GREAT observations reveal strong self-absorption in [CII] 158 µm emission from NGC 2024

Urs U. Graf

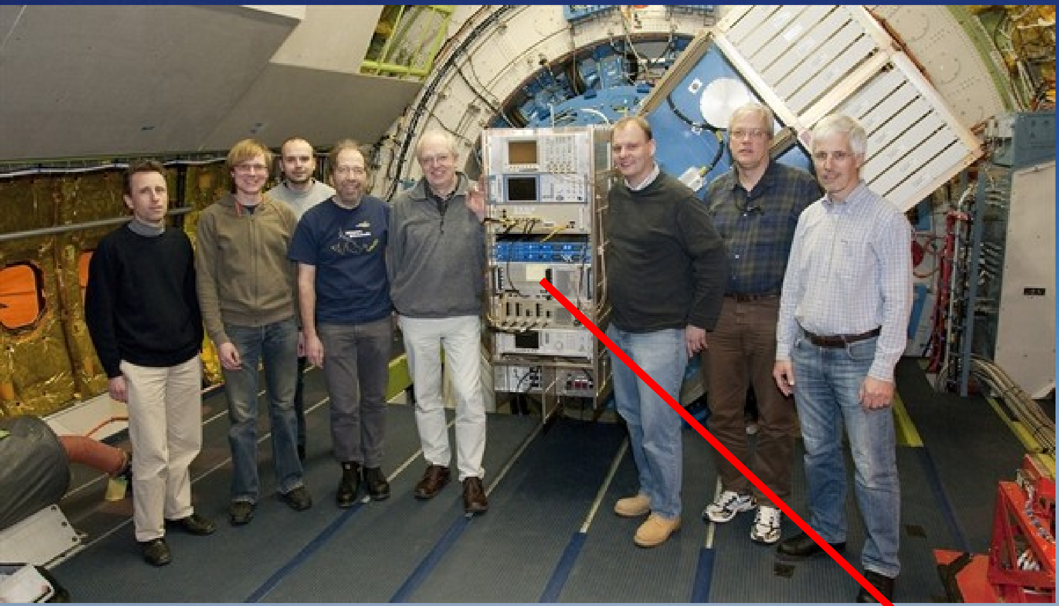
Collaborators and Acknowledgements

- **U.U. Graf, R. Simon, J. Stutzki, S.W.J. Colgan, X. Guan, R. Güsten, C.E. Honingh, H.-W. Hübers, GREAT special volume: A&A 2012, Vol. 542, L16**
- **The GREAT team**
- **SOFIA staff in Palmdale and beyond**

Outline

- **GREAT Introduction**
- **NGC 2024:**
  - **Introduction**
  - **[^{12}CII] map**
  - **[^{13}CII] map**
  - **Line profile analysis**
  - **[CII] Hyperfine line ratios**

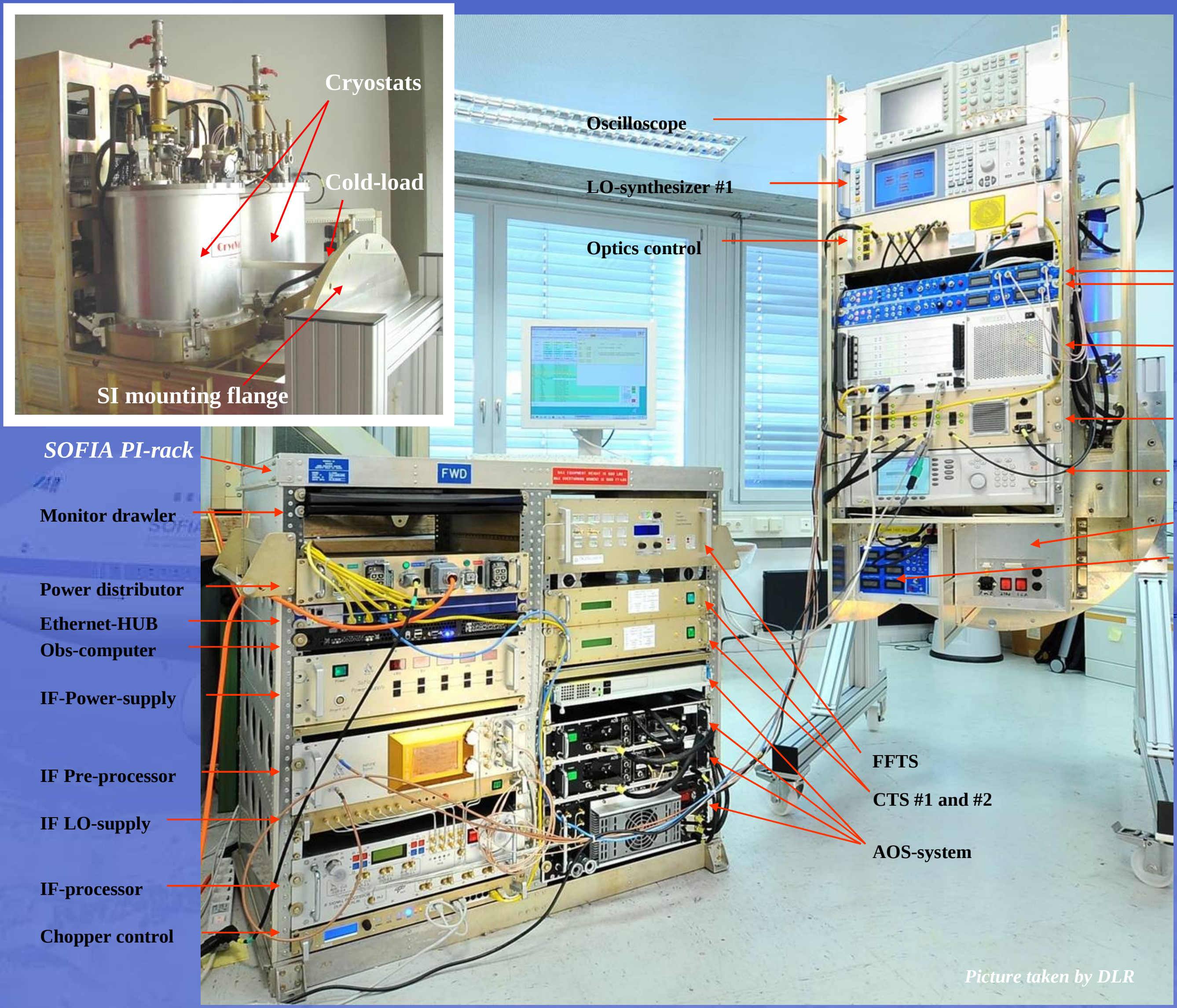
The GREAT team (part of it)



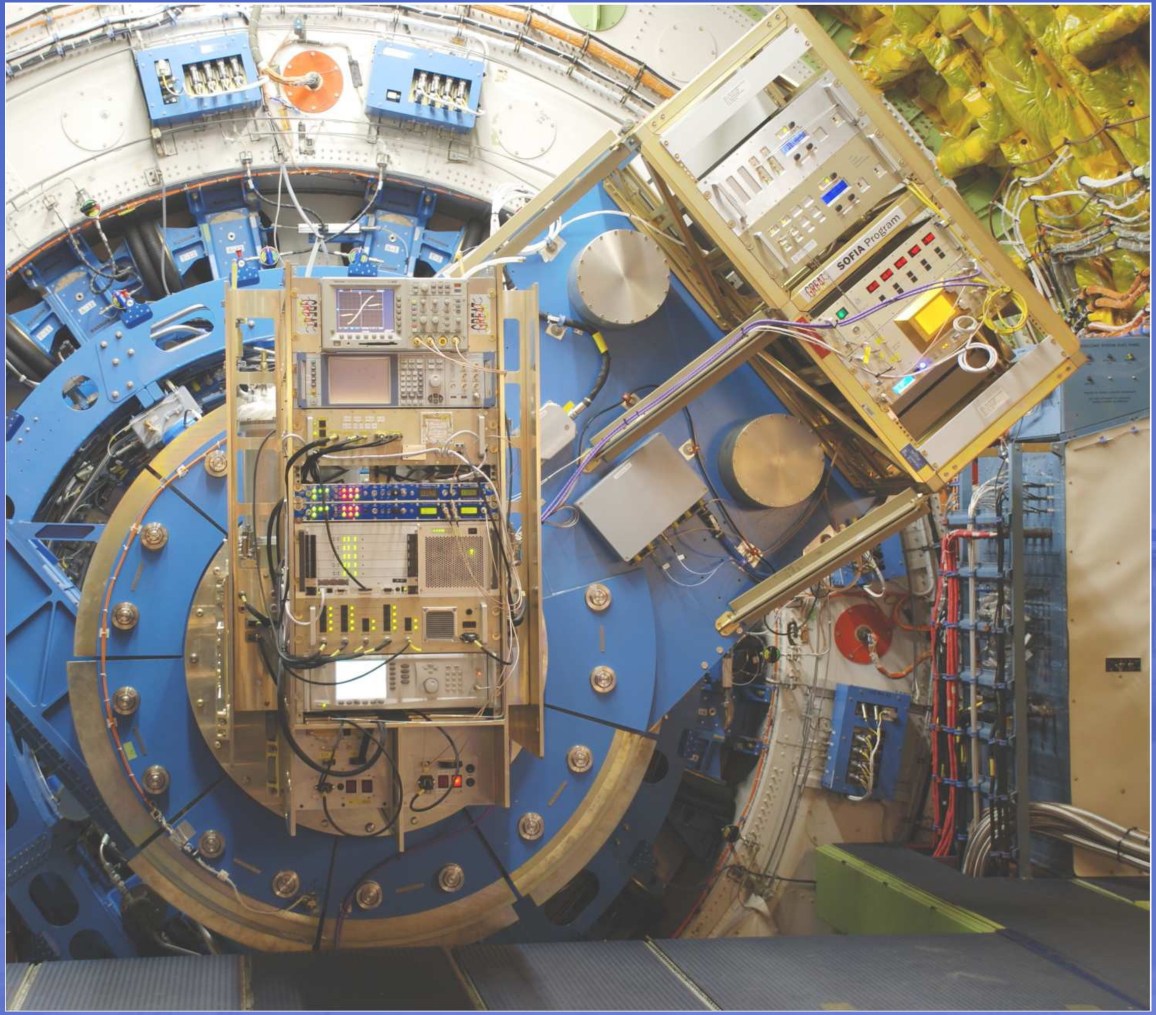
GREAT: a modular dual color heterodyne spectrometer

Basic Science observing period (2011): mostly L1 (~1400 GHz) and L2 (~1900GHz)

