Transport and Accretion in Planet-Forming Disks

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SEVENTH FRAMEWORK PROGRAMME

Protostars & Planets VI

Outline

- Introduction
- MHD processes
  - Magneto-rotational instability
  - Disk-driven winds
- Gravitational instability
- Hydrodynamical processes
  - Vortex production mechanisms
  - Other hydrodynamical instabilities
- Observational signatures
- Conclusions and perspectives

An accretion problem...

- Gas can fall on the central object only if it looses angular momentum.
- One needs a way to transport angular momentum outward to have accretion:
  «angular momentum transport problem»

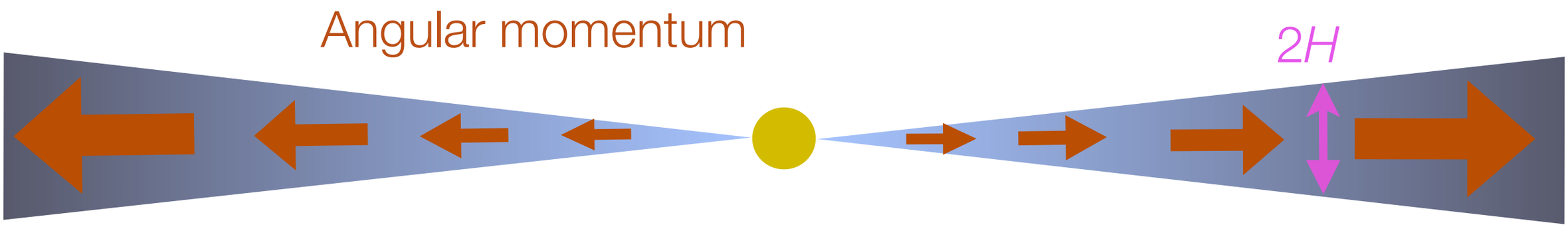
First idea: molecular viscosity

- Theoretical accretion rate due to viscous transport is very small compared to observational constrains

Credit: C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Other ways to extract angular momentum in discs?

Angular momentum transport processes
I- turbulent transport



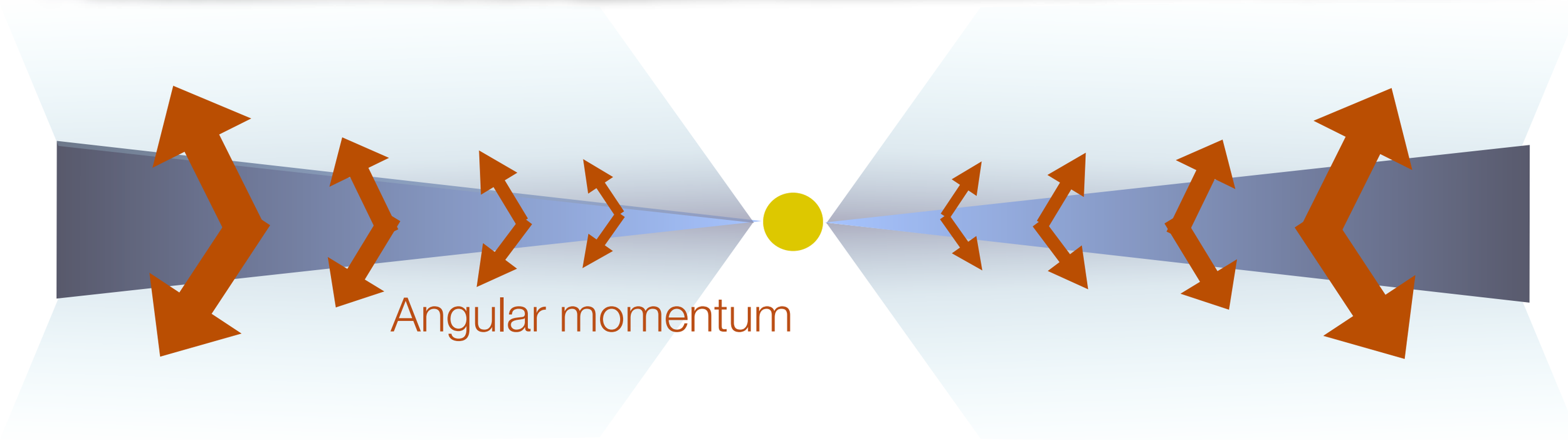
- Transport angular momentum in the bulk of the disc
- Suggested by Shakura & Sunyaev (1973) A&A, 24, 337
- Turbulence leads to enhanced transport («mixing length theory»)
- One defines a turbulent viscosity

$$\nu_t = \alpha c_s H$$

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

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

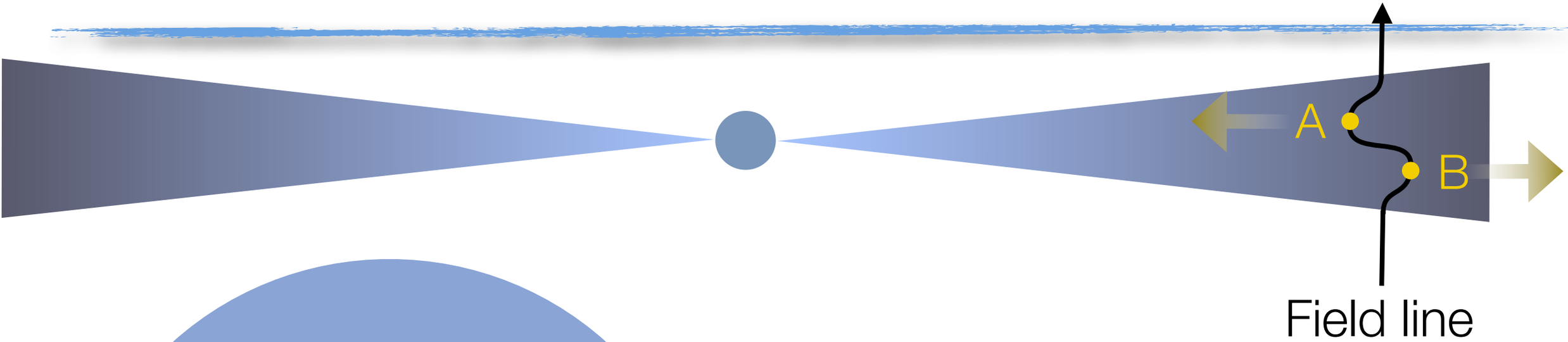
Angular momentum transport processes
II- disc wind

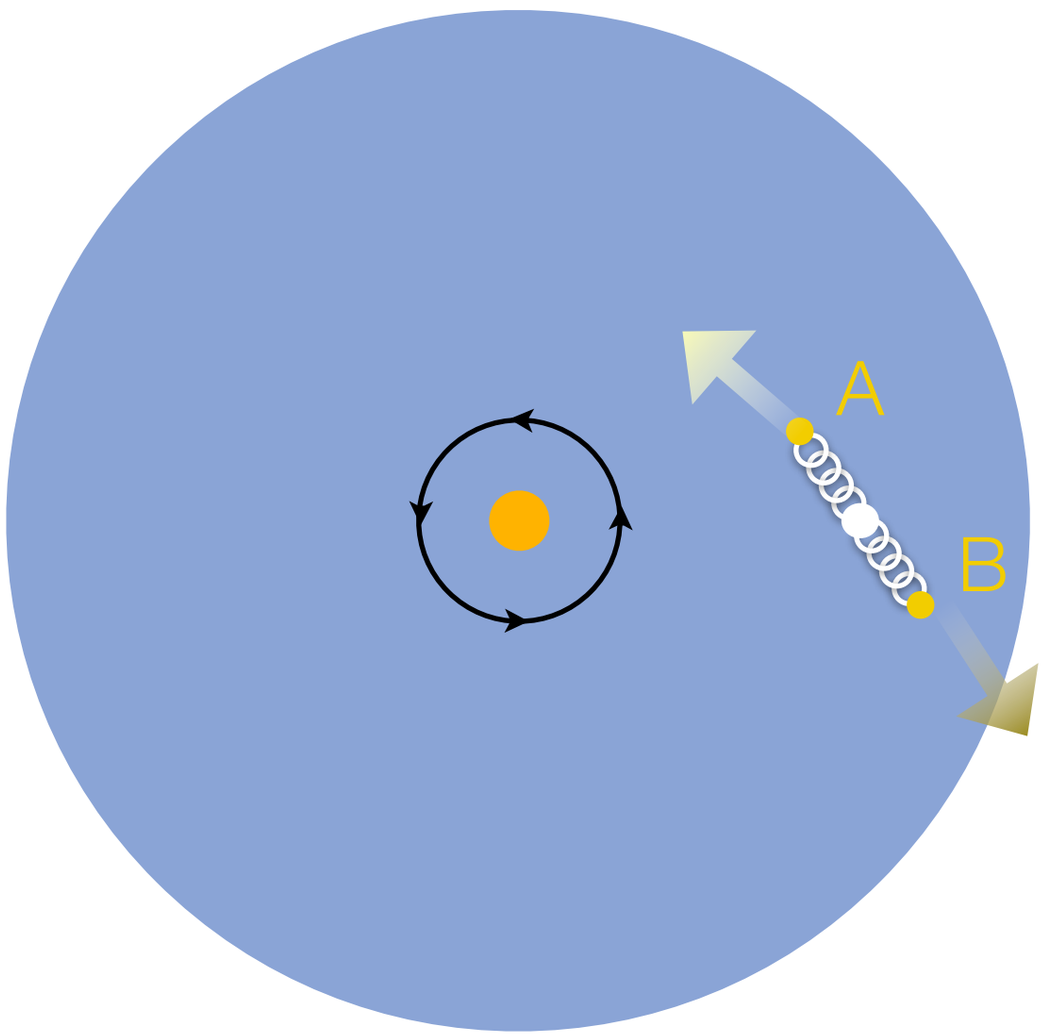


- Angular momentum *extracted* from the disc by a magnetic wind
  [Blandford & Payne 1982, MNRAS, 199, 883]
- Magnetic field exerts a torque on the disc surface which generates accretion (not described by α−disc!)

