The High/Intermediate velocity HI cloud population of the Small Magellanic Cloud

Frances Buckland-Willis, Post-doc at LPENS

Collaborators: Marc-Antoine Miville-Deschênes, Antoine Marchal, Naomi McClure-Griffiths, GASKAP team

Neutral Hydrogen in the Universe

Hydrogen exists in the neutral phase typically between 50-8000K

Below 50K hydrogen is mostly molecular

Above 8000K it becomes collisionally ionised

CNM
Typically 50-500K

UNM/LNM
Typically 500-5000K

WNM
Typically 5000-8000K

Phases determined by heating and cooling balance

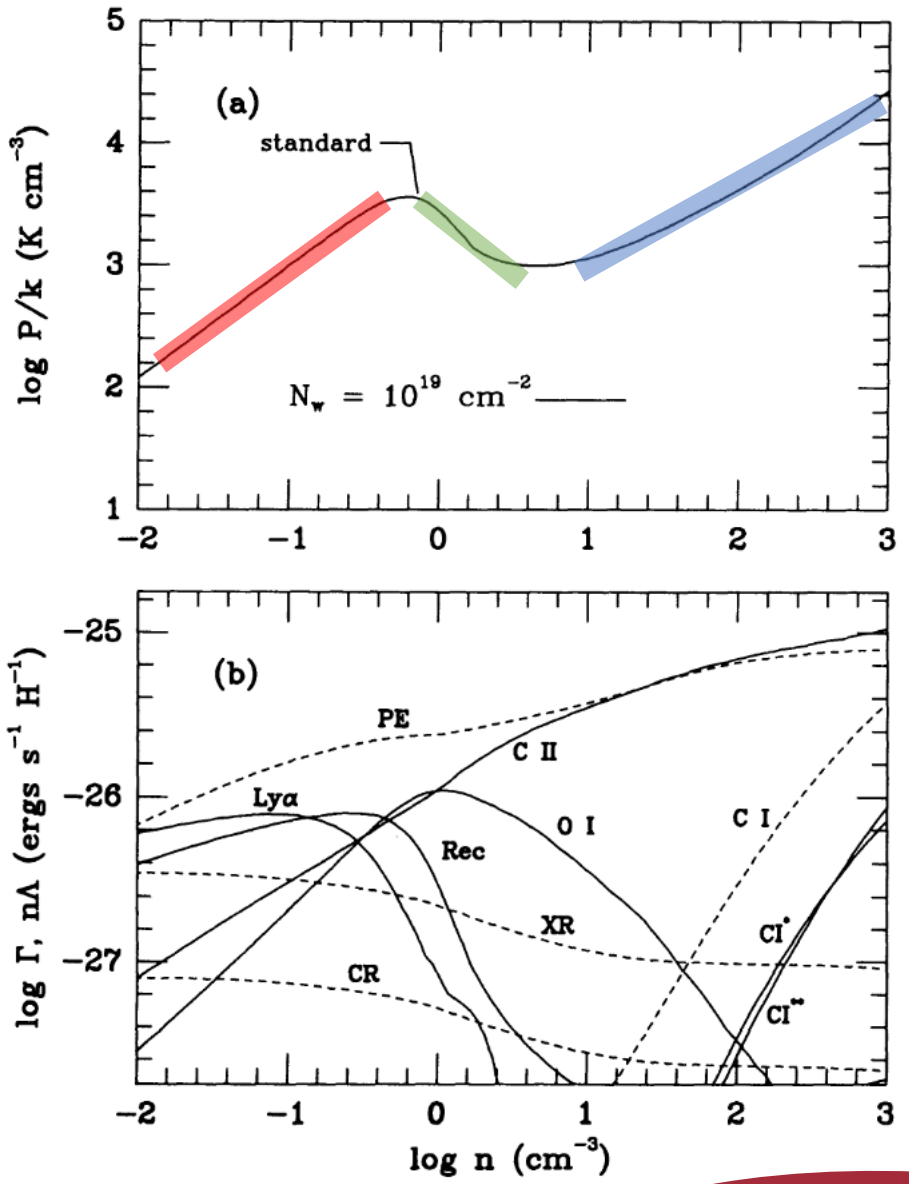
Photoelectric heating dominates at all densities

Cooling is dominated by different processes at different densities

UNM will form stable CNM or WNM if perturbed

CNM and WNM can coexist within certain pressure windows

Figure 3(a) and (b) Wolfire et al. 1995



Observation of the HI

HI can be observed in emission or absorption

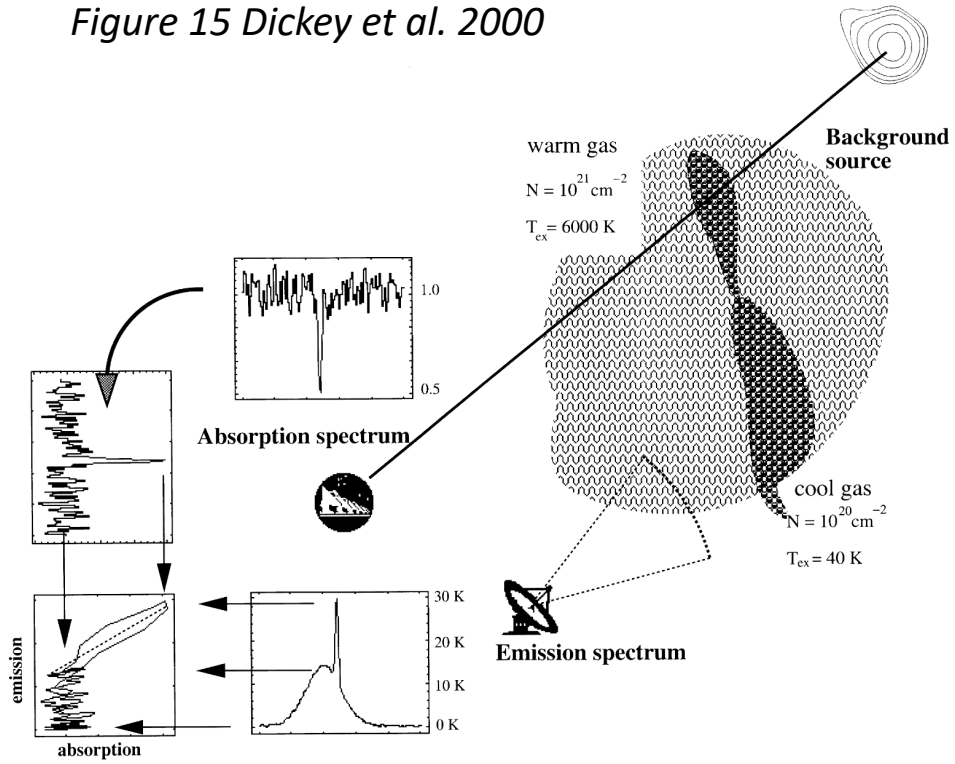
Absorption spectra require background radio continuum sources

Emission spectra can be observed wherever HI is present

Absorption spectra are sensitive to smaller scales than emission

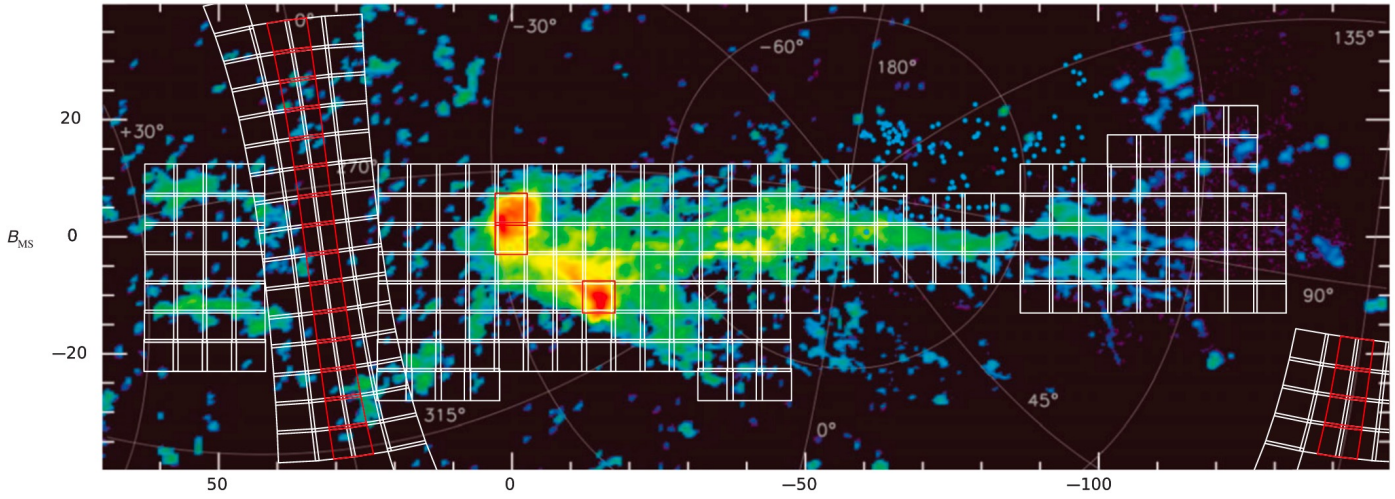
Both measurements are needed to fully define the two phase medium

