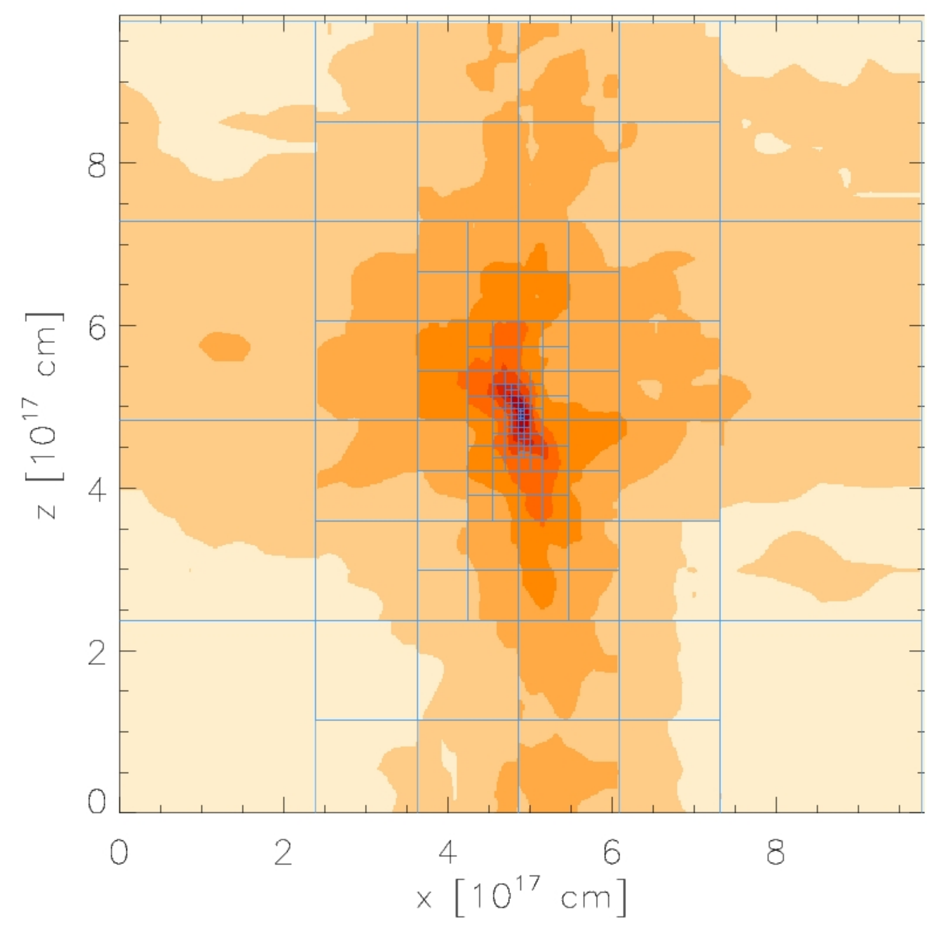
Modelling Star Formation with AMR[*] Simulations

Robi Banerjee

ITA



3D MHD, AMR Simulations of collapsing cloud cores

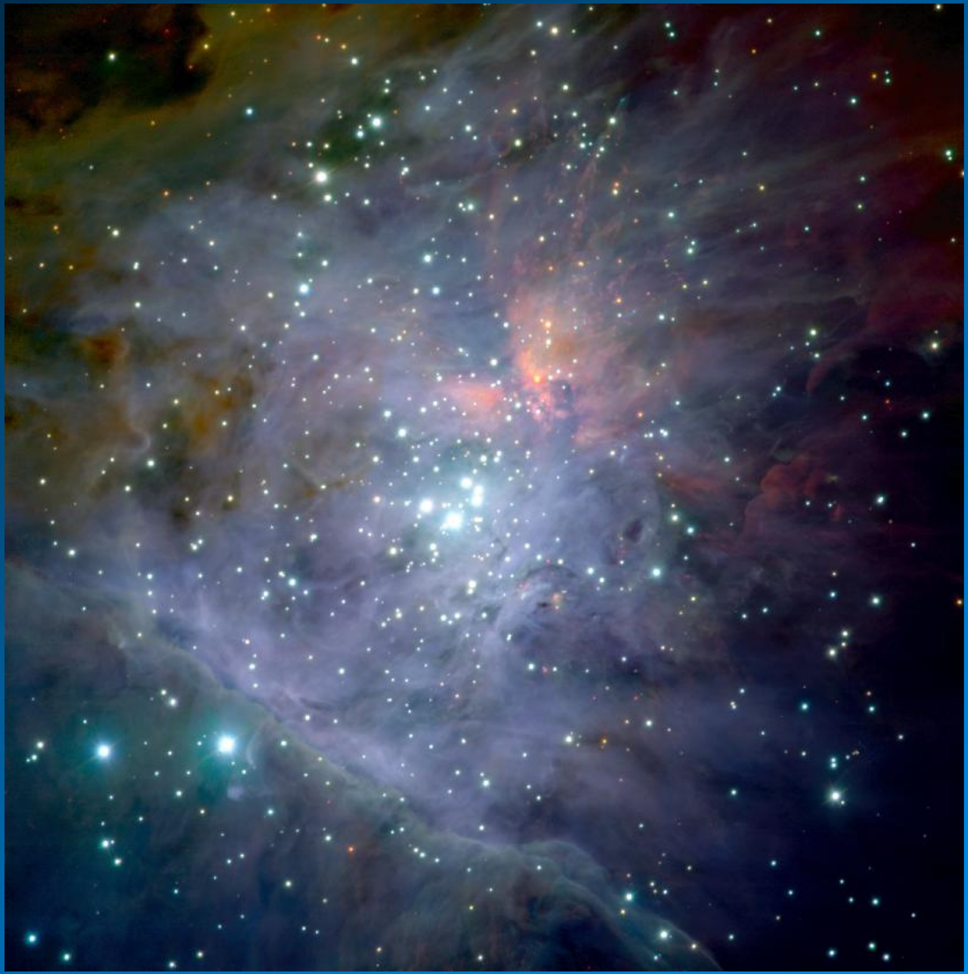
[*] Adaptive Mesh Refinement

Outlook

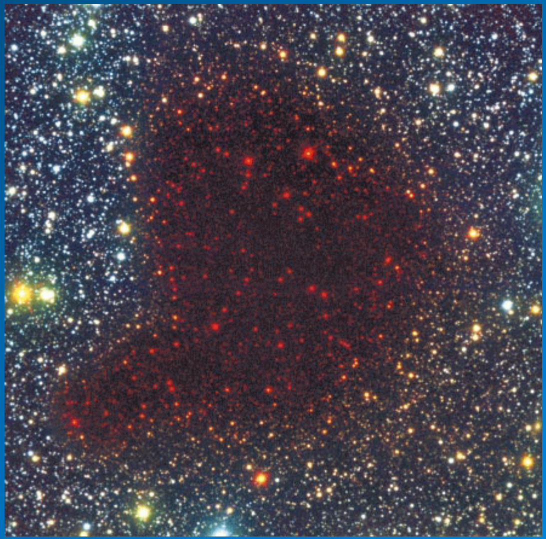
- Motivation / Introduction
- Numerical Method, AMR
- Modelling Cloud Cores
- Hydro Collapse Simulations
- ... with Magnetic Fields
- Outflows and Jets
- Turbulence
- Massive Stars
- Ongoing and Future Projects

Introduction

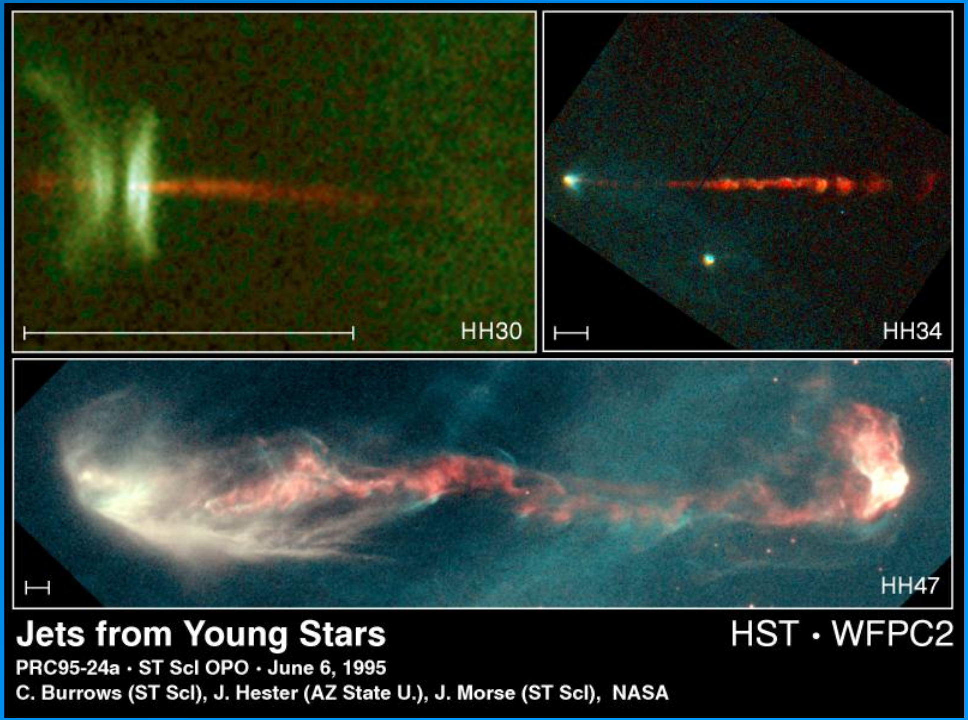
- Present day Star Formation in (Giant) Molecular Clouds (GMCs)
- Stars form out of collapsing cloud cores



Orion Nebula (M 42), Star Forming region *(HST image)*



Barnard 68, Cloud core (cold, self shielded) *(Alves, Lada & Lada, Nature 2001)*



Jets from Young Stars HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

Motivation for numerical simulations

Problems

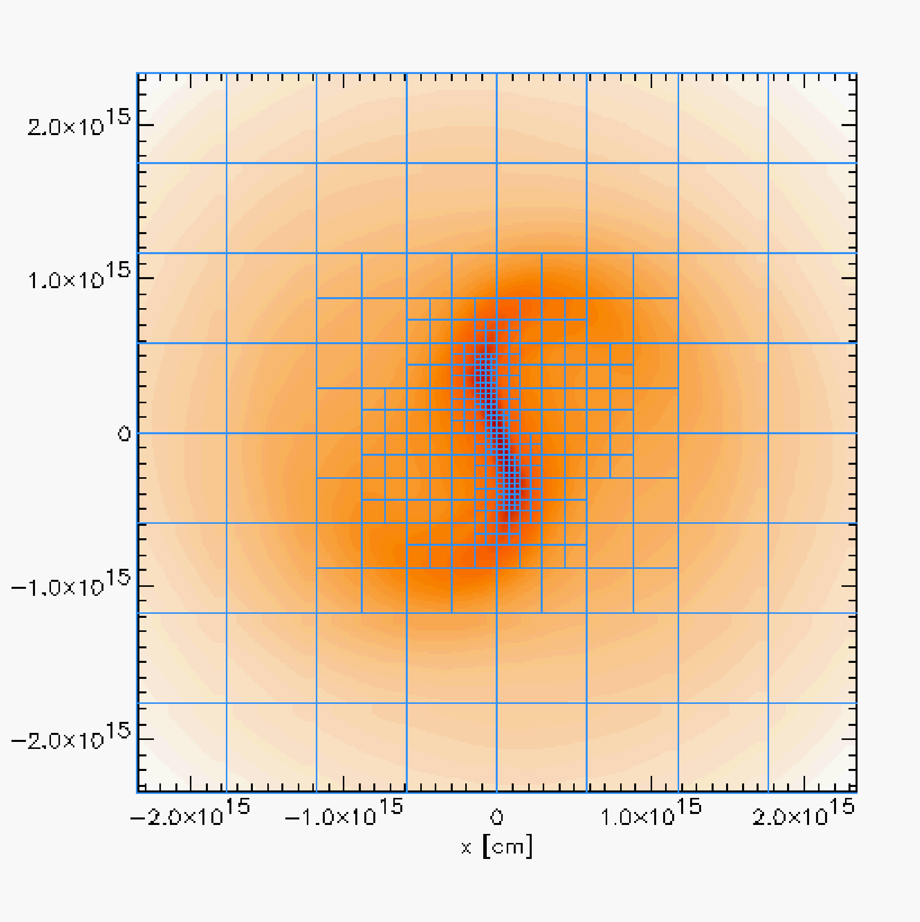
- Self **Gravity**: non-linear interactions
- Non-vanishing **angular momenta** ⇒ disk formation
- Chemical evolution, **Cooling** & Heating
- **Magnetic Fields**: Jets and Outflows?
- Radiation Feedback

Horsehead Nebula (Barnard 33) in the OMC
NOAO image

Solution ⇒ **Direct Numerical Simulations**

Numerical Method

FLASH* Code



**Alliance Center for Astrophysical Thermonuclear Flashes (ASC), University of Chicago*

Current Version: 3.0

- 3D **Grid** based MHD integrator for parallel computing (MPI)
- Hydro solver: PPM, Kurganov
- MHD solver: MUSCL (van Leer) with div**B** cleaning
- Gravity: multigrid or multipole, periodic or isolated BCs
- **AMR**: block structured (PARAMESH library);
  block resolutions vary by factors of **two**
- Refinement on own choice (e.g. gradient, curvature, density, etc.)
- IDL routines for visualization