MHD processes

The magnetorotational instability (MRI)





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

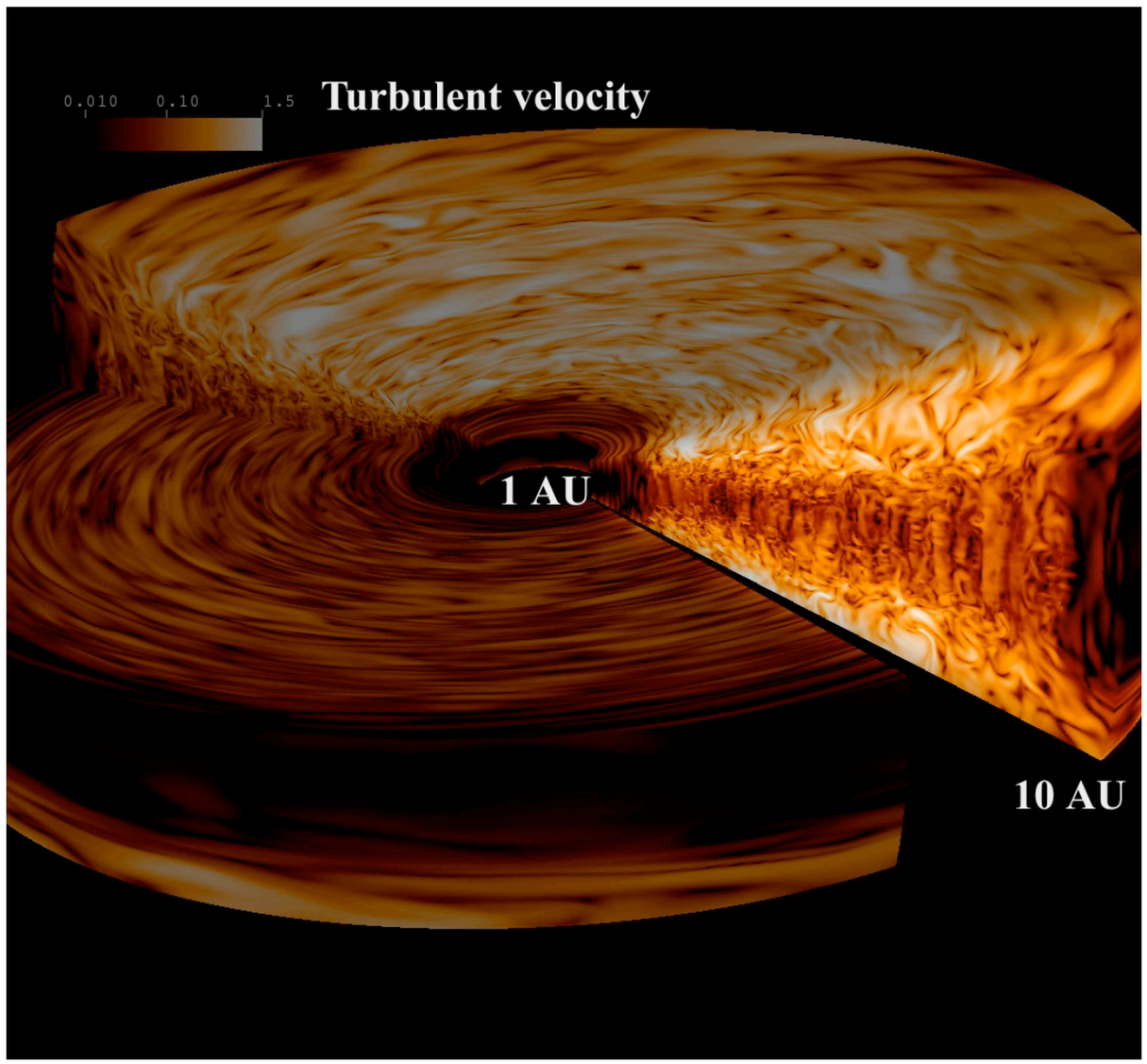
Ideal MHD instability, modified (possibly suppressed) by nonideal effects

Ideal MRI: main properties

Global simulations are consistent with box simulations *in the same conditions*

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

[Hawley+ (1995), ApJ, 440, 742 ; Fromang & Nelson (2006), A&A, 457, 343 ; Sorathia+ (2012), ApJ, 749, 189]



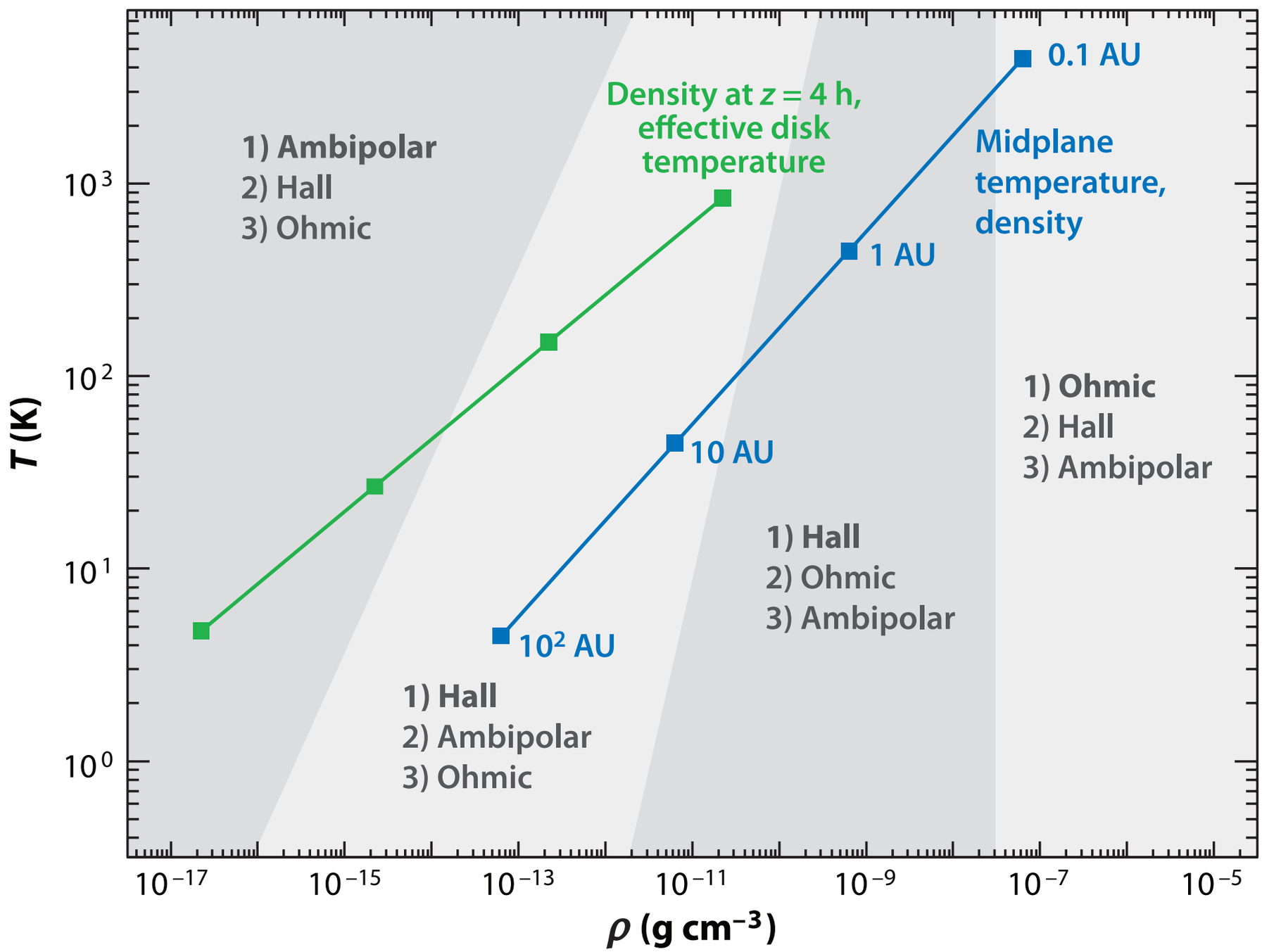
[Flock+ 2011, ApJ, 735, 122]

Nonideal MHD effects (1)

- Protoplanetary discs are far from being in the ideal MHD regime: very low ionisation fraction $\sim 10^{-13}$

- 3 nonideal effects enters the scene
  - Ohmic resistivity (electrons-neutrals collisions)
  - Hall effect (electrons-ions drift)
  - Ambipolar diffusion (electrons-neutral drift)

Nonideal MHD effects (2)

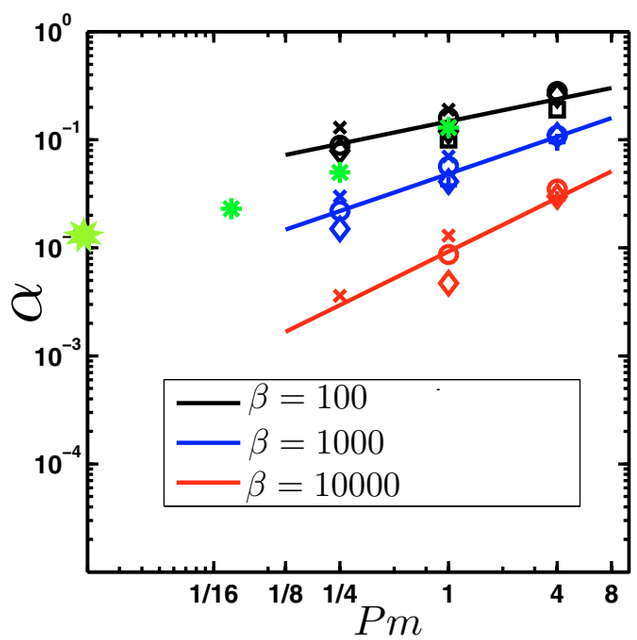


[Kunz & Balbus (2004), MNRAS, 348, 355
Armitage (2011), ARA&A, 49, 195]

The magnetic Prandtl number crisis

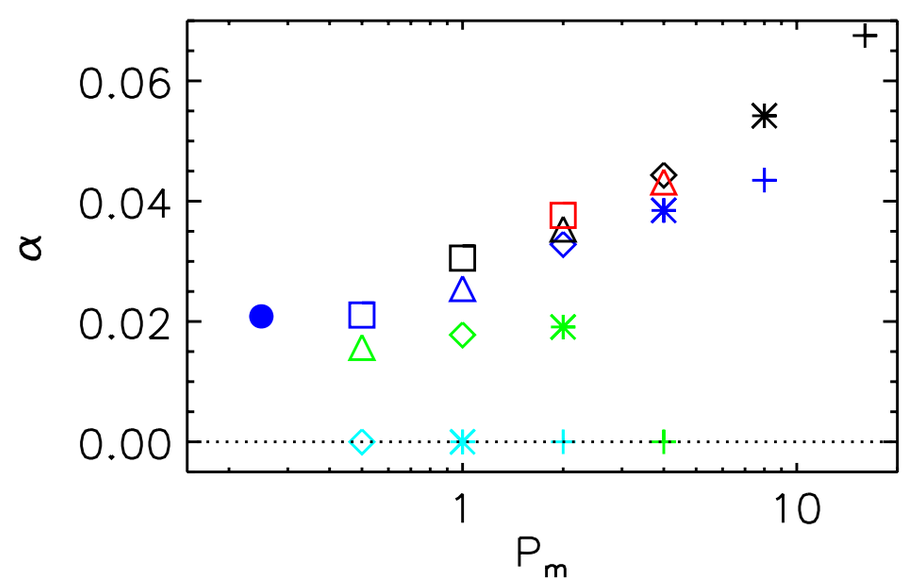
- Pm compares Ohmic diffusion to viscous diffusion
- Pm<<1 in protoplanetary discs (Ohmic diffusion more important)

unstratified
mean vertical field



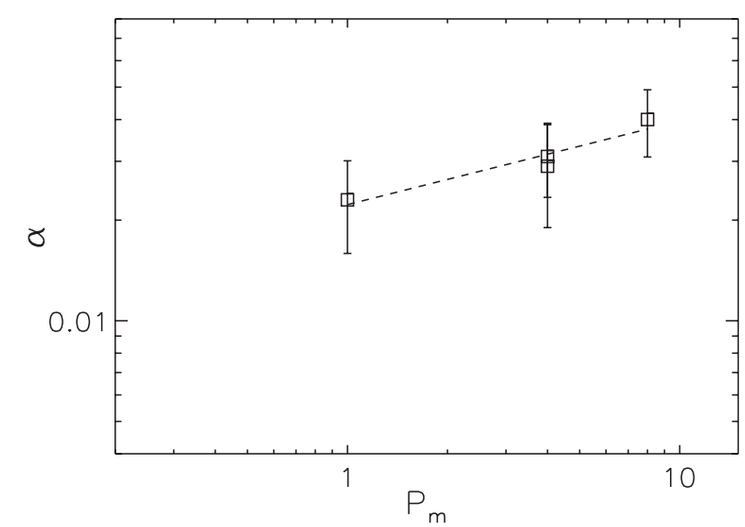
[Longaretti & Lesur (2010), A&A, 516, A51]

unstratified
mean toroidal field



[Simon & Hawley (2009), ApJ, 707, 833]

