Collapse of Massive Cloud Cores

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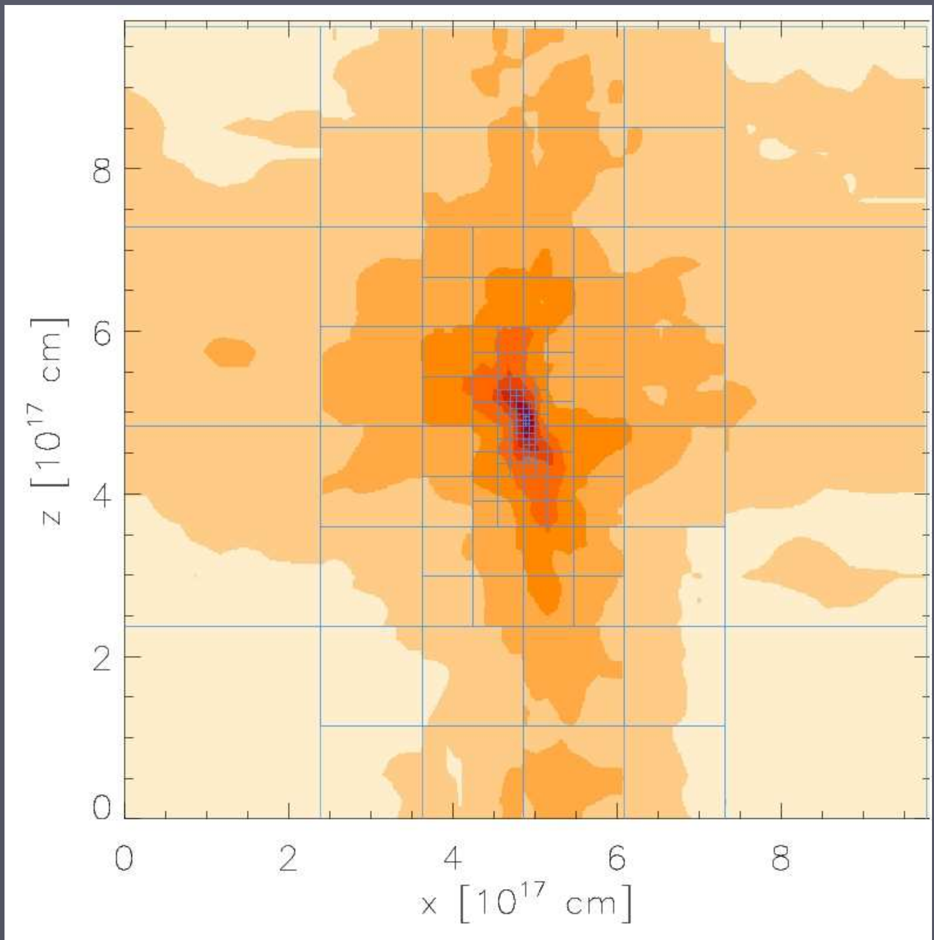
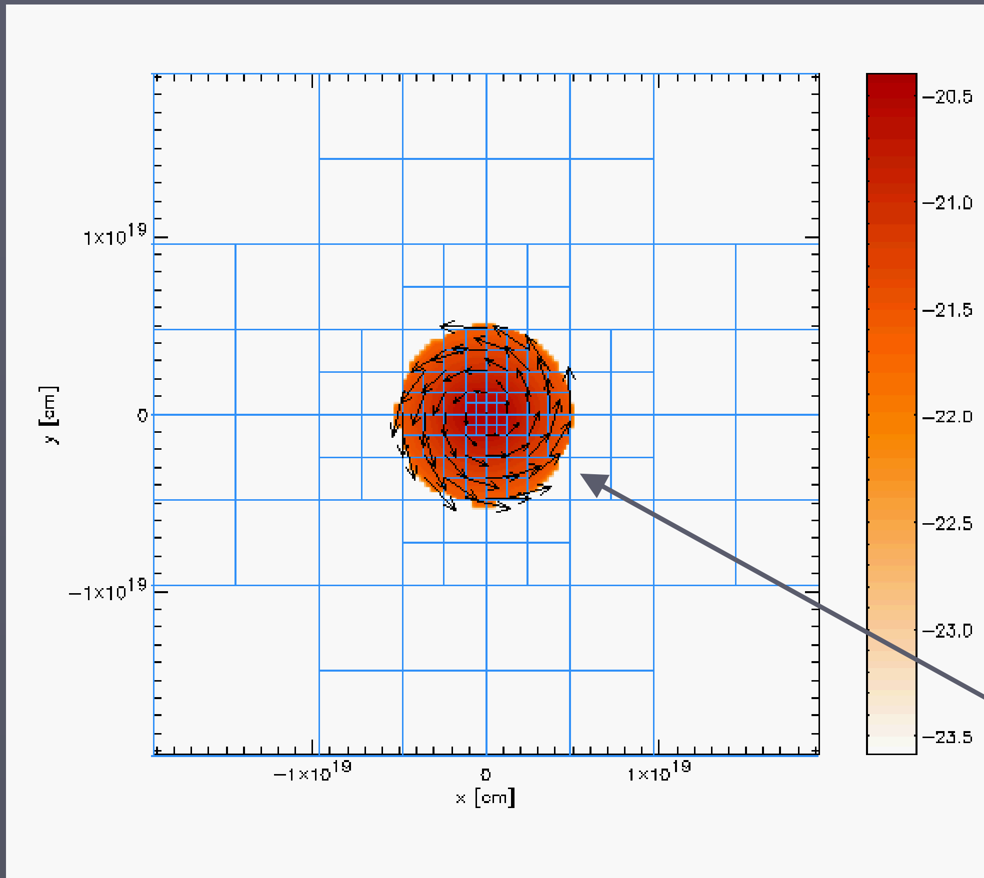
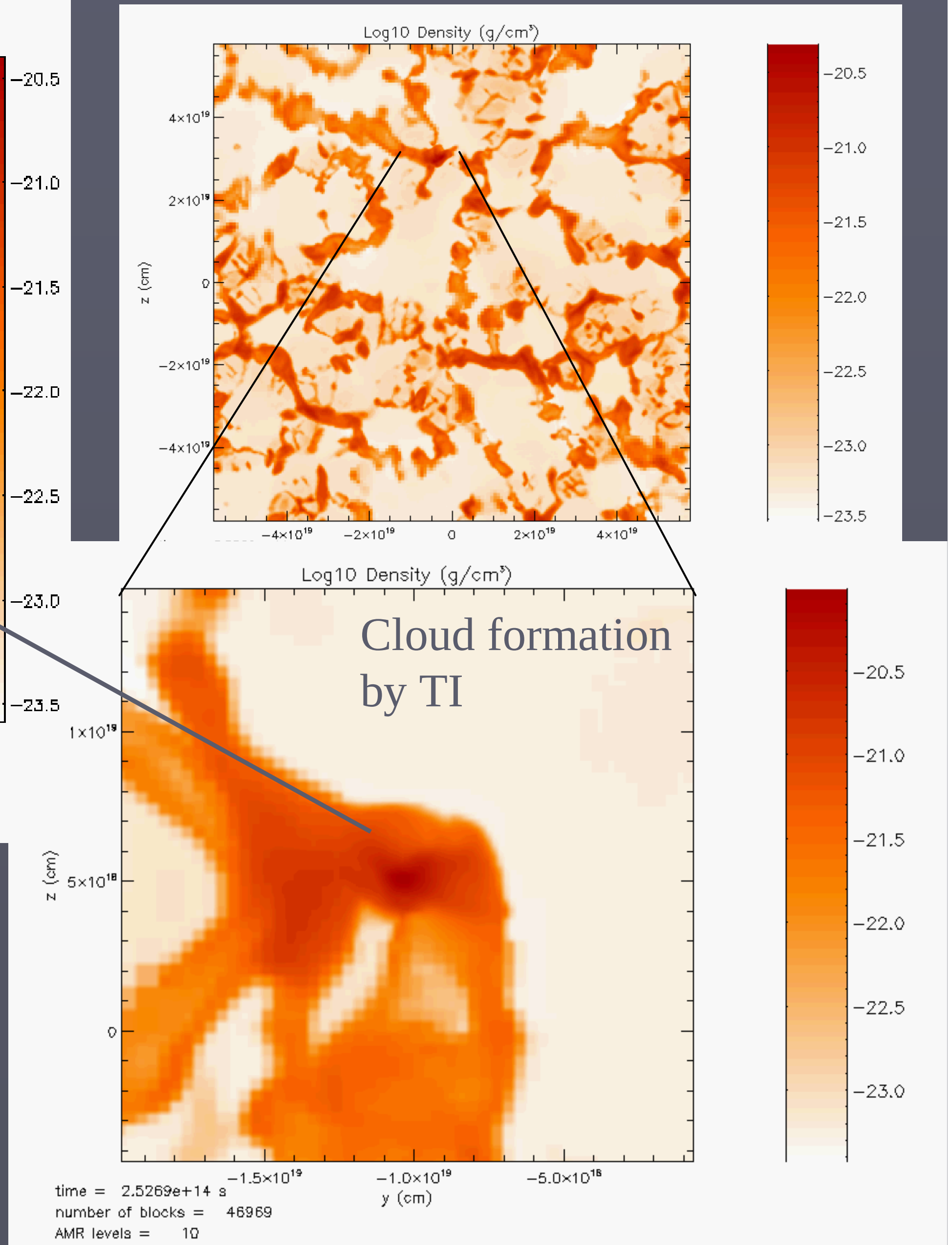


Based on 3D MHD, AMR* Simulations

*Adaptive Mesh Refinement

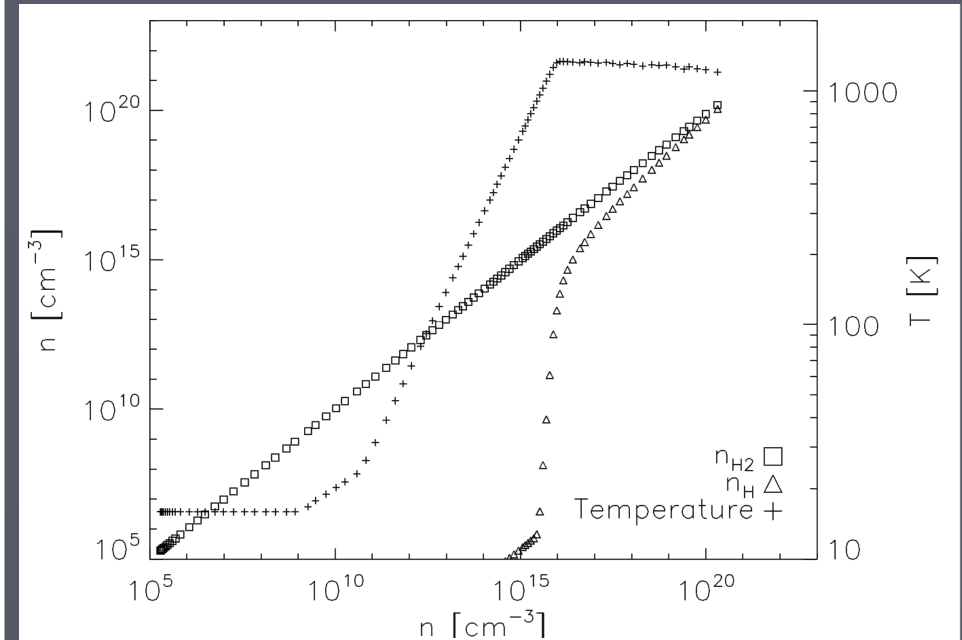
Collapse of Hydrostatic Cores

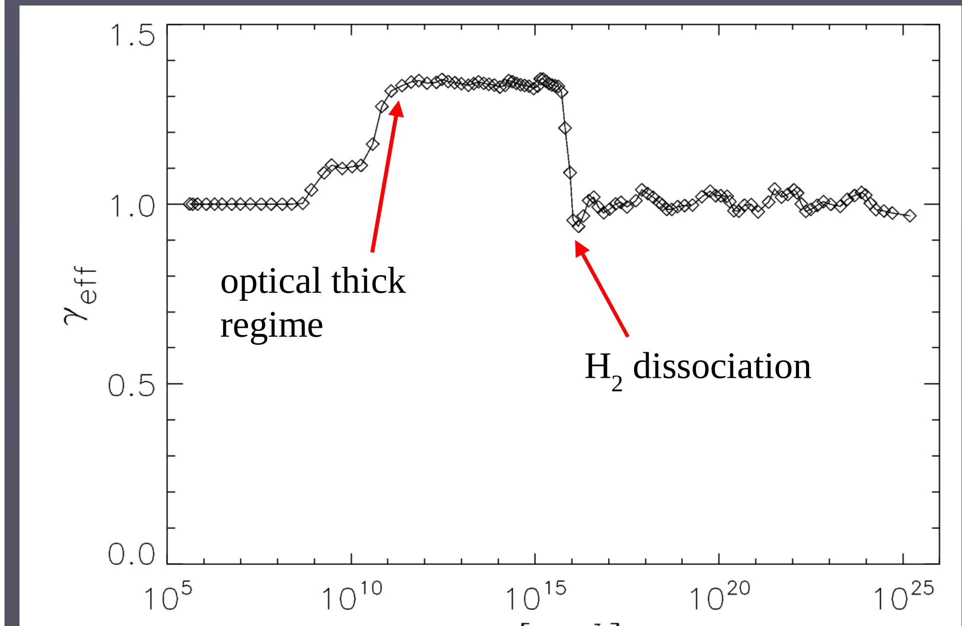




- Slowly rotating Bonnor-Ebert-Spheres
- Mass ~ 170 M_{sol}
- Radius ~ 1.6 pc
- Core density: 10^3 cm^{-3}
- Cooling due to molecular excitations, gas-dust interaction

