Formation and evolution of protoplanetary discs

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1. Disc Formation

2. Angular momentum transport
   - Self-gravity
   - Magnetic fields

3. Hydrodynamic instabilities

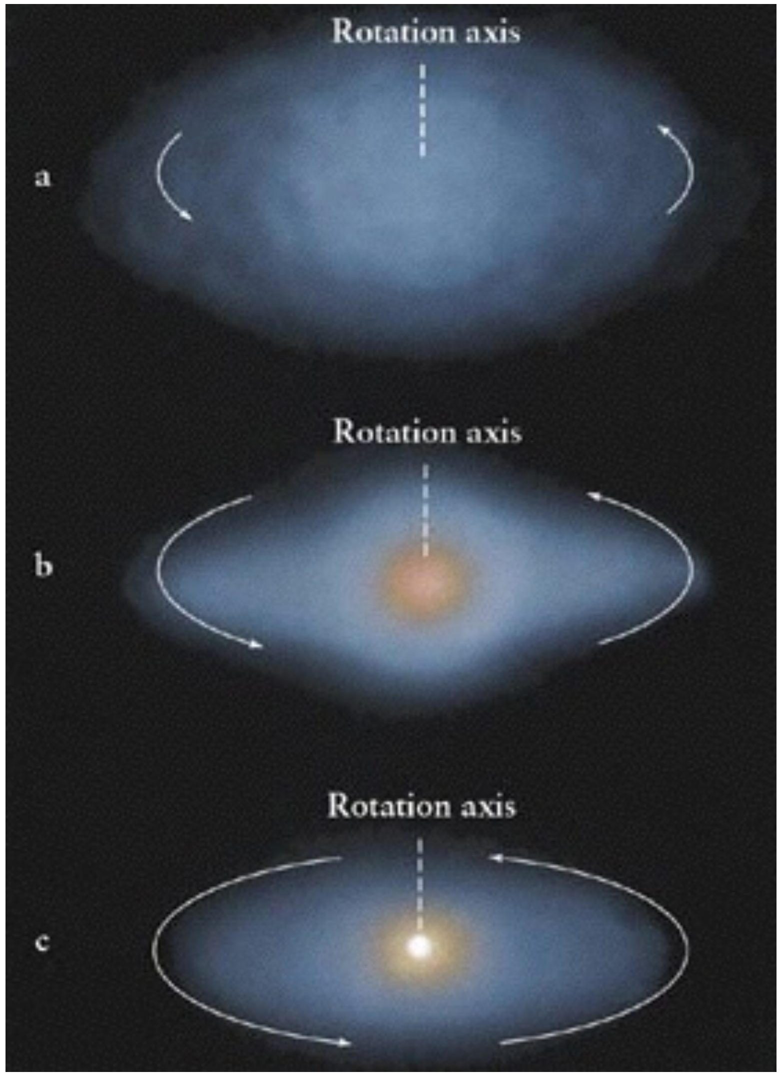
4. Dispersal via photoevaporation

Disc formation

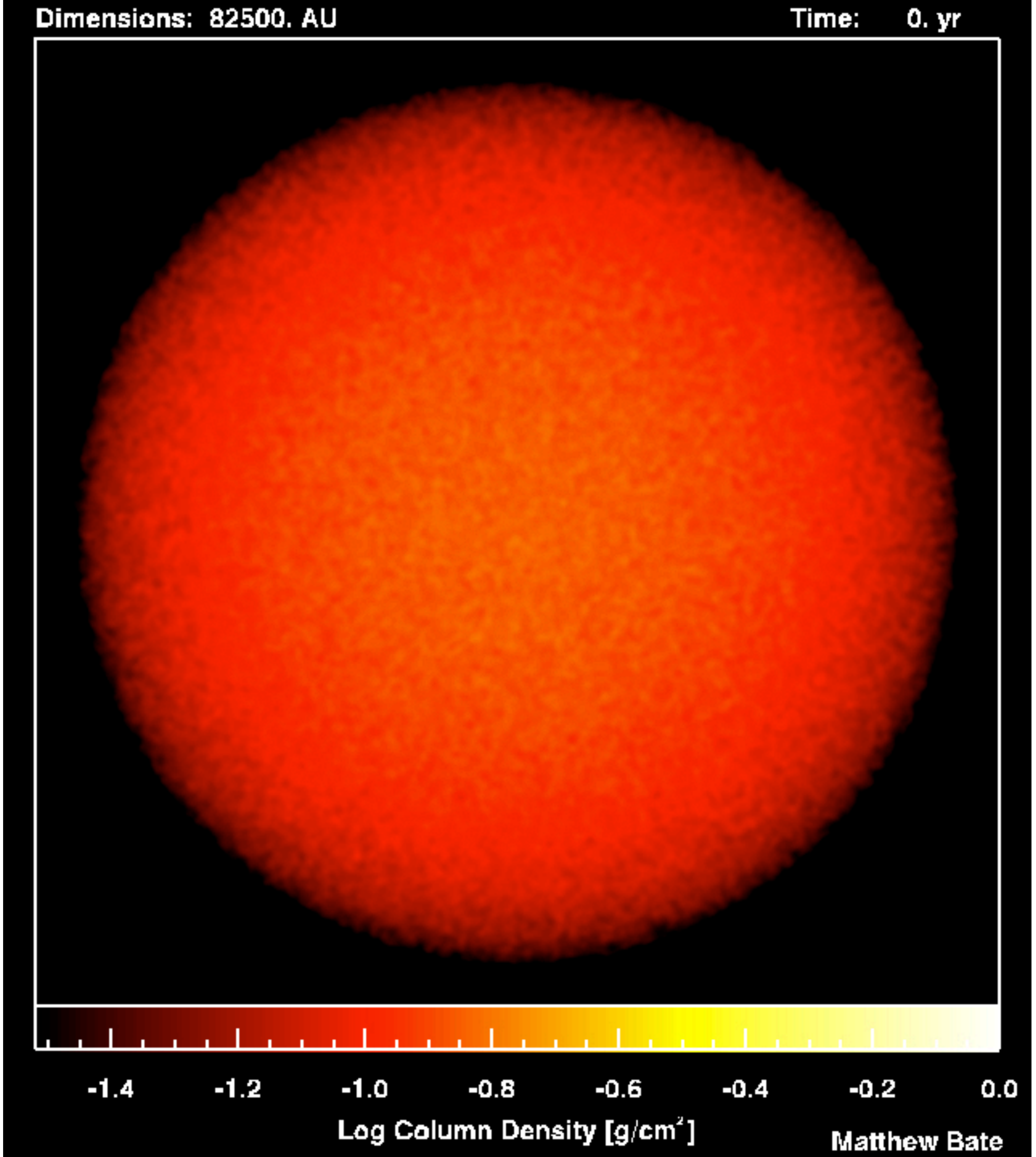
Disc formation without magnetic fields

- Angular momentum conservation during collapse of rotating spherical cloud leads to disc formation

- What about in a more realistic scenario of star formation in a turbulent cloud with no net angular momentum?



- Discs form readily during the fragmentation of turbulent clouds
- Angular momentum originates from the shear associated with locally convergent flows

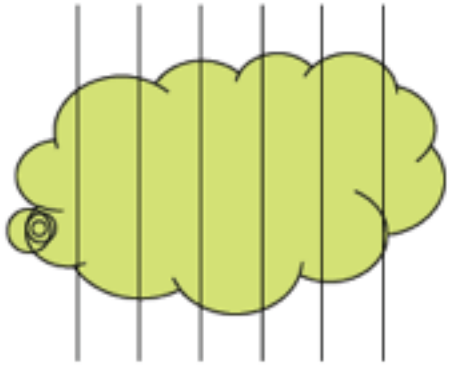


Disc formation with magnetic fields

- Pre-stellar clouds are observed to be magnetised through OH Zeeman measurements (Troland & Crutcher 2008)

- For cloud core to collapse require

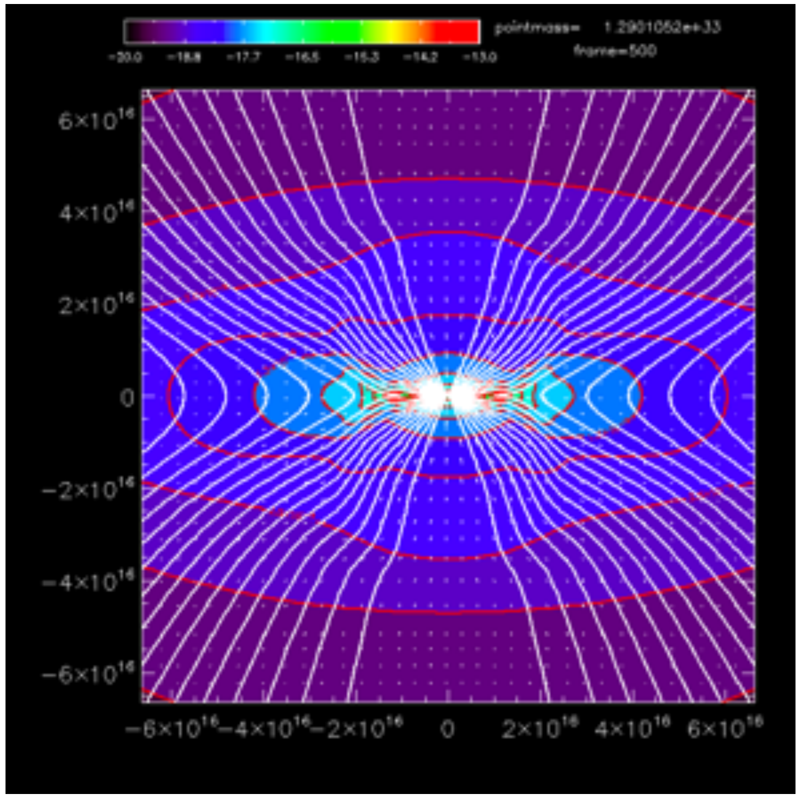
$$\lambda = \frac{\left(\frac{M}{\Phi}\right)}{\left(\frac{1}{2\pi G^{1/2}}\right)} = \frac{\left(\frac{\Sigma}{B}\right)}{\left(\frac{1}{2\pi G^{1/2}}\right)} > 1$$



(for ideal MHD!)

- For $1 < \bar{\lambda} < 10$ collapse with magnetic field aligned with rotation axis ⟶ magnetic-braking catastrophe (Allen et al 2003) Non-ideal effects not the solution (e.g Krasnopolsky et al 2012).

- Misaligning field and rotation axis helps: disc formation for $\bar{\lambda} \sim 4$ (Ciardi & Hennebelle 2010)



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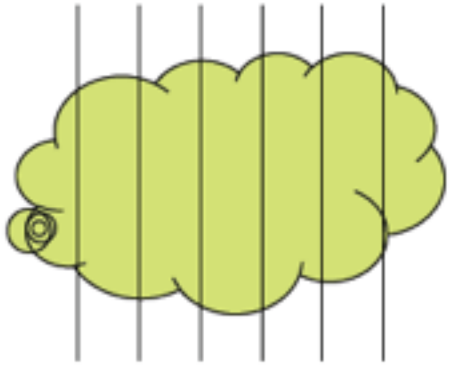

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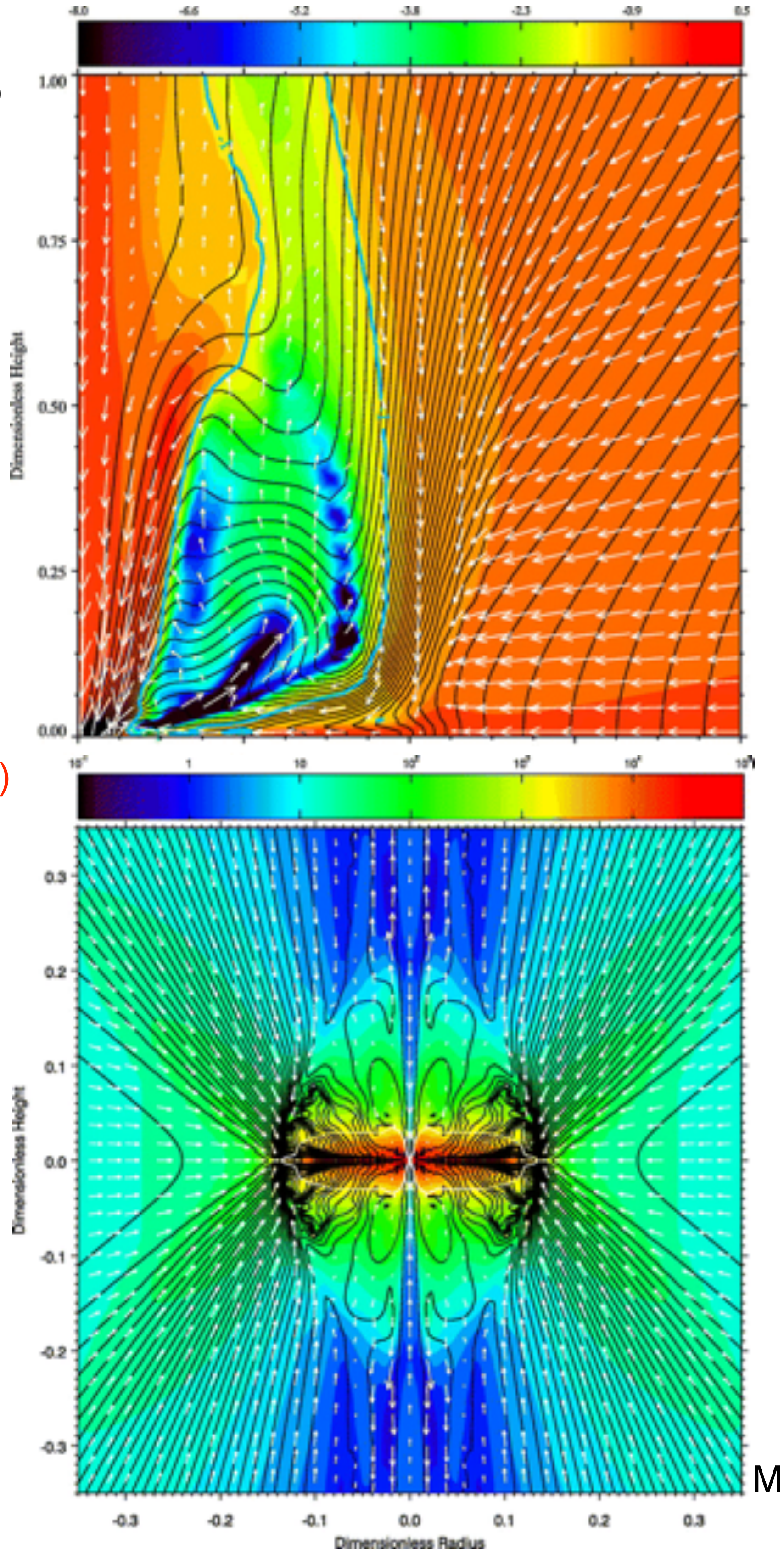

Mellon & Li (2008)

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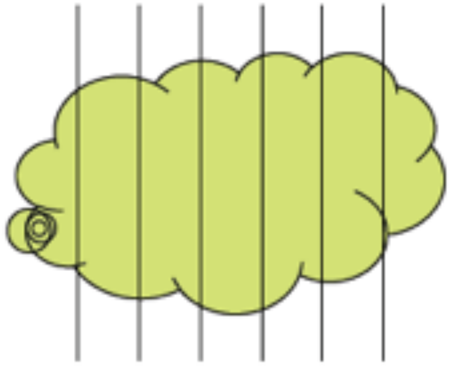

