[CII] Optical Depth and Self-Absorption in M17SW

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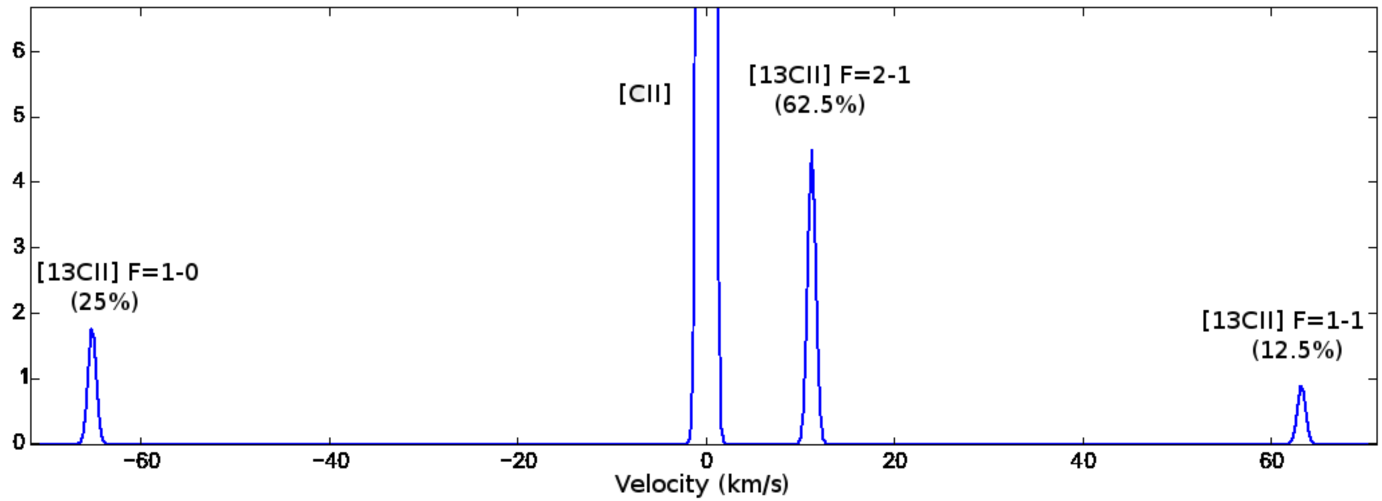
[^{13}CII] hyper-fine structure line

- C^+ has only two fine structure levels in the ground state with an energy difference of 91.25 K. The ionization potential of carbon is 11.2 eV.
- Emission is produced by collisional excitation followed by radiative decay at 1.9 THz.
- The hyper-fine structure of the $^{13}C^+$ isotope due to the extra neutron, it is splitted into three hfs-components.

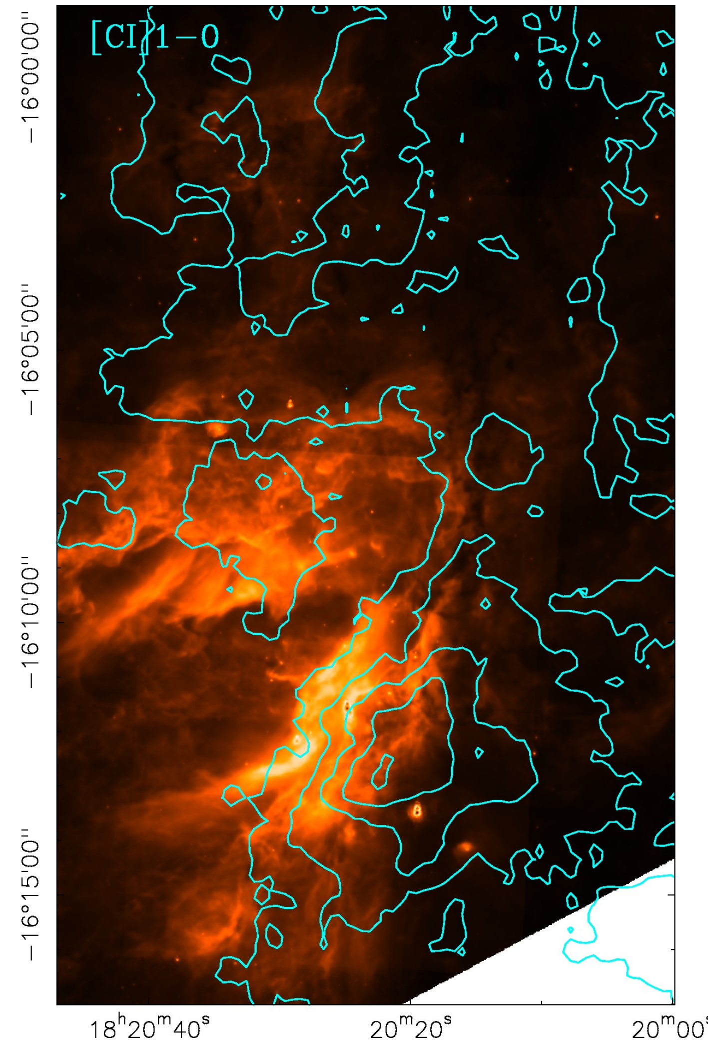


[^{12}CII] and [^{13}CII] spectral signature

Line	Statistical g_u	Weight g_l	Frequency ν (GHz)	Vel. offset $\delta v_{F \to F'}$ (km/s)	Relative intensity $s_{F \to F'}$
[^{12}CII] $^2P_{3/2}-^2P_{1/2}$	4	2	1900.5369	0	–
[^{13}CII] F=2→1	5	3	1900.4661	+11.2	0.625
[^{13}CII] F=1→0	3	1	1900.9500	-65.2	0.250
[^{13}CII] F=1→1	3	3	1900.1360	+63.2	0.125

M17SW

- **It is considered one of the brightest and most massive star forming regions in the Galaxy, located at 1.9 kpc of distance.**
- **The cloud is illuminated by a cluster (>100) of OB stars.**
- **M17SW presents an edge-on geometry, very well suited for studying the PDR structure.**