Cooling

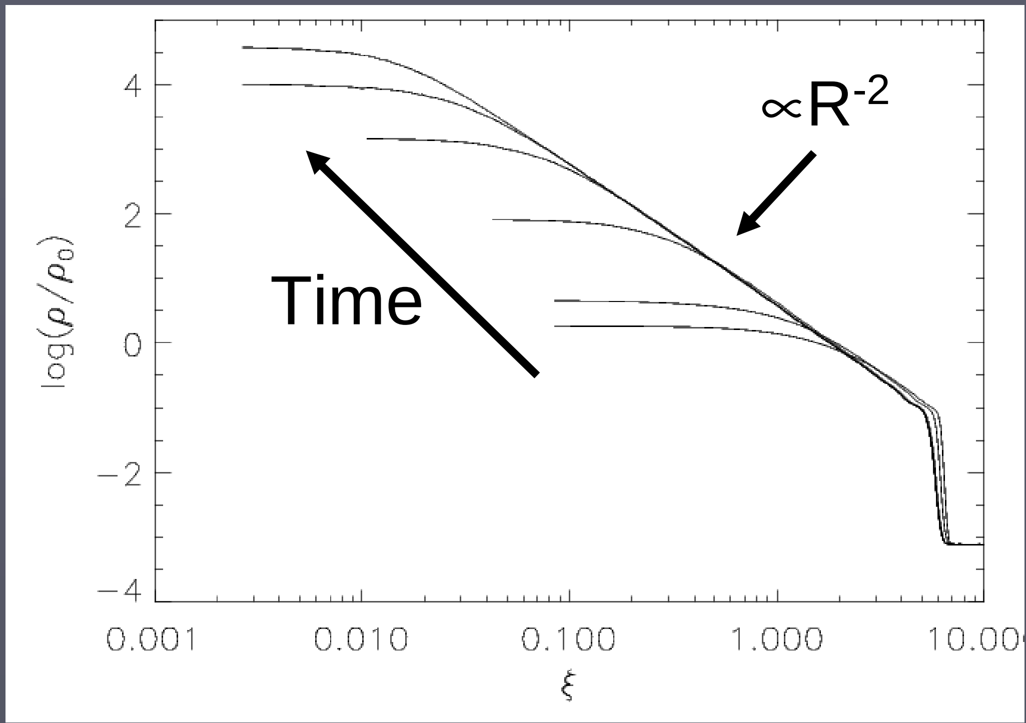


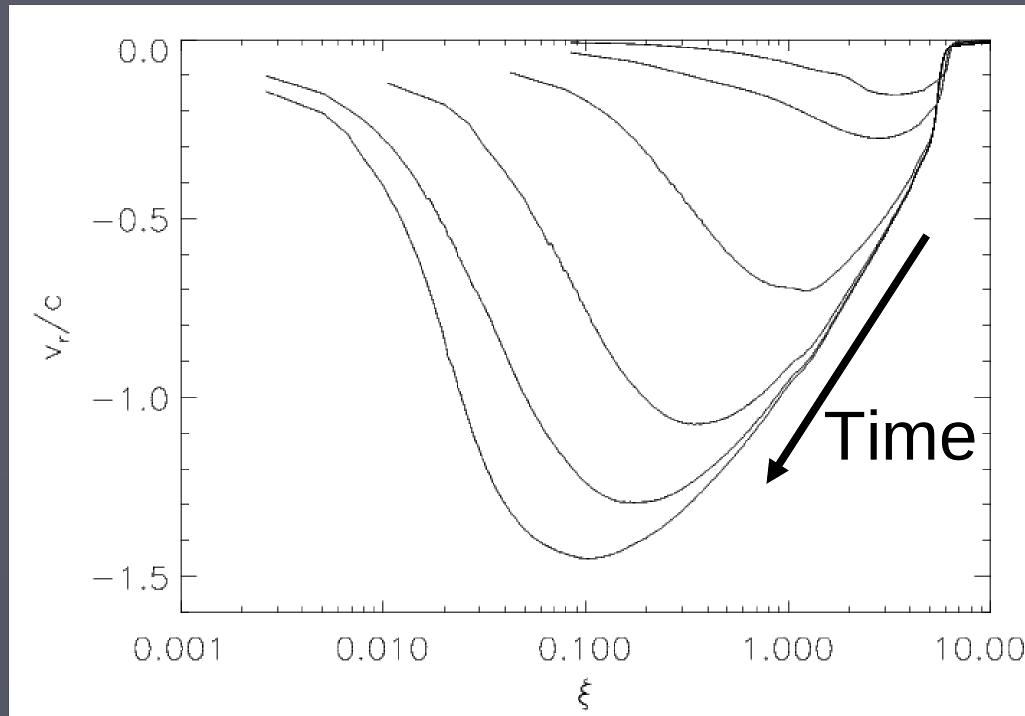


RB, Pudritz & Anderson 2006

- Molecular cooling *(Neufeld & Kaufman, 1993; Neufeld et al. 1995)*; main coolants H_2O, CO, H_2, O_2 ⇒ efficient cooling in lower density regime: $n < 10^7$
- **Dust**-gas interactions *(Goldsmith 2001)* keeps the gas isothermal until $n \sim 10^{11}\ cm^{-3}$ ⇒ scale of warm core: R = few x 10 AU
- **Optically thick** at $n \sim 10^{11}\ cm^{-3}$ ⇒ heating with $T \sim n^{1/3}$ ('local' radiation diffusion approximation)
- H_2 **dissociation** at ~ 1200 K *(Shapiro & Kang 1987)* ⇒ isothermal collapse (second collapse; *Larson 1969*)
- dissociation process is "self-regulating" due to strong temperature dependence

Isothermal Collapse





density

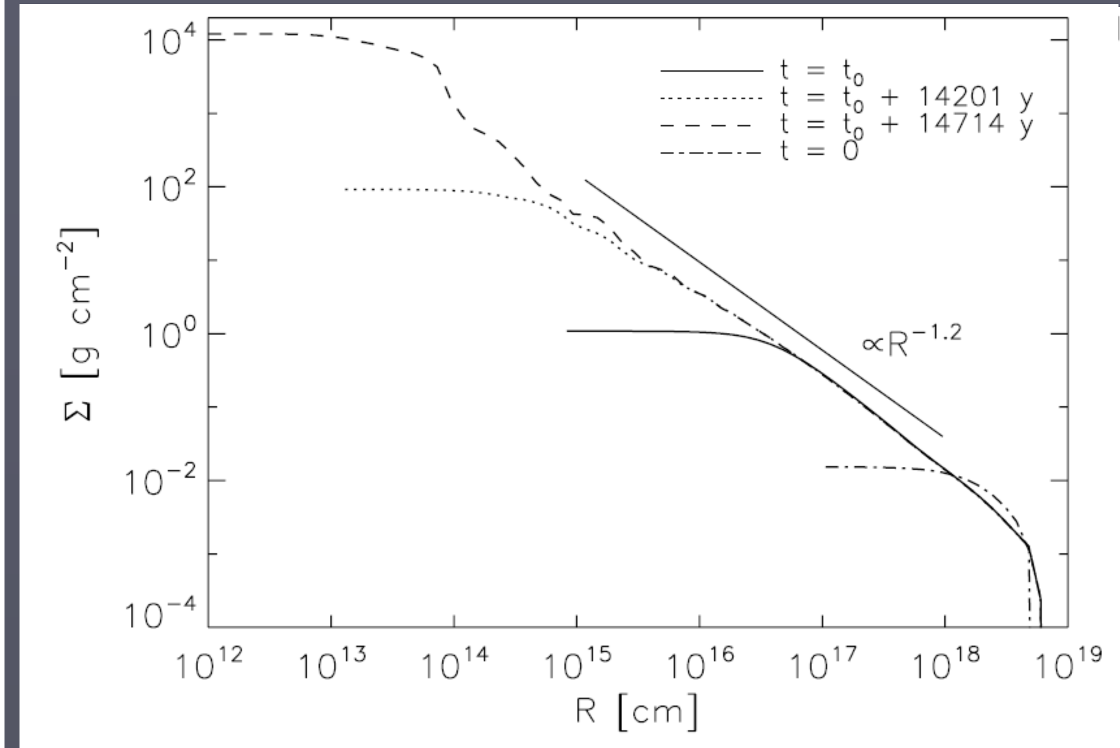
infall velocity

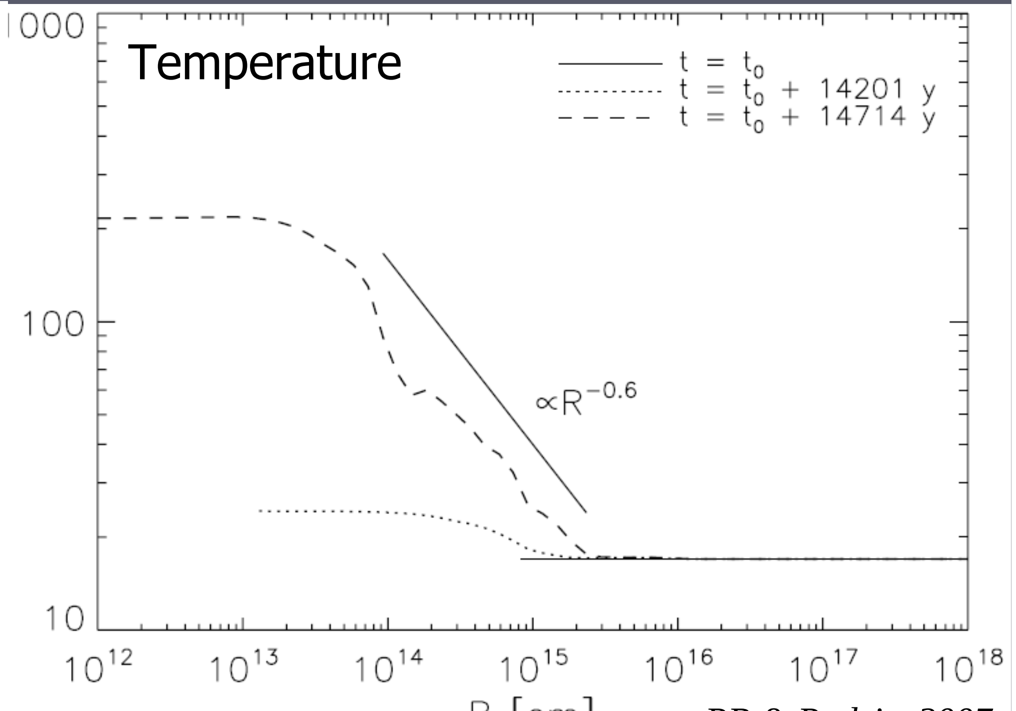
Outside-in

non-homologous collapse

(Larson ´69, Penston ´69, Forster & Chevalier ´93, Hennebelle et al. 2003 ...)

