# Numerical Models of Phil's World: Recent Progress

Dense Cores in Dark Clouds LXV

Oct. 21-23, 2009

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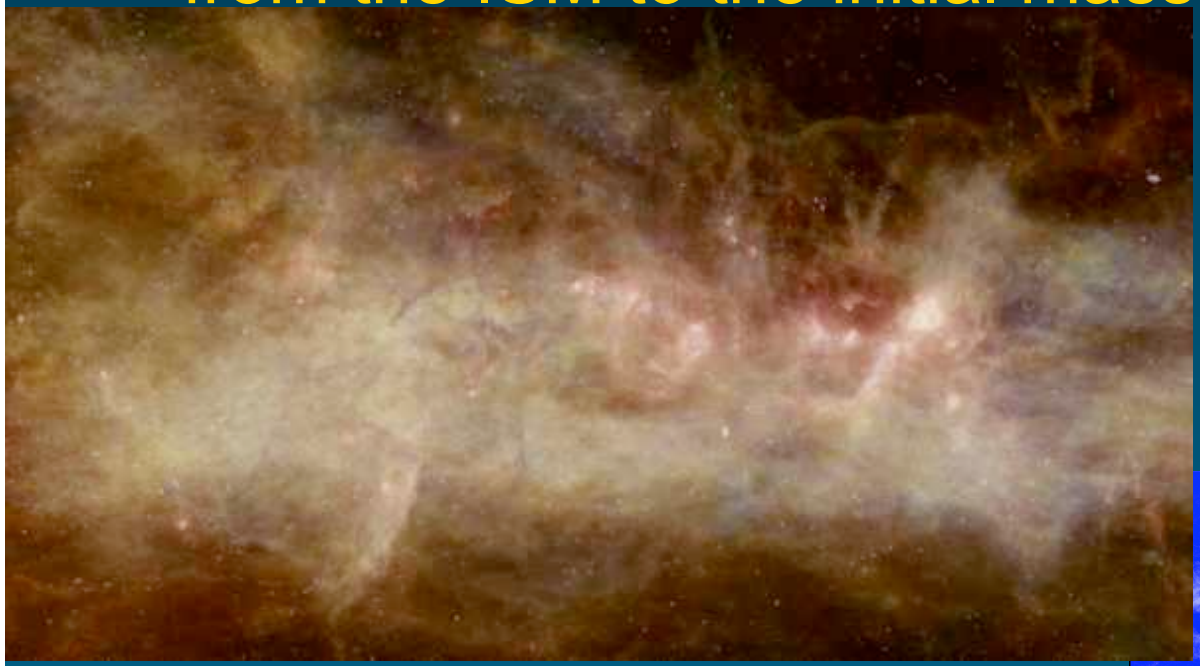
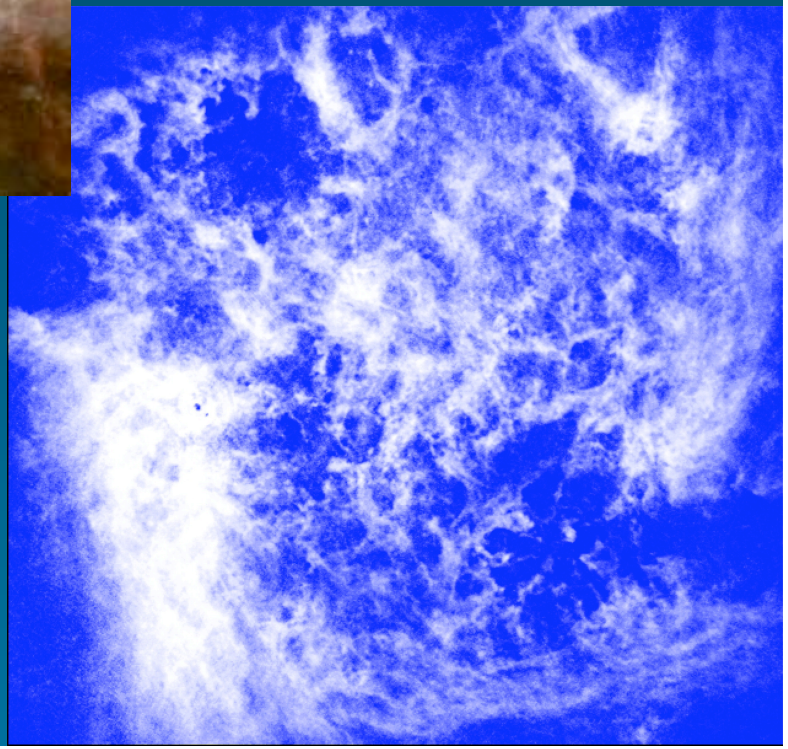
# 1. Star formation as a shocking multi-scale process - from the ISM to the initial mass function (IMF):

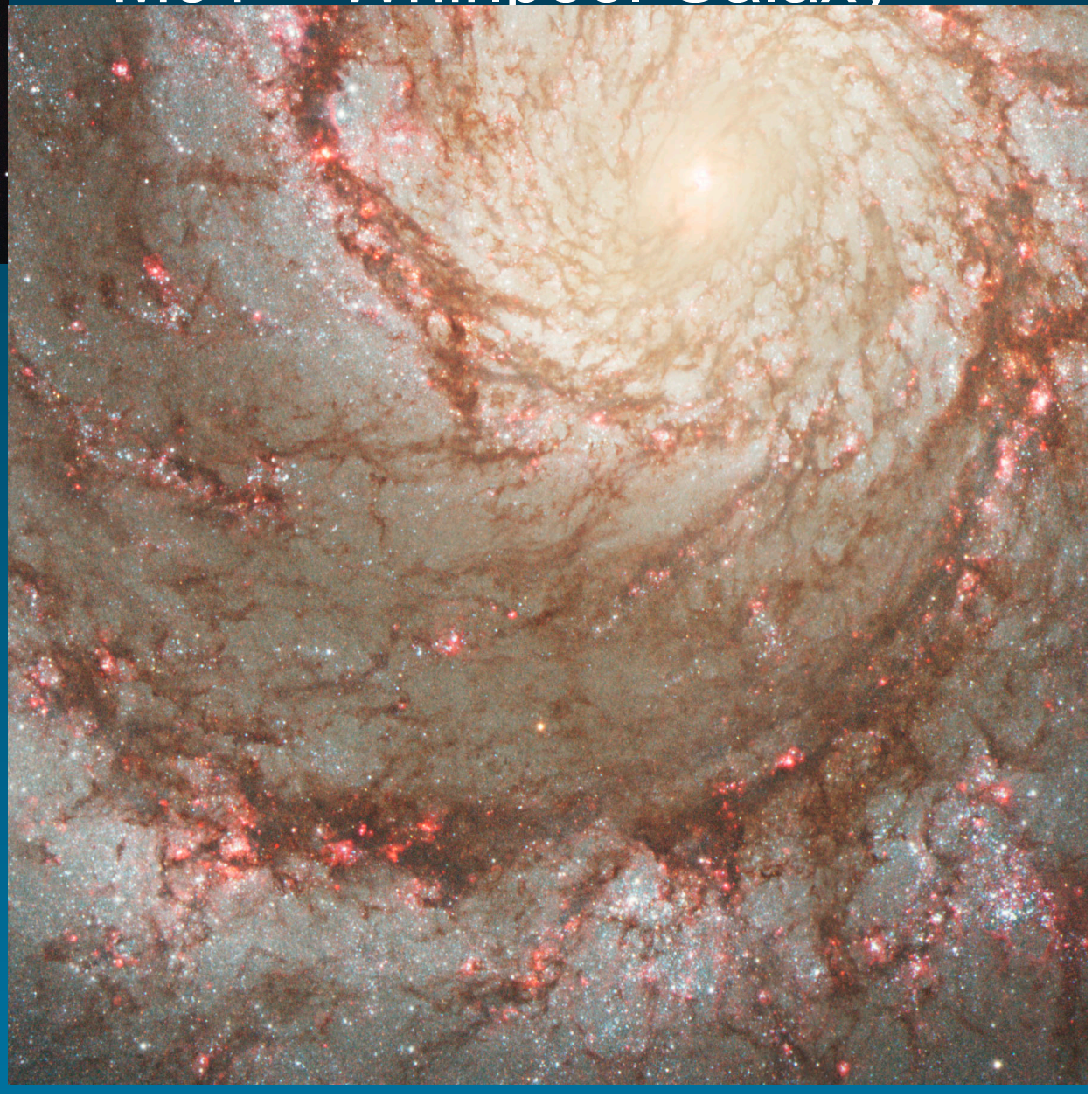


HI in LMC – Elmegreen et al 2001



Canadian Galactic Plane Survey - HI in midplane of Milky Way - near Perseus

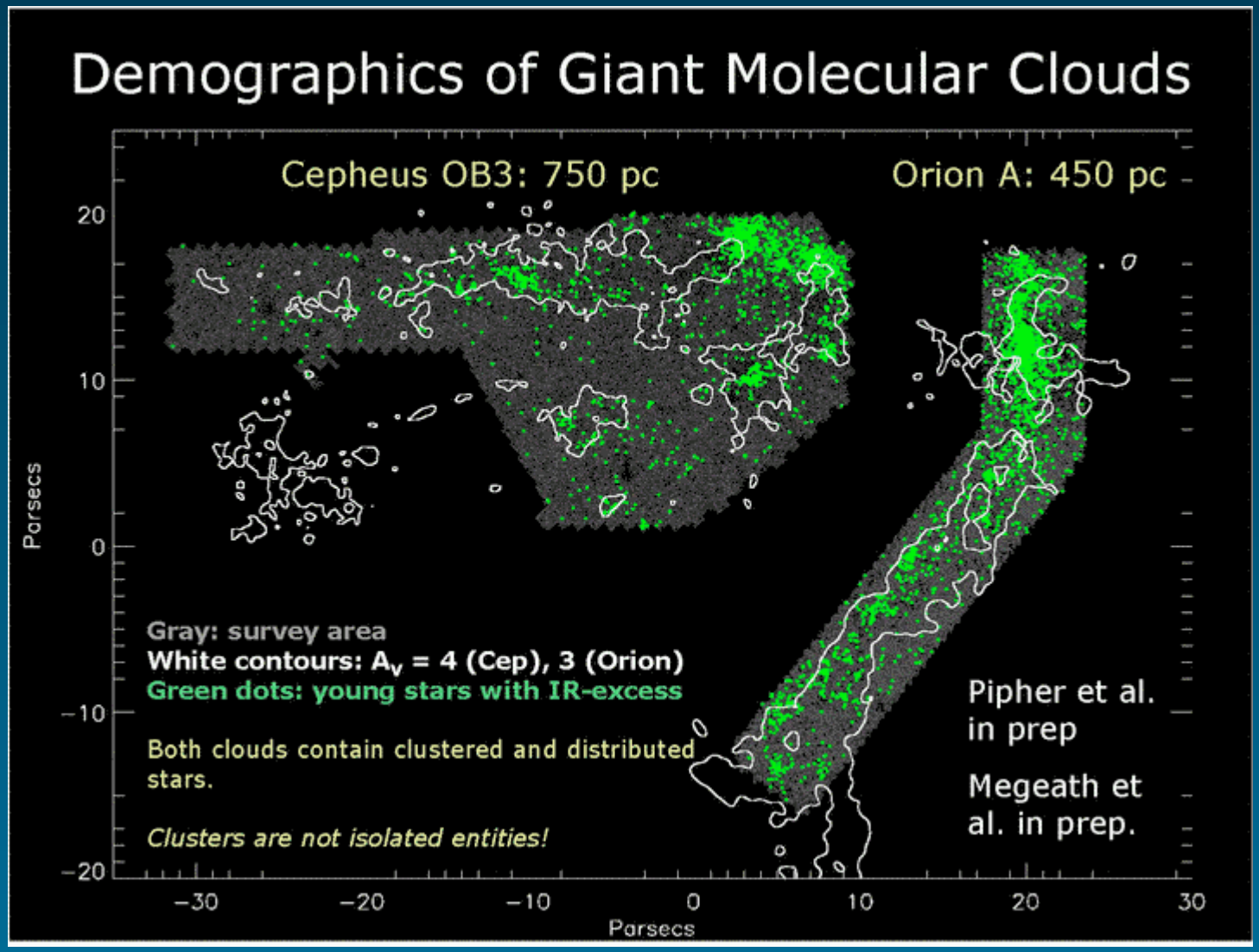
# Molecular gas
# M51 – Whirlpool Galaxy



Global spiral waves and shocks, and associated star formation.

Molecular clouds associated with dust seen in HST image

# Filaments – home to cores, stars, clusters…

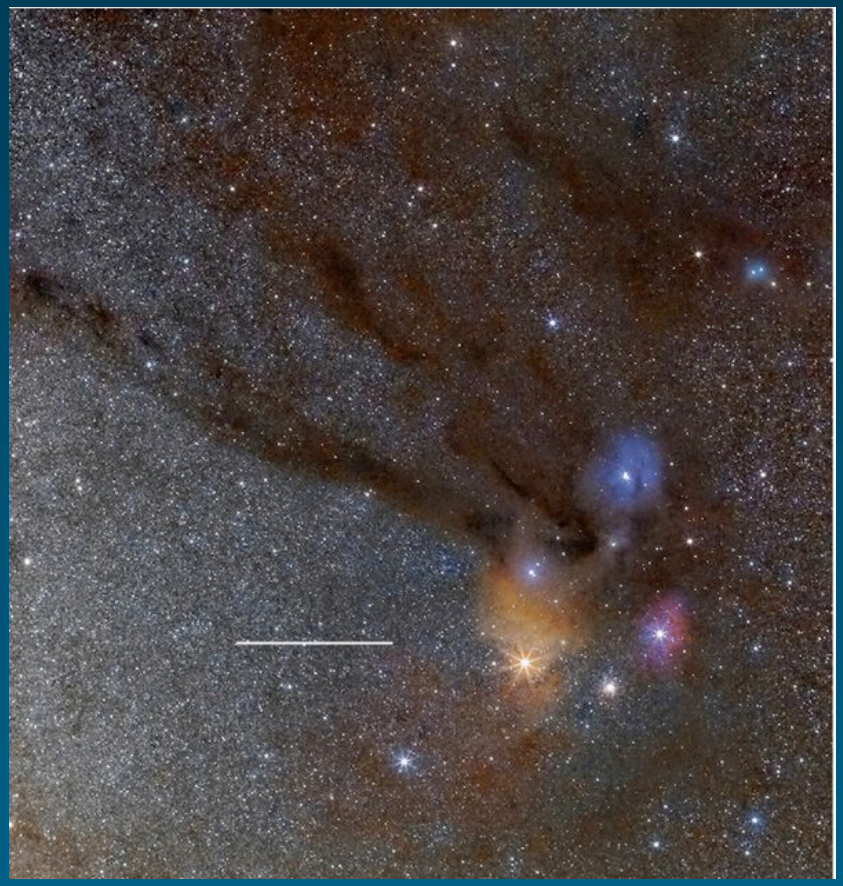



Megeath et al

c2d Spitzer legacy results:

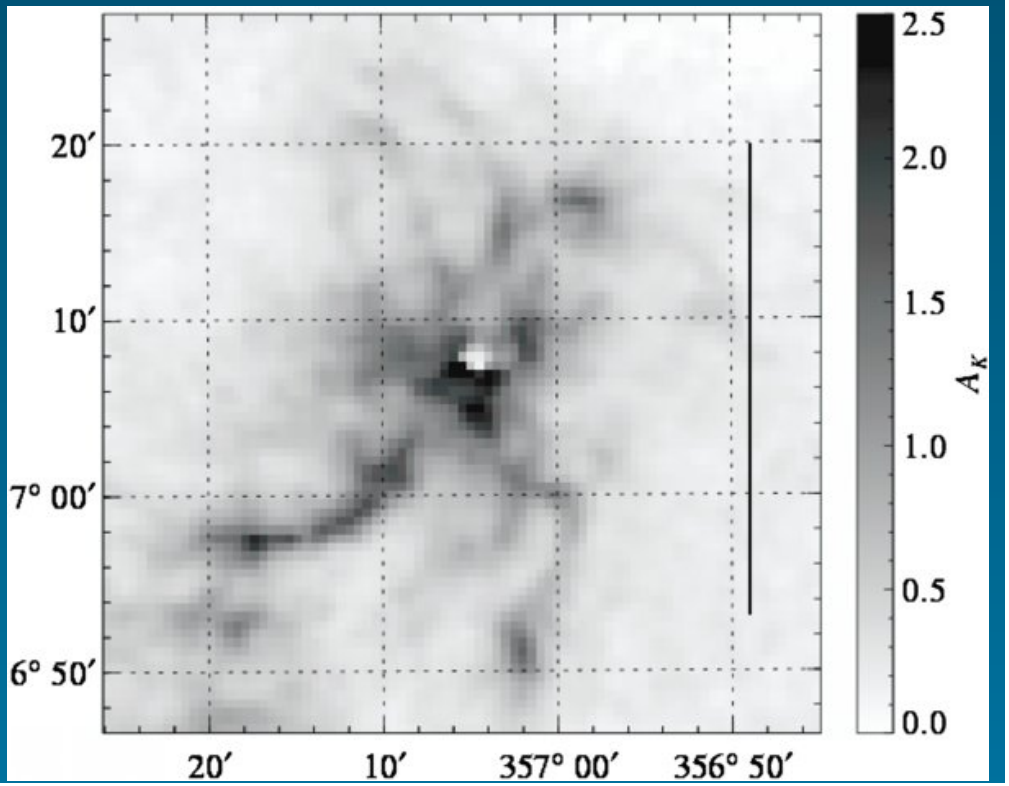
90% of stars lie within loose clusters.

