The radio view of diffuse molecular gas

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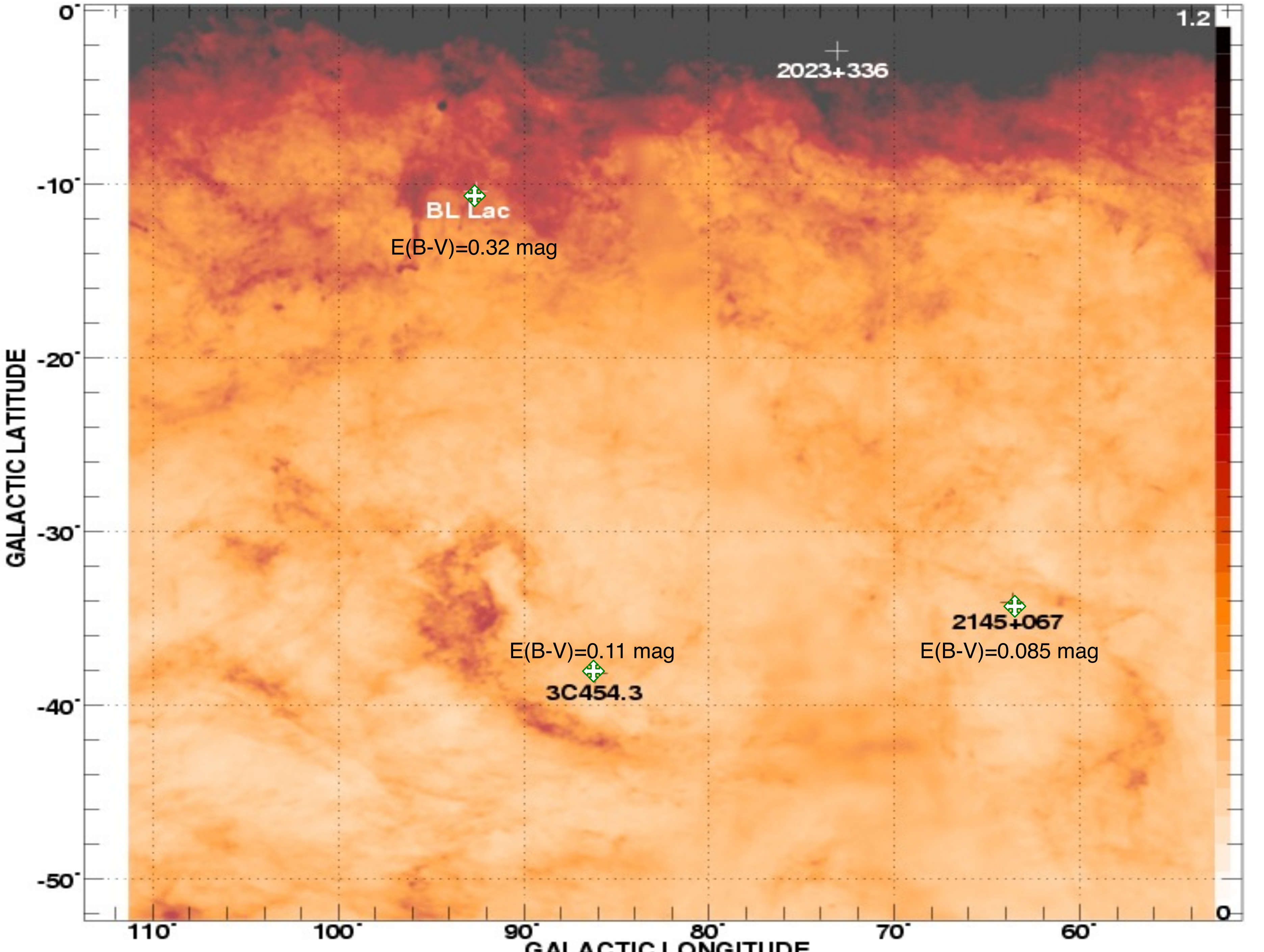
https://www.cv.nrao.edu/~hliszt/BordeauxPCMI2024/

Rough outline

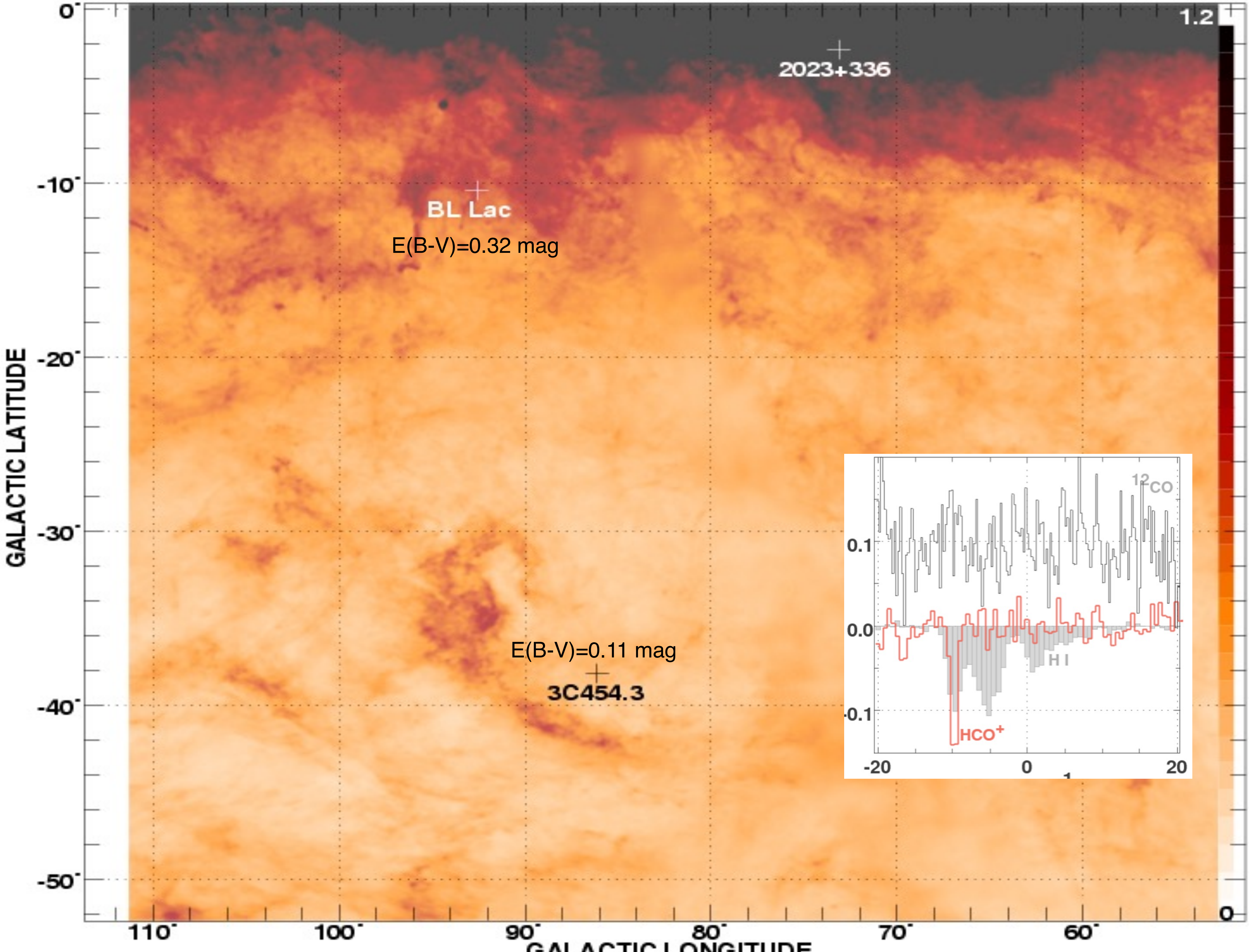
- Molecules – complex ones – in diffuse clouds
- Using HCO^+ to trace H_2 and explain DNM
- Complexity on diffuse cloud sightlines
  - Excitation, physical conditions and a confusion of chemistry and excitation

Timeline of Molecules in Diffuse Clouds

	30's-60's	70's	80's	90's	00's	10's	20's
UV		H_2, HD, OH, CO			N_2		
Optical	CH, CH^+, CN	C_2		NH	C_3	OH^+	
IR				CO, H_3^+	CH_3, C_2H_2	HF, C_{60}^+	
radio		OH, CO CH	*c*-C_3H_2	HCO^+, H_2CO CN, HCN, HNC C_2H, l-C_3H_2 CS, SO, H_2S, HCS^+ SiO NH_3	HOC^+	HCO CH_3CN *c*-C_3H, *l*-C_3H, C_3H^+ CF^+	H_2CCO HC_3N (not HNCO) C_4H, CH_3CHO (not CH_3OH) C_2S (not C_2N, C_2O)
Submm				H_2O HF	HCl	CH, CH^+ OH^+, OH_2^+, OH_3^+ NH, NH_2,NH_3 SH, SH^+ ArH^+ H_2Cl^+, HCl^+	



2023+336
BL Lac
E(B-V)=0.32 mag
E(B-V)=0.11 mag
3C454.3
2145+067
E(B-V)=0.085 mag
1.2
0
GALACTIC LATITUDE
GALACTIC LONGITUDE
0°
-10°
-20°
-30°
-40°
-50°
110°
100°
90°
80°
70°
60°



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0°
-10°
-20°
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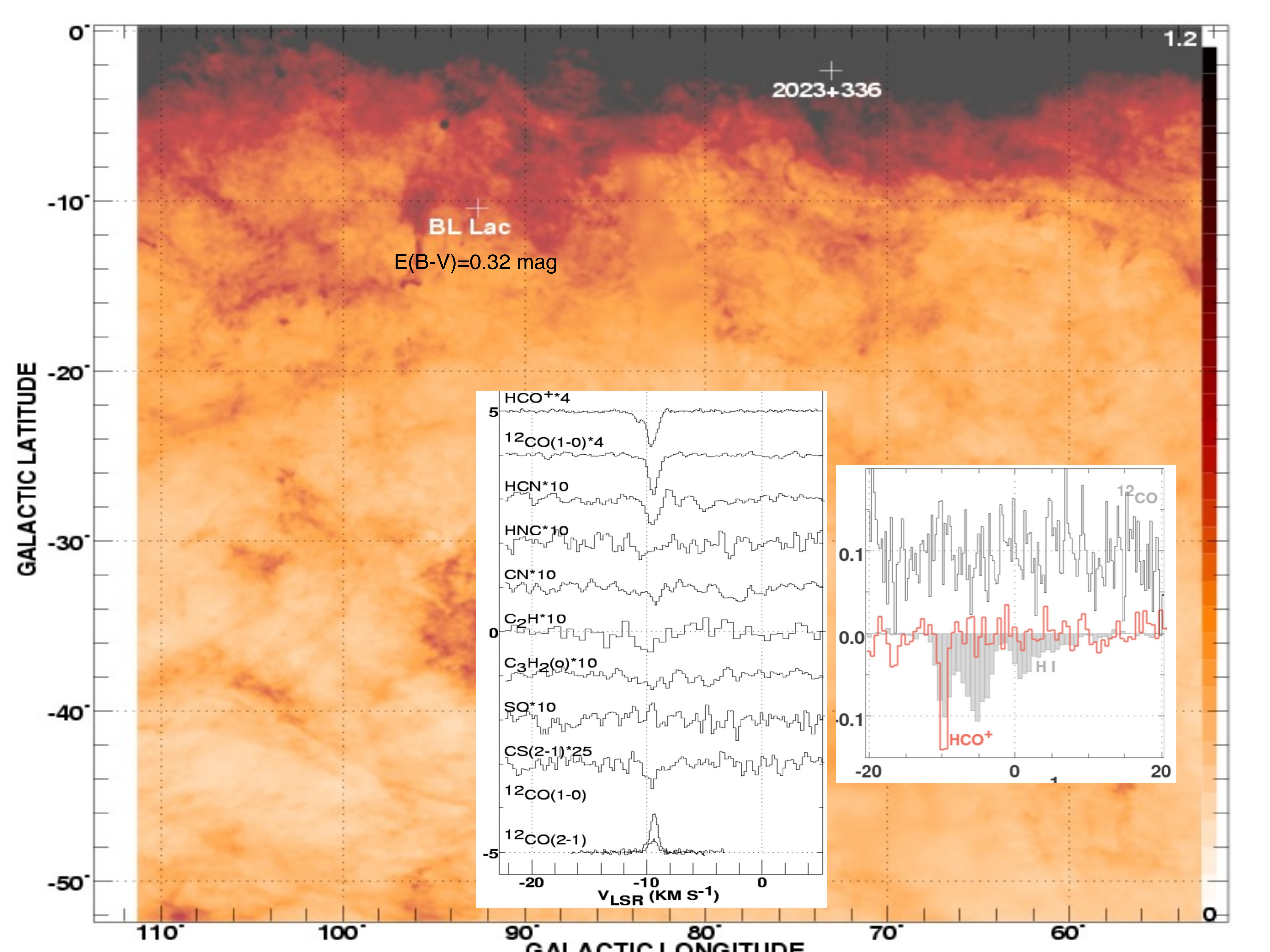
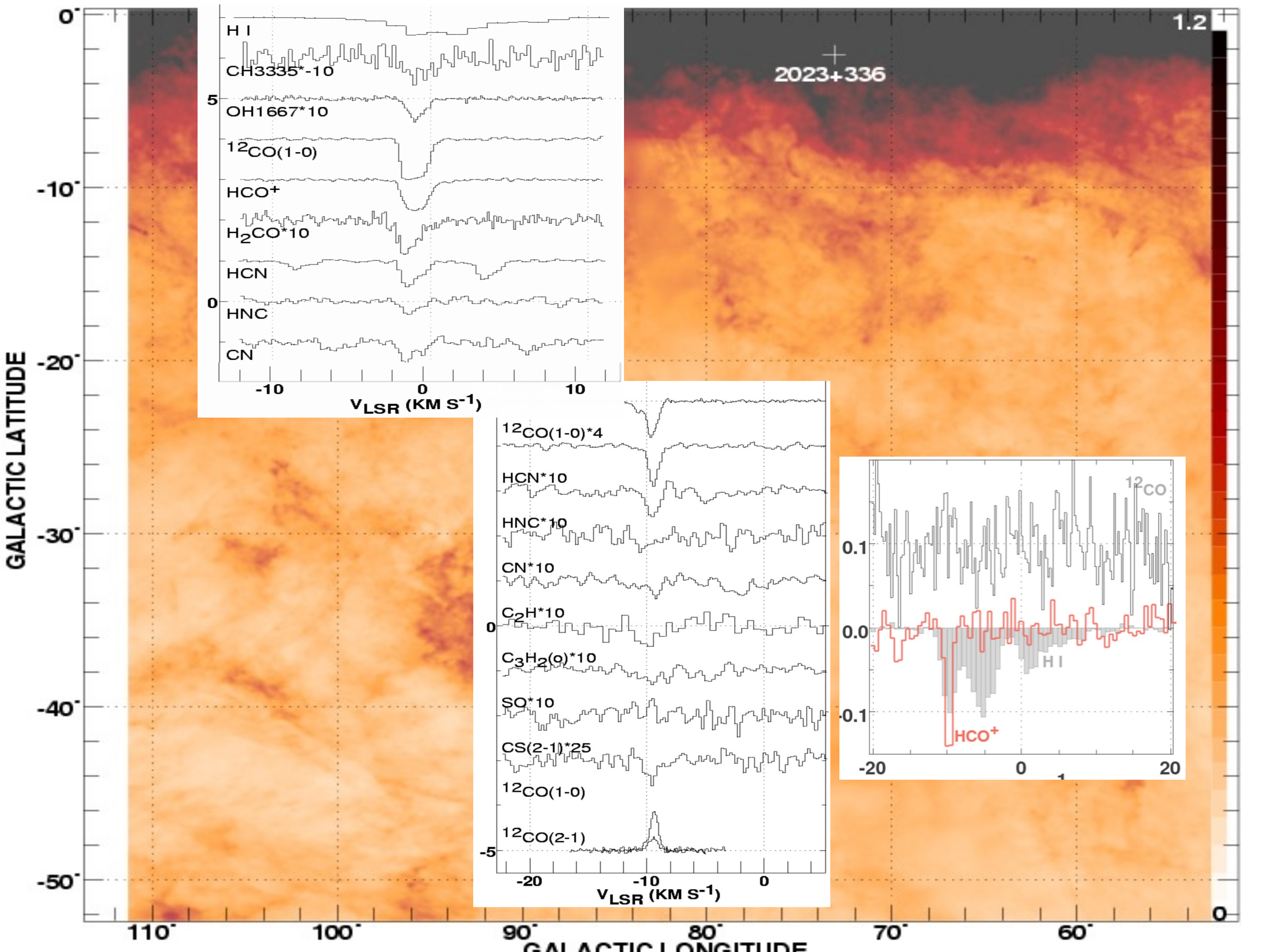
-40°
-50°
110°
100°
90°
80°
70°
60°
1.2
0
12CO
HCO+
H I
0.1
0.0
-0.1
-20
0
20



