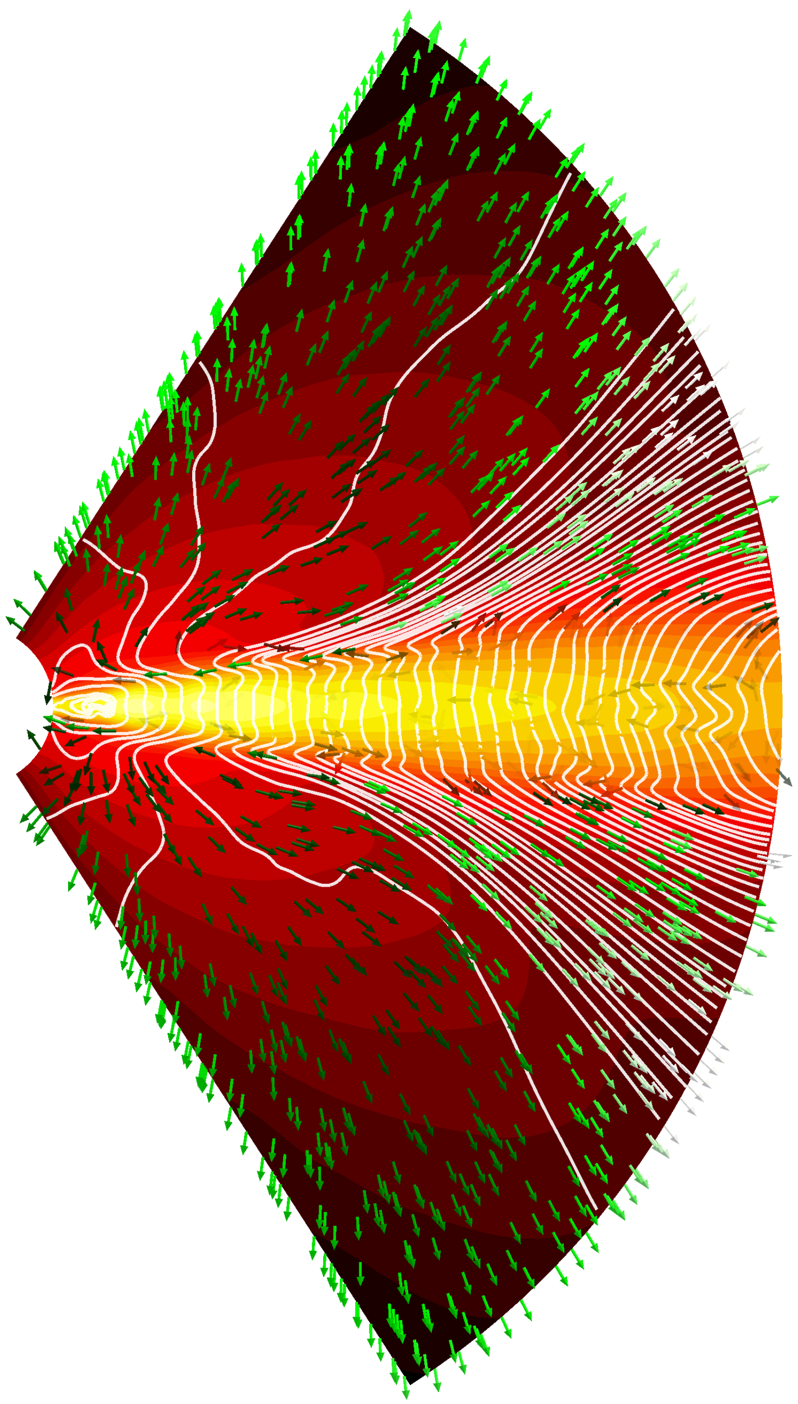
Global dynamics of protoplanetary disks

The combined influence of non-ideal MHD and winds



Geoffroy Lesur (IPAG, Grenoble)

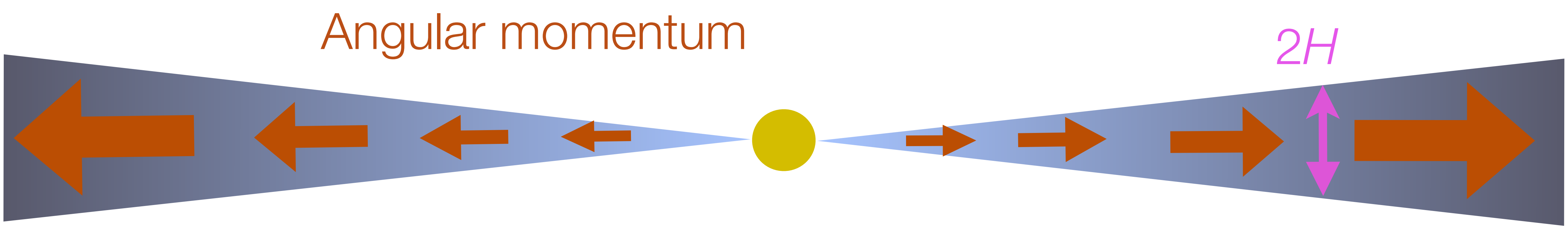
with

William Béthune & Jonathan Ferreira

Disks, Dynamos, and Data: Confronting MHD Accretion Theory with Observations

Angular momentum transport processes

I- turbulent (viscous) transport



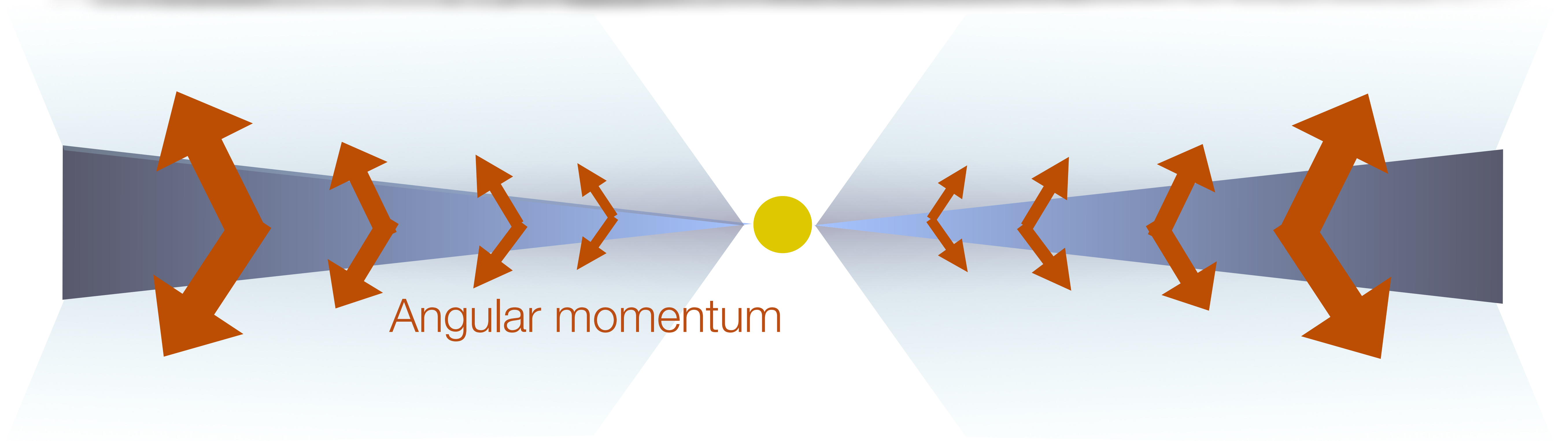
- Transport angular momentum in the bulk of the disc
- Suggested by Shakura & Sunyaev (1973)
- Turbulence leads to enhanced transport («mixing length theory»)
- One defines a turbulent viscosity

$$\nu_t = \alpha c_s H$$

α: «turbulent transport»; c_s: «sound speed»; H: «1/2 disc thickness»

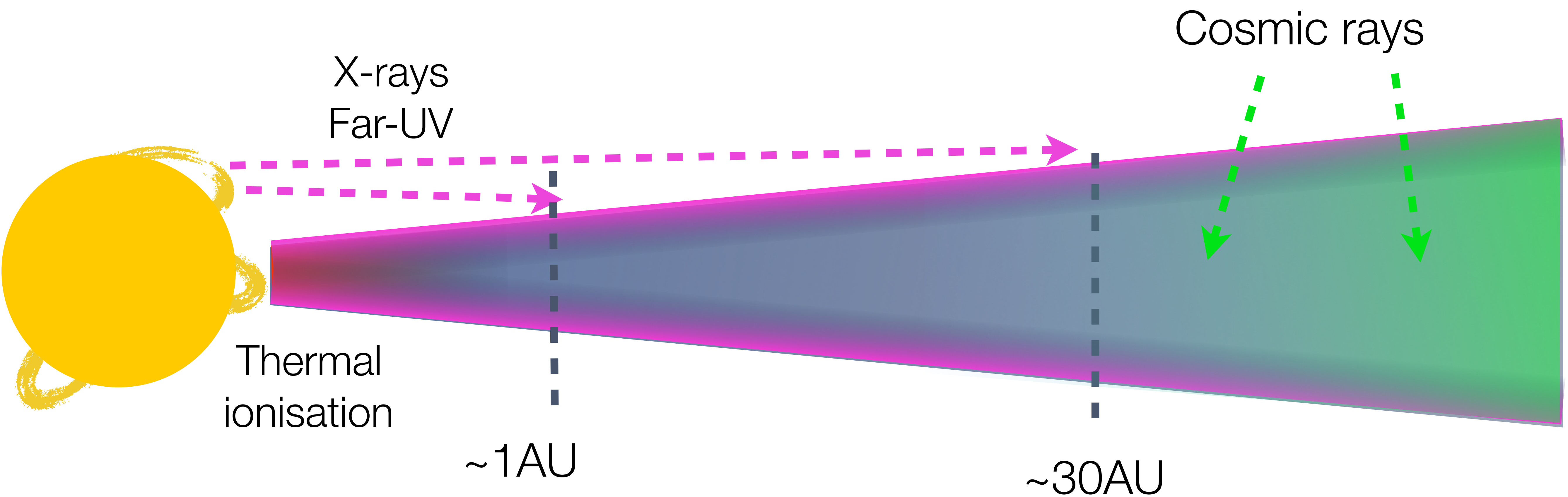
$\alpha \sim 10^{-3}$ to explain observed accretion rates

