MHD Simulations: A few Astrophysical Applications

ElisaBete de Gouveia Dal Pino

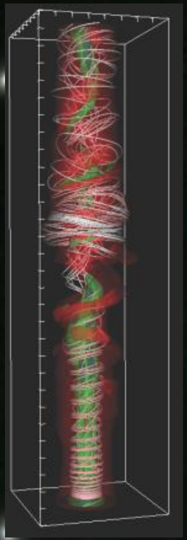
IAG-USP

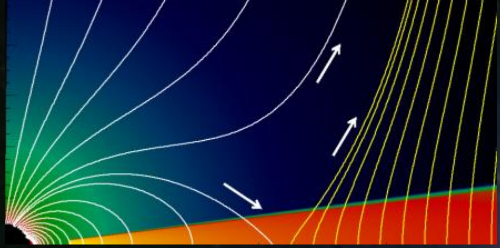
ISYA, Socorro, Colombia, July 2018

E. de Gouveia Dal Pino, Notes on Plasma Astrophysics (and all bibliography inside):

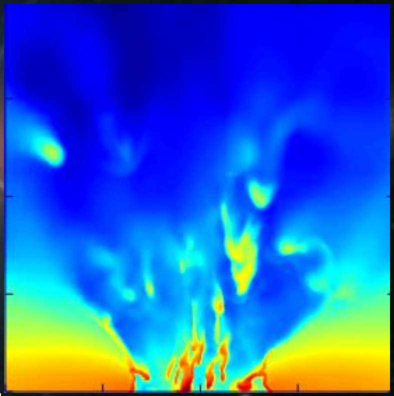
http://www.astro.iag.usp.br/~dalpino/?q=teaching

MHD Simulations

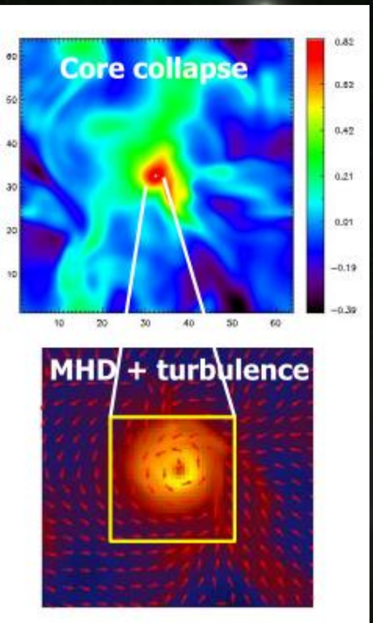




Jets & accretion disks



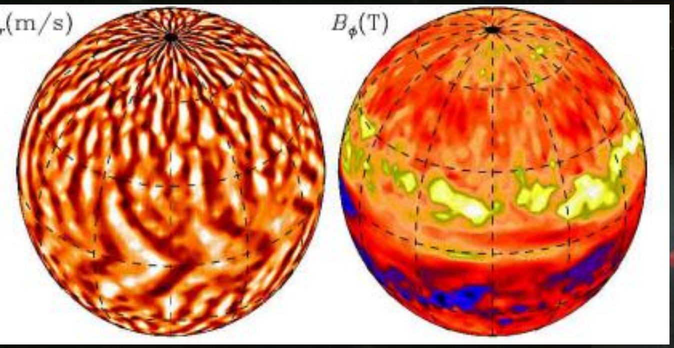
Galactic winds

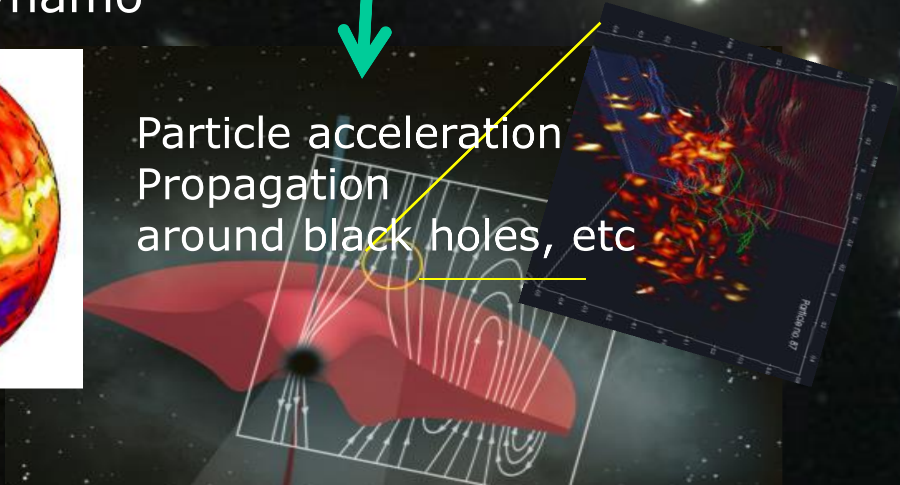


Star Formation - Magnetic turbulence connection

Clusters of Galaxies

Solar Dynamo





Particle acceleration
Propagation
around black holes, etc

ASTROPHYSICAL FLUIDS:
in IDEAL MHD DESCRIPTION

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{v},$$

$$\rho\frac{d\vec{v}}{dt} = -\vec{\nabla}p + \rho\vec{g} + \frac{1}{c}\vec{J}\times\vec{B}$$

$$\frac{du}{dt} = -\frac{p}{\rho}(\nabla\cdot\mathbf{v}) - \mathcal{L},$$

$$\frac{d\mathbf{B}}{dt} = -\mathbf{B}(\nabla\cdot\mathbf{v}) + (\mathbf{B}\cdot\nabla)\mathbf{v},$$

IDEAL MHD EQS. IN CONSERVATIVE FORM

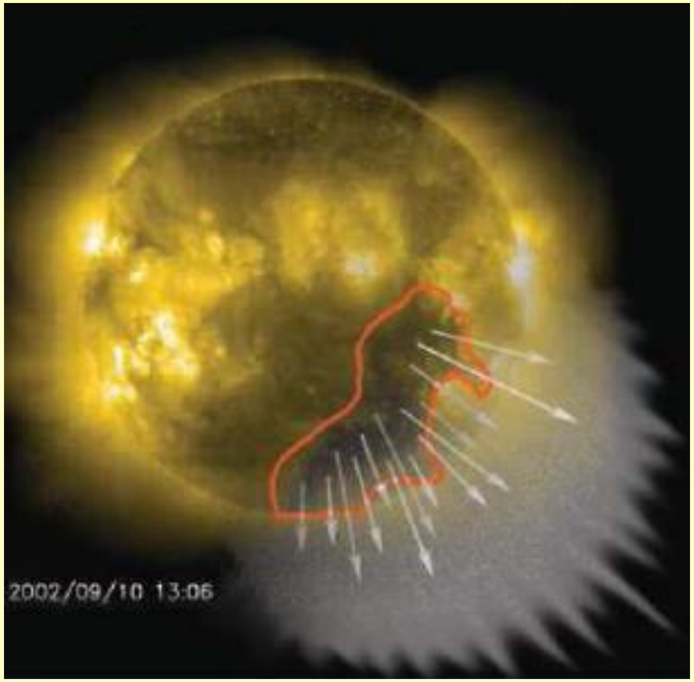
$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{T}(\boldsymbol{U}) = \boldsymbol{S}(\boldsymbol{U})$$

U: conservative variables, *T*: flux of *U* (per time per area); *S*: sources

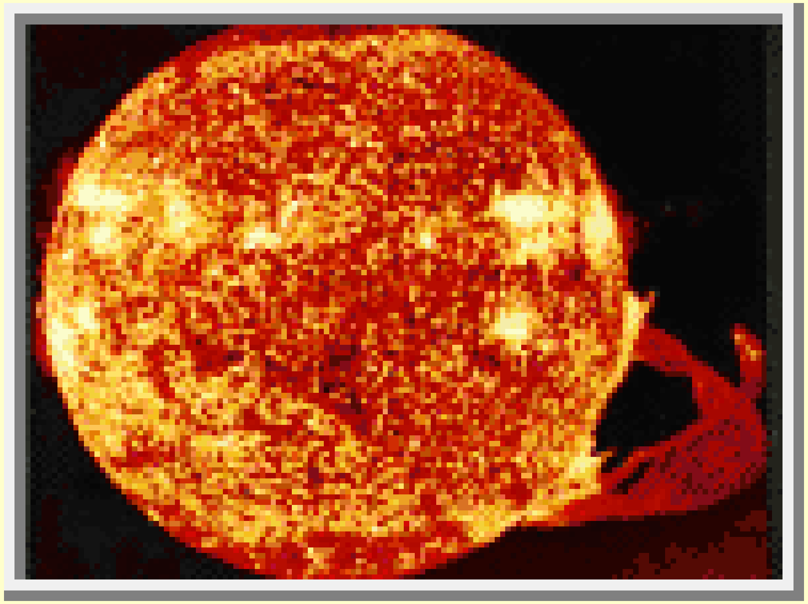
$$\frac{\partial}{\partial t}\begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ E \\ \boldsymbol{B} \end{pmatrix} = -\boldsymbol{\nabla} \cdot \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v} + \left(P + \frac{\boldsymbol{B}^2}{8\pi}\right)\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \\ (E + P + \frac{\boldsymbol{B}^2}{8\pi})\boldsymbol{v} - \frac{(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{B}}{4\pi} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{pmatrix}^T + \begin{pmatrix} 0 \\ \rho \boldsymbol{a} \\ \rho \boldsymbol{v} \cdot \boldsymbol{a} \\ 0 \end{pmatrix}$$