GREAT in the Lab



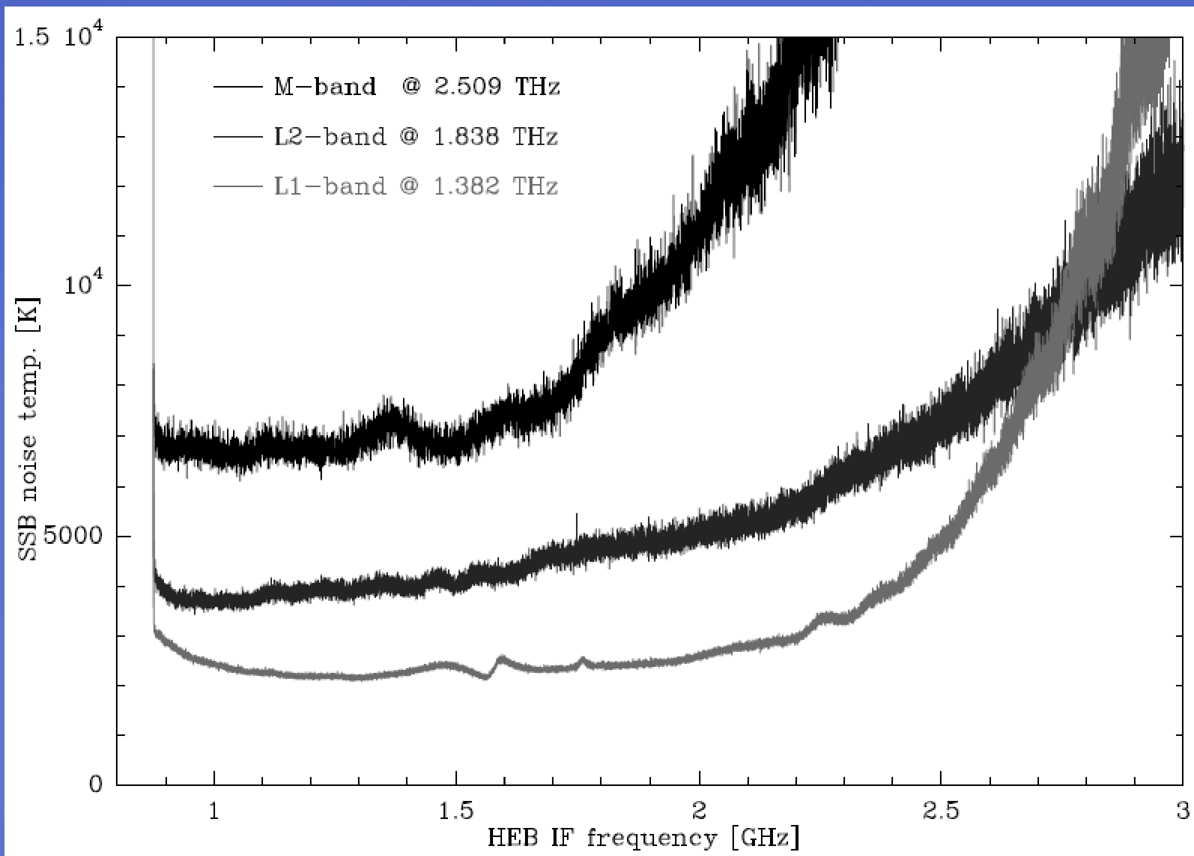
… and in SOFIA



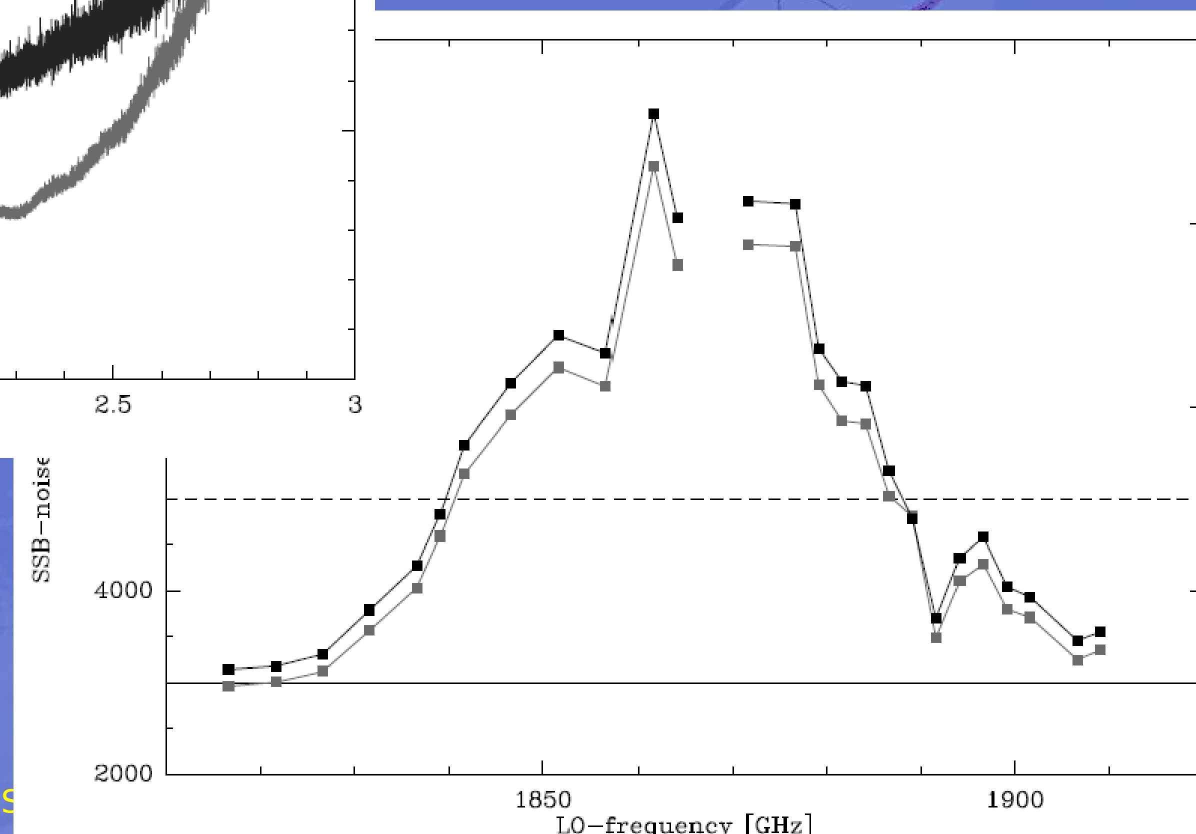
GREAT configuration during NGC 2024 observations (Nov 2012):

- **L2 (1900 GHz)**
- **M (2500 GHz, experimental) – inoperable due to LO failure**

Receiver Noise Temperature

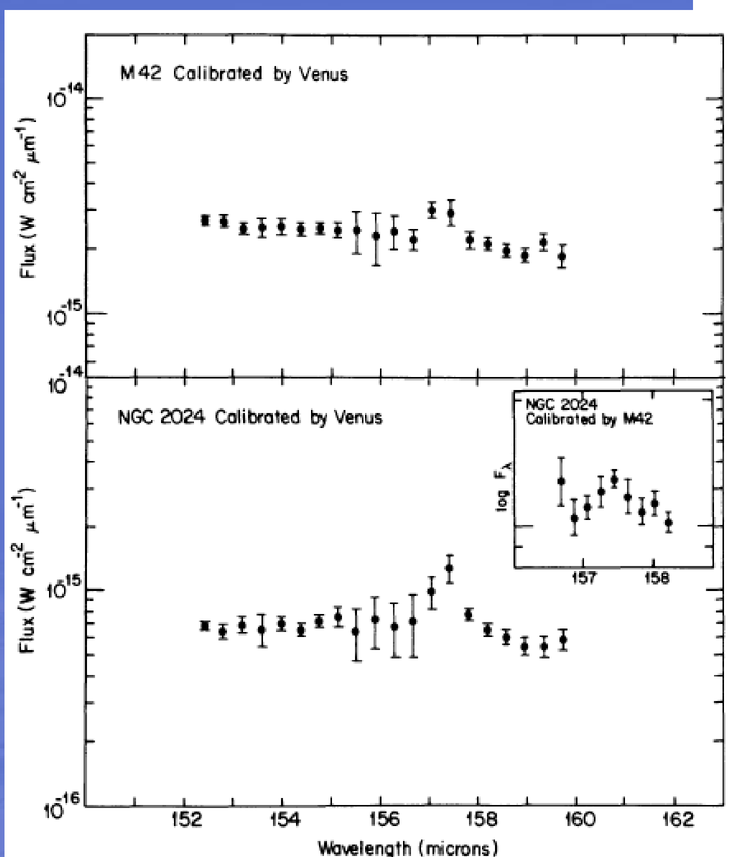


T_{RX} ~ 4000 K @ 1.9 THz



First Detection of Interstellar [CII] was made in NGC 2024

Russell et al. 1980



DETECTION OF THE 157 MICRON (1910 GHz) [C II] EMISSION LINE FROM THE INTERSTELLAR GAS COMPLEXES NGC 2024 AND M42

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Received 1980 April 7; accepted 1980 May 28

ABSTRACT

We present the first detection of the [C II] fine-structure emission line at a wavelength of 157 μm. The [C II] line strengths are 7.1×10^{-16} and 1.0×10^{-15} W cm^{-2}, respectively, in NGC 2024 and M42. The line-to-continuum ratio is higher in NGC 2024 where the continuum is 7.0×10^{-16} W cm^{-2} μm^{-1}, in contrast to M42 where it assumes a value of 2.6×10^{-15} W cm^{-2} μm^{-1}. The respective luminosities in the line are ~50 and 80 $L_\odot$. The observations were obtained with a stressed Ge:Ga photoconductor.

