50+ years of thermal instability

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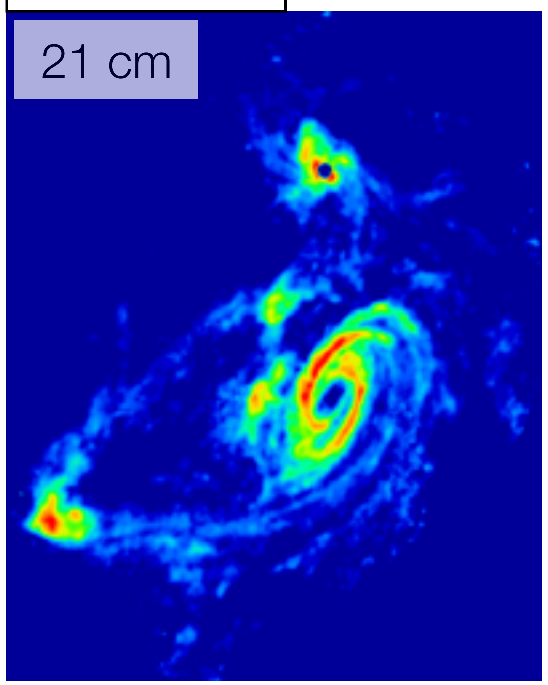
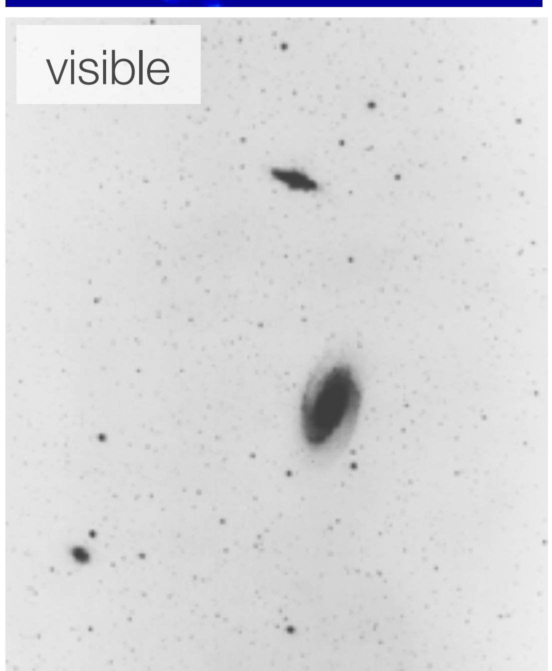
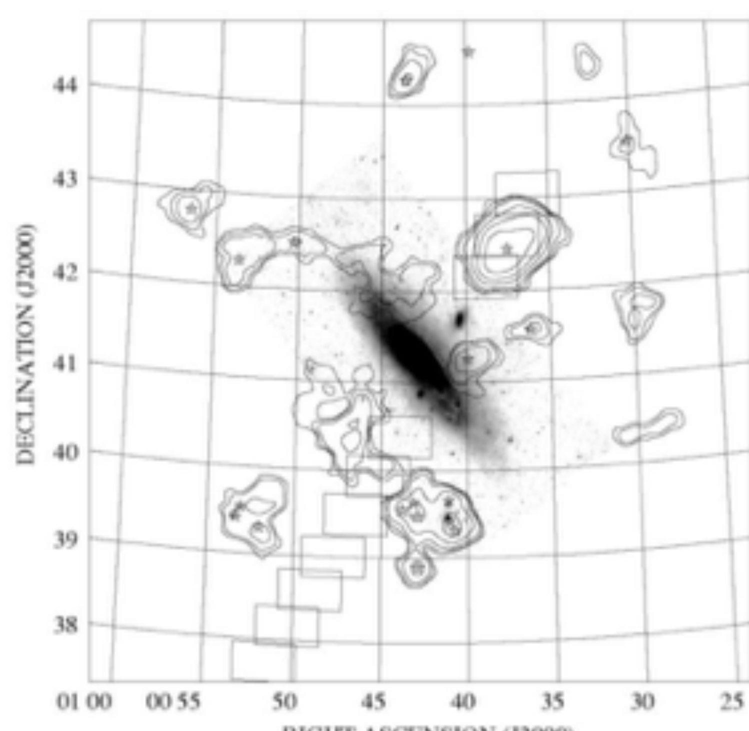
HI in galaxies

M81, M82



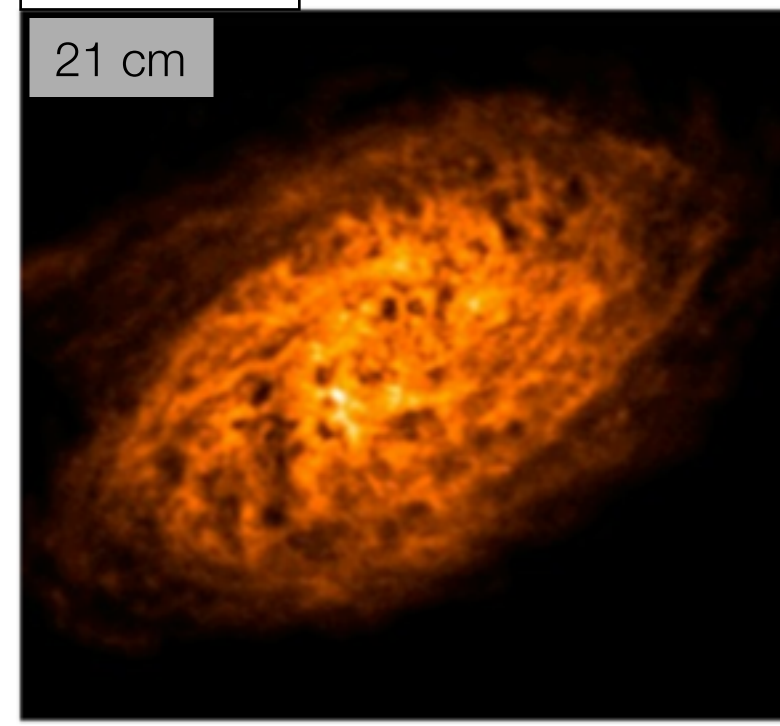


- The diffuse atomic and neutral gas (HI) traces the larger picture of the evolution of baryons in galaxies, from the ISM to stars and back
  - HI holes : supernova explosions
  - Interactions between galaxies
  - disk-halo interactions



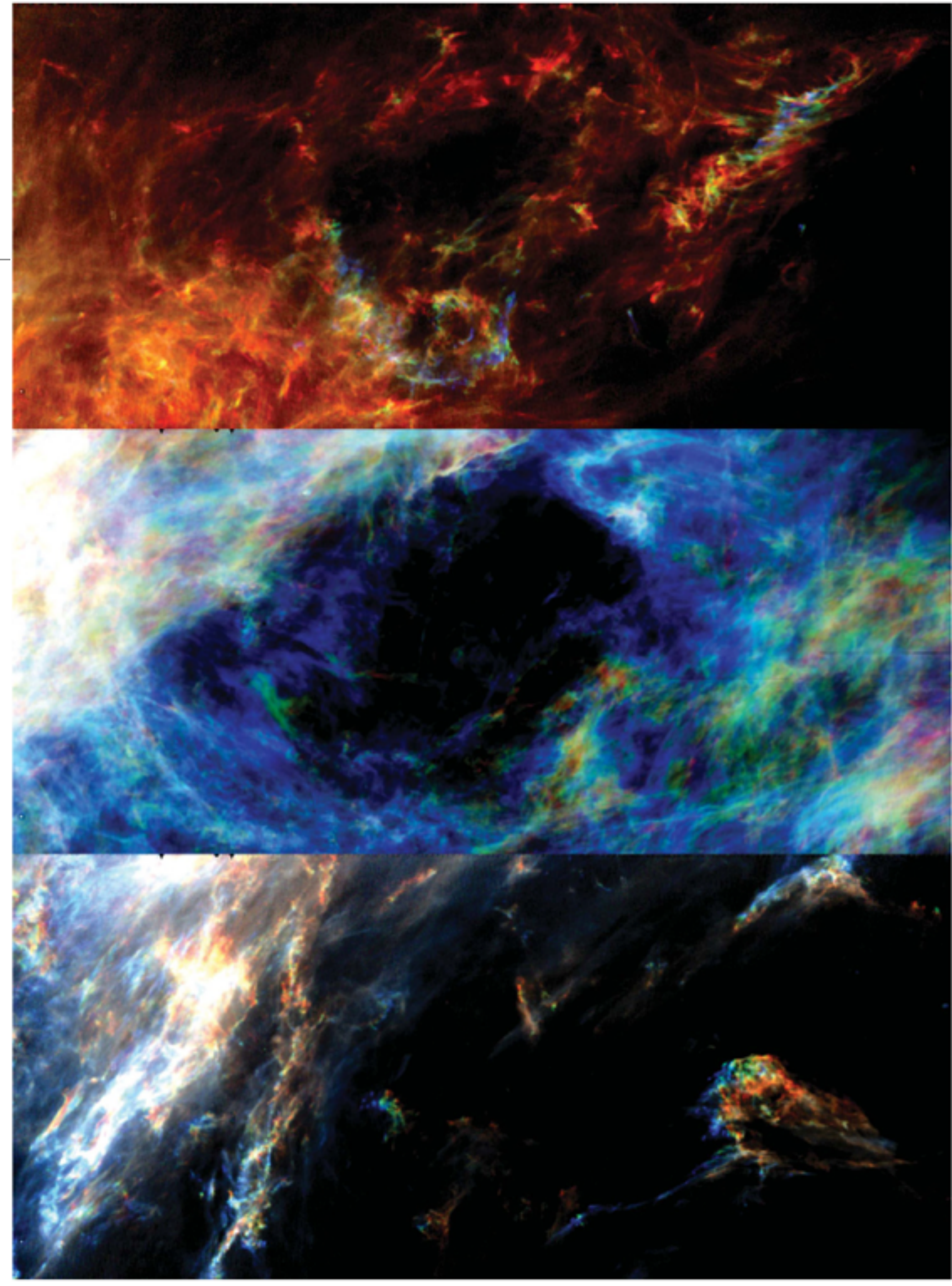
M31 in HI - Thilker et al (2004)

NGC 2403



HI in the ISM

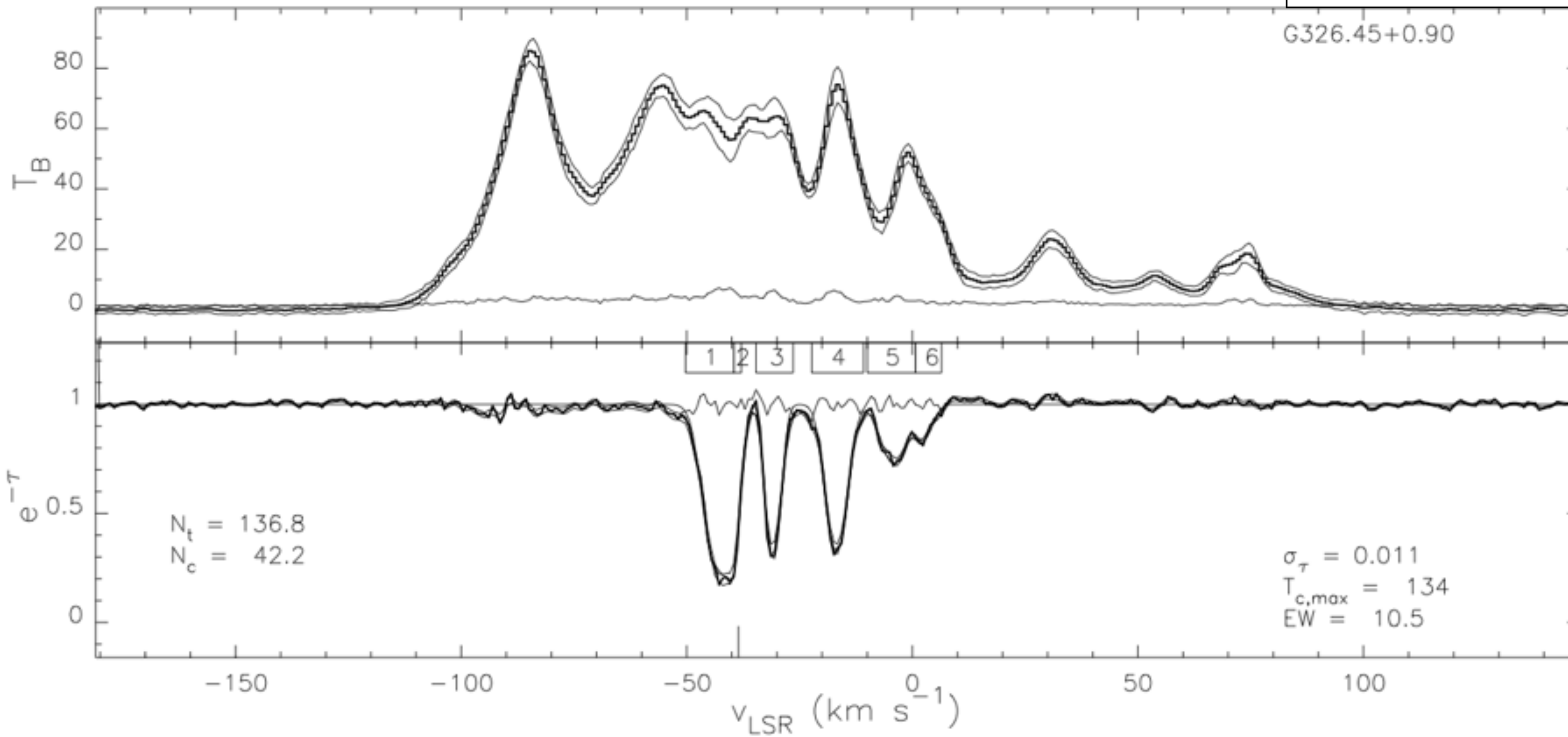
- HI dominates the mass of the ISM : 60% (20% of the mass is in molecular clouds)
- HI is the skin of molecular clouds but most of it is the wispy and diffuse gas from which molecular clouds form



GALFA HI survey
Peek et al. (2011)

The HI is multi-phase

Dickey+ (2003)



- 21 cm transition : emission and absorption are different.
- Only the narrow (cold) features appear in absorption.

THERMAL INSTABILITY

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Received June 4, 1964; revised March 30, 1965

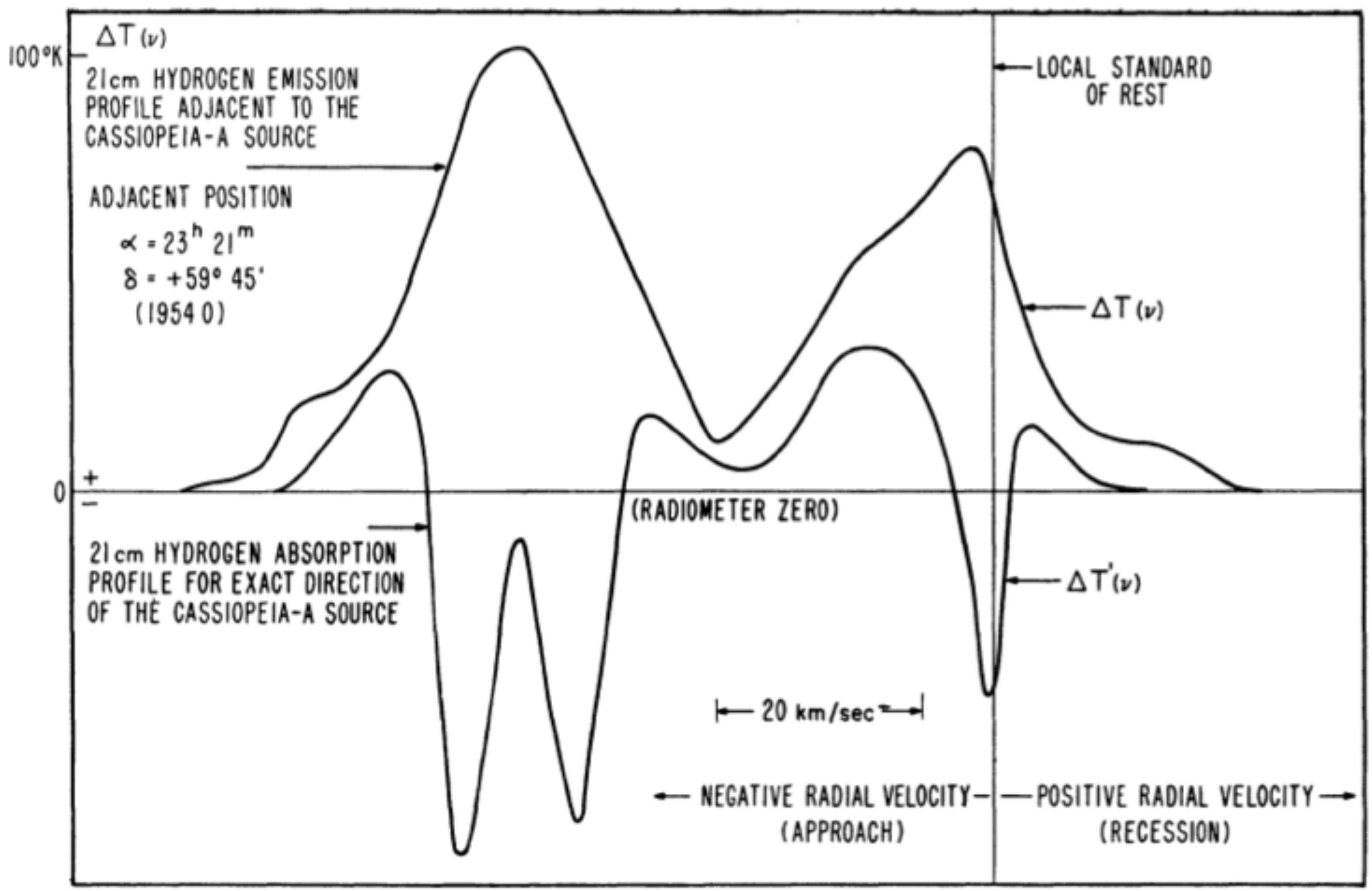
I. INTRODUCTION

a) Condensations Not Due to Gravitation

Most astronomical objects owe their existence to self-gravitation. However, there is a class of objects, including solar prominences, interstellar clouds, and condensations in planetary nebulae, whose existence cannot be explained in this way, as their calculated gravitational energies are far smaller than those due to internal pressure. In each case it appears reasonable to assume that internal pressure is being balanced by pressure in an external diffuse medium. It then appears likely that the objects in question are formed from the diffuse medium by some kind of condensation process not involving gravitation. The present paper aims at understanding such a condensation process. It is believed that the calculations presented will find a variety of astronomical applications, including those already cited. Perhaps the most exciting possibility is that the origin of galaxies may be explained along these lines.

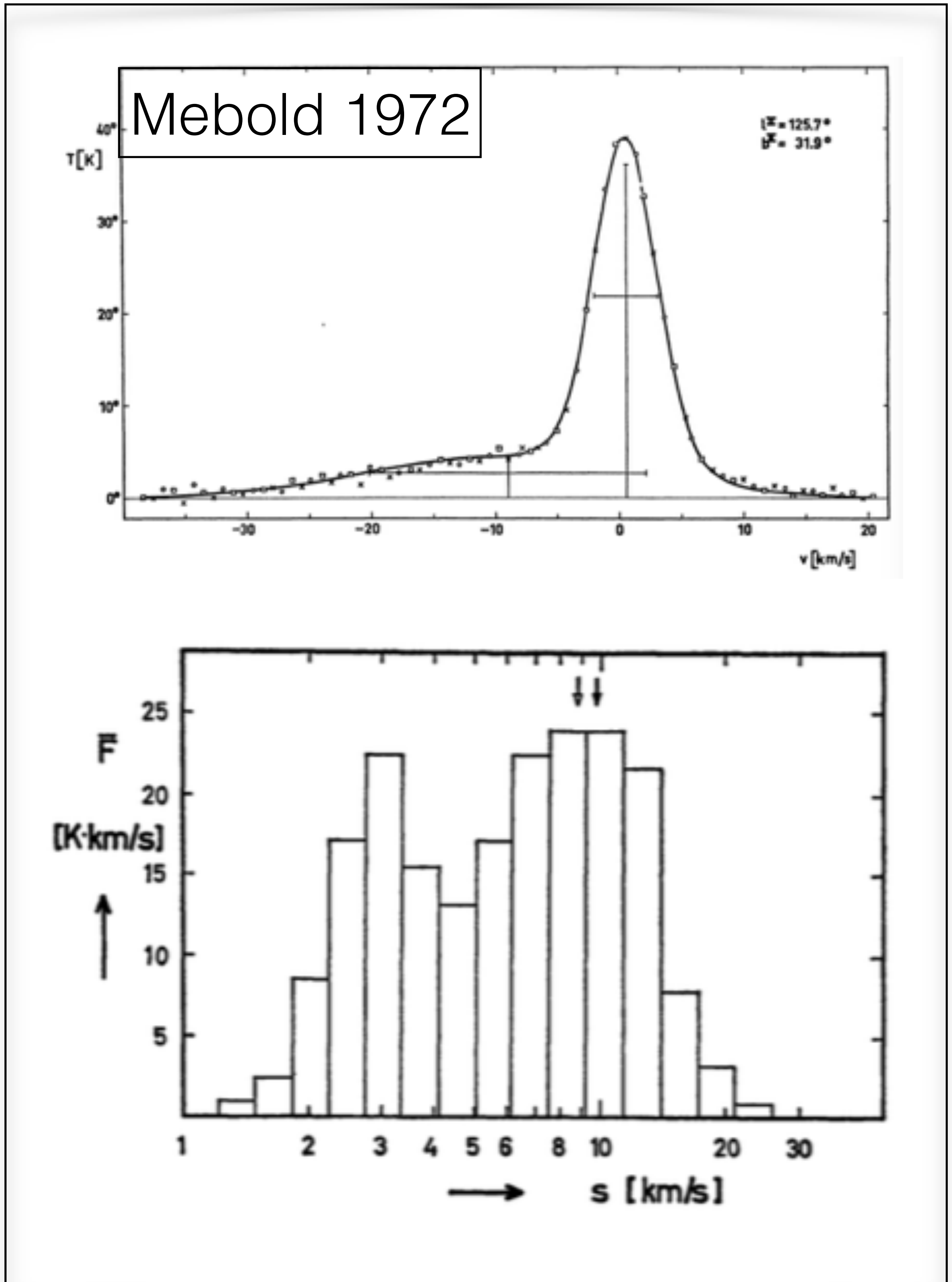
- **Parker (1953, ApJ)** : *If the thermal equilibrium of the medium is a balance between temperature-independent energy gains and temperature-dependent radiative losses, instability results if, the losses increase with decreasing temperature*
  - cooler regions cools more effectively than surroundings
  - temperature rapidly drops below the initial equilibrium value
- **Zanstra (1955 - Gas Dynamics in Cosmic Clouds)** : pressure equilibrium would naturally result in compression of the cool region and expansion of the hot ones. —> formation of cool condensation in a hot medium. He suggested that condensation in planetary nebulae form this way
- **Spitzer (1956, ApJ)** suggested that spiral arms might condense out of the galactic halo in a similar manner
- **Gold and Hoyle (1959 - Paris Symposium on Radio Astronomy)** argued that galaxies could similarly condense from the intergalactic medium.
- **Field (1965, ApJ)** : set the theoretical background for the instability criteria, in the presence of thermal conduction, magnetic field, rotation, gravity and expansion.

First 21 cm observations of the Milky Way



Hagen et al. (1955)

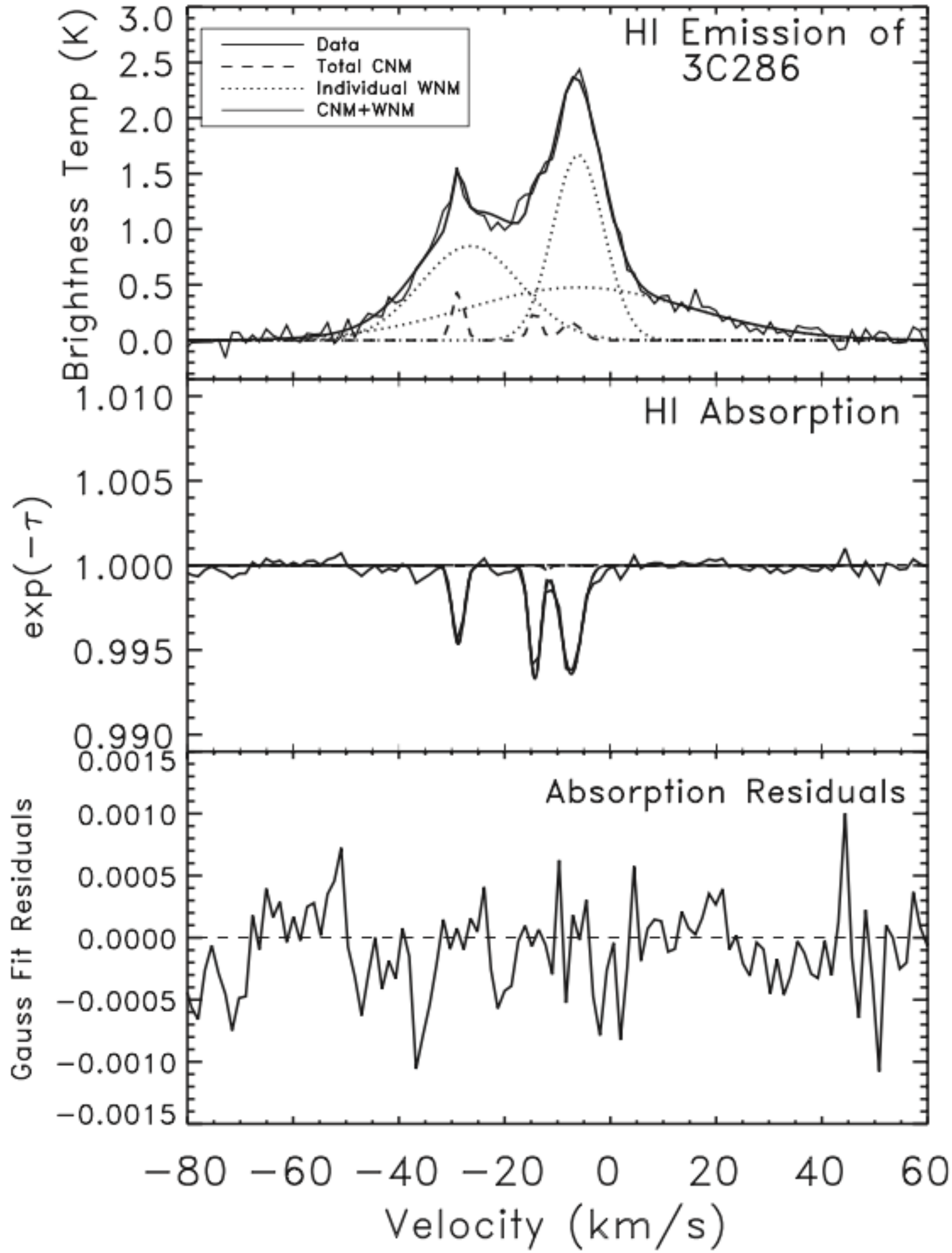
The two phase model



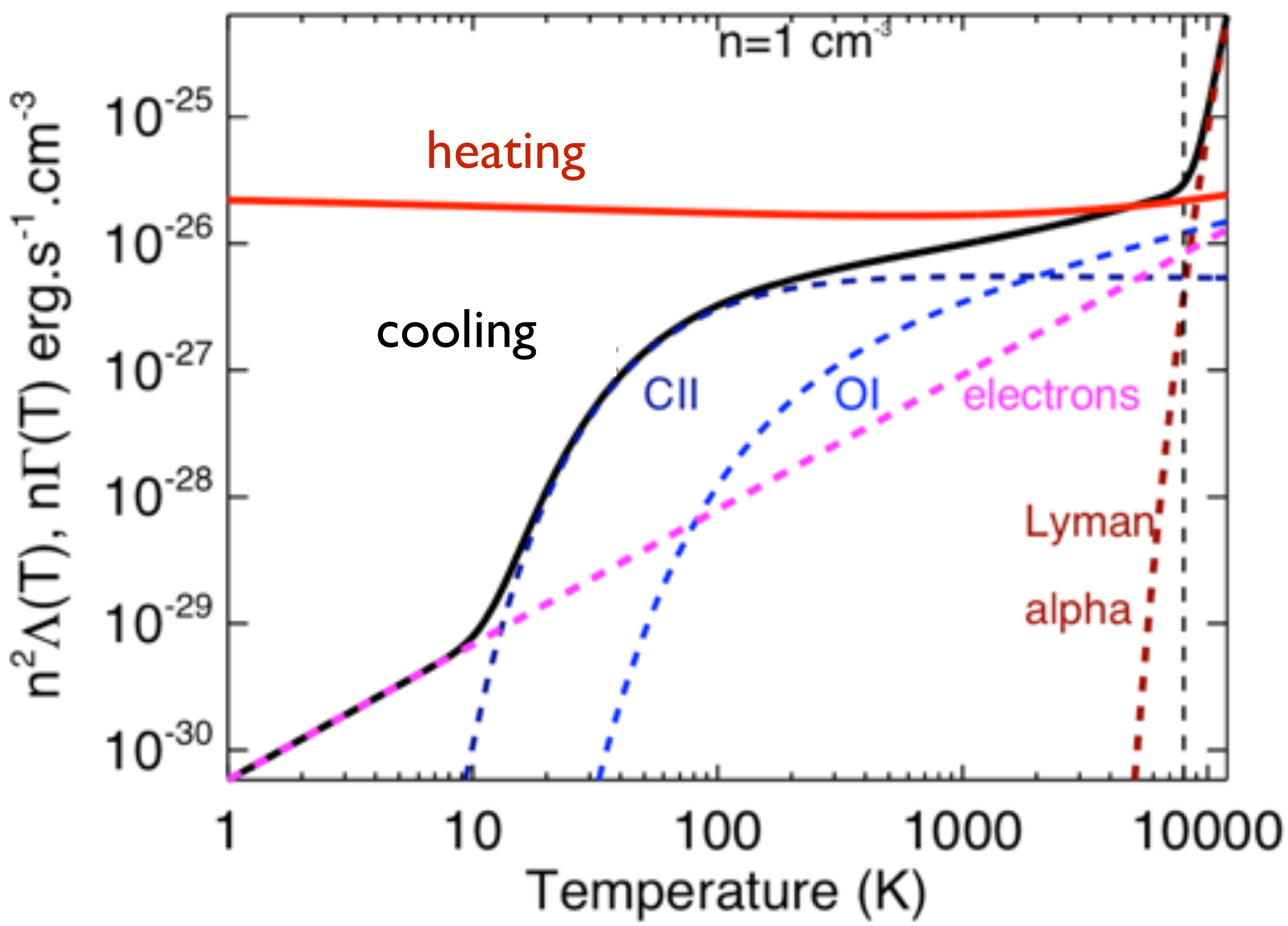
- Comparison of HI emission and absorption are compatible with a two-component model (Clark 1965, Heiles 1967, Grahl 1968, Radhakrishnan+1969, Mebold 1969)
- Cold (T<80 K) and optically thick HI clouds are in approximate pressure equilibrium with a homogeneous high temperature (T > 1000 K), low density (n ~ 0.5 cm-3) intercloud medium.
- Theory have shown that such a model can persist thermodynamically (Field+ 1969, Goldsmith+ 1969, Habing & Goldsmith 1971…)
- Until the 1990s, the exact temperature of the warm phase is not well determine (600 < T < 15 000 K).