Pros

- modular, easy to use
- large community: e.g. multi fluid nuclear reactions, RT module, N-body particles, cosmology
- support from developers

Cons

- resource consuming
- not very fast
- block structured AMR (will be improved with newer versions)

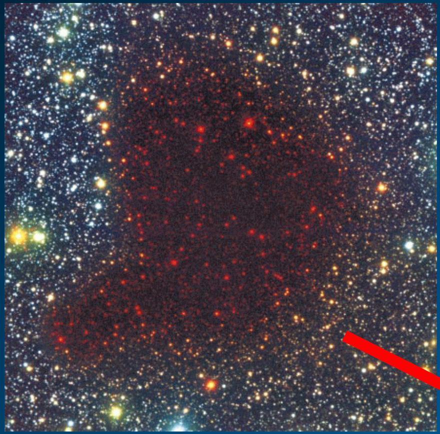
Numerical Method

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} &+ \nabla \cdot (\rho \mathbf{v}) = 0 \\
\frac{\partial \rho \mathbf{v}}{\partial t} &+ \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_* = \rho \mathbf{g} + \nabla \cdot \tau \\
\frac{\partial \rho E}{\partial t} &+ \nabla \cdot (\mathbf{v}(\rho E + p_*) - \mathbf{B}(\mathbf{v} \cdot \mathbf{B})) = \rho \mathbf{g} \cdot \mathbf{v} + \nabla \cdot (\mathbf{v} \cdot \tau + \sigma \nabla T) + \nabla \cdot (\mathbf{B} \times (\eta \nabla \times \mathbf{B})) \\
\frac{\partial \mathbf{B}}{\partial t} &+ \nabla \cdot (\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = -\nabla \times (\eta \nabla \times \mathbf{B})
\end{aligned}
$$

$$
\begin{aligned}
p_* &= p + \frac{B^2}{2}, \\
E &= \frac{1}{2} v^2 + \varepsilon + \frac{1}{2} \frac{B^2}{\rho}, \\
\tau &= \mu \left((\nabla \mathbf{v}) + (\nabla \mathbf{v})^{T} - \frac{2}{3} (\nabla \cdot \mathbf{v}) \right)
\end{aligned}
$$

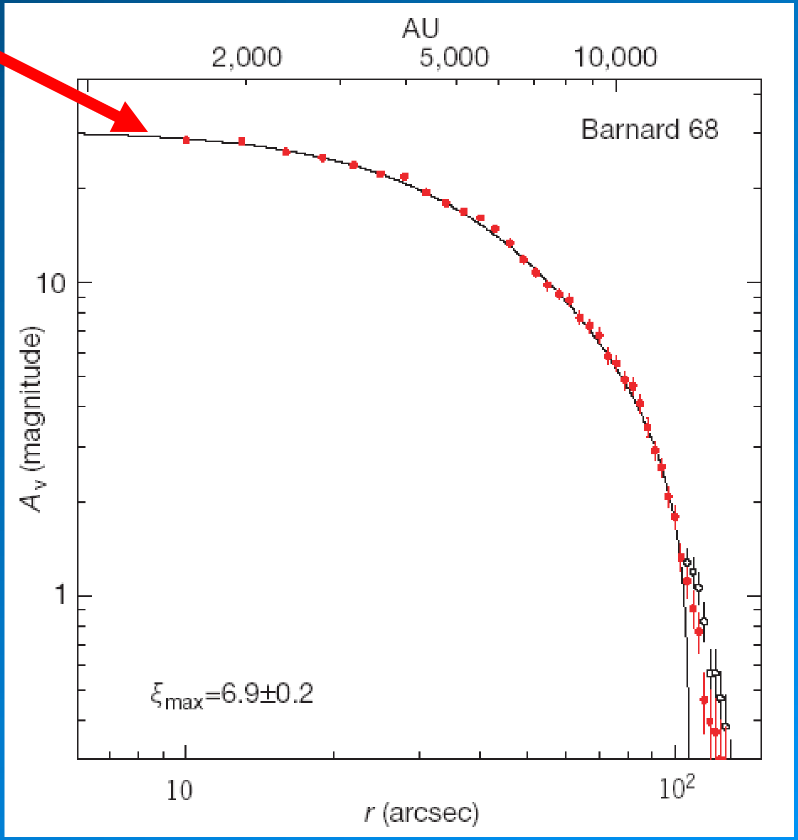
Applications

Collapse of Hydrostatic Cores



Bok Globule B 68

Dust column density profile in terms of visual extinction follows a BE-Profile mass ~ 2.1 M_{sol}



Molecular Clouds in hydrostatic equilibrium follow a **Bonnor-Ebert**-Profile

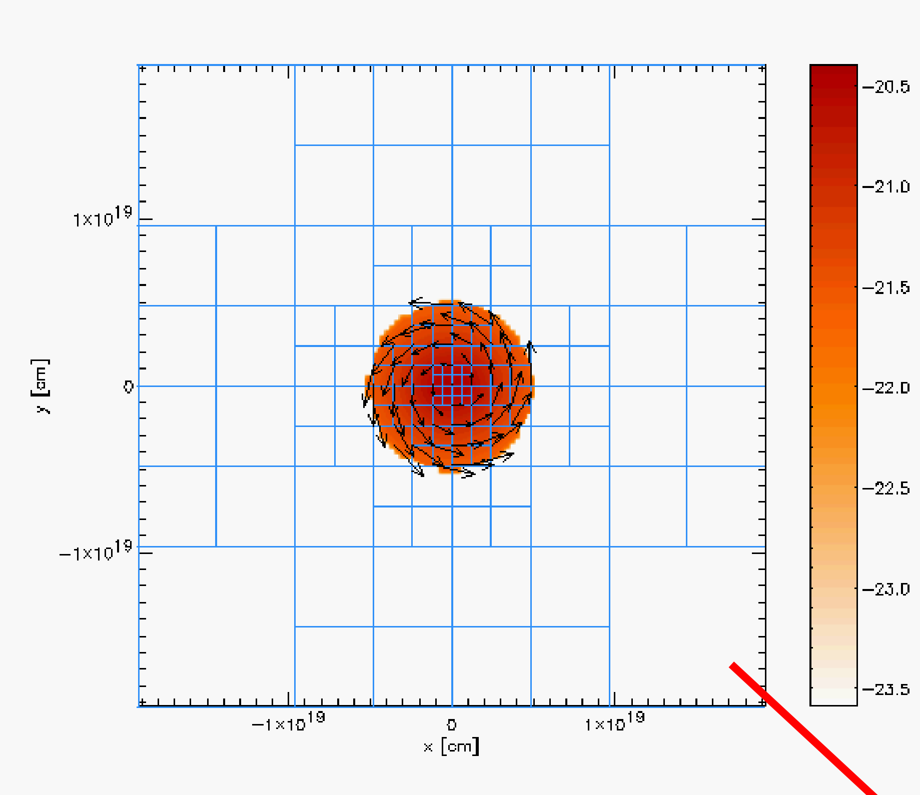
Critical BE Sphere:
$\xi = 6.451$

Other observational evidences:

- Coalsack globule 2, M ~ 4.5 M_{sol}, *(Racca, Gomez & Kenyon, 2002)*
- Dark globule B335, M ~ 14 M_{sol}, *(Harvey et al. 2001)*

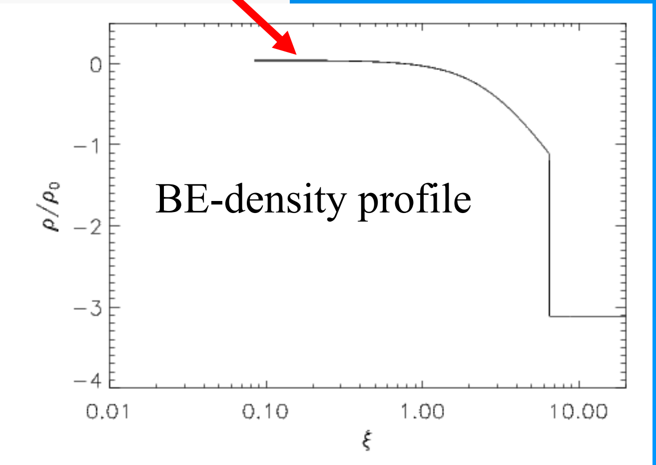
Collapse of Hydrostatic Cores

- Slowly rotating Bonnor-Ebert-Spheres
- Low Mass M ~ 2.1M_{sol}
- High Mass ~ 170 M_{sol}
- **Cooling** due to molecular excitations, gas-dust interaction, H_2 dissociation
- AMR ⇒ resolves **Jeans length** with more than 8 grid points during collapse *(Truelove et al. 1997)*
- Up to 27 refinement levels (dynamical range ~ 10^7)

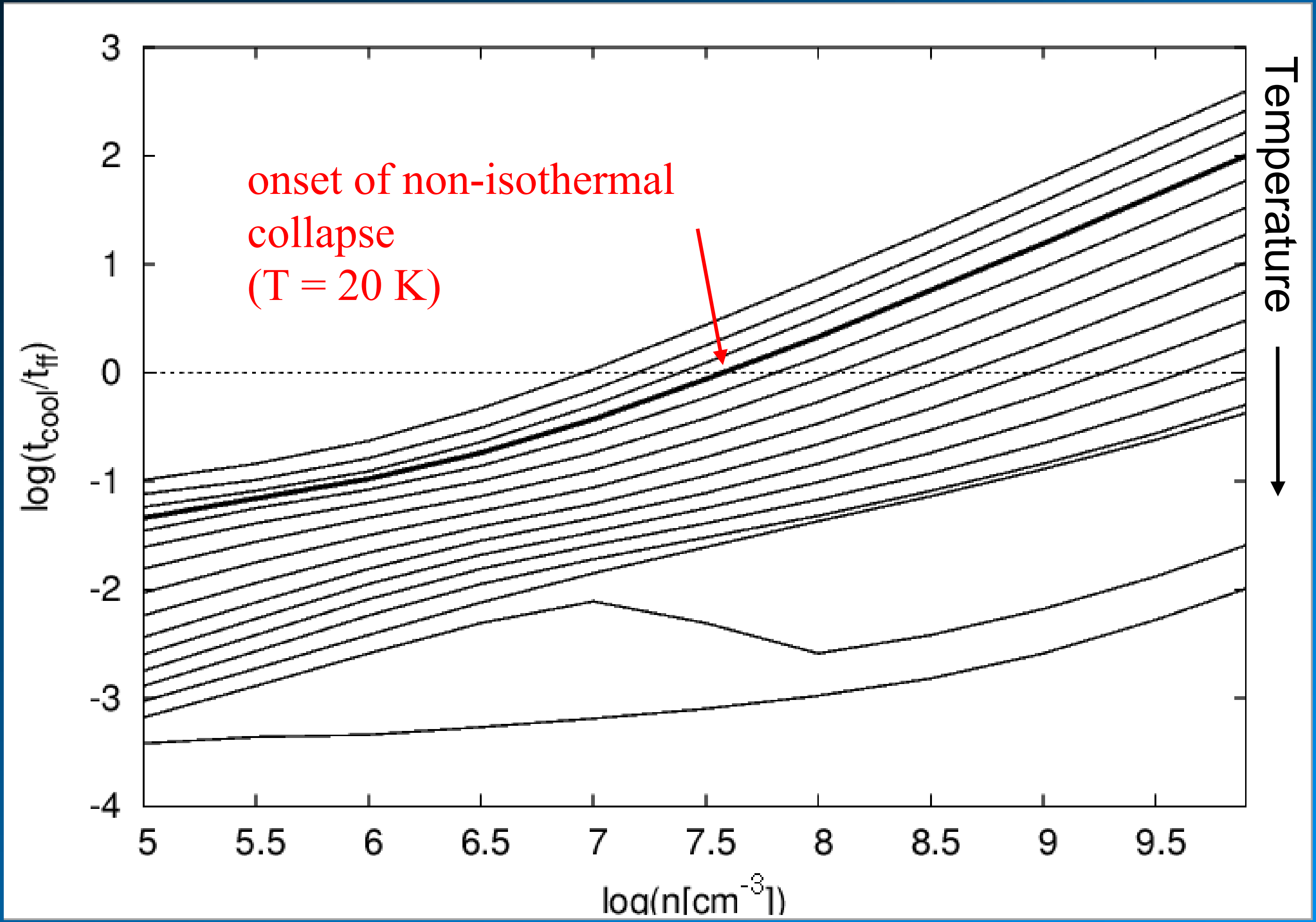


Initial conditions:

- cool molecular cloud (T = 16 K)
- hot ambient, low density, medium (pressure match at the sphere boundary)
- $\Omega t_{ff} = 0.1 - 0.4$



