Collapse of Massive Cloud Cores & Outflows

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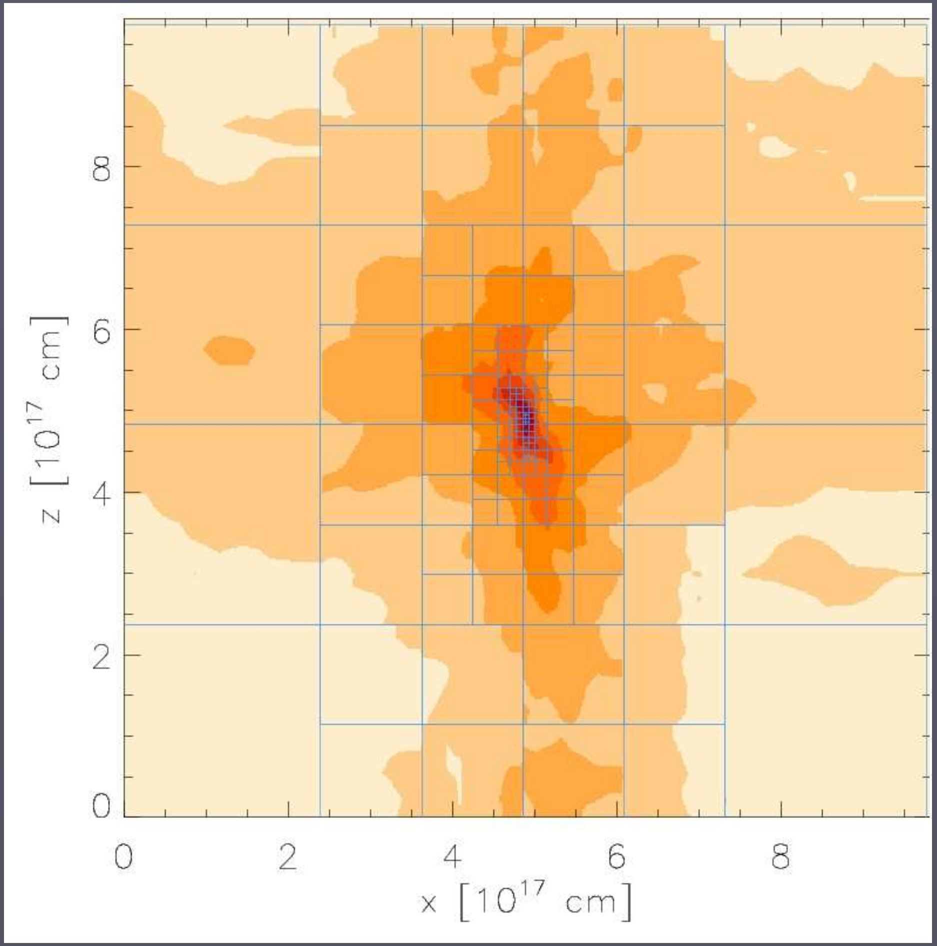


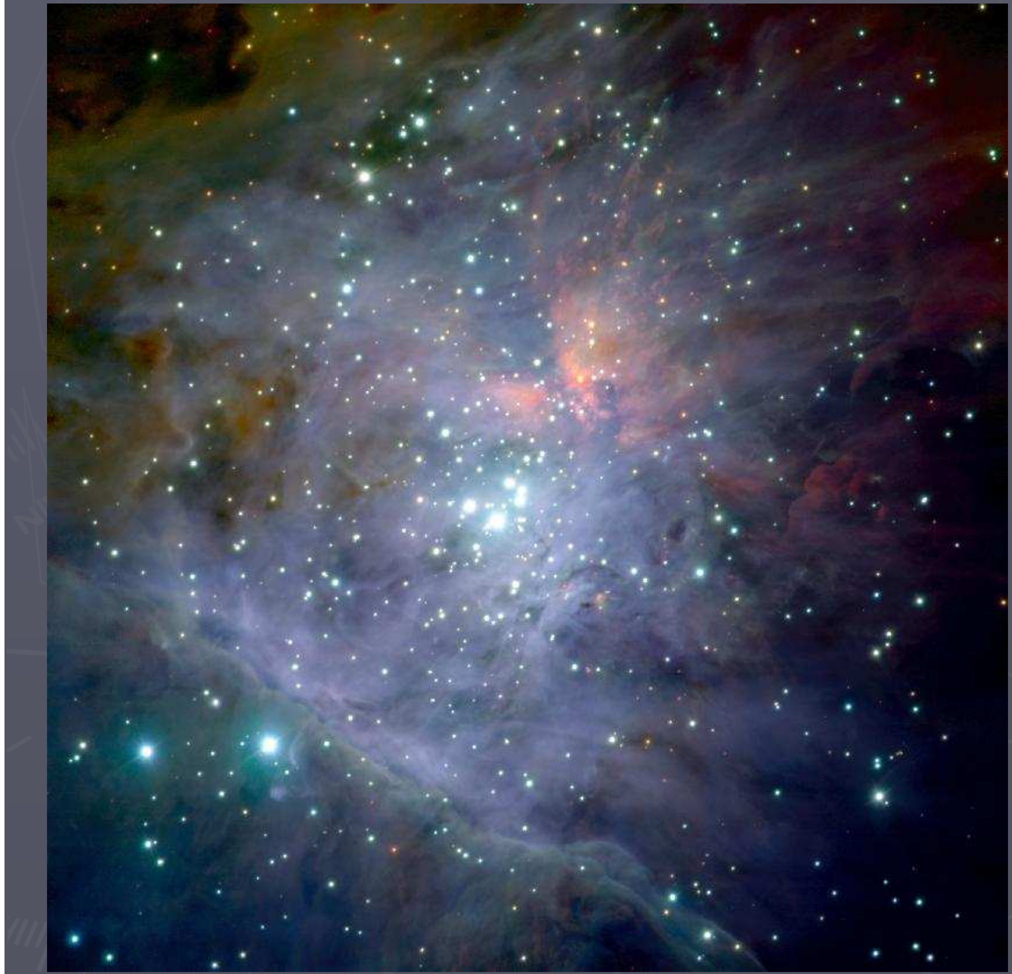
Based on 3D MHD, AMR* Simulations

Collaborators:
Ralph Pudritz
Ralf Klessen
Christian Fendt

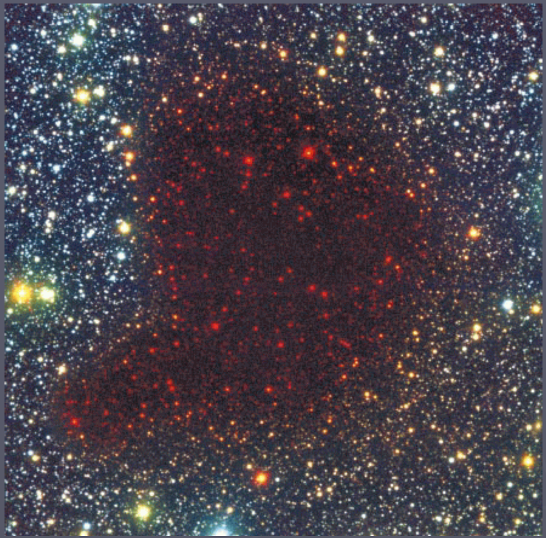
*Adaptive Mesh Refinement

Contemporary Star Formation

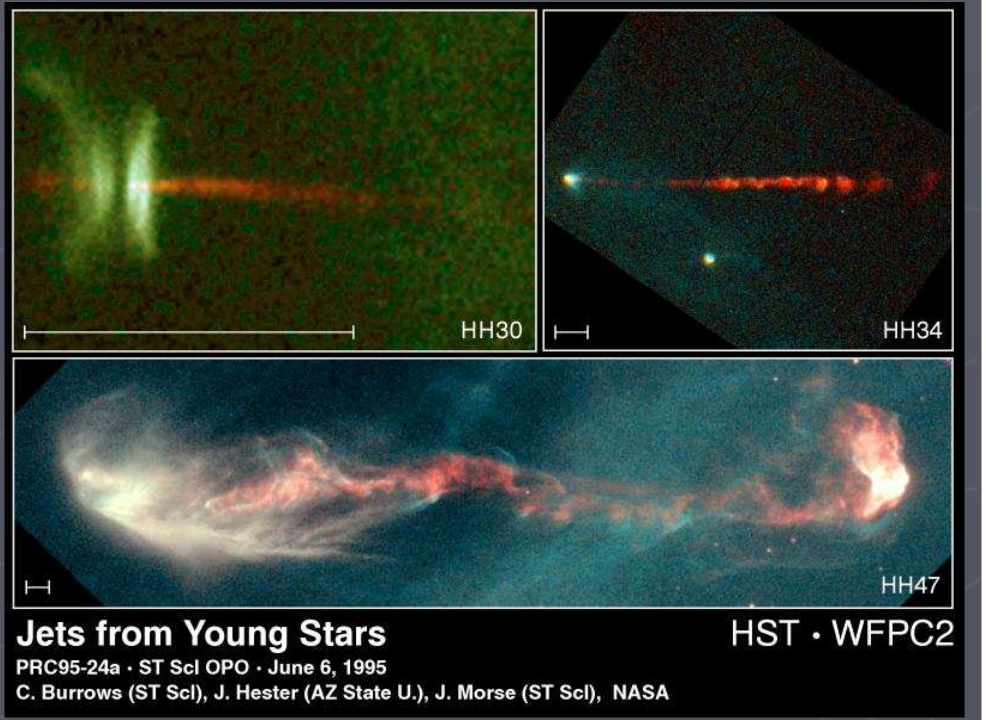
- Star Formation in turbulent (Giant) Molecular Clouds



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

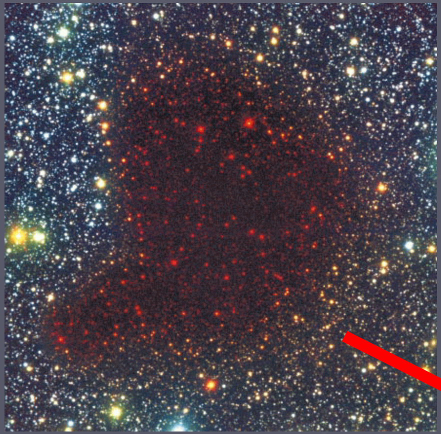


Barnard 68,
Cloud core (cold, self shielded)
(Alves, Lada & Lada, Nature 2001)



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

Collapse of Hydrostatic Cores

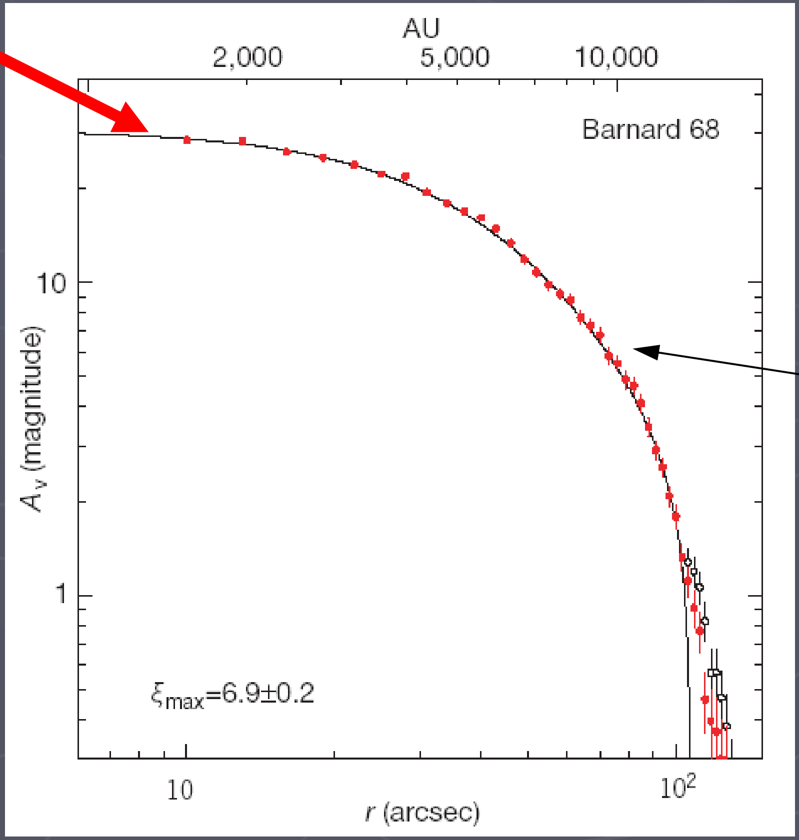


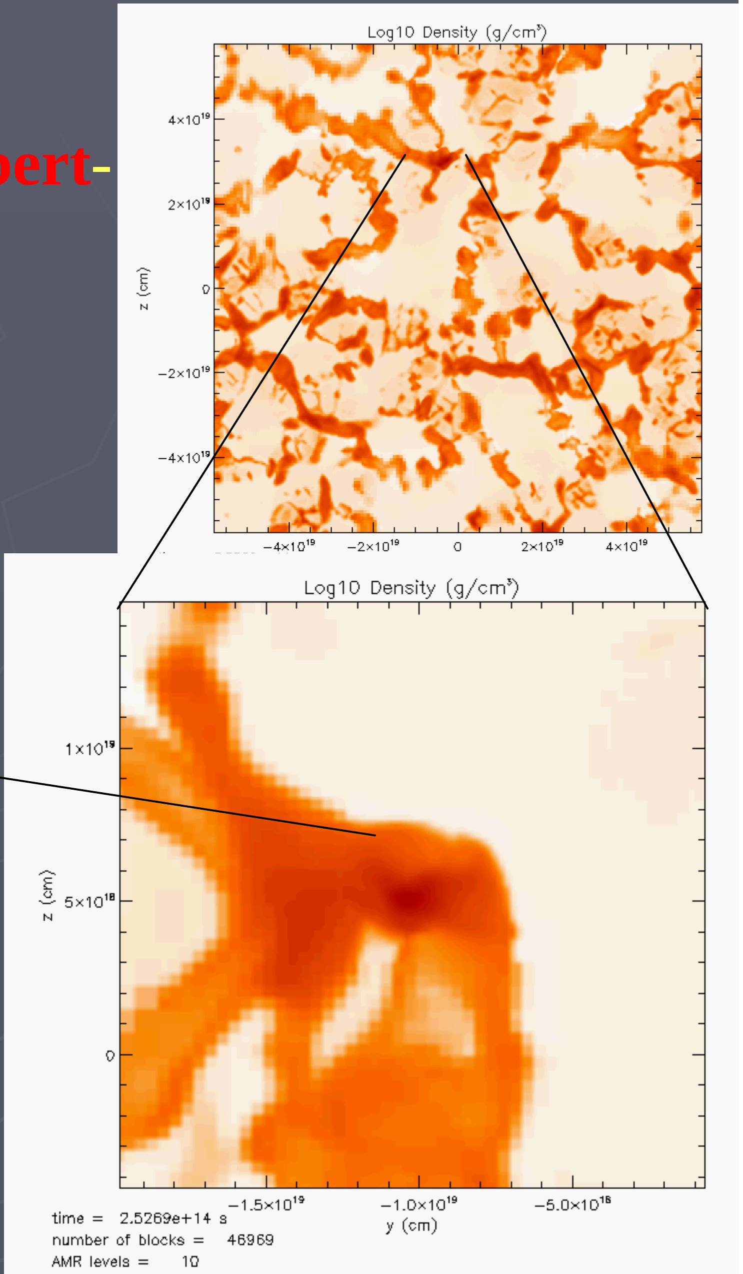
Bok Globule B 68

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

Compilation of BE spheres:
Lada et al. 2007 PPV

Molecular Clouds in hydrostatic equilibrium follow a **Bonnor-Ebert-**Profile;
Critical BE Sphere: $\xi = 6.451$

