ESA/ESTECH, Noordwijk, the Netherlands, 10/29/2015

Towards a Global Evolutionary Picture of Protoplanetary Disks

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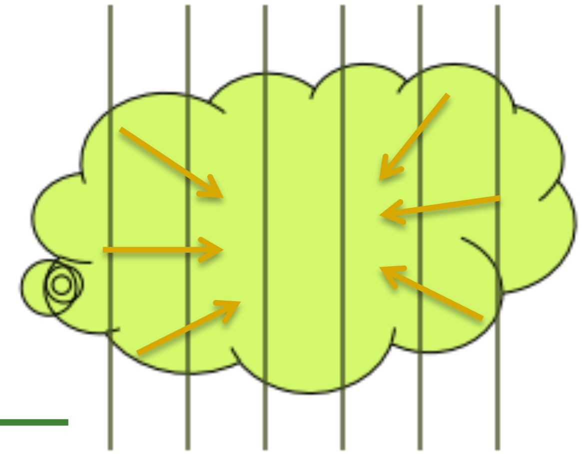
Prelude: initial condition



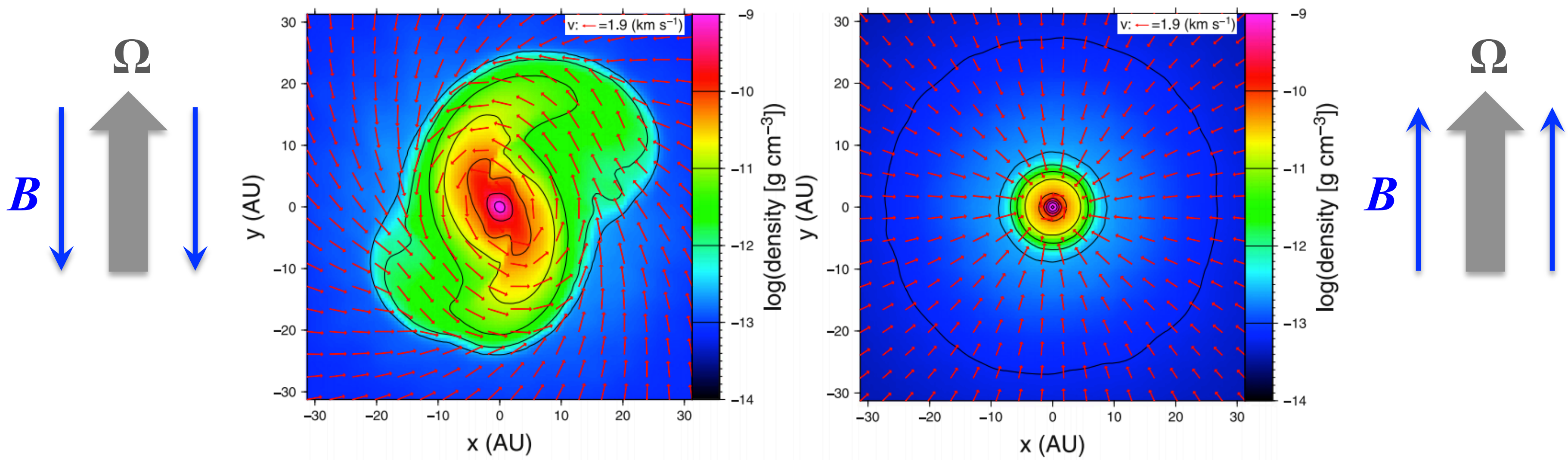
- Protostellar cores threaded by strong B field
  (e.g. Crutcher, 12, Hull+13)
- ~100 AU disk formation in class 0 phase
  (e.g., Tobin+12,15,Murillo+13,Ohashi+14,Harsono+14,Yen+15)

- Magnetic breaking catastrophe? (Mellon & Li 08)

  Problem largely solved by turbulent collapse/misaligned field/non-ideal MHD

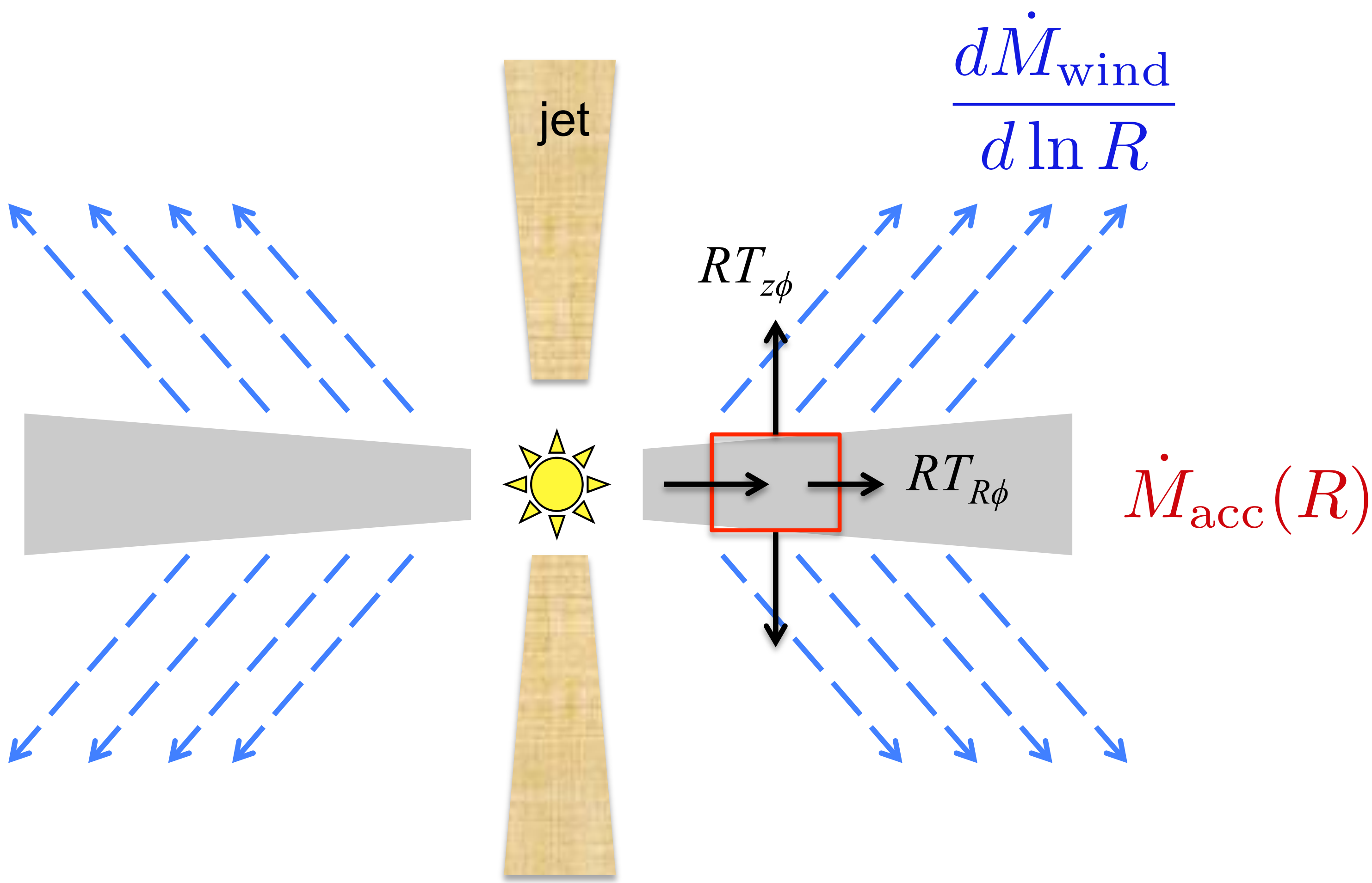
  (e.g. Machida+10,Santos-Lima+11, Seifried+12,13, Joos+12,13, Li+13, Tomida+13,15)

- Hall-effect induced bimodality (Tsukamoto+15):



What drives global disk evolution

- Angular momentum transport (radially/vertically)
- Mass loss (via disk wind)



Radial transport of angular momentum

$$T_{R\phi} = \overline{\rho v_R v_\phi} - \frac{\overline{B_R B_\phi}}{4\pi} + \frac{\overline{g_R g_\phi}}{4\pi G} \equiv \alpha P$$

hydro turbulence — Maxwell stress — self-gravity

Prescribe radial profile of α => disk evolution is straightforward.

