Squaring the circle in YSO

The origin of accretion in weakly ionised protoplanetary discs

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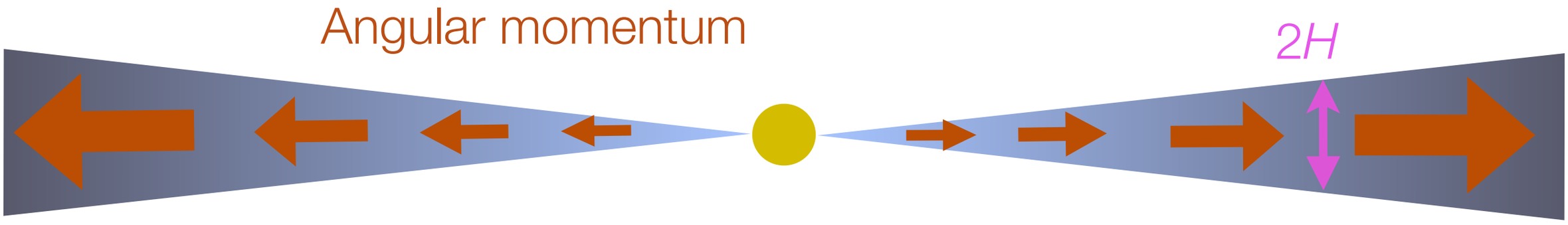
Accretion/Outfow In Young Stellar Objects

Angular momentum transport processes
I- turbulent (viscous) transport



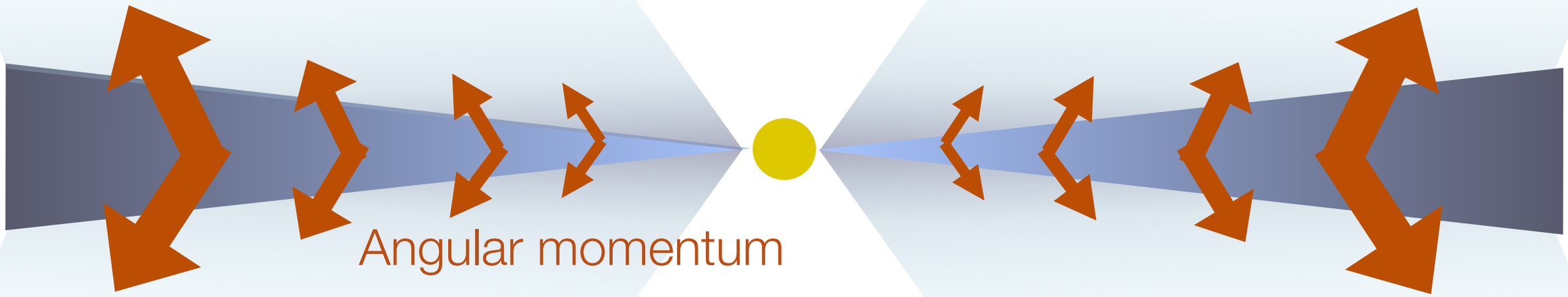
- Transport angular momentum in the bulk of the disc
- Suggested by Shakura & Sunyaev (1973) A&A, 24, 337
- Turbulence leads to enhanced transport («mixing length theory»)
- One defines a turbulent viscosity

$$\nu_t = \alpha c_s H$$

«turbulent transport» «sound speed» «1/2 disc thickness»

$$10^{-3} < \alpha < 10^{-2}$$

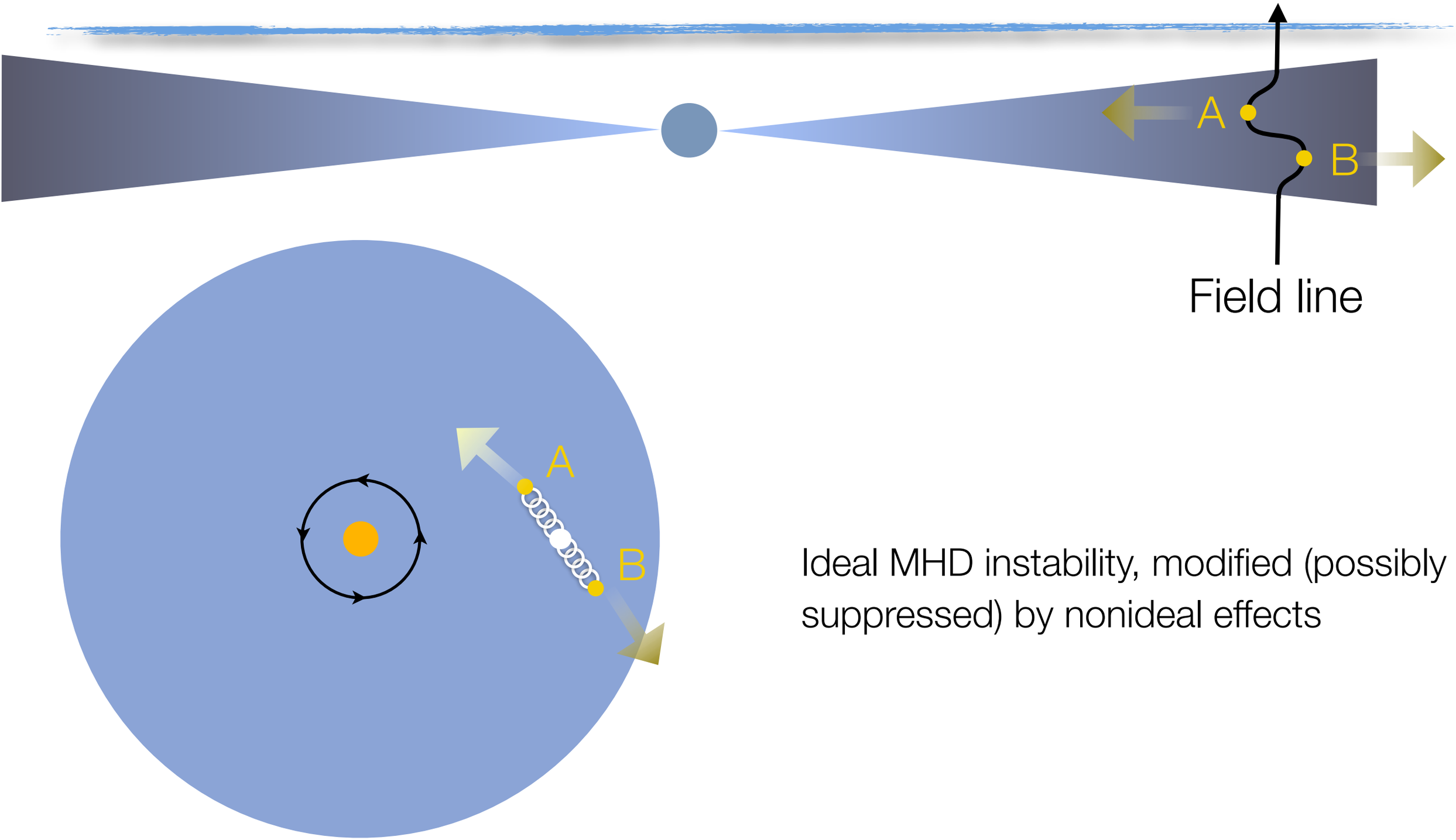
Angular momentum transport processes
II- disc wind



- Angular momentum *extracted* from the disc by a magnetic wind
  [Blandford & Payne 1982, MNRAS, 199, 883]
- Magnetic field exerts a torque on the disc surface which generates accretion (not described by α−disc!)

MHD processes

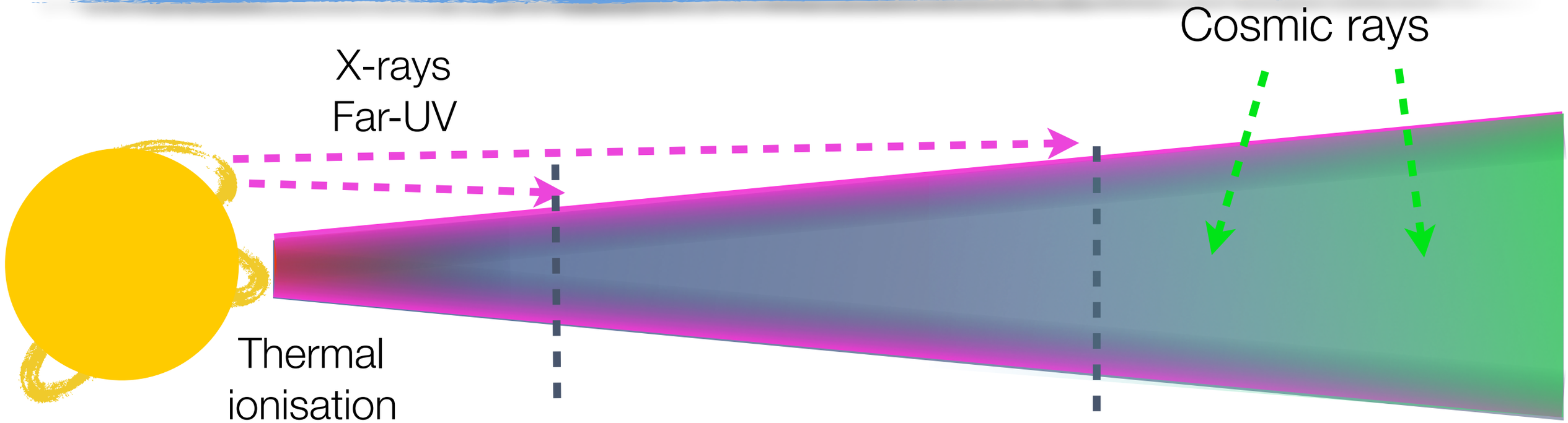
The magnetorotational instability (MRI)



