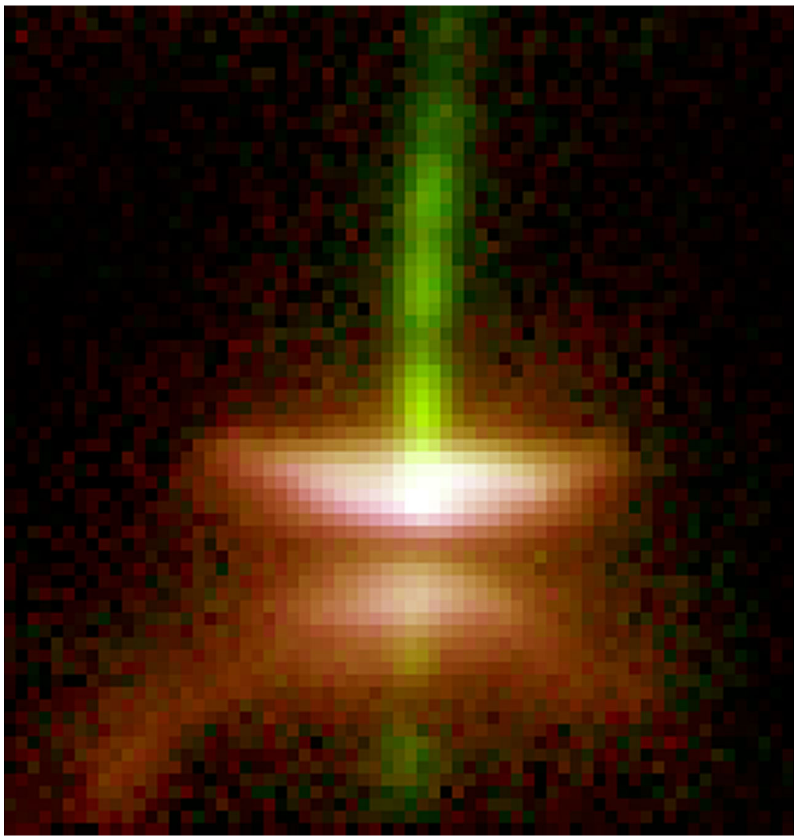
Non-ideal MHD in PPDs, NBI, Copenhagen, 08/05/2014

Gas Dynamics in Protoplanetary Disks

with Ohmic, Hall and Ambipolar Diffusion



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Bai, 2014a, ApJ, in press
Bai, 2014b, ApJ, submitted
Bai & Stone, 2014, ApJ, submitted

Outline

- Introduction/methodology
- Inner disk: wind solutions
  - The aligned vs anti-aligned cases
  - Issues with symmetry, grain abundance
  - Stability of the wind solutions
- Outer disk: layered accretion
  - Expectation of the MRI with AD+Hall
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  - B flux concentration and zonal flow
- Role of grains on the gas conductivity
- Summary and outlook

Non-ideal MHD effects: scalings

Induction equation (grain-free):

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times \left[\frac{4\pi\eta}{c} \boldsymbol{J} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{e n_e} - \frac{(\boldsymbol{J} \times \boldsymbol{B}) \times \boldsymbol{B}}{c \gamma \rho \rho_i} \right]$$

inductive **Ohmic** **Hall** **AD**

$$\sim \frac{n}{n_e} \qquad \sim \frac{n}{n_e} \frac{B}{\rho} \qquad \sim \frac{n}{n_e} \frac{B^2}{\rho^2}$$

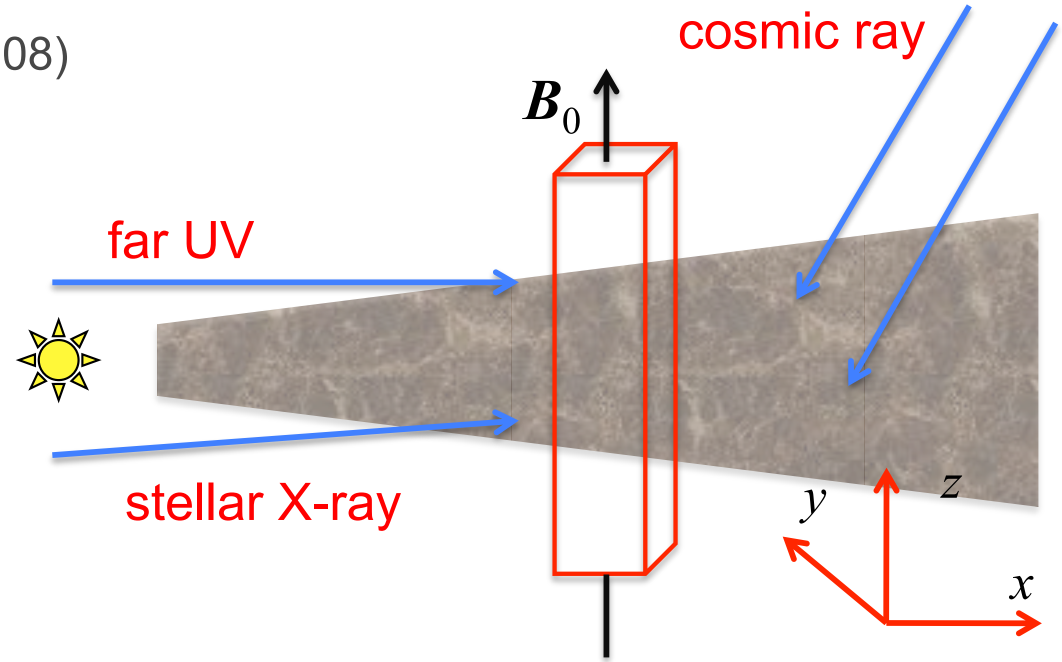
midplane region of the inner disk ↓ inner disk surface and outer disk

Intermediate heights in the inner disk

Midplane in the outer disk (up to ~60 AU)

Shearing-box simulations

- Athena MHD code (Stone et al., 2008)
- Chemistry based on complex network w/wo grains.
- MMSN disk, CR, X-ray and FUV ionizations, 0.1μm grain abundance 10^{-4}.
- Magnetic diffusivities from interpolating lookup table



β_0=$P_{gas,mid}/P_{mag,net}$

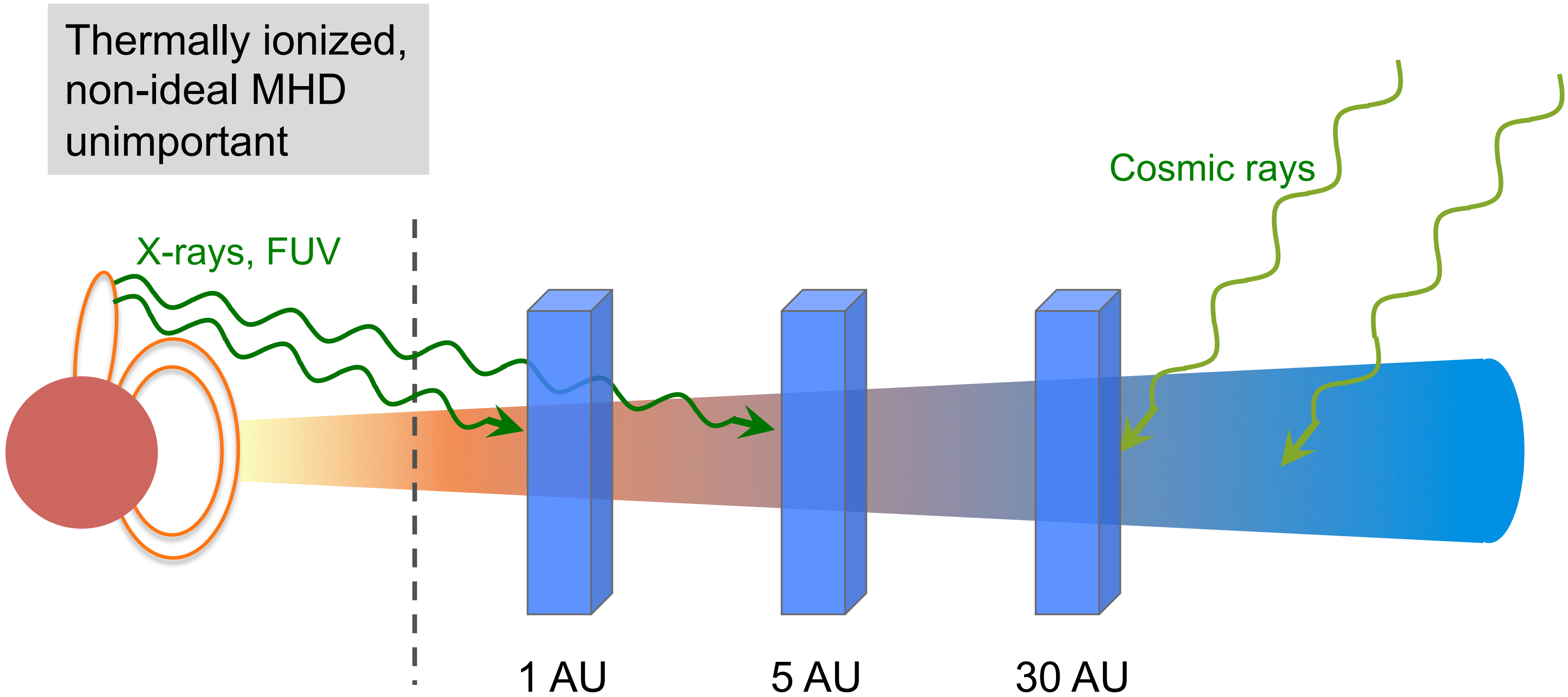
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}^T \boldsymbol{v} + \mathrm{T}) = \rho \left[2\boldsymbol{v} \times \boldsymbol{\Omega} + 3\Omega^2 x \hat{\boldsymbol{x}} - \Omega^2 z \hat{\boldsymbol{z}} \right]$$

EoS is isothermal

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times [\eta_O \boldsymbol{J} + \eta_H (\boldsymbol{J} \times \hat{\boldsymbol{B}}) + \eta_A \boldsymbol{J}_\perp]$$

The plan



Scan through disk radii: relative importance of the 3 non-ideal effects vary.

Perform simulations with different β_0 (default=10^5) and polarities.

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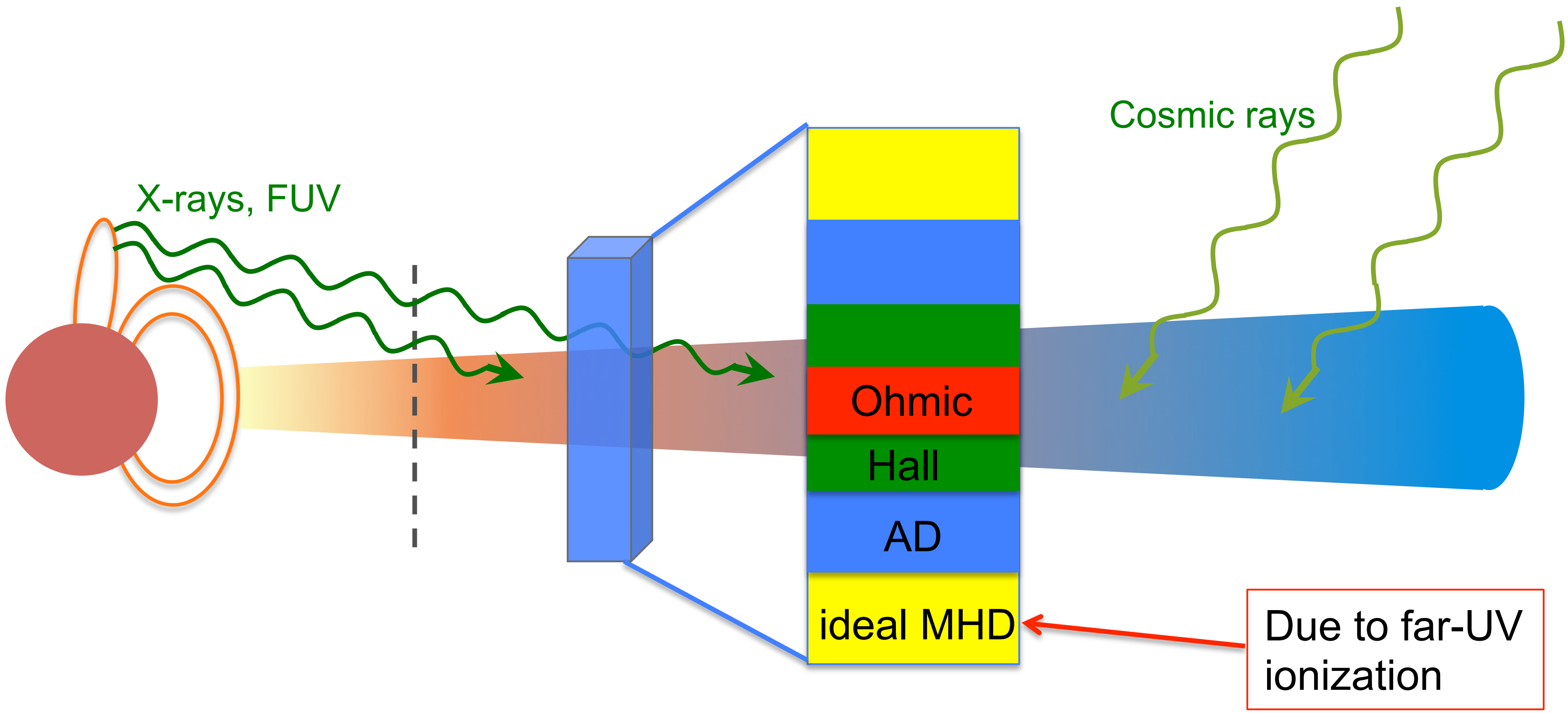
Inner disk: R<10AU



