# Identification of fast magnetic reconnection events in accretion disks under the action of MHD instabilities

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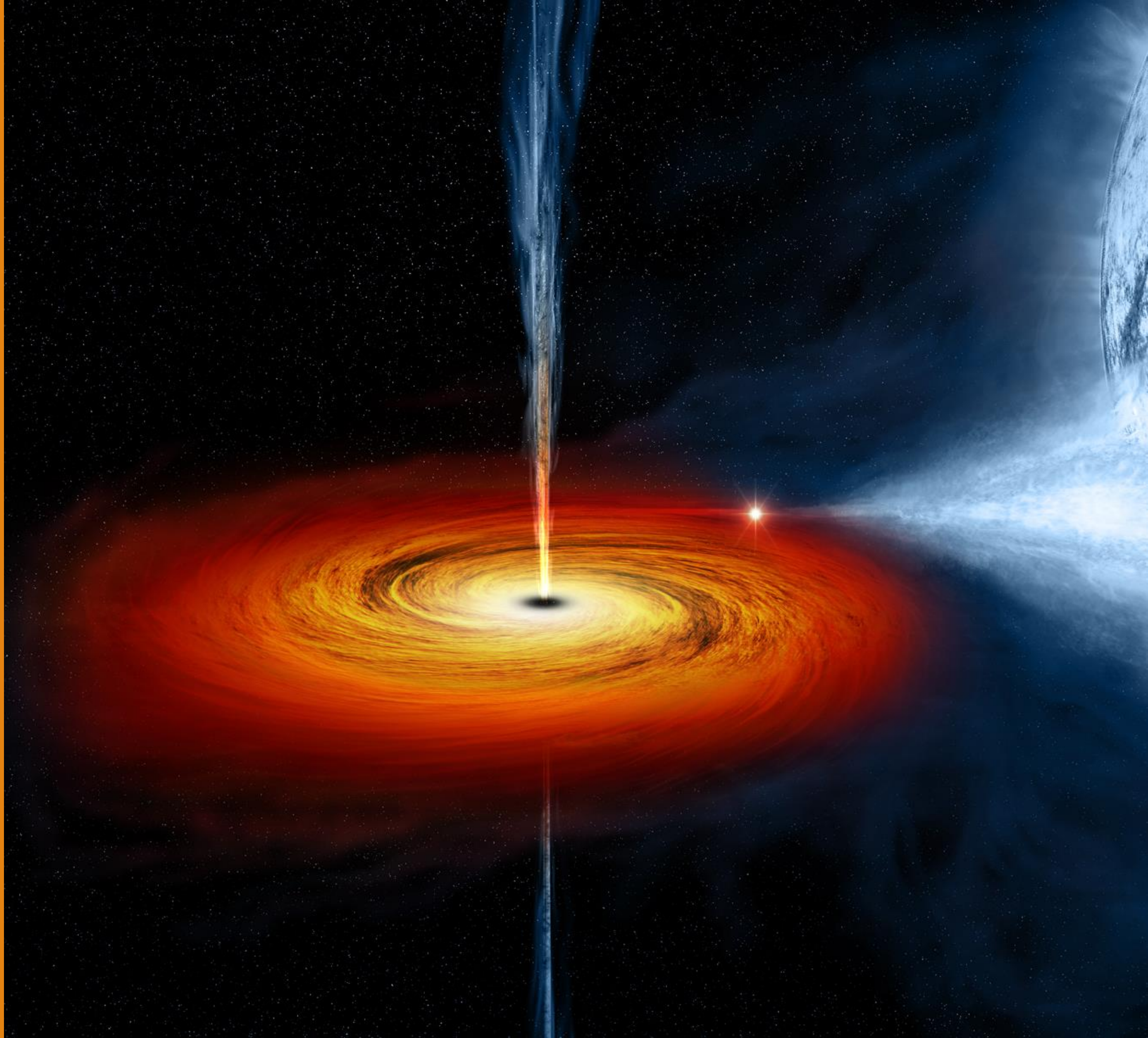
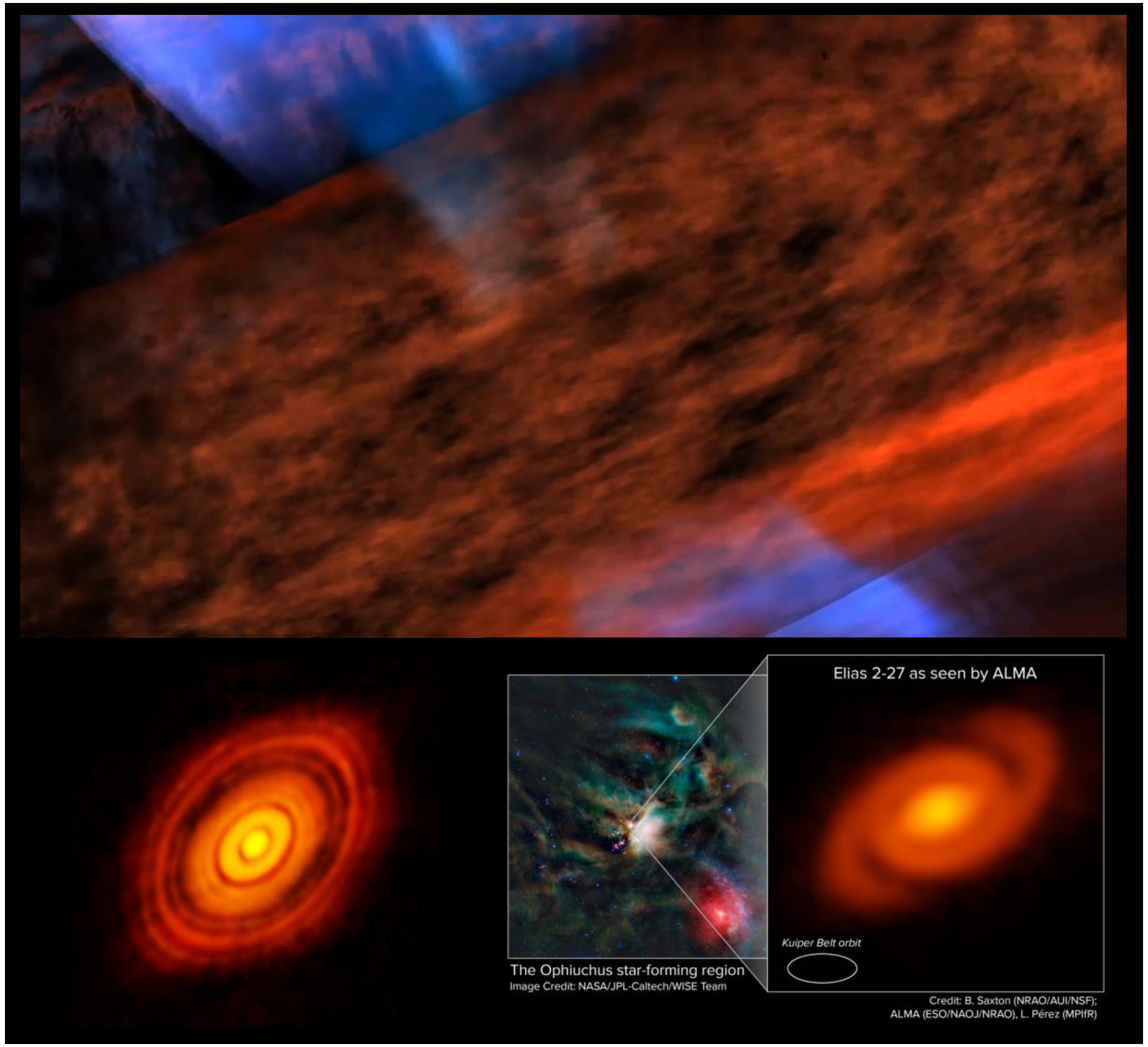
MAGNETIC FIELDS IN THE UNIVERSE VI: FROM LABORATORY AND STARS TO THE PRIMORDIAL STRUCTURES



# Outline

- Magnetic reconnection in accretion disk systems
- Numerical simulations with a shearing-box approach
- MHD instabilities in accretion disks
- Identification of fast magnetic reconnection events in the surroundings of accretion disks
- Conclusions

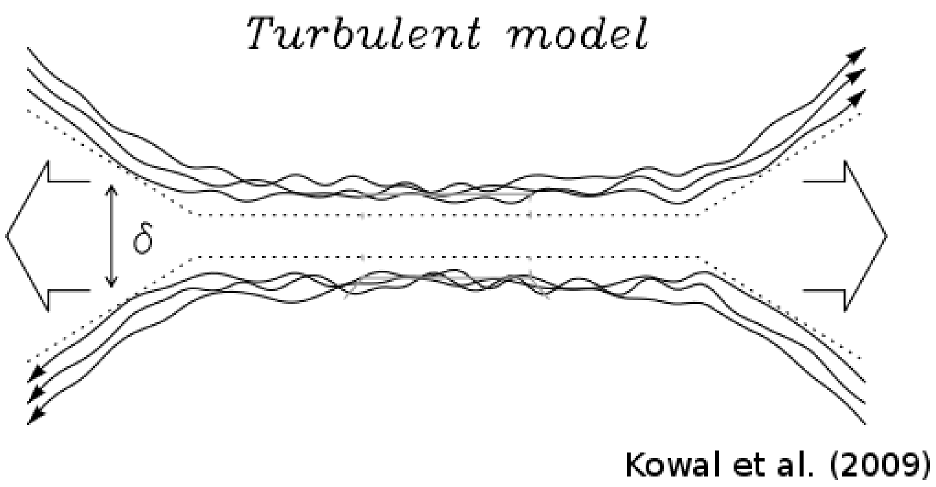
# Accretion disk systems

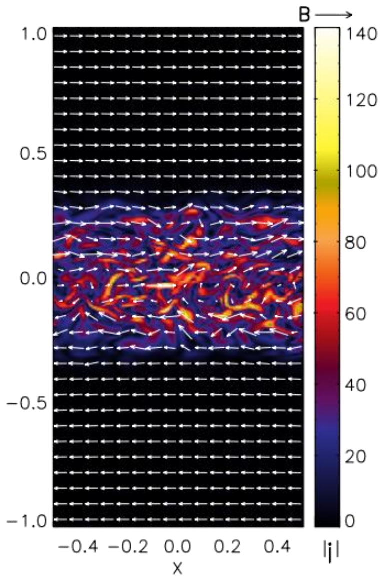


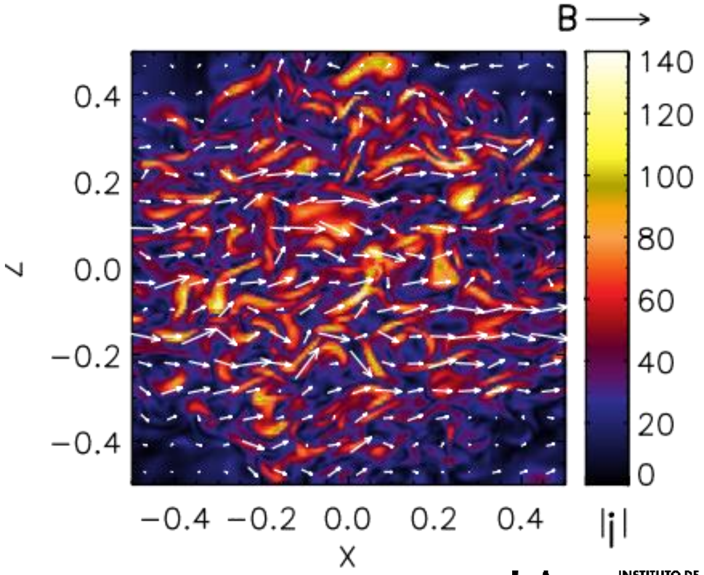

- Accretion disks systems are believed to be very common structures in the Universe
- These systems are associated to:
  - Black Hole Binaries (BHBs)
  - Active Galactic Nuclei (AGNs)
  - Young Stellar Objects (YSOs) and so protoplanetary disks
- The formation of a turbulent corona above and below accretion disks plays an important role in magnetic reconnection events
- These events could explain the flare emissions in X-ray (YSOs) and in radio and gamma-ray (BHBs and AGNs)

