Phases et turbulence dans le milieu interstellaire

Patrick hennebelle

Edouard Audit (CEA, Saclay)

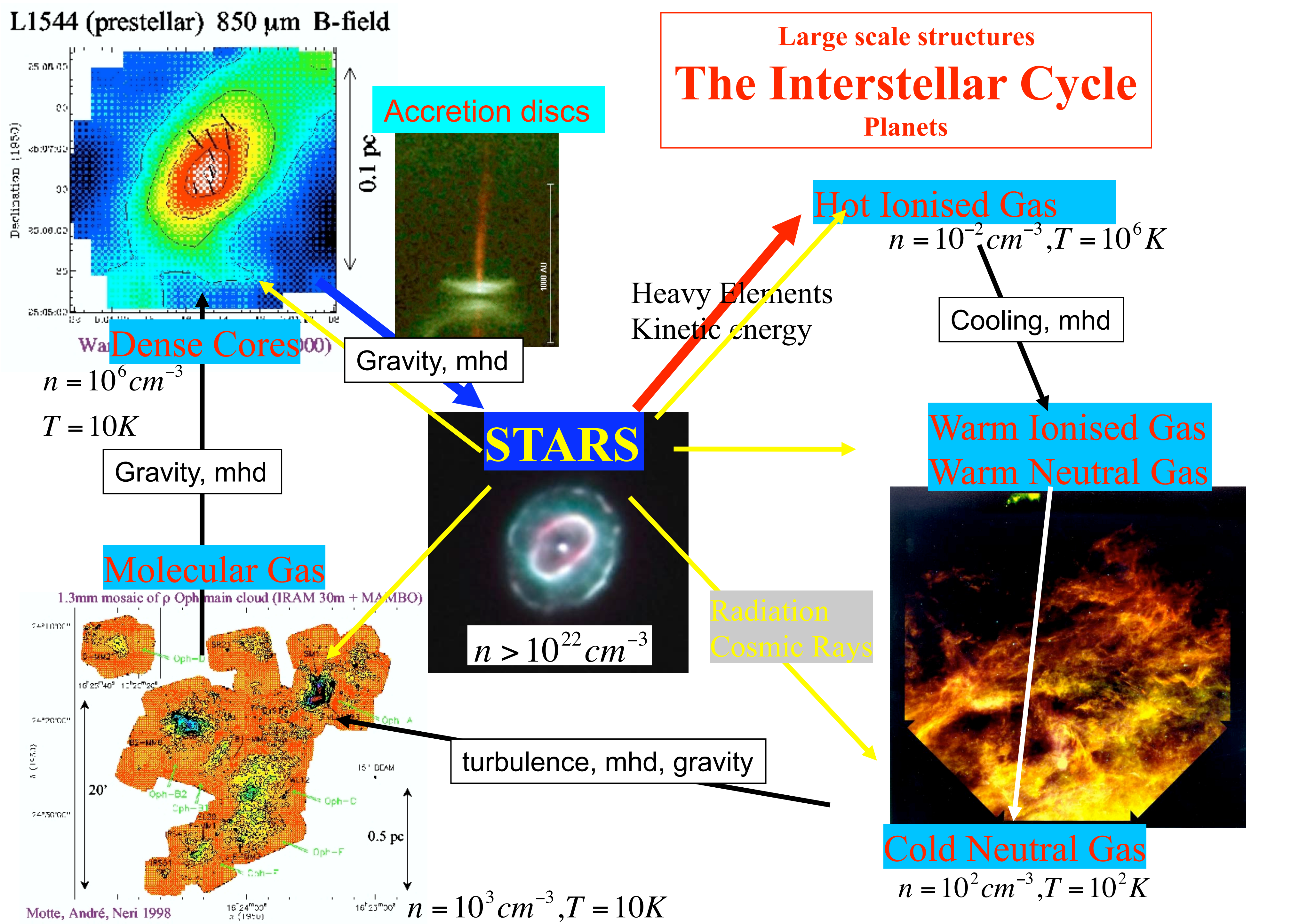
Plan

Aspects thermodynamiques : phases du MIS

Aspects dynamiques : turbulence compressible

Turbulence à 2-phases

Formation des nuages moléculaires
Impact du champ magnétique


Large scale structures
The Interstellar Cycle
Planets
L1544 (prestellar) 850 μm B-field
0.1 pc
Accretion discs
1000 AU
Dense Cores
$n = 10^6 cm^{-3}$
$T = 10K$
Gravity, mhd
Gravity, mhd
STARS
$n > 10^{22} cm^{-3}$
Hot Ionised Gas
$n = 10^{-2} cm^{-3}, T = 10^6 K$
Heavy Elements
Kinetic energy
Cooling, mhd
Warm Ionised Gas
Warm Neutral Gas
Radiation
Cosmic Rays
Molecular Gas
1.3mm mosaic of ρ Oph main cloud (IRAM 30m + MAMBO)
20'
0.5 pc
Motte, André, Neri 1998
$n = 10^3 cm^{-3}, T = 10K$
turbulence, mhd, gravity
Cold Neutral Gas
$n = 10^2 cm^{-3}, T = 10^2 K$

Outstanding questions regarding star formation:

The low star formation efficiency within the Galaxy
(2 orders of magnitude below naive estimate)
Zuckerman & Evans 1977

The distribution of stars as function of mass: the initial mass function

The binary fraction and binary characteristics

Many others…

Plan

Aspects thermodynamiques : phases du MIS

Aspects dynamiques : turbulence compressible

Turbulence à 2-phases

Formation des nuages moléculaires
Impact du champ magnétique

Atomic hydrogen: a thermally bistable Medium

Warm Neutral Medium (0.5 cm^{-3}, 10^4 K)

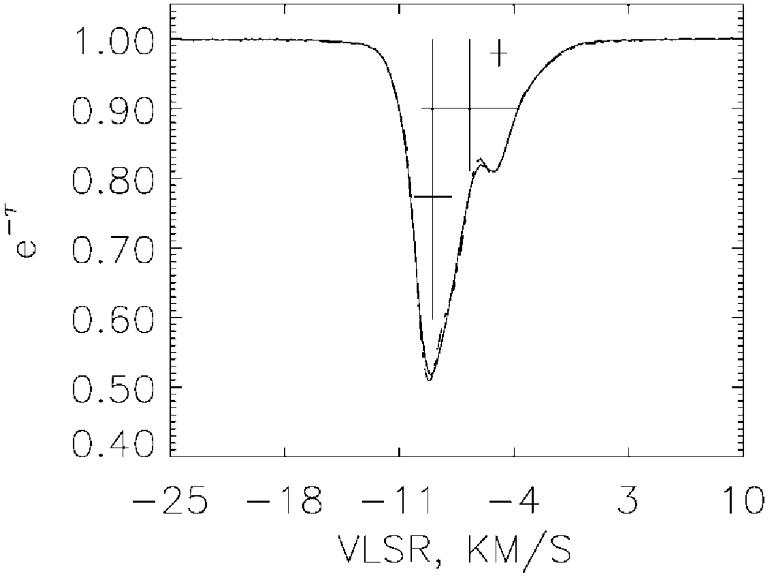
Cold Neutral Medium (50 cm^{-3}, 10^2 K)

HI Spectra (21cm)

