Properties of diffuse clouds

Harvey Liszt

NRAO & North American ALMA Science Center

Charlottesville, VA

SCIENTIFIC COMMITTEE ON FREQUENCY ALLOCATIONS FOR RADIO ASTRONOMY AND SPACE SCIENCE

IUCAF

Radio Astronomy Space Science iucaf.org

Diffuse gas and diffuse clouds

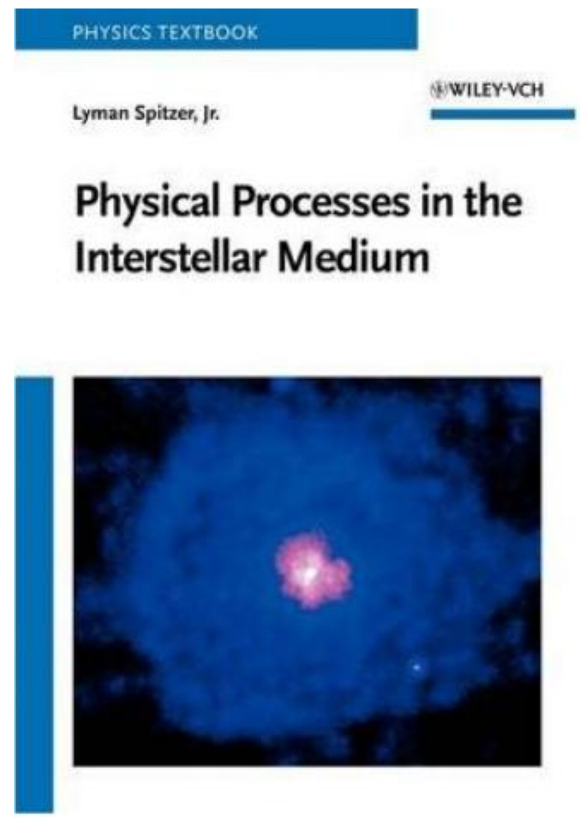
- The meaning of “diffuse” has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)

Diffuse gas and diffuse clouds

- The meaning of “diffuse” has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)

1967

1979



Diffuse gas and diffuse clouds

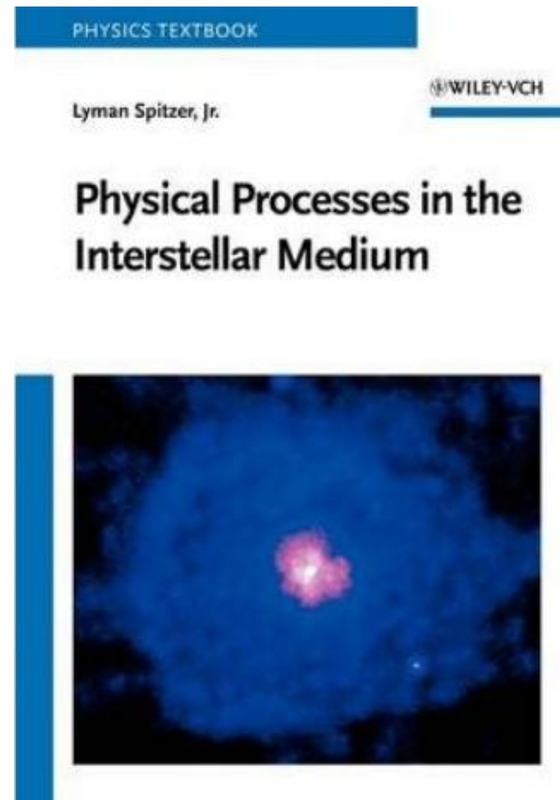
- The meaning of "diffuse" has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)

1967

UV:
Copernicus
O VI
H_2

λ2.6mm:
KP 12m
CO Emission

1979



Diffuse gas and diffuse clouds

- The meaning of “diffuse” has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - **Could be an isolated entity – a “diffuse cloud”**

Diffuse gas and diffuse clouds

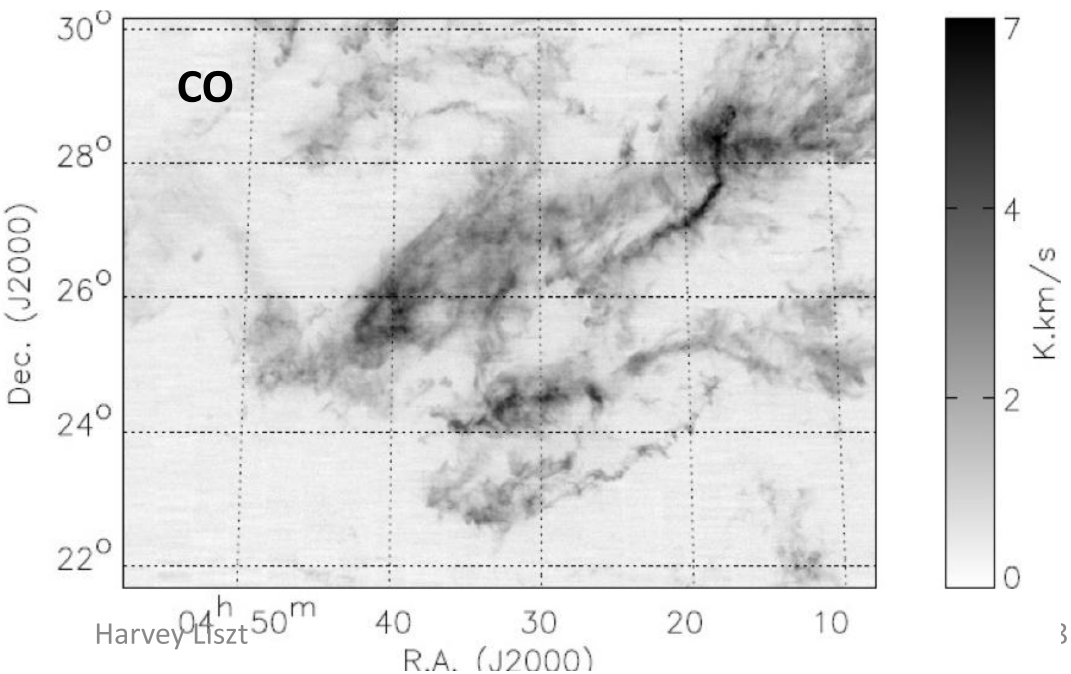
- The meaning of "diffuse" has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - **Could be an isolated entity – a "diffuse cloud"**
    - $N(H) \lesssim 2 \times 10^{21}$ cm^{-2} (1 mag)
    - $N(H) \sim 4 \times 10^{20}$ cm^{-2}, $n(H) \sim 30$ cm^{-2}, $D \sim 4$ pc, $E_{B-V} \sim 0.07$ mag
      - Spitzer "standard" H I cloud but derived from reddening
      - Mean free path locally: ~5 per kpc provide all the local H I

Diffuse gas and diffuse clouds

- The meaning of "diffuse" has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - Could be an isolated entity – a "diffuse cloud"
  - **Could be a line of sight thru a cloud complex**

Diffuse gas and diffuse clouds

- The meaning of “diffuse” has changed over time
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - Could be an isolated entity – a “diffuse cloud”
  - **Could be a line of sight thru a cloud complex**



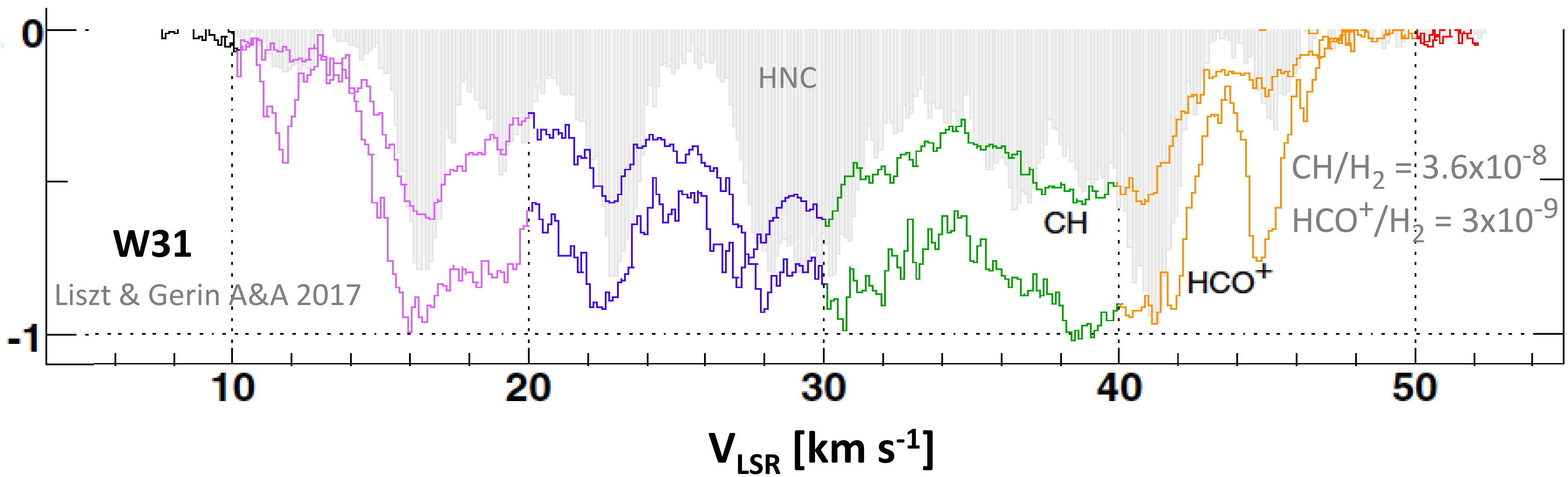
P. Goldsmith et al. FCRAO
1’ CO mapping of Taurus
ApJ 2008

Diffuse gas and diffuse clouds

- The meaning of “diffuse” has changed
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - Could be an isolated entity – a “diffuse cloud”
  - **May be seen in directions with high total A_V**

Diffuse gas and diffuse clouds

- The meaning of "diffuse" has changed
  - WAS: gas outside the immediate environment of a star
  - NOW: gas where *locally* $A_V \lesssim 1$ mag (ie transparent)
  - Could be an isolated entity – a "diffuse cloud"
  - **May be seen in directions with high total A_V**

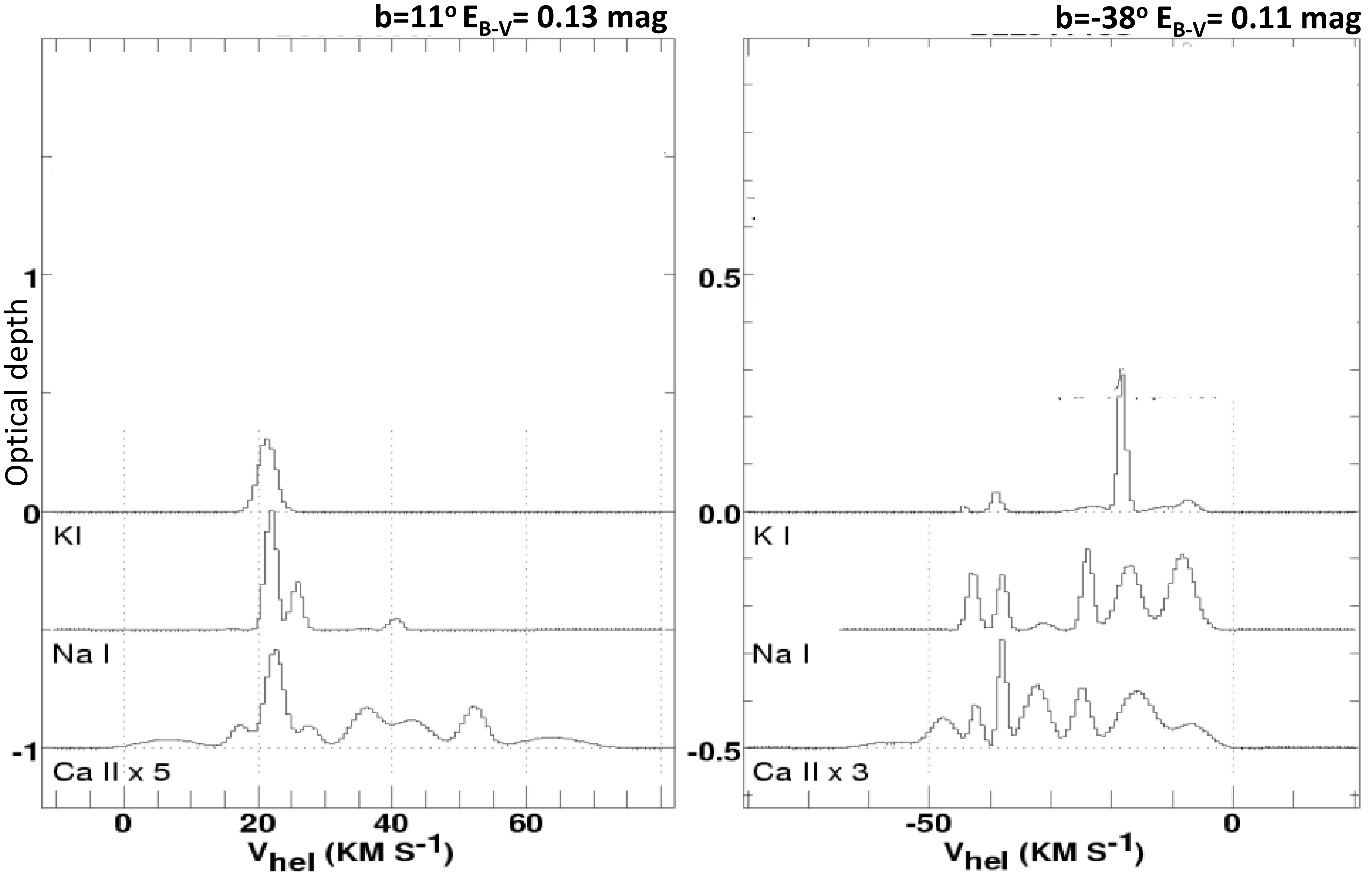


Gerin et al. 2010, A&A, 518, 110; 2010, 521, 16; Godard et al 2010, A&A 520, 20

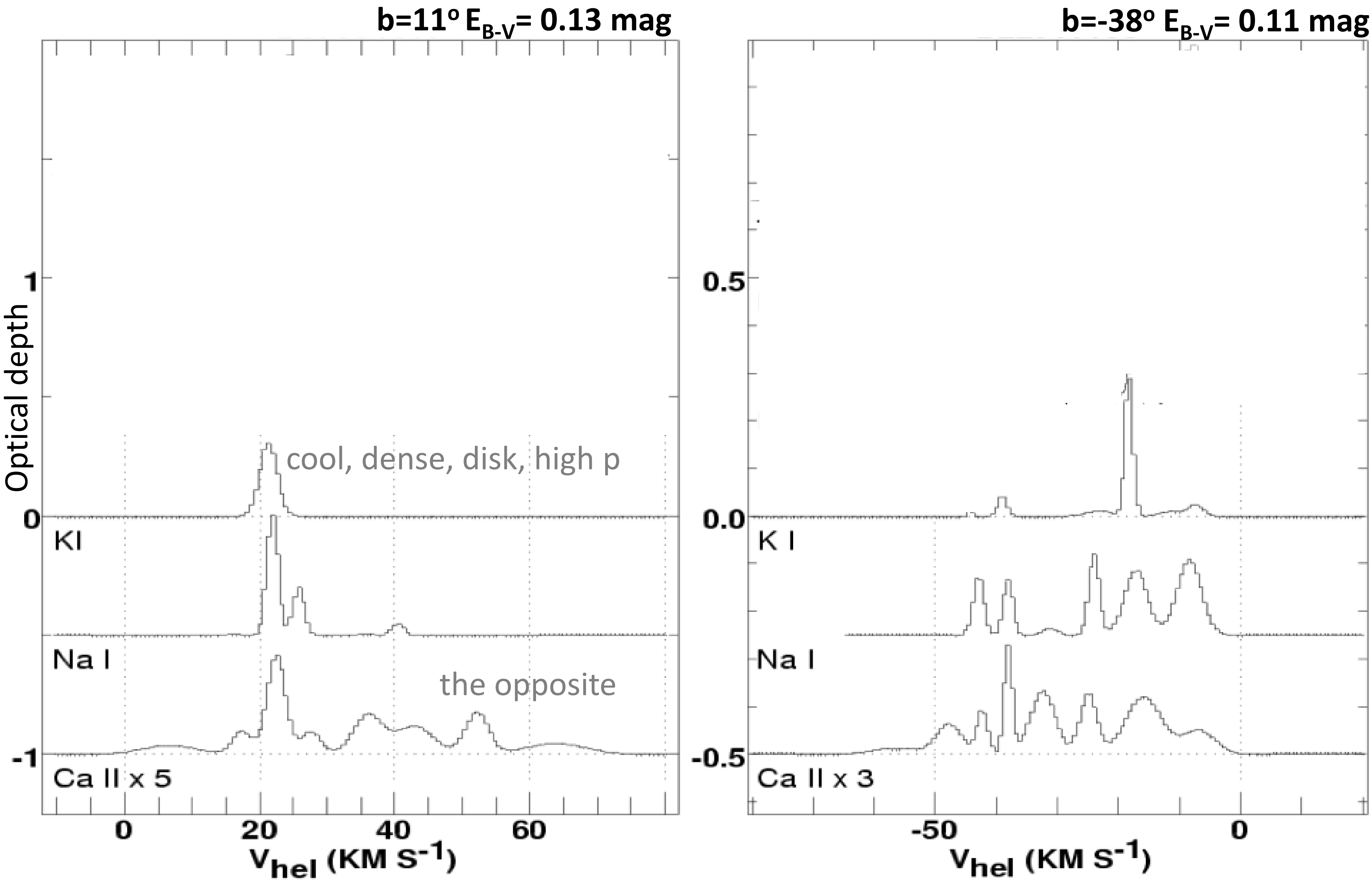
1948: Optical diffuse atomic clouds

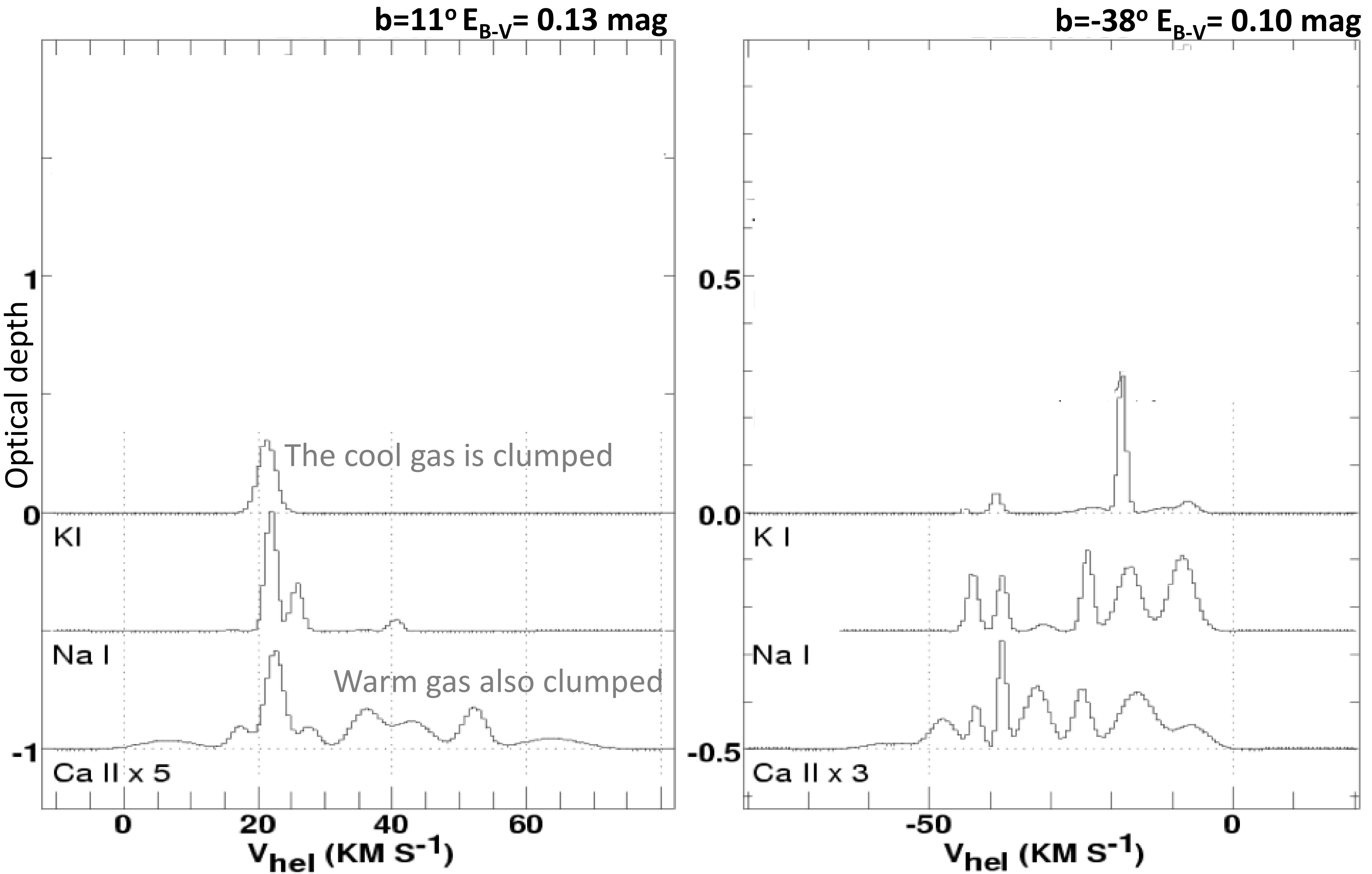
(Tappe 2004, thesis Onsala)