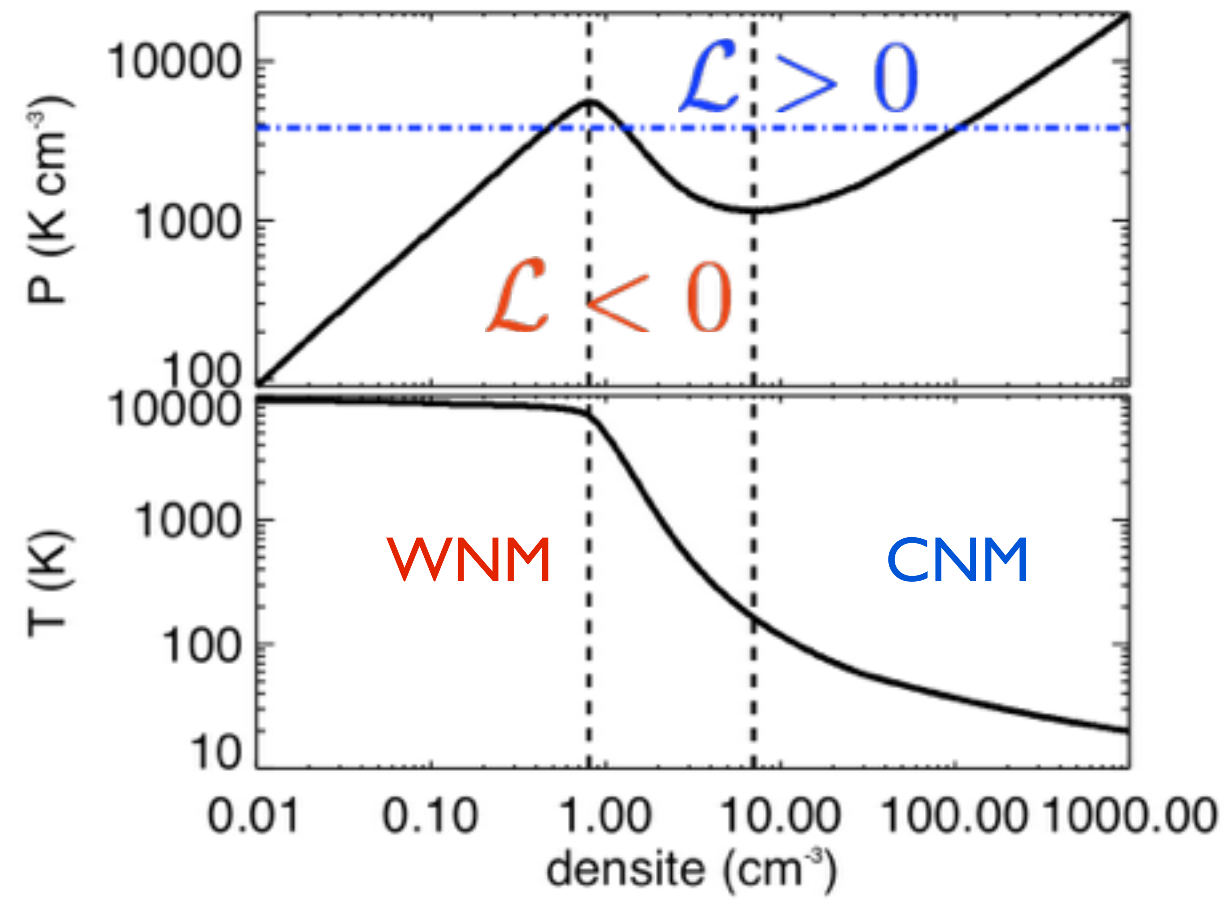
CNM - WNM absorption vs emission

- Joint fit on a Gaussian basis
  - Heiles & Troland (2003a,b)
  - Stanimirovic & Heiles (2005)
  - Begum+ (2010)
  - Murray+ (2015, 2017)



Thermal instability of the HI





- Heating : photoelectric effect on dust grains
- Cooling
  - Electrons recombination on grains
  - CII, OI
  - H Lyman-alpha

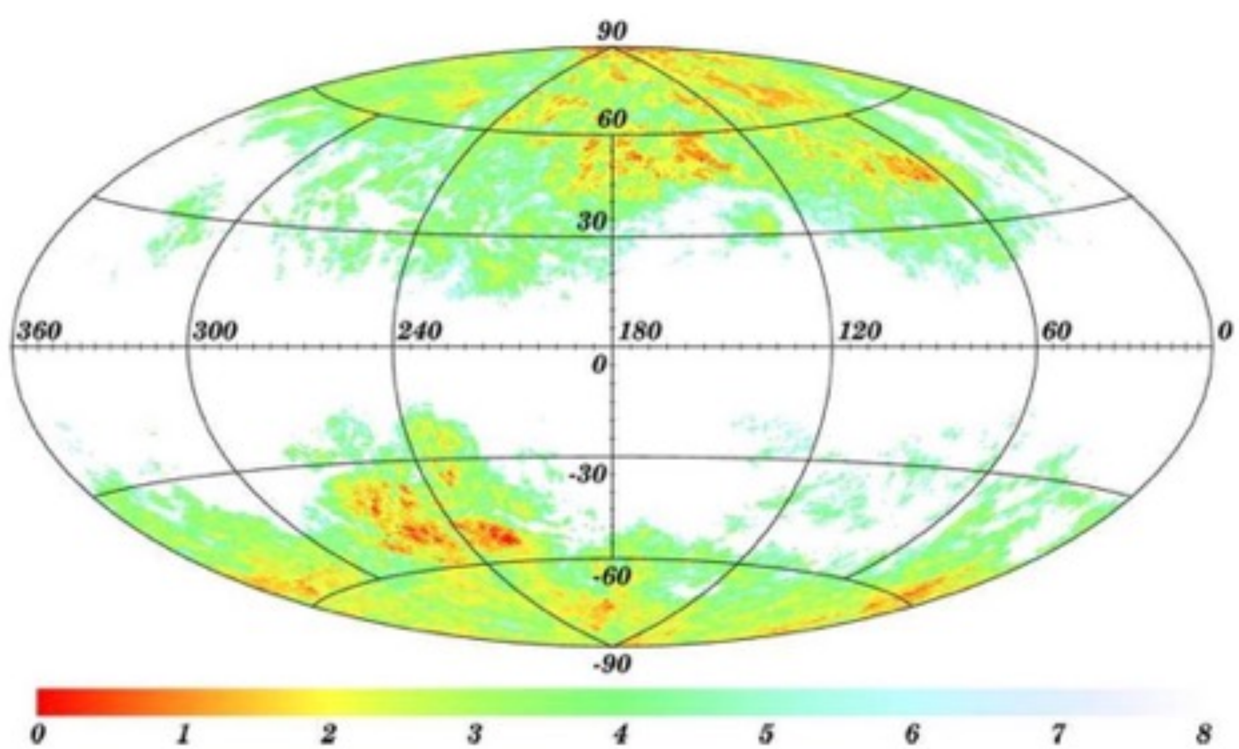
Wolfire et al. (1995, 2003)

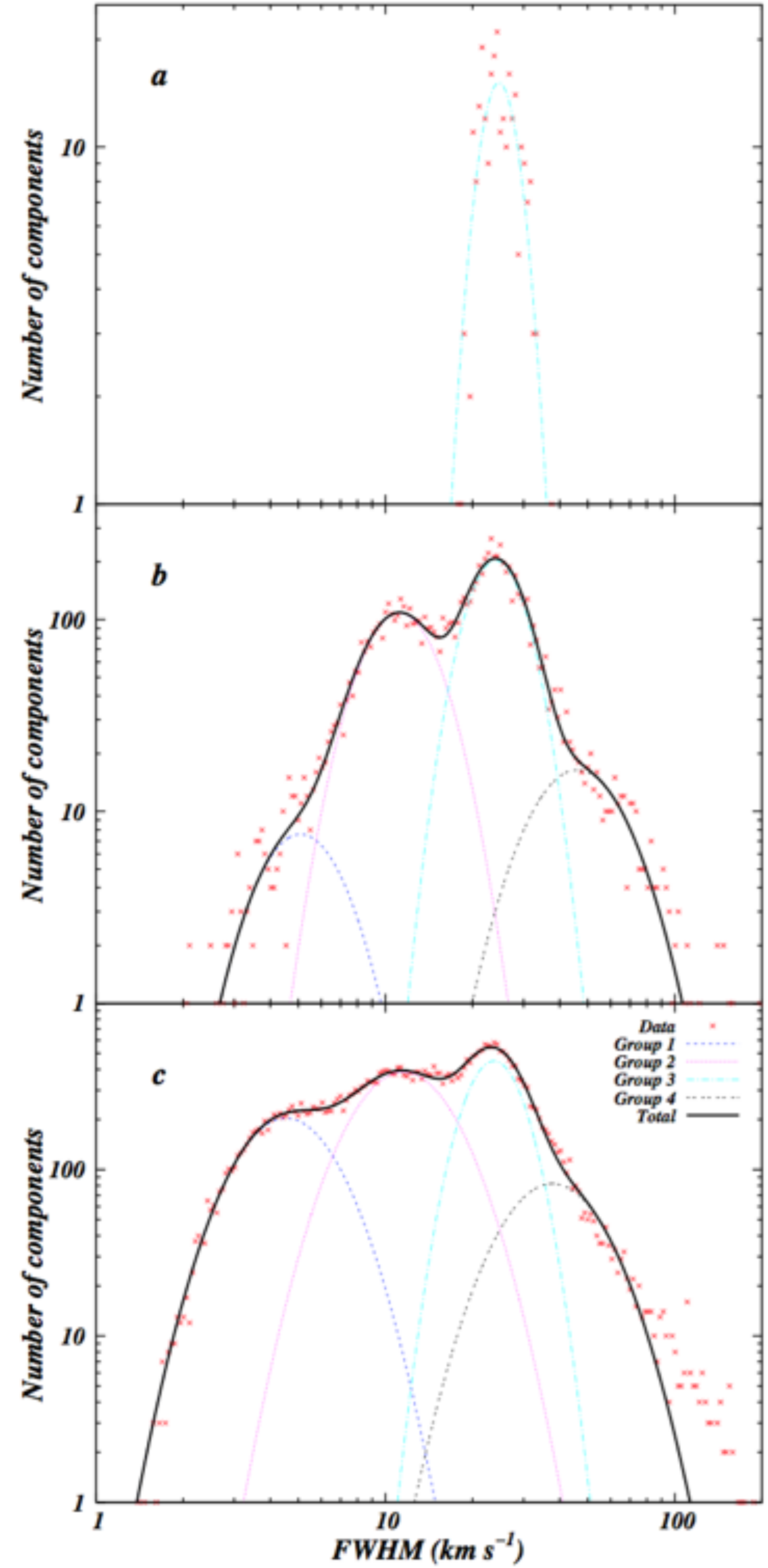
$$\mathcal{L}(n,T) = n^2\Lambda(n,T) - n\Gamma(n,T) = 0$$

- The thermal instability is not a purely dynamical instability like Rayleigh-Taylor or gravitational instability.
- It is specific to the inter-stellar/galactic media. It depends on metallicity and on the presence of small dust grains.

Is-it that simple ?

- Heiles & Troland (2003) : ~50% of the WNM is thermally unstable.
- Confirmed by emission-only analysis : Haud & Kalberla (2007)

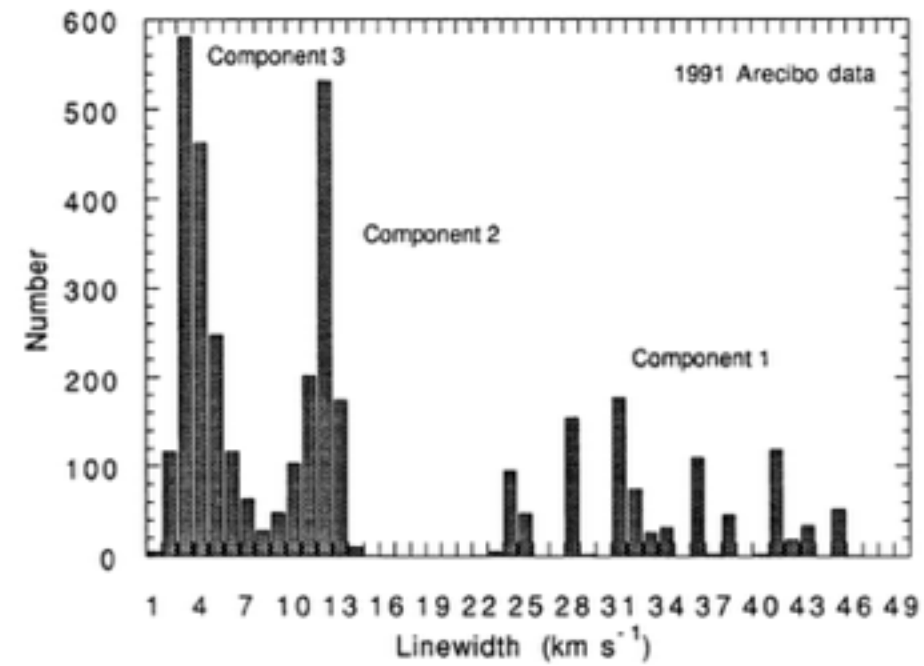


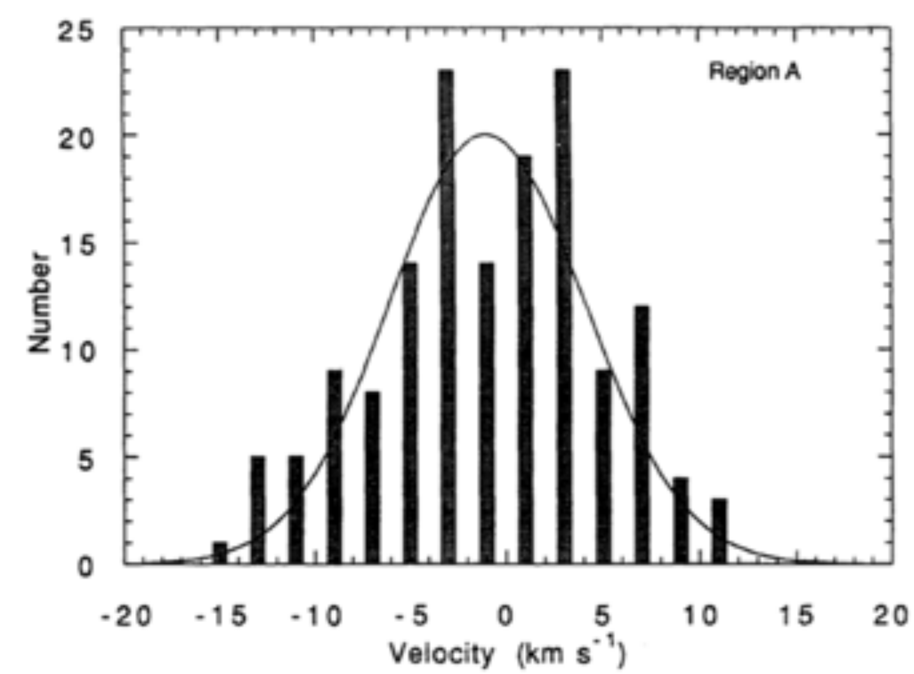


Hint of three-component HI in early 21cm data at high galactic latitude

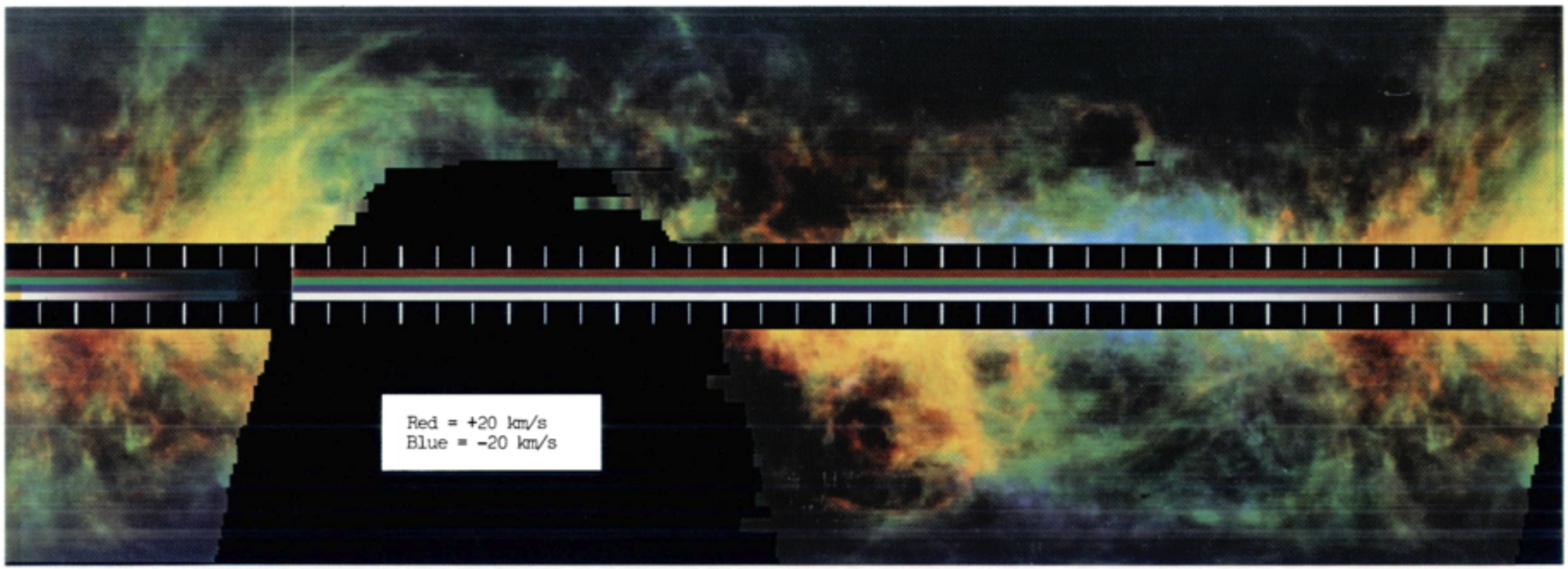
Verchuur & Magnani (1994)

- A pervasive feature of FWHM ~ 12 km/s
  - corresponds to Tk ≤ 3100 K
  - some could be due to superposition of unresolved cool features in the beam
- Narrow features of FWHM~3 km/s (between 2 and 6 km/s)
  - the CNM-CNM velocity dispersion is the same as the velocity dispersion of the large component (~12 km/s)

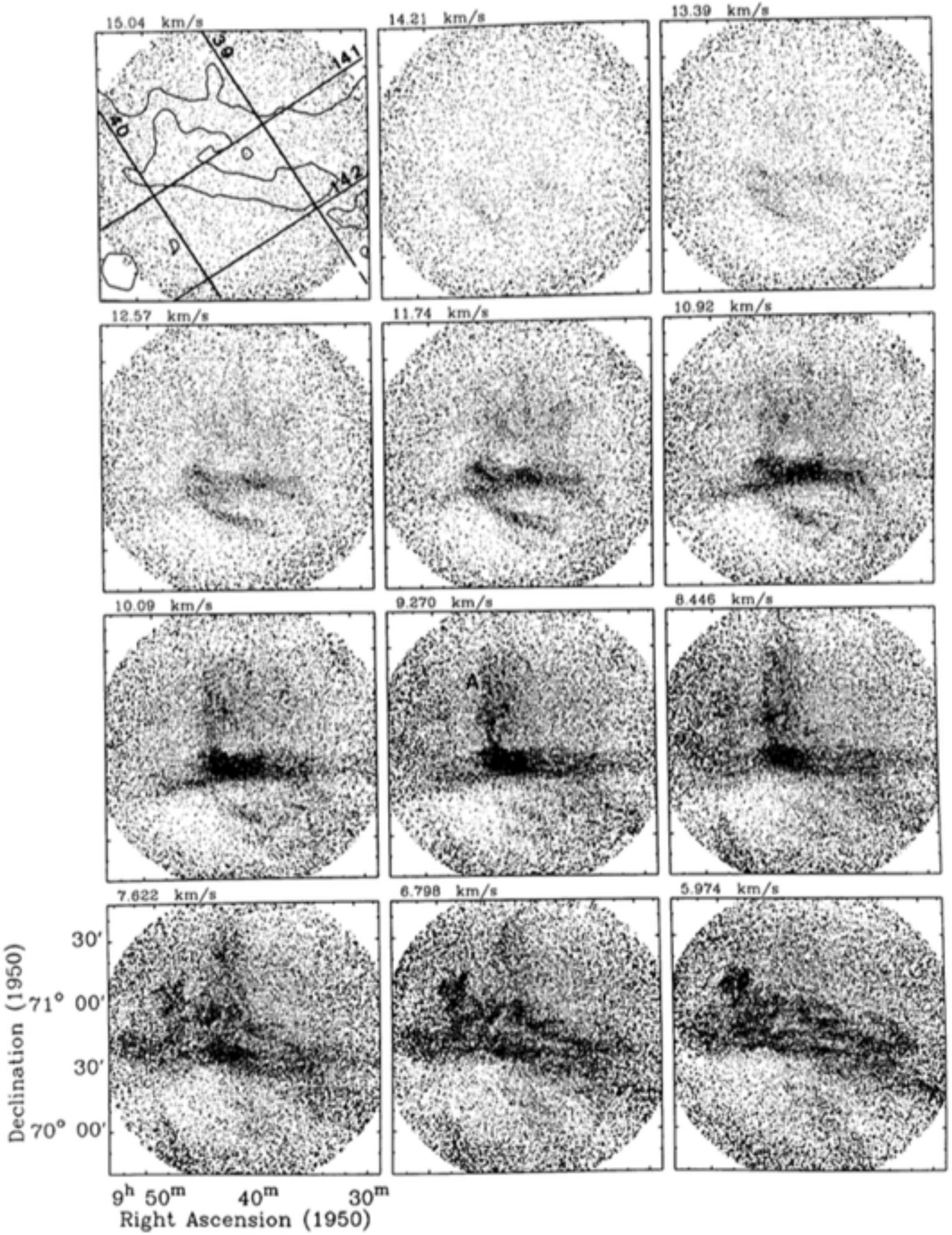




The complex structure of the HI

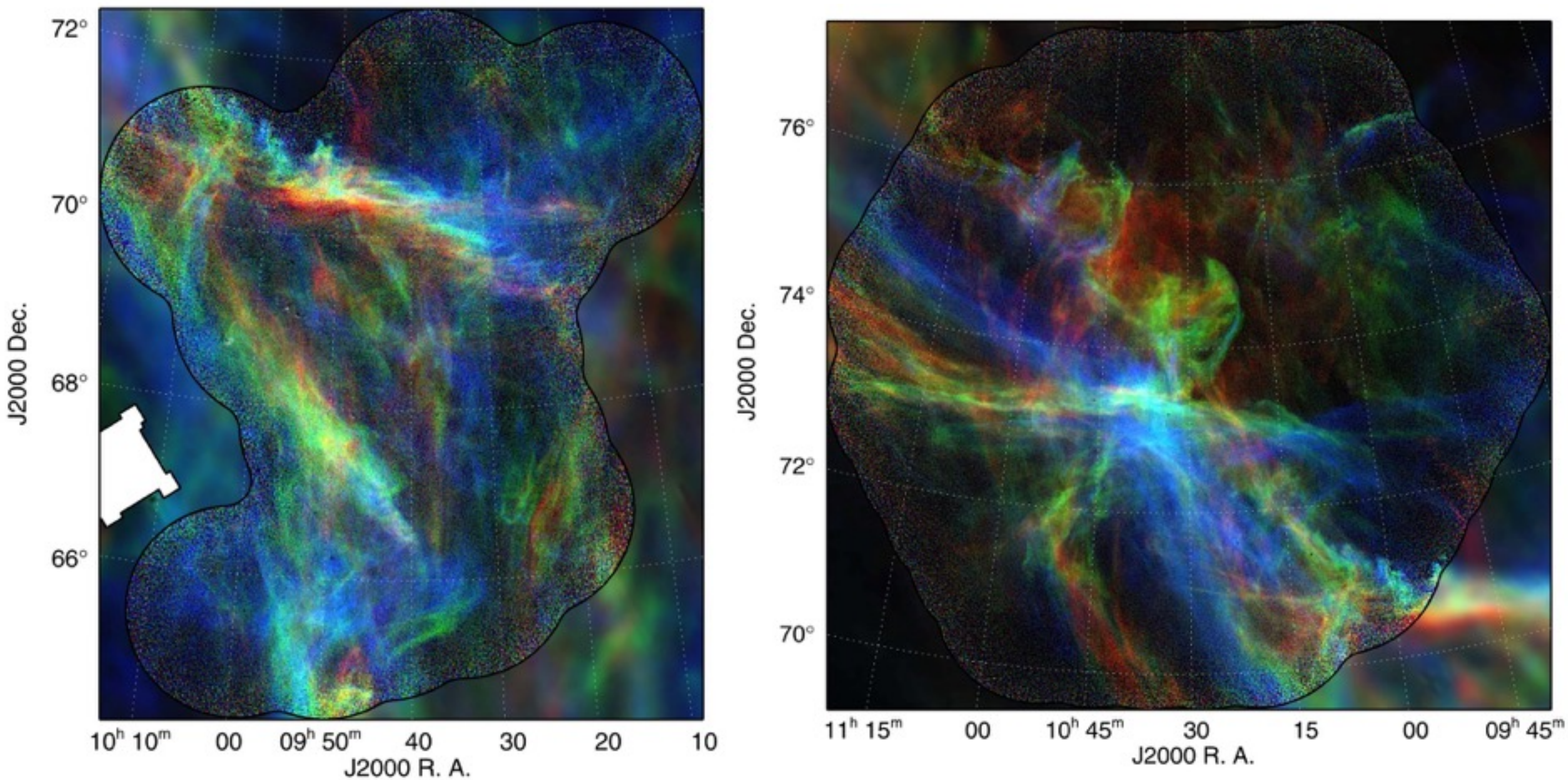


Hat Creek 21 cm data (Heiles & Jenkins 1976)


15.04 km/s
14.21 km/s
13.39 km/s
12.57 km/s
11.74 km/s
10.92 km/s
10.09 km/s
9.270 km/s
8.446 km/s
7.622 km/s
6.798 km/s
5.974 km/s
39
40
141
142
A
Declination (1950)
30′
71° 00′
30′
70° 00′
9h 50m
40m
30m
Right Ascension (1950)

Joncas+ (1992)

High galactic latitude 21 cm data



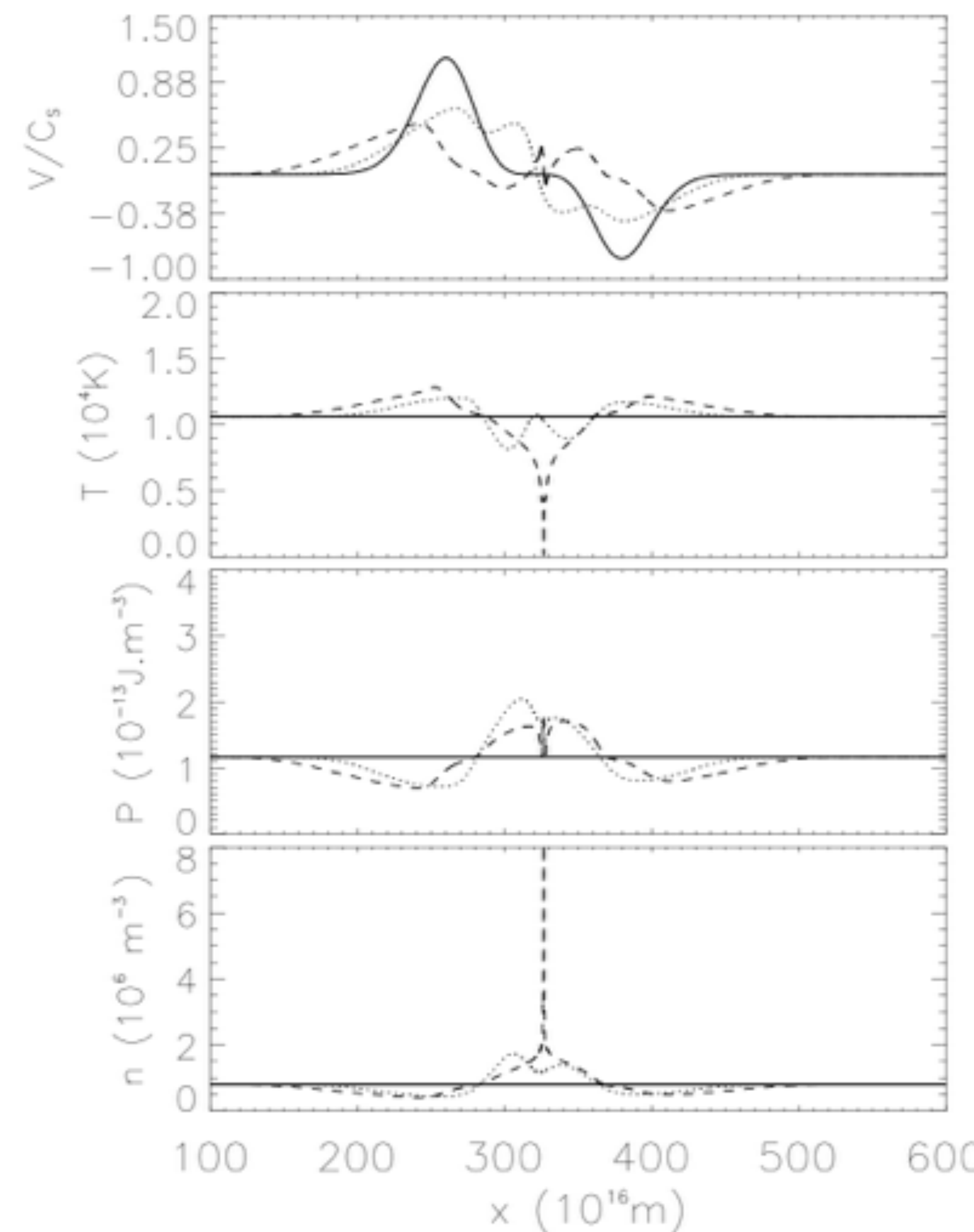
Blagrave+ (2017)

DRAO + GBT : 1 arcmin resolution

Dynamics of the thermal instability: the advent of numerical simulations

- Observations showed a significant amount of gas in the thermally unstable regime
- Thermal instability models are static (Field 1965, 1969…).
- The interstellar medium is turbulent and out of equilibrium.
- A dynamical view emerged
- Hennebelle & Perault (1999); Hennebelle & Perault (2000); Vazquez-Semadeni + (2000); Sanchez-Salcedo + (2002); Vazquez-Semadeni + (2003); Piontek & Ostriker (2005); Gazol + (2005); Audit & Hennebelle (2005); Hennebelle & Audit (2007); Gazol & Kim (2010); Seifried + (2011); Saury + (2014)

Hennebelle & Perault (1999)



three different times: 0 (full line), 3.0 (dotted line), 7.5 10^{13} s (dashed line).