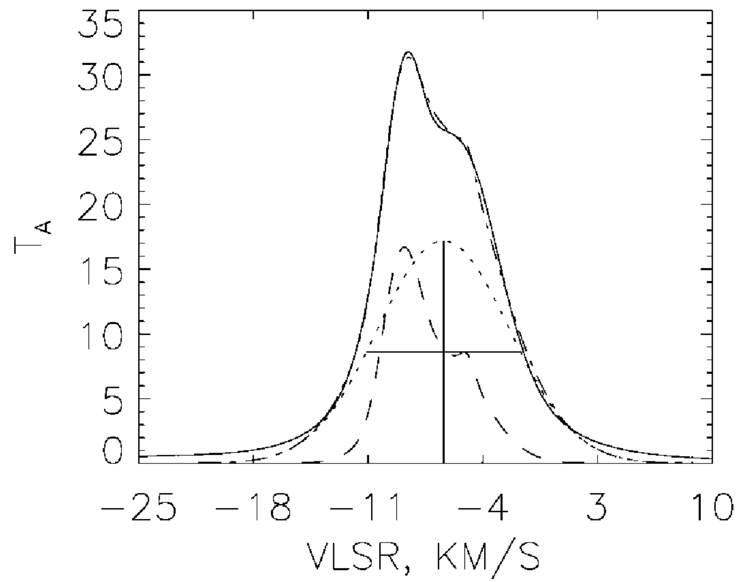
Absorption: $\int n/T\, dl$

Emission: $\int n\, dl$

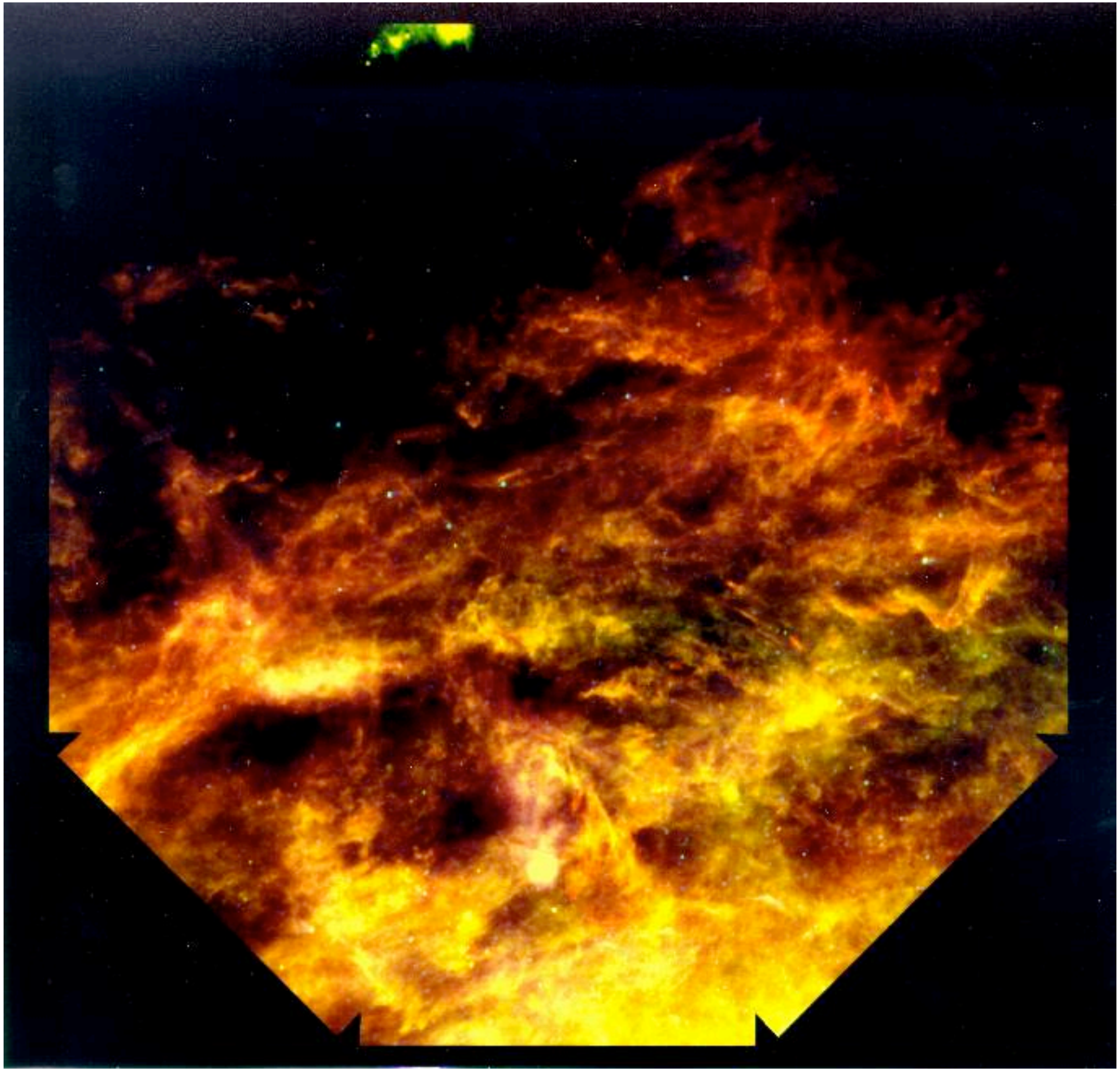
Absorption



Emission



Heiles 2001



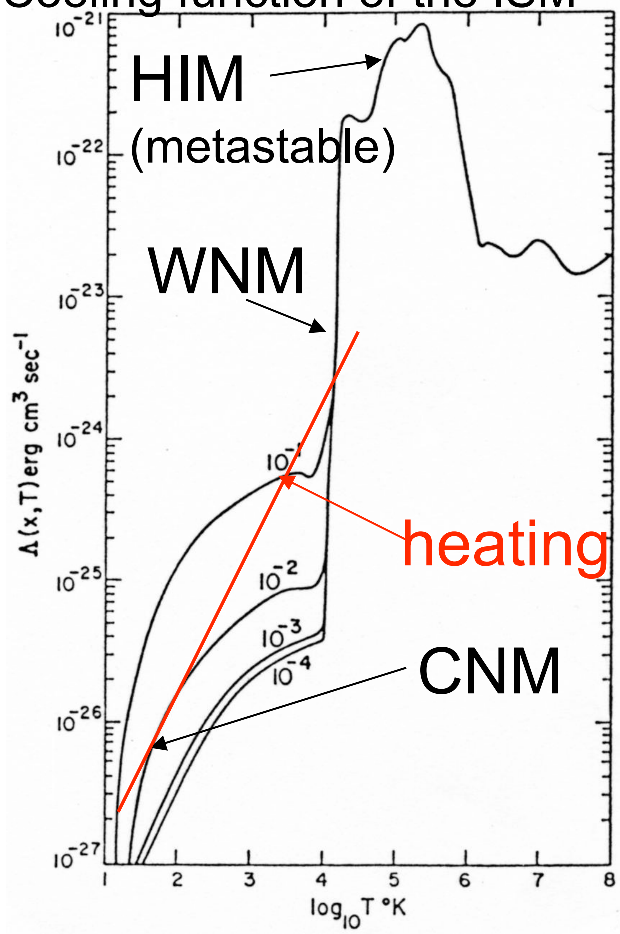
Galactic south pole (IRAS)

Thermal Processes and Thermal Instability

cooling:
due to collisional excitation followed
by a radiative deexcitation
(photon energy is lost)
H (Lyman alpha) for T> 1000K,
O and C+ for T < 1000 K
-mainly proportional to the square of density
-strong dependence on the temperature

heating:
due to photoelectric effect on small
dust grains and PaH
-mainly proportional to the density
-weak dependence on the temperature

Cooling function of the ISM



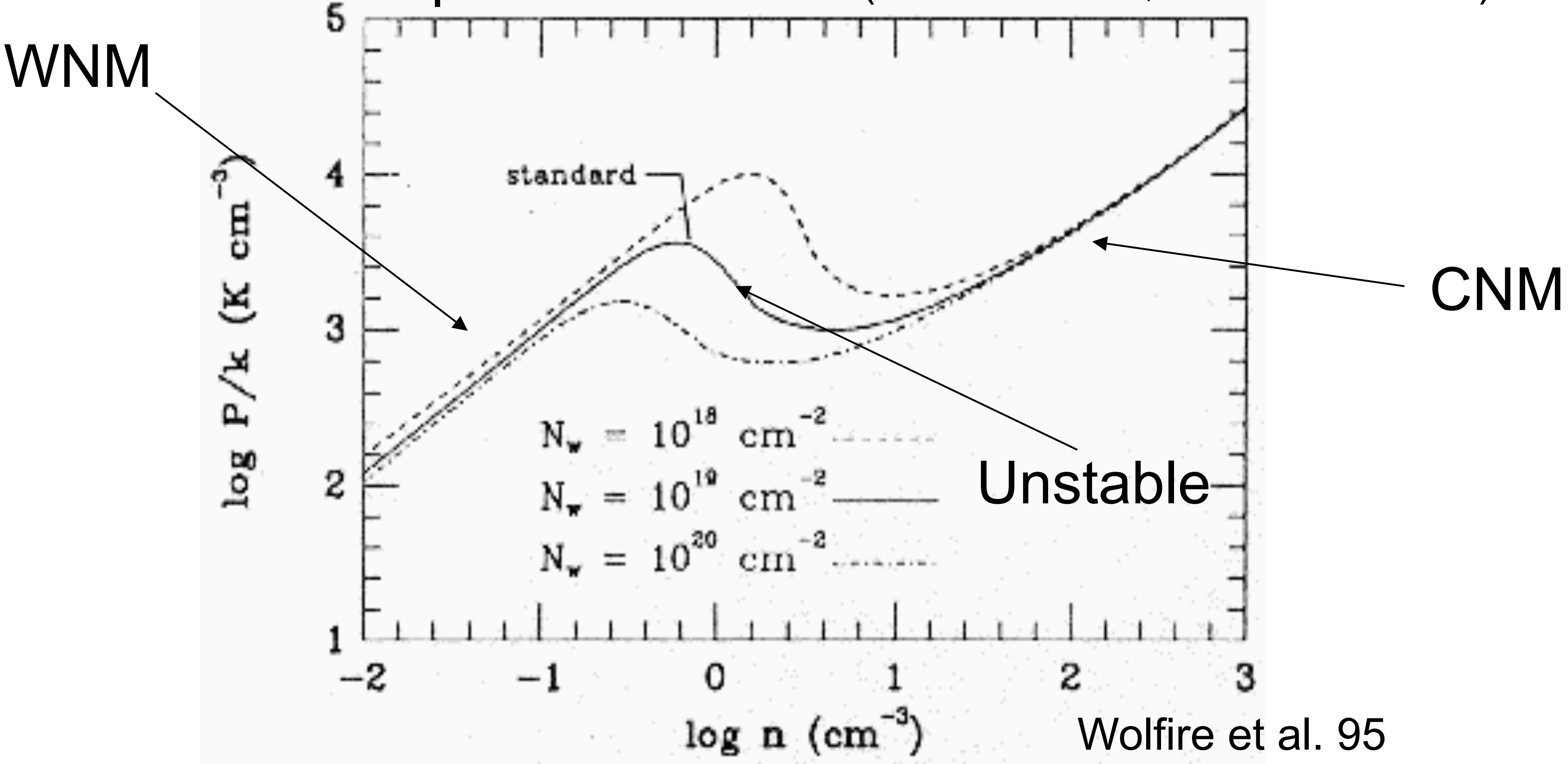
Dalgarno & Mac Cray 72

$$\rho \frac{d\varepsilon}{dt} = \Gamma\rho - \Lambda(T)\rho^2$$

If Λ(T) does not vary much with T,
the gas is very unstable

Need to take into account proper cooling:

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



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

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

A brief Description of the ISM

The Gas

The ISM is very inhomogeneous in density and temperature.

HIM : Hot Ionised Medium
ionised, 10^6 K, 0.01 cm^{-3}

WIM : Warm Ionised Medium
ionised, 8000 K, 0.5 cm^{-3}

WNM : Warm Neutral Medium
atomic neutral, 8000 K, 0.5 cm^{-3}

CNM : Cold Neutral Medium
atomic neutral, 70 K, 50 cm^{-3}

HIM, WIM, WNM and CNM (↕): Near Pressure equilibrium; > 50% of the ISM; Fill the volume

Molecular Hydrogen :
neutral, 10 K, 10^3-10^6 cm^{-3}

Molecular Hydrogen (↕): Self-gravitating

Plan

Aspects thermodynamiques : phases du MIS

Aspects dynamiques : turbulence compressible

Turbulence à 2-phases

Formation des nuages moléculaires
Impact du champ magnétique

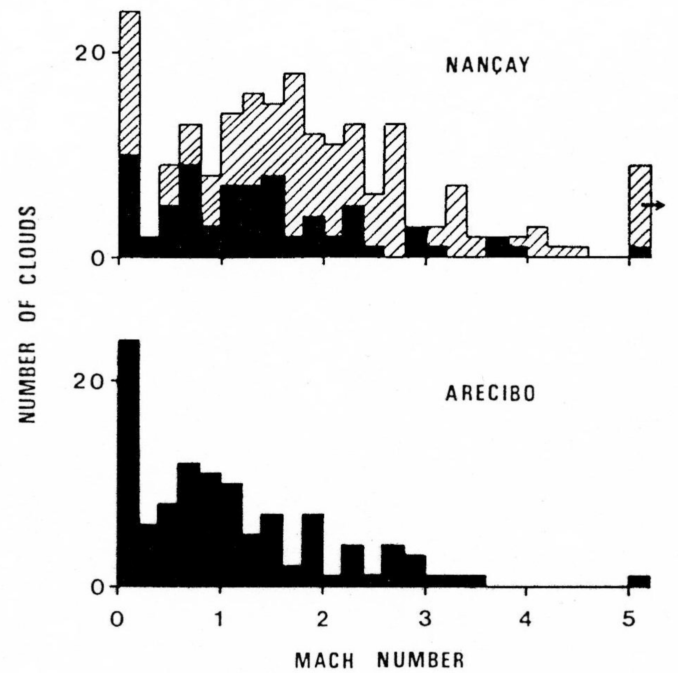
The Mechanical Energies

Thermal Energy:
P/k=4000 K/cm^3, Utherm=10^{-12} erg/cm^3

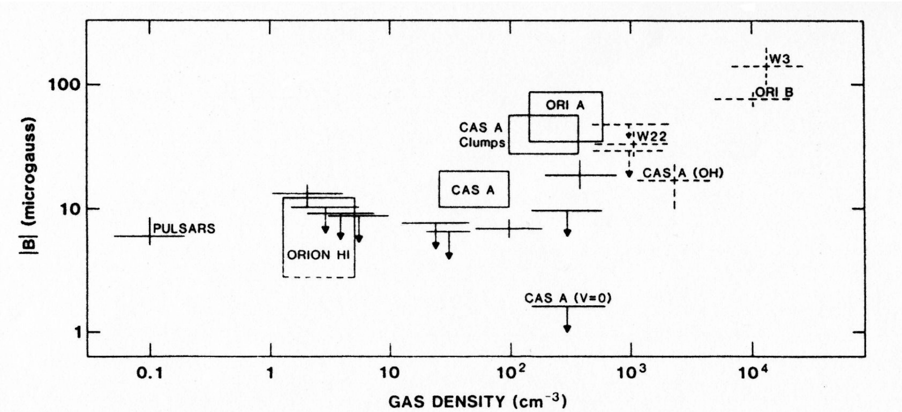
Turbulent Energy:
sonic to supersonic velocity dispersion
(up to Mach 5)
=> Eturb / Etherm = 1-20

Magnetic Energy:
magnetic intensity: 5 μG
=> Emag / Etherm = 1-5

=> Energy near Equipartition



PDF of the Mach number
in HI clouds (Crovisier 91)



Magnetic Intensity
as a function of density
(Troland & Heiles 86)

Big powerlaws in the sky….. Turbulence ?