(Evans et al 2009, ApJS



## The role of filamentary structure:

clusters of stars form in special places: hub - filament systems - in self gravitating sheets (Myers 2009)



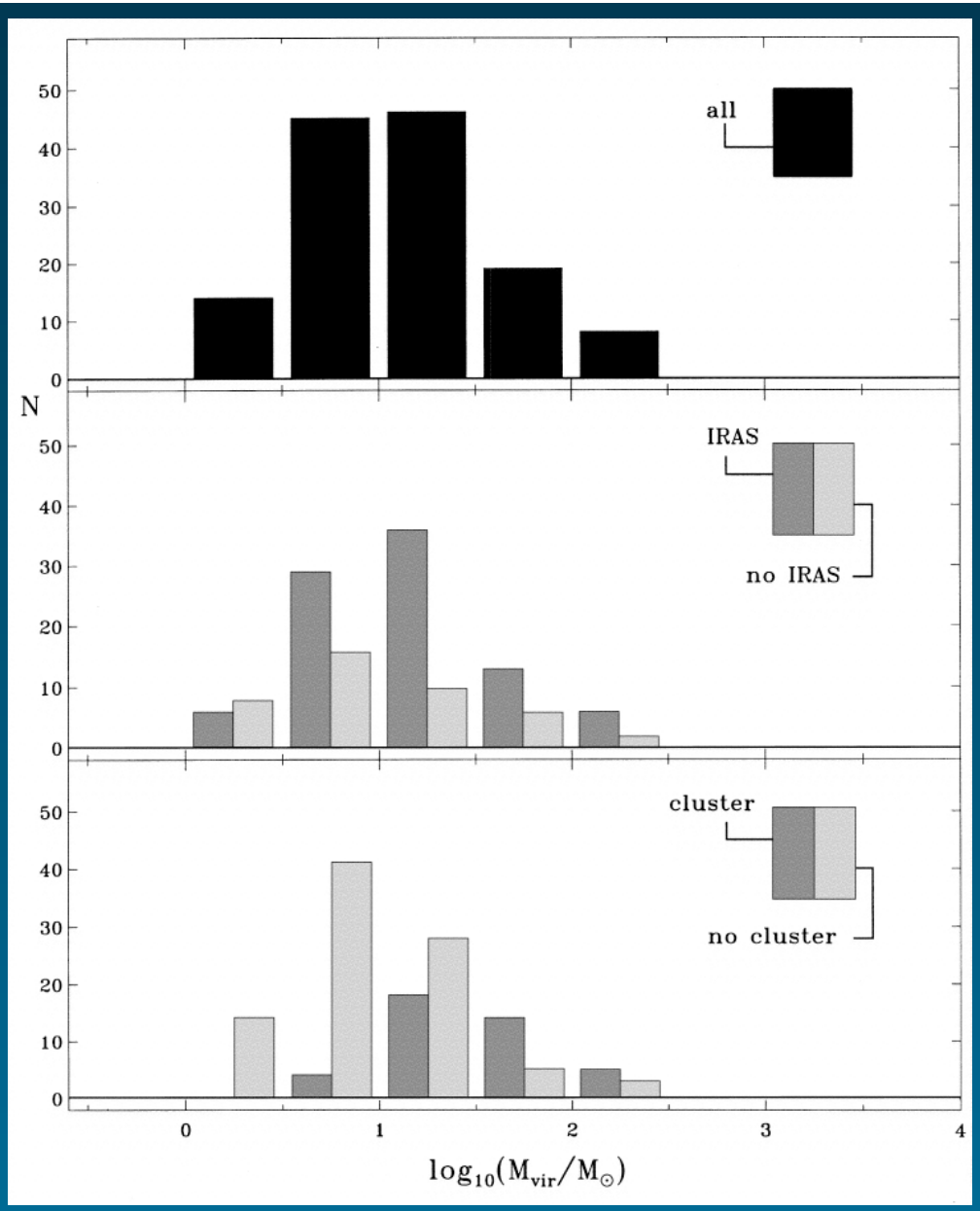

Above: Rho-Oph

Right: Pipe Nebula

# Cores as sites of individual star formation formation:

Field started by Myers and Benson:

- Individual stars form in cores
- "Core Mass Function" and core properties obey well defined, widely observed, distributions
- CMF tracks the IMF: Motte et al 1998, Testi & Sargent, Johnstone et al 2001, Enoch et al 2008

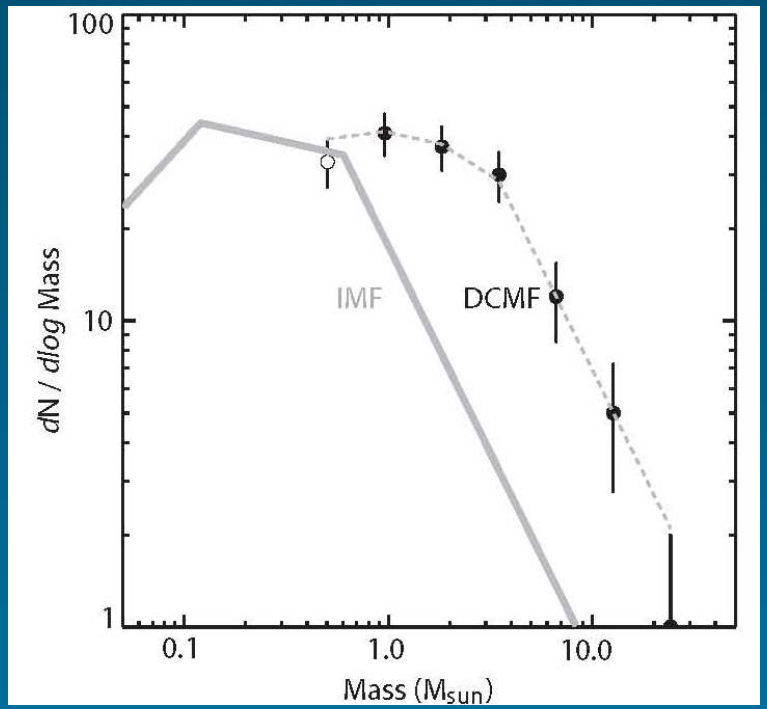



Jijina, Myers, & Adams 1999

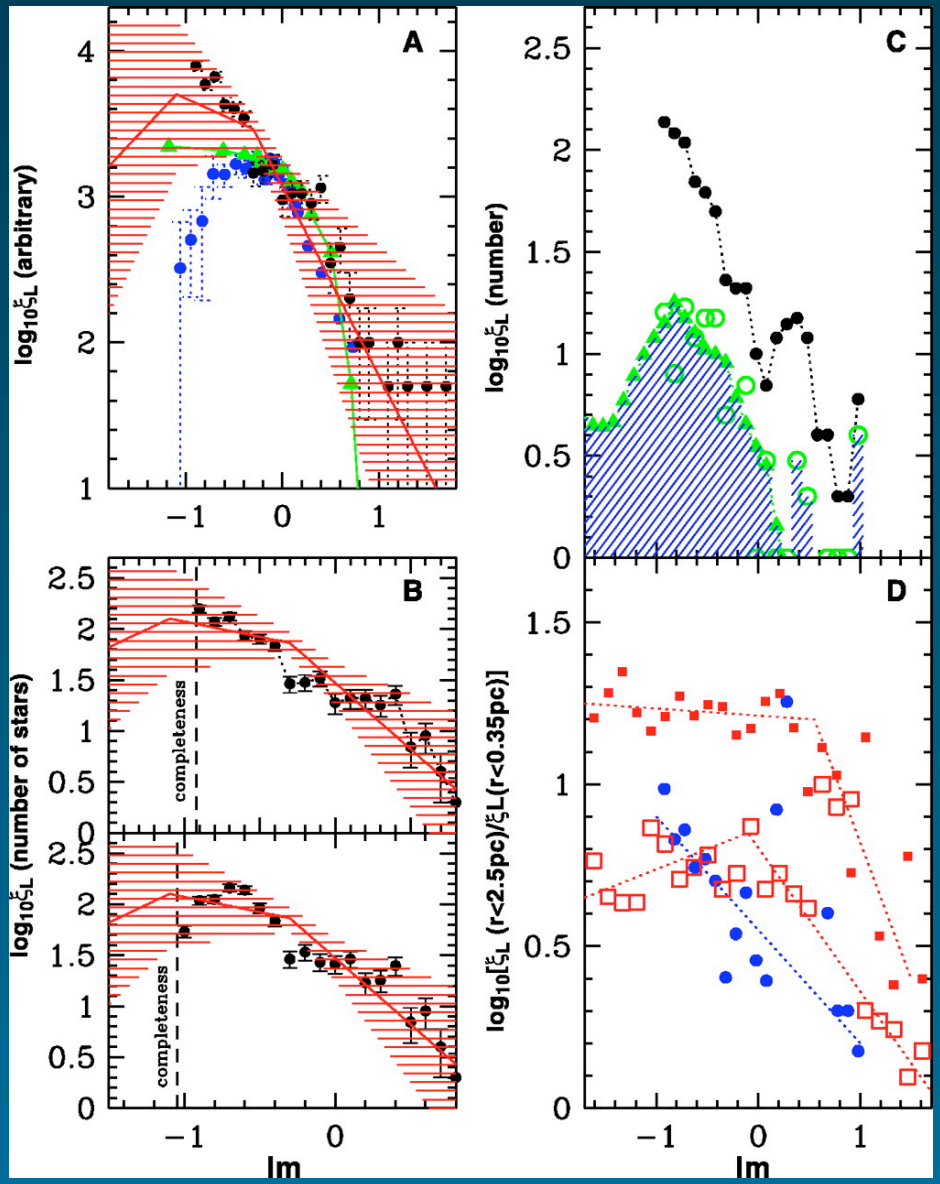
# Stellar mass spectrum - the “initial mass function” (IMF)

- Broken power laws(Salpeter) at high mass: - 1.35 if plotted with log $M_*$)
- Lognormal + power law (Cabrier 2003, Hennebelle + Chabrier 2007)

## Link between CMF and IMF:




Alves et al 2007 (Pipe Nebula)




Kroupa 2002, Science

# Phil's world:
# star formation fundamentals

- Physics of cores – from low to high mass stars
- Turbulence, CMF, and structure
- Origin of the IMF?

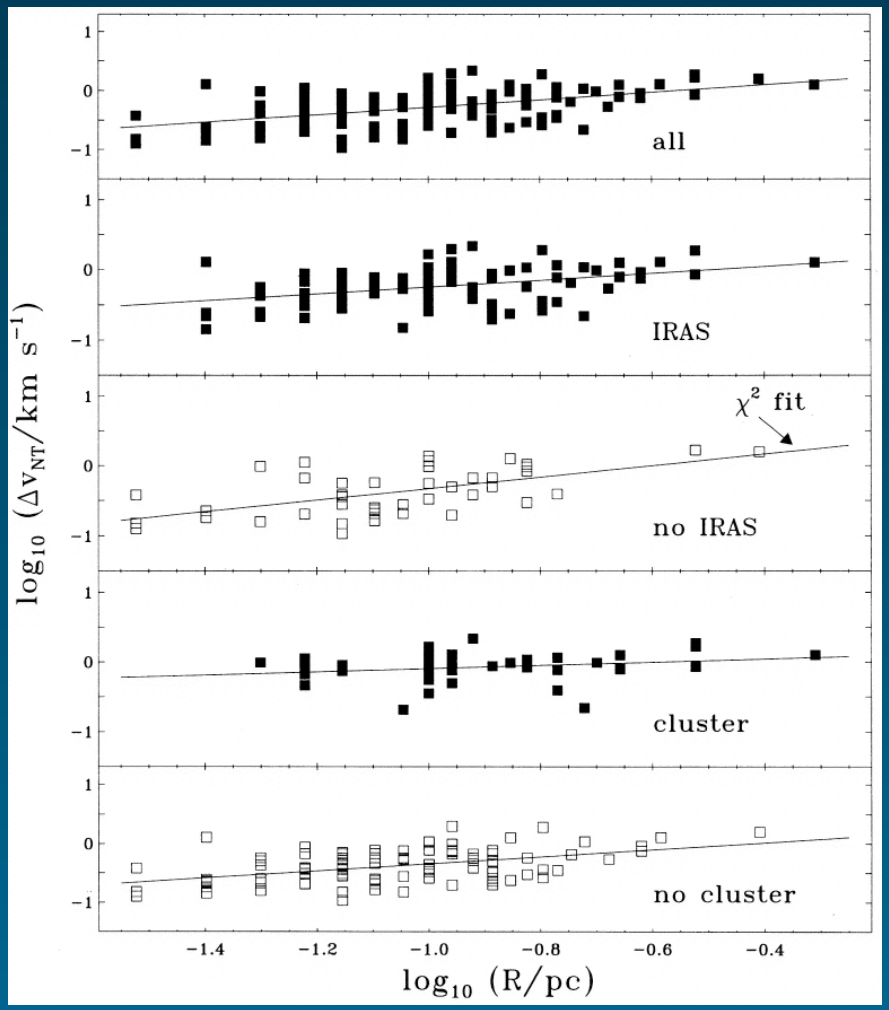
# 1. The physics of cores – from low to high mass stars

- Going beyond the Singular Isothermal Sphere - Myers & Fuller (1992) “TNT” model

- SIS models do not work on large scales, or form massive stars - need model for non-thermal structure on larger scales…
- combine observed thermal motions on small scales (<0.01 pc), with non thermal motions (0.1pc) on larger scales.
- works for masses 0.2 – 30 solar masses:

  time formation times (0.1-1.0 million yrs) fall within constraints of later data.

