What molecular cloud properties influence massive star formation?

The Formation of Molecular Cores from Turbulent Flows

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What is the initial condition necessary to form a massive star?

The rapid formation of a massive dense core, by converging supersonic flows, is the most direct way to get started (turbulent fragmentation).

Massive cores: 1. Predicted to form in turbulent clouds *(Padoan and Nordlund 2002)*
2. Found in numerical simulations *(Padoan et al. 2007)*
3. Found in molecular clouds *(Motte et al. 2007)*

Main differences from low-mass cores:

1. Massive cores are much more rare,
because of the power law mass function from the turbulence scaling.
--> *Stellar IMF*

2. The star may already be growing while the rest of the core is still being assembled,
because the collapse starts at the first BE mass and is faster than L/V.
--> *Strong mass inflow that overcomes the stellar radiation*

3. The core buildup must eventually interact with an UC HII region
--> *Long lifetime and variety of morphologies of UC HII regions.*

This talk:

Most numerical results are compared with observations of *low-mass* cores.
But the formation mechanism of massive cores may be the same.

ALMA: Large samples of massive pre-stellar cores studied to the current level of detail of low-mass cores?

See next two talks (Evans, Motte).

DRSPs:

2.1.4	*Density and temperature profile in high-mass cores*	*Bacmann*	*155*
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---------------- *For further discussion:*

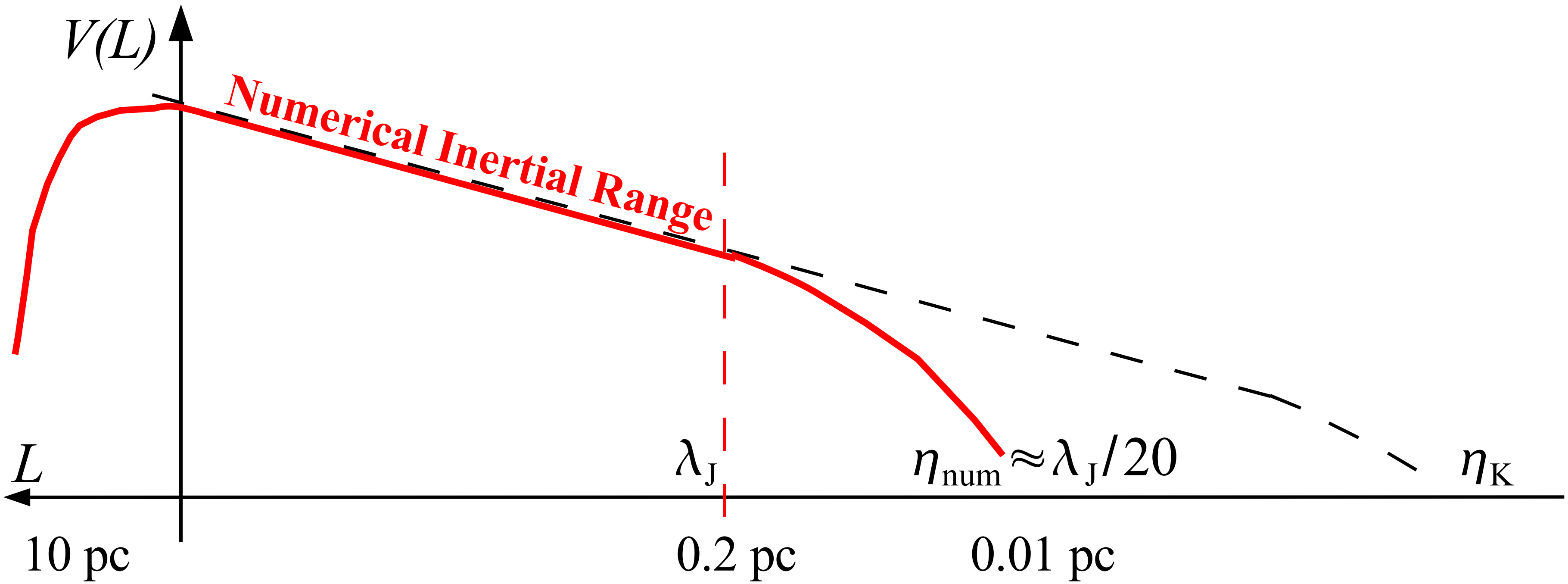
7. Velocity and Density statistics

8. Turbulent Heating (may control the gas temperature in some massive cores)

1. Simulations of Turbulent Fragmentation

Reynolds Number: $Re = \frac{U_0 L_0}{\nu} \approx 10^8 \Rightarrow \eta_K = \left(\frac{\nu^3}{\epsilon}\right) \approx 7\text{x}10^{13}\,\text{cm}$

Factor of ten in INERTIAL RANGE scales --> **~1000^3 cells, or ~1000^3 particles**

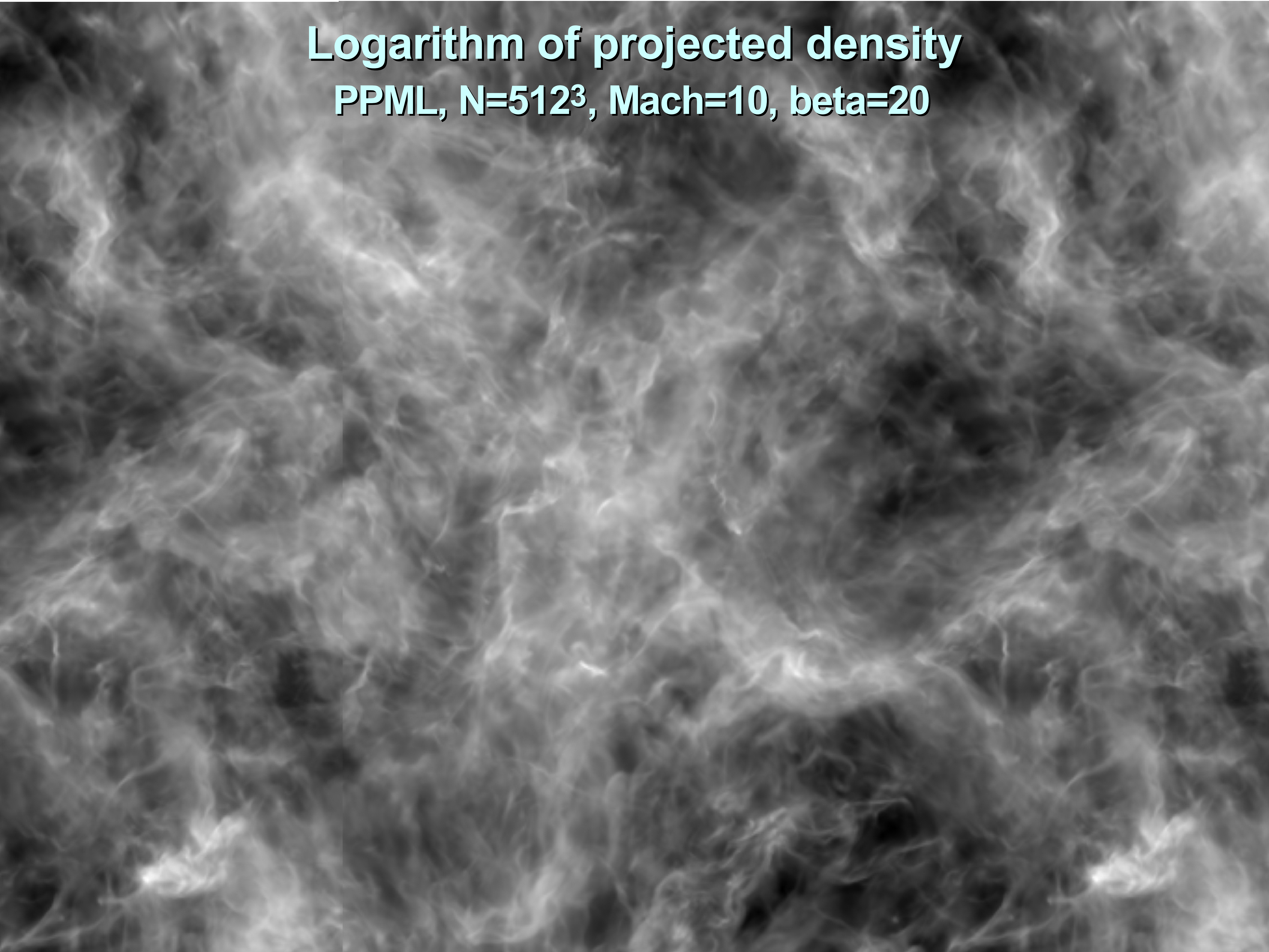


Bate et al. (2003): **3.5x100^3** particles

Ballesteros-Paredes et al. (2006): **59^3** particles --> ***No inertial range***.

Logarithm of projected density

PPML, $N=512^3$, Mach=10, beta=20



AMR Movie: Gravitational Collapse in MHD Supersonic Turbulence

Dimensional Scaling Parameters: $L = 5.6\,\mathrm{pc}\ ;\ \ T = 10\,\mathrm{K}\ ;\ \ \bar{n} = 230\,\mathrm{cm}^{-3}$

Non-Dimensional Parameters: $\beta_{\mathrm{i}} = 22.2\ ;\ \ \beta = 0.2\ ;\ \ M_{\mathrm{A}} = 2.8\ ;\ \ M_{\mathrm{S}} = 8.9$

- AMR criterion: ¼ Jeans length
- Refinement: 4 levels, factor of 2
- Root grid: 512^3
- Effective Resolution: 8192^3

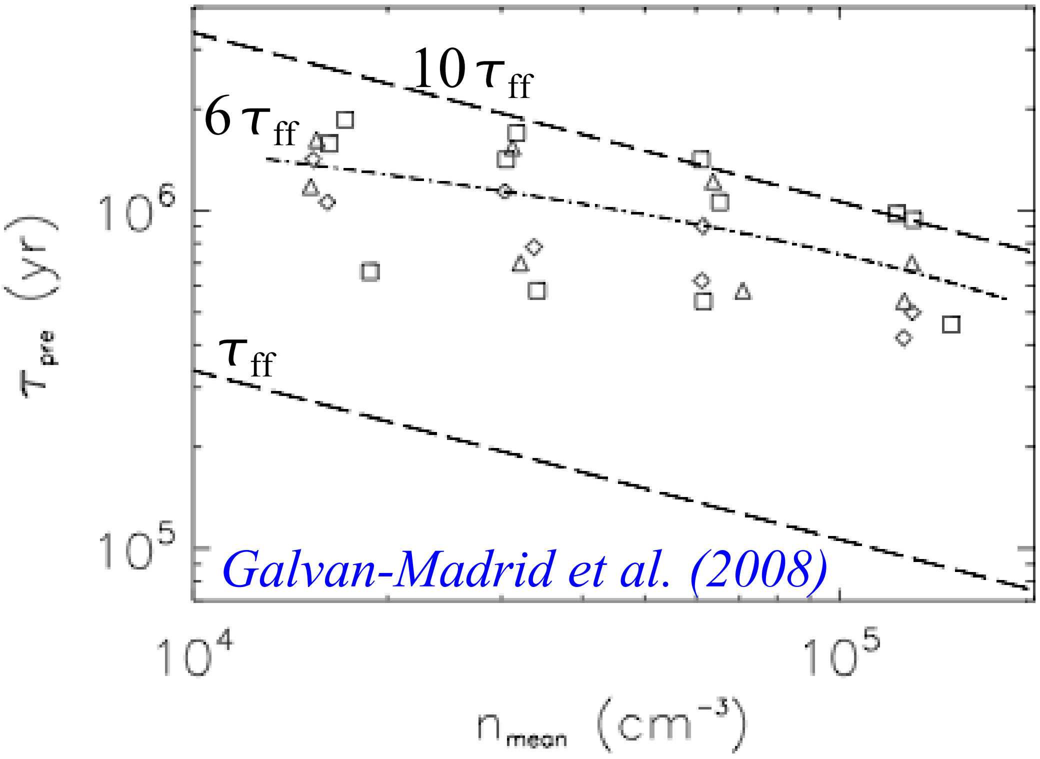
- Li's MHD solver (2nd order in time and space; HLLC Riemann solver)
- Gardiner & Stone CT for the induction equation
- Balsara AMR for interpolation.

