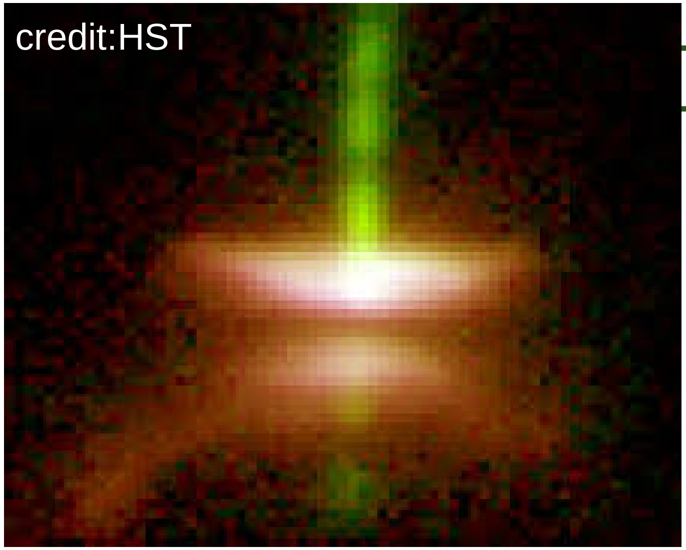
Accretion in Stellar Systems, Cambridge, MA 08/09/2018

Accretion and Outflows in Protoplanetary Disks


credit:HST

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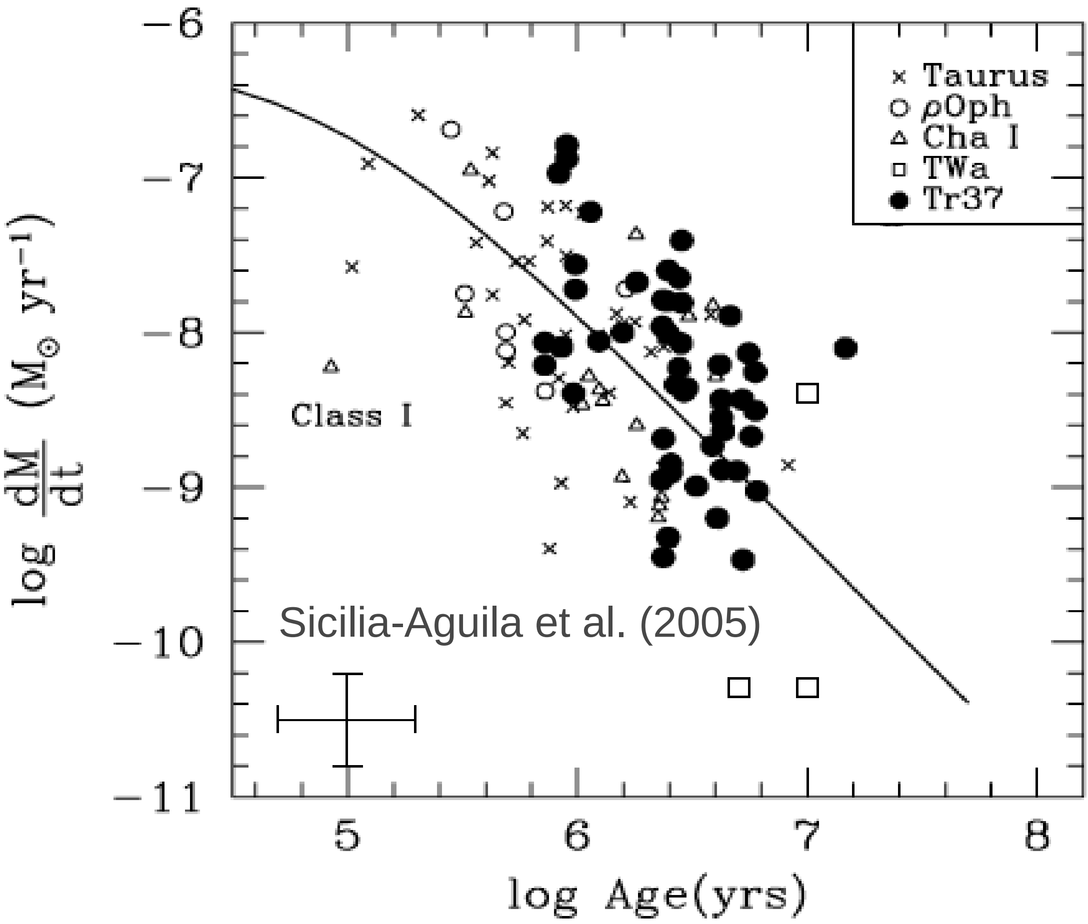
Accretion in PPDs

Accretion rate is measured based on the UV excess (accretion shock):

$$L_{\mathrm{acc}} \approx 0.8 \frac{GM\dot{M}}{R_*}$$



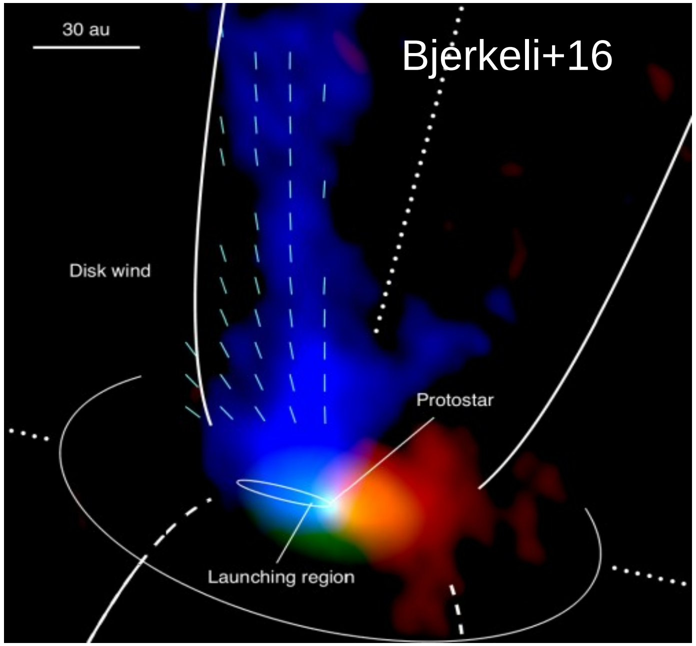
Sicilia-Aguila et al. (2005)

Typical PPD accretion rate $\sim 10^{-8} M_{\odot}\,\mathrm{yr}^{-1}$.

Accretion rate decreases with stellar age.

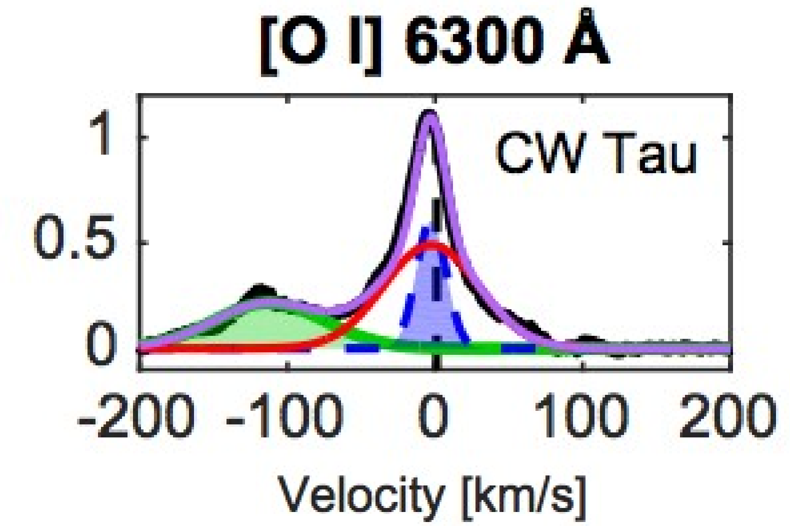
Outflows from PPDs

- Disk wind signatures are ubiquitous in PPDs (e.g., Cabrit 2007).