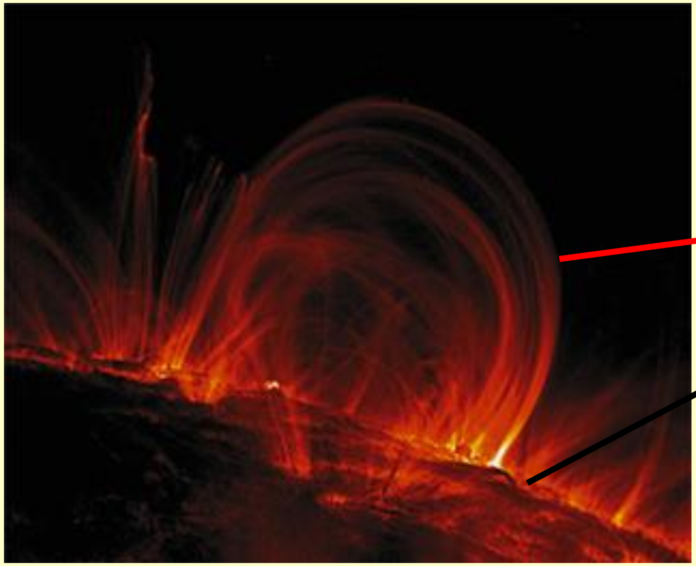
$$E = \frac{p}{\gamma - 1} + \frac{\rho \boldsymbol{v}^2}{2} + \frac{\boldsymbol{B}^2}{8\pi}$$

E: total energy density; ***a***: acceleration vector of external forces (ex. gravity)



Solar Magnetic Fields



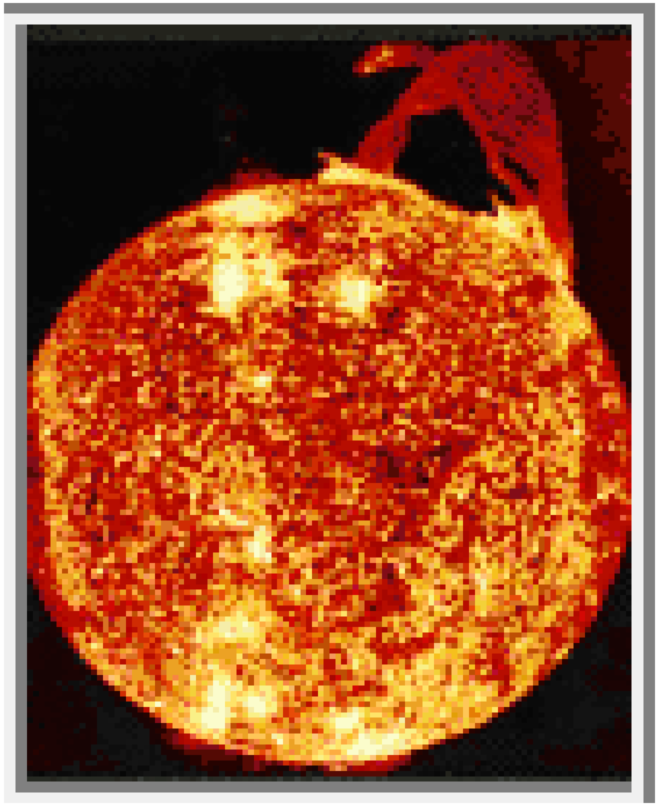


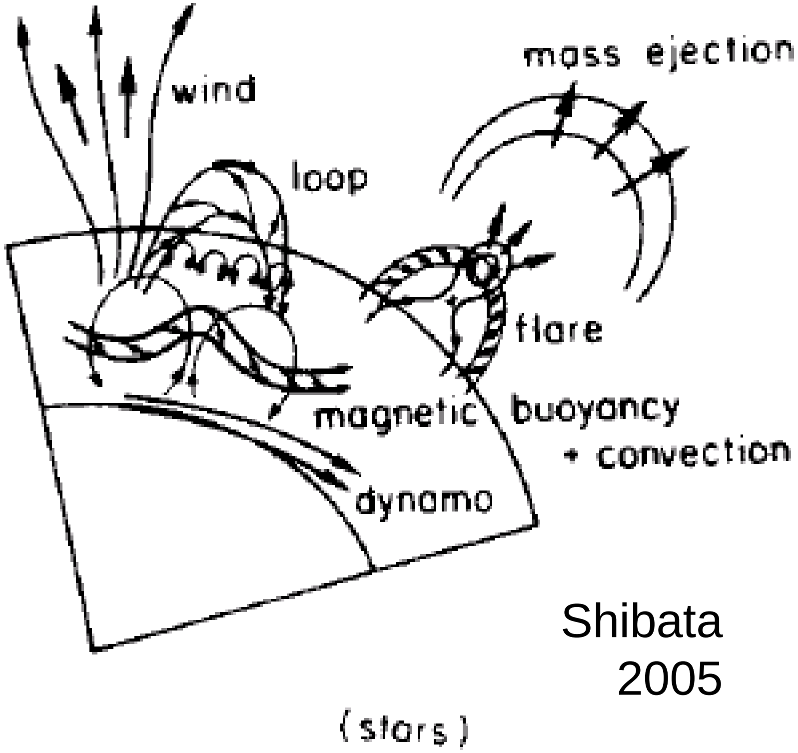
Sun: conductive fluid (PLASMA)
In the corona: 2×10^6 K
magnetic loops: 30,000-100,000 km)
Sunspots: **B = 500-4000 B_{Terra}**

What is the origin of magnetic fields in the Sun ?

Dynamo

Dynamo: converstion of Rotation + Convection motions of charged fluid into **B**





Shibata 2005

Dynamo: Generation of Magnetic Fields

Dynamo: generates magnetic fields: obviously does not conserve magnetic flux → NON IDEAL MHD

$$\boxed{\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v}_e \times \vec{B}) + \frac{\eta c^2}{4\pi} \vec{\nabla}^2 \vec{B} - \frac{c}{n_e^2 e} \vec{\nabla} n_e \times \vec{\nabla} p_e}$$