Hydro processes	GI, VSI (GSF), baroclinic/ convective, zombie vortex… spiral shocks
MHD processes	turbulent stress (due to the MRI) laminar stress (i.e., spiral field)

see G. Lesur's talk for more details about these processes

see E. Borobyov's talk for early disk evolution with GI

α-disk model OK only when radial transport of AM dominates

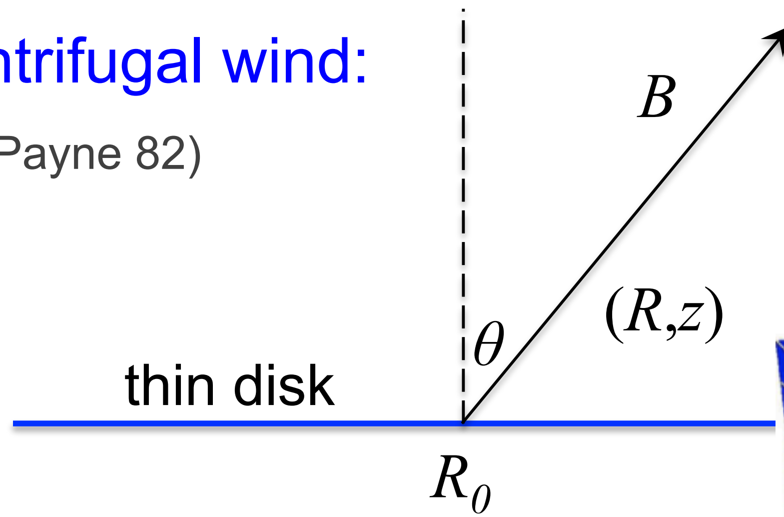
Vertical transport: magnetized disk wind

$$T_{z\phi} = \rho v_z \Delta v_\phi - \frac{B_z B_\phi}{4\pi}$$

Requires external B field threading disk.

Magneto-centrifugal wind:

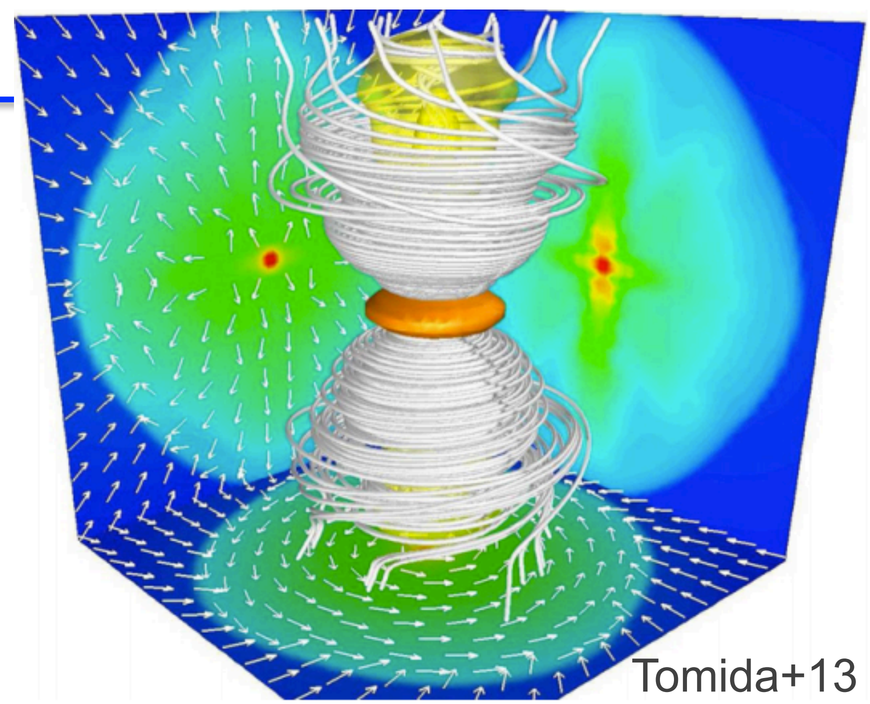
(Blandford & Payne 82)



strong poloidal field enforces corotation.

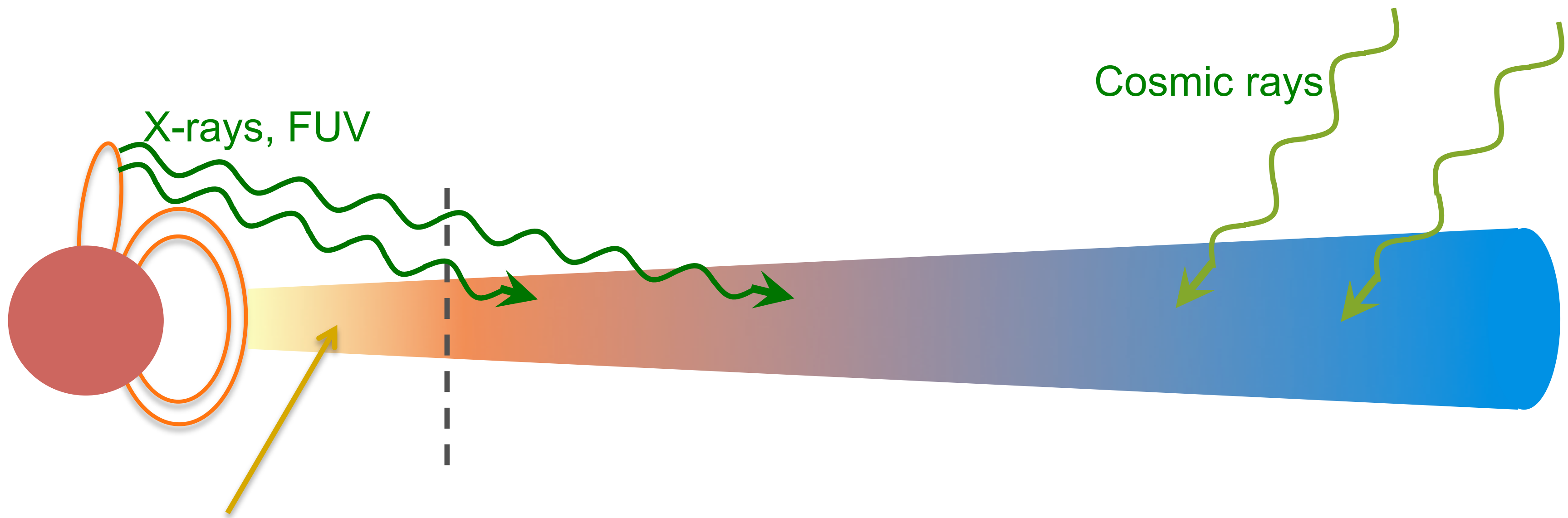
"Magnetic tower": (e.g. Lynden-Bell 03)

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



Tomida+13

Disk microphysics: source of ionization



Thermal ionization zone: ionization of Na/K above ~800 K (Desch & Turner 15)

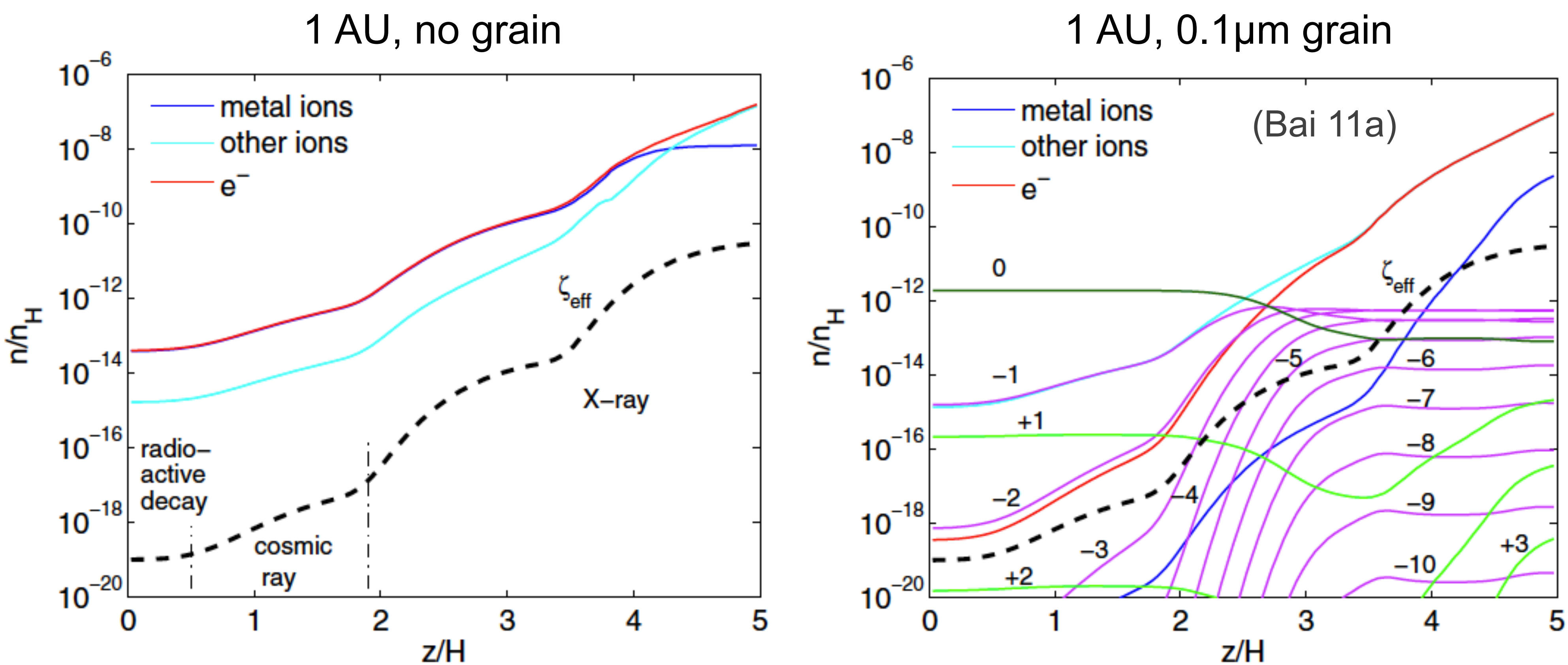
Cosmic-ray ionization: large penetration depth, can be affected by wind (Umebayashi & Nakano 81, Cleeves+13)

Stellar X-ray ionization: modest penetration depth (Igea & Glassgold 99, Ercolano & Glassgold 13)

Stellar Far UV ionization: fully ionize C, S with small penetration depth (Perez-Becker & Chiang 11)

Radioactive decay: time-dependent, ~10^{-19} s^{-1} (Umebayashi & Nakano 09).

