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Towards Realistic Understanding of (boring) Protoplanetary Disks

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Reminder:

- If you don’t understand it, invoke turbulence.

- If you still don’t understand it, invoke magnetic field.

Occurrence rate of “magnetic talks”: 3/56 -> 4/80

See S. Suriano, J. Wurster & C. Dougados’s talks

Why boring disks?

- So far, they seem to be the majority.

  e.g., M. Ansdell, L. Cieza & G. Herczeg's talks, Q&A in M. Bate's talk.

- We don't even understand boring disks, let alone more complex ones.

  - Angular momentum transport
  - Gas kinematics (flow structure/turbulence/wind)
  - Disk structure (density/temperature/chemical)
  - Long-term evolution and dispersal

Why boring disks?

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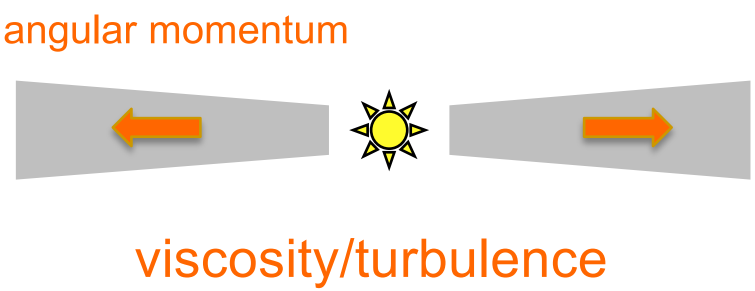
- We don't even understand boring disks, let alone more complex ones.

Goal: Obtain the 0^{th} order picture for the overall gas dynamics of PPDs.

Angular momentum transport: mechanisms

Need to account for PPD accretion rate of ~$10^{-8} M_\odot\,\mathrm{yr}^{-1}$. (e.g., Hartmann+ 98)

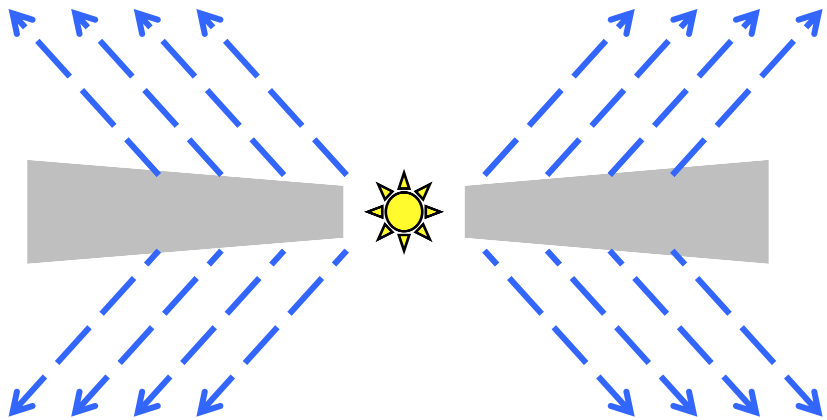
Radial transport:



By the MRI, hydro turbulence, and/or laminar Maxwell stress

MHD mechanisms sensitive to ionization; hydro mechanisms sensitive to thermodynamics

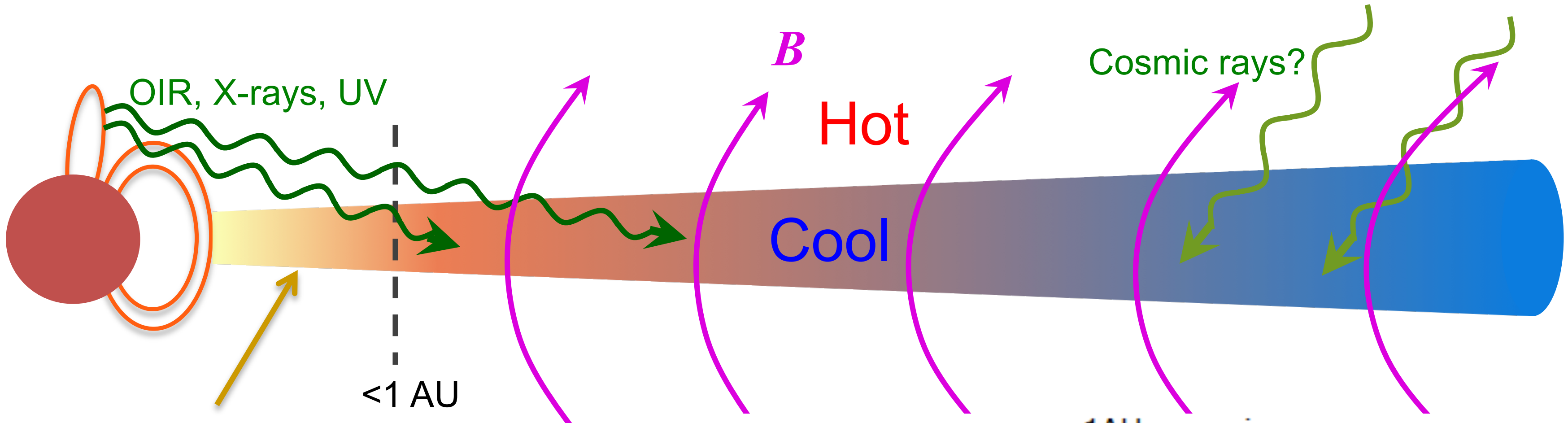
Vertical transport:



By magnetized disk wind

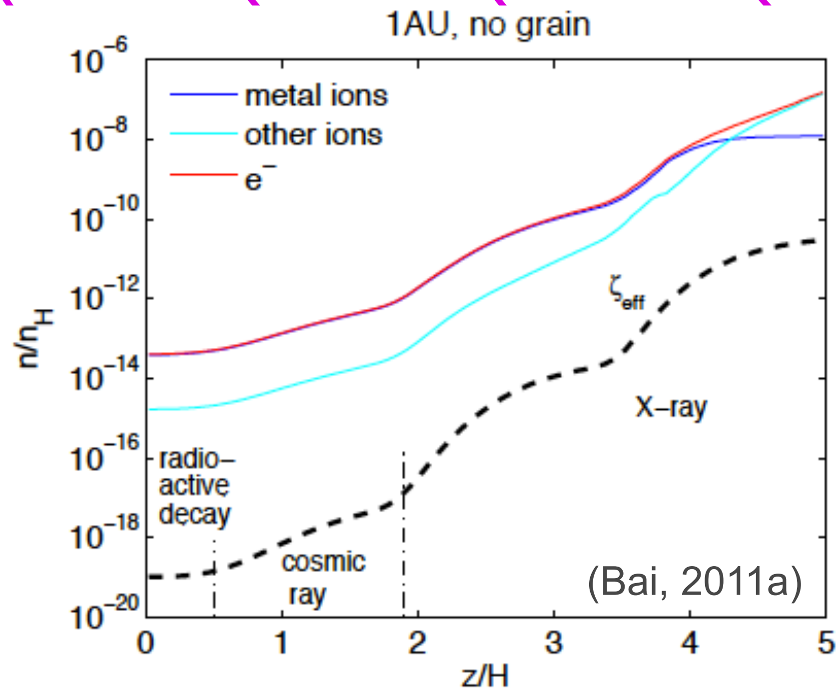
Wind properties are sensitive to disk physics

Governing disk microphysics



Thermal ionization of Na, K

(need ~10^3K, e.g., Desch & Turner 15)