2. Core Equilibrium and Lifetime

Tilley & Pudritz (2004), Vazquez-Semadeni et al. (2005), Ballesteros-Paredes et al. (2005), Dib et al. (2007), Galvan-Madrid et al. (2008):

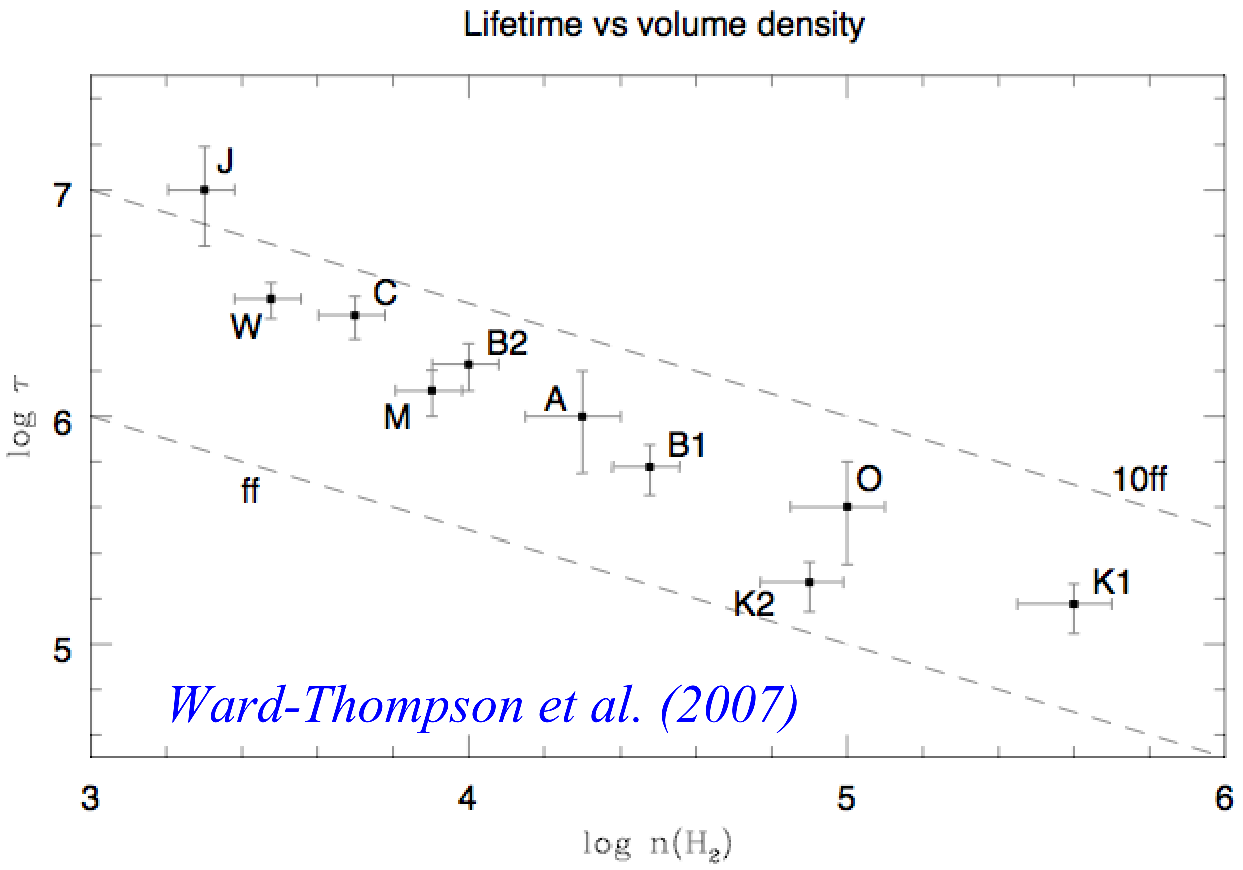
- Cores are out of equilibrium, either transient or collapsing structures
- No magneto-static structure as in the ICs of the AD model of core formation
- Short lifetimes, but longer than free-fall

Lifetime: Formation Time + Free-Fall Time (prestellar cores)
Formation Time + Dispersion Time (failed cores)



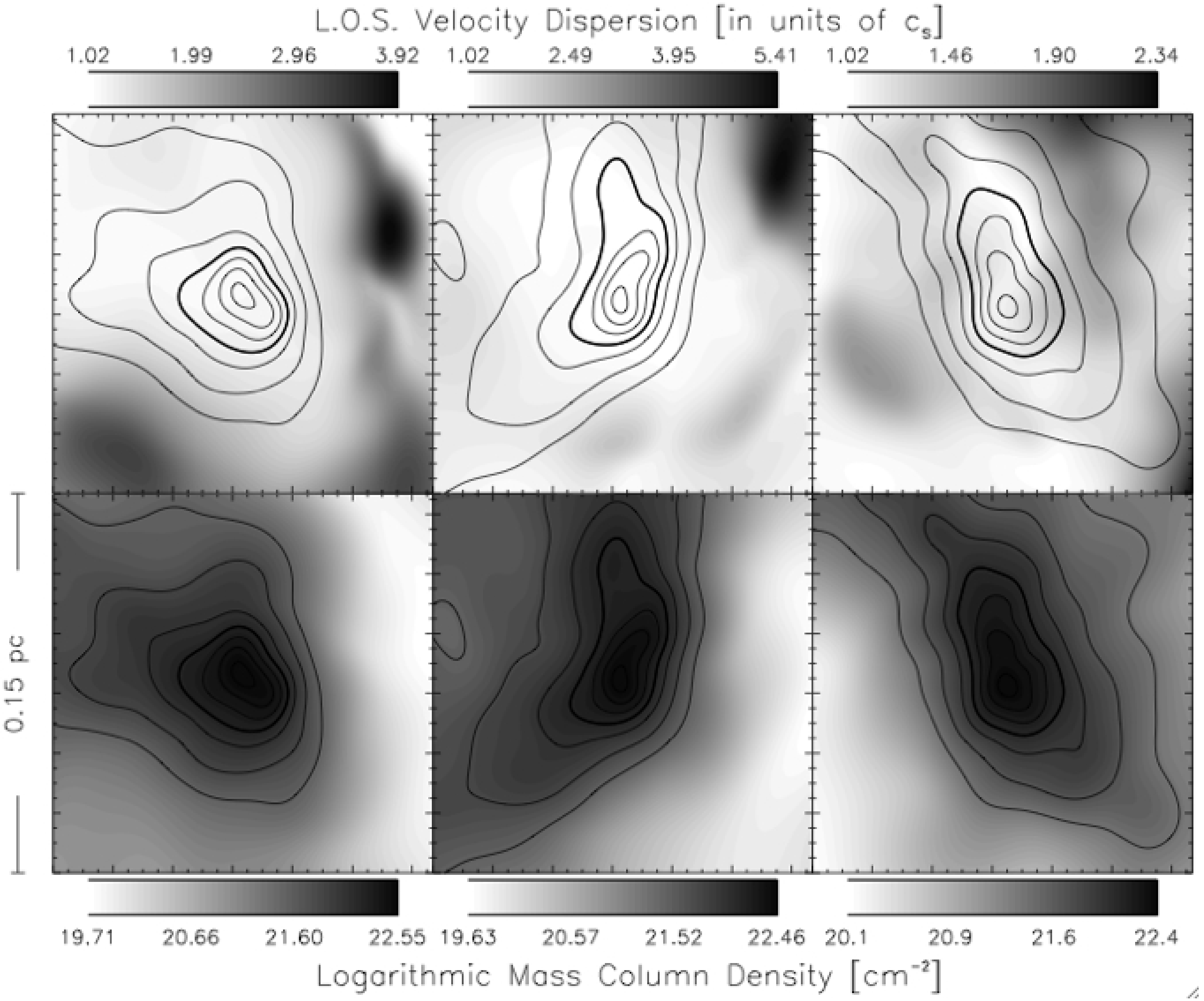
Galvan-Madrid et al. (2008)

A lifetime of a few free-fall times is confirmed by the observations:

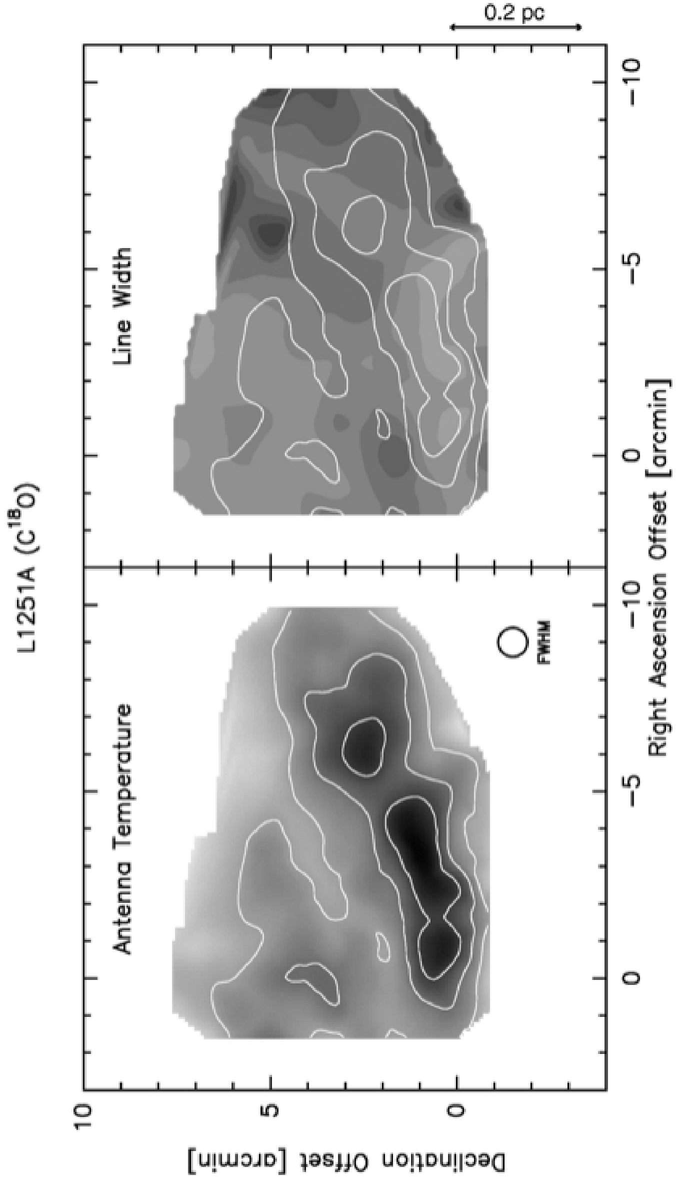


3. Core Internal Kinematics

Klessen et al. (2005), Offner et al. (2008):
Quiescent cores are found in simulations of supersonic HD turbulence.