stratified
mean toroidal field



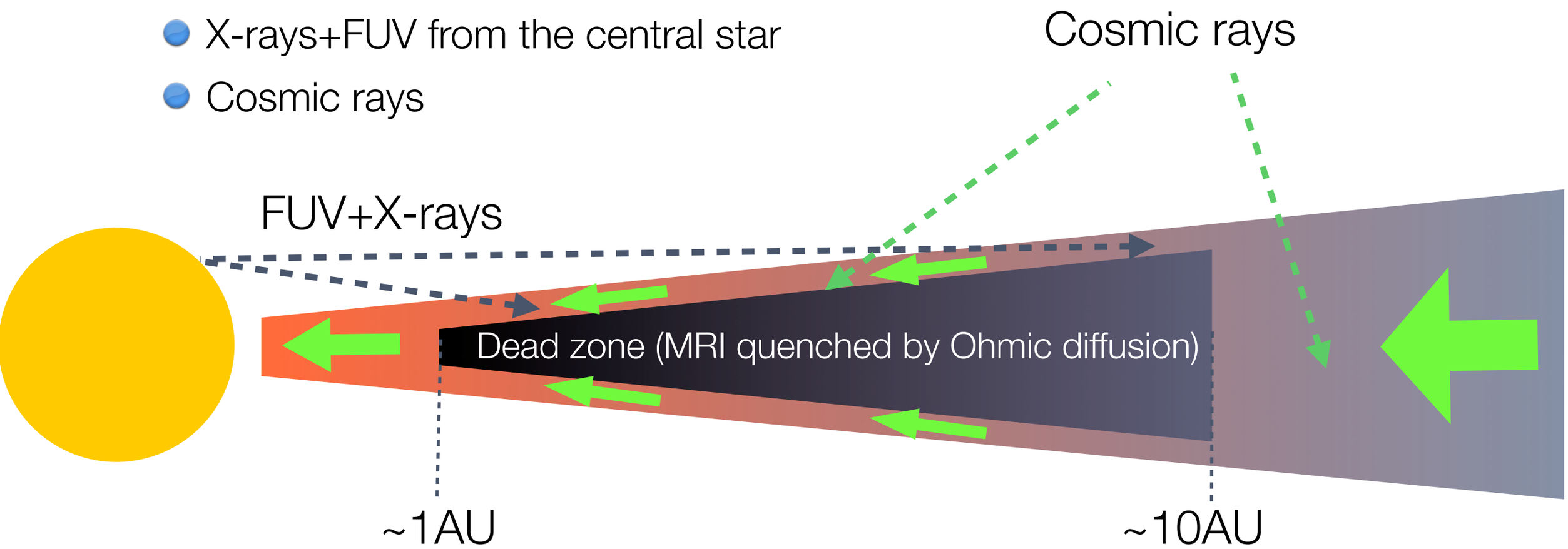
[Simon+ (2011), ApJ, 730, 94]

$\alpha(Pm \ll 1)$?

Dead Zones
Ohmic diffusion picture

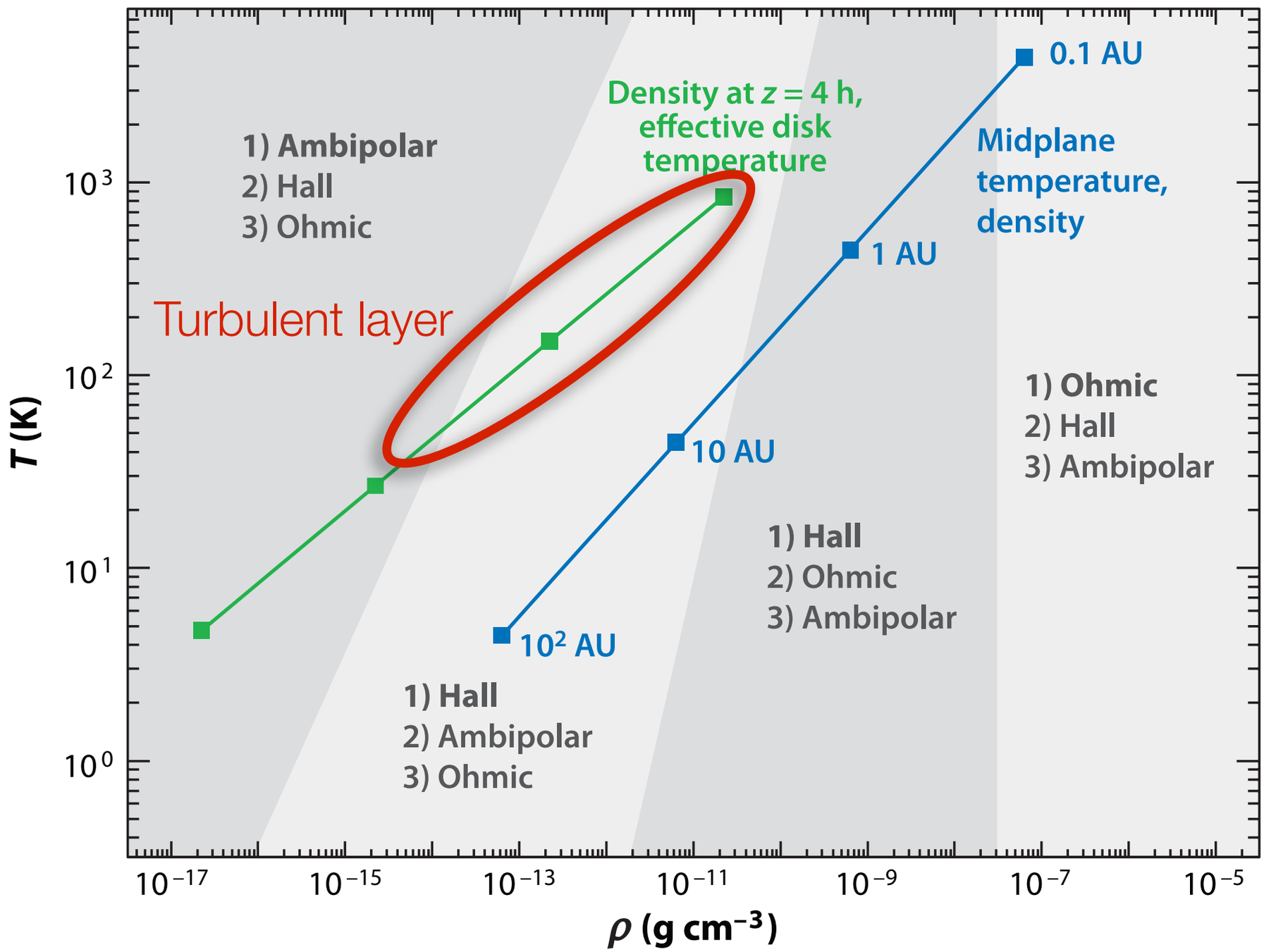
Sources of ionisation in discs include

- Thermal ionisation
- X-rays+FUV from the central star
- Cosmic rays



Layered accretion? [Gammie 1996, ApJ, 457, 355]

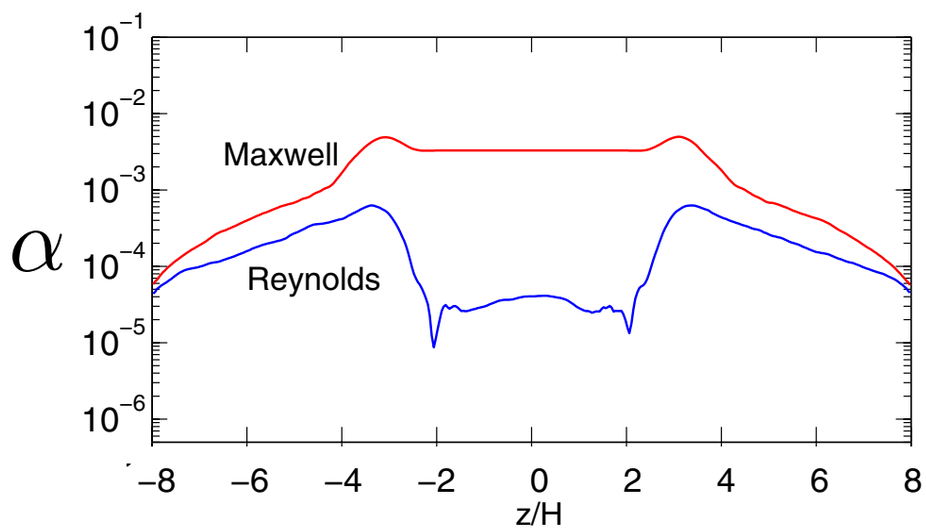
Nonideal MHD effects (2)



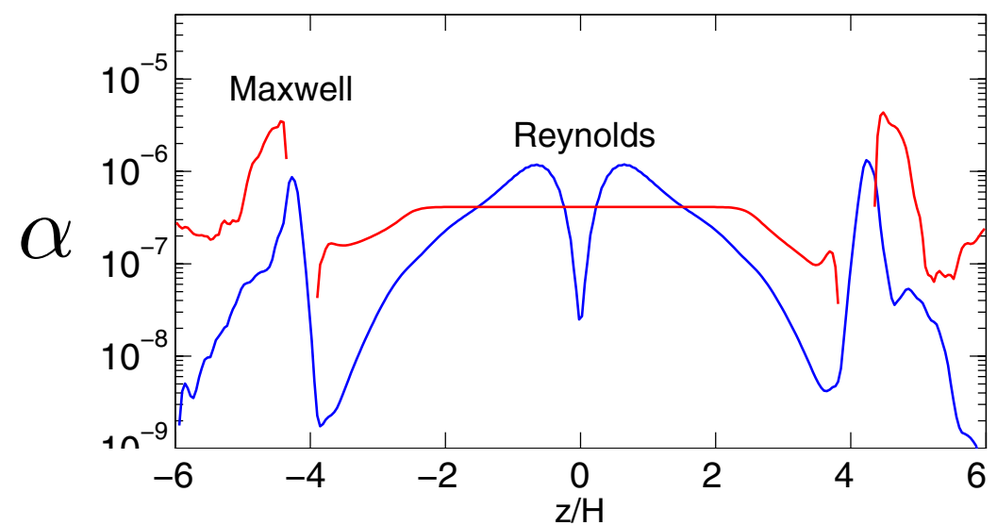
[Kunz & Balbus (2004), MNRAS, 348, 355
Armitage (2011), ARA&A, 49, 195]

Dead zones
Ambipolar diffusion makes it worse

- Turbulent layers are dominated by *ambipolar diffusion & Hall effect*
- If the disc is not threaded by a mean vertical field, ambipolar diffusion kills the MRI in the turbulent layer: $\alpha < 10^{-4}$ [Bai's poster 2S049 ; Bai & Stone (2013), ApJ, 769, 76]



Ohmic diffusion only



Ohmic+ambipolar diffusion

@1AU

- Results depend strongly on FUV ionisation, PAHs, chemistry, grains...