# Turbulent magnetic reconnection in collisional flows

- Lazarian & Vishiniac (1999) model (Kowal's talk):
  - Reconnection triggered by tubulence
  - Several reconnection points (at all scales) due to the wandering magnetic field lines
  - "Fast" reconnection
  - $V_{rec} \simeq V_A M_A^2$




Numerical simulations (Kowal et al. 2009, 2012)

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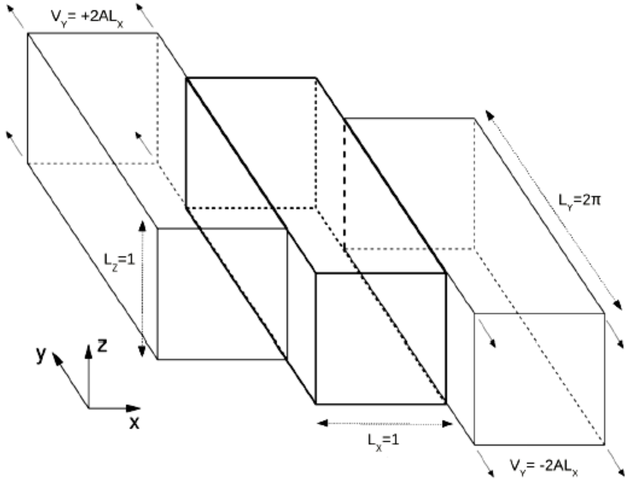
# MHD numerical simulations of accretion disks and corona

MAGNETIC RECONNECTION UNDER THE ACTION OF MHD INSTABILITIES

# Aims

- The formation of a large scale poloidal magnetic field by the arising of loops due to the Parker-Rayleigh-Taylor instability
- The role of Parker-Rayleigh-Taylor and magnetorotational instabilities in the formation of a turbulent magnetized corona around accretion disks
  - Where magnetic reconnection events could occur
- The identification of fast magnetic reconnection events by the statistical analysis of the reconnection rate in the corona and disk

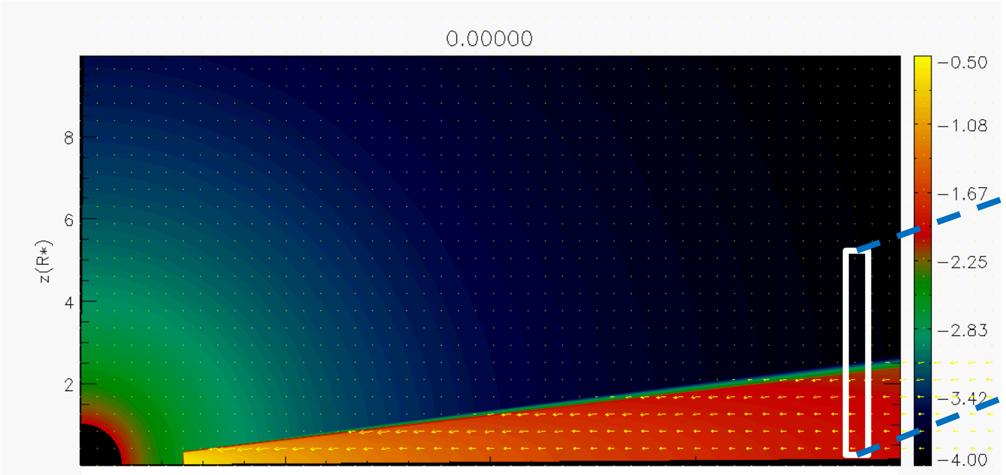
# Numerical method (shearing-box)



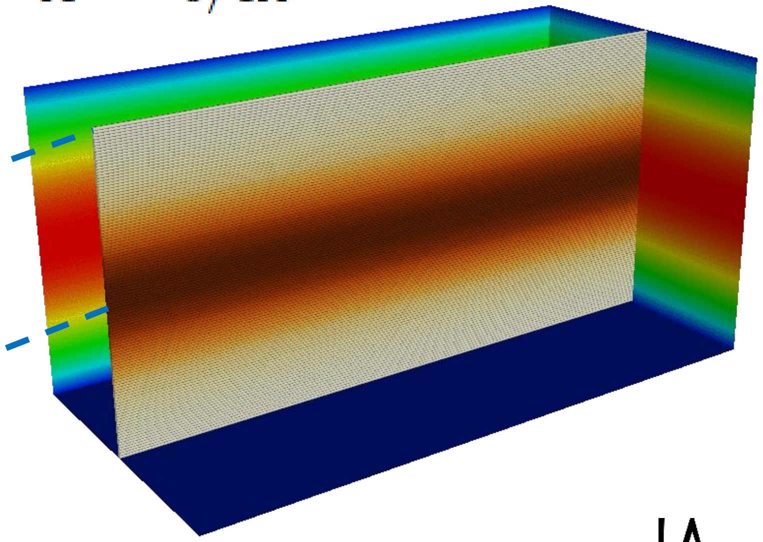

- Shearing-Box (Hawley et al., 1995):
  - A steady flow with a linear shearing velocity:

$$v_y = 2Ax, \quad \text{com} \quad A = -\frac{\Omega}{2}q, \quad q = -\left.\frac{d\log\Omega(R)}{d\log R}\right|_{R=R_0}$$

  - For a Keplerian disk: $A = -3/4\Omega$




Kadowaki (master's thesis, 2011)



Kadowaki et al. (2017, in prep.)

# Numerical method (shearing-box)

- MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla.\left[\rho \boldsymbol{v}\boldsymbol{v} + \left(P + \frac{\boldsymbol{B}.\boldsymbol{B}}{8\pi}\right)\boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}\right] = \rho \boldsymbol{g}$$

$$\frac{\partial E}{\partial t} + \nabla.\left[\left(E + P + \frac{\boldsymbol{B}.\boldsymbol{B}}{8\pi}\right)\boldsymbol{v} - \frac{(\boldsymbol{v}.\boldsymbol{B})\boldsymbol{B}}{4\pi}\right] = \rho \boldsymbol{g}.\boldsymbol{v}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{v}) = 0$$

# Numerical method (shearing-box)

- Momentum equation:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla . \left[ \rho \boldsymbol{v}\boldsymbol{v} + \left( P + \frac{\boldsymbol{B}.\boldsymbol{B}}{8\pi} \right) \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \right] = \rho \boldsymbol{g}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}.\nabla \boldsymbol{v} = -\frac{1}{\rho}\nabla (P + \frac{B^2}{8\pi}) + \frac{(\boldsymbol{B}.\nabla)\boldsymbol{B}}{4\pi\rho} - 2\boldsymbol{\Omega} \times \boldsymbol{v} + 2q\Omega^2 x\widehat{\boldsymbol{x}} - \Omega^2 z\widehat{\boldsymbol{z}}$$

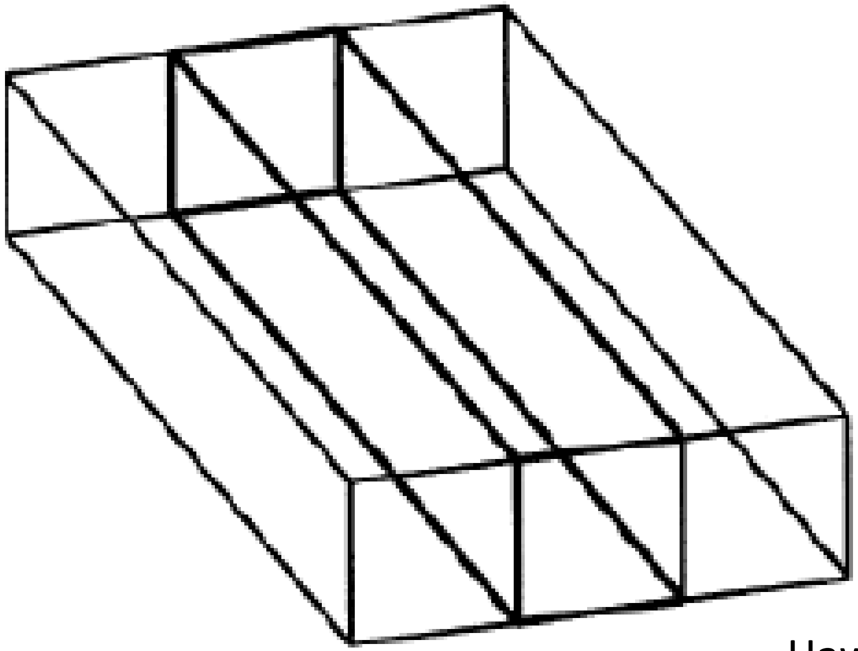
Coriolis Force (Radial and Azimuthal components)

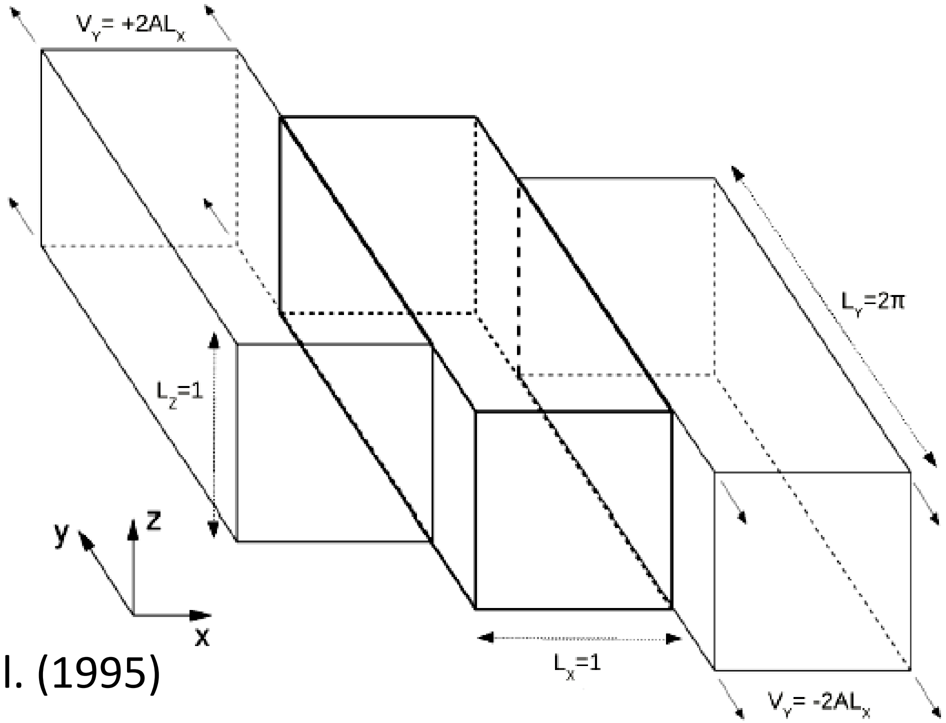
Centrifugal + Gravitational Forces (Radial component)

Gravity (Vertical component)