Density of electrons
within WIM (Rickett et al. 1995)

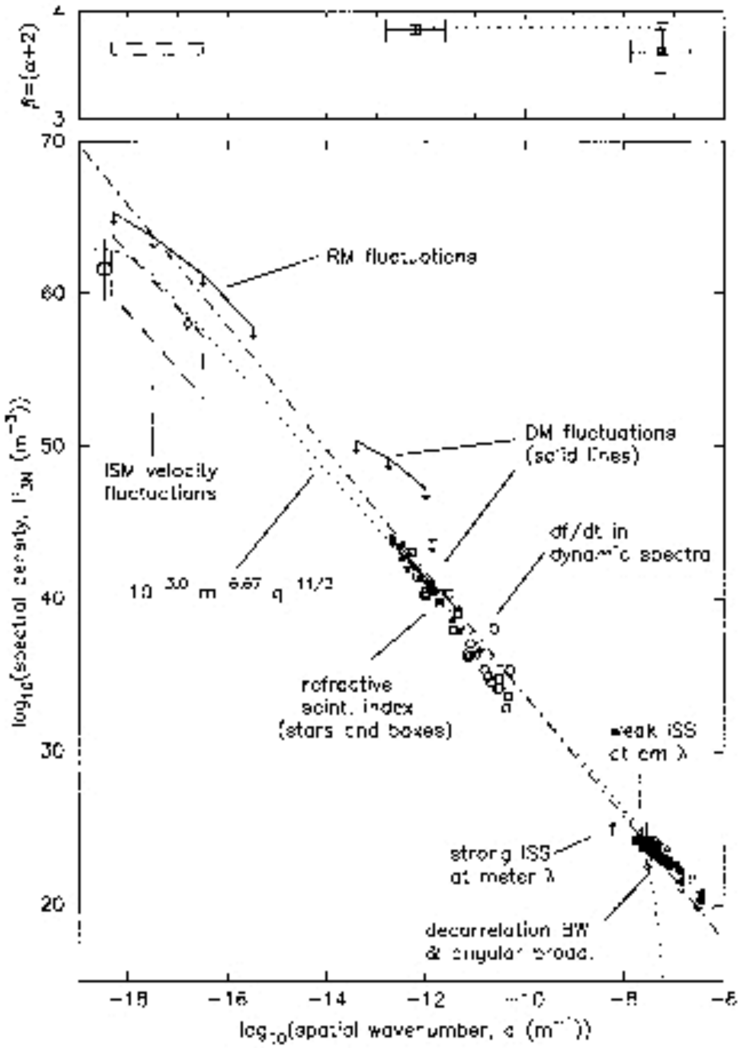


FIG. 1.—*Lower panel:* Logarithmic plot of inferred three-dimensional electron density power spectrum vs. wavenumber. References for the observations and symbols for the technique involved are given in the text; from high to low wavenumber the data are from angular broadening, coherence bandwidth, weak DISS at centimeter wavelengths, strong DISS at meter wavelengths

Intensity of HI and dust emission
Gibson 2007

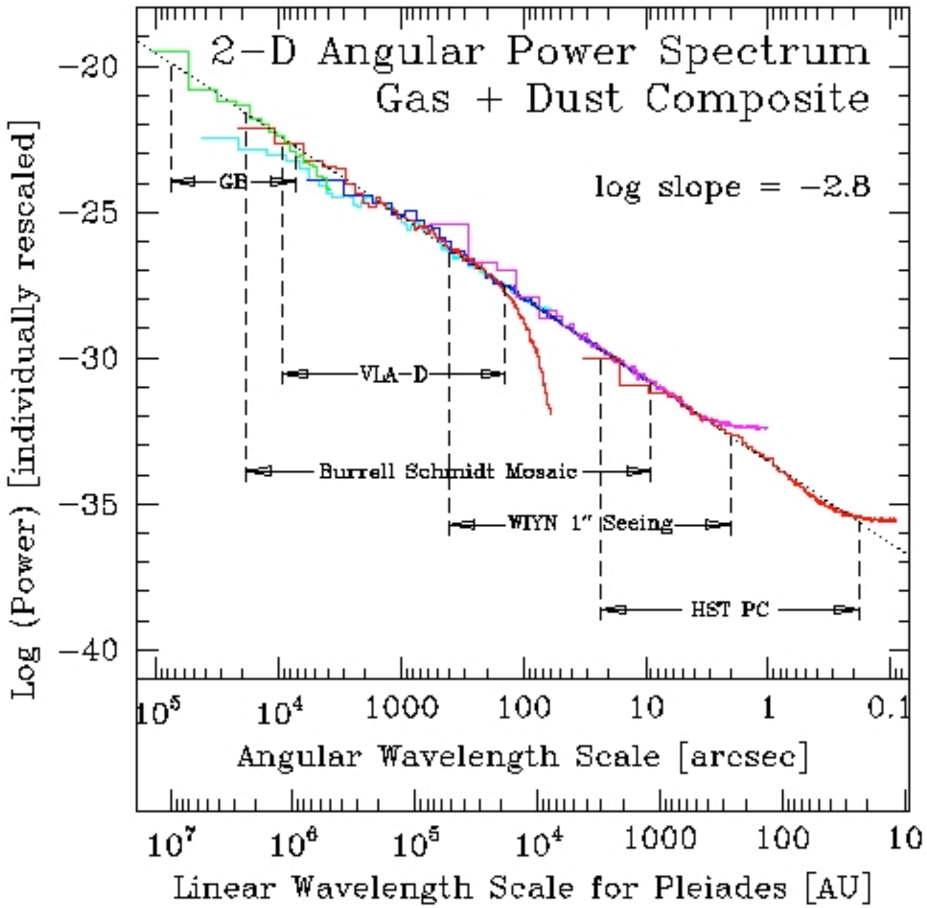


Figure 4. Composite of the optical and H I angular power spectra shown in Figures 1-3. The relative scalings have been adjusted to fit a uniform power law, but the slope of each spectrum is unaltered. The dashed lines mark ranges of measurement for each data set. "Wavelength" = 1/spatial frequency. The maximum wavelength of any image is the image width, and the minimum is either twice the beam width or twice the pixel width, whichever is greater.

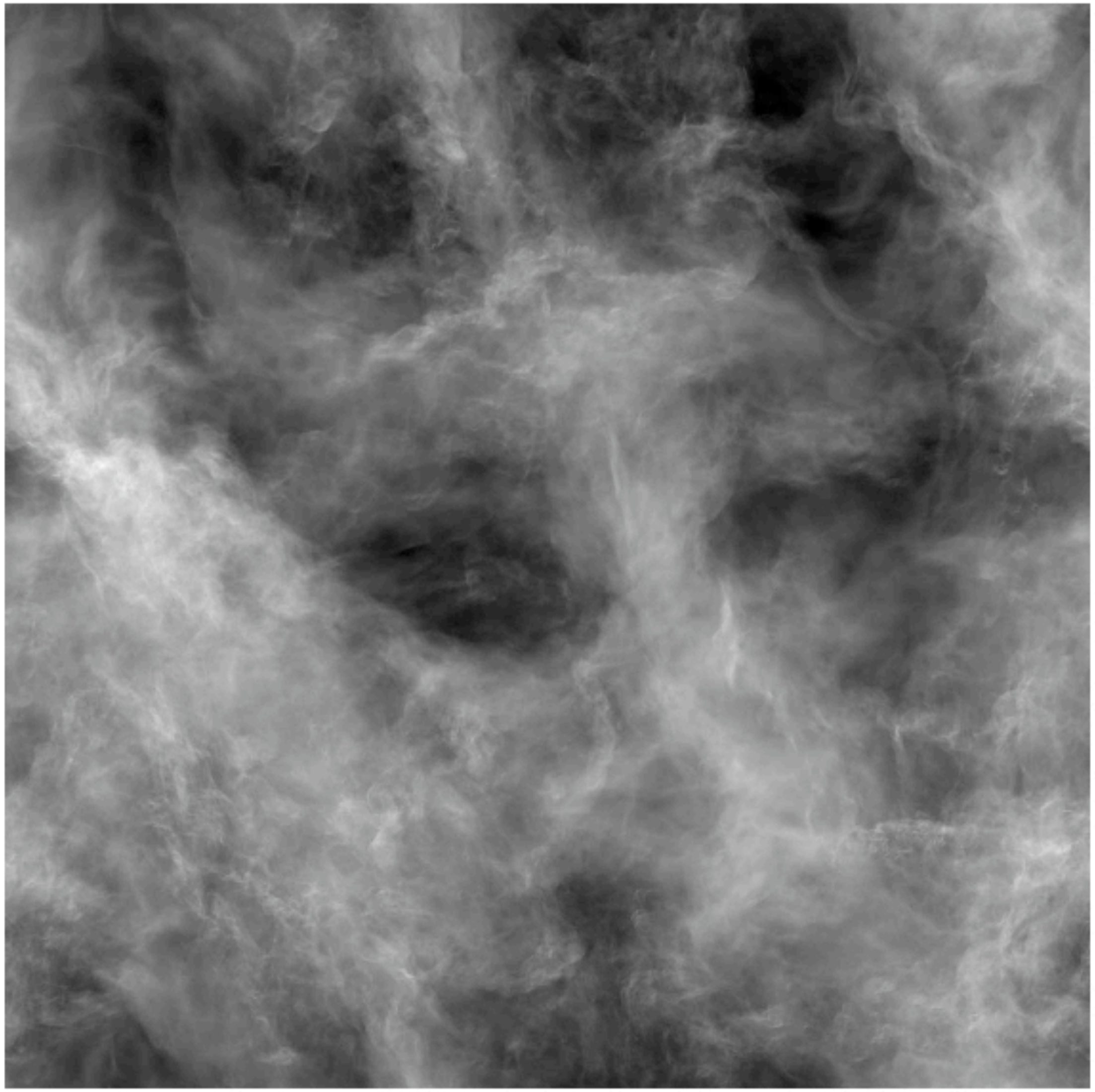
Supersonic isothermal turbulence

(amongst many others e.g. Scalo et al. 1998, Passot & Vazquez-Semadeni 1998, Padoan & Nordlund 1999, Ostriker et al. 2001, MacLow & Klessen 2004, Beresnyak & Lazarian 2005, Kritsuk et al. 2007)

3D simulation of supersonic isothermal turbulence with AMR 2048 equivalent resolution Kritsuk et al. 2007

Random solenoidal forcing is applied at large scales ensuring constant rms Velocity.