2023+336
BL Lac
E(B-V)=0.32 mag
GALACTIC LATITUDE
GALACTIC LONGITUDE
1.2
0
HCO+*4
12CO(1-0)*4
HCN*10
HNC*10
CN*10
C2H*10
C3H2(o)*10
SO*10
CS(2-1)*25
12CO(1-0)
12CO(2-1)
VLSR (KM S-1)
12CO
H I
HCO+



GALACTIC LATITUDE
GALACTIC LONGITUDE
0°
-10°
-20°
-30°
-40°
-50°
110°
100°
90°
80°
70°
60°
1.2
0
2023+336
H I
CH3335*-10
OH1667*10
12CO(1-0)
HCO+
H2CO*10
HCN
HNC
CN
VLSR (KM S-1)
12CO(1-0)*4
HCN*10
HNC*10
CN*10
C2H*10
C3H2(o)*10
SO*10
CS(2-1)*25
12CO(1-0)
12CO(2-1)
12CO
H I
HCO+

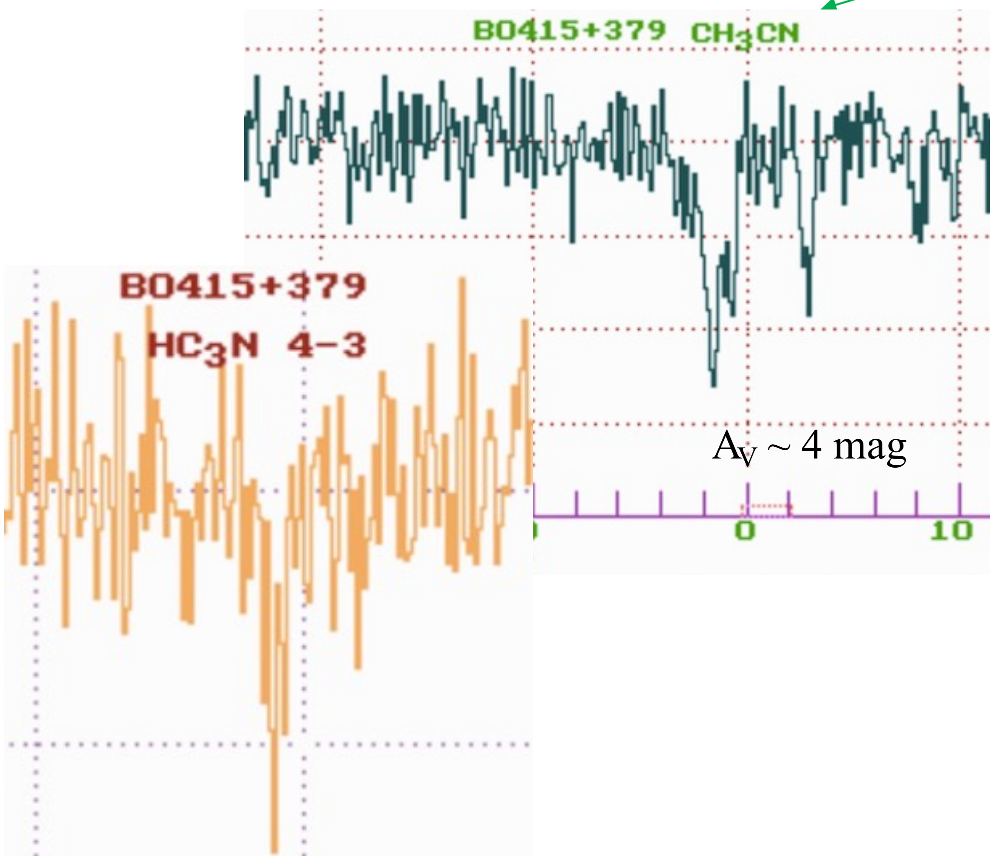
Lessons drawn

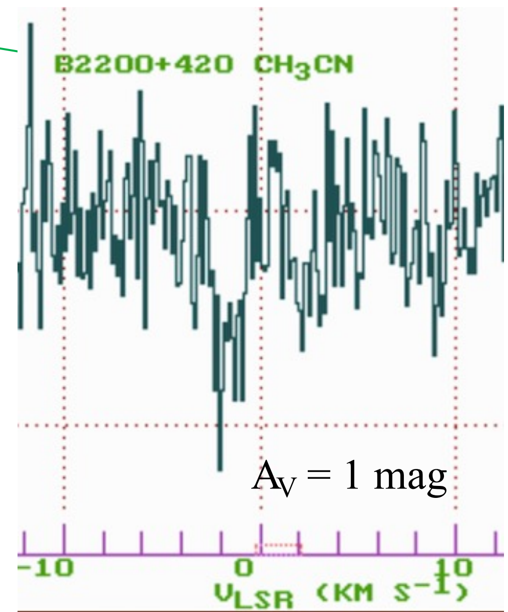
- Trace molecules seen when E(B-V) ~ 0.08, H_2 ~ 0.1 H
- Abundances are surprisingly similar to TMC-1
  - Hydrides, hydrocarbons, HCN/HNC/CN, CS/SO, H_2CO, NH_3
- Some surprisingly large molecules at A_V = 1 mag
- Diffuse conditions often prevail at A_V >> 1 mag
  - High extinction sightlines formed by superposition

Surprisingly complex species at A_V = 1 mag

Liszt, Gerin, Pety, Beasley 2018 ApJ, 856..151 36.8 GHz VLA

– H_2CO, NH_3, c-C_3H_2, CH_3CN

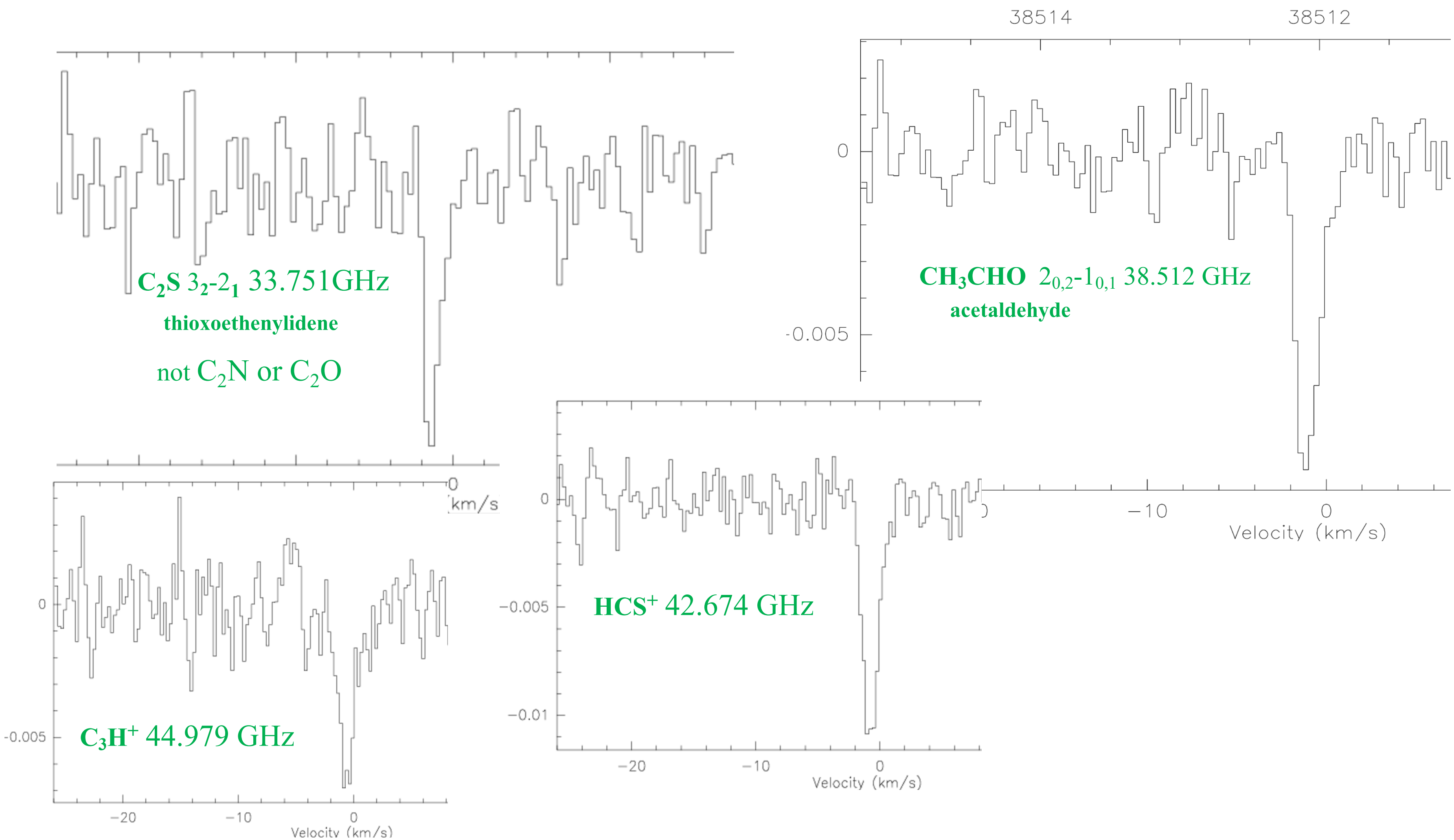




Cernicharo, Tercero, Gerin, Liszt 2024

Acetaldehyde and C_2S at A_V = 1 mag

- **Bl Lac flared to 10+ Jy during Q-band test sweep at RT40m!**



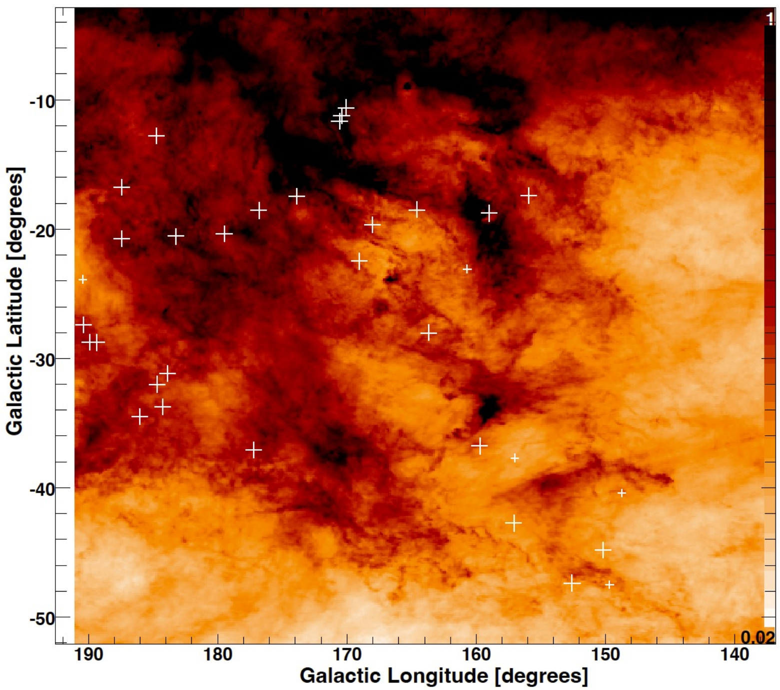
HCO^+ absorption has been most useful

- Chemically ubiquitous
- Easily observable with $\mu_D = 3.9$ Debye
- Traces H_2 with $HCO^+/H_2 = 3x10^{-9}$
- Explains CO via $HCO^+ + e \rightarrow CO + H$
- Detectable even when CO emission isn't
- A model of CO should explain HCO^+

