Prestellar core formation: modern updates on a classical problem

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THE LUMINOSITY FUNCTION AND STELLAR EVOLUTION

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ABSTRACT

The evolutionary significance of the observed luminosity function for main-sequence stars in the solar neighborhood is discussed. The hypothesis is made that stars move off the main sequence after burning about 10 per cent of their hydrogen mass and that stars have been created at a uniform rate in the solar neighborhood for the last five billion years.

Using this hypothesis and the observed luminosity function, the rate of star creation as a function of stellar mass is calculated. The total number and mass of stars which have moved off the main sequence is found to be comparable with the total number of white dwarfs and with the total mass of all fainter main-sequence stars, respectively.

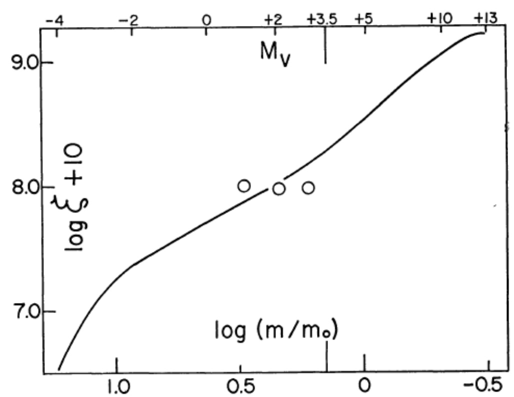


FIG. 2.—The logarithm of the "original mass function," ξ, plotted against the mass, $\mathfrak{M}$, in solar units.

IV. DISCUSSION

Figure 2 and Table 2 show that the "original" mass and luminosity functions ξ and ψ are, in fact, fairly smoothly varying functions without any very rapid change of slope. For log $(\mathfrak{M}/\mathfrak{M}_\odot)$ between -0.4 and $+1.0$, ξ is given reasonably well by the approximation

$$\xi(\mathfrak{M}) \approx 0.03 \left(\frac{\mathfrak{M}}{\mathfrak{M}_\odot}\right)^{-1.35}. \quad (5)$$

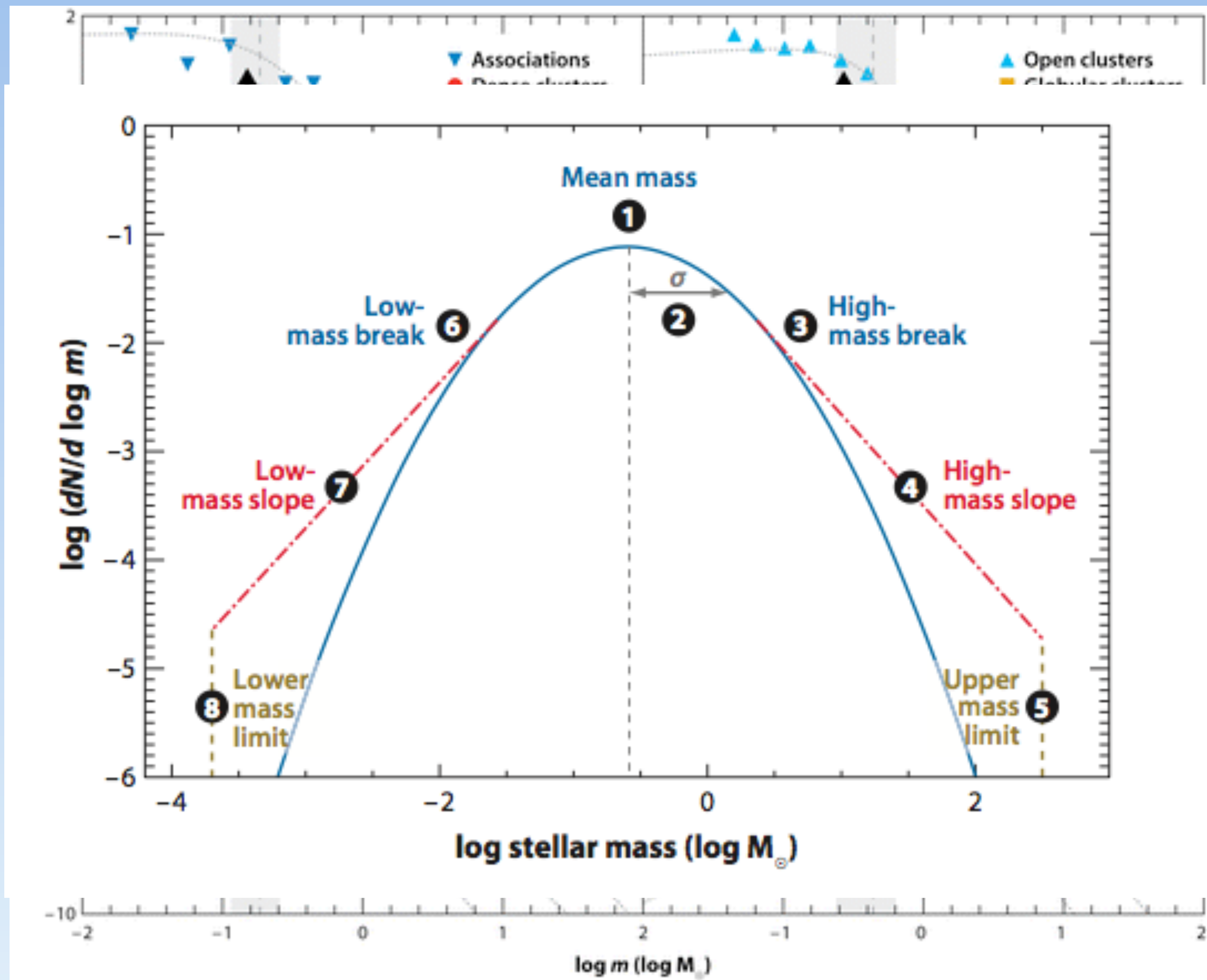
Salpeter (1955)
>4000 citations in ADS

- 15^{th} most cited article
- Most cited article pre-1970

We defined the "original mass function," $\xi(\mathfrak{M})$, by

$$dN = \xi(\mathfrak{M})\, d(\log_{10} \mathfrak{M}) \frac{dt}{T_0},$$

Stellar IMF observations

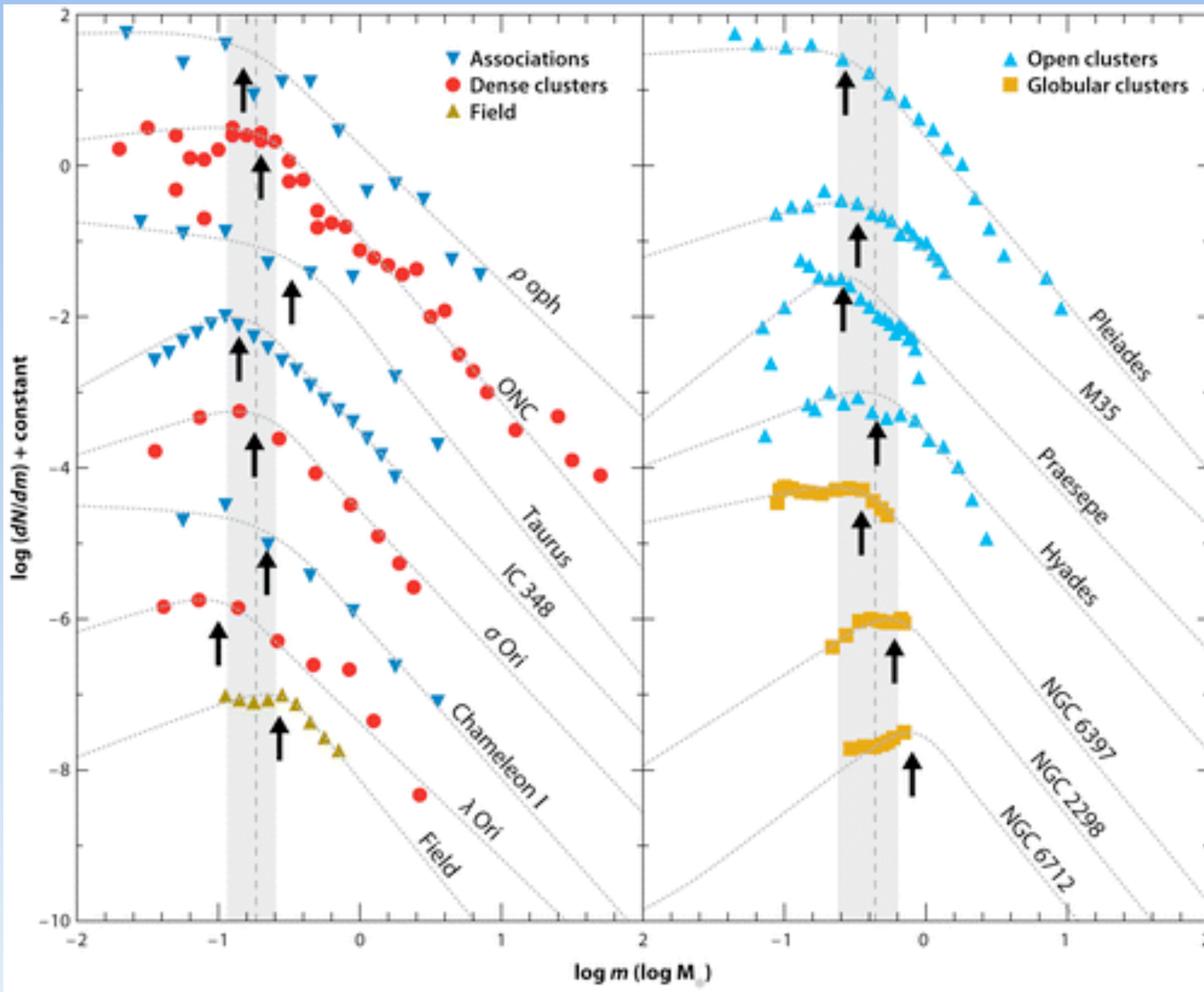


Bastian N, et al. 2010.
Annu. Rev. Astron. Astrophys. 48:339–89

Milky Way:

- High-mass ($M > M_\odot$) consistent with Salpeter power-law: $dN/dlogM \propto M^{-1.35}$
- Low-mass consistent with lognormal, peak at $\sim 0.2\text{-}0.3 M_\odot$ (Chabrier 2003, Kroupa 2001)

Stellar IMF observations



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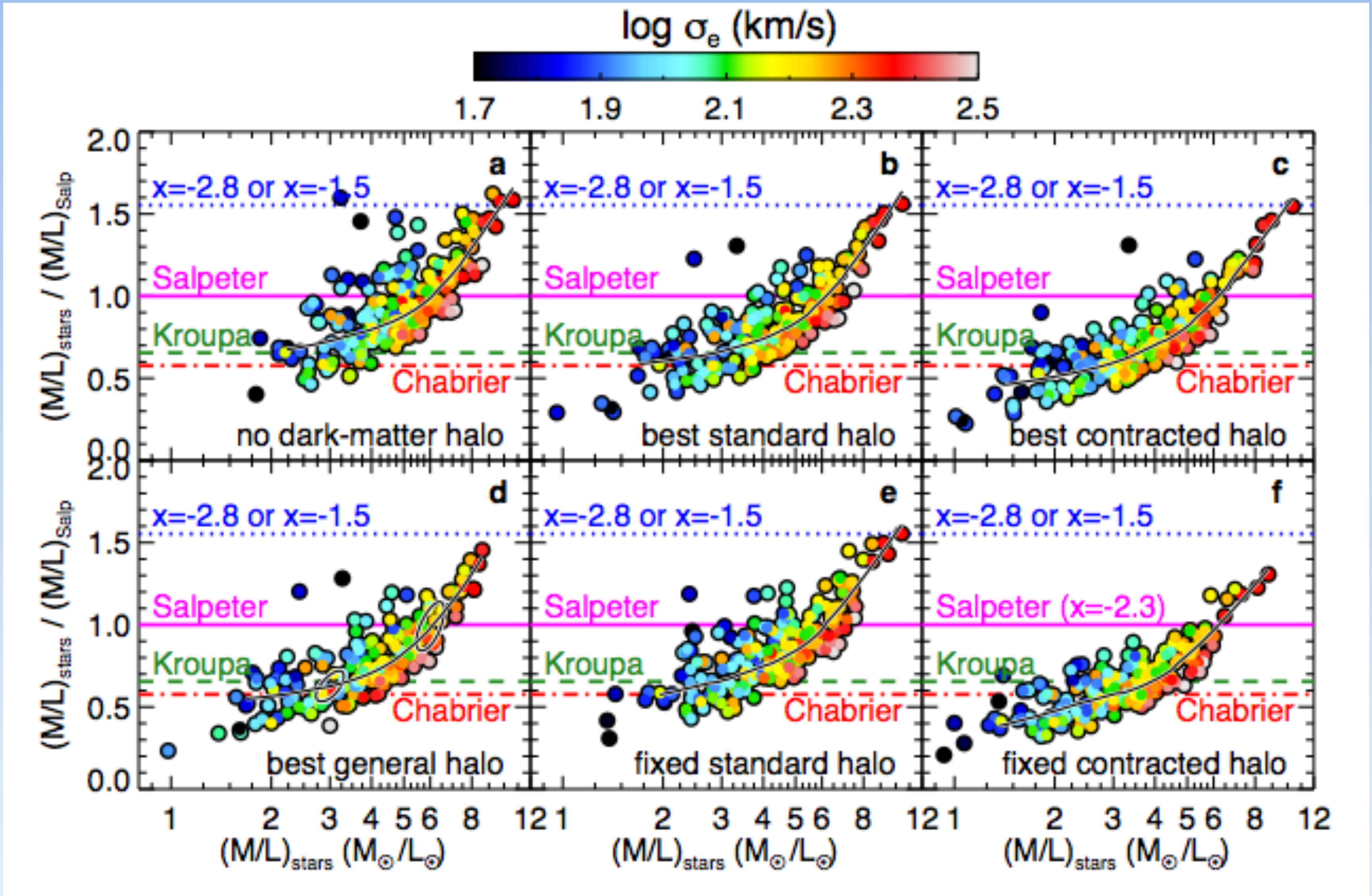
Salpeter (2002) on the "universal" IMF:
"Developments (or lack thereof) in the 45 years since have been good for me personally, but bad for science… the theory of star formation has suffered greatly by not having clear-cut observational variations, which would have to be predicted by a correct theory."

Varying IMF



Cappellari et al (2013)

Outline

- GMC and core properties
- Classical theory of star formation
- Dynamic core formation in turbulent GMC environments
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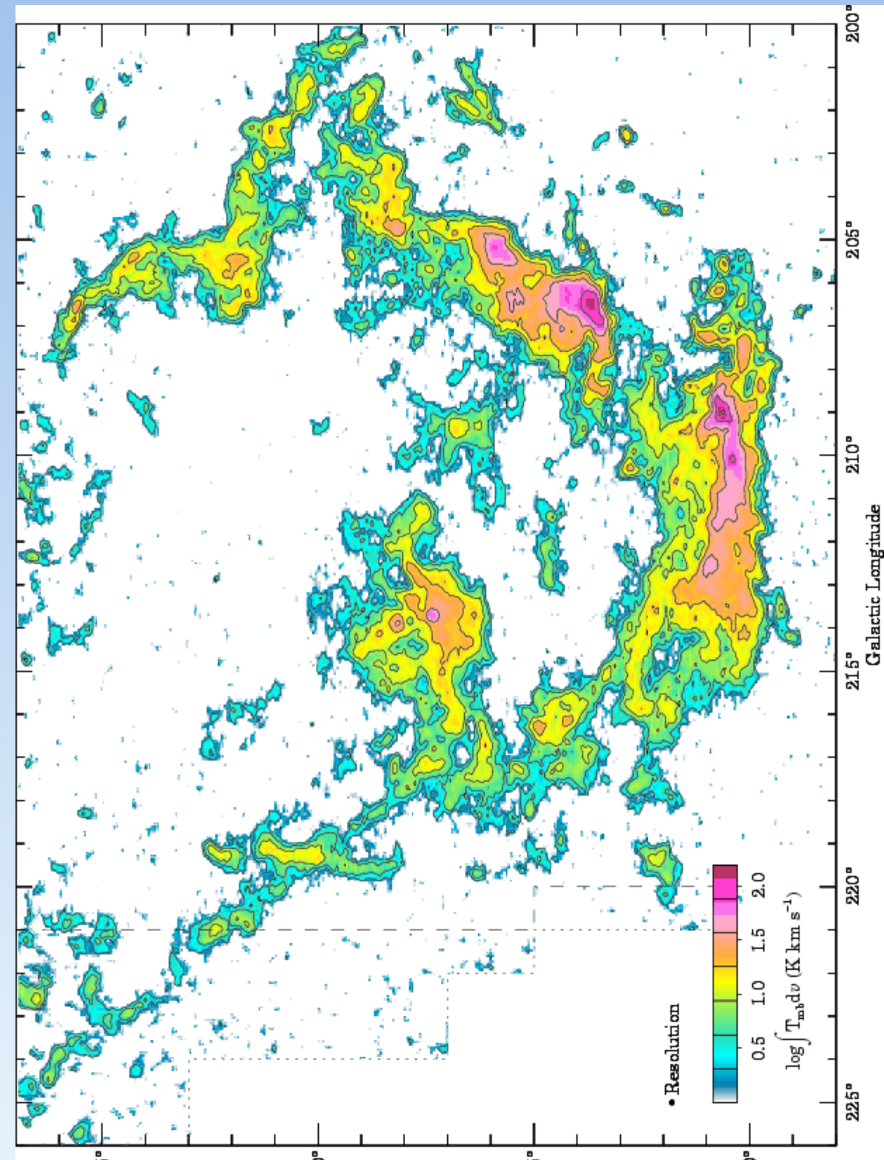
Giant Molecular Clouds

- All star formation in the MW takes place within molecular clouds: low mass “dark clouds” or massive giant molecular clouds (GMCs)
- Gas in molecular clouds is very cold and dense: $T \sim 10$ K, $n \gtrsim 100$ cm^{-3}
- Structure is GMCs is hierarchical:
  - Sheets and filaments
  - Clumps
  - Cores
- GMCs and largest clumps/filaments are self-gravitating:

  $$P_{eff} \sim G\Sigma_{gas}^{2} >> P_{\text{diffuse ISM}}$$
- Smaller moderate-density clumps/ filaments may be transient
- Very dense cores are self-gravitating



Orion-Monoceros in CO (Wilson et al 2005)

GMC Turbulence

- Gas velocity dispersions in MW SF regions follow "universal" relation:

  $\delta v_{turb,los} = 1 \mathrm{kms}^{-1} (L/pc)^{1/2}$
- True both from cloud to cloud, and within clouds (Larson 1981, Solomon et al 1987, Heyer & Brunt 2004)
- Sonic scale, where

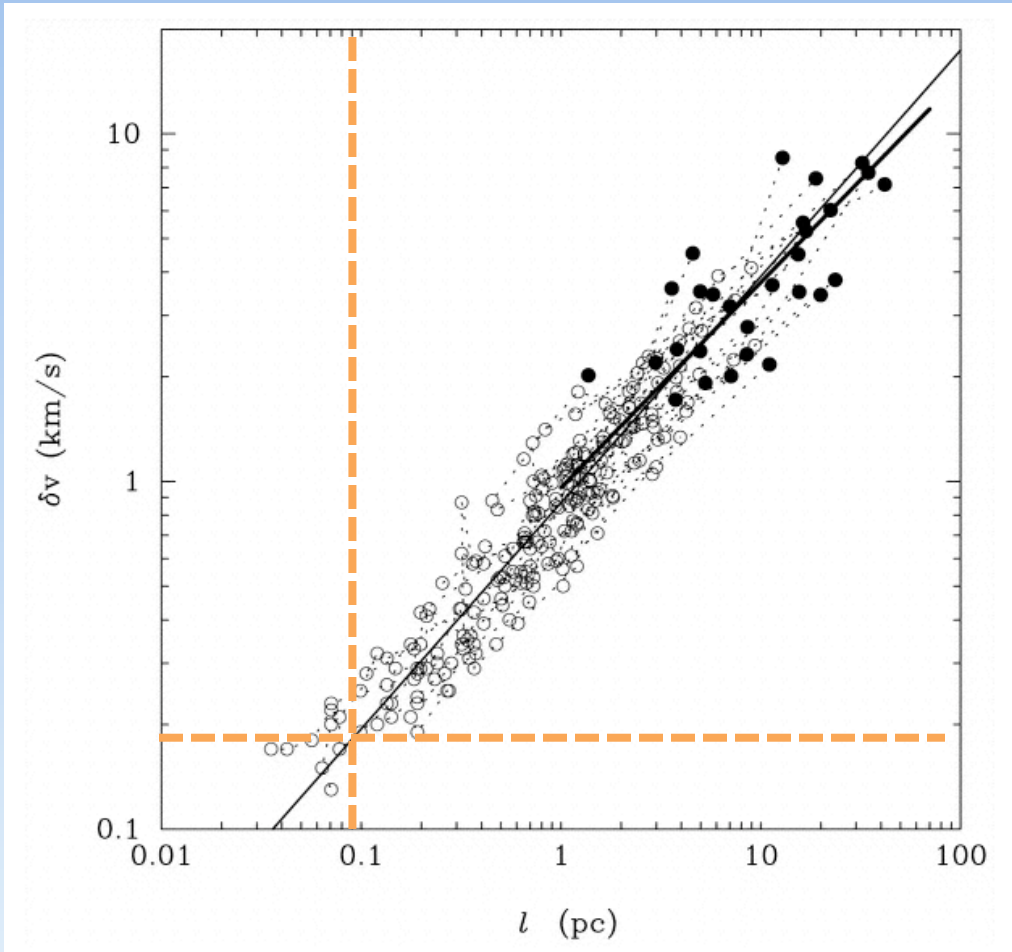
  $v_{turb}(L_{sonic}) = c_s = 0.2 \text{ km s}^{-1}$

  is $L_{sonic} \sim 0.1$ pc
- $\delta v(s) \propto s^{1/2}$ linewidth size is consistent with Burgers spectrum in gravitationally bound clouds with $\Sigma \sim$const:

$$v^2(R) \sim GM/R \sim G(\Sigma R^2)/R \sim G\Sigma R$$

$$\delta v(s) \sim (G\Sigma R)^{1/2}(s/R)^{1/2}$$

- Simulations reproduce observed velocity scalings



Heyer & Brunt (2004)

Turbulence and density structure

- In simulations of strongly-turbulent systems, high-density post-shock structures develop in regions of converging flow
- Successive compressions and rarefactions are independent:

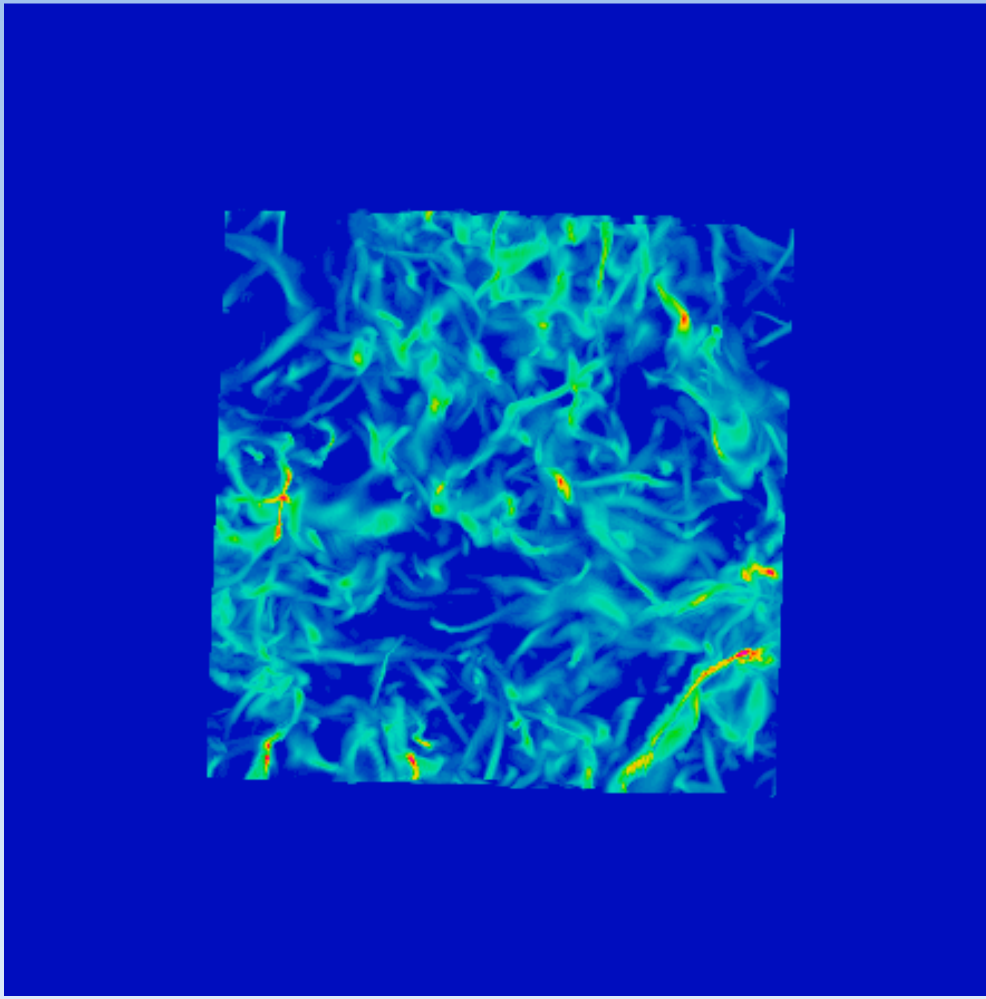
$$x \equiv \ln \frac{\rho}{\bar{\rho}} = \sum_i \ln(1 + \delta_i)$$

resulting in a log-normal distribution:

$$f_{V,M}(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(x \pm \mu)^2}{2\sigma^2}\right]$$