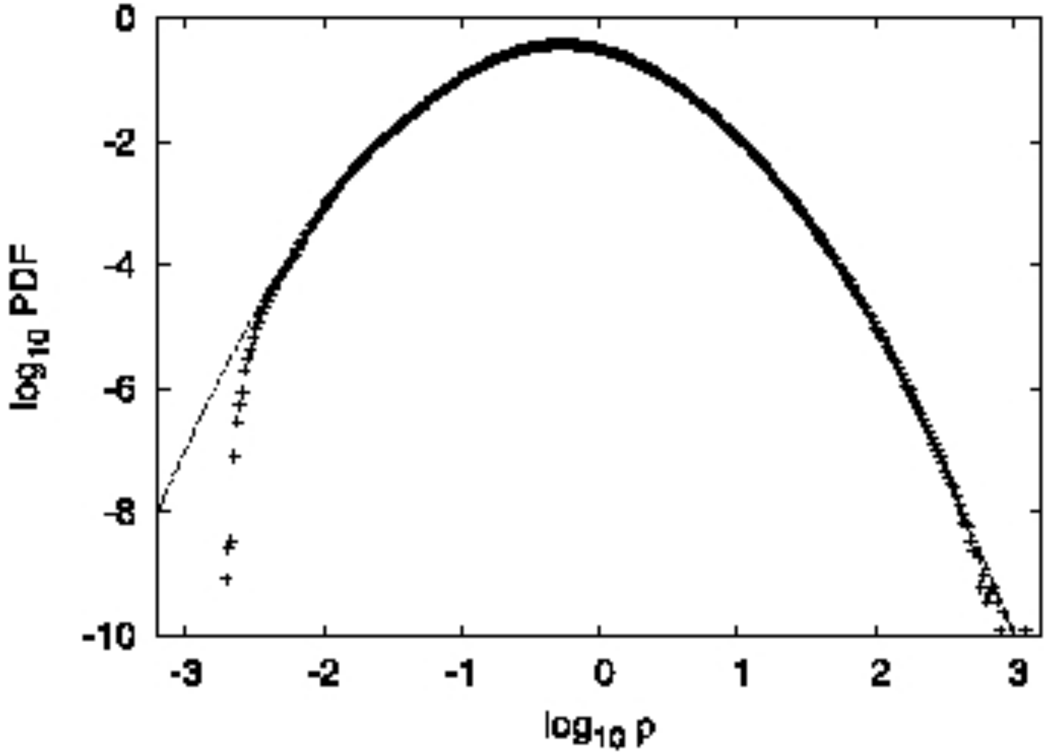
Typically Mach=6-10



Kritsuk et al. 2007

PDF of density field

(Padoan et al. 1997, Kritsuk et al. 2007)



A lognormal distribution:

$$P(\delta) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\delta + \sigma^2/2)^2}{2\sigma^2}\right)$$

$$\delta = \ln(\rho/\overline{\rho}), \sigma^2 \approx \ln\left(1 + 0.25 \times M^2\right)$$

$$\frac{\sigma_\rho}{\overline{\rho}} \approx bM^2$$

$$P(\rho)d\rho = P(\delta)d\delta$$

$$\sigma_\rho^2 = \int (\rho - \overline{\rho})^2 P(\rho) d\rho$$

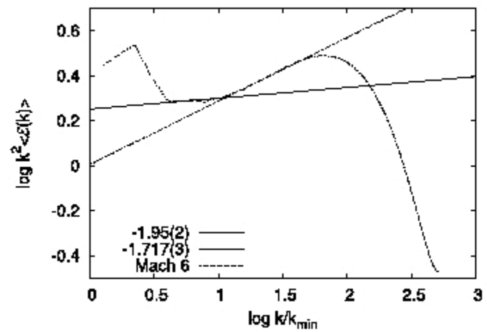
$$= \overline{\rho}^2 \int (\exp(\delta) - 1)^2 P(\delta) d\delta$$

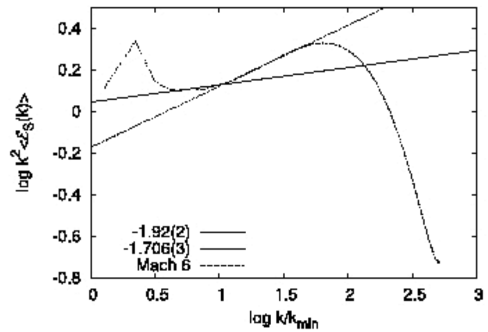
Power spectra of

-velocity

-incompressible modes

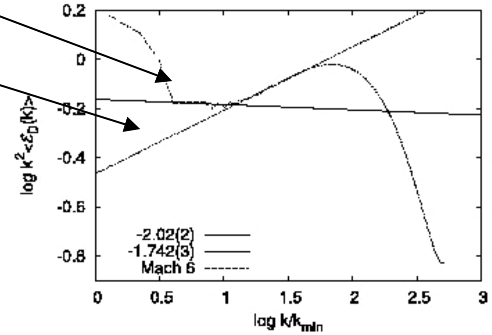
-compressible modes





Inertial domain

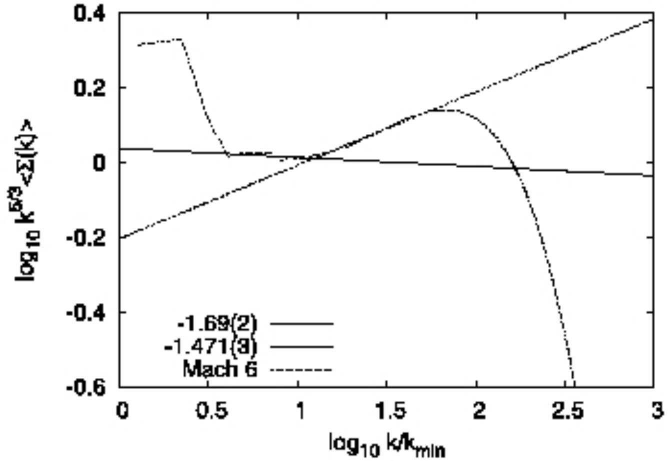
Bottle neck effect



Value between around 1.9 between K41 and Burgers

Kritsuk et al. 2007

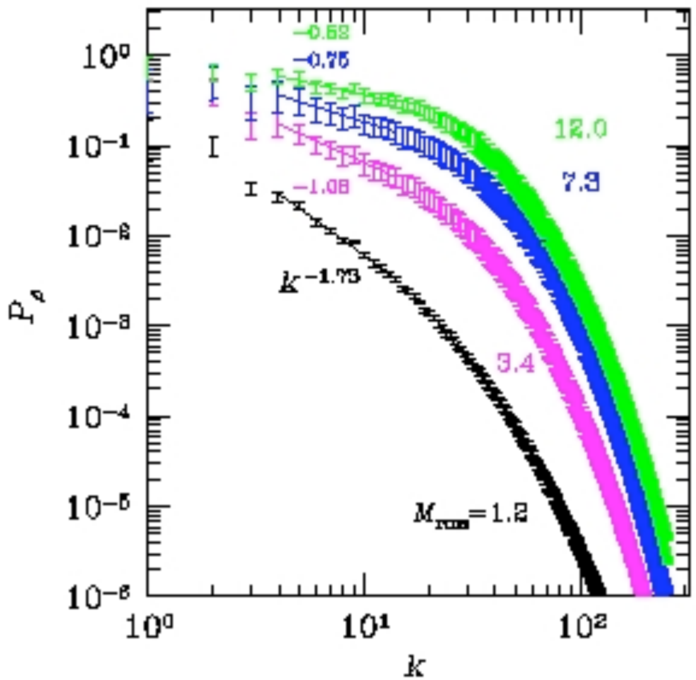
Power spectra of corrected velocity



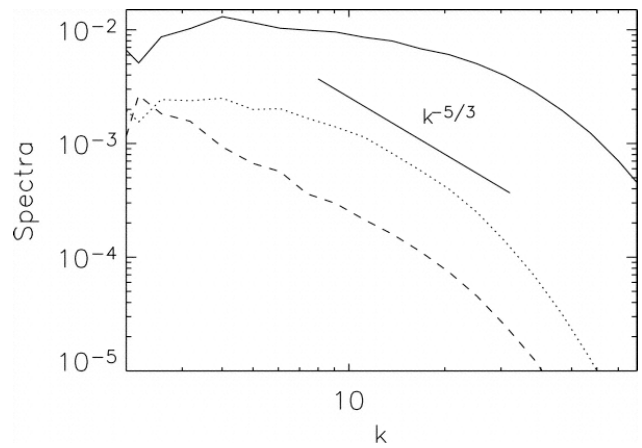
$$\varepsilon = \frac{\rho v^3}{l} \Rightarrow \rho^{1/3} v \approx l^{1/3}$$

Value 1.69 i.e. closer to K41

density power spectrum



Logarithm of density power spectrum



(Beresnyak et al. 2005, Kritsuk 2007, Federath et al. 2008)

For low Mach numbers,
The PS is close to K41
Whereas for high Mach numbers
The PS becomes much flatter
("Peak effect", PS of a Dirac is flat)

Index close to Kolmogorov
Due to:

$$\partial_t \delta + v.\nabla\delta = -\nabla v$$

Plan

Aspects thermodynamiques : phases du MIS

Aspects dynamiques : turbulence compressible

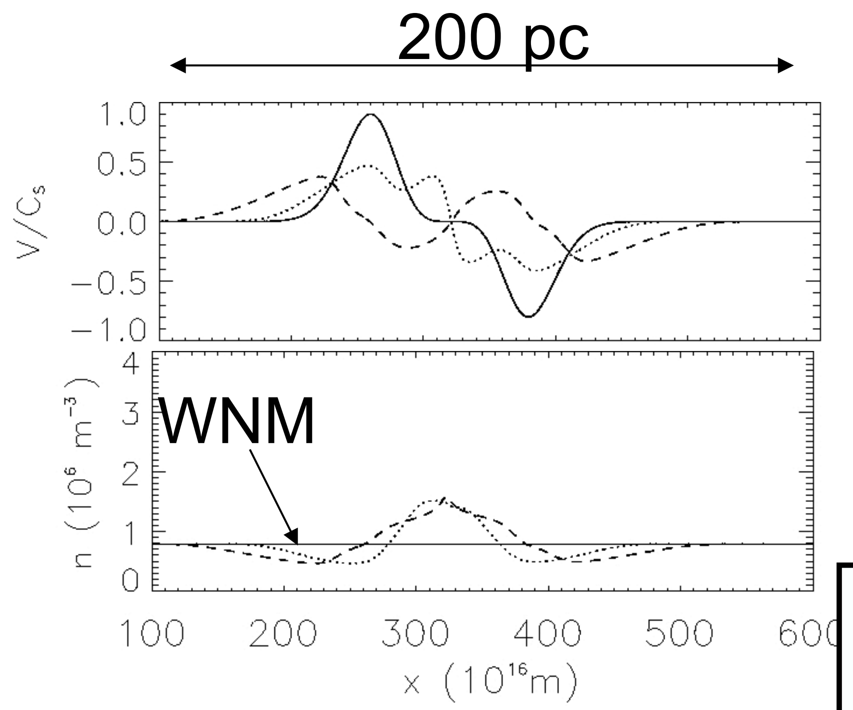
Turbulence à 2-phases

Formation des nuages moléculaires
Impact du champ magnétique

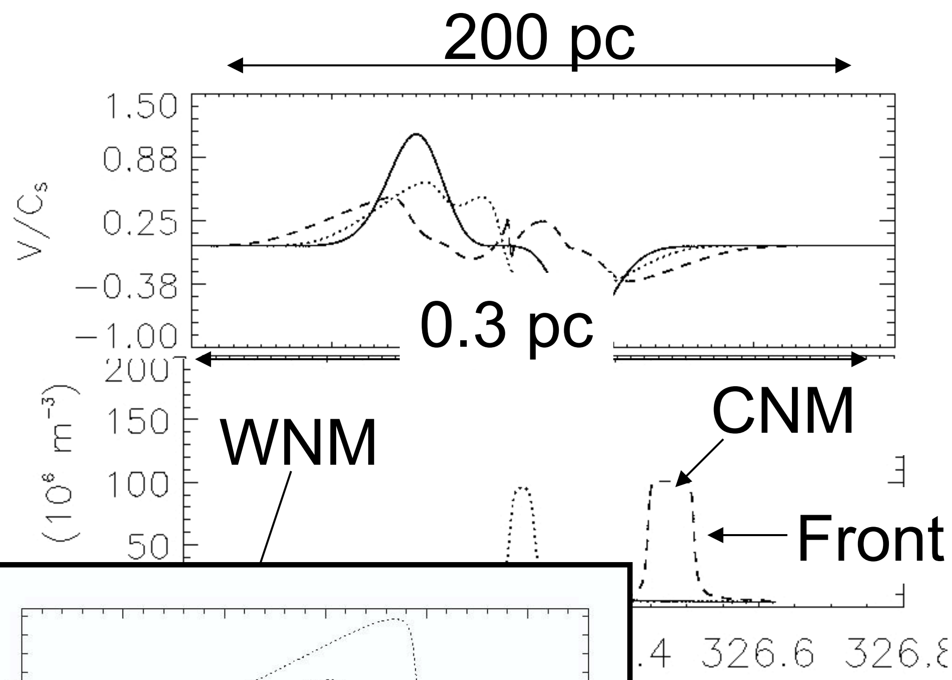
Dynamical triggering of thermal instability

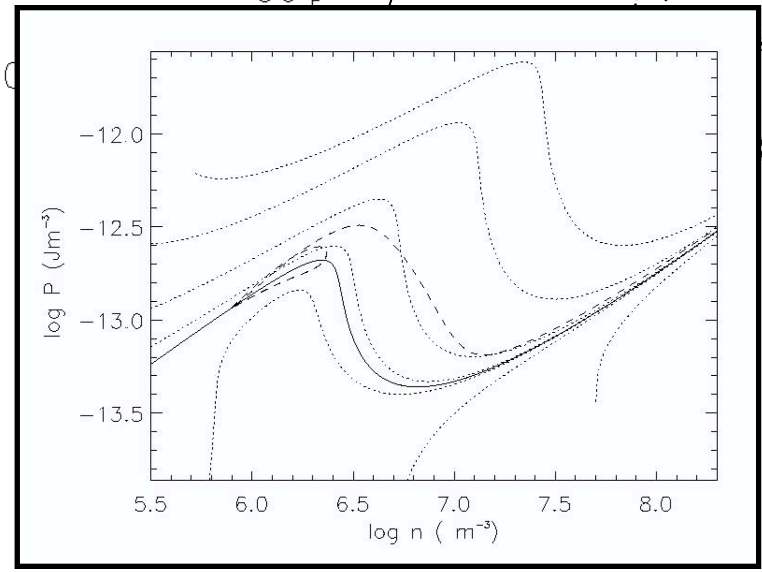
(Hennebelle & Pérault 99, Koyama & Inutsuka 2000, Sanchez-Salcedo et al. 2002)

A converging flow which does not trigger thermal transition:



A **slightly** stronger converging flow does trigger thermal transition:





⇒WNM is linearly stable but non-linearly unstable

Hennebelle & Pérault 99

Thermal transition induced by the propagation of a shock wave

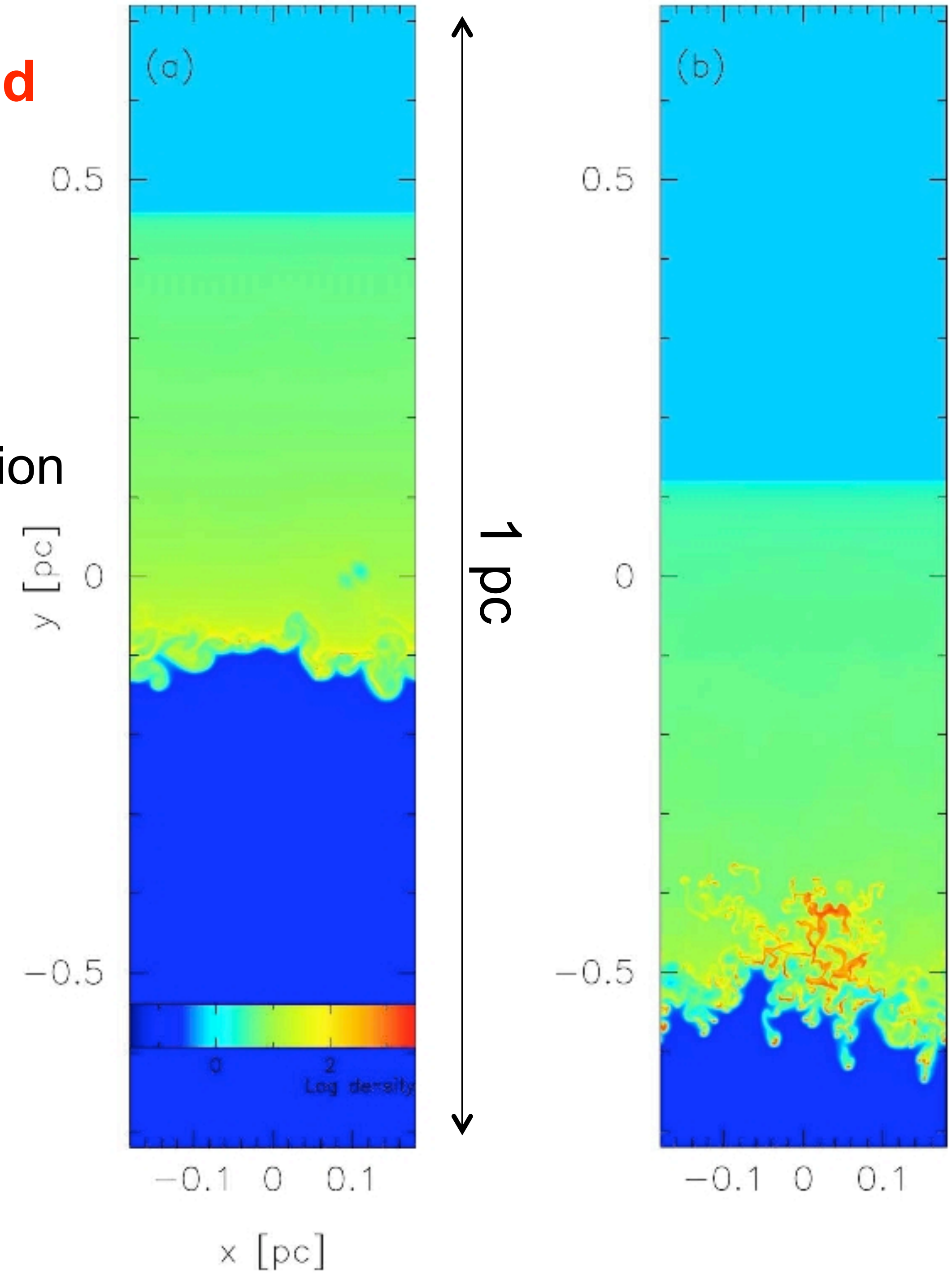
(Koyama & Inutsuka 02)

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, Heitsch et al. 05, 06, Vazquez-Semadeni et al. 06)