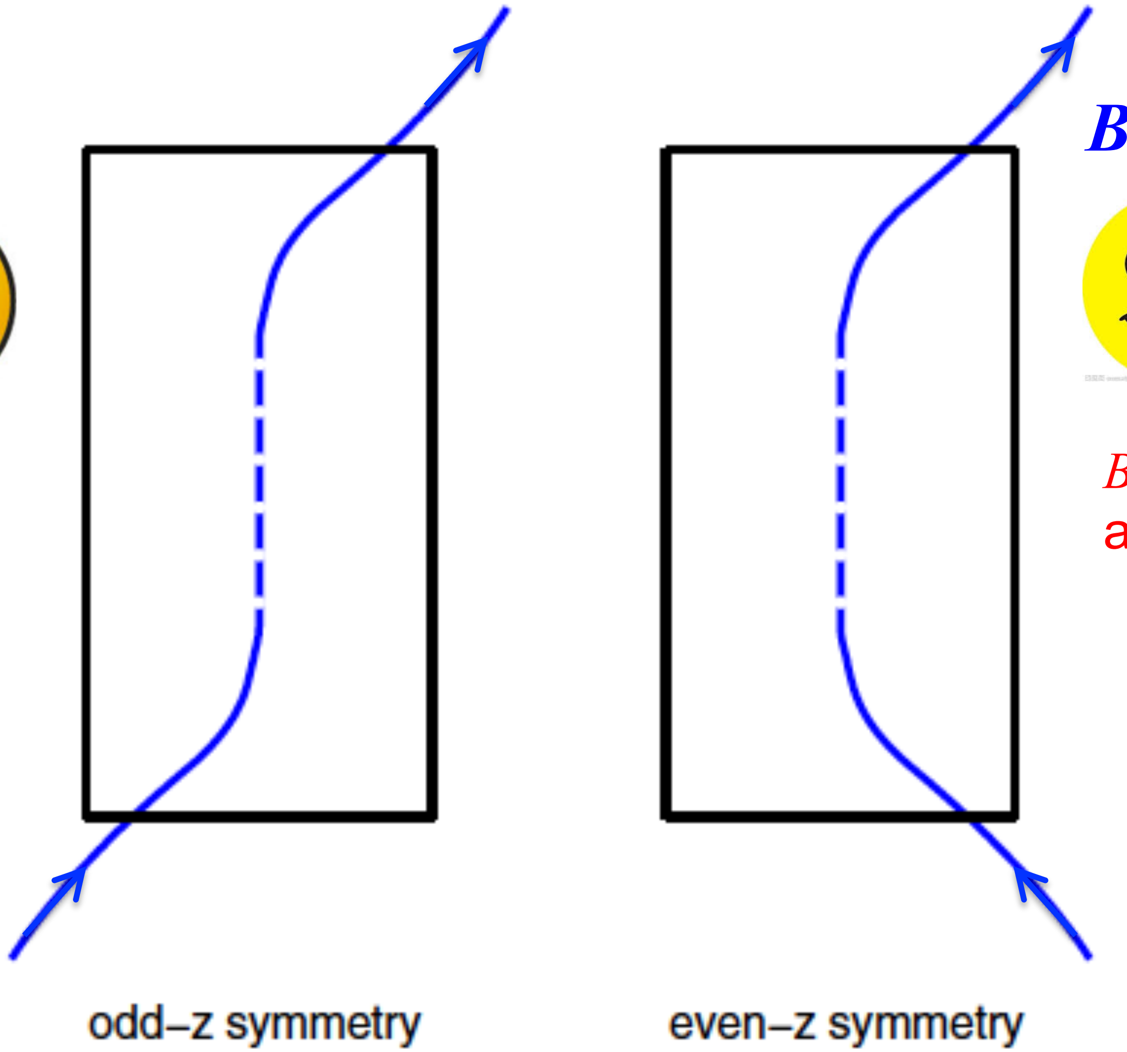
All three non-ideal MHD effects are important.

Symmetry of wind solutions

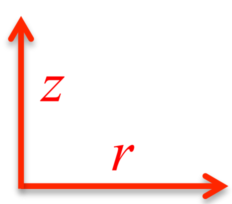
Always launches an outflow in the presence of net vertical B field.

Horizontal B field must flip in order to achieve a physical wind geometry.

B_r, B_ϕ don't change sign

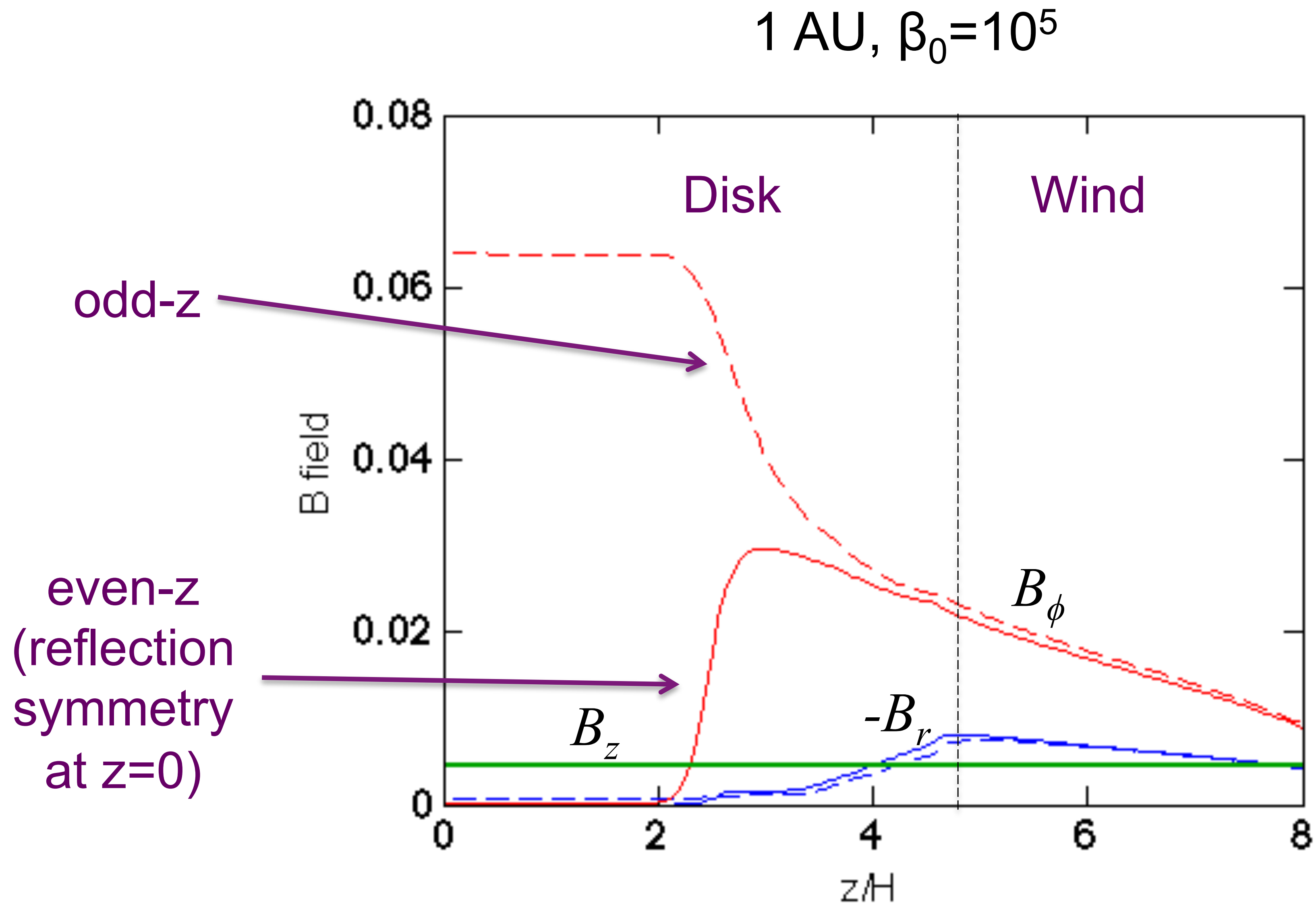


B_r, B_ϕ change sign across the disk

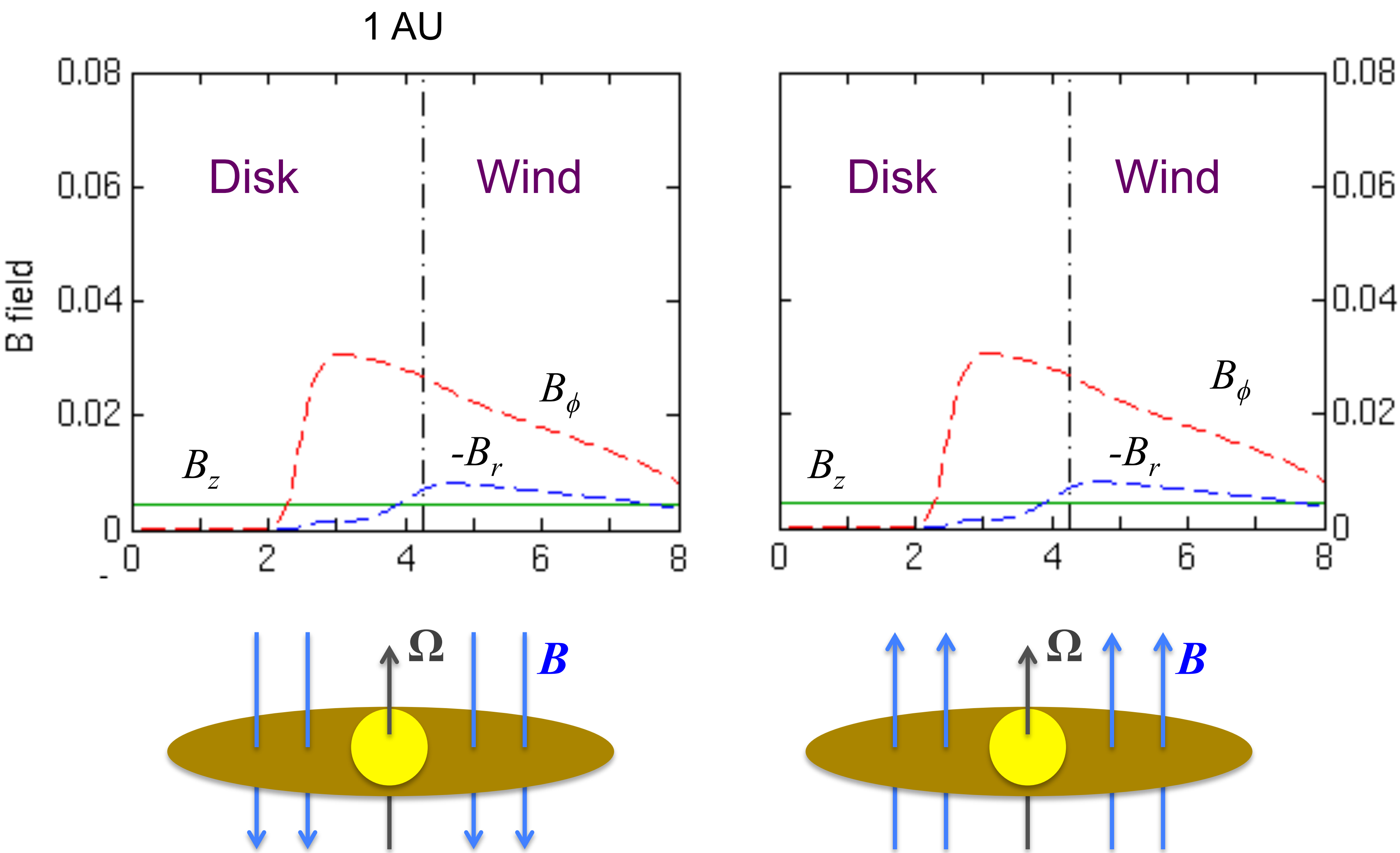


Hall-free wind solution

(Bai & Stone, 2013b)