Figure 15 Dickey et al. 2000



GASKAP survey

Figure 3 Dickey et al. 2013



The Galactic ASKAP survey is one of 9 large surveys selected by the CSIRO to have dedicated observing time with ASKAP

GASKAP will observe part of the Galactic Plane and the entirety of the Magellanic system

Pilot observations began in 2019, full survey observations commenced in 2023

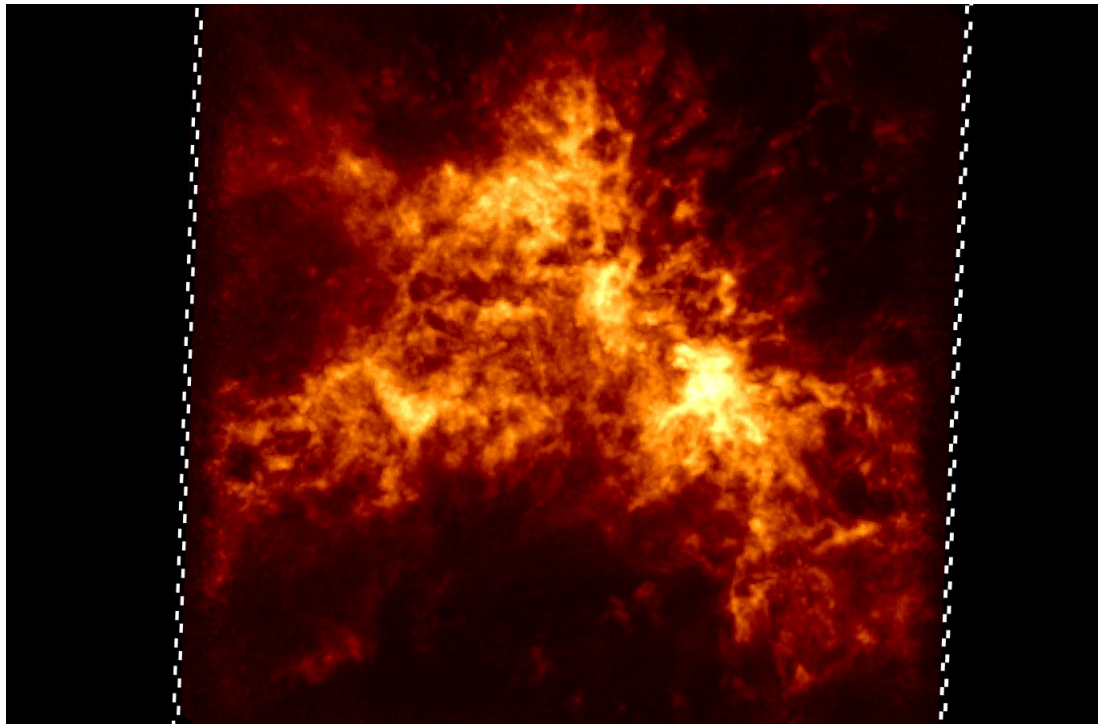
The Magellanic Clouds will be observed for 200hrs, the low-latitude Galactic plane for 50hrs and all other fields for 12.5hrs

The GASKAP survey will improve upon the resolution and sensitivity of previous surveys and allow for comparison with infrared, mm and sub-mm tracers

New era of HI observations

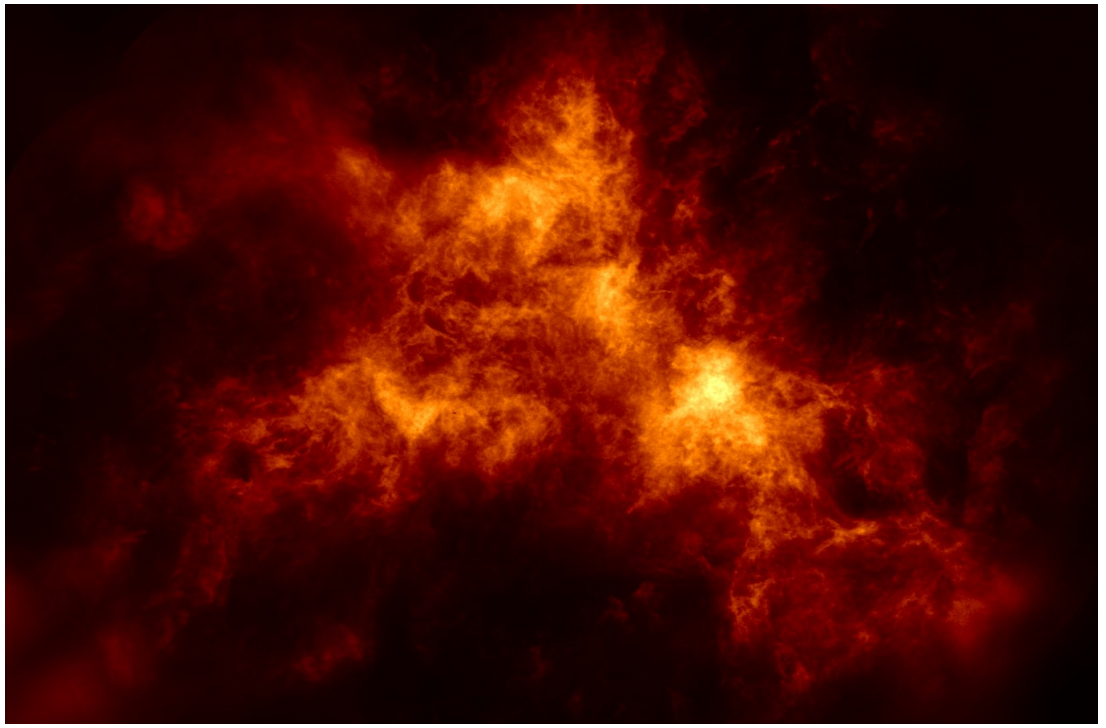
Compare for yourselves!

98” resolution



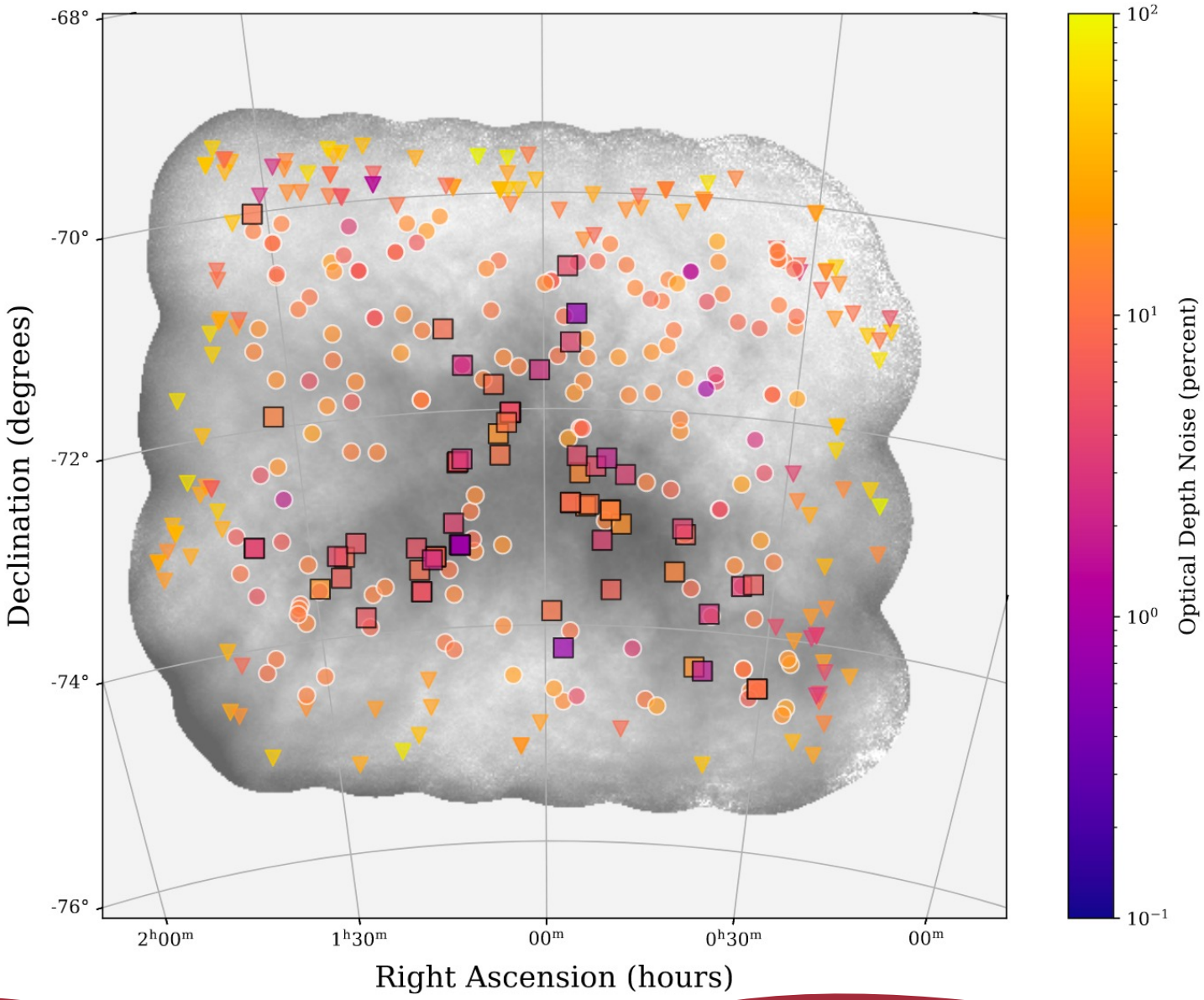
ATCA-Murriyang (Parkes) mosaiced image from Stanimirovic et al. 1999

30” resolution



ASKAP-Murriyang (Parkes) mosaiced image from Pingel et al. 2022

Figure 3 Dempsey et al. 2022



Source density is an intrinsic limit on the ability to directly constrain the optical depth

The source density will increase in subsequent surveys as sensitivity is improved, which will also probe lower optical depths

Uncovering new structures in the Magellanic periphery

Structures at considerable deviation velocities were first highlighted in *McClure-Griffiths et al. 2018*

These features have relatively compact morphologies and show strong gradients over a few 10s of km/s

So, are these structures cold, warm or something in between?