The bulk of the disk is
extremely weakly ionized

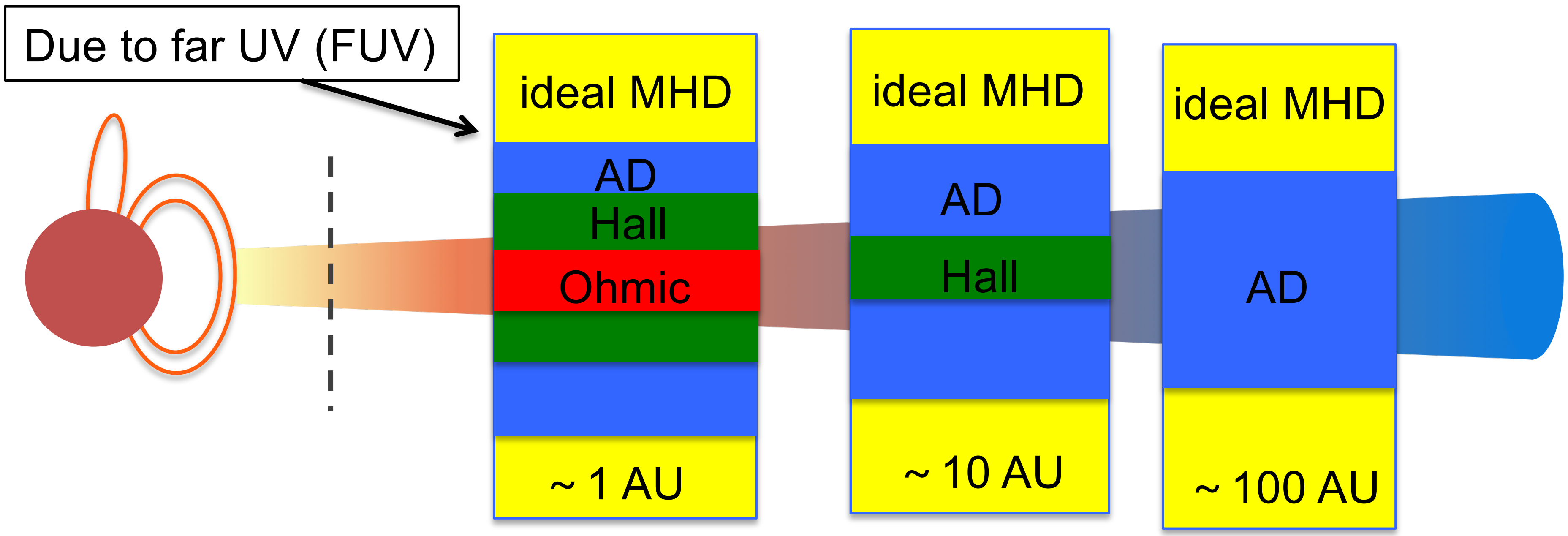
Disk microphysics: non-ideal MHD effects

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

Non-ideal MHD terms

inductive **Ohmic** **Hall** **Ambipolar diffusion (AD)**

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



Disk microphysics: non-ideal MHD effects

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

inductive **Ohmic** **Hall** **Ambipolar diffusion (AD)**

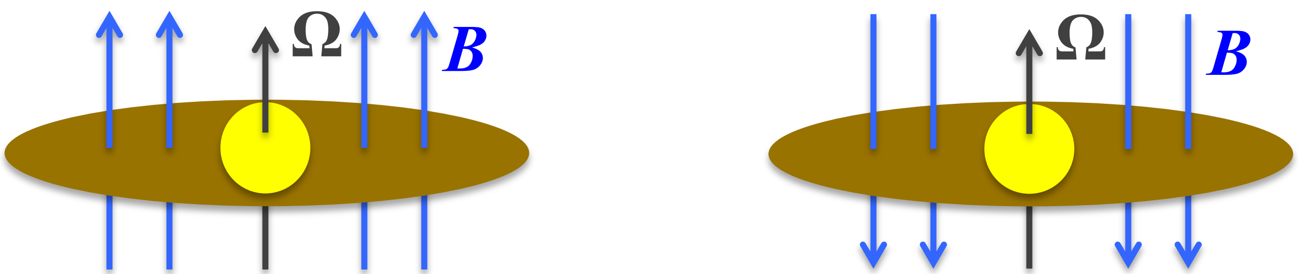
-	-	-	(-)^2= +	(-)^3= -

The Hall term is Polarity Dependent!

See also
J. Wurster's talk

What happens when we flip magnetic field?

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



Brief historical notes (incomplete)

1970s: Viscous accretion theory developed (Shakura & Sunayev 73, etc.), but it is well known that molecular viscosity is far insufficient.

1980s-1990s: MHD wind theory (require strong field) is developed and is popular (Blandford & Payne 82, Pudritz+83, Shu+94, etc.).

Viscous accretion theory widely applied (e.g. Pringle 81, Hartmann+98).

1990s-2000s: MRI was (re)discovered (Balbus & Hawley 91), dominating the market.

Layered accretion proposed (Gammie 96), with intense studies of non-ideal MHD (e.g., Wardle 99), mostly Ohmic resistivity (e.g., Armitage 2011 for review).

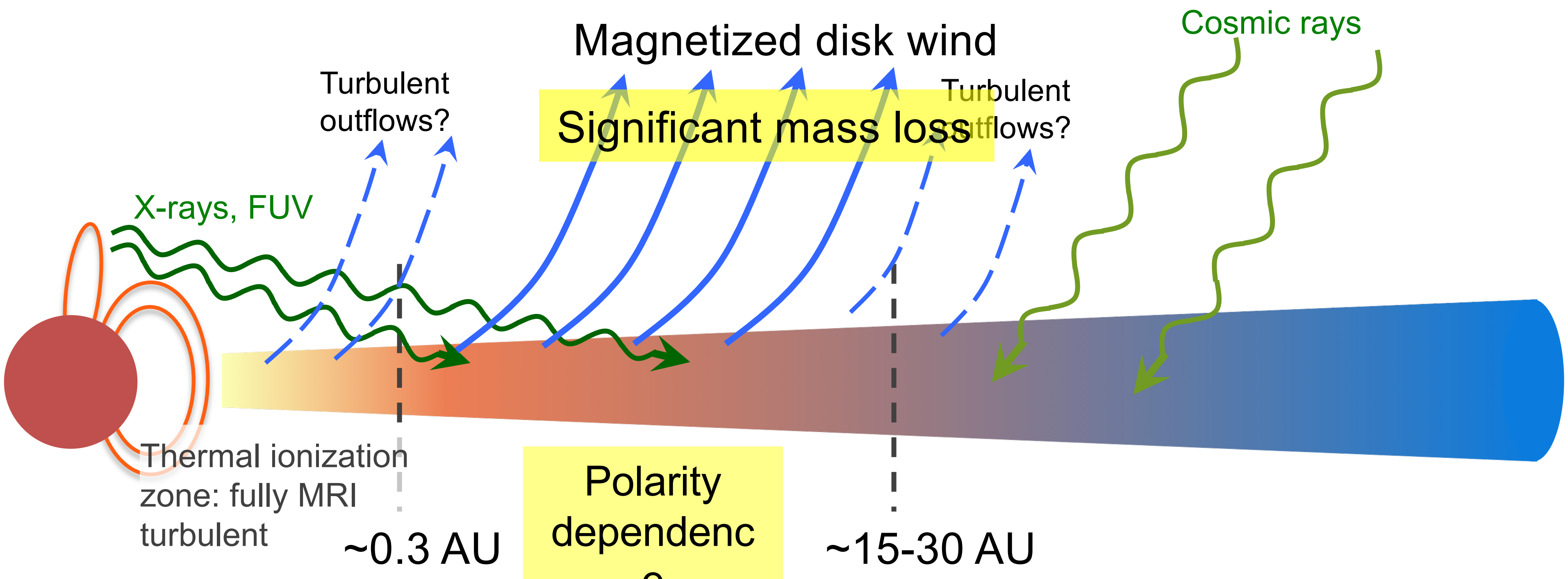
Wind theory continues (e.g., Wardle Konigl 93), though less popular.

2010s: Hall and AD better understood via simulations (e.g., Sano, Wardle, Kunz, Stone, Bai, Lesur, Gressel, Simon; Turner et al. 14 for a review).

