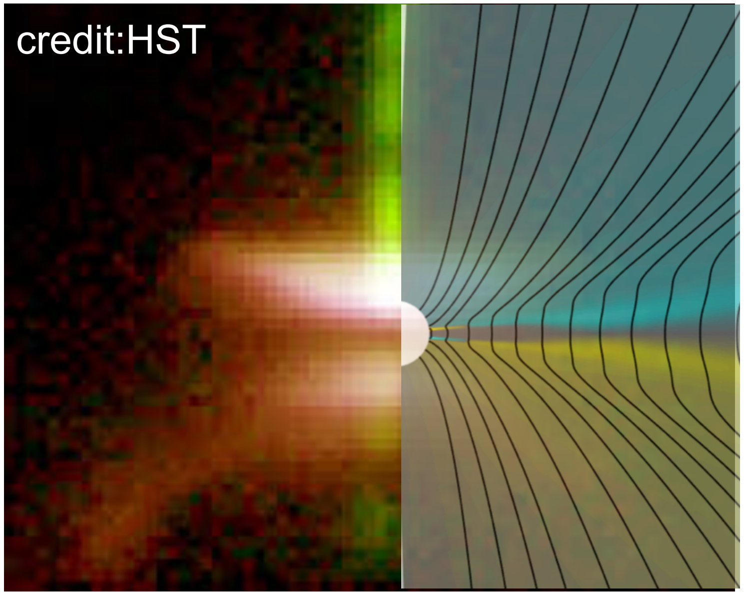
Confronting MHD Accretion Theory with Observations, 02/06/2017

Towards Realistic Simulations of Protoplanetary Disks



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With thanks to J. Stone and J. Goodman

Outline

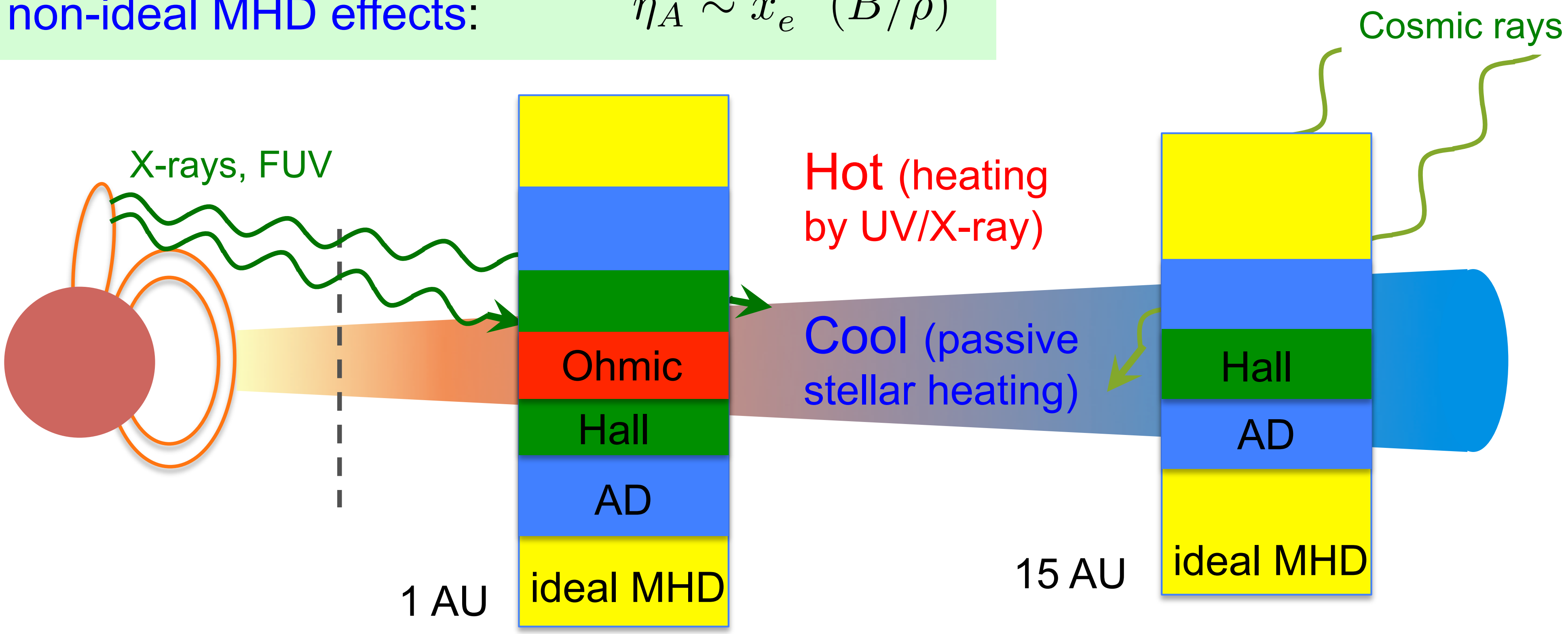
- Summary of recent development and outstanding Issues
- Kinematics of PPD disk winds
- Magnetic flux evolution in PPDs
- Towards realistic simulations
- Summary

Main physical ingredients

1. The bulk disk is heated by irradiation (T_{disk} is passively determined).
2. The bulk disk is externally ionized, with very low ionization degree.
3. The disk surface is substantially hotter and much better ionized.

With B field, its coupling to the gas is described by non-ideal MHD effects:

$$\eta_O \sim x_e^{-1}$$
$$\eta_H \sim x_e^{-1}(B/\rho)$$
$$\eta_A \sim x_e^{-1}(B/\rho)^2$$



Importance of net B_z and disk winds

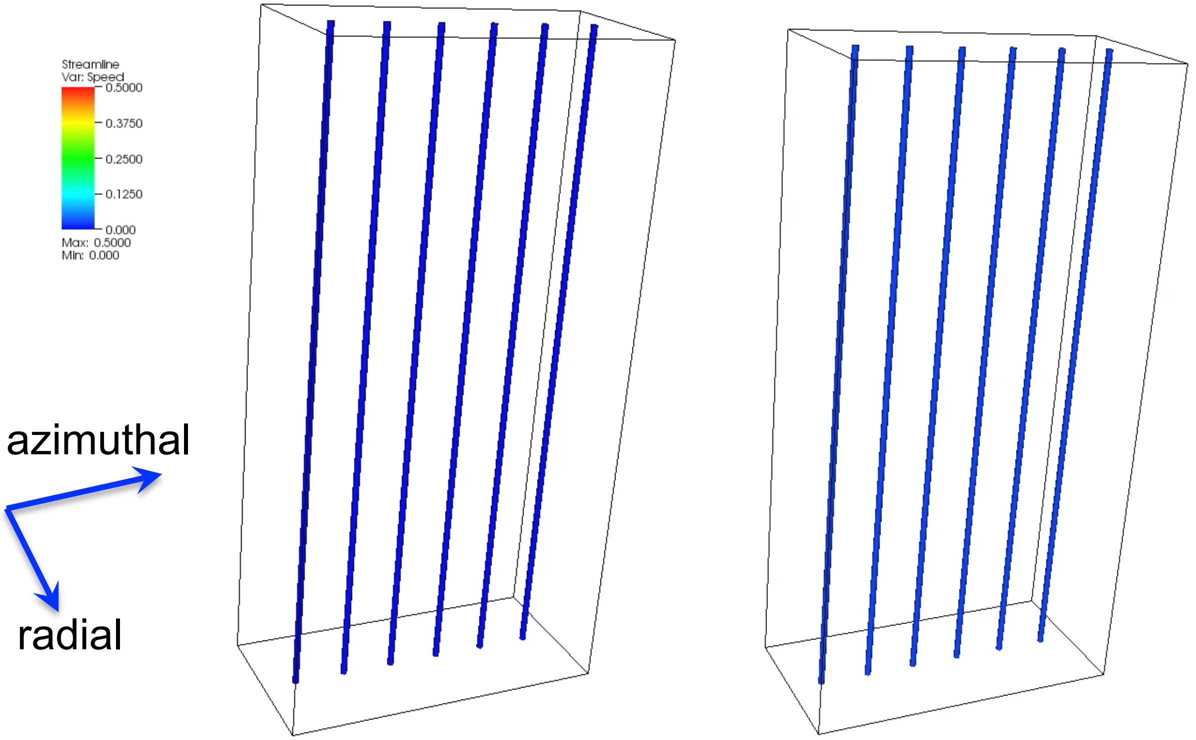
When all non-ideal MHD effects are taken into account, the MRI is largely suppressed throughout the bulk disk without net B_z.

With net B_z, launching a disk wind/outflow is a natural consequence.

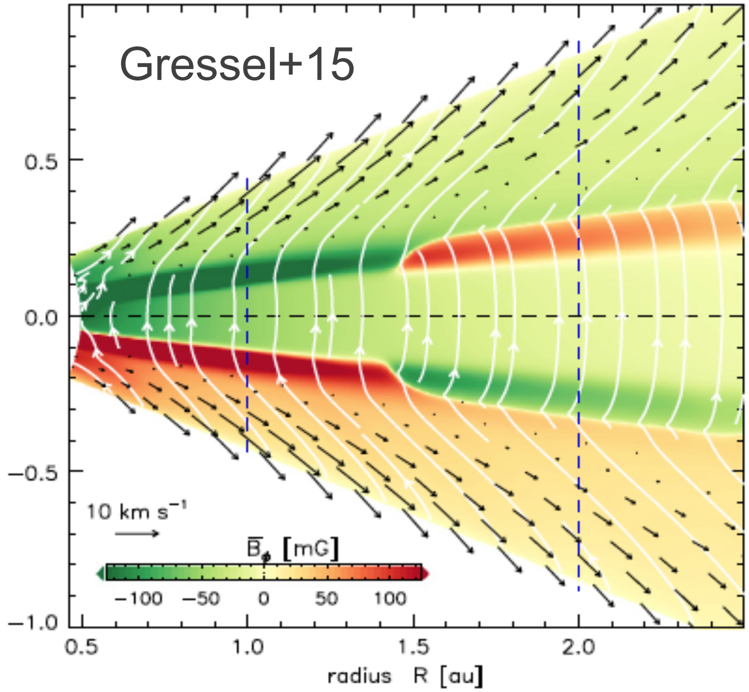
(Bai & Stone 13b, Simon, Bai+ 13a,b)

Ohmic ONLY Ohmic + AD

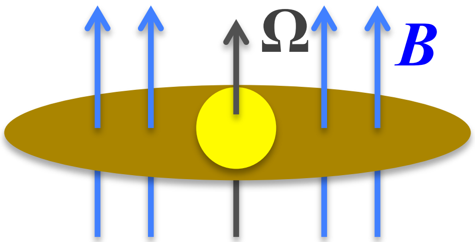
color: field strength



(Bai & Stone, 2013b)

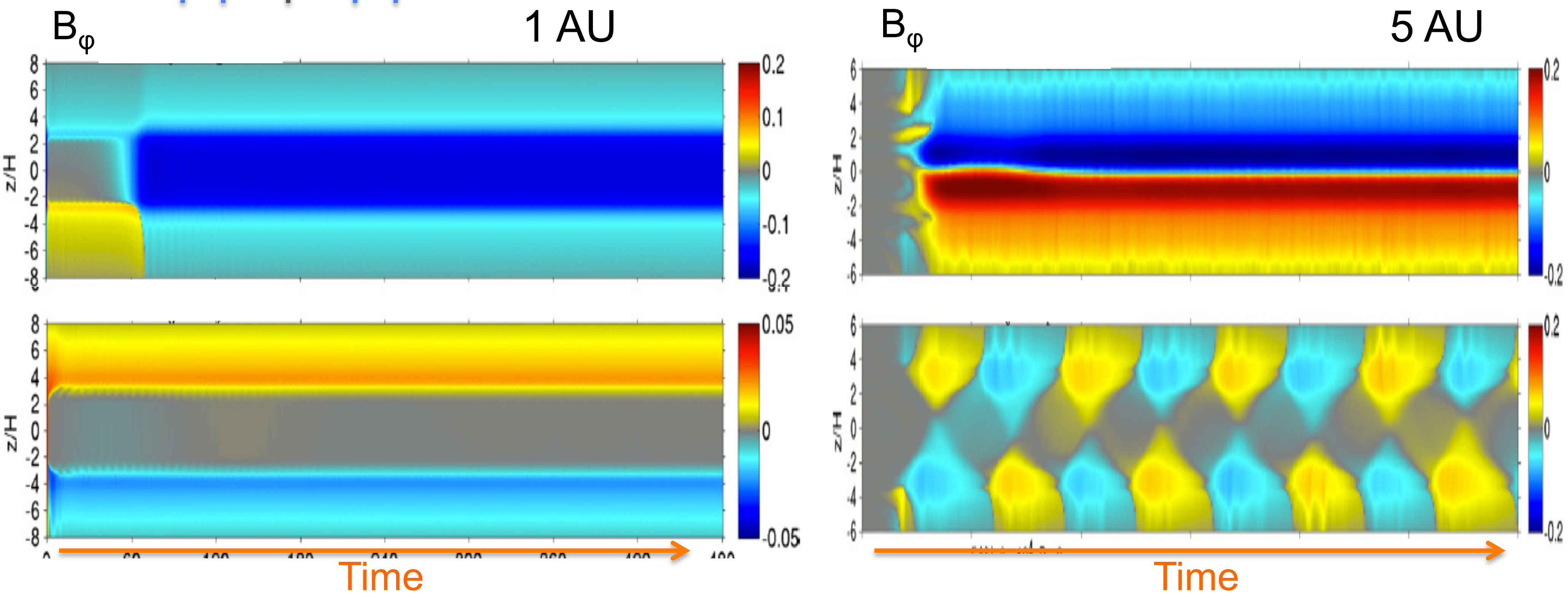


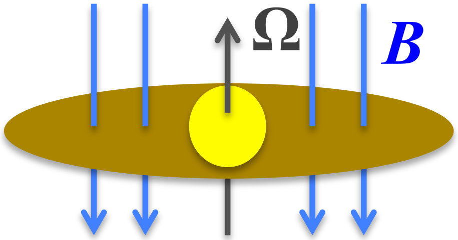
The Hall effect and internal disk dynamics



Hall-shear instability amplifies horizontal field.