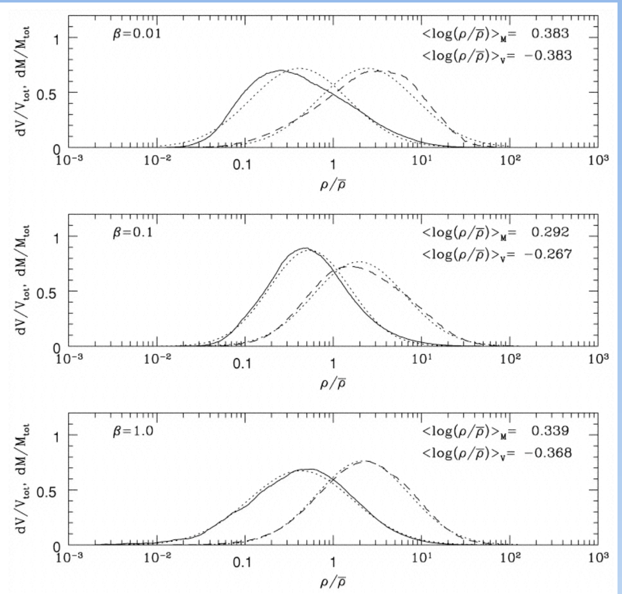
with $\mu=\sigma^2/2$

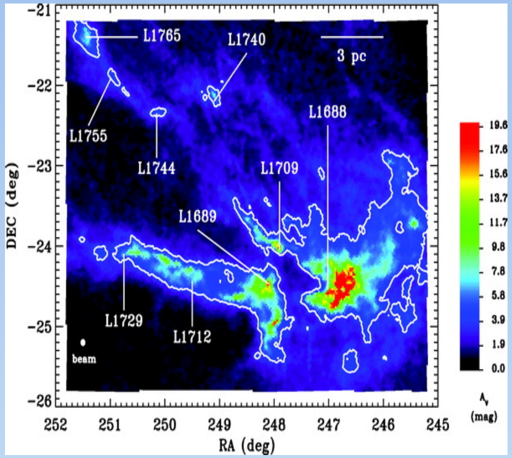
- Value of $\mu=\langle\ln(\rho/\rho_0)\rangle$ increases with the Mach number ⇒ more-turbulent systems have:
  - higher mass-weighted density
  - lower volume filling factor

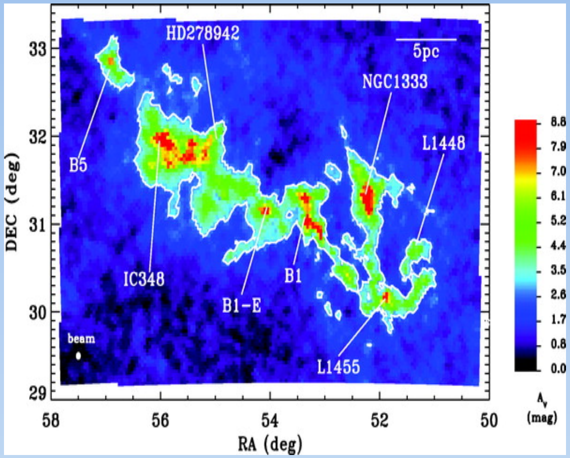


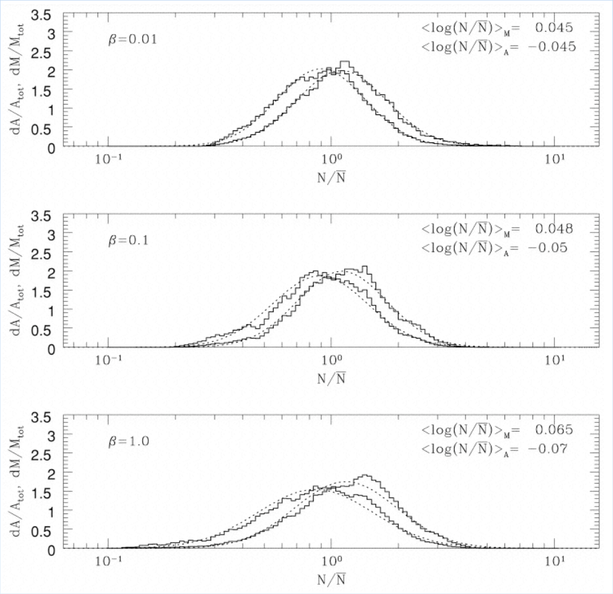
Ostriker, Stone & Gammie (2001)

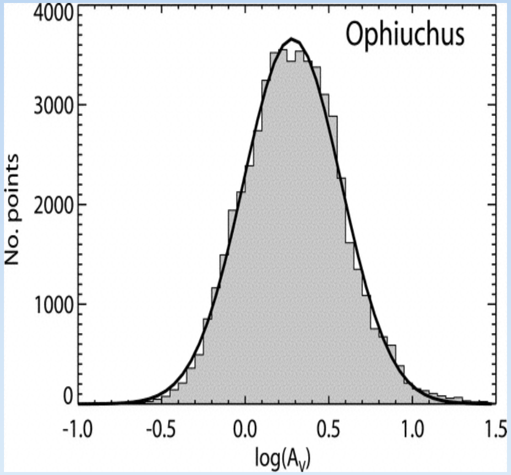
Density and column PDFs

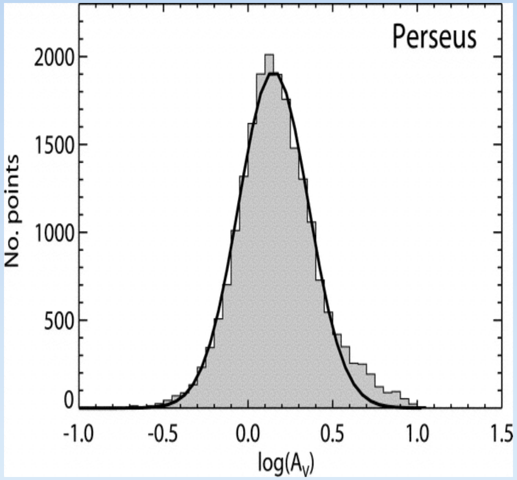












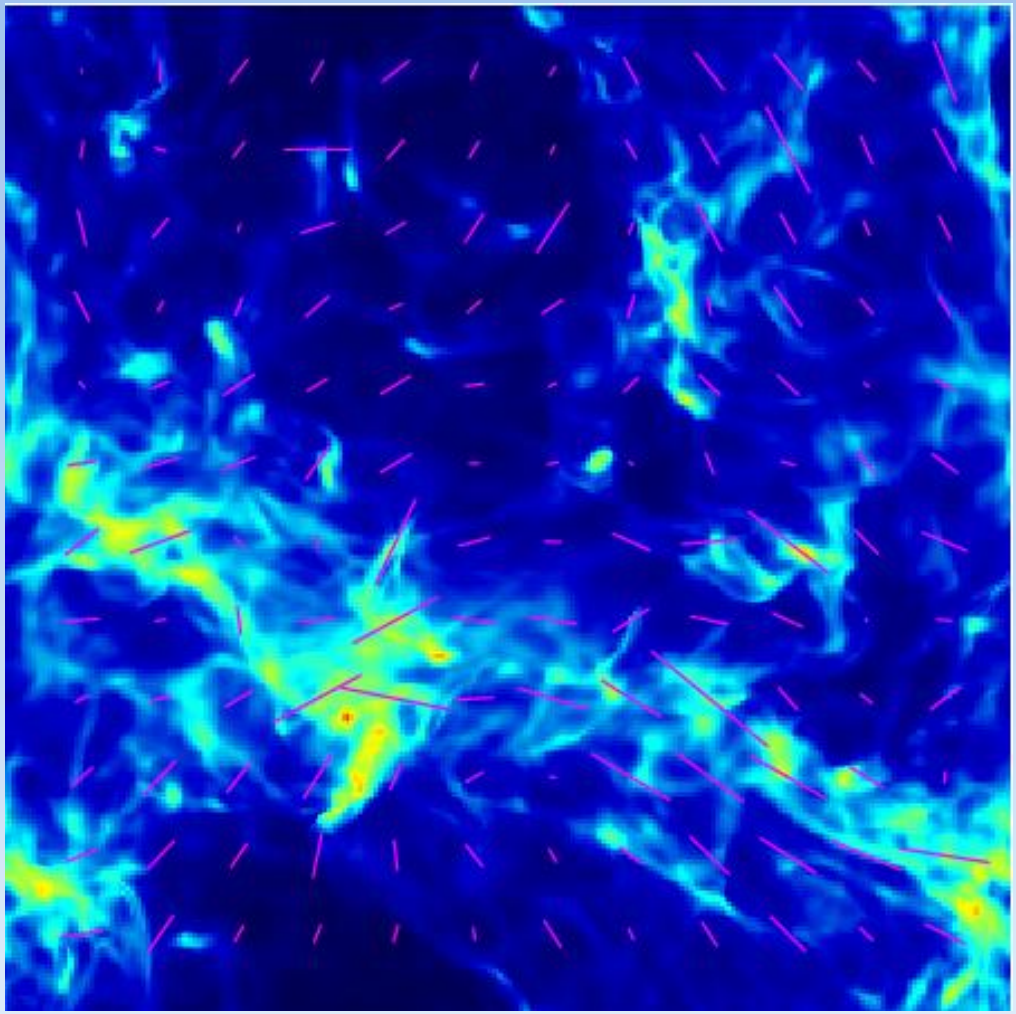
Ridge et al (2006) –PDF from extinction

Column density PDF is also lognormal, with smaller σ (Ostriker et al 2001)

Turbulence and density structure

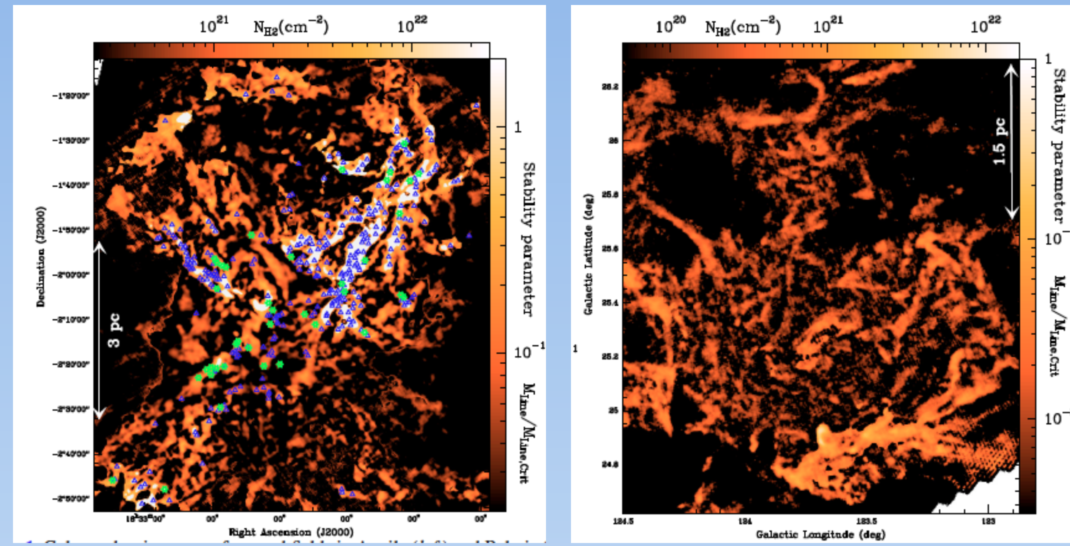
- Because compression is due to turbulence, and largest-scale velocities dominate the turbulence

  ⇒ the largest scales also dominate the density structure
- This has important consequence that star formation lies along large **filaments** and is **clustered**

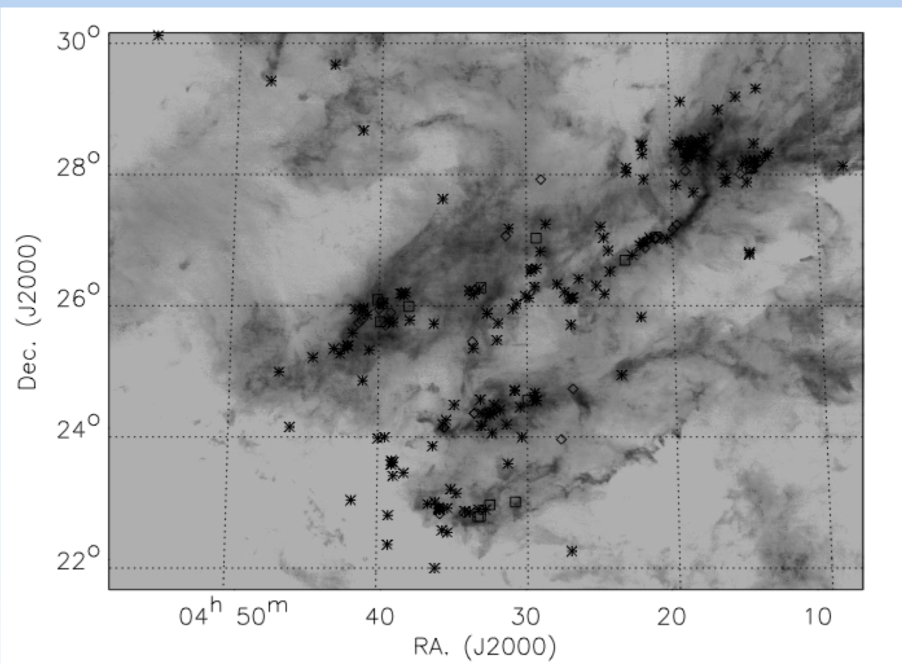


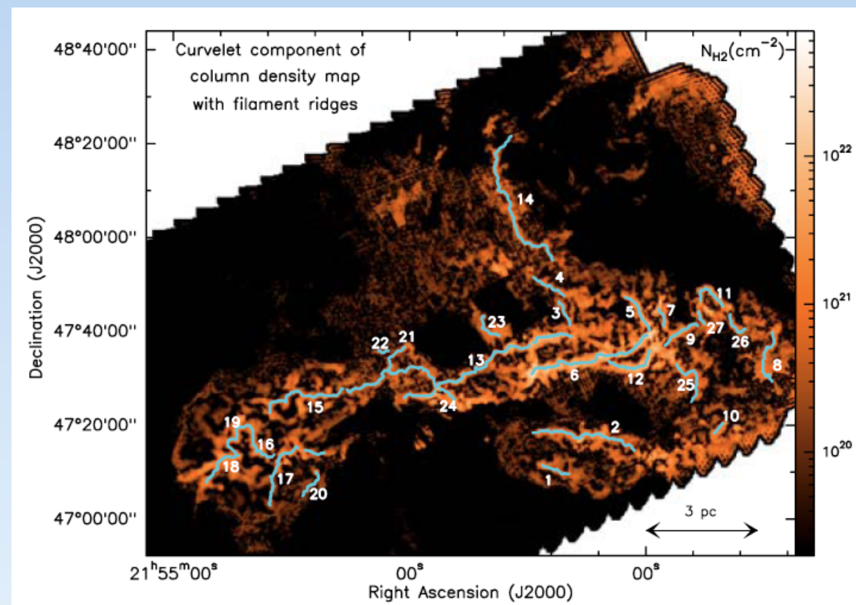
Ostriker, Stone & Gammie (2001)

Filaments in molecular clouds



Herschel: Aquila; Polaris Flare (Andre et al 2010)

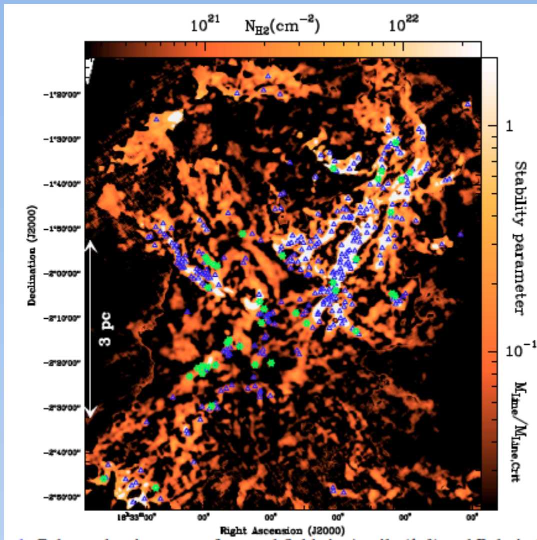


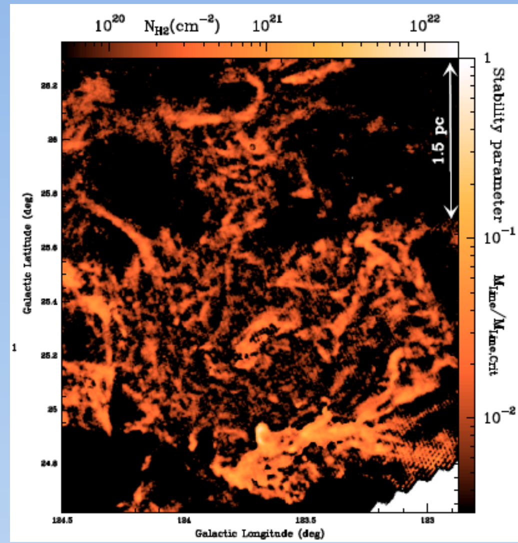


Herschel: IC 5146 (Arzoumanian et at 2011)

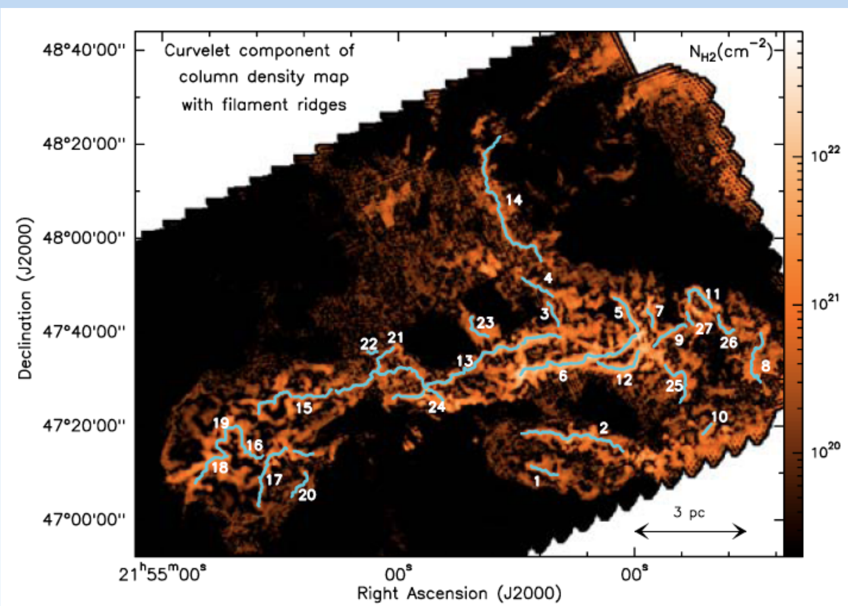
CO: Taurus cloud (Goldsmith et al 2008)

Filament widths





Herschel: Aquila cloud; Polaris Flare cloud (Andre et al 2010)



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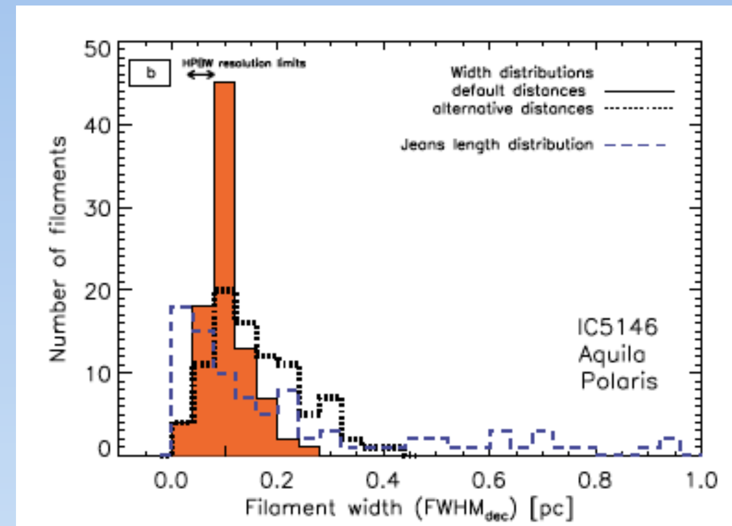
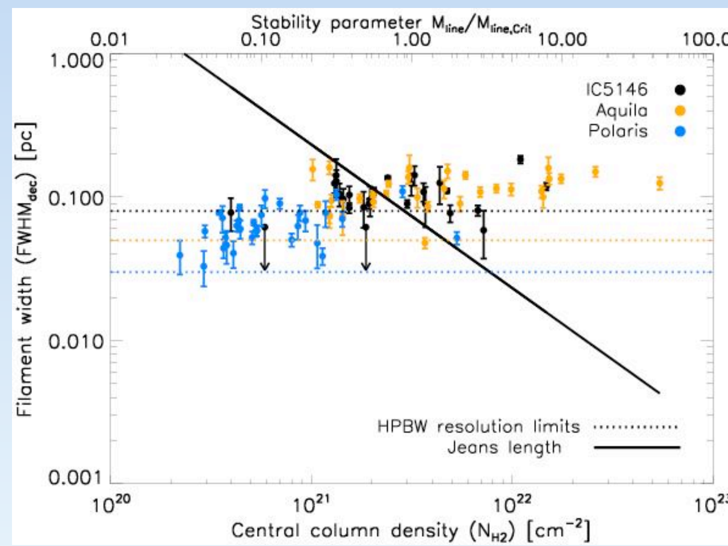
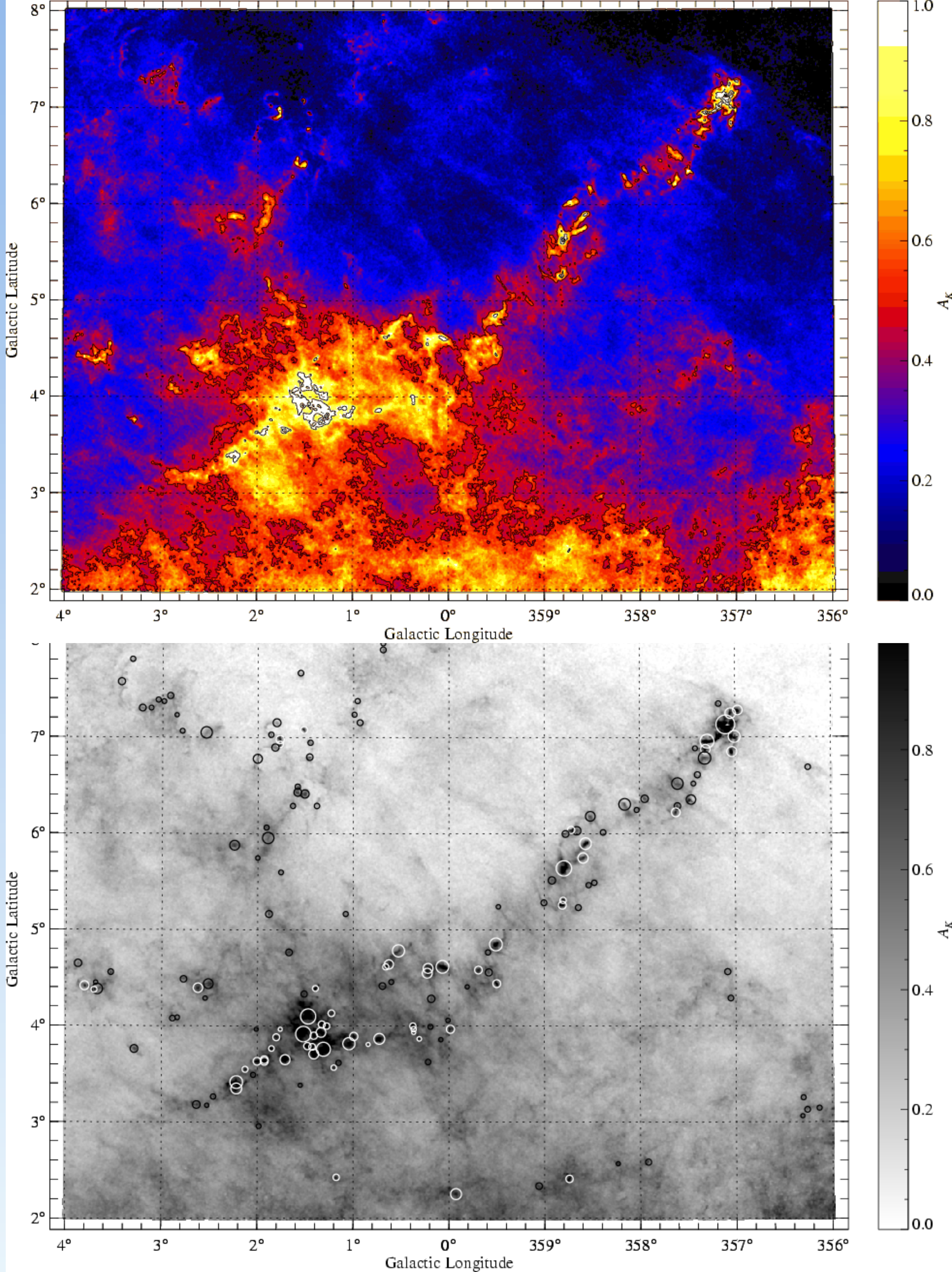