Importance of grain size and abundance



- Ionization level strongly depends on grain size/abundance as long as grain abundance > ionization fraction.
- Grains can become the dominant charge carrier.

Disk microphysics: non-ideal MHD effects

Generalized Ohm's law is in tensor form: $\boldsymbol{J} = \boldsymbol{\sigma}(\boldsymbol{B}, \boldsymbol{E})\boldsymbol{E}$

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**

Ohmic: $\sim \frac{n}{n_e}$ Hall: $\sim \frac{n}{n_e}\frac{B}{\rho}$ AD: $\sim \frac{n}{n_e}\frac{B^2}{\rho^2}$

Ohmic: midplane region of the inner disk

Hall: Intermediate layer @ inner disk; Midplane towards outer disk

AD: inner disk surface and outer disk

Further complications:

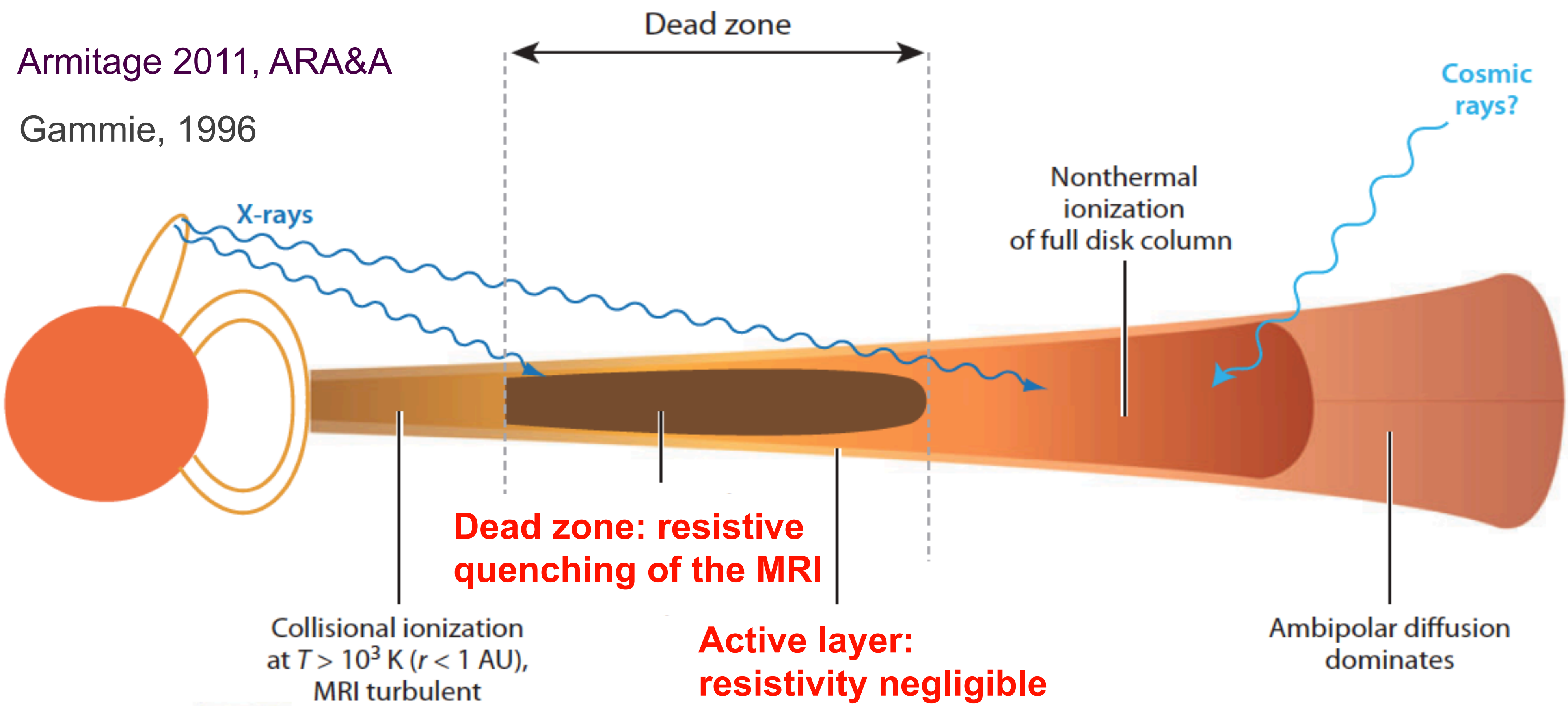
Non-linear Ohm's law (Okuzumi+15)

Complex dependence of diffusivities on B (Wardle 07, Bai 11b, Xu & Bai, in prep)

Ohmic resistivity only

Armitage 2011, ARA&A

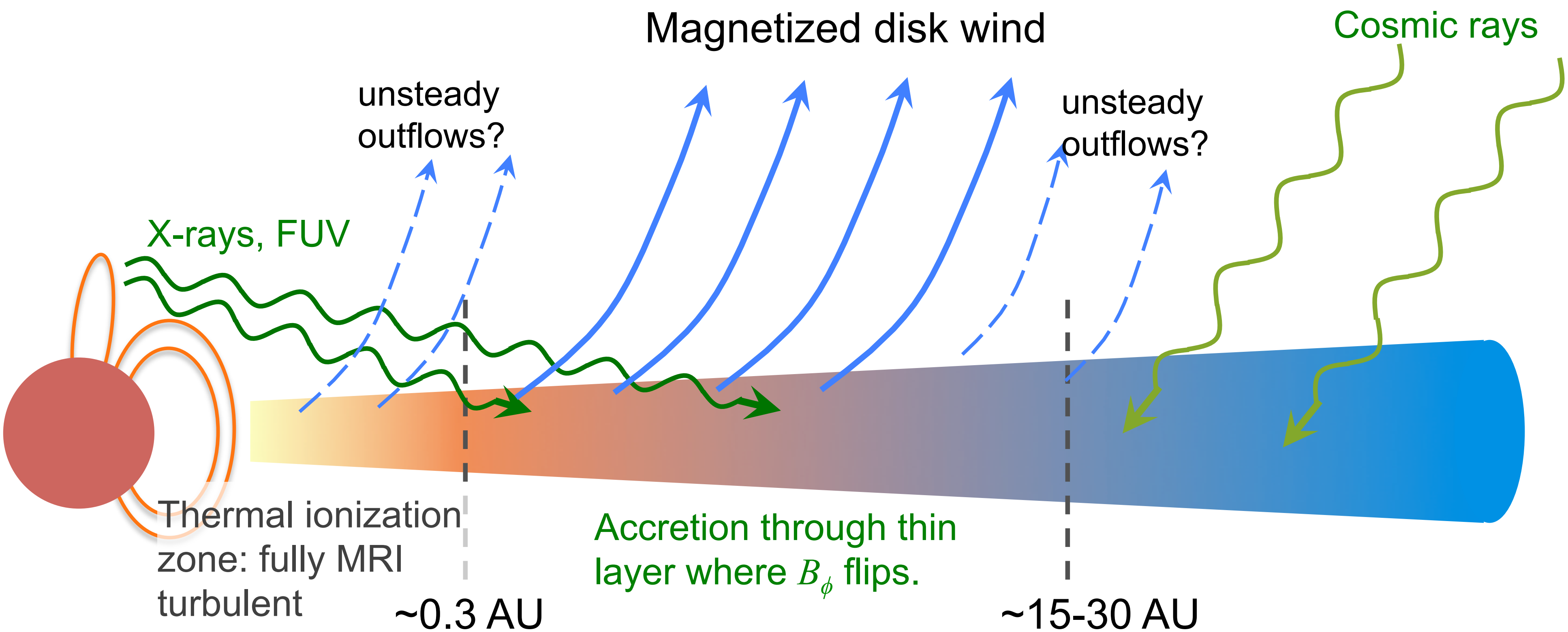
Gammie, 1996



- Semi-analytical studies already indicated that MRI is insufficient to drive rapid accretion when including the effect of ambipolar diffusion (Bai & Stone, 2011, Bai, 2011a,b, Perez-Becker & Chiang, 2011a,b).

Ohmic + ambipolar diffusion

(Bai & Stone 13b, Bai, 2013, Simon, Bai+ 13a,b, Gressel+15)



MRI suppressed by Ohmic+AD, disk largely laminar.

