Turbulence and fragmentation in the interstellar medium.

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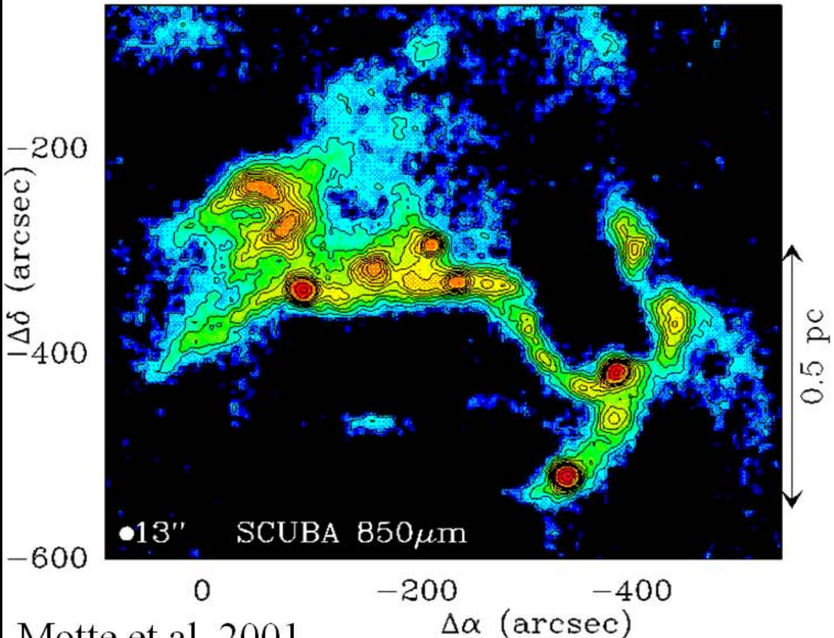
Goals

- HI represent more than 50% of MIS.
- Study the formation and structure of molecular clouds which forme in HI region.
  => **Initial conditions for stellar formation**
- Study the formation and the distribution of the cold structures that form. (pre-stellar cores)
- Understand the dynamical properties of thermally bi-stable HI flows, properties of turbulence.
- Comparison with observations

Origine de la fonction de masse initiale

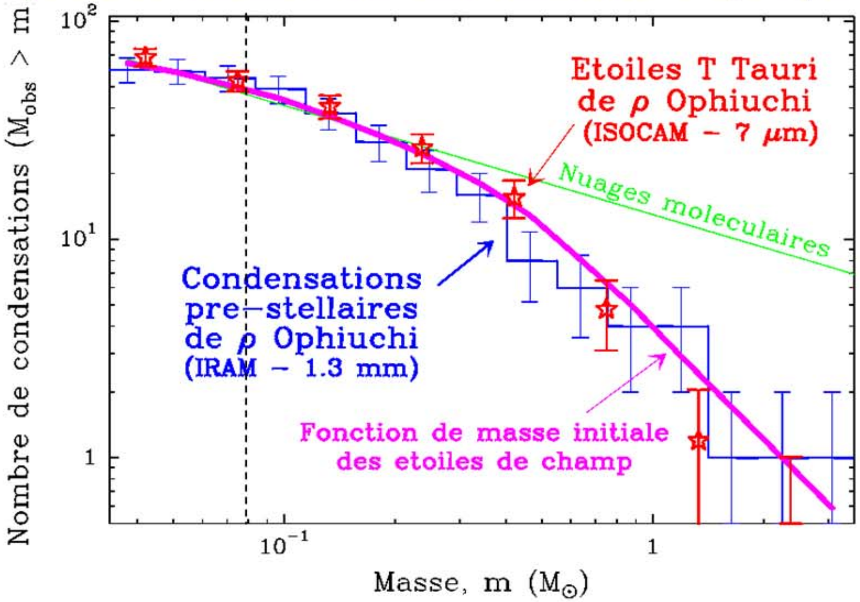
➲ La distribution de masse des condensations pré-stellaires est compatible avec « l'IMF» des étoiles

Le proto-amas NGC2068 à 850 μm



Motte et al. 2001

Spectre de masse des condensations de ρ Oph



Motte, André, Neri 1998 + Bontemps et al. 2001

- IMF principalement fixée par la fragmentation au stade pré-stellaire.

- Après la dissipation du champ magnétique et de la turbulence qui soutient à grande échelle (ou plutôt à faible densité) le nuage contre la gravité.

A simplified physical model…

Hydrodynamic with cooling and conduction

→ **no gravity, no chemistry, no magnetic fields…**

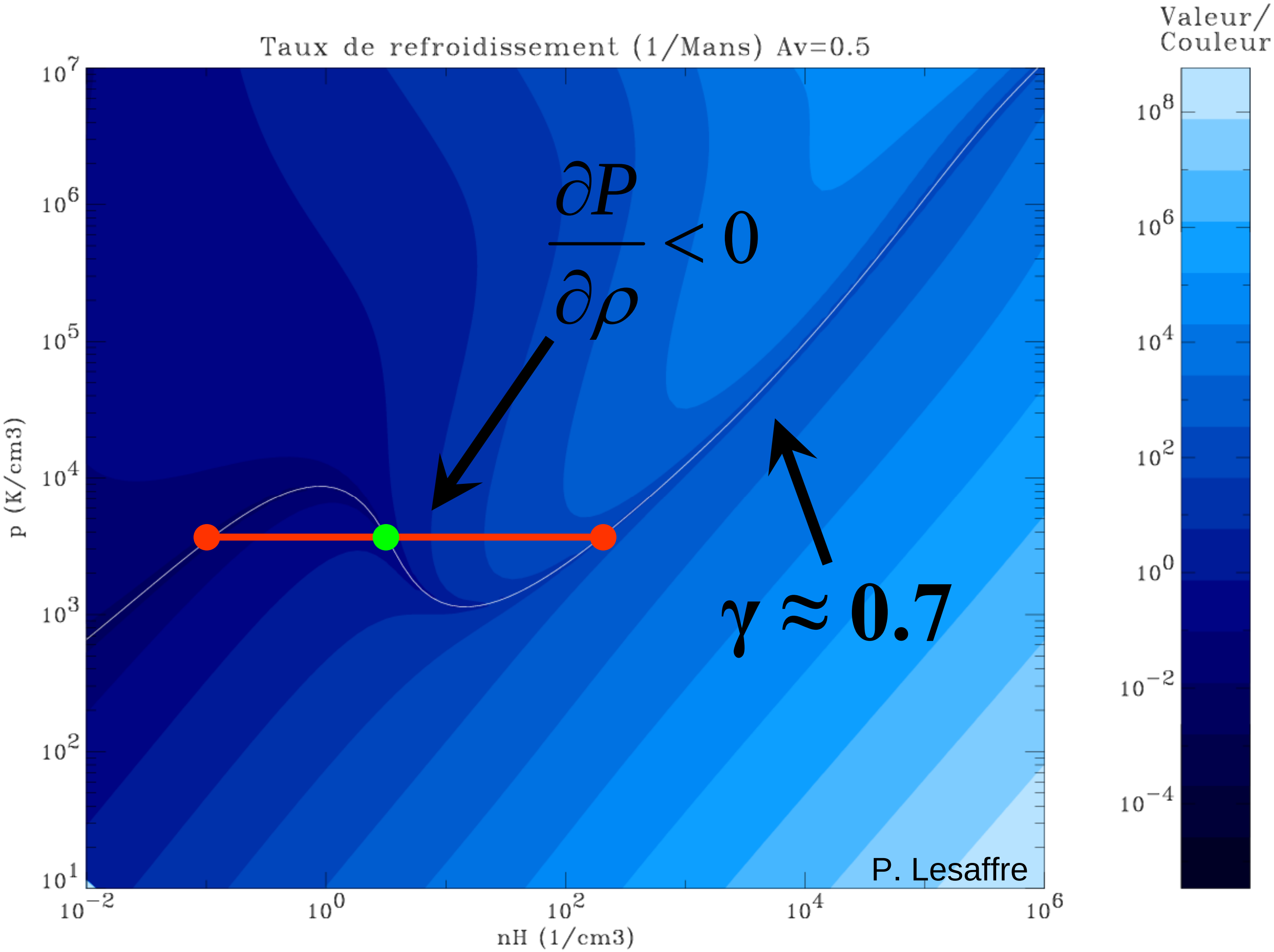
$$\partial_t \rho + \nabla.[\rho u] = 0,$$

$$\partial_t \rho u + \nabla.[\rho u \otimes u + P] = 0,$$

$$\partial_t E + \nabla.[u(E+P)] = -\mathcal{L}(\rho, T) + \nabla(\kappa(T)\nabla T)$$

The cooling function

Wolfire et al. (1995, 2003)



A Very Large Scale Dynamics

- **cooling length of the WNM** : $\tau_{cool}\, C_s \sim 10$ pc
  the length at which WNM is non-linearly unstable

- **size of CNM structures** : $\lambda_{struct} \sim \tau_{cool}\, C_s / 100 \sim 0.1$ pc
  the cooling length divided by the ratio between the density of the phases

- **size of the thermal front separating the phases** : $\sim 10^{-3}$ pc
  length over which thermal diffusion is efficient

- **size of shocked CNM** : $\lambda_{struct} / M^2 \sim 10^{-3}$ pc
  The CNM structures undergo collisions and shocks at about the sound speed of the warm phase (10 km/s)

We need a resolution of about 10^4-10^5 !

Initial conditions…

One want to resolve the small cold "*pre-stellar*" cores, but the turbulence is driven by large scale flows.

- Large scale studies of the WNM dynamics (~ 10^2-10^3 pc)

  (Gazol et al., Piontek & Ostriker 2004 …)

- Studies of the fragmentation on small scales (~ 10 pc)

  (Koyama & Inutsuka, Vazquez-Semadi et al. …)