1948: Optical diffuse atomic clouds



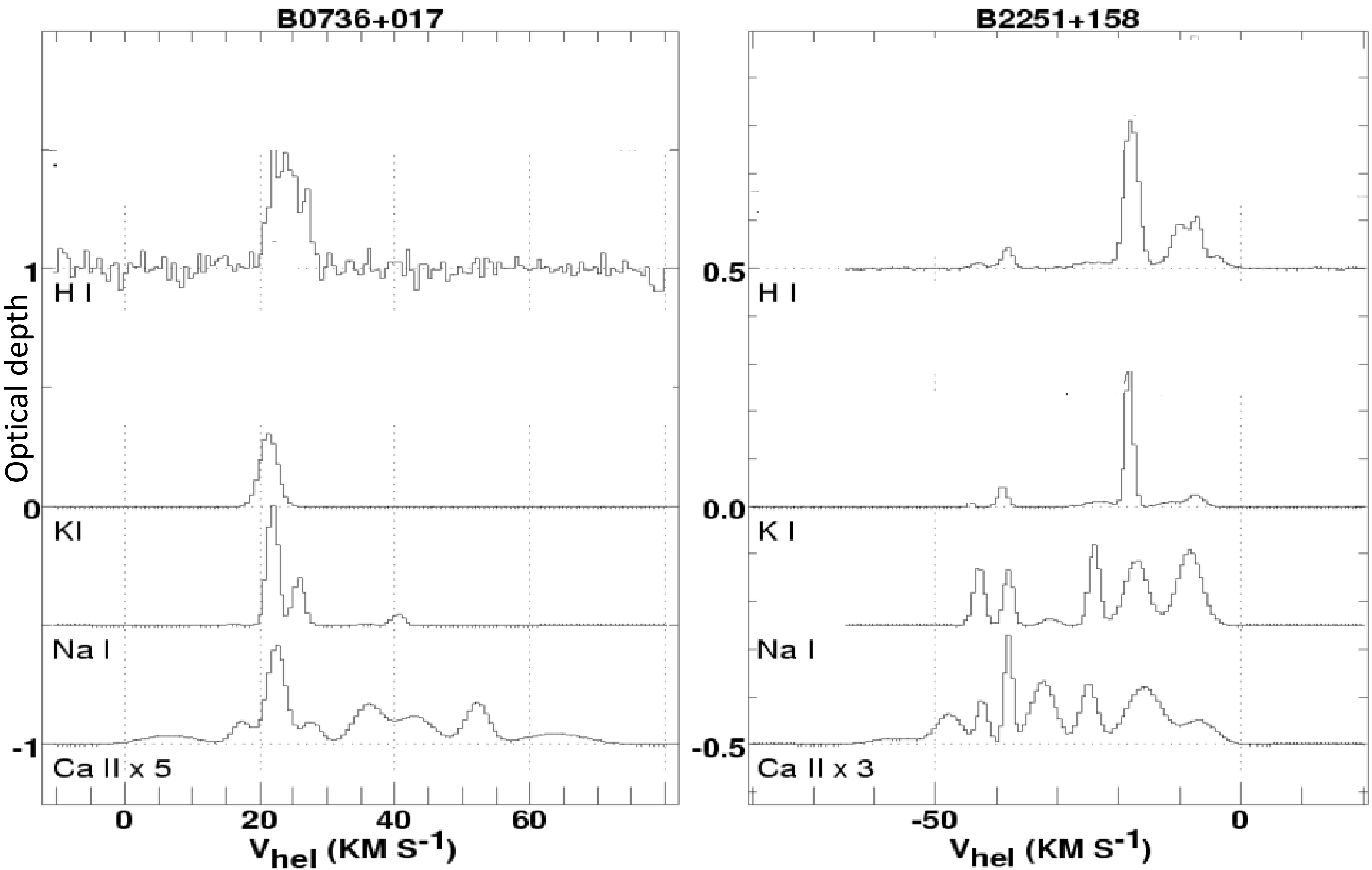
1948: Optical diffuse atomic clouds



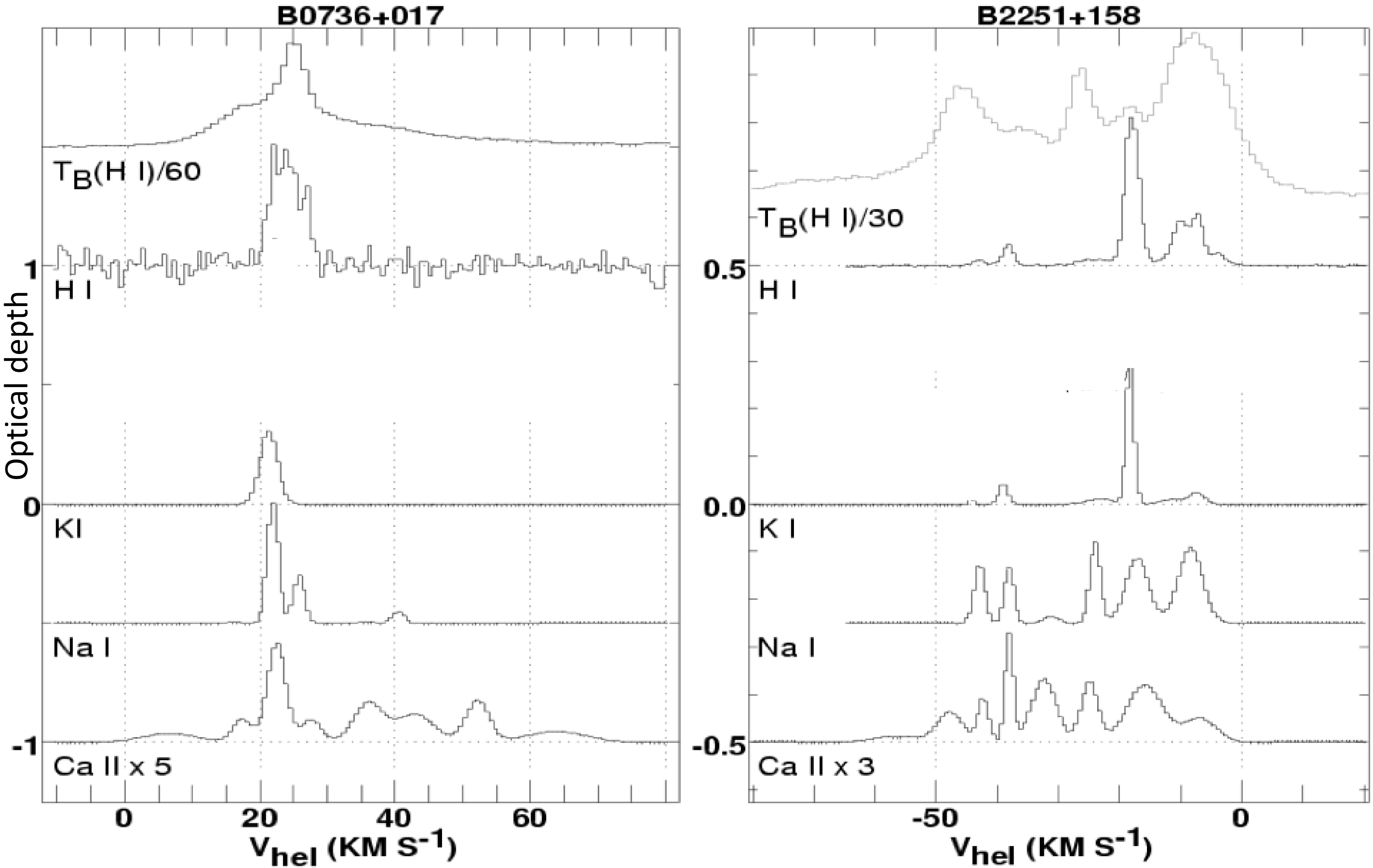


b=11º E_{B-V}= 0.13 mag
b=-38º E_{B-V}= 0.10 mag
Optical depth
The cool gas is clumped
Warm gas also clumped
K I
Na I
Ca II x 5
K I
Na I
Ca II x 3
1
0
-1
0.5
0.0
-0.5
0
20
40
60
-50
0
V_hel (KM S^-1)
V_hel (KM S^-1)

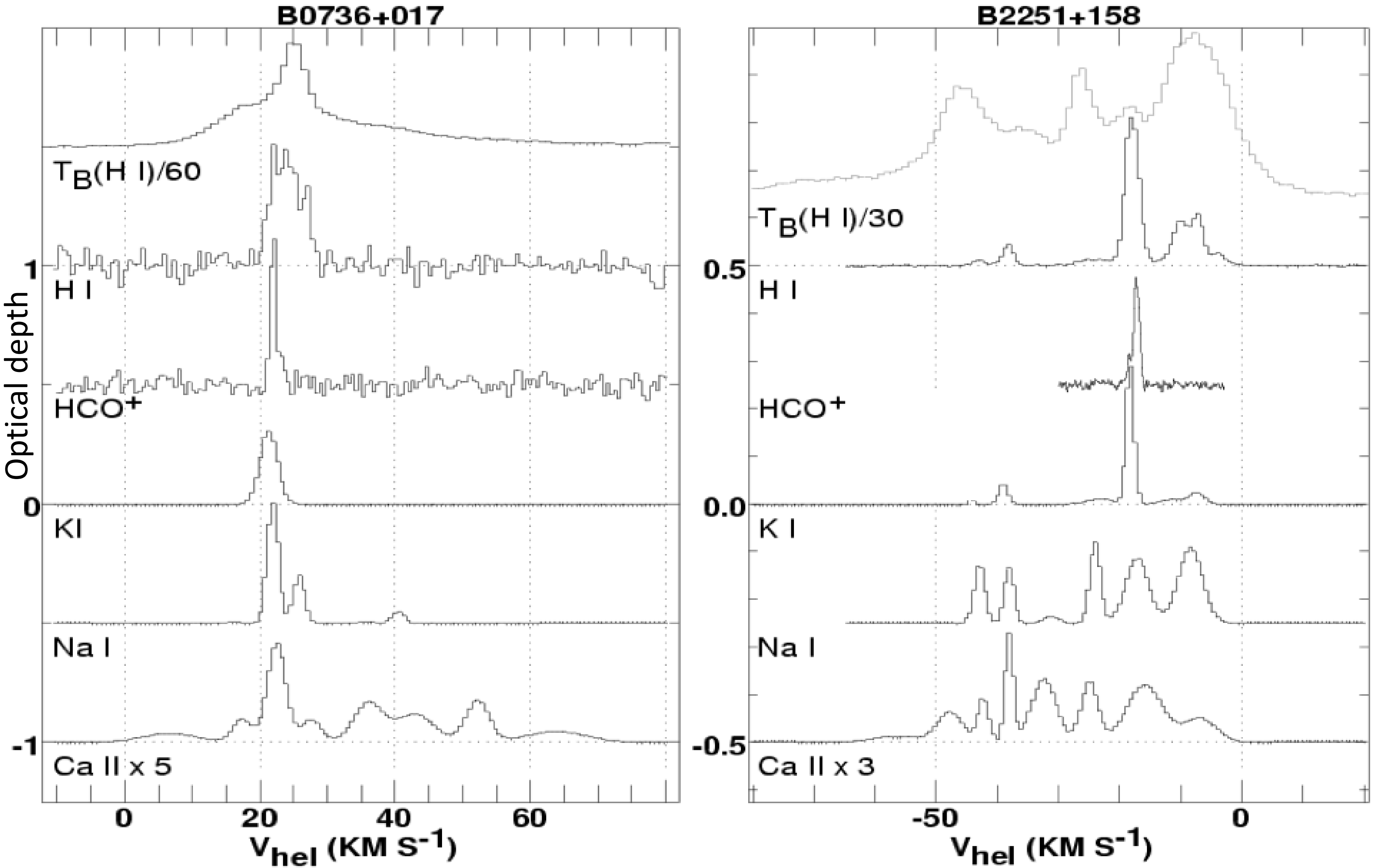
1965: Optical/radio diffuse/H I atomic clouds



1965: Optical/radio diffuse/H I atomic clouds



1995: Optical/radio diffuse molecular gas



How much ‘diffuse’ gas?

- $M_{HI} \sim 2\text{-}3\times10^9\ M_{sun}$
  - $\Sigma_{HI} \sim 6\ M_{sun}/pc^2$, $3 < R_{gal} < 15$ kpc

How much ‘diffuse molecular’ gas?

- $M_{HI} \sim 2\text{-}3 \times 10^9\ M_{sun}$
  - $\Sigma_{HI} \sim 6\ M_{sun}/pc^2$, $3 < R_{gal} < 15$ kpc
- Locally, ~1/3 of H in diffuse clouds is in H_2
  - Estimates from UV/optical H I, H_2 & CH absorption

L&L 2002, A&A, 391, 693

How much ‘diffuse molecular’ gas?

- $M_{HI} \sim 2\text{-}3 \times 10^9\ M_{sun}$
  - $\Sigma_{HI} \sim 6\ M_{sun}/pc^2$, $3 < R_{gal} < 15$ kpc
- Locally, ~1/3 of H in diffuse clouds is in H_2
  - Estimates from UV/optical H I, H_2 & CH absorption

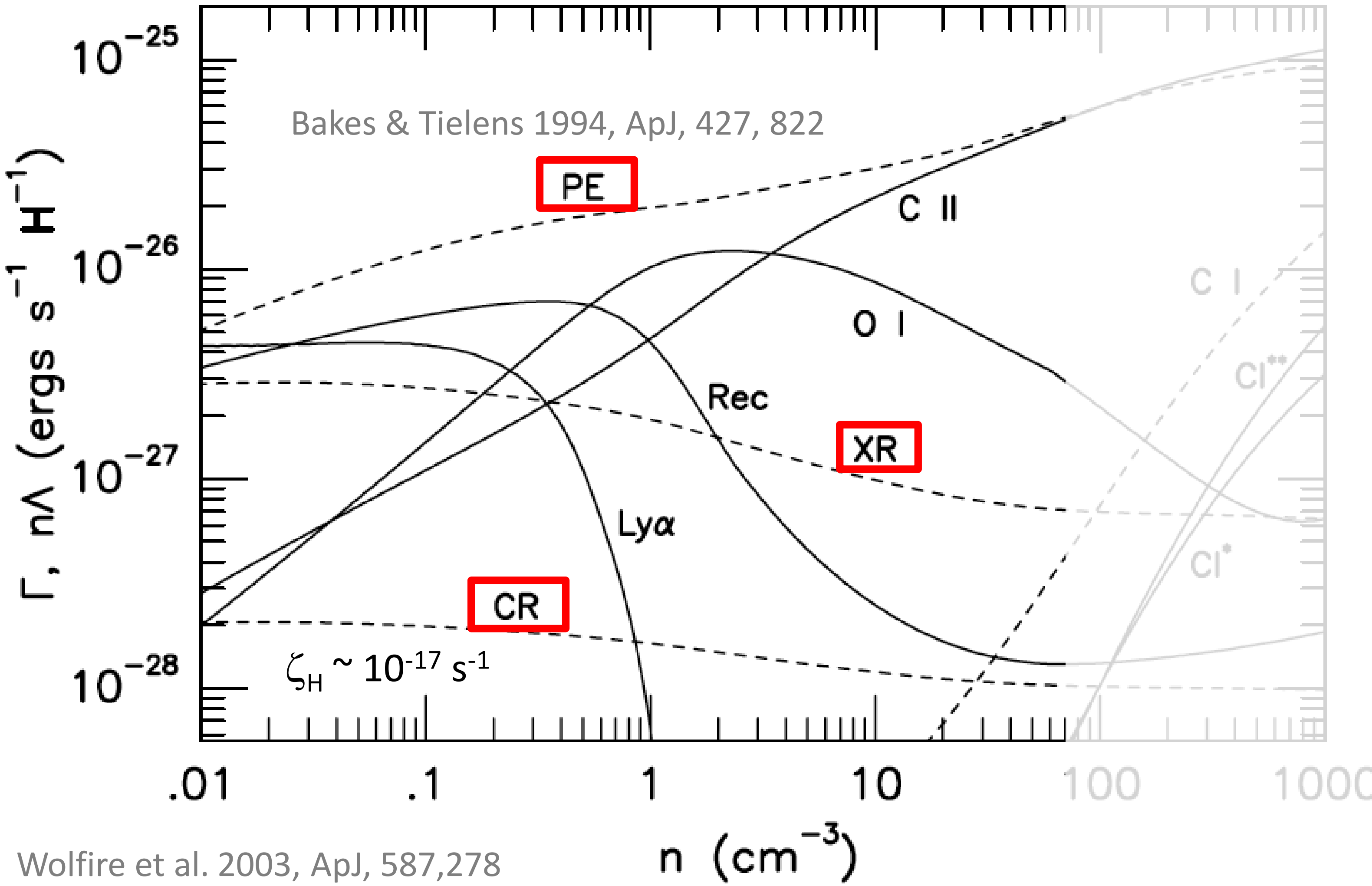
L&L 2002, A&A, 391, 693

- Locally, 1/2 of H is H_2 overall
  - $\langle n_H \rangle = 1.2\ cm^{-3}$ (Spitzer 1967; very old number)
  - $\langle n(\text{H I}) \rangle = 0.6\ cm^{-3}$ (Dickey & Lockman ARAA 1990)
- *Locally, most H_2 is in the diffuse gas*

How much ‘diffuse molecular’ gas?

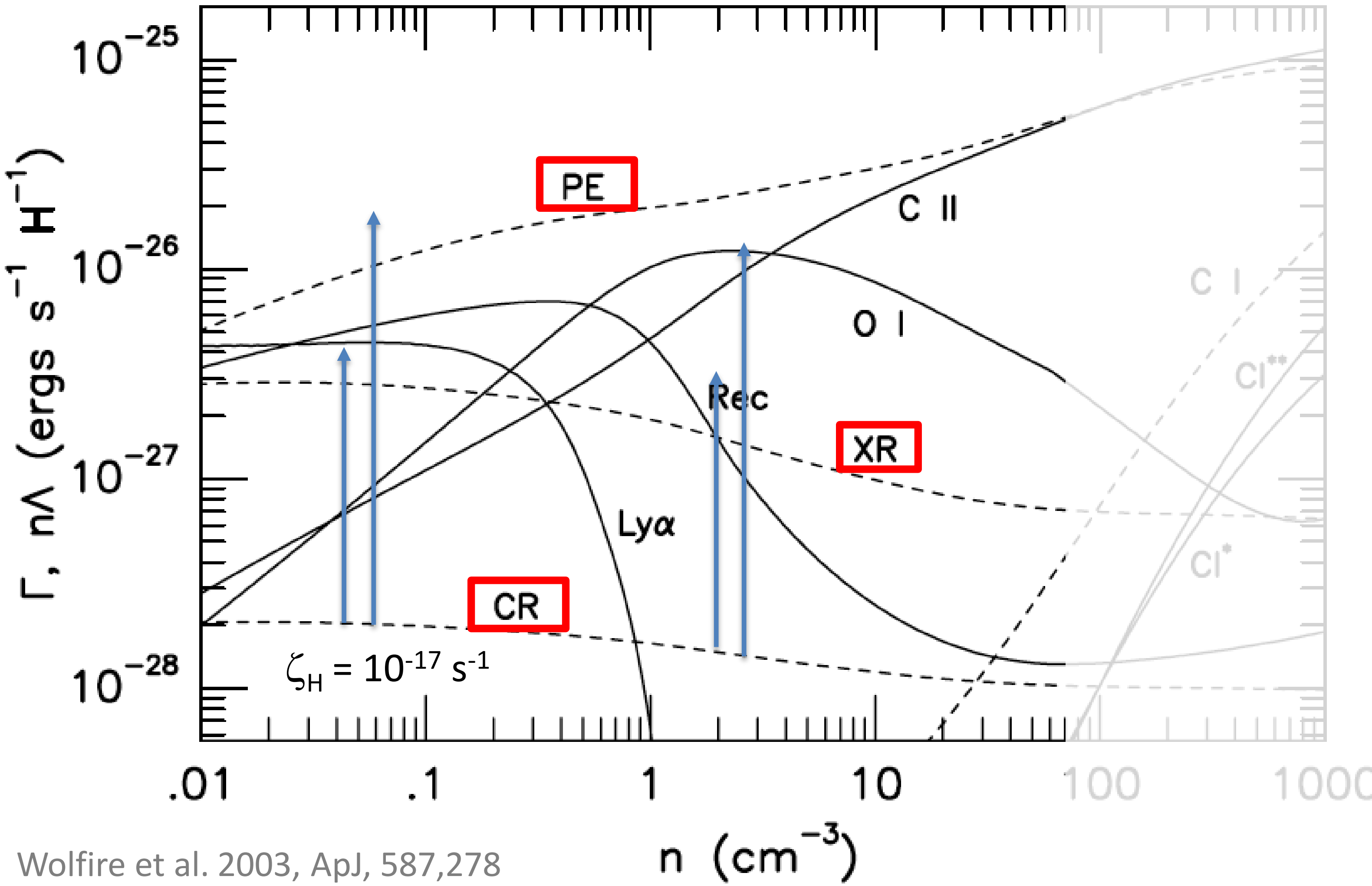
- $M_{HI} \sim 2\text{-}3 \times 10^9 \ M_{sun}$
  - $\Sigma_{HI} \sim 6 \ M_{sun}/pc^2$, $3 < R_{gal} < 15$ kpc
- Locally, ~1/3 of H in diffuse clouds is in H_2
  - Estimates from UV/optical H I, H_2 & CH absorption
- Locally, 1/2 of H is H_2 overall
  - $\langle n_H \rangle = 1.2 \ cm^{-3}$ (Spitzer 1967; very old number)
  - $\langle n(H\ I) \rangle = 0.6 \ cm^{-3}$ (Dickey & Lockman ARAA 1990)
- *Locally, most H_2 is in the diffuse gas*
  - CO in this gas is very bright per CO molecule
    - A contaminating signal if looking for dense gas in CO

But why ‘clouds’?



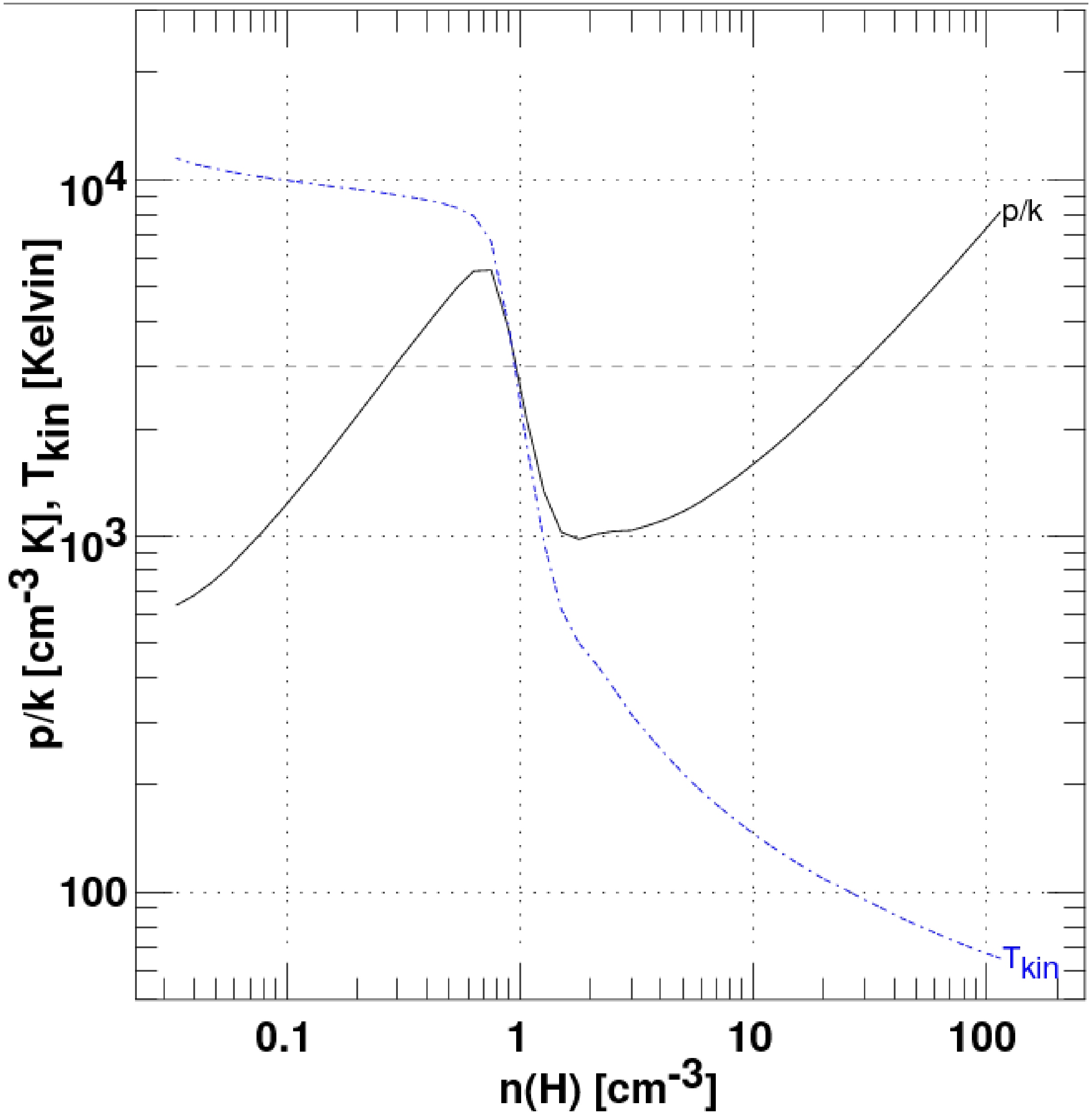
Wolfire et al. 2003, ApJ, 587,278

But why 'clouds'?