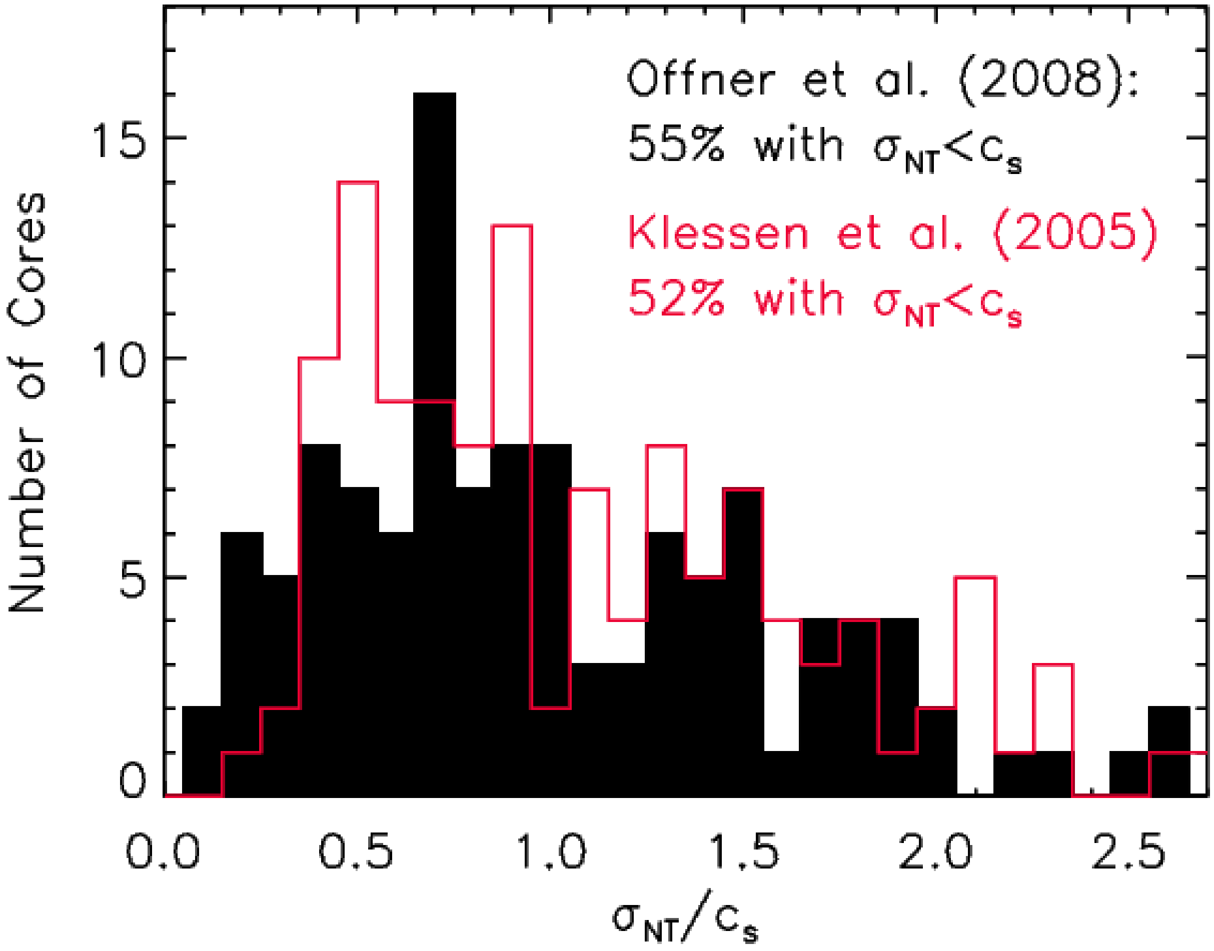


Klessen et al. 2005



Goodman et al. 1998

But a bit less than half of the cores are not quiescent:



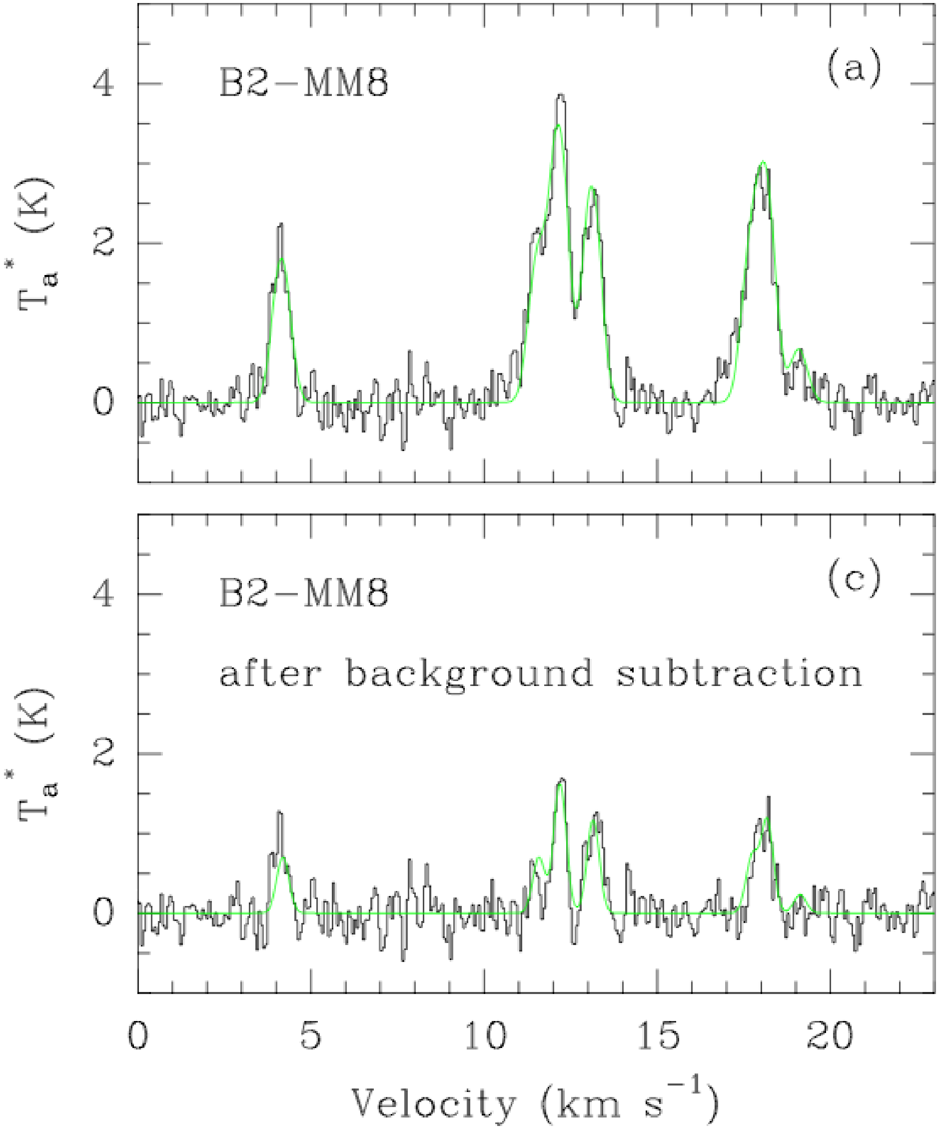
Non-quiescent cores could be in the process of formation (or “fake” cores).

Where are the non-quiescent cores in real molecular clouds?
(Andre et al. 2007; Kirk et al 2007; Rosolowsky et al. 2008; Foster et al. 2008)

They can be found, if one treats the observations like the simulations.

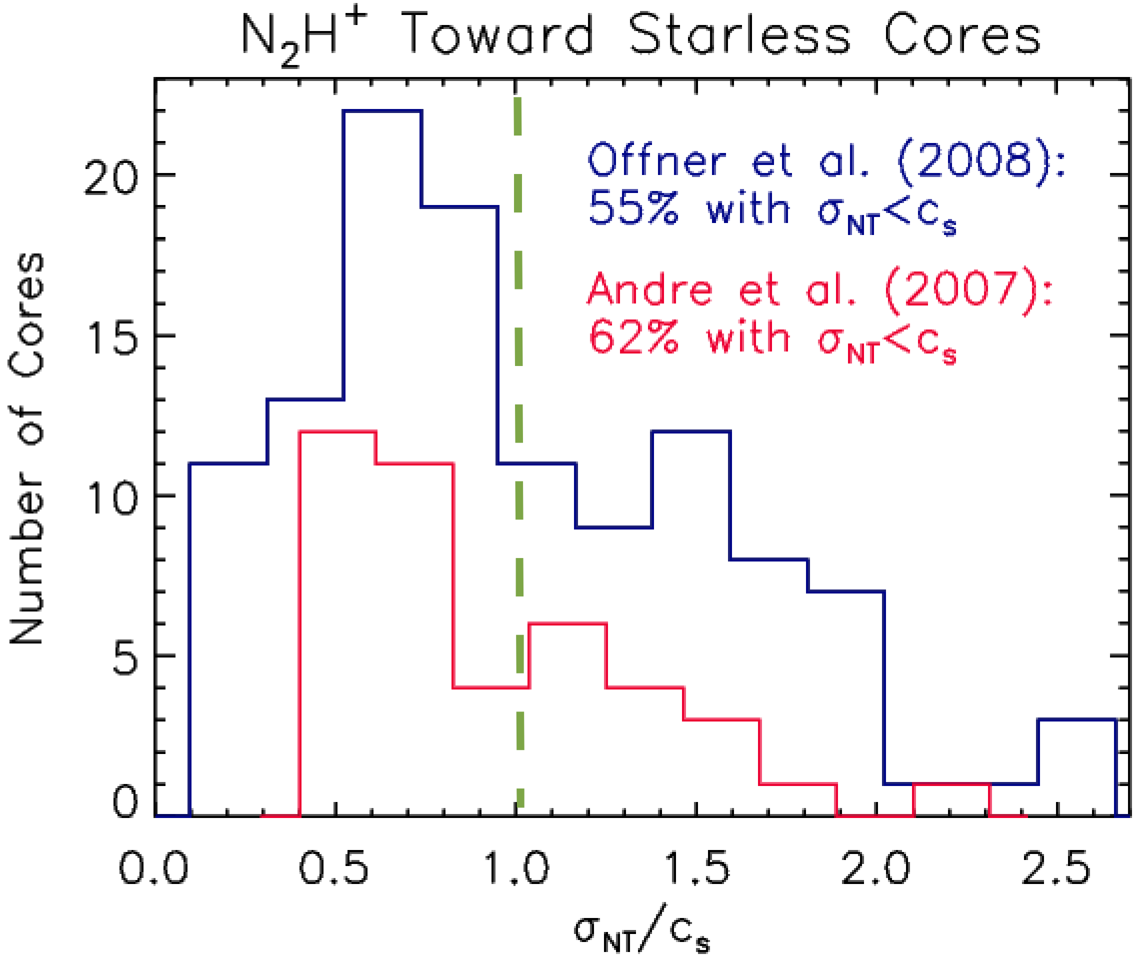
Andre et al. (2007):

1. Multiple-component gaussian fitting (Gaussclumps – Stutzki & Gusten 1990)
2. Background subtraction



None of this was done by Klessen et al. (2005) and Offner et al. (2008).

Without background subtraction (but still Gaussian fitting):
Only 60% of Ophiucus cores appear to be quiescent.