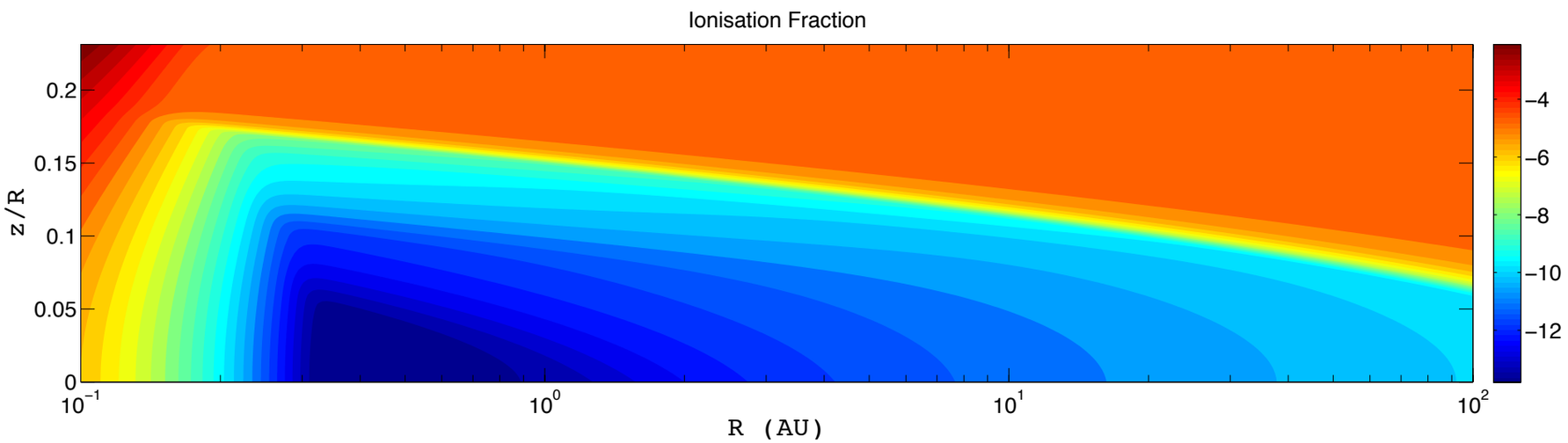
[Balbus, & Hawley (1991) ApJ, 376, 214]
[Balbus (2003) ARA&A, 41, 555]

Ideal MHD instability, modified (possibly suppressed) by nonideal effects

Ionisation sources in protoplanetary discs



Optimistic picture: shielding of cosmics [Cleeves+2013]
FUV and X-rays [Gomez de Castro's talk] is neglected

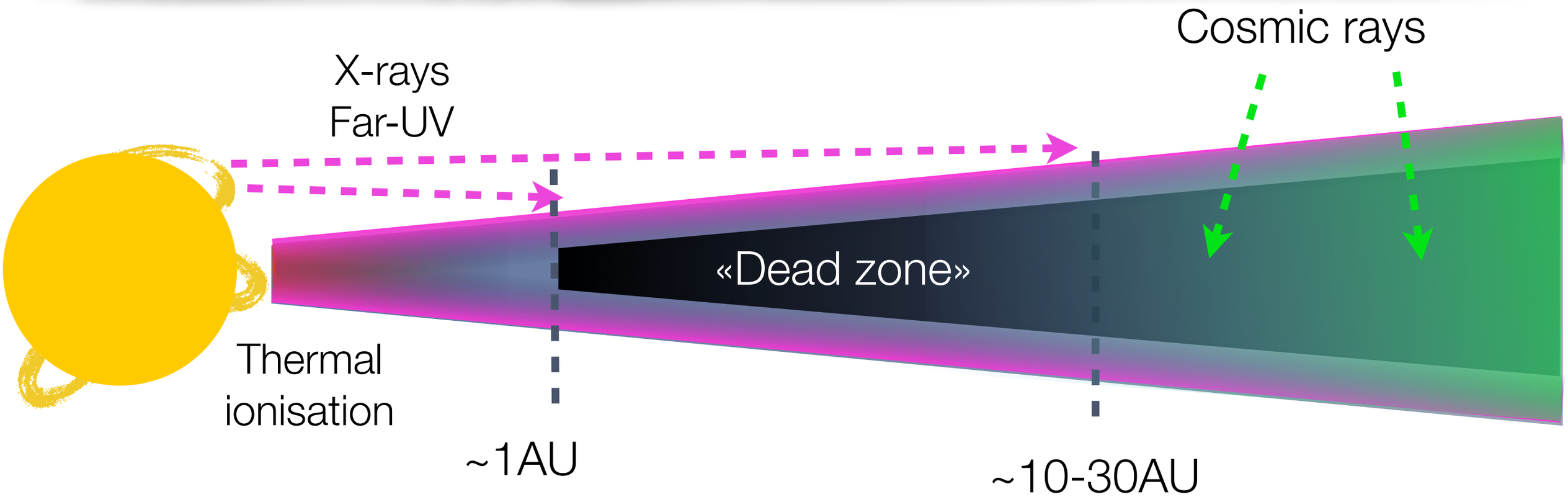


The ionisation fraction is very low
Exact value is strongly model dependent (grains, metallicity)

Question to observers #1:

Can we get observational constrains on the ionisation fraction in protoplanetary discs ?

Dead zone in protoplanetary discs



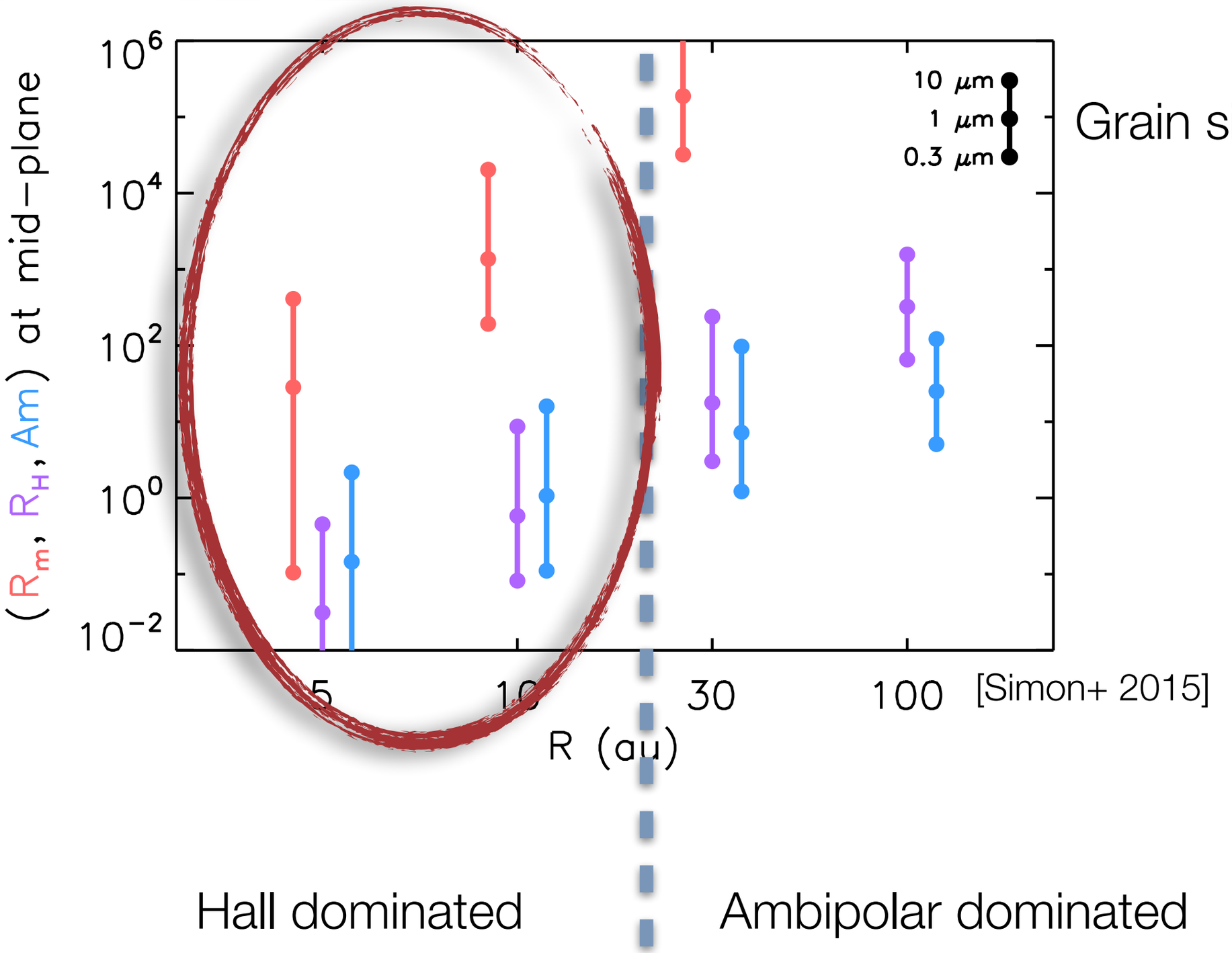
3 non ideal effects enter the scene

- Ohmic diffusion (collisions between electrons and neutrals)
- Ambipolar Diffusion (collisions between ions and neutrals)
- Hall Effect (drift between electrons and ions)