Angular momentum transport processes
II- disc wind



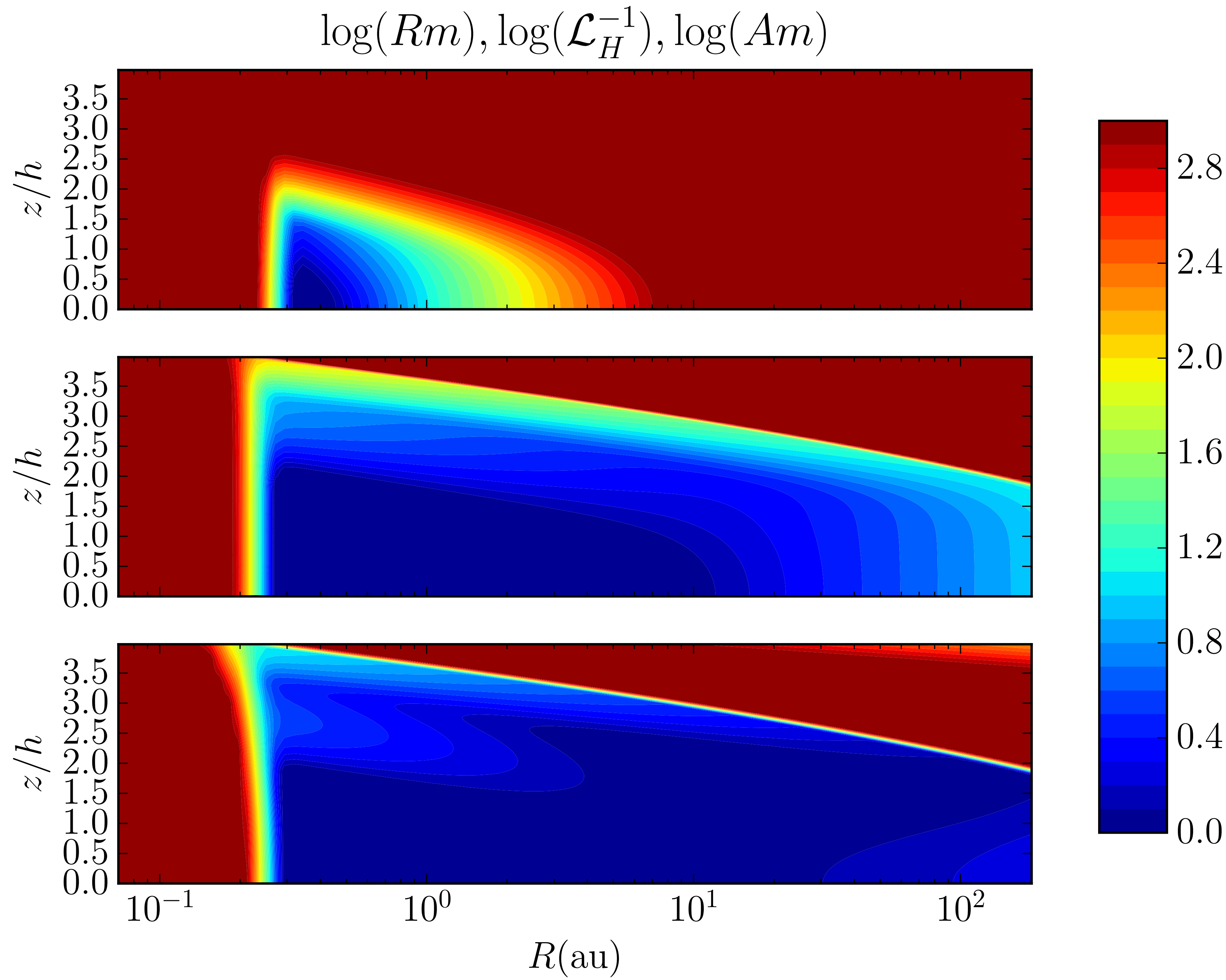
- Angular momentum *extracted* from the disc by a magnetic wind
  [Blandford & Payne 1982]
- Magnetic field exerts a torque on the disc surface which generates accretion (not described by α−disc!)

Ionisation sources in protoplanetary discs



Non-ideal MHD

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



Polarity matters!

Induction equation

Ideal, Ohmic, Hall, Ambipolar

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times \left[\boldsymbol{v} \times \boldsymbol{B} - \eta_O \boldsymbol{J} - \eta_H \boldsymbol{J} \times \hat{\boldsymbol{b}} + \eta_A \boldsymbol{J} \times \hat{\boldsymbol{b}} \times \hat{\boldsymbol{b}}\right] \quad ; \quad \boldsymbol{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \boldsymbol{B}$$

$\partial_t \boldsymbol{B} \propto B$; Ideal $\propto B$; Ohmic $\propto B$; Hall $\propto B^2$; Ambipolar $\propto B^3$

Under field reversal, each term changes sign except the Hall term.

The dynamics is sensitive to the field polarity whenever Hall is important

Zero net flux MRI

Let's assume no external field is threading the disc (MRI-dynamo)

➡ What is needed for the MRI-dynamo to be alive?

$$Rm \gtrsim 10^3 — 10^4 \quad \text{and} \quad Am \gtrsim 1 — 10$$

[Fleming & Stone 2000,
Ilner & Nelson 2008,
Oishi & MacLow 2011]

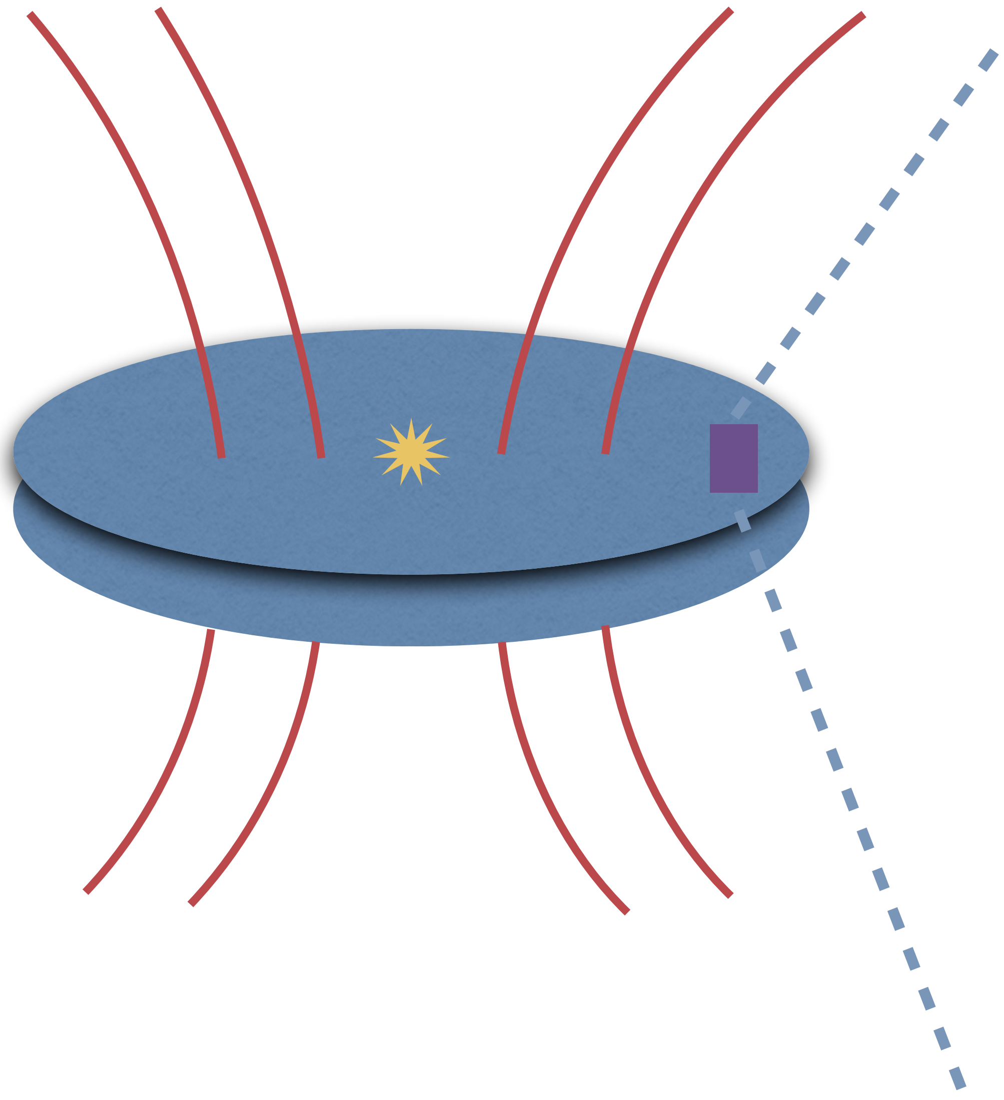
[Hawley & Stone 1998
Bai & Stone 2011]