Large-scale CO outflow (young disk)

Forbidden line emission:



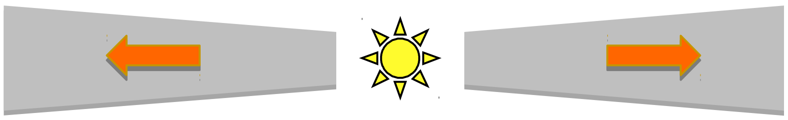
Simon et al. (2016)

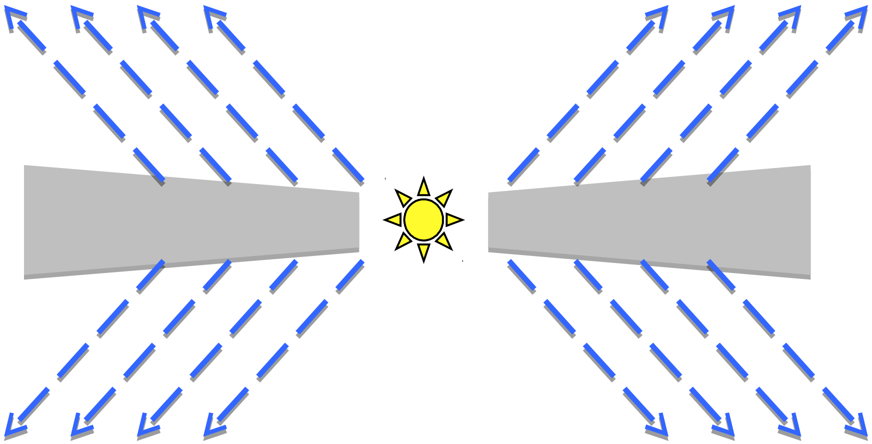
- Inferring mass loss rate is extremely difficult. Mass loss rate *from the inner disk* may reach ~0.1-1 M_{acc} (Natta+14).

What drives angular momentum transport?

Radial transport:

Vertical transport:





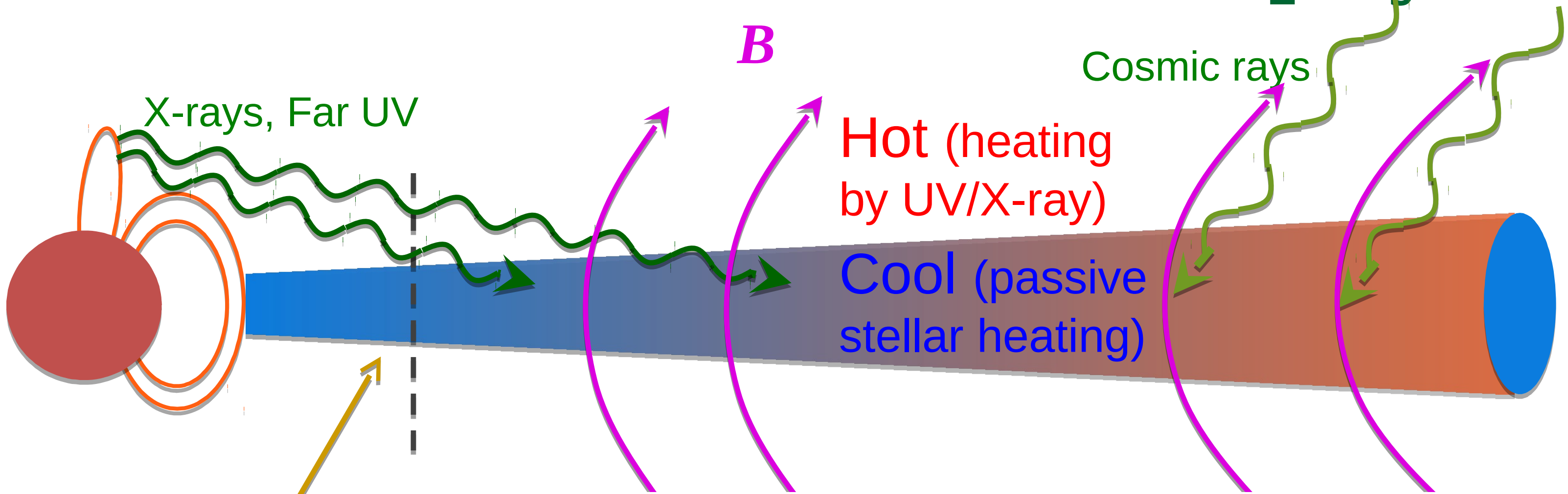
By magneto-rotational instability (MRI, Balbus & Hawley 1991)

By magnetized disk wind (e.g., Blandford & Payne 1982)

Requires gas and magnetic field to be well coupled!

Wind properties are sensitive to disk physics!

Understand the disk microphysics



X-rays, Far UV

B

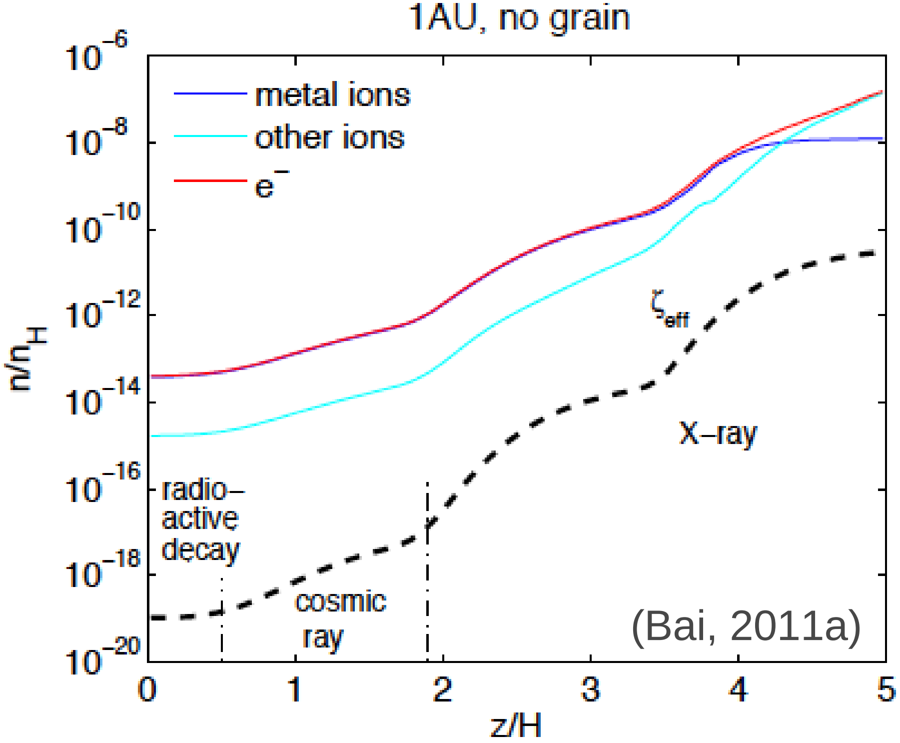
Cosmic rays

Hot (heating by UV/X-ray)

Cool (passive stellar heating)

Thermal ionization

The bulk of the disk is extremely weakly ionized



(Bai, 2011a)

Disk microphysics: non-ideal MHD effects

Induction equation (grain-free):

resistivity

$$\frac{\partial \boldsymbol{B}}{\partial t} = c\nabla \times \boldsymbol{E} = \nabla \times (\boldsymbol{v}_e \times \boldsymbol{B})$$

$$\boldsymbol{v}_e = \boldsymbol{v} + (\boldsymbol{v}_e - \boldsymbol{v}_i) + (\boldsymbol{v}_i - \boldsymbol{v})$$