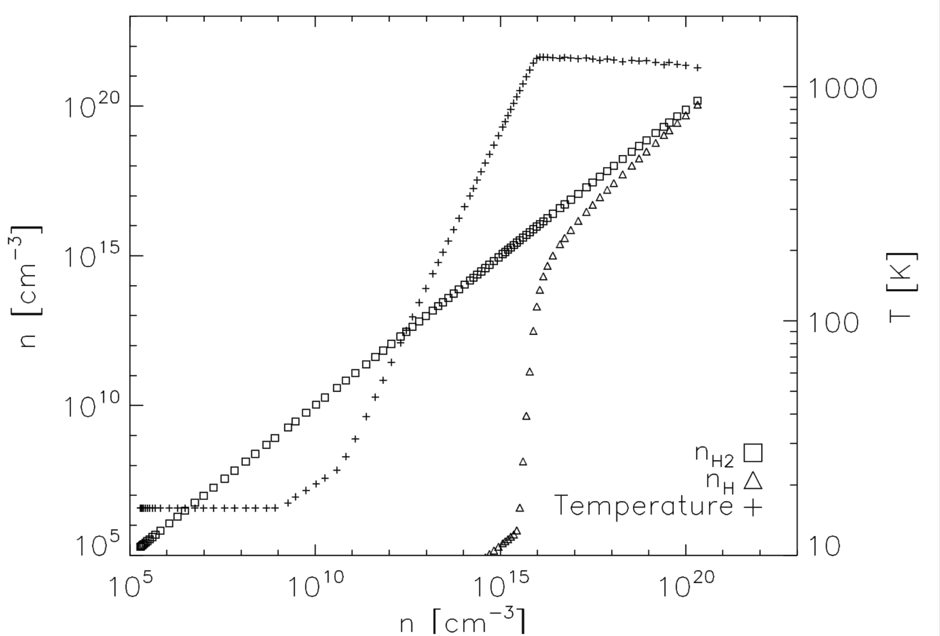
Effect of molecular line cooling

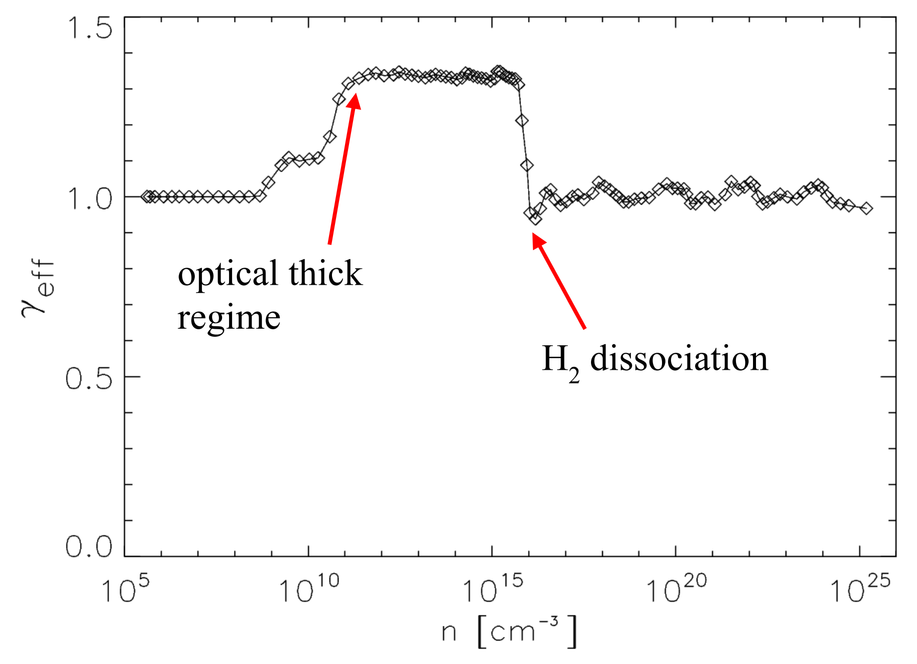


- Main coolants: H_2O, CO, H_2, O_2
- Efficient cooling in low density regime $n\sim10^{7.5}$ **(no dust)** ⇒ isothermal collapse
- Cooling sets a fixed physical length scale, $r \sim c/(G\rho_{crit})^{1/2}$ where $t_{cool} \sim t_{ff}$ ⇒ warm core and **shocked** gas

Cooling data from *Neufeld & Kaufman, ApJ, 1993, and Neufeld, Lepp & Melnick, ApJS, 1995:* radiative losses due to collisional excitations

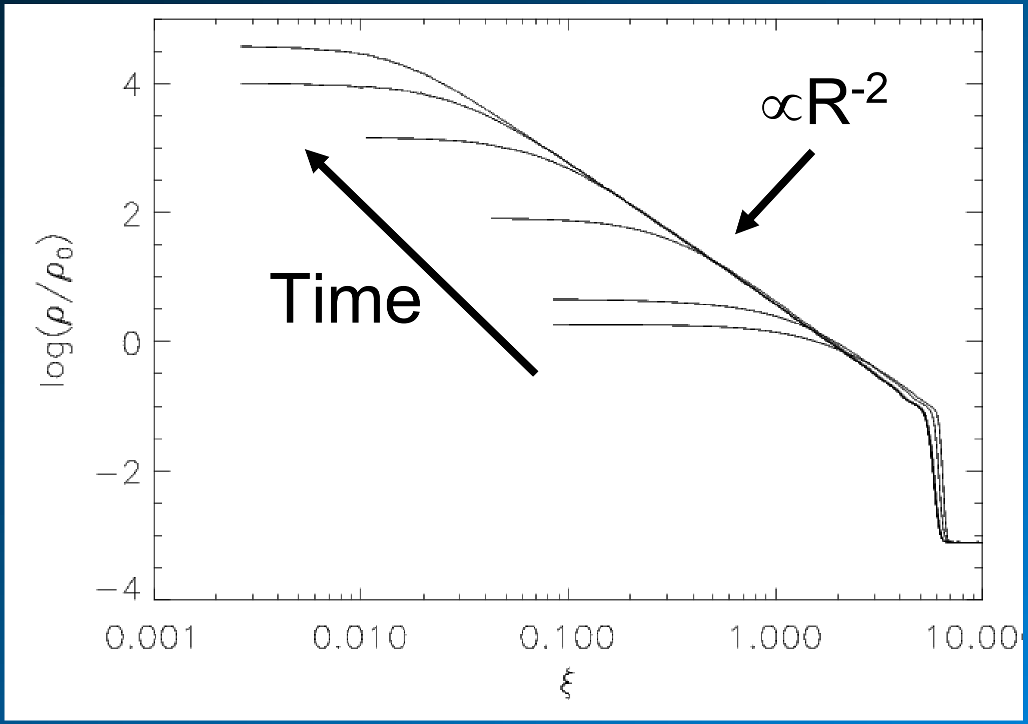
Cooling with Dust & H_2 dissociation



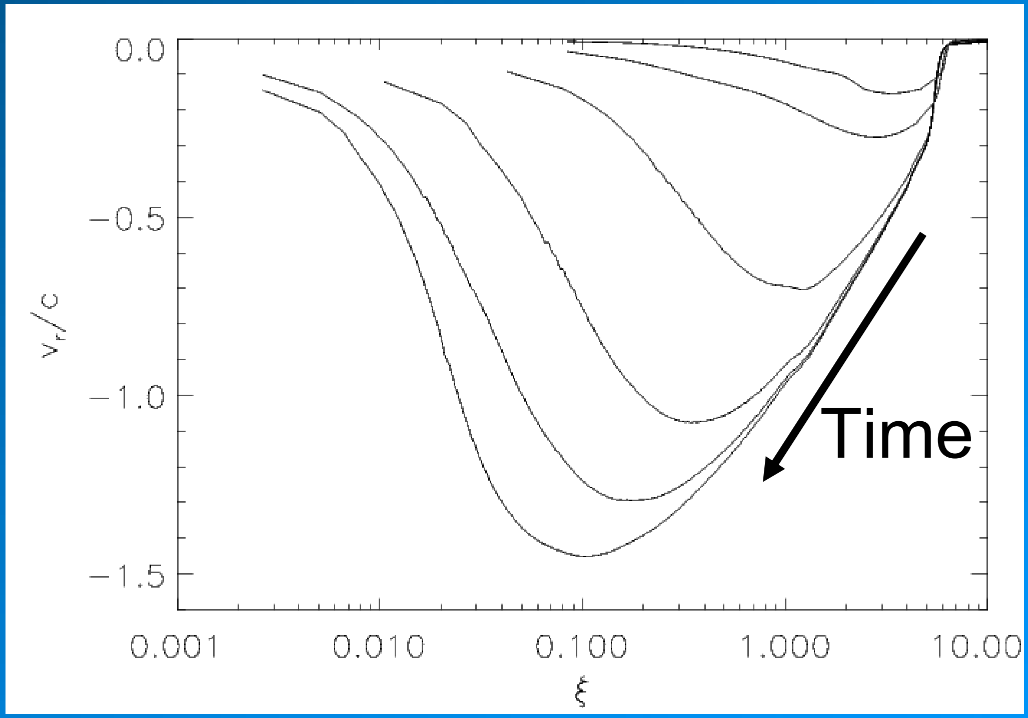


- **Dust**-gas interactions *(Goldsmith 2001)* keeps the gas isothermal until n~10^{11} cm^{-3} ⇒ scale of hot core: ~ few x 10 AU
- **Optically thick** at n ~10^{11} cm^{-3} ⇒ heating with T ~ $n^{1/3}$
- H_2 **dissociation** at ~ 1200 K *(Shapiro & Kang 1987)* ⇒ isothermal collapse (second collapse; *Larson 1969*)
- dissociation process is “self-regulating” due to strong temperature dependence