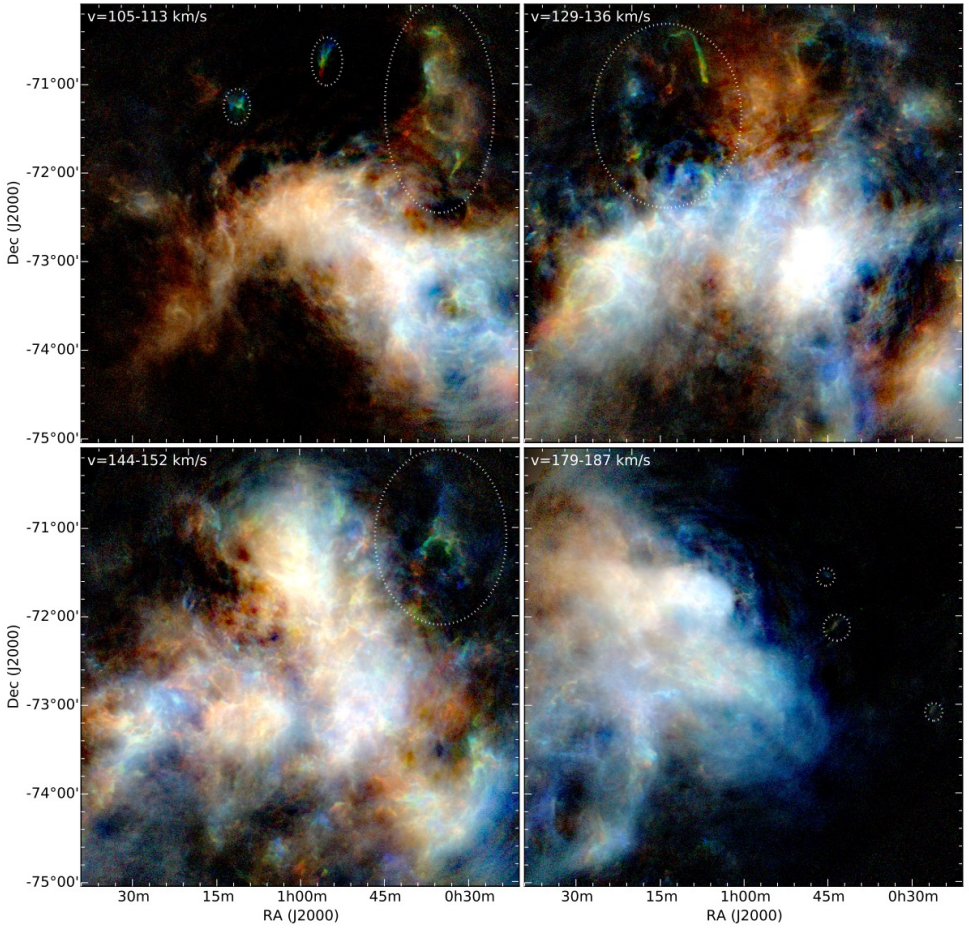
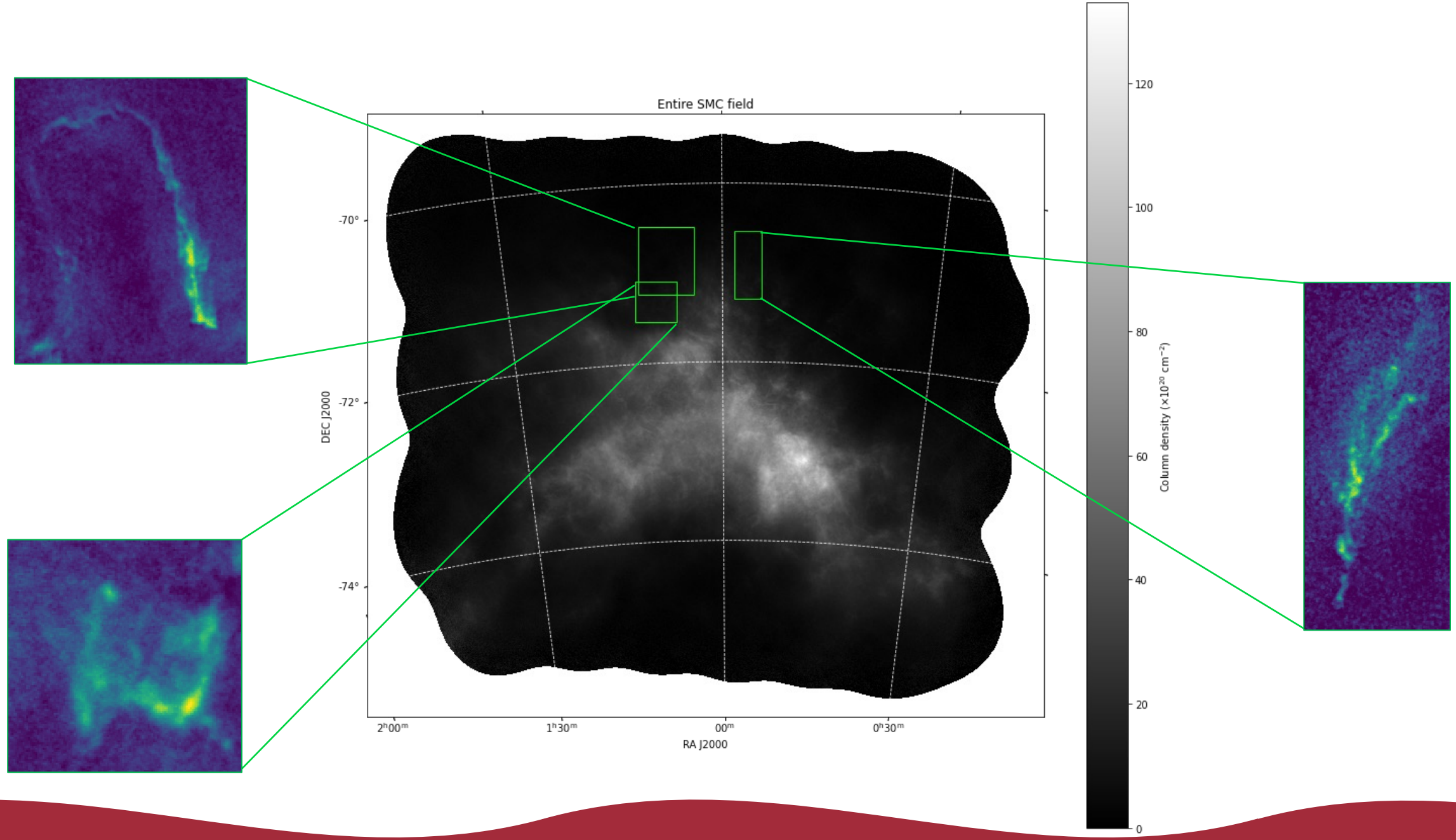


Figure 2 McClure-Griffiths et al. (2018)


Entire SMC field
-70°
-72°
-74°
DEC J2000
2h00m
1h30m
00m
0h30m
RA J2000
120
100
80
60
40
20
0
Column density (×10^20 cm^-2)

How do we characterise these clouds?

