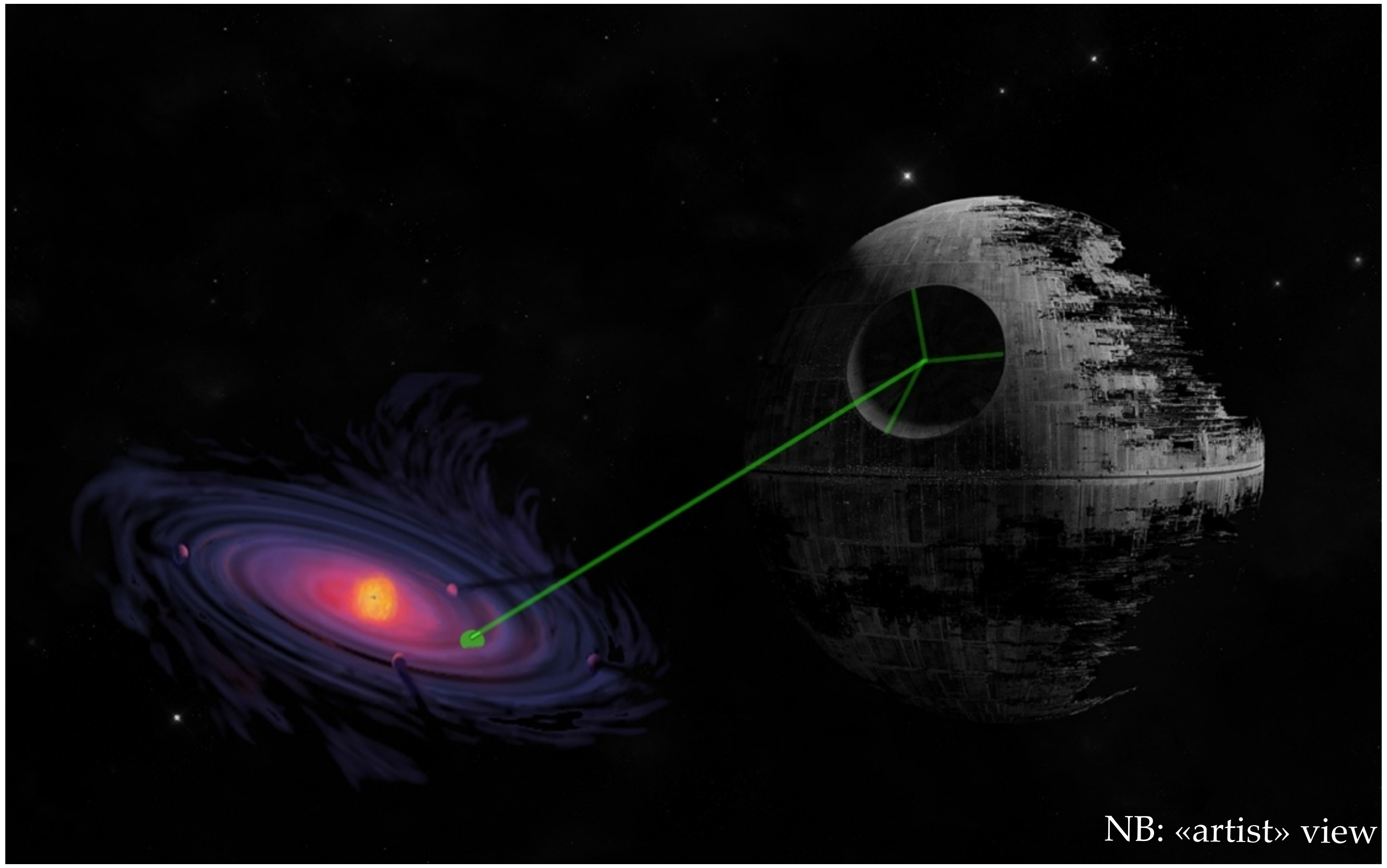
THANATOLOGY

Episode 2: Stratification Strikes Back



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with

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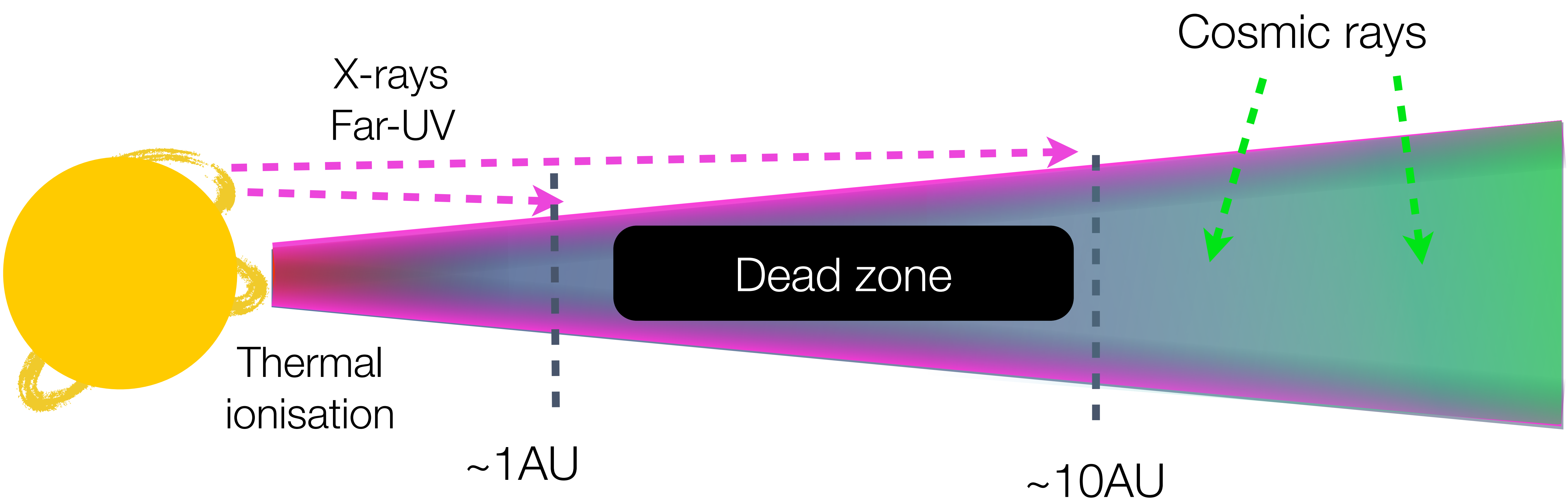
Sébastien Fromang (CEA Saclay)

Non-ideal MHD, Stability and dissipation in Protoplanetary discs

København, 4-8 August 2014

Motivation: the dead zone paradigm



- How large is the dead zone?
- What's happening inside the dead zone?

Non ideal dynamics

- Induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \boldsymbol{B} - \eta_O \boldsymbol{J} - \eta_A \boldsymbol{J}_\perp - \eta_H \boldsymbol{J} \times \boldsymbol{e_B} \right)$$

Ideal Ohmic Ambipolar Hall

where

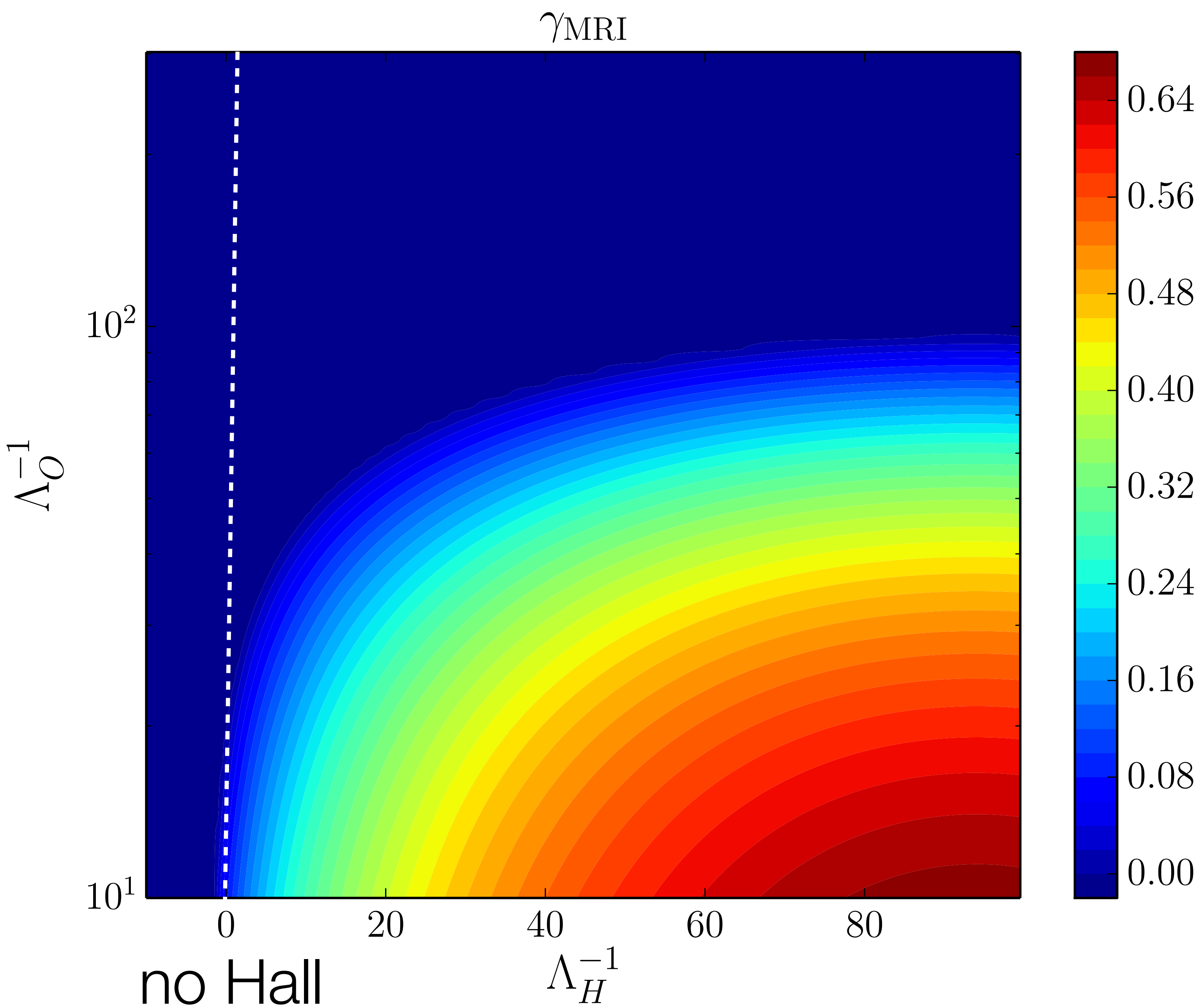
$$\boldsymbol{e_B} = \frac{\boldsymbol{B}}{|\boldsymbol{B}|}$$

$$\boldsymbol{J}_\perp = \boldsymbol{J} - \boldsymbol{J} \cdot \boldsymbol{e_B}$$

The 3 nonideal effects have to be taken into account to characterise dead zones

MRI in the Hall regime

Linear stability analysis



$$\Lambda_\eta = \frac{v_{\rm A}^2}{\eta\Omega}$$

Ohmic Elsasser number

$$\Lambda_{\rm H} = \frac{en_e B_z}{\rho c \Omega}$$

Hall Elsasser number

«Hall diffusion increases or decreases the MRI-active column density by an order of magnitude or more...»