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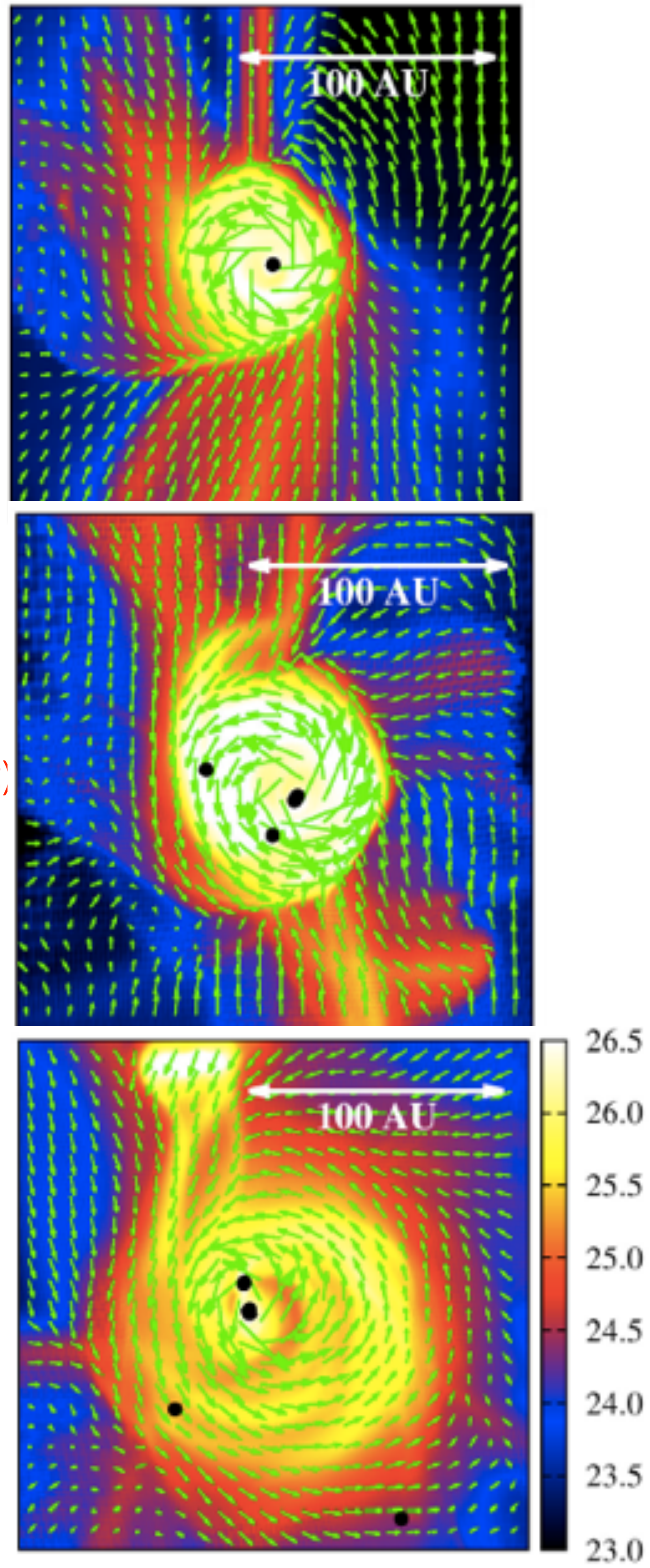
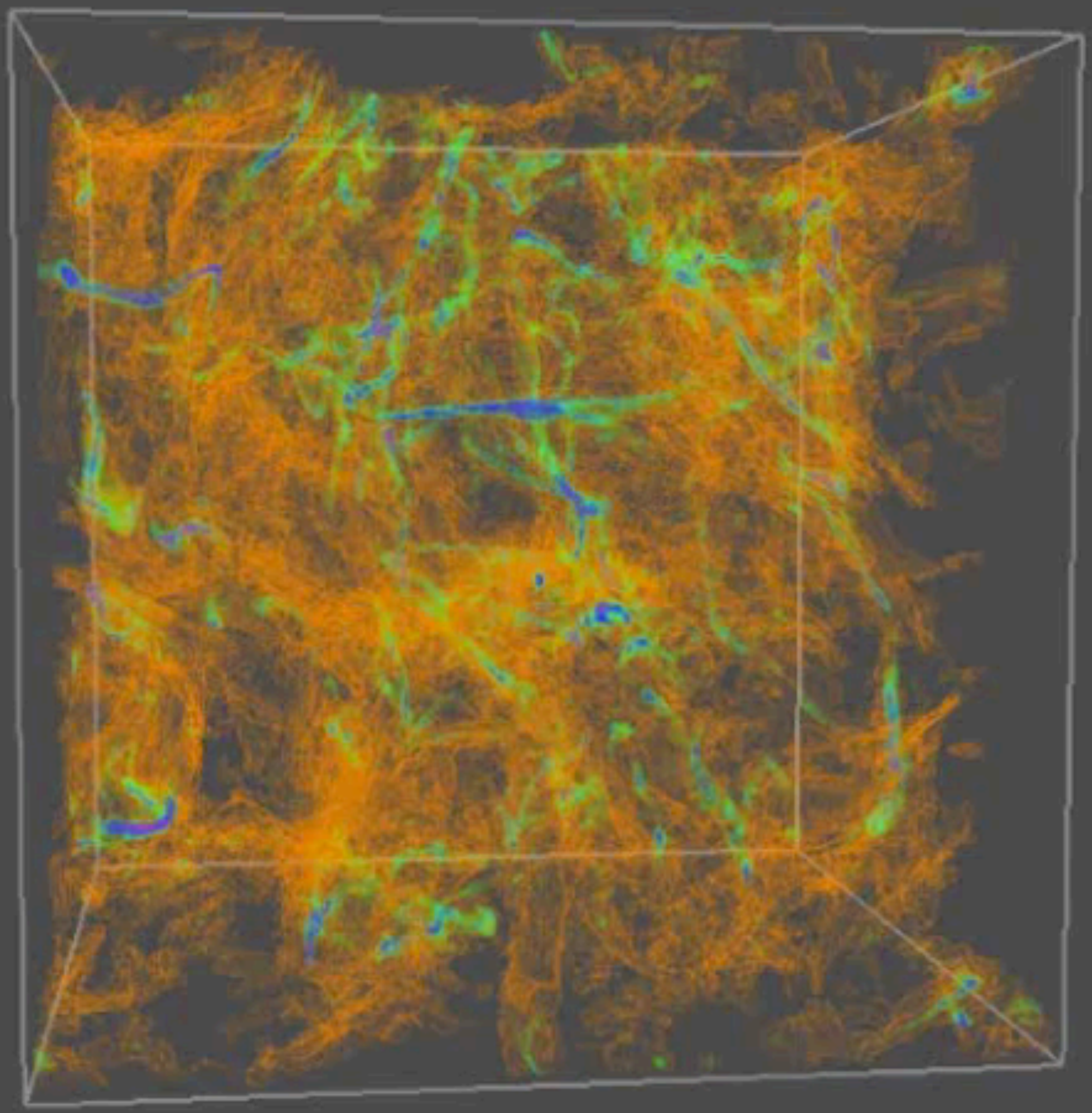
- Discs form efficiently in a turbulent magnetised cloud (Seifried et al 2012, 2014; Joos et al 2013; Nordlund et al 2014)

- Why?
  - Turbulent diffusion of field
  - Turbulent envelope surrounds disc and is not easily torqued by magnetic field
  - Local misalignment of field and rotation axis



Seifried et al (2012)



Nordlund et al (2014)

Angular momentum transport

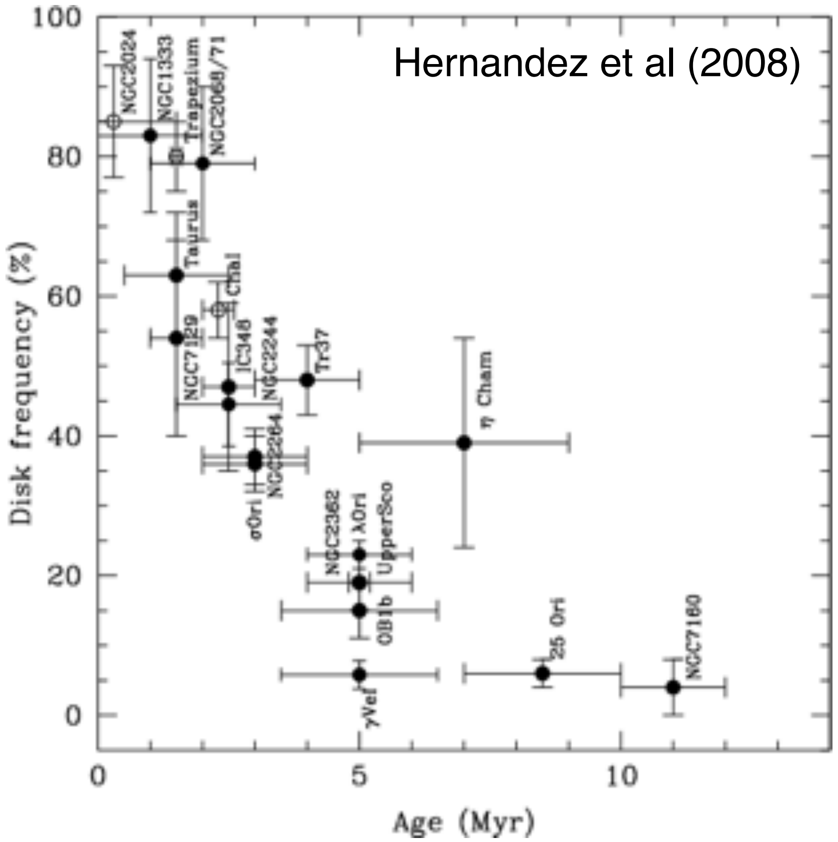
Requirement for angular momentum transport

- Circumstellar discs observed to have finite life times ~ 3 - 10 Myr (e.g. Haisch et al 2001)

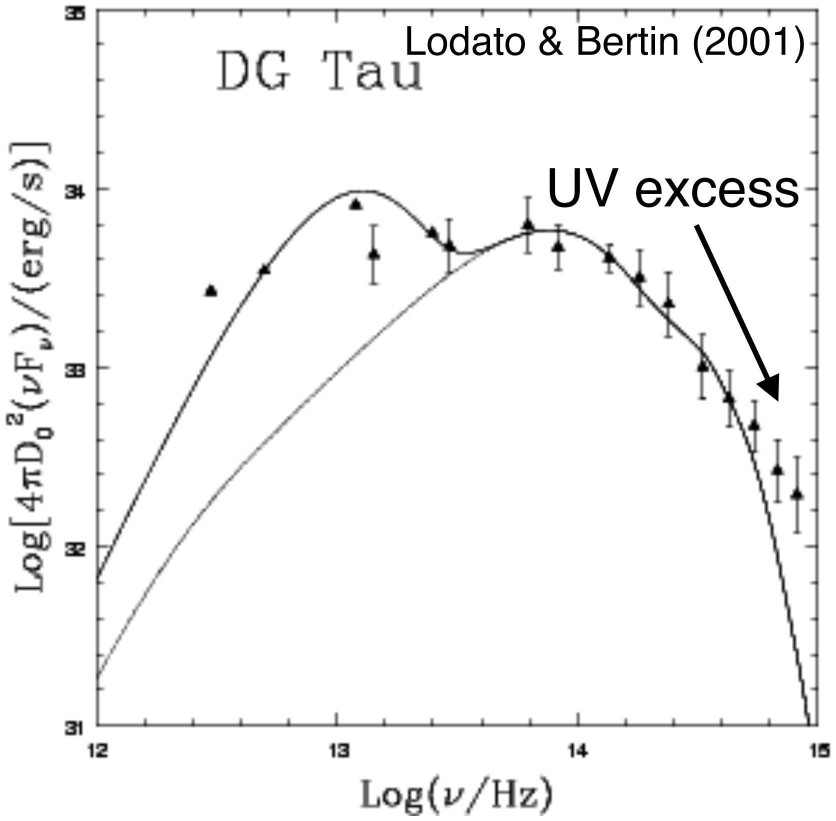
- UV excess indicates that T Tauri stars accrete at rates 10^{-9} - 10^{-7} M_{Sun} / year (Hartmann et al 1998)

- Gas must lose angular momentum to accrete onto star: $j=(GMR)^{1/2}$

- Molecular viscosity too small to explain observed accretion rates and disc life times



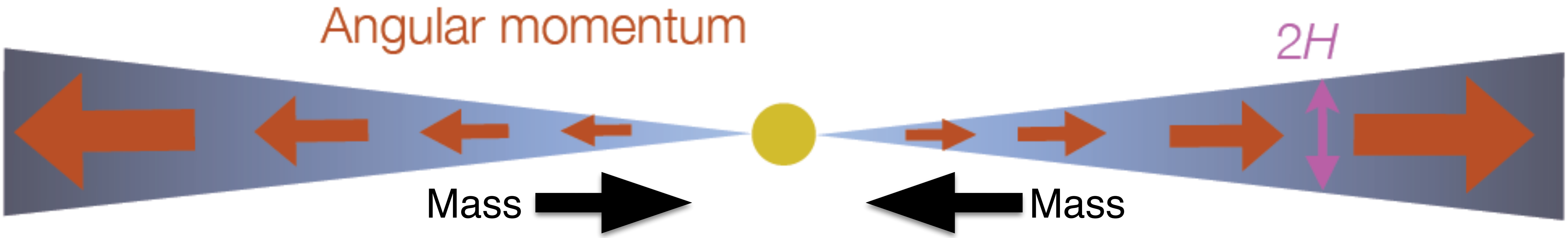
Hernandez et al (2008)



Lodato & Bertin (2001)

UV excess

Internal transport of angular momentum

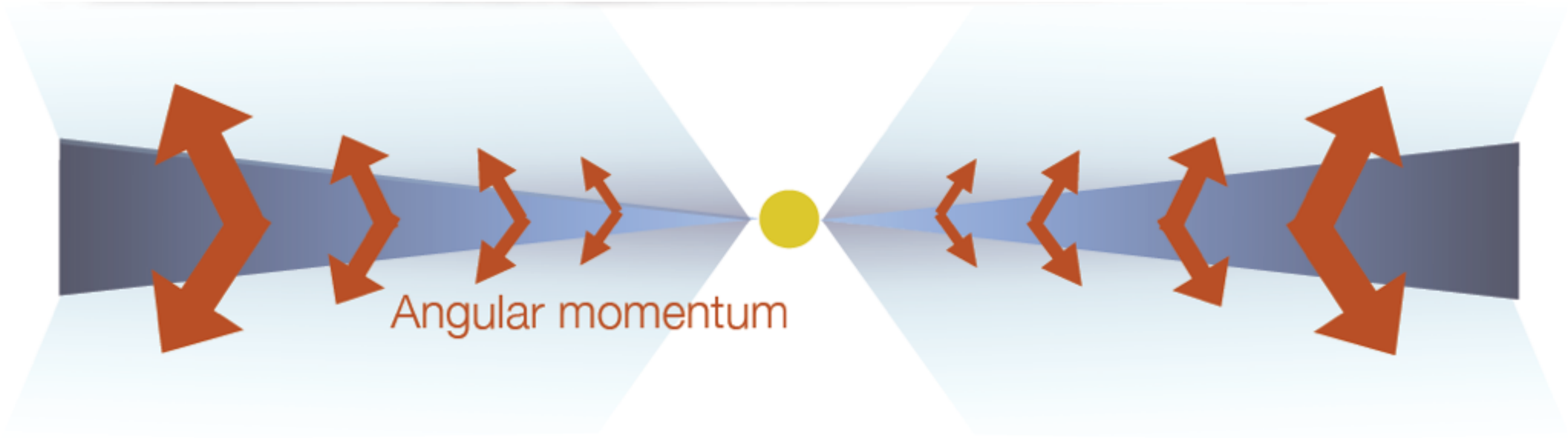


- Turbulence in disc gives rise to angular momentum transport (Shakura-Sunyaev 1973)
- Viscous stress ~ αP (P=gas pressure)
- Turbulent kinematic viscosity $\nu_t = \underset{\text{Dimensionless coefficient}}{\alpha}\,\underset{\text{Sound speed}}{c_s}\,\underset{\text{Disc semi-thickness}}{H}$

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

Image courtesy of G. Lesur

Angular momentum extraction via a wind



- Angular momentum extracted from disc by a magnetised wind
  (Blandford & Payne 1982)

- Angular momentum is removed from the disc - not redistributed
  → this process cannot be modelled using α-prescription

Image courtesy of G. Lesur

Self-gravity

- Criterion for local stability against gravitational instability Q = $\frac{c_s \Omega}{\pi G \Sigma} > 1,$

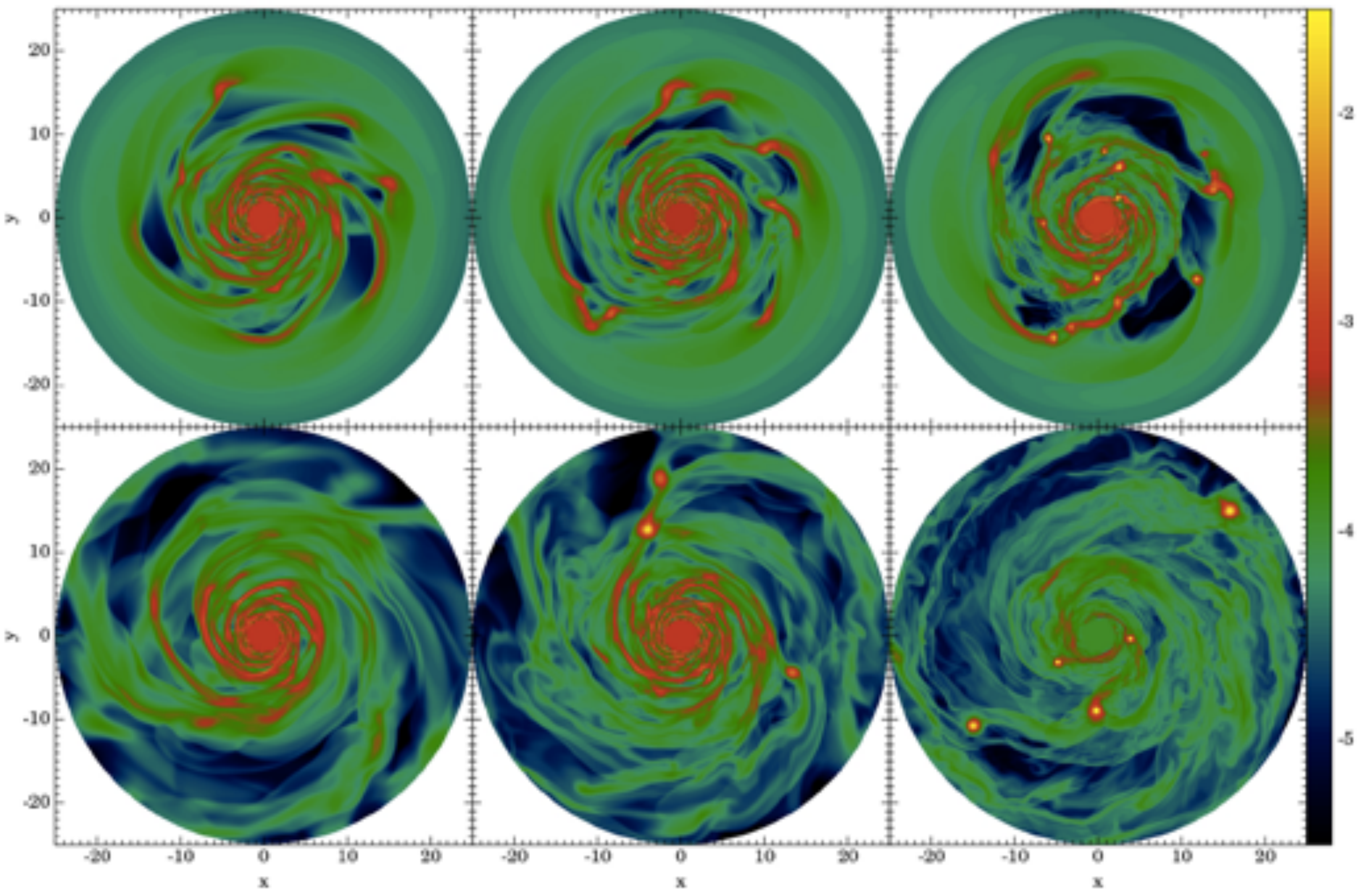
Toomre (1964)