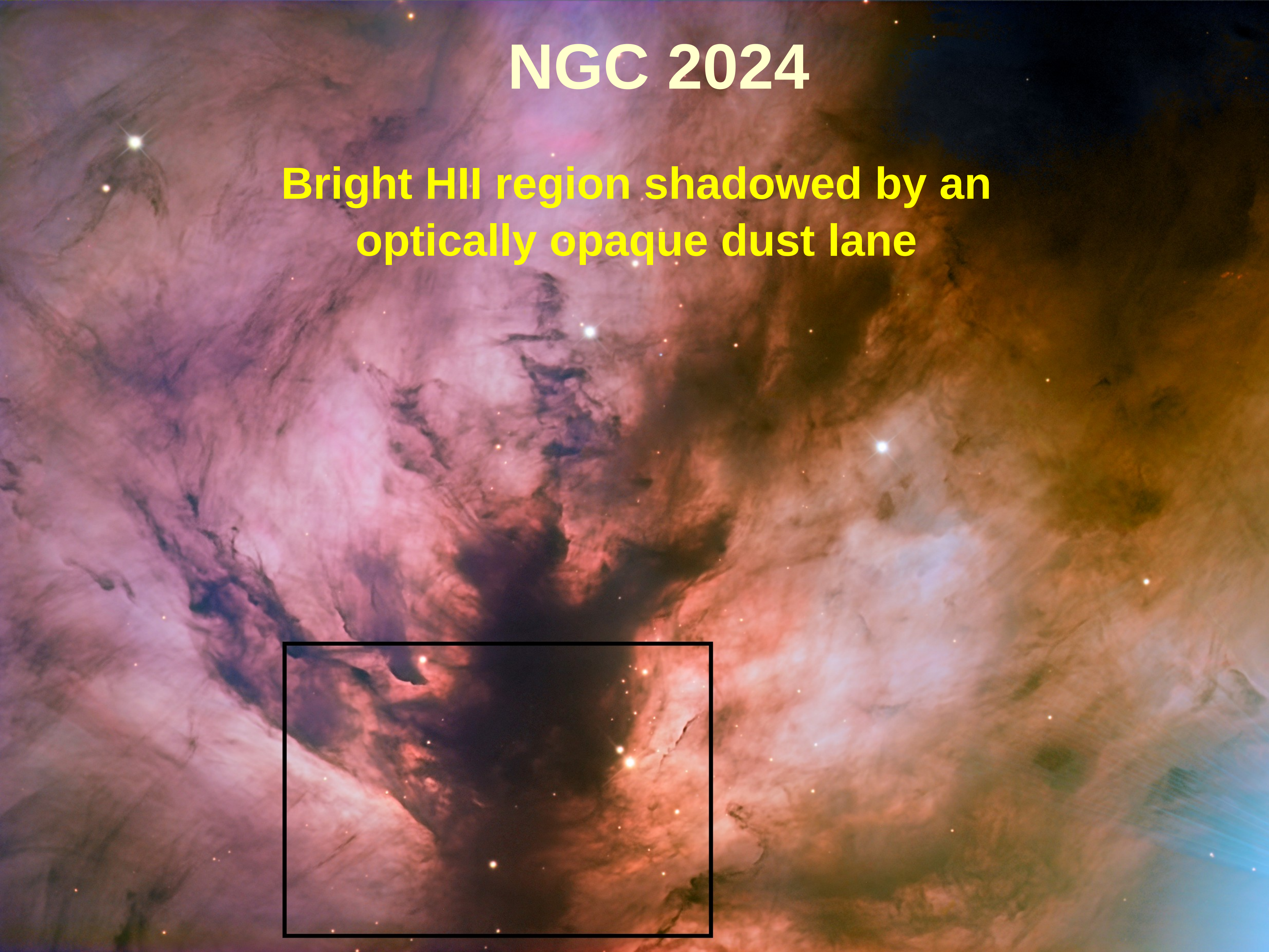
Subject headings: forbidden lines — infrared: spectra — interstellar: matter — nebulae: individual — nebulae: Orion Nebula

I. INTRODUCTION

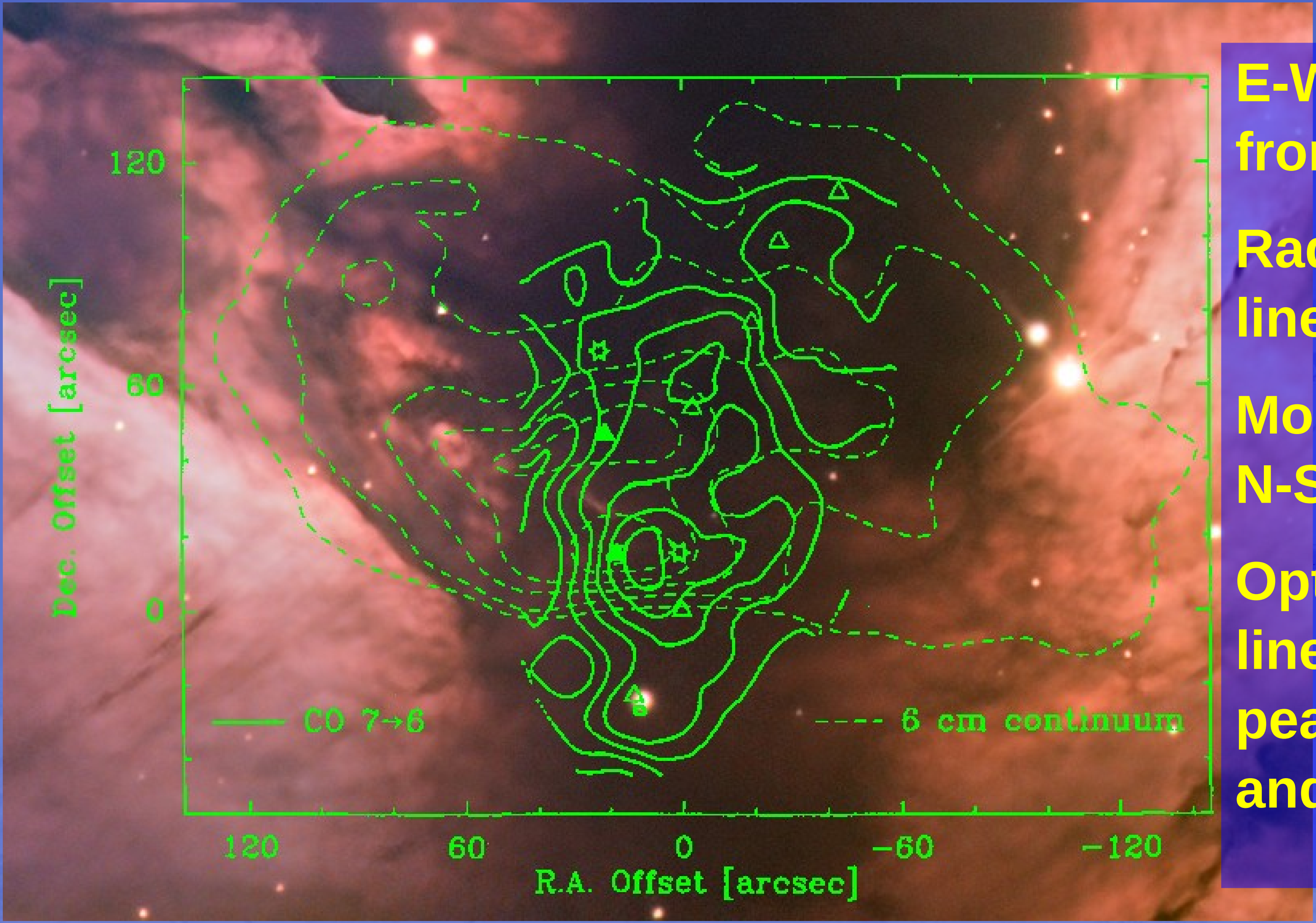
The fine-structure transition of singly ionized carbon, [C II], has long been considered to be one of the principal means for cool interstellar atomic clouds to radiate energy into space. At temperatures below 200 K [C II] emission has been predicted to dominate the cooling of gas clouds (Dalgarno and McCray 1972). Although this line has been discussed in theoretical studies for well over a decade, practical difficulties (including a lack of sensitive high-resolution far-infrared spectrometers and an uncertainty in the actual line position) have prevented direct observation.

IV. CONCLUSION

We have obtained the first observations of the 157 μm [C II] cooling line. On the assumption that the 157 μm [C II] radiation emanates from the same region as 63 μm [O I] radiation, i.e., from neutral H I layers surrounding the H II domain, we can derive approximate gas temperatures. Optical depth effects in the 157 μm line may be significant but have not been taken into account in our calculations because our data base is still too restricted.


NGC 2024
Bright HII region shadowed by an
optically opaque dust lane

NGC 2024 (zoomed)