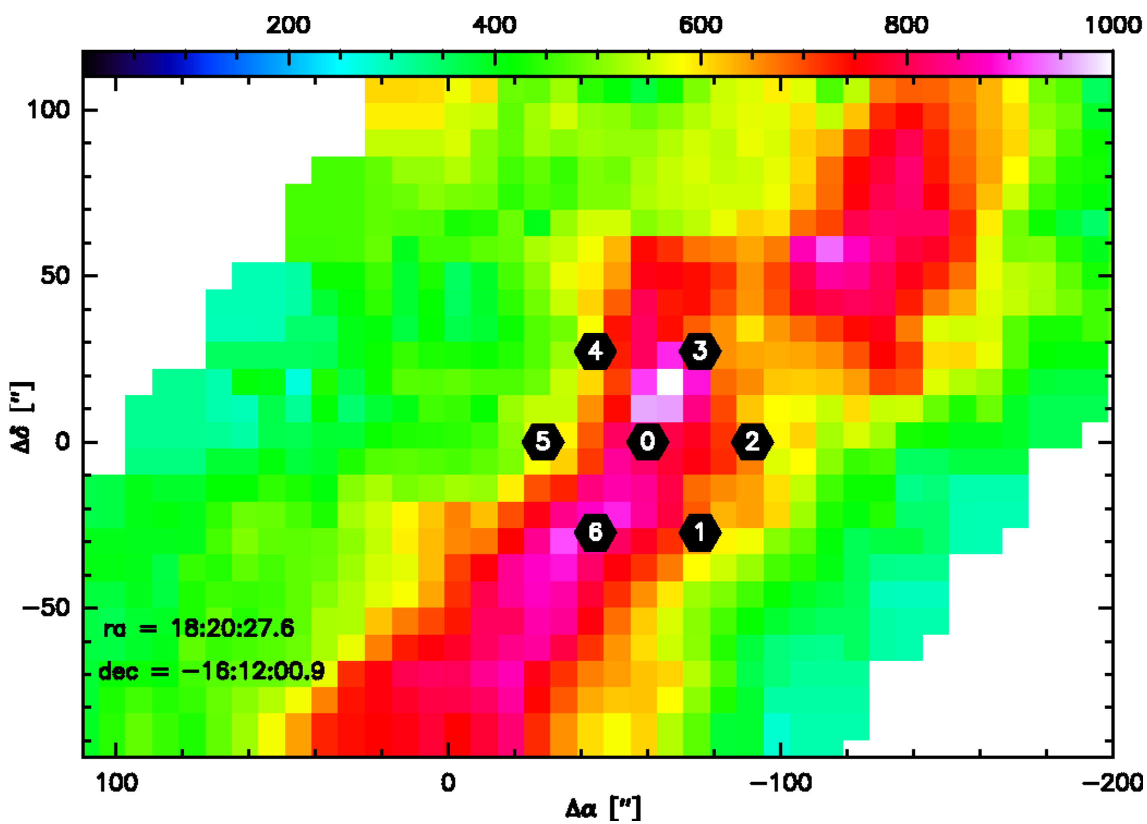


M17 8 µm Spitzer map and [CI] $^3P_1$-$^3P_0$ NANTEN2/SMART integrated intensity map in contours

Observations

- **Observations were done using the SOFIA/upGREAT 7x2 pixels array receiver during the June 2016 campaign.**
- **The array was centered around the [CII] peak.**
- **Deep integration (~30 min t_{on}) with high S/N ~ 300 for [^{12}CII] and ~ 7 for [^{13}CII] F=1-0 with a rms of 0.2 K.**

M17SW [CII] integrated intensity map (Pérez-Beaupuits et al. 2012) with the 7 upGREAT pixels



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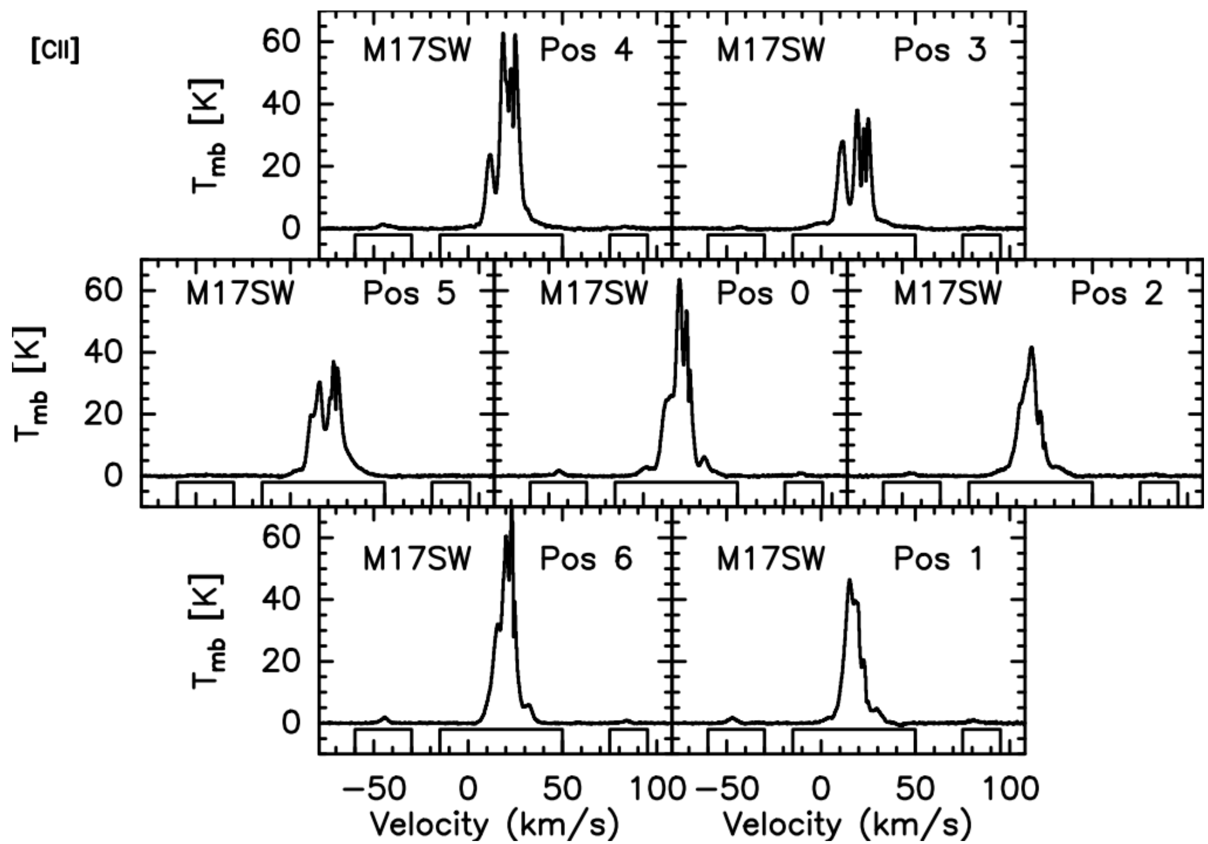
Zeroth Order Analysis

- **As a first approximation, it was assumed that the source has a single homogeneous layer with the same excitation temperature (T_{ex}) for both isotopes.**
- **[^{13}CII] was scaled up assuming the elemental abundance ratio $^{12}C/^{13}C$ of 40.**

M17SW [CII] observations



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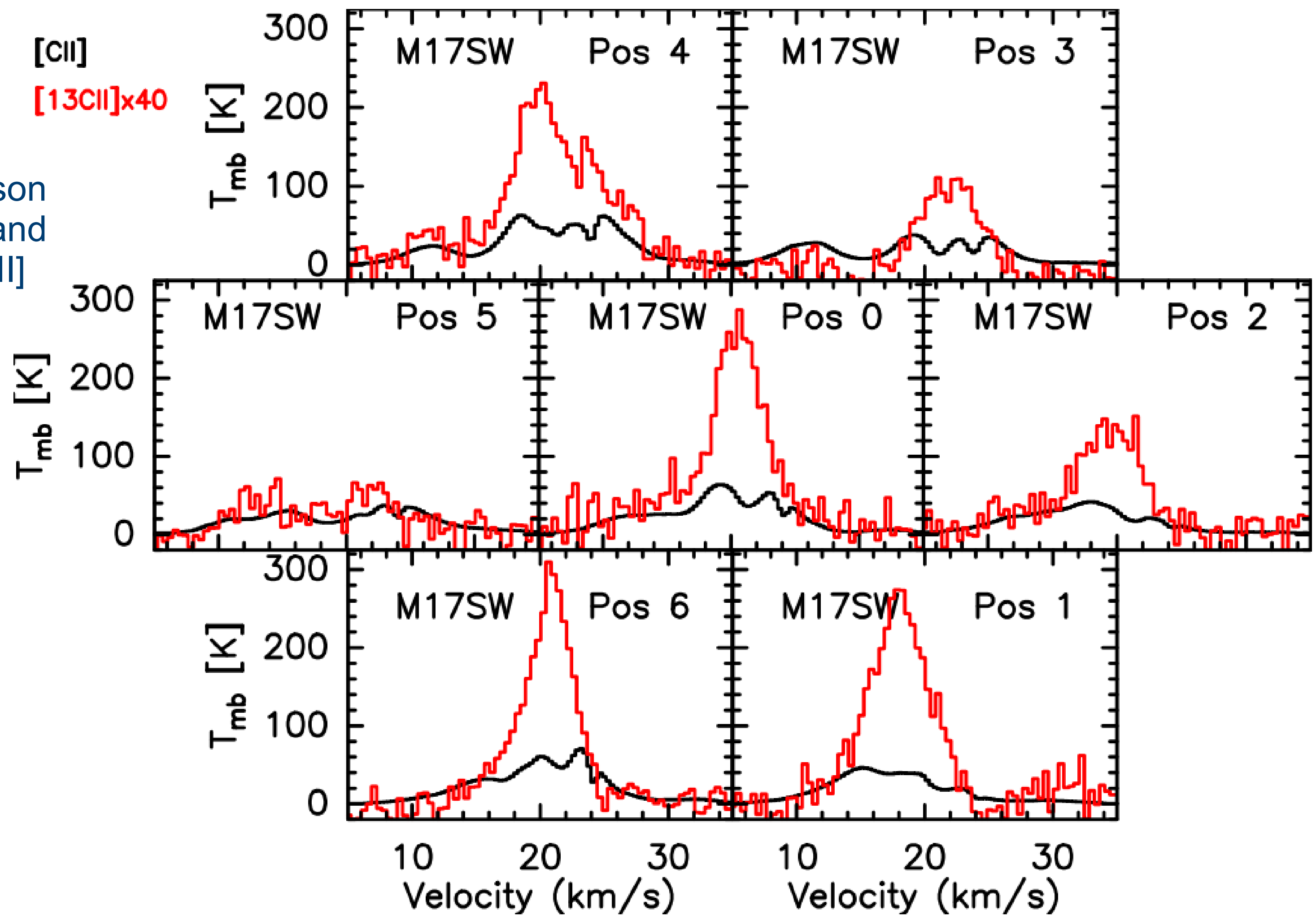
Zeroth Order Analysis