Characteristic time and scales

cooling time of the WNM : $$t_{\text{cool}} = \frac{k_{\mathrm{B}} T}{(\gamma - 1) n \Lambda}$$

crossing time in the WNM : $$t_{\text{crossing}} = \frac{d}{c_{\mathrm{S}}}$$

$t_{\text{cool}} < t_{\text{crossing}}$ $$\lambda_{\text{cool}} = t_{\text{cool}} \times c_{S,wnm} \sim 22\mathrm{pc}$$

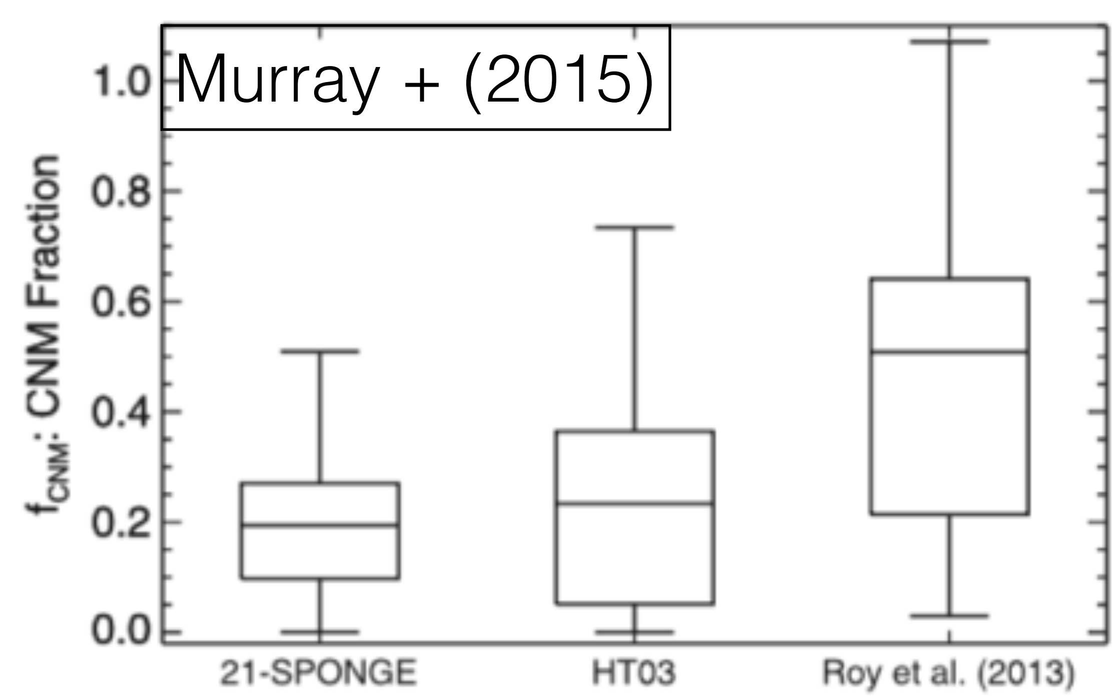
dynamical time of turbulence : $$t_{\mathrm{turb}} = \frac{L_S}{v_{\mathrm{S}}}$$

Observational constraints

- Warm Neutral Medium (WNM)
  - T ~ 8000 K
  - n ~ 0.5 cm-3
  - L = 265 pc
    this is HWHM of WNM disk at R_{Sun}
  - σ_{tot} = 10.2 km s^{-1}
    from Haud & Kalberla (2007)
    - σ_{therm} = 8.3 km s^{-1}
    - σ_{turb} = 5.9 km s^{-1} (Mach < 1)
  - σ_{1pc}(WNM) = 0.89 km s^{-1}

$$\sigma_{\rm turb} \propto \sigma_{\rm 1pc} \left(\frac{L}{1\,{\rm pc}} \right)^{1/3}$$

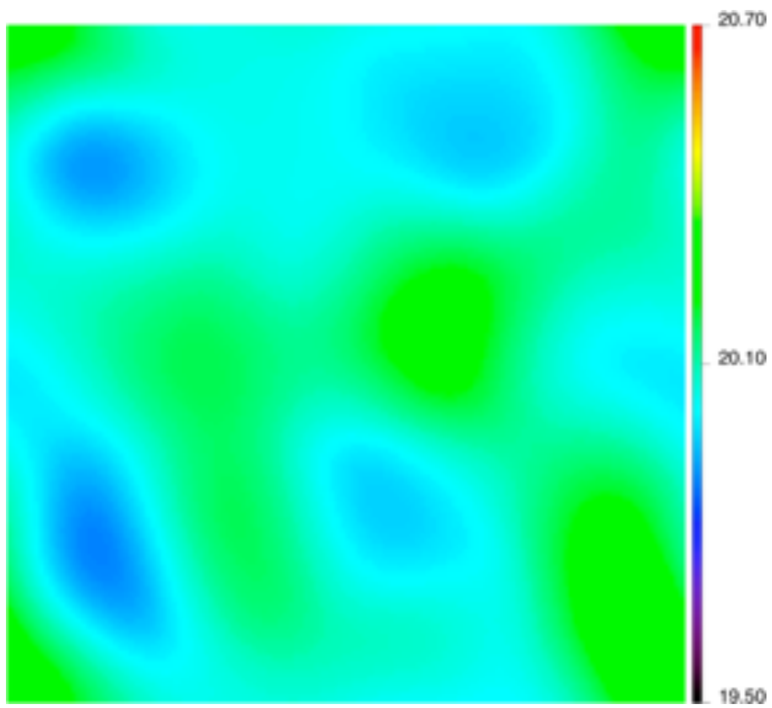
- CNM - WNM in pressure equilibrium
  - volume(WNM) ~ 100 x volume(CNM)
- Mass fraction (Heiles & Troland 2003)
  - CNM ~ 0.4 (volume filling factor 1%)
  - WNM ~ 0.3
  - Thermally unstable ~ 0.3

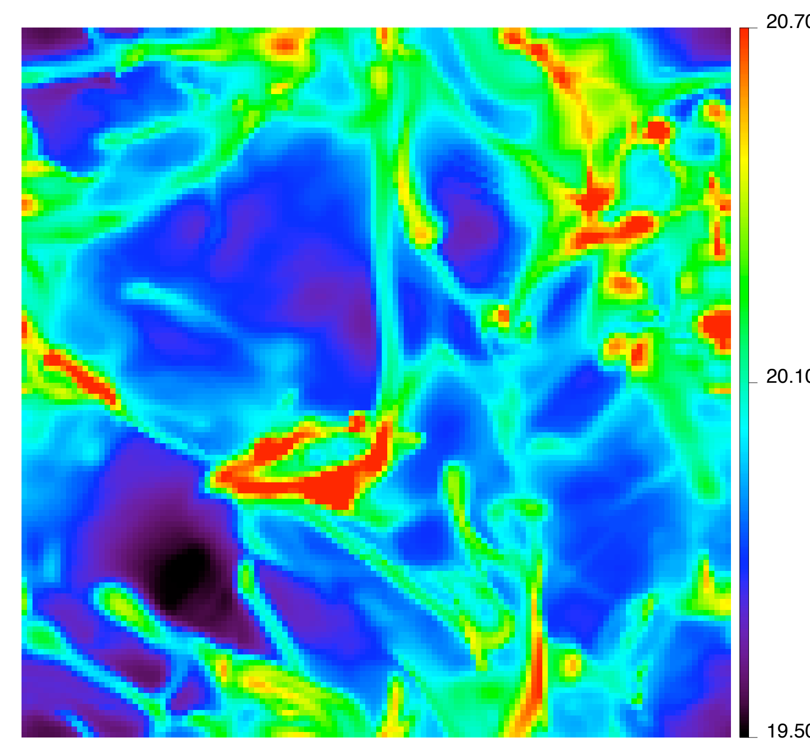


Methodology

Saury et al. (2014)

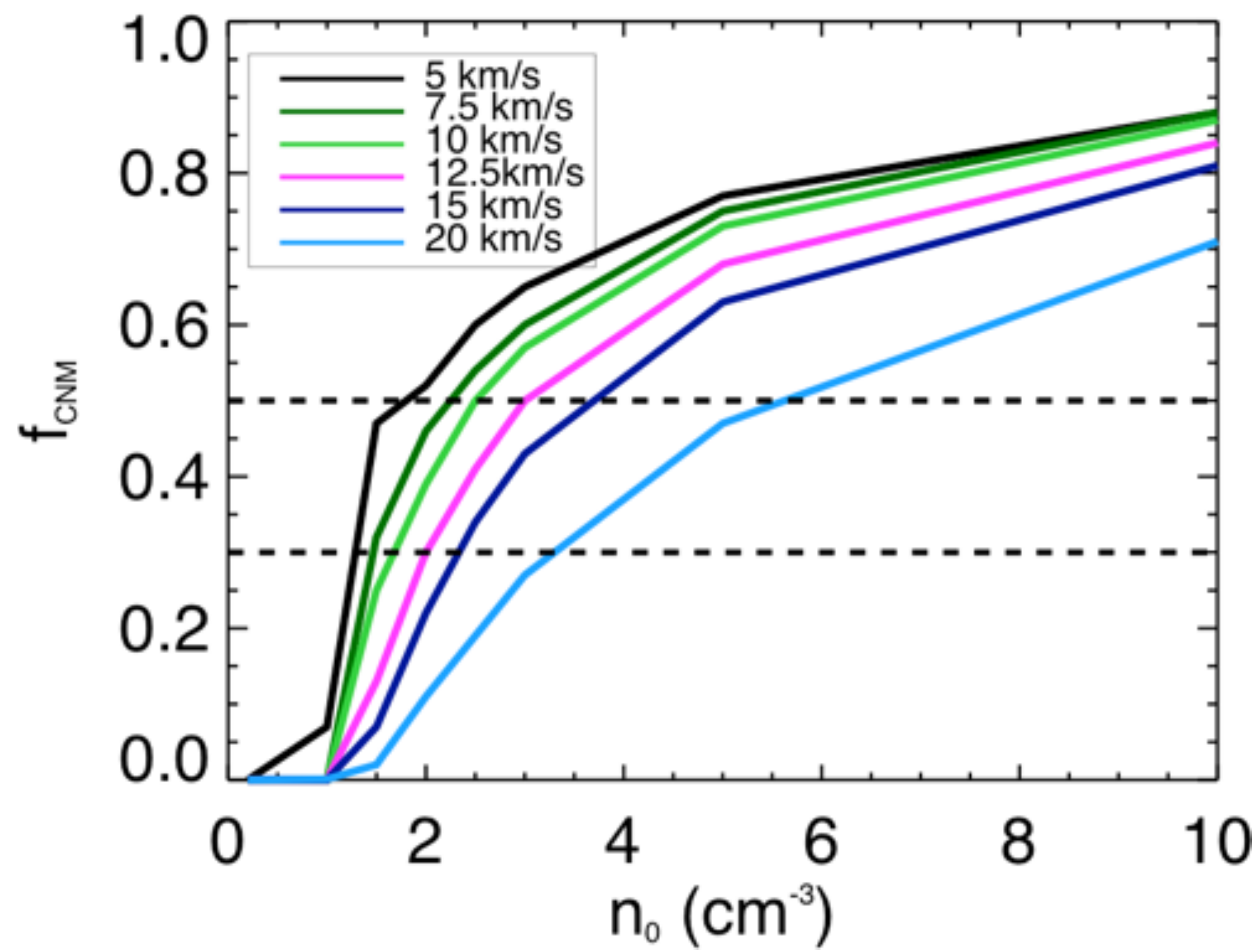
- Initial conditions
  - Box of 40 pc
  - T = 8000 K
  - v = 0 km/s
  - $0.2 \leq n \leq 10$ cm-3
  - $5 \leq v_{turb} \leq 20$ km/s
  - $0 \leq \zeta \leq 1$
- Exploration : 90 simulations at low resolution (128^3)
- Detailed study of the CNM structure : two 1024^3 simulations



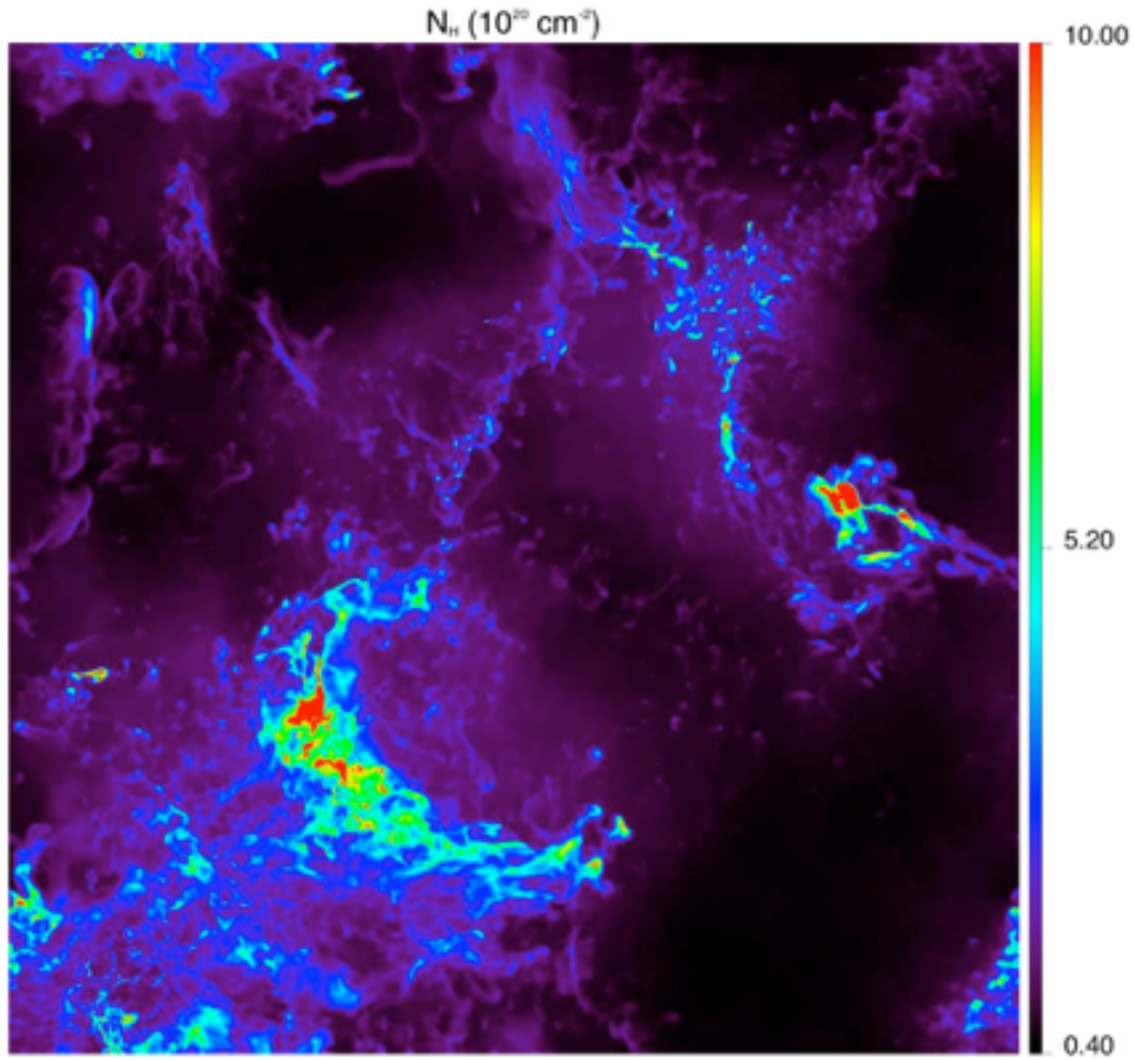


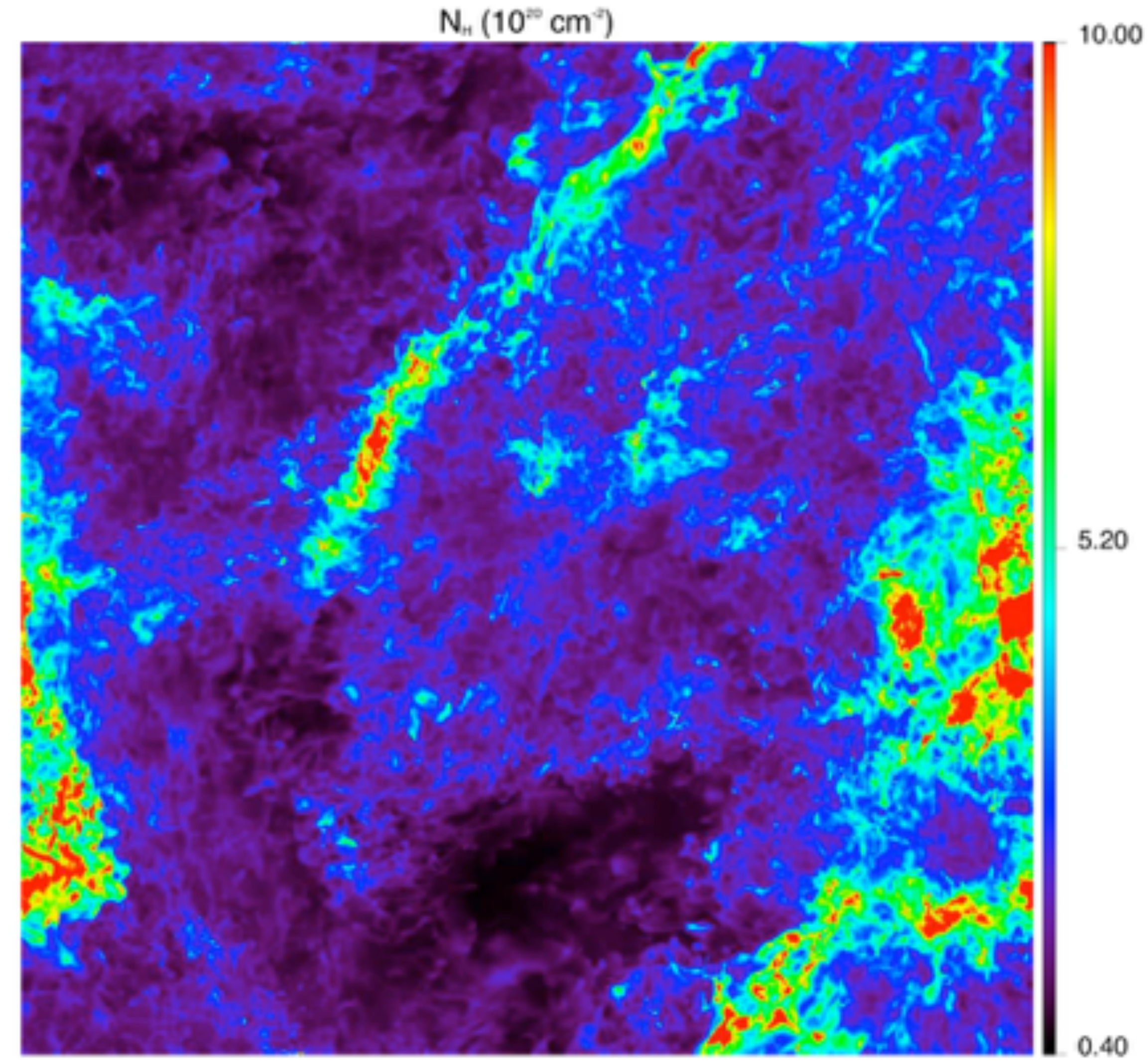
Impact of the WNM initial density and of the amplitude of the turbulent motions

- Case of “natural” turbulence; equal energy in solenoidal and compressive modes
  - No CNM if $n_{wnm} < 1.5\ cm^{-3}$
  - Transition less efficient for stronger turbulent motions
- Turbulence in a thermally bi-stable flow is non-symmetric
  - **CNM forms if $t_{cool} < t_{dyn}$**
- The turbulence does not trigger the phase transition at the mean density of the WNM. **Some compression is required.**



Higher resolution simulations (1024^3)



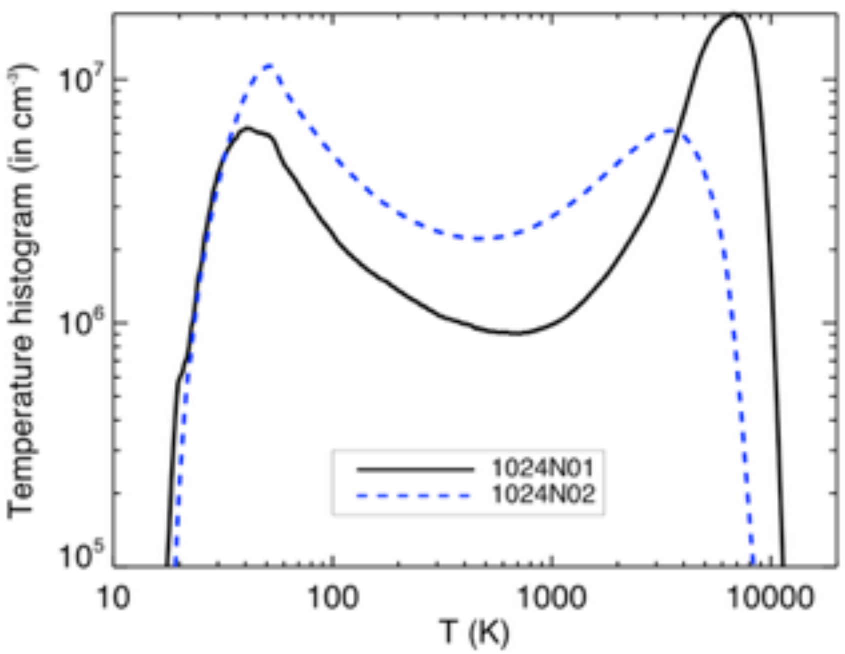


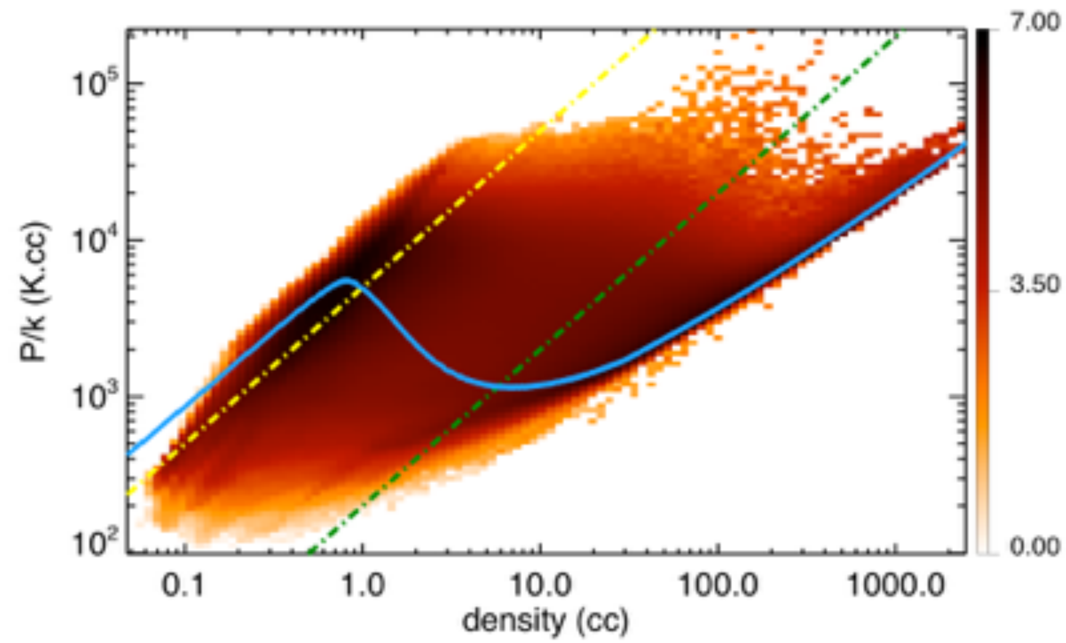
n_{wnm} = 1.0 cm^{-3}
Majority of compressible modes : $\zeta = 0.2$

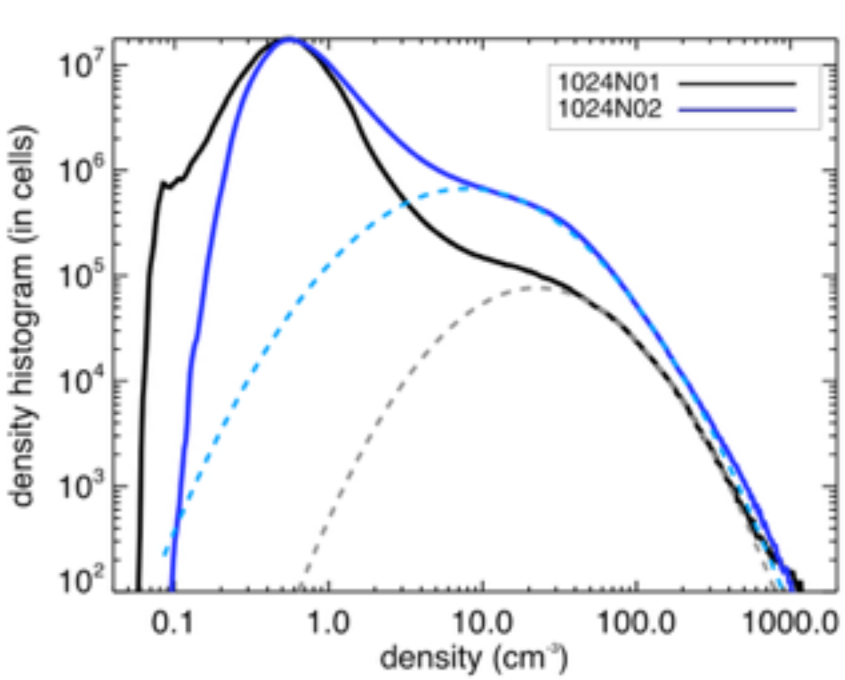
n_{wnm} = 2.0 cm^{-3}
Natural turbulence : $\zeta = 0.5$

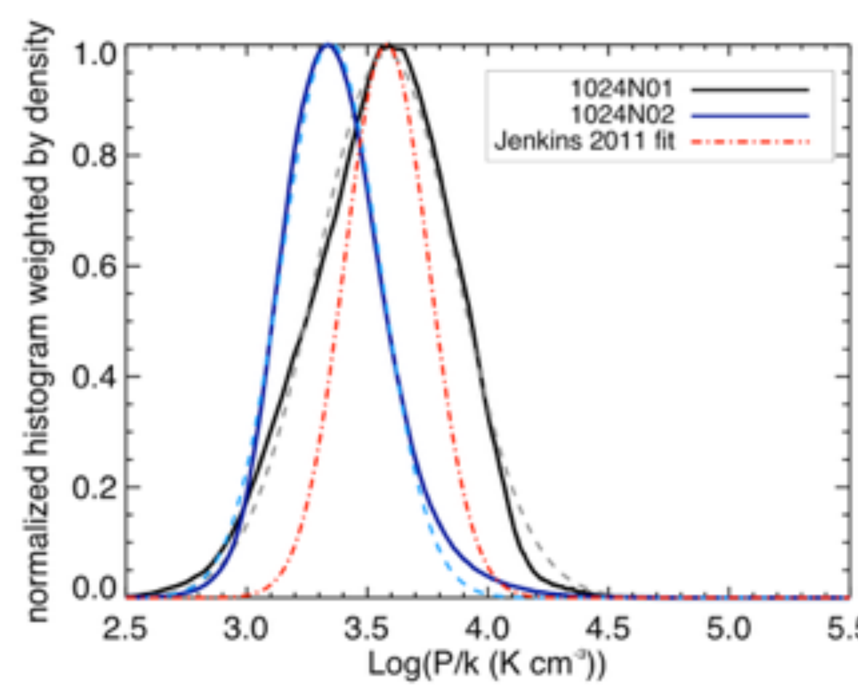
Distributions

1024N01 ; n=1 cm^{-3}, compressive turbulence
1024N02 ; n=2 cm^{-3}, natural turbulence