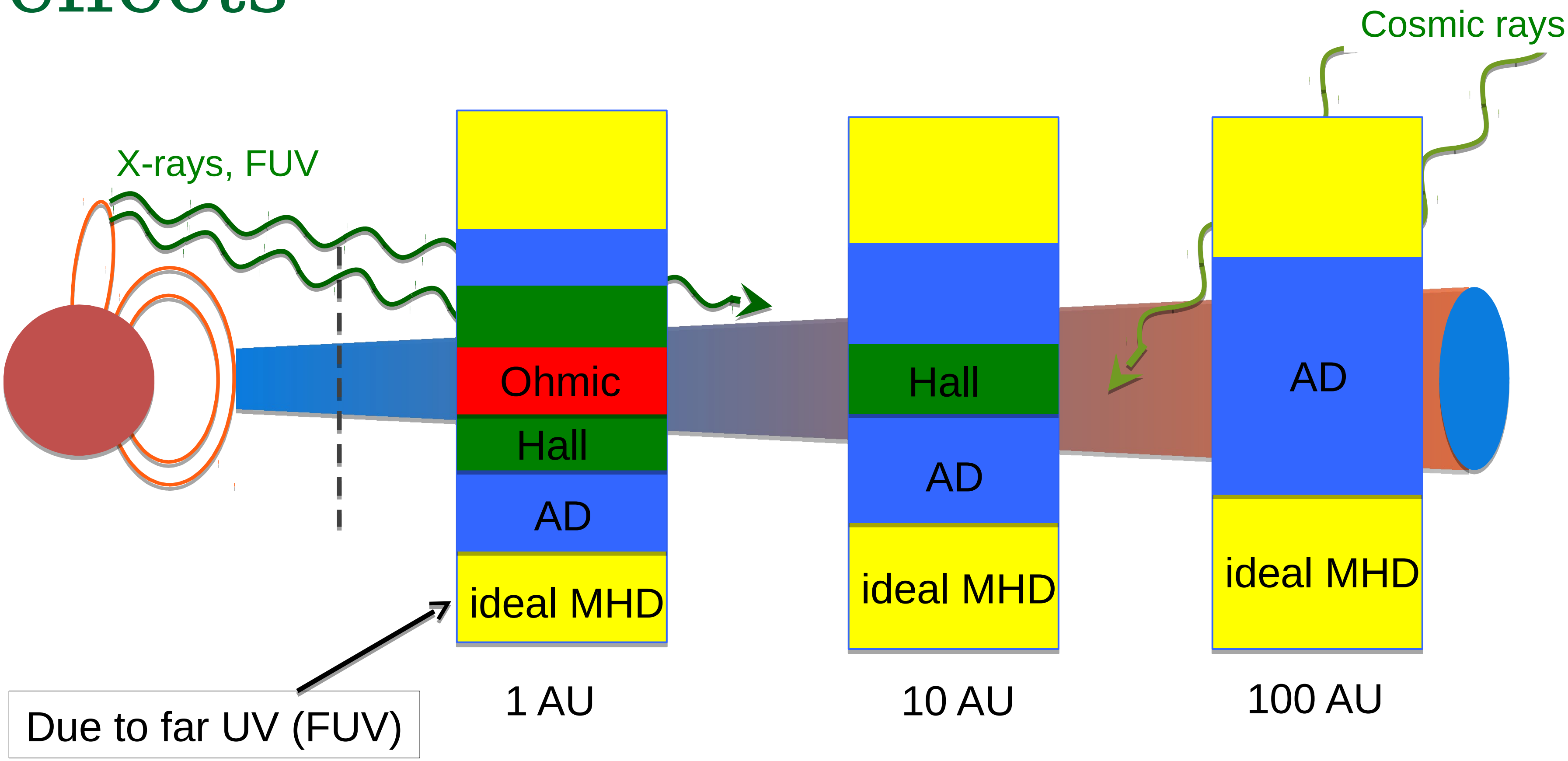
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \boxed{\nabla \times \left[\frac{4\pi\eta}{c}\boldsymbol{J} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{en_e} - \frac{(\boldsymbol{J}\times\boldsymbol{B})\times\boldsymbol{B}}{c\gamma\rho\rho_i}\right]}$$

Non-ideal MHD terms

inductive Ohmic Hall Ambipolar diffusion (AD)

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

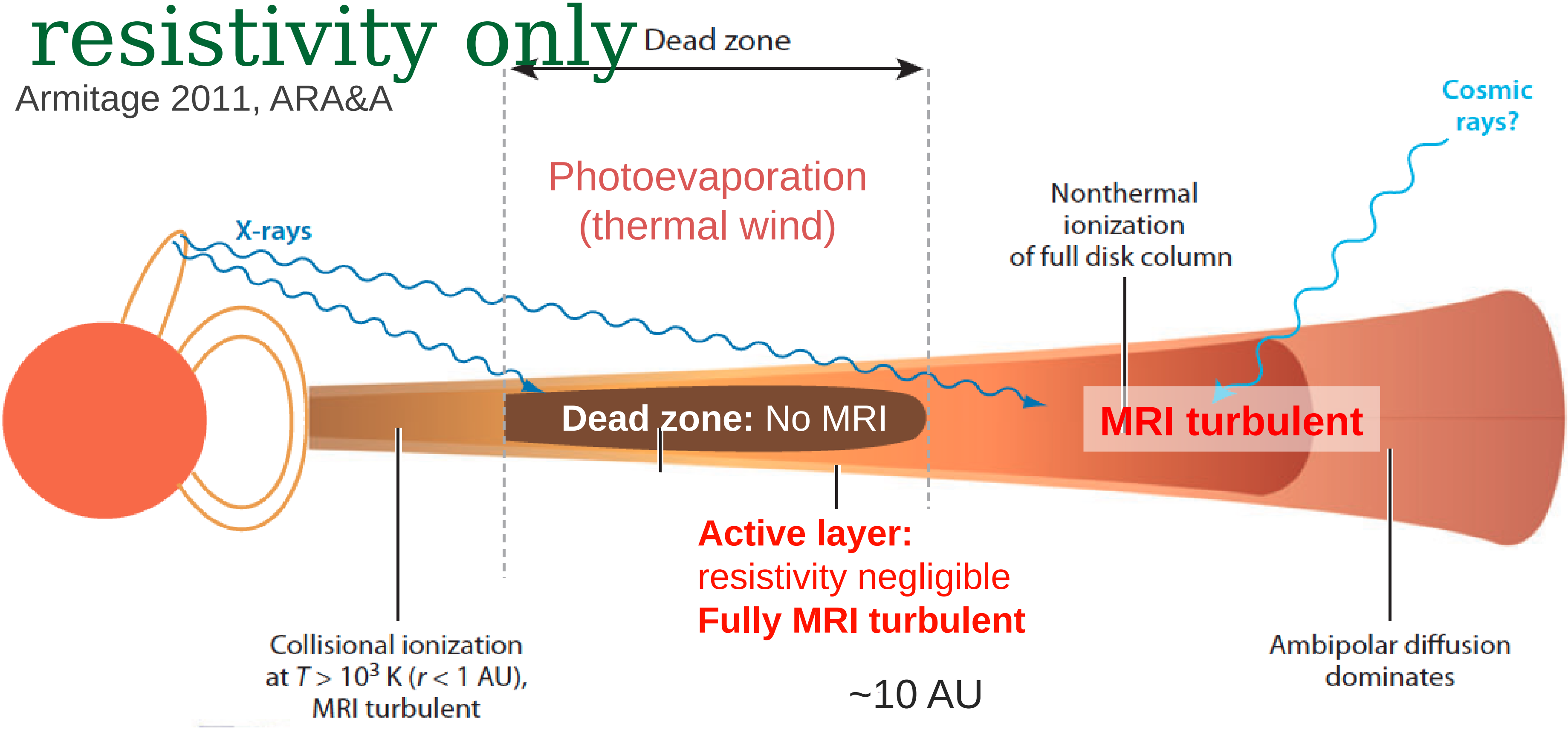
Disk microphysics: non-ideal MHD effects



Due to far UV (FUV)

Conventional understanding: resistivity only

Armitage 2011, ARA&A



Photoevaporation (thermal wind)

