Formation of molecular clouds, filaments and prestellar condensations

Patrick Hennebelle

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Overview

Formation of molecular clouds from diffuse gas
-observations
-2-phase turbulence
-formation of molecular clouds from diffuse gas
-statistics
-star formation

Formation of filaments and cores within molecular clouds
-by pure MHD turbulence
-by turbulence but selected by gravity
-by pure gravity
-a fully gravo-turbulent picture

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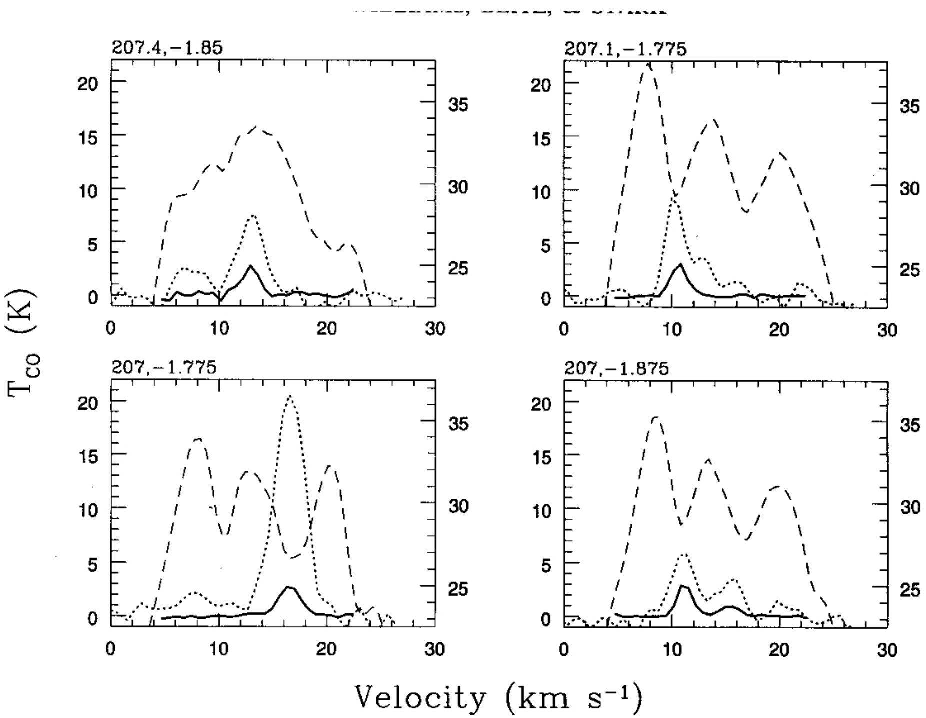
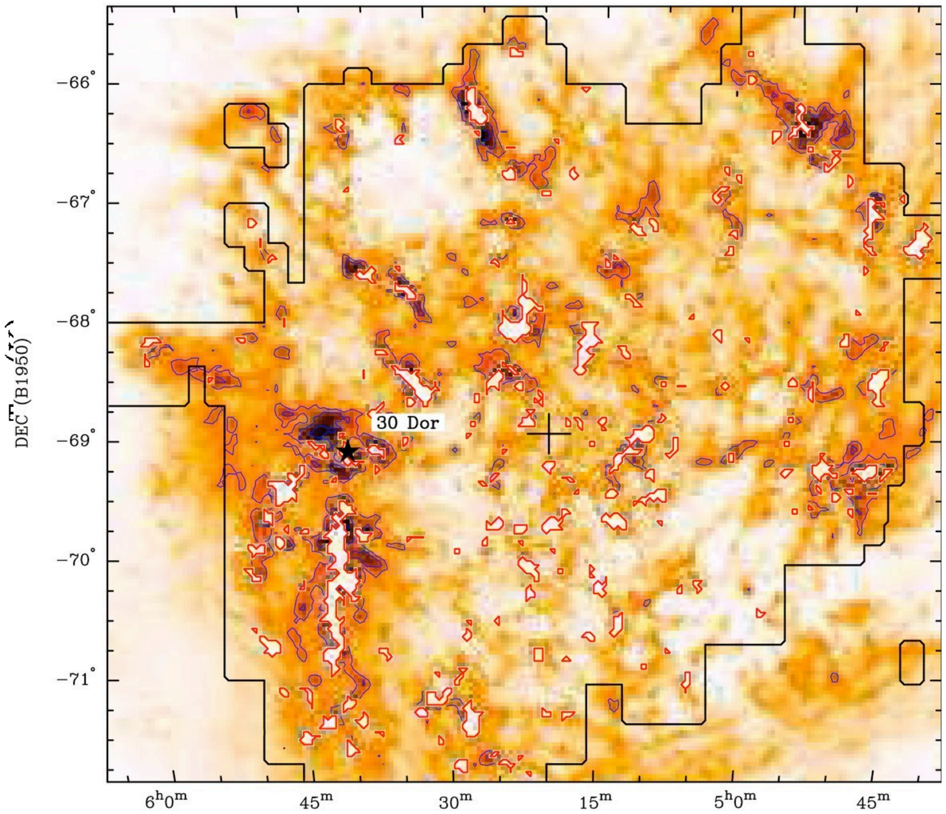
Tight correlation between HI and CO



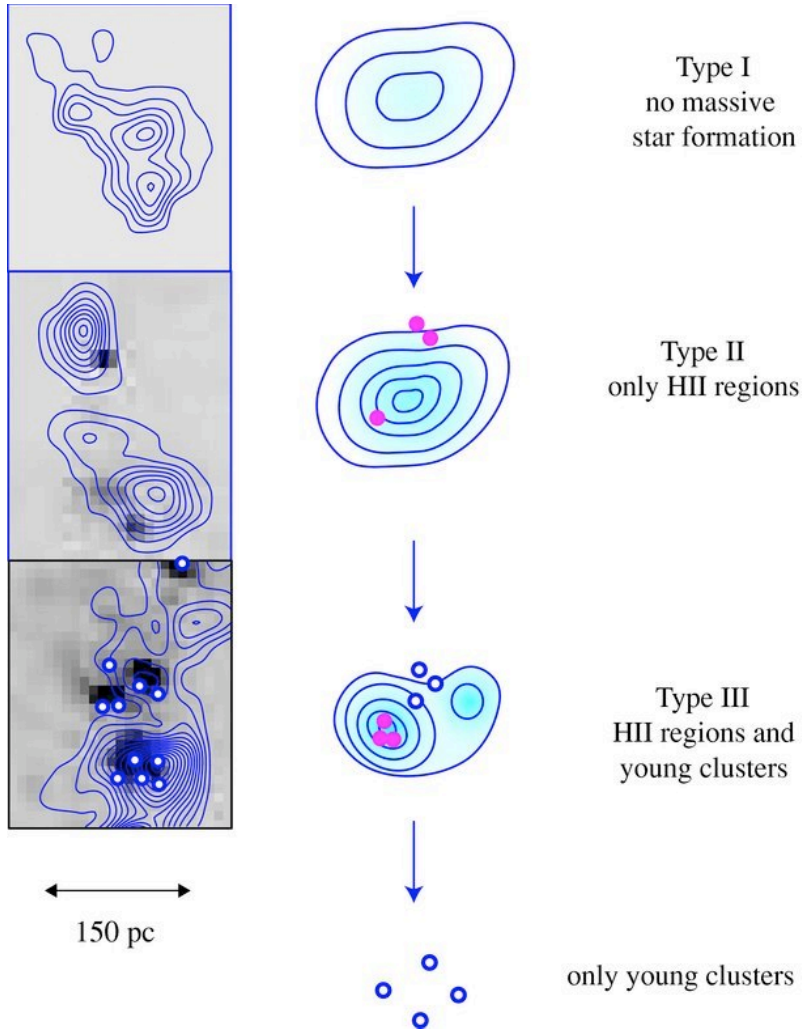


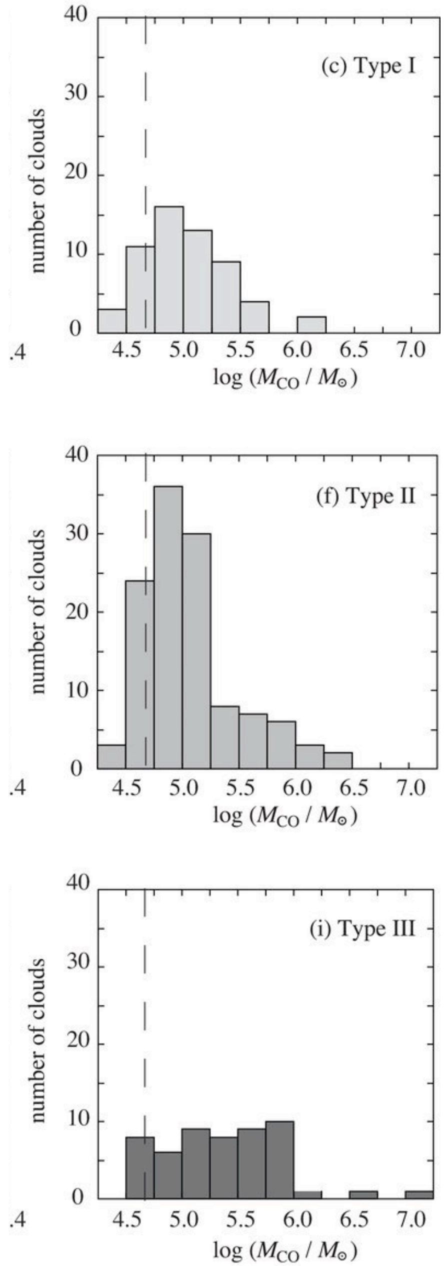
Williams, Blitz and Stark 1994
Infer a close anti-correlation between HI and CO emission in the Rosette MC

Wong et al. 2009: correlation between HI and CO in the LMC (second Nanten survey)

CO peak always associated with HI but HI not always associated to CO.

Molecular clouds in the LMC (Blitz et al. 07, Kawamura et al. 09, Fukui & Kawamura 2010)
An evolutionary sequence ?





=> accretion rate onto GMC: few times $10^{-2}M_*/yr$?

Formation of molecular clouds from diffuse HI

Molecular clouds form out of the HI and are surrounded by an HI halo

=>Suggest that connecting MC and HI spatially and temporally could be important

Attempt to form MC starting from atomic gas is important :

-self-consistent way of generating structures within the cloud

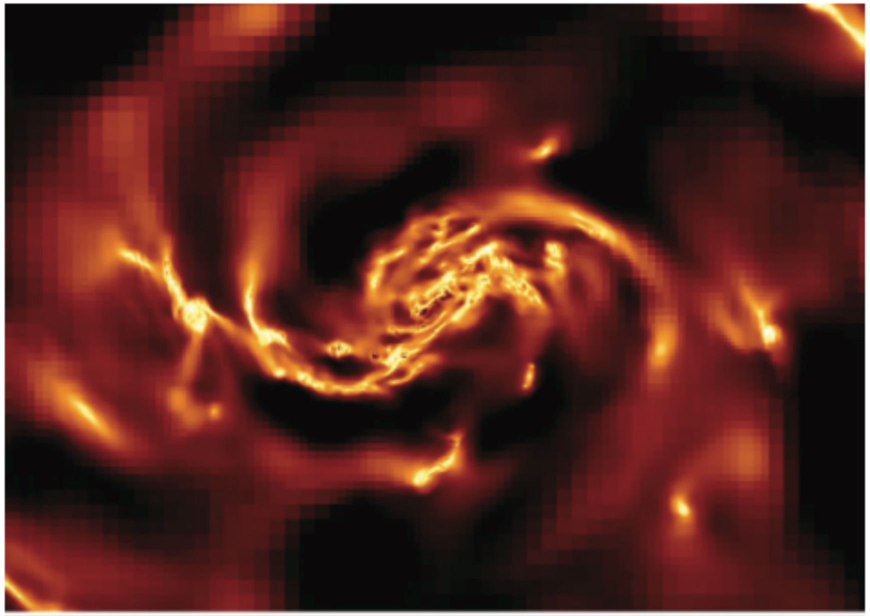
-self-consistent energy input from the outside

(non star forming cloud have a significant amount of turbulence)

At large scales, from the galactic disk: de Avillez & Breitschwert 05, Young & MacLow 06, Dobbs et al. 06, 08, Tasker & Tan 09, Bournaud et al. 08

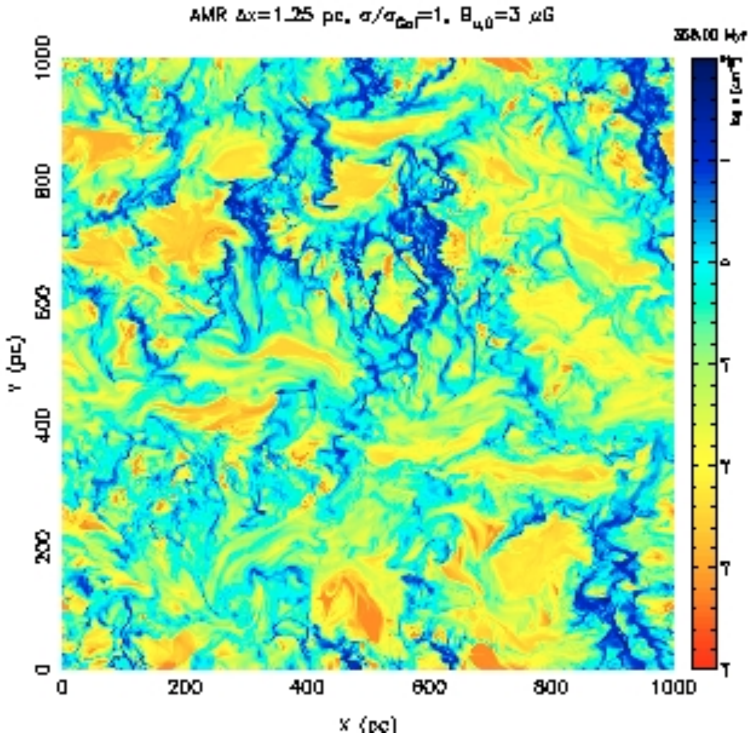
Focussing on a single cloud: Vazquez-Semadeni et al. 2007, 2011, Hennebelle et al. 2008, Banerjee et al. 2009, Heitsch et al. 2008, Inoue et al. 2009

Simulating whole galaxies



Bournaud et al. 2010

Simulating parts of galaxies



de Avillez 2005

In all cases the dense from by condensation of the diffuse gas

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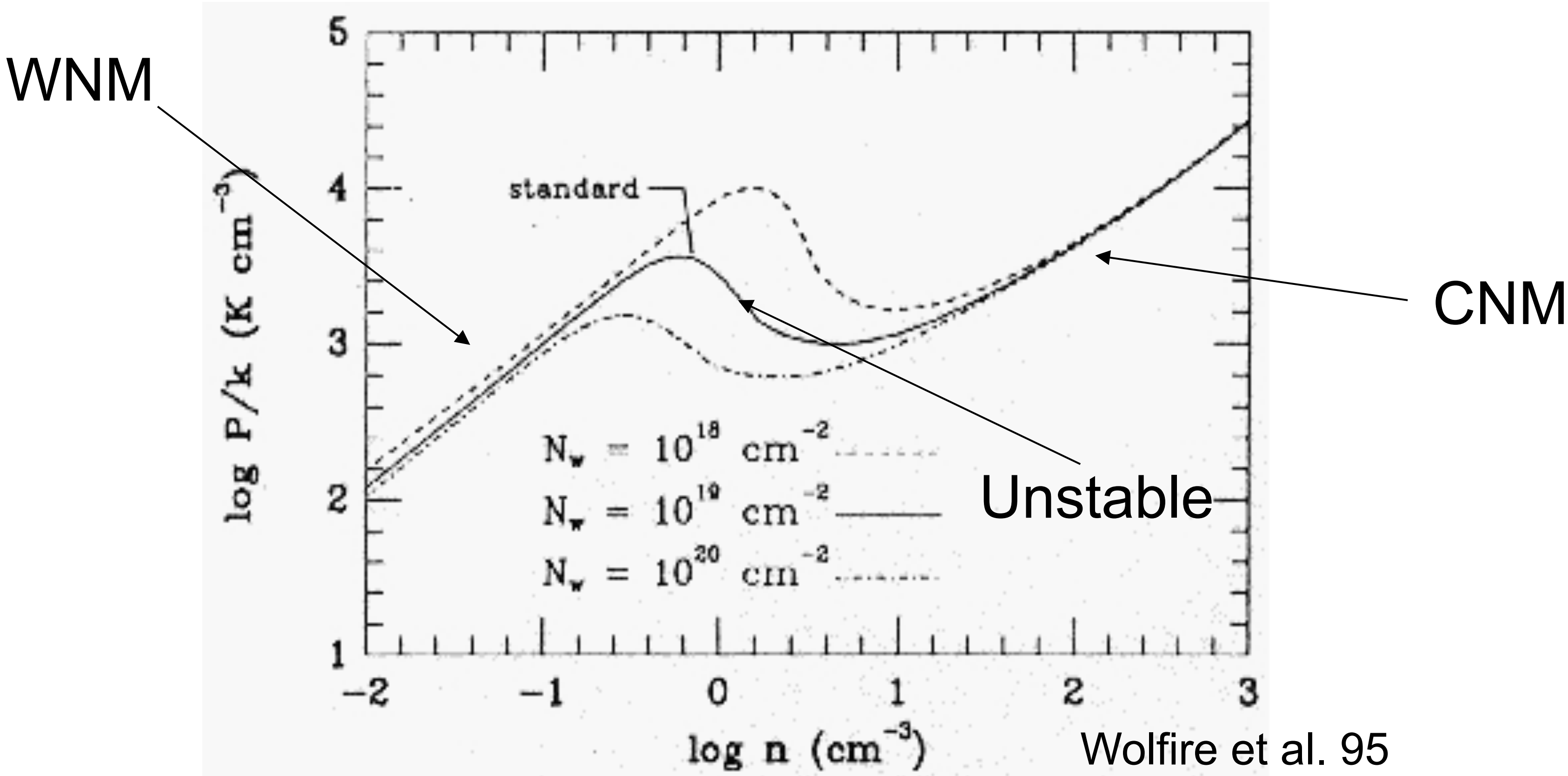
2-phase structure of the ISM

