From Molecular Clouds to Protostellar Discs

Contemporary Star Formation in Numerical Simulations

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Collaborators:

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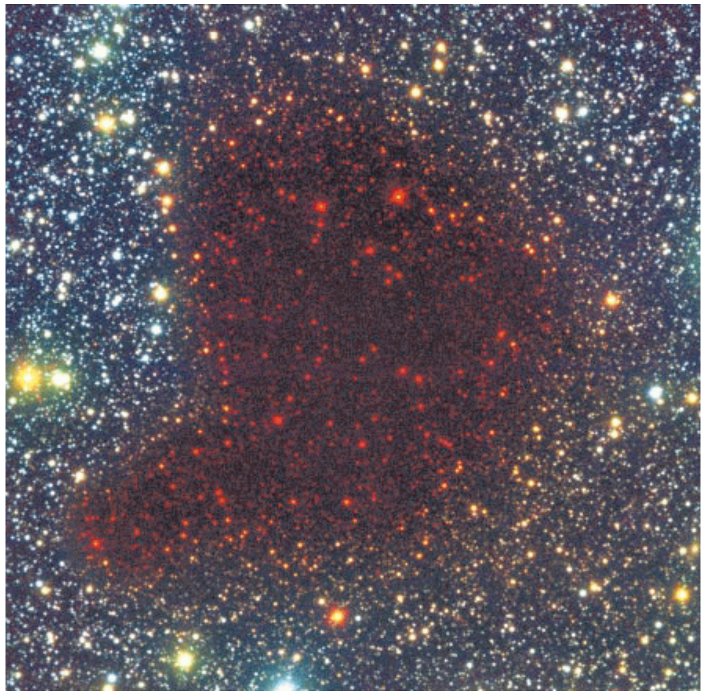
Outlook

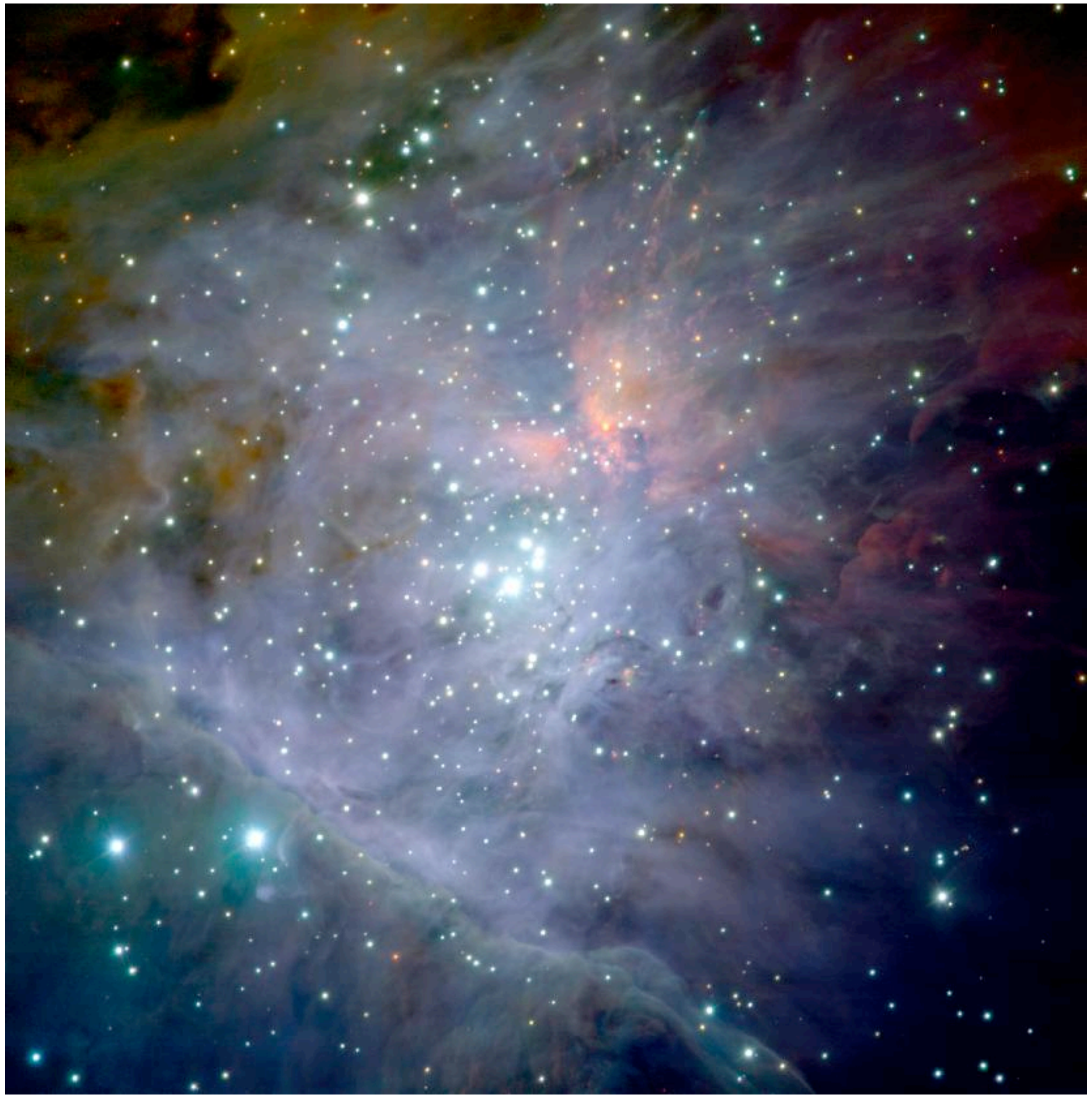
- Introduction
- Formation of Molecular Clouds Formation
- Collapse of Magnetized Cores
- Early Stages of Jets and Outflows
- Collapse of Turbulent Cores
- Massive Star Formation
- Jet driven Turbulence
- Summary

Introduction

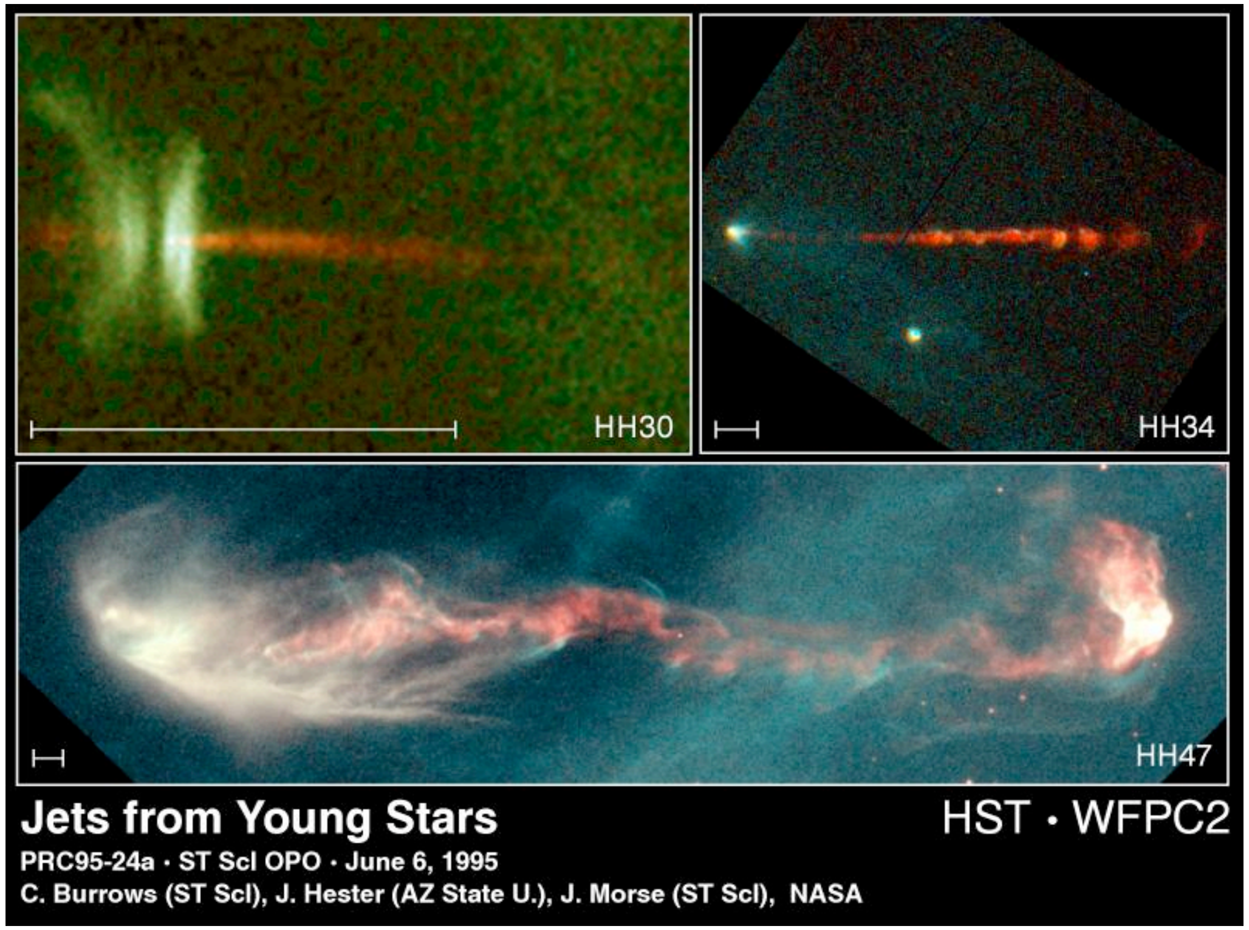
- Present day Star Formation happens in Giant Molecular Clouds (GMCs)
- Stars form out of collapsing cloud cores
- Feedback: outflows, jets, radiation, ...



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



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



Motivation

Problems:

Horsehead Nebula (Barnard 33) in the OMC

NOAO image

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- Self gravity $\longrightarrow$ non-linear interactions

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- Angular momentum $\rightarrow$ disk formation

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Horsehead Nebula (Barnard 33) in the OMC

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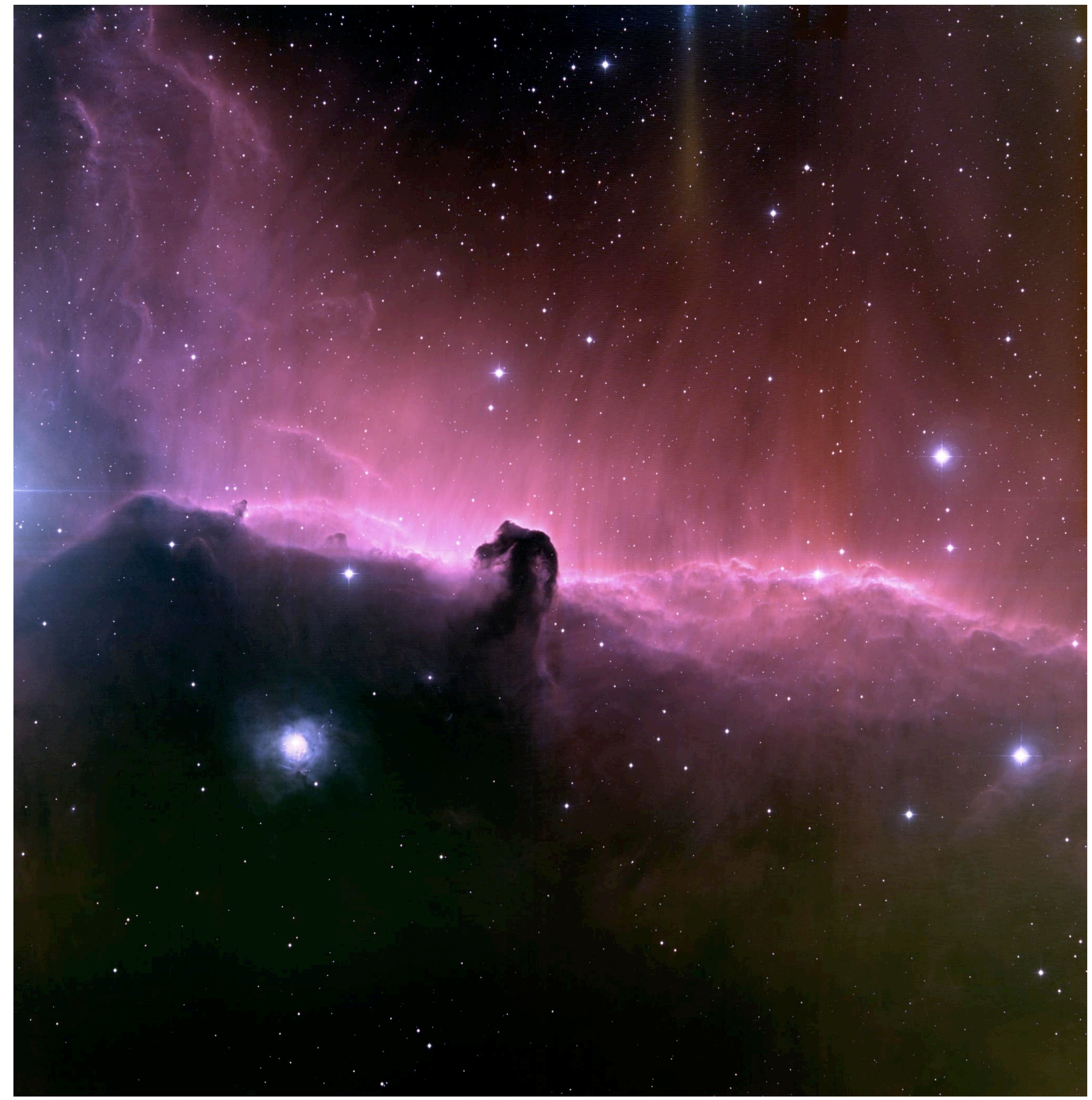
Motivation

Problems:

- Self gravity → non-linear interactions
- Angular momentum → disk formation
- Chemistry → heating & cooling
- Magnetic fields → jet & outflows



Horsehead Nebula (Barnard 33) in the OMC

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Motivation

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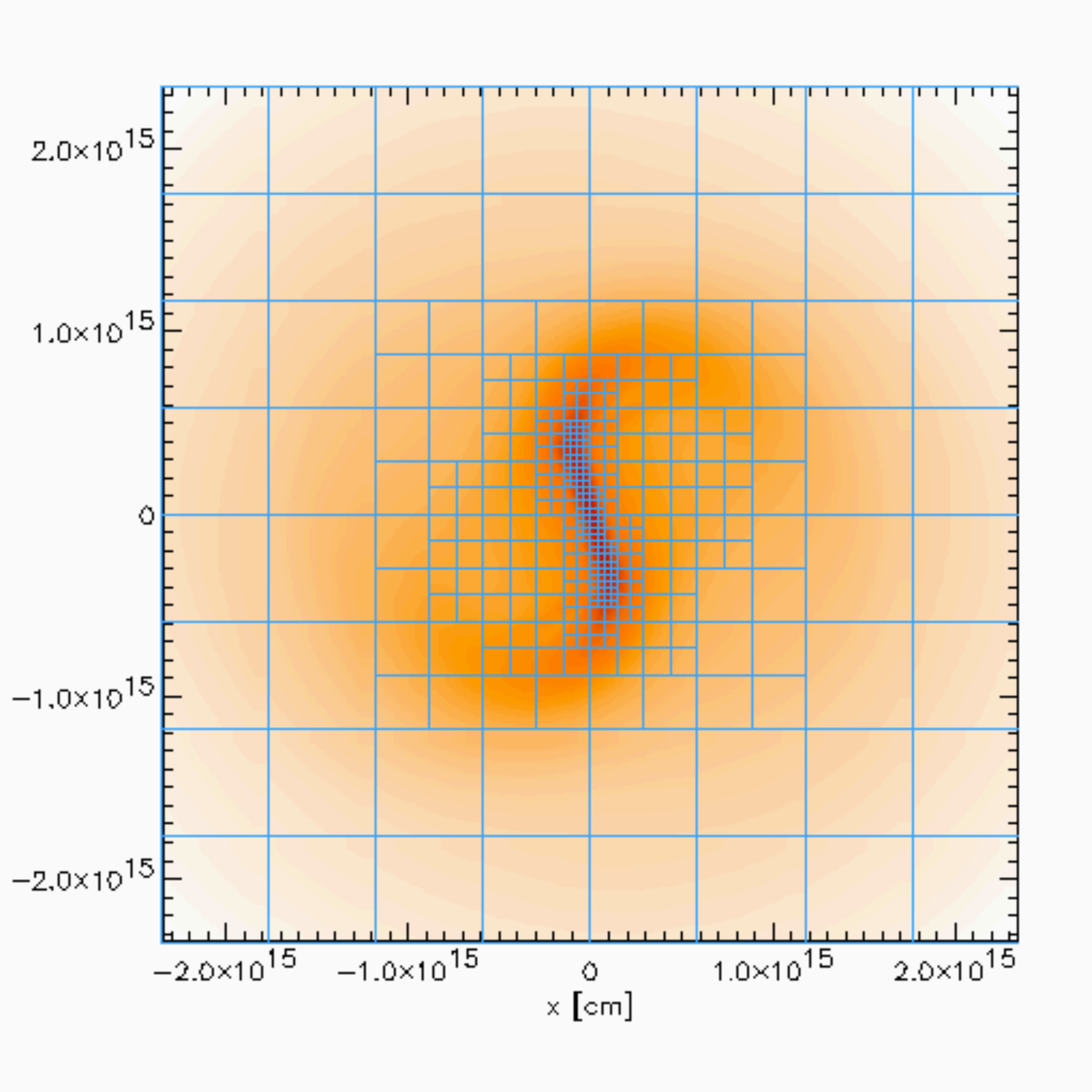
Horsehead Nebula (Barnard 33) in the OMC

NOAO image

use 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 solvers: PPM, Kurganov
- MHD solvers: 8Wave (Roe-type), HLLE with div**B** cleaning; ambipolar diffusion (*D.Duffin*)
- Lagrangian **sink** particles (*R.B. 2008*)
- **FLASH3**: unsplit scheme, staggered mesh
- Gravity: multigrid or multipole, periodic or isolated BCs
- **AMR**: block structured (PARAMESH library); block resolutions vary by factors of **2**
- Refinement on own choice (e.g. gradient, curvature, density, Jeans length, etc.)
- IDL routines for visualization

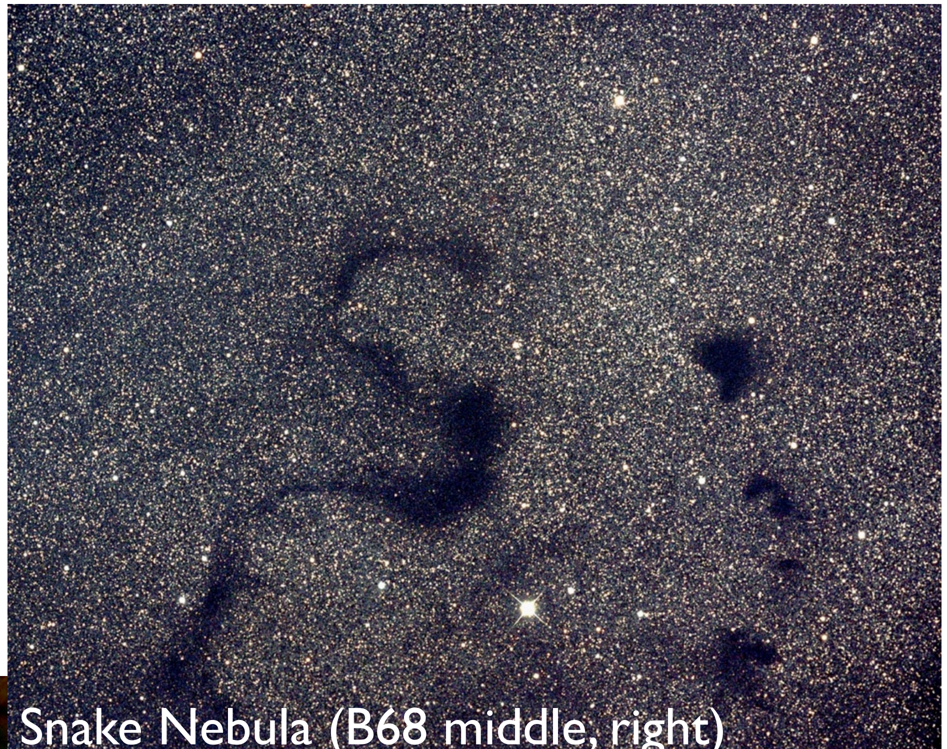
Pros

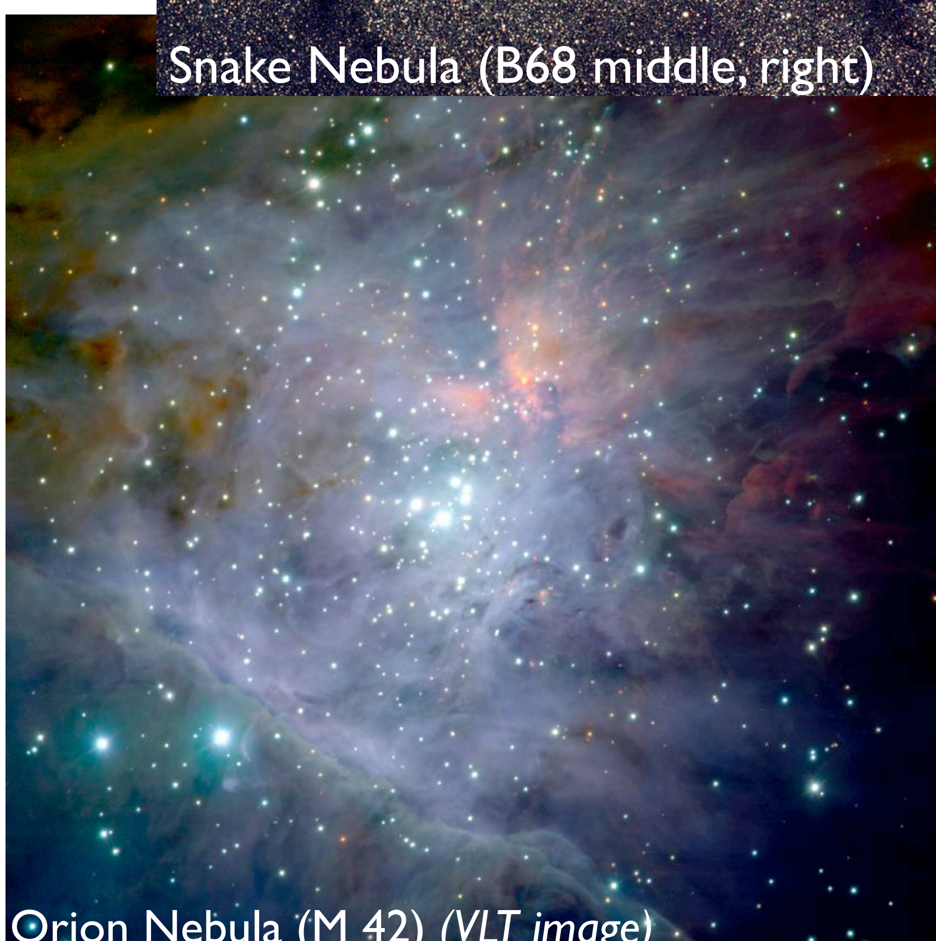
- modular, easy to use
- large community: e.g. multi fluid nuclear reactions, RT module, N-body particles, cosmology
- support from developers

Contras

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

Formation of Molecular Clouds

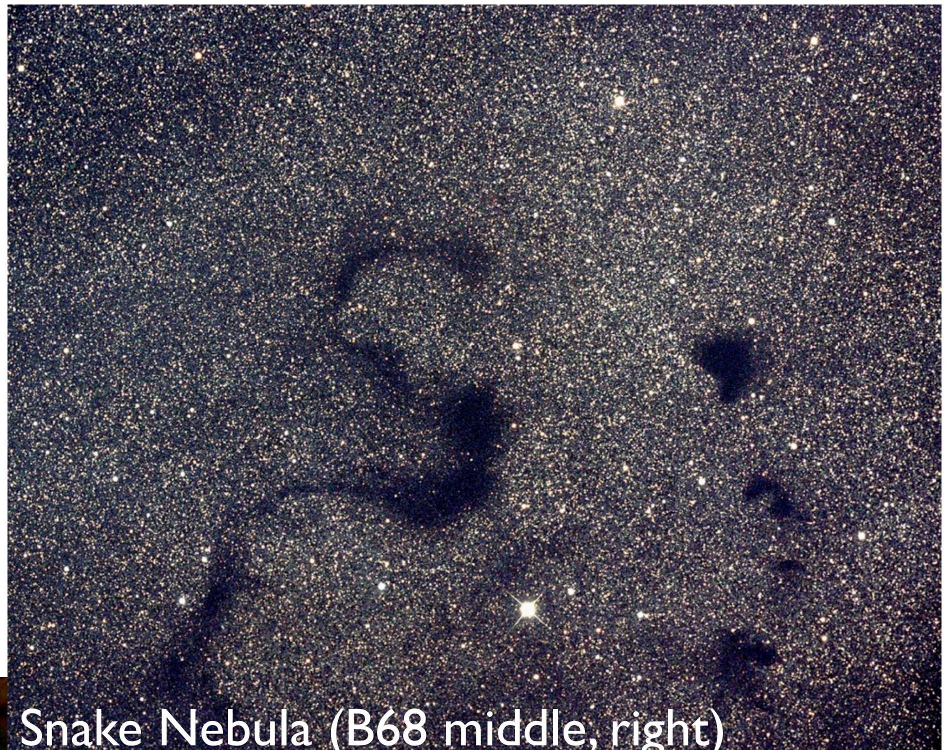

Snake Nebula (B68 middle, right)


Orion Nebula (M 42) *(VLT image)*

Key questions:

- ISM two/three phase medium? (*McKee & Ostriker 1977*, SN regulated)
- Warm neutral medium (WNM) + Cold neutral medium (CNM) in pressure equilibrium? (*Field, Goldsmith, Habing 1969*)
- How and under which conditions do form MCs? e.g. triggered thermal instability? (e.g. *Hennebelle & Perault '99, Koyama & Inutsuka '00, Heitsch et al. '05, Vazquez-Semadeni et al. '07*)
- Lifetime: long lived (e.g *C. McKee*) vs. short lived (e.g *B. Elmegreen*)

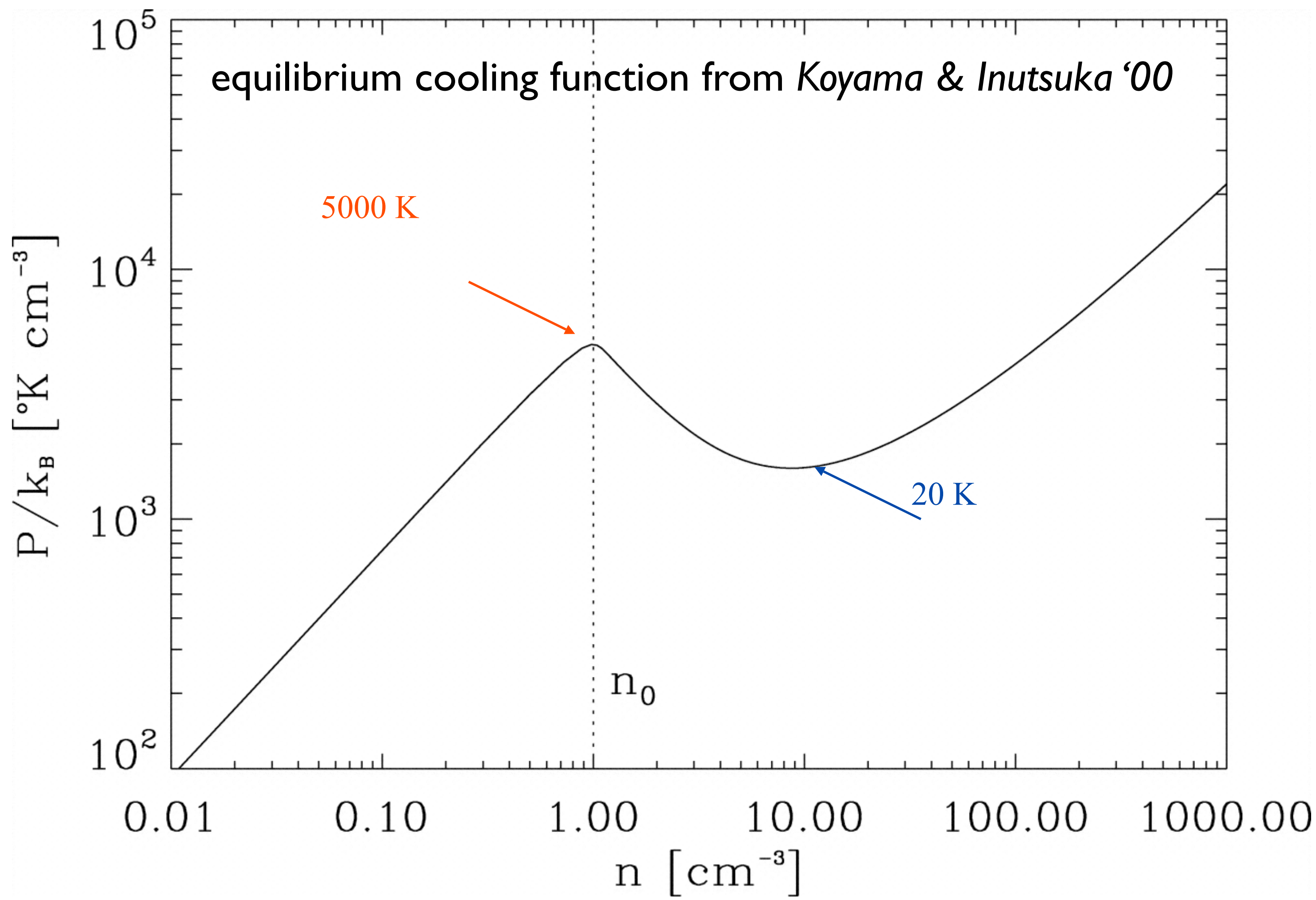
Formation of Molecular Clouds



Snake Nebula (B68 middle, right)

Orion Nebula (M 42) *(VLT image)*

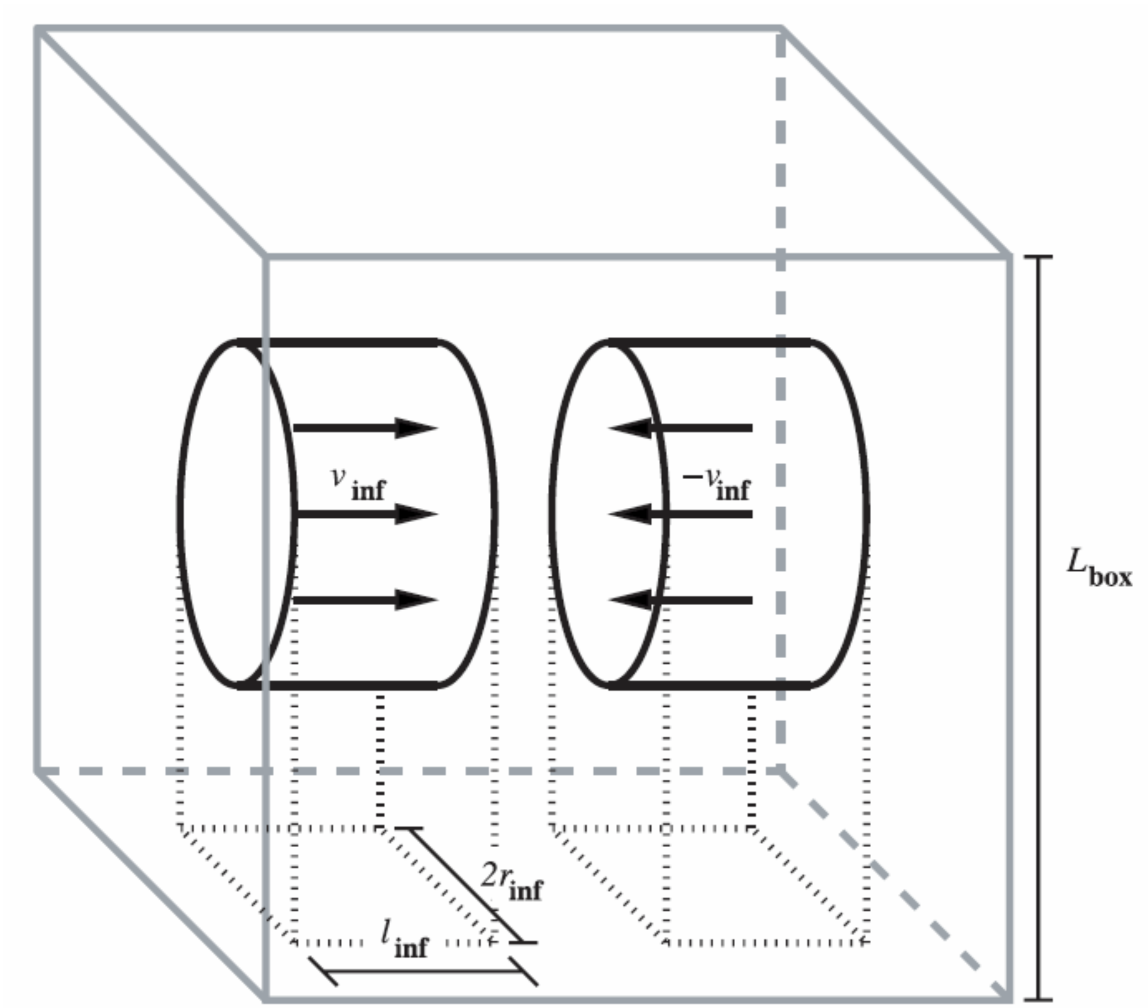
Formation out of the warm neutral atomic medium (WNM) via thermal instability?



Thermally **unstable** medium at $n = 1\mathrm{cm}^{-3}$

Formation of Molecular Clouds

Model description



Vazquez-Semadeni et al. 2007

Large scale converging flows:

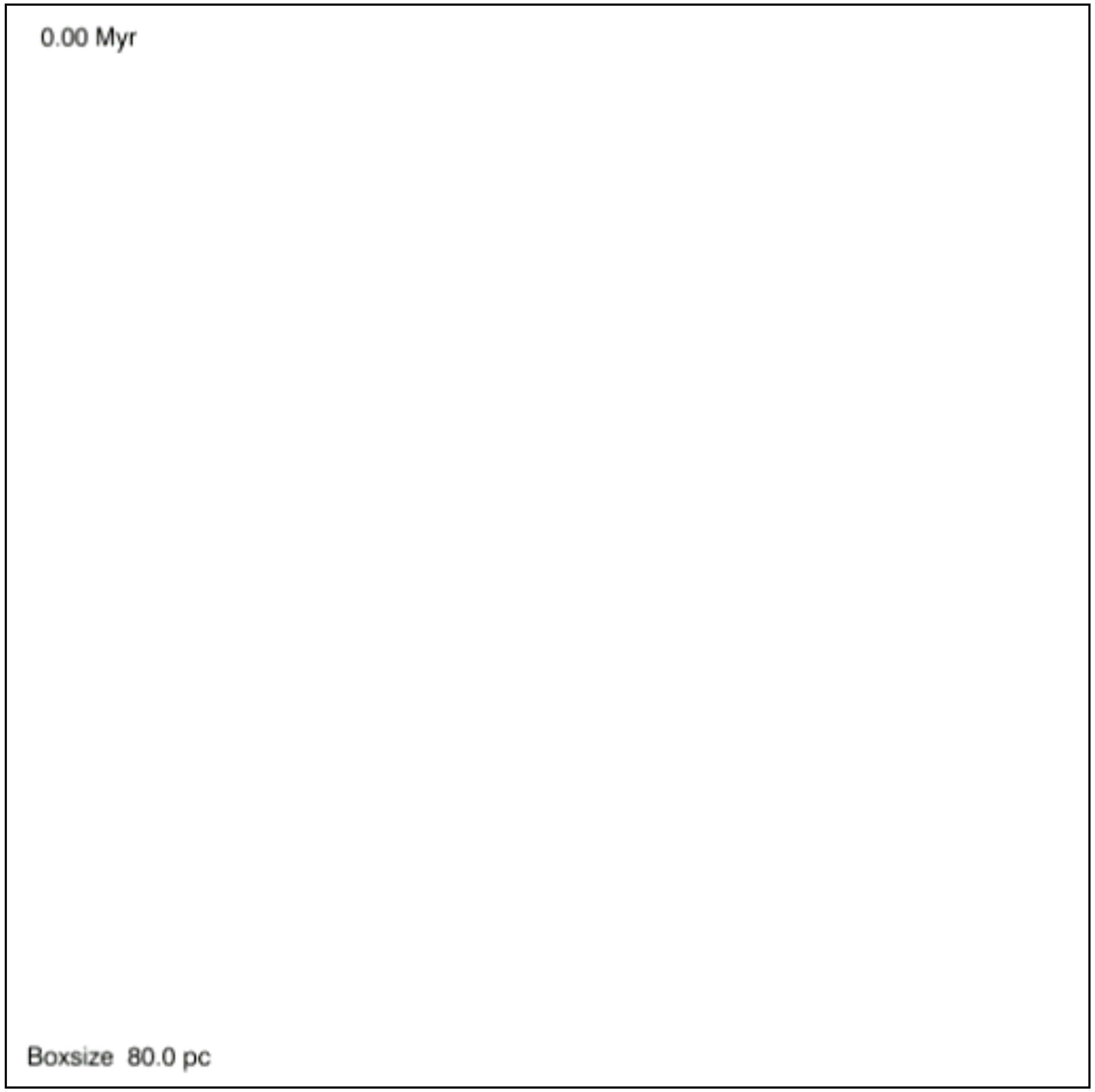
- e.g. swept up material by galactic spiral arms

Fiducial model parameter:

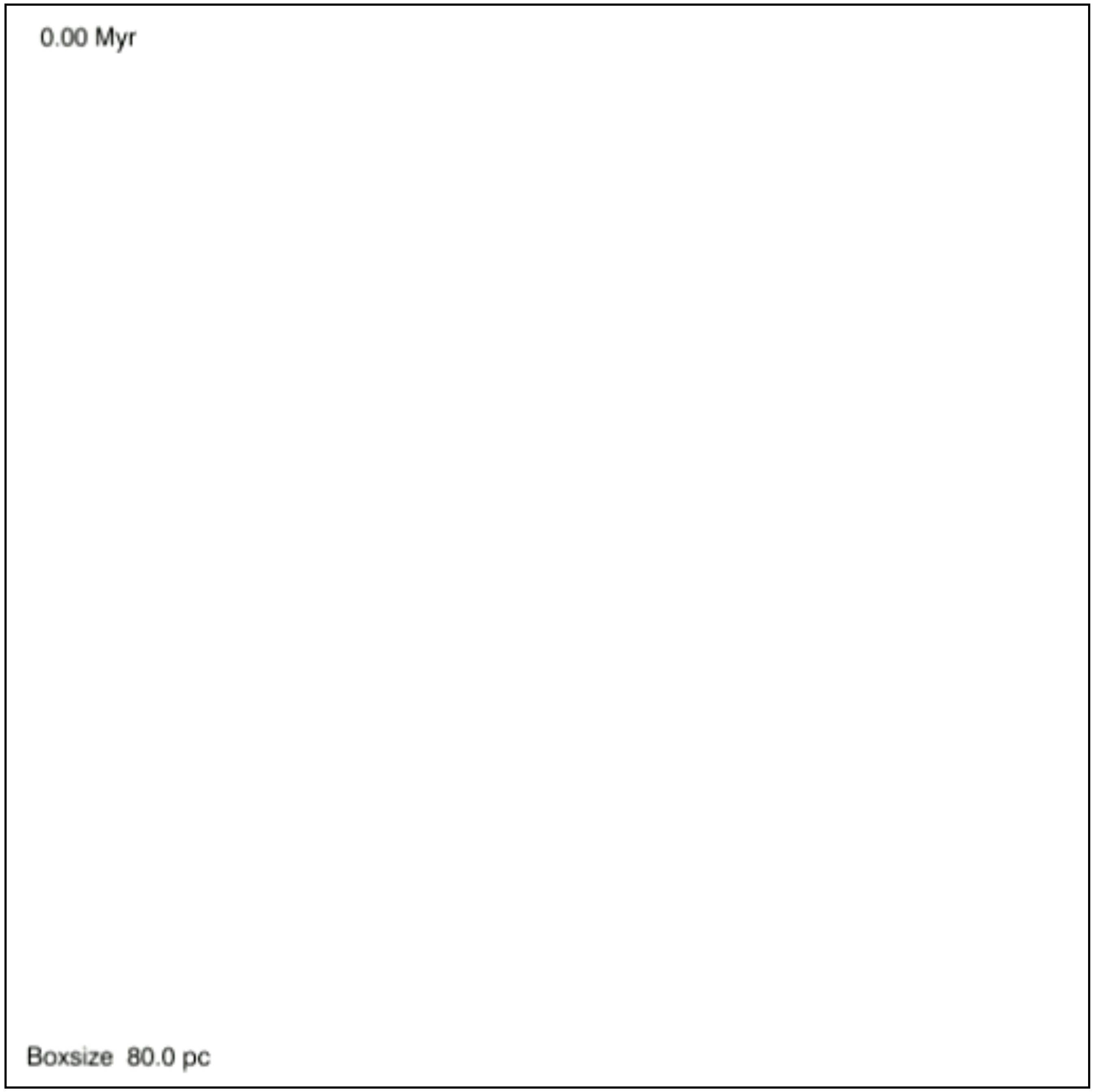
- $L_{box} = 256$ pc
- $l_{inf} = 112$ pc
- $r_{inf} = 32$ pc
- $v_{inf} = 5.7$ km/sec $= 1.22\ M_a$
- $n = 1\ cm^{-3}$
- $T = 5000$ K
- $B = 1\mu G$ aligned with the flow