# Numerical method (shearing-box)

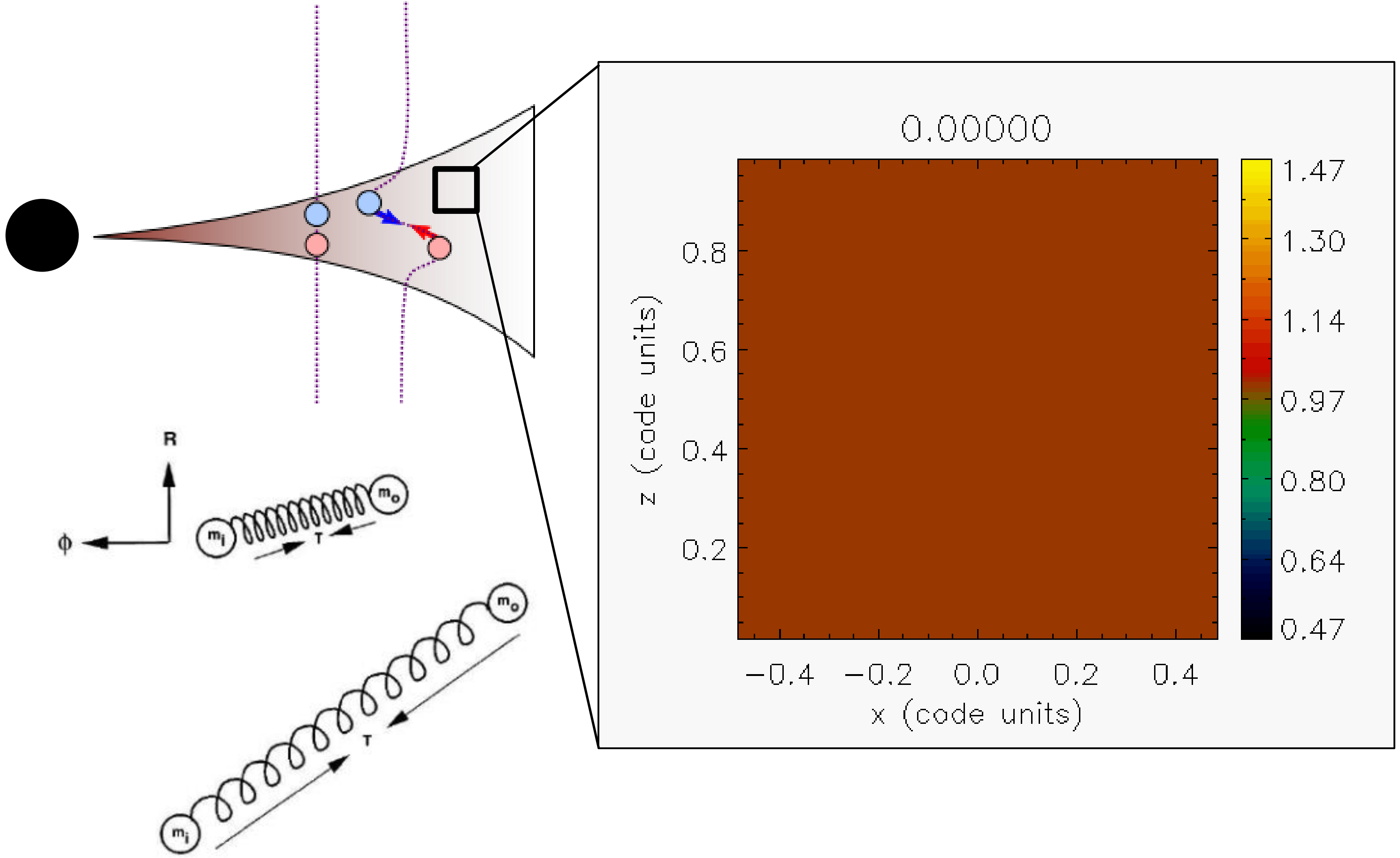
- Boundary Conditions:
  - Computational domain: $L_x, L_y$ e $L_z$
  - Strictly periodic in all the boundaries at $t = 0$
  - The shearing is produced by the slipping of the boundaries in $x$ direction






Hawley et al. (1995)

# MHD instabilities
# Magnetorotational instability (MRI)




- A weak magnetic field exerts an elastic force between two fluid elements
- This force transfers angular momentum to the outer region
  - Making possible the accretion in Keplerian regimes
- Linear regime: Amplification of the magnetic field (dynamo effect)
- Non-linear regime: Saturation of the magnetic field and formation of turbulence

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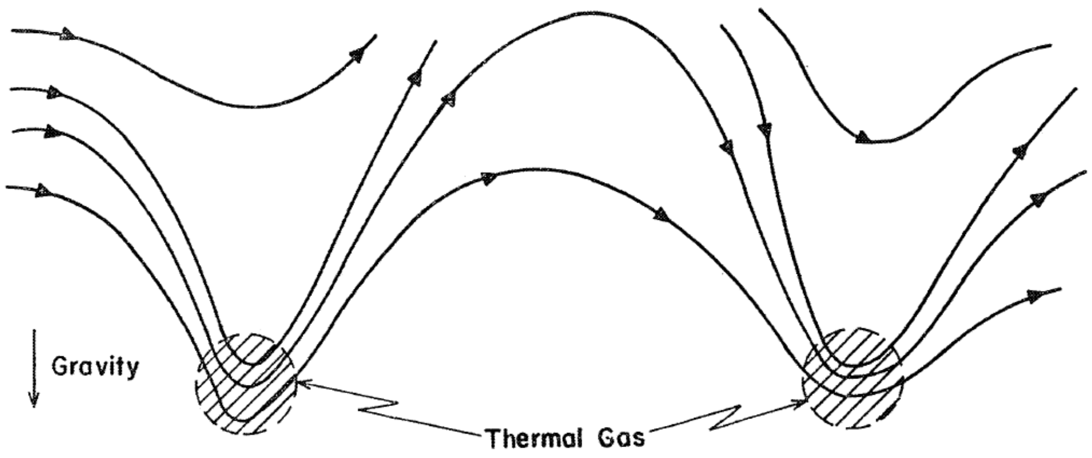
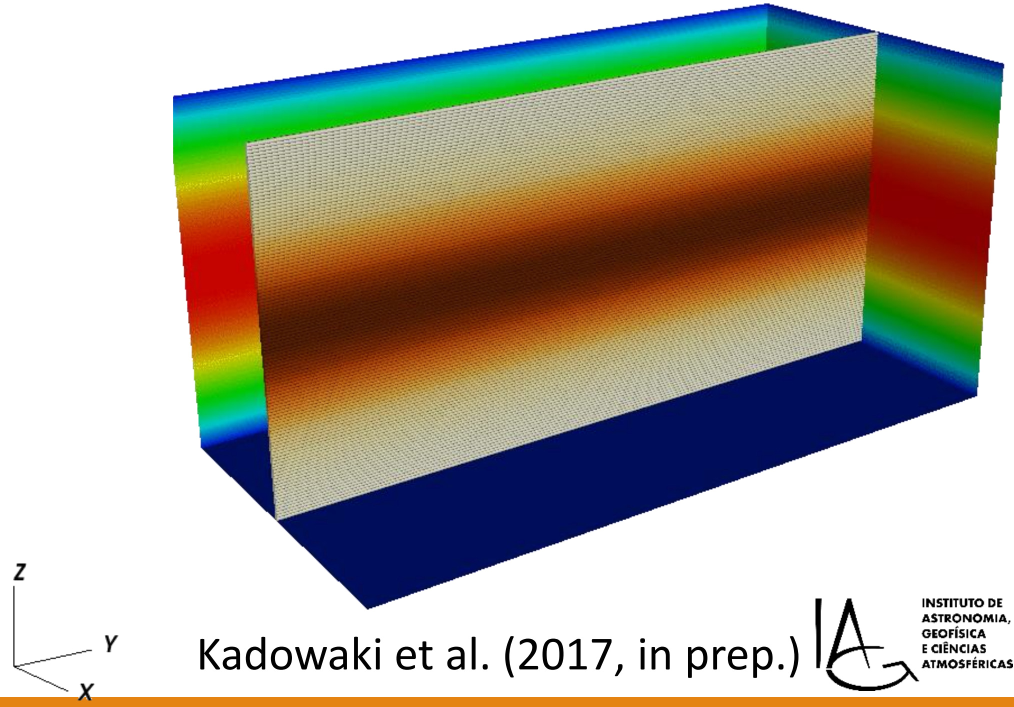
# MHD instabilities
# Parker-Rayleigh-Taylor instability

- Instability driven by strong magnetic fields:
  - $\beta = \frac{P_{thermal}}{P_{magnetic}} = 1$ (Magnetic buoyance)
  - Azimuthal magnetic field ($\perp \vec{g}$)
  - Formation of magnetic loops → Magnetic reconnection → Release of energy in the coronal region

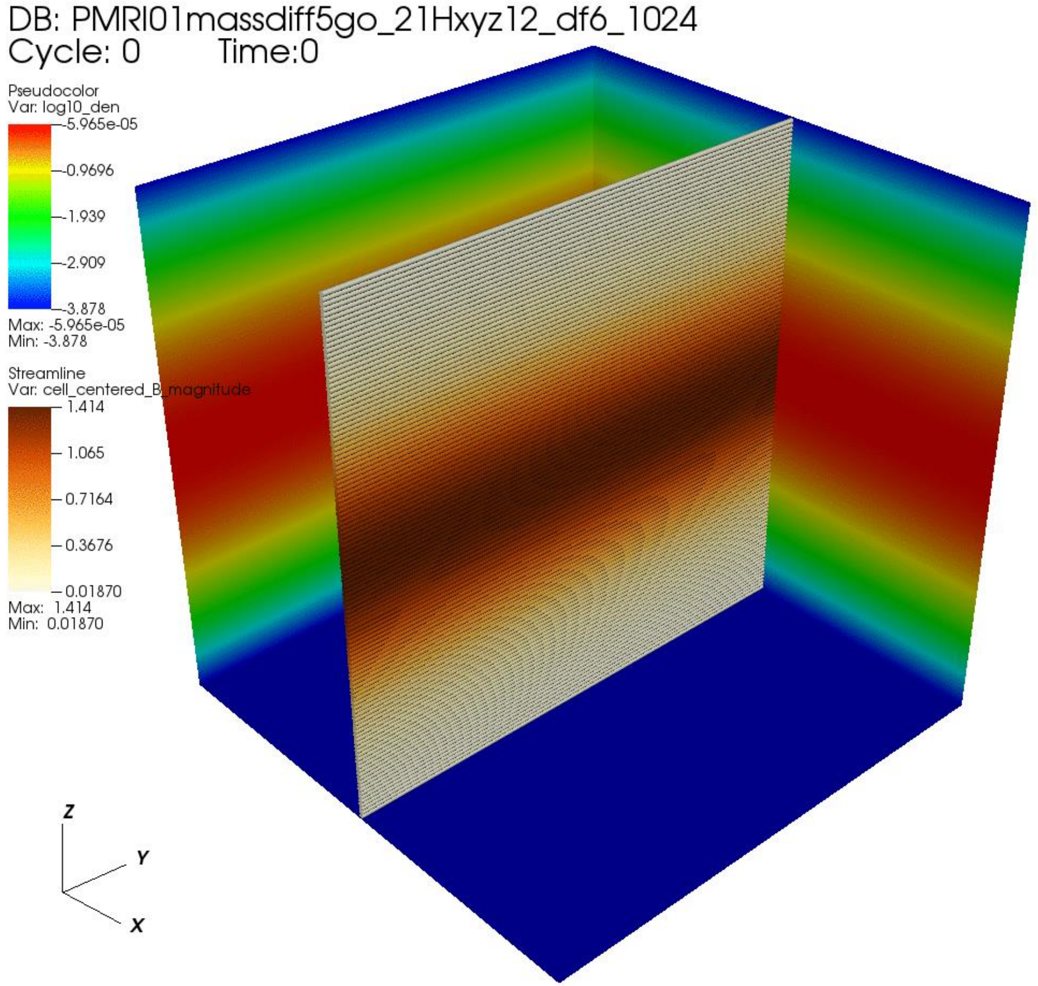



Parker (1966)



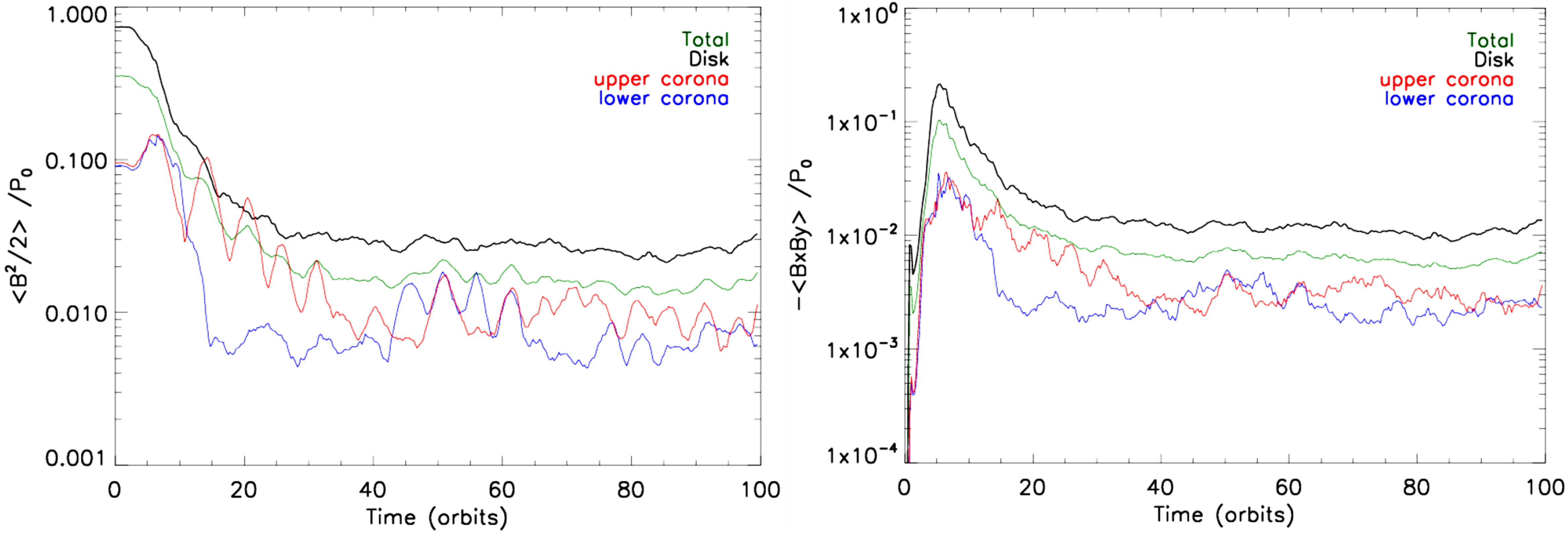

Kadowaki et al. (2017, in prep.)