Thermal equilibrium curve (Field et al. 69, Wolfire et al. 95)



Wolfire et al. 95

Field 65: performs linear stability analysis of the radiatively cooling fluid equations. Obtains the isobaric criteria for instability:

$$\left.\frac{\partial P}{\partial \rho}\right)_{L=0} \le 0$$

Thermal transition induced by the propagation of a shock wave

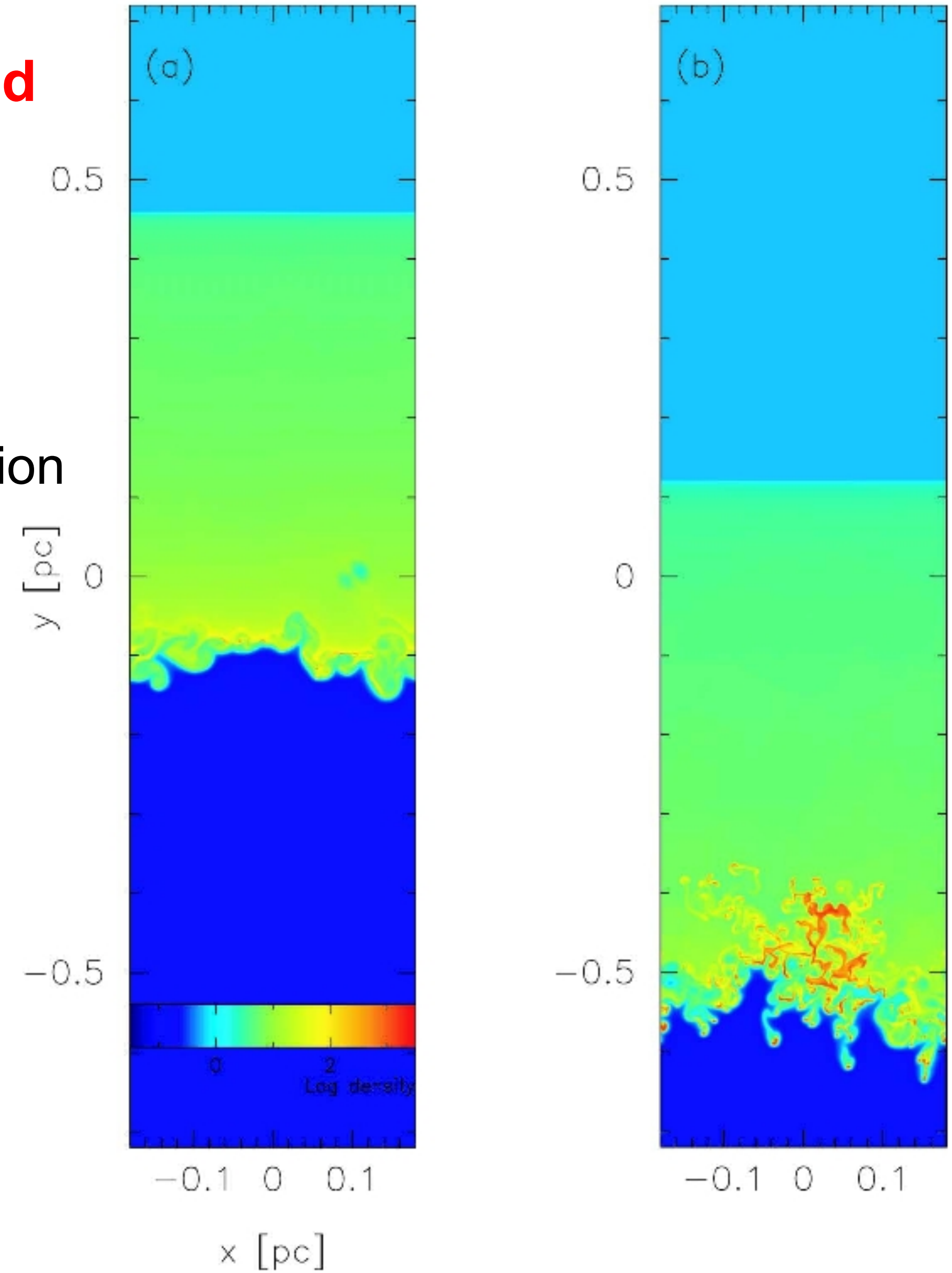
(Koyama & Inutsuka 02)

2D, cooling and thermal diffusion

The shock is unstable and thermal fragmentation occurs.

The flow is very fragmented
Complex 2-phase structure

The velocity dispersion of the fragments is a fraction of the WNM sound speed.



Turbulence within a bistable fluid

(Koyama & Inutsuka 02,04, Kritsuk & Norman 02, Gazol et al. 02, Audit & Hennebelle 05, 07, 10, Heitsch et al. 05, 06, 08, Vazquez-Semadeni et al. 06, 07)

-Forcing from the boundary

-Statistical stationarity reached

-complex 2-phase structure

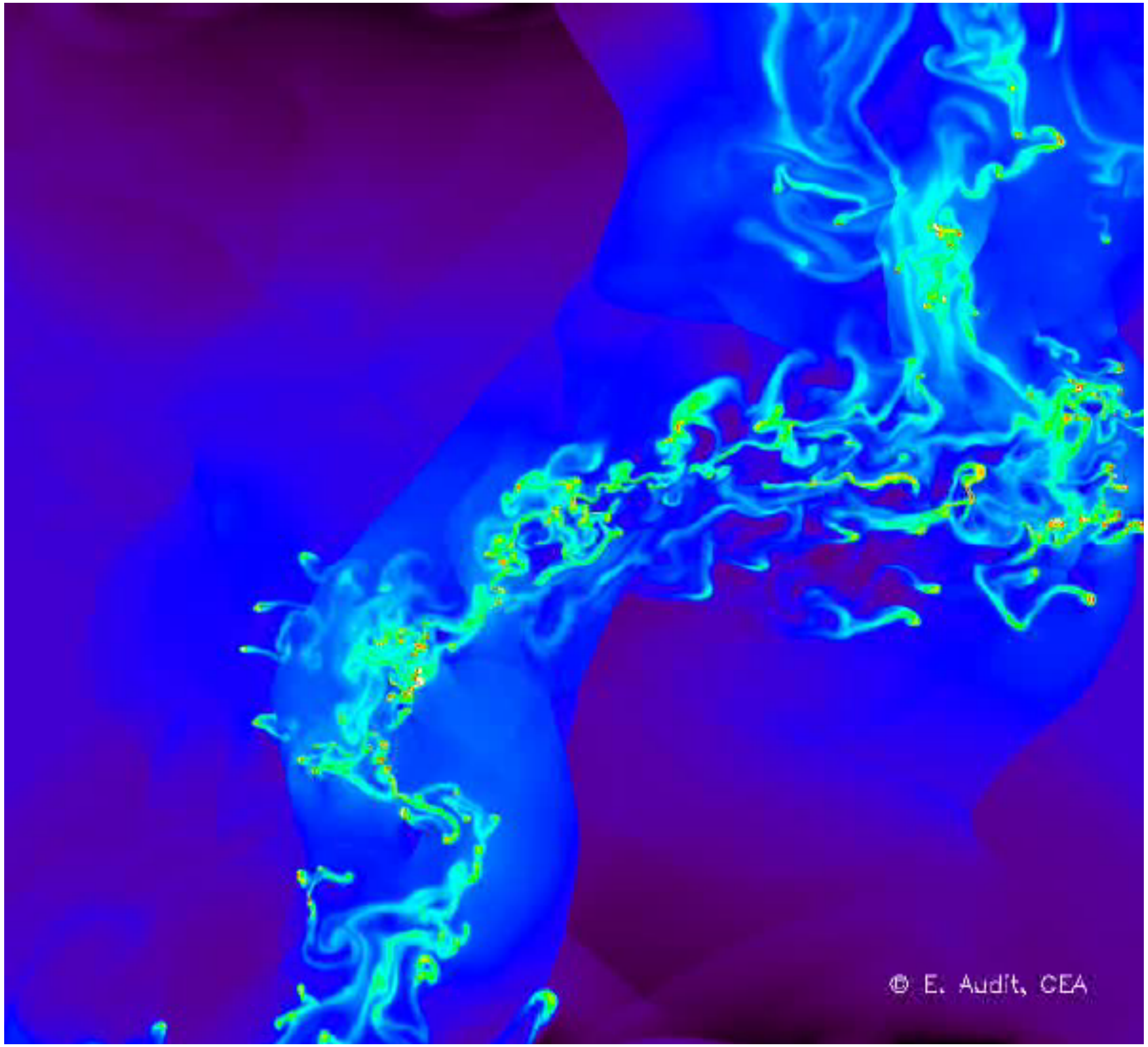
-cnm very fragmented

-*turbulence* in CNM is maintained by interaction with WNM

2500^2

Audit & Hennebelle 05

20 pc



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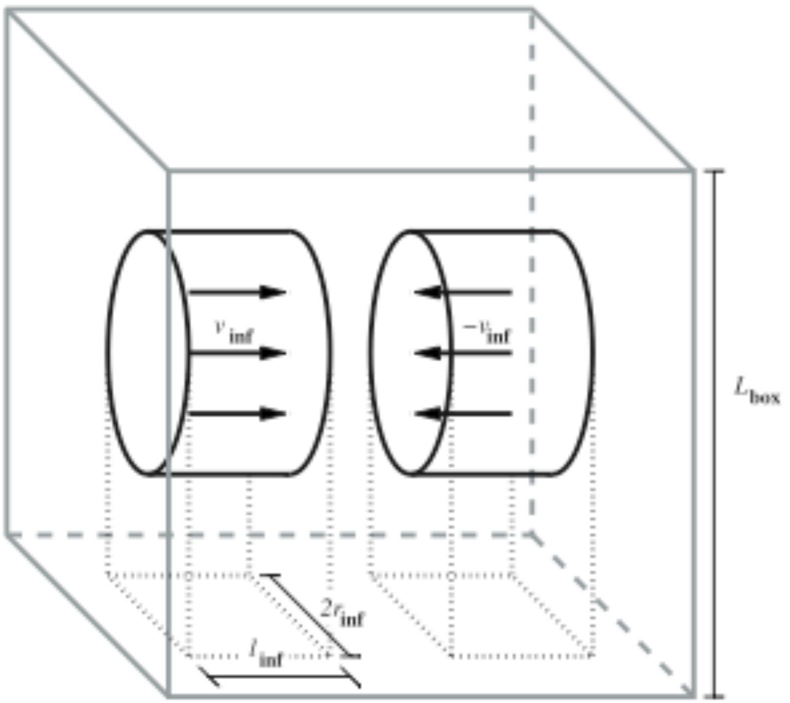
Formation of a *molecular clouds* from HI

(Vazquez-Semadeni et al. 07, Hennebelle et al. 08, Heitsch et al. 08, Banerjee et al. 09)

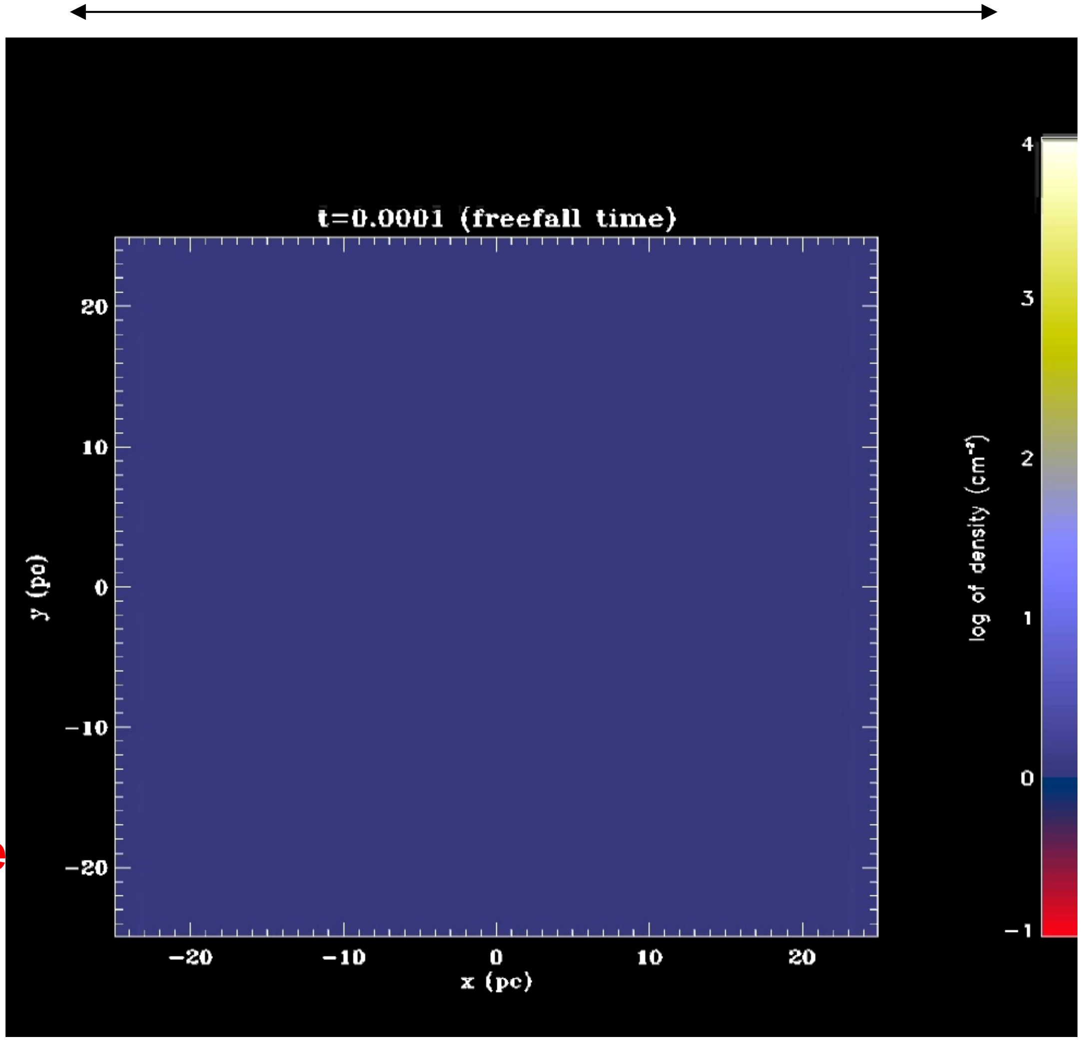
Flow of WNM (density 1cc), velocity 20km/s each side, initial magnetic field 5μG

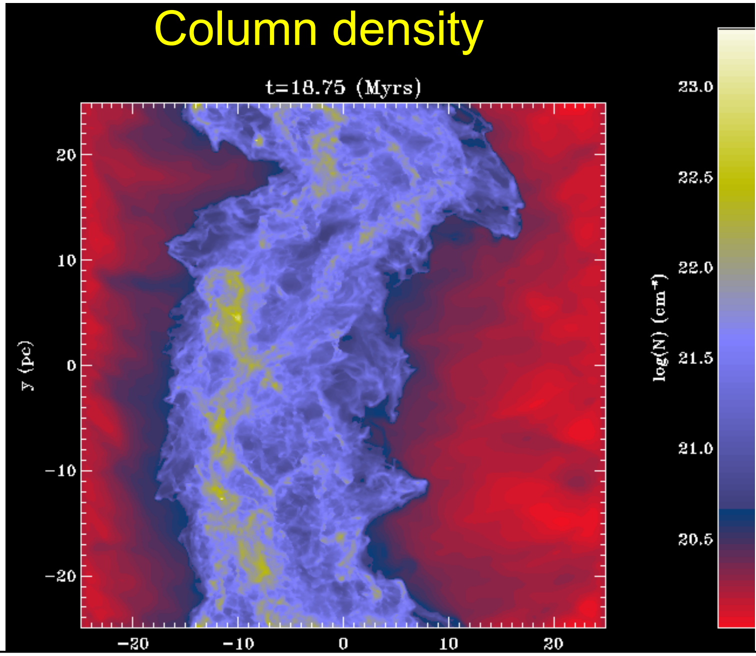
Colliding flows...