Arzoumanian et at 2011

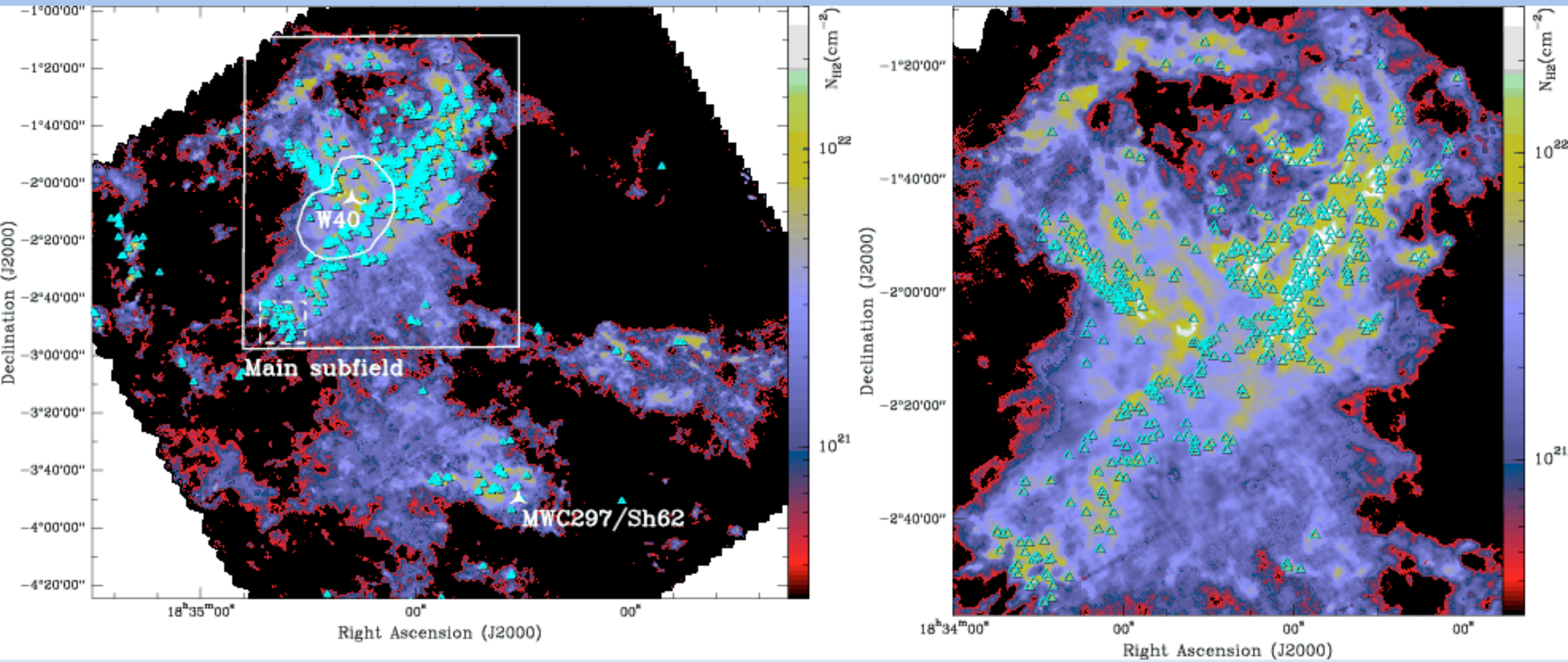
Molecular cores

- Molecular cores ($n>10^4$ cm^{-3}) are identified and observed using dense molecular tracers (NH_3, CS, $C^{18}O$, etc), mm, sub-mm, far-IR continuum, and extinction mapping
- Column density contrast is often small because of surrounding foreground and background gas



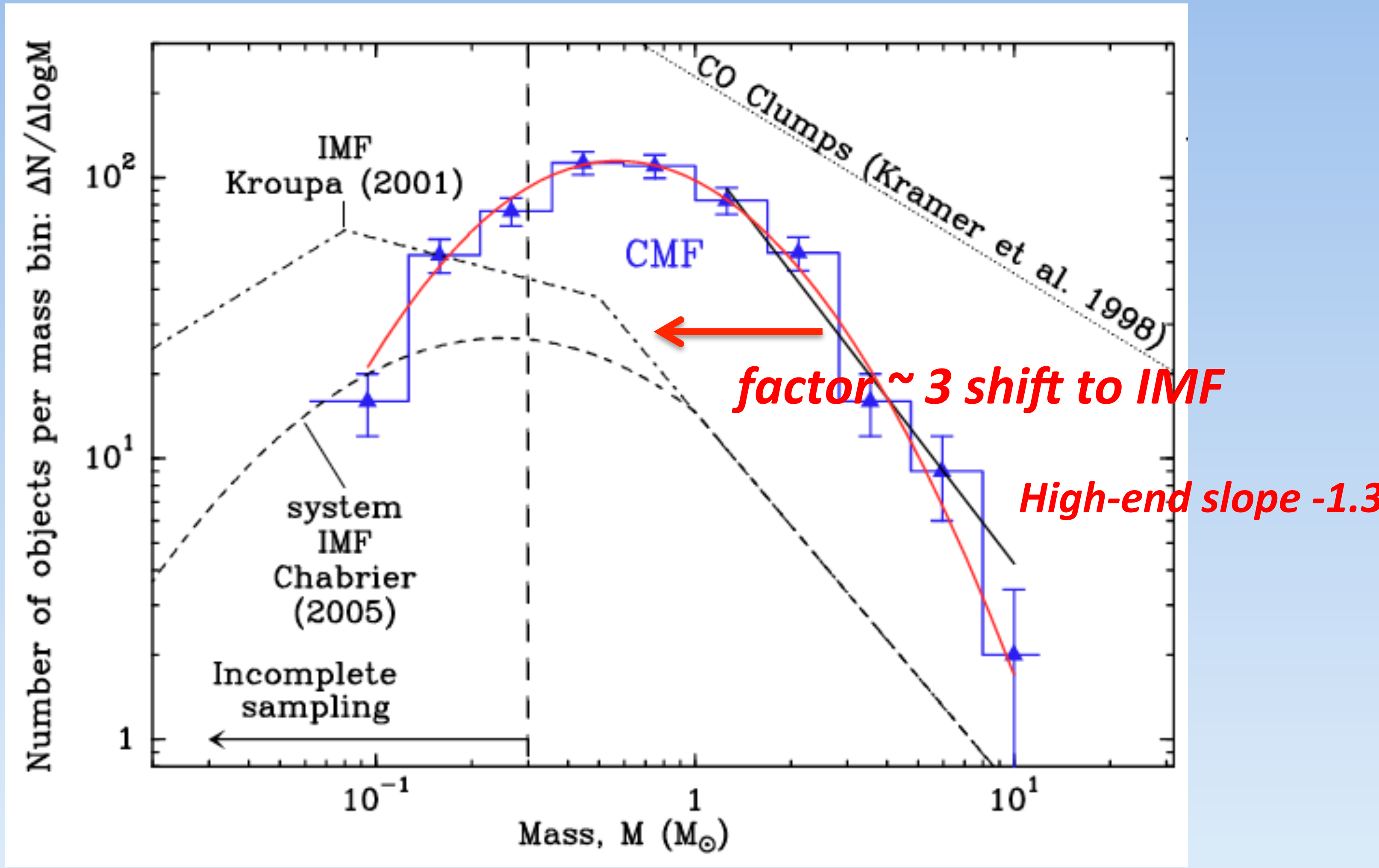
Pipe nebula extinction map and cores (Alves et al 2007)

Prestellar Core Mass Function (CMF)



Konyves et al (2010): Aquila cloud map with core positions from *Herschel* Gould Belt survey

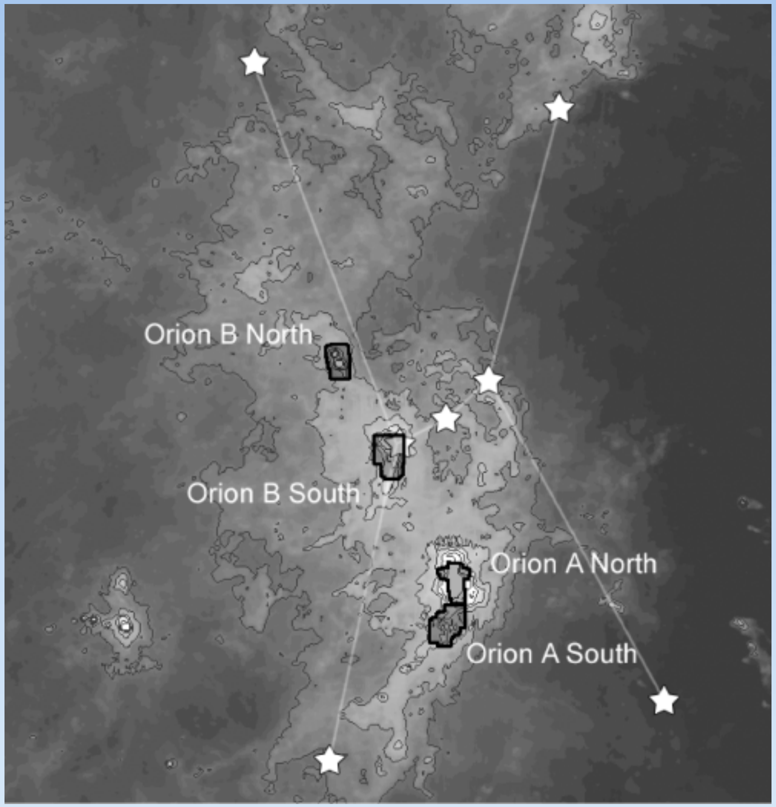
Prestellar Core Mass Function (CMF)

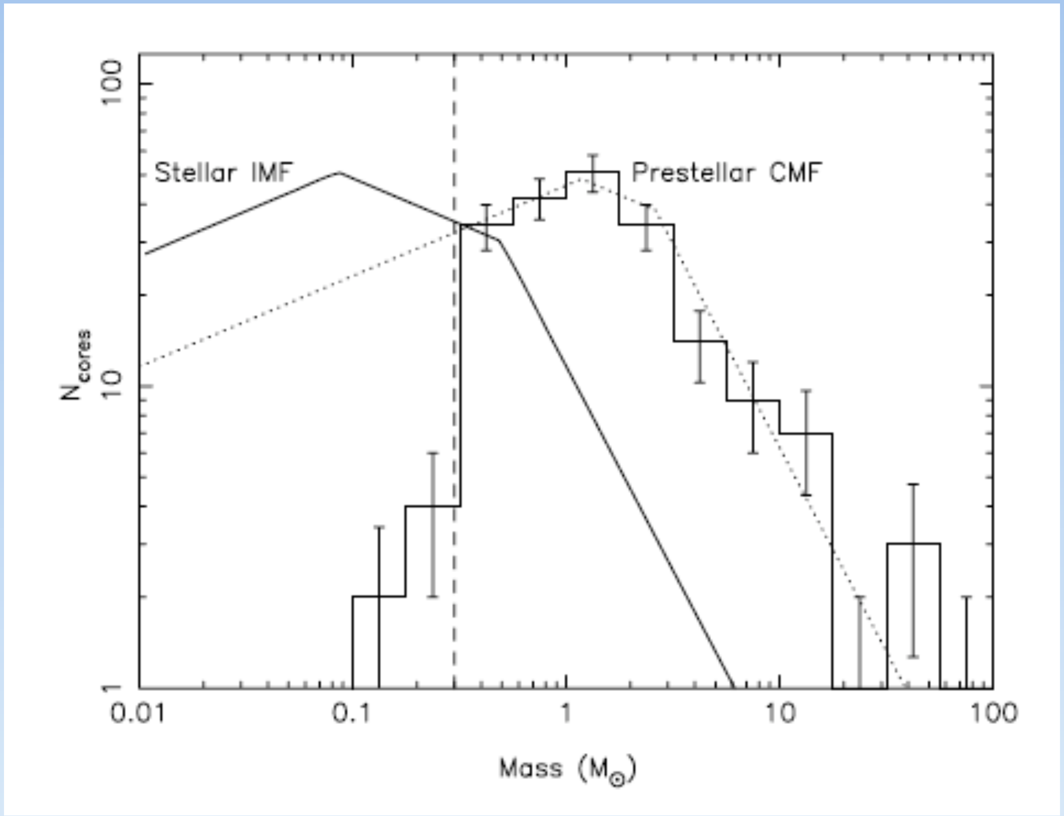


Konyves et al (2010): CMF in Aquila from *Herschel*

See also.: Motte et al (1998), Testi & Sargent (1998), Johnstone et al (2000), Onishi et al (2002), Enoch et al (2006), Alves et al (2007), Nutter & Ward-Thompson (2007)

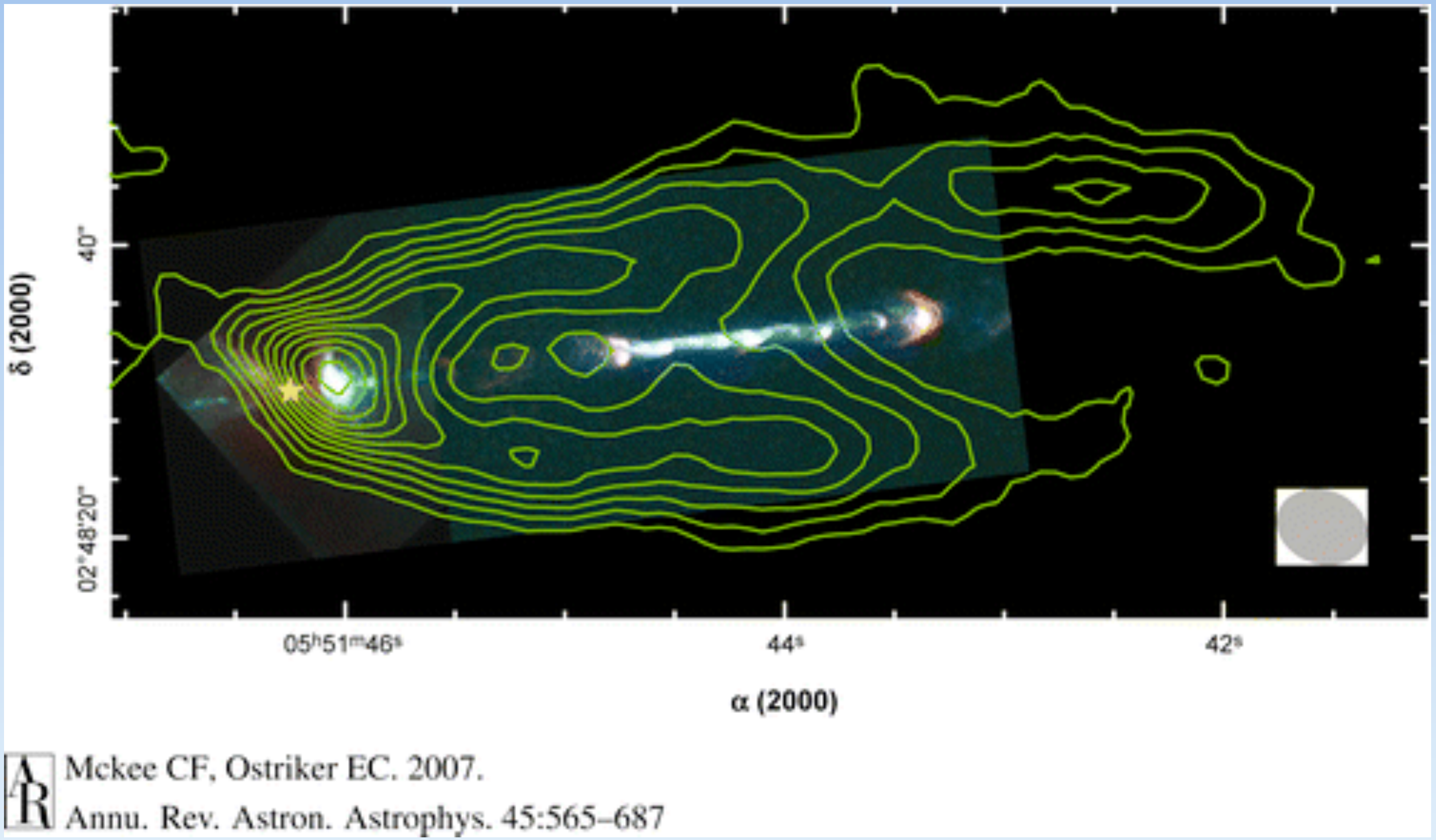
Core mass function in Orion





sub-mm CMF (Nutter & Ward-Thompson (2007)

Core-to-star efficiency: outflows



HH 111 jet and outflow system – composite of HST and J=1-0 CO (courtesy of C.F. Lee)

Prestellar core properties

- High density: $n \gtrsim 10^4$ cm^{-3}
- Centrally concentrated; consistent with isothermal equilibrium "Bonnor Ebert"sphere

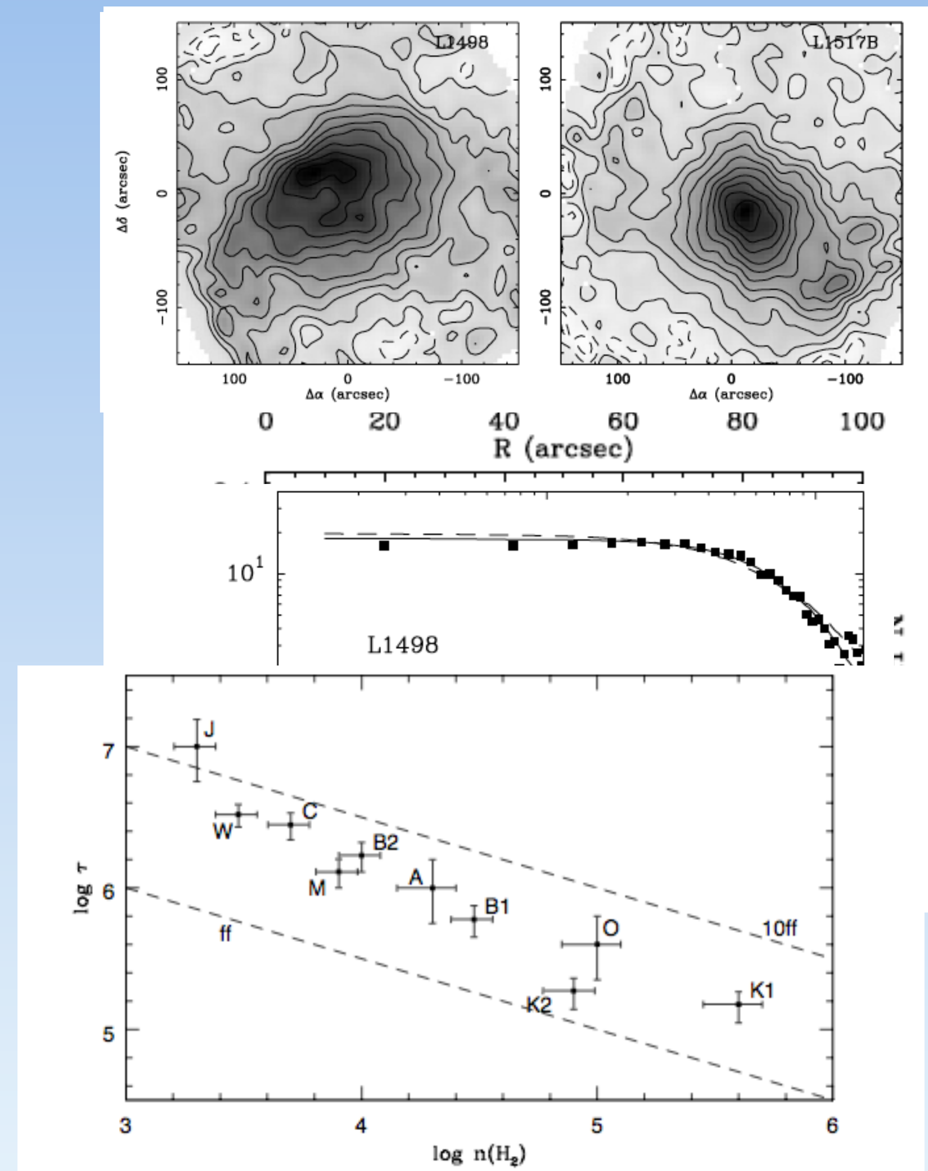
  (Ward-Thompson et al 1994, Evans et al 2001, Caselli et al 2002, Lada et al 2003, Tafalla et al 2004, Kirk et al 2005, Kandori et al 2005)

- Subsonic internal turbulent velocity
  (Myers 1983; Goodman et al. 1998; Kirk et al.2007; Andre et al 2007; Lada et al. 2008)
- Duration of prestellar phase
  ~ few× gravitational free-fall time

$$t_{ff} \equiv \left(\frac{3\pi}{32G\rho}\right)^{1/2} = 1.4\times 10^5\mathrm{yr}\left(\frac{n_H}{10^5\mathrm{cm}^{-3}}\right)^{-1/2}$$

~ embedded protostellar lifetime

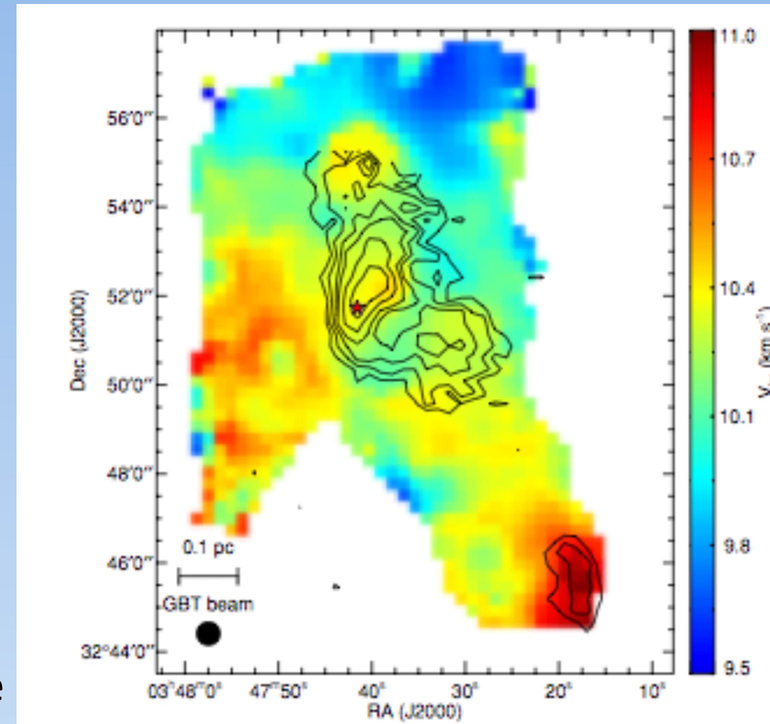
(Hatchell et al 2007, Ward-Thompson et al 2007, Enoch et al 2008, Evans et al 2009)



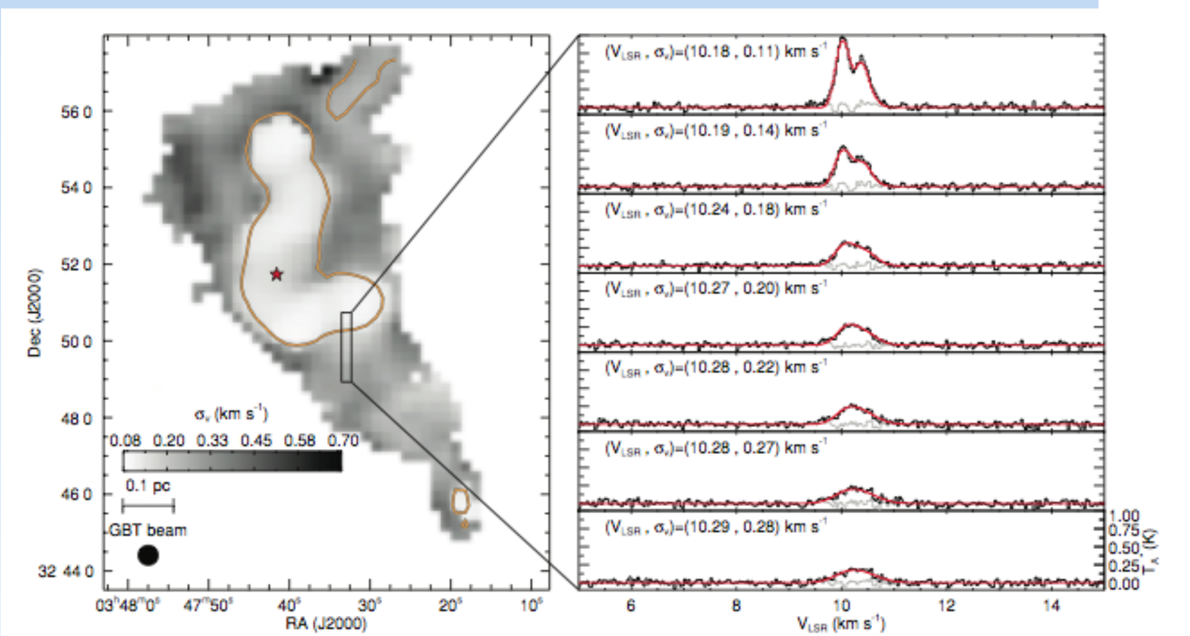
Ward-Thompson et al (2007)

Velocity-coherent core

Pindeda et al (2010): GBT NH_3 observations of 11 $M_\odot$ B5 core in Perseus

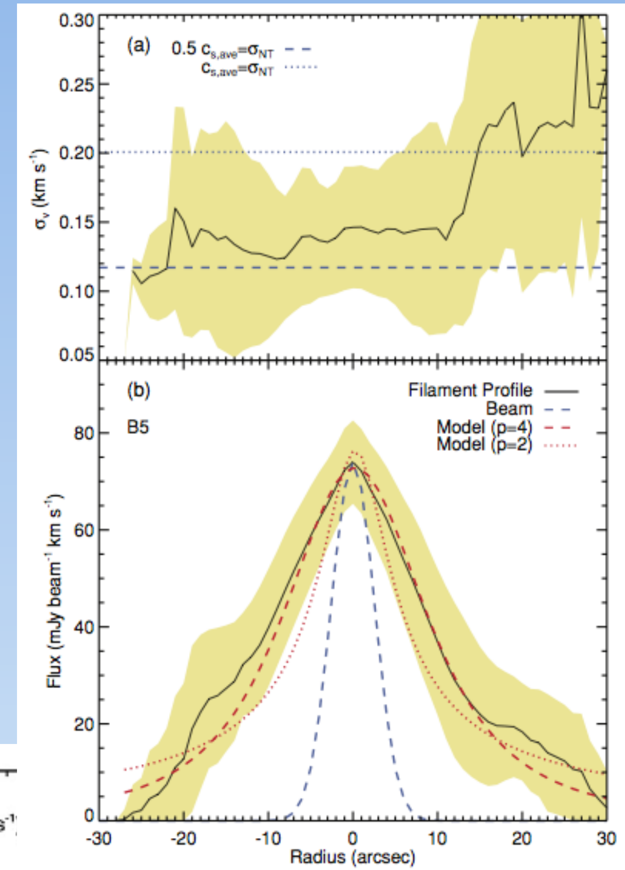


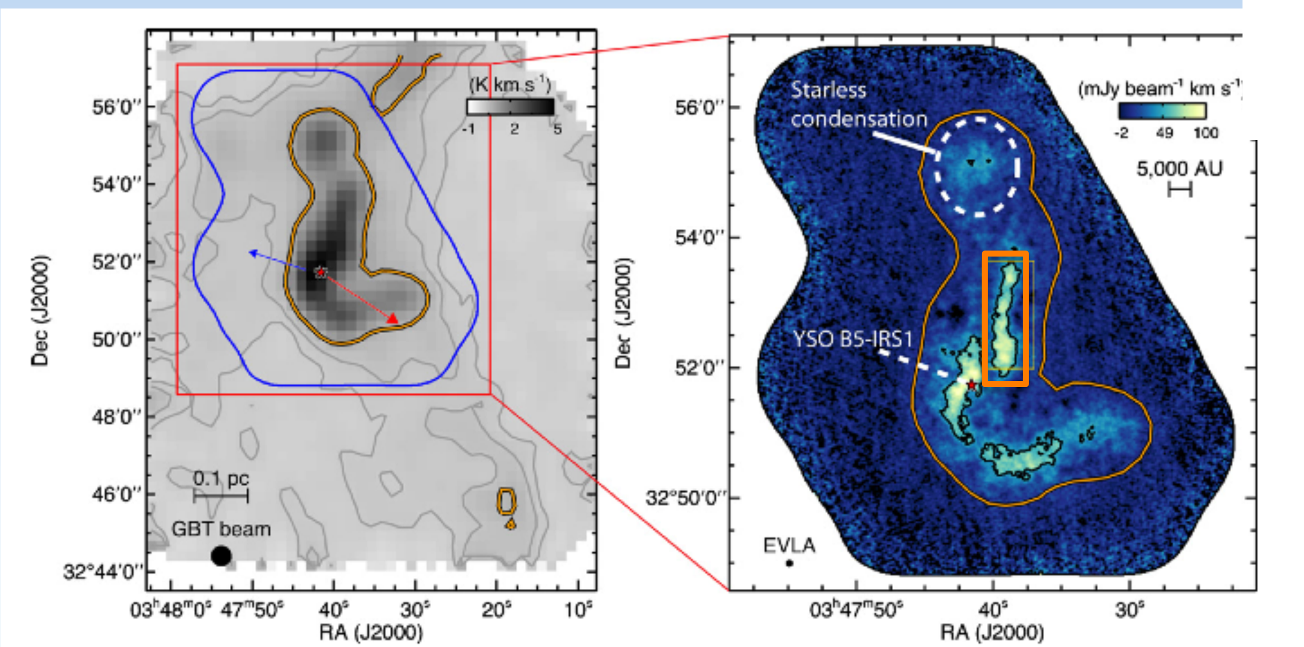
Velocity dispersion subthermal in sub-mm dense core