(Kunz 08, Lesur+14, Bai 14,15, Simon+15)





Horizontal field is reduced towards zero at midplane.

Outstanding issues

- 1. Wind kinematics.

  How rapid do PPDs lose mass?

  What is the relation with photo-evaporation?

  What are the observational signatures?

- 2. Origin and transport of magnetic flux.

  Where is net B_z coming from?

  How is B flux distributed?

  How does B flux evolve through the disk?

- 3. Angular momentum transport and flow structure.

  What drives disk accretion (contribution from wind vs. Maxwell stress)?

  What is the flow structure in the disk?

  Are the flows symmetric about the disk midplane?

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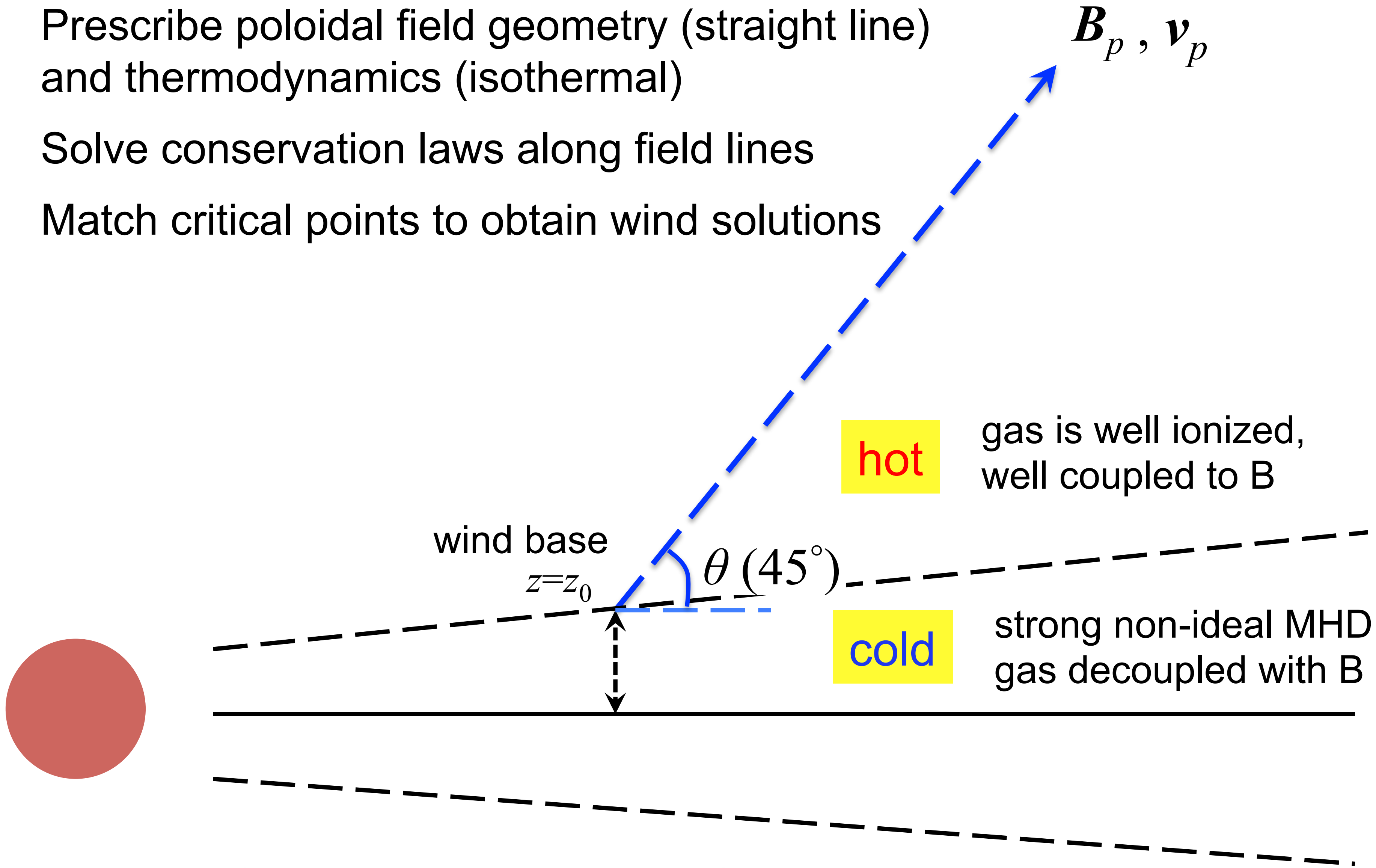
A semi-analytical model of PPD disk wind

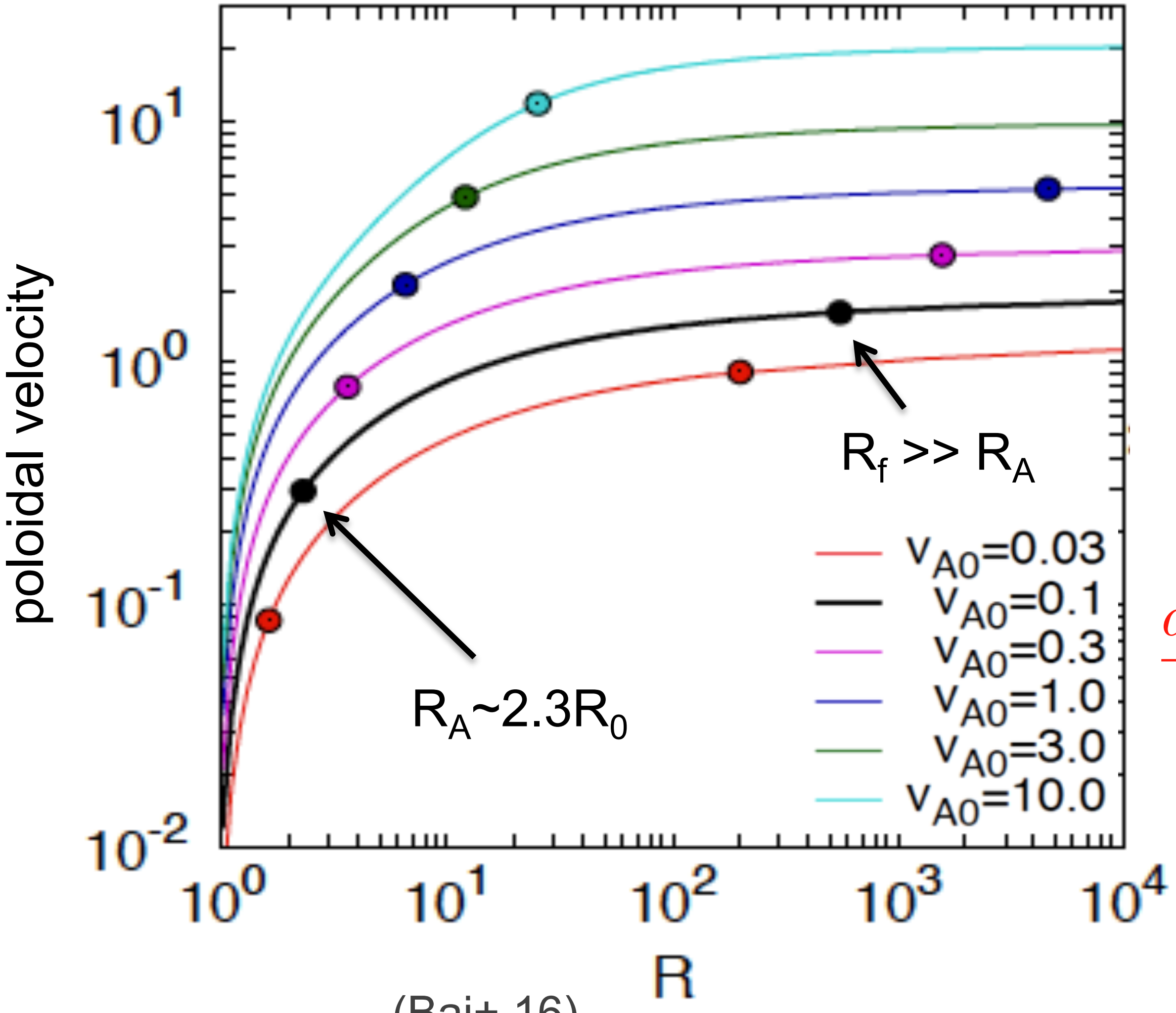
- Prescribe poloidal field geometry (straight line) and thermodynamics (isothermal)
- Solve conservation laws along field lines
- Match critical points to obtain wind solutions



(Bai, Ye, Goodman, Yuan, 2016)

a). Alfven radius and mass loss rate

Expected wind launching conditions @ 1AU: $v_{A0} \approx 0.1 v_K$ (black)



(Bai+ 16)

Alfven radius R_A:

$$v_p = v_{Ap}$$

Specific angular momentum:

$$l \approx \Omega_0 R_A^2$$

$$\frac{d\dot{M}_{\rm wind}/d\ln R}{\dot{M}_{\rm acc}} = \frac{1}{2}\frac{1}{(R_A/R_0)^2 - 1}$$

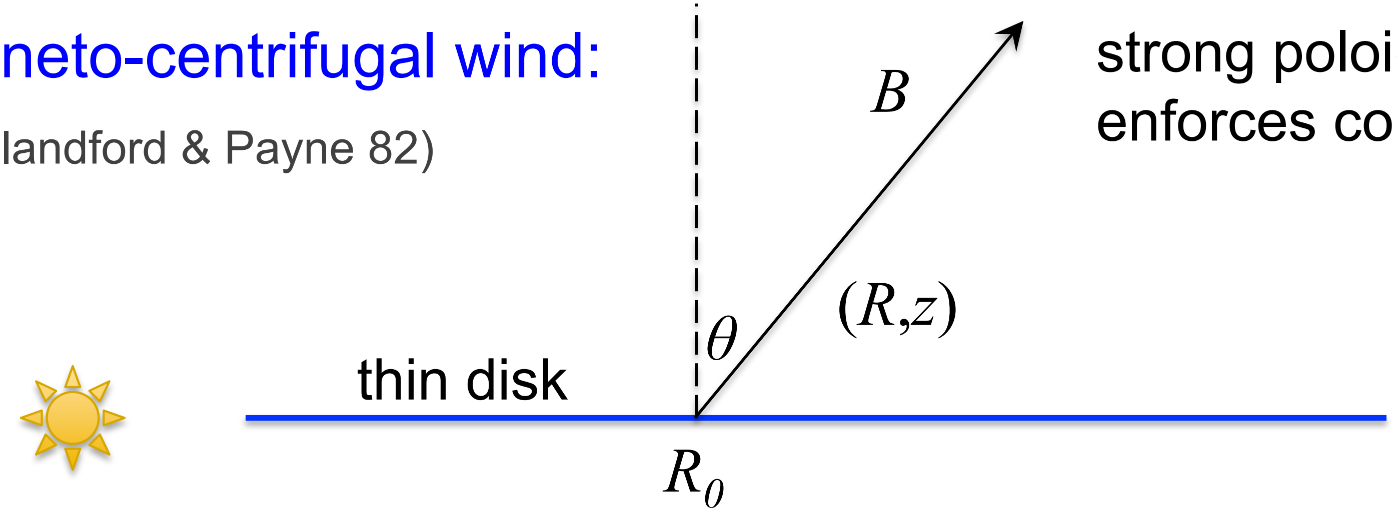
$\sim$ 0.1-0.2

Update: can be more significant.