MRI damped by AD

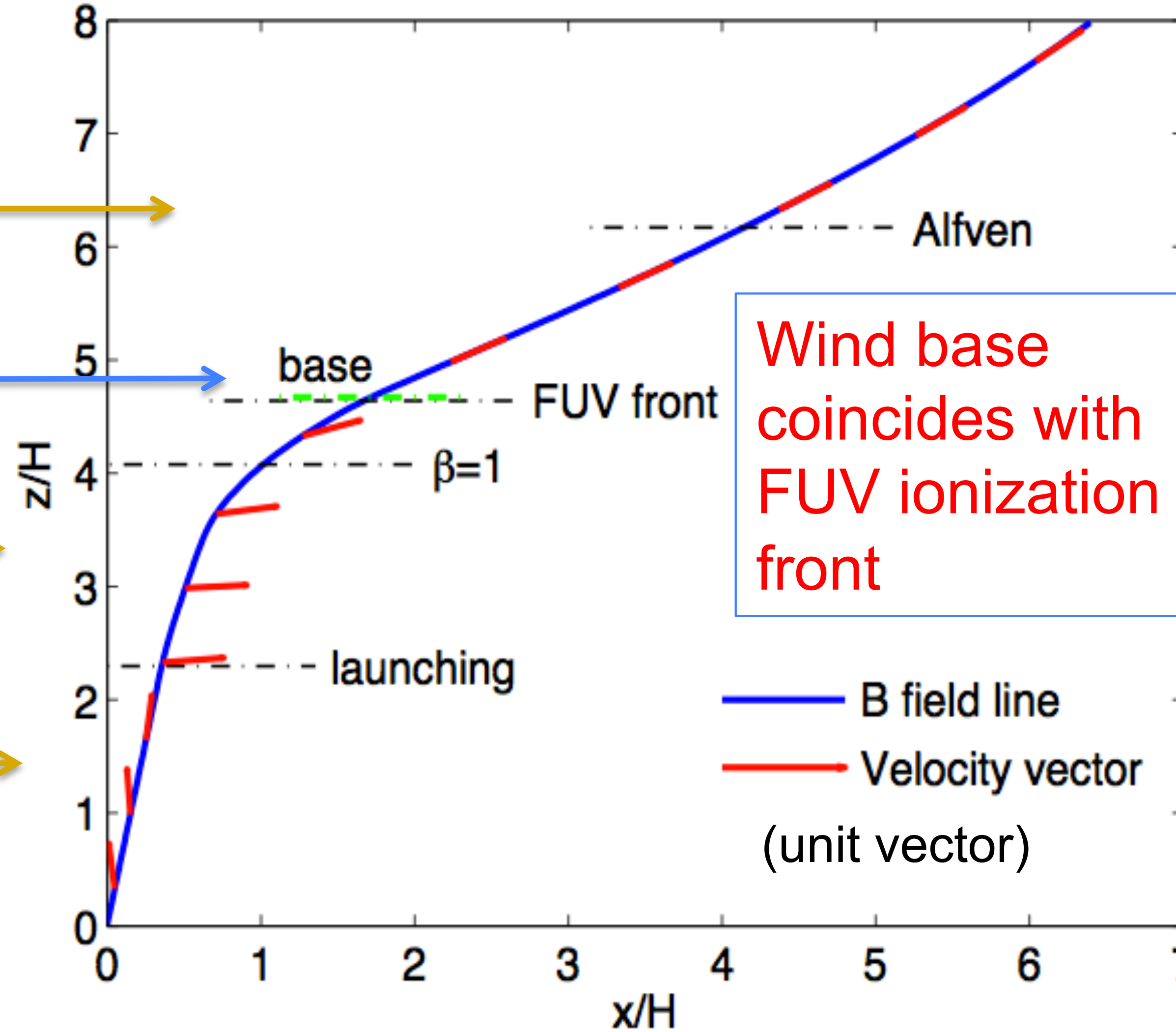
Wind launching process (inner PPDs)

ideal MHD

wind base: super-Keplerian rotation

AD dominated

Ohmic dominated

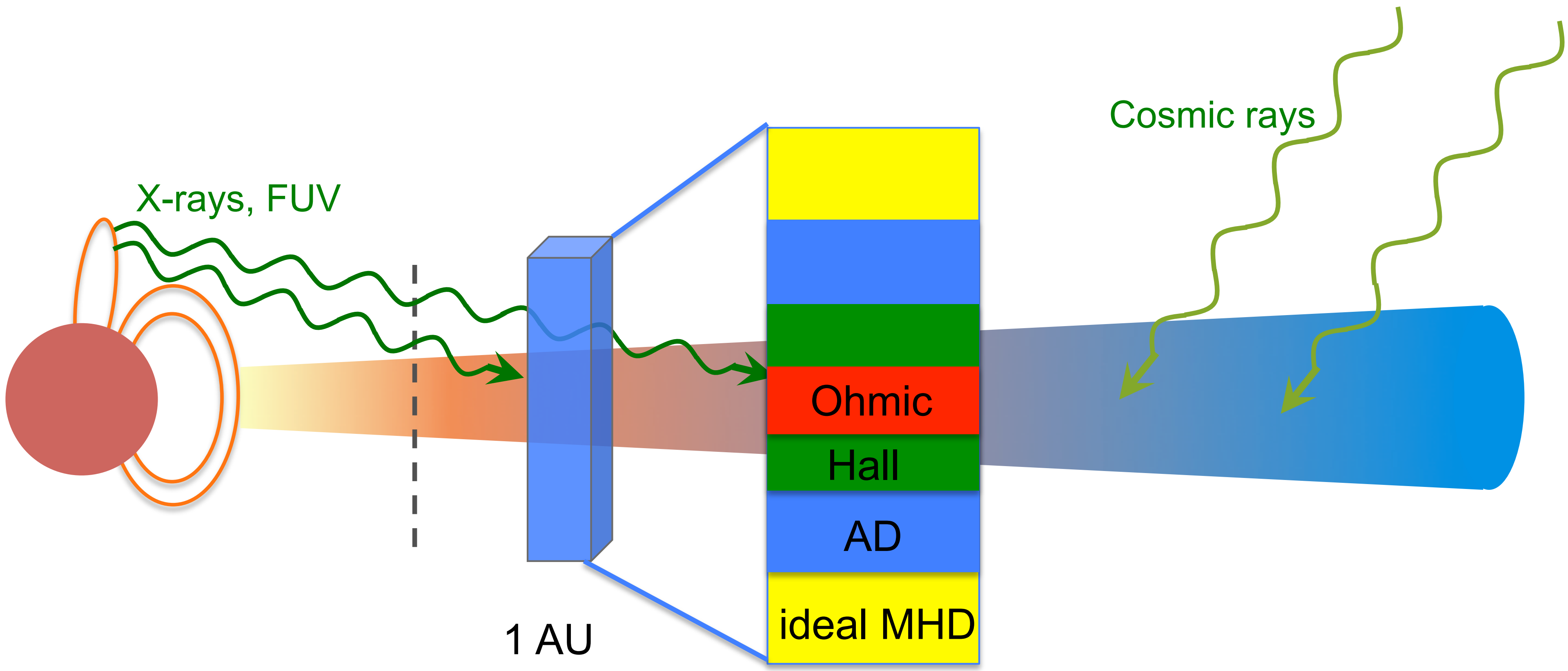


Wind base coincides with FUV ionization front

To achieve the right accretion rate, only need a weak Bz, but it ~equi-partition at wind base.

(Bai & Stone, 2013b)

Adding the Hall effect: inner Disk



All three non-ideal MHD effects are important.

Unstratified simulations: Kunz & Lesur 13 (local), O'Keeffe & Downes 14 (global)

Stratified simulations in shearing-box: Lesur+14, Bai 14,15, Simon+15

Dependence on grain abundance

- **Grain-free:** (Lesur+14, Simon+15)

  $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0:$ Very strong B field amplification to near equi-partition, considerable α (up to 0.1) to transport AM.

  $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0:$ Bursty behavior with enhanced α at ~5-10 AU.

- **Modest grain abundance** (0.1μm, 0.01 solar): (Bai, 14,15)

  $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0:$ Modest B field amplification well below equi-partition, enhanced but small α ($\ll 0.01$).