Formation of Molecular Clouds

the non-magnetic case



edge-on view

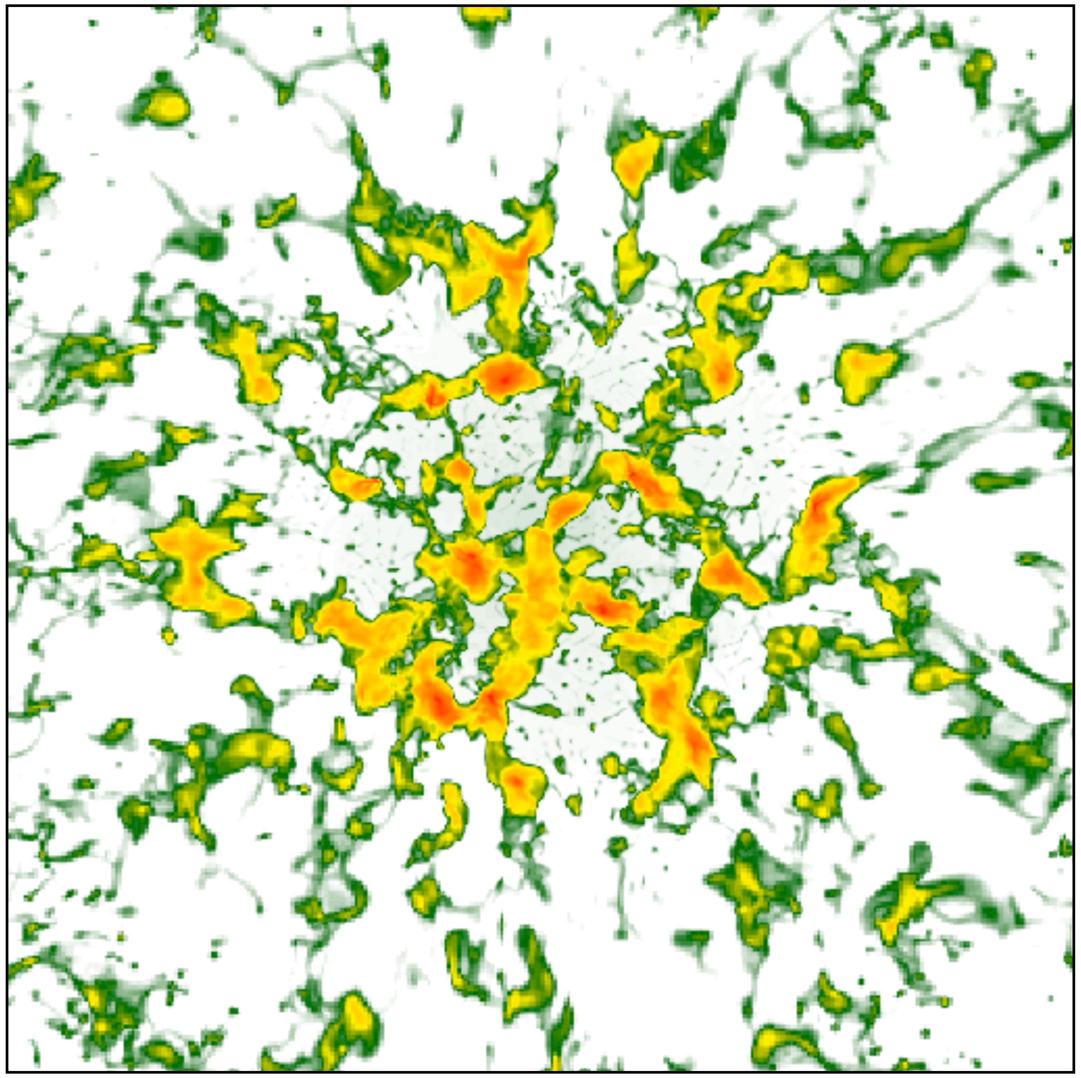


face-on view

Formation of Molecular Clouds

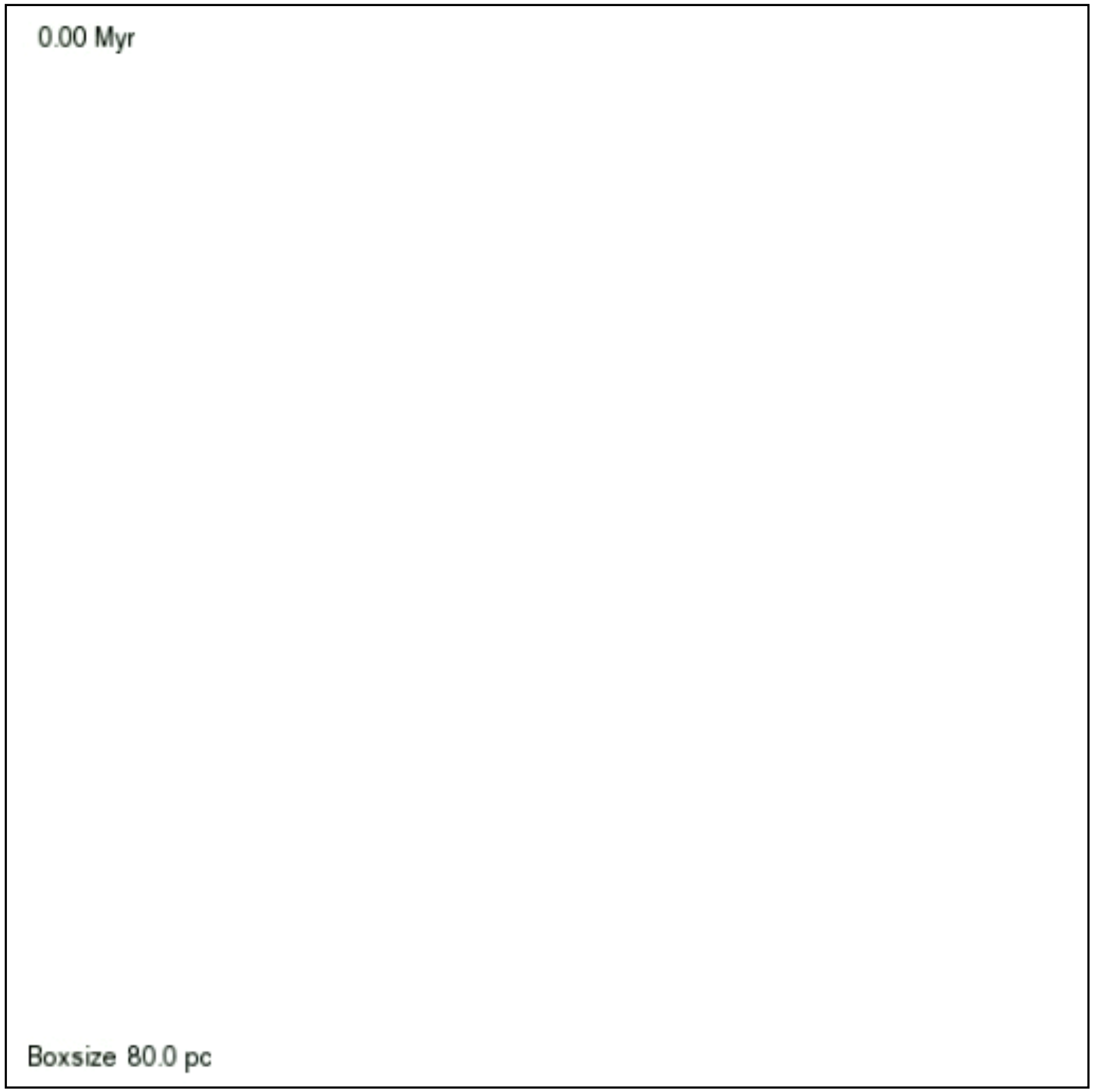
main properties of MCs:

- highly patchy and clumpy
- high fraction of substructure
- cold dense molecular clumps coexist with warm atomic gas
- not a well bounded entity
- dynamical evolution (different star formation modes: from low mass to high mass SF?)

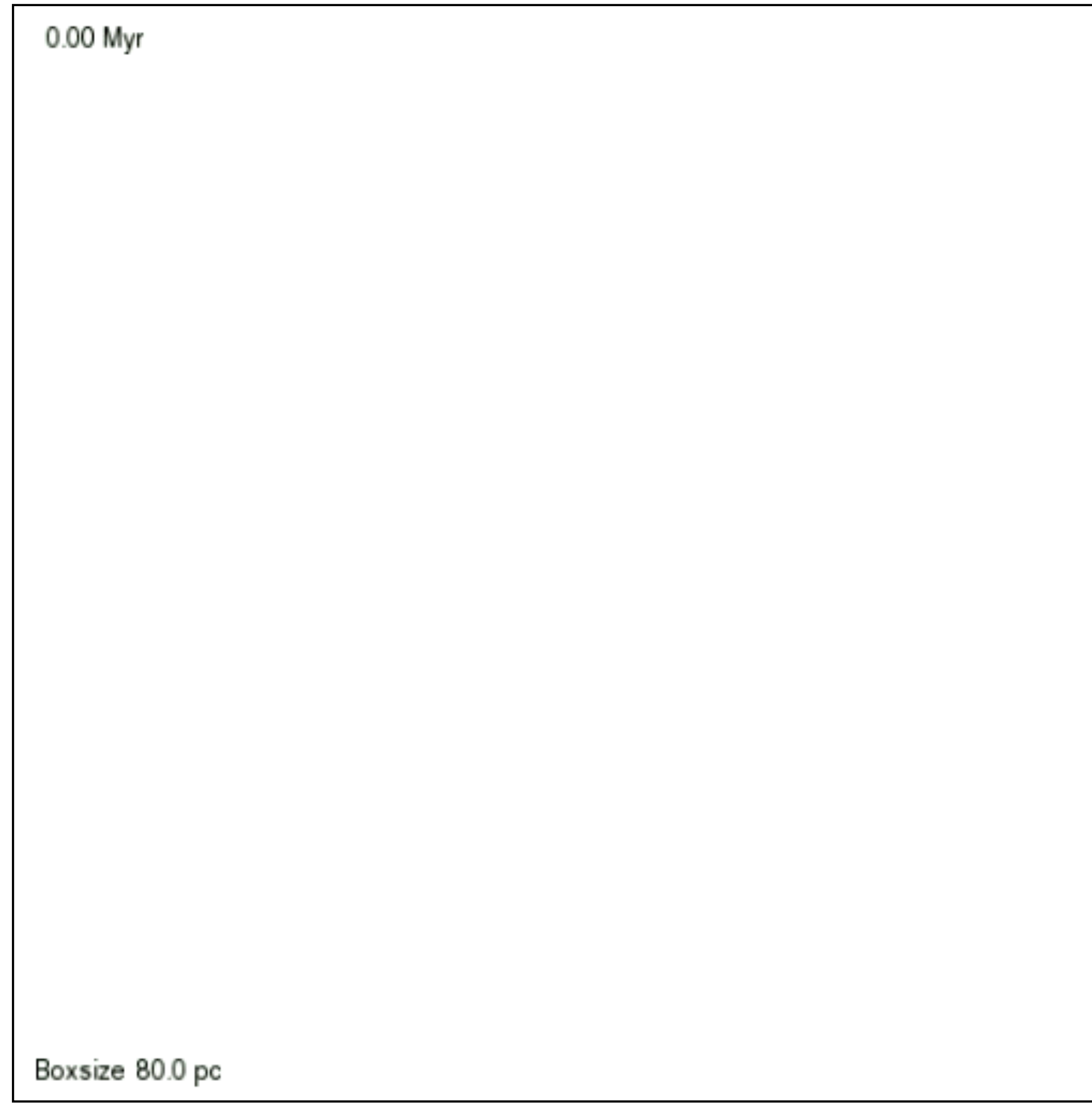


Formation of Molecular Clouds

the weakly magnetized ($B_x = 1\mu G$) case



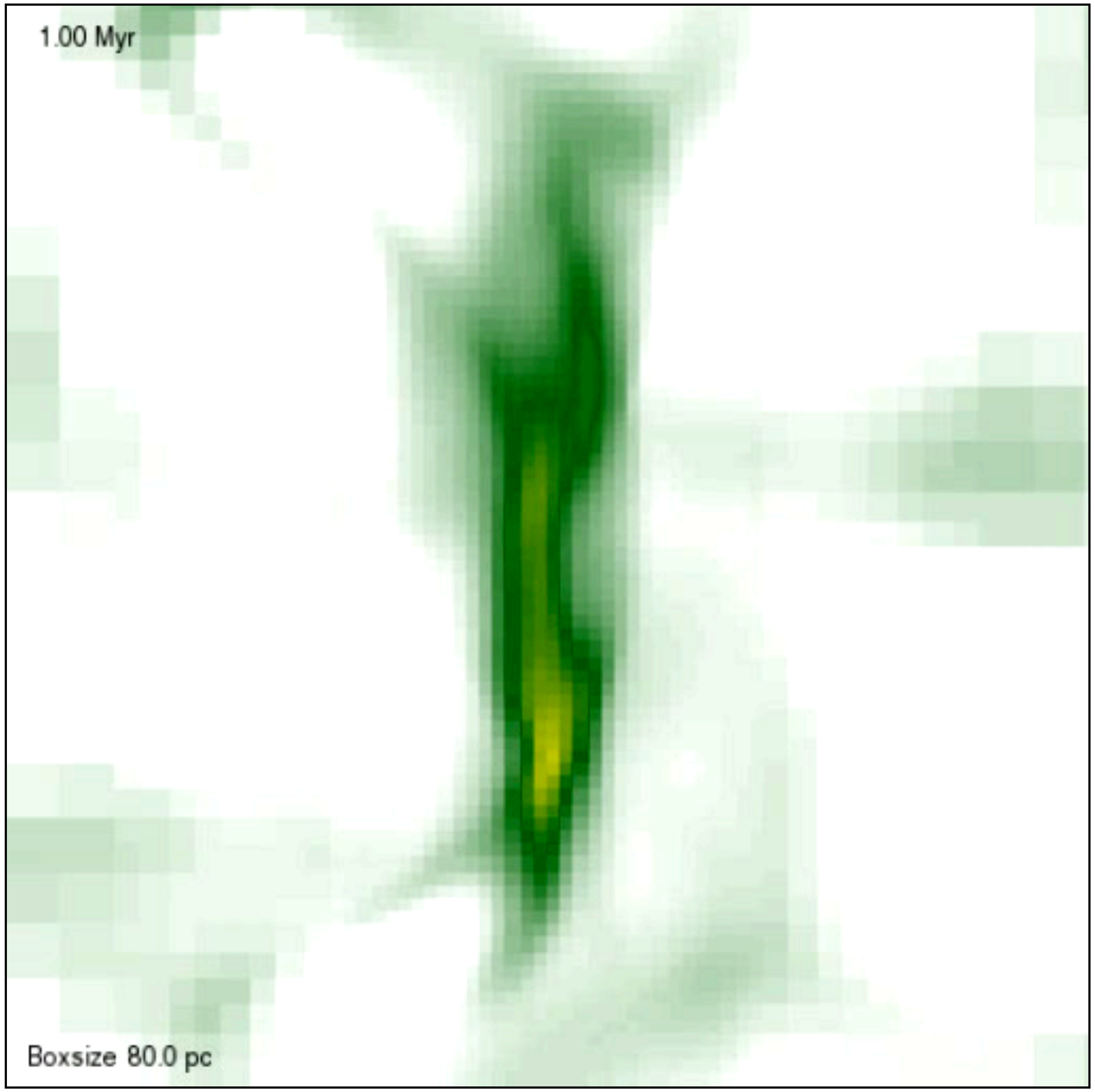
edge-on view



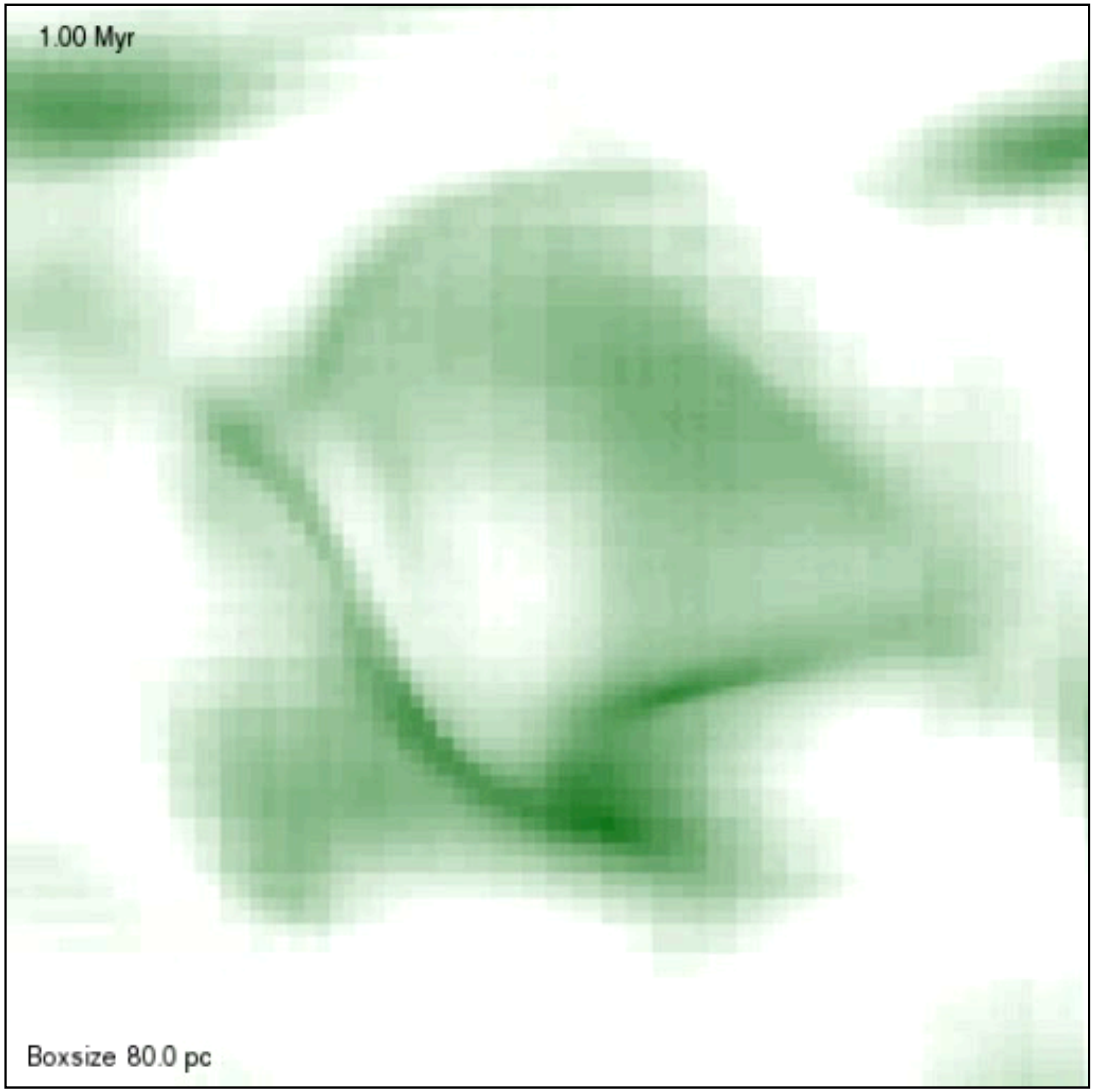
face-on view

Formation of Molecular Clouds

the strong magnetized ($B_x = 3\mu G$) case



edge-on view



face-on view

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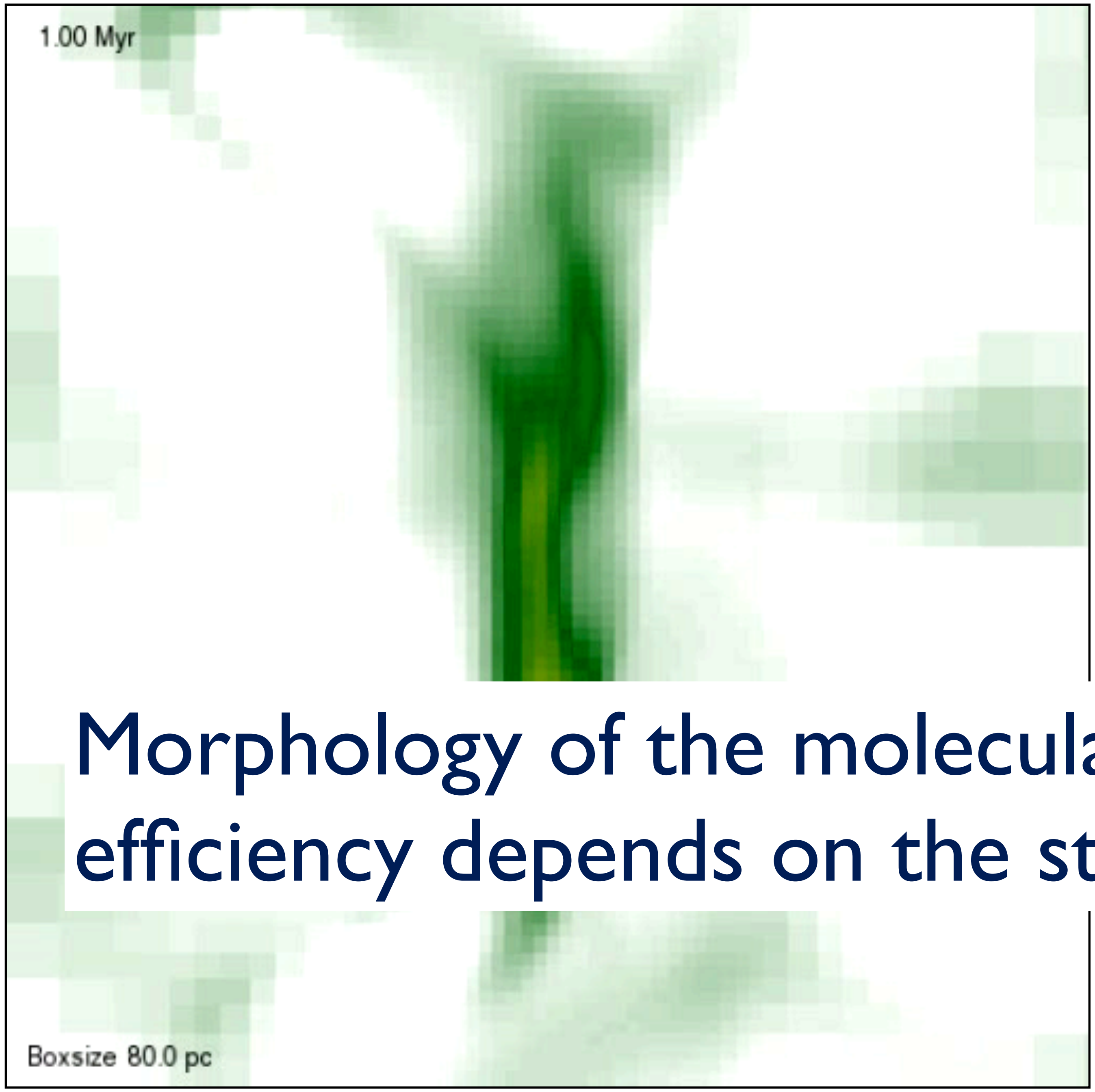
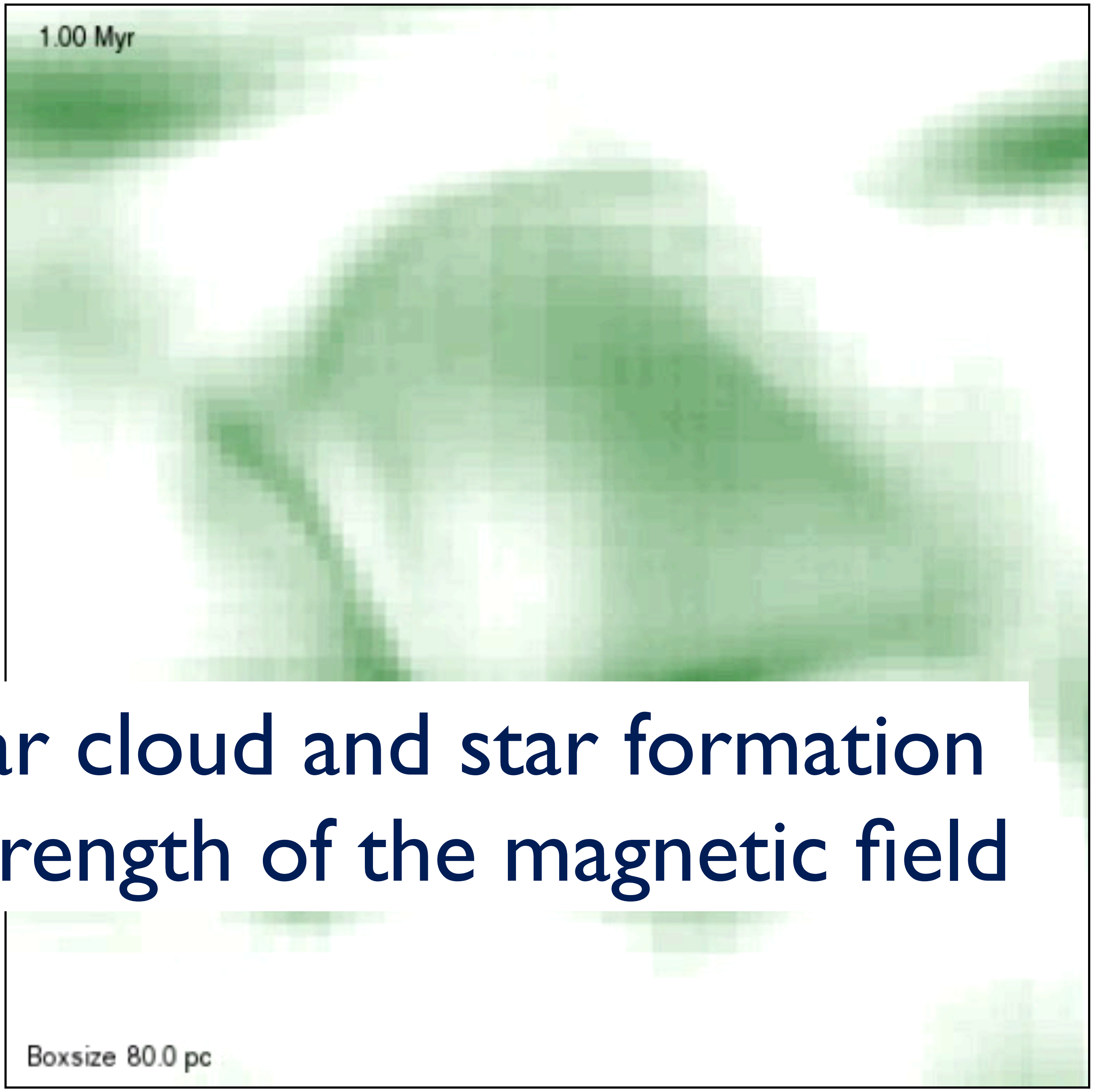


edge-on view

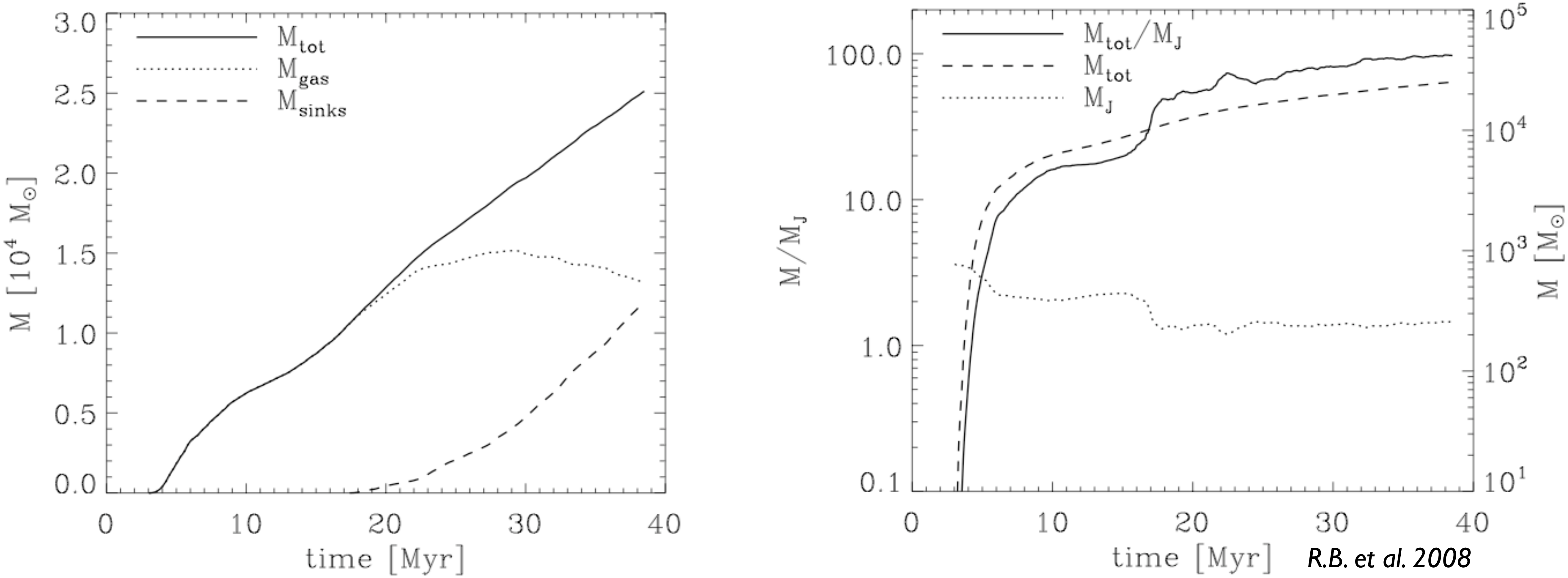


face-on view

Morphology of the molecular cloud and star formation efficiency depends on the strength of the magnetic field

Formation of Molecular Clouds

time evolution of the molecular gas

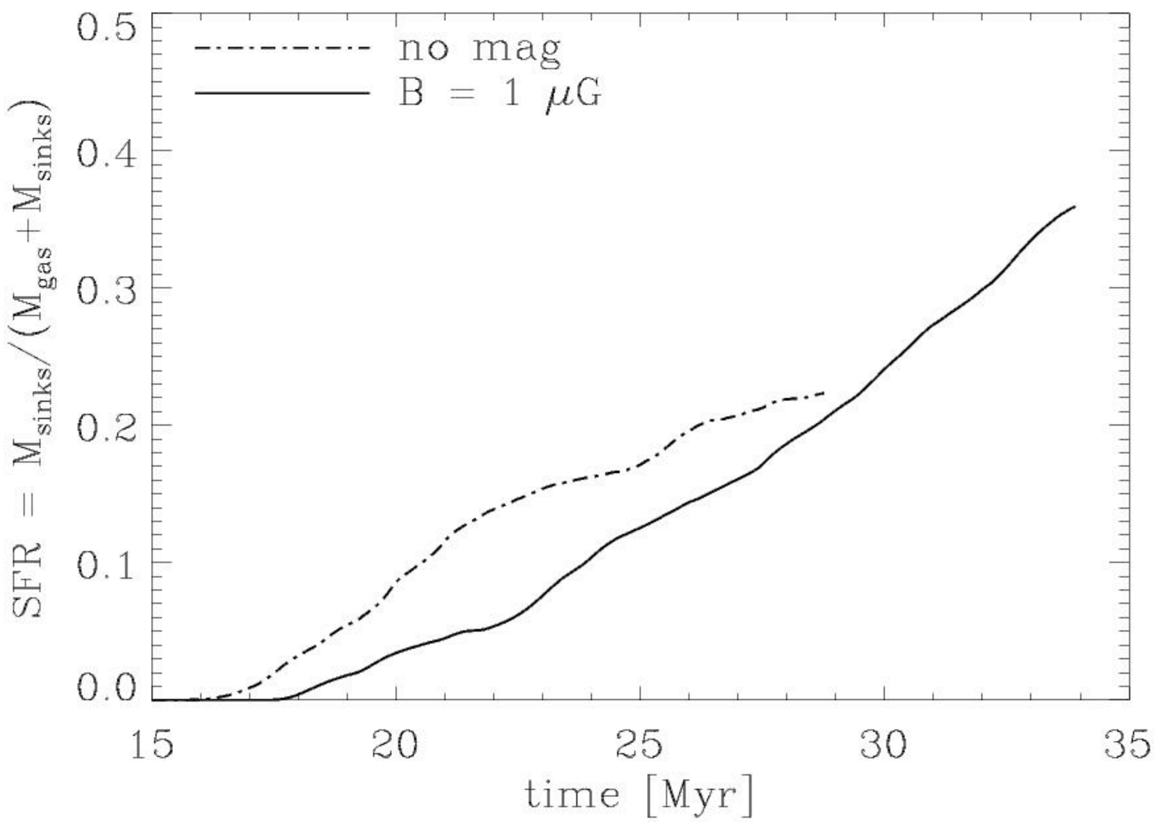


R.B. et al. 2008

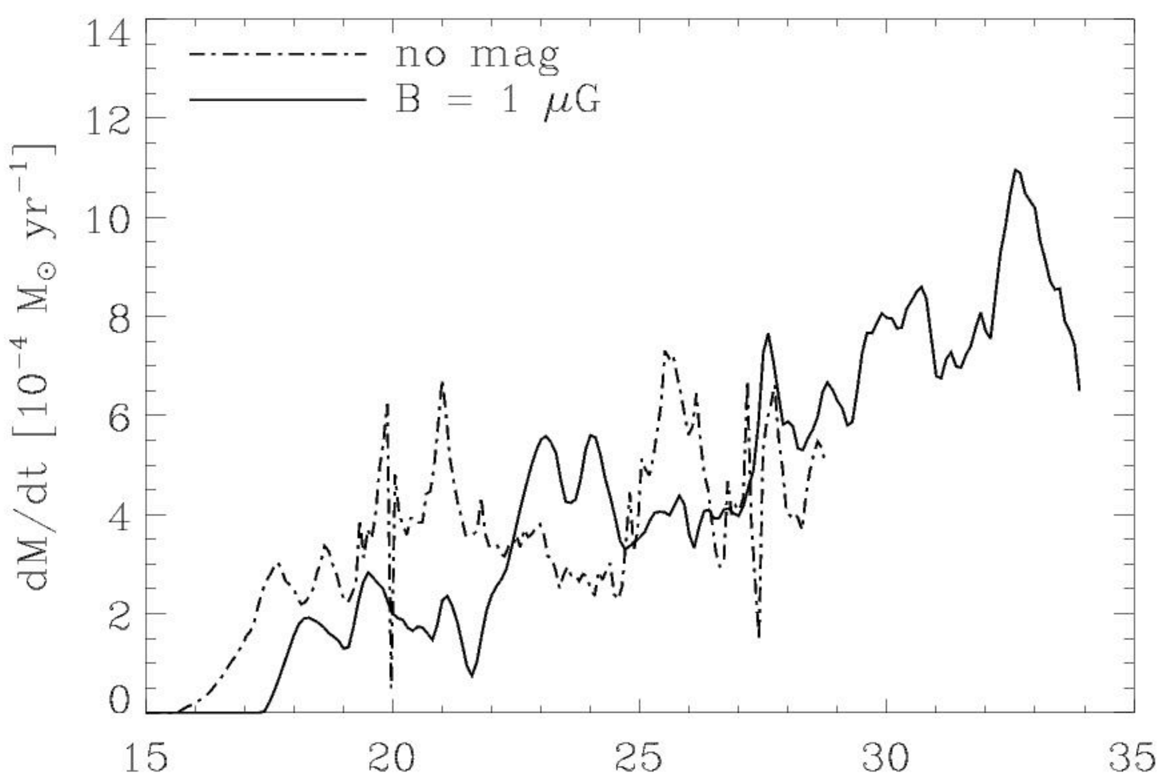
- first appearance of molecular clumps ~ 5 Myr
- star formation at ~ 17 Myr ($\Delta t \sim 2\ t_{ff}$)
- increasing star formation efficiency (~ 0.4)

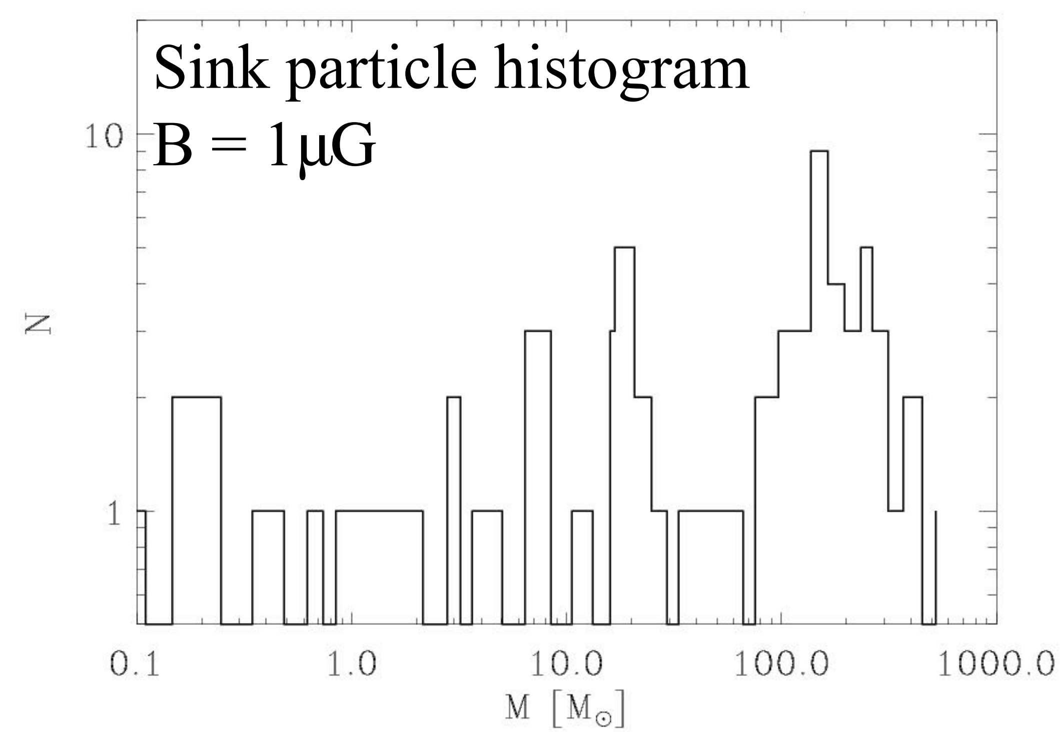
Formation of Molecular Clouds

Star formation efficiency

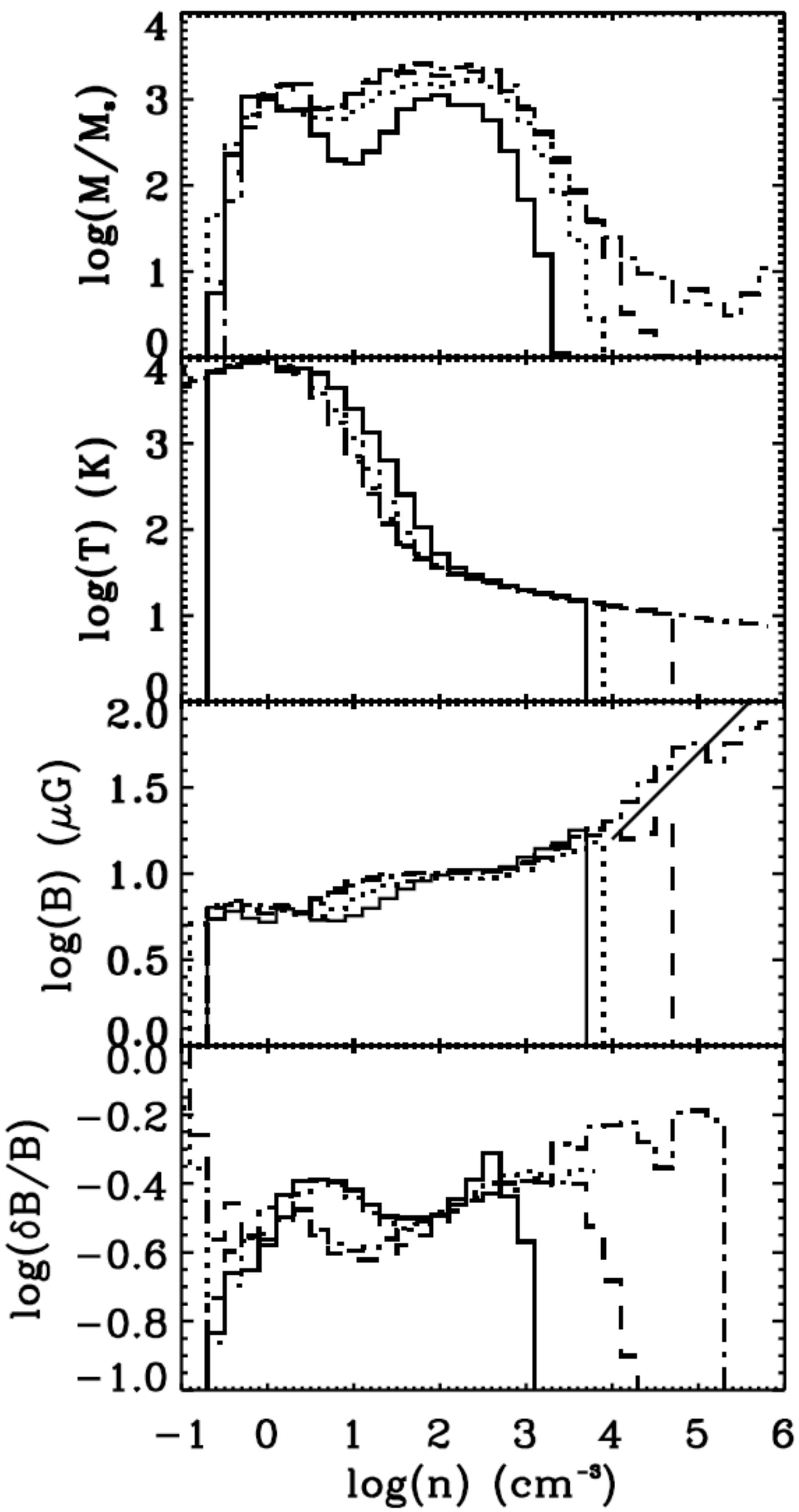


- $SFR_{no\text{-}mag} > SFR_{mag}$
- Note: assumes **equal** conversion factor: sinks → stars
- increasing mass accretion rate: $dM/dt \sim 10^{-4} - 10^{-3}\ M_\odot/yr$