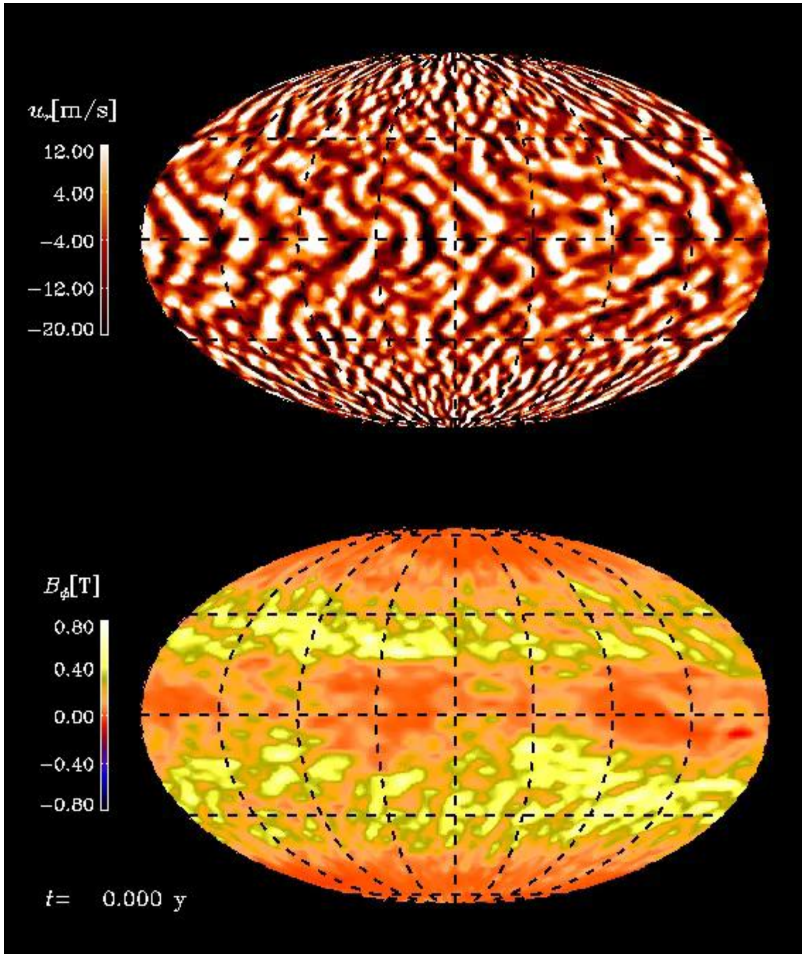
....+ new terms

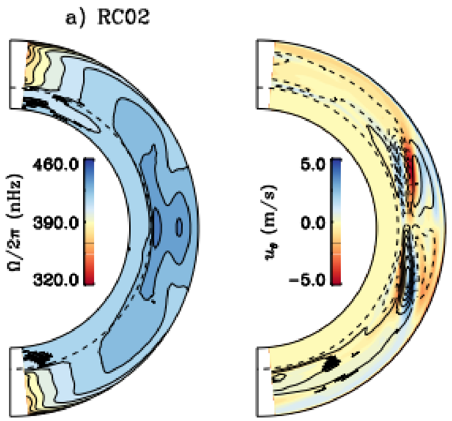
Biermann Battery

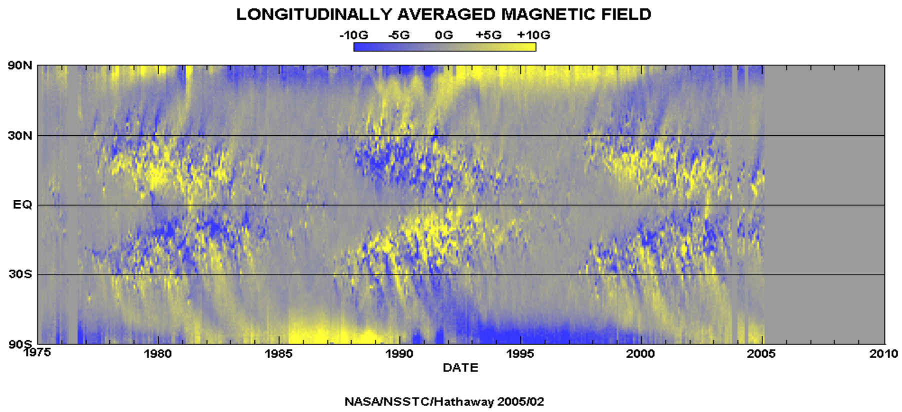
See dynamo theory in Chapter 7 in my Notes on Plasma Astrohpysics:

http://www.astro.iag.usp.br/~dalpino/?q=teaching

Solar Dynamo 3D MHD simulations

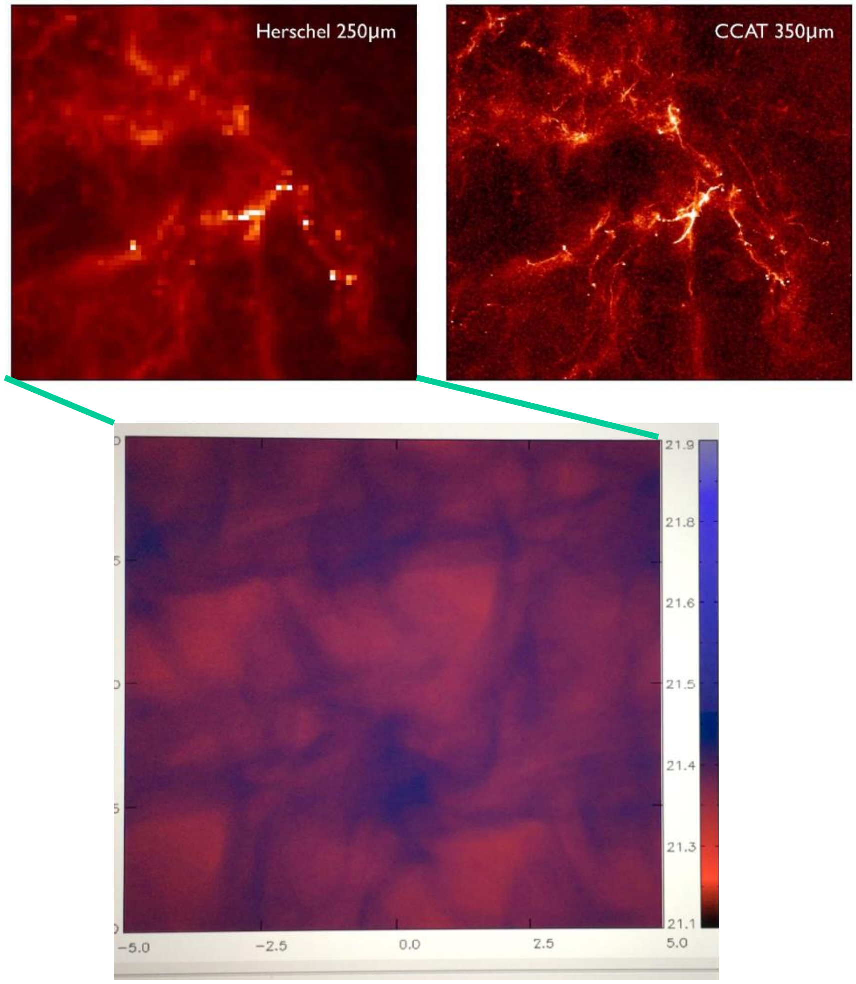




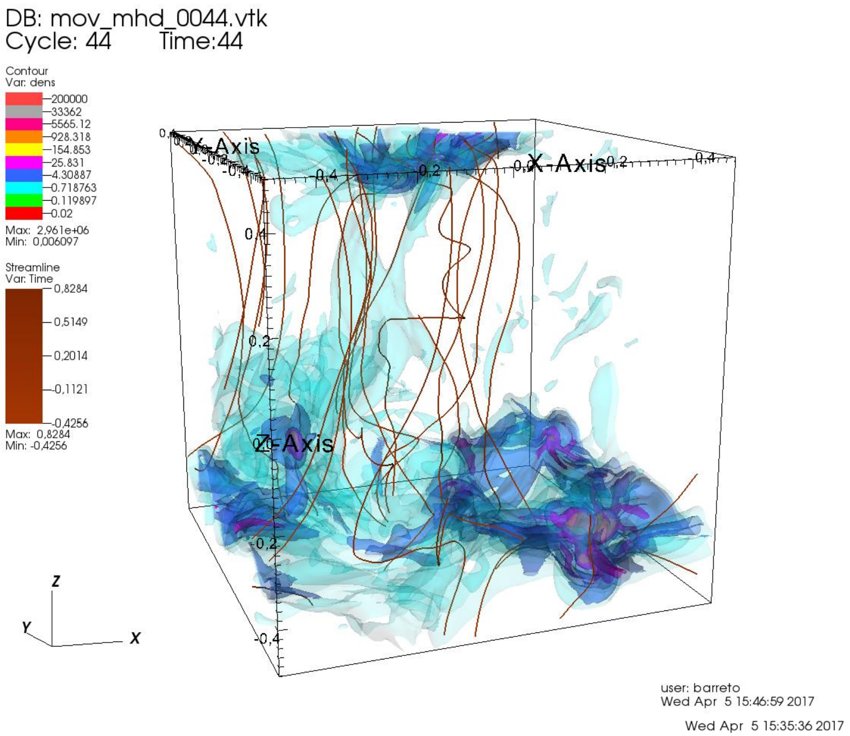


Guerrero, Smolarkiewicz, de Gouveia Dal Pino, Kosovichev, & Mansour, ApJ 2016a, ApJ *Letters* 2016b

3D MHD Simulations of turbulent molecular clouds



- Turbulent clouds: gas accumulates along the field lines forming filaments as observed in diffuse interstellar medium



Santos-Lima, de Gouveia Dal Pino, Lazarian, MNRAS 2013; Barreto, de Gouveia Dal Pino, Melioli, Santos-Lima, in prep.

Distribution of direction of Magnetic fields in the ISM filaments

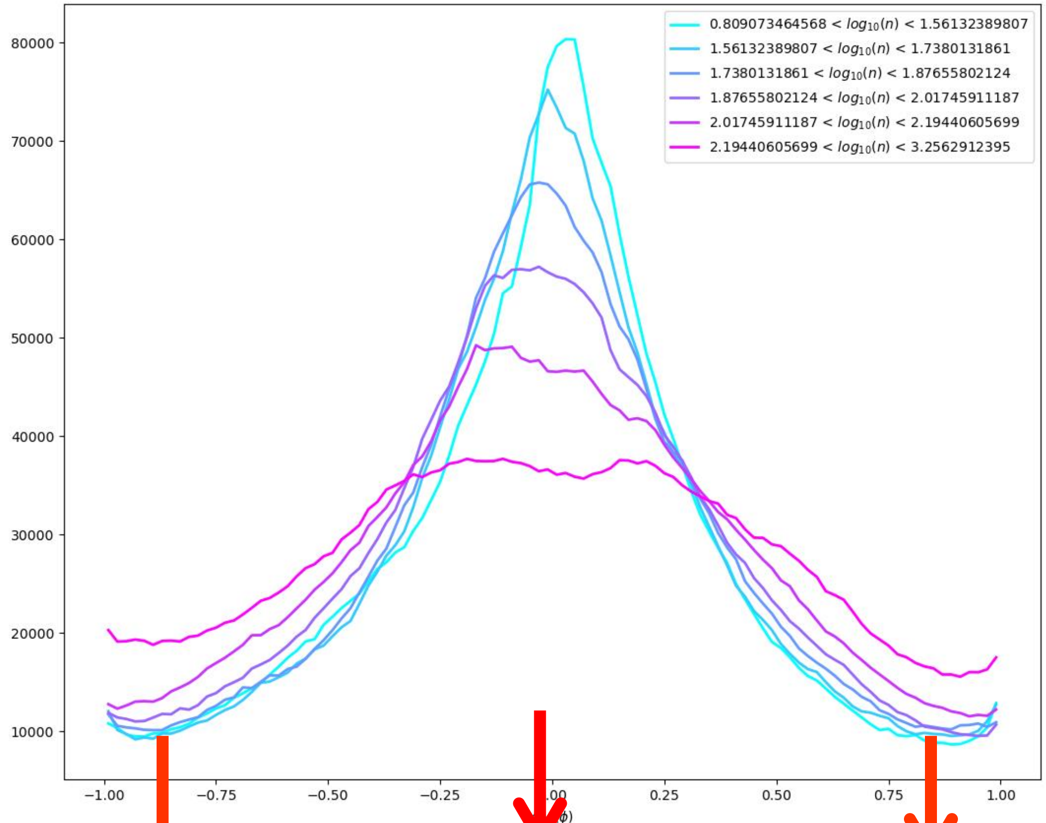
- In diffuse regions:

Filaments // B
Because pressure
Forces prevail

- In collapsing regions:

Filaments $\perp$ to B
because gravity
dominates and
matter
accumulates more
easily $\perp$ to B

$V_{mean} = 1.8\ C_s$



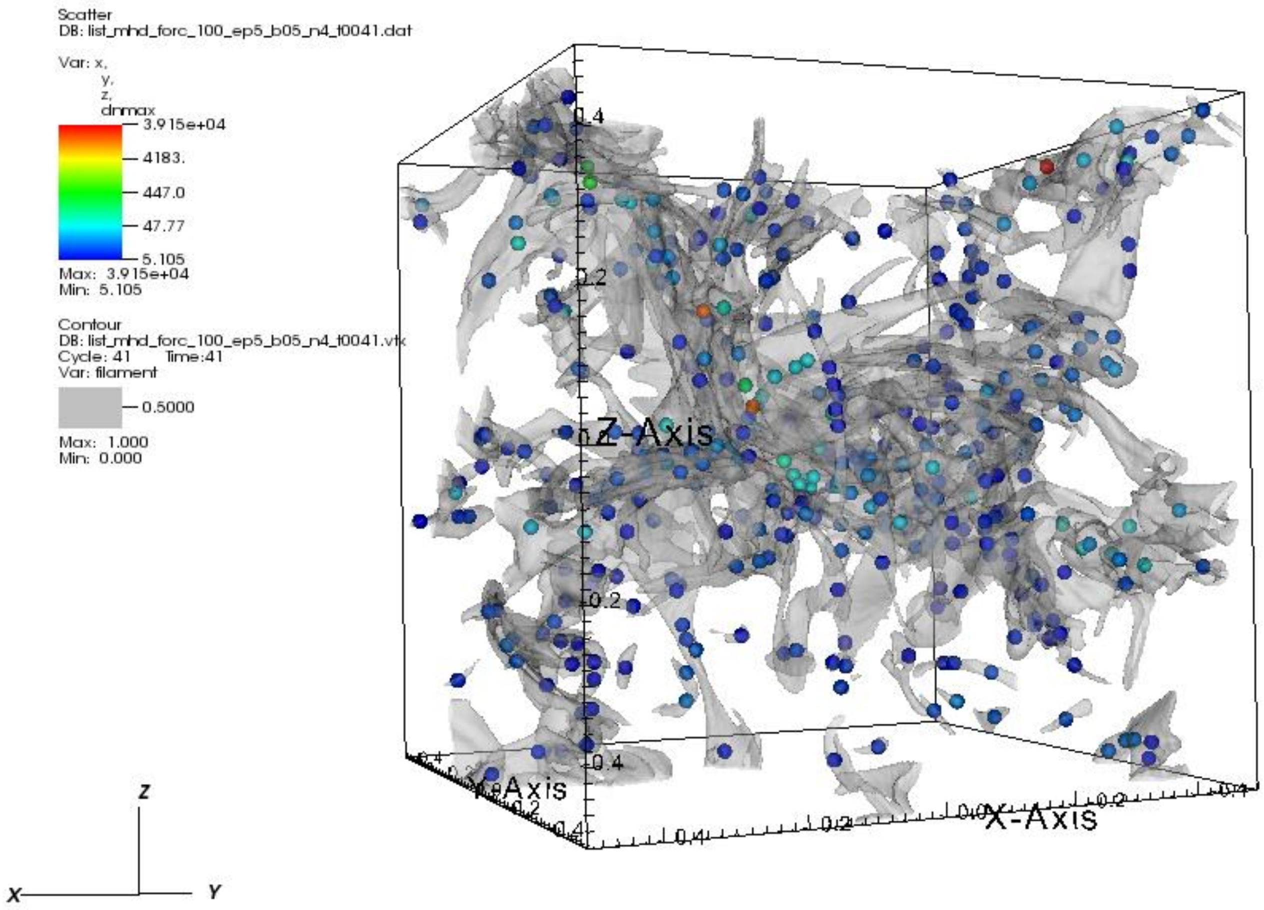
$\beta = p/pM = 0.3$

Normal

Filaments // to B

Normal

Star formation clumps Search



$V_{mean} = 3.3\ C_s$

$\beta = 3$

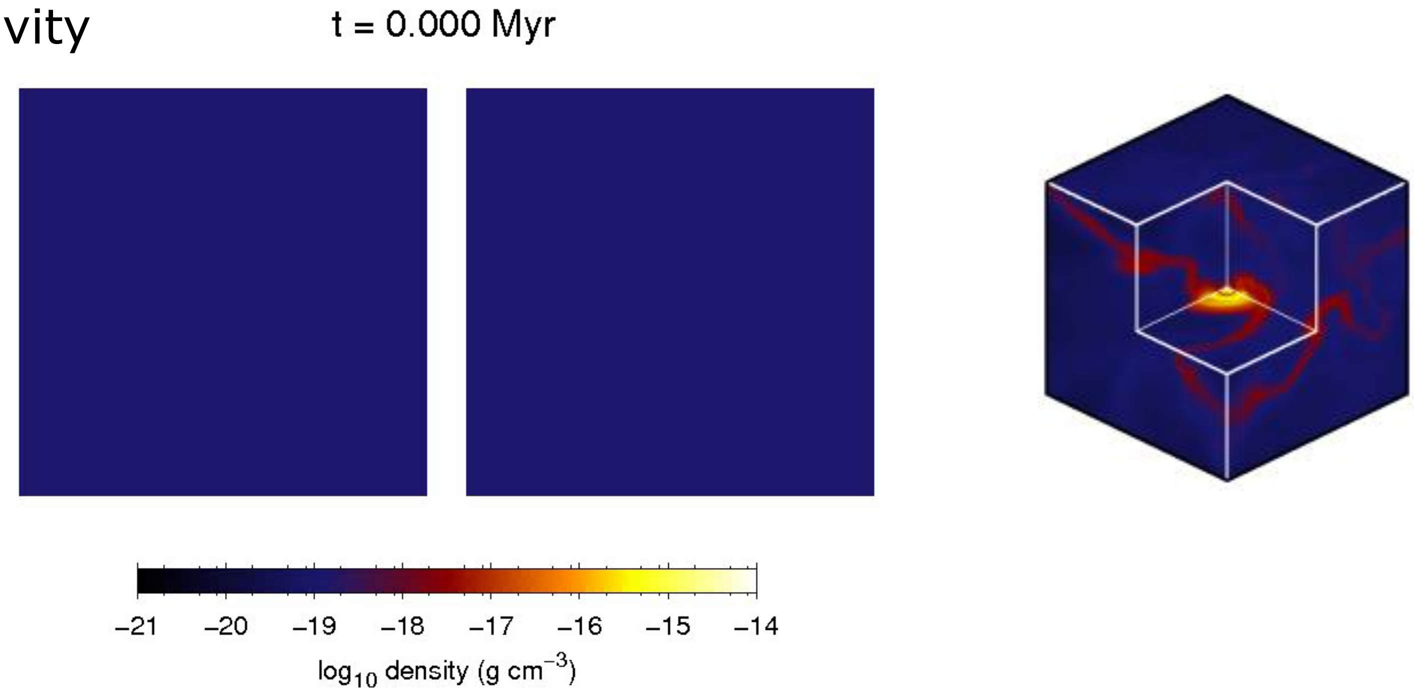
$= 2.0\ t_{ff}$

user: barreto
Thu Jun 14 16:08:23 2018

Barreto, de Gouveia Dal Pino, Melioli, Santos-Lima, in prep

3D MHD simulations of Star Formation: Core collapse and proto-stellar disk formation