Distributions

1024N01 ; n=1 cm^{-3}, compressive turbulence
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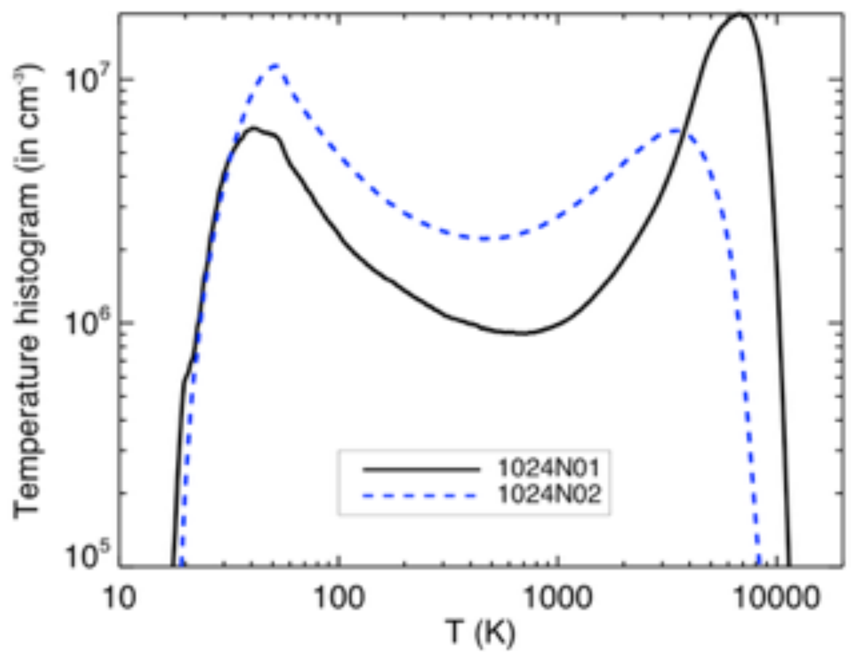
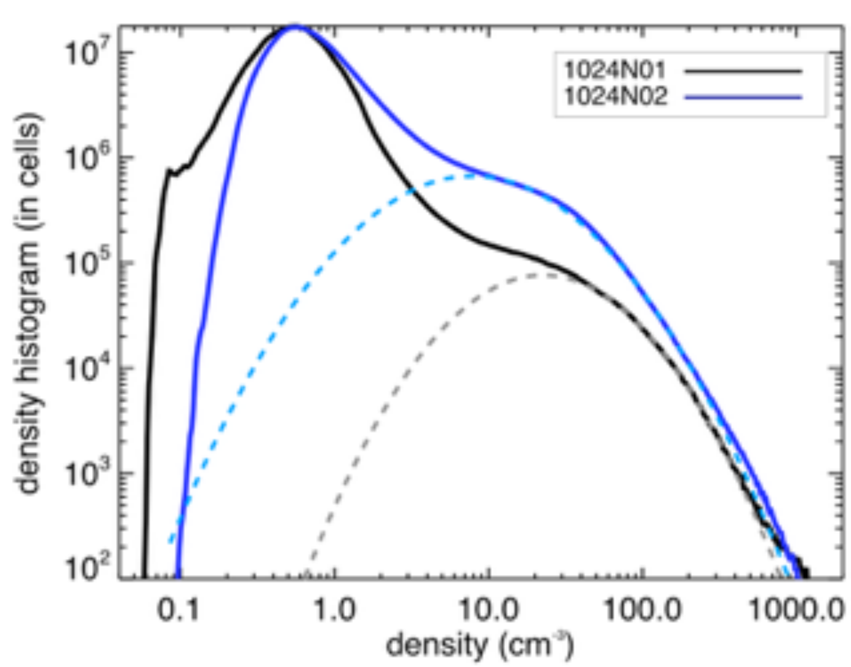
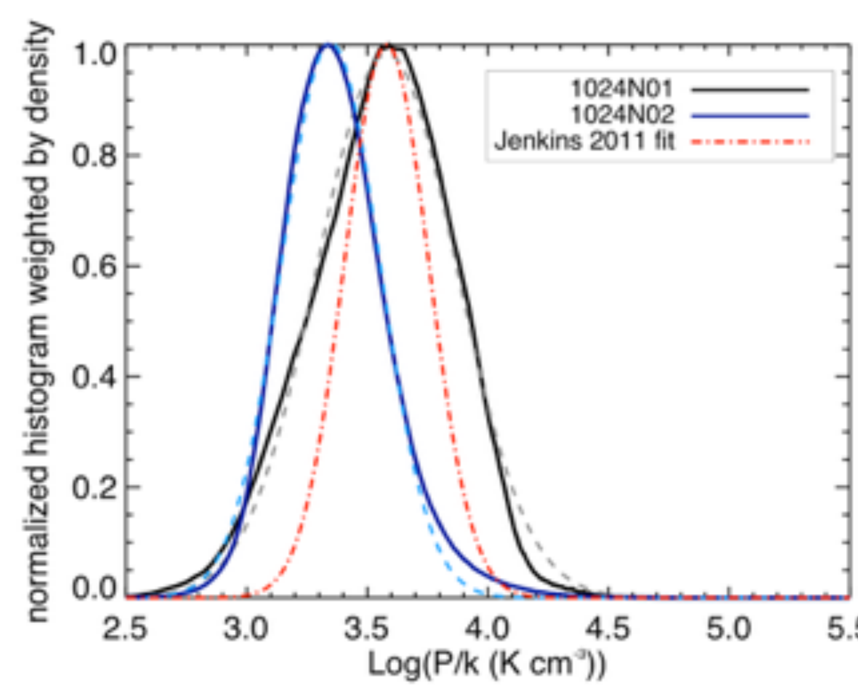


Jenkins et al. (2011) :
<P> = 3800 K cm^{-3}

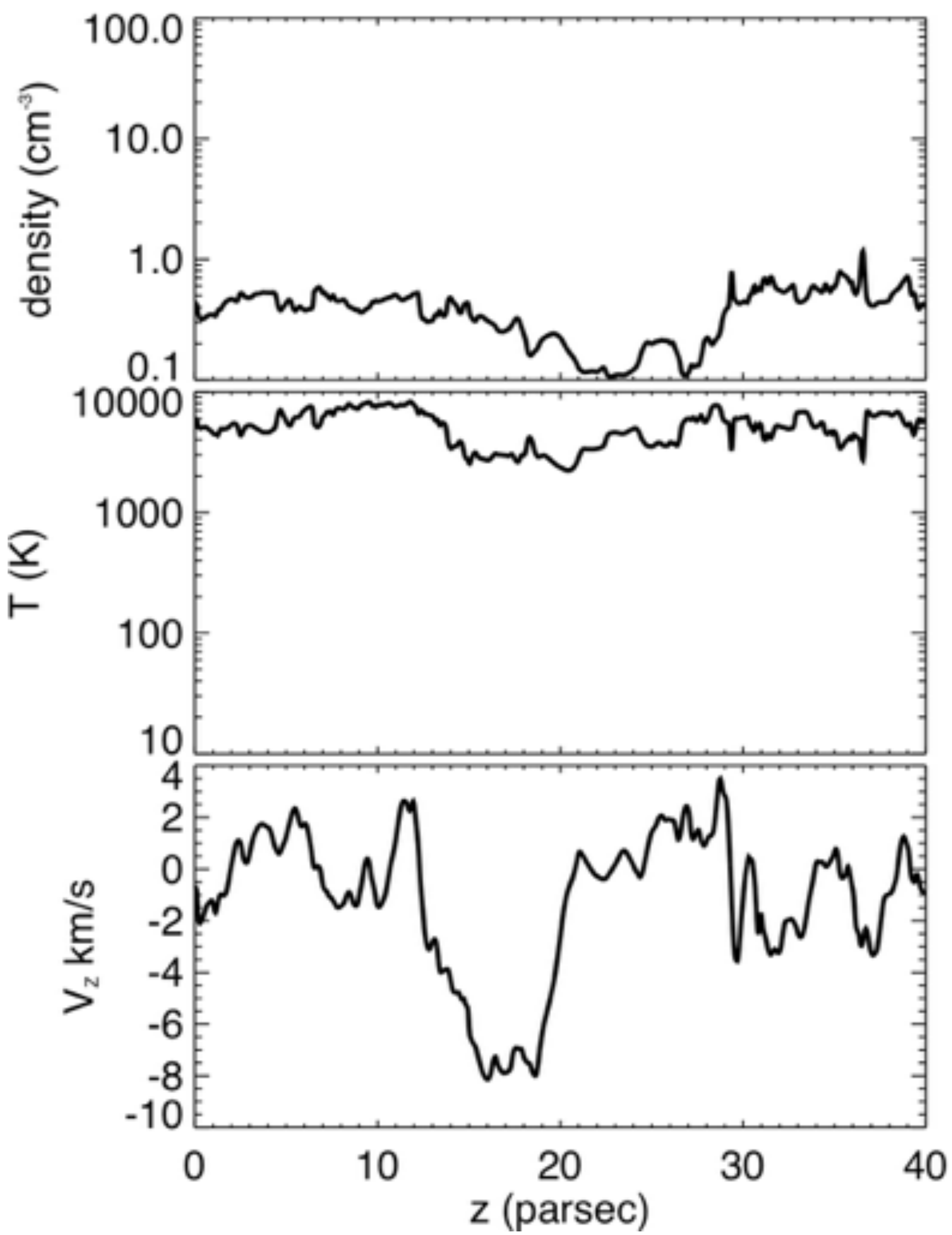
<P$_{01}$> = 3800 K cm^{-3}
<P$_{02}$> = 2200 K cm^{-3}

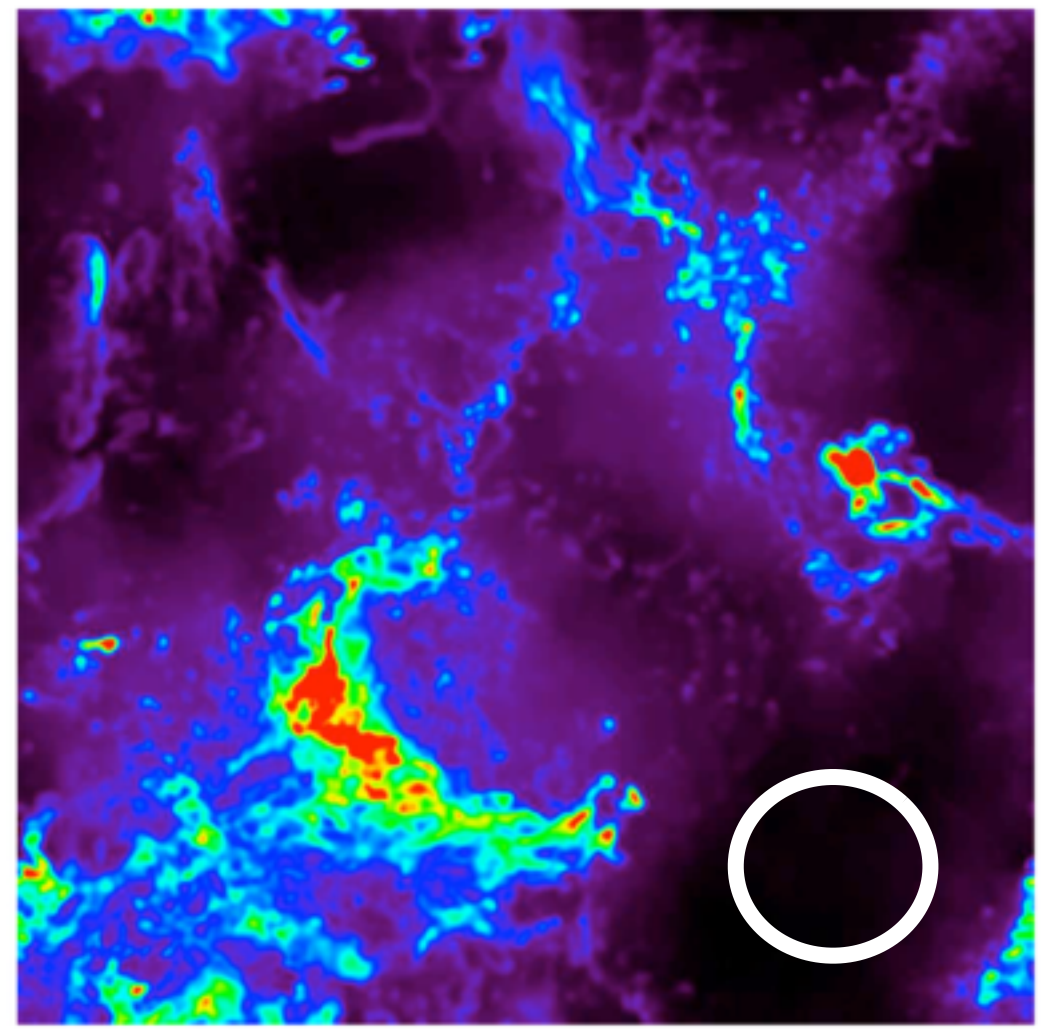
The pressure of the box is stabilized in the range where the bistability of the HI is allowed





What is on the line of sight of an HI cloud ?





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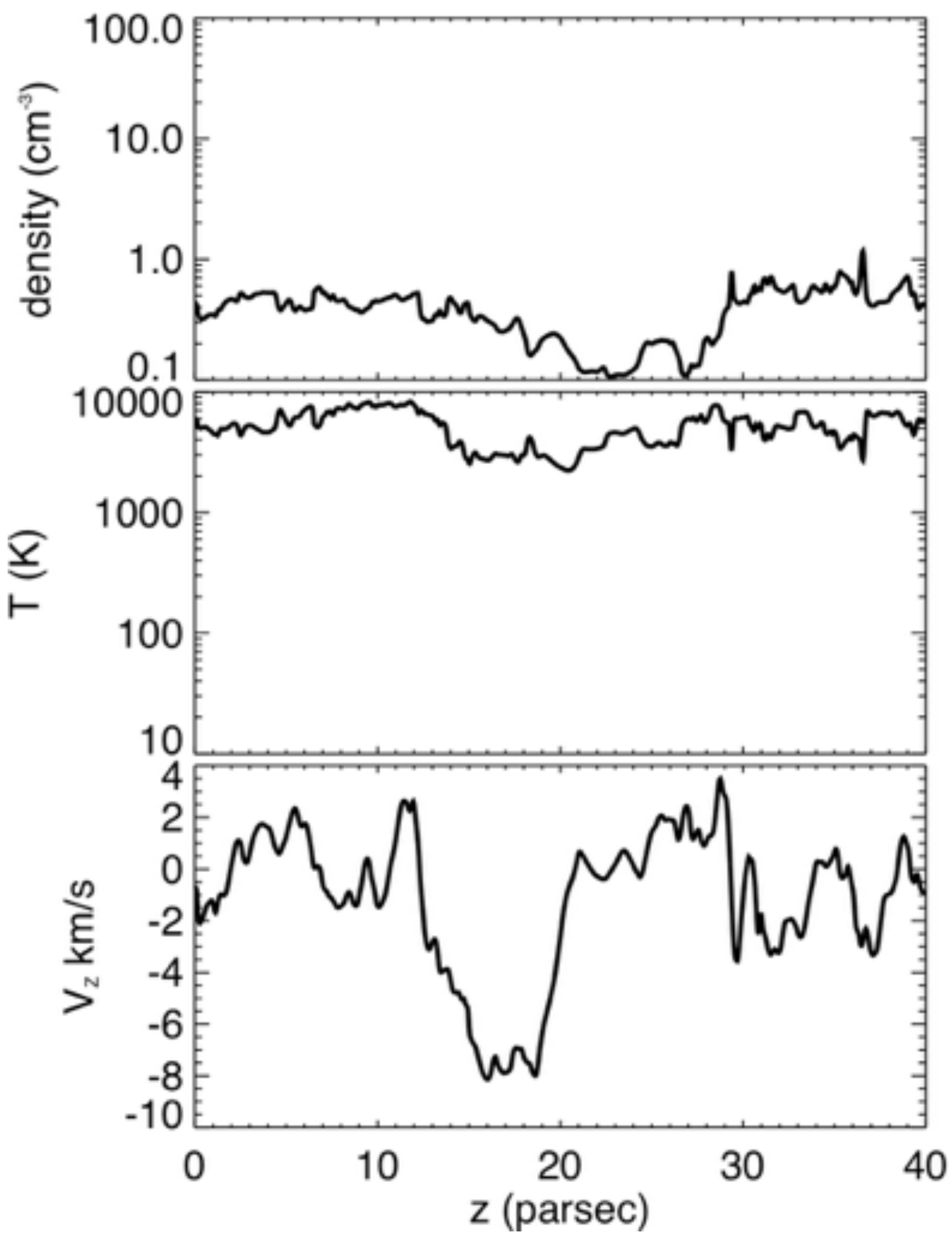

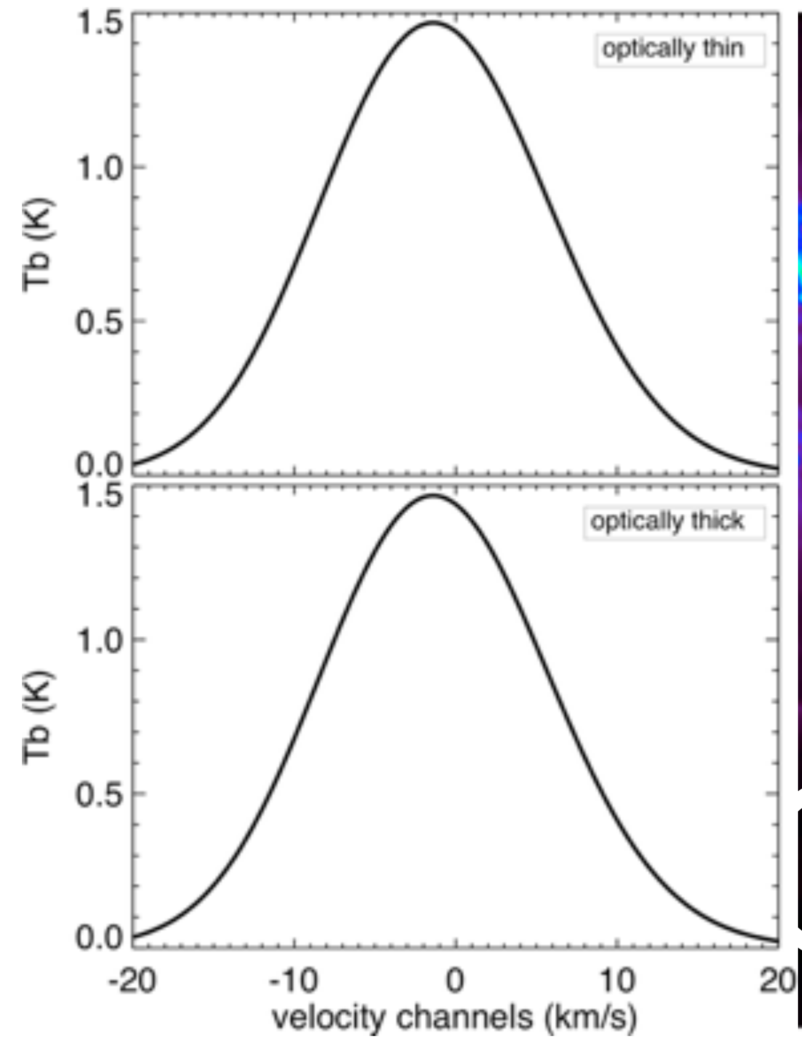

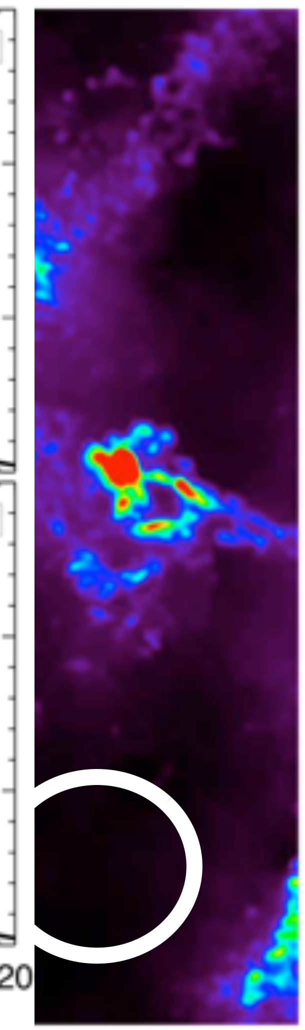

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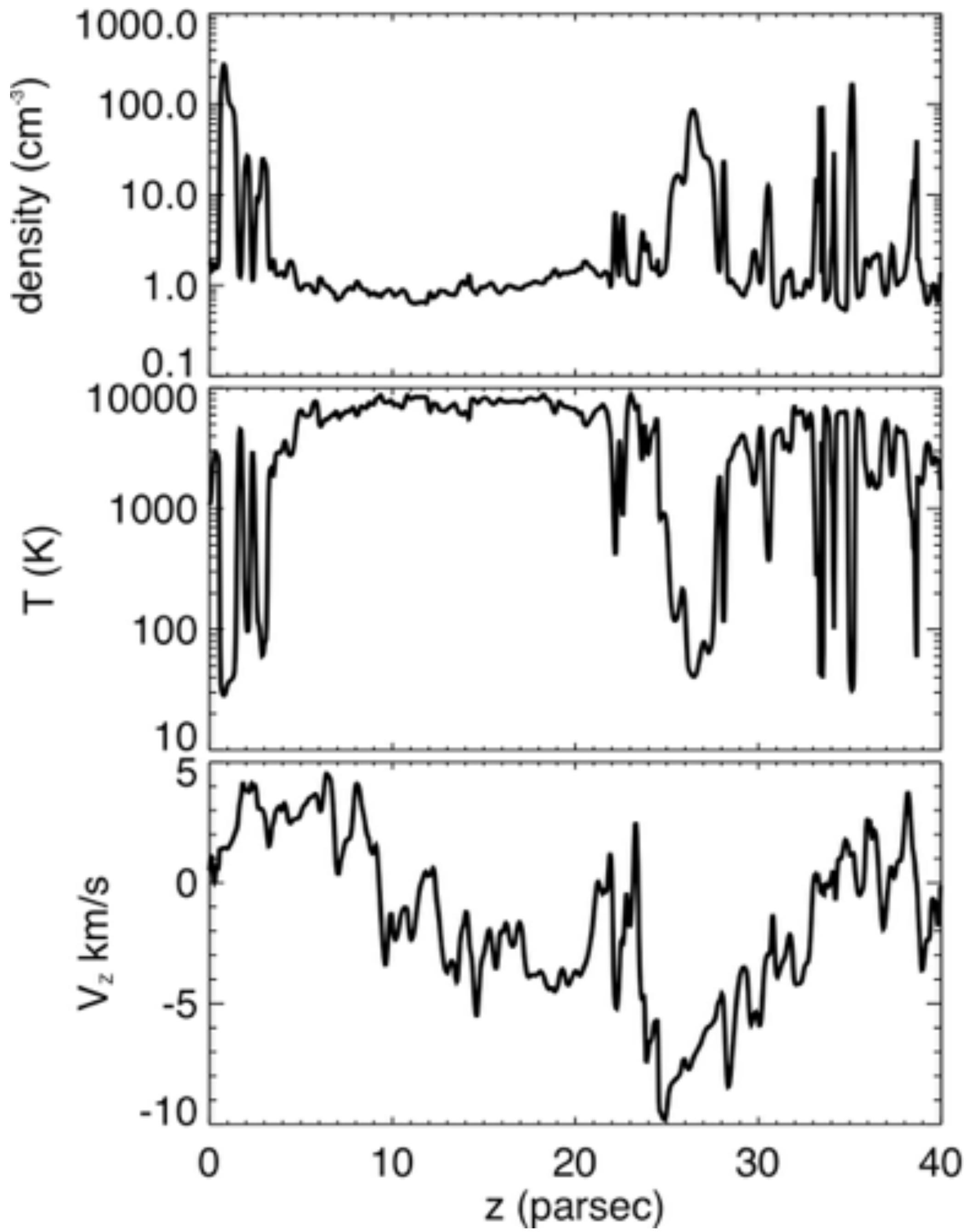

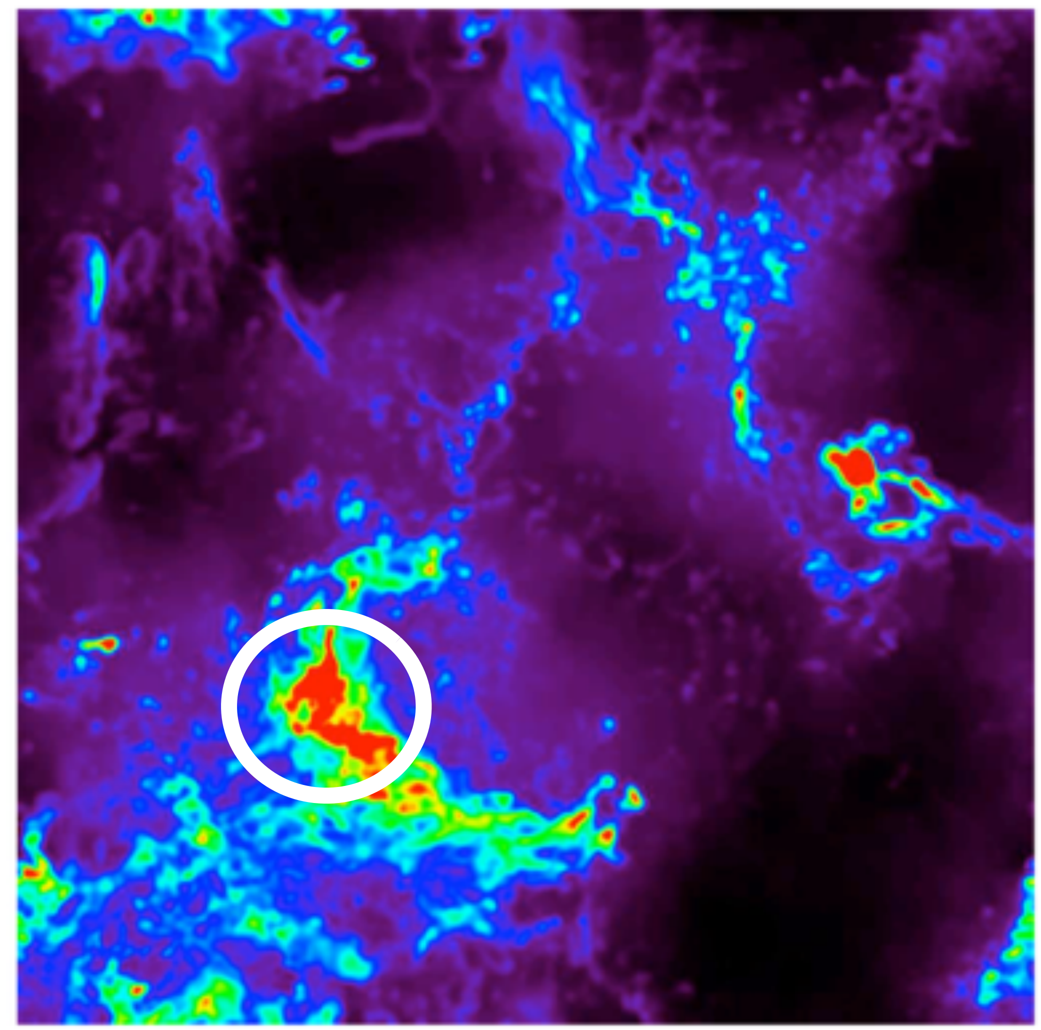

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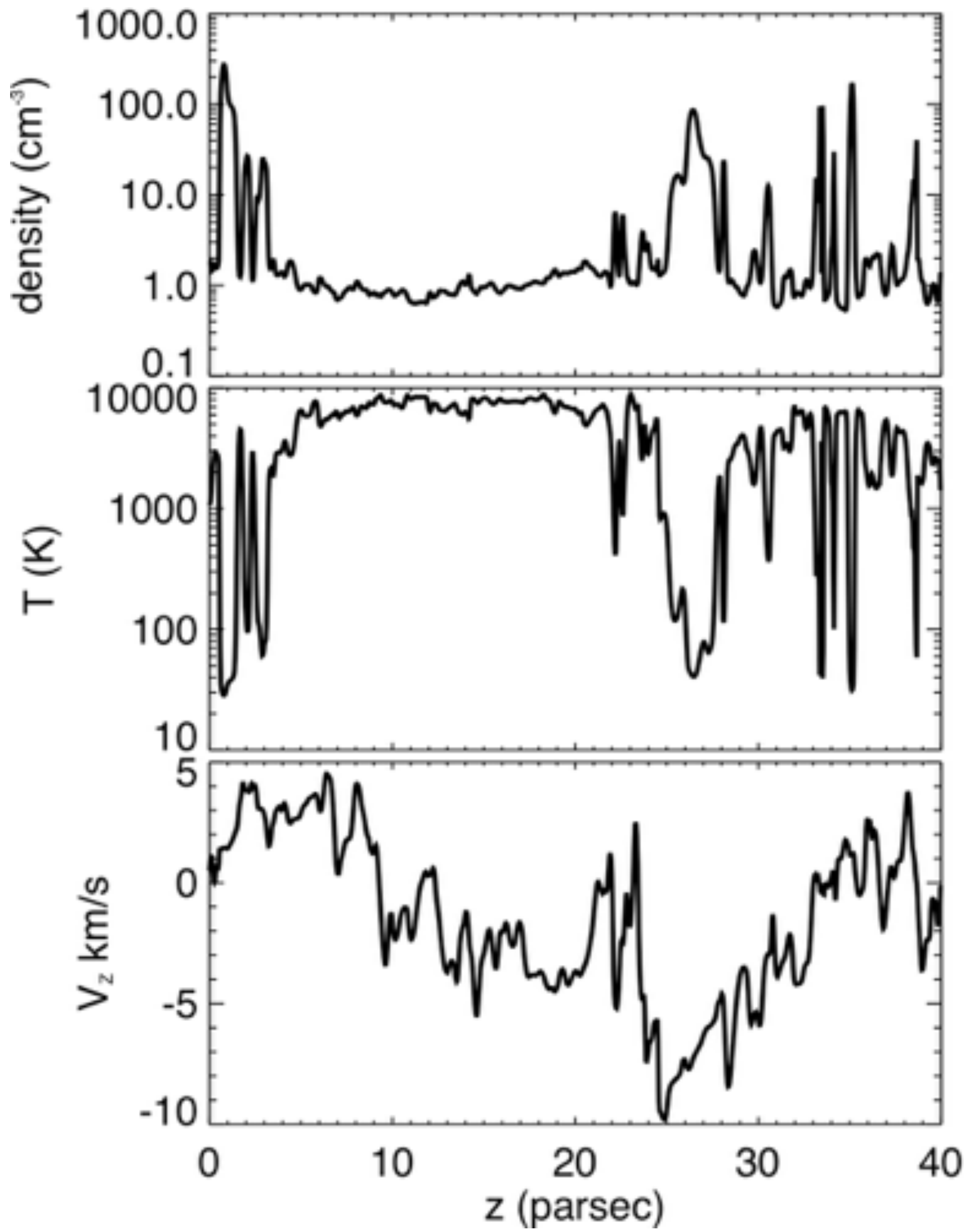