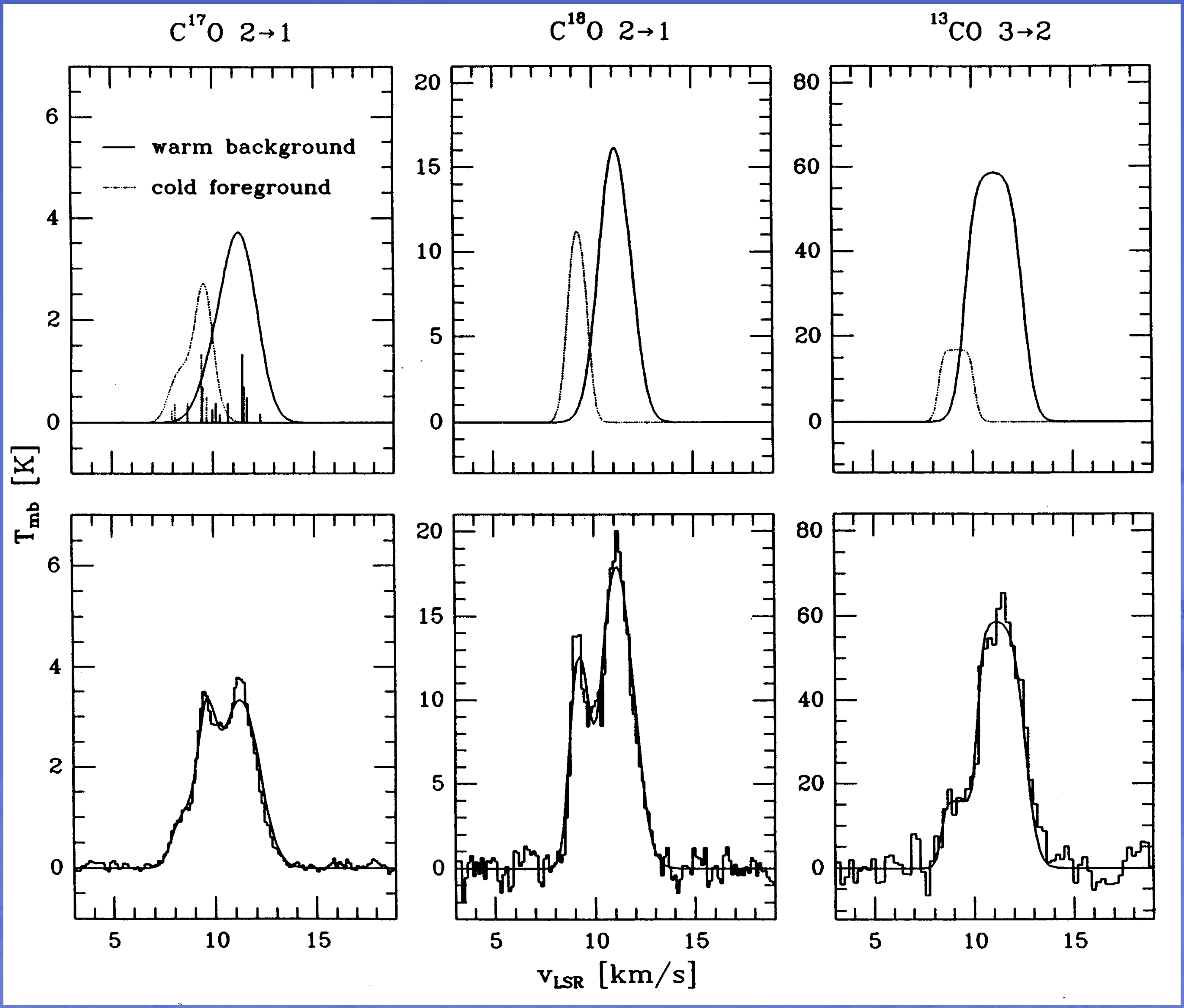
E-W Ionization front

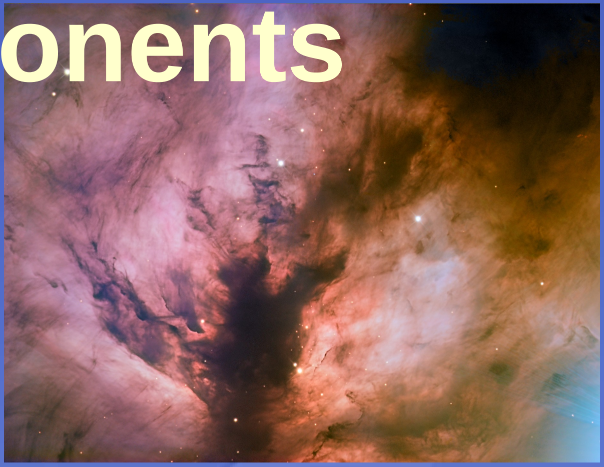
Radio absorption lines at 9 km/s

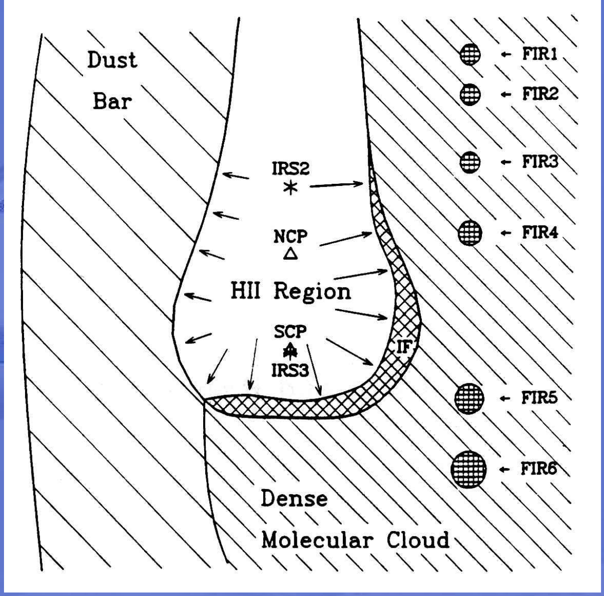
Molecular lines N-S extended

Optically thin CO lines have 2 peaks @ 9 km/s and 11 km/s

Standard source model: 2 emission components



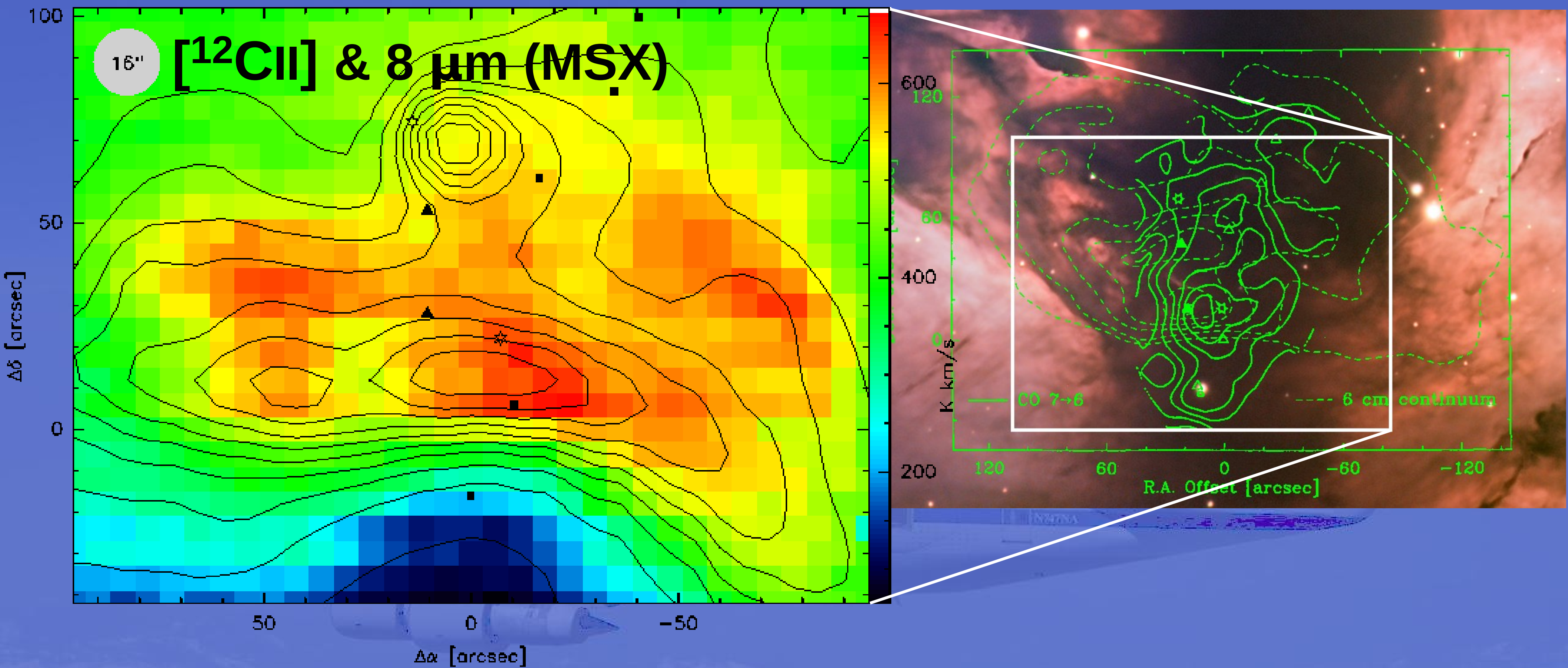




cold fore-ground @9 km/s

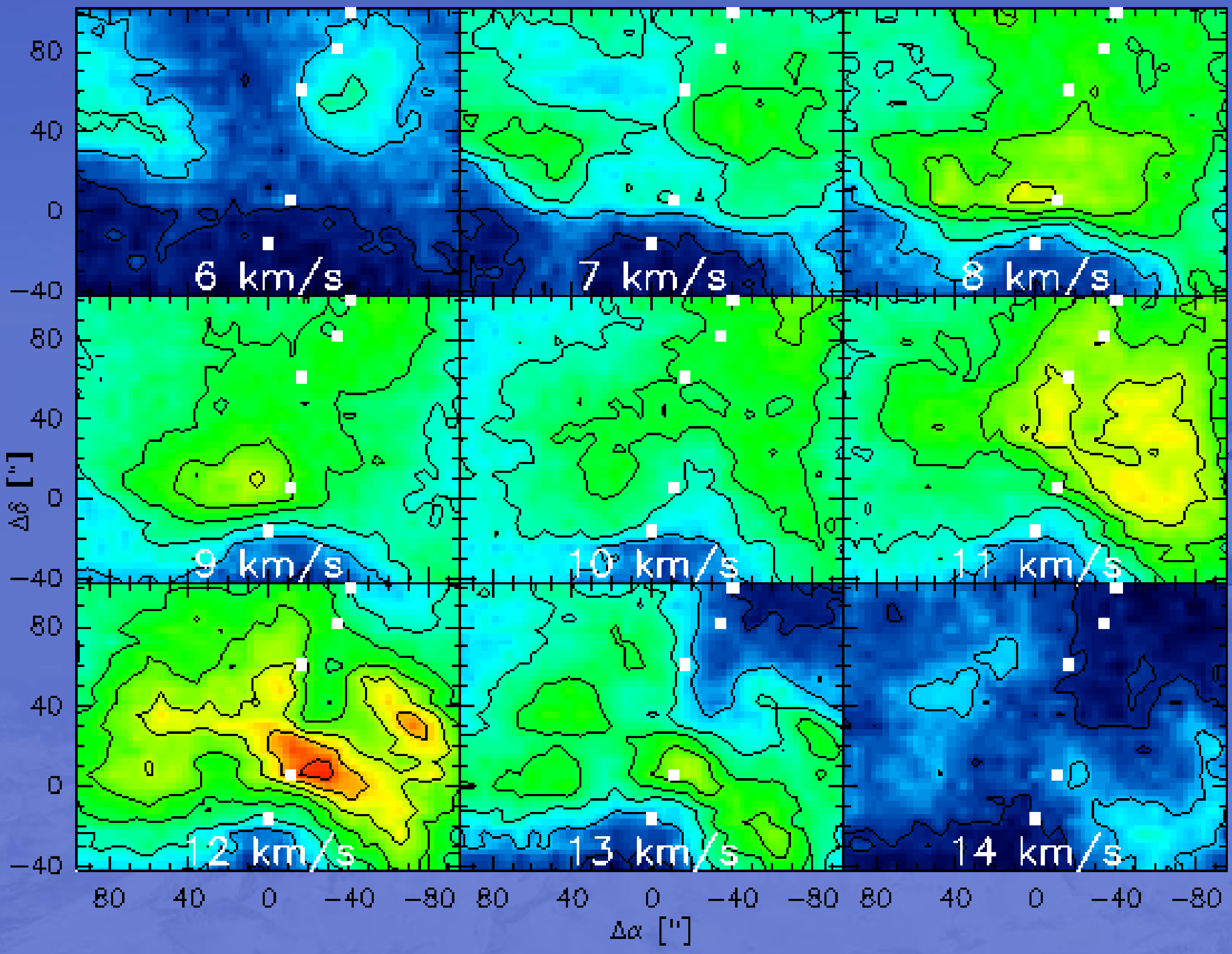
warm back-ground @11 km/s

[CII] integrated intensity map



- [CII] is very strong: > 600 K km/s
- Closely follows 8 µm continuum (i.e. UV heated dust)

