# The Formation of Cores, Filaments, and Disks in Magnetized Molecular Clumps

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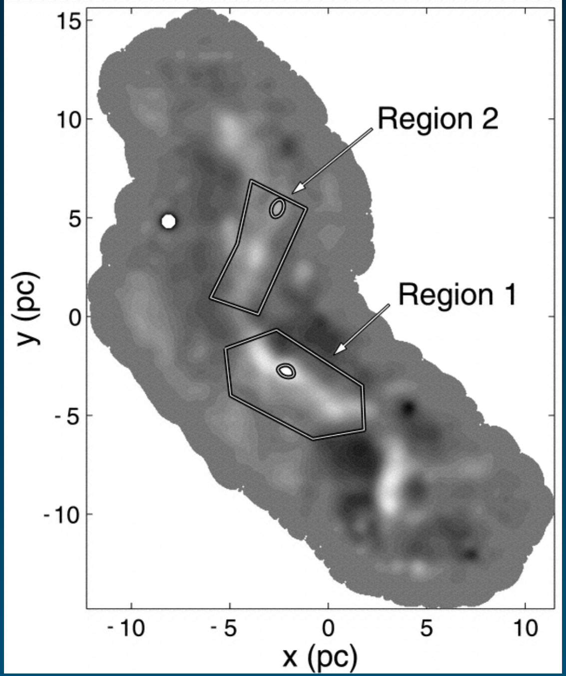
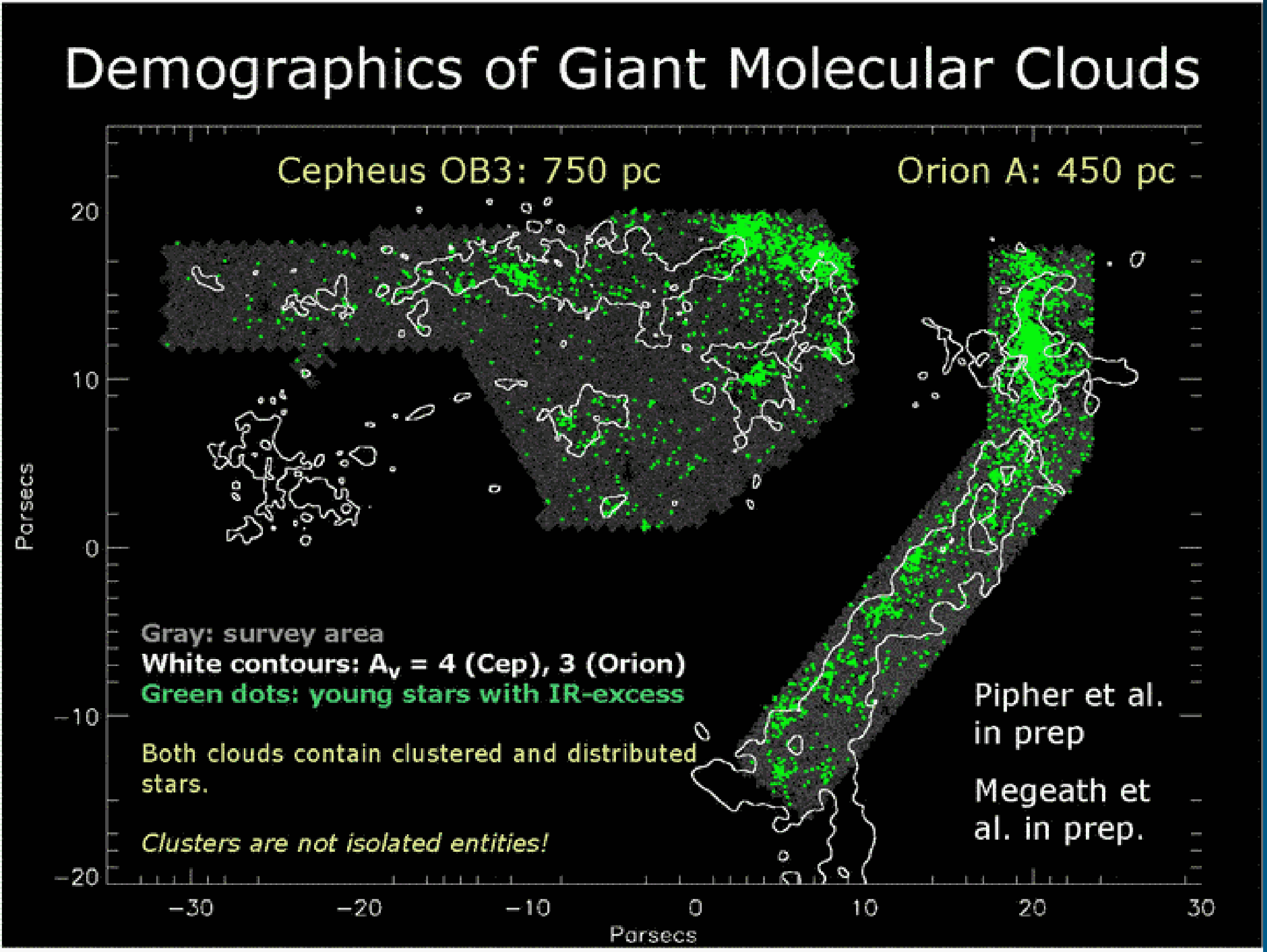
KITP 07: Star formation through cosmic time

# Structure formation by supersonic turbulence:

- star forming environments are filamentary on many scales,
- B field important in denser regions?



Eg. Fiege et al (2004) infrared dark cloud: 22 pc long.



Demographics of Giant Molecular Clouds

Gray: survey area

**White contours: $A_V$ = 4 (Cep), 3 (Orion)**

Green dots: young stars with IR-excess

Both clouds contain clustered and distributed stars.

*Clusters are not isolated entities!*

Pipher et al. in prep

Megeath et al. in prep.

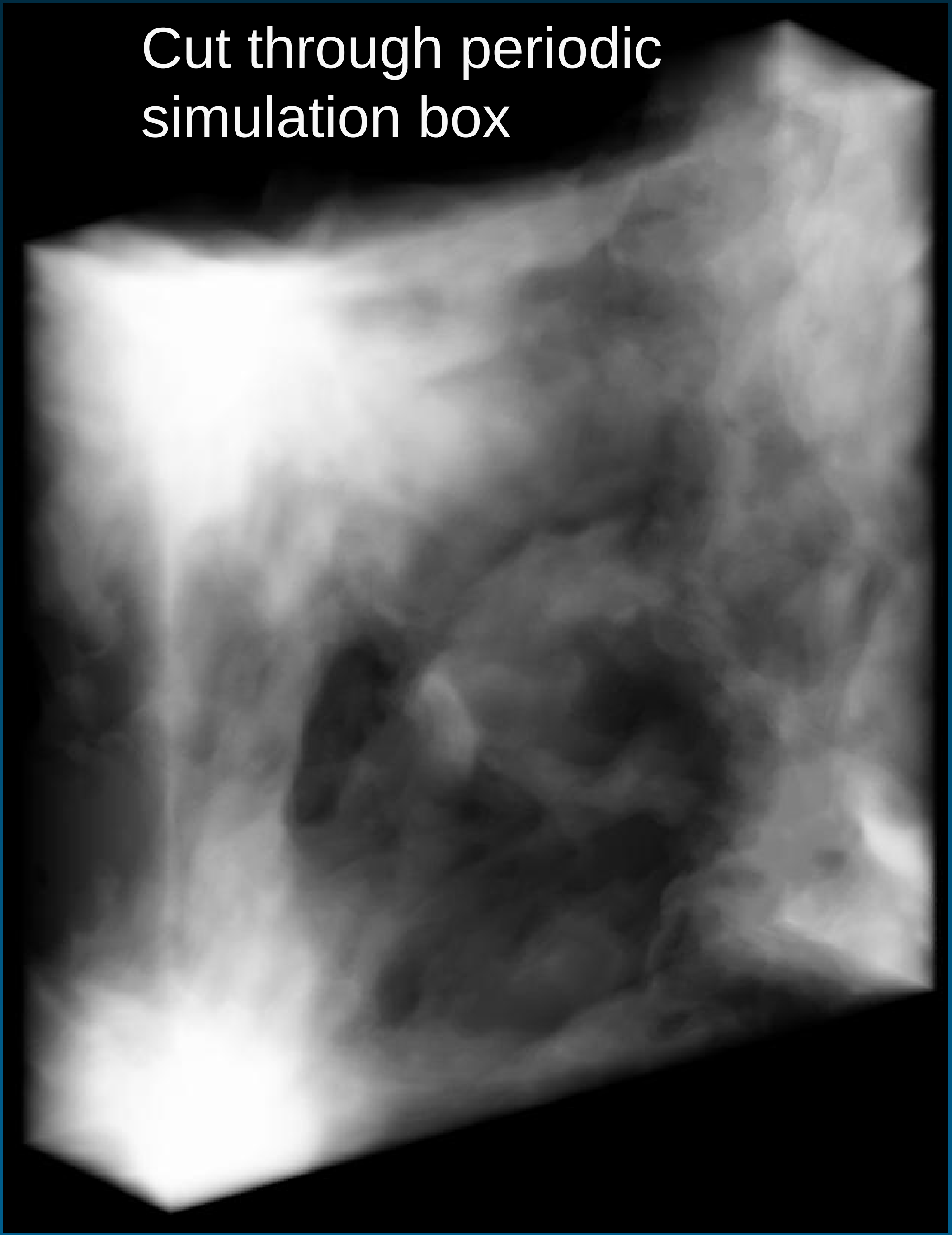
Reviews: Klein et al 2007, MacLow & Klessen 2004, McKee & Ostriker 2007

T. Megeath; KITP 07 talk

# Background: Turbulent (hyrdo) fragmentation in cluster forming clump

(Tilley & Pudritz 2004)

- Initial Kolomogorov or Burger’s velocity field –
  - initial uniform density;
  - ZEUS 3D + good gravity solver;
  - periodic B.C.; 256 or 512 cubed simulations;
  - Truelove criterion (1997): resolve local Jeans length with at least 4 pixels
  - hydro simulations, isothermal gas…



Cut through periodic simulation box

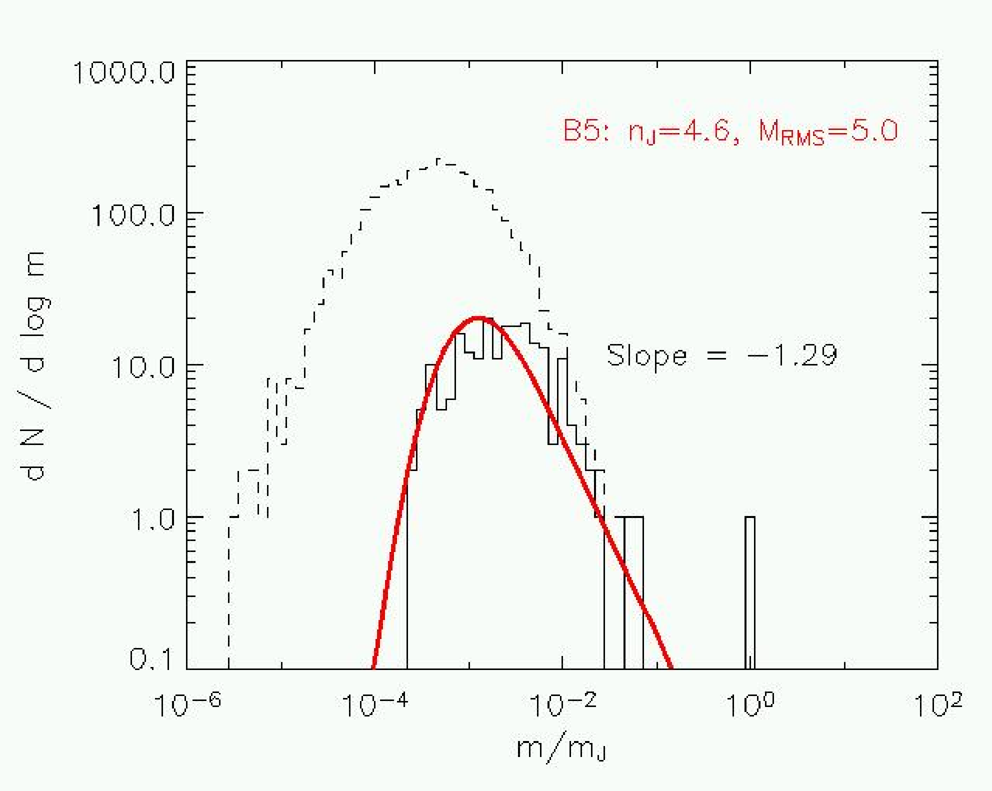
# - Initial properties of cluster forming, clump simulation (clumps from Lada & Lada 1991) - Results…. peak of CMF is hundreds of times lower in mass than Jeans length in initial medium

$$m_{tot} / m_{\Theta} = 119 n_J^{2/3} (L / pc)(T / 20K) = 105$$

$$(L = .32pc; \quad T = 20K; \quad (c_s = 0.4kms^{-1}); \quad n_J = 4.6; \quad M_{rms} = 5.0)$$

$$m_{peak} = 0.05 m_{\Theta};$$

$$j_{peak} \cong 3 \times 10^{21} cm^2 s^{-1}$$



Dashed: all fluctuations

Solid: bound fluctuations (cores) - evaluated by complete $\ddot{I} \le 0$

- A semi-analytic theory for expected distribution of cores created by turbulent fragmentation:

  - modification of lognormal distribution of fragments - by turbulence - with a power law spectrum (gamma index) (Padoan & Nordlund 2002 – PN02) (analagous to Press-Schechter):

- Number of collapsing cores:

$$N(m) \propto m^{-3/(4+\gamma)} \int_0^m p(m_J)\,dm_J$$

- For Kolomogorov, spectral index of turbulence is -5/3 giving observed exponent = -1.29

# I: Cluster formation in magnetized clumps

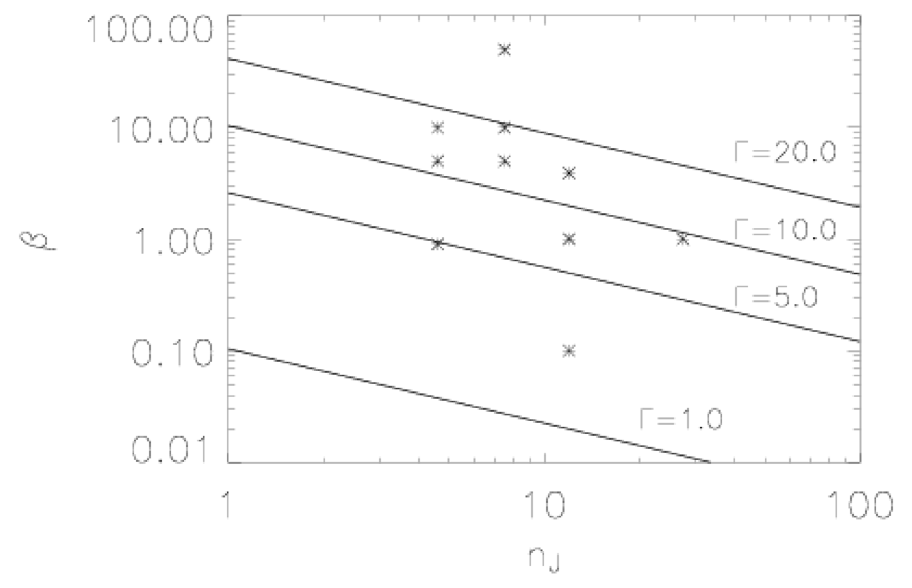
(Tilley & Pudritz, MNRAS 2007):

Next step – importance of B: Repeat hydro calculations, but introduce initial uniform field with initial, supercritical mass to flux ratio:

$$\Gamma = 2\pi G^{1/2}\rho L / B$$
$$= 3.12 n_J^{1/3} \beta^{1/2}$$

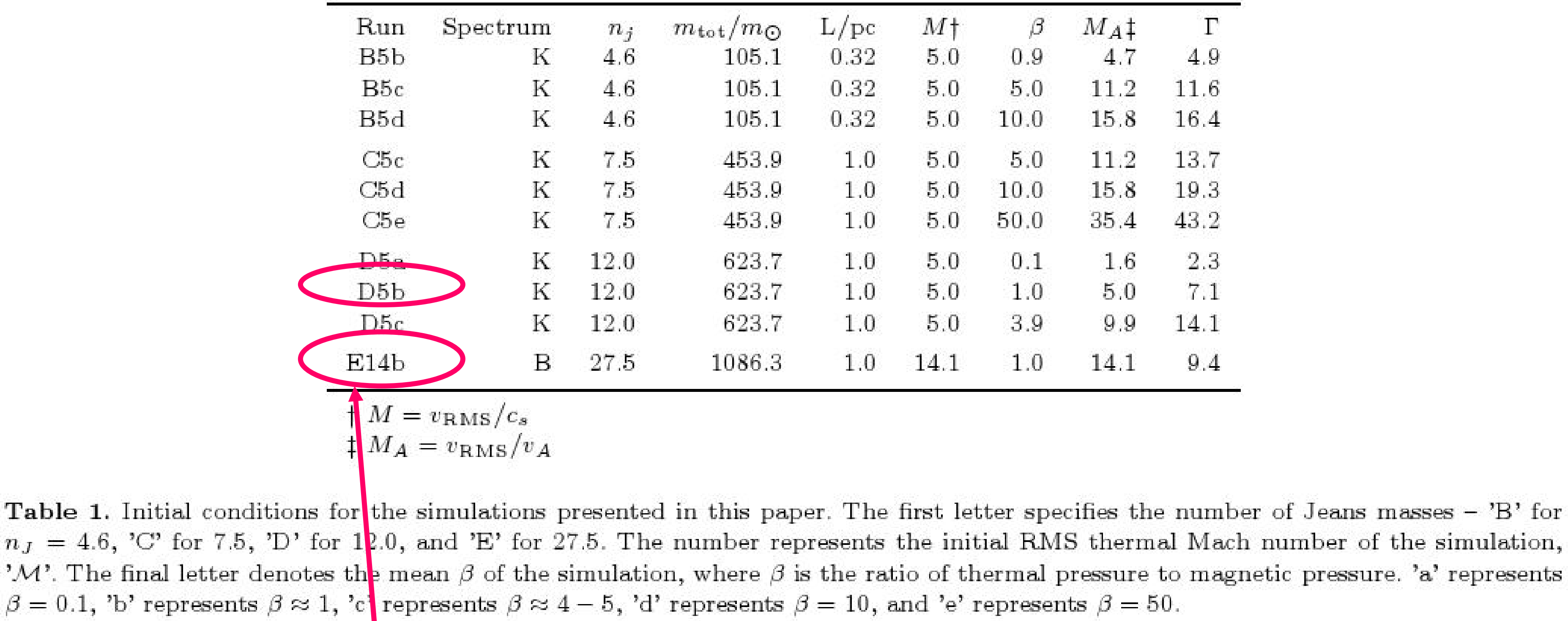
B field scales as:

$$\frac{B}{\mu G} = 16.8 n_j \beta^{-1/2} \left( \frac{m_{tot}}{100 M_{\Theta}} \right)^{-1}$$



Models; range of initial conditions

# Model runs: meant to cover range of cluster forming clumps, 100s to 1000s of solar masses, with initial modest to high mass to flux….



| Run | Spectrum | $n_j$ | $m_{tot}/m_\odot$ | L/pc | $M$† | $\beta$ | $M_A$‡ | $\Gamma$ |
|---|---|---|---|---|---|---|---|---|
| B5b | K | 4.6 | 105.1 | 0.32 | 5.0 | 0.9 | 4.7 | 4.9 |
| B5c | K | 4.6 | 105.1 | 0.32 | 5.0 | 5.0 | 11.2 | 11.6 |
| B5d | K | 4.6 | 105.1 | 0.32 | 5.0 | 10.0 | 15.8 | 16.4 |
| C5c | K | 7.5 | 453.9 | 1.0 | 5.0 | 5.0 | 11.2 | 13.7 |
| C5d | K | 7.5 | 453.9 | 1.0 | 5.0 | 10.0 | 15.8 | 19.3 |
| C5e | K | 7.5 | 453.9 | 1.0 | 5.0 | 50.0 | 35.4 | 43.2 |
| D5a | K | 12.0 | 623.7 | 1.0 | 5.0 | 0.1 | 1.6 | 2.3 |
| D5b | K | 12.0 | 623.7 | 1.0 | 5.0 | 1.0 | 5.0 | 7.1 |
| D5c | K | 12.0 | 623.7 | 1.0 | 5.0 | 3.9 | 9.9 | 14.1 |
| E14b | B | 27.5 | 1086.3 | 1.0 | 14.1 | 1.0 | 14.1 | 9.4 |

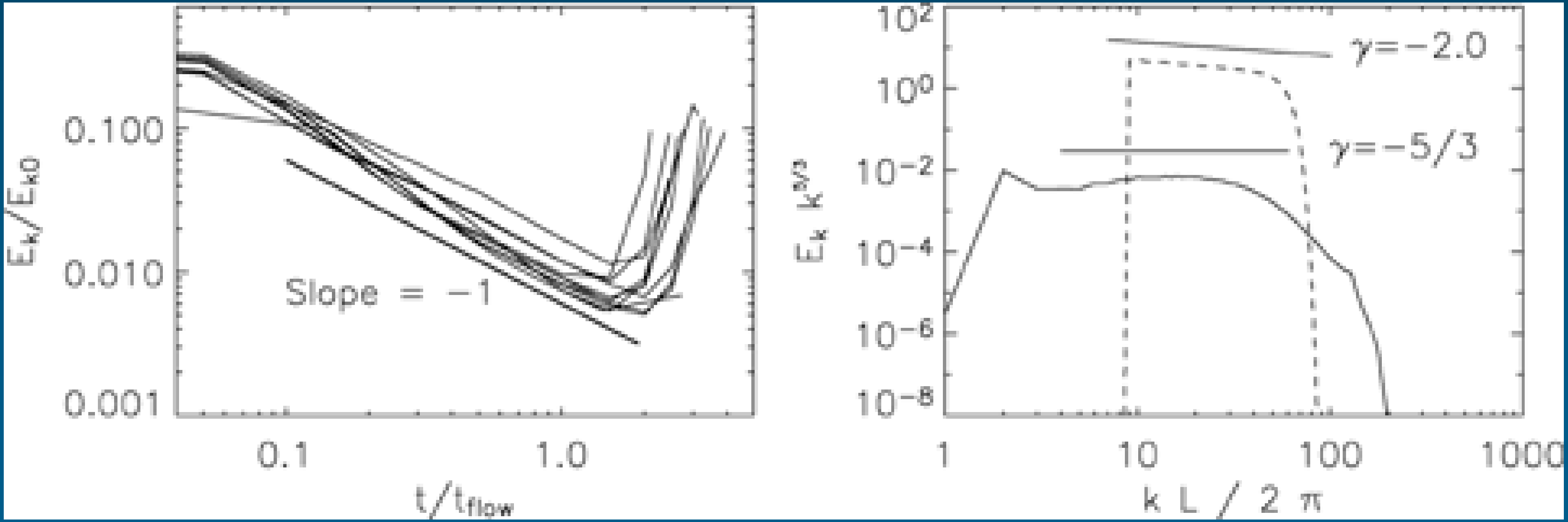
† $M = v_{\rm RMS}/c_s$
‡ $M_A = v_{\rm RMS}/v_A$

**Table 1.** Initial conditions for the simulations presented in this paper. The first letter specifies the number of Jeans masses – 'B' for $n_J = 4.6$, 'C' for 7.5, 'D' for 12.0, and 'E' for 27.5. The number represents the initial RMS thermal Mach number of the simulation, '$\mathcal{M}$'. The final letter denotes the mean $\beta$ of the simulation, where $\beta$ is the ratio of thermal pressure to magnetic pressure. 'a' represents $\beta = 0.1$, 'b' represents $\beta \approx 1$, 'c' represents $\beta \approx 4-5$, 'd' represents $\beta = 10$, and 'e' represents $\beta = 50$.

Models we focus on later in talk….