- Equivalent to $m_{\text{disc}}/M_{\text{star}} \sim H/R$
- Spiral shocks heat gas
- Gas cools at a rate $\tau_{\text{cool}} = \frac{\Sigma c_s^2 / \gamma(\gamma - 1)}{2\sigma_{\text{SB}} T_{\text{eff}}^4}$
- Nonlinear evolution depends on local cooling rate (Gammie 2006)

1) $\tau_{\text{cool}} \Omega \lesssim 3 - 5$

Disc fragments into bound clumps

Paardekooper et al (2011)



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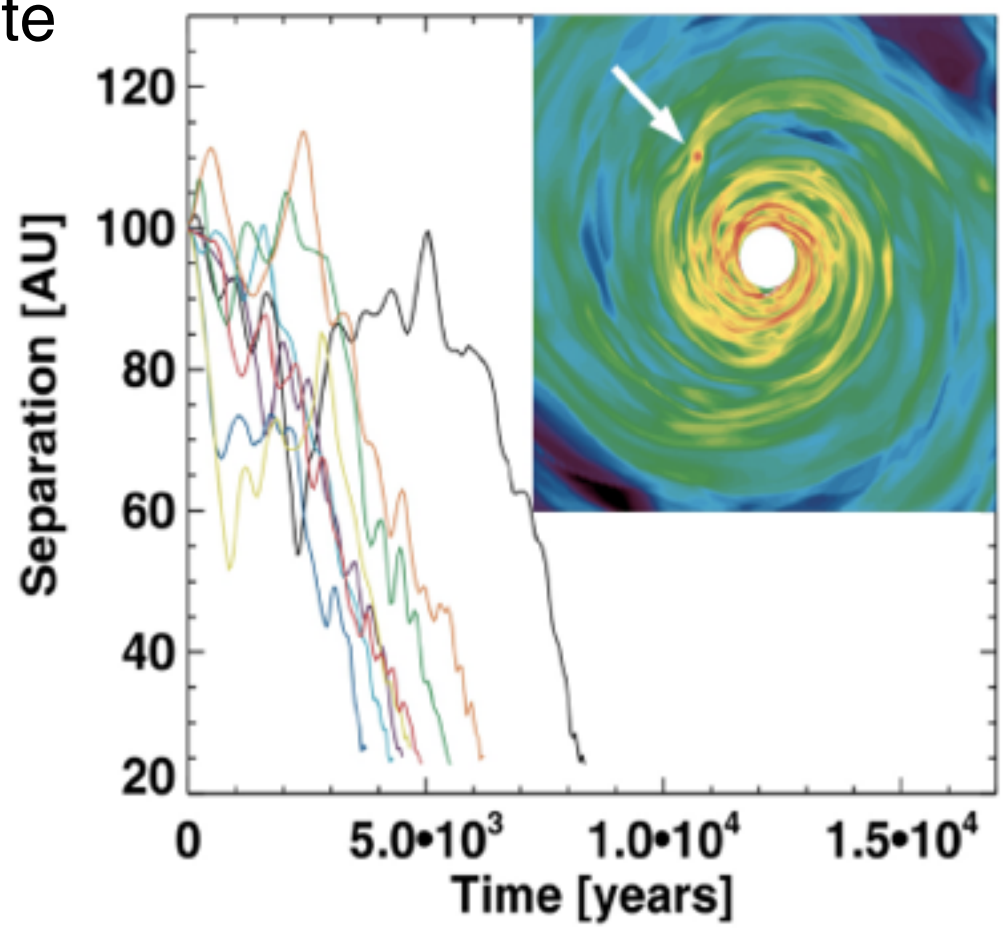
Disc fragments into bound clumps

Clumps migrate inward rapidly

Baruteau et al (2011)



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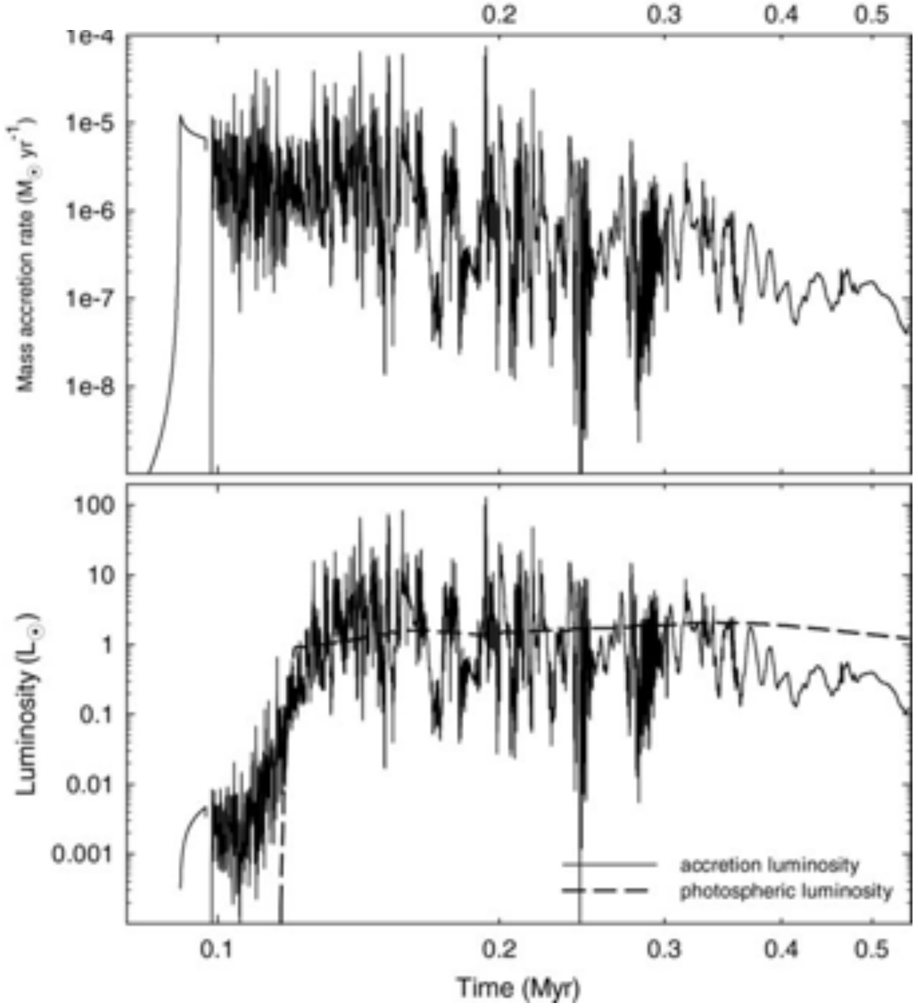
Delivery of gas to central disc regions in bursts may explain FU Orionis and EX Lupi outburst phenomena

Vorobyov & Basu (2012)



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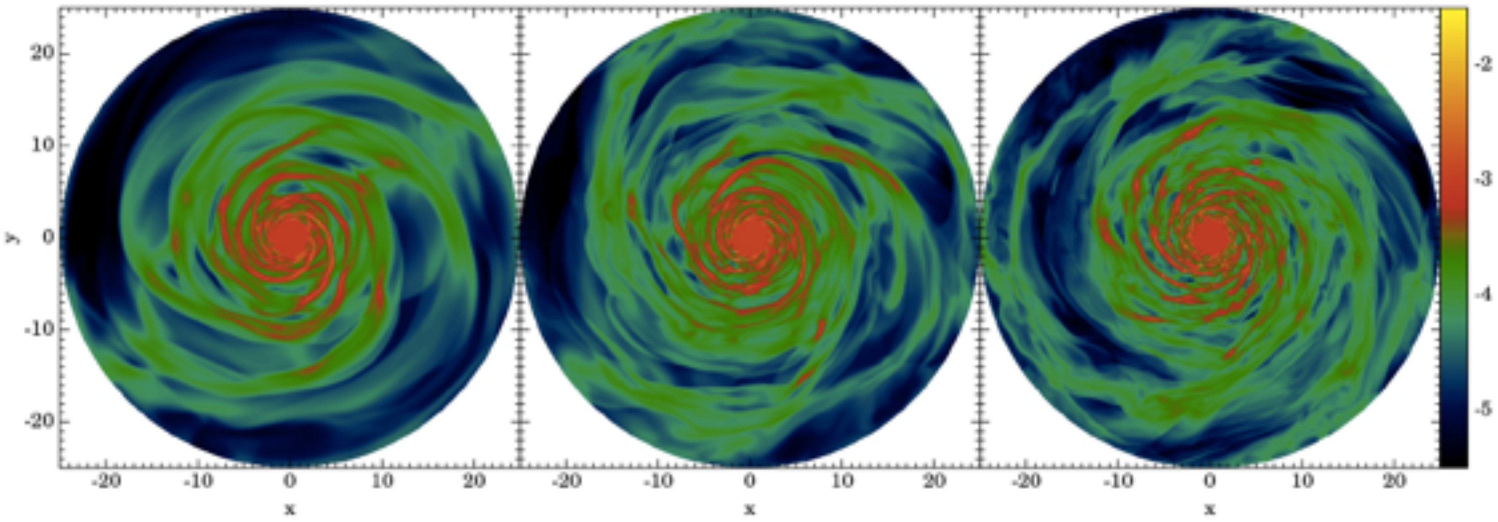

Disc maintains a state of gravito-turbulence where spiral shock heating is balanced by radiative cooling

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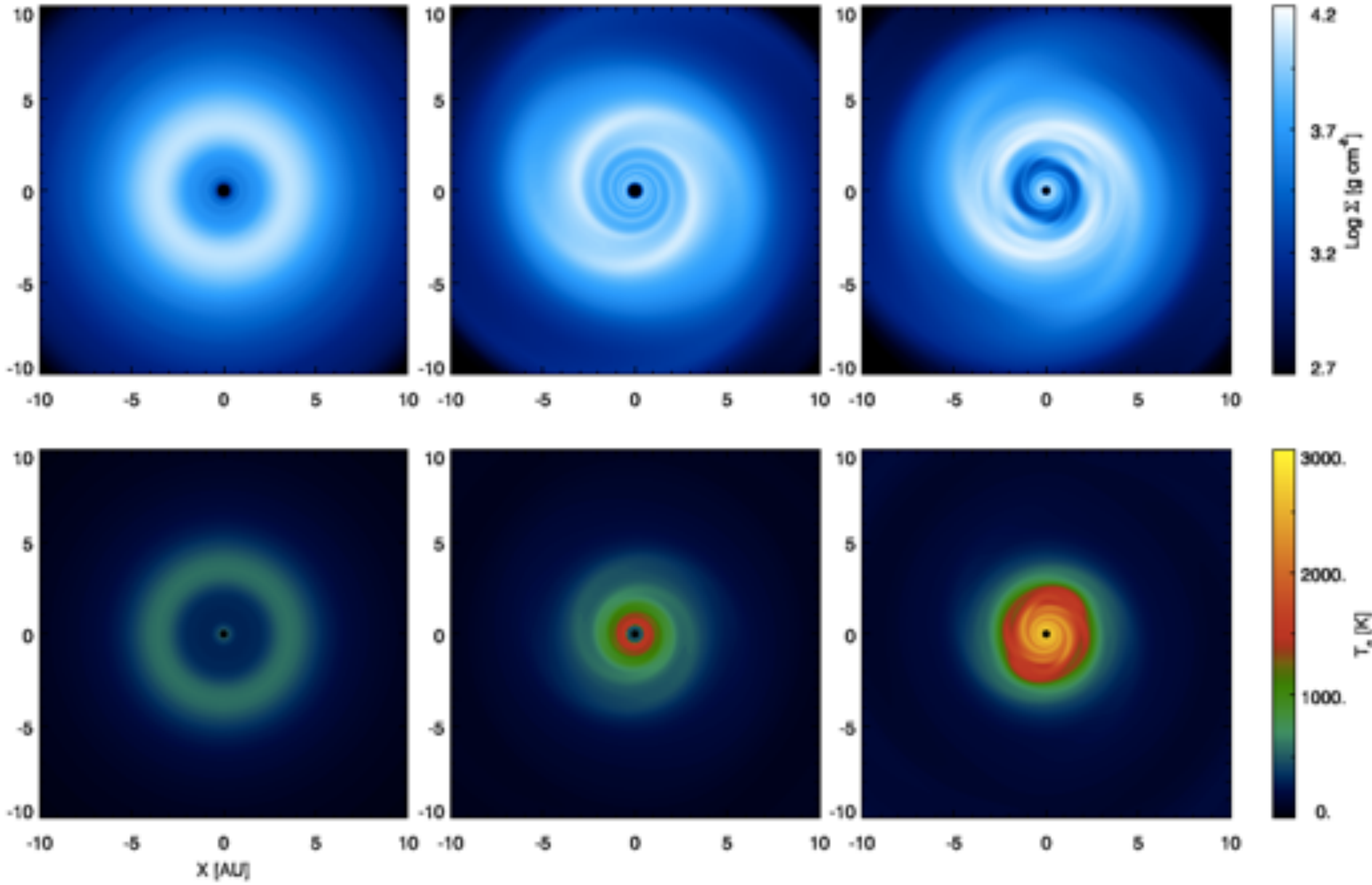
Disc maintains a state of gravito-turbulence where spirals shock heating is balanced by radiative cooling

FU Orionis outbursts may still occur → temperature rise in inner disc via accretion and spiral shocks → MRI



Bae et al (2014)