Isothermal Bonnor-Ebert collapse



density



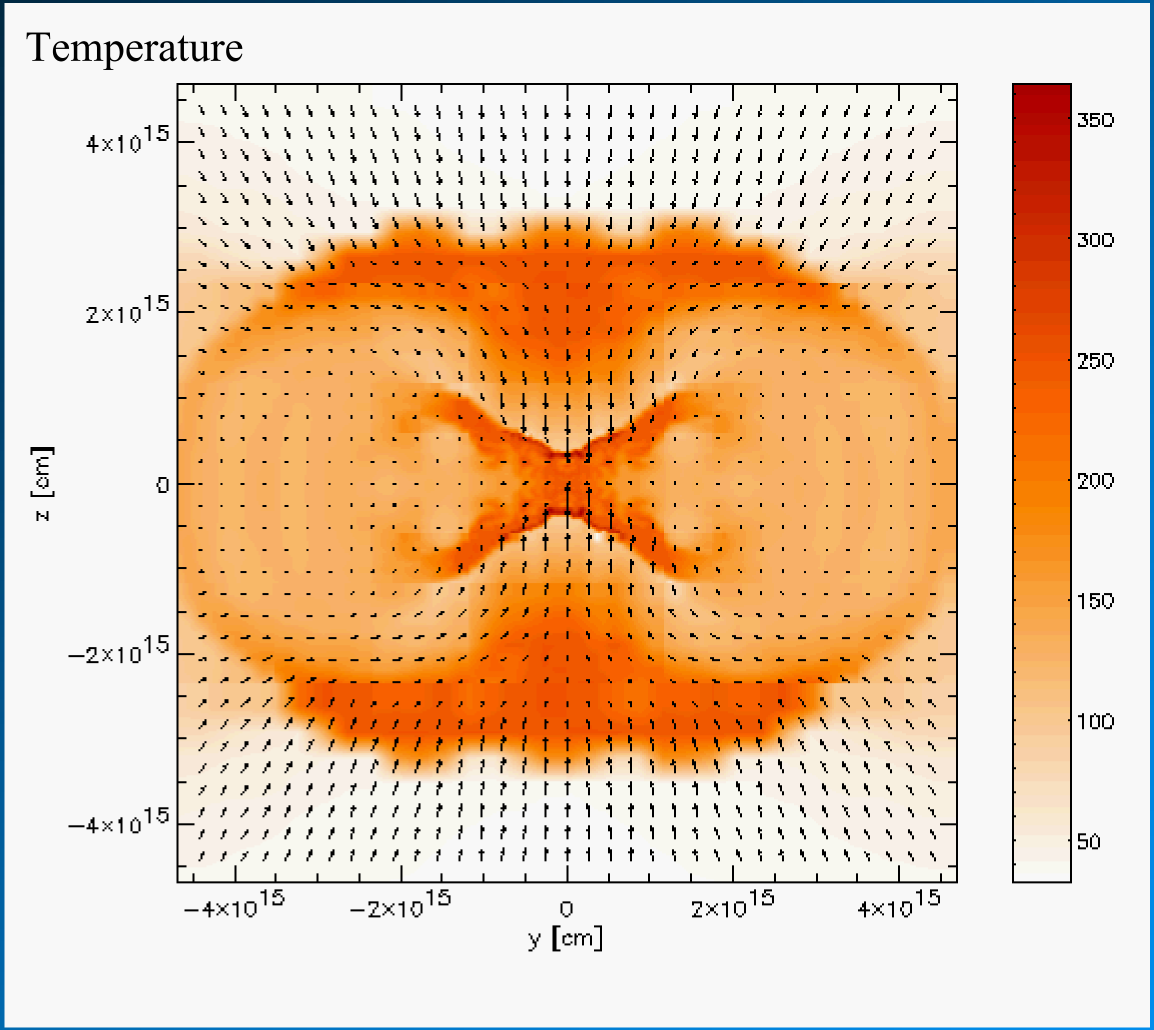
radial velociy

Outside-in

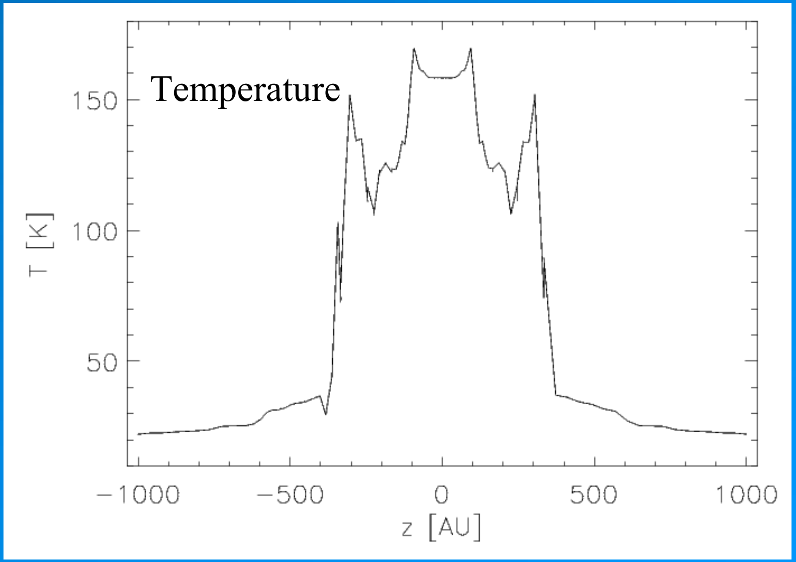
non-homologous collapse

Non-isothermal collapse phase

Shock structures



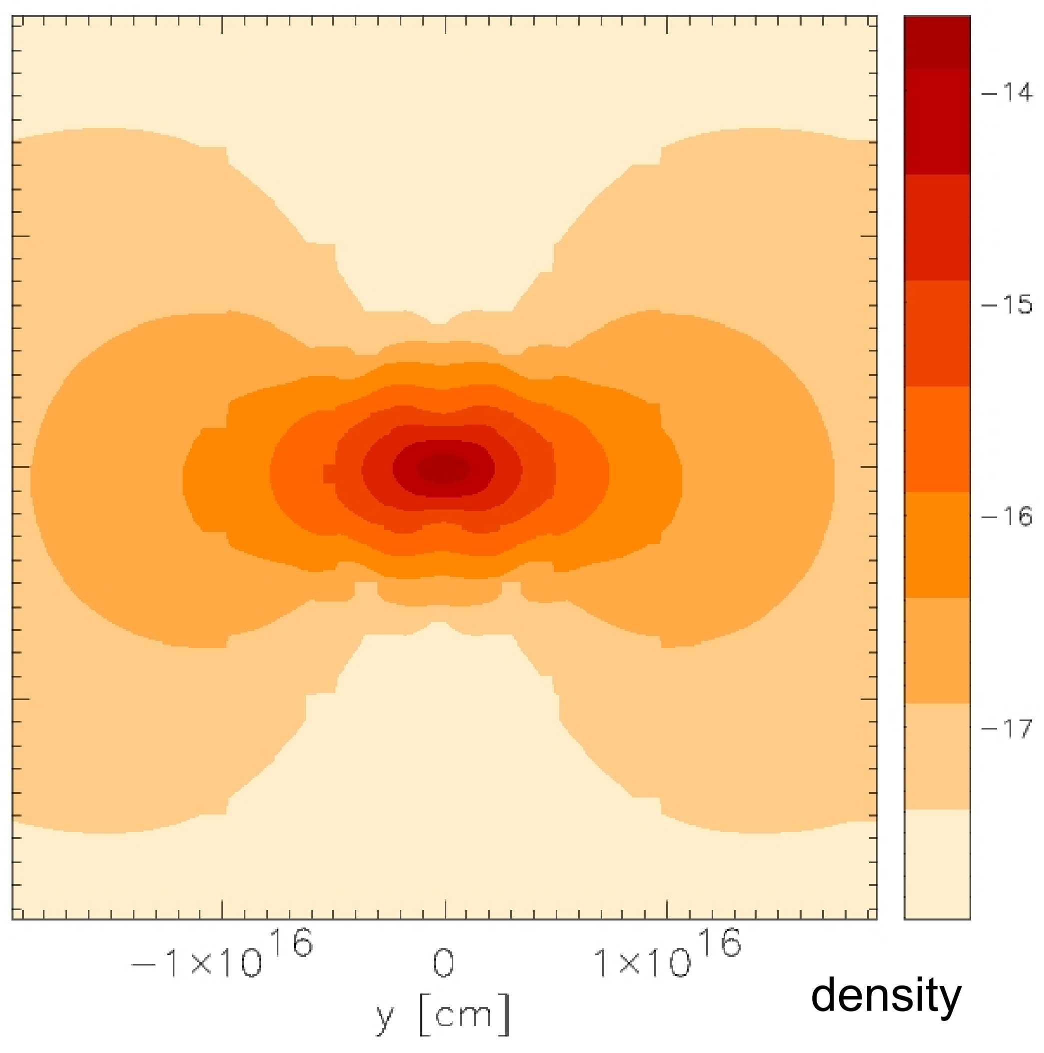
At least 2 shock fronts build up during the collapse with Mach numbers ~ 2 - 4



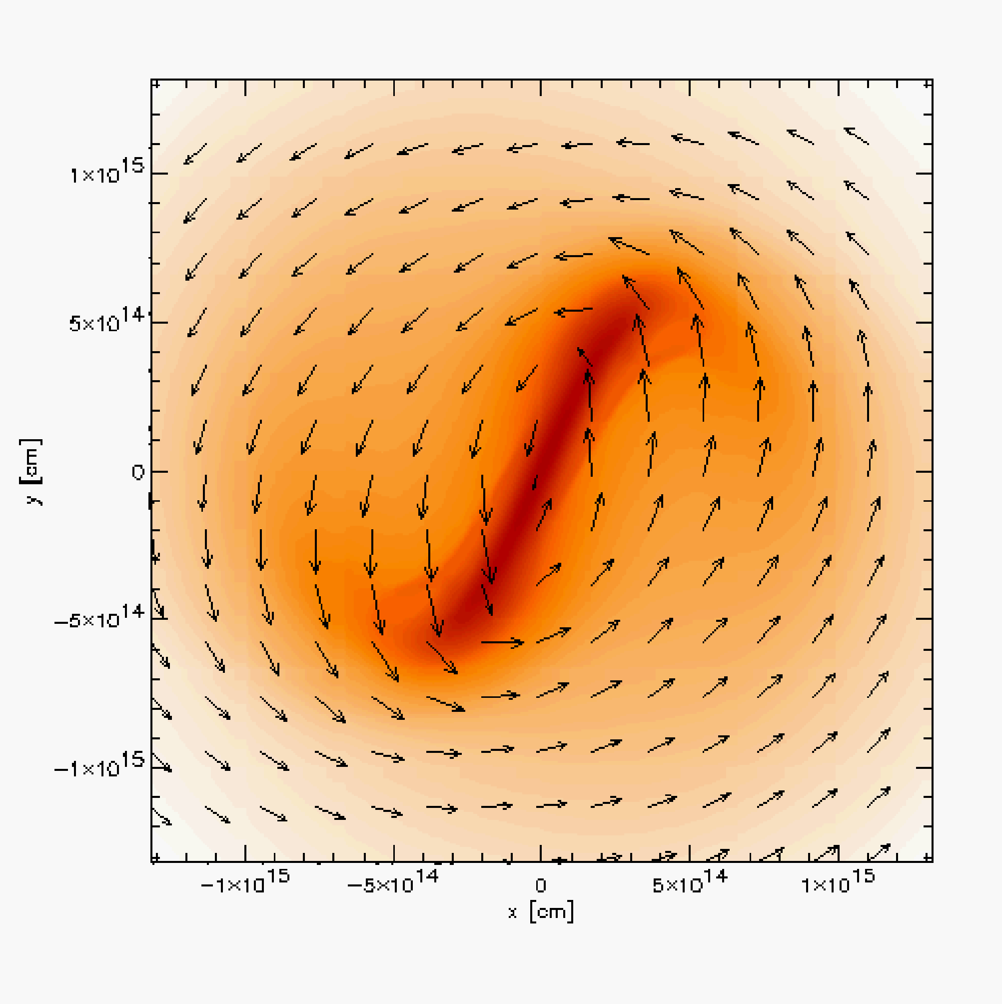
Note: only molecular line cooling
no dust-gas interaction

Disk Formation / Disk Structure

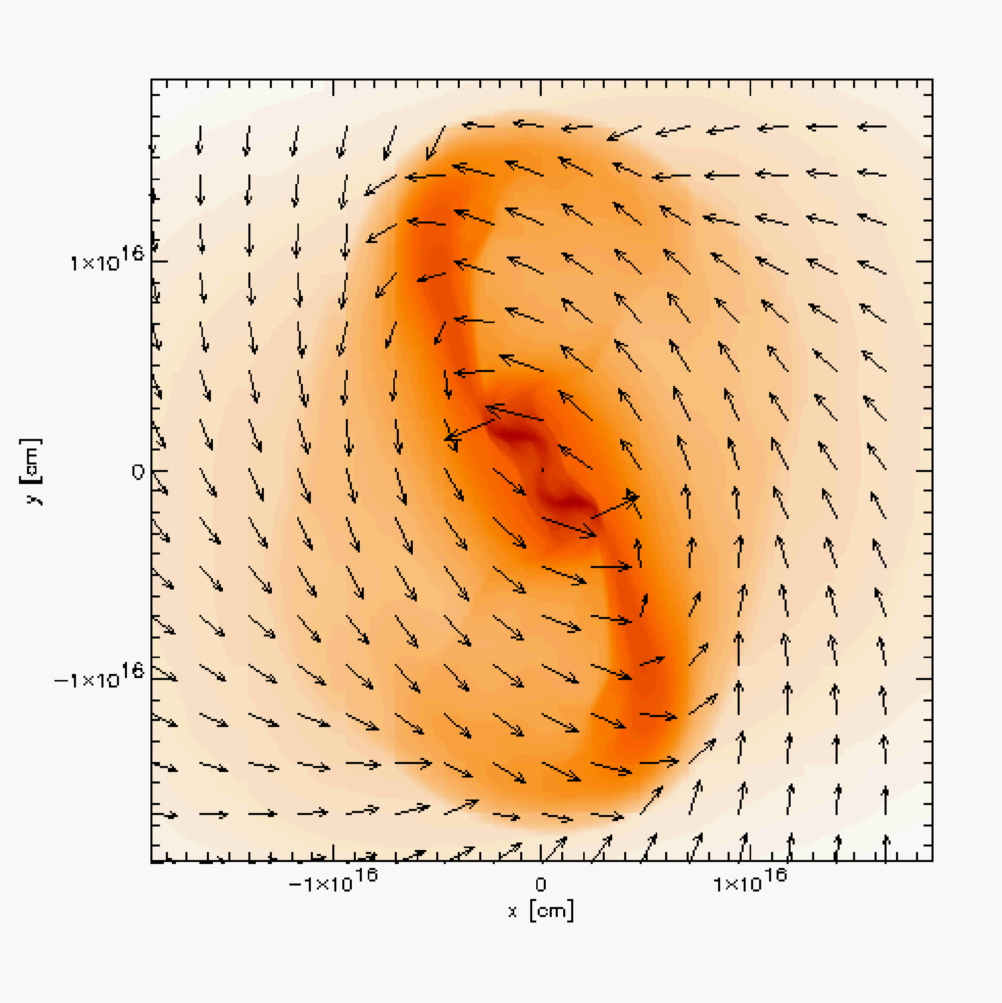
- Angular momentum conservation ⇒ formation of a **disk**
- Initial rotation determines disk size and structure (e.g. spiral arms, ring, binaries)
- Size of protodisk: few 100 AU – 10^3 AU depending on initial spin
- BE case: $\Omega f_{ff} = 0.1$ ⇒ **bar** formation;
- $\Omega f_{ff} = 0.2$ ⇒ **fragmentation** *(Matsumoto & Hanawa 2003, Banerjee et al. 2004)*
- Transport (redistribution) of angular momentum due to spiral arms and magnetic fields