Dead zone: No MRI

MRI turbulent

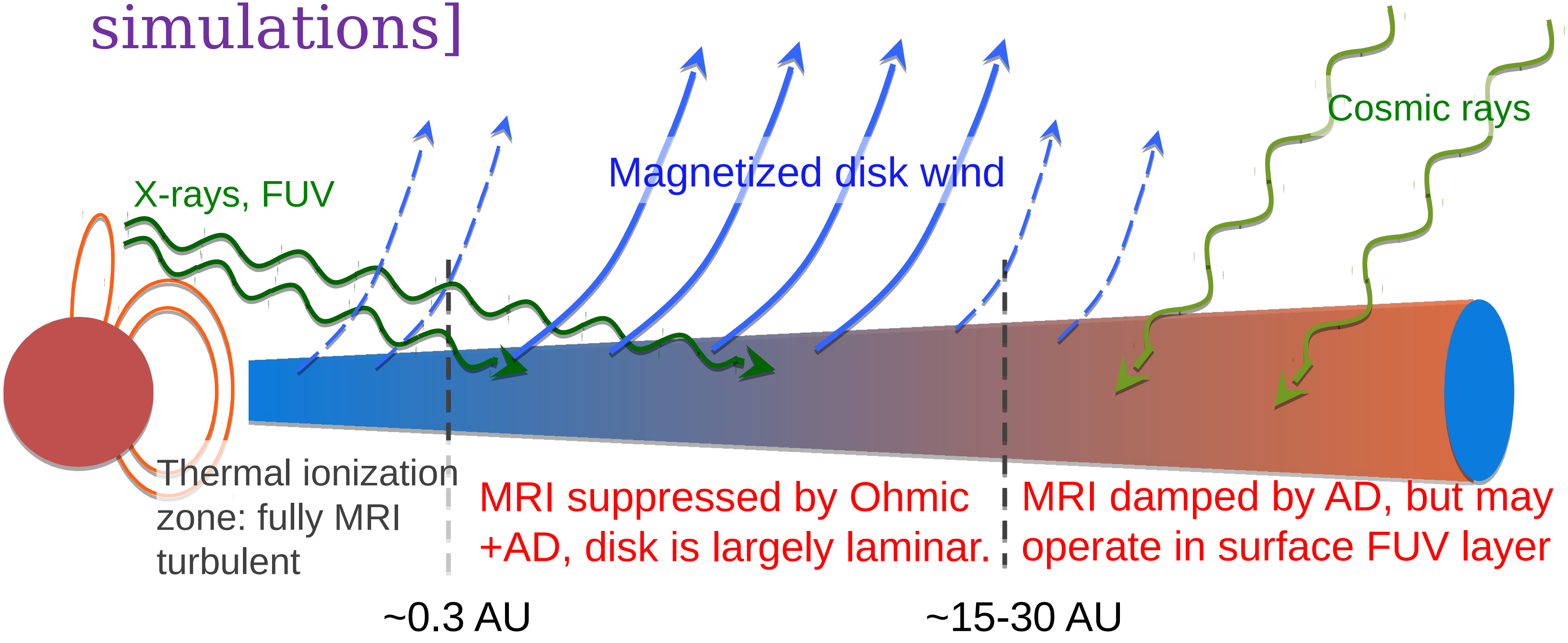
Active layer:
resistivity negligible
Fully MRI turbulent

~10 AU

Theory: Gammie, 1996; Sano et al., 2000; Fromang et al., 2002; Semenov et al., 2004; Ilgner & Nelson, 2006,2008; **Bai & Goodman, 2009**; Turner & Drake, 2009…

Simulations: Fleming & Stone, 2003; Turner et al. 2007; Ilgner & Nelson, 2008; Turner & Sano, 2008, Oishi & Mac Low, 2009…

Recent development [based on local simulations]



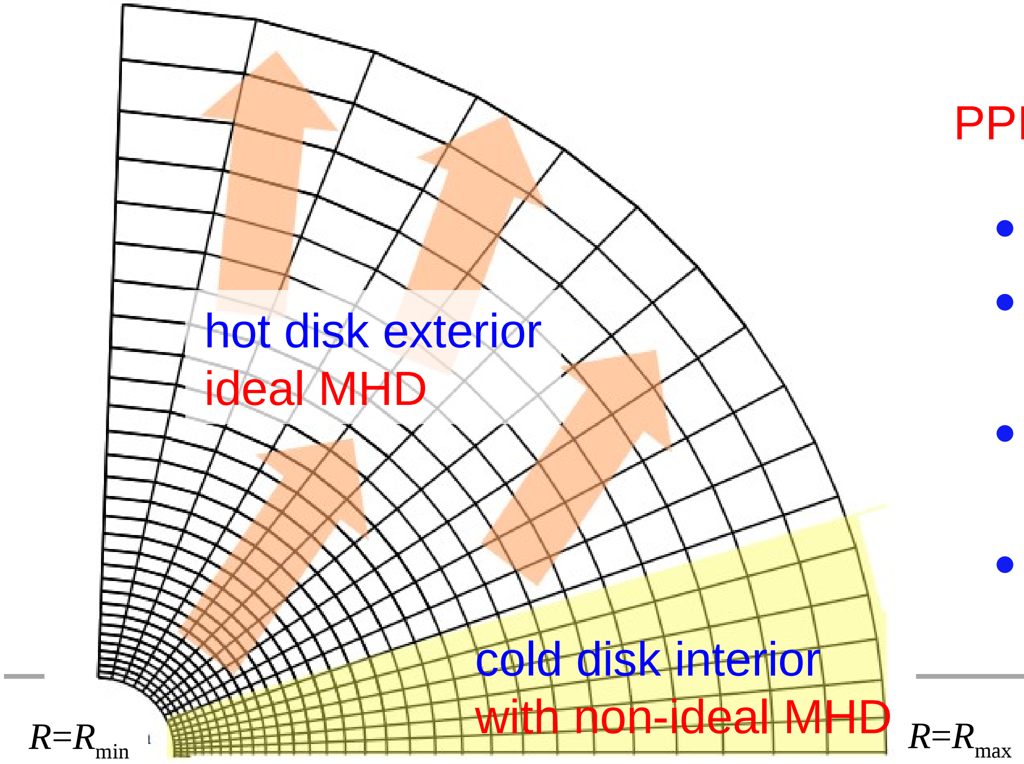
- The MRI is suppressed/damped by the combined effect of Ohmic+AD.
- A large-scale (poloidal) field threading the disk is essential, launching a magnetized disk wind that drives accretion.

(e.g., Bai & Stone 13b, Bai, 13, Simon, Bai+13a,b, Gressel+15)

Global simulations with Athena++

- Cartesian/curvilinear coordinates, flexible grid spacing, static/adaptive mesh refinement, general relativity…
- Performance: ~3-4 times faster than Athena, scalable to 10^5 cores, hybrid parallelization
- Implemented and tested all 3 non-ideal MHD effects.

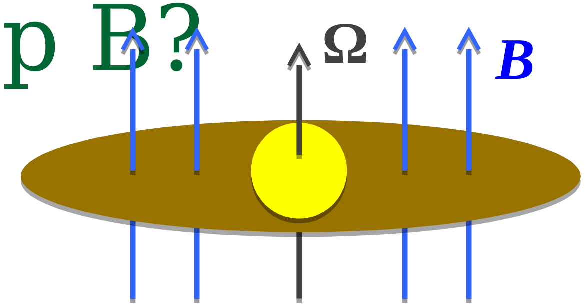
Stone et al. in prep

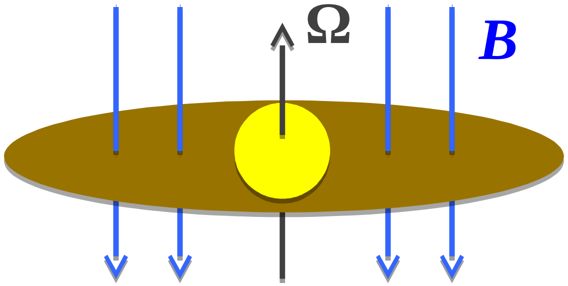


PPD simulation setup:

- Axisymmetric, spherical-polar grid
- Log spacing in r, power law spacing in θ, extending to near the pole
- Ray-tracing + ionization chemistry to determine magnetic diffusivities
- Simplified thermodynamics for disk exterior

The Hall effect: what happens if we flip B?





Lorentz force: $\sim \boldsymbol{J}\times\boldsymbol{B}$ is unaffected.