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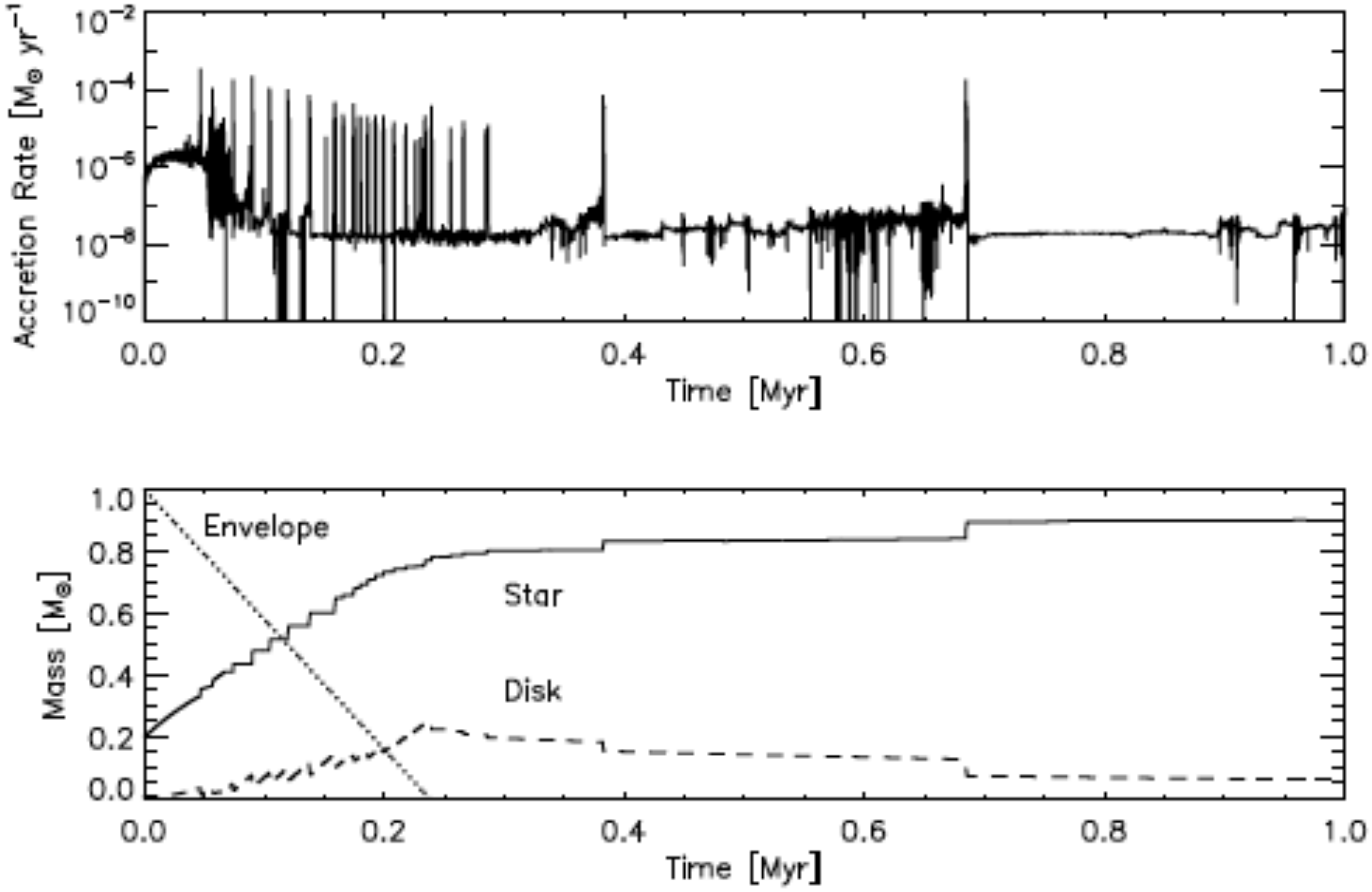
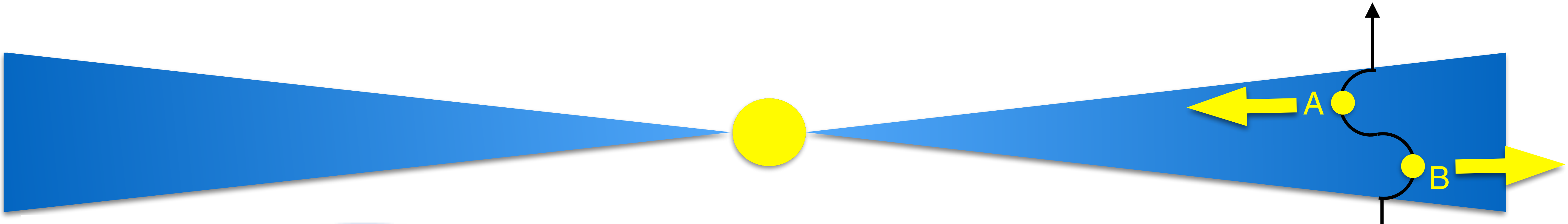
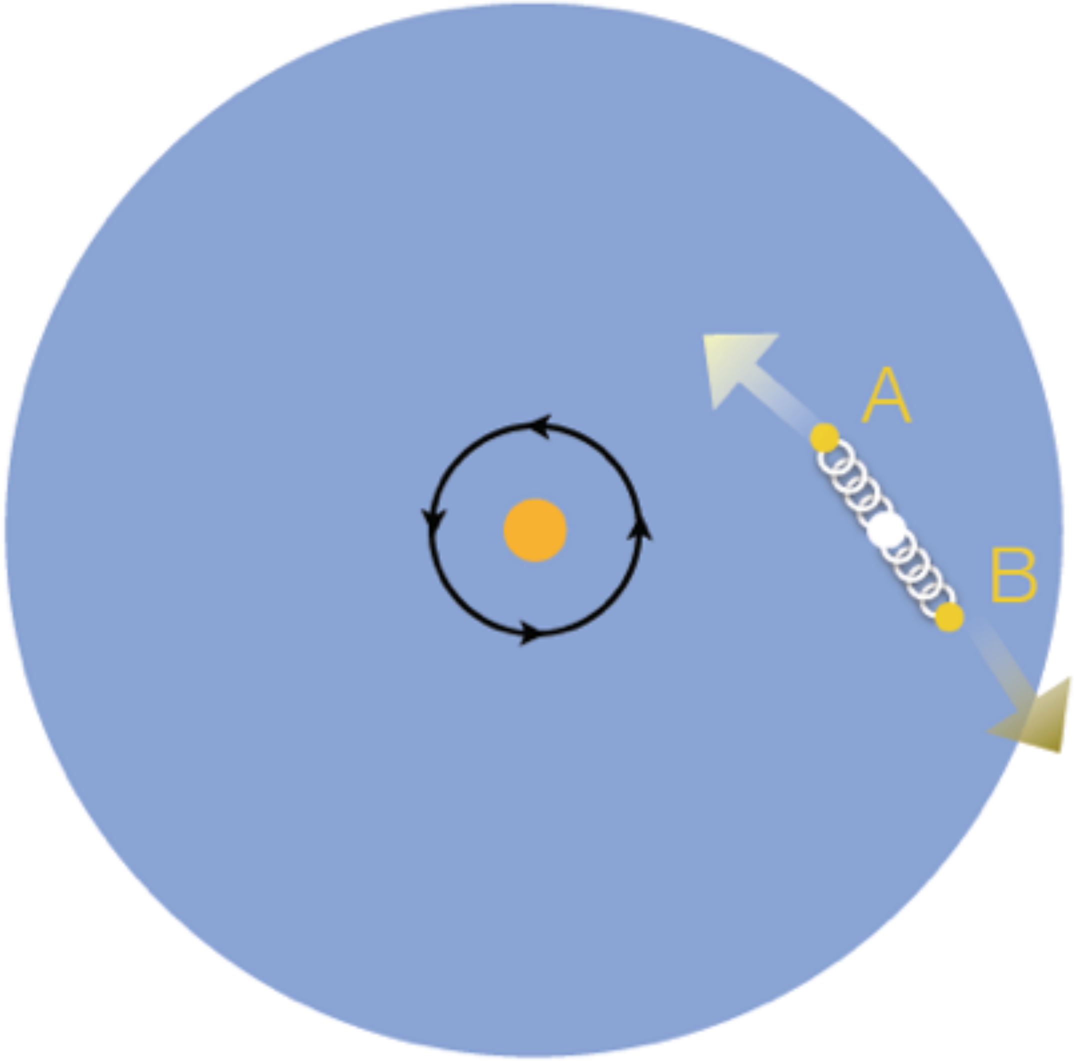


Magnetic fields

The Magnetorotational Instability (MRI)



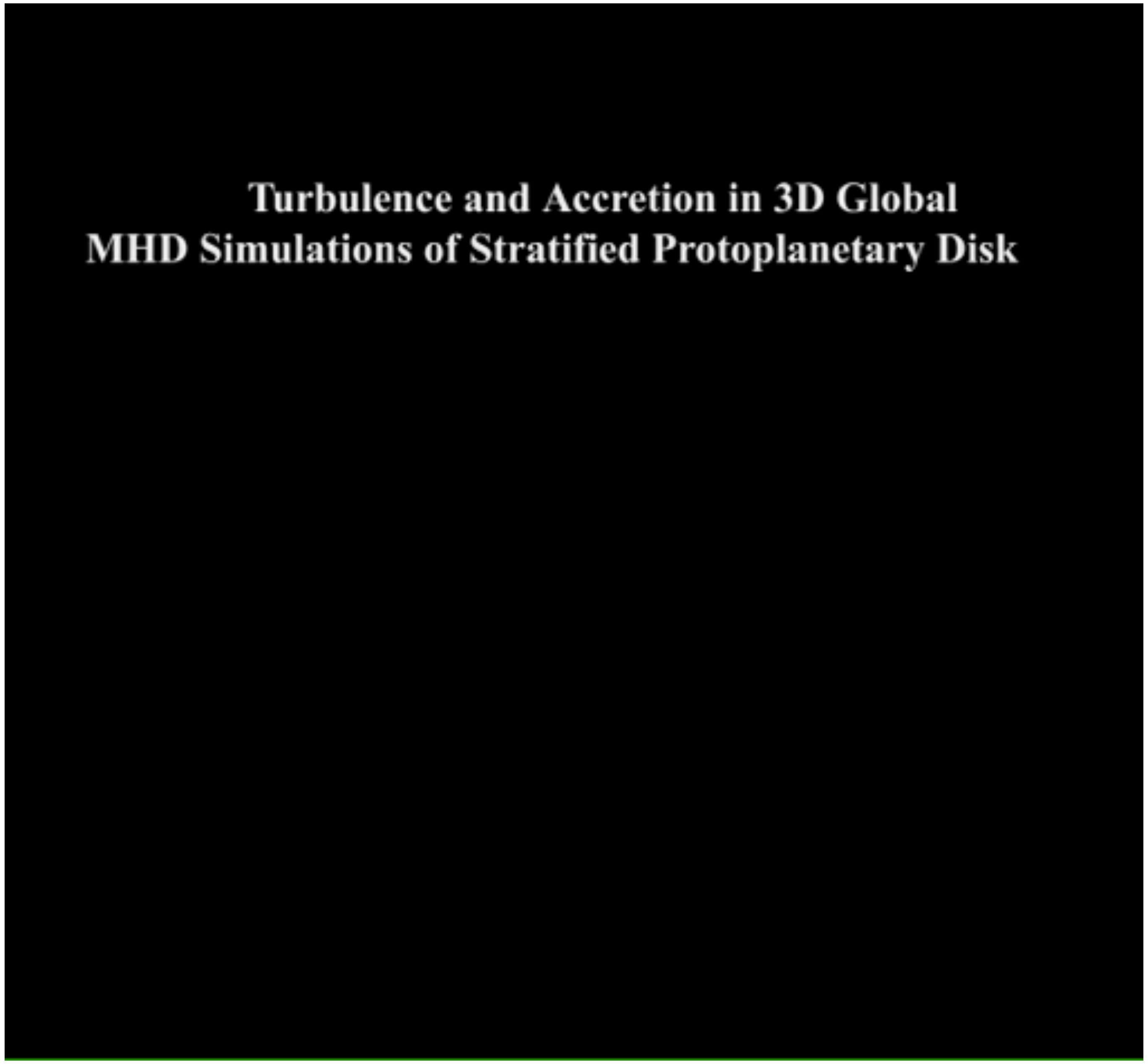


- Ideal MHD instability (Balbus & Hawley 1991)
- Growth time < orbital time scale
- Modified or even quenched by non-ideal MHD effects

Images courtesy of G. Lesur

Simulations (local and global) produce $\alpha \sim 10^{-3}$ - 10^{-2} for same initial conditions

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



Turbulence and Accretion in 3D Global
MHD Simulations of Stratified Protoplanetary Disk

Flock et al (2011)

Non-ideal MHD effects

The ionisation fraction in protoplanetary discs is very low:
$x(e^-) \sim 10^{-12} - 10^{-13}$ near the midplane

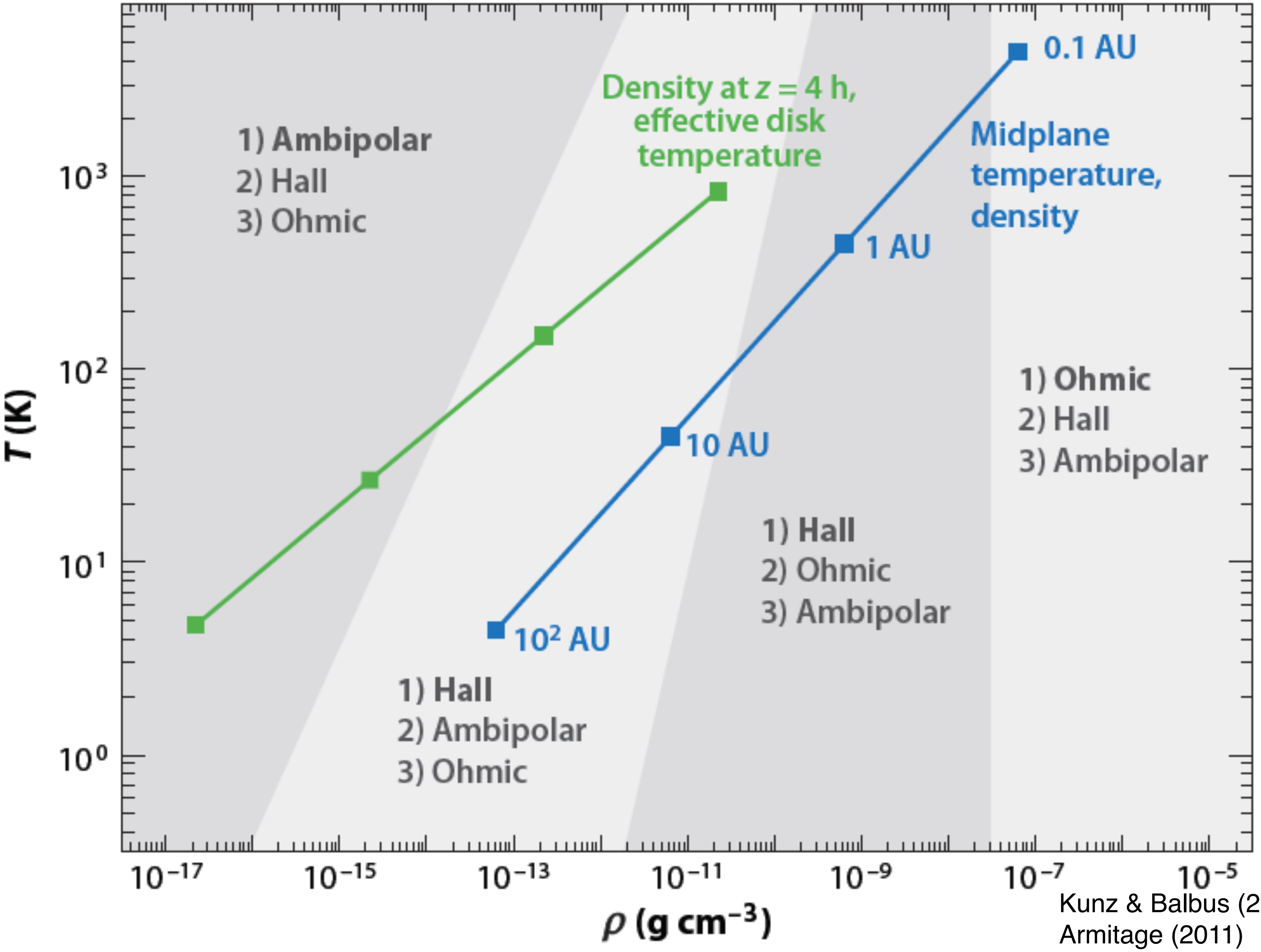
→ PPDs are far from being in the ideal MHD limit

Three non-ideal MHD effects need to be considered

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

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\underbrace{\mathbf{v} \times \mathbf{B}}_{\text{Advection, bending/stretching}} - \underbrace{\eta \nabla \times \mathbf{B}}_{\text{Ohmic}} - \underbrace{\frac{\mathbf{J} \times \mathbf{B}}{e n_e}}_{\text{Hall}} + \underbrace{\frac{(\mathbf{J} \times \mathbf{B}) \times \mathbf{B}}{c \gamma \rho_i \rho}}_{\text{Ambipolar}} \right]$$

Non-ideal MHD effects

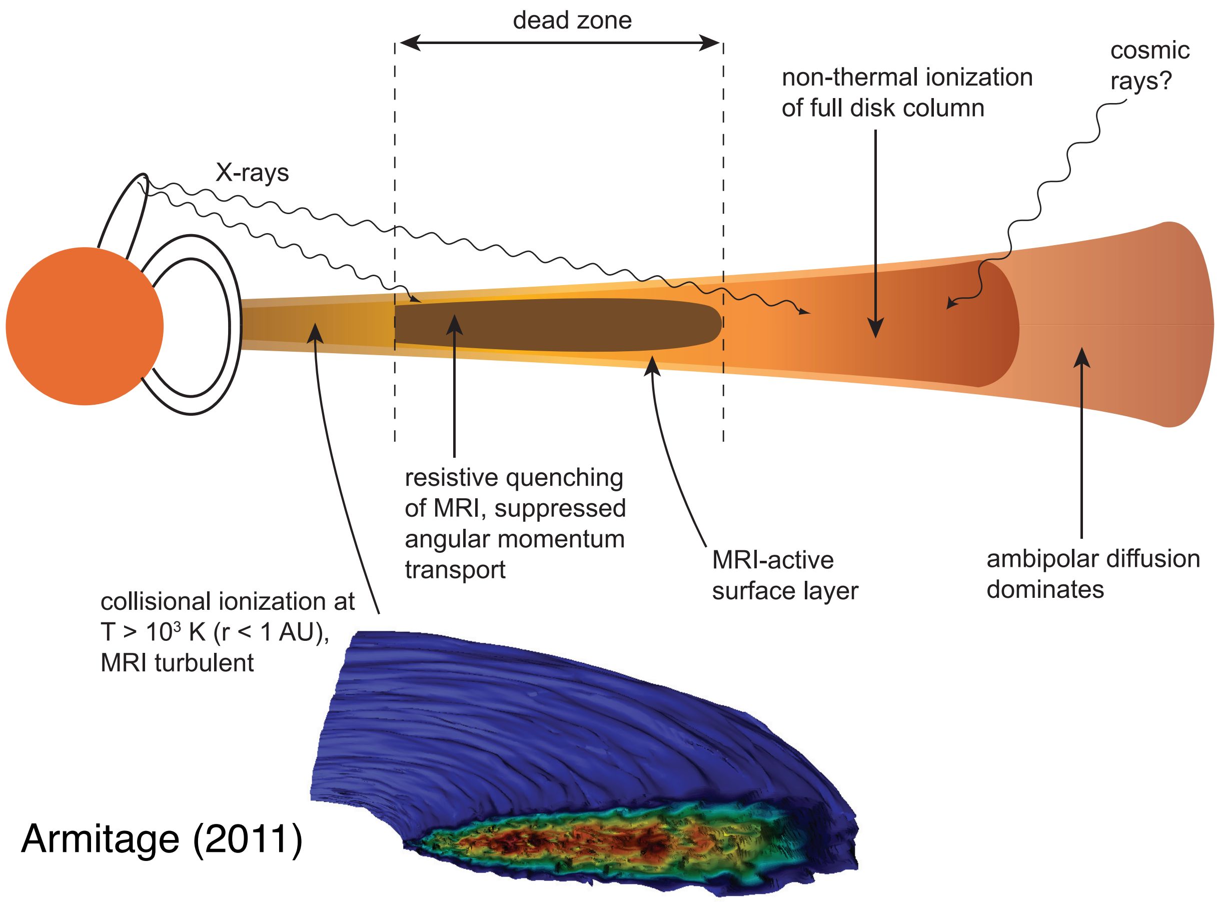


Kunz & Balbus (2004)
Armitage (2011)

Ohmic resistivity

- Disc is thermally ionised inside ~ 0.3 AU (potassium ionised at T > 1000 K)

- Between 0.3 - 20 AU have layered accretion (Gammie 2006)
  - dead zone near midplane - Ohmic diffusion dominates
  - active layer near surface - ionised by stellar X-rays & galactic cosmic rays?



dead zone

non-thermal ionization of full disk column

cosmic rays?

