Critical hydromagnetic processes in star formation: ambipolar diffusion in 3D

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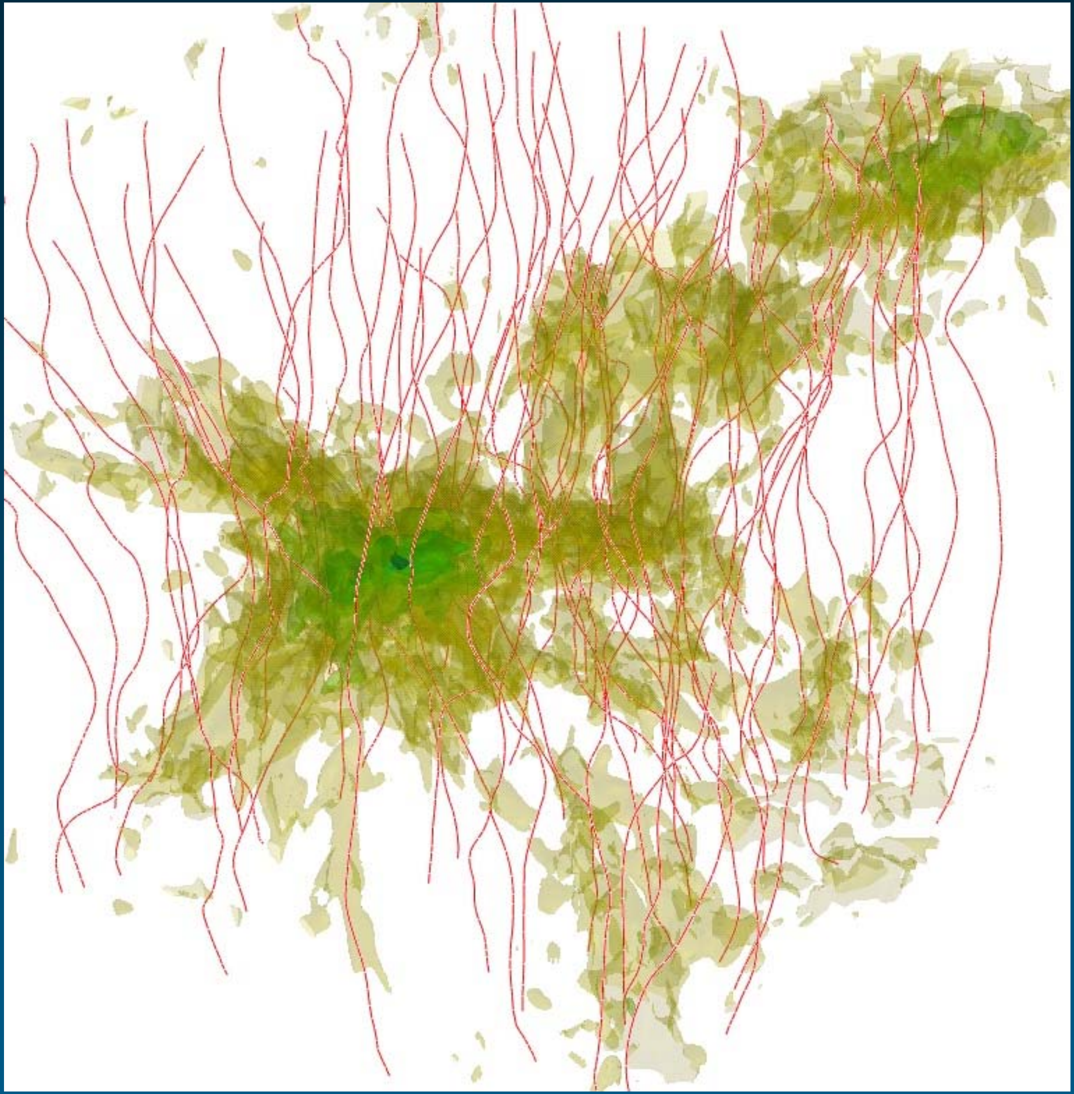
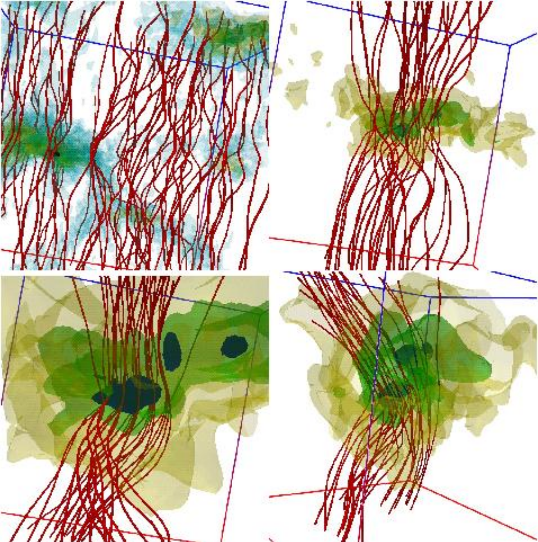


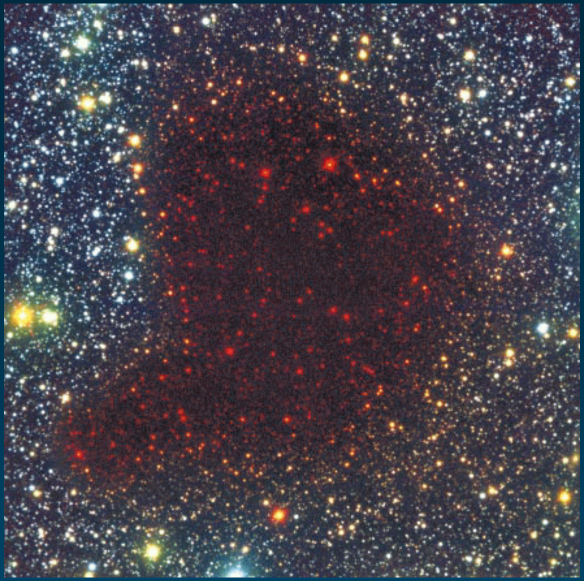
Simulating cluster formation in magnetized, self-gravitating, gas clumps (Tilley & Pudritz II; MNRAS, 2007)

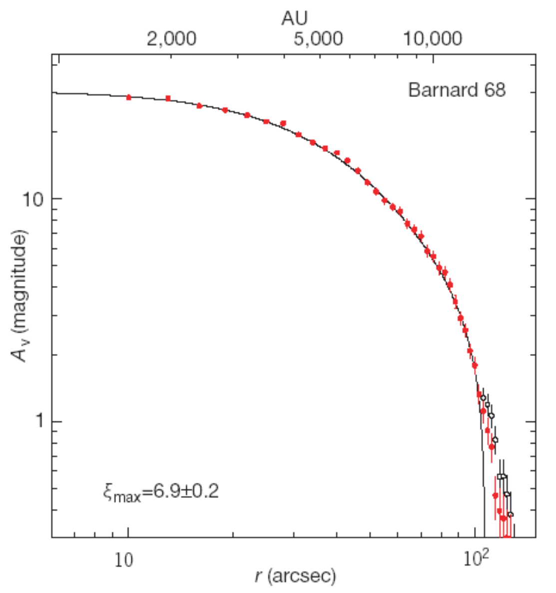
Supersonic turbulence fragments clouds into filaments & dense cores in which stars form (eg. Klessen & MacLow, Padoan & Nordlund, review McKee & Ostriker 2007)

Good correspondence between core mass function and IMF (eg. Motte et al 2001)



Gravitational collapse of core: formation of a star/disk/jet





Why B fields matter (in ideal coupling):

- collapse rate

- accretion shocks (lessen compression) and disk heating

- formation of accretion disk (eg. magnetic supported pseudo-disks)

- magnetic braking of disk by torsional waves, magnetic tower flows, and disk winds -> accretion rates

- fragmentation of disk – binaries, planets,

Infrared image Barnard 68 (Alves et al 2001): excellent fit with Bonner-Ebert model -> excellent initial condition W

Ambipolar diffusion: coupling far from perfect in molecular gas (low ionization fraction). What then?

- Ions (and electrons) feel magnetic forces
- Everything feels *gravity* and collisional friction
- Frictional force mediates magnetic force upon neutral species

- Reduce effective magnetic support (eg. Fiedler & Mouschovias 1993), and braking
- Solve magnetic flux problem (Mestel & Spitzer 1956). But on what scale?