# Numerical results (Resolution: $256^3$)




- **Athena code (Stone et al., 2008, 2010)**
- **Model PMRIg_21H_oxyz12**
- **Initial conditions:**
  - Isothermal system
  - Magnetostatic equilibrium
  - Azimuthal magnetic field ($B_y$)
  - $\beta = 1.0$
  - Initial Gaussian perturbation in the Keplerian velocity field
- **Boundaries conditions:**
  - $x$: Shearing-periodic
  - $y$: Periodic
  - $z$: Outflow
- $12H \times 12H \times 12H$ ($H = C_S\Omega^{-1}$)
- $256H \times 256H \times 256H$ cells

# Numerical results (Resolution: $256^3$)




$$\alpha \equiv \frac{T_{xy}}{P} = \frac{T_{xy}}{\rho c_s^2} \qquad T_{xy} = -B_x B_y + \rho u_x u_y$$

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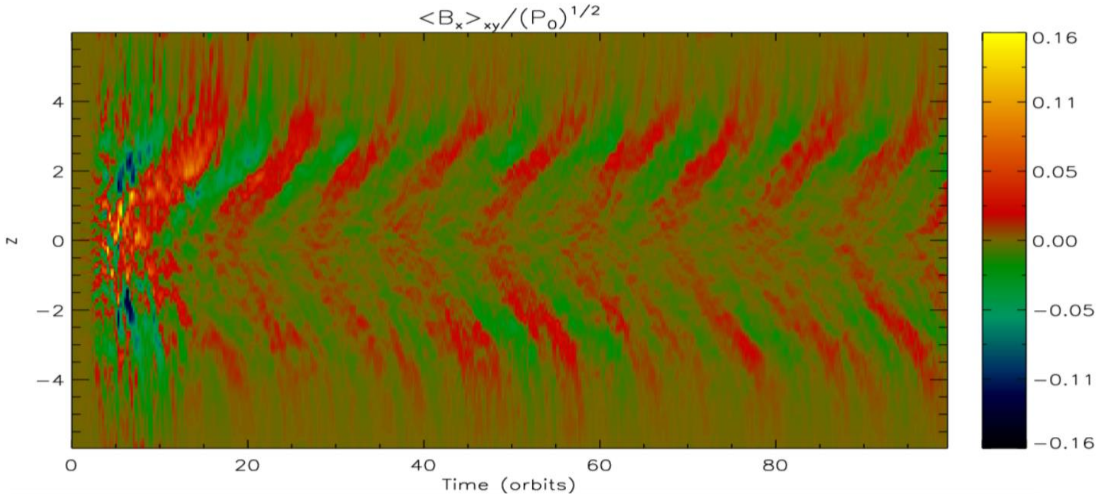
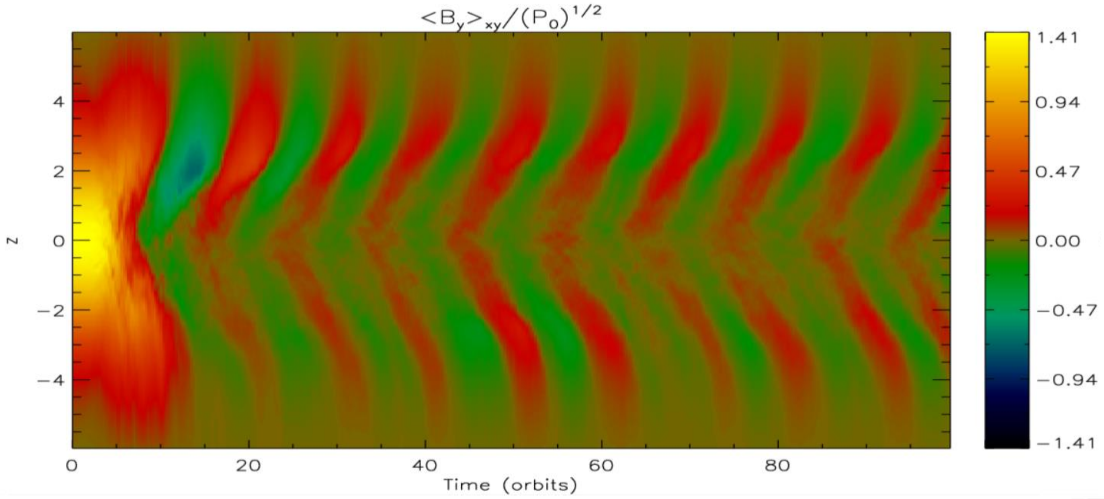
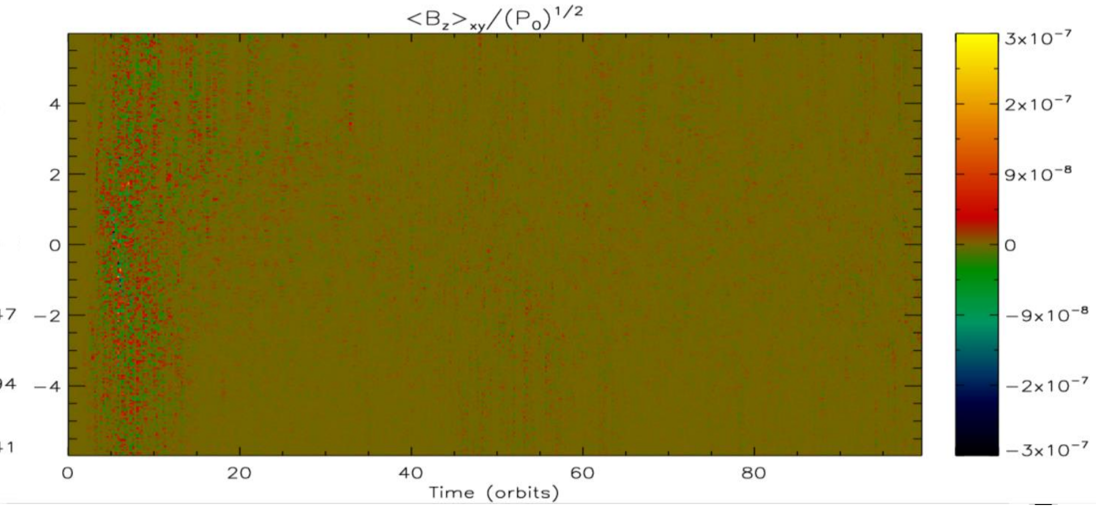
# Numerical results (Resolution: $256^3$)




- Transition between PRTI and MRI
- Polarity inversions due to the action of the dynamo triggered by MRI
- Zero net flux field ($\langle B_z \rangle \cong 0$)