Wind-driven accretion revived (e.g., Bai & Stone 13, Gressel+15): MRI largely suppressed and only weak field is needed to launch wind.

Several hydrodynamic instabilities identified (e.g., Lyra & Umurhan 18 for review).

A (biased) summary of current understandings



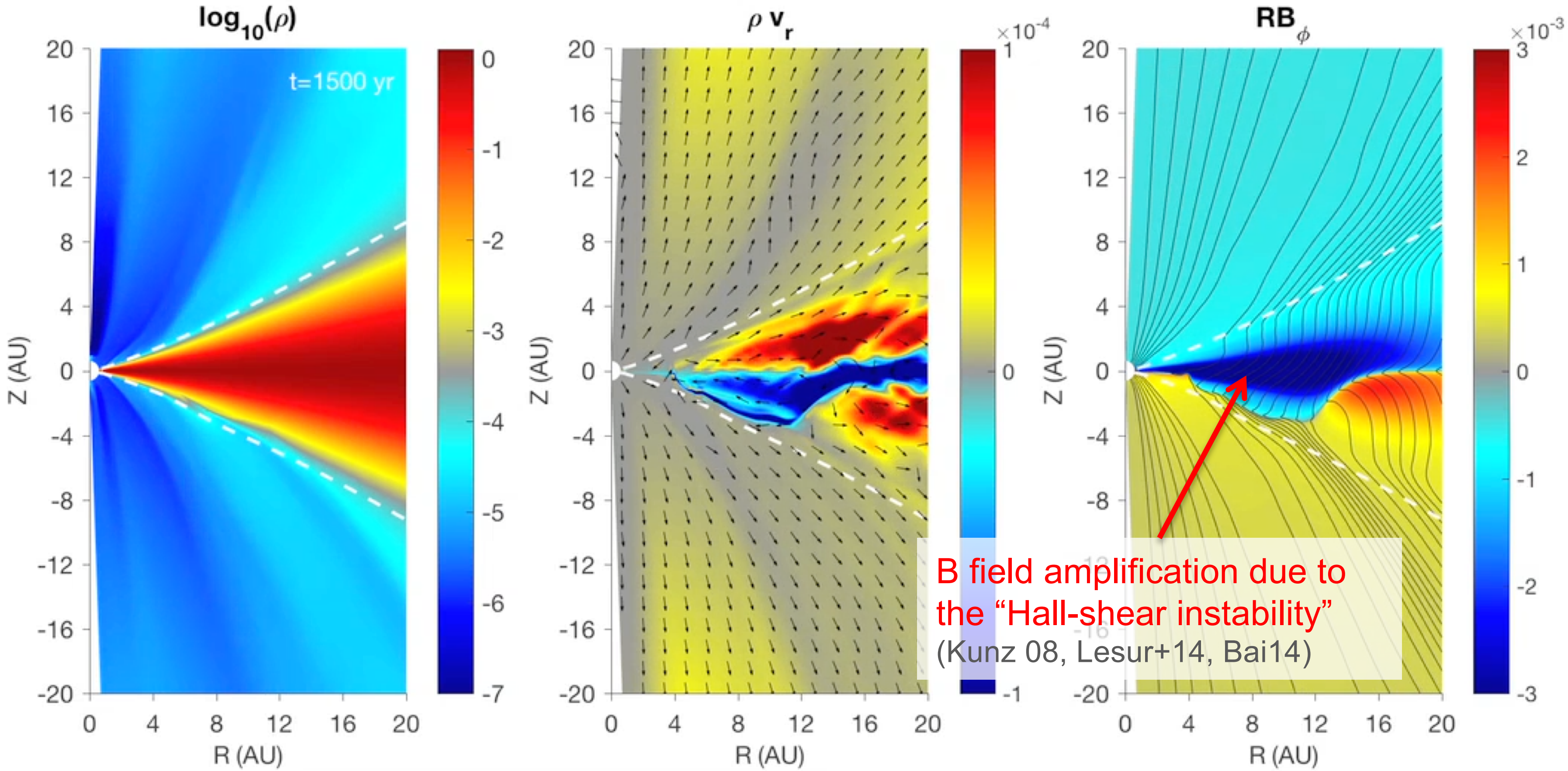
MRI suppressed by Ohmic +AD, disk is largely laminar.

MRI damped by AD, but may operate in surface FUV layer

e.g., Bai, 2013, Simon+2015

A recent global simulation of PPDs

2D axisymmetric, all 3 non-ideal MHD effects + equi. chemistry, aligned case.



The disk is asymmetric about the midplane!

Bai, 2017

Understand the complex flow structure

Rate of angular momentum loss = Torque

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

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

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

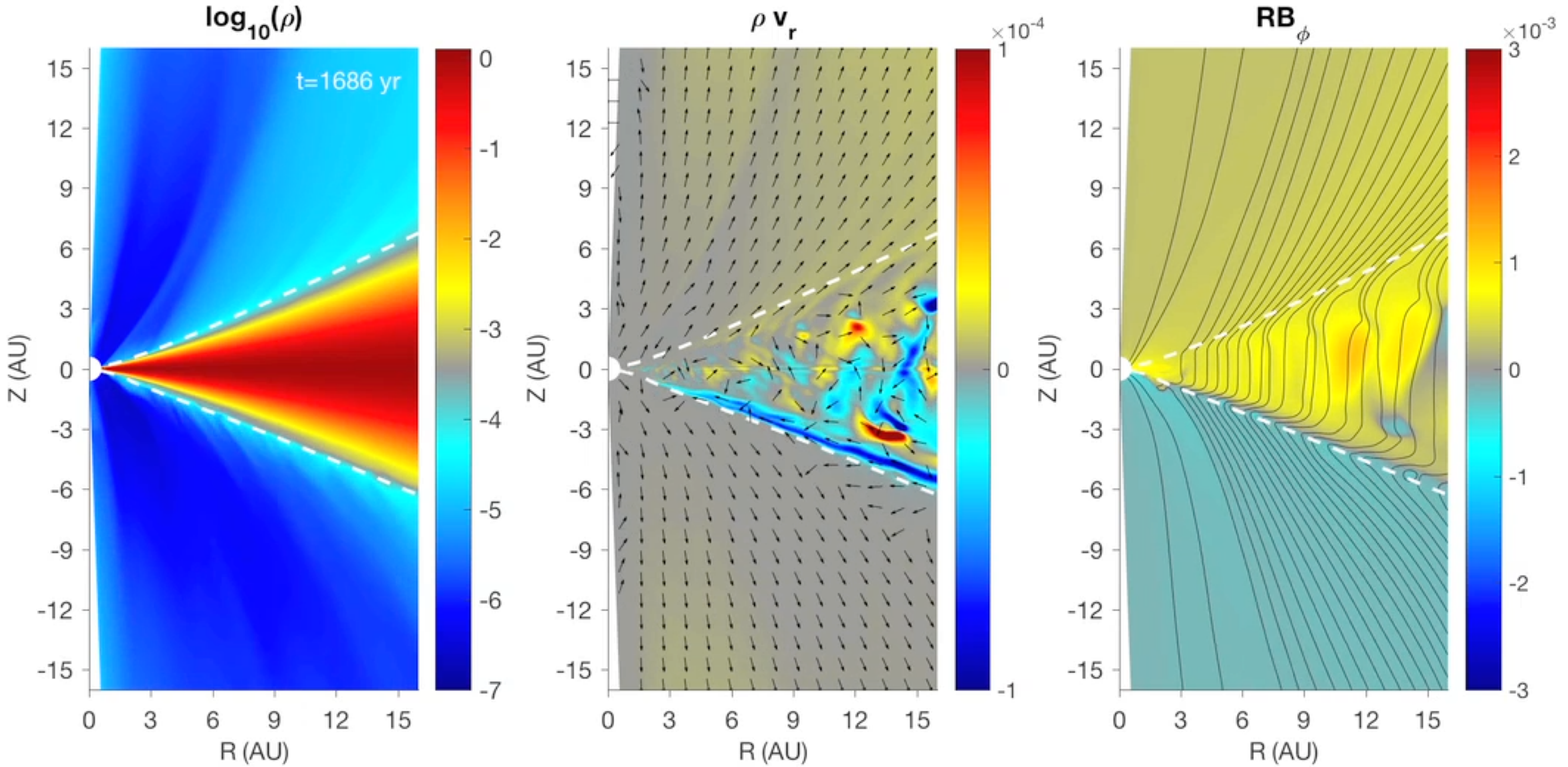
=> $$-\frac{1}{2}\rho\Omega_K v_R \approx -\frac{B_z}{4\pi}\frac{dB_\phi}{dz}$$

Flow structure is largely set by the vertical gradient of B_ϕ

This is set by non-ideal MHD

A recent global simulation of PPDs

2D axisymmetric, all 3 non-ideal MHD effects + equi. chemistry, anti-aligned case.