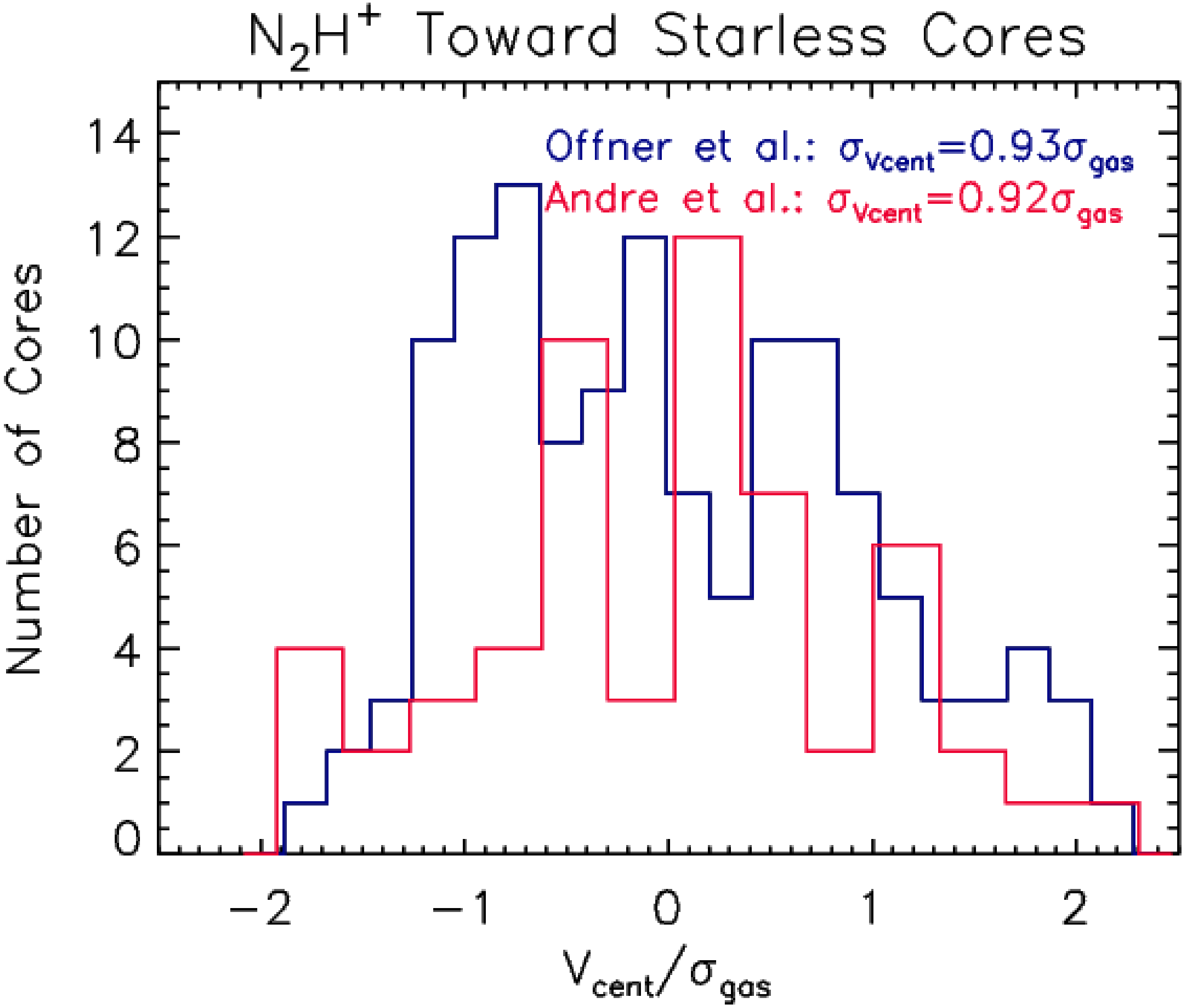


Good agreement between simulations and observations.

4. Core-to-Core Kinematics

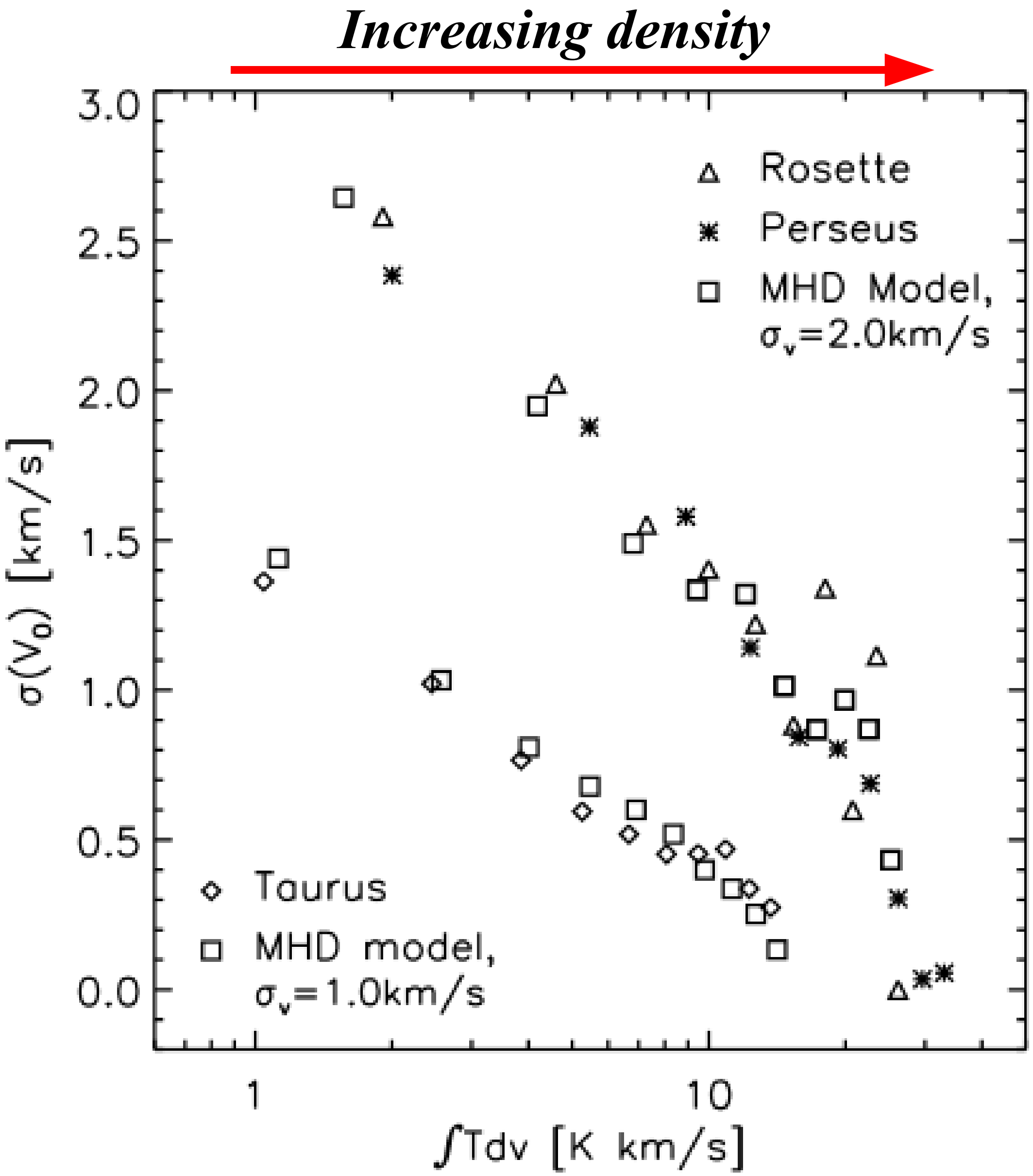
The core-to-core velocities in simulations are of the order of the gas rms velocity.

The same in the observations:



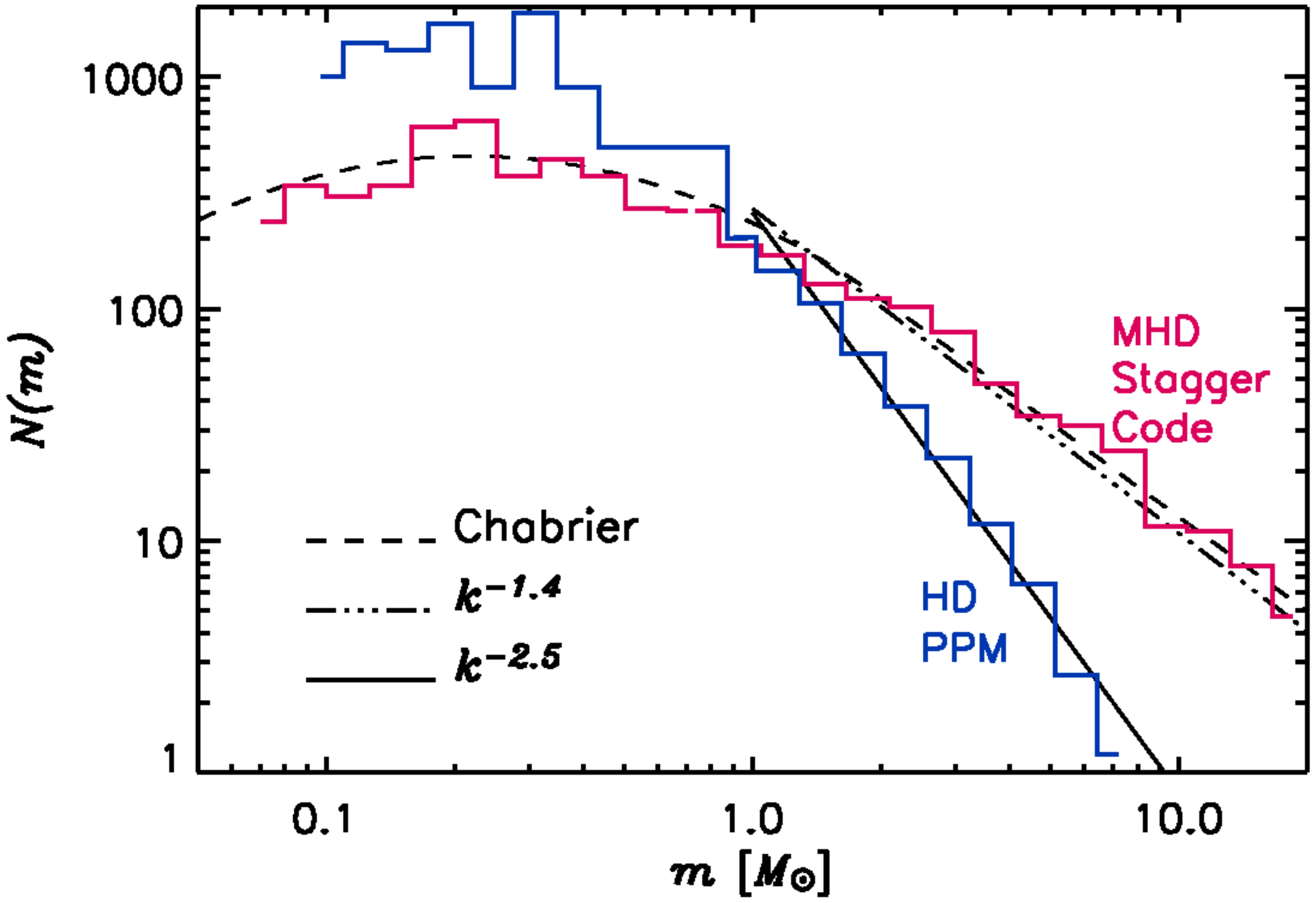
Padoan et al. (2001):
Higher density --> Lower region-to-region velocity dispersion

The exact same correlation is found in molecular clouds.