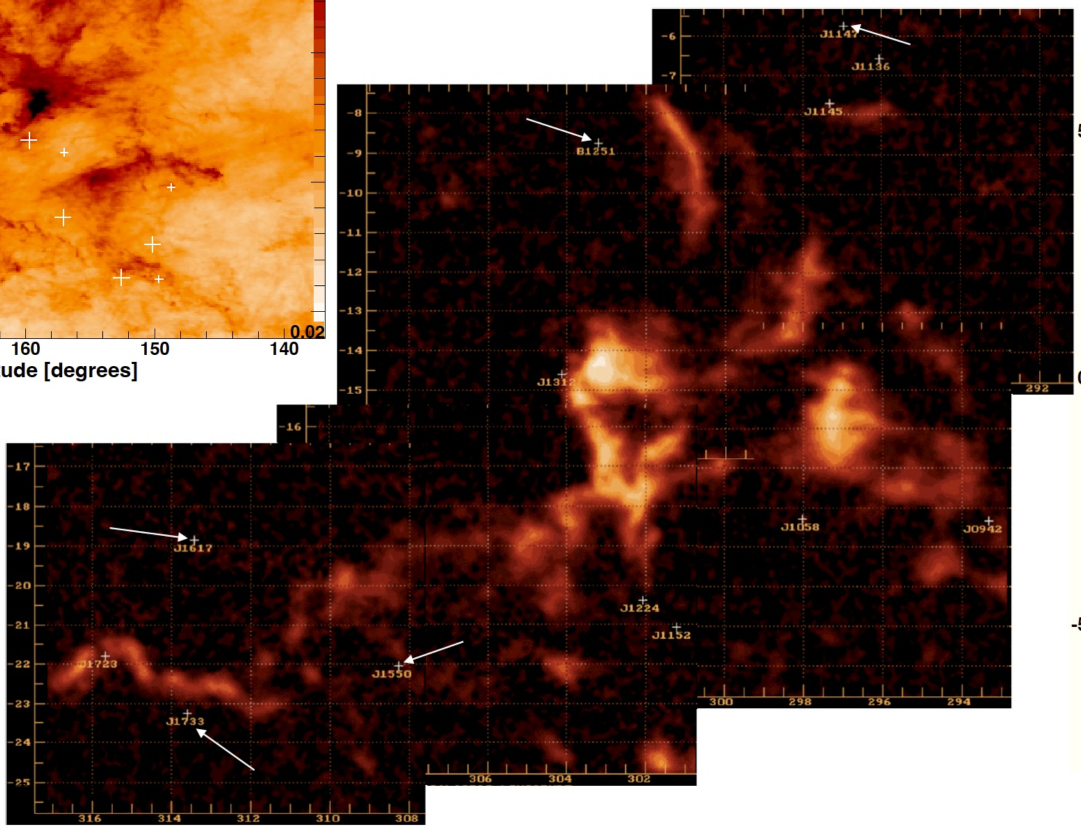
46 directions studied in HCO^+ absorption

Liszt, Gerin, Grenier A&A
2018, 617, 74; 2019, 627, 95; 2023, 675, 145

E(B-V) in the anticenter



W_{CO} in Chamaeleon



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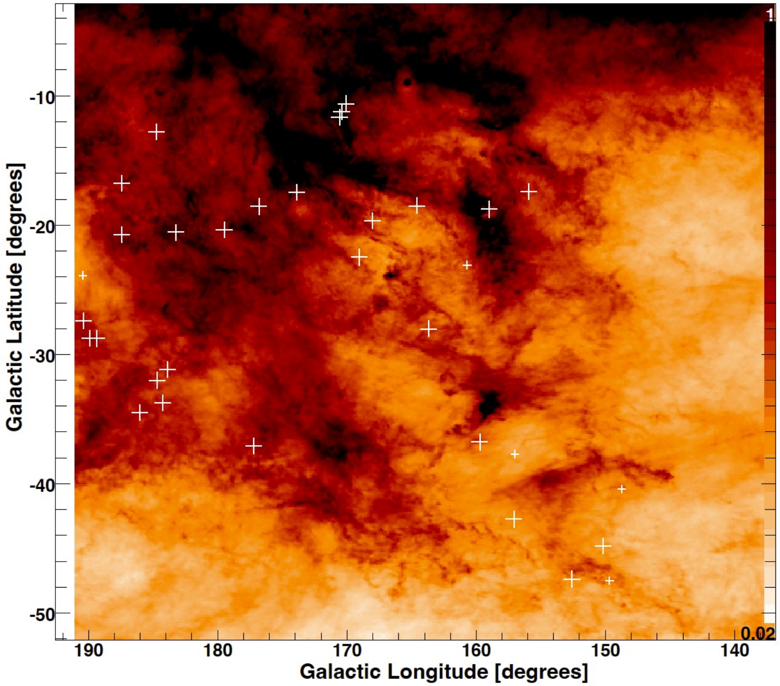

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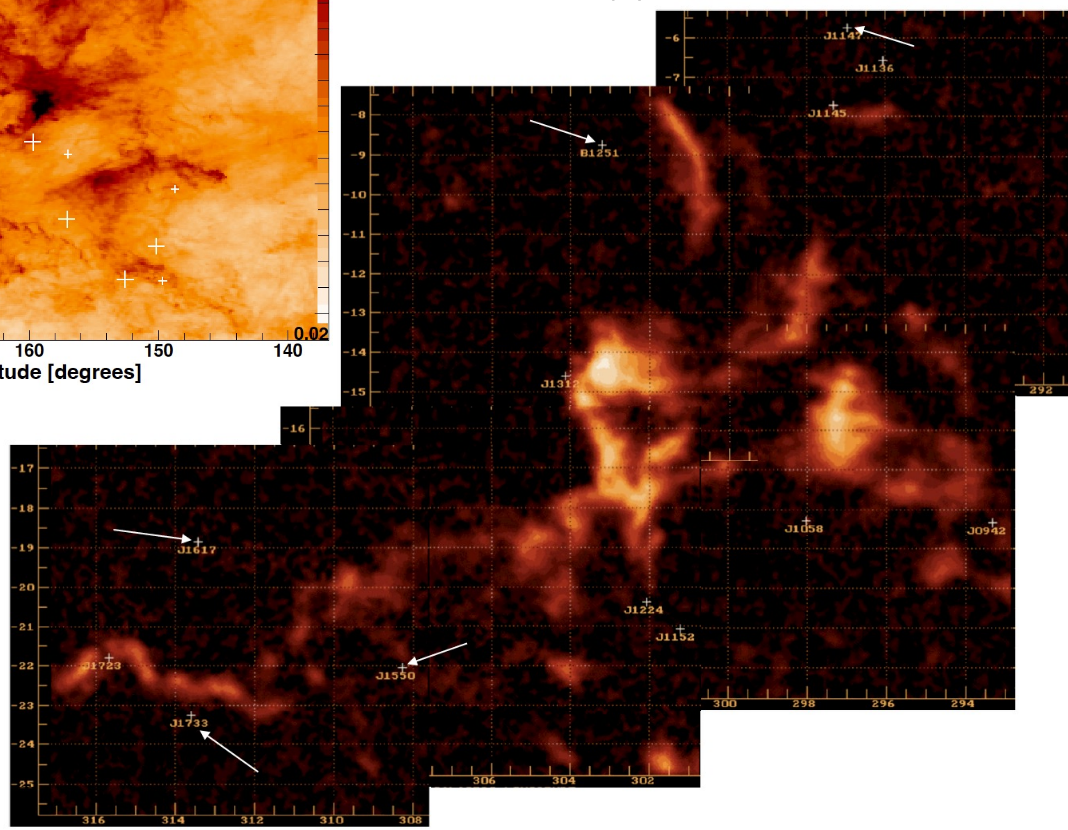

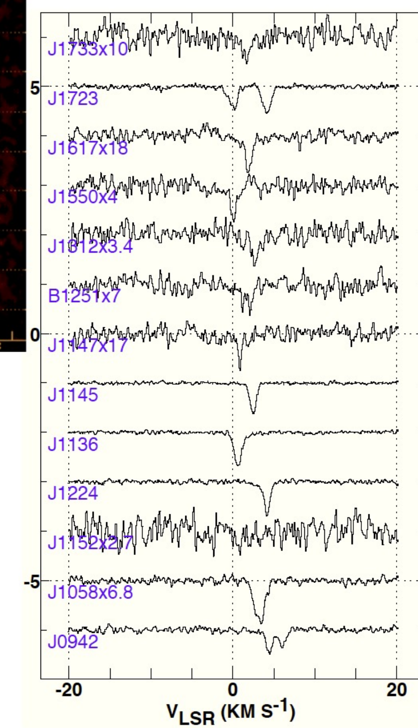

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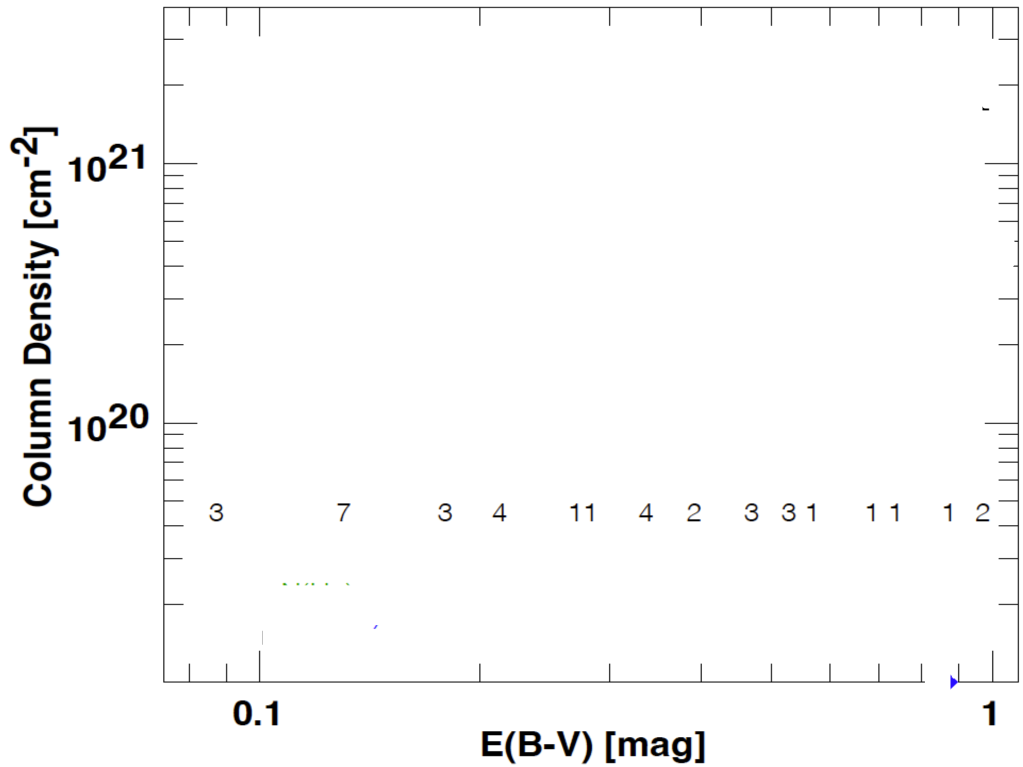
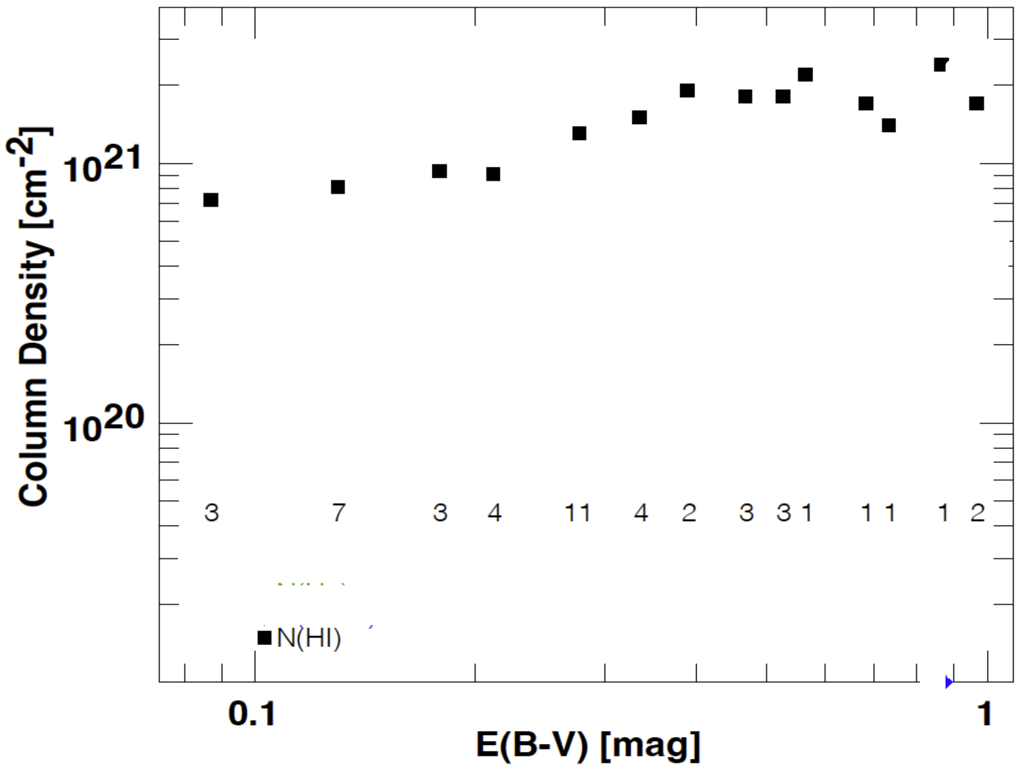
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption



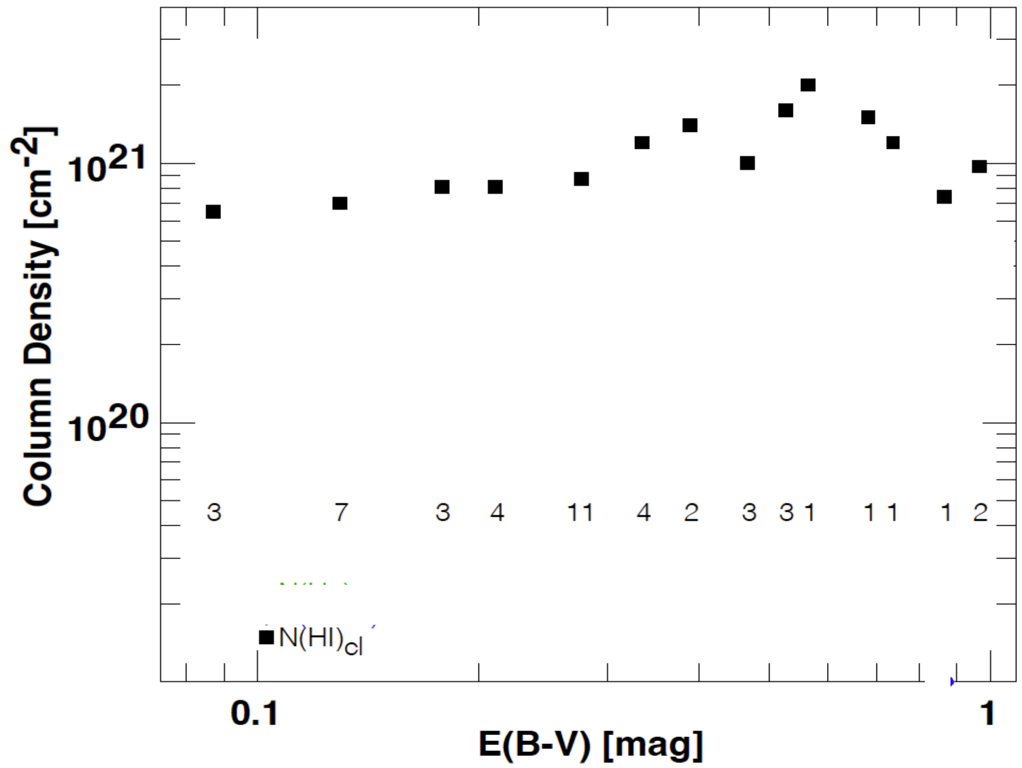
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

Total N(H I) varies much less than E(B-V)



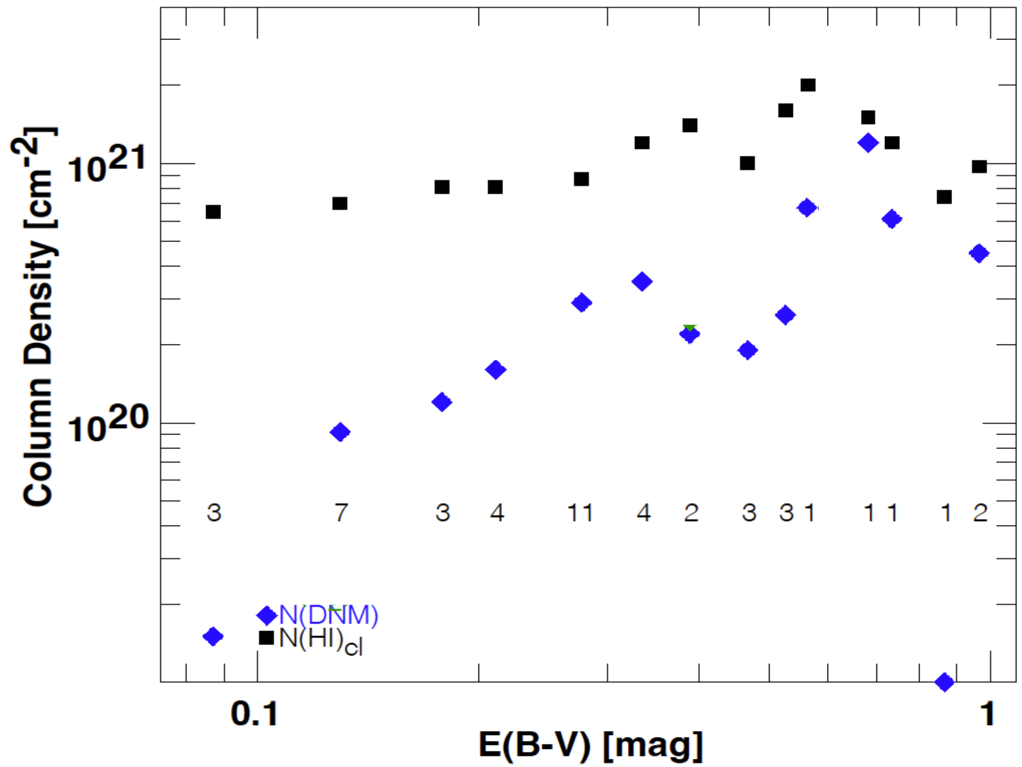
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

N(H I) directly associated with the clouds varies little, falls at high E(B-V)



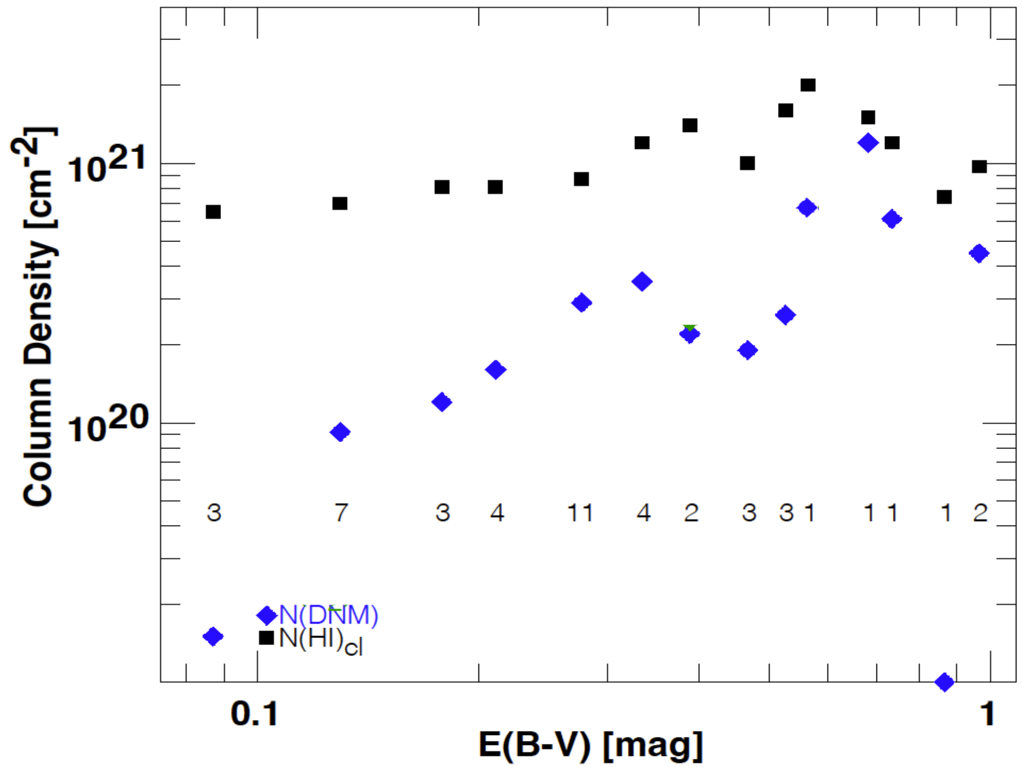
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

N(DNM)/N(H I) peaks at 0.5-1.0



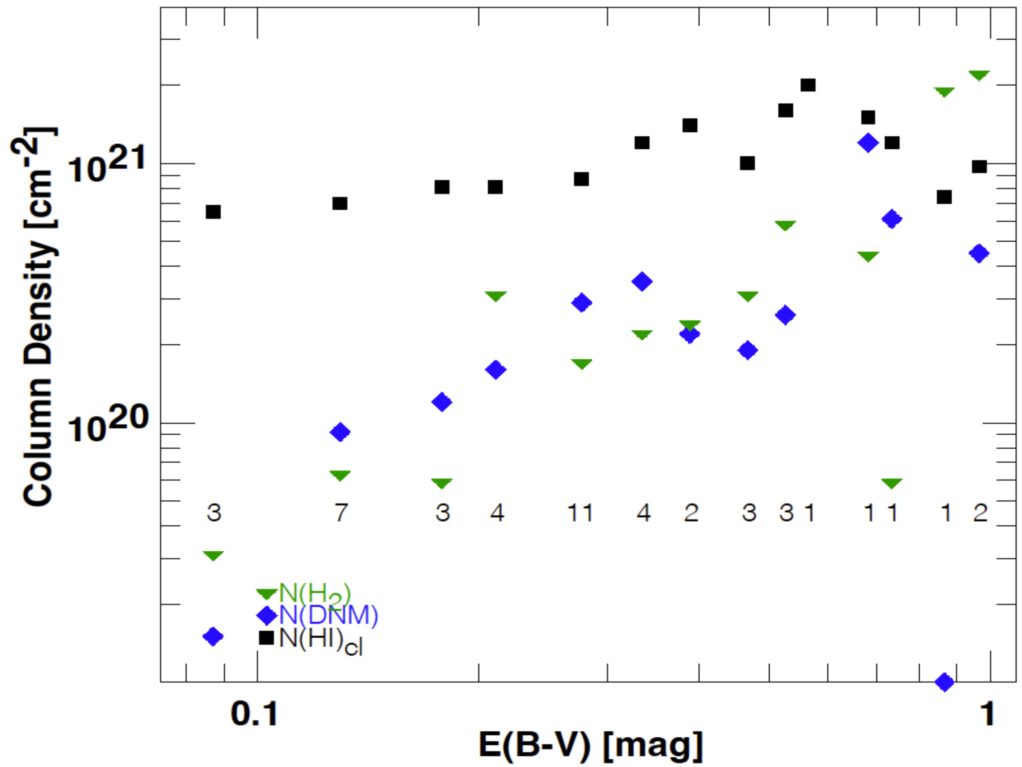
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