- [^{13}CII] overshoots the [^{12}CII] emission at the line center and matches at the line wings.
- [^{12}CII] line profiles shows absorption dips not present in [^{13}CII].

M17SW comparison between [^{12}CII] and the scaled up [^{13}CII]



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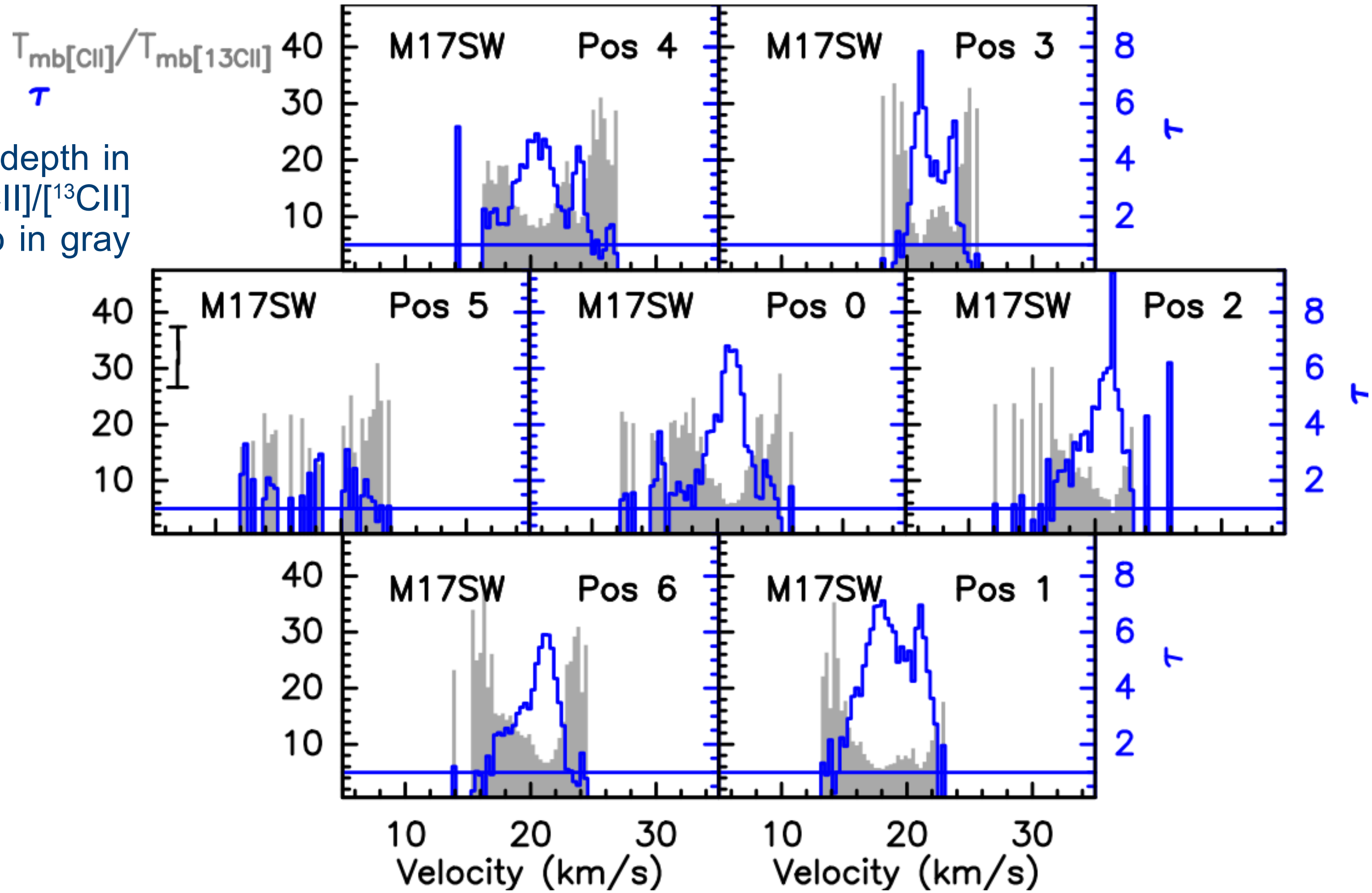
Zeroth Order Analysis

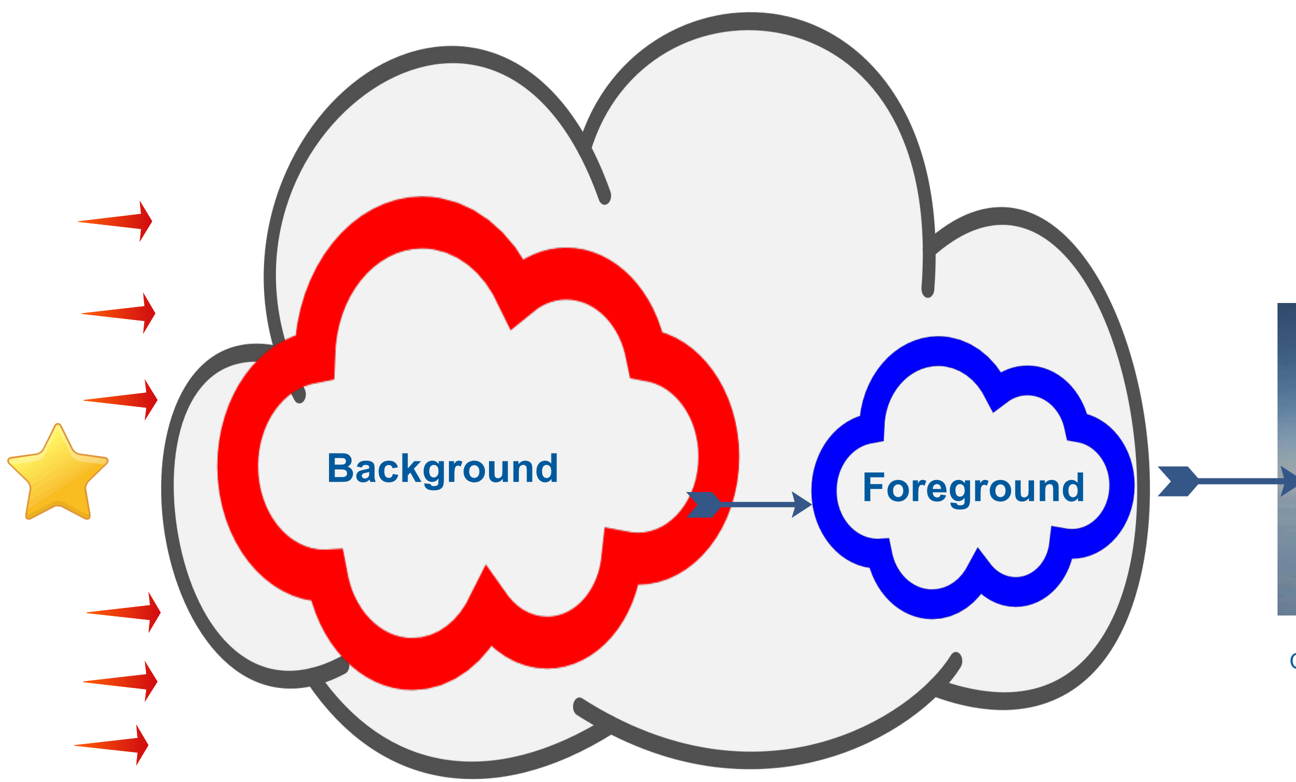
- The emission is optically thick in the line center with a τ between 4 and 8.
- The [^{12}CII]/[^{13}CII] ratios are between 15 and 30, well beloe the 40 assumed before.