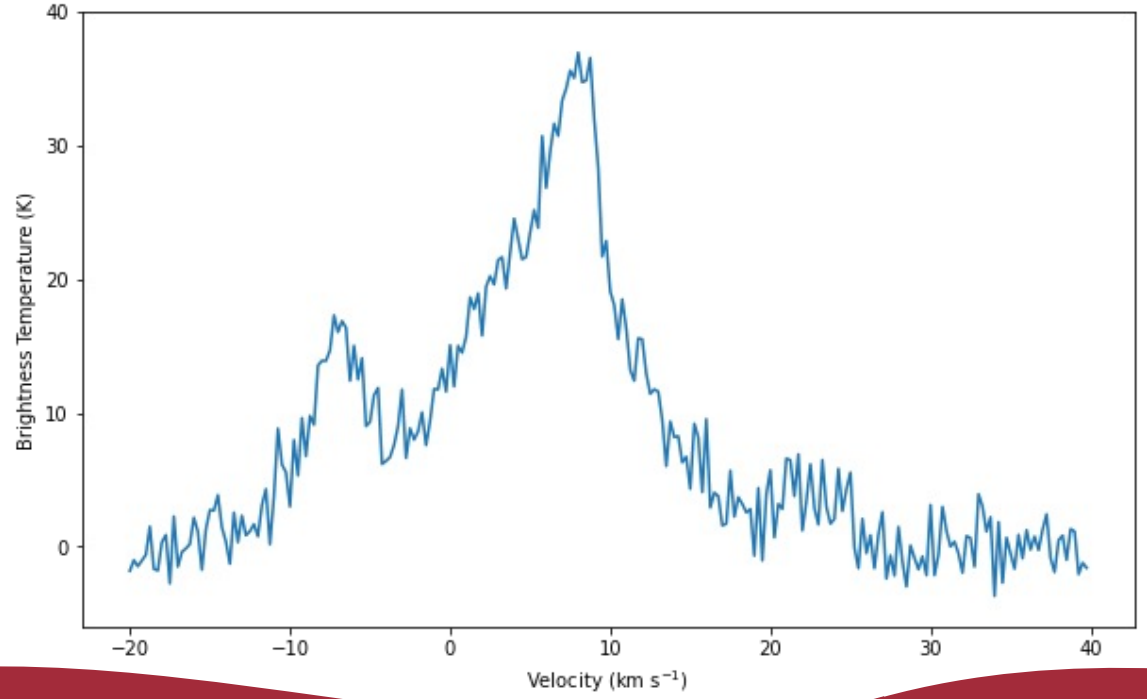
Gaussian decomposition

Gaussian decomposition is a method used to extract physical meaning from HI spectra, both emission and absorption.

The spectra are modelled as a sum of wide and narrow Gaussian components, for emission spectra:

$$T_B(v) = \sum_{n=1}^{N} a_n \exp\left(\frac{-(v-\mu_n)^2}{2\sigma_n^2}\right)$$

$$\sigma_{tot}^2 = \sigma_{kin}^2 + \sigma_{turb}^2$$



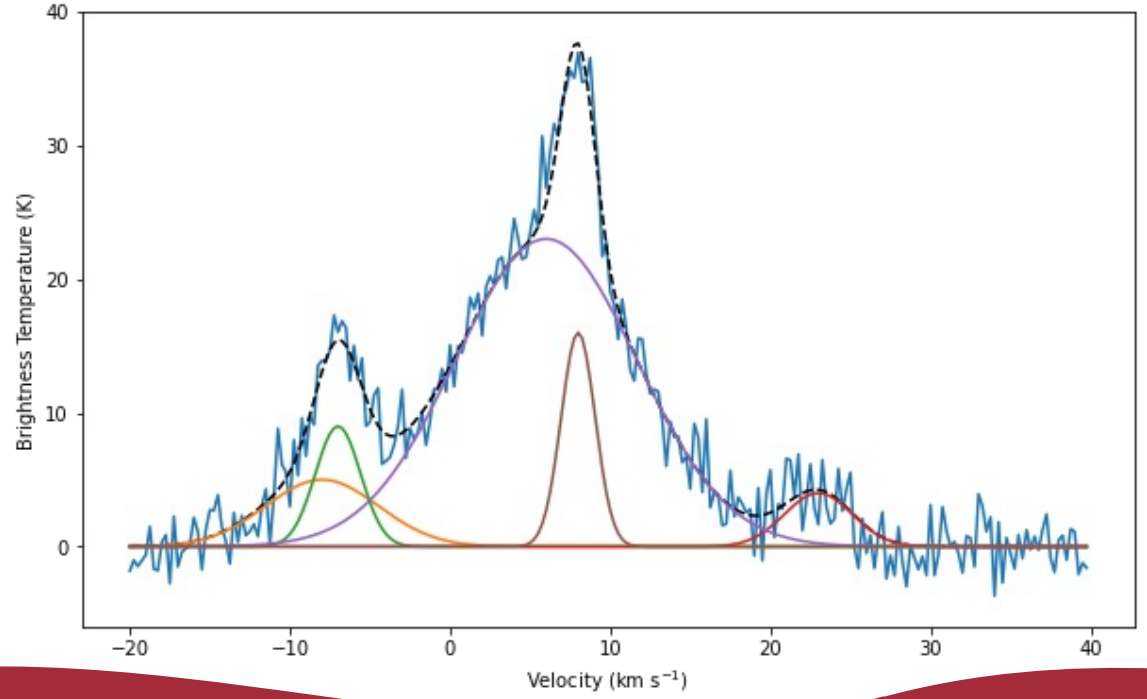
Gaussian decomposition

Gaussian decomposition is a method used to extract physical meaning from HI spectra, both emission and absorption.

The spectra are modelled as a sum of wide and narrow Gaussian components, for emission spectra:

$$T_B(v) = \sum_{n=1}^{N} a_n \exp\left(\frac{-(v-\mu_n)^2}{2\sigma_n^2}\right)$$

$$\sigma_{tot}^2 = \sigma_{kin}^2 + \sigma_{turb}^2$$



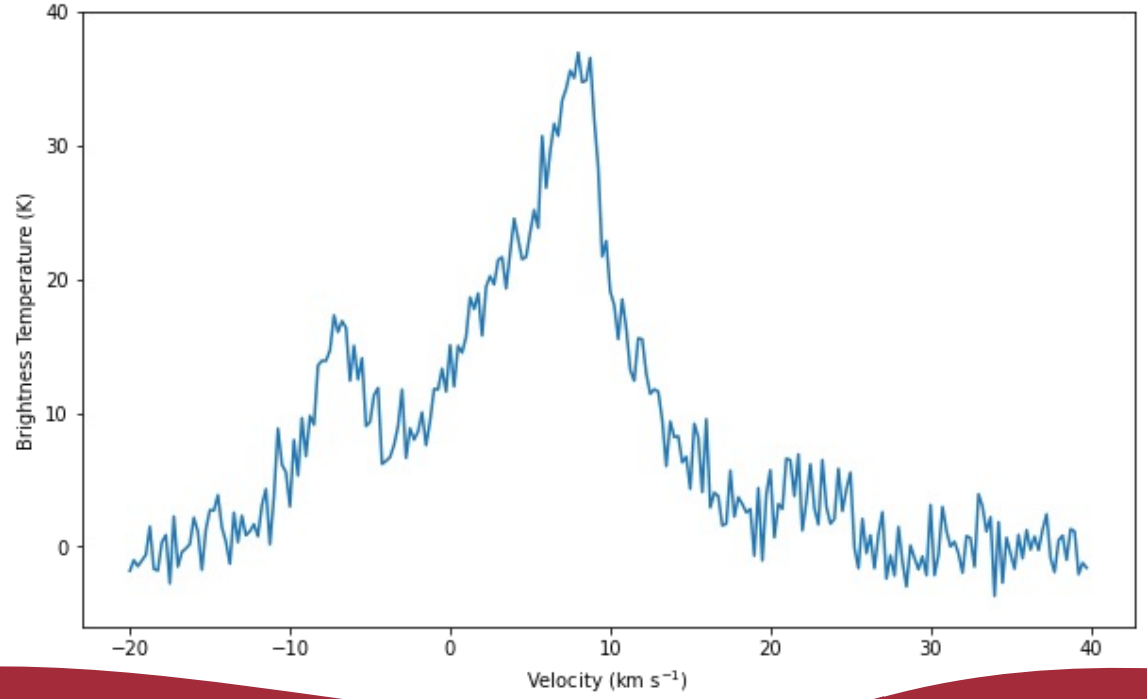
Gaussian decomposition

Gaussian decomposition is a method used to extract physical meaning from HI spectra, both emission and absorption.

The spectra are modelled as a sum of wide and narrow Gaussian components, for emission spectra:

$$T_B(v) = \sum_{n=1}^{N} a_n \exp\left(\frac{-(v-\mu_n)^2}{2\sigma_n^2}\right)$$

$$\sigma_{tot}^2 = \sigma_{kin}^2 + \sigma_{turb}^2$$



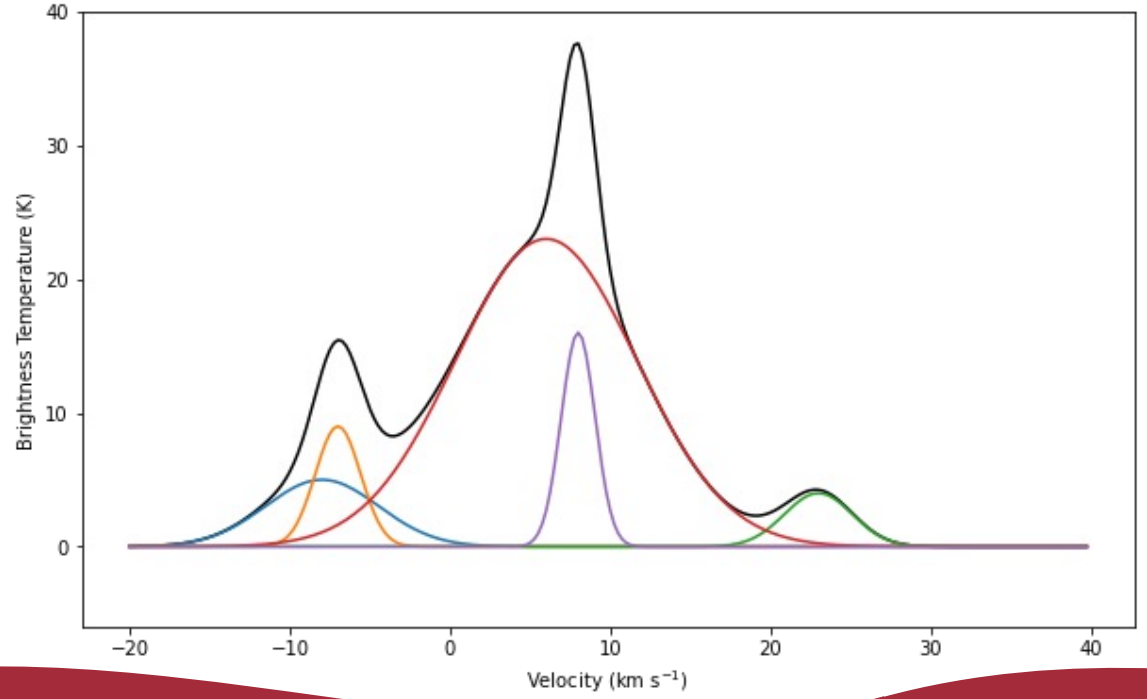
Gaussian decomposition

Gaussian decomposition is a method used to extract physical meaning from HI spectra, both emission and absorption.