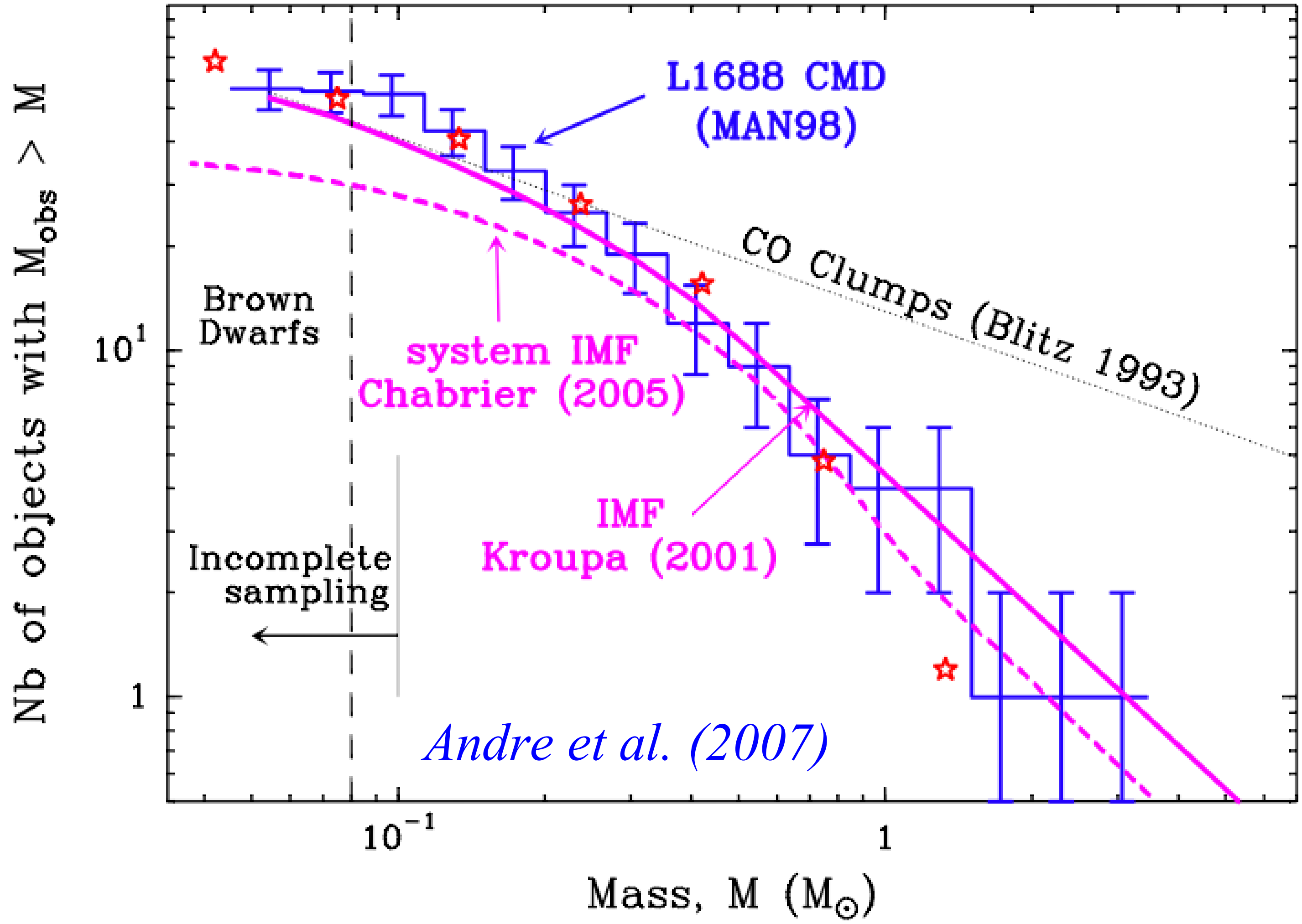

Increasing density

5. Core Mass Function

Padoan et al. (2007):
No self-gravity, 1000^3, $\mathrm{Mach}_s=10$ --> Power law mass function above 2 solar masses, consistent with Salpeter (much steeper without magnetic field!)



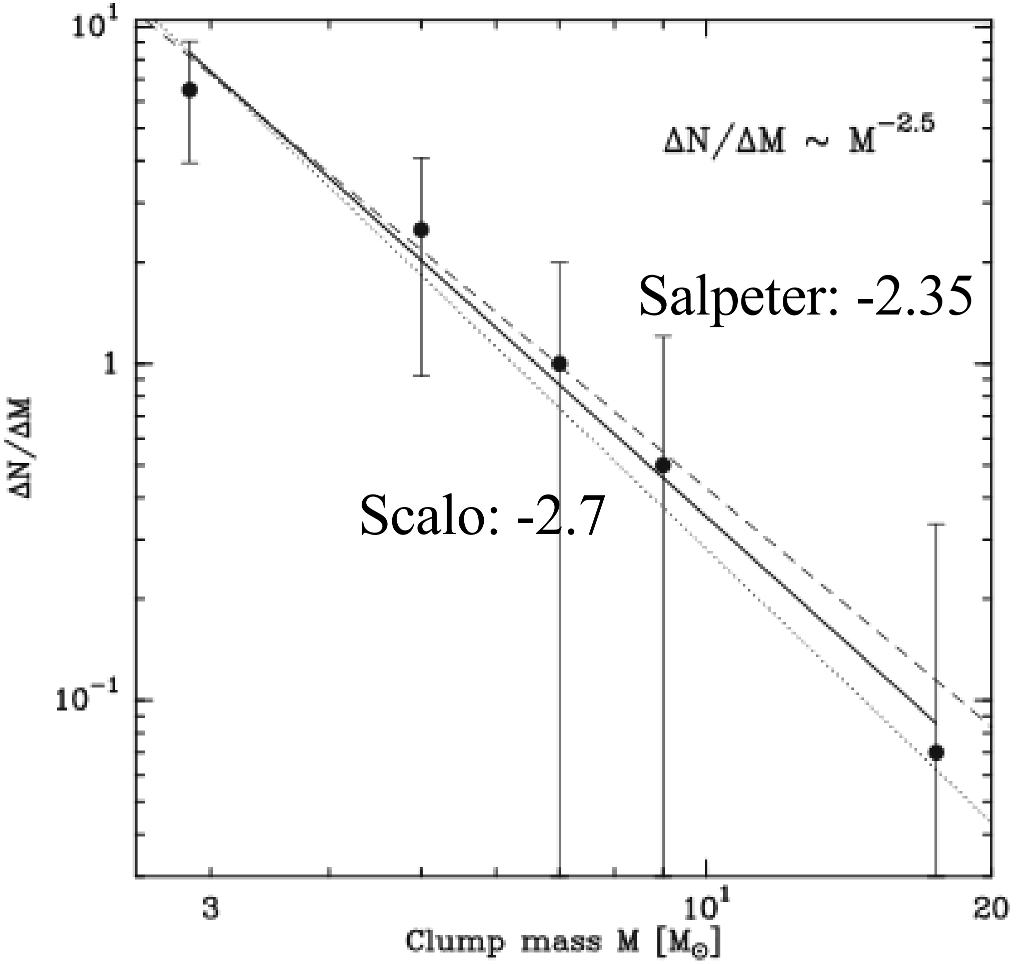
The observed core mass distribution suggests that initial conditions from turbulence are relevant for the IMF.



No density-mass correlation, so the lifetime is not mass-dependent (contrary to the suggestion of Clark et al. 2007). The core IMF can be directly related to the stellar IMF.

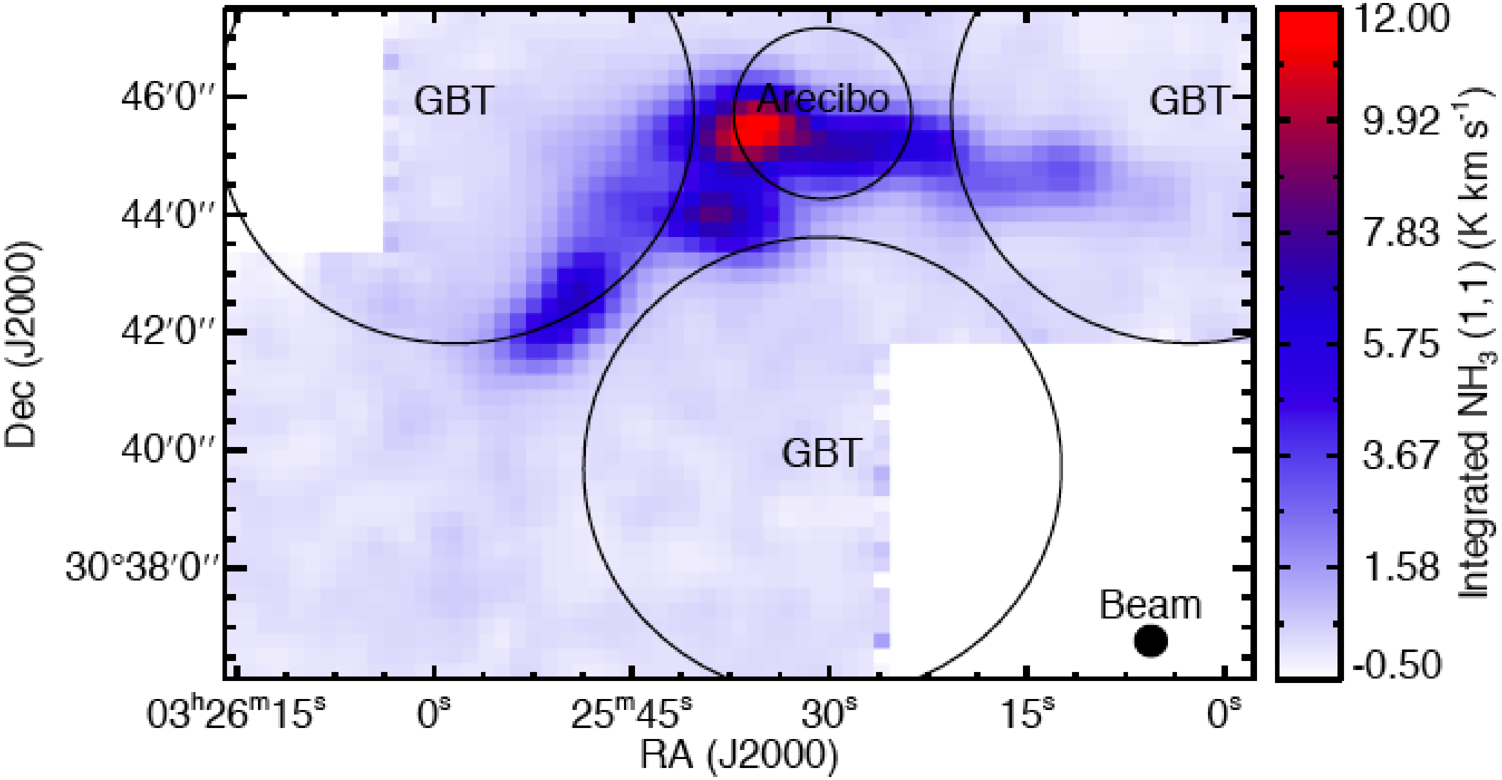
Is the same true for massive cores?