M17SW optical depth in blue and [^{12}CII]/[^{13}CII] abundance ratio in gray per velocity bin



Multi-component Analysis

- The [^{12}CII] spectra with complex velocity structure and absorption dips shows that the single layer assumption is insufficient.
- The objective is to explain the [^{12}CII] and [^{13}CII] line profile by a composition of multiple Gaussians components.
- The model contains 2 layers, a background emission layer and a foreground absorption layer.



Credit: getdrawings.com, pngtree.com, iconsplace.com

Credit: NASA/Jim Ross

Multi-component Analysis

- The plan is to use the radiative transfer equation to derive the excitation temperature (T_{ex}), [^{12}CII] column density (N_{12}(CII)), the velocity center (v_{LSR}) and the FWHM velocity width (Δv_{LSR}).

- Three basic assumptions were done:

  - T_{ex} is the same for [^{12}CII] and [^{13}CII].
  - [^{13}CII] is optically thin.
  - If [^{12}CII] does not have a visible [^{13}CII] counterpart above noise level, [^{12}CII] emission is not affected by self-absorption effects.

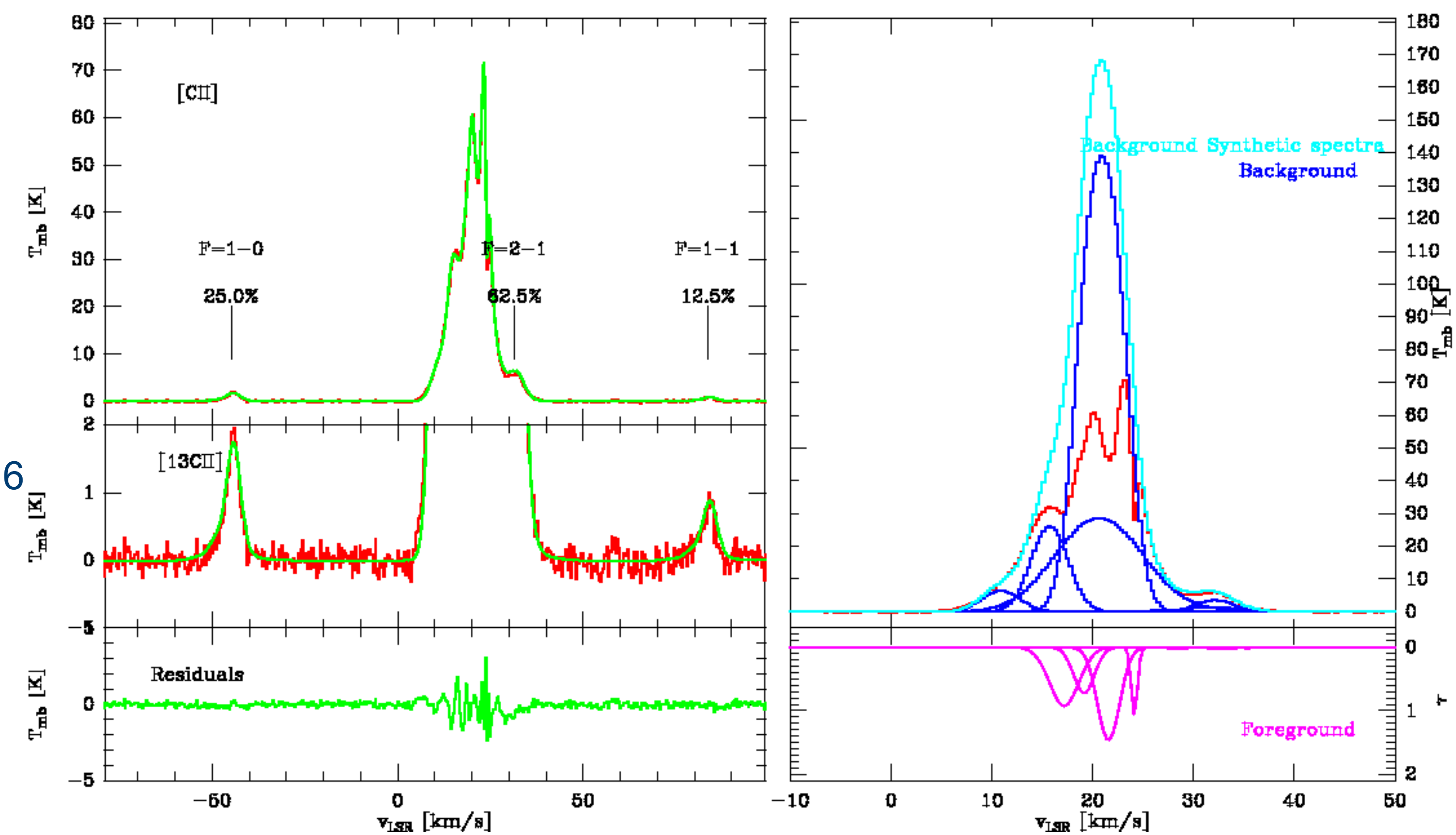
Multi-component Analysis

- **M17SW fitted parameters**

	Background	Foreground
Excitation temperature T_{ex}	180-250 K	20 - 45 K
Column Density (N(CII))	$3x10^{18} – 9x10^{18}$ cm^{-2}	$4x10^{17} – 3x10^{18}$ cm^{-2}
Equivalent visual extinction (Av)	12 - 41 mag	2 – 13 mag