Adding the Hall effect (reflection symmetry at z=0)



(Bai, 2014a)

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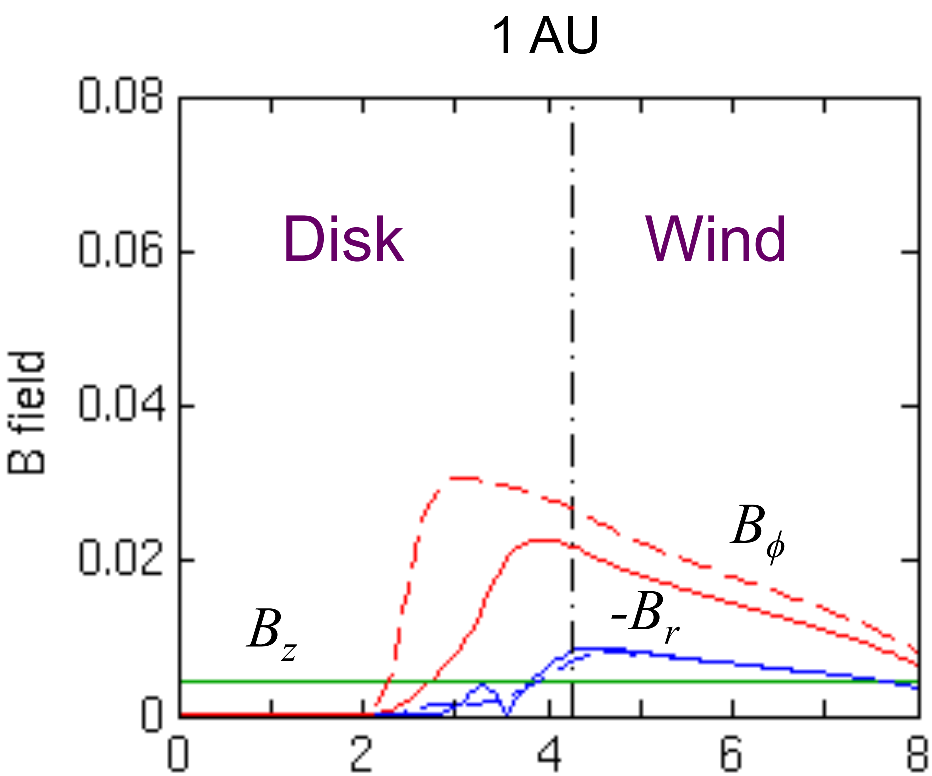
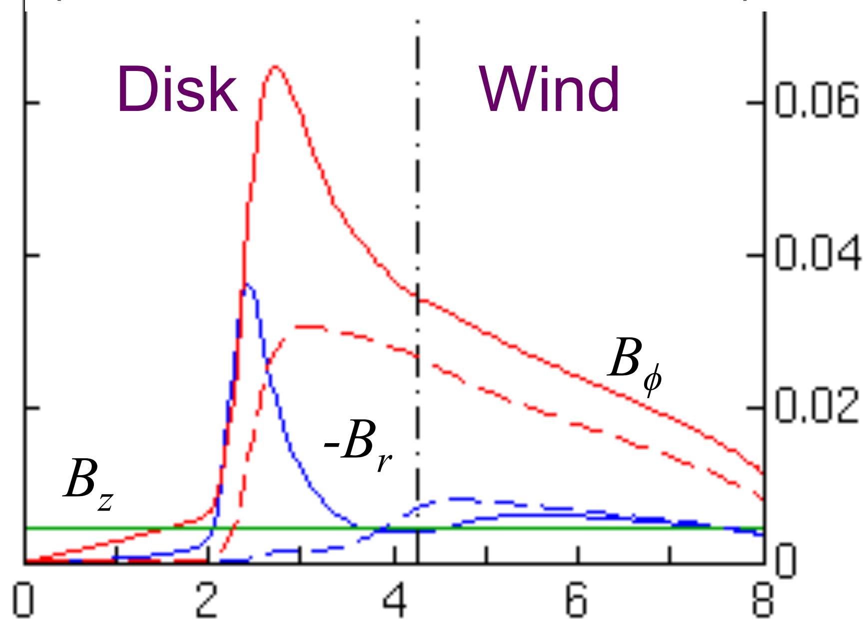
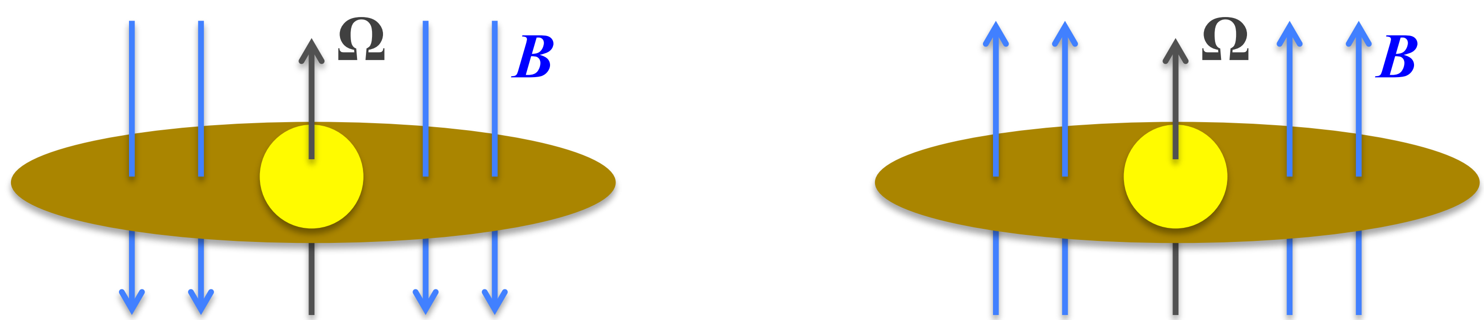


Amplification of horizontal field due to the Hall-shear instability

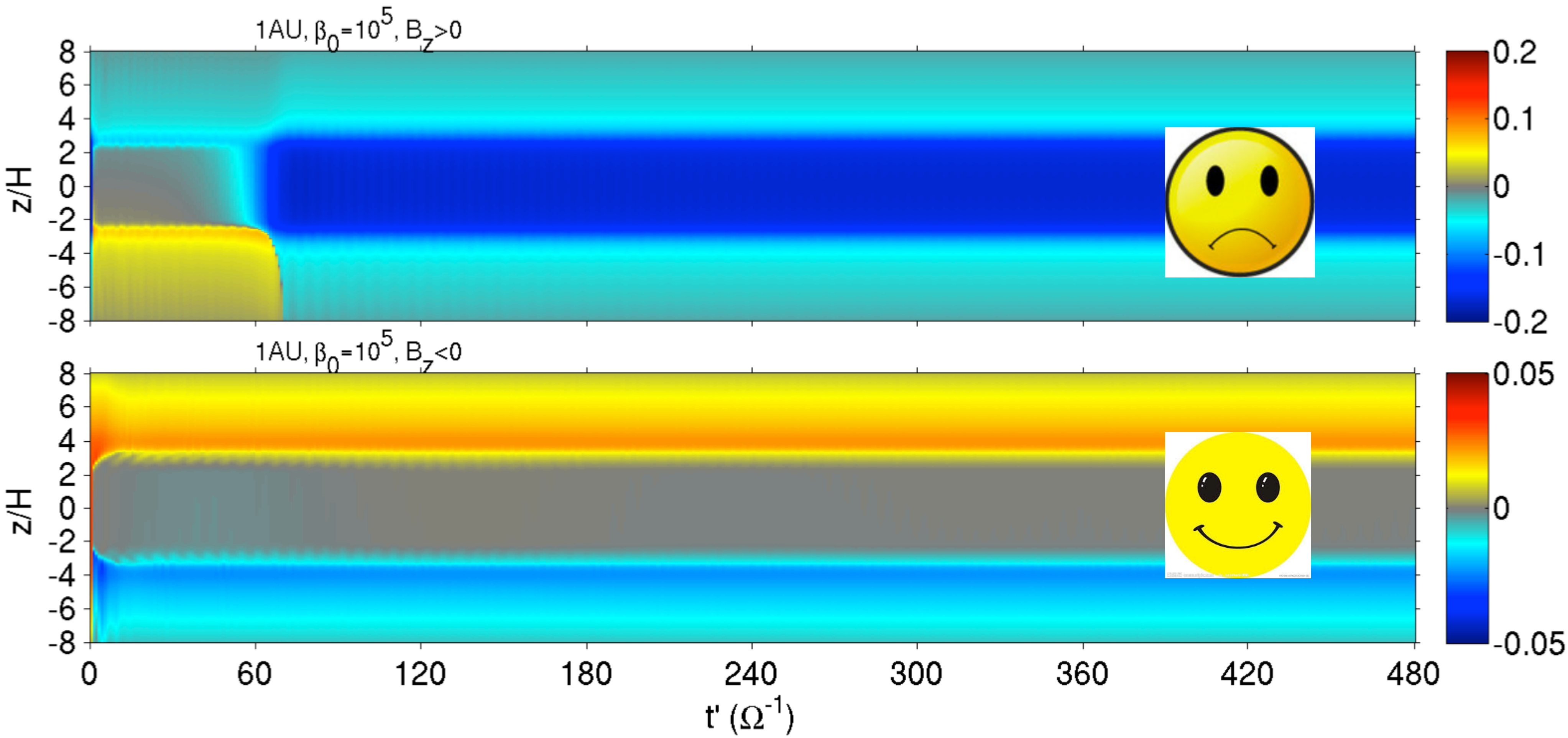
(Kunz, 2008, Lesur et al. 2014)





(Bai, 2014a)

Issue with symmetry: full-disk simulations



With $B_z>0$ (at 1 AU), the system relaxes to unphysical wind configuration…

With $B_z<0$, physical wind configuration can always be realized.