Amplitude of these effects depends strongly on location & composition

Nonideal MHD effects

Ambipolar
Hall
Ohmic



Grain size

Hall dominated

Ambipolar dominated

Hall MRI

Depends on field polarity

[Wardle 1999, Balbus & Terquem 2001, Kunz 2008]

- Nonideal MHD induction equation

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

Ideal Ohmic Hall Ambipolar

- Reverse field polarity $\boldsymbol{B} \to -\boldsymbol{B}$ $\boldsymbol{J} \to -\boldsymbol{J}$

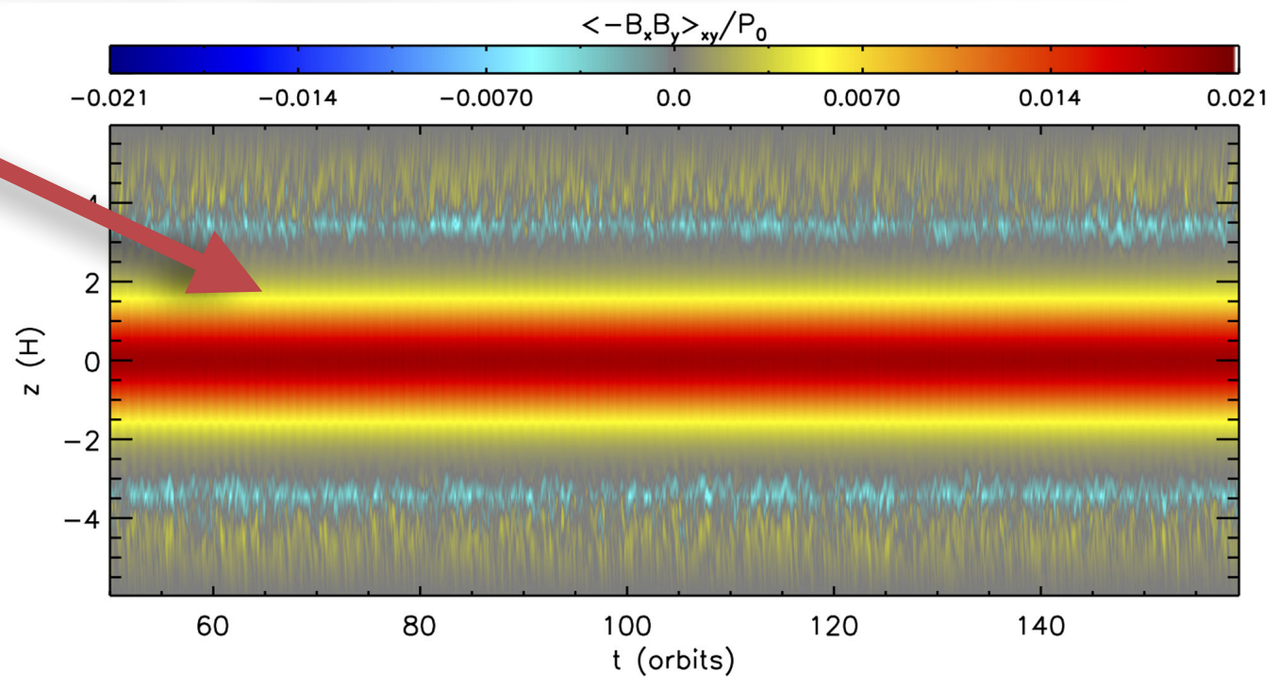
$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \boldsymbol{B} - \frac{4\pi}{c}\eta \boldsymbol{J} + \frac{\boldsymbol{J} \times \boldsymbol{B}}{e n_e} + \frac{c}{\gamma \rho \rho_i} (\boldsymbol{J} \times \boldsymbol{B}) \times \boldsymbol{B} \right)$$

→ Dynamics depends on field polarity

Hall MRI

Depends on field polarity

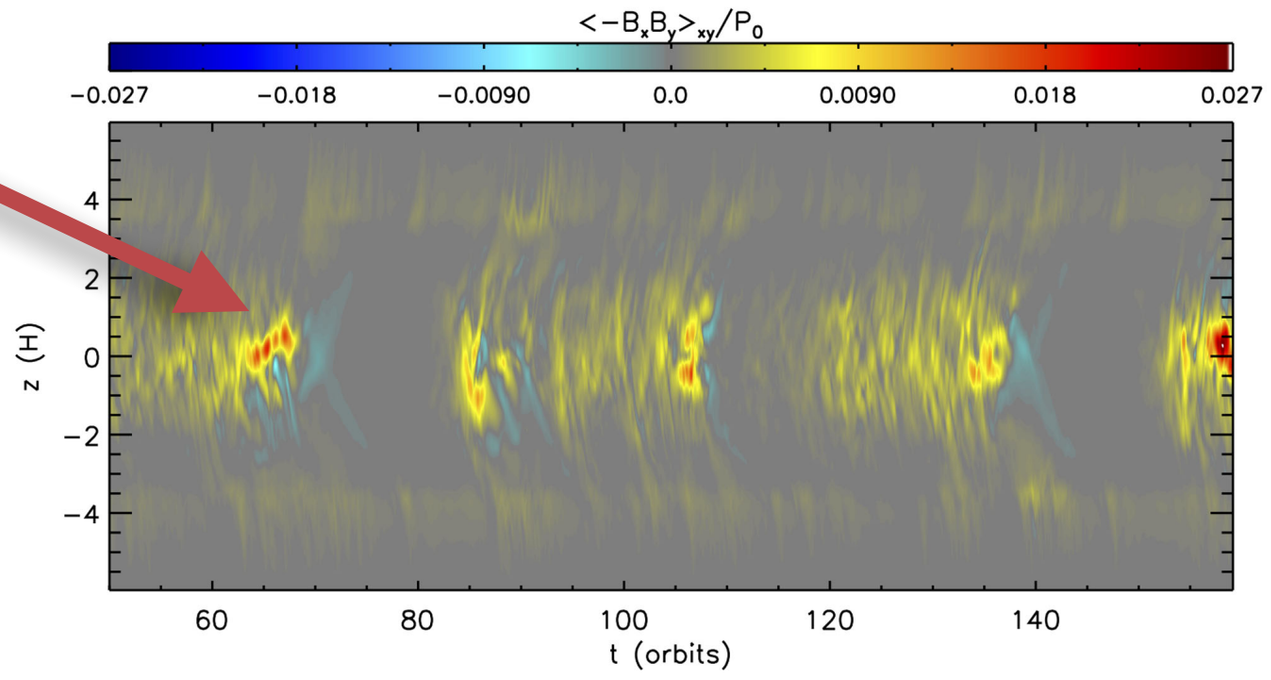
"laminar" stress



$$\boldsymbol{\Omega} \cdot \boldsymbol{B} > 0$$

@ 5AU

turbulent bursts



$$\boldsymbol{\Omega} \cdot \boldsymbol{B} < 0$$

Disc dynamics depends strongly on $\boldsymbol{\Omega} \cdot \boldsymbol{B}$

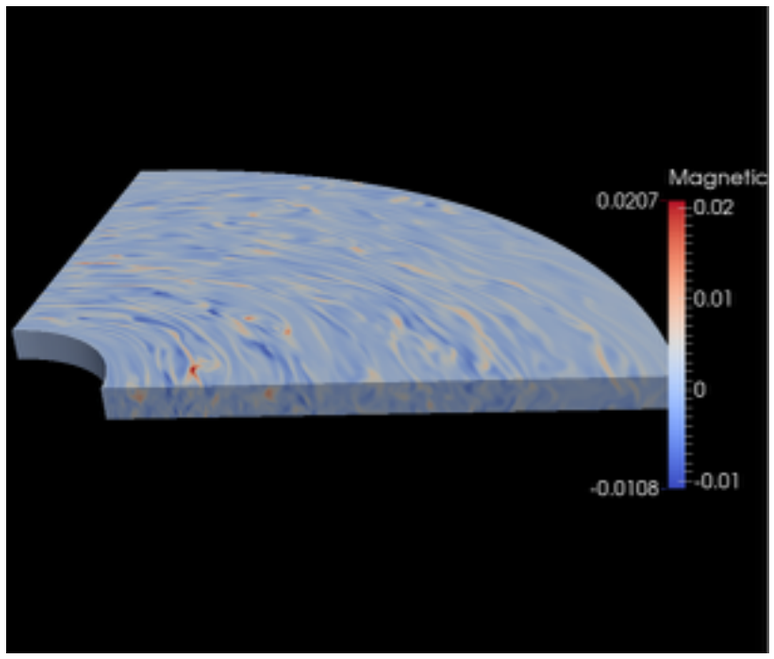
[Lesur+2014, Bai 2014, O'Keeffe+ 2014, Simon+2015]

