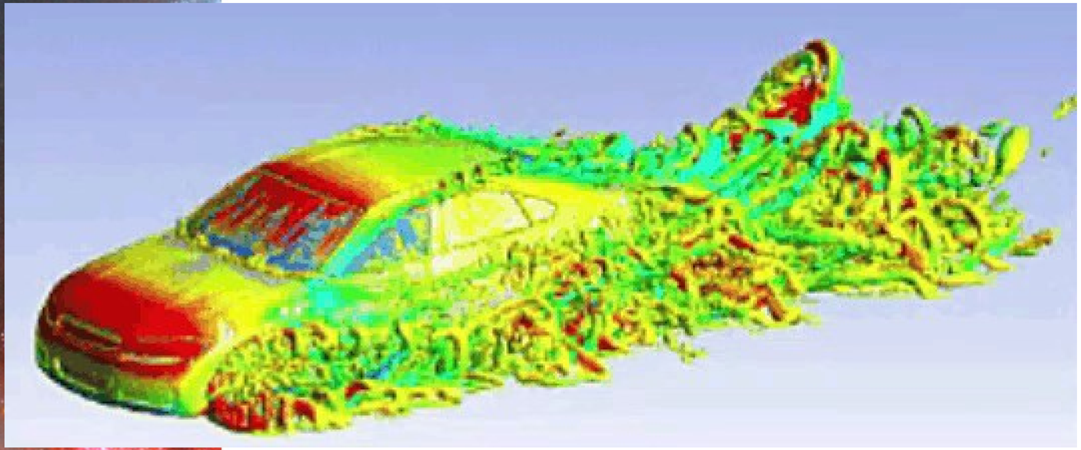


1. Por que a turbulência se desenvolve?

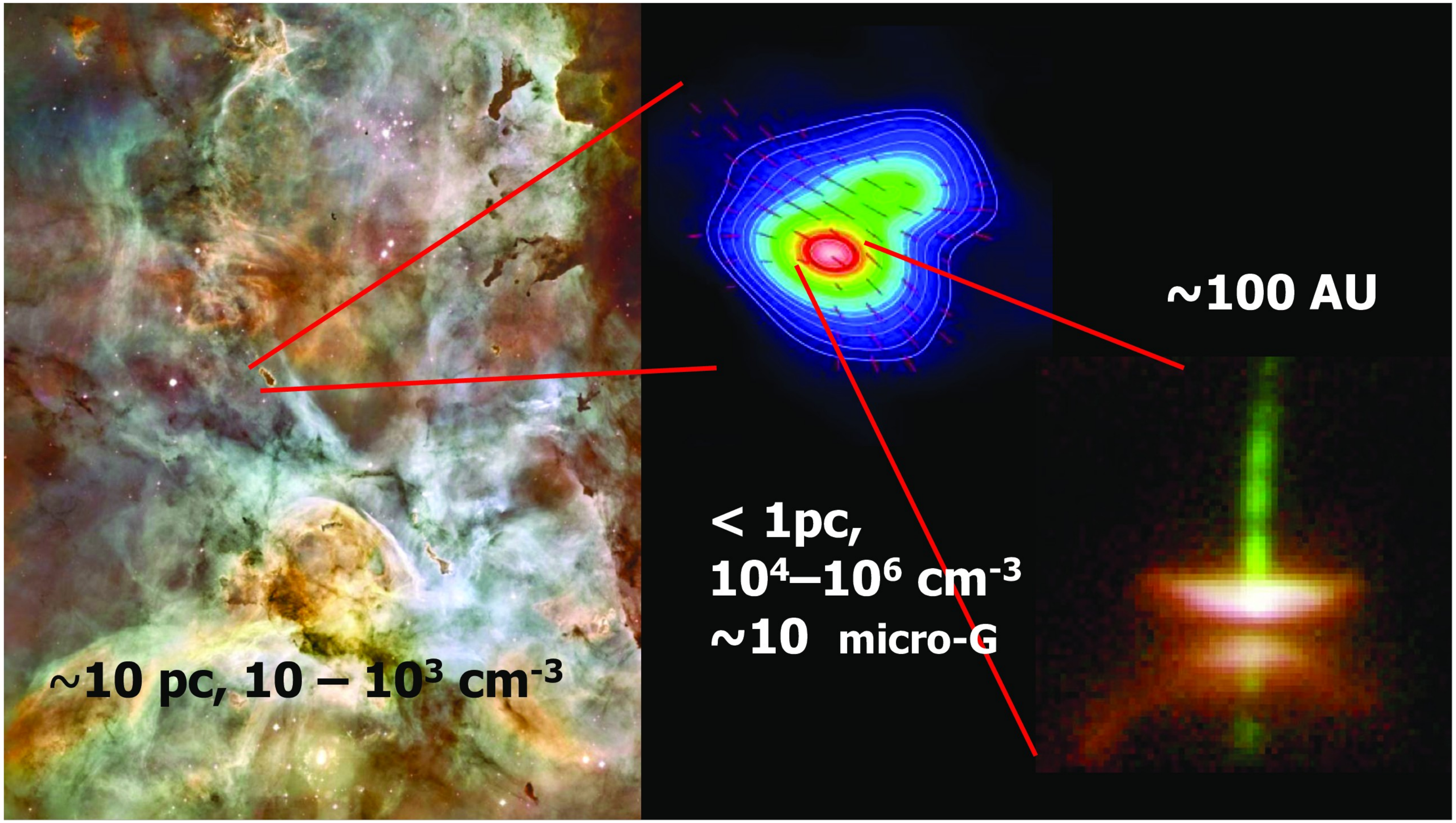
2. Como compreendemos a turbulência?

3. **Quais são os efeitos da turbulência?**

   ➡ Na astrofísica

- ***Controle da taxa de reconexão/difusão magnética***
- ***Amplificação magnética***
- ***Aceleração e transporte de raios cósmicos***

Star Formation not well understood in neither scale



~10 pc, 10 – 10^3 cm^{-3}

< 1pc,
10^4–10^6 cm^{-3}
~10 micro-G

~100 AU

Magnetic fields and turbulence affect star-formation

Magnetic fields

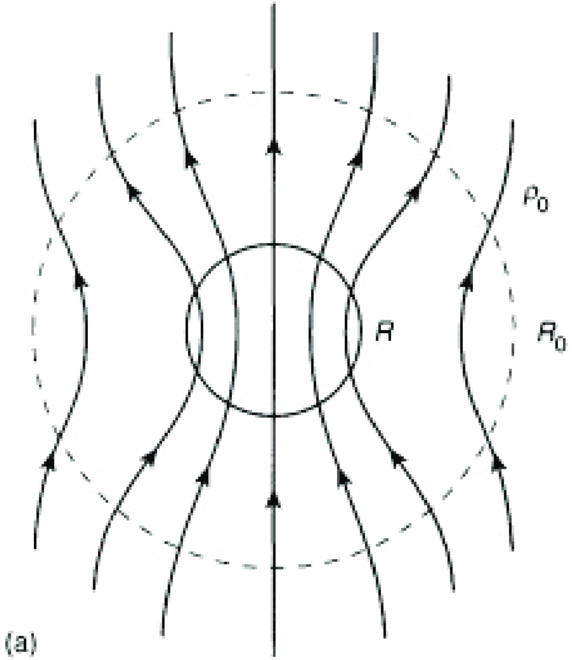
- Exert forces against gravitational collapse: subcritical and supercritical molecular cloud cores
- Field line torques can brake rotation of protostelar disks

MHD turbulence

- Supersonic and trans-Alfvénic (e.g. Vazquez-Semadeni et al.)
- Important for the structuring of the ISM and star-formation
- Sources of turbulence in the ISM:
    - SN shocks
    - Spiral waves
    - Outflows from YSOs

Need for mass-flux decoupling

Magnetic flux in new stars (T-Tauri) $<<$ Magnetic flux of the molecular cloud progenitor — **Magnetic flux problem**



Required diffusivity $\sim 10^3 \eta_{Ohm}$ (Shu et al. 2006)

How is the excess of magnetic field removed from the clouds?