- Model: density follows isothermal behaviour at small scales thermal scales, and 1/r at larger nonthermal scales
- Accretion rates for massive stars (3-30 solar masses), are 7-10 times larger than low mass stars (0.2 – 3 solar masses)
- Truncation by outflows
- This paper spawned many other studies…

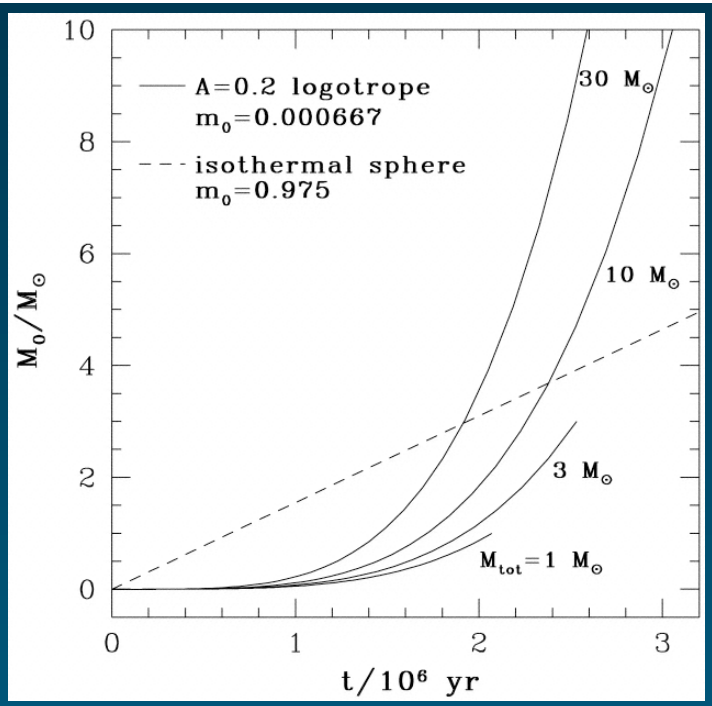



Jijina et al 1999

- Limit of massive stars in highly turbulent media – "logatropes" (n ~ 1/r)

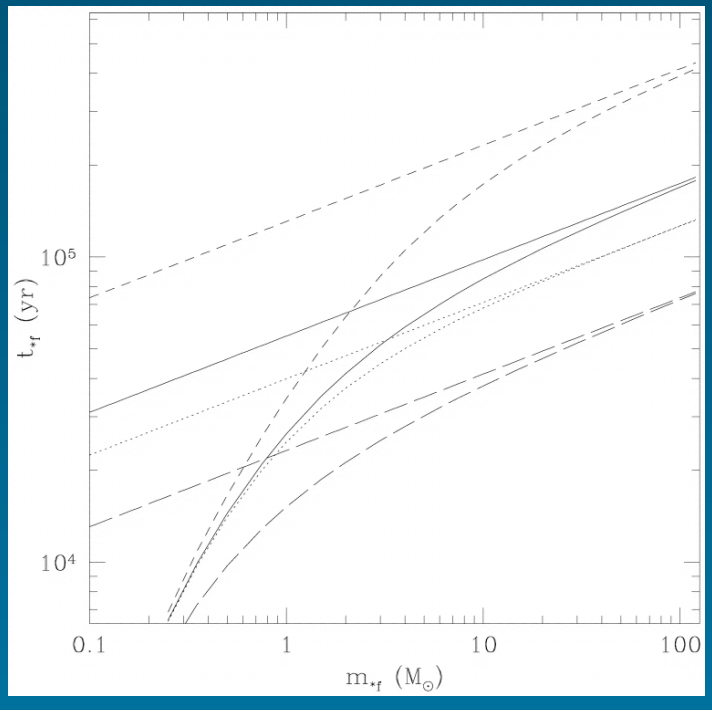
  (McLaughlin & Pudritz 1997)

  - model for HMS (Osorio et al 1999, 2009)



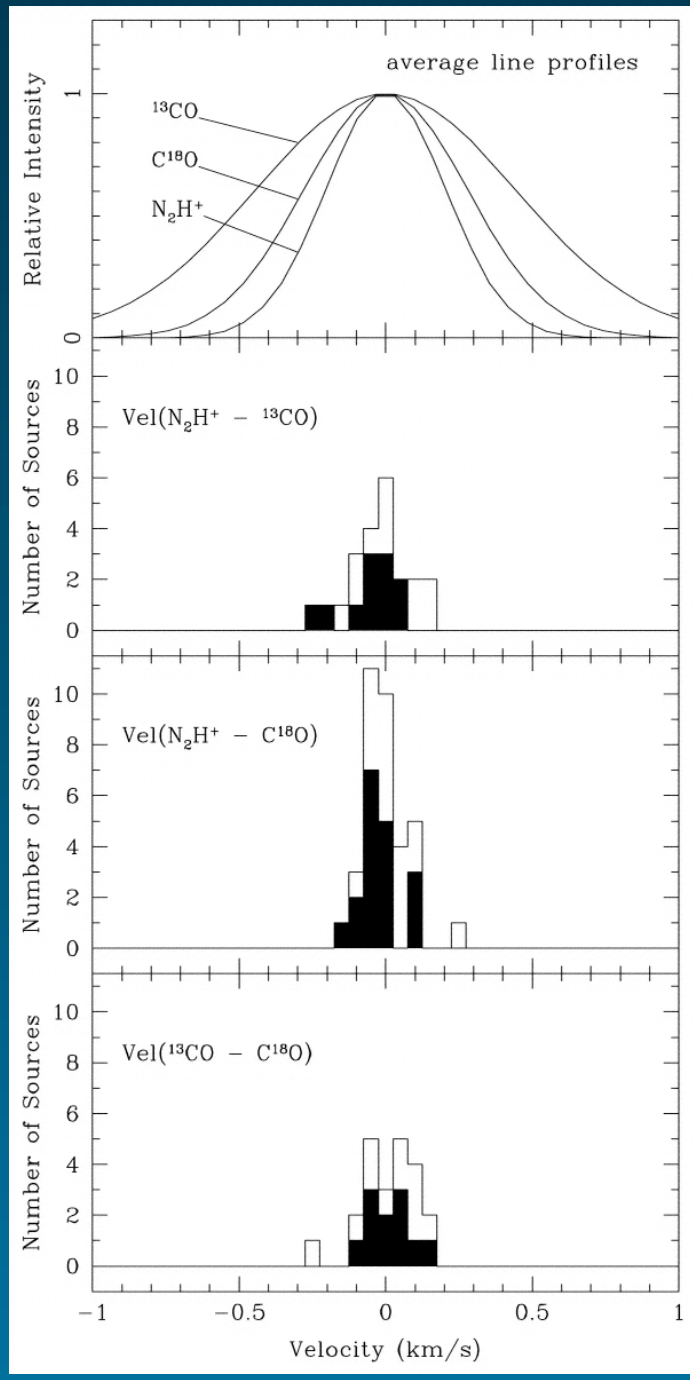

- Intermediate model with adiabatic index (n ~ 1/r^(1.5))

  McKee & Tan (2003)



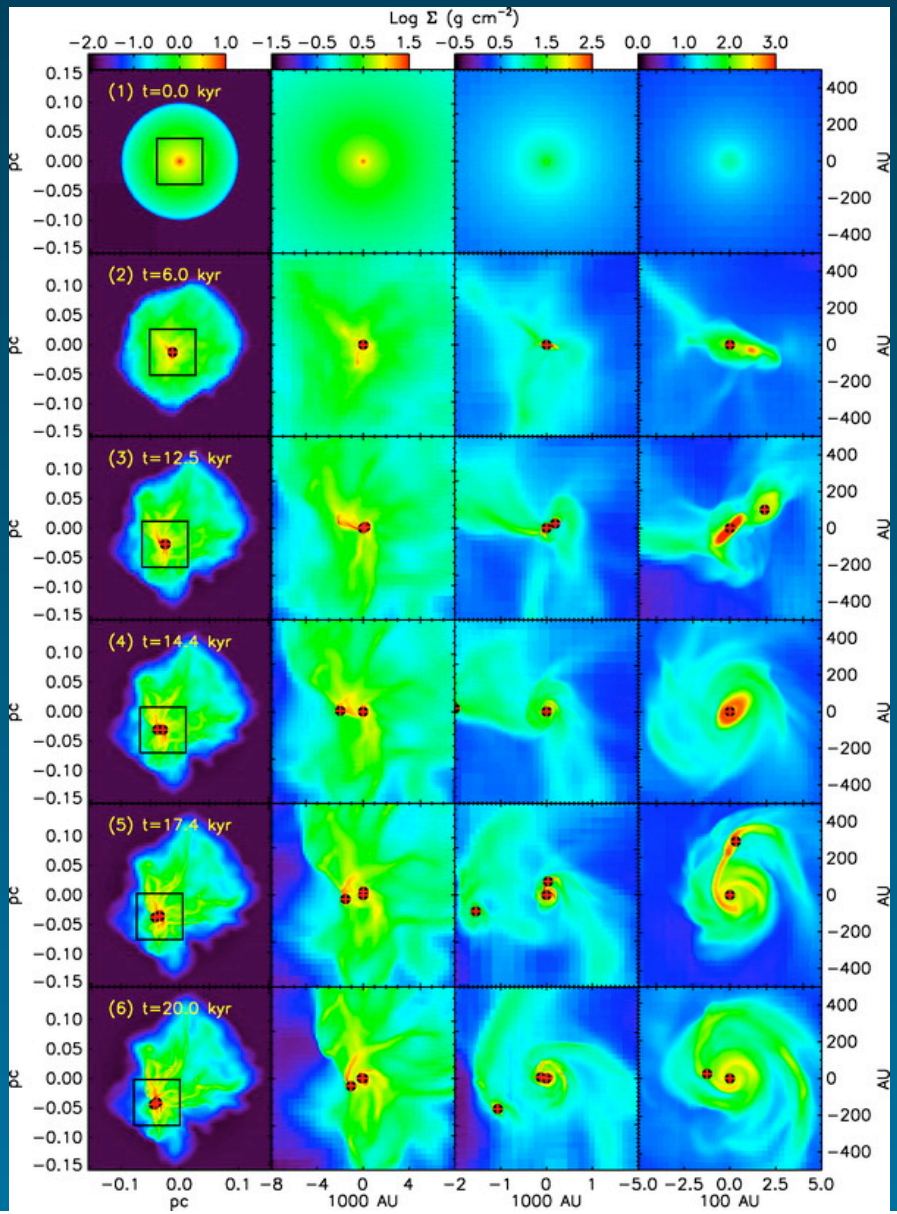
## Stellar Mass: Cores as isolated reservoirs vs. competition in cluster potential well ?

- Cores as “kernels” for accretion from larger scales (Myers 2000)
- Cores and stars have small relative velocities (Walsh et al 2004) – whither competitive accretion?
- Yet - cores are not “isolated” from their environments as are Bonner Ebert spheres
- Most mass arrives from larger scales. Environment matters – particularly *density* (Myers 2009).



# Do massive stars from massive “cores” - include radiative feedback

- Problem with turbulent extended cores – fragment into too many pieces – massive star would not form.
- A possible solution – radiative feedback from massive star prevents fragmentation – massive star forms – within one core (Krumholtz, Klein, & McKee 2007)
- How about a cluster?



## 2. Turbulence, CMF, and large scale structure

- The numerical revolution – in 1990s, better computers and codes open up star formation and establish a new paradigm

  (work of Padoan, Nordlund, Klessen, MacLow, Ostriker, Stone, Bate, Bonnell,… )
- Can turbulence reproduce core, filament, CMF properties?

Simulations; Porter et al 1994; Ostriker et al. 2001, Klessen &Burkert 2001; Padoan et al 2001; Bonnell & Bate 2002,…

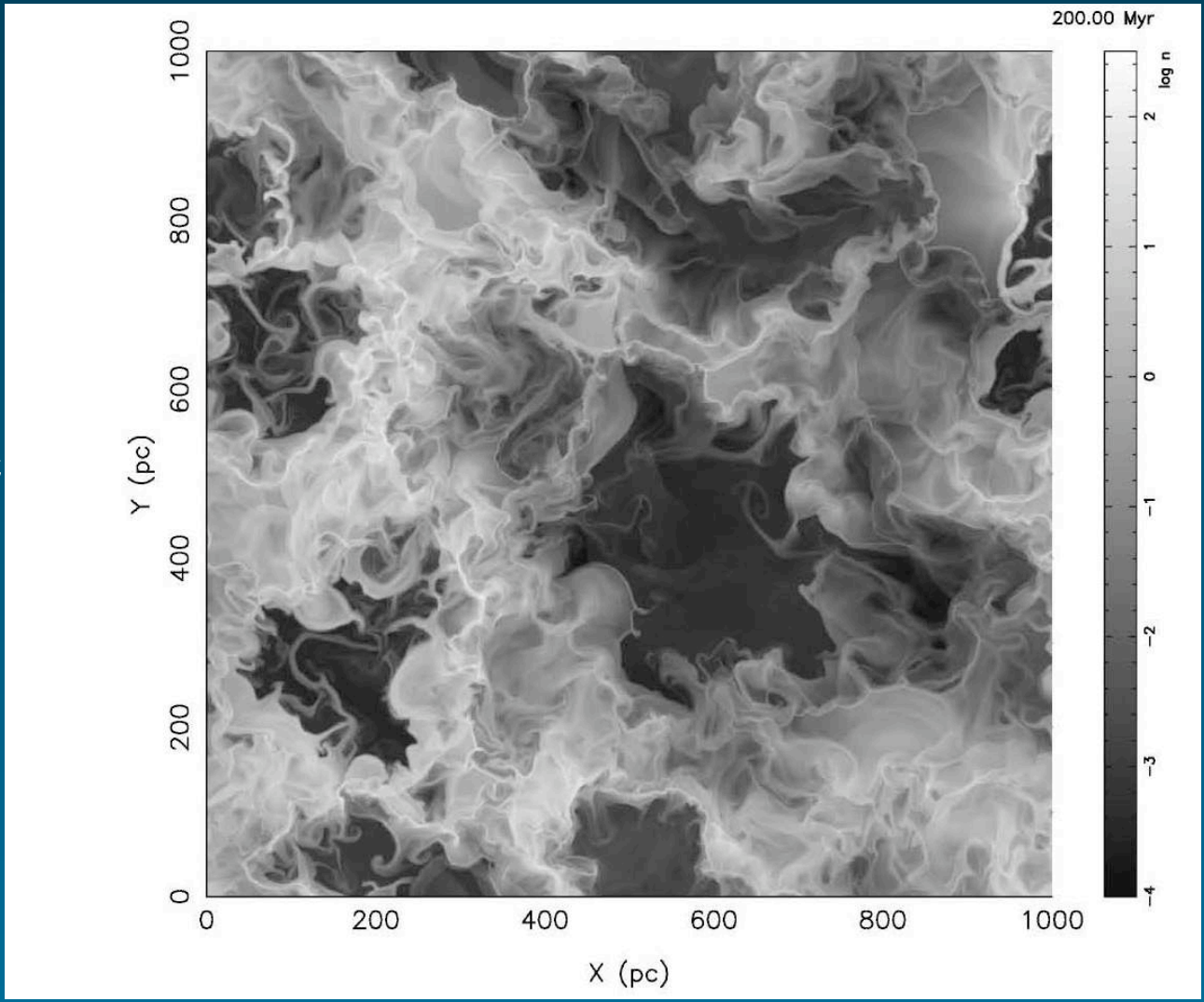
Reviews: MacLow & Klessen 2004, Klein et al 2007, McKee & Ostriker 2007, Klessen, Krumholtz, & Heitsch 2009, Elmegreen & Scalo 2003

# Super Nova driven structure and turbulence in the galactic disk

3D, SN driven shocks:

Simulations done for galactic disk with numerical resolution 1.25 pc

Broad range in density enhancements, several orders of magnitude



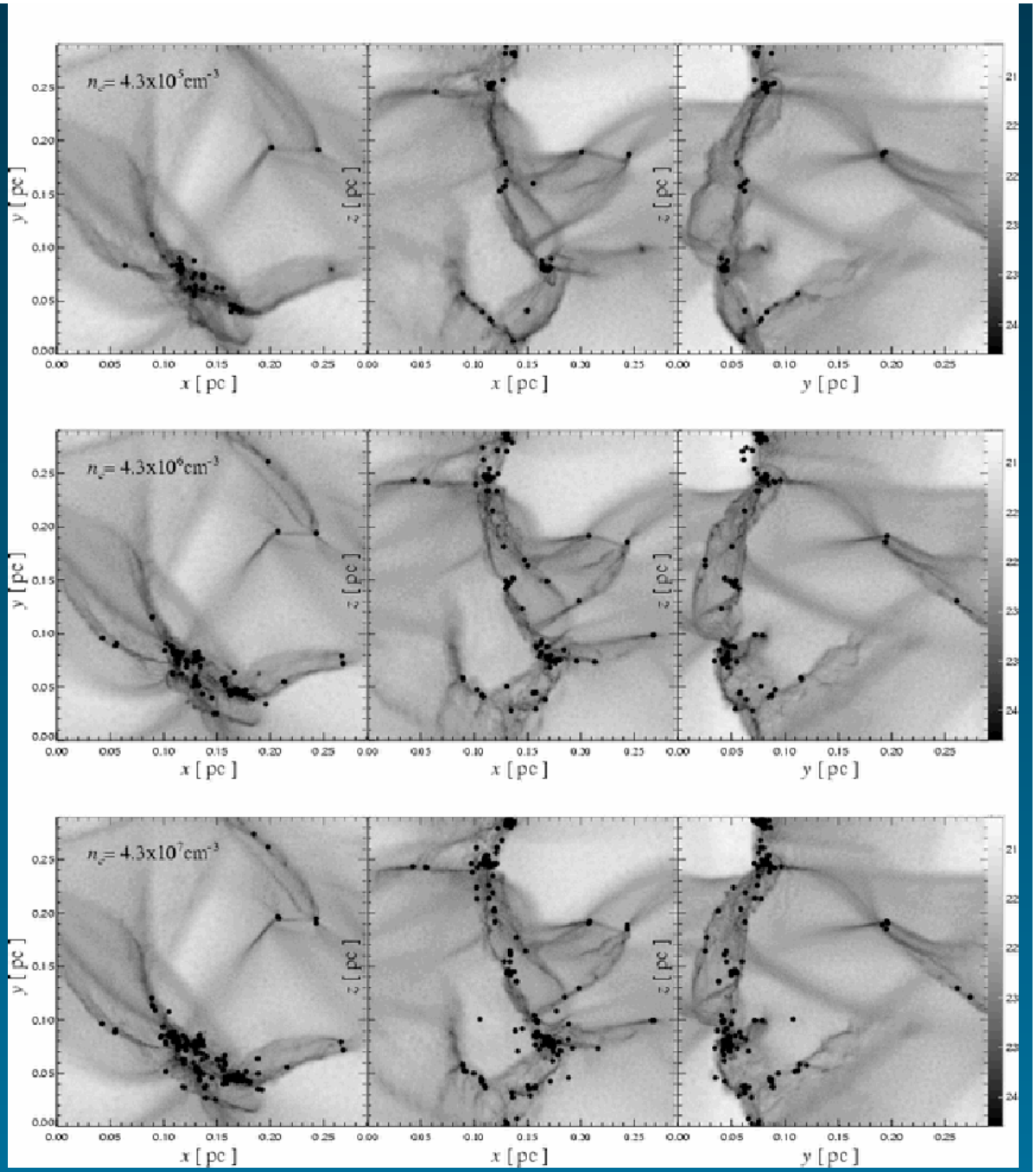

Avillez & Breitschwerdt (2003) – density contrast

# Structure formation in molecular gas

Periodic boxes, uniform initial density, initial "turbulent" velocity field either driven or not, simple cooling prescriptions, SPH codes often used..