→ Dead zones are definitely *dead*

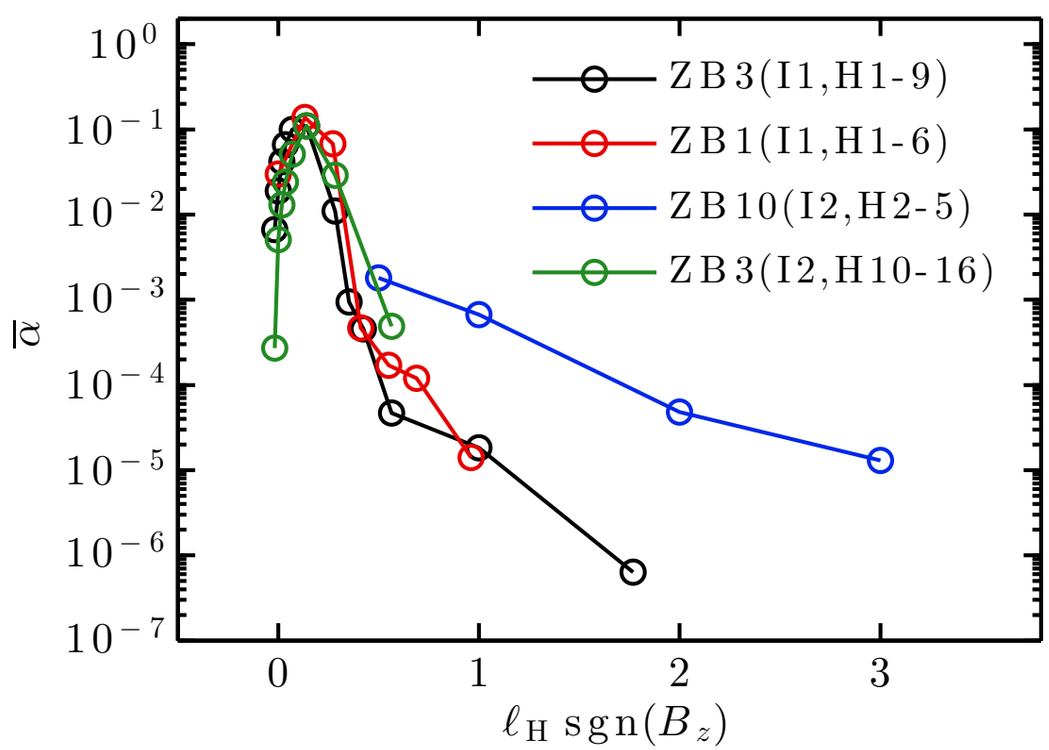
Hall effect
might not save the MRI

- Hall effect could revive dead zones
  [Wardle & Salmeron (2012), MNRAS, 422, 2737]

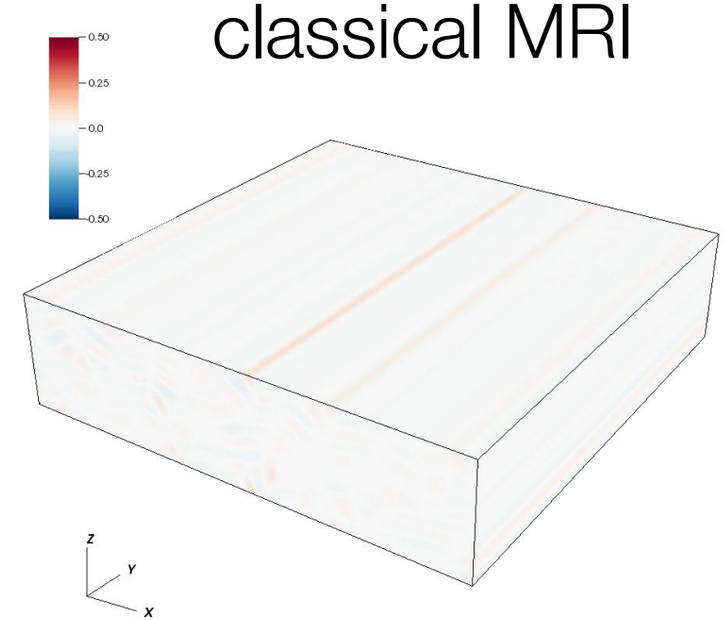
- Despite being strongly unstable to the MRI, Hall dominated discs do not produce turbulence but zonal fields whenever

$$\ell_{\rm H} \equiv \left(\frac{m_{\rm i} c^2}{4\pi Z^2 e^2 n_{\rm i}}\right)^{1/2} \left(\frac{\rho}{\rho_{\rm i}}\right)^{1/2} \gtrsim 0.2H$$

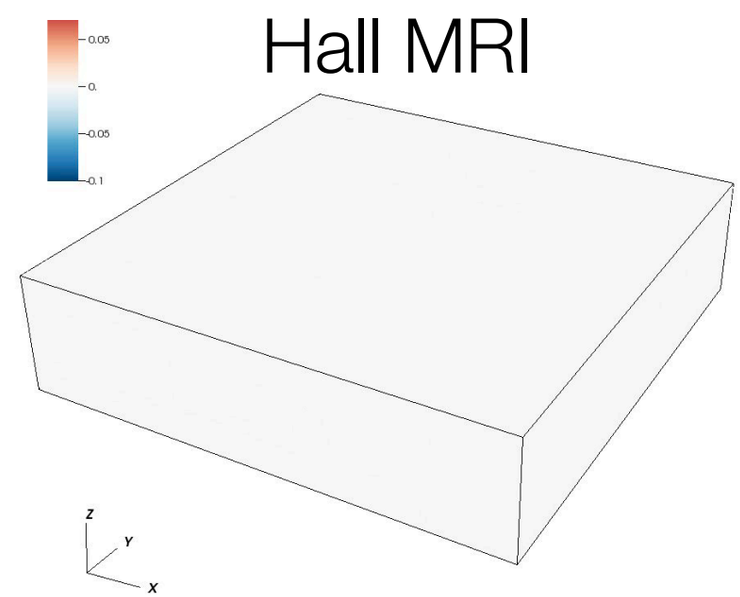
[Kunz & Lesur (2013), MNRAS, in press]



classical MRI



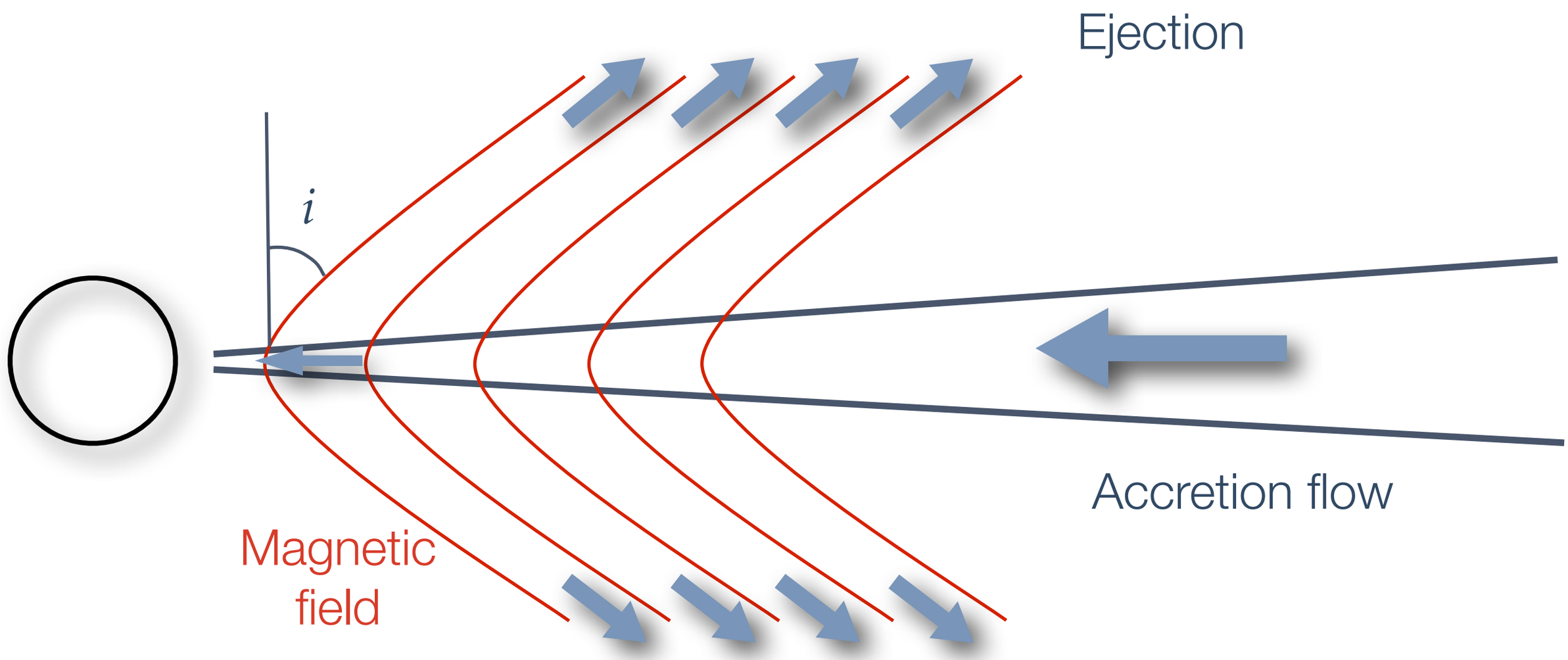
Hall MRI



Disc winds

Disc winds
Blandford & Payne paradigm

[Blandford & Payne (1982), MNRAS, 199, 883]



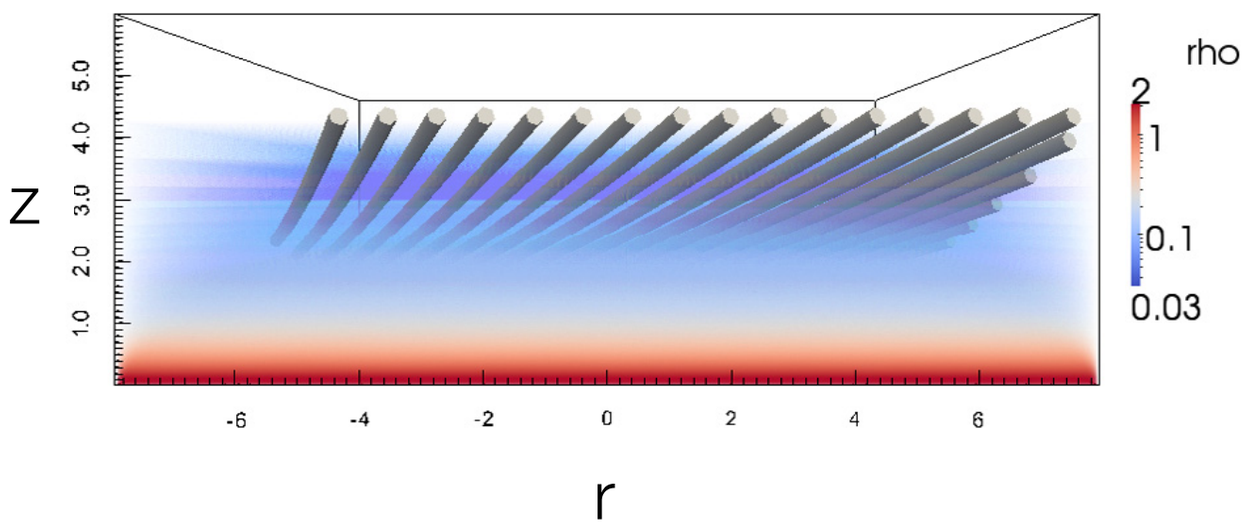
- Need a large scale *mean field*
- Magneto-centrifugal ejection when i>30°
- Requires $\beta \equiv \frac{P_{\rm Th}}{P_{\rm Mag}} \sim 1$ [Murphy+ (2010), A&A, 512, 82]