The spectra are modelled as a sum of wide and narrow Gaussian components, for emission spectra:

$$T_B(v) = \sum_{n=1}^{N} a_n \exp\left(\frac{-(v-\mu_n)^2}{2\sigma_n^2}\right)$$

$$\sigma_{tot}^2 = \sigma_{kin}^2 + \sigma_{turb}^2$$



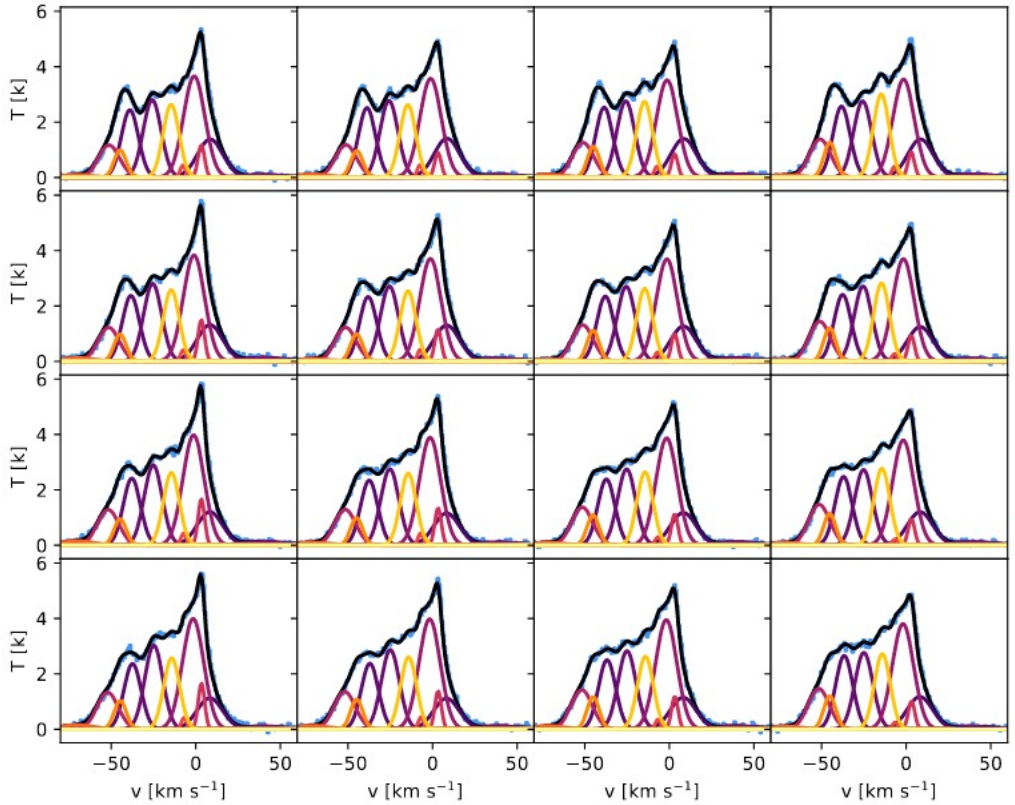
Newer algorithms have implemented methods to converge to spatially consistent solutions

ROHSA (Marchal et al. 2019) forces spatial regularisation in the fitting regime

This allows the CNM and WNM spatial distribution to be well constrained

Users still need to specify fitting parameters

Figure 15 Marchal et al. 2019



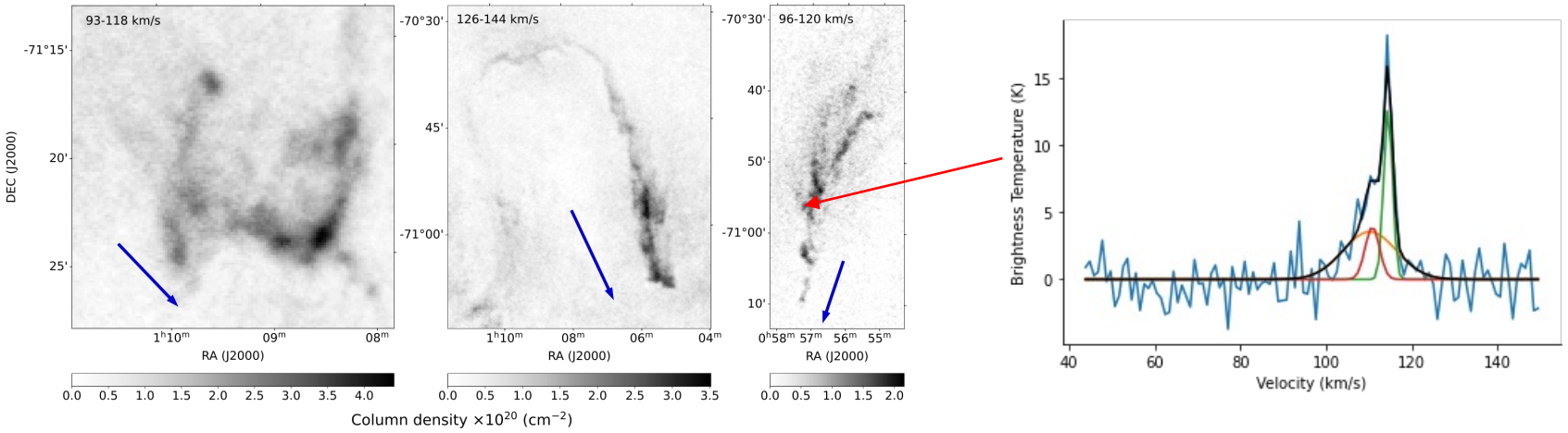
Best fit solutions

All clouds are well described by 3 component models

Cloud	Component 1				Component 2				Component 3			
	A (K)	v (km s^{-1})	σ_v (km s^{-1})	$\langle T_k \rangle$ (K)	A (K)	v (km s^{-1})	σ_v (km s^{-1})	$\langle T_k \rangle$ (K)	A (K)	v (km s^{-1})	σ_v (km s^{-1})	$\langle T_k \rangle$ (K)
Gamma	0.99	102	6.48	5081	1.81	113	1.29	201	2.65	107	1.48	265
Alpha	2.35	108	7.77	7305	6.51	104	1.97	470	0.43	80	9.35	10578
Hook	2.87	135	3.99	1926	0.71	124	6.17	4606	2.84	132	1.32	211