[Wardle & Salmeron (2012)]

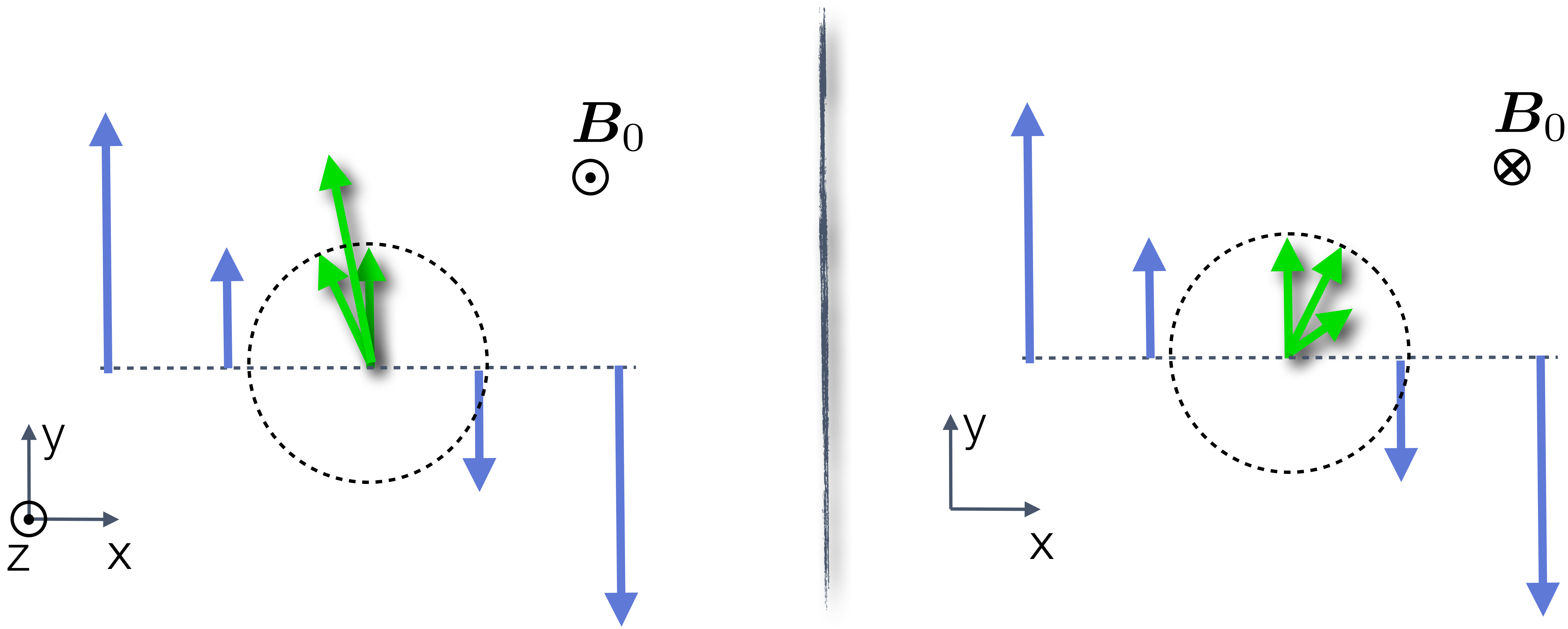
The Hall-Shear instability (HSI)

[Kunz 2008]

- Linearised induction equation with a uniform field and shear

$$\partial_t \boldsymbol{b} = (\cancel{\boldsymbol{B}_0 \cdot \boldsymbol{k}})\boldsymbol{v} + \eta_H (\boldsymbol{k} \cdot \boldsymbol{e}_{B_0}) \boldsymbol{k} \times \boldsymbol{b} - S b_x \boldsymbol{e}_y$$

- Describes a sheared whistler wave



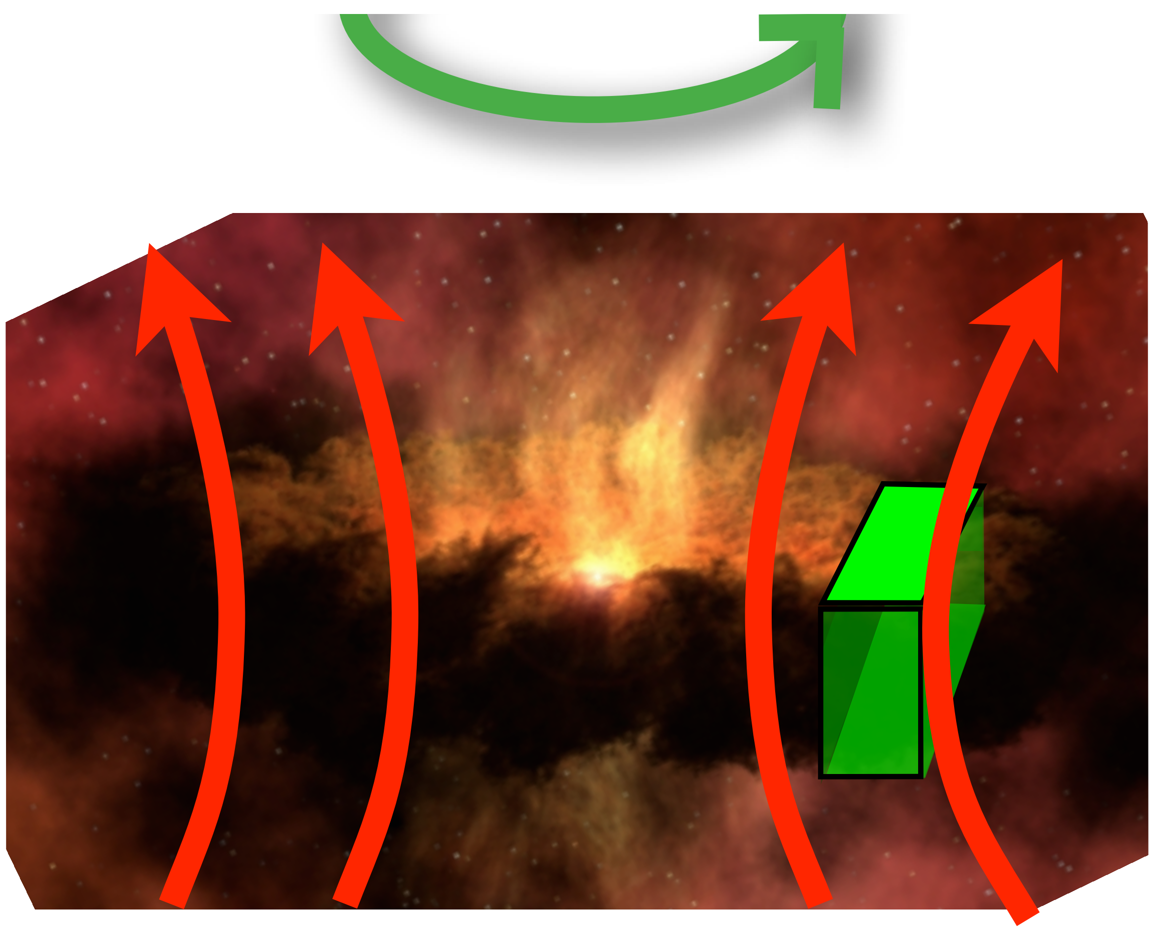
$$\gamma = \left[\eta_H k^2 \sigma (S - \eta_H k^2 \sigma)\right]^{1/2}$$