Sink particles trace collapsing regions

Result: shocks produce filaments that are sites of star formation

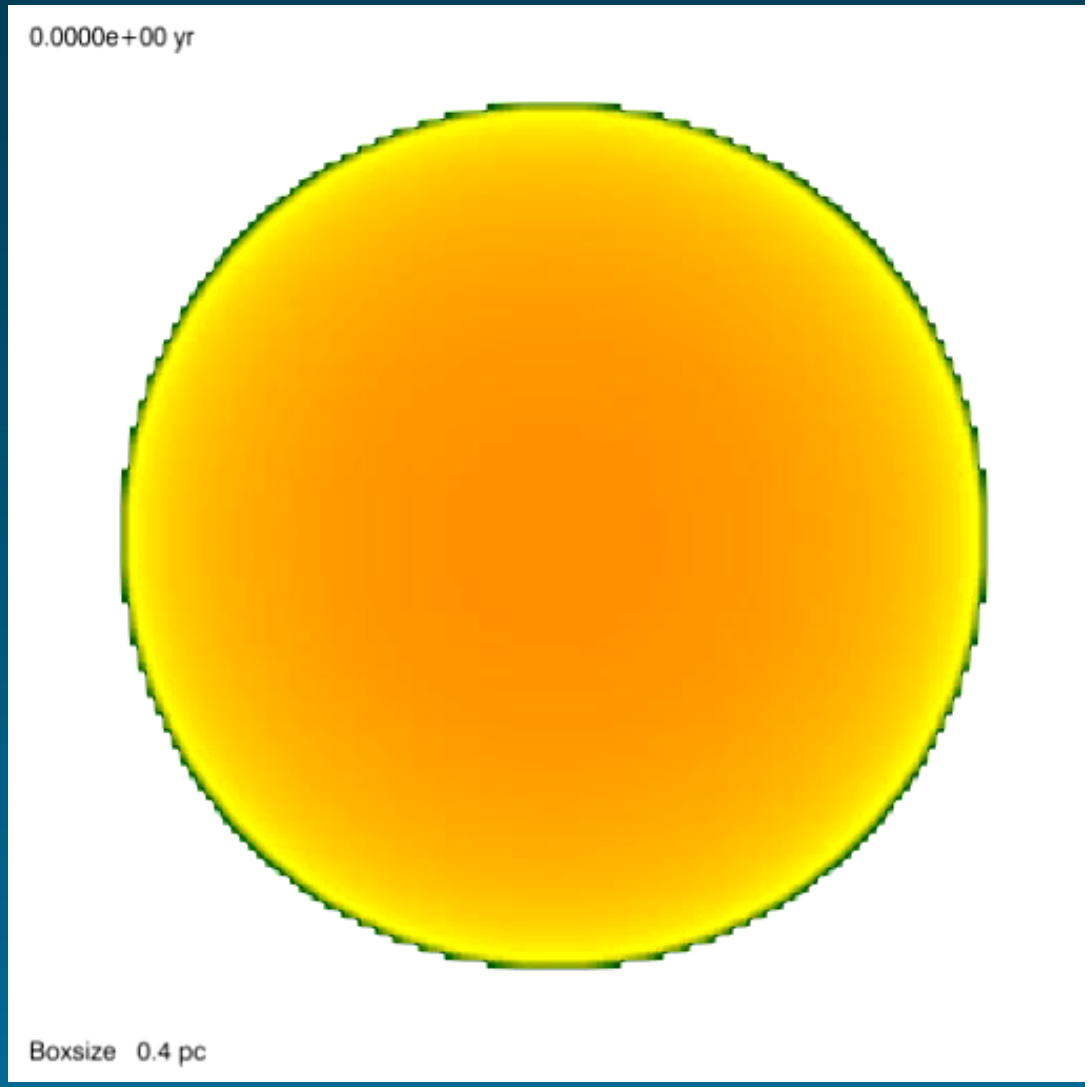



Jappsen et al 2005

# Star cluster – FLASH AMR code

Initial state - top hat density profile with:

total mass: 100 M_sol
radius: 0.16 pc
density: 10^5 cm^(-3)
temperature: 10 K
sound speed: 0.19 km/sec
Jeans mass: 0.94 M_sol
turbulence: rms-velocity: 0.89 km/sec = 5 Mach
spectrum: Burgers, decaying
kinetic/grav. energy = 0.25



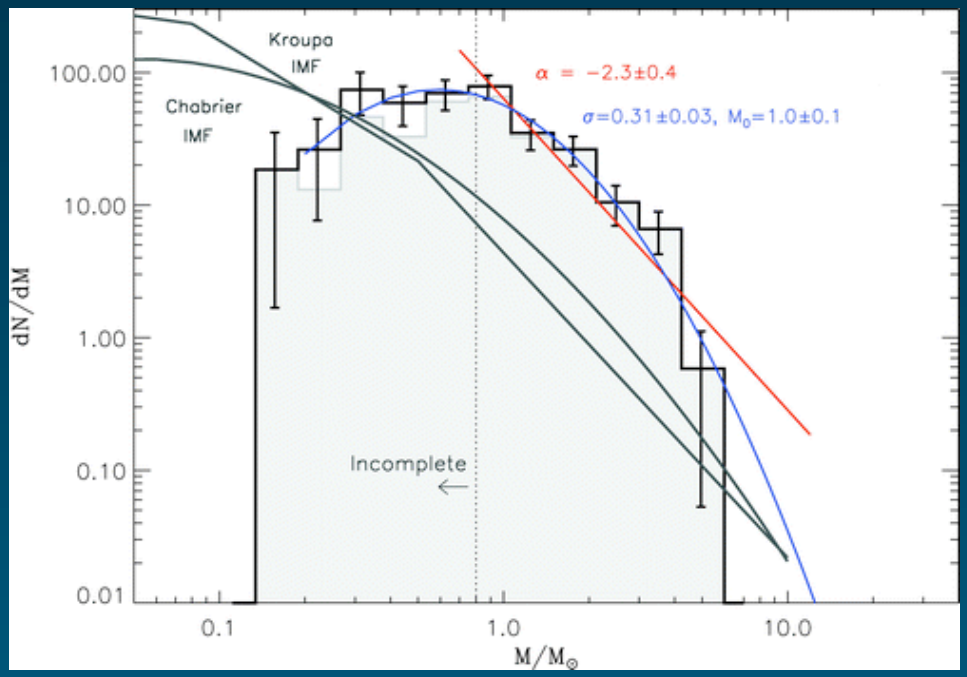

Collapse and star formation over several 10^5 yrs

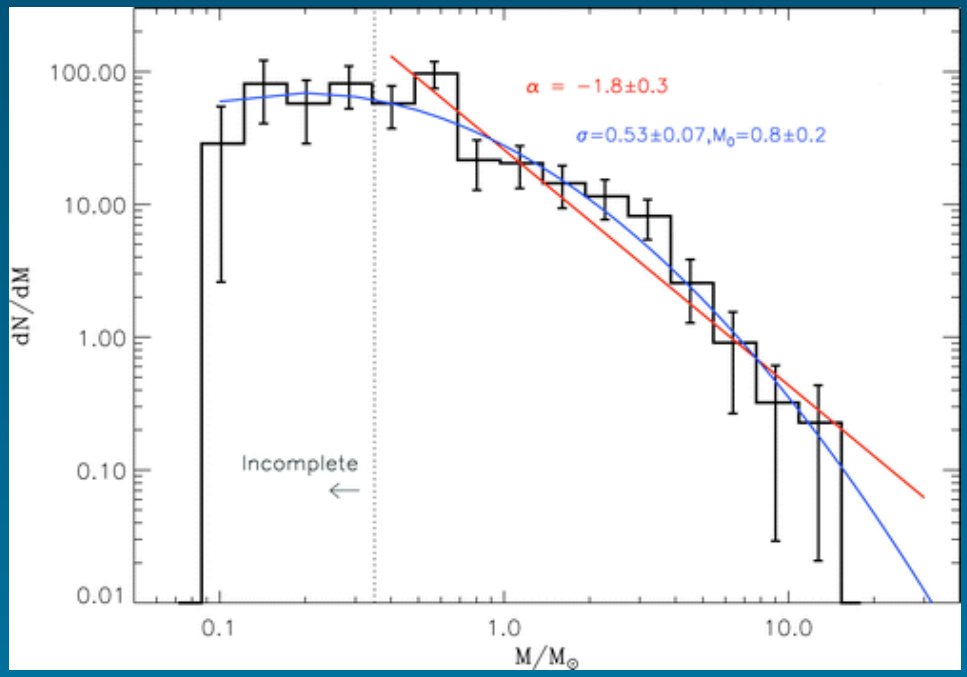
Banerjee & Pudritz, in prep

50,000 cpu hours

# Observed prestellar and protostellar CMDs (Enoch et al 2008)

- Prestellar have steeper, Salpeter-like slopes (-2.3) than protostellar (-1.8)
- Lognormal fits also work, prestellar has narrower dispersion than protostellar
- Conversion time scale: 0.45 Myr.



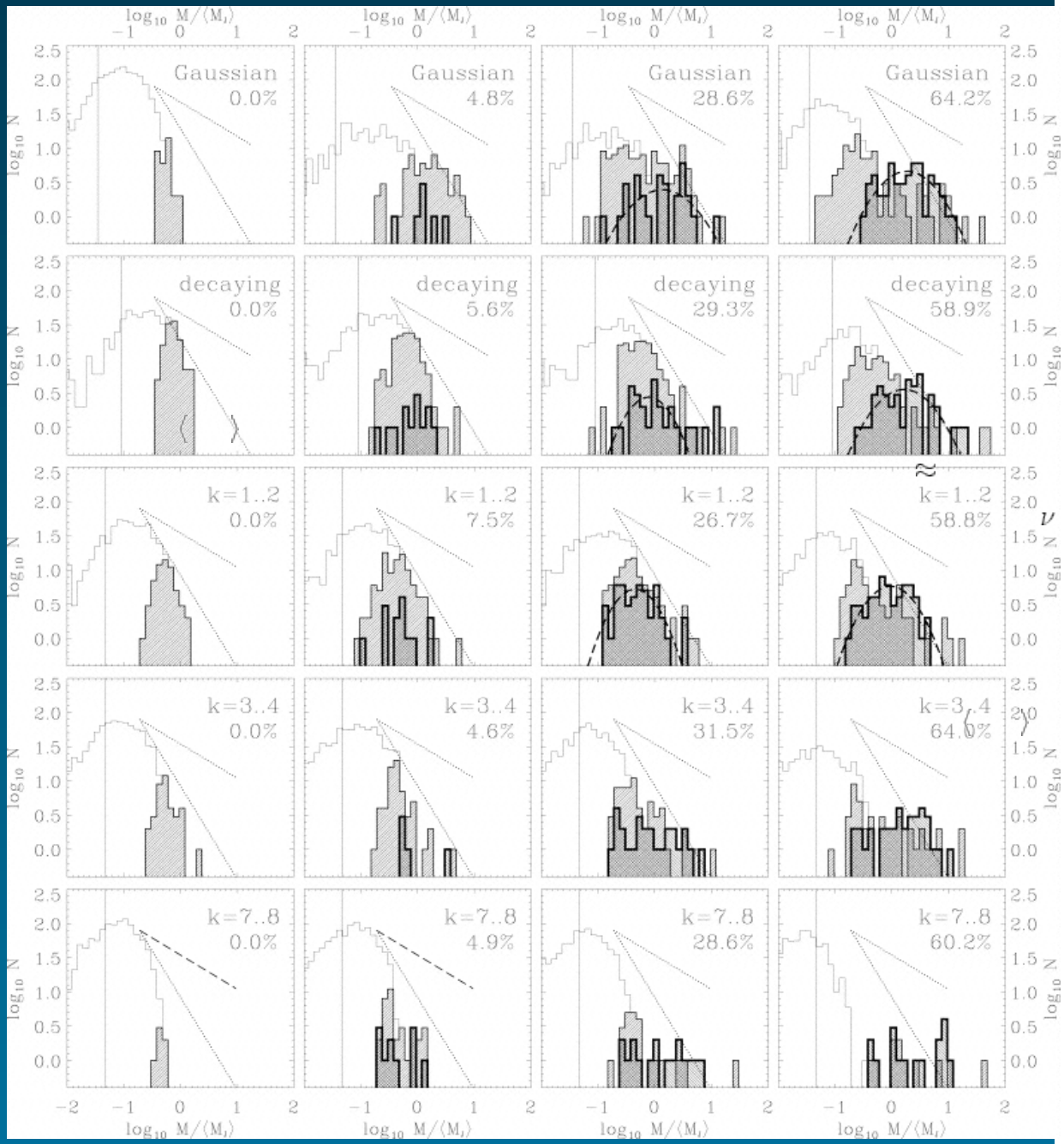
# Mass spectra of cores – turbulent box simulations

- Gas cores
- Self gravitating cores
- collapsed cores

Bottom 3 models driven until gravity turned on, driving scale indicated

Lognormal fits to collapsing objects

Klessen, 2001



- Semi-analytic theory (Padoan & Nordlund 2002): modification of lognormal distribution of fragments - by turbulence with a power law spectrum (gamma index)