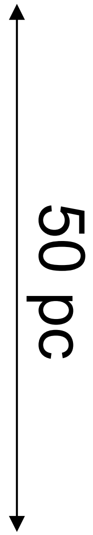


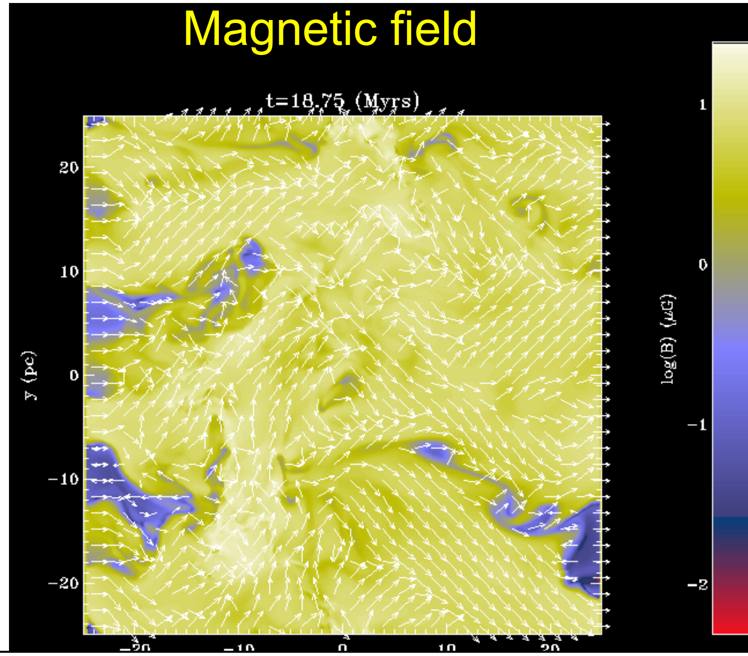
...are a theorist simplistic view. Better picture: large scale compressible turbulence.

50 pc

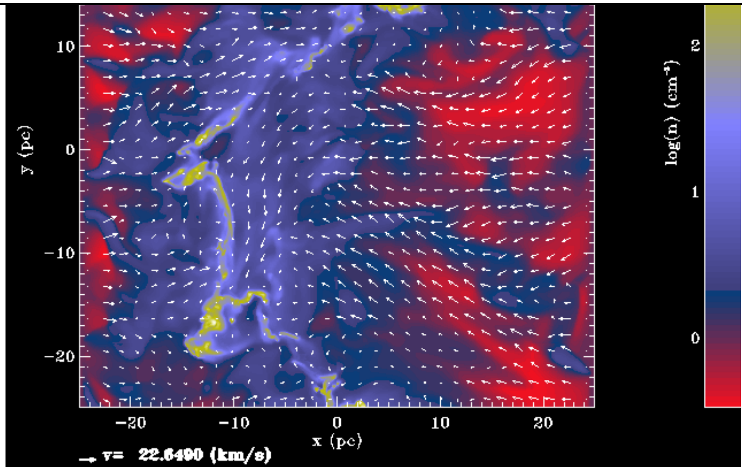


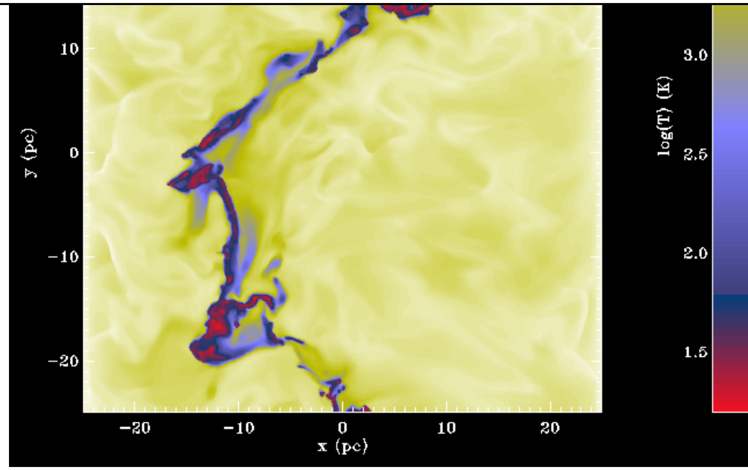




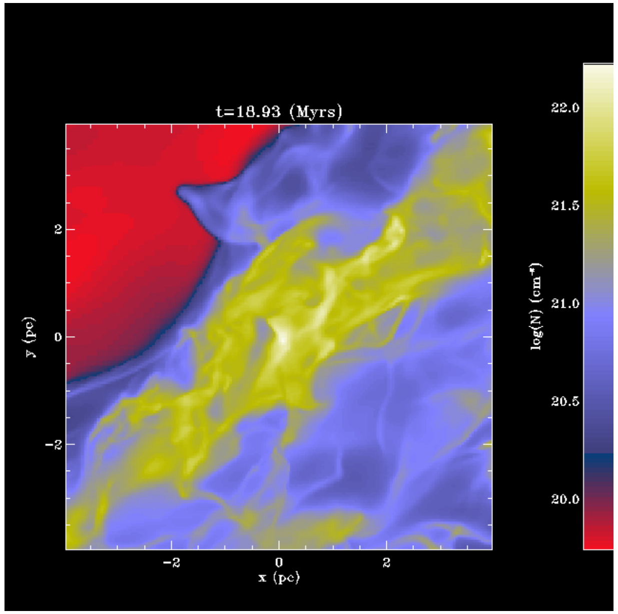


Although the cloud appears as a single phase entity in projection, its structure is not very different from the CNM/ WNM structure. Clumps are bounded by WNM which provides them a confining pressure.

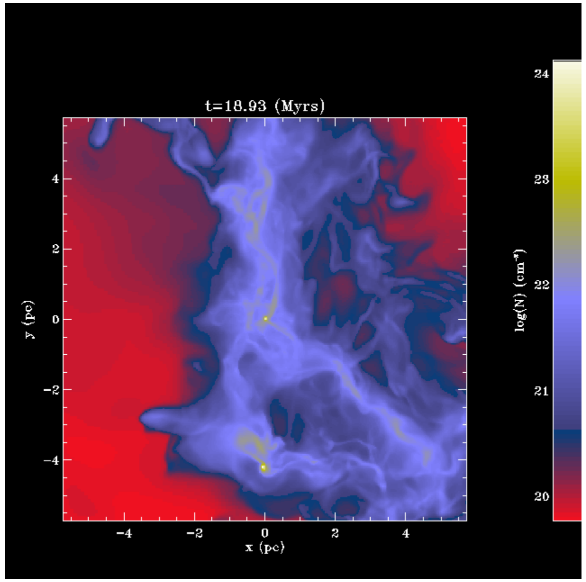




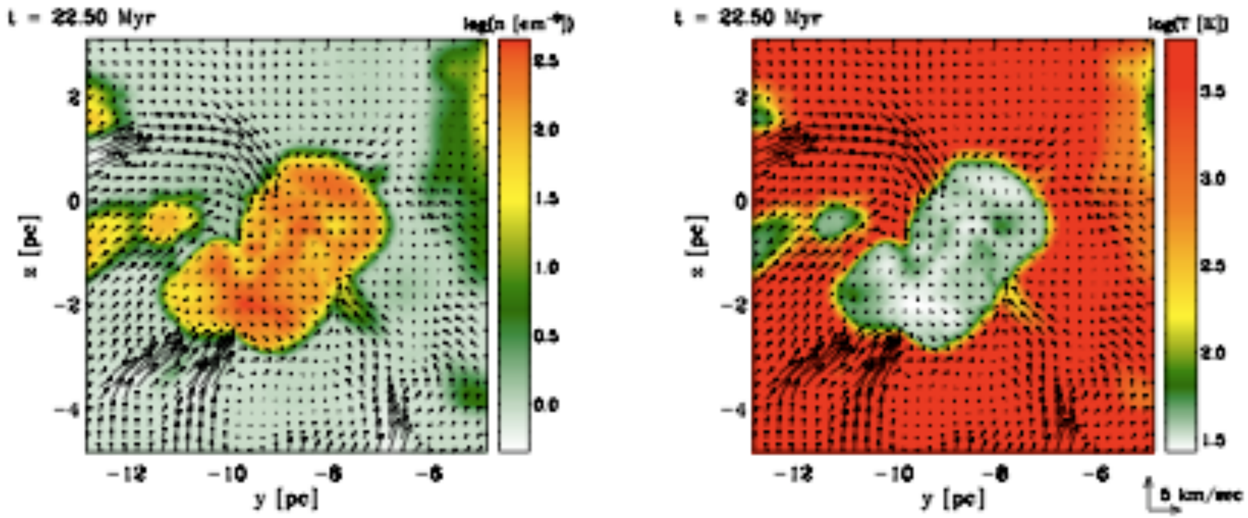
Few examples of clumps



Starless



Star already formed



Banerjee et al. 09

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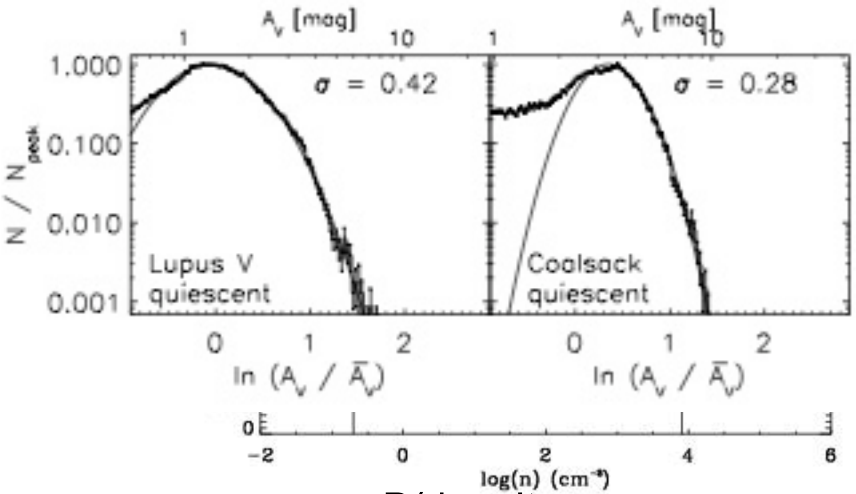
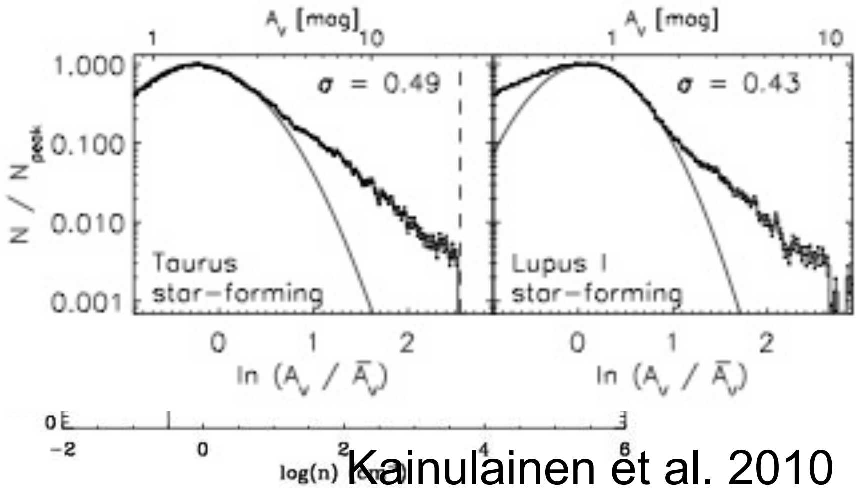
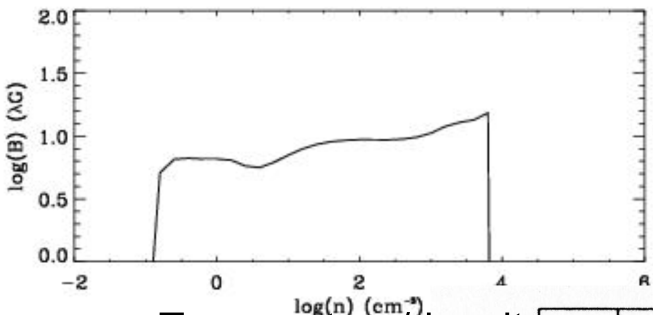
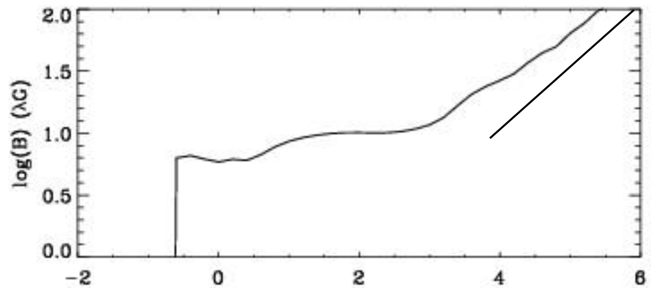




Kainulainen et al. 2010

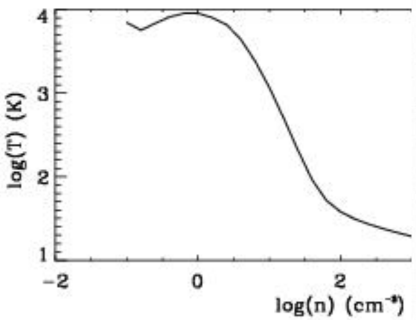
B/density

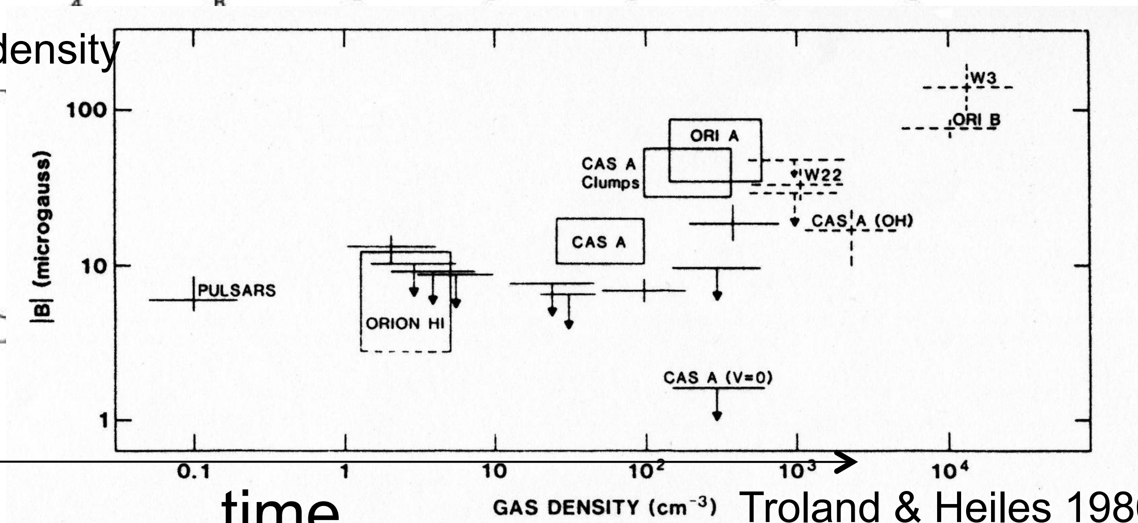




$$B \propto \rho^{1/2}$$

Temperature/density





time

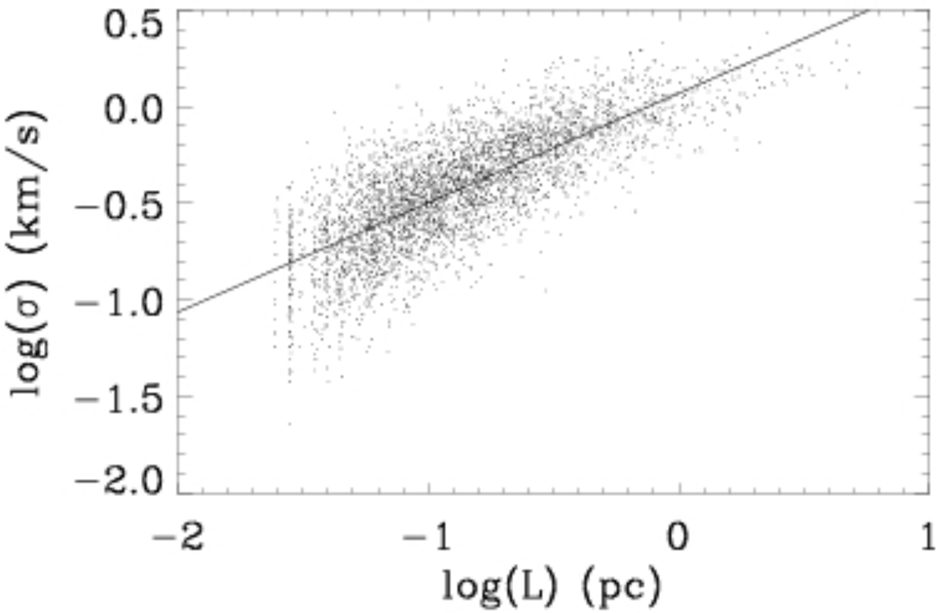
Troland & Heiles 1986

Vazquez-Semadeni 1994, Kritsuk et al. 2007, Hennebelle et al. (2008), Banerjee et al. (2009)

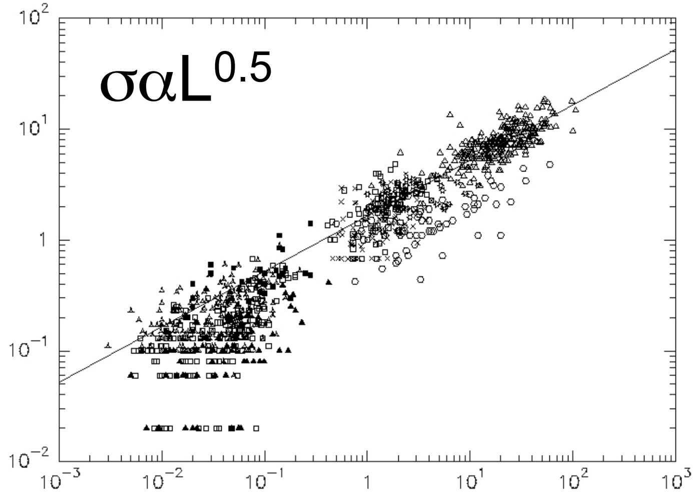
Internal clump velocity dispersion

(density > 2500 cm^{-3})

$$\sigma(L) \approx 1\,\mathrm{km s^{-1}} \left(L/1pc\right)^{0.5}$$



Compatible with Larson law
=>is turbulence within GMC driven from outside ?
=>is it driven by continuous accretion of HI ?