Model
Data
Background
Foreground τ

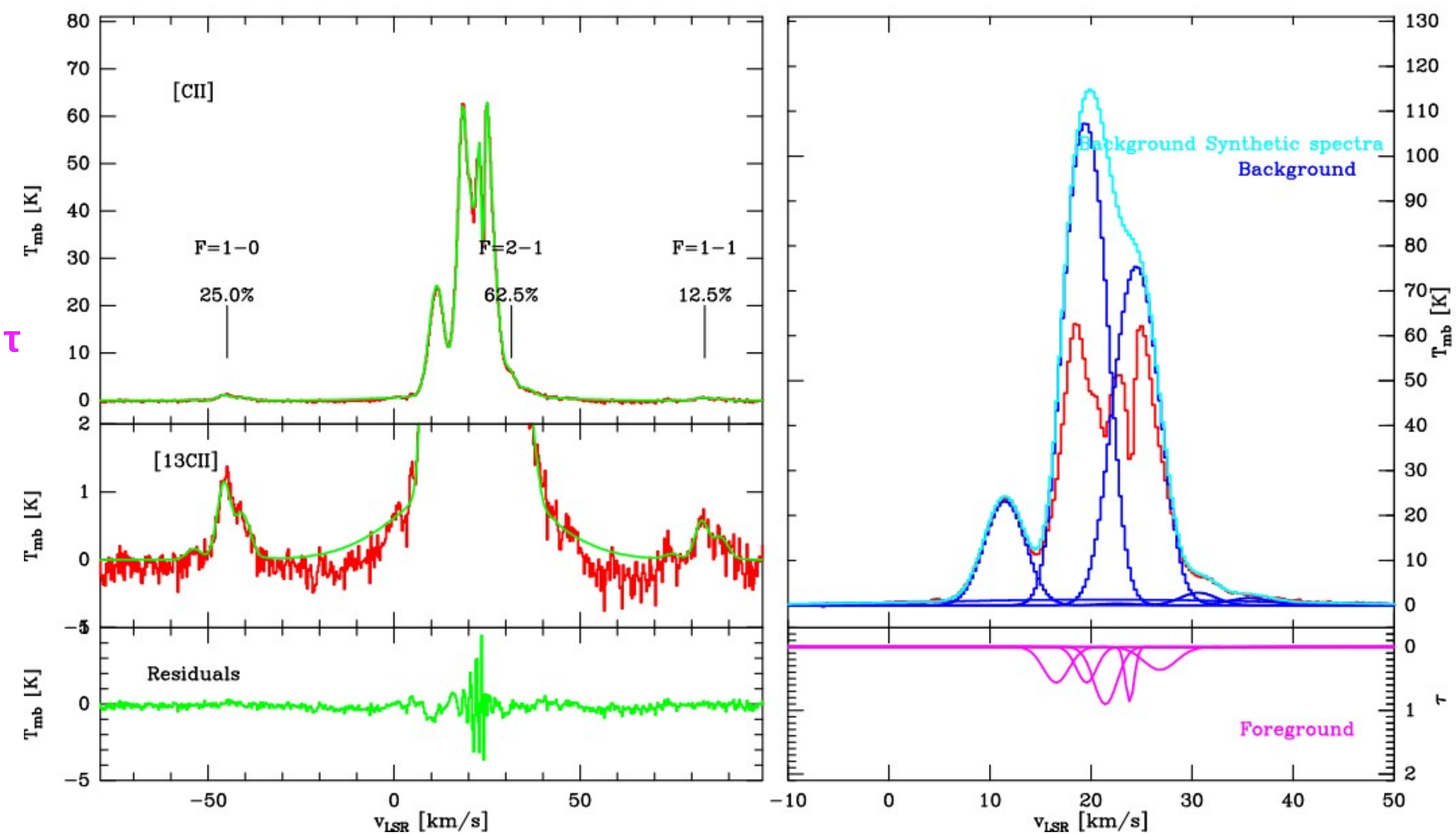
M17SW position 6



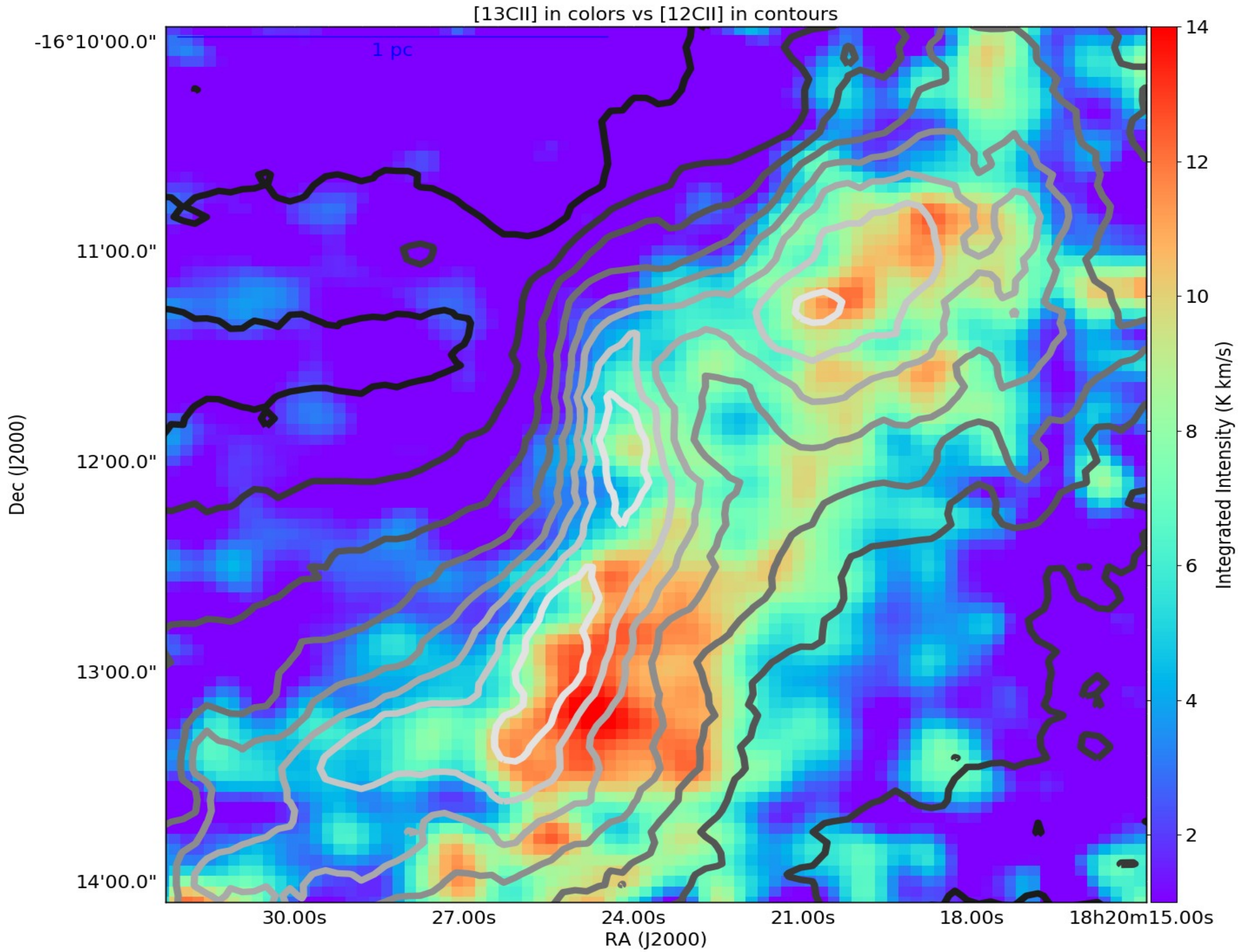
Multi-component Analysis

- **The background is composed by high temperature broad emission components with extremely high column density.**
- **The foreground is composed by low temperature narrow absorption notches with high column density.**