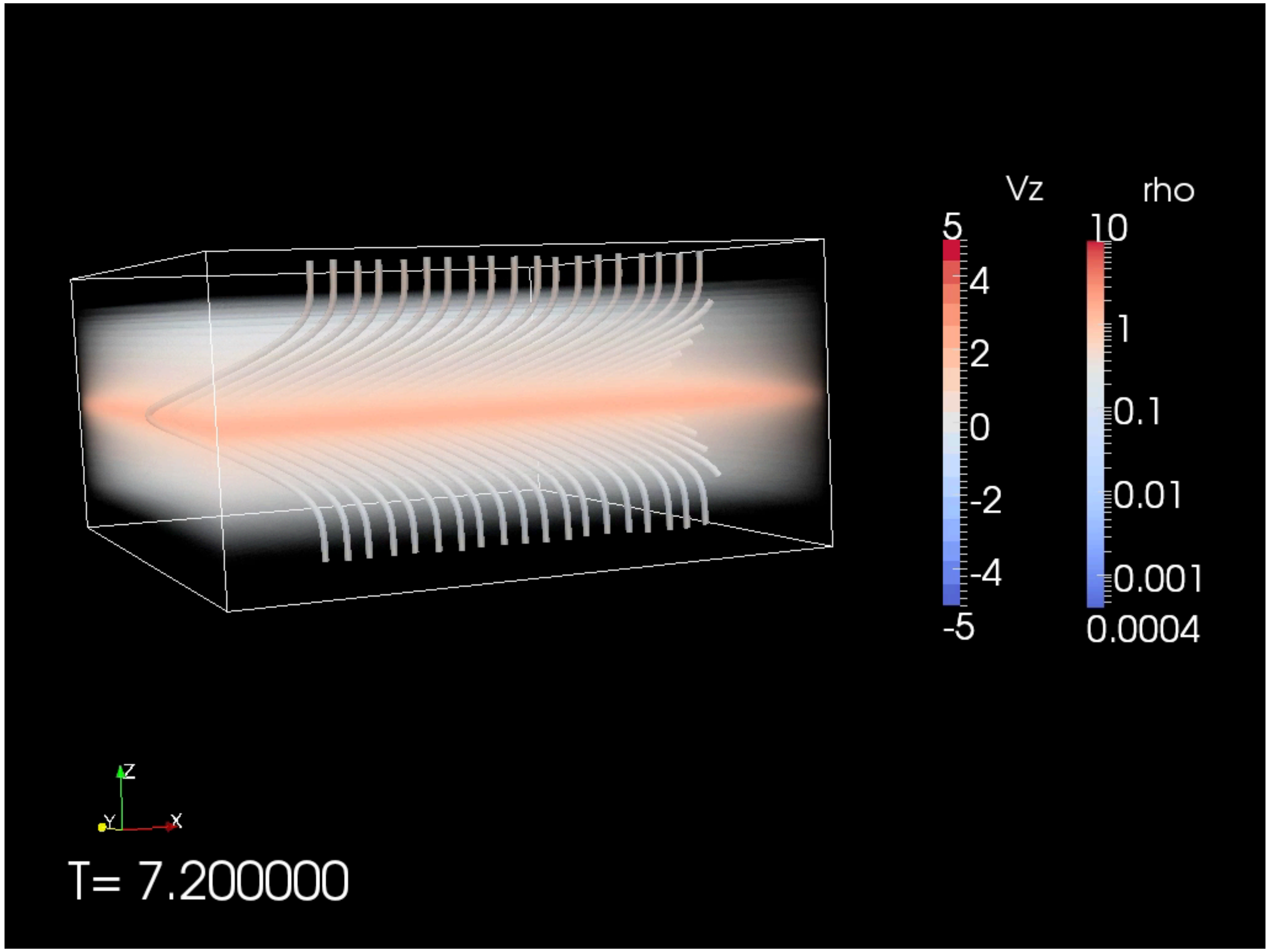
zero net flux MRI is inexistent below ~3H

↙ Look for a non-MHD process
[see R. Nelson's talk]

↘ Add an external field
(reduce the critical Rm and Am)

Adding an external poloidal field





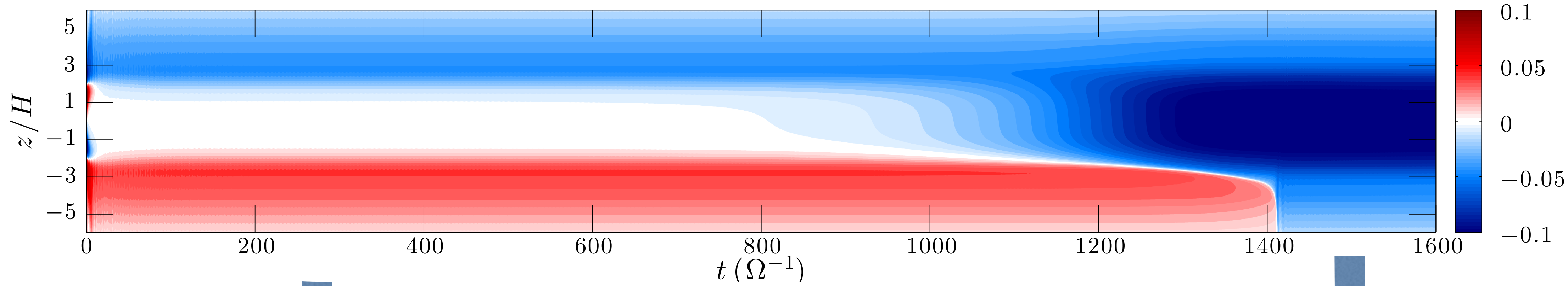
[Lesur+2013]

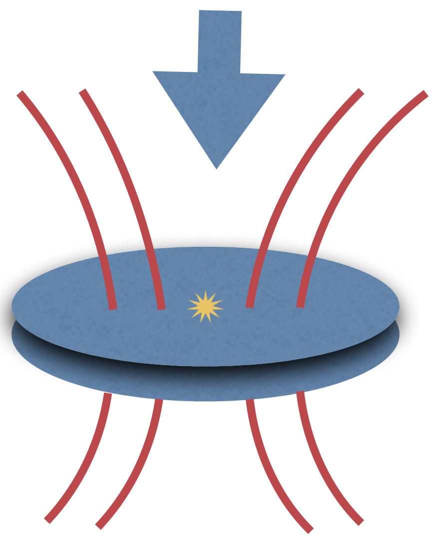
MRI spontaneously produces magnetized winds in the presence of an external poloidal field (true *both* in ideal and non-ideal MHD)

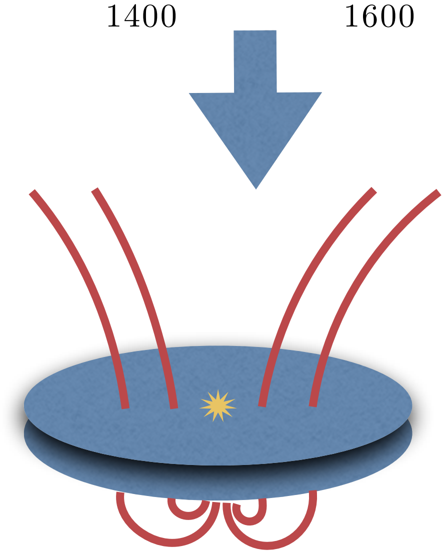
Non-ideal shearing boxes

With an external field

$$B_y(t) = B_\varphi(t)$$







[Lesur+2014]

- No angular momentum actually extracted from the disc
- No accretion!

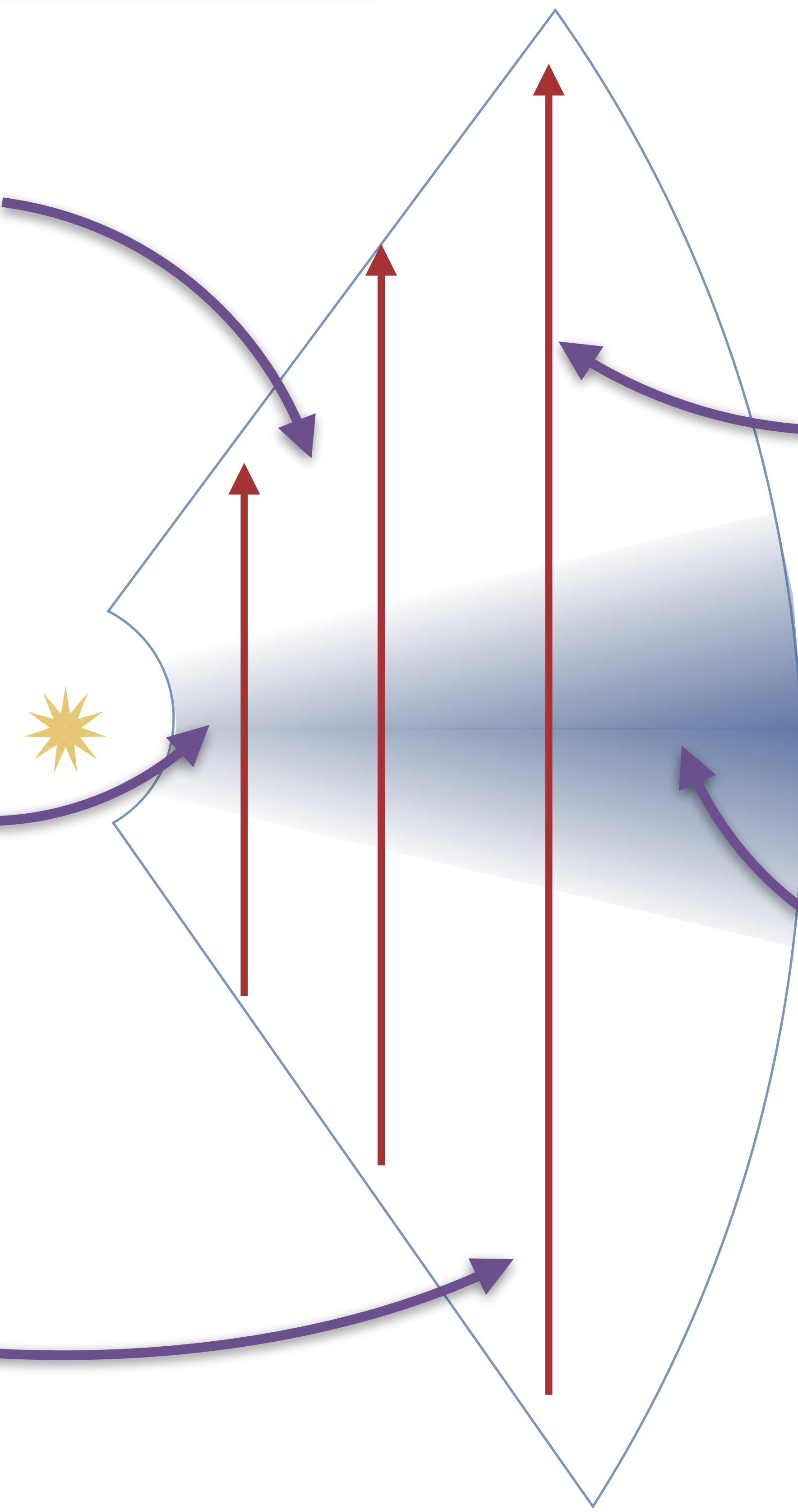
Shearing box is not adapted to wind-emitting discs