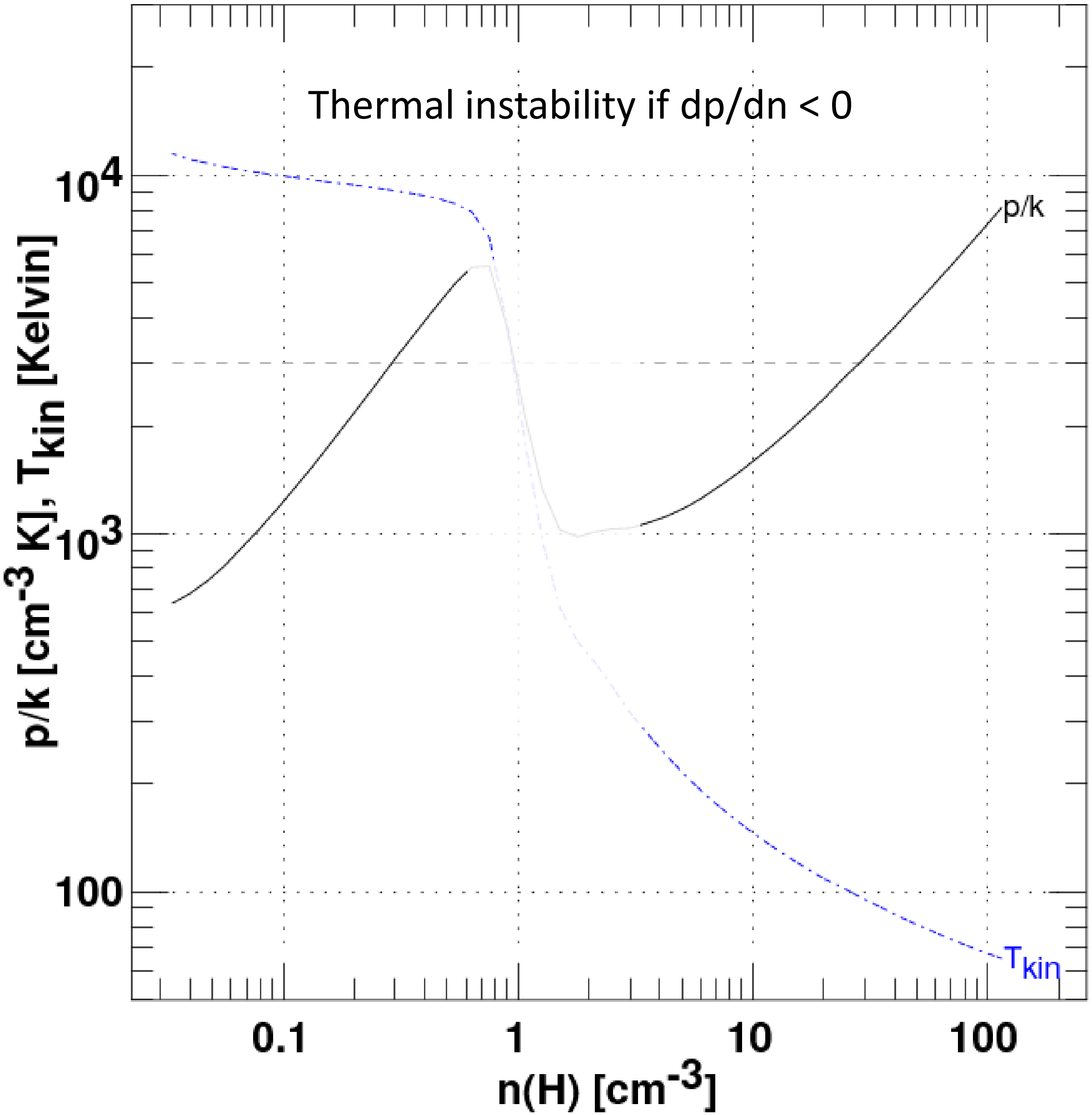


Wolfire et al. 2003, ApJ, 587,278

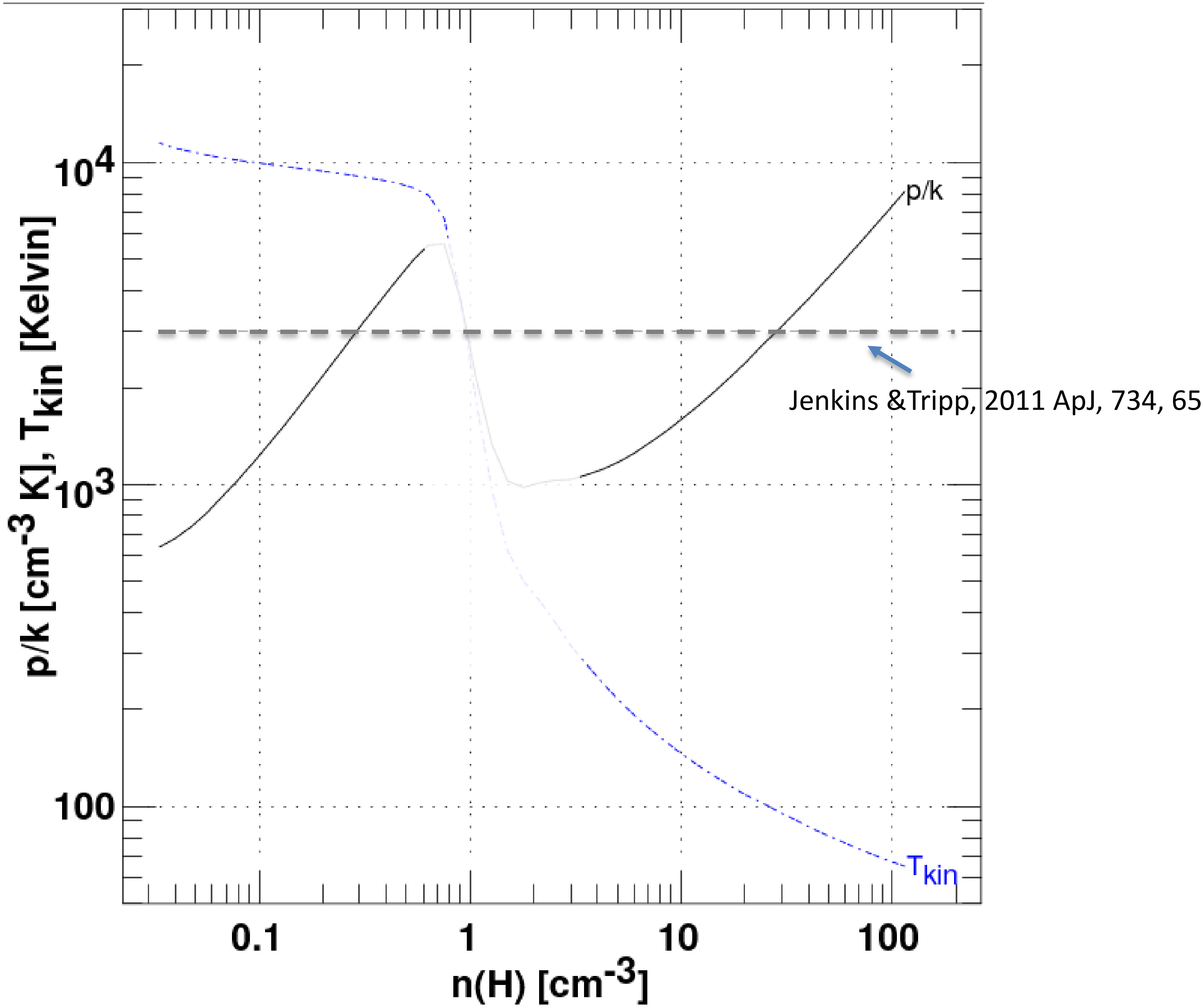
But why ‘clouds’?



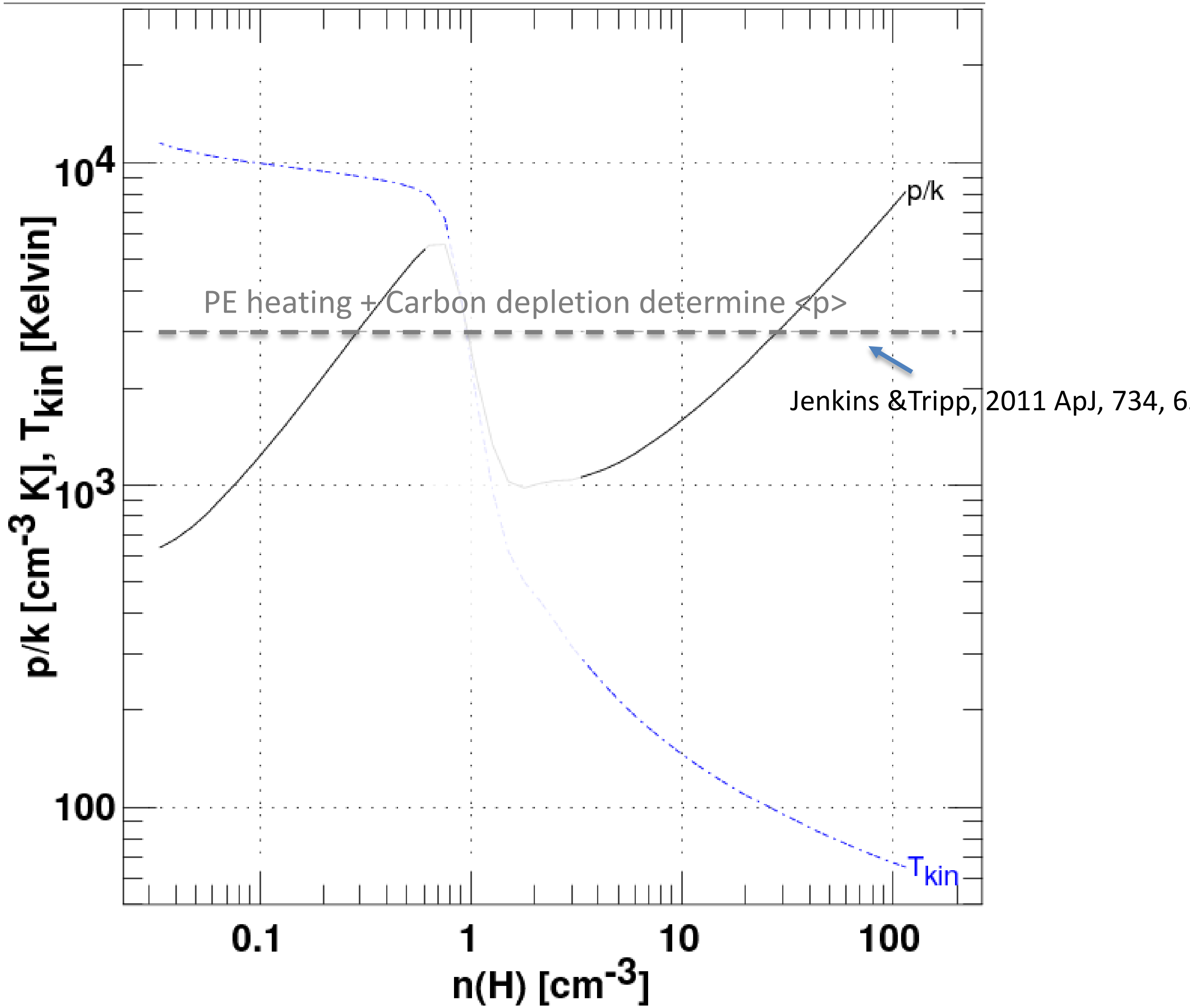
But why ‘clouds’?



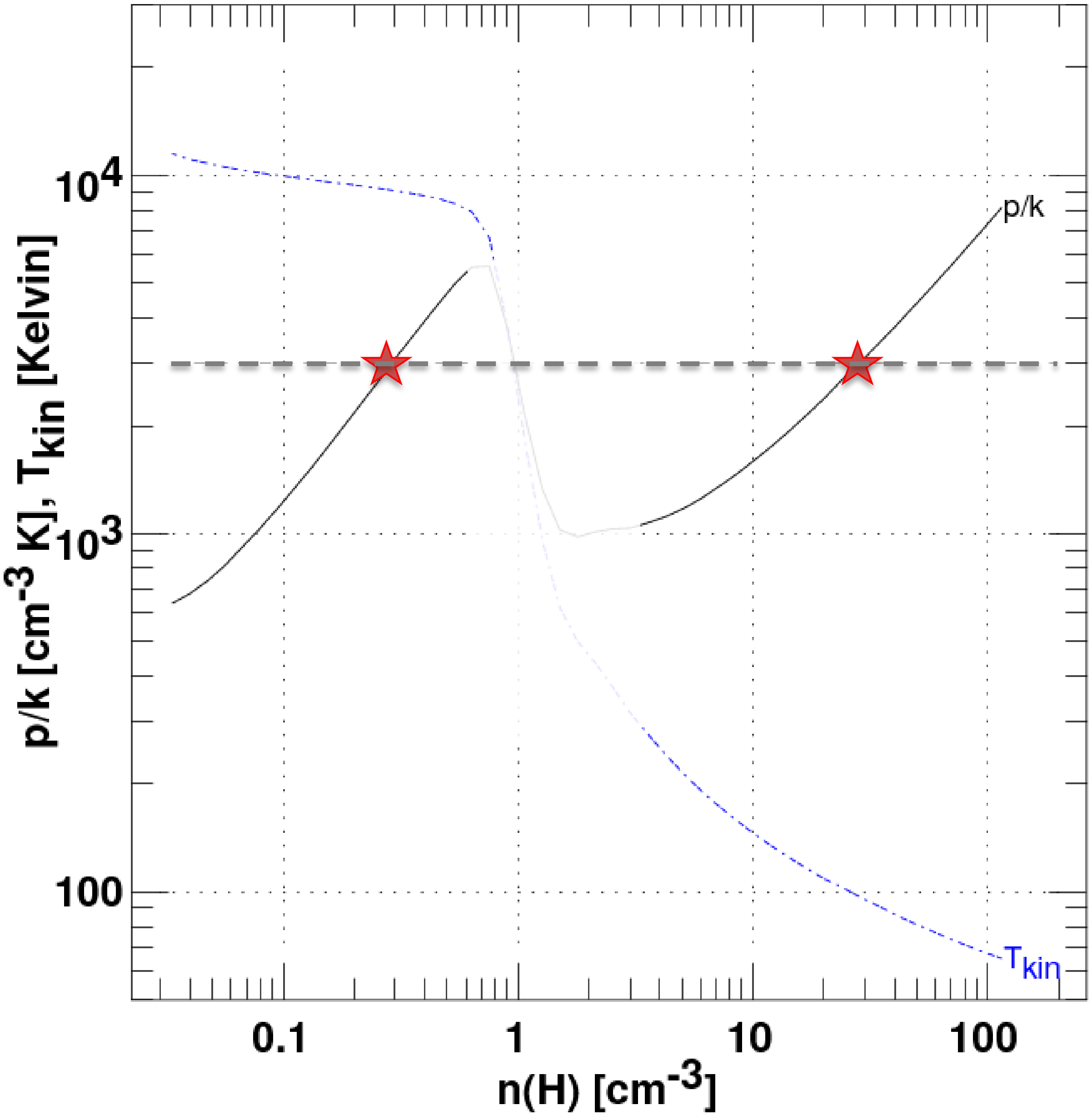
But why 'clouds'?



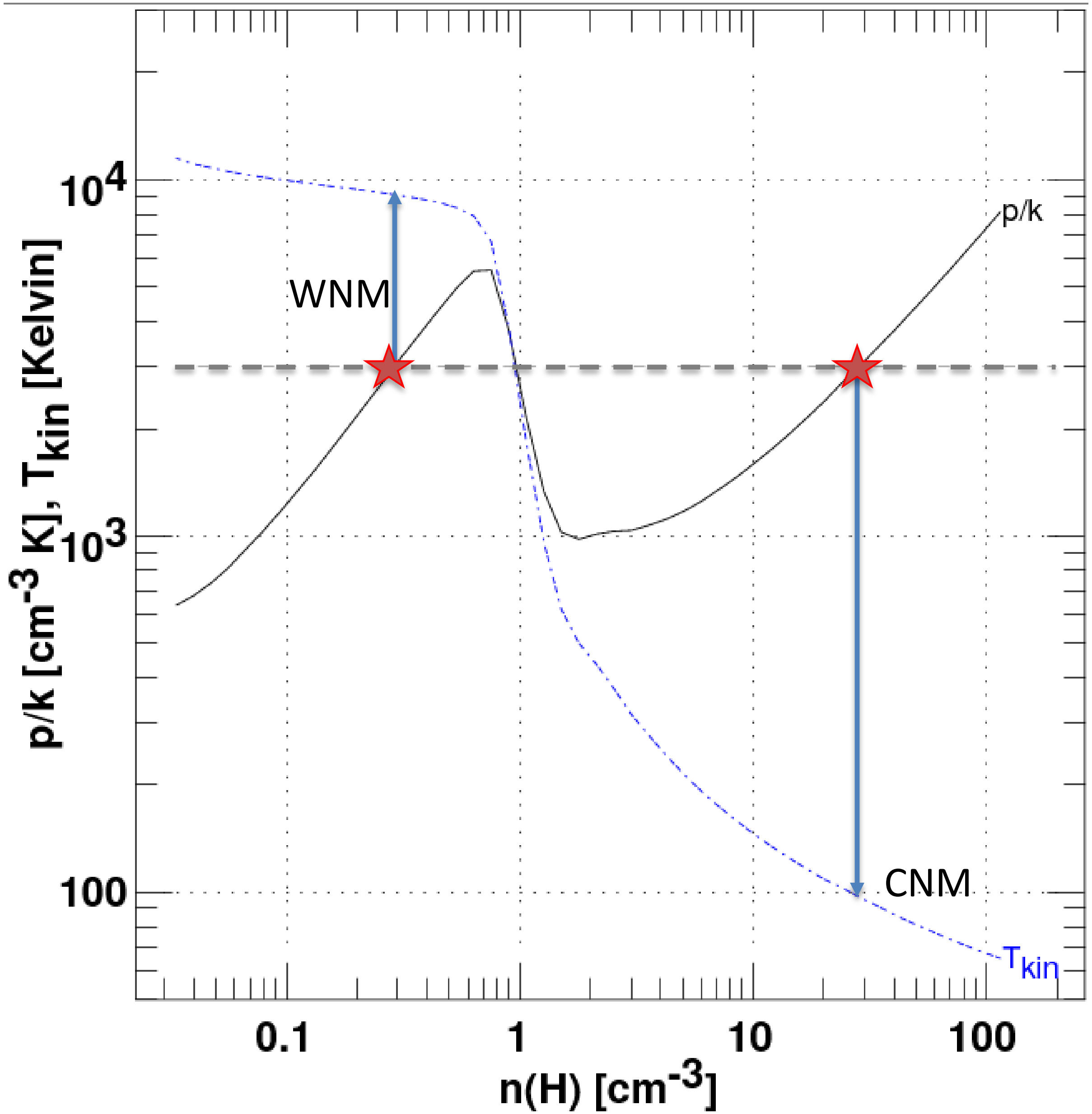
But why ‘clouds’?



But why 'clouds'?



But why 'clouds'?



A two-phase substrate is the default

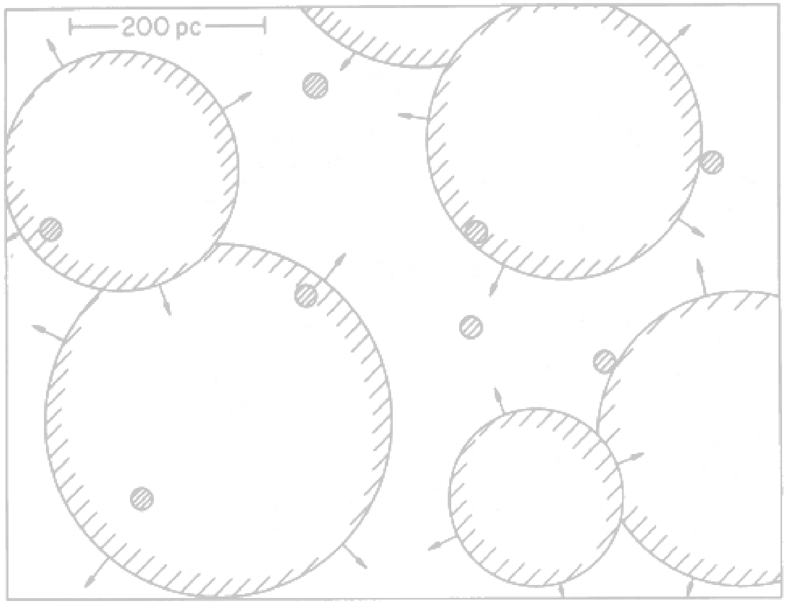
- Two-phase equilibrium is a kind of default
  - Volume-filling warm neutral gas (WNM) ~8000 K
  - Clumped (few %) cold neutral gas (CNM) ~80 K

- The thermal pressure is not controlling
  - Not the real dominant influence
  - But a kind of default that happens when nothing else is going on

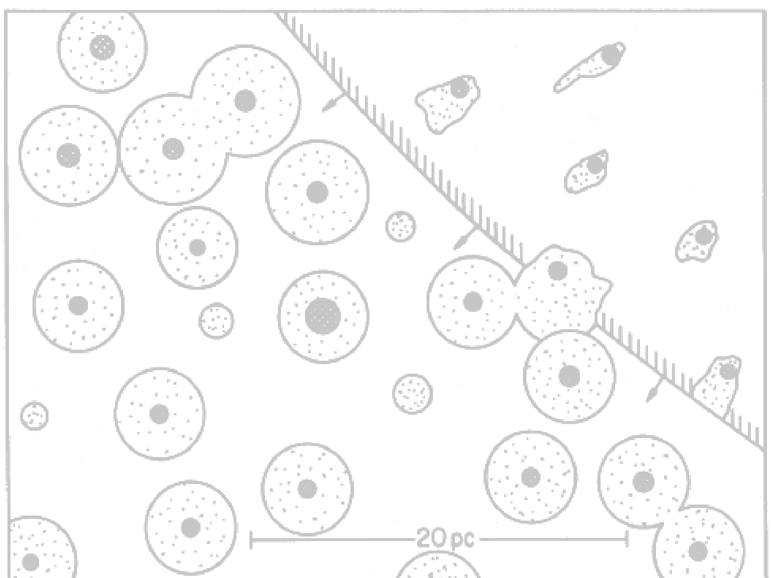
A multi-phase medium is the reality

Cox&Smith 1974 ApJ,189,105;McKee&Ostriker 1977, ApJ 218,148; Miao Li, J. Ostriker et al.2015 - 2018

- SNR expand into the disk stirring it up, making:
  - Pervasive hot ionized gas (HIM)
    - ~ 10^6 K, 60% of disk, controlled by SN rate and <p>
    - Gas imagined by Spitzer (1956) to contain high-z clouds
  - Widespread warm ionized & warm neutral gas
    - Envelopes of discrete clouds (has to be clumped)
    - ~ 10^4 K, 40% of disk
      - partly-ionized hydrogen (WIM)
      - neutral hydrogen (”classical” WNM)
  - Highly confined CNM cores of warm envelopes
    - Seen as diffuse clouds 1-2% of the disk volume