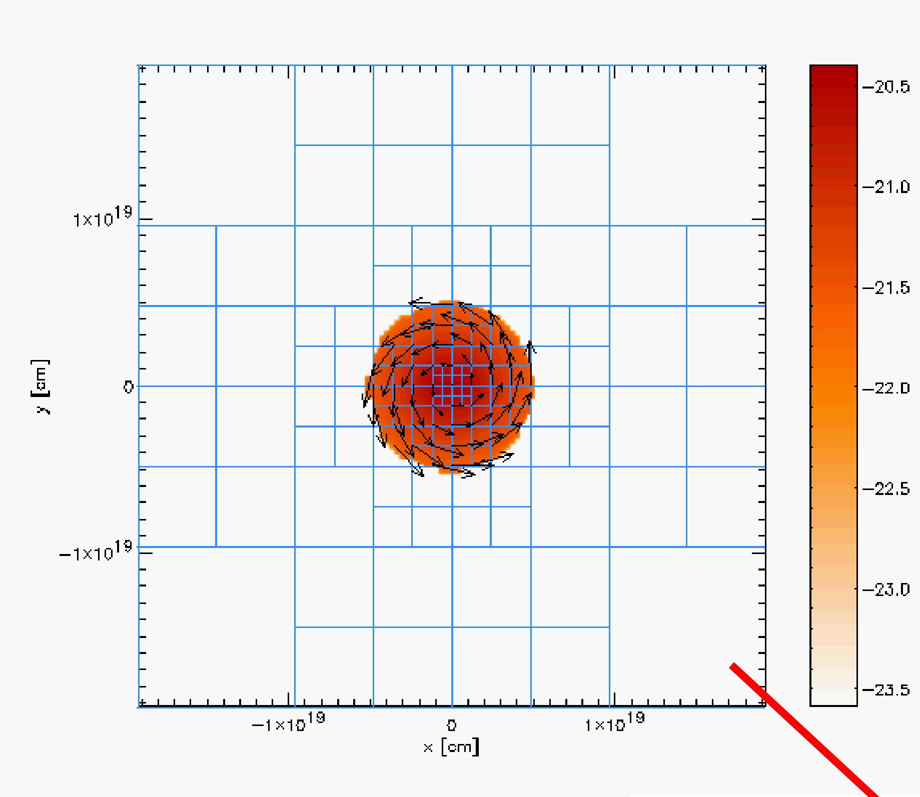




Collapse of Hydrostatic Cores

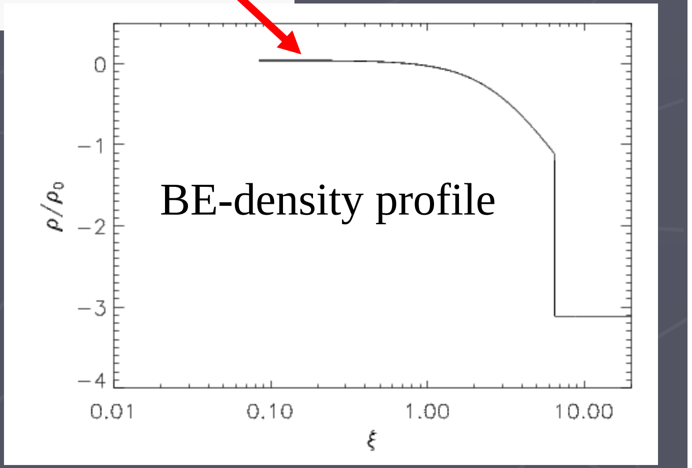
- Slowly rotating Bonnor-Ebert-Spheres
- Low Mass M ~ $2.1 M_{sol}$
- High Mass ~ $170\ M_{sol}$
- **Cooling** due to molecular excitations, gas-dust interaction, H_2 dissociation
- AMR ⟹ resolves **Jeans length** with more than 8 grid points during collapse *(Truelove et al. 1997)*
- Up to 27 refinement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

(http://flash.uchicago.edu)

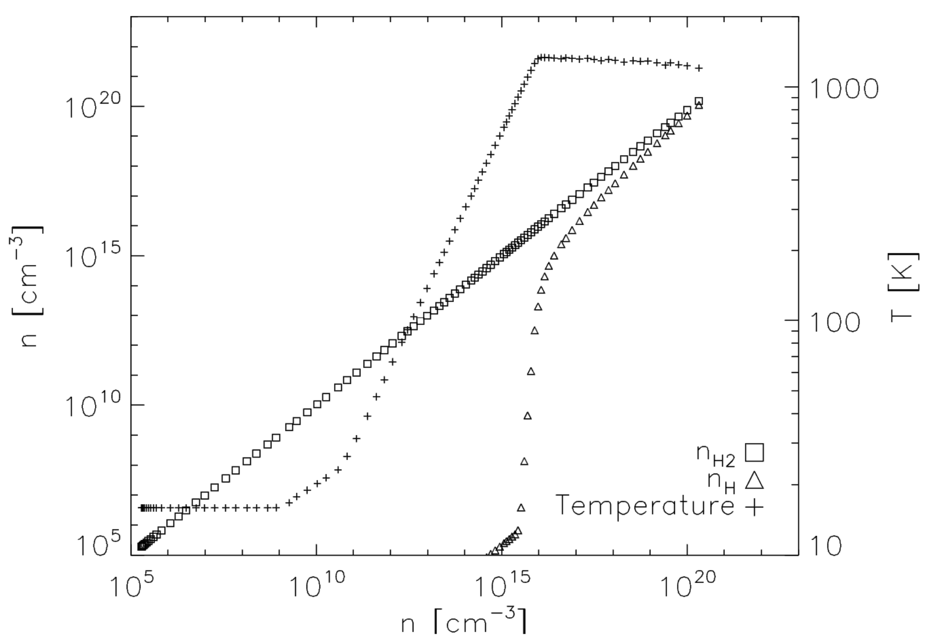


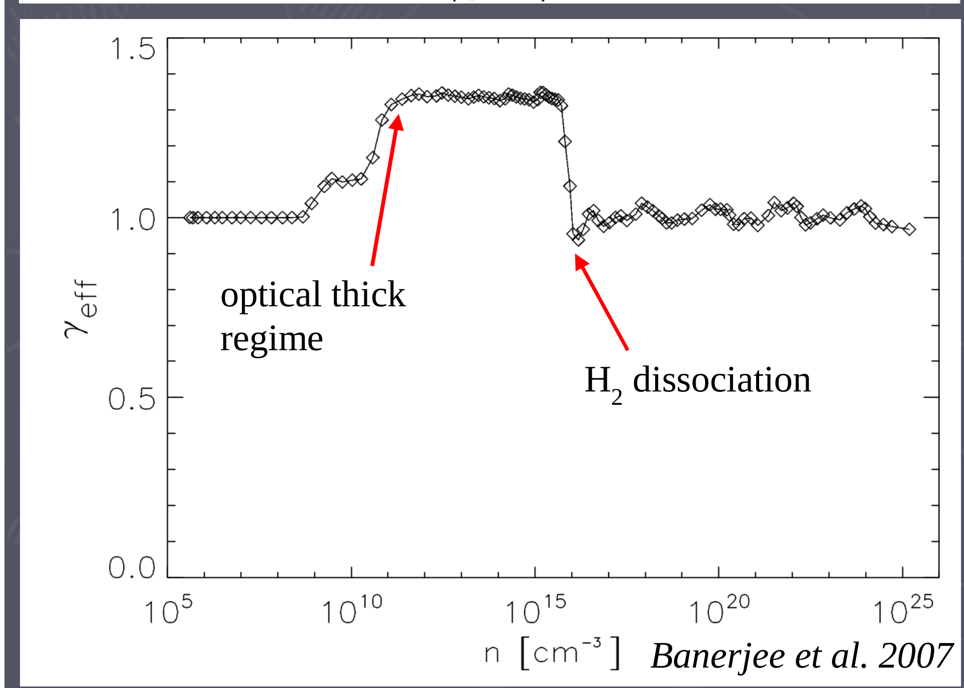
Initial conditions:

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



Cooling

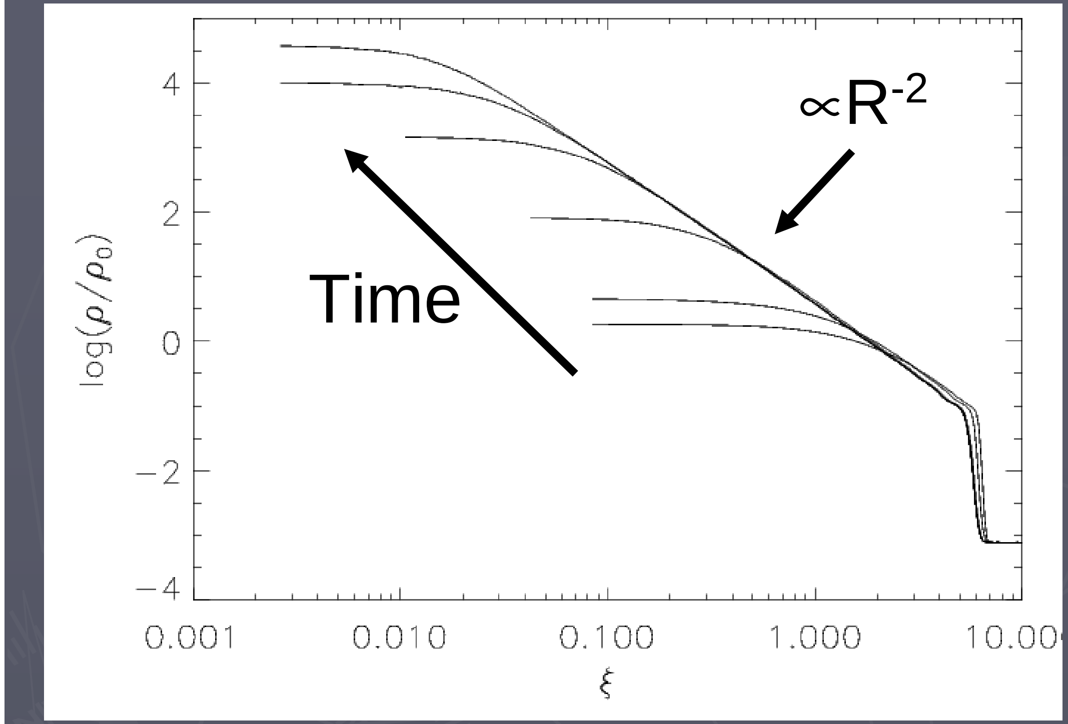


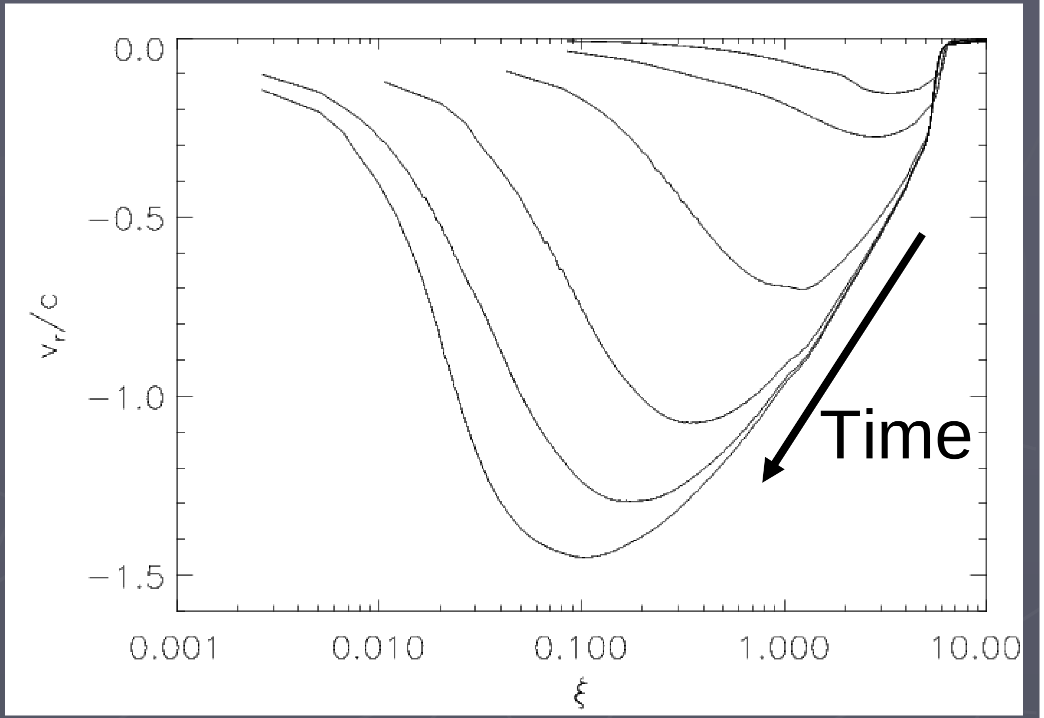


Banerjee et al. 2007

- 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 hot 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