  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

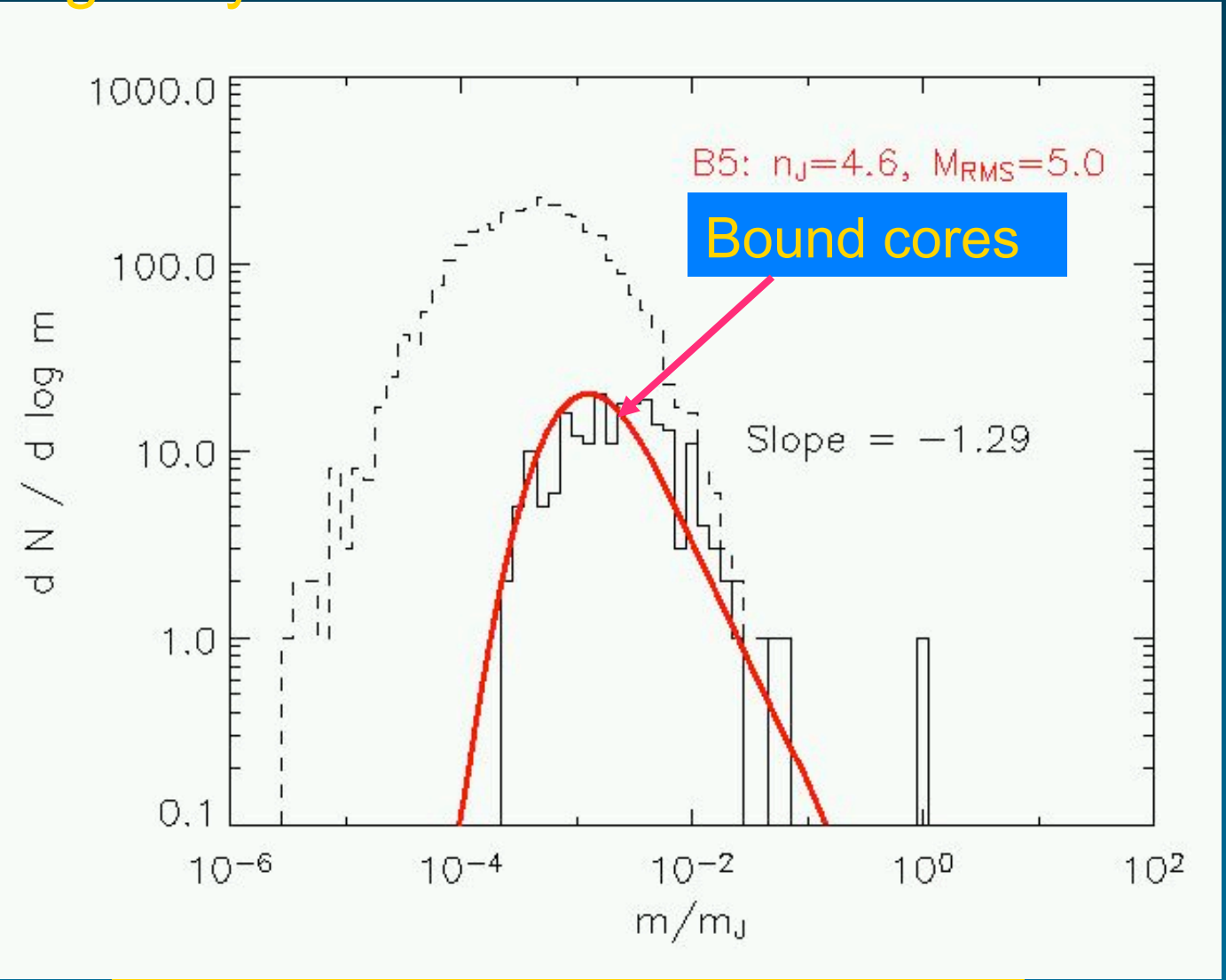
- Lognormal + power law – consequence of thermal support of gas + turbulent pressure at high mass (Hennebelle & Chabrier 2008)

# Mass spectrum of "cores" (Tilley & Pudritz 2004 – hydro turb + gravity

Decaying turbulence in box:

Dashed: all fluctuations

Solid: bound or collapsing – using all terms of virial theorem used



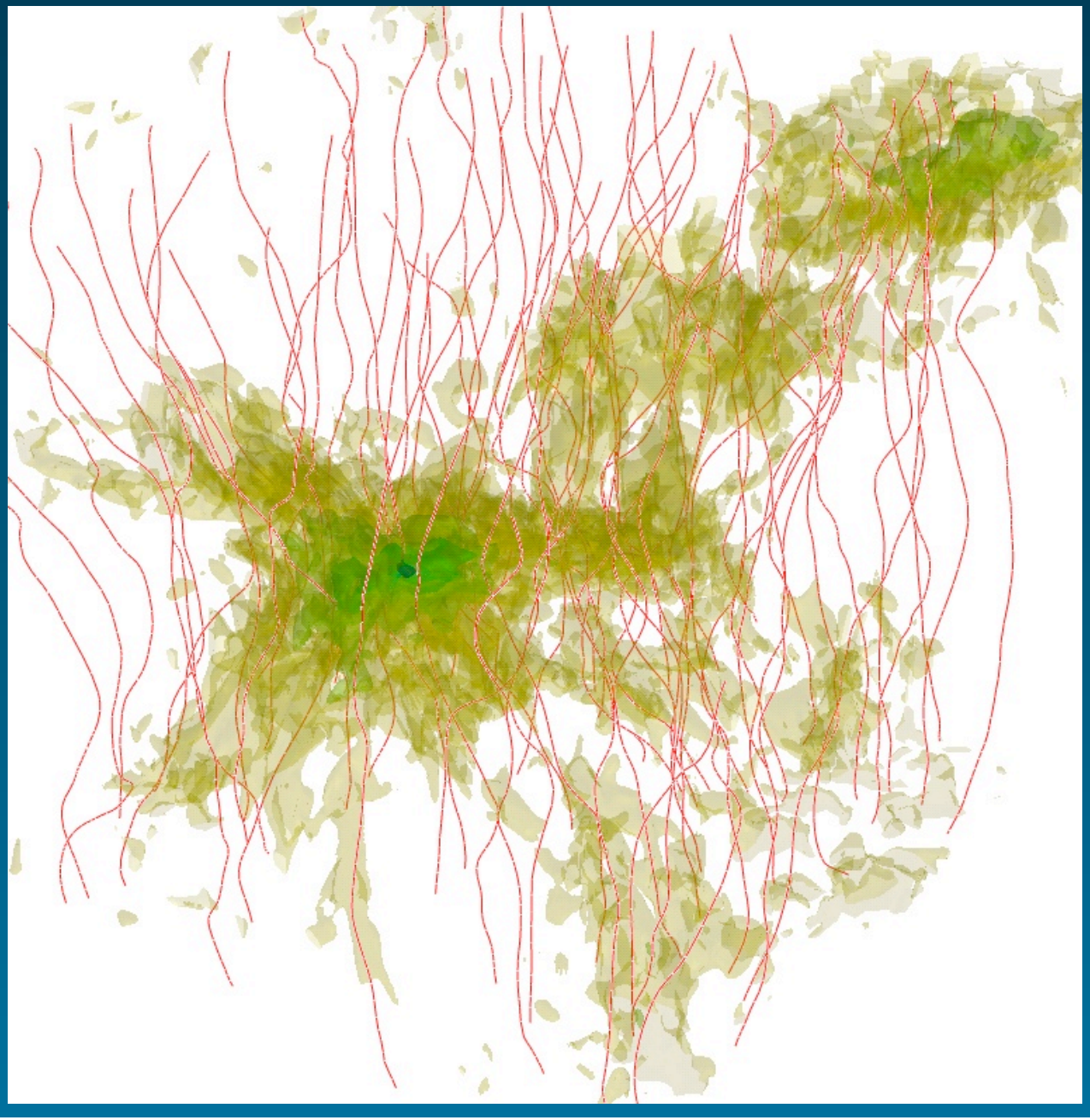

$$M_{peak} \cong 10^{-3} M_J = 10^{-3} M_{tot} / n_J$$

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

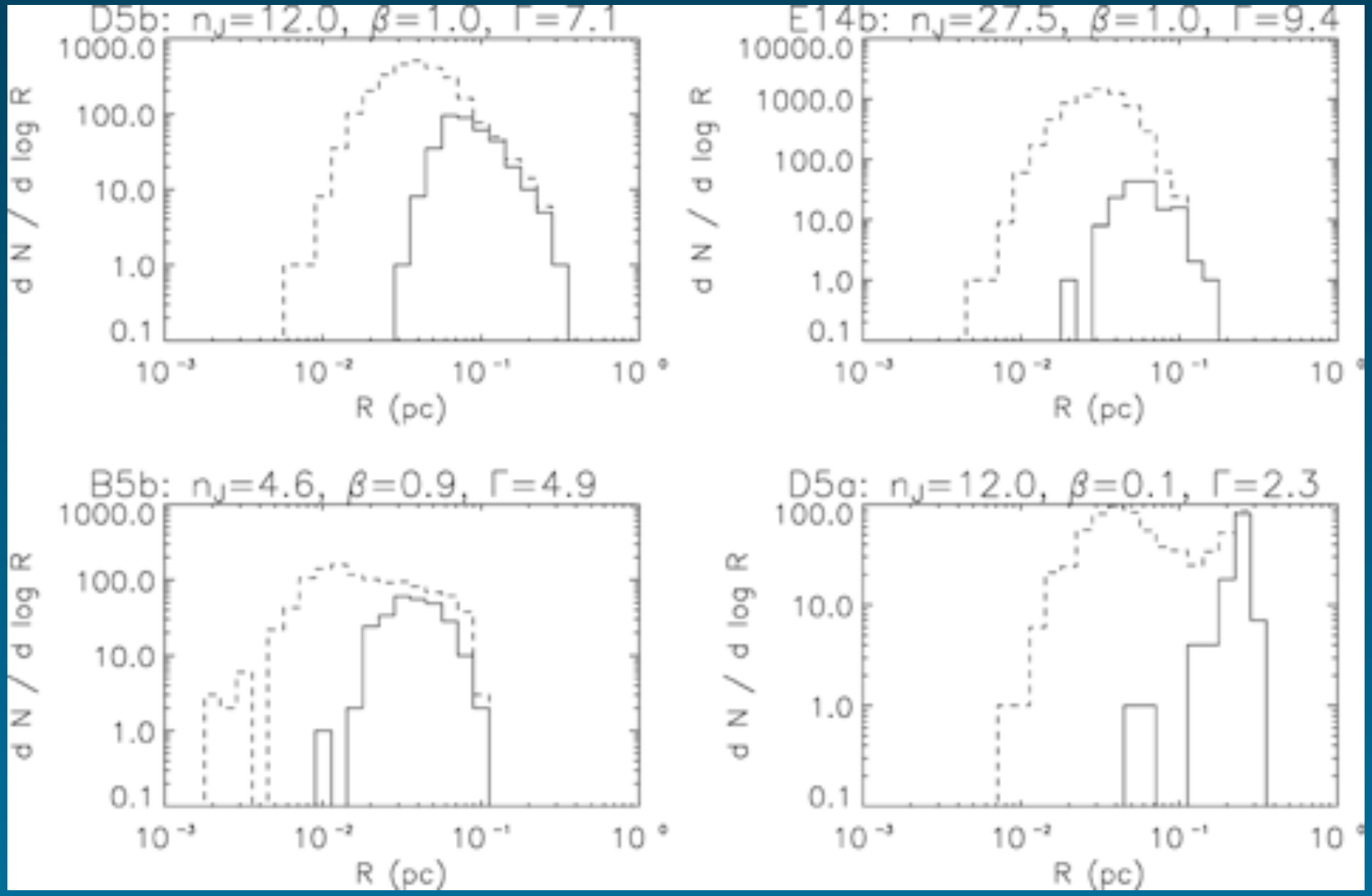
More Jeans masses:

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

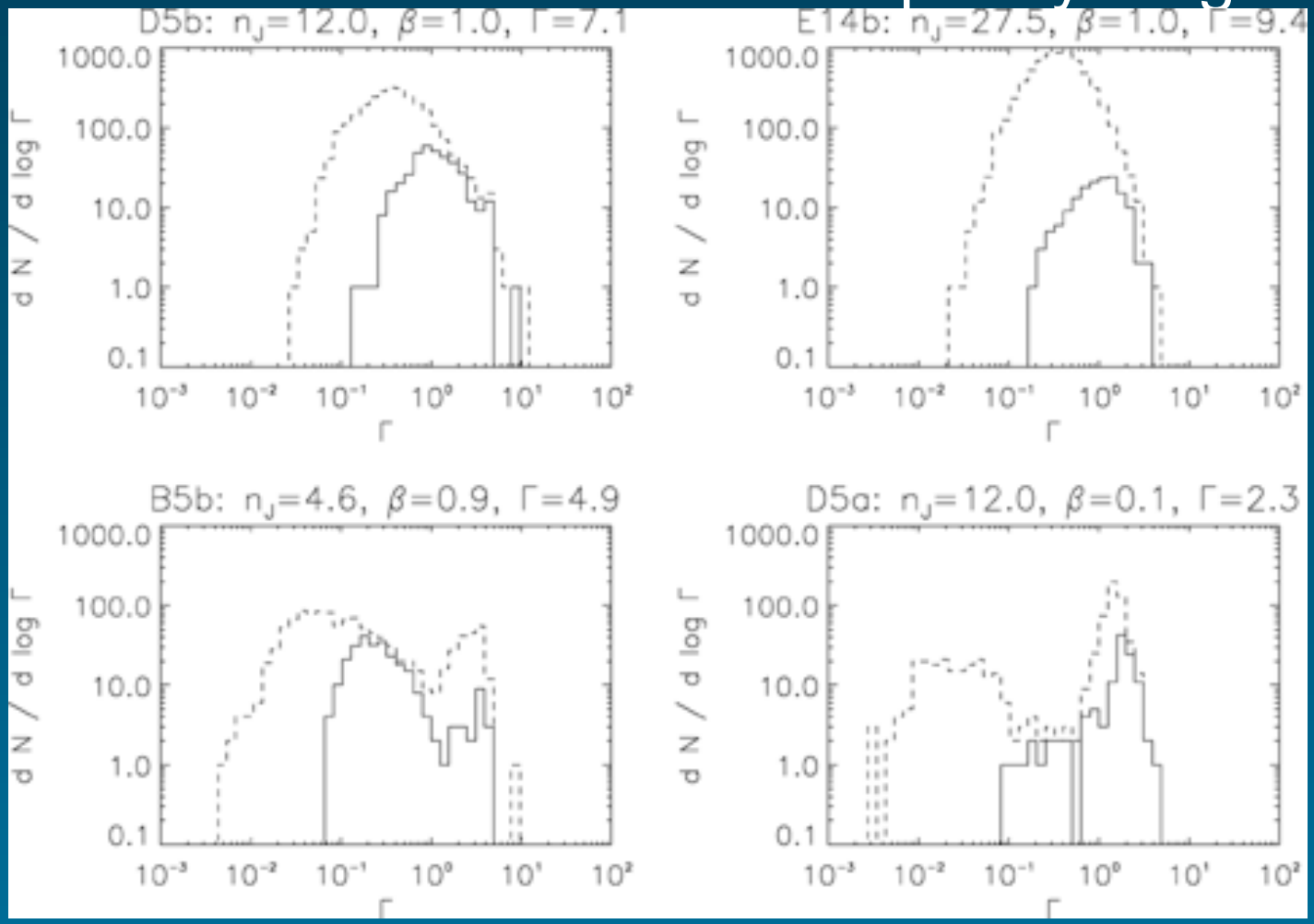
$$n_J = 27.5;$$
$$\beta = 1.0$$
$$M_A = 14.1$$
$$\Gamma = 9.4$$



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



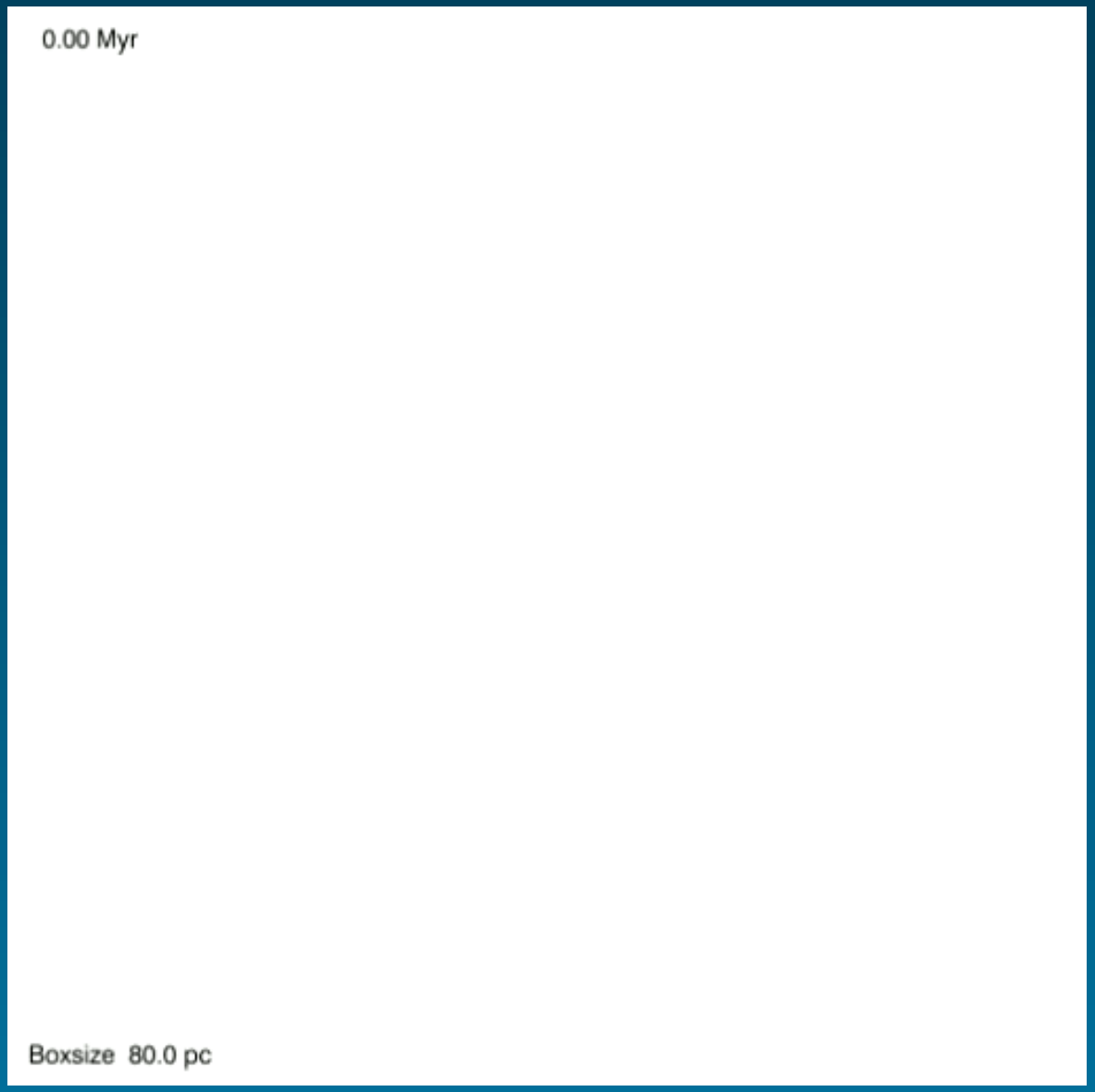
Core, mass to flux distributions: local core mass to flux ratio is always *reduced* from initial uniform gas distribution!  Bulk cloud *could* be poorly magnetized