Two flavors of magnetized disk wind

Magneto-centrifugal wind:

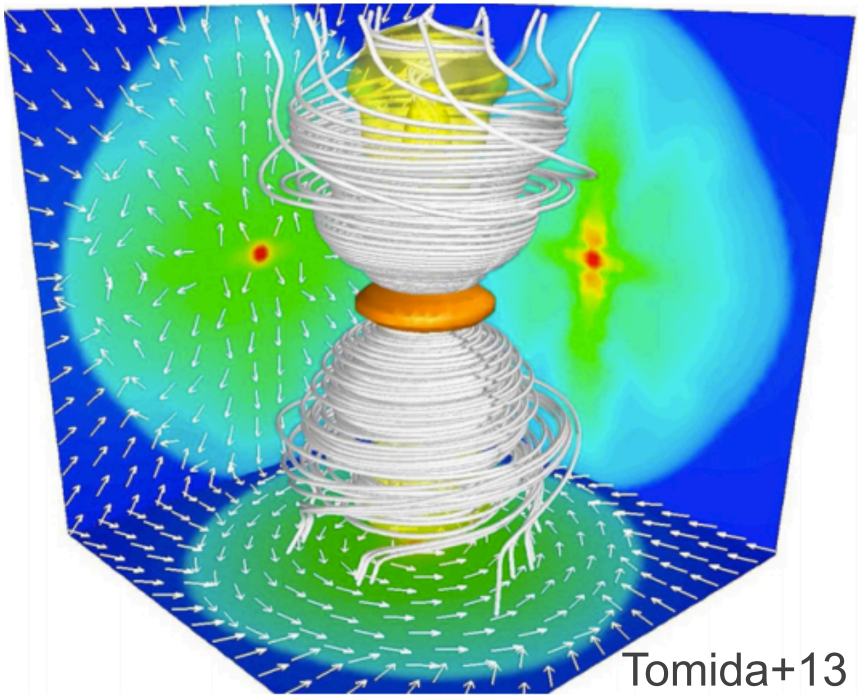
(Blandford & Payne 82)



strong poloidal field
enforces corotation.

“Magnetic tower”: (e.g. Lynden-Bell 03)

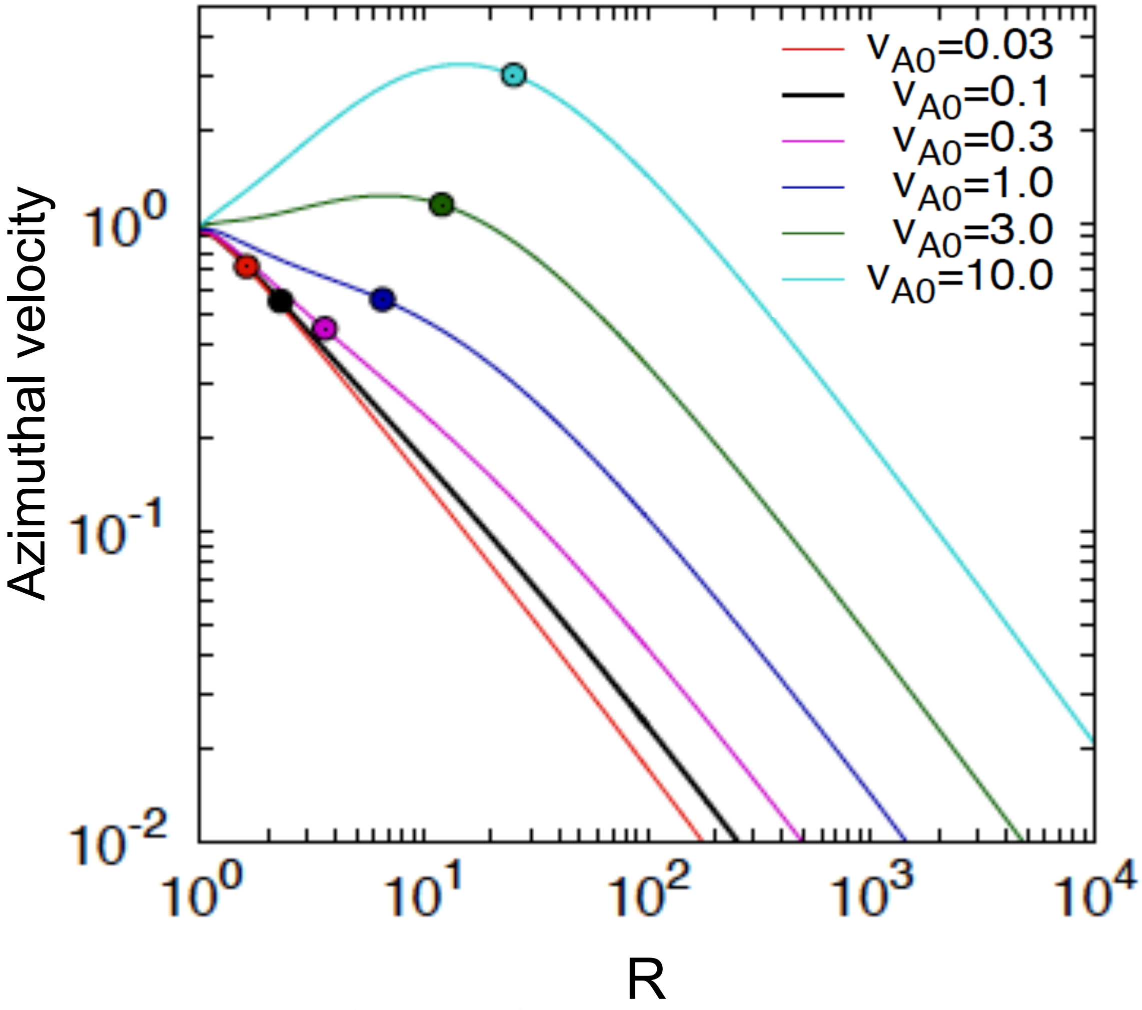
Weak poloidal field shear-amplified & twisted, outflow driven by magnetic pressure gradient (of toroidal field).



Tomida+13

b). Wind driving mechanism

Expected wind launching conditions @ 1AU: $v_{A0} \approx 0.1 v_K$

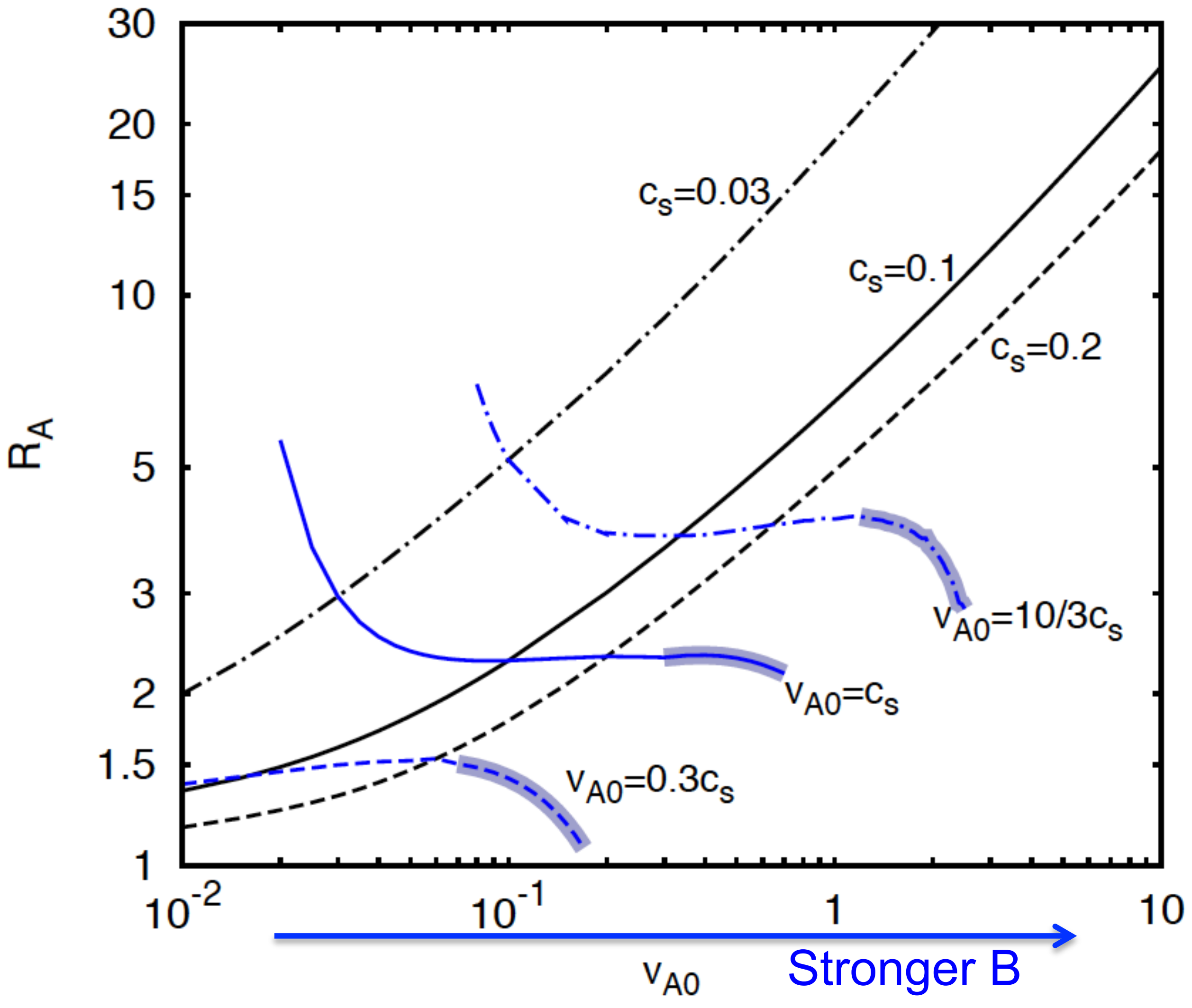


(Bai+ 16)

Corotation NOT enforced unless B_p unrealistically-strong

Implication: near wind base, not easily distinguishable from Keplerian rotation.

c). Thermal effect: magneto-photoevaporation?