# Dynamics in our decaying turbulent flow:

- start with region with significant turbulent energy
- decays naturally as expected theoretically
- gravity becomes important as dense regions evolve and interact – KE now increases
- spectral evolution also takes place… so initial spectrum not important



# Cluster formation in magnetized clouds (Tilley & Pudritz, MNRAS 2007)

More Jeans masses:

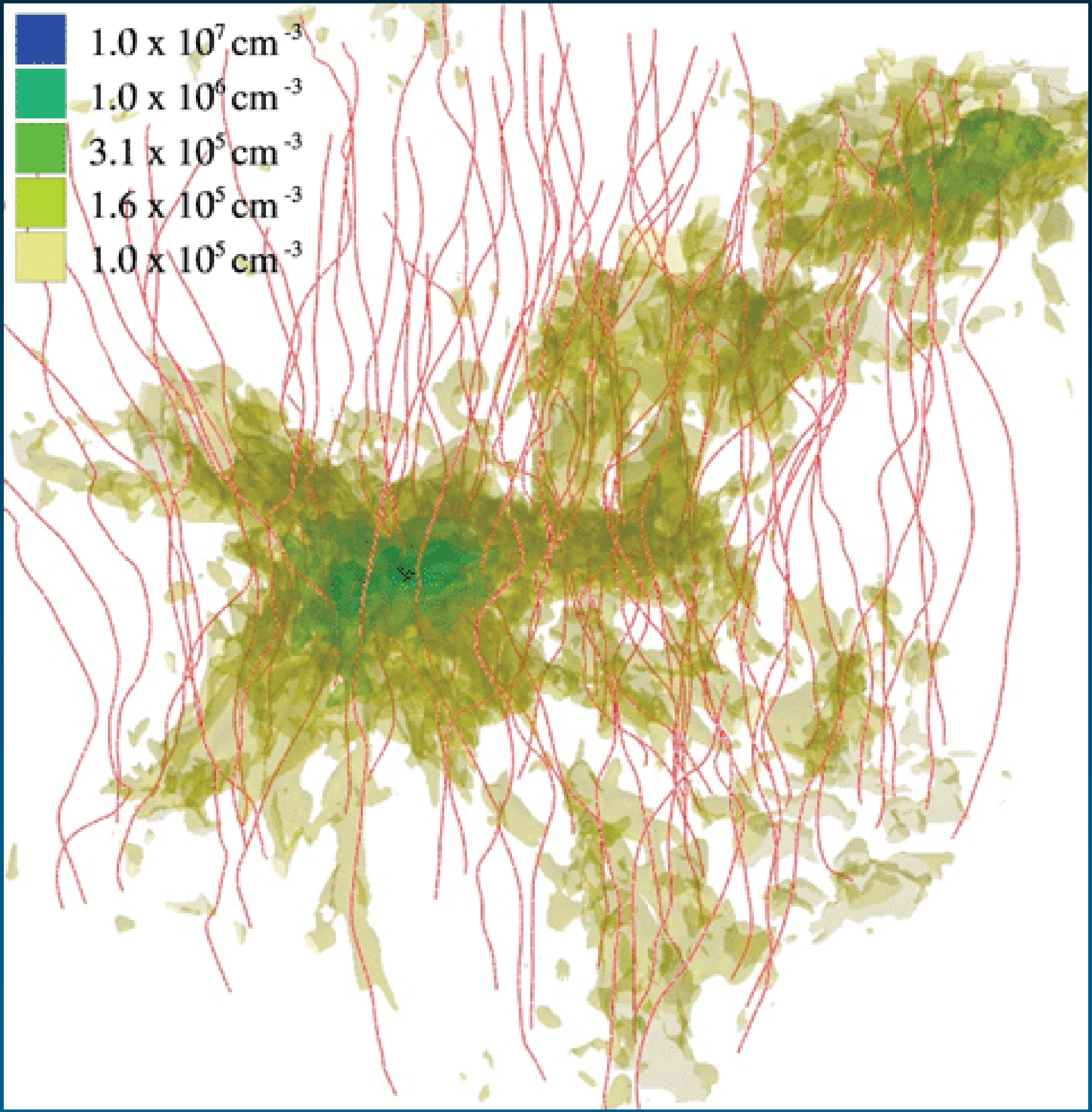
Turbulence breaks up clouds into dense cores which form before big sheets are organized…

$$n_J = 27.5;$$

$$\beta = 1.0$$

$$M_A = 14.1$$

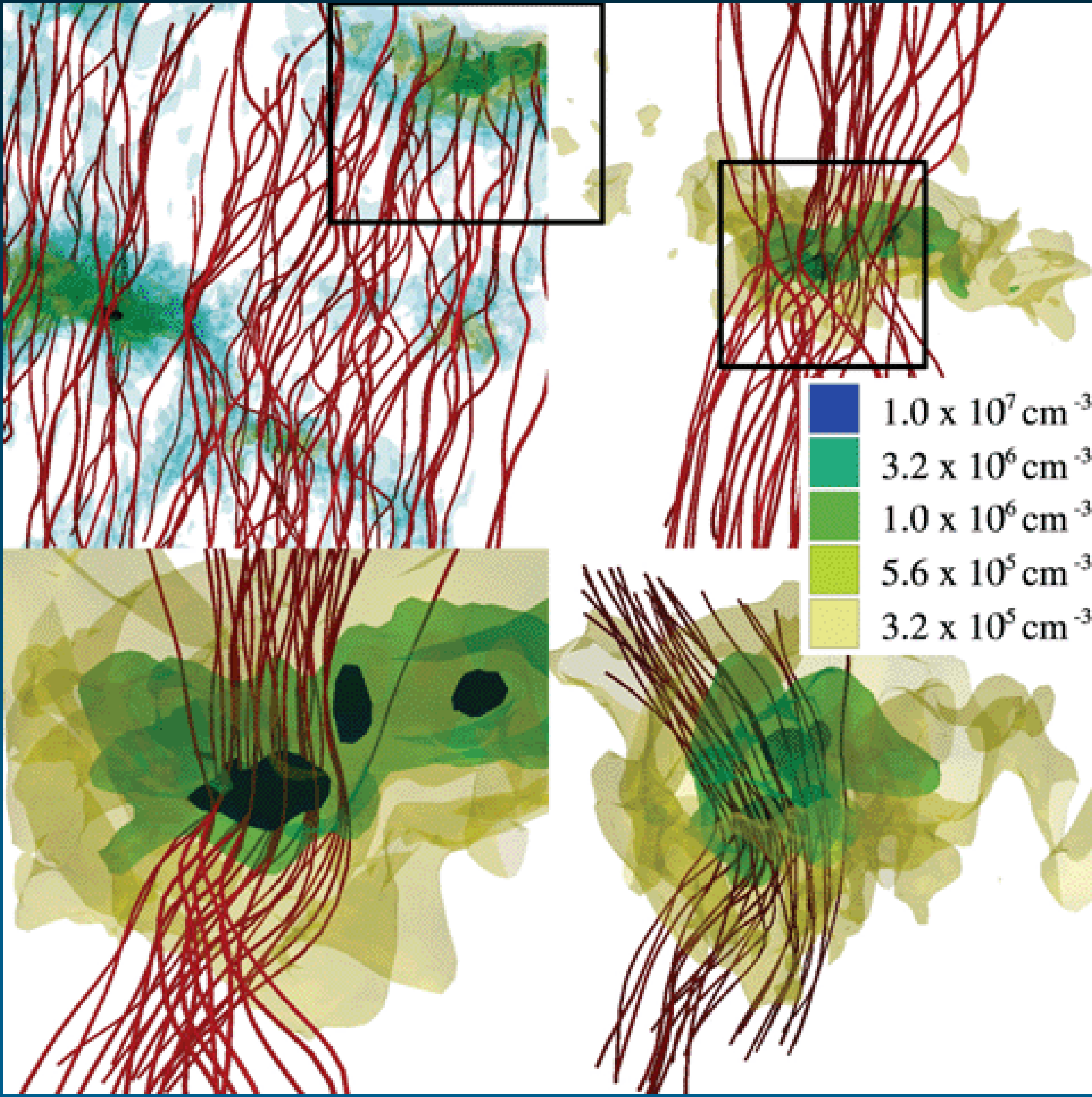
$$\Gamma = 9.4$$



Close-up:

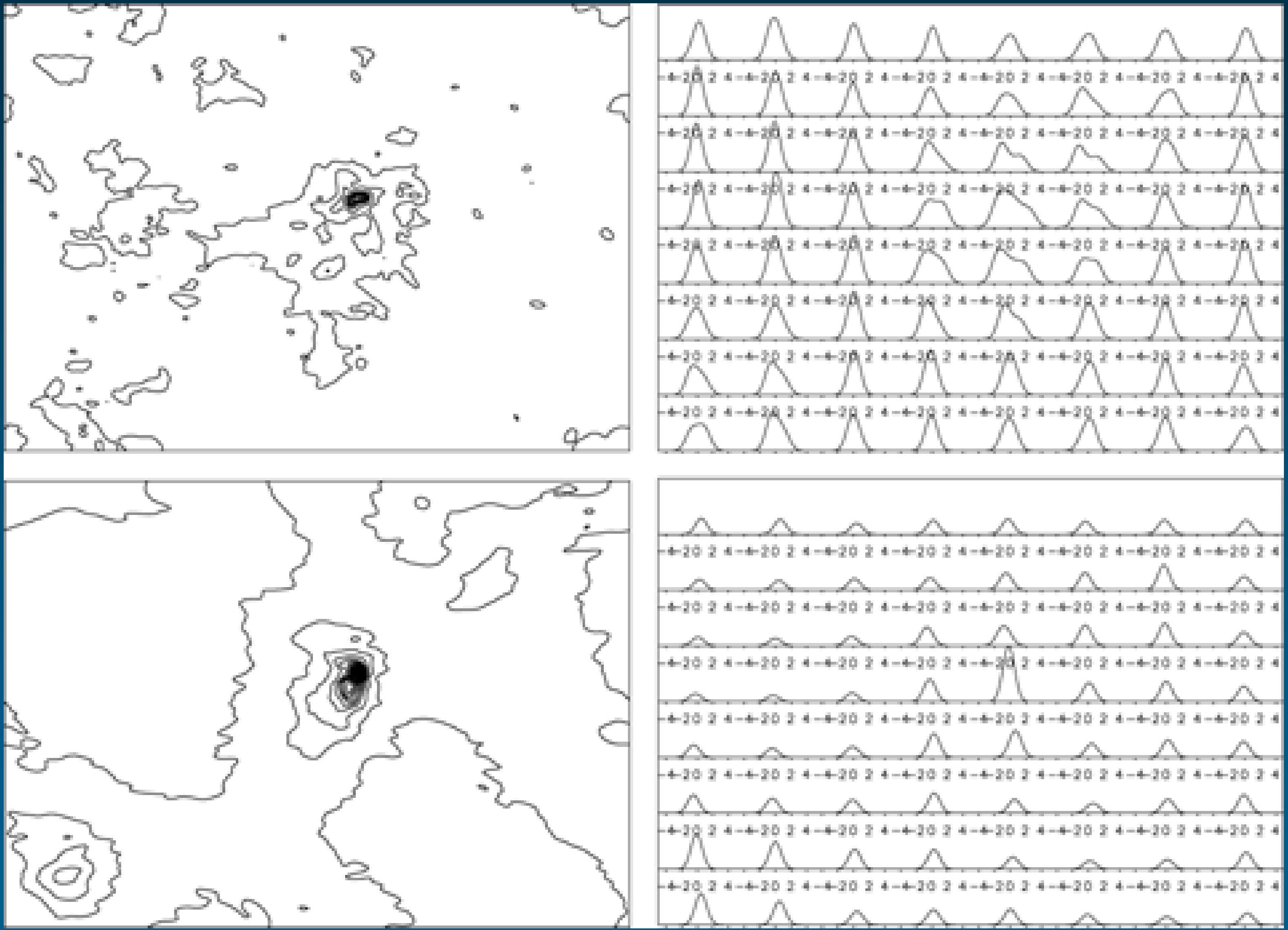
- spinning cores emit flux of Alfven waves extracting some angular momentum

Stage set for magnetized collapse… and formation of jets

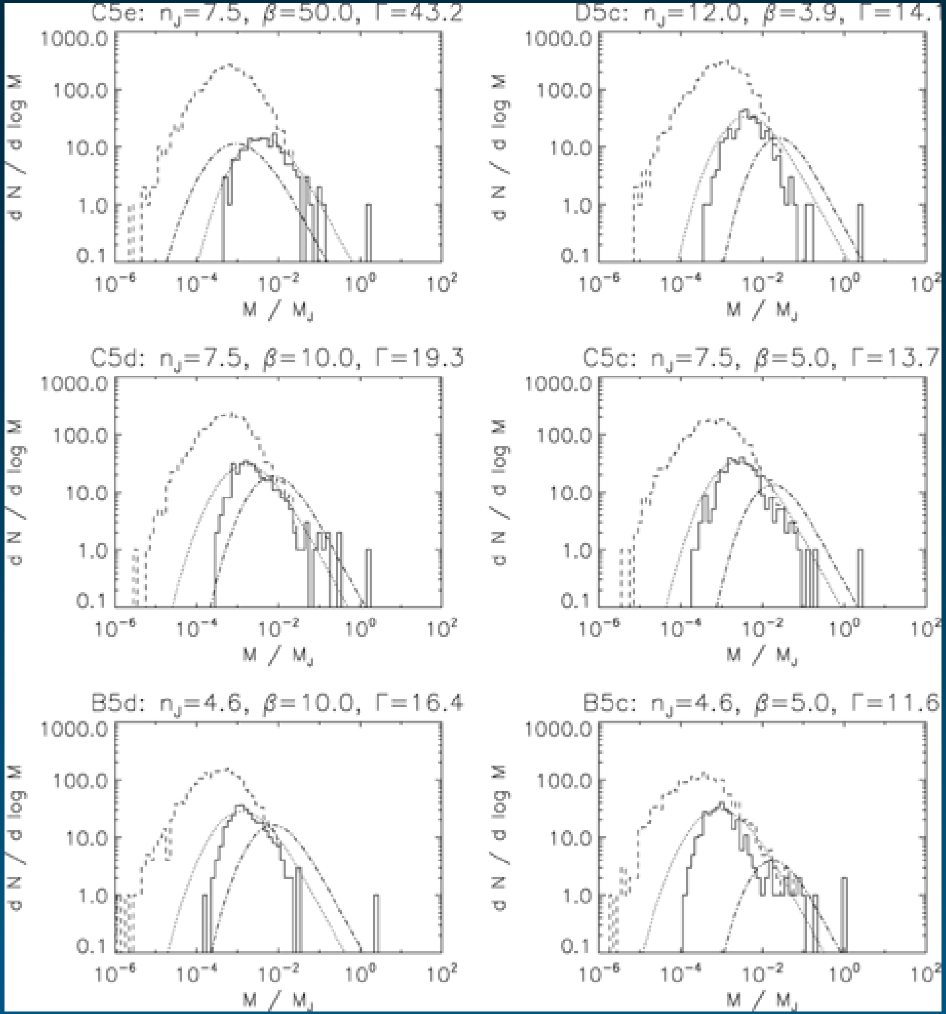


# Ammonia/CS (optically thin) emission from model:

- densities $n \approx 10^4 - 10^7$ (20K gas)