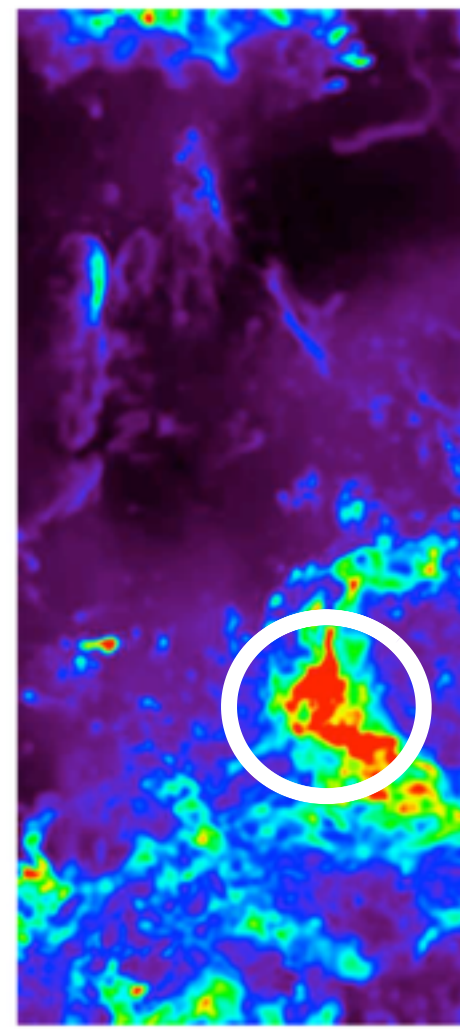

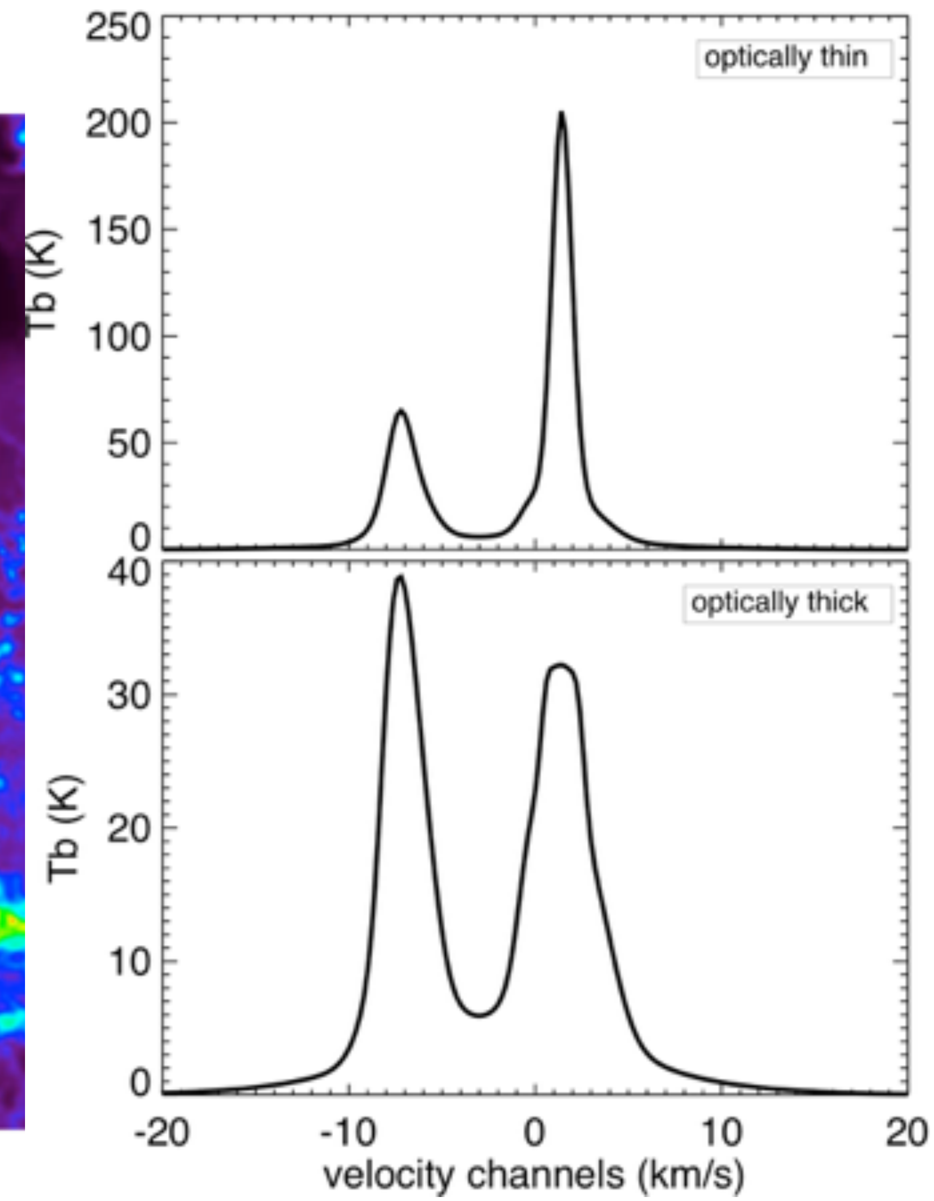

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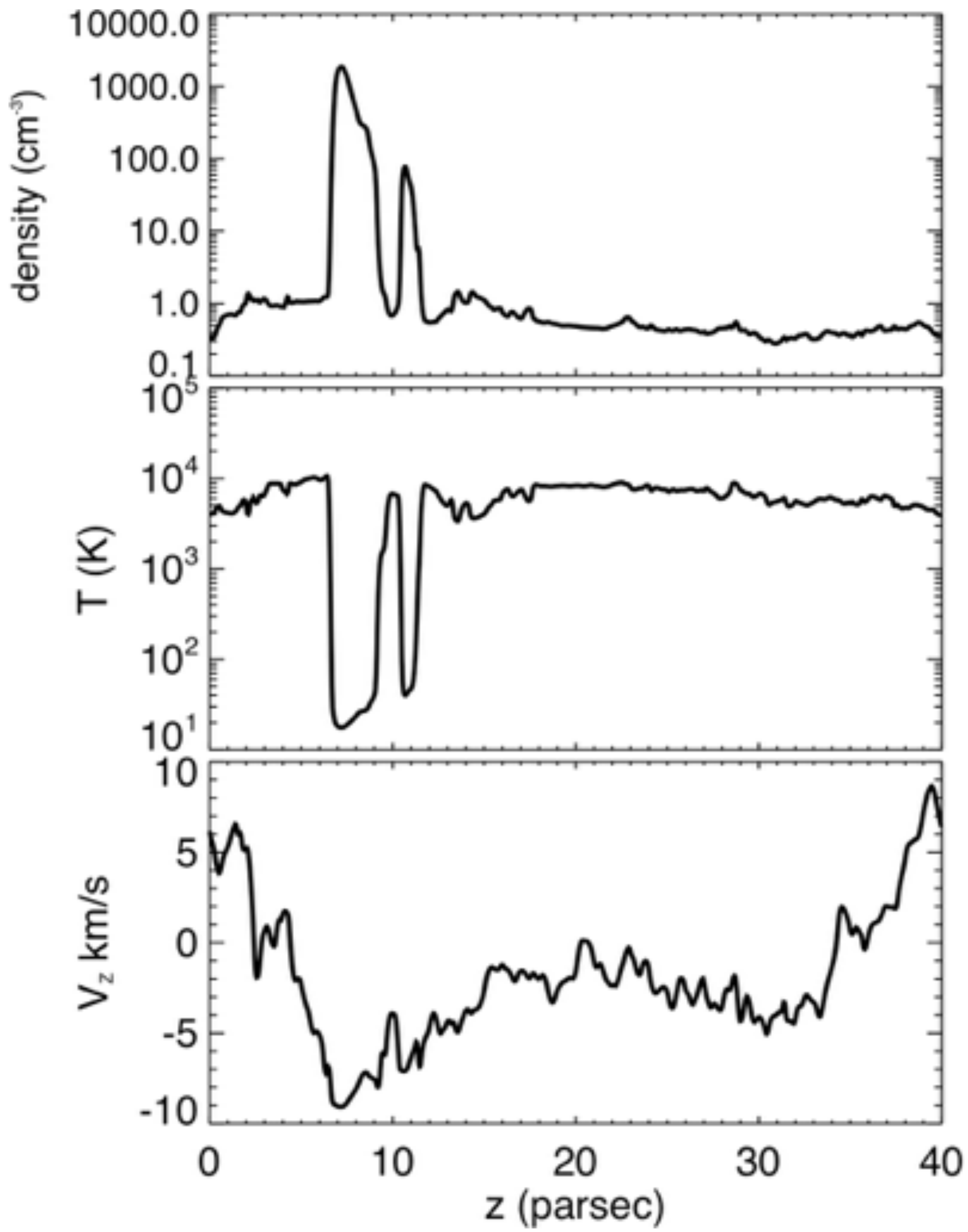

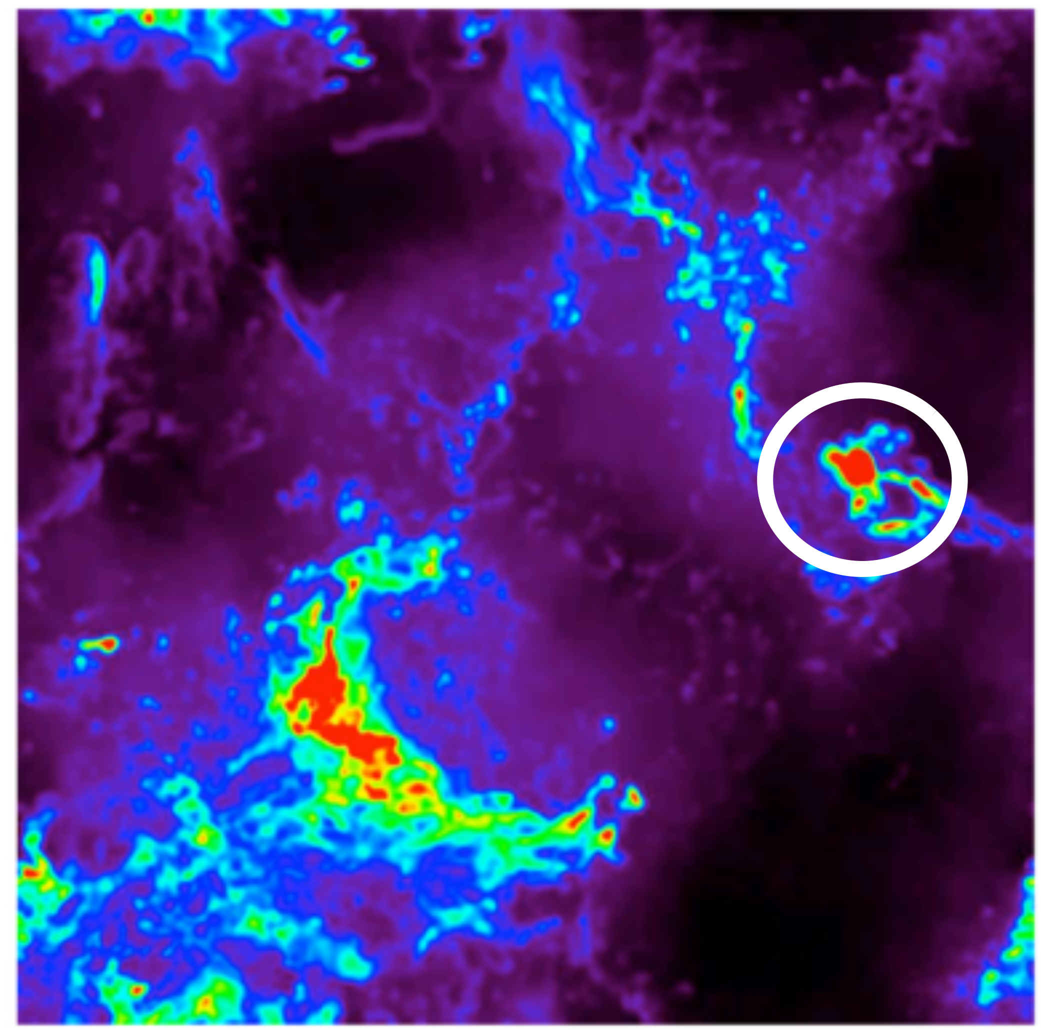

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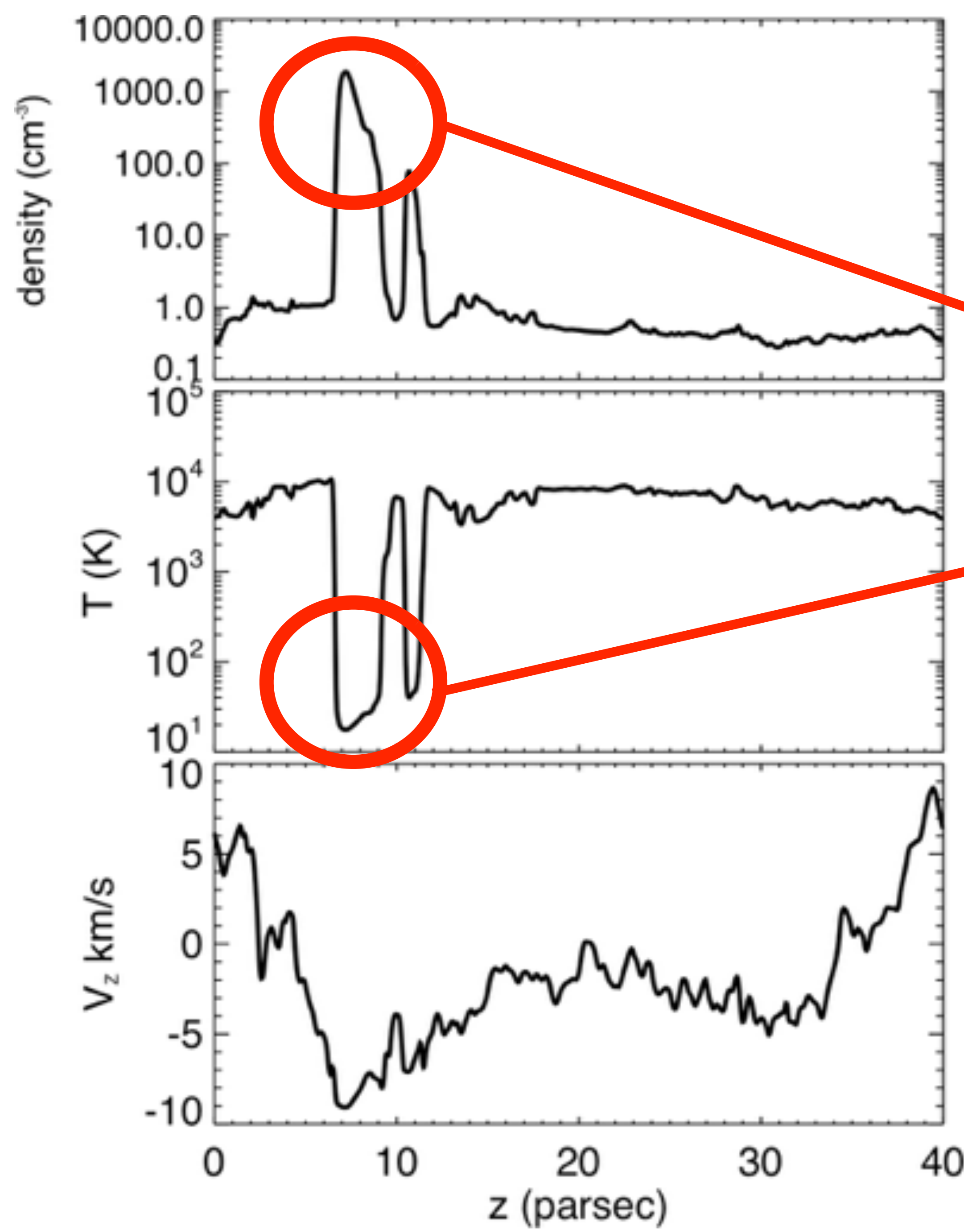
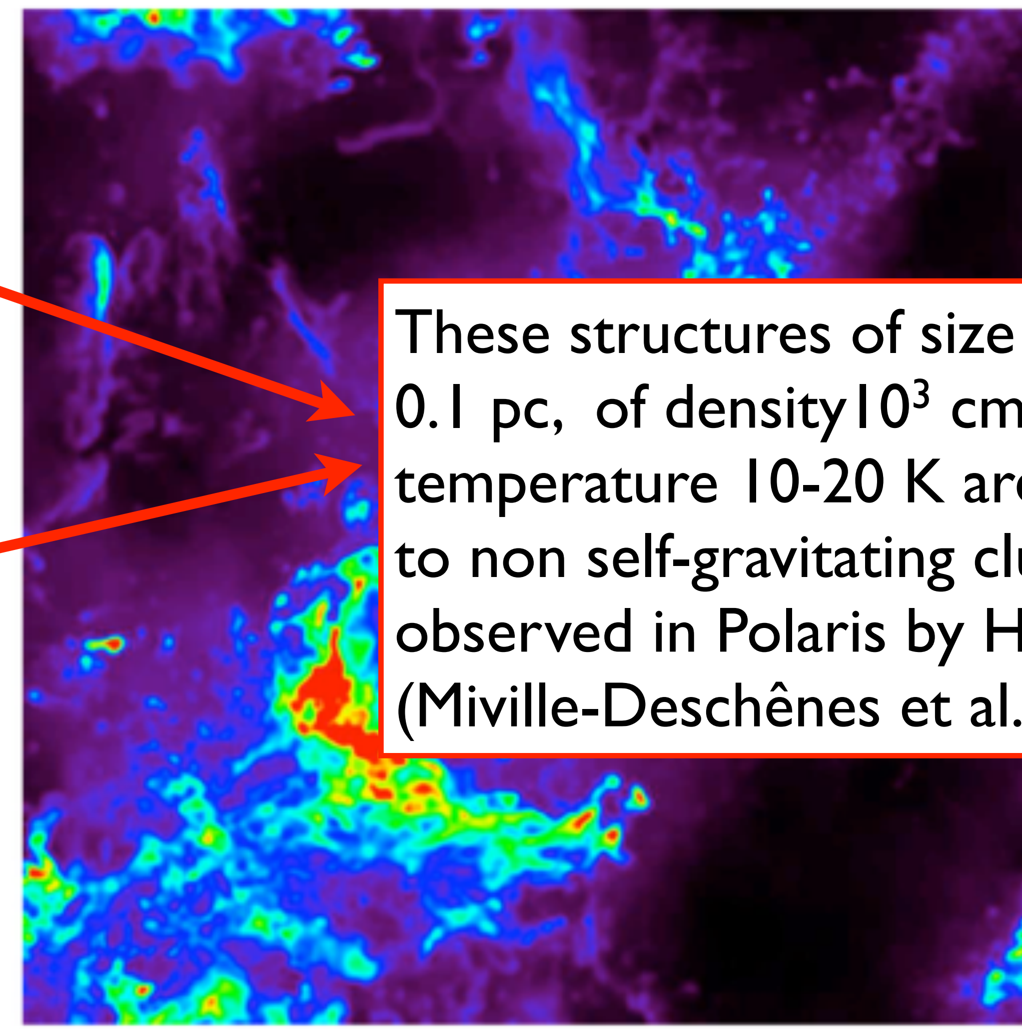
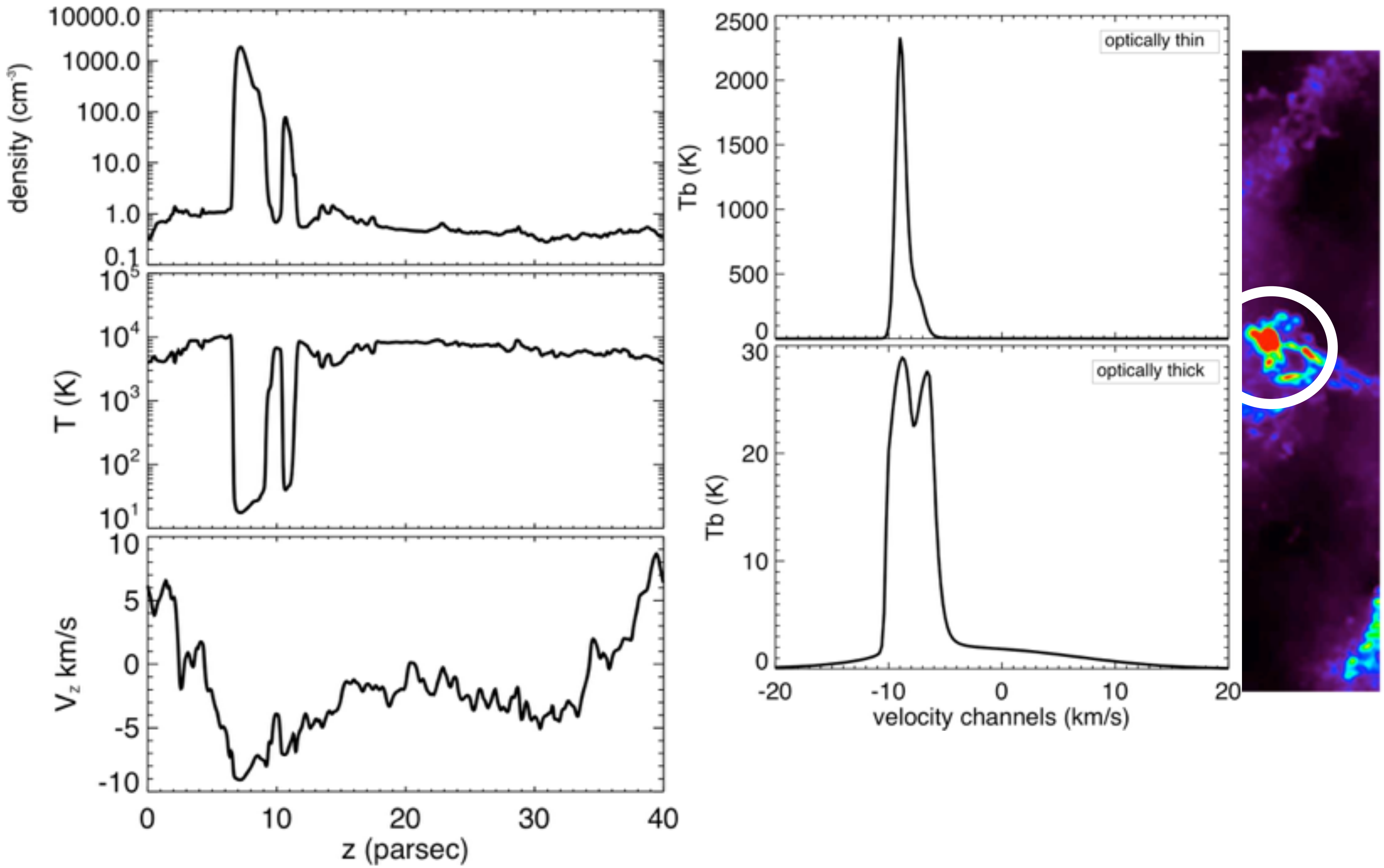




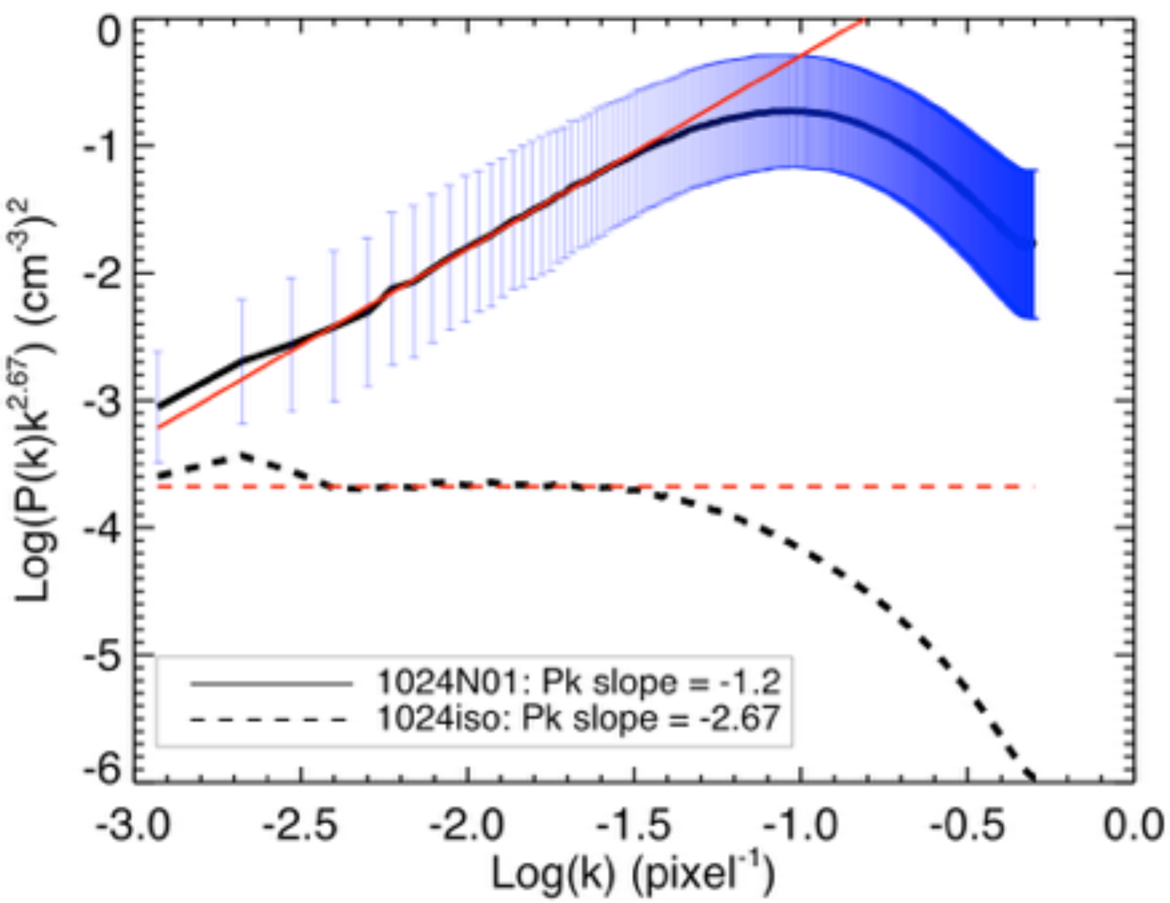
These structures of size of a few 0.1 pc, of density 10^3 cm^{-3} and of temperature 10-20 K are similar to non self-gravitating clumps observed in Polaris by Herschel (Miville-Deschênes et al., 2010)

What is on the line of sight of an HI cloud ?

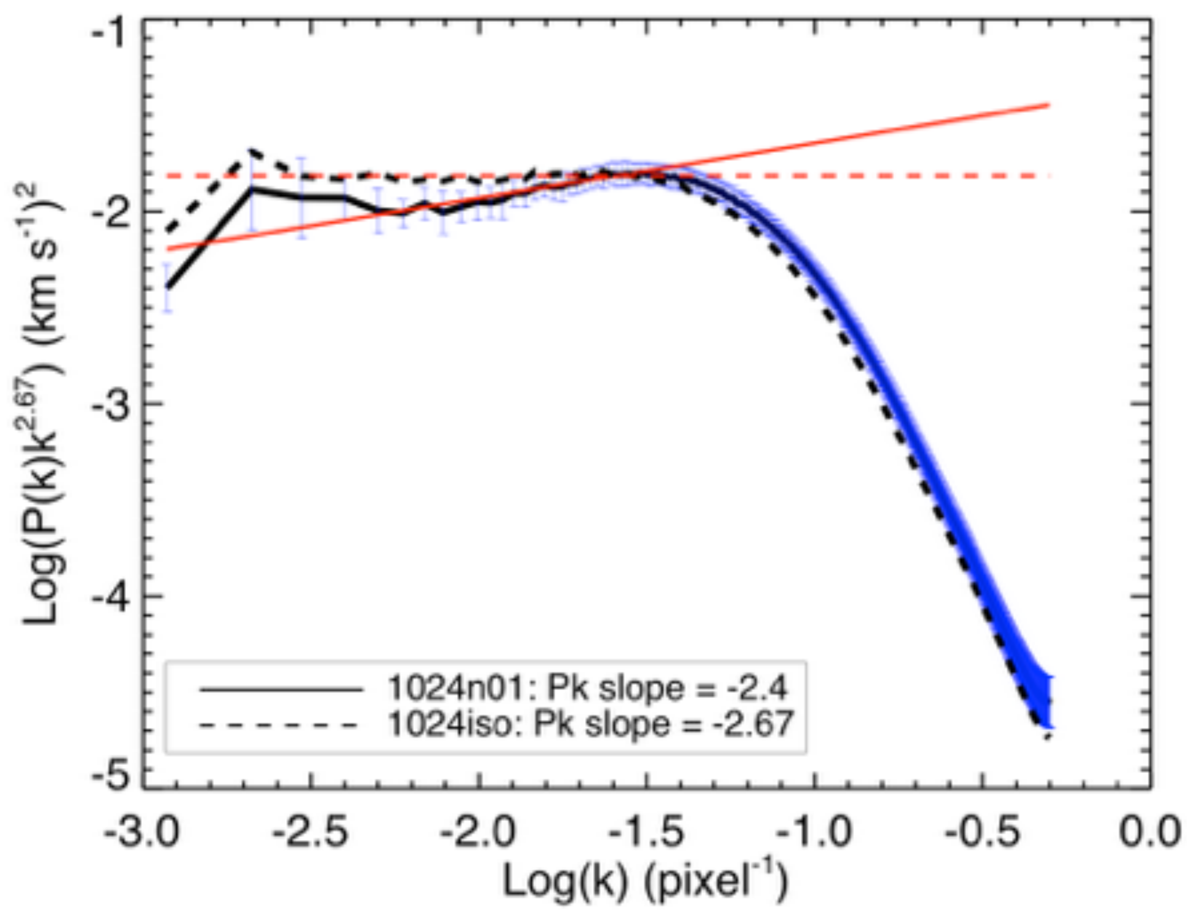


Power spectra : thermally bi-stable turbulence

Density : P(k) $k^{8/3}$



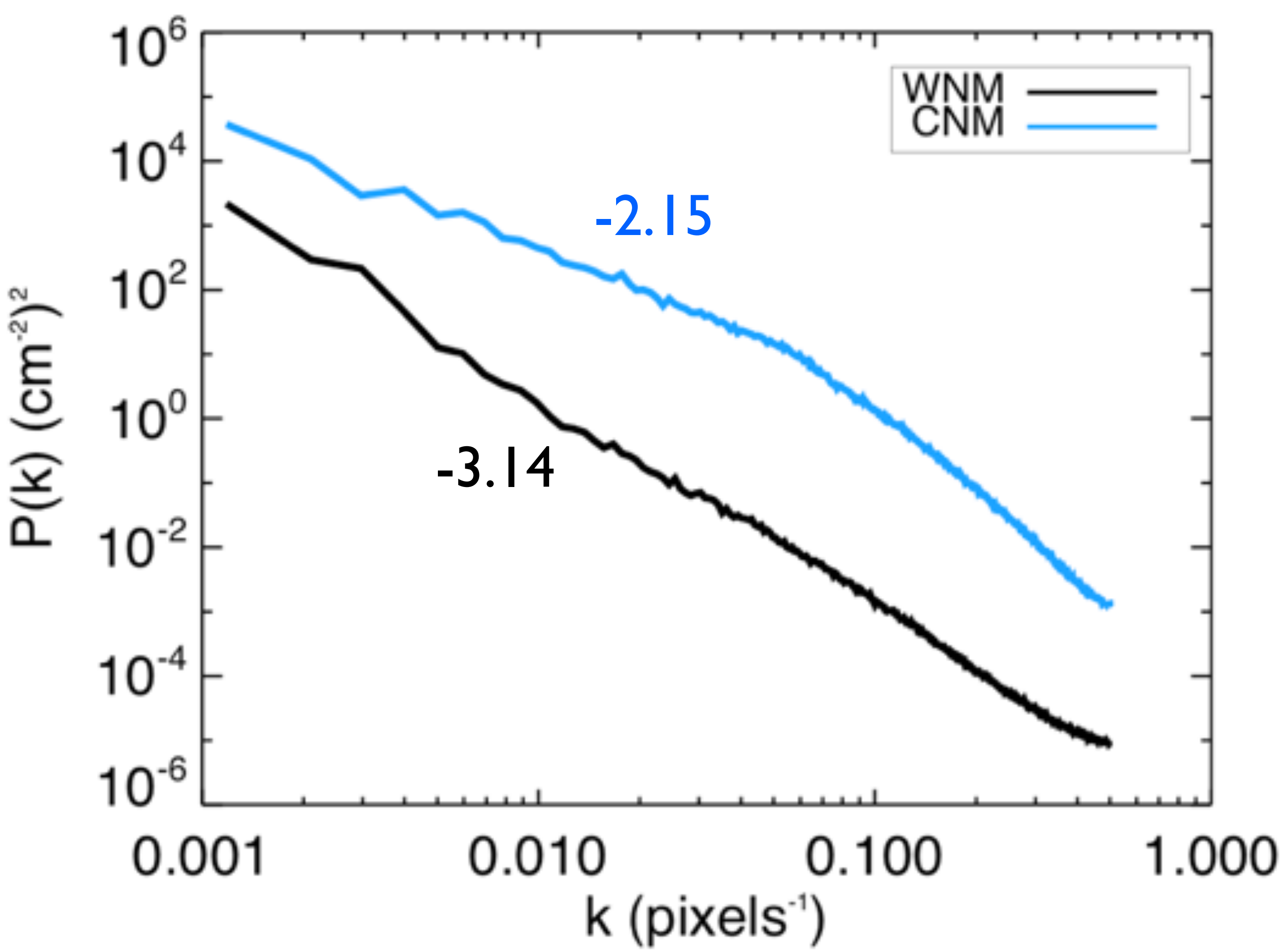
Velocity : P(k) $k^{8/3}$

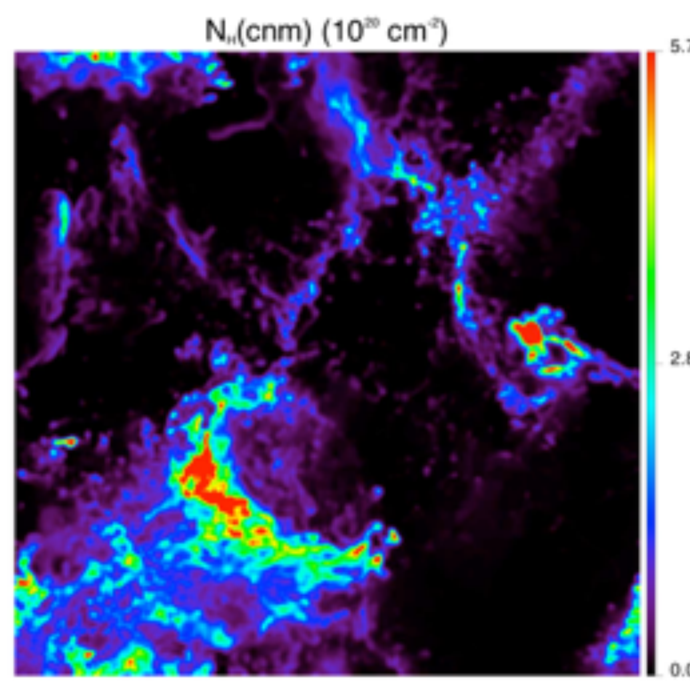


Density power spectrum is flatter (-1.2) than Kolmogorov (-2.67 in 2D)