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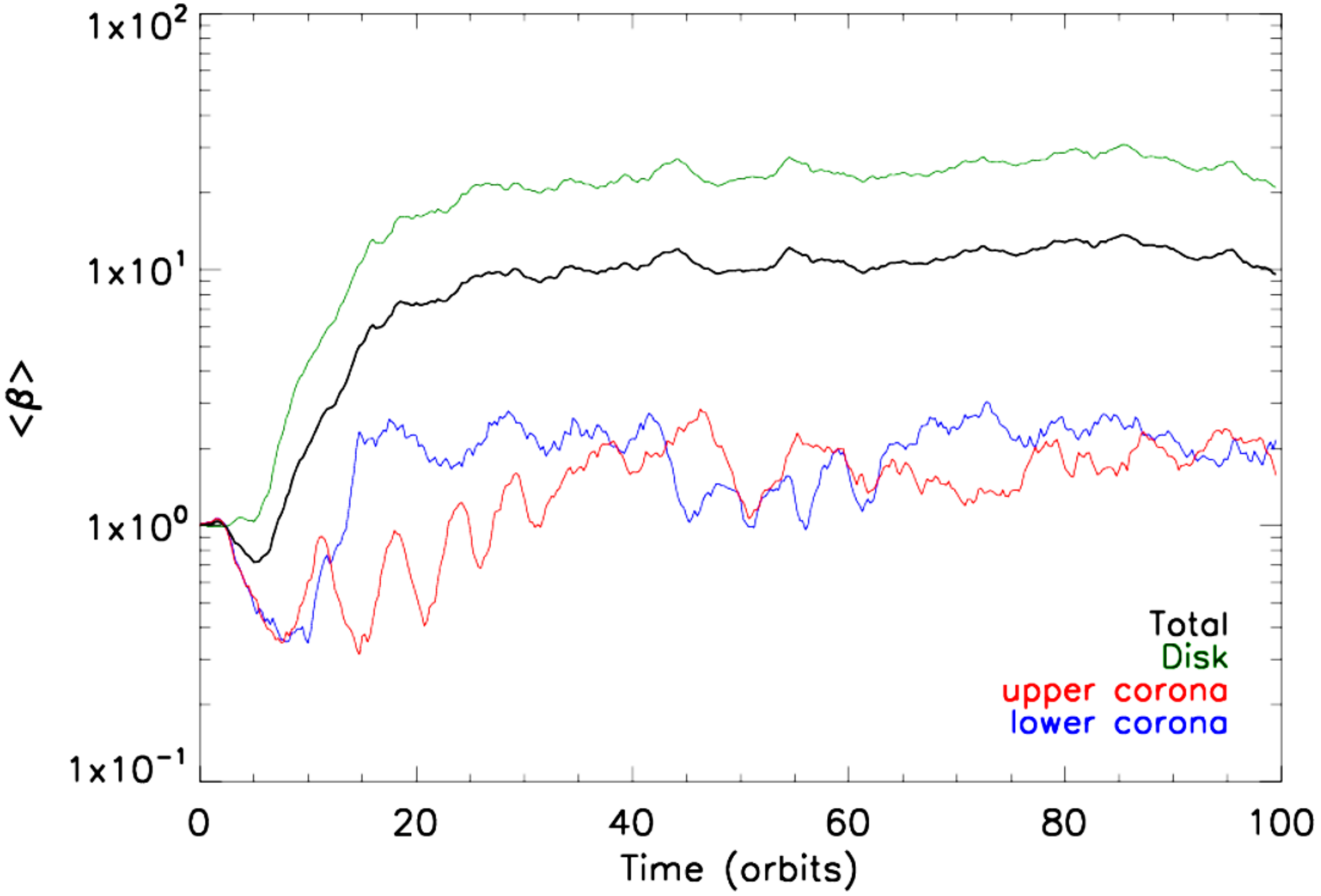
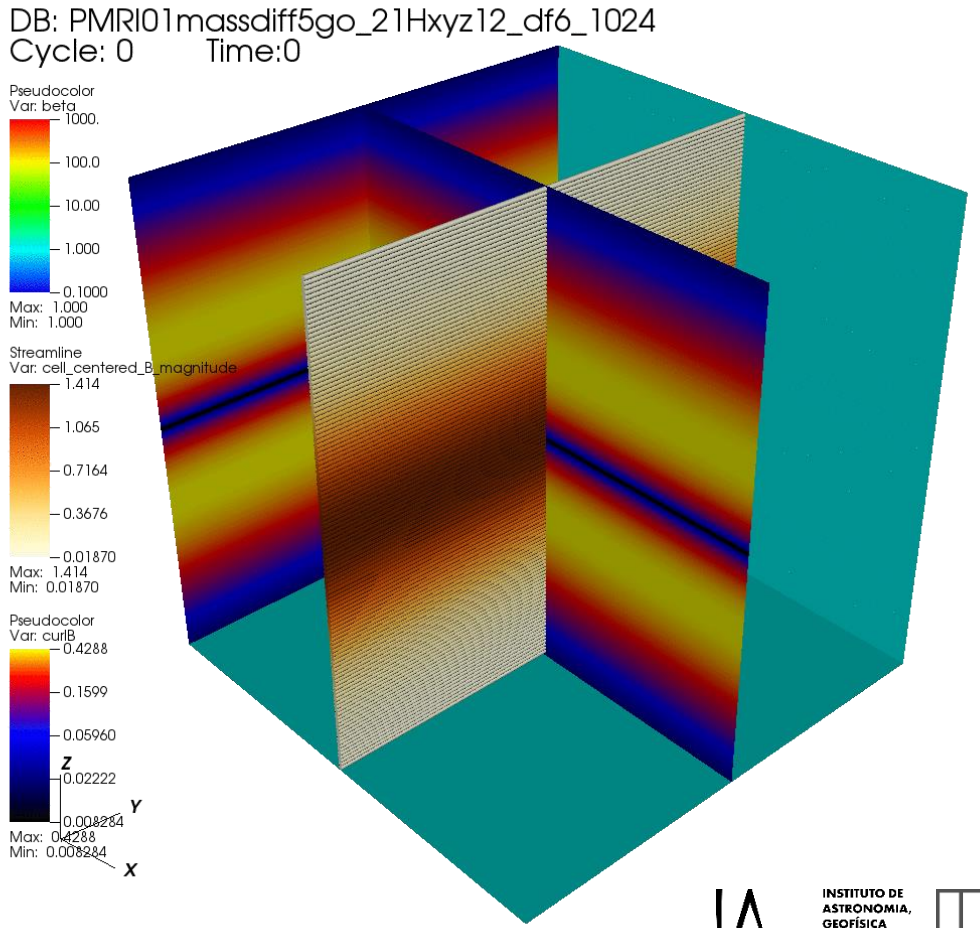
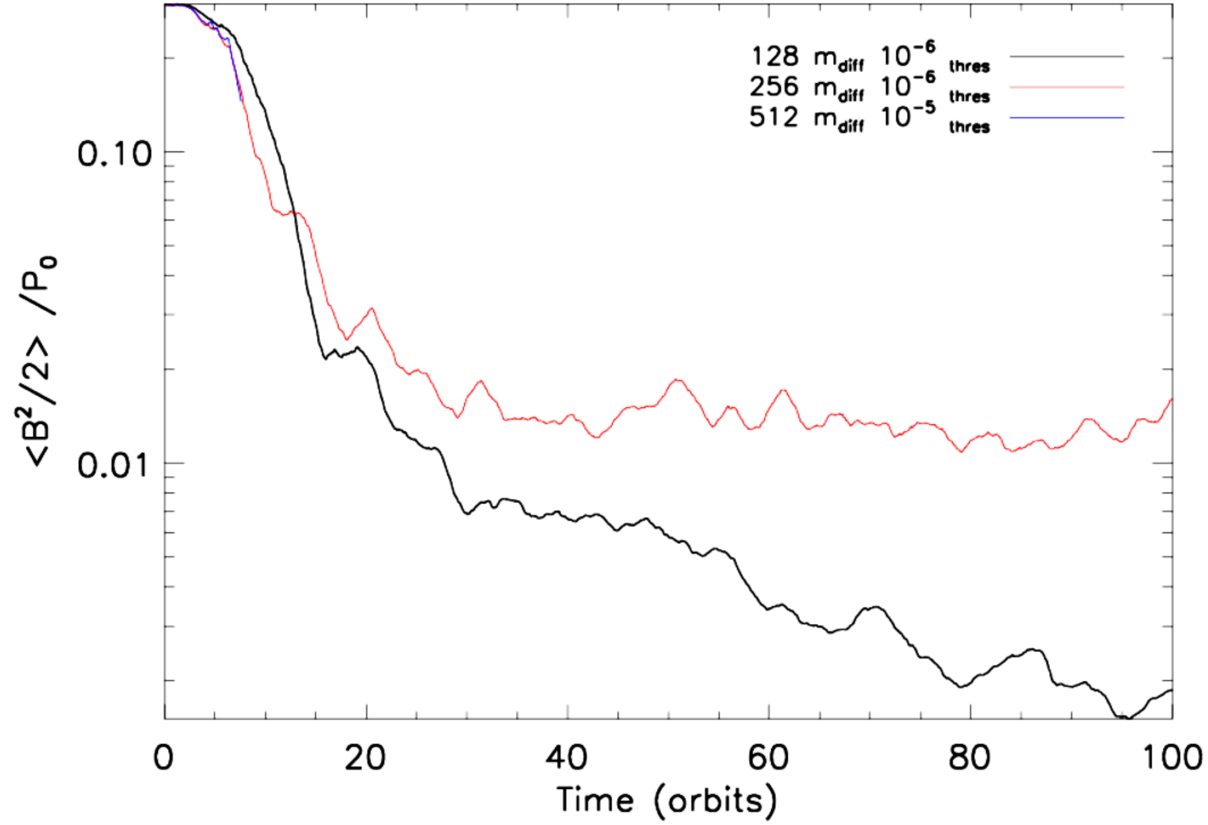
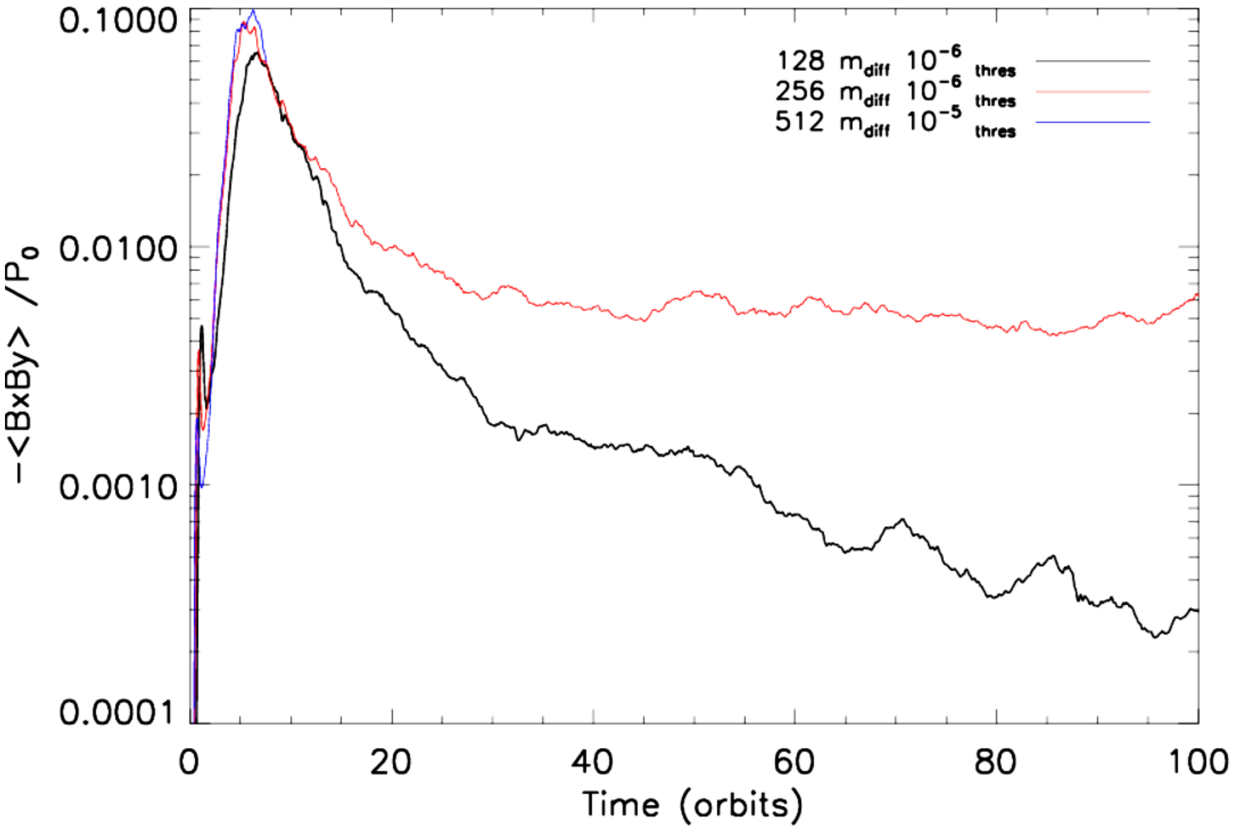


# Numerical results (Comparison)



# Identification of fast magnetic reconnection events in accretion disks

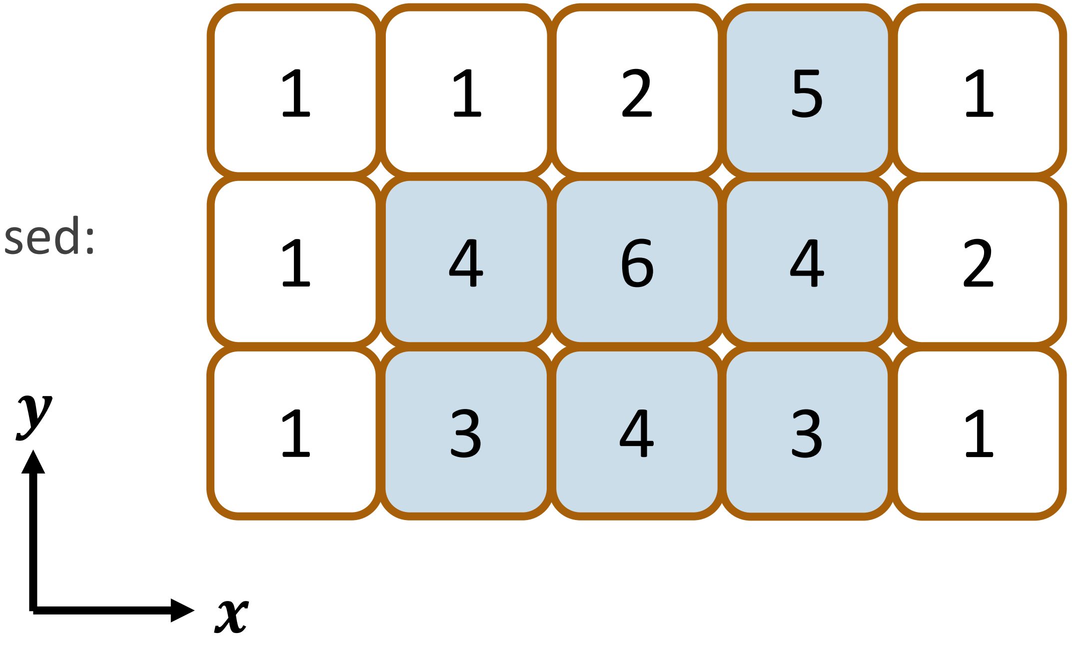
STATISTICAL ANALYSIS OF THE MAGNETIC RECONNECTION RATE

# Algorithm

- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 1st step: Sample of cells with $j_0 > \varepsilon \langle \vec{\nabla} \times \vec{B} \rangle$

For $\varepsilon = 1$

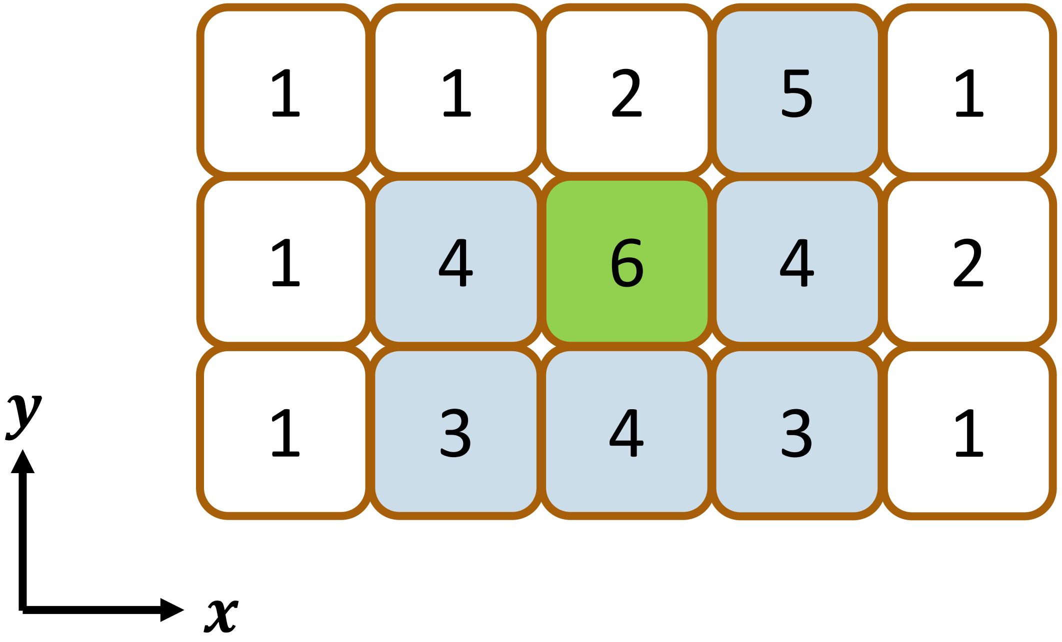
In this work, we have used:
$\varepsilon = 5$