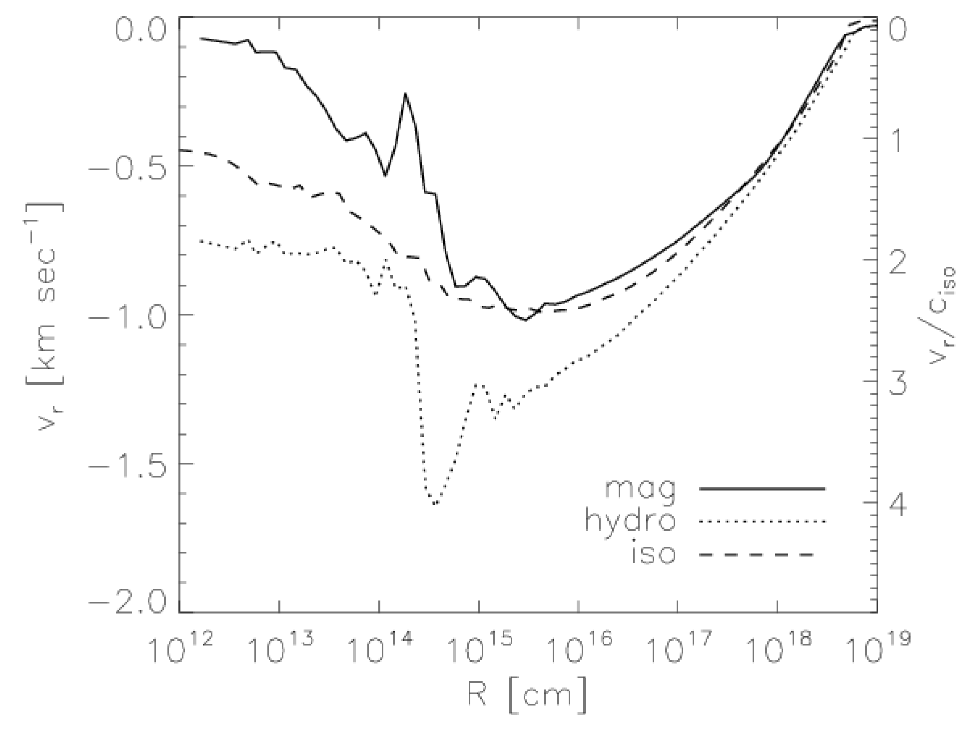
infall velocity

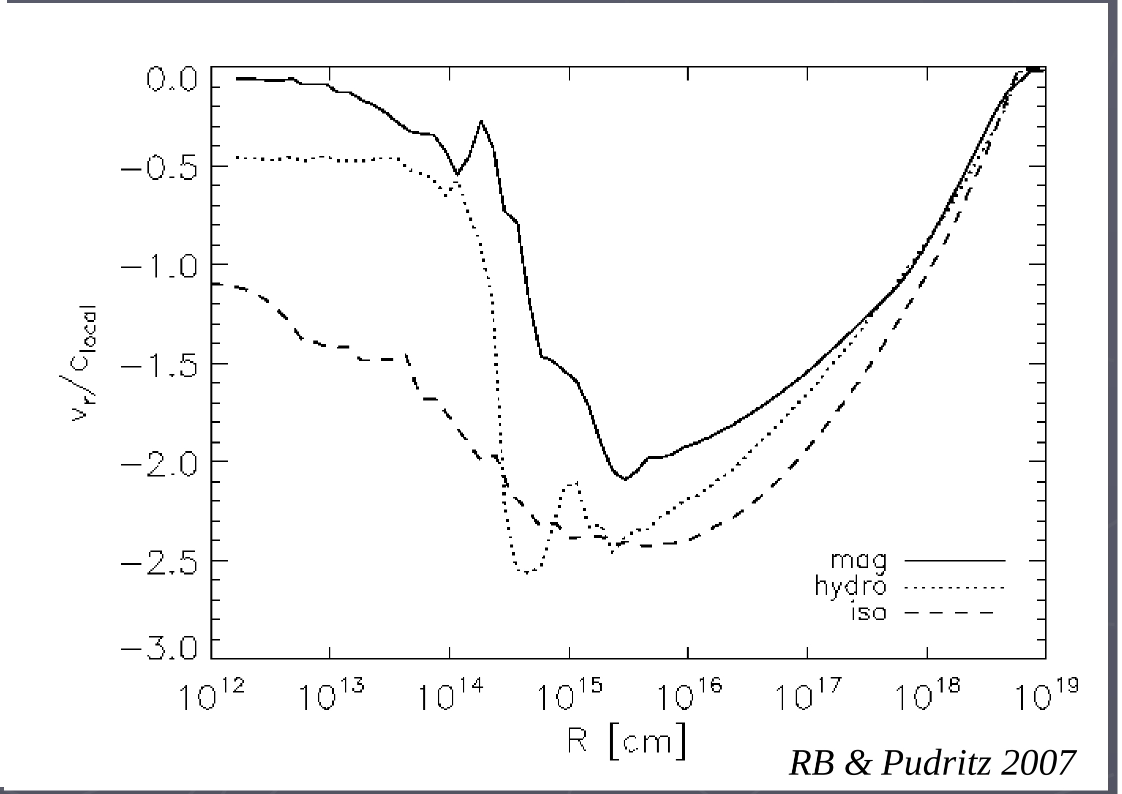
Outside-in

non-homologous collapse

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

Collapse of Massive Cloud Cores



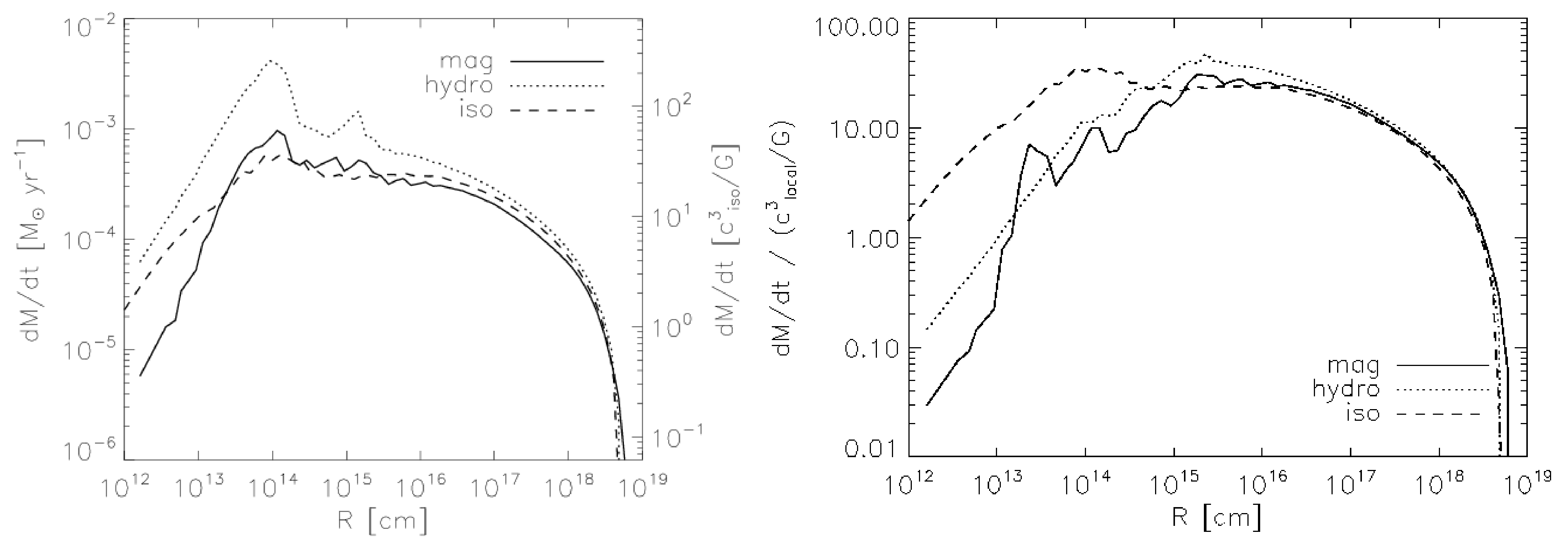


RB & Pudritz 2007

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

Mass accretion

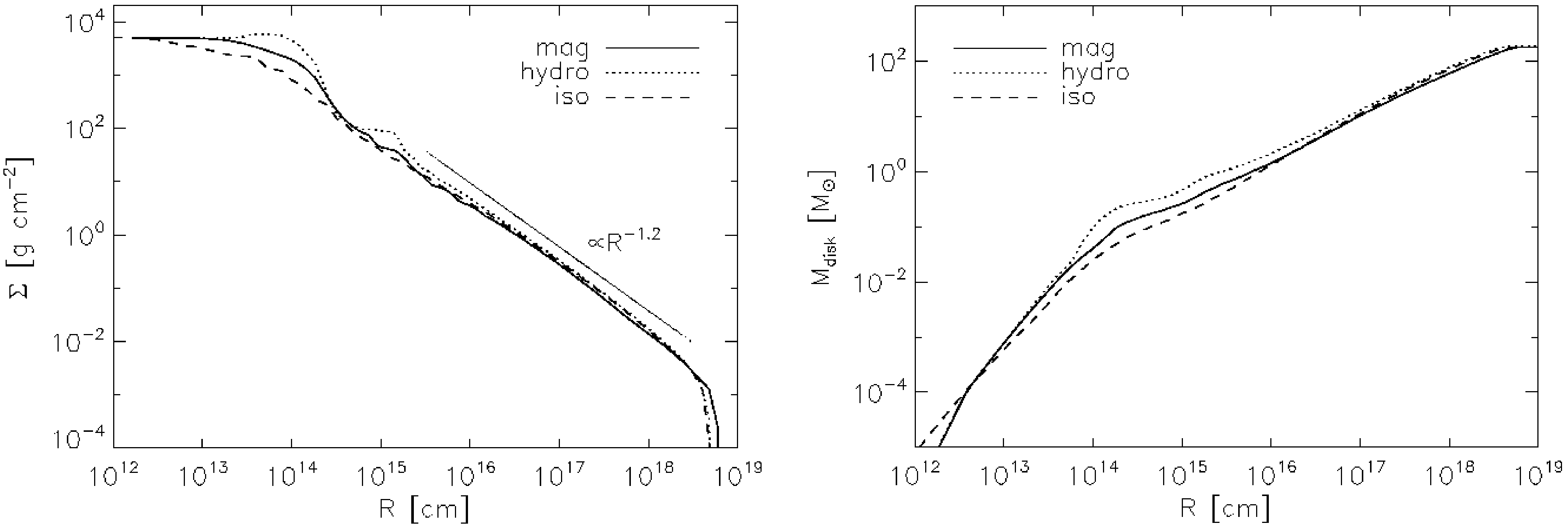
comparision



- dM/dt ~ v^3/G = Mach^3 $c^3/G \gg c^3/G$
- Higher speed of sound ⇒ higher accretion rate

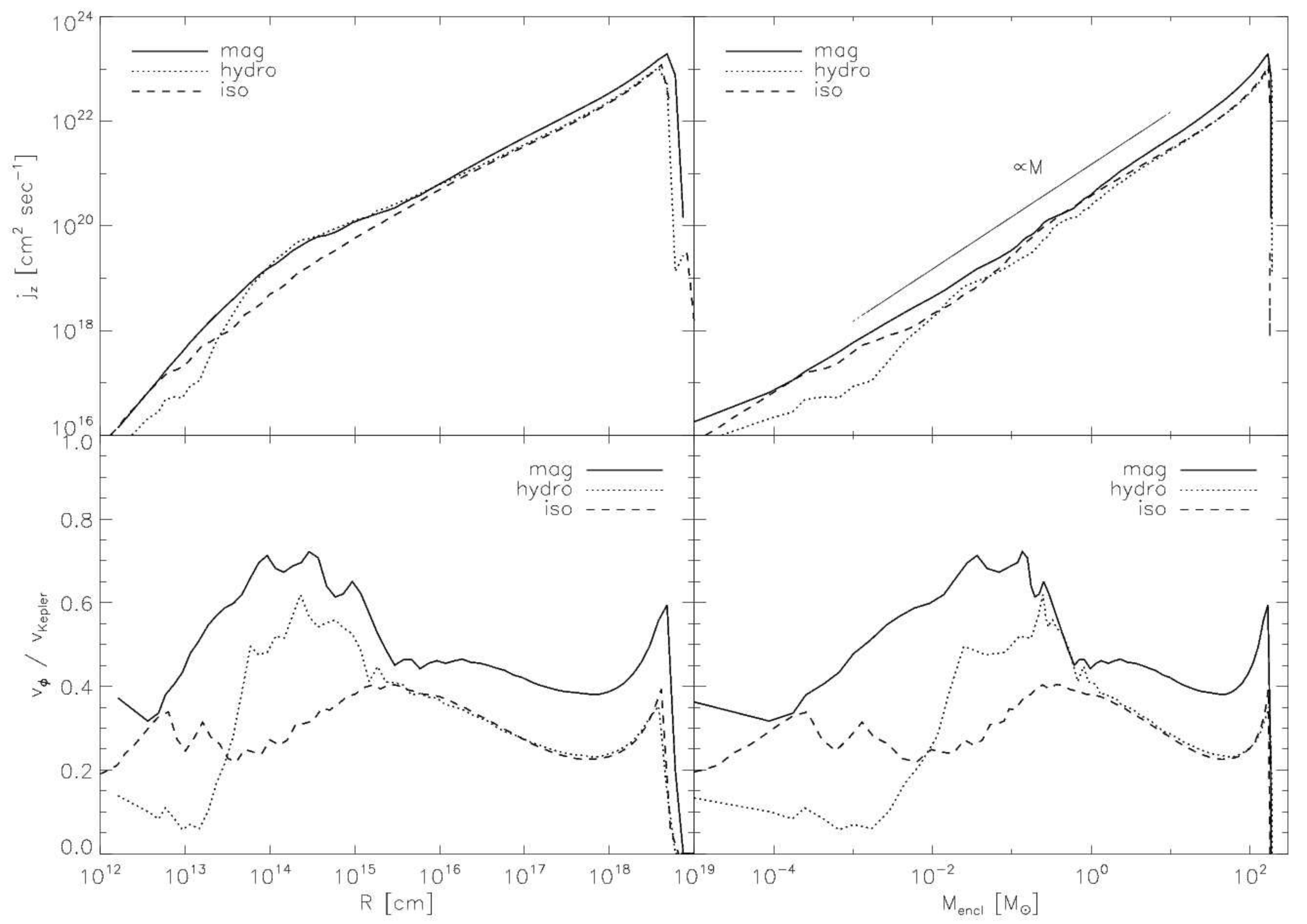
$$\dot{M} = 20 - 100\ c^3 / G$$

Density and Mass distribution



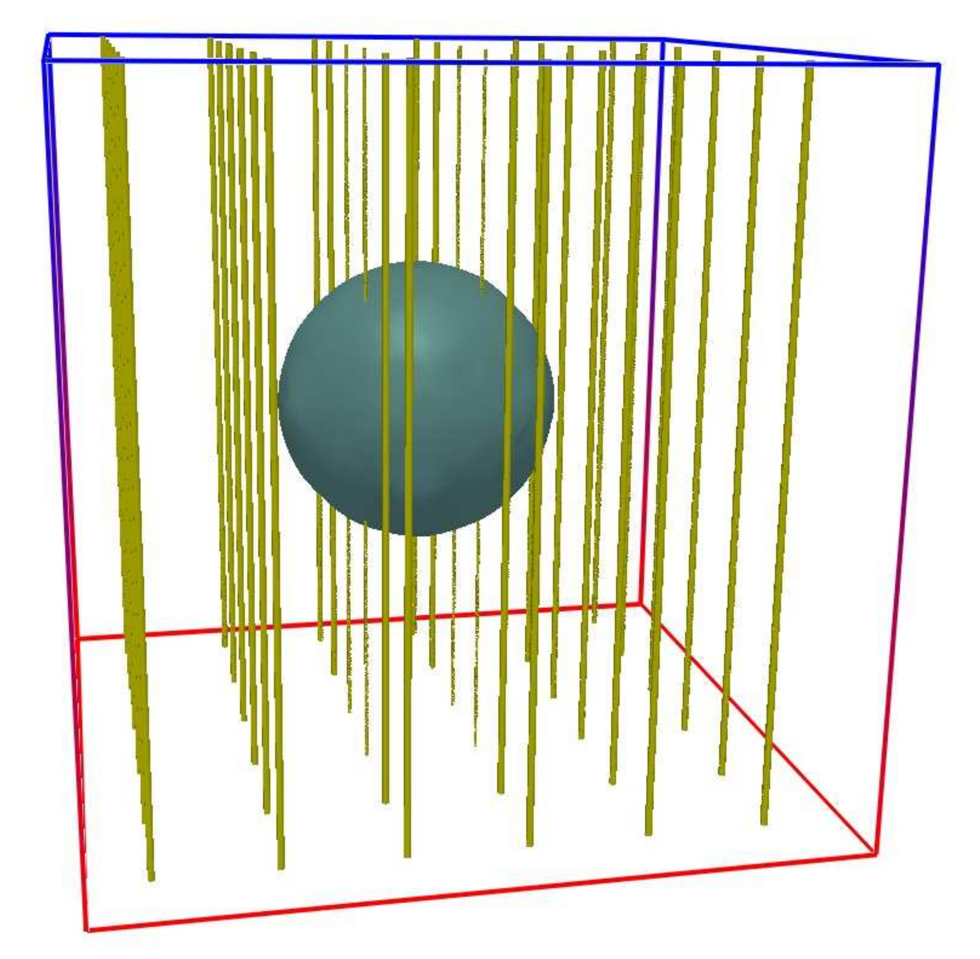
- So far disk dominated (after t ~ t_{ff})
- $1M_{sol}$ at few x 10^{15} cm