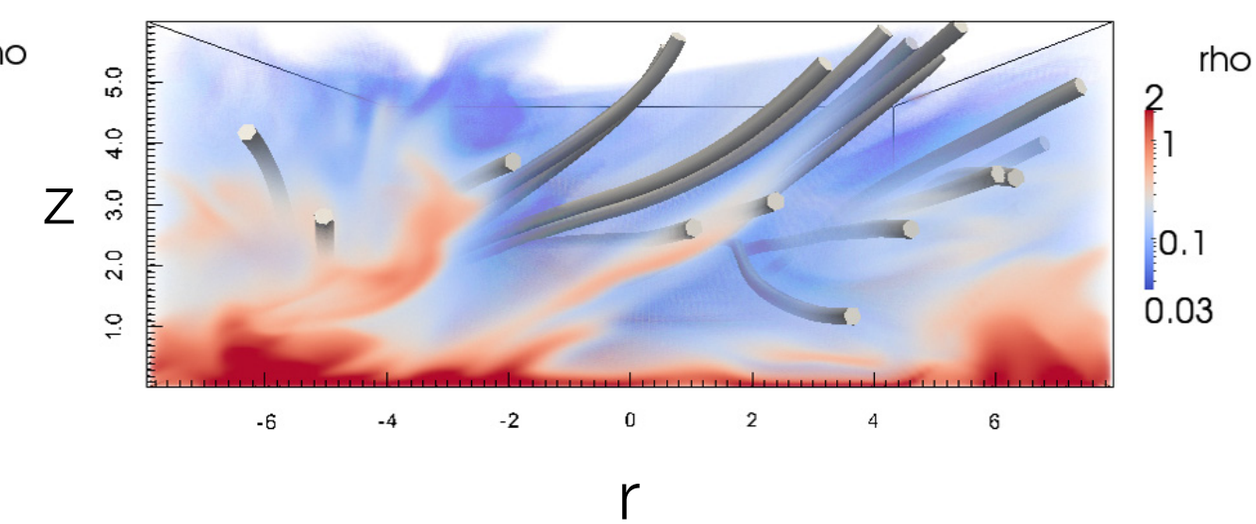
Jet formation

Coexistence of MRI and strong disc winds?

$$\beta \equiv \frac{P_{\mathrm{Th}}}{P_{\mathrm{Mag}}} = 10$$

- For strongly magnetised discs, the MRI spontaneously evolves into discs winds
  [Moll (2012), A&A, 548, 76 ; Lesur+ (2013), A&A, 550, A61]





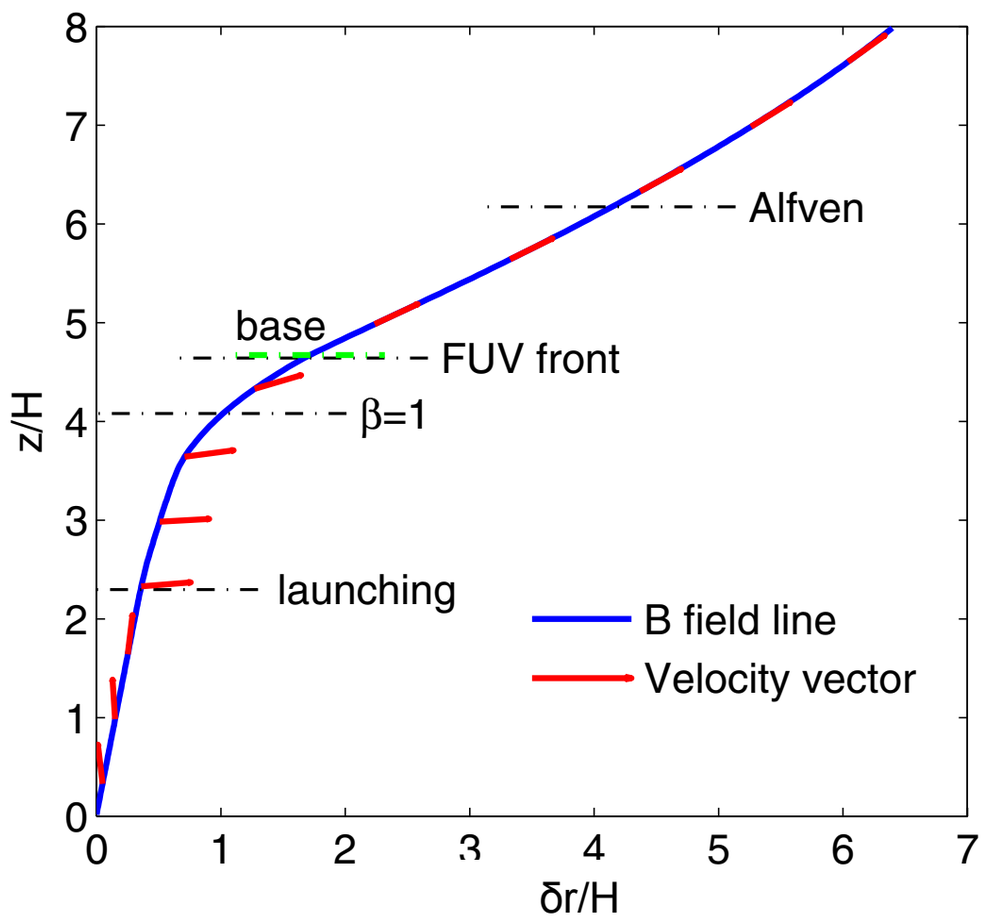
[Lesur+ (2013), A&A, 550, A61]

- Precursor of variability in jets?

Disc winds in weakly magnetised discs

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

- Stratified box simulations with a mean vertical field always show «weak» magnetically driven winds
  [Suzuki & Inutsuka (2009), ApJ, 691, L49 ; Fromang+ (2013), A&A, 552, A71 ; Bai & Stone (2013), ApJ, 767, 30]
- Could explain $\dot{M}_{\rm Acc} \sim 10^{-8}\ M_\odot/{\rm yr}$ in «dead» parts of the disc & in outer parts
  [Bai & Stone (2013), ApJ, 769, 76 ; Simon+ (2013) arXiv:1306.3222]



Bai & Stone (2013), ApJ, 769, 76

- BUT: some quantitative results (eg mass loss rate in the wind) depend *strongly* on the box size!
  [Suzuki+ (2010), ApJ, 718, 1289 ; Lesur+ (2013), A&A, 550, A61 ; Fromang+ (2013), A&A, 552, A71]

Conclusions regarding MHD processes

The MRI is likely to be absent/insufficient in large parts of protoplanetary discs (1 to 10-30 AU)

- Results depend *crucially* on non-ideal MHD effects (controlled by heating/cooling, CRs, FUV, PAHs, dust settling, chemistry...)
- Hall effect will probably not save the MRI
- Weak magneto-centrifugal winds might be the answer (but many numerical artefacts in box simulations)

→ Global MRI+wind simulations are the next step

Gravitational instability

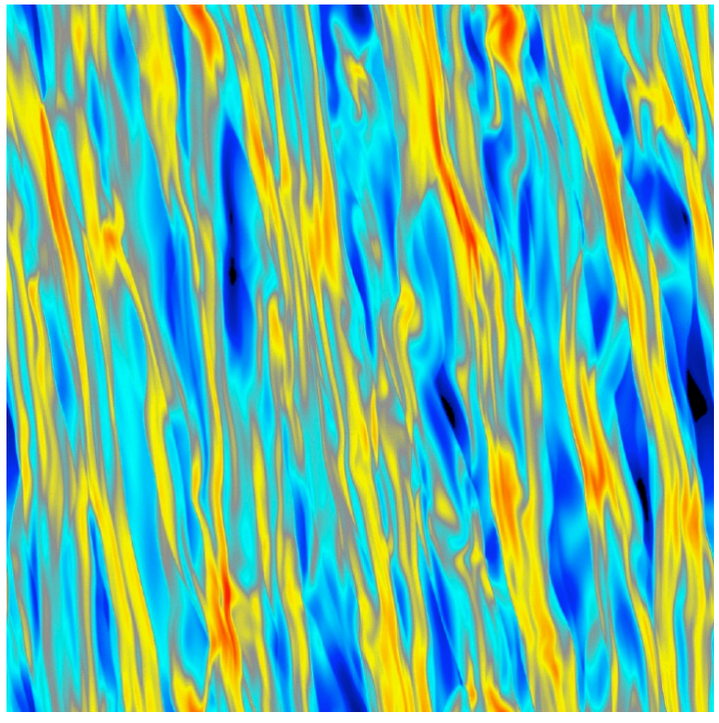
Gravitational instability
General criteria

- Criterion for a disc to be gravitationally unstable $Q = \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1$

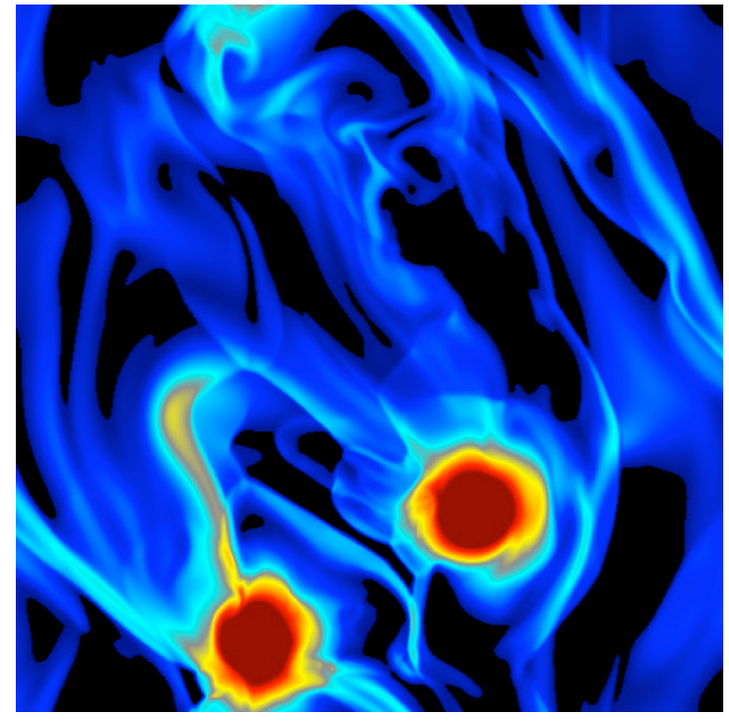
[Toomre (1964) ApJ, 139, 1217]

- Outcome of GI (fragmentation/gravito-turbulence) depends on the cooling time τ_c

$\tau_c = 10\Omega^{-1}$



$\tau_c = 2\Omega^{-1}$

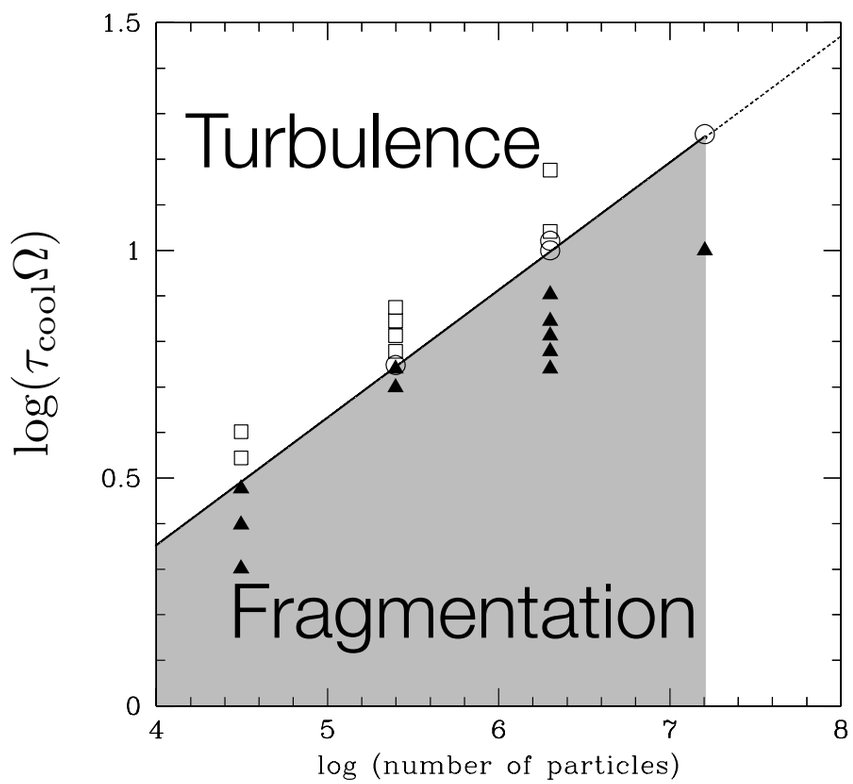


[Gammie (2001), ApJ, 553, 174]