Global simulations

Numerical setup

Coronal heating (due to X-rays & F/E-UV)
constant $T_{corona} > T_{disc}$

Poloidal field threading the disc



Disc including Ohmic diffusion, Hall effect & Ambipolar diffusion

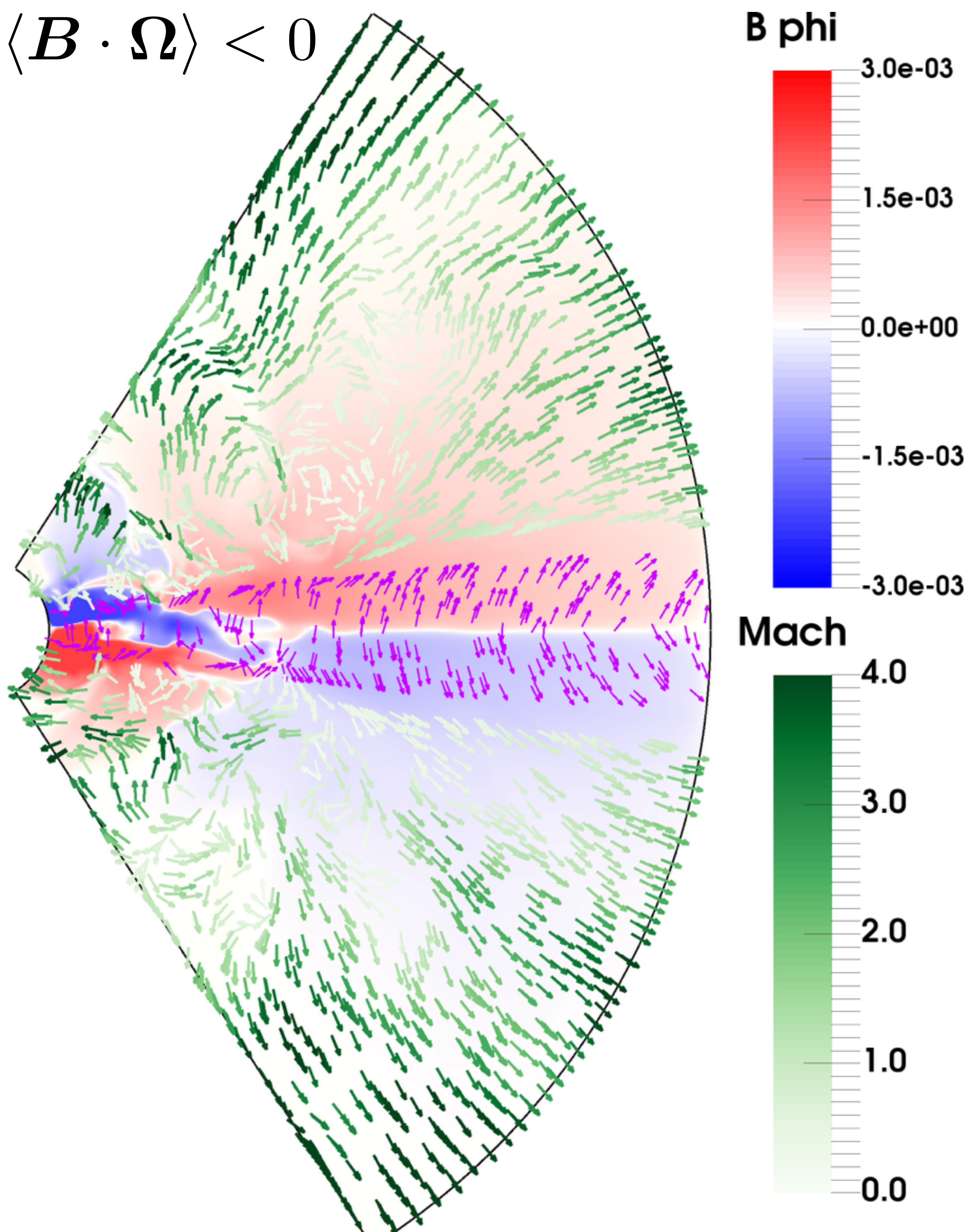
Ionisation fraction computed on the fly from the density structure

2.5D (axisymmetric) grid (except for a few full 3D simulations)
Pluto code, static mesh refinement

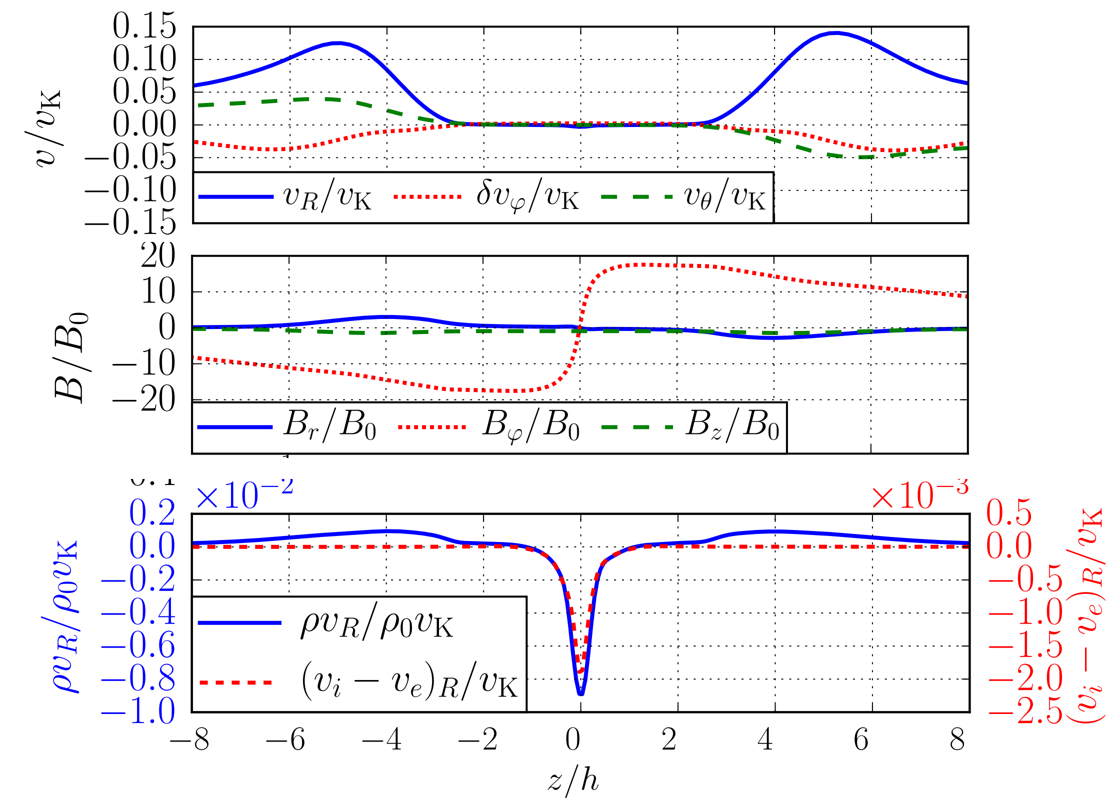
Global simulations
Classical bipolar outflows

@10->100 AU

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



[Béthune, Lesur & Ferreira 2017]



- Symmetric bipolar outflow
- Magnetic field dominated by B_φ
- Accretion in the disc midplane
- Large scale fluctuations $\frac{\delta v_{\rm disc}}{c_s} \simeq 0.2$