Note $\boldsymbol{J}=\frac{c}{4\pi}\nabla\times\boldsymbol{B}$

Induction equation (no grain):

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

inductive Ohmic Hall AD

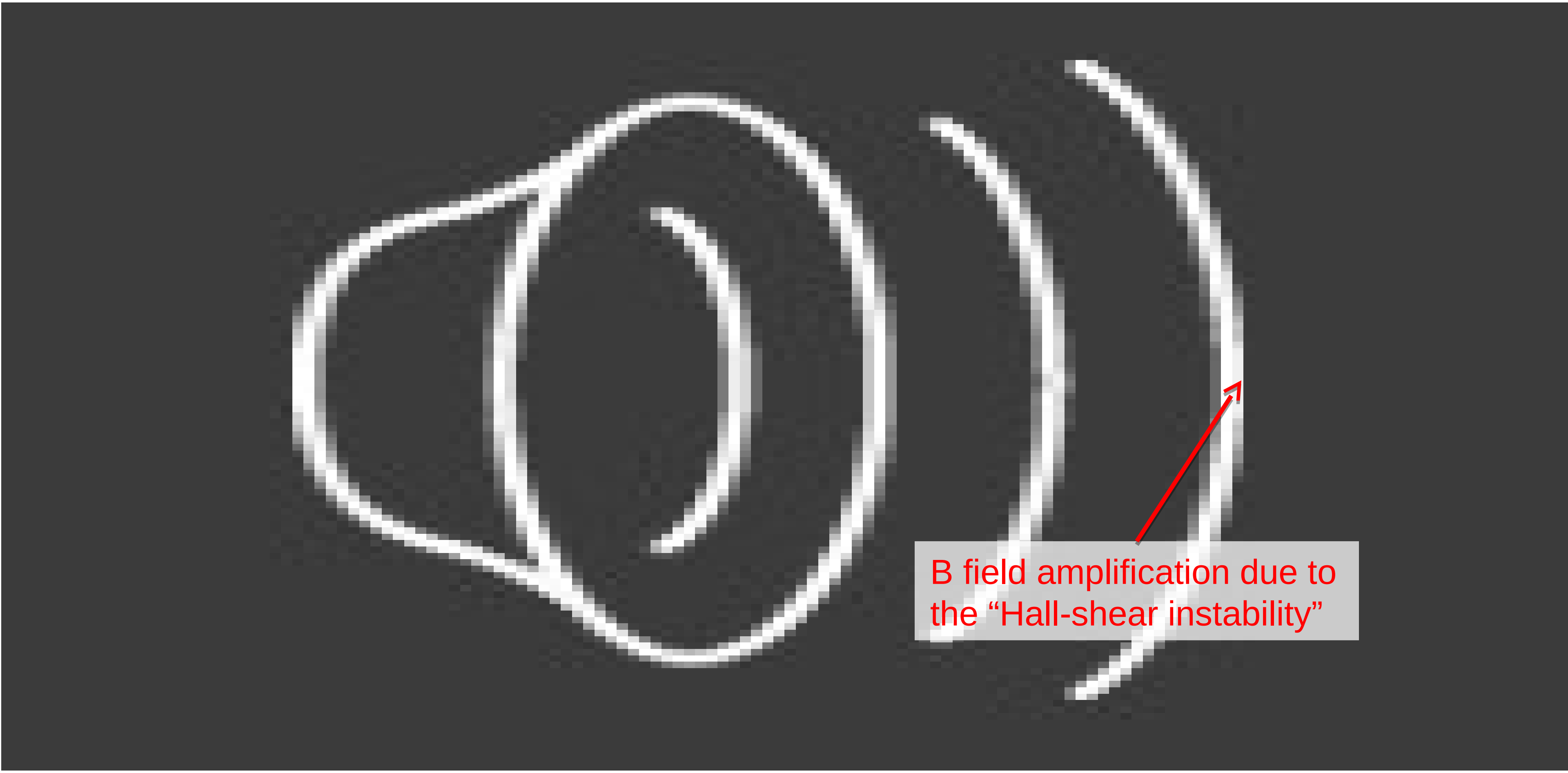
$-$ $-$ $-$ $(-)^2=+$ $(-)^3=-$

The Hall term is Polarity Dependent!

Earlier local simulations if PPDs that include the Hall effect: Bai 14,15, Lesur+14, Simon+15

Towards realistic simulation of PPDs

2D axisymmetric, all 3 non-ideal MHD effects included, aligned case.



B field amplification due to the "Hall-shear instability"

The disk is asymmetric about the midplane!

Complex flow structures -> transport of solids in disks

Bai, 2017

Understand the complex flow structure

Rate of angular momentum loss = Torque

$$\frac{d(\rho v_K R)}{dR} v_R$$

$$(\boldsymbol{F} \times \boldsymbol{r})_z \approx F_\phi R$$

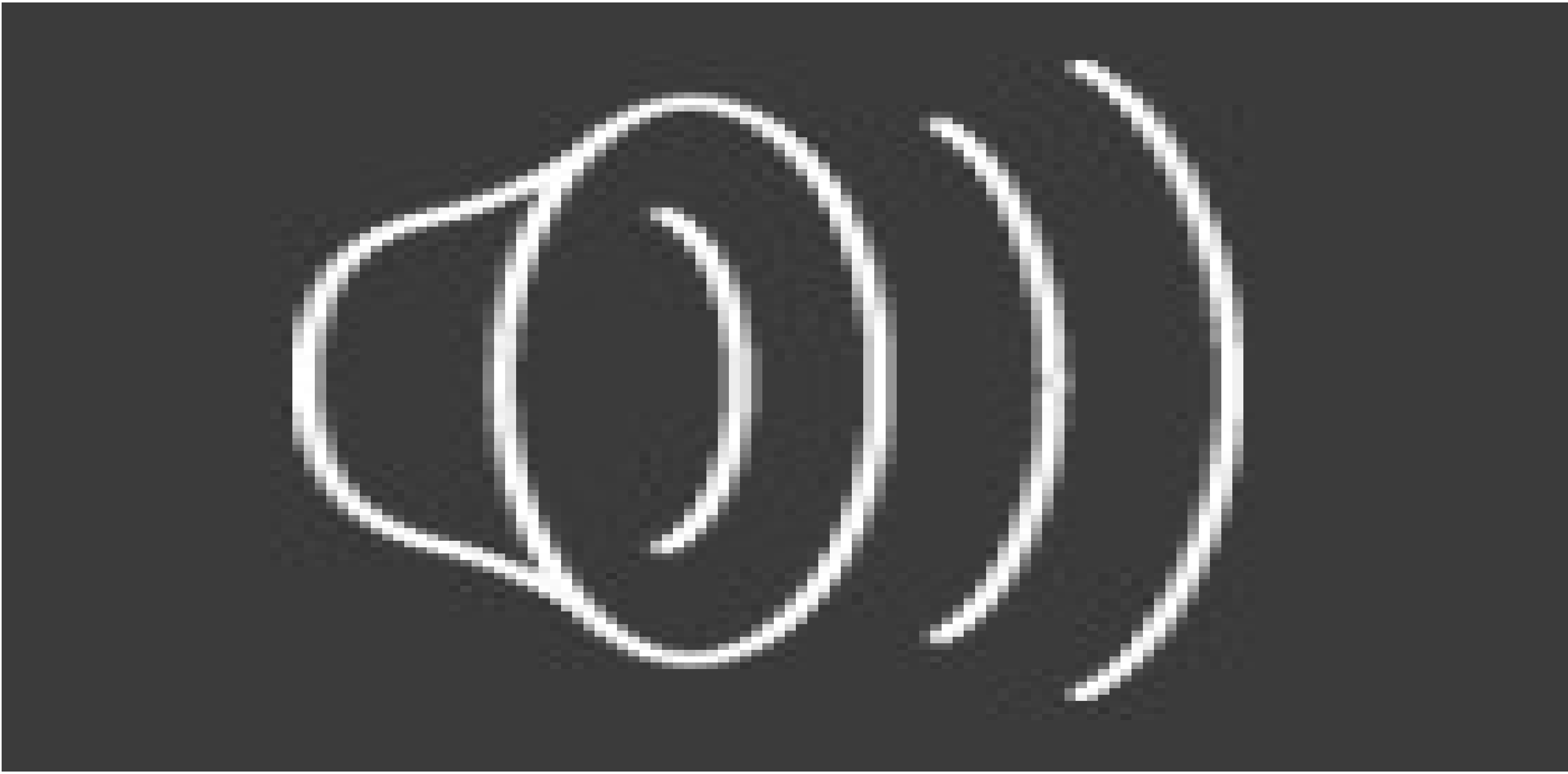
$$= J_R B_z R \sim \frac{dB_\phi}{dz} B_z R$$

=> $$-\frac{1}{2}\rho \Omega_K v_R \approx -\frac{B_z}{4\pi}\frac{dB_\phi}{dz}$$

Flow structure is largely set by the vertical gradient of B_ϕ

Towards realistic simulation of PPDs

2D axisymmetric, all 3 non-ideal MHD effects included, anti-aligned case.