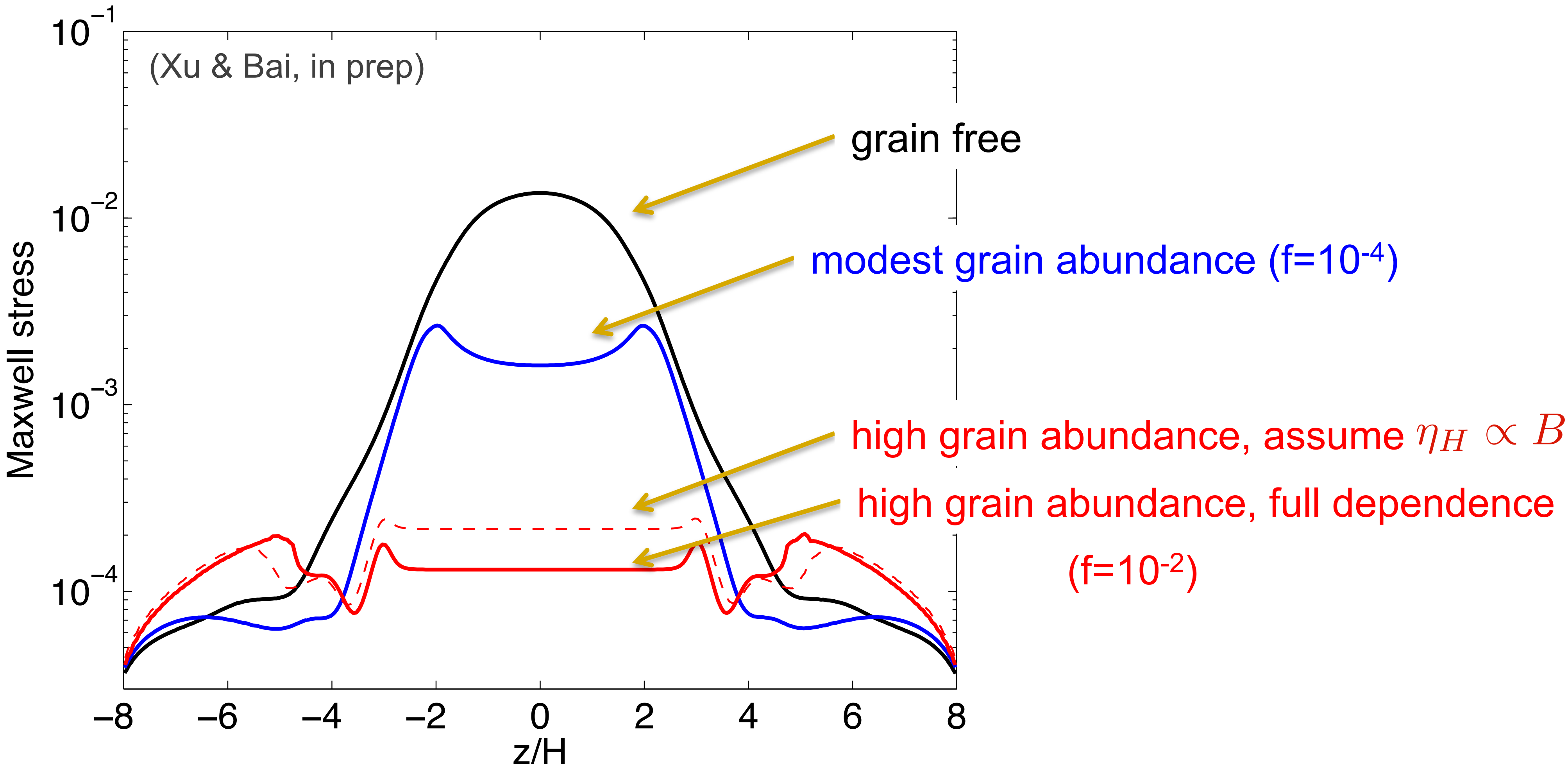
  $\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0:$ Horizontal B field reduced to almost 0, no bursty behavior.

- **High grain abundance** (0.1μm, solar): (Xu & Bai, in prep)

  $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0:$ Hall diffusivity changes sign at normal field strength, B field amplification suppressed.

Dependence on grain abundance

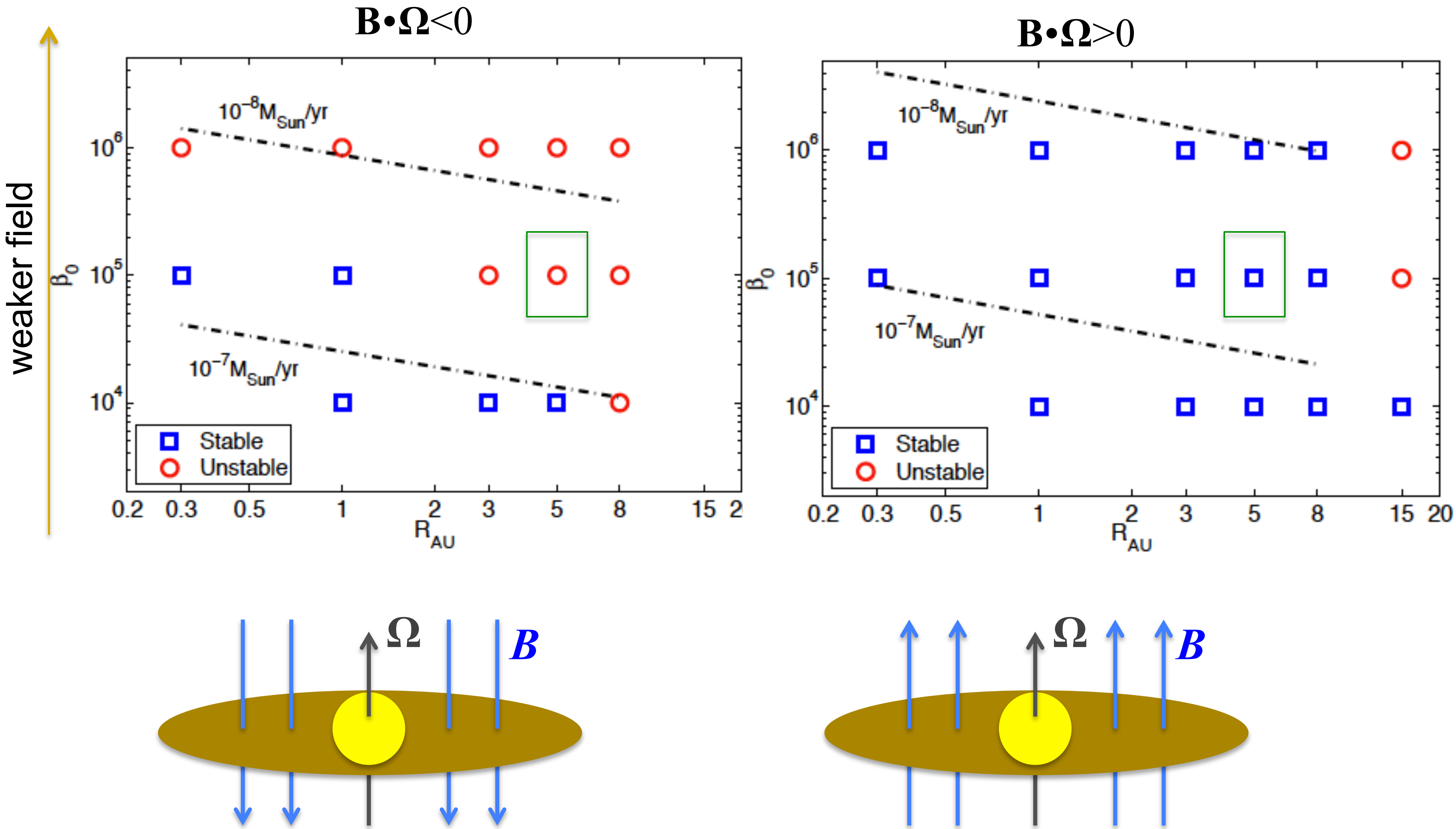
1 AU, $\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$:



Assume grain size a=0.1μm

Wind transport is still more efficient.

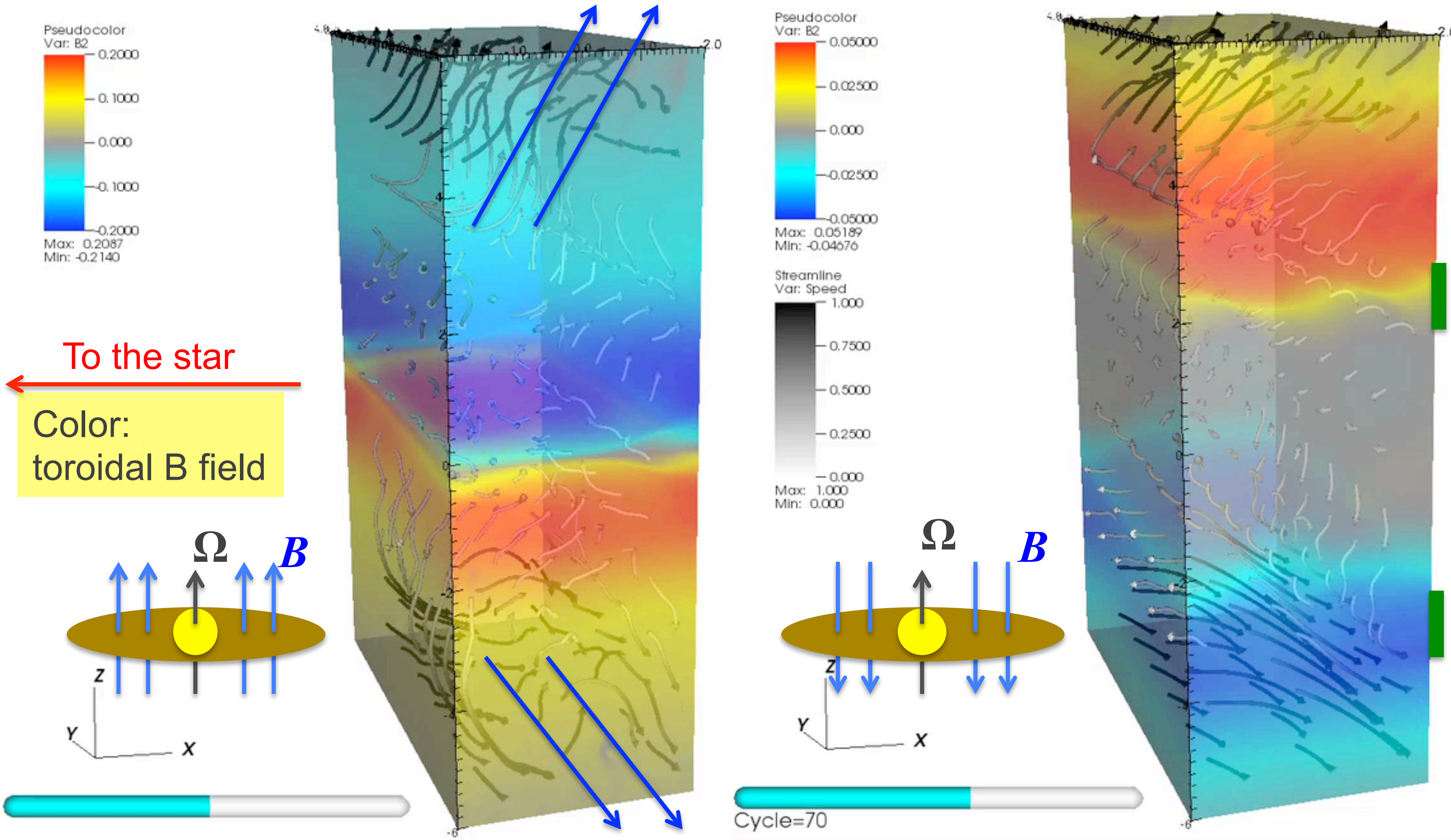
Wind solutions modified, but some gets unstable