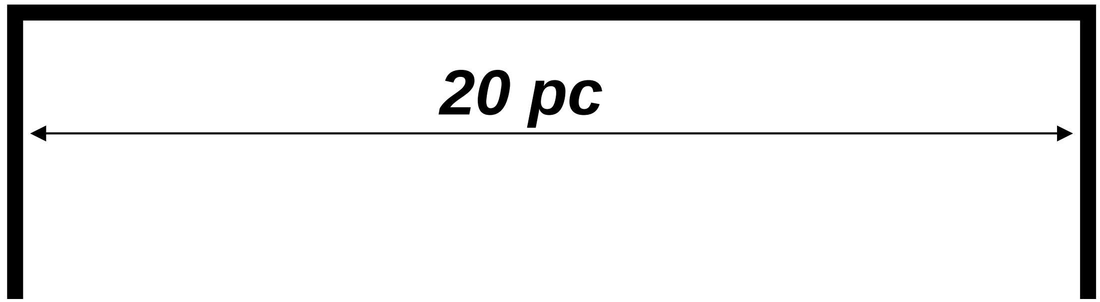
→ «*forcing*» in real space

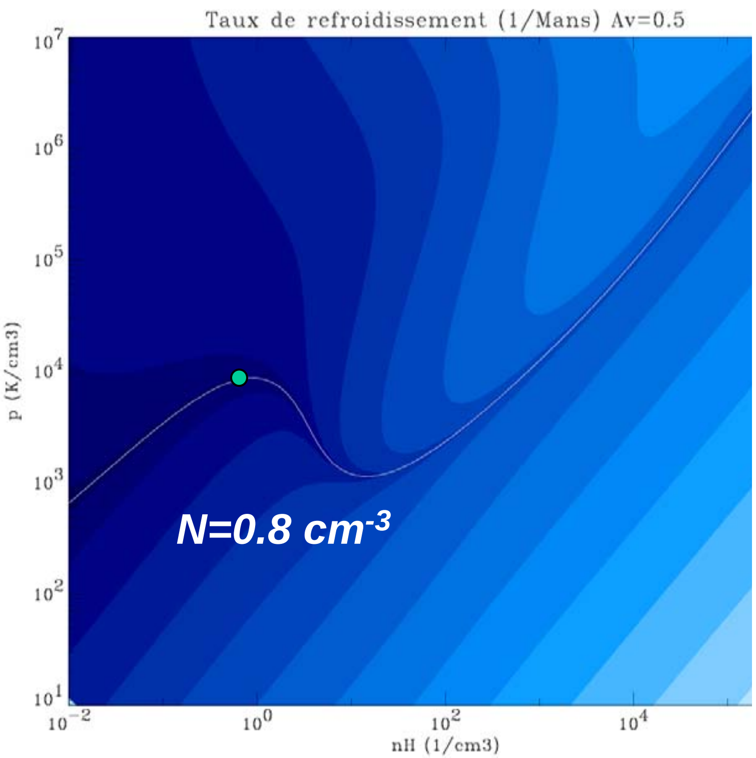
- Studies of turbulence (scale free or few pc)

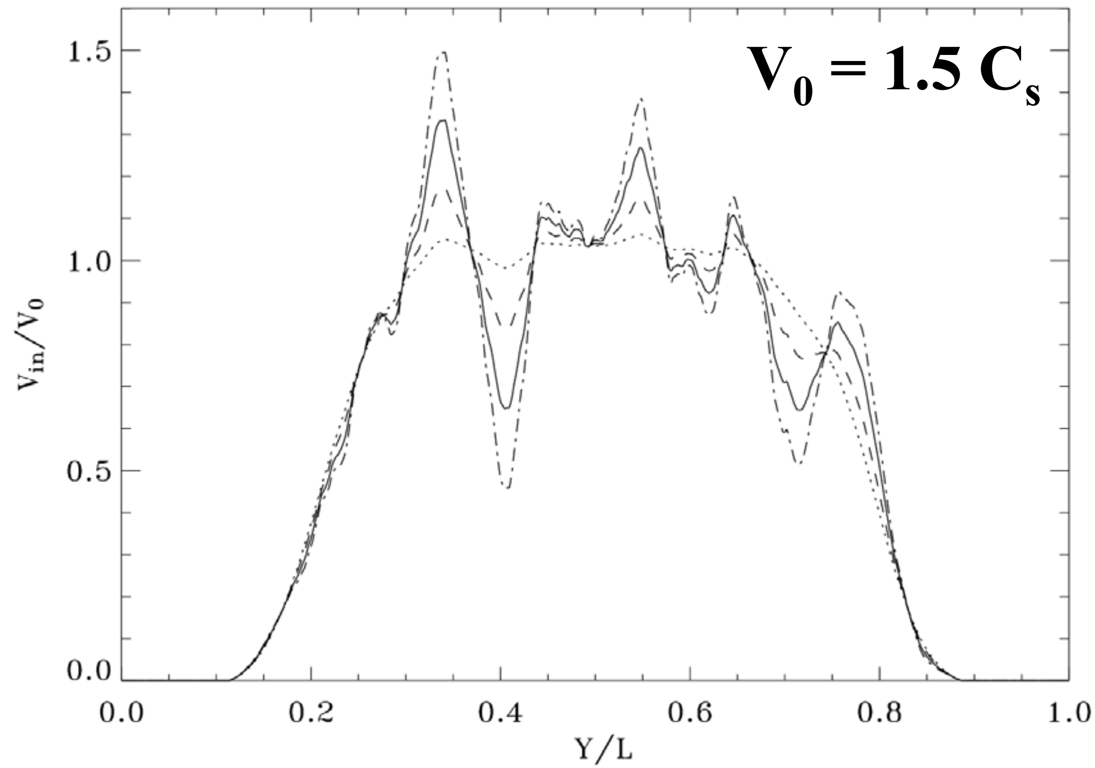
  (Kritsuk et al., Padoan et al., …)

Forcing in Fourier space or starting from unstable gaz

Initial conditions

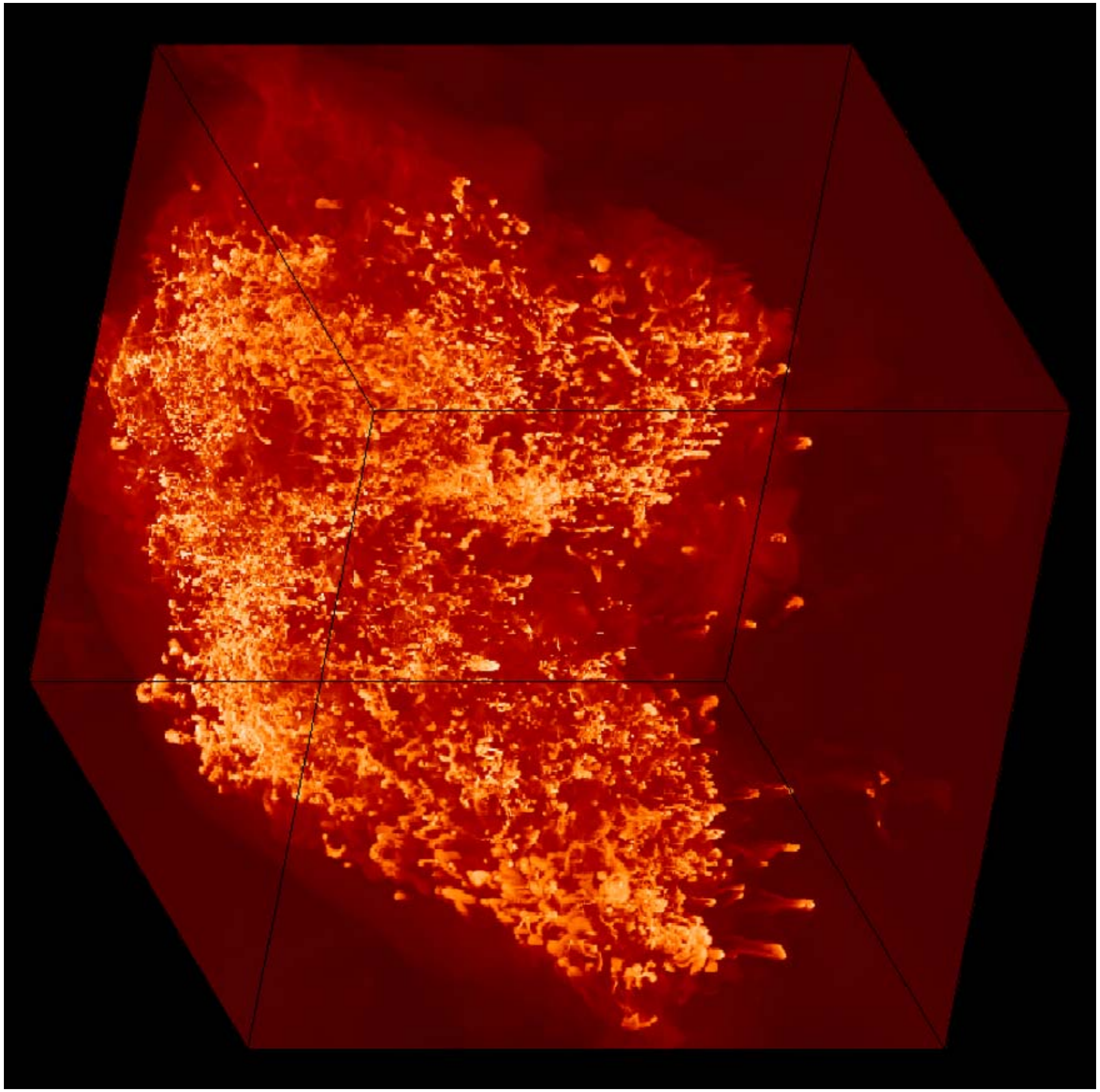




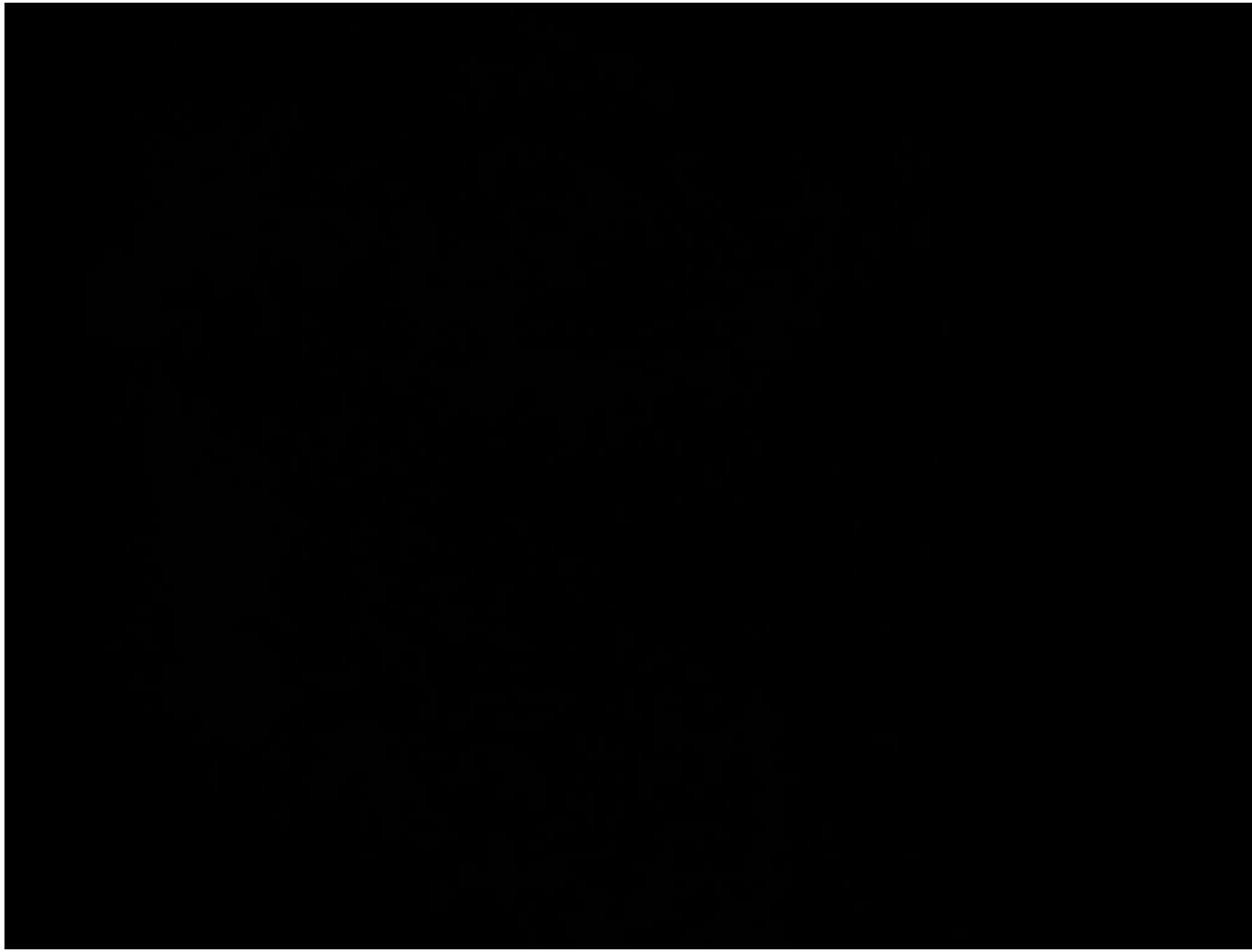


- 3 bi-stable runs with increasing turbulence
- 1 isothermal run
- 1 polytropic run γ=0.7