- Field evolution dependent on current
  - J ~ Curl B
  - Diffusion: straighten field lines
  - non-diffusive terms: different effects!
    - Brandenburg & Zweibel 1994

- Since $\rho_{ion} << \rho_{neutral}$ can use single fluid approx.
  - Eliminate MHD equations for ions; get MHD for neutrals
  - Chemistry: $\rho_{ion} \sim (\rho_{neutral})^{1/2}$
  - Valid up to about $n_{gas} = 10^{10}$ cm^{-3}
    - Tassis & Mouschovias 2007, Nakano et al. 2002
- Computionally inexpensive procedure.
- Alternative: Multiple Fluids (eg. turbulence fragmentation Li, P.K. et al 2007), separate active chemistry

- Implemented into FLASH AMR code (Fryxell et al. 2000) as a MHD sub-module
  - Possible to use in extensive range of problems (more later)
  - Code tests: C shocks, collapse of uniform magnetized spheres
- Must consider $\nabla . B$ terms to ensure stability of the code
- Time steps:

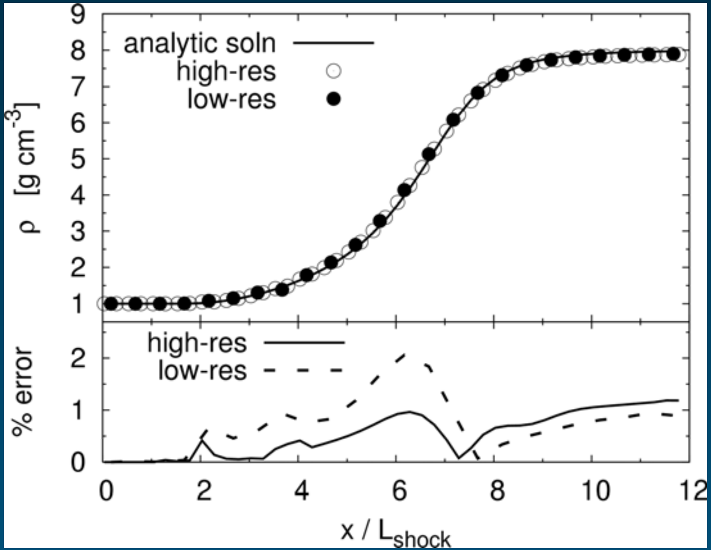
  Courant condition

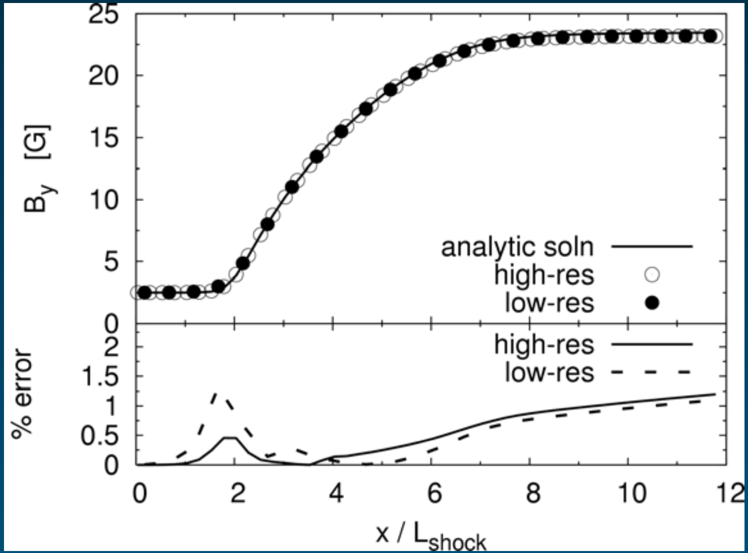
$$\tau_{AD} = T_o (\Delta x)^2 / \eta_{AD} \qquad (\eta_{AD} = \beta_{AD} B^2)$$

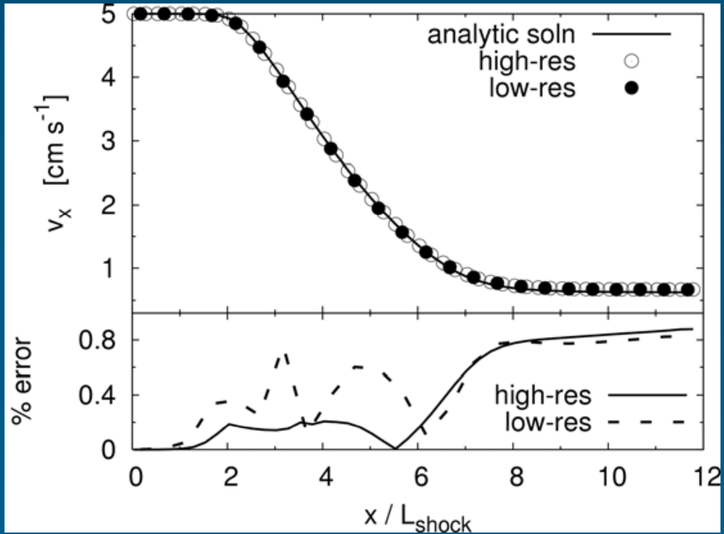
Isothermal C-Shock Tube

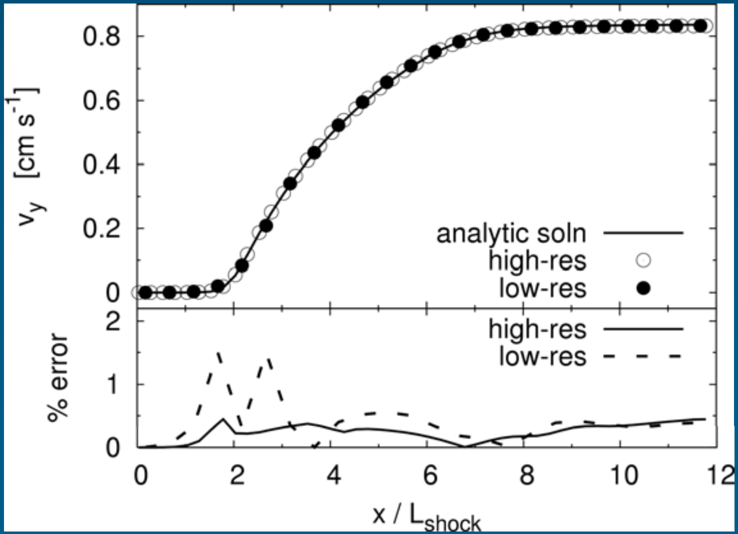
Testing FLASH with AD: C shocks (non-isothermal)

(analytic solutions following Wardle 1991, Draine 1986)









Collapsing, magnetized, rotating, and cooling BE spheres in 3D (Duffin & Pudritz 2007a, & b)

- Low mass Bonnor-Ebert sphere
  - Barnard 68 (2.1 solar masses)
  - Study magnetic braking, fragmentation
- High Mass Bonnor-Ebert sphere (168 solar masses) (Chini et al 2004)
  - Study the collapse, down to the onset of outflows and magnetic decoupling in the disk.
- Extensive cooling taken from previous work (Banerjee & Pudritz 2007)
  - Molecules, dust, radiative transfer in optically thick regimes.

Cloud ionization due to cosmic rays (Fielder & Mouschovias 1993, Hosking & Whitworth 2004):

$$n_i = K\left(\frac{n_n}{10^5\,cm^{-3}}\right)^{1/2} + K'\left(\frac{n_n}{10^3\,cm^{-3}}\right)^{-2}$$

Detailed balance for ions: friction (ion-neutral collisions) balances Lorentz force -> one fluid model:

$$u_d = u_i - u_n = \beta_{AD}(\nabla \times B)\times B$$

$$\beta_{AD} = 1/(\mu_o \gamma_{AD} \rho_i \rho_n)$$

Initial conditions in models:

$$\rho_o(gcm^{-3}) = \left(\frac{high-mass: 3.35\times10^{-21}}{low-mass: 9.81\times10^{-19}}\right)$$

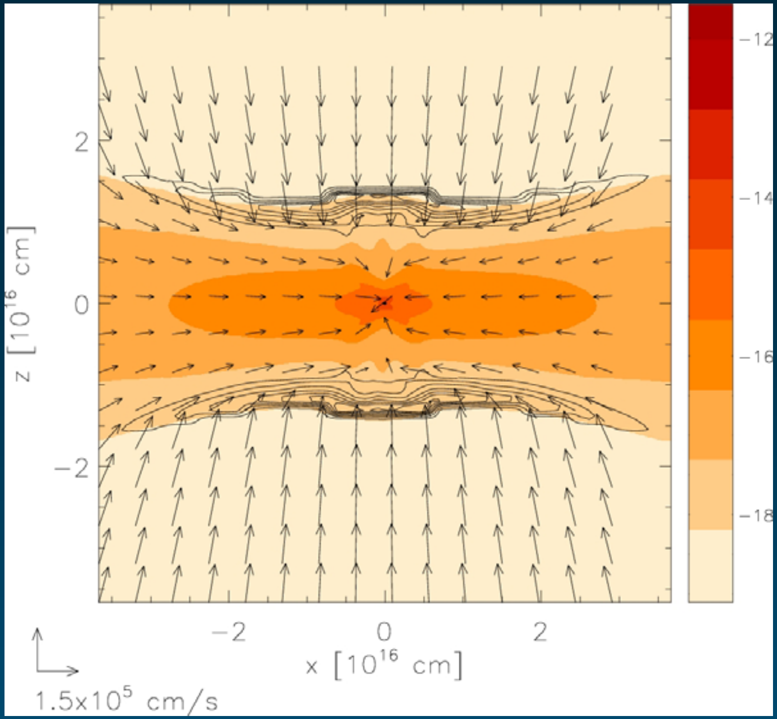
$$c_s(kms^{-1}) = \left(\frac{0.408}{2.458}\right)$$