Collapse of Massive Cloud Cores

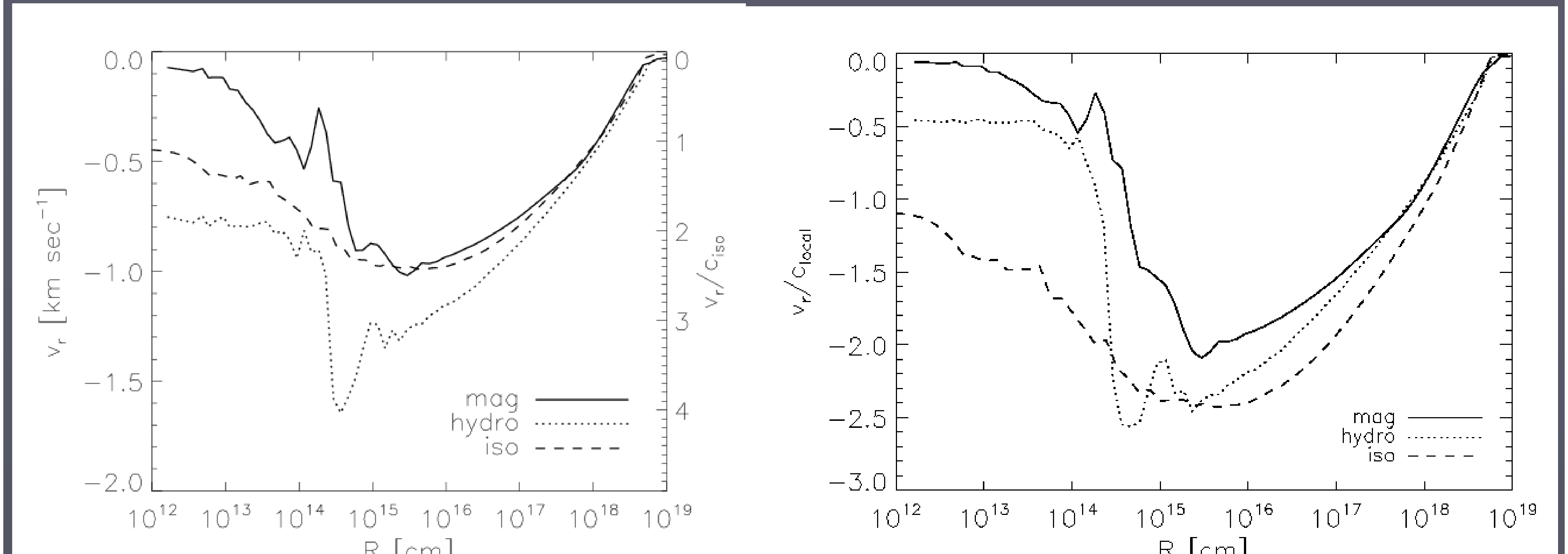




RB & Pudritz 2007

Evolution of warm core region

Collapse of Massive Cloud Cores

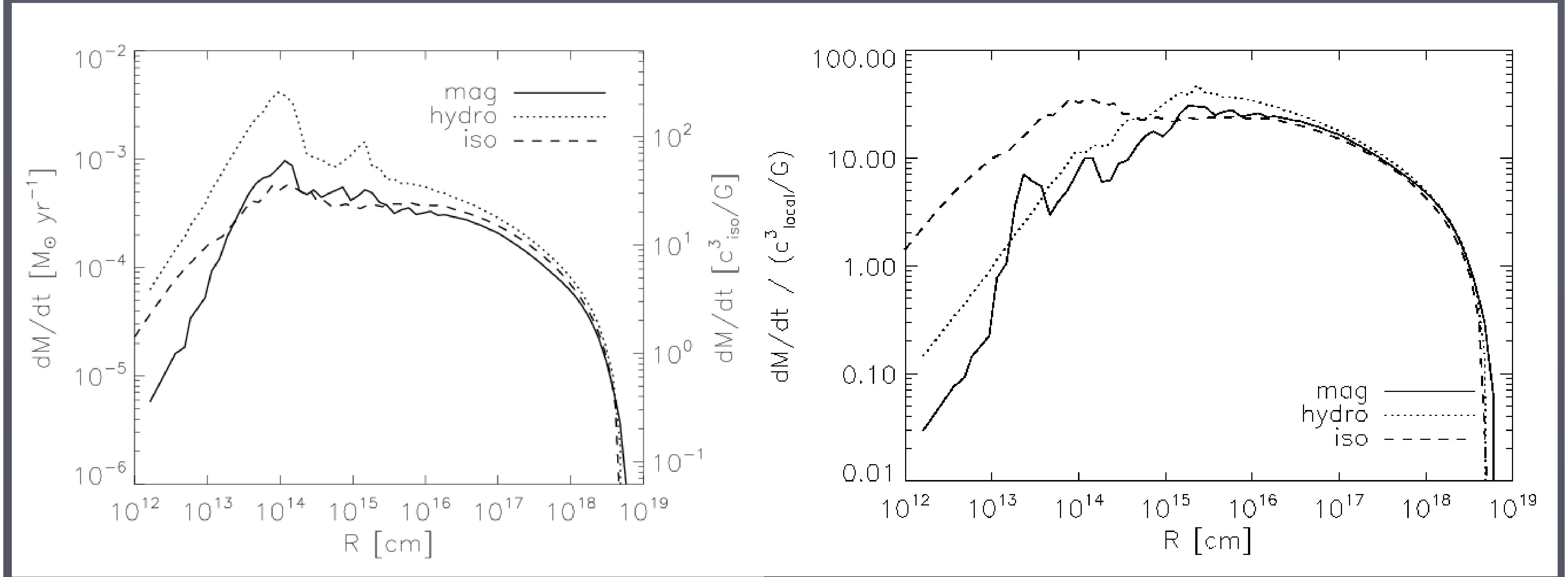


RB & Pudritz 2007

- **Supersonic** in-fall velocities
- Observations: eg. Furuya et al 2006, Beltrán 2006

Mass accretion

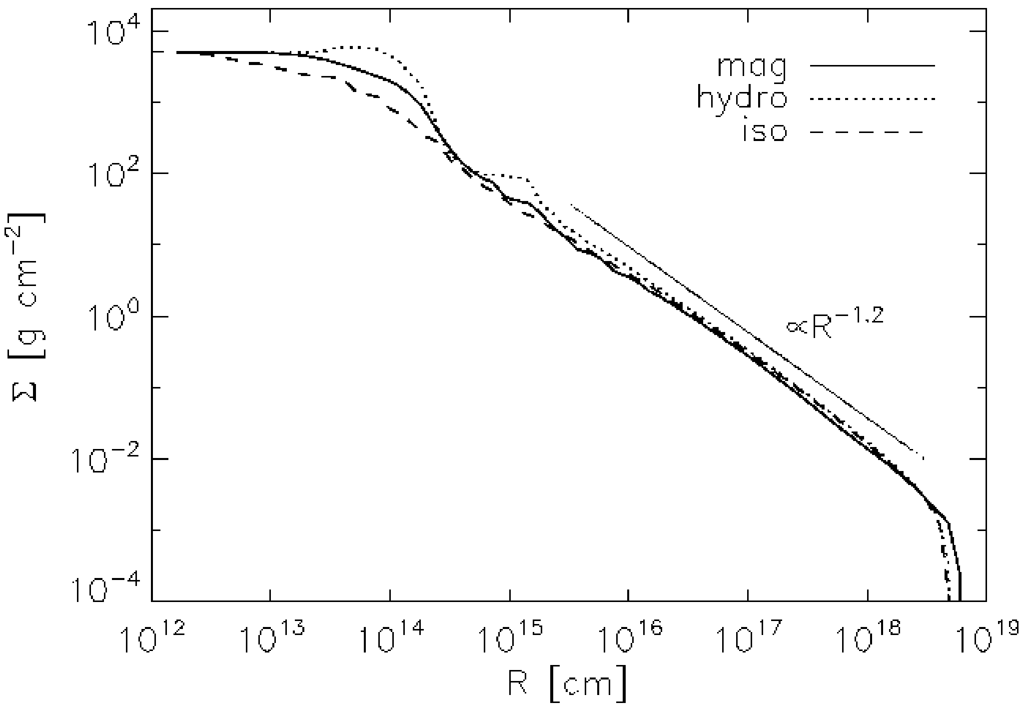
comparision

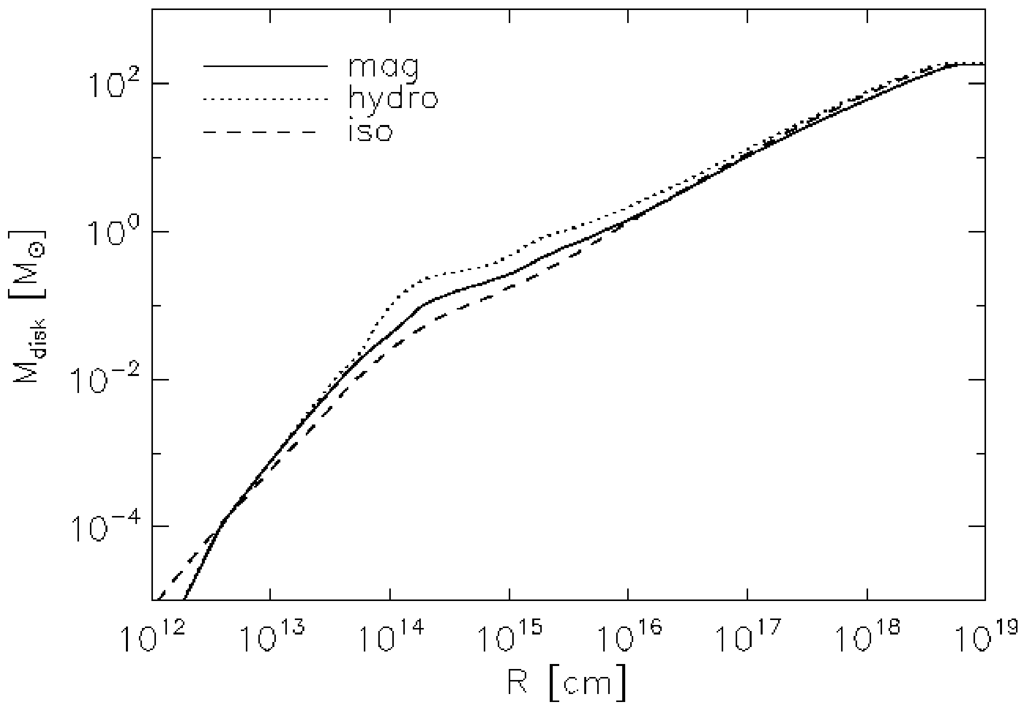


- dM/dt ~ v^3/G = $\mathrm{Mach}^3\, c^3/G >> c^3/G$
- Higher speed of sound ⇒ higher accretion rate