Maximum kinetic temperature

$$< T_k >= 121 < \sigma >^2$$



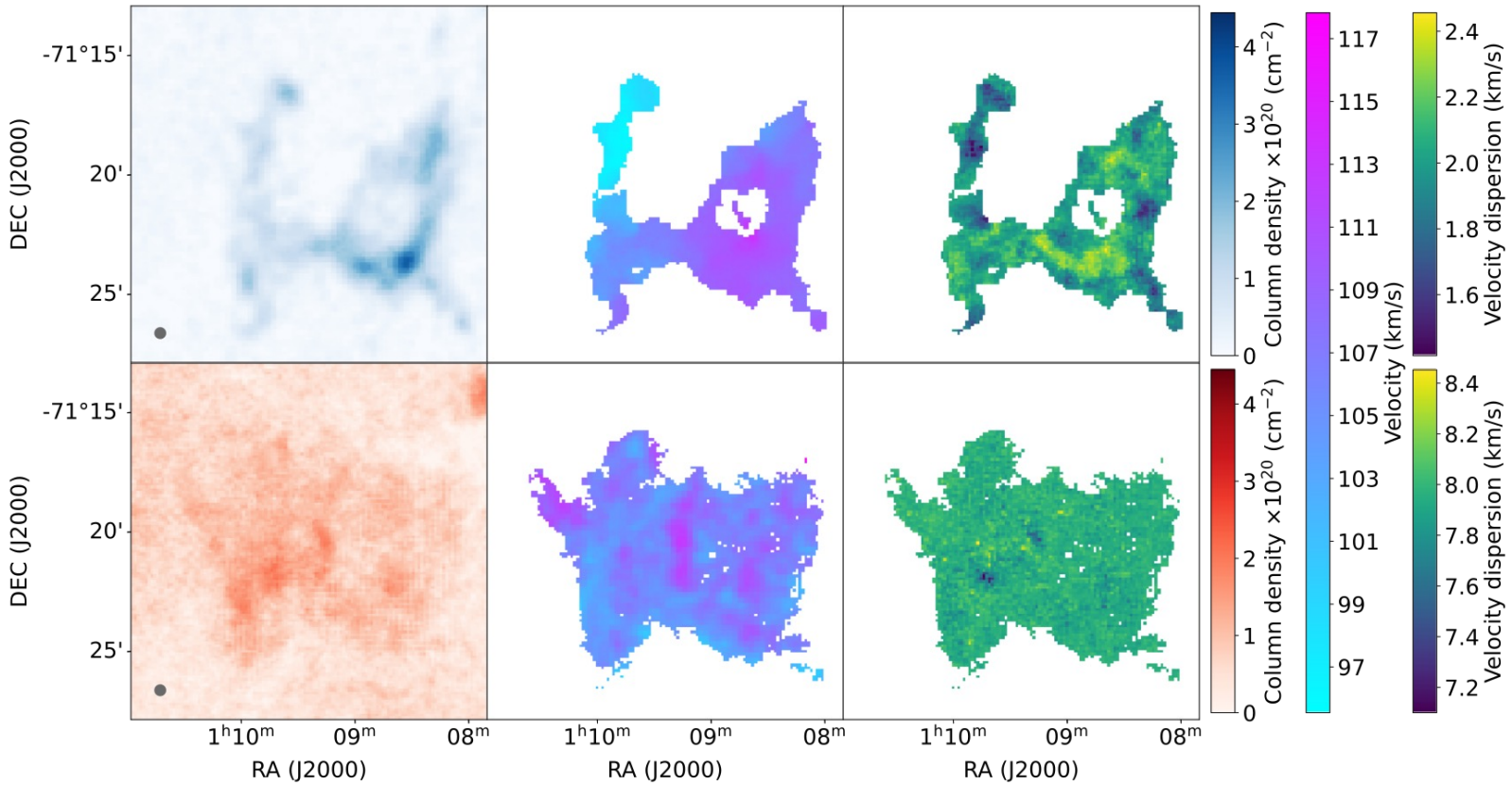
Alpha Cloud

Velocities of each phase do not align at edges of cloud

CNM appears to be enveloped by WNM

Cavity in western side of cloud previously catalogued as an HI shell

CNM velocity gradient is aligned with direction of the main body of the SMC



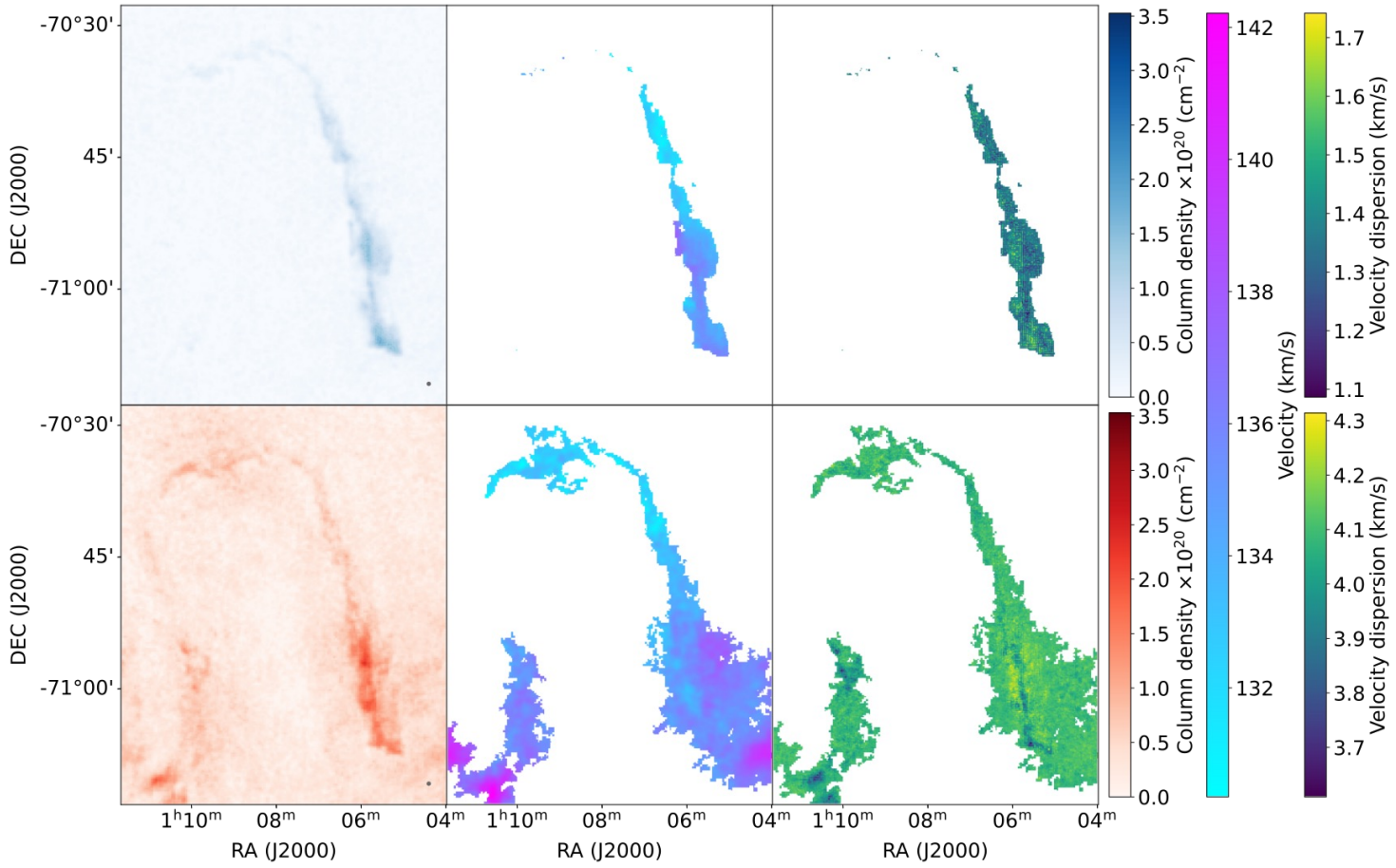
Hook Cloud

Smaller velocity gradient along the north south direction

CNM is enveloped by the UNM along the entirety of the loop

Central area of the loop is clearly void of CNM and WNM

Both phases are well coupled dynamically



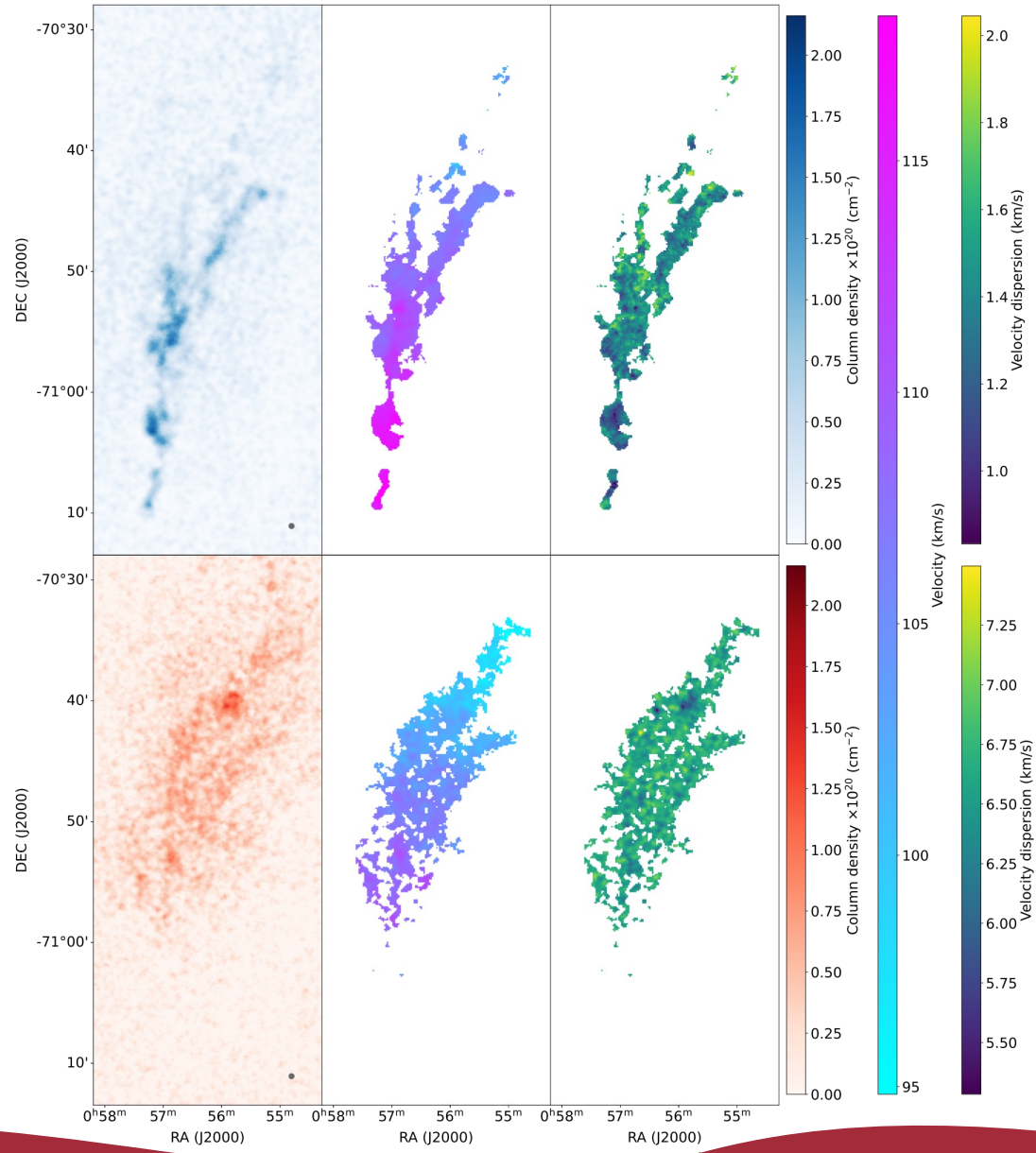
Gamma Cloud

Velocity gradient moves south to north along the cloud length