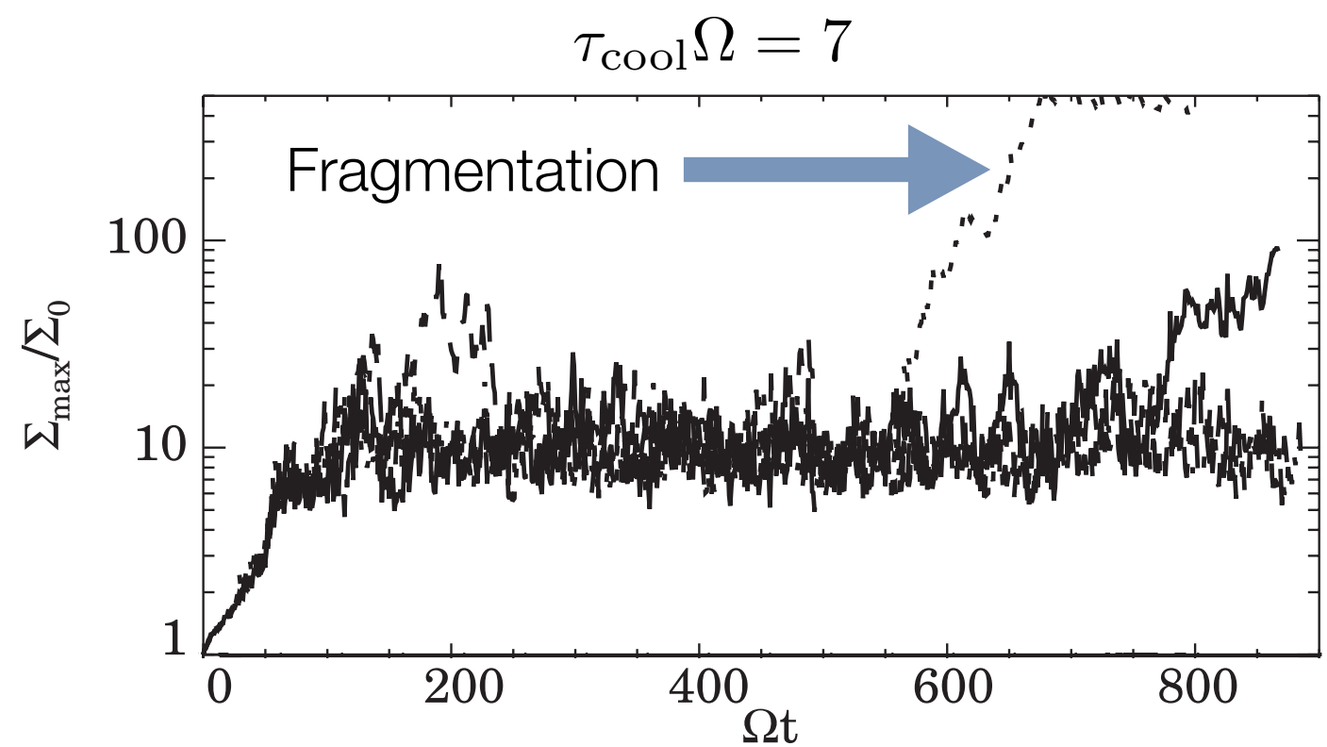
- Gravito-turbulence gives $\alpha = \frac{1}{9/4\gamma(\gamma-1)\Omega\tau_c}$

Gravitational instability
fragmentation inevitable?

- Fragmentation condition depends on numerical resolution and is stochastic !



[Meru & Bate (2011), MNRAS, 411, L1–L5]



[Paardekooper (2012), MNRAS, 421, 3286]

→ Gravito-turbulence might not be *long lived*

Conclusions on gravitational instability

Gravitational instability can be active in dense & cold disc regions (outer parts of young discs)

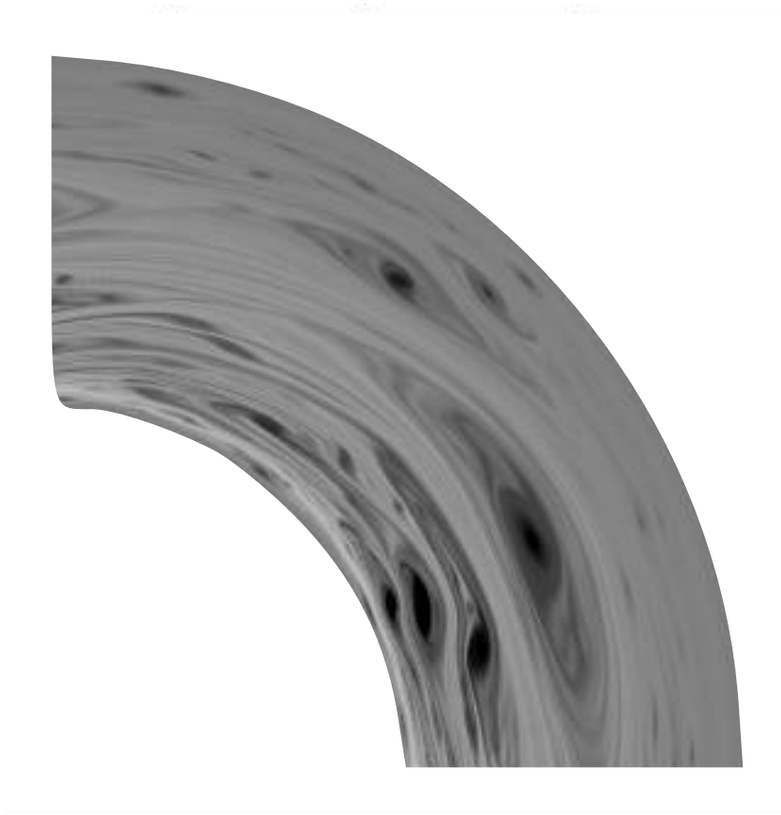
- Outcome of GI still uncertain (resolution sensitivity, stochastic fragmentation). Maybe GI always lead to fragmentation?
- Behaviour & convergence with more realistic cooling function ?

  [Michael+ (2012), ApJ, 746, 98 ; Steiman-Cameron+ (2013), ApJ, 768, 192]

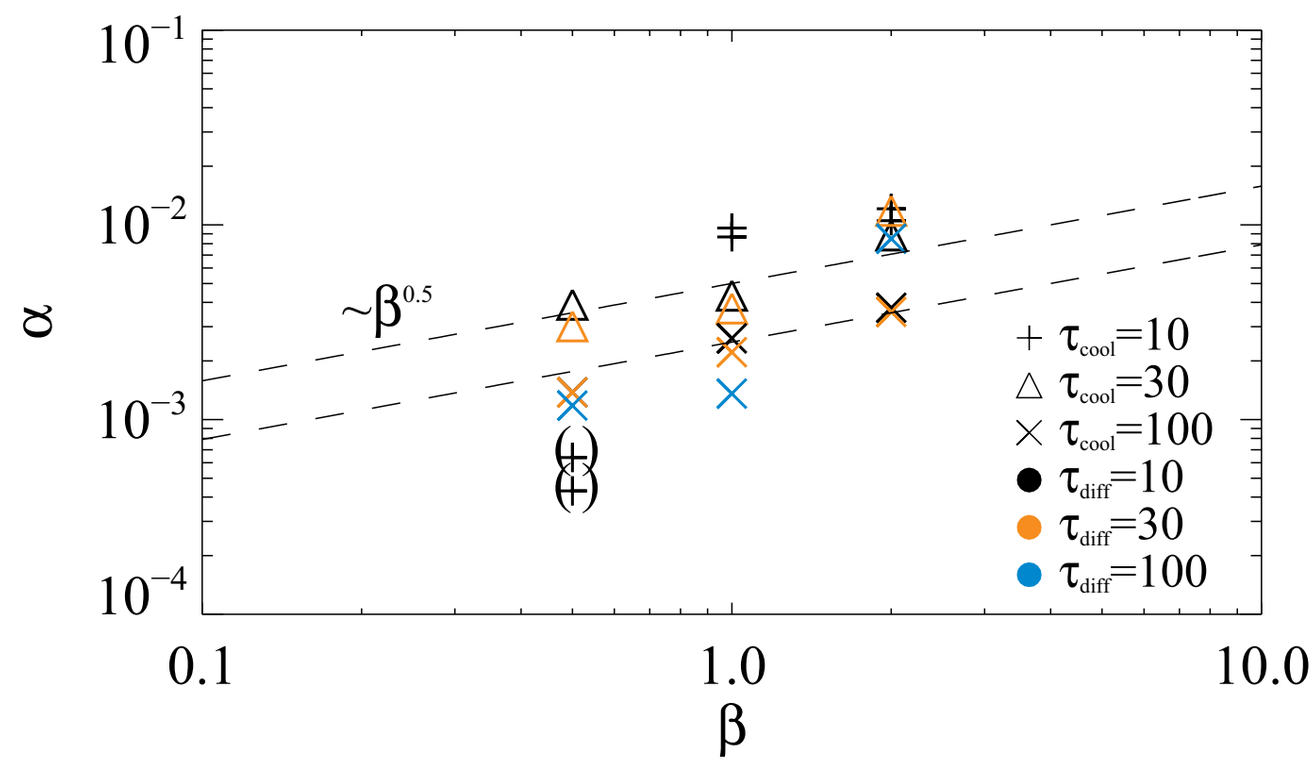
Hydrodynamic instabilities

Baroclinic instability

- Driven by the radial entropy gradient $\beta \equiv -\frac{d \ln S}{d \ln R} > 0$ [Klahr & Bodenheimer (2003), ApJ, 582, 869]
- Cooling, heating and finite amplitude perturbations are essential
  [Petersen+ (2007), ApJ, 658, 1252 ; Lesur & Papaloizou (2010), A&A, 513, 60]
- Leads to $\alpha \sim 10^{-3}$—10^{-2}