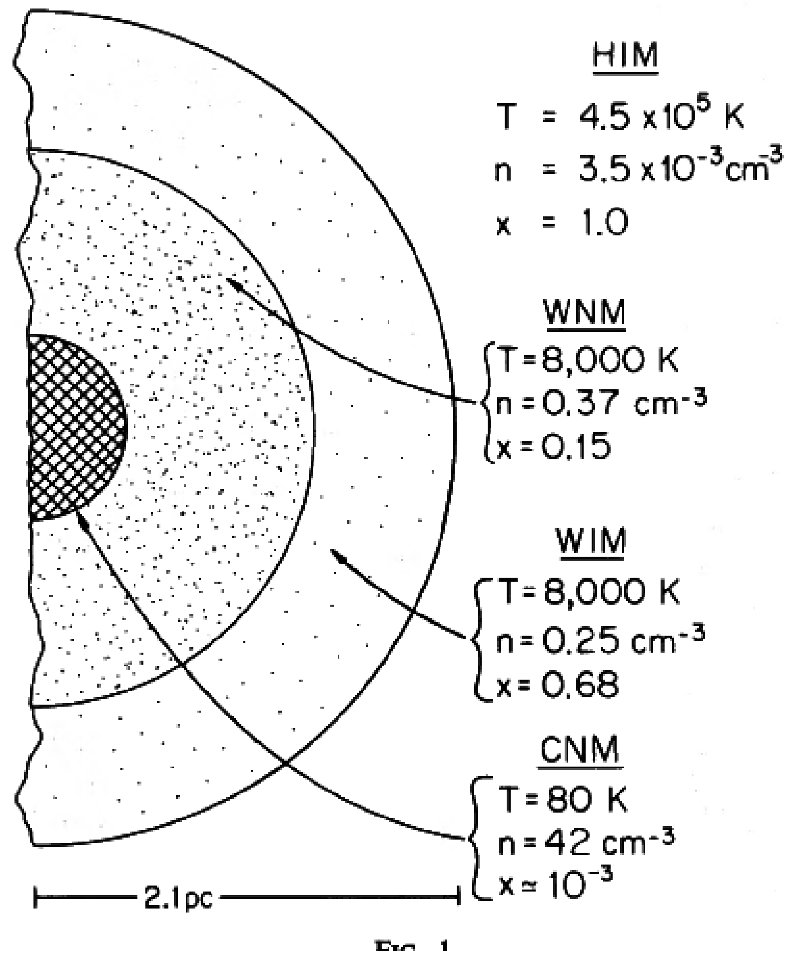


A LARGE SCALE VIEW



A CLOSE UP VIEW

A SMALL CLOUD

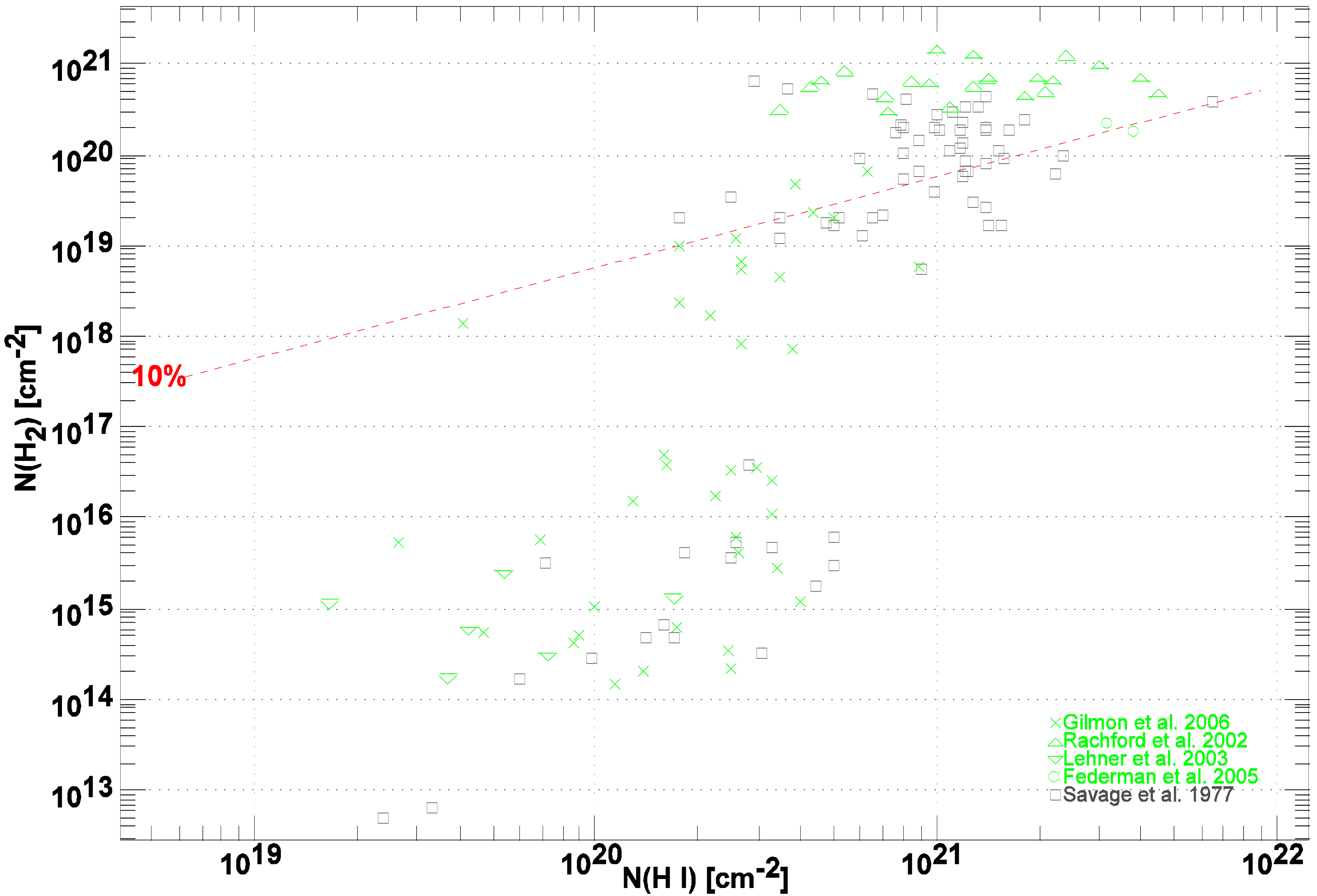


McKee&Ostriker 1977, ApJ 218,148;

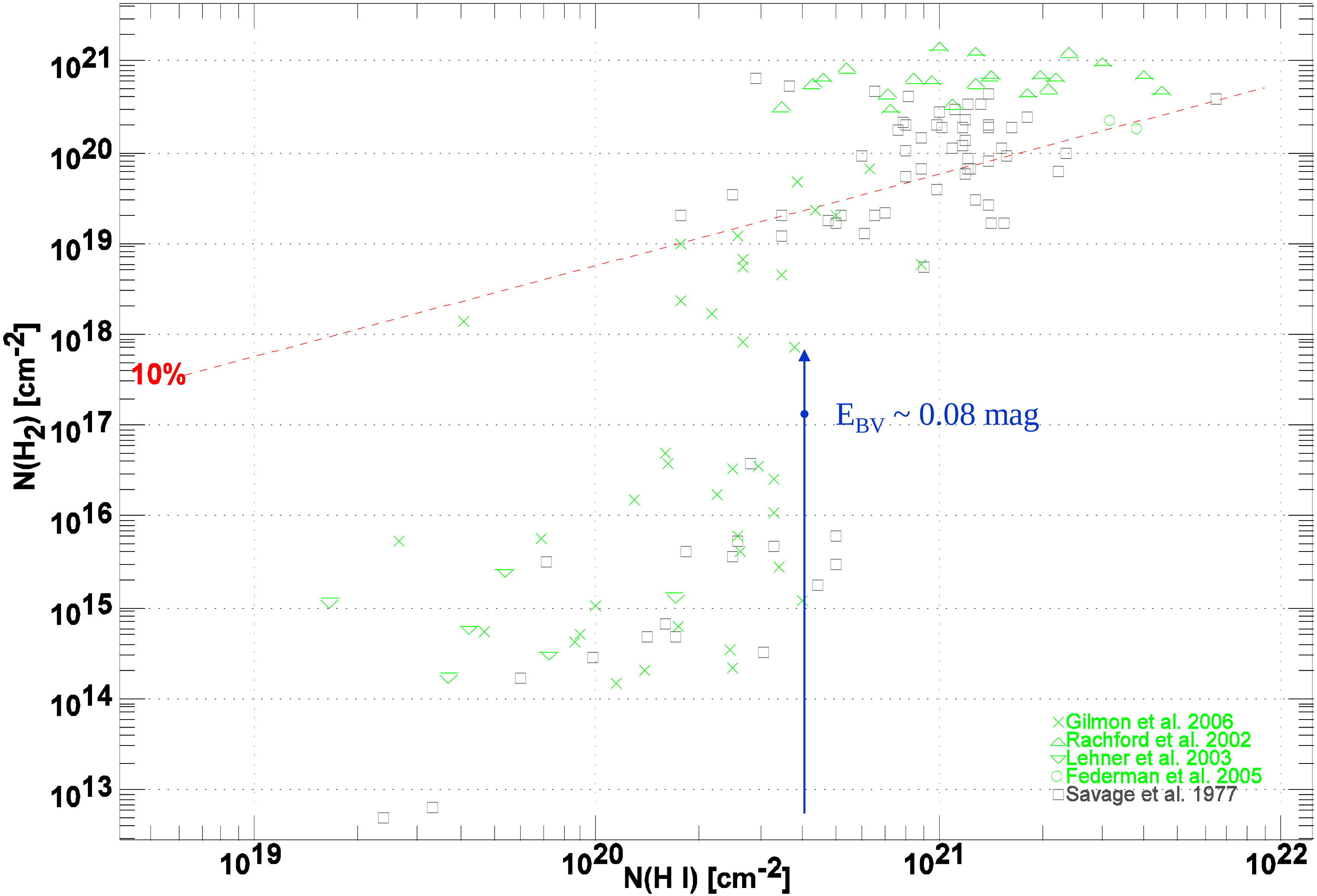
How is the H I mass divided up?

- *In the local disk mid-plane* CNM has
  - 1-2% of volume vs ~ 60% for HIM
  - 10,000 x higher density than HIM (for similar pressure nT)
  - *Where there is CNM it dominates the mass*
- *In the local disk mid-plane* CNM has
  - 1-2% of volume vs < 40% for WNM+WIM
  - 100 x higher density than Warm gas
  - Few times more <n(H)> than WNM+WIM

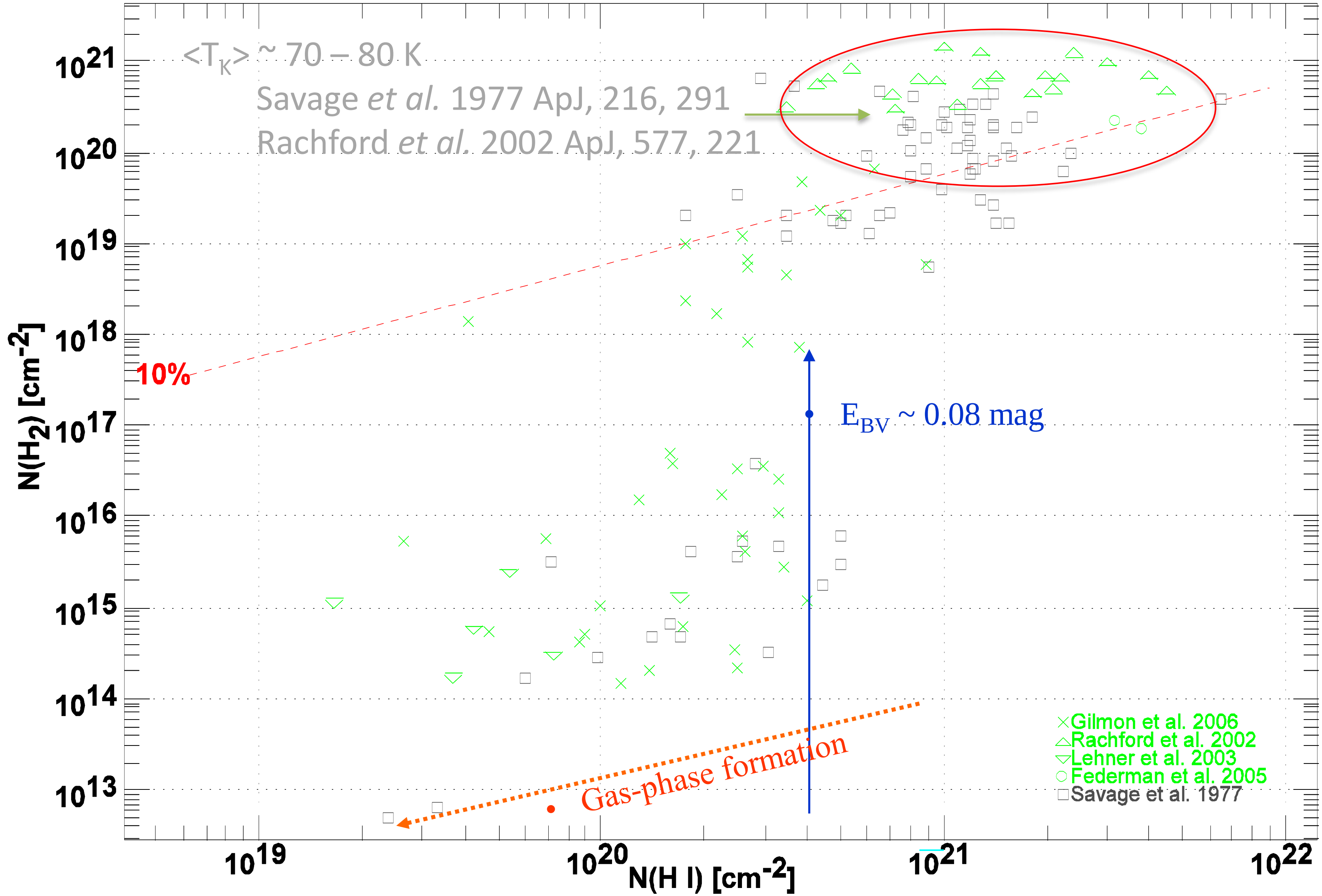
H I and H_2 in diffuse gas



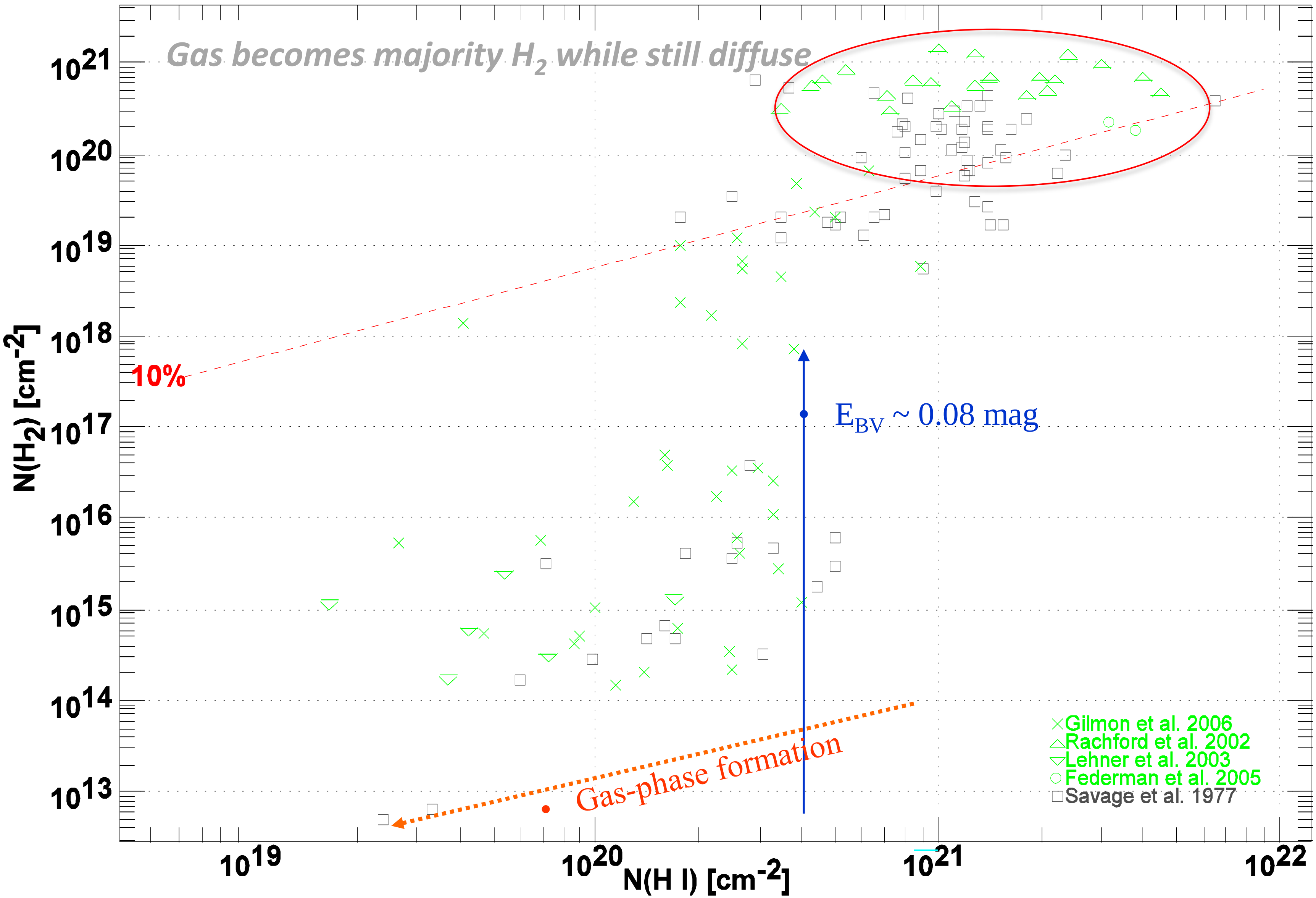
H I and H_2 in diffuse gas



H I and H_2 in diffuse gas

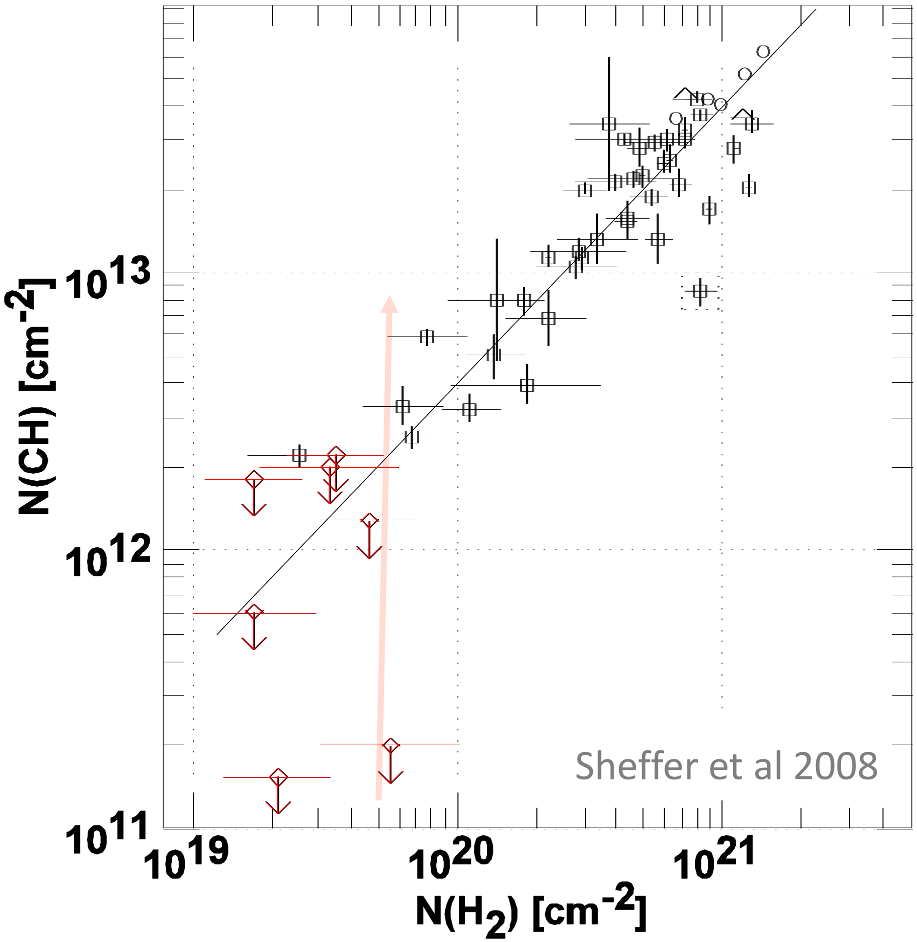


H I and H_2 in diffuse gas

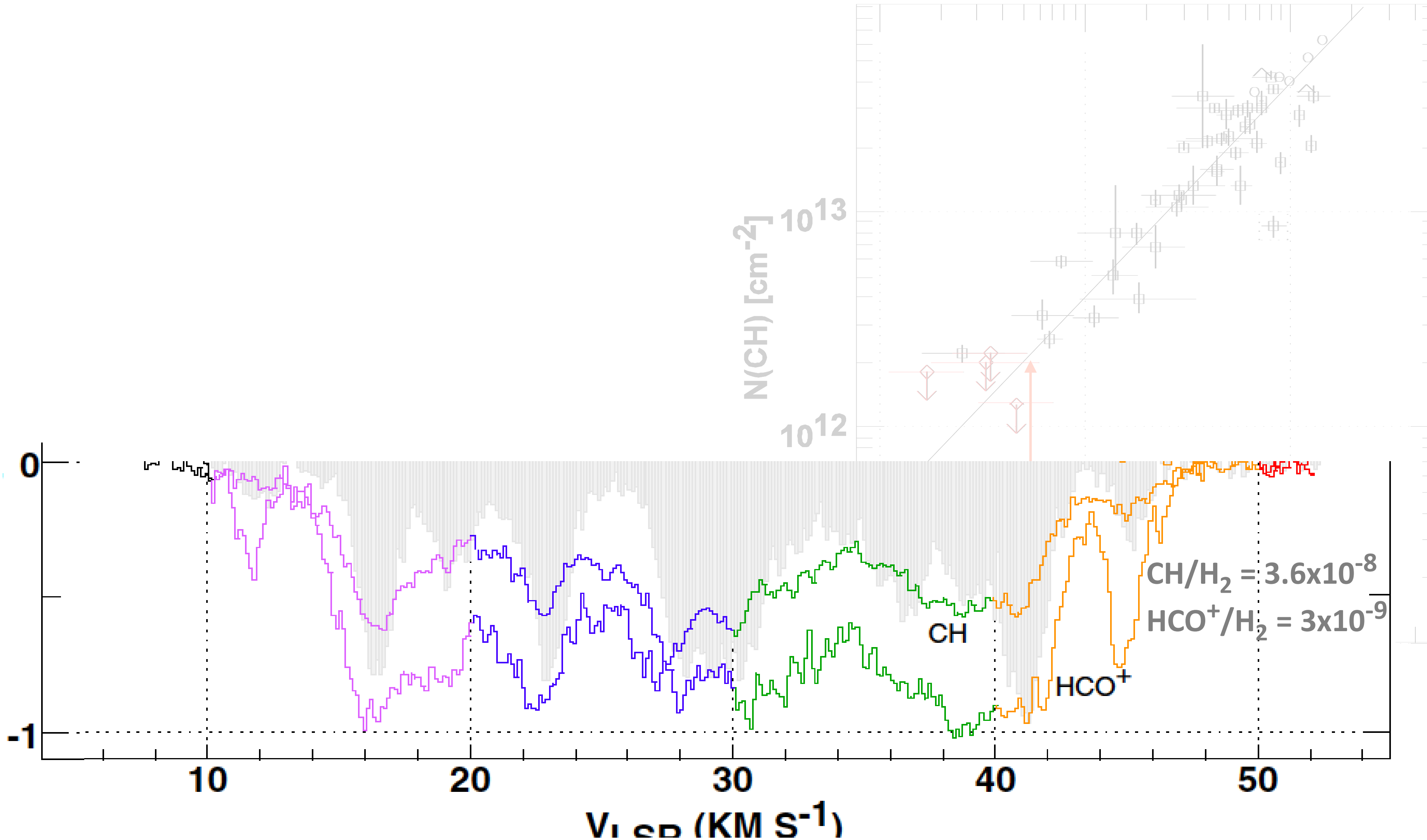


A touch of observational chemistry

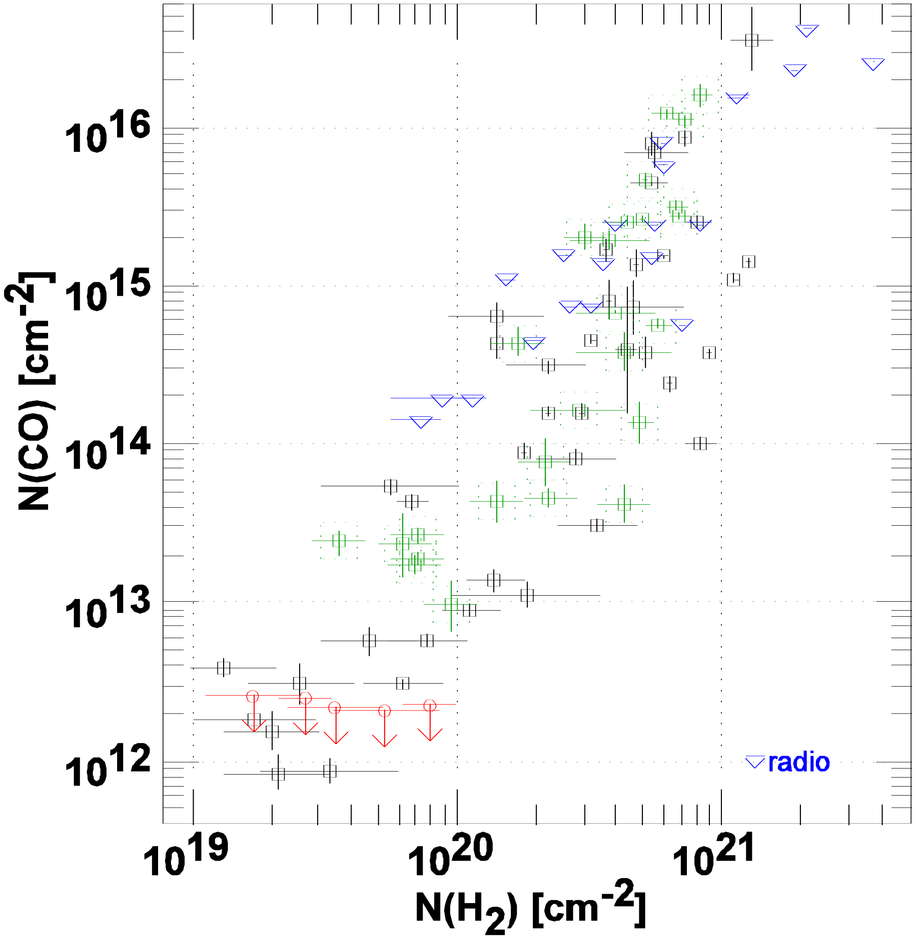
CH traces H_2 if $N(H_2) > 5x10^{19}$ cm^{-2}