(Bai+ 16)

The Alfvén radius strongly depends on

$$v_{A0}/c_s$$

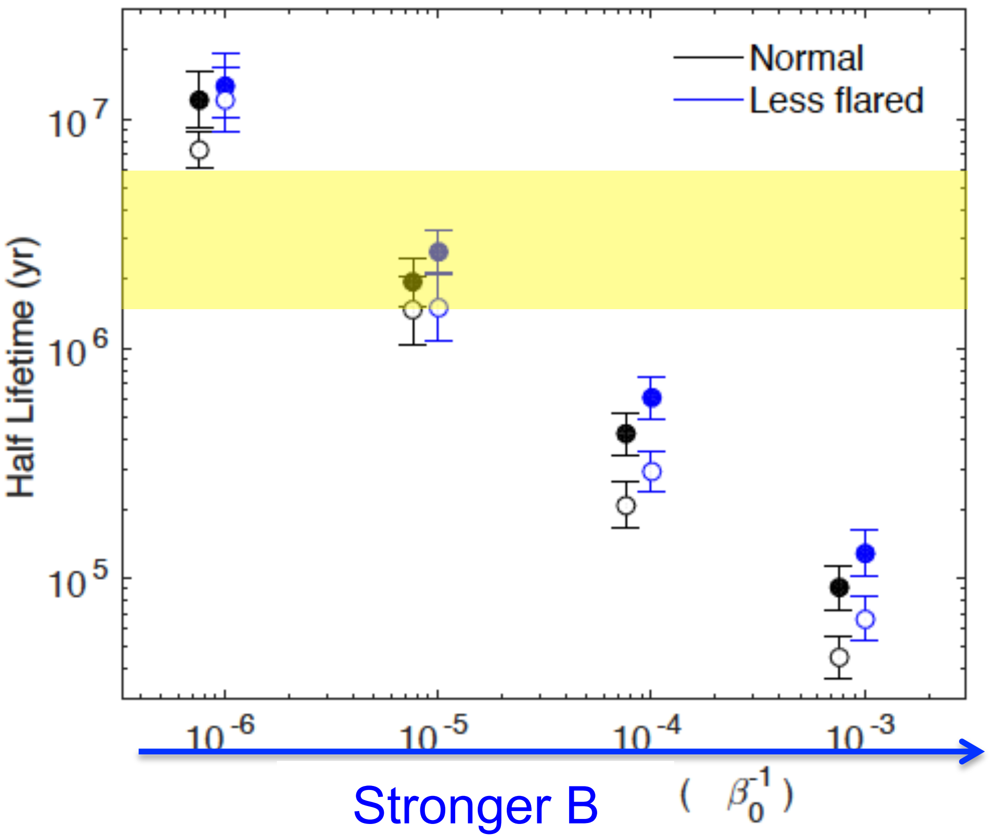
B field strength

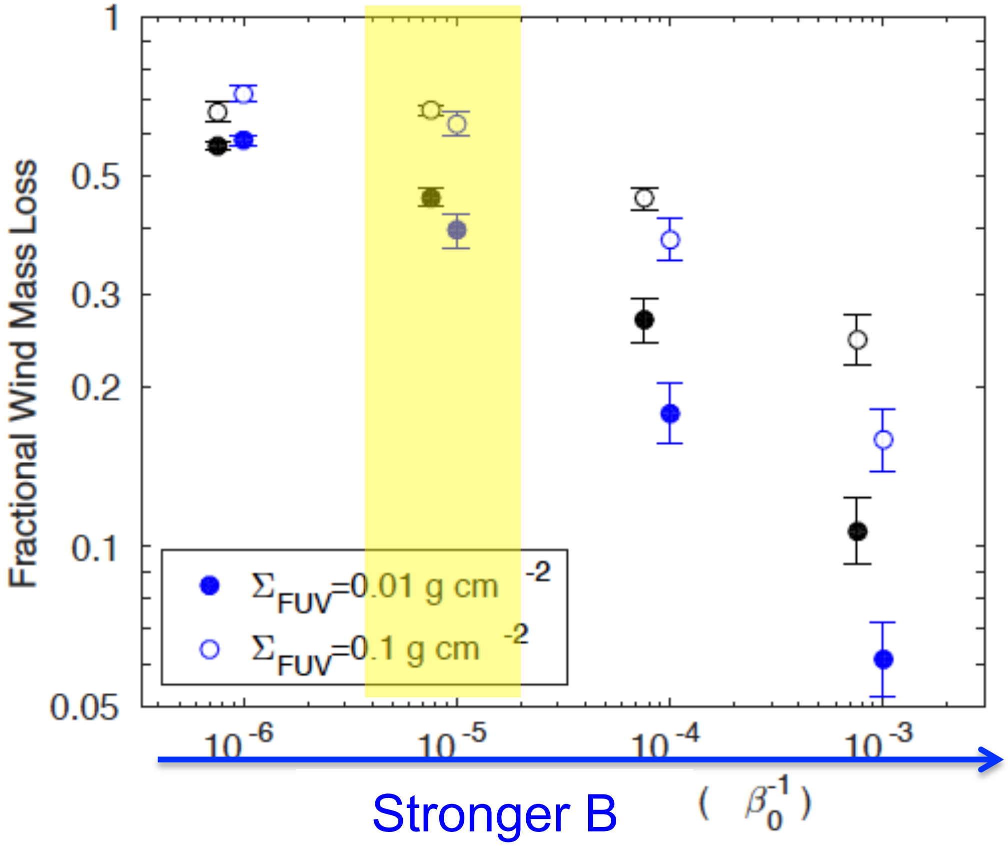
External heating

Both effects strongly affect the efficiency of wind-driven accretion!

Evolution timescale and fractional mass loss

(Bai, 2016)



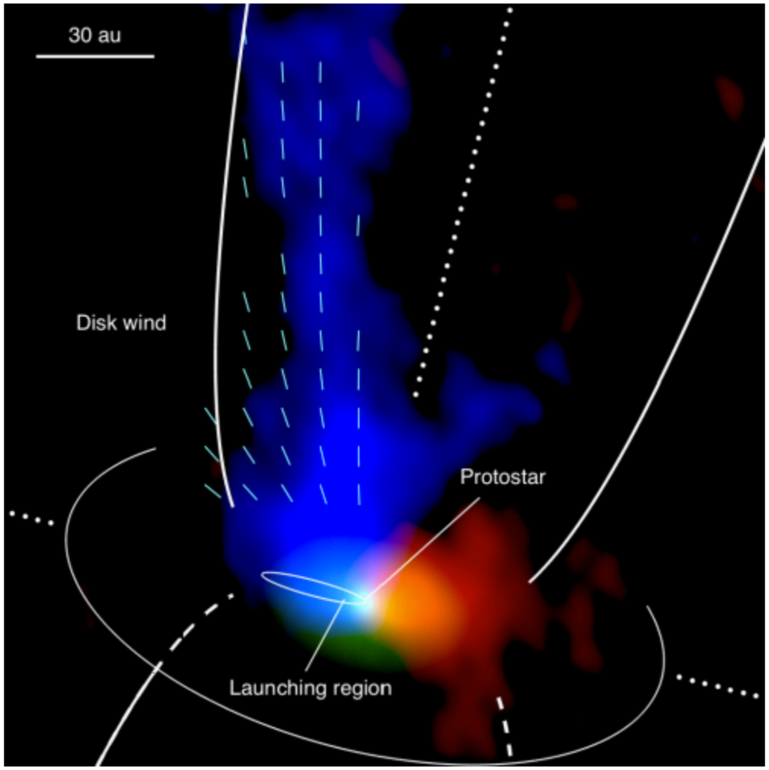


The disk loses comparable or more mass through wind than through accretion.

Dust settle towards midplane => enhance dust-to-gas ratio => promote planet formation

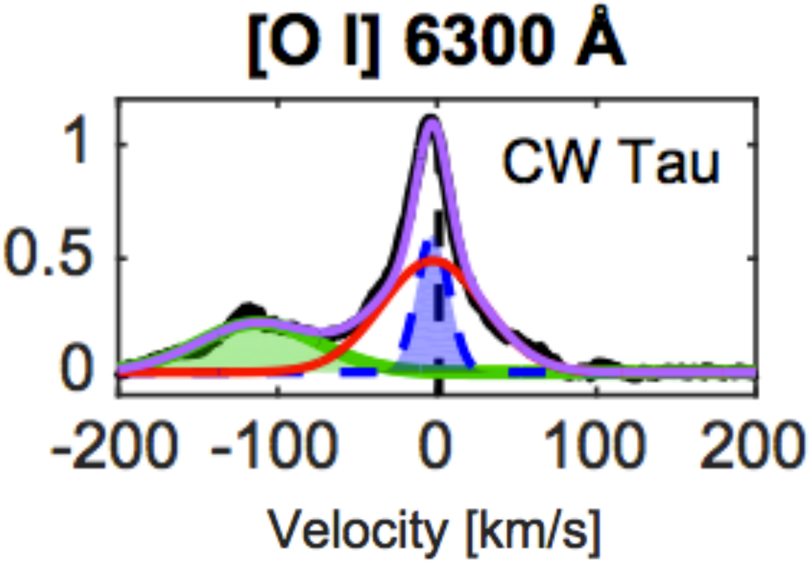
Observational evidence of disk wind

Large-scale CO outflow in a young system



Bjerkeli+16

Forbidden line emission:



Simon, Pascucci+16

(See also Hargitan+95, Pontoppidan+11, Bast+11, Herczeg+11, Brown+13, Rigliaco+13, Natta+14 …)

- The broad and narrow components of the low velocity component correspond to wind launched from ~0.05-0.5 AU and ~0.5-5 AU.
- Inferring mass loss rate is extremely difficult. Mass loss rate from the inner disk may reach ~0.1-1 M_{acc} (Natta+14).

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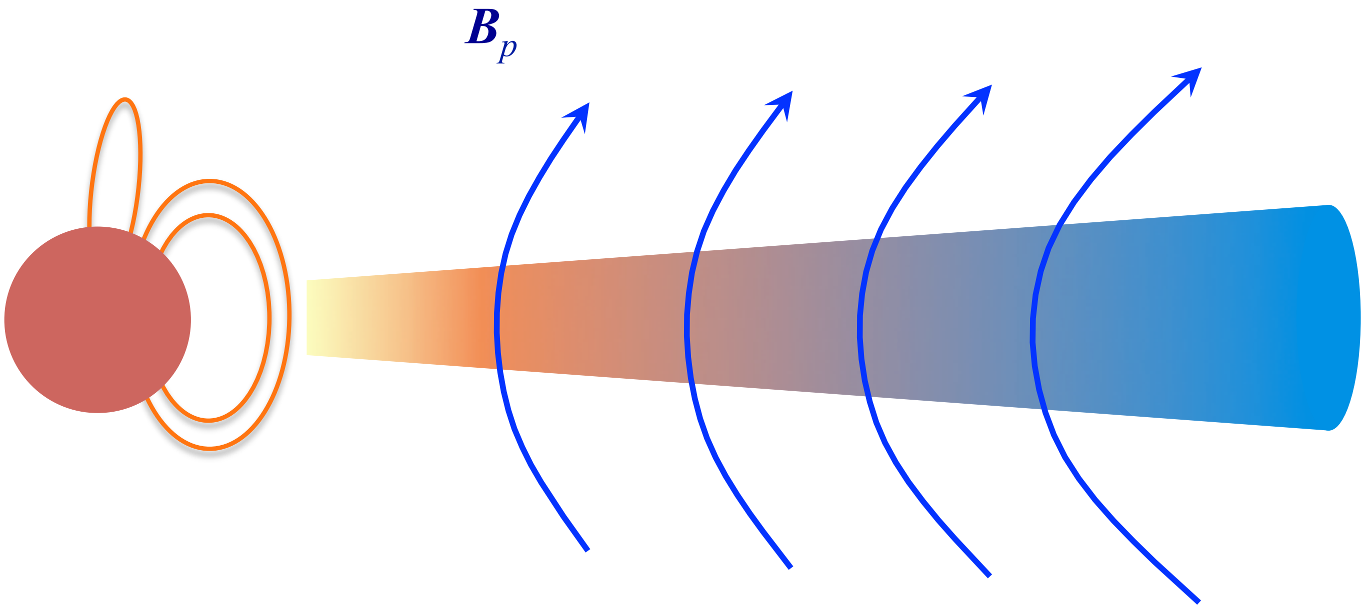
Magnetic flux transport: conventional theory



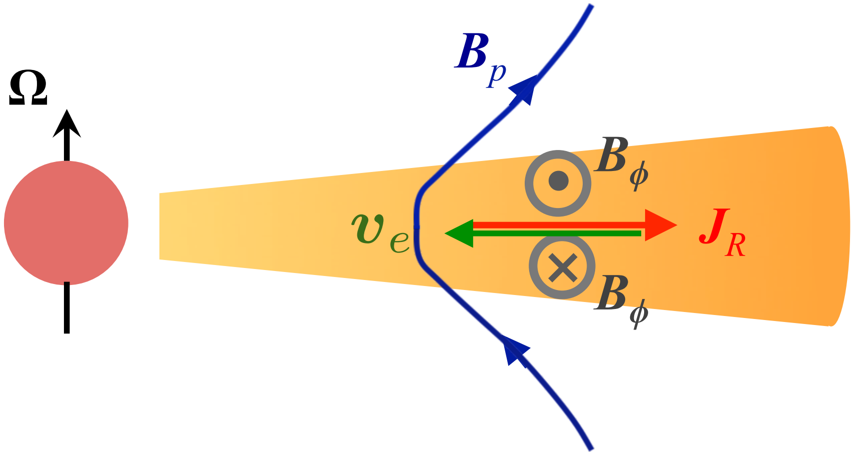
- Accretion advects flux inward.
- Resistivity/turbulence diffuses flux outward.