Agrees with Padoan and Nordlund 2002 conclusion

# Making clouds by colliding gas streams… structure in dynamic sheets

- Thermodynamic
- Instability in colliding streams starts the formation of filaments and clumps



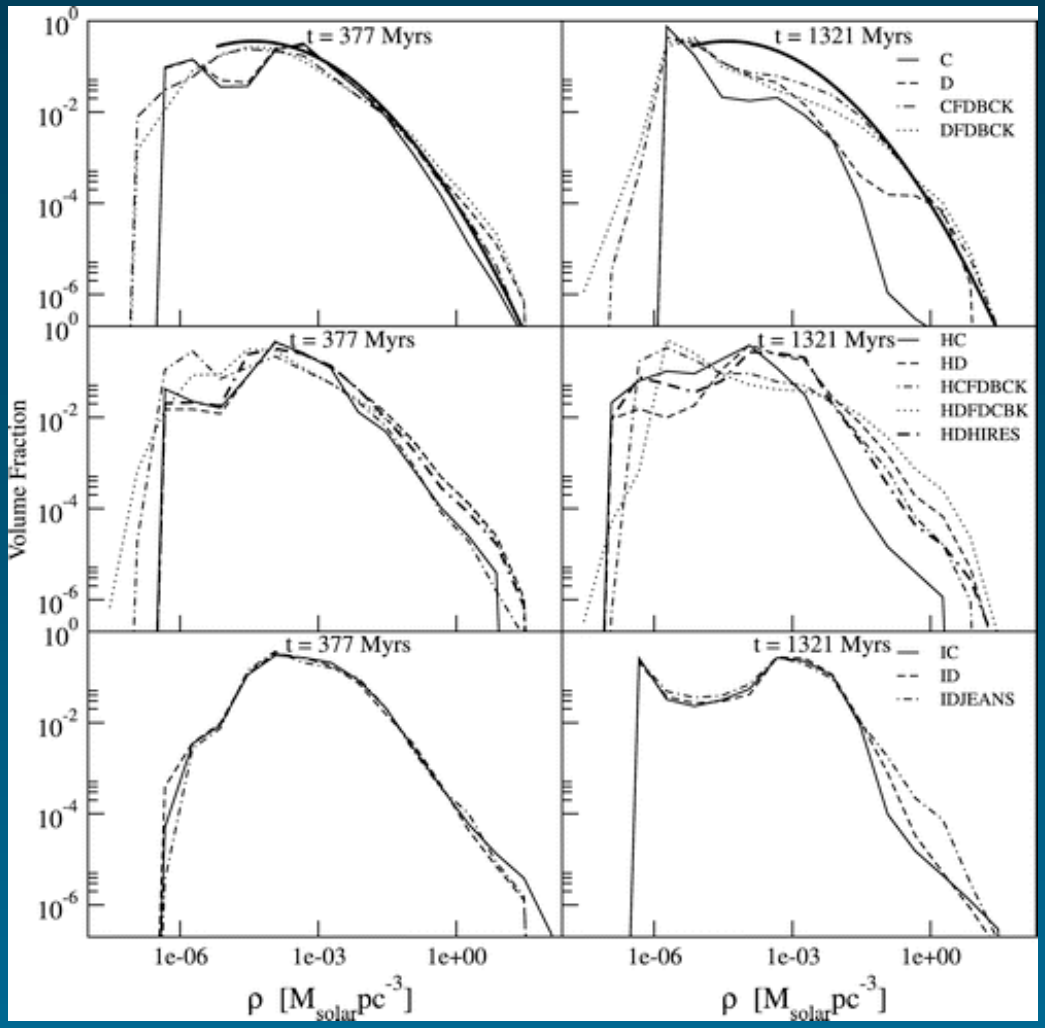

Banerjee et al 2008

## Structure of the ISM:

evaluate the density Probability Distribution Function (PDF) for galactic simulations including a SN generated ISM:

Lognormal – in spite of different methods of heating etc.

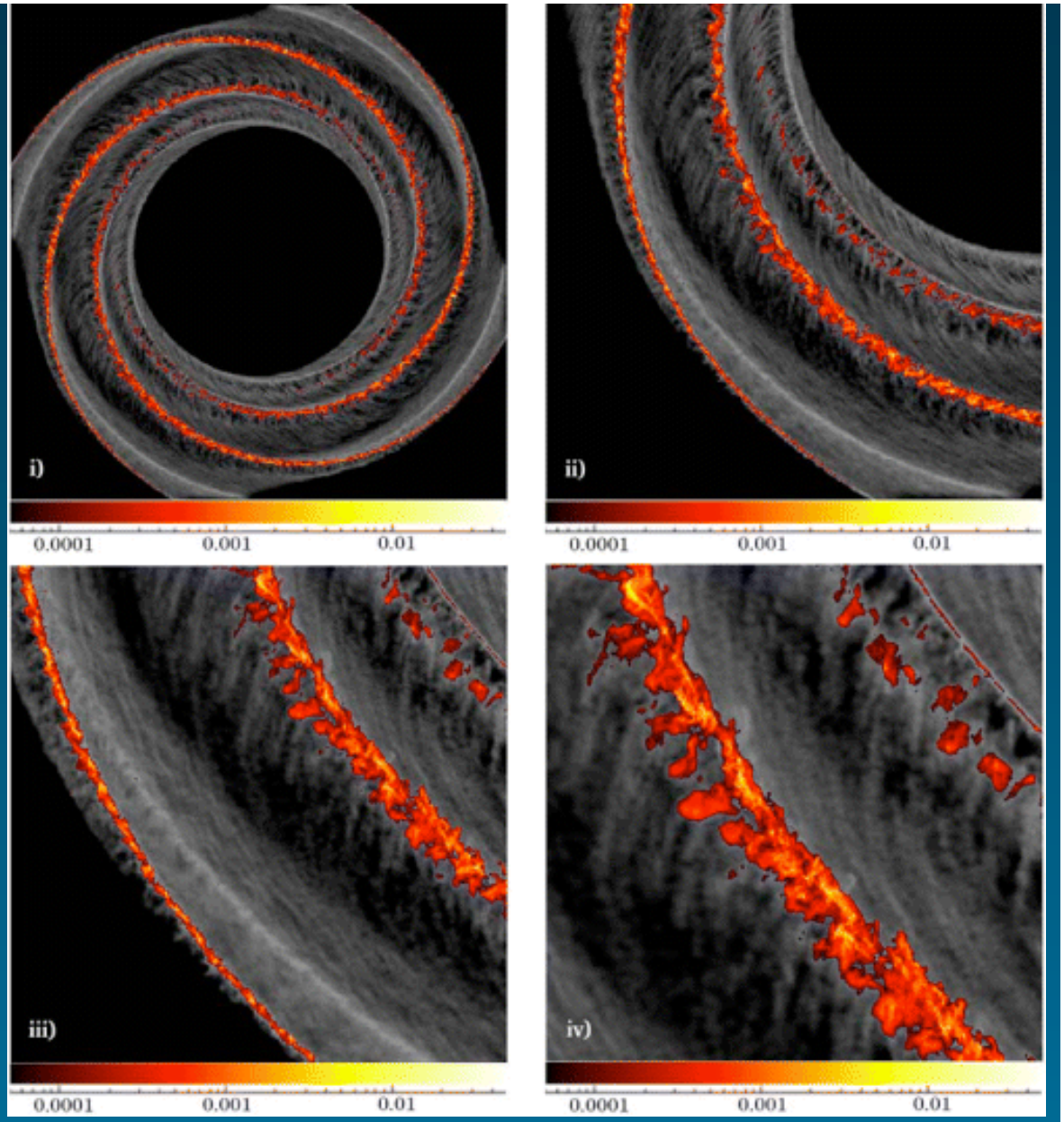
(also Wada & Norman 2001, 2007)




Tasker & Bryan 2008

# Galactic scale: spiral shocks induce molecular cloud formation

- Spiral shock waves compress gas to high density, and create large velocity dispersion…ie, turbulence




Dobbs et al, 2006, MNRAS: column density map of clouds of molecular hydrogen (red)..20kpc to 3kpc frames

# Shock generated structure and the CMF

## (Kevlahan & Pudritz 2009)

- Density changes after n shock passages (spirit of arugment by Adams):

$$\rho^{(n)} = \prod_{j=0}^{n}(1+\mu^{(j)}(x)); \text{ normalized to } \rho_{\mathrm{o}}$$

- Consider shock strengths to be identically distributed random variables, in interval

$$\mu \in [0, 2/(\gamma-1)]$$

- Take log of both sides, apply central limit theorem. Get a log-normal distribution for density PDF:

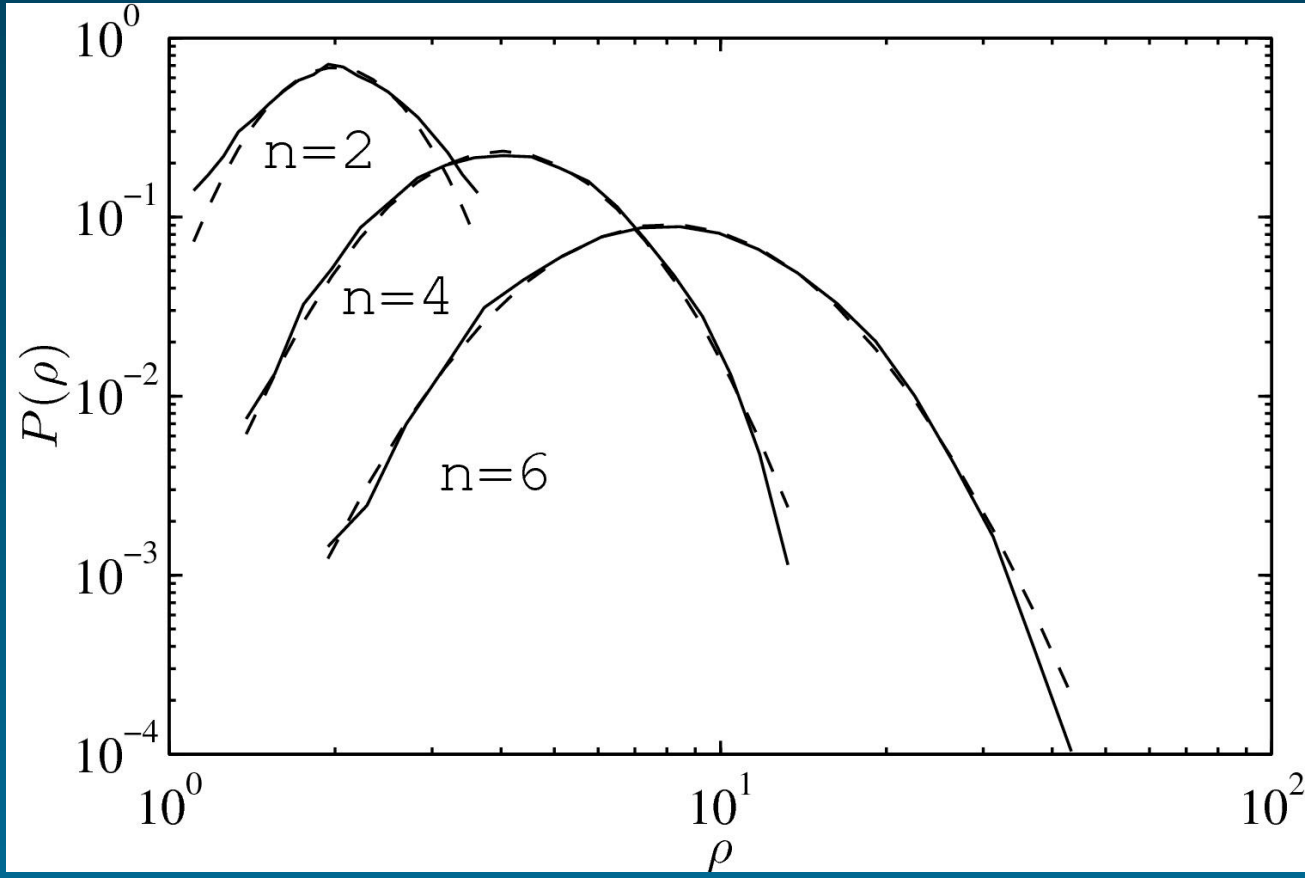
$$P(\rho) = \frac{1}{\sqrt{2\pi\sigma\rho}} \exp\left(-\frac{(\log(\rho) - \overline{\log\rho})^2}{2\sigma^2}\right)$$

$$\overline{\log\rho} = \frac{n}{2}\ln\frac{\gamma+1}{\gamma-1},$$

$$\sigma^2 = \frac{n}{12}\ln\frac{\gamma+1}{\gamma-1}$$

# Rapid generation of lognormal density PDFs

- Convergence rapid – 3 or 4 shock passages suffices.
- Mean and width grow with number of shock passages (ie. mean RMS Mach number increases)
- Broadest distributions for nearly isothermal gas.
- In self gravitating medium, collapse sets in for dense enough fluctuations



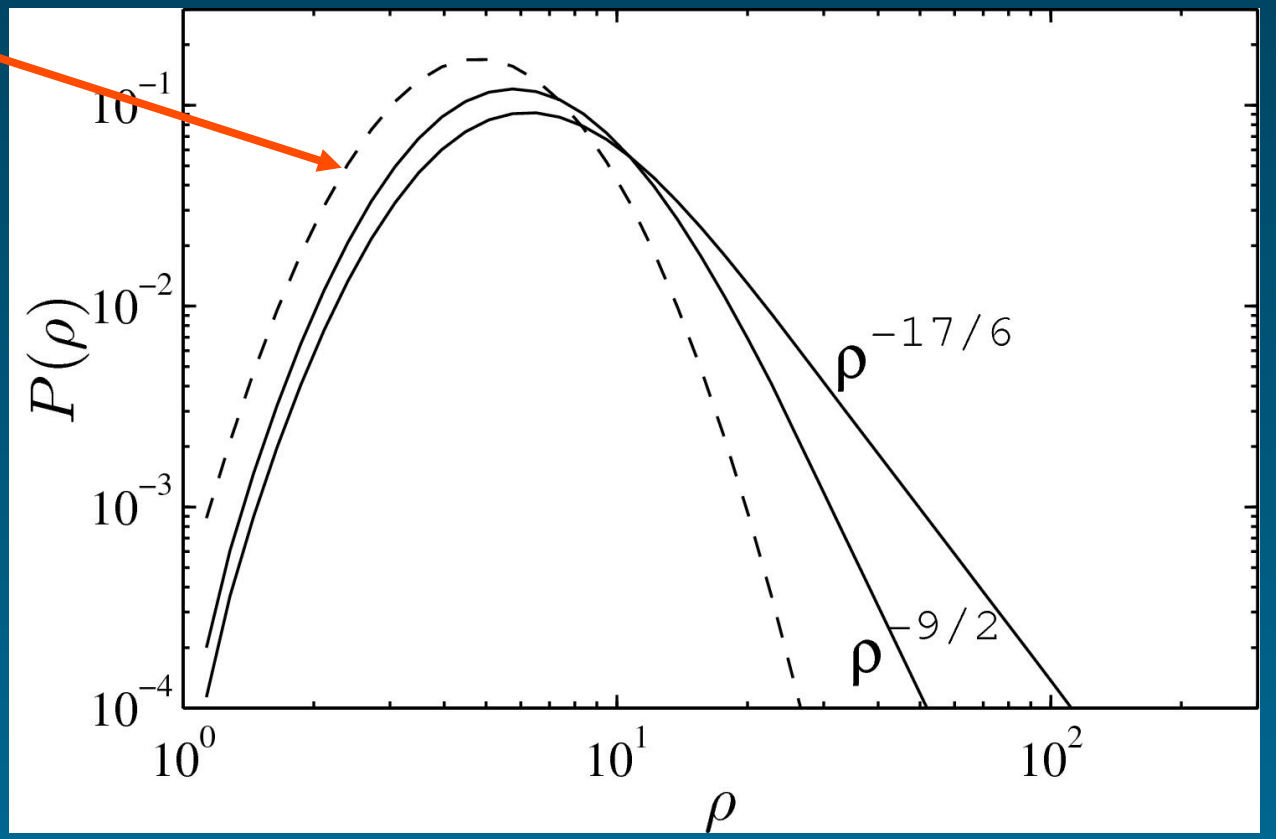

Kevlahan & Pudritz 2009

# Generation of power-law tail of PDF - feedback?

Initial lognormal distribution ----

Instant and injection shocks (-17/6 and -9/2)