X-rays

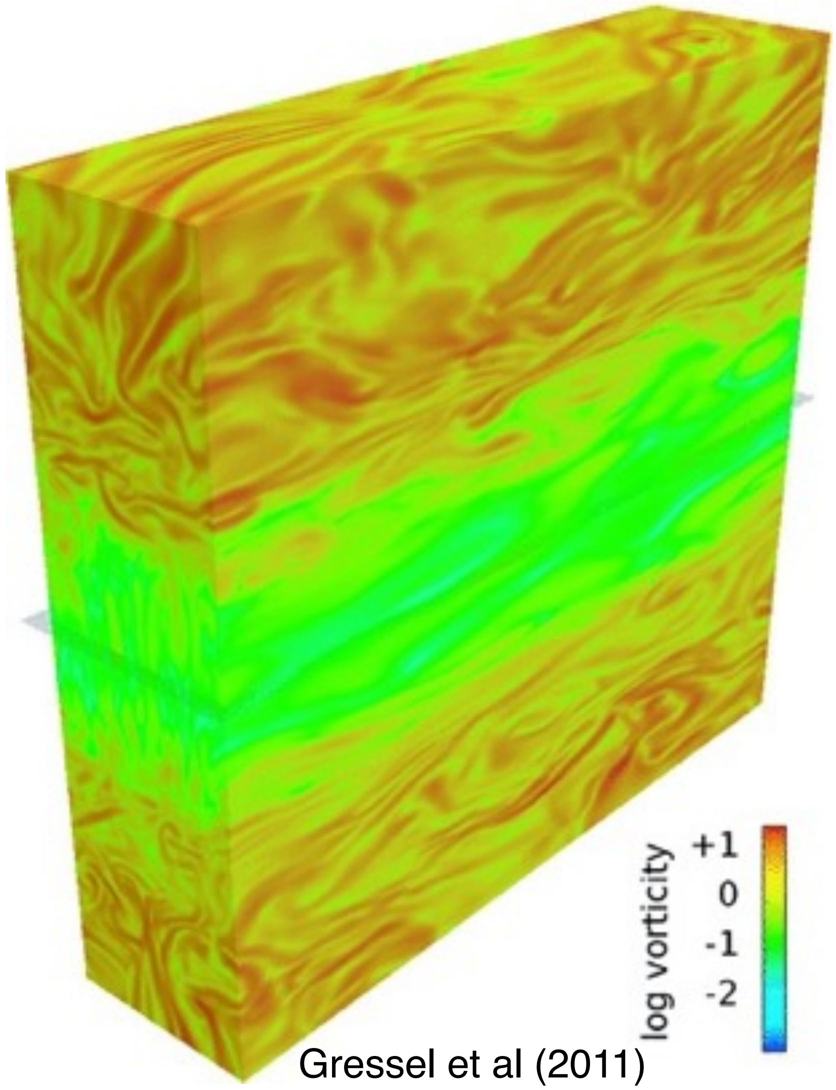
resistive quenching of MRI, suppressed angular momentum transport

MRI-active surface layer

ambipolar diffusion dominates

collisional ionization at $T > 10^3$ K (r < 1 AU), MRI turbulent

Armitage (2011)



Gressel et al (2011)

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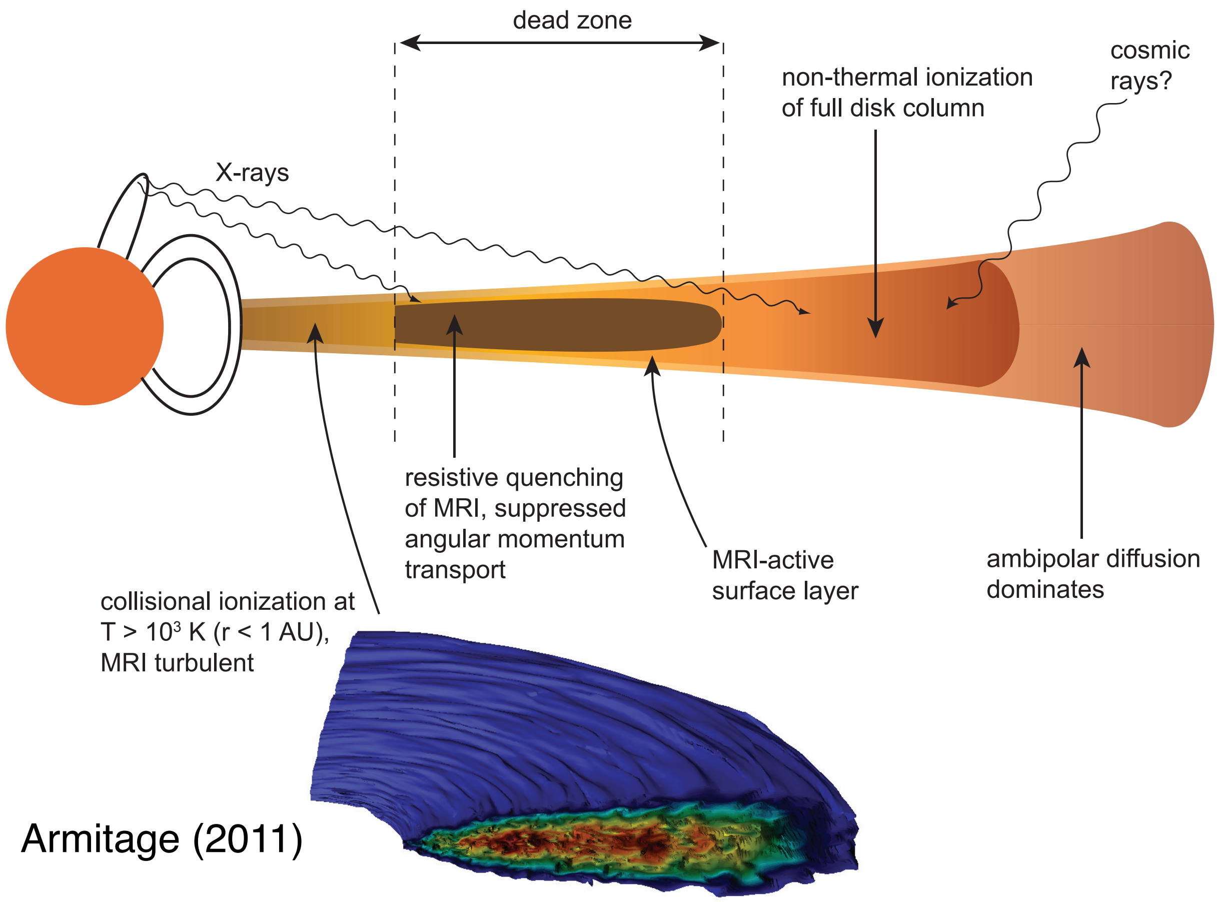

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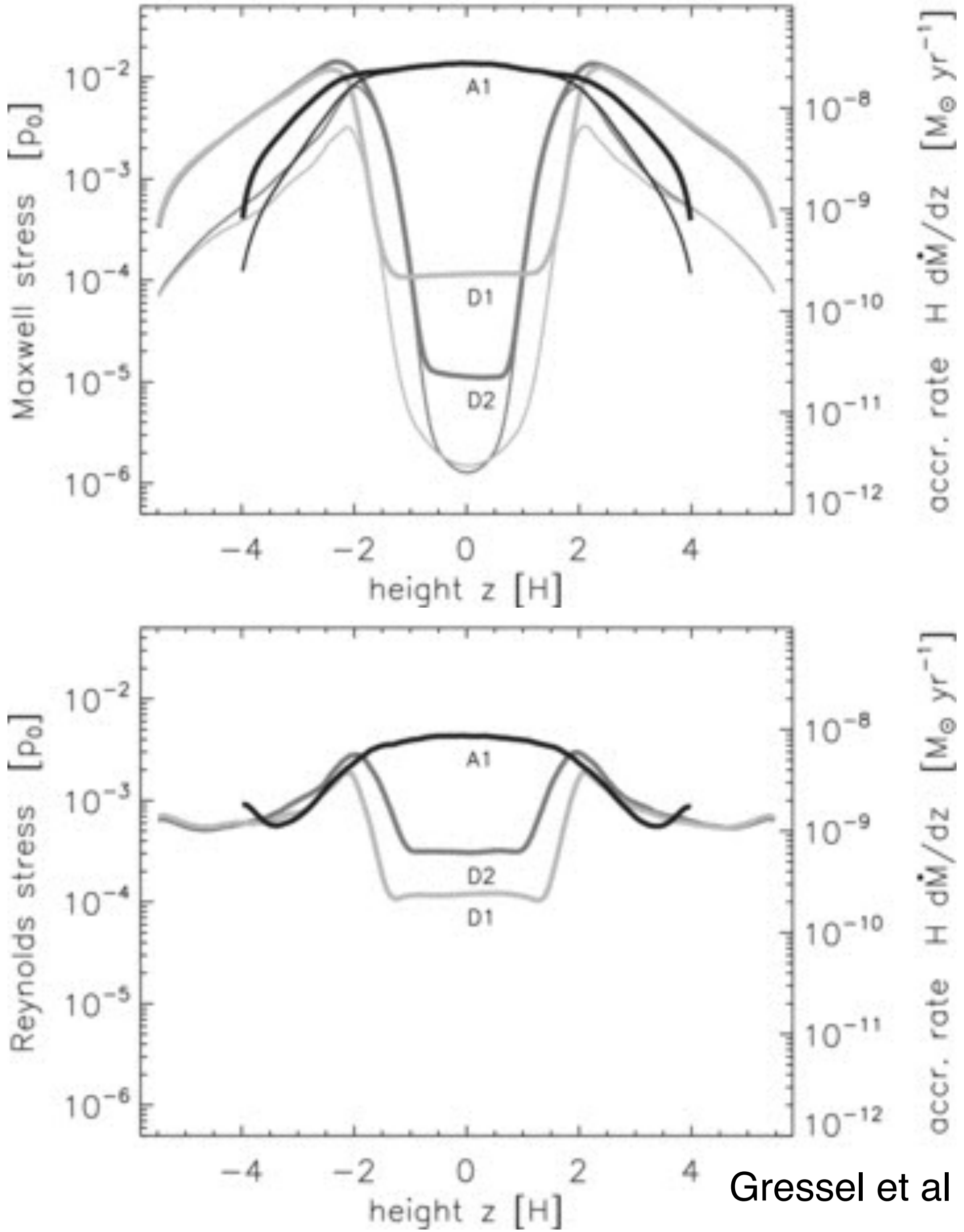
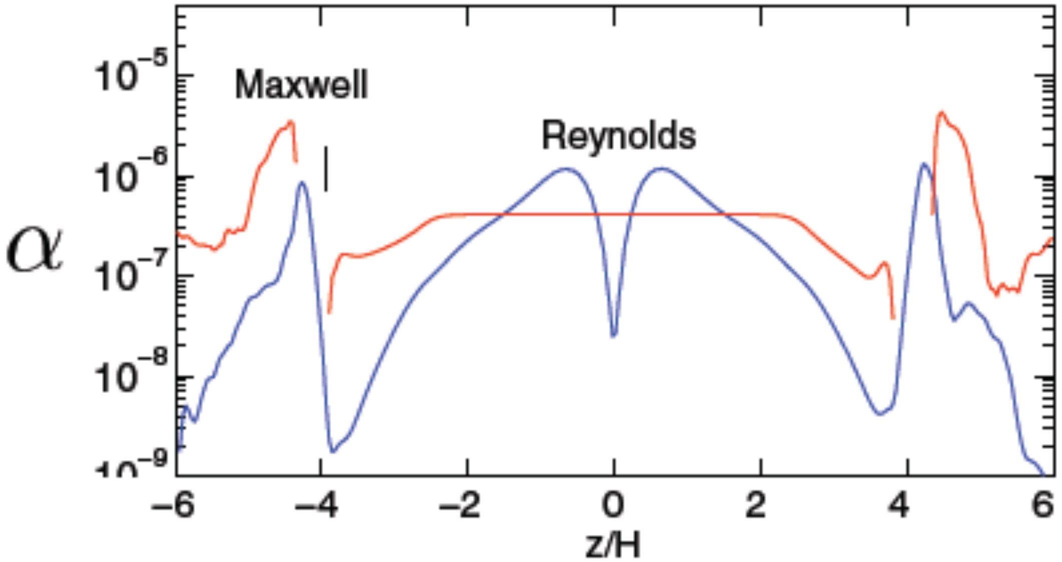


Gressel et al (2011)

Ambipolar diffusion - no net B-field

- Disc surface layers dominated by ambipolar diffusion
- In absence of a mean magnetic field turbulent stresses are very small



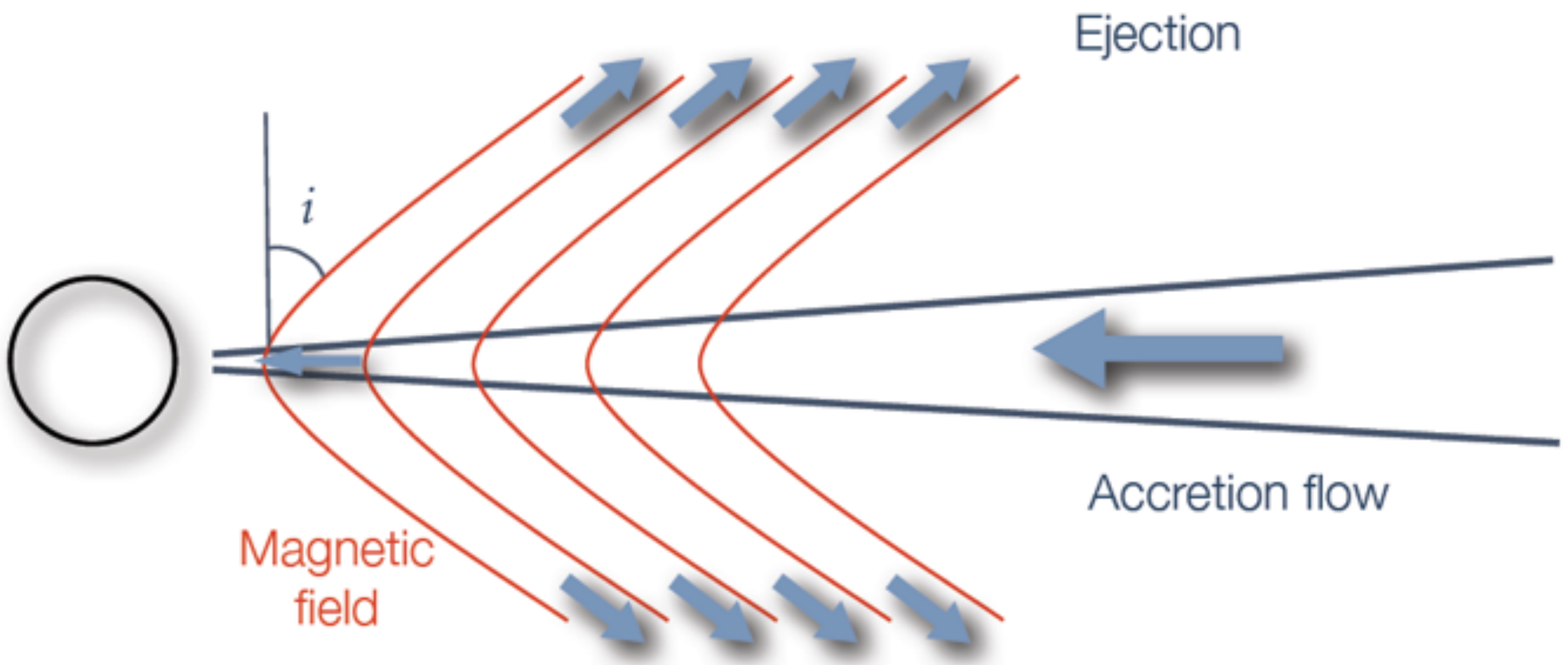
Ohmic+ambipolar diffusion

@1AU

Bai & Stone (2013)