(Bai, 2014)

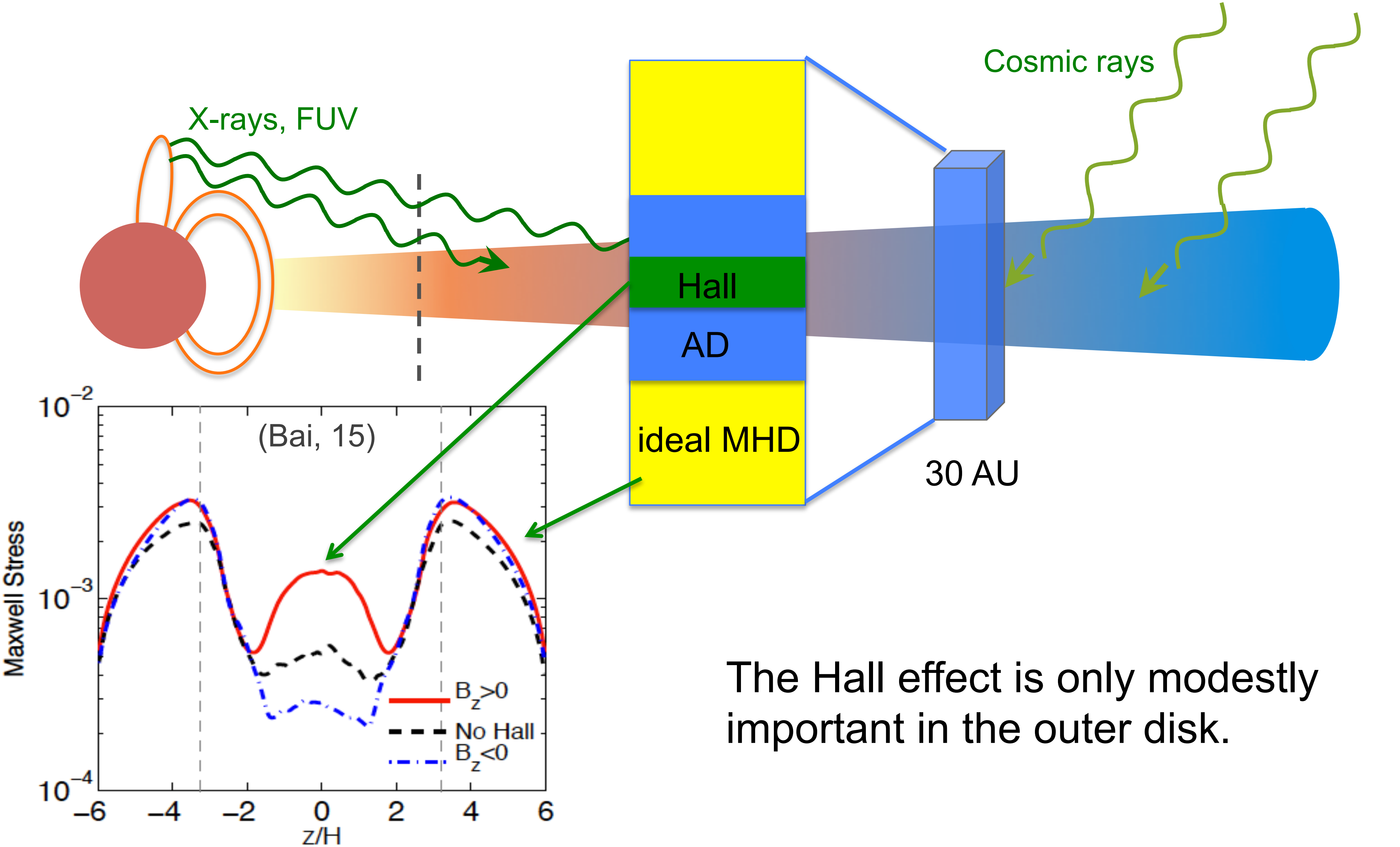
Representative results at 5 AU

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



Adding the Hall effect: outer disk

(Bai 15, Simon+15)



The Hall effect is only modestly important in the outer disk.

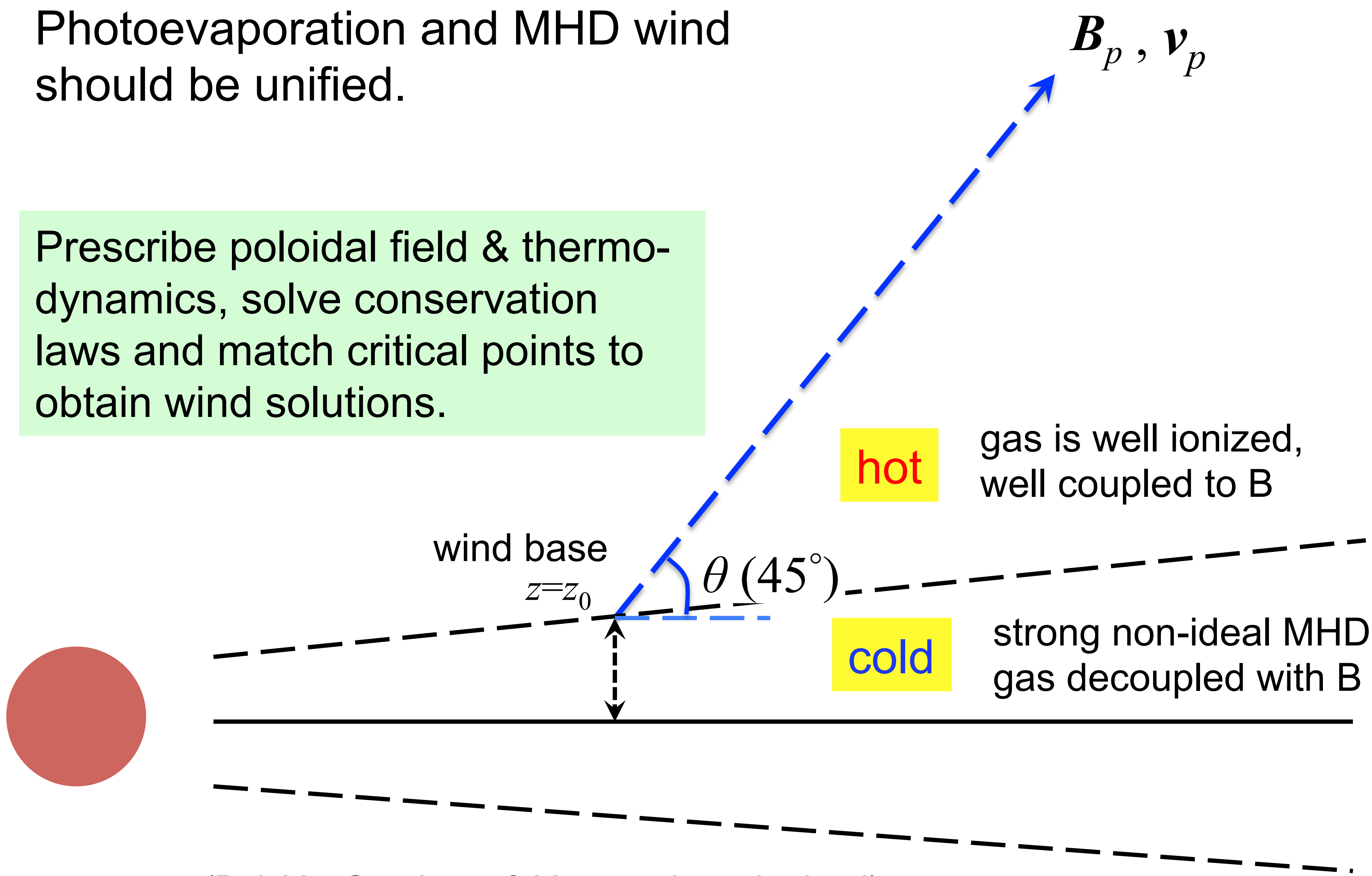
Current status

- Net vertical magnetic flux is essential through entire disk.
- Disk microphysics is much better understood, but its parameter dependence is complex, especially on the ionization chemistry and grains (in the inner disk).
- Launching of disk wind is natural consequence of net Bz, with two major issues to be addressed:
    - Global wind structure and kinematics.
    - Local simulations have issues with wind symmetry.
- Level of turbulence/role of MRI less clear in outer disk (e.g., Simon+15, Flaherty+15): depend on FUV penetration (A. Gomez de Castro's talk). Wind likely dominates transport.