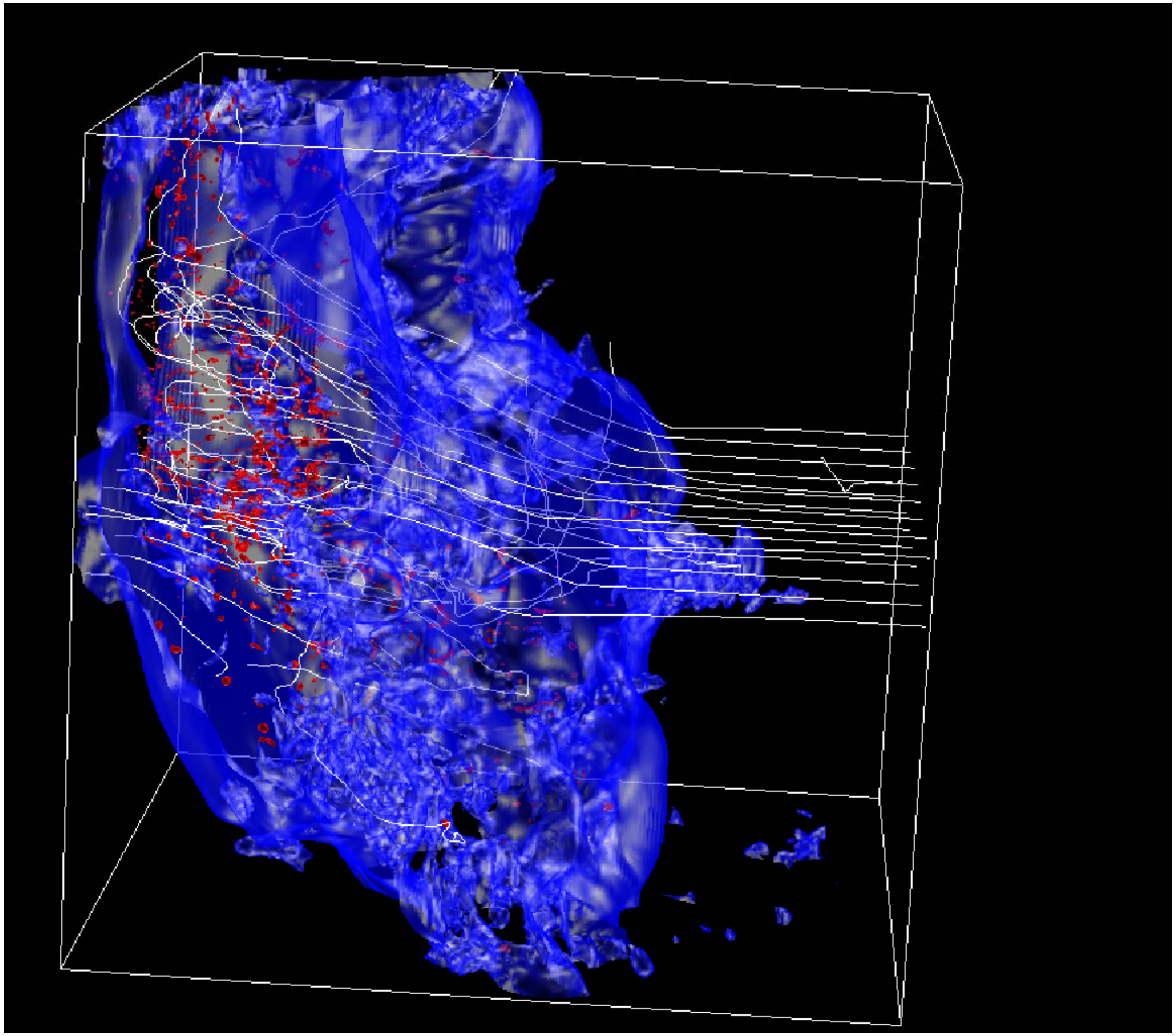
3D Simulation (1200^3)



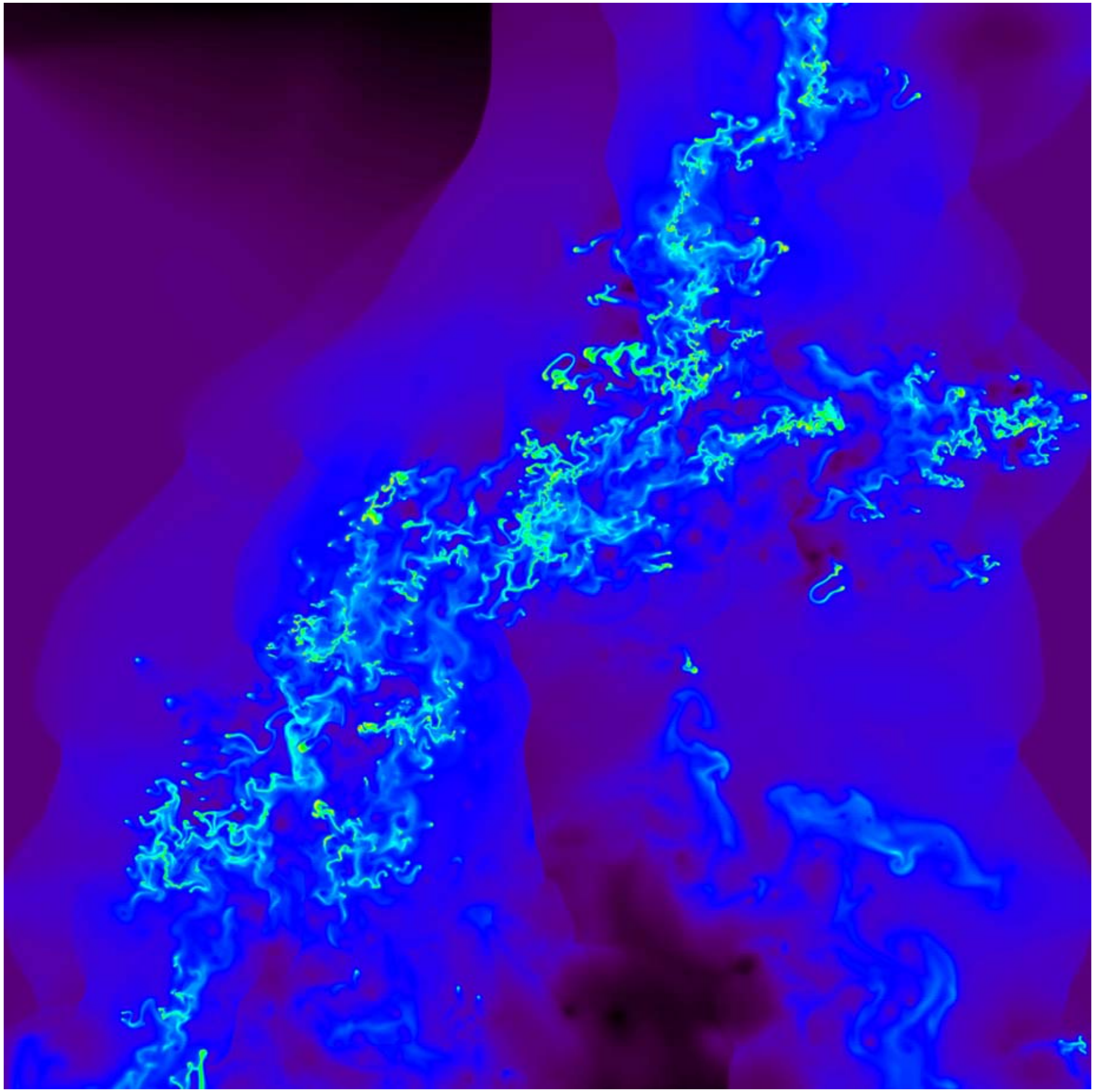
3D Simulation (1200^3)



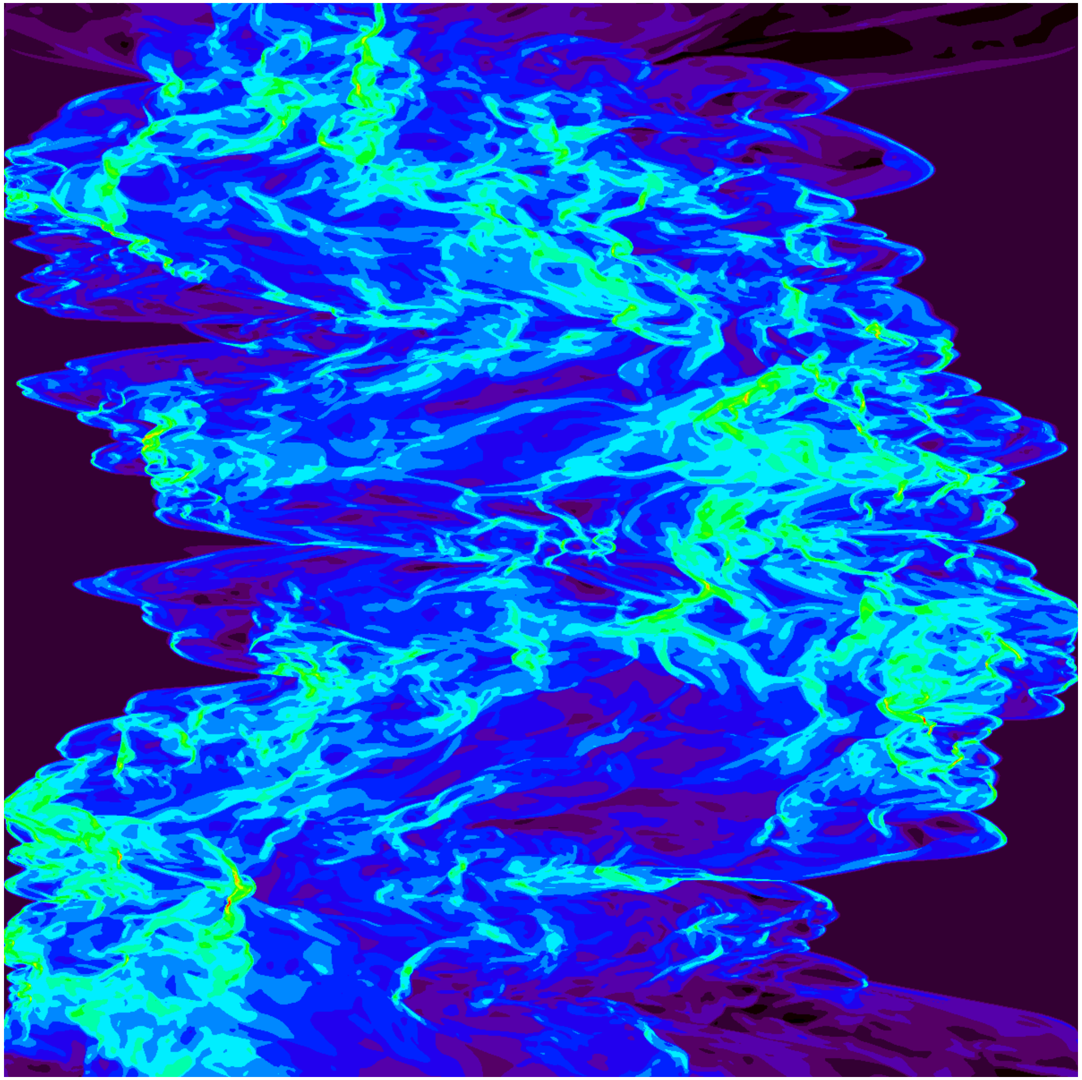
3D Simulation (1200^3)