Point: power law tail may be the result of “feedback” from massive star by blast wave.. no more than a few…



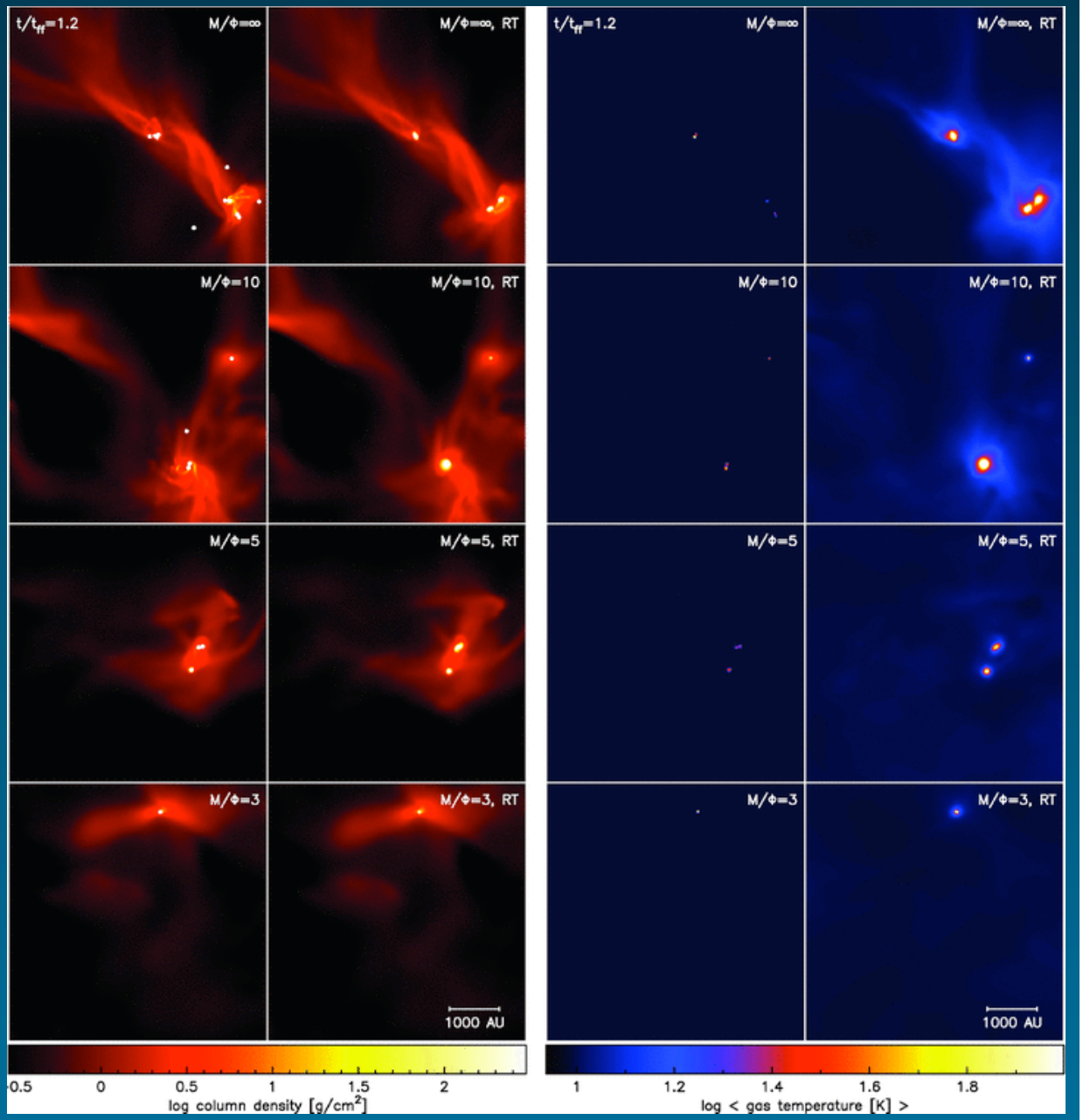
# Reducing star formation efficiency – magnetic and radiation fields

- Hydro simulations in cluster regions have high star formation efficiencies (> 50%)… nothing to prevent most gas being used up.
- c2d results (Evans et al 2009); clouds are 3-6% up to 15-30 % efficient in forming stars
- Magnetic fields suppress fragmentation - when mass to flux low and near critical value
- Radiation fields suppress fragmentation by gas heating and raising the Jeans length

SPH simulations of magnetic and radiative feedback: Price & Bate 2009

Left 2 columns: column densities, mass to flux decreasing downwards (more magnetized): barotropic and RT

Right 2 columns: gas temperature showing heating effects: barotropic and RT

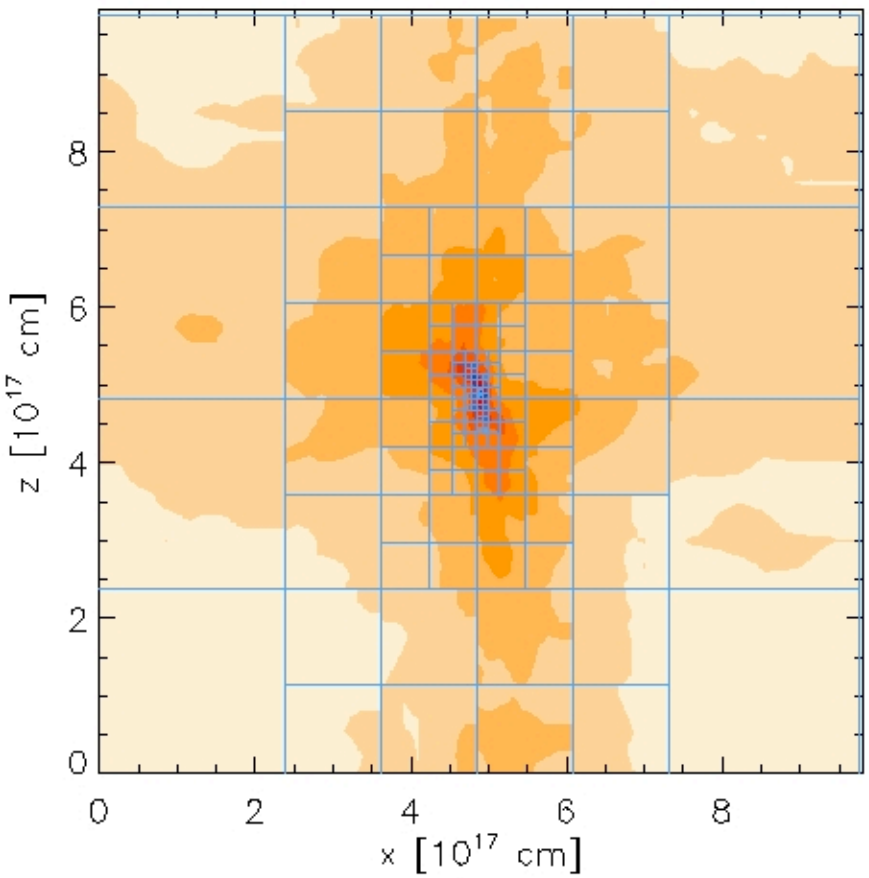


# Filamentary accretion – filaments to disks and stars

## FLASH – Adaptive Mesh Refinement (AMR) simulation:

(Banerjee, Pudritz, & Anderson 2006: start with TP04 )

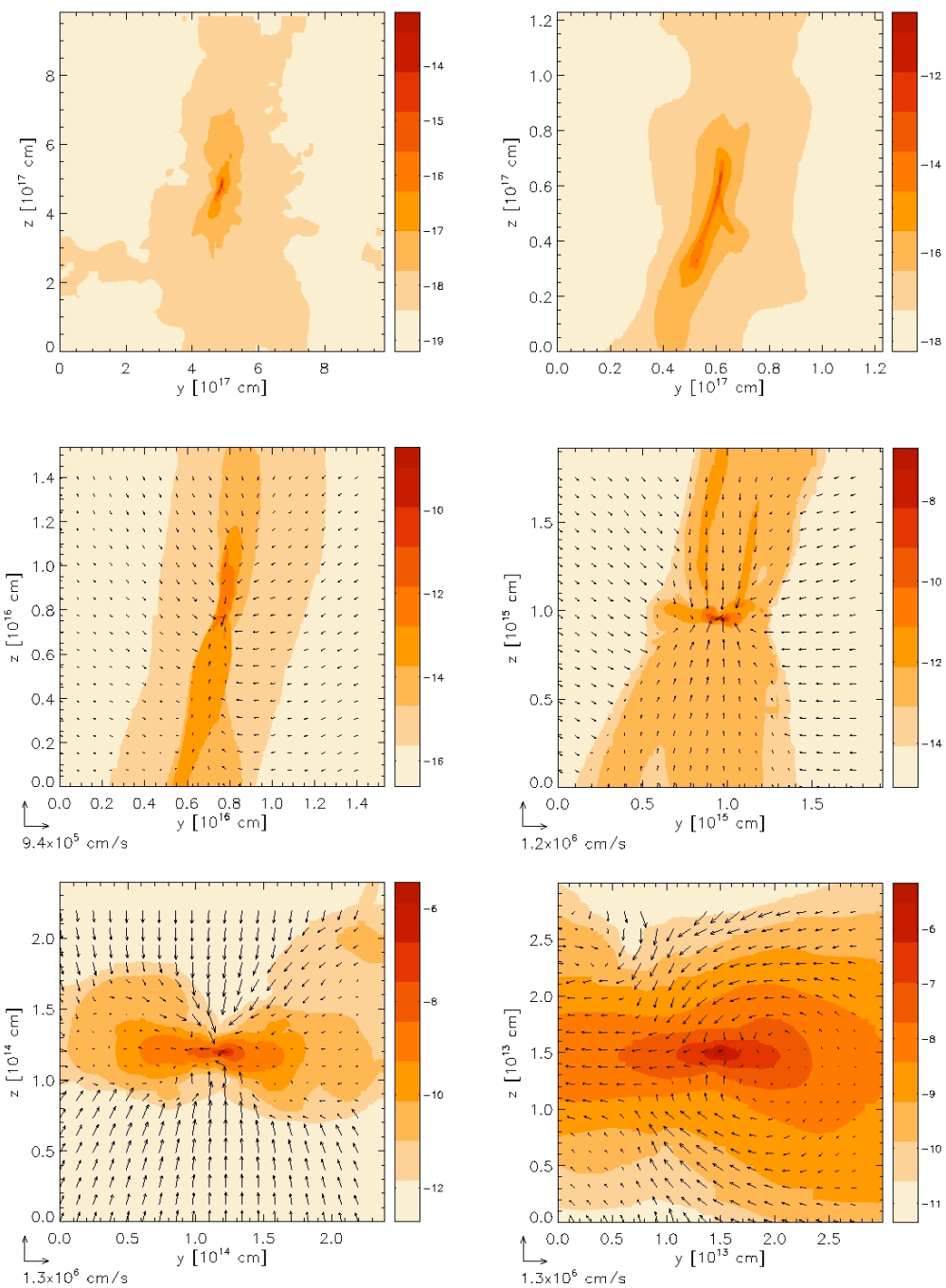
- Dynamically, self adjusting grid:
  * Grid adjusts to resolve local Jeans length (Truelove et al 1997);
- Wide variety of coolants including molecular + dust cooling, $H_2$ formation and dissociation, heating by cosmic rays, radiative diffusion for optically thick gas, etc.

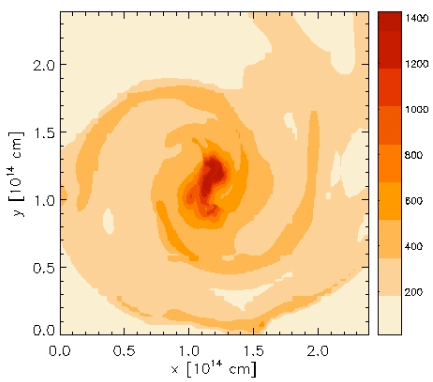


Filamentary structure: from 0.1 pc down to sub AU scale

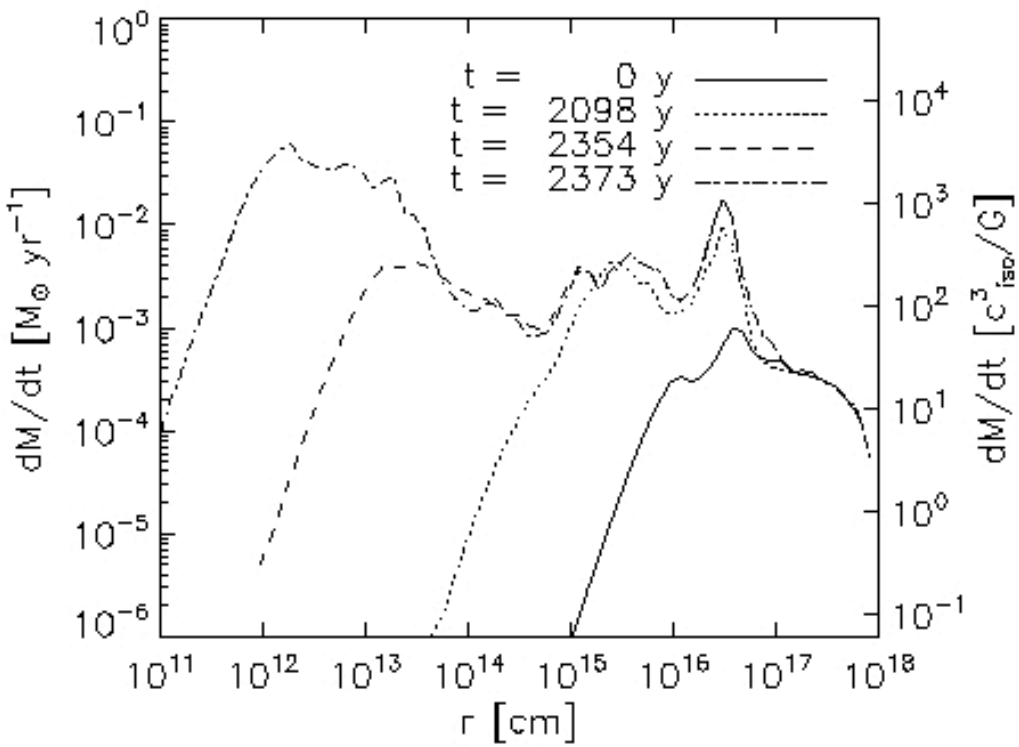
- Large scale filamentary collapse onto a growing disk:

x-y plane along filament: same as for x-y plane: true filamentary collapse



# Evolution of accretion rates: radiation field will be strongly quenched if exceed $\dot{M} \cong 10^{-3} M_{\Theta} yr^{-1}$



