MRI-driven outflows in accretion disks

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Outline

I. Angular momentum transport in accretion disks

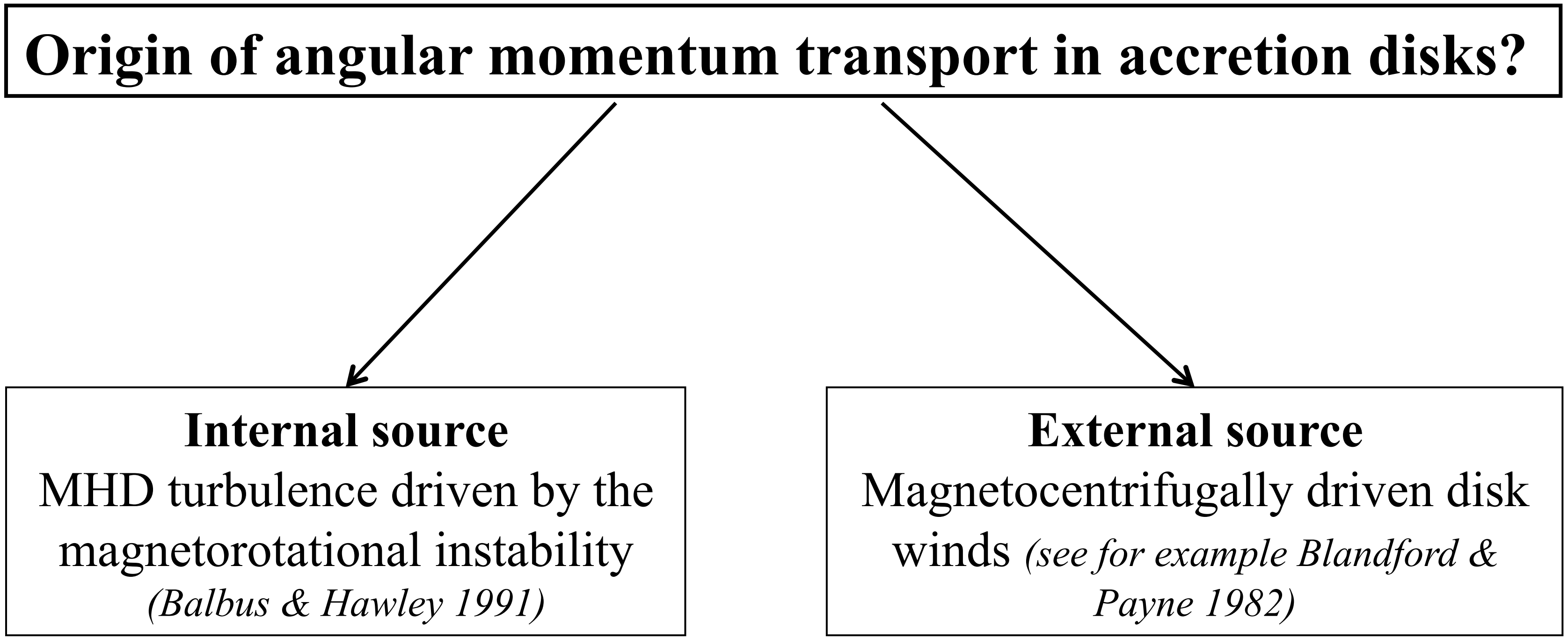
- MHD turbulence vs. disc winds
- Numerical methods

II. Local outflows from turbulent discs (Fromang et al. 2013)

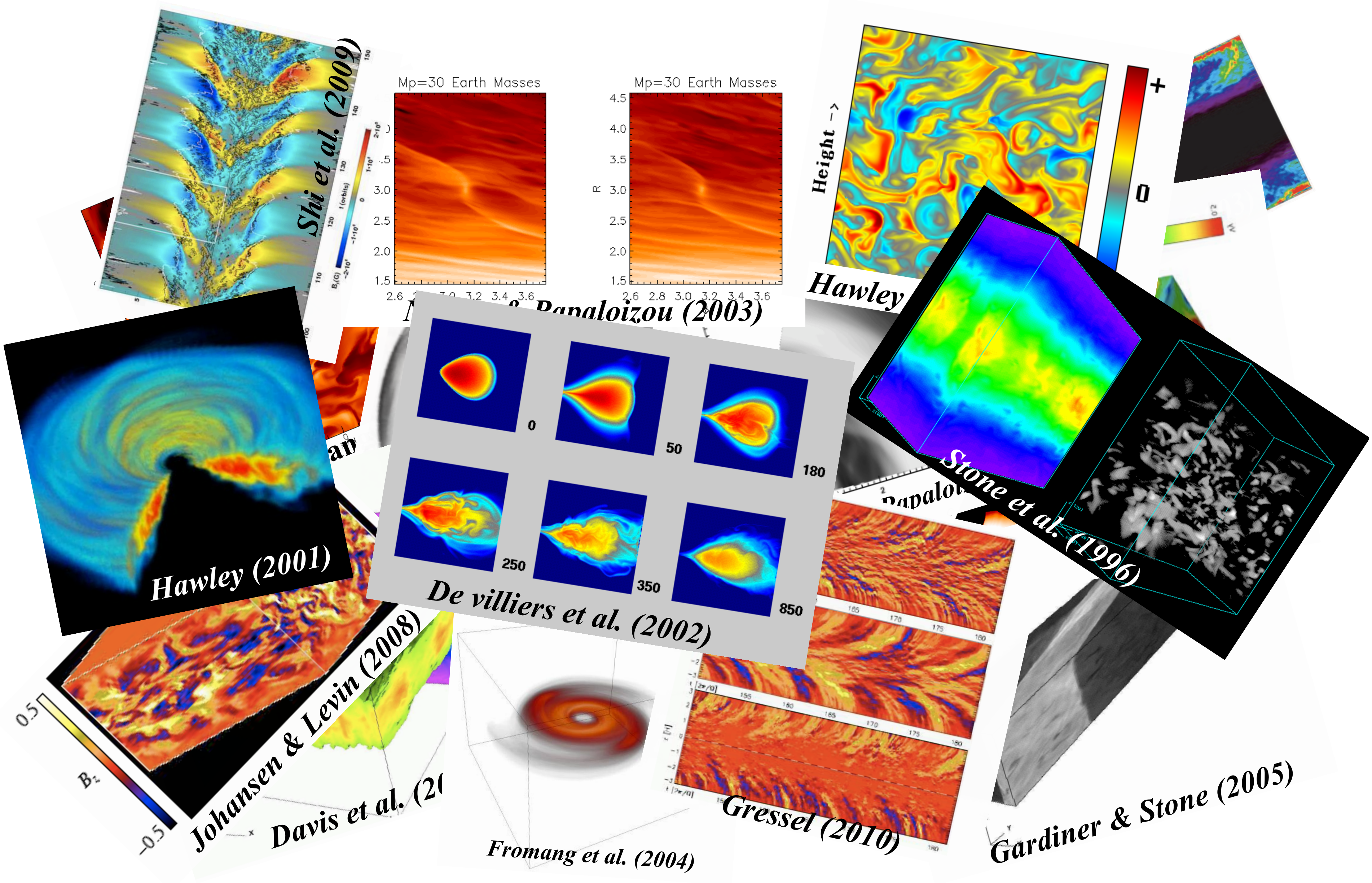
- Stratified shearing boxes simulations
- Connexion with classical theory