Beuther and Schilke (2004): Mass Spectrum of IRAS 19410+2336
(Plateau de Bure Interferometer, ~1" + IRAM 30m, ~11")



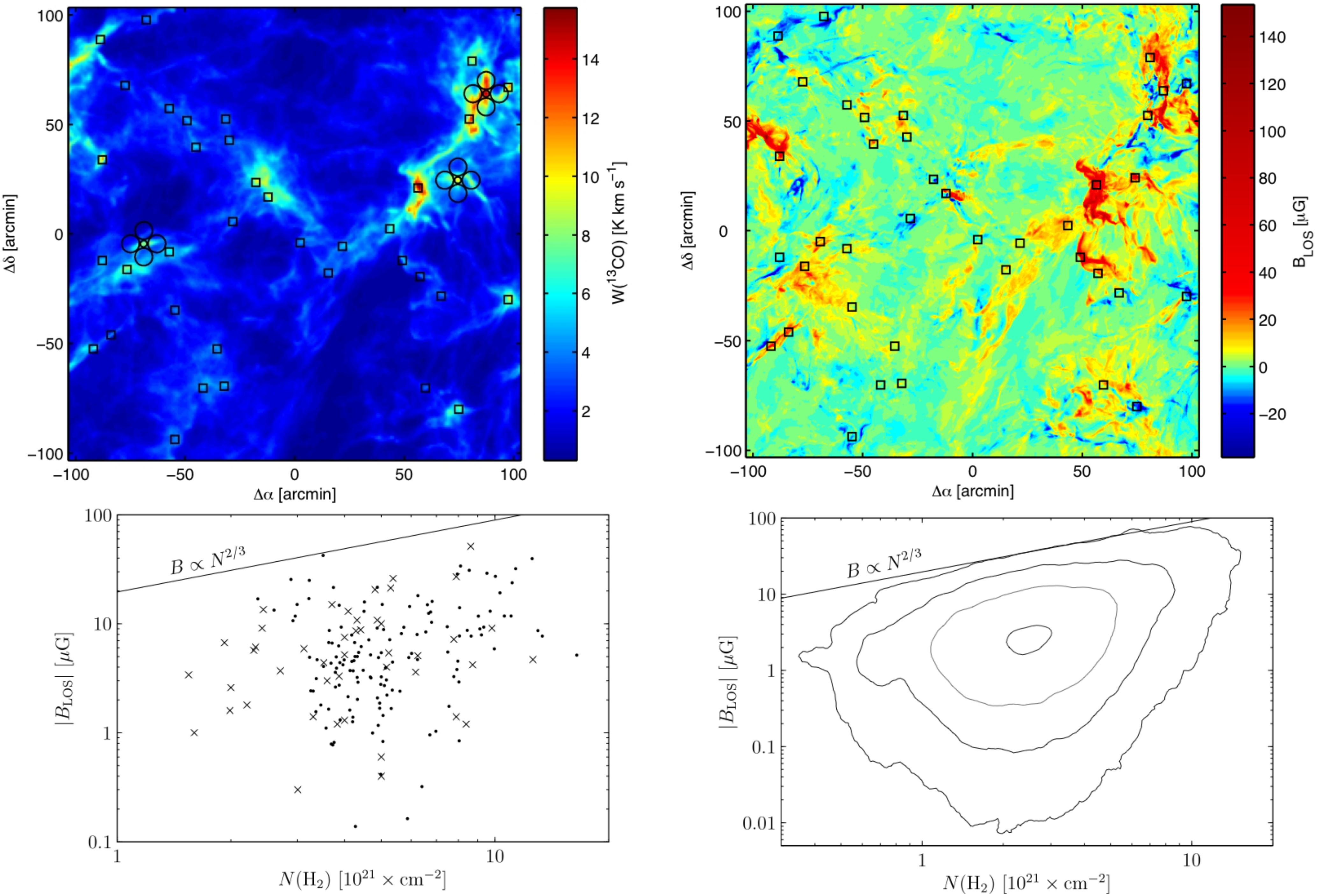
6. Core Magnetic Field

1. Crutcher (1999), Bourke et al. (2001), Crutcher and Troland (2000), Crutcher et al. (2004), Troland and Crutcher (2008): **Most cores are supercritical.**
2. Mouschovias et al. (2006): Even if cores are supercritical, **the core envelopes are subcritical**, as predicted by the AD model.
3. Crutcher et al. (2008): **On the contrary, the envelope is even more supercritical than the core.**

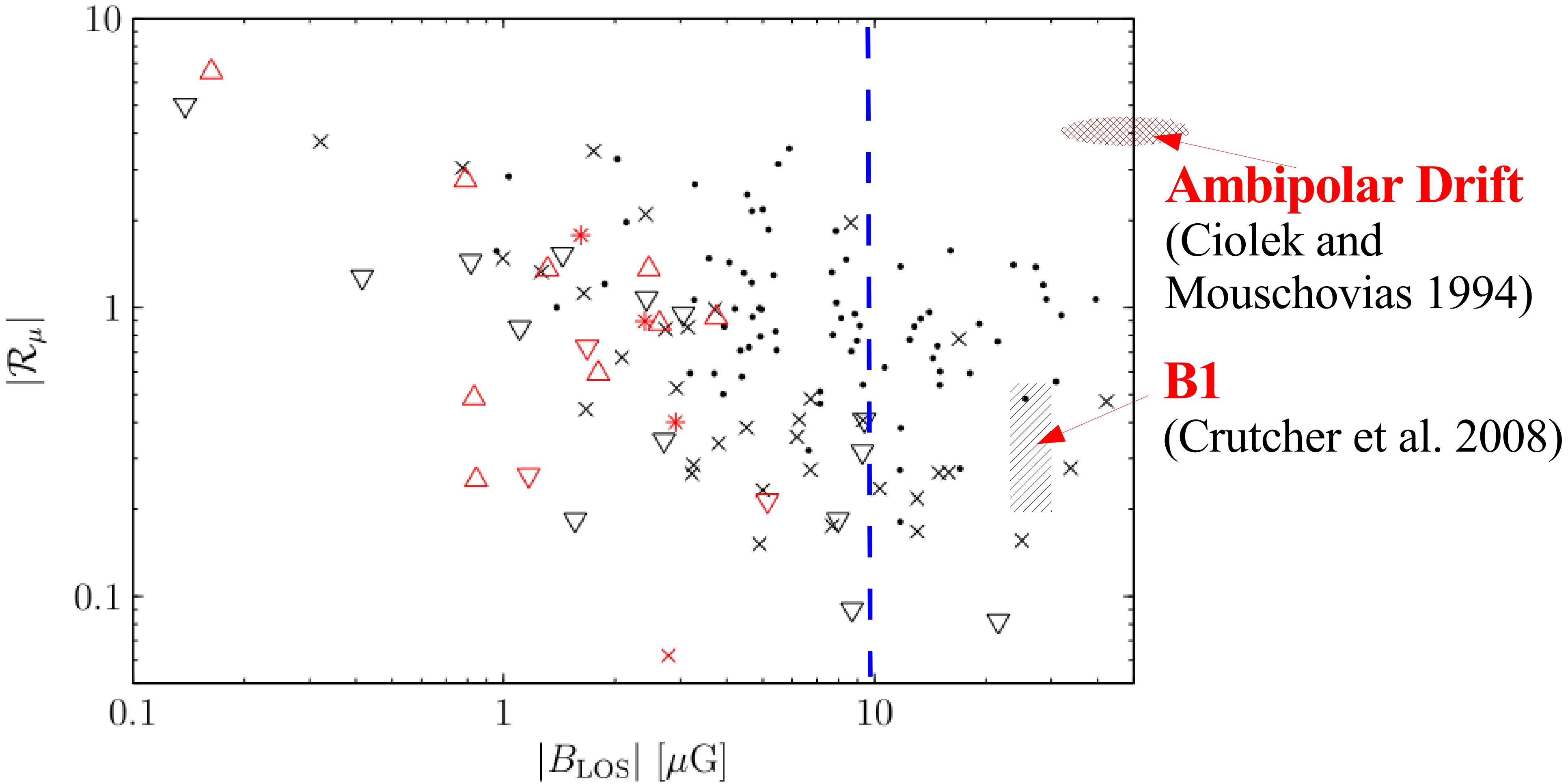


L1444 (Pineda et al., in preparation)

Lunttila et al. (2008): Synthetic Zeeman from supersonic and super-Alfvenic turbulence



Relative mass-to-flux ratio: $R_\mu = \frac{[N(\mathrm{H}_2)/B_{\mathrm{LOS}}]_{\mathrm{core}}}{[N(\mathrm{H}_2)/B_{\mathrm{LOS}}]_{\mathrm{envelope}}} = \frac{[N(\mathrm{OH})/B_{\mathrm{LOS}}]_{\mathrm{core}}}{[N(\mathrm{OH})/B_{\mathrm{LOS}}]_{\mathrm{envelope}}}$



Ambipolar Drift
(Ciolek and Mouschovias 1994)

B1
(Crutcher et al. 2008)

Supersonic, super-Alfvenic turbulence: Large scatter in Rmu
Rmu < 1 (for B>10 muG)

Ambipolar drift model of core formation: Rmu > 1 (~ 4)

Crutcher et al. (2008): **Rmu = 0.37+-0.18** (for the core B1)

Effect of supersonic MHD turbulence:

Formation of cores, including massive ones, with the following properties:

- Lifetime of a few free-fall times
- No magneto-static equilibrium
- Internal velocity dispersion primarily subsonic
- Core-to-core velocity lower than the gas rms velocity
- Power law mass distribution consistent with Salpeter
- Magnetically supercritical
- Relative mass-to-flux ratio < 1, unlike the ambipolar drift model

All these *numerical* results are consistent with the observations, at least for low-mass cores.

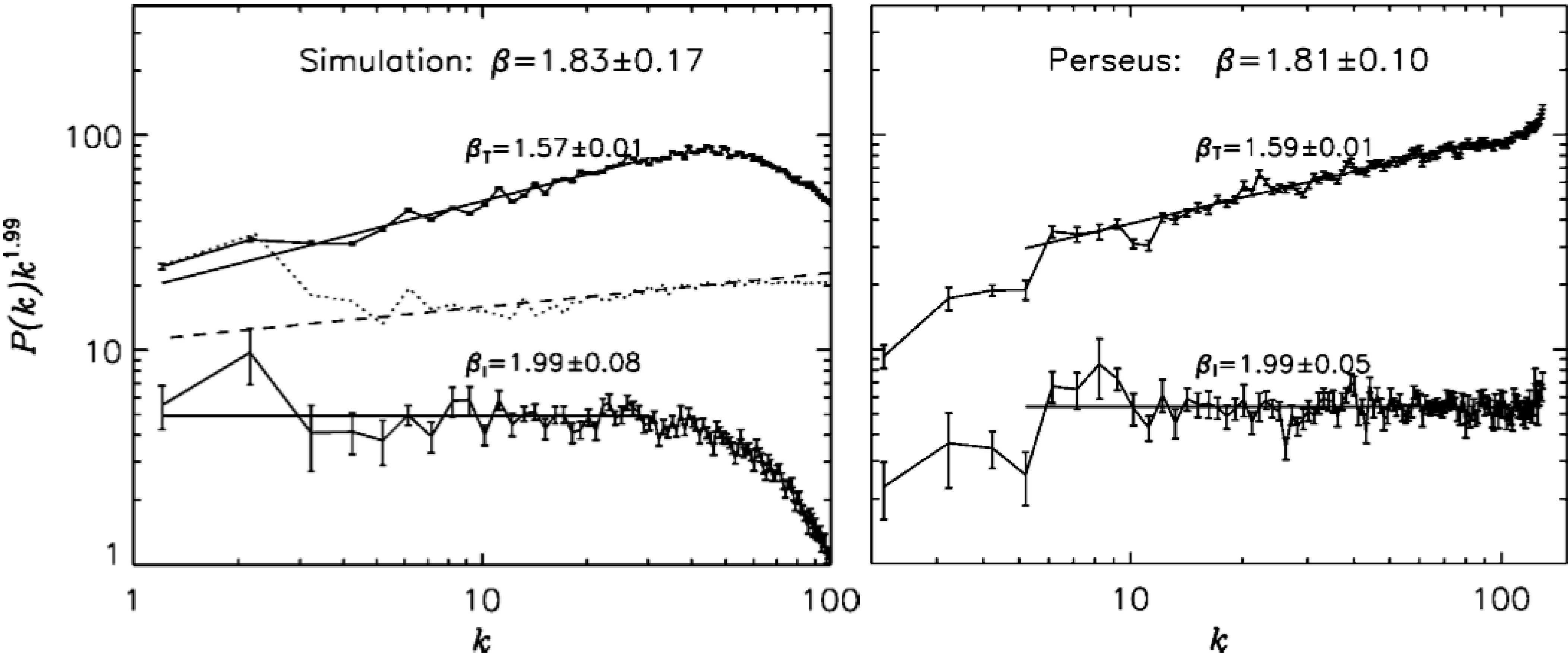
Can we repeat this comparison with massive cores?
What is ALMA role on this?