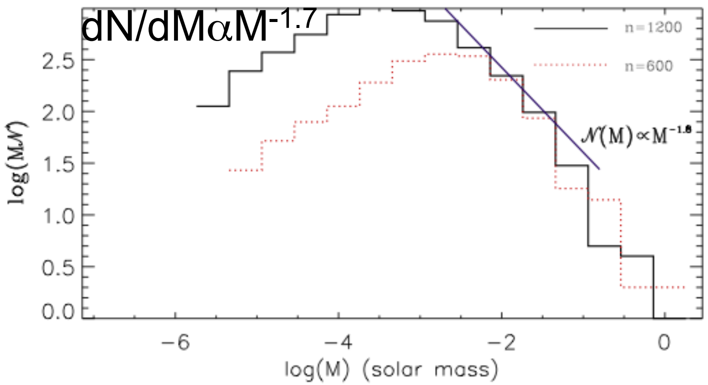


Falgarone 2000

Klessen & Hennebelle (2010)
Goldbaum et al. (2011)

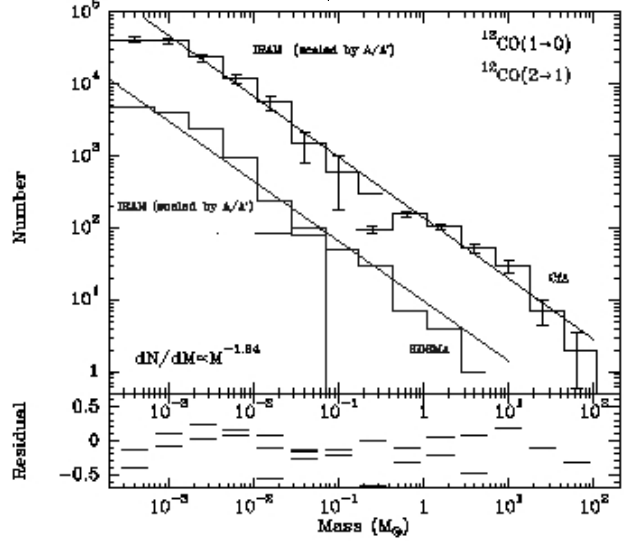
Mass spectrum and mass size

Mass spectrum of clumps



Universal Mass Spectrum

dN/dM α $M^{-1.6\text{-}1.8}$ (Heithausen et al .98)

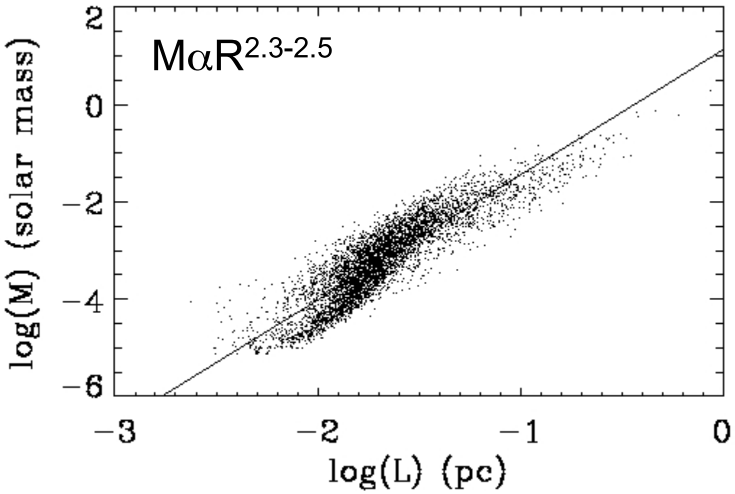


Link between the Kolmogorov exponent and the CO clump power spectrum

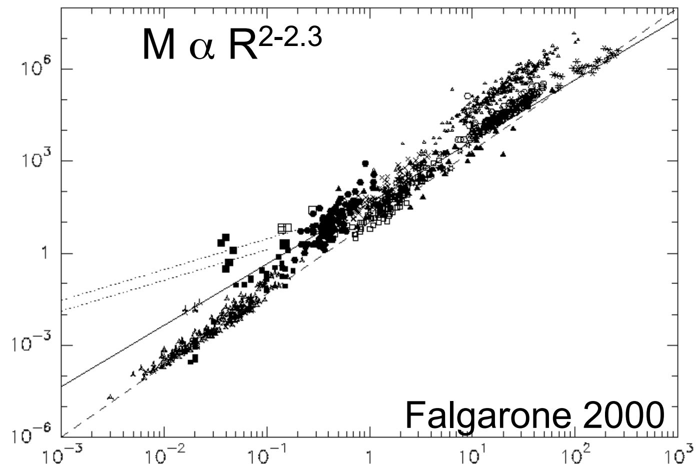
$$\frac{dN}{dM} = M^{-\left(2-\frac{n'-3}{3}\right)}$$

$$n' = \frac{11}{3} \Rightarrow \frac{dN}{dM} \propto M^{-1.78}$$

Mass versus size of clumps



Mass versus size of CO clumps



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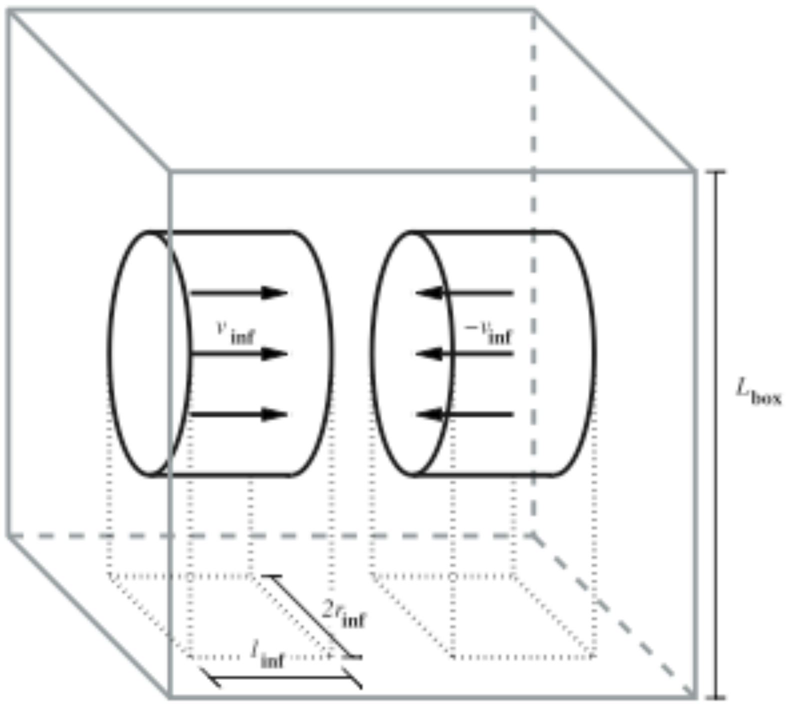
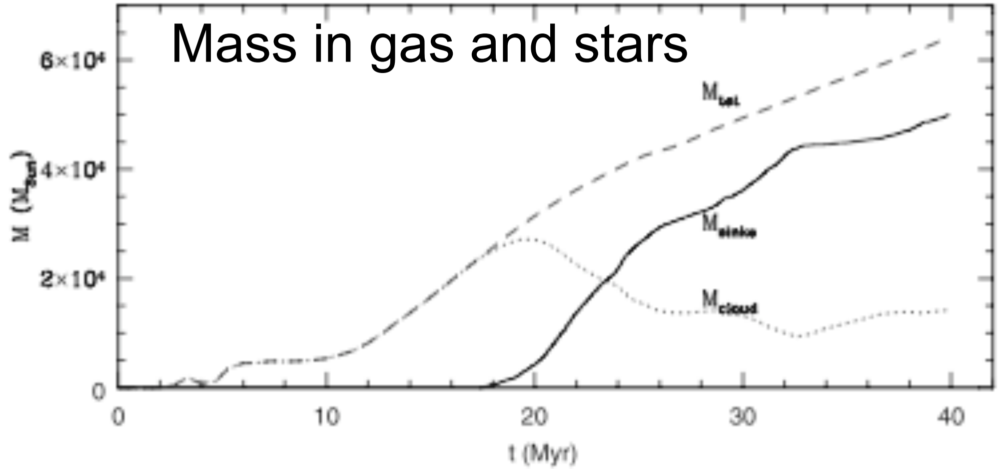
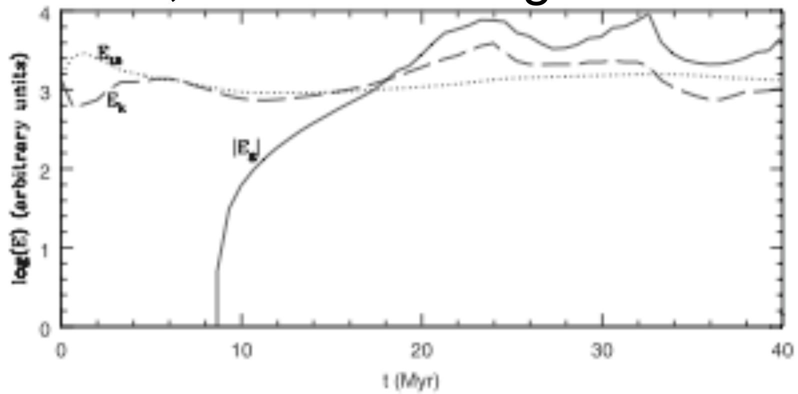
Star formation in a molecular cloud formed from HI

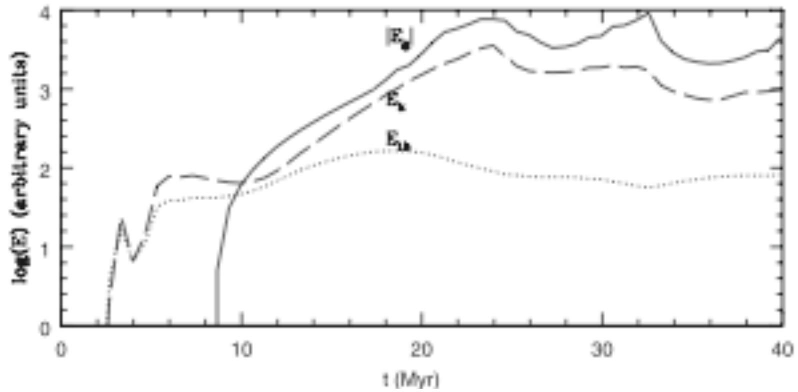
(Vazquez-Semadeni et al. 07)





Ekin, Etherm and Egrav





The star formation is starting and happening *while* the cloud is accreting.

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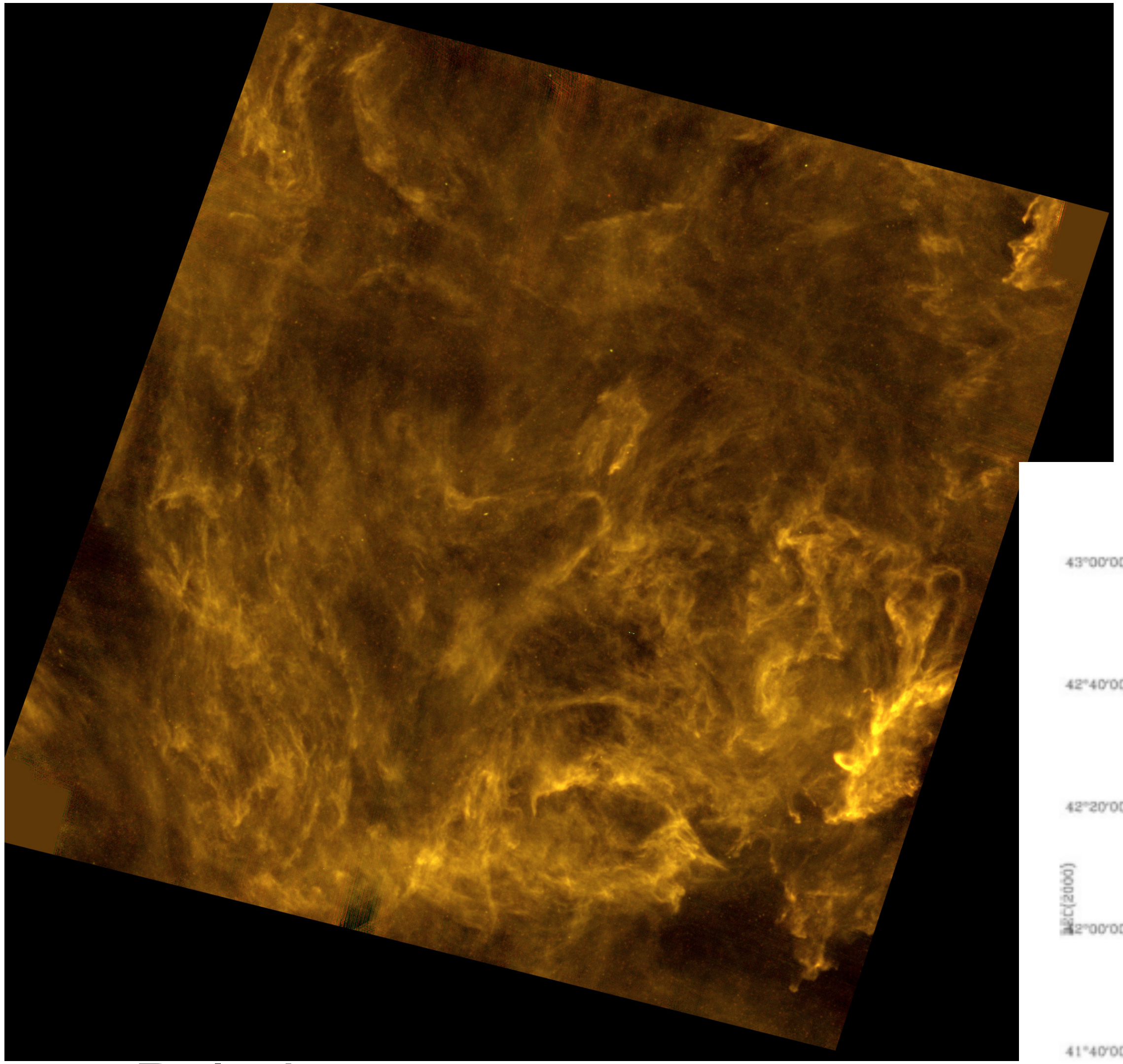
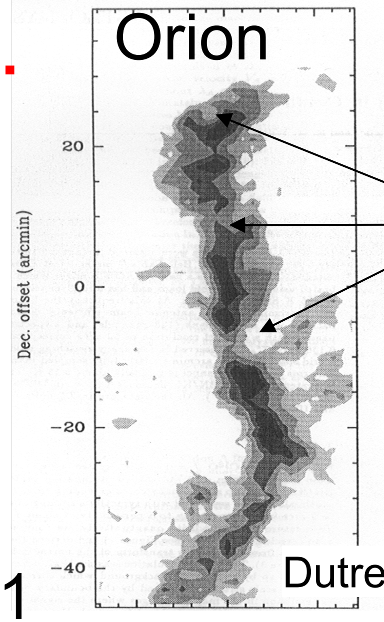
A large diversity of observed filaments…