[CII] Channel maps

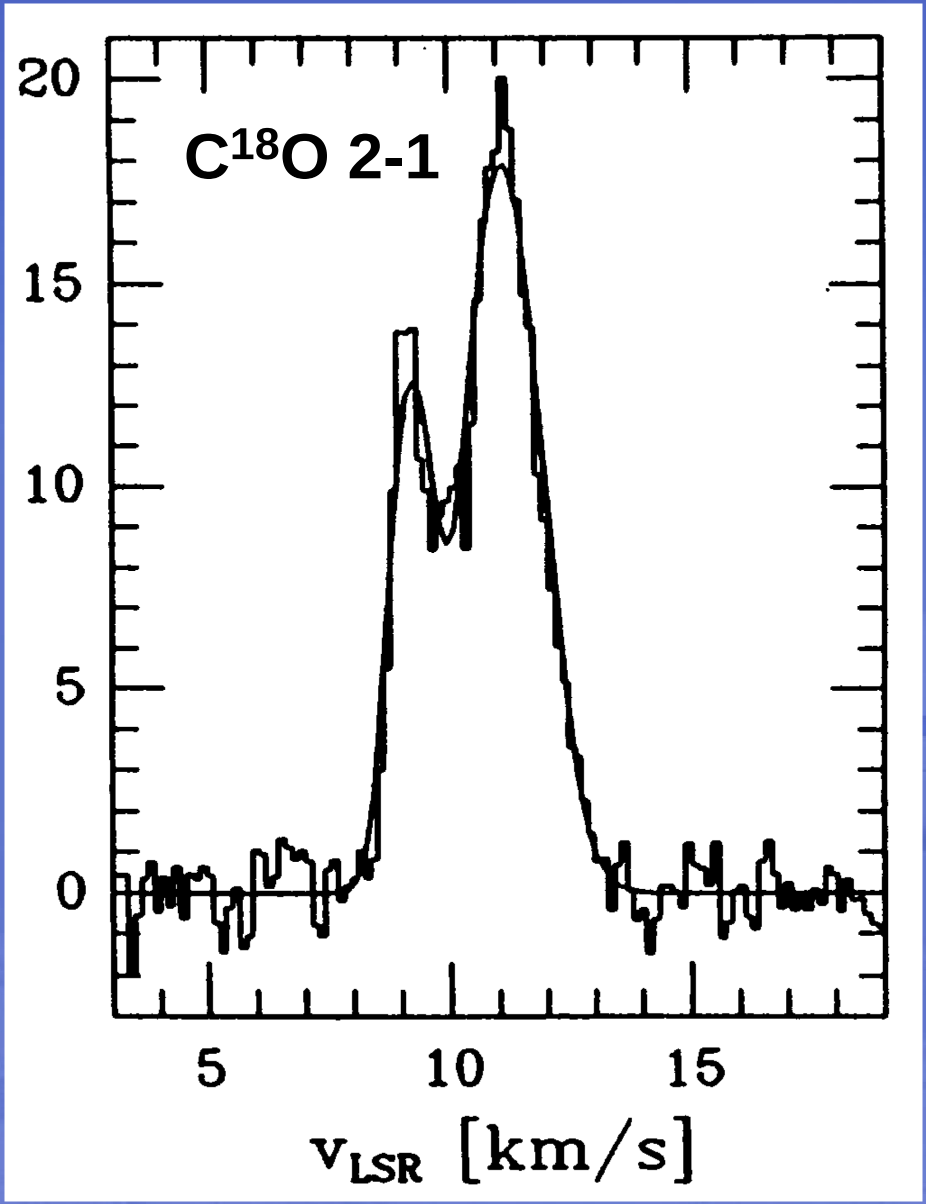


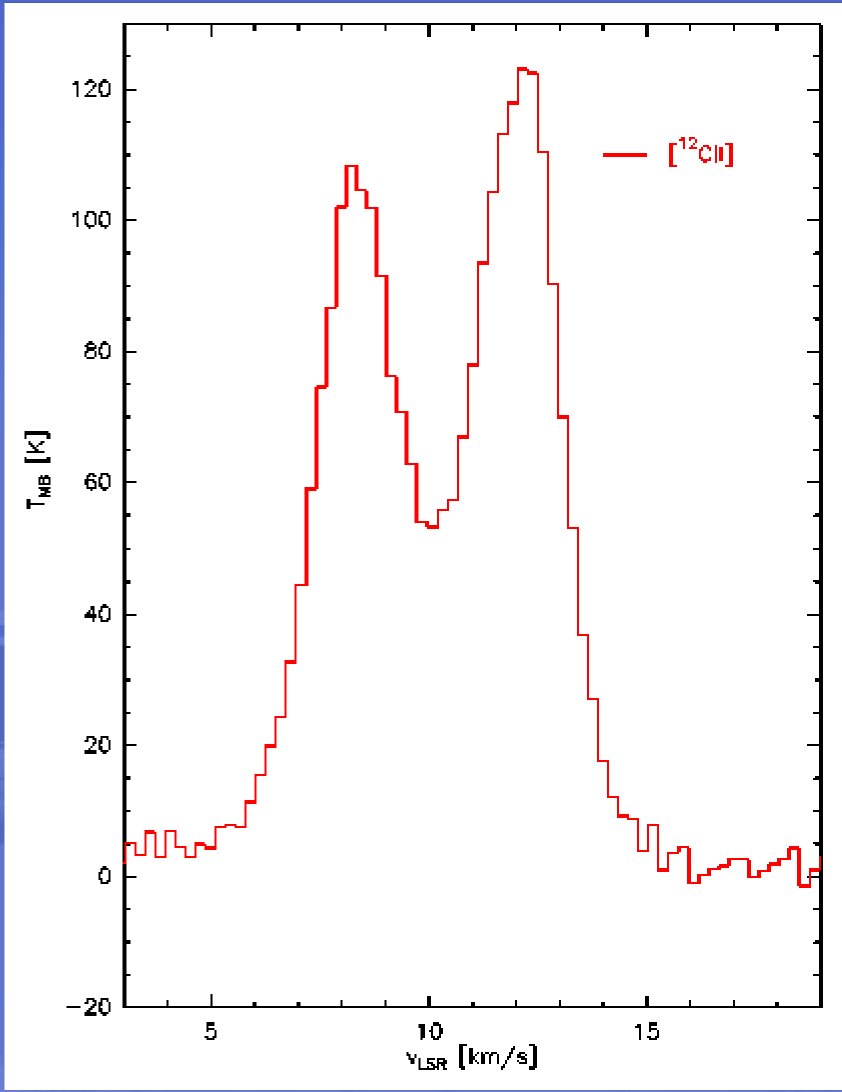
2 main velocity components: 8-9 km/s and 11-12 km/s

Dip at 10 km/s

Slight spatial anticorrelation between the 2 velocity components

C^{18}O 2-1 vs. [CII] near FIR5





Suggests 2 emission components in [CII] too, but we also got [^{13}CII]...

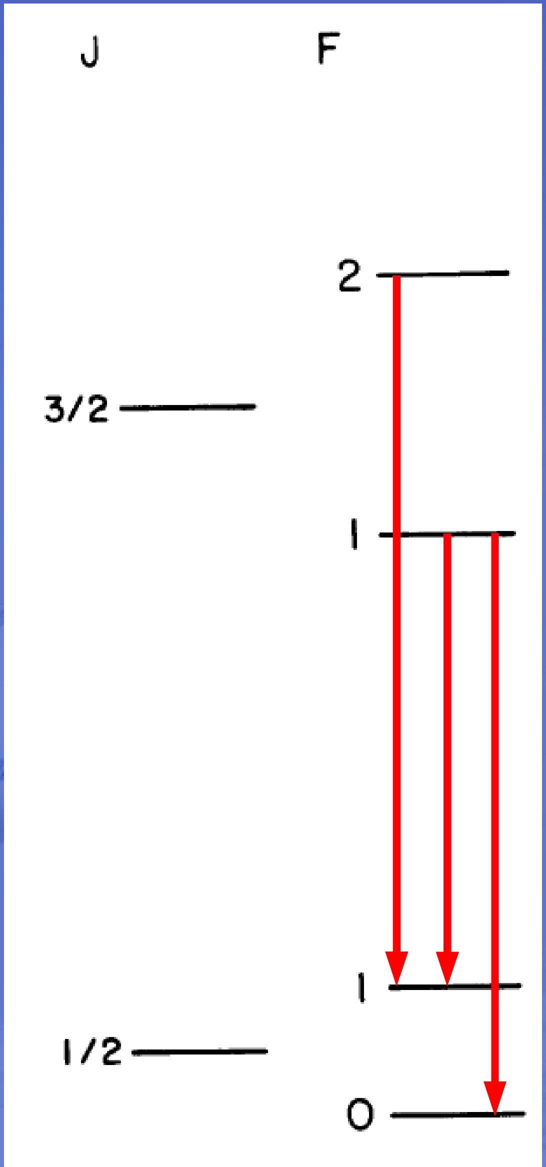
CII fine structure lines at 1.9 THz

CONSTANTS FOR C II DETERMINED BY LMR

Constant	Value
$E(^{12}C^{+\,2}P_{3/2} \leftarrow {}^2P_{1/2})$ ...	1900.5369(13) GHz
$E(^{13}C^{+\,2}P_{3/2} \leftarrow {}^2P_{1/2})$ ...	1900.5458(21) GHz
$g_{J=1/2}$	0.66576(11)
$g_{J=3/2}$	1.33412(11)
$\frac{1}{4}(A_{1/2}-3A_{3/2})$	80.3(7) MHz