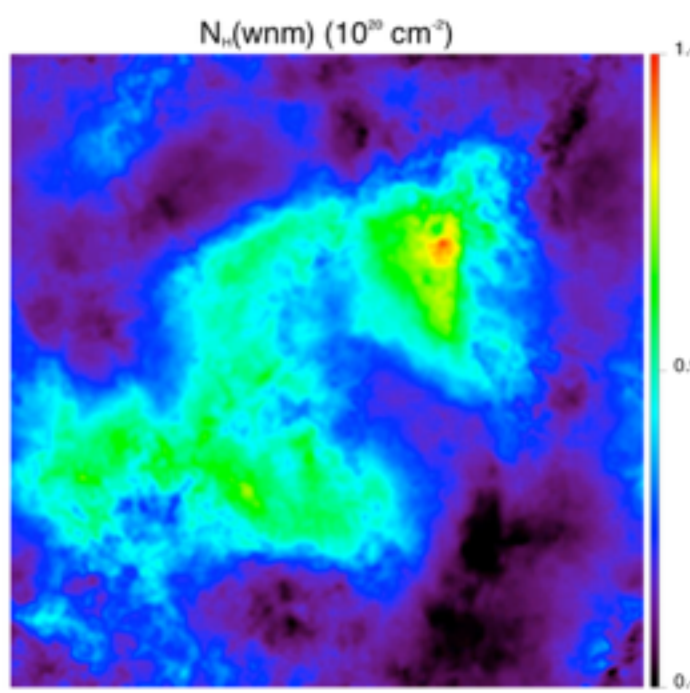
Velocity power spectrum stays close to Kolmogorov

Power spectra : bi-stable turbulence



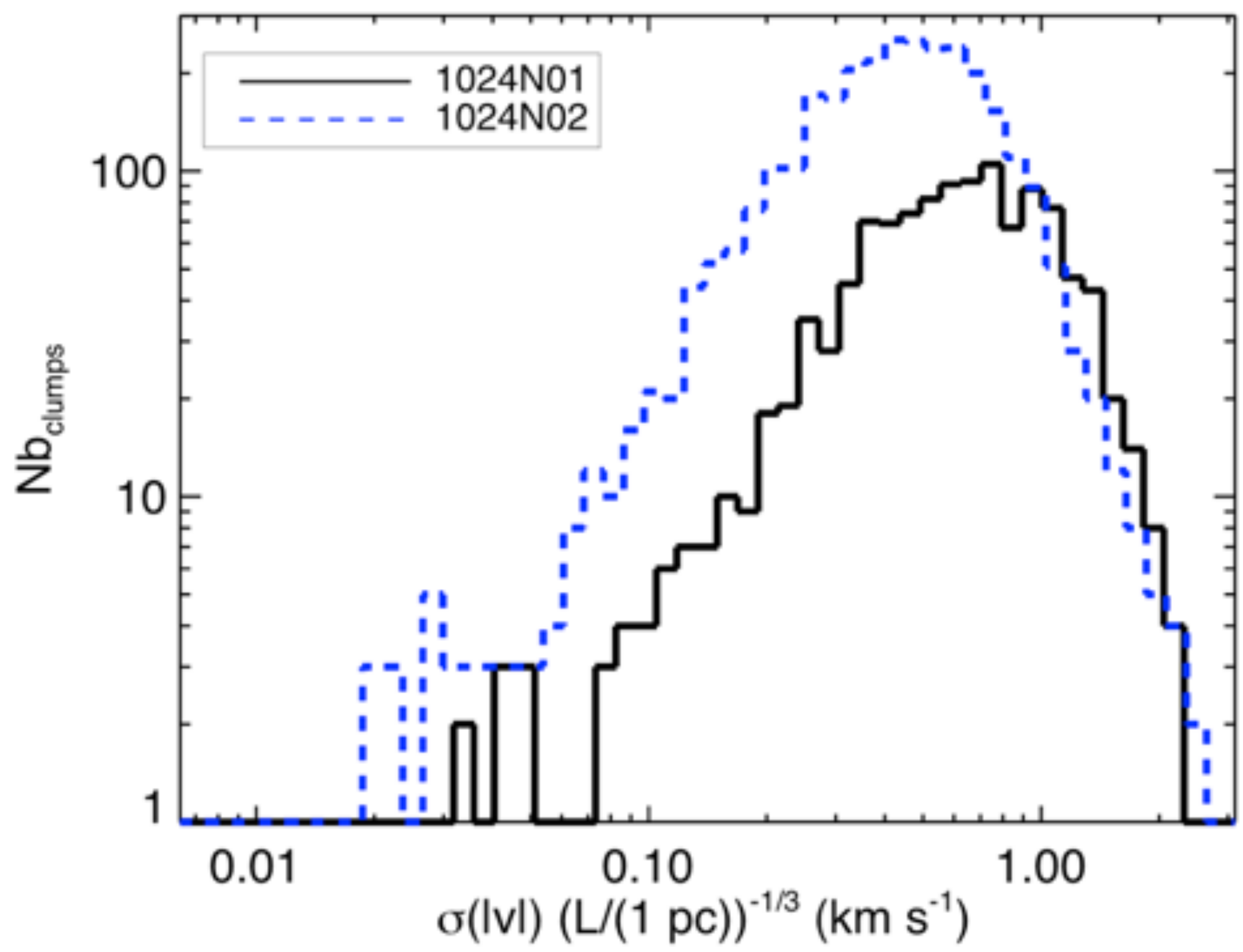


CNM



WNM

Clumps internal velocity



$$\sigma_{1\mathrm{pc}} = \frac{\sigma(|\mathbf{v}|)}{L_{\mathrm{pc}}^{-1/3}}$$

=> internal motions of the clumps are transsonic

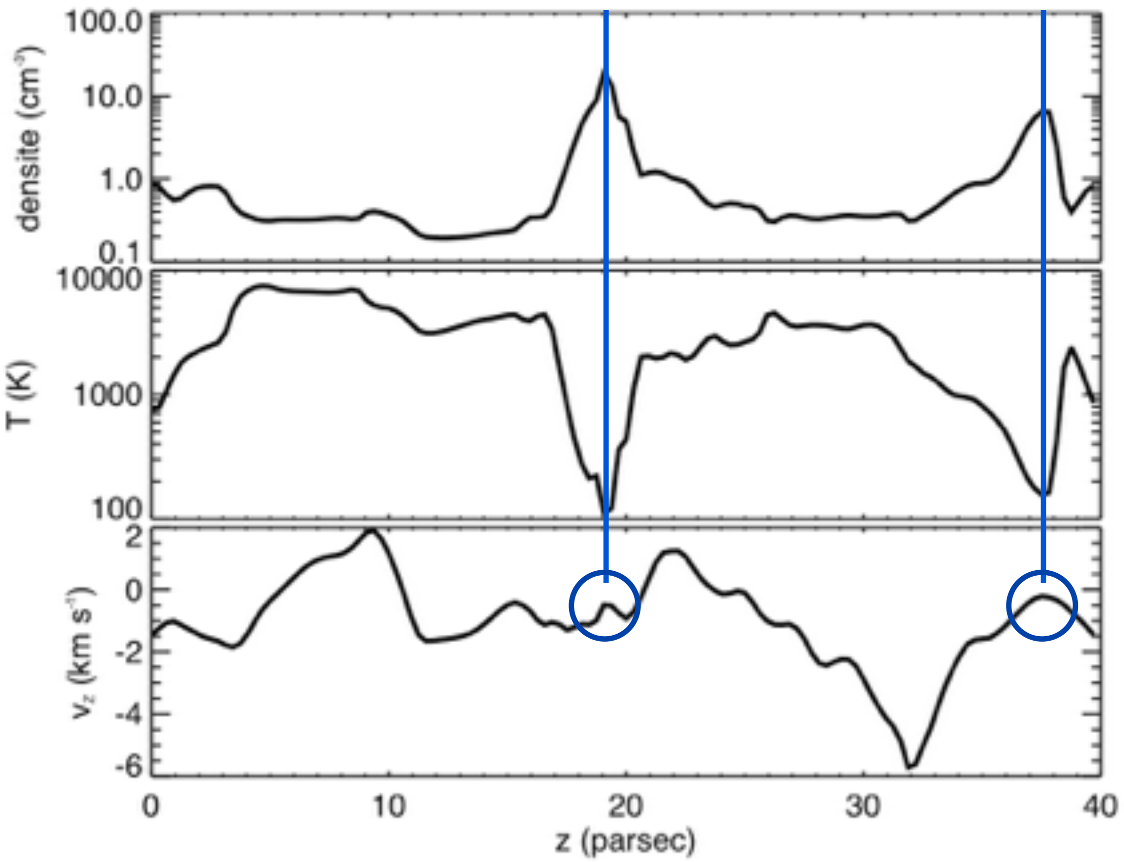
σ_{1pc} = 0.5 et 0.8 km s-1

to be compared with
σ_{1pc}(wnm) = 0.89 km s-1.

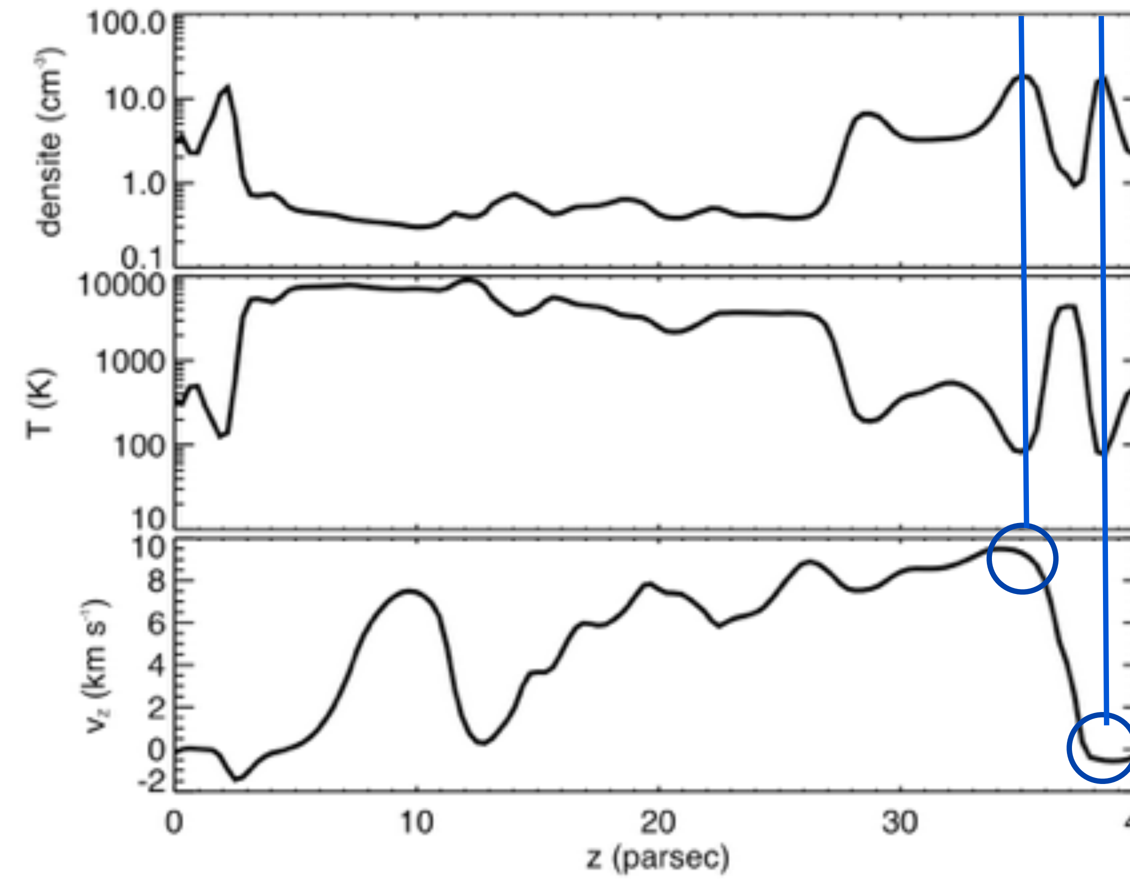
The internal dynamics of the clumps is related to WNM dynamics

Velocity dispersion

σ_{turb}(cnm) = 0.2 km s-1



σ_{turb}(cnm) = 4.7 km s-1



2 cold structures
Uniform velocity inside the structures
Low relative velocity between the 2 clumps
=> low velocity dispersion

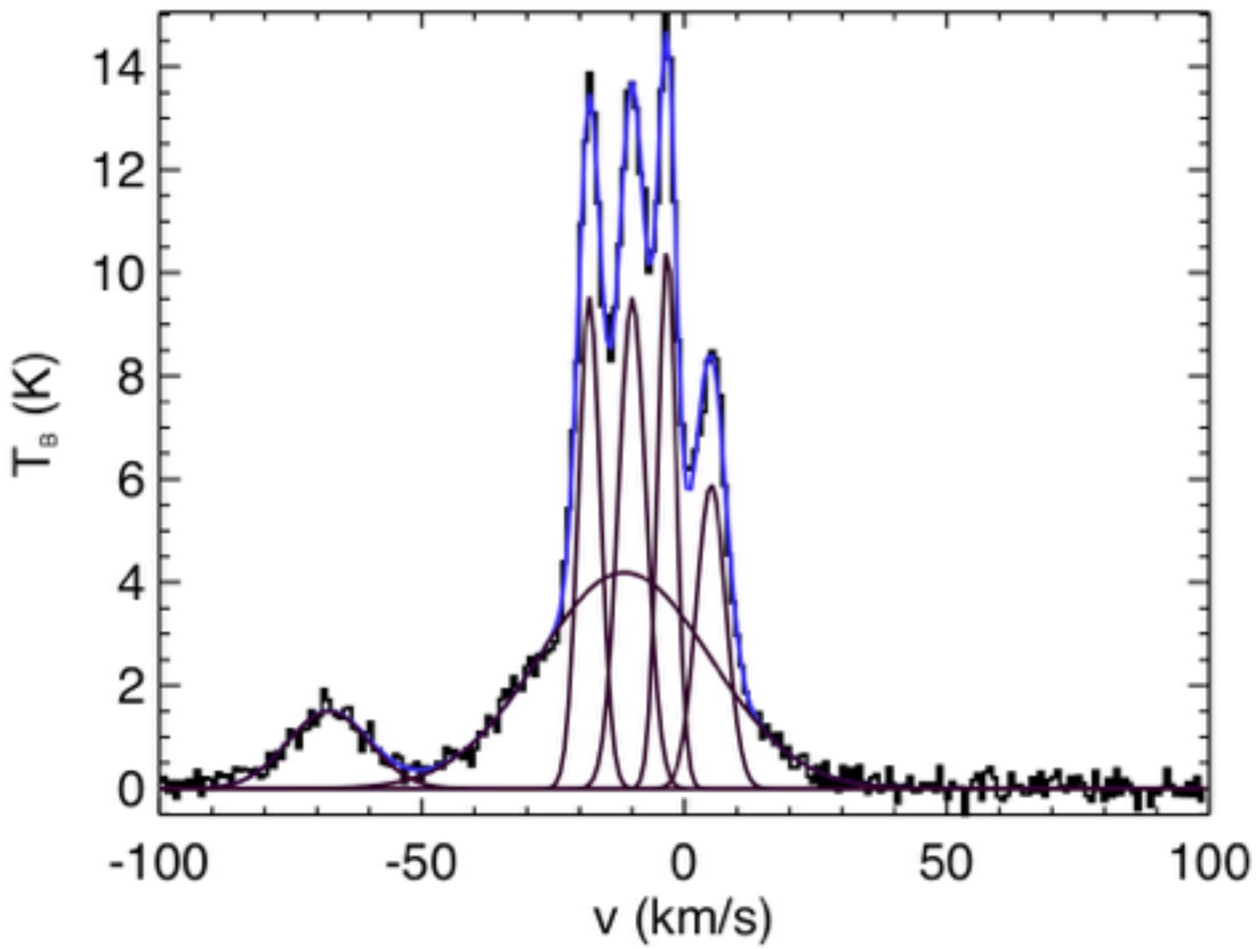
Many cold structures
Uniform velocity inside the structures
High relative velocity between the clumps
=> High velocity dispersion

The CNM clumps have subsonic internal velocities.
Line broadening => due to the relative motions between clumps along the line of sight

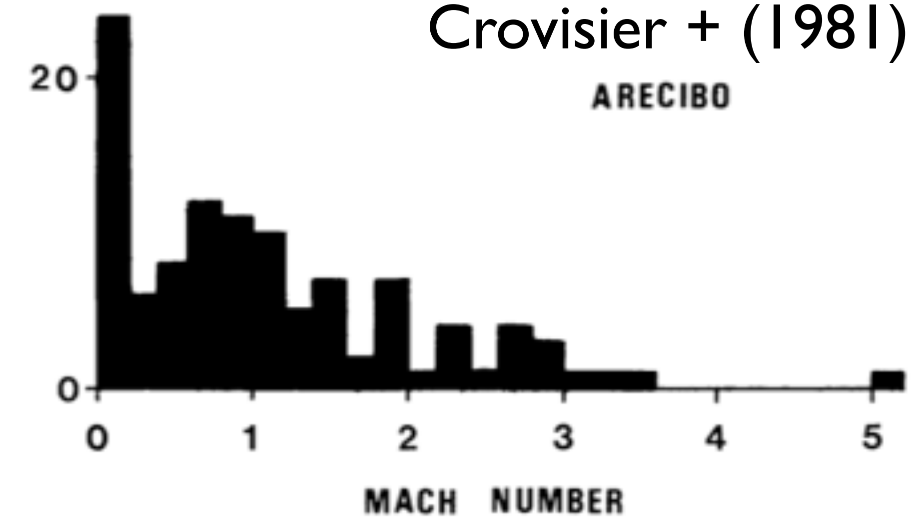
Saury et al. (2013)

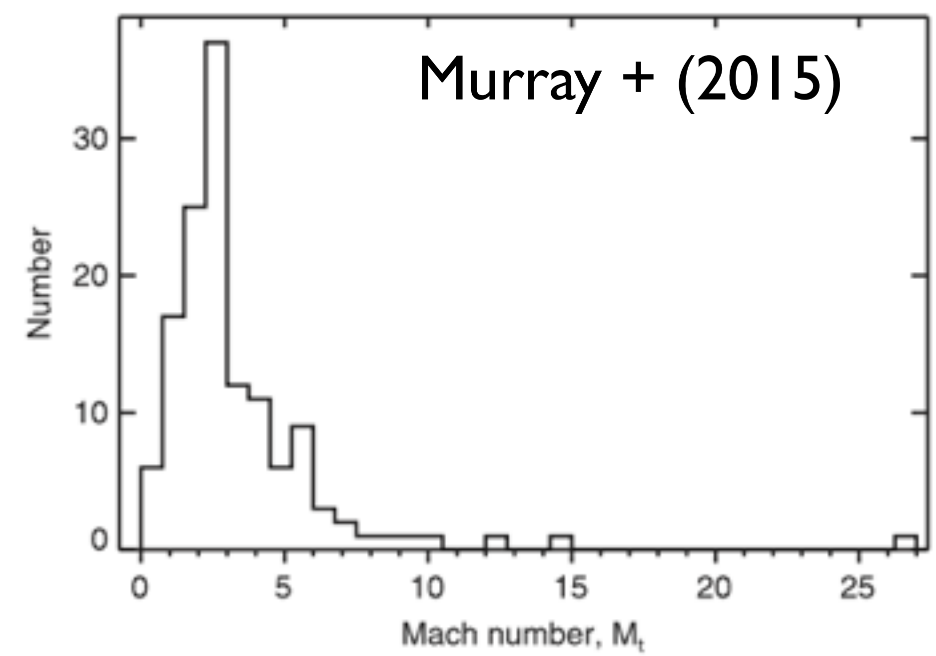
The HI observables: 21 cm profiles

High latitude cloud in Polaris
GHIGLS data (Martin et al. 2015)



Crovisier + (1981)





- Presence of cold gas(T~100K) and of warm gas (T~8000K)
- Thermal broadening ~ turbulent broadening =>

$$Mach = \frac{\sigma_{\rm turb}}{\sigma_{\rm therm}} \sim 1$$

What have learned ?

- Specific heating and cooling processes of the ISM leads to two thermally stable states in pressure equilibrium
- In non-stationary conditions, a significant amount (~1/3) of the gas is in the thermally unstable regime.
- The amount of gas in each state depends on the local comparison of the cooling time and the dynamical time
- Pressure is key (and not amplitude of turbulent motions). An increase of the WNM pressure is required to trigger the phase transition. Turbulence alone can not do it. The pressure can be converging flows or simply the weight of the galactic layer.
- Once the WNM is at higher pressure, turbulence drives the gas away from the thermal equilibrium, placing a significant fraction of the gas at thermally unstable temperatures and triggering the formation of cold structures
- The density structure of the CNM is extremely contrasted, filling only a few percent of the volume.
    - WNM and CNM structures are likely to have sub/trans-sonic motions. The relative motion of CNM clouds follow the velocity dispersion of the warm phase are thus supersonic with respect to their own temperature.
    - The density power spectrum of the diffuse ISM is similar to high Mach number turbulence even though it is not.

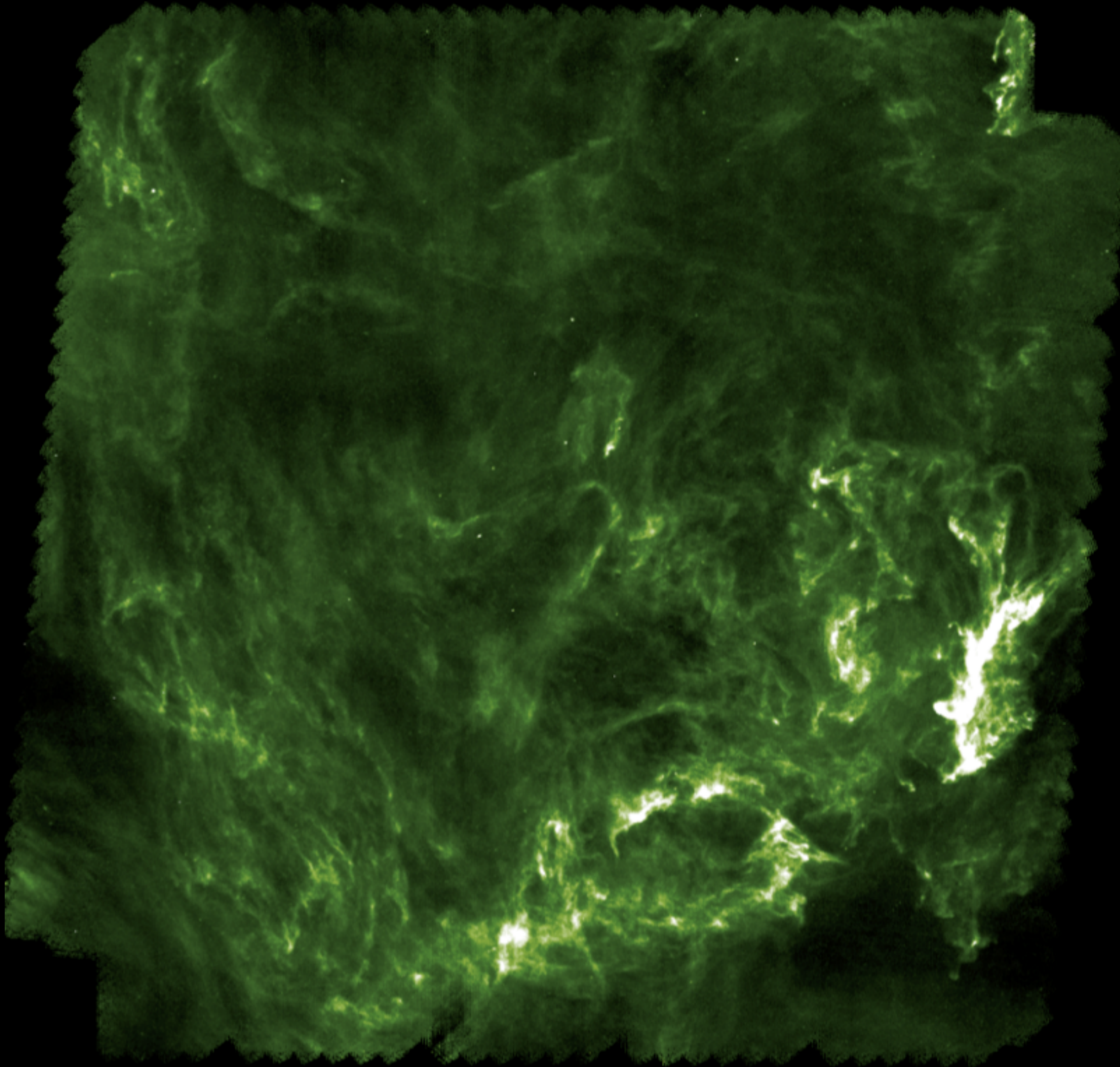
the road ahead

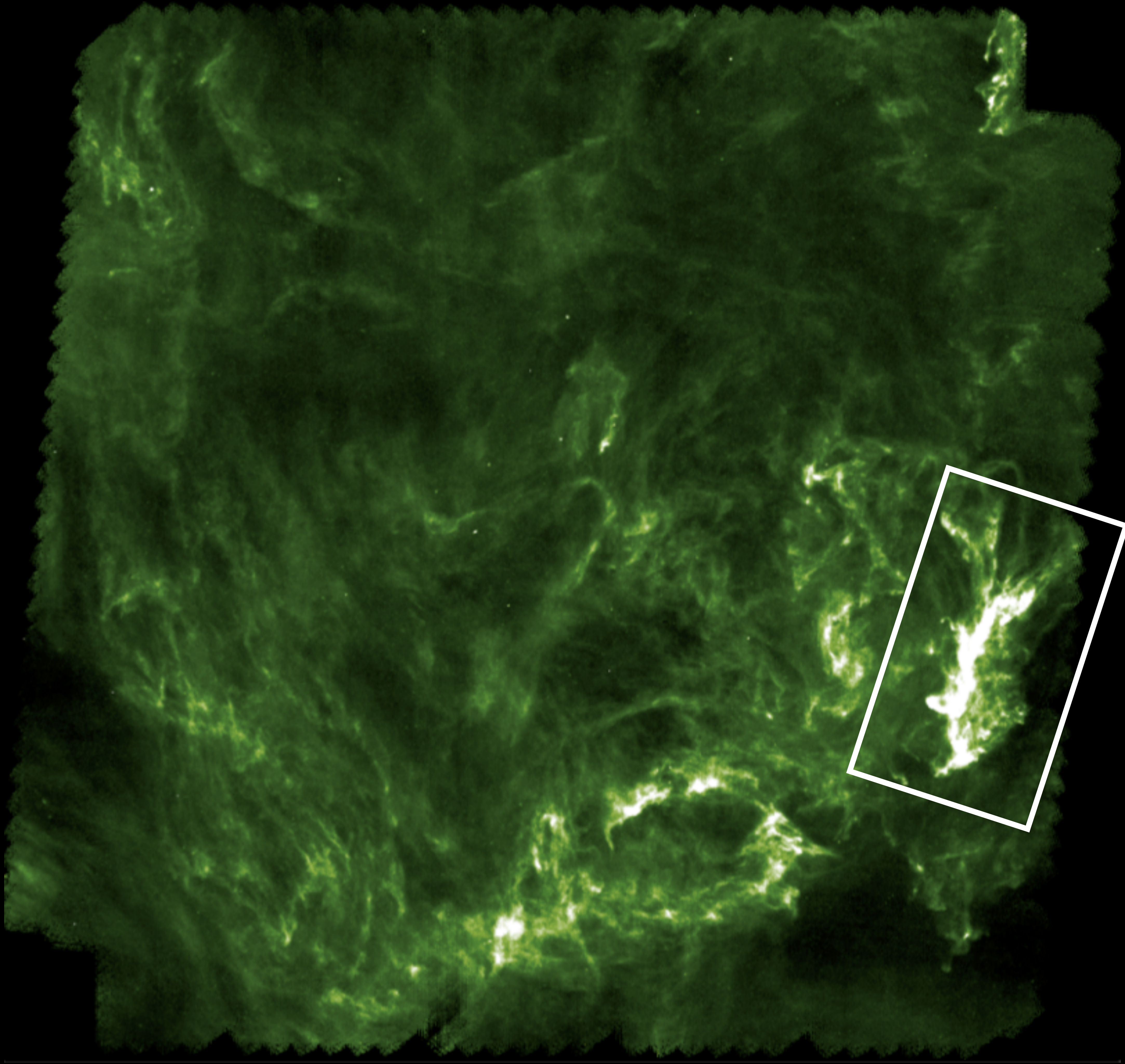
- Turbulence in a multi-phase medium
- Small-scale structure : TSAS, energy dissipation
- Properties of the WNM : <u>difficult to observe</u>
- Star formation in multi-phase medium (HI-H2 transition)
- Dealing with large datasets : SKA !!!!
- Built on the past results, do not rediscover

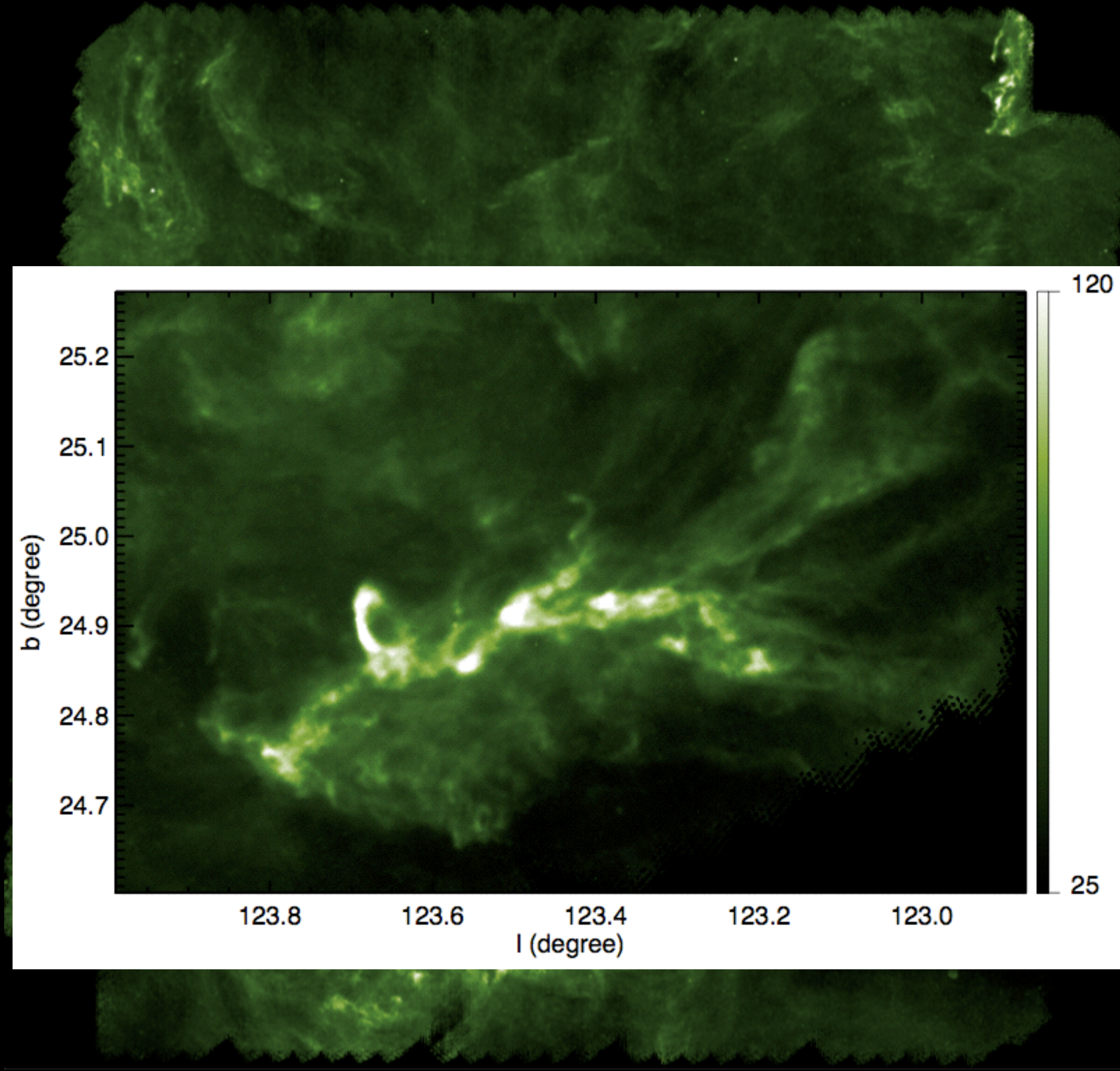
Turbulence of a multi-phase medium

"We find that turbulence in a thermally bistable flow like the atomic interstellar hydrogen, is somewhat different from turbulence in a supersonic isothermal gas."