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

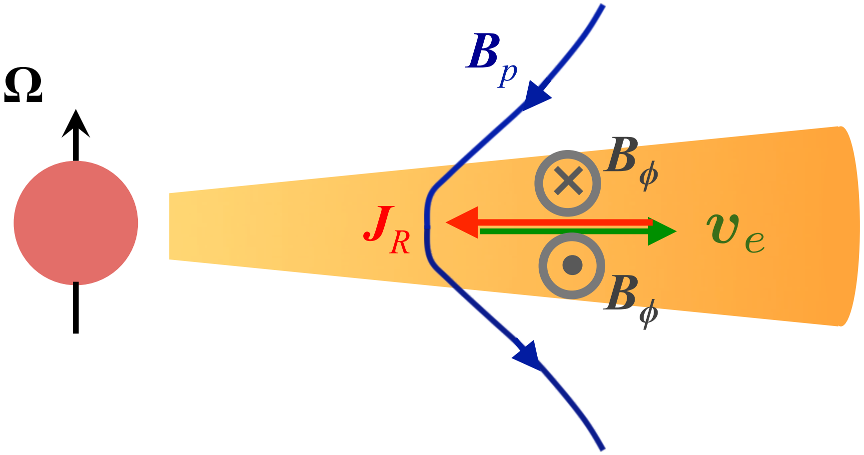
Need to incorporate wind and other non-ideal MHD physics (Bai, 14)

Hall-effect-induced magnetic flux transport

In Hall dominated regime, B flux transport governed by electron-ion drift.



Inward transport at midplane



Outward transport at midplane

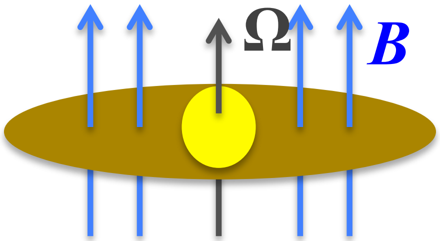
The Hall effect leads to polarity dependent transport of magnetic flux in PPDs!

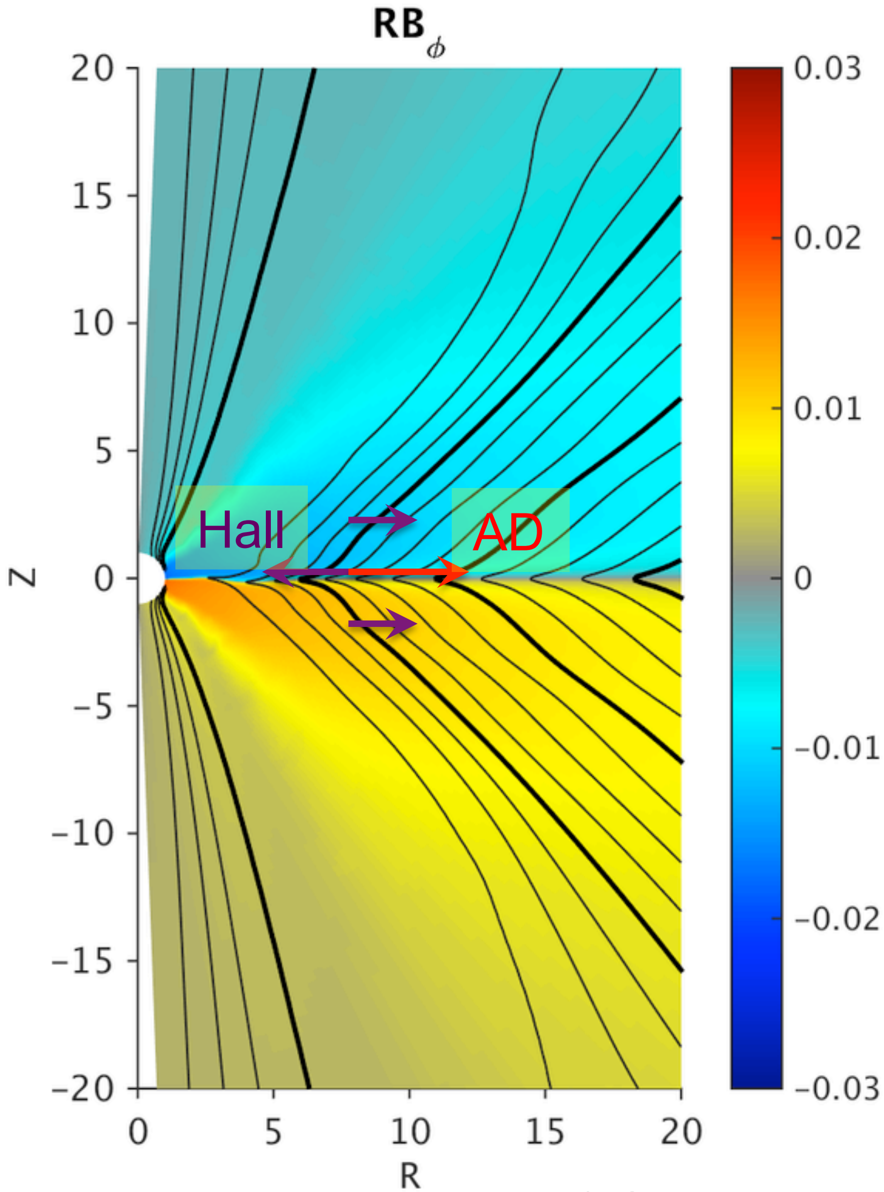
Beyond midplane, direction of transport depends on vertical gradient of B_ϕ, which can be more subtle.

Controlled experiments on B flux transport

Physically motivated diffusivity profile for outer disks (>10 AU):

Midplane is Hall dominated, transition to AD dominated upper layer up to ~2H





Bai & Stone 2017

B flux rapidly advected radially inward at midplane, but outward otherwise.

Global manifestation of the Hall-shear instability (Kunz 08, Lesur+14, Bai 14,15)

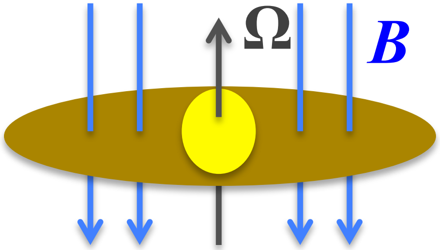
AD diffuse B flux outward at midplane.

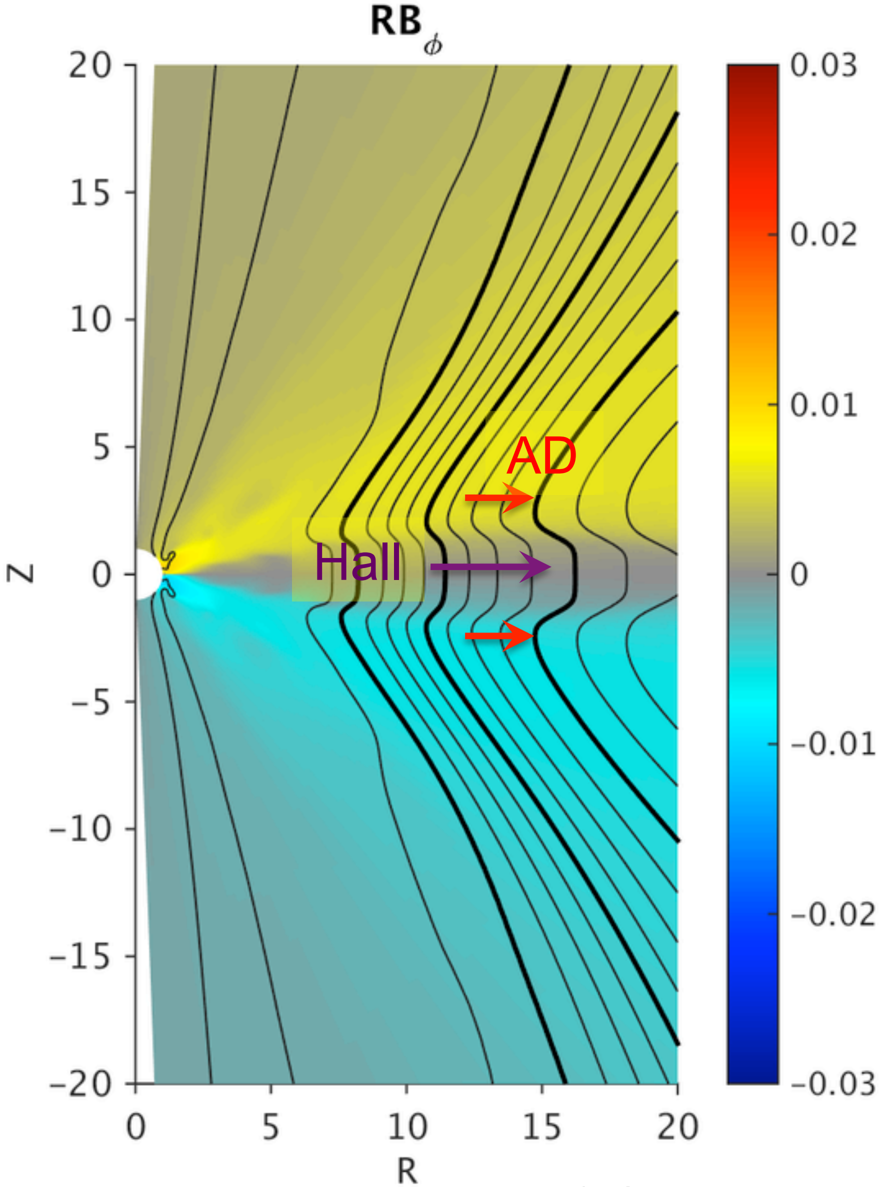
In the end: slow outward transport.

Controlled experiments on B flux transport

Physically motivated diffusivity profile for outer disks (>10 AU):

Midplane is Hall dominated, transition to AD dominated upper layer up to ~2H





Bai & Stone 2017

B flux is advected radially outward near the disk midplane.

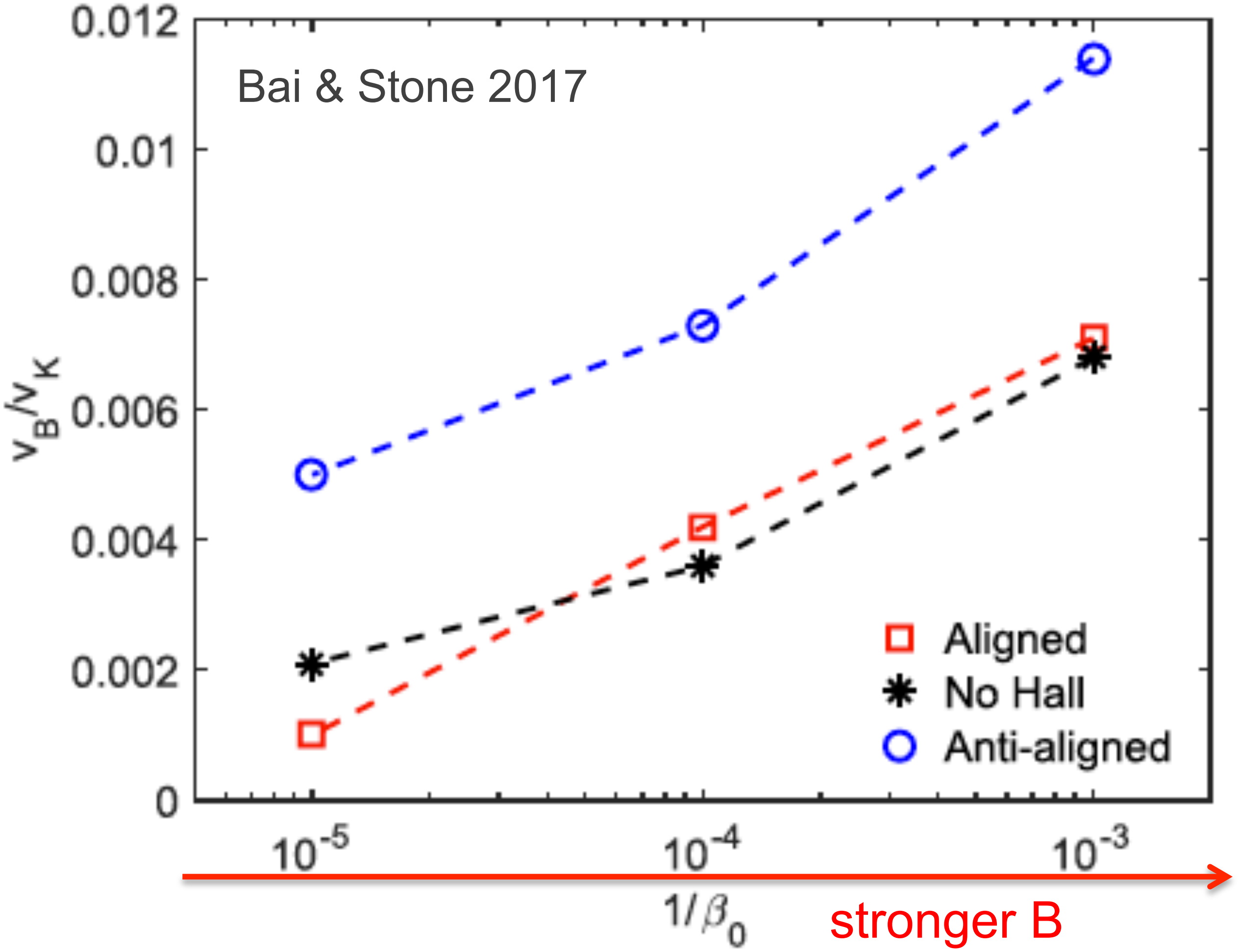
B field is largely vertical at midplane (Bai 14,15)

AD catches up at upper layers and transports B flux outwards.