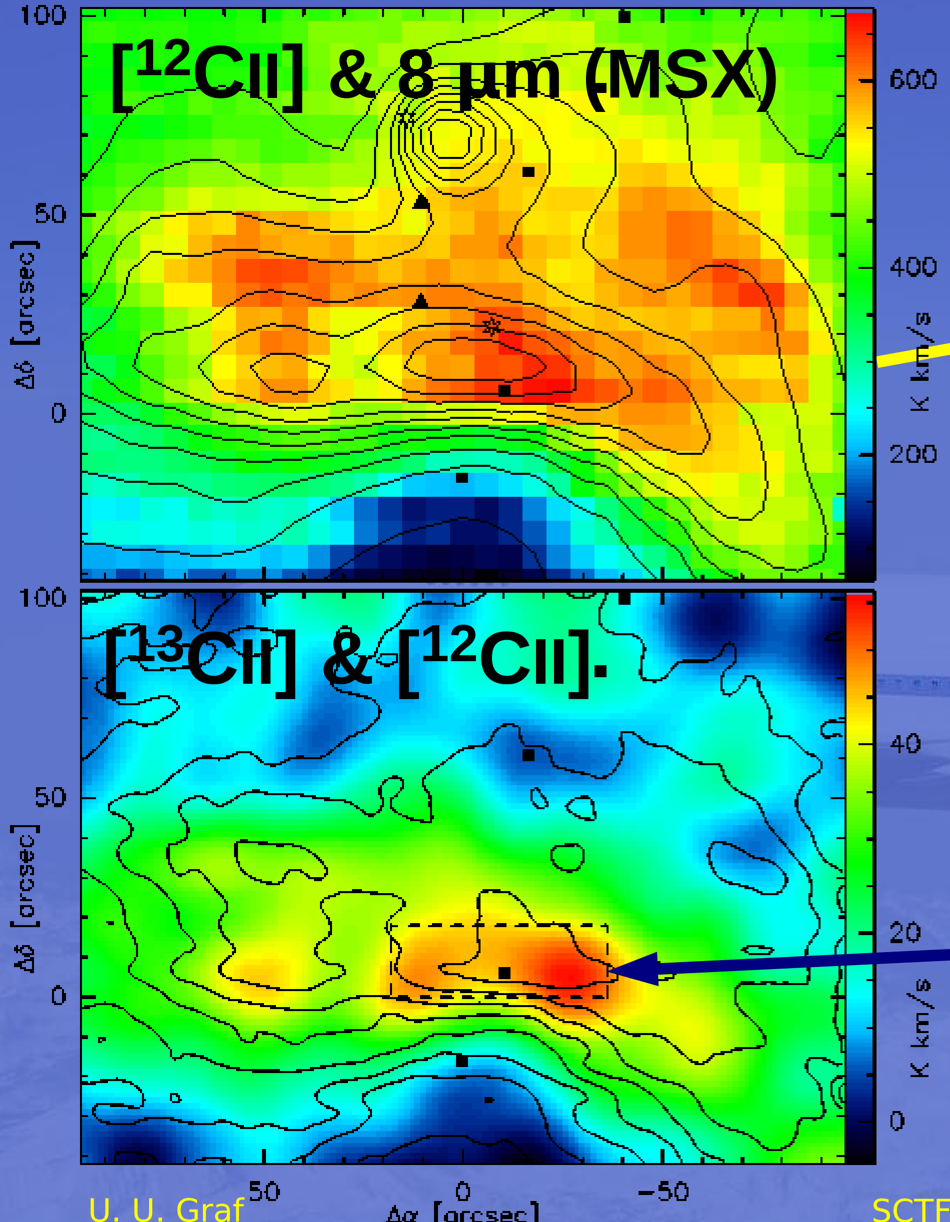
ESTIMATED ZERO-FIELD TRANSITION FREQUENCIES FOR ^{13}C II

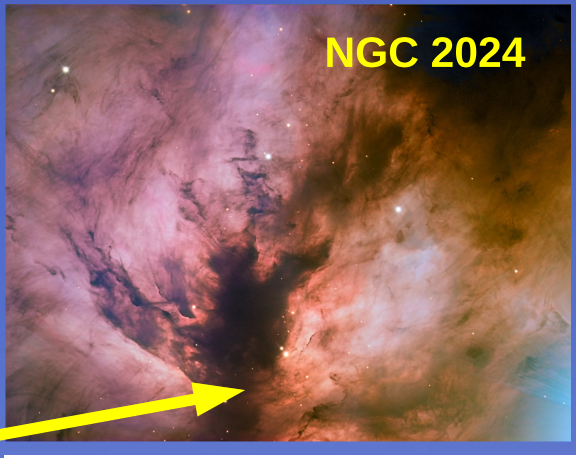
Transition $F' \leftarrow F''$	Frequency (GHz)	Relative Intensity	$\Delta(^{13}$C II ^{12}C II) (km s^{-1})
$2 \leftarrow 1$	1900.4661(23)[a]	44.4%	−11.2
$1 \leftarrow 1$	1900.136(10)[b]	20.0	−63.2
$1 \leftarrow 0$	1900.950(15)[b]	35.6	65.2