(Bai, 2014a)

Angular momentum transport

Radial transport of angular momentum by (laminar) Maxwell stress:

$$\dot{M} \sim \alpha_{\rm Max} \sim \int B_r B_\phi dz$$

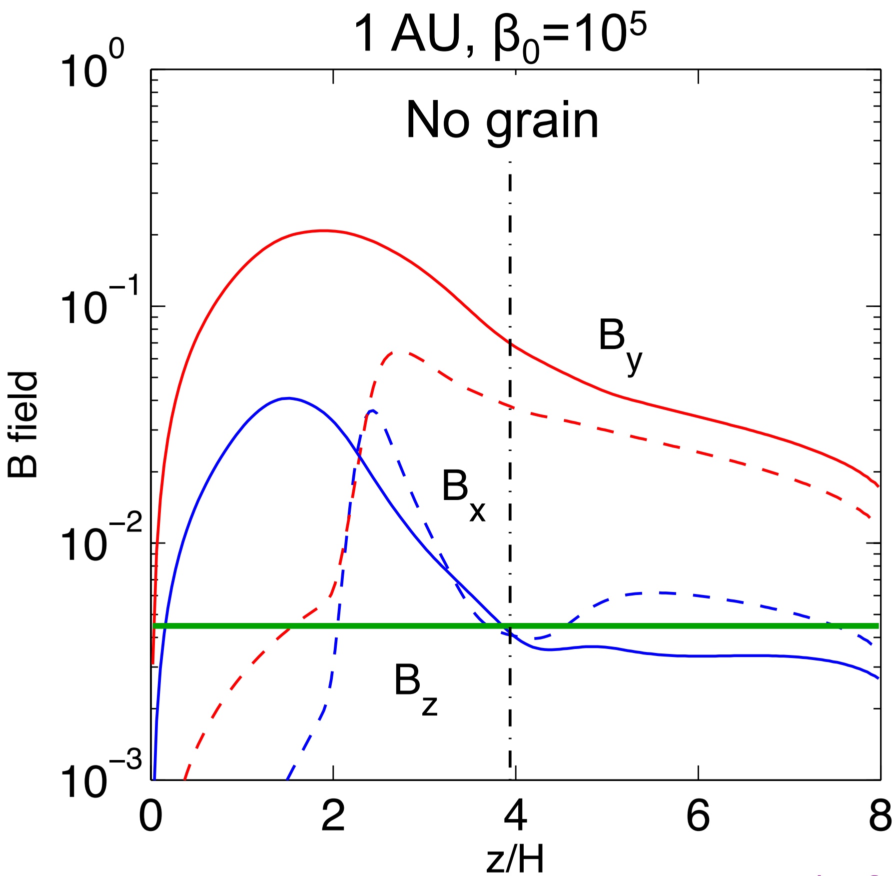
Vertical transport of angular momentum by magnetocentrifugal wind:

$$\dot{M} \sim R \times (B_z B_\phi)\Big|_{z=z_b}$$

As long as a physical wind geometry is achieved, wind-driven accretion always dominates over magnetic braking:

$\beta_0 \sim 10^{5-6}$ is sufficient to achieve accretion rate of 10^{-7-8} $M_\odot$/yr.

Effect of grain abundance/chemistry (B_z>0)



Increasing the ionization fraction toward disk midplane greatly enhances magnetic field amplification, hence α_{Max}.

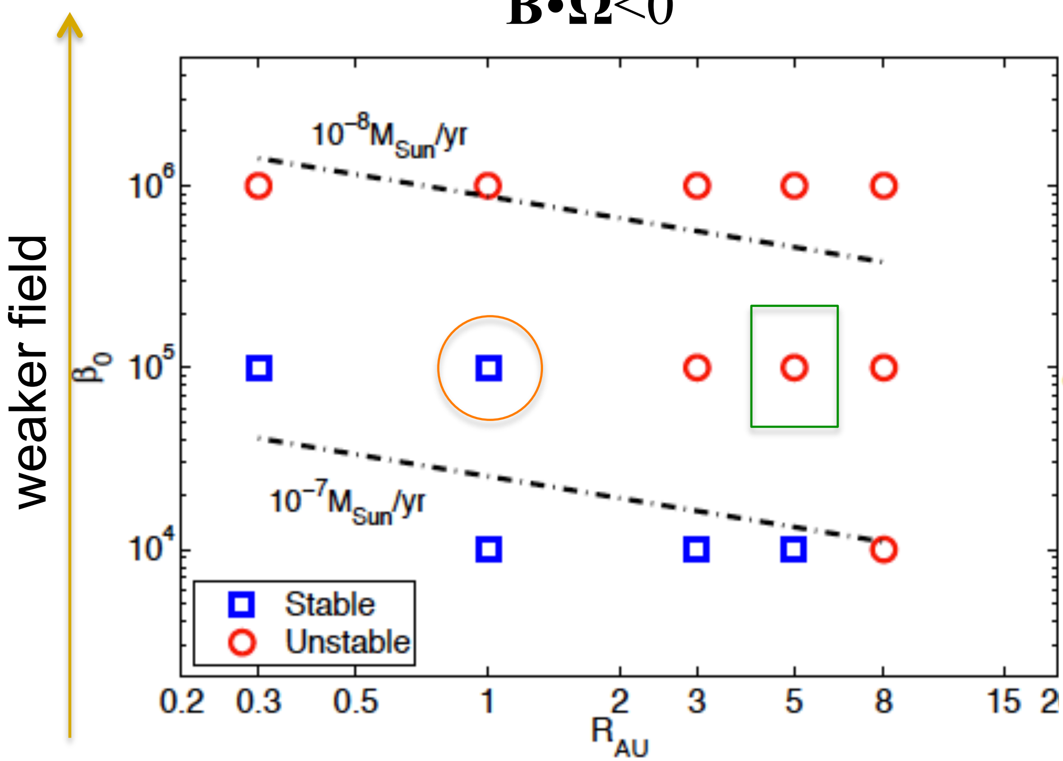
Wind-driven accretion rate depends very weakly on the chemistry.

(reflection symmetry)

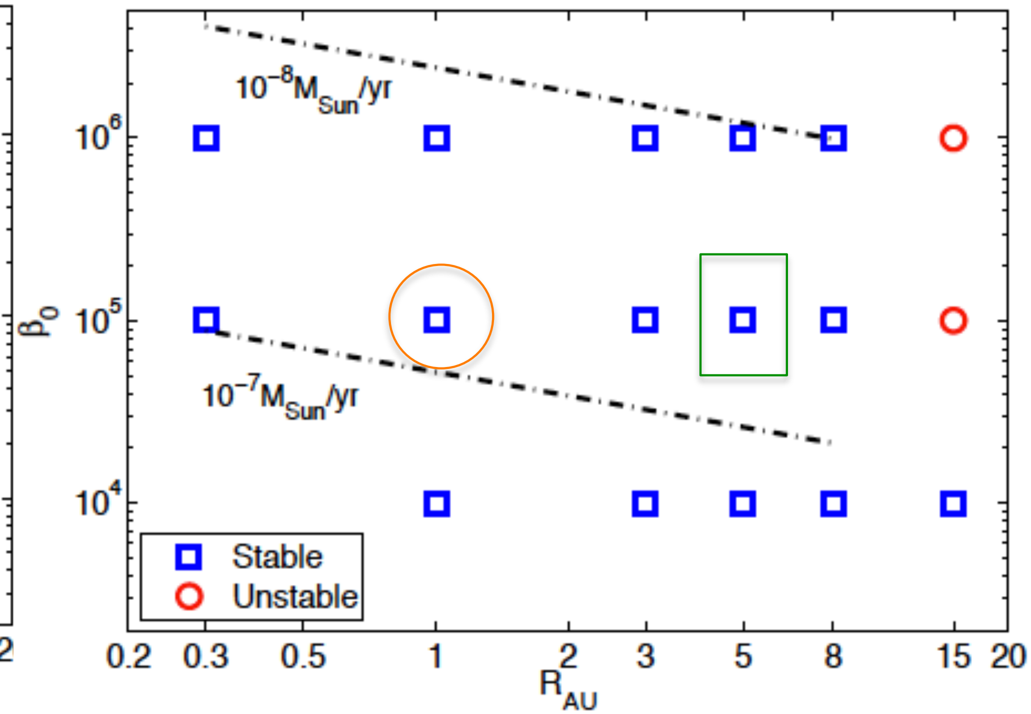
α_{MAX}	Even-z	Odd-z
With grain	1.1×10^{-3}	4.5×10^{-3}
No grain	1.1×10^{-2}	1.4×10^{-2}
Lesur et al. 2014	--	5.0×10^{-2}

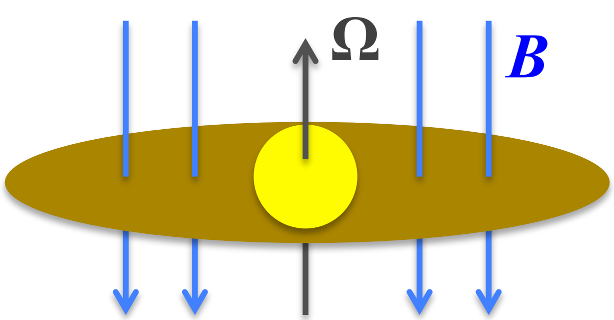
Range of stability (to MRI)

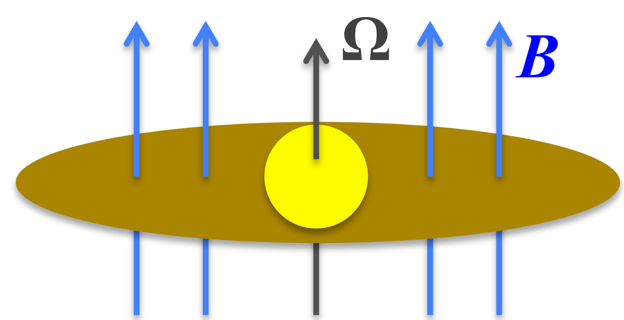
B•Ω<0



B•Ω>0

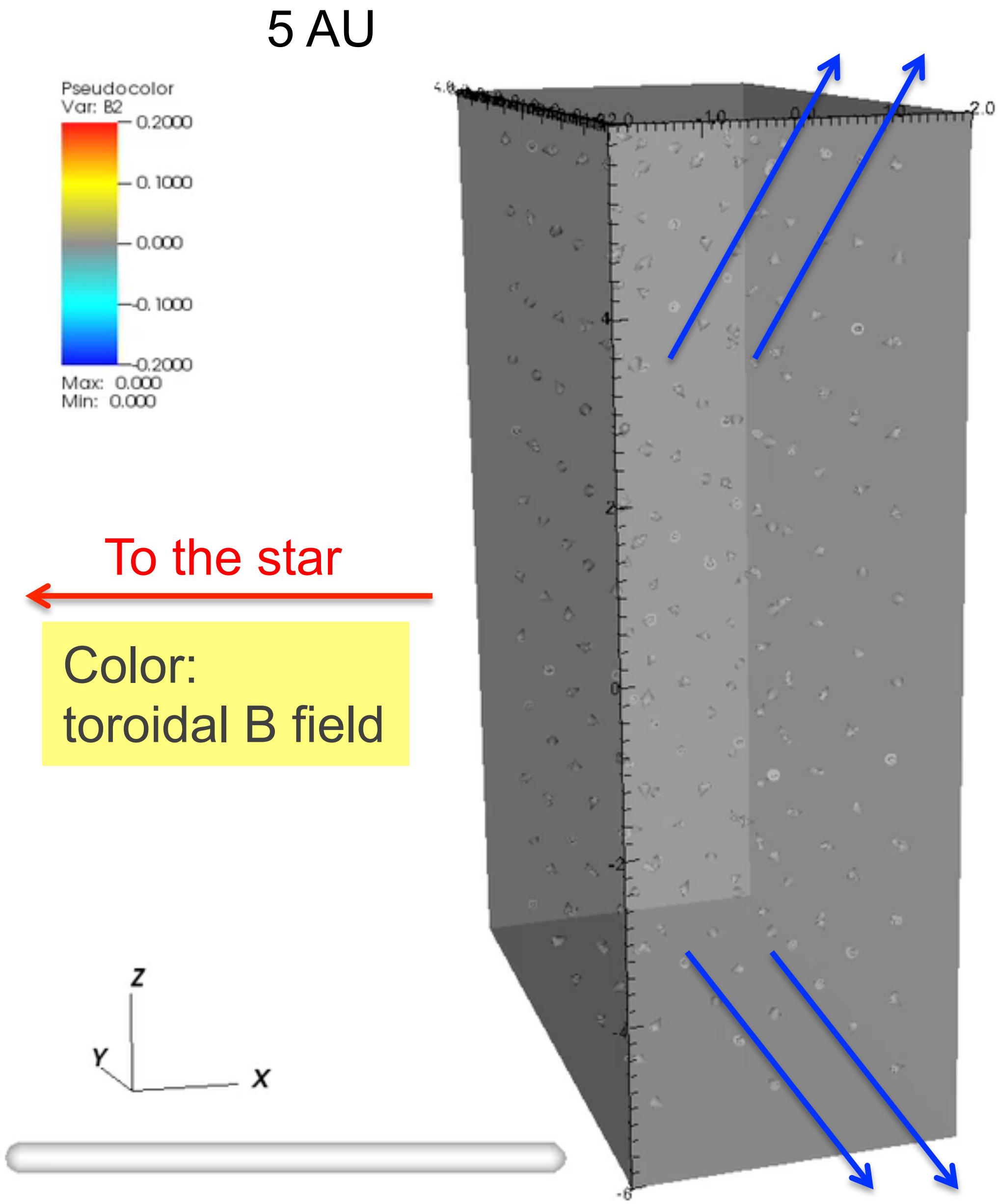




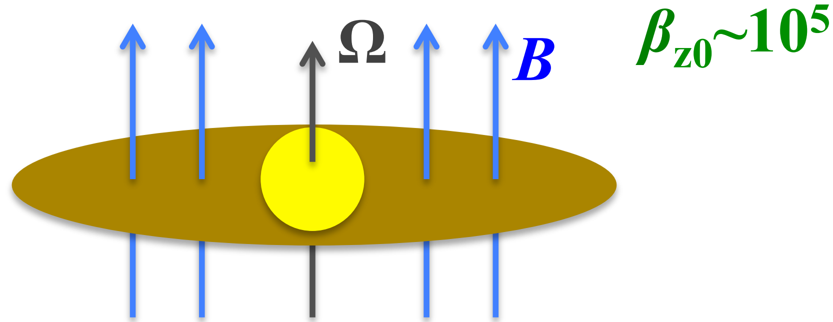


(Bai, 2014a)

Achieving physical wind geometry at 5 AU



(Bai, 2014b)



Midplane strongly magnetized, with B_ϕ reversing sign.