$$\dot{M} = 20 - 100\ c^3 / G$$

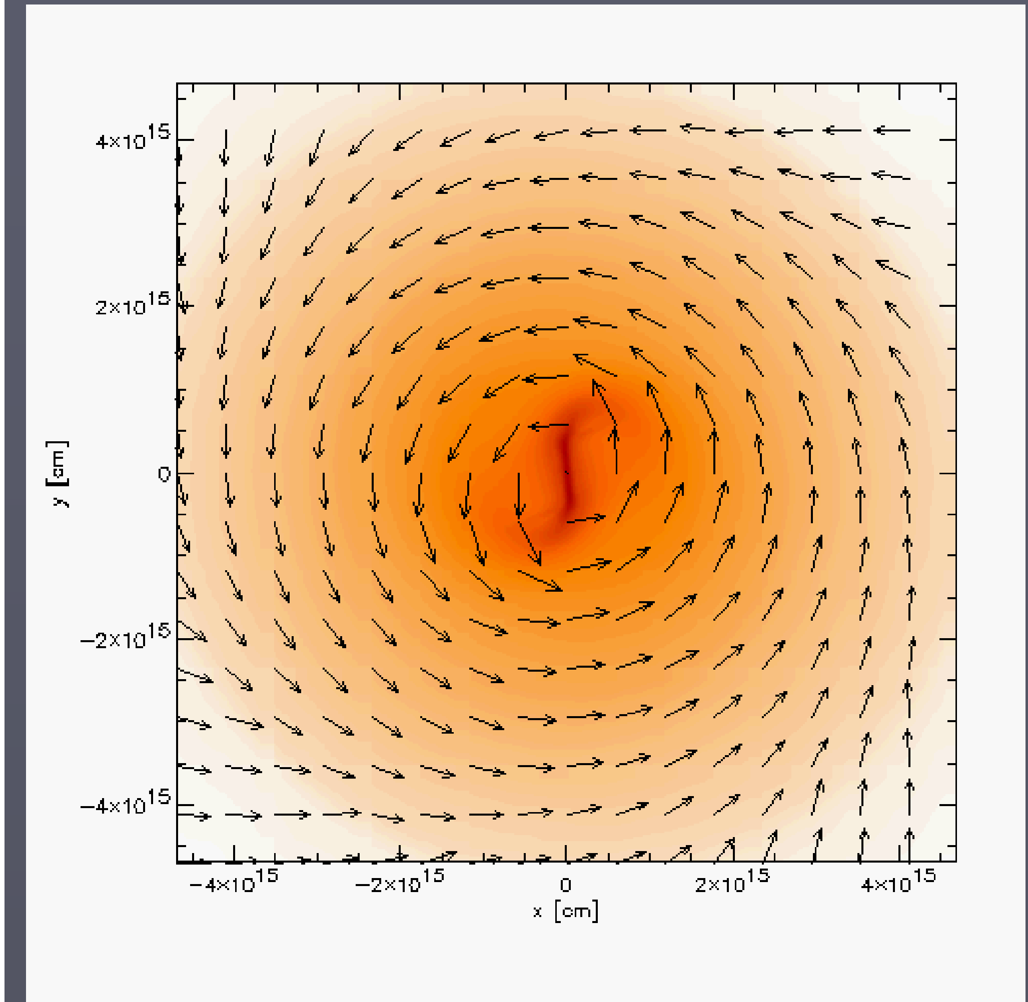
Density and Mass distribution

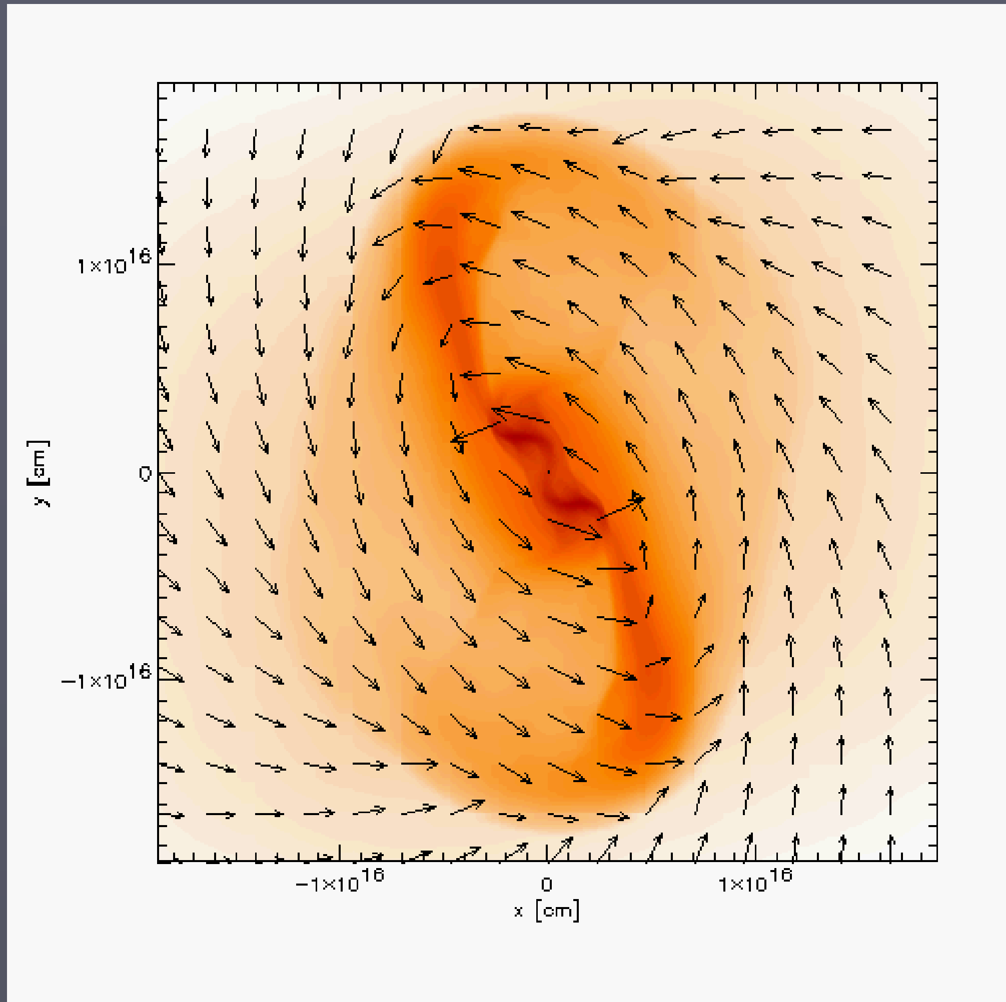




- So far disk dominated (after $t \sim t_{ff}$)
- Massive disk
- $1M_{sol}$ at few x 10^{15} cm

Disk Structure, Fragmentation





initial rotation: $t_{ff}\ \Omega = 0.1$

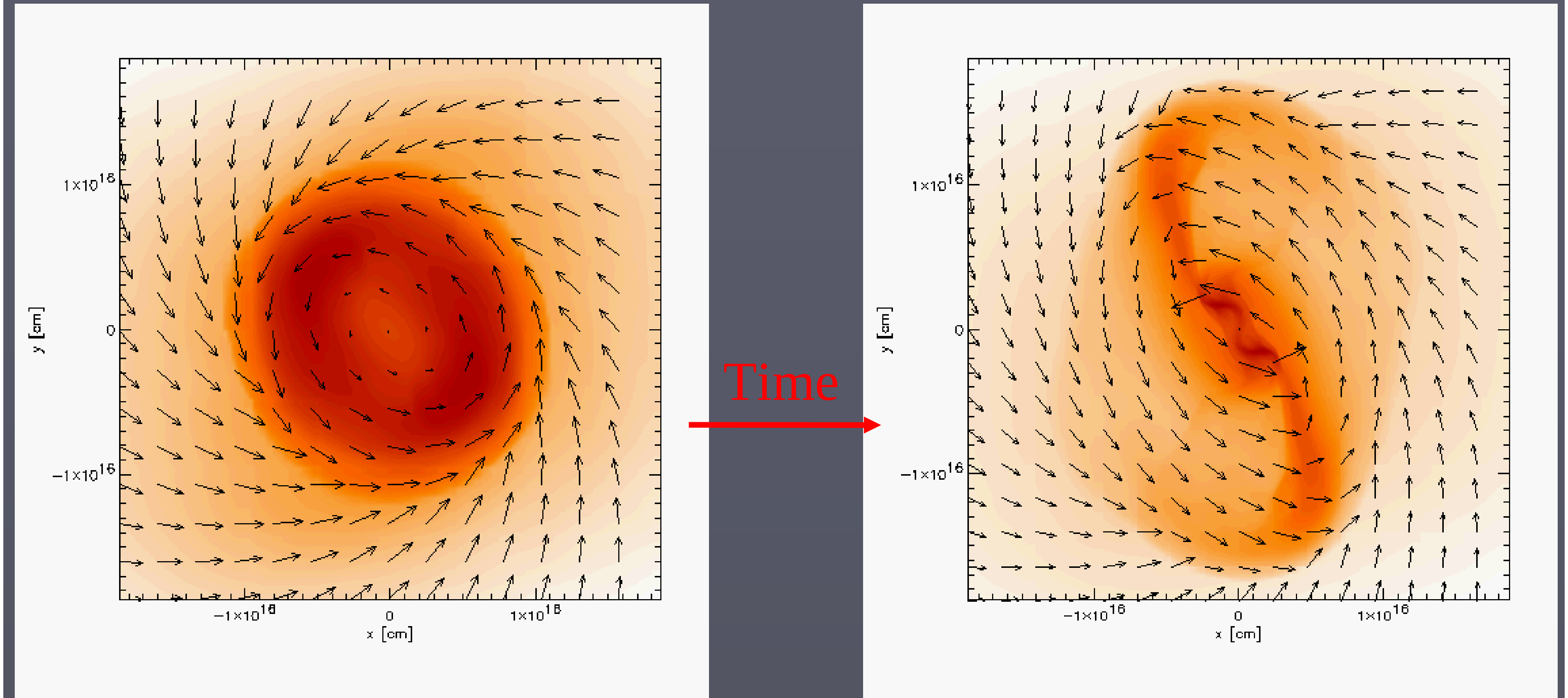
($\Omega = 2.8 \times 10^{-15}$ rad/sec)

$\Rightarrow$ bar

initial rotation: $t_{ff}\ \Omega = 0.2$

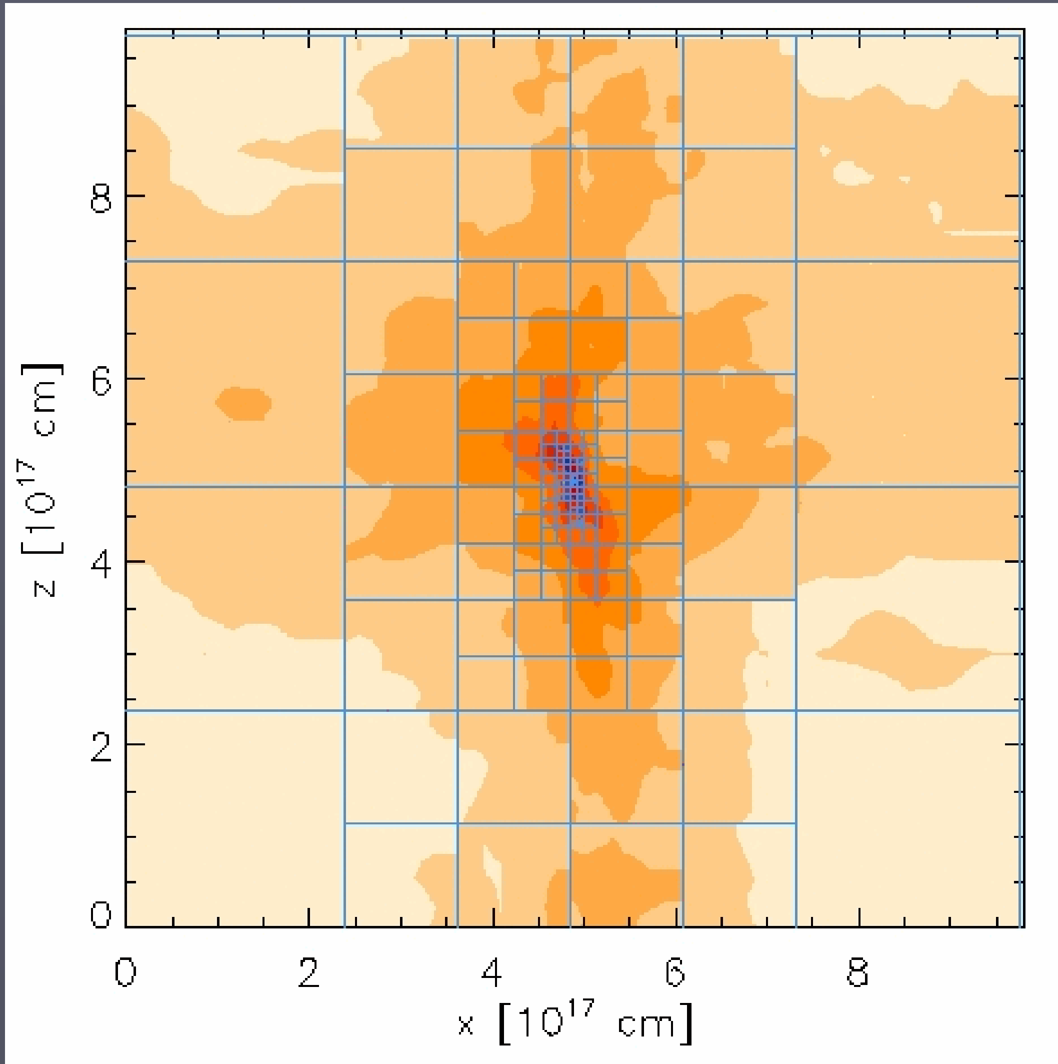
$\Rightarrow$ fragmentation into binary

Fragmentation



initial rotation $t_{ff}\ \Omega = 0.2$: ring => binary
ring size ~ 10^{16} cm (cf. inner torus in M 17, *Chini et al. 2004*, Poster: Hoffmeister, Nielbock)