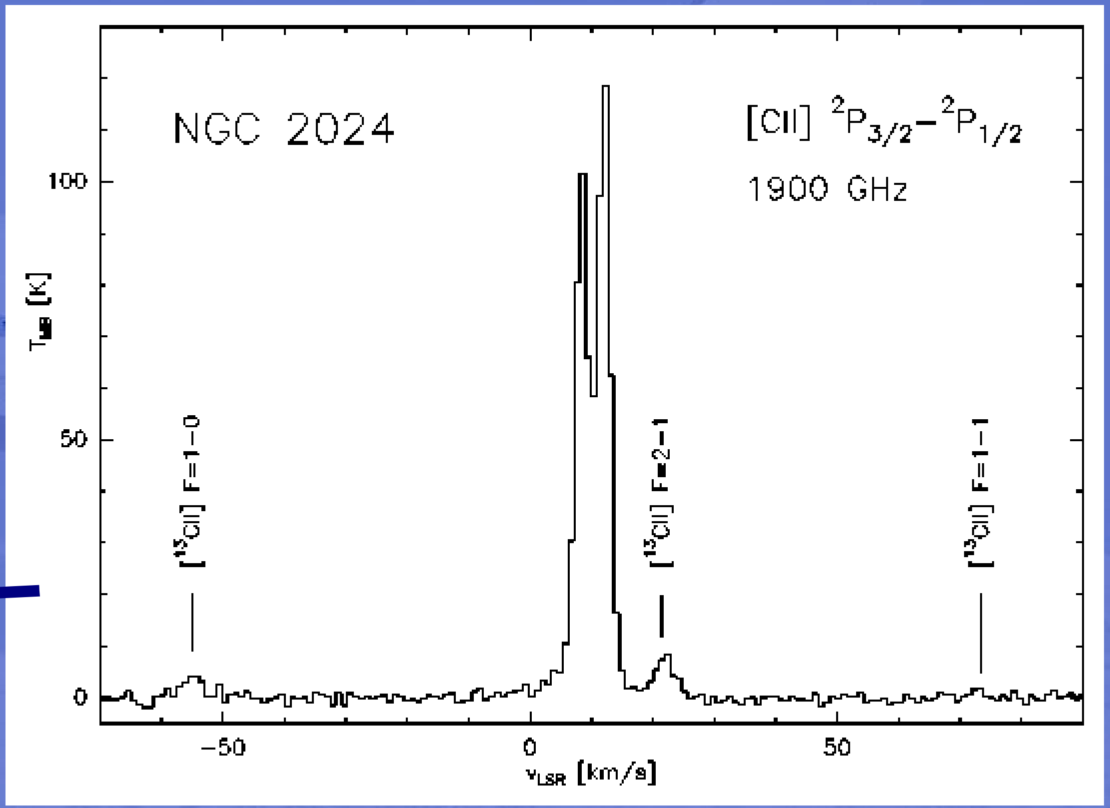
Cooksy, Blake, Saykally 1986

Strong [12CII] & [13CII] emission

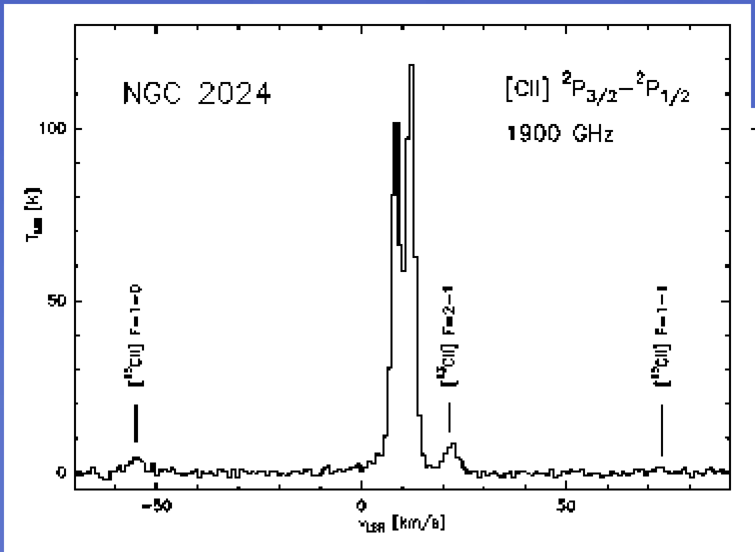


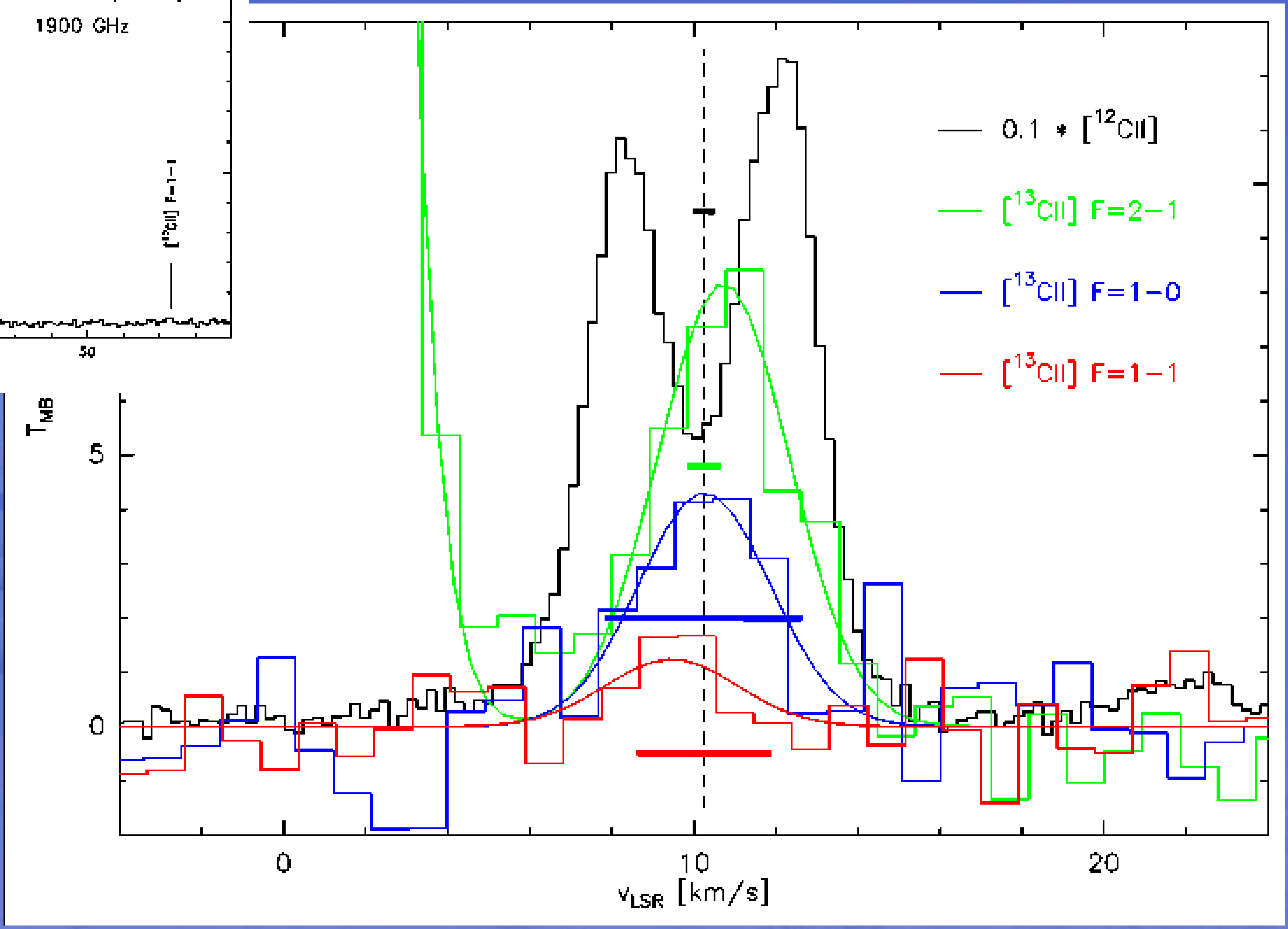


All three [13CII] HFS satellites detected



[^{13}CII] reveals self-absorption!





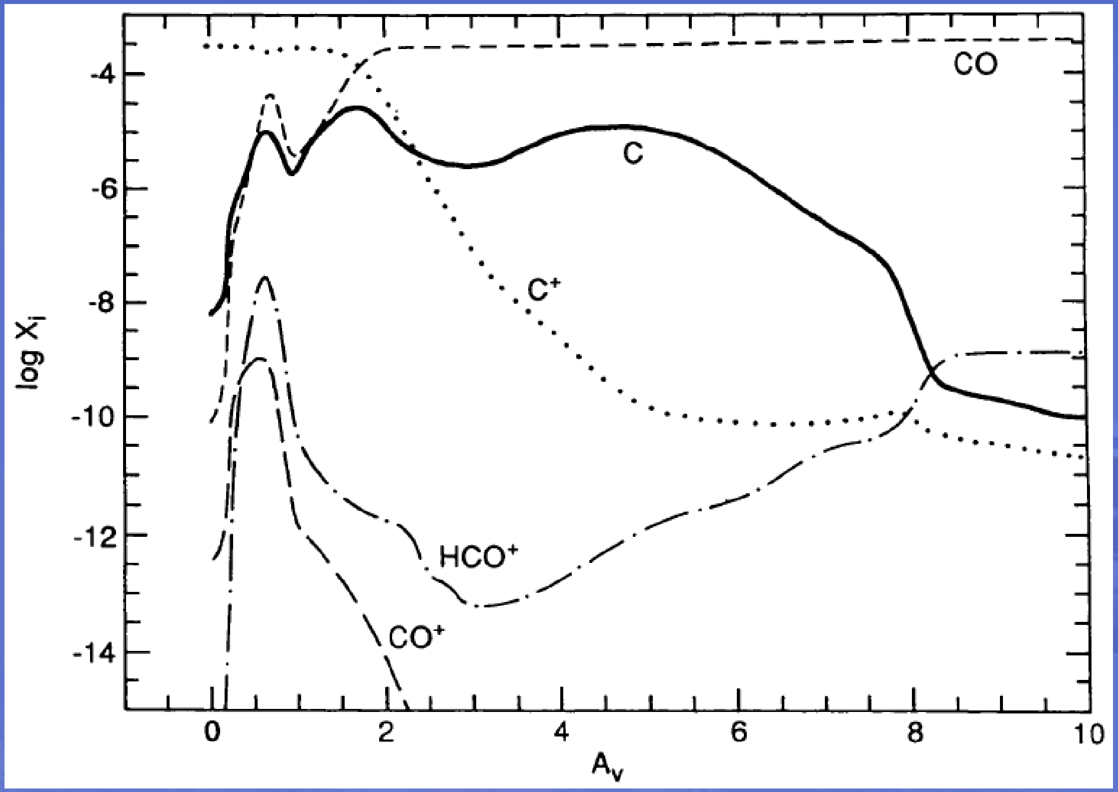
Data replotted on common v_{LSR} scale

[^{12}CII] line divided by 10

Physical Properties

- [^{13}CII] emission requires column density of
  $N(^{13}C^+) \approx 2.6 \times 10^{17}\ cm^{-2} \rightarrow N(H) \approx 1.6 \times 10^{23}\ cm^{-2}$
  This is as high as the molecular column density!
- Temperature of background component not well constrained due to foreground absorption, but needs to be >165 K, probably several 100 K
  Optically thin limit: 800 K
- Temperature of absorbing foreground: $T_{FG} < 90$ K
- Column density of absorbing foreground:
  $N_{FG}(C^+)\ \ 10^{18}\ cm^{-2} \rightarrow N_{FG}(H) \approx 10^{22}\ cm^{-2}$

HII region / molecular cloud IF → Photon Dominated Region (PDR)



- C^+, C, CO layered within ~1-2 A_V ($N_{H_2} = 10^{21}\,cm^{-2}$)
- Many (10-100) IFs required for large column density of warm CO emission

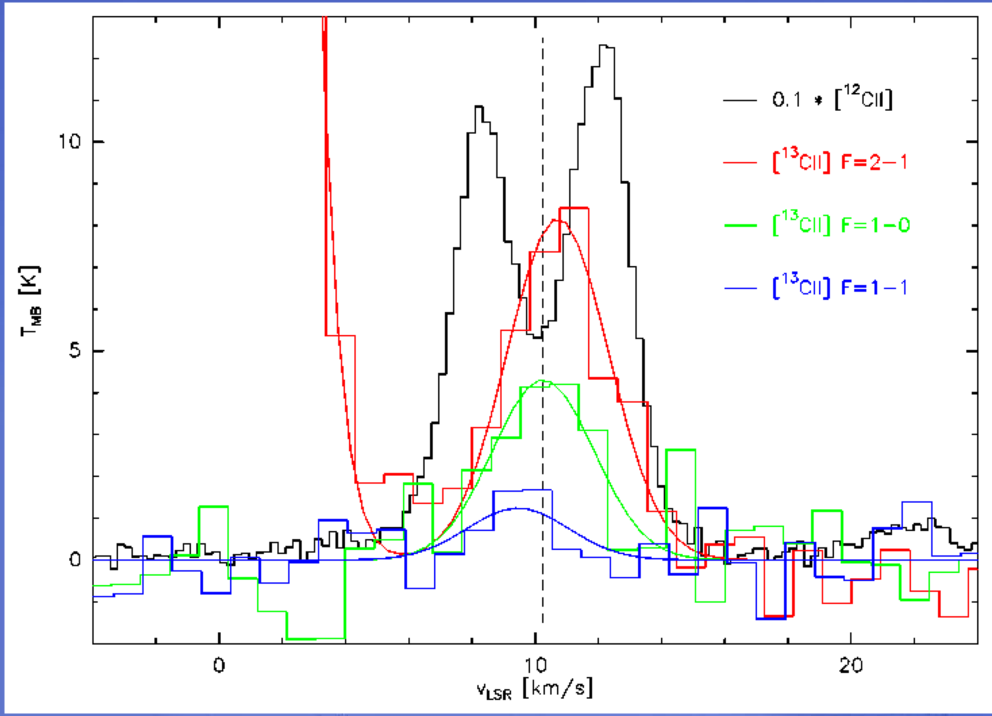
→ Clumpy interface

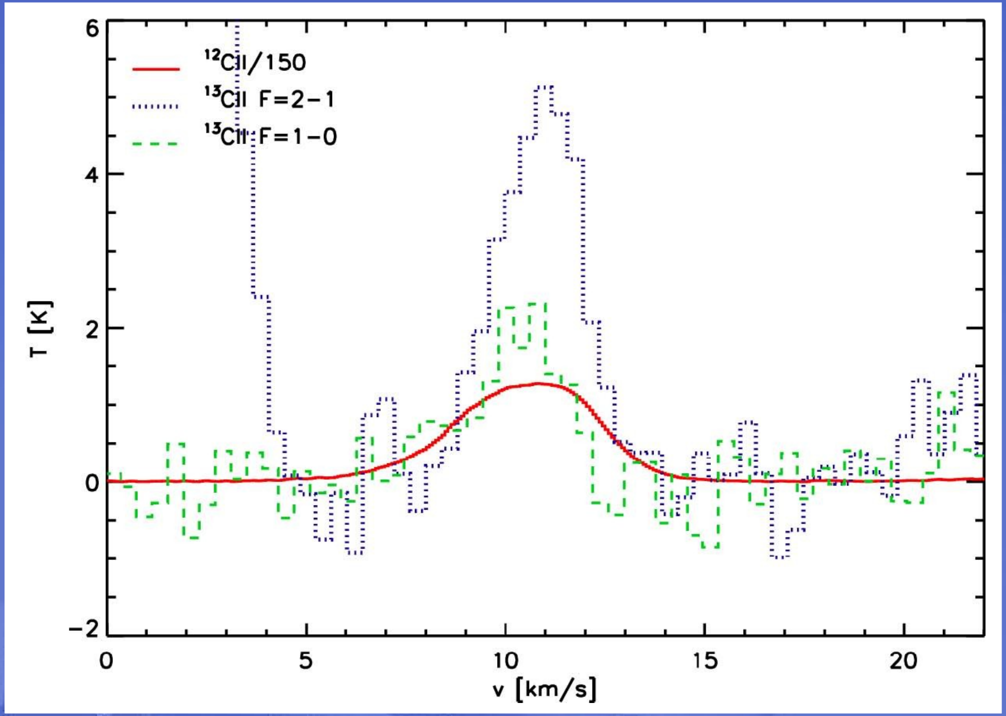
→ C^+, C, and warm CO spatially coexistent

PDR Modelling

- One PDR surface cannot produce the strong emission that we observe
- Edge-on geometry (ionization front) may help locally
- Clumpiness could make the difference. Preliminary estimates show that a clumpy cloud model can reproduce the observed intensities
- Need more data for detailed modelling

Anomalous Hyperfine Ratio ?