Formation of Molecular Clouds



Hennebelle, R.B., et al. 2008

Statistical properties

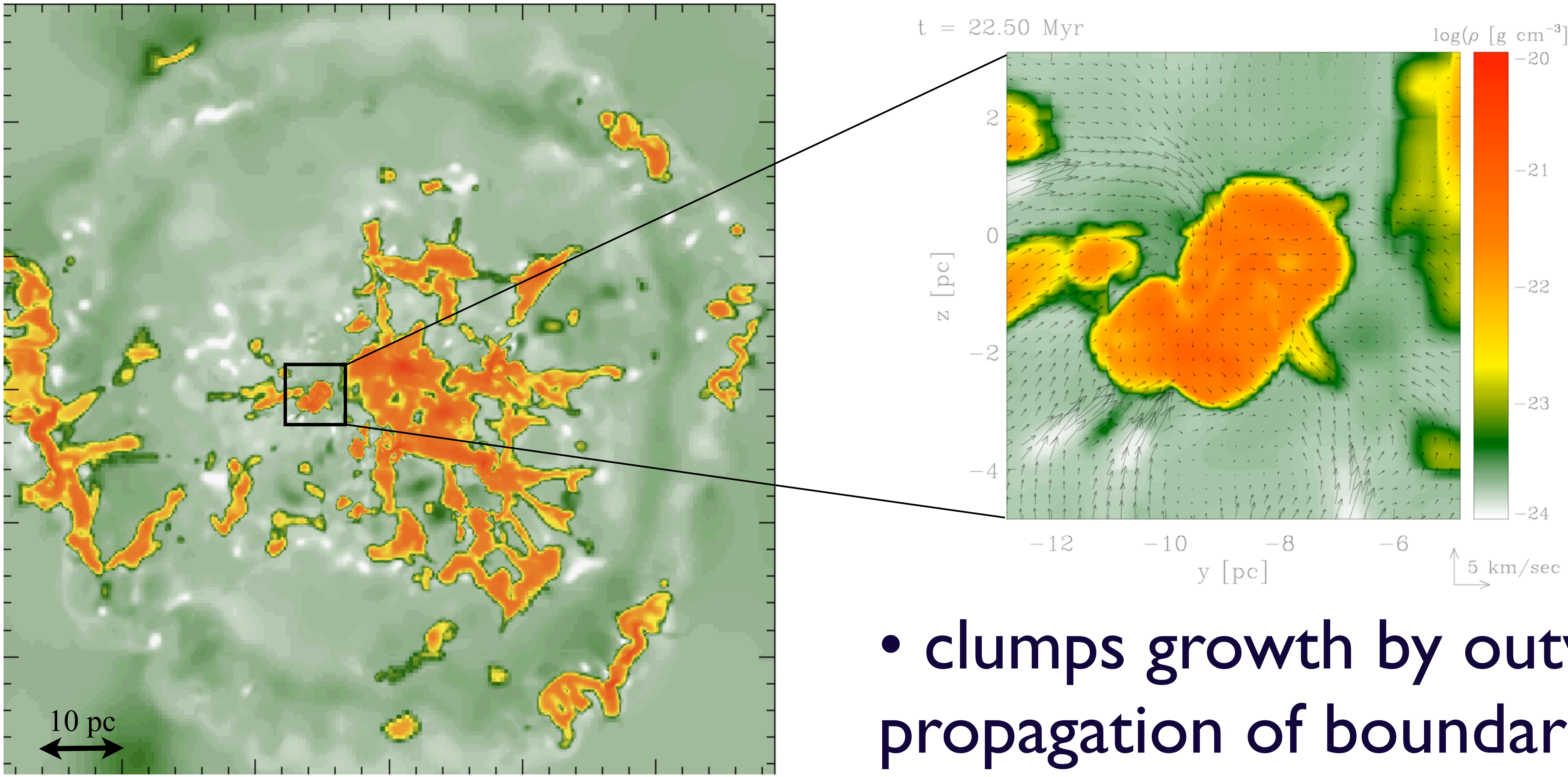
- mass peaks in the molecular phase, $n > 10^2$ cm^{-3}
- warm atomic and cold molecular gas coexist
- B weakly dependent in the low density gas
- $B \propto n^{0.5}$ in the dense gas ($n > 10^3$ cm^{-3})

consistent with observations (e.g. *Crutcher 1999*)

- δB varies smoothly with density

Formation of Molecular Clouds

morphology and clump evolution

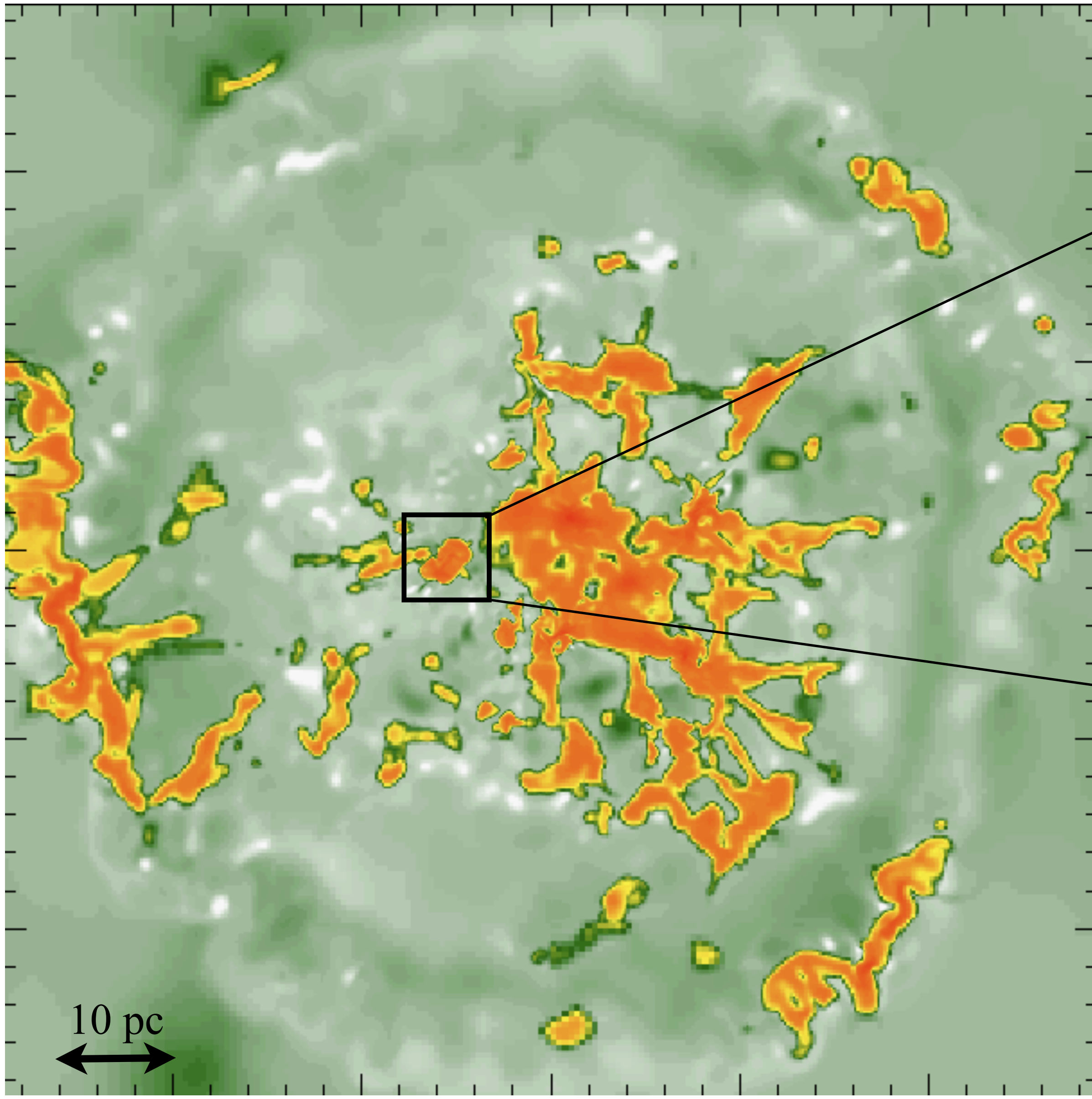


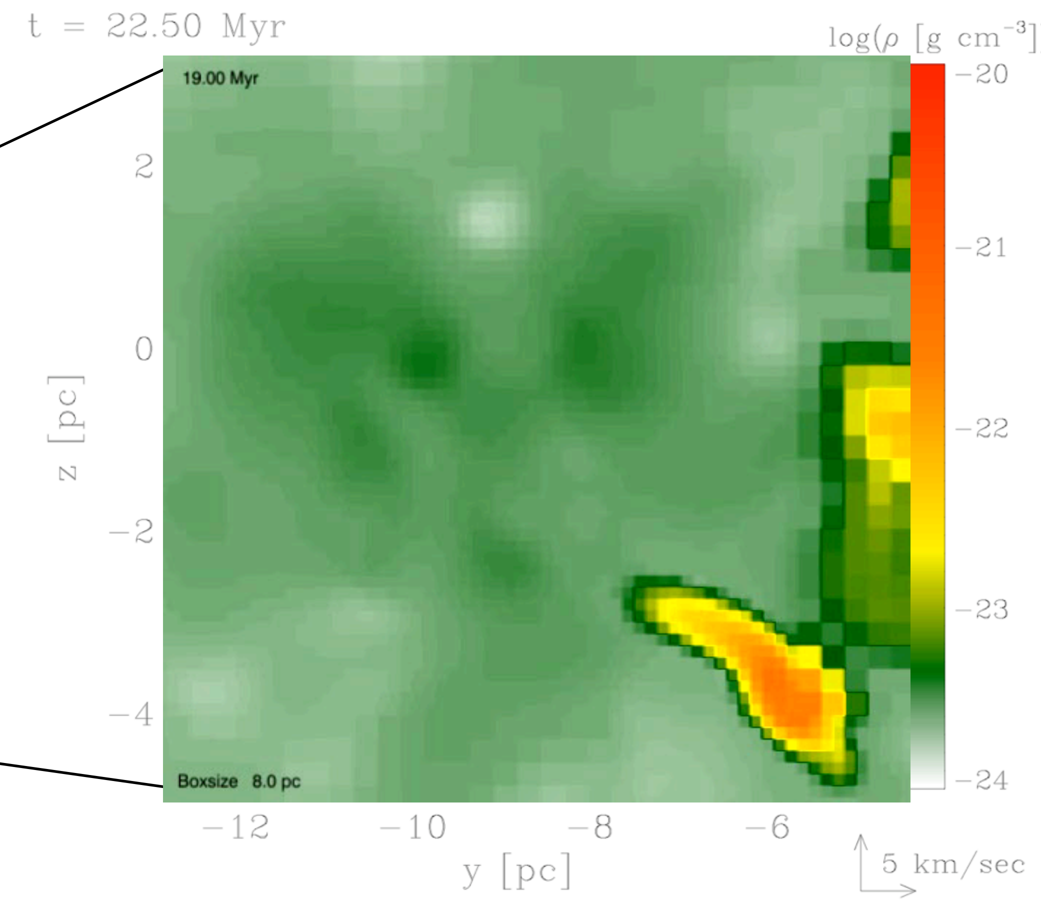
- MCs are inhomogeneous
- cold clumps embedded in warm atomic gas

- clumps growth by outward propagation of boundary layers and coalescence

Formation of Molecular Clouds

morphology and clump evolution





- clumps growth by outward propagation of boundary layers and coalescence

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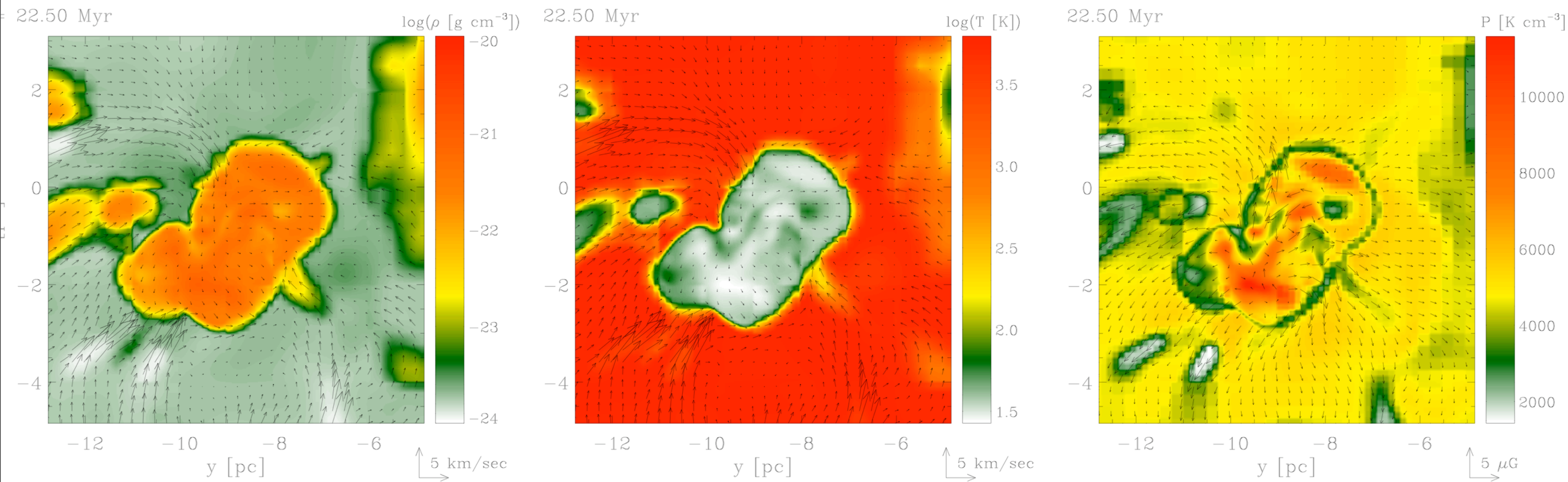
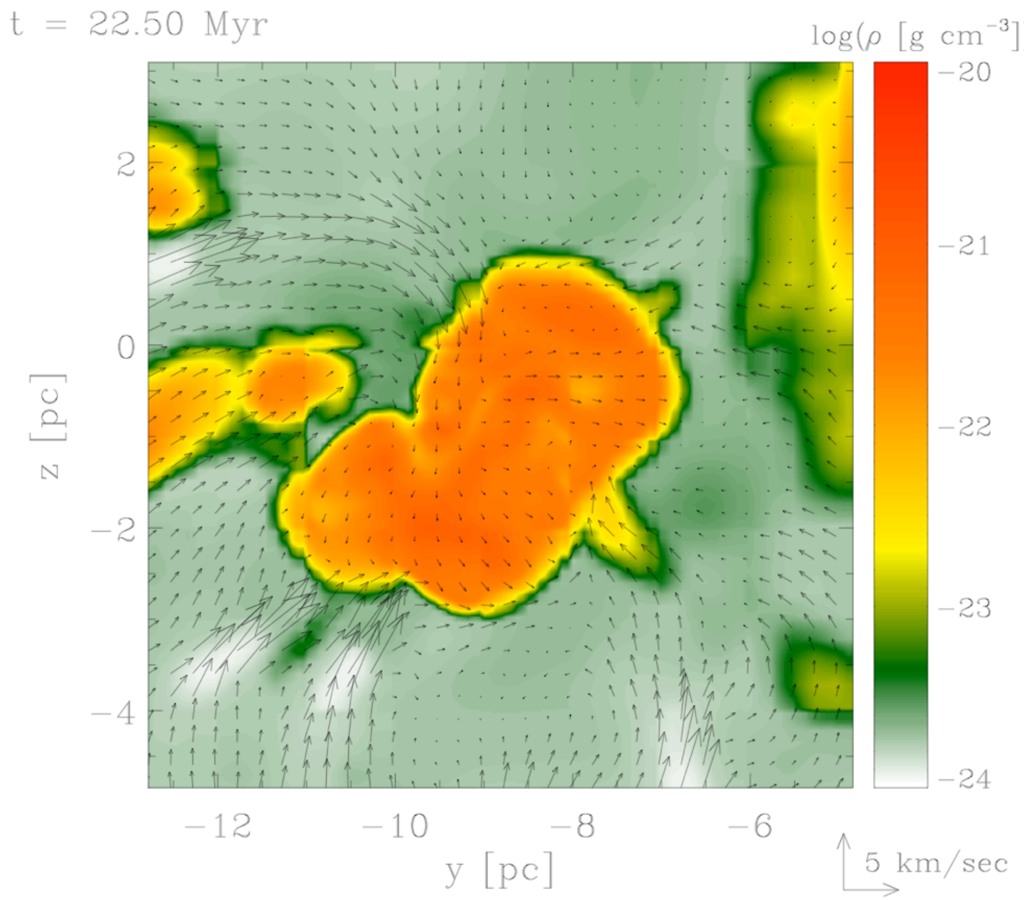
Formation of Molecular Clouds

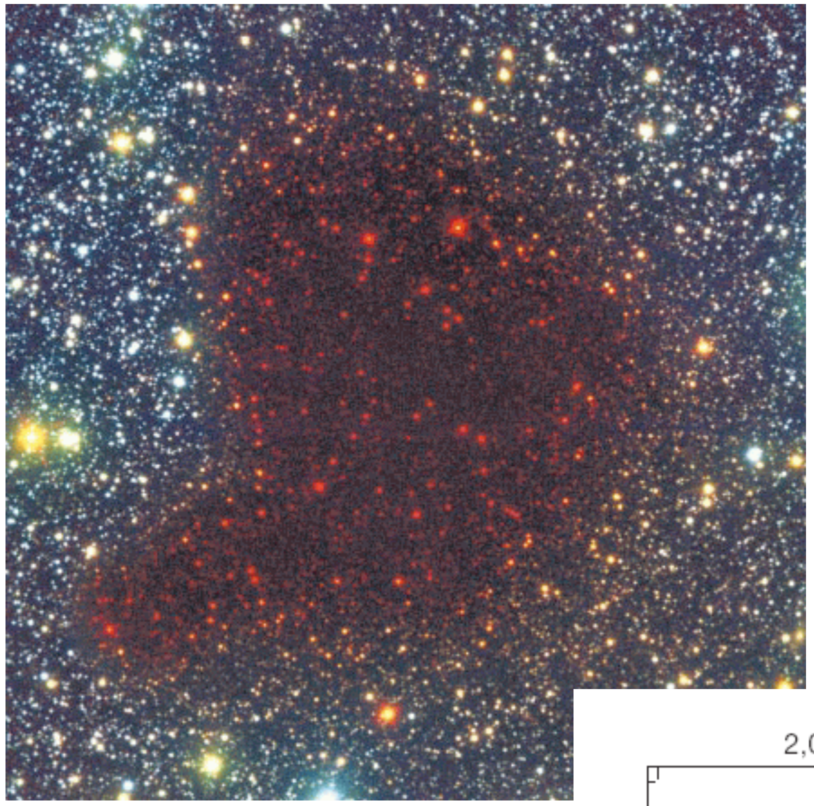
clump morphology



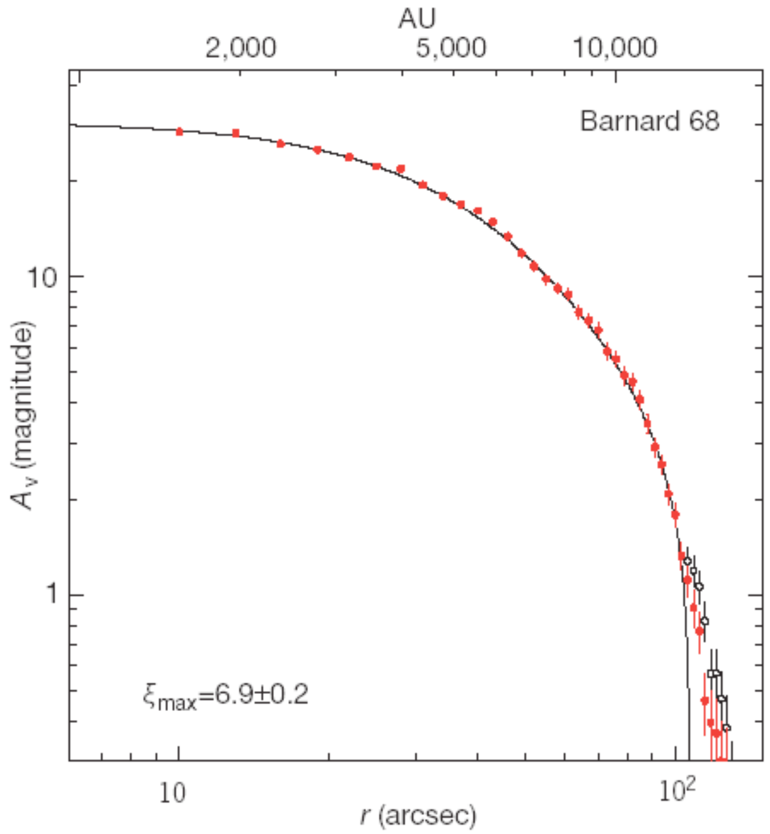
- cold clumps are in pressure equilibrium with their warm surroundings
- in-falling gas streams along field lines
- BE type density profiles

Collapse of magnetized cores



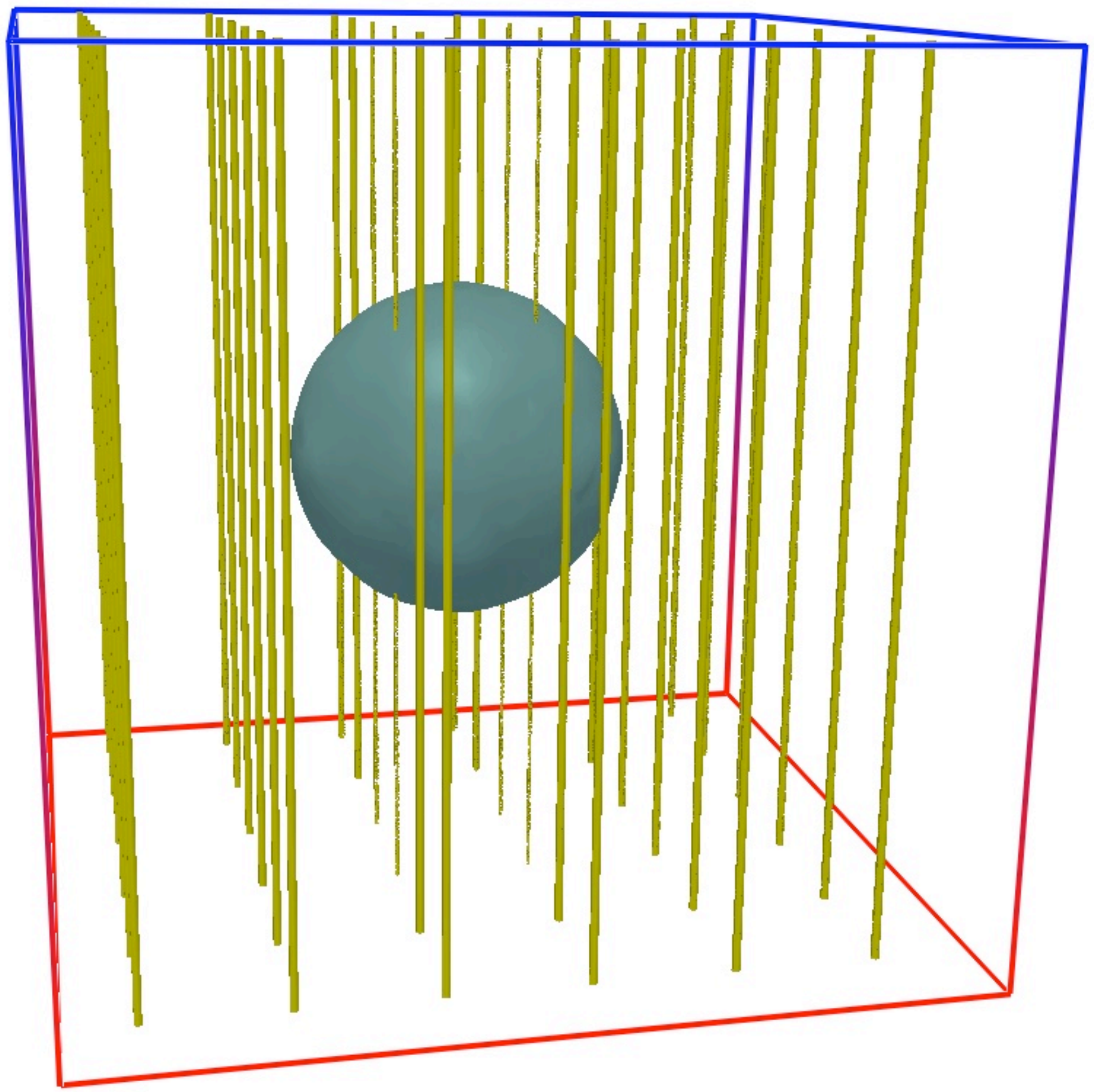


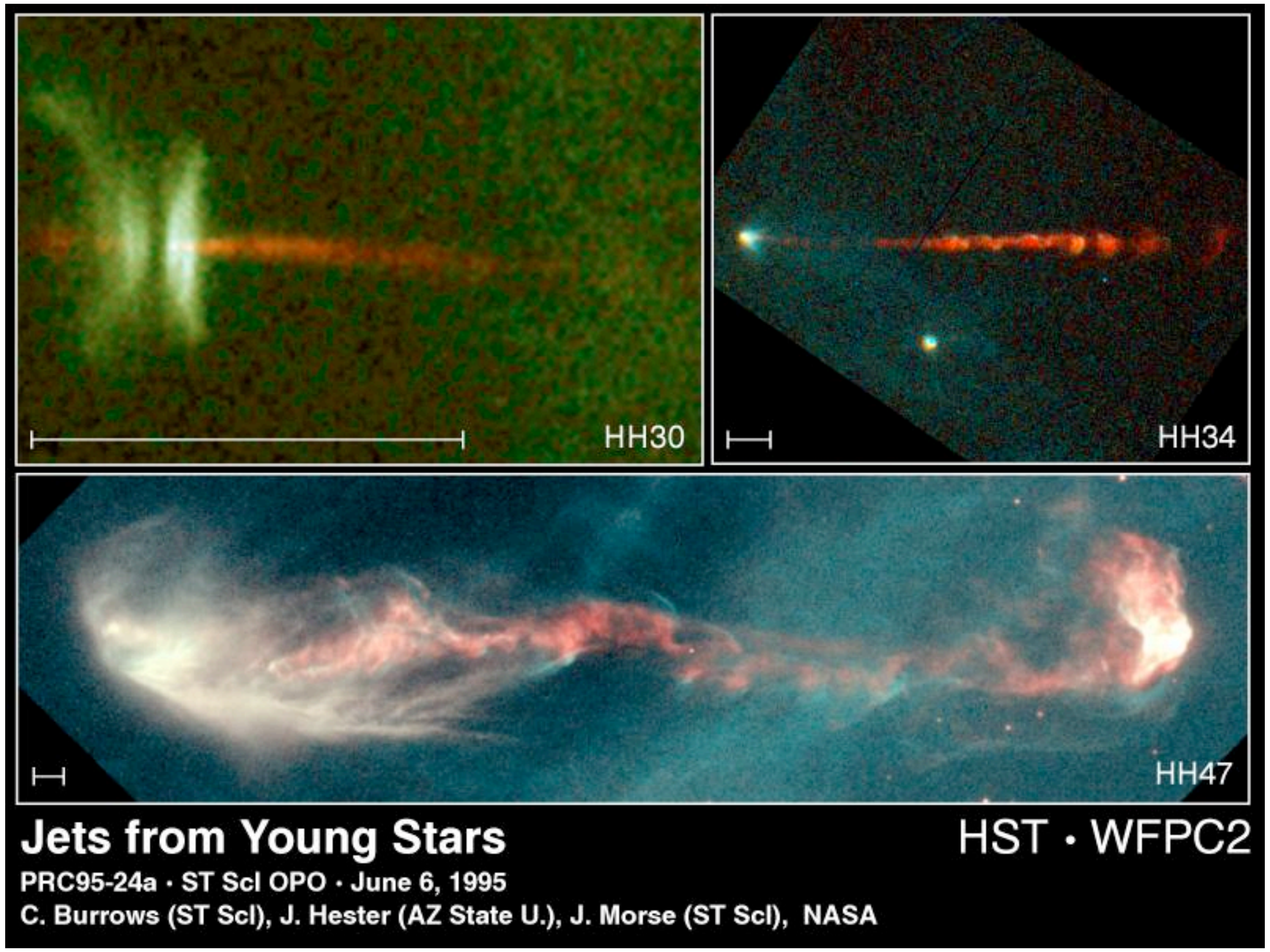
B68 *Alves et al. 2001*



Fate of magnetized core?

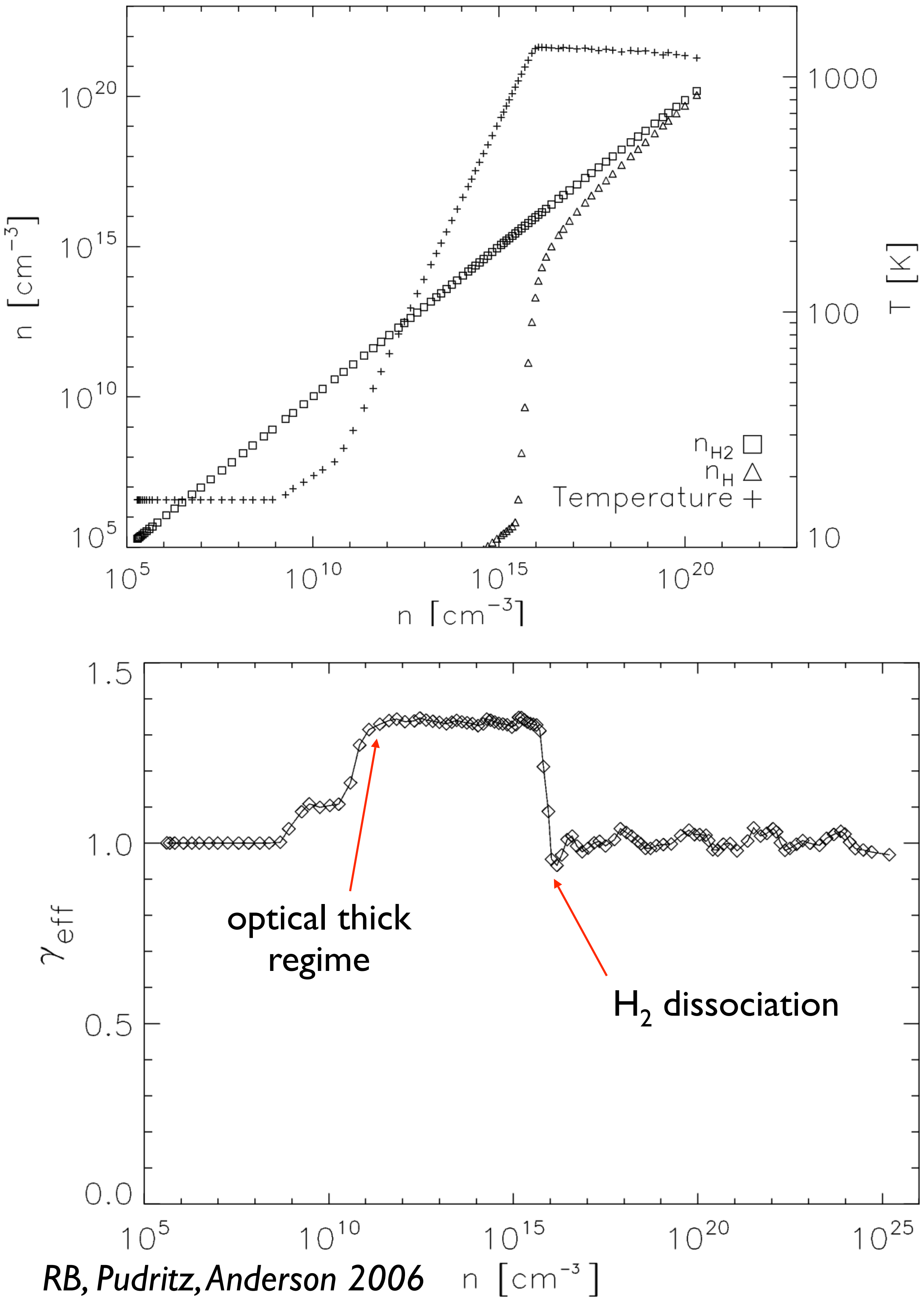
Collapse of magnetized cores





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

Collapse of magnetized cores



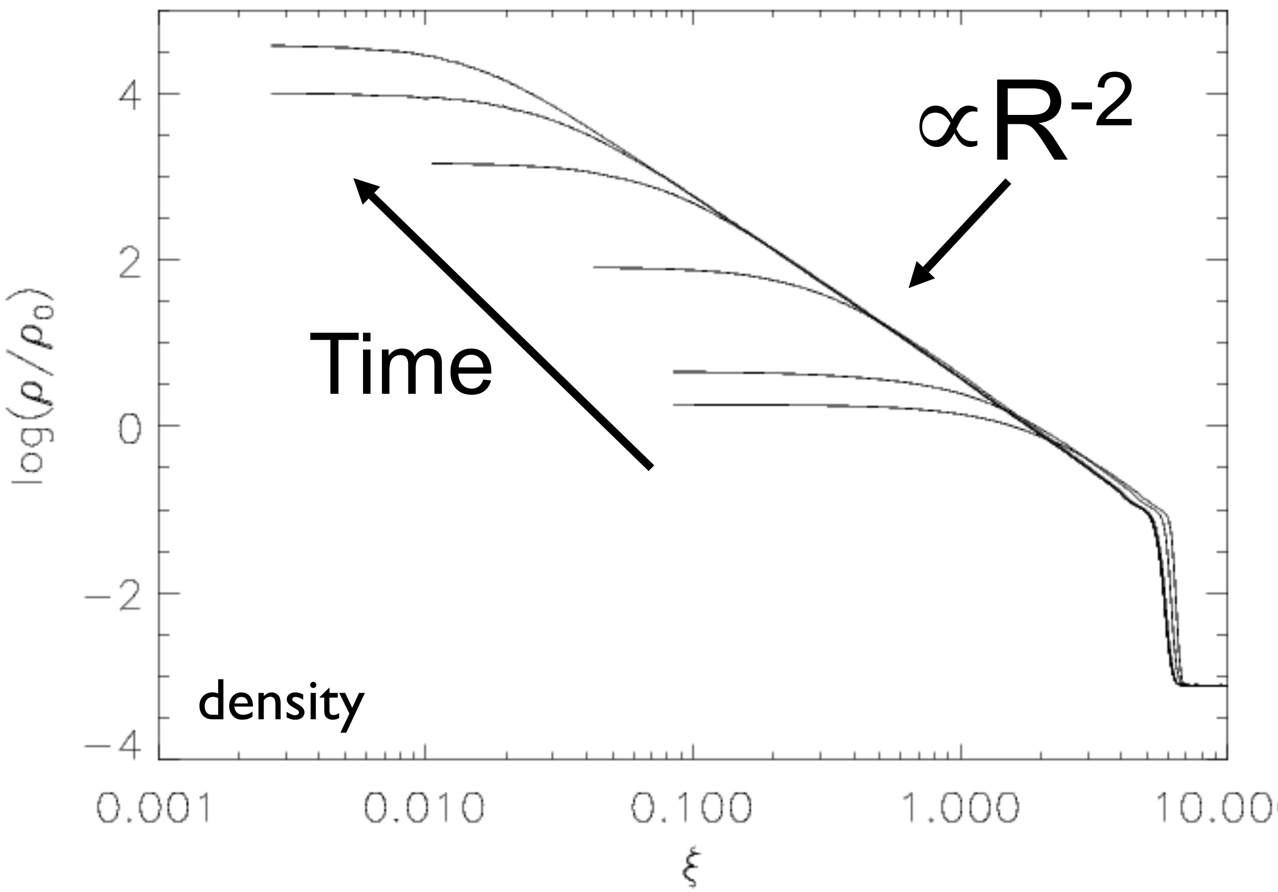
RB, Pudritz, Anderson 2006

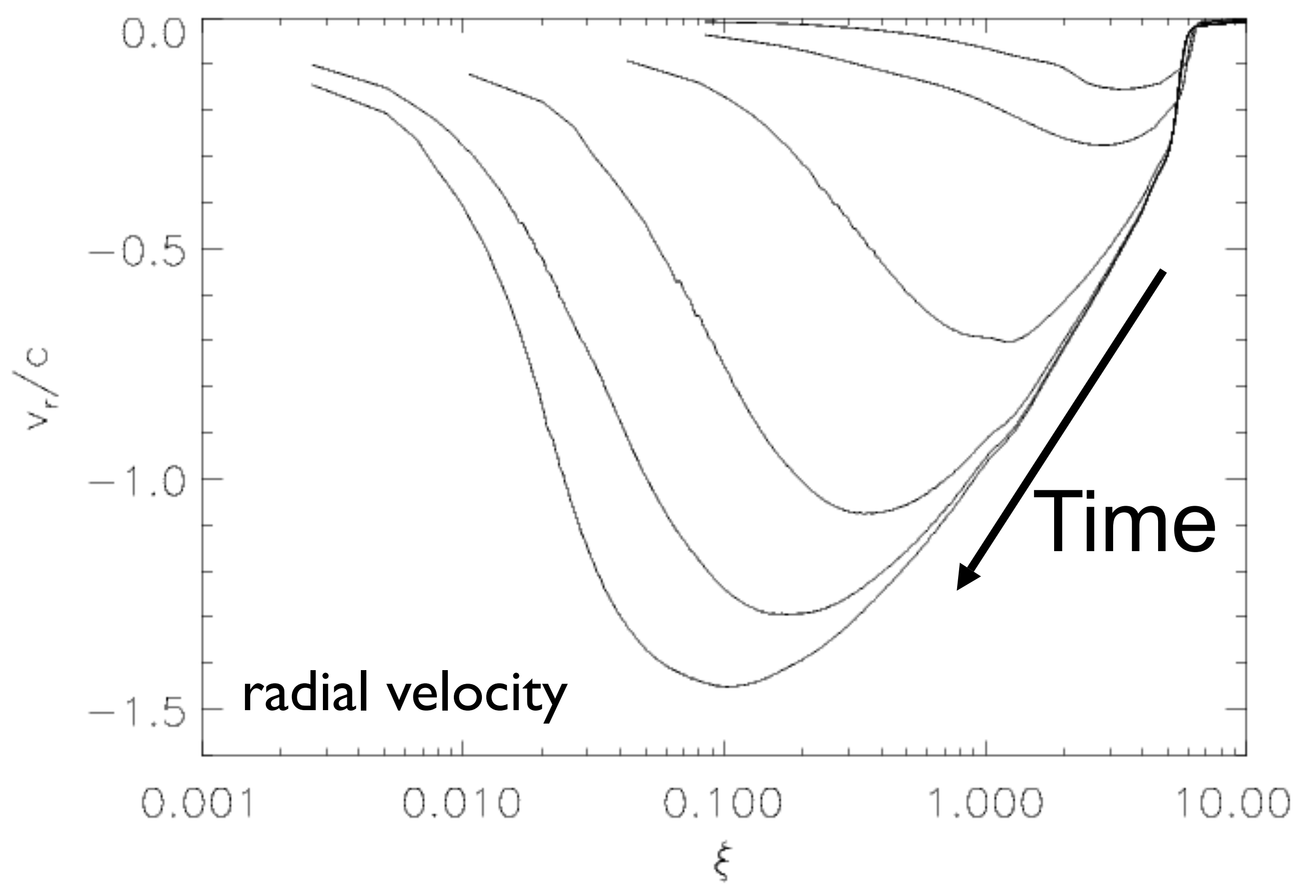
Cooling

- **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

Collapse of magnetized cores

Isothermal Bonnor-Ebert collapse





Outside-in

non-homologous collapse

Onset of large scale outflow:

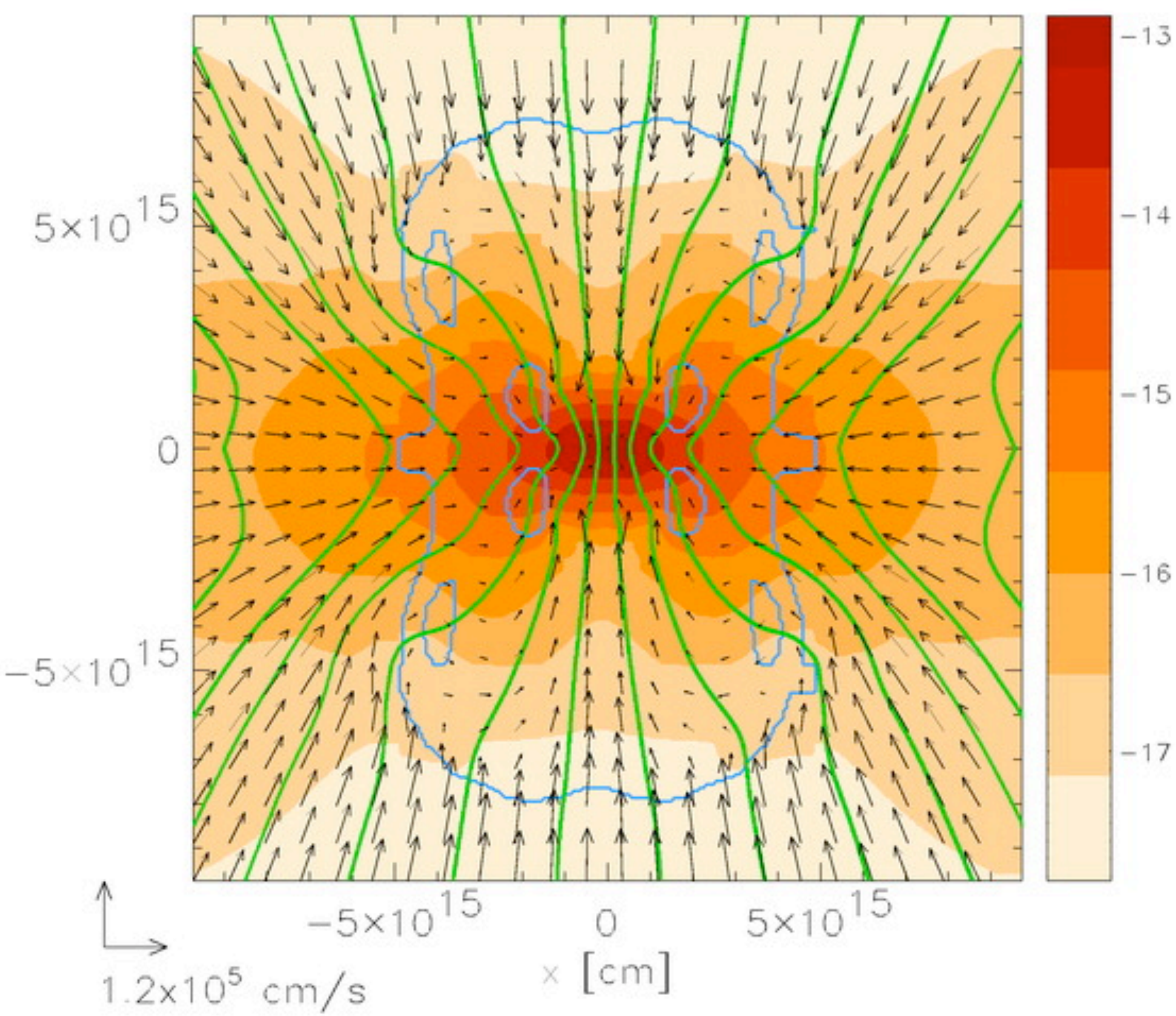
at few 100 AU

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

Onset of large scale outflow:

at few 100 AU

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



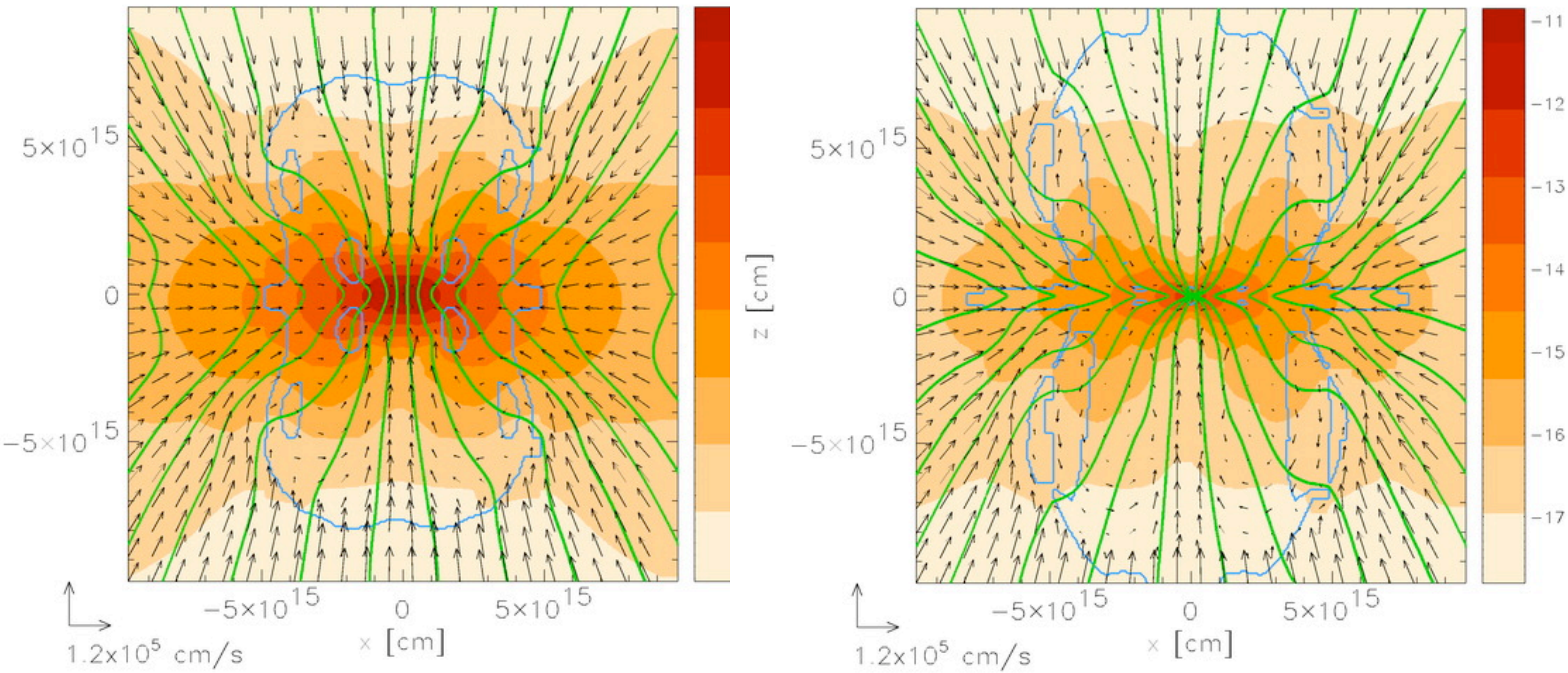
collapse phase

pinched in magnetic field

Onset of large scale outflow:

at few 100 AU
magnetic tower configuration (e.g. *Lynden-Bell 2003*)

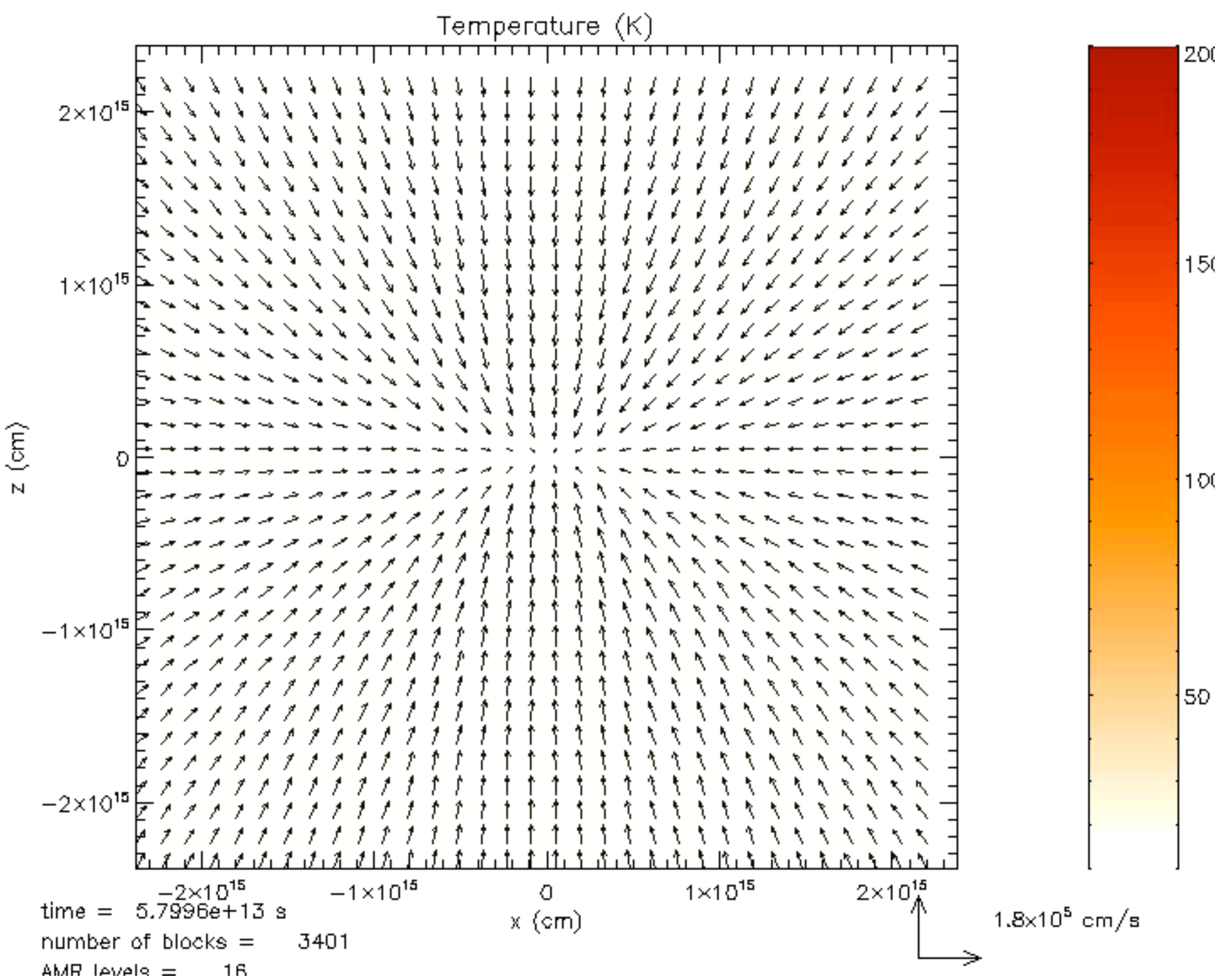
Banerjee & Pudritz 2006



collapse phase
pinched in magnetic field

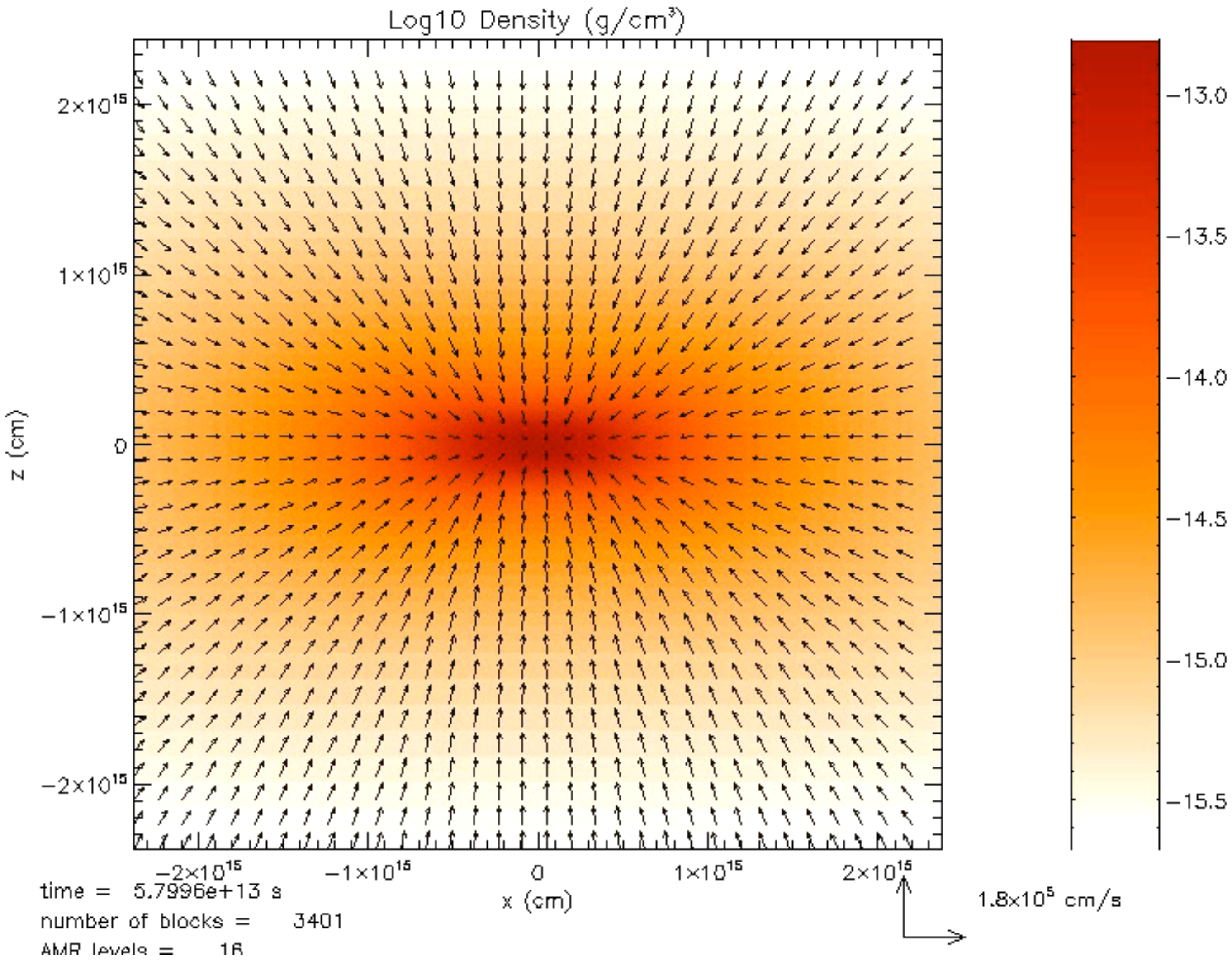
.... 1430 years later:
onset of a large scale outflow

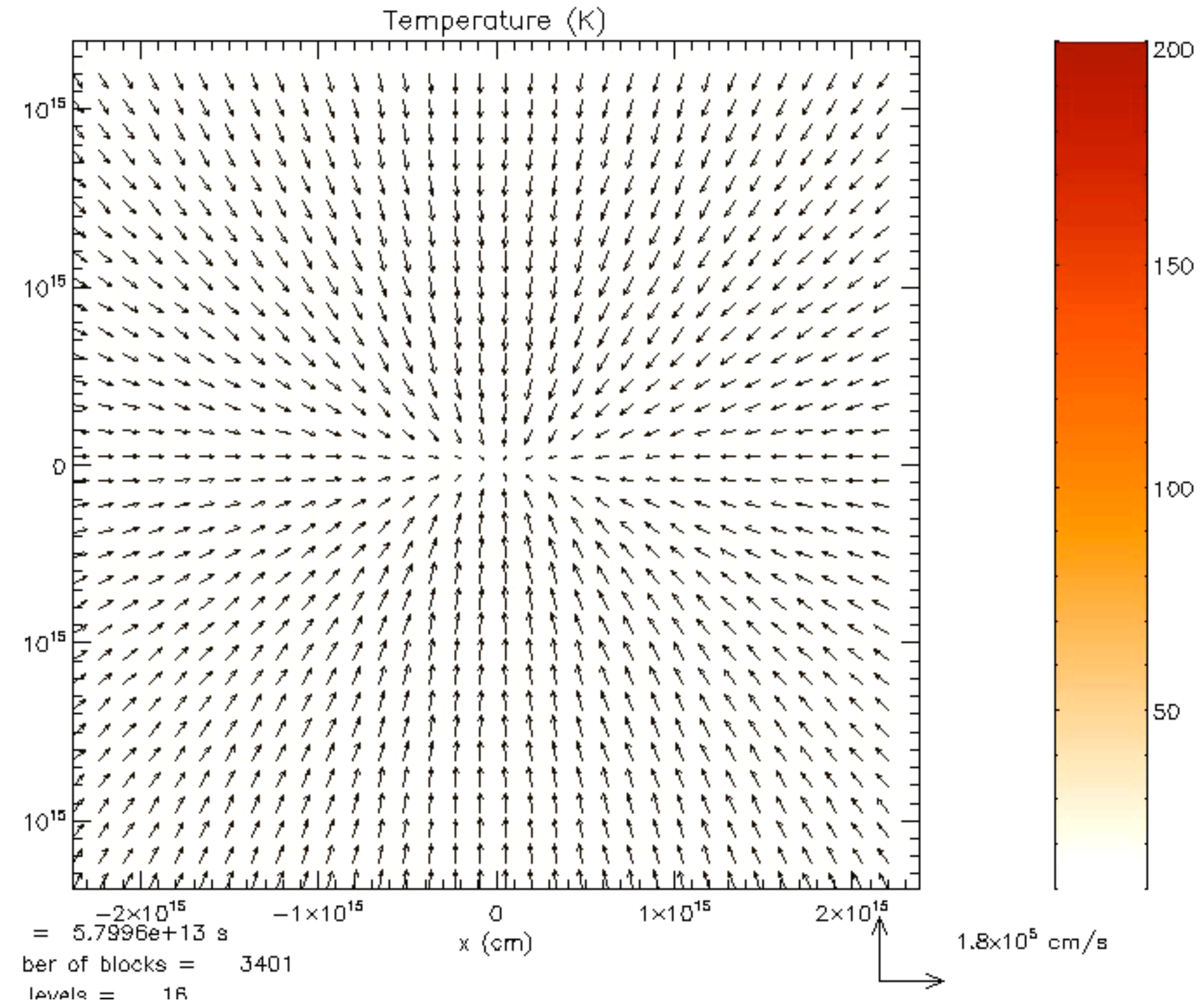
Onset of large scale outflow: Magnetic tower



- build up of toroidal field → magnetic pressure
- outward propagation of shock fronts
- magnetic bubble

Onset of large scale outflow: Magnetic tower





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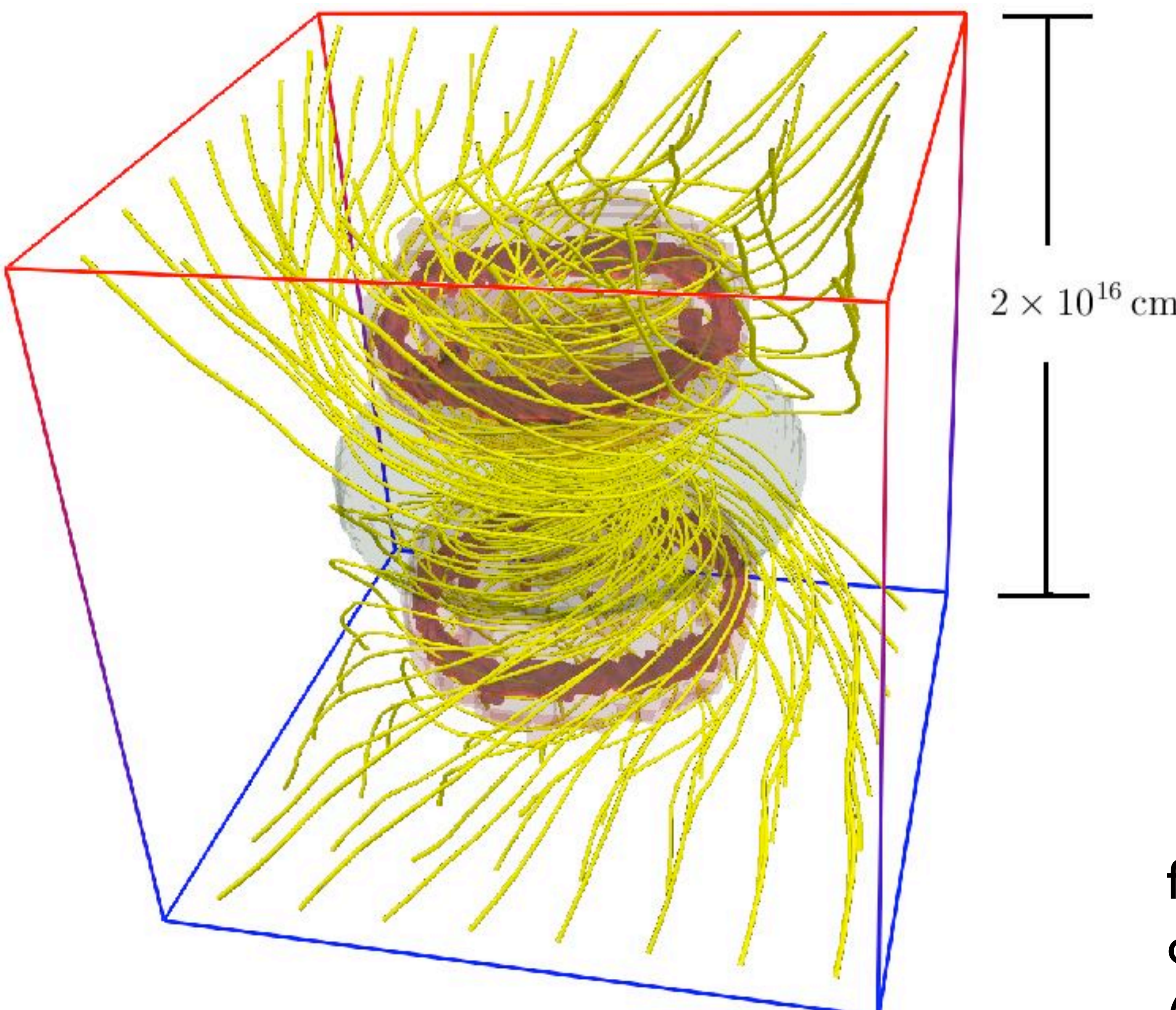
Collapse of magnetized cores

Large scale outflow



- Magnetic field is **compressed** with the gas
- Rotating disk generates **toroidal** magnetic field $\Rightarrow$**outflow**

- Shock fronts are pushed outwards (magnetic tower)
- Outflow velocities v ~ 0.4 km/sec, M ~ 2-3
- Accretion: funneled along the rotation axis and through disk

for massive star formation:
outflow cavities can channel radiation
(Krumholz et al. 2004)

Collapse of magnetized cores

Onset of inner disk jet

launch inside 0.07 AU

- jets rotate and carry off angular momentum of disk

Collapse of magnetized cores

Onset of inner disk jet

launch inside 0.07 AU

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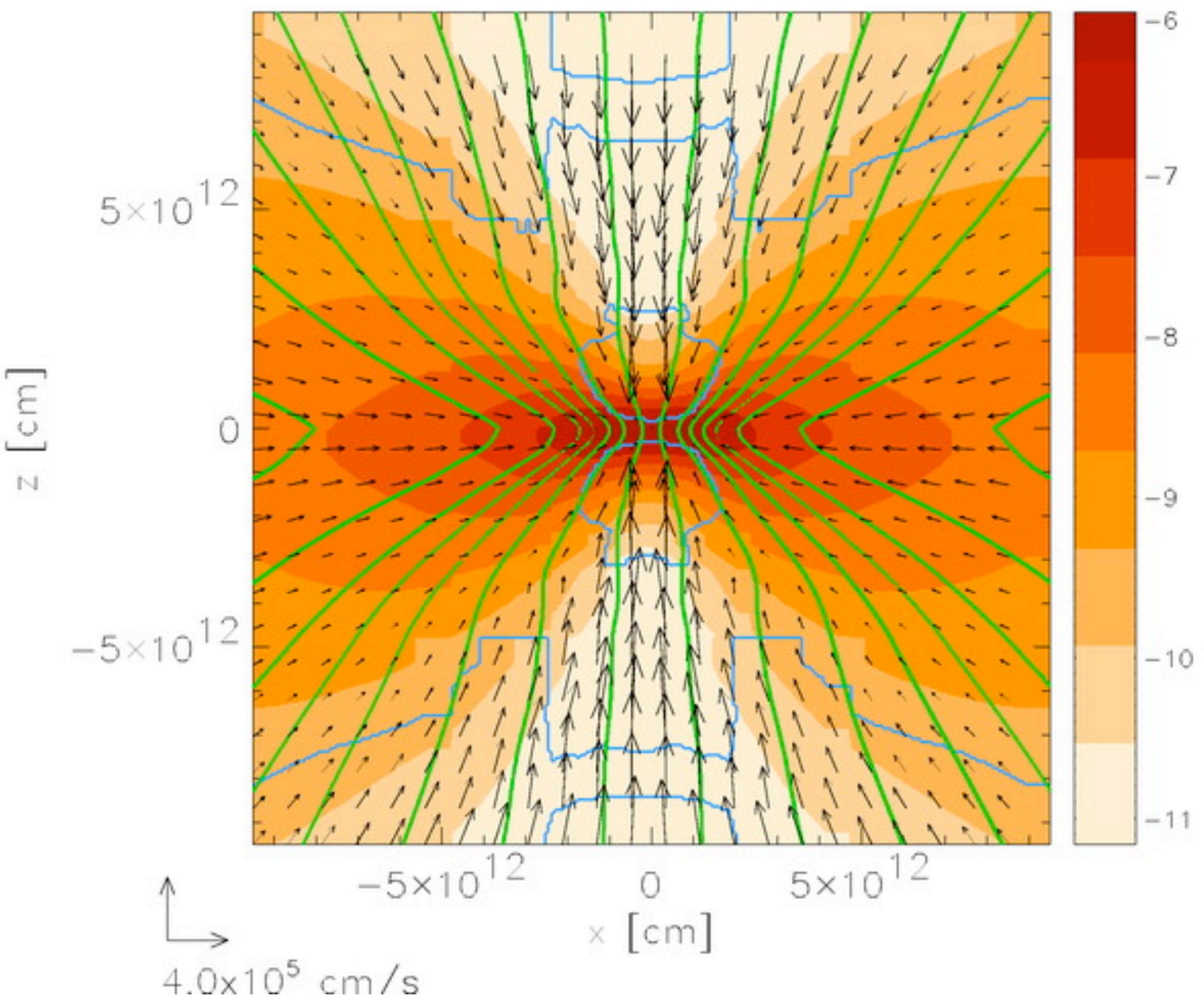


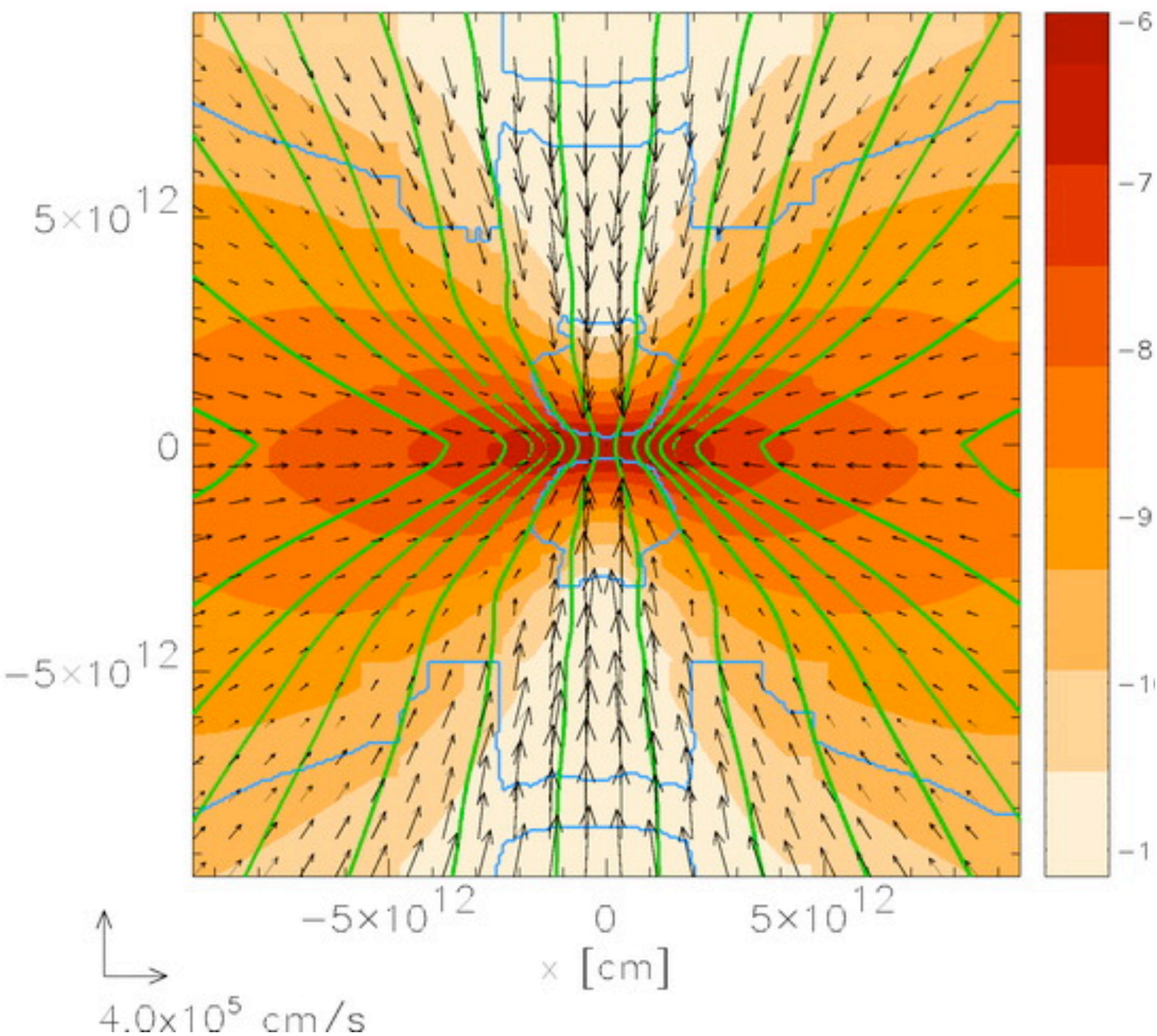
infall only

Collapse of magnetized cores

Onset of inner disk jet

launch inside 0.07 AU

- jets rotate and carry off angular momentum of disk



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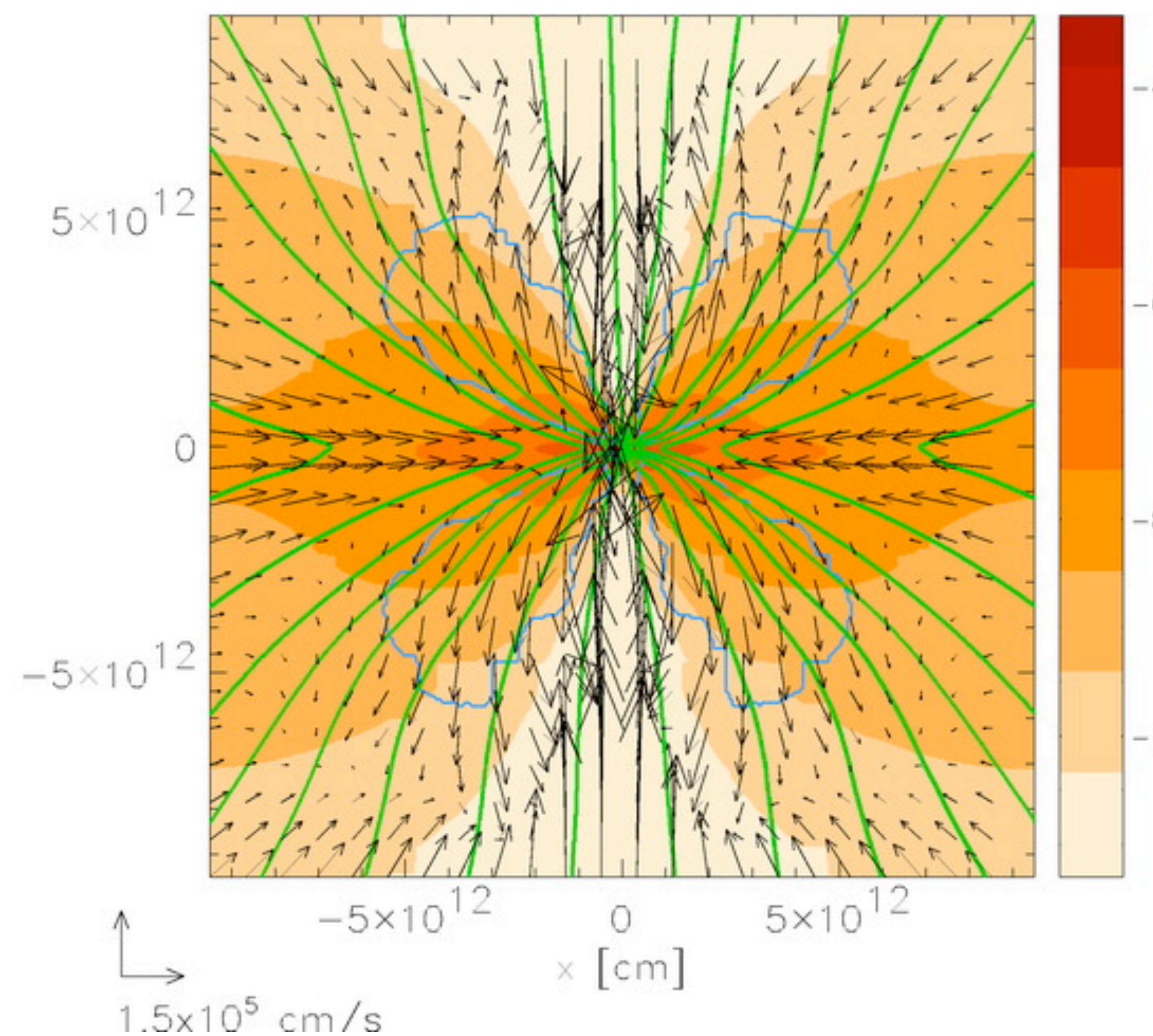
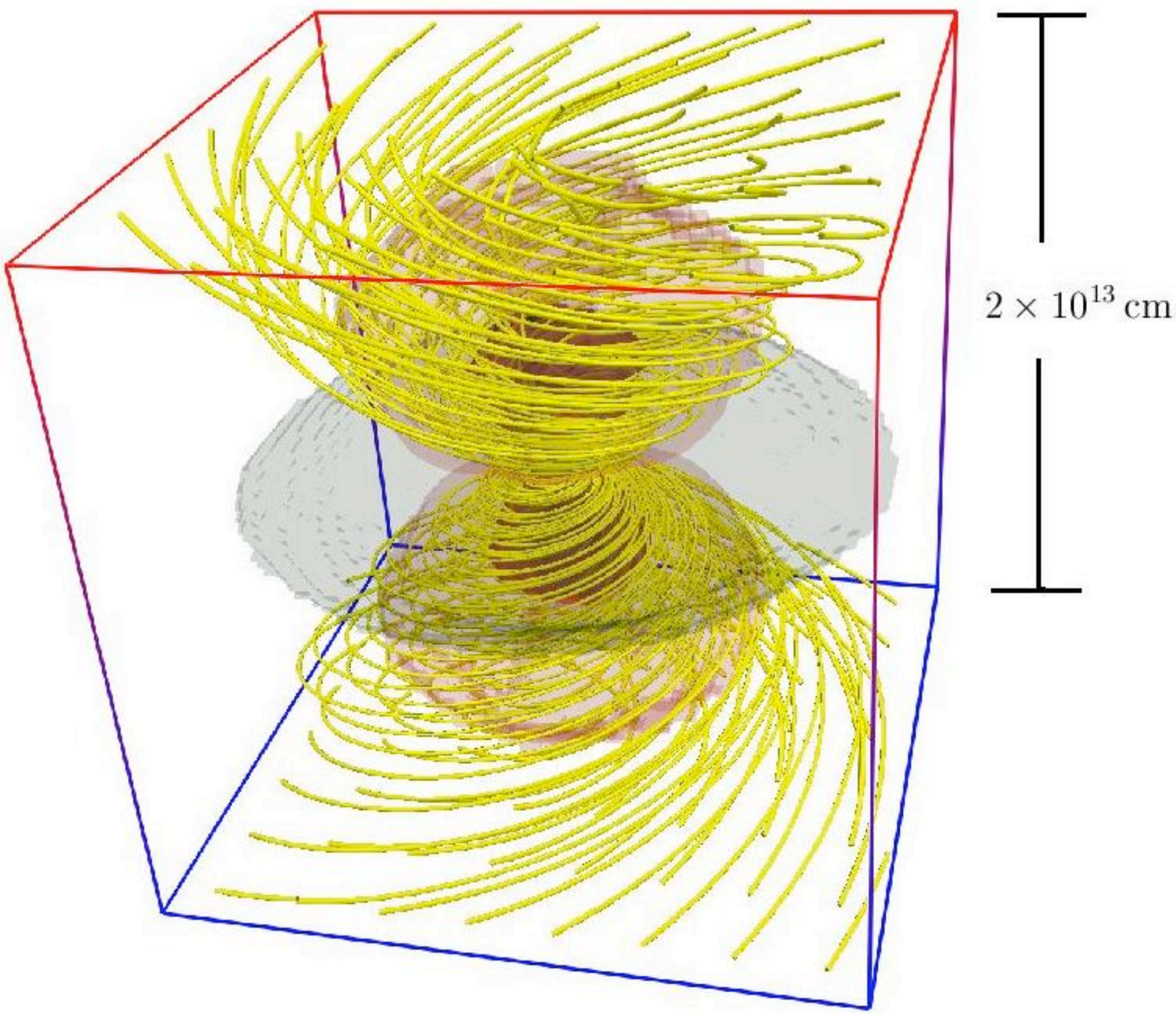


... 5 month later: flow reversal

Collapse of magnetized cores

small scale disk jet

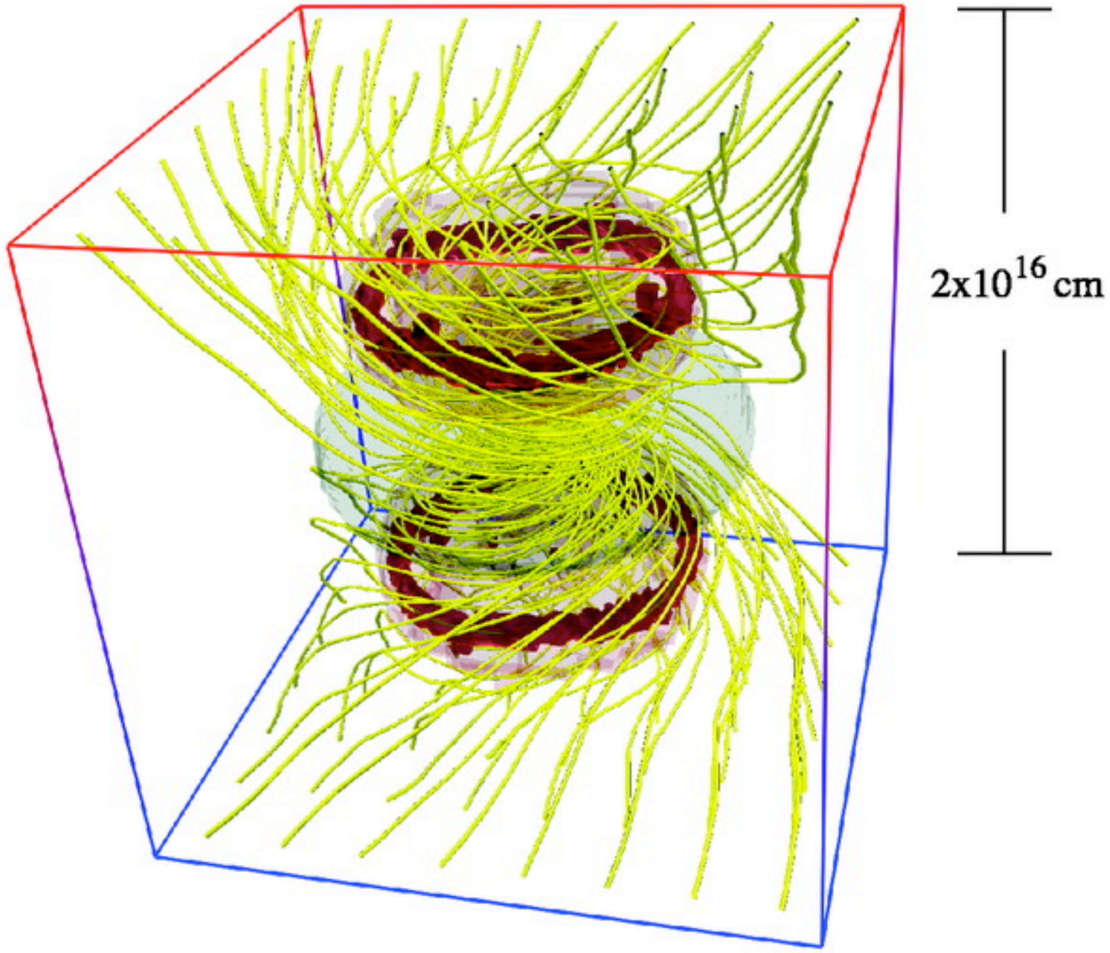


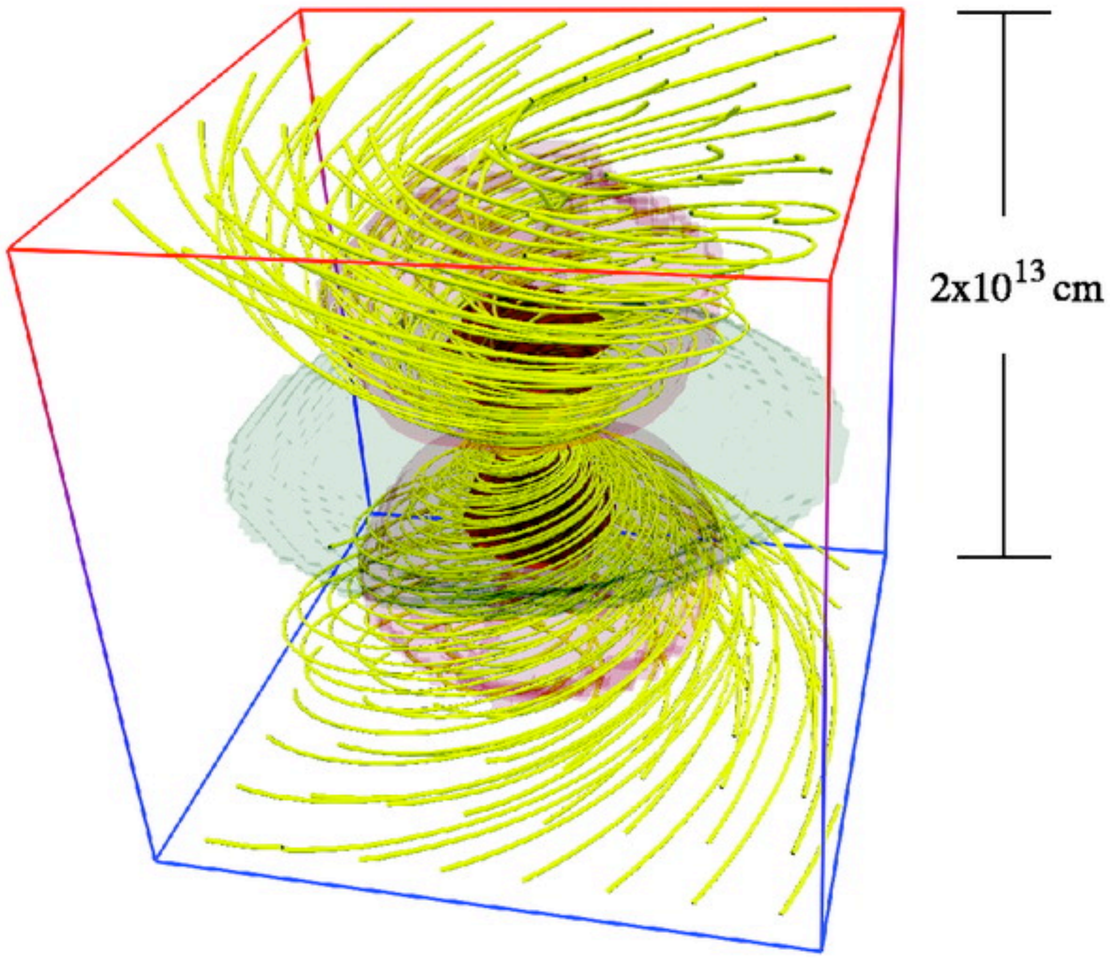
- Magnetic field strongly pinched and warped
- Angle with disk plane < 60°
  → magneto-centrifugal jet launch
- "Onion" shaped velocity structure
- Outflow velocities
  v ~ 4 - 5 km/sec, Mach ~ 4