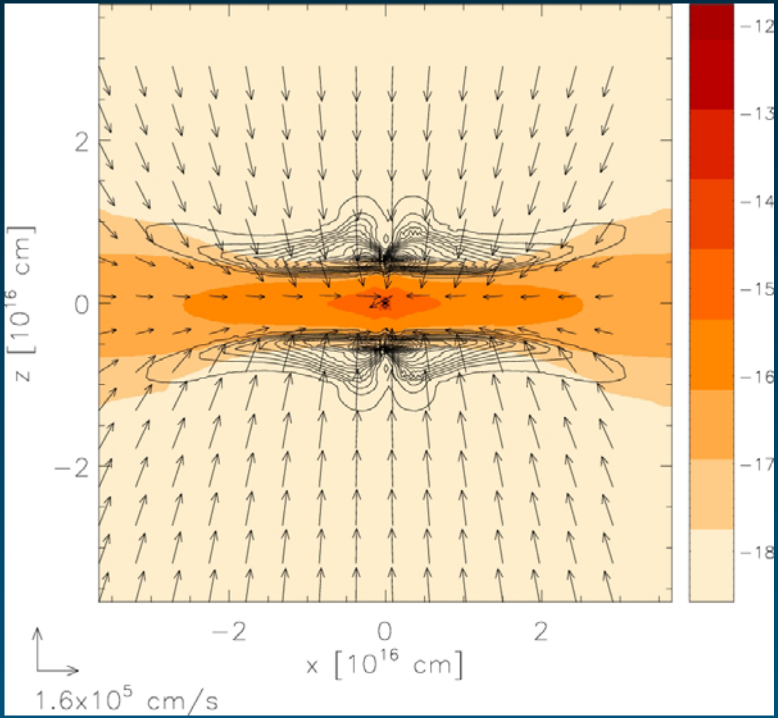
$$B_o(\mu G) = \left(\frac{1.36}{14.0}\right)$$

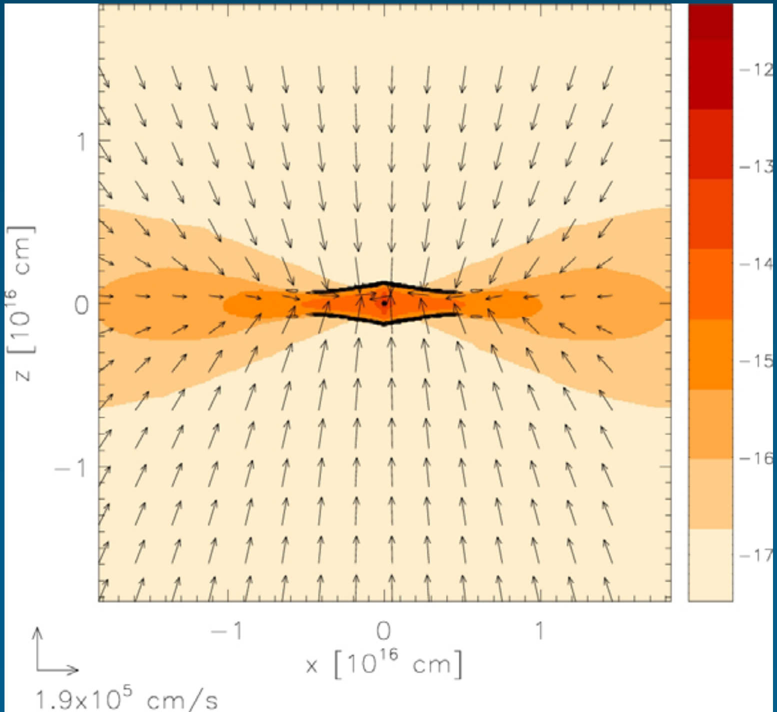
$$\Omega_o(s^{-1}) = \left(\frac{1.10\times10^{-14}}{1.89\times10^{-13}}\right)$$

$$\Omega_o t_{ff} = 0.4(ideal \quad case)$$

Collapse and disk formation: accretion shocks





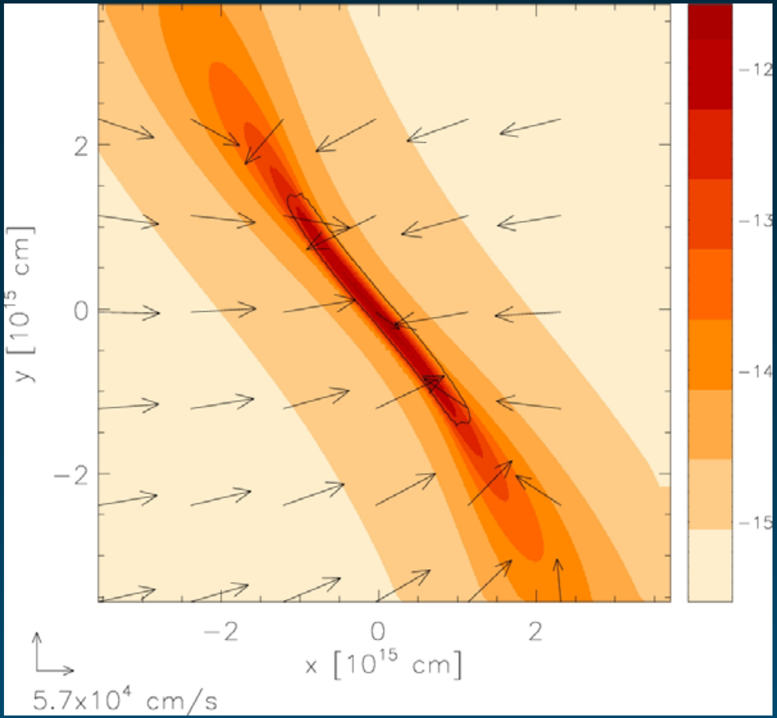


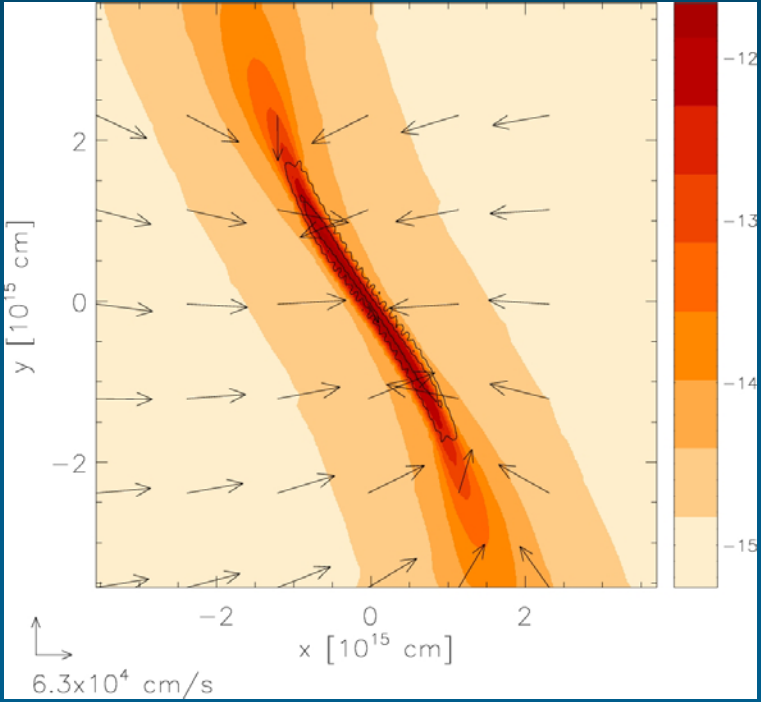
Clockwise: ideal MHD, AD, hydro; massive disk case