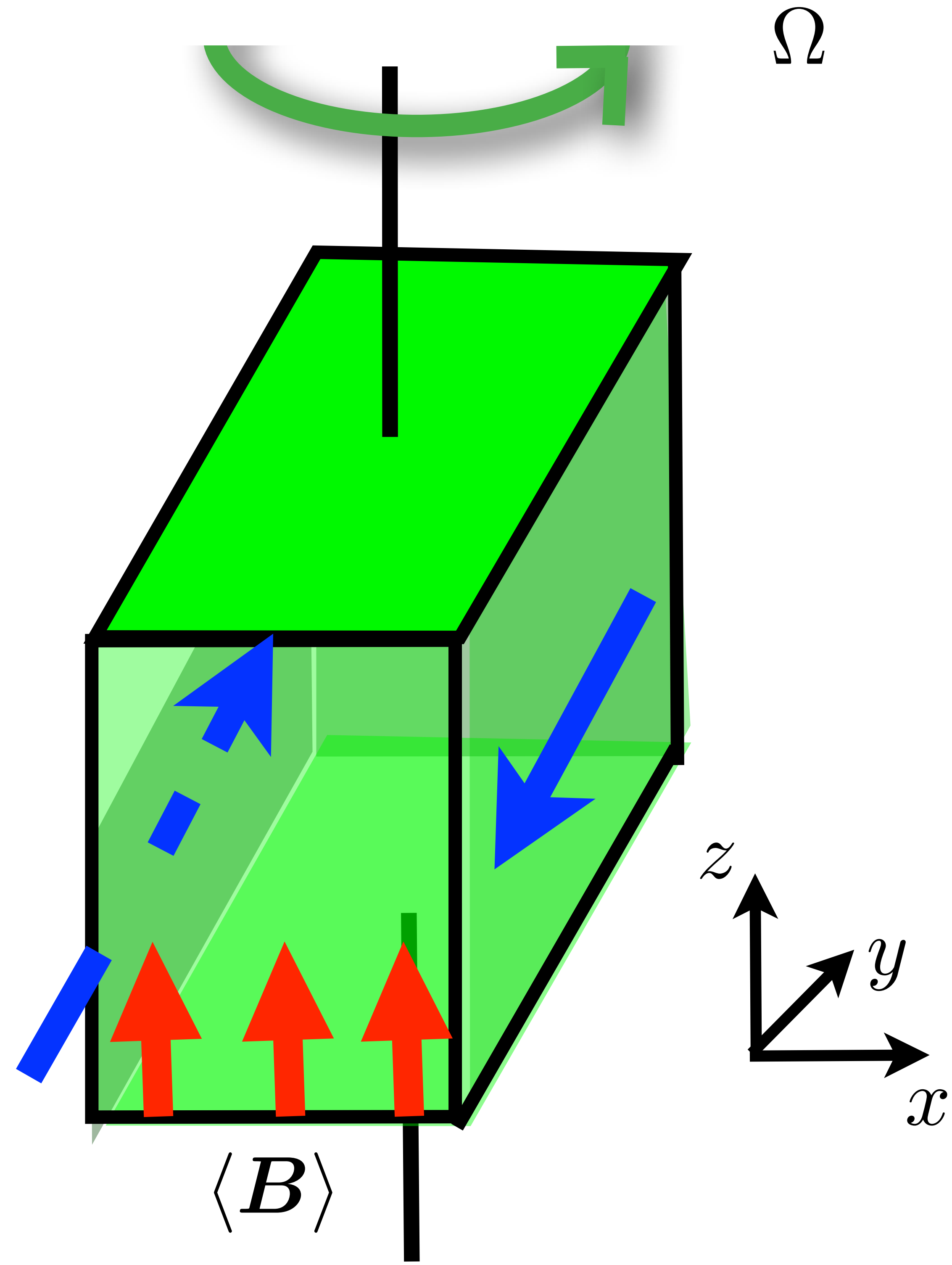
with $\sigma = \boldsymbol{e}_{B_0} \cdot \boldsymbol{e}_z$

Nonlinear dynamics of Hall-dominated dead zones

[Lesur et al. 2014, Bai 2014]

The shearing box model

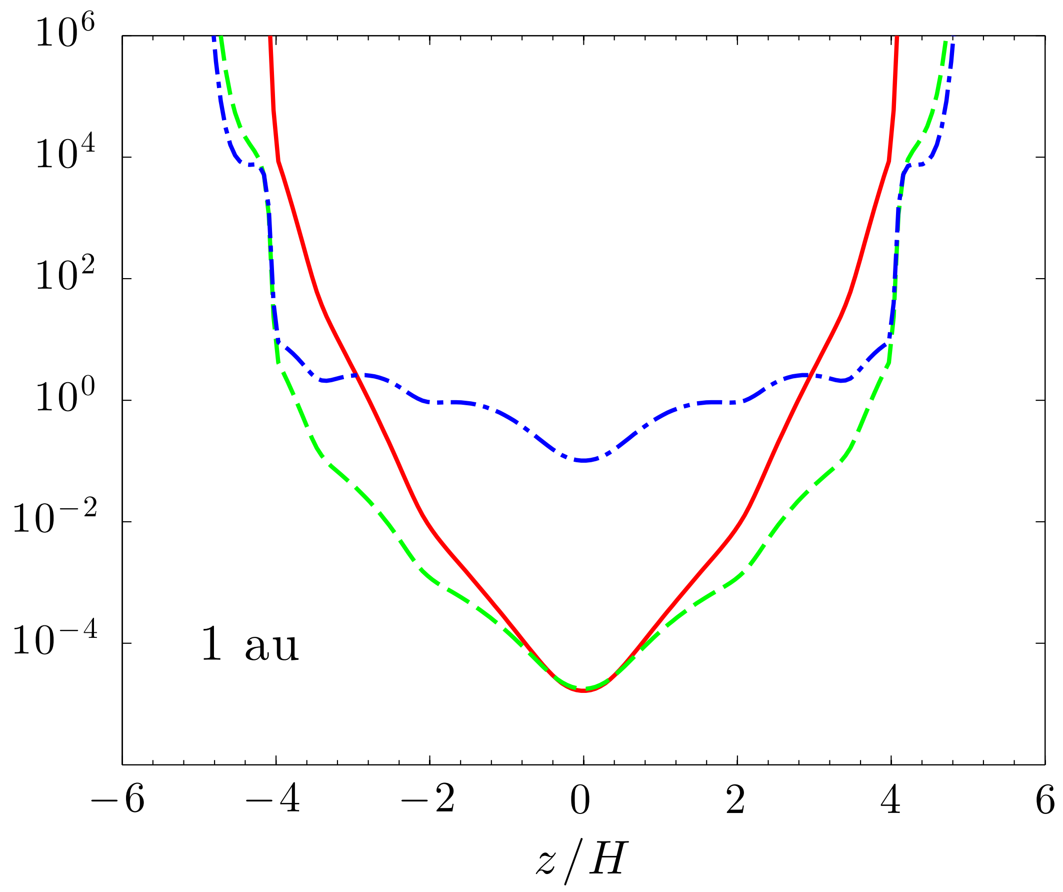


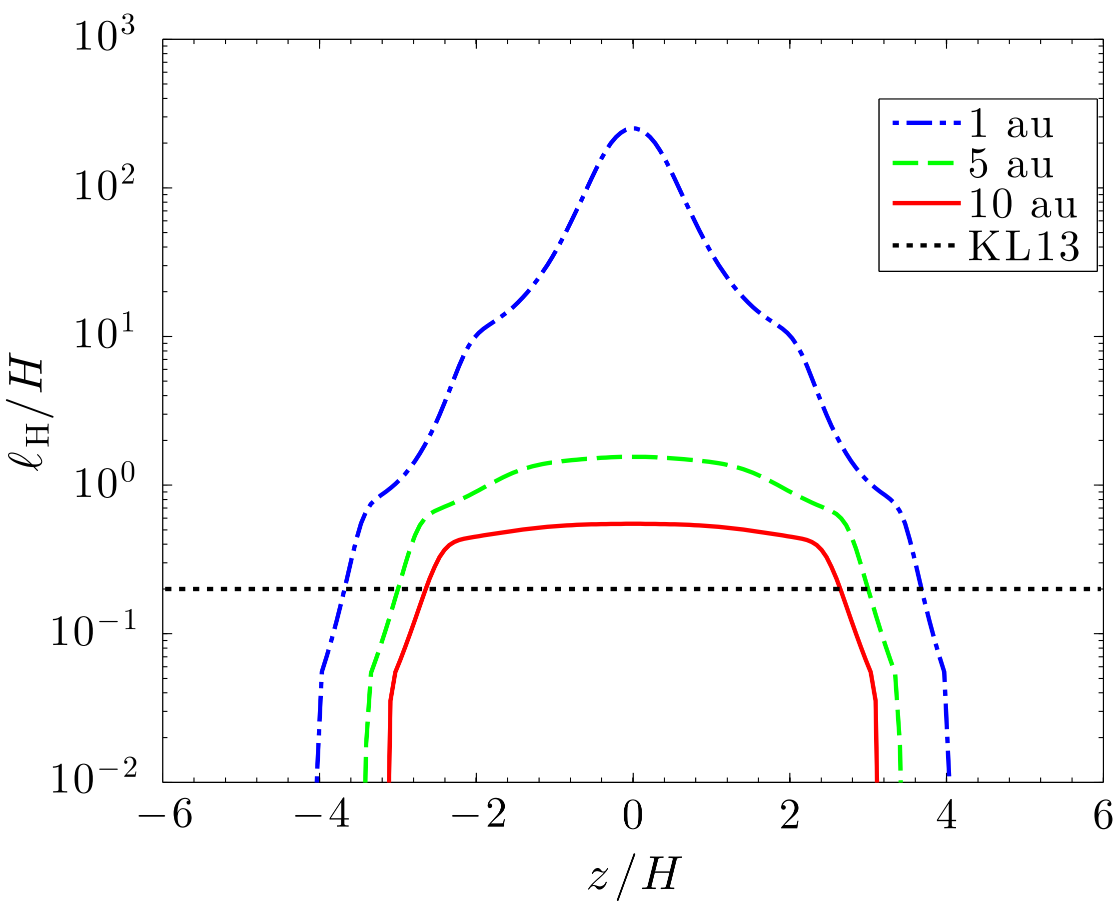


- Fully compressible (isothermal EOS)
- Vertically stratified

Diffusivity profiles

- Ionisation sources: cosmic ray, X-ray, FUV, RA decay
- Consider a simplified reaction network: metal-free and grain-free