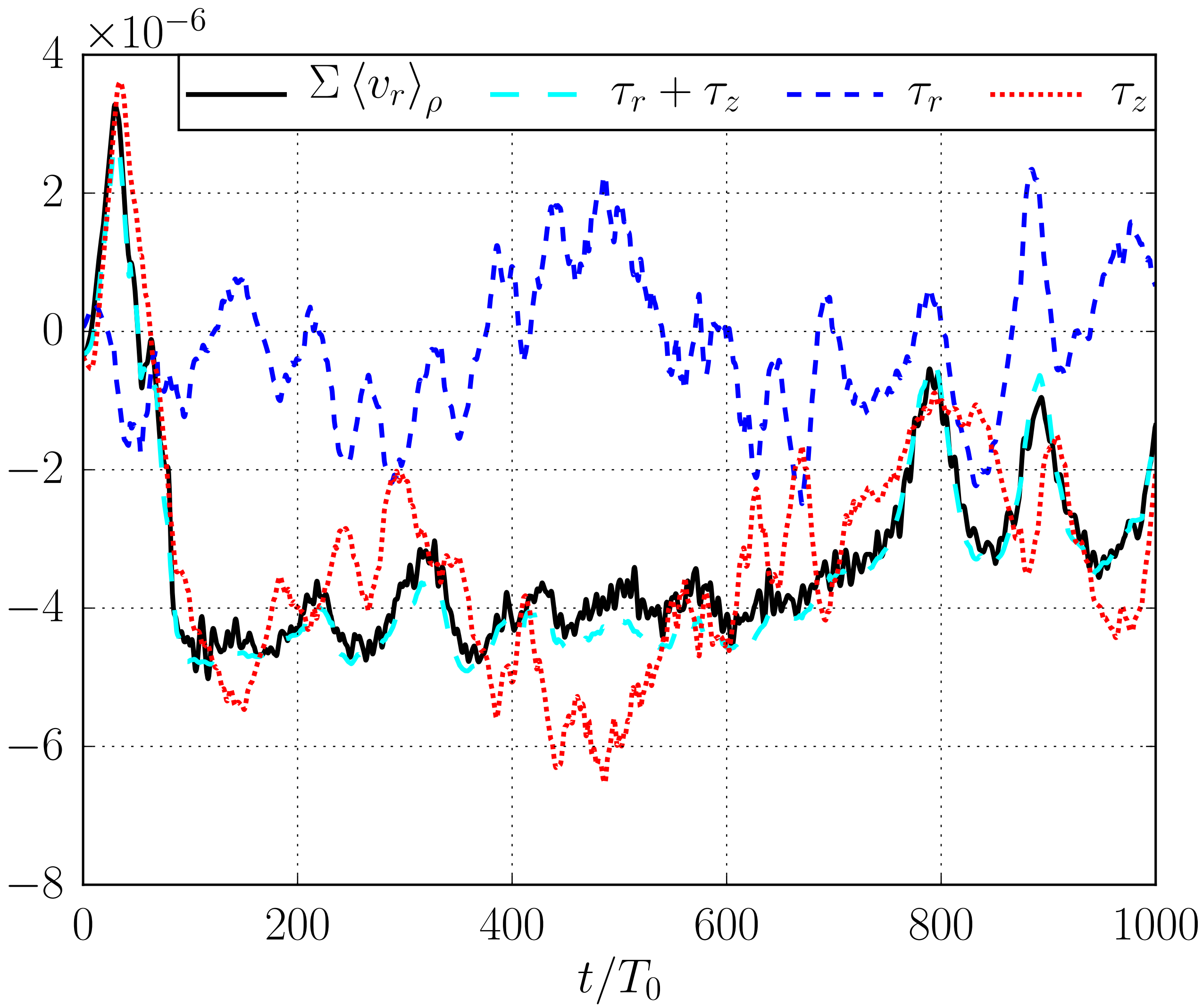
Global simulations

Accretion mechanism

$$\Sigma\langle v_r\rangle_\rho = -\frac{1}{\partial_r\left[r\langle v_\varphi\rangle\right]}\left(\frac{1}{r}\partial_r\left[2r^2H(r)\langle\mathcal{T}_{r\varphi}\rangle\right] - r\left[\langle\mathcal{T}_{z\varphi}\rangle\right]_{-H}^{+H}\right)$$

Angular momentum transported radially in the disc $= \tau_r$

Angular momentum extracted by the wind $= \tau_z$



wind-driven accretion

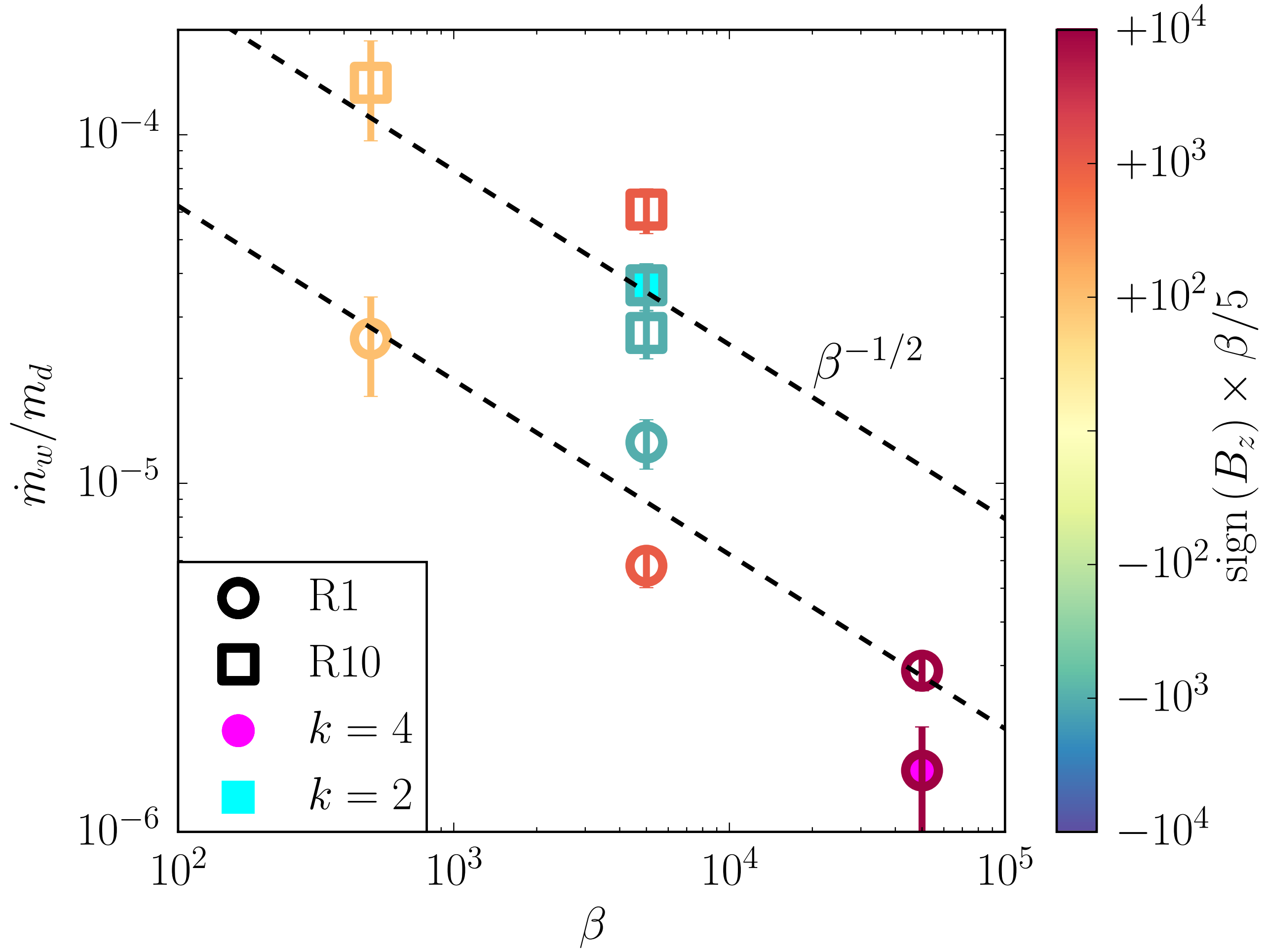
$$\dot{M}_{\rm acc} = 1.1 \times 10^{-7}\, M_\odot.{\rm yr}^{-1}$$

@50 au

$$\dot{M}_{\rm wind} = 2.3 \times 10^{-7}\, M_\odot.{\rm yr}^{-1}$$

@10-100 au

Scaling relation



Integrated between 1au and 100au:

$$\dot{M}_W \approx 3 \times 10^{-5} \beta^{-1/2}\ M_\odot.\,\mathrm{yr}^{-1}$$

Problem solved!

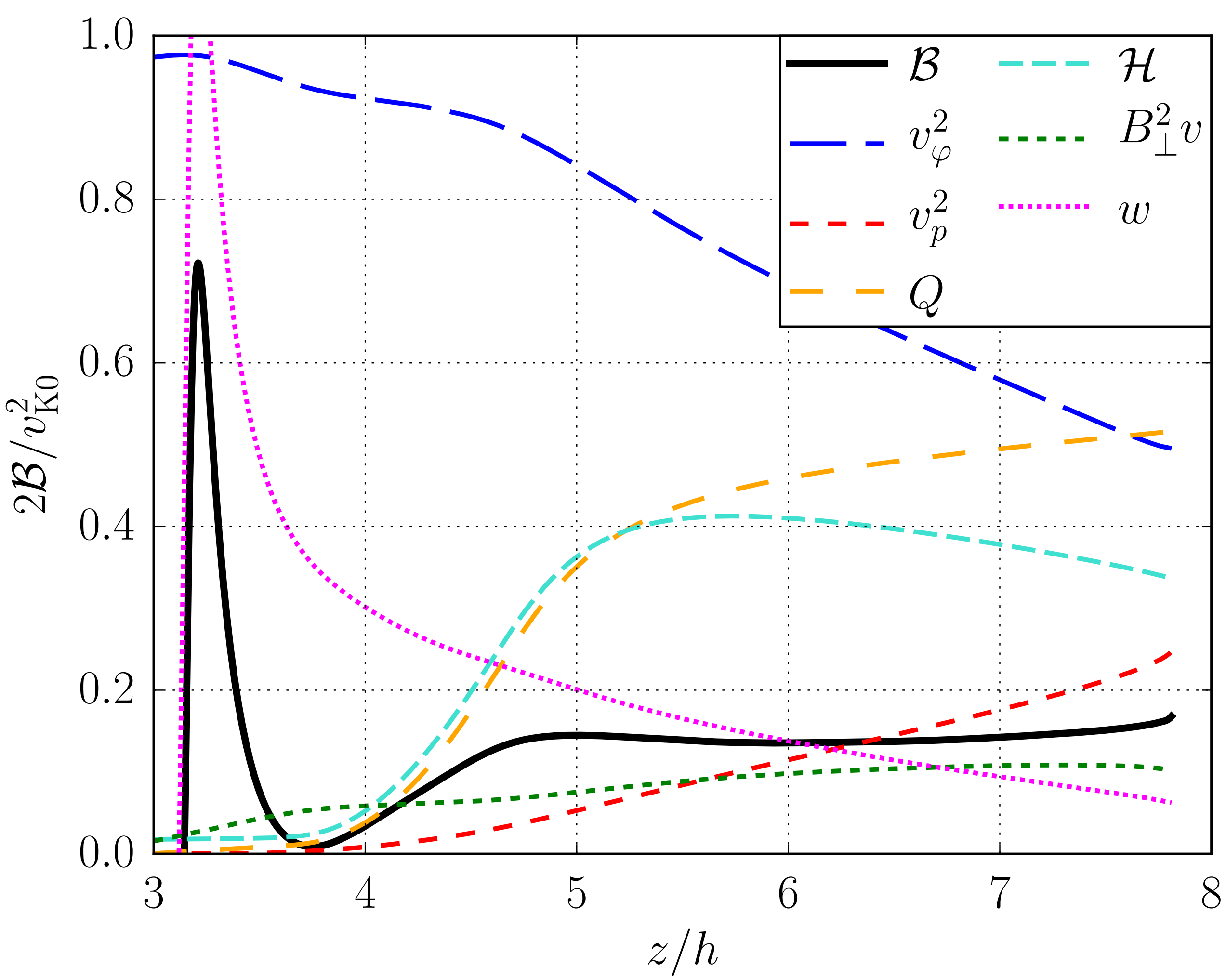
But it's not so simple…

Wind energetics

Energy is conserved along poloidal streamlines

$$\mathcal{B} = \frac{v_\varphi^2}{2} + \frac{v_p^2}{2} + \Phi_G + \frac{B_\perp^2 v_p + w_p}{\rho v_p} + \mathcal{H} - \int \delta Q \mathrm{d}\ell$$