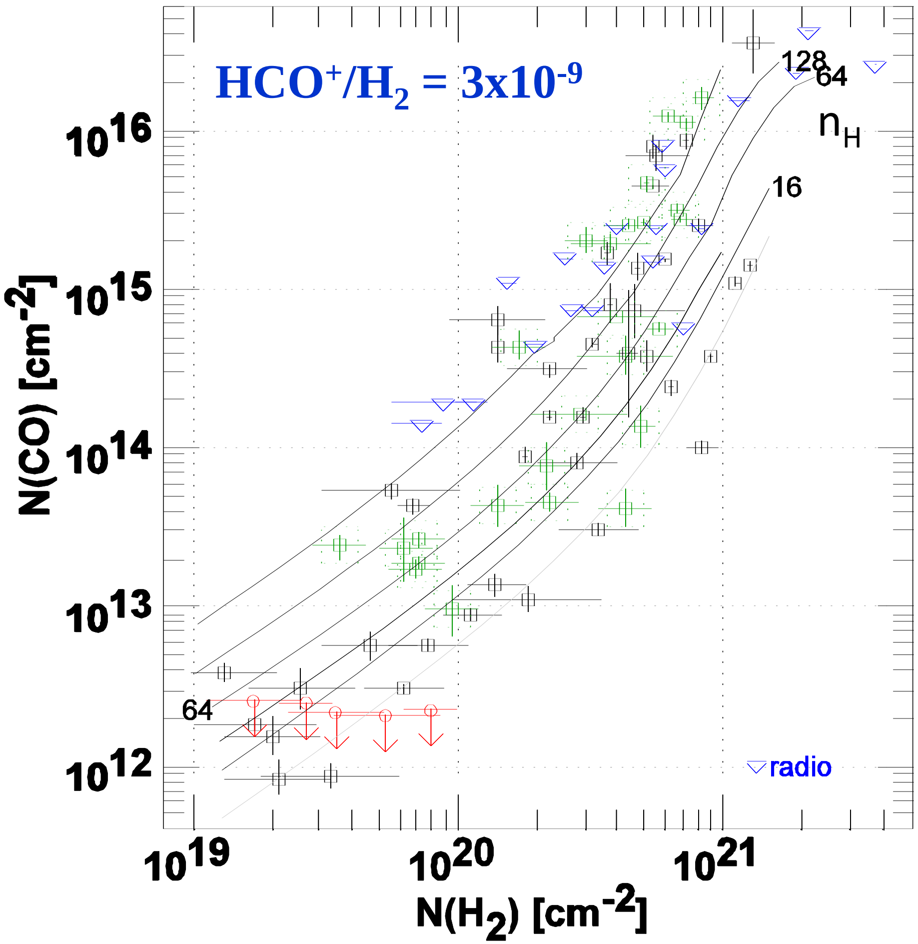
HCO^+/H_2 also fixed at $3x10^{-9}$



What about CO?

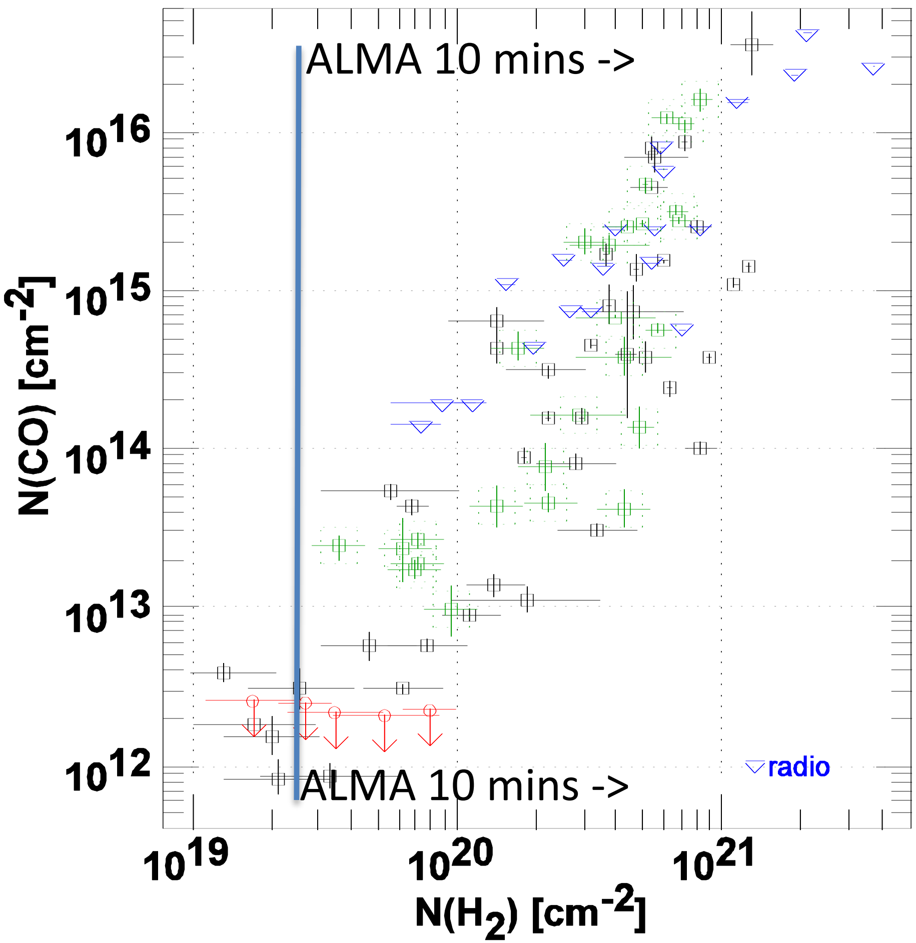


Presence of HCO⁺ explains CO

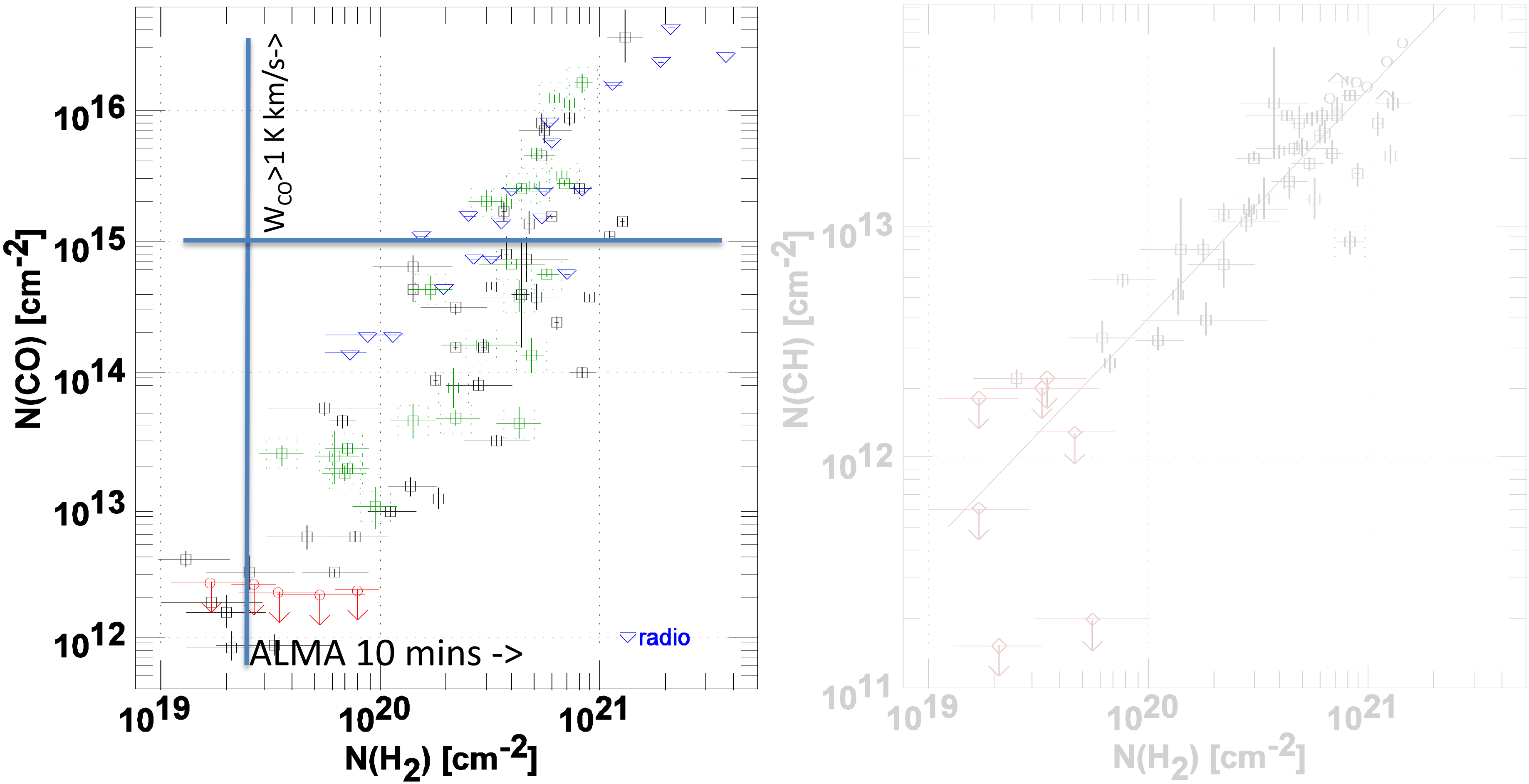


Liszt, 2007 A&A,476,291; Visser et al 2009, A&A, 503, 323

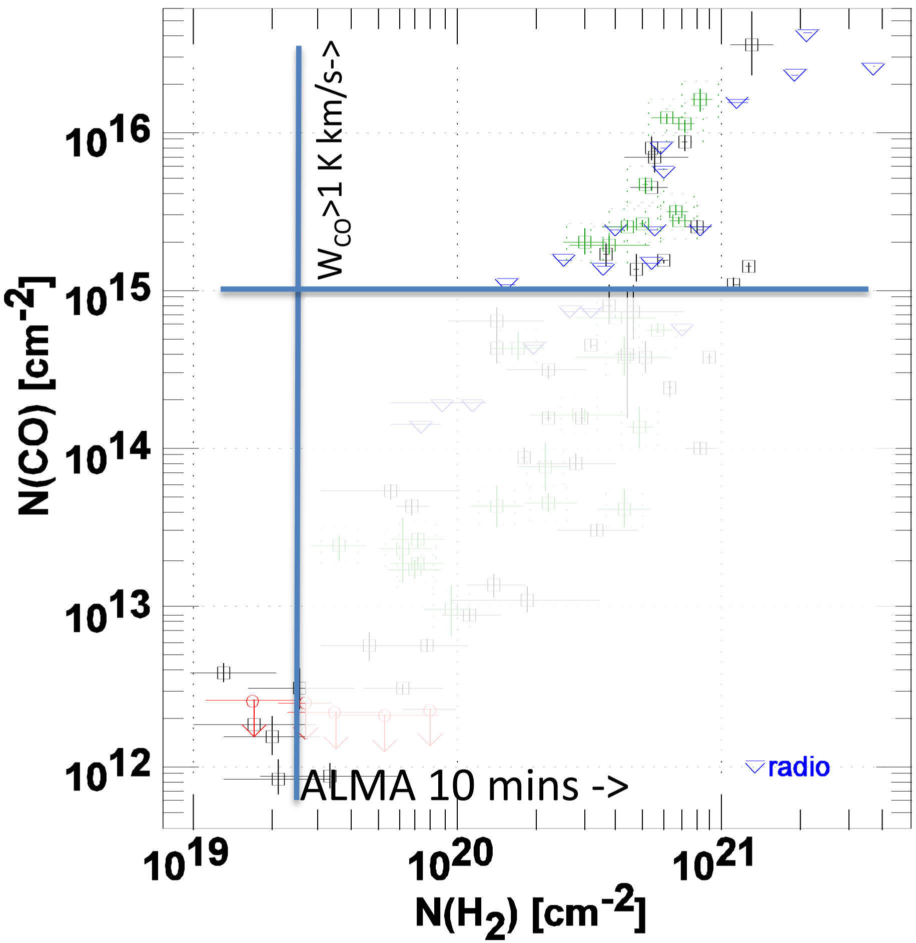
ALMA quick-look HCO^+ detection limit $N(H_2)$~$3x10^{19}$ cm^{-2}