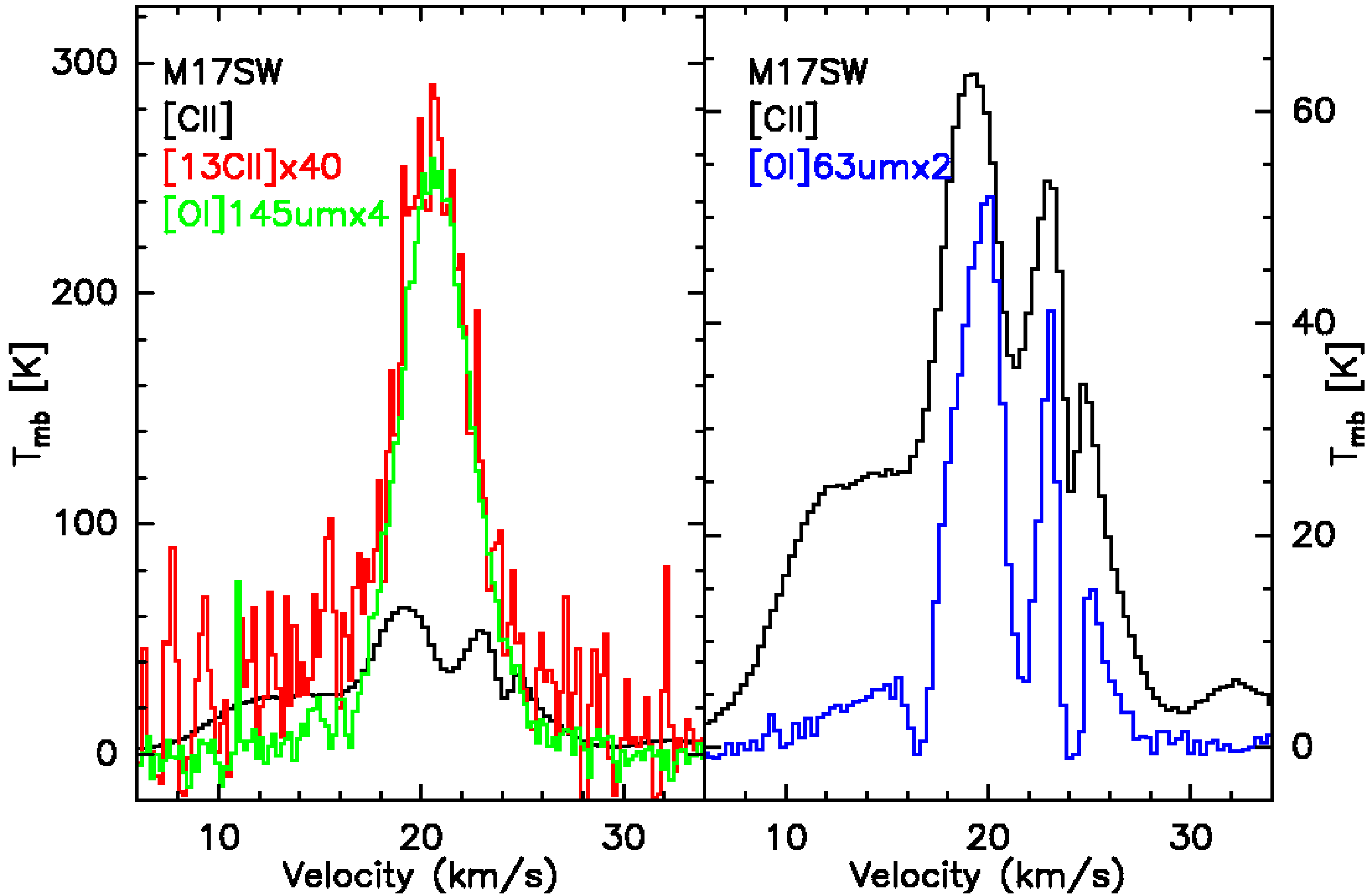
Model
Data
Background
Foreground τ



[^{13}CII] integrated intensity map



[^{12}CII] and [^{13}CII] vs [OI] emission



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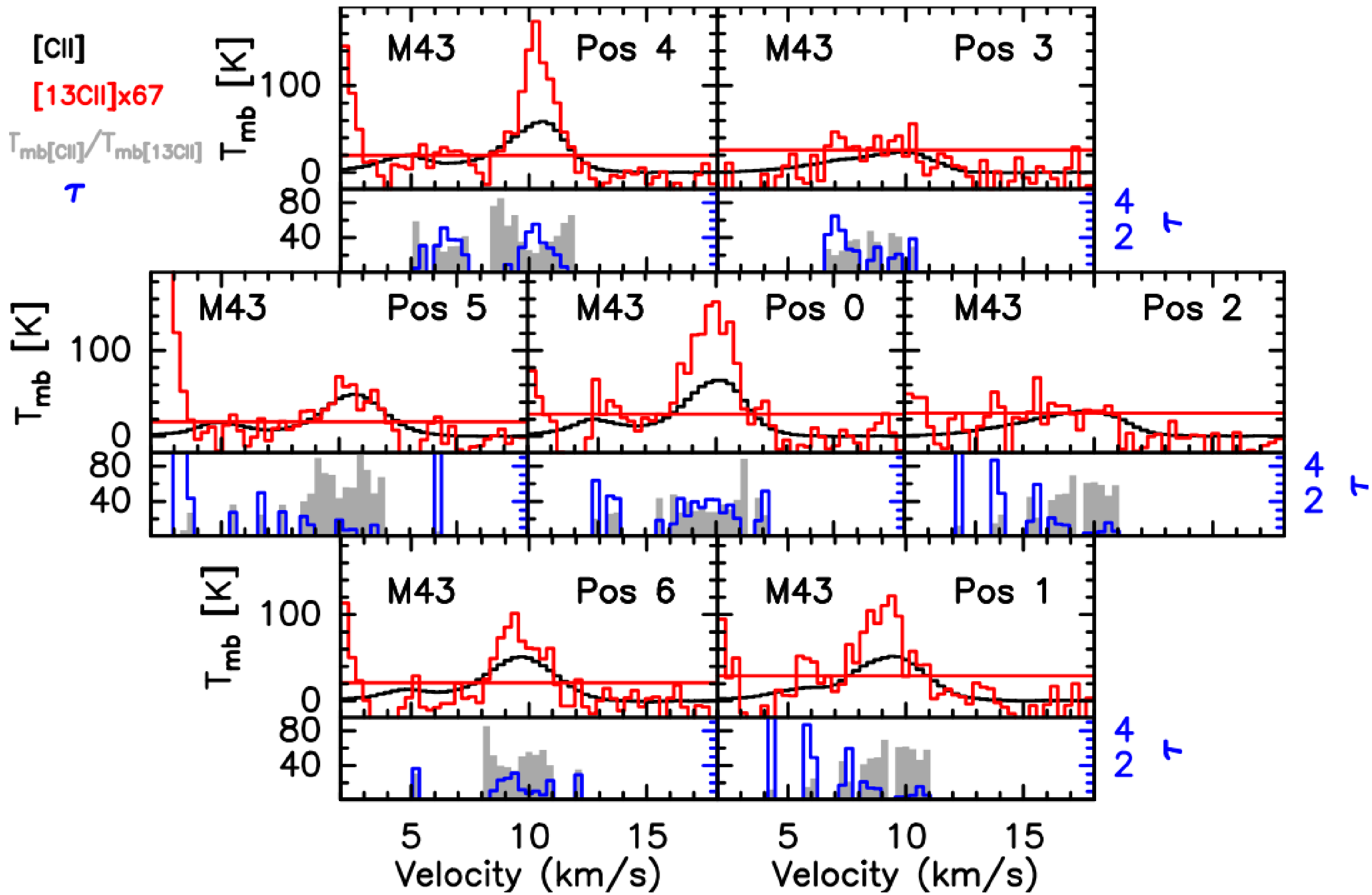
Summary

- The observations and analysis confirm the long standing suspicion that the [^{12}CII] emission is heavily affected by self-absorption effects and high optical depth.
- The absorbing dips change the profile of the [CII] line, mimicking separate velocity components.
- The high column densities of the warmer background are difficult to explain in the present PDR-model context and ISM phases.
- The large A_v derived here can be interpreted as several layers of C^+ stacked on top of the other. This situation could be enhanced by fractal and clumply material.
- For the foreground, the nature of the material is much more puzzling. The [CII] is ionized, cold lower density material. It is not diffuse gas.