Decline of N(DNM) at high E(B-V) means CO did its job



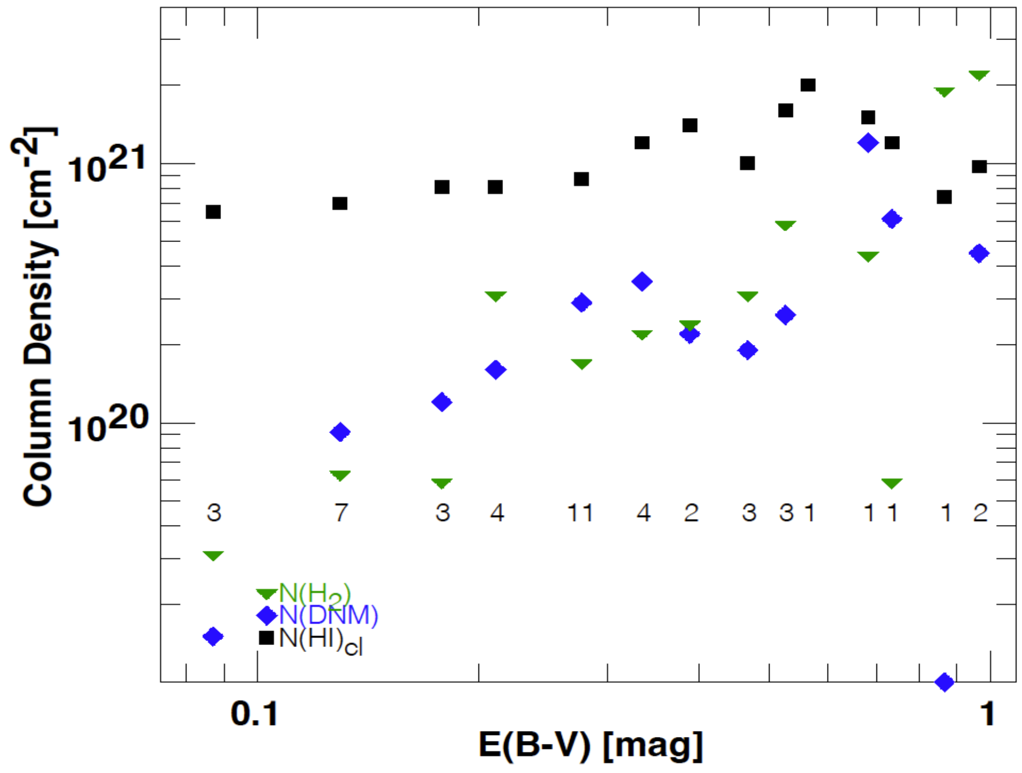
H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

N(H_2) mimics N(DNM) but doesn't fall



H I, DNM and H_2 in 46 directions studied in HCO^+ absorption

The medium was mostly atomic but the DNM was molecular



Excitation in diffuse clouds

Emission from polar species HCO^+, HCN is ubiquitous at ~1% CO, a sign of diffuse gas

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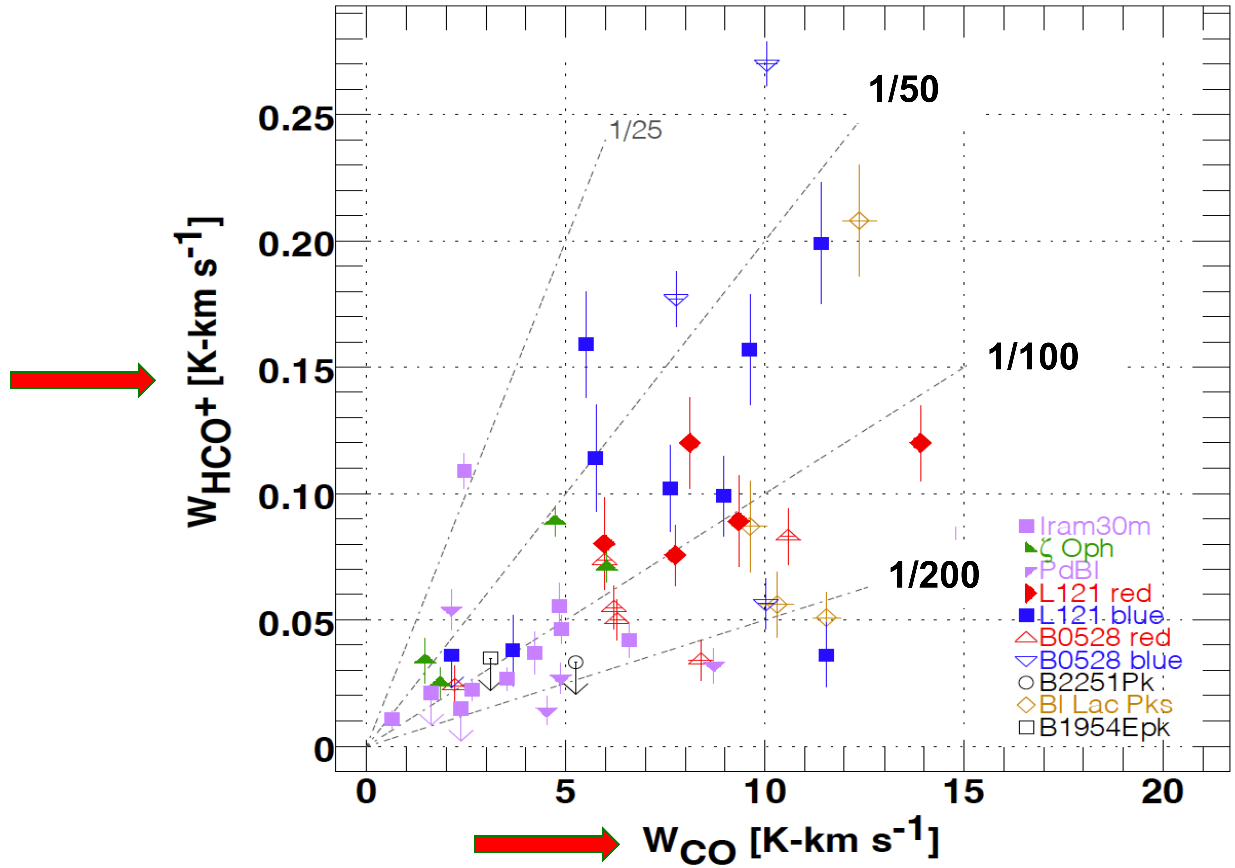
Emission from polar species HCO^+, HCN is ubiquitous at ~1% CO, a sign of diffuse gas



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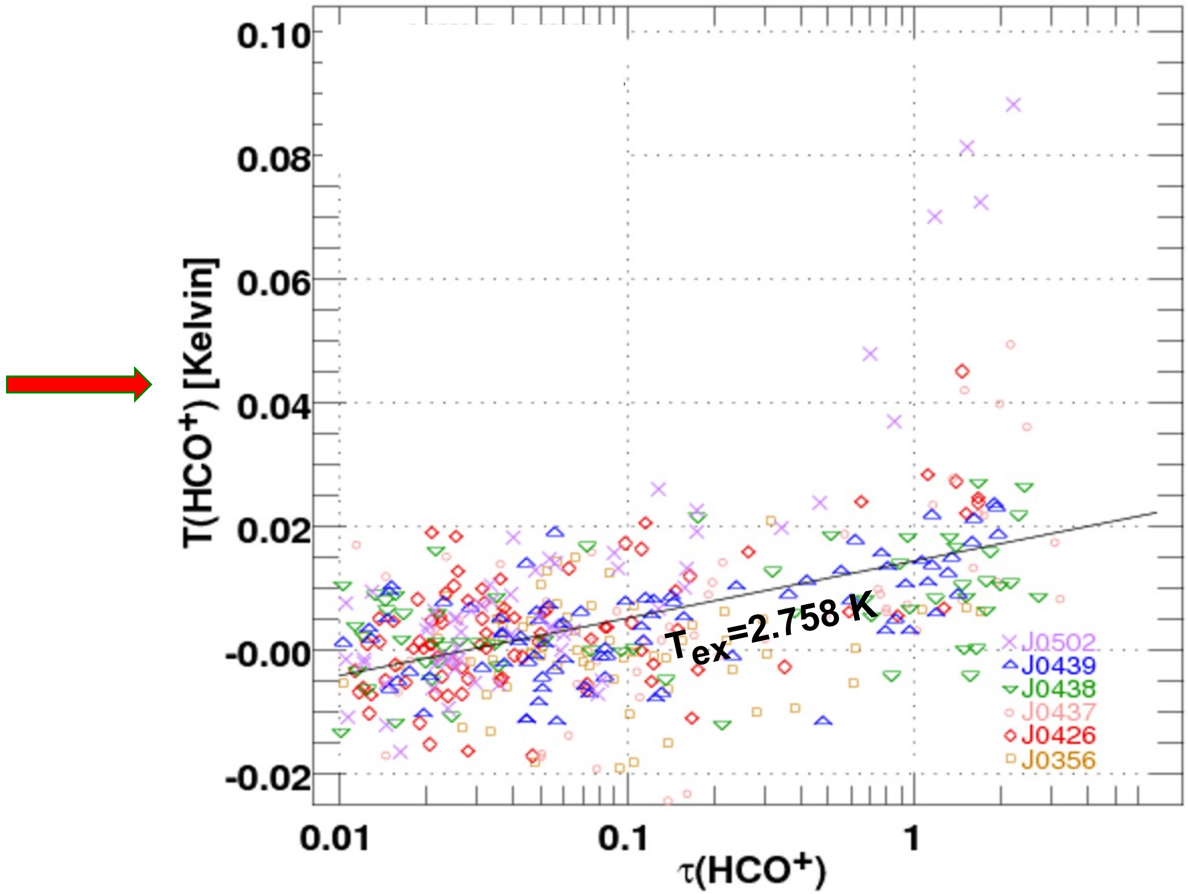
Physical conditions in diffuse clouds

Weak excitation, mostly from e^-, hinders determination of ambient conditions



Physical conditions in diffuse clouds

Weak emission yields an emission measure

(Liszt & Pety 2016, ApJ, 823, 124)

$$\int T_B dv = (\lambda^2/8 \times 10^5\pi)(hc/k) \int n(\mathrm{H})\gamma_u n(\mathrm{Y})dL.$$

$$\gamma_u = 0.0875\gamma_u(\mathrm{He}) + x_e\gamma_u(e) + (f_{\mathrm{H_2}}/2)\gamma_u(\mathrm{H_2})$$

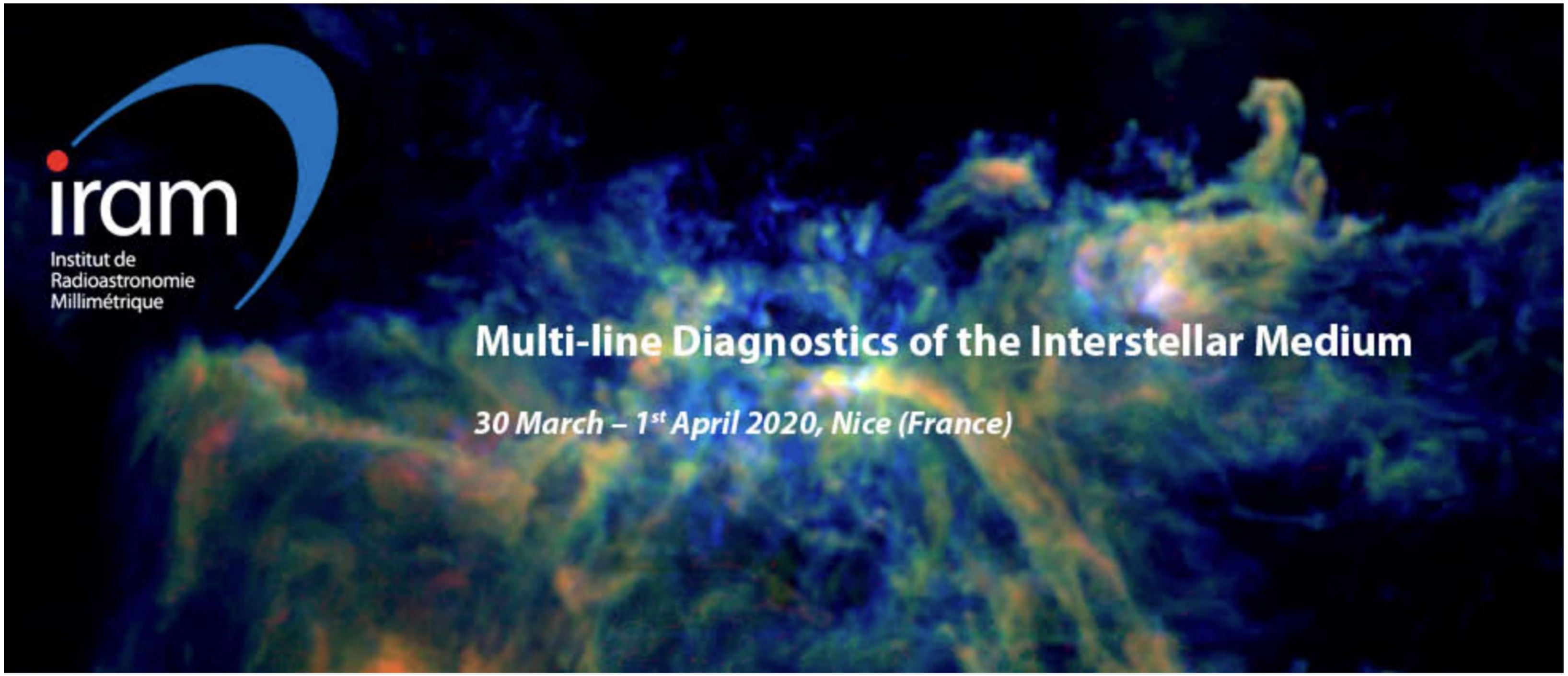
$$C_u = n(\mathrm{H})\gamma_u$$

$$C_u = \Sigma_{j<j_u}\Sigma_{j'\geqslant j_u} f_j C_{j,j'}/(1 + p_\nu(T_{\mathrm{cmb}}))$$