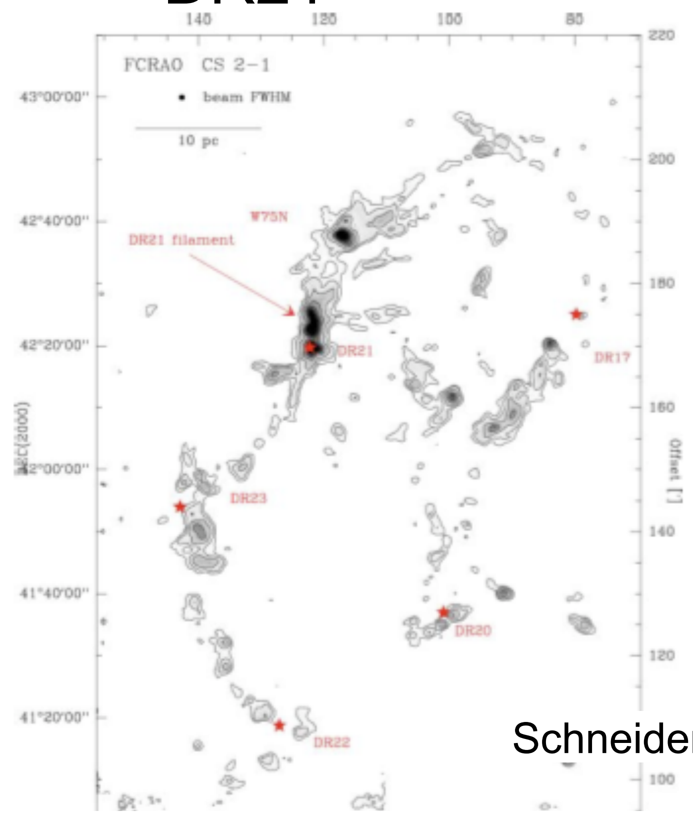


Polaris
from the goult belt survey
André et al. 2010



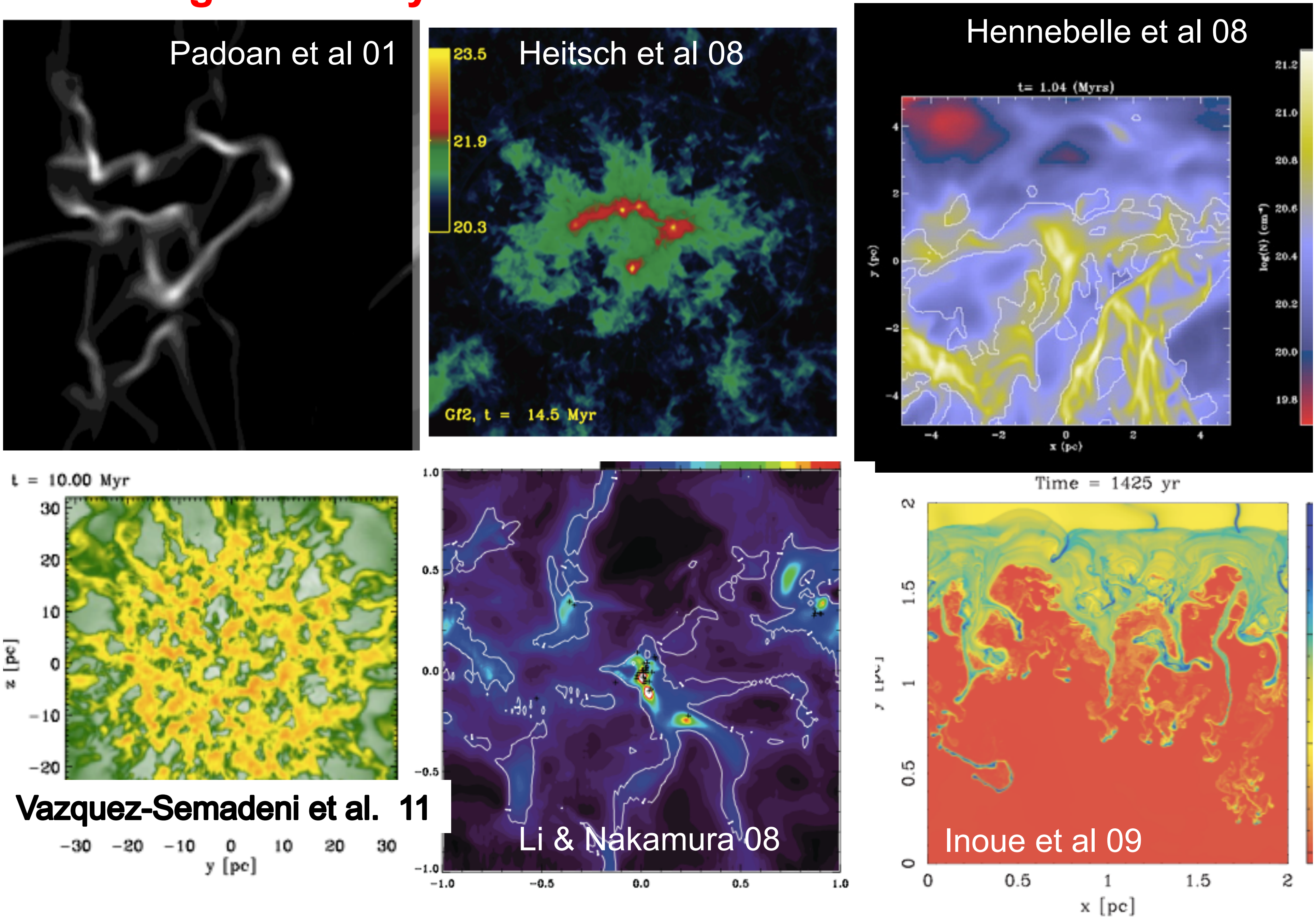
Dutrey et al 91

DR21



Schneider et al 10

A large diversity of simulated filaments…



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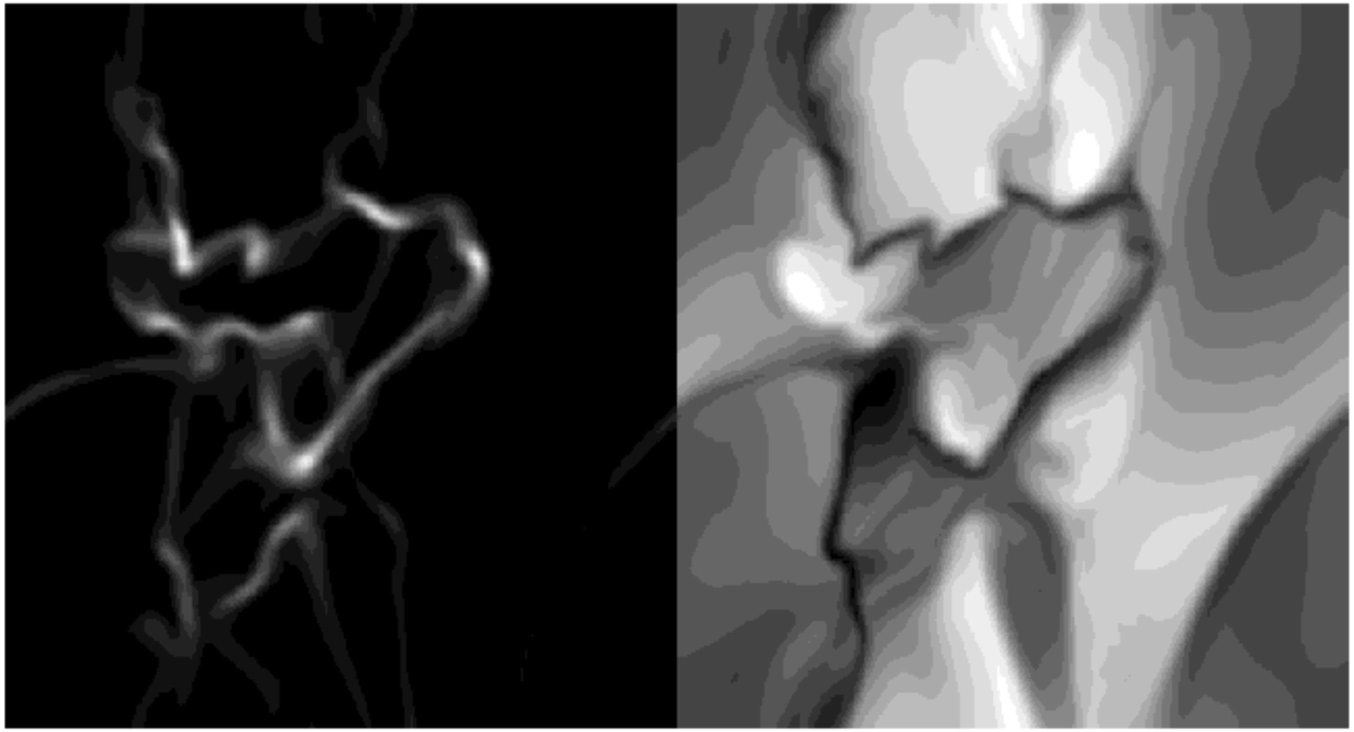
Formation of structures induced by turbulence (and not by gravity)

Padoan et al. 01



3D density field velocity field (norm)

A turbulent molecular cloud (Mach 10).
Includes the magnetic field (supercritical) but not gravity.

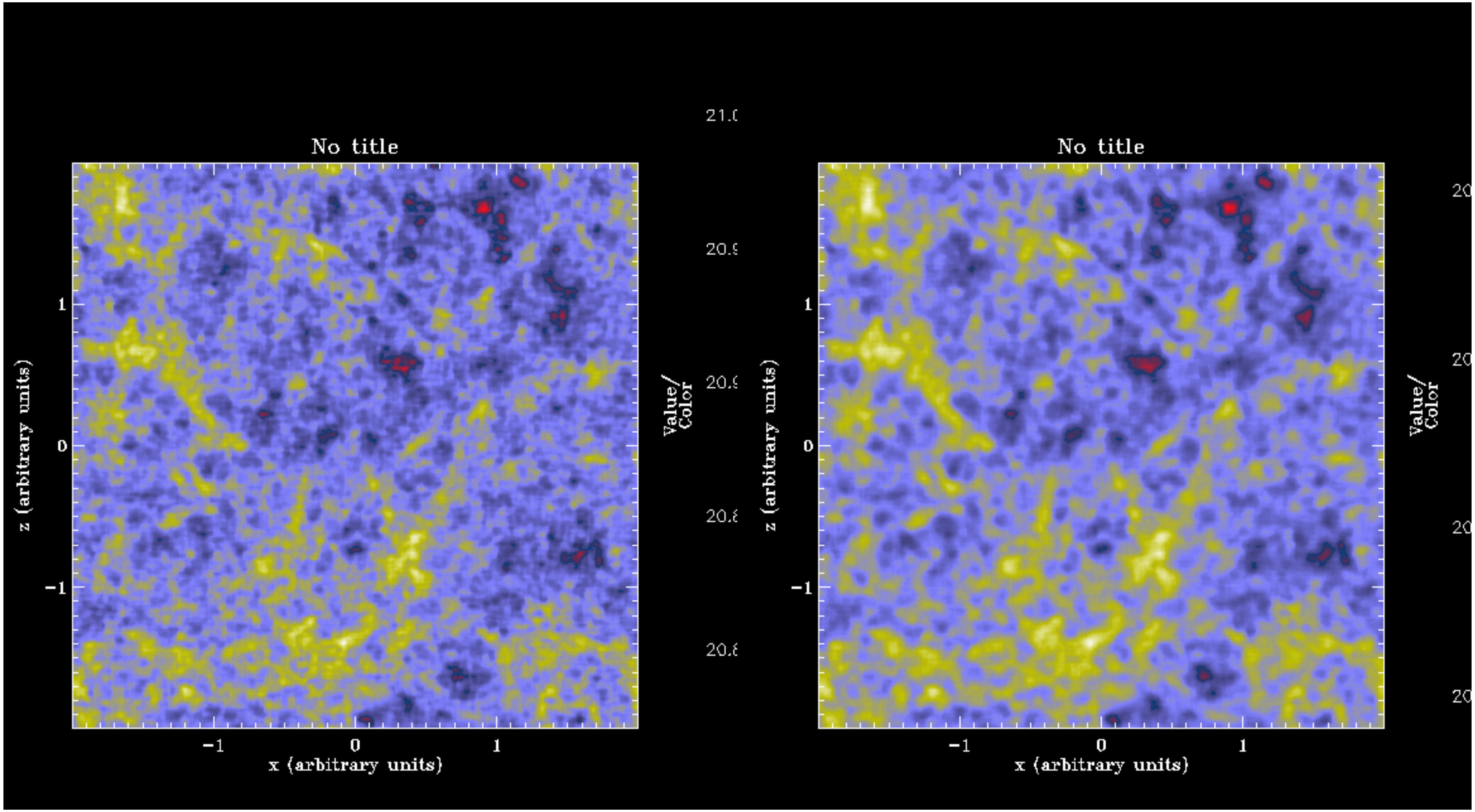
Proposition: filaments are intersection of shocked sheets

Comparison between hydro and MHD simulations

Decaying turbulence, 2 phase-medium, no gravity, 5 cm^{-3}

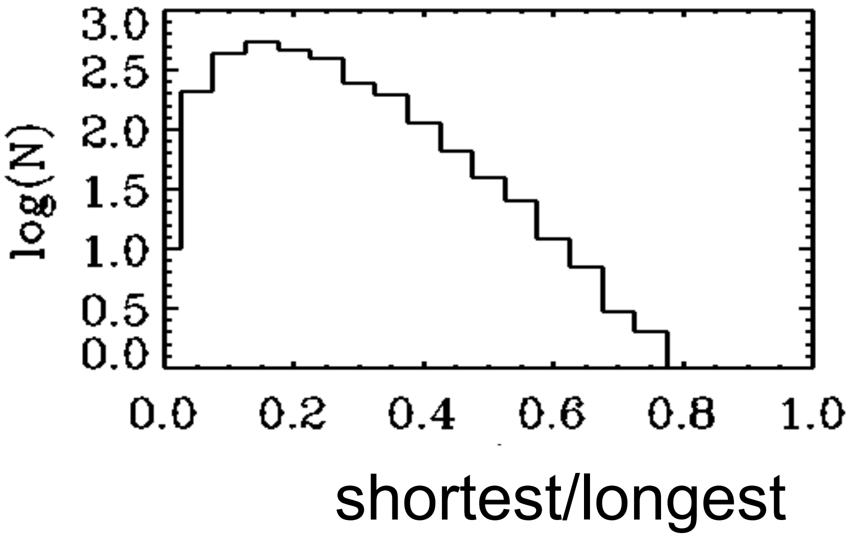
Initial Mach (wrt cold gas) : 10, B=0 or 5 μG

HYDRO MHD

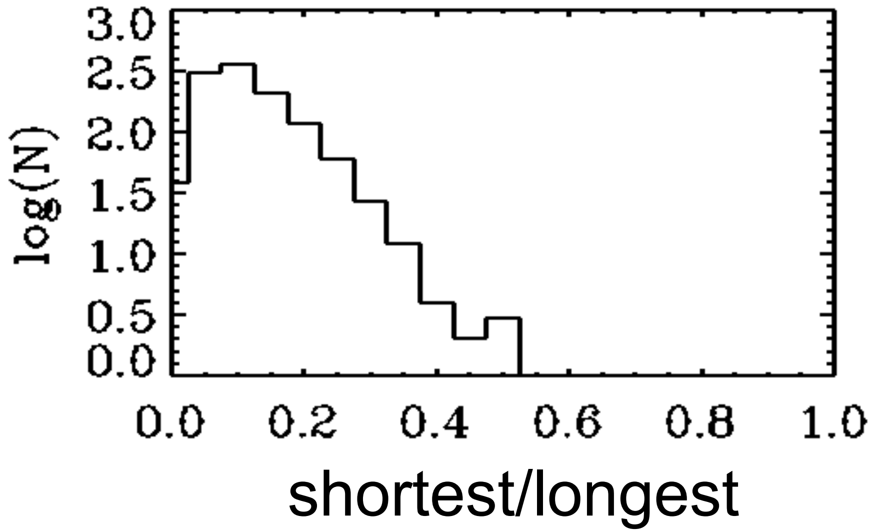


Aspect ratio of clumps denser than 200 cm^{-3}

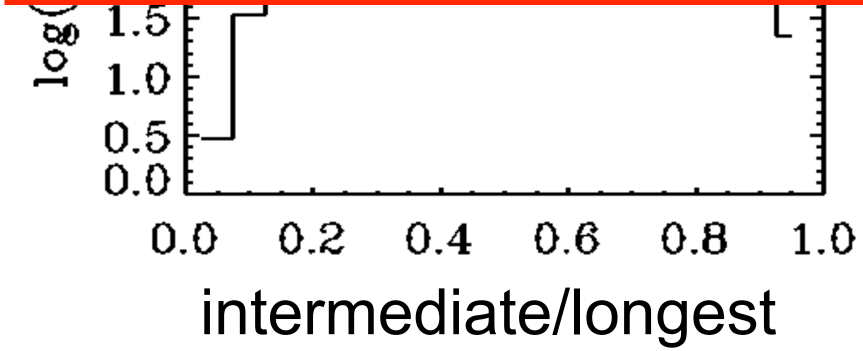
HYDRO

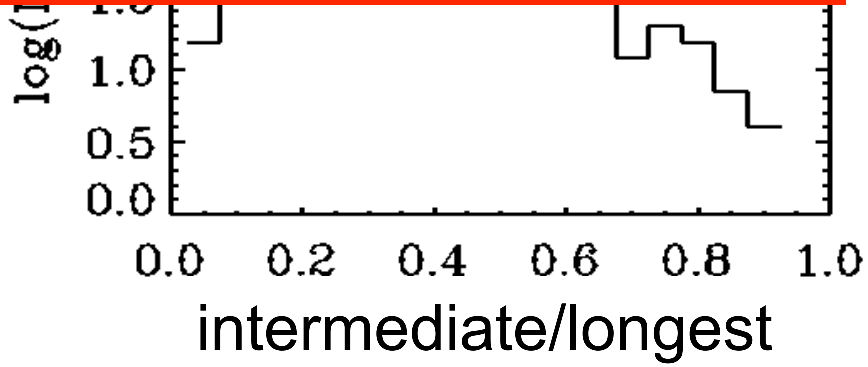


MHD



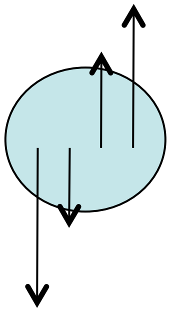
MHD simulations are more filamentary while magnetic field should reduce the strength of the shocks…