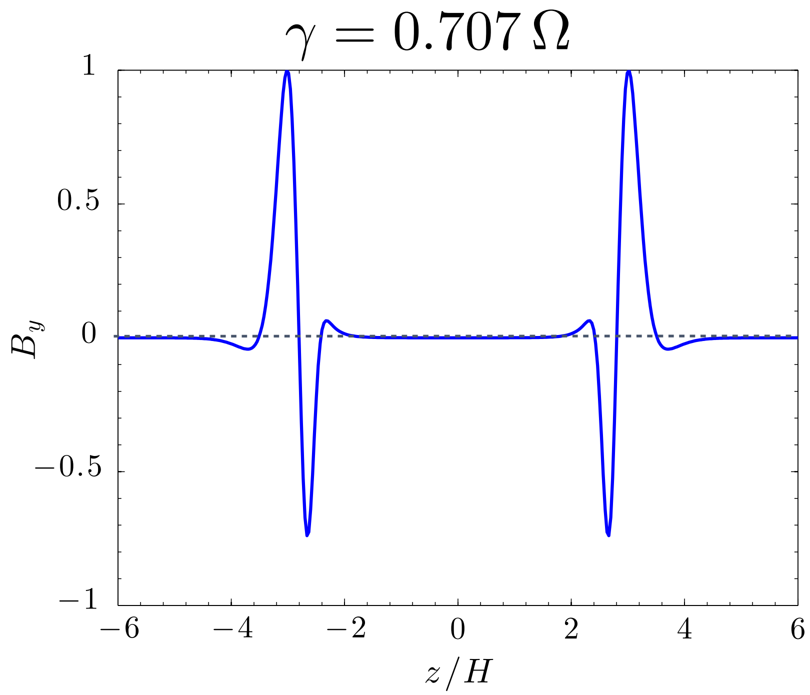


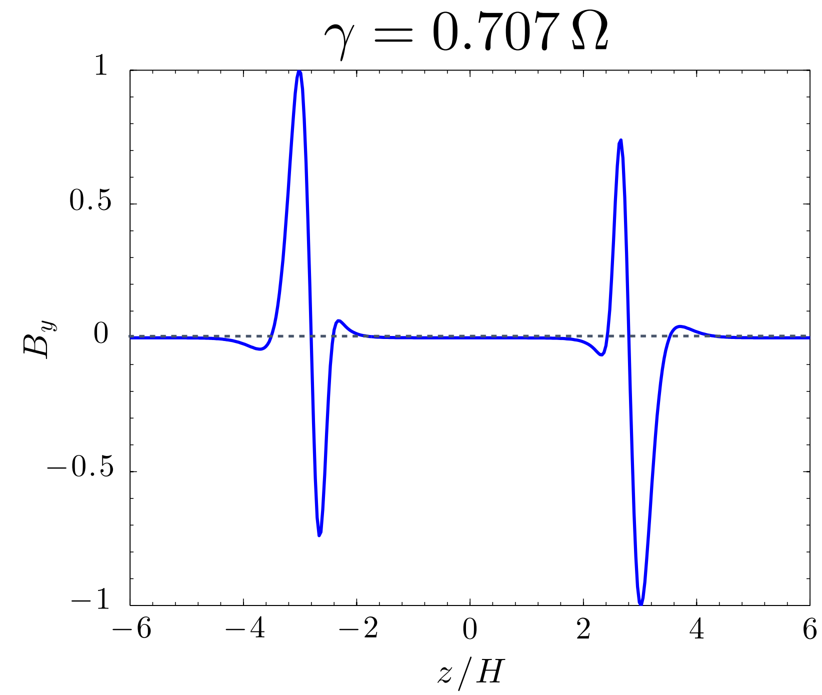


Most unstable linear eigenmodes @ 1AU

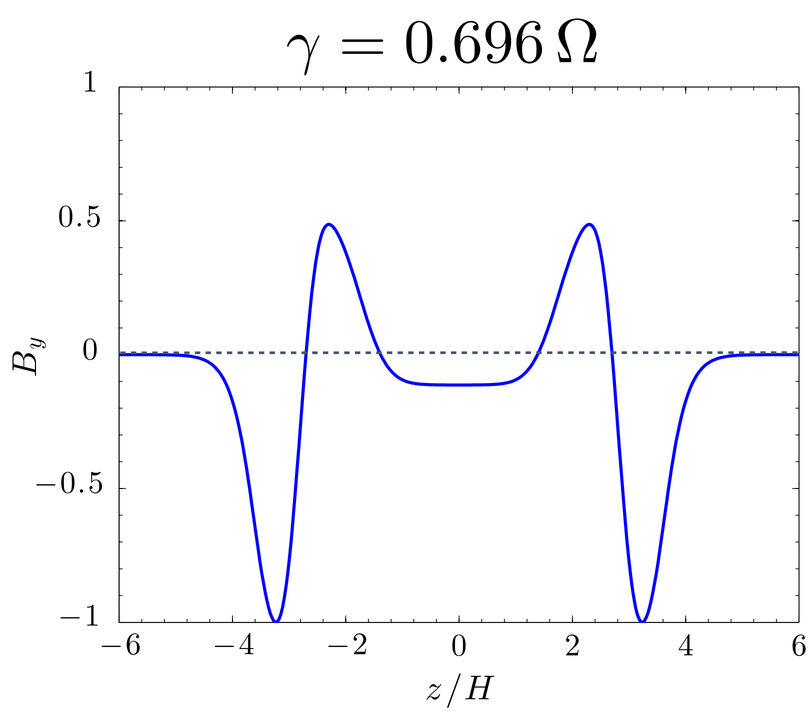
symmetric | antisymmetric

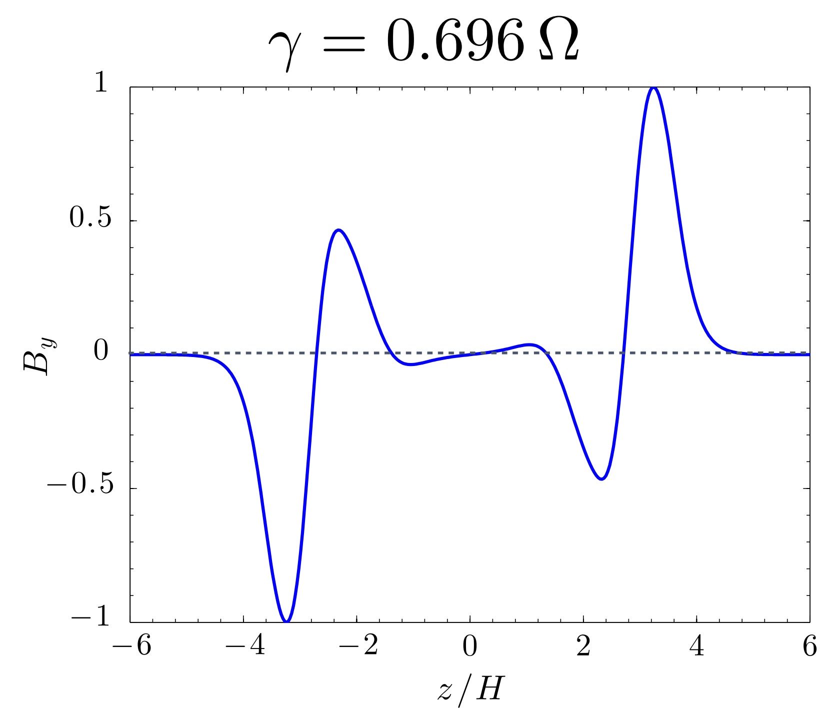
O+A





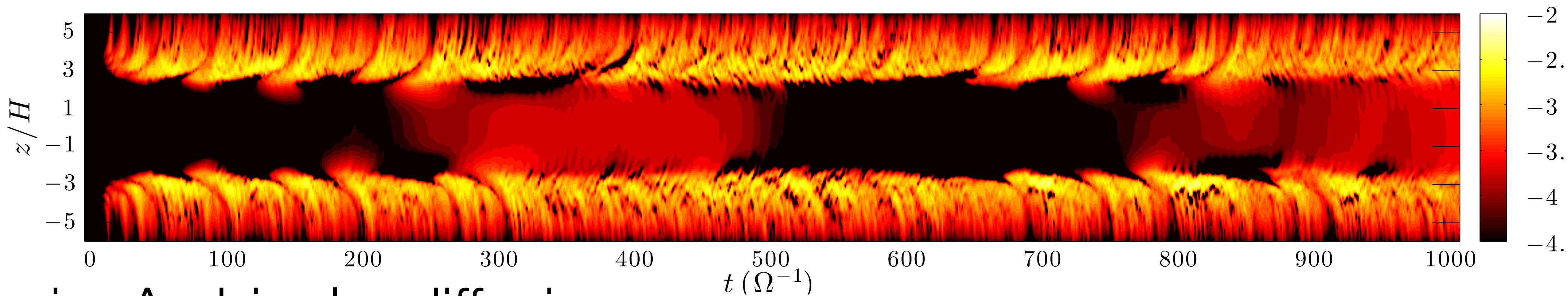
O+A+H



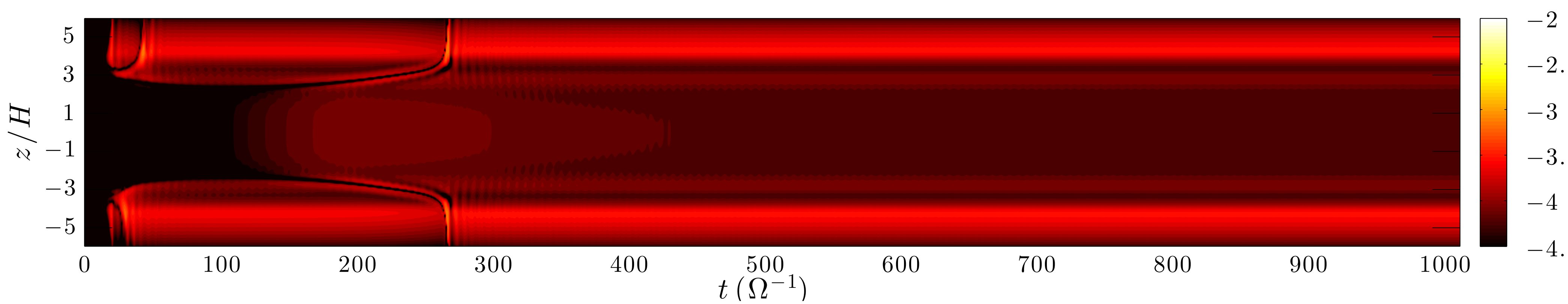


Dead zone dynamics @ 1AU

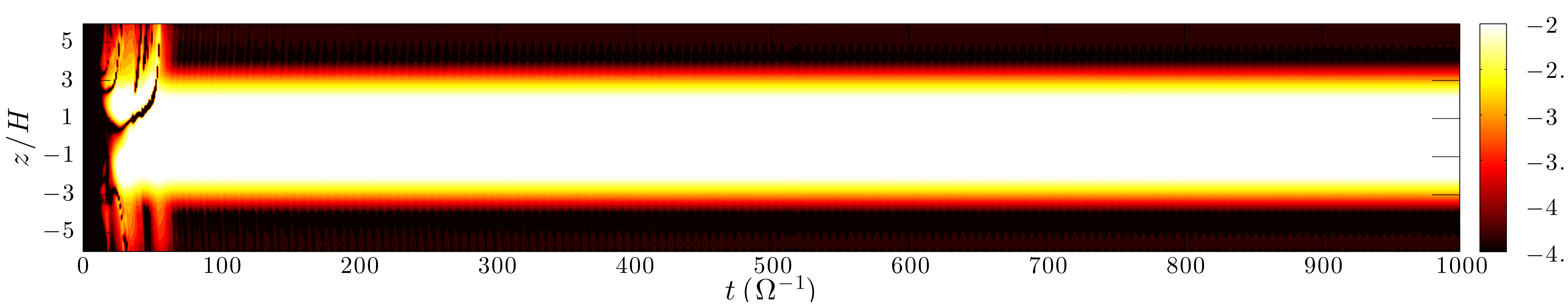
- Ohmic diffusion only