Classical solution

Ambipolar Diffusion (AD)

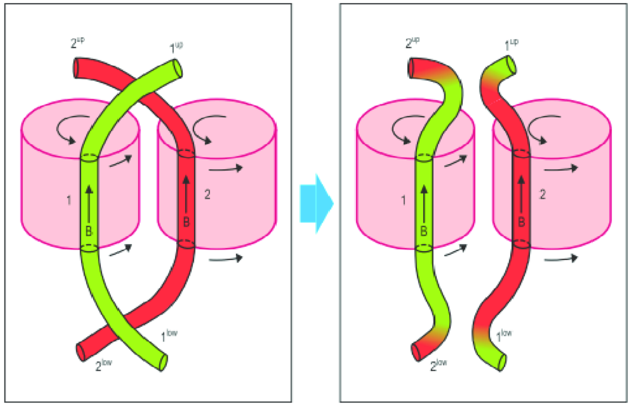
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \nabla \times \left\{ \frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c \gamma_{in} \rho \rho_i} \right\}$$

- Efficiency has been challenged by observations (Crutcher et al. 2008), theory (Shu et al. 2006), and numerical simulations (Krasponolsky et al. 2010, 2011; Li et al. 2011)

Reconnection Diffusion: new scenario

Fast reconnection induced by turbulence (Lazarian & Vishniac 1999, Kowal et al. 2009) allows change in topology of the field: **transport of field lines becomes efficient**.

➡ **Turbulence breaks frozen-in condition** (Lazarian 2005, 2011; Eyink et al. 2011; tested by Santos-Lima et al. 2010, 2012, 2013; de Gouveia Dal Pino et al. 2012; Leao et al. 2013)

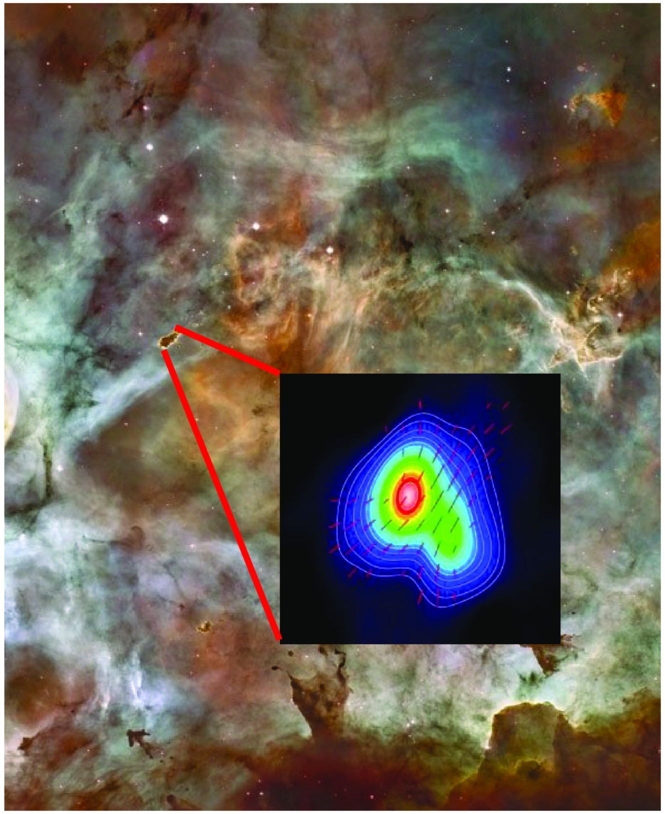


Prediction:

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

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

Reconnection Diffusion in clouds



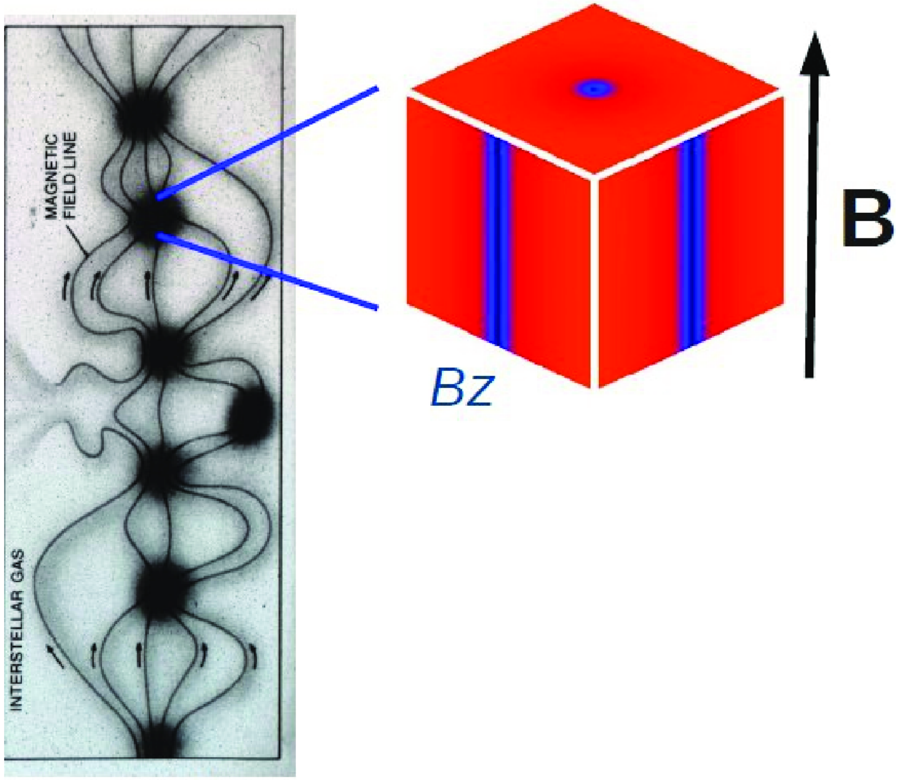
Embedded magnetic flux should be partially removed from denser to less dense regions by reconnection diffusion

⬇

Can allow cloud clump collapse and can solve the magnetic flux problem!

Testing reconnection diffusion in gravitating clouds: 3D MHD simulations

- Gravitational potential with cylindrical symmetry
- Periodic BCs
- Isothermal EOS
- Initial setups:
    - equilibrium (subcritical cloud)
    - out-of-equilibrium (supercritical cloud)
- Continuous injection of trans-sonic turbulence



From **Crutcher** (IAU2009 JD15)

Testing reconnection diffusion in gravitating clouds: 3D MHD simulations

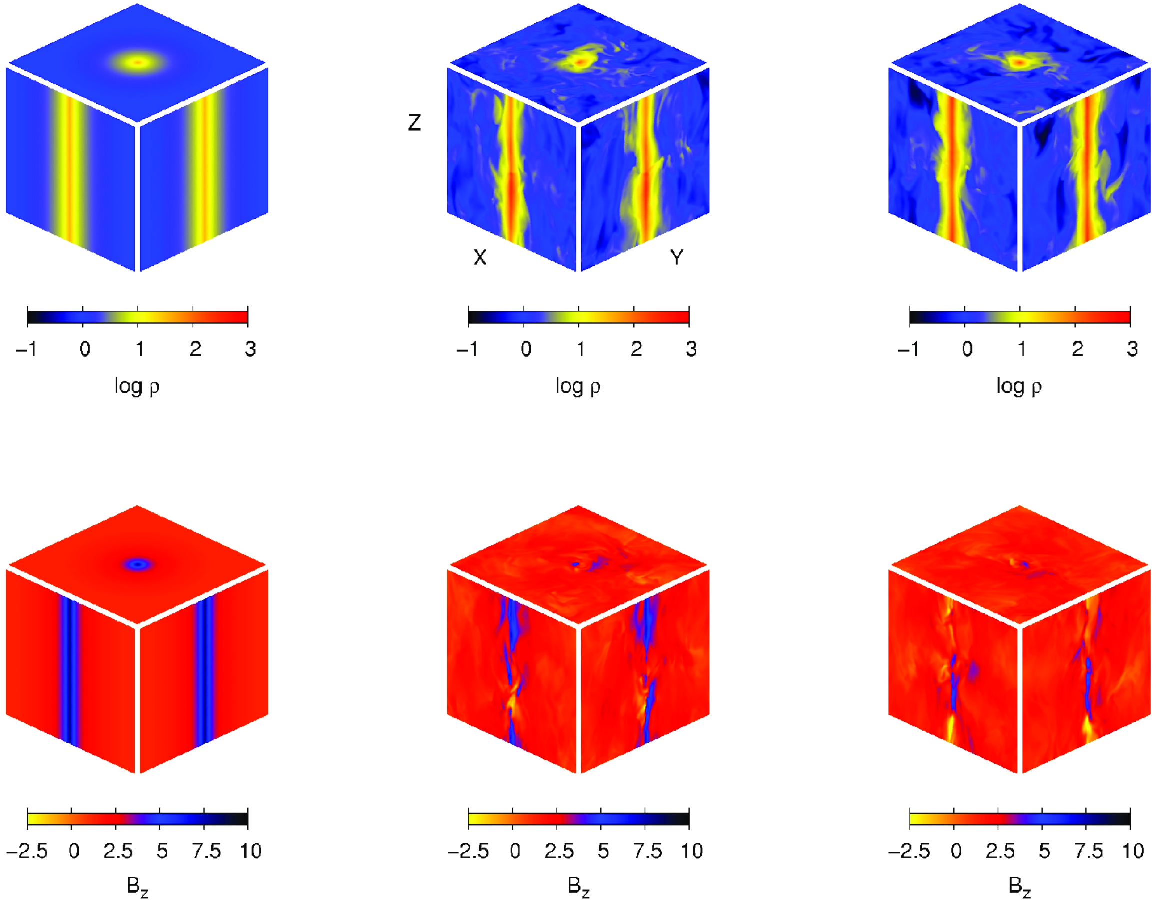
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -c^2 \nabla \rho + \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Psi + \mathbf{f}$$