Disk Formation / Disk Structure

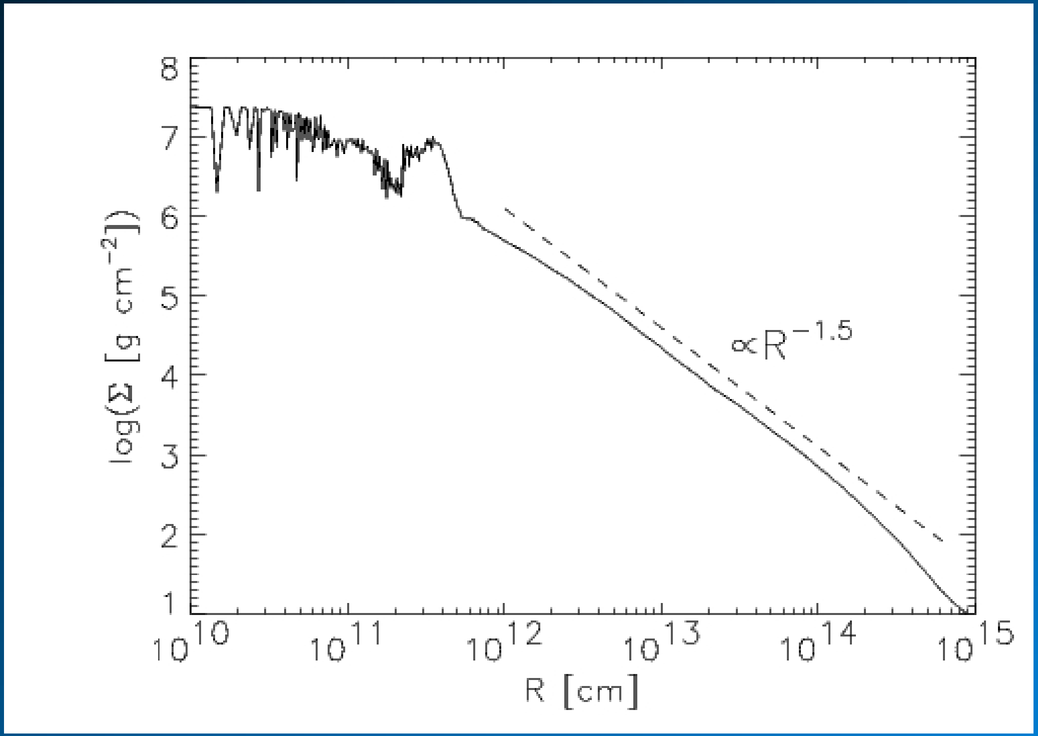


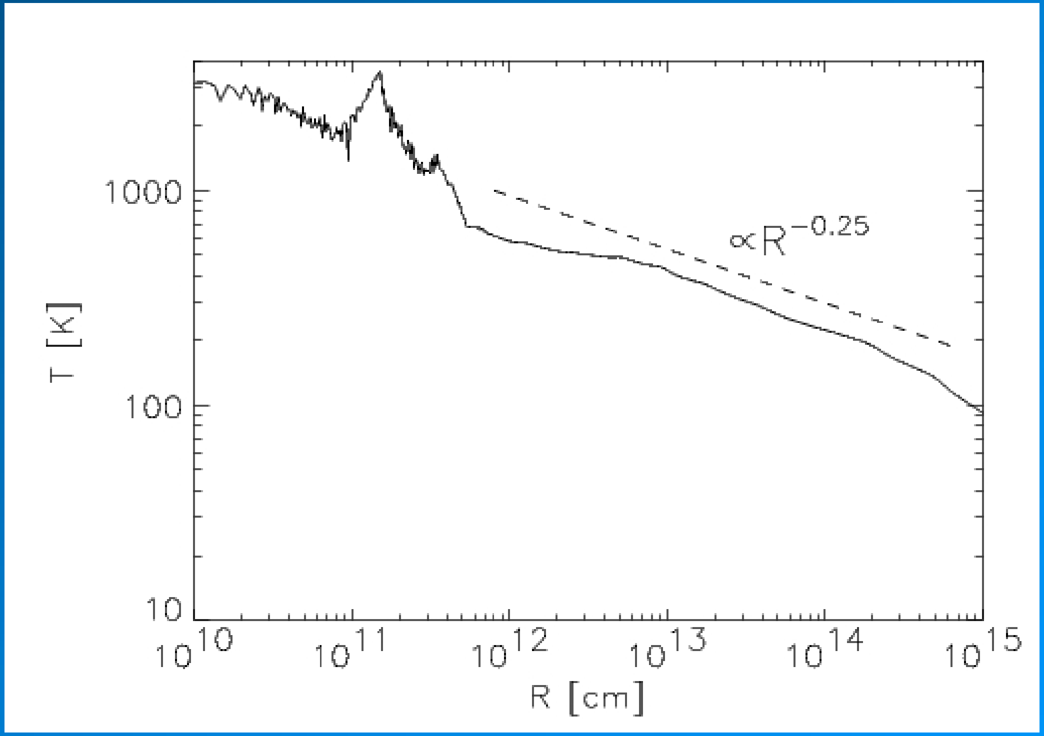
bar formation with
slow roation



fragmention with faster initial rotation

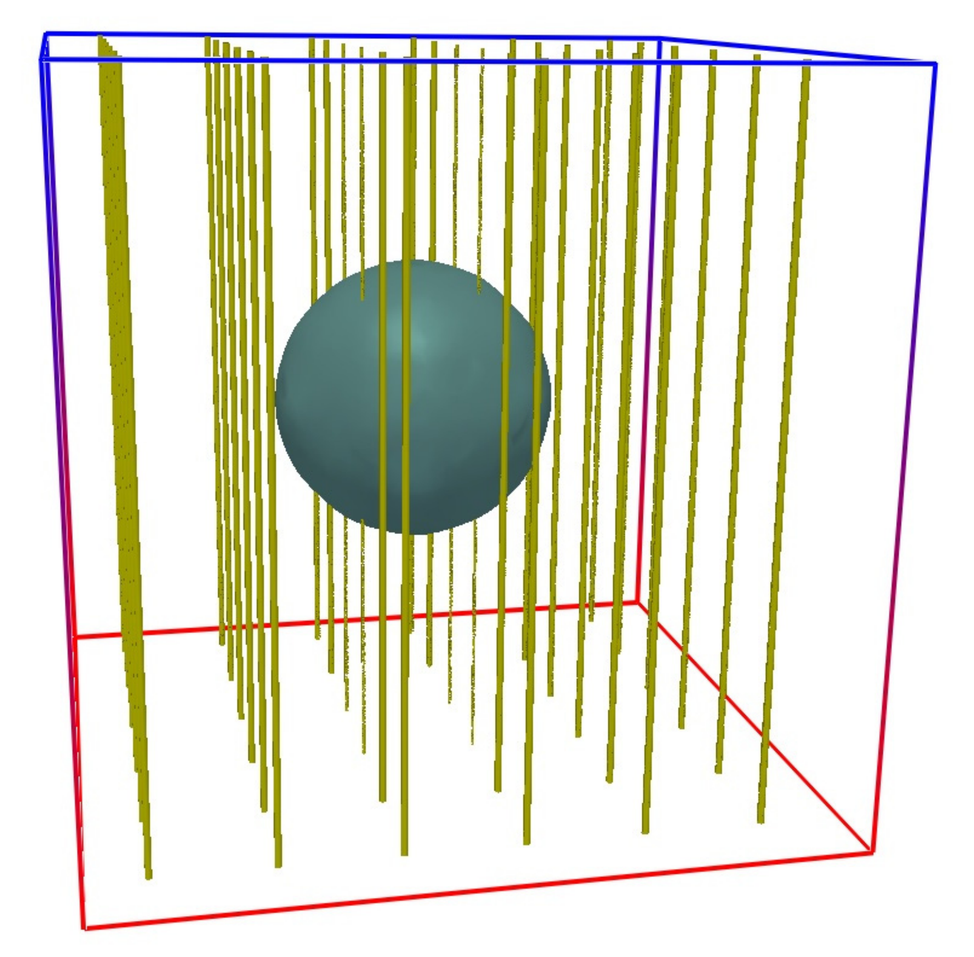
Disk structure

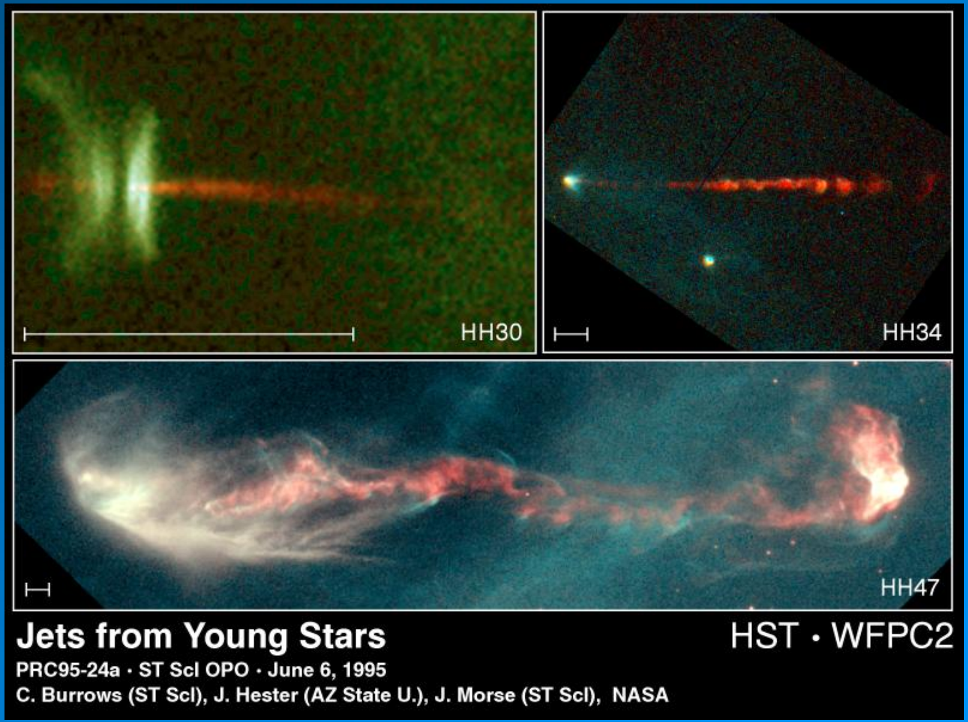




- Disk profile: Hayashi-type $\propto R^{-3/2}$ *(Hayashi, 1981)*
- Shallow temperature profile $\propto R^{-1/4}$