Ambipolar diffusion - with net vertical B-field

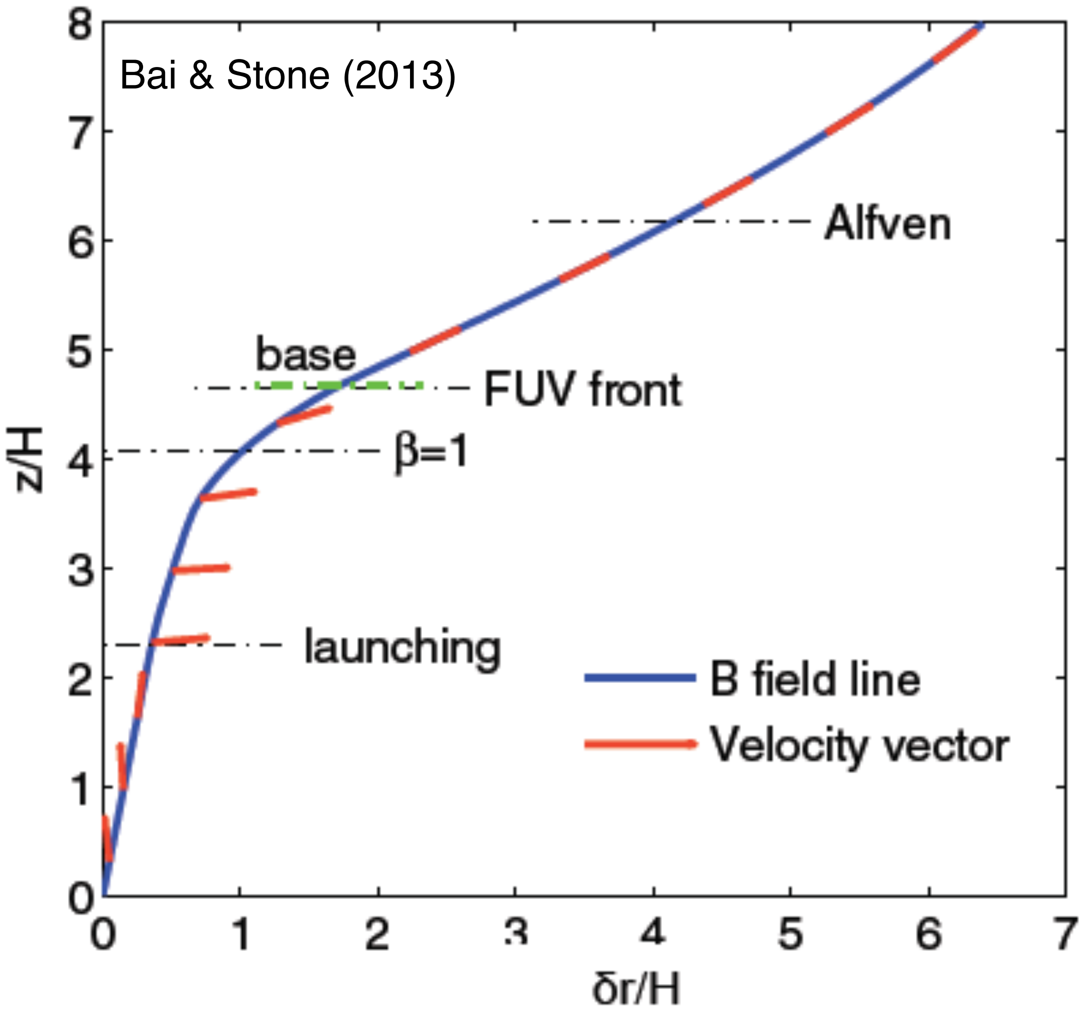
- Disc surface layers dominated by ambipolar diffusion
- In presence of a mean vertical magnetic field a magneto-centrifugally driven wind is launched



- In traditional magnetised wind picture (Blandford & Payne 1982):
  - require strong vertical magnetic field
  - angle of inclination between B-field and rotation axis $i > 30^o$

Ambipolar diffusion - with net vertical B-field

- Disc surface layers dominated by ambipolar diffusion
- In presence of a mean vertical magnetic field a magneto-centrifugally driven wind is launched from the disc surface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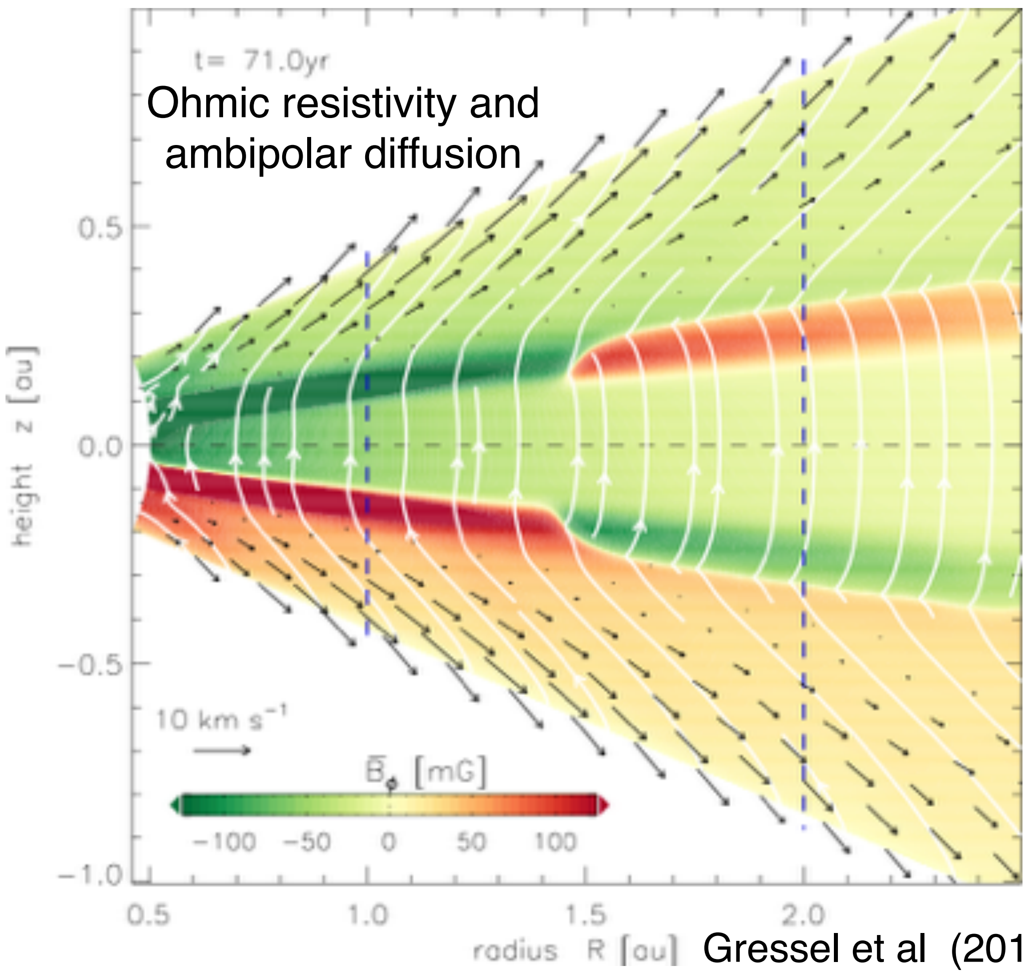
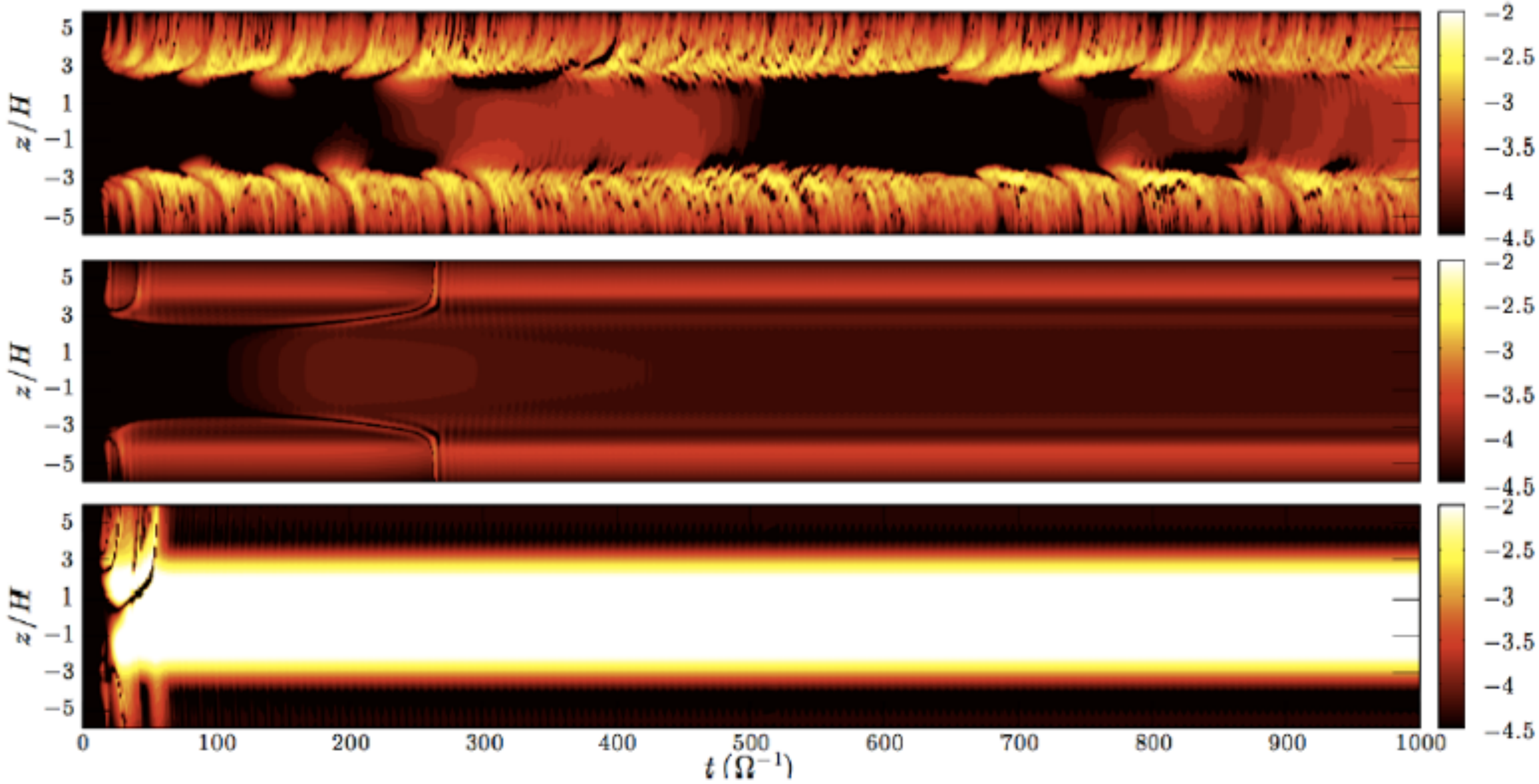

Ohmic resistivity and ambipolar diffusion

Gressel et al (2015)

- Can potentially explain accretion rates ~ 10^{-8} M_{Sun} / year
- Note that details (such as mass loss rates in wind) depend on simulation details such as the height of the computational domain

The Hall Effect

- Hall effect might be able to revive dead zones if **Ω . B** > 0 (Salmeron & Wardle 2012)



- Inclusion of Hall effect in disc where *x(e$^-$)* determined with grain free chemistry leads to dramatic increase in magnetic stress in mid plane regions (Lesur et al 2014)

- Horizontal field is amplified and stress arises from field winding in a laminar disc - disc is not turbulent!

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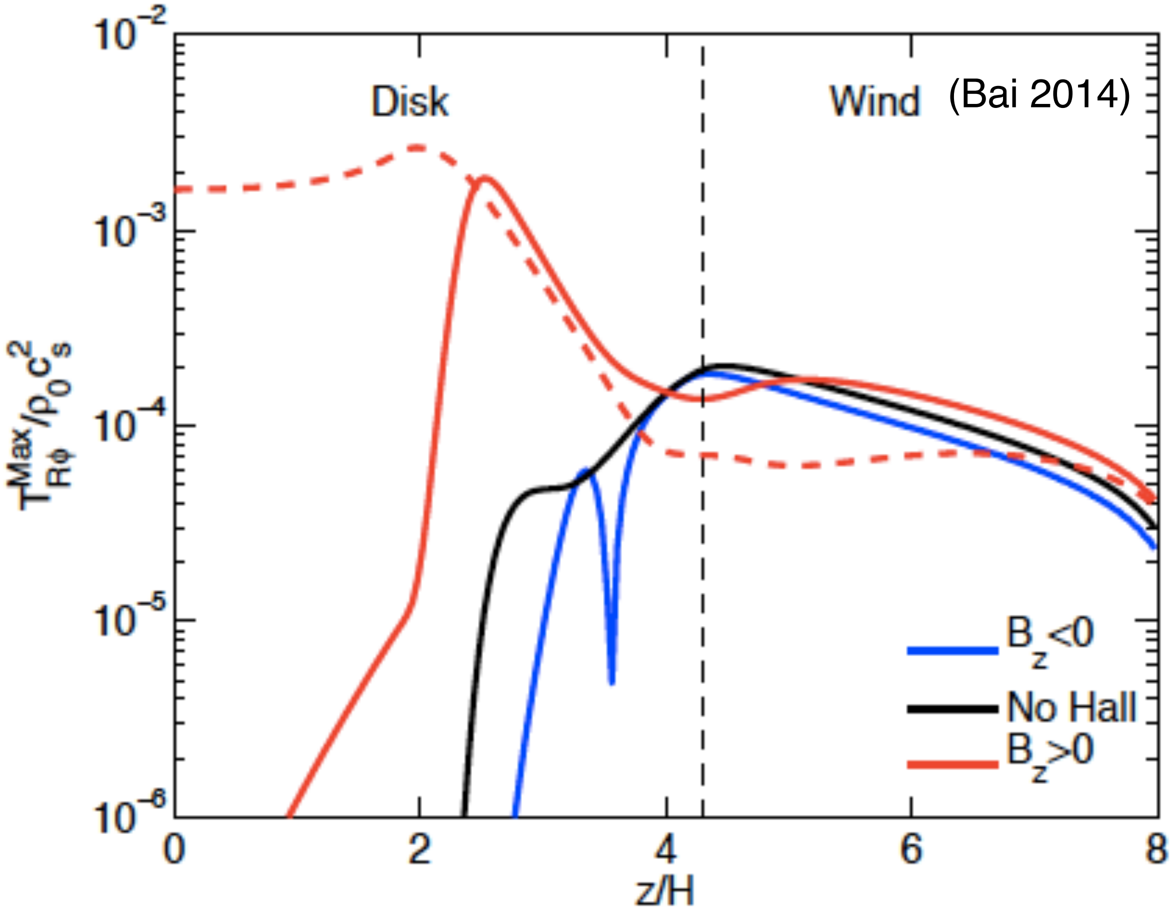
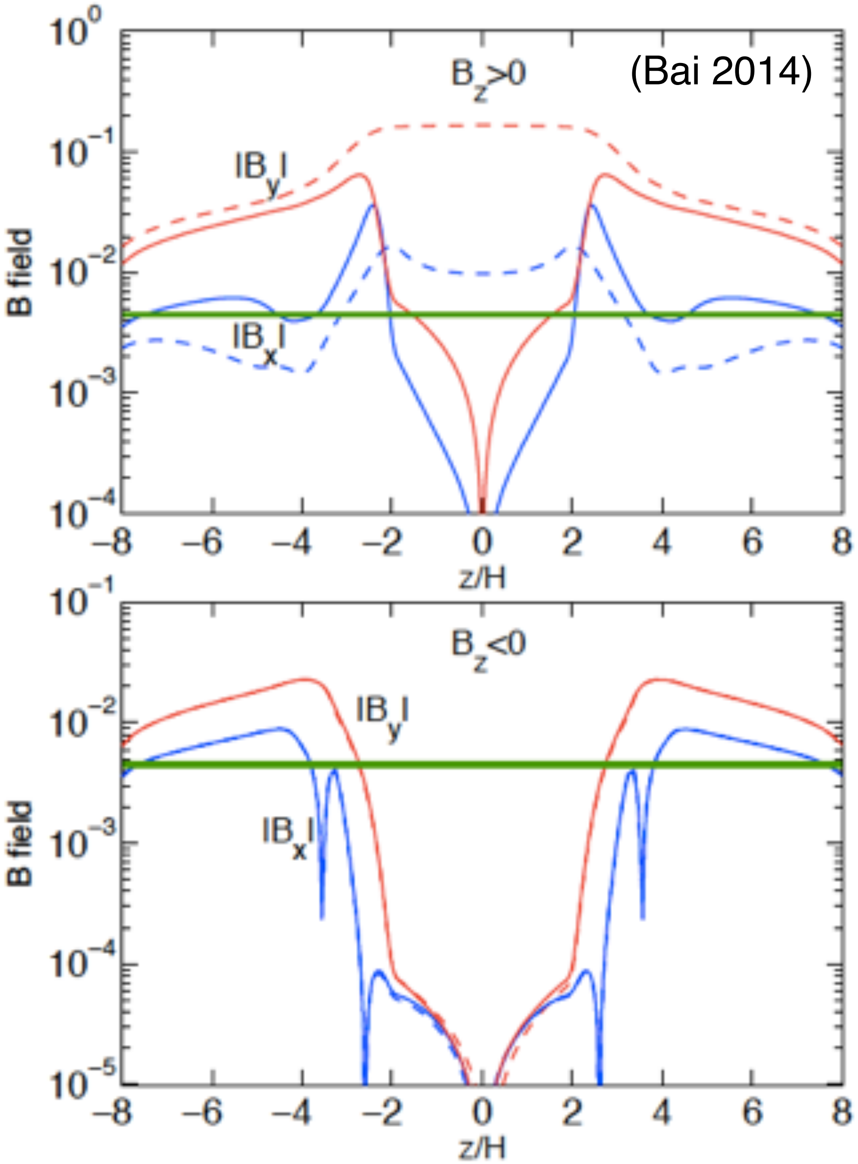