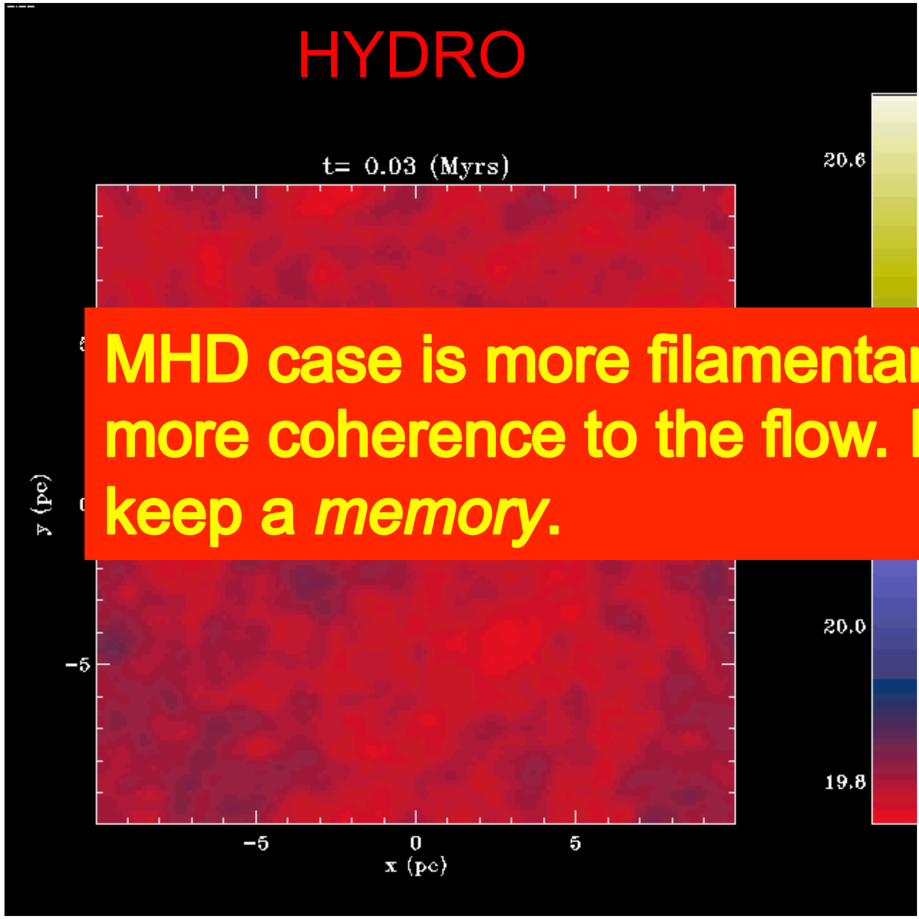


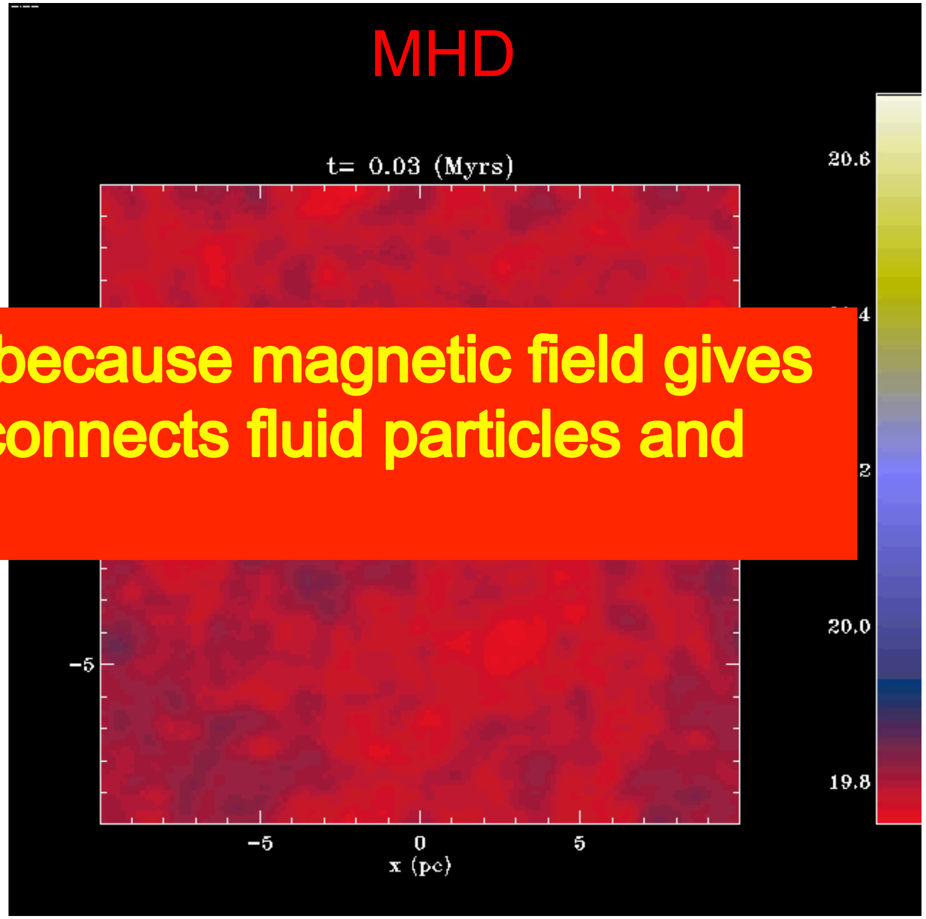


Impact of an initial shear

Mach 5 turbulence initially







MHD case is more filamentary because magnetic field gives more coherence to the flow. It connects fluid particles and keep a *memory*.

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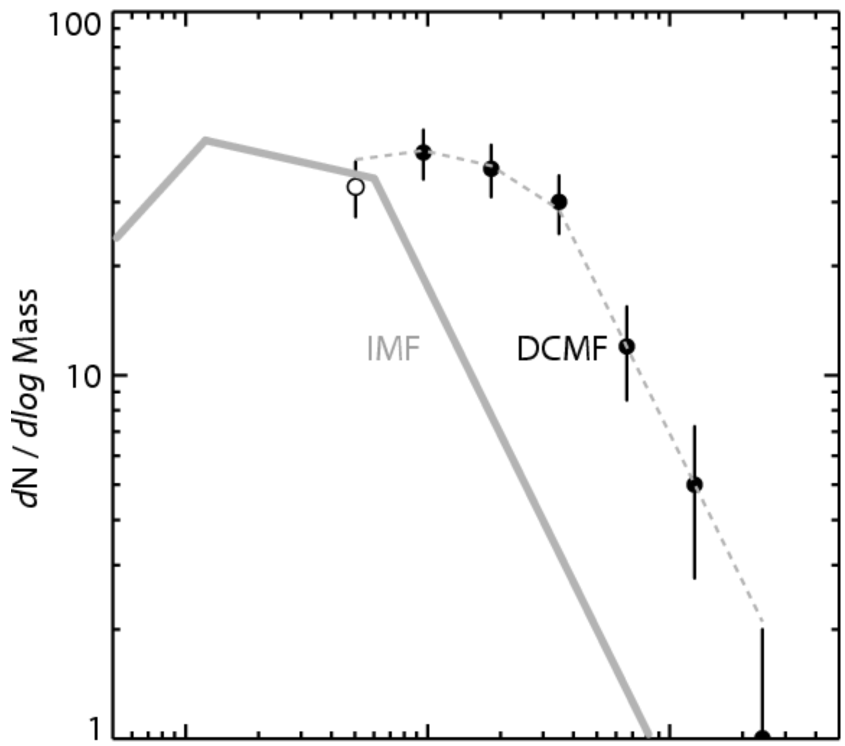
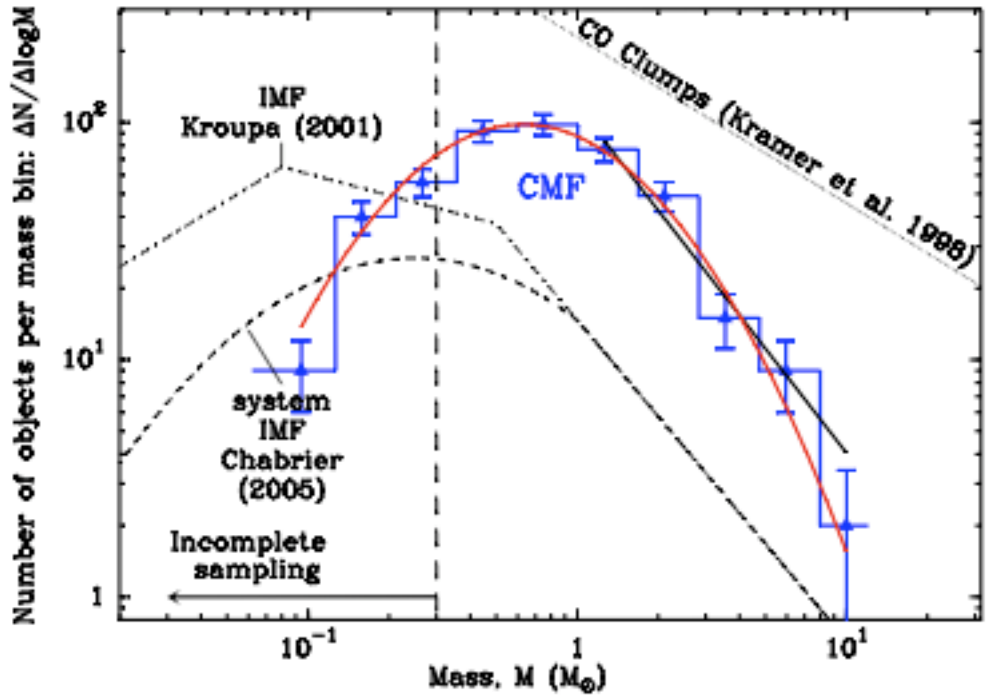
Similarity between IMF and CMF

(Motte et al. 1998, Testi & Sargent 1998, Alves et al. 2007, Johnstone et al. 2002, Enoch et al. 2008, Simpson et al. 2008)



Alves et al. 2007



Konyves, André et al. 2010

Core as density fluctuations created by turbulence and selected by gravity

Principles of Press-Schecter analysis

Used in cosmology to predict the mass spectrum of DM haloes: =>*very successful*

-consider a spectrum of density fluctuations (Gaussian in the cosmological case) characterized by its powerspectrum and smooth it at scale R

-setup a criterion to decide which perturbations have to be considered (collapse time should be smaller than the age of the universe)

-sum over the corresponding fluctuations

In the case of Molecular clouds

(Padoan et al. 1997, Hennebelle & Chabrier 2008, 2009, 2011, Hosking 2011, 2012)

-assume that the density PDF is log-normal (e.g. Vazquez-Semadeni 1994, Federrath et al. 2011)

-the power-spectrum of log ρ is close to Kolmogorov

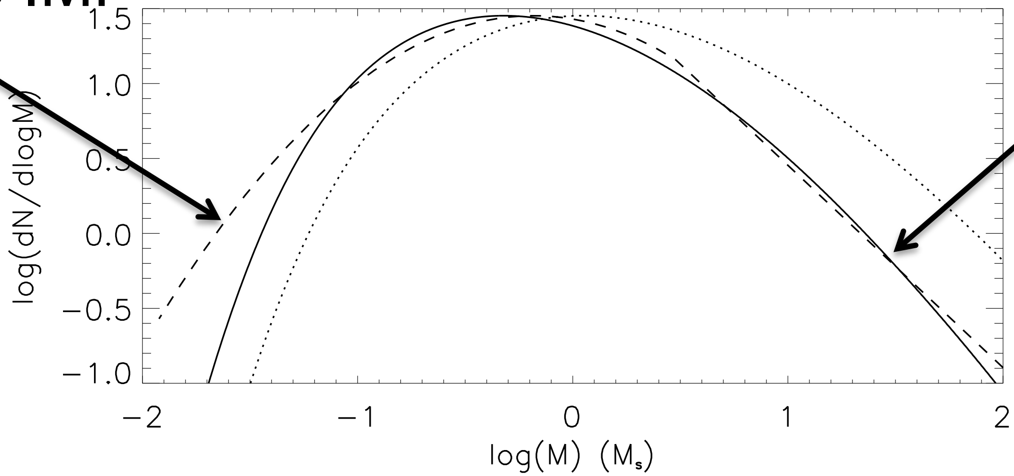
-consider self-gravitating structures

$$M_{tot}(R) = \bar{\rho} L^3 \int_{\delta_c}^{\infty} \frac{1}{\sqrt{2\pi\sigma(R)^2}} \exp\left(-\frac{\delta^2}{2\sigma(R)^2}\right) d\delta$$

$$= L^3 \int_{M(R)}^{\infty} \frac{dN}{dM'} M' P(M, M') dM'$$

Comparison between predicted CMF and Chabrier IMF

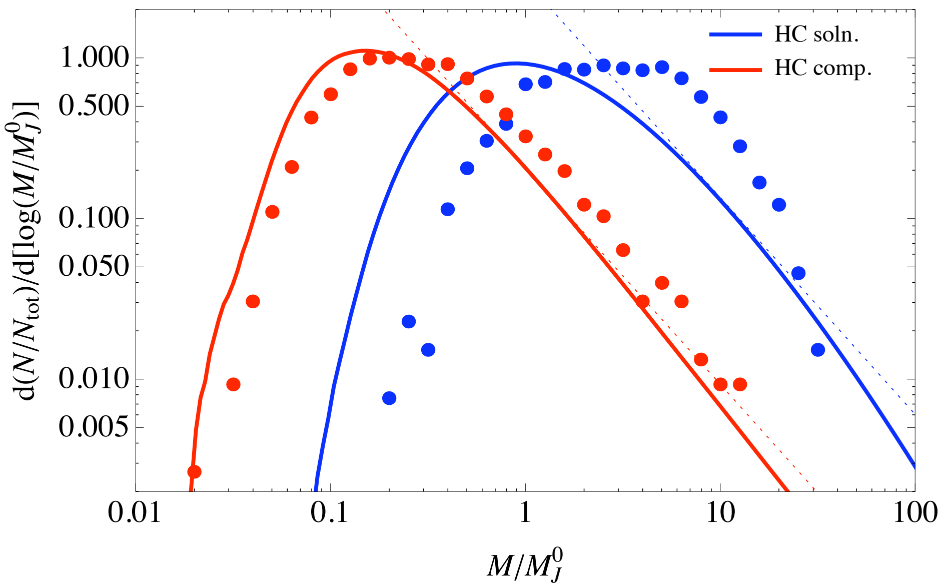
Chabrier's IMF



Analytical prediction

Hennebelle & Chabrier 2008
Hennebelle & Chabrier in prep

Comparison with high resolution numerical simulations



Schmidt et al. 2010

Overview

Formation of molecular clouds from diffuse gas
-observations
-2-phase turbulence
-formation of molecular clouds from diffuse gas
-statistics
-star formation

Formation of filaments and cores within molecular clouds:
-by pure MHD turbulence
-by turbulence but selected by gravity
-by pure gravity
-a fully gravo-turbulent picture

Fragmentation of sheet into filaments

Classical Jeans analysis: $$\omega^2 = C_s^{\ 2} k^2 - 4\pi G \rho_0$$

The largest mode (k=0) has the fastest growth rate.
Could be a problem for forming filaments by gravity but things are different for a self-gravitating sheet.

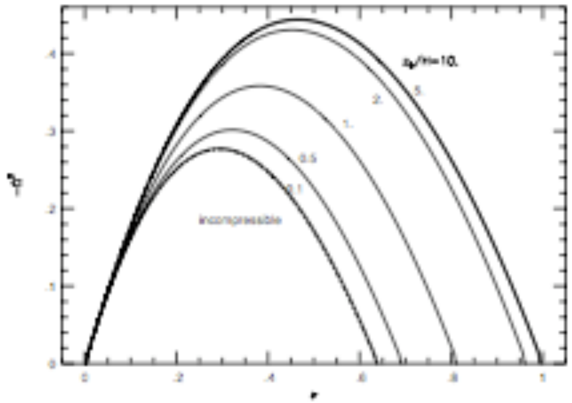
Linear stability of the self-gravitating sheet
(Spitzer 78, Nagai et al. 98)

idem: $k > k_{crit} \Rightarrow \omega^2 > 0$ but for:

$$k \rightarrow 0 \Rightarrow \omega^2 \propto -k^2$$

more unstable mode = typical width of the filaments : λ_J

Dispersion relation



=>Fragmentation of a sheet into filaments

Note that Nagai et al. also infer that the orientation of the filaments depend on the magnetic field.
Along the field when Pext is large and perpendicular to it otherwise.

Fragmentation of sheet into filament

Exact Equilibrium Solutions in 2D (Schmid-Burgk 1976, Myers 2009)

$$\frac{n}{n_c} = \frac{1 - A^2}{[\cosh(z/l_M) + A\cos(x/l_M)]^2},$$

$$l_M \equiv \frac{\sigma}{\sqrt{2\pi G m n_c}}$$

Fragmentation of a sheet into filaments

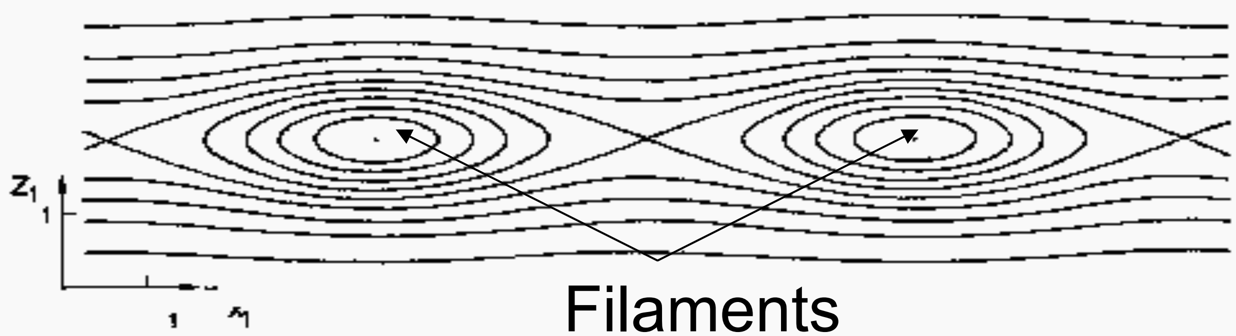


FIG. 1.—Lines of constant density for the case $A = 0.17$. Density along neighboring lines differs by $\rho_{max}/10$

Fragmentation of Filament in Cores

Self-gravitating filaments (Ostriker 64) :
-profile in $1/r^4$

$$\rho(r) = \rho_0 / (1 + (r / l_0)^2)^2 \ , l_0 = C_s / \sqrt{\pi G \rho_0}$$

as for the self-gravitating sheet there is a more unstable wavelength
Suggest: the dense cores are elongated structures with a spatial period close to the Jeans Length.