-Magnetic pressure contributes to scale height

- Max Temp: 95 K, 177K, and 140 K respectively

- T contours spacing; 20 K

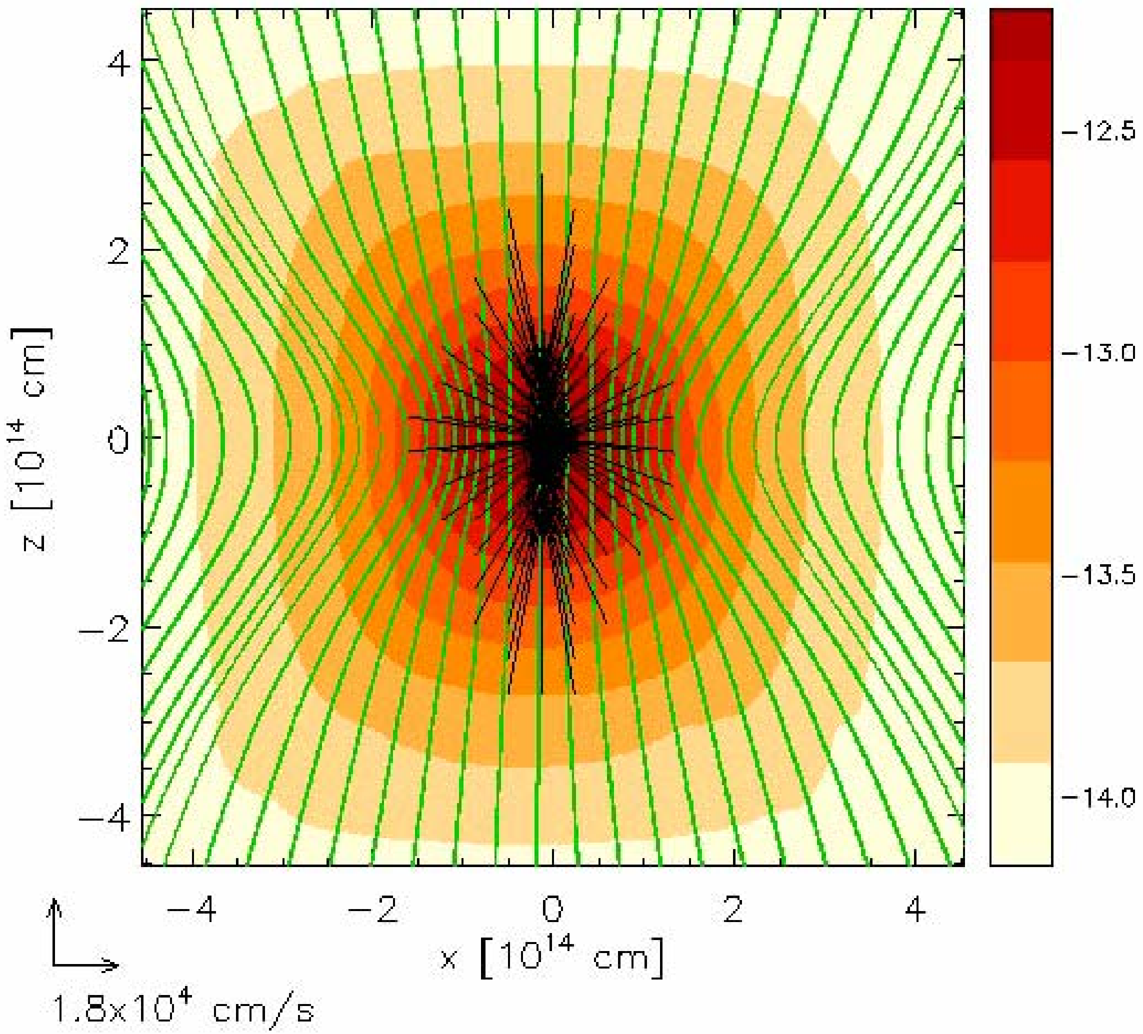




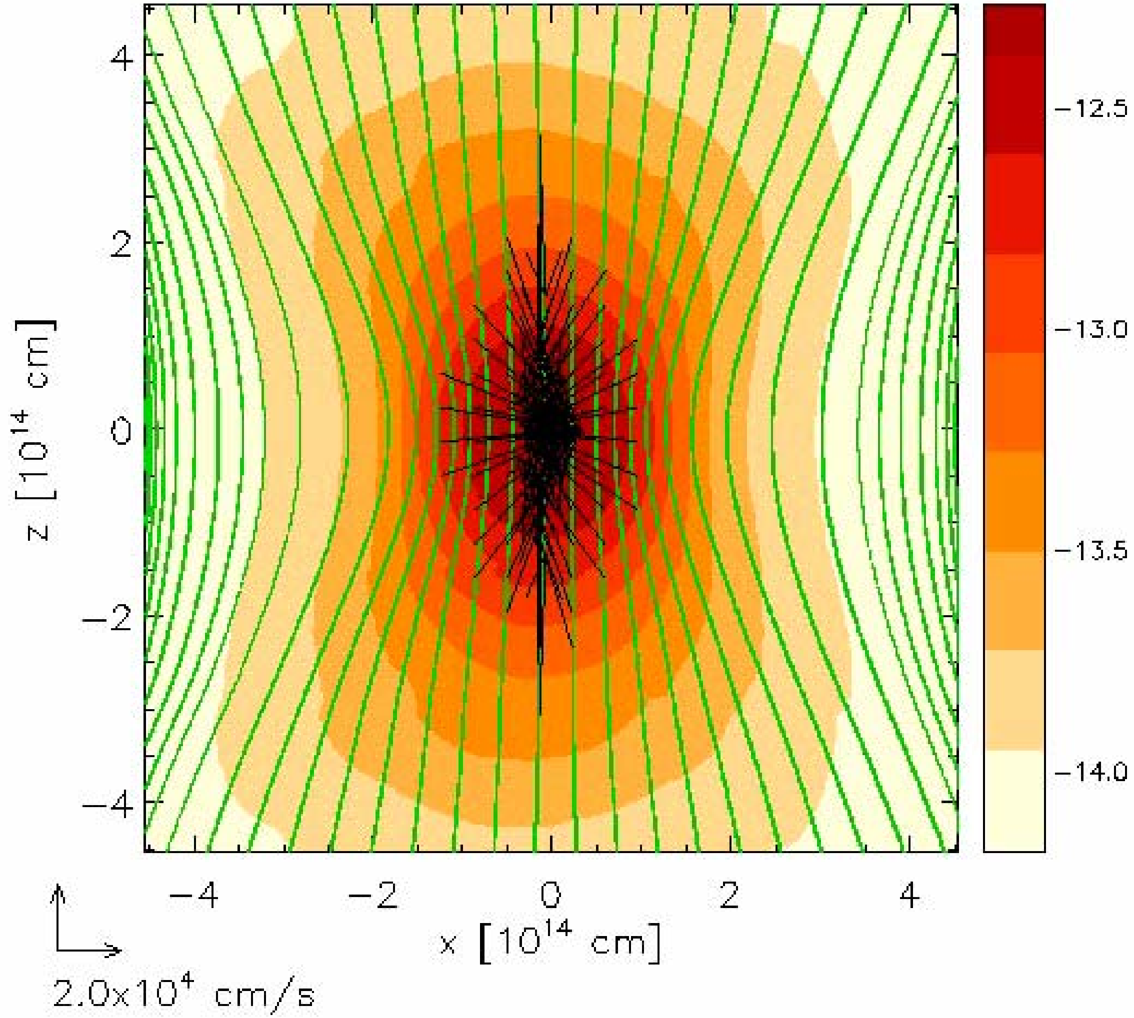
Barred disk (massive case): ideal vs AD MHD)

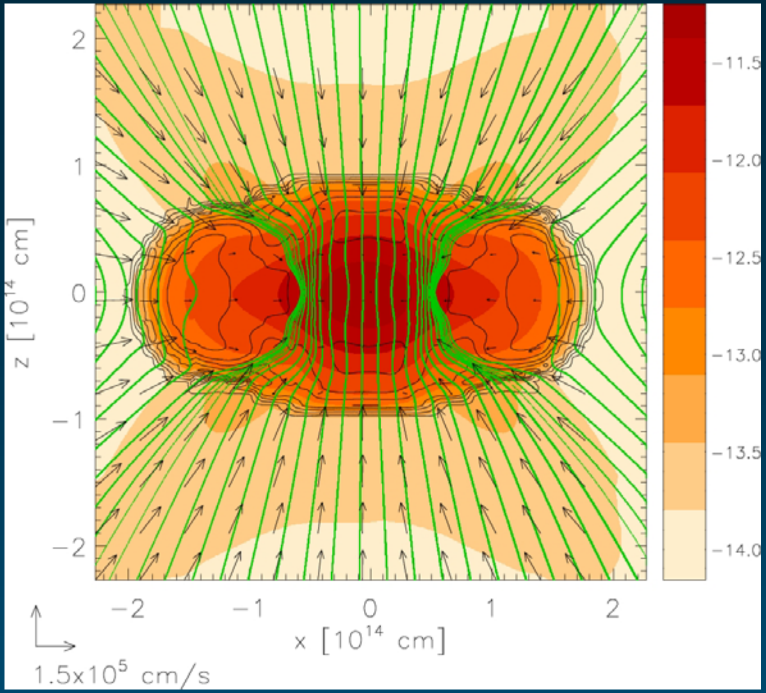
- x-y (disk plane) view
- Bar only slightly “thicker” in ideal (top) vs AD (ie, more magnetic pressure support)
- Bar will transport significant amounts of angular momentum – see later slide