(Bai 2014)



(Bai 2014)

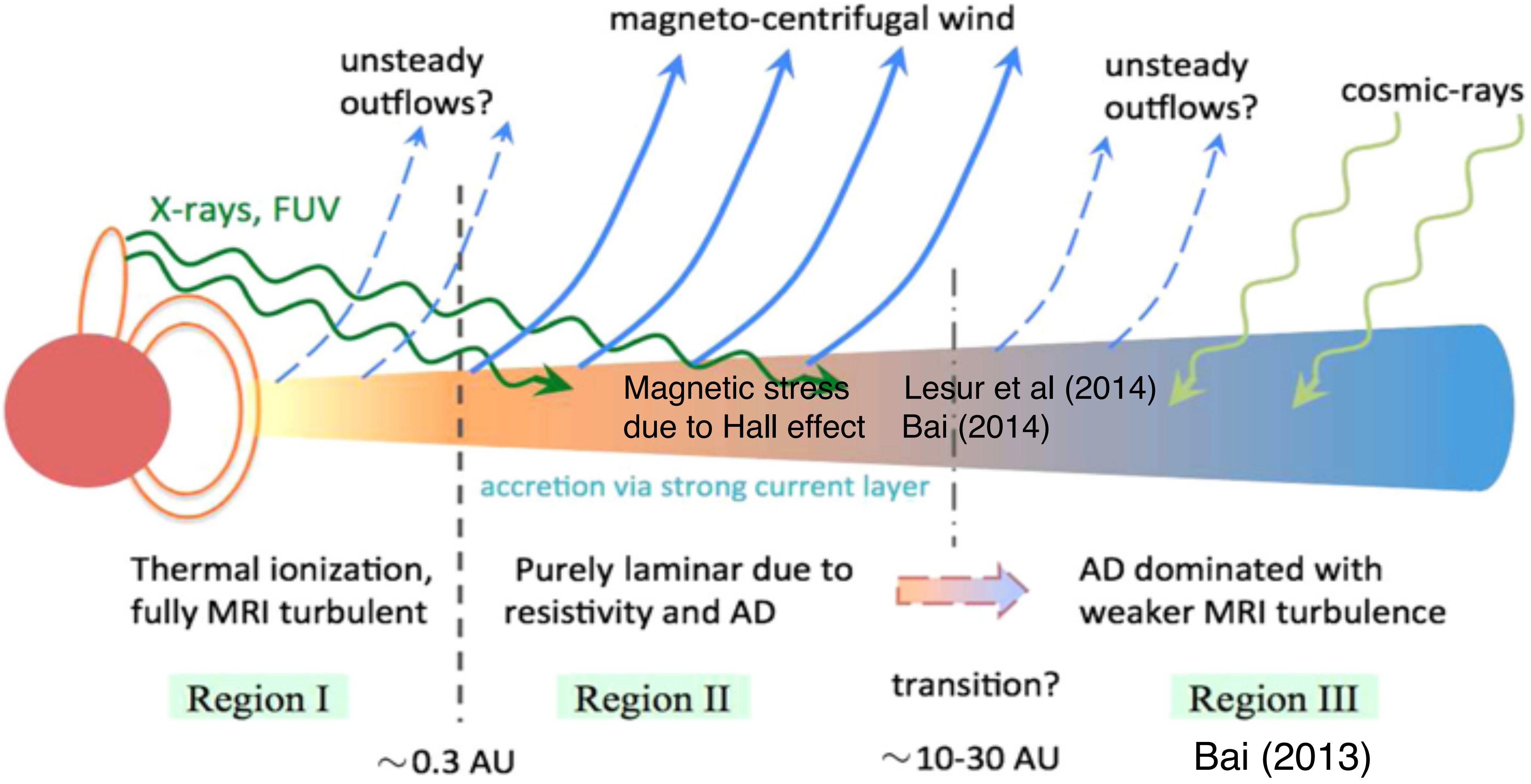
- Inclusion of dust grains in disc chemistry changes *$x(e^-)$* and the magnitudes of Ohmic resistivity, ambipolar diffusion and Hall effect - horizontal field amplification reduced

- Inclusion of Hall effect still produces significant stress in mid plane when $\mathbf{\Omega . B} > 0$ (Bai 2014)

Summary of MHD effects

- Fully developed MRI-turbulence present only in inner few x 0.1 AU
- Magneto-centrifugal wind between ~ 0.3 - 20 AU with significant mid-plane stress if $\mathbf{\Omega} . \mathbf{B} > 0$
- Outer regions sustain weak MRI-turbulence modified by ambipolar diffusion

  (Simon et al 2013; Bai 2015)
- All results depend on details of chemistry, dust properties, FUV, X-rays, CRs, computational set-up, …



Magnetic stress due to Hall effect

Lesur et al (2014)
Bai (2014)

Bai (2013)

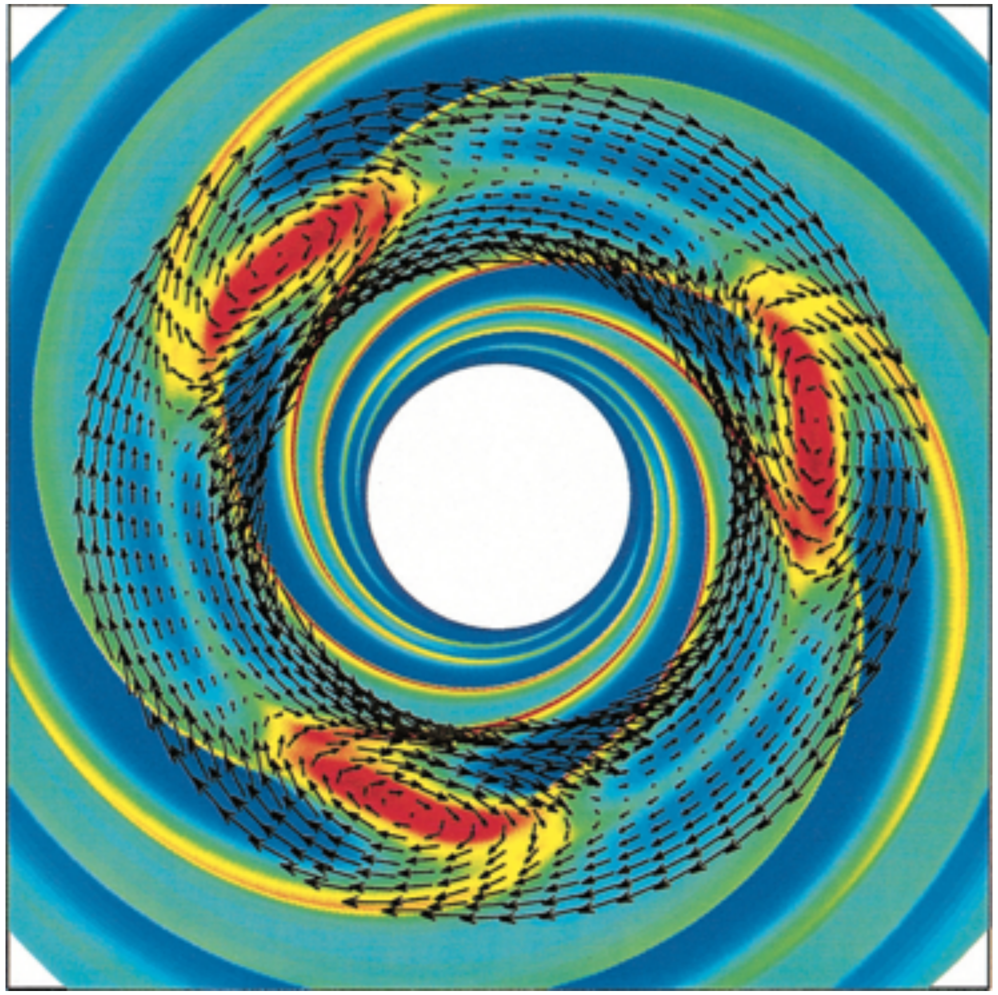
Hydrodynamic instabilities

Rossby wave instability (RWI)

- Driven by a radial extremum in the quantity $\mathcal{L} = \frac{\Sigma}{2\omega_z}\left(\frac{P}{\Sigma^\gamma}\right)^{2/\gamma}$

  (Lovelace et al 1999; Li et al 2000)

- The linear instability saturates by forming ~ 3 - 5 anticyclonic vortices that tend to merge into a single vortex over time



Li et al (2001)

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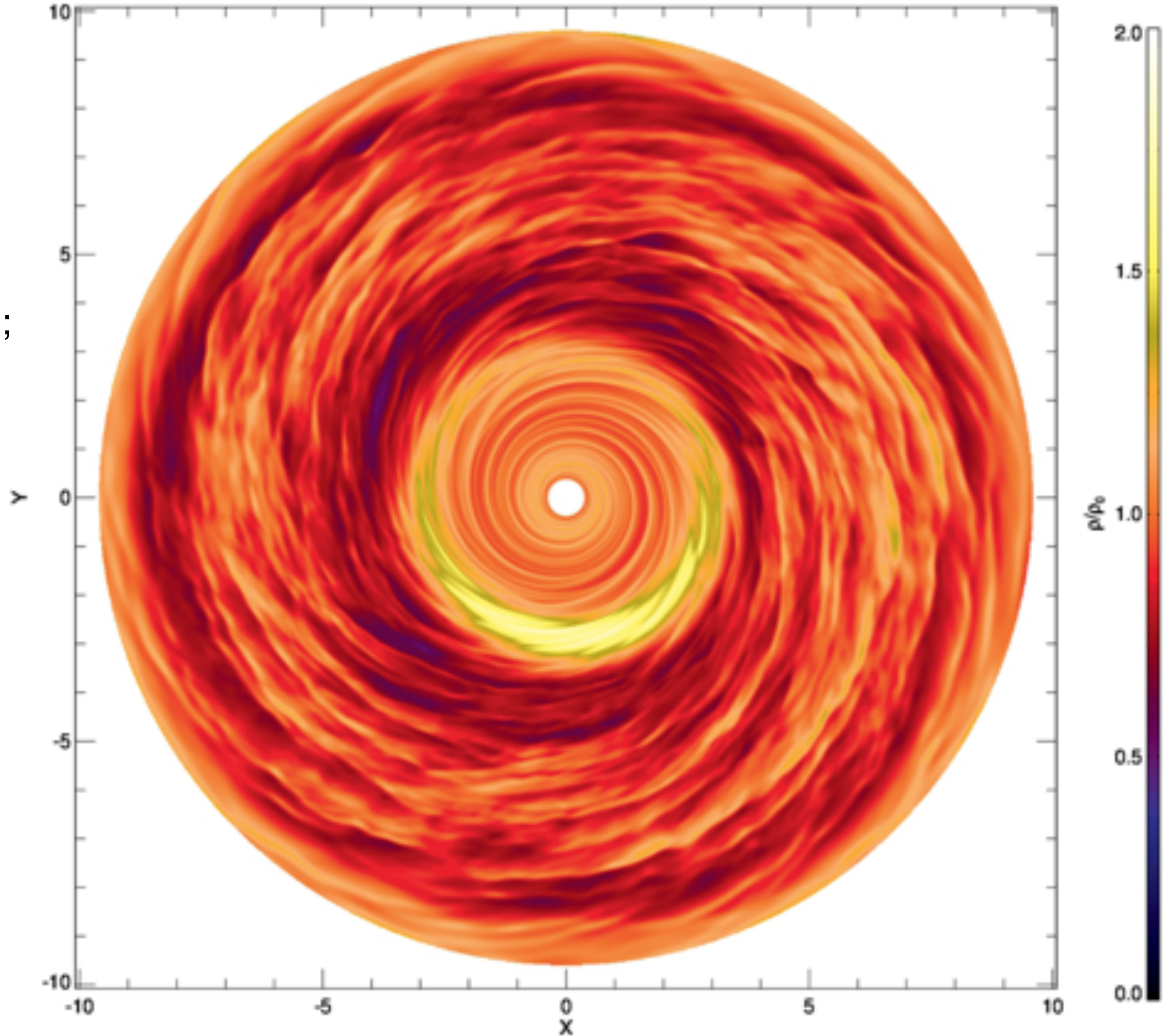
- RWI can be triggered at:

  - interface between active and dead zones (Lyra & MacLow 2002; Varnier & Tagger 2006; Lyra et al 2014; Faure et al 2014)



Lyra et al 2014

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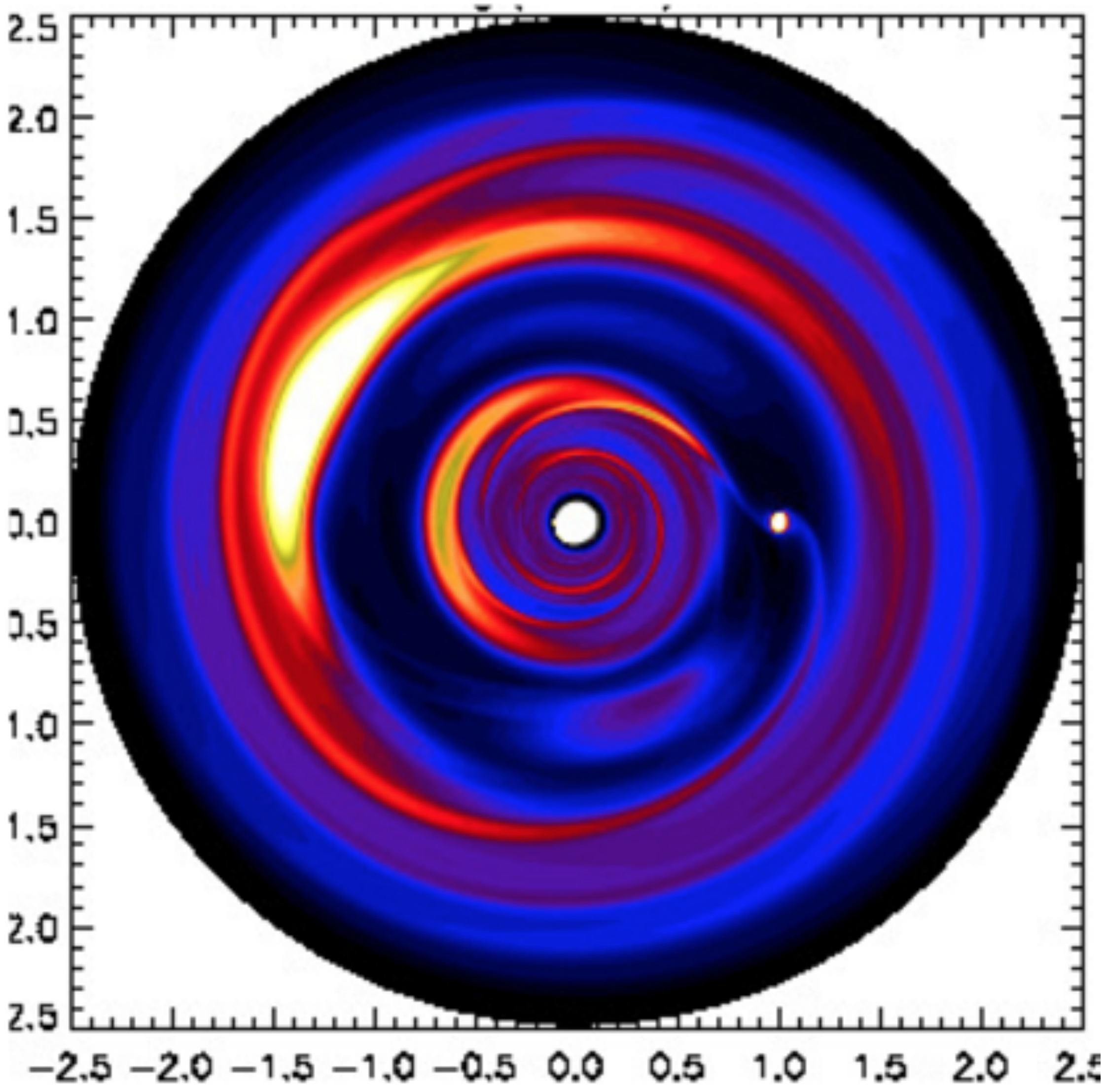
  - edge of a gap formed by a planet
    (de Val-Boro et al 2006; Lin & Papaloizou 2011)