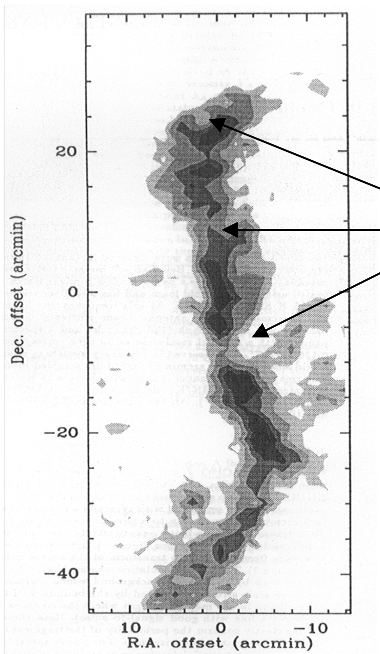


Fig. 1. $C^{18}O$ $J = 1-0$ integrated area map. Contours levels are 1, 1.7, 2.6, 3.5, 4.2 $K.km \cdot s^{-1}$. The different clumps are roughly delineated by the 2.6 $K.km \cdot s^{-1}$ level.

cores

Dutrey et al 91

Development of the gravitational instability in a filament:

Formation of an elongated core

Fiege & Pudritz 00

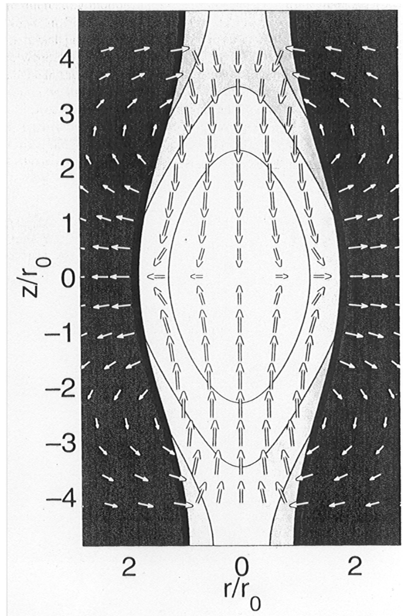


Figure 4. We show the eigenmode corresponding to the most unstable mode of a truncated Ostriker model with mass per unit length $m/m_0 =$ 5 $(m/m_{vir} = 0.199)$. For this mode, $r_0 k_{z,max} = 0.462$ and $-\omega^2 (4\pi G \rho_c)^{-1} =$ 0.449.

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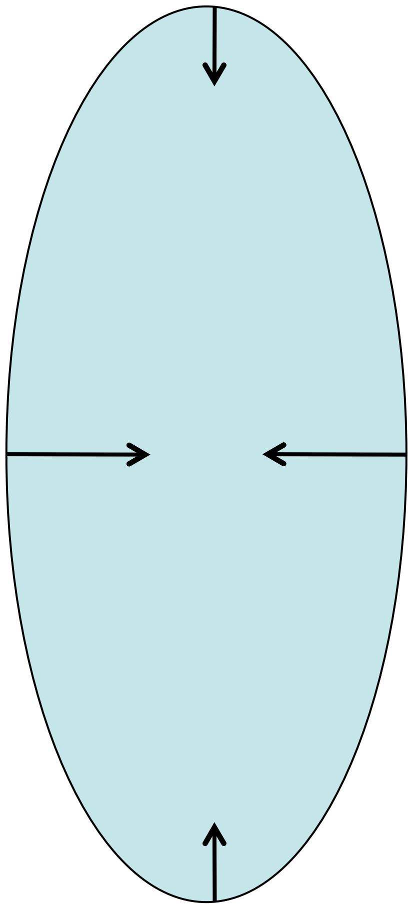
Gravitational amplification of anisotropies seeded by turbulence

(Mestel et al. 71)

$$F_z \propto \frac{\phi}{l}$$

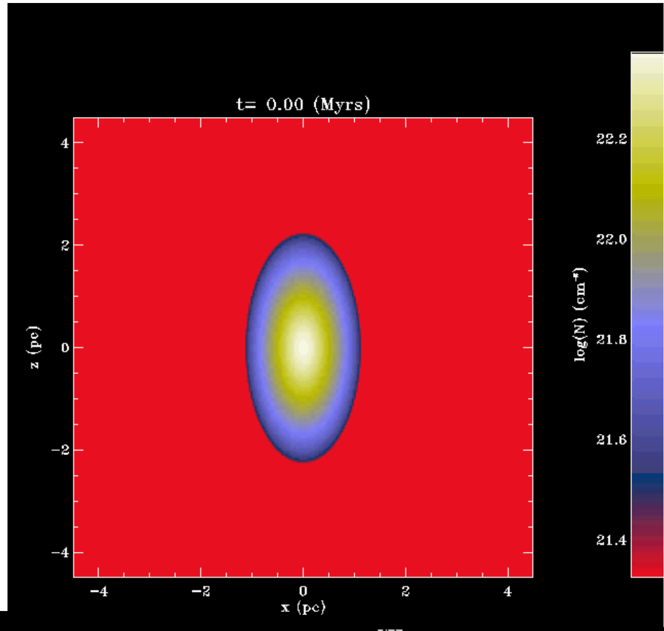
$$F_r \propto \frac{\phi}{r}$$

$$\Rightarrow F_z \leq F_r$$

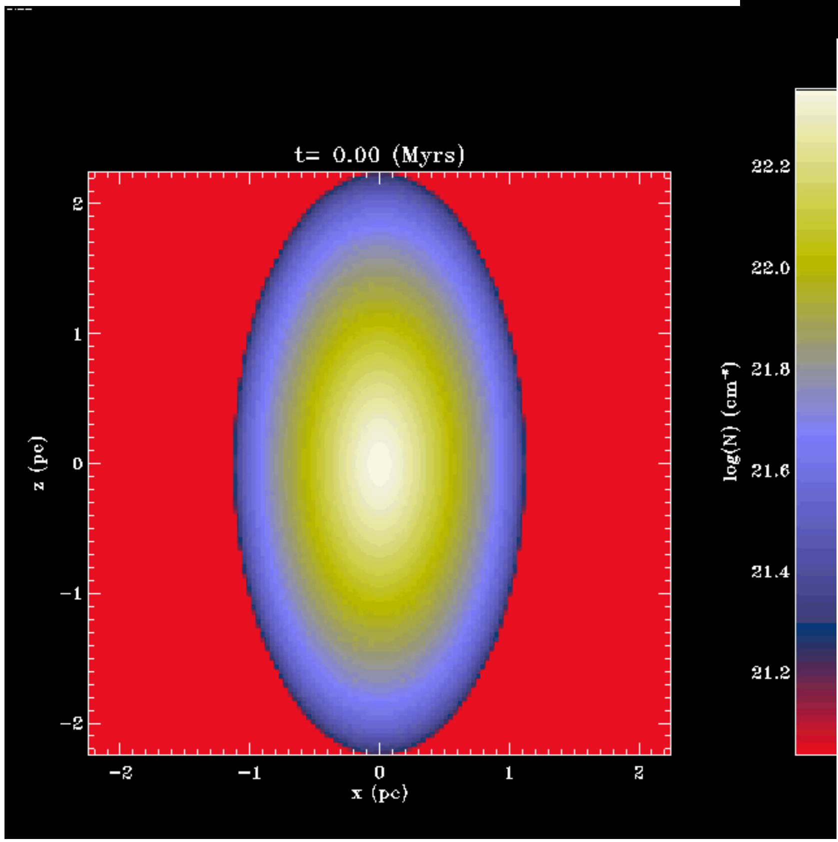


Formation of filaments by gravitational amplification

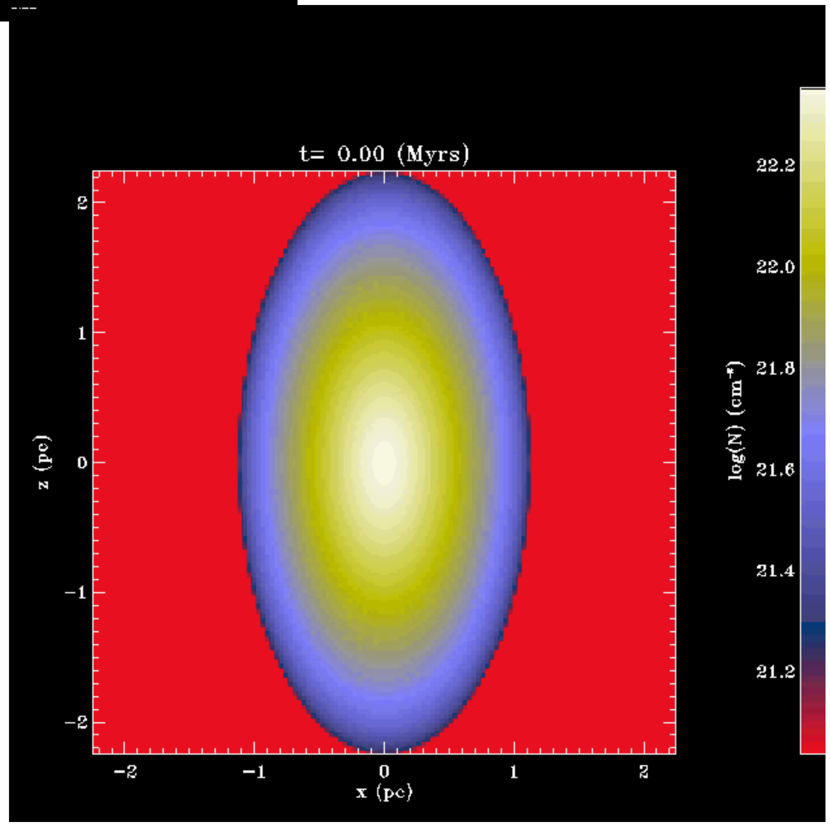
Gravity
No turbulence



Gravity
Turbulence



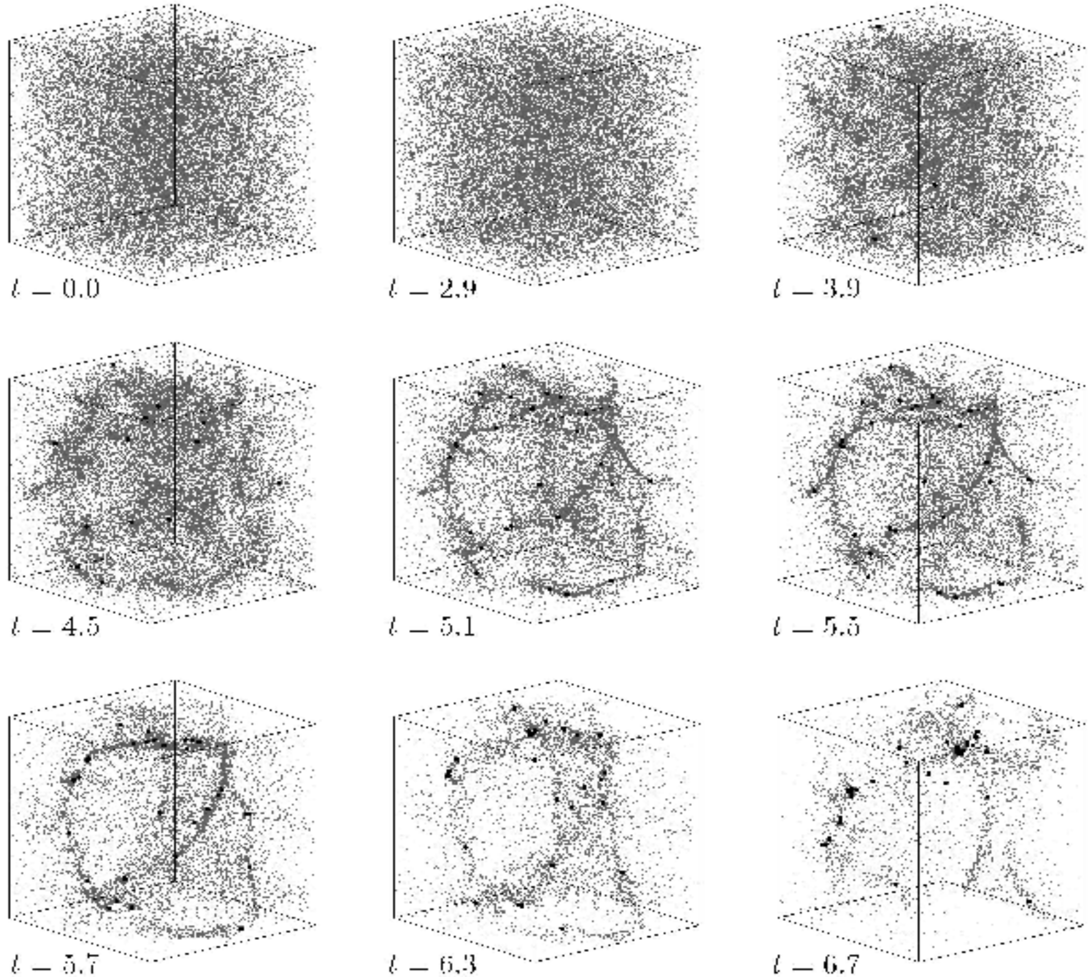
Gravity
Turbulence
+MHD



Formation of filament in gravo-turbulent simulations

Evolution of the density field
of a molecular cloud

The calculation (SPH technique)
takes gravity into account but not
the magnetic field.



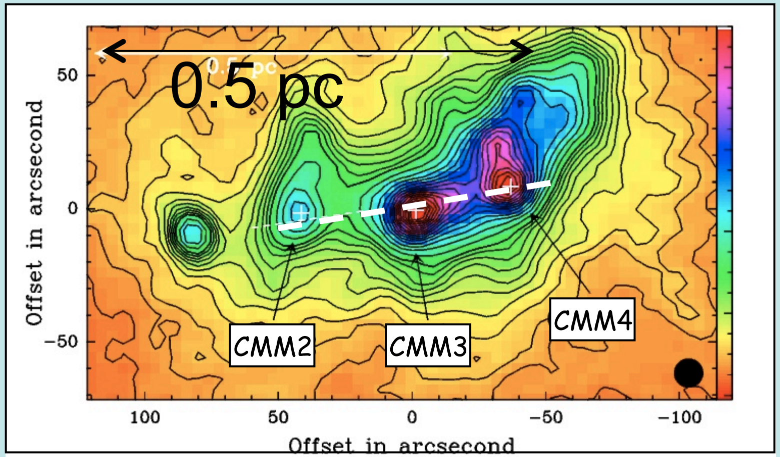
Klessen & Burkert (01) and many others

Turbulence induces the formation of filaments, which become self-gravitating and collapse

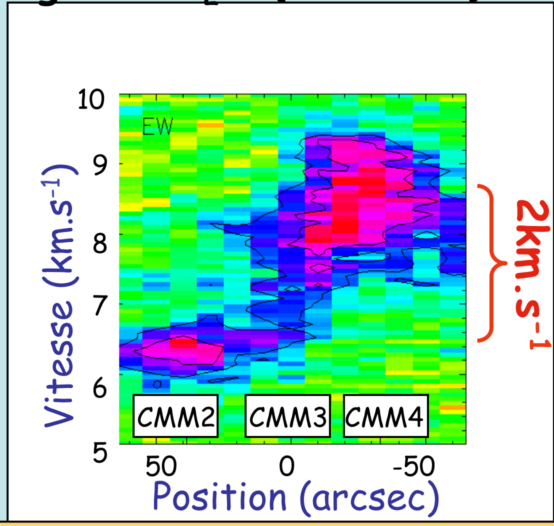
Comparaisons Observations 30m/Simulations
« Best-fit» Simulation