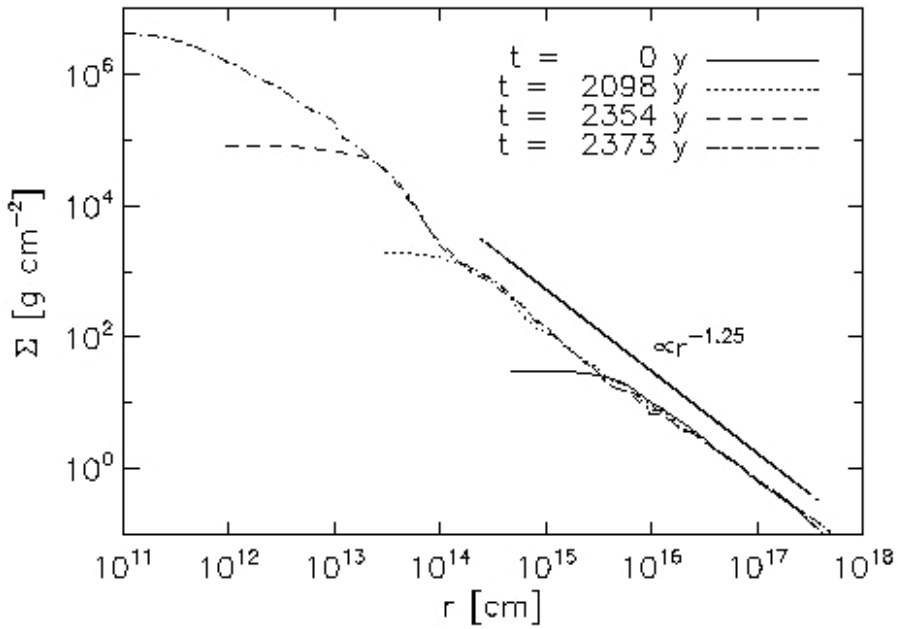

We find huge accretion rates 10 times this value:

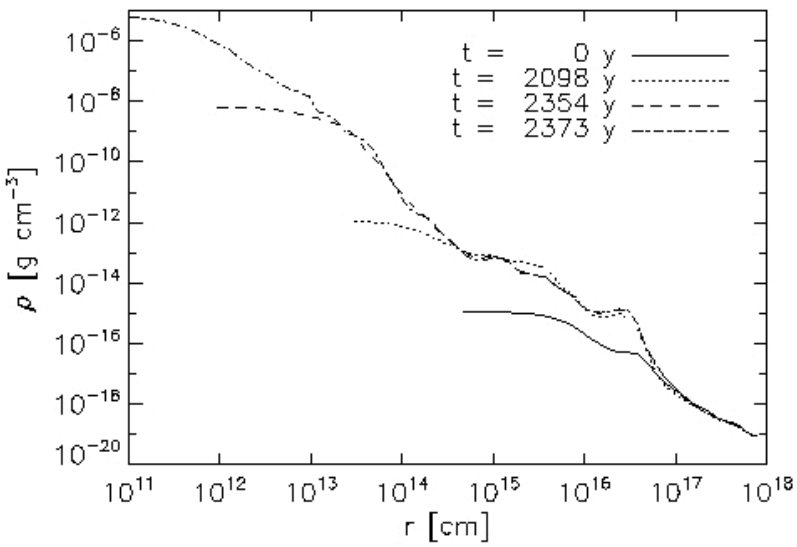
***Accretion rate exceeds naïve SIS model by 1,000 – and Bonner-Ebert sphere collapse by 20:

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

Evolution of radial column and volume density profiles during collapse:
- different structure in “envelope” vs central core region… manifestation of cooling

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



# 3. The IMF

- Stellar mass is the outcome of the competition between collapse and core dispersal (Myers 2008)
- Collision times between cores long – so they can remain “isolated” (Evans et al 2009)
- Thus, cores can map onto stars (Enoch et al 2008

# Wide variety of stellar masses possible…

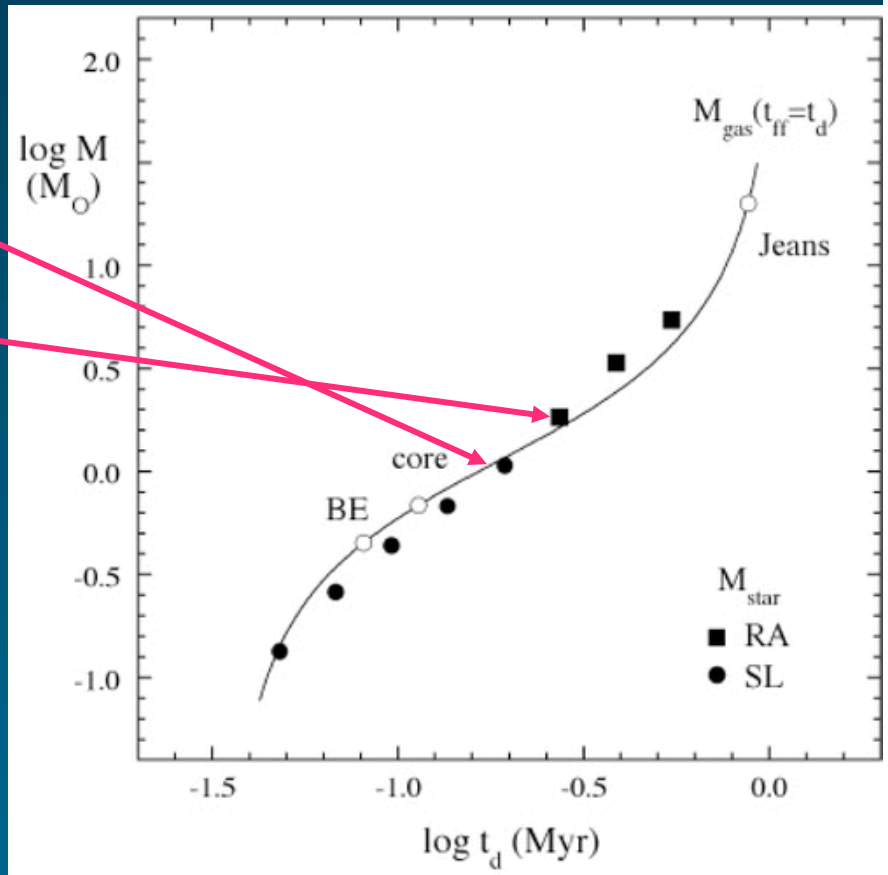
- Self- limiting

  vs

  runaway accretion
- Depends on free-fall vs dispersal times

$$t_{ff}/t_d > 1; < 1$$

- Constant CMF/IMF implies $t_d \sim (0.4\text{-}0.8)t_{ff}$

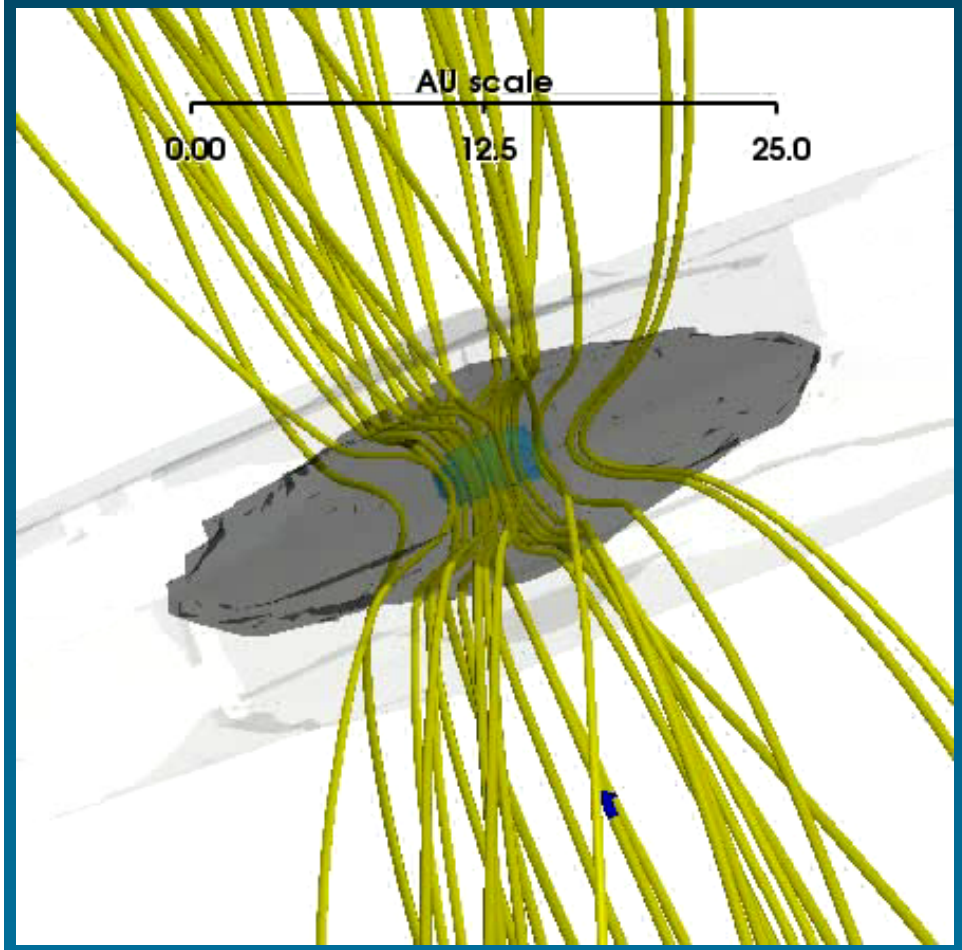


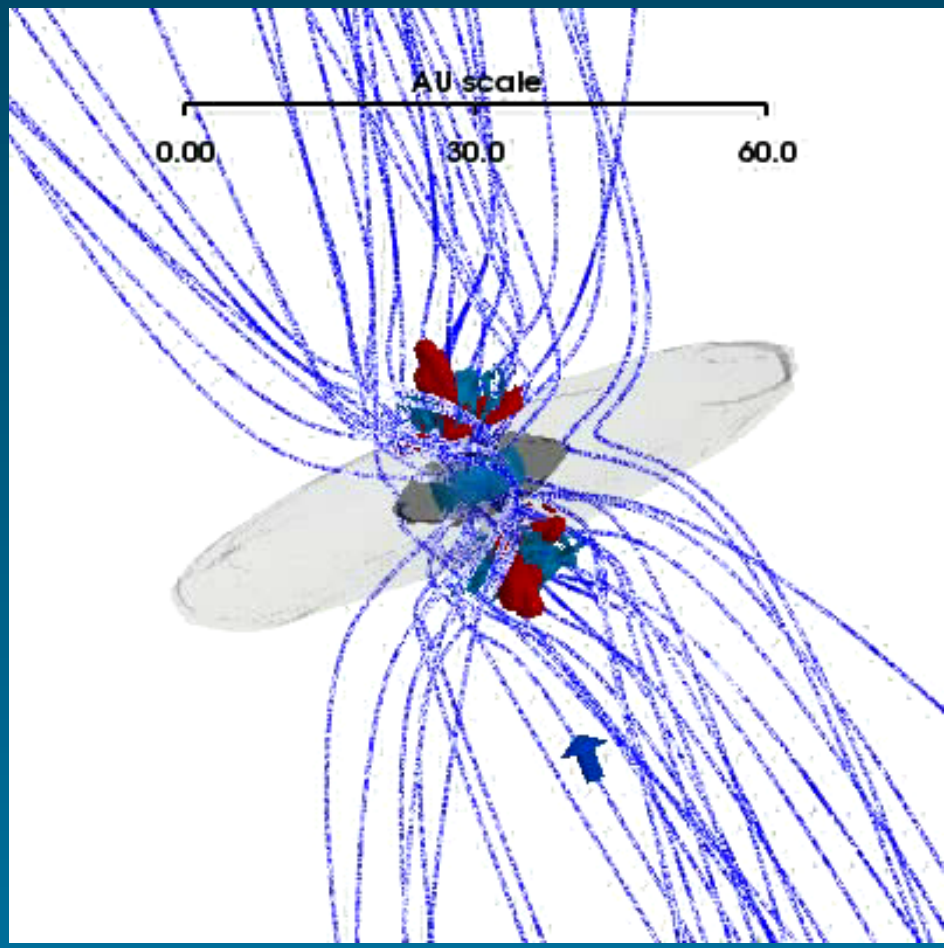

Gentle disruption speed required
0.4 km per sec

Myers 2008

Early history of disks, outflows, and binary stars (Duffin & Pudritz 2009)

- outflows as a consequence of gravitational collapse, (Banerjee & Pudritz 2007)… magnetic tower flows on scale of disks (10s of AU) – low velocity 0.3 -0.4 km/sec - Myers's dispersal




Ideal MHD

Ambipolar Diffusion

# Summary:

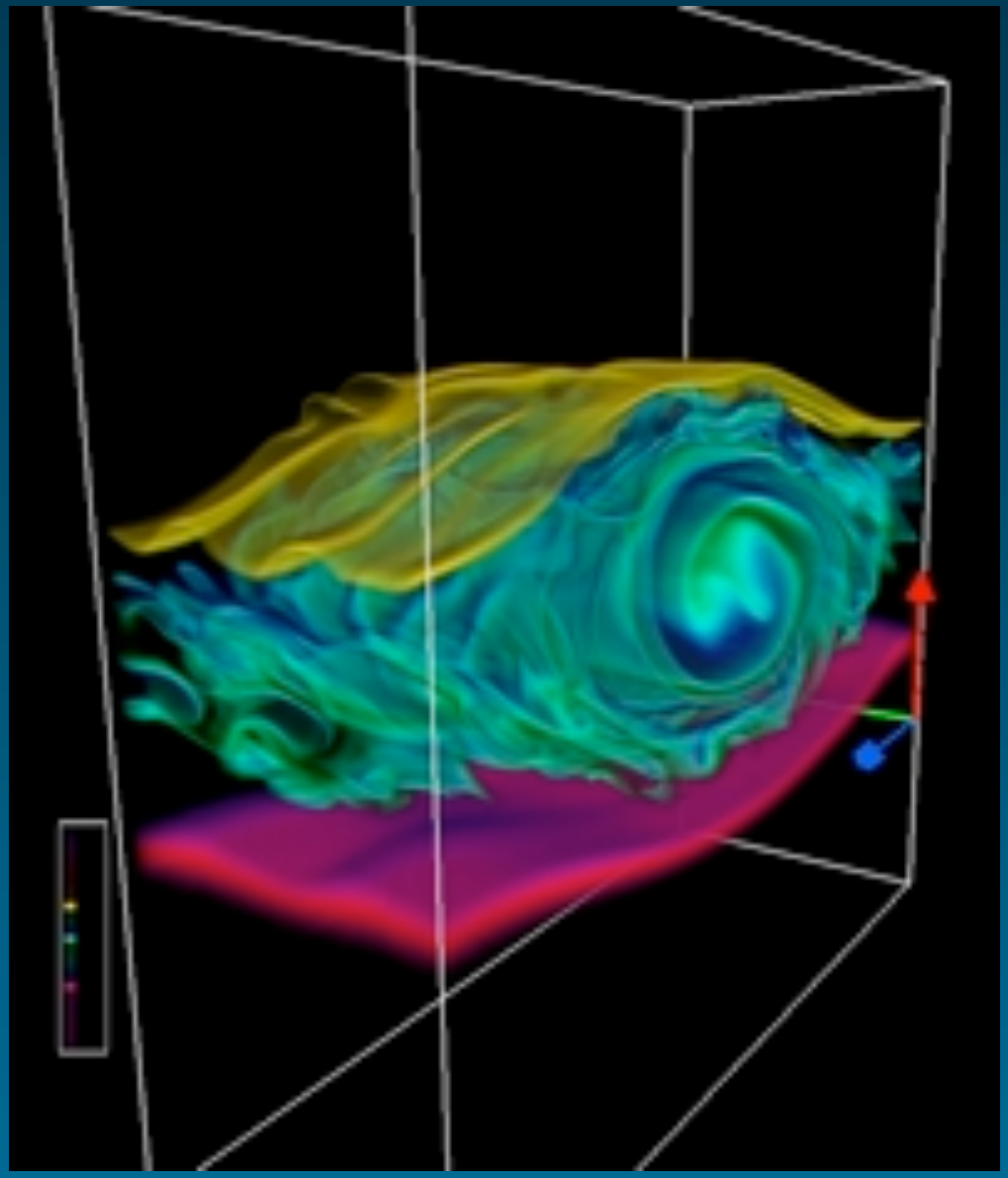
Happy Birthday and thank you!

– from theorists and computatiional

astrophysicists around the globe..

How do filaments form?
In shocks - generation of vortex filaments

Shocks generate vortex sheets at “kinks”, which break up into system of regularly spaced vortex filaments.



http://www.vapor.ucar.edu/gallery

B. Jamroz, E. Lee, and T. Stein