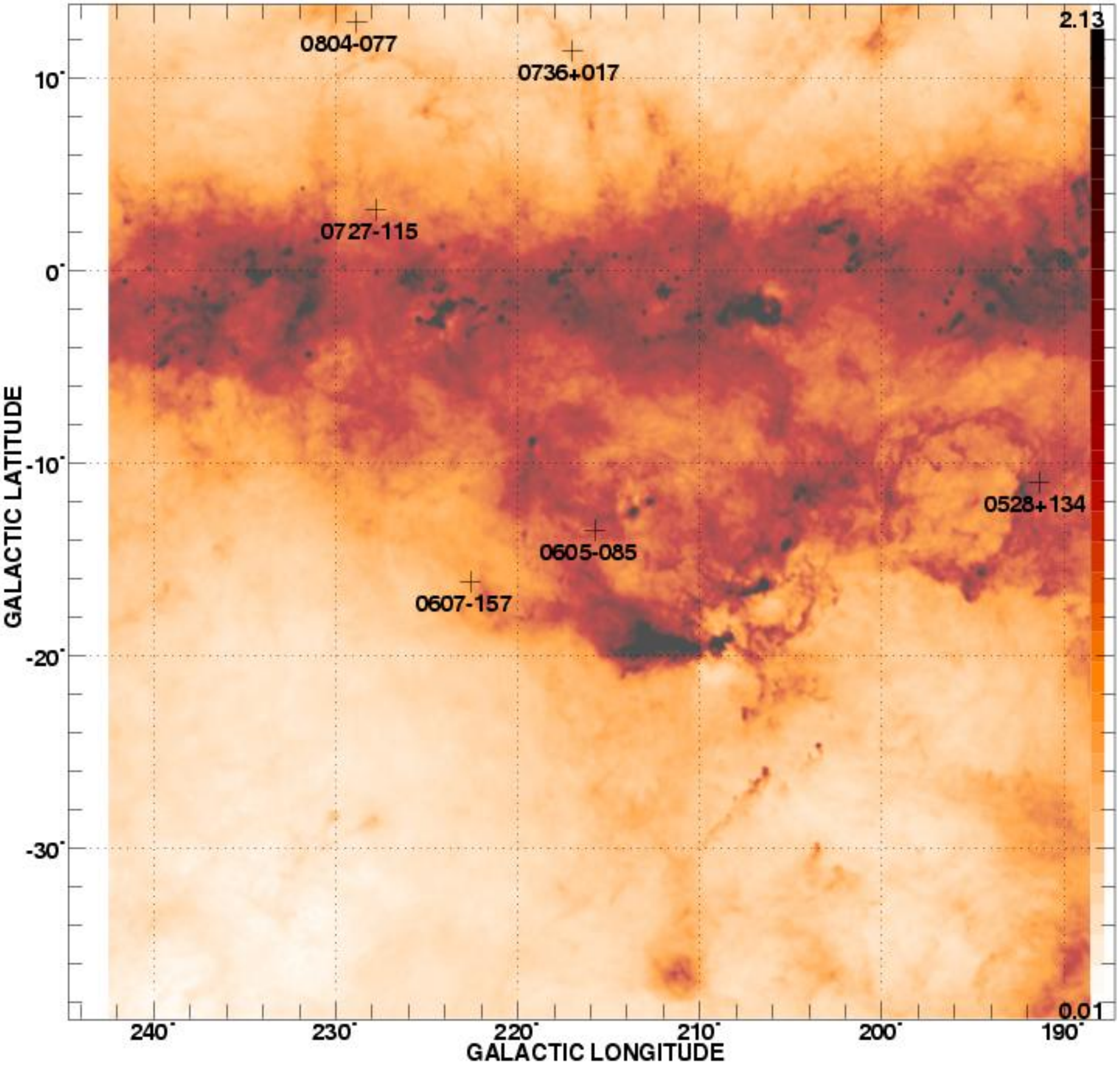


CO Survey Limit W_{CO} ~ 1 K-km/s



Much diffuse molecular gas only visible in absorption

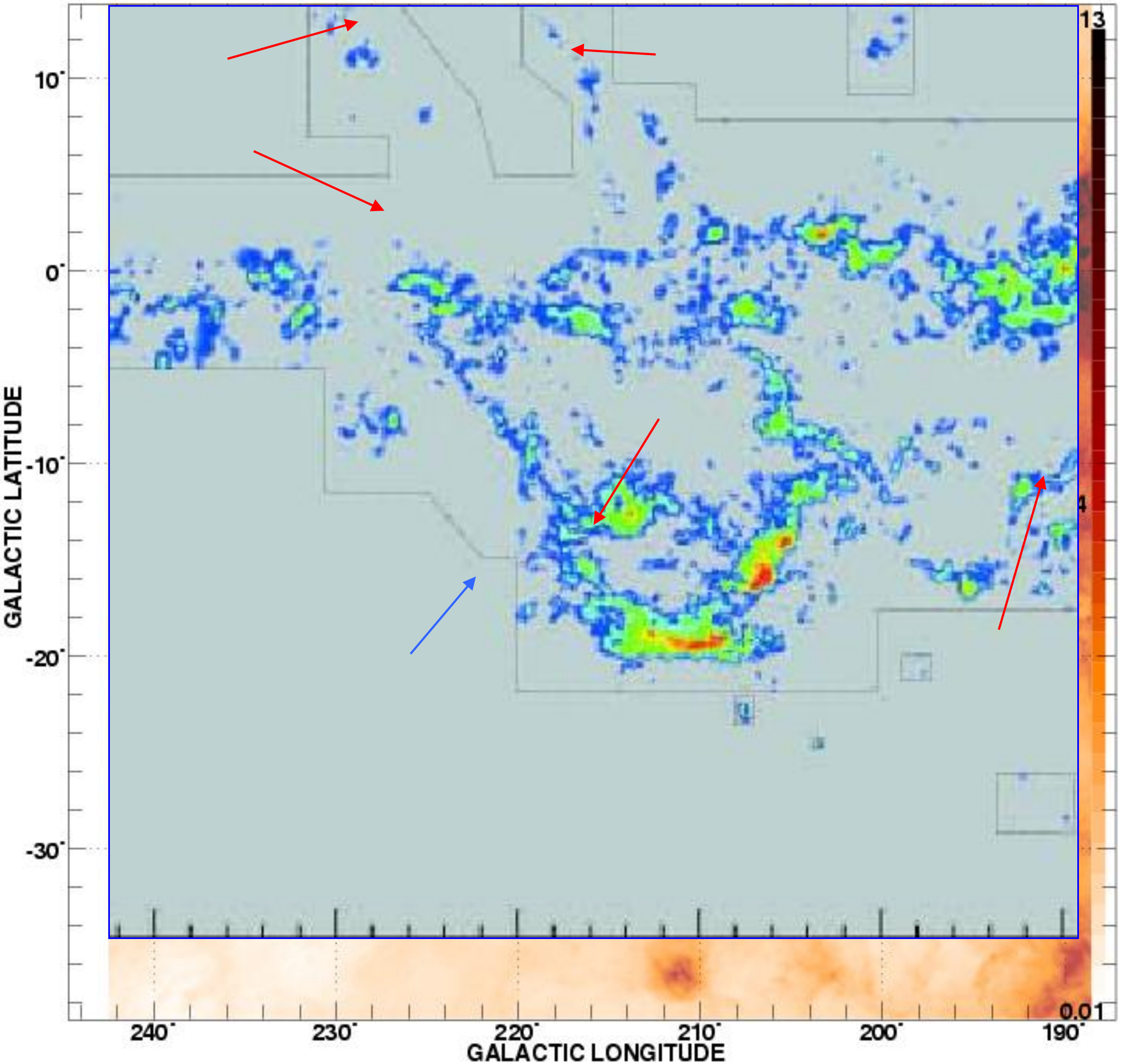




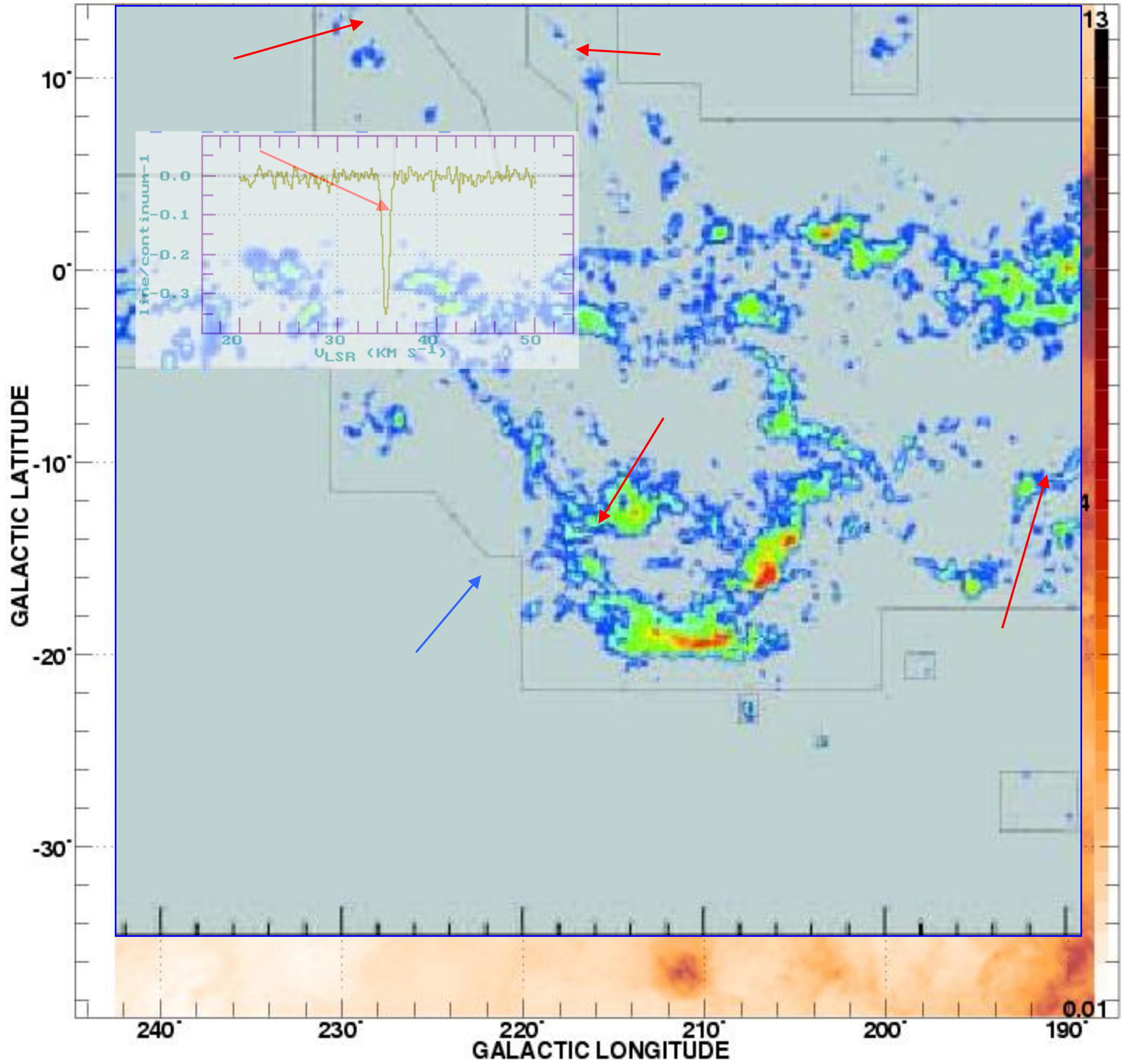
Monoceros in E_{B-V}

Monoceros in CO

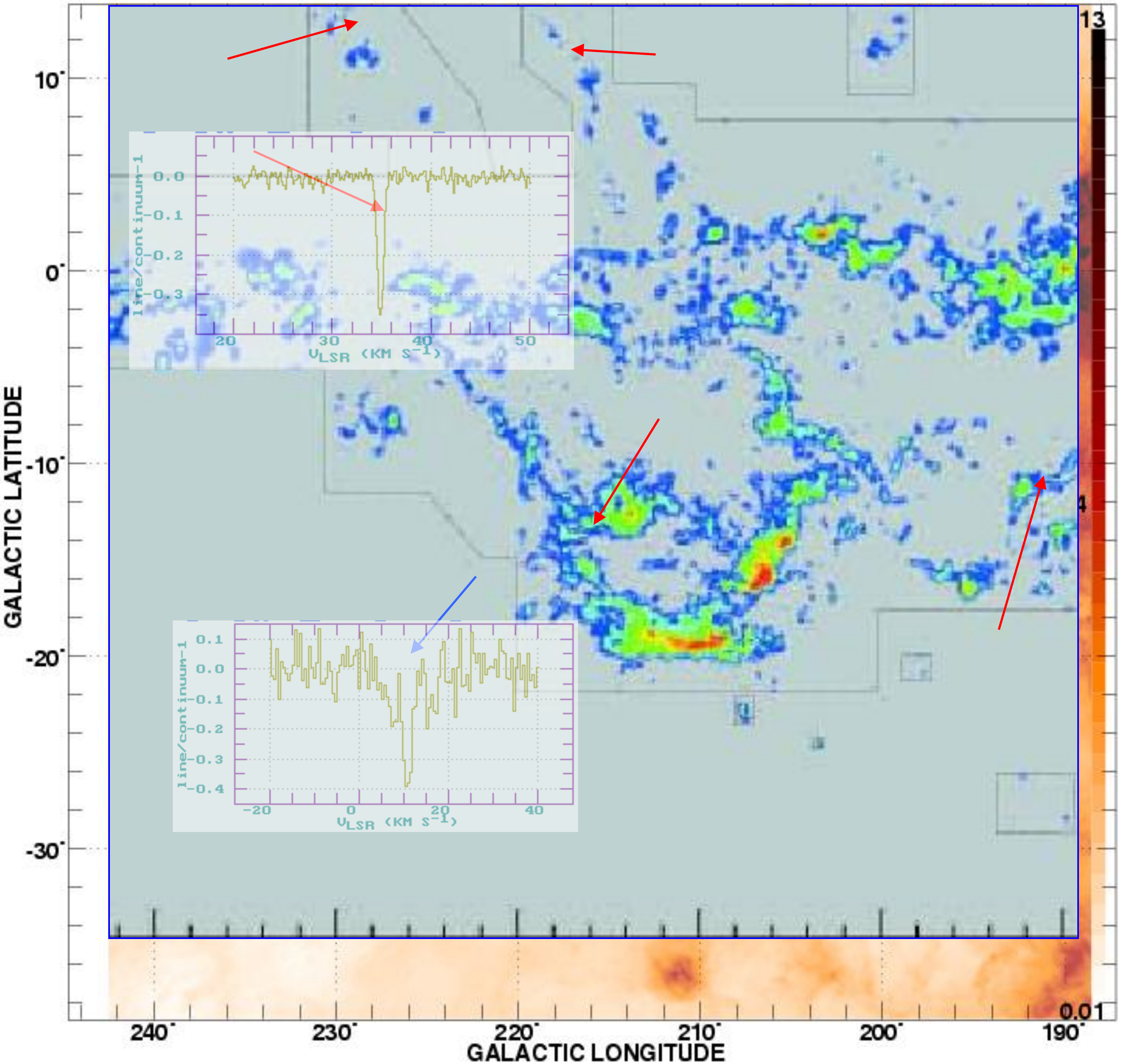
(Hartmann, Dame, Thaddeus 2000)



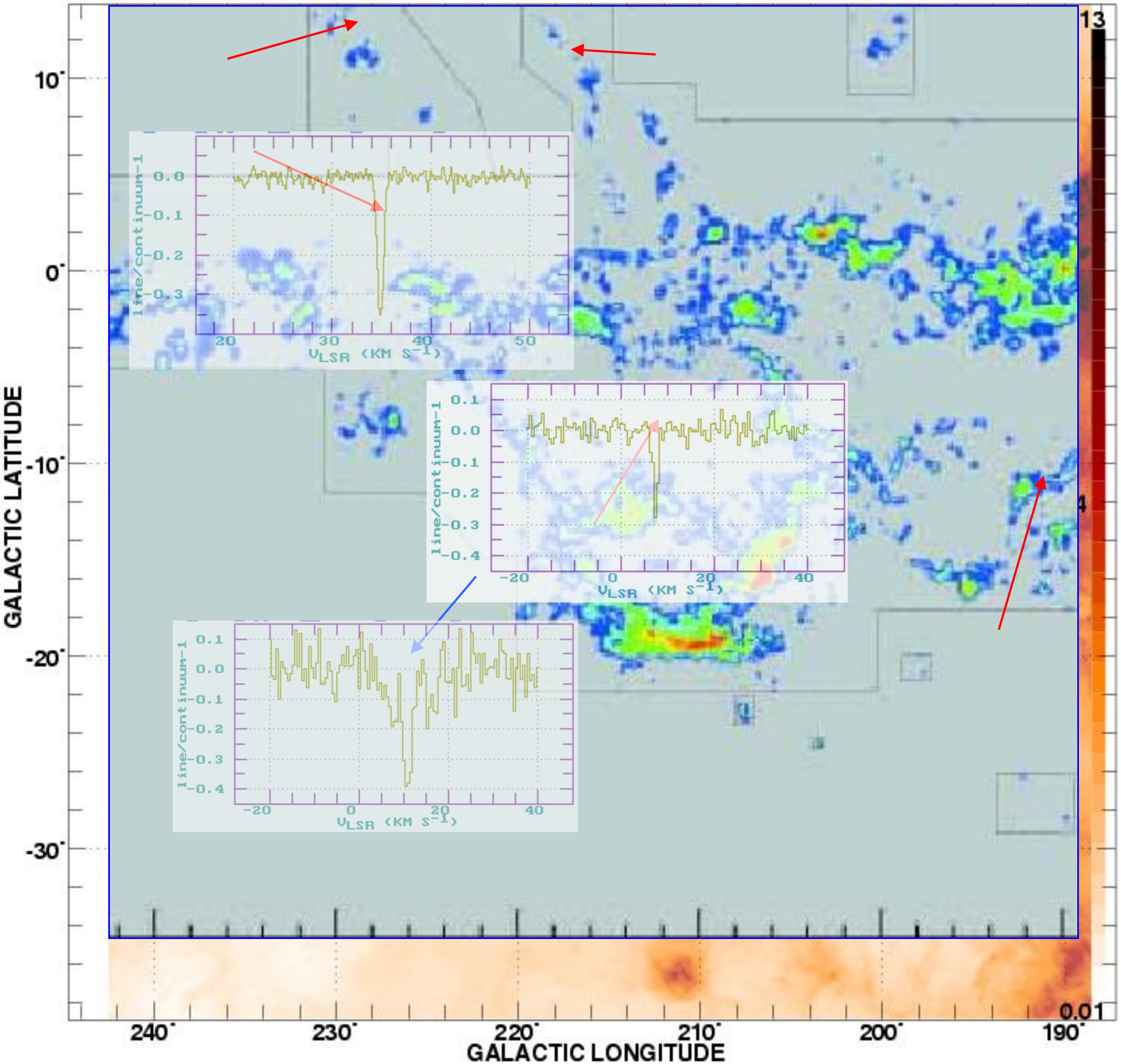
Monoceros in CO & HCO$^+$



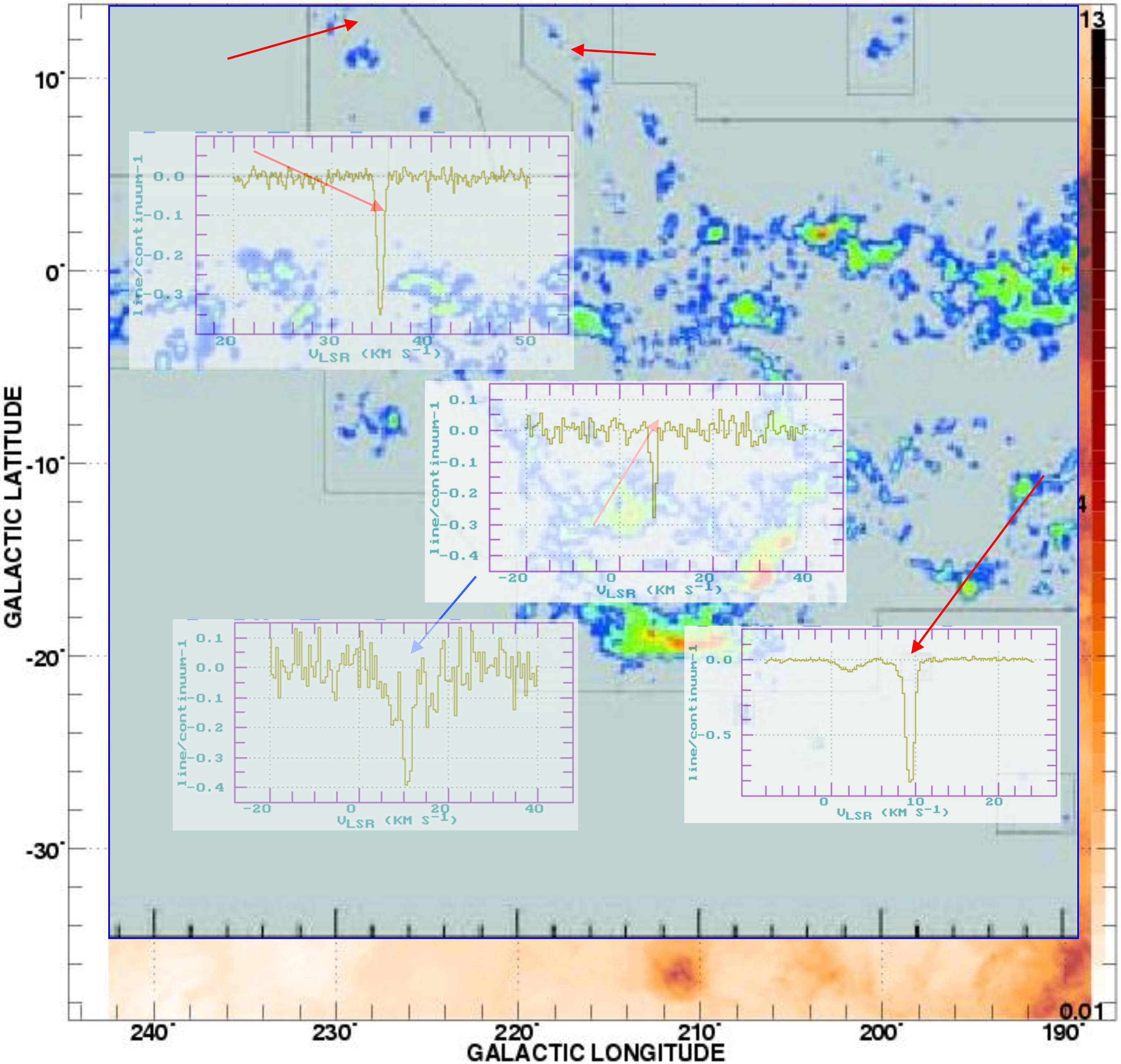
Monoceros in CO & HCO^+



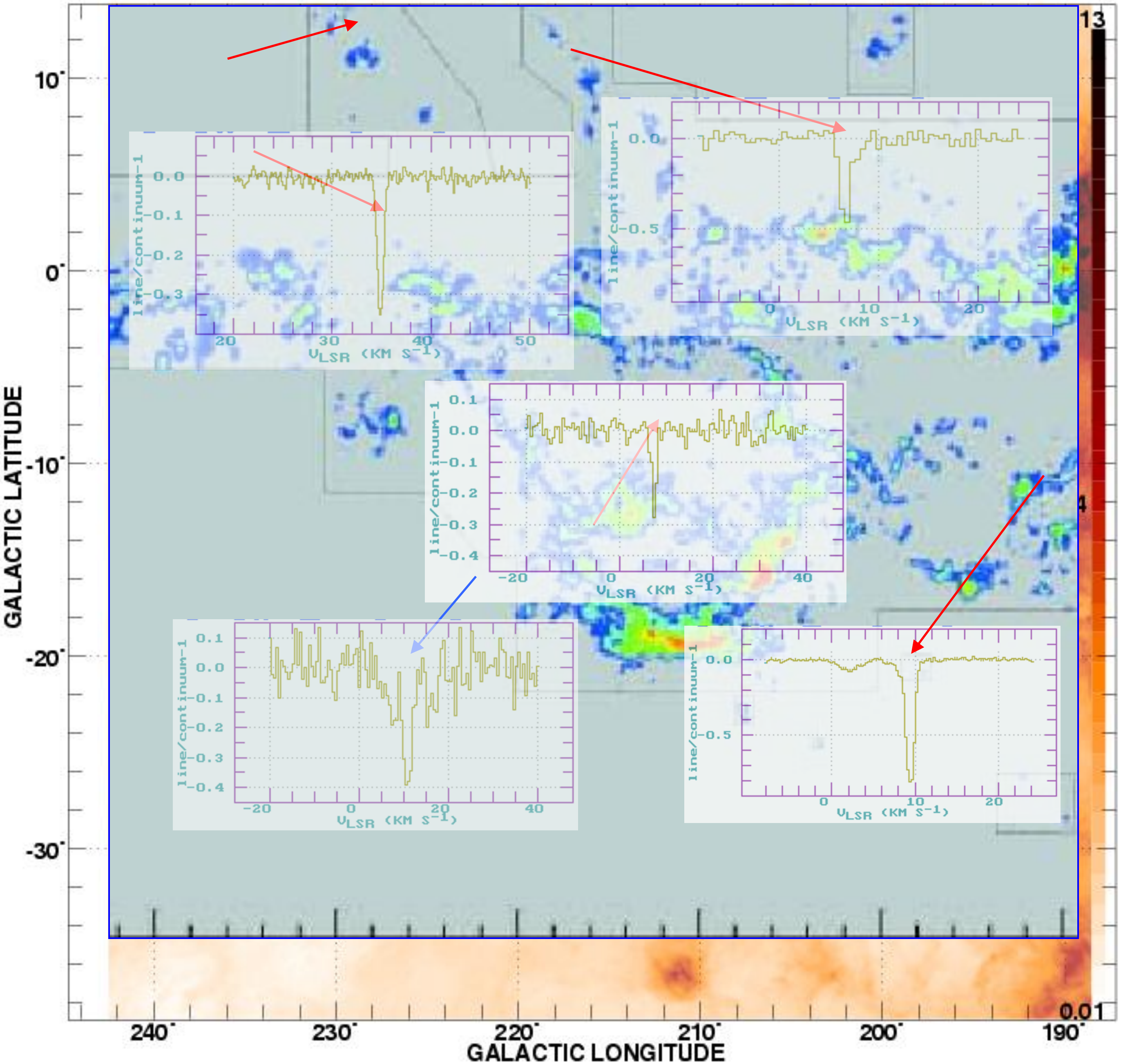
Monoceros in CO & HCO^+

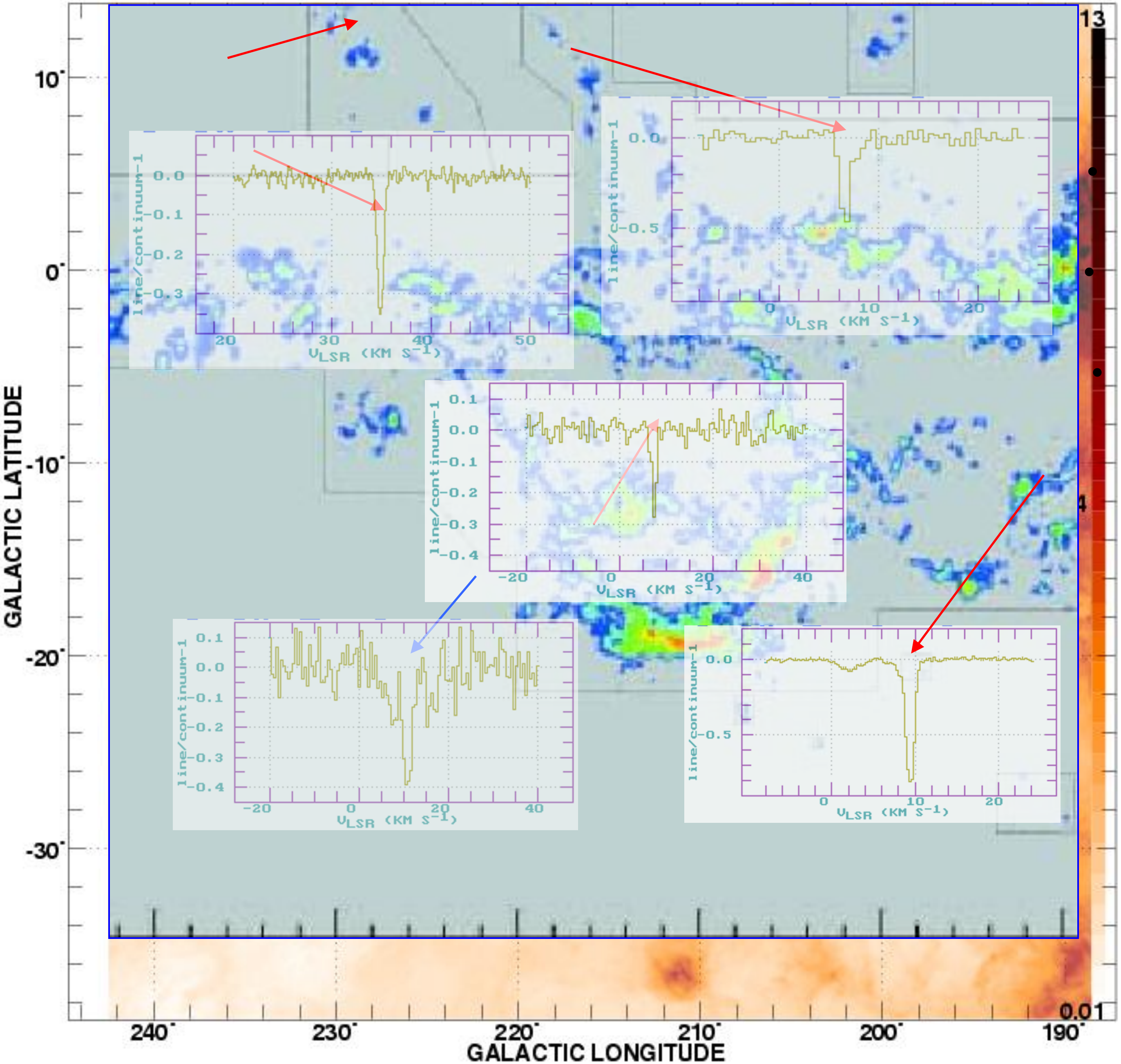


Monoceros in CO & HCO^+



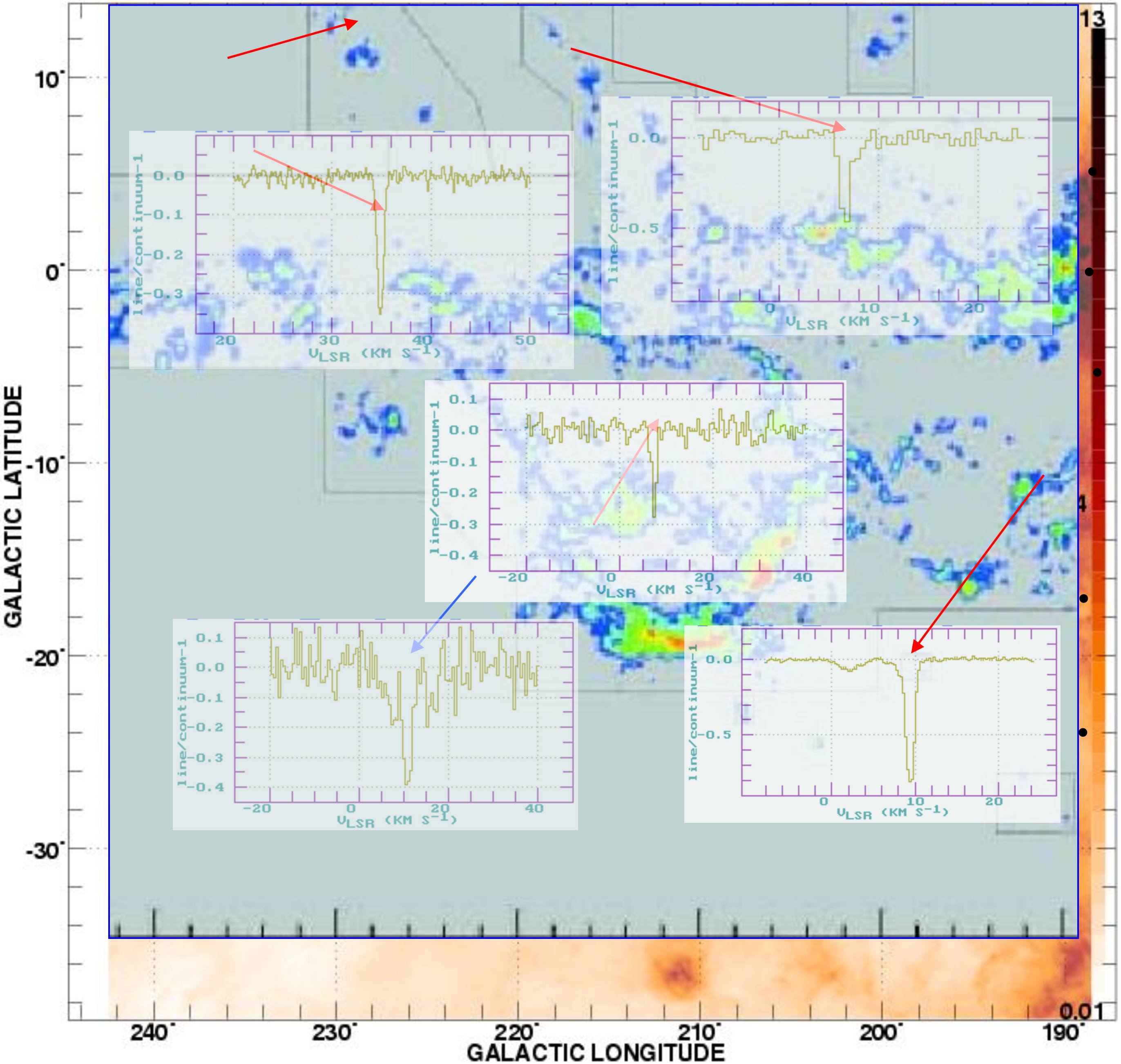
Monoceros in CO & HCO^+





Monoceros in CO & HCO^+

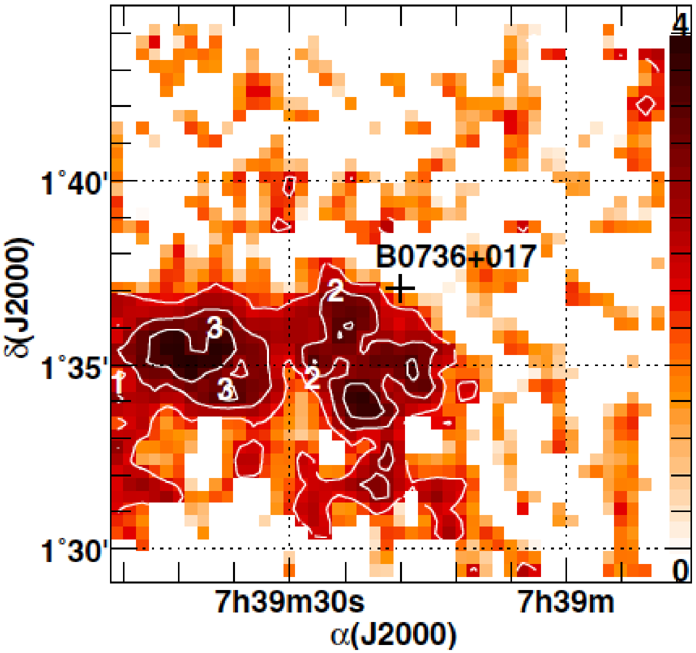
- H_2 not fully traced by CO
- $N(H_2)$ ~ same w/, w/o CO
- CO emission in this map at $W_{CO} < 10$ K km/s is from diffuse molecular gas