Velocity-coherent core/filament

Pineda et al (2011): GBT+ELVA NH_3





Outline

- GMC and core properties
- Classical theory of star formation:
  collapse of individual cores
- Dynamic core formation in turbulent GMC environments
- Summary

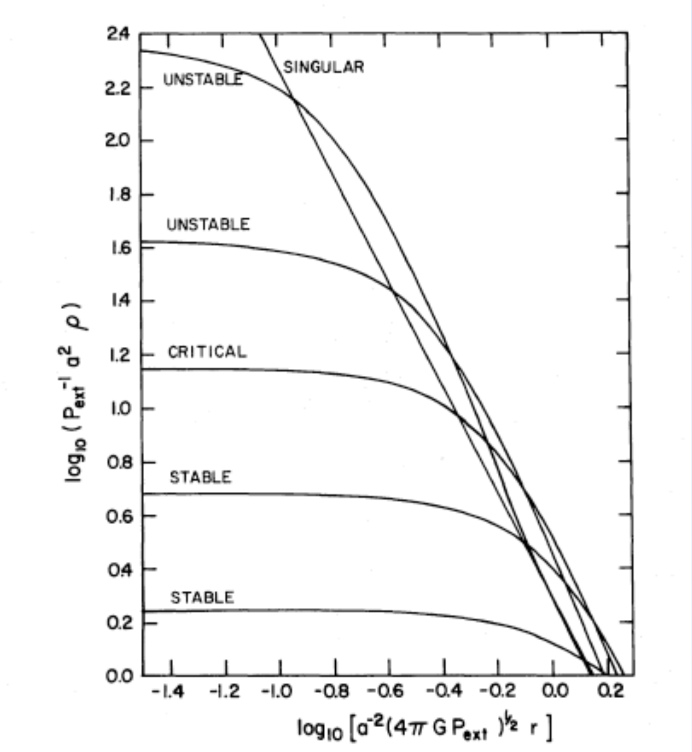
Classical theory: isothermal spheres

- Maximum spherical mass that can be supported by thermal pressure at a given temperature and external pressure is the crical Bonnor-Ebert mass (Bonnor 1956, Ebert 1955):

$$M_{BE} = 1.2\frac{v_{th}^4}{\left(G^3 P_{edge}\right)^{1/2}} = 1.2\frac{v_{th}^3}{\left(G^3 \rho_{edge}\right)^{1/2}} = 1.5 M_{\odot}\frac{\left(T/10K\right)^{3/2}}{\left(n_{edge}/10^4\,cm^{-3}\right)^{1/2}}$$

- More centrally-concentrated spheres are unstable, less concentrated spheres are stable

Shu (1977)

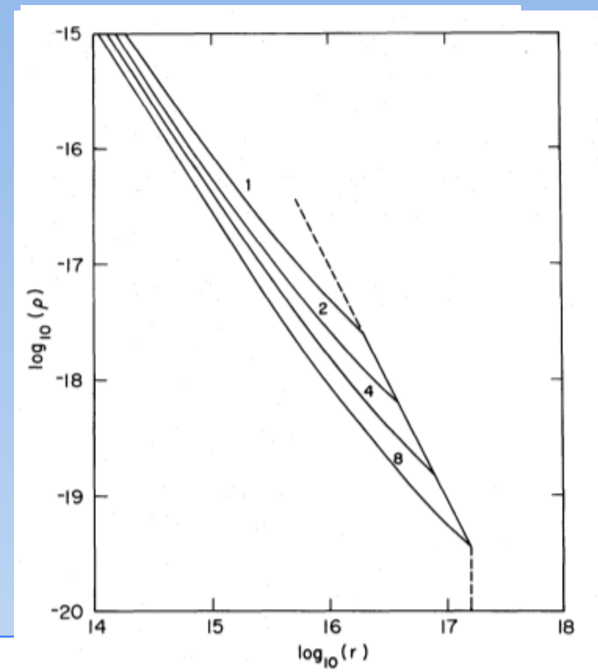


Core collapse

- Collapse of initial static core is "outside-in" (Larson 1969, Penston 1969) followed by "inside-out" (Shu 1977, Hunter 1977)
- Inside initially has low velocity; wave of collapse starts in outer core and redistributes mass to attain singular profile:

$$\rho_{\mathrm{LP}} = 8.9\frac{c_s^4}{4\pi G r^2}$$

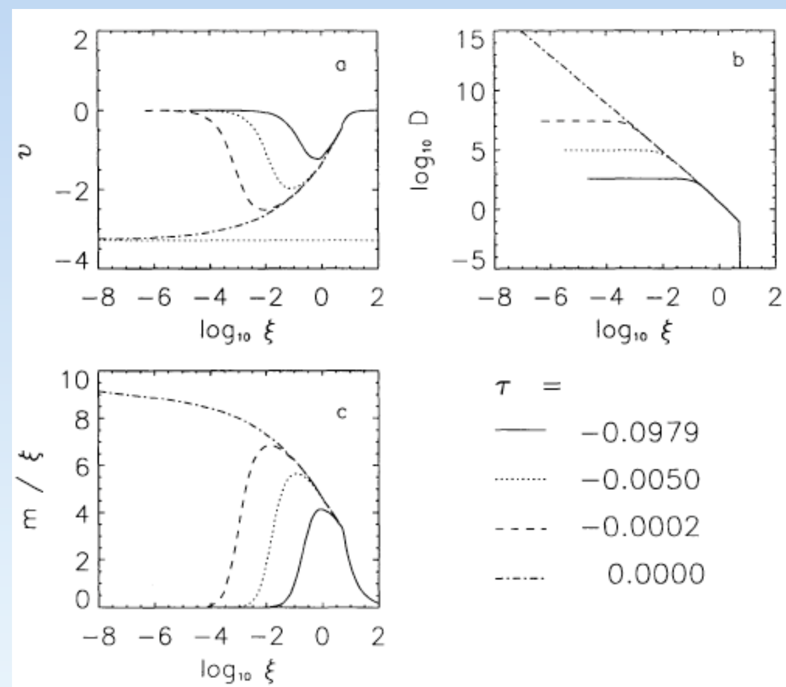
- After central density $\rightarrow\infty$, rarefaction starts to propagate outward from the center as gas accretes onto the protostar: $t_{\mathrm{infall}}(r) \propto \rho^{-1/2} \propto r$
- In infalling region, $v \propto r^{-1/2}$, $\rho \propto r^{-3/2}$



Shu (1977): self-similar expanding rarefaction wave

son (1969): form initial ere; approaches -similar sol'n

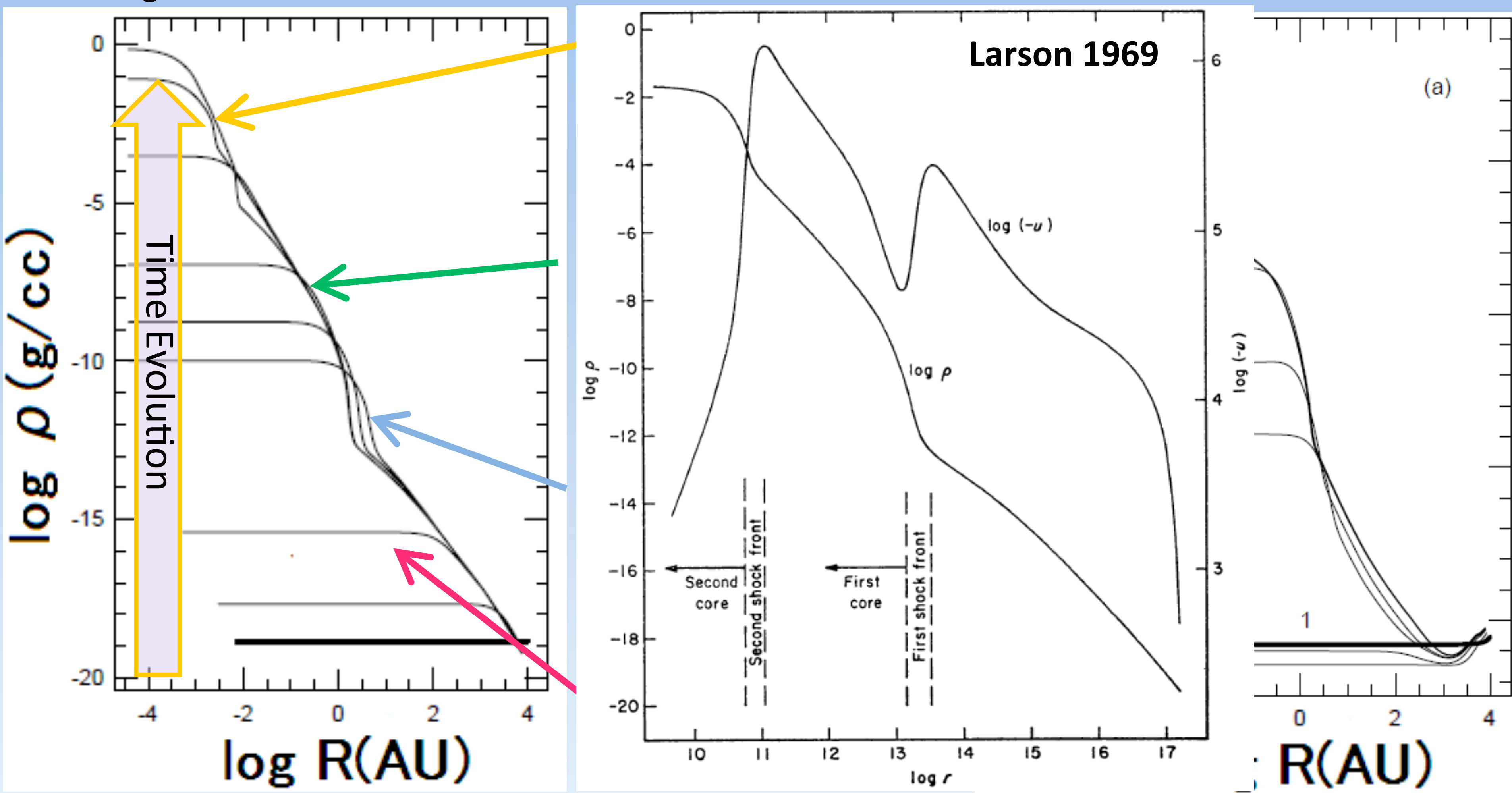
$$\eta = 8{\cdot}86x^{-2}.$$



Foster & Chevalier (1993): near-critical initial sphere

Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000



Radiation transfer and chemistry control late evolution.

Post-collapse dynamics

- Gas tends to conserve angular momentum and spins up as it collapses toward the center; centrifugal effects drive gas into disk
- Differential rotation in the inflow tends to amplify the magnetic field, which brakes rotation and accelerates radial motion
- Very active current research area is understanding collapse+rotation+magnetic fields+ambipolar diffusion +resistive dissipation
- Magnetic braking catastrophe?
  - Magnetic braking too efficient; prevents formation of disk

  Mellon & Li 2008, 2009; Li et al 2011; Hennebelle & Fromang 2008
  - Small disk forms early due to diffusive effects; braking is reduced in non-aligned case; braking declines with envelope accretion; turbulence can reconnect B and reduce braking

  Dapp et al 2012, Machida et al 2011, Joos et al 2012, Tomida et al 2013, Machida & Hosokawa 2013, Seifried et al 2012,2013

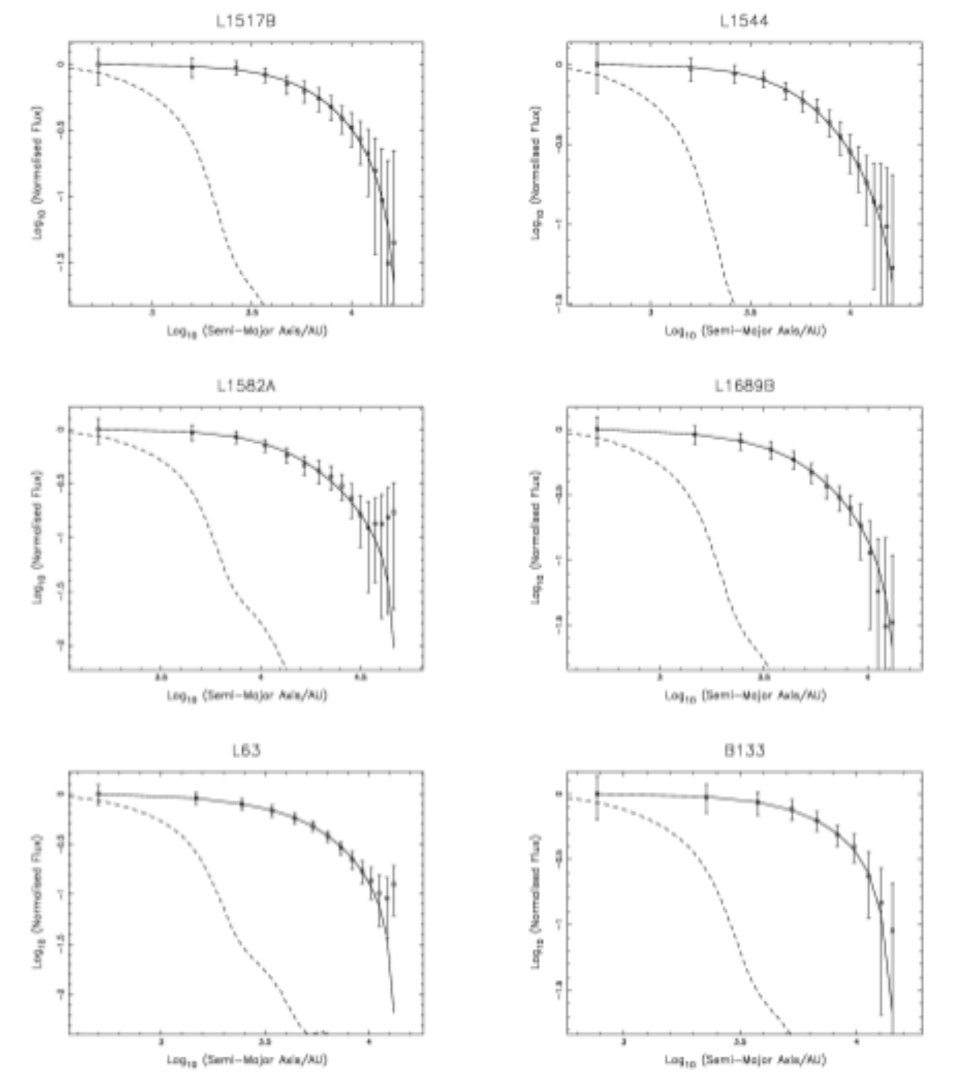
Origin of cores?

Observed dense cores are similar to unstable BE sphere; can lead to stars with realistic masses

$$M_{\rm BE} = 1.2 \frac{v_{\rm th}^4}{(G^3 P_{edge})^{1/2}}$$

$$= 1.5 M_\odot \frac{(T/10K)^{3/2}}{(n_{edge}/10^5 {\rm cm}^{-3})^{1/2}}$$

- How are **quiet** cores created in a **turbulent** cloud?
- How does cloud **environment** determine **core mass** distribution?



Kirk et al (2005): 850 μ core profiles compared to BE spheres

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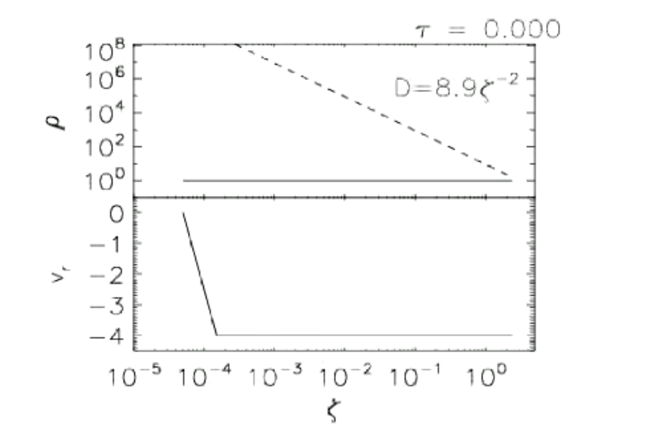
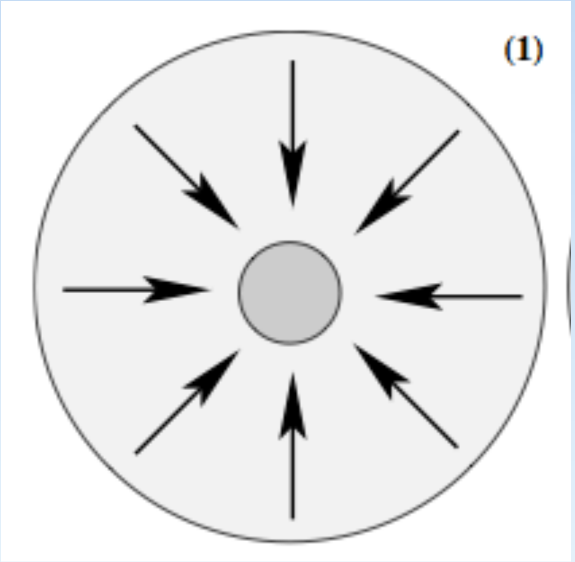
Supersonic spherical inflow

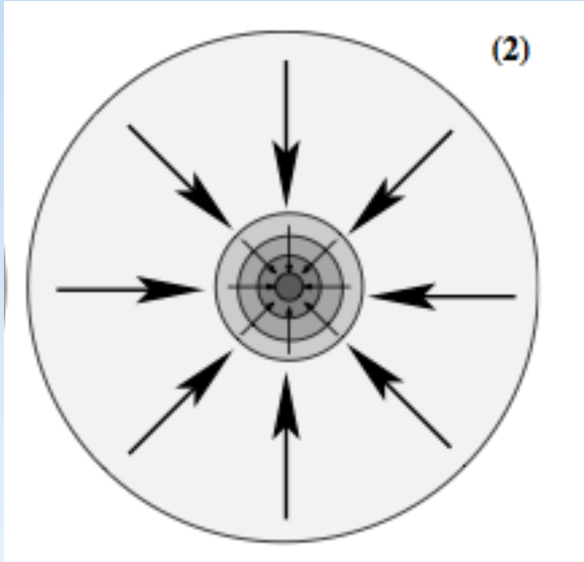
- Supersonic converging flows create dense post-shock regions
- Post-shock velocity is subsonic: $v_{post} / c_s \sim c_s / v_{pre}$
- Mass builds over time
- Core becomes gravitationally unstable
- Collapse and then infall develop:
  - $t_{supercrit} \sim t_{infall} \sim t_{ff}(\langle\rho\rangle)$
  - $t_{build} \sim$ 10-20 t_{ff}



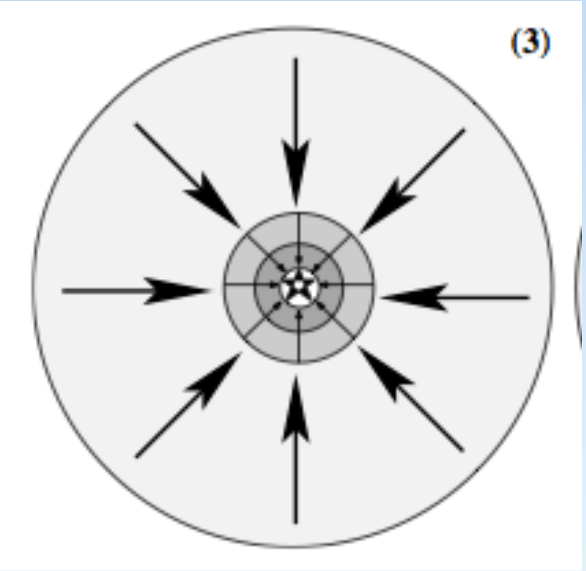
Gong & Ostriker (2009)



Core building

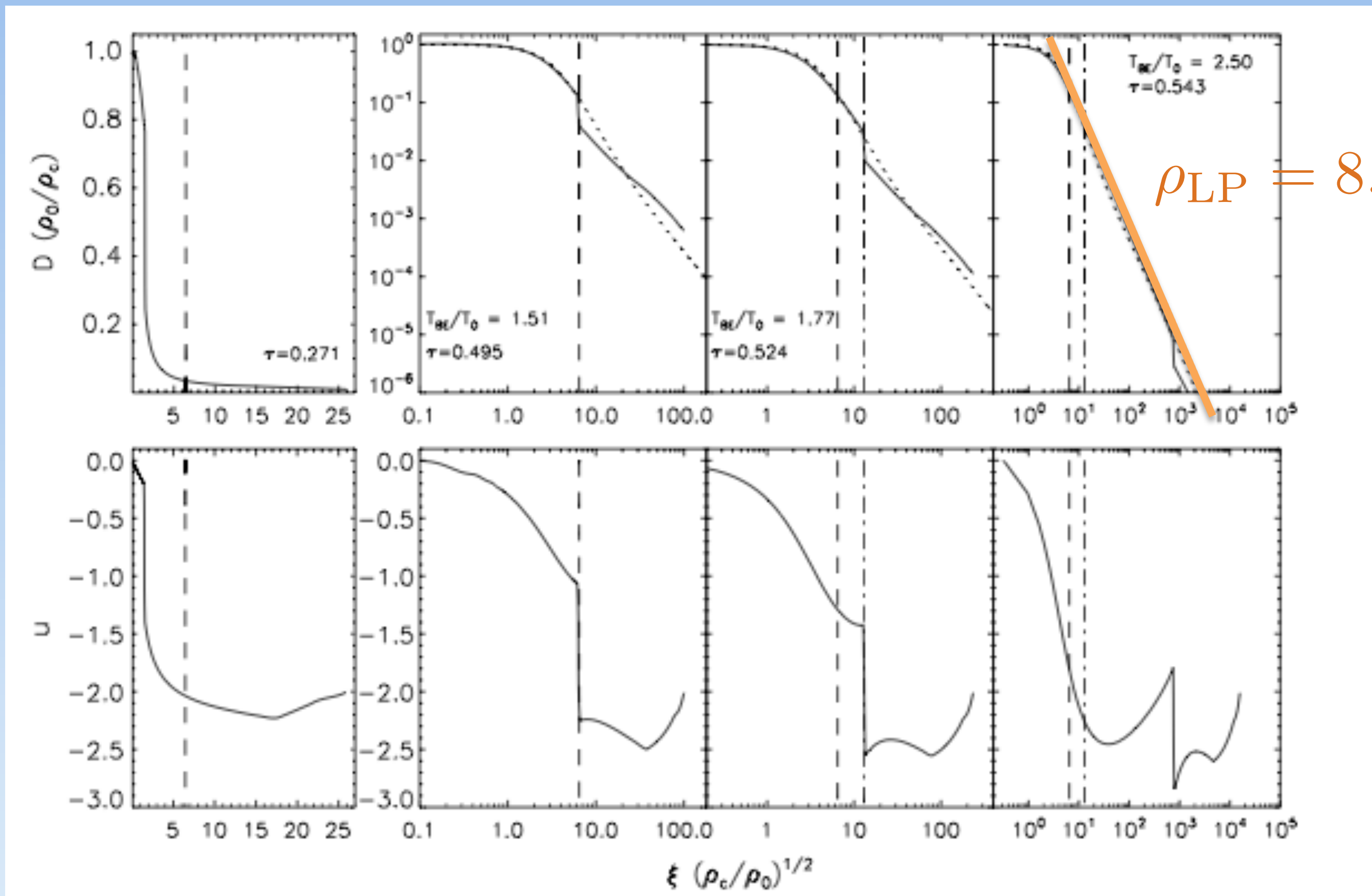


Core collapse



Envelope infall

Density & velocity profiles, Mach 2 inflow



$$\rho_{\rm LP} = 8.9 \frac{c_s^4}{4\pi G r^2}$$

Gong & Ostriker 2009

Larson (1969):

It may be noted that the asymptotic similarity solution which we have derived depends only on the gas constant $\mathscr{R}$ and the temperature T of the collapsing cloud, and not on any other properties of the cloud. Thus for clouds with the same $\mathscr{R}$ and T, the collapse solution in the inner part of the cloud should eventually approach the same behaviour in all cases, regardless of such factors as the initial density or the mass of the cloud. This explains the close similarity found