Hall effect

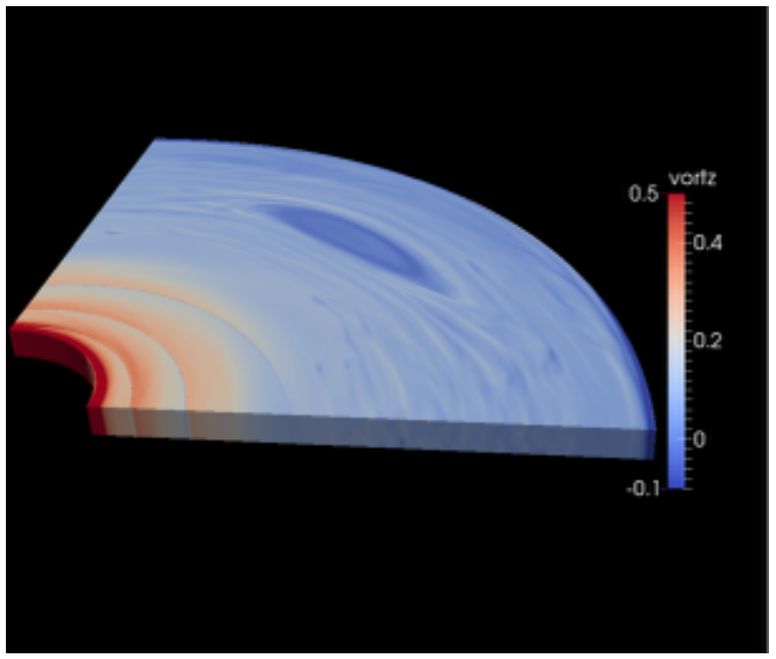
can drive large scale structure formation

Very weak Hall effect → Strong Hall effect

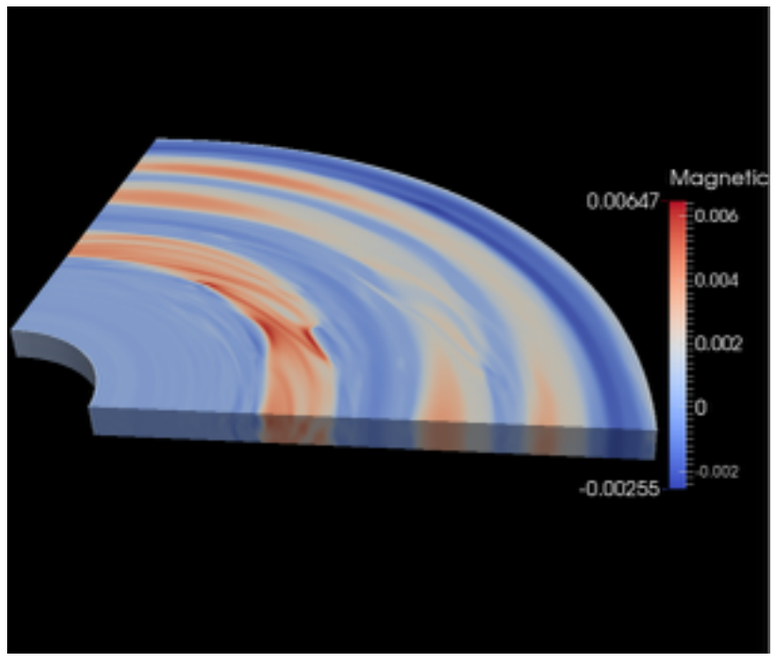
[Bethune+2015 in prep]



3D turbulence



Large scale vortices

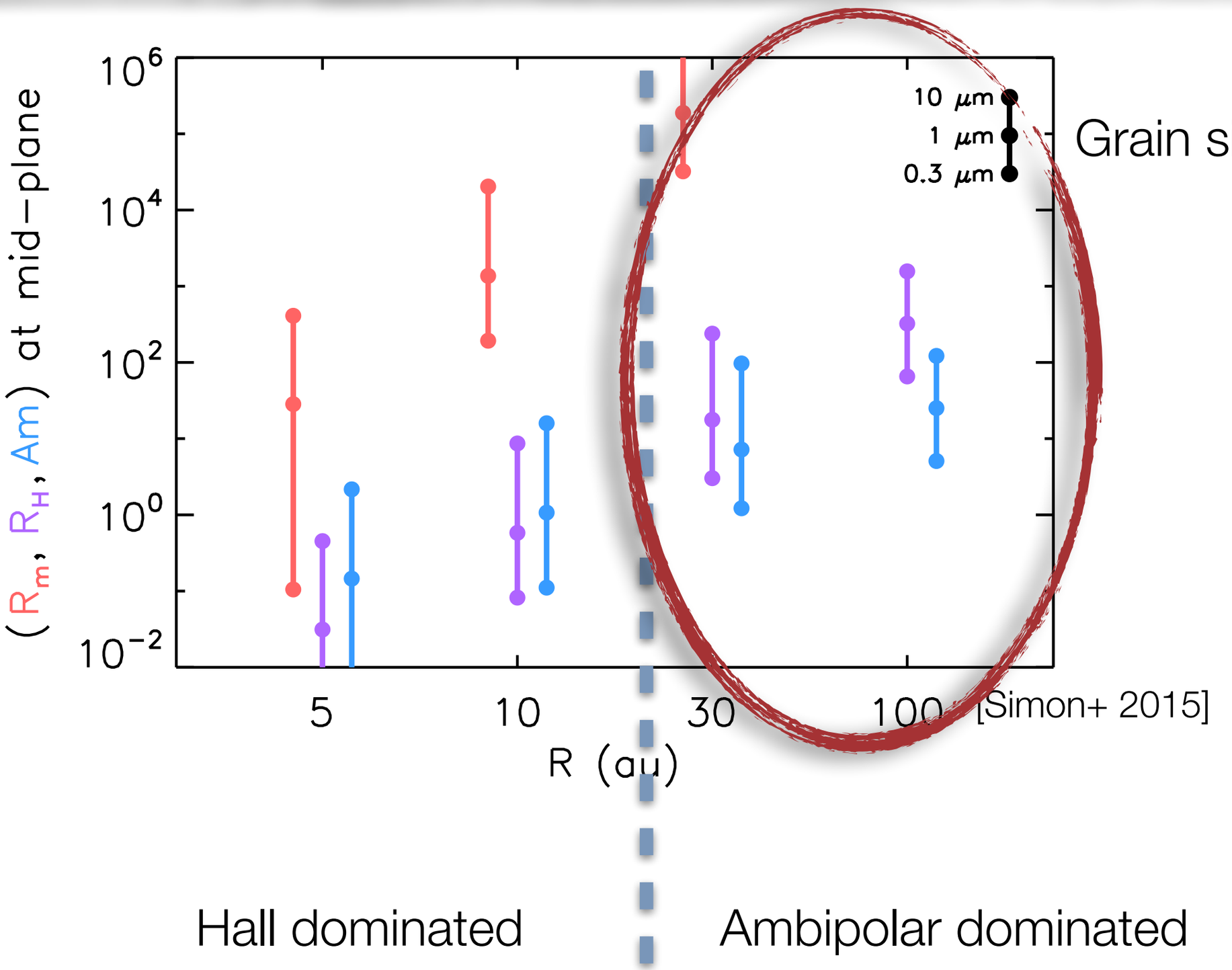


Large scale zonal flows "rings"

- Despite being strongly unstable to the MRI, Hall dominated discs can spontaneously organise [Kunz & Lesur 2013, Bethune+2015 in prep]
- Very weak or no turbulence

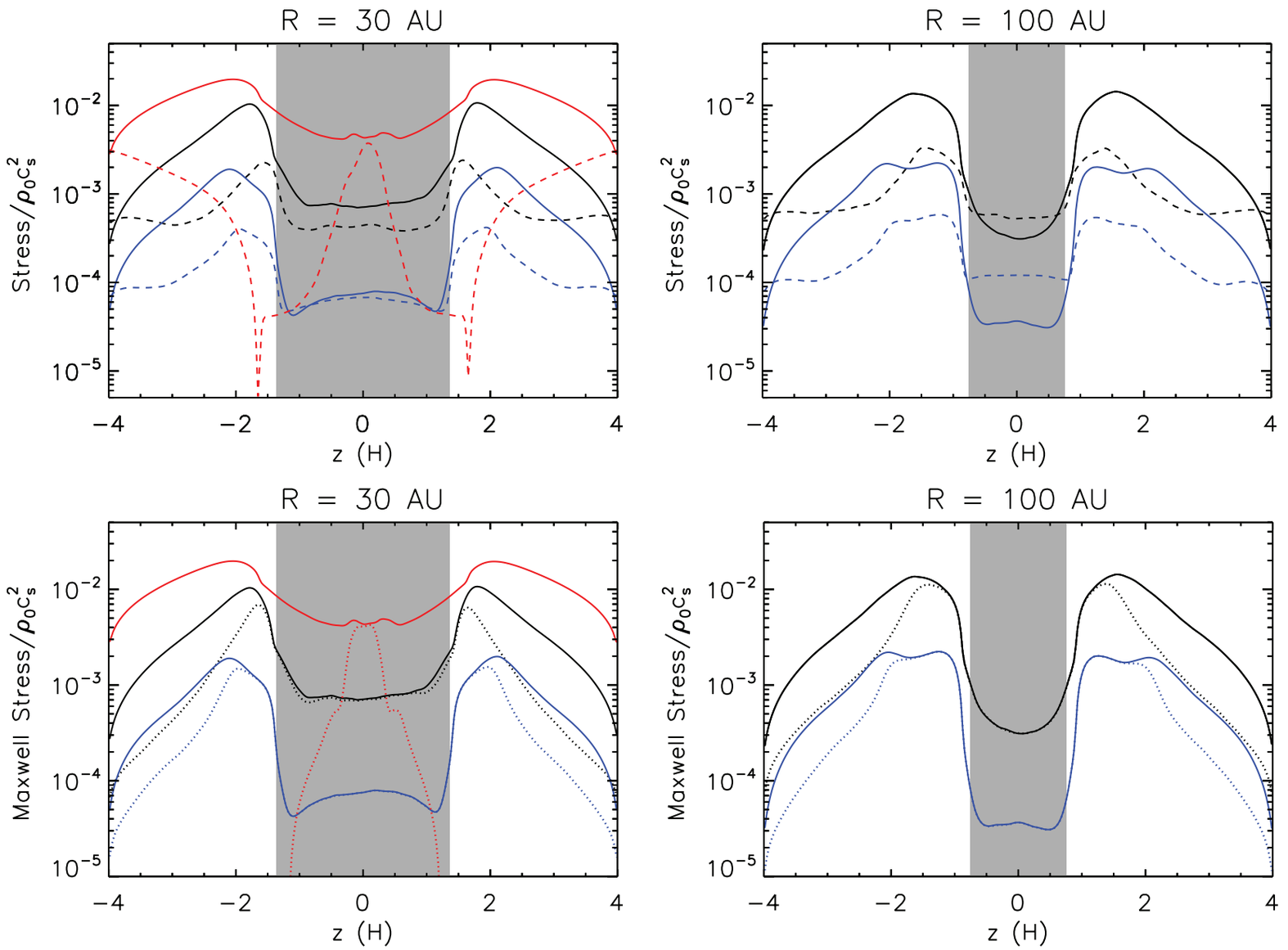
Nonideal MHD effects

Ambipolar
Hall
Ohmic



Ambipolar diffusion

Stabilises the outer disc



[Simon+2014]