Symmetry breaking, surface accretion flow

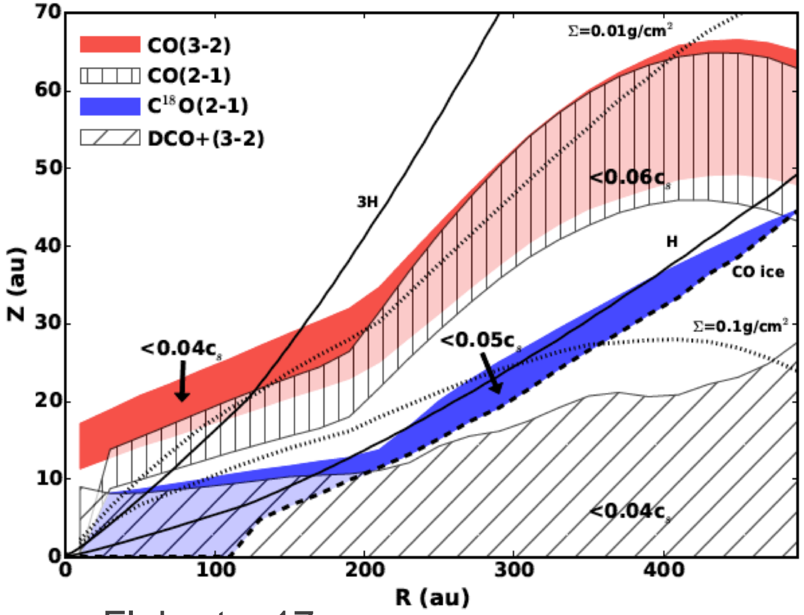
Bai, 2017

Level of turbulence (outer disk)

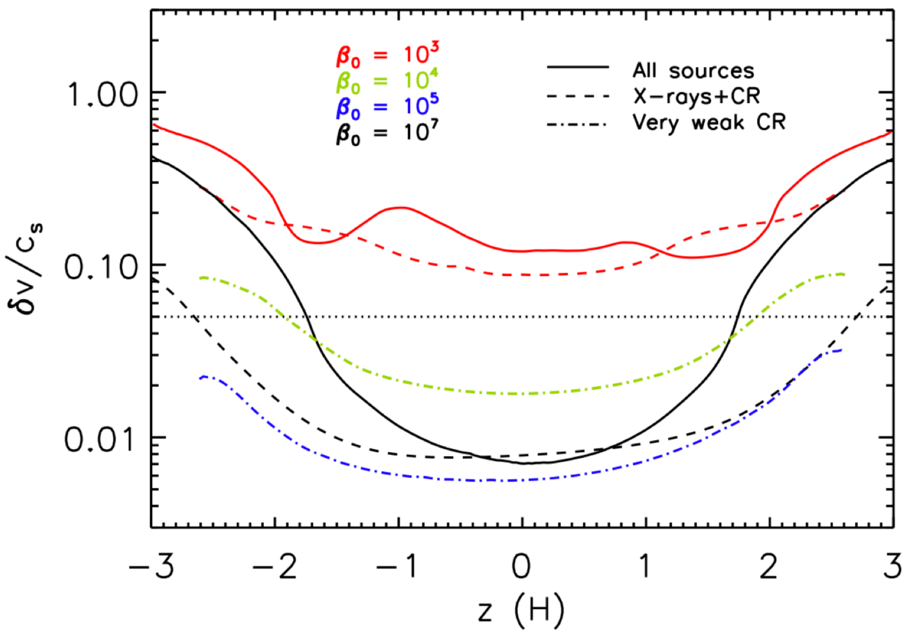
Expected to have weak (damped) midplane + stronger surface MRI turbulence

(e.g., Perez-Becker & Chiang 11, Simon+13,15, Bai 15).

HD 163296



Flaherty+17

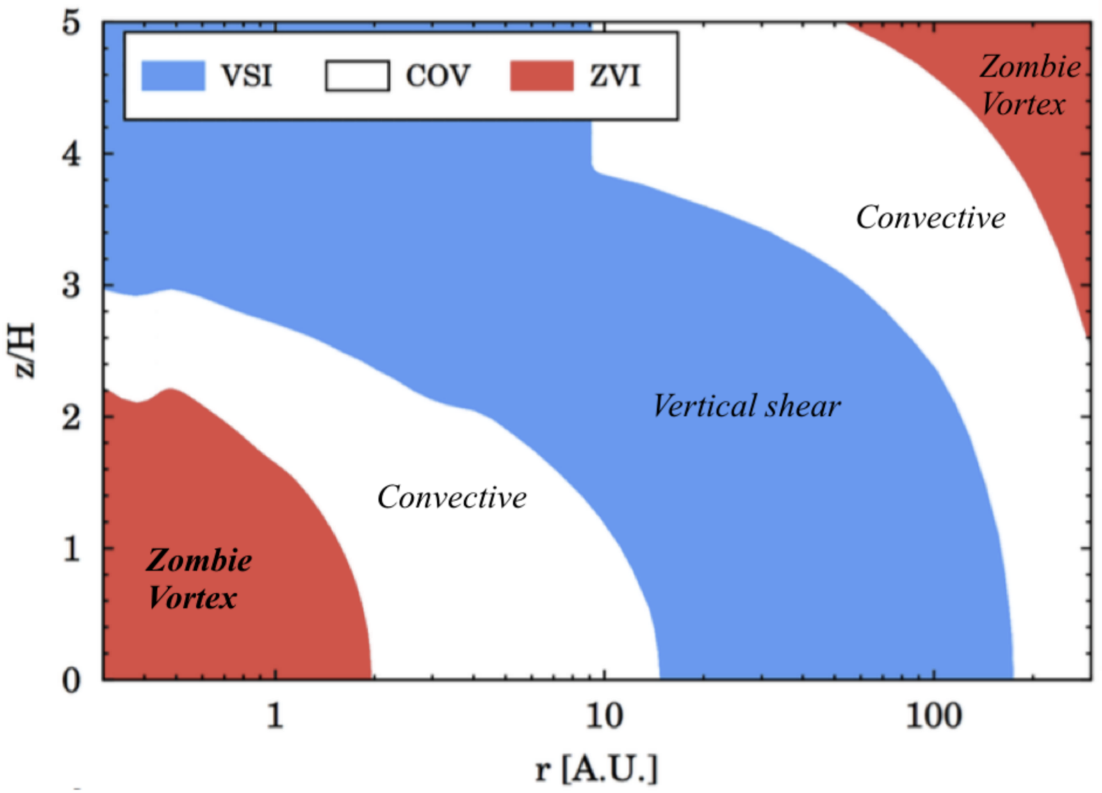


Simon,Bai+18

See Teague+16,18, Flaherty+18 on TW Hya
Pinte+16 for HL Tau (indirect)

Require weak field + weak ionization.