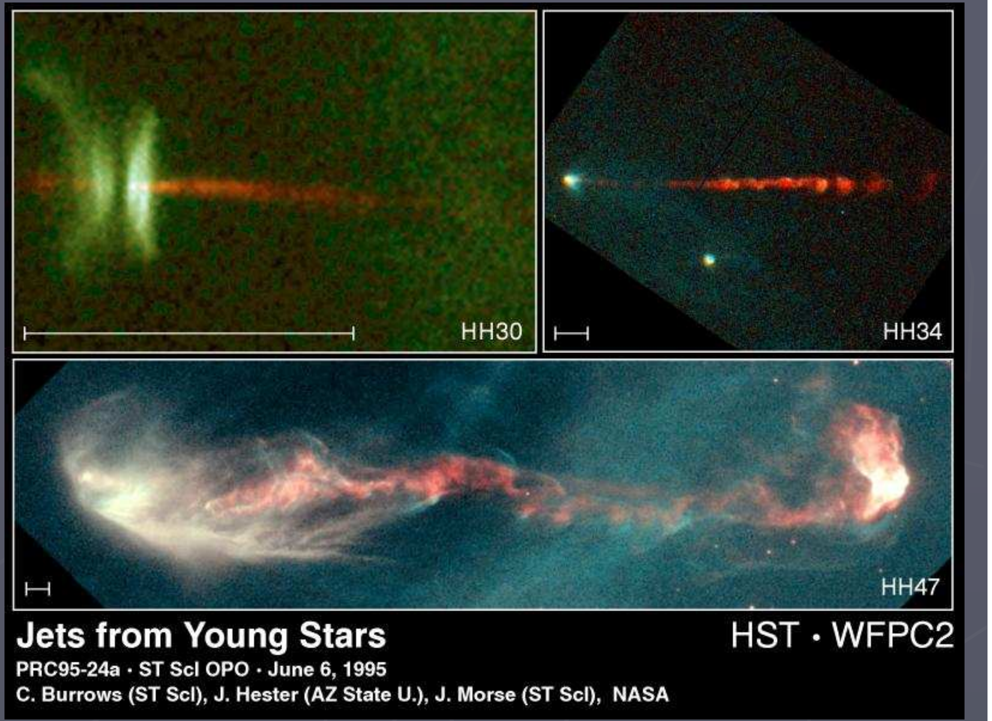
Angular Momentum



Banerjee & Pudritz 2007

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; $P_{therm}/P_{mag} \sim 80$; $B \sim 10\ \mu$Gauss

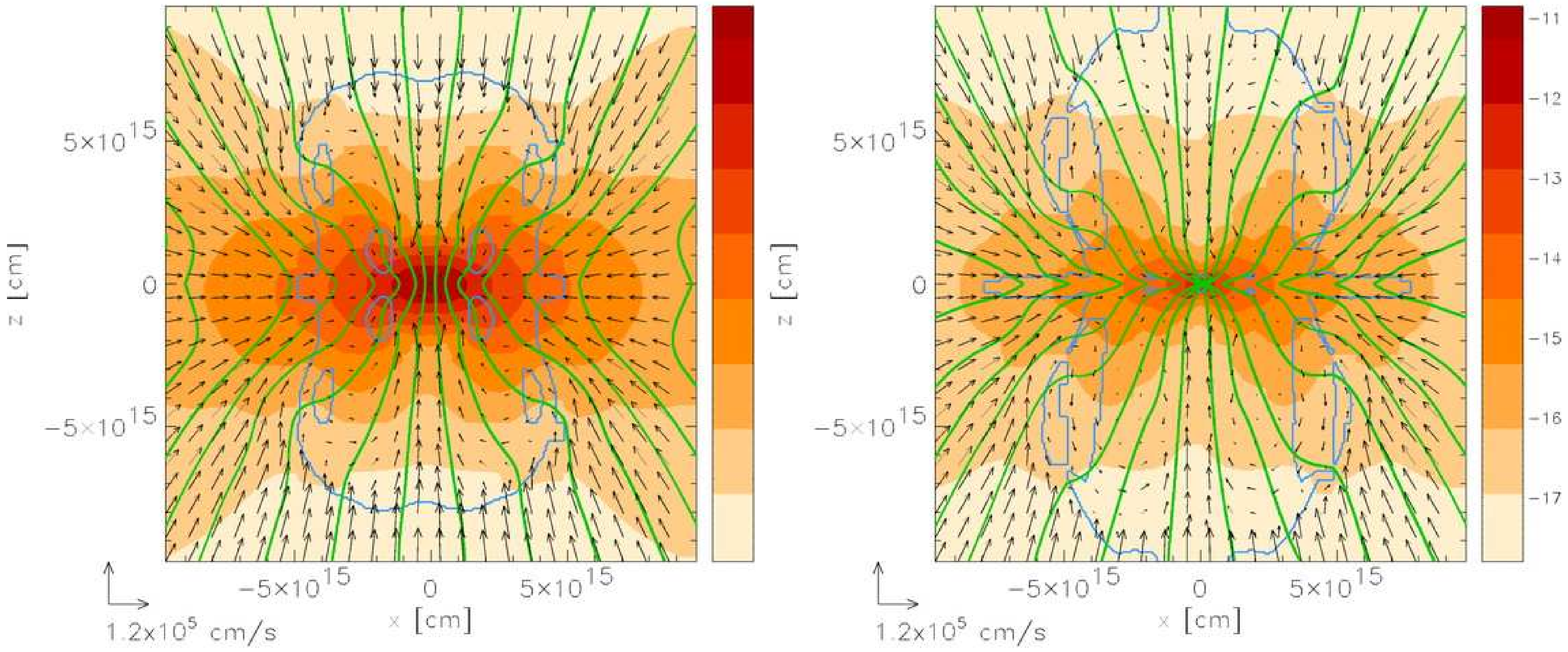
Similar simulations by:
Machida et al. 2005
Fromang et al. 2006

Onset of large scale outflow:

at few 100 AU

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

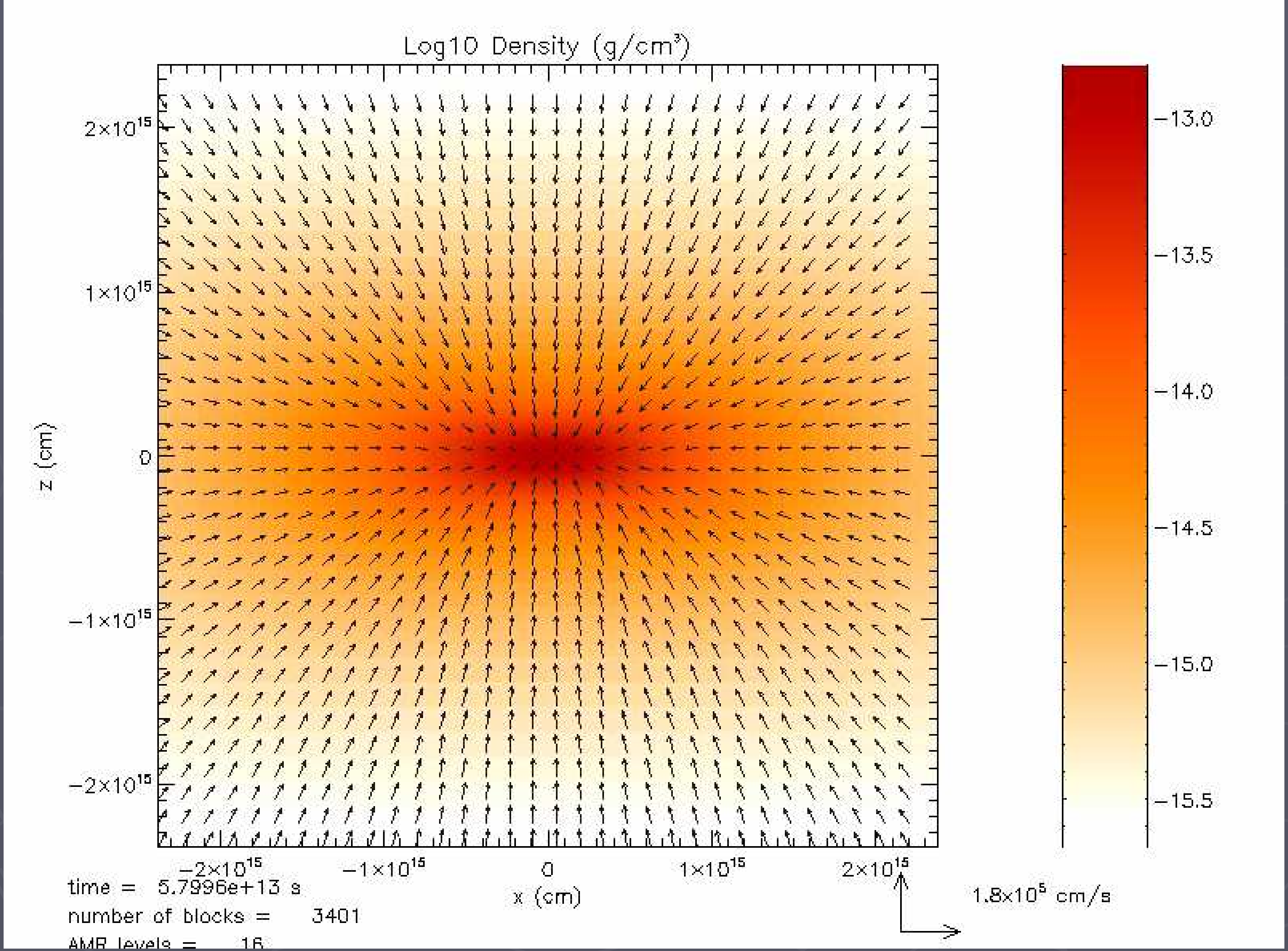
Banerjee & Pudritz 2006



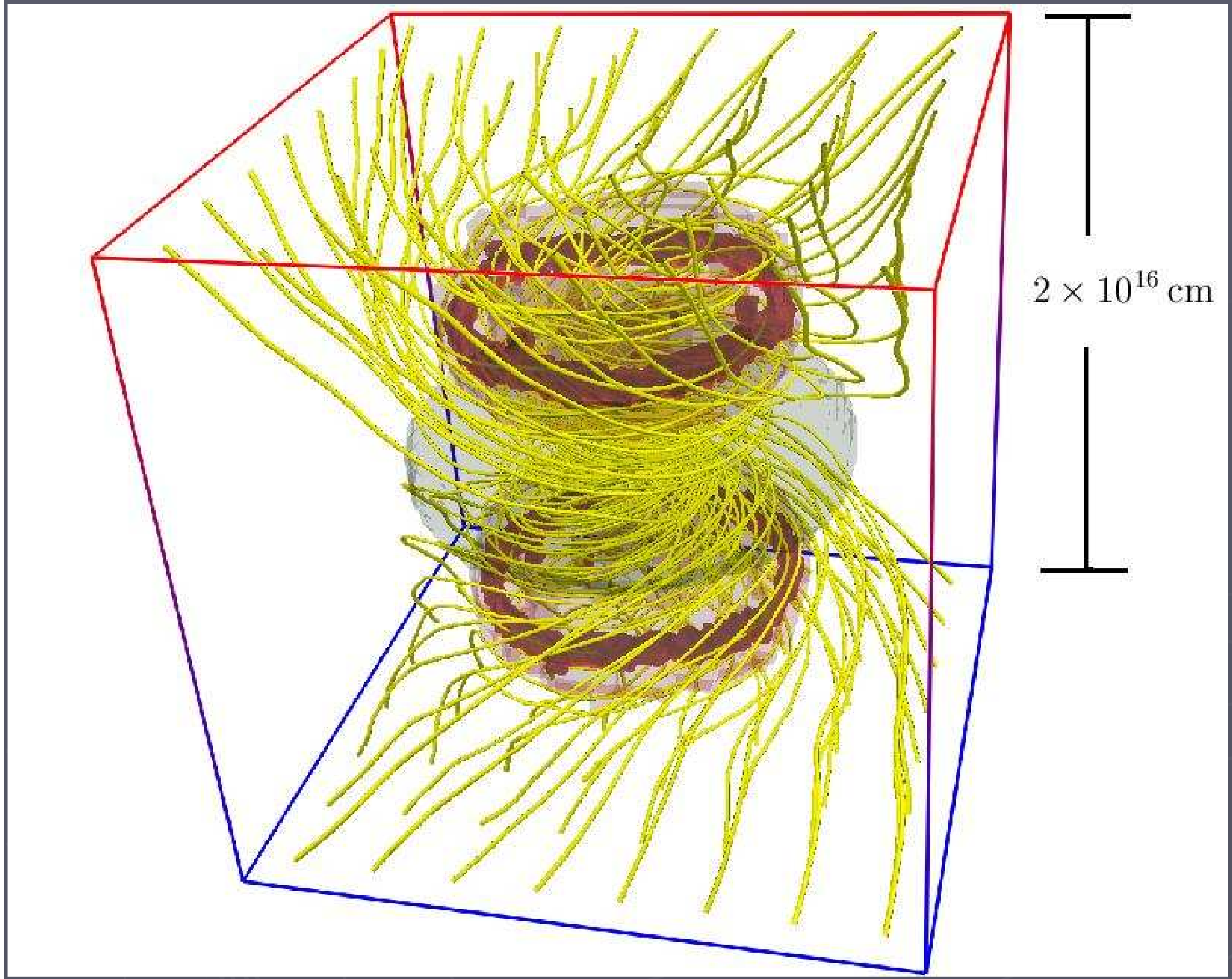
collapse phase
pinched in magnetic field

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

Onset of large scale outflow:
Magnetic tower



Large scale outflow

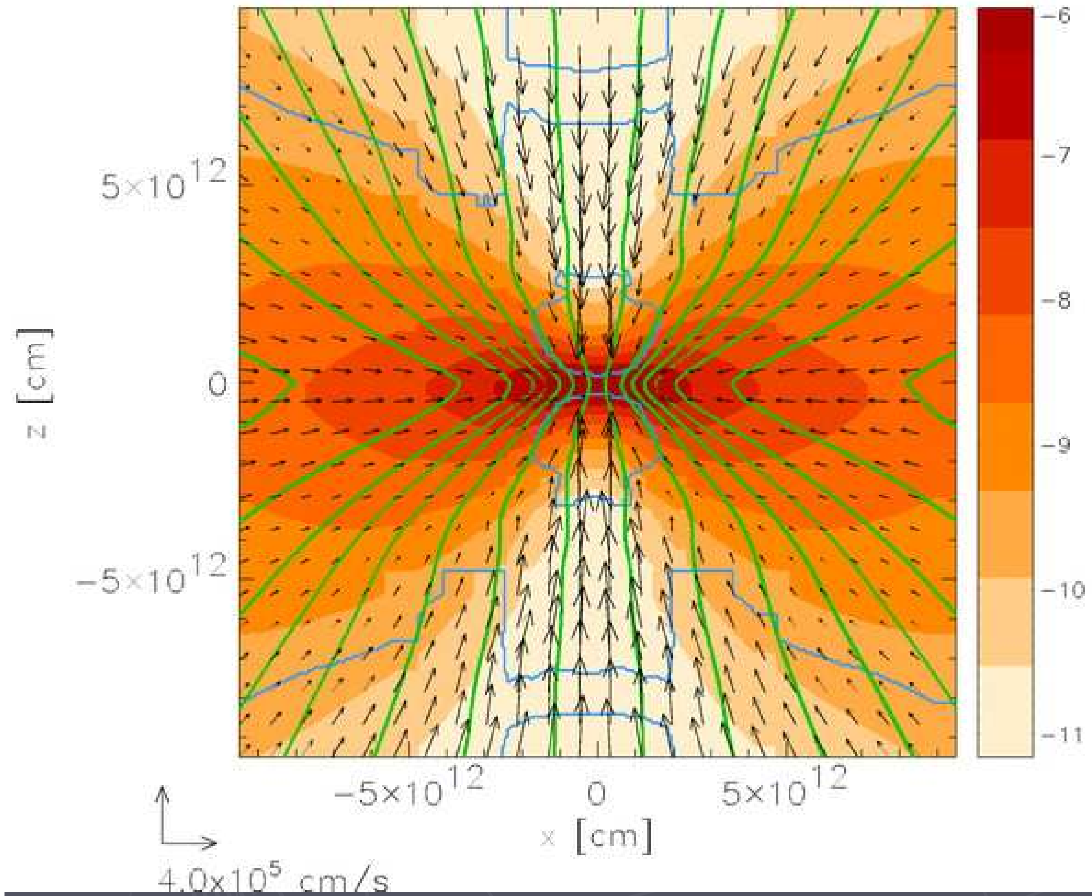


- Magnetic field is **compressed** with the gas
- Rotating disk generates **toroidal** magnetic field
- Shock fronts are pushed outwards (magnetic tower; *Lynden-Bell 2003*)
- Outflow velocities v ~ 0.4 km/sec
- Accretion funneled along the rotation axis, through disk