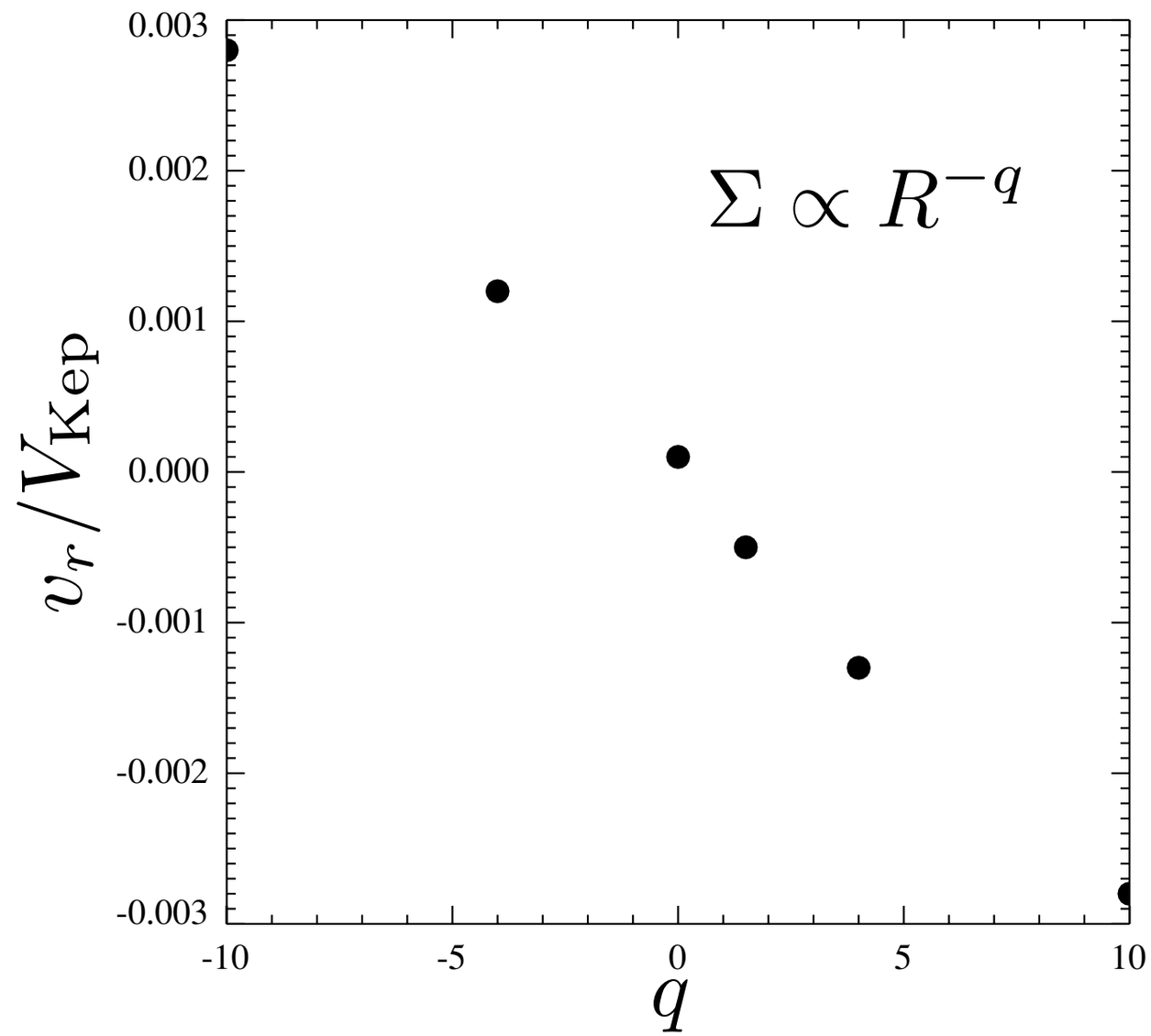
Petersen+ (2007), ApJ, 658, 1252



Raettig+ (2013), ApJ, 765, 115

Problems with the vortex scenario

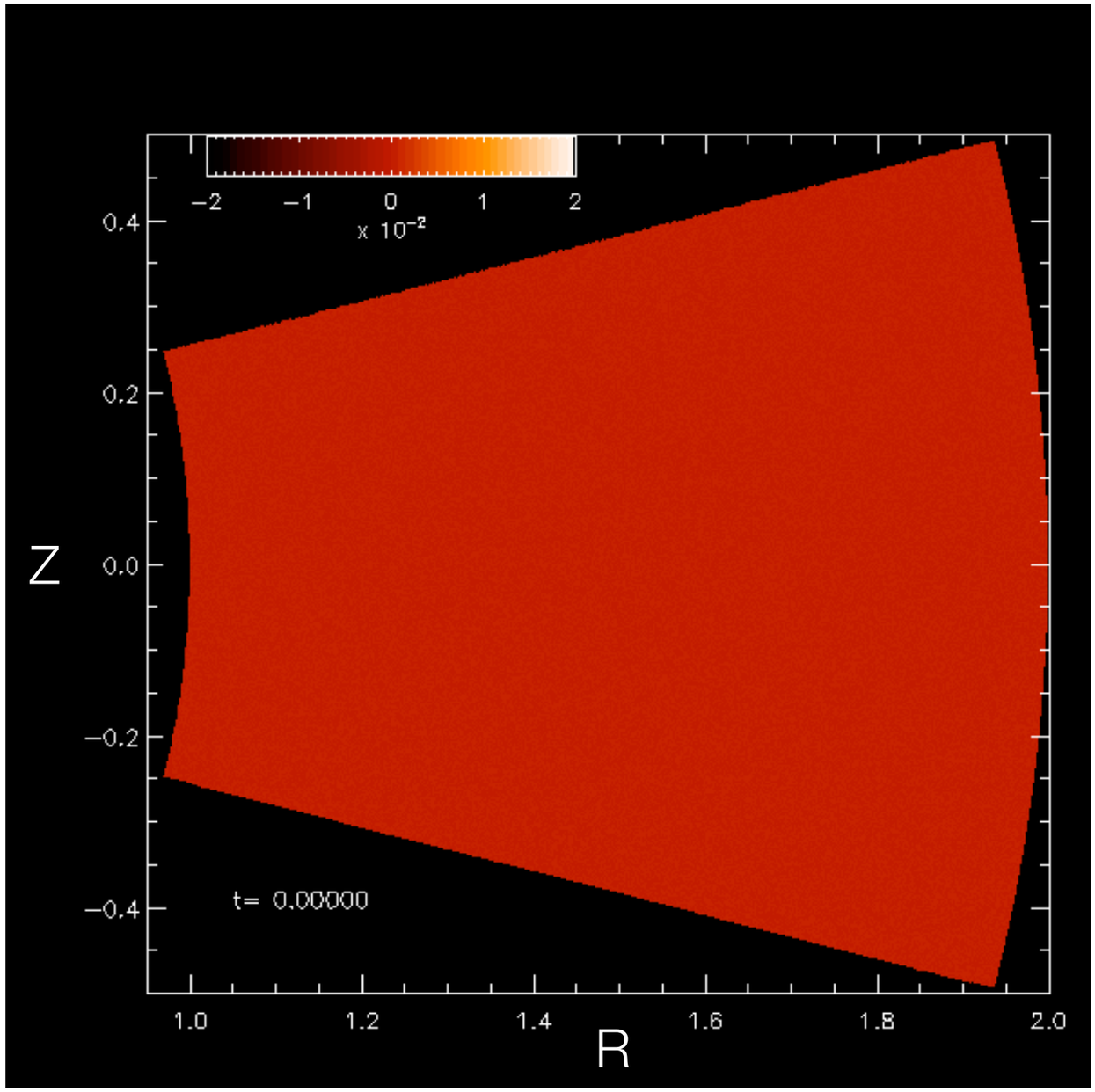
- Vortices are unstable in 3D [Lesur & Papaloizou (2009), A&A, 498, 1]
- 3D circulation complicates the picture [Meheut+ (2010), A&A, 516, 31]
- Vortices migrate
  [Paardekooper+ (2010), ApJ, 725, 146]



GSF instability

- Vertical shear instability (Goldreich-Schubert-Fricke=GSF)
  - appears in «locally isothermal» discs: T(R)
  - can give $\alpha \sim 10^{-3}$

    [Urpin & Brandenburg (1998), MNRAS, 294, 399;
    Urpin (2003), A&A, 404, 397;
    Nelson+ (2012), arXiv:1209.2753]



Nelson+ (2012), arXiv:1209.2753

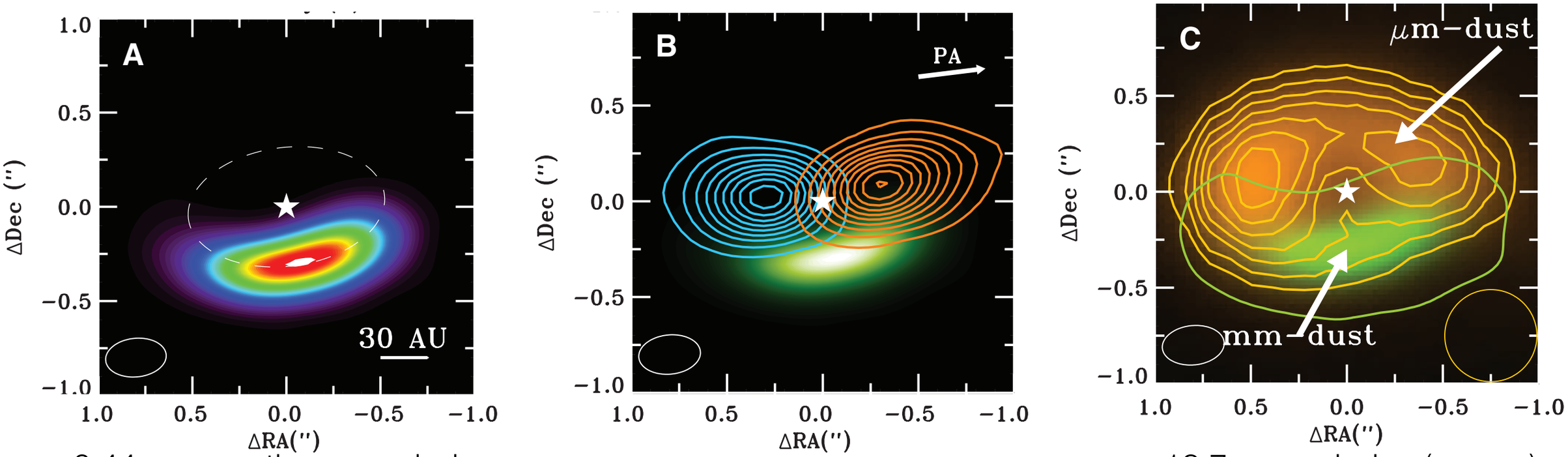
Conclusions on hydrodynamical processes

- Hydro candidates are *thermally driven.* Precise heating/cooling computations are needed in order to assess their existence in discs.
- Vortices are an interesting hypothesis since they can trap dust. But uncertainties remain regarding their evolution on long timescales.

Observing transport mechanisms

Non-axisymmetric dust accumulation

[van der Marel+ (2013), Science, 340, 1199]