There is no critical density for detection, only a critical COLUMN DENSITY

A multi-line multi-species approach to n(H), x_e and more

Gerin, Liszt, Pety, Faure 2024, A&A, 686, 49



A multi-line multi-species approach to n(H), x_e and more

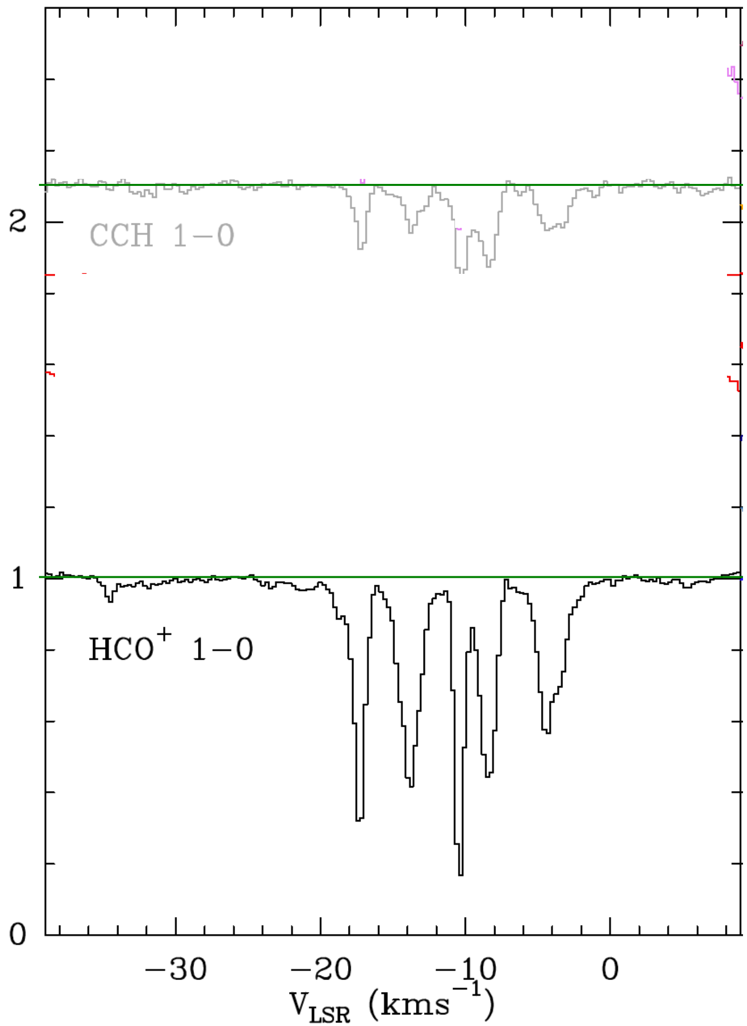
Gerin, Liszt, Pety, Faure 2024, A&A, 686, 49

B0355+508 NRAO 150 *l* = 150.4^o, *b* = -1.6^o

A sightline at low Galactic latitude with A_V ~ 4 mag dominated by 5 features with $N(HCO^+)$ ~ 10^{12} cm^{-2} ~ ½ BL Lac