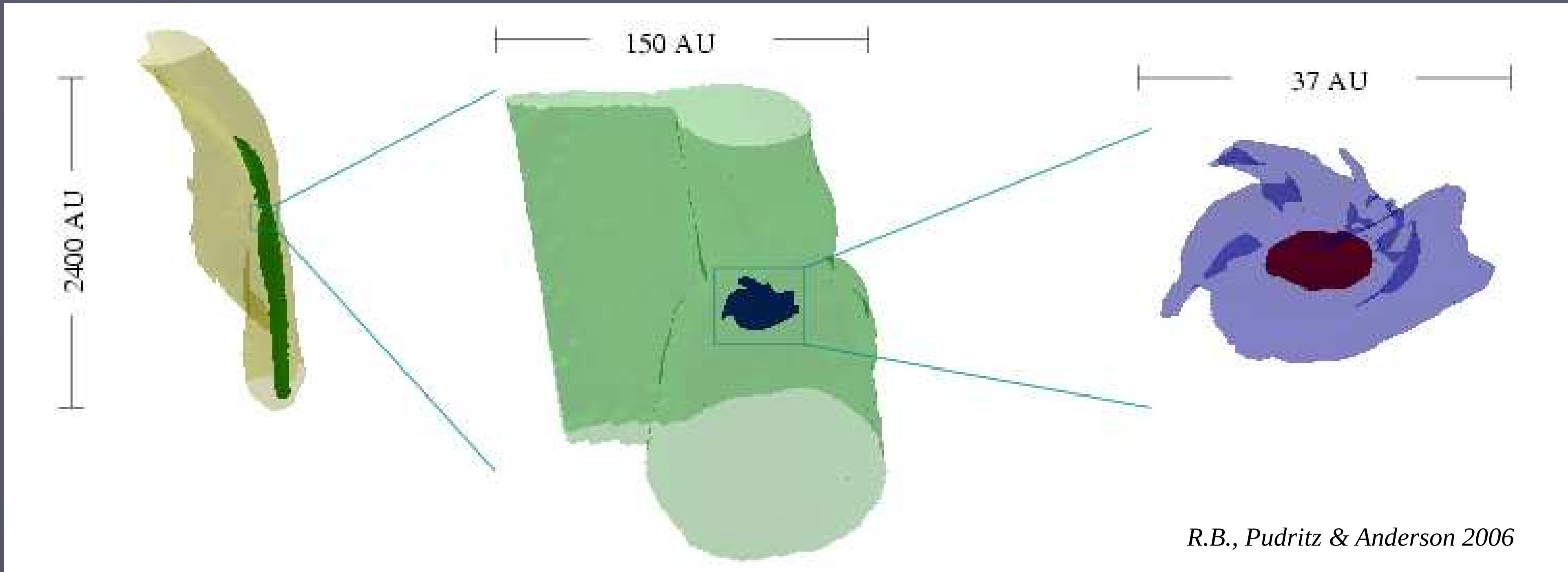
Collapse of massive turbulent cores



Initial setup as "seen" by the FLASH code

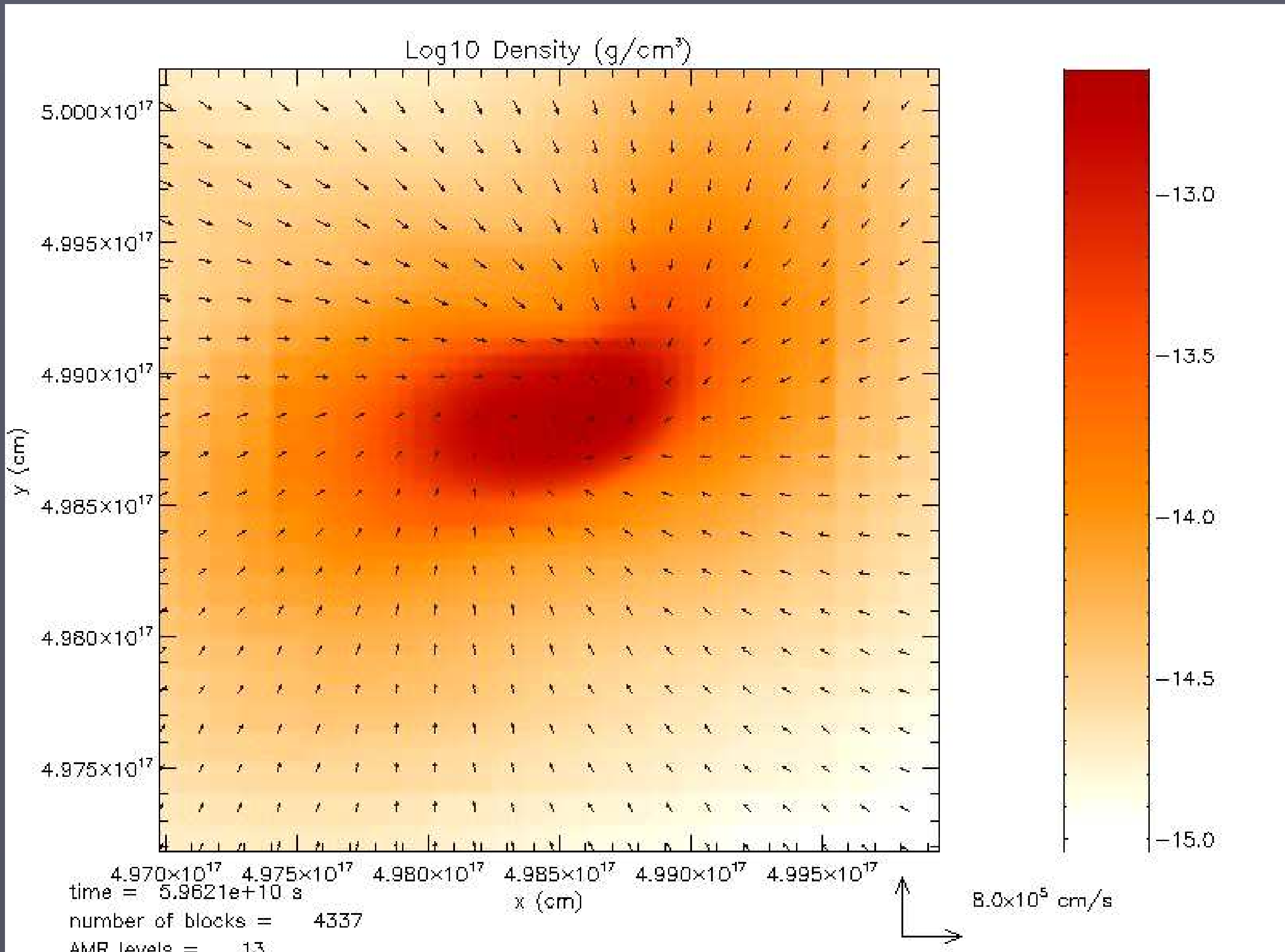
- Initial data from *Tilley & Pudritz 2004*: ZEUS simulations of core formation within a supersonic **turbulent** environment
- L = 0.32 pc, M_{tot} = 105 M_{sol}
- Follow the collapse of the densest most massive region: ~ 23 M_{sol}
- Final resolution: ~ R_{sol}