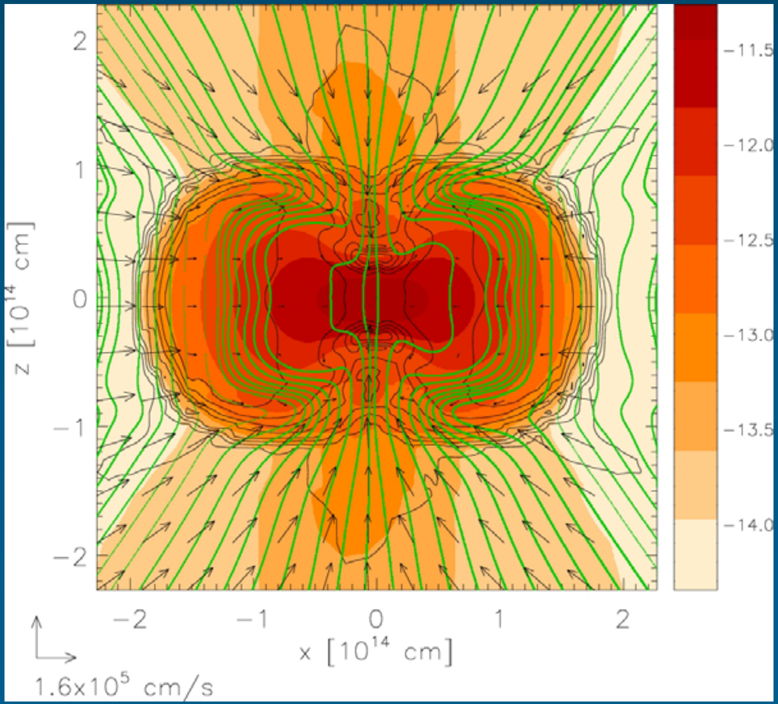
Movie – collapse and disk evolution under ideal MHD



Movie – collapse and disk evolution under AD

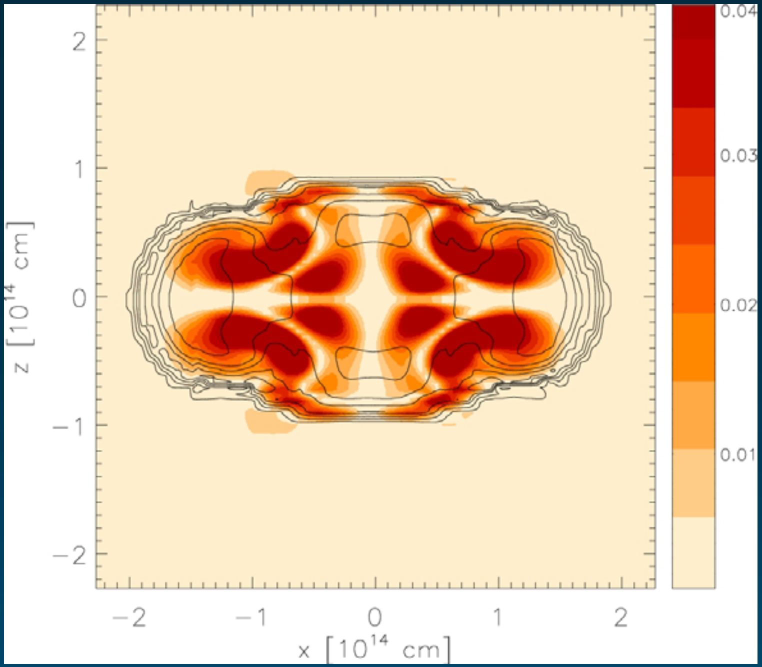


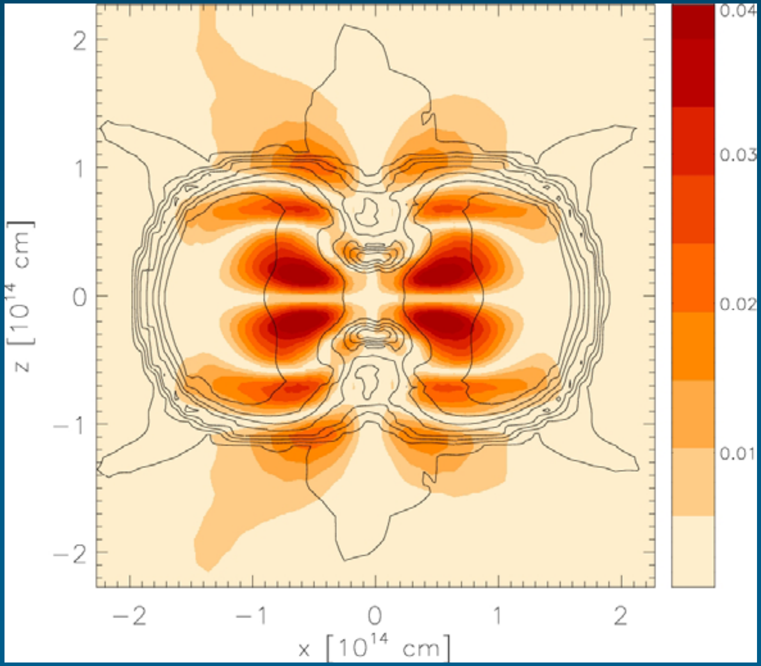




Ideal vs AD collapses (high mass model)

- Still in early phases of collapse (disk dominates mass)
- Magnetic tower flow launched because of accumulating toroidal field (eg. Uchida & Shibata 1985, Banerjee & Pudritz 2006) – on 10 AU scales
- Layered accretion in AD case – through coupled surface layers
- Decoupled zone in AD case – field lines “left behind”

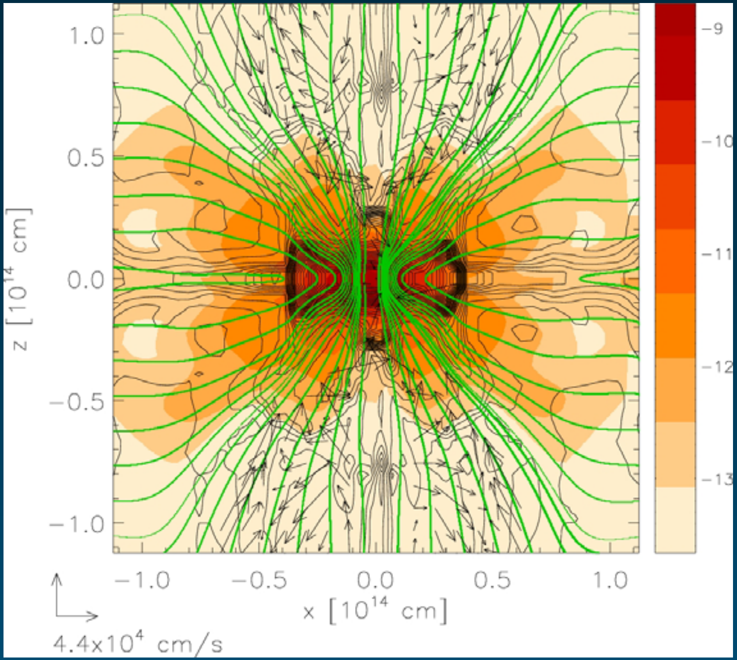


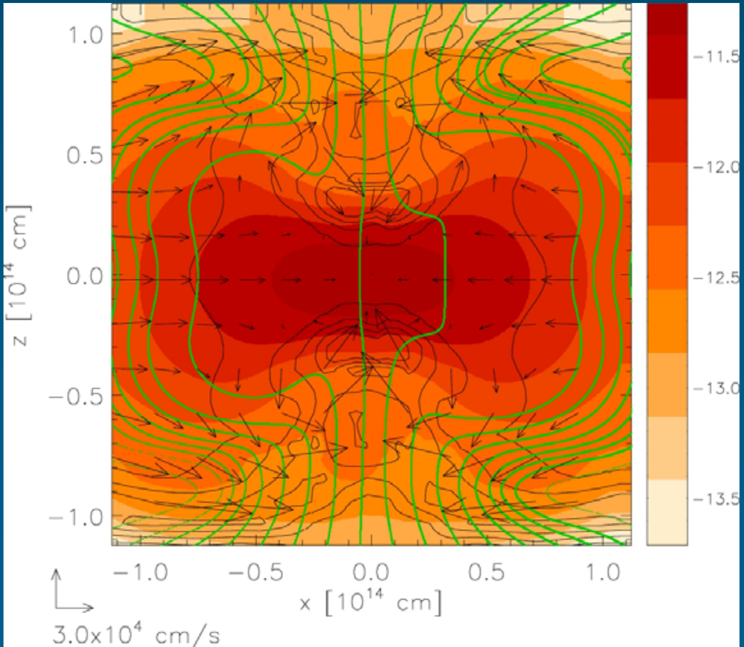


Toroidal magnetic fields – in disk and tower flow: ideal vs AD

- Toroidal field generated by twisting field lines in rotating inflow.
- Ideal case (top); toroidal field confined to disk..
- AD case (bottom): toroidal field has already managed to propogate upwards.
- Values at 10 AU: 0.1G (ideal) vs. 0.04 G (AD)
- Toroidal field vital for angular momentum extraction…