Comments and Questions.....

7. Velocity and Density Statistics

Lazarian and Pogosyan (2000): From intensity map to velocity power spectra

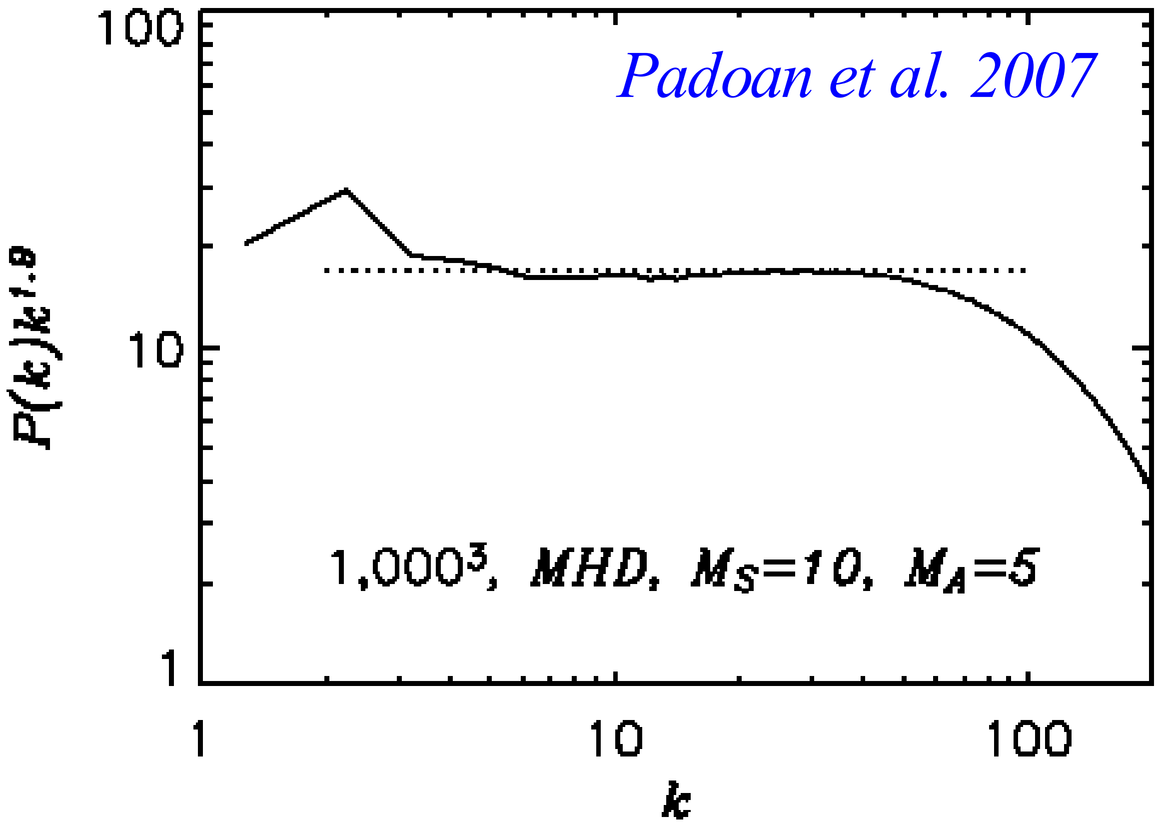
Padoan et al. (2006): Velocity power spectrum in Perseus



Power-law velocity power spectrum

Kolmogorov: $k^{-5/3}$, Burgers: k^{-2}

Supersonic MHD turbulence: $E(k) \propto k^{-1.9}$ $(E_C / E_S \approx 0.2)$



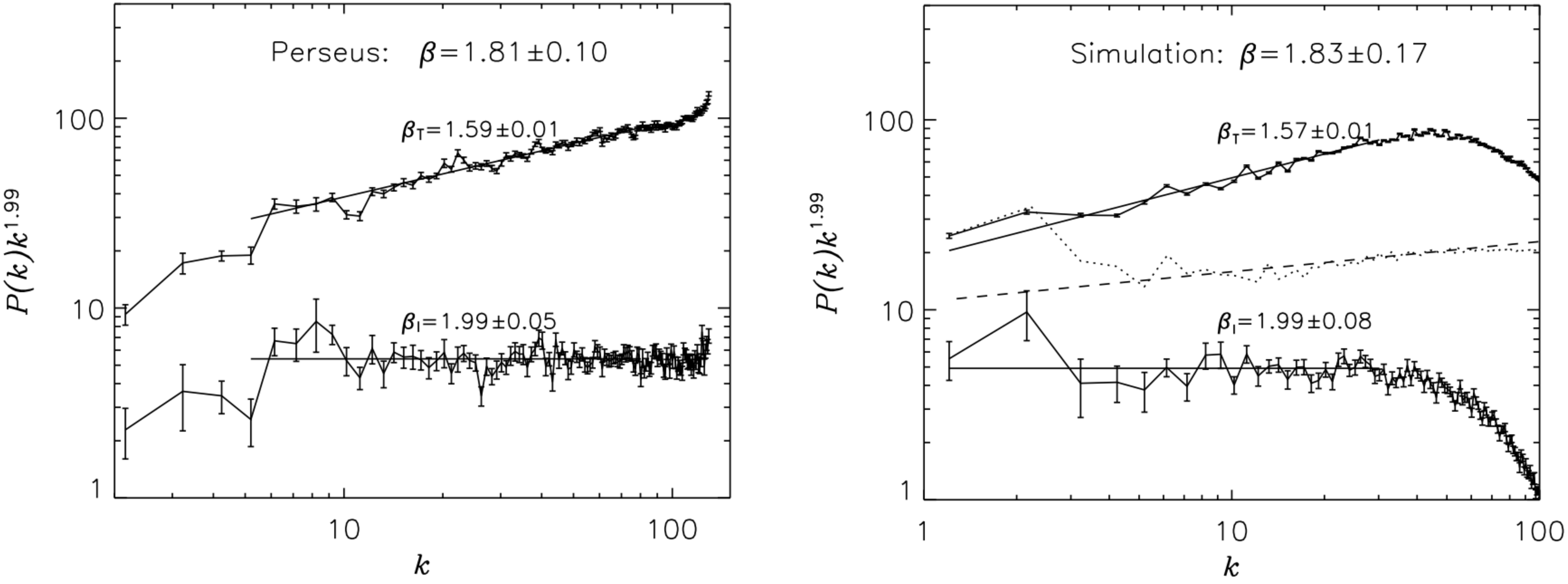
Larson (1979, 1981): $E(k) \propto k^{-1.74}$ $(1\,\mathrm{pc} < l < 1000\,\mathrm{pc})$

Perseus Velocity Power Spectrum

The velocity power spectrum can be inferred from the comparison of the power spectra of projected density and single velocity channel maps:

$$\beta = 1 + 2\,(\beta_\mathrm{I} - \beta_\mathrm{T})$$

(Lazarian & Pogosyan 2000)

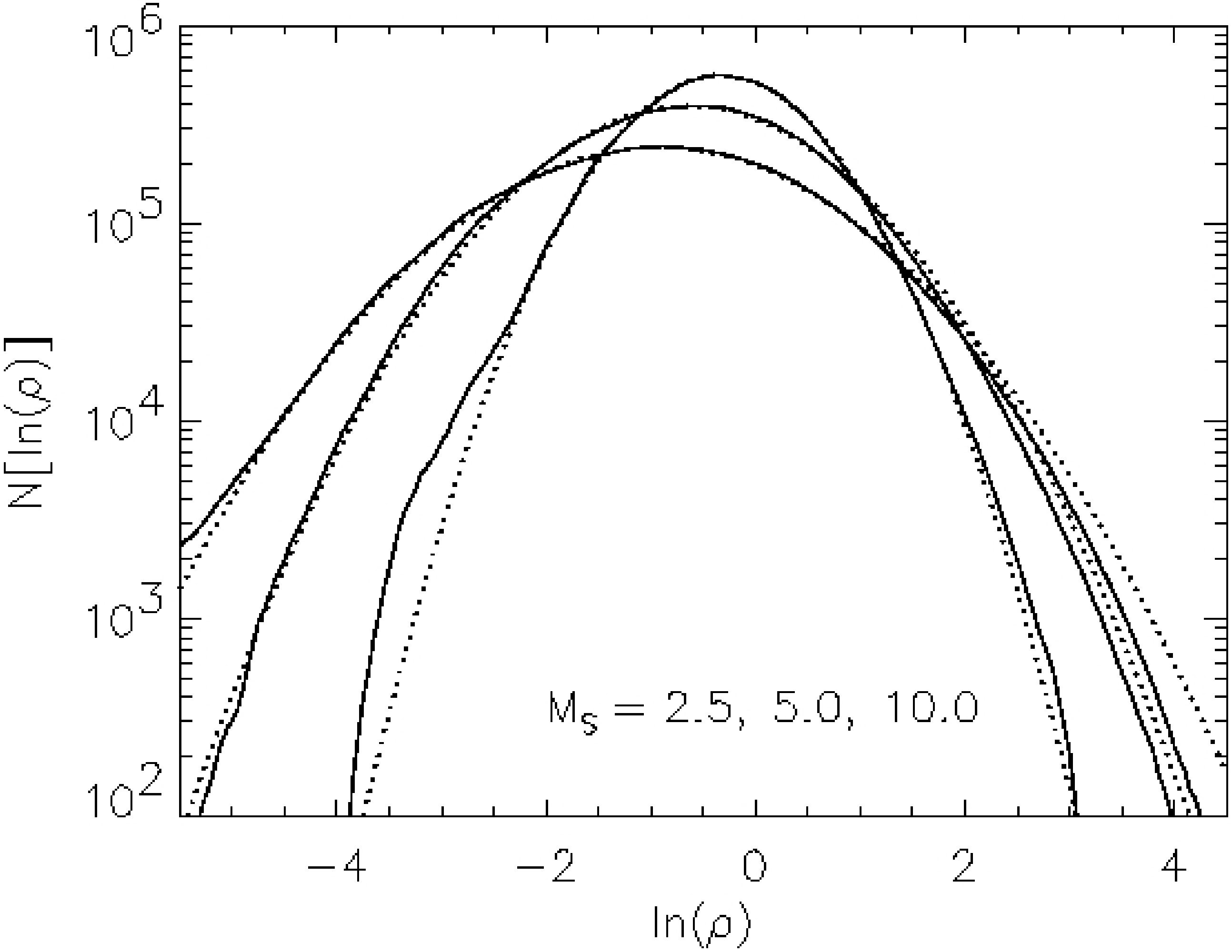


In Perseus: $\beta_\mathrm{I} = 1.99 \pm 0.05\,;\quad \beta_\mathrm{T} = 1.59 \pm 0.01 \quad\Rightarrow\quad \boldsymbol{\beta = 1.81 \pm 0.10}$