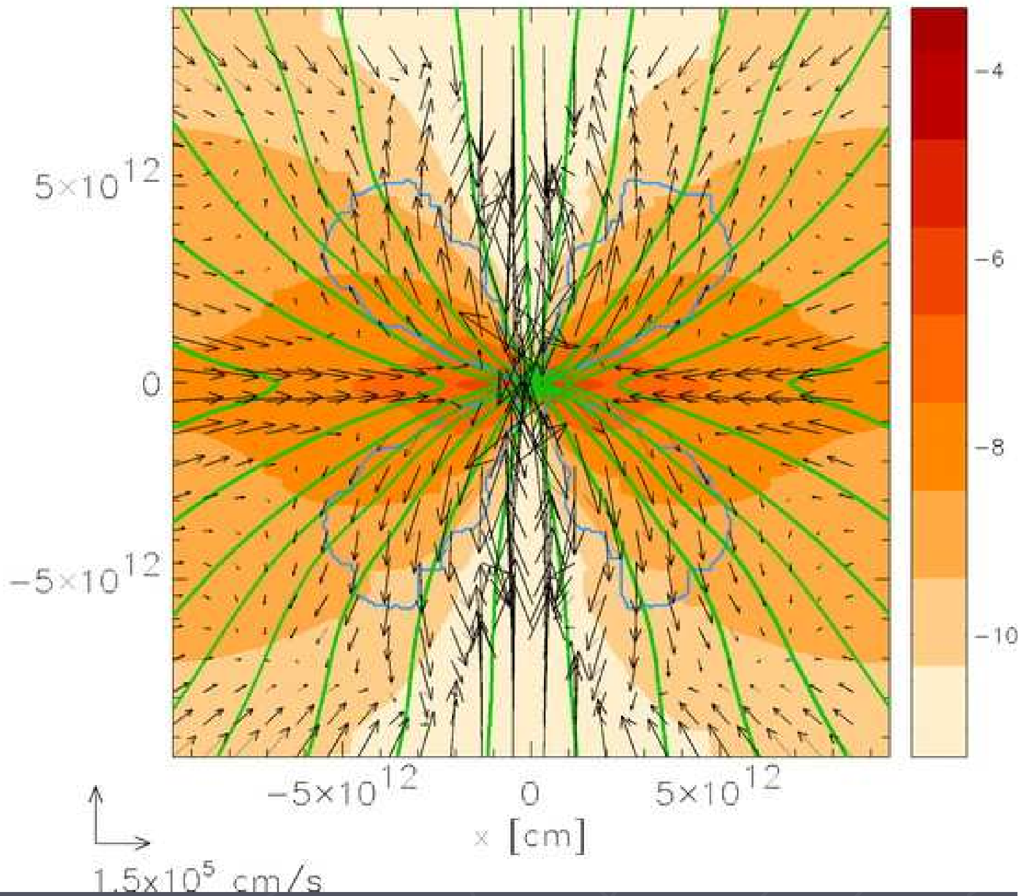
Onset of inner disk jet

launch inside 0.07 AU

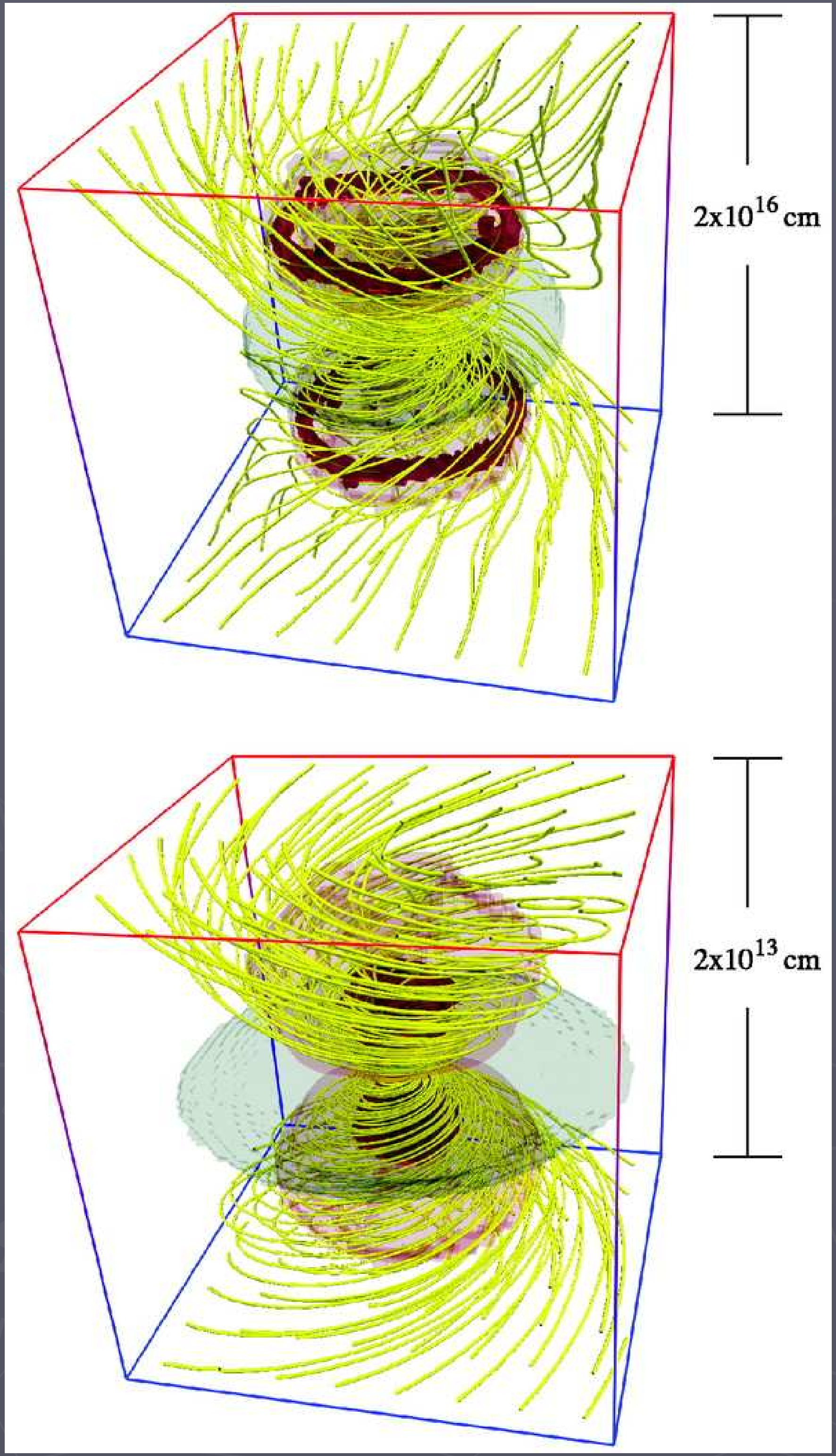
- magneto-centrifugally launched jet (*Blandford & Payne 1982*)
- jets rotate and carry off angular momentum of disk



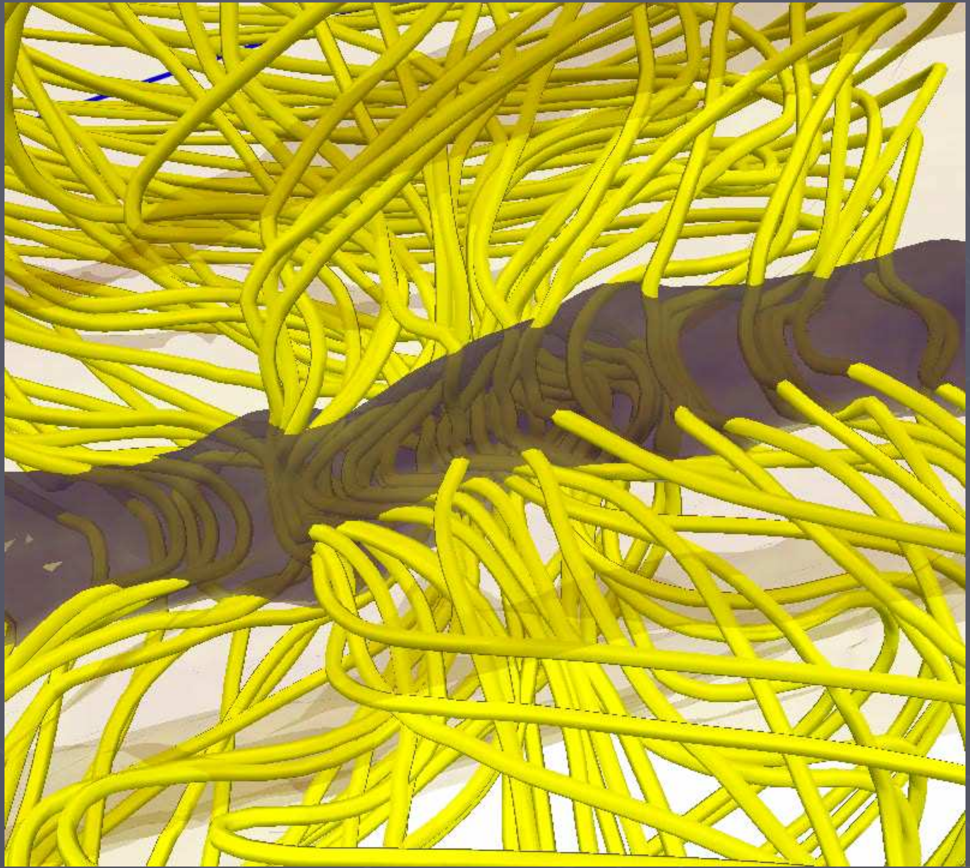
infall only



... 5 month later: flow reversal

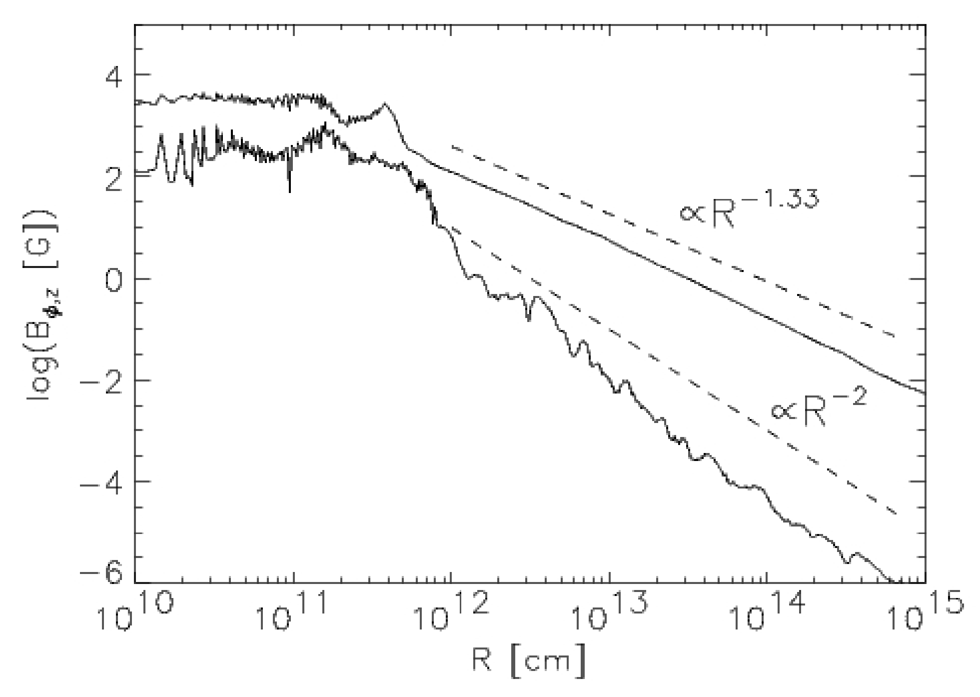


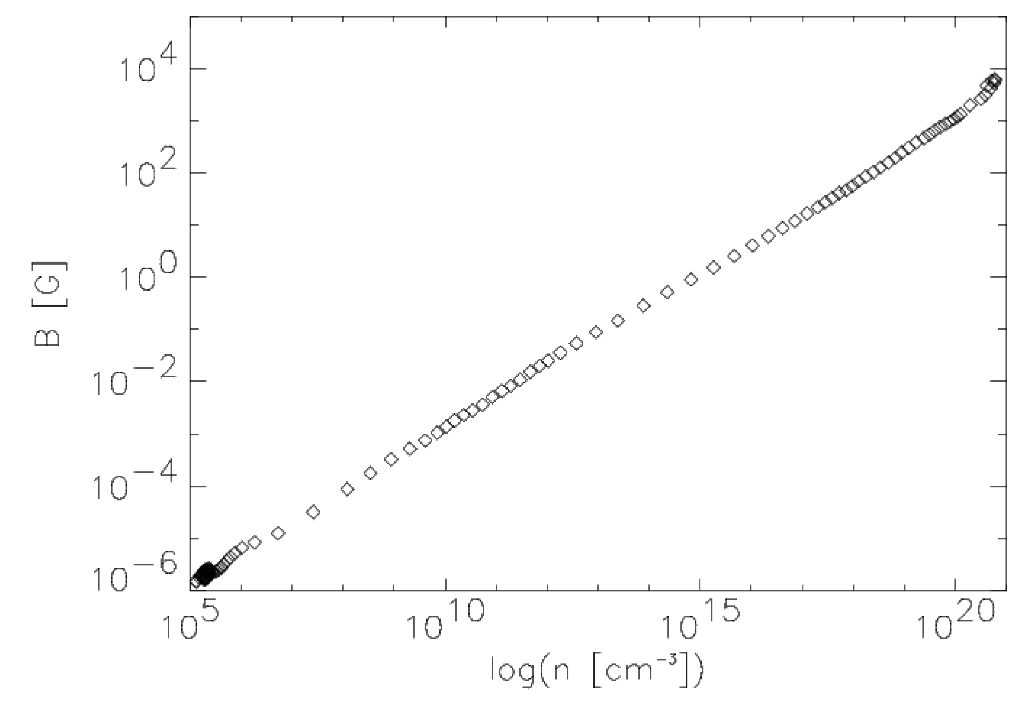
3D Visualization of field lines, disk, and outflow:
- Upper; magnetic tower flow
- Lower; zoomed in by 1000, centrifugally driven disk wind