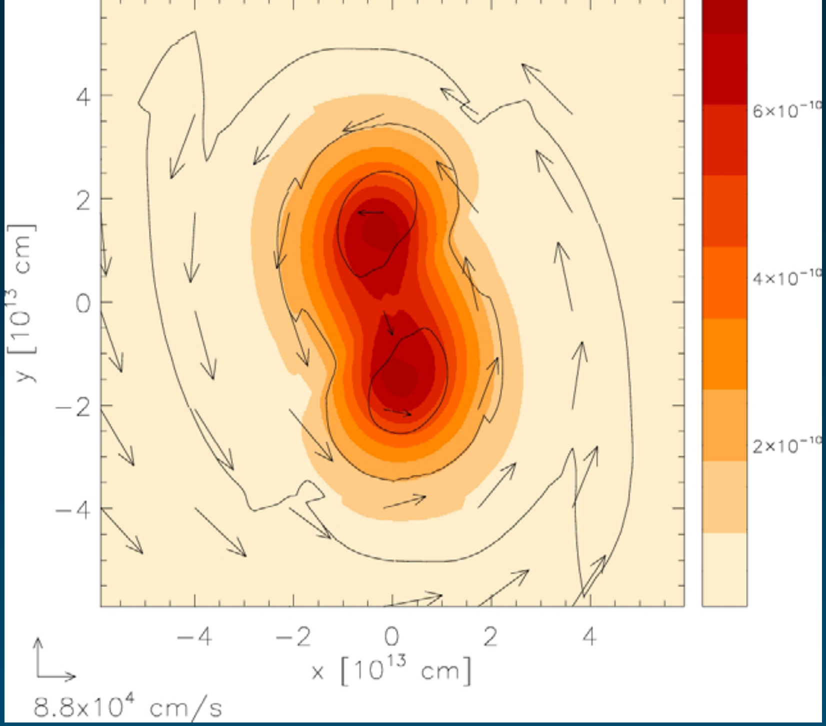
Magnetic tower outflows: ideal vs AD MHD

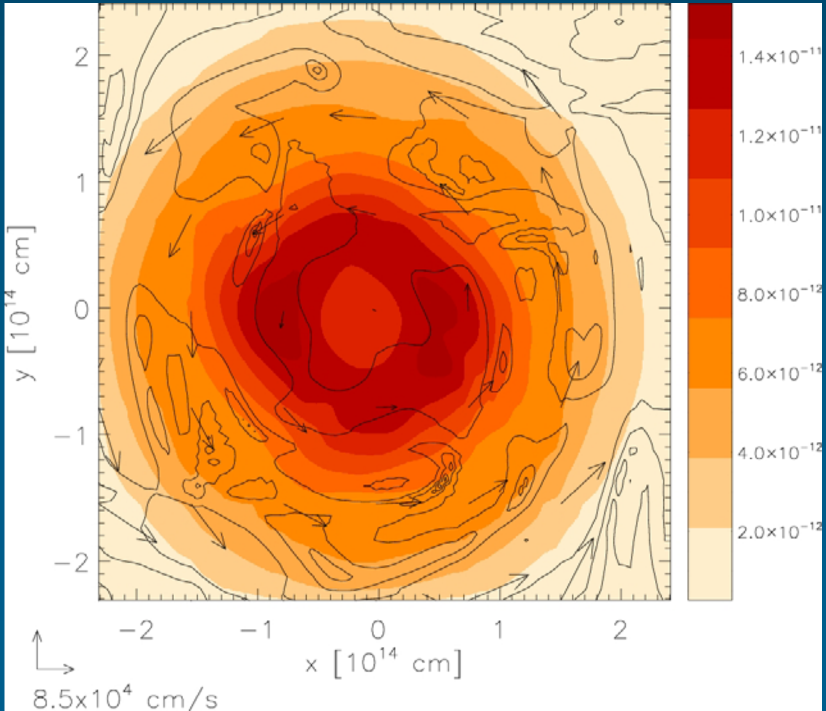




- High mass case
- Magnetic tower flow (eg. Lynden-Bell 2003): just getting started in ideal case
- Starts slightly earlier in AD case; good coupling in surface regions
- Layered accretion in AD case akin to ideal case. High pressure in these flows create conditions for tower flow.
- Very first manifestation of outflow! Starts long before the star is assembled through accretion.
- Initiated (AD case) at central densities of n = 10^(12), speed of 0.25 km per sec. Ideal case, at higher density, and speed 0.04 km per sec.

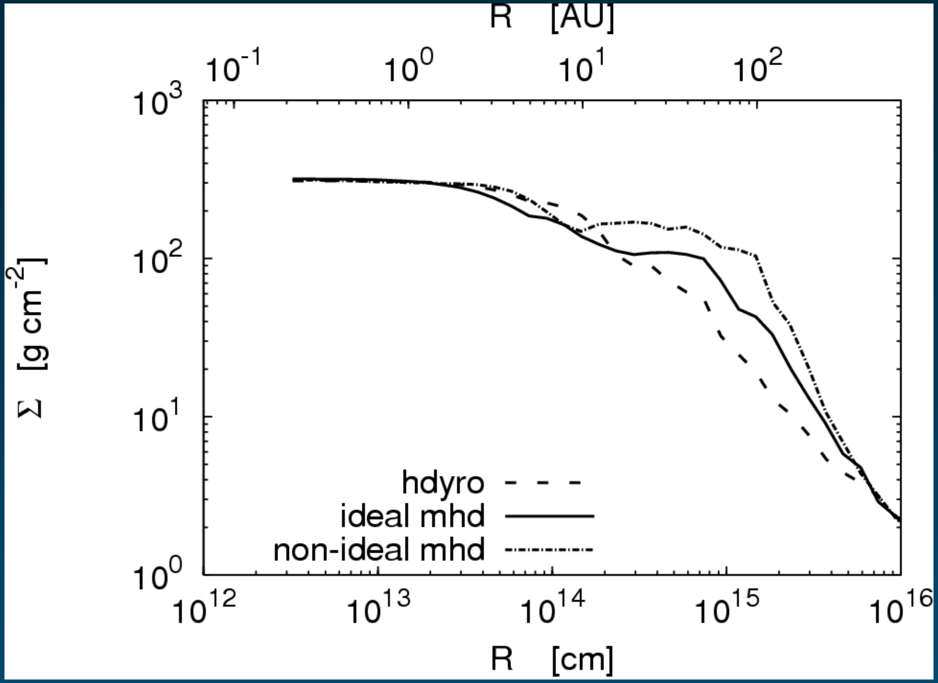
Disk fragmentation (low mass model): ideal vs AD MHD

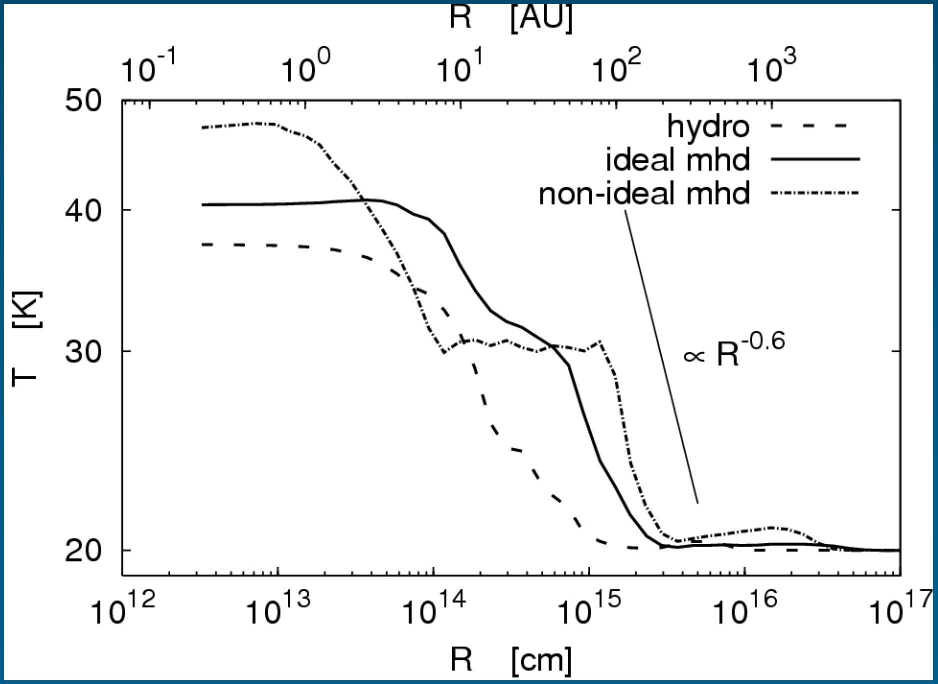




- Fragmentation is dramatically increased by scales of an order of magnitude.
- Upper: ideal, fragment separation: 2-3 AU
- Lower: AD, fragment separation 10 AU
  - Effective loss of pressure support leads to more hydrodynamic instabilities (by comparing Banerjee et al. 2004 and Banerjee & Pudritz 2006)