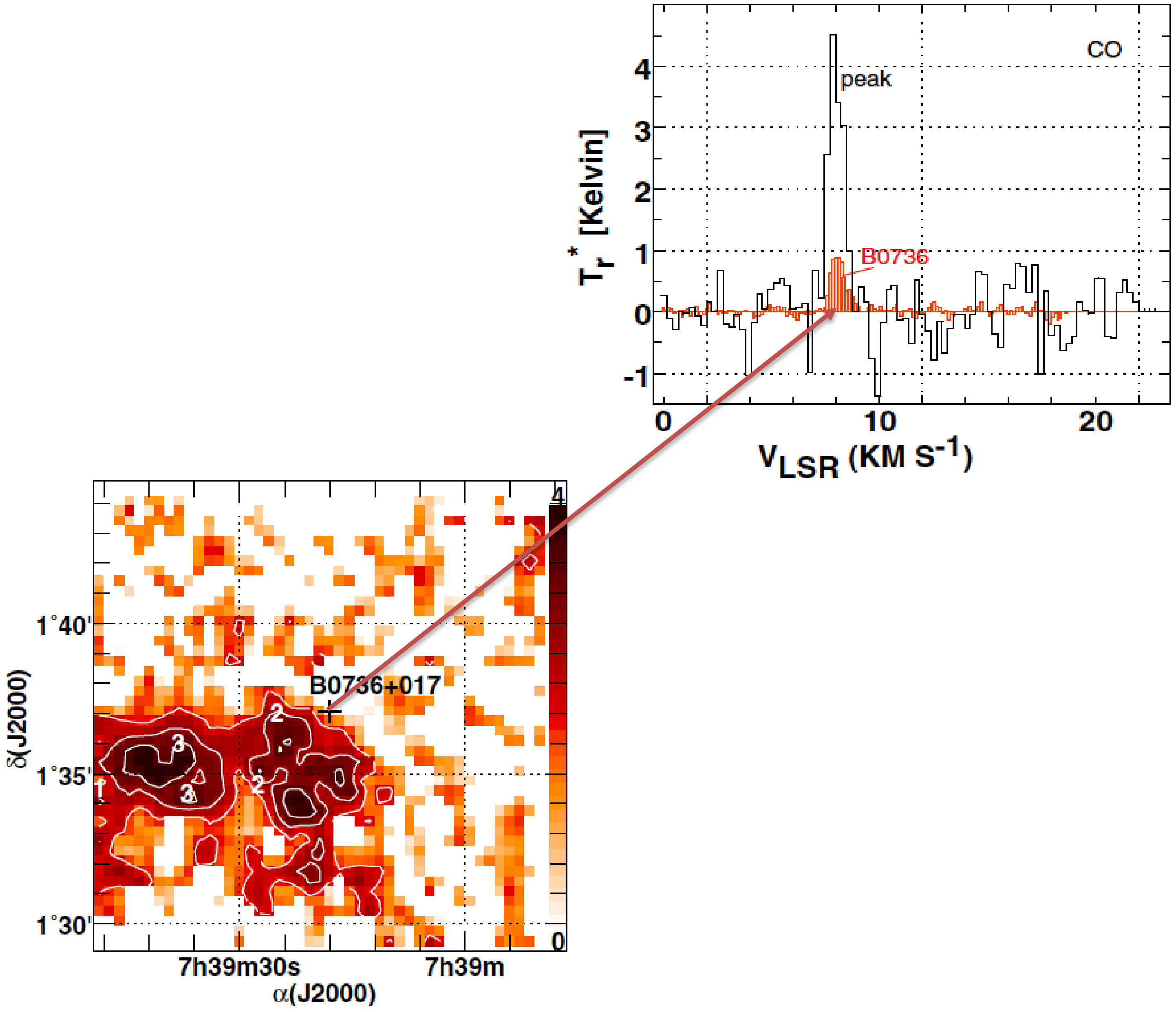


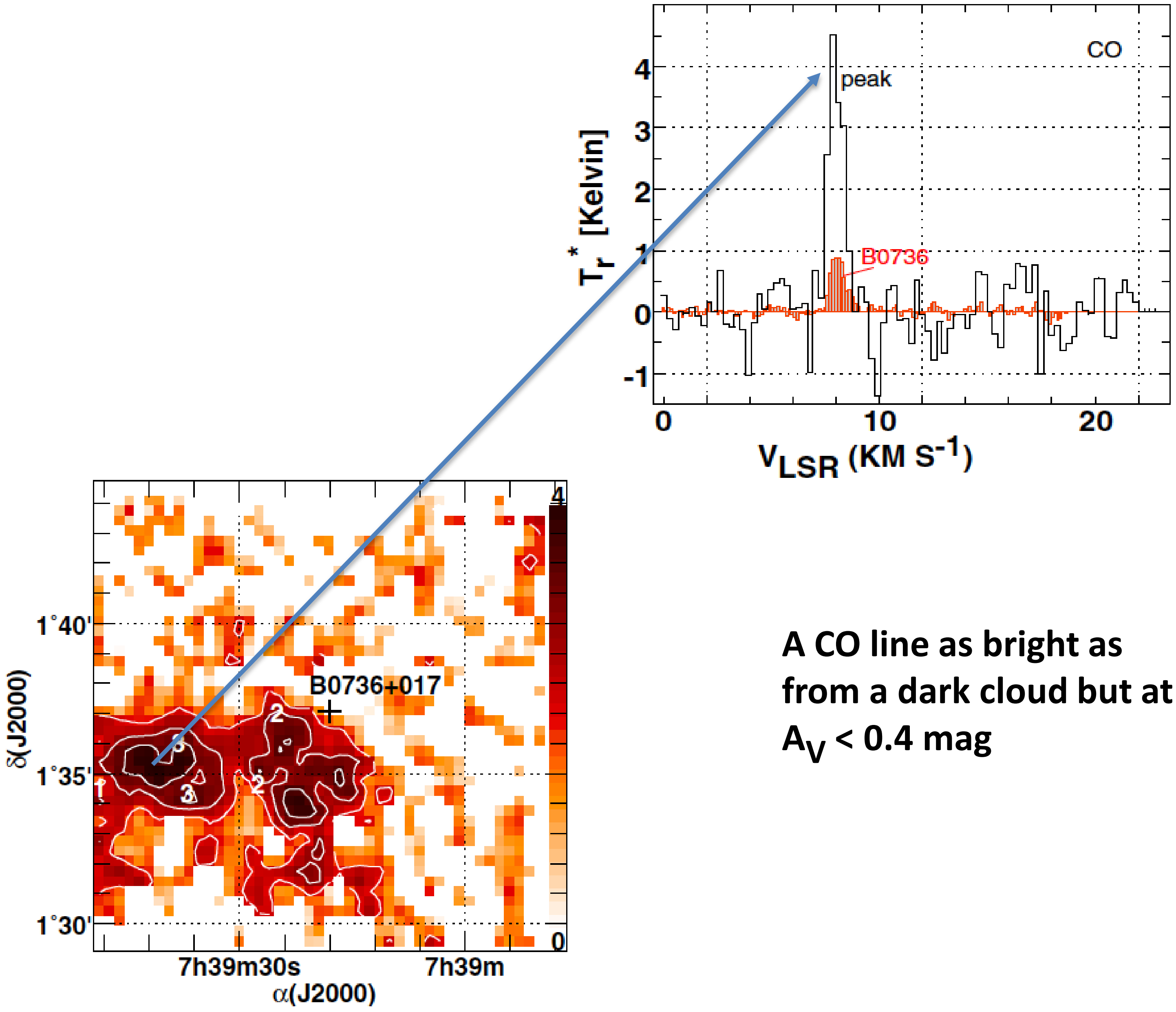
Monoceros in CO & HCO^+

- H_2 not fully traced by CO
- $N(H_2)$ ~ same w/, w/o CO
- CO emission in this map at $W_{CO} < 10$ K km/s is from diffuse molecular gas
- **The CO sky is an image of the CO chemistry**, **not the H_2 mass**

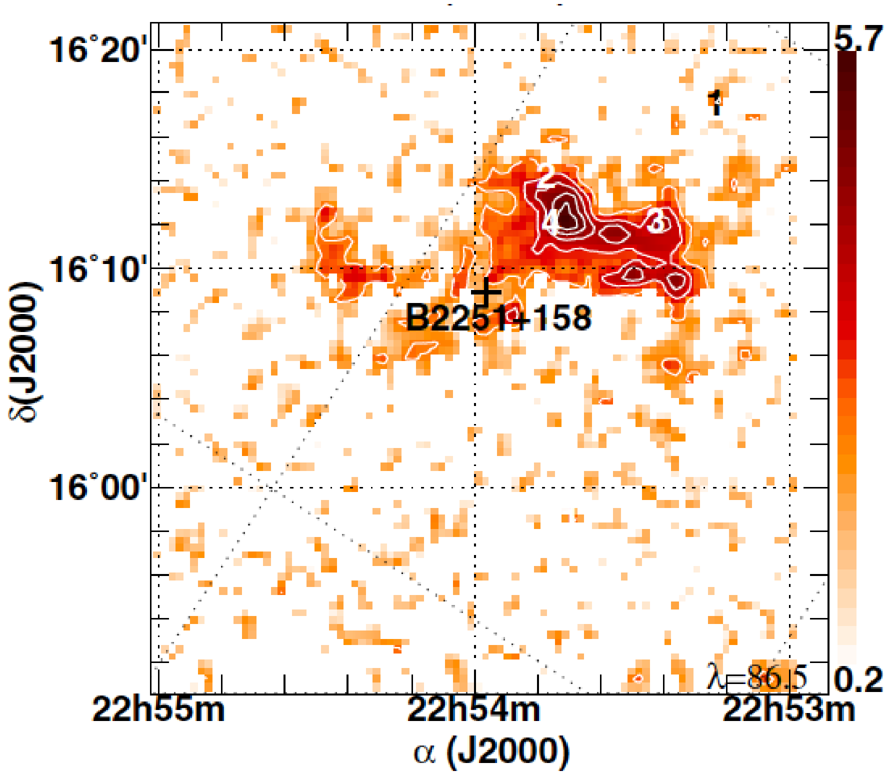
A closer look around B0736 and B2251



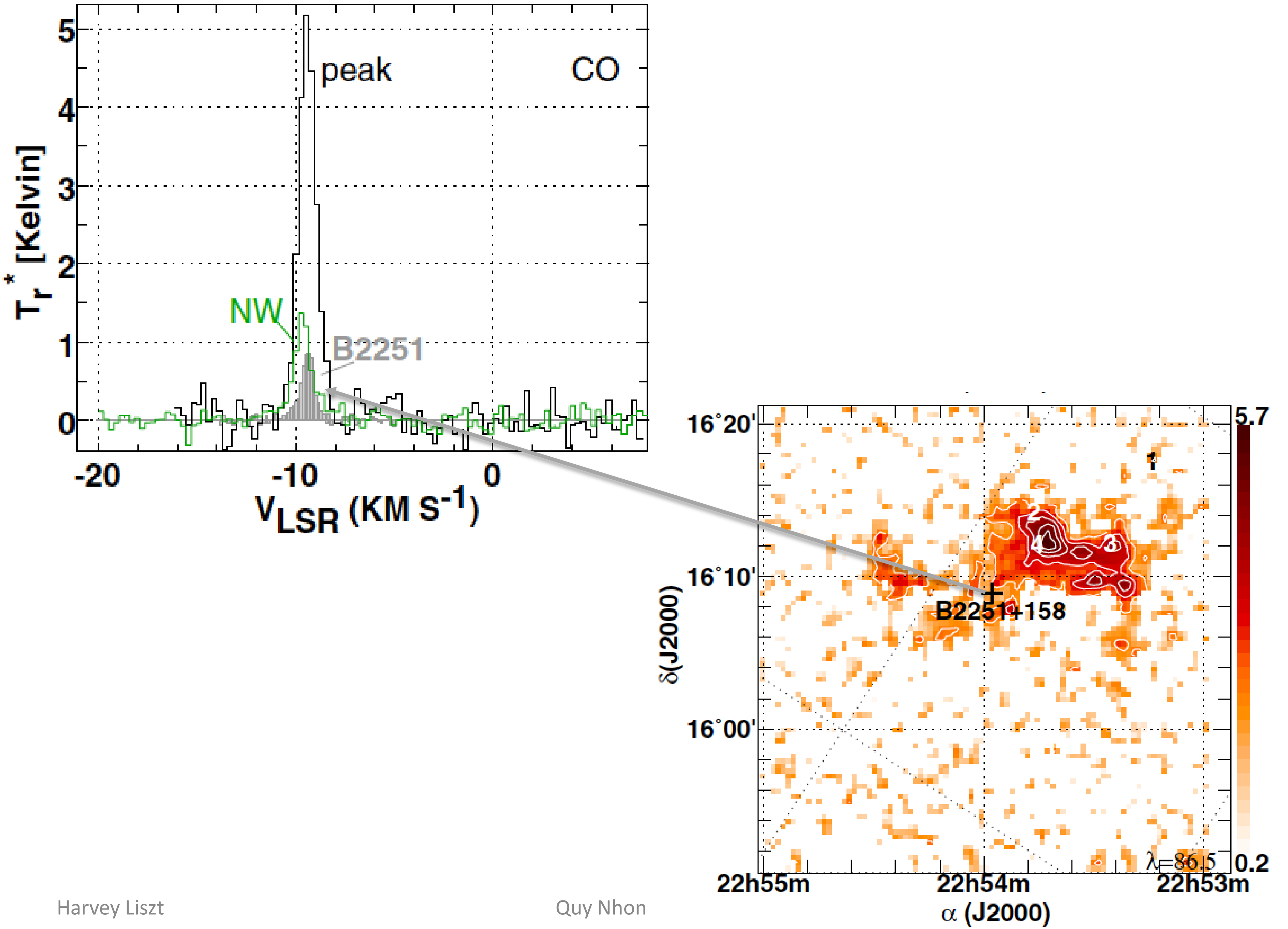

CO
peak
B0736
T_r^* [Kelvin]
V_{LSR} (KM S^{-1})
B0736+017
1°40'
1°35'
1°30'
δ(J2000)
7h39m30s
7h39m
α(J2000)



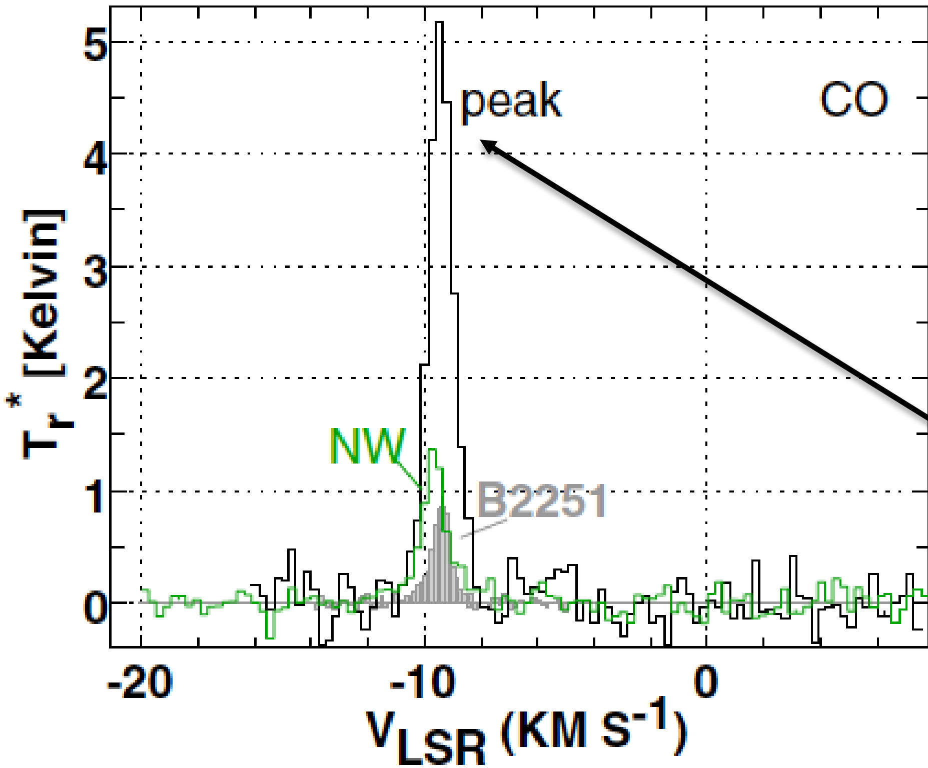
A CO line as bright as from a dark cloud but at $A_V < 0.4$ mag

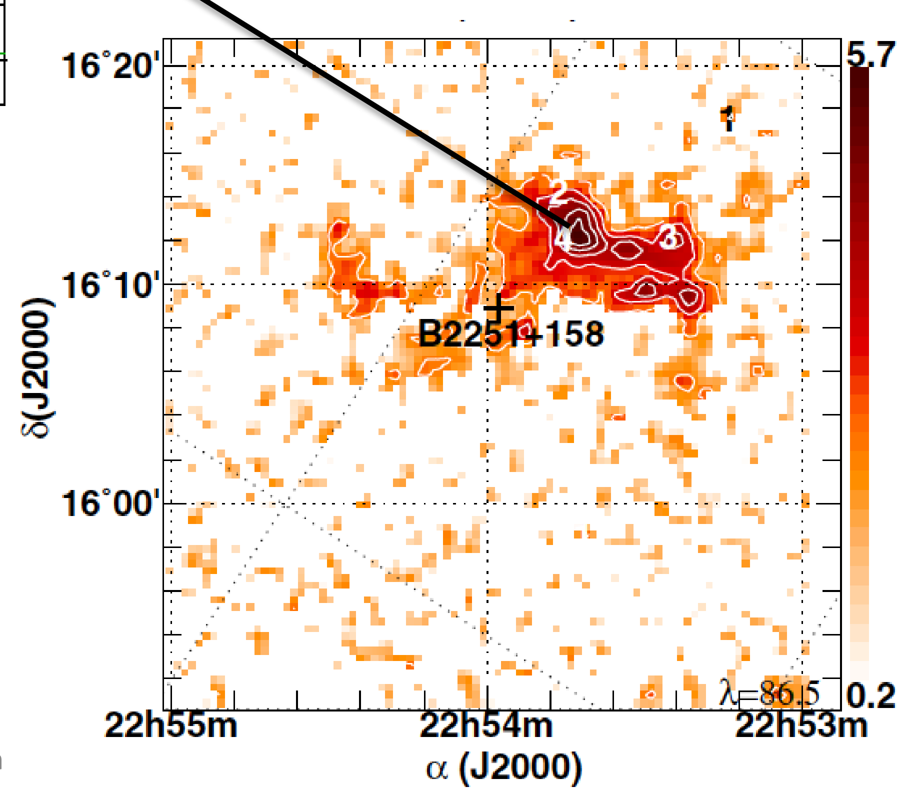


16°20'
16°10'
16°00'
δ(J2000)
22h55m
22h54m
22h53m
α (J2000)
B2251+158
1
2
3
4
5.7
0.2
λ=86.5



CO
peak
NW
B2251
T_r^* [Kelvin]
V_{LSR} (KM S^{-1})
-20
-10
0
0
1
2
3
4
5
16°20'
16°10'
16°00'
δ(J2000)
B2251+158
22h55m
22h54m
22h53m
α (J2000)
5.7
0.2
λ=86.5

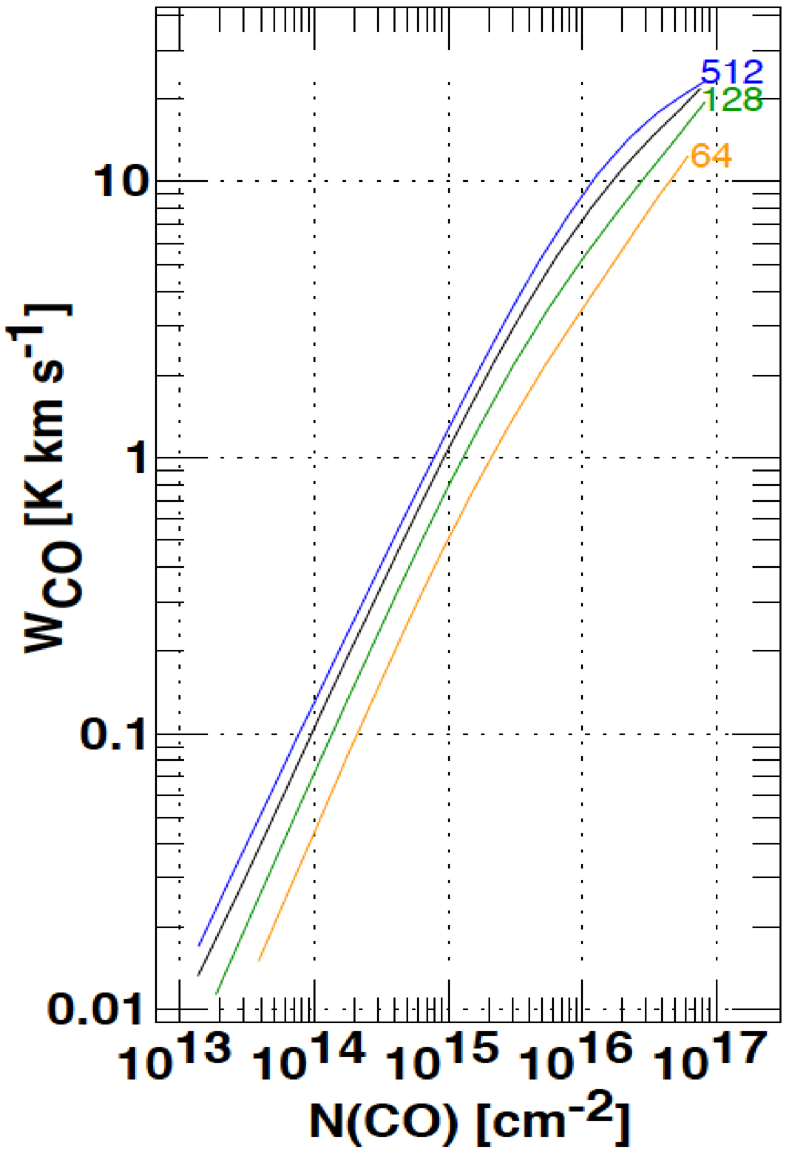




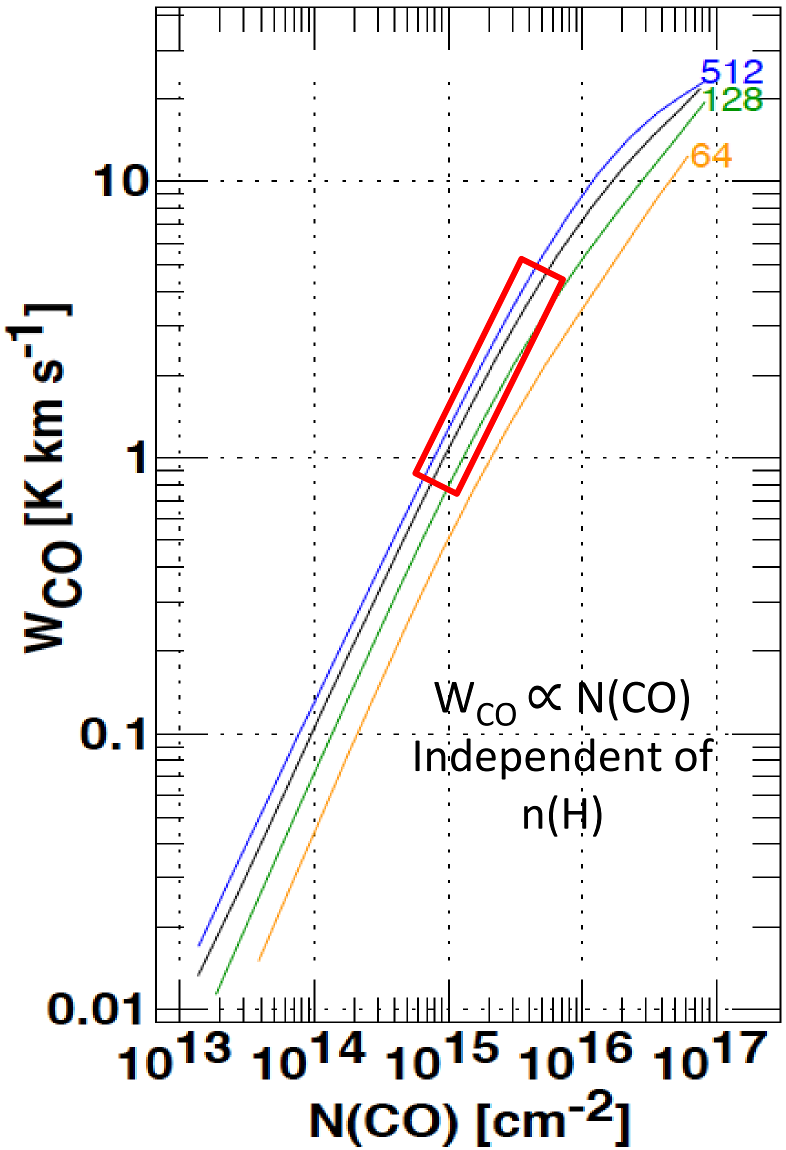
Liszt & Pety, 2012, A&A, 541A, 58

Why CO so bright, variable?