Observations: FU Ori disk
Donati et al. Nature 2005

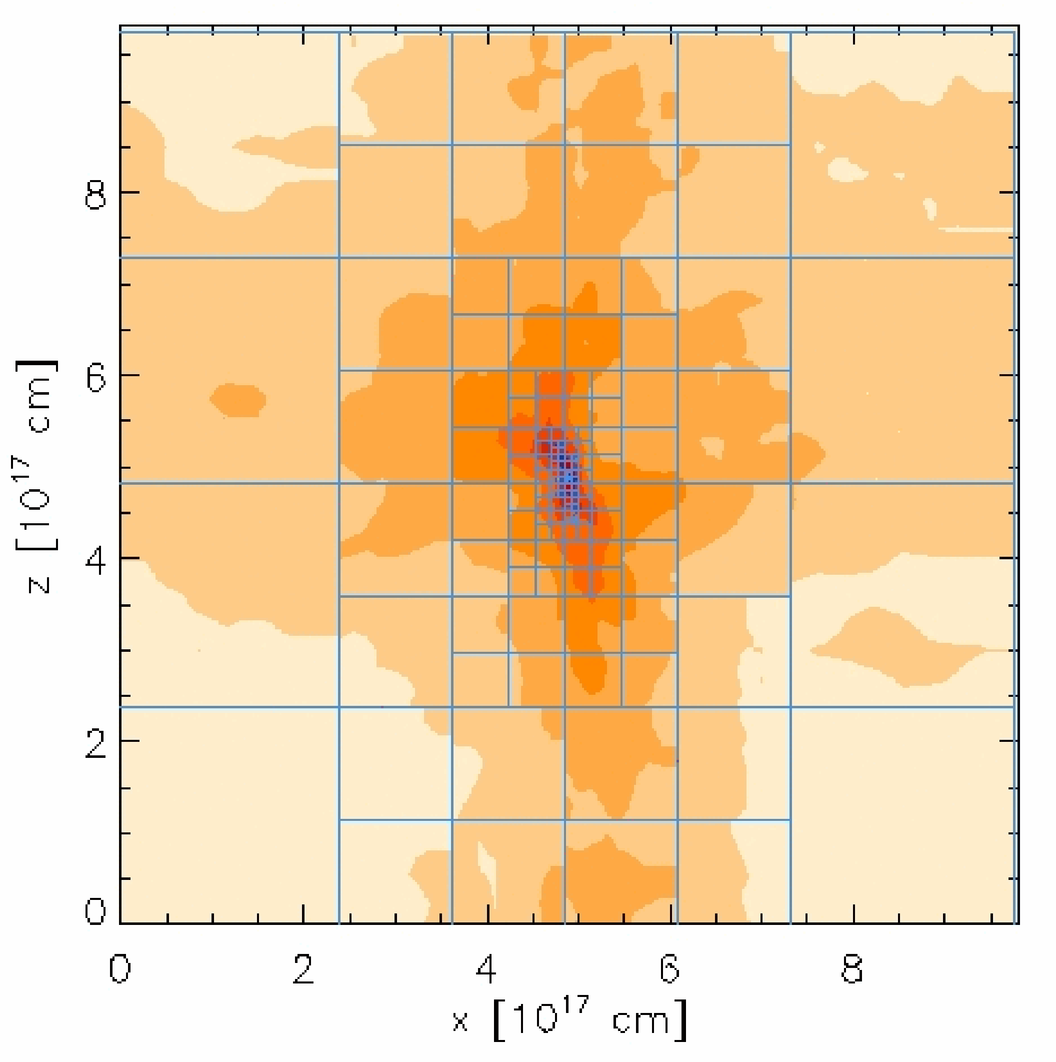
Magnetic field structure / evolution





- $B_z > B_\phi$ 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)*

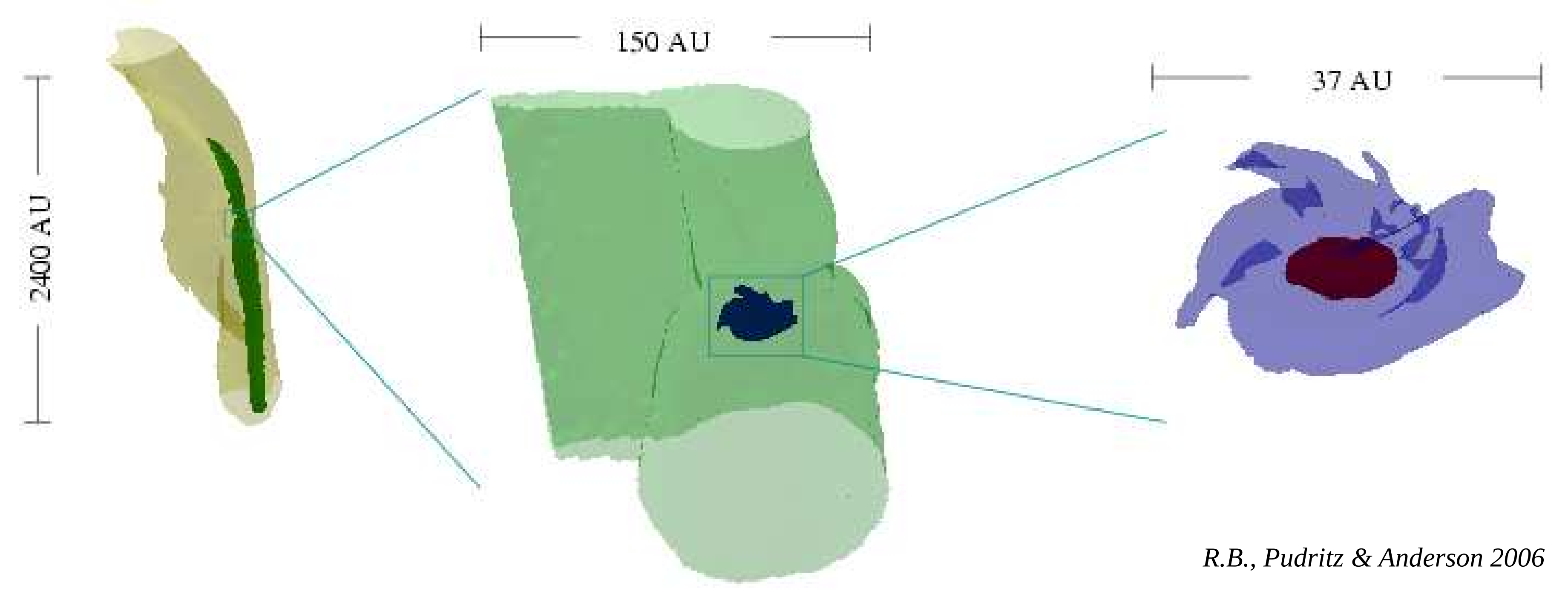
Collapse with supersonic turbulence



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}

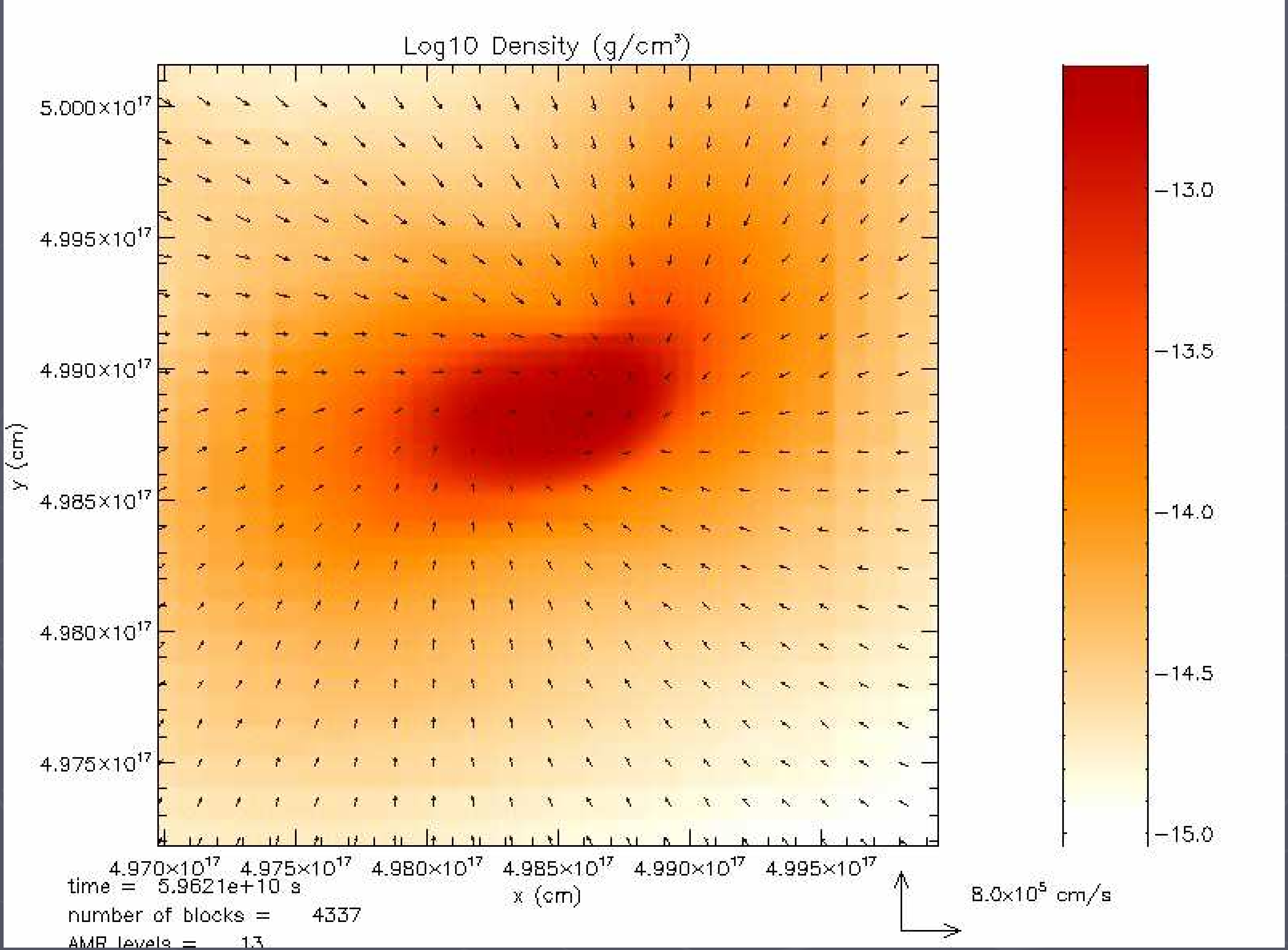
Collapse with supersonic turbulence



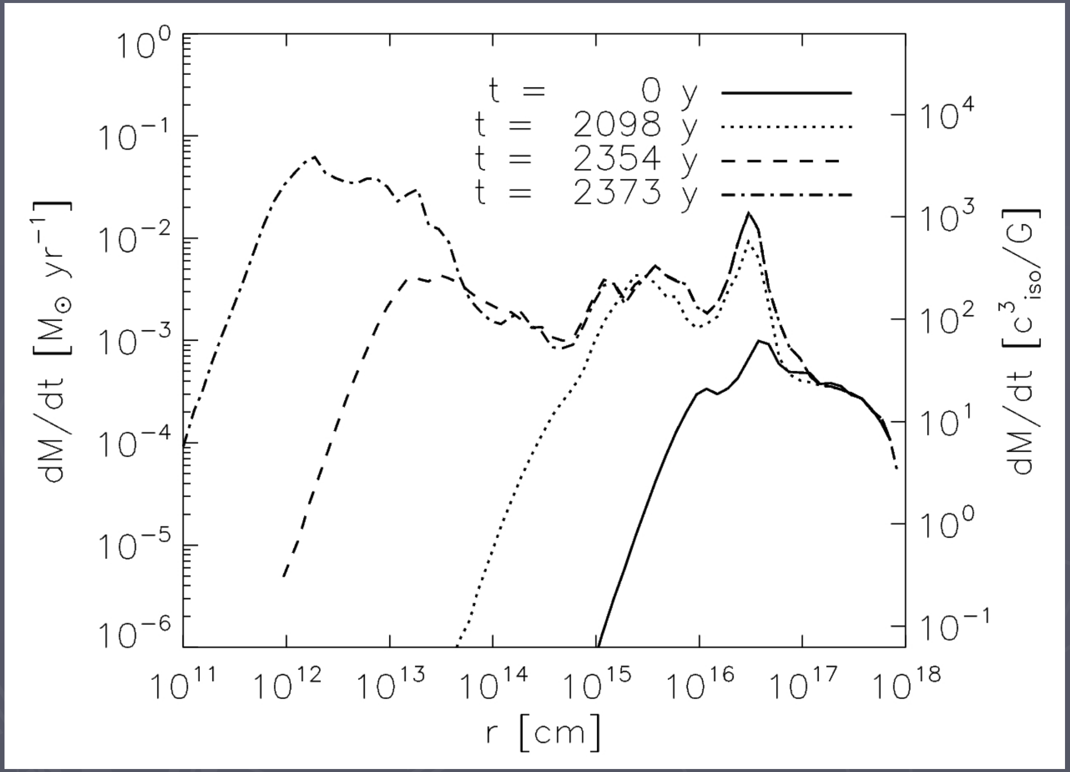
R.B., Pudritz & Anderson 2006

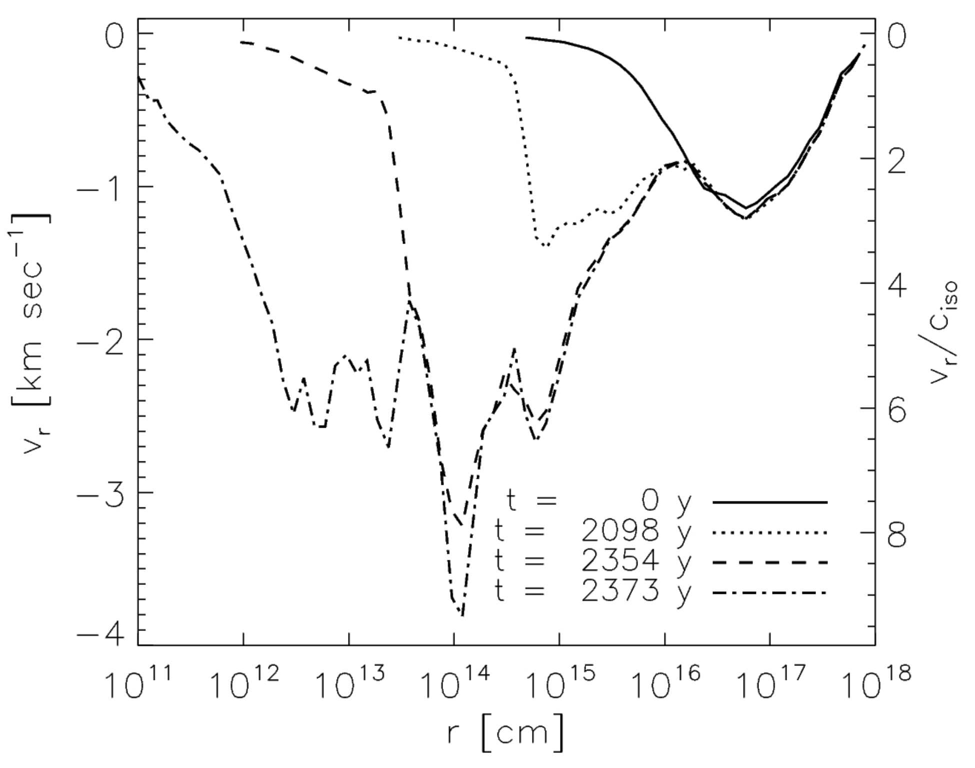
- **Filament** with an attached sheet
- small **disk** within the filament (perpendicular)
- adiabatic (optically thick) core
- very efficient gas **accretion** through the filament