In the end: rapid outward transport.

Parameter dependence

As controlled experiments, we focus on general trends.

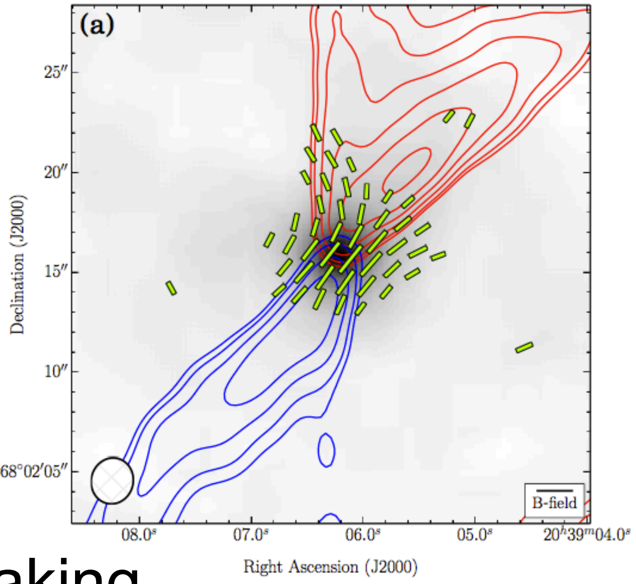

Bai & Stone 2017

stronger B

Anti-aligned case loses flux about 2 times as fast.

Outward flux transport is faster with stronger magnetization.

Implications on disk formation



- Protostellar cores threaded by strong B field

  (e.g. Crutcher, 12, Hull+13)

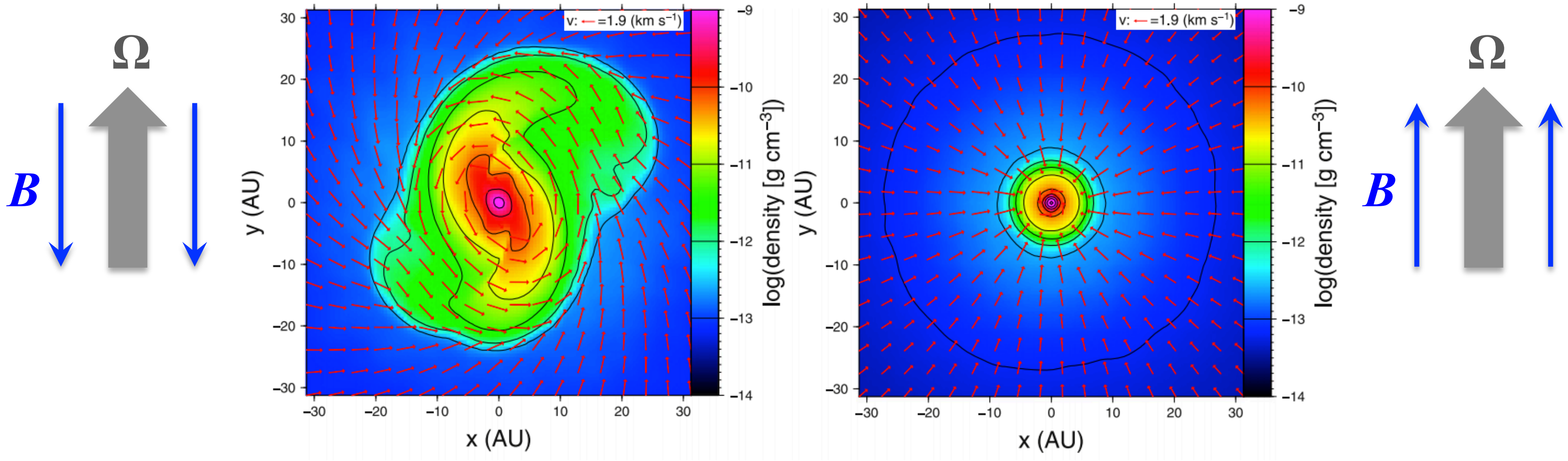
- ~100 AU disk formation in class 0 phase

  (e.g., Tobin+12,15,Murillo+13,Ohashi+14,Harsono+14,Yen+15)

- Disk formation must avoid strong magnetic braking.

(e.g. Mellon & Li08, Machida+10, Santos-Lima+11, Seifried+12,13, Joos+12,13, Li+13, Tomida+13,15)

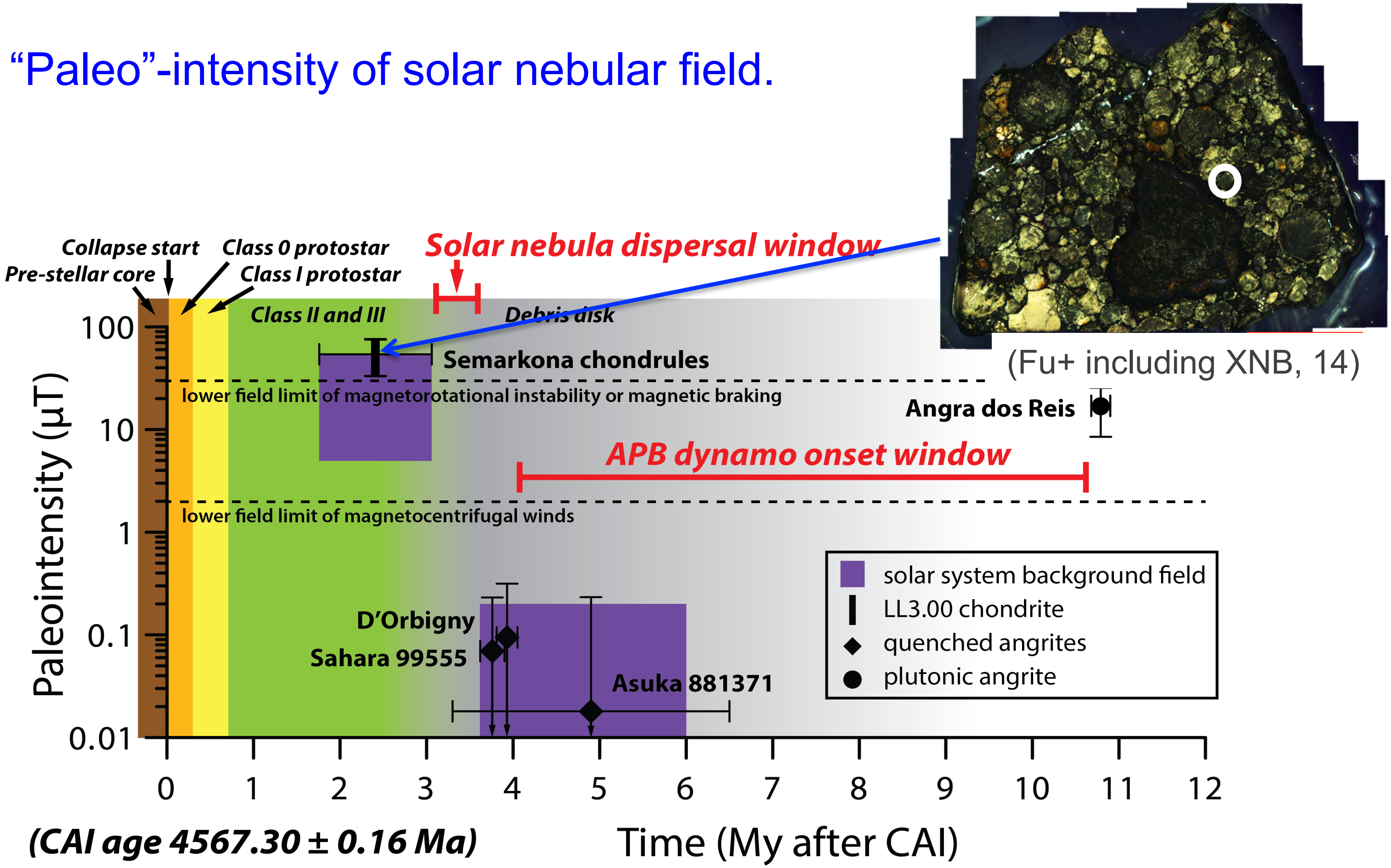
- Hall-effect induced bimodality: (Tsukamoto+15, Wurster+16)



Consistent with different rates of B flux transport for the two polarities.

Magnetic field “observations”

“Paleo”-intensity of solar nebular field.



(Fu+ including XNB, 14)

(Wang, Weiss, Bai+, in press)