$\langle | \vec{j} | \rangle = 2.6$

# Algorithm

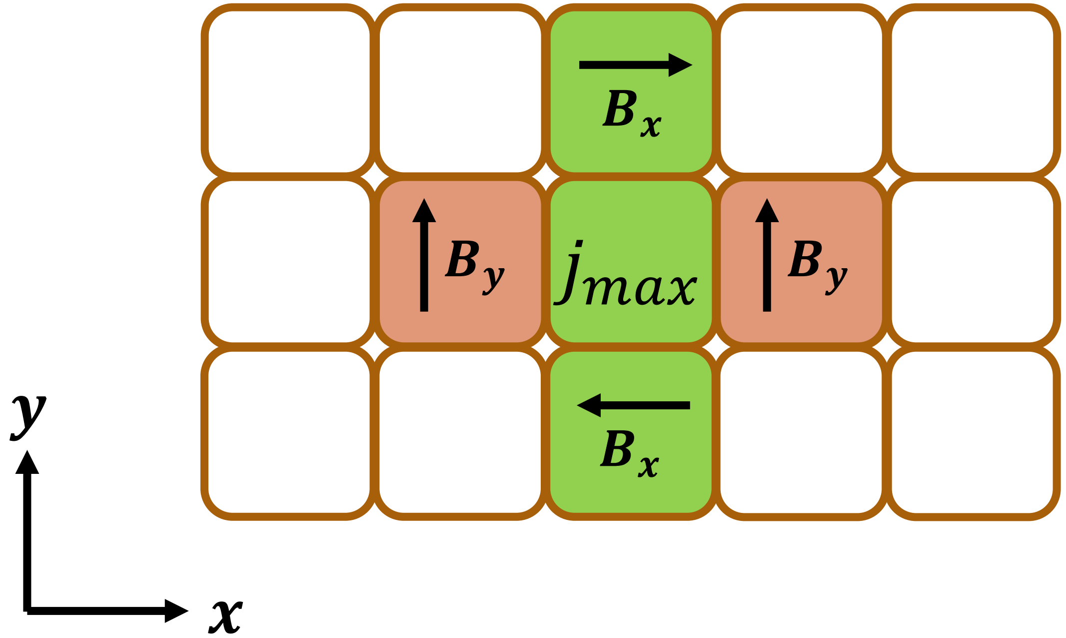
- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 2nd step: Sample of cells with local maxima $j_{max} = MAX(\, j\,)_{n_x \times n_y \times n_z}$




$$j_{max} = 6 = MAX(\, j)_{3\times3}$$

# Algorithm

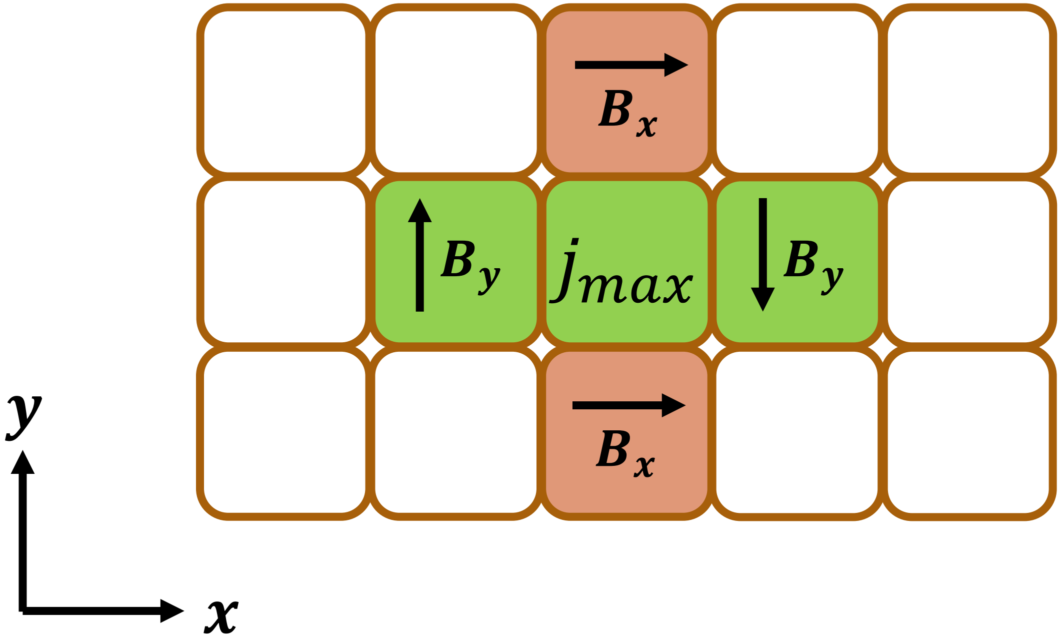
- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 3rd step: Check if the local maxima is between opposite magnetic field polarity




Confirmed!

# Algorithm

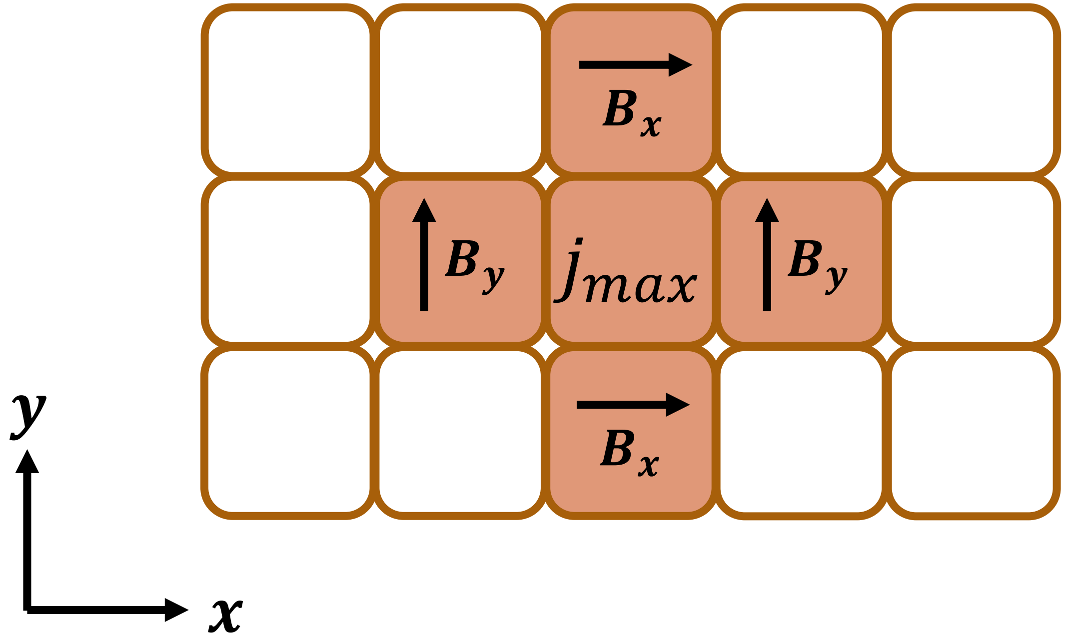
- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 3$^{st}$ step: Check if the local maxima is between opposite magnetic field polarity




Confirmed!

# Algorithm

- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 3[st] step: Check if the local maxima is between opposite magnetic field polarity

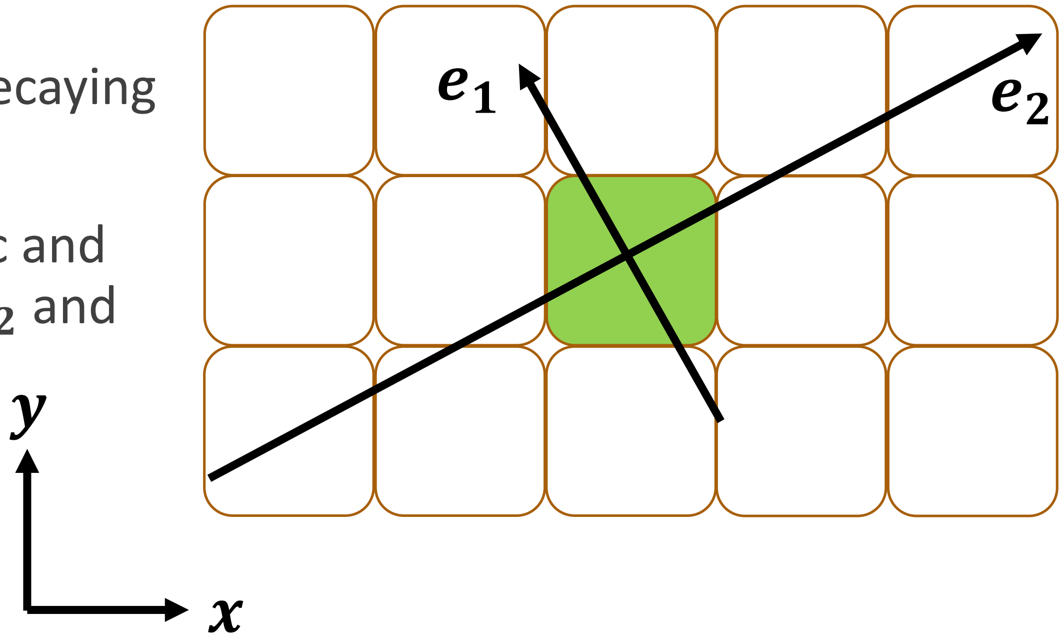



Rejected!

# Algorithm

- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 4st step: Evaluate the eigenvectors of the Hessian matrix

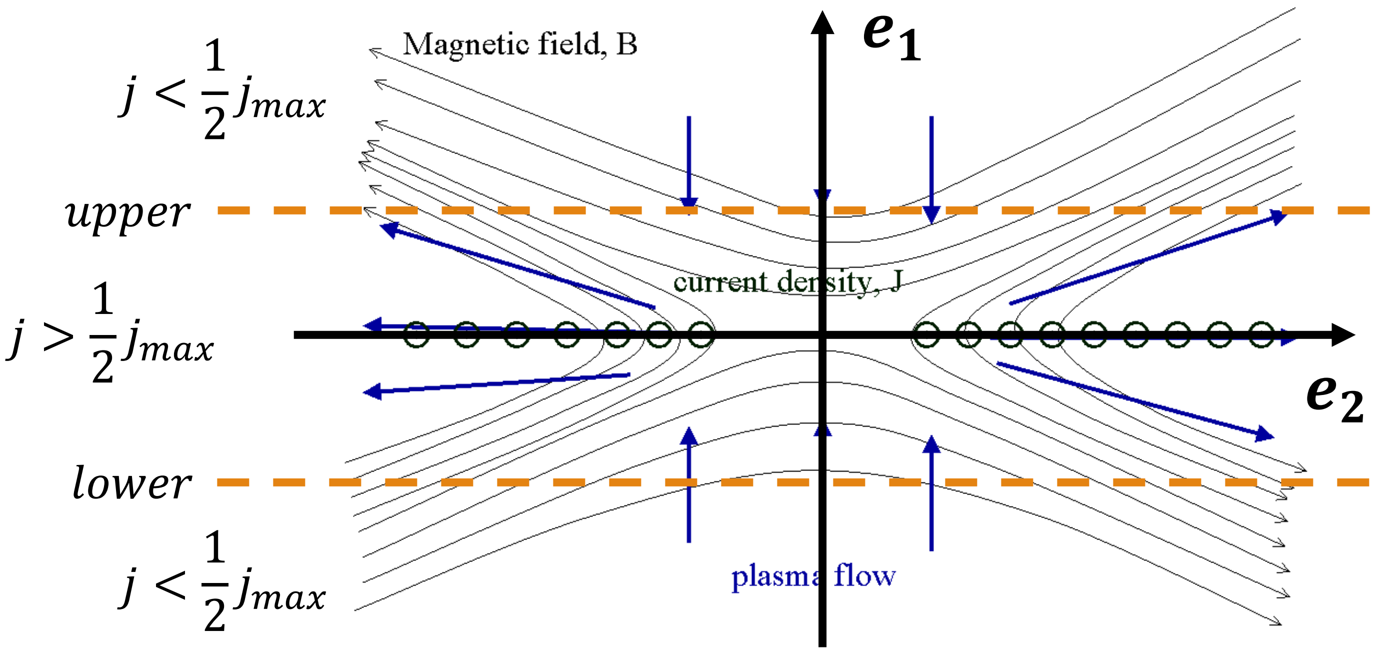
- $\boldsymbol{e_1}$: Indicates the fastest decaying of $j$ (Thickness)
- Projection of the magnetic and velocity fields along $\boldsymbol{e_1}$, $\boldsymbol{e_2}$ and $\boldsymbol{e_3}$ directions




$$H = \begin{bmatrix} \partial_{xx}j & \partial_{xy}j & \partial_{xz}j \\ \partial_{yx}j & \partial_{yy}j & \partial_{yz}j \\ \partial_{zx}j & \partial_{zy}j & \partial_{zz}j \end{bmatrix}$$