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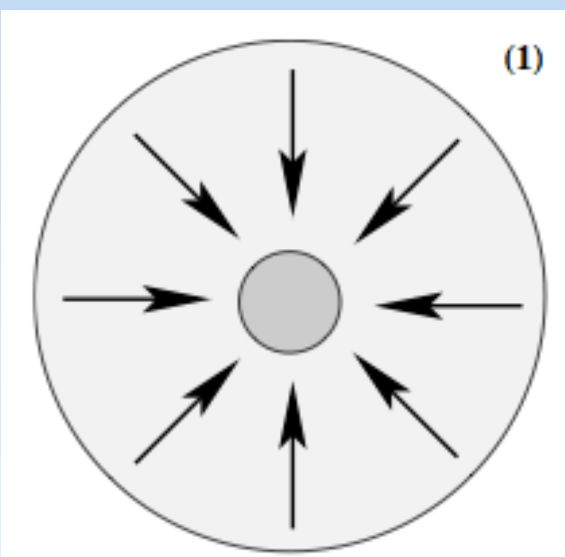
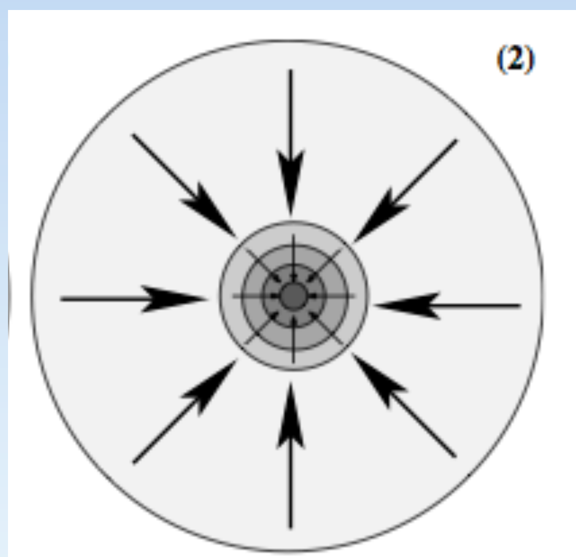
  - $t_{build} \sim 10\text{-}20\ t_{ff}$

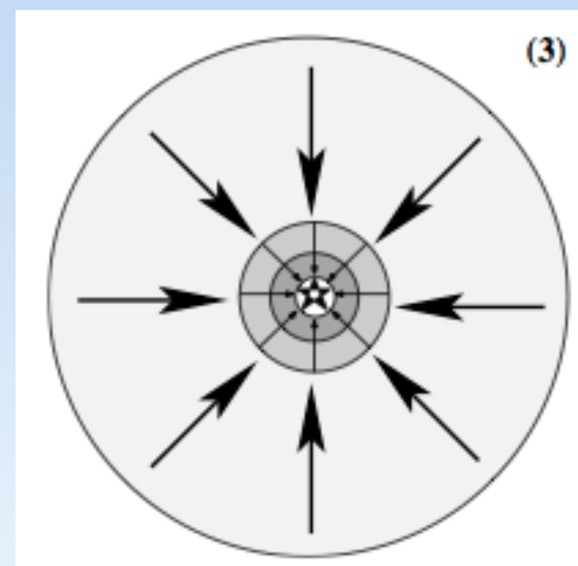
Gong & Ostriker (2009)



Core building

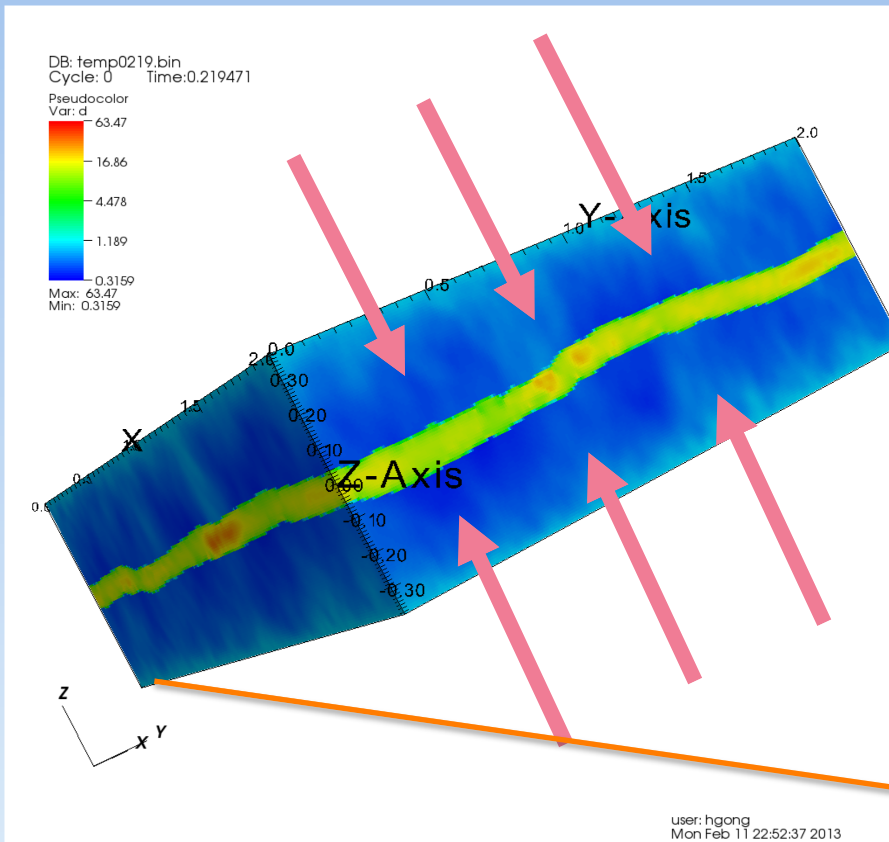


Core collapse



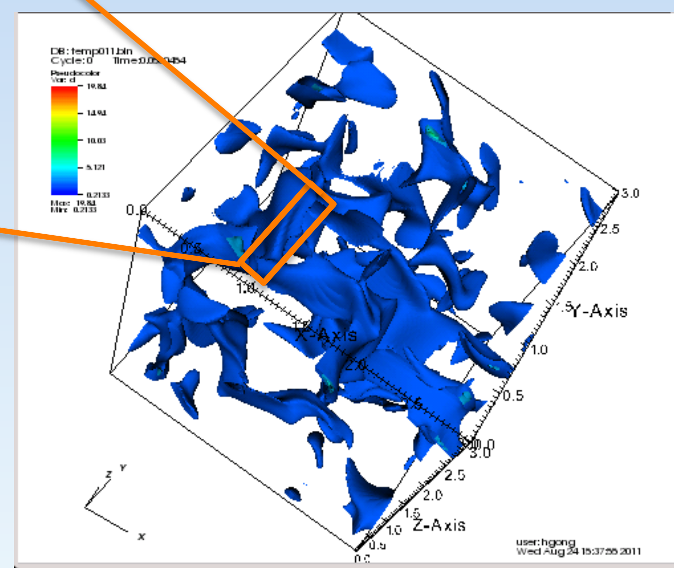
Envelope infall

Planar converging flow in turbulent cloud



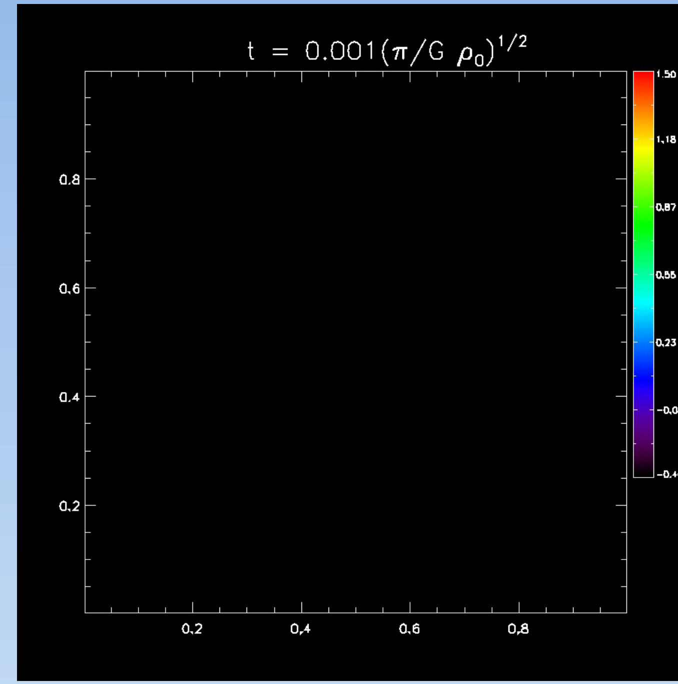
- Focus on local shocked region in a large cloud
- Range of inflow Mach numbers (v_{in}/c_s)
- Additional turbulence included
- Box size corresponds to

$$L = 0.08\mathrm{pc}\frac{v_{\mathrm{in}}}{c_s}\left(\frac{\Sigma_{\mathrm{cloud}}}{100M_{\odot}\mathrm{pc}^{-2}}\right)^{-1}$$

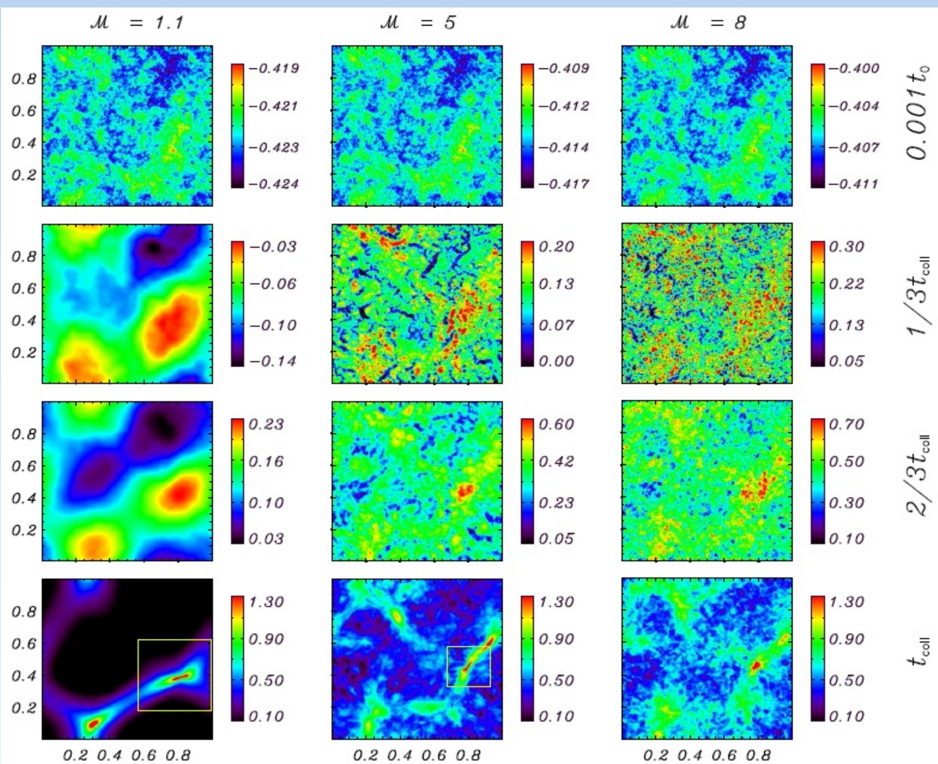


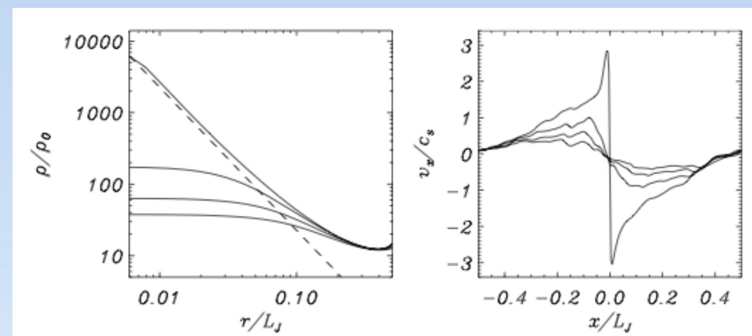
Core formation and collapse

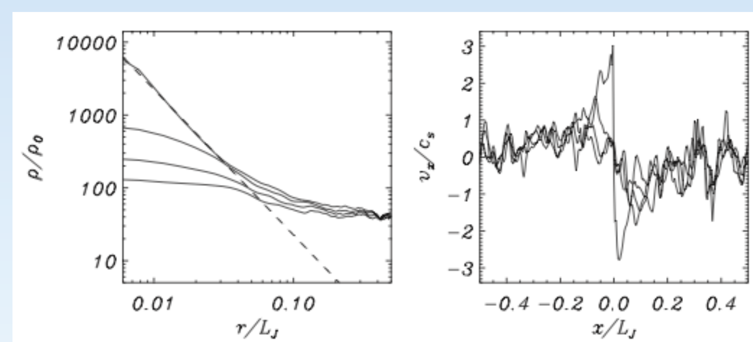
- Range of simulations with v_{in}/c_s=1.1-9
- Filaments develop
- Core collapse is similar to LP sol'n
- Time to first collapse ~ 0.5 Myr $(v_{in}/km/s)^{1/2}$



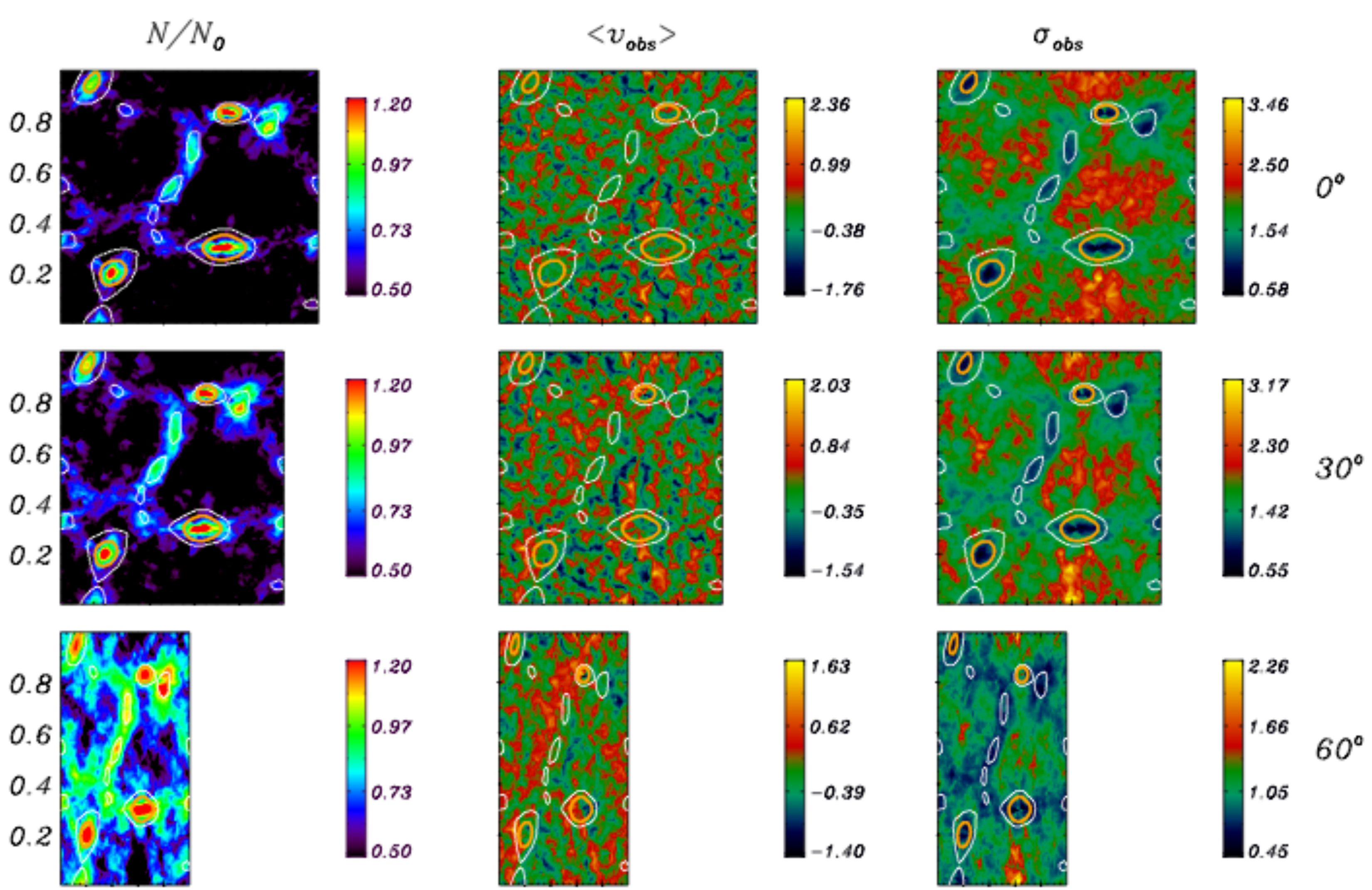
Gong & Ostriker (2011)