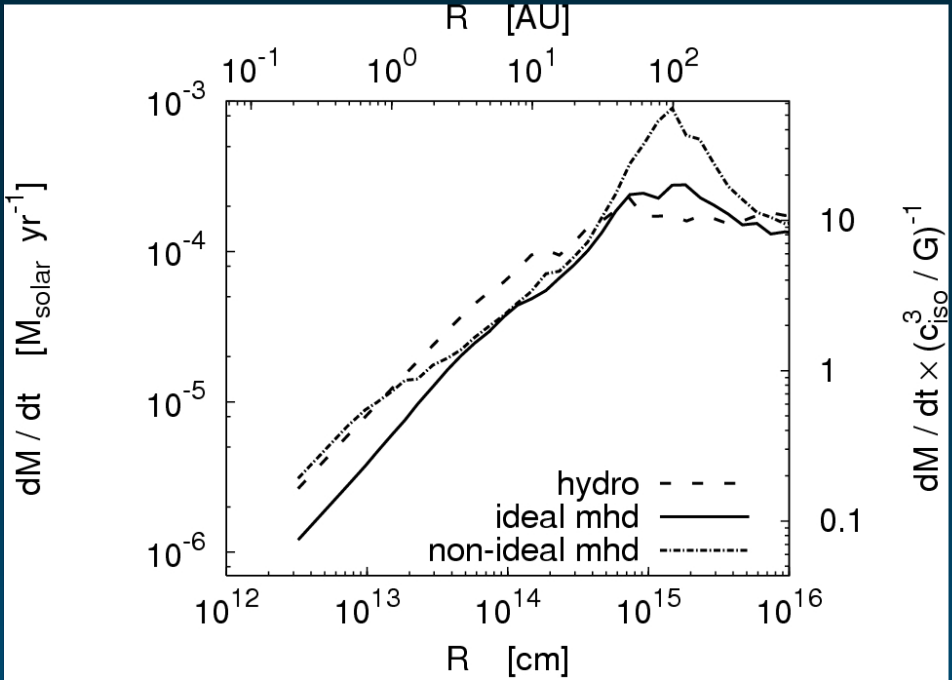
Column density and temperature profiles (high mass case)

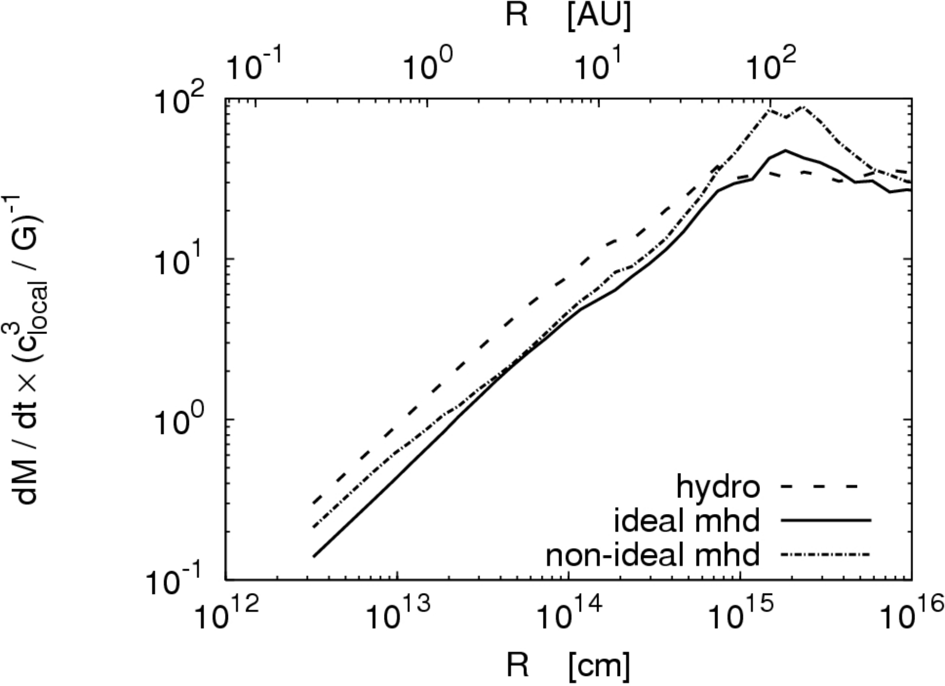




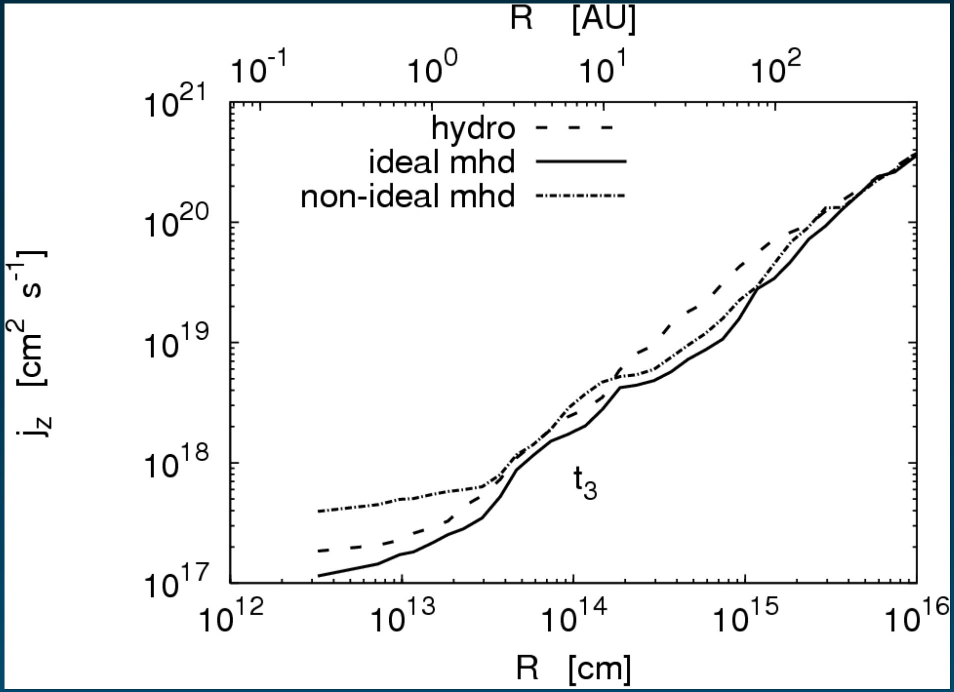
- Compare hydro, ideal, and AD cases; for all models when column of 300 gm per cm^3 attained.
- C-shock and AD heating significant out to 100 AU.