Collapse with supersonic turbulence



Mass accretion



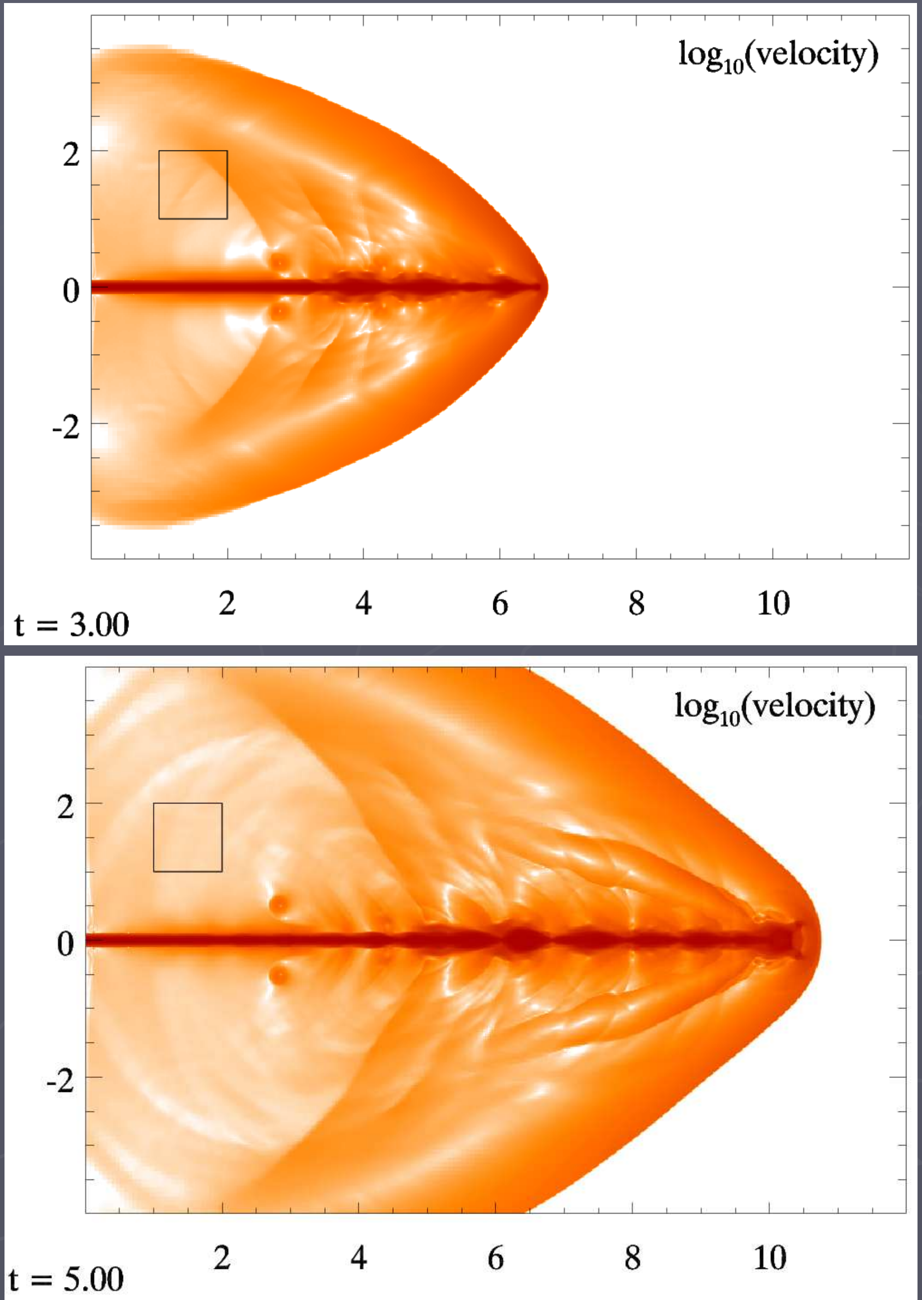


- Very **high** mass accretion rates: up to 10 $v_{in}^3/G \sim 10\, M^3\, c^3/G$
- Mass accretion rates are higher than limits from radiation pressure by burning **massive** stars
  (e.g. *Wolfire & Cassinelli 1987*: 10^{-3} M_{sol}/year)
- Protostars and disks assemble very **rapidly** within a supersonic turbulent environment

Jet-driven Turbulence?

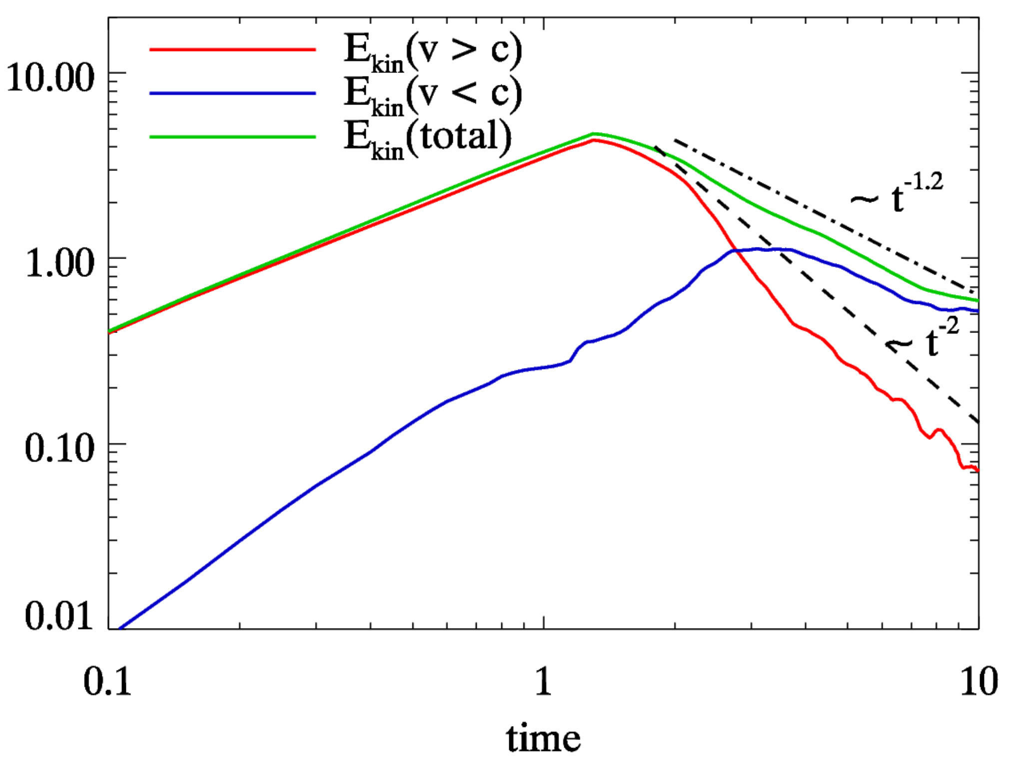
YSO jets as driving engines for supersonic turbulence in molecular clouds (e.g. *Norman & Silk 1980, Li & Nakamura 2006, Nakamura & Li 2007*)

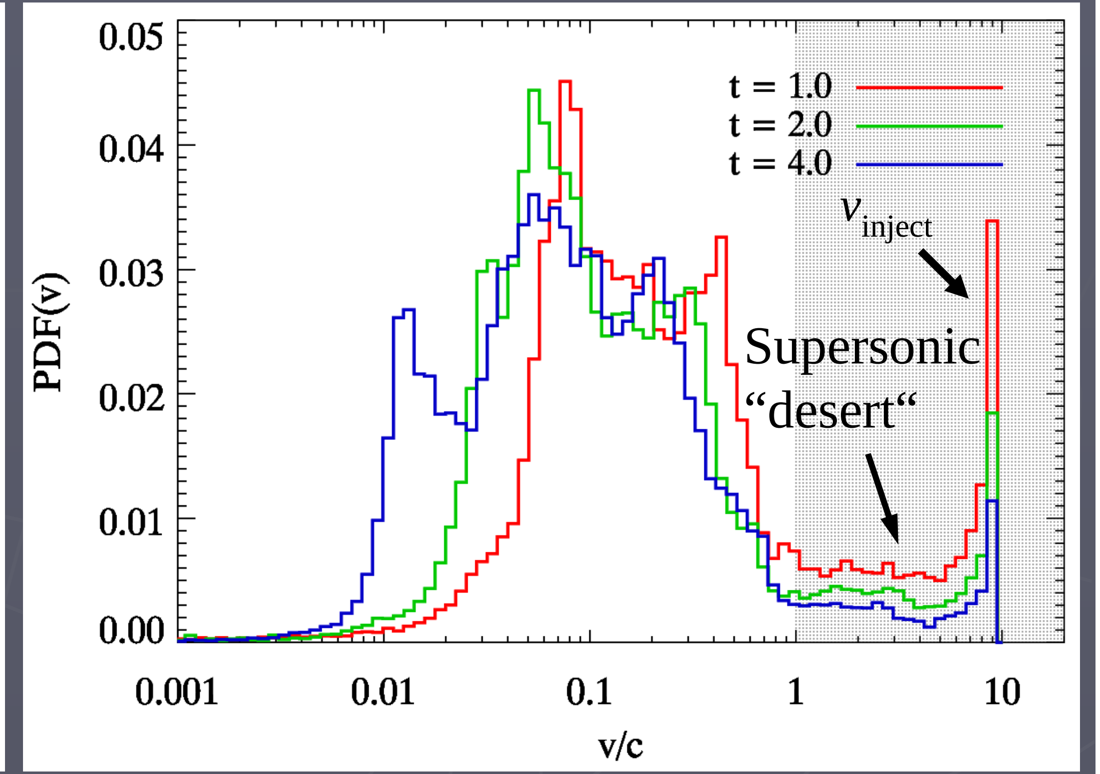
- Energetics OK
- Would lead to self-regulating star formation



RB, Klessen & Fendt 2007

But ...





Supersonic fluctuations decay quickly:

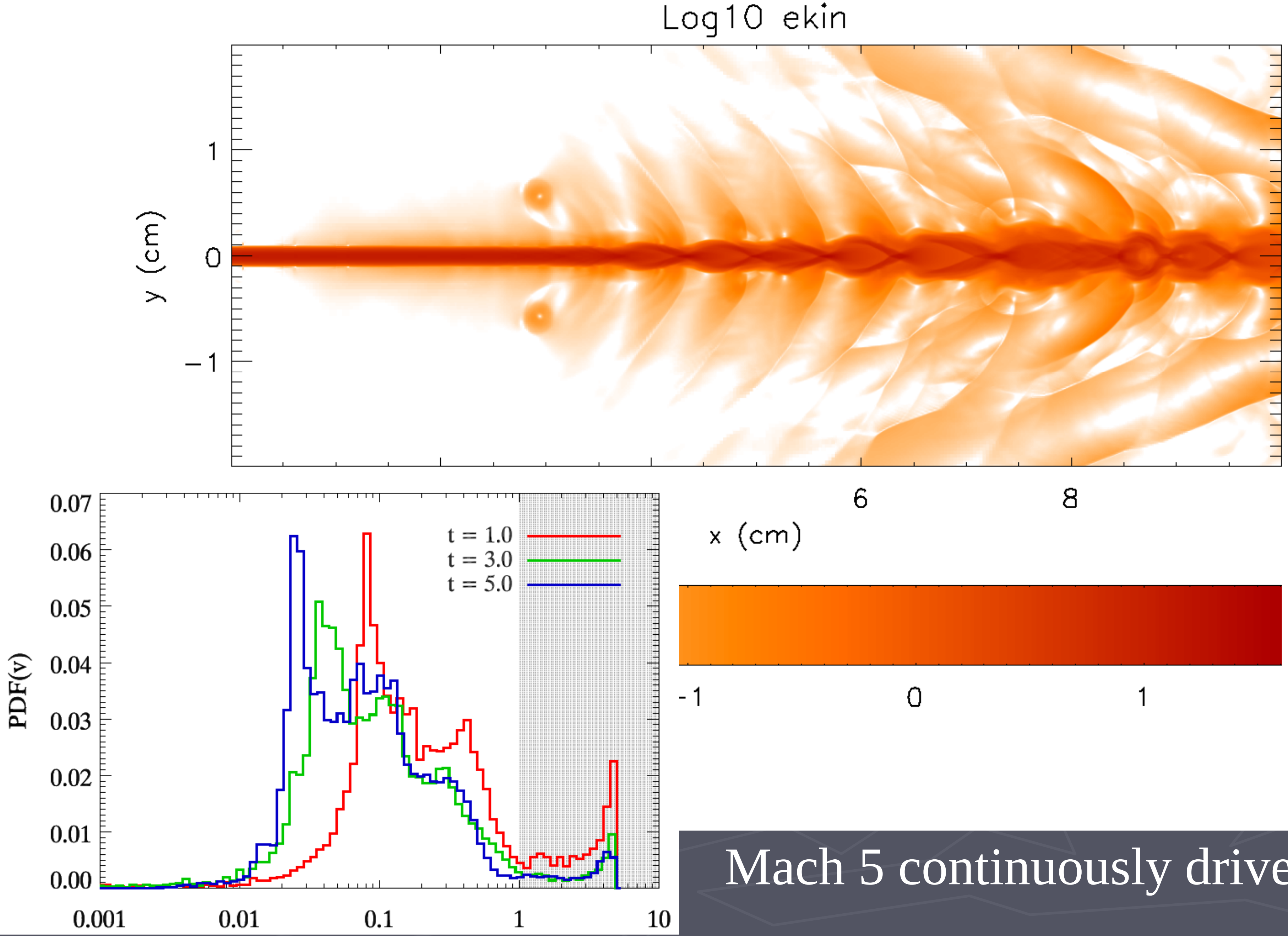
$$E_{\text{kin}}(v > c) \propto t^{-2}$$

do **not** spread

do **not** occupy a large volume fraction

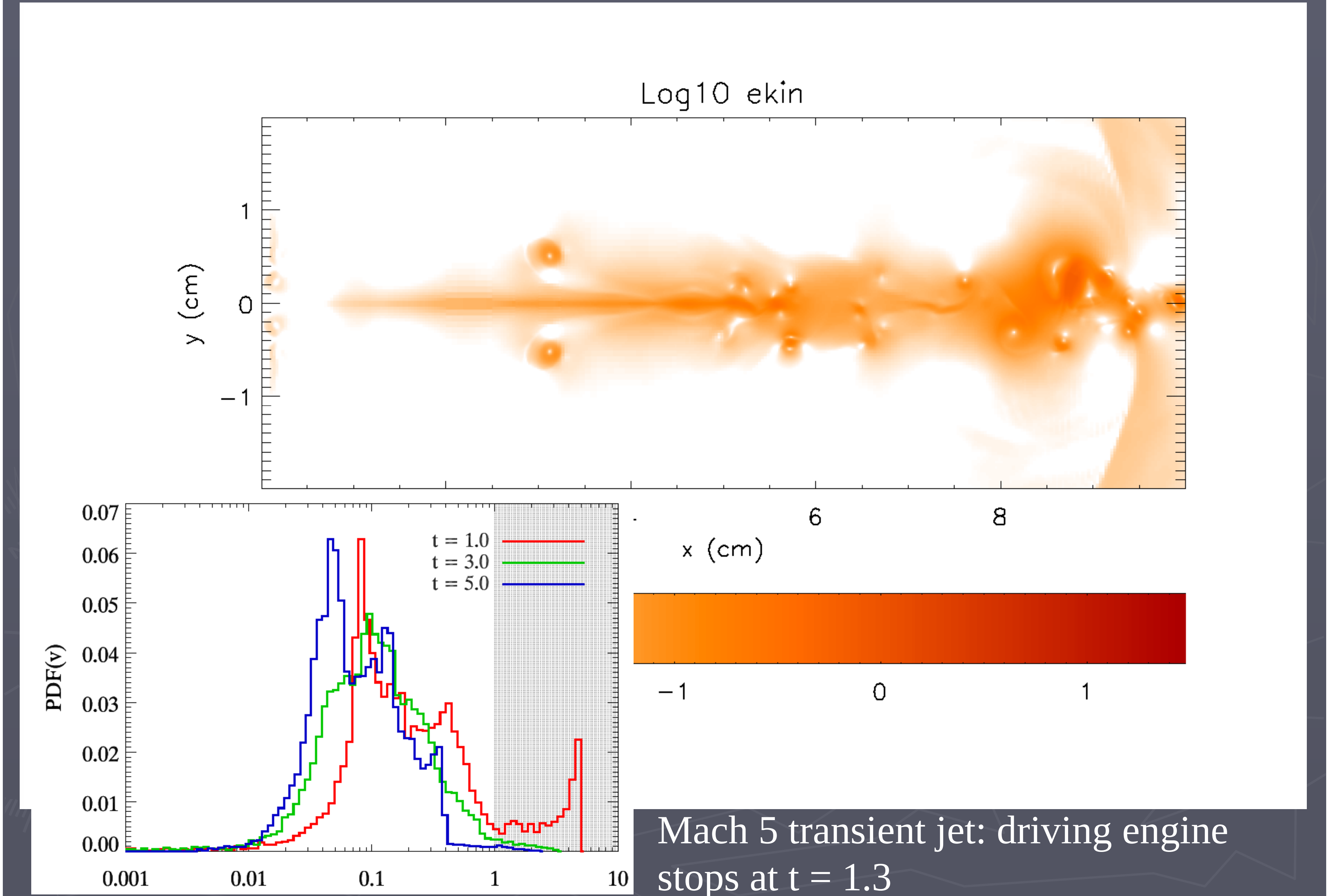
→ jet-driven supersonic turbulence unlikely

Jet-driven Turbulence?