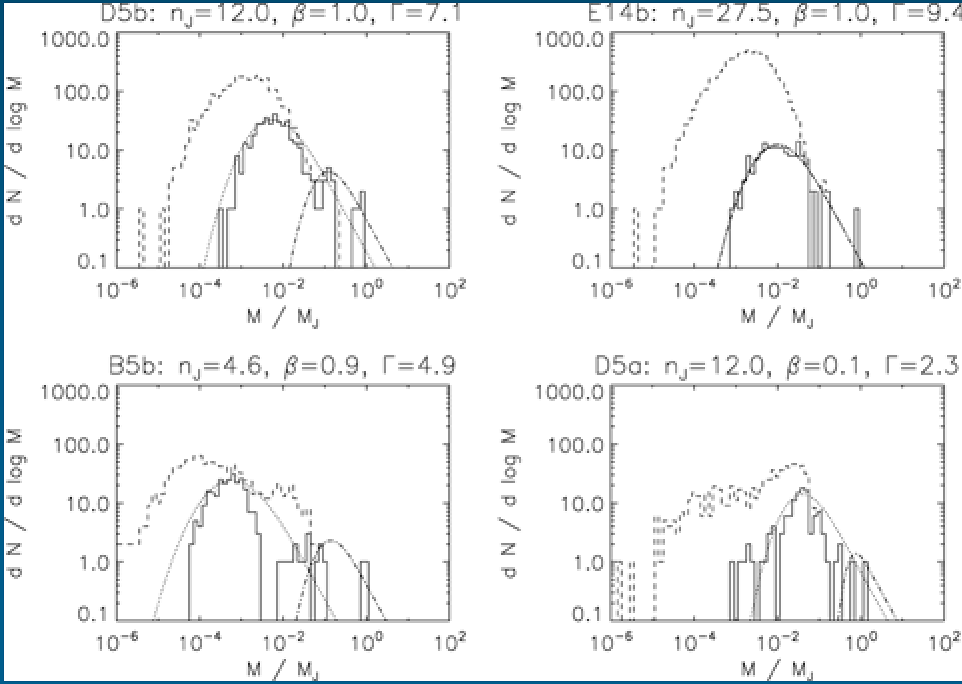


Column density map convolved by Gaussian, FWHM 32 pixels: at Orion, 16 arcsec



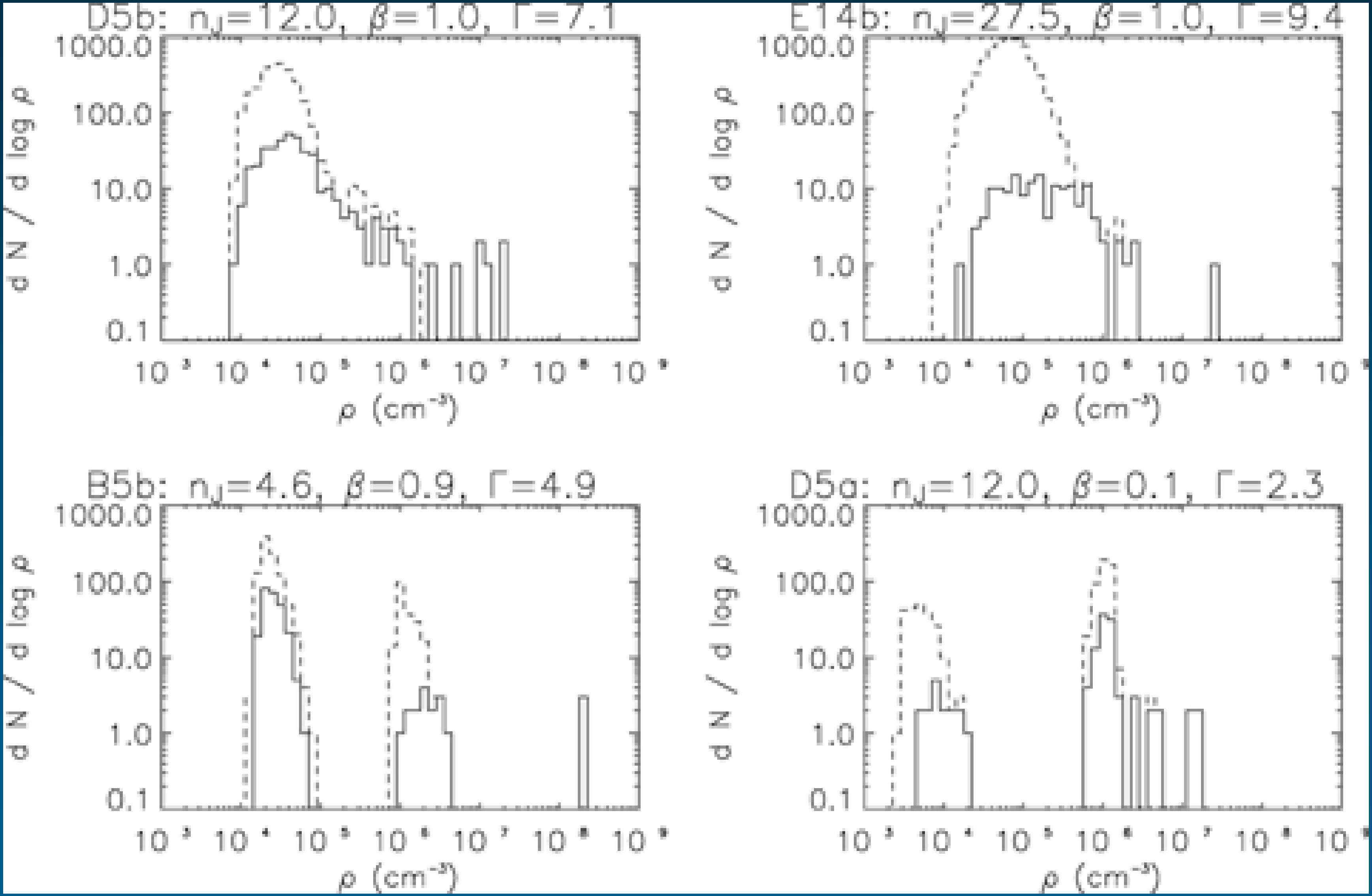
## Core mass functions (CMFs):

- Numerical data compared with PN02 models
- Even when corrected for BE mass and defn of Jeans length – PN02 misses peaks of numerical CMFs