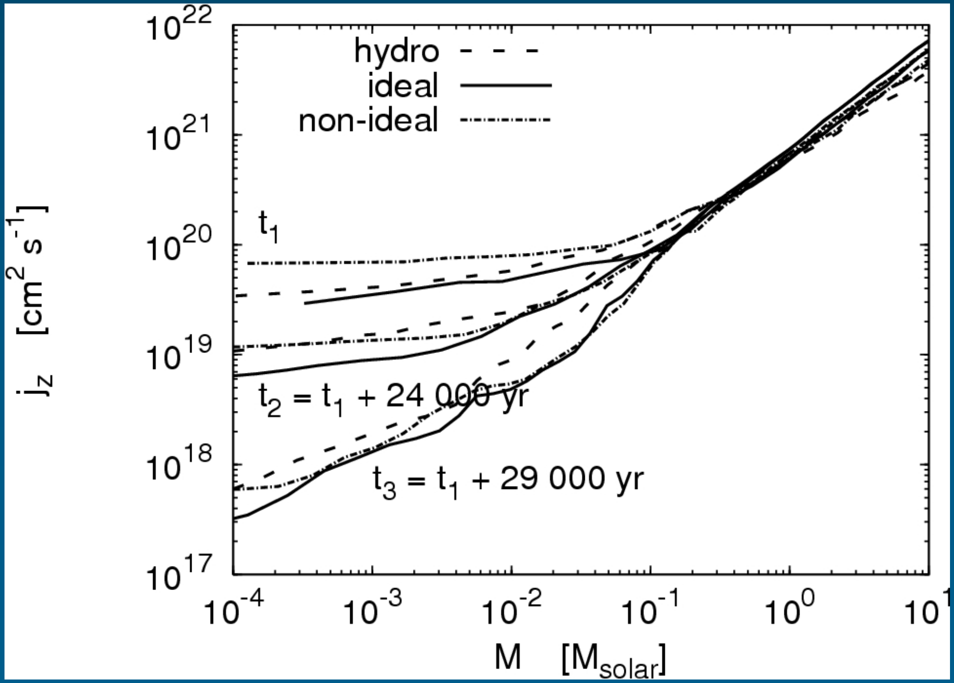
Accretion rates: Ideal vs AD MHD





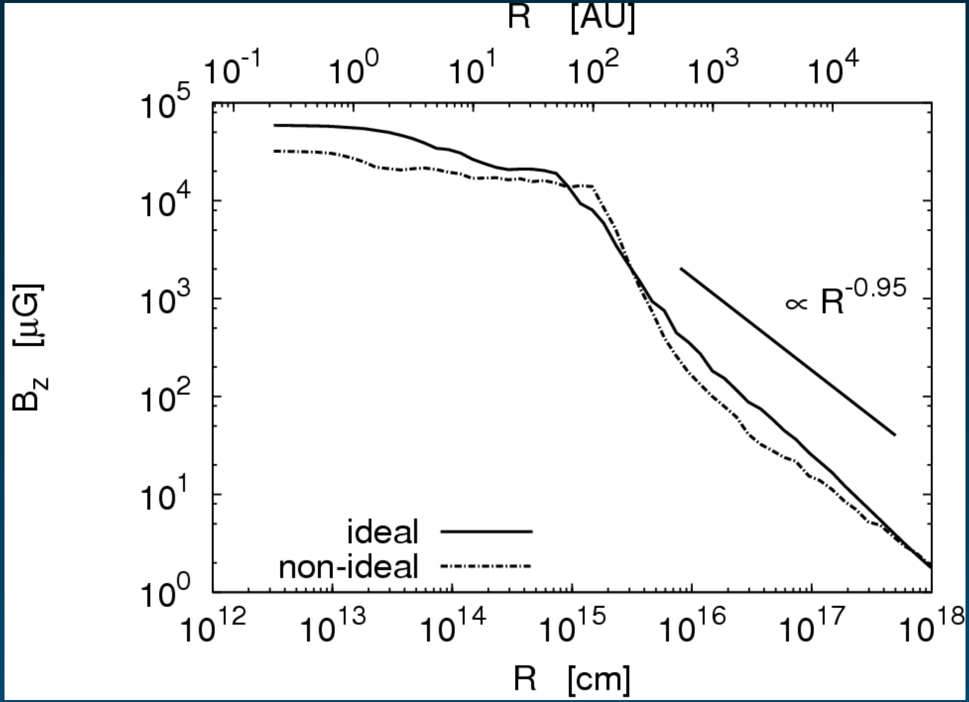
- Accretion rates on the order of 10^{-3} M_{sol} / yr
- More hydrodynamic behaviour where ambipolar diffusion is the strongest (densest regions)
- Important to form massive stars!

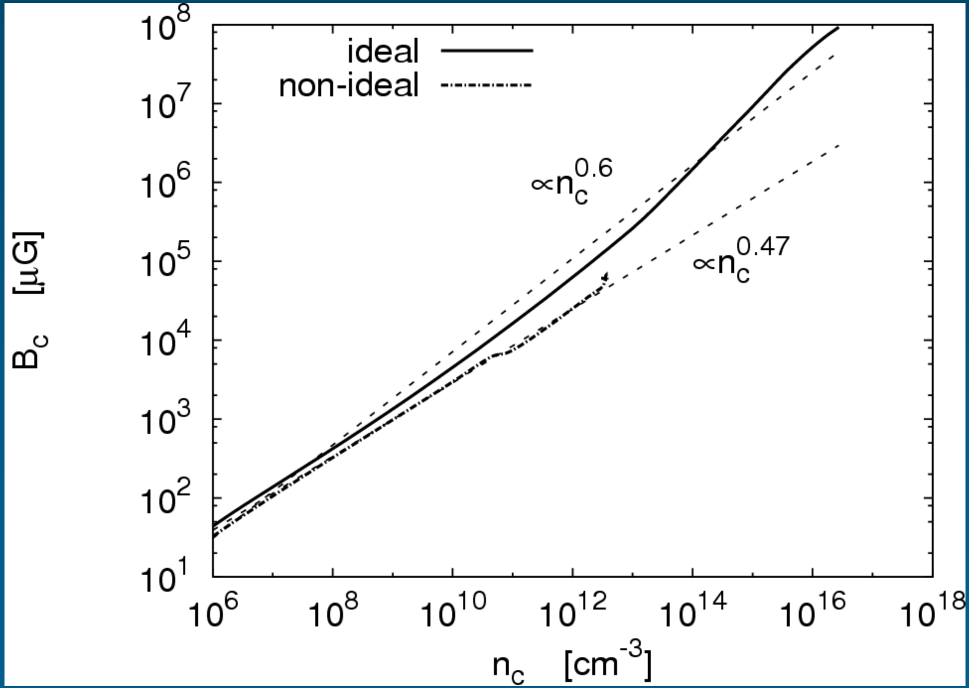




Angular momentum extraction: B vs. hydro

- Transport of angular momentum by bar, and magnetic torques
- Hydro and ideal MHD comparable
- Inner regions, AD reduces efficiency by decoupling





Magnetic field distributions: ideal vs AD

- High mass (top): B_z radial distribution in disk

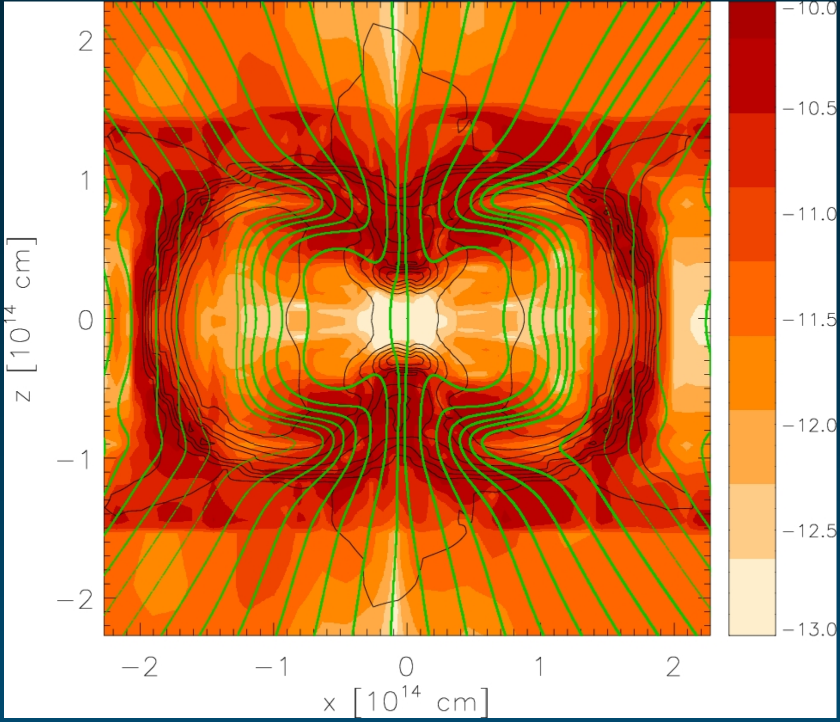
  - At 1AU: 0.032 G (AD) case – only factor of 1.8 less than ideal case.

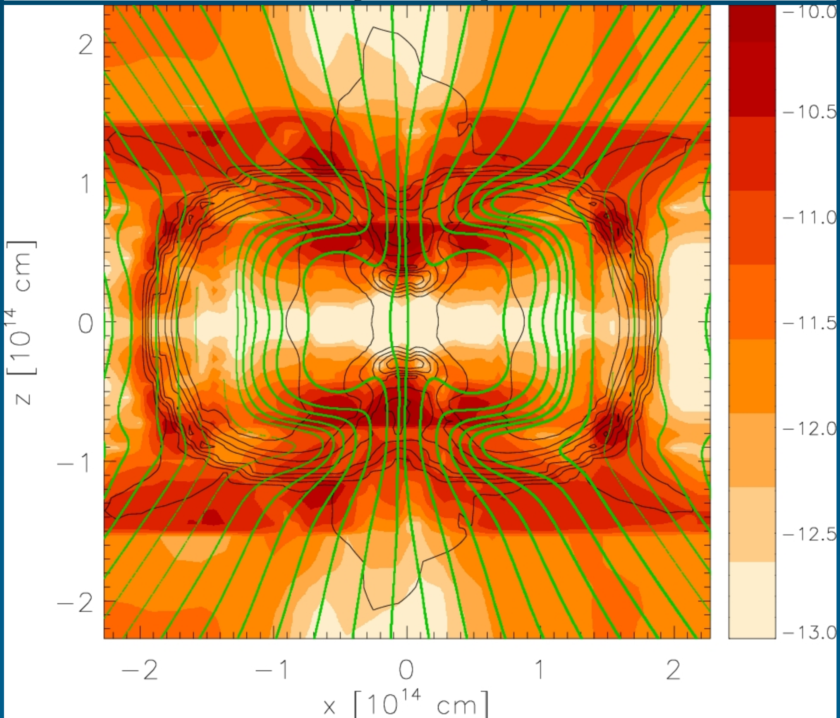
- Low mass (bottom):

  Ideal case: $B_c \propto n_c^{0.6}$

  AD case: $B_c \propto n_c^{0.47}$

- AD case matches Desch & Mouschovias (2001)





Decoupled zone (about 10 AU in extent): diffusion vs non-aligned currents

- Time evolution of magnetic field (induction equ) has two comparable terms relating to “AD”:

Top (purely diffusive):

$$\left|\nabla\times(\eta_{AD} J / \mu_o)\right|$$

Bottom (non-aligned currents): $\left|\nabla\times(\mu_o\beta_{AD}(J.B)B)\right|$

Conclusions about AD effects:

- High mass accretion persists
- Magnetic braking still efficient in collapsing cloud
- AD drift heating significant and important (C shock)
- Fragmentation more pronounced, approaching hydro results
- In these early phases, AD has not yet reduced field strength in surface of disk
- Outflows (magnetic towers) still launched, perhaps earlier
- Accretion through surface layers
- Decoupled zone forms at midplane, and out to 10 AU
  (field lines lag behind compared to active layers)