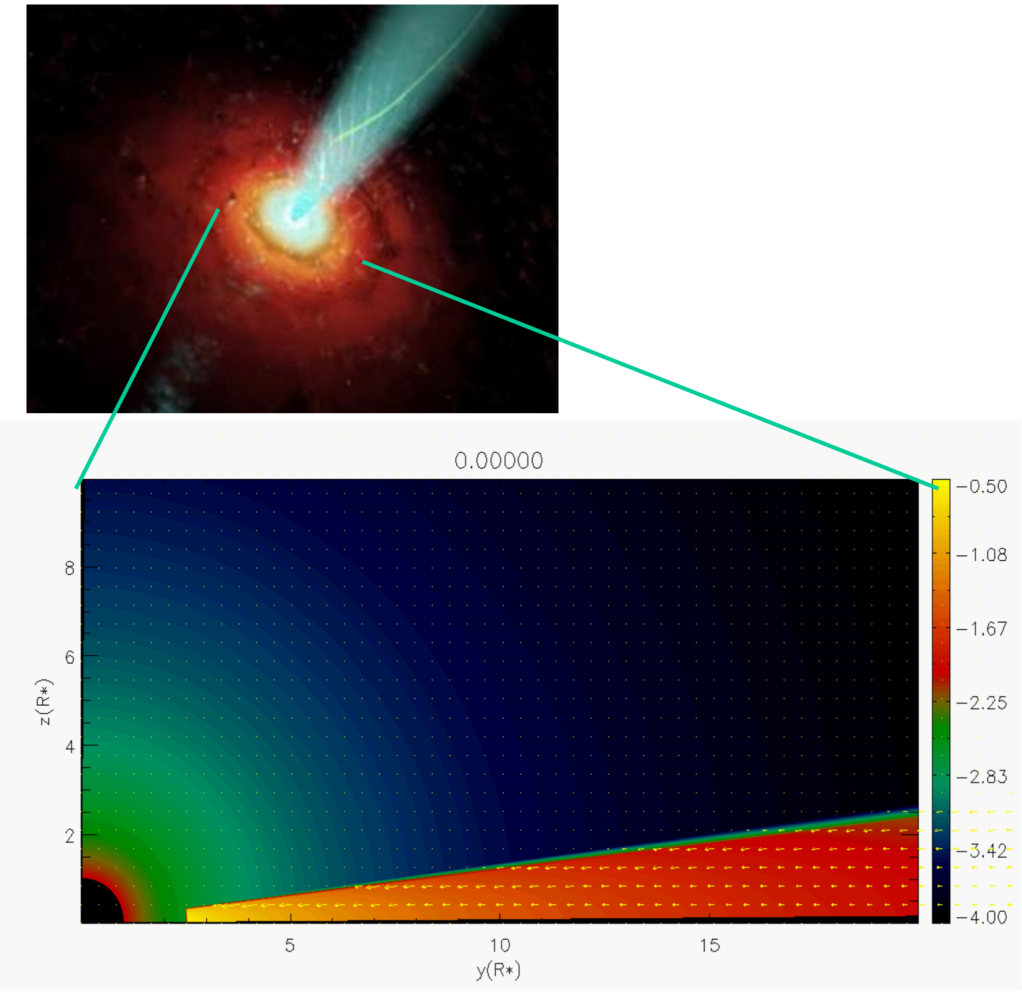
Magnetic fields (MFs) and turbulence influence star formation: turbulence helps the removal of excess of MF that is dragged-in (via **turbulent reconnection**), and allows the core and disk to form under the action of gravity



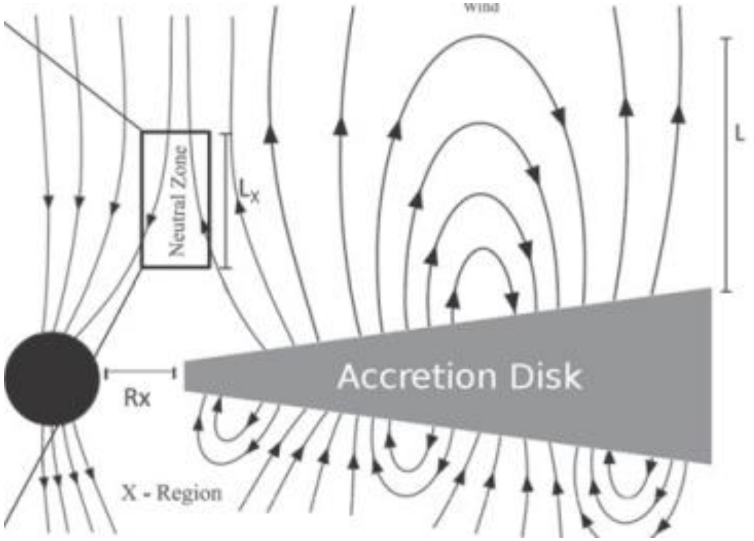
Santos-Lima, de Gouveia Dal Pino, Lazarian, ApJ 2012

MNRAS 2013

MHD simulations of Accretion Disks around compact sources: **Global**



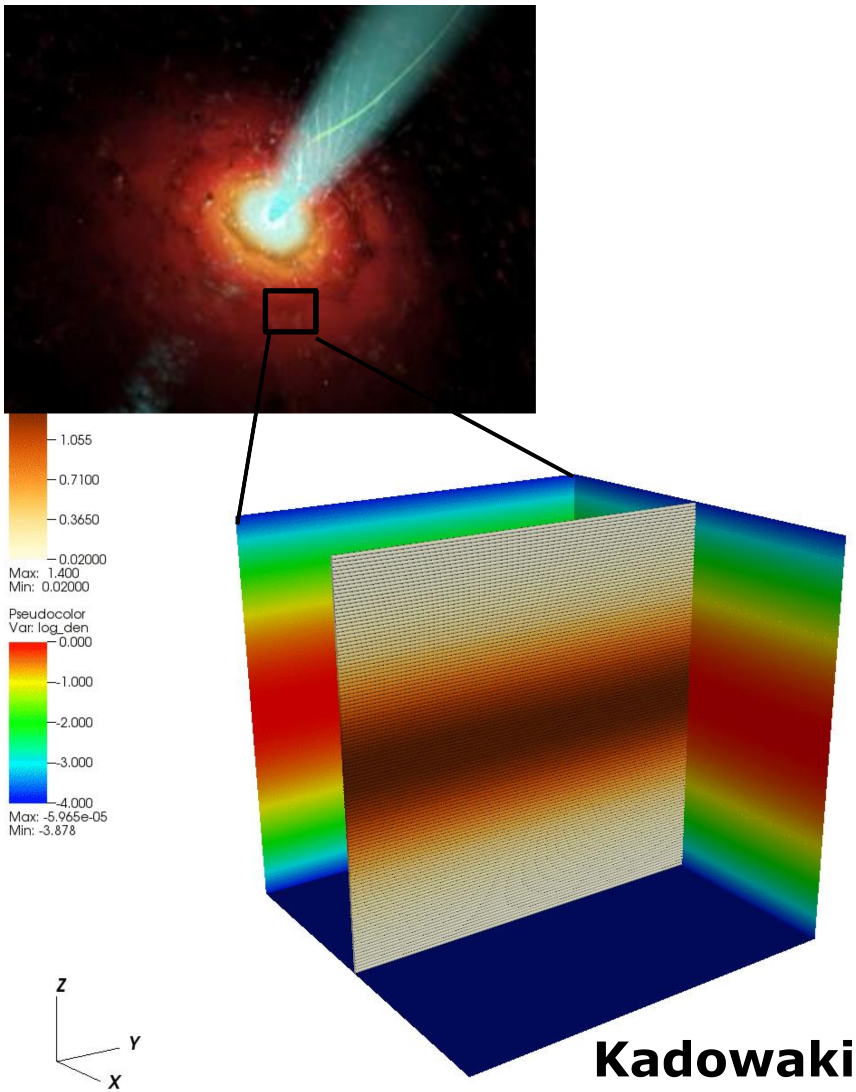
- **Magneticc Reconnection and plasmon ejection: as in the Sun**