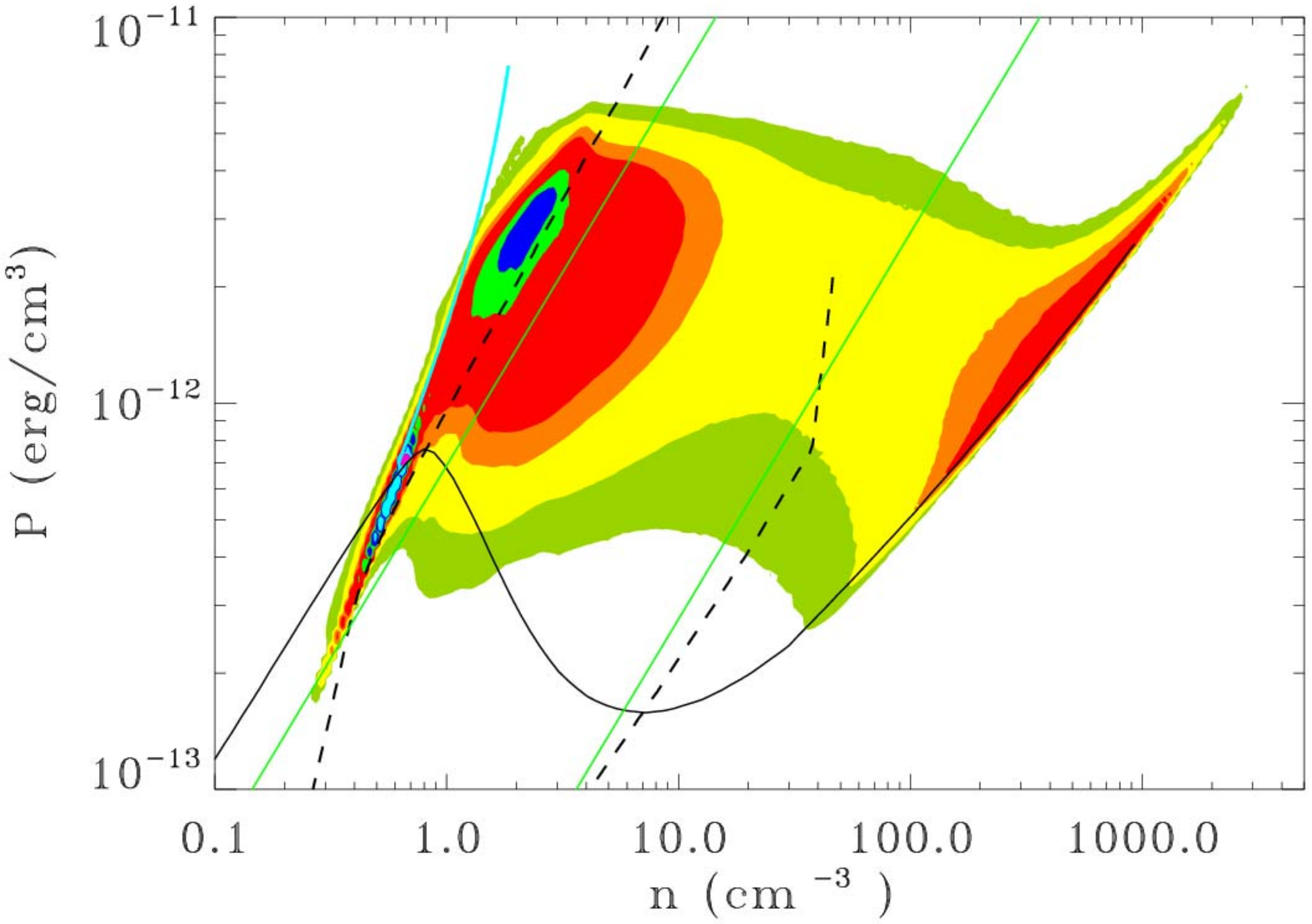
Bistable flow



Isothermal flow



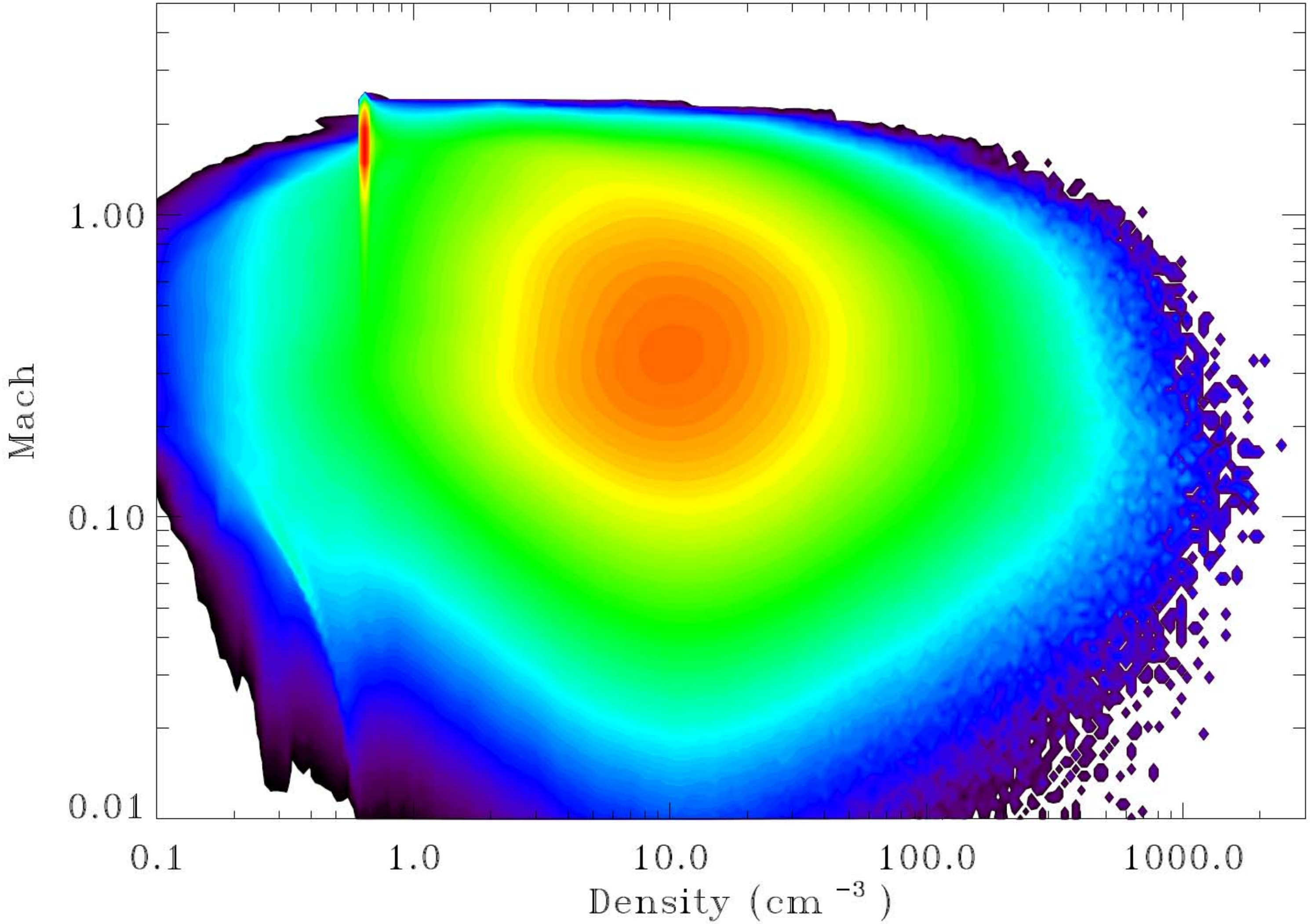
Histogram in the density-Pressure plan



Fraction of cold and unstable gaz

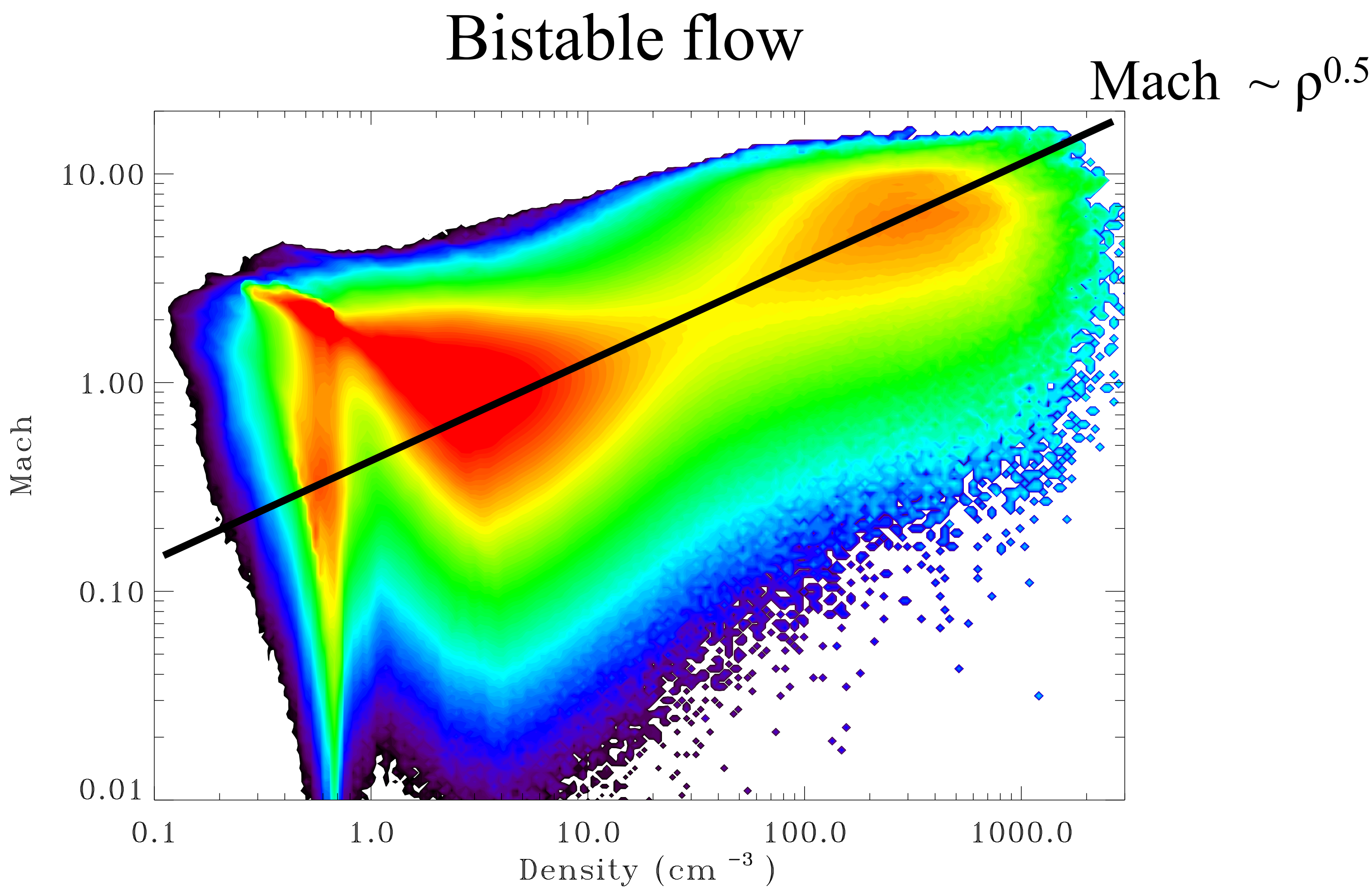
	Cold + unstable gas	Cold gas
A=1 (weakly turbulent)	0.570	0.121
A=2 (medium turbulence)	0.569	0.039
A=4 (strong turbulence)	0.358	0.002