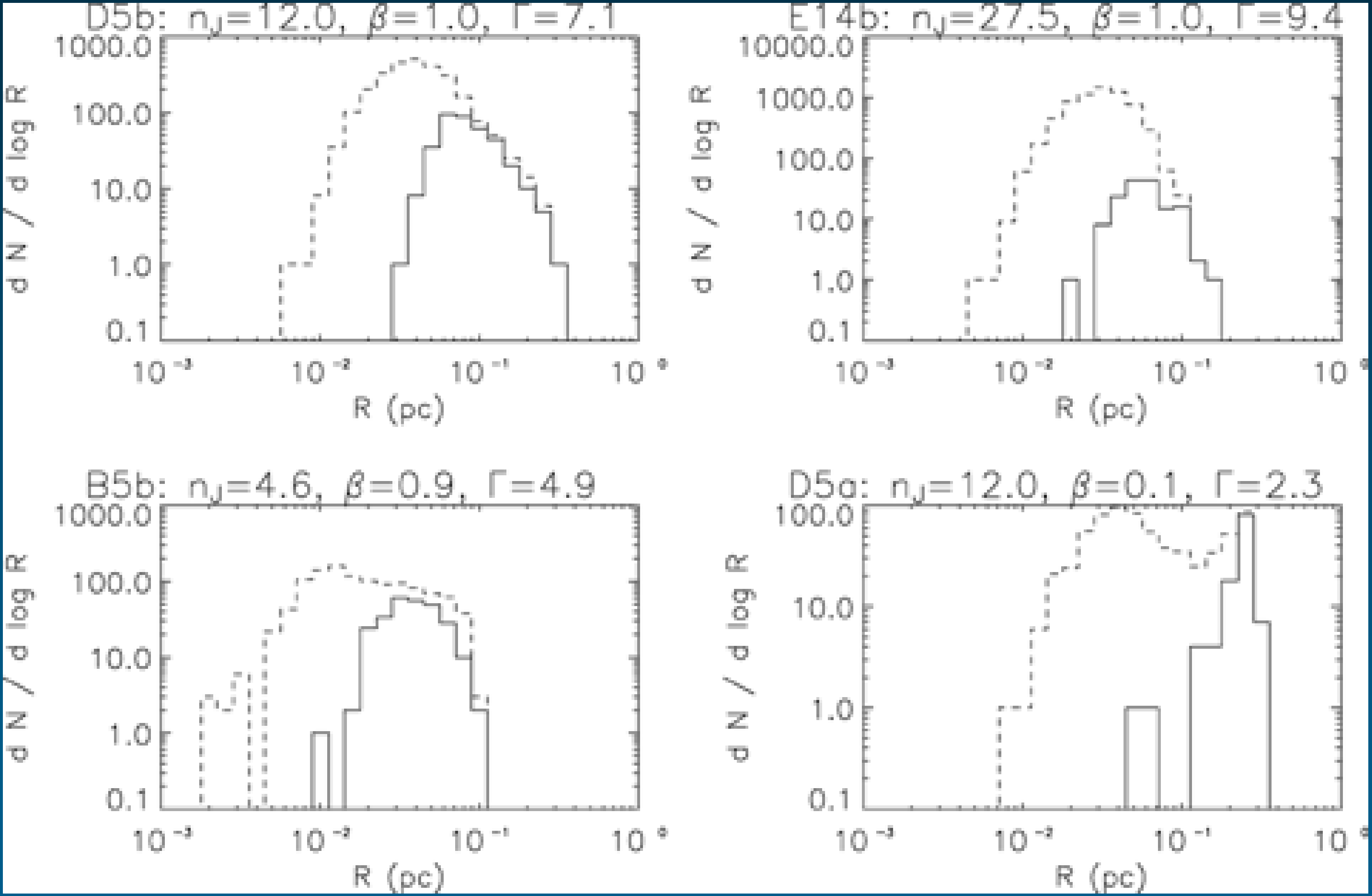


PN02 theory: peak of CMF at scale where Alfven Mach no. ~ 1

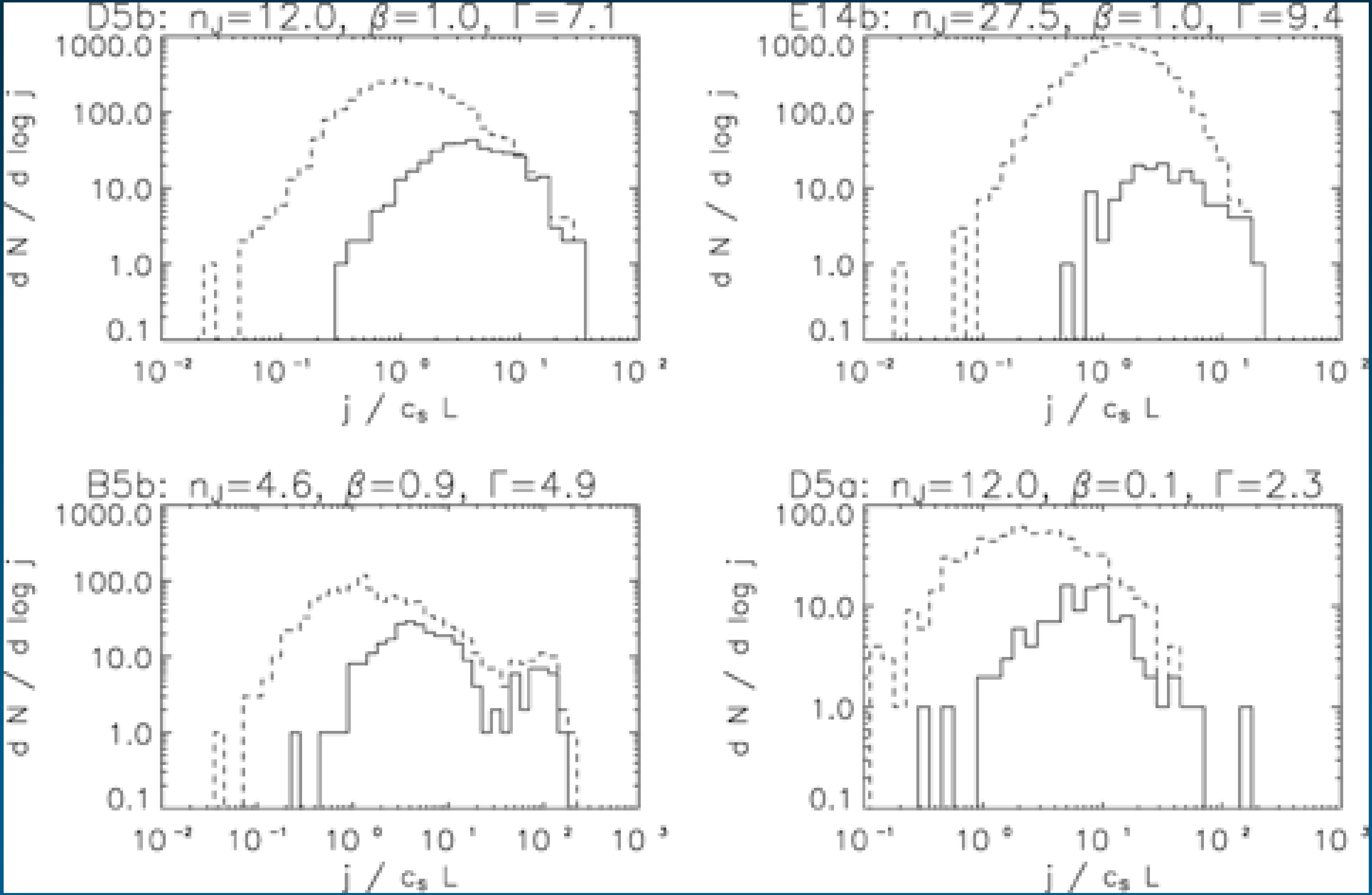
# Core, density distributions: range up to 10^7



# Core radius distributions: range from few .01 to 0.1 pc



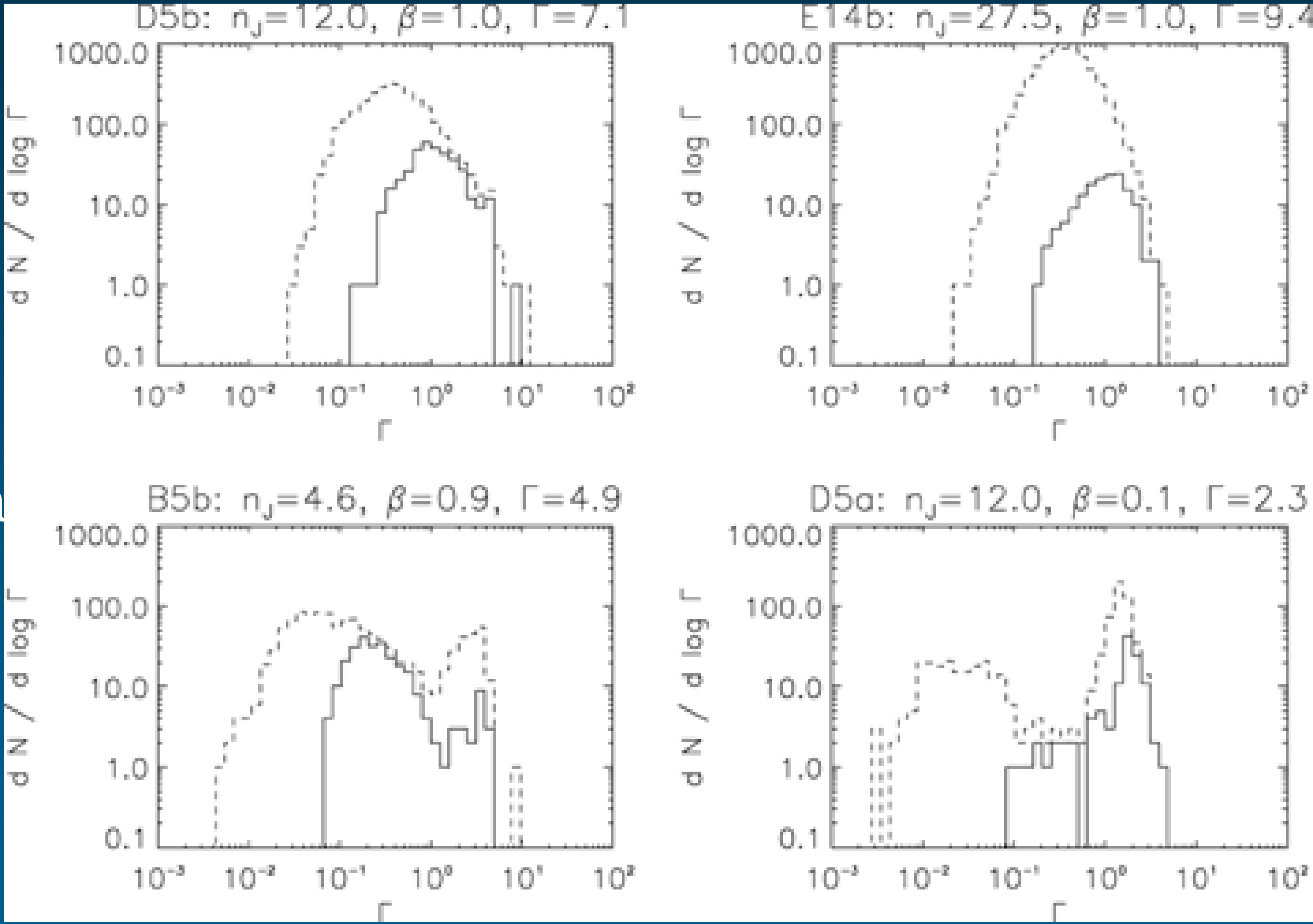
# Core, specific angular momentum distributions…



# Core, mass to flux distributions: local core Gamma is always *reduced* from initial uniform gas distribution! Ranges from supercritical to sub-critical

Arises from fragmentation of the gas..

(consider formula for Gamma)



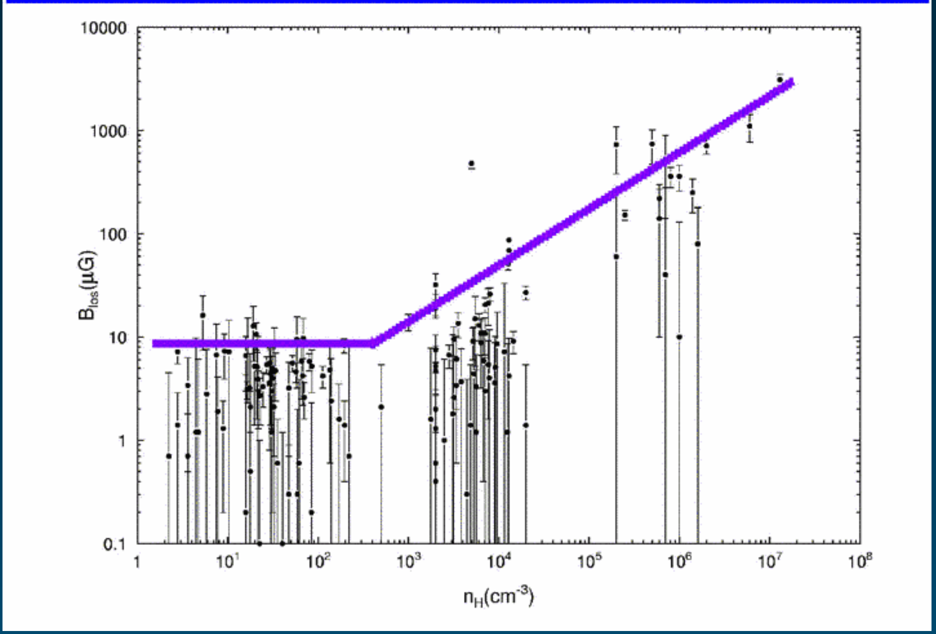
# Compare with distribution of B fields measured in cores (see Crutcher, KITP 2007 talk)

- Distribution of values of mass to flux values for cores is now supported by the data.
- Take home: initial clumps strongly supercritical – some cores

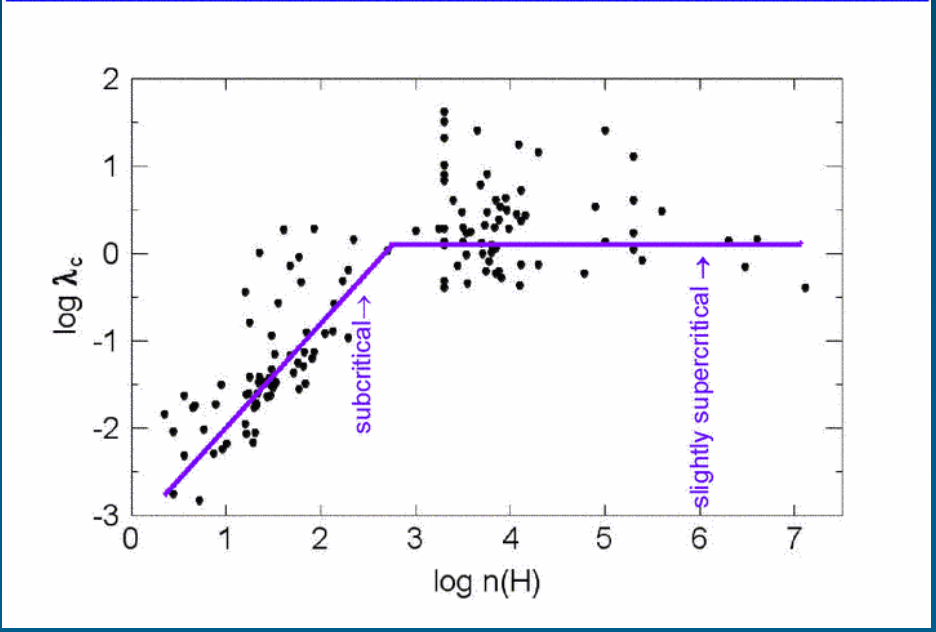
become strongly magnetized - later, and even sometimes subcritical.

(see PN02 and earlier)

Results for Field Strength



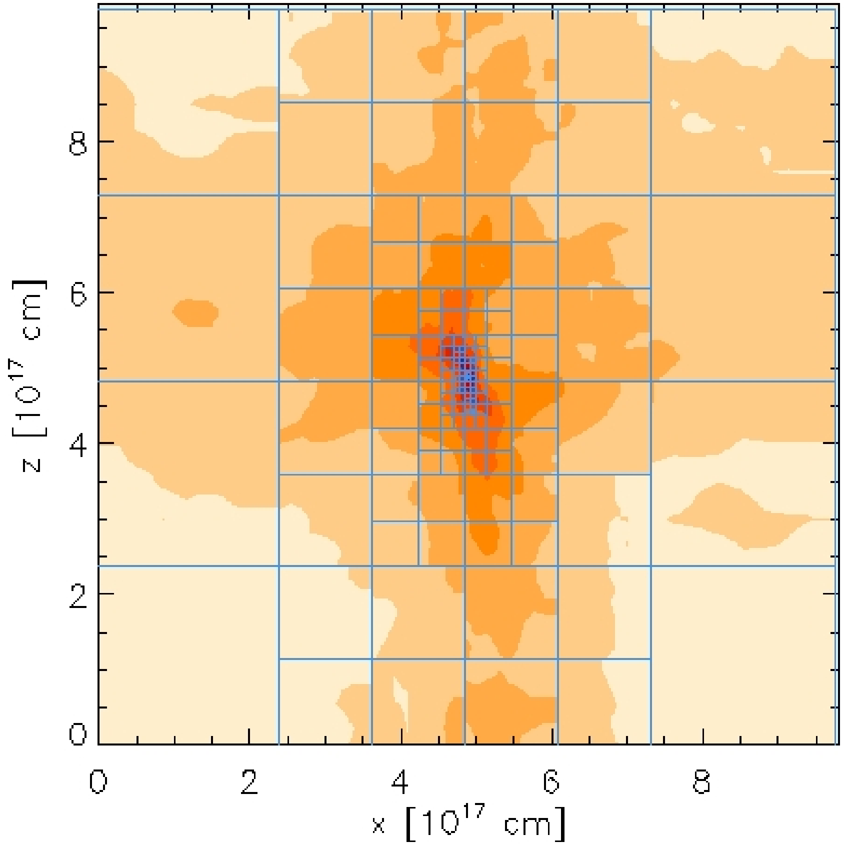
Results for Mass/Flux



# II: Following filamentary collapse and disk formation: FLASH – Adaptive Mesh Refinement (AMR) hydro simulation (Banerjee, Pudritz, & Anderson 2006):

- Grid adjusts dynamically to resolve local Jeans length (Truelove et al 1997); we use 12 pixels
- We added a wide variety of coolants including molecular + dust cooling, $H_2$ formation and dissociation, heating by cosmic rays, radiative diffusion, etc.