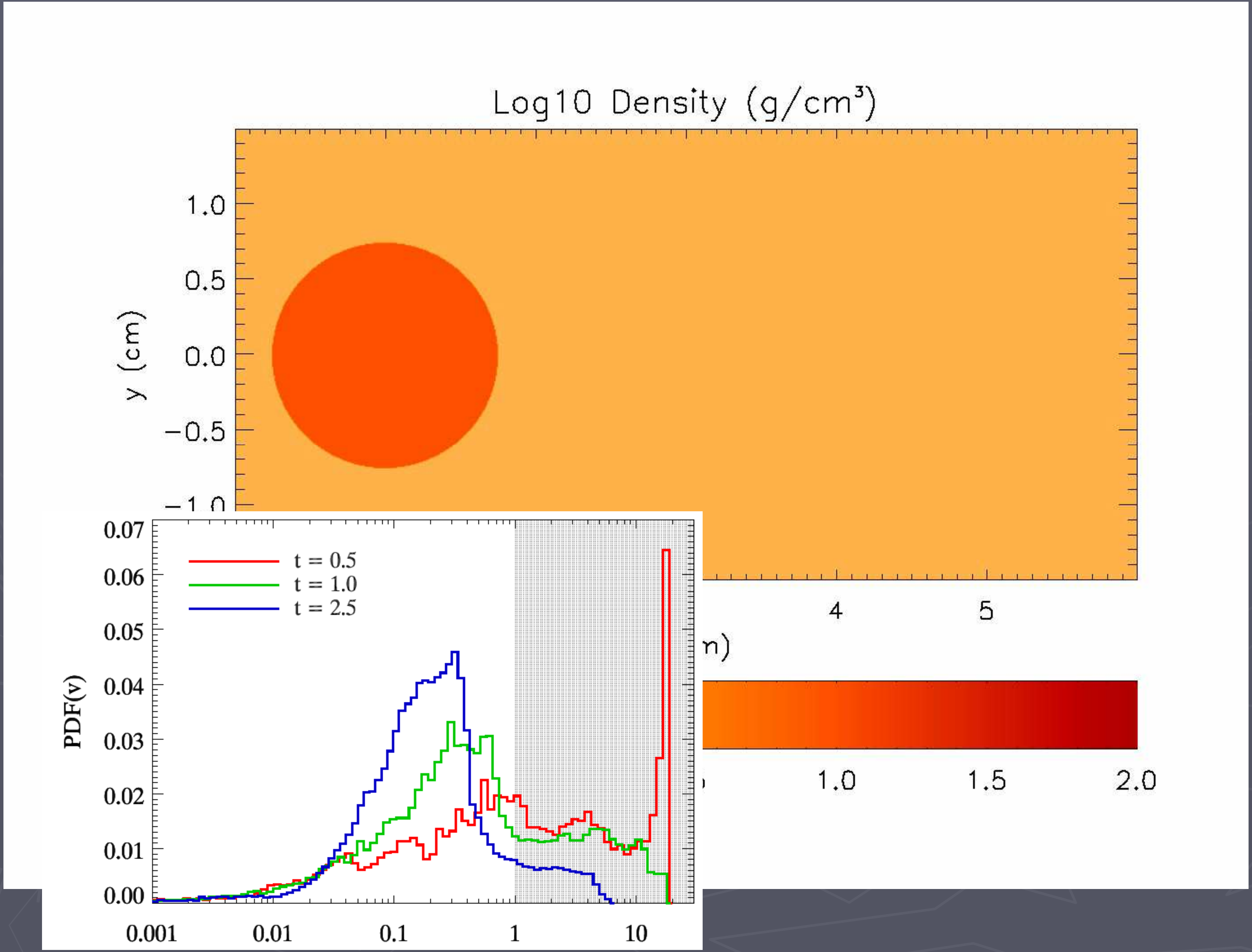
Mach 5 continuously driven jet

Jet-driven Turbulence?

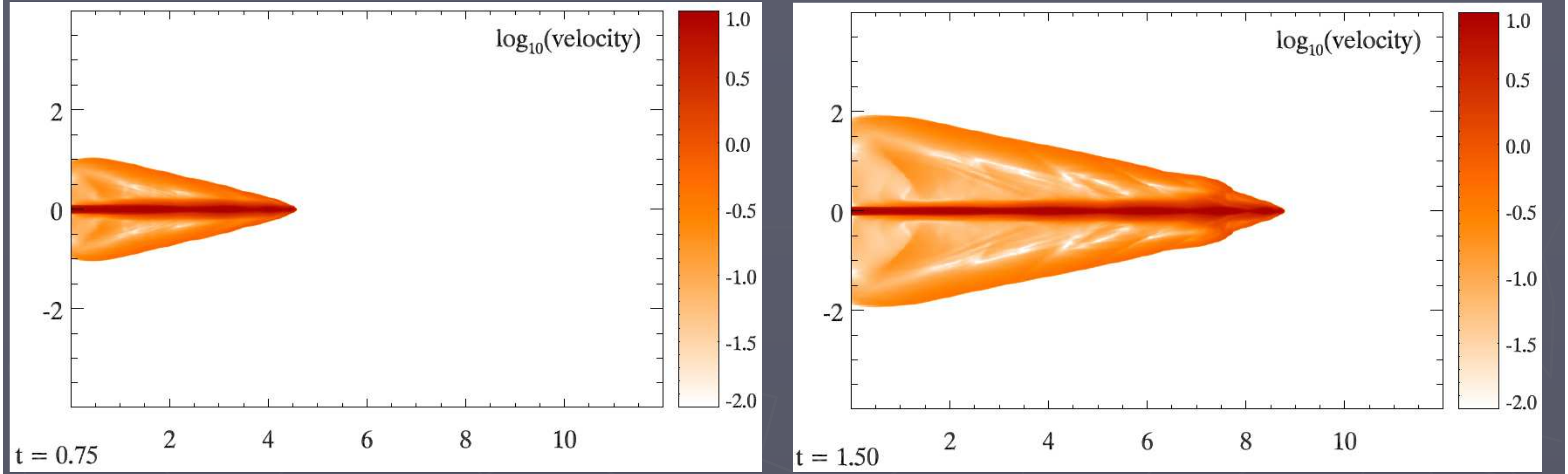


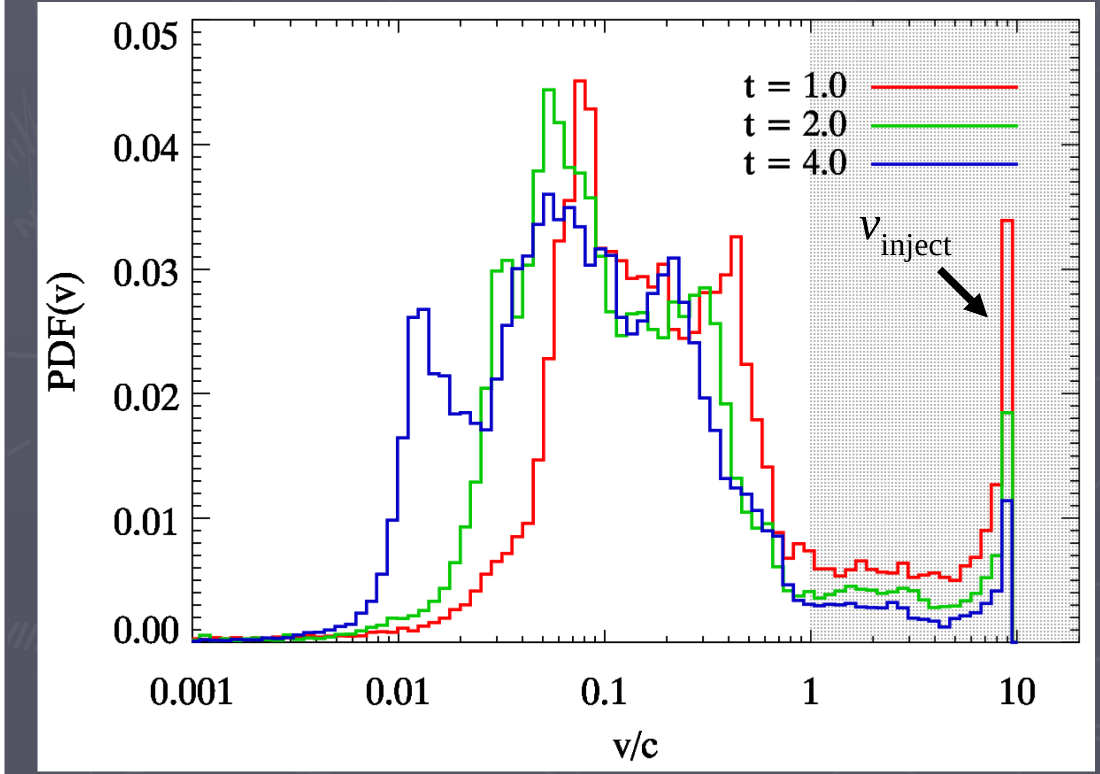
Mach 5 transient jet: driving engine stops at t = 1.3

Jet-Clump interaction



High Velocity Jets





Mach 10 jet

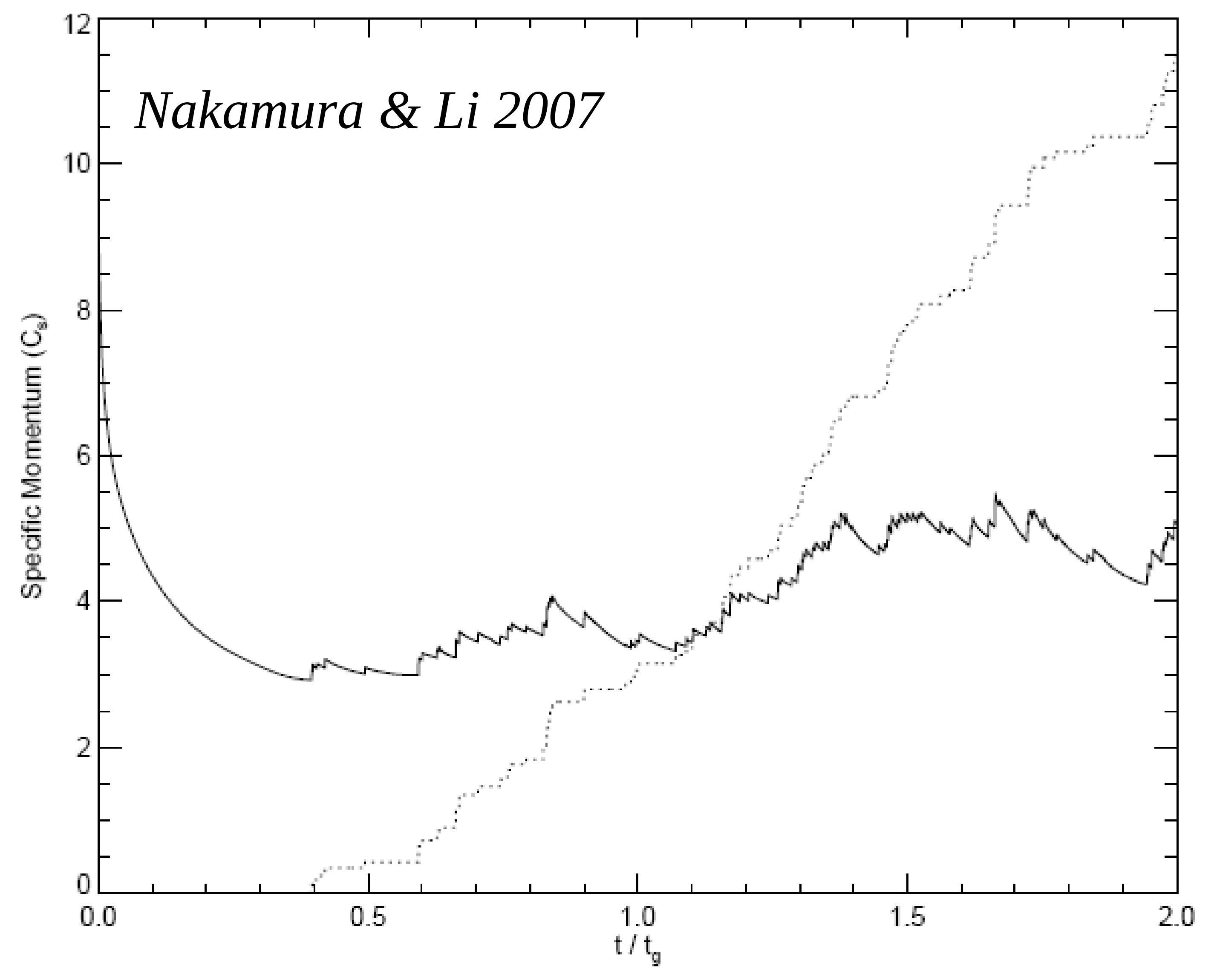
- better collimation
- entrains less gas

Summary

- Supersonic infall velocities
- High accretion rates, up to 10^{-3} M_{sol}/year (20-100 x SIS)
  $dM/dt \sim v^3/G = Mach^3\, c^3/G$
- Quick massive star assembly ~ few x 10^4 years
- Angular momentum transfer by outflows and bars in the proto-disk
- Outflows and Jets launched already during collapsing phase
- Outflow blown cavities (channels for radiation pressure, *Krumholz et al. 2005*)
- Jet driven supersonic turbulence unlikely

QUESTIONS

- Radiation Feedback from massive stars (Krumholz, Klein)?
- Do early type jets/outflows persist?
- What is the driving engine for supersonic turbulence?



Nakamura & Li 2007