Histogram in the Density-Velocity plan



Isothermal flow

Histogram in the Density-Velocity plan

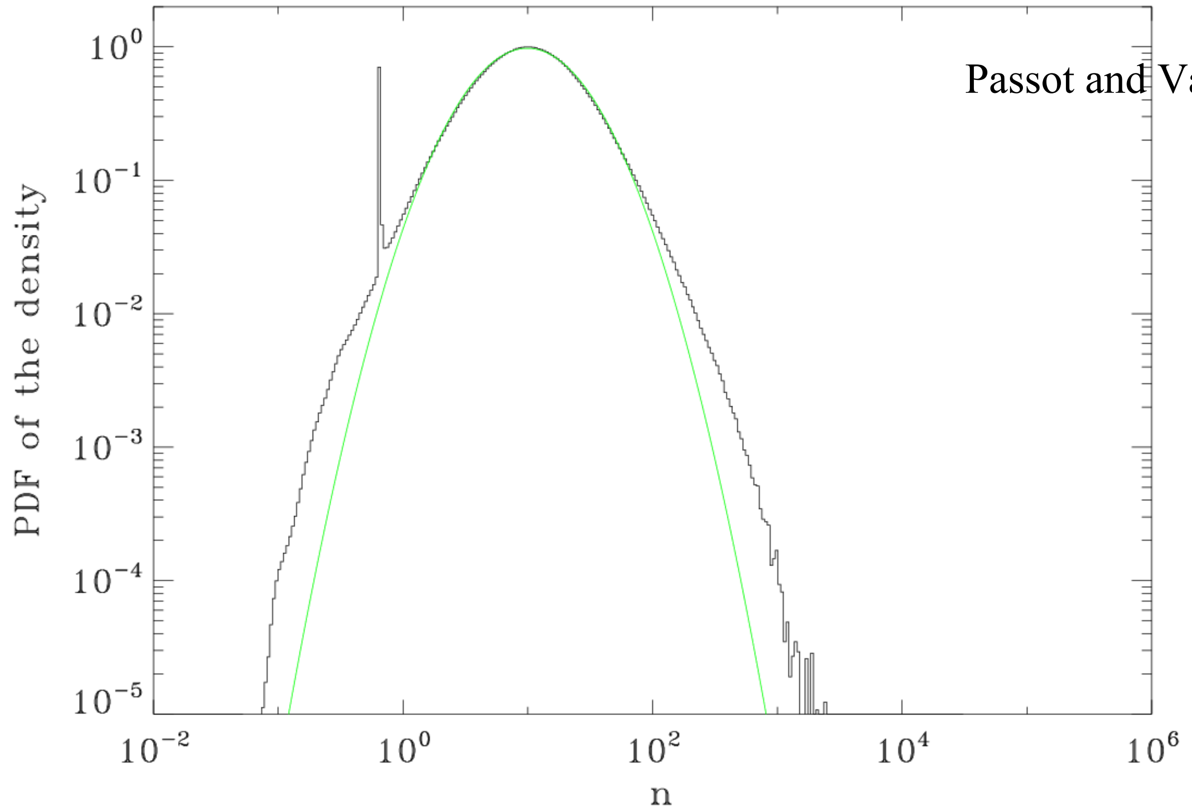


PDF of the density, isothermal flow - $\gamma = 1$

Padoan et al., 97

Passot and Vazquez-Semadeni, 98

Federrath et al., 08



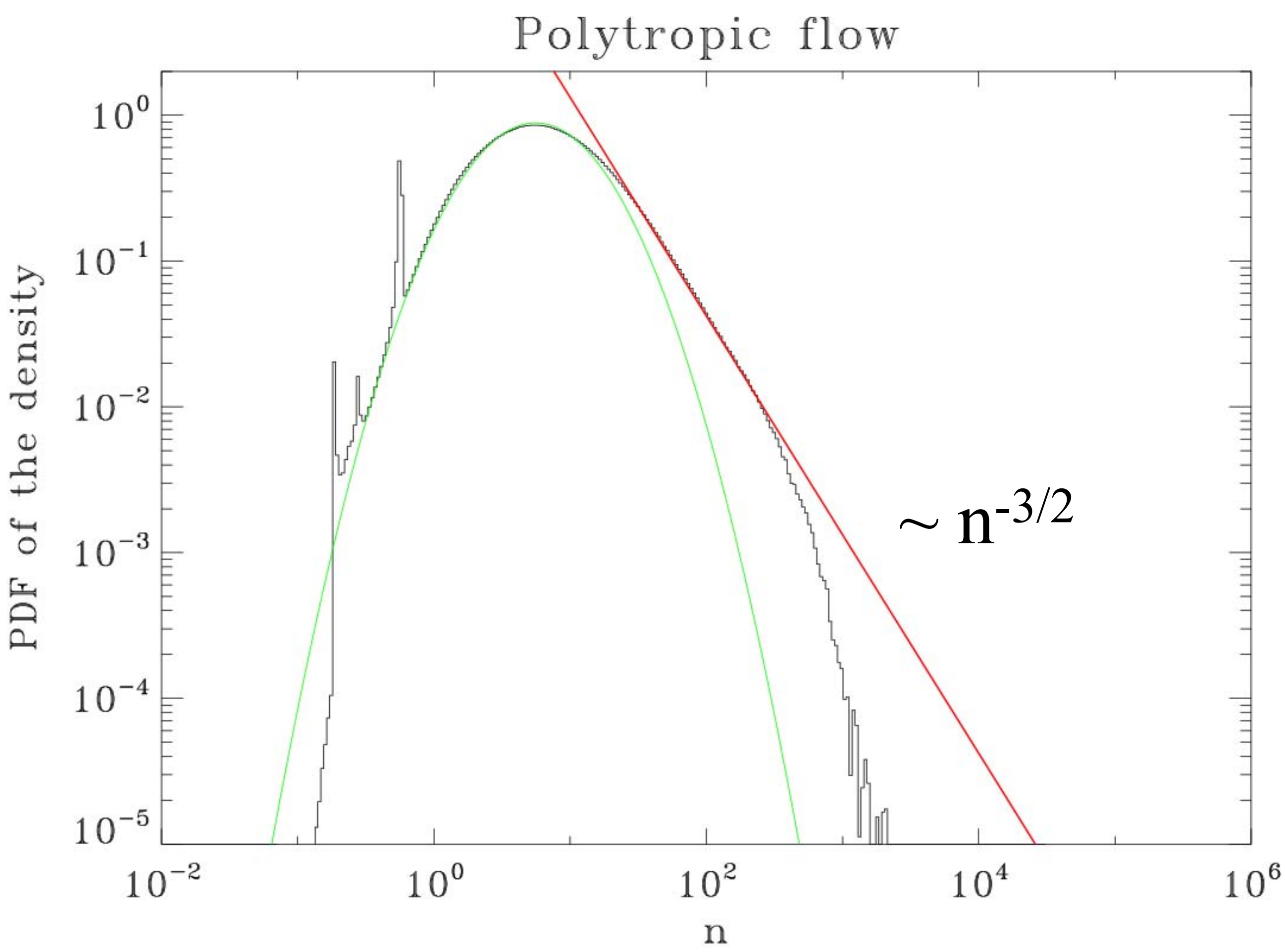
$$P(n) = \frac{a}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\ln(n) - \ln(\bar{n}) - 0.5\sigma^2)}{2\sigma^2}\right)$$