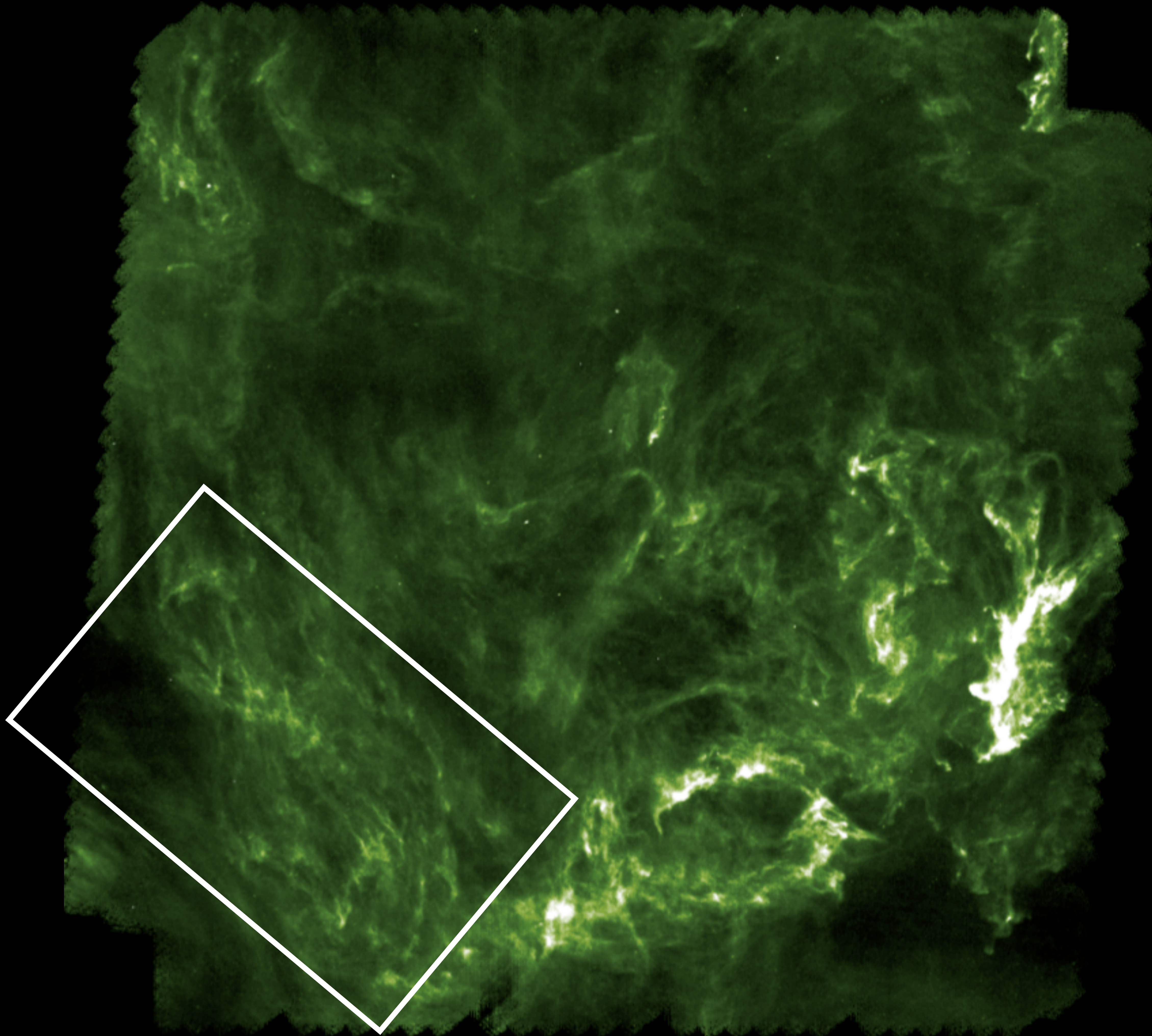
Hennebelle & Audit (2007)

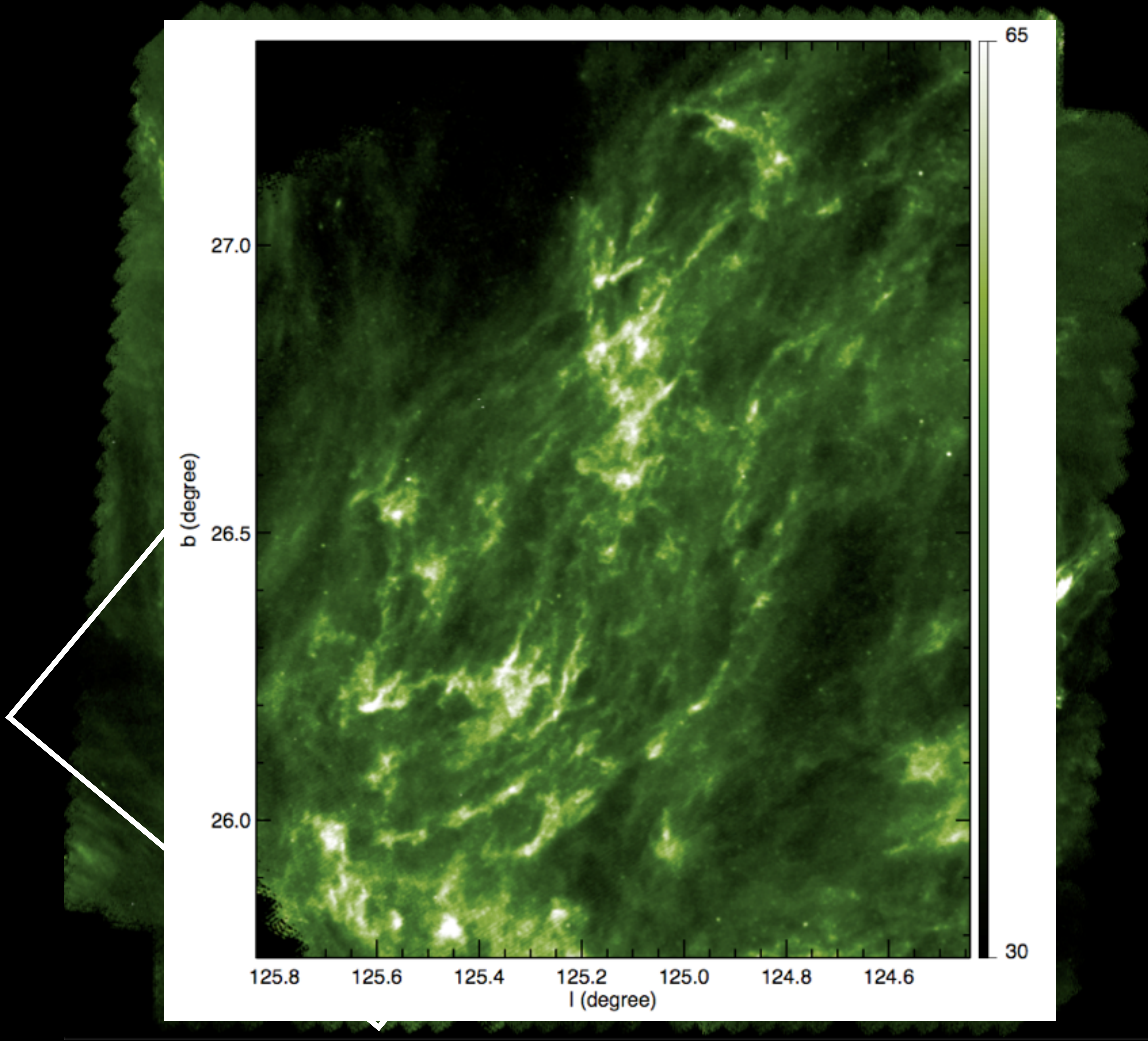






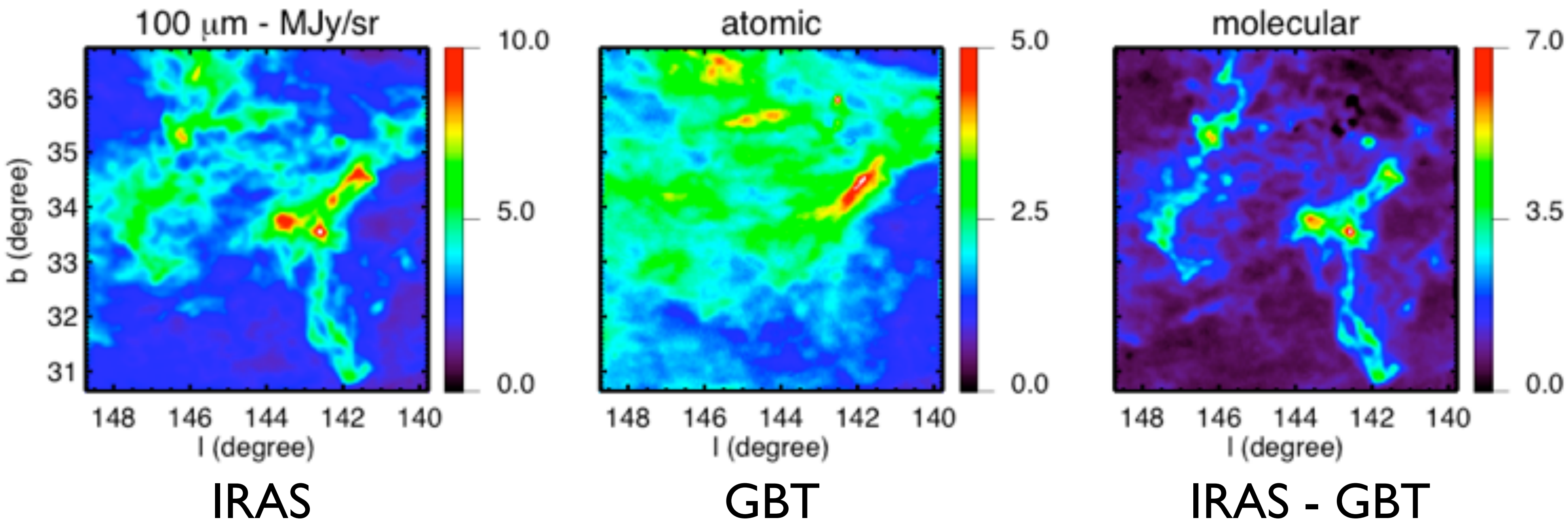
120
25
25.2
25.1
25.0
24.9
24.8
24.7
b (degree)
123.8
123.6
123.4
123.2
123.0
l (degree)



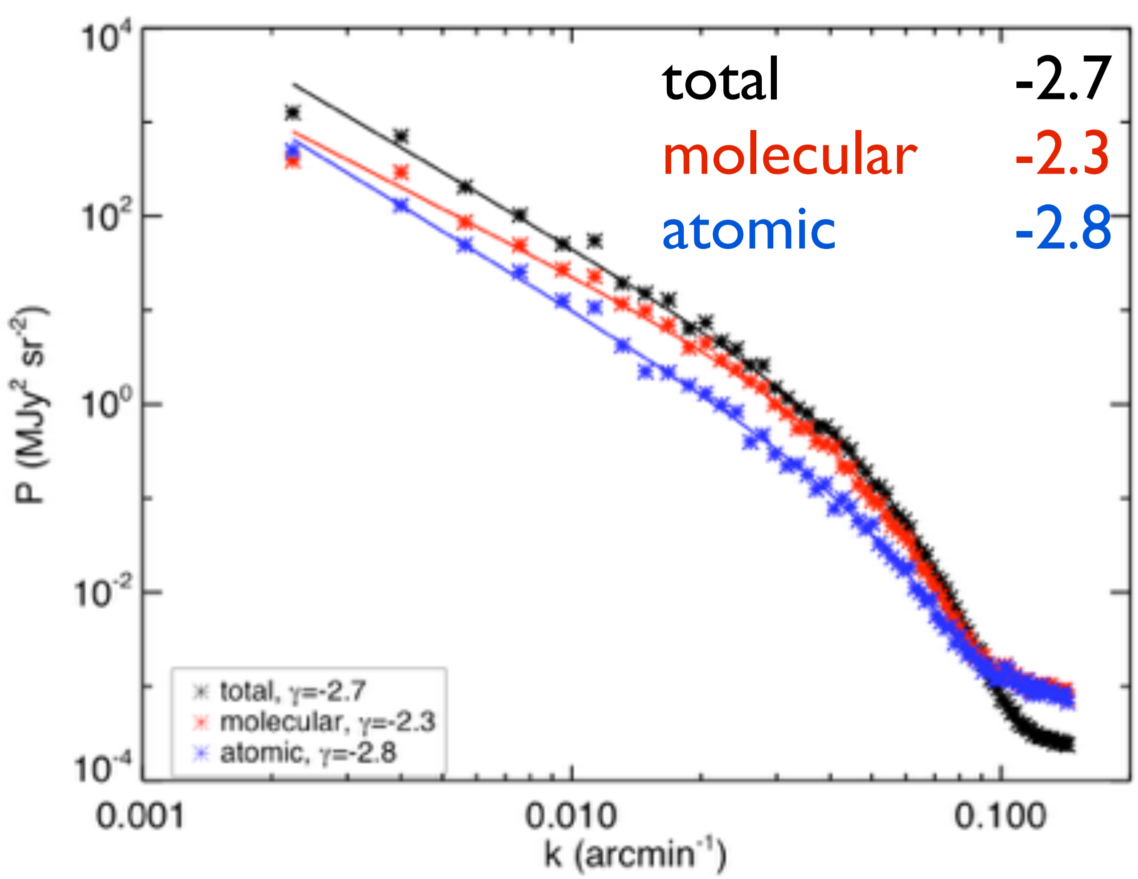


65
30
27.0
26.5
26.0
b (degree)
125.8
125.6
125.4
125.2
125.0
124.8
124.6
l (degree)

The interstellar turbulence



Ursa Major : diffuse HI at high latitude

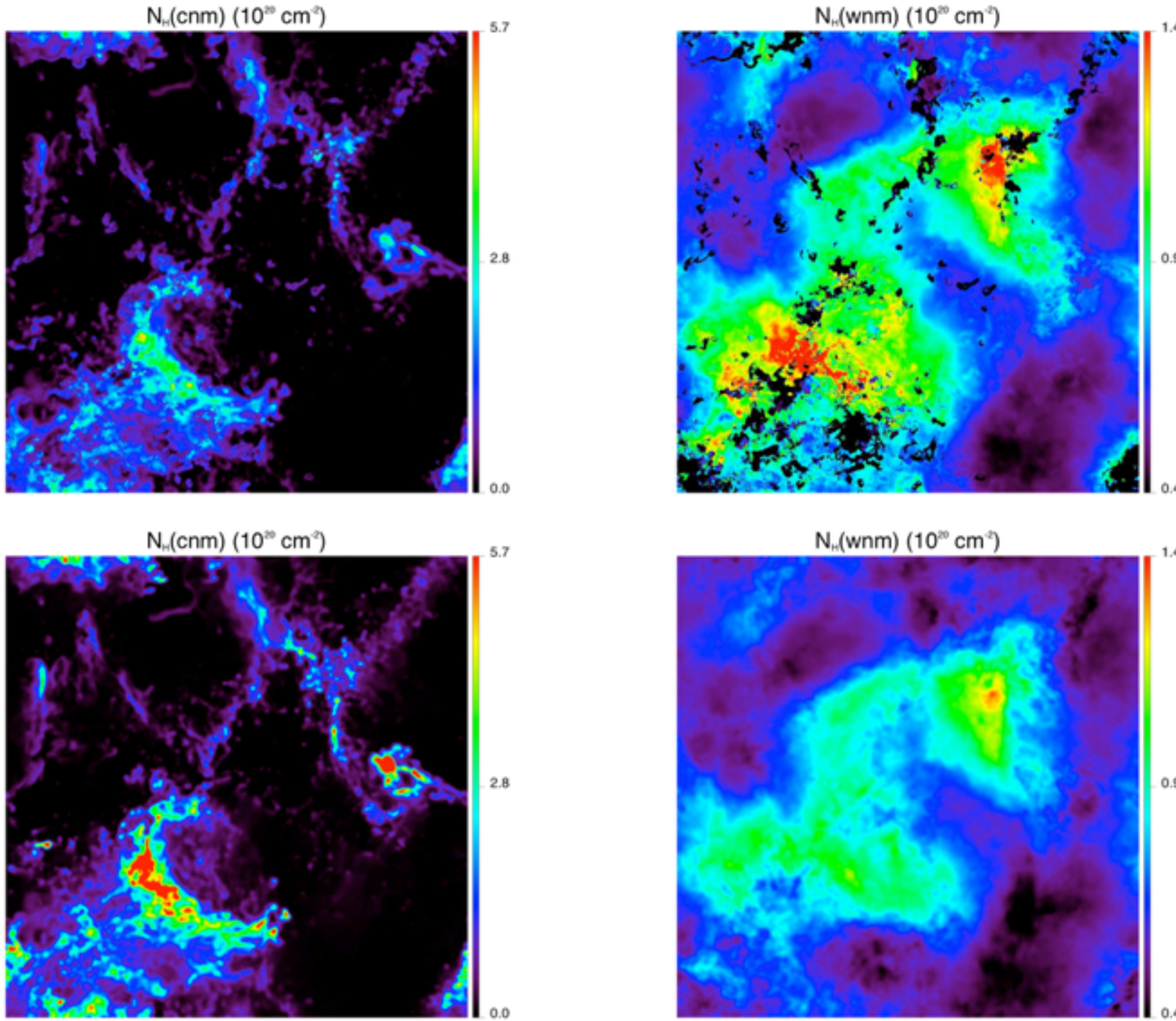


- Diffuse HI clouds => power spectrum steeper than molecular clouds
- How does the transition WNM-CNM shapes the structure of the interstellar medium ?