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

- $\mathbf{f}$: drives non-helical turbulence
- $\eta_{\mathbf{Ohm}} = \mathbf{0}$
- 2nd order shock-capturing Godunov scheme (AMUN code - https://www.amuncode.org/)

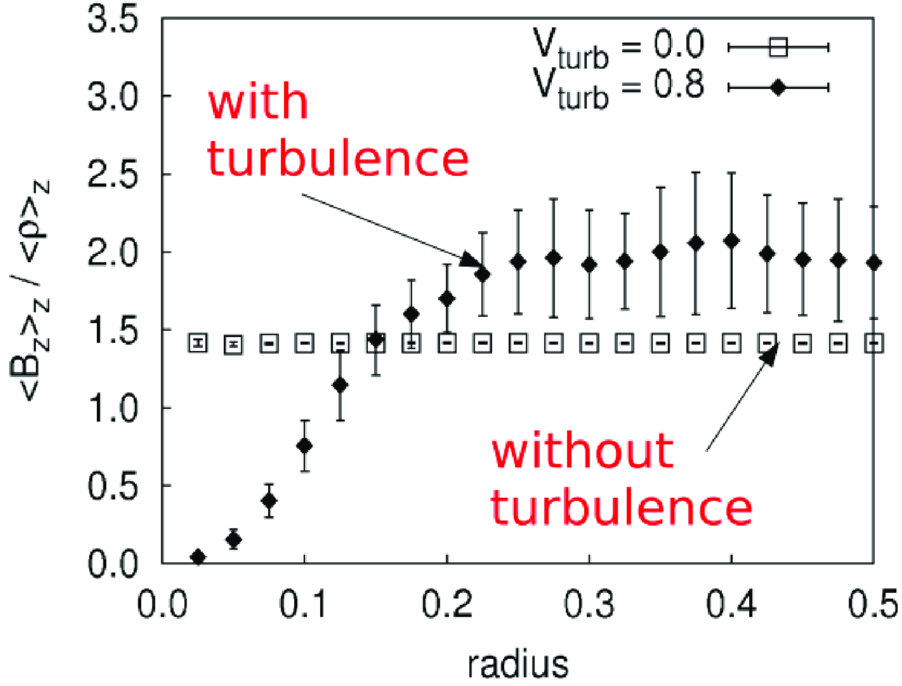
Magnetic Field diffusion in gravitating clouds: 3D MHD simulations



Santos-Lima et al. 2010, ApJ

Magnetic field diffusion in gravitating clouds: 3D simulations

(starting out-of-equilibrium)

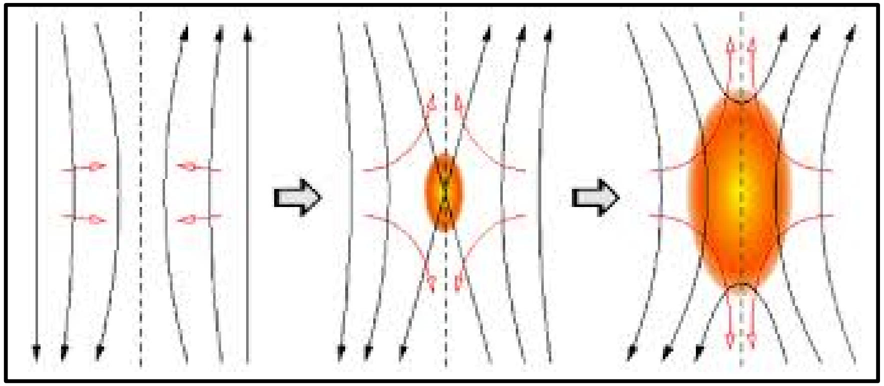


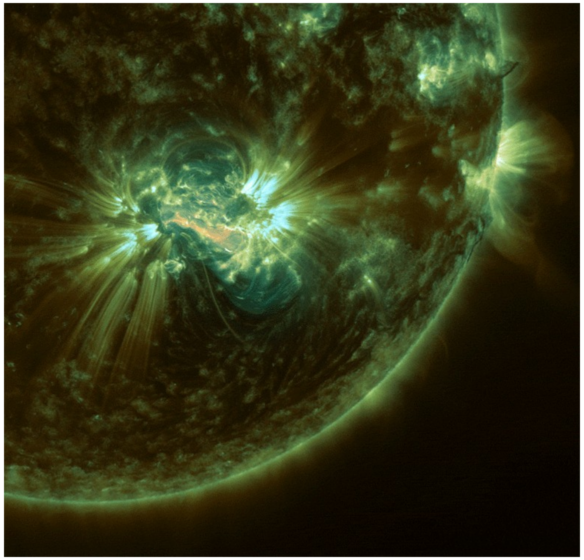
- Removal of magnetic flux from the central regions (strong-gravity);
- Gas inflow into the central region;
- **Reduction of the flux-to-mass ratio in the central region.**

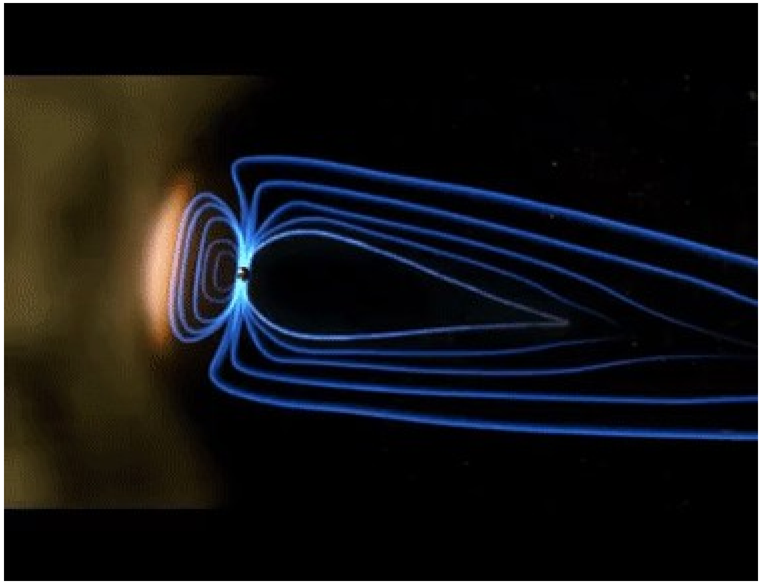
(Santos-Lima et al., ApJ, 2010)