The outer disc is less sensitive to the Hall effect [Bai 2015, Simon+2015]

Quenching of the midplane turbulence by ambipolar diffusion

The role of the MRI in PPdiscs

For R>1AU, the MRI is strongly affected by nonideal effects

- α values are not sufficient to explain observed accretion rates (no turbulence)
- Large scale structures (rings & vortices) can appear spontaneously
- If Hall-dominated, the dynamics depends on the field polarity

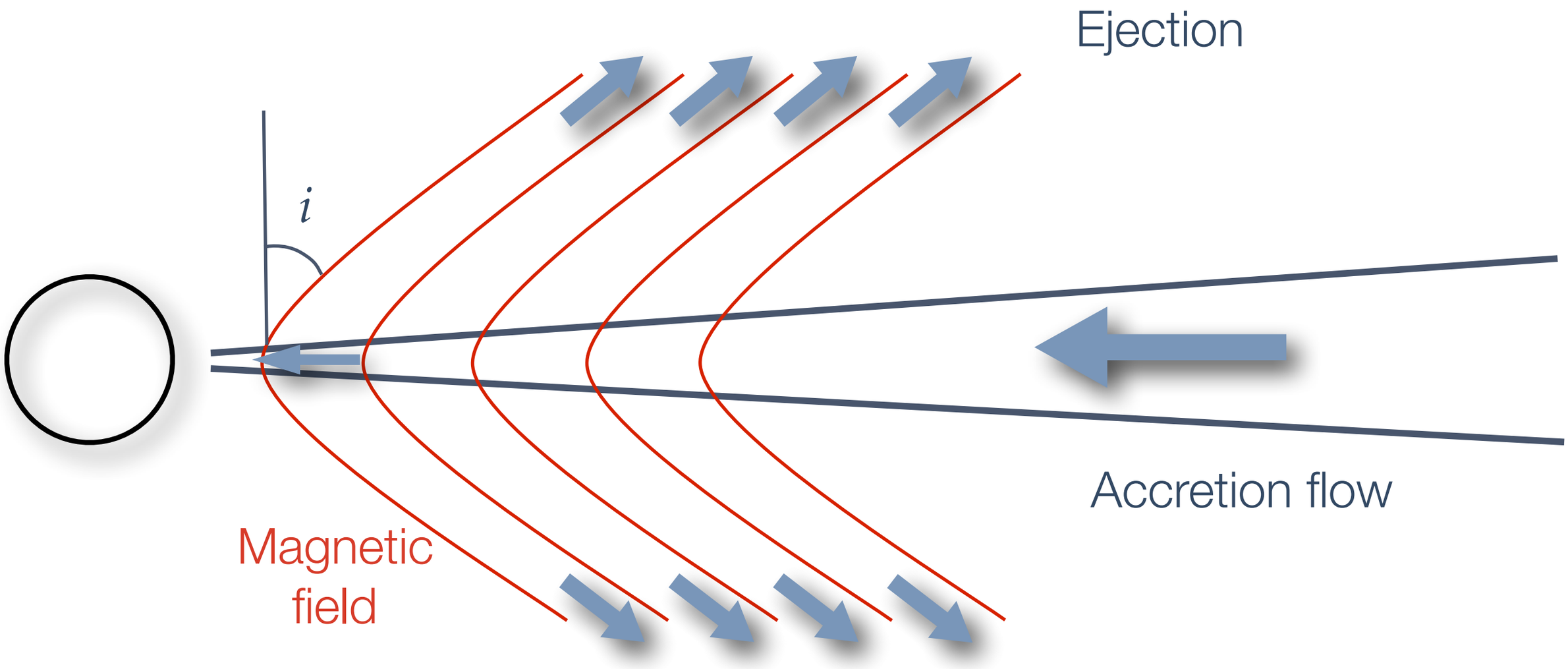
Questions to observers #2:

- Is the disc midplane turbulent ? (could be tested with dust settling ?)
- Do we observe structures (rings, vortices) in planet-free discs?
- Do we observe a dichotomy in PPD evolution (field polarity sensitivity) ?

Disc winds

Disc winds
Blandford & Payne paradigm

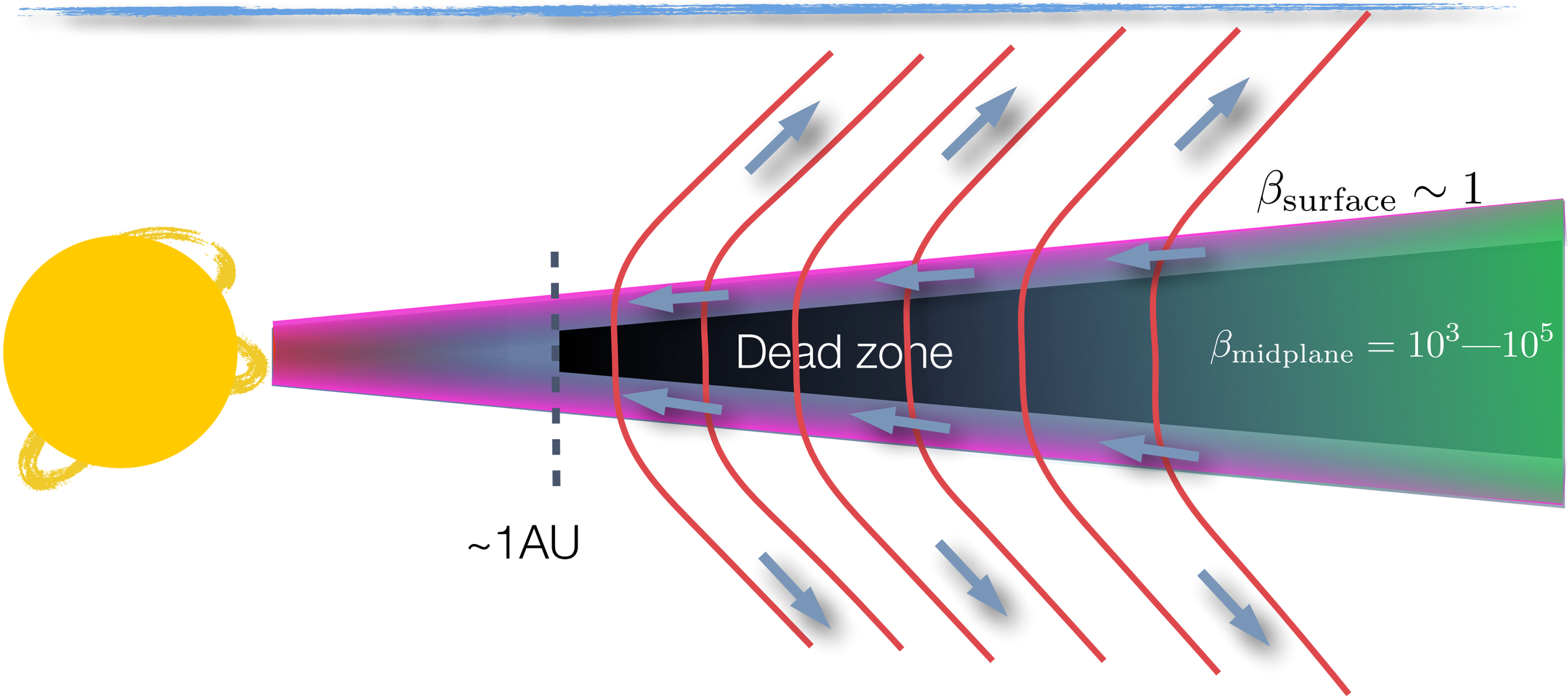
[Blandford & Payne (1982)]



- Need a large scale *mean field*
- Magneto-centrifugal ejection when i>30°
- Requires $\beta \equiv \frac{P_{\rm Th}}{P_{\rm Mag}} \sim 1$ [Murphy+ (2010)]