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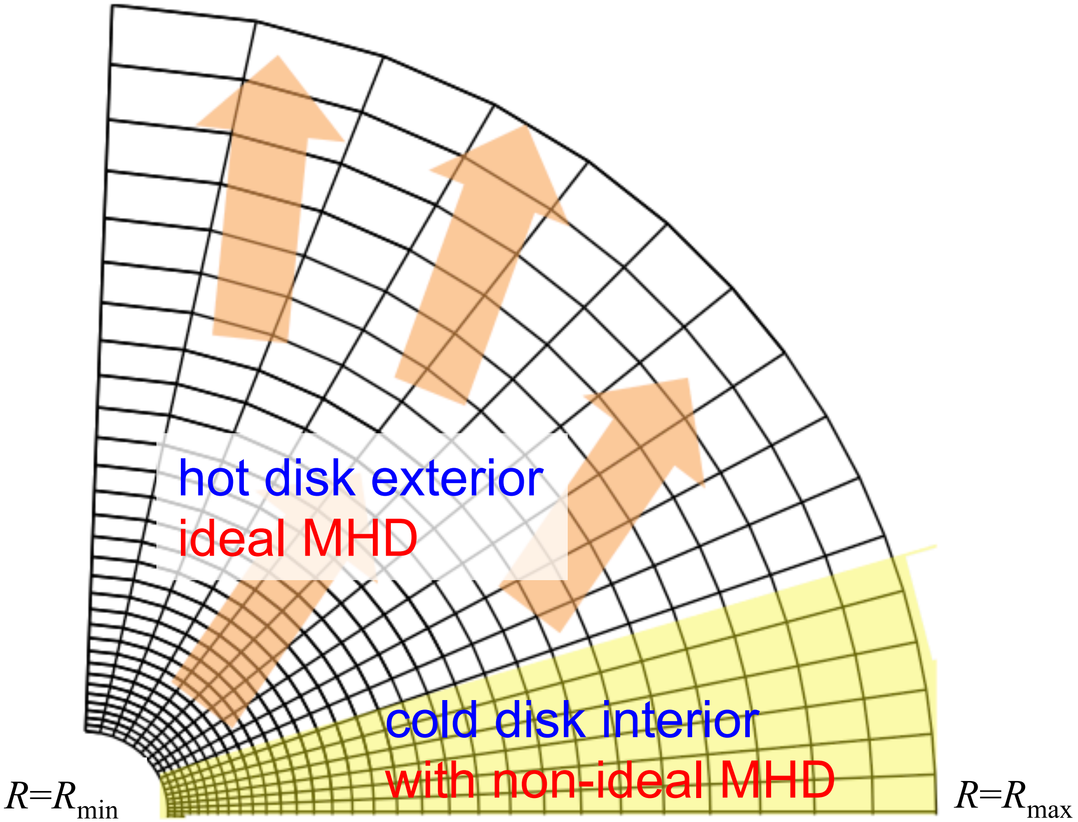
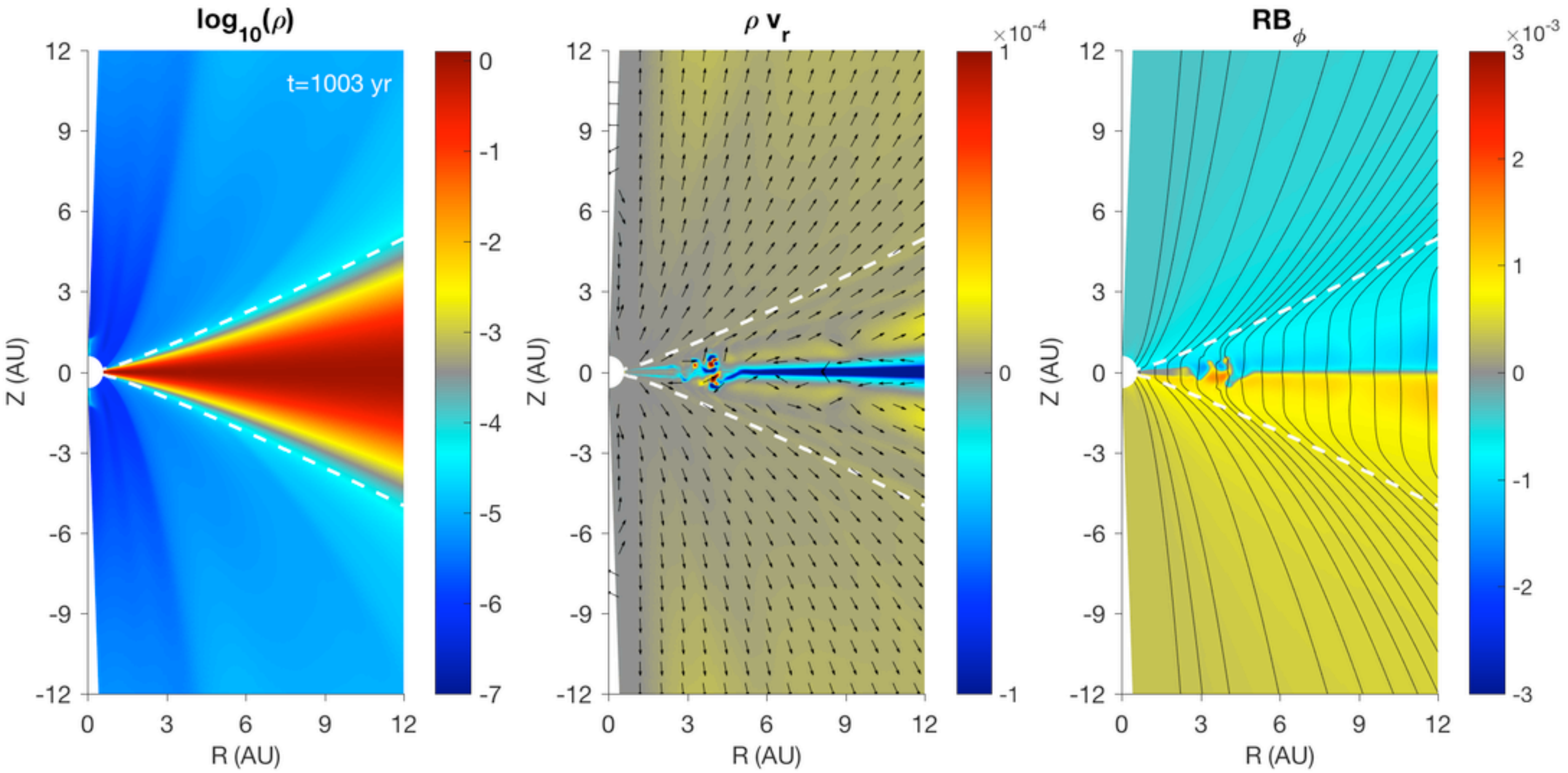
Global simulations

- Athena++ MHD code: spherical-polar grid, log spacing in r, power-law spacing in θ, domain extending to near the pole.



- Flared disk with cold disk interior + warm exterior
- Ray-tracing to determine the disk interior-exterior boundary + ionization profile
- Magnetic diffusivity in disk interior based on pre-computed table from a complex chemical network
- Enhanced ionization towards ideal MHD for exterior.

Fiducial simulation with Ohmic + AD



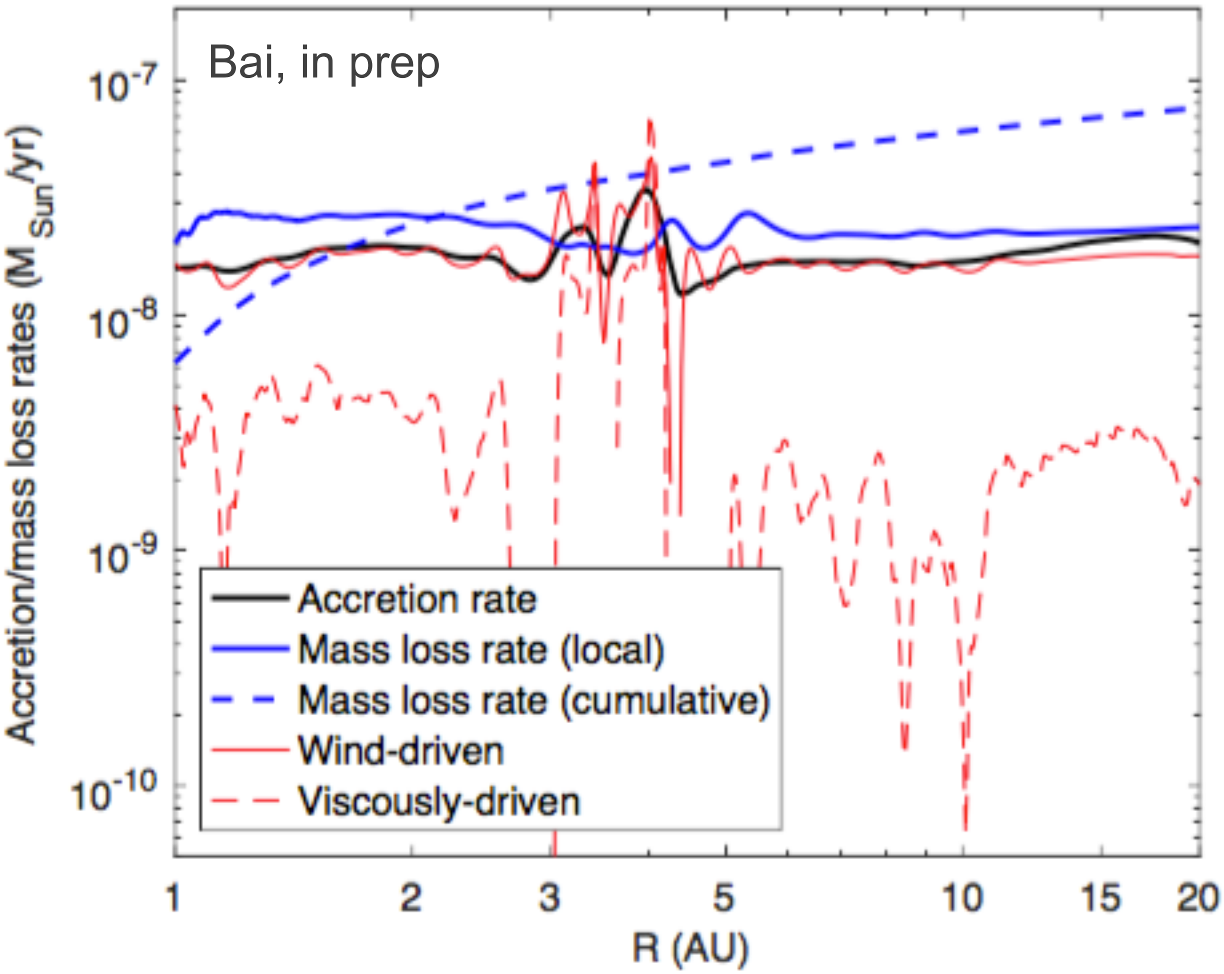
Bai, in prep

Domain size: 0.6 AU-60 AU

$\beta_0=10^5$, $\Sigma_{FUV}=0.03$ g cm^{-2}

Alfven point is close to the wind base
=> excessive mass loss!

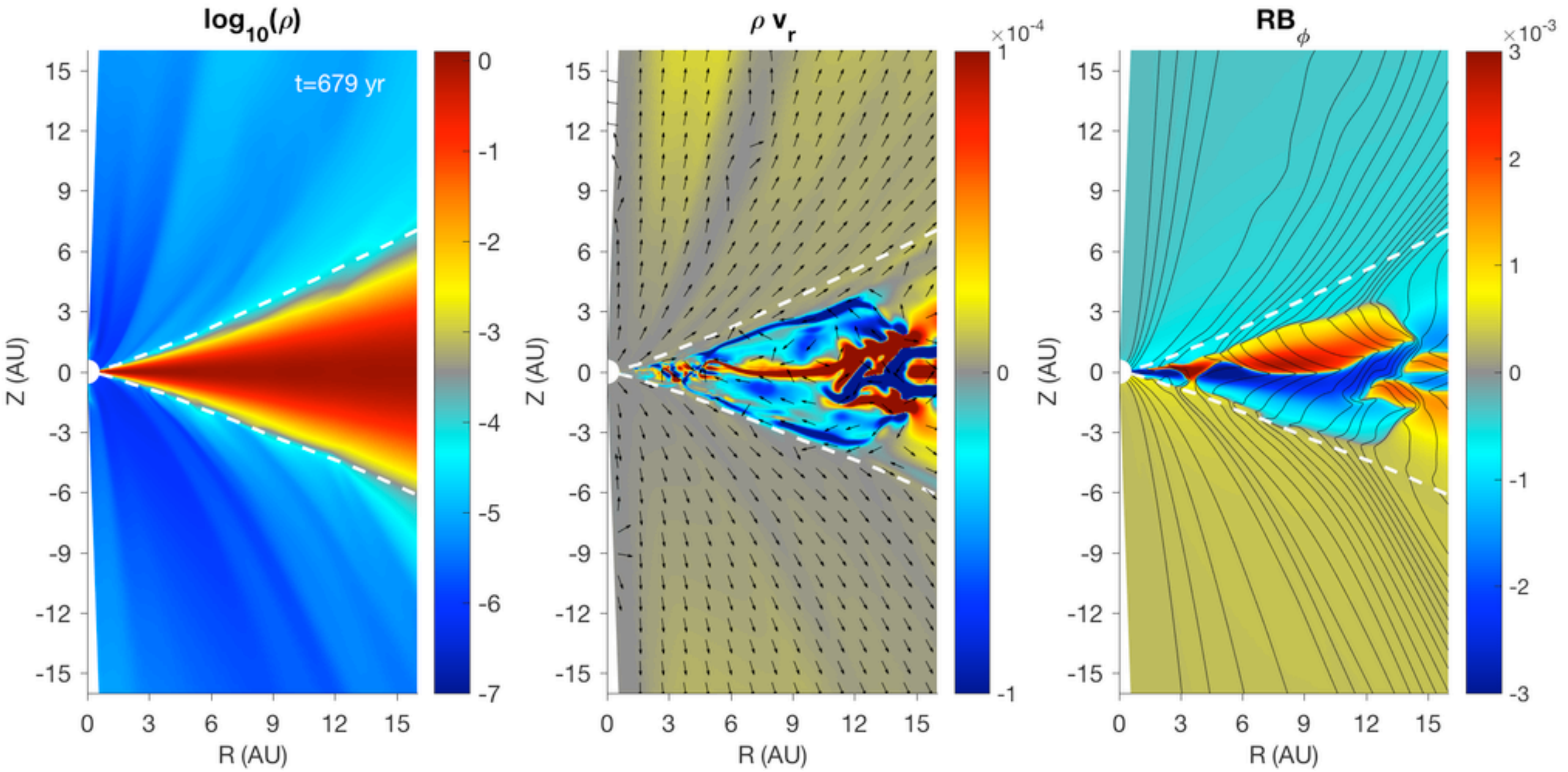
Angular momentum transport, mass loss



Mass loss rate larger than original semi-analytical predictions (for understandable reasons).

B flux is transported outward, but very slowly.