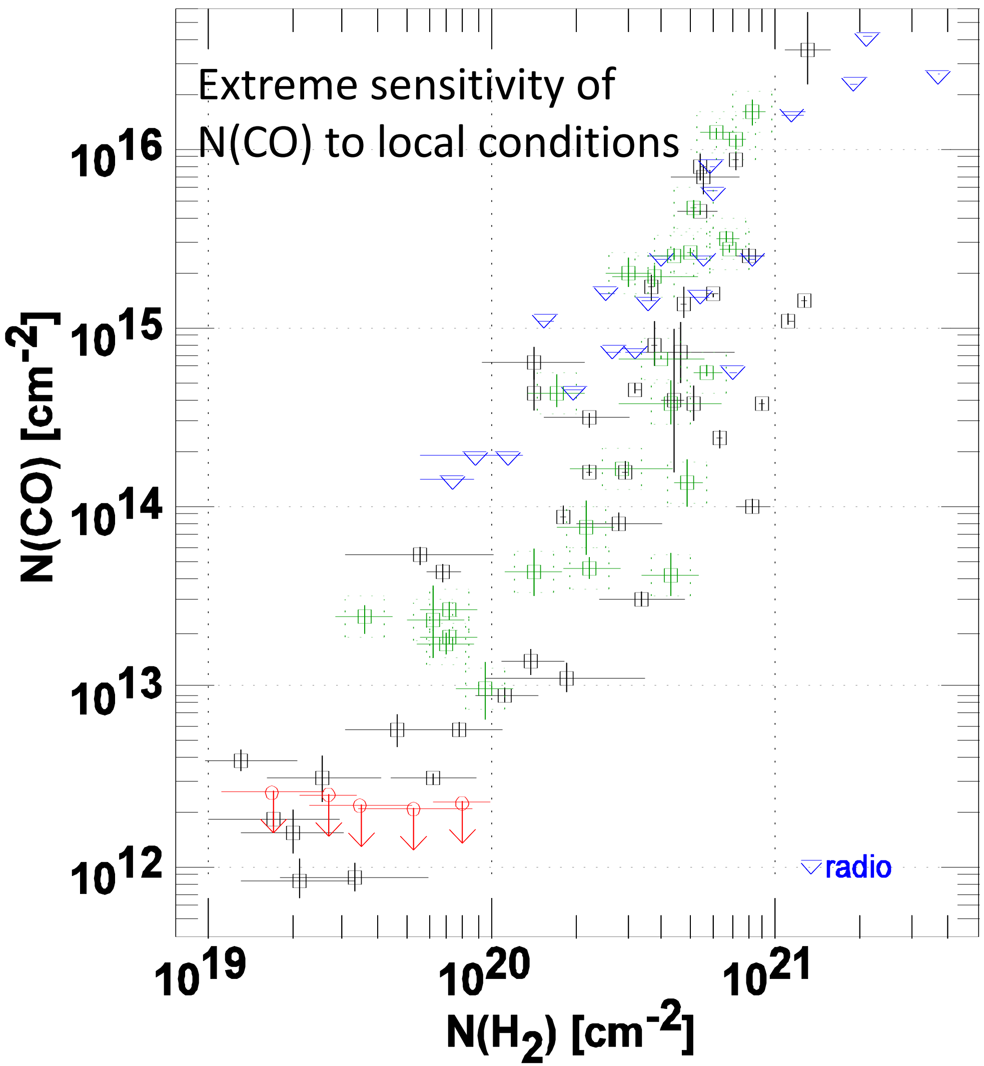
Why CO so bright, variable?

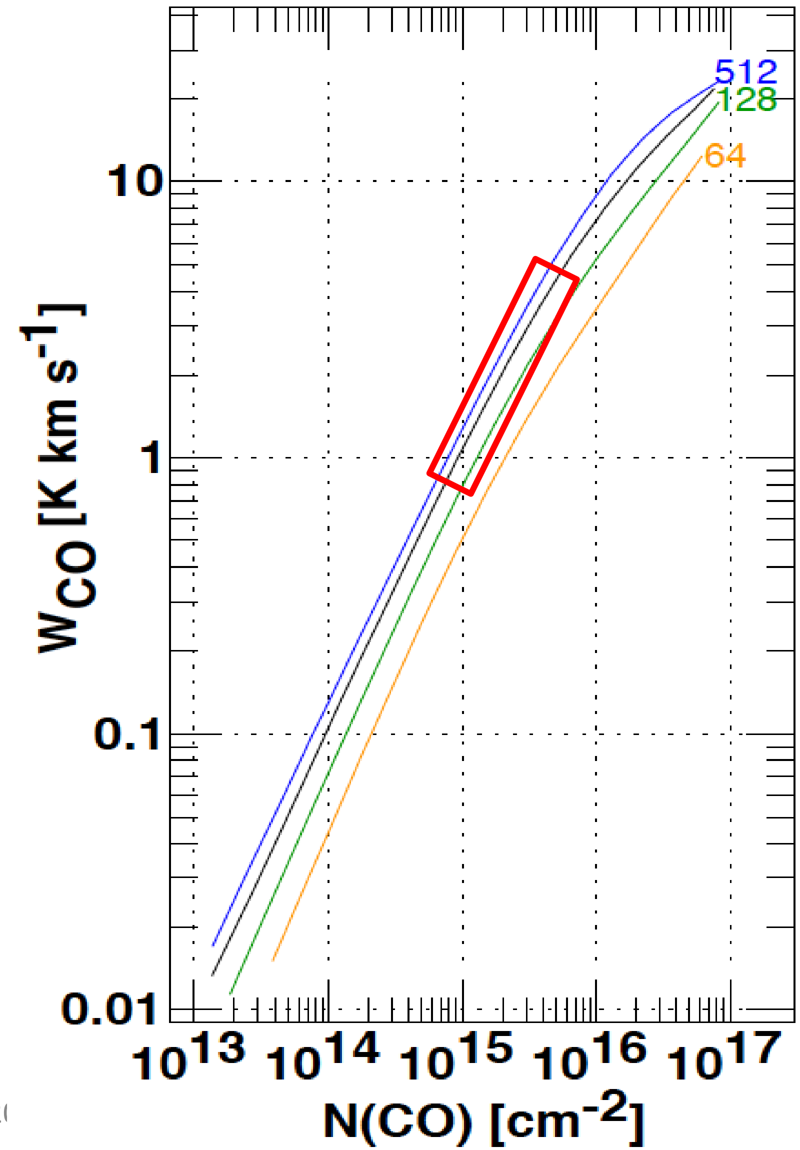


Why CO so bright, variable?

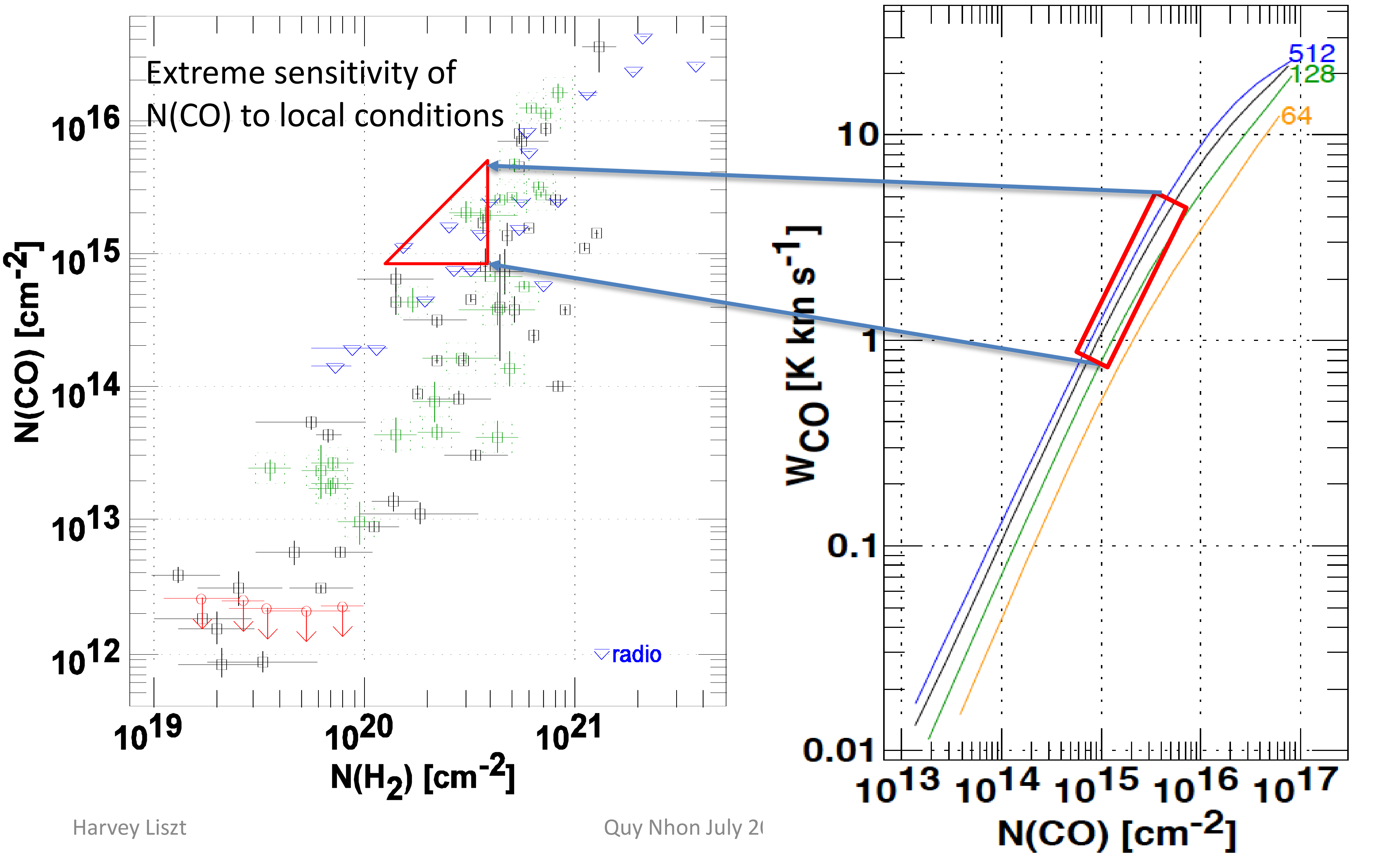


Why CO so bright, variable?





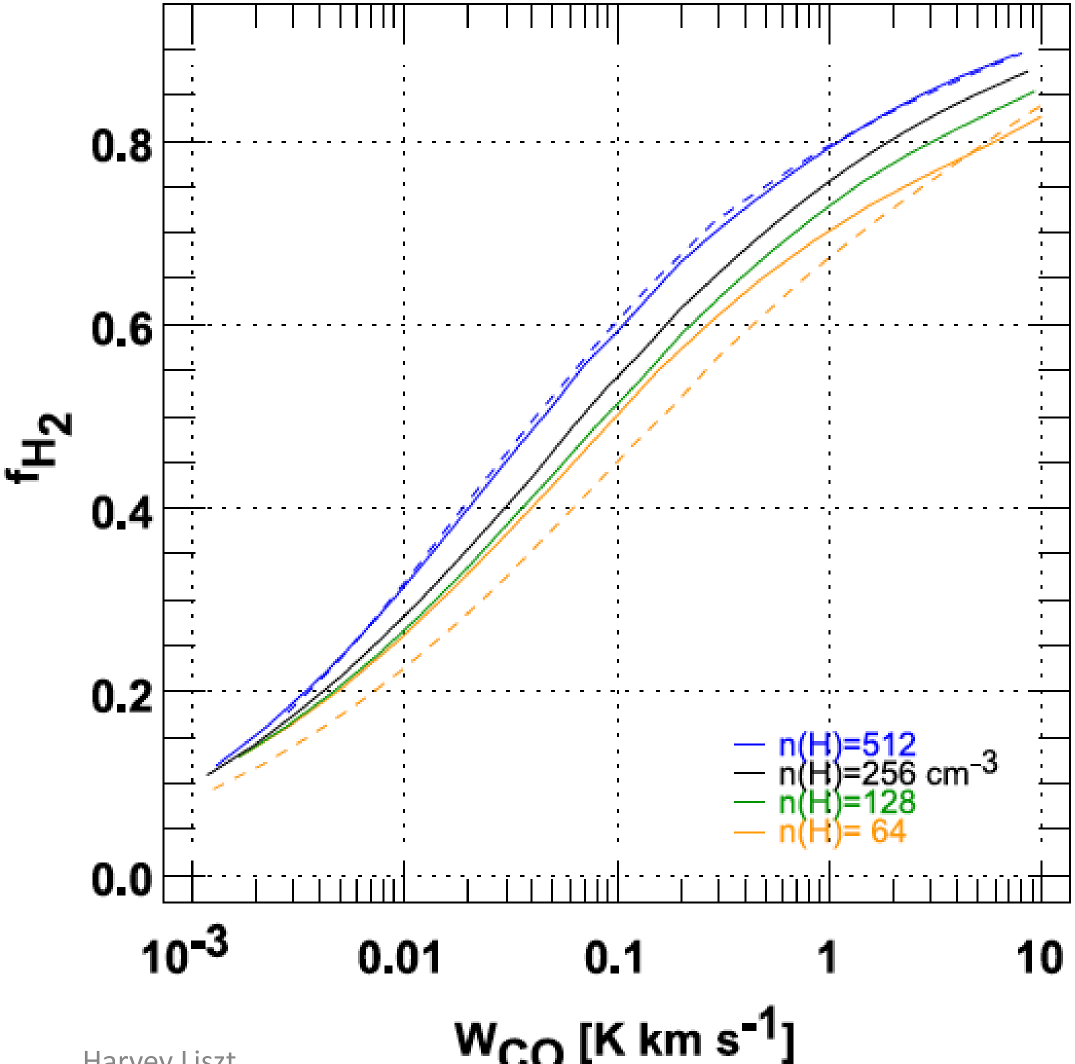
Why CO so bright, variable?



Implications for detecting more CO

Implications for detecting more CO

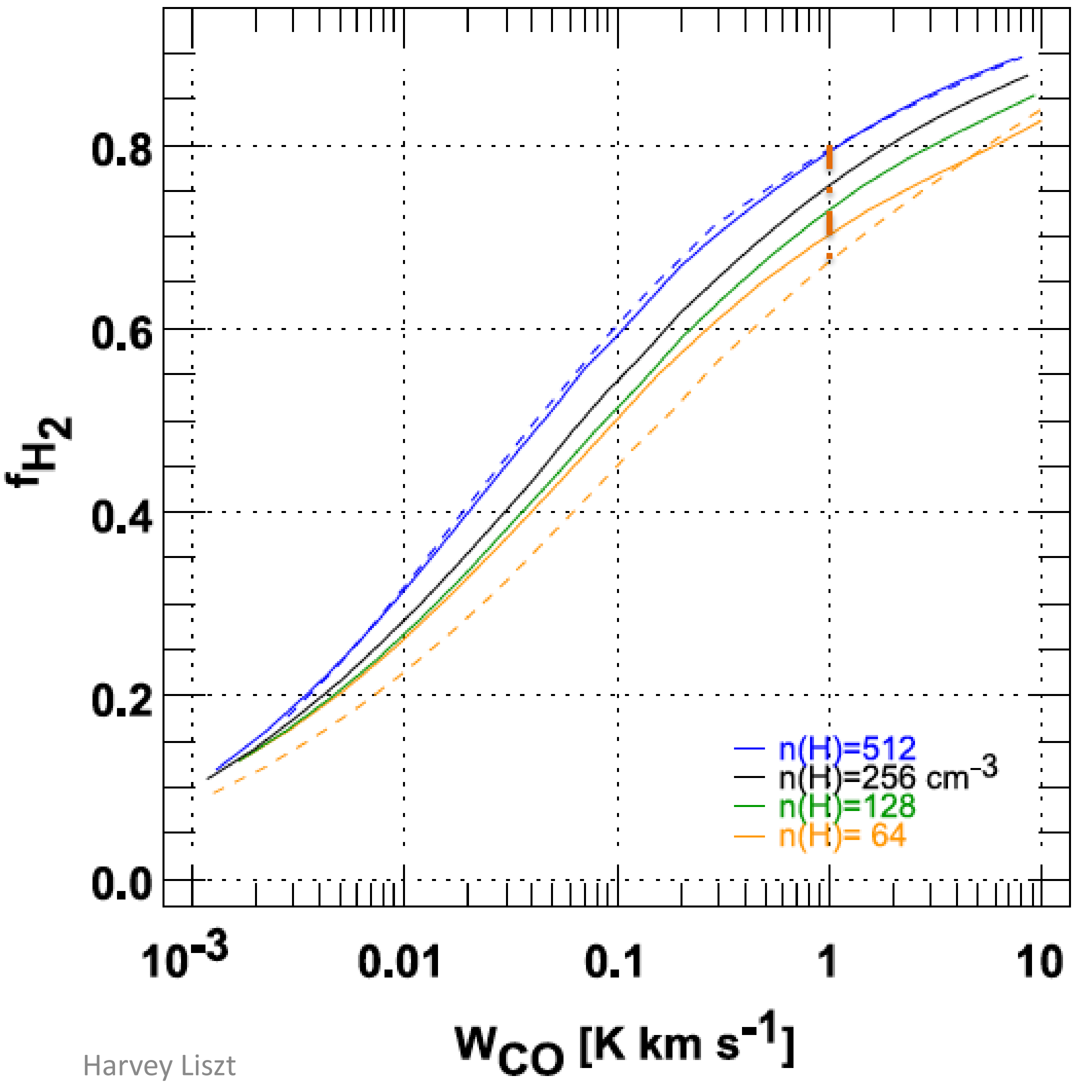
THE ASTROPHYSICAL JOURNAL, 835:138 (12pp), 2017 February 1



Harvey Liszt

Implications for detecting more CO

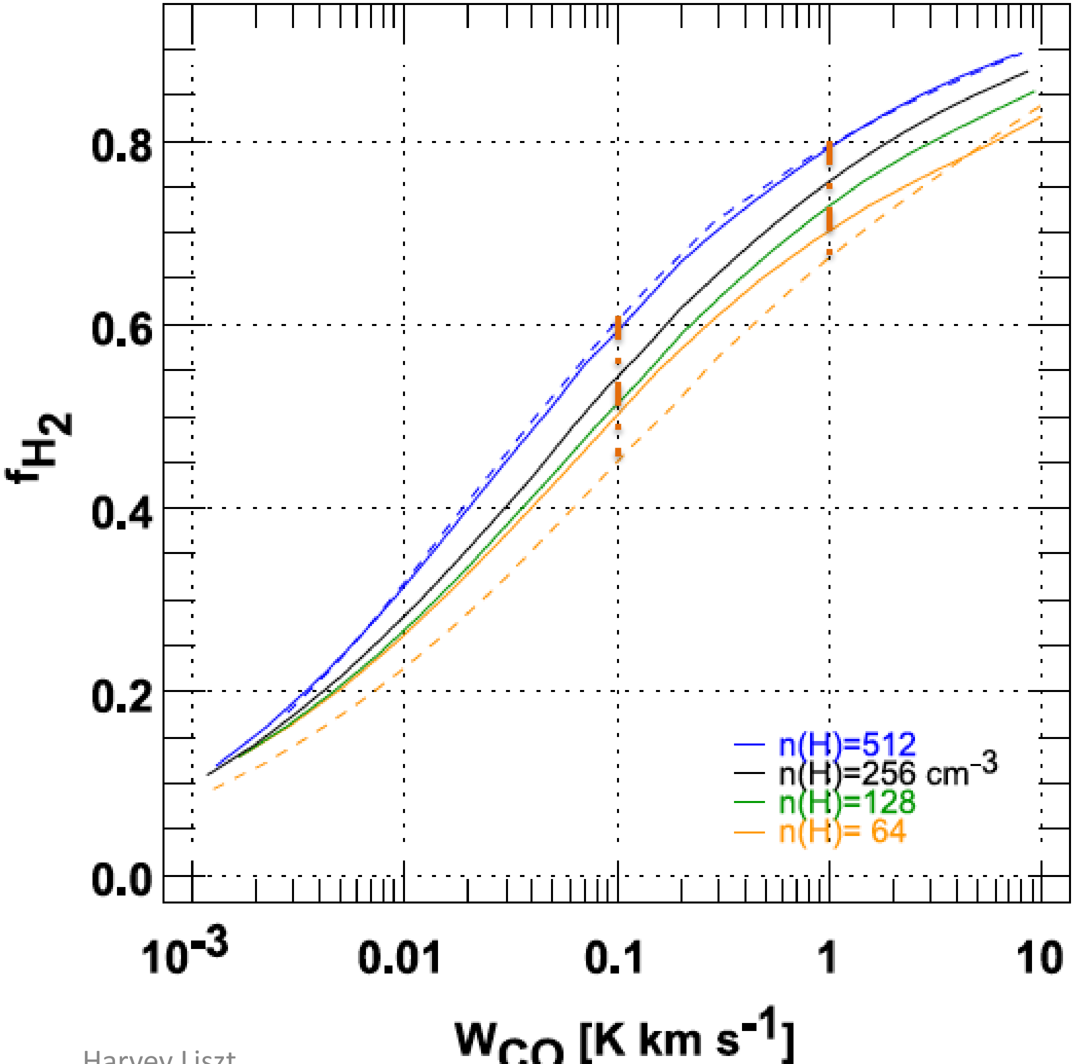
The Astrophysical Journal, 835:138 (12pp), 2017 February 1



CO emission at typical survey limits W_{CO} = 1 K-km/s is from majority-H_2 gas, f_{H2} ~ 65-80%

Implications for detecting more CO

THE ASTROPHYSICAL JOURNAL, 835:138 (12pp), 2017 February 1