III. The case of protoplanetary disks (Lesur et al. 2014)

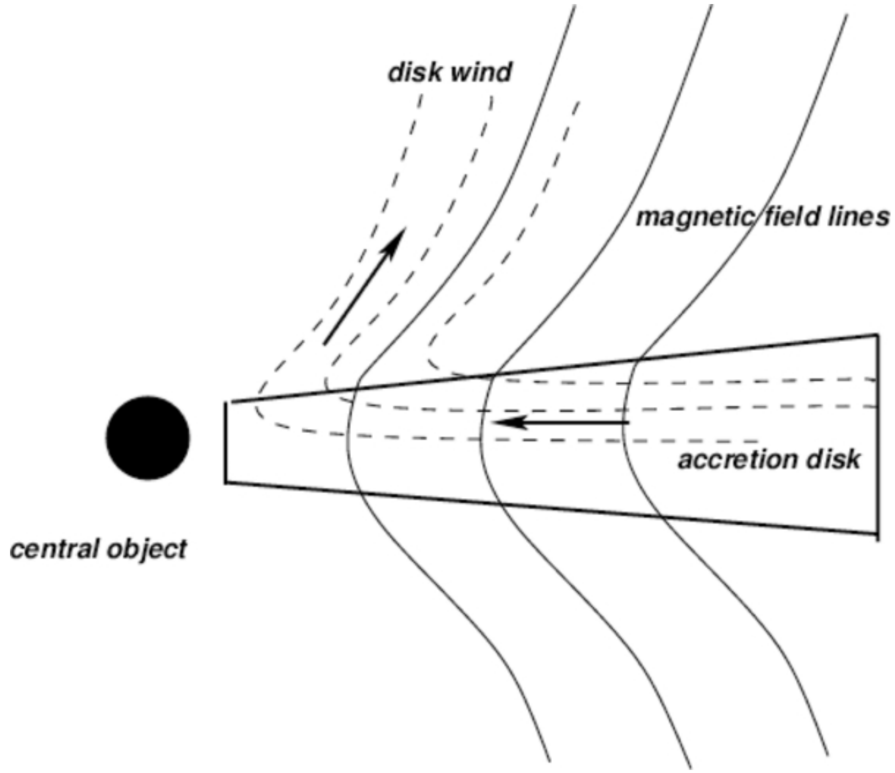
- B-field dissipation in PP disks
- The Hall effect: local simulations
- Including Ohmic, Hall & ambipolar: results & problems


Origin of angular momentum transport in accretion disks?
Internal source
MHD turbulence driven by the magnetorotational instability
(Balbus & Hawley 1991)
External source
Magnetocentrifugally driven disk winds (see for example Blandford & Payne 1982)

MRI-driven MHD turbulence



Launching a jet: current models

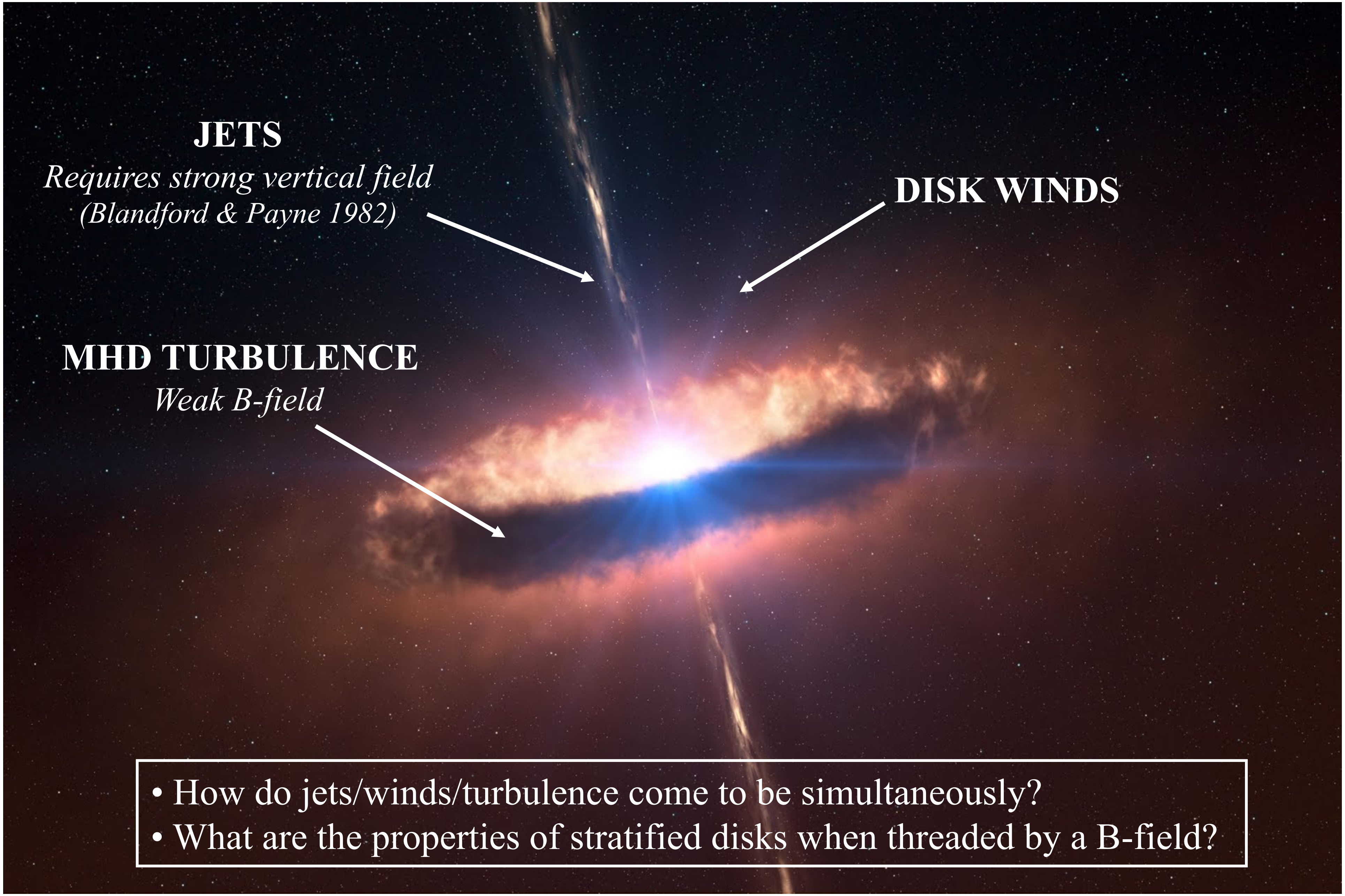


Sheikhnezami (2012)

Conditions:

- Magnetic flux perpendicular to the disk
- Magnetic diffusion (to oppose accretion) $\Rightarrow \alpha_M \sim 1$ (turbulence)
- Strong B-field: $\beta \sim 1$

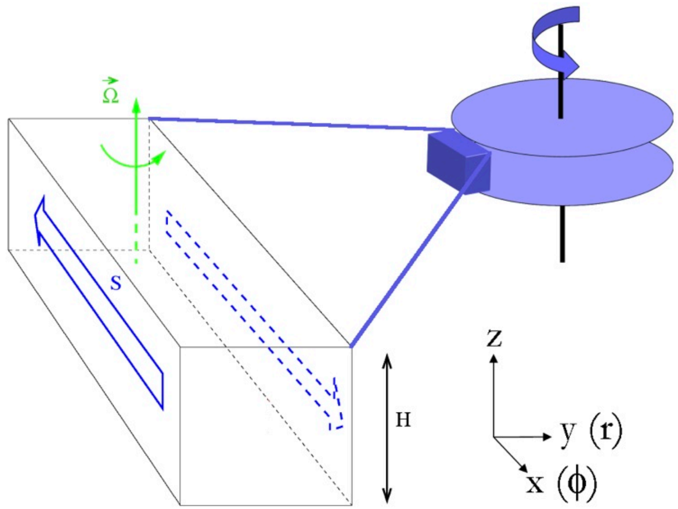
Based on Blandford & Payne (1982)

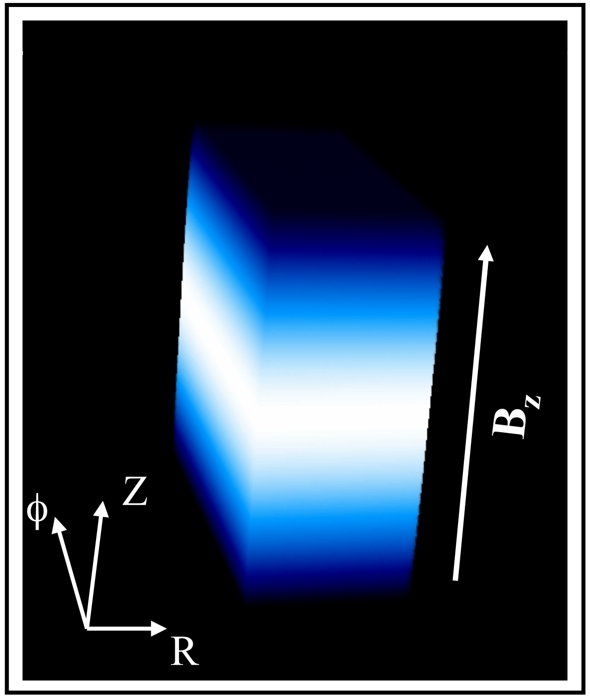

JETS
Requires strong vertical field
(Blandford & Payne 1982)
DISK WINDS
MHD TURBULENCE
Weak B-field
• How do jets/winds/turbulence come to be simultaneously?
• What are the properties of stratified disks when threaded by a B-field?