Kinetic Gravitational Poynting flux Enthalpy Heating

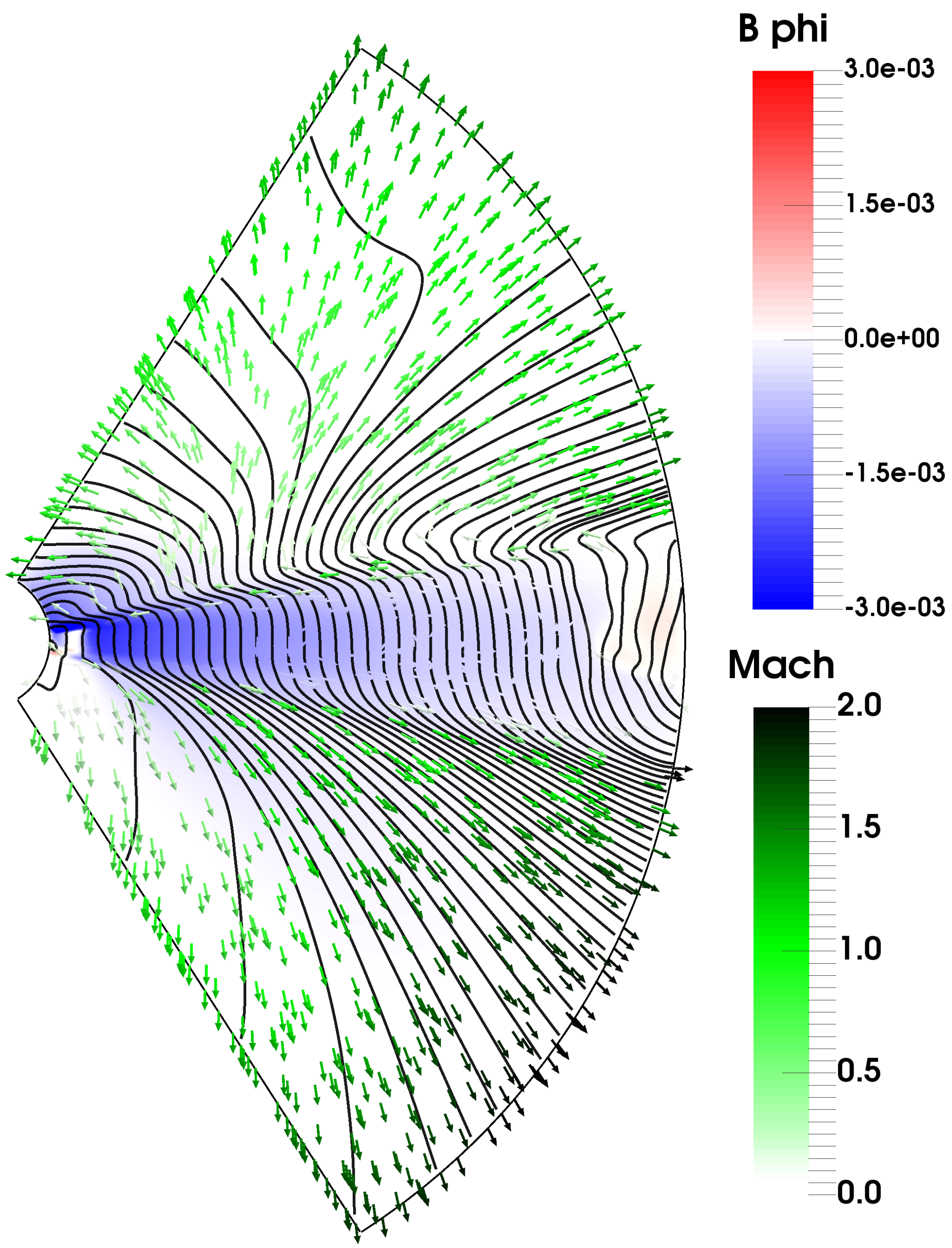


- Wind is asymptotically free: $\mathcal{B} > 0$
- Thermal pressure (& heating) have a significant contribution to the energy budget
- Mixture of purely magnetic and photo-evaporation wind: *magneto-thermal wind*

[see also Bai's talk]

Symmetry breaking

Winds are not necessarily bipolar…

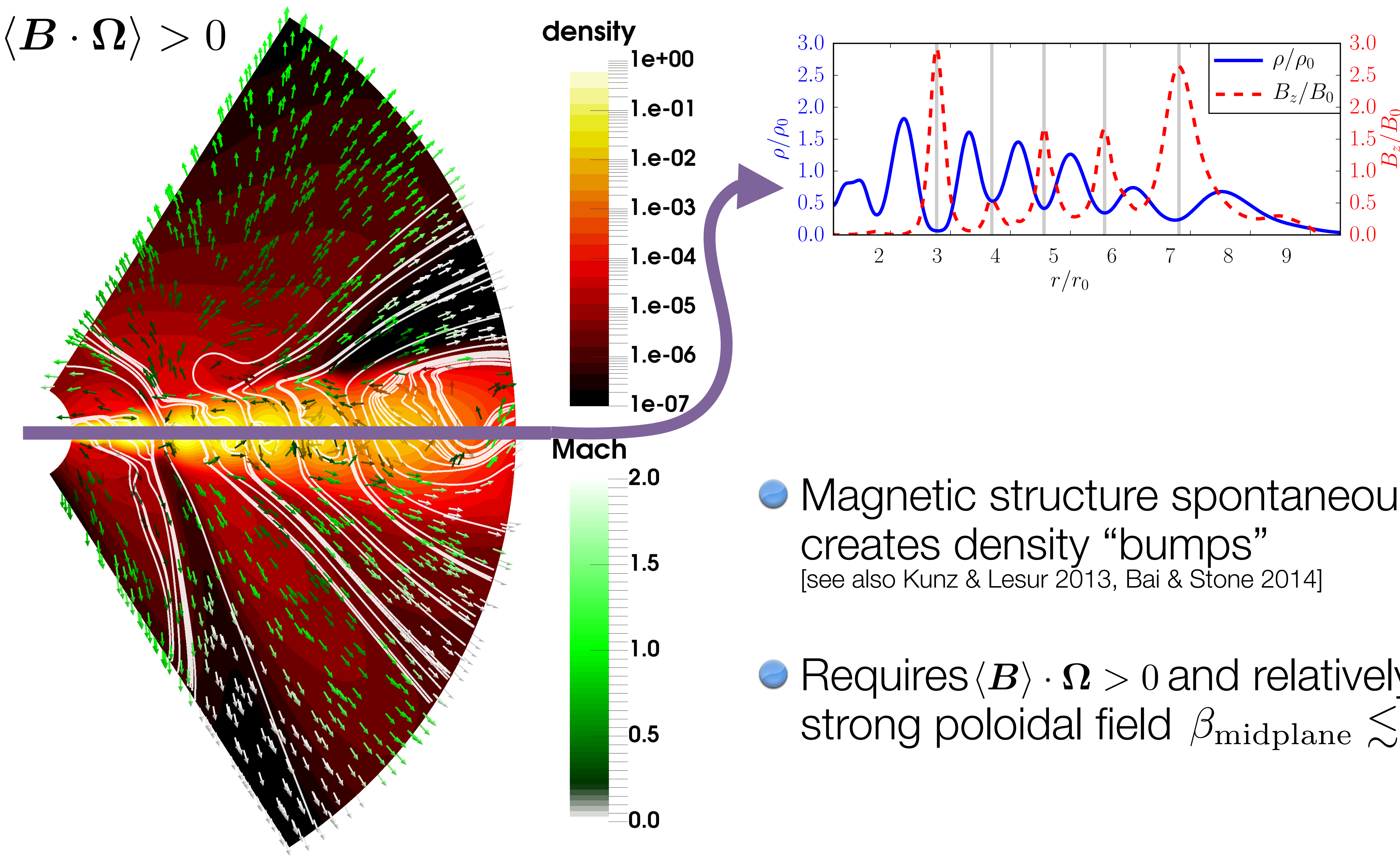


- Strong accretion in the surface layers
- Dissymmetric wind launching (factor of a few in $\dot{M}_{\rm wind}$)
- Configuration usually favoured when $\langle \boldsymbol{B} \rangle \cdot \boldsymbol{\Omega} > 0$
- Also seen in shearing box: due to Hall-shear instability (HSI) in the midplane.