Magnetic Fields





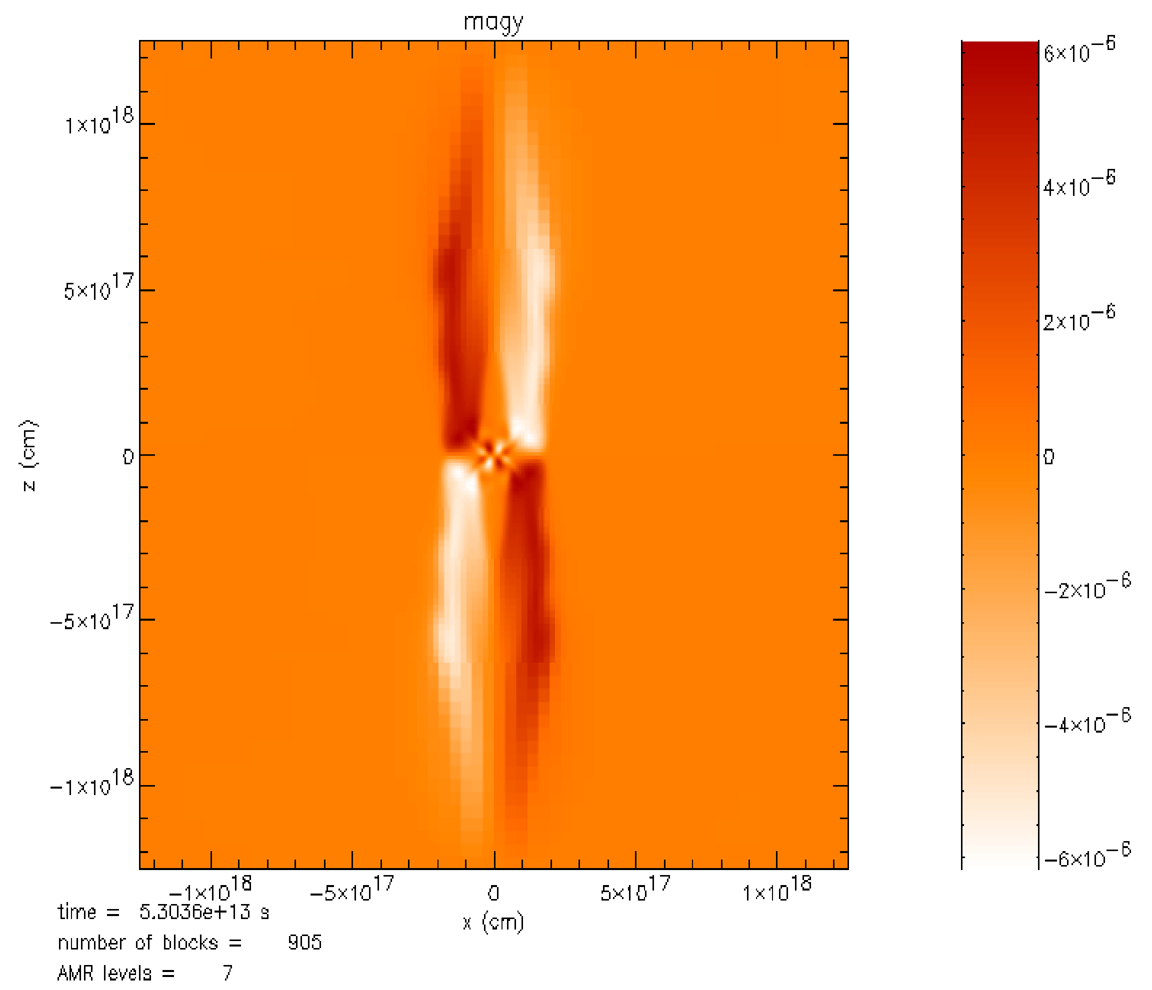
Jets from Young Stars

HST • WFPC2

PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

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

Pre-collapse, Magnetic braking

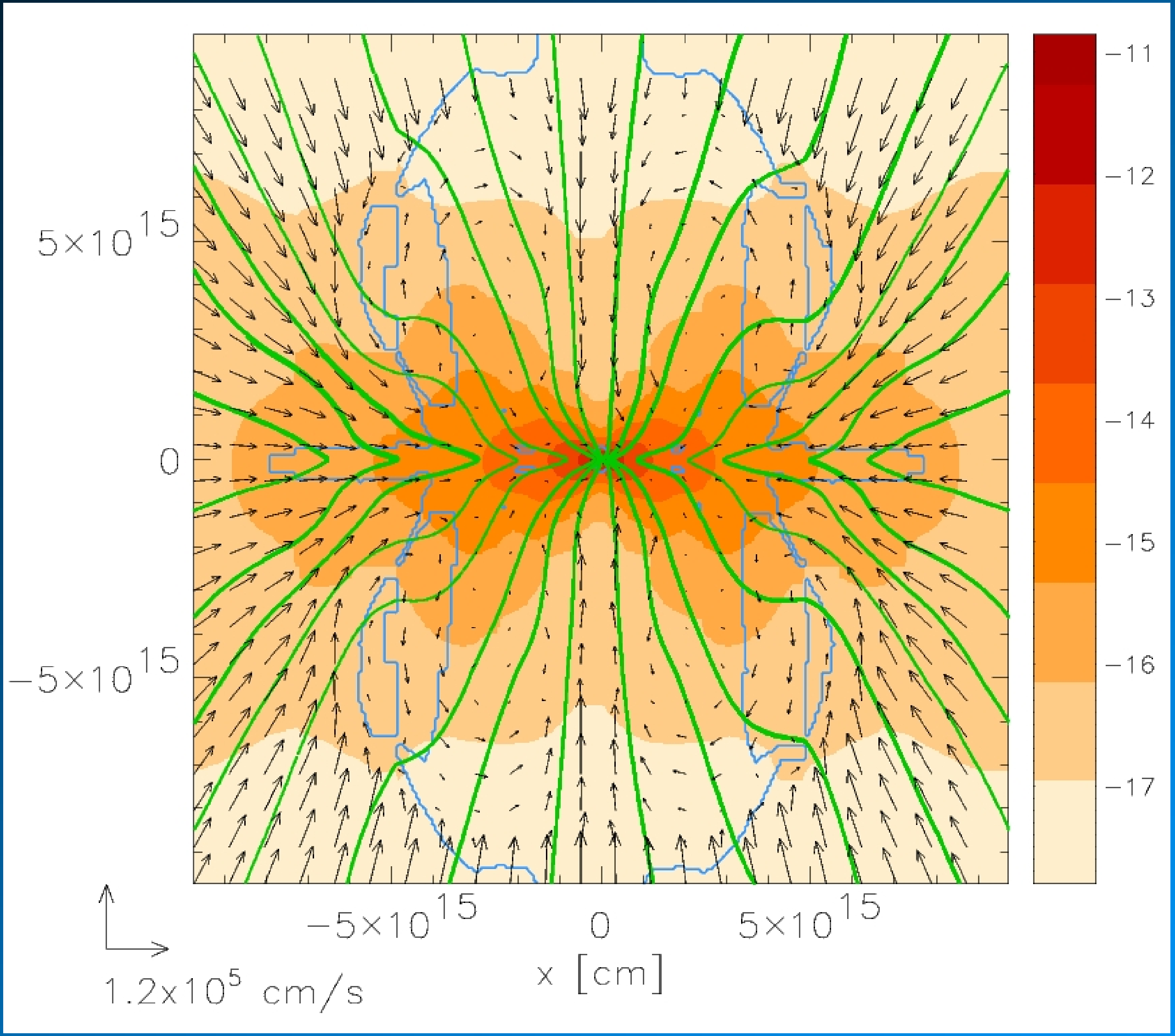


- Linear regime: torsional Alfven wave is launched in the ambient medium (Poynting flux)
- Loss of initial angular momentum ⇒**Magnetic braking** *(Mouschovias & Paleologou, 1980)*
- Spin down time:

$$\tau_{\rm damp} \approx \frac{\pi R}{4\, v_{\rm A,ext}}\, \delta$$

- In our case: ~ 10^6 years

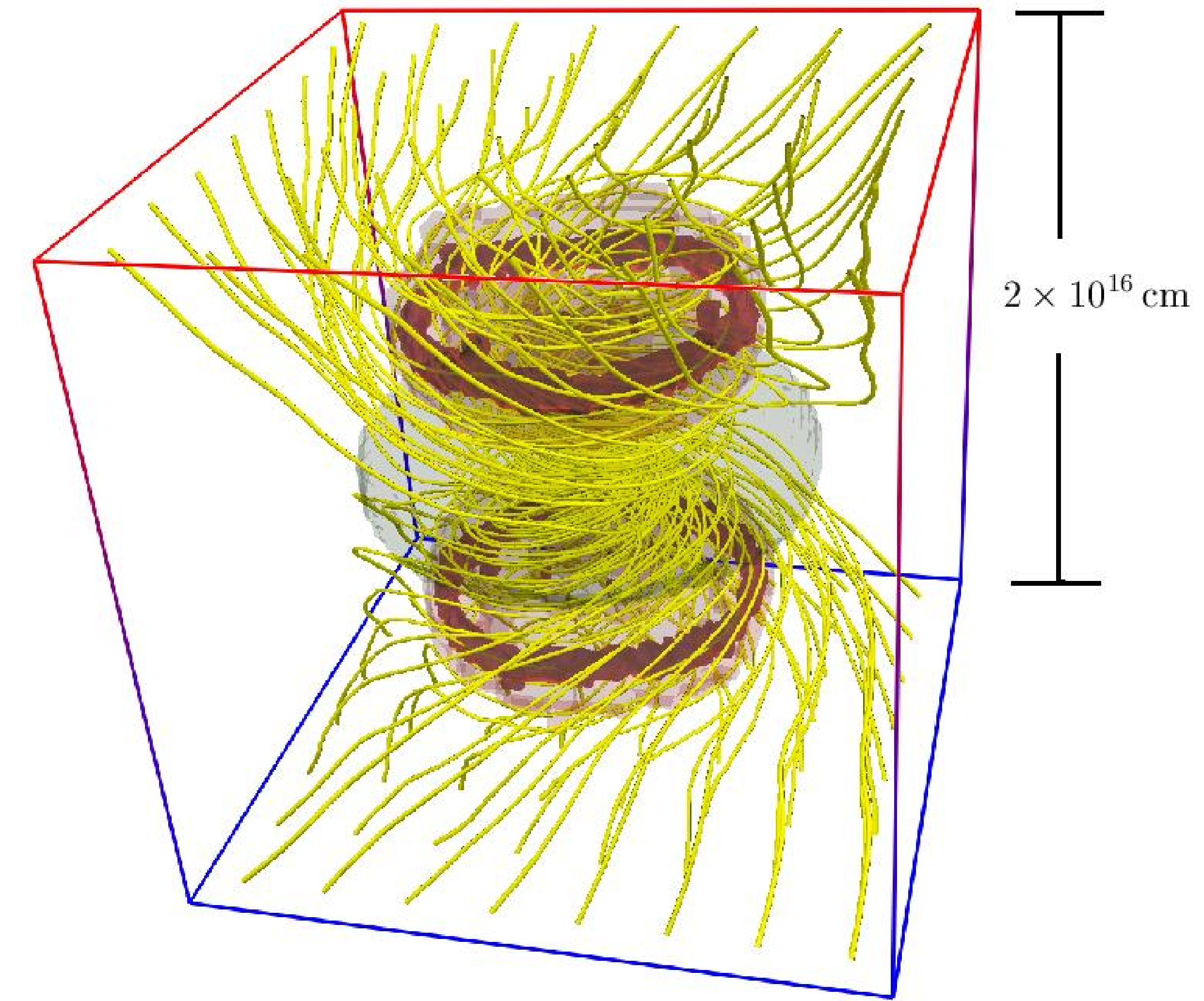
Large scale outflow



Banerjee & Pudritz 2006

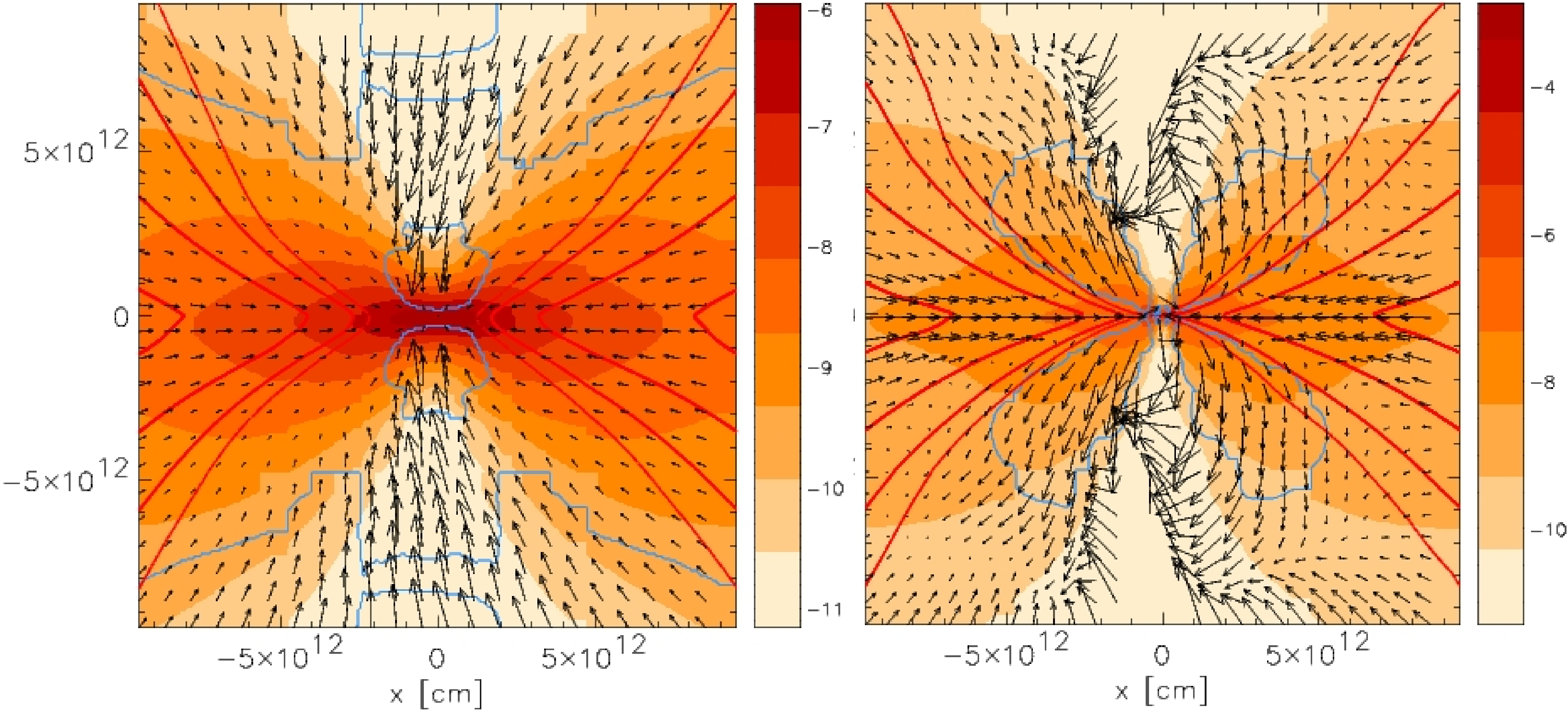
- Magnetic field is **compressed** with the gas
- Rotating disk generates **toroidal** magnetic field ⇒ **outflow** *(Blandford & Payne, 1982)*
- Shock fronts are pushed outwards (magnetic tower; *Lynden-Bell 2003*)
- Outflow velocities v ~ 0.4 km/sec, M ~ 2-3
- Accretion: funneled along the rotation axis, through disk

Large scale outflow



- Magnetic field is **compressed** with the gas
- Rotating disk generates **toroidal** magnetic field $\Rightarrow$ **outflow** *(Blandford & Payne, 1982)*
- Shock fronts are pushed outwards (magnetic tower; *Lynden-Bell 2003*)
- Outflow velocities v ~ 0.4 km/sec, M ~ 2-3
- Accretion: funneled along the rotation axis, through disk