(Pure) hydrodynamic instabilities



Lyra & Umurhan 18; see also Malygin+17, Pfeil & Klahr 19

Vertical shear instability (VSI):

(e.g., Nelson+13, Stoll & Kley 14, Lin & Youdin 15, Richard+16, Magner & Klahr 18)

Needs vertical shear + fast cooling.

Subcritical baroclinic instability / convective overstability (SBI/COV):

(e.g., Lesur & Papaloizou 10, Raettig+ 13, Klahr & Hubbard 14, Lyra 14)

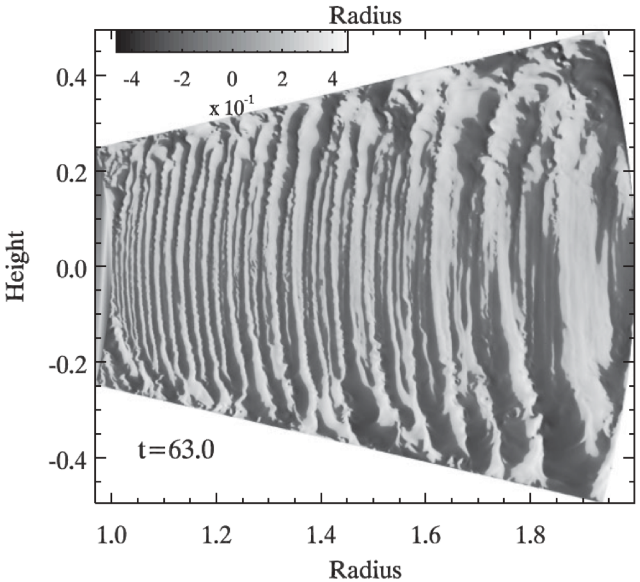
Needs negative radial entropy gradient + modest thermal relaxation.

“Zombie vortex” instability (ZVI): needs near adiabatic + finite amp. perturbations.

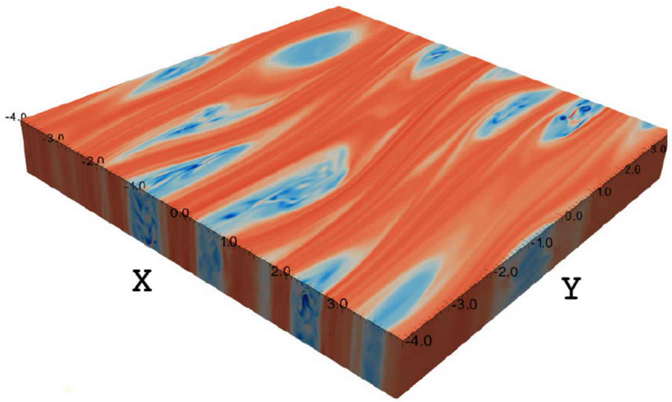
(e.g., Marcus et al. 13,15, Lesur & Latter 16, Umurhan+16)

(Pure) hydrodynamic instabilities

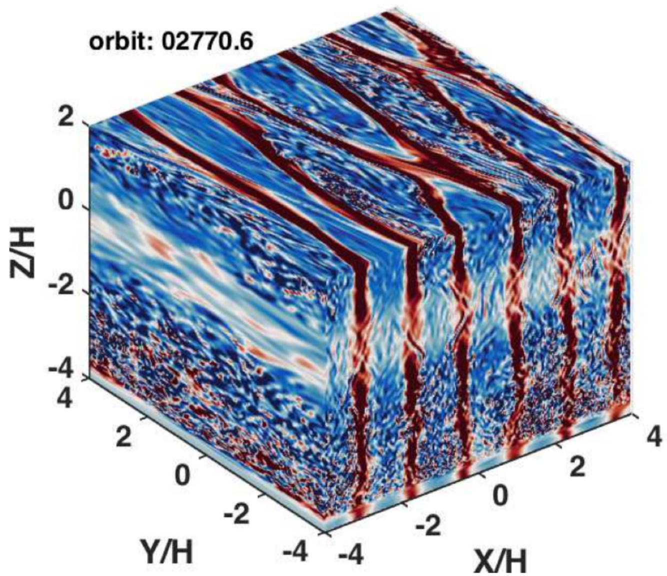
VSI:



SBI:



ZVI:



Nelson+13

Lesur & Papaloizou 2010

Barranco+ 18

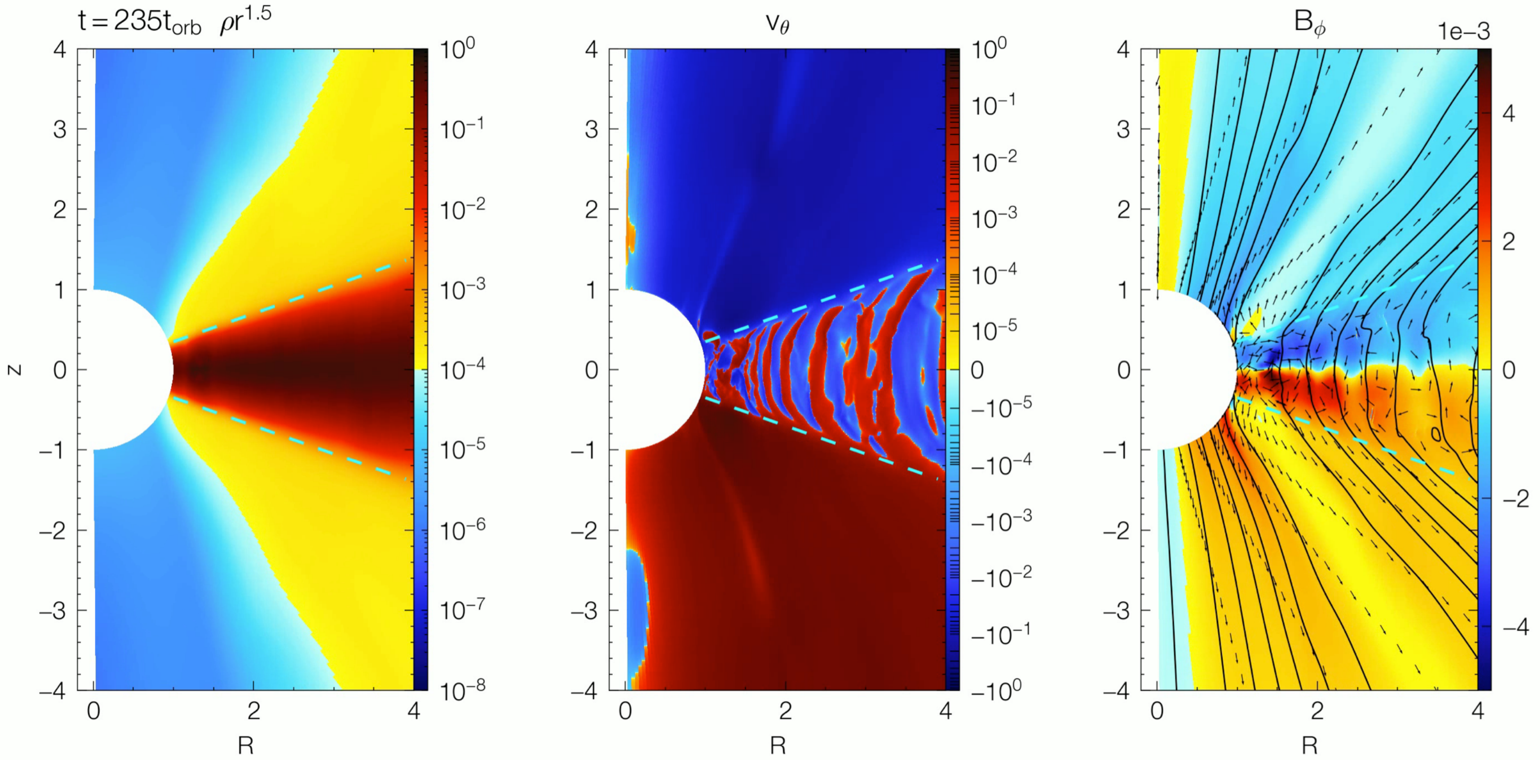
See M.-K. Lin’s talk

Saturate into turbulence, outward angular momentum transport with $\alpha \lesssim 10^{-3}$.