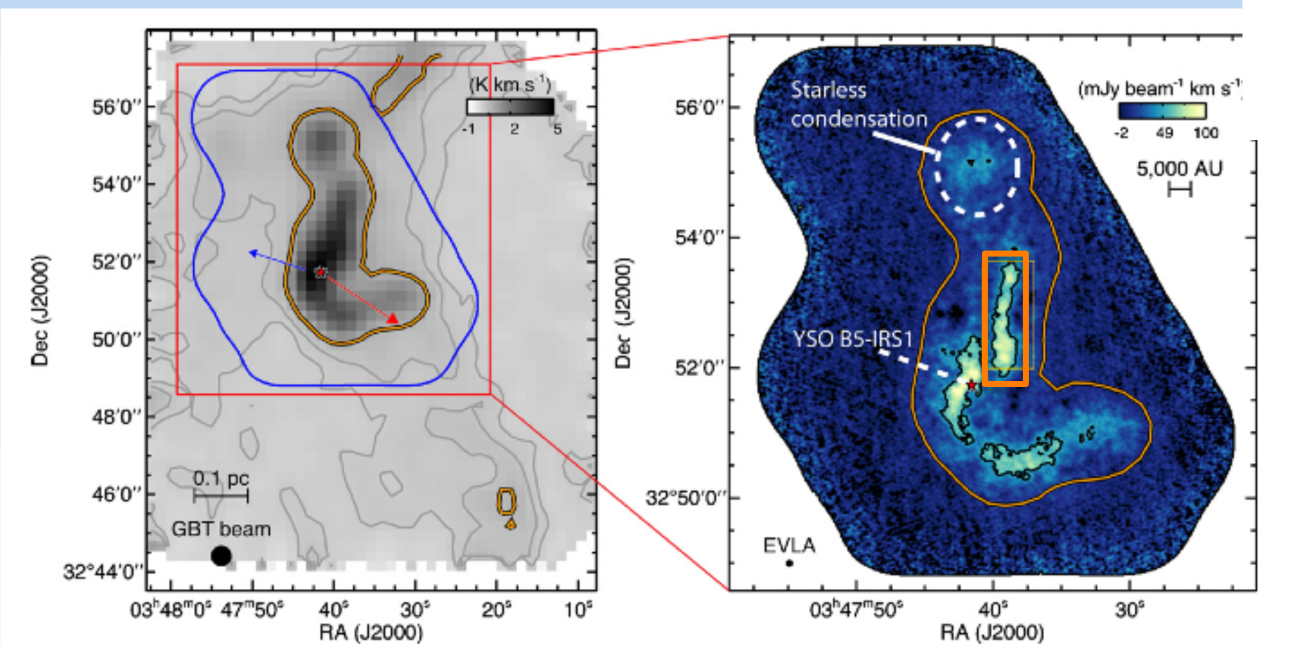


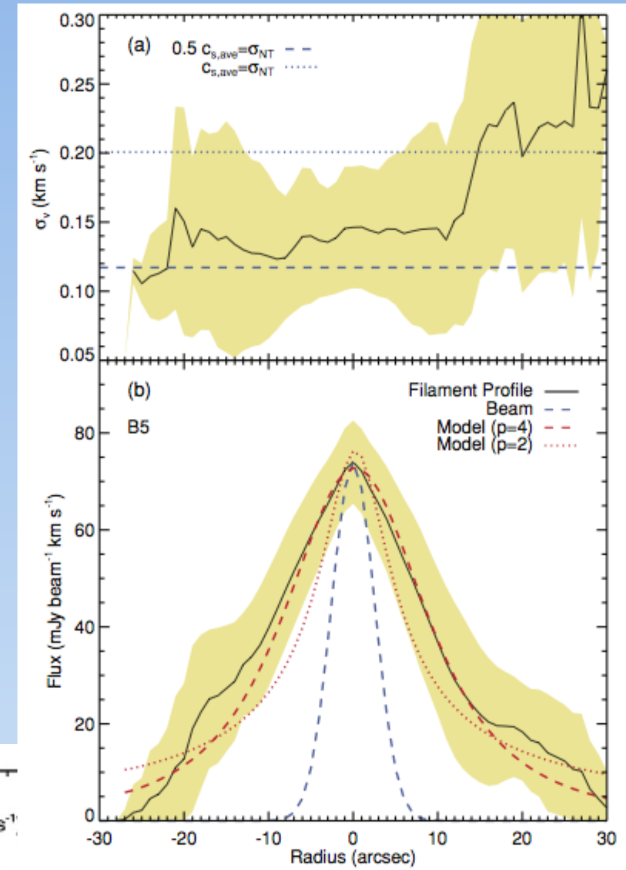
Velocity-coherent cores and filaments



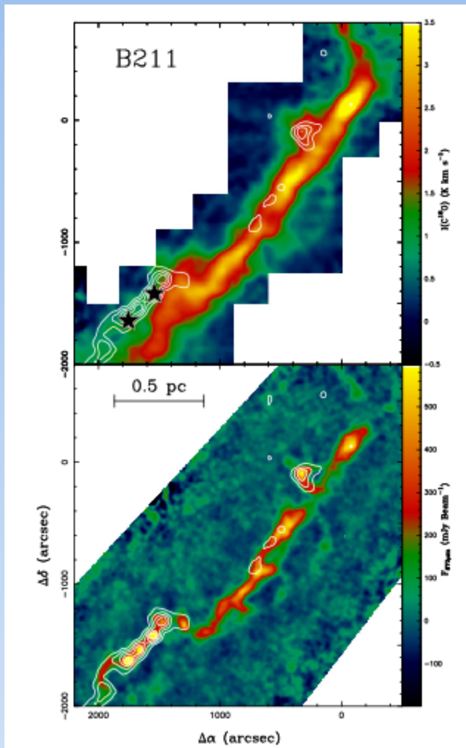
Velocity-coherent core/filament

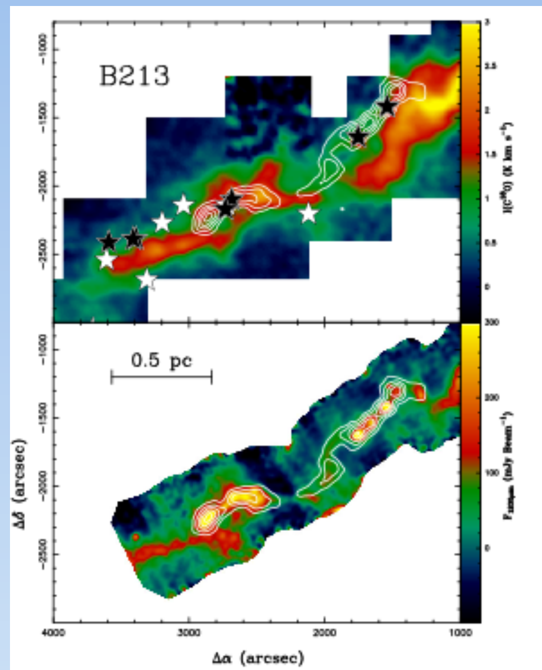
Pindeda et al (2011): GBT+ELVA NH_3



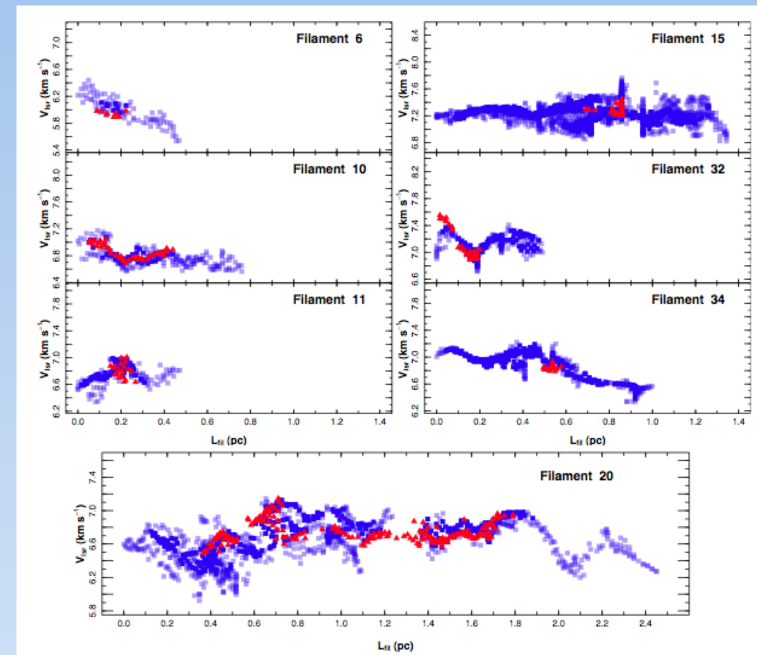


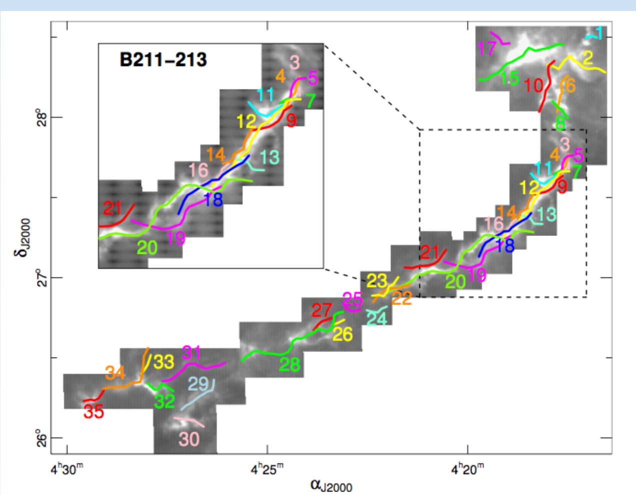
Velocity-coherent filaments

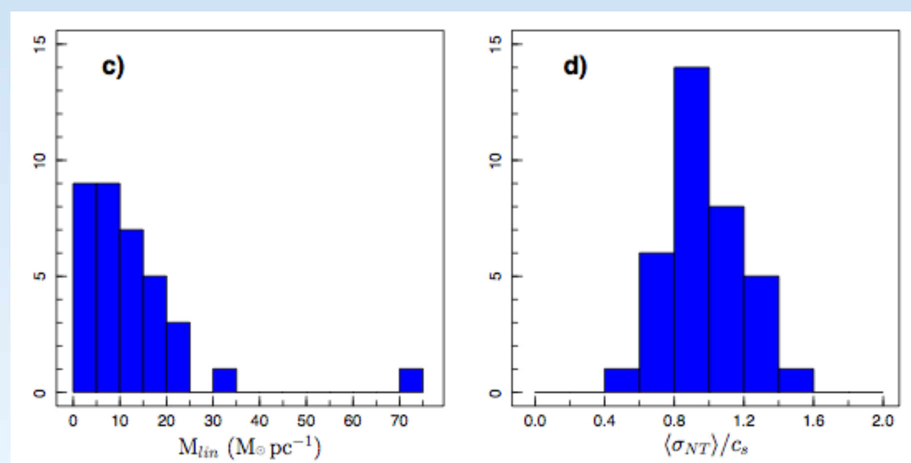




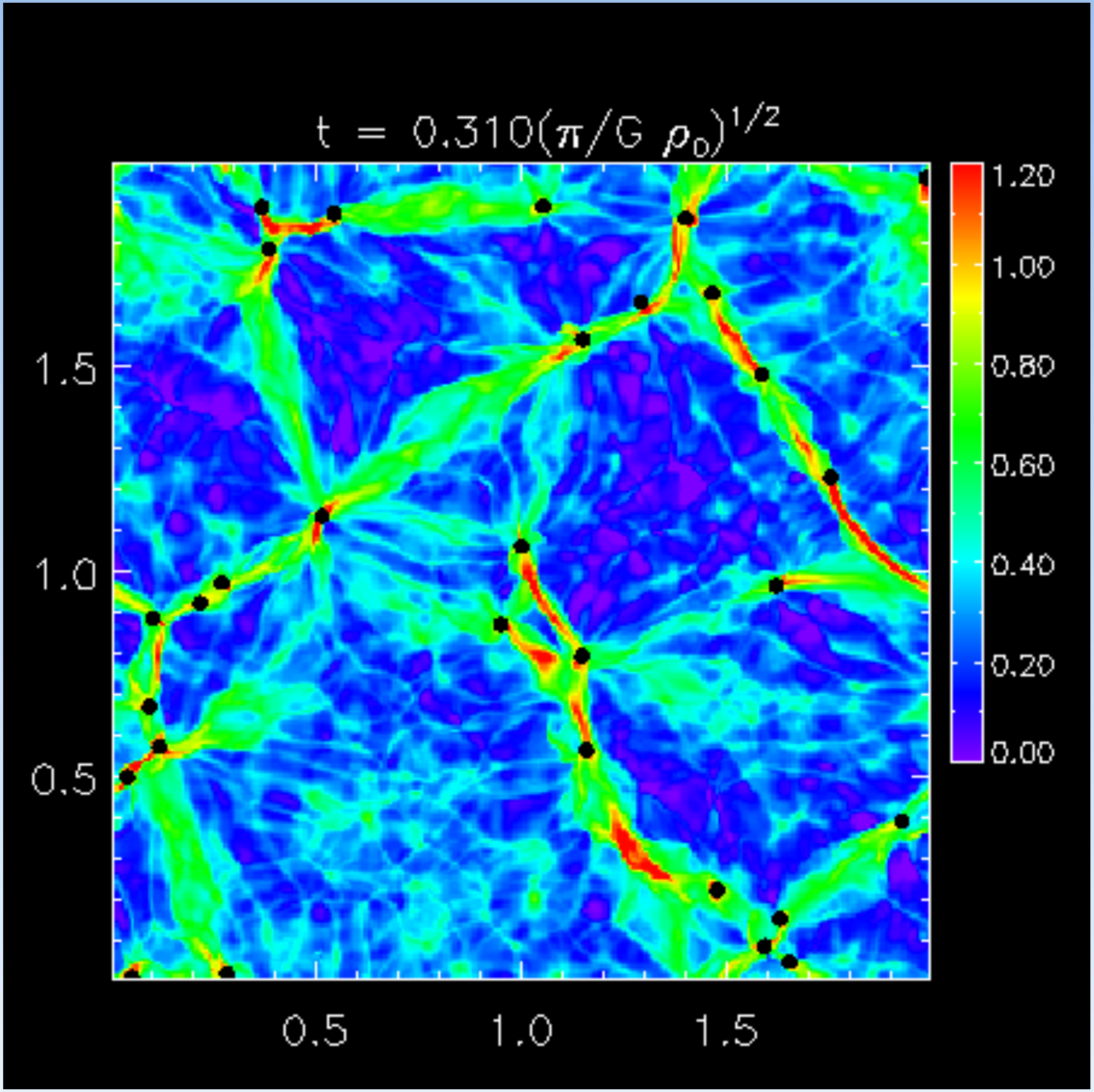
Taurus $C^{18}O$, N_2H^+ Hacar et al (2013)



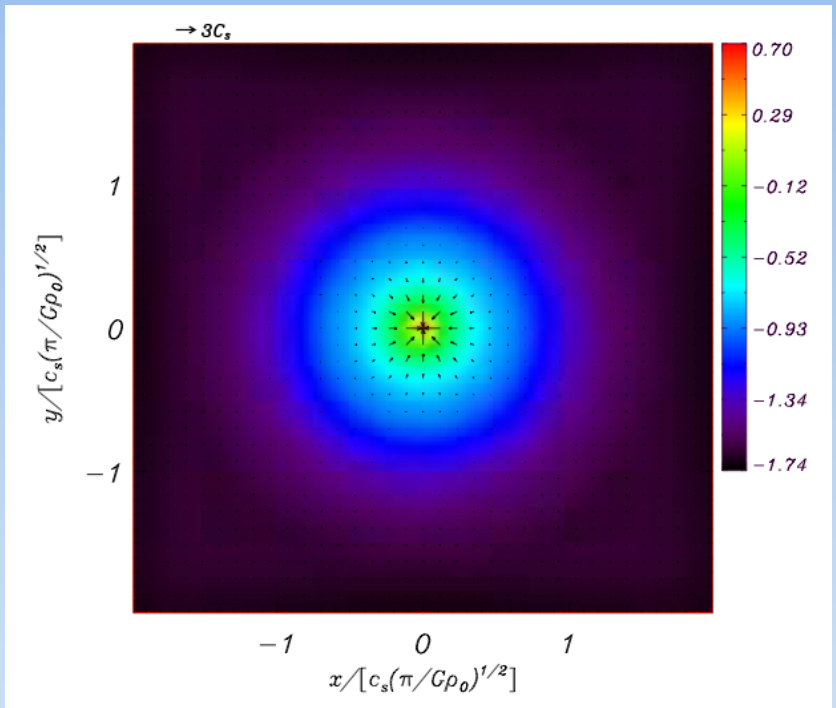


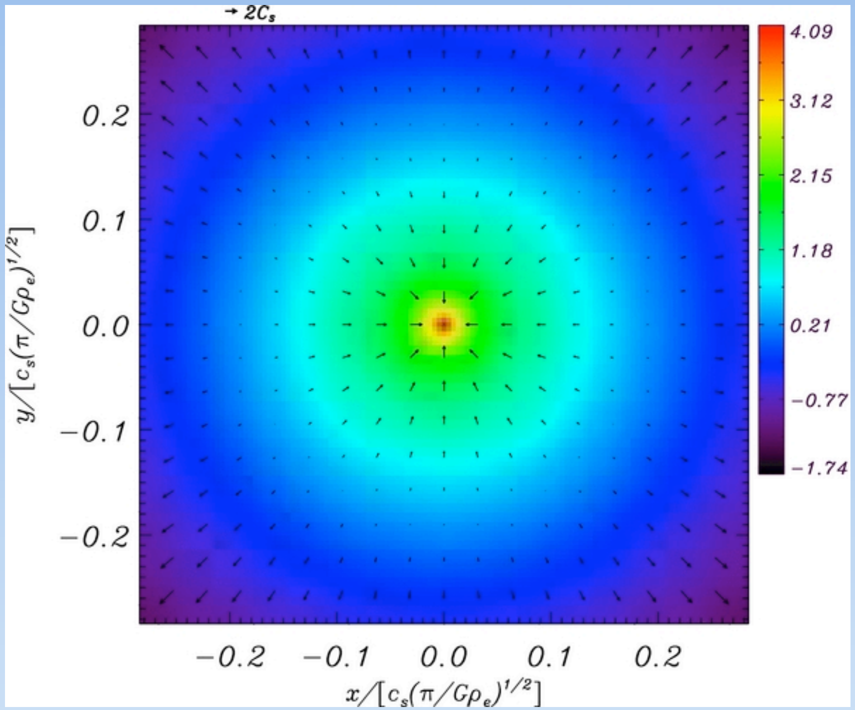


Star formation in filaments



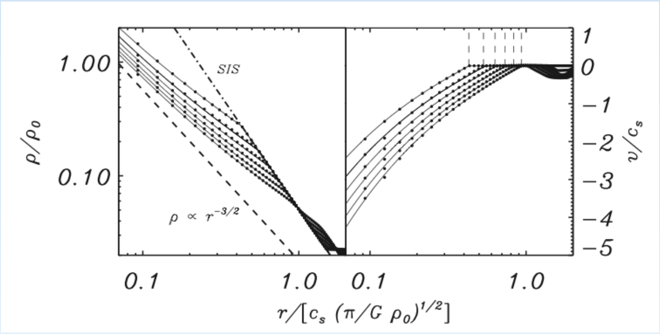
Sink particles in *Athena*

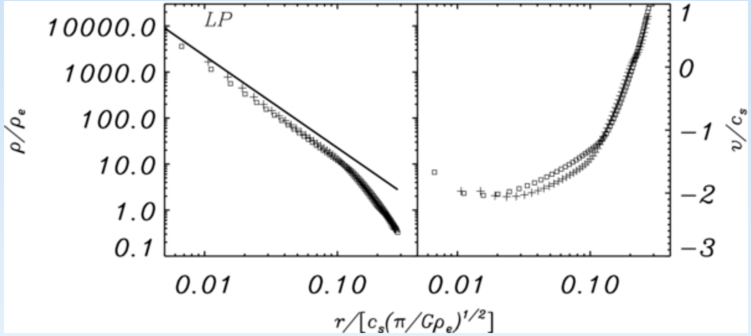


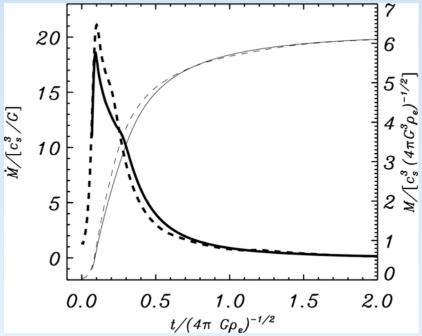


Collapse of singular isothermal sphere

Collapse of unstable BE sphere

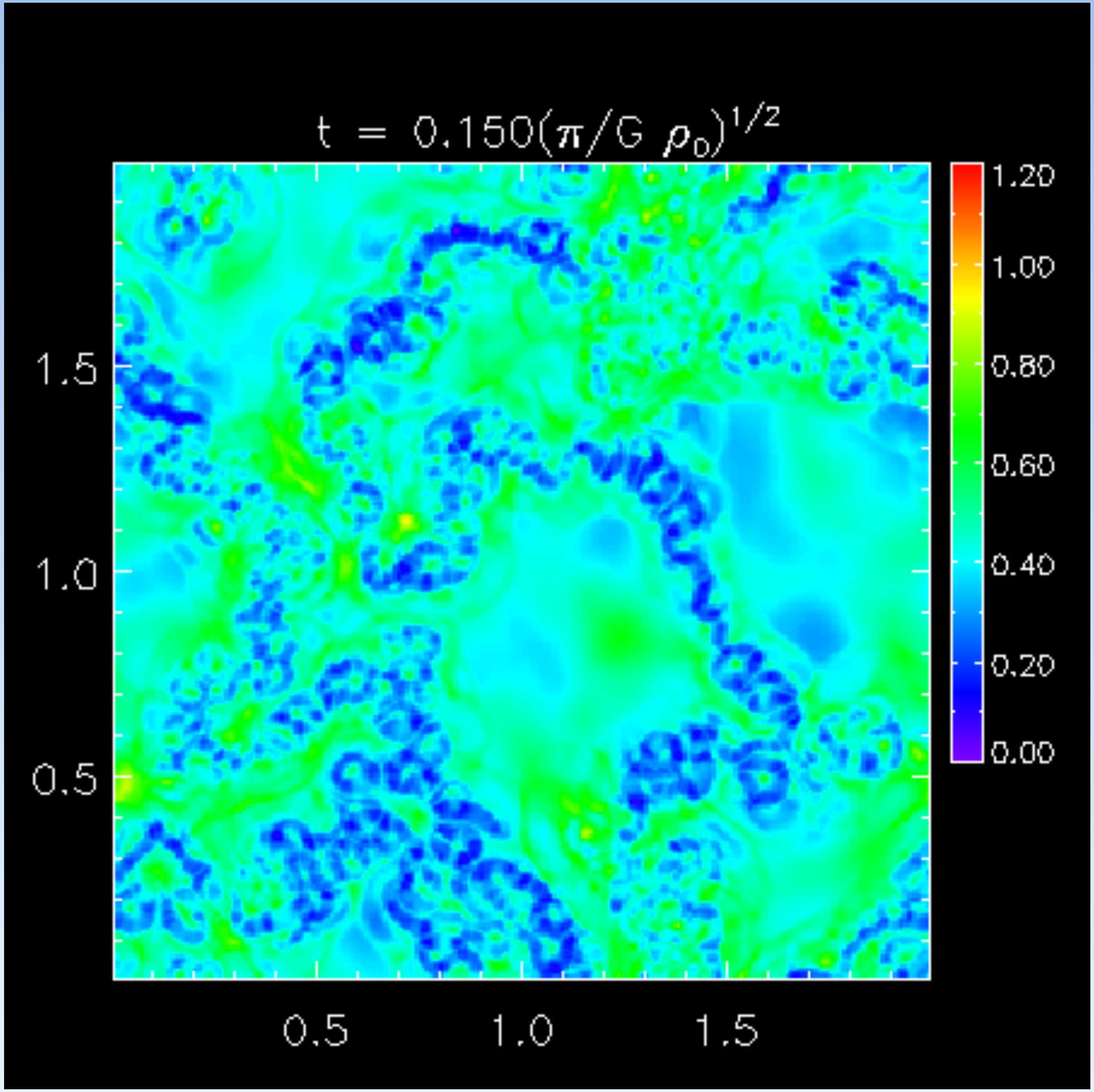






Gong & Ostriker (2013)

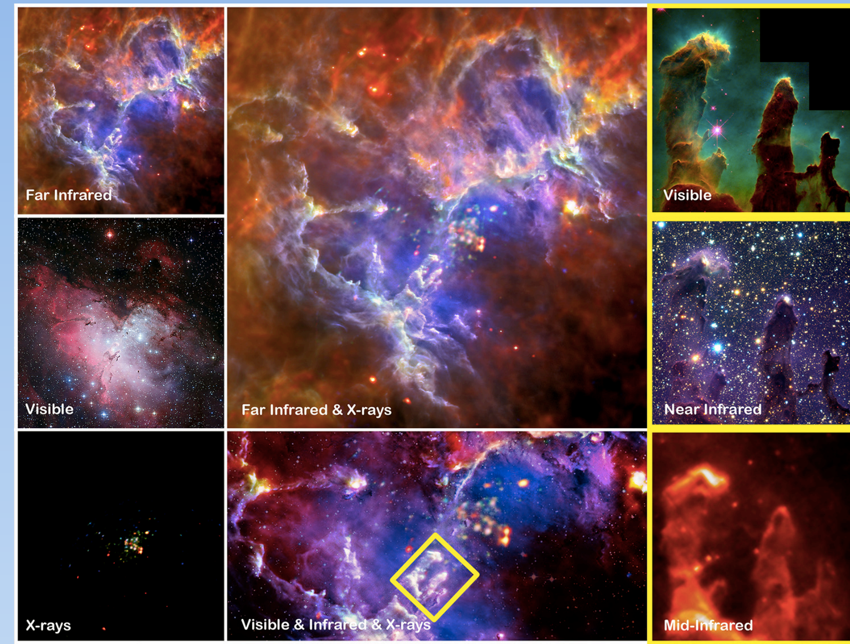
Star formation in filaments



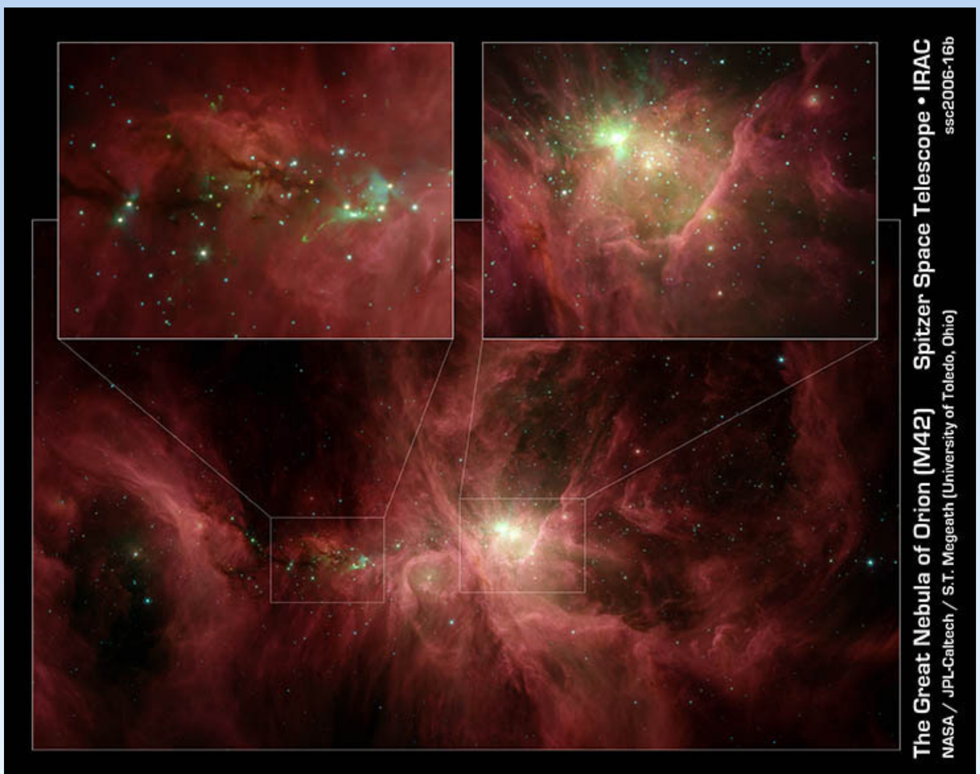
See *Munan Gong* to learn more about this project!

The need for feedback

- Without feedback, all the mass in a cloud would end up being accreted
- Can be halted/turned around by:
  - Protostellar outflows (MHD)
  - HII regions (photoionization, winds)
  - Radiation pressure
  - Supernova blasts

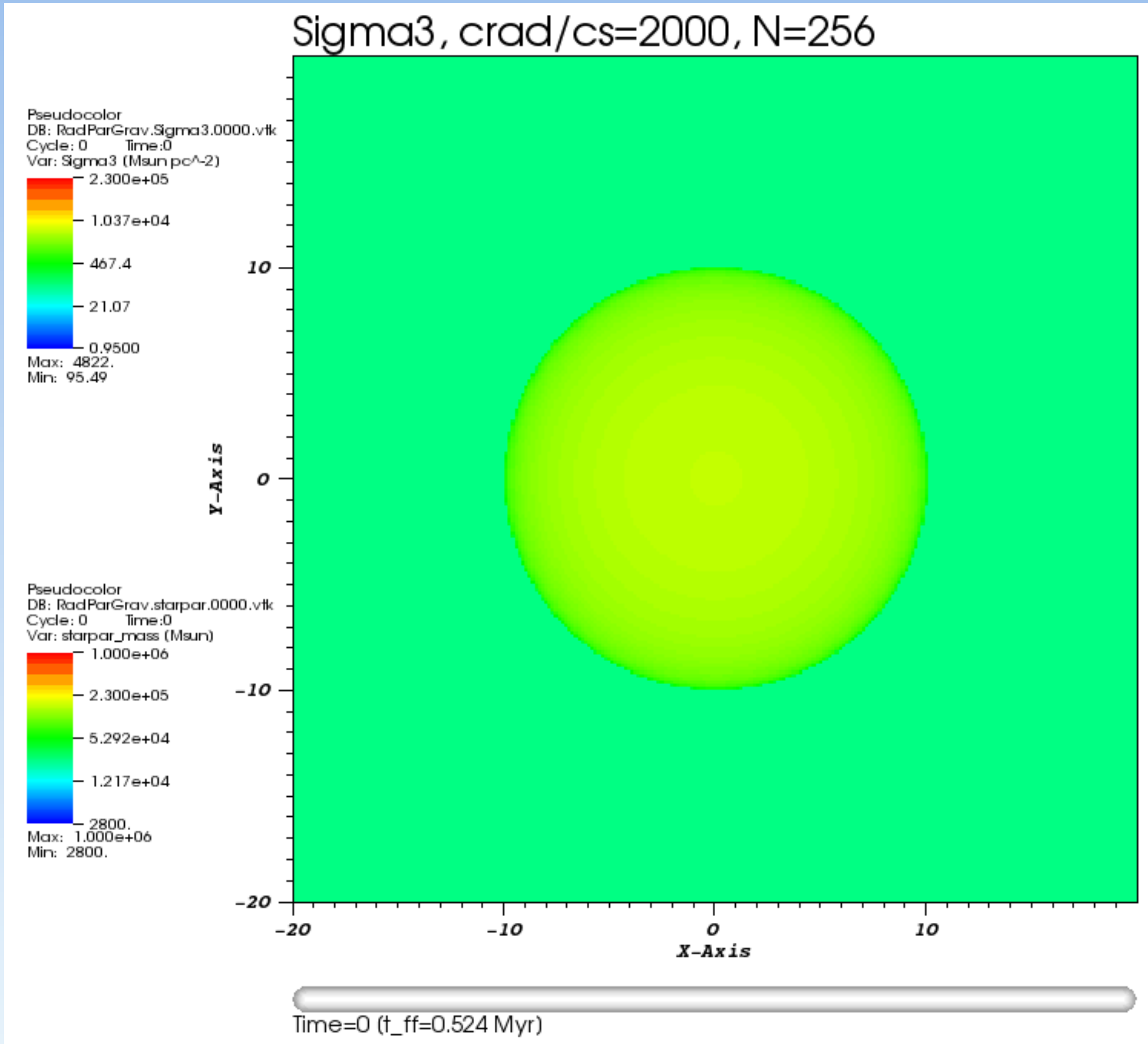


Eagle nebula/M16



Herschel: Carina nebula

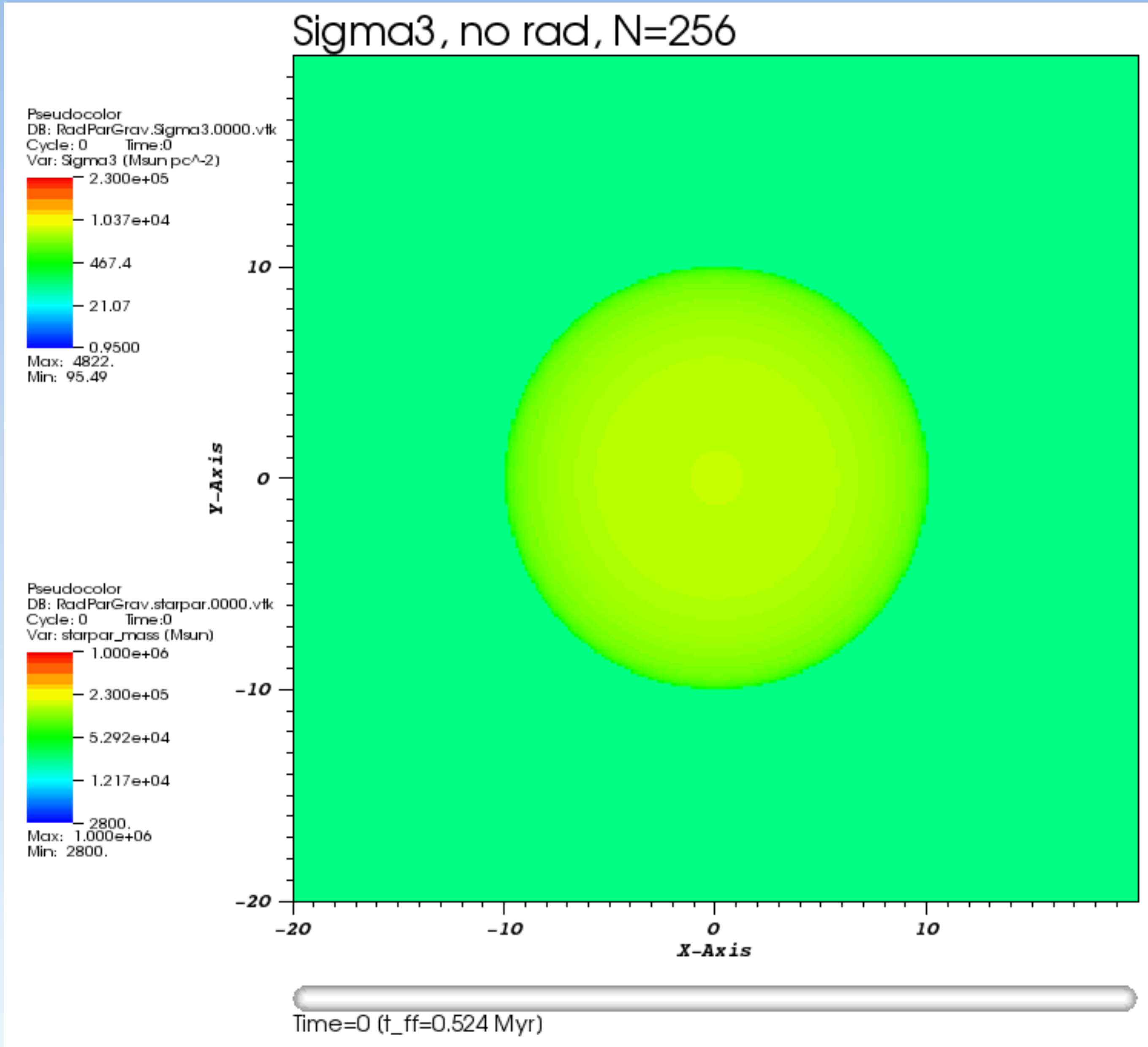
Example: radiation pressure



Skinner & Ostriker (2013)