[Kunz 2008, Lesur+2014,Bai 2014]

Self-organisation

In wind-emitting discs



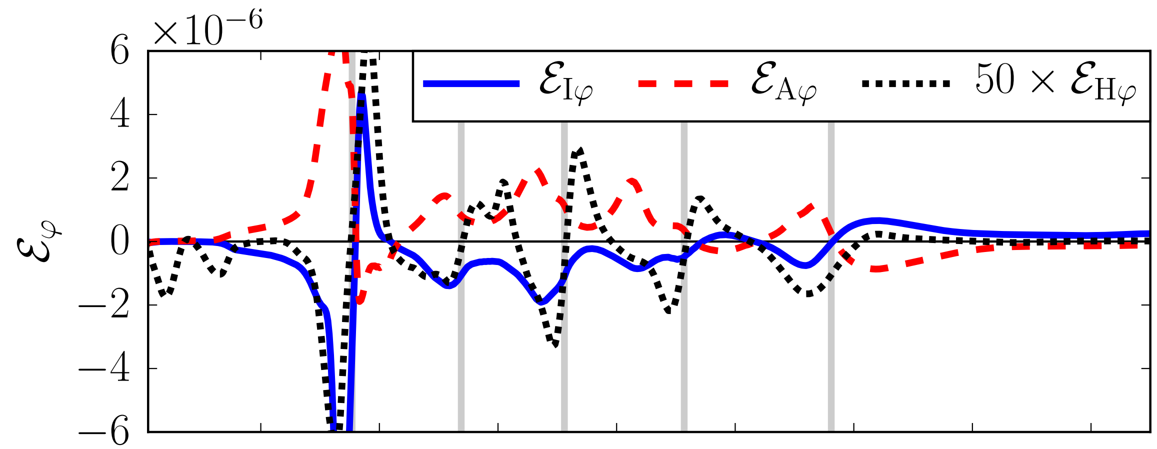
- Magnetic structure spontaneously creates density "bumps"
  [see also Kunz & Lesur 2013, Bai & Stone 2014]

- Requires $\langle \boldsymbol{B} \rangle \cdot \boldsymbol{\Omega} > 0$ and relatively strong poloidal field $\beta_{\mathrm{midplane}} \lesssim 10^3$

X

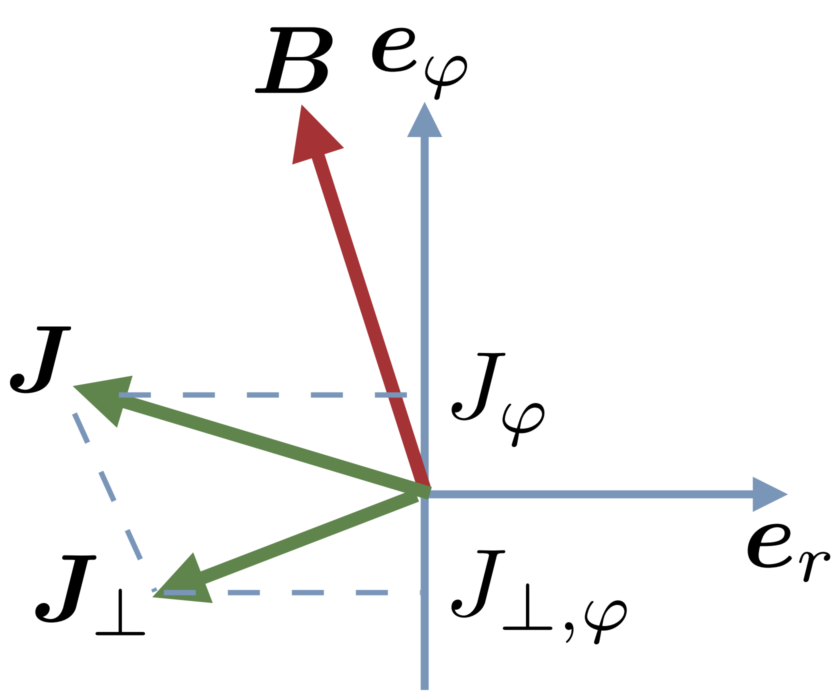
Induction equation

$$\left\langle \frac{\partial B_z}{\partial t} \right\rangle_{\varphi,z} = -\frac{1}{r}\frac{\partial}{\partial r}\left\langle r(\mathcal{E}_{I,\varphi} + \mathcal{E}_{H,\varphi} + \mathcal{E}_{A,\varphi}) \right\rangle_{\varphi,z}$$



Ambipolar diffusion is acting like an anti-diffusion for B_z!

$$\mathcal{E}_{A,\varphi} = -\eta_A J_{\perp,\varphi}$$

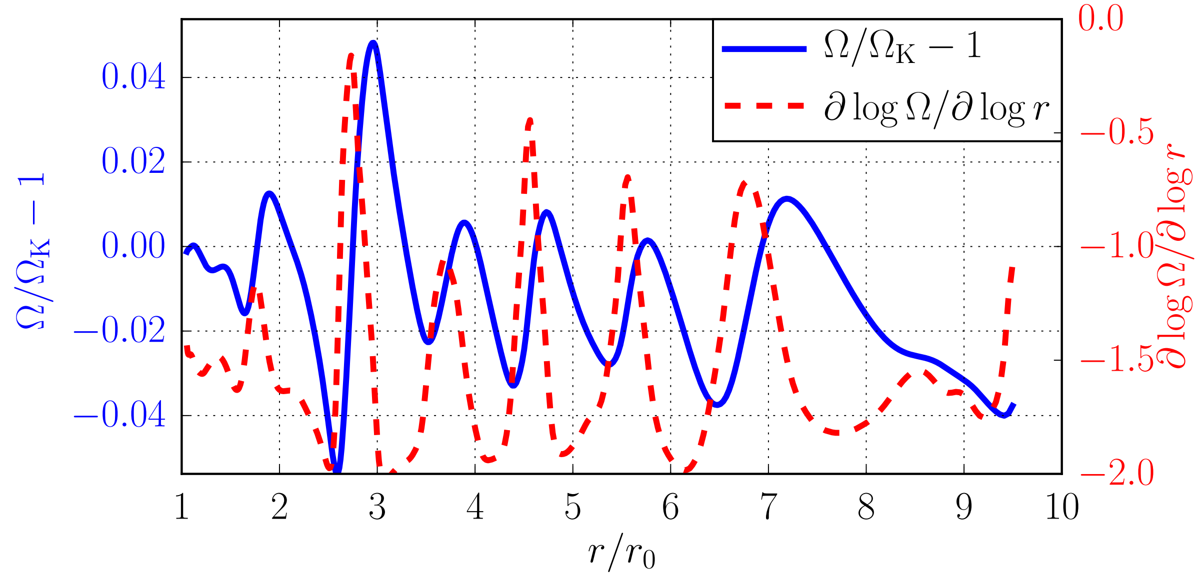


J_φ and $J_{\perp,\varphi}$ have opposite sign

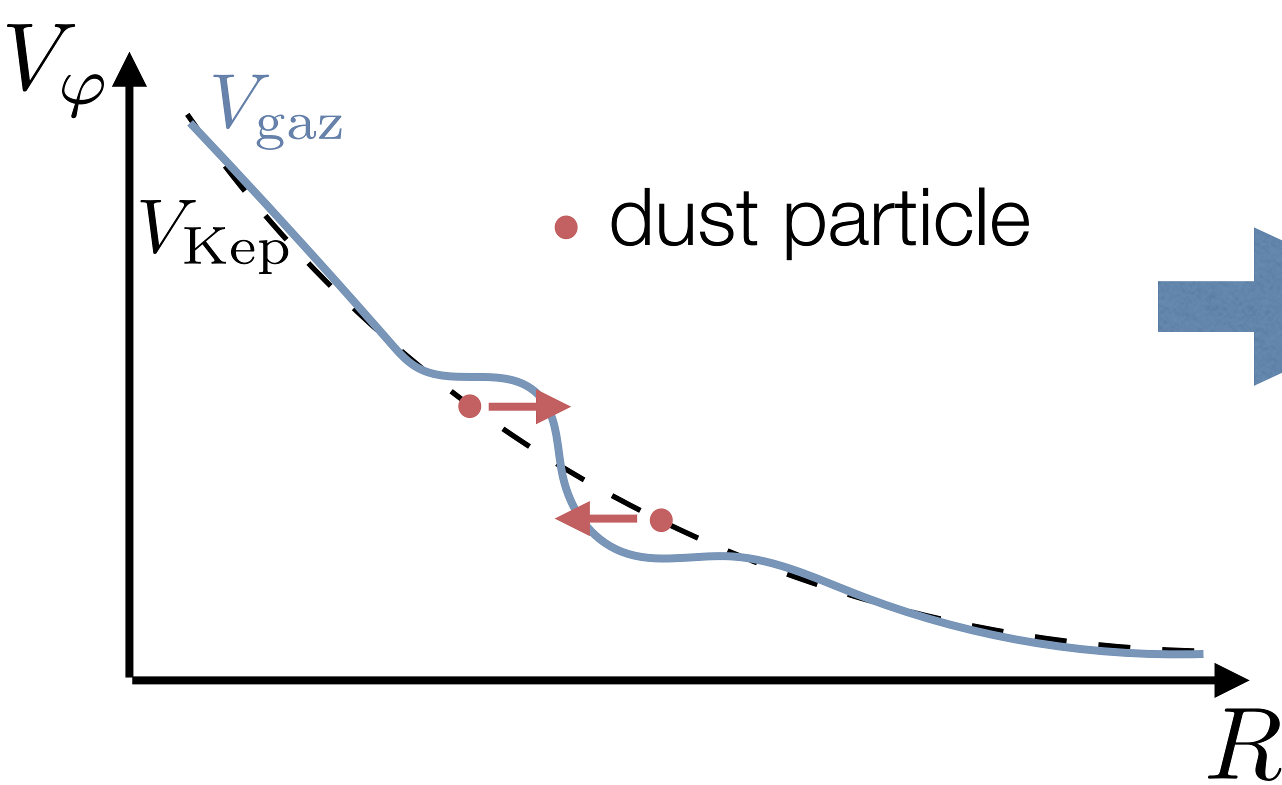
The magnetic and current configuration of the wind allows self organisation