Collapse of massive turbulent cores

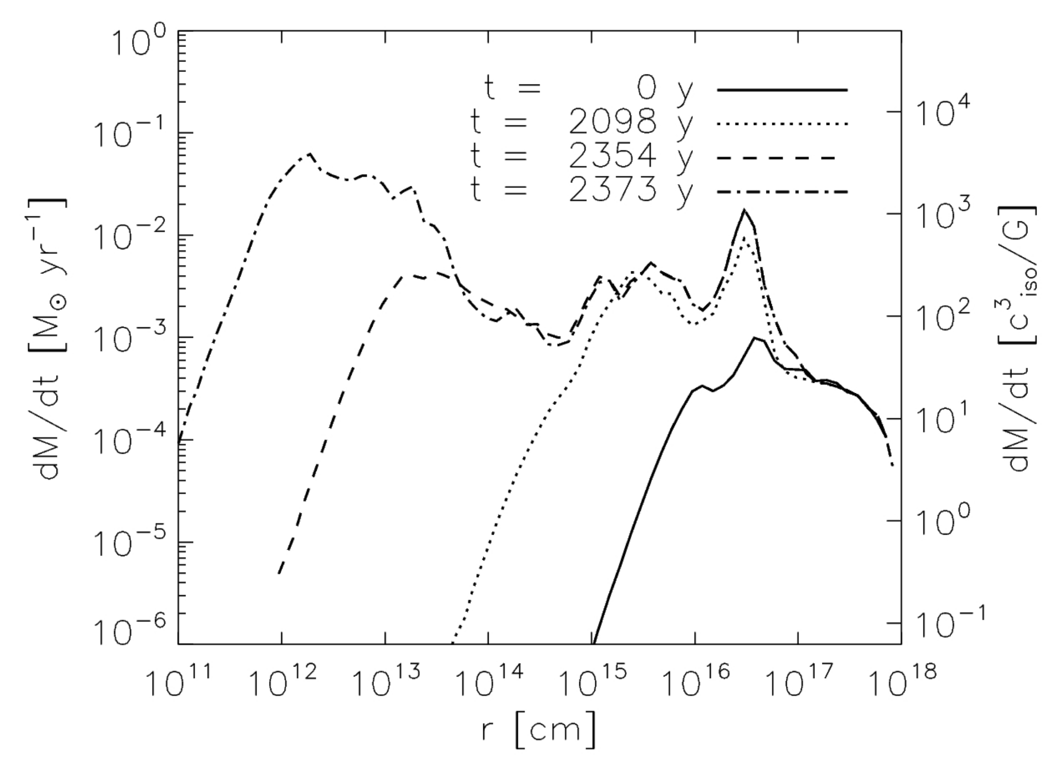


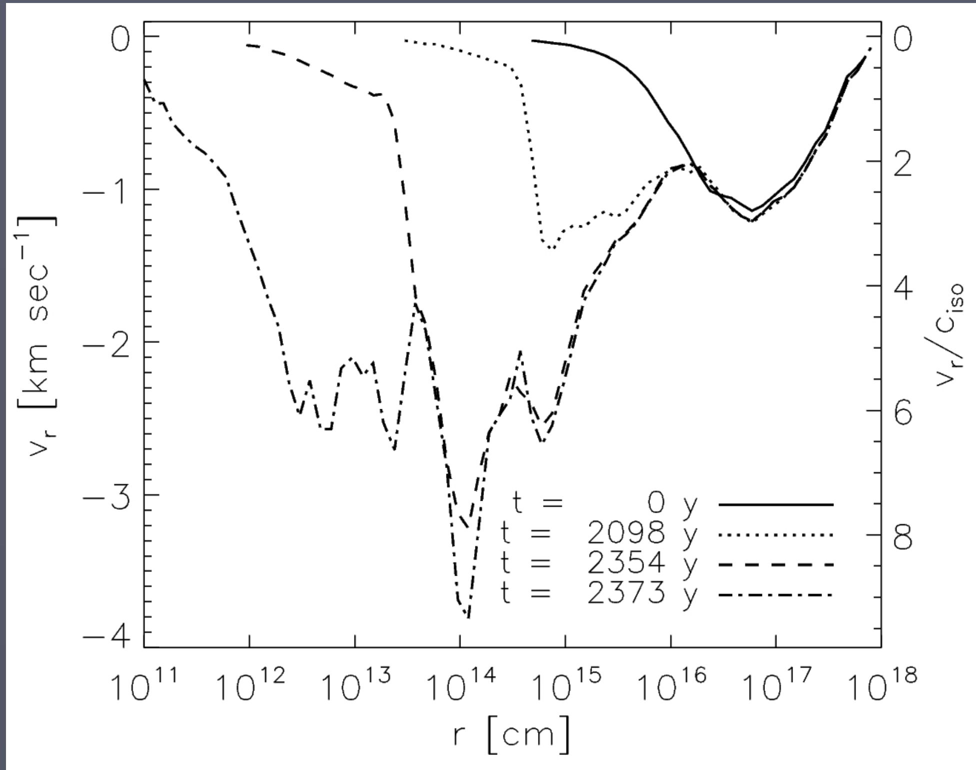
- **Filament** with an attached sheet
- small **disk** within the filament (perpendicular)
- adiabatic (optically thick) core
- very efficient gas **accretion** through the filament

Collapse of massive turbulent cores



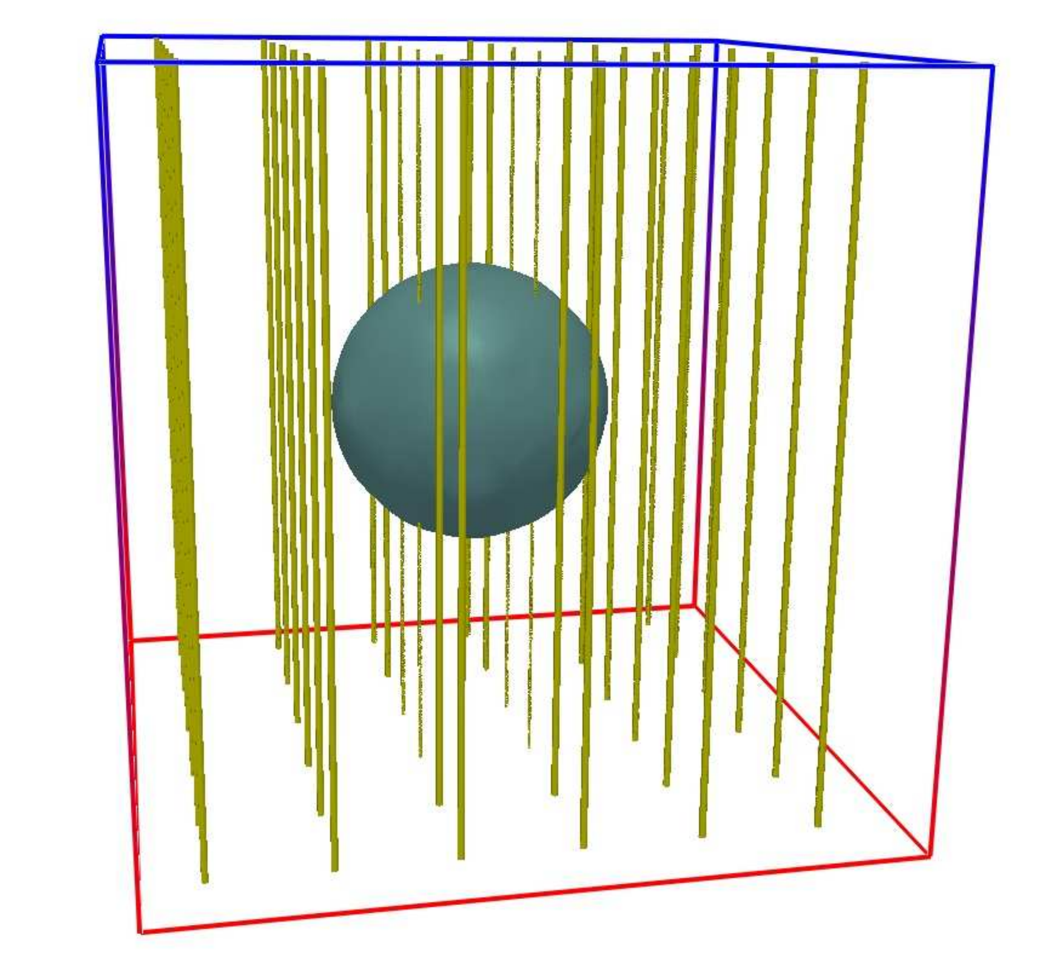
Mass accretion

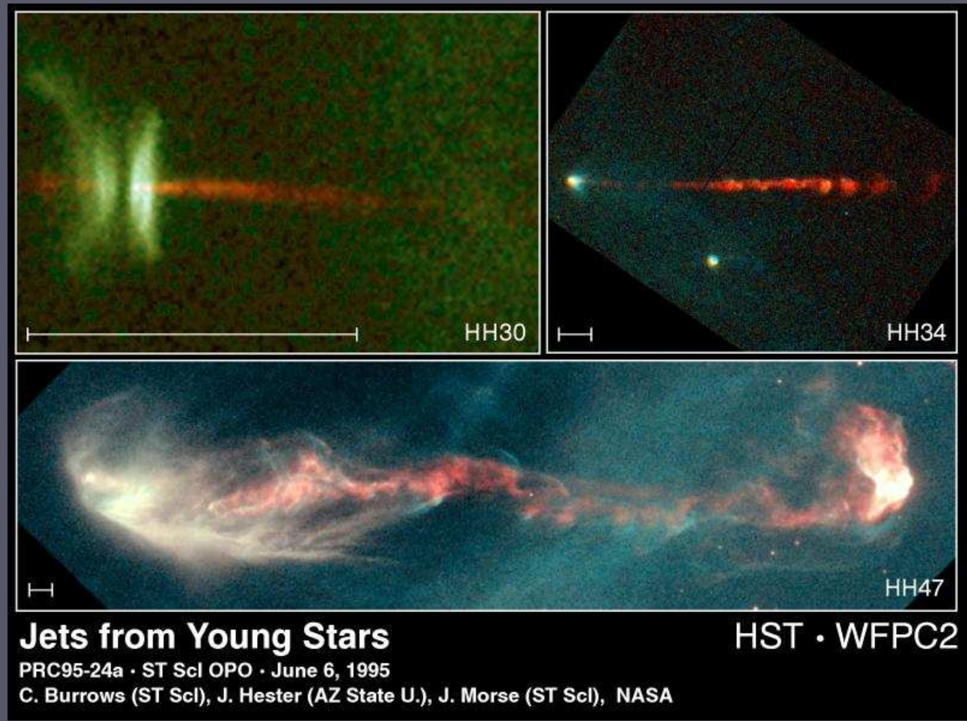




- Very **high** accretion rates: up to 10^{-3} - 10^{-2} M_{sol}/year
- Mass accretion rates are higher than limits from radiation pressure by burning **massive** stars
  (e.g. *Wolfire & Cassinelli 1987*: 10^{-3} M_{sol}/year)
- Protostars and disks assemble very **rapidly** within a supersonic turbulent environment (*McKee & Tan 2002, 2003*)

Magnetic Fields





- Jets / Outflow from YSOs magnetically driven?
- **Ideally** coupled to the gas (no ambipolar diffusion)
- Initially not dominant; $P_{therm}/P_{mag} \sim 80$; $B \sim 10\ \mu$Gauss

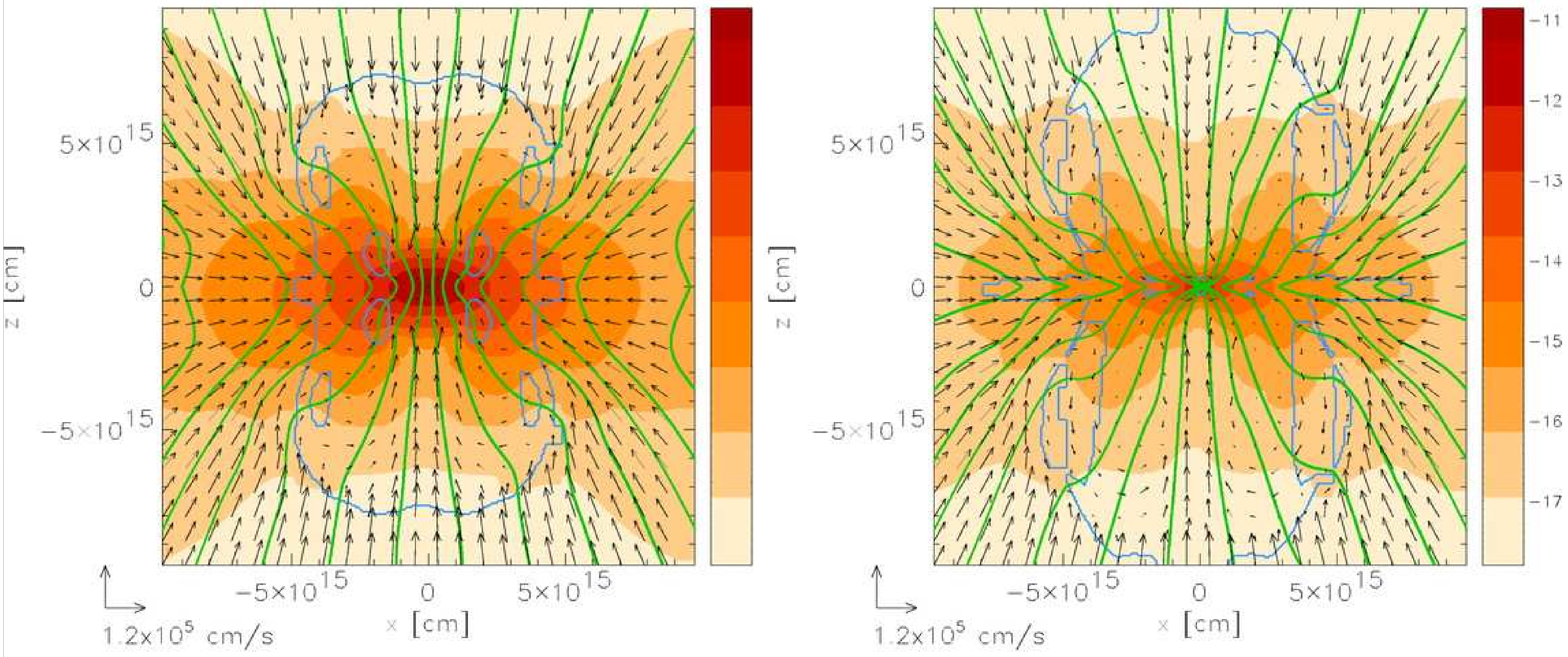
Similar simulations by:
Machida et al. 2005
Fromang et al. 2006

Onset of large scale outflow:

at few 100 AU

magnetic tower configuration (e.g. *Lynden-Bell 2003*)