Thank you for your attention

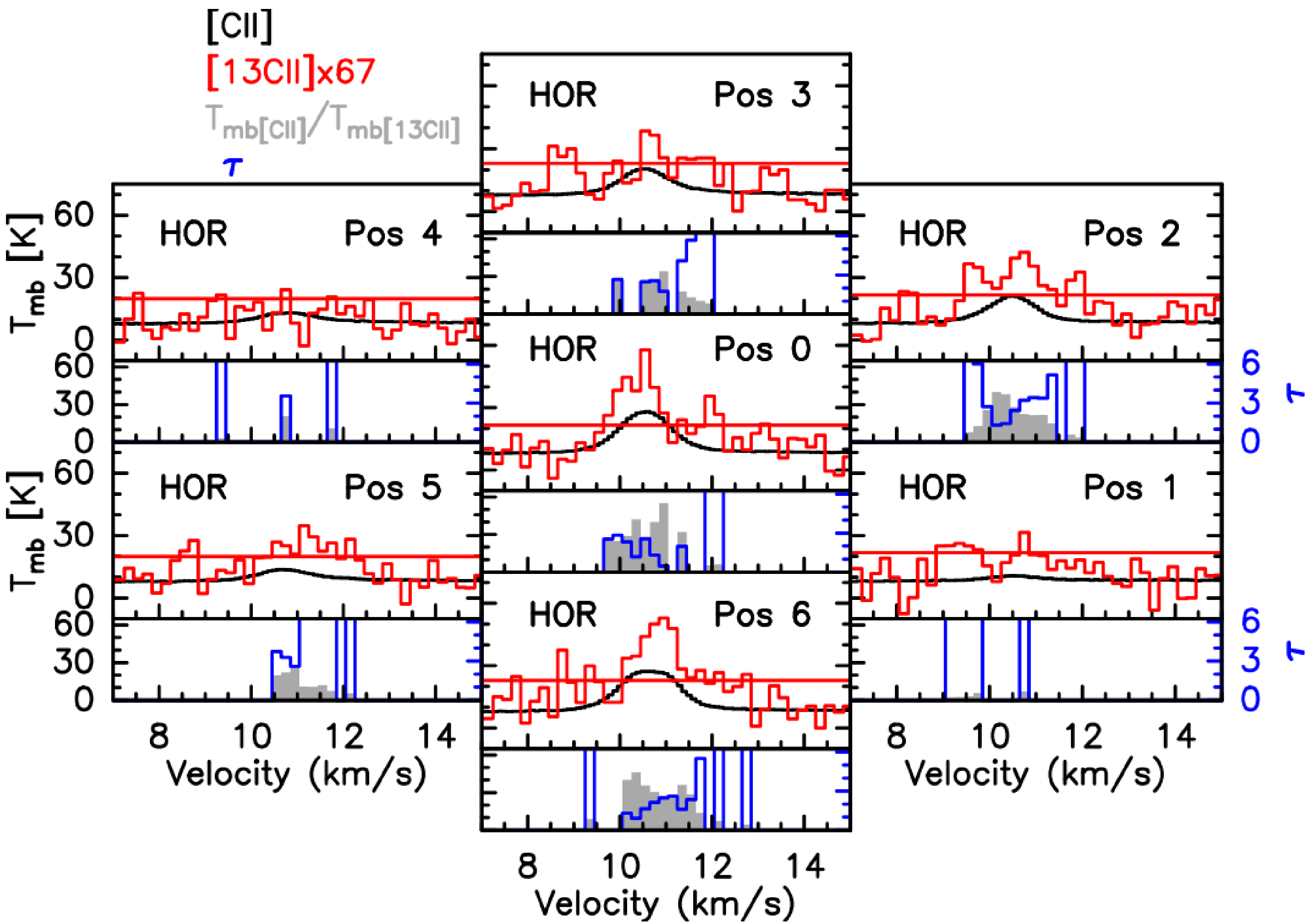
M43 τ and abundance ratio

- The [12]C/[13]C ratio assumed is 67.
- The optical depth for the peak positions ~2.



Horsehead PDR τ and abundance ratio

- The $^{12}C/^{13}C$ ratio assumed is 67.
- The optical depth for the peak positions ~1.8



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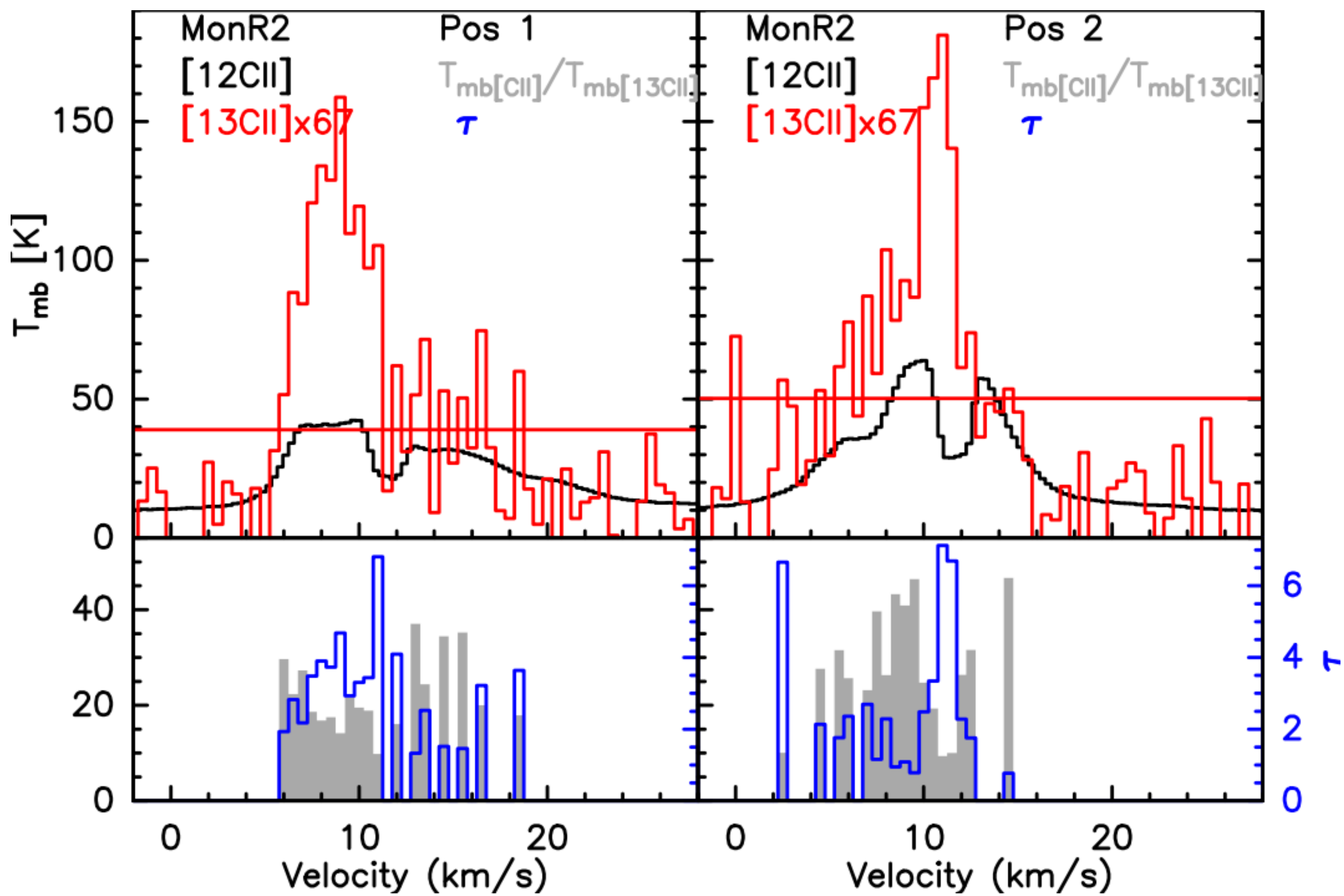
Monoceros R2 τ and abundance ratio

- The $^{12}C/^{13}C$ ratio assumed is 67.
- The optical depth for the peak positions ~7.