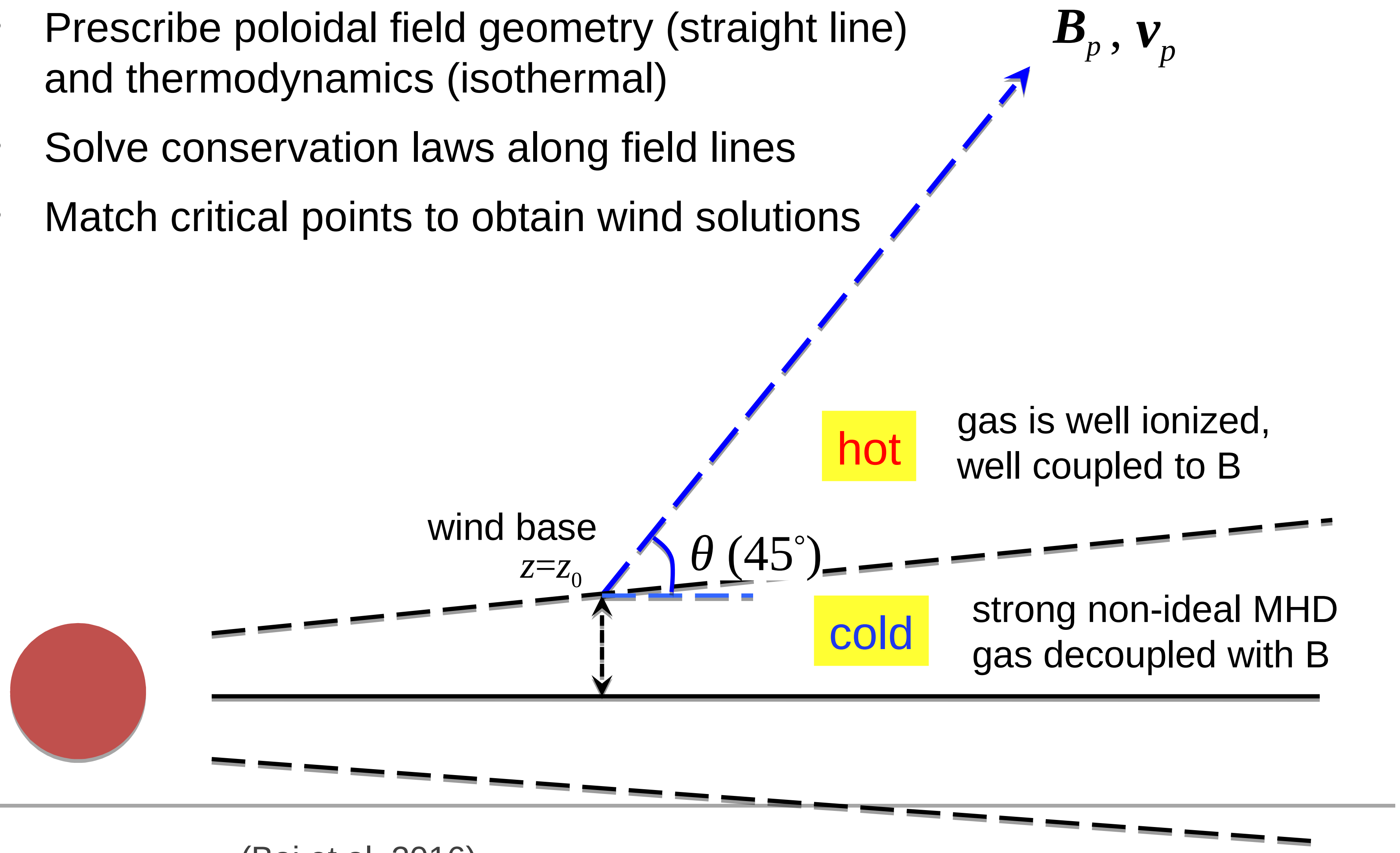


Symmetry breaking, surface accretion flow

Bai, 2017

Wind kinematics and mass loss: toy model

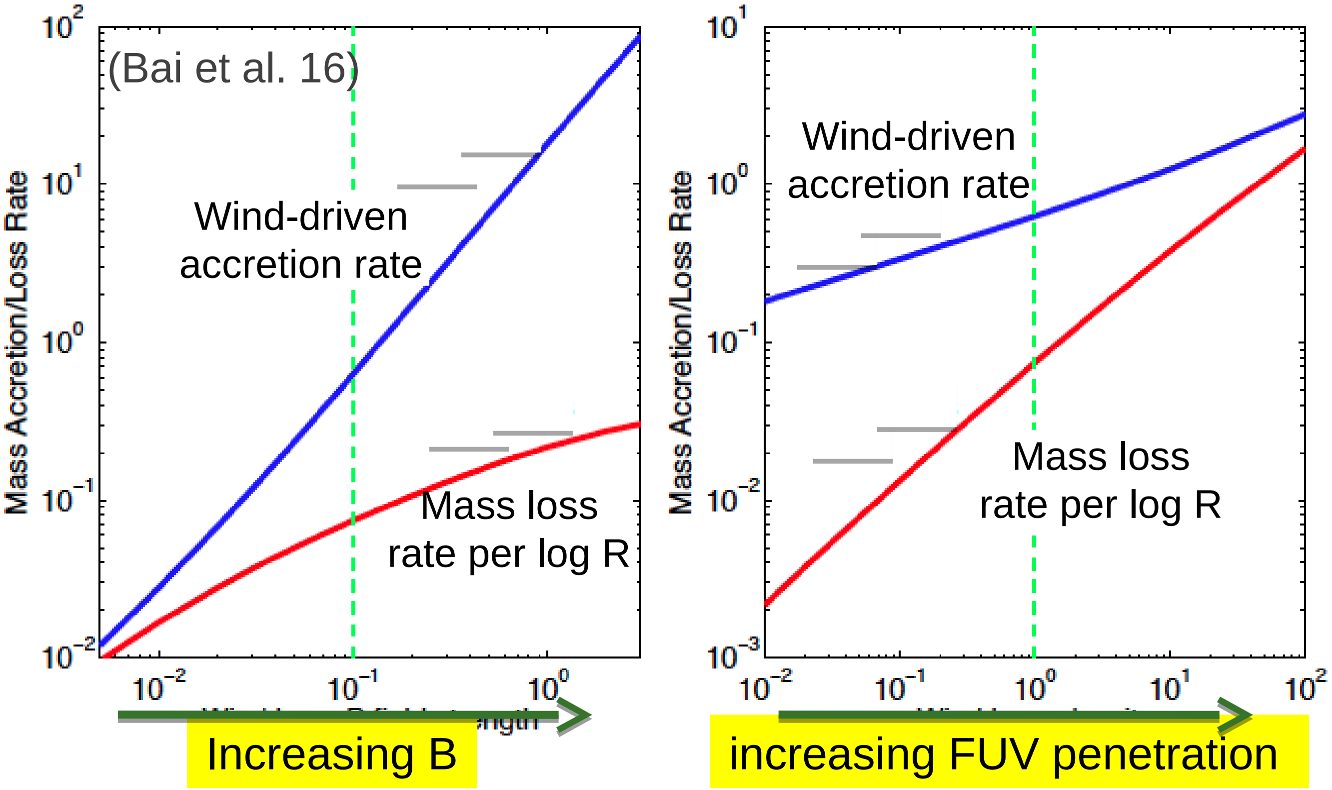
- Prescribe poloidal field geometry (straight line) and thermodynamics (isothermal)
- Solve conservation laws along field lines
- Match critical points to obtain wind solutions



(Bai et al. 2016)

Wind kinematics and mass loss: toy model

Initial study: semi-analytic approach considering external heating/ionization.