Numerical methods

The shearing box model

- **Local approximations**
- **MHD equations + dissipation (or not)**
- **Isothermal EQS**





- **Density stratification in vertical direction**
- **Magnetic field**
  - ✓ Purely vertical, uniform
  - ✓ $\beta = P_{th}/P_{mag} = 10^4$ and 10^5
- **Boundary conditions: outflow**

Two codes

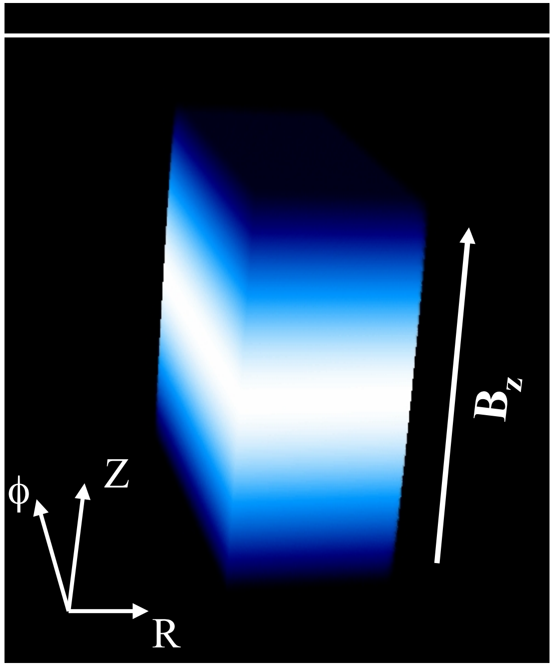
- **RAMSES** *(Teyssier 2002, Fromang et al. 2006)*
- **PLUTO** *(Mignone et al. 2007)*

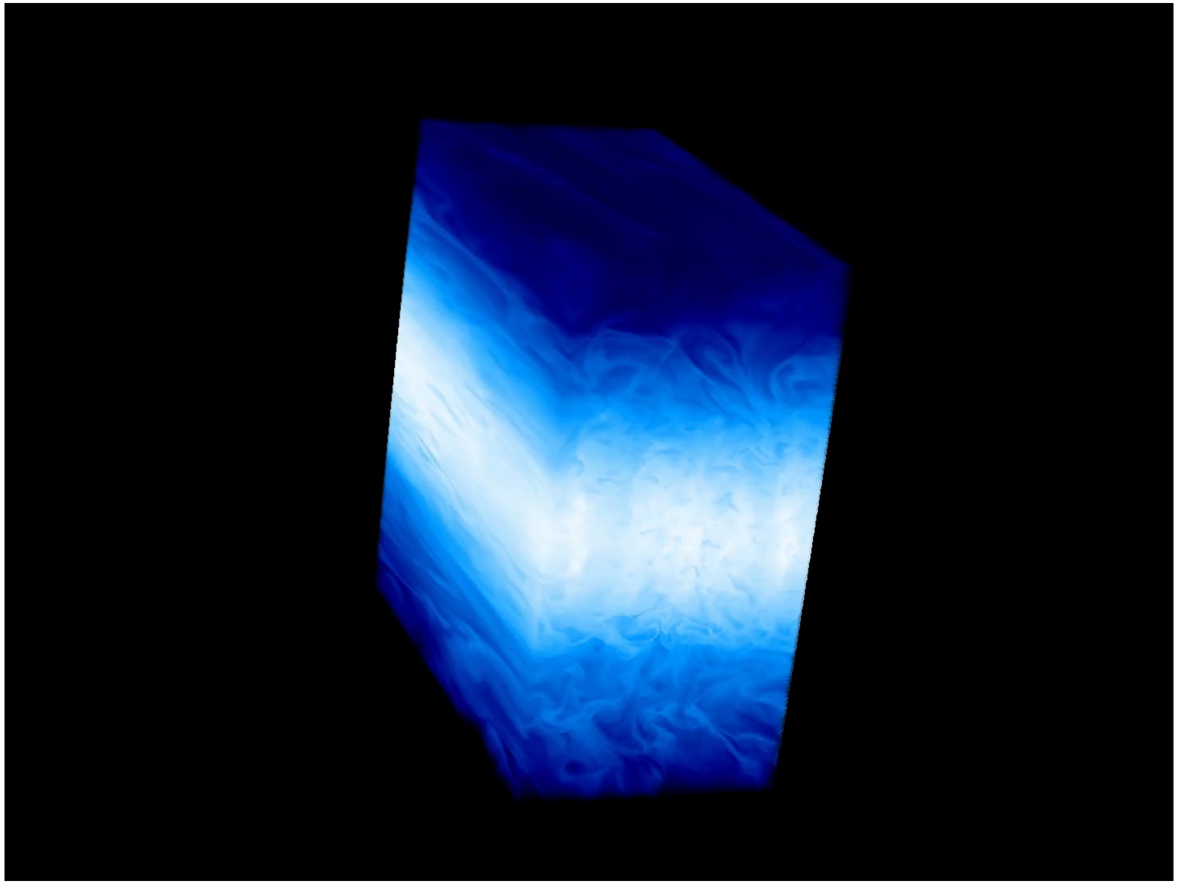
Local outflows from turbulent discs

Fromang, Latter, Lesur & Ogilvie, 2013, A&A

General flow properties

Movie:
B.Thooris (CEA/Saclay)
D.Pomarede (CEA/Saclay)
Software: SDvision

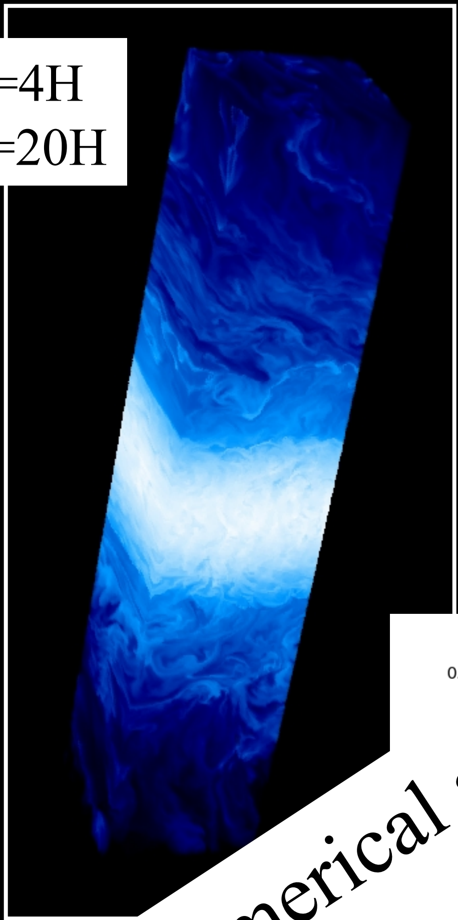




Typical turbulent flow in the equatorial plane
$\alpha \approx 10^{-2}$
Powerful outflow launched through the surfaces