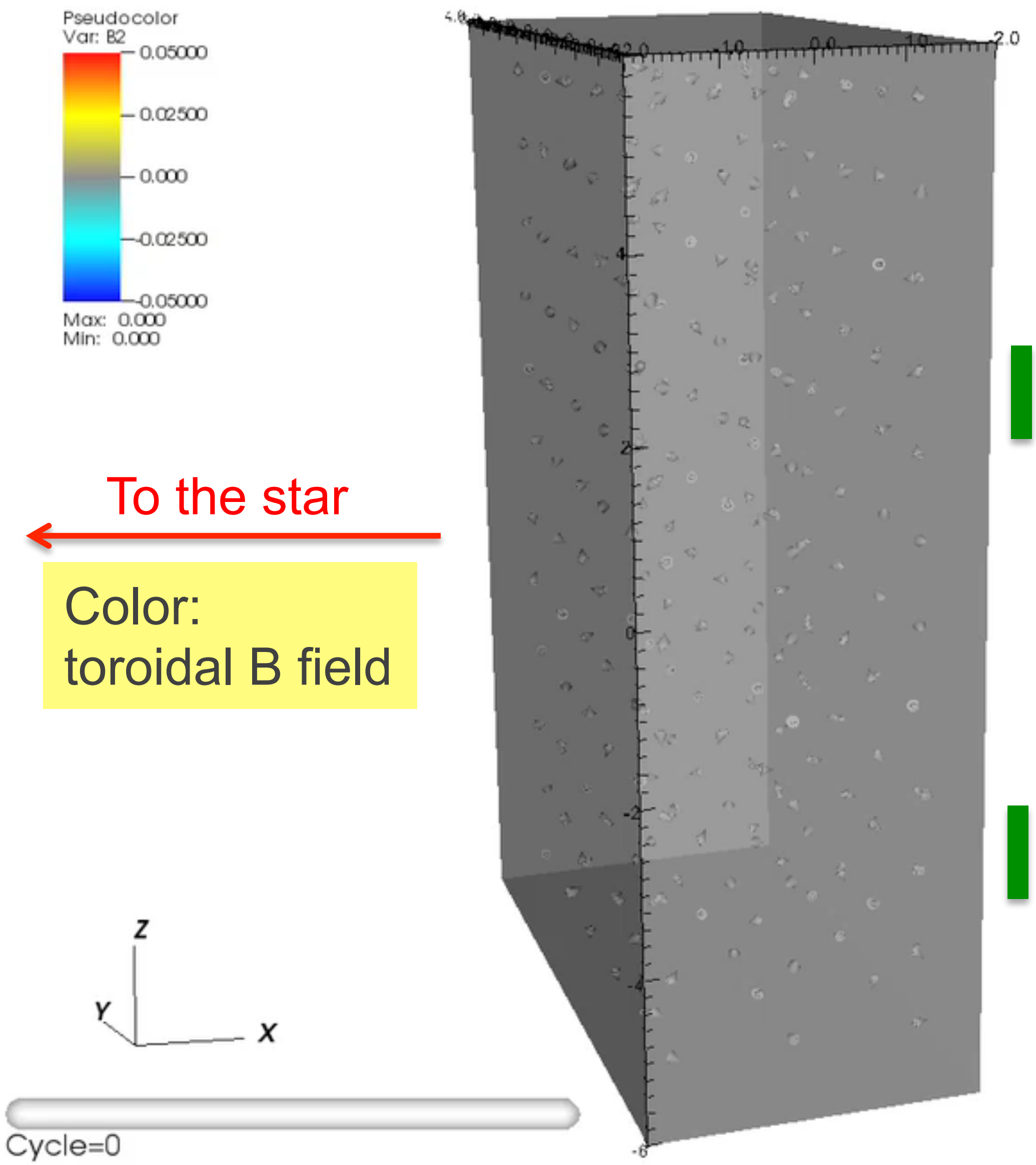
System is stable to MRI, and midplane is weakly turbulent (resulting from reconnection).

Launching of magneto-centrifugal wind.

When MRI sets in with $B_z<0$

$\beta_{z0}\sim 10^5$

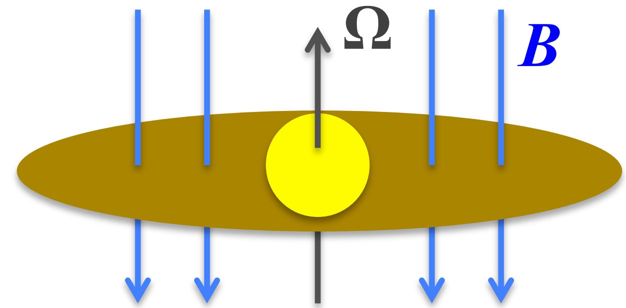
5 AU



To the star

Color:
toroidal B field

(Bai, 2014b)

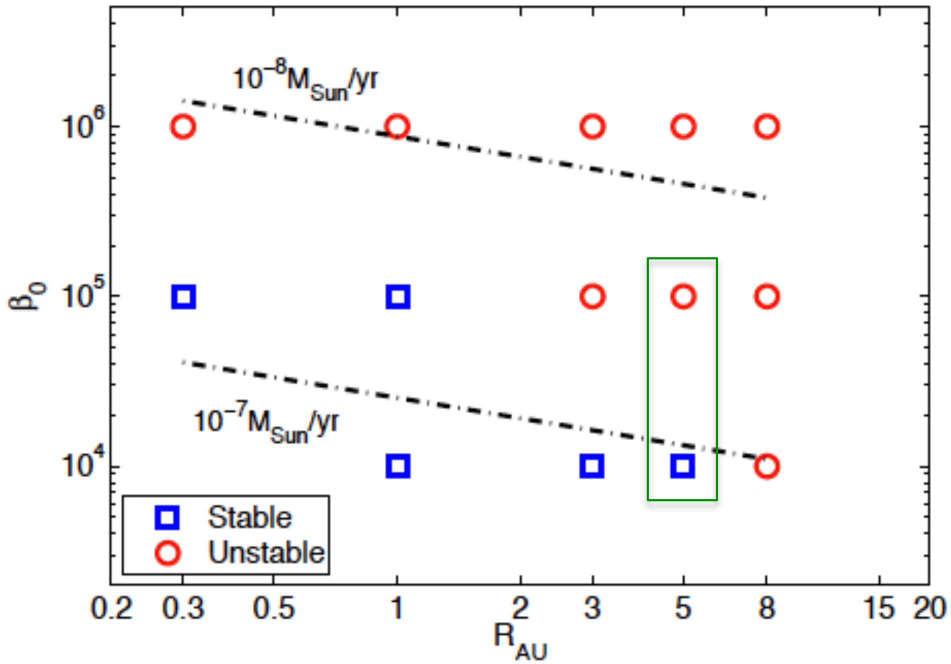


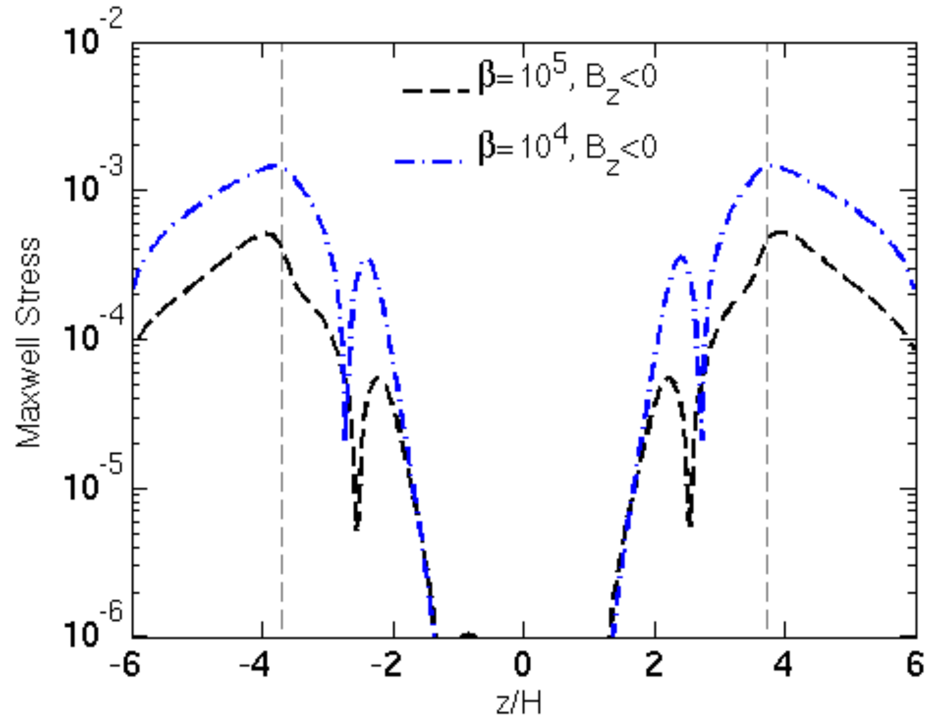
Midplane region is weakly magnetized and weakly turbulent (from surface MRI turbulence)

The system is unstable to the MRI ~2-3H off the midplane.

B_ϕ and outflow alternating directions due to MRI

Issue with angular momentum transport ($B_z<0$)





Relatively strongly magnetized: $\beta_0 \sim 10^4$

Relatively weakly magnetized: $\beta_0 \sim 10^5$

Wind has symmetry issues, need global simulations.

Strong disk wind that drives accretion rate $>10^{-7}\ M_\odot \mathrm{yr}^{-1}$.

Weak MRI that drives accretion rate $\sim 10^{-9}\ M_\odot \mathrm{yr}^{-1}$.