Do these hydro instabilities survive in PPDs launching MHD winds?

Interplay between VSI and MHD winds

VSI is suppressed if the MRI operates (Latter & Papaloizou 18).



Can Cui
(Shanghai Astro. Obs)

As long as the MRI is suppressed, the VSI can well coexist in wind-driven PPDs.

Wind launching can modify vertical shear profile, thus affecting the VSI.

Cui & Bai, in prep

Wind and disk outflows

Photoevaporation (thermal driving):

(see e.g., Alexander+14 for a review)

Three flavors: EUV, far-UV, X-ray.

FUV/X-ray likely yield significant mass loss of ~10^{-8} $M_\odot$/yr.

There is also external photo-evaporation.

See 5 talks tomorrow afternoon session.

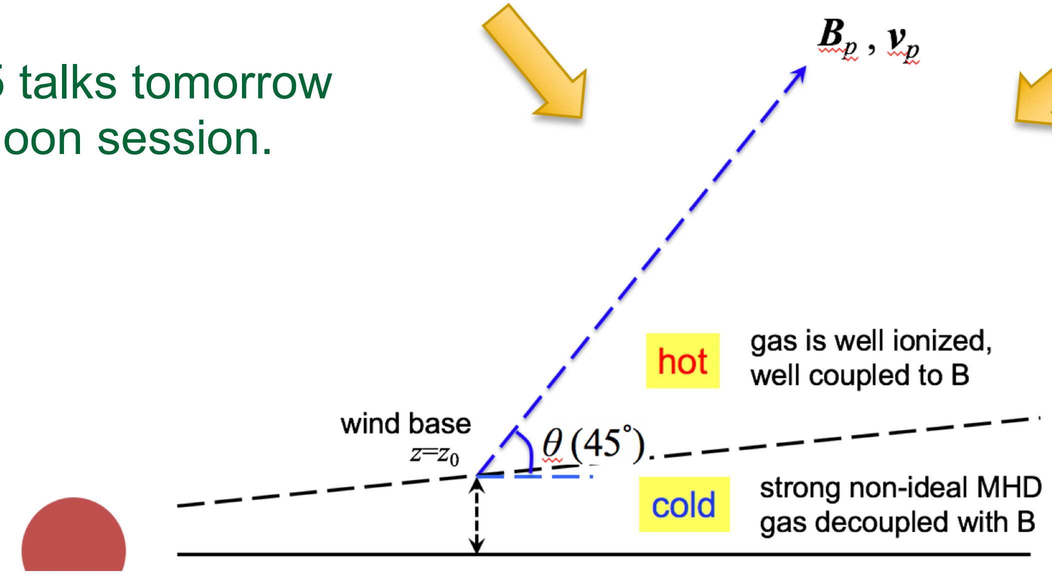
MHD wind (magnetic driving):

(e.g., Ferreira+95,97, Fendt+02, Konigl+10)

Wind typically assumed to be cold.

Generally require strong vertical field (β~1 at midplane).

Resulting wind is typically launched by centrifugal acceleration.



Unified picture:

Magneto-thermal wind

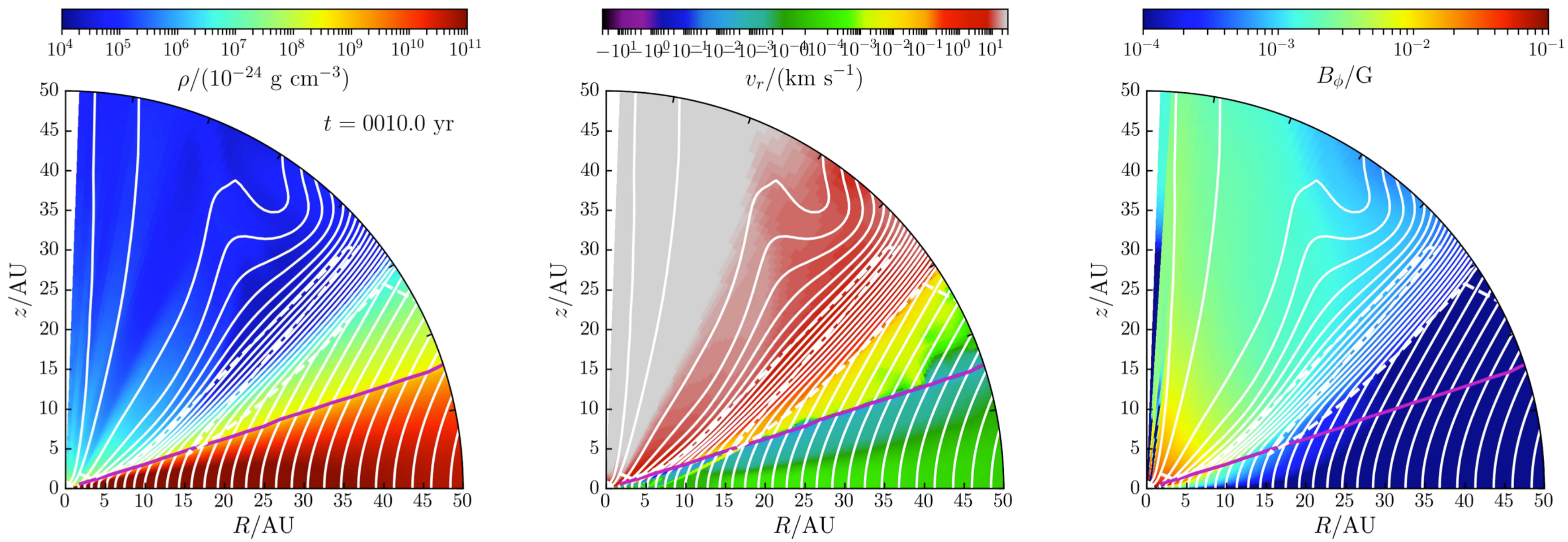
(Bai+16)

See also C. Dougados's talk

Most realistic calculations

Thermodynamics in the wind is sensitive to chemistry, which is NOT in equilibrium.