Reconexão magnética

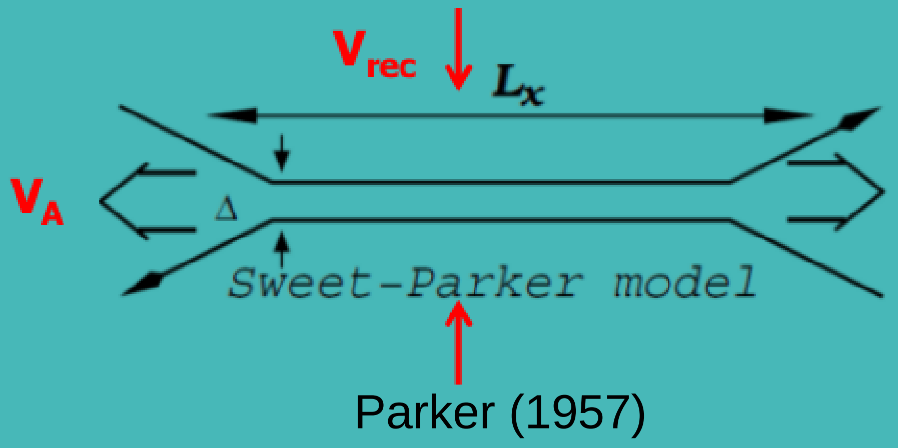
- Aproximação de tubos de fluxo de diferentes polaridades







Reconexão magnética



$$V_{rec} \sim v_A \, (\Delta / L)$$

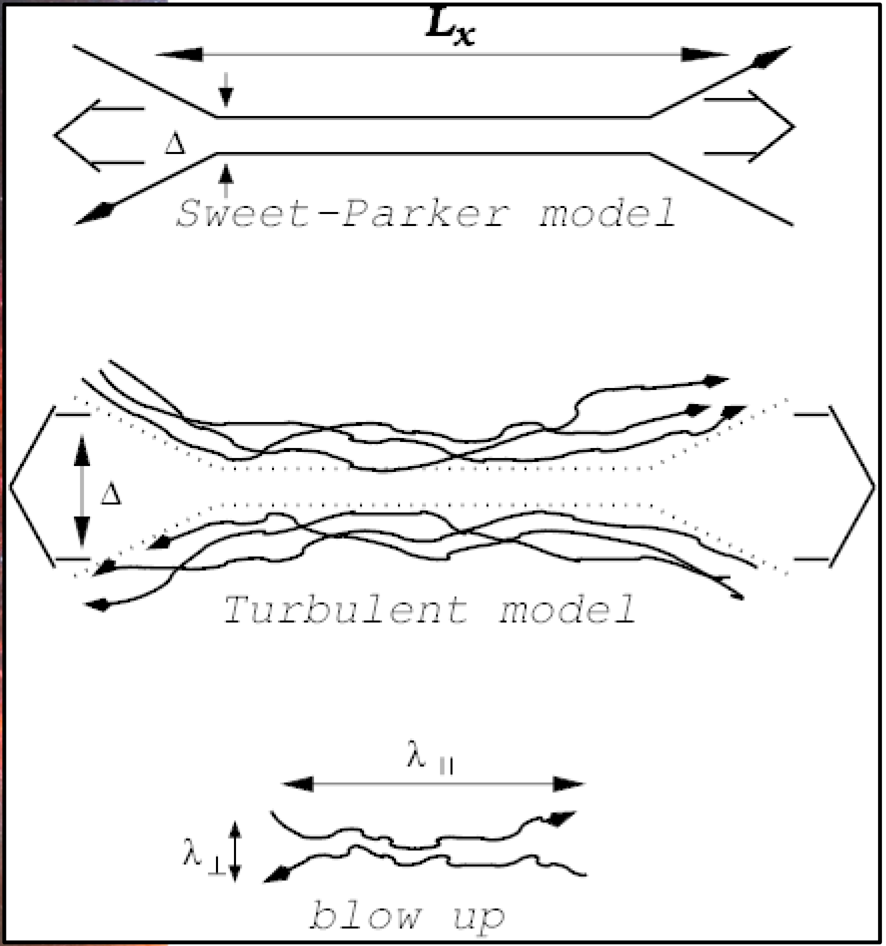
$$S = L \, v_A / \eta$$

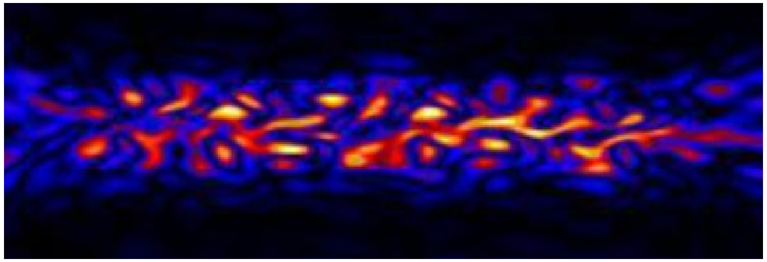
Very large
small
in astrophysics

$$V_{rec} \underbrace{\sim v_A \, S^{-1/2} << 1}_{slow}$$

$$V_A = (B \,/\, 4 \,\pi\, \rho)^{1/2}$$

Reconexão magnética turbulenta





$$\boxed{V_{\rm rec} = V_{\rm A}\left(\frac{l}{L}\right)^{1/2}\left(\frac{v_l}{V_{\rm A}}\right)^2}$$

It is fast!

Lazarian & Vishniac (1999)

- ***Controle da taxa de reconexão/difusão magnética***

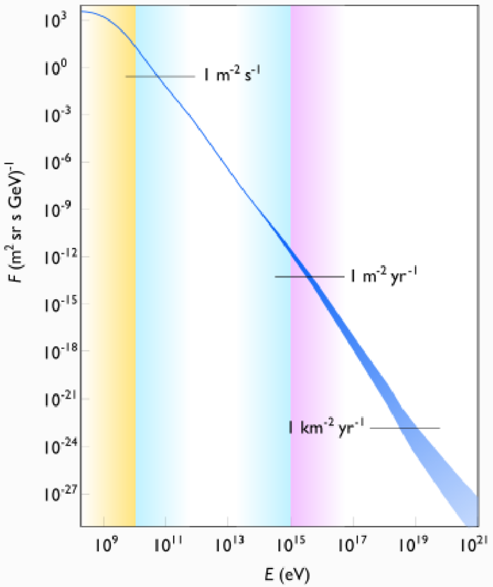
- ***Amplificação magnética***

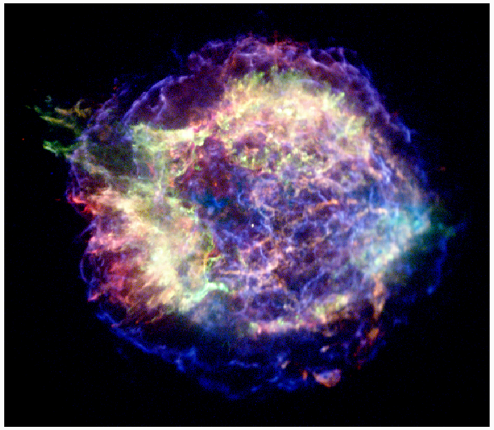
- ***Aceleração e transporte de raios cósmicos***

Cosmic rays

CRs are energetic particles with $10^8 < E < 10^{22}$ eV.

Galactic CRs: $E < 10^{15}$ eV (*the knee*).





The main GCR sources: supernova remnants (SNRs) shocks.