(Bai et al. 16)

Wind-driven accretion rate

Mass loss rate per log R

Increasing B

Wind-driven accretion rate

Mass loss rate per log R

increasing FUV penetration

Both B field strength and thermal effects matter:

Magneto-thermal disk wind!

The disk loses about comparable amount of mass through accretion and wind (Bai, 2016).

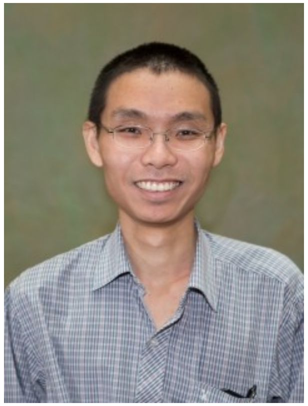
NEW: coupling dynamics+ chemistry (time-dependent)

2D axisymmetric simulations

Ohmic resistivity + ambipolar diffusion

Ray-tracing + full time-dependent chemistry to determine magnetic diffusivities and heating/cooling rates.

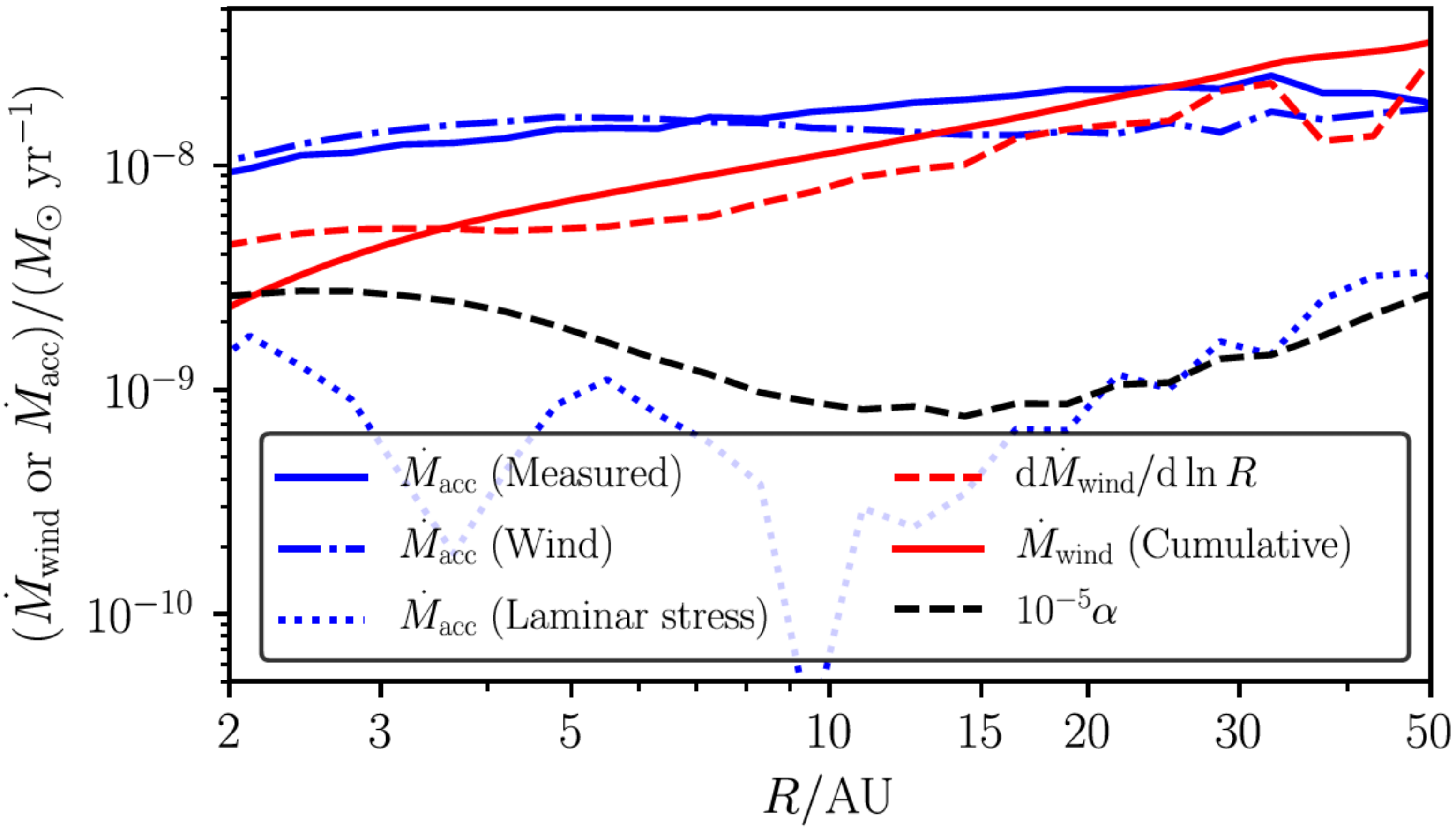
Future: predictions for wind observations.



Lile Wang (Princeton->CCA)

(Wang, Bai & Goodman, in prep)

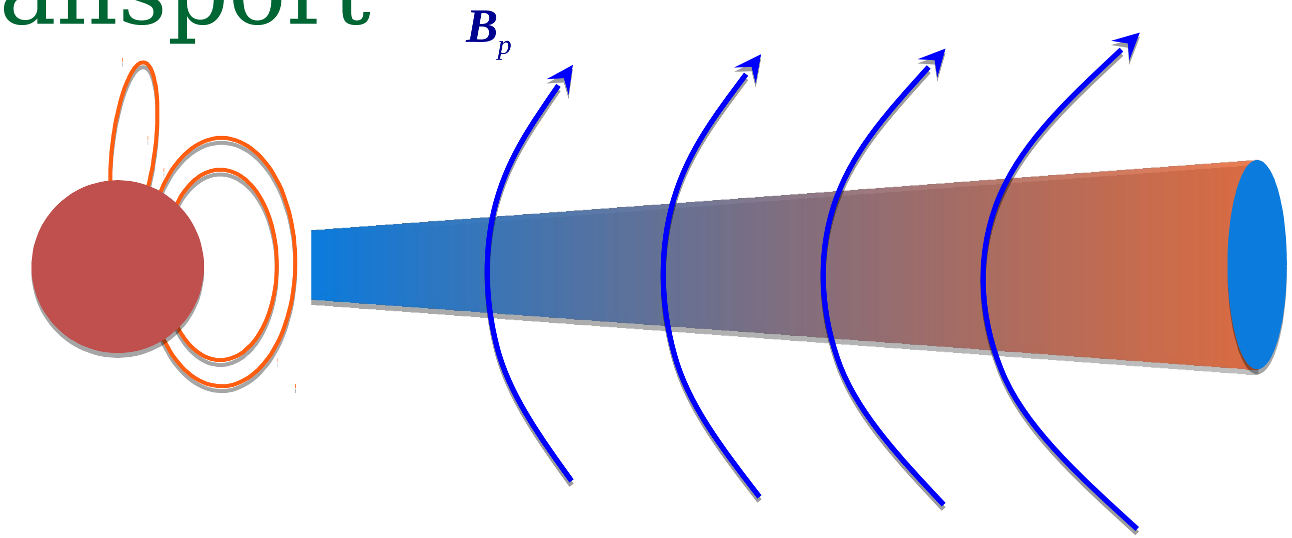
Accretion vs. mass loss



Mass loss is indeed comparable to wind-driven accretion rates.

(Wang, Bai & Goodman, in prep)

More fundamental problem: B flux transport



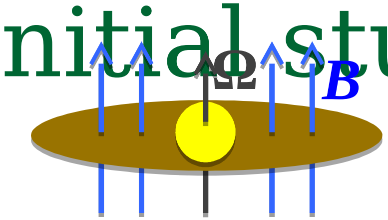
Conventional picture:

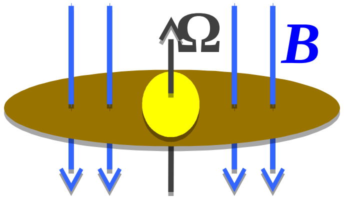
- Accretion advects flux inward.
- Resistivity/turbulence diffuses flux outward.