# Algorithm

- We have adapted the algorithm of Zhdankin et al. (2013) and extended to a 3D analysis
- 5st step: Evaluate the magnetic reconnection rate




$$\left\langle \frac{V_{in}}{V_A} \right\rangle = \frac{1}{2} \left( \left. \frac{V_{e_1}}{V_A} \right|_{lower} - \left. \frac{V_{e_1}}{V_A} \right|_{upper} \right)$$

$$V_A = \sqrt{\frac{\left( {B_{e_1}}^2 + {B_{e_2}}^2 + {B_{e_3}}^2 \right)}{\rho}}$$

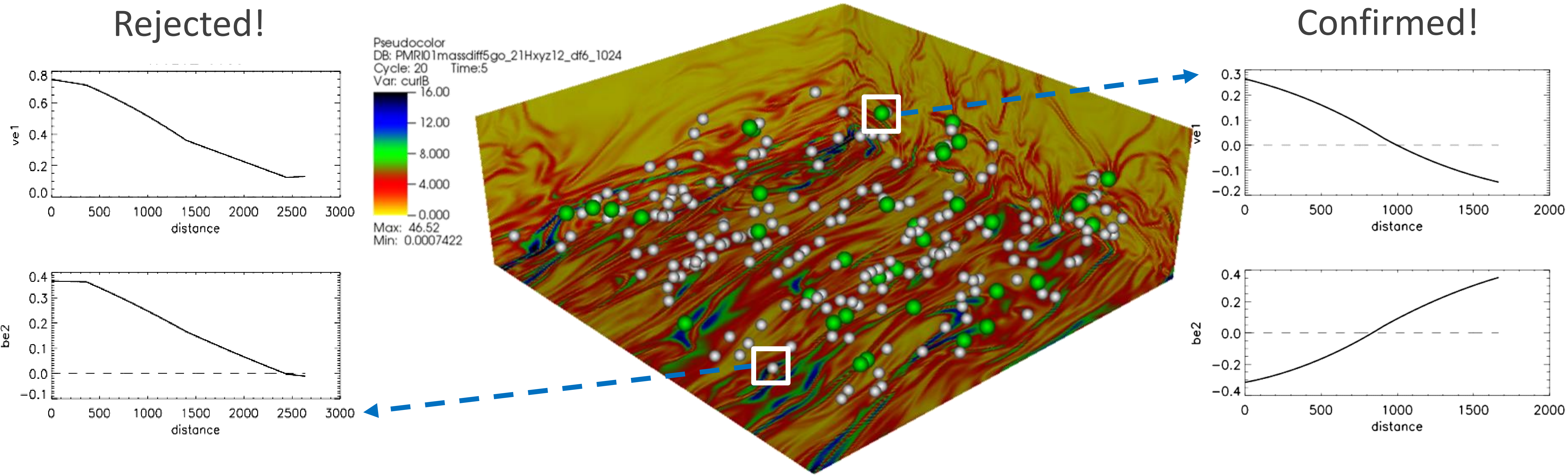
Similar to Kowal et al. (2009)

# Magnetic reconnection rate (Resolution: $256^3$)

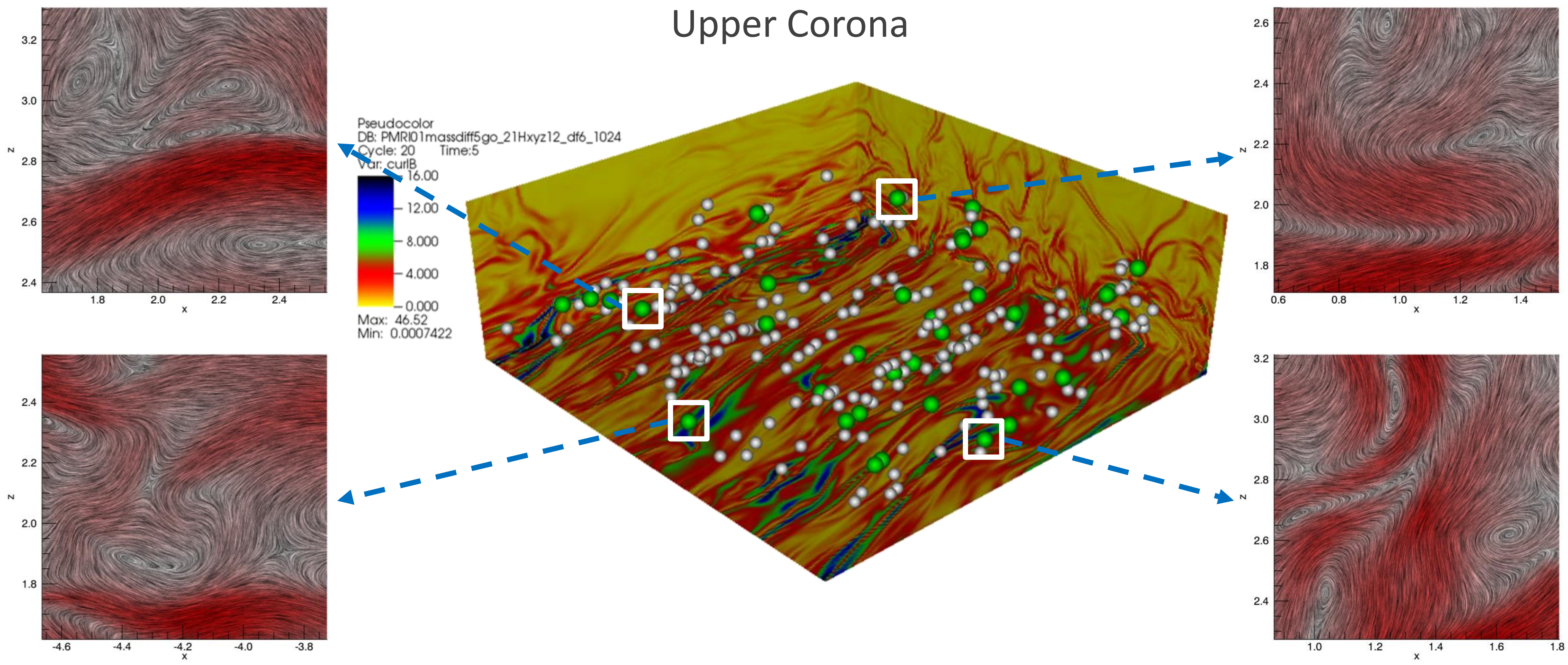
## Upper Corona

Rejected!

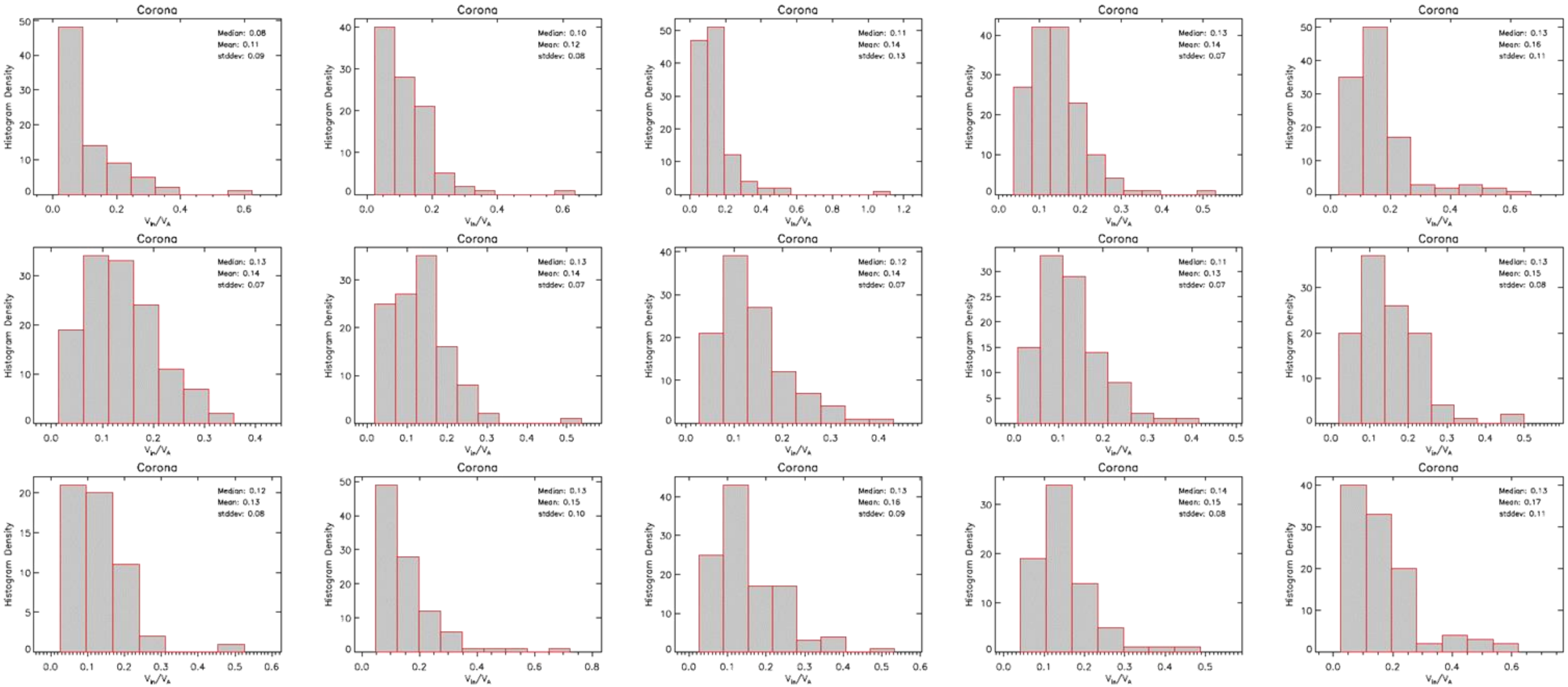
Confirmed!