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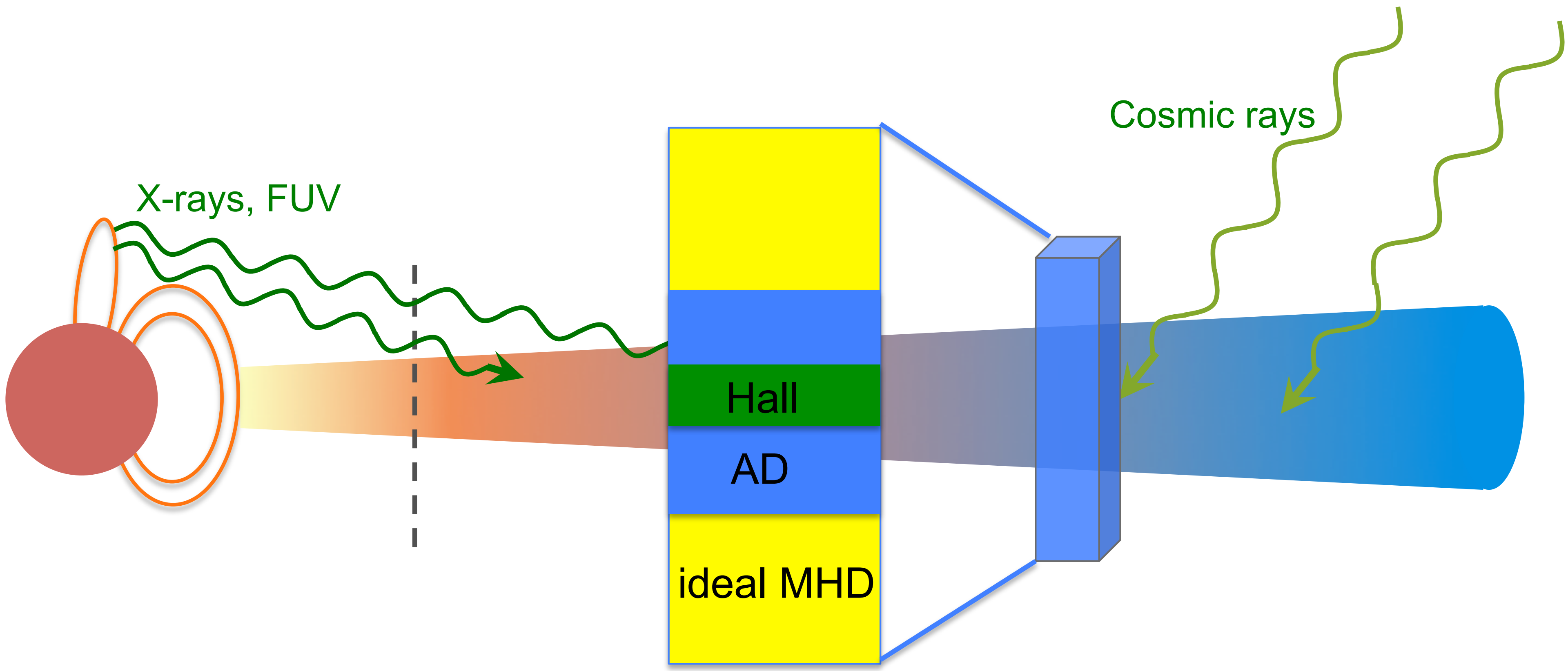
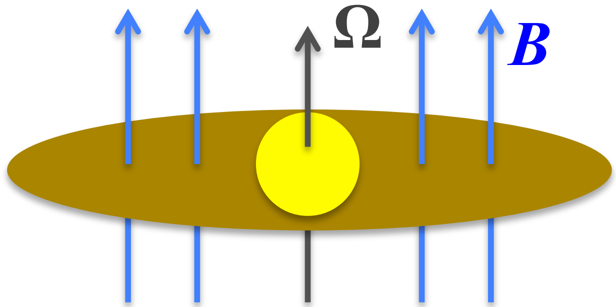
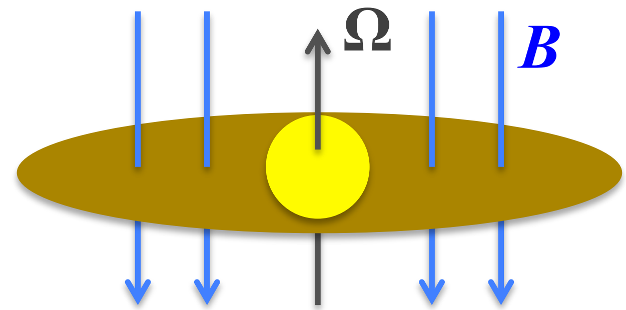
Outer disk: R>15 AU



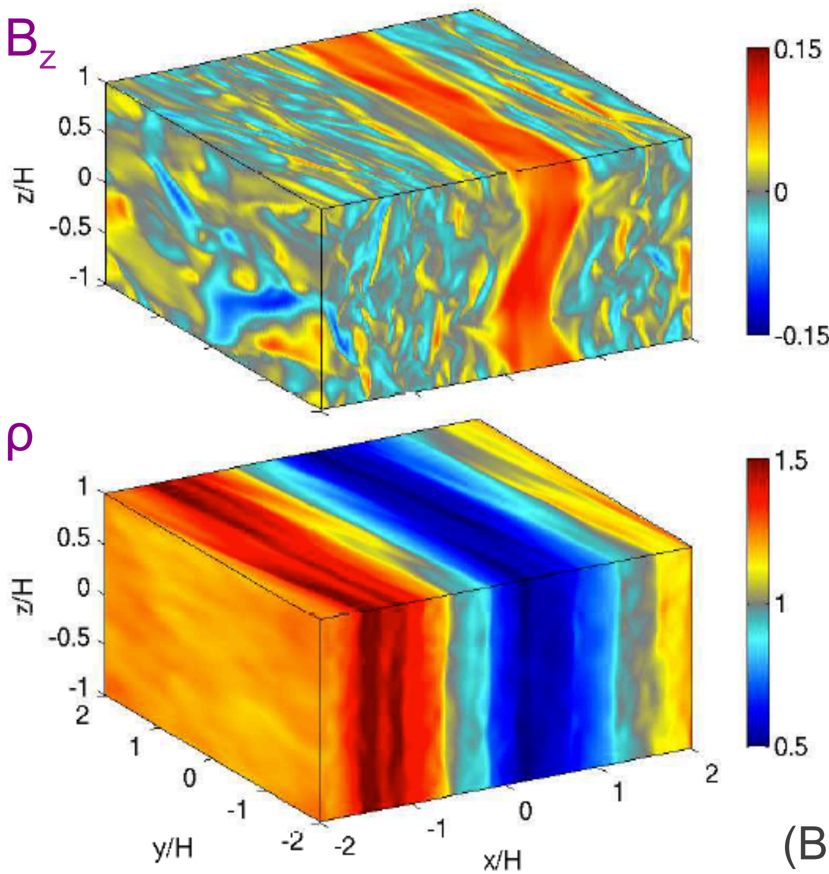
Ohmic resistivity is negligible, Hall effect dominates near the midplane.

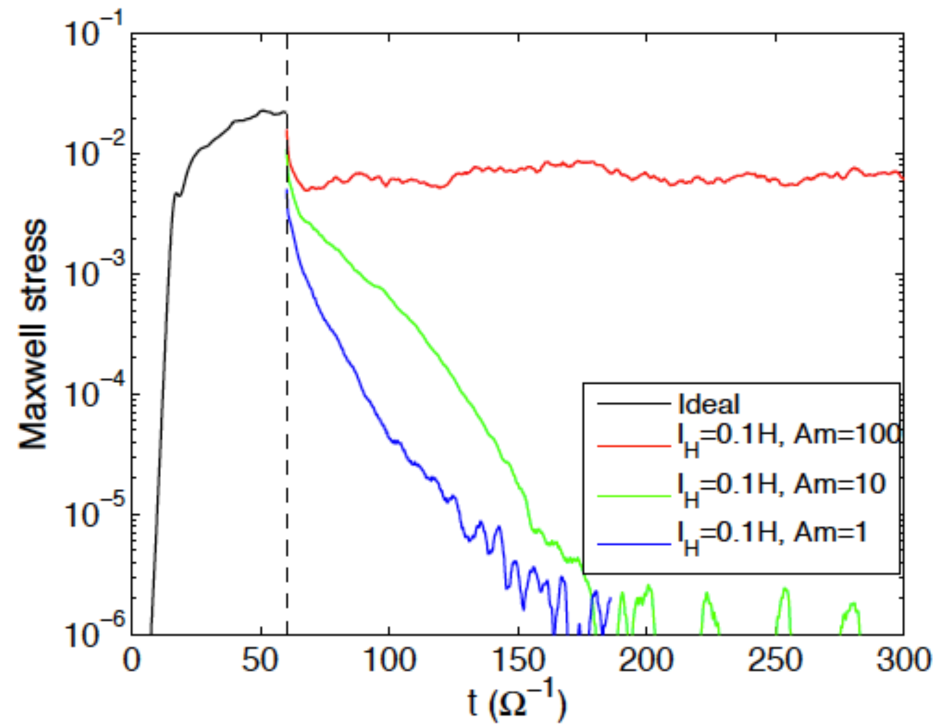
MRI in the presence of Hall + AD





l_H=0.3H, Am=1



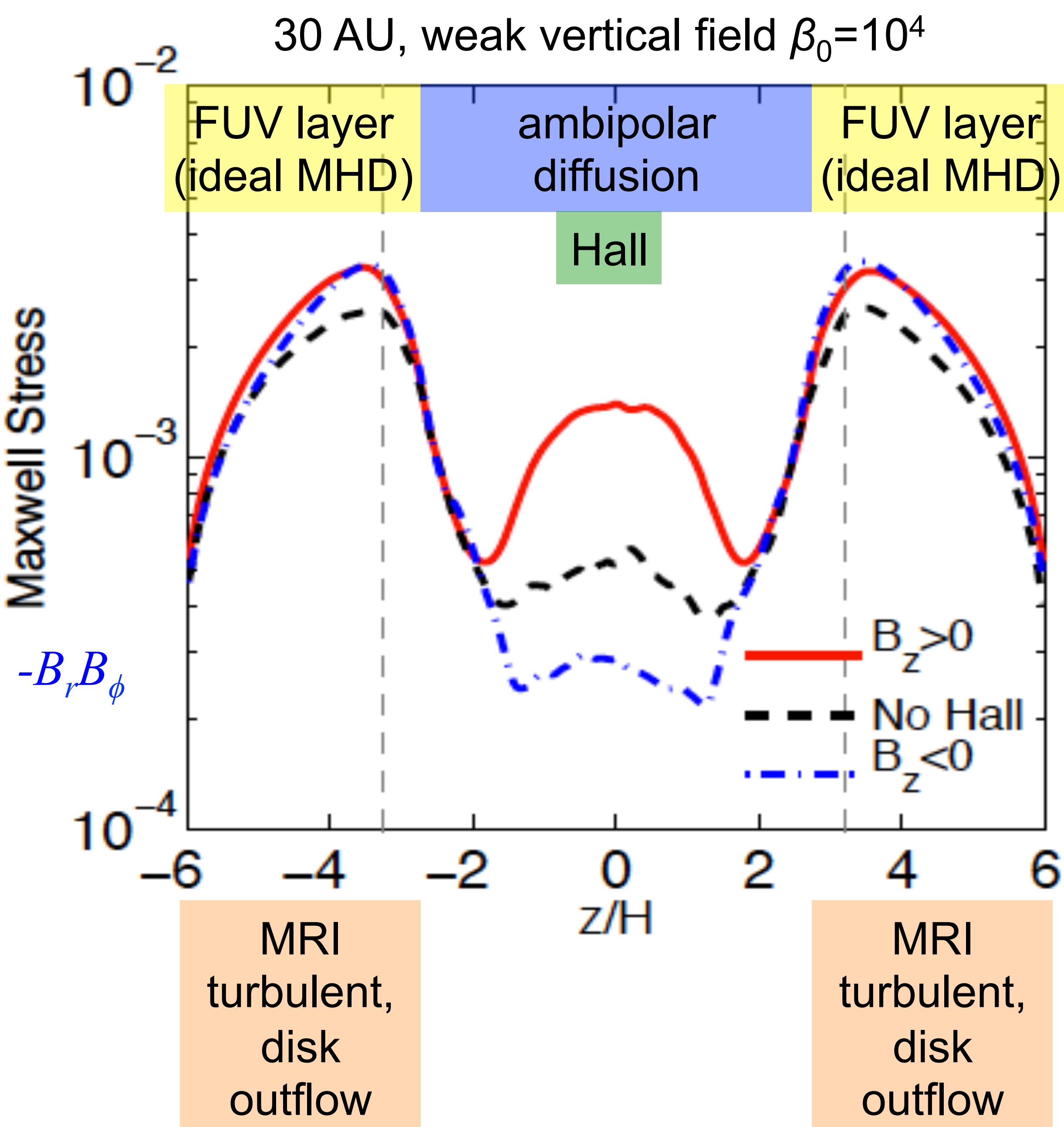


(Bai, 2014b)

MRI is suppressed

Angular momentum transport

(Bai, 2014b)



Midplane Maxwell stress is modestly affected by the Hall effect.

MRI in the FUV layer is sufficient to drive rapid accretion.