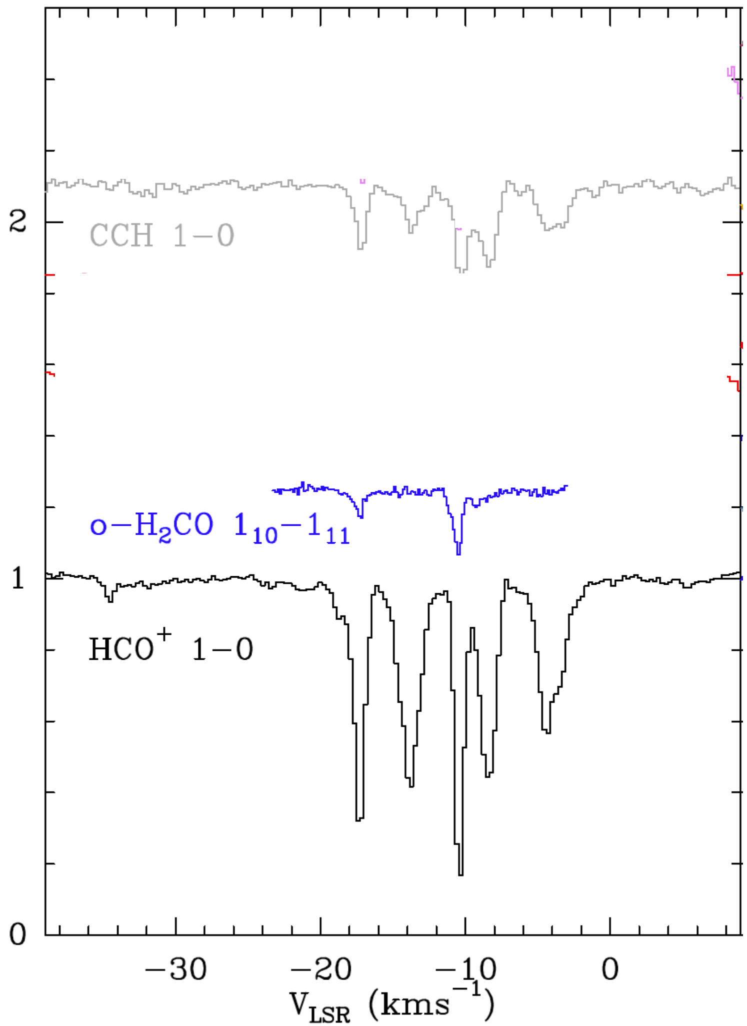
Five features with ~same HCO^+, C_2H

B0355+508 NRAO 150 l = 150.4°, b = -1.6°



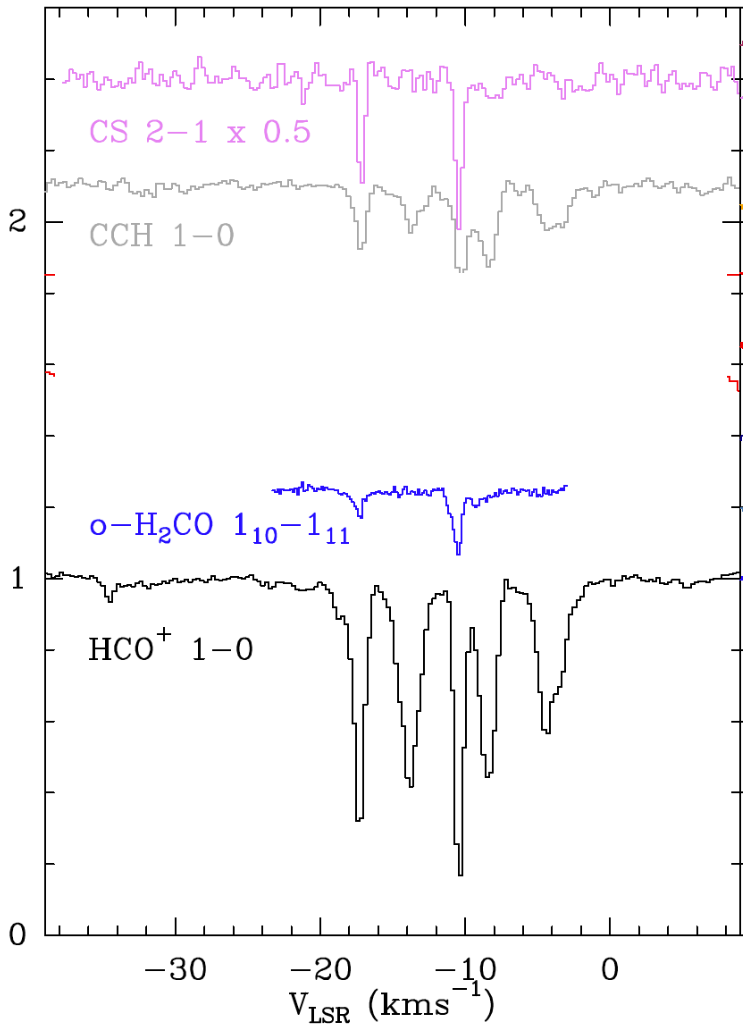
Two appear in λ6cm H_2CO

B0355+508 NRAO 150 $l = 150.4^o$, $b = -1.6^o$



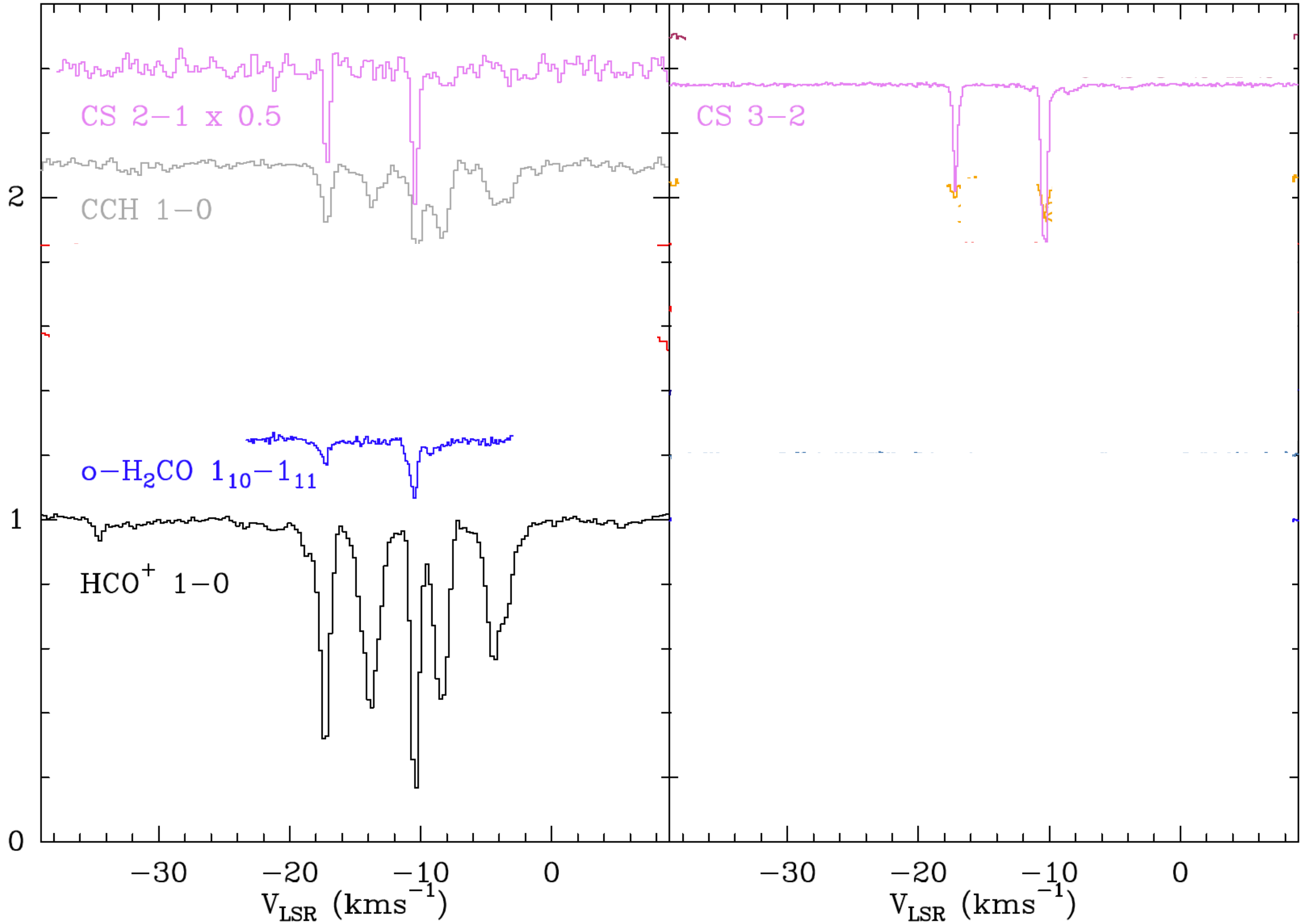
Two appear in λ6cm H_2CO & CS 2-1

B0355+508 NRAO 150 $l = 150.4^o$, $b = -1.6^o$



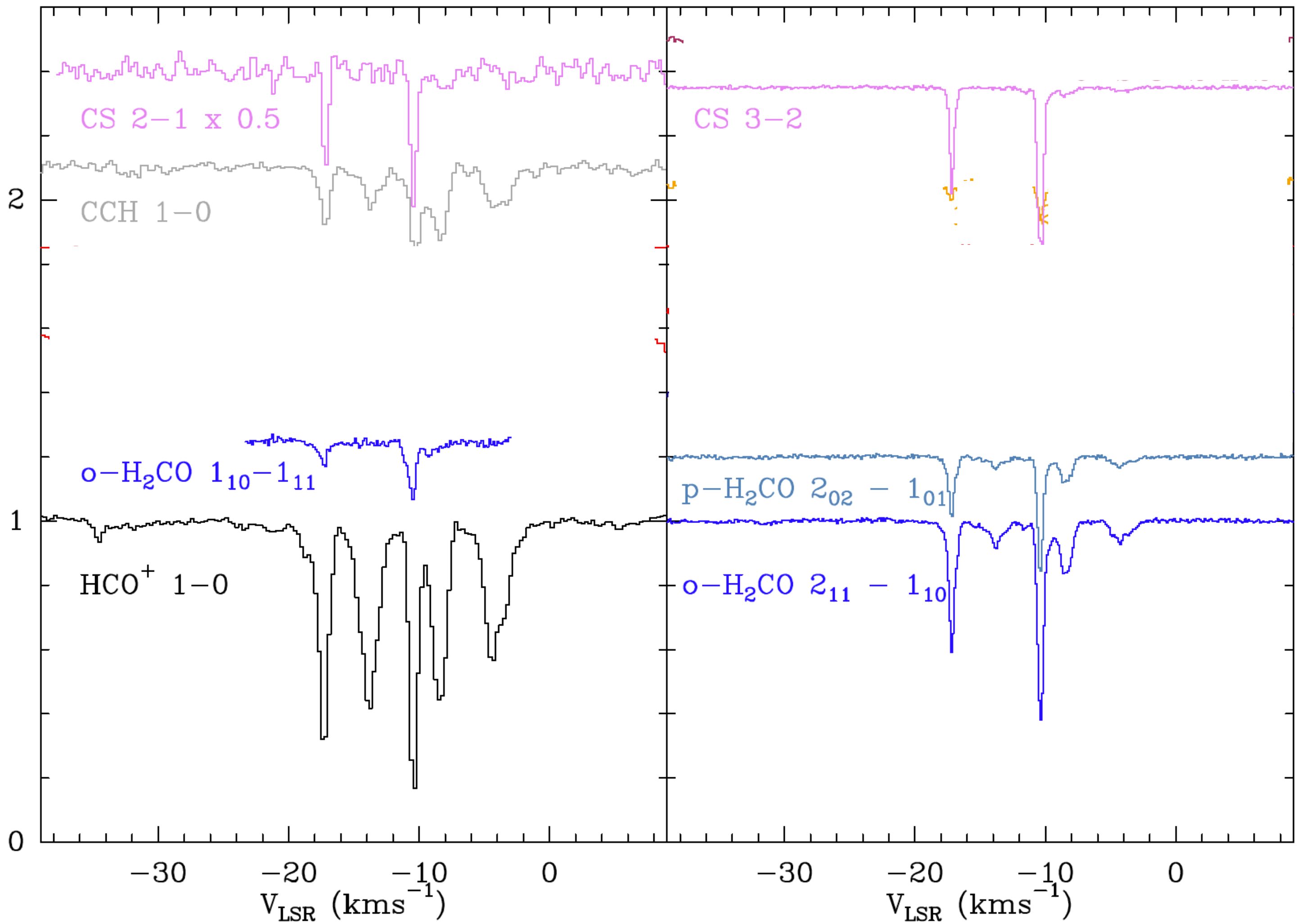
Two appear in λ6cm H_2CO & CS 3-2

B0355+508 NRAO 150 l = 150.4°, b = -1.6°



But look at λ2mm H_2CO!

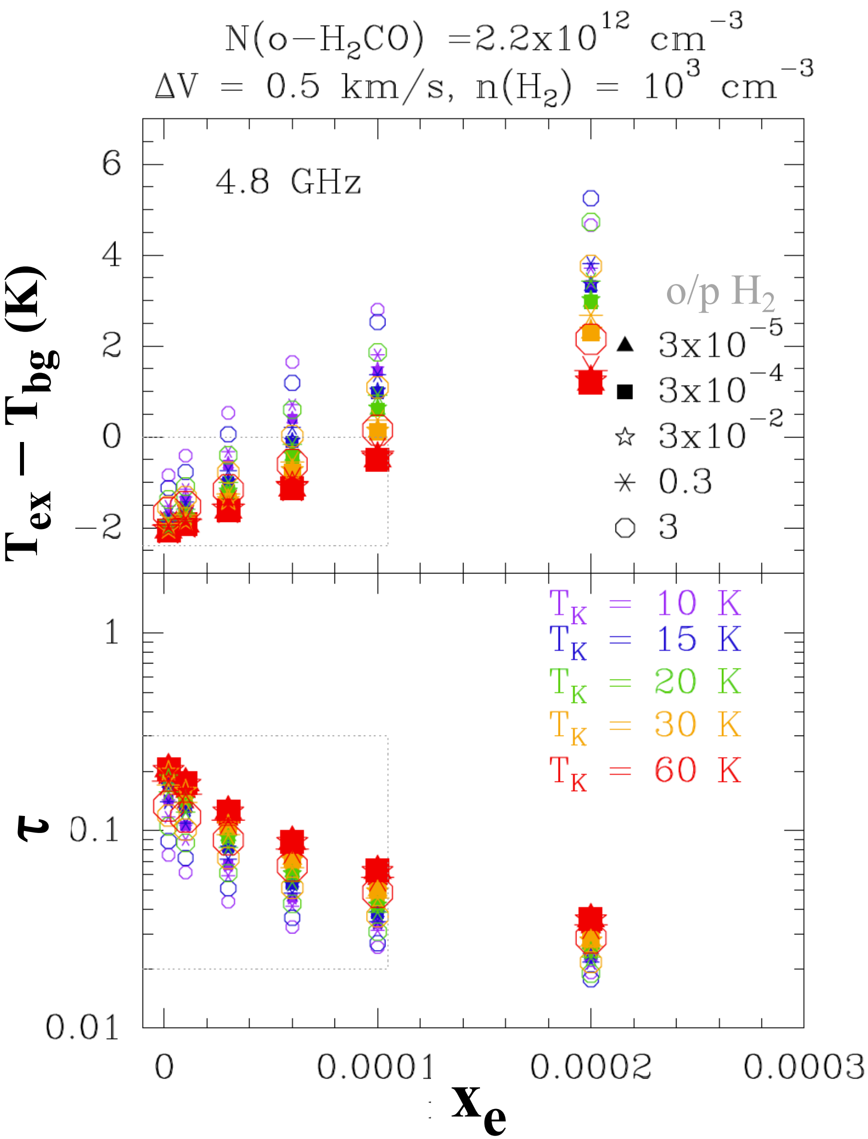
B0355+508 NRAO 150 $l = 150.4^{o}$, $b = -1.6^{o}$



So, what was going on?

- High $\tau_{CS}(3\text{-}2)/\tau_{CS}(2\text{-}1)$ implied $n \sim 3x10^3$ cm^{-3}
- The high density made us think about the ionization fraction
- Electron excitation was believed to suppress anomalous λ6cm H_2CO absorption
  - But e^- excitation rates had never been computed
    - Because H_2CO doesn't exist in diffuse gas!
- Maryvonne approached Alexandre who produced rates almost immediately

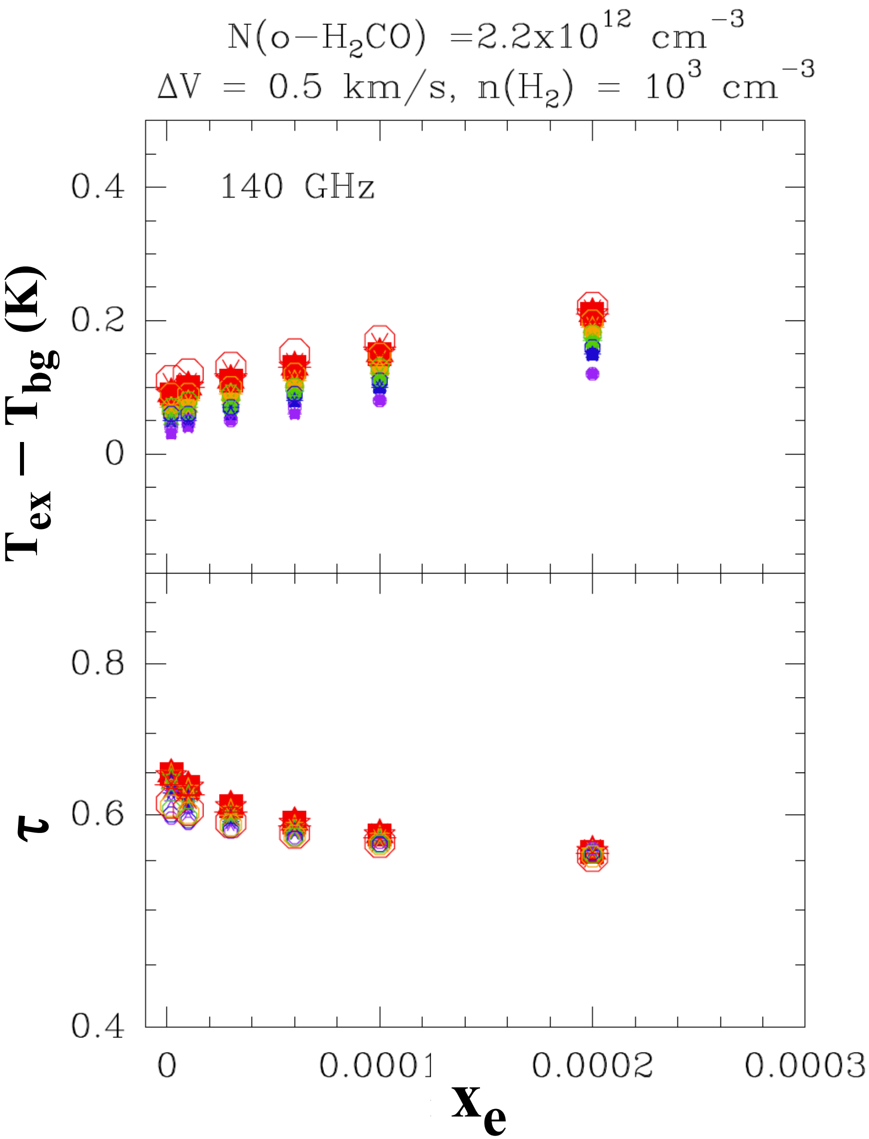
λ6cm absorption can be quenched!



- Anomalous λ6cm absorption $T_{ex} < T_{cmb}$ requires $x_e < \xi_C$

- λ6cm absorption quenched by
  - o/p $H_2 \rightarrow 3$
  - $x_e \rightarrow \xi_C$
  - $T_K \rightarrow 10$ K

λ2mm absorption traces N(H_2CO)



- λ2mm optical depth has weak dependence on conditions, traces N(H_2CO)

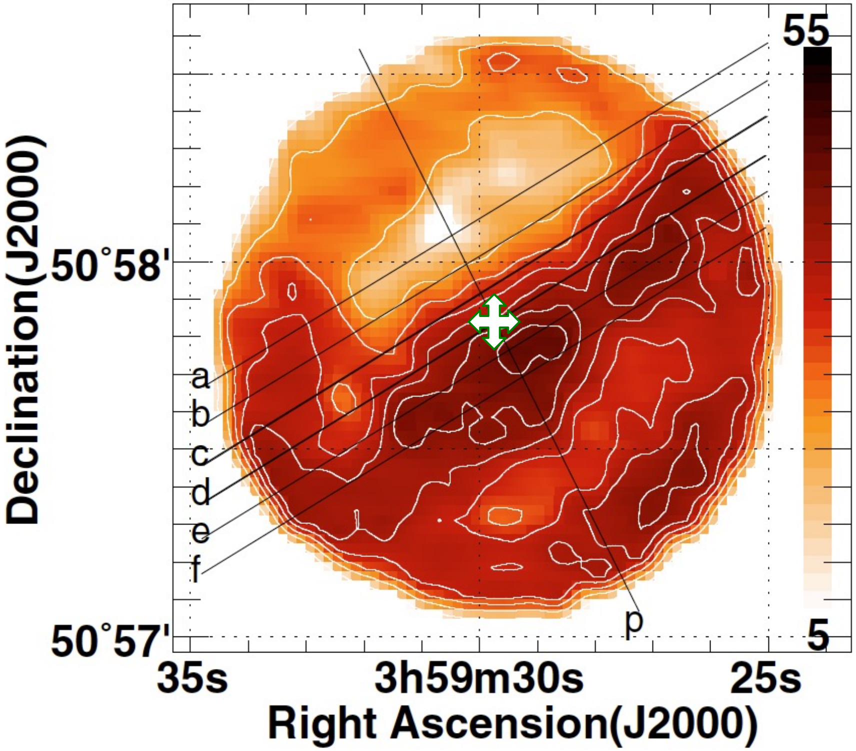
What did we learn?

- Features without λ6cm lines are diffuse
  - electron fraction $x_e \sim 2x10^{-4}$, $n(H_2) \sim$ few100 cm^{-3}
- Features with λ6cm H_2CO & high CS have
  - high $n(H_2) \sim 2500\ cm^{-3}$
  - low $x_e \sim 3x10^{-5} \sim \xi_C/10$
  - Carbon largely recombined, N(C I) >> N(CO)
  - Higher CS/H_2 & H_2CO/H_2
    - $CS/H_2 \sim 10^{-8}$, 4x higher
    - $H_2CO/H_2 \sim 6.5x10^{-9}$, 2.5 x higher

Way back in 2008 … A&A 489, 217

Imaging galactic diffuse gas: bright, turbulent CO surrounding the line of sight to NRAO150★,★★,★★★

J. Pety[1,2], R. Lucas[1], and H. S. Liszt[3]



Hybrid synthesis at 6" resolution!