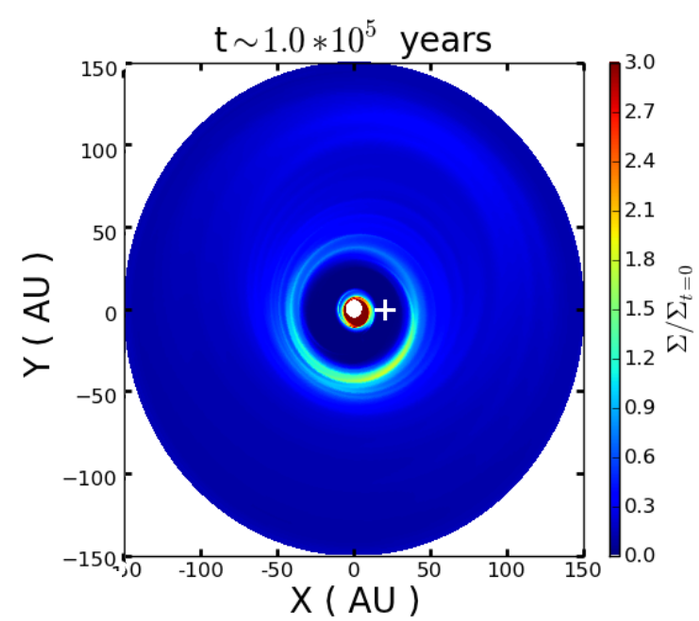


0.44-mm continuum emission

CO 6-5 emission velocity contour

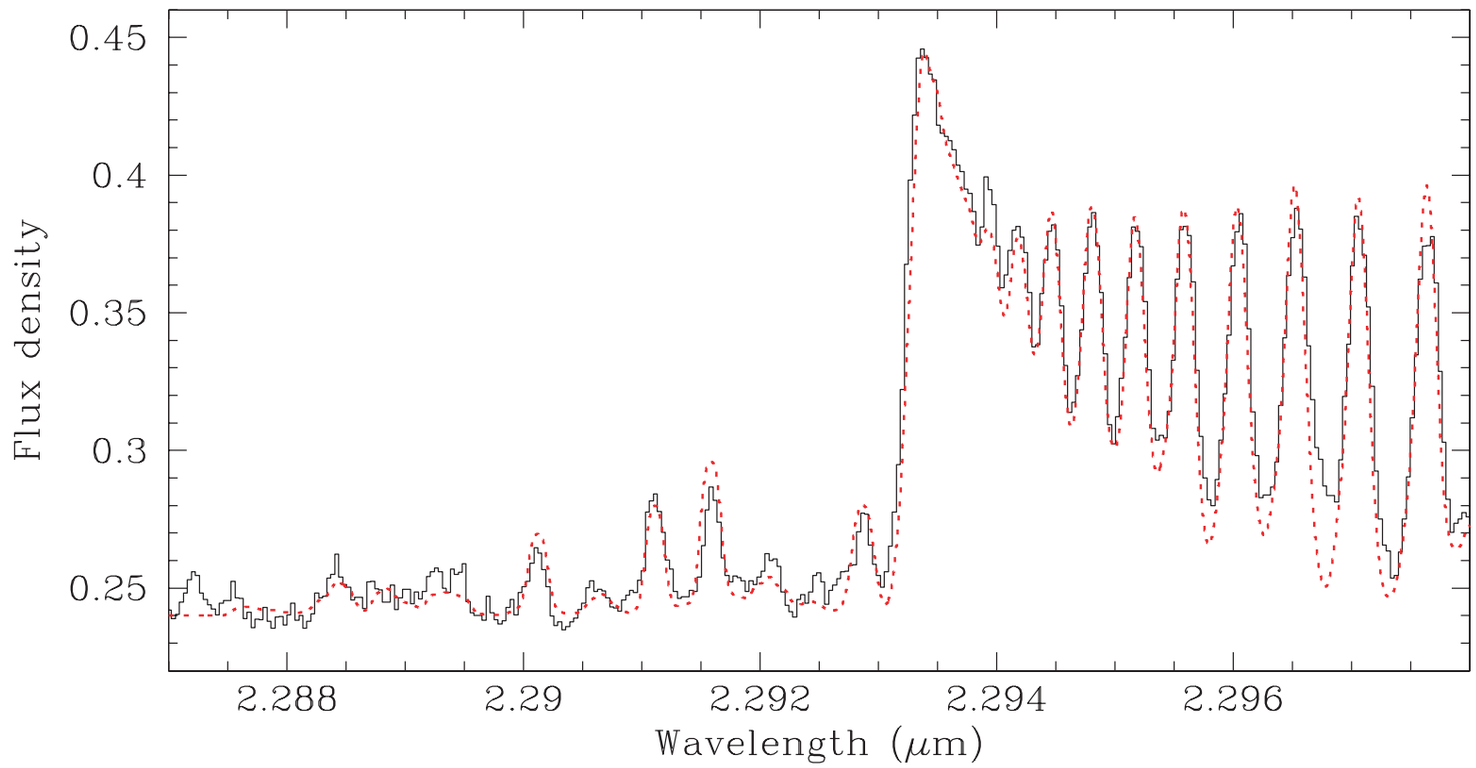
18.7 μm emission (orange)

- Indication of a large scale vortex at 63 AU
- Vortex at the edge of a gap cleared by a giant planet?
- Problem: a 10 M_{Jup} planet at 20 AU generates a vortex at 40 AU (assuming a $\alpha = 10^{-4}$ disc)
- Alternative scenario: baroclinic vortices?



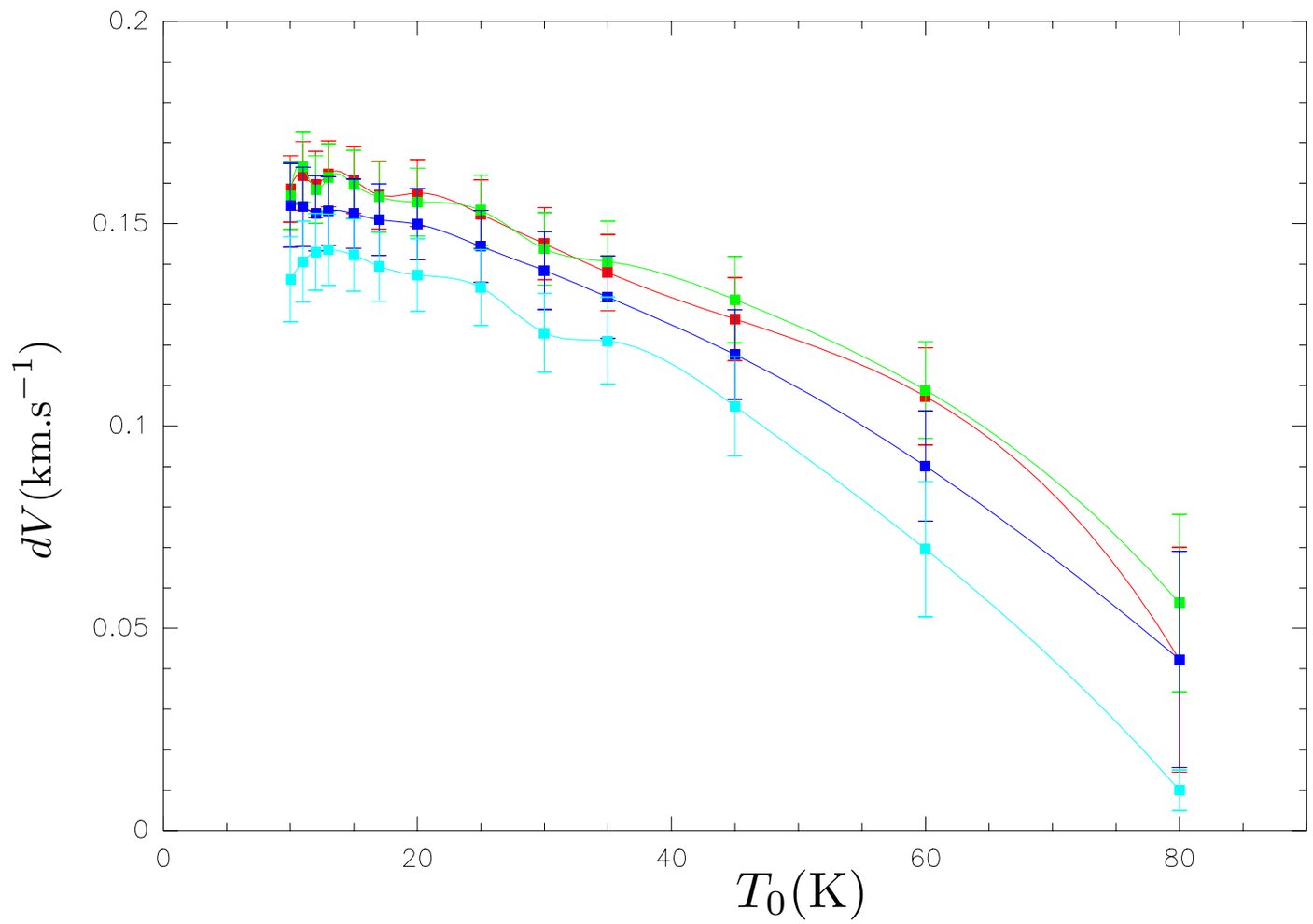
Turbulence in the inner disc (0.1 AU)?

[Najita+ (2009), ApJ, 691, 738]



- Spectrum (black) of V1331 Cyg in the 2.3 μm region (H_2O+CO)
- Model (red) with a 4 km/s line broadening (CO thermal dispersion 0.9km/s)
- Signature of sonic turbulence? (winds excluded: no line asymmetry)

Turbulence in the outer disc?



[Guilloteau+ 2012, A&A, 548, 70]
see also [Hughes+ (2011), ApJ, 727, 85]

- CS J=3-2 transition in DM-tau
- Best fit gives a turbulent broadening ~0.11 km/s at 300 AU
- Signature of turbulence at ~50% of the sound speed?

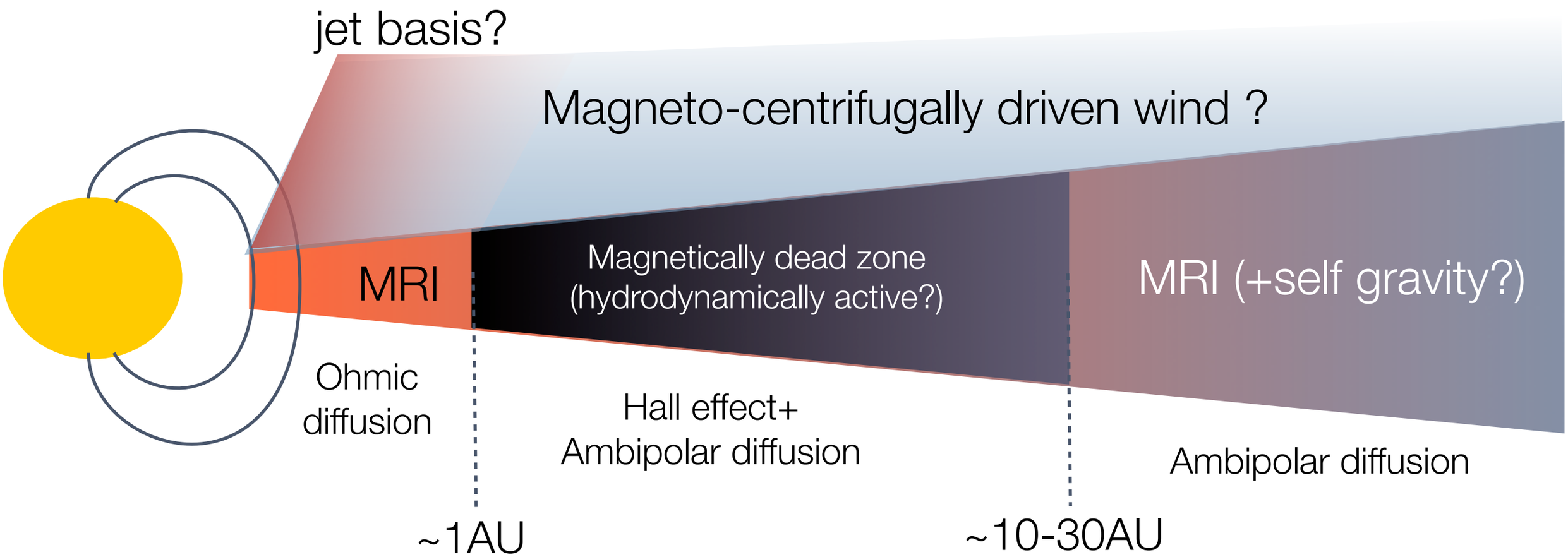
Conclusions on observations

- Non thermal broadening of spectral lines probably due to subsonic motions (could be turbulence, but could also be vortices or wind in the outer disc).
- Indications of large scale vortices. Planet scenario not entirely satisfactory (baroclinic vortices?).

Perspectives:

- Higher resolution observations should make the distinction between small scale structures (~turbulence) and large scale features (vortices, wind)

Conclusions & perspectives



Magnetically dead zones are the current bottleneck in transport theory

- Is the dead zone really magnetically dead? (improve chemistry)
- Need for global wind models including *all* of the nonideal MHD effects
- Go beyond simplistic thermodynamics: realistic equation of state with radiative transfer (& chemistry ?)