-Forcing from the boundary

-Statistical stationarity reached

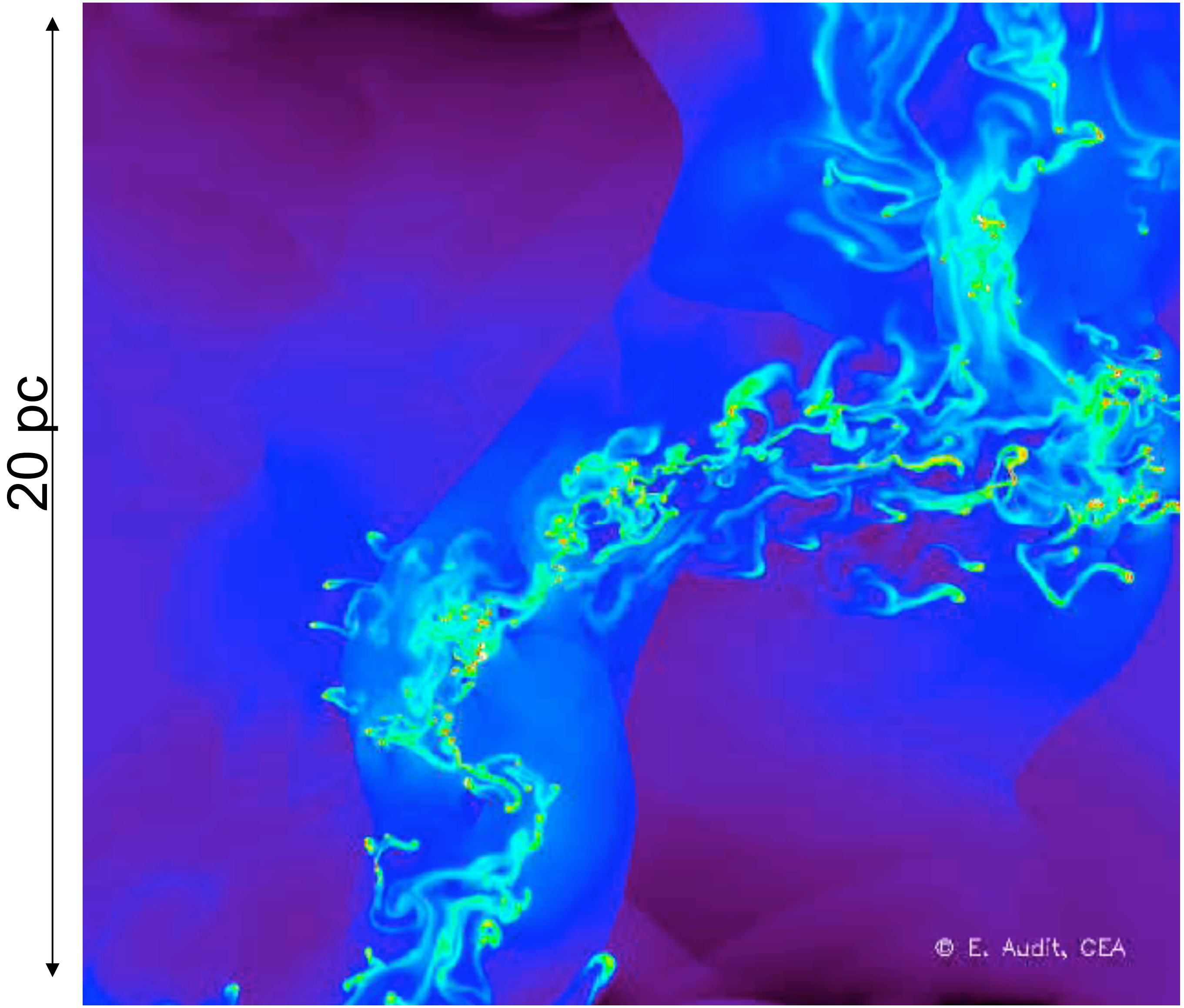
-complex 2-phase structure

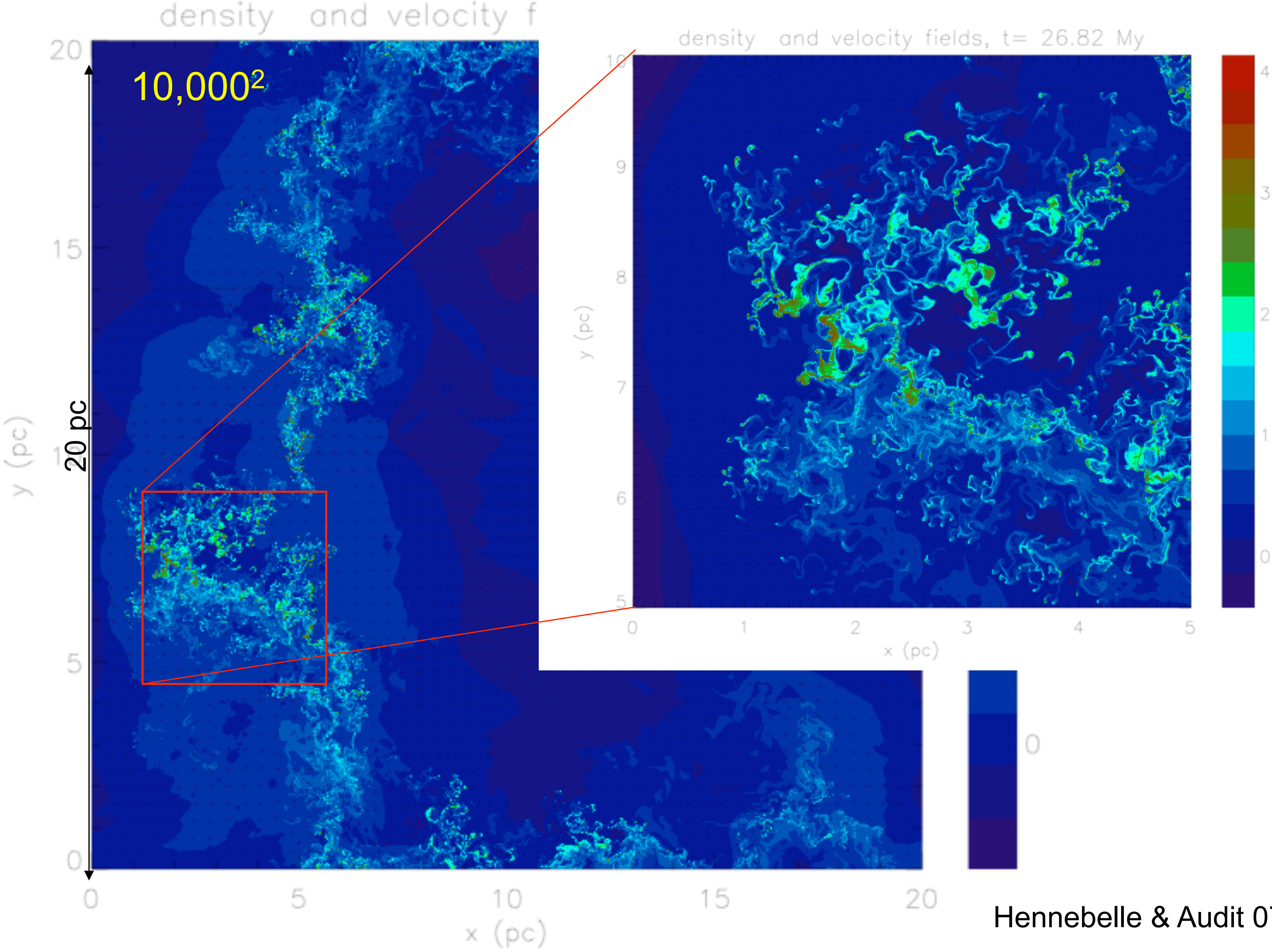
-cnm very fragmented

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

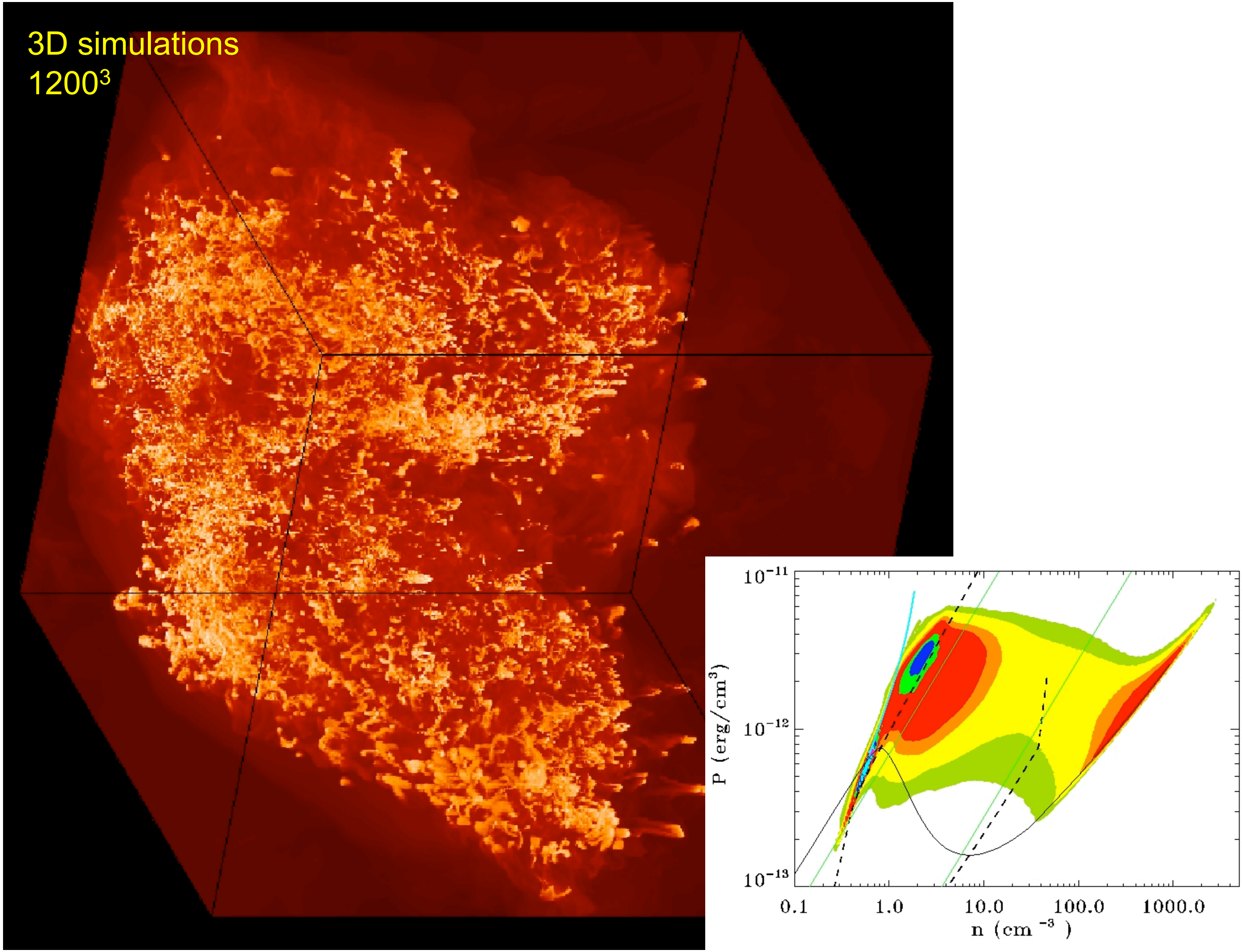
2500^2

Audit & Hennebelle 05





Hennebelle & Audit 07

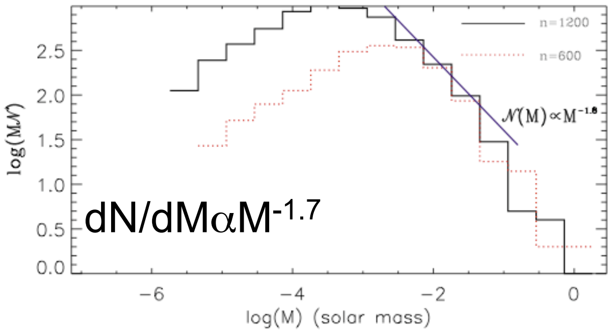


3D simulations
1200³
P (erg/cm³)
10⁻¹¹
10⁻¹²
10⁻¹³
0.1
1.0
10.0
100.0
1000.0
n (cm ⁻³)

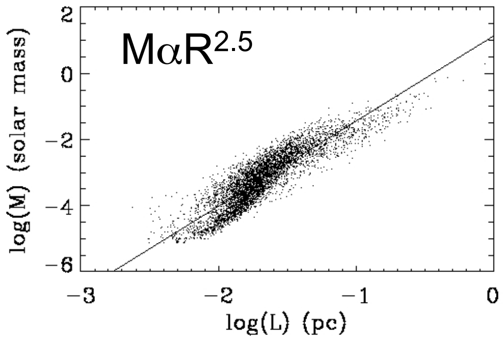
Forming molecular clouds self-consistently from diffuse gas

Statistics of structures:

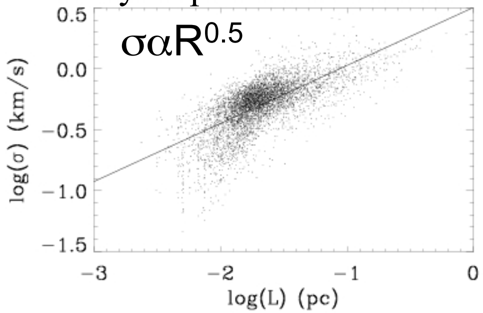
Mass spectrum of clumps



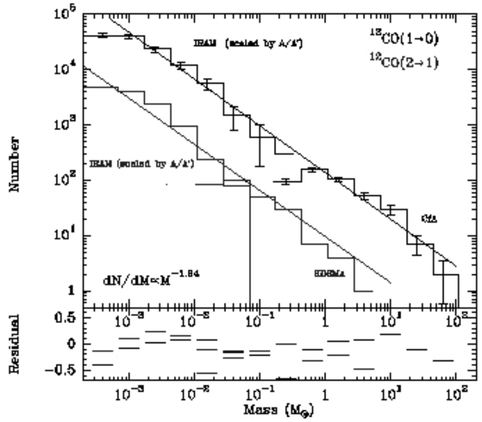
Mass versus size of clumps



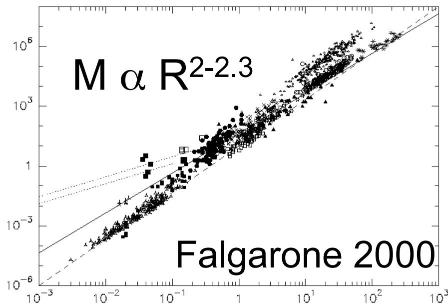
Velocity disp. versus size of clumps



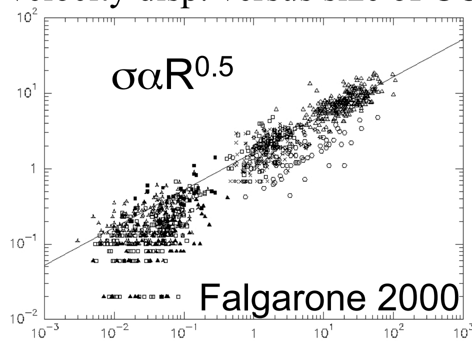
Universal Mass Spectrum
$dN/dM \propto M^{-1.6\text{-}1.8}$ (Heithausen et al .98)