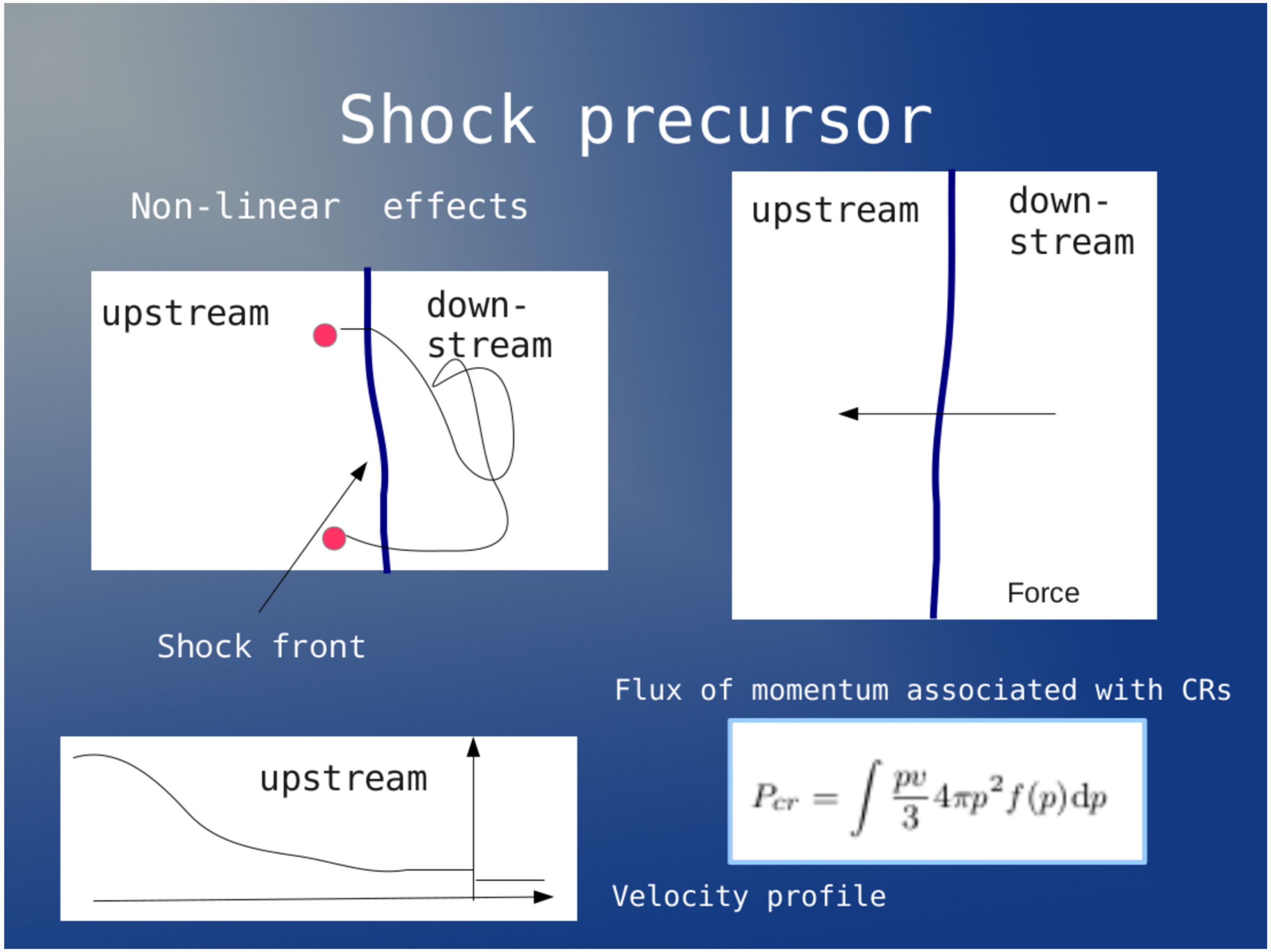
Accelerated through DSA (diffusive shock acceleration).

But!

ISM magnetic field is too weak to accelerate CRs up to the *knee*.

Cosmic rays

CR pressure can be comparable to the pressure of the background medium → produce dynamical effects on the background plasma and magnetic field.



$$P_{cr} = \int \frac{pv}{3} 4\pi p^2 f(p) dp$$

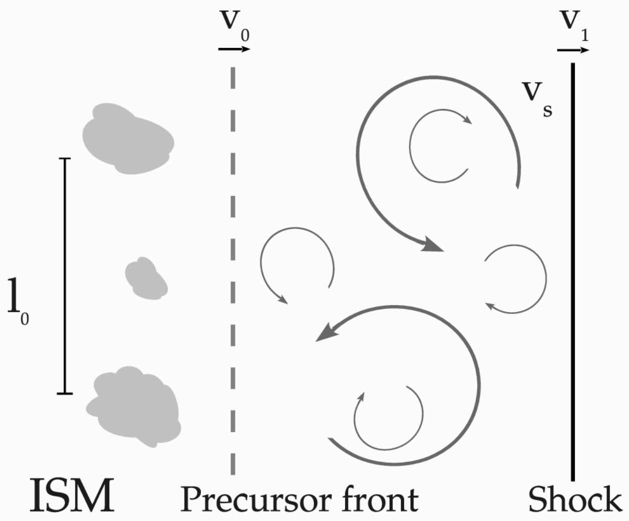
The model

The fluid elements passing through the precursor have density inhomogeneities → ISM turbulence.

Inhomogeneous plasma flows into the precursor with speed v_0 → decelerated by the CR pressure gradient to v_1.

The interaction between the fluid and the CR pressure creates velocity perturbations, partially solenoidal:

$$v_s = A_s \left(v_0 - v_1 \right), \text{ with } A_s \leq 1.$$



BJL09 model

SSD dynamo

Solenoidal velocities develop a turbulent cascade → amplify weak magnetic field through the turbulent Small-Scale Dynamo (SSD).

Three main stages:

- the kinematic stage (magnetic energy grows exponentially)
- the linear stage (magnetic energy grows linearly) and
- the saturation stage.

e.g., Cho+ 2009, ApJ **693**:1449.

In the linear stage magnetic energy increases as:

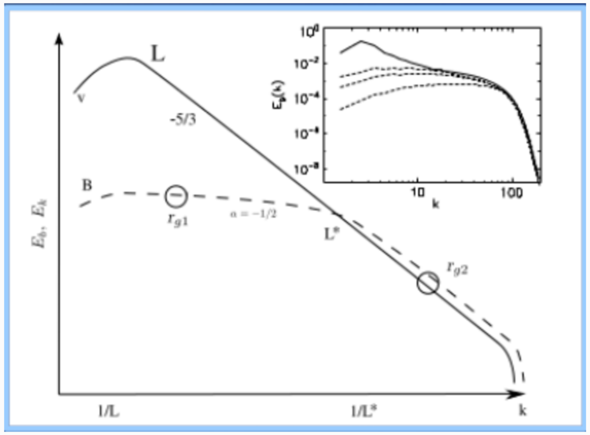
$$\frac{1}{8\pi}\frac{dB^2}{dt} = A_d \epsilon$$

ϵ: energy transfer rate of the turbulence $\epsilon = \rho v_s^3 / l$

A_d: SSD efficiency of the SSD

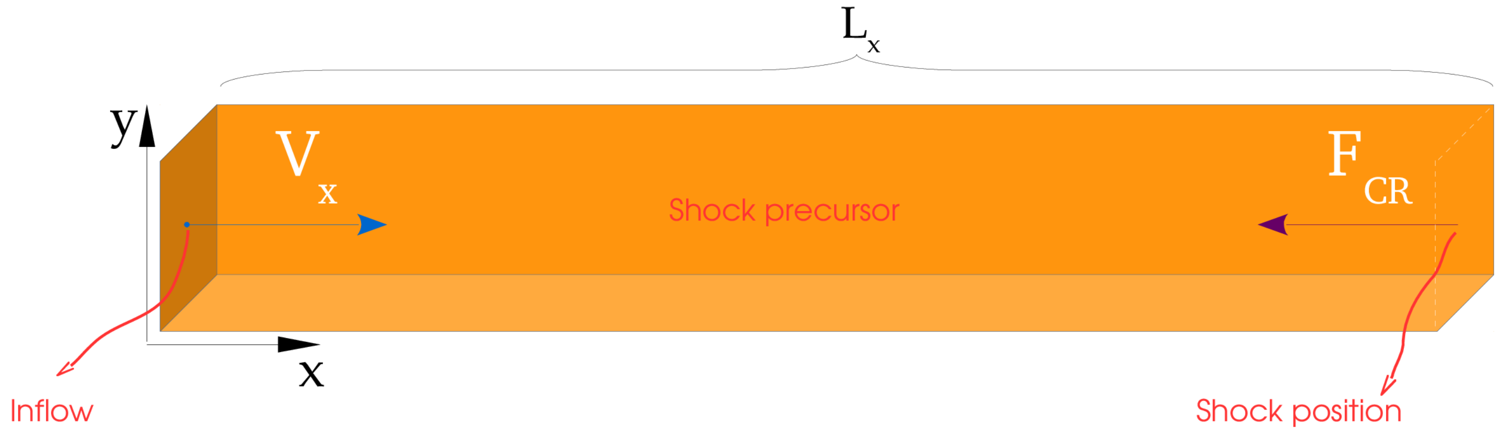
Landau & Lifshitz (1960)