Observational evidence?
Zeeman measurements of FU Ori by *Donati et al. 2005* (~ 1kG field)

3D Visualization of field lines, disk, and outflow:

- Upper; magnetic tower flow
- Lower; zoomed in by 1000, centrifugally driven disk wind





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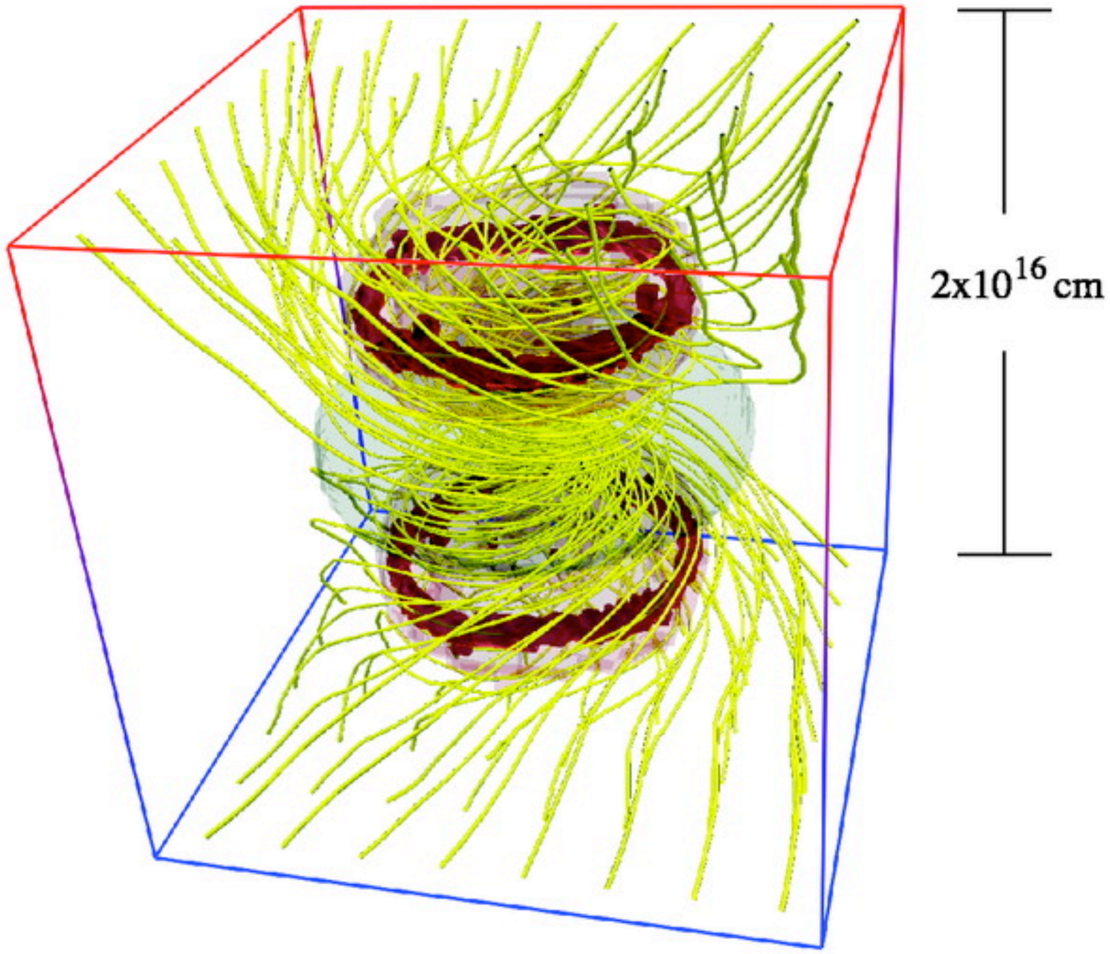
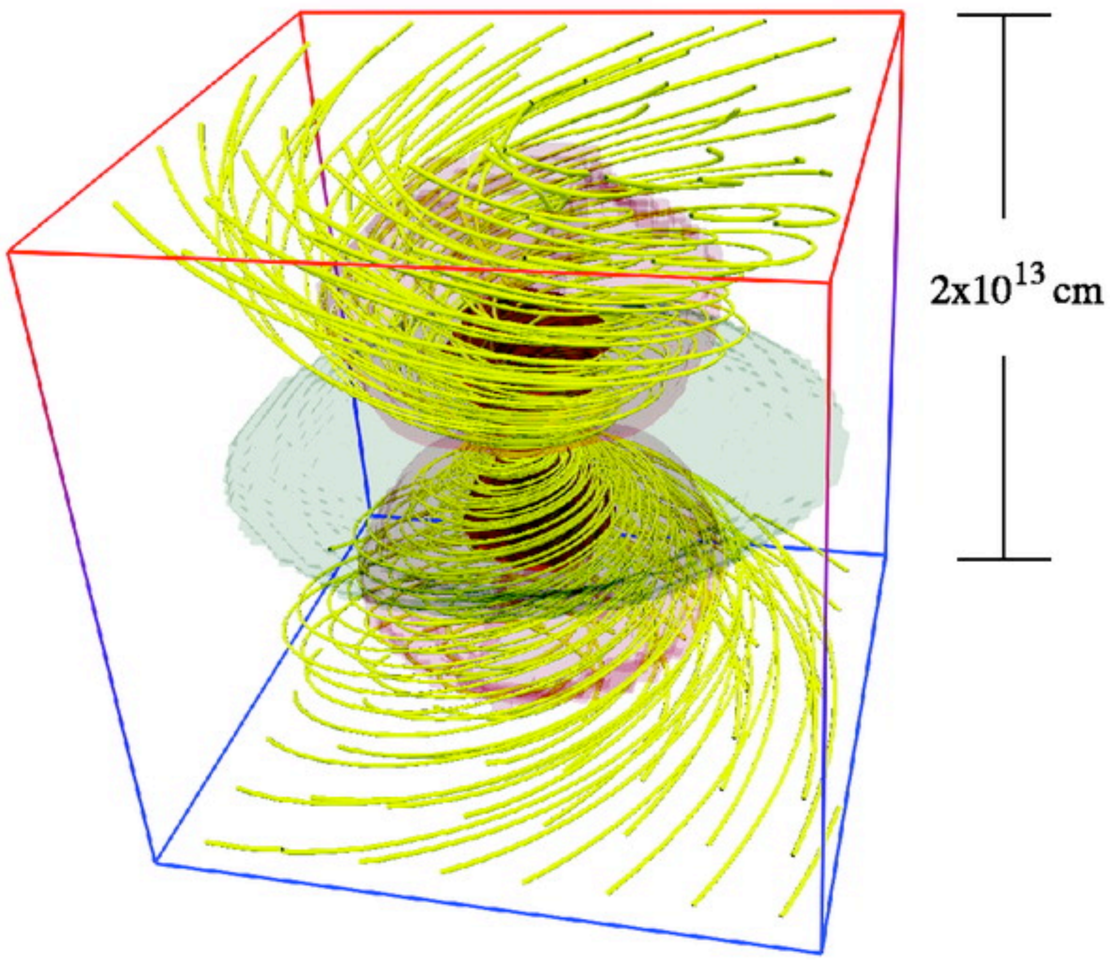
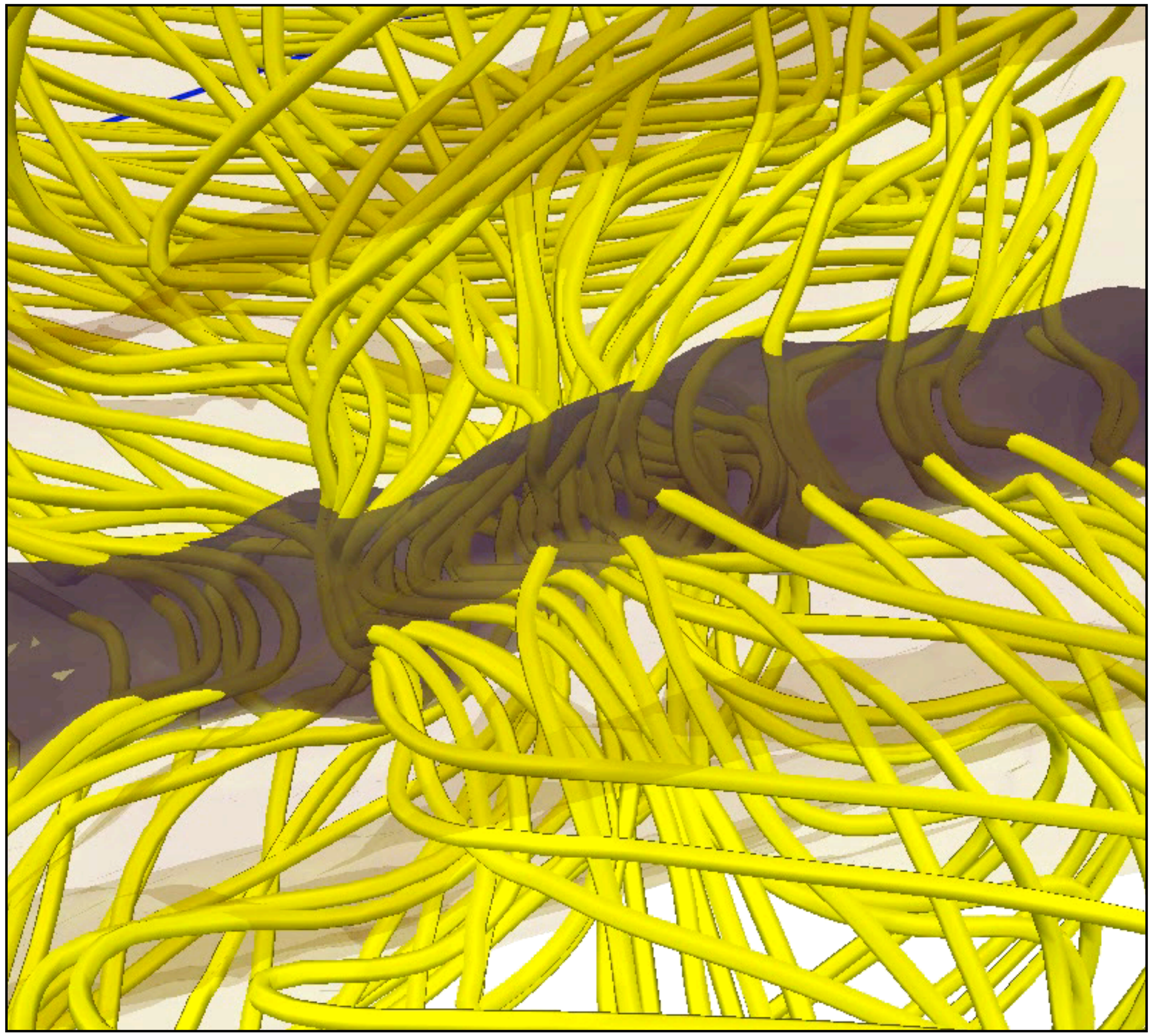
- Lower; zoomed in by 1000, centrifugally driven disk wind

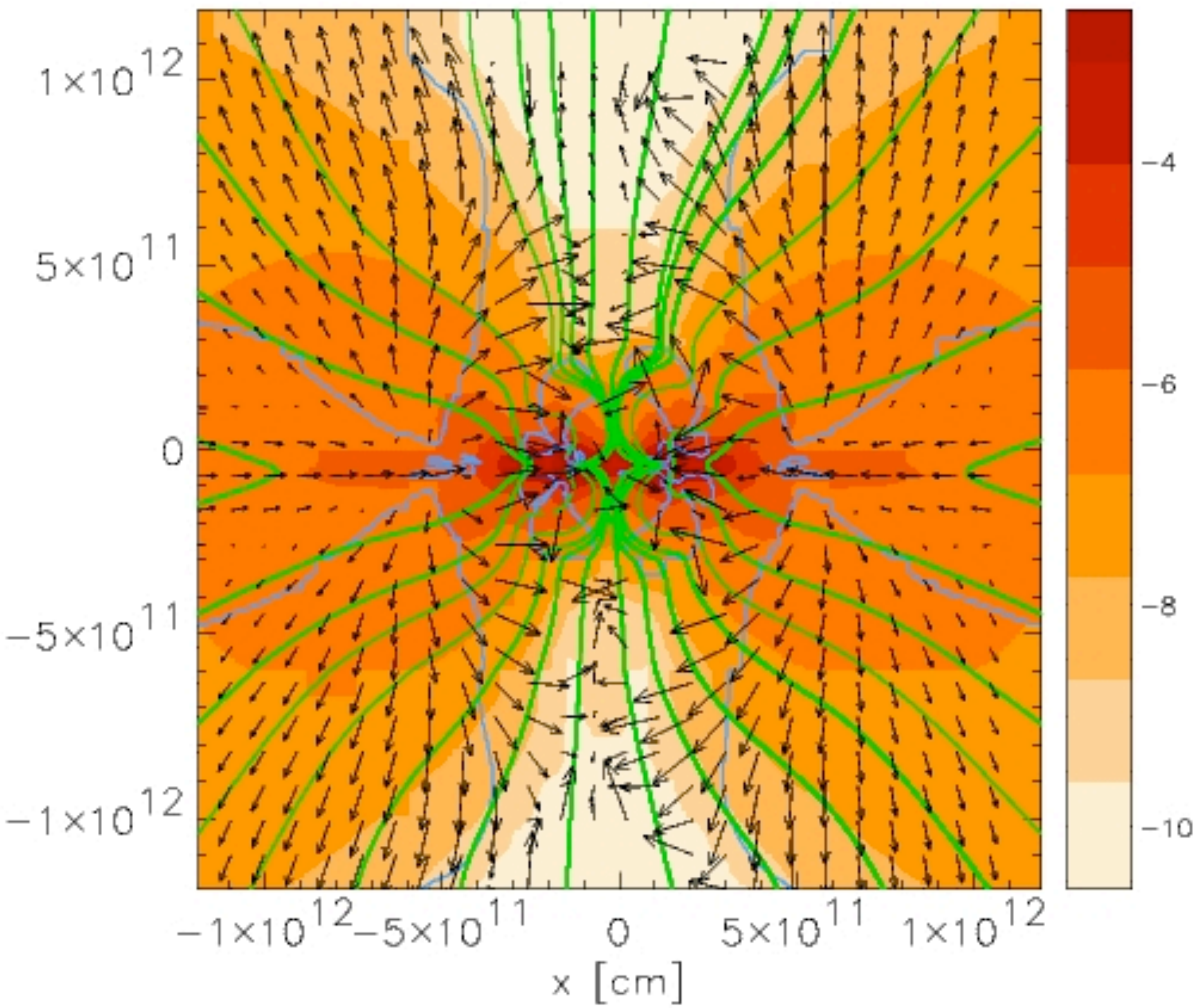




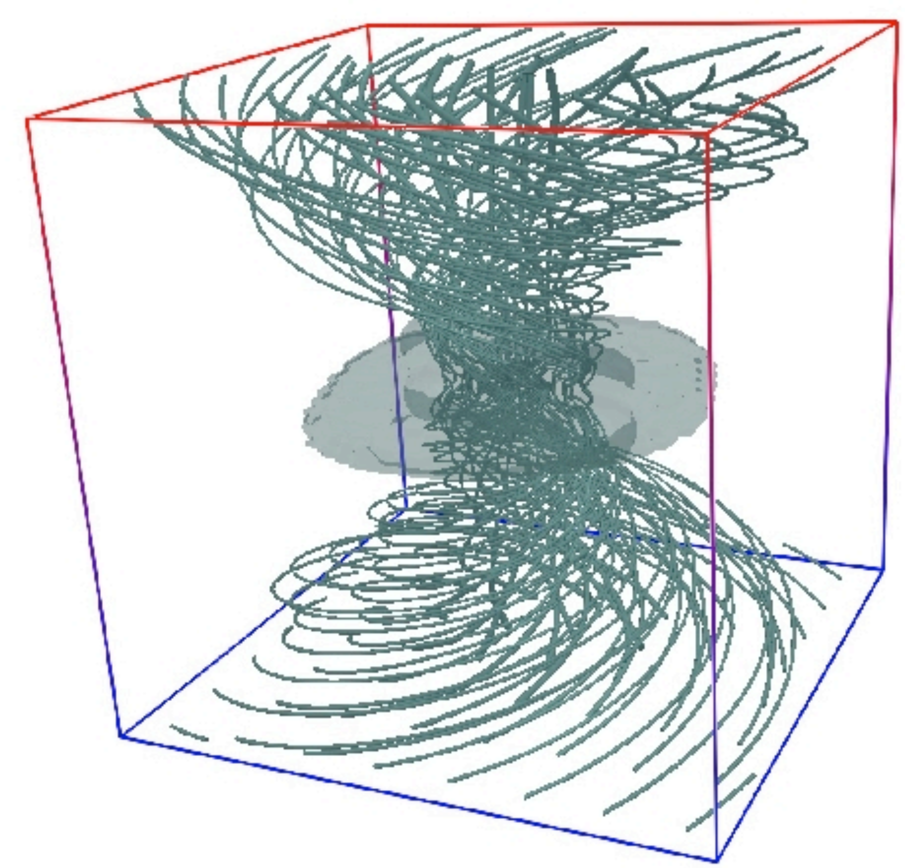


Collapse of magnetized cores

star forming region



- Strongly directed outflow
- Wind extract angular momentum → slowly spinning protostars?

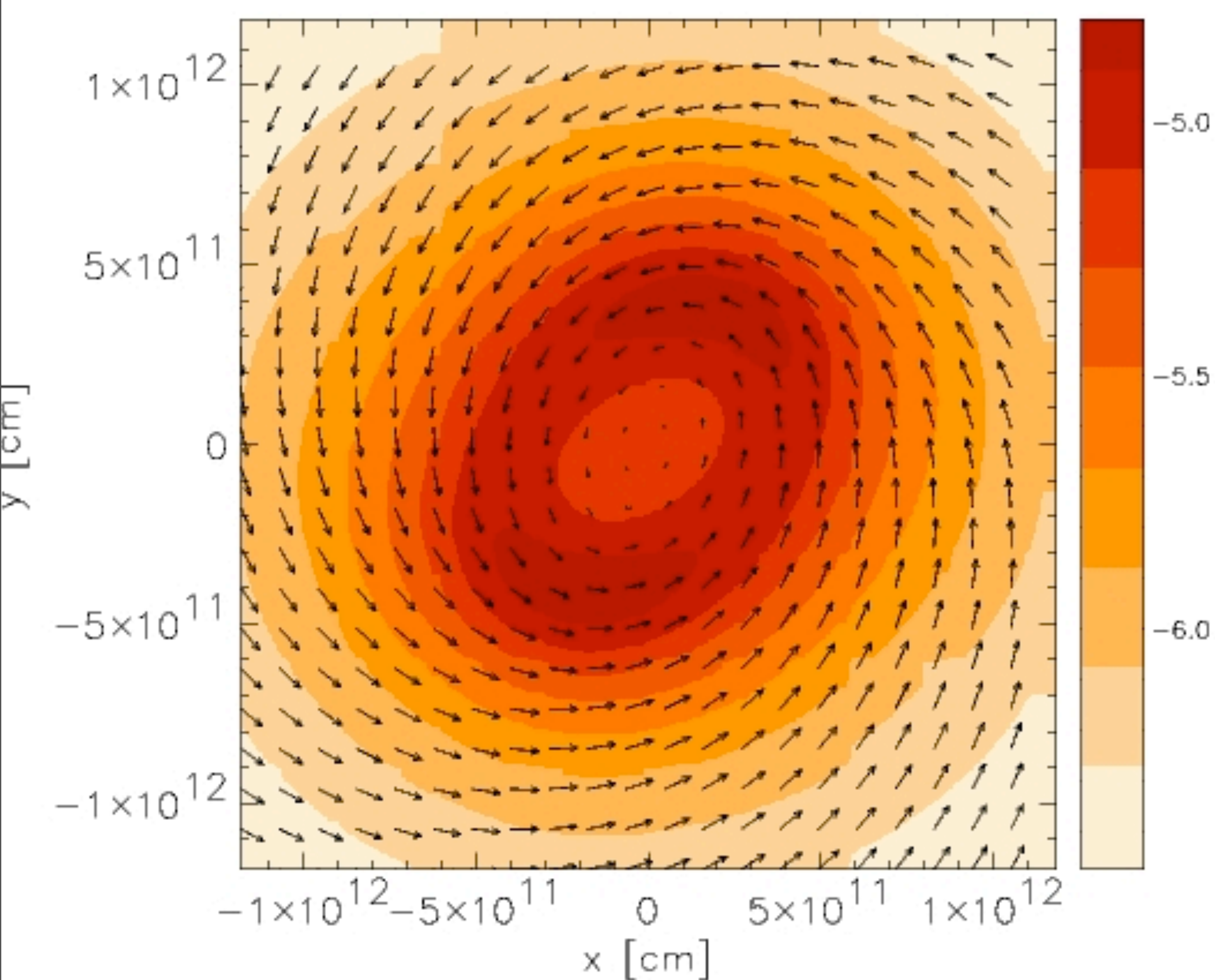


Collapse of magnetized cores

star forming region: disk structure

Collapse of magnetized cores

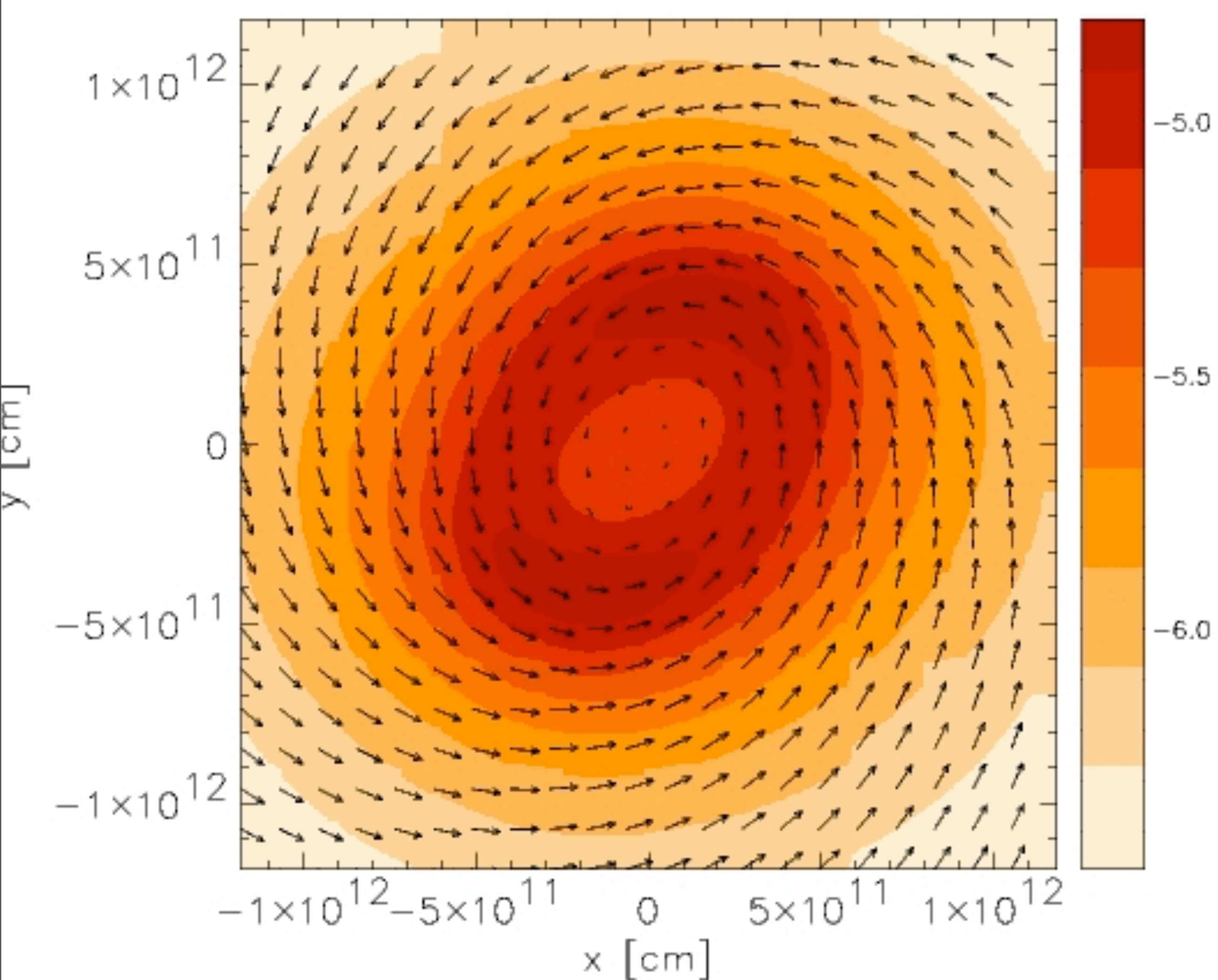
star forming region: disk structure



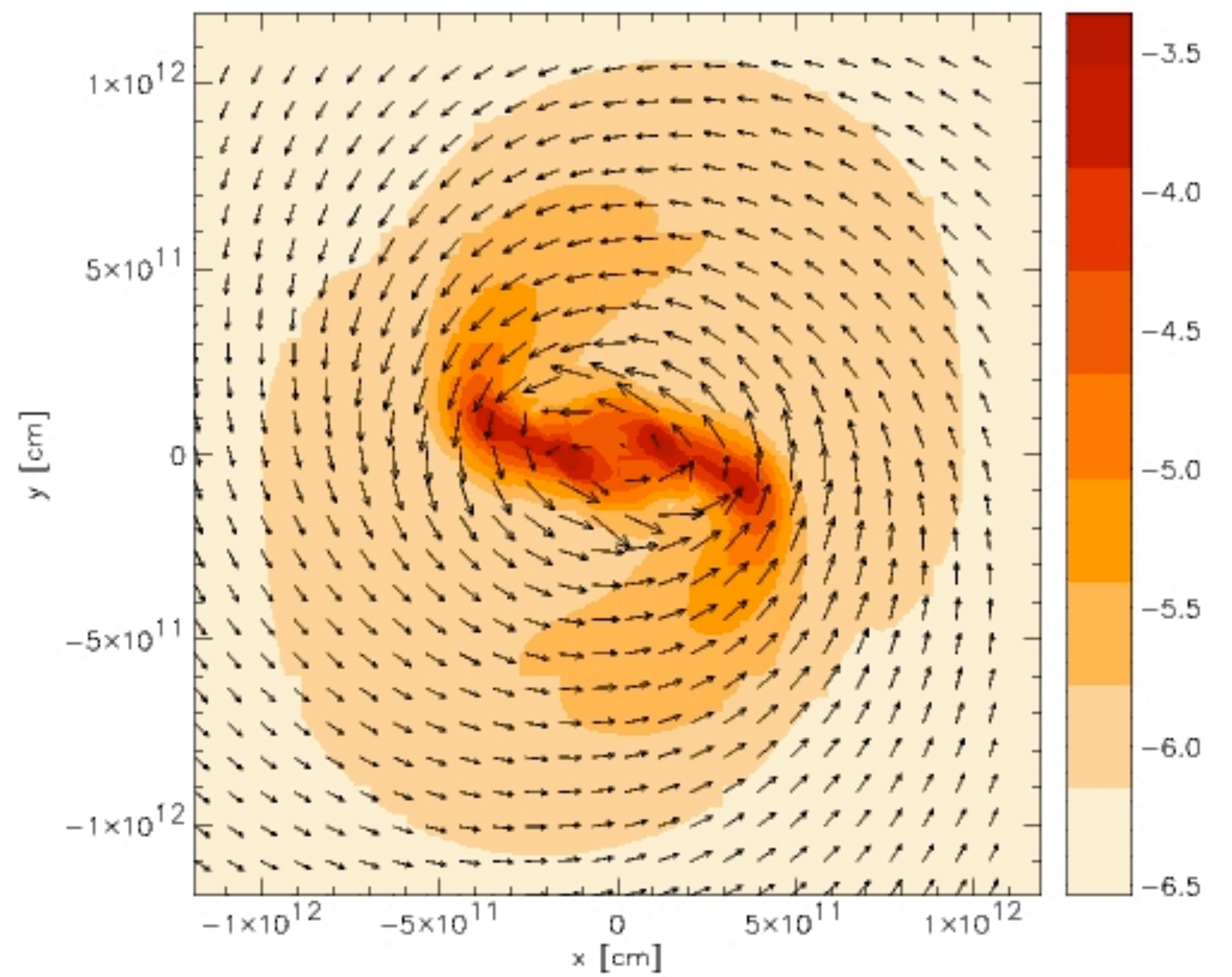
a ring structure ...

Collapse of magnetized cores

star forming region: disk structure



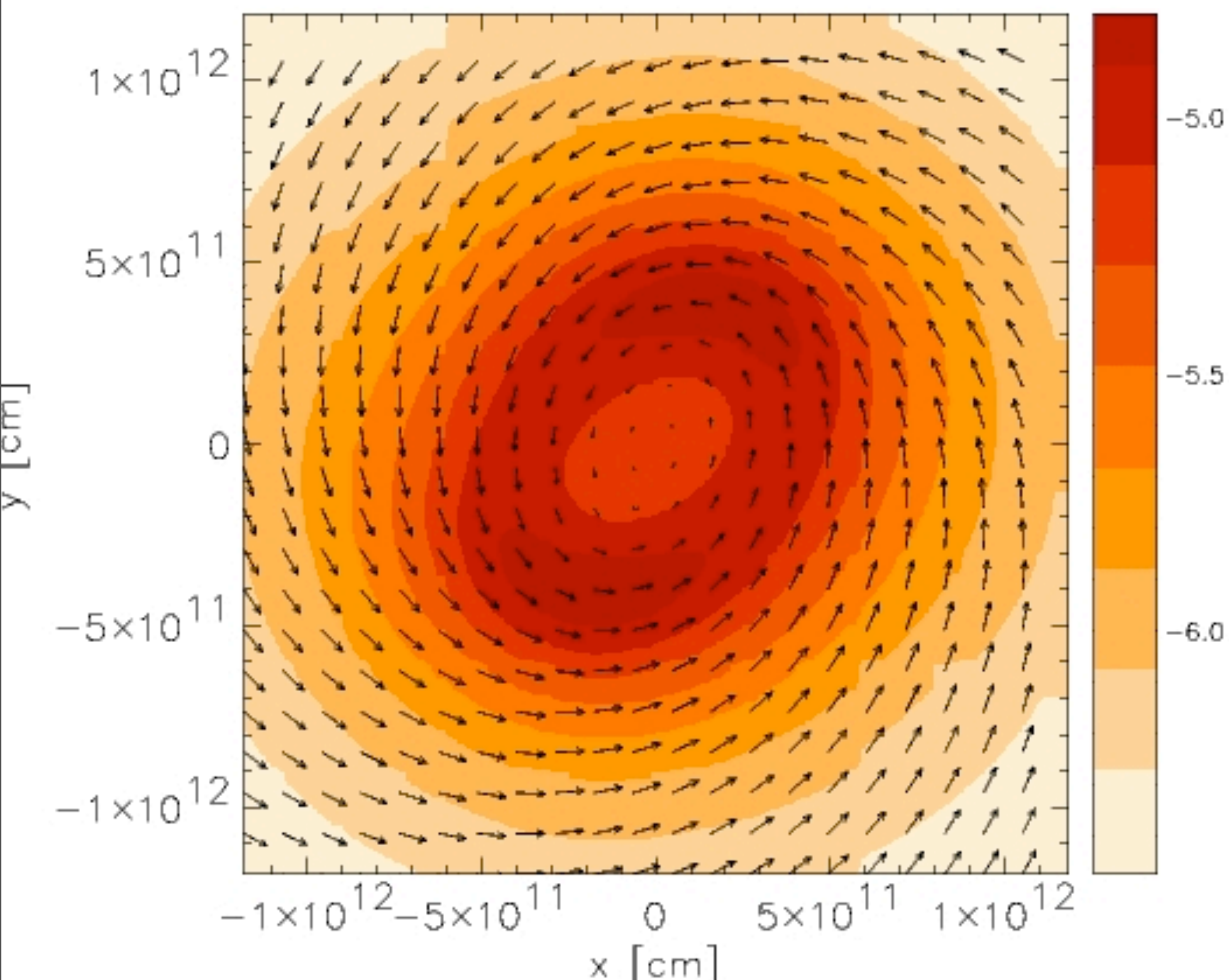
a ring structure ...



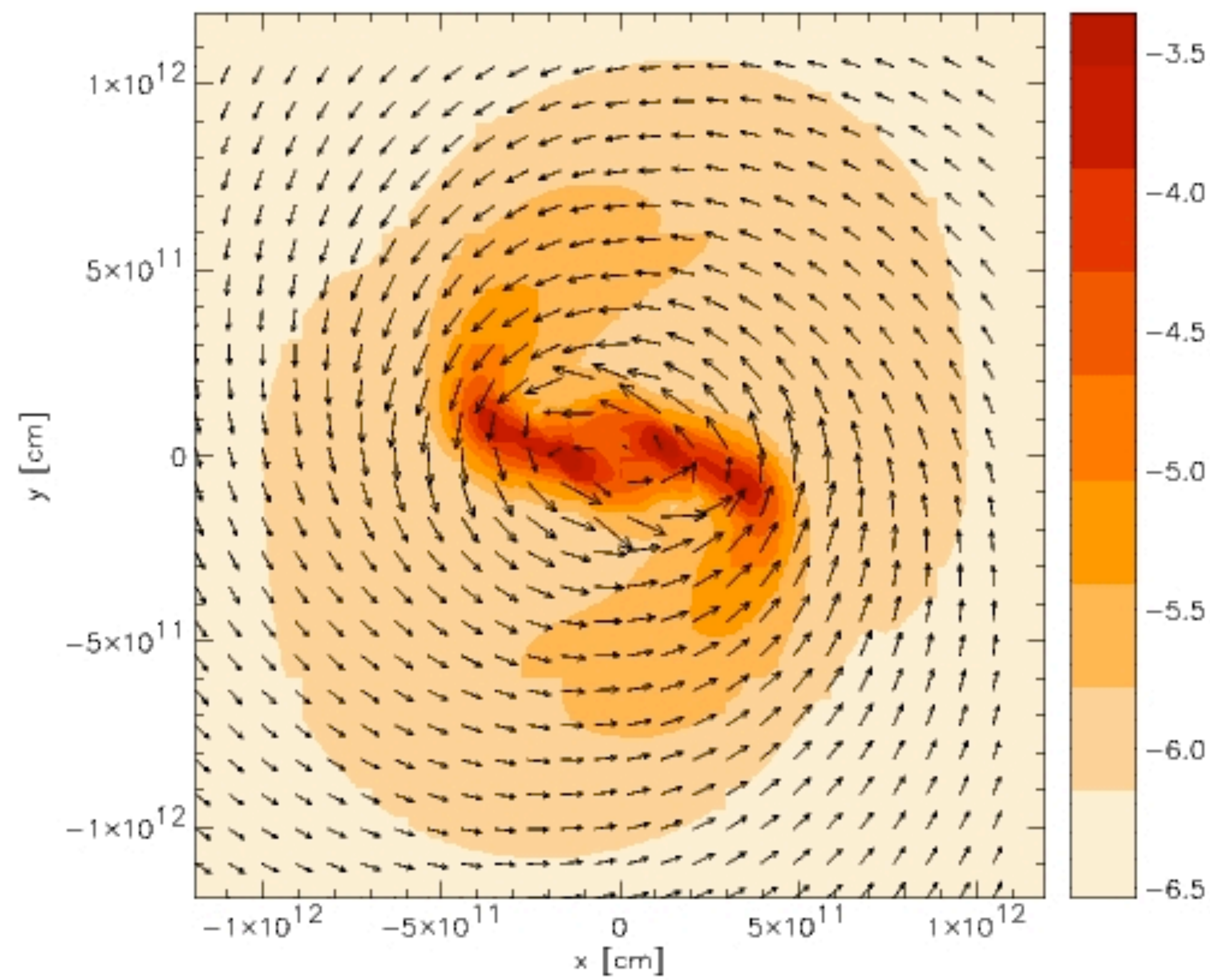
... collapses to a binary system?

Collapse of magnetized cores

star forming region: disk structure



a ring structure ...

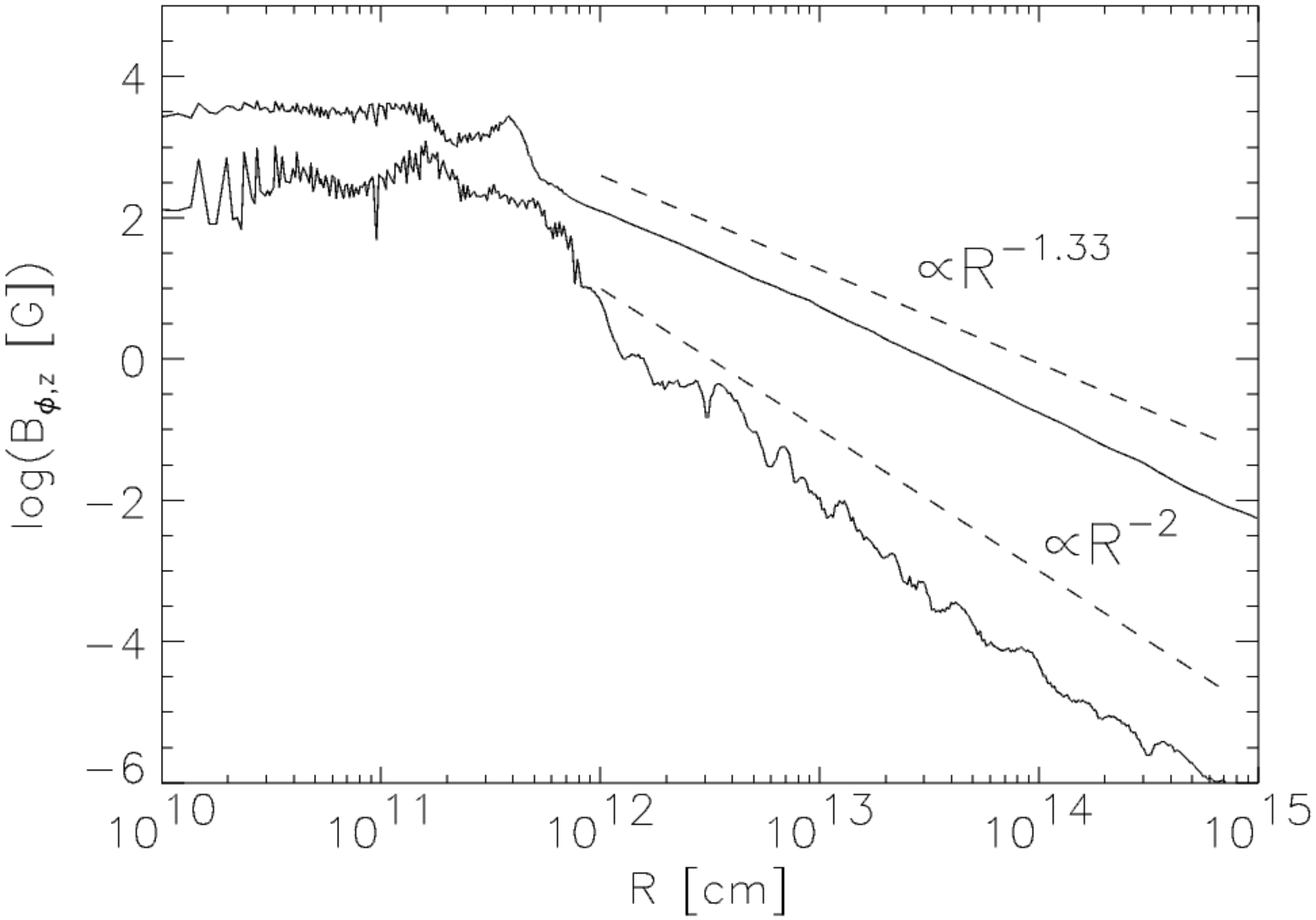


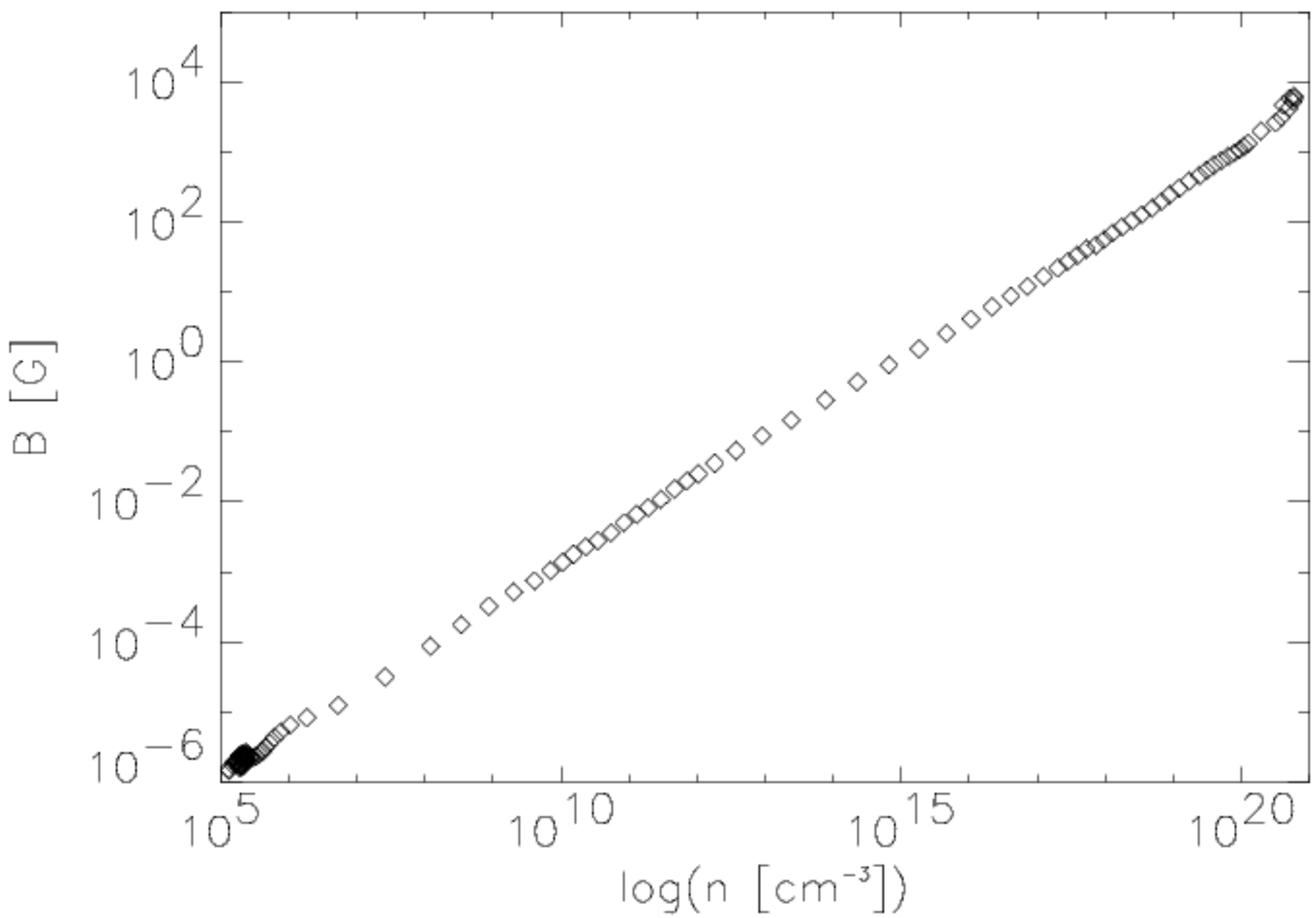
... collapses to a binary system?