Mass loss from PPDs: magnetized wind

Photoevaporation and MHD wind should be unified.

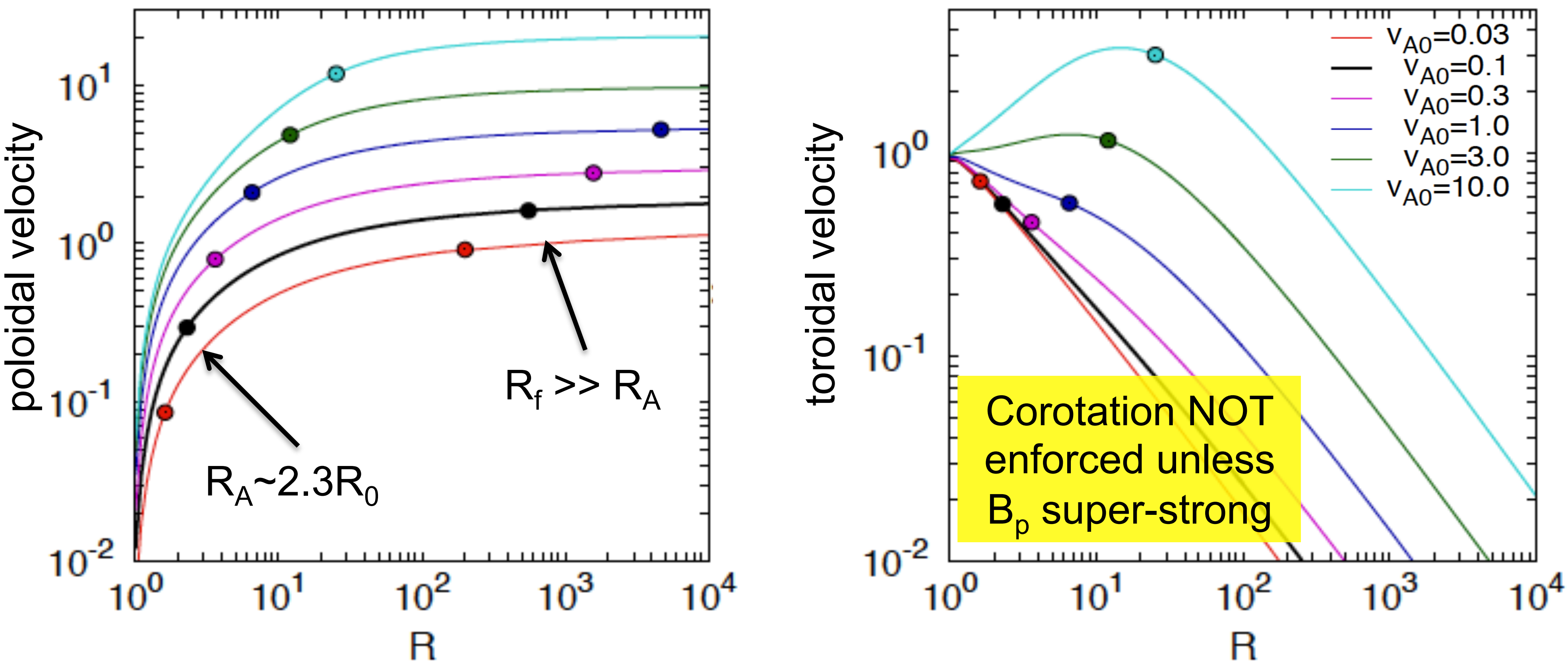
Prescribe poloidal field & thermo-dynamics, solve conservation laws and match critical points to obtain wind solutions.



(Bai, Ye, Goodman & Yuan, to be submitted)

Wind kinematics

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

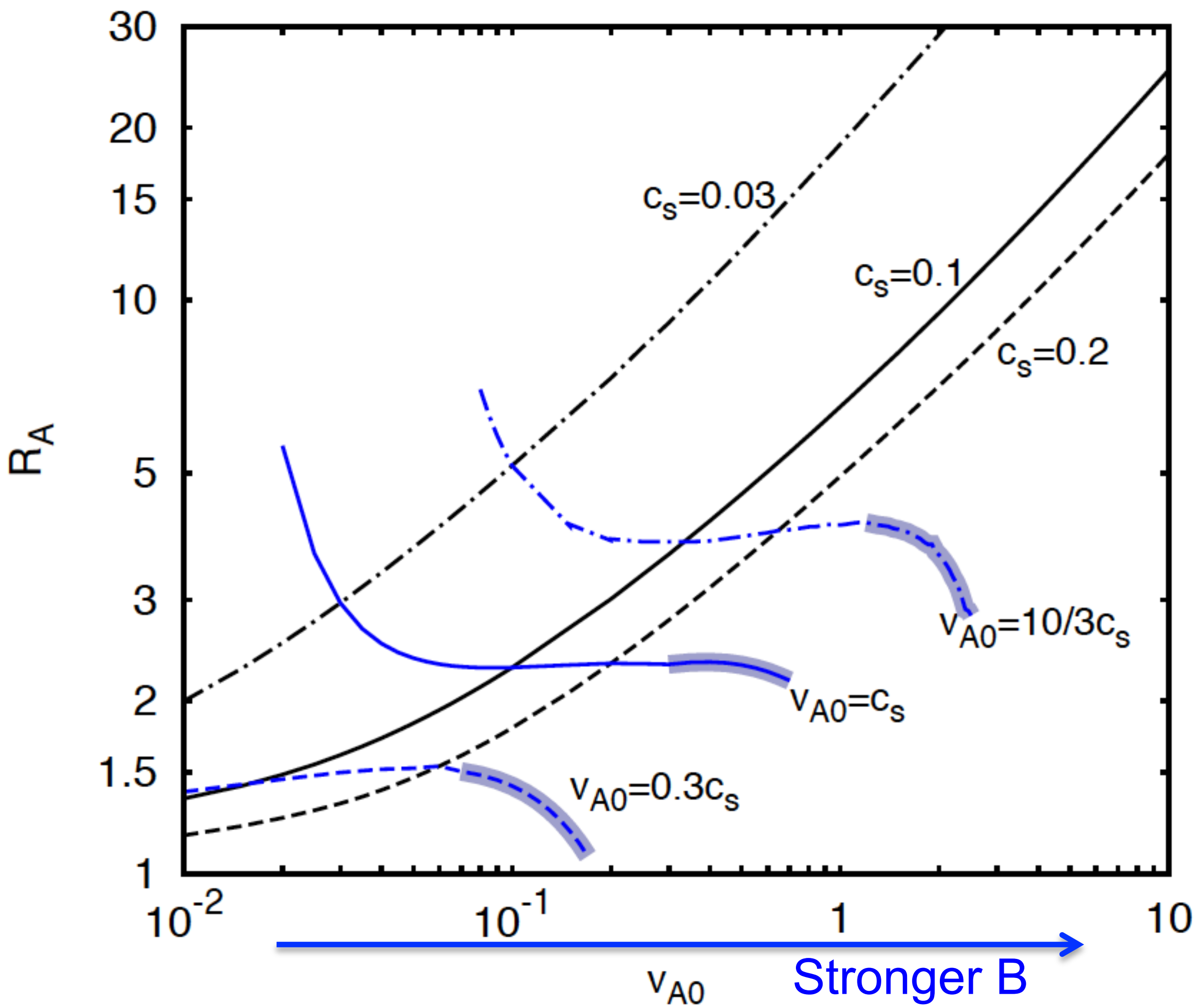


$$\frac{d\dot{M}_{\rm wind}}{d\ln R} = \frac{1}{2}\frac{\dot{M}_{\rm acc}}{(R_A/R_0)^2-1}$$

~ 0.12 (can be significant)

In general, PPD wind is driven by magnetic pressure gradient.

Thermal effect: magneto-photoevaporation?



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!