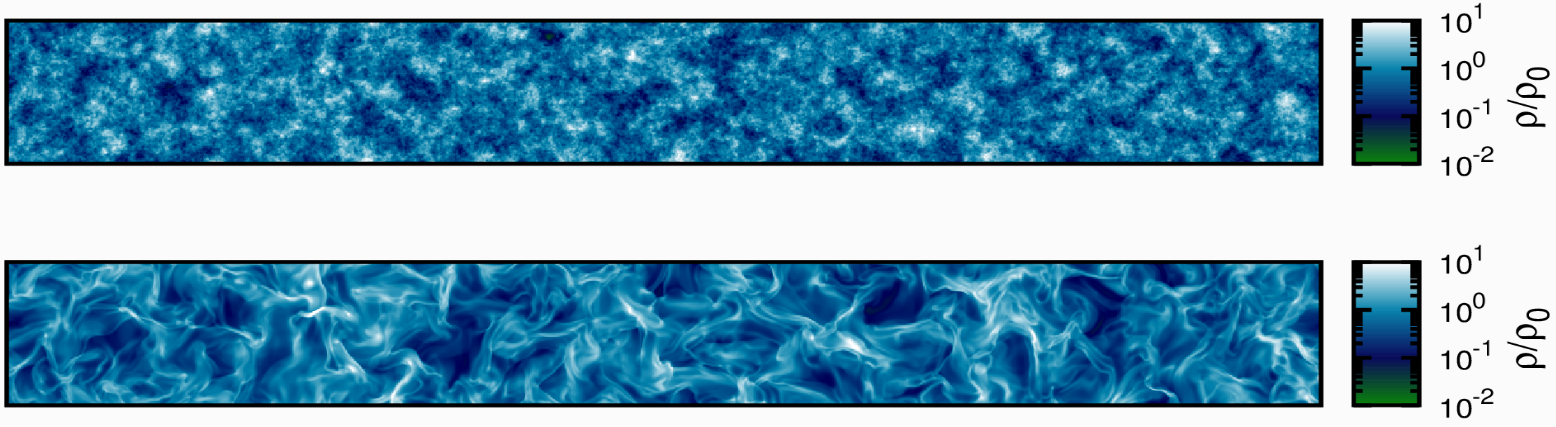
Inverse cascade



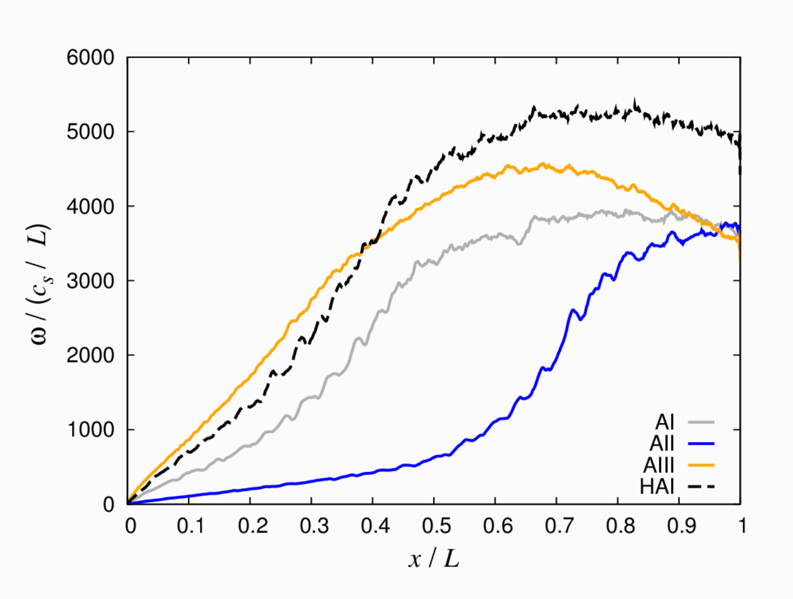
MHD setup

3D MHD simulations of a supersonic flow in the shock referential frame.

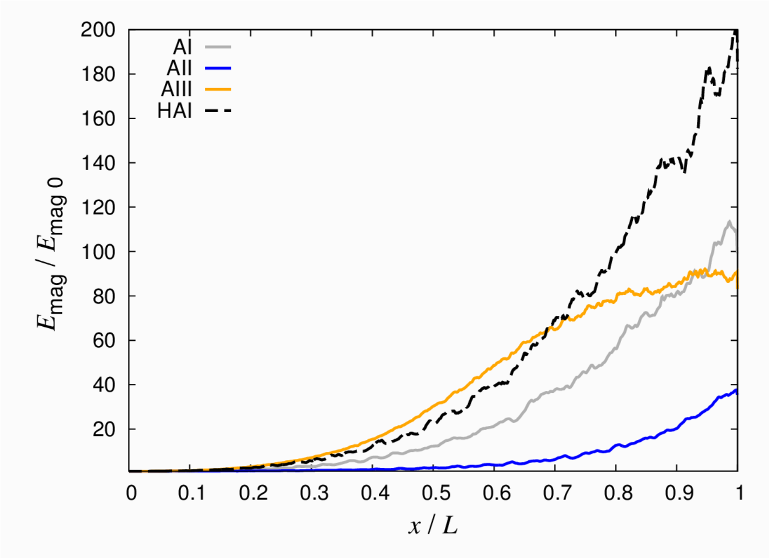




- Vorticidade



- Energia magnética



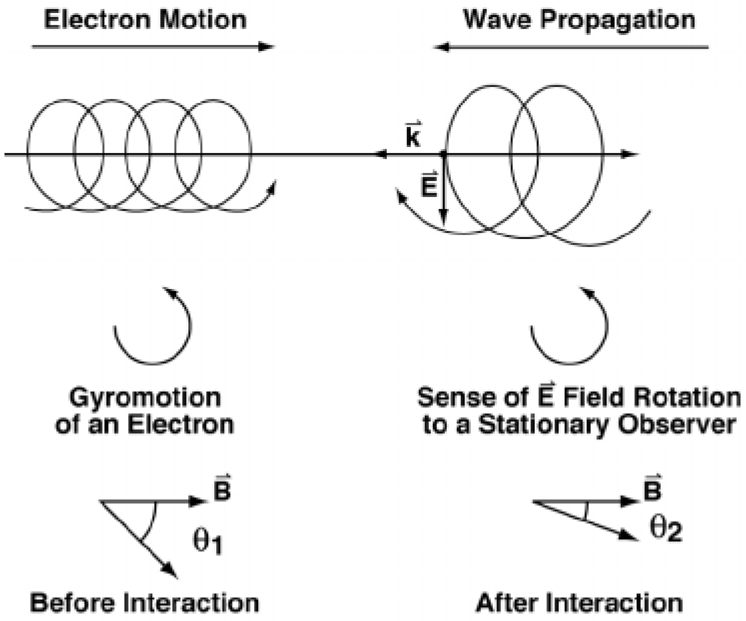
del Valle, Lazarian, Santos-Lima (2016)