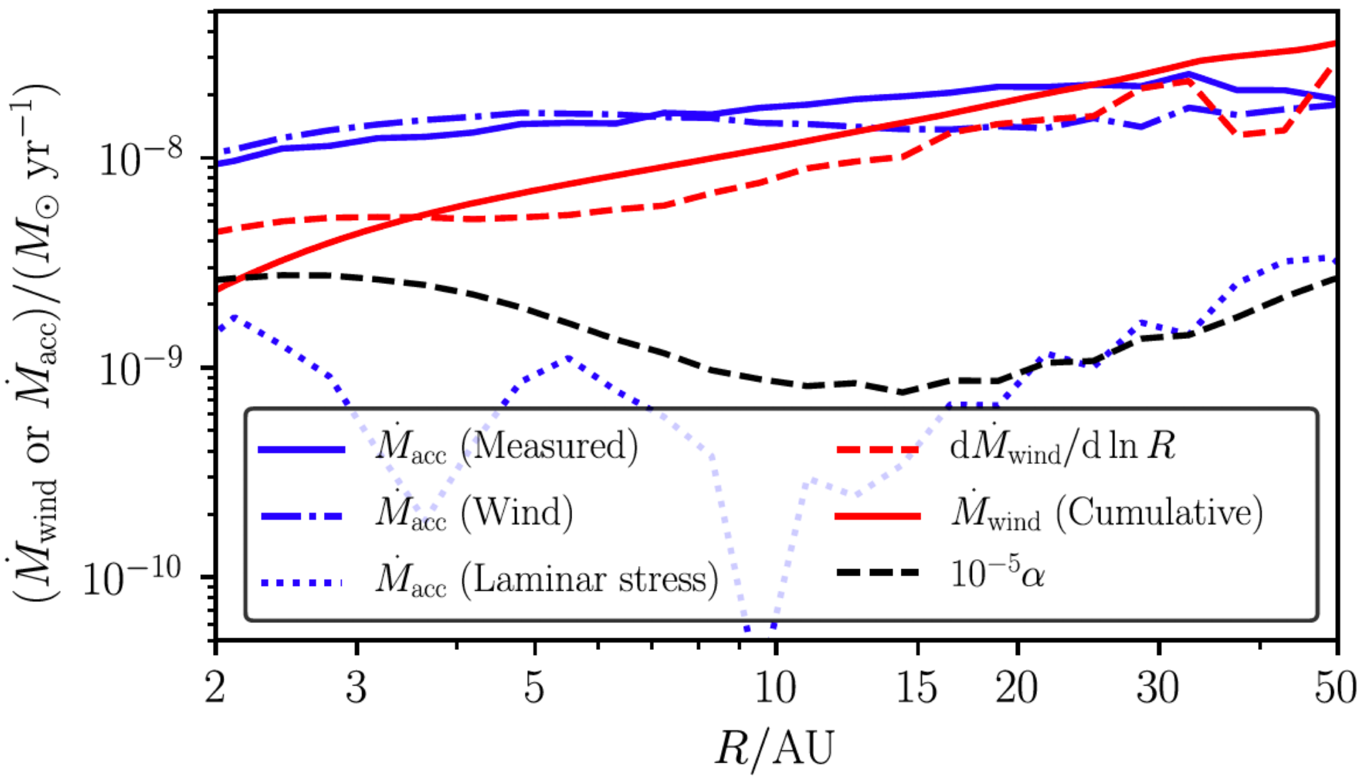
=> Need to couple chemistry with (non-ideal) MHD!



2D axisymmetric simulations with time-dependent chemistry using Athena++ with a reduced network based on Rui Xu, Bai & Oberg (2019).

(Lile Wang, Bai & Goodman 2019)

Accretion vs. mass loss



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

EUV can be important for wind kinematics.

Wind heating dominated by ambipolar diffusion.

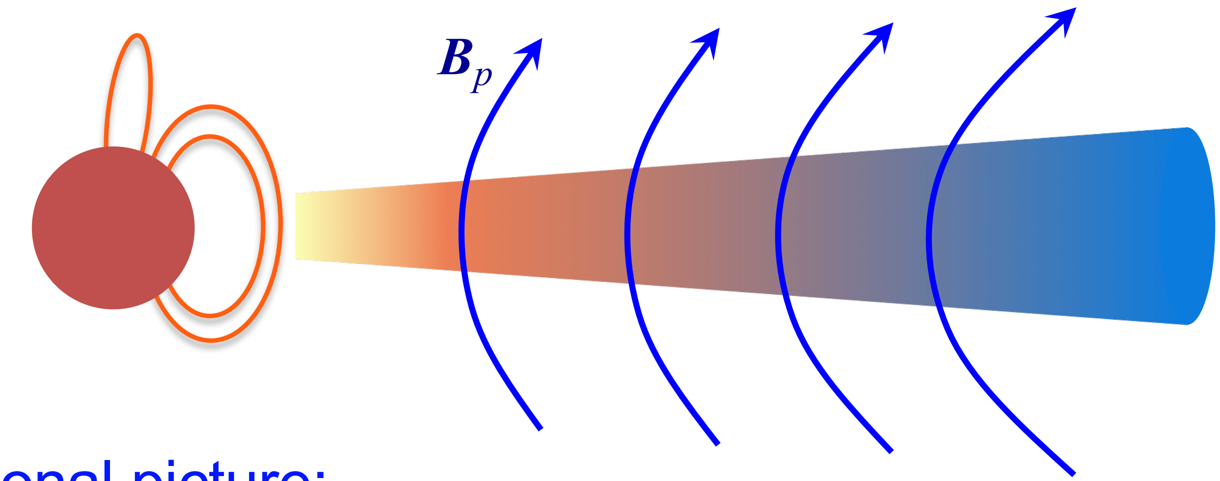
See also talks by Z. Xu & E. Rigliaco

(Lile Wang, Bai & Goodman 2019)

More fundamental problem: B flux transport

Rates of wind-driven accretion / mass outflow is largely set by B flux distribution through the disk.

But what determines the poloidal B flux?



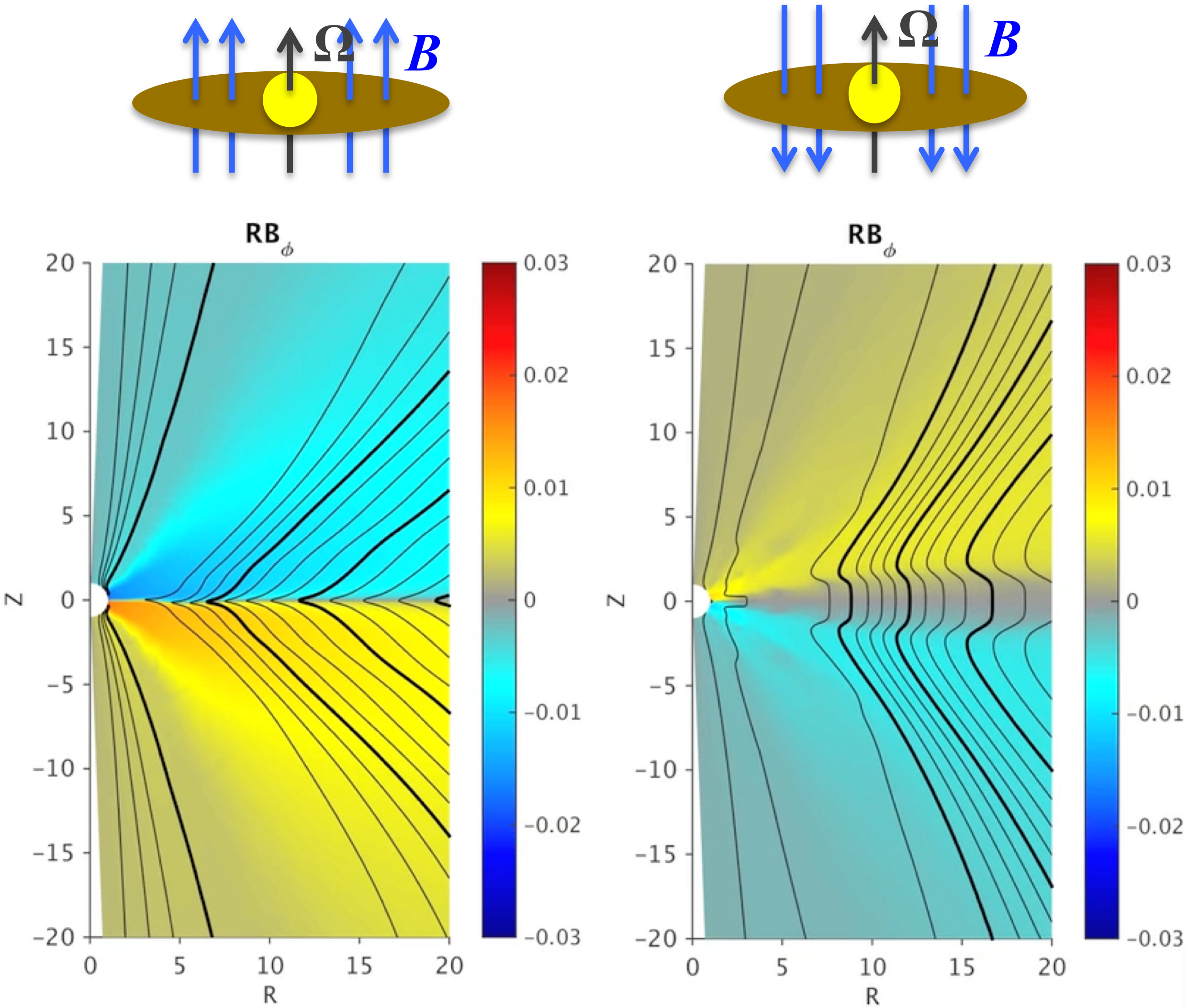
Conventional picture:

- 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)

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

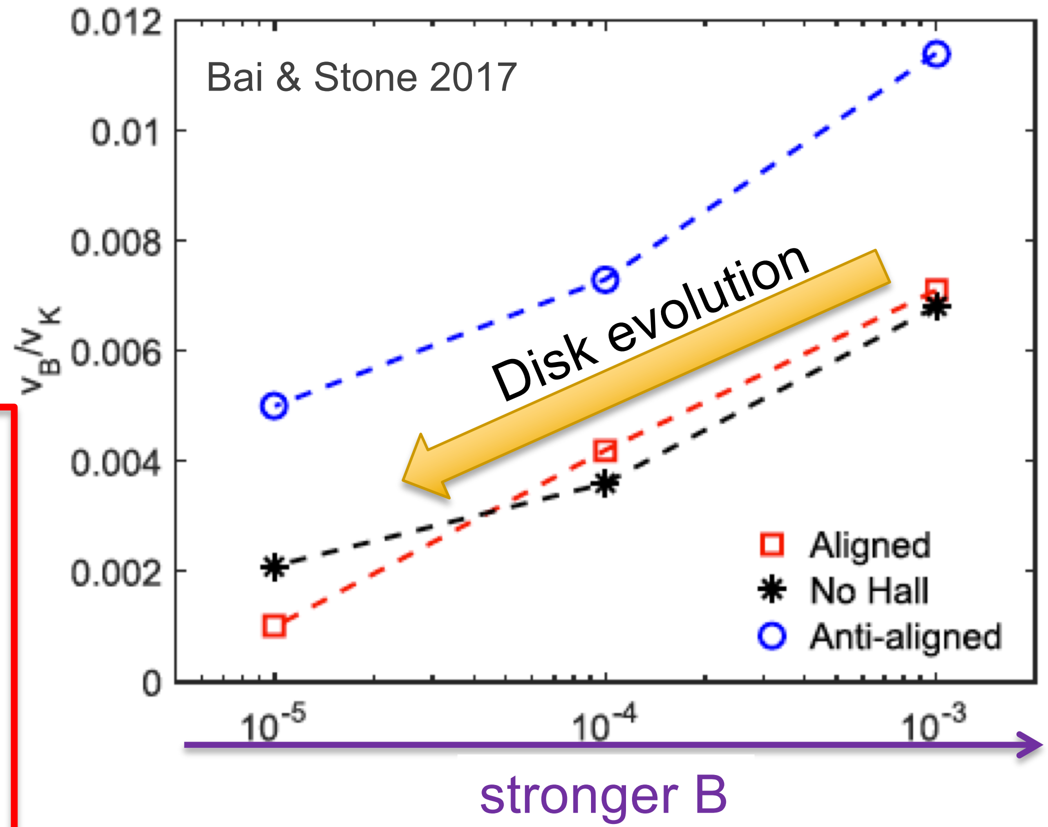
As controlled experiments, we focus on general trends.

Late phase:

weak B flux

low accretion rate
slow transport

long-lived



Early phase:

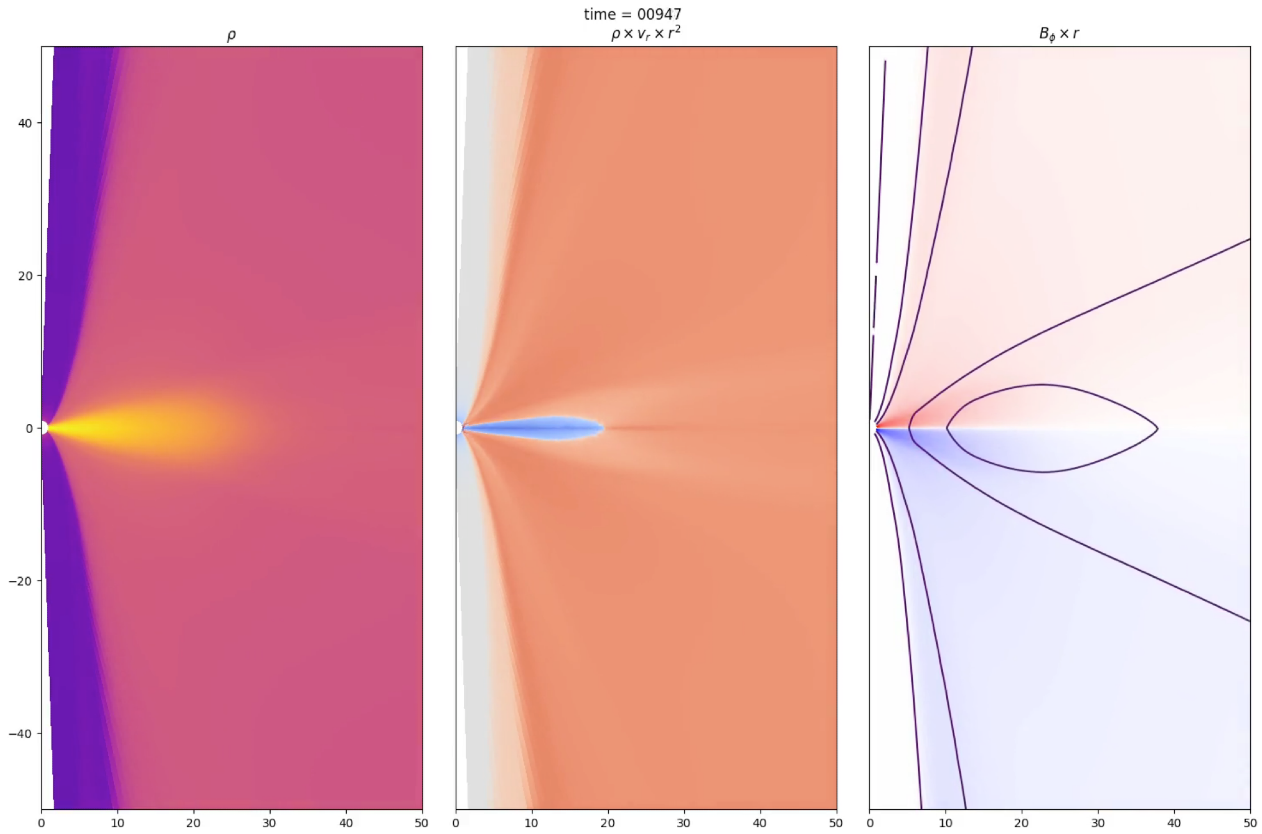
strong B flux

high accretion rate
fast transport

short-lived

Bai & Stone, 2017

The role of disk outer boundary



In reality, disks have finite size, transitioning to an envelope or ISM.

Disk magnetic flux is lost through dissipation around/beyond outer truncation.

Envelope is blown away by the wind.

There is also significant mass loss analogous to external photoevaporation.

(Haifeng Yang & Bai, in prep)

Summary

- Angular momentum transport: likely wind-dominated, with contributions from hydrodynamic instabilities.
- Flow structure is complex, and depends on the polarity of poloidal B field.
- Disk wind is magneto-thermal in nature, with significant mass loss.
- Long-term disk evolution is governed by the transport of poloidal B flux, which is likely dissipated over time.