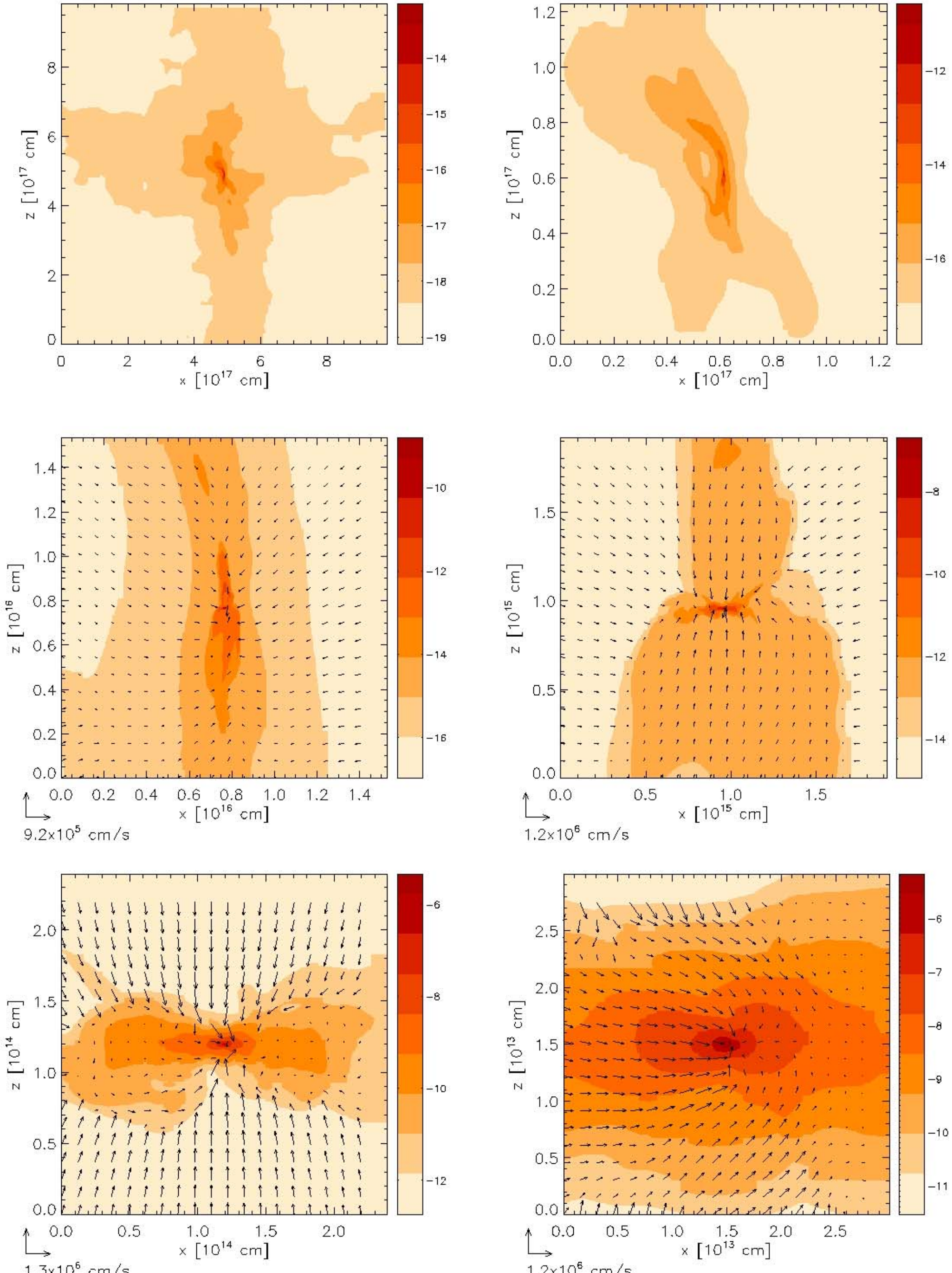
[Next project: B fields + AD + sink particles]



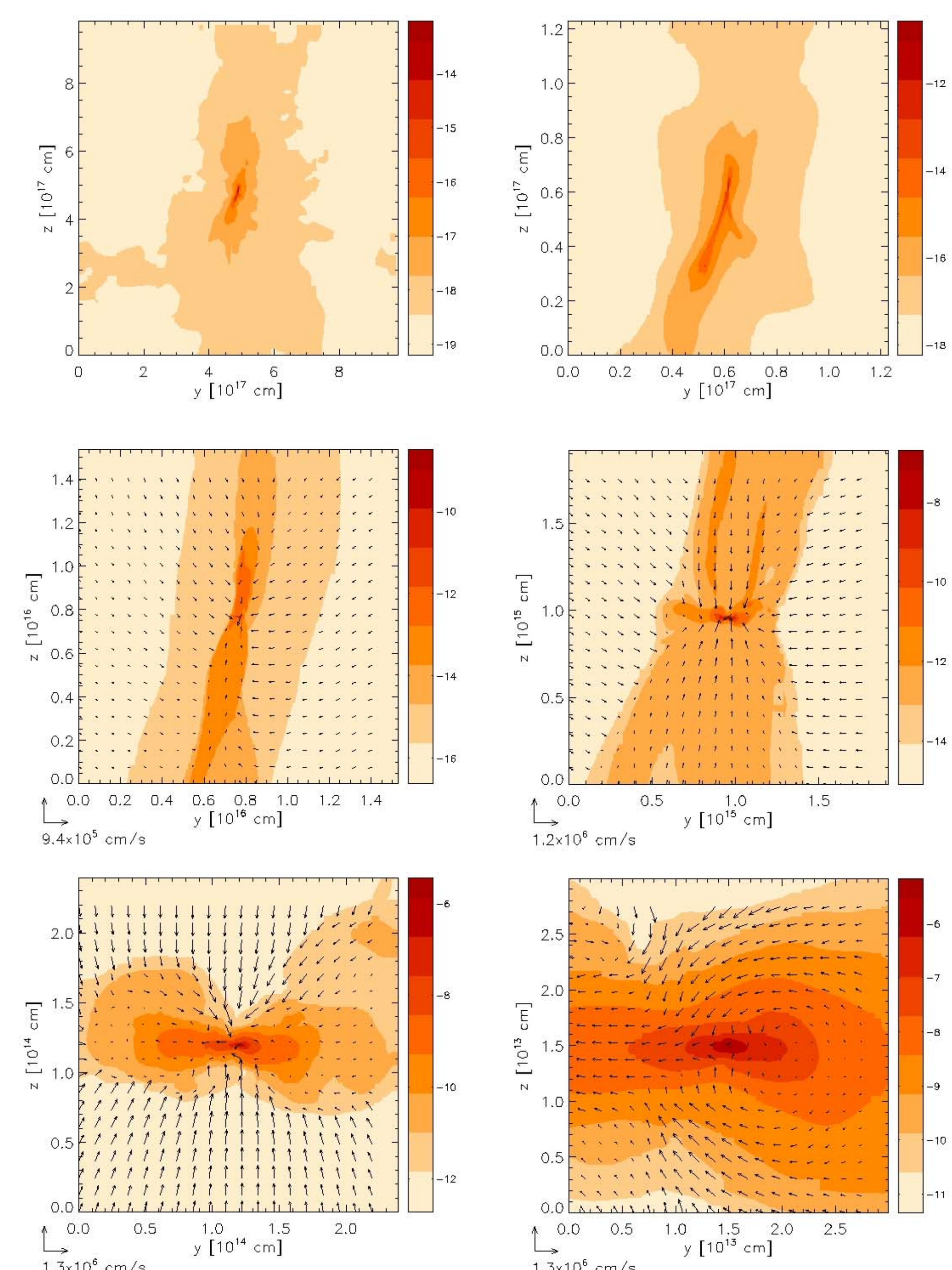
Filamentary structure: from 0.1 pc down to sub AU scale

- Large scale filamentary collapse onto a growing disk:

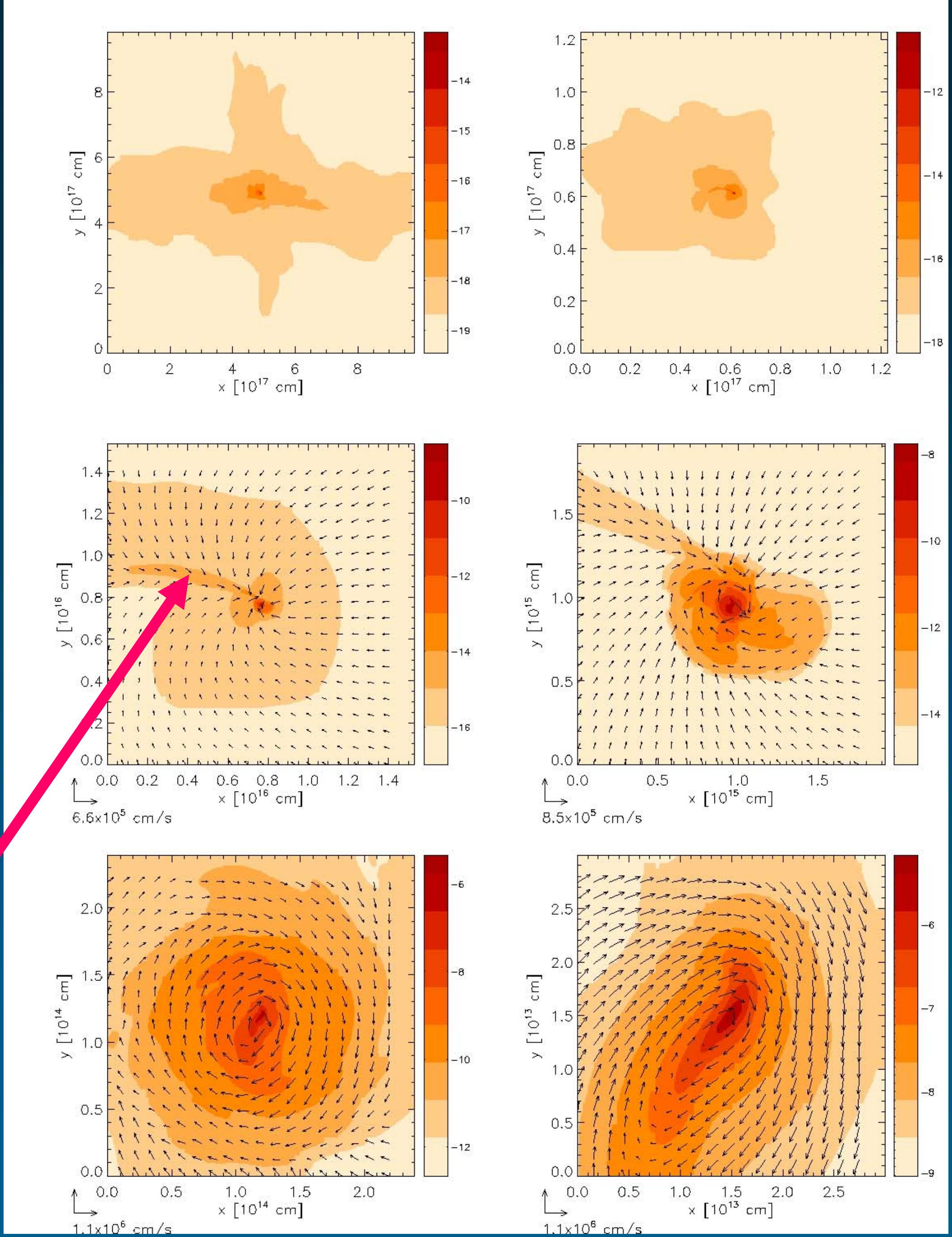
x-z plane.