- ***Controle da taxa de reconexão/difusão magnética***

- ***Amplificação magnética***

- ***Aceleração e transporte de raios cósmicos***

Interação partícula-onda



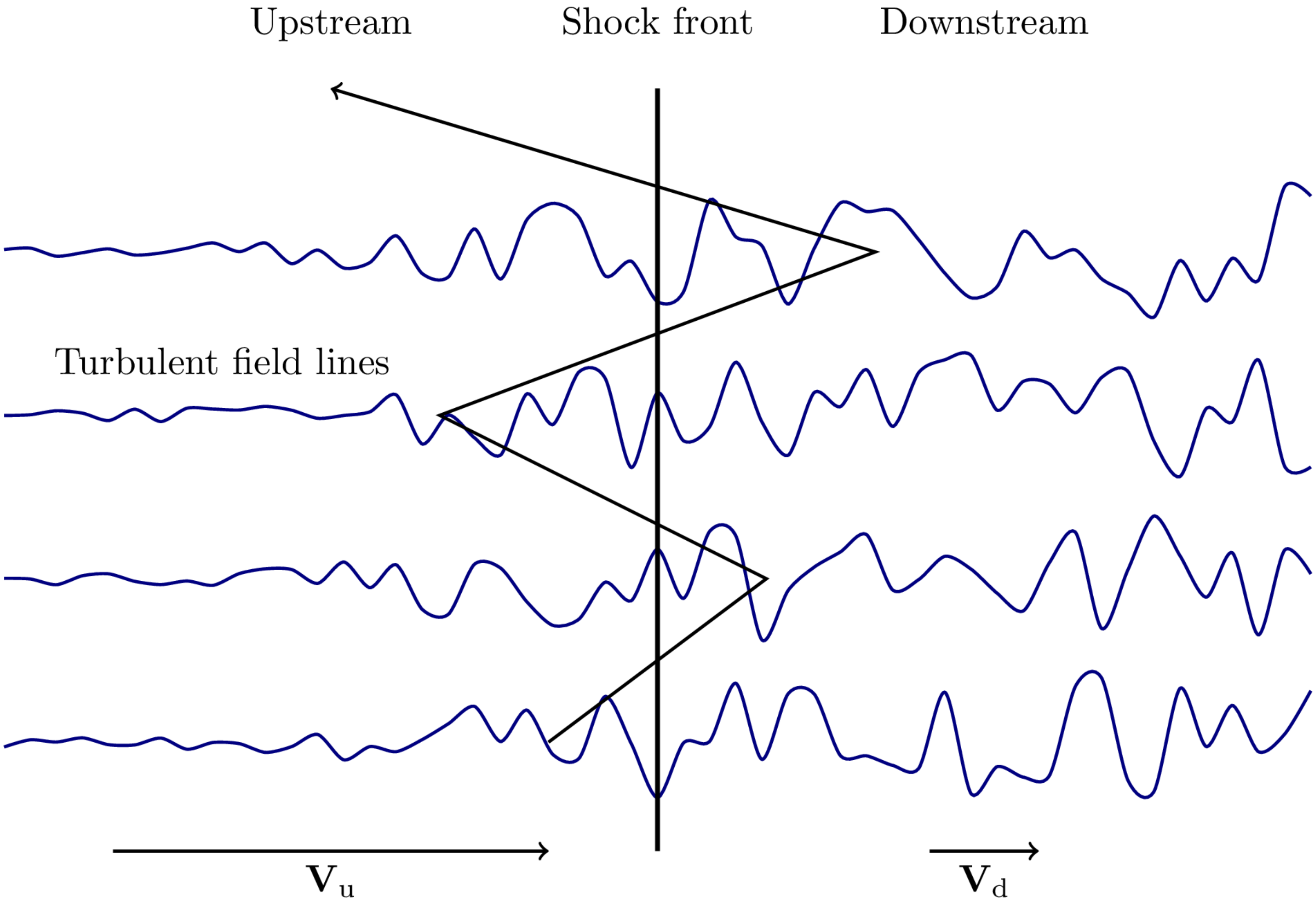
QL Fokker-Planck coefficient

- Parallel propagating waves with circular polarization
- Static limit ($\Gamma \to 0$)
- $\Omega \gg \Re\{\omega_{R,L}\}$

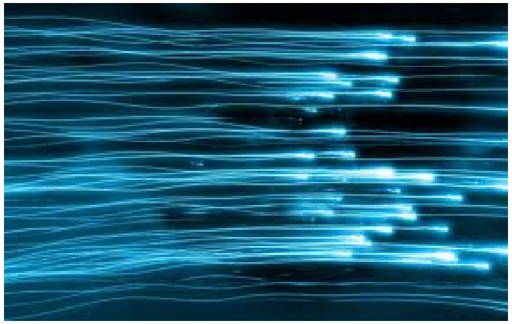
$$D_{\mu\mu}^{QL} = \frac{\pi\Omega^2(1-\mu^2)}{2} \int dk \frac{|\mathbf{B}(k)|^2}{B_0^2} \times$$
$$\times \left\{[1-\overline{\sigma_H(k)}]\delta(v\mu k - \Omega) + [1+\overline{\sigma_H(k)}]\delta(v\mu k + \Omega)\right\}$$

Lebiga, Santos-Lima et al. (2018)

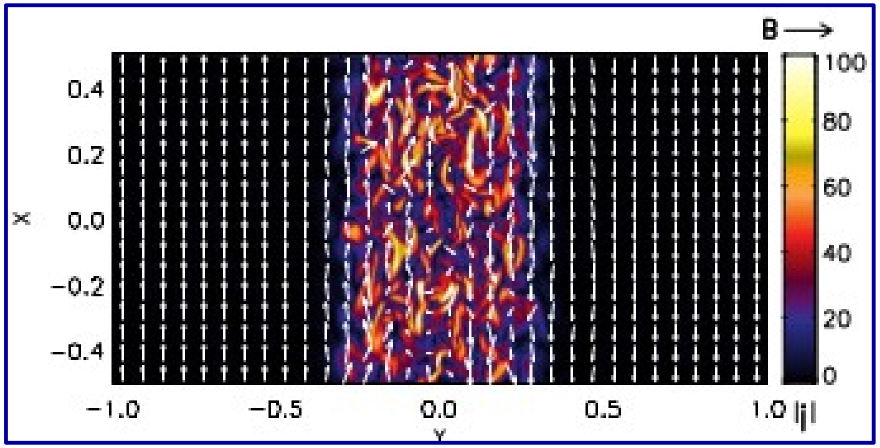
Diffusive Shock Acceleration



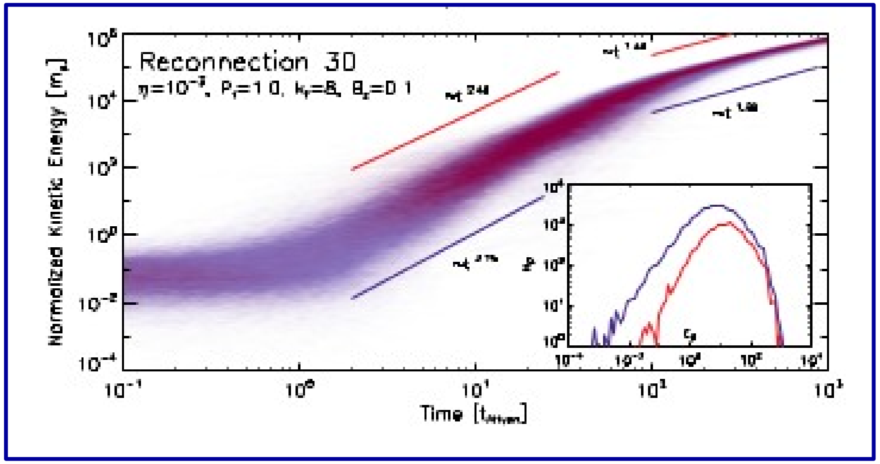
First order Fermi acceleration in magnetic reconnection