# Magnetic reconnection rate (Resolution: $256^3$)



# Magnetic reconnection rate (Resolution: $256^3$)

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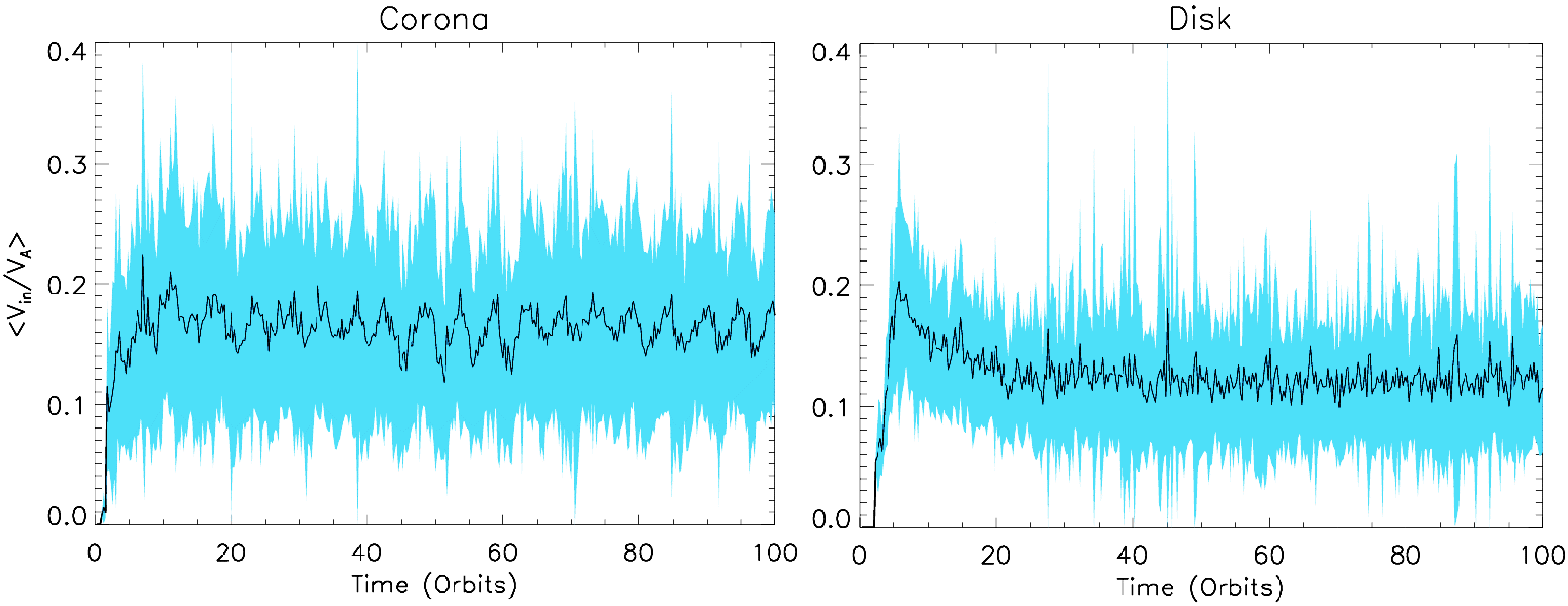
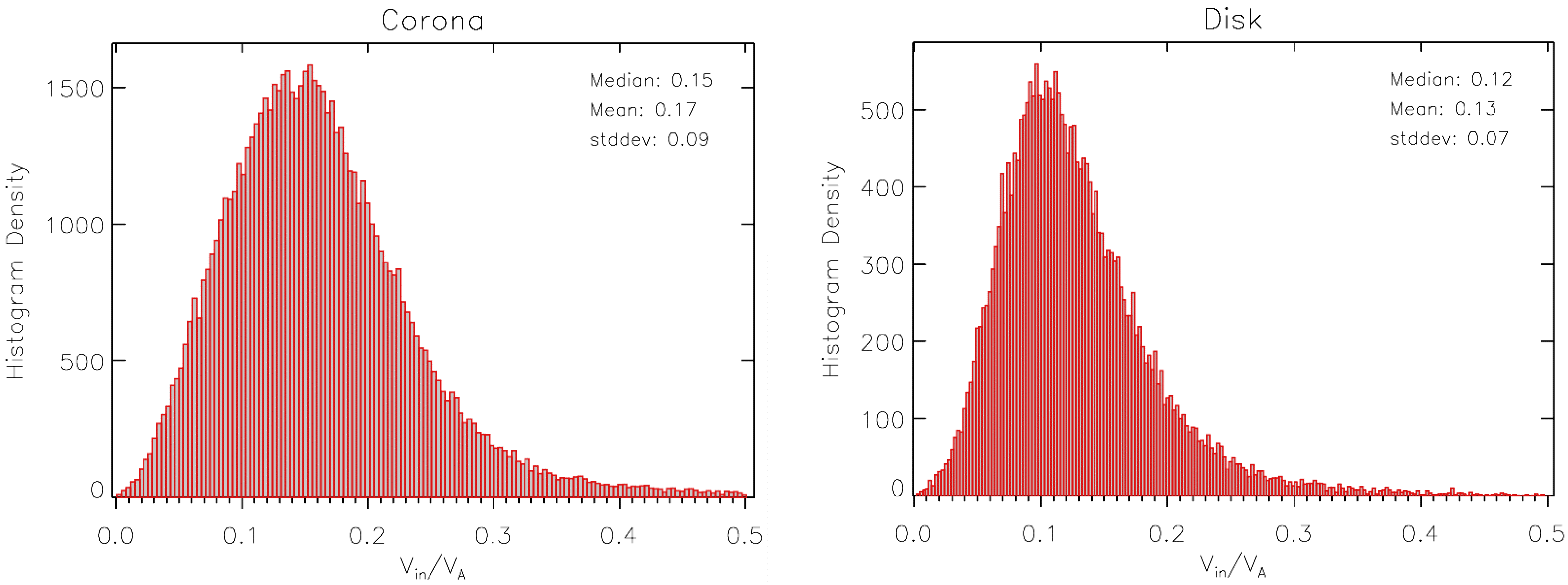
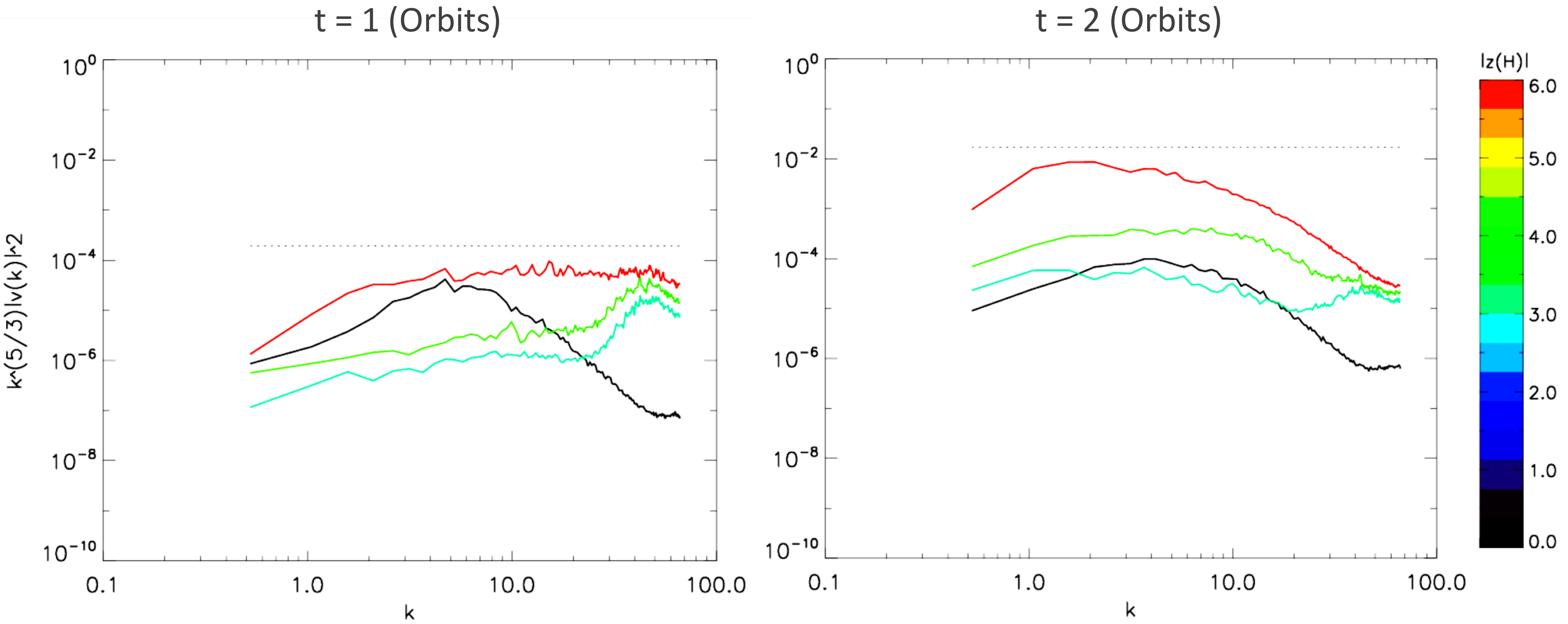
# Magnetic reconnection rate (Resolution: $256^3$)



# Magnetic reconnection rate (Resolution: $256^3$)

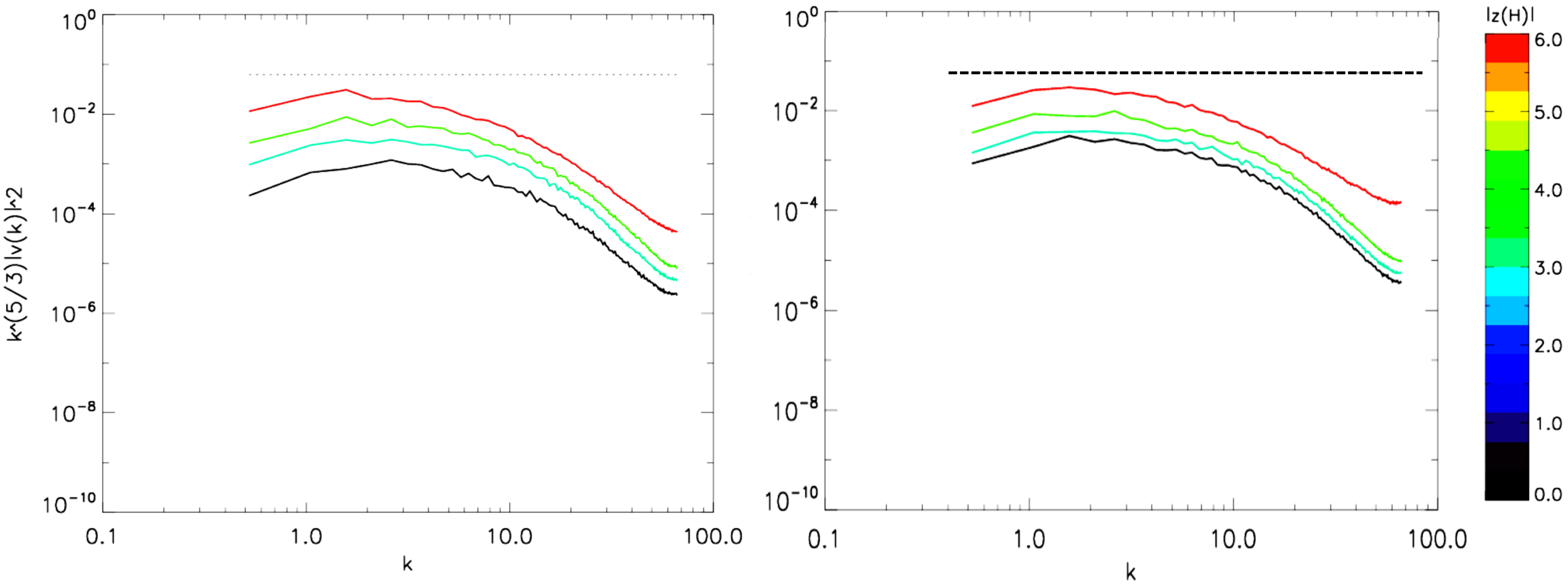


# Power spectrum (Resolution: $256^3$)



# Power spectrum (Resolution: $256^3$)

t = 4 (Orbits) t = 5 (Orbits)



# Conclusions

Kadowaki, de Gouveia Dal Pino & Stone (2017, in prep.)

- Our simulations have revealed the arising of magnetic loops due to the PRTI followed by the development of turbulence due to PRTI and MRI
- Even with an initial high magnetized regime, the disk evolves to a gas-pressure dominant regime with a magnetized corona
  - Transport of magnetic field from the disk to the corona by buoyance process
- We have evaluated the magnetic reconnection rates and detected the presence of fast magnetic reconnection events, as predicted by the theory of turbulence-induced fast reconnection (Lazarian & Vishiniac, 1999)
- The algorithm applied to this work has demonstrated to be an efficient tool for the identification of magnetic reconnection sites in numerical simulations

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# Thank you!