de Gouveia Dal Pino & Lazarian 2005

Kadowaki, de Gouveia Dal Pino, Singh ApJ 2015

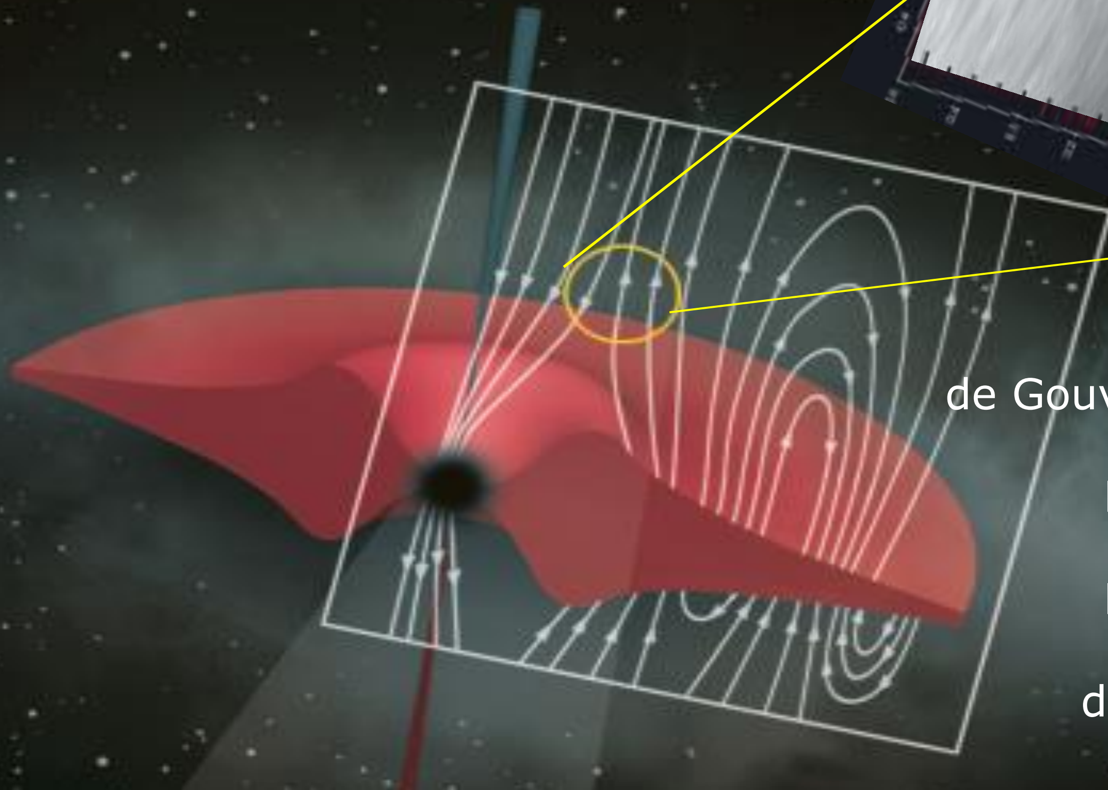
3D MHD Simulations of Accretion disks: **Shearing box**

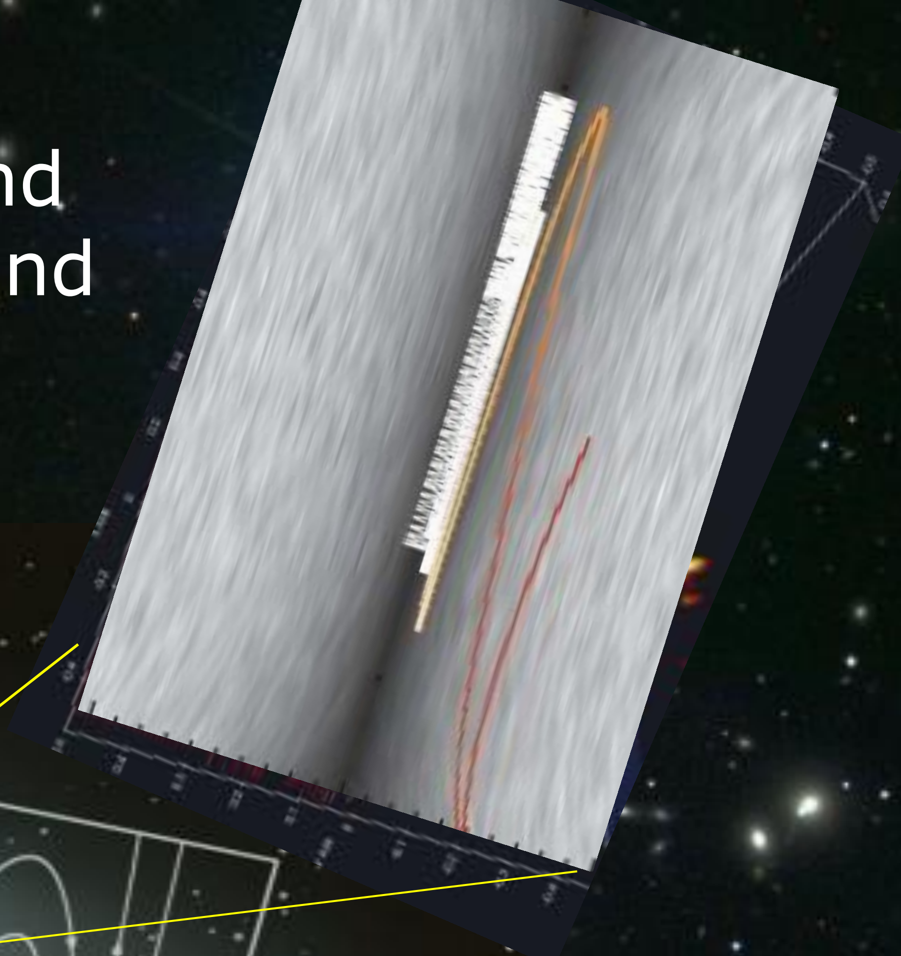


- Magnetic fields drive the transport of angular momentum
- Magnetic fields arise from the accretion disk and build a corona around the disk just like on the solar surface
- There is plenty of reconnection too

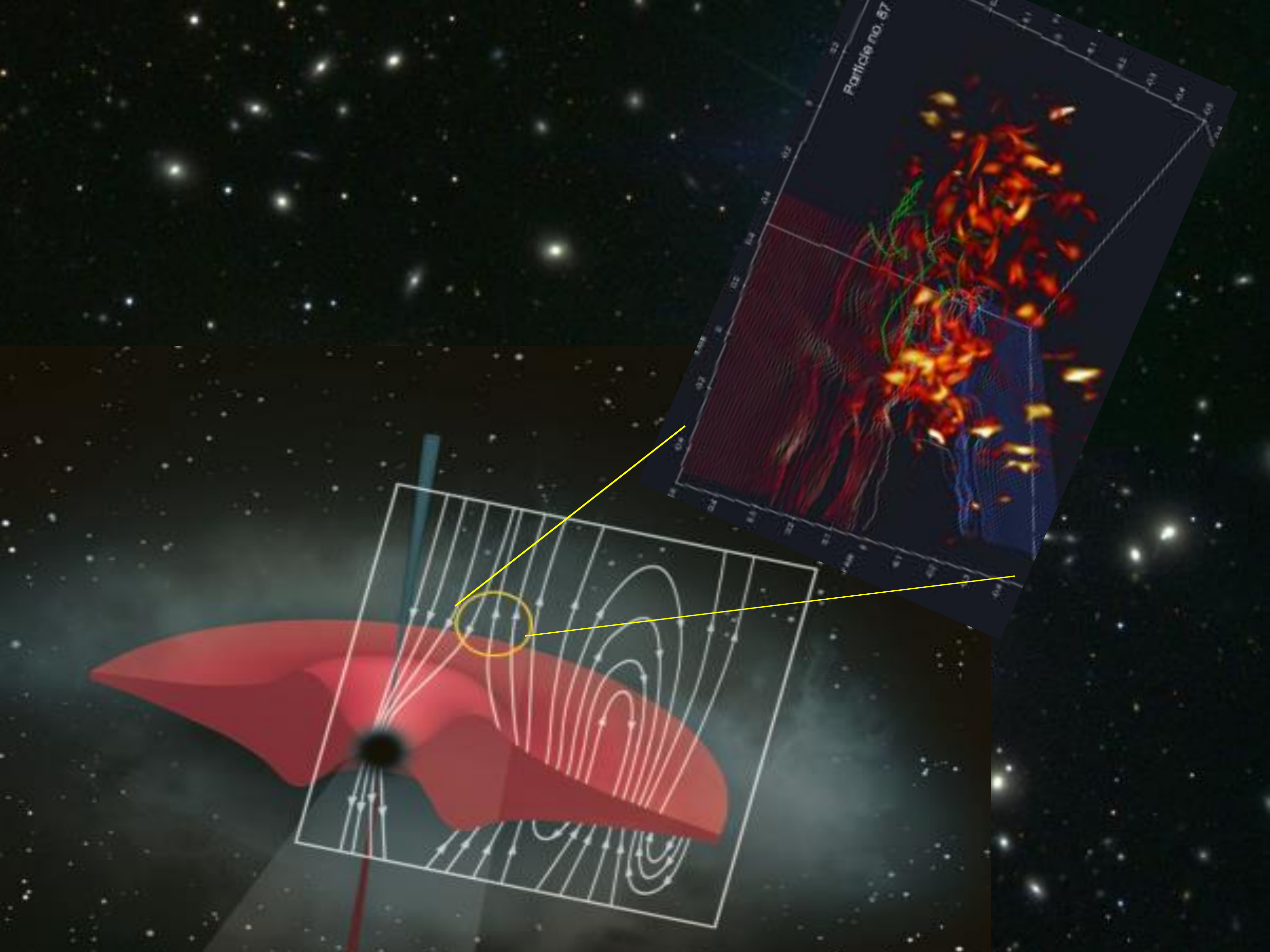
Kadowaki, de Gouveia Dal Pino, Stone ApJ 2018