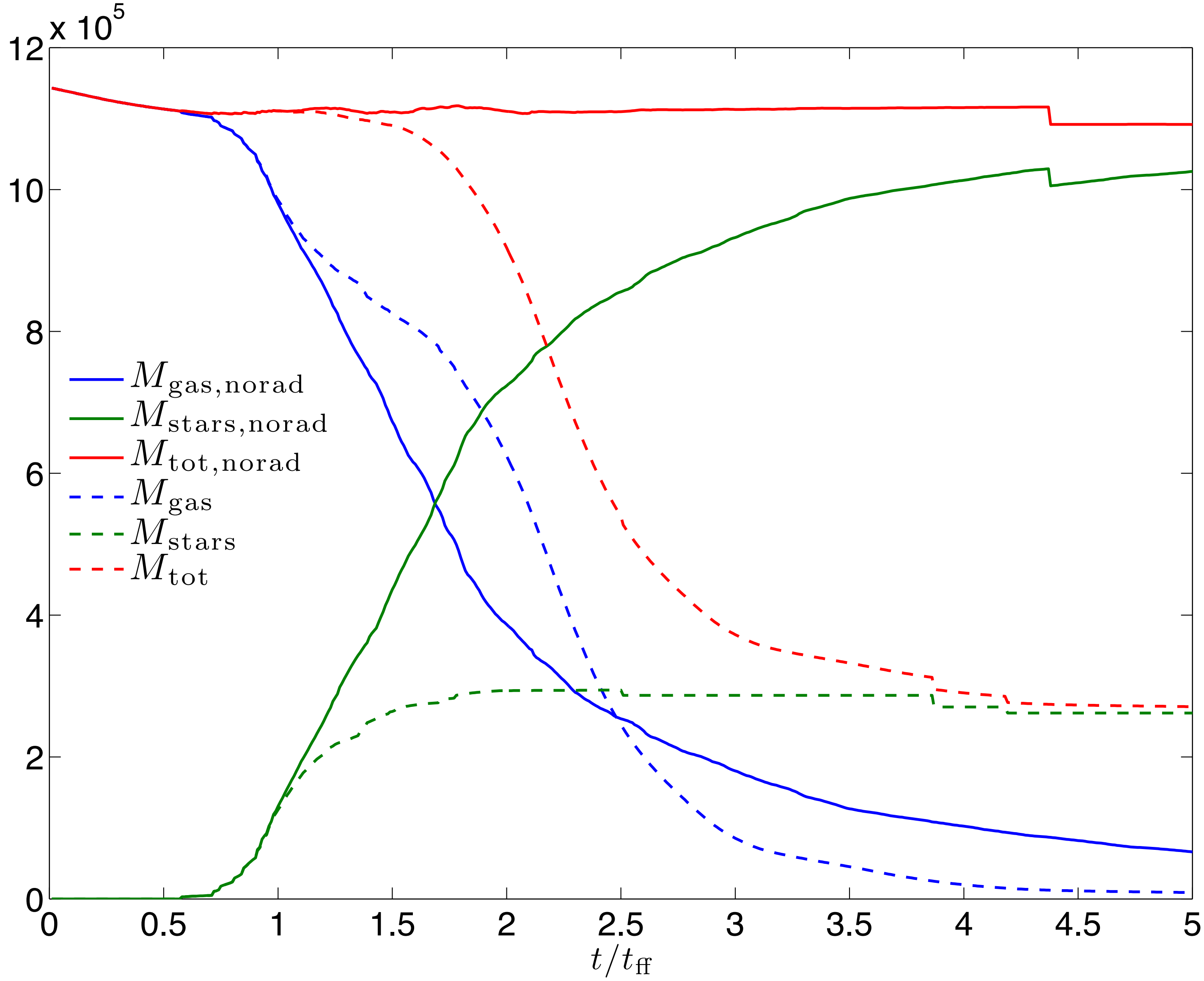
10^6 $M_\odot$ initial cloud with RHD for reprocessed IR

without radiation



Skinner & Ostriker (2013)

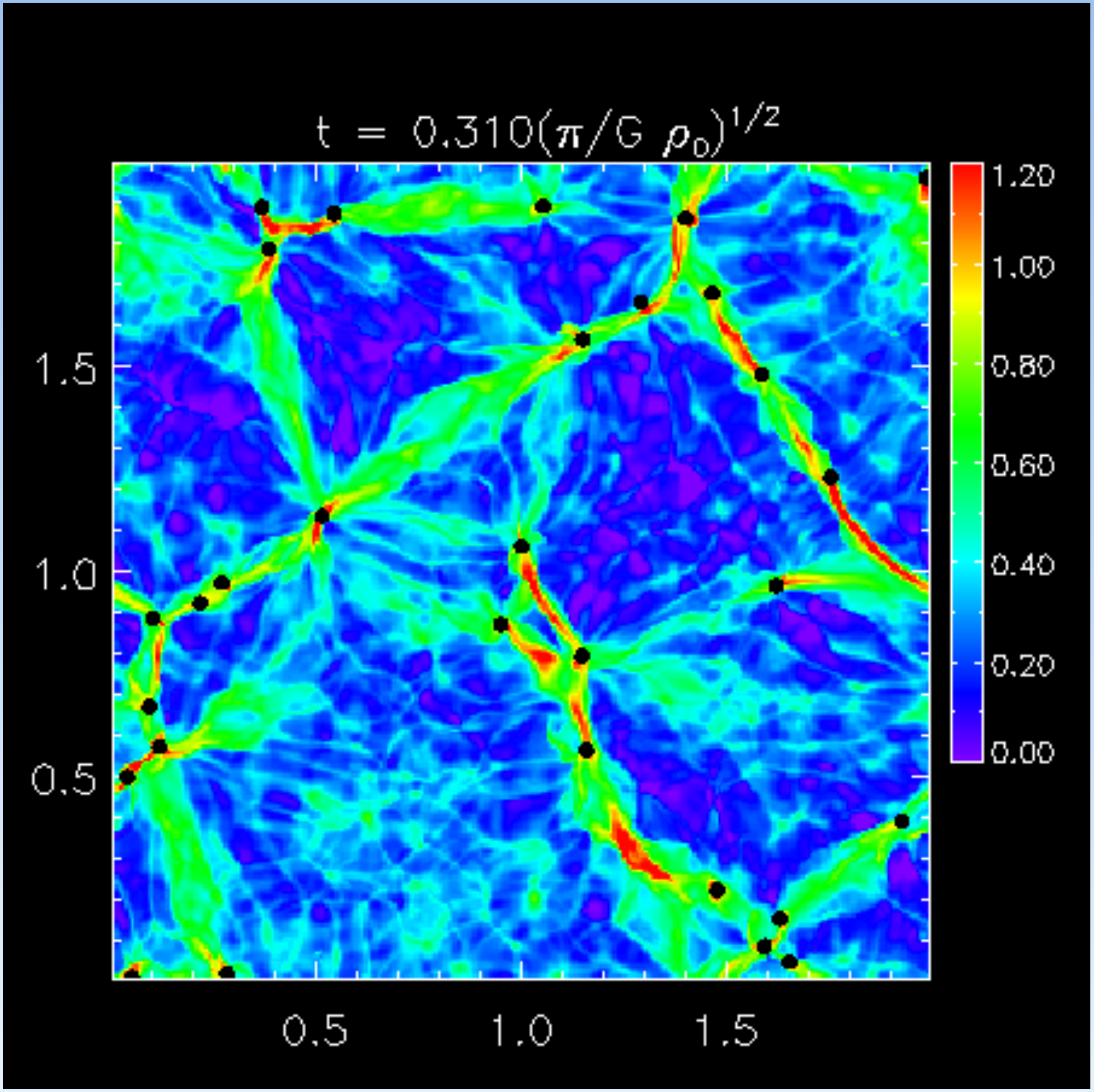
$10^6 M_\odot$ initial cloud



Skinner & Ostriker (2013)

t_{ff}=0.52 Myr

Star formation in filaments



Why filaments?

Turbulence:

- For shocked converging flow of wavelength L_{pre}

$$L_{\mathrm{post}} = L_{\mathrm{pre}}\,\rho_{\mathrm{pre}}/\rho_{\mathrm{post}} \qquad \text{mass conservation}$$
$$= L_{\mathrm{pre}}\,[v_{\mathrm{in}}(L_{\mathrm{pre}})/c_s]^{-2} \qquad \text{shock jump condition}$$
$$= L_{\mathrm{pre}}\,[(L_{\mathrm{pre}}/L_{\mathrm{sonic}})^{1/2}]^{-2} \qquad \text{turbulent scaling law}$$
$$= L_{\mathrm{sonic}}$$

- For cloud with virial parameter $\alpha_{\mathrm{vir}}=2E_{\mathrm{kin}}/E_{\mathrm{grav}}$

$$L_{\mathrm{sonic}} = \frac{10c_s^2}{3\pi\alpha_{\mathrm{vir}}G\Sigma_{\mathrm{cloud}}}$$

~ 0.1 pc for typical GMC conditions

- Post-shock edge-on structures would appear filamentary

Why filaments?

Gravity:

- Self-gravitating layer:

$$2H = \frac{2c_s^2}{\pi G \Sigma_{\rm layer}} \sim 0.05 \text{ pc} \quad \text{for } \Sigma_{\rm layer} = 100\ M_\odot\ \text{pc}^{-2}$$

- Minimum wavelength for instability in layer:

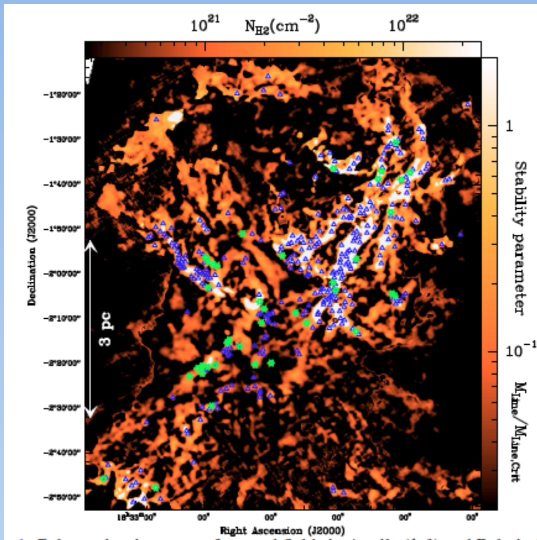
$$\lambda = \frac{2c_s^2}{G\Sigma_{\rm layer}} = \pi(2H)$$

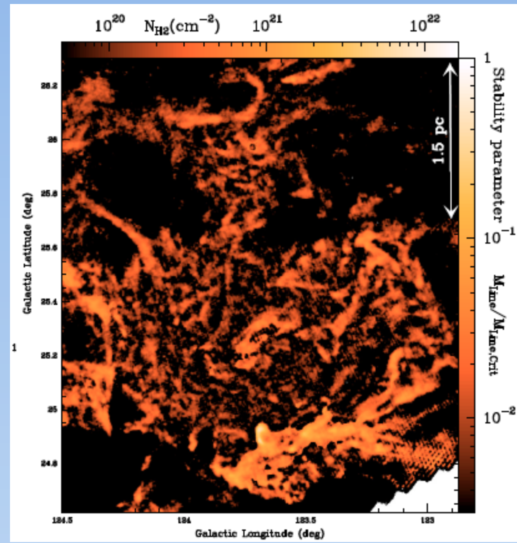
- Gravitational collapse is along short axis first; increases aspect ratio (cf Lin, Mestel, & Shu 1965)
- Isothermal self-gravitating cylinder (Ostriker 1964):

$$\rho(R)/\rho_c = \left[1 + \frac{R^2}{2c_s^2/\pi G \rho_c}\right]^{-2}$$

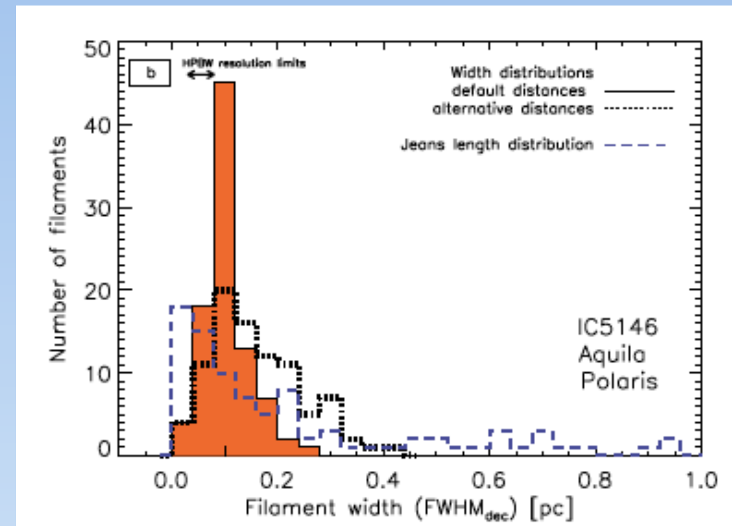
- Maximum mass/length $= 2c_s^2/G = 15\ M_\odot\ \text{pc}^{-1}$

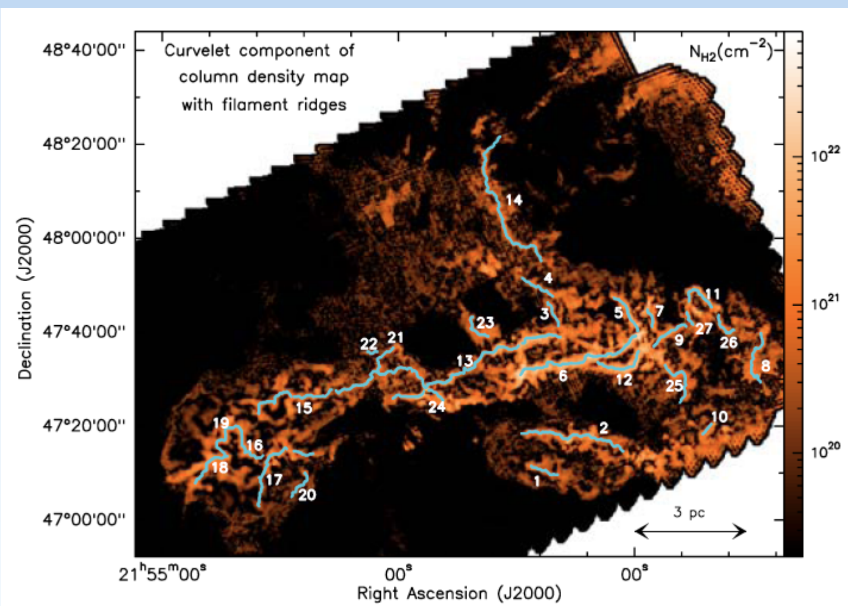
Filament widths



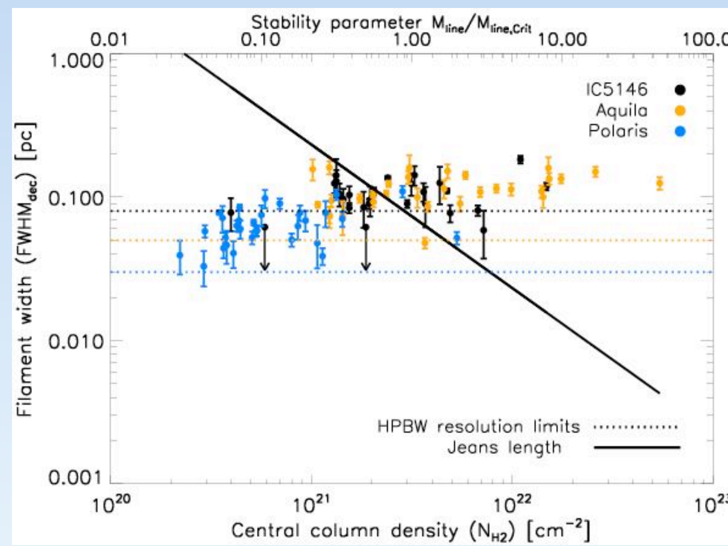


Herschel: Aquila cloud; Polaris Flare cloud (Andre et al 2010)



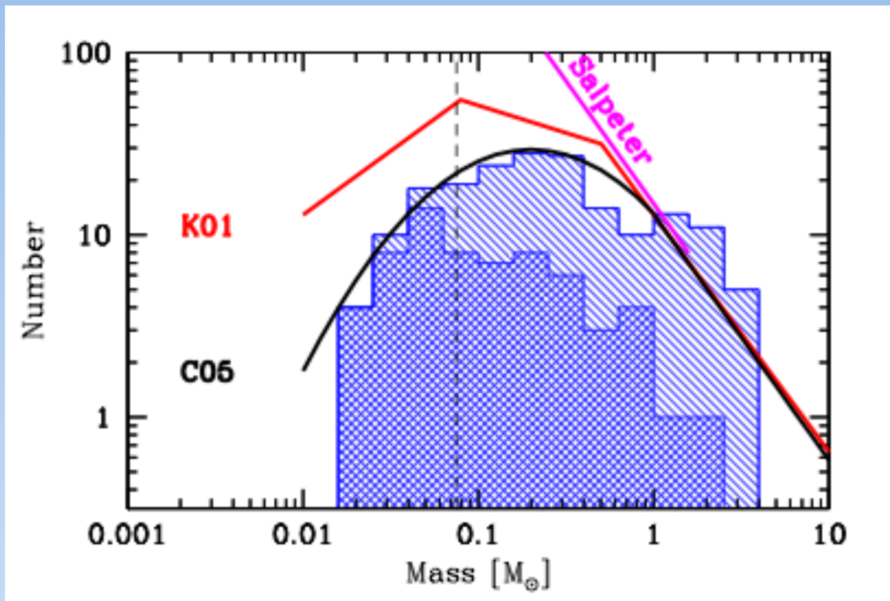


Herschel: IC 5146 (Arzoumanian et at 2011)

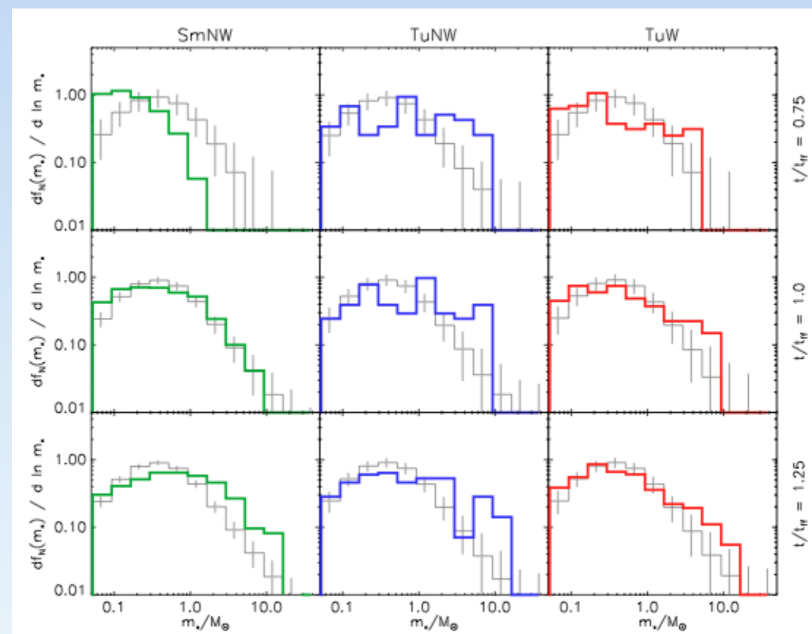


Arzoumanian et at 2011

IMF from simulations?

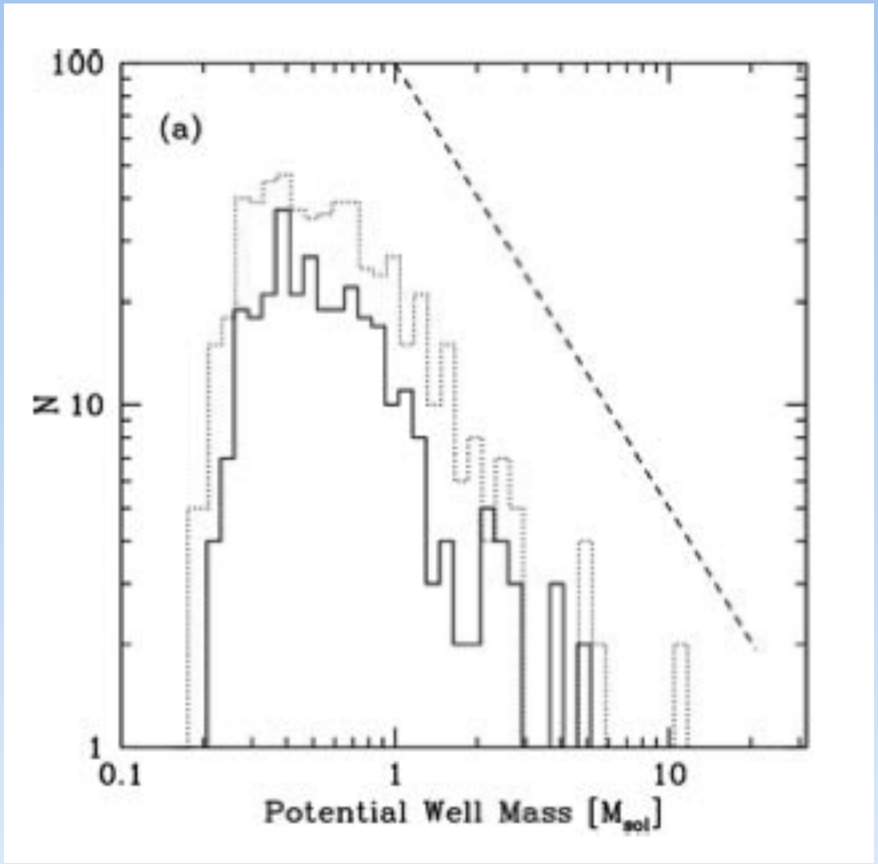


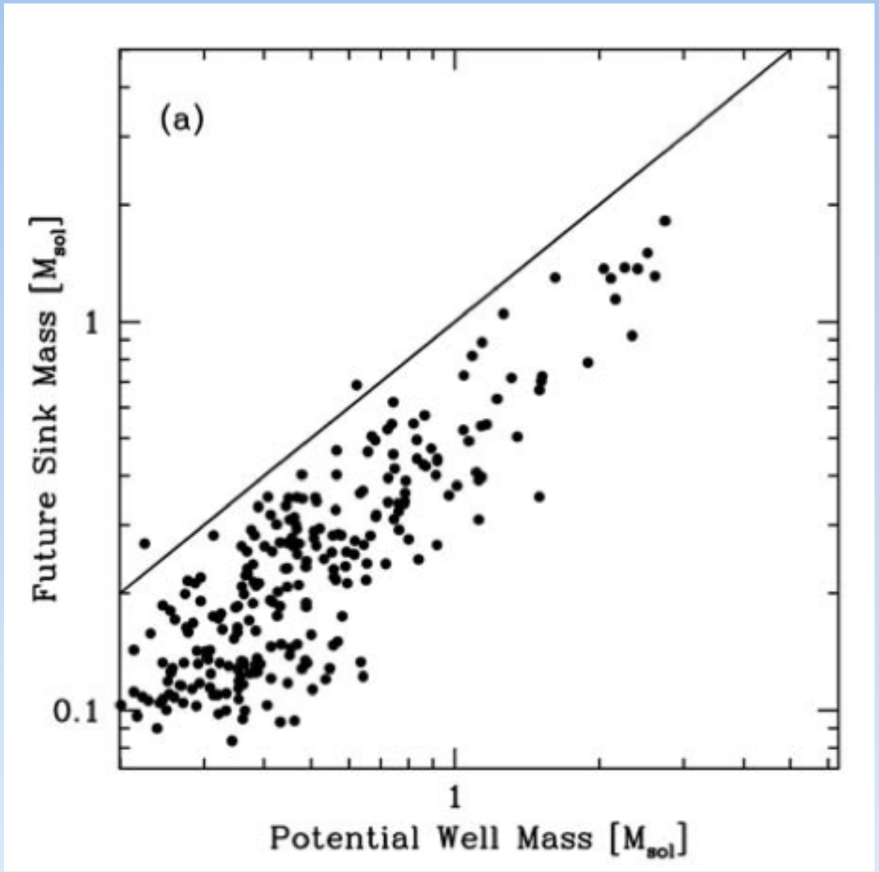
Bate (2012): SPH cluster simulation with RHD
$M=500M_{\odot}$, $R=0.4$ pc; $n_{init}=5\times10^{4}cm^{-3}$



Krumholz et al (2013): AMR cluster simulation with RHD $M=1000M_{\odot}$, $R=0.3$ pc, $n_{init}=5\times10^{4}cm^{-3}$

CMF and IMF in simulations





Smtih et al (2009): SPH simulation; 10^4 $M_\odot$ turbulent cloud

CMF theory?