[^{12}CII] N(CII) integrated intensity

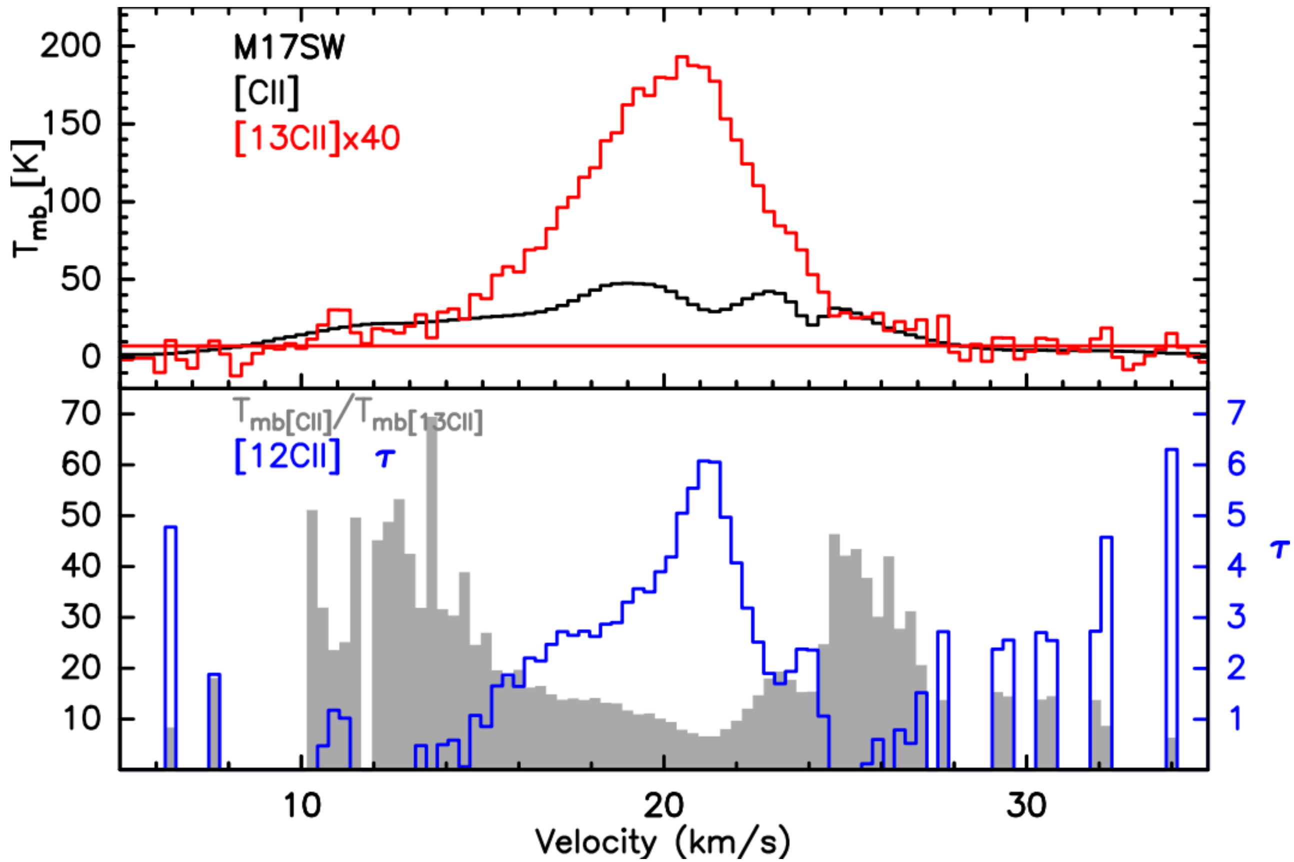
- **For the four sources, the [^{12}CII] column density derived from the scaled-up optically thin [^{13}CII] was estimated, as well as the column density directly from the [^{12}CII].**

	[^{13}CII]				Optically thin [^{12}CII]			Ratio
Positions	[^{13}CII] Int. Intensity (K km/s)	N_{min}([^{13}CII]) (cm^{-2})	N_{min}([CII])^a [^{13}CII] (cm^{-2})	$A_{v,min}$^{b} [^{13}CII] (mag.)	[^{12}CII] Int. Intensity (K km/s)	N_{min}([CII])^c [^{12}CII] (cm^{-2})	$A_{v,min}$^{d} [^{12}CII] (mag.)	$\frac{A_{v,min}([^{13}CII])^b}{A_{v,min}([^{12}CII])^d}$
M43 0	5.5	2.5E16	1.7E18	7.4	283.1	1.3E18	5.6	1.3
M43 1	4.3	1.9E16	1.3E18	5.7	249.2	1.1E18	4.9	1.2
M43 2	2.6	1.2E16	7.7E17	3.4	172.2	7.7E17	3.4	1.0
M43 3	2.6	1.1E16	7.6E17	3.4	134.0	6.0E17	2.6	1.3
M43 4	5.5	2.5E16	1.7E18	7.4	270.1	1.2E18	5.3	1.4
M43 5	3.7	1.6E16	1.1E18	4.9	227.4	1.0E18	4.5	1.1
M43 6	4.1	1.8E16	1.2E18	5.4	237.9	1.1E18	4.7	1.1
HOR 0	1.2	5.3E15	3.6E17	1.6	39.6	1.8E17	0.8	2.0
HOR 1	0.7	3.1E15	2.1E17	0.9	11.2	5.0E16	0.2	4.2
HOR 2	1.4	6.1E15	4.1E17	1.8	26.6	1.2E17	0.5	3.4
HOR 3	1.0	4.7E15	3.1E17	1.4	25.7	1.1E17	0.5	2.7
HOR 4	0.3	1.2E15	8.4E17	0.4	14.8	6.6E16	0.3	1.3
HOR 5	0.9	3.9E15	2.6E17	1.2	14.7	6.5E16	0.3	4.0
HOR 6	1.6	7.0E15	4.7E17	2.1	41.5	1.9E17	0.8	2.5
MonR2 1	12.2	5.5E16	3.7E18	16.3	410.8	1.8E18	8.1	2.0
MonR2 2	11.4	5.1E16	3.4E18	15.2	477.0	2.1E18	9.5	1.6
M17SW 0	41.6	1.9E17	7.4E18	33.0	657.2	2.9E18	13.1	2.5
M17SW 1	39.1	1.7E17	7.0E18	31.1	460.1	2.1E18	9.1	3.4
M17SW 2	26.9	1.2E17	4.8E18	21.3	458.1	2.0E18	9.1	2.3
M17SW 3	16.5	7.4E16	2.9E18	13.1	489.9	2.2E18	9.7	1.3
M17SW 4	45.1	2.0E17	8.1E18	35.9	722.7	3.2E18	14.4	2.5
M17SW 5	14.1	6.3E16	2.5E18	11.2	521.7	2.3E18	10.4	1.1
M17SW 6	34.3	1.5E17	6.1E18	27.3	617.7	2.8E18	12.3	2.2

[a] [^{12}CII] column density derived from the scaled-up [^{13}CII] column density.
[b] [^{12}CII] equivalent visual extinction derived from the scaled-up [^{13}CII] column density.
[c] [^{12}CII] column density derived directly from the [^{12}CII] integrated intensity assuming optically thin regime.
[d] [^{12}CII] equivalent visual extinction derived directly from the [^{12}CII] integrated intensity assuming optically thin regime.

[^{12}CII]/[^{13}CII] abundance ratio

- **The analysis highly depend on the assumed ratio, it could be possible to derive the ratio directly from the wing emission with high S/N.**
- **For M17Sw, 6 or 7 positions were averaged to analyze the ratio.**



M17SW average spectra

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