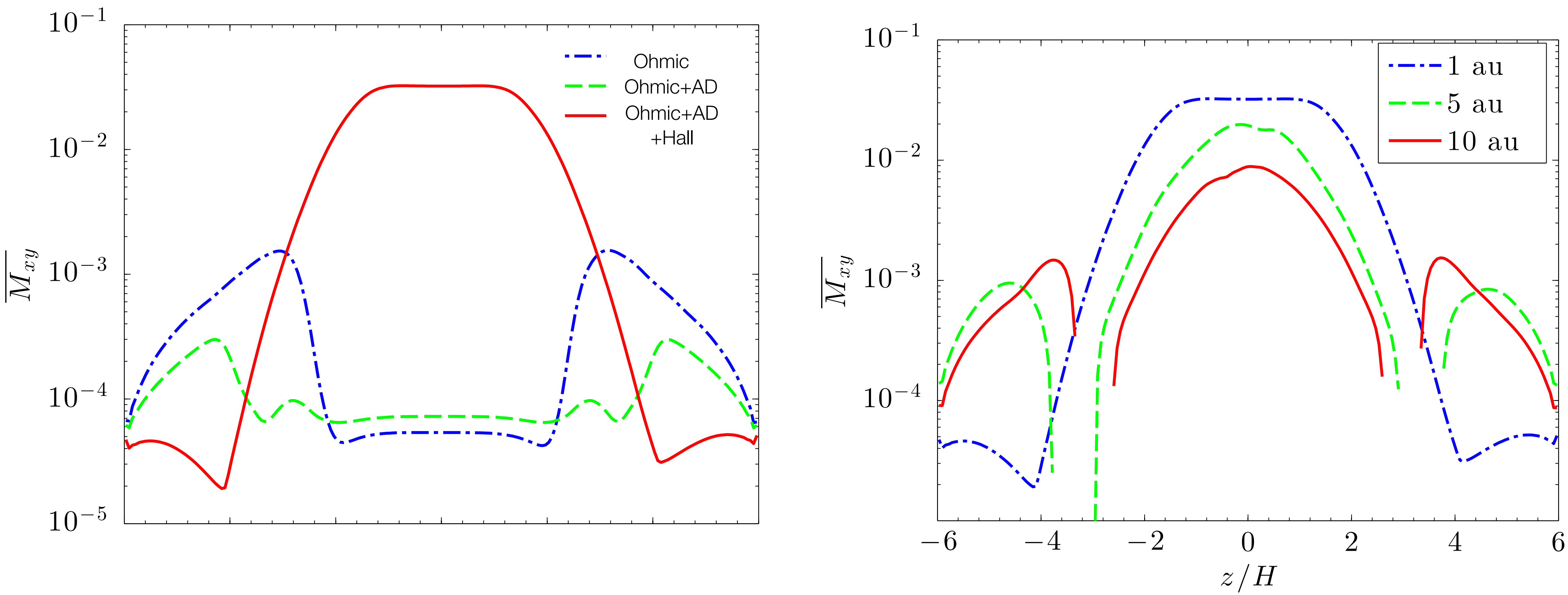
- Ohmic+Ambipolar diffusion



- Ohmic+Ambipolar+Hall

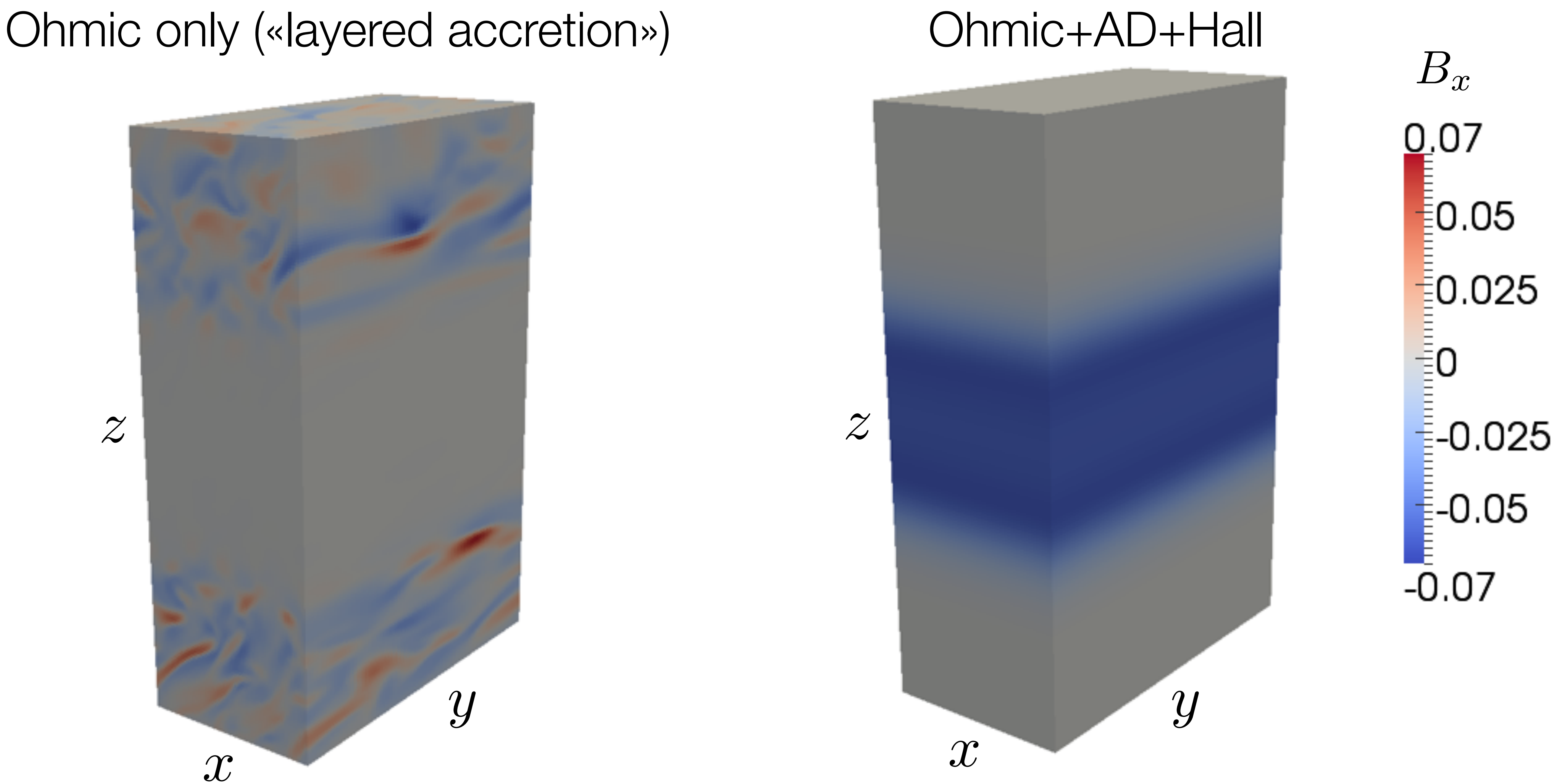


Stress profiles



For positive $\langle B_z \rangle$, the Maxwell stress in the midplane is increased by more than one order of magnitude.

Flow snapshots



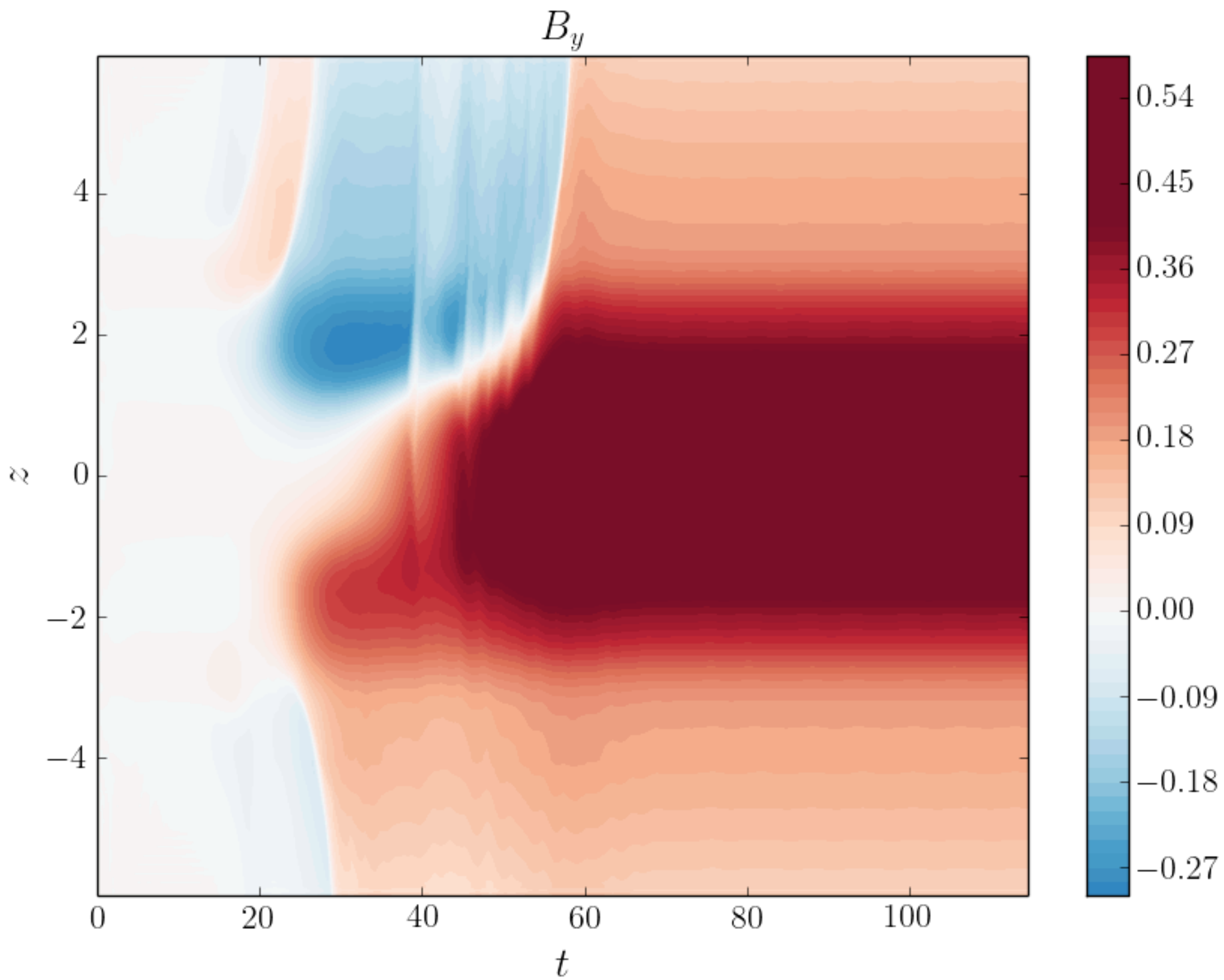
Transport not due to «turbulence»

Locality of the turbulent transport?