Magnetic reconnection and Particle acceleration around Black hole sources

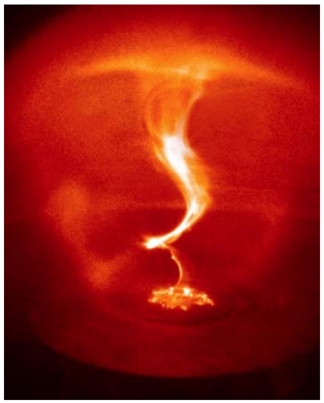


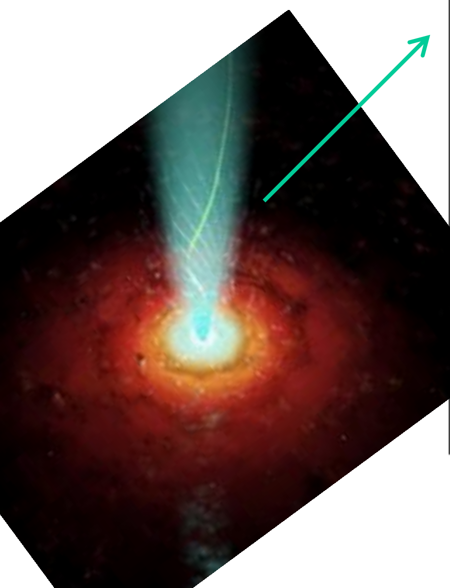


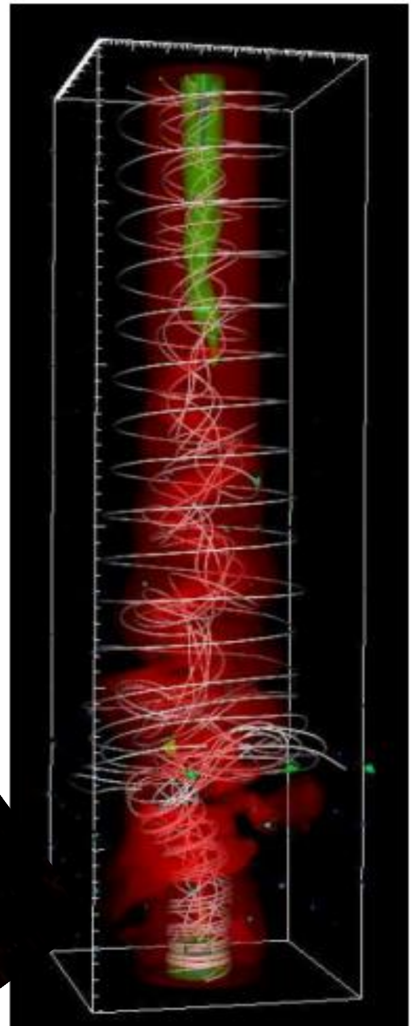
de Gouveia Dal Pino & Lazarian, A&A 2005
Kowal, de Gouveia Dal Pino & Lazarian ApJ 2011
Kowal, de Gouveia Dal Pino & Lazarian PRL 2012
del Valle, de Gouveia Dal Pino, Kowal, ApJ 2016



3D Relativistic-MHD Simulations of Jets







- Magnetic fields influence origin, acceleration and propagation of jets everywhere in the Universe

- formation of kinks that distort the helical structure and break the lines causing magnetic reconnection

Singh, Mizuno, de Gouveia Dal Pino, ApJ 2016

Winds in active galaxies driven by AGN and Supernovae feedback

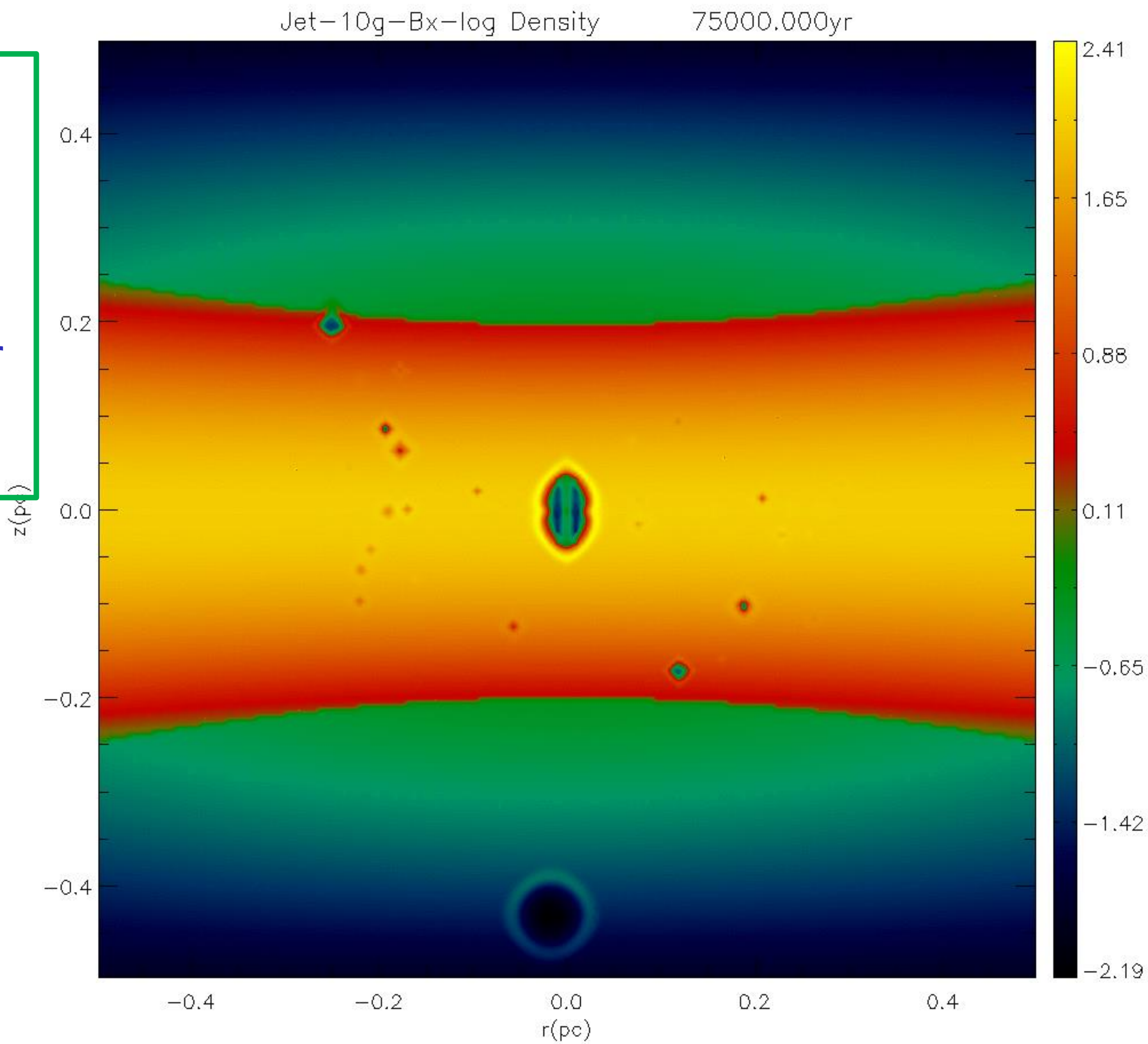
MHD radiative cooling simulations of nuclear region ($1kpc^3$) of active galaxy:

taking into account star formatin, SNe wind + AGN outflow feedbacks

AGN outflow (10^o opening angle)

Initial $B_x = 0.76\ \mu G$

Clavijo, de Gouveia Dal Pino, Melioli 2018)