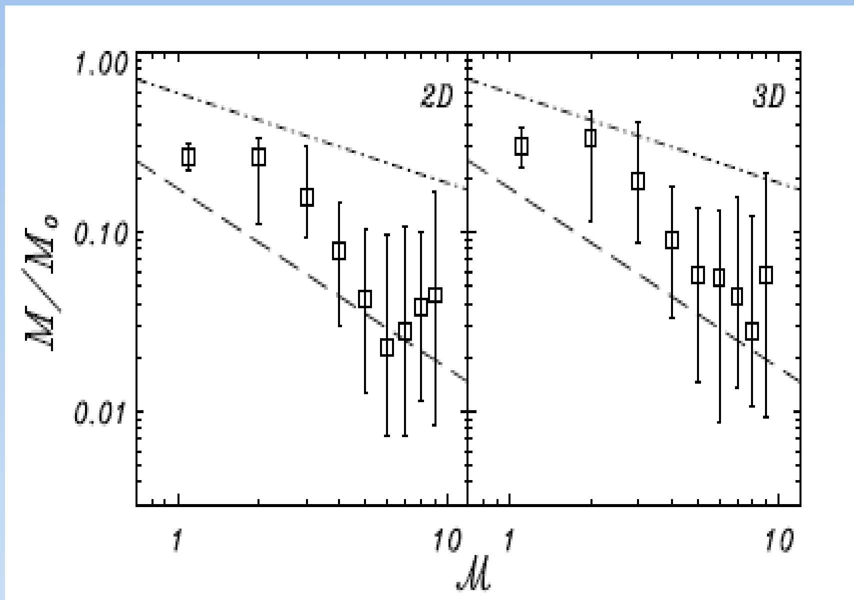
- Scaling and parameter dependence still a conceptual challege for theory
- What process determines the high-end slope of the mass function?
  - Power-law slope is suggestive of coagulation/fragmentation processes, or spectrum of overdense structures from turbulence, but no satisfactory theory to date
- What process determines the peak of the mass function?
  - For Galactic GMCs, $m_{\rm peak}$ is similar to Bonnor-Ebert mass using

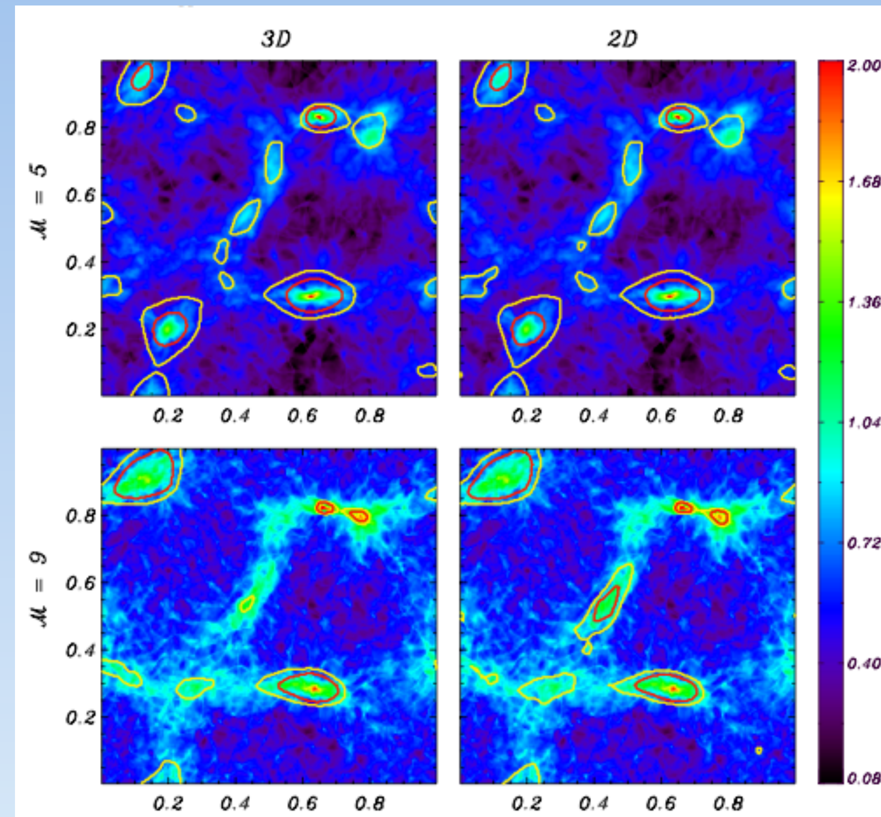
$$P_{\rm ext} = \bar{\rho} v_{\rm turb}^2 = 1.4 \alpha_{\rm vir} G \Sigma_{\rm cloud}^2$$

$$M_{BE} \to 1.2 \frac{c_s^4}{(G^3 \bar{\rho} v_{\rm turb}^2)^{1/2}} = \frac{c_s^4}{\alpha_{\rm vir}^{1/2} G^2 \Sigma_{\rm cloud}} \sim 0.6 M_\odot \frac{(T/10{\rm K})^2}{\Sigma_{\rm cloud}/100 M_\odot {\rm pc}^{-2}}$$

  - Similarity is intriguing…

Median core mass at time of first collapse





Core identified by the largest closed contour of gravitational potential

At this time, median value between:

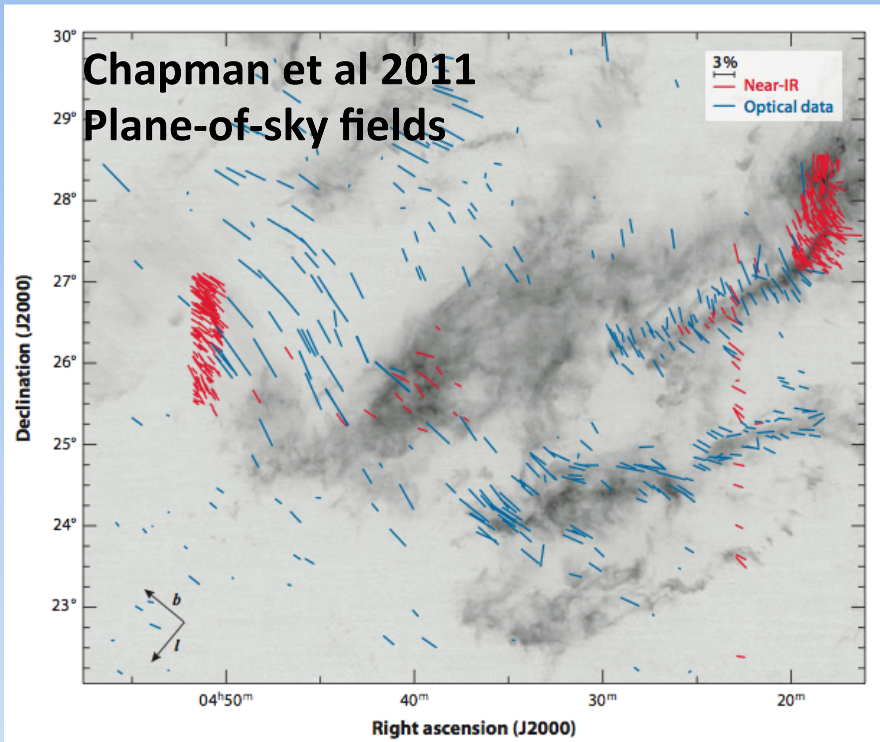
- expected mass of the first core to collapse $M \propto (v_{in}/c_s)^{-1/2}$
- expected minimum mass that can collapse at late time $M \propto (v_{in}/c_s)^{-1}$

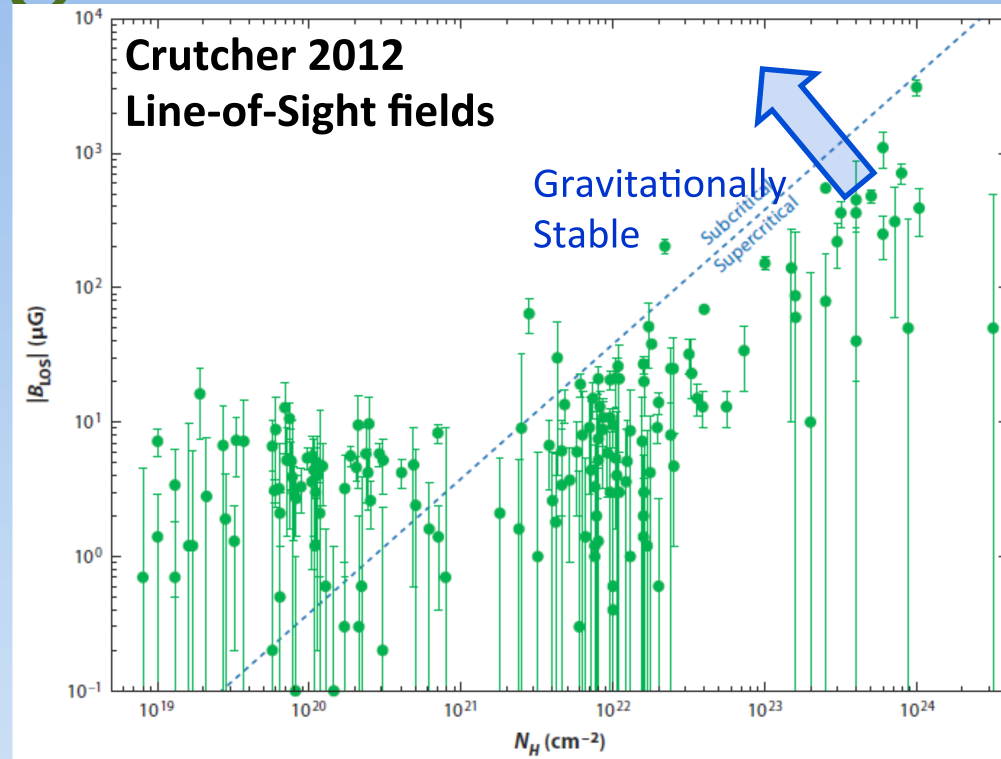
For physical mass scale, multiply by

$$1.9\ M_\odot \times (v_{in}/c_s)(T/10K)^2(\Sigma/100 M_\odot\ pc^{-2})^{-1}$$

Gong & Ostriker (2011)

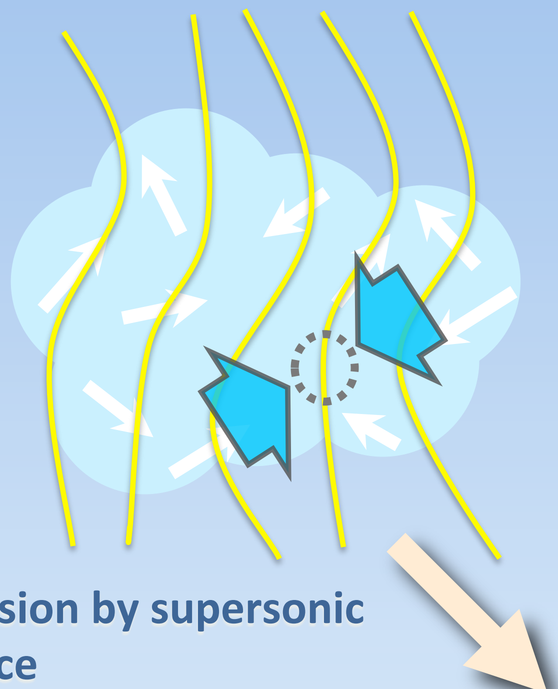
Role of magnetic Fields



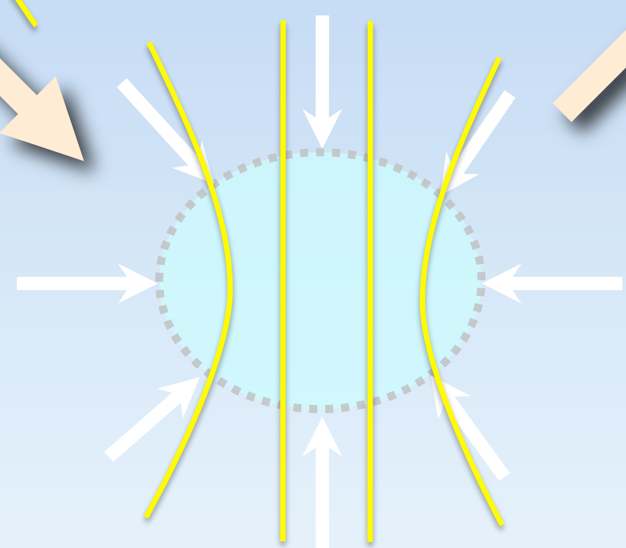


- With magnetic field frozen to matter, $M/\Phi = \Sigma/B$ =const.
- $E_{grav}/E_{mag} \sim (GM^2/R)/(B^2R^3) \sim G(M/\Phi)^2$
- Minimum M/Φ for collapse is $1/(2\pi G^{1/2})$
- Observed dense cores have $M/\Phi \sim$ 2-3 ×critical value
- But: M_{crit} for lower-density "pre-core" gas typically tens of $M_\odot$ - larger than observed cores
- Sphere: $M_{crit}=0.007\ B^3/(G^{3/2}\rho^2)$

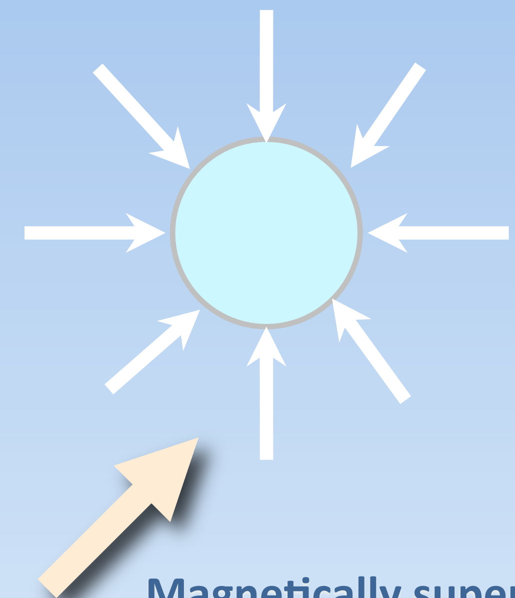
Core formation with turbulence, magnetic field, and ambipolar diffusion



Compression by supersonic turbulence

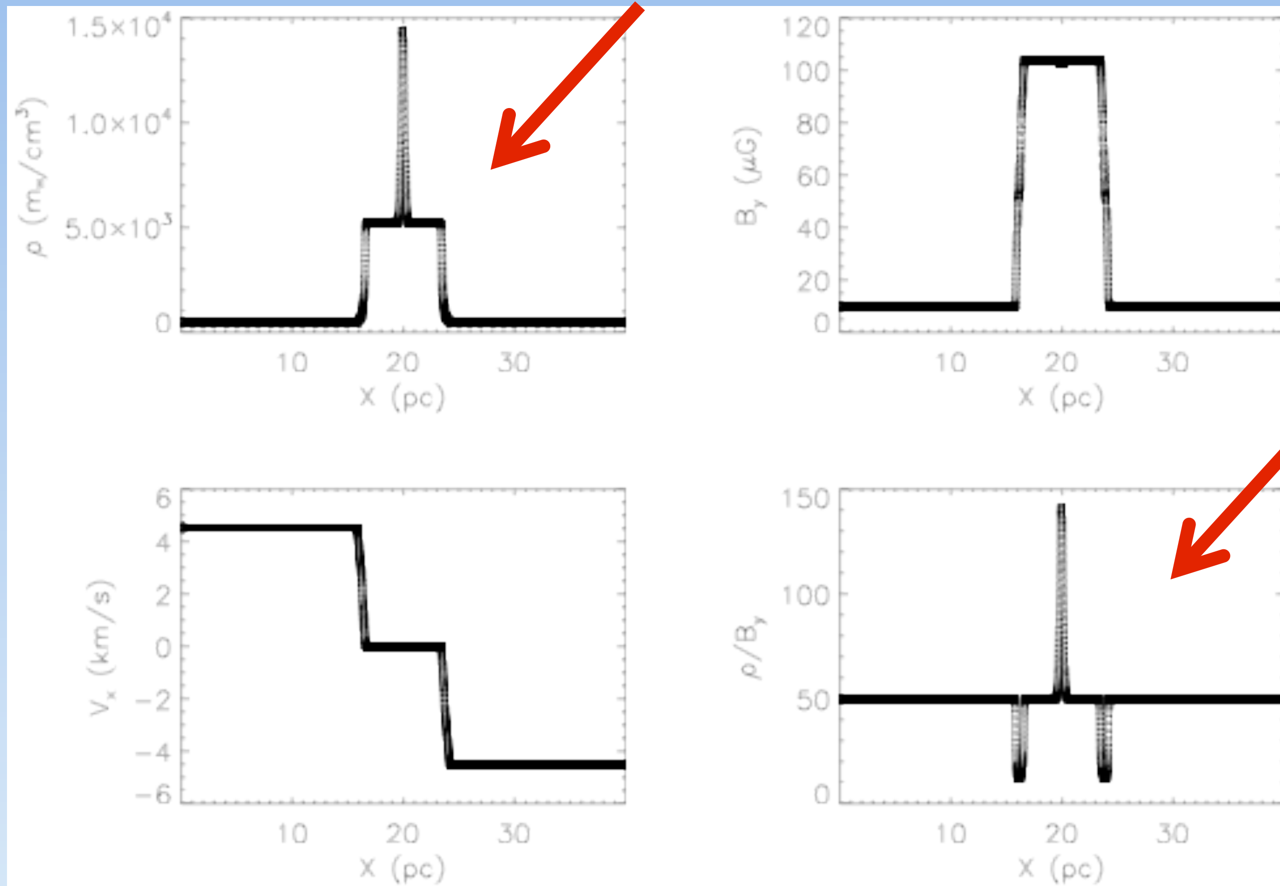


Lose magnetic support by field-aligned flow and rapid ambipolar diffusion



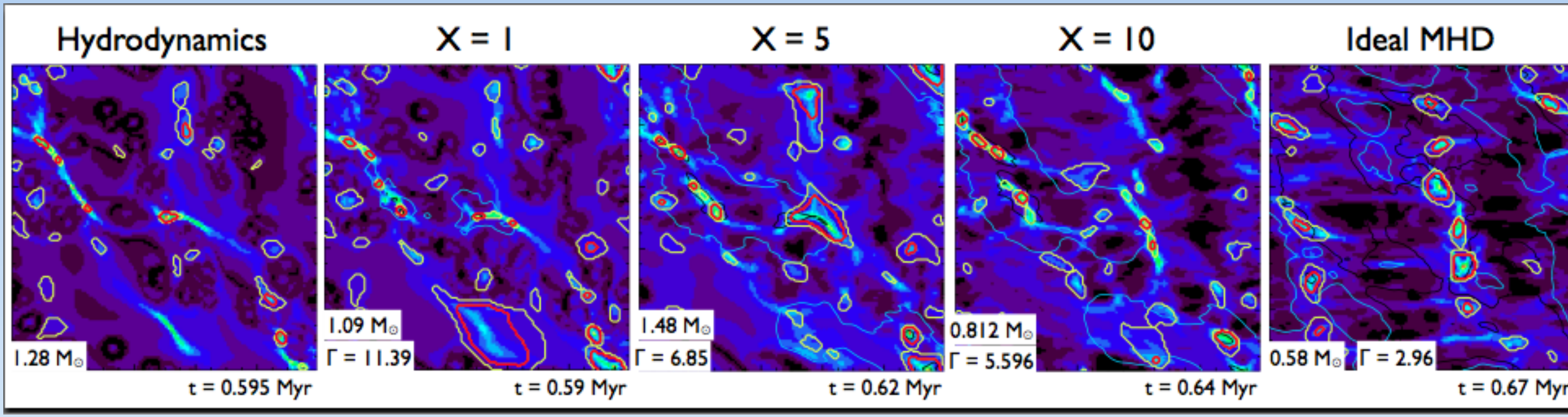
Magnetically supercritical core can collapse

1-D converging flow



(Chen & Ostriker 2012)

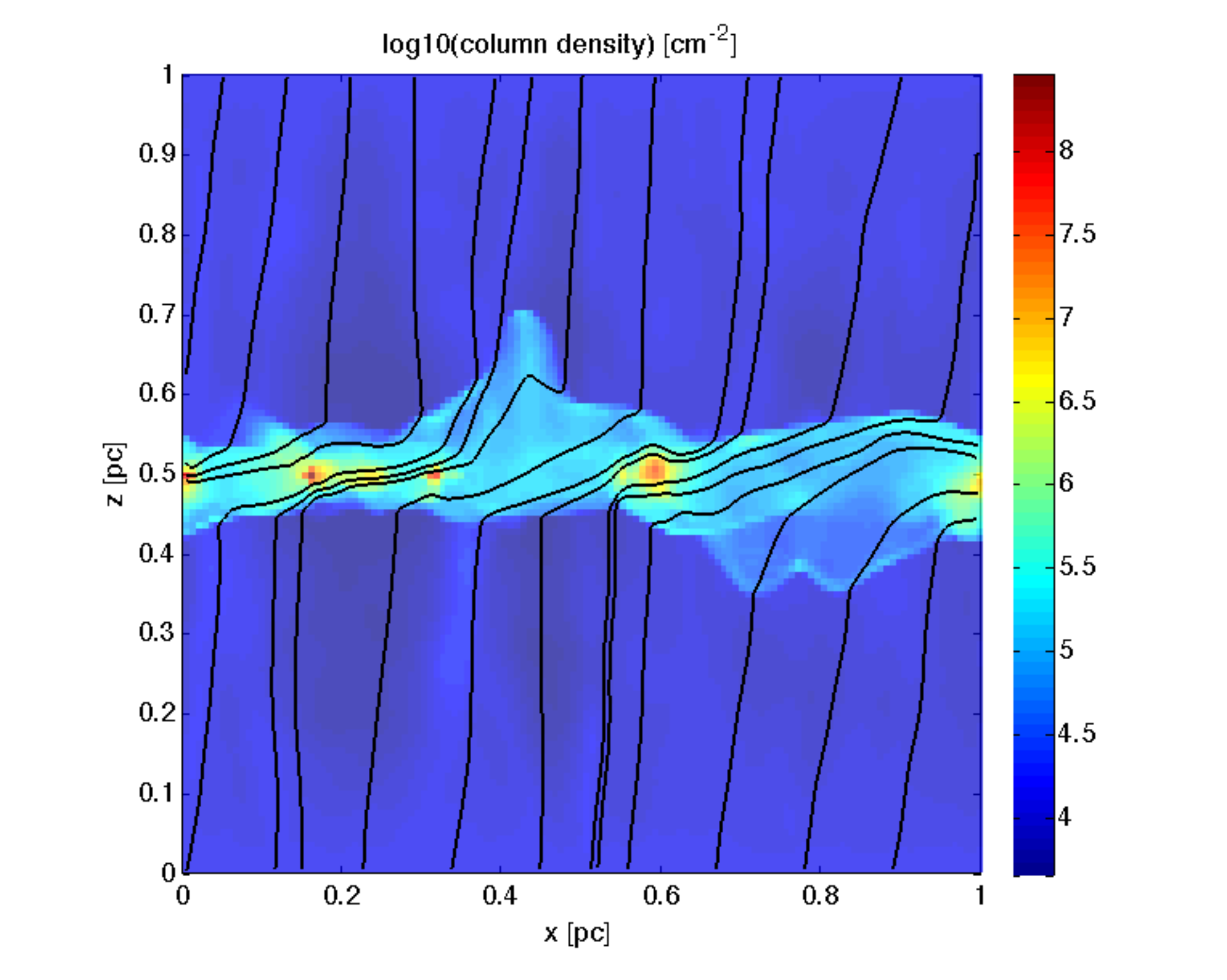
- Shock has transient phase in which neutrals do not "see" *B*
- Initial gas compression is very strong
- Transient duration is neutral-ion drift time $\sim(v/v_A)^{1/2}/(\alpha_{in}\rho_{i0})$
- M/Φ has large increase; subcritical can become supercritical



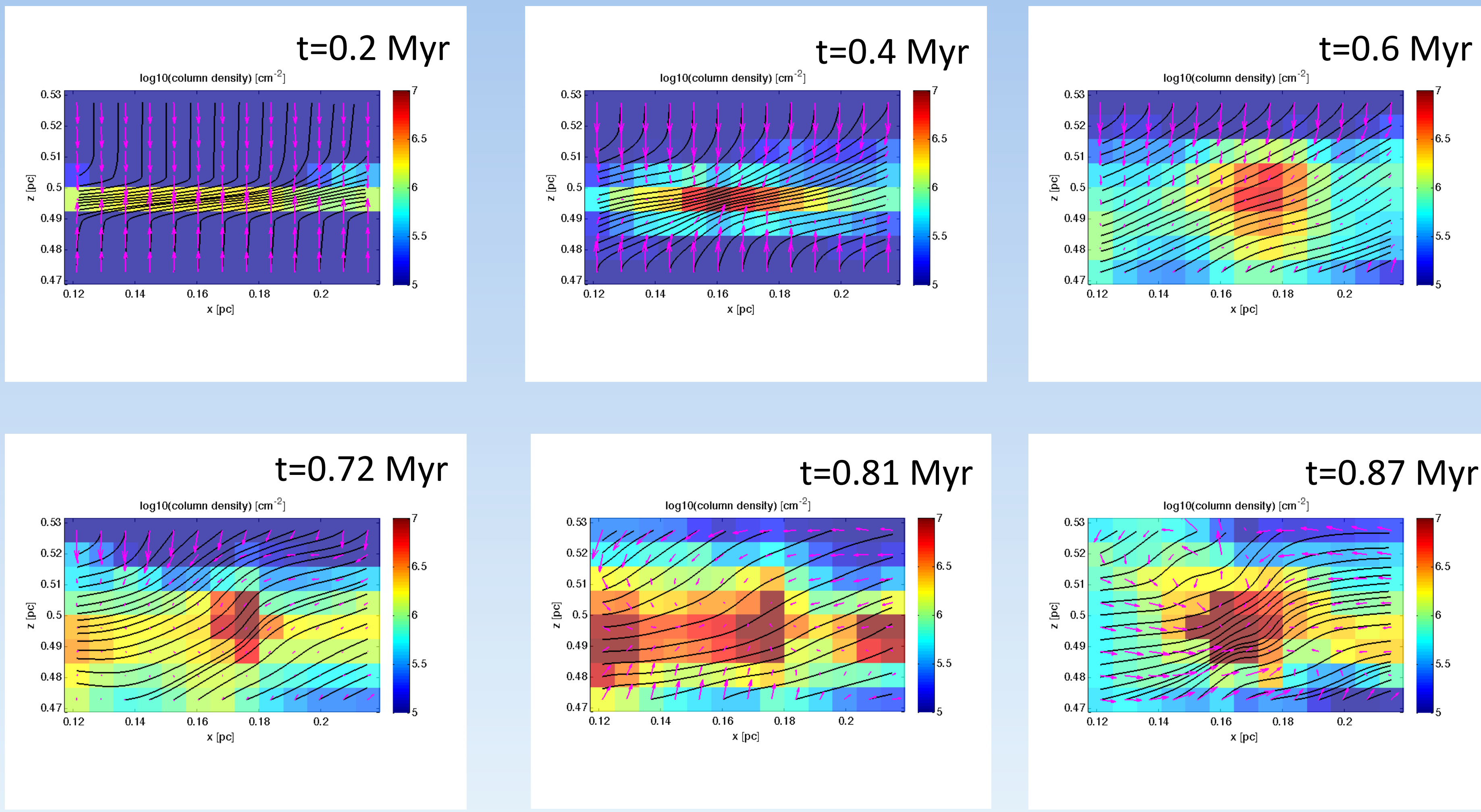
(Chen & Ostriker 2013)

Higher ionization ➔

field-aligned mass collection



field-aligned mass collection



(Chen & Ostriker 2013)

Summary

- Molecular clouds are pervaded by strong turbulence, which creates hierarchical structure
- Core formation is a highly dynamic, but produces quiescent structures via shocks
- Evolution of dynamically-formed cores is outside-in collapse followed by inside-out infall, very similar to classical theory
- Minimum core mass may be set by turbulent pressure in cloud, analogous to M_{BE}
- Filaments are initiated by turbulence and grow by gravity, with cores developing simultaneously
- Magnetic effects are significant but sub-dominant