CNM and WNM overlaps in the middle of the cloud

WNM envelope exists only at the north of the cloud, furthest from the SMC

Quite extended head-tail morphology extending away from the SMC



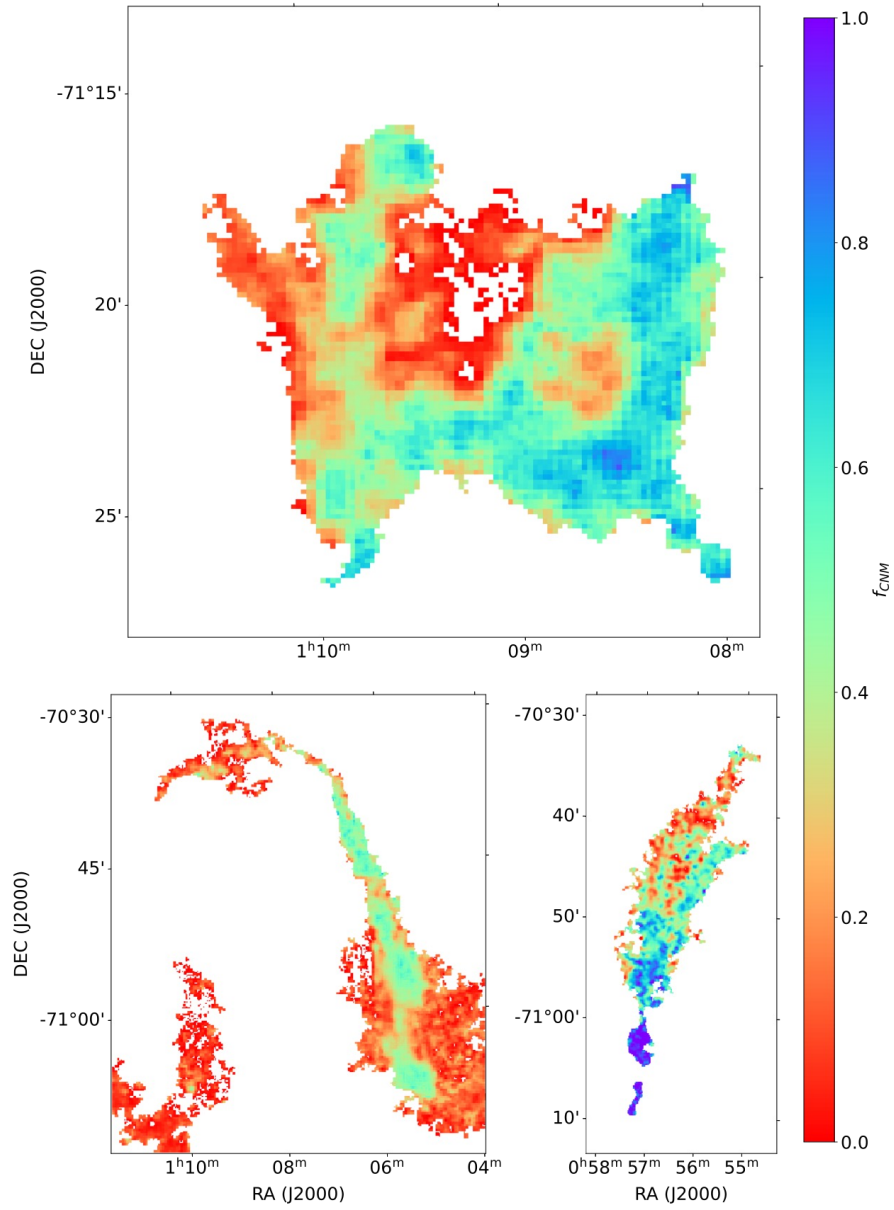
CNM fraction

The CNM fraction varies through the clouds

$$f_{CNM} = \frac{N_{(HI,CNM)}}{N_{(HI,CNM)} + N_{(HI,UNM)} + N_{(HI,WNM)}}$$

For Clouds Alpha and Gamma the CNM fraction increases towards the SMC

For the Hook Cloud the CNM fraction is enhanced only on the western edge



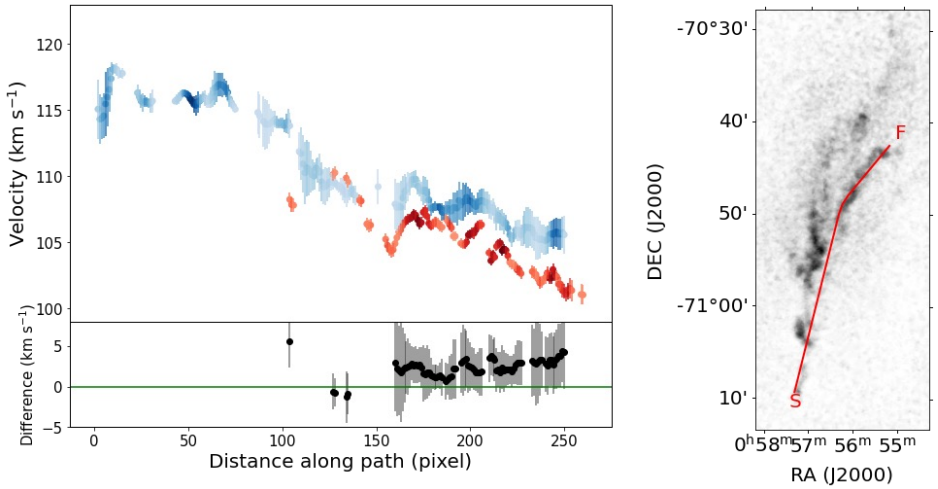
Velocity structure

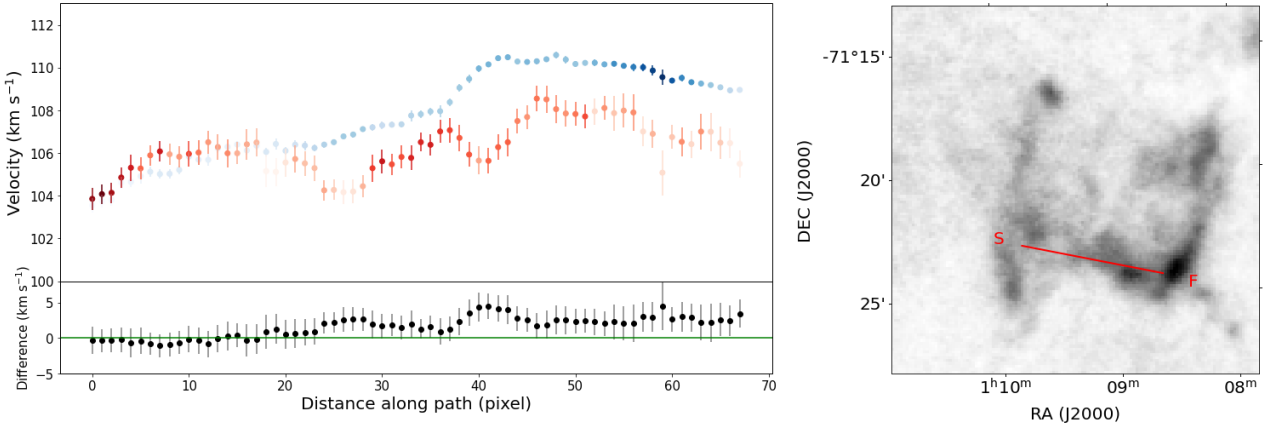
The CNM and WNM show similar velocity gradients but become offset closer to the SMC