Self-organisation

Observational implications



Gaz rotation velocity oscillates around the Keplerian profile



Self-organisation should lead to observable structures in the dust disc

Self-organisation in 3D

2D

vs

3D

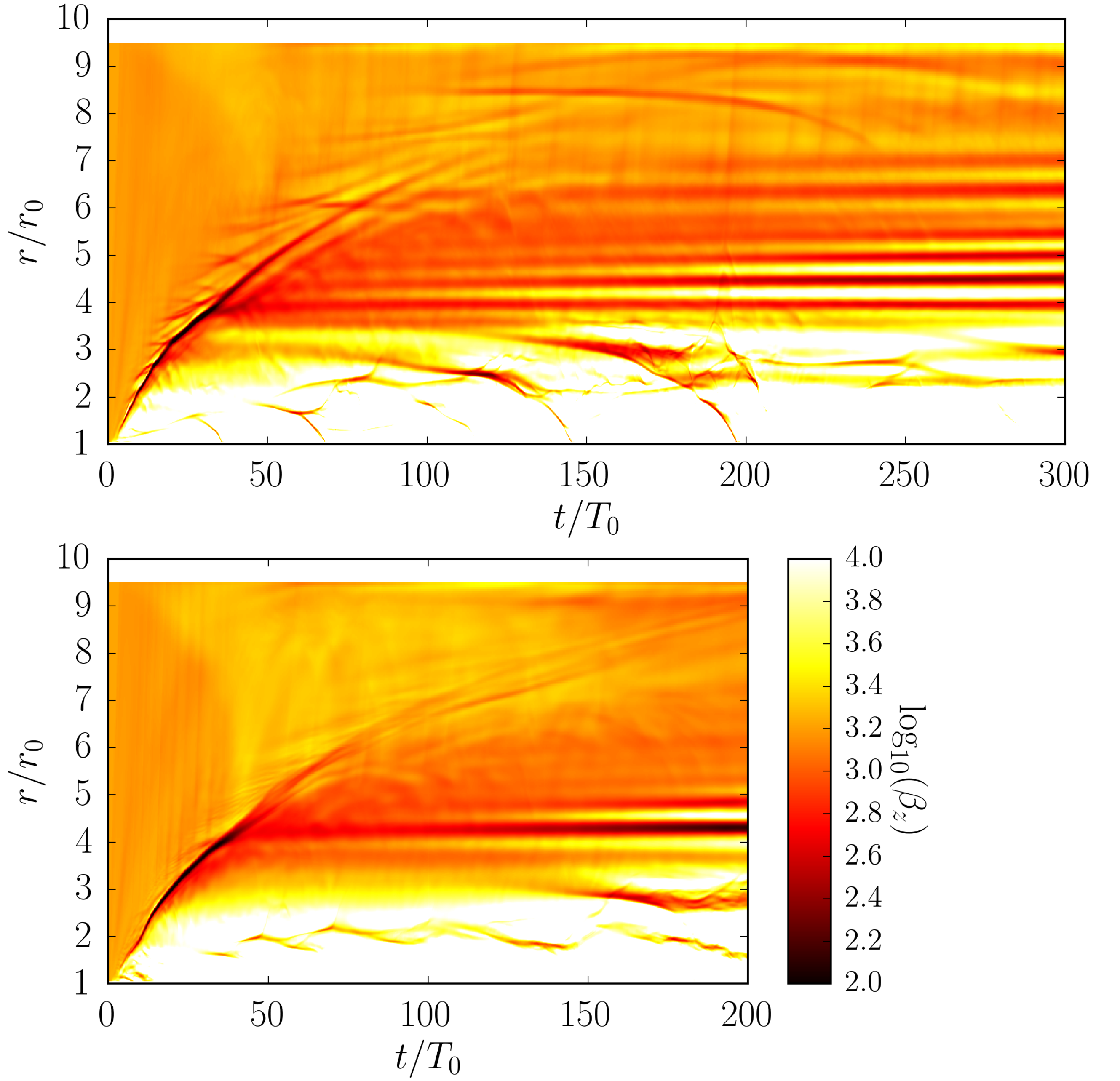
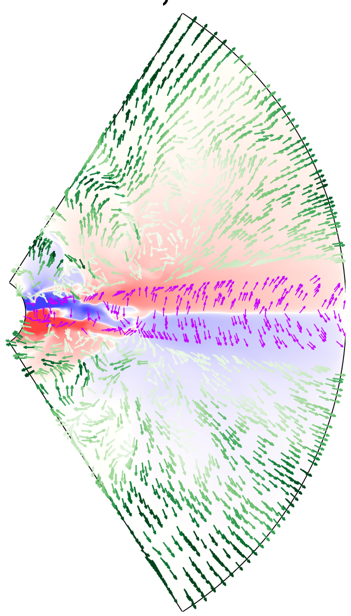
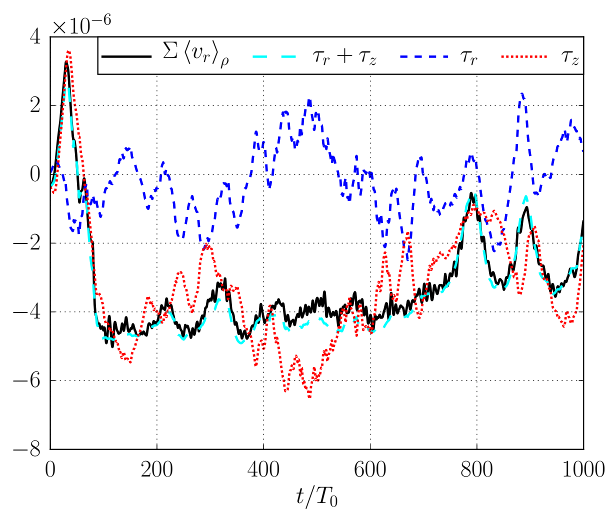


Fig. 30. Space-time diagram of vertically and azimuthally averaged β_z in runs R1-P3 (*upper panel*) and 3D-R1-P3 (*lower panel*); only the first $300T_0$ of the two-dimensional run are shown.

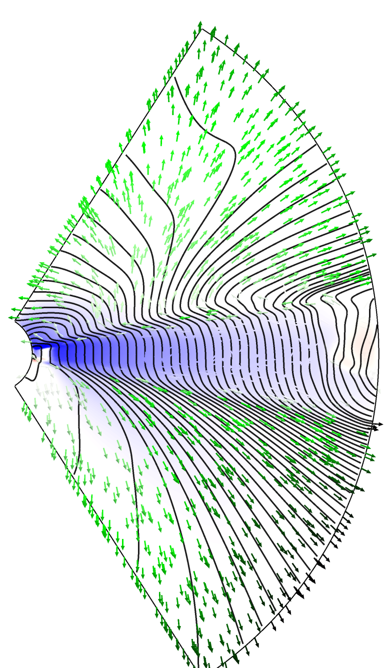
Conclusions and take home message

- Magnetized winds can drive accretion when the disc is threaded by an external field, even in “dead” discs.

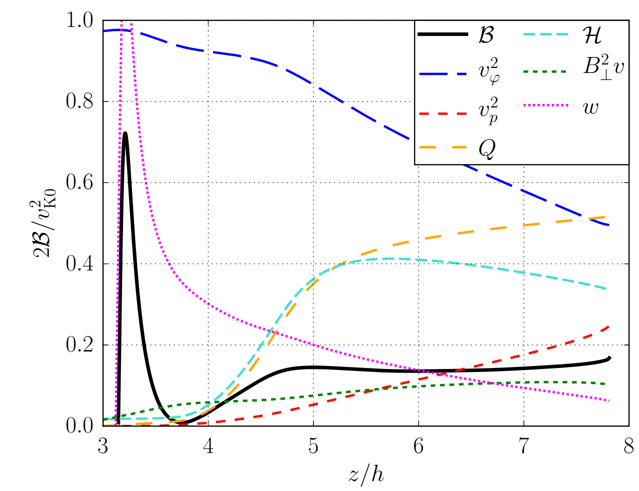




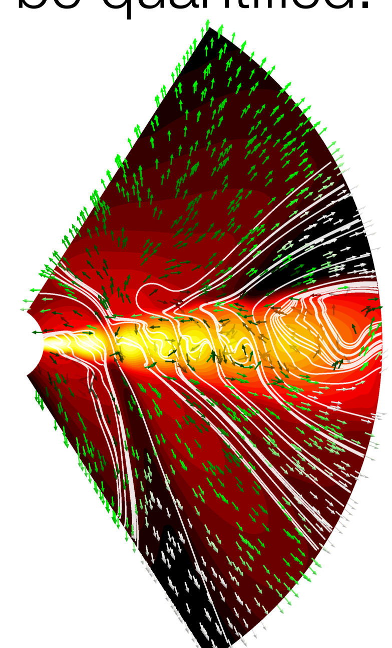
- Global wind configuration depends on the polarity of the external field

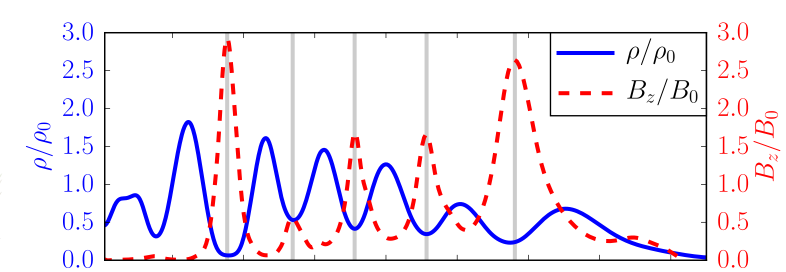


- Heating in the corona is dynamically important. Wind properties depends on it (especially mass loss rates).



- Self-organisation is present in disc-emitting discs. Impact on dust disc is to be quantified.





Open questions

- External field configuration? (polarity, long term evolution, initial condition). X. Bai & N. Dzyurkevich talks
- Quantitative predictions for wind properties? (requires a proper treatment of X-ray & UV heating)
- Dust disc observables? (dust concentration, settling with winds)

Thank you!