Mass versus size of CO clumps



Velocity disp. versus size of CO clumps



Plan

Aspects thermodynamiques : phases du MIS

Aspects dynamiques : turbulence compressible

Turbulence à 2-phases

Formation des nuages moléculaires
Impact du champ magnétique

Formation of molecular clouds

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

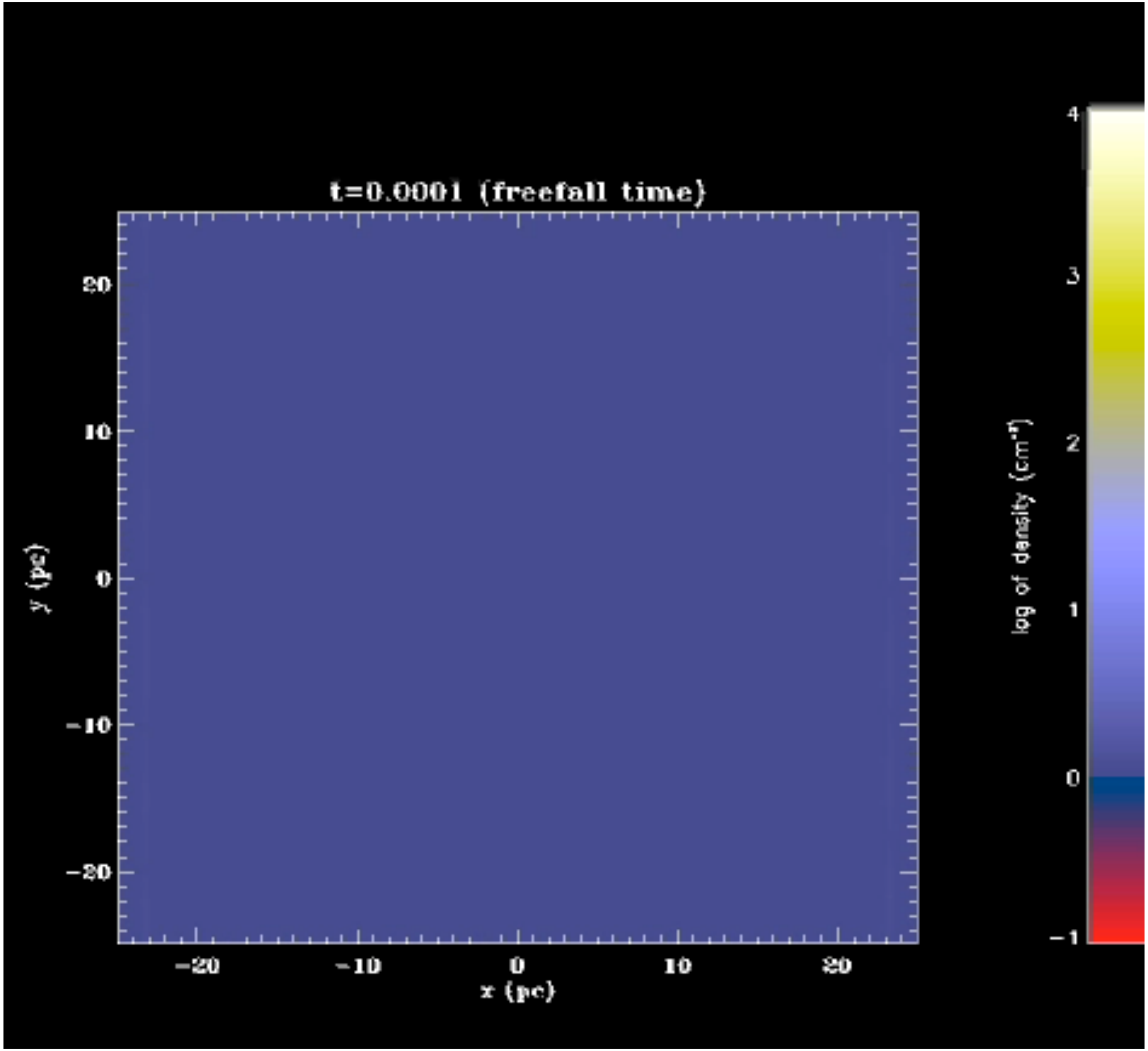
Suggest that connecting MC and HI spatially and temporally could be important

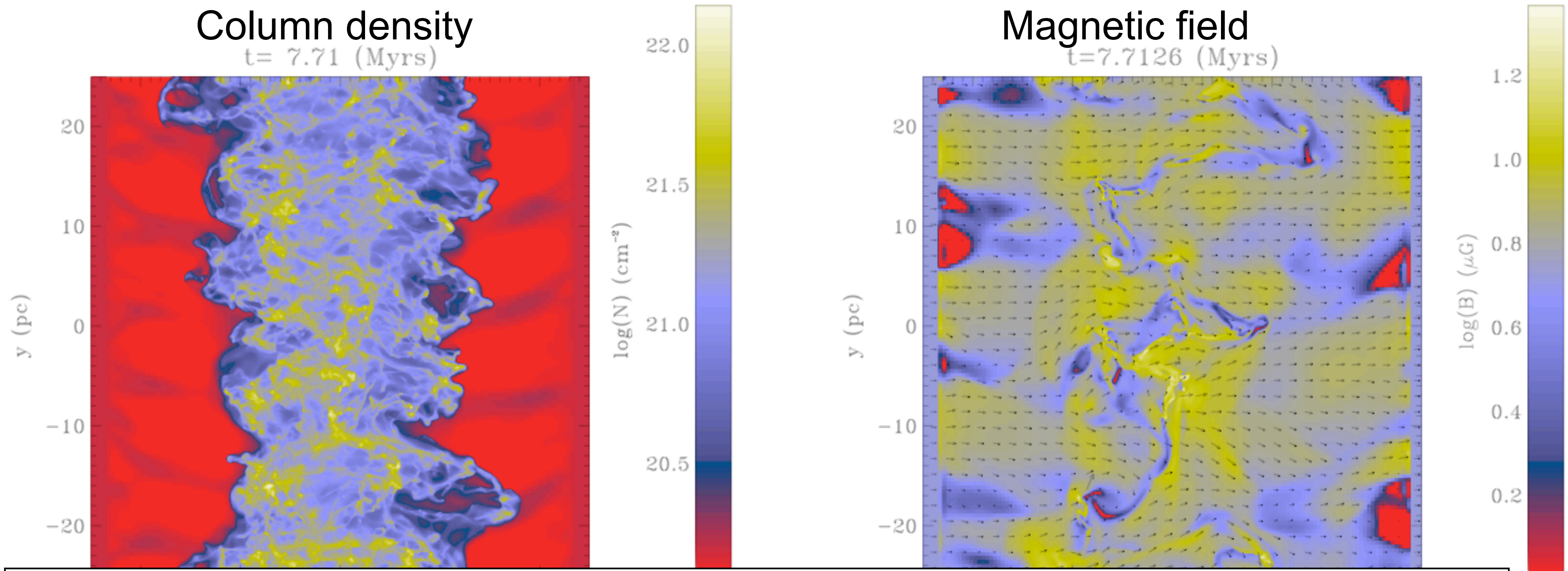
Attempt to form MC starting from WNM

-self-consistent way of generating structures within the cloud

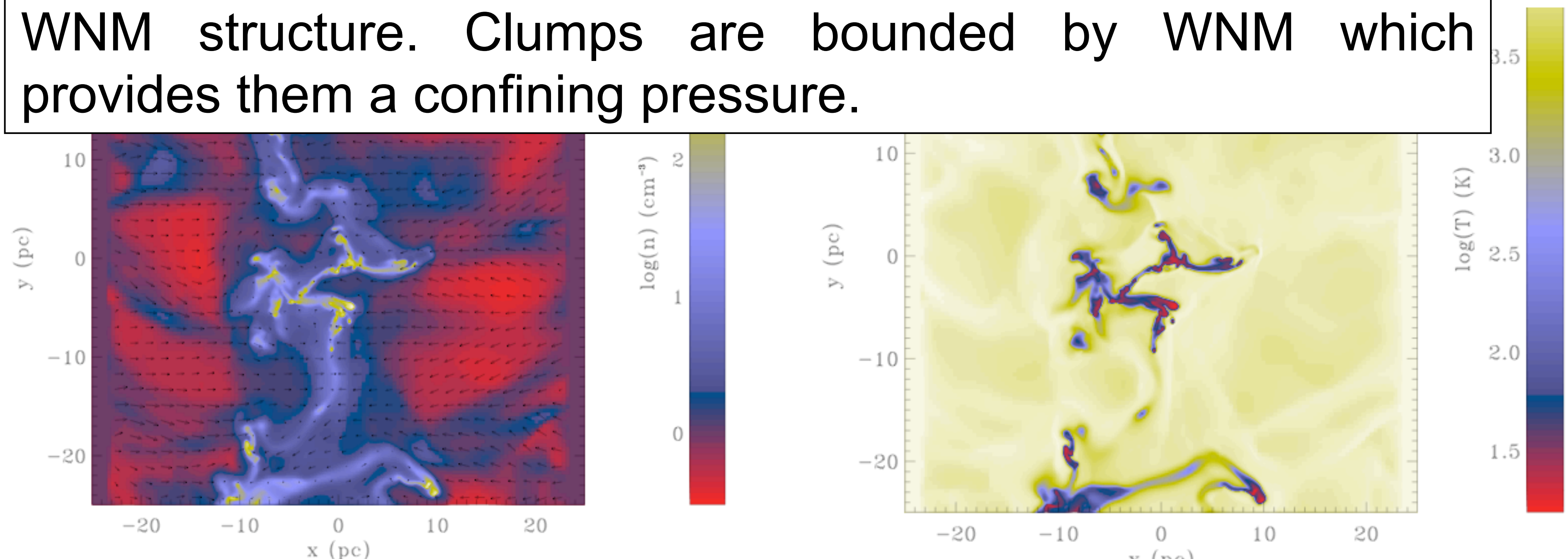
-self-consistent energy input from the outside