The WNM velocity at the base of the Alpha cloud is more deviant from the SMC

The offset in the gamma cloud is relatively constant

There is no significant offset for the Hook cloud





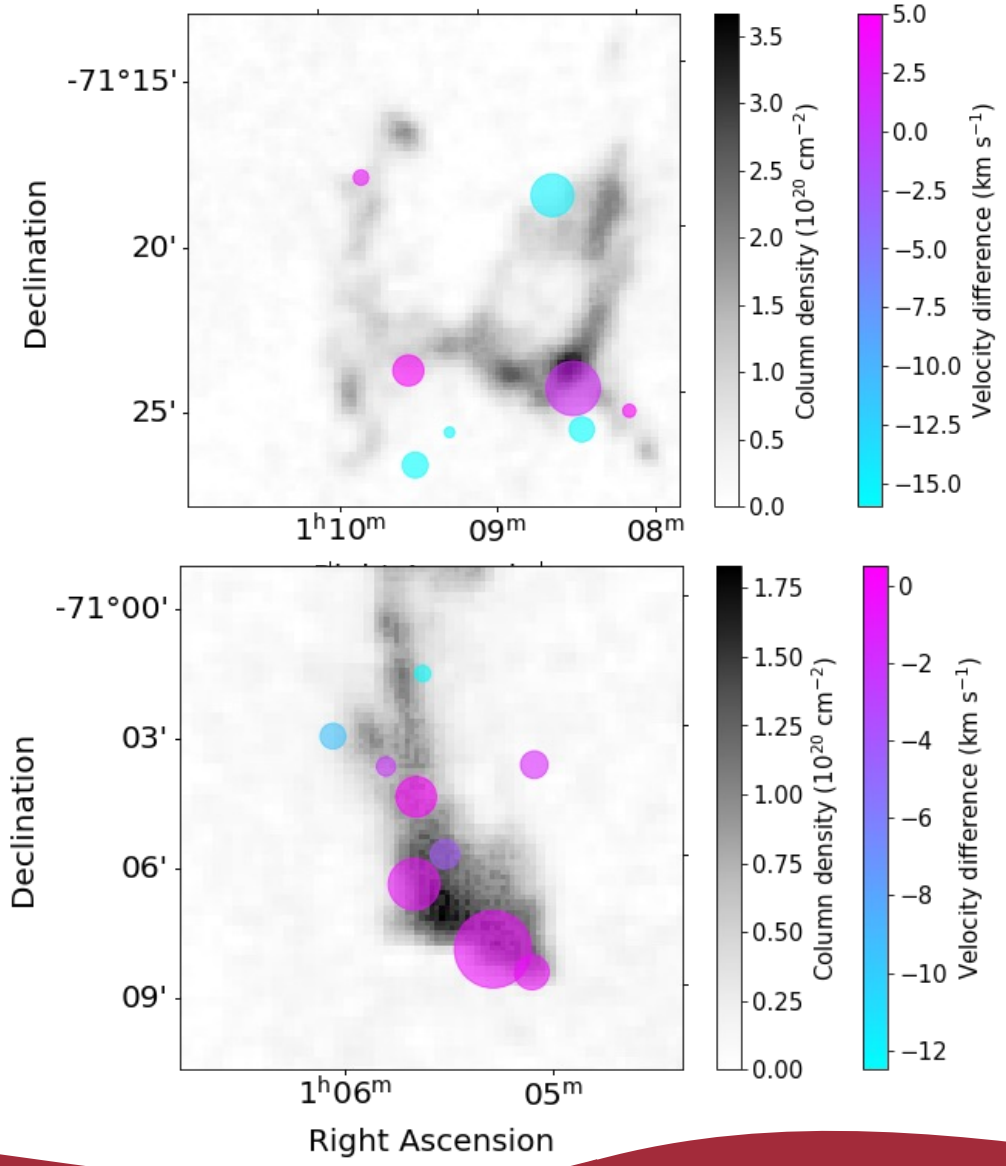
Comparison with CO

CO (2-1) measurements from Di Teodoro et al. (2019) can be compared with the velocity structure determined for these clouds

The Alpha cloud has two distinct CO clump populations when grouped by velocity

Only one of these relates to the HI cloud and closely matches the CNM

The Hook cloud CNM and UNM velocities closely match the CO velocities



Measuring clump density

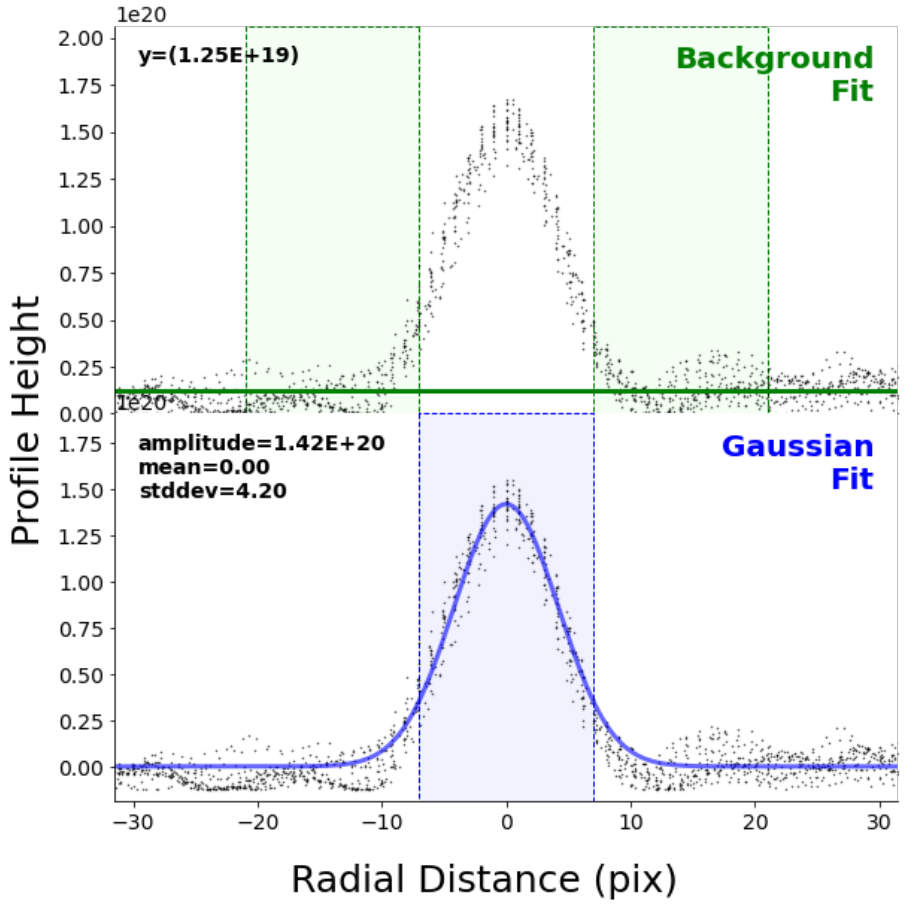
All clouds were treated as filaments, through which a path can be defined

A path along the densest section of each cloud was constructed using radfil (Zucker et al. 2018)

A Gaussian profile was fit to all profiles along the path to determine the FWHM of the cloud

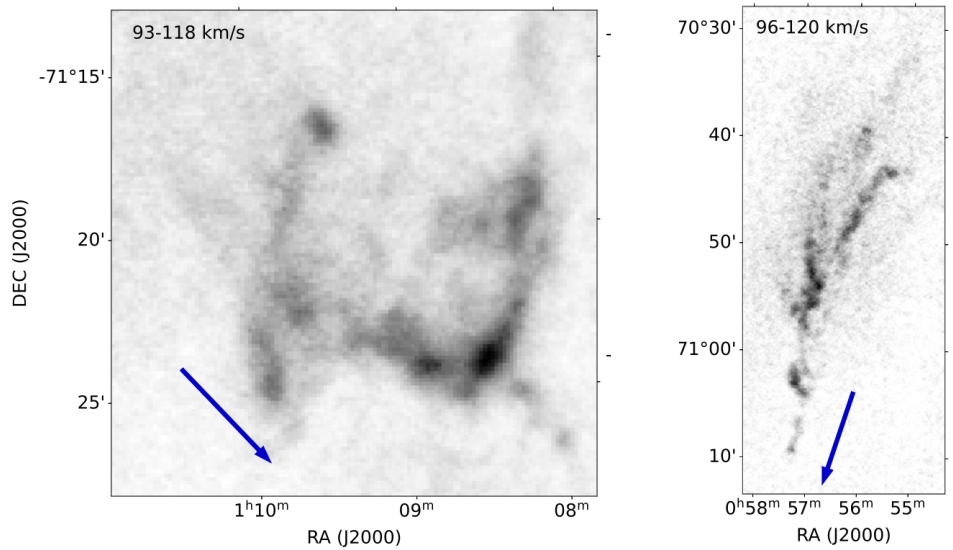
Physical widths range from 20-33pc

Number densities range from 1-5 cm^{-3}

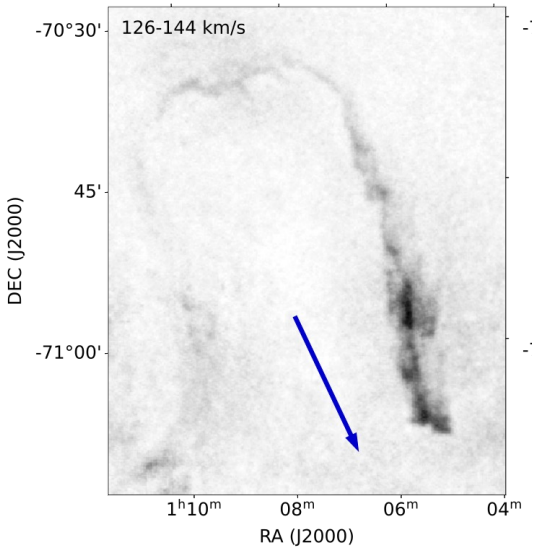


So, what could have formed these clouds?

Forces from the galaxy



Expansion from stellar processes



Future prospects

The SKA should start scientific operations in 2028 and the SKA-MID will have a maximum baseline of 150km

This represents a factor of 25 improvement and will allow for structures of order 0.1pc to be resolved at the distance of the SMC

This will be essential to reveal the small scale structure of the galaxy, typically where the CNM is located

It will also lead to an increase in absorption source density

Figure 7 Marchal et al. 2021