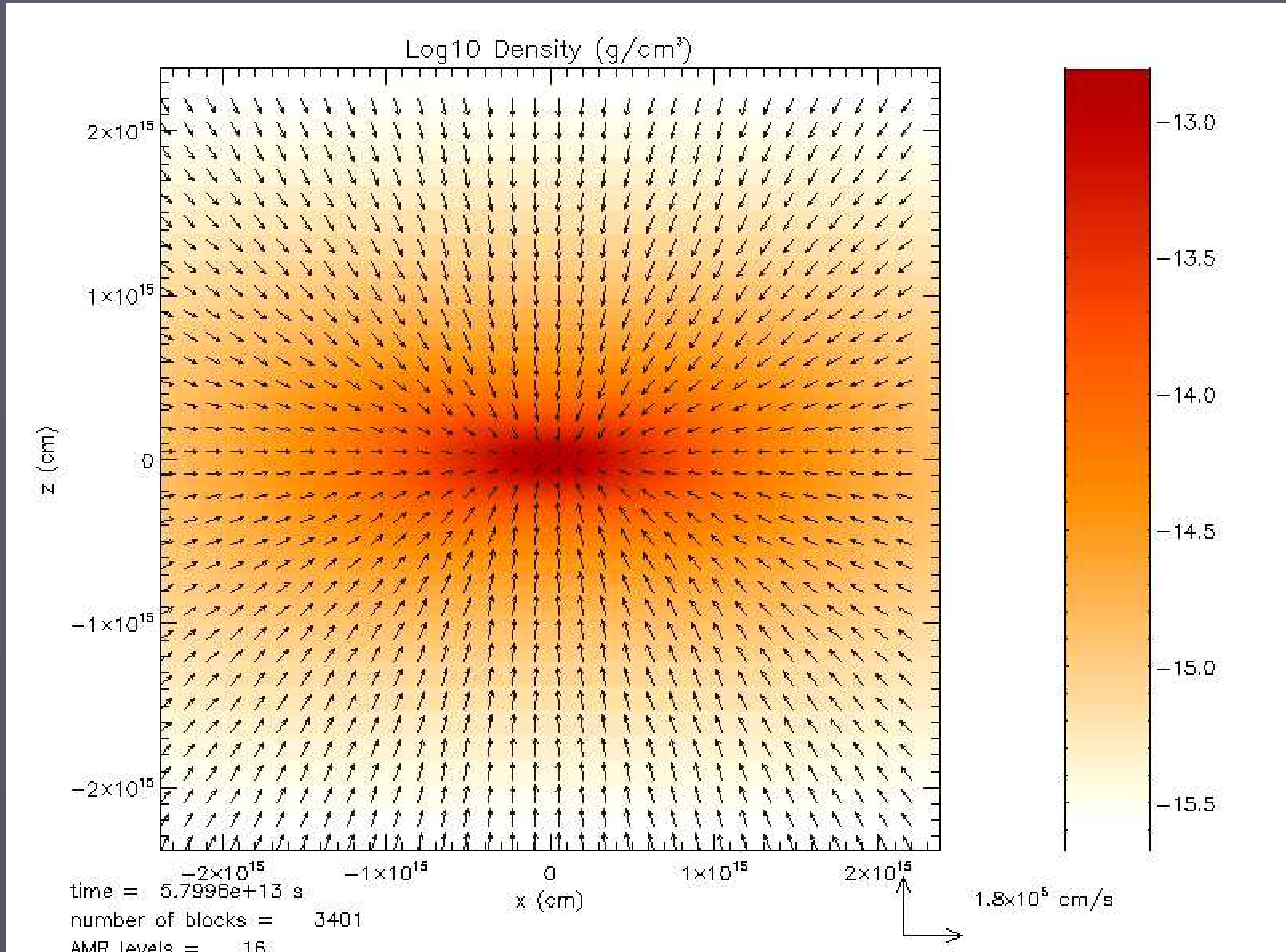
Banerjee & Pudritz 2006



collapse phase
pinched in magnetic field

.... 1430 years later:
onstet of a large scale outflow

Large scale outflow

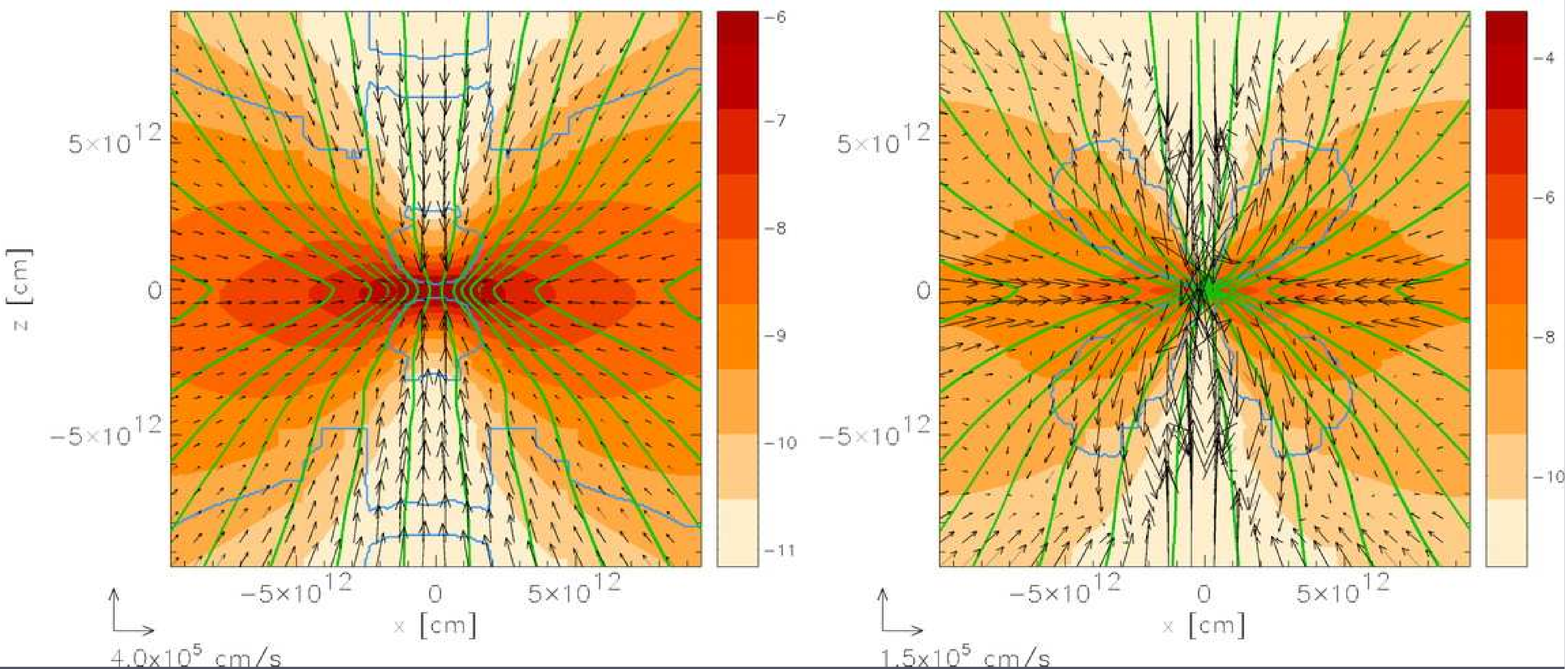


- Magnetic field is **compressed** with the gas (hourglass configuration)
- Rotating disk generates **toroidal** magnetic field
- Shock fronts are pushed outwards (magnetic tower; *Lynden-Bell 2003*)
- Outflow velocities v ~ 0.4 km/sec
- Accretion funneled along the rotation axis and through the disk

Onset of inner disk jet

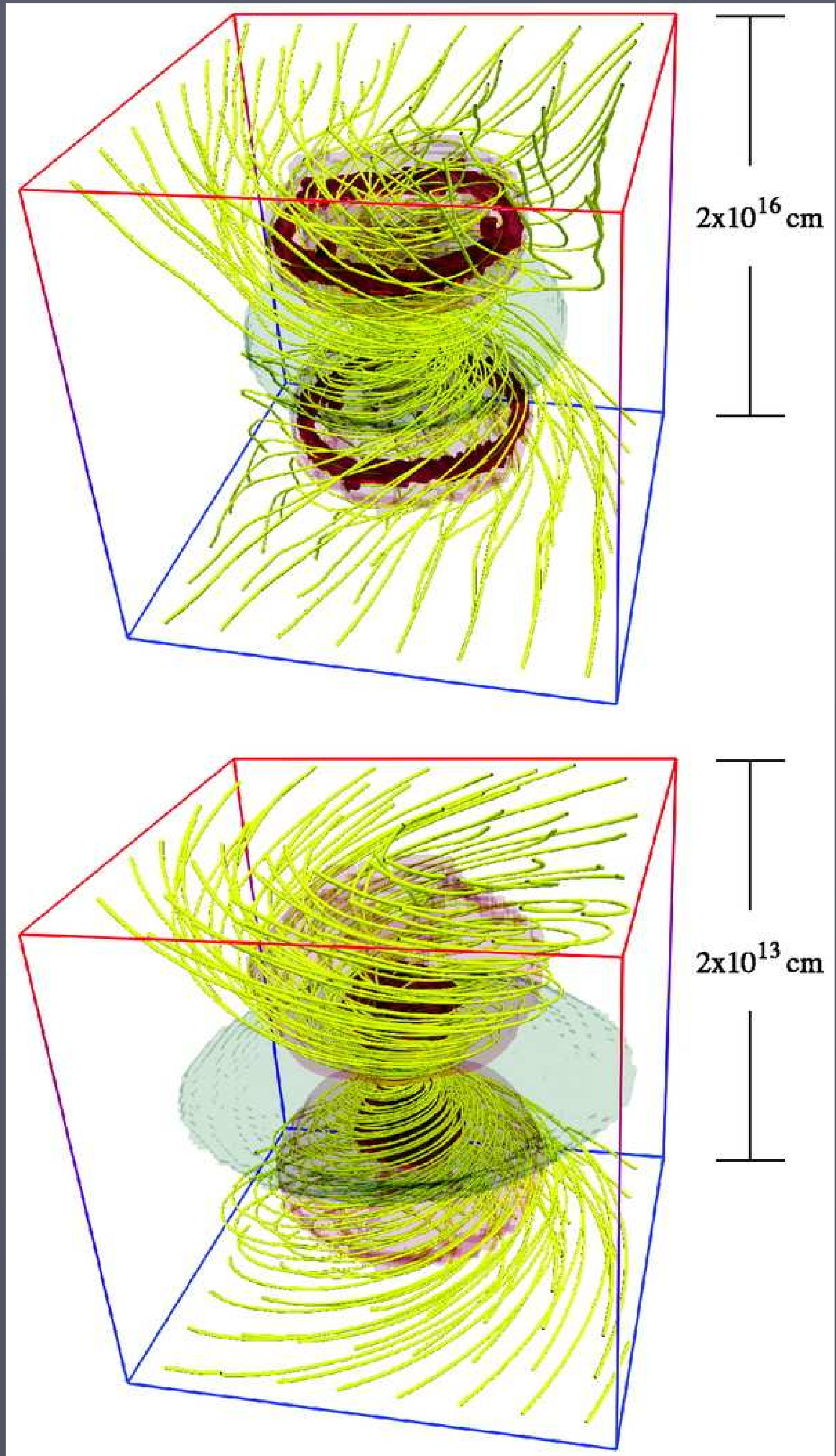
launch inside 0.07 AU

- magneto-centrifugally launched jet (*Blandford & Payne 1982*)
- jets rotate and carry off angular momentum of disk