Comparison observations-simulations : gaussians decomposition

CNM
gaussians

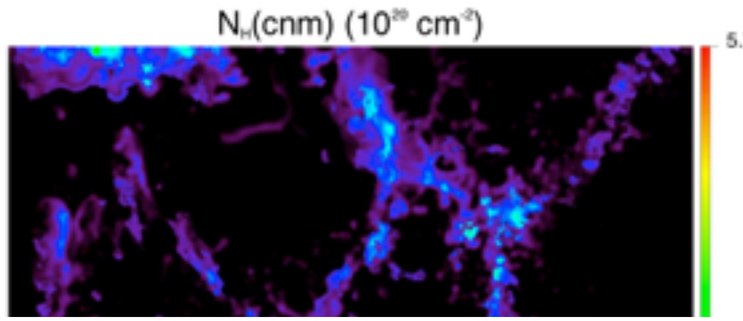
WNM
gaussians

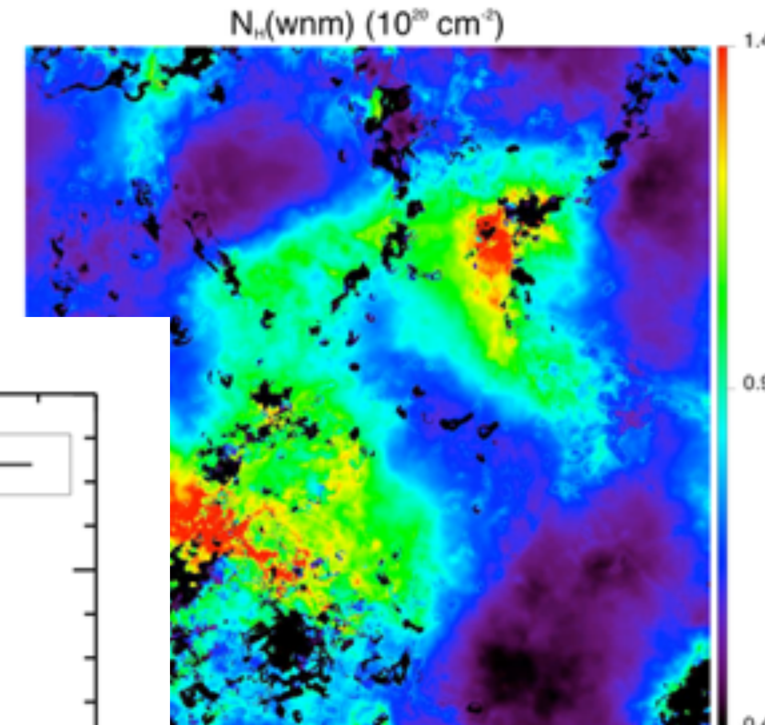


CNM
theory

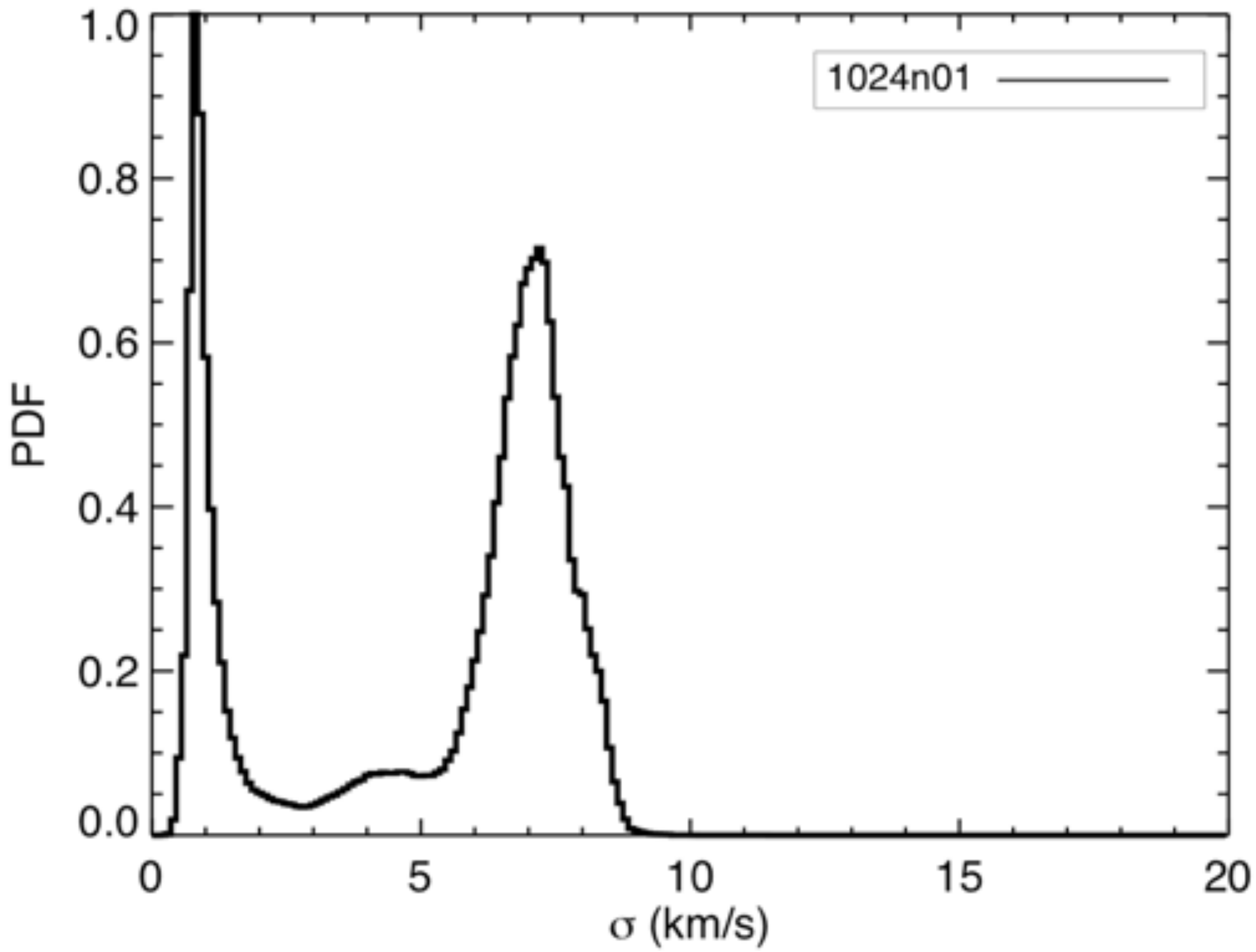
WNM
theory

Comparison observations-simulations : gaussians decomposition





CNM
g

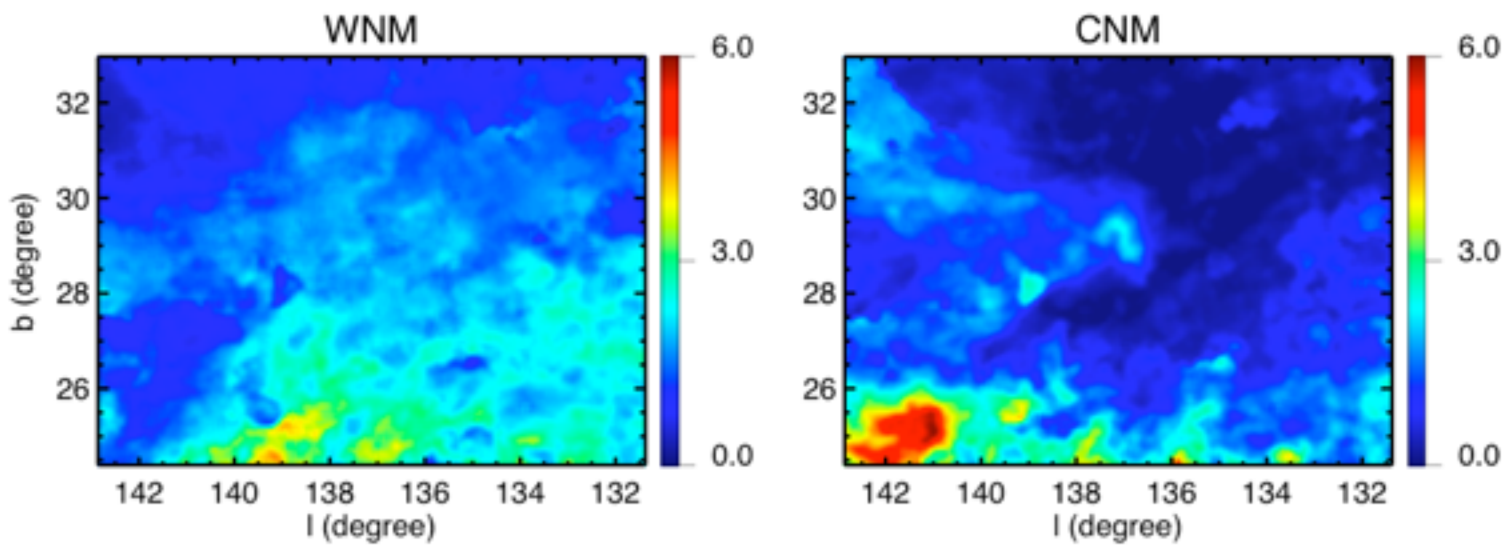


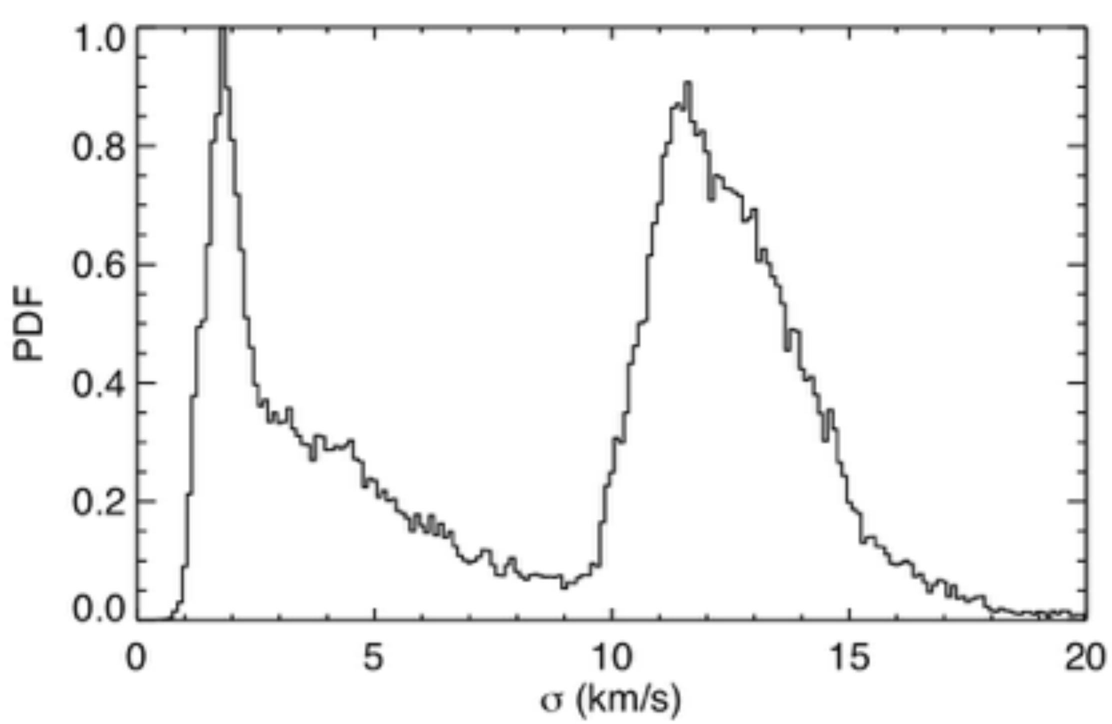
WNM
gaussians

The gaussians narrower than 5 km s^{-1} represent 35% of the mass

Theoretically, 45% of the mass has a temperature below 3000 K

Comparison observations-simulations : gaussians decomposition





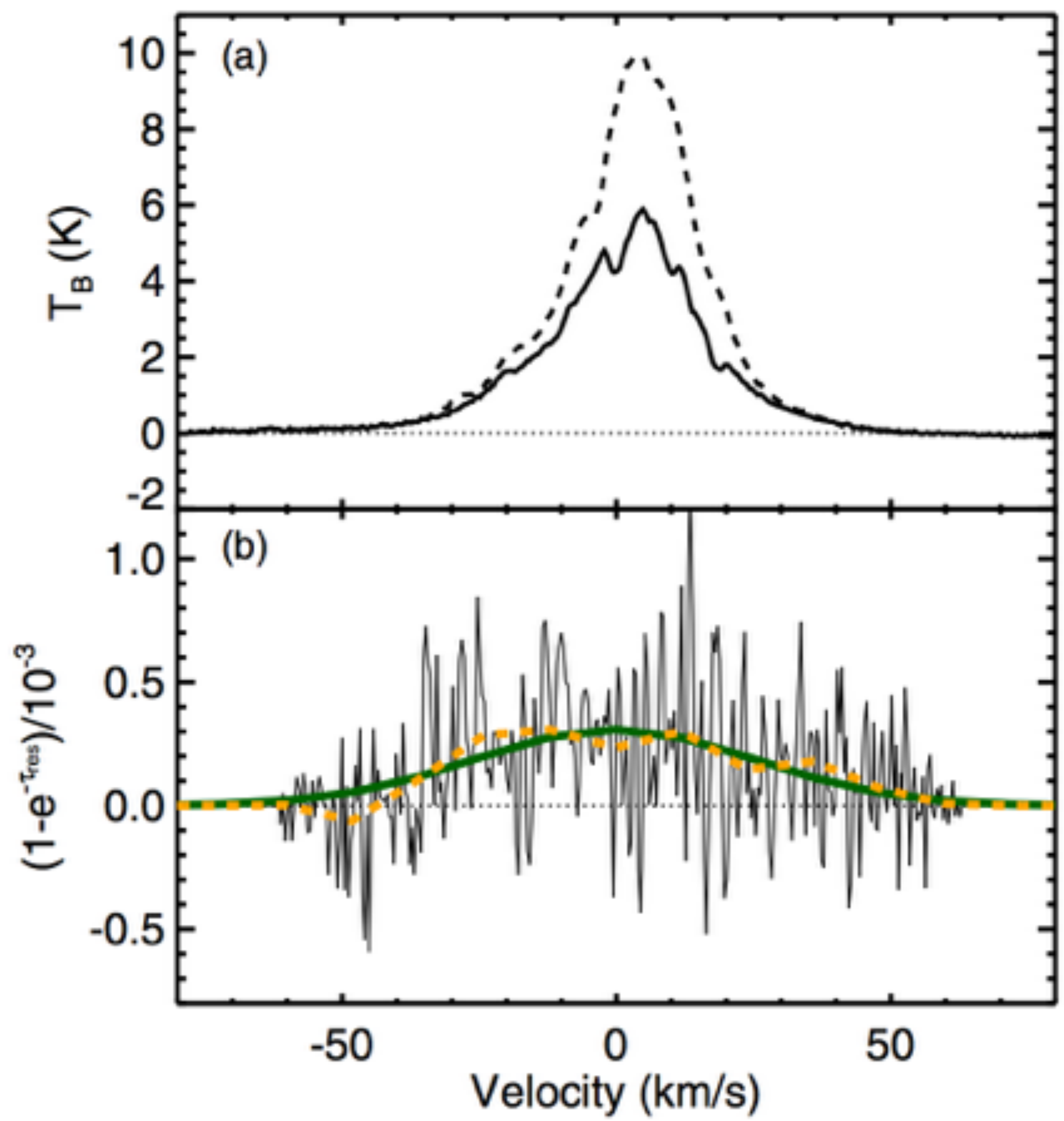
SPC field observed with the GBT

Column density maps of WNM and CNM re-built from the gaussian decomposition

Histograms weighted by the column density of each gaussian
=> 39% of the mass is lying in the gaussians narrower than
6 km s^{-1} ~ 4500 K
This fraction vary from 6 to 65% depending on the fields

work in progress…

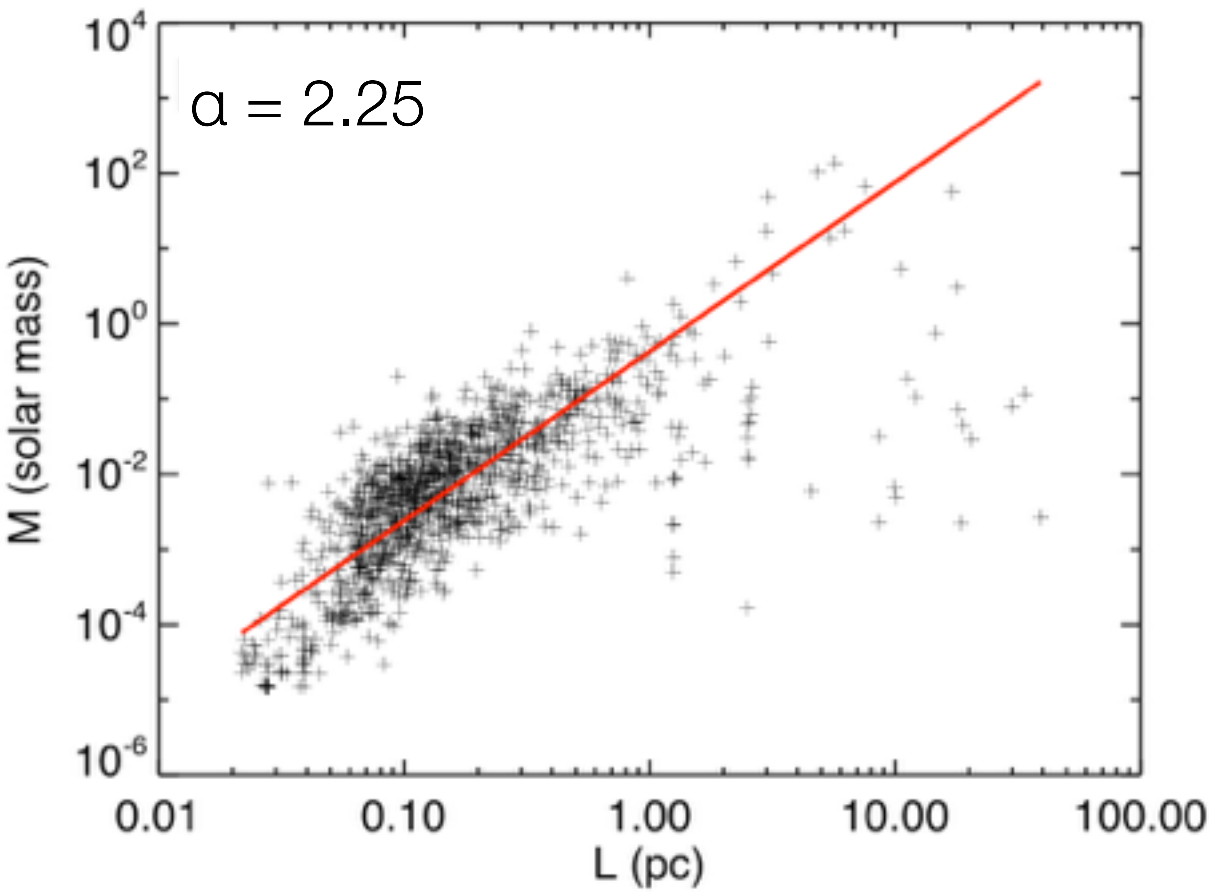
warm gas in absorption



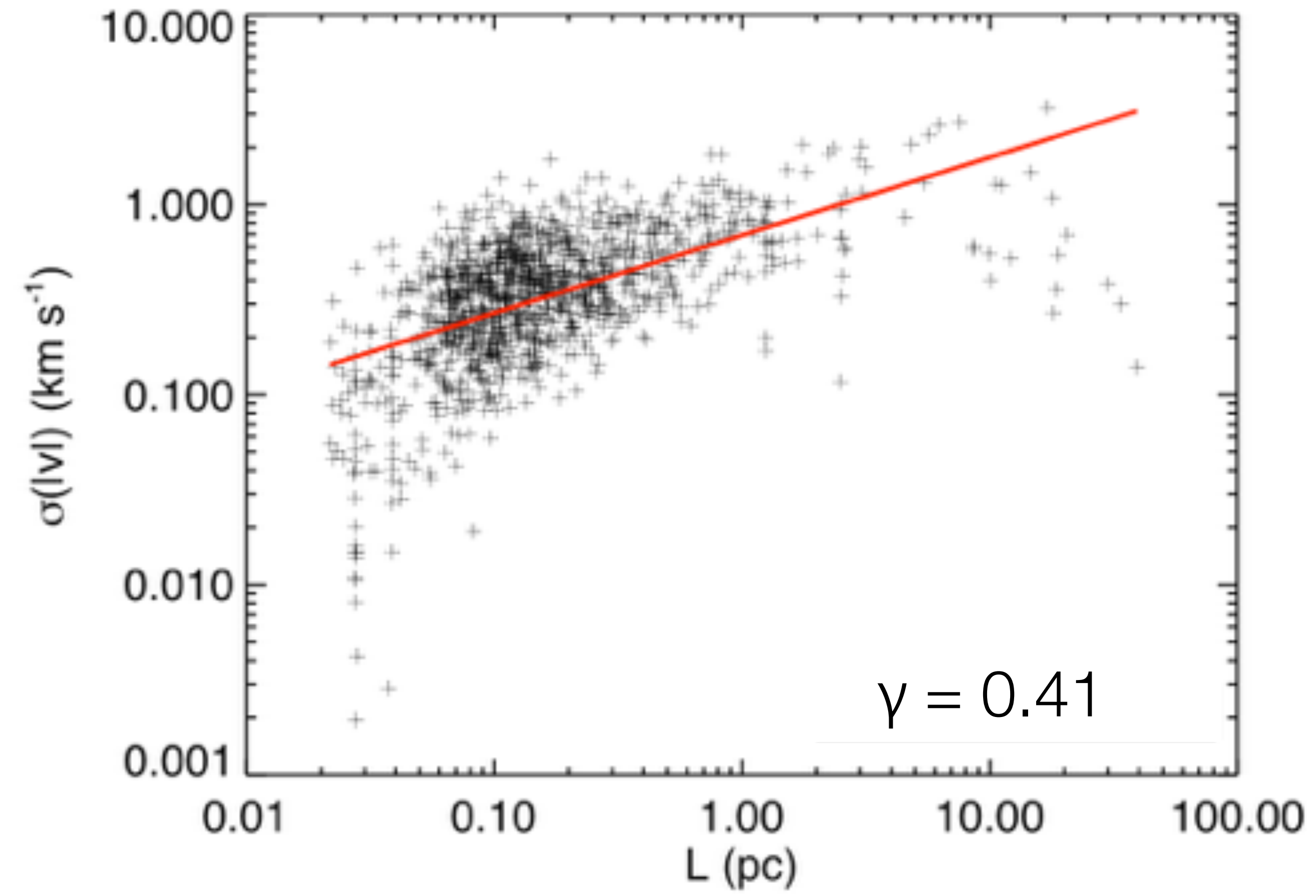
Murray+ 2014

CNM vs molecular clouds

Mass



Velocity dispersion

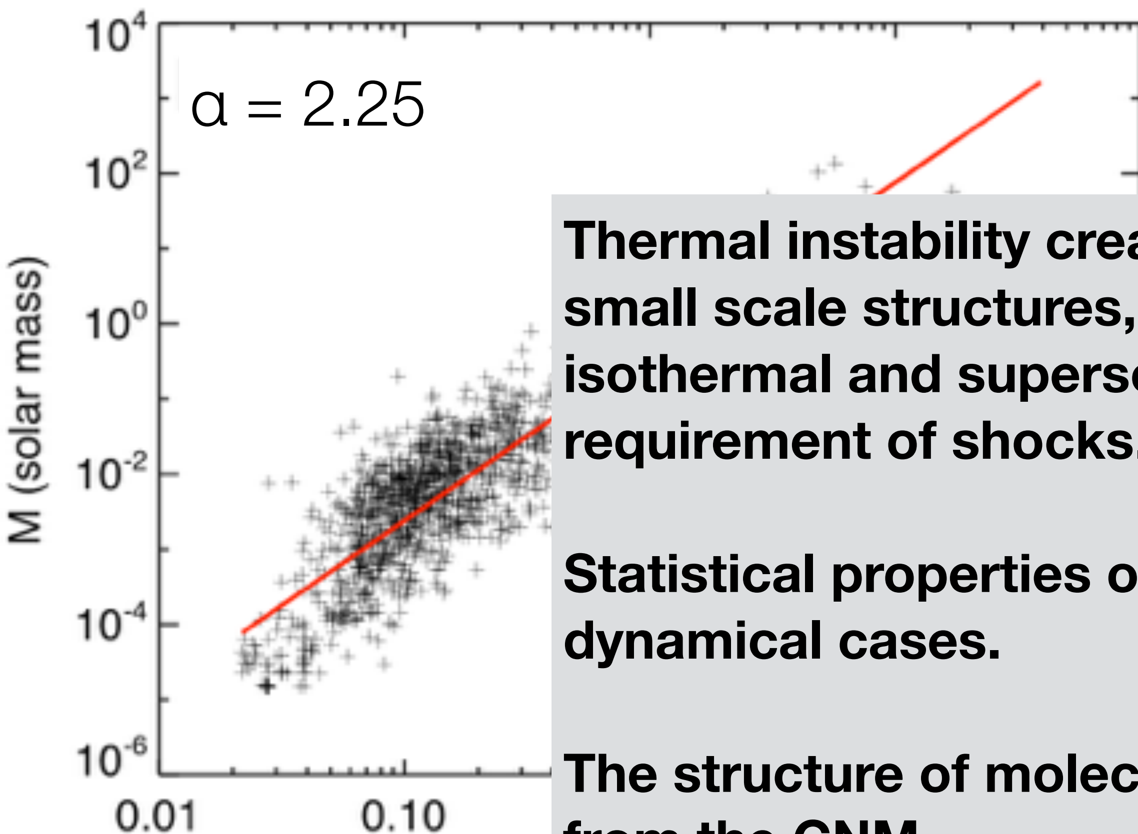


Molecular clouds observations :
Elmegreen & Falgarone (1996) $2.2 < \alpha < 2.5$
Roman-Duval et al. (2010) $\alpha = 2.36$

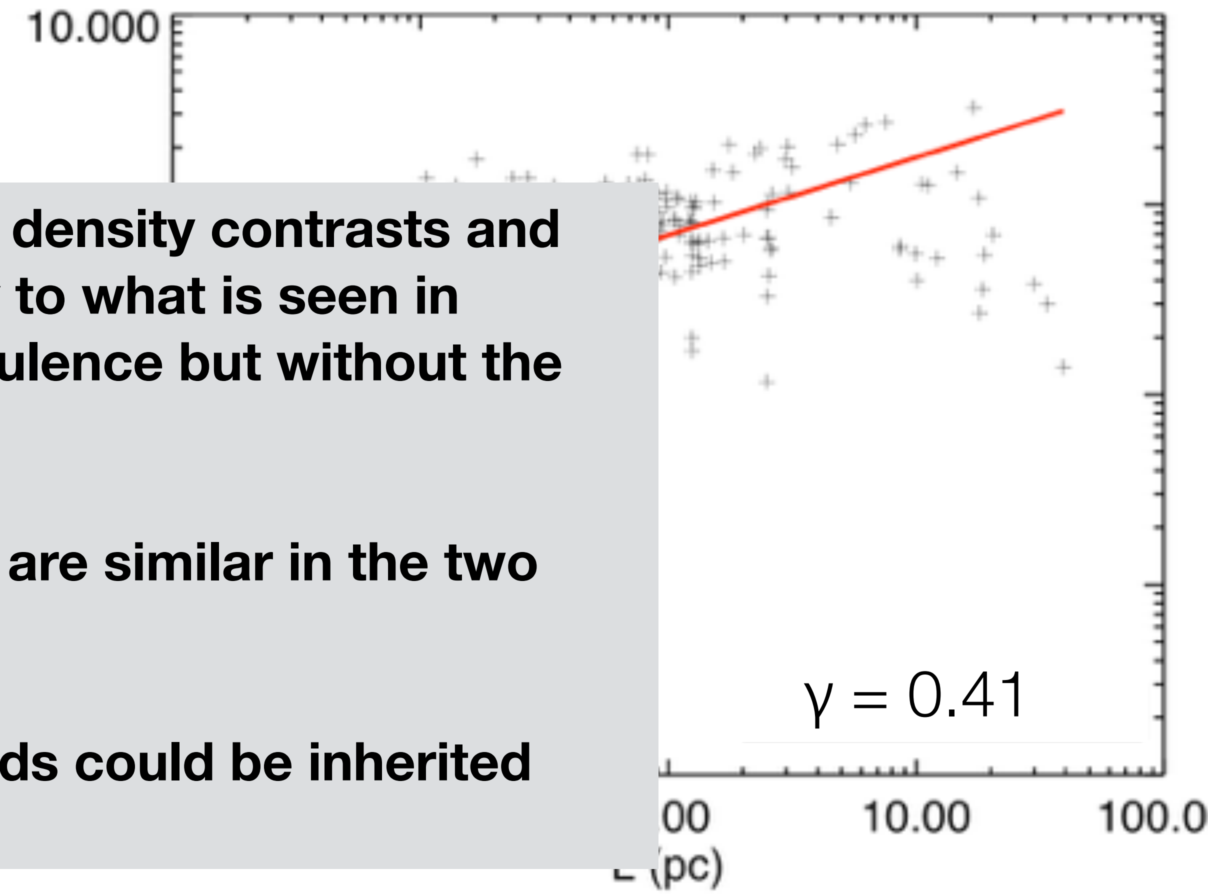
Molecular clouds observations :
Larson (1981) $\gamma = 0.37$
Heyer & Brunt (2004) $\gamma = 0.5$

CNM vs molecular clouds

Mass



Velocity dispersion



Thermal instability creates high density contrasts and small scale structures, similarly to what is seen in isothermal and supersonic turbulence but without the requirement of shocks.

Statistical properties of density are similar in the two dynamical cases.

The structure of molecular clouds could be inherited from the CNM

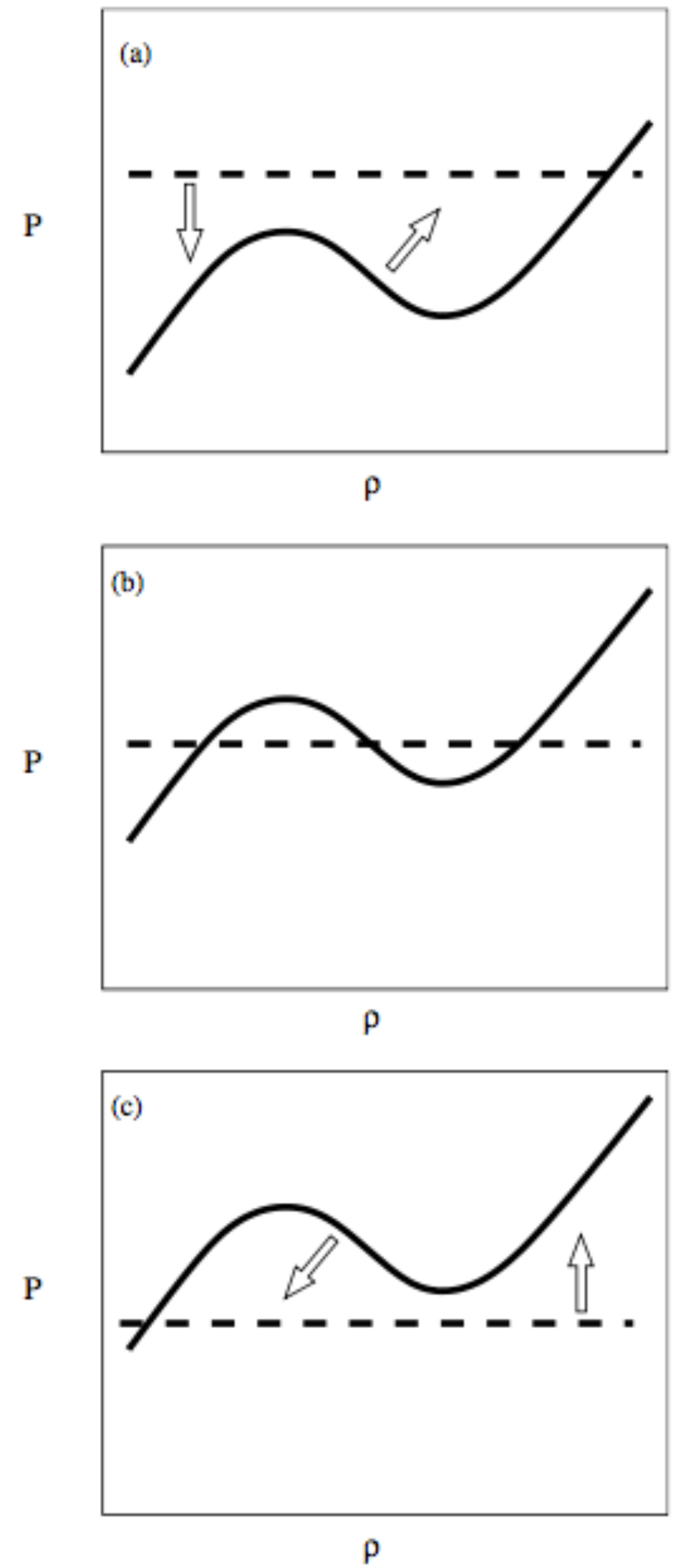
Molecular clouds observations :
Elmegreen & Falgarone (1996) $2.2 < \alpha < 2.5$
Roman-Duval et al. (2010) $\alpha = 2.36$

Molecular clouds observations :
Larson (1981) $\gamma = 0.37$
Heyer & Brunt (2004) $\gamma = 0.5$

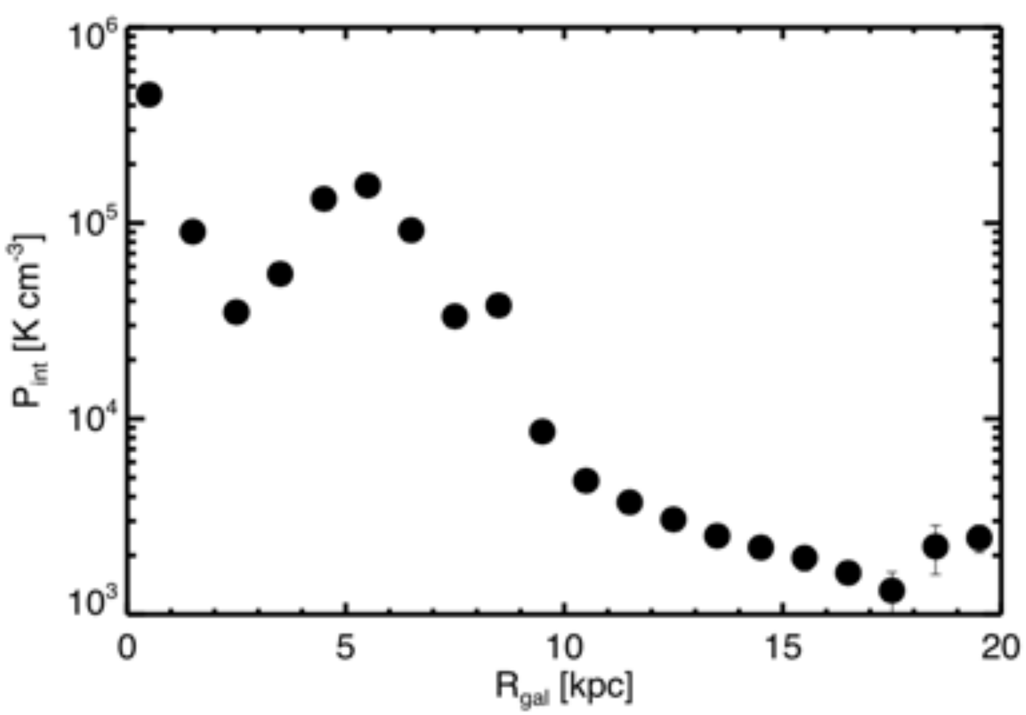
CNM formation and star formation

- Compatible with models of Ostriker+ (2010) showing that pressure sets the formation of cold structure and then the star formation rate

Ostriker et al. 2010



Miville-Deschenes+ (2017)



CNM formation and star formation

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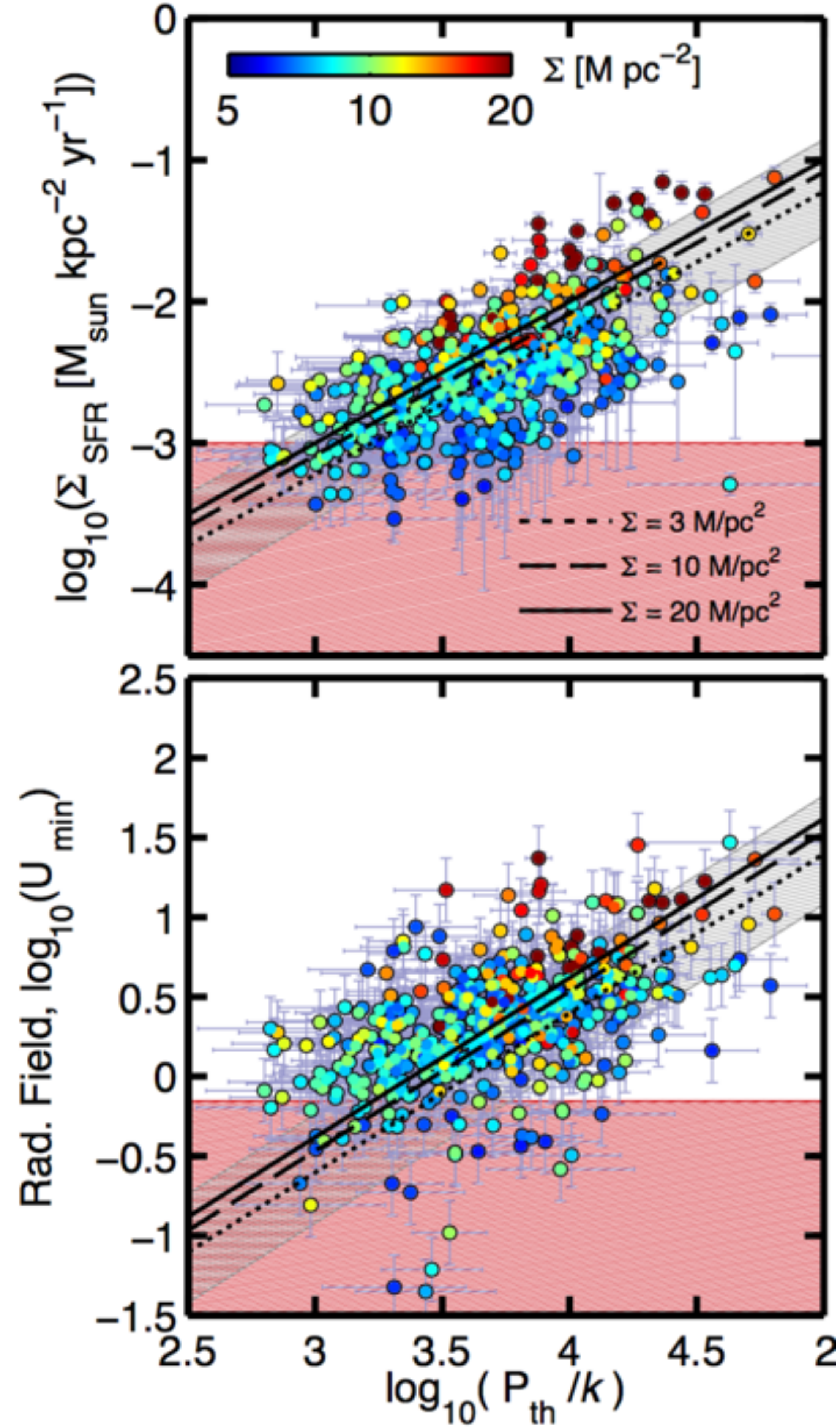
Herrera-Camus+ (2017)



Miville-Deschenes+ (2017)