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

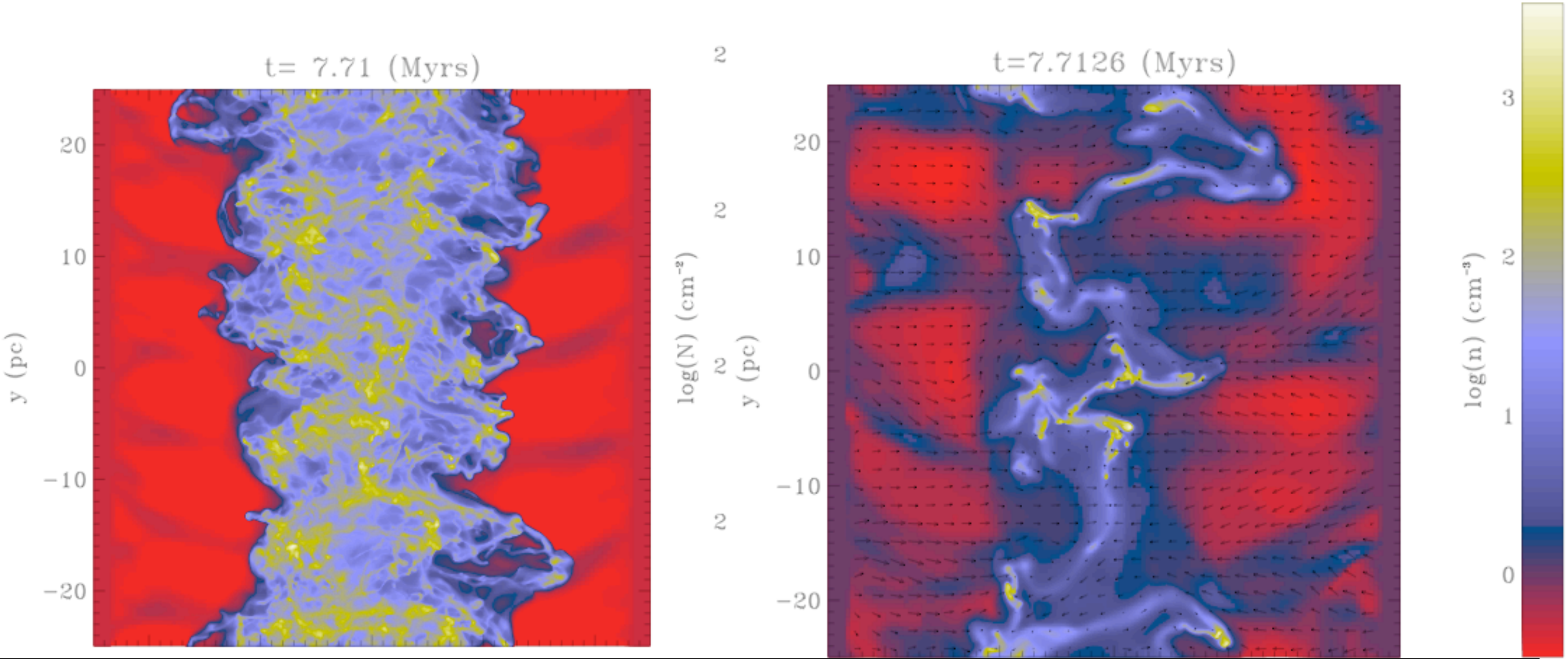

t=0.0001 (freefall time)
20
10
0
−10
−20
y (pc)
−20
−10
0
10
20
x (pc)
4
3
2
1
0
−1
log of density (cm⁻³)



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.

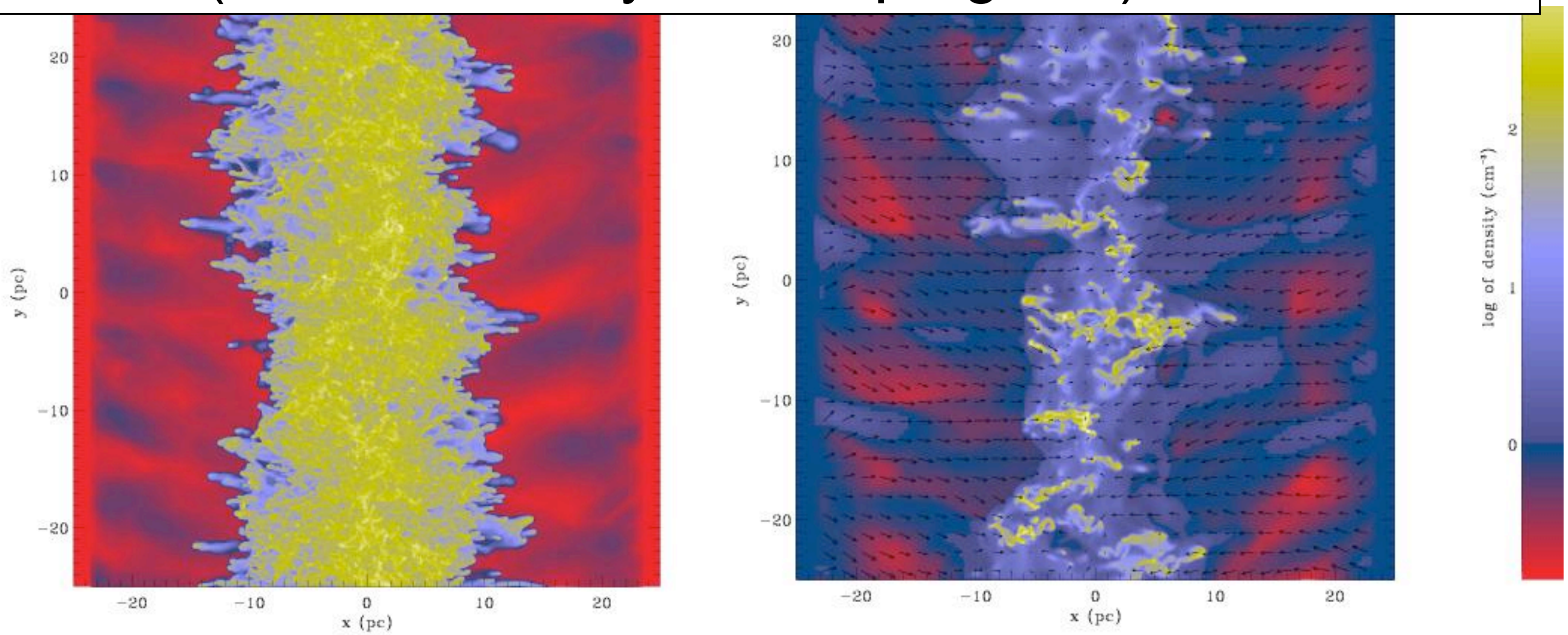


MHD case

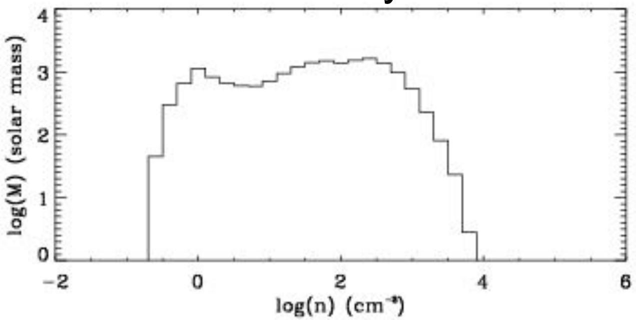


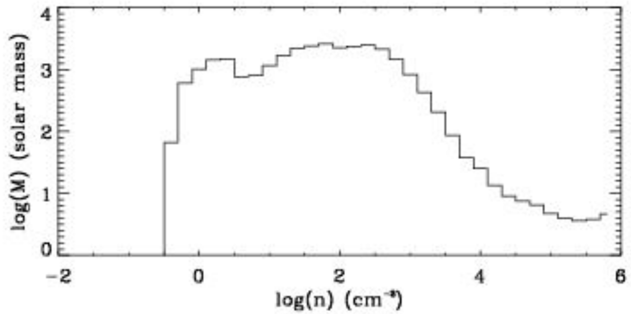
Magnetic field has a big impact on the cloud and clumps structure (statistical analysis is in progress).

hydro case

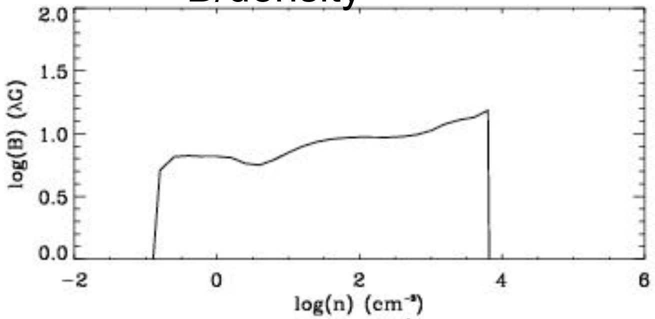


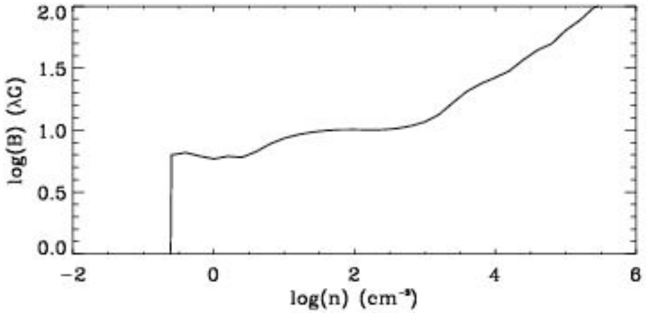
Mass/density



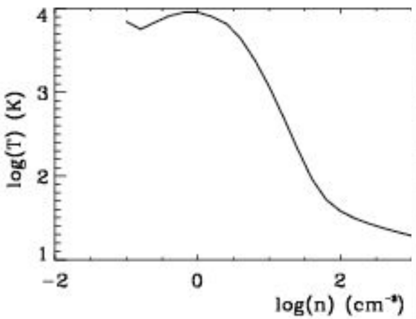


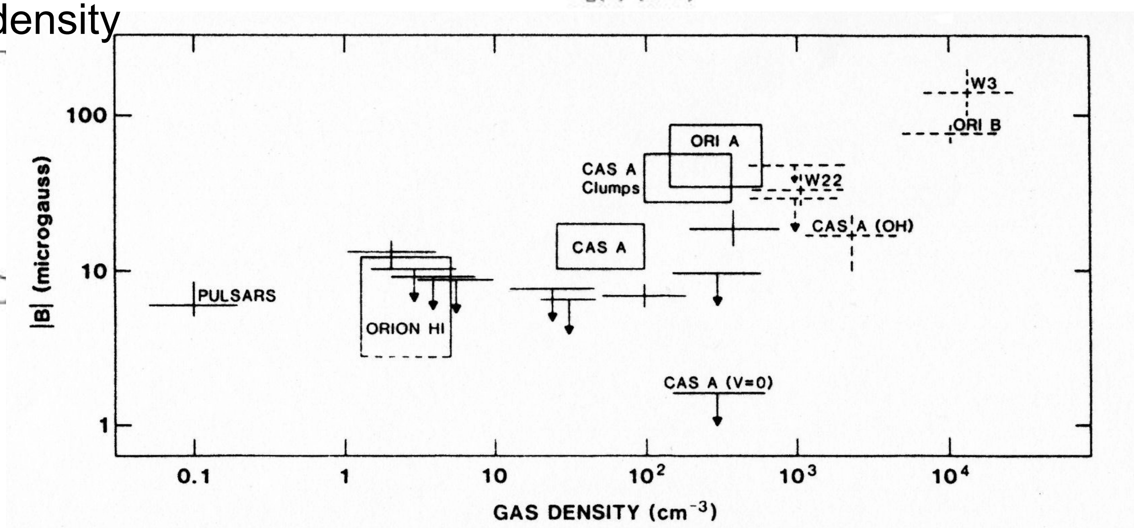
B/density





Temperature/density





Troland & Heiles 1986

Conclusion