Surface winds in weakly magnetised discs

$$\beta \equiv \frac{P_{\rm Th}}{P_{\rm Mag}} = 10^3\text{—}10^5$$

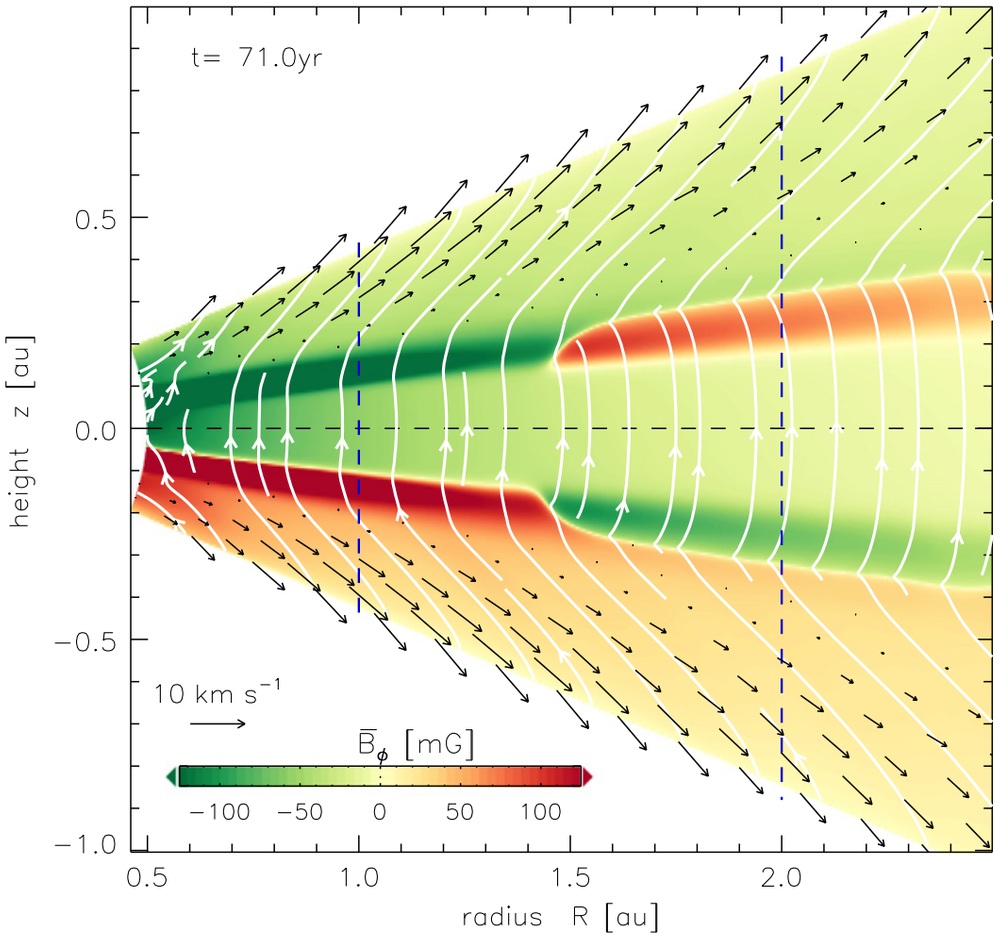


- "Weak" field $B \simeq 0.8\, R_{\rm au}^{-13/8} \left(\frac{\beta_{\rm midplane}}{10^3}\right)^{-1/2}$ G
- Bulk flow is decoupled from the field
- Only the disc "surface" (ionised by FUVs) feels the field.
- Blandford & Payne paradigm applied at the disc surface only [Bai+ 2013]

Disc winds

Mass loss rate issue

Ohmic+ambipolar diffusion



$$\dot{M}_{\rm wind} \simeq 10^{-8}\, M_\odot/{\rm yr}$$

$$\dot{M}_{\rm acc} \simeq 10^{-9}\, M_\odot/{\rm yr}$$

[Gressel+2015]

- $\dot{M}_{\rm wind} > \dot{M}_{\rm acc}$ is energetically impossible !
- Mass loss rates are generally overestimated (vertical boundary artefact)
  [Suzuki+ (2010) ; Bai+ (2013) ; Lesur+ (2013) ; Fromang+ (2013)]

Questions to observers #3:

- Do we observe winds in the outer part of PPDs that could be explained by magnetic acceleration? How strong are these winds?
- Can we put constraints on magnetic field strength & topology in PPDs?

Hydrodynamic instabilities

is there something alive in dead zones?

Baroclinic instability (=radial convection)

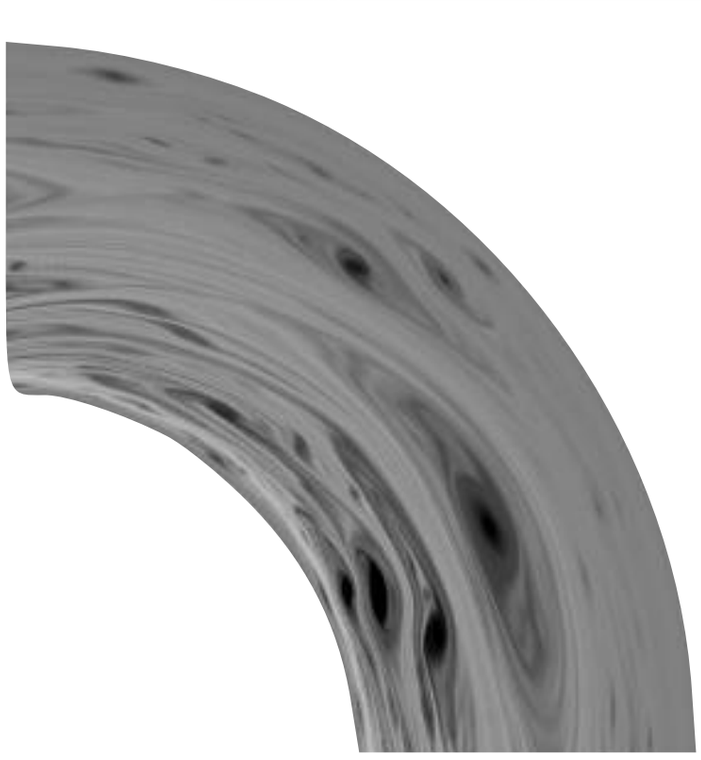
- Driven by the radial entropy gradient [Klahr & Bodenheimer (2003)]

assuming $\Sigma \propto R^{-a}$, $\frac{H}{R} \propto R^{b}$

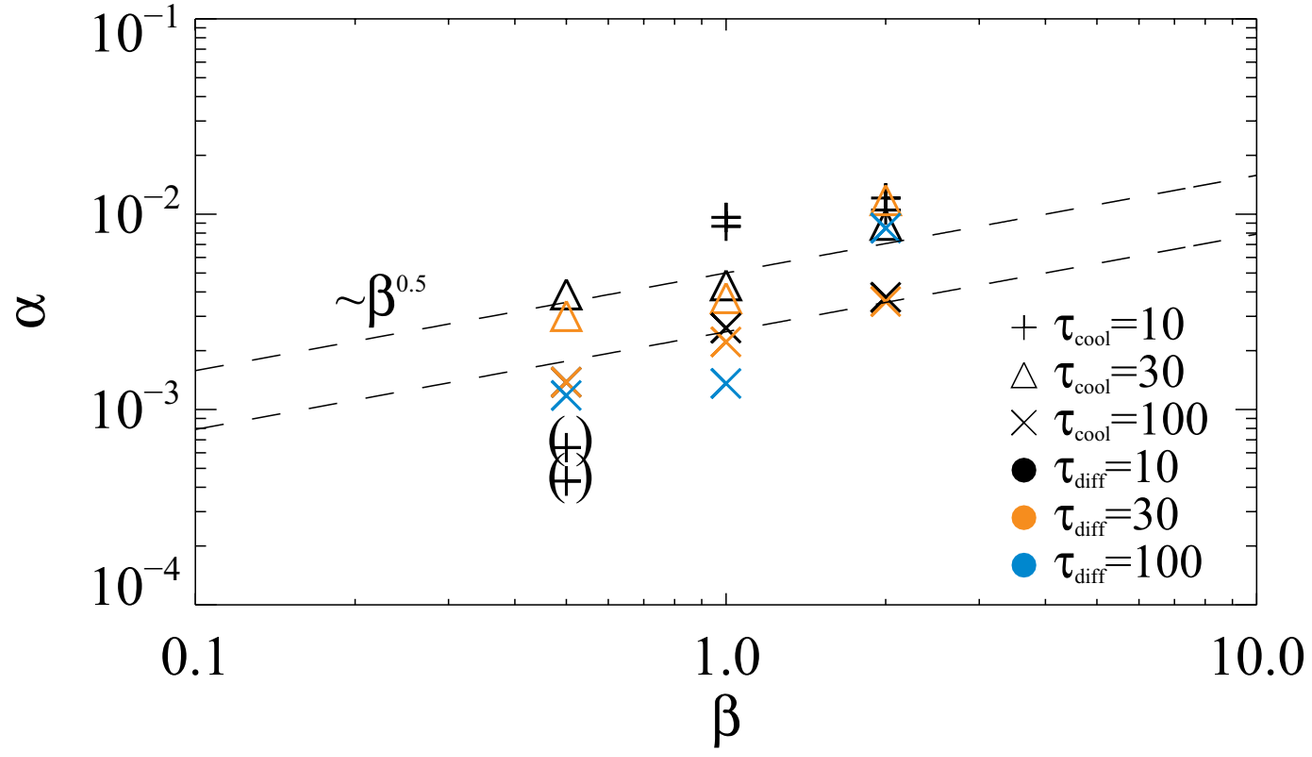
$$\frac{a}{2} + 2b - 1 < 0 \Rightarrow \text{instability}$$