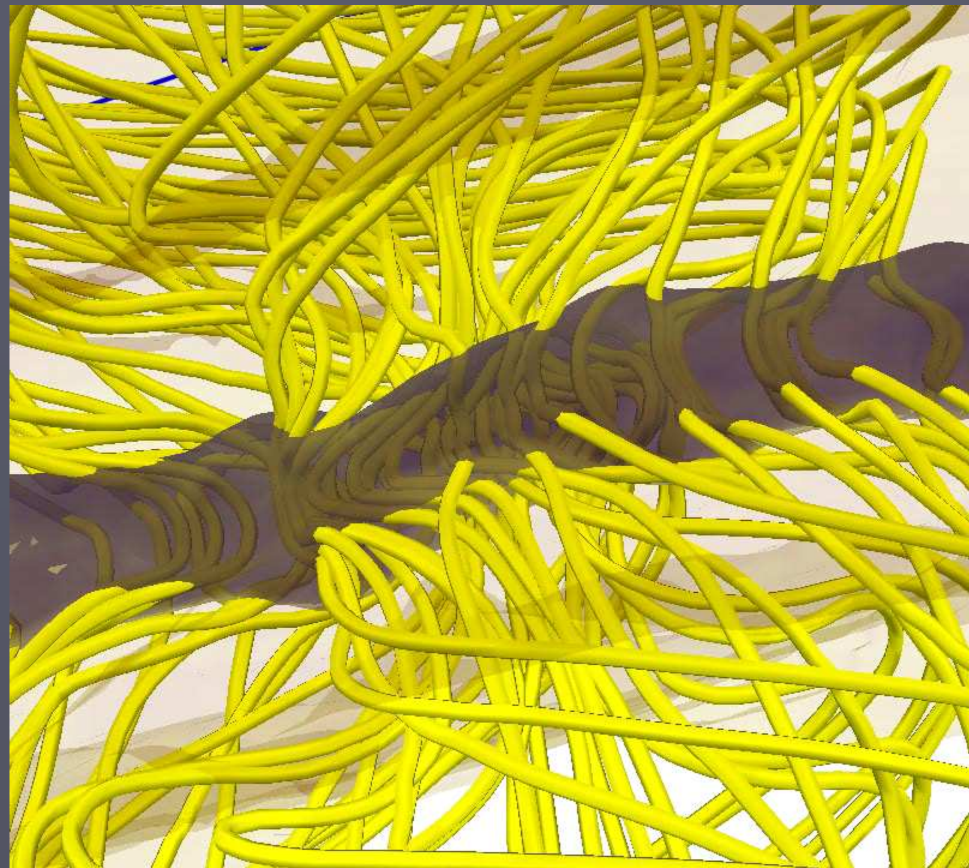


infall only

... 5 month later: flow reversal



3D Visualization of field lines, disk, and outflow:
- Upper; magnetic tower flow
- Lower; zoomed in by 1000, centrifugally driven disk wind

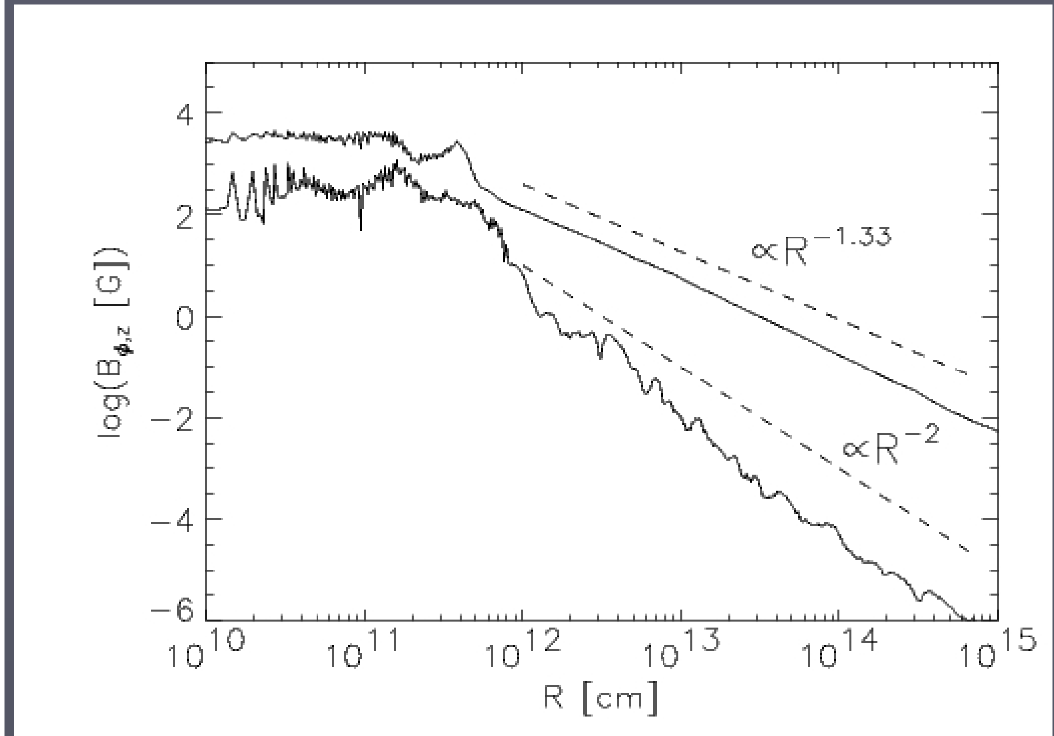


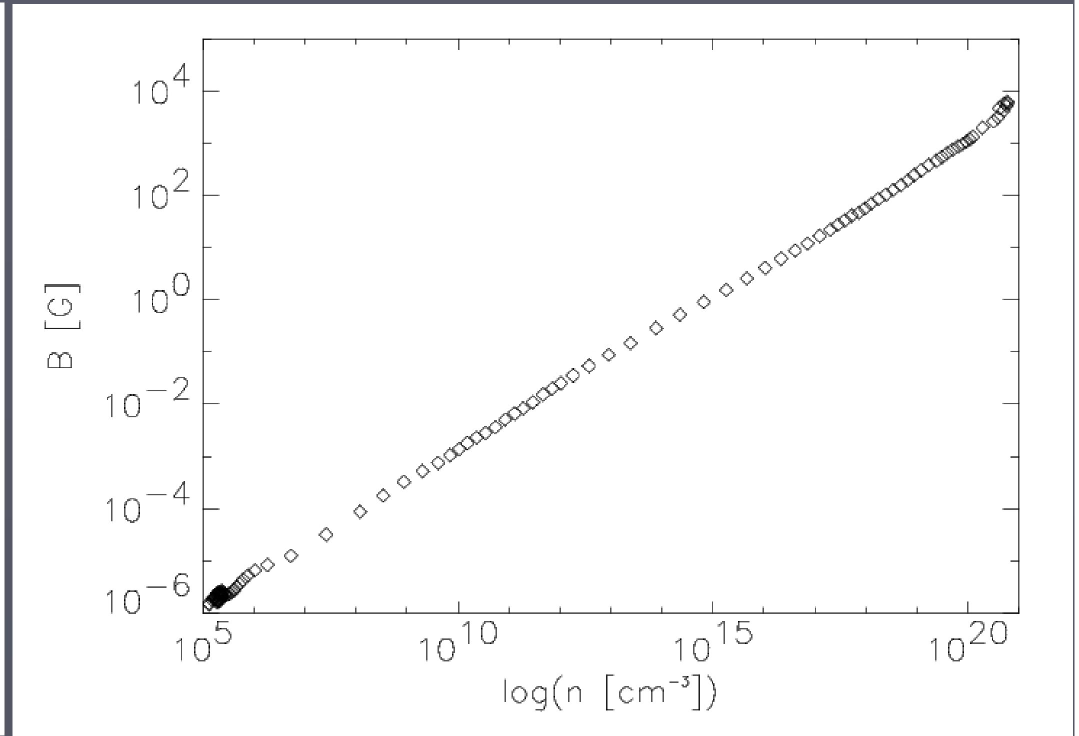
Observations: FU Ori disk
Donati et al. Nature 2005

Summary

- Supersonic infall velocities
- High accretion rates, up to 10^{-3} M_{sol}/year
  $dM/dt \sim v^3/G = Mach^3\, c^3/G$
- Quick massive star assembly ~ few x 10^4 years
- Large massive disks possible
- Binary formation in the disk
- Outflows and Jets launched already during early collapsing phase
- Outflow blown cavities (channels for radiation pressure, *Krumholz et al. 2005*)

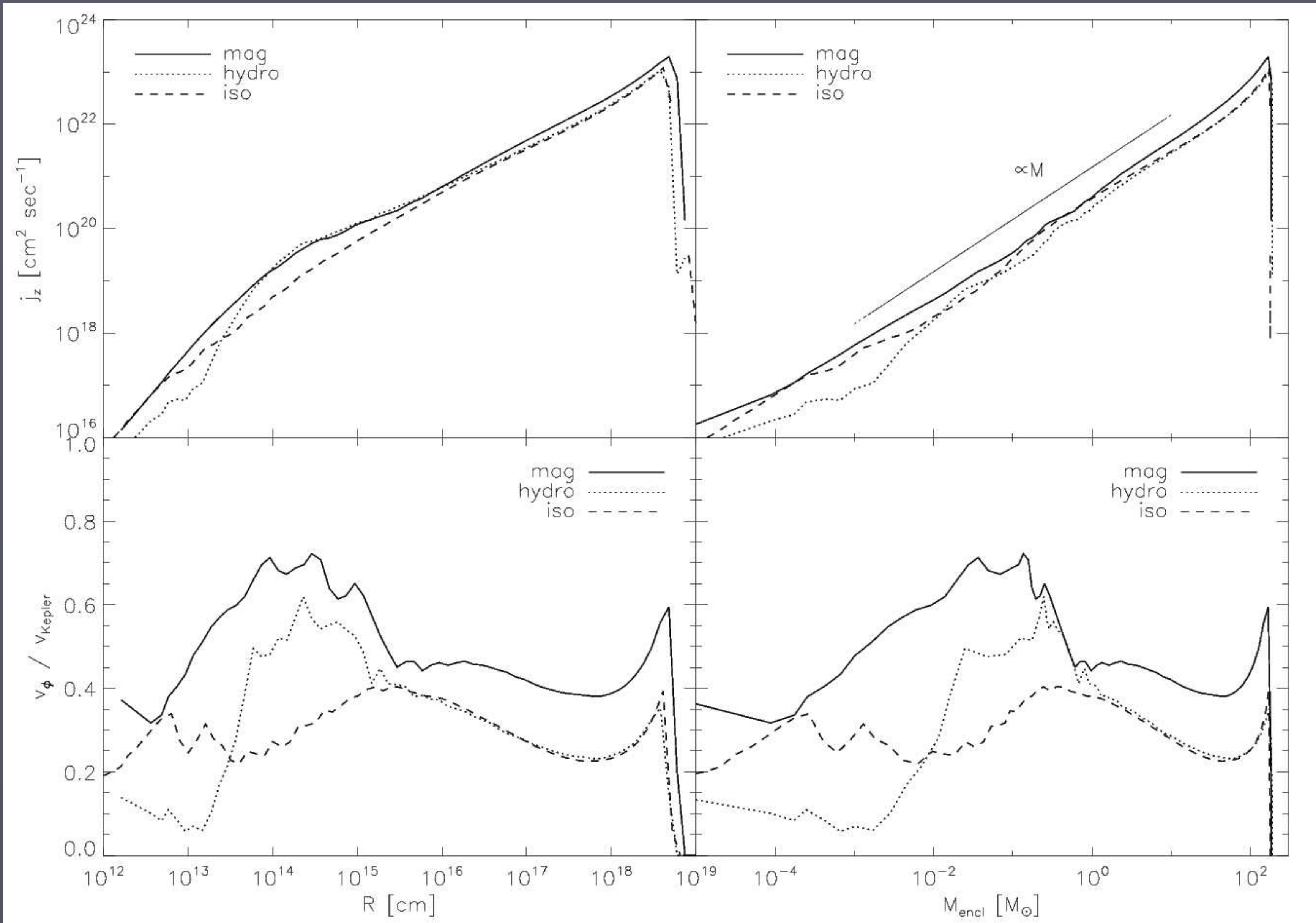
Magnetic field structure / evolution





- $B_z > B_\phi$ in the core and disk (expectation from a stationary accretion disk $B \propto R^{-1.25}$; *Blandford & Payne 1982*)
- $B_{core} \propto n^{0.6}$
- Expected field strength in the protostar ~ $10^4 – 10^5$ G
- Potential seed field for Ap stars *(Braithwaite & Spruit, 2004)*

Angular Momentum



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