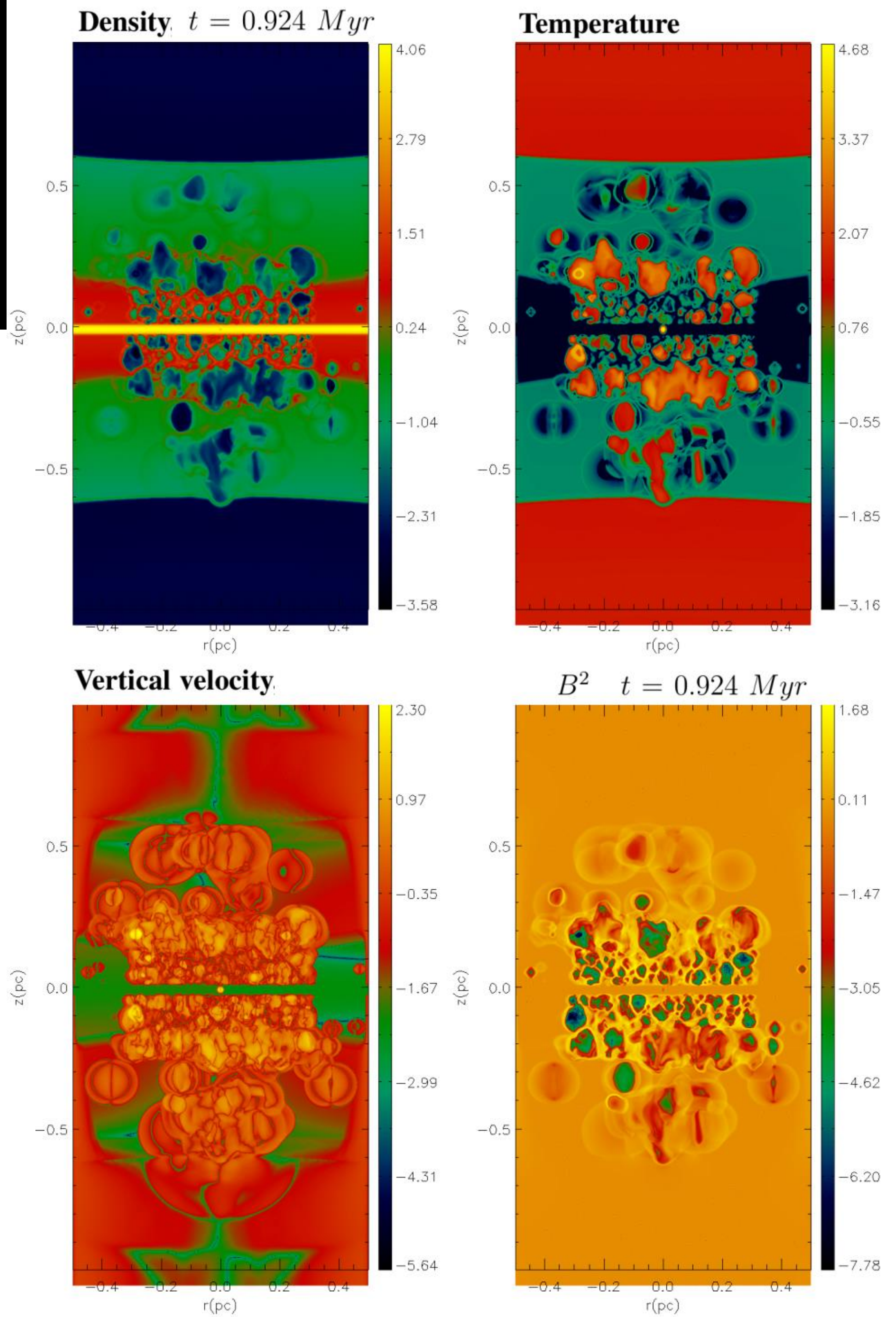


Winds in active galaxies driven by AGN and Supernovae feedback

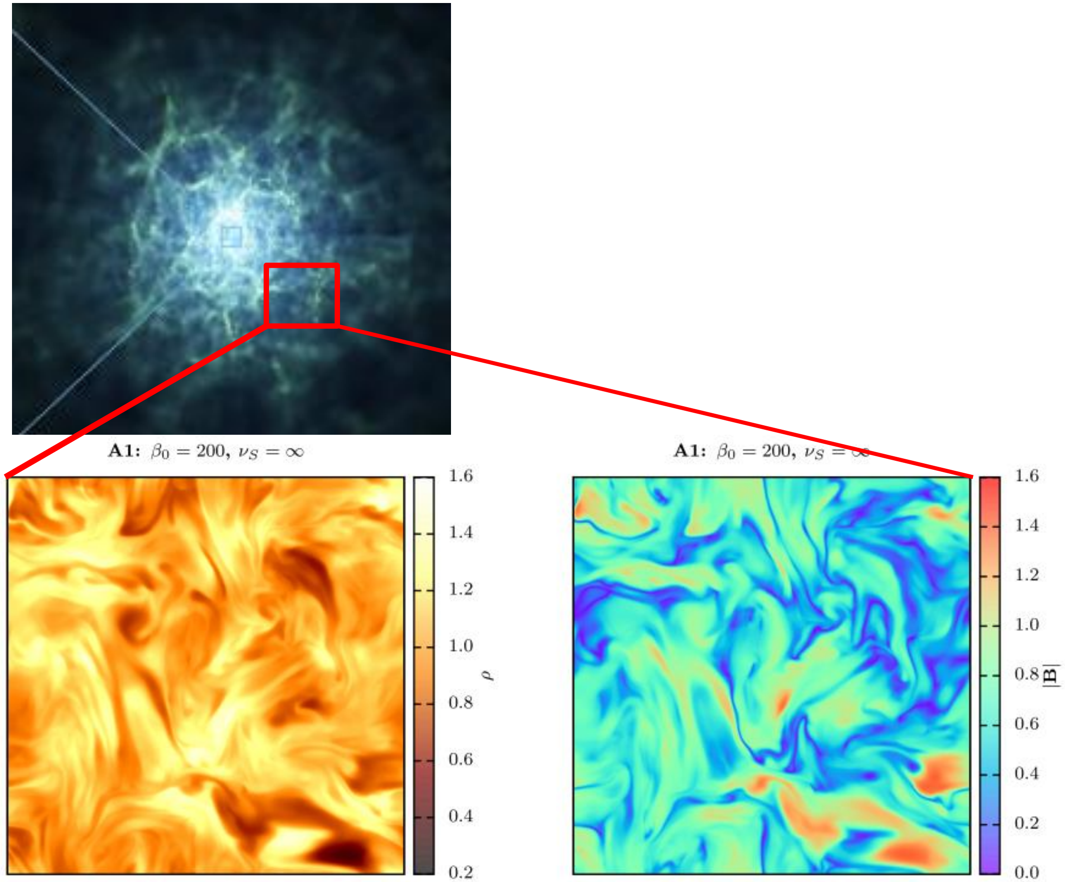
AGN spherical wind: injected in galaxy after SNe wind fully developed

AGN and supernovae driven winds drive ultra fast and hot outflows: v> 10.000 km/s ($T > 10^7$ K, n > 100 cm^{-3}) -> ~ Observations

Clavijo, de Gouveia Dal Pino, Melioli 2018)



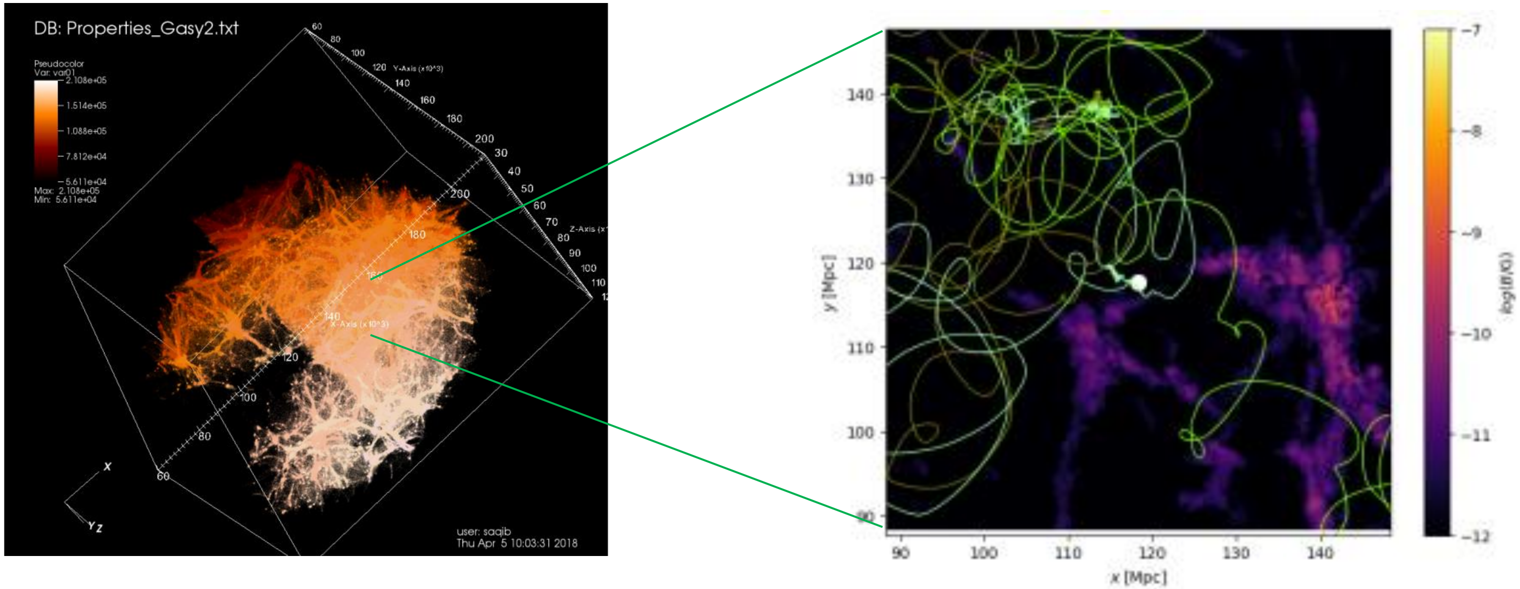
3D MHD Simulations of the Intergalactic Medium: magnetic fields amplified by turbulence



- MFs influence galaxies and intergalactic gas evolution and dynamics, and cosmic ray propagation

Santos-Lima, de Gouveia Dal Pino et al., ApJ 2014
Nakwaki, Kowal, Santos-Lima, de Gouveia Dal Pino, F.-Goncalves, MNRAS 2016
Santos-Lima, Yan, de Gouveia Dal Pino & Lazarian, MNRAS 2016
Santos-Lima, de Gouveia Dal Pino, et al. MNRAS 2016; 2018

Cosmological MHD simulations and CR Propagation



Left: cosmological MHD simulation (200 Mpc^3) (Dolag et al. 2004) containing density distribution of filaments with cluster of galaxies.
Right: magnetic field distriubtion in a slice of the domain.
Trajectories of CR particles with E = 10^{17} eV (green lines).
White circle: observer position, and white star: source position.

(Alves-Batista, de Gouveia Dal Pino, Hussein, Dolag, in prep.)

OBRIGADA