- Requires fast cooling [Petersen+ (2007) ; Lesur & Papaloizou (2010)]

- Leads to $\alpha \sim 10^{-3}$—10^{-2}



Petersen+ (2007), ApJ, 658, 1252

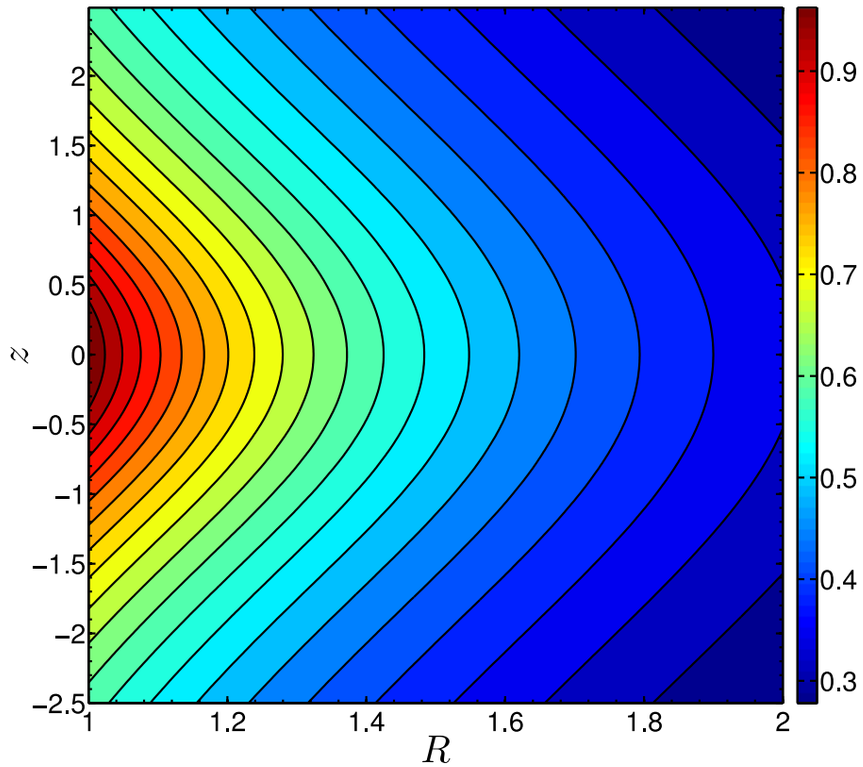


Raettig+ (2013), ApJ, 765, 115

Vertical shear instability (VSI)

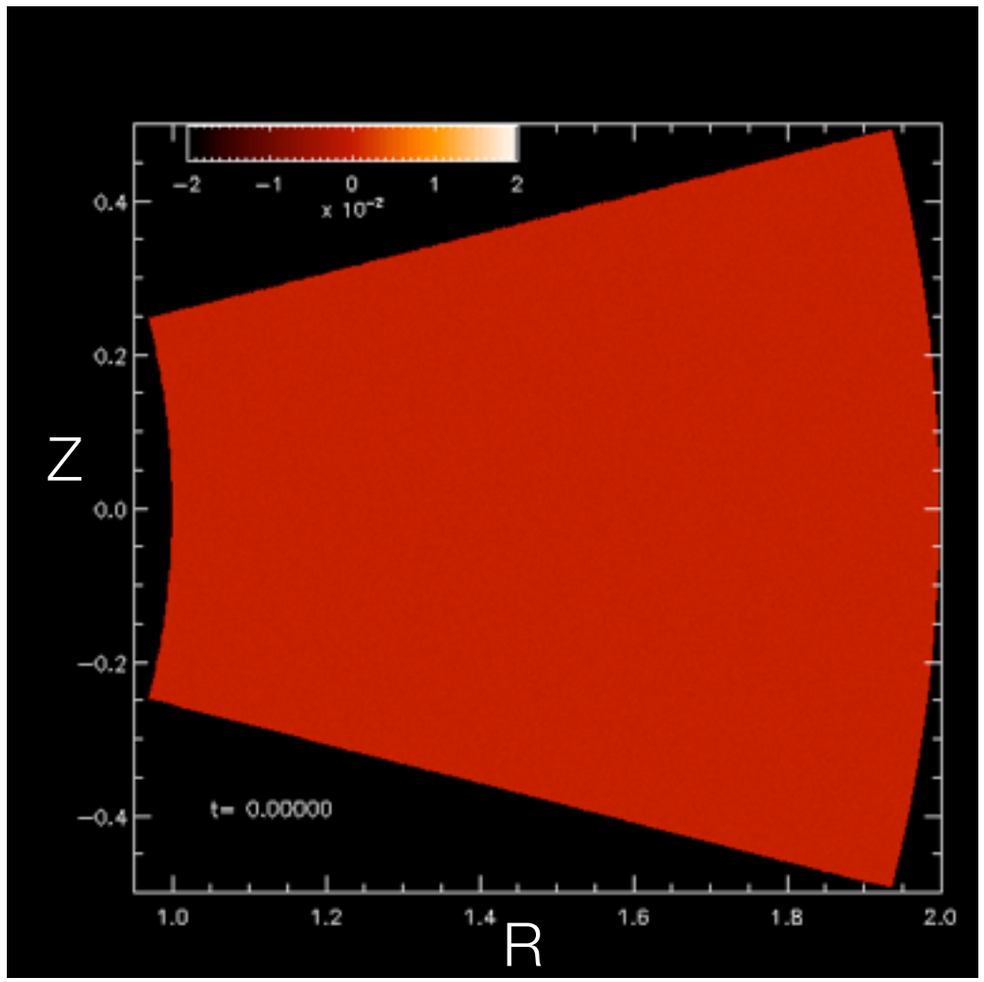
[Urpin & Brandenburg (1998), Urpin (2003) ; Nelson+ (2013) ; Barker & Latter (2015)]

- appears in baroclinic discs: $\Omega(r, z)$
- Relies on fast cooling function to sustain vertical shear (thermal wind equation)
- Most effective for 5 AU < R < 50 AU [Lin & Youdin 2015]
- Give $\alpha \lesssim 10^{-3}$



(a) Ω

Rotation profile in a locally isothermal disc [Barker & Latter 2015]