Advection-diffusion framework (Lubow+94) with more recent development (Guilet & Ogilvie 12-14, Okuzumi,Takeuchi+14)

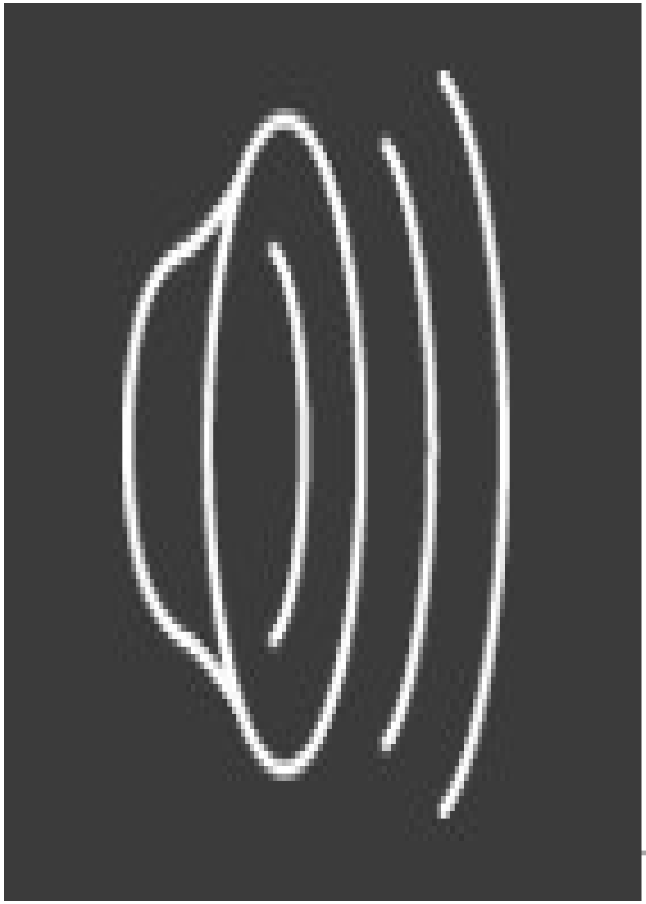
Need to incorporate wind and other non-ideal MHD physics (Bai, 14)

How does magnetic flux evolve: initial study

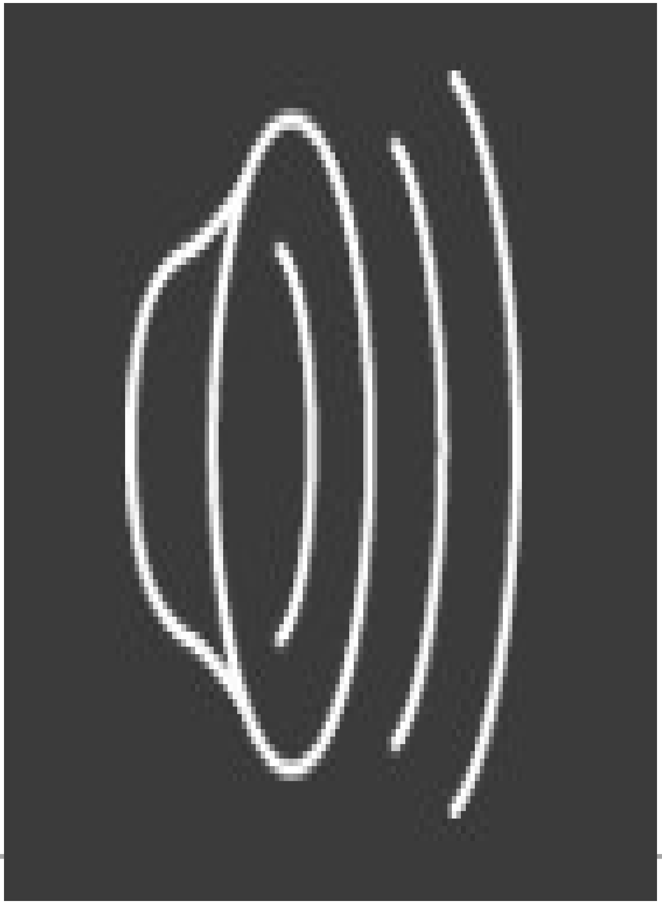




Bai & Stone, 2017



Slow outward transport



Rapid outward transport

In 2D, controlled experiment:

Hall-dominated midplane

+

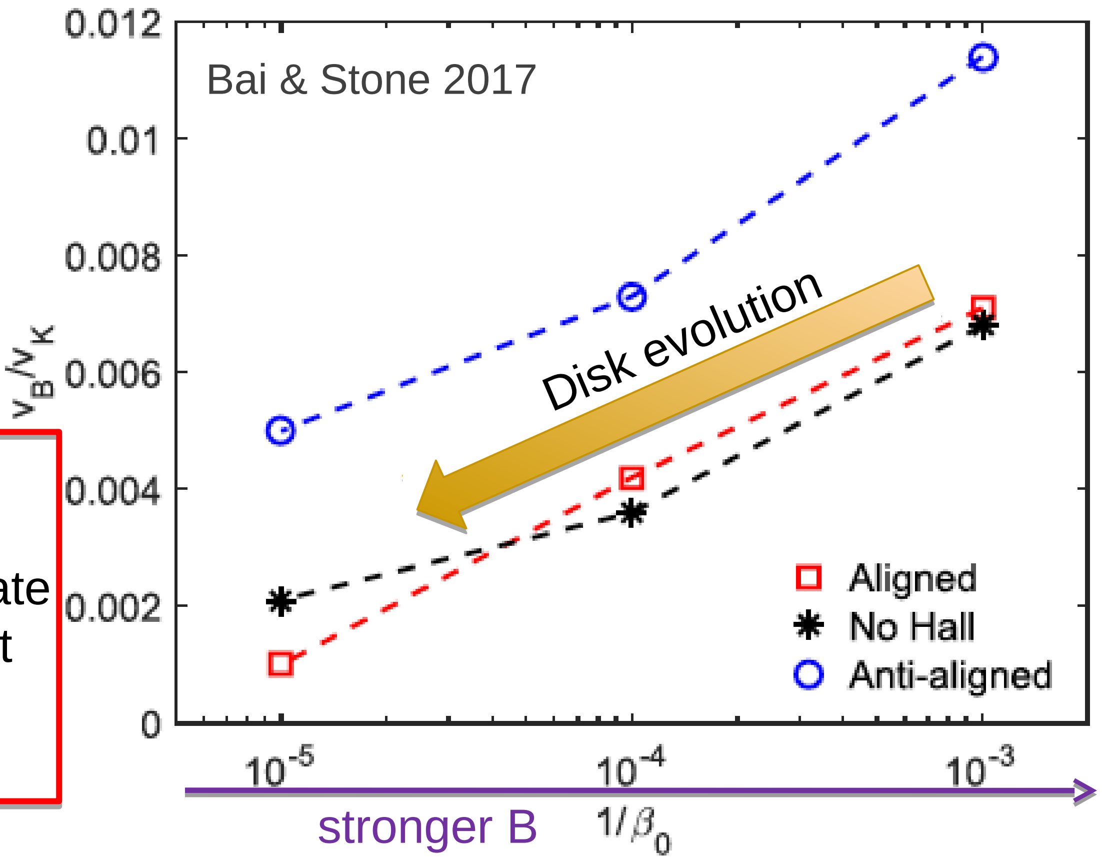
AD-dominated surface

+

ideal MHD wind zone

Rate of flux transport

As controlled experiments, we focus on general trends.



Late phase:

weak B flux

↓

low accretion rate

slow transport

↓

long-lived

Early phase:

strong B flux

↓

high accretion rate

fast transport

↓

short-lived

Bai & Stone, 2017

Summary

- Non-ideal MHD effects associated with weak ionization, are essential for understanding PPD gas dynamics.
- Paradigm shift from MRI-driven disk evolution to wind-driven disk evolution.
- The Hall effect makes gas dynamics dependent upon B field polarity, giving complex and unusual flow patterns.
- The disk wind is magneto-thermal in nature, with significant mass loss comparable to accretion rate.
- Eventually, disk evolution is governed by the evolution of poloidal magnetic flux threading the disk.