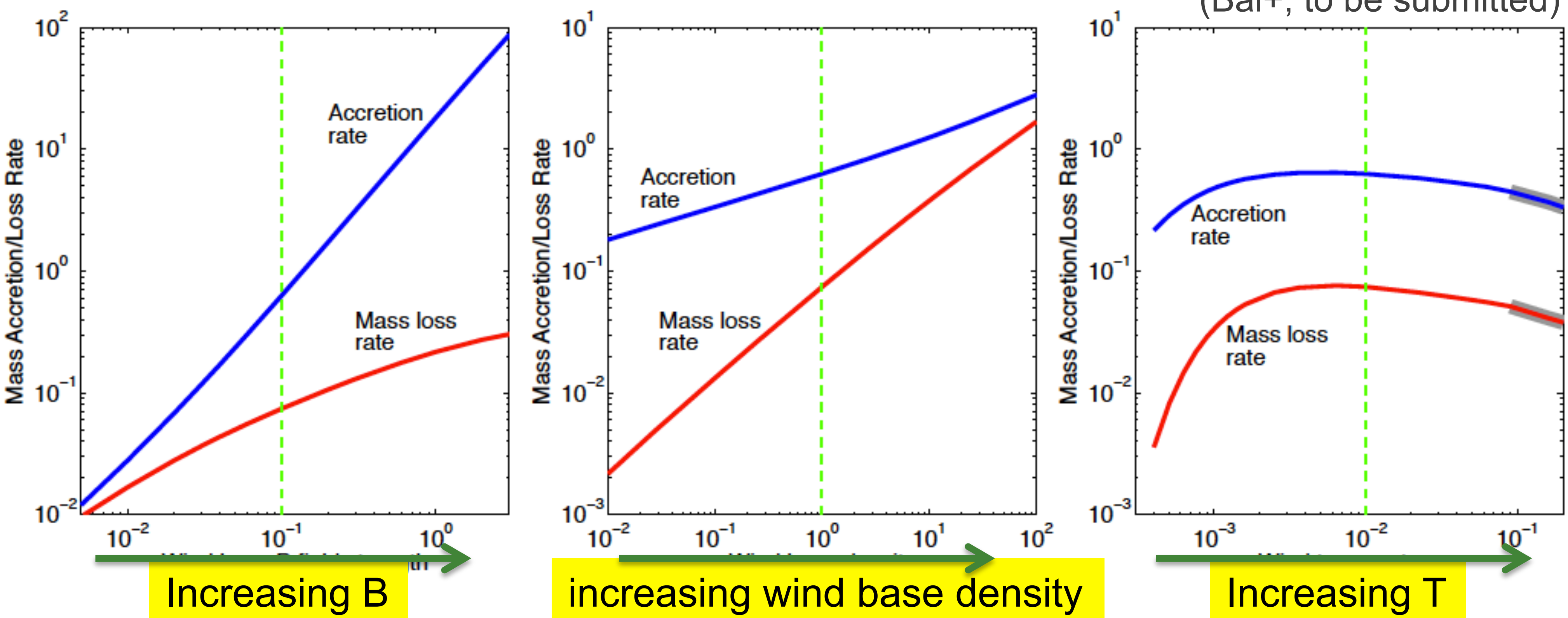
With B field, mass loss rate is always higher than pure thermally driven wind.

Towards a global picture: wind-driven accretion

- Dependence on v_{A0}/c_s translates to:
  a. Physical field strength B
  b. Penetration depth of FUV => density at wind base
  c. Wind temperature

Note $v_{A0} = \frac{B_{p0}}{\sqrt{4\pi\rho_b}}$

(Bai+, to be submitted)

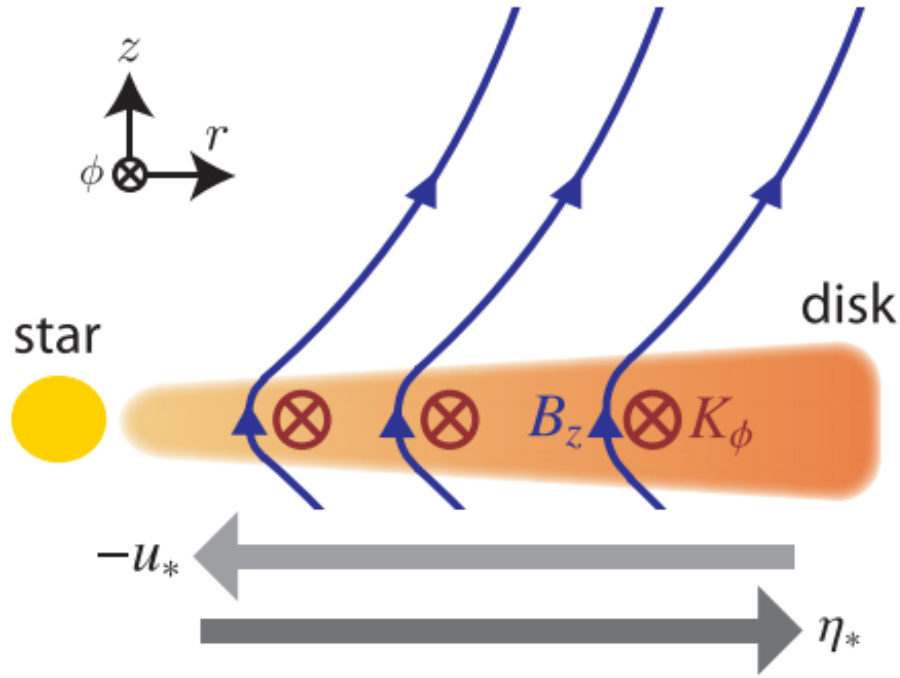


Towards a global picture: wind-driven accretion

- Need to know the distribution of magnetic flux

Magnetic flux transport:

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



Okuzumi+14

Need to incorporate wind and non-ideal MHD physics.

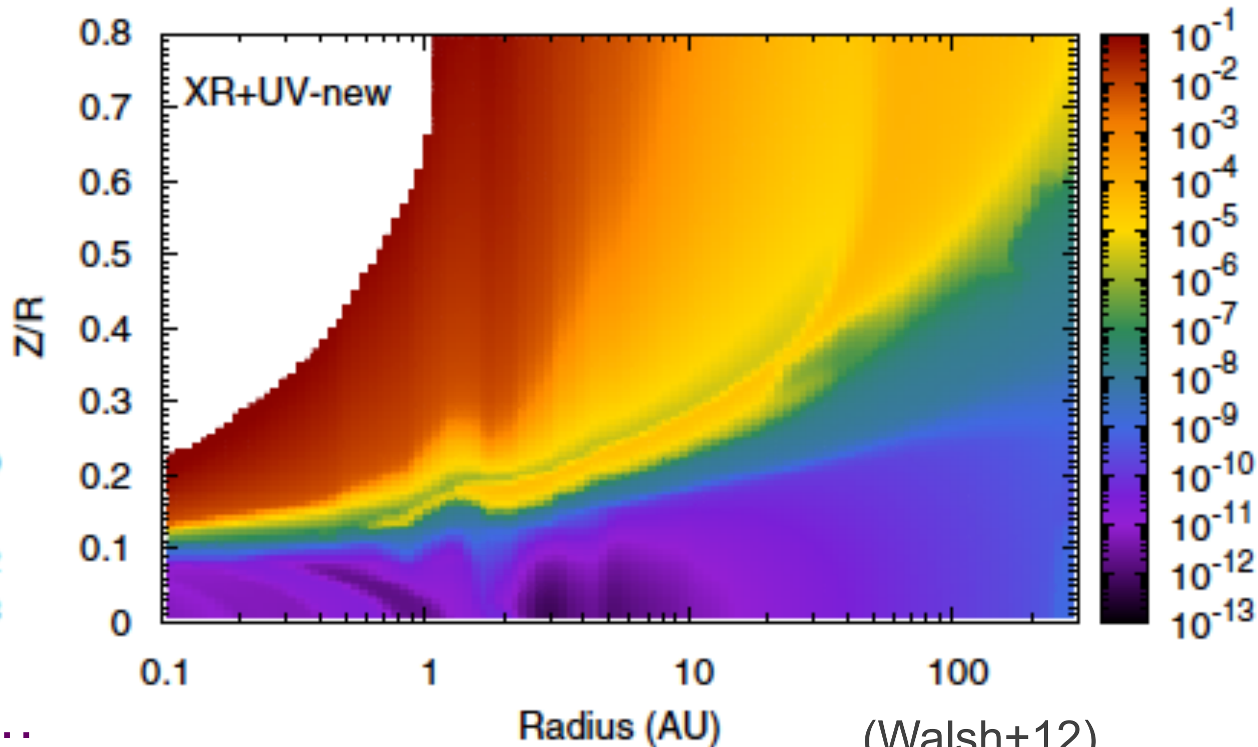
(e.g., Bai 14, Tsukamoto+15)

Towards a global picture: wind-driven accretion

- Need to know how deep FUV penetrates

A complex task of coupling UV radiative transfer and photo-chemistry.

(e.g., Glassgold+04, Nomura & Millar 05, Woitke+09, Walsh+10,12, Bethell & Bergin 11, Akimkin+ 13)



(Walsh+12)

and with wind dynamics…

(e.g., Panoglou+12)

Main source of UV opacity on tiny dust grains: how abundant are they?

Summary

- Initial condition: disk formation to be better understood
  - Hall effect can induce a bimodality in disk size, as well as amount of B flux
- MRI is disfavored, accretion is largely wind driven
  - Inner disk: suppressed by Ohmic+AD; outer disk: strongly damped by AD
  - MND wind launching from far-UV ionization front.
- Hall effect is polarity dependent, important at inner disk
  - Disk dynamics depends on grain abundance: more grains suppress activities.
  - Despite unsettled issues, wind still likely dominates AM transport.
- Disk wind-driven accretion as the key to global disk evolution
  - Results strongly depend on both B flux distribution and thermal effects
  - Need to better understand magnetic flux transport