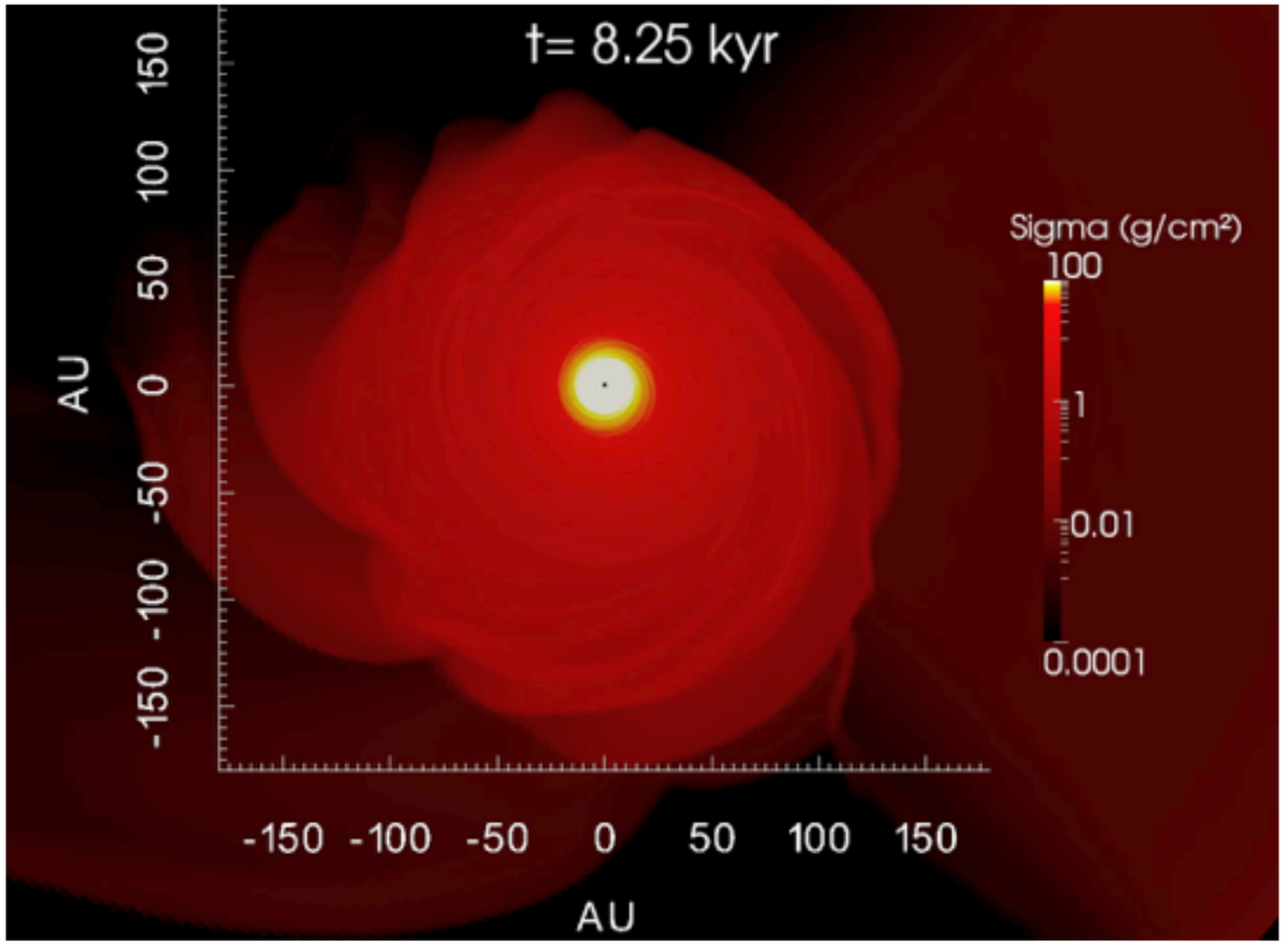


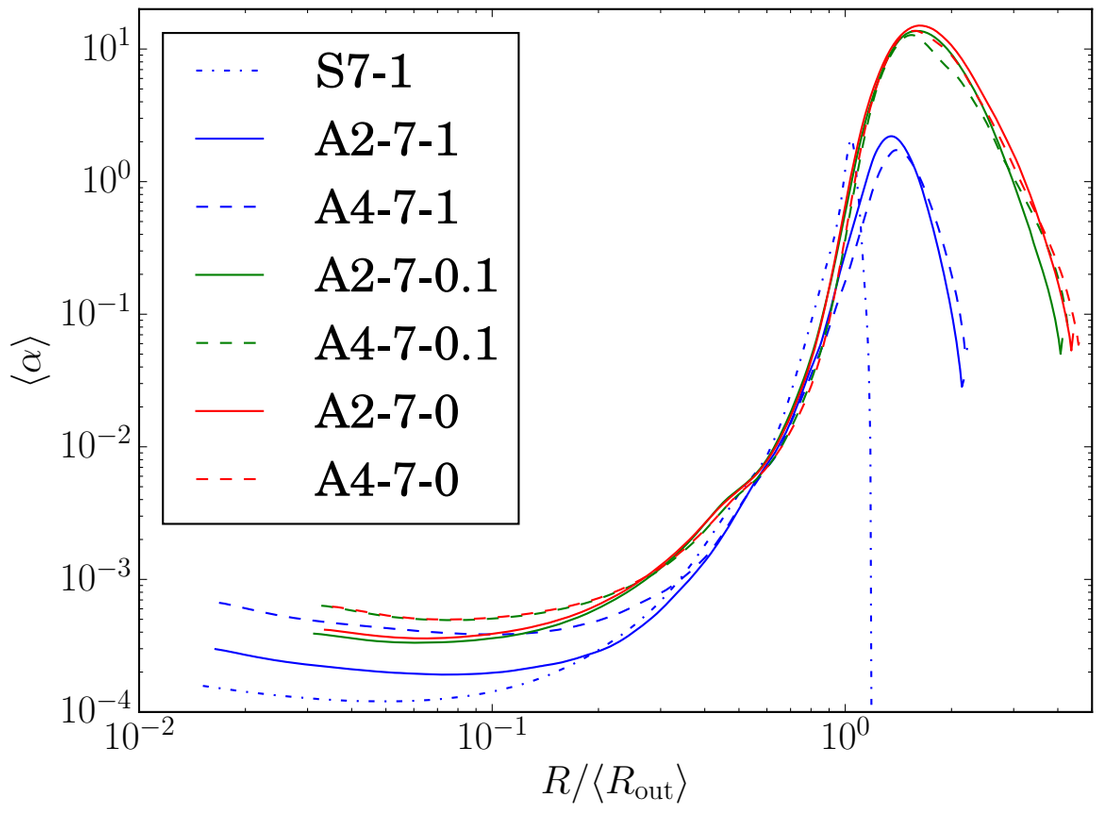
Nelson+ (2013)

Interaction with an external enveloppe

$$\dot{M}_{\rm enveloppe} = 10^{-7}\, M_\odot\, {\rm yr}^{-1}$$

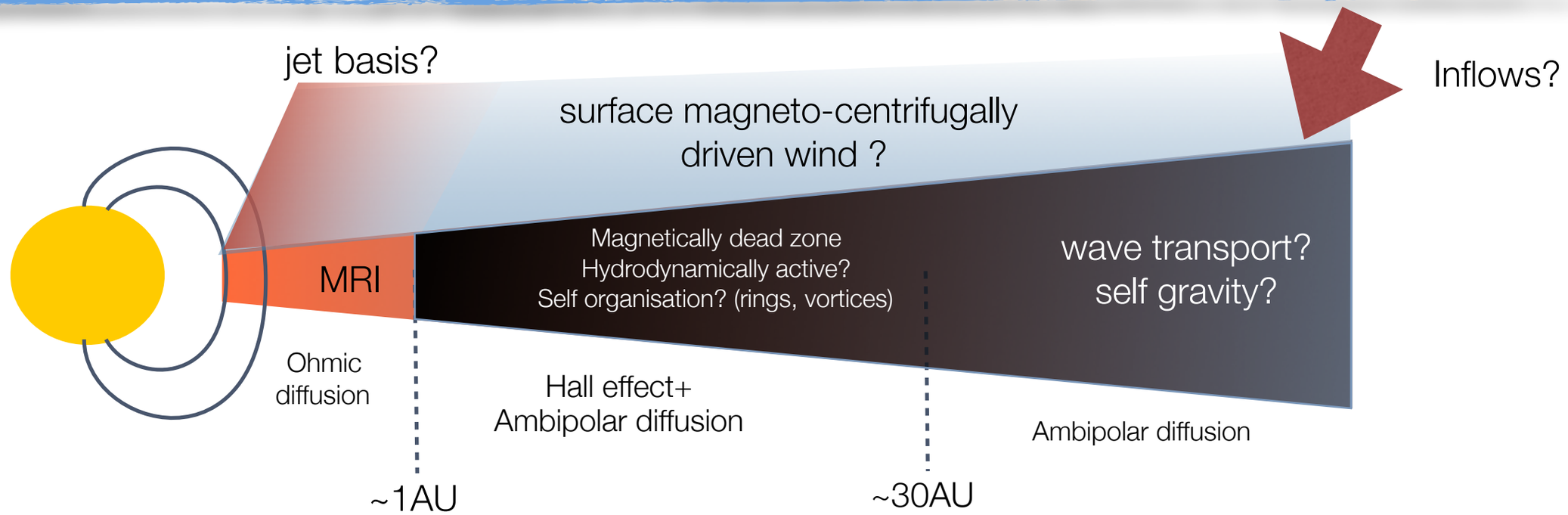
No Self Gravity





A falling enveloppe might be sufficient to drive accretion through spiral waves transport [Lesur+ 2015]

Conclusions & perspectives



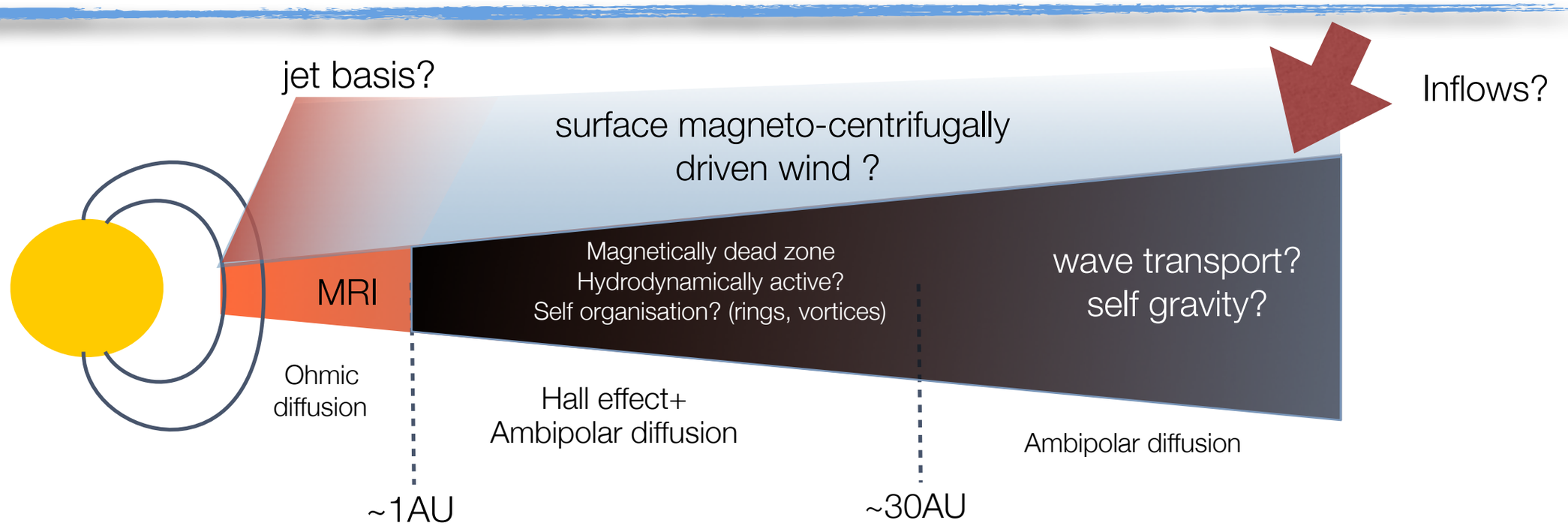
Dead zones are the current bottleneck in disc modelling

- MHD-driven turbulence is insufficient to explain accretion rates
- No reliable theoretical constraint on winds due to numerical limitations
- Hydro processes are still largely speculative (thermodynamics, inflows?)

But some interesting developments

- Prediction of magnetically driven surface winds in the outer disc
- Sensitivity to the field polarity in Hall dominated regions
- Spontaneous formation of rings and vortices is possible

List of questions to observers



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