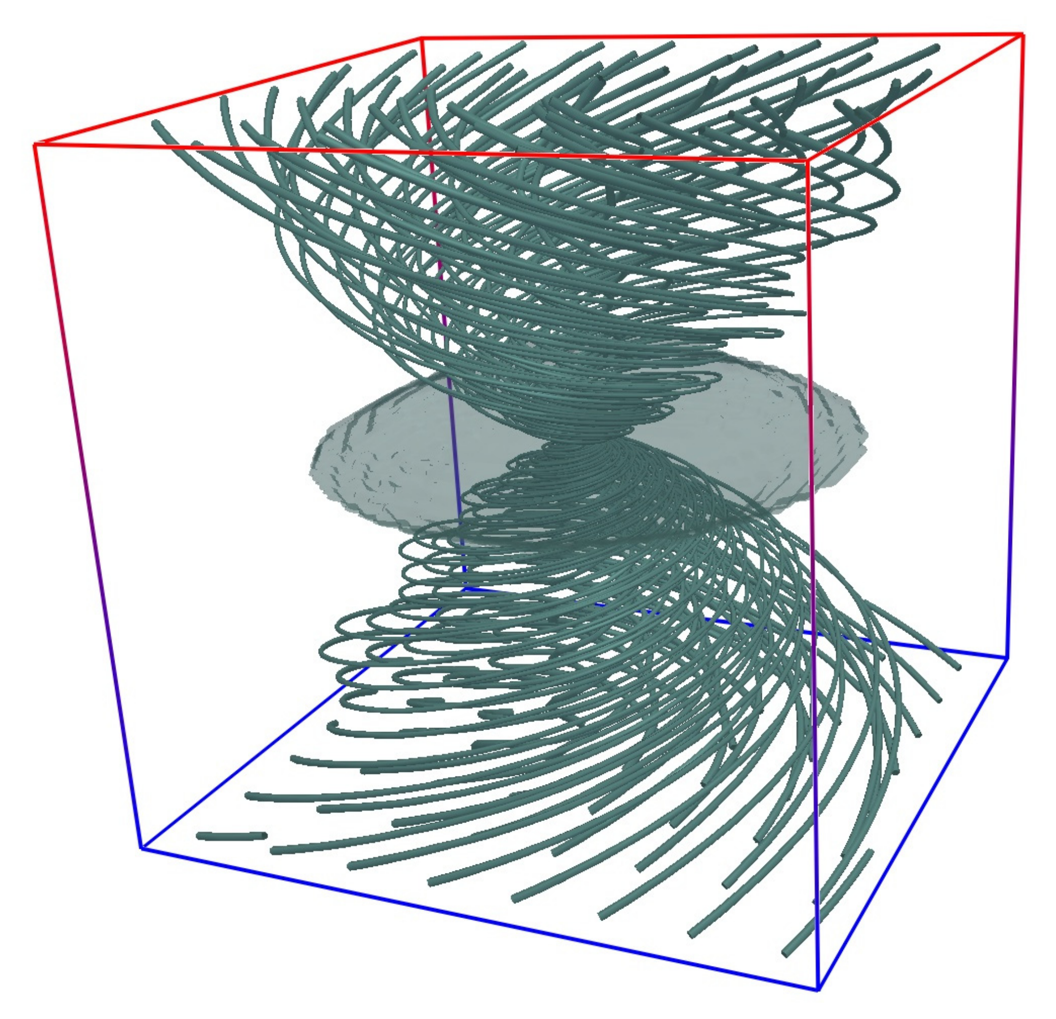
Jets from the inner disk



Inner disk, collapse phase

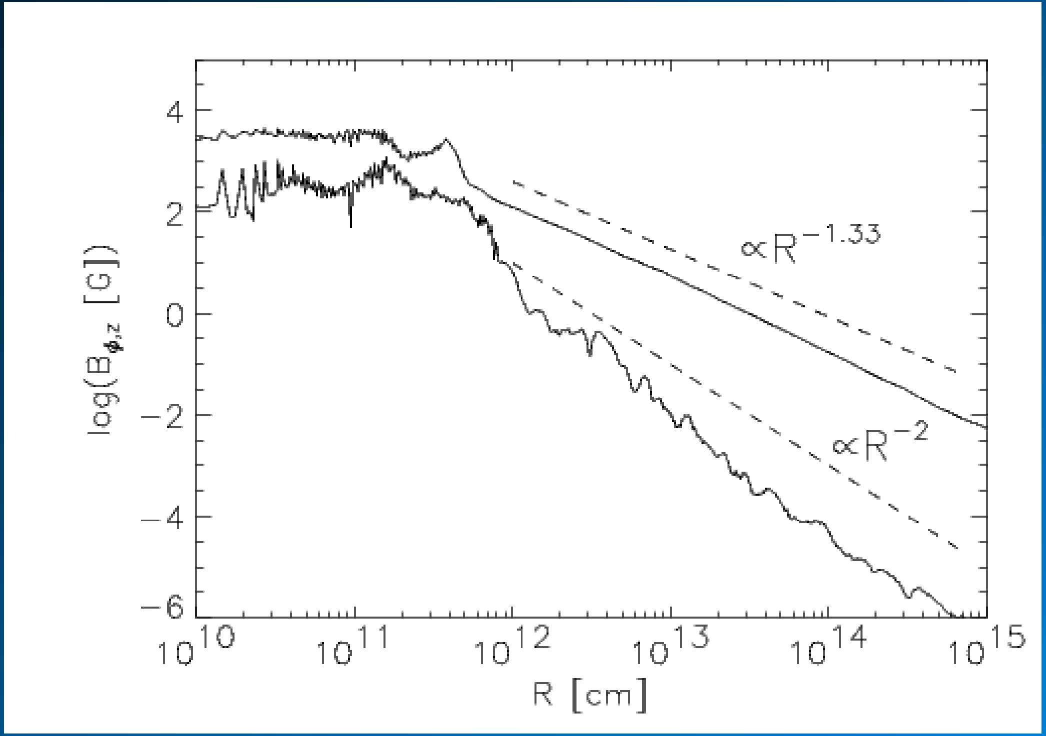
5 month later: a Jet is launched

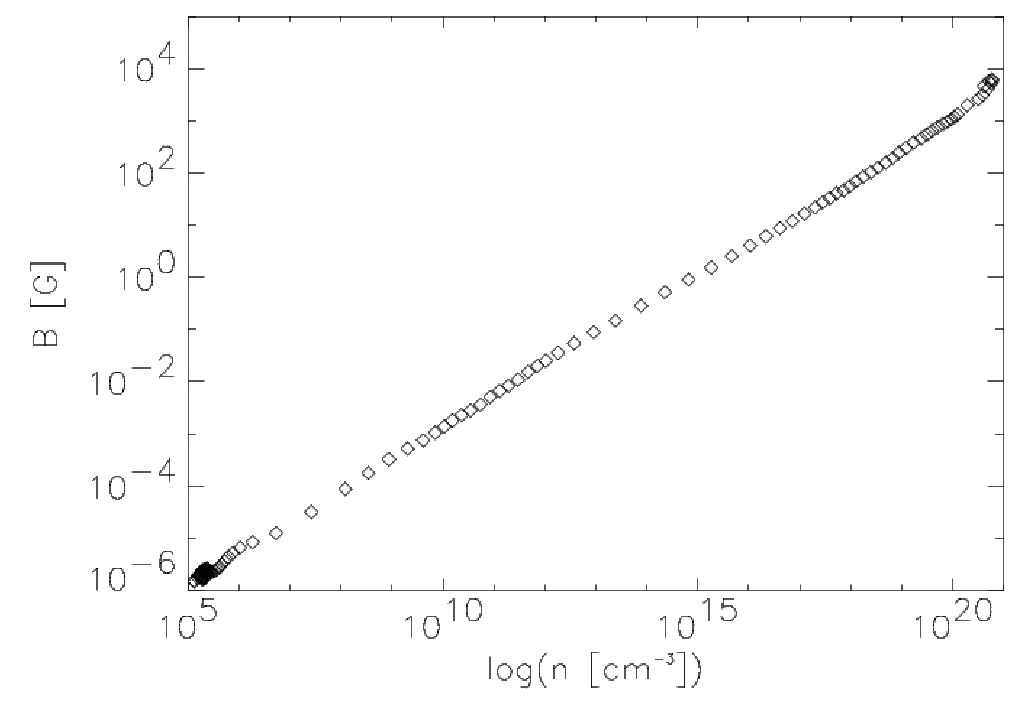
Jets from the inner disk



- Strongly pinched and warped field structure
- Jet velocities v ~ 3 km/sec Super-sonic (M ~ 4), Super-Alfvénic

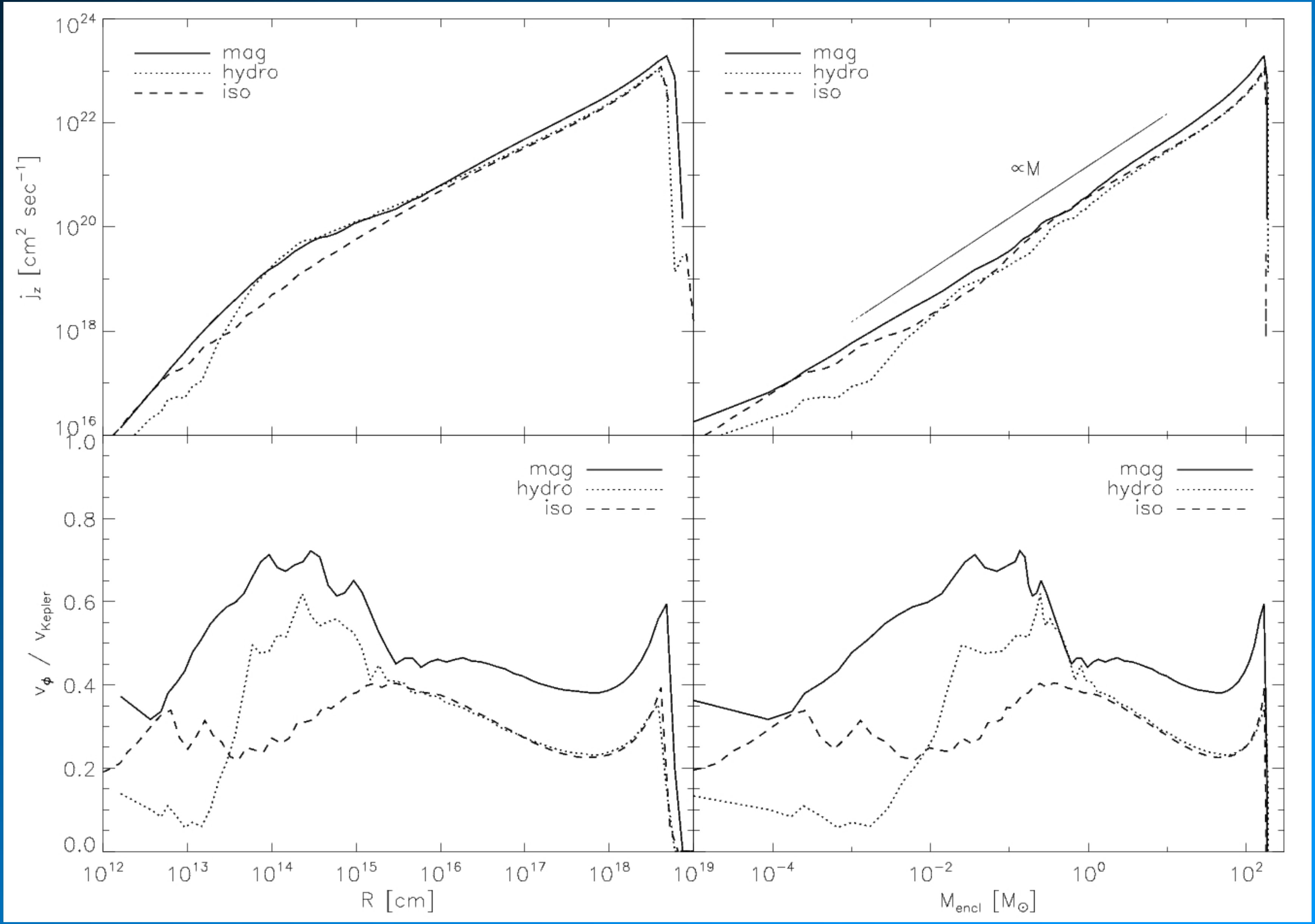
Magnetic field structure / evolution





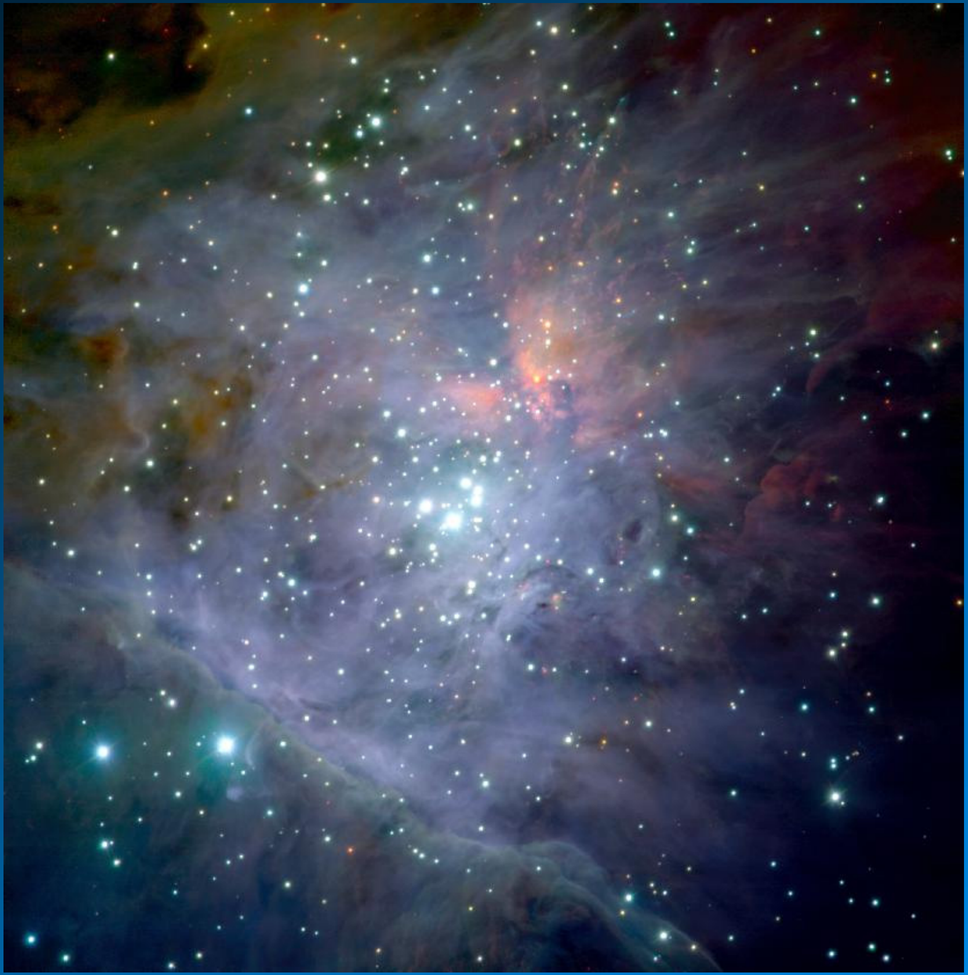
- $B_z > B_\phi$ in the core and disk (expectation from a stationary accretion disk $B \propto R^{-1.25}$; *Blandford & Payne 1982*)
- $B_{core} \propto n^{0.6}$
- Expected field strength in the protostar ~ $10^4 – 10^5$ G
- Potential seed field for Ap stars *(Braithwaite & Spruit, 2004)*