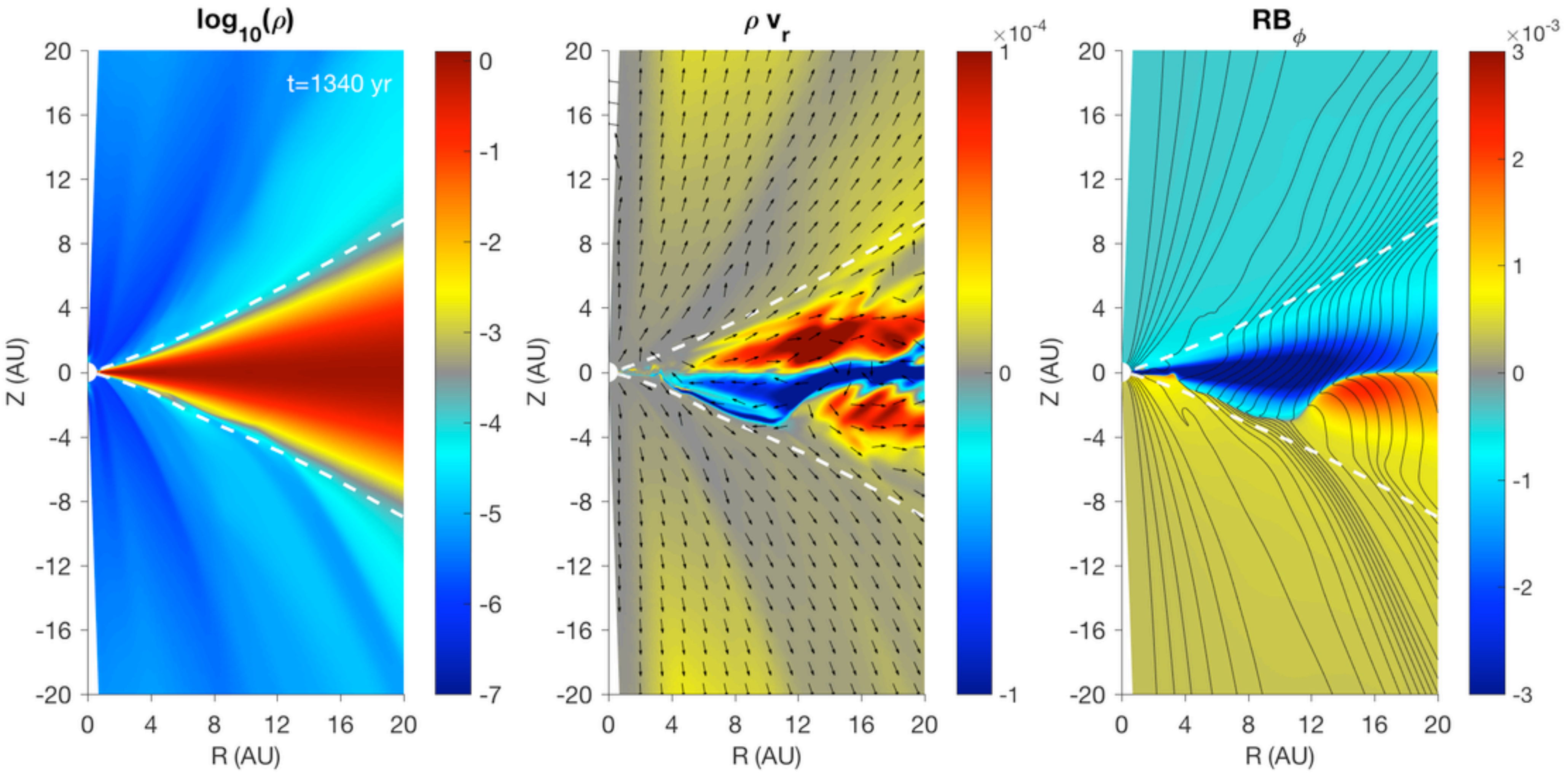
Fiducial simulation with Hall: aligned case



Bai, in prep

Results depend on initial condition…

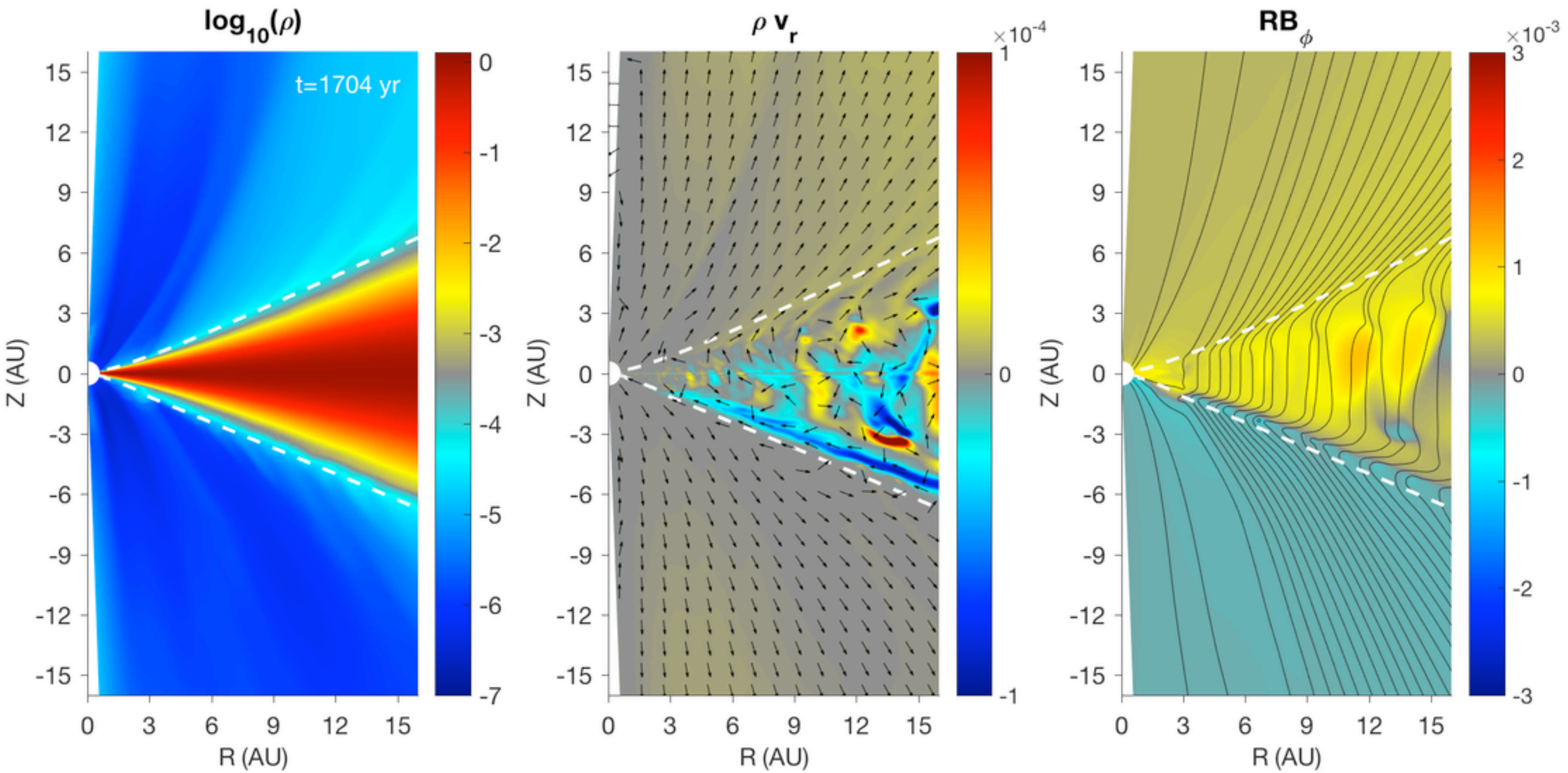
Fiducial simulation with Hall: aligned case



Bai, in prep

A probably more reasonable outcome…

Fiducial simulation with Hall: anit-aligned case

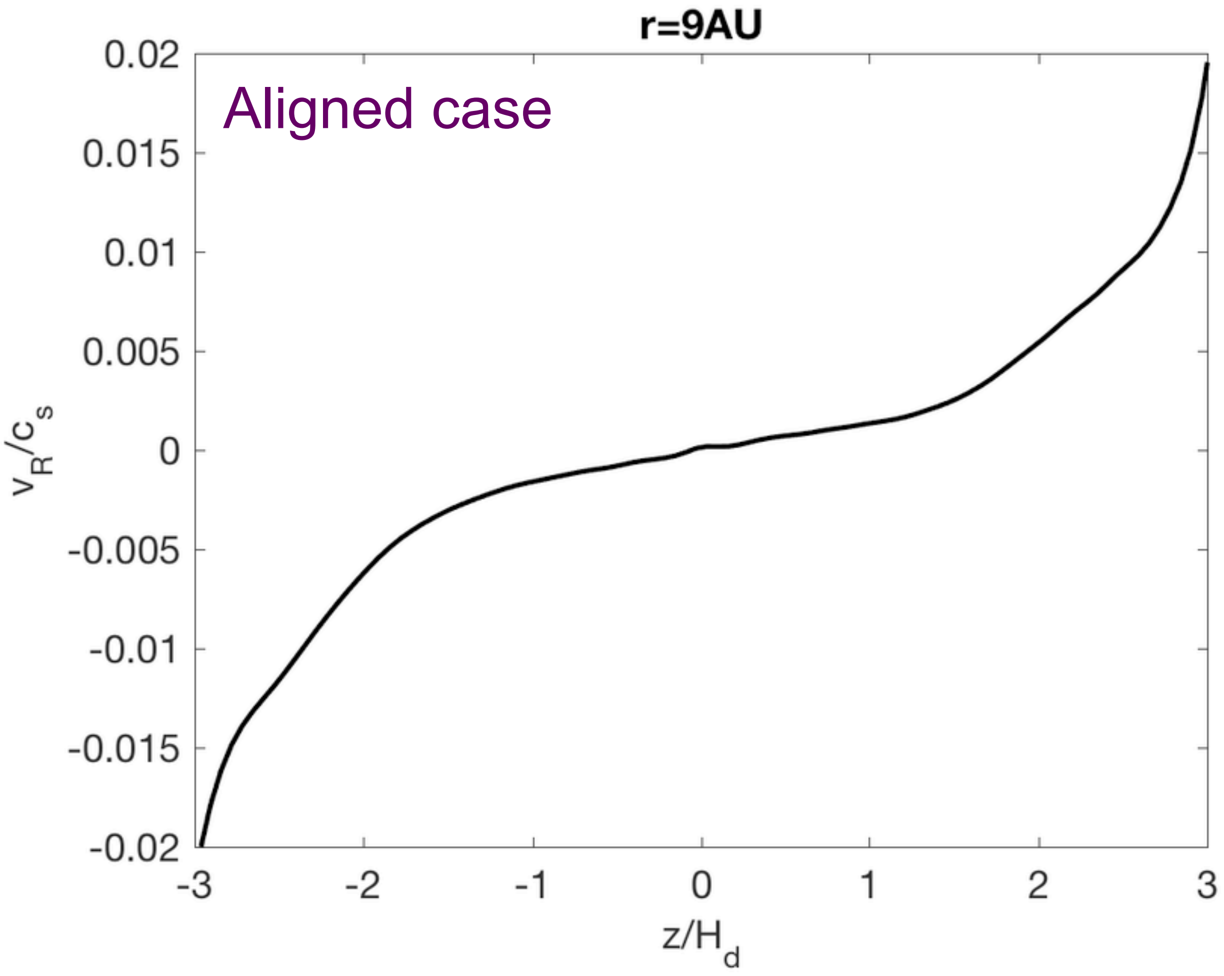


Bai, in prep

Transition from symmetric to asymmetric configuration, which is related to oscillations found in local simulations.

Implications on transport of solids

Mineralogy and isotopic composition of meteorites/comets reveal plenty of evidence for outward transport of solids from the inner solar system.



Strongly coupled solids can undergo meridional circulation.

Different circulation patterns at small/large radii.

Outstanding issues

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- 2. Origin and transport of magnetic flux.

  Where is net B_z coming from?

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Summary

- 1. Wind kinematics.

  PPD wind is launched by B pressure gradient, with total mass loss rate no less than accretion rate.

  Thermodynamics near the wind base matters.

- 2. Origin and transport of magnetic flux.

  The disk loses B flux over time.

  Anti-aligned polarity loses B flux faster by a factor of ~2.

  More strongly magnetized disk loses B flux faster.

- 3. Angular momentum transport and flow structure.

  Wind dominates AM transport, with significant contribution from Maxwell stress in the aligned case.

  Due to the Hall effect, the inner disk tend to become asymmetric. Large-scale meridional circulation is present in the aligned case.