10 000 protons injected

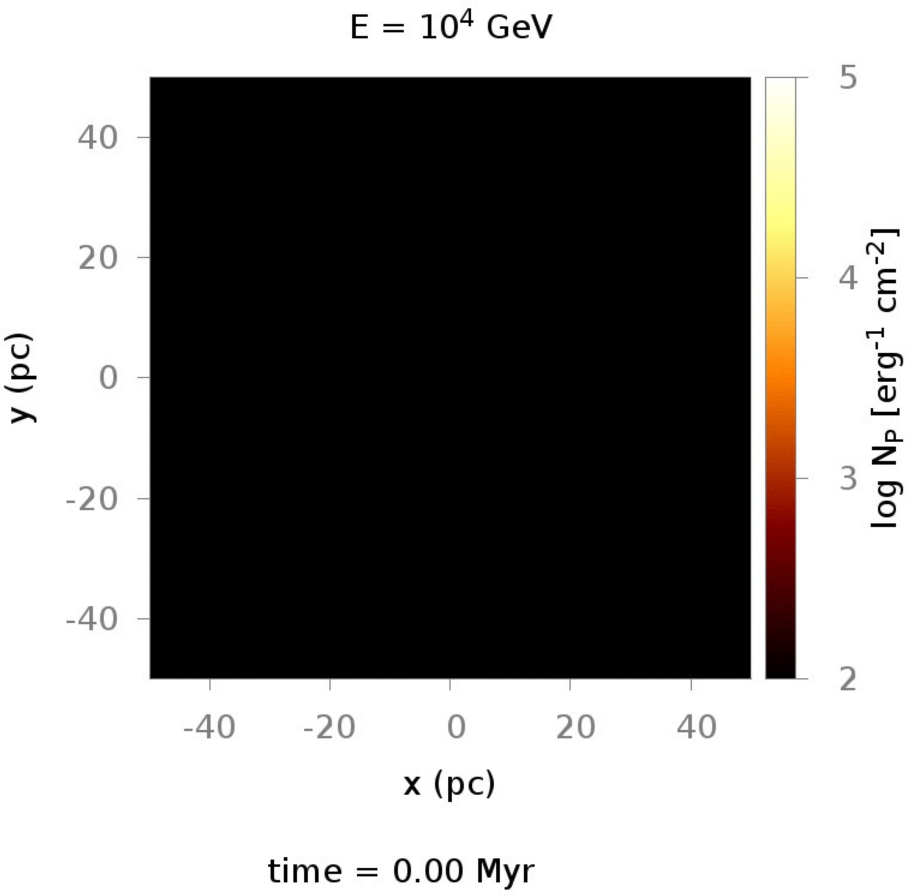


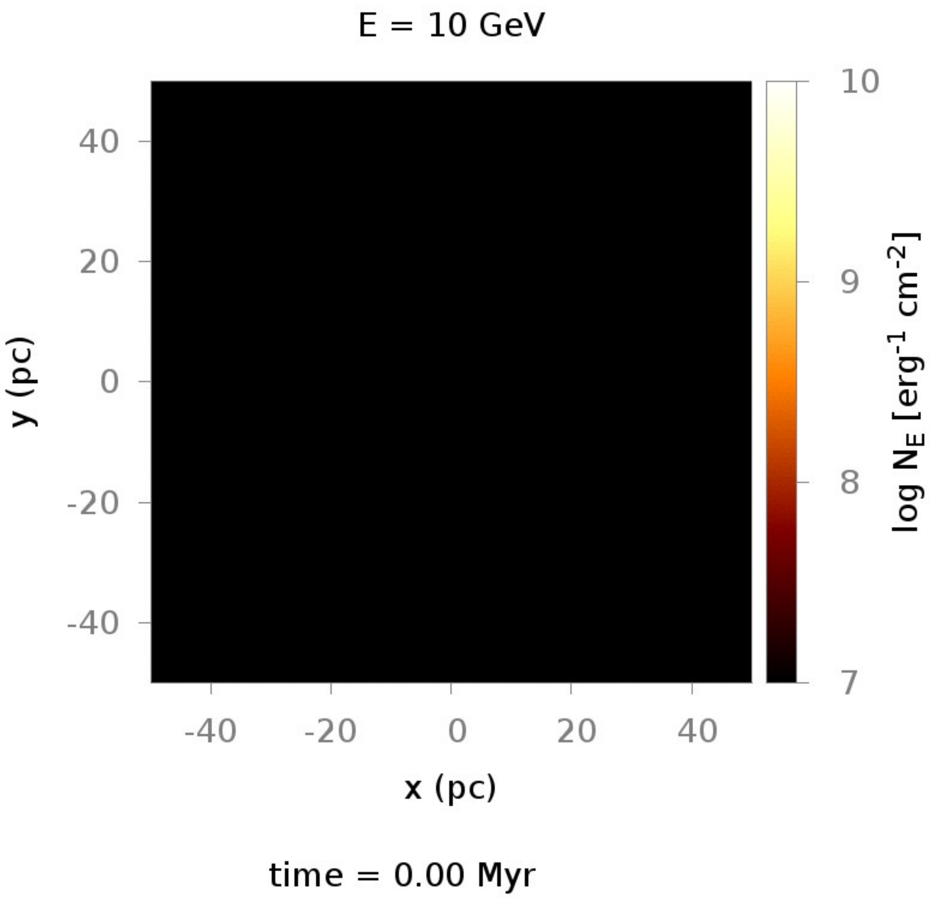
$$\frac{d}{dt}(\gamma m\,\mathbf{u}) = q[(\mathbf{u}-\mathbf{v}) \times \mathbf{B}].$$



Kowal et al. (2012)

- Simulação de propagação de raios cósmicos em nuvem molecular, acelerados no vento de estrelas fugitivas

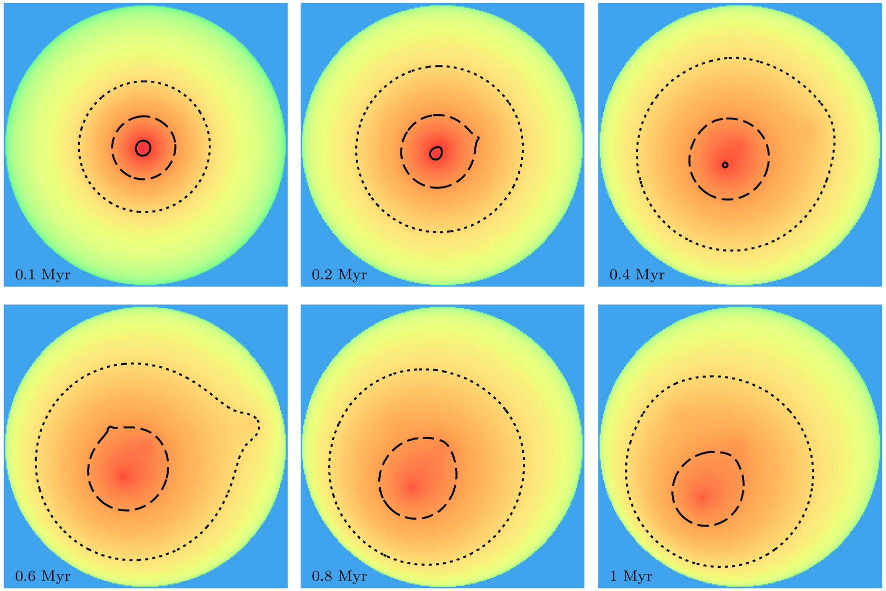


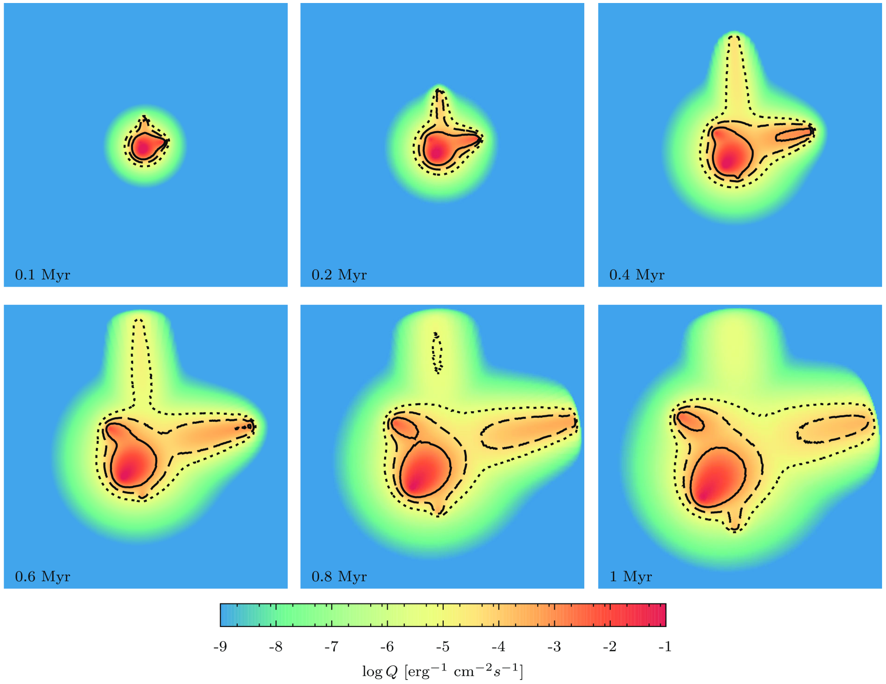


del Valle, Romero, Santos-Lima (2015)

- Simulações de propagação de raios cósmicos com differentes coeficientes de difusão

*Emissividade em **10 GeV***





del Valle, Romero, Santos-Lima (2015)

Take home message

- Turbulência é onipresente em plasmas astrofísicos e é um ingrediente chave para se entender/modelar diversos dos fenômenos ocorrendo nestes meios.
- Computação de alto desempenho é uma das principais ferramentas de investigação teórica de processos astrofísicos envolvendo turbulência.
- A maior parte destes processos ainda não são totalmente compreendidos.