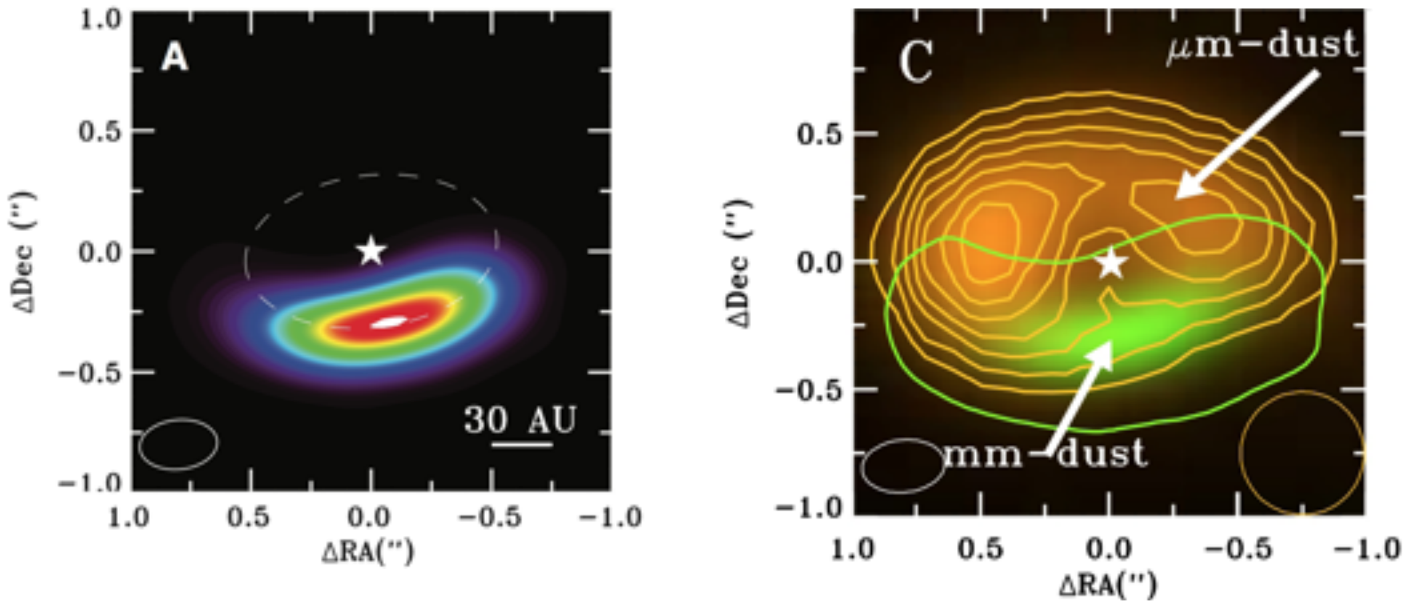


Lin (2012)

Rossby wave instability (RWI)

- Driven by a radial extremum in the quantity $\mathcal{L} = \frac{\Sigma}{2\omega_z}\left(\frac{P}{\Sigma^{\gamma}}\right)^{2/\gamma}$
- The linear instability saturates by forming ~ 3 - 5 anticyclonic vortices that tend to merge into a single vortex over time

Van de Marel et al. (2013)



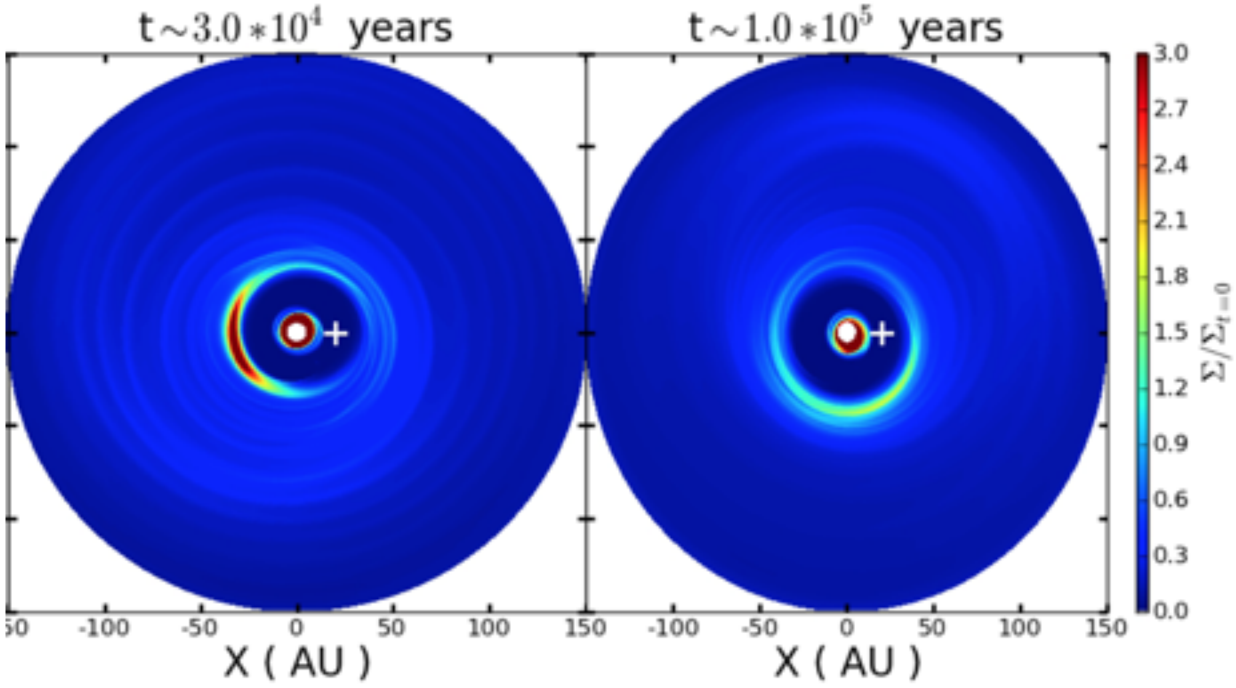
- RWI can be triggered at:

  - interface between active and dead zones
    (Lyra & MacLow 2002; Varnier & Tagger 2006; Lyra et al 2014; Faure et al 2014)

  - edge of a gap formed by a planet
    (de Val-Boro et al 2006; Lin & Papaloizou 2011)

- Vortices trap dust efficiently
  - possible that Oph IRS 48 hosts a planet-induced vortex?

(Van de Marel et al. 2013)



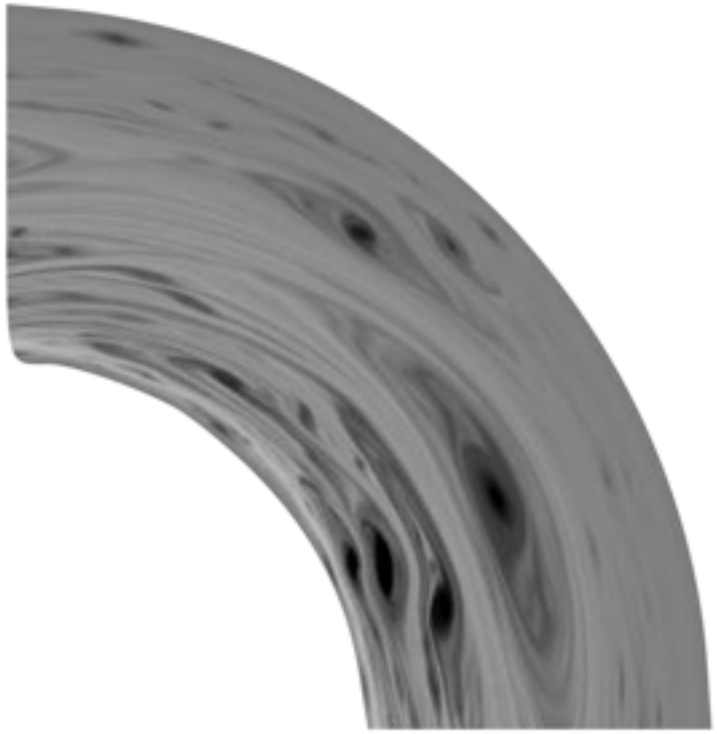
Subcritical baroclinic instability (SBI)

- Requires a negative entropy gradient $$\frac{d\log(P\rho^{-\gamma})}{d\log R} < 0$$
  (Peterson et al 2007)

- Nonlinear instability - requires finite-amplitude perturbations
  (Lesur & Papaloizou 2010)

  - needs to be triggered by linear instabilities:
    e.g. convective overstability or vertical shear instability?
    (Klahr & Hubbard 2014; Lyra 2014; Nelson et al 2013)

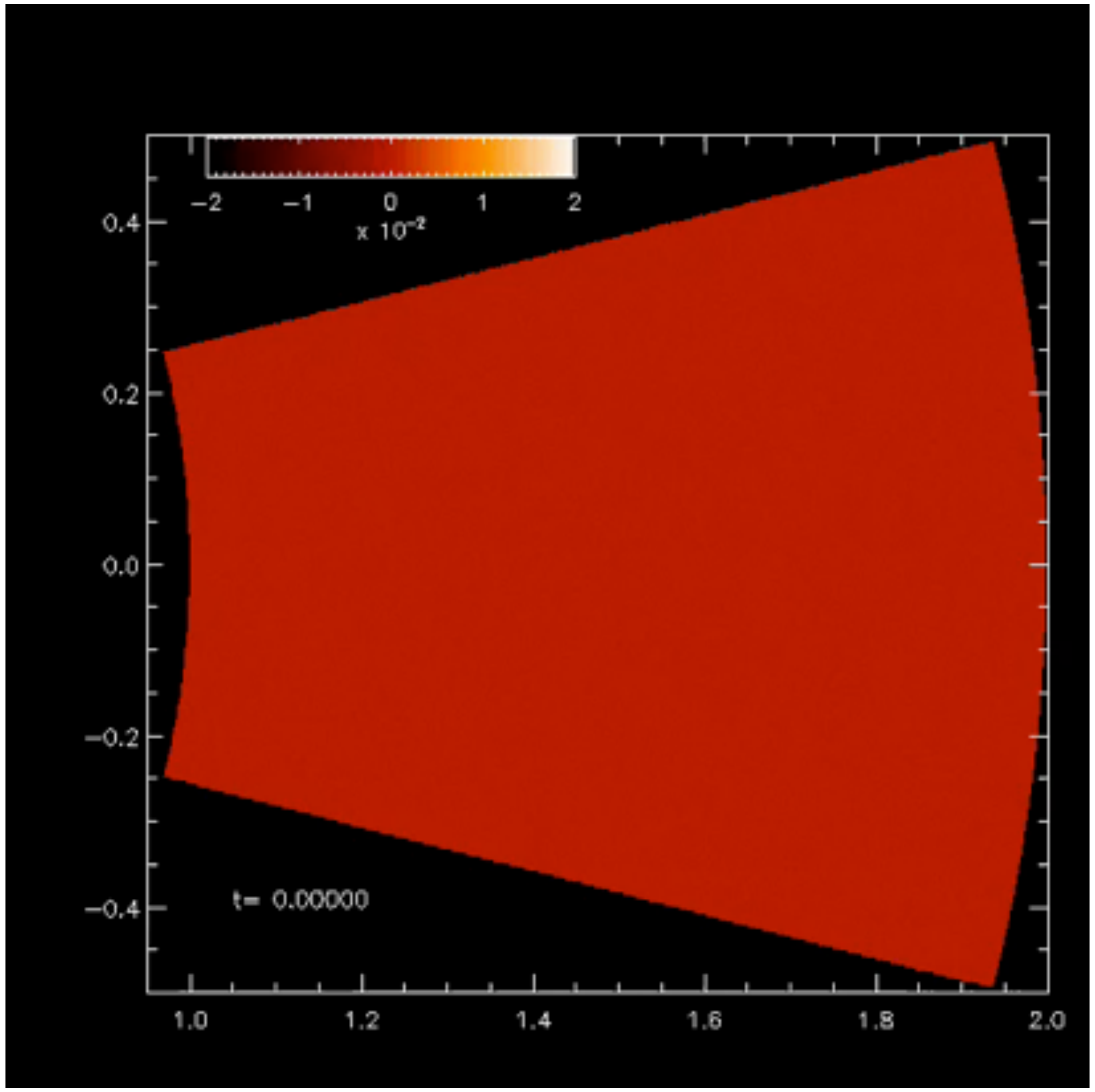
- Sustaining vortices requires short thermal relaxation time scale
  - most likely to operate in outer disc regions (Lesur & Papaloizou 2010)



- (Peterson et al 2007)

Vertical shear instability (VSI)

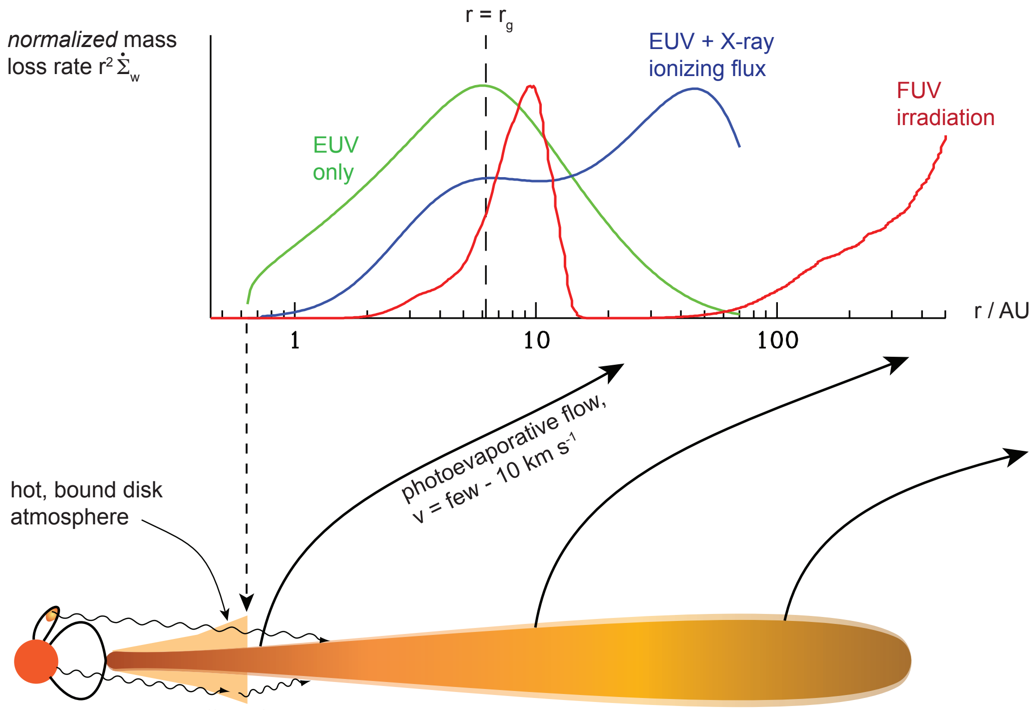
- Linear instability (Goldreich & Schubert 1967; Fricke 1968; Urpin 2003; Nelson et al 2013)
- Arises because a disc with T=T(R) has vertical shear
- Requires thermal relaxation times
  < local orbital period - very short!
  - likely to operate in outer regions of
  protoplanetary discs (Nelson et al 2013; Lin & Youdin 2015)
- In nonlinear saturated state it can
  generate $\alpha \sim 10^{-4}$ - 10^{-3}
- Also generates vortices
  (Richard, Nelson & Umurhan 2015)



Disc dispersal

Photoevaporation

- Viscous evolution of protoplanetary discs cannot account for their complete dispersal - or rapid time scales inferred for disc removal (Kenyon & Hartmann 1995)
- Heating of disc surface by EUV, FUV and X-ray photons leads to hydrodynamic escape beyond radius $r_g = \frac{GM_*}{c_s^2}$ (sound speed ~ escape velocity from central star)
- External evaporation by O stars in Orion leads to mass loss rates ~ 6 x 10^{-7} M_{sun} / yr and disc life times ~ 10^5 yr (Johnstone et al 1998; Henney et al 2002)
- X-ray and FUV photons from central star dominate evaporation of isolated T Tauri stars with mass loss rates ~ 10^{-8} M_{sun}/yr (assuming L_X ~ 10^{30} erg/s) (Gorti & Hollenbach 2009; Owen et al 2010)



Armitage (2011)