But: **magnetic fields prevent early (large scale) fragmentation**

Collapse of magnetized cores

magnetic field structure and evolution

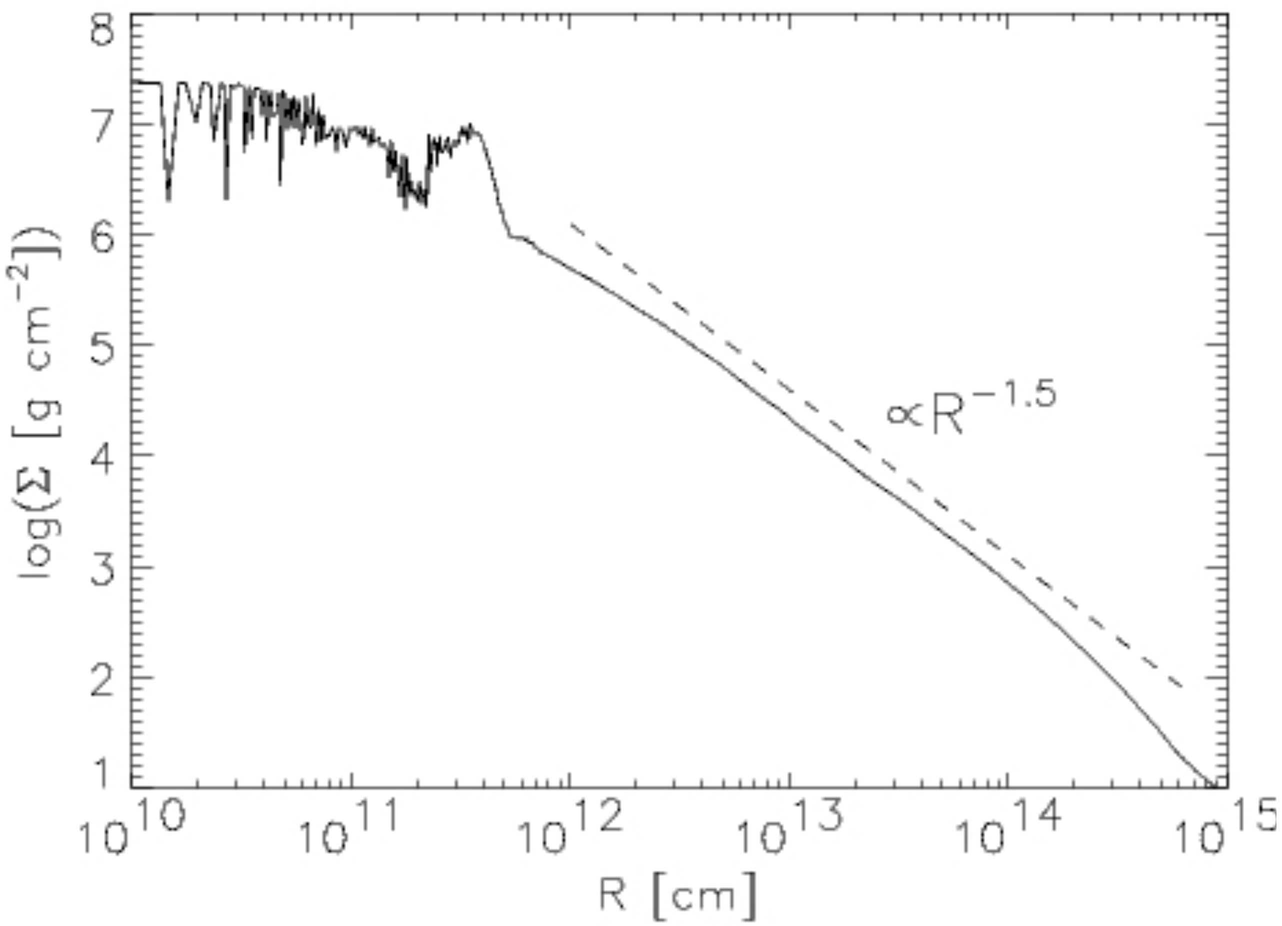


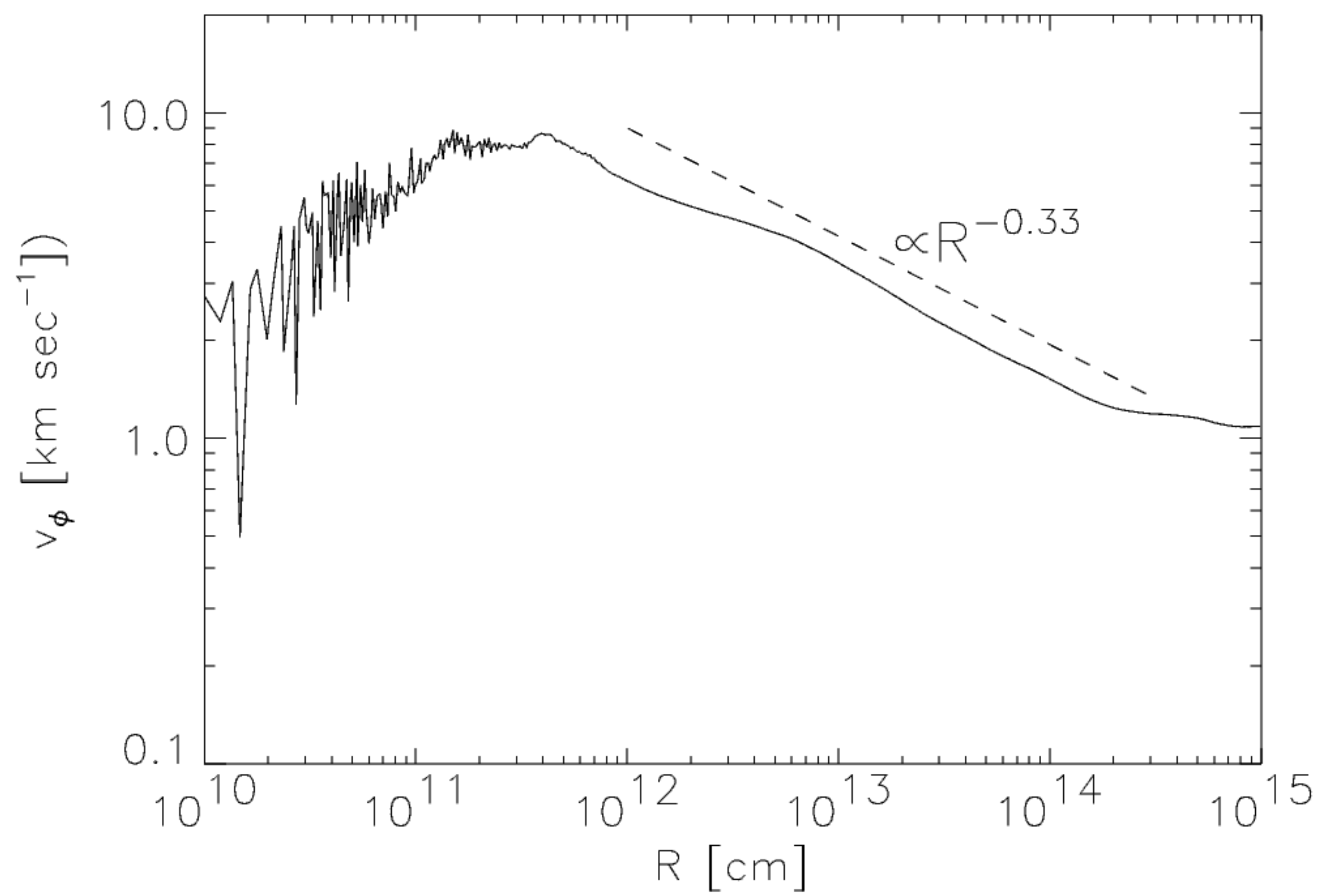


- $B_z > B_\varphi$ in the core and disk (expectation from a stationary accretion disk $B \propto R^{-1.25}$; *Blandford & Payne 1982*)
- $B_{core} \propto n^{0.6}$
- Expected field strength in the protostar ~ $10^4 - 10^5$ G
- Potential seed field for Ap stars *(Braithwaite & Spruit, 2004)*

Collapse of magnetized cores

disk properties

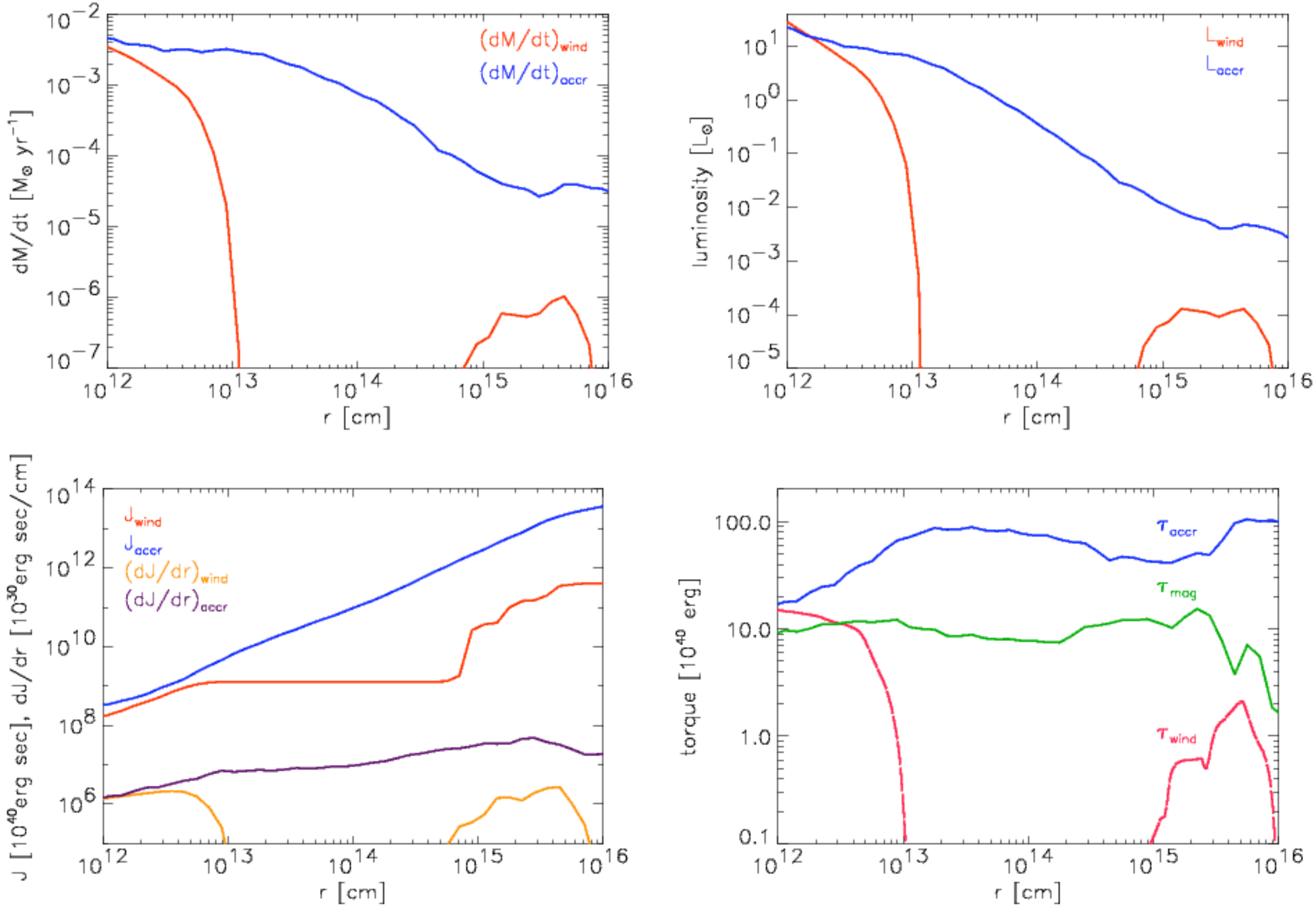




- Disk profile: Hayashi-type $\Sigma \propto R^{-3/2}$ *(Hayashi, 1981)*
- non-Keplerian rotation ⇒ disk still contracting

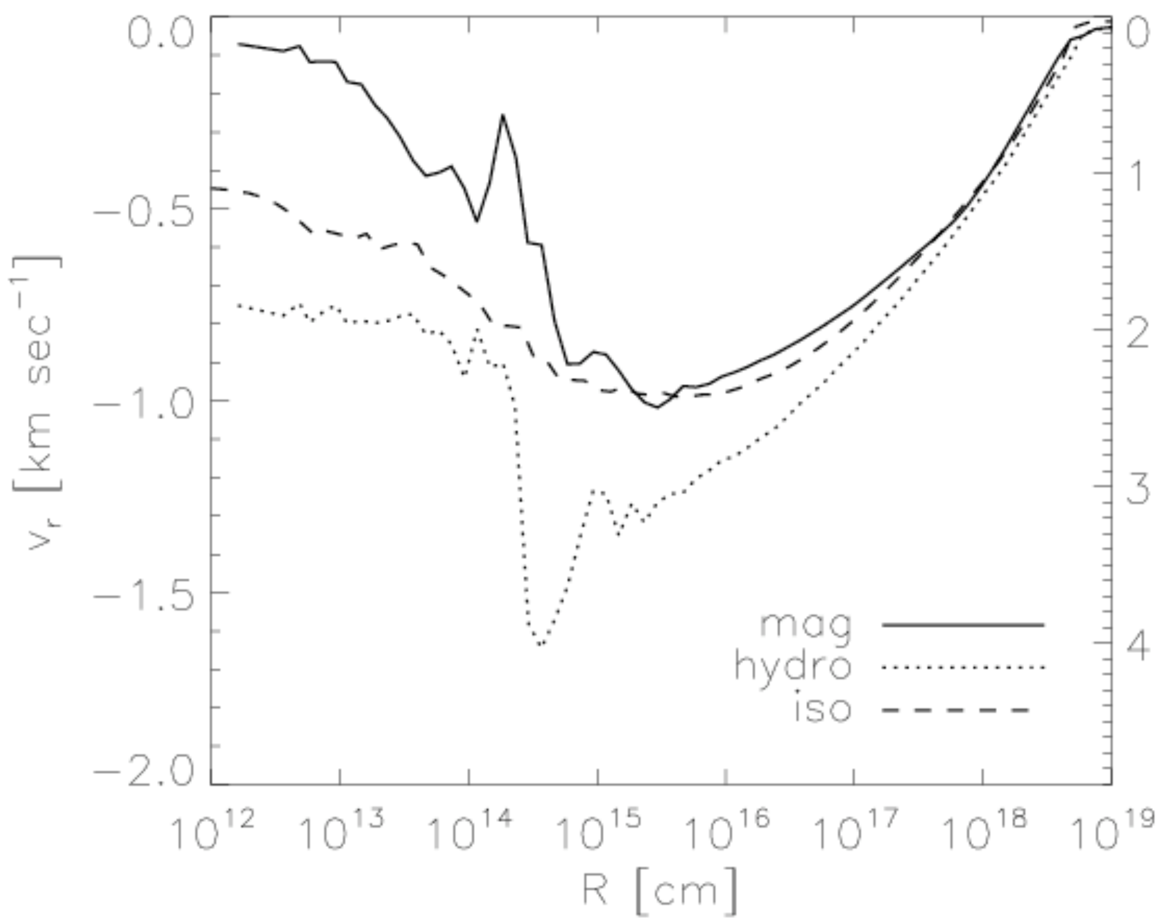
Collapse of magnetized cores

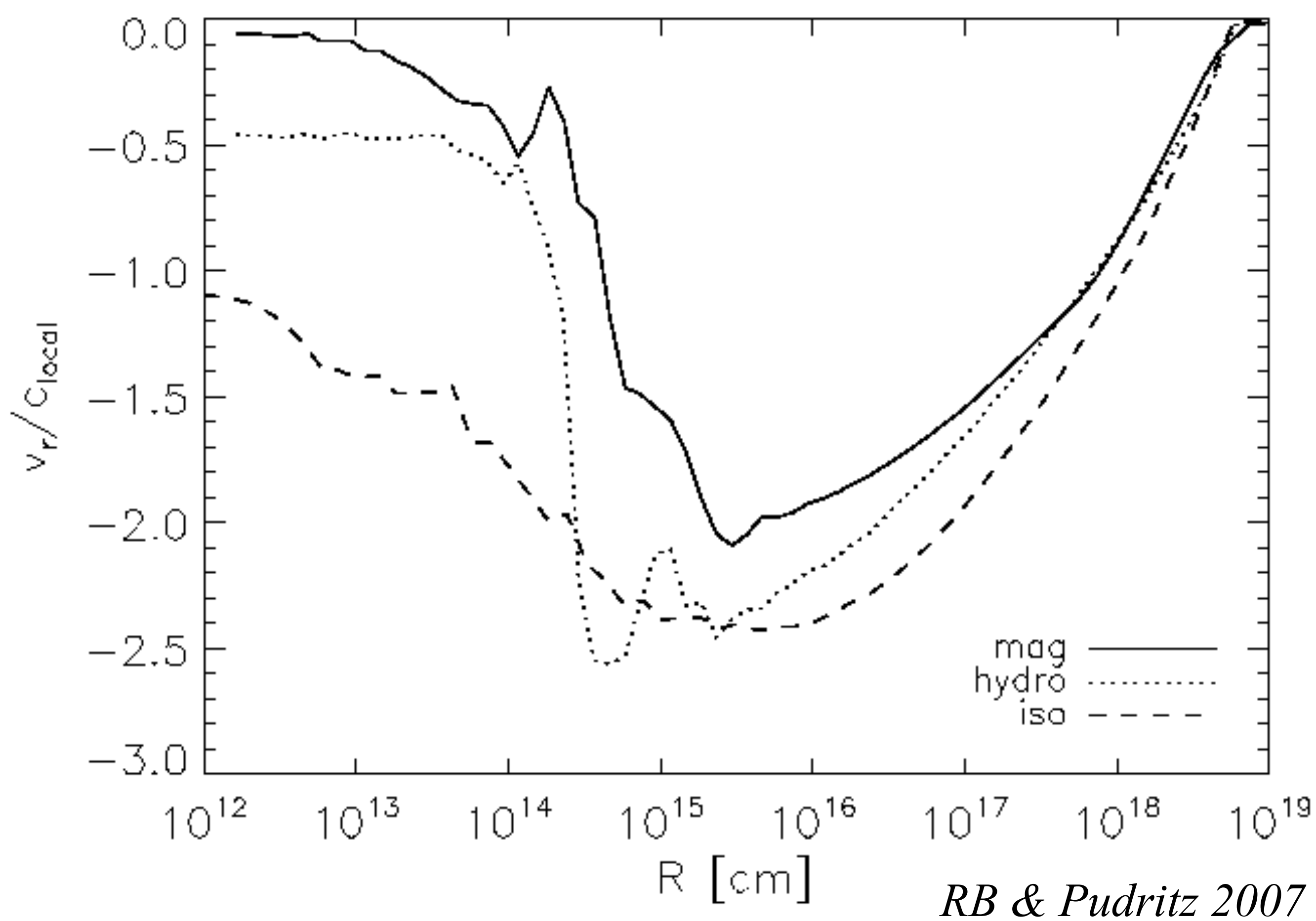
disk properties



Collapse of massive cores

consequence for **massive star** formation



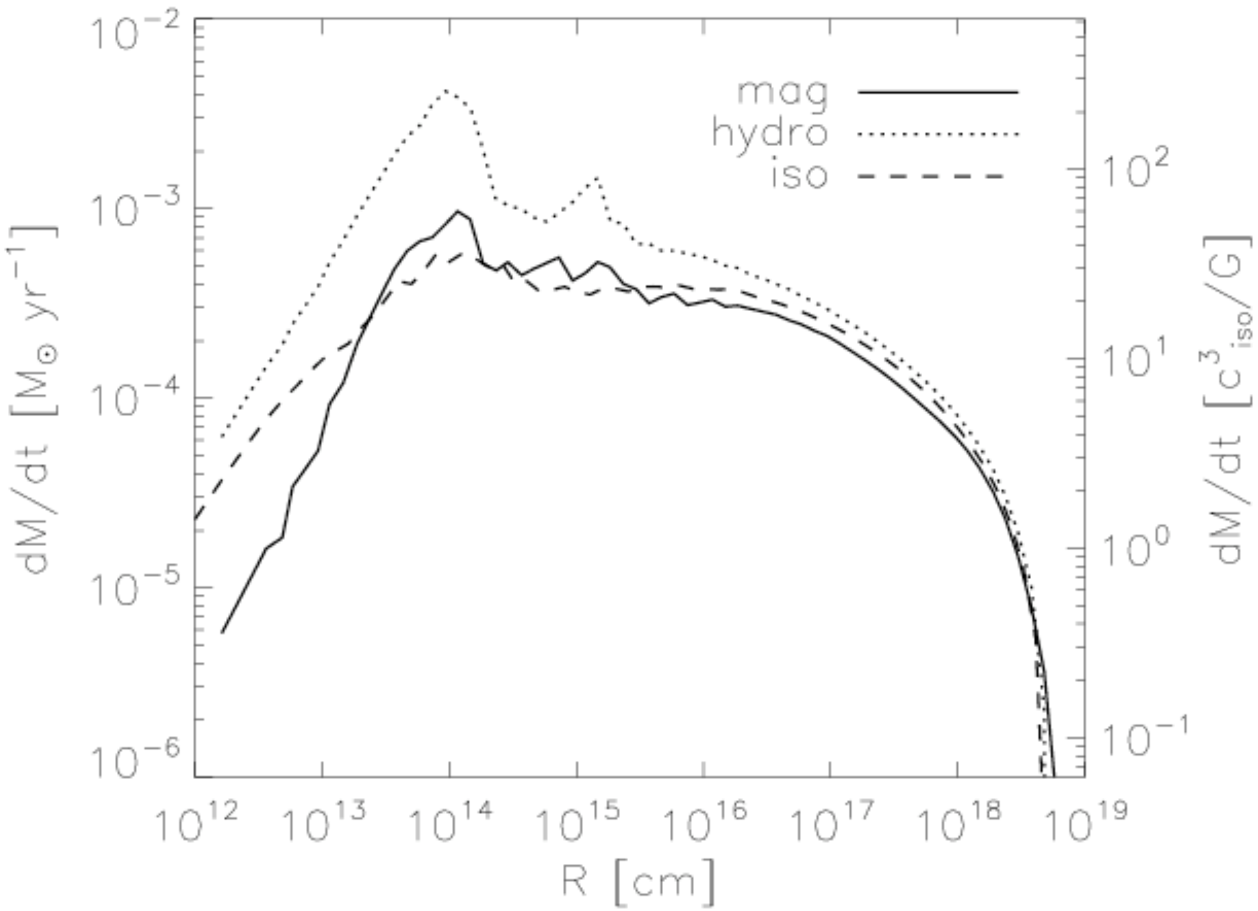


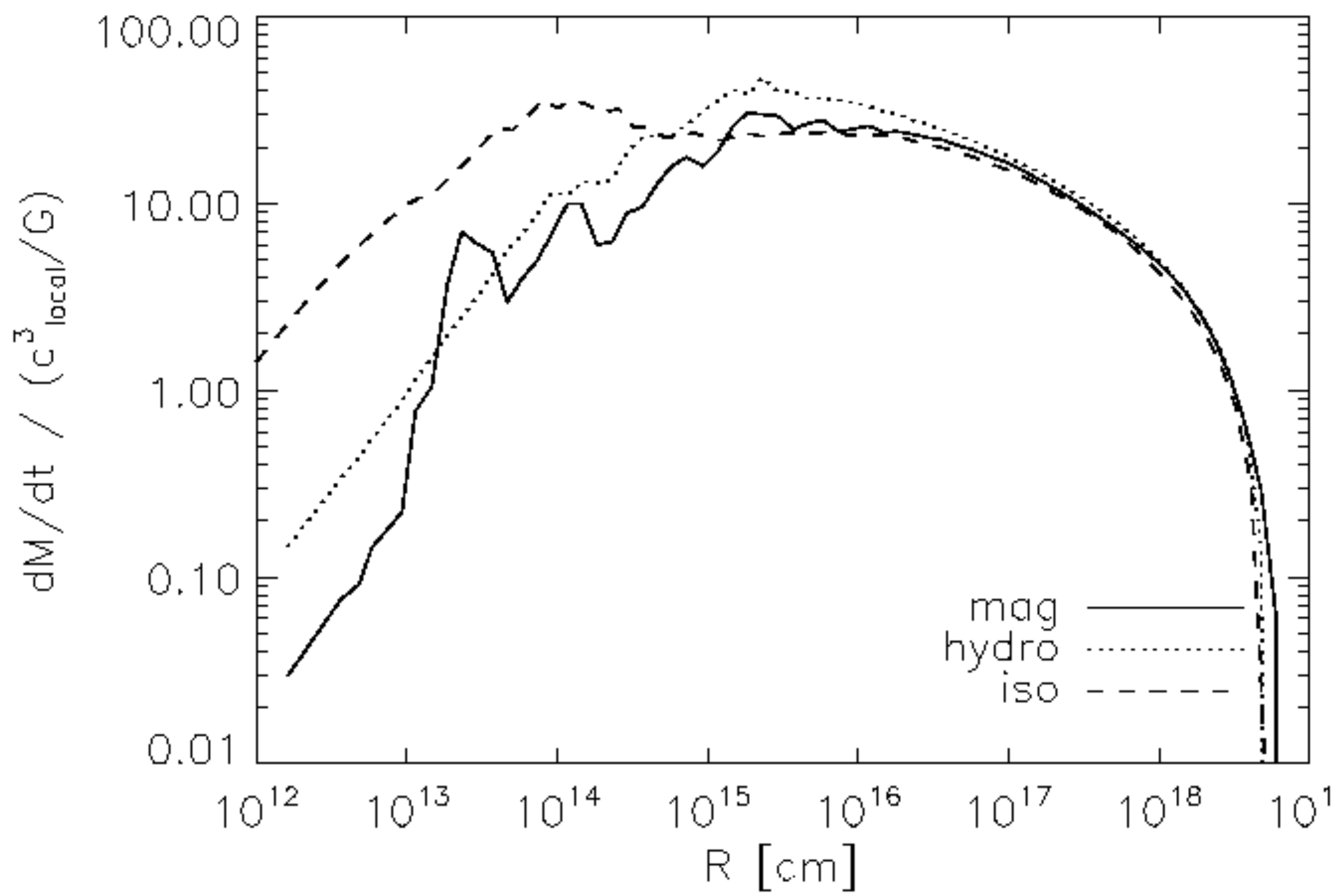
RB & Pudritz 2007

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

Collapse of massive cores

consequence for **massive star** formation

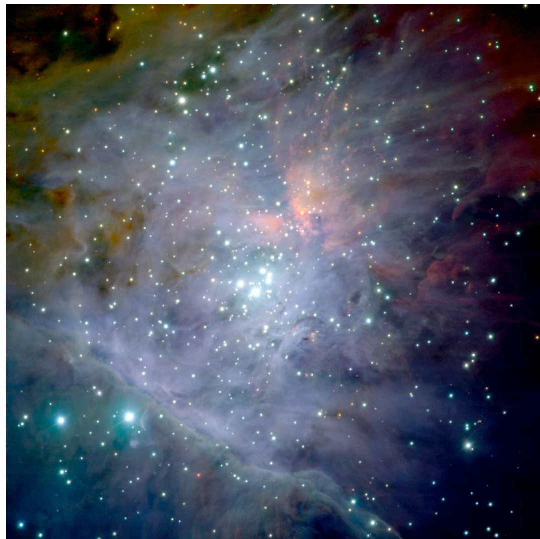




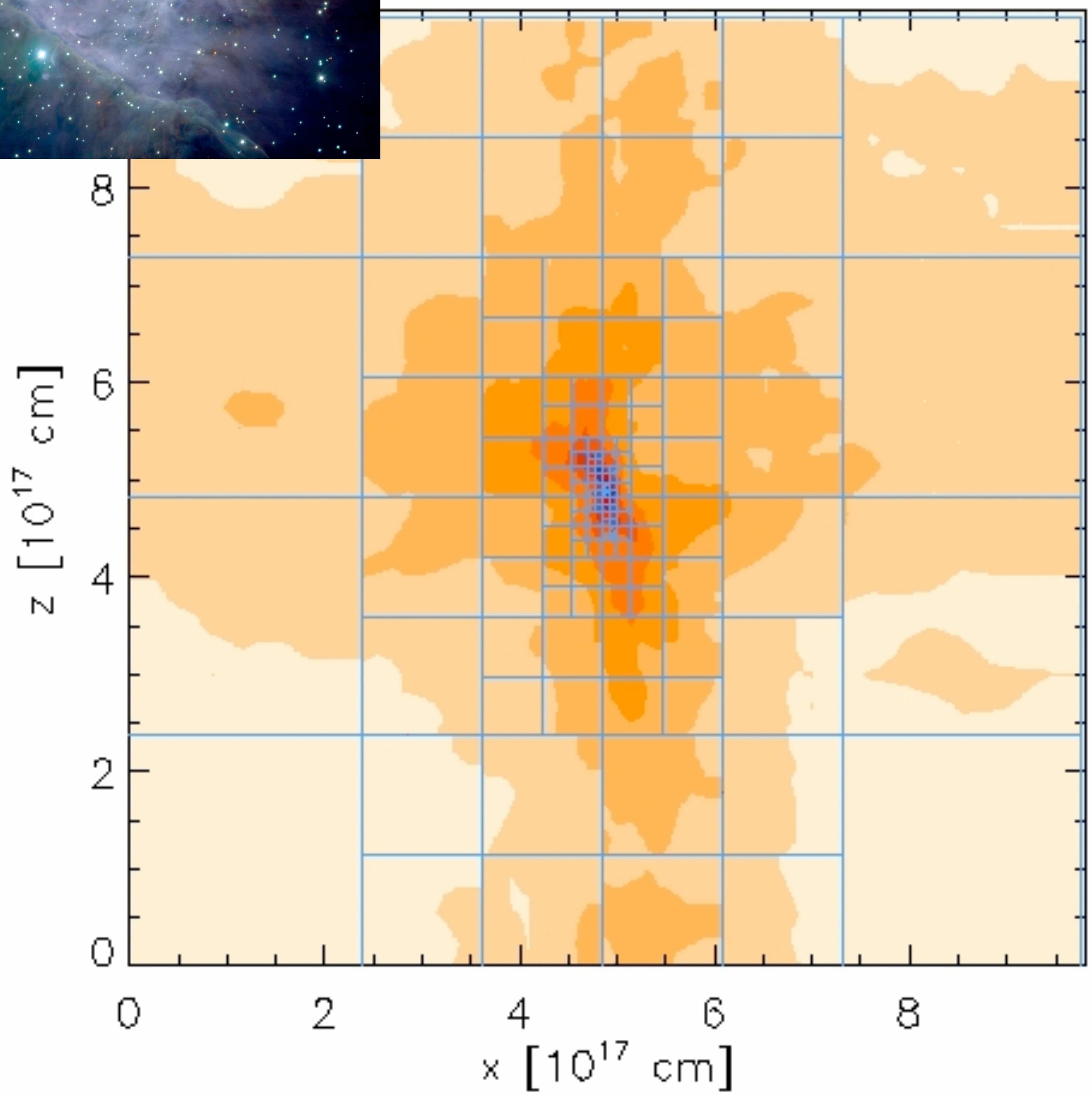
- $dM/dt \sim v^3/G = Mach^3\ c^3/G >> c^3/G$ (SIS)
- Higher speed of sound ⇒ higher accretion rate

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

Collapse of turbulent cores

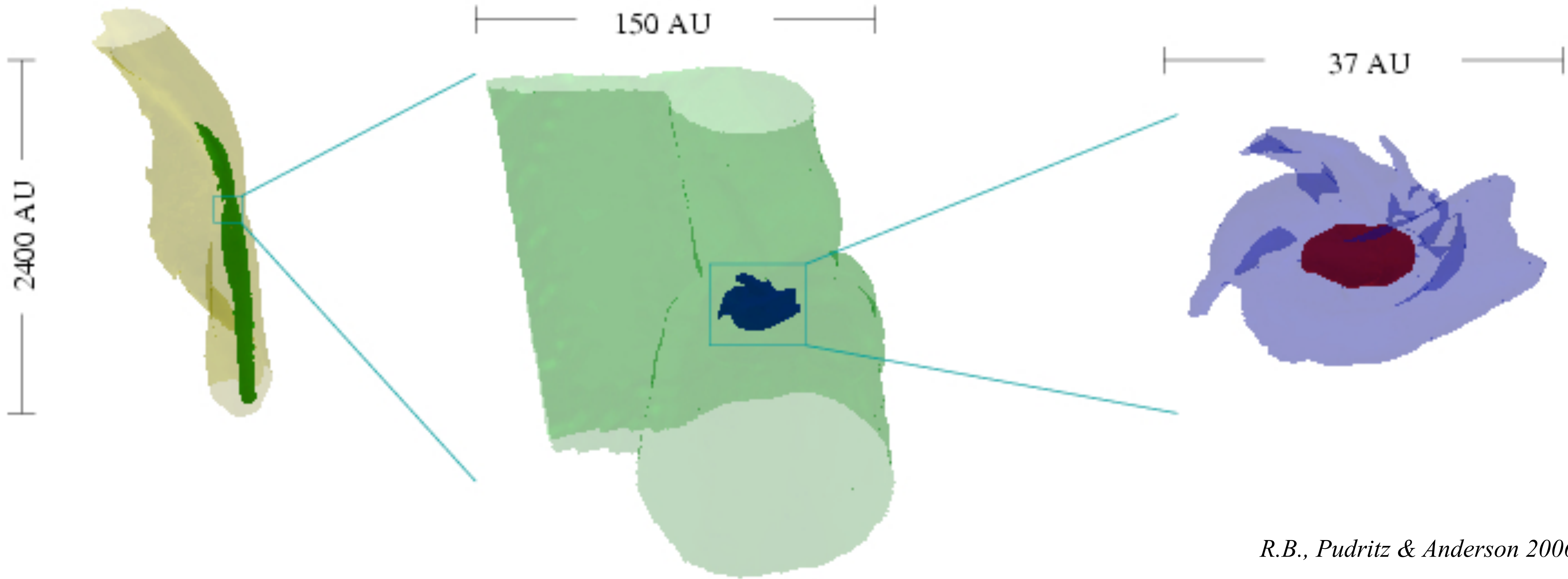


SF out of **turbulent** molecular clouds
(e.g. *Mac Low & Klessen 2004*)



- 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: $\sim 23\ M_{sol}$
- Final resolution: $\sim R_{sol}$