- y-z plane along filament:  same as for x-y plane  -  are seeing a true filamentary collapse



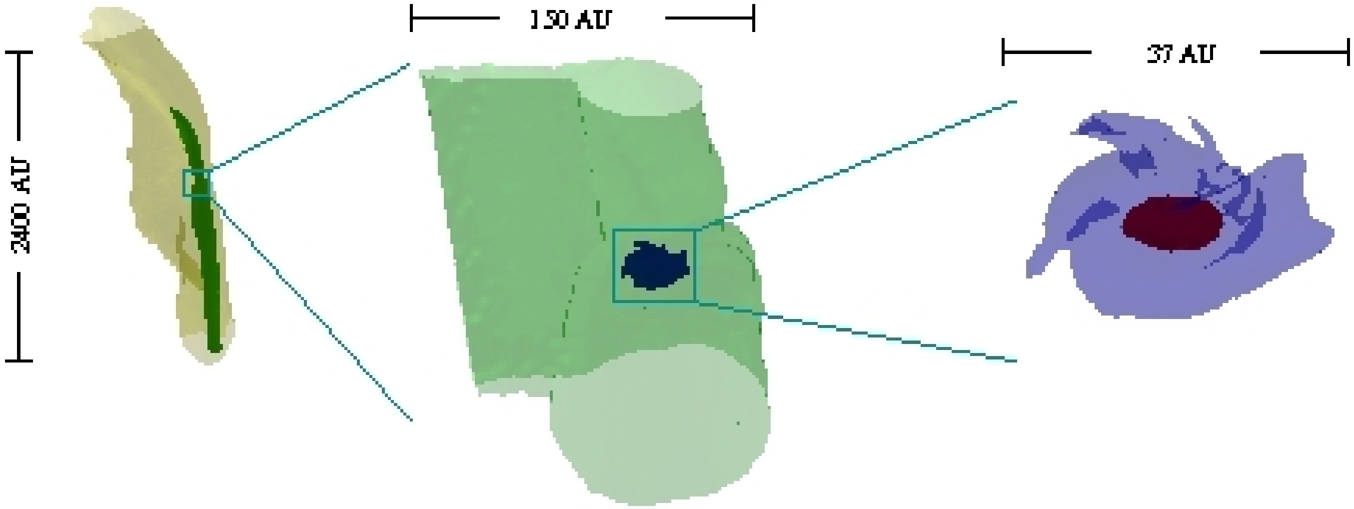
- Cut through disk midplane (x-y)
- accretion from an off-centre sheet of material disk provides angular momentum of the disk.
- highest resolution shows spiral wave structure
- sheet formation – notice velocity shear..



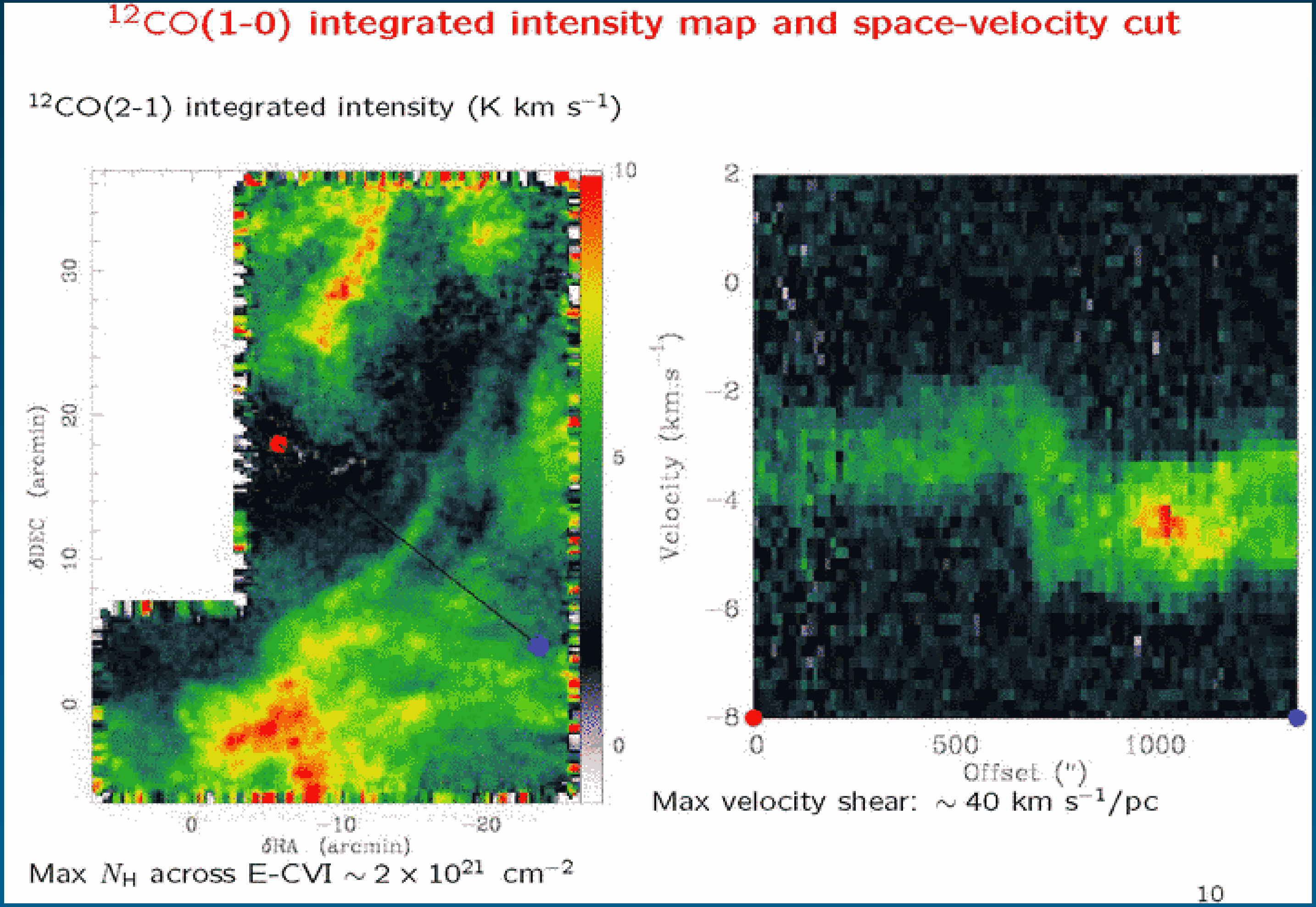
Filamentary collapse and formation of a protostellar accretion disk.

- Filament itself developing out of a sheet-like larger structure.

- Disk surprisingly “regular” in spite of highly non-uniform formation conditions.



# Shearing structures: does sheet formation explain observed velocity shear structures? [see Falgarone & Hily-Blant, KITP 07 talks]



**$^{12}$CO(1-0) integrated intensity map and space-velocity cut**

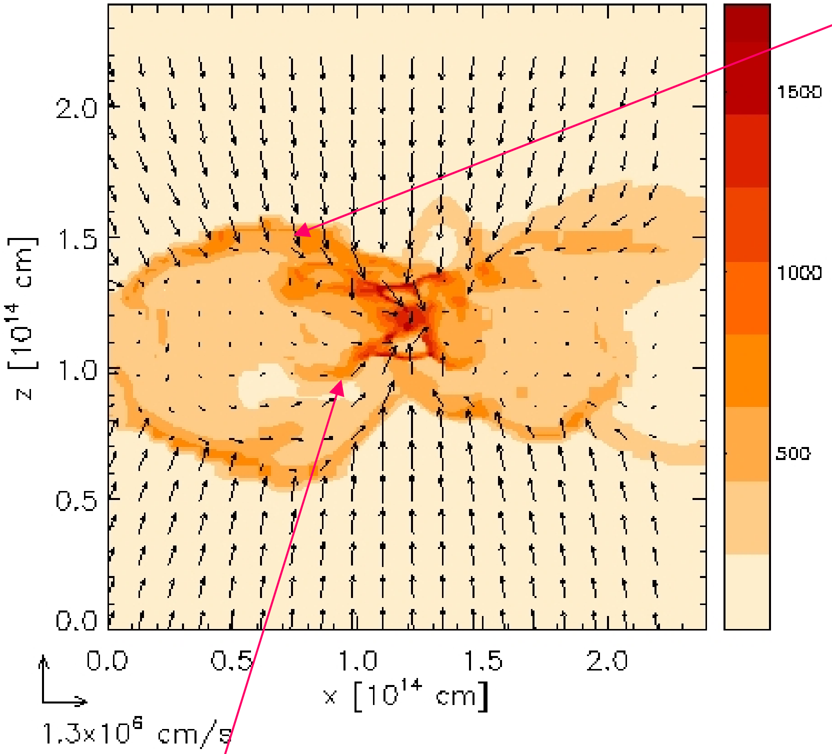
$^{12}$CO(2-1) integrated intensity (K km s$^{-1}$)

Max $N_H$ across E-CVI $\sim 2 \times 10^{21}$ cm$^{-2}$

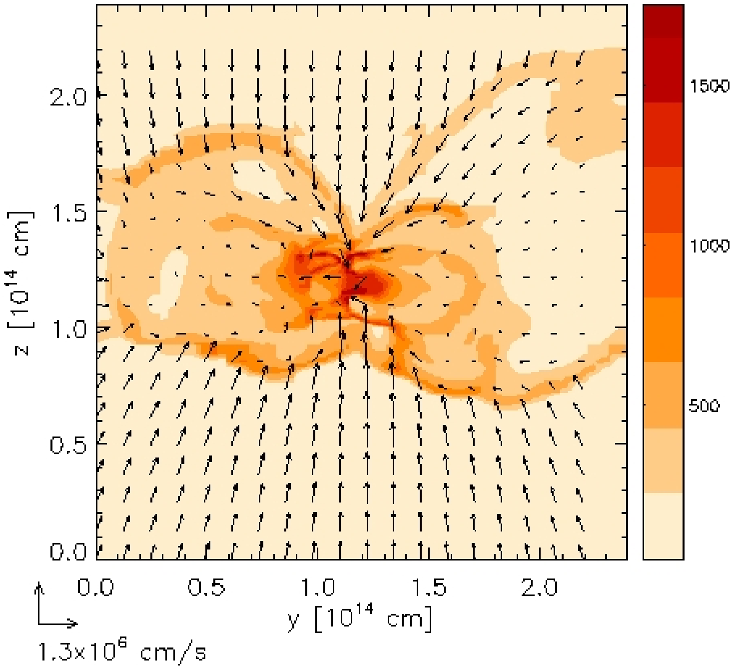
Max velocity shear: $\sim 40$ km s$^{-1}$/pc

# Disk temperature structure and cooling:

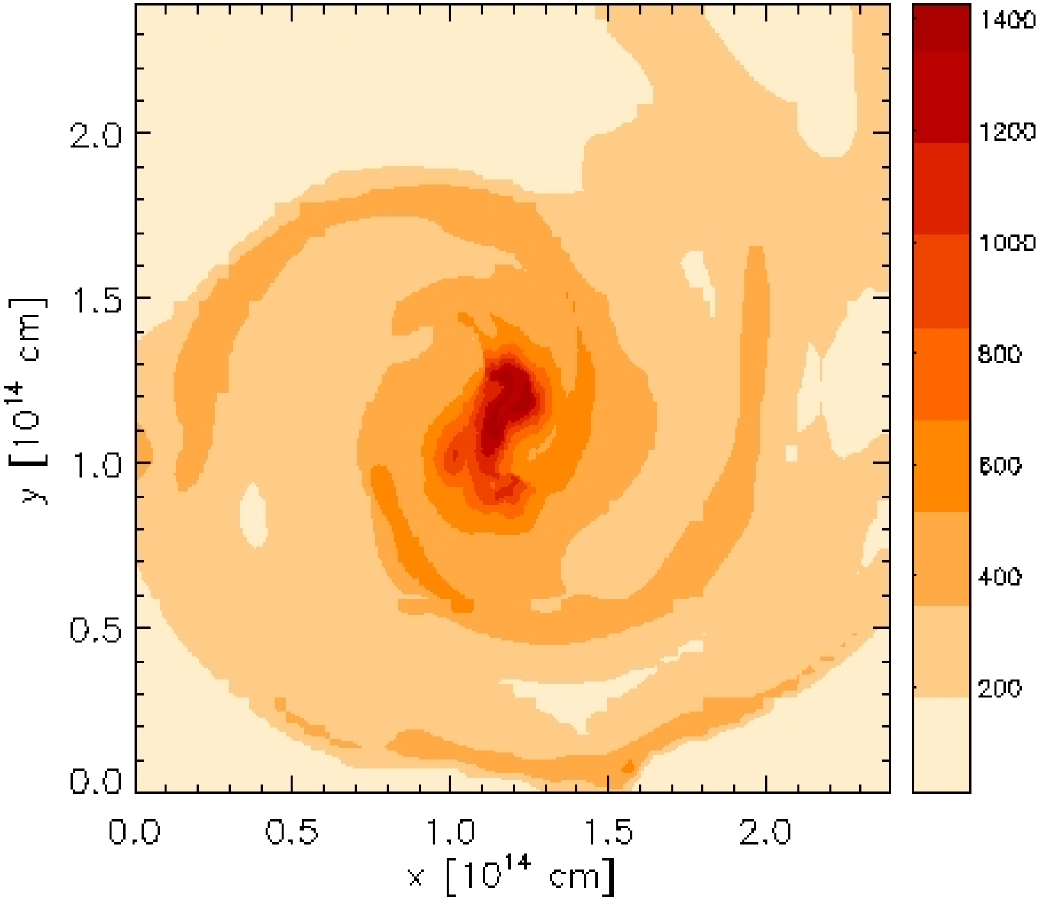
First shock set by dust cooling – on 10 AU scale