Outflows: effect of the box size

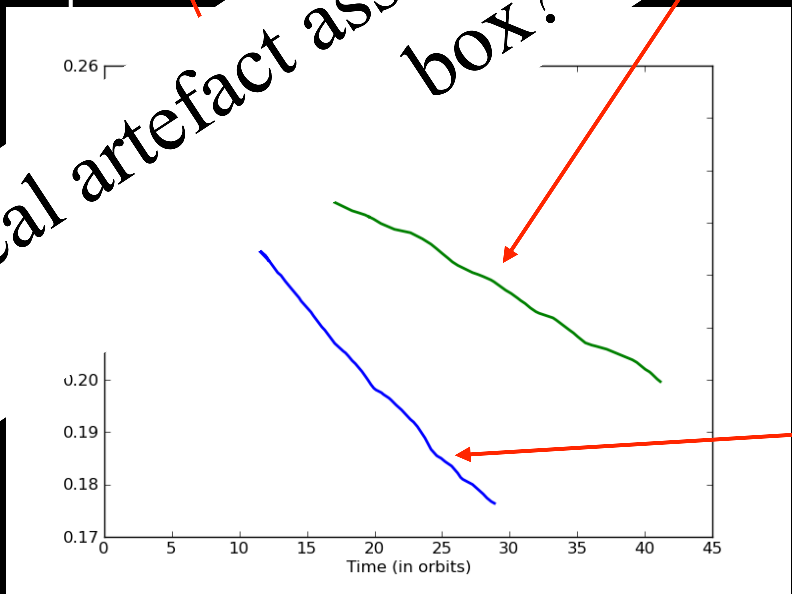
Lx=4H
Lz=20H



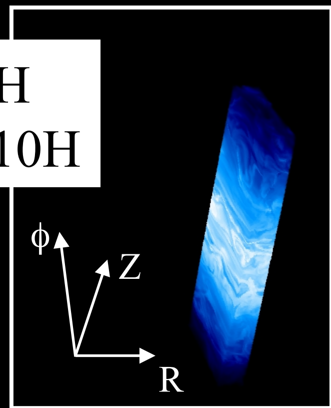
- 64 cells/H
- Ly=4H
- Re=Rm=3000
- β=10^4

Lx=4H
Lz=1

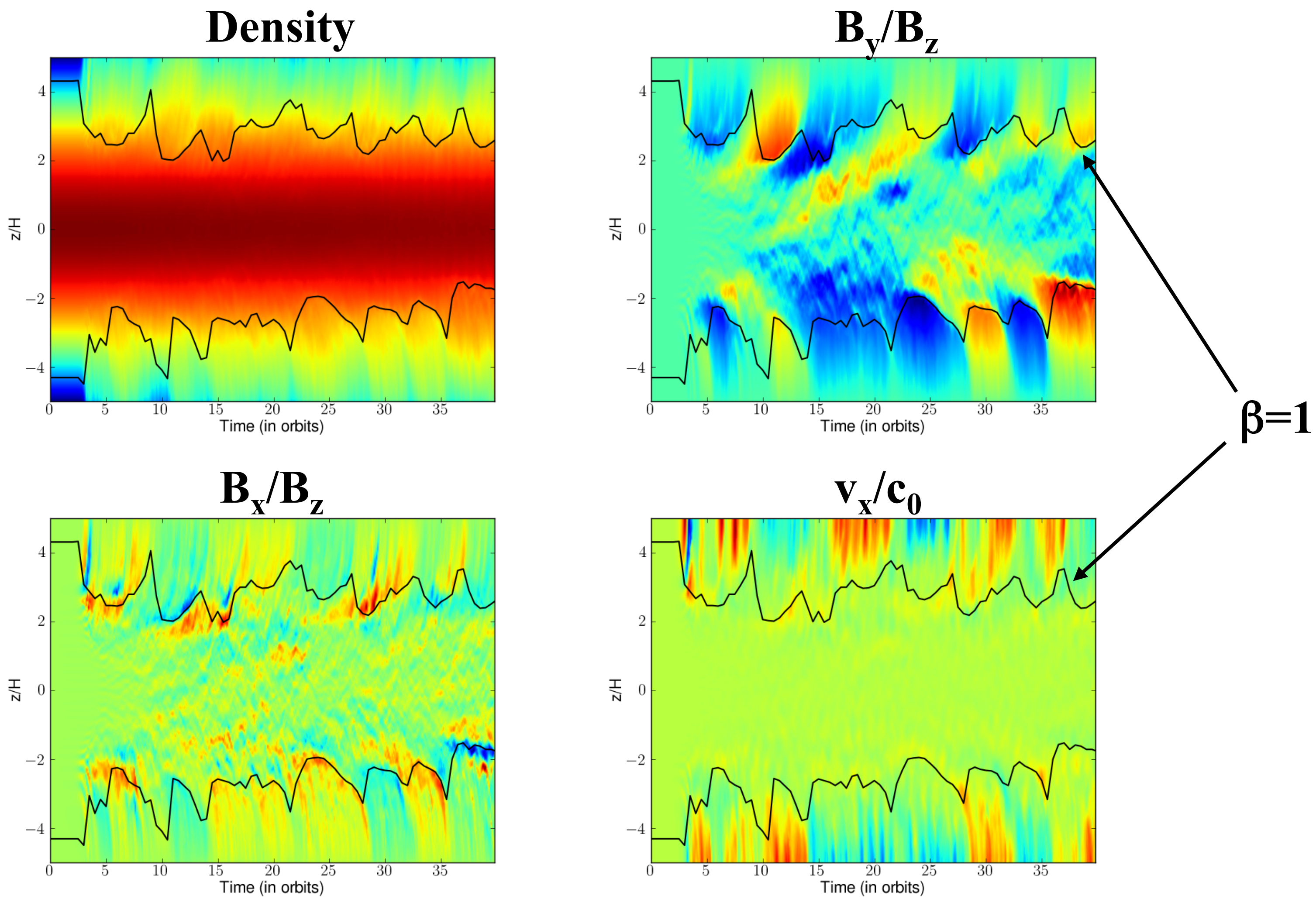
Numerical artefact associated with the shearing box?