$$\sigma^2 = \ln(1 + b^2 \mathcal{M}^2)$$

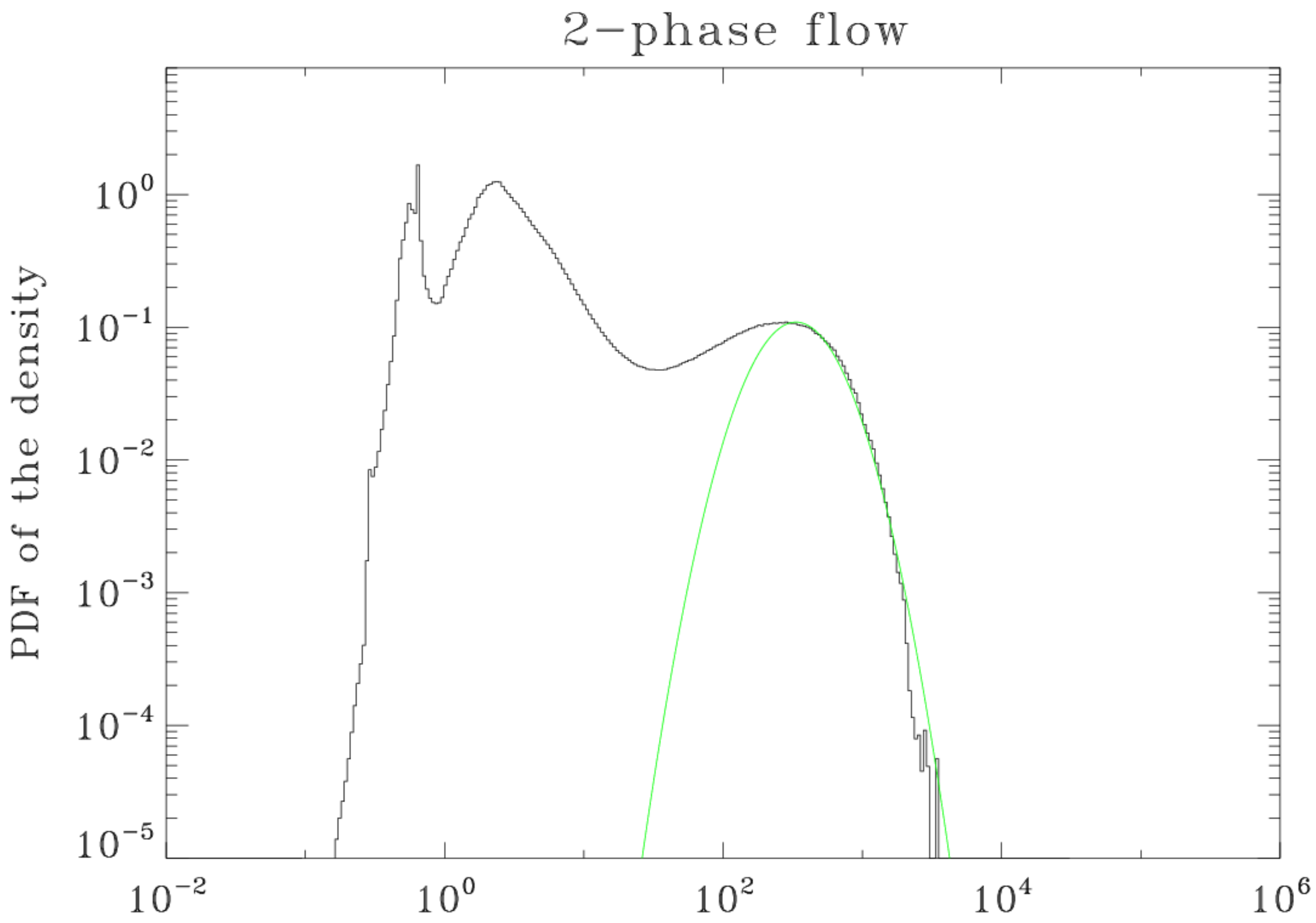
$\mathcal{M} = 3.5$ and $b = 0.33$

PDF of the density, polytropic flow - γ=0.7

Passot and Vazquez-Semadeni, 98

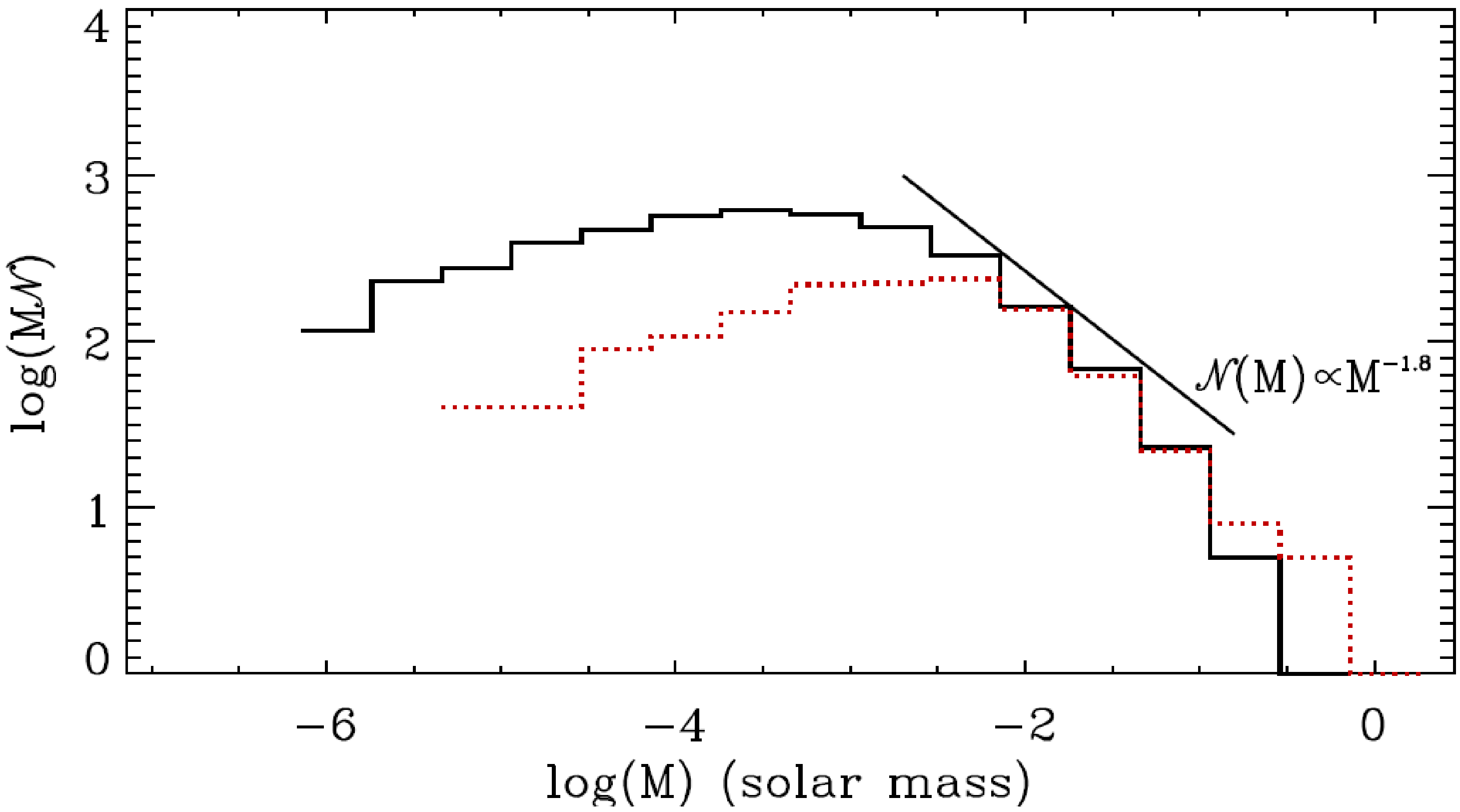


PDF of the density, 2-phase flow

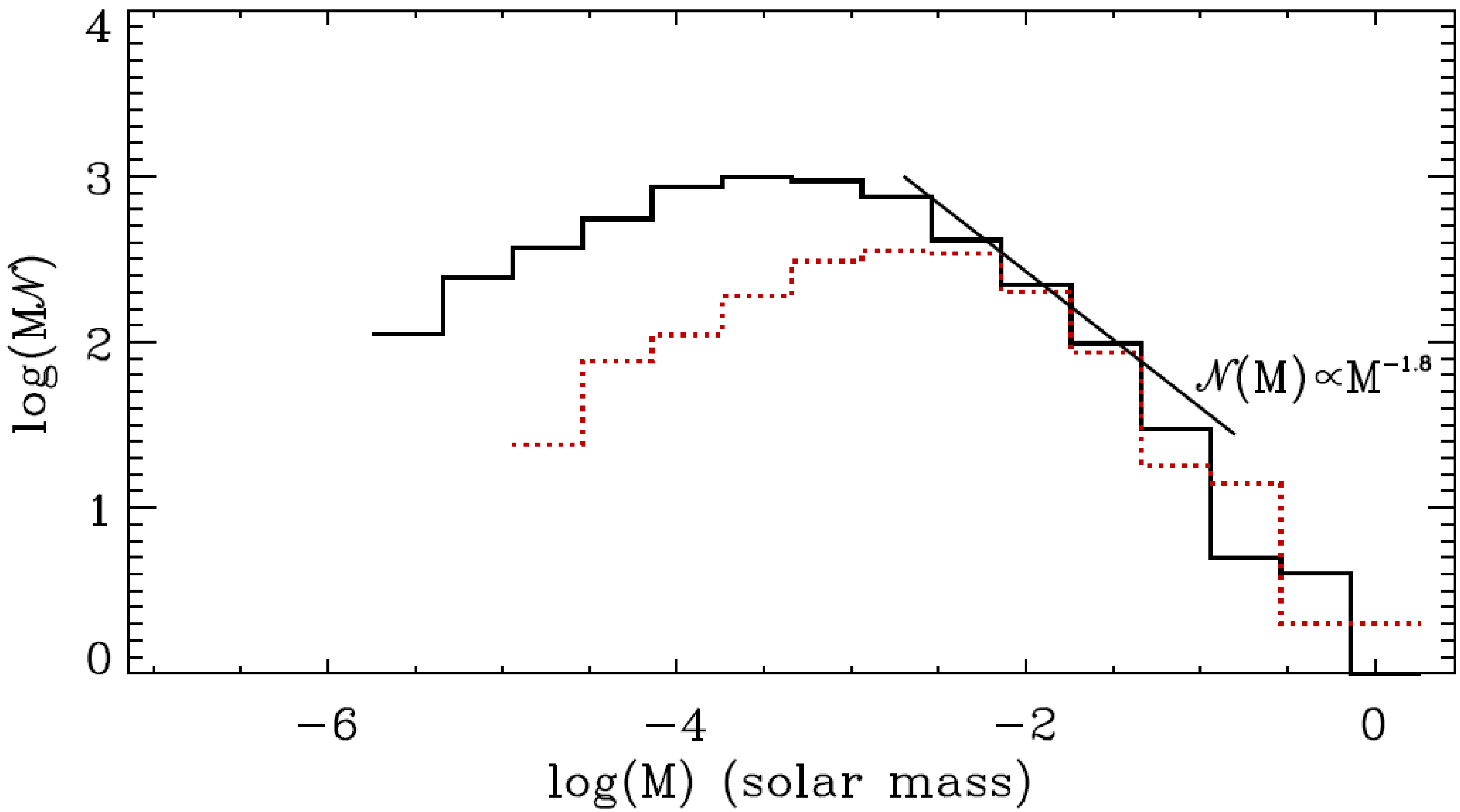


What is the proper PDF to use when modelling molecular clouds ?