(Padoan et al. 2006; data from *Ridge et al. 2006)*

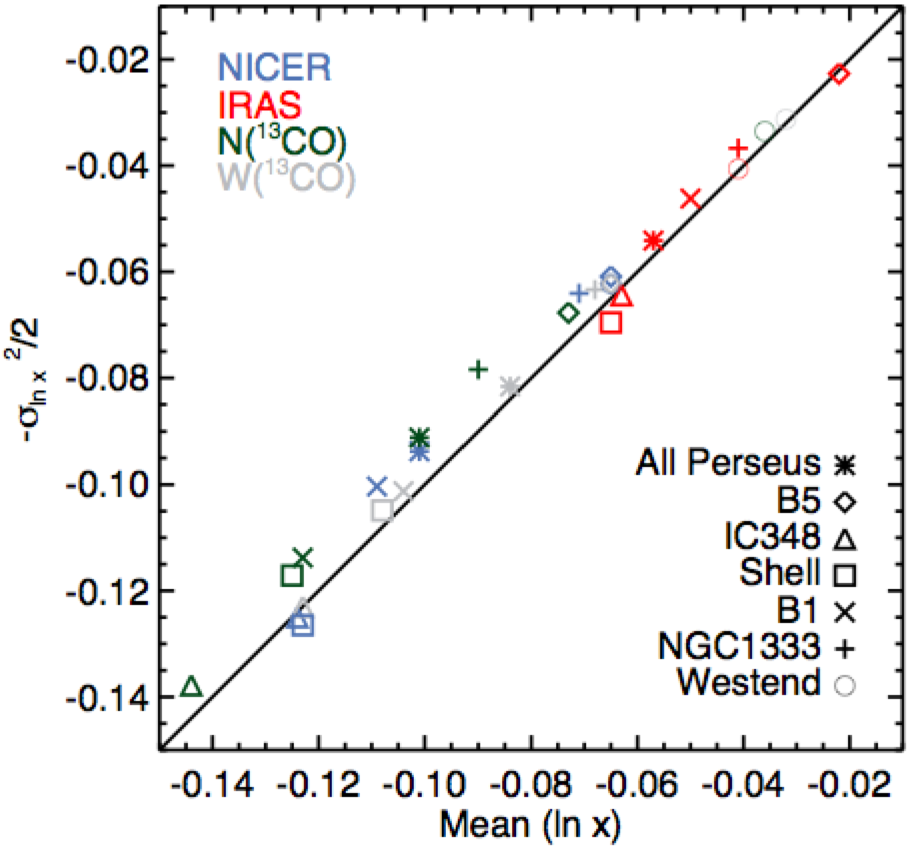
Lognormal PDF of gas density

$$\sigma_{\rho} \approx M_S/2 \qquad \sigma^2_{\ln\rho} \approx \ln\left(1+M_S^2/4\right)$$

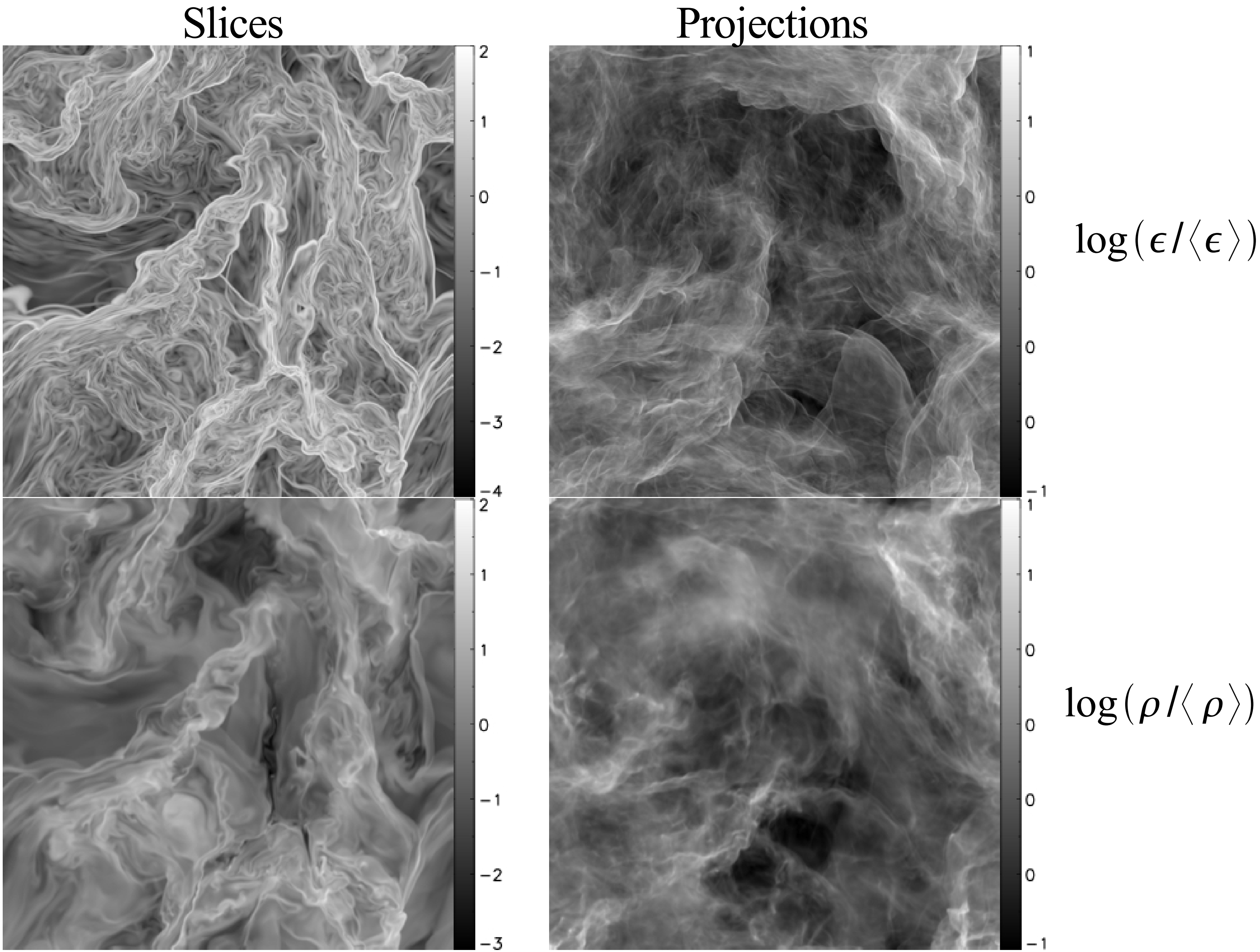


(Vazquez-Semadeni 1994; ***Nordlund & Padoan 1999****; Ostriker et al. 2001)*

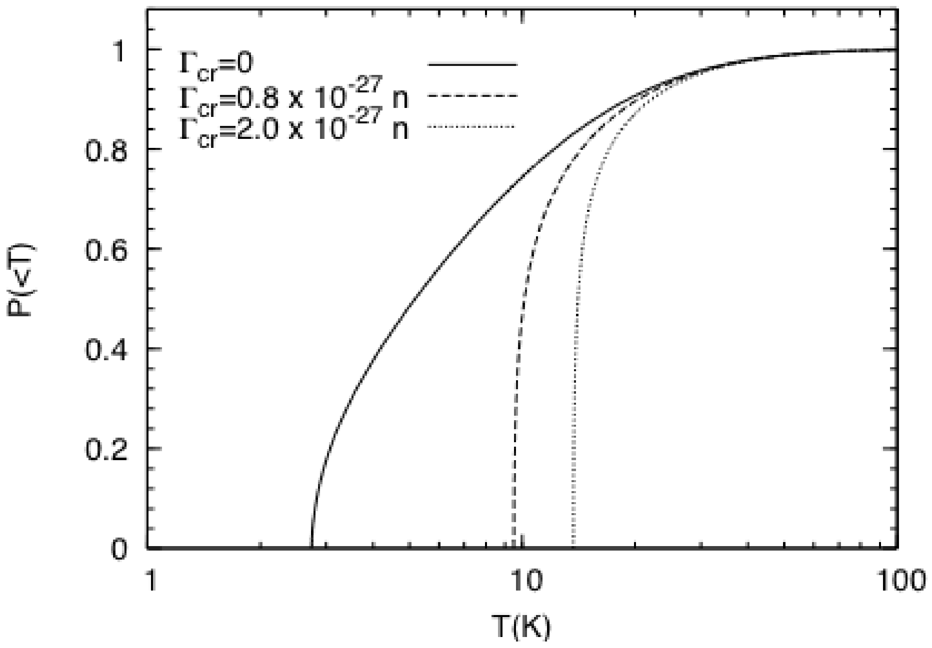
Log-Normal PDF of gas density (Goodman et al. 2008):



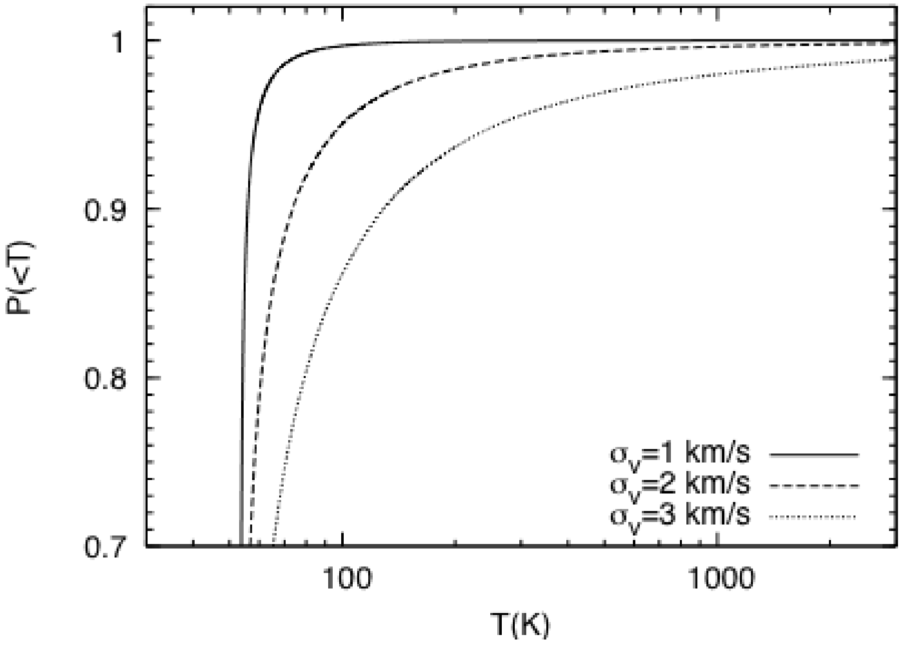
8. Turbulent Heating *(Pan and Padoan 2008)*



Cumulative probability of temperature smaller than T in MCs of size 1pc



Cumulative probability of temperature smaller than T in diffuse HI clouds



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