Lx=H
Lz=10H



Outflow structure: spacetime diagram

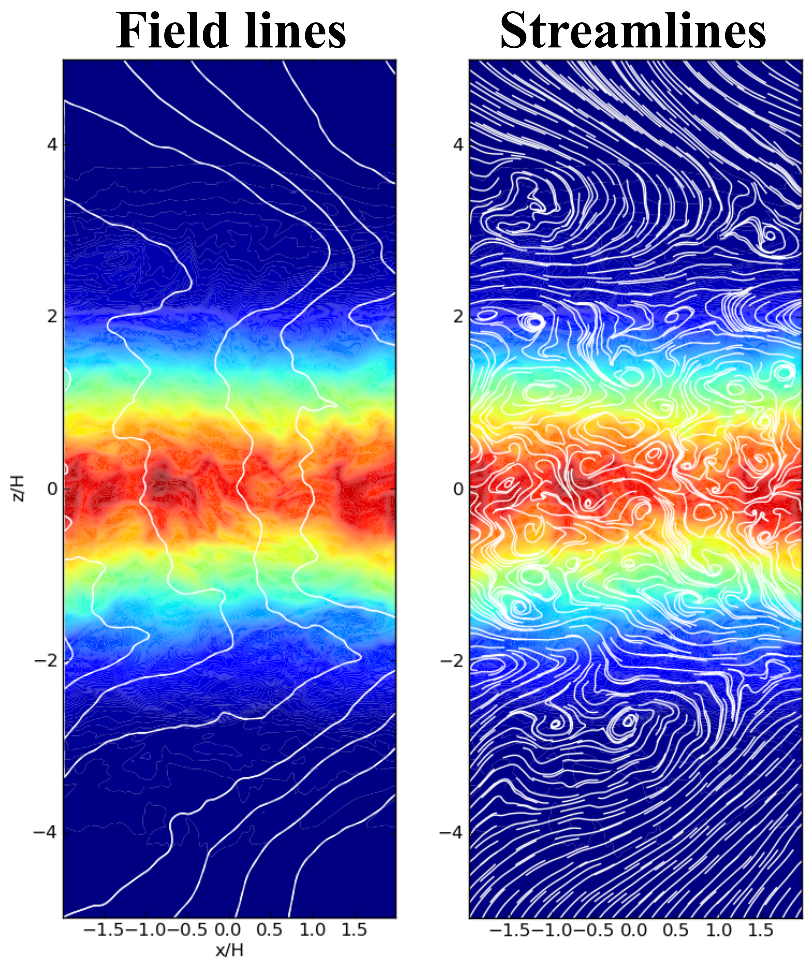


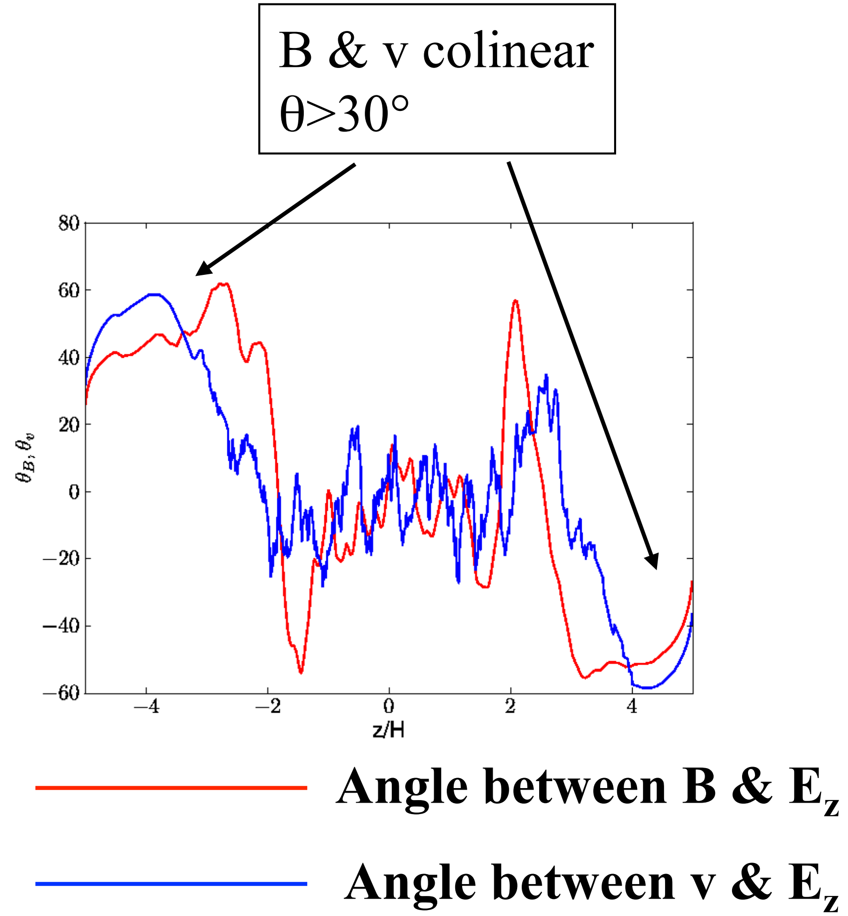
⇒ **Bursty ejection: cycles with period of a few orbits**

⇒ **« Unphysical » geometry of the wind structure**

Flow stucture during a single burst

- Consider one burst
- Time averaged simulation data (example: 22<t<27)





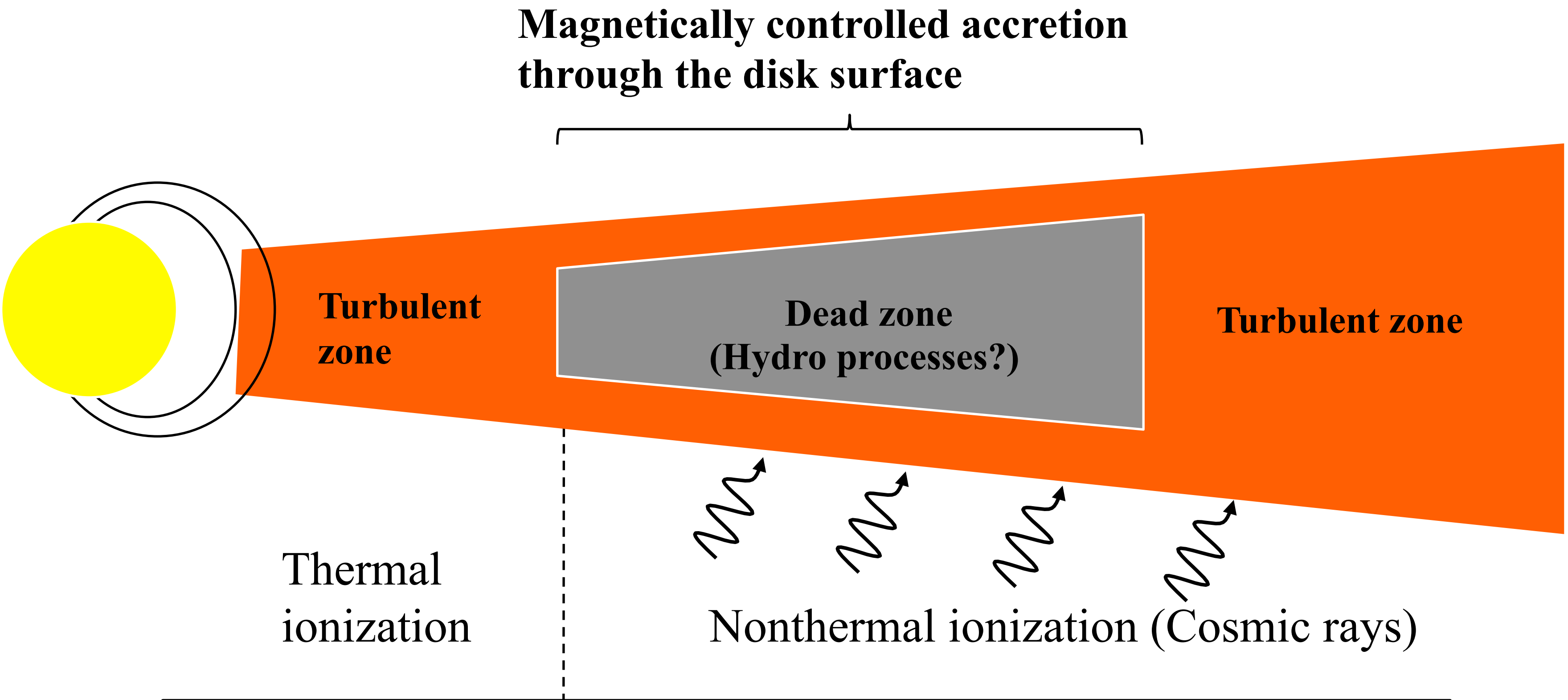
MAGNETOCENTRIFUGAL LAUNCHING POSSIBLE!
(Blandford & Payne 1982)

The case of protoplanetary discs

Lesur, Kunz & Fromang, 2014, A&A

Layered accretion in PP disk

Gammie (1996)



Pro's of the Dead zone paradigm:

- tentatively accounts for T-Tauri accretion rates
- provides a « quiet » environment for planet formation
- confirmed by numerical simulations (Fleming & Stone 2003)

Con's:

- only based on an estimate of the Ohmic diffusivity

Non-ideal MHD: the induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left(\boldsymbol{v} \times \boldsymbol{B} - \underbrace{\frac{4\pi\eta}{c}\boldsymbol{J}}_{\text{Ohmic dissipation}} - \underbrace{\frac{4\pi\eta_H}{c}\boldsymbol{J} \times \hat{\boldsymbol{B}}}_{\text{Hall effect}} - \underbrace{\frac{4\pi\eta_A}{c}\boldsymbol{J}_\perp}_{\text{Ambipolar diffusion}} \right)$$

Ohmic dissipation: $\eta_H \sim \frac{T^{1/2}}{x_e}$ → $Rm = \frac{v_A^2}{\eta\Omega}$

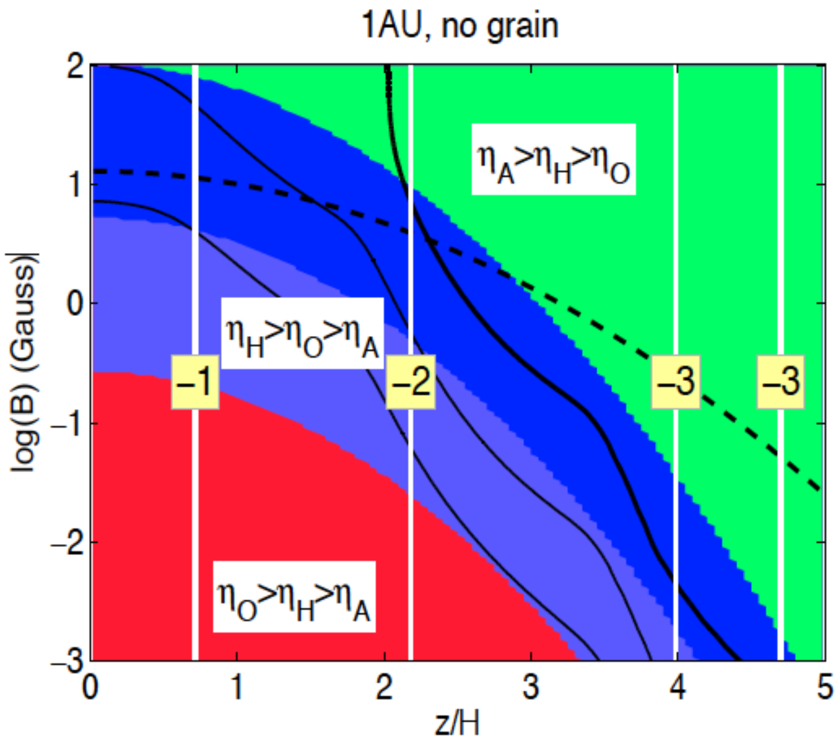
Hall effect: $\eta_H \sim \frac{cB}{4\pi e n_e}$ → $\chi = \frac{v_A^2}{\eta_H \Omega}$

Ambipolar diffusion: $\eta_A \sim \frac{B^2}{4\pi\gamma_i \rho_i \rho}$ → $Am = \frac{v_A^2}{\eta_A \Omega}$

Elsasser numbers

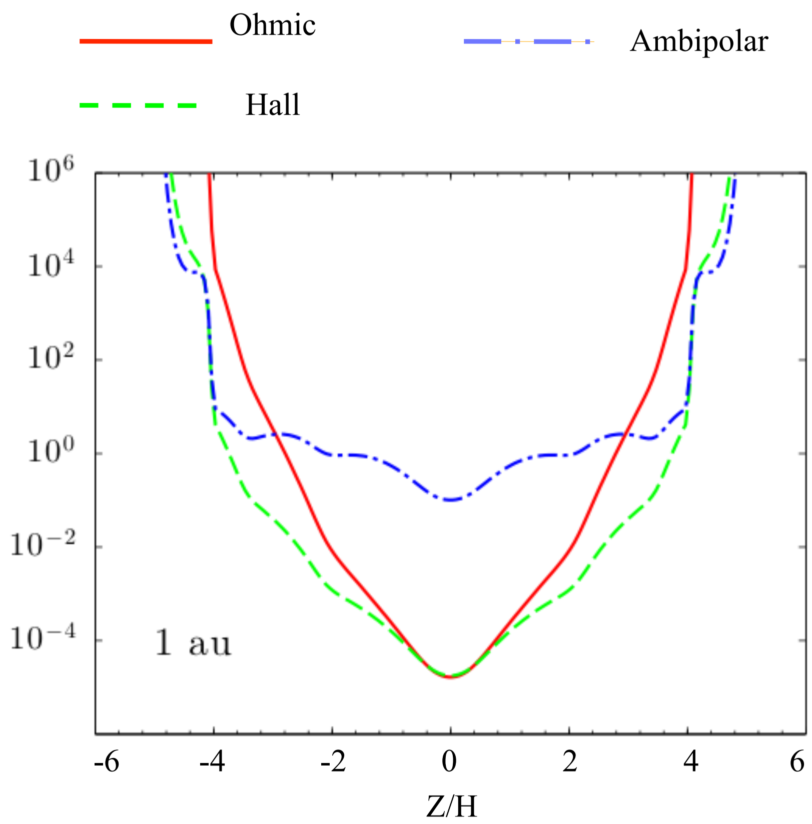
Non ideal MHD in PP disks?

Resistivities



Bai (2011)

Elssasser numbers @ 1AU

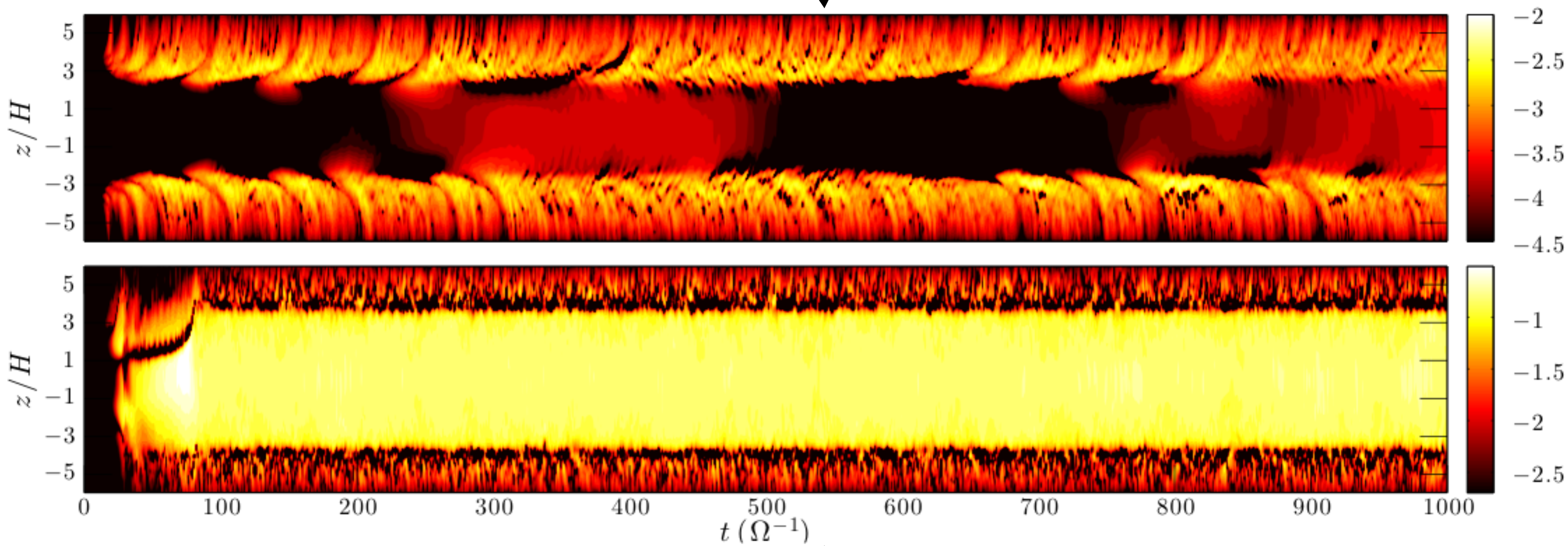


Lesur et al. (2014)

Hall term dominant dissipation term in large part of PP disks!

The effect of the Hall term (β=10^5)

Ohmic dissipation alone @ 1AU
Stress tensor spacetime diagram: α=2.5 10^{-3}



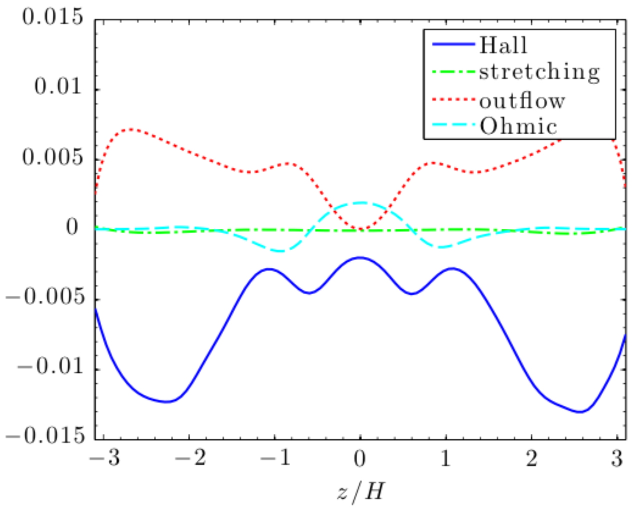
Ohmic dissipation + Hall effect (@ 1 AU)
Stress tensor spacetime diagram: α=4.5 10^{-1}

- Large stress & azimuthal field in the Hall dominated region
- Flow laminar in the disk midplane, powerful outflows

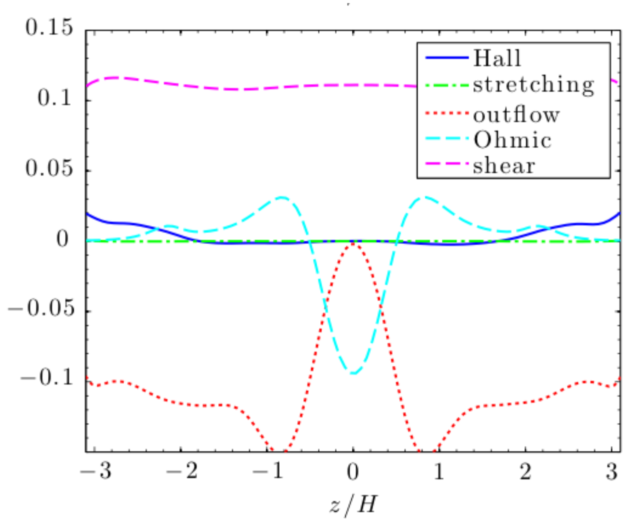
Physical origin of the midplane stress

Evolution equations

$$\begin{cases} \dfrac{\partial\langle B_x\rangle}{\partial t} = \dfrac{\partial\langle B_x v_z\rangle}{\partial z} - \dfrac{\partial\langle B_z v_x\rangle}{\partial z} - \dfrac{\partial}{\partial z}\left(\dfrac{c}{\sqrt{4\pi e n_e}}\dfrac{\partial\langle B_y\rangle}{\partial z}\right) + \dfrac{\partial}{\partial z}\left(\eta\dfrac{\partial\langle B_x\rangle}{\partial z}\right) \\ \dfrac{\partial\langle B_y\rangle}{\partial t} = \underbrace{\dfrac{\partial\langle B_y v_z\rangle}{\partial z}}_{\text{Outflow}} - \underbrace{\dfrac{\partial\langle B_z v_y\rangle}{\partial z}}_{\text{Stretching}} - \underbrace{\dfrac{\partial}{\partial z}\left(\dfrac{cB_0}{\sqrt{4\pi e n_e}}\dfrac{\partial\langle B_x\rangle}{\partial z}\right)}_{\text{Hall}} + \underbrace{\dfrac{\partial}{\partial z}\left(\eta\dfrac{\partial\langle B_y\rangle}{\partial z}\right)}_{\text{Ohmic}} \underbrace{- q\Omega\langle B_x\rangle}_{\text{Shear}} \end{cases}$$



Bx evolution equation



By evolution equation

Physical origin of the stress

Evolution equations

$$\begin{cases} \dfrac{\partial\langle B_x\rangle}{\partial t} = \dfrac{\partial\langle B_x v_z\rangle}{\partial z} - \dfrac{\partial}{\partial z}\left(\dfrac{c}{\sqrt{4\pi e n_e}}\dfrac{\partial\langle B_y\rangle}{\partial z}\right) \\ \dfrac{\partial\langle B_y\rangle}{\partial t} = \dfrac{\partial\langle B_y v_z\rangle}{\partial z} + \dfrac{\partial}{\partial z}\left(\eta\dfrac{\partial\langle B_y\rangle}{\partial z}\right) - q\Omega\langle B_x\rangle \end{cases}$$

Outflow — Hall — Ohmic — Shear

- Hall term creates large negative Bx (due to large drift velocity of electrons)
  ➔ balanced by outflow
- Shear flow creates large By out of Bx
  ➔ balanced by ohmic dissipation (midplane) and outflow (upper layers)

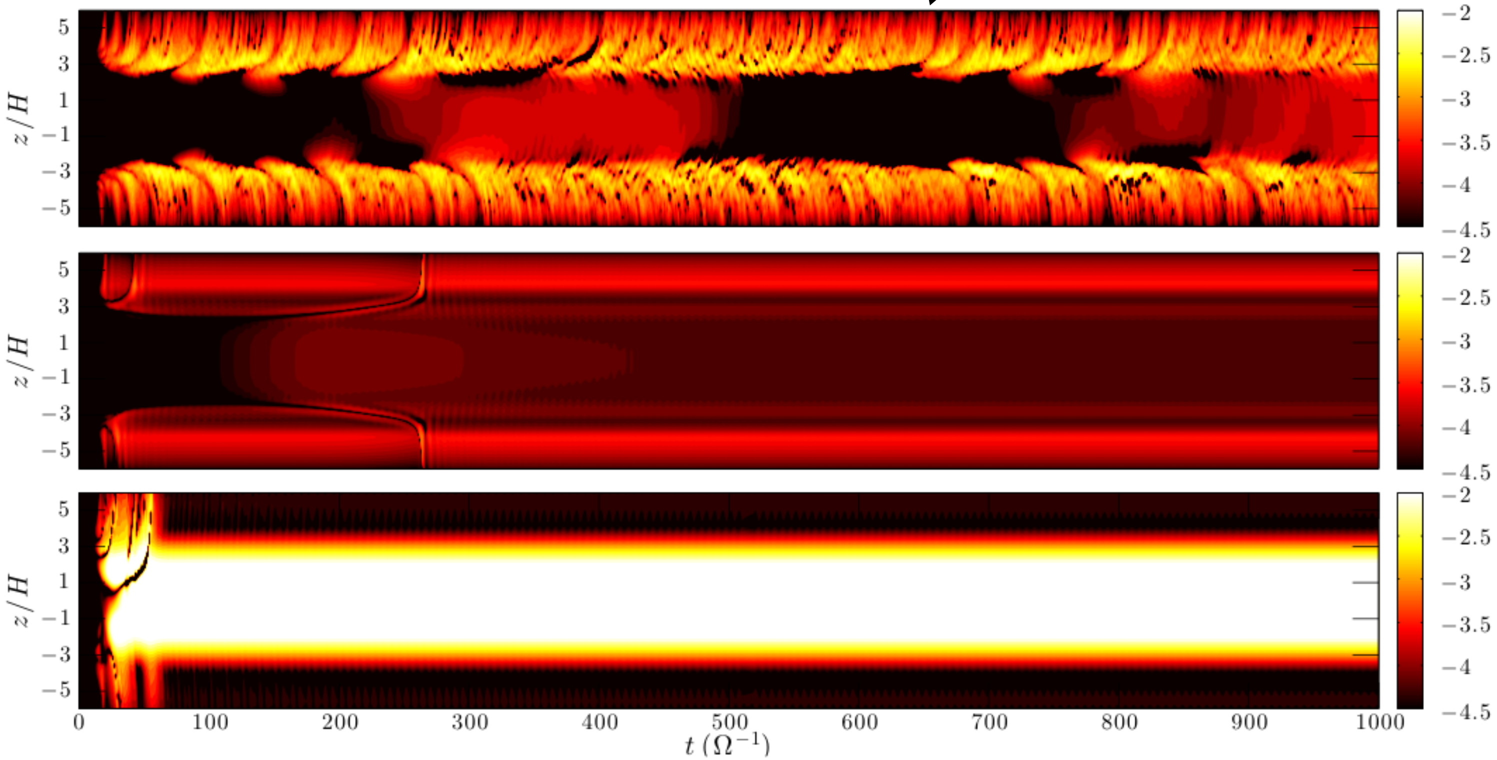
Hall-shear instability *(Kunz 2008)* balanced by Ohmic dissipation and outflows

LARGE STRESS IN HALL DOMINATED REGION

Putting things together (Ohm+Hall+Ambipolar)

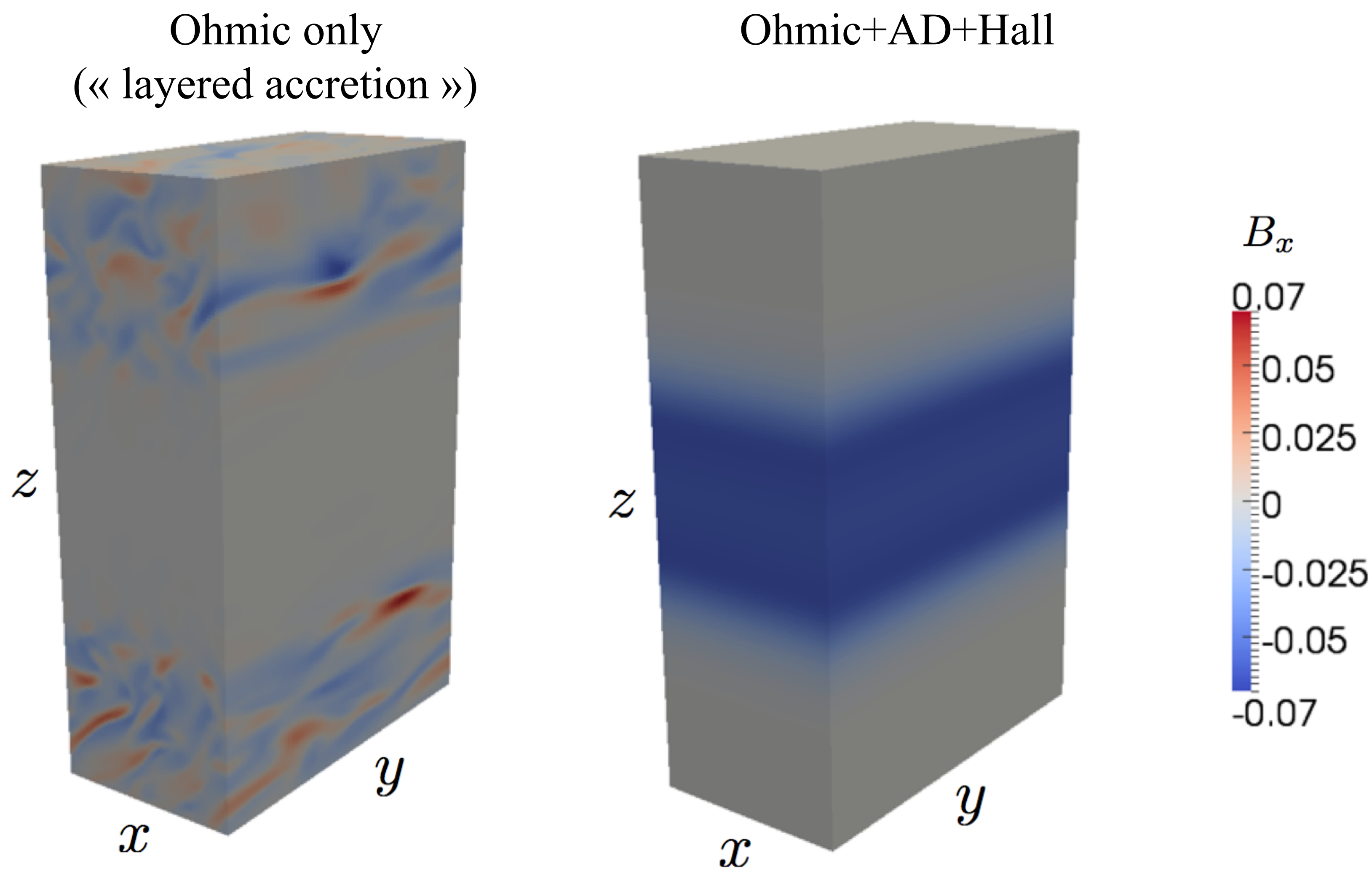
Ohmic + Ambipolar (1AU)
α=5.9 10^{-4}

Ohmic dissipation alone (1AU)
α=2.5 10^{-3}



Ohmic + Ambipolar + Hall(1AU)
α=5.0 10^{-2}

Transport not due to turbulence

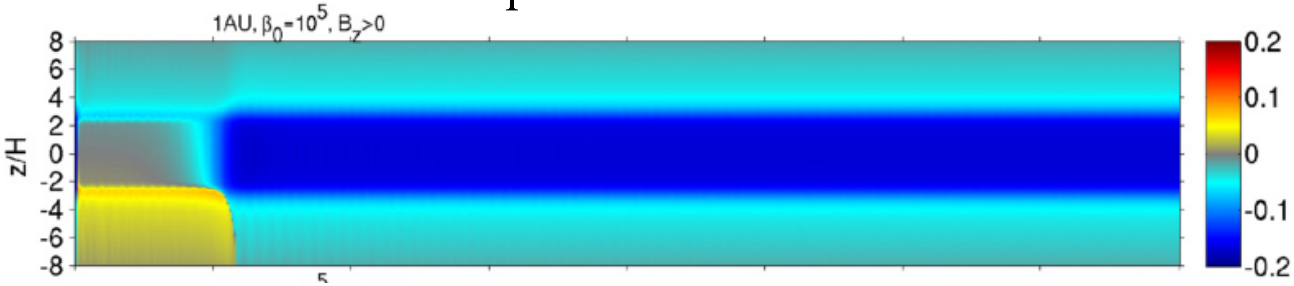


Locality of angular momentum transport?

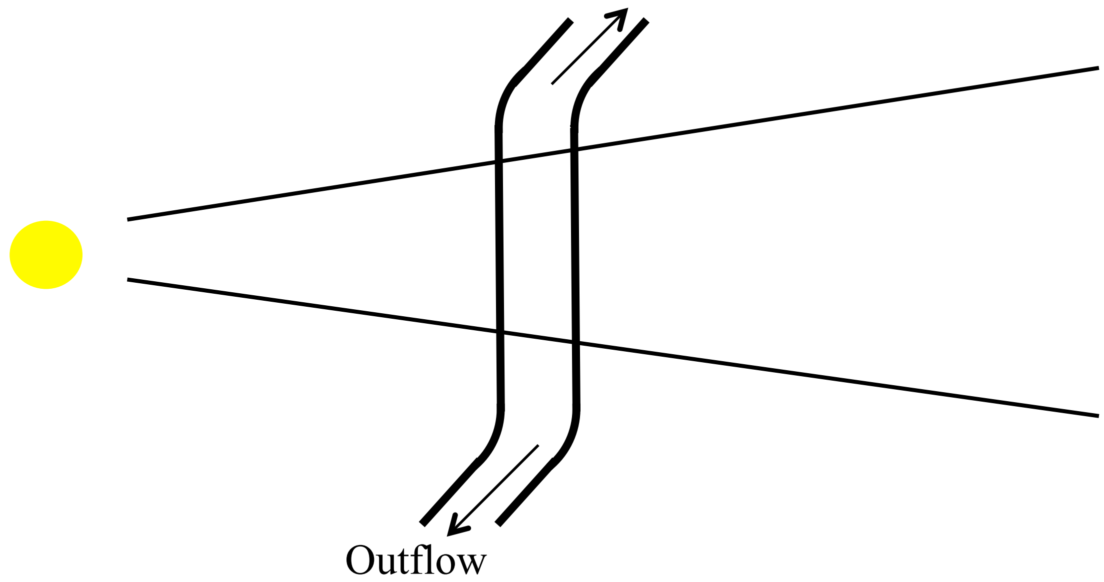
Balbus & Papaloizou (1999)

Current status & problems

Results confirmed by Bai & Stone (2014) using 1D simulations performed with Athena…



…but issues remains associated with the symmetry of the solution



Conclusions

- **MRI in shearing box simulations drives a strong wind when a vertical field is present**
- **Typical B&P type of solutions seem to coexist with MRI-driven turbulence**

- **Hall term changes the flow properties**
- **Laminar midplane region, yet strong torque**

- **Numerical artefact(s) seem(s) to affect the simulation**

  ⇒ Quantitative estimate of wind properties unreliable…

  <u>⇒ Global simulations required</u>