Second shock arising from $H_2$ dissociation…

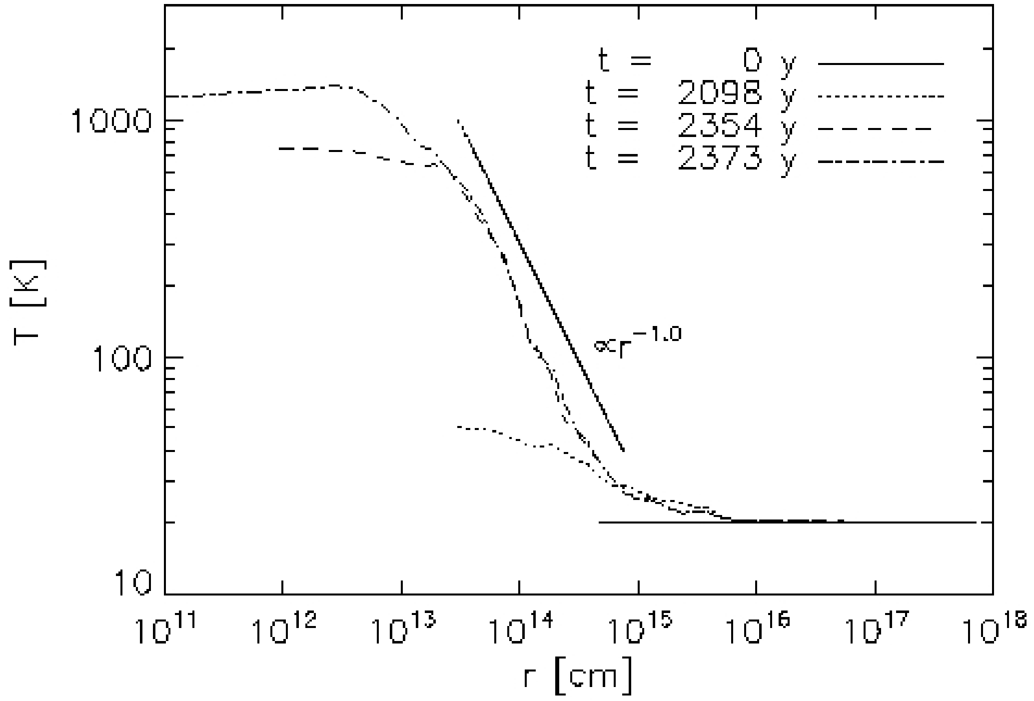


- Spiral waves in disk – appear to connect to a central bar



# Evolution of radial temperature profile

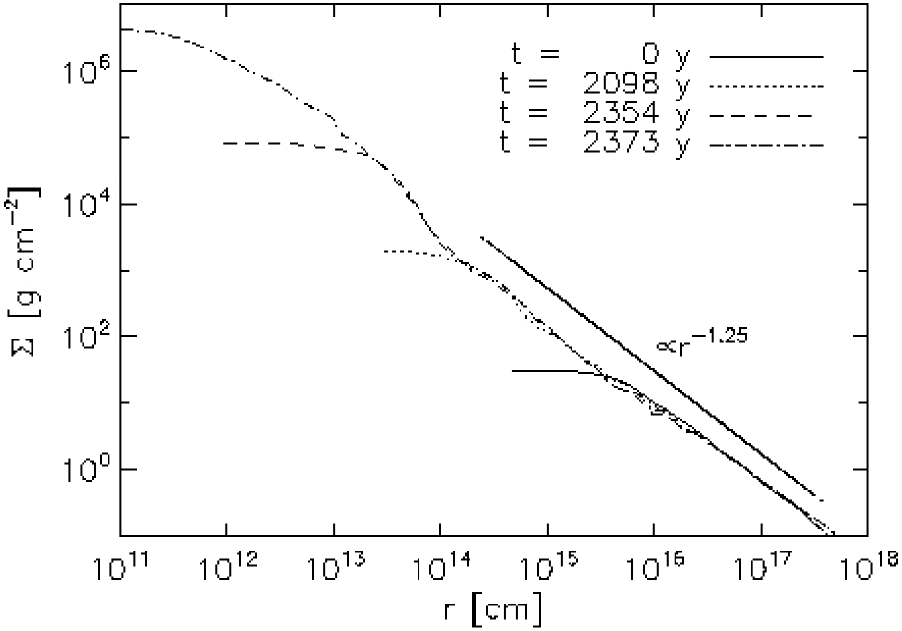
- Sharp transition to warm gas occurs at few 10s AU – marks the boundary of first accretion shock.
- Perhaps the most distinct observational feature

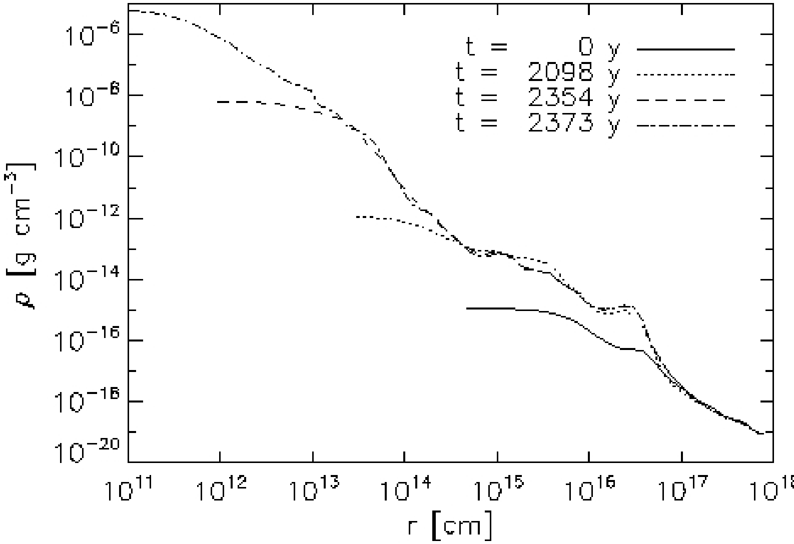


$$T \propto r^{-1}$$

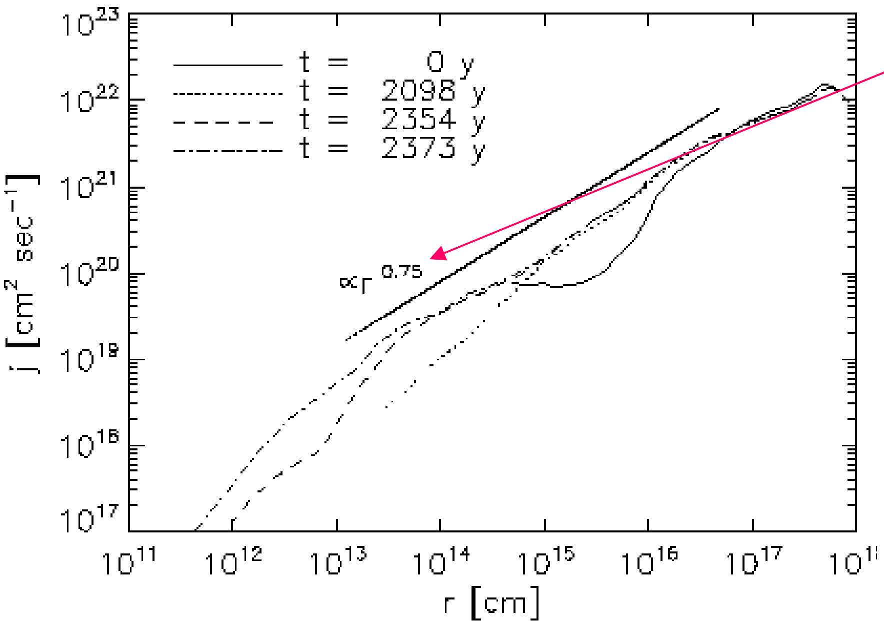
# Evolution of radial column and volume density profiles during collapse:

$$\Sigma \propto r^{-1.25}$$

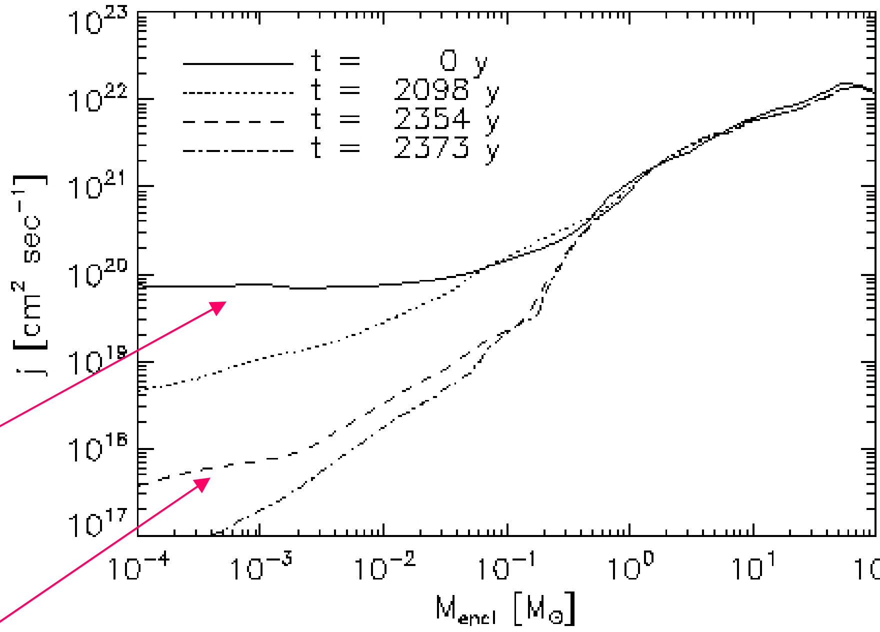




# Evolution of angular momentum profiles



Left: specific angular momentum $j_z$: stable…

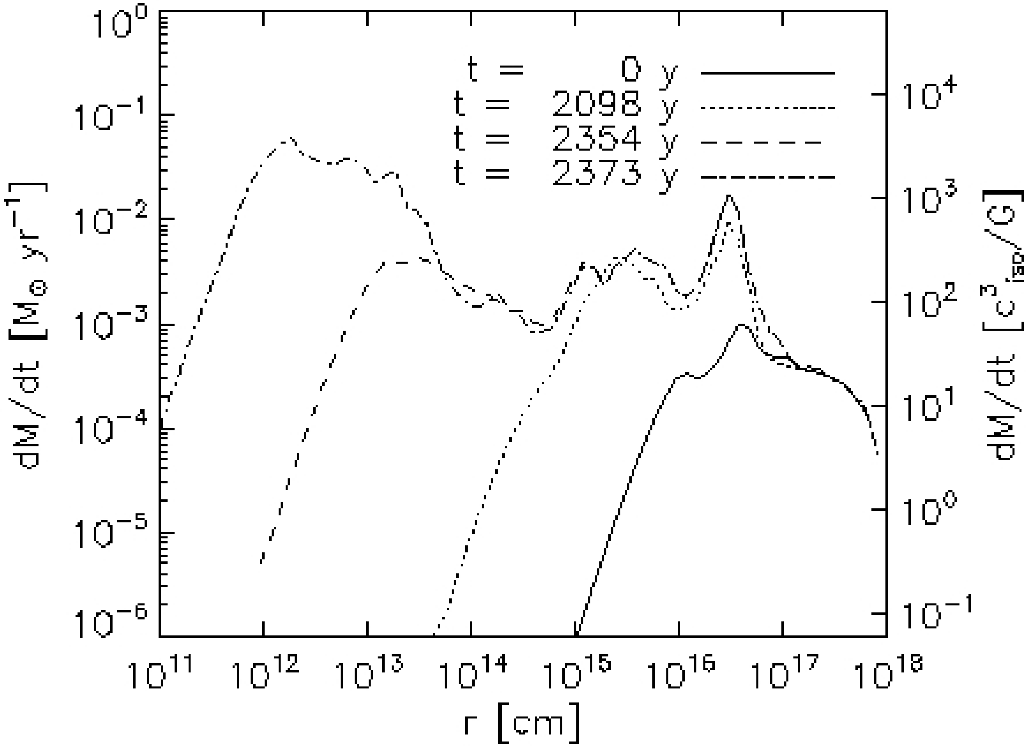


Right: Angular momentum per mass shell decreases with time:

extraction by spiral wave torque

# Evolution of accretion rates: radiation field will be strongly quenched if exceed

$$\dot{M} \simeq 10^{-3} M_{\Theta} yr^{-1}$$



We find huge accretion rates 10 times this value:

***Accretion rate exceeds naïve SIS model by 1,000 – and Bonner-Ebert sphere collapse by 20:

$$\dot{M} \simeq 10^{-2} M_{\Theta} yr^{-1} \simeq 10^{3} c_{iso}^{3} / G$$

# Filamentary flow summary:

- Filamentary collapse drives very high accretions rates – would allow massive star to form directly by accretion.
- High accretion results from supersonic gas motion and probably funneling of large amount of material into narrow filaments
- In absence of magnetic field – spiral wave torques extract angular momentum from accreting gas.