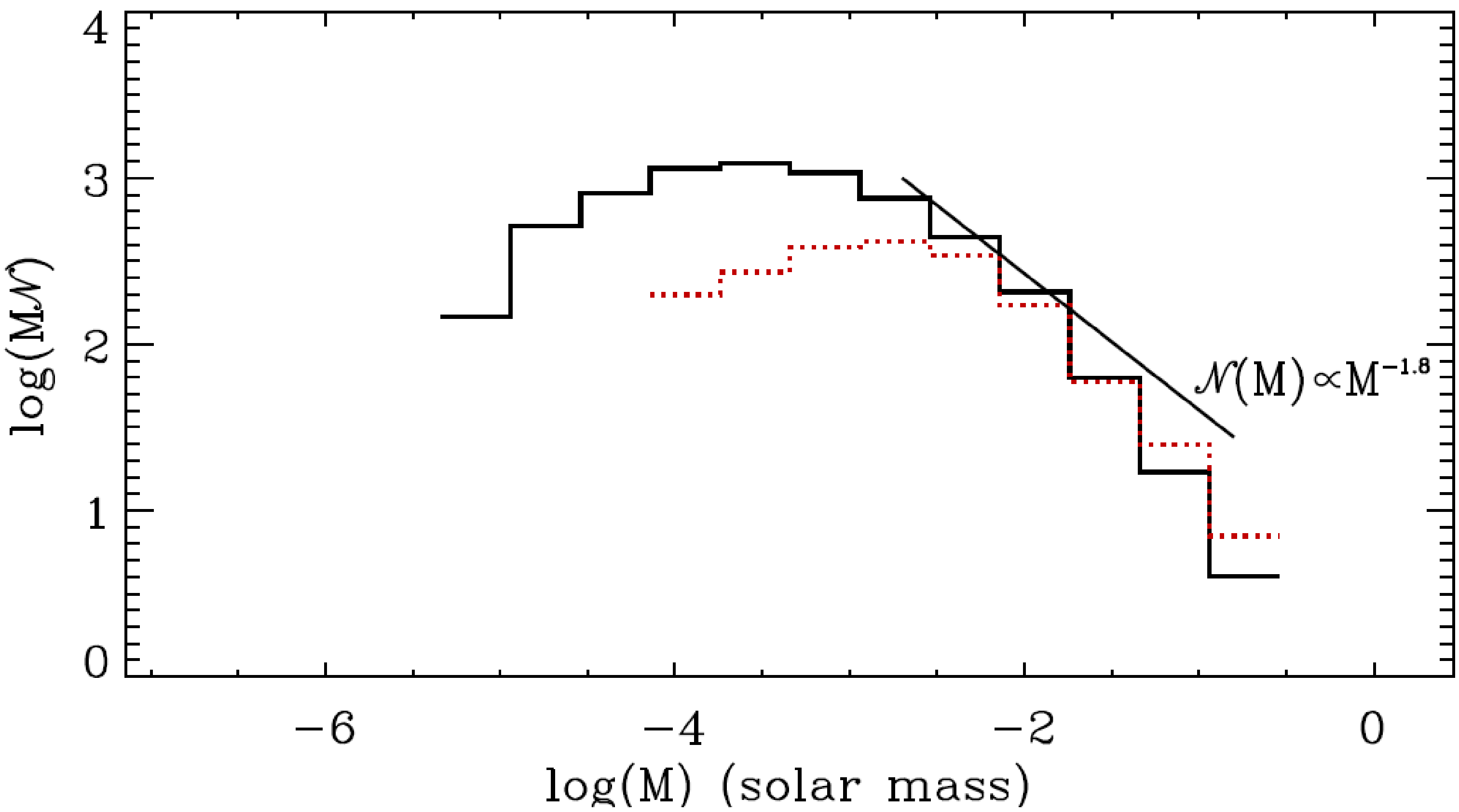
Masse spectrum, 2-phase flow, $n_c = 10 \text{ cm}^{-3}$



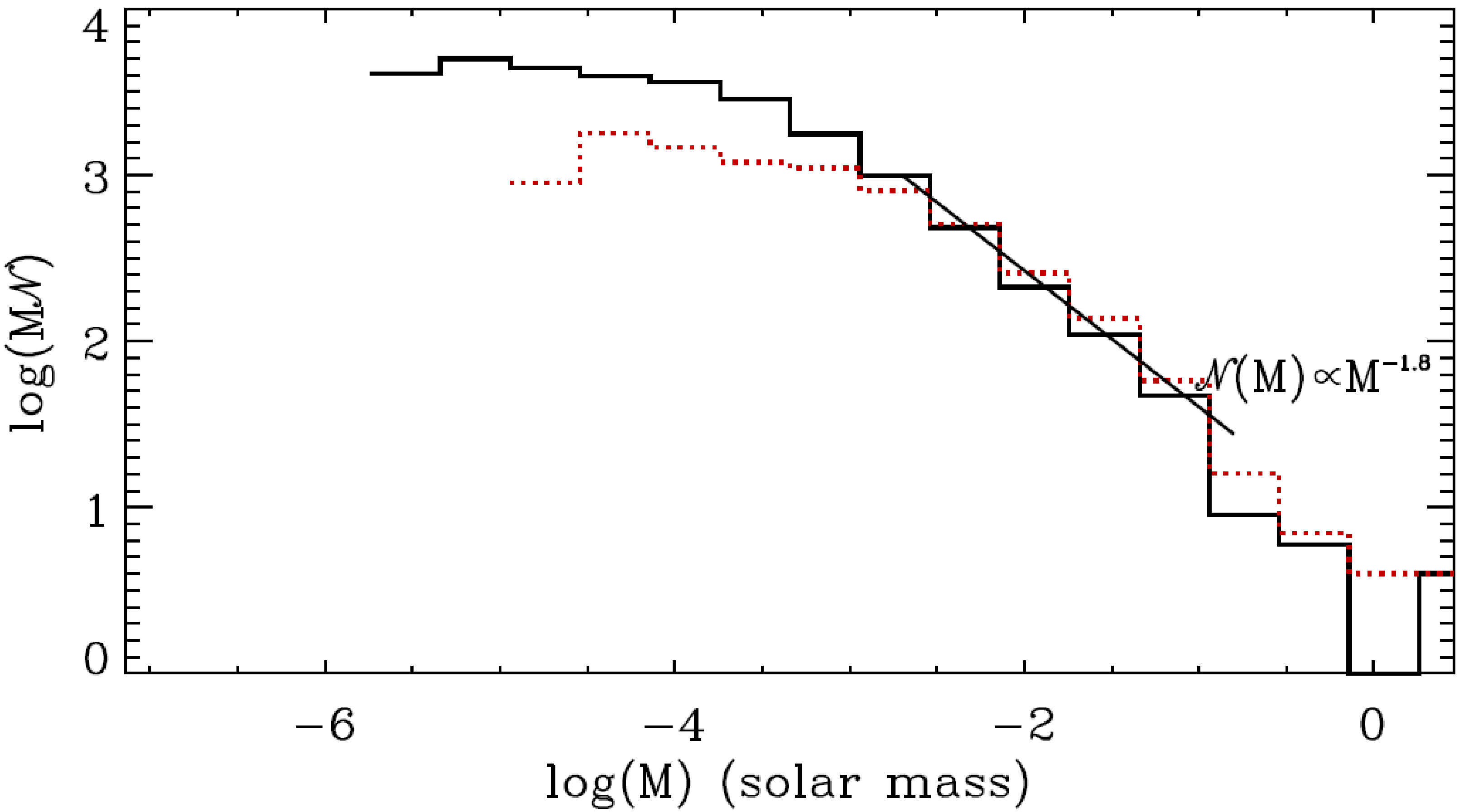
Masse spectrum, 2-phase flow, n_c = 30 cm^{-3}