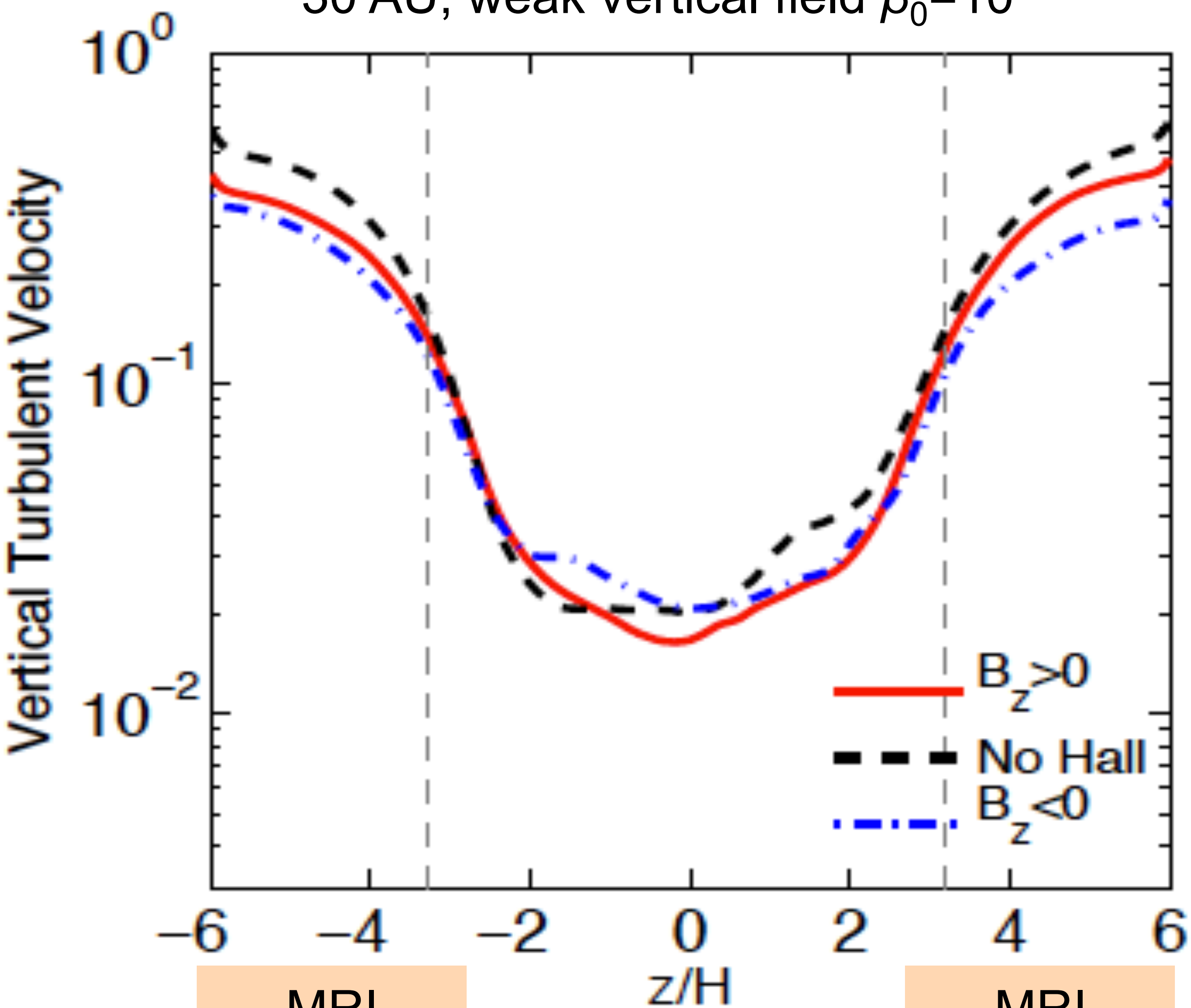
(Perez-Becker & Chiang, 2011; Simon, Bai, et al. 2013)

Disk outflow can also play a role, but its contribution is uncertain based on local simulations.

Layered turbulence

(Bai, 2014b)

30 AU, weak vertical field $\beta_0=10^4$



MRI turbulent, disk outflow

"dead zone"?

MRI turbulent, disk outflow

Anti-aligned field geometry:

MRI is suppressed in the midplane.

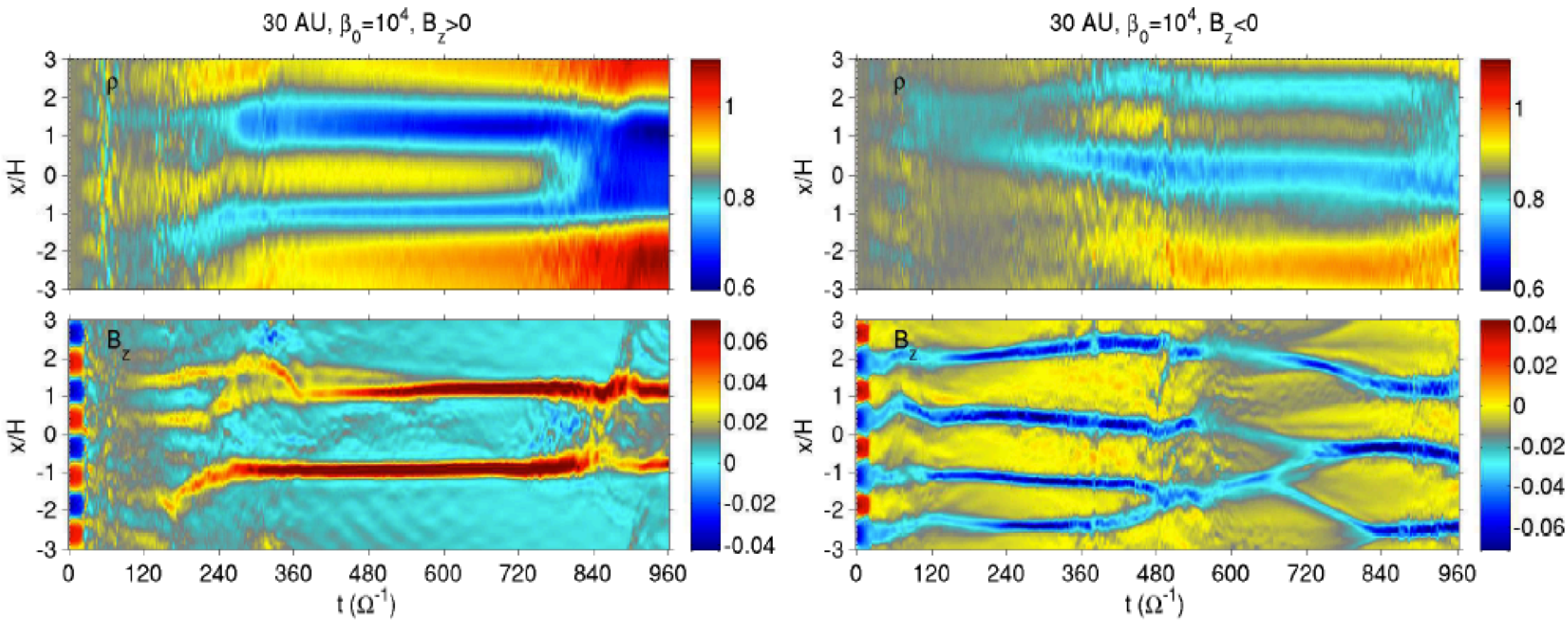
Aligned field geometry:

MRI is weakened by stronger mean field + B flux concentration.

$\delta v_z \sim 10^{-2} c_s$ is a good proxy at disk midplane

See also J. Simon's talk

Magnetic flux concentration and zonal flows



(Bai, 2014b)

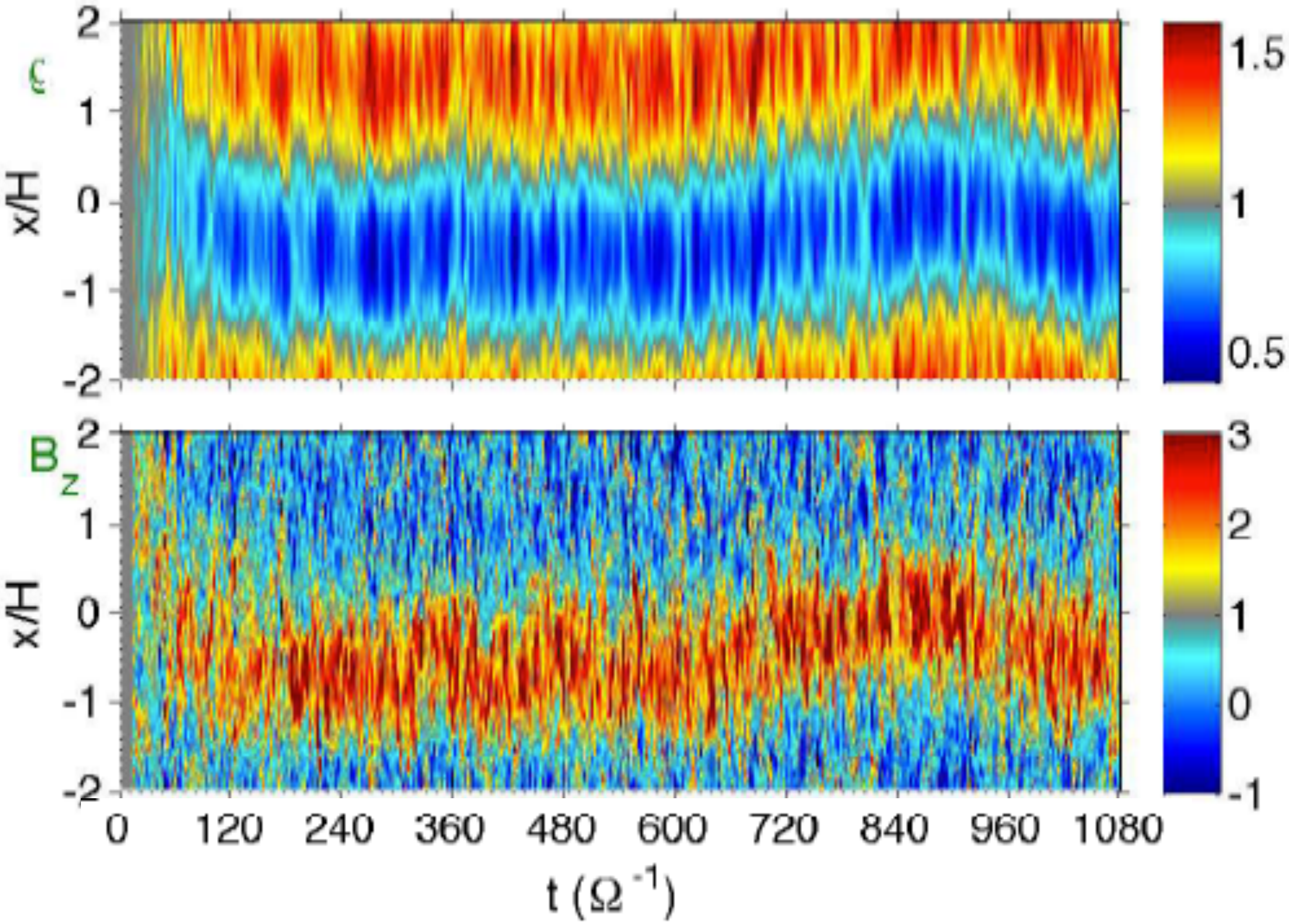
Very strong zonal flow with density contrast of ~30% (see also Simon & Armitage, 2014).

Magnetic flux concentration into thin shells: mean $B_z \approx 0$ outside of the shells.

Magnetic flux concentration is significant at R>15 AU.

B flux concentration as a result of MRI

(Bai & Stone, 2014)



Unstratified, ideal MHD simulations with β_0=1600.

Cause: recurrent action of channel flows followed by reconnection (e.g., Sano & Inutsuka 2001) enhances local mass-to-flux ratio.