Angular Momentum



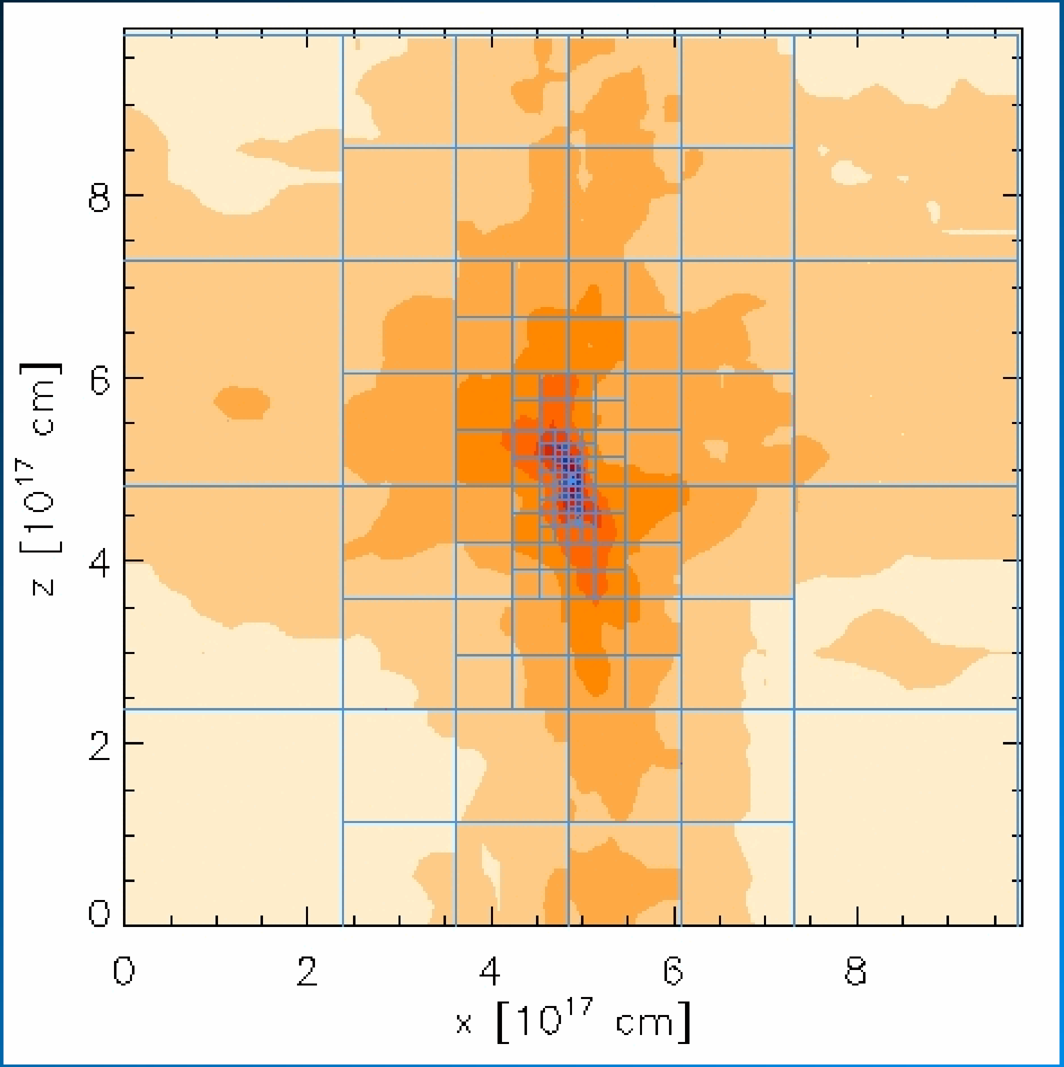
Banerjee & Pudritz in preparation

Turbulence



- Star Formation takes place in a **supersonic turbulent** envrionment (e.g. *Mac Low & Klessen 2004*)
- Hydrostatic cores??? (but *Shu et al. 1987, Mouschovias*)

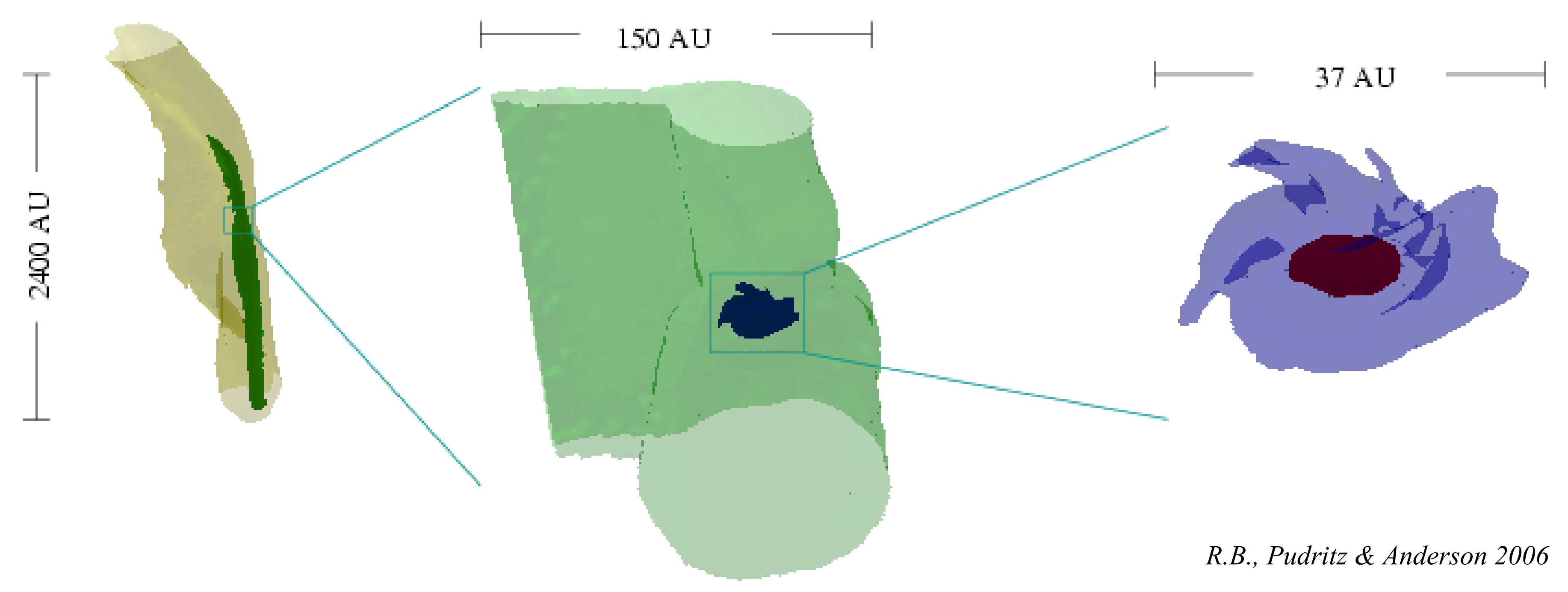
Collapse with supersonic turbulence



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}

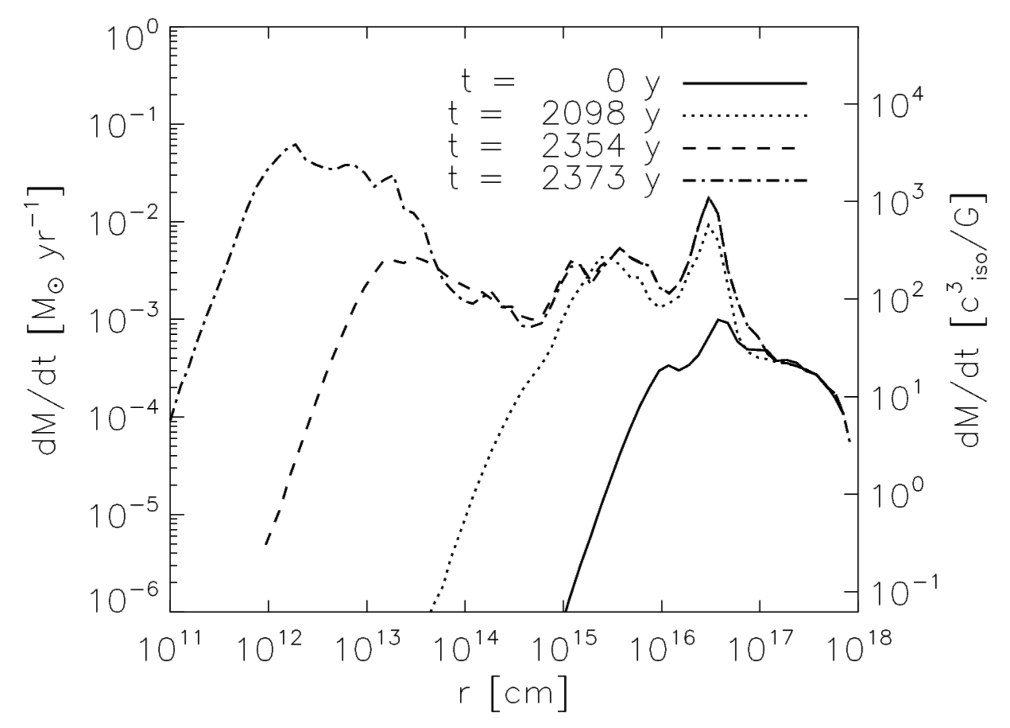
Collapse with supersonic turbulence

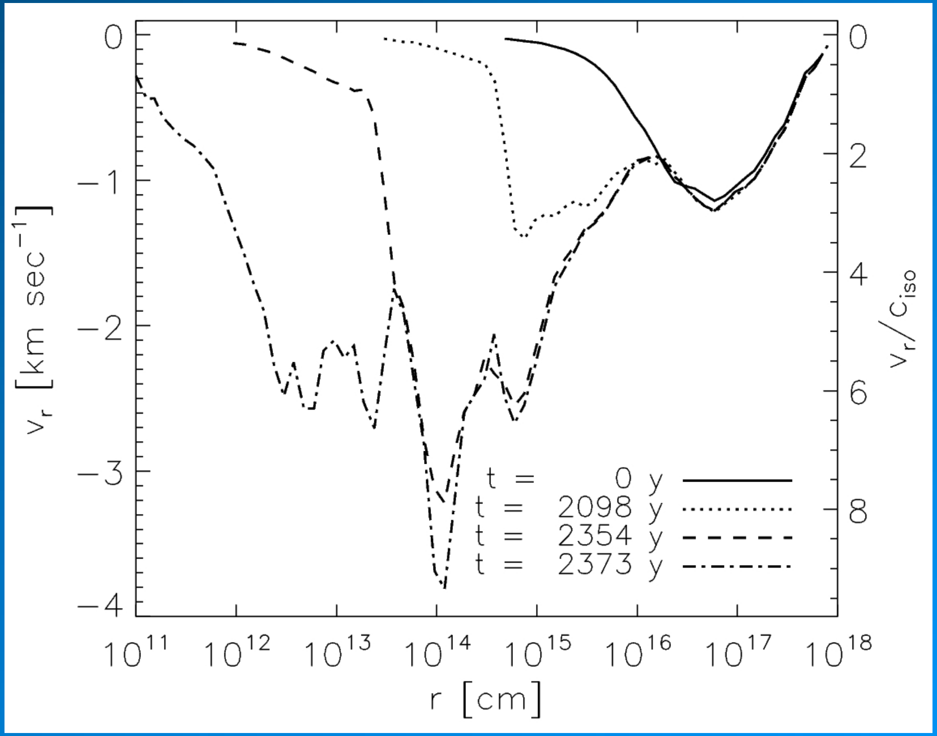


R.B., Pudritz & Anderson 2006

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

Mass accretion





- Very **high** mass accretion rates: up to 10 $v_{in}^3/G \sim 10\, \mathcal{M}^3\, c^3/G$ (cf. Shu '77 $dM/dt \sim c^3/G$)
- 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

Ongoing & Future Projects

- Feedback from Jets ⇒ **Turbulence** from Jet-clump interactions?
- Clump/Core formation by colliding flows *(Vazques-Semandeni et al. 2006)*
- Include **Radiative Transfer** (Formation of massive stars; *Thomas Peters*)
- Precessing Jets (with *Christian Fendt*)

Summary

- Numerical simulations help to understand the star formation process
- Chemistry/**Cooling** important
- Magnetically driven **outflows** and **jets** from protstellar disk
- Magnetic fields reduce/prevent fragmentation
- **Turbulence** plays an important role (stucture of cloud cores, accretion rates)
- No stage of hydrostatic cores in a turbulent environment: assembly of protostars is a very rapid process