Masse spectrum, 2-phase flow, $n_c = 100\ cm^{-3}$

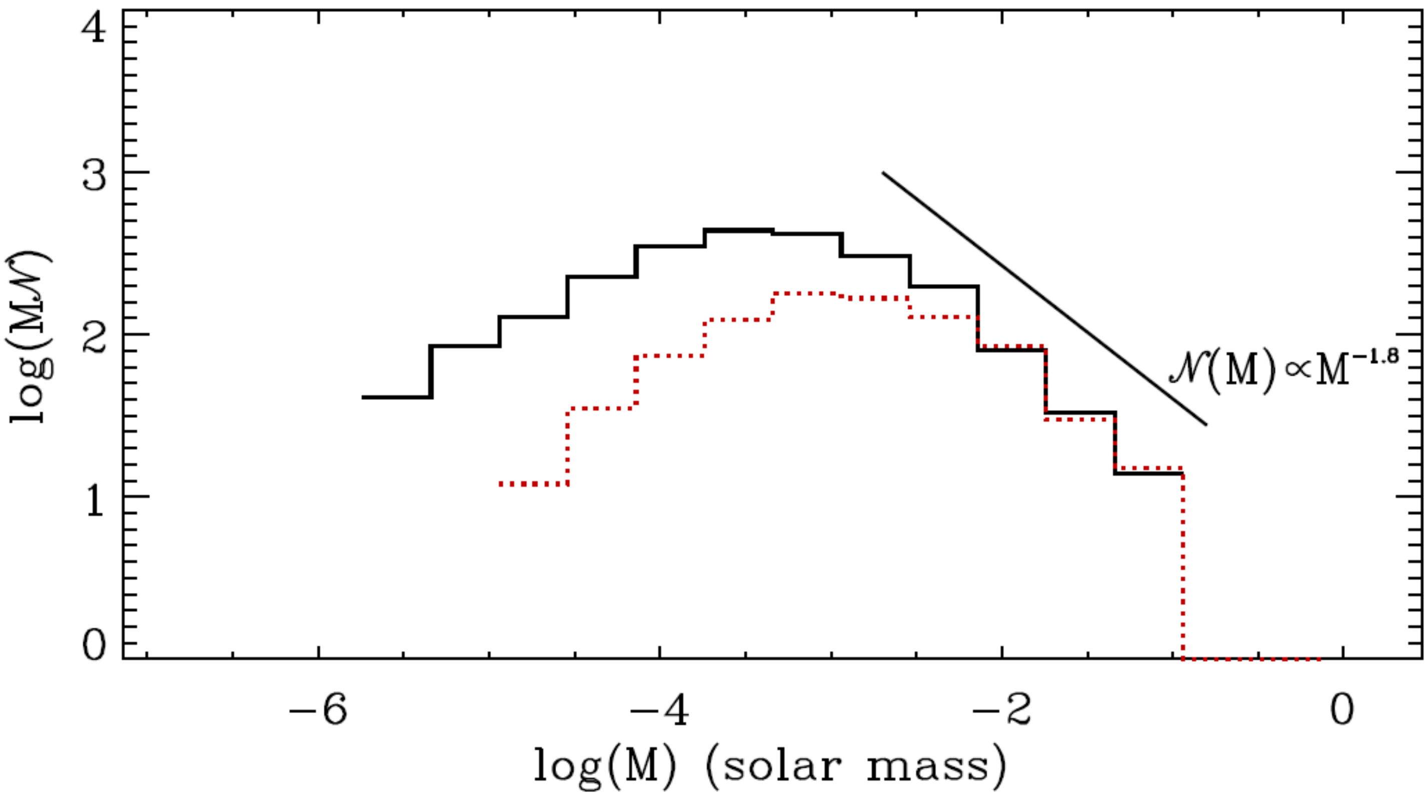


Masse spectrum, isothermal flow, $n_c = 30\ cm^{-3}$



Masse spectrum, 2-phase flow, n_c = 30 cm-3

Stronger turbulence



Mass distribution of CNM structures

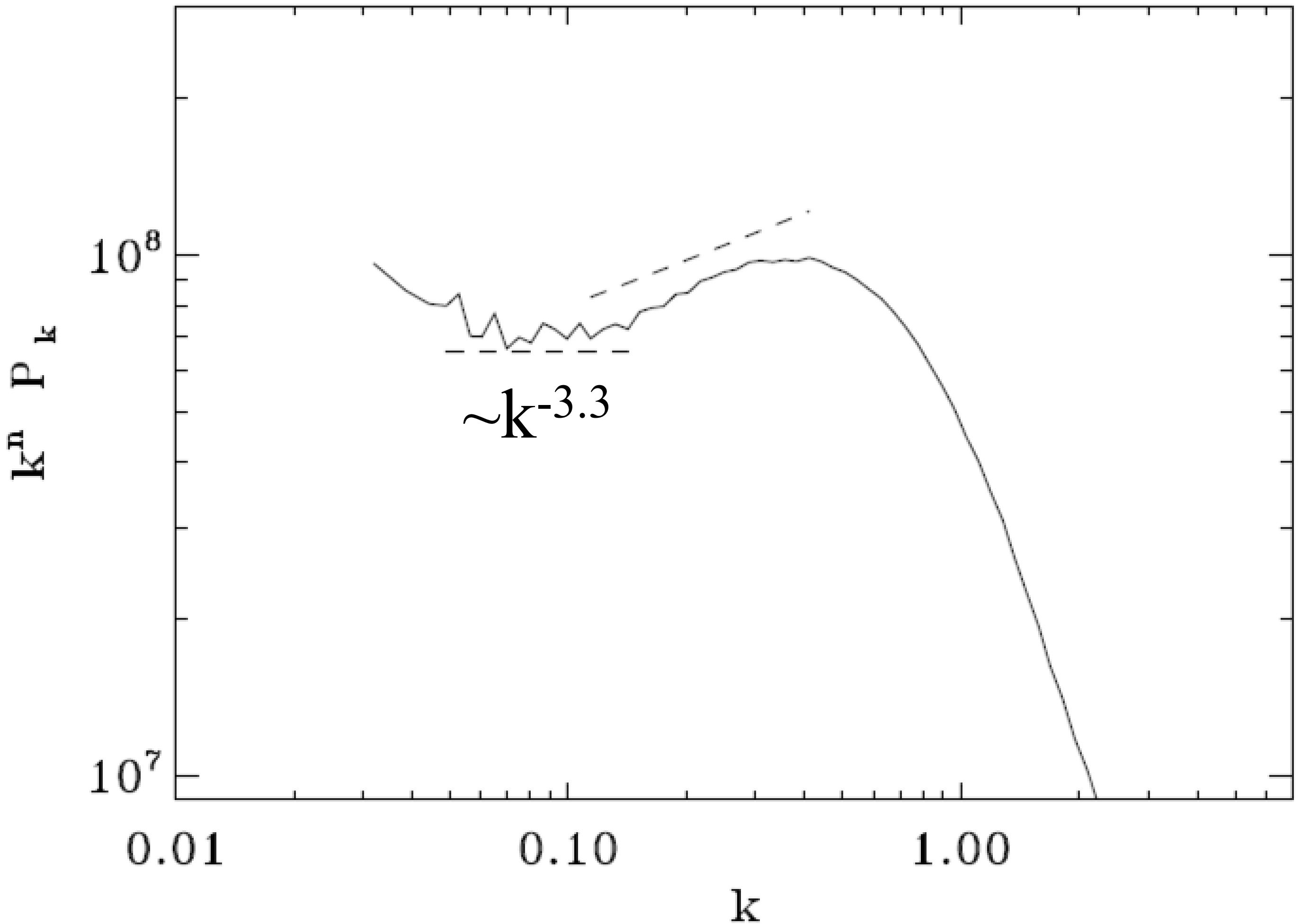
Hennebelle & Audit 07, Hennebelle & Chabrier 08, Dib et al. 08

Press et Schechter type model : $N(M) \sim M^{-16/9}$

(structures form from density fluctuations in the trans-sonic WNM)

Extension to the supersonic case : $\dfrac{dN}{dM} \propto M^{-2+\frac{n'-3}{3}}$

Power spectrum of the logarithm of the density



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(structures form from density fluctuations in the trans-sonic WNM)

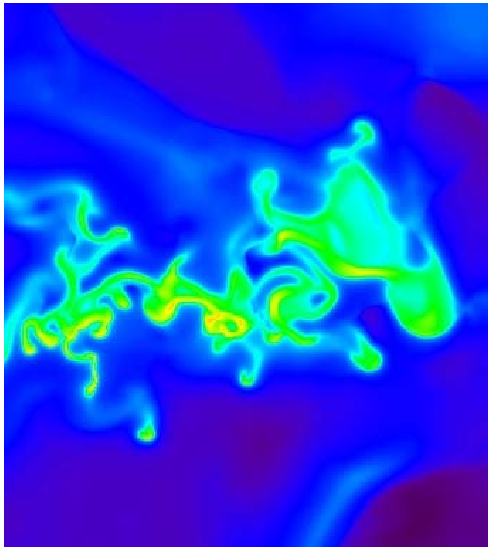
Extension to the supersonic case : $\frac{dN}{dM} \propto M^{-2+\frac{n'-3}{3}}$

$\rightarrow M^{-1.9}$

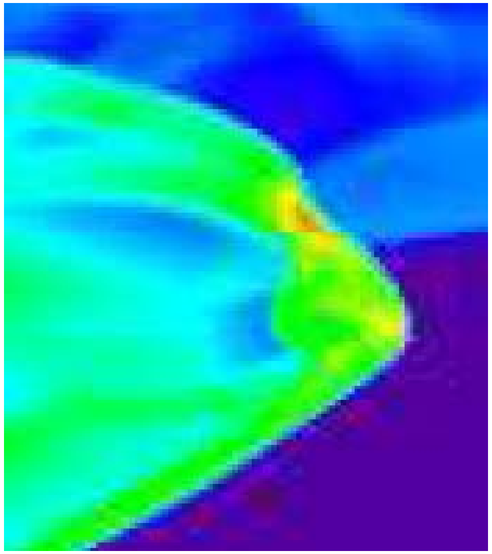
- Does not depends on the degree of turbulence
- Does not depends on the definition of structures
- Does not depends on the gas thermodynamics
- …Does not depends on the models !

Structures vs. Overdensities…

2-phase



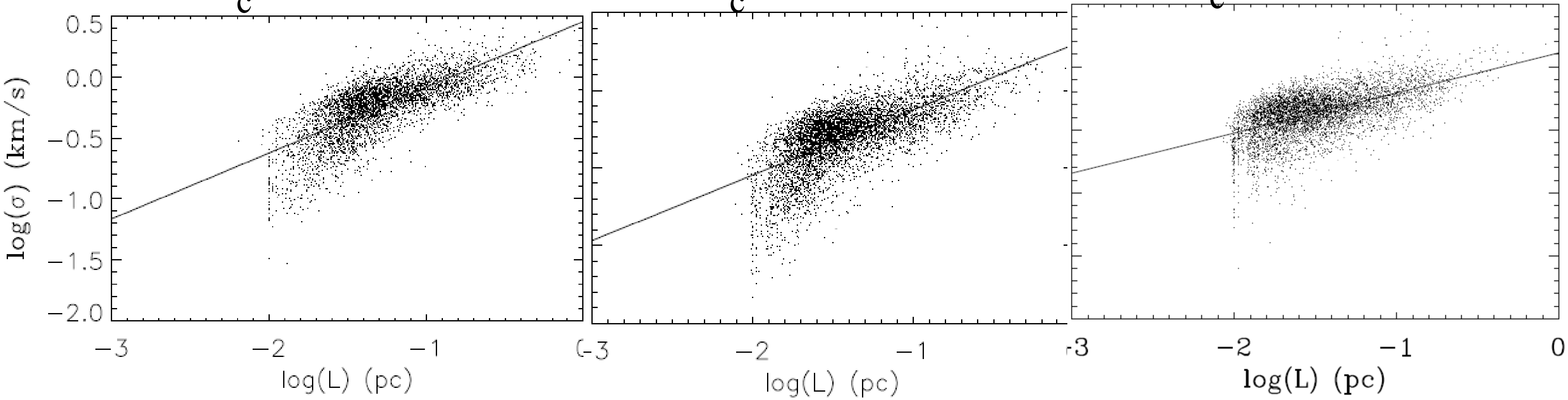
isothermal



In 2-phase flows, structures are stable, long lived, and roughly in pressure equilibrium.

Velocity dispertion vs Size

$n_c = 10\ \mathrm{cm}^{-3}$ $n_c = 30\ \mathrm{cm}^{-3}$ $n_c = 100\ \mathrm{cm}^{-3}$



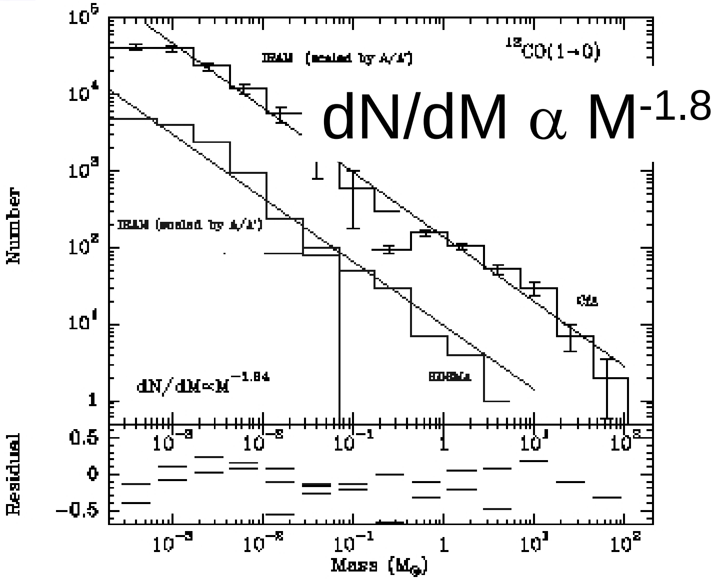
$\sigma \sim 3.3$ kms $(L/1pc)^{0.53}$ $\sigma \sim 2.0$ kms $(L/1pc)^{0.43}$ $\sigma \sim 1.2$ kms $(L/1pc)^{0.33}$

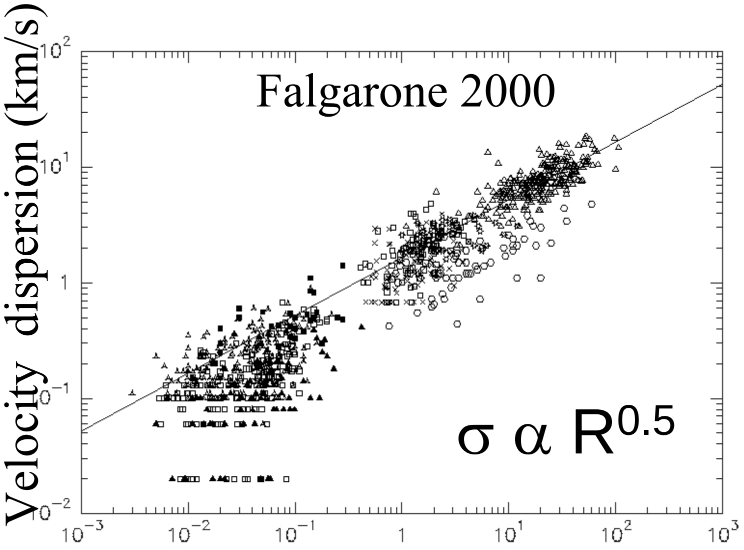
$\rightarrow n_c\ \sigma^2(L)$

Isothermal : $\sigma \sim 5.0$ kms $(L/1pc)^{0.55}$ (independant of n_c)

CO clumps $\sigma \sim 0.8$ kms ($n \sim 3000\ \mathrm{cm}^{-3}$)

Observational results





Universal Mass Spectrum
dN/dM α $M^{-1.6-1.8}$ (Heithausen et al .98)

Velocity dispersion versus
size of CO clumps

Conclusions

- Density PDF strongly depends on the thermal properties of the gas
- Dense structures formed in isothermal and bistable flow have some similar properties which are consistent with observations…
- … but they also exhibit large differences.
- Properties of turbulence strongly affected by thermal instability.
- Dependence on the forcing…?