Similar effects have been reported in the literature though not discussed in detail.
(Hawley, 2001; Steinacker & Papaloizou, 2002; Zhu et al. 2013)

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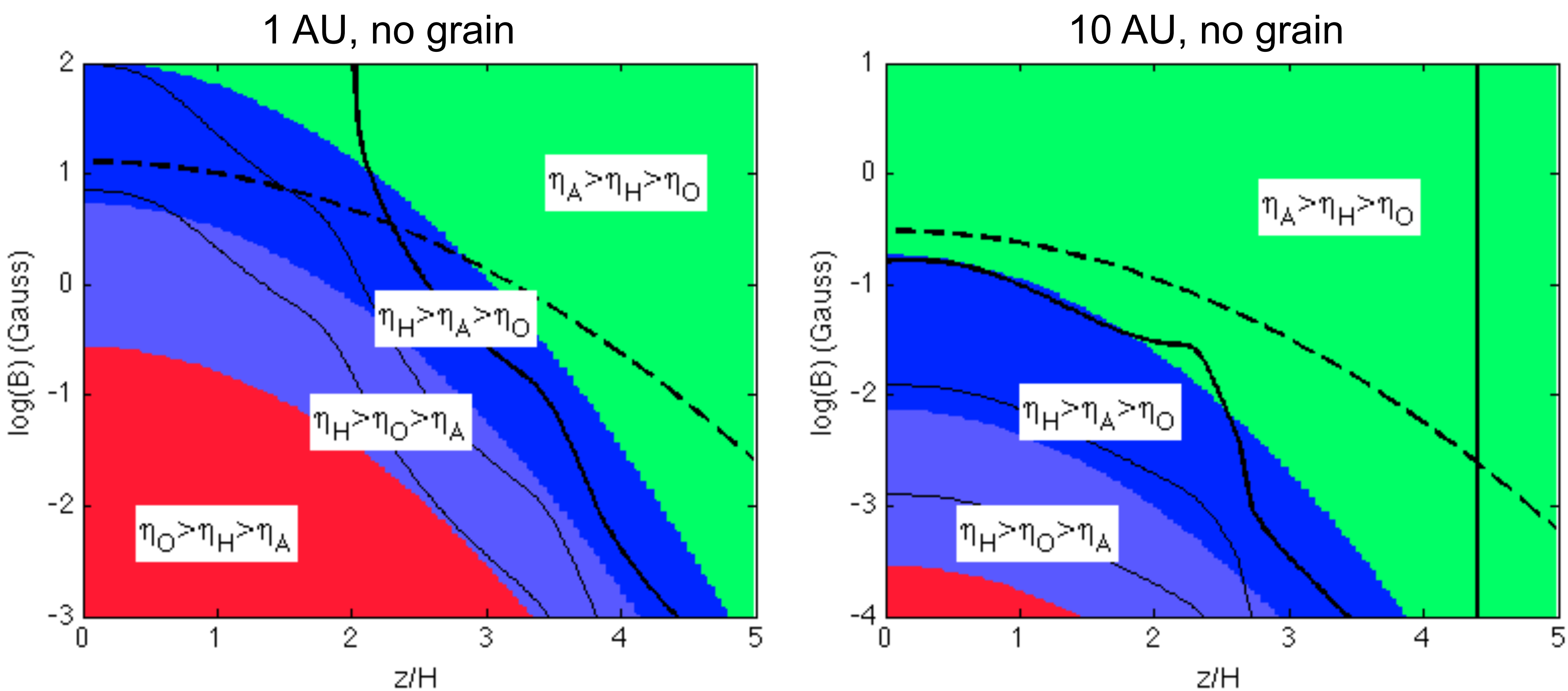
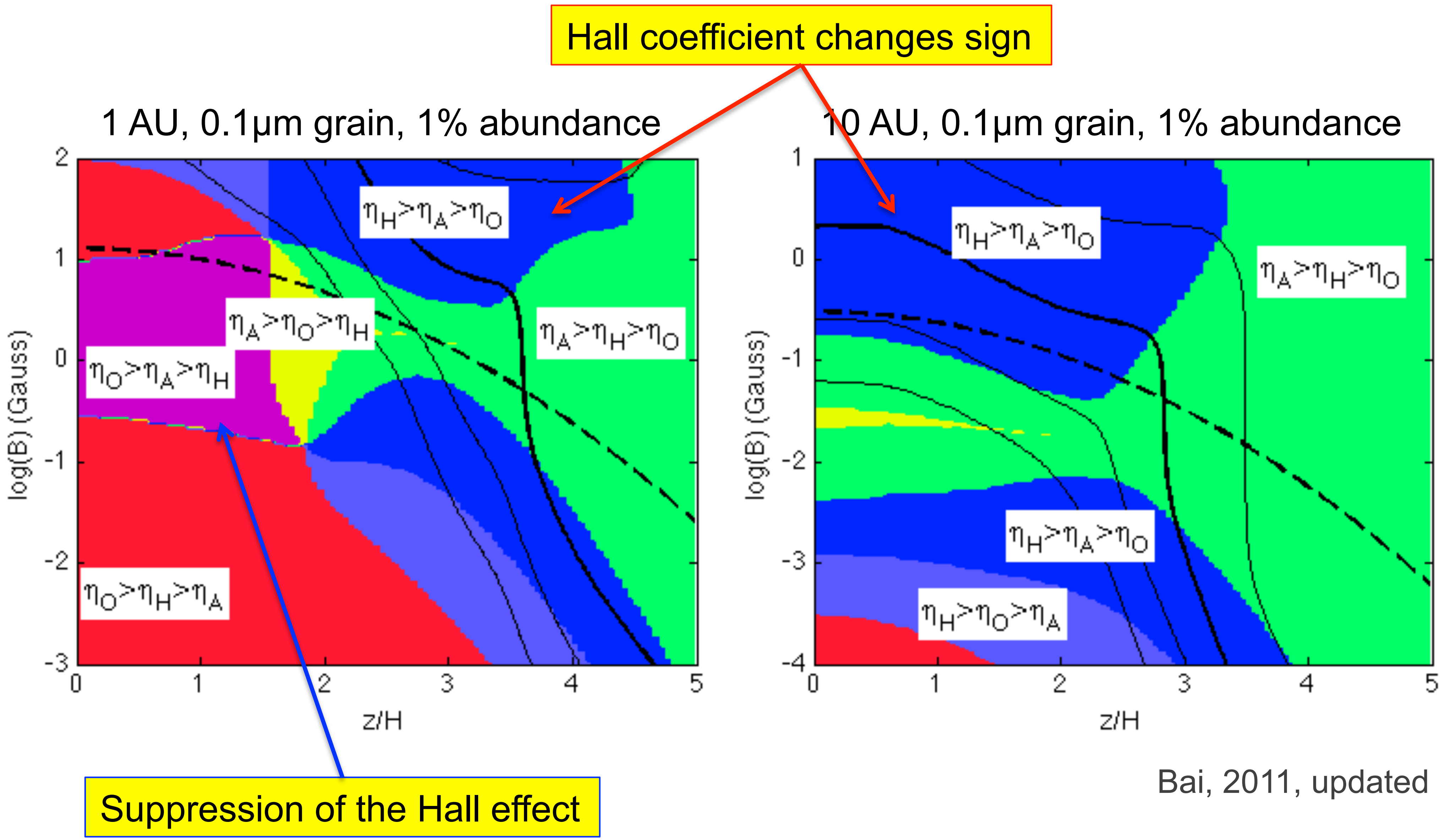
Role of charged grains



Bai, 2011

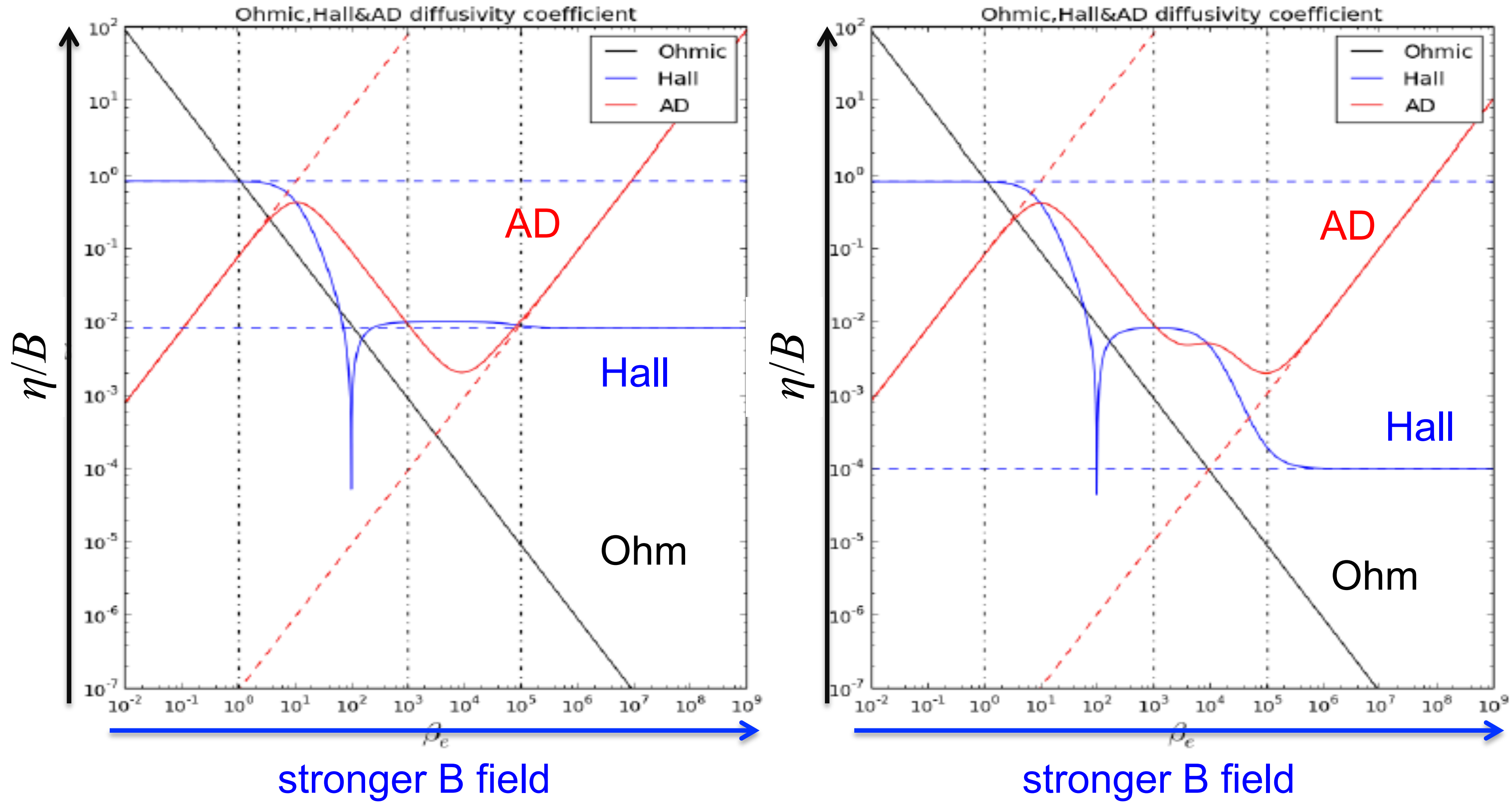
Role of charged grains



Bai, 2011, updated

Role of charged grains

By Rui XU, Peking University



Condition for the Hall coefficient to change sign: $\beta_g^2 < \beta_i^2 (1 - \frac{n_e}{n_i})$

Summary: inner disk

- When **B** is aligned with **Ω**:
  - Over a wide range of parameters, the system is stable to MRI, i.e., laminar.
  - Strong amplification of horizontal B field, depending on chemistry => strongly enhanced radial angular momentum transport by magnetic braking.
  - Efficient wind-driven accretion, which dominates magnetic braking.
  - Major issue with symmetry: tends to be unphysical for wind at small radii.
- When **B** is anti-aligned with **Ω**:
  - System is laminar up to 3-5 AU, more susceptible to the MRI.
  - Horizontal B field is reduced, with negligible magnetic braking.
  - Angular momentum transport relies on wind.
  - When unstable to the MRI, giving oscillating outflows but very weak angular momentum transport.

Summary: outer disk

- Overall gas dynamics:
  - Layered accretion: MRI mainly operates in the surface FUV layer. In the midplane, MRI is damped ($B_z>0$) or suppressed ($B_z<0$).
  - Level of turbulence $\delta v\sim$ a few $\times\ 10^{-2}c_s$ at midplane, $\delta v\sim c_s$ at surface.
  - MRI is sufficient for angular momentum transport for $\beta_0\sim10^4$.
  - Wind/outflow with similar symmetry issues as the ideal MHD case.
- Magnetic flux concentration:
  - B flux distribution in PPDs is highly non-smooth, concentrates into thin shells.
  - Generic consequence of the MRI turbulence, further enhanced by AD.
  - Association with zonal flows may lead to global pressure bumps.

Outlook

- Shearing-box framework is the main limiting factor to address various issues with disk wind/outflow.
  - First step extension by including vertical shear (McNally & Pessah, 2014)?
- Global simulations with net vertical flux is essential.
  - Resolving symmetry issues, wind kinematics, etc. (Gressel, Suzuki's talks)
- Need better understandings of disk conductivity.
  - With grains: non-linear dependence on B field strength, reverse the Hall term.
- Magnetic flux transport is more tricky than previously thought.
  - Additional transport due to non-ideal MHD effects (especially Hall).
  - Need to take into account its patchy distribution (e.g., Uzdensky & Spruit, 2005).