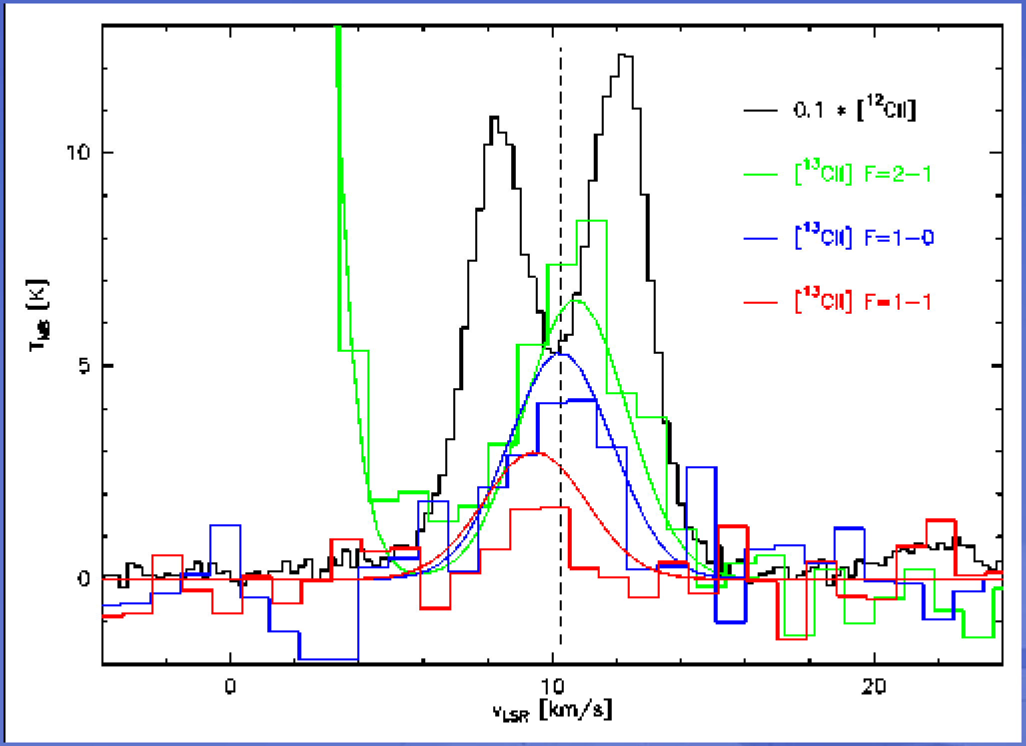
Orion Bar, Ossenkopf et al. 2011

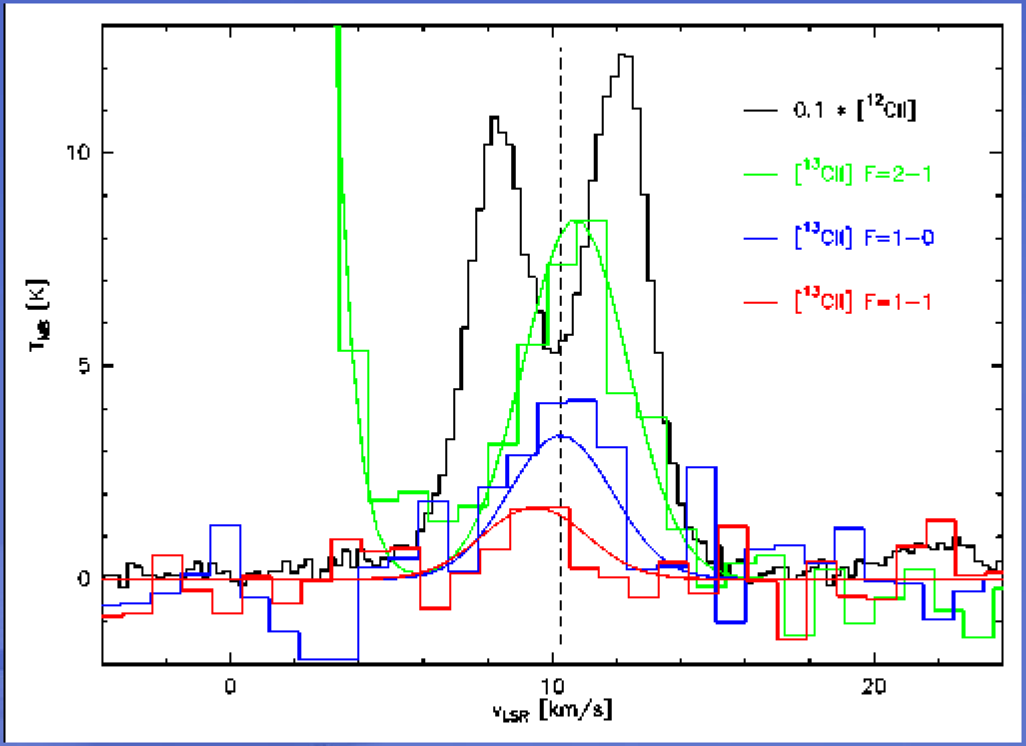
ESTIMATED ZERO-FIELD TRANSITION FREQUENCIES FOR ^{13}C II

Transition $F' \leftarrow F''$	Frequency (GHz)	Relative Intensity		
2 ← 1	1900.4661(23)[a]	44.4%	62.5 %	59.9%
1 ← 1	1900.136(10)[b]	20.0	12.5 %	8.8%
1 ← 0	1900.950(15)[b]	35.6	25.0 %	31.4%

- **2-1/1-0 ratio should be 1.25**
- **measured ratio is ~2**
- **D. Neufeld: Corrected HFS weights yield ratio of 2.5**

Simultaneous Fit with Fixed Hyperfine Ratios





Original HF ratios **Recalculated HF ratios**

Fit is believable now !

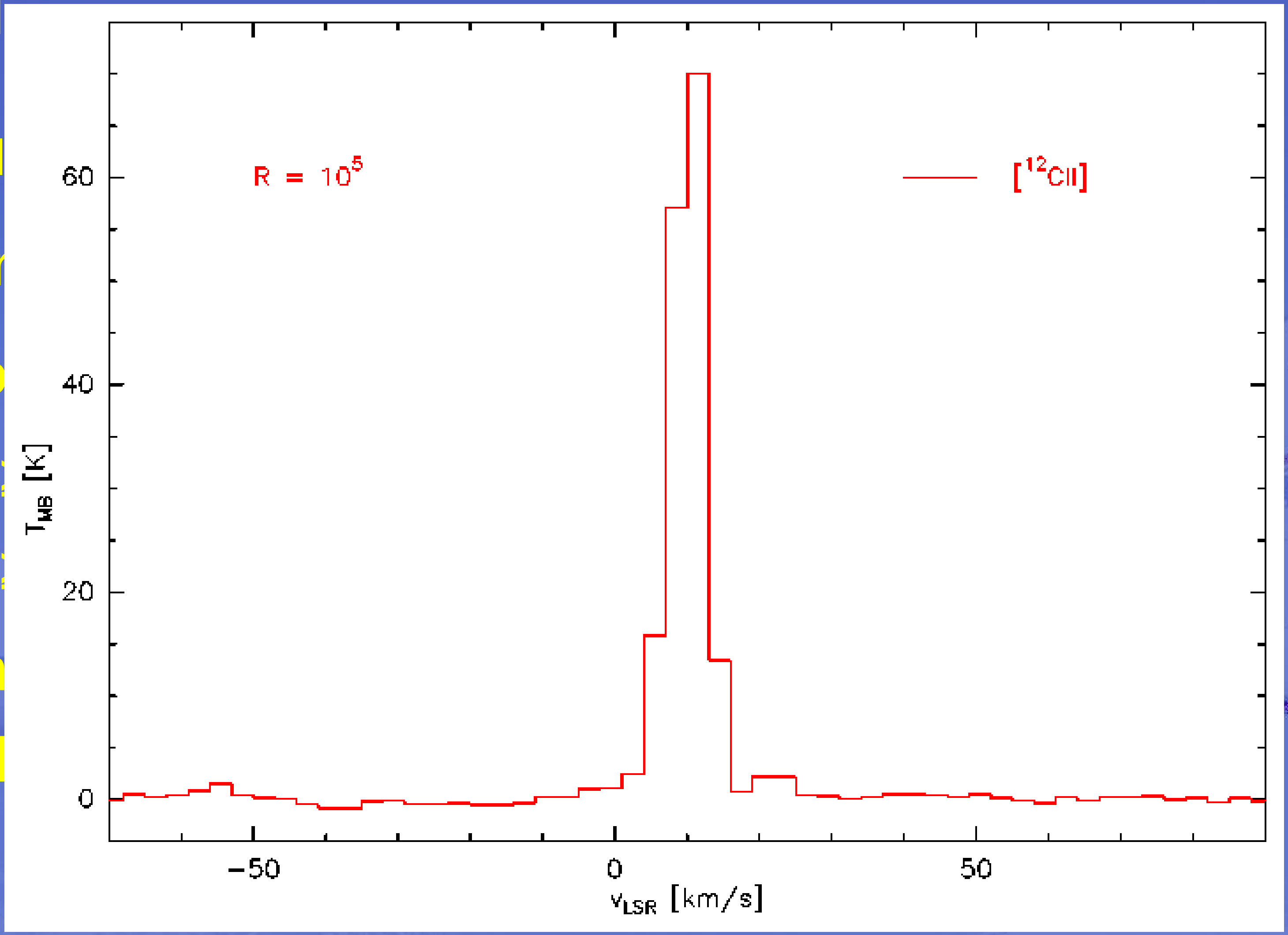
Conclusion

- [CII] is self-absorbed
- Kinematic signature differs from CO isotopes
- Column densities are very high:
  - $\geq 10^{23}$ cm^{-2} @ several 100 K in background
  - $\geq 10^{22}$ cm^{-2} @ $<$100 K in absorbing foreground
- Anomalous hyperfine intensity ratio probably explained by error in original paper

High spectral resolution is crucial!

Conclusion

- [CI
- Kir
- Co
  - –
  - –
- An
exp



High spectral resolution is crucial!

Thank You