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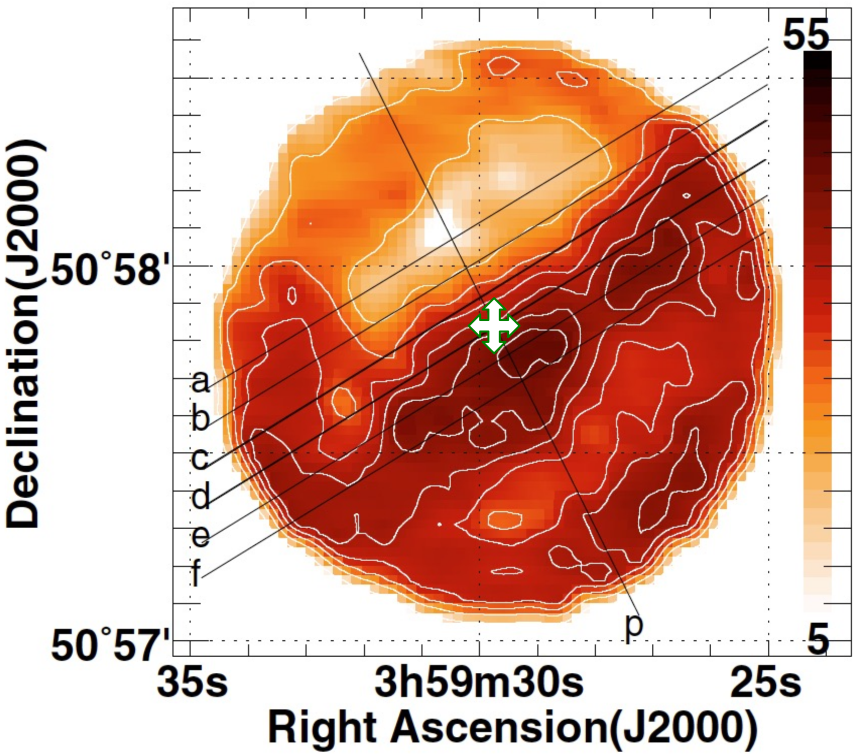
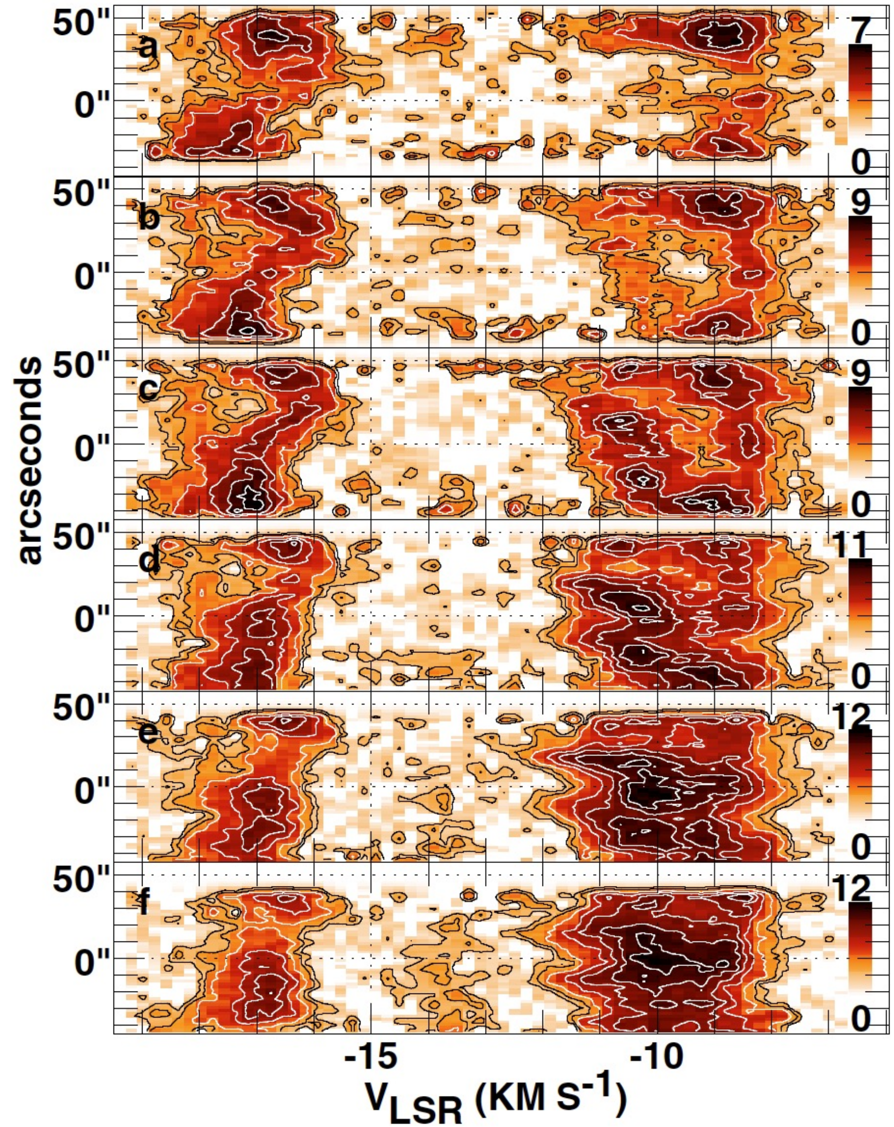




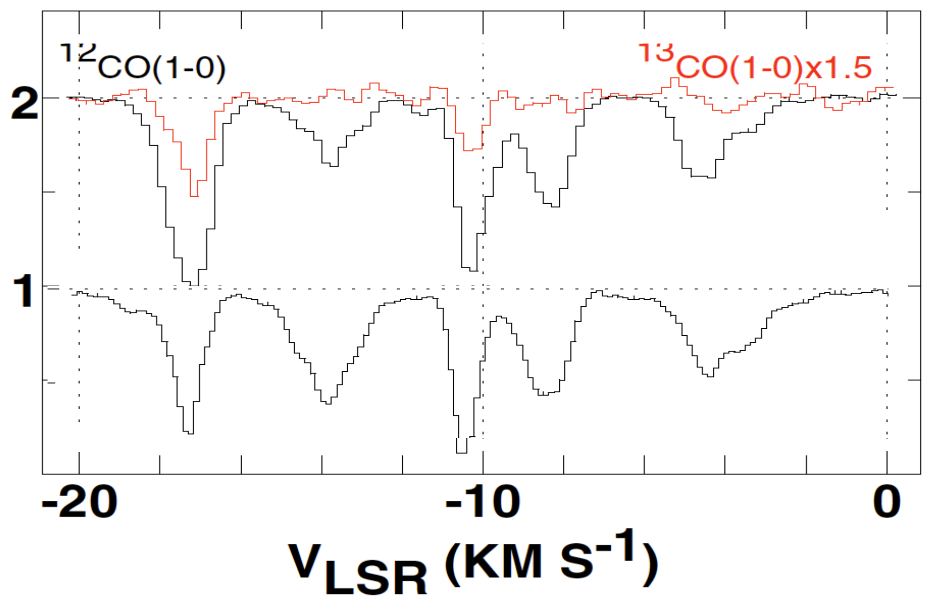
Hybrid synthesis at 6” resolution!

Thanks, that's it, what's next?

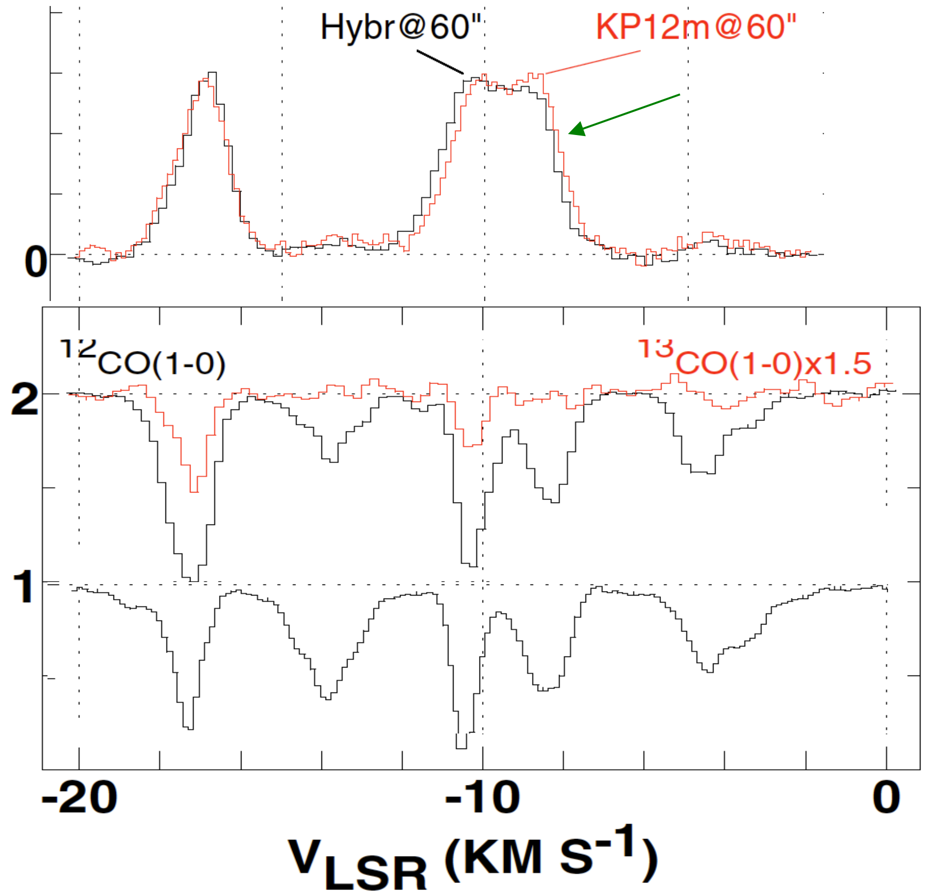
- Detections & abundances from the RT40m sweep
  - 72 – 84 GHz sweep at IRAM was less revealing
- Characterization of physical conditions
  - HCO^+ traced H_2 in the DNM analysis but features with same N(HCO^+) can be very different
    - 2 dex scatter in N(CO) at same N(H_2) in UV
- Is chemistry just a matter of getting dynamics right as Alex Dalgarno surmised at Asilomar in 2005?
  - Simulations still don't make HCO^+ even if H_2 ~ OK

CODA: CO across the $C^+ \rightarrow$ C I $\rightarrow$ CO transition

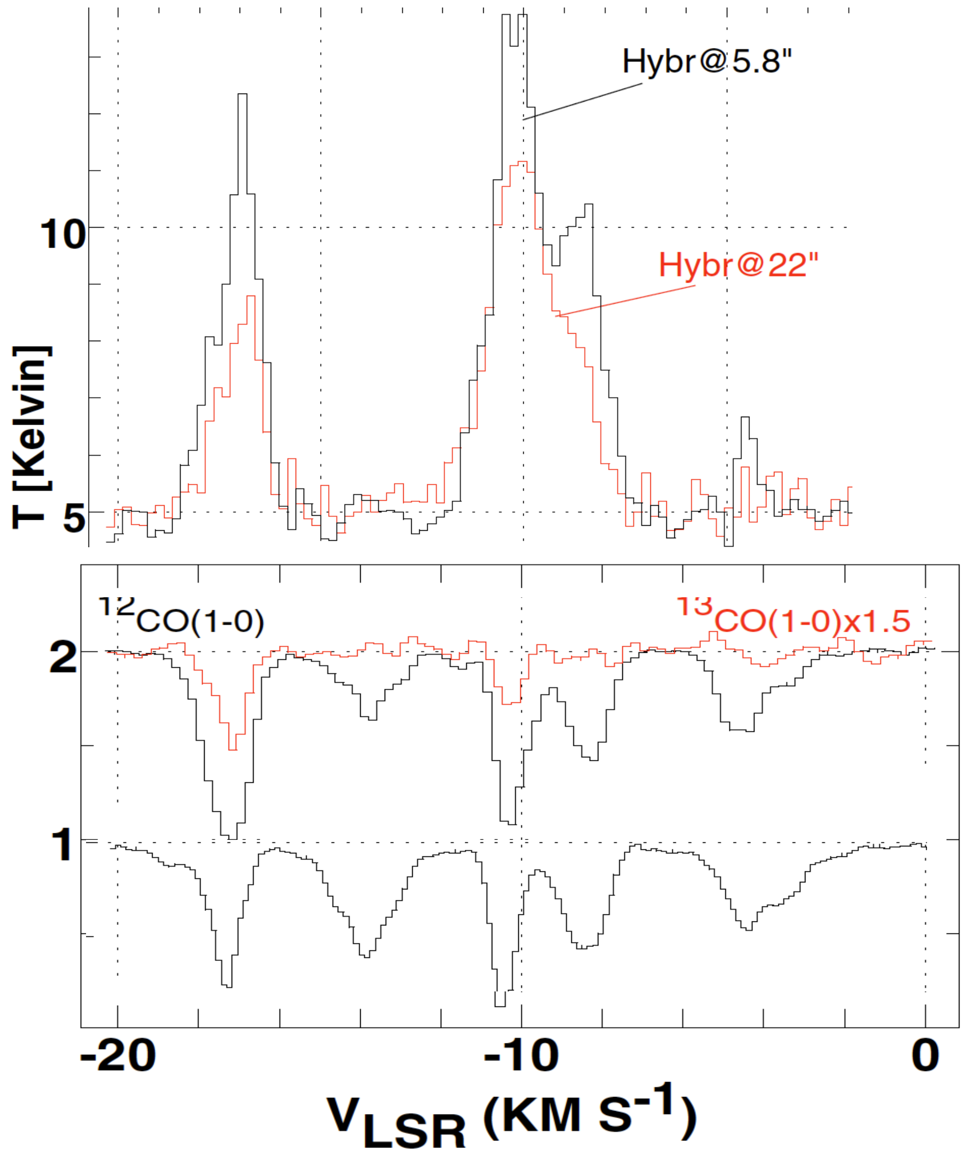
There is CO absorption in all HCO^+ components



One diffuse component is bright in CO, others dim



CO absorption and emission converge at 6”



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Thanks, that's really all