Collapse of turbulent cores

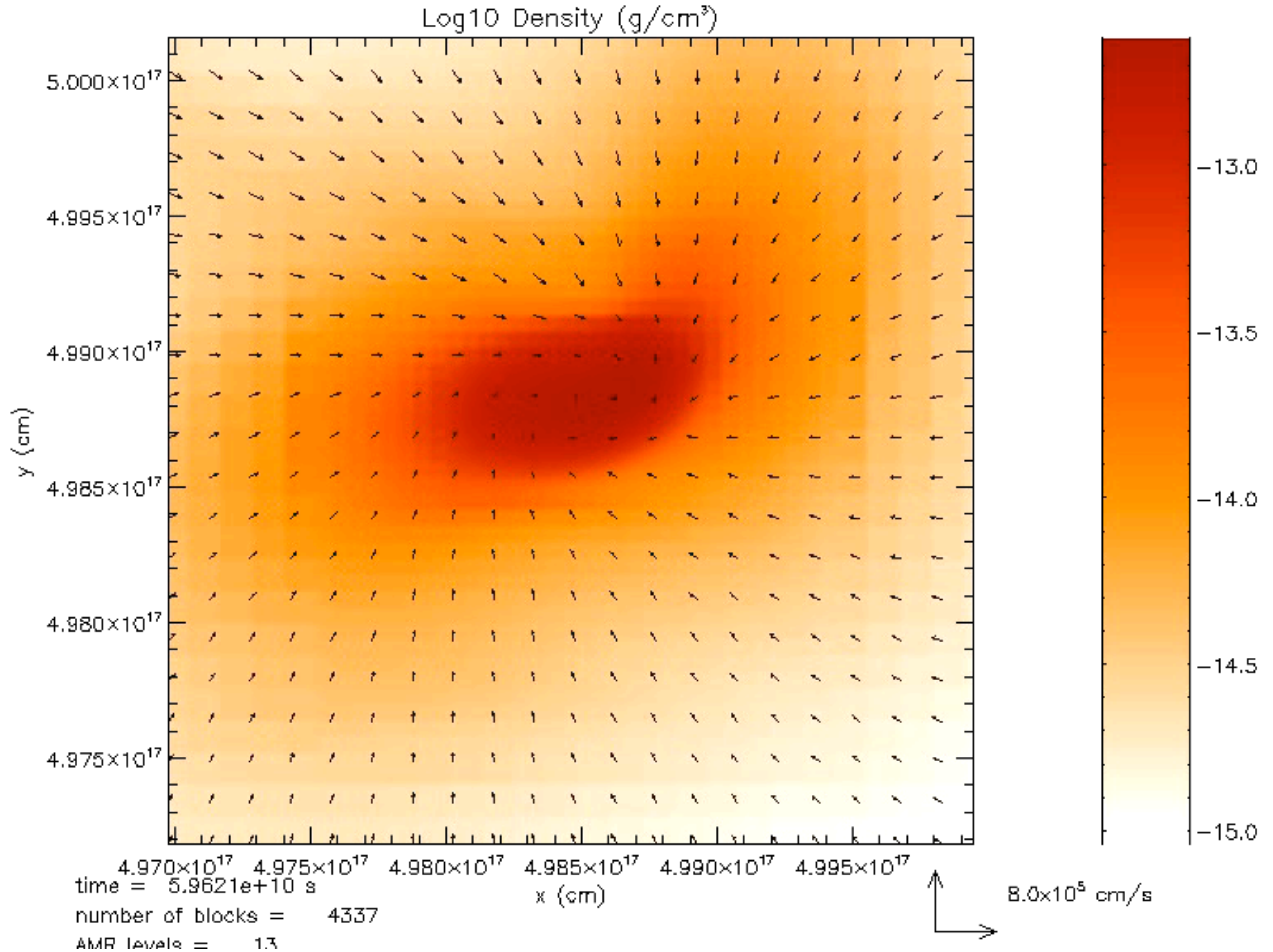


R.B., Pudritz & Anderson 2006

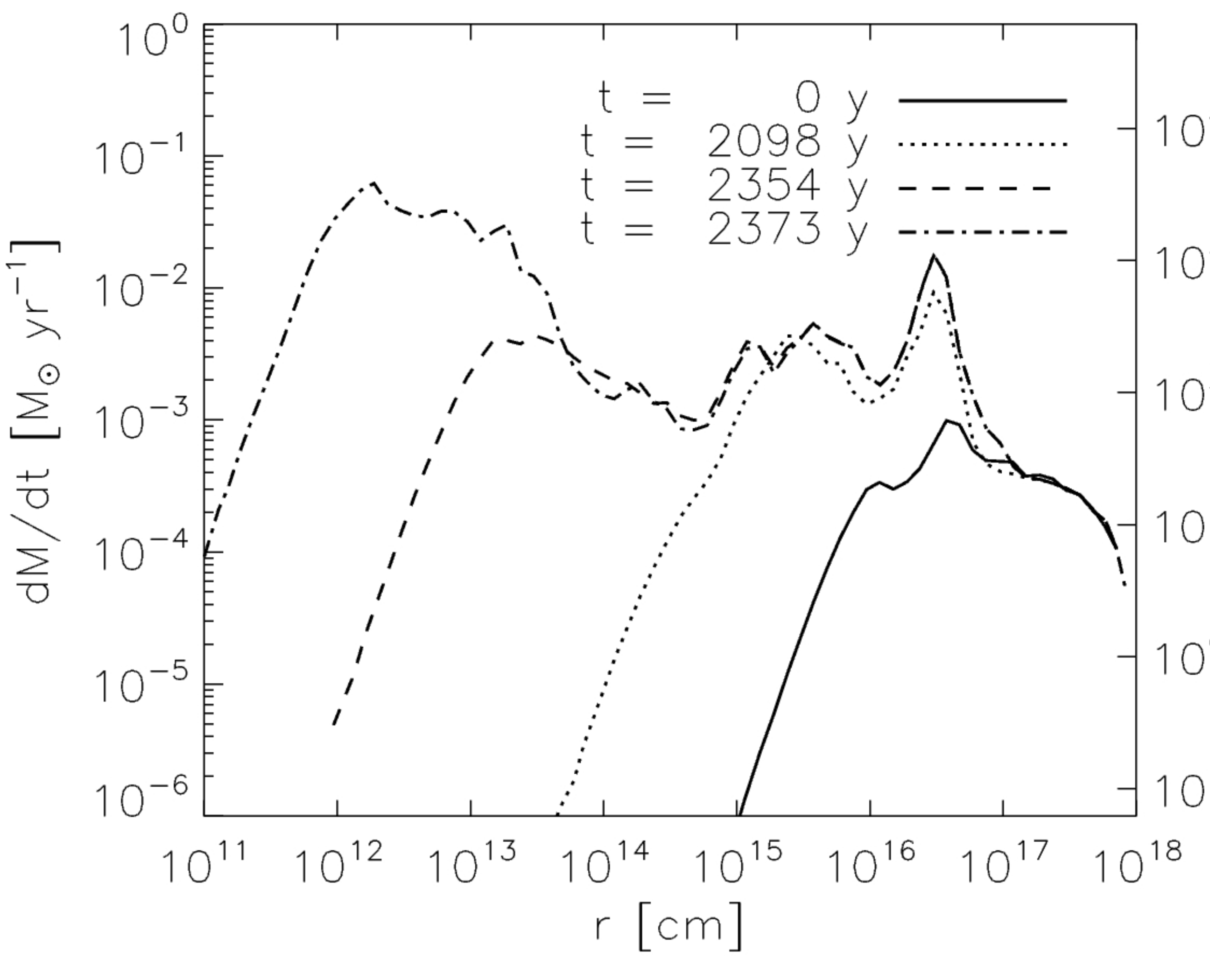
- **Filament** with an attached sheet
- small **disk** within the filament (perpendicular)
- adiabatic (optically thick) core
- very efficient gas **accretion** through the filament

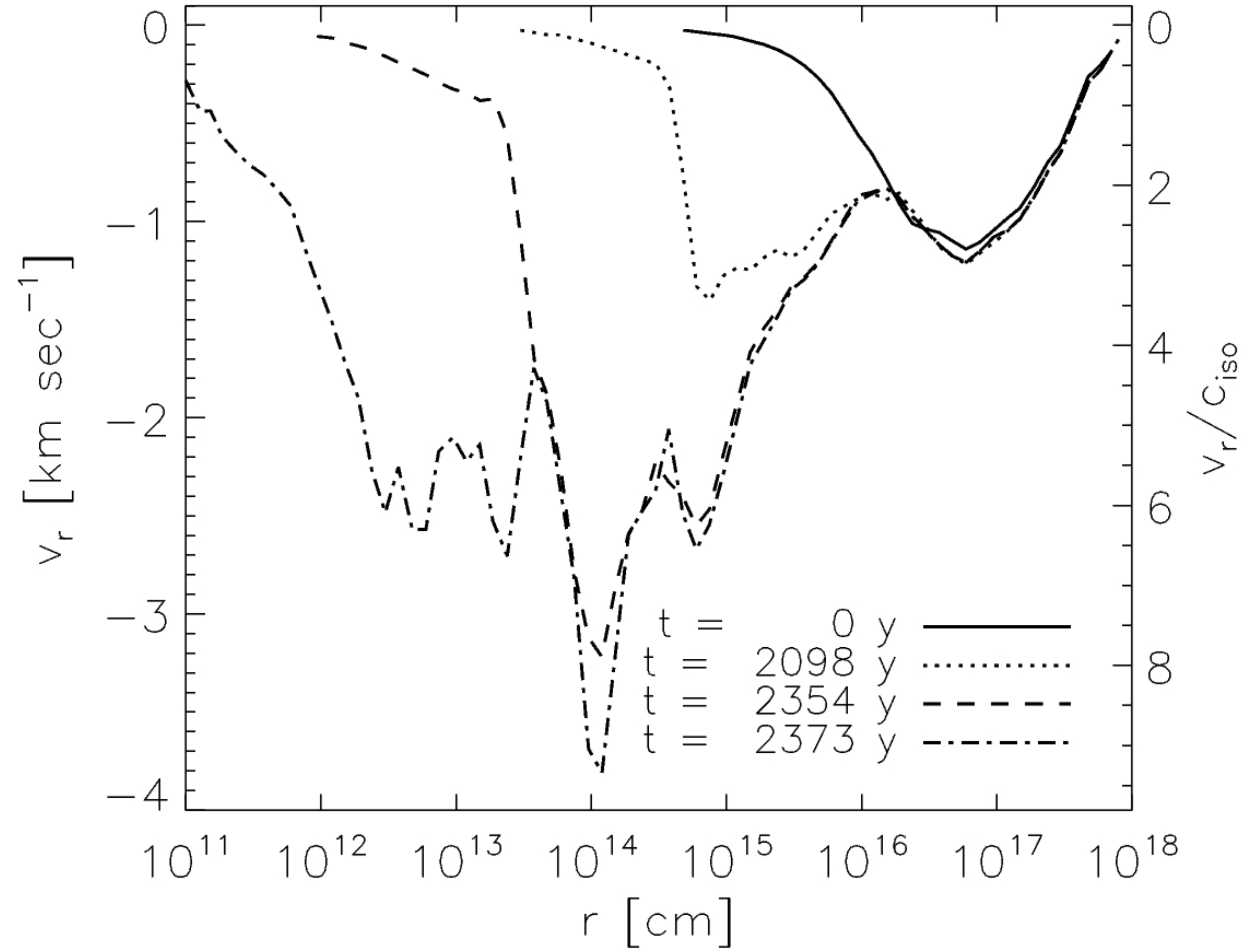
Collapse of turbulent cores

Collapse of turbulent cores



Mass accretion

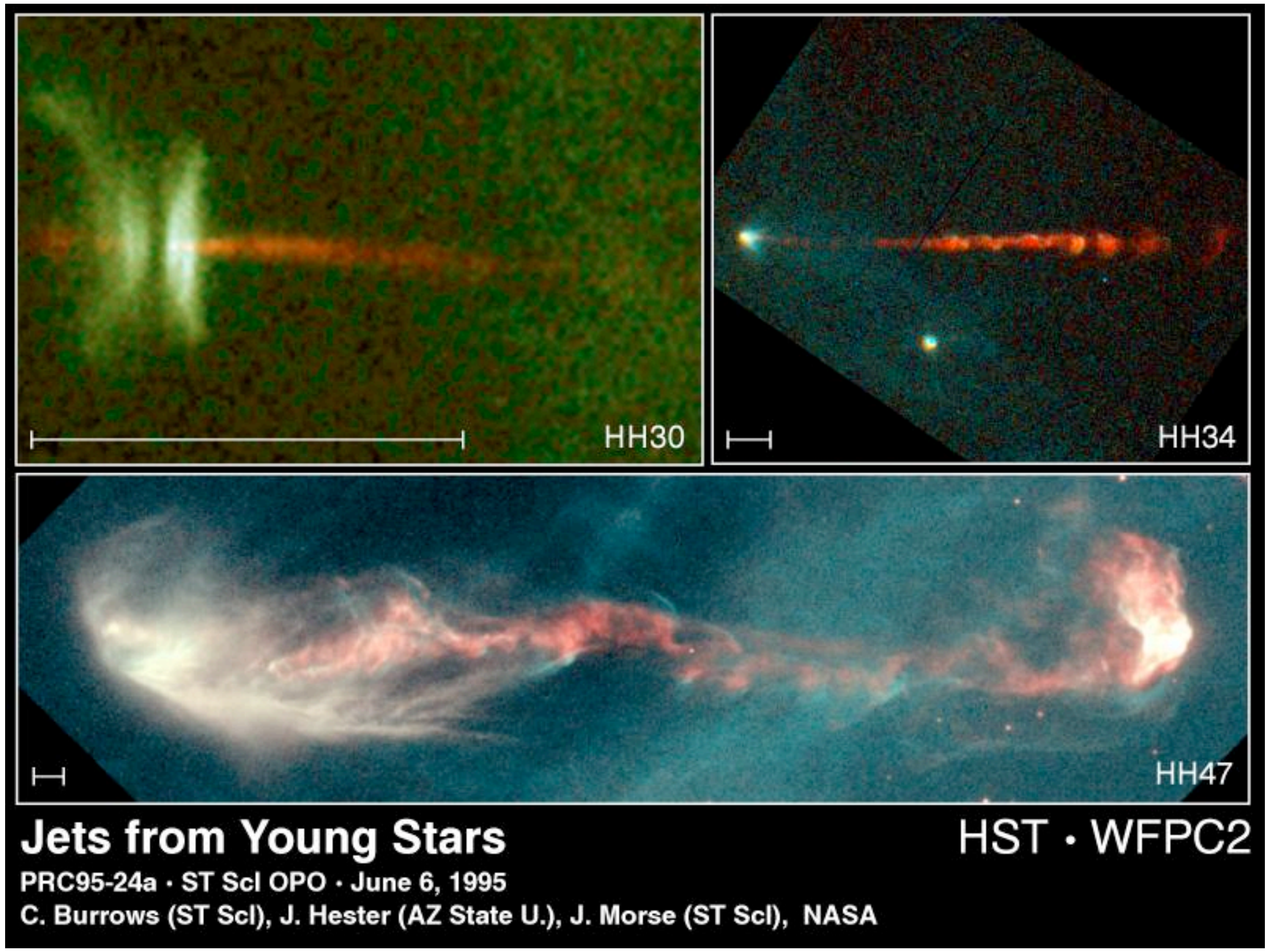




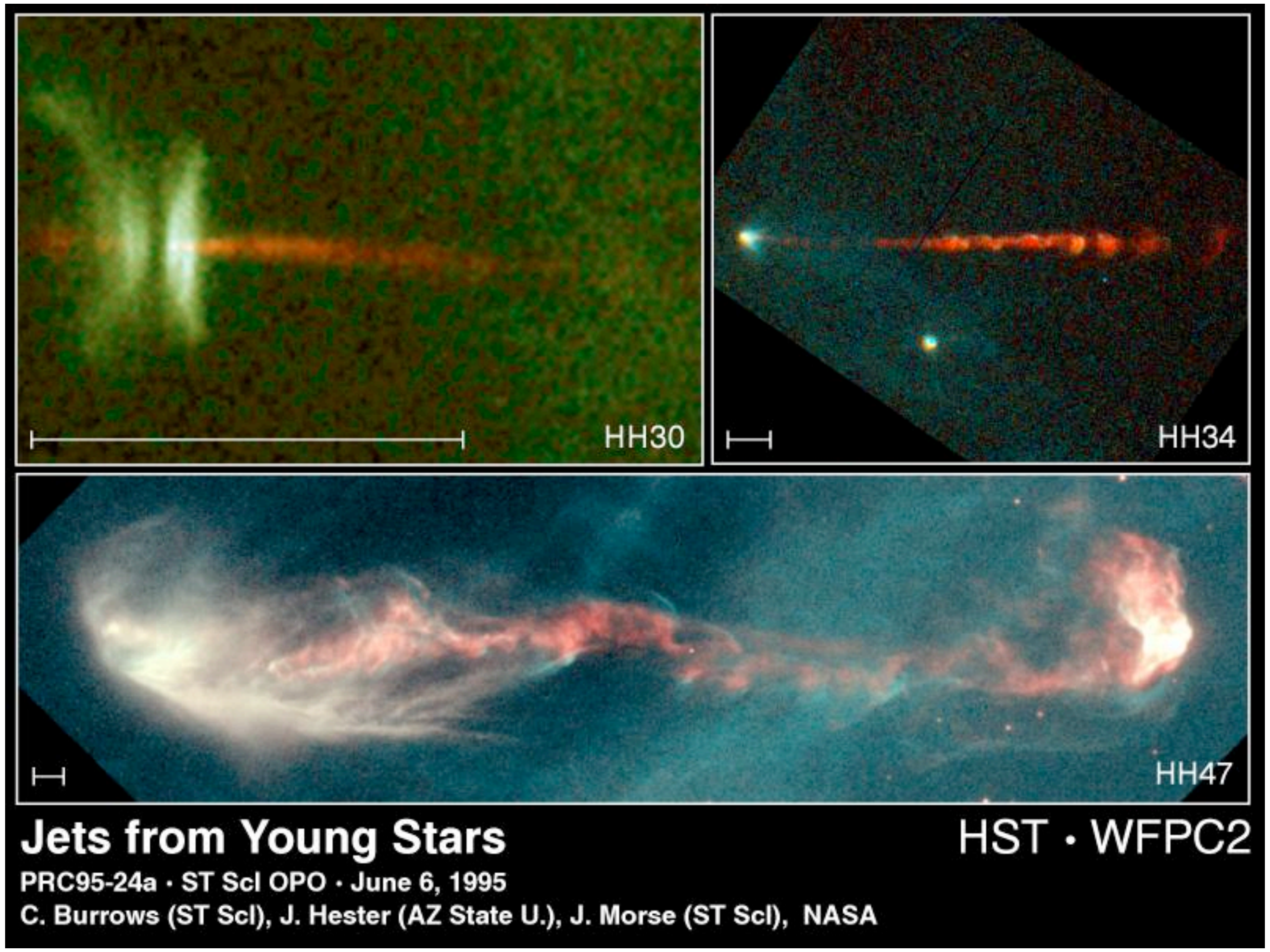
- Very **high** accretion rates: up to 10^{-3} - 10^{-2} M_{sol}/year
- Mass accretion rates are higher than limits from radiation pressure of **massive** stars (e.g. *Wolfire & Cassinelli 1987*: 10^{-3} M_{sol}/year)
- Protostars and disks assemble very **rapidly** within a supersonic turbulent environment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

Driving of turbulence?

Supersonic turbulence decays quickly and has to be maintained
(eg. *Mac Low et al.* , *Padoan et al.*)



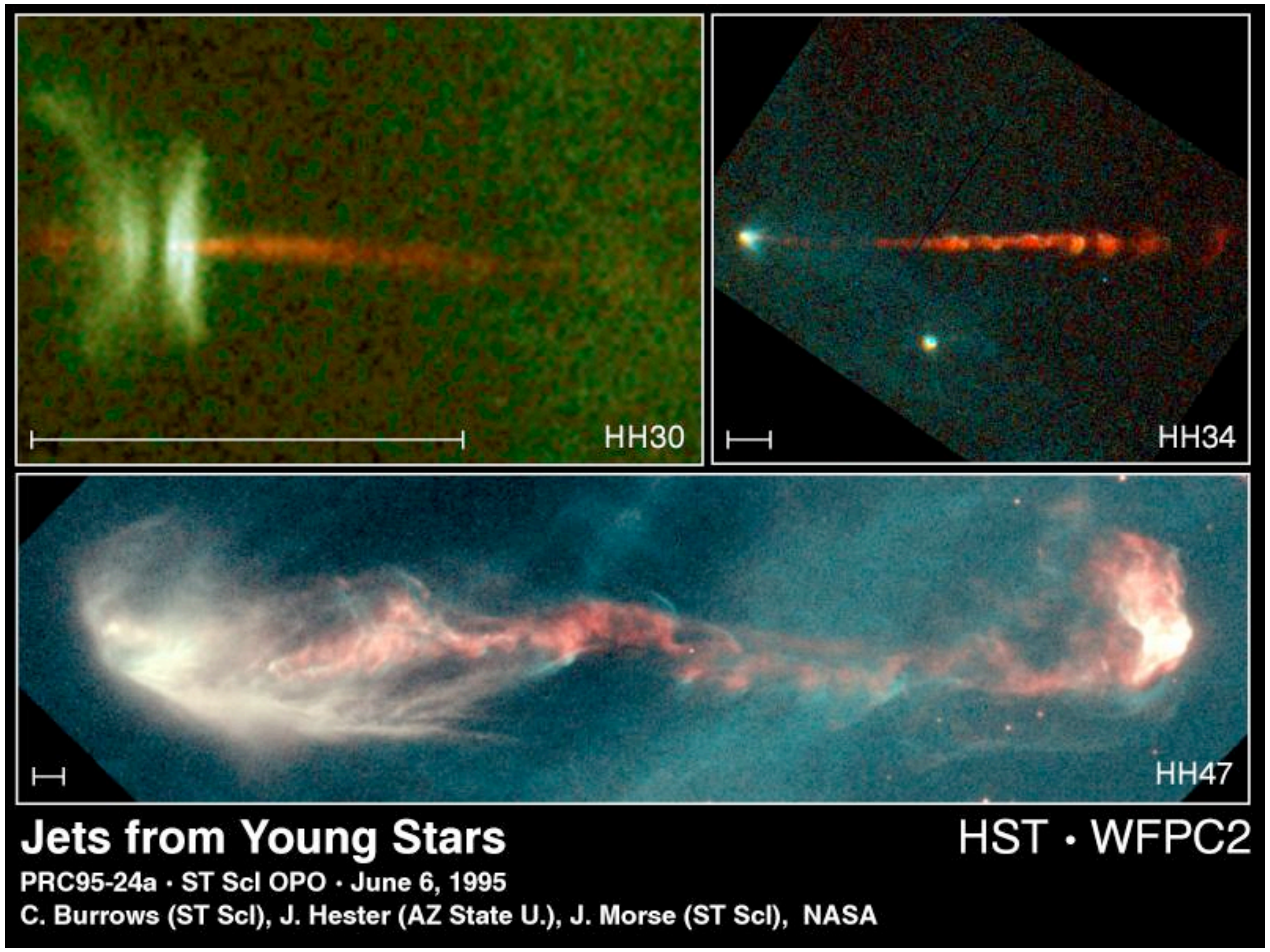
Driving of turbulence?



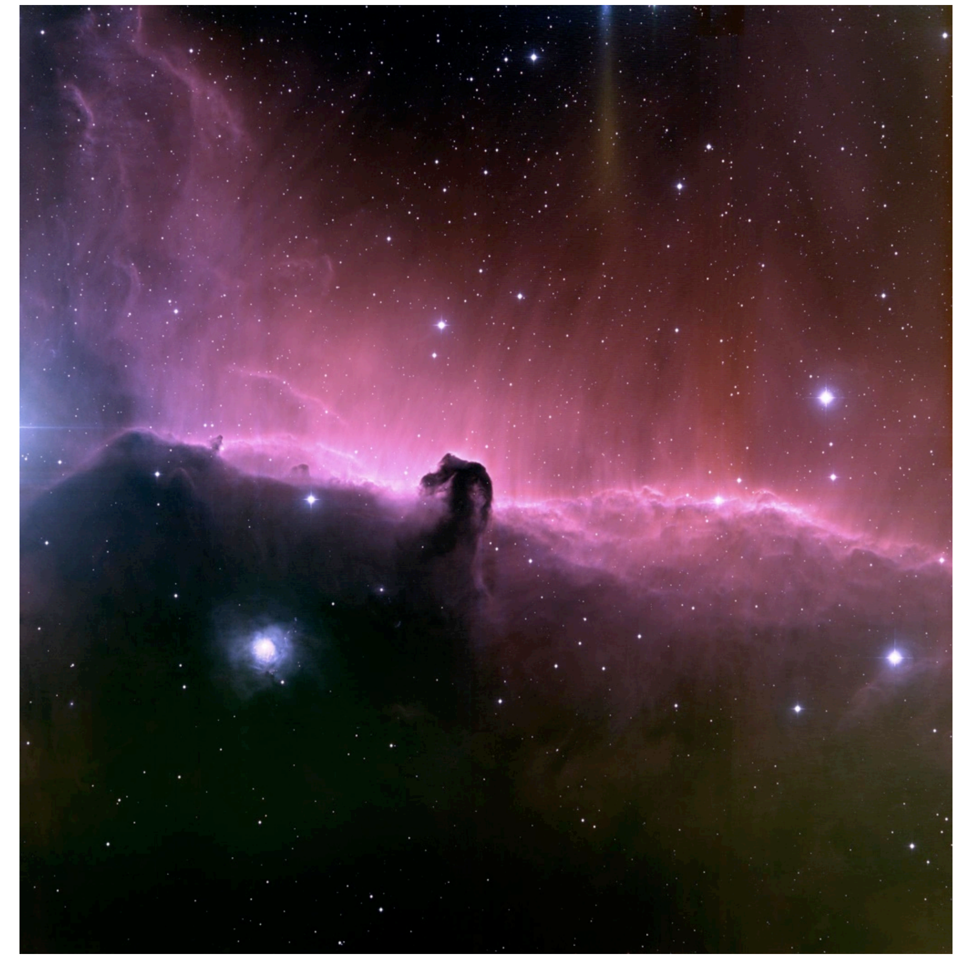
Driving of turbulence?

External driving

• e.g. SN, MRI, large scale flows, radiation from massive stars, ...

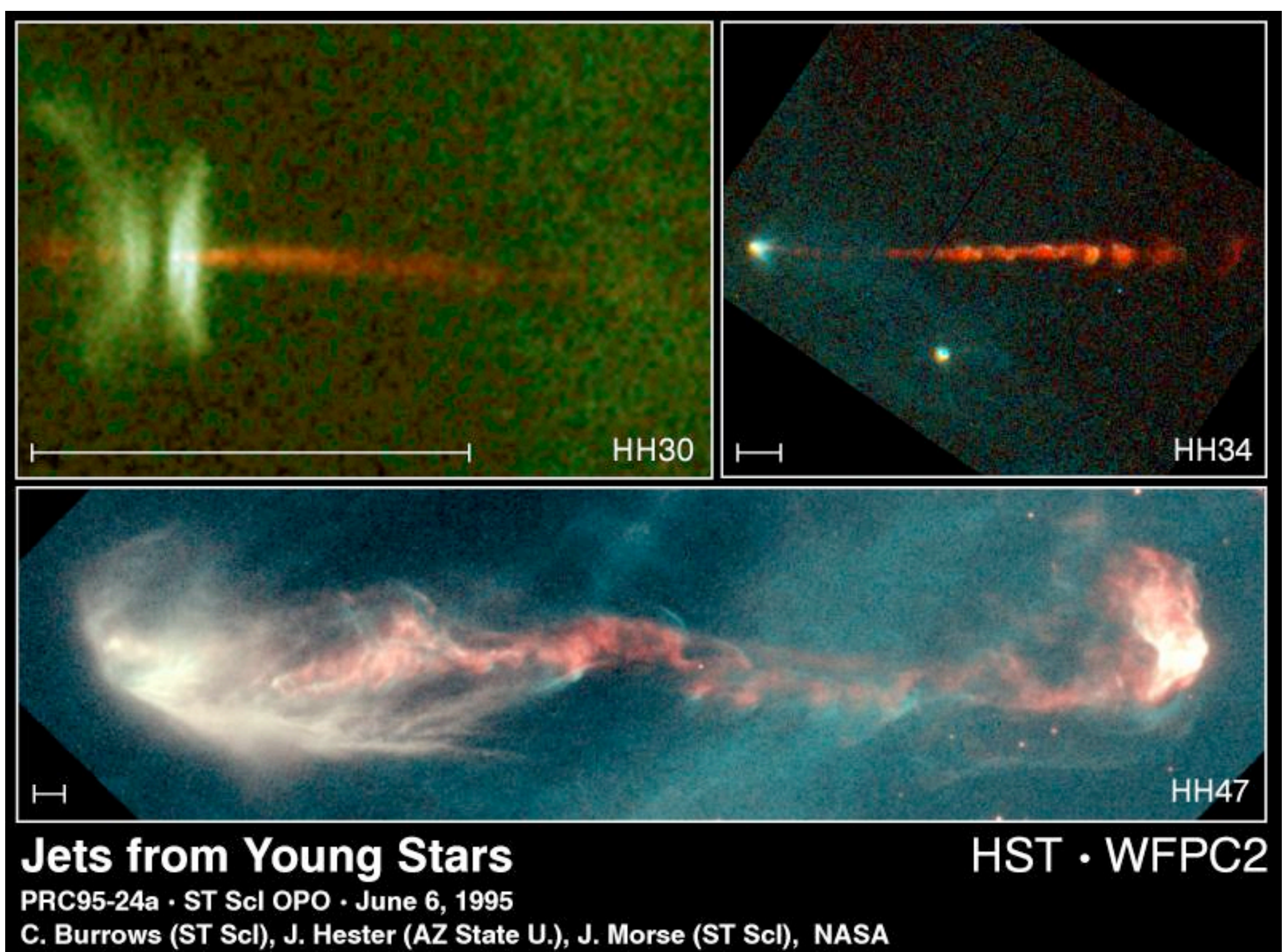


Driving of turbulence?



External driving

- e.g. SN, MRI, large scale flows, radiation from massive stars, ...



Internal driving

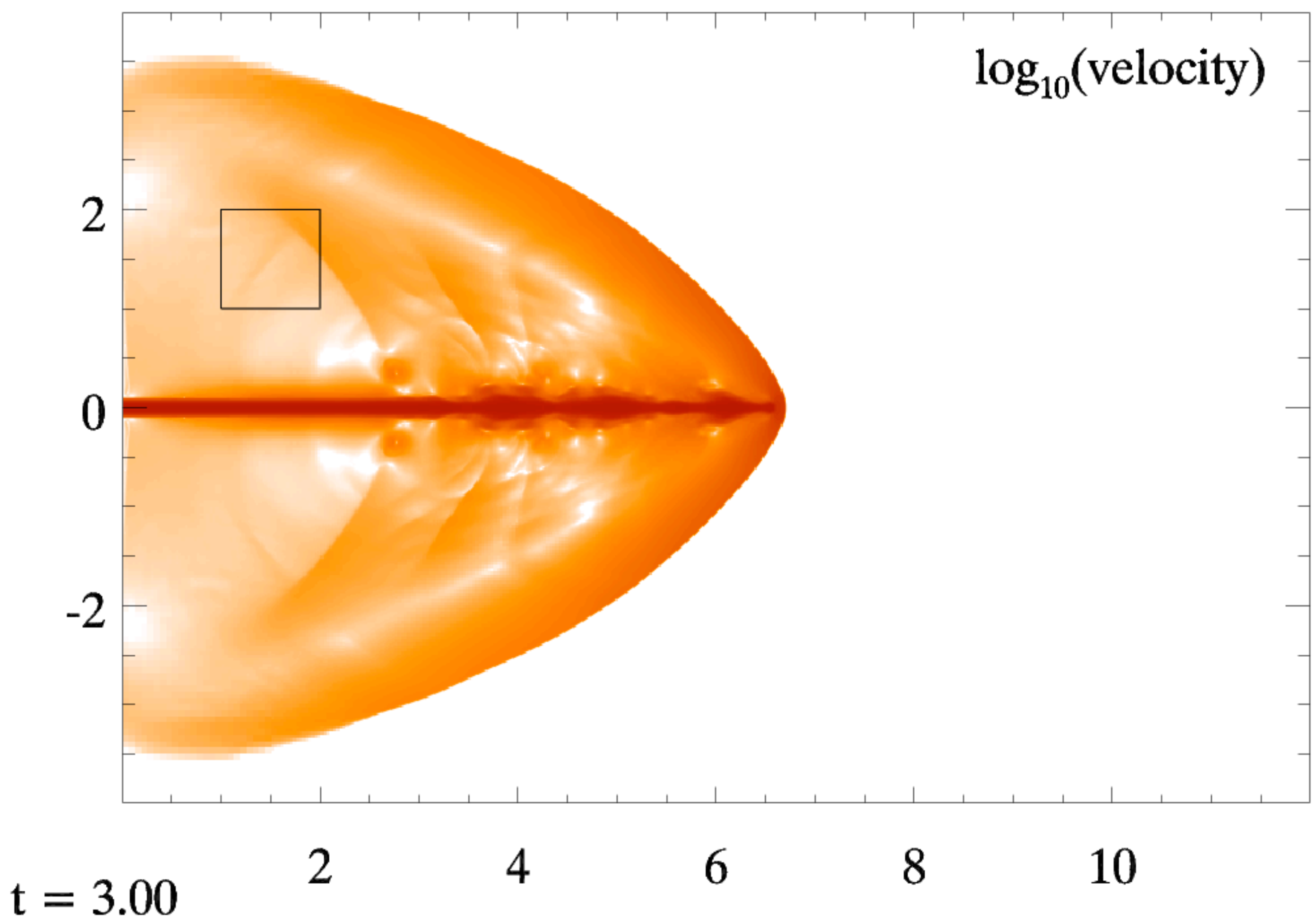
- e.g. radiation from low mass stars, outflows & jets

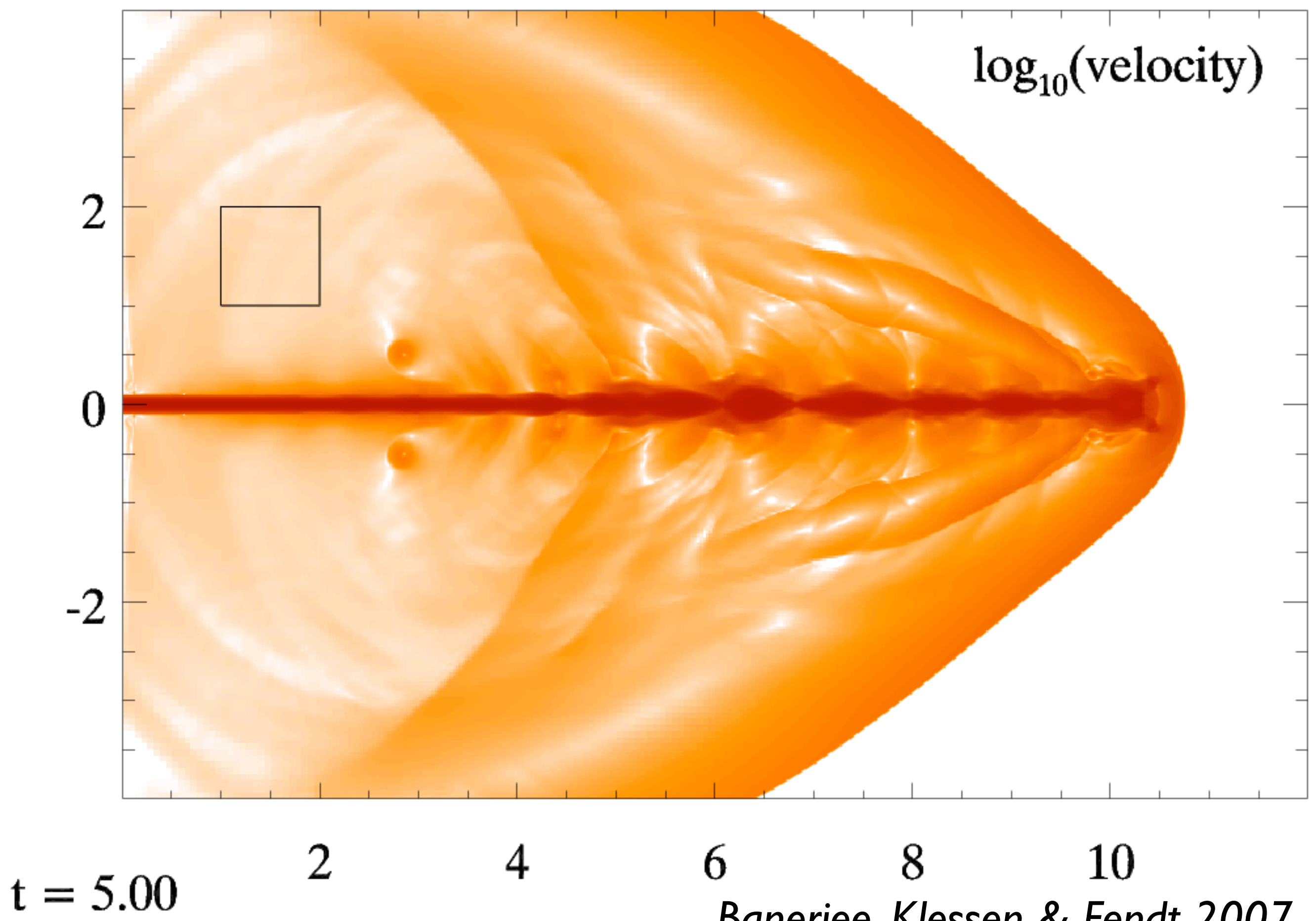
→ **self-regulating SF**

(eg. *Norman&Silk 1980, Li&Nakamura 2006*)

Jet-driven turbulence?

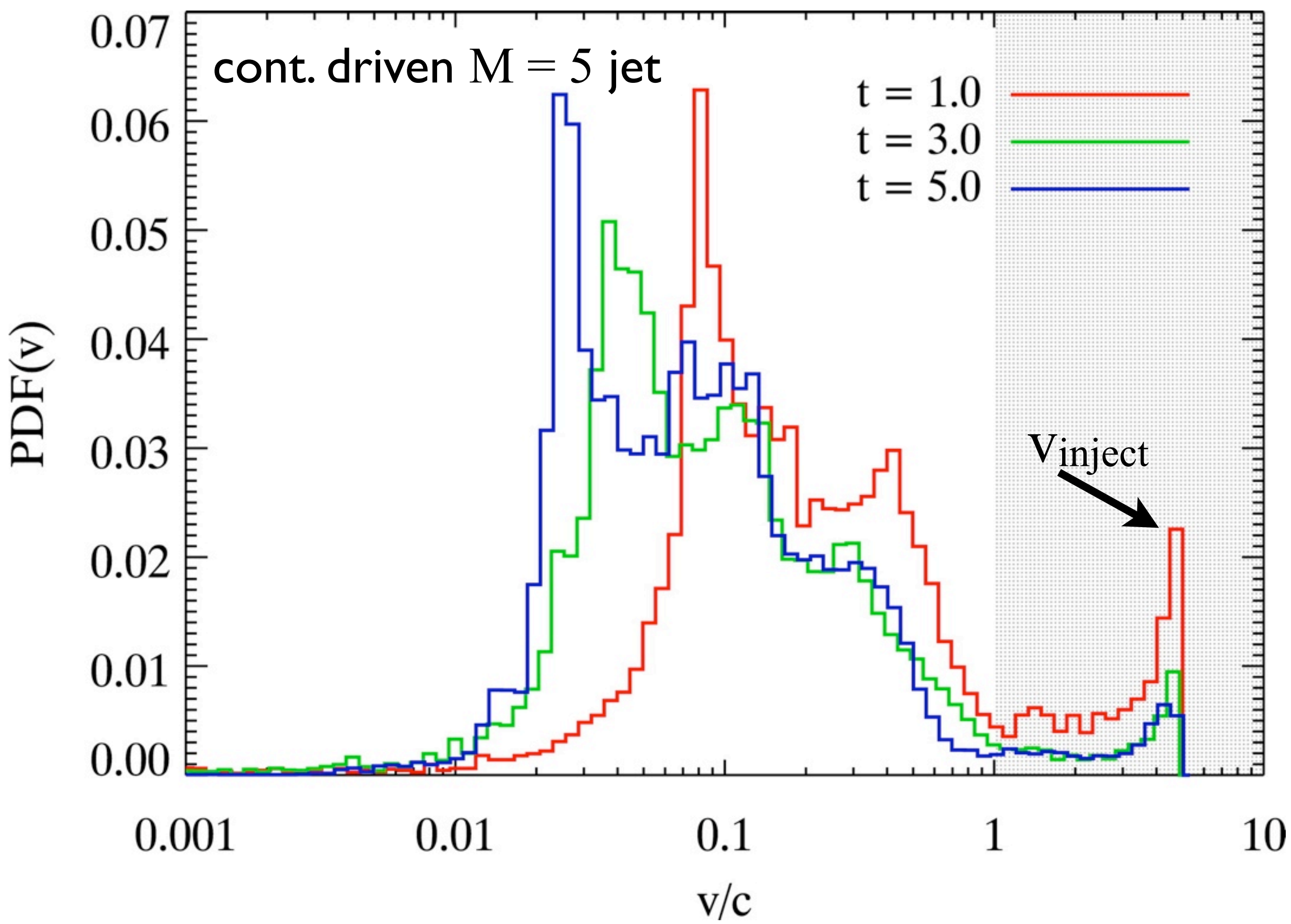
- numerical experiments with single, high Mach number jets (momentum injection)
- detailed analysis with velocity PDFs

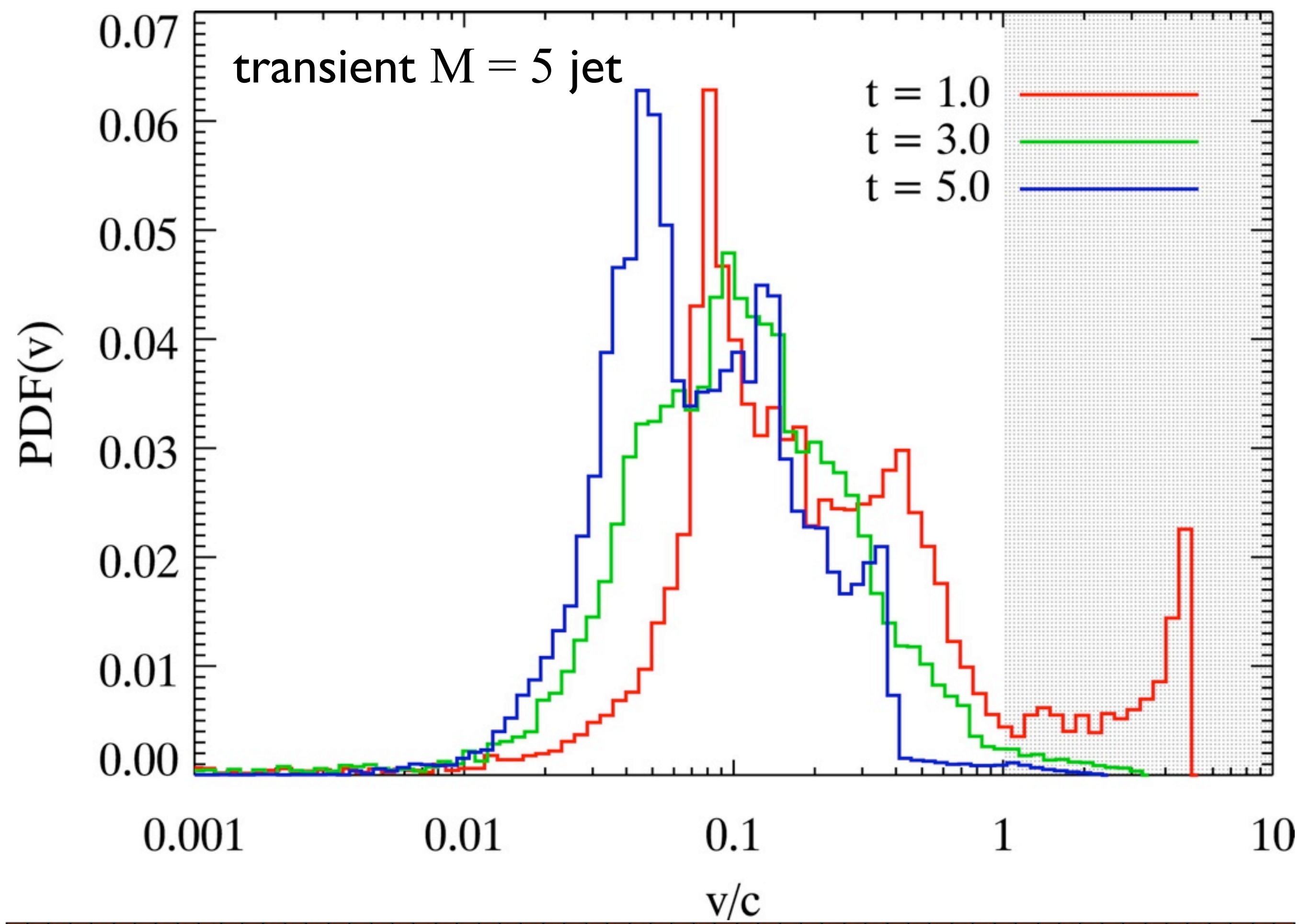




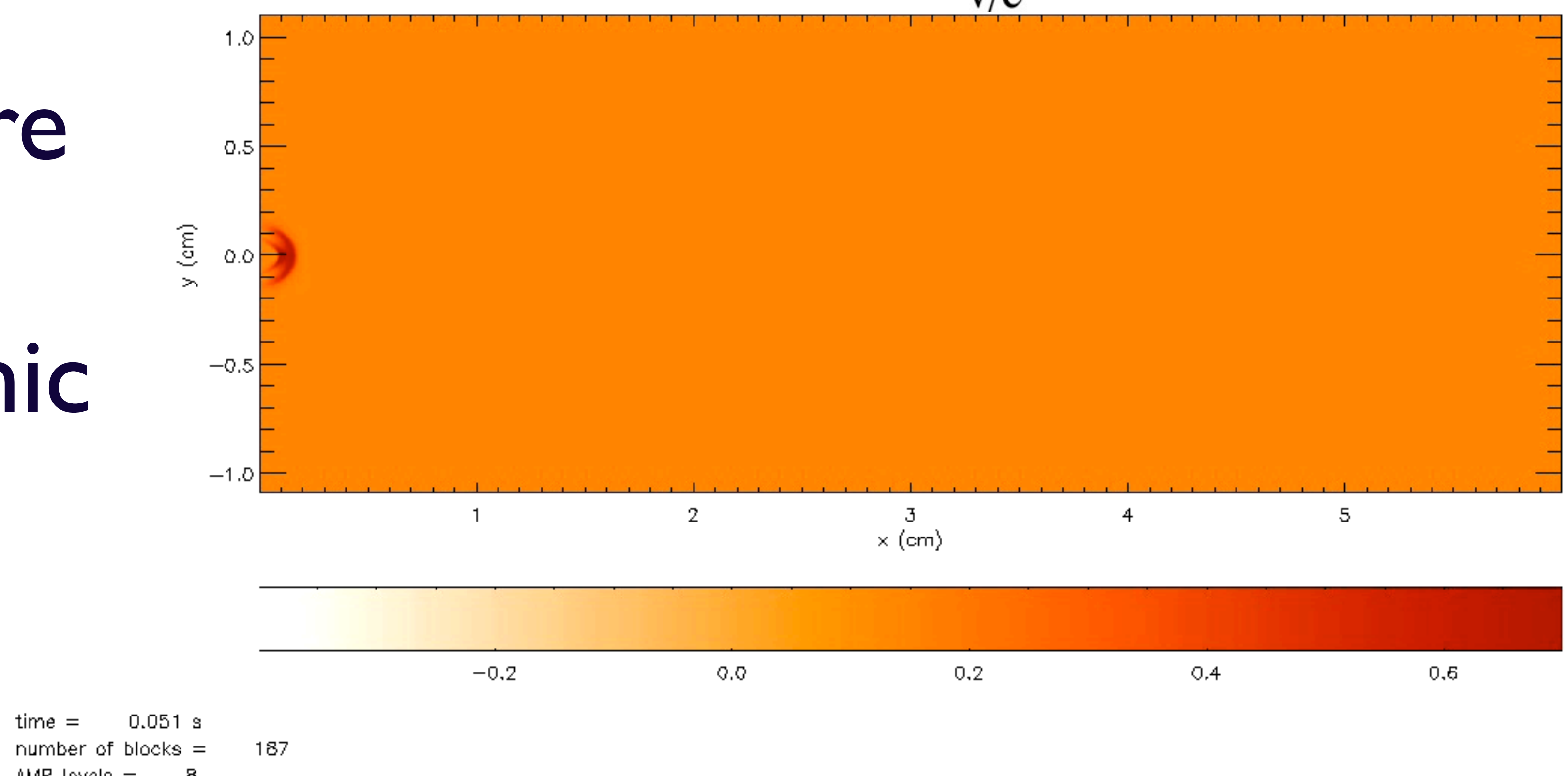
Banerjee, Klessen & Fendt 2007

Jet-driven turbulence?