Peretto et al. 2007

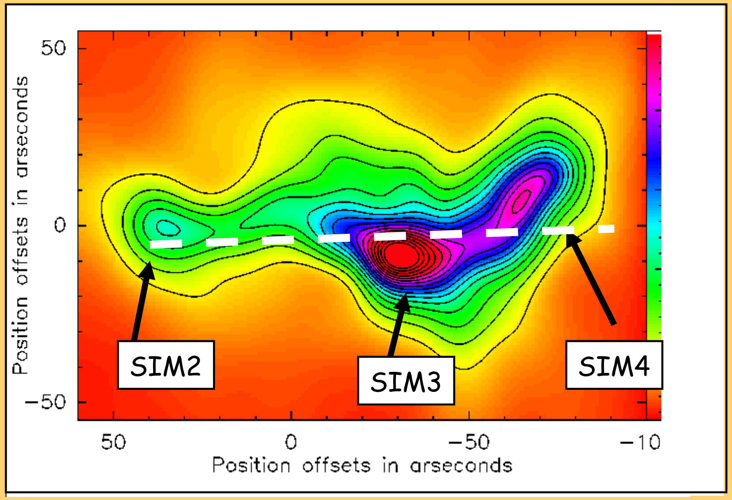
Continuum 1.2mm 30m



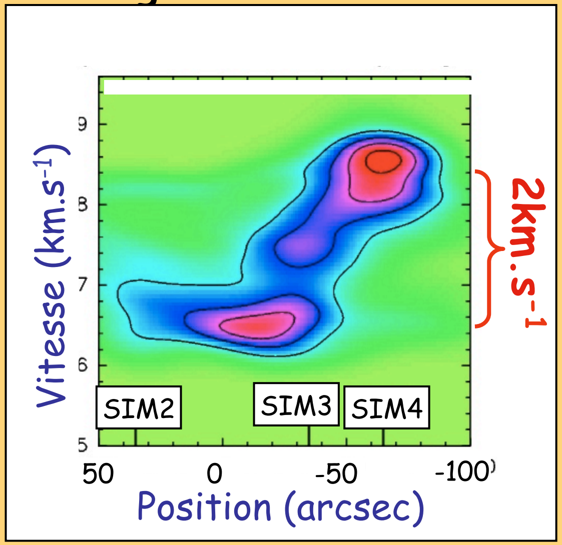
Diag. PV N_2H^+(101-012) 30m



Carte colonne densité simulée 30m



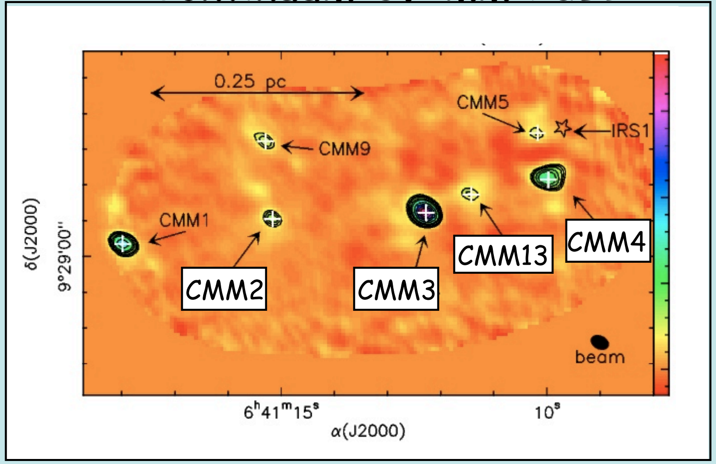
Diag. PV simulé 30m



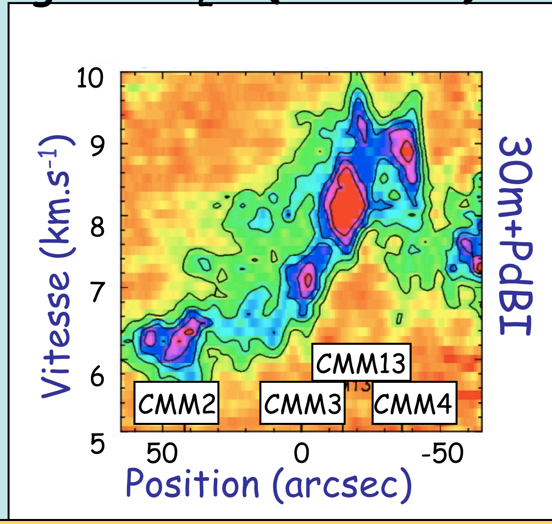
Comparaisons Observations PdBI

Peretto et al. 2007

Continuum 3.2mm PdBI



Diag. PV N_2H^+(101-012) PdBI



Carte colonne densité simulée PdBI

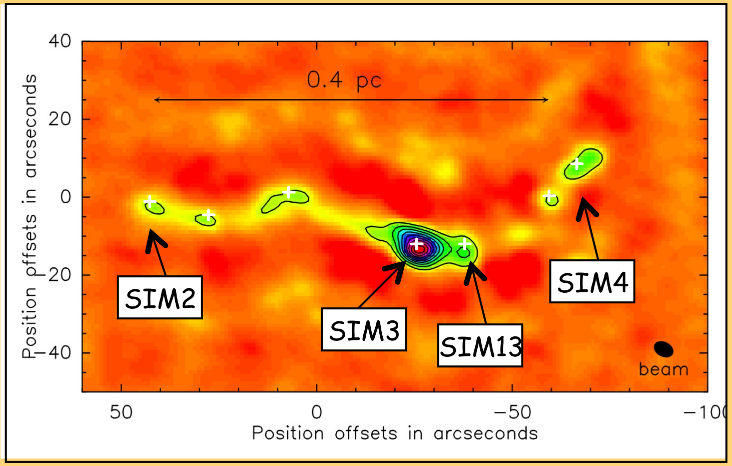
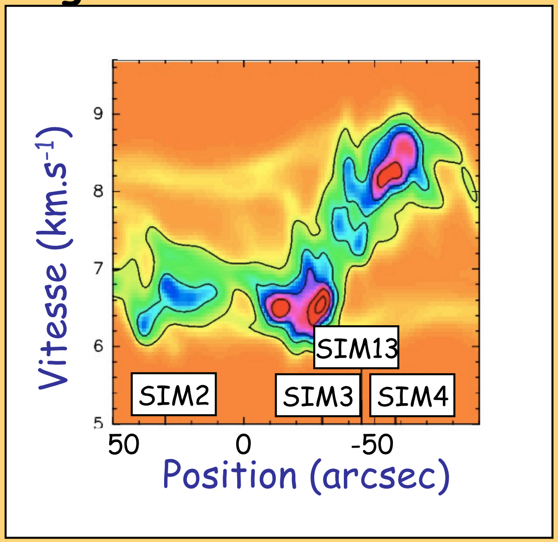
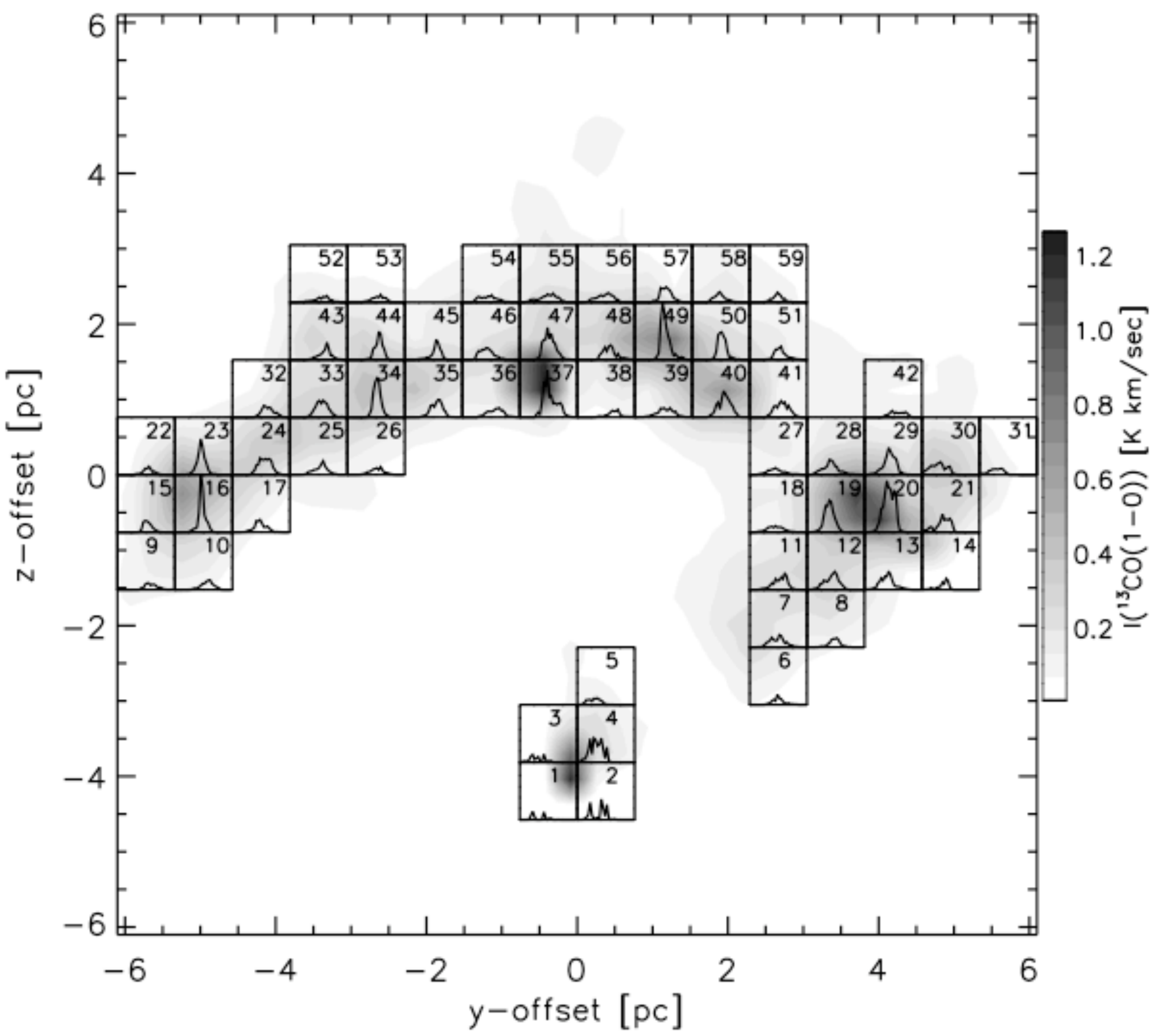


Diagramme PV simulé PdBI

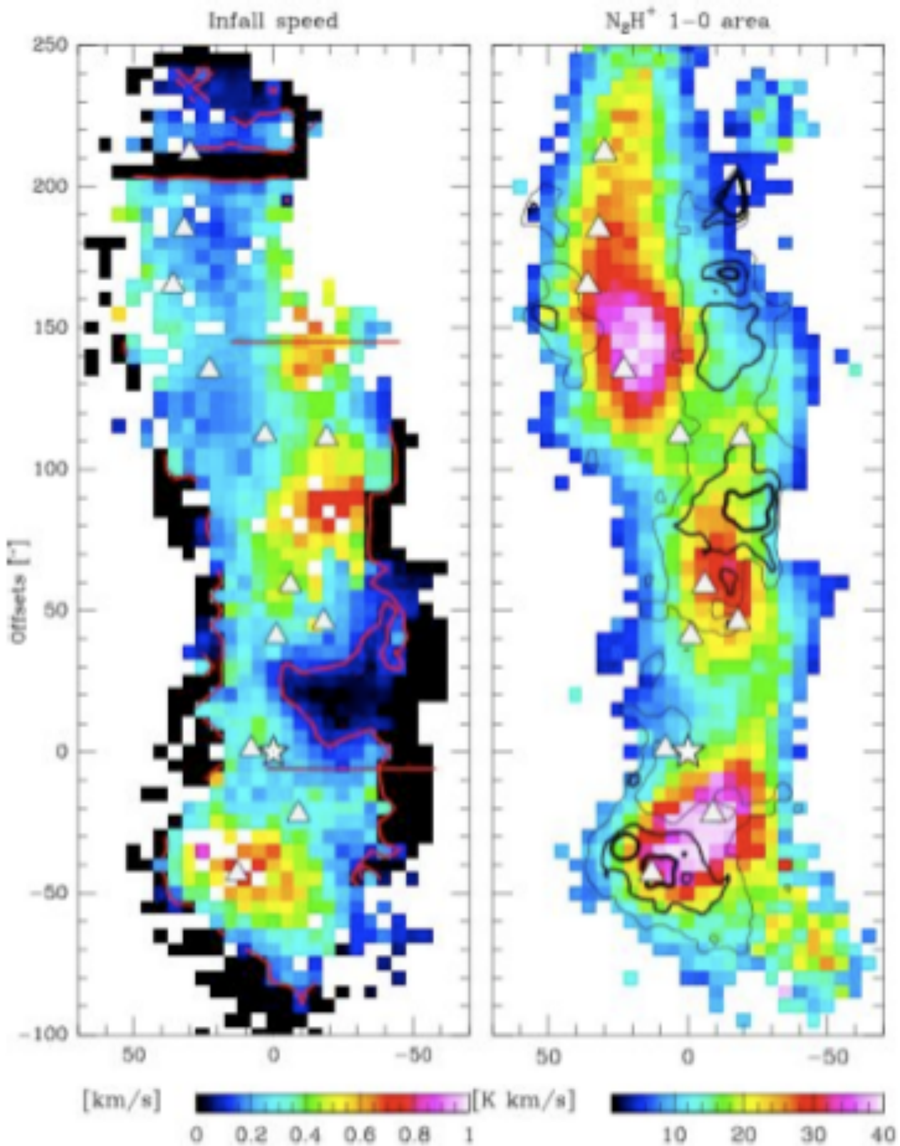


Modeling and synthetic observations of the Pipe nebula

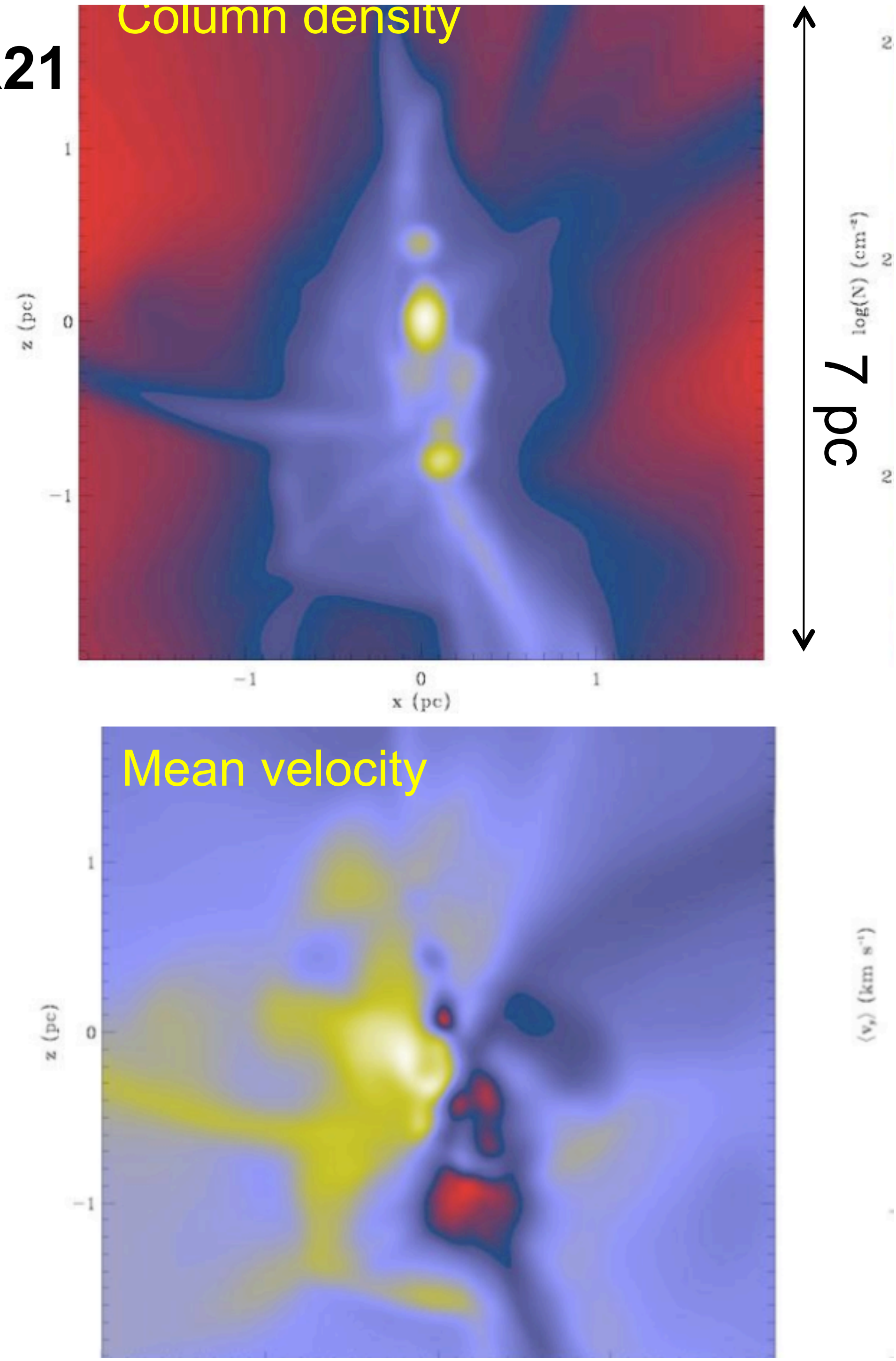
Heitsch et al. 08



Observations and model of DR21



Schneider et al. 2010



Conclusion

Numerical simulations suggest that molecular clouds may also have a 2-phase structure (WNM interclump medium)

-Reproduce various statistics of the observed ISM

-In a first phase turbulence is driven by accretion from the outside by the accretion of diffuse HI

2-phase turbulent accreting flow paradigm ?

Various regimes an ways to form filaments and cores:

-pure MHD turbulence (role of the shear and of B) forms filaments

-selection by gravity of turbulent density fluctuations forms core

-gravitational fragmentation can form filaments from layers and cores from filaments

-observations suggest some filaments (NGC2264c, Pipe, DR21 ?) are globally collapsing while fragmenting