[Balbus & Papaloizou 1999]

Zonal structures

Stratified simulations do not exhibit zonal flow structures (see Kunz's talk)

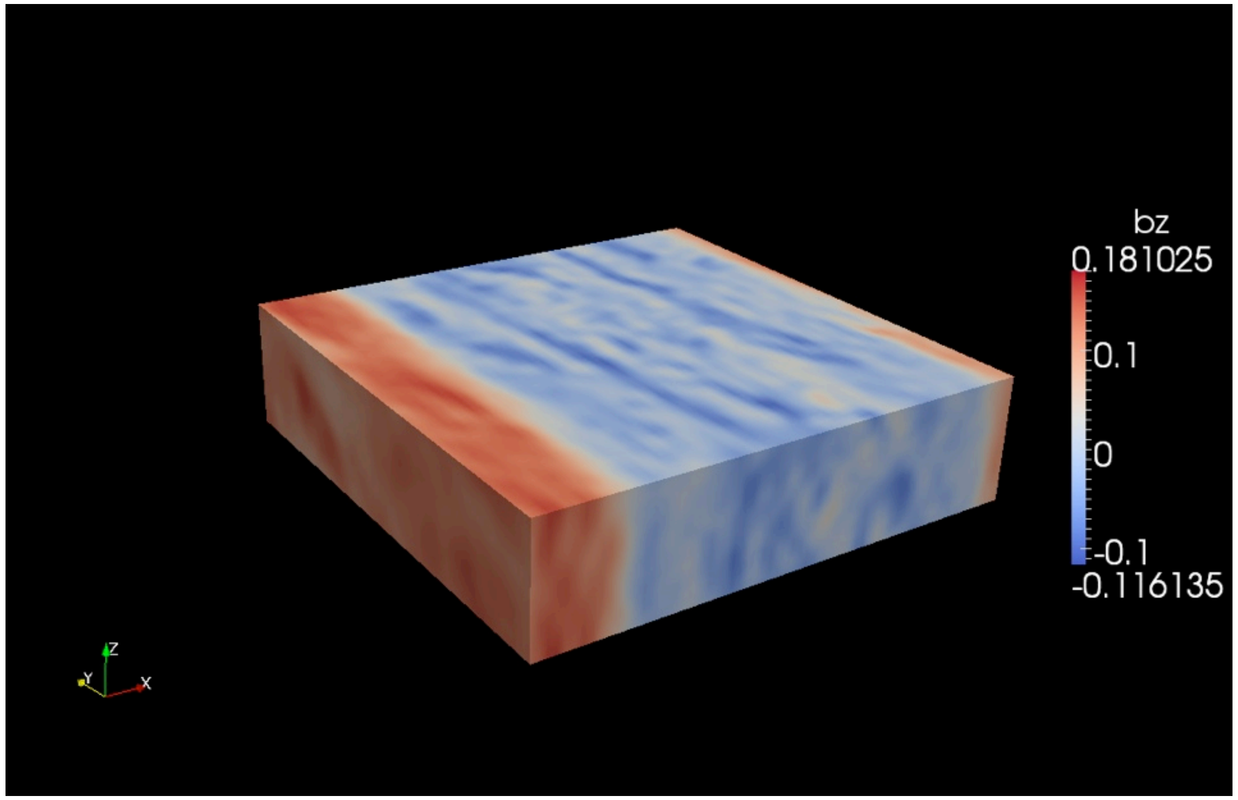


Expulsion of one B_y polarity

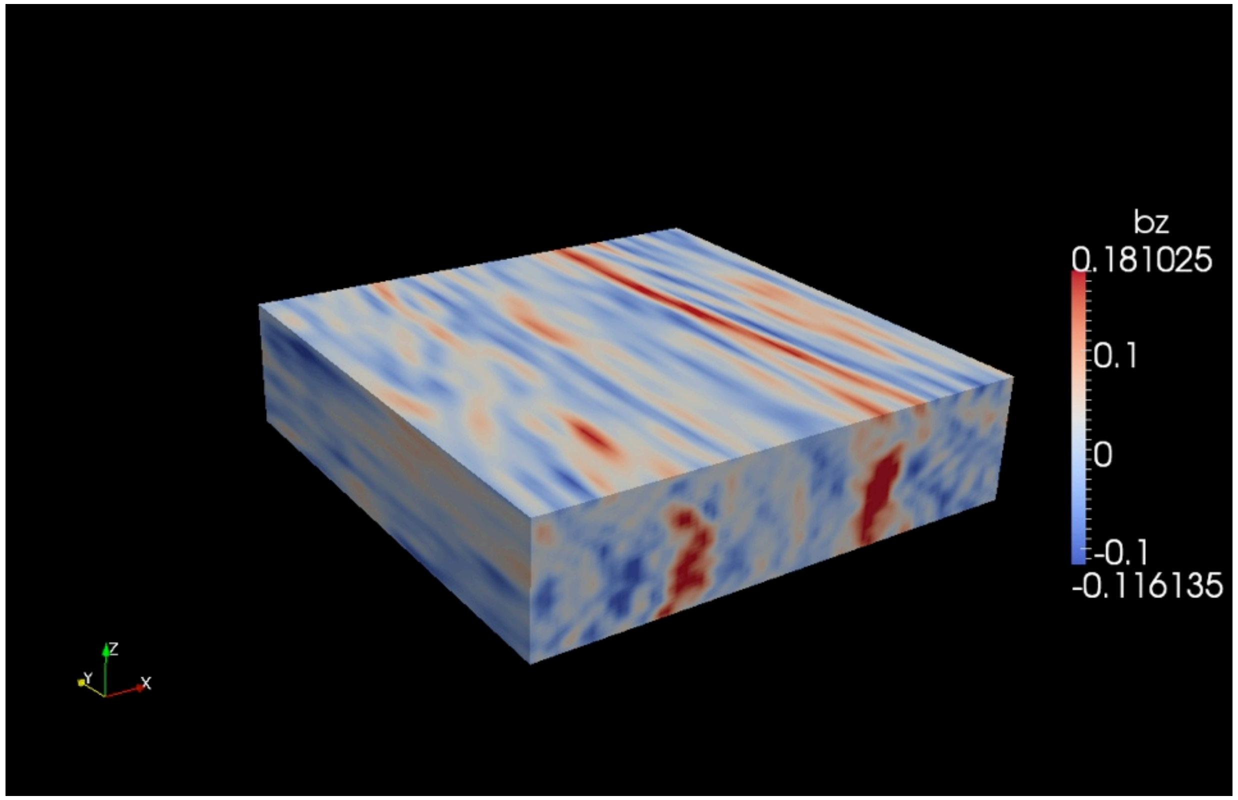
$$\rightarrow \langle B_y \rangle \sim 200 \langle B_z \rangle$$

Zonal structures (2)

Non stratified illustration



$$\langle B_y \rangle = 0$$



$$\langle B_y \rangle = 50 \langle B_z \rangle$$

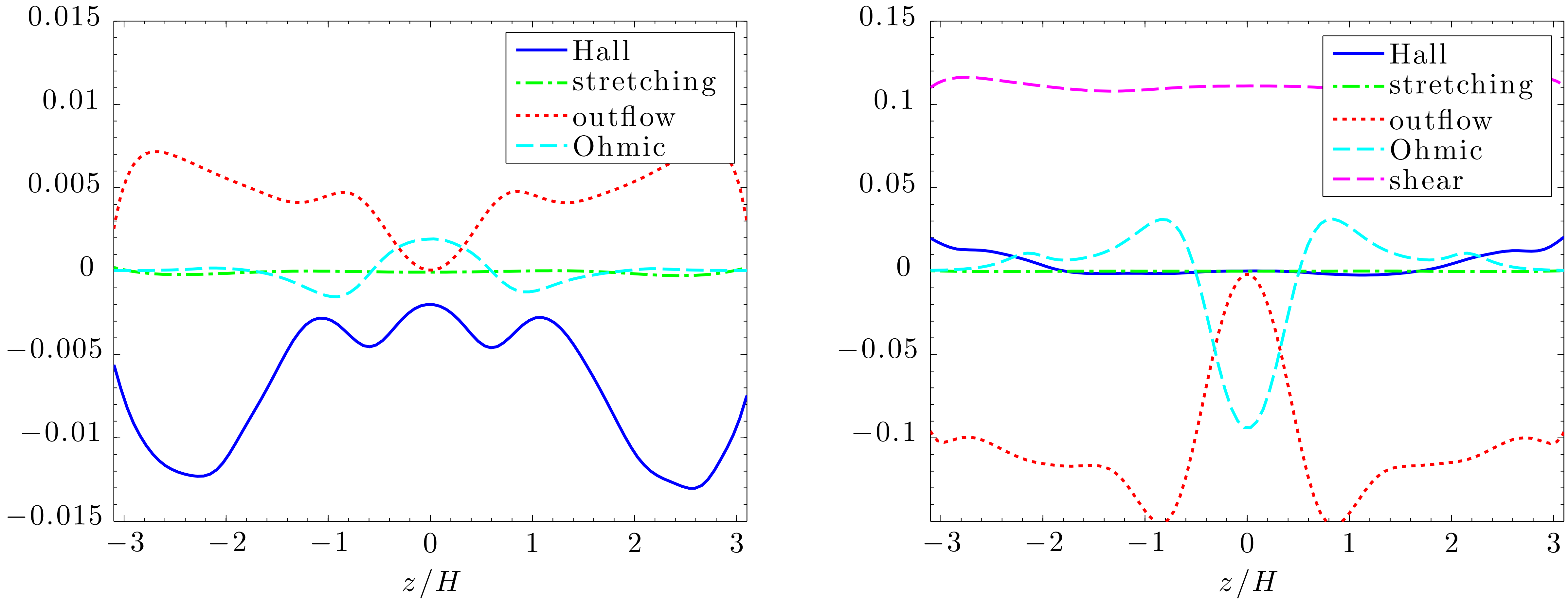
Strong toroidal fields prevents the formation of zonal flows in the disc midplane (see also Kunz & Lesur 2013)

Midplane dynamical balance

Induction equation

$$\frac{\partial\langle B_x\rangle}{\partial t} = \underbrace{\frac{\partial\langle B_x v_z\rangle}{\partial z}}_{\text{outflow}} - \underbrace{\frac{\partial\langle B_z v_x\rangle}{\partial z}}_{\text{stretching}} - \underbrace{\frac{\partial}{\partial z}\frac{c(\langle J_x B_z\rangle - \langle J_z B_x\rangle)}{\sqrt{4\pi} e n_e}}_{\text{Hall}} + \underbrace{\frac{\partial}{\partial z}\eta\frac{\partial\langle B_x\rangle}{\partial z}}_{\text{Ohmic}},$$

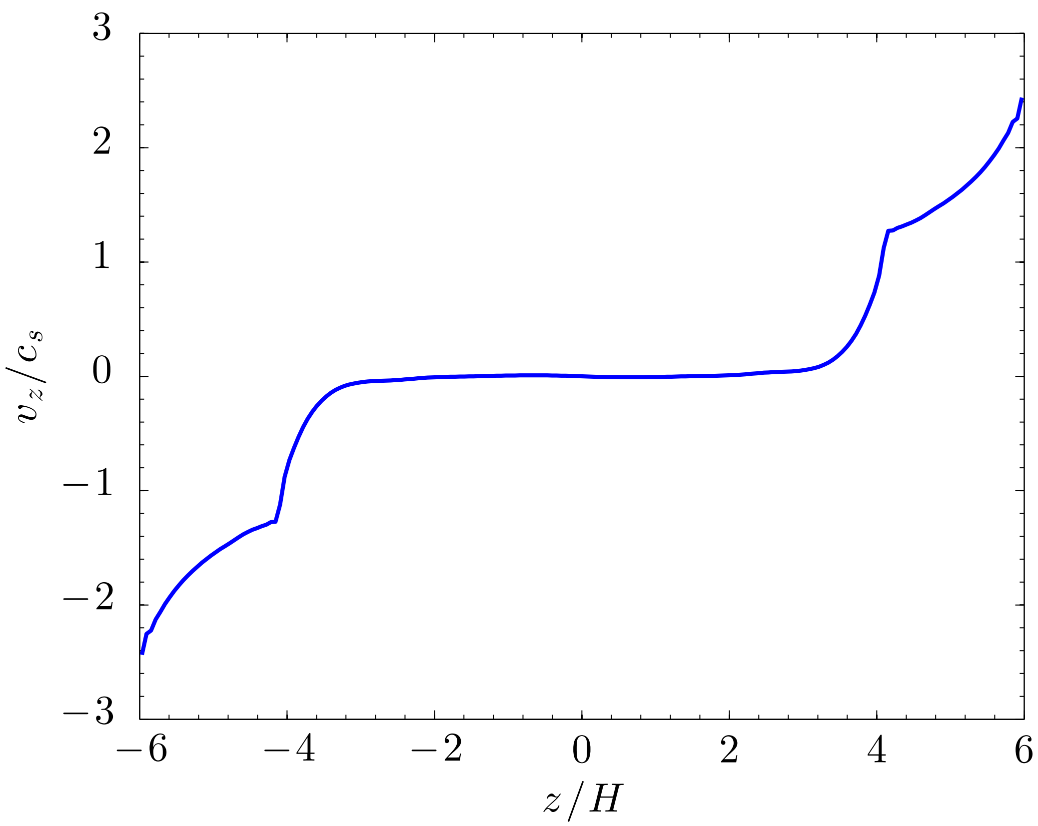
$$\frac{\partial\langle B_y\rangle}{\partial t} = \underbrace{\frac{\partial\langle B_y v_z\rangle}{\partial z}}_{\text{outflow}} - \underbrace{\frac{\partial\langle B_z v_y\rangle}{\partial z}}_{\text{stretching}} - \underbrace{\frac{\partial}{\partial z}\frac{c(\langle J_y B_z\rangle - \langle J_z B_y\rangle)}{\sqrt{4\pi} e n_e}}_{\text{Hall}} + \underbrace{\frac{\partial}{\partial z}\eta\frac{\partial\langle B_y\rangle}{\partial z}}_{\text{Ohmic}} - \underbrace{q\Omega\langle B_x\rangle}_{\text{shear}}$$

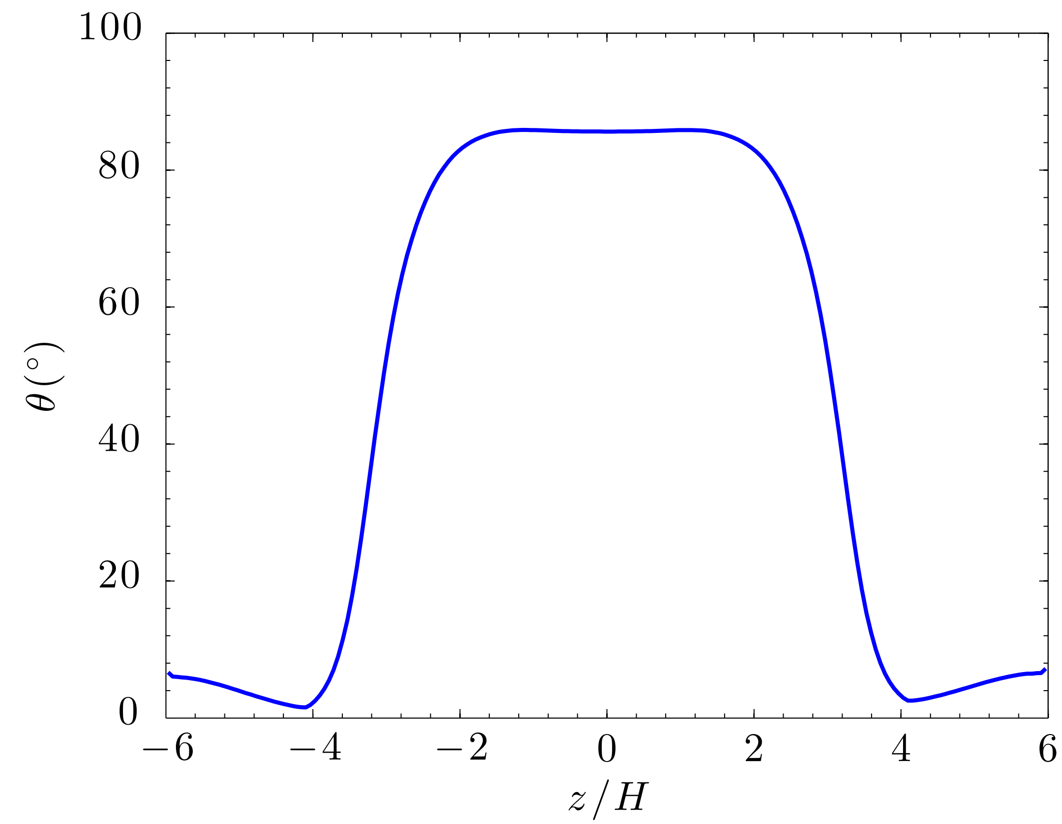


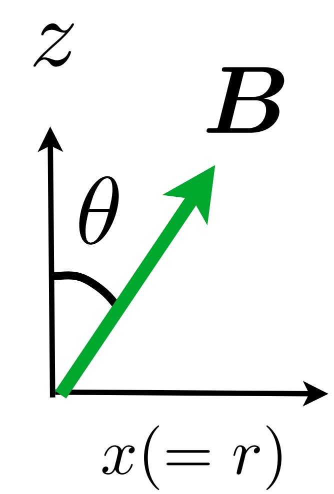
Midplane balance = HSI stabilised by outflow + diffusion

Outflows

- Outflows are found in every stratified simulations with a mean field [Suzuki & Inutsuka 2009, Moll 2012, Ogilvie 2012, Lesur+2013, Fromang+2013, Bai & Stone 2013, Simon+2013,...]





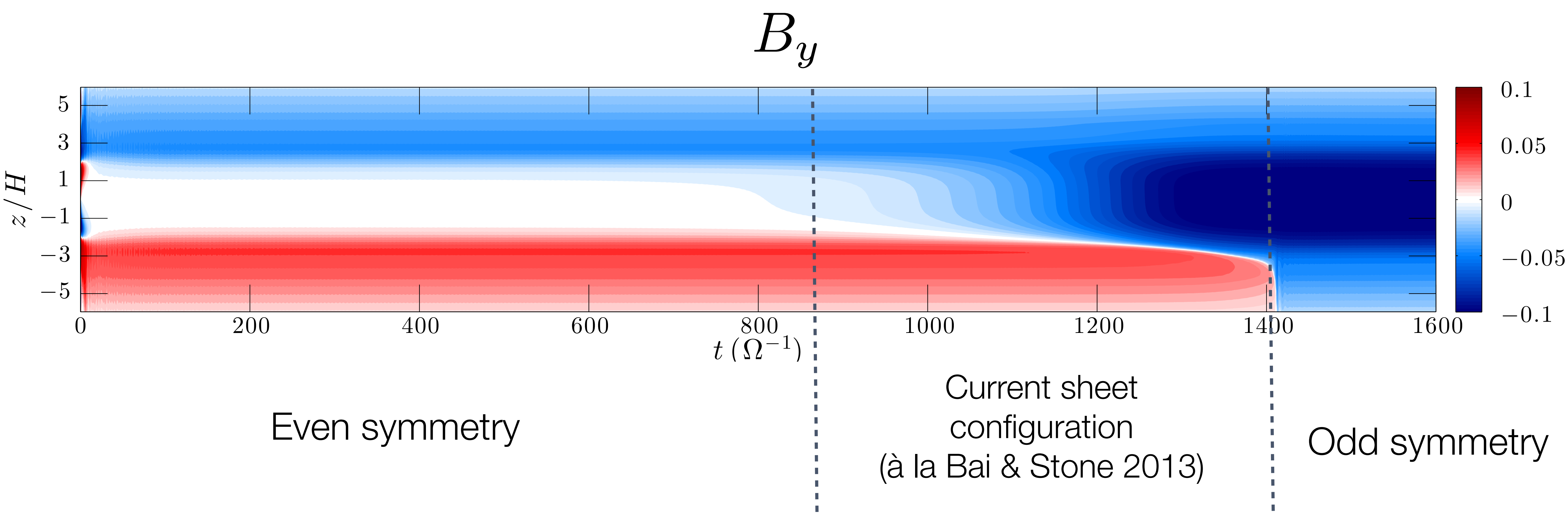


Fully nonideal simulations produce magnetised outflows *but:*

- Blandford & Payne critical angle criterion not satisfied: $\theta < 30^\circ$
- Wrong symmetry! ($\theta(z) > 0$)

Outflows

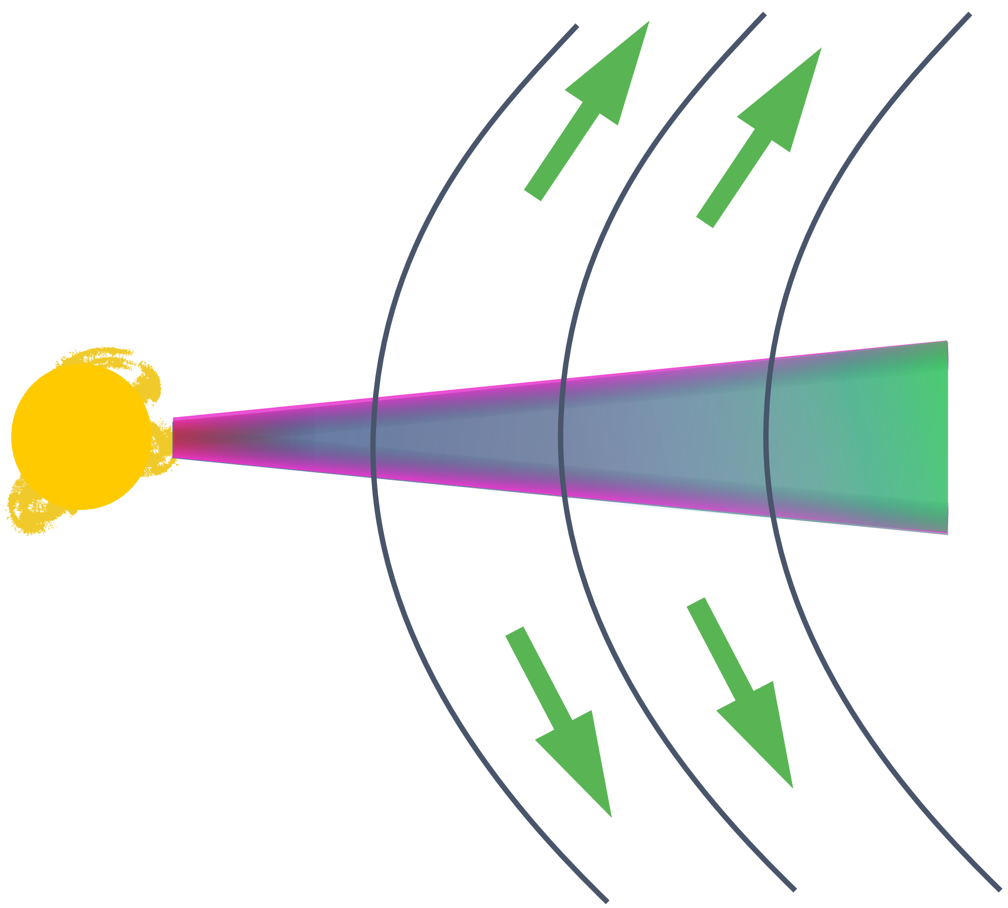
- Symmetry problem is *not* specific to the Hall-dominated regime



Outflows: a problem of symmetry

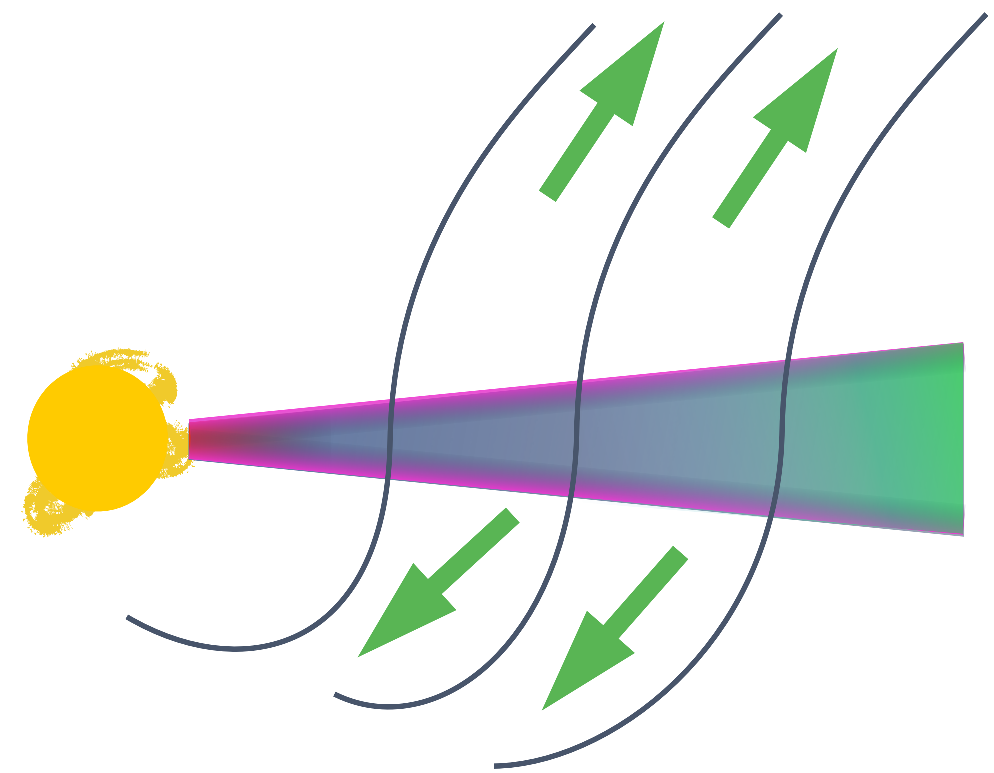
- The shearing box model has (too) many symmetries
- Symmetry $R \to -R$ is likely to create spurious solutions

«even symmetry»



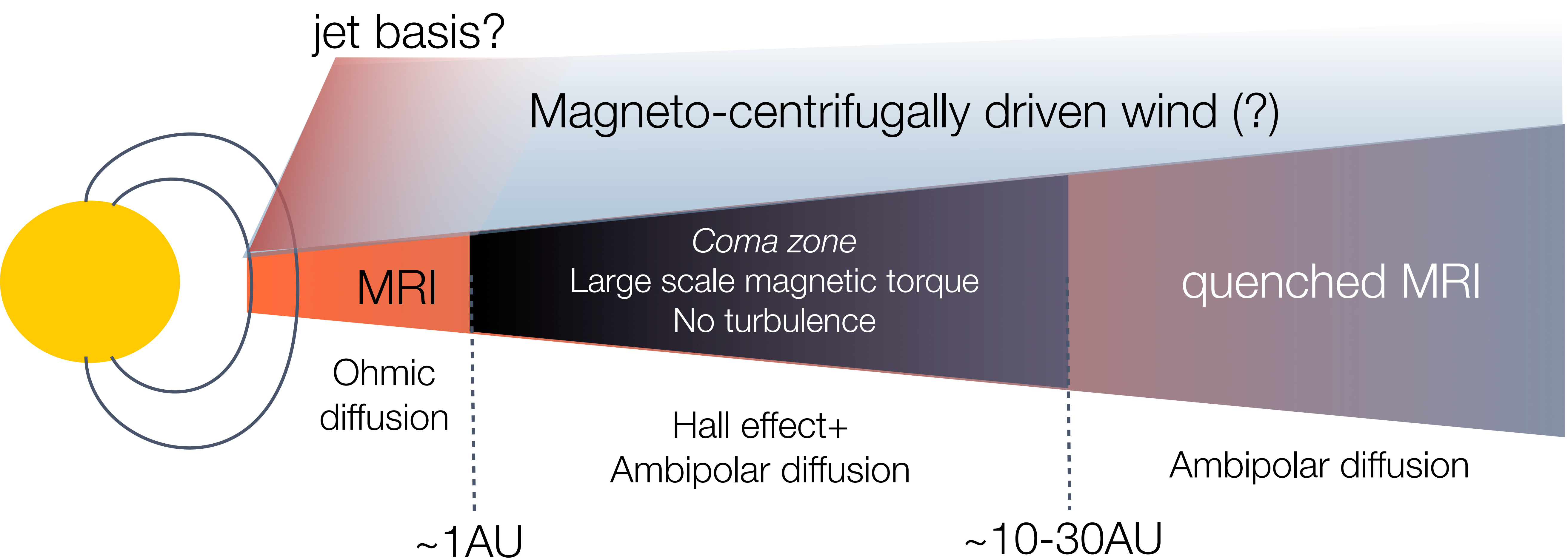
Favoured in global setups
Unstable in shearing boxes
Angular momentum *is* extracted

«odd symmetry»



Favoured in shearing boxes
No angular momentum extracted from the disc

Conclusions



The future: global simulations

- Break the degeneracy $R \to -R$
- Locality of the large scale magnetic torque
- Outflow properties (mass loss rate)
- Field polarity sensitivity?