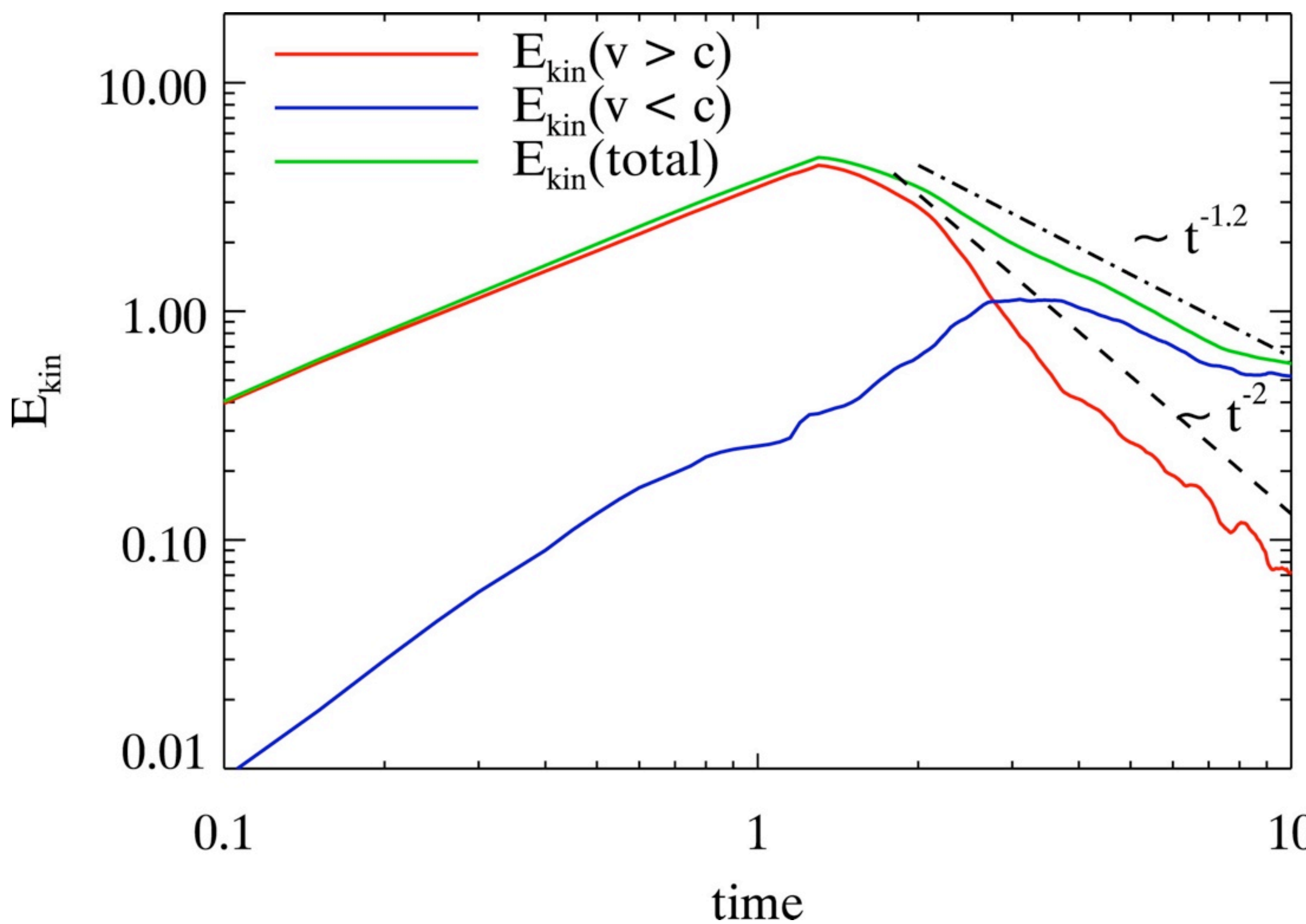


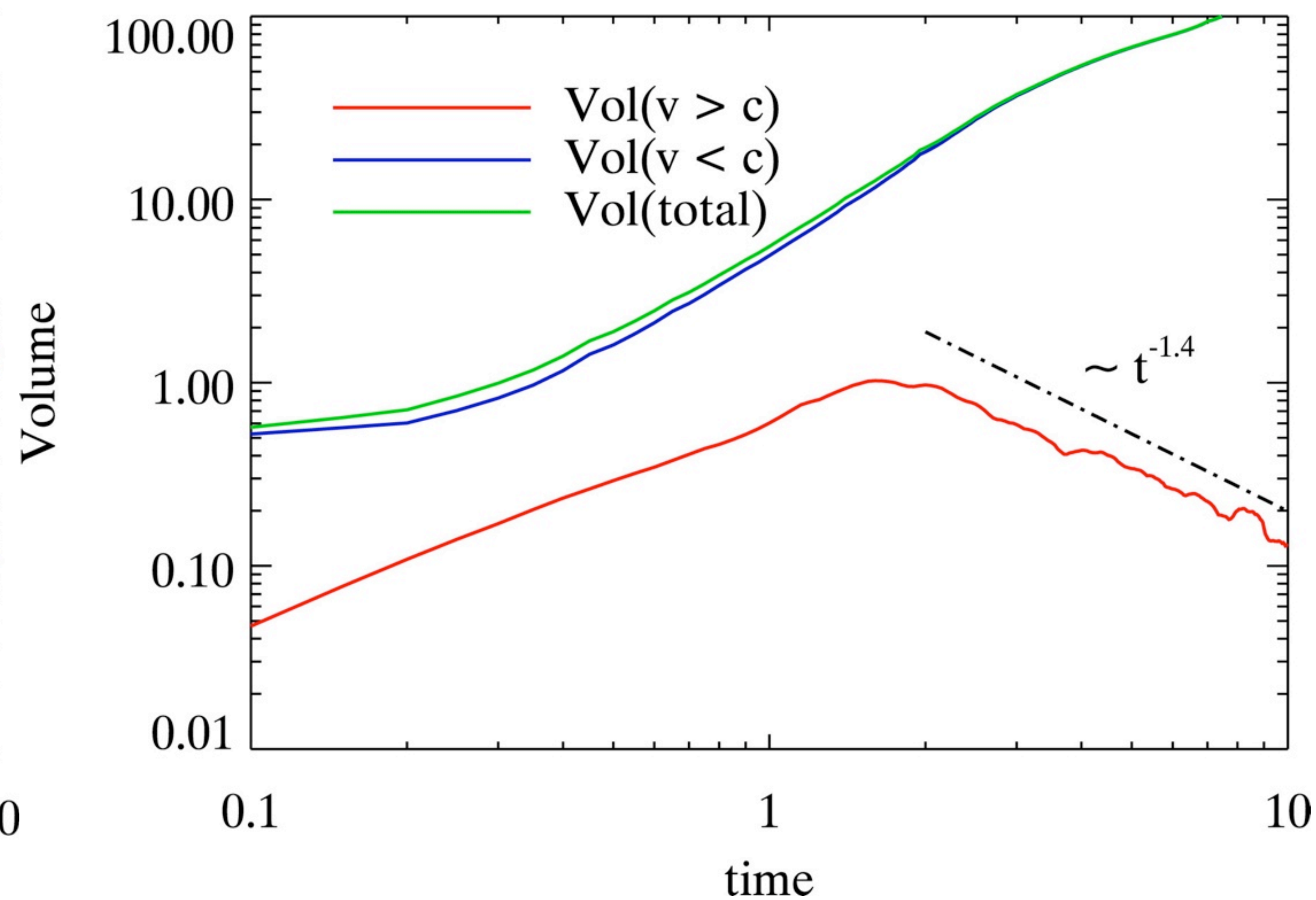


- turbulent motions are sub-sonic
- very **little** supersonic fluctuations

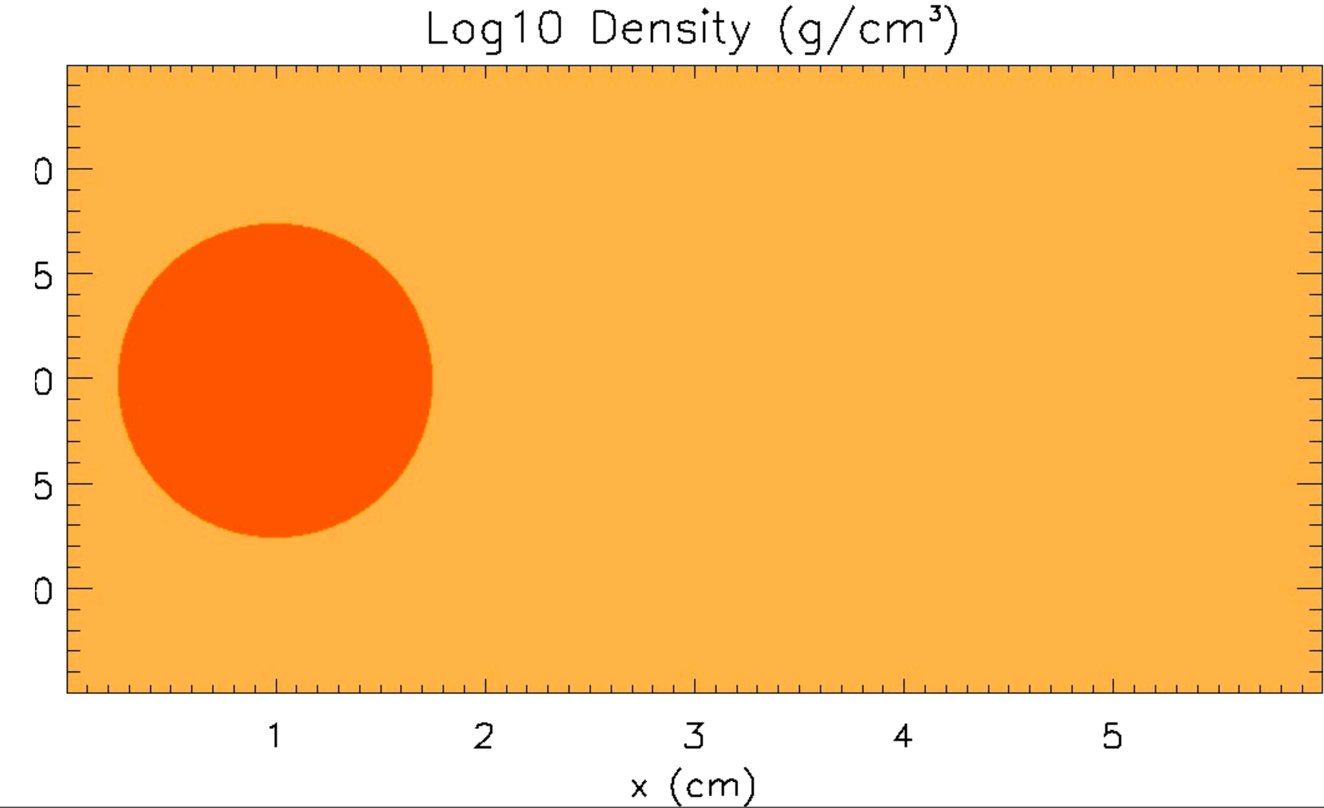


Jet-driven turbulence?

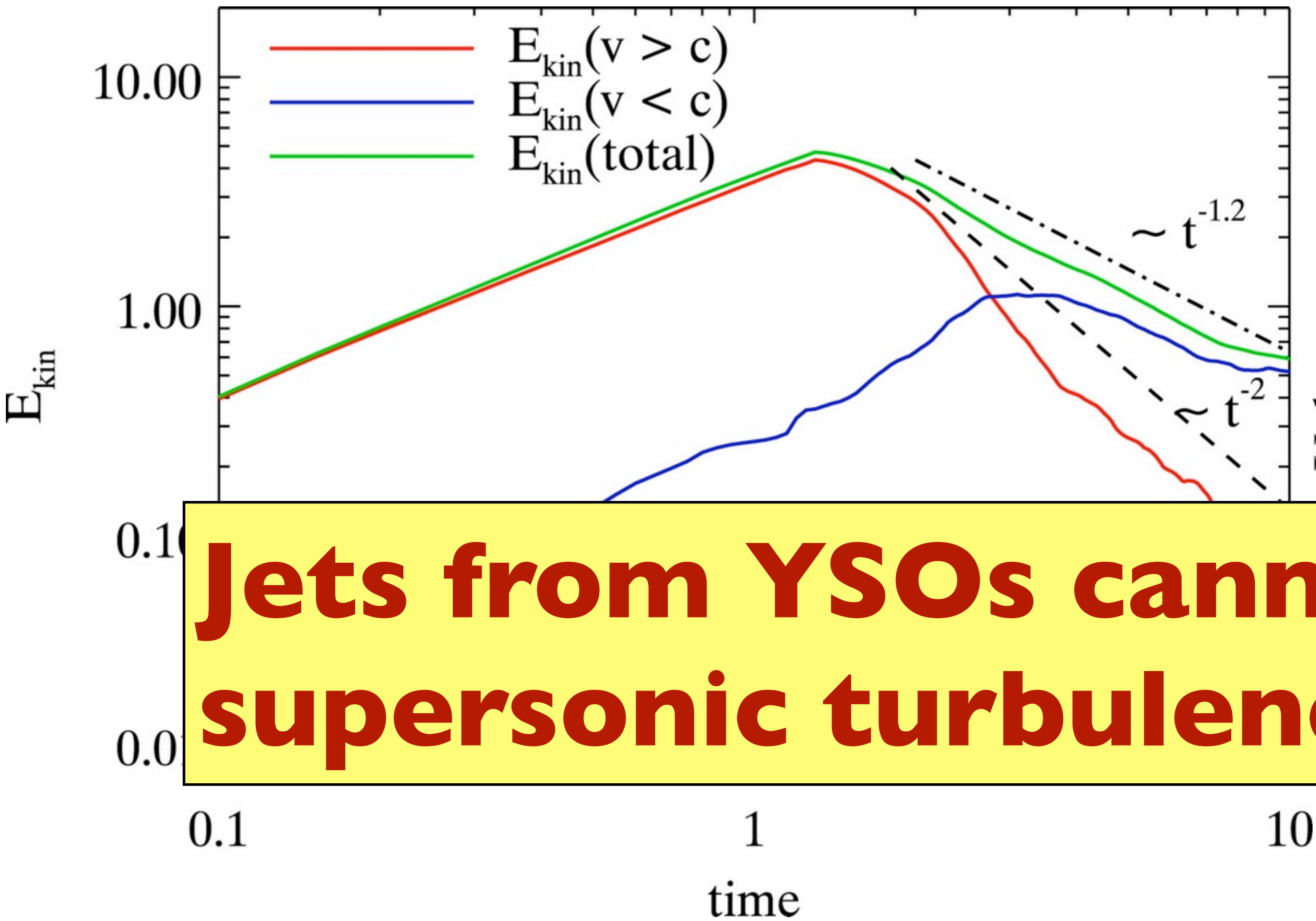


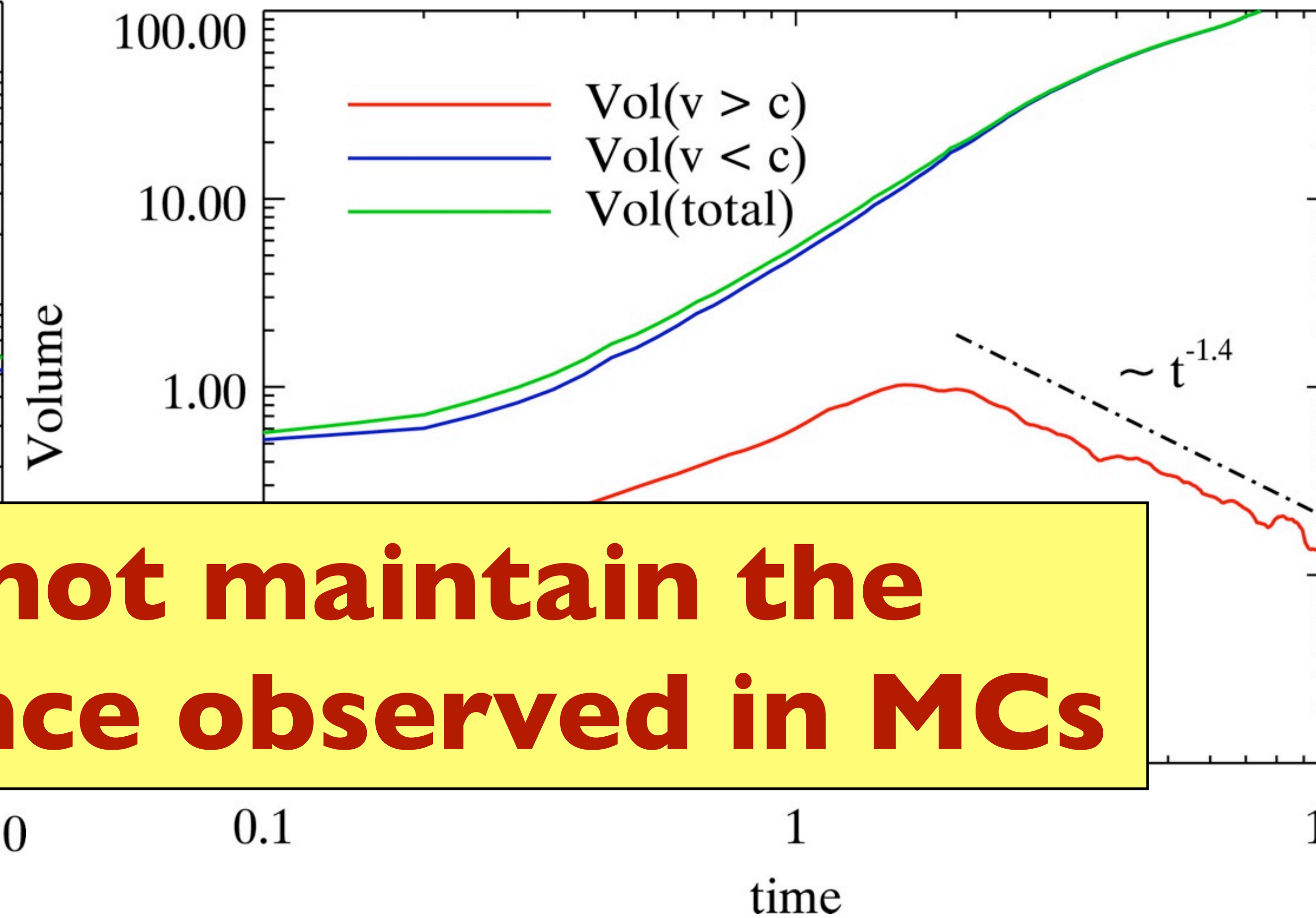


- supersonic fluctuations decay **quickly**: $E \propto t^{-2}$ (*Mac Low et al. '98*)
- supersonic fluctuations occupy only a **small** fraction of all fluctuations



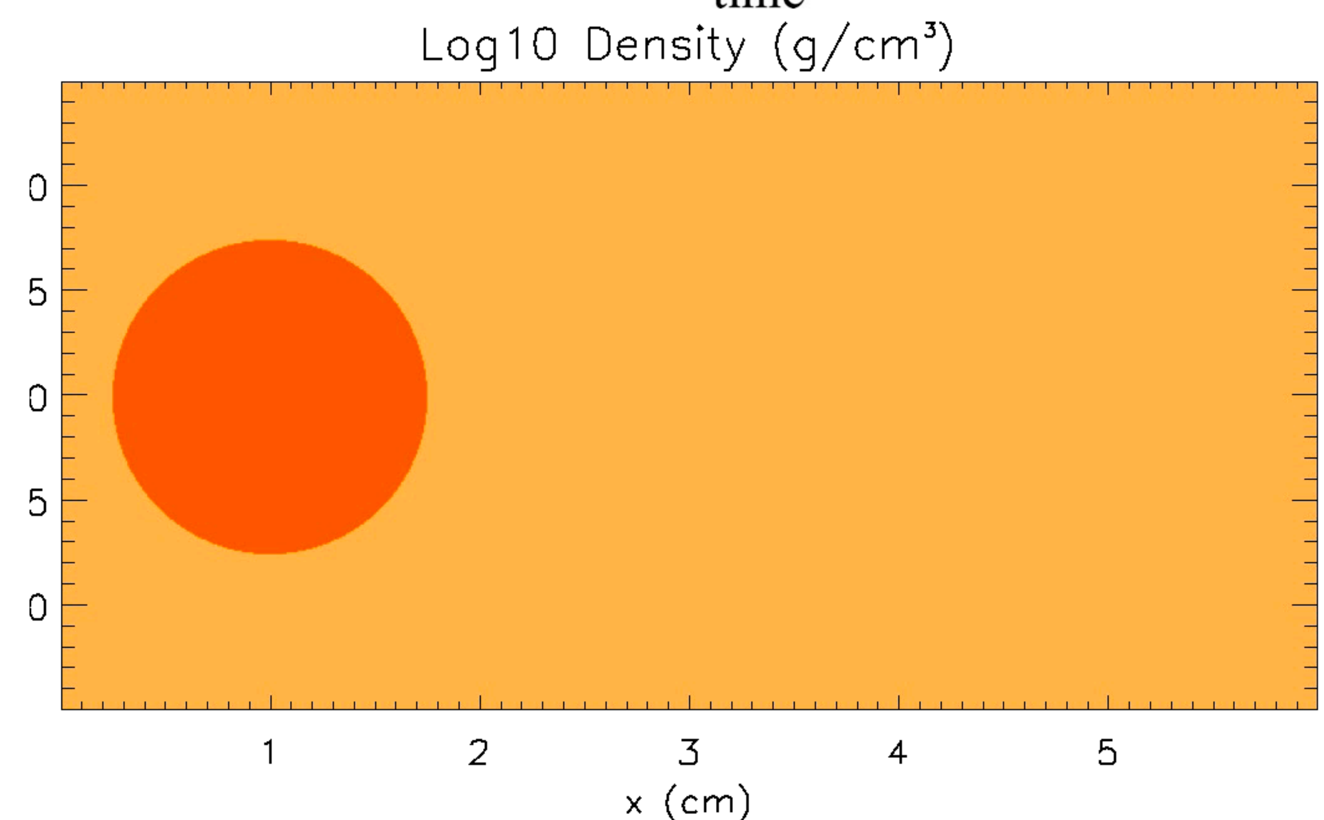
Jet-driven turbulence?



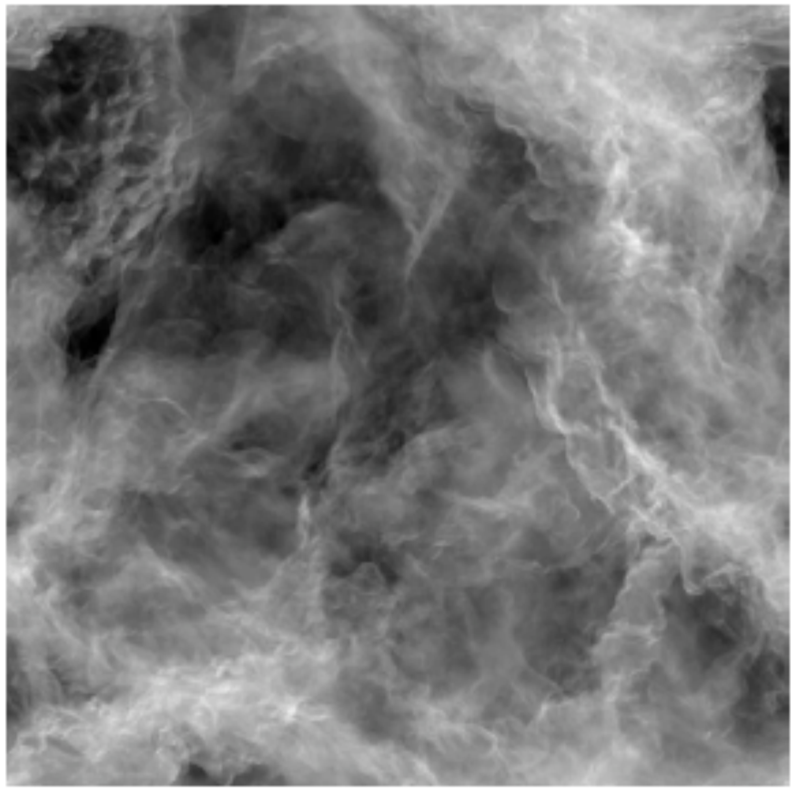


Jets from YSOs cannot maintain the supersonic turbulence observed in MCs

- supersonic fluctuations decay **quickly**: $E \propto t^{-2}$ (*Mac Low et al. '98*)
- supersonic fluctuations occupy only a **small** fraction of all fluctuations

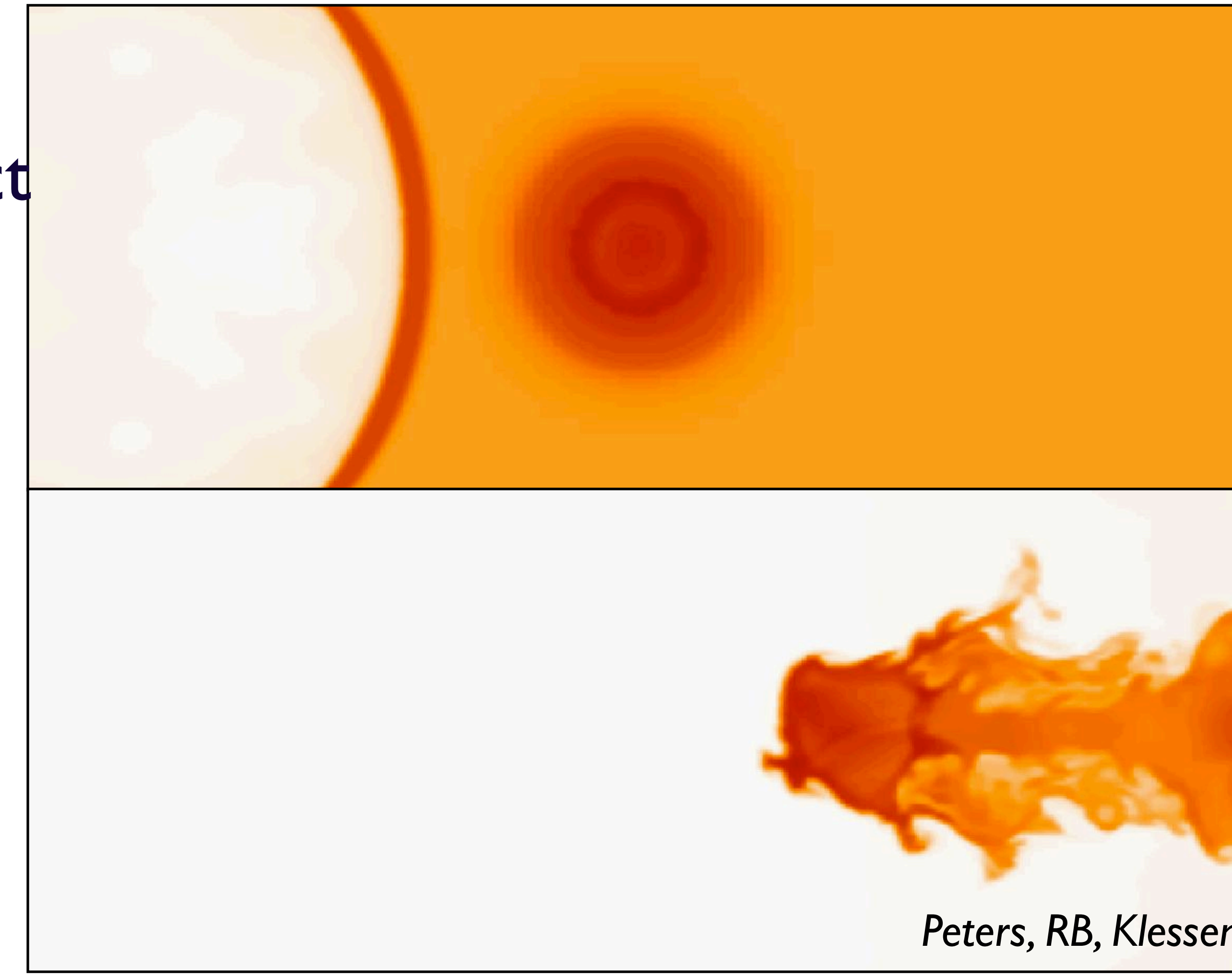


Turbulence



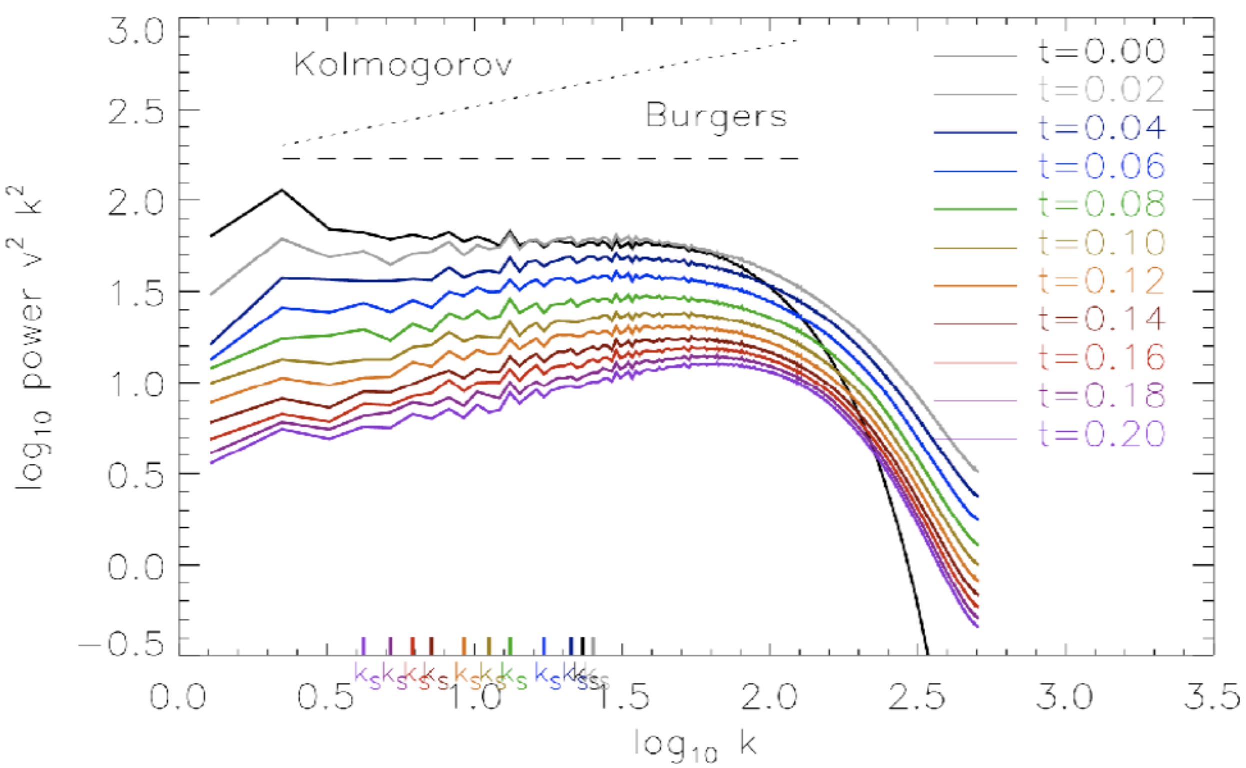
KITP Turbulence comparison project (*Padoan et al.*)

Ch.Federrath



Peters, RB, Klessen

Ionization front driven turbulence
Ionizing radiation from a nearby (~ 3 pc) massive star



- Outflows in cluster environments (*S.Horn et al.*)

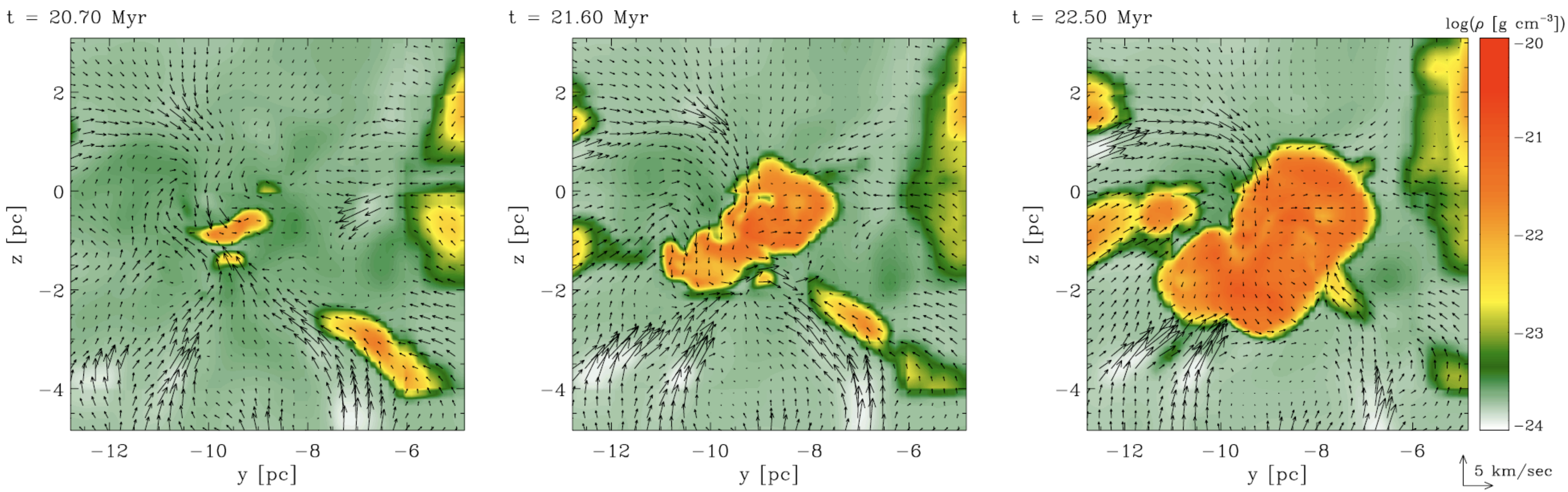
Summary

- Molecular clouds can form at the cross section of **converging** flows by thermal instability
- MCs are **dynamic** objects with no distinct boundaries
- **Jets** and **outflows** are launched during the collapse of magnetized cores
  $\Longrightarrow$ angular momentum transport
- Collapse of **turbulent** cores naturally lead to disk formation
- Very **high** accretion rates $\Longrightarrow$ massive star formation
- ISM turbulence **unlikely** driven by jets from young stellar objects

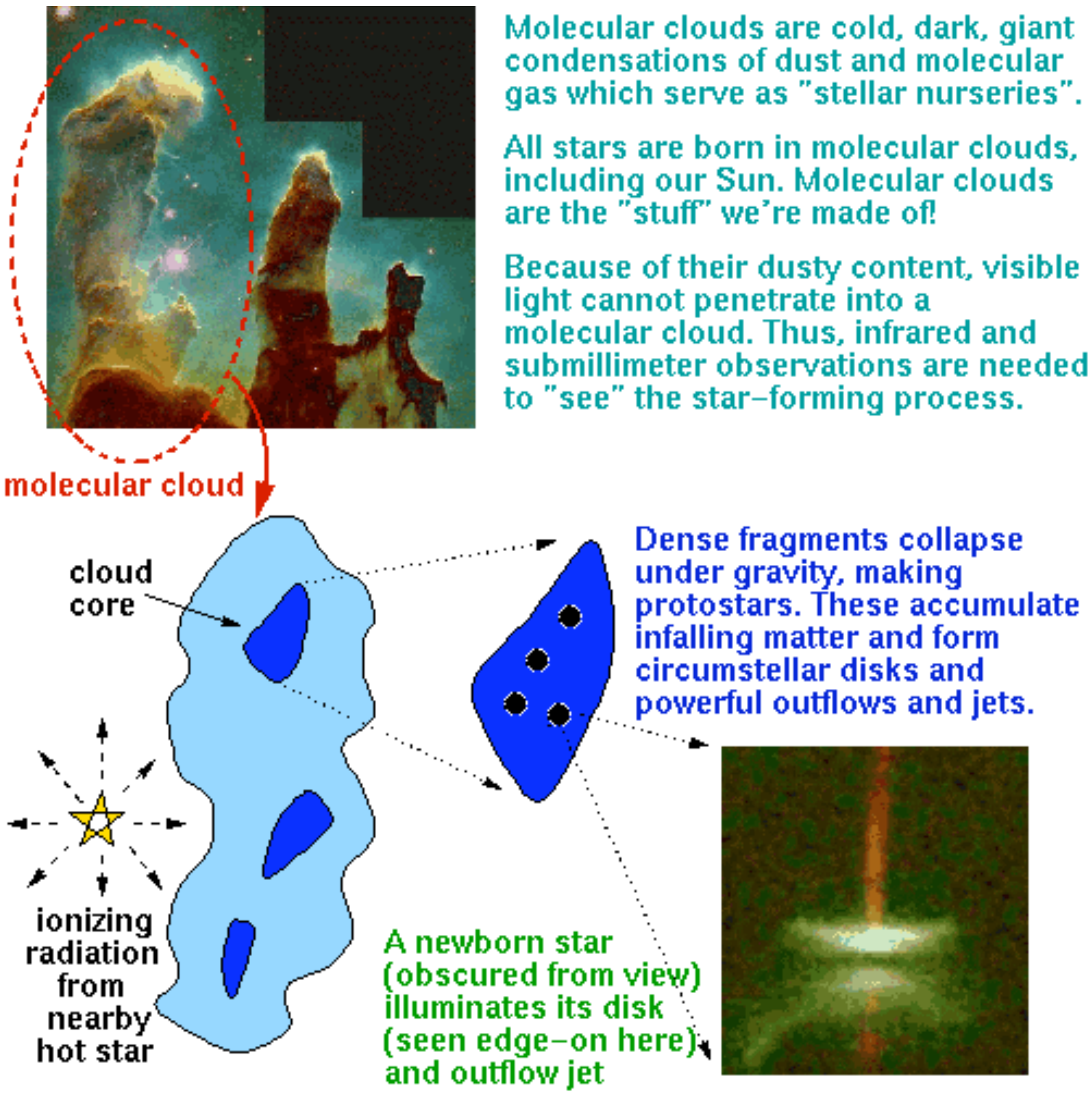
Thank you!

Formation of Molecular Clouds

clump evolution and morphology



• clump growth by outward propagation of boundary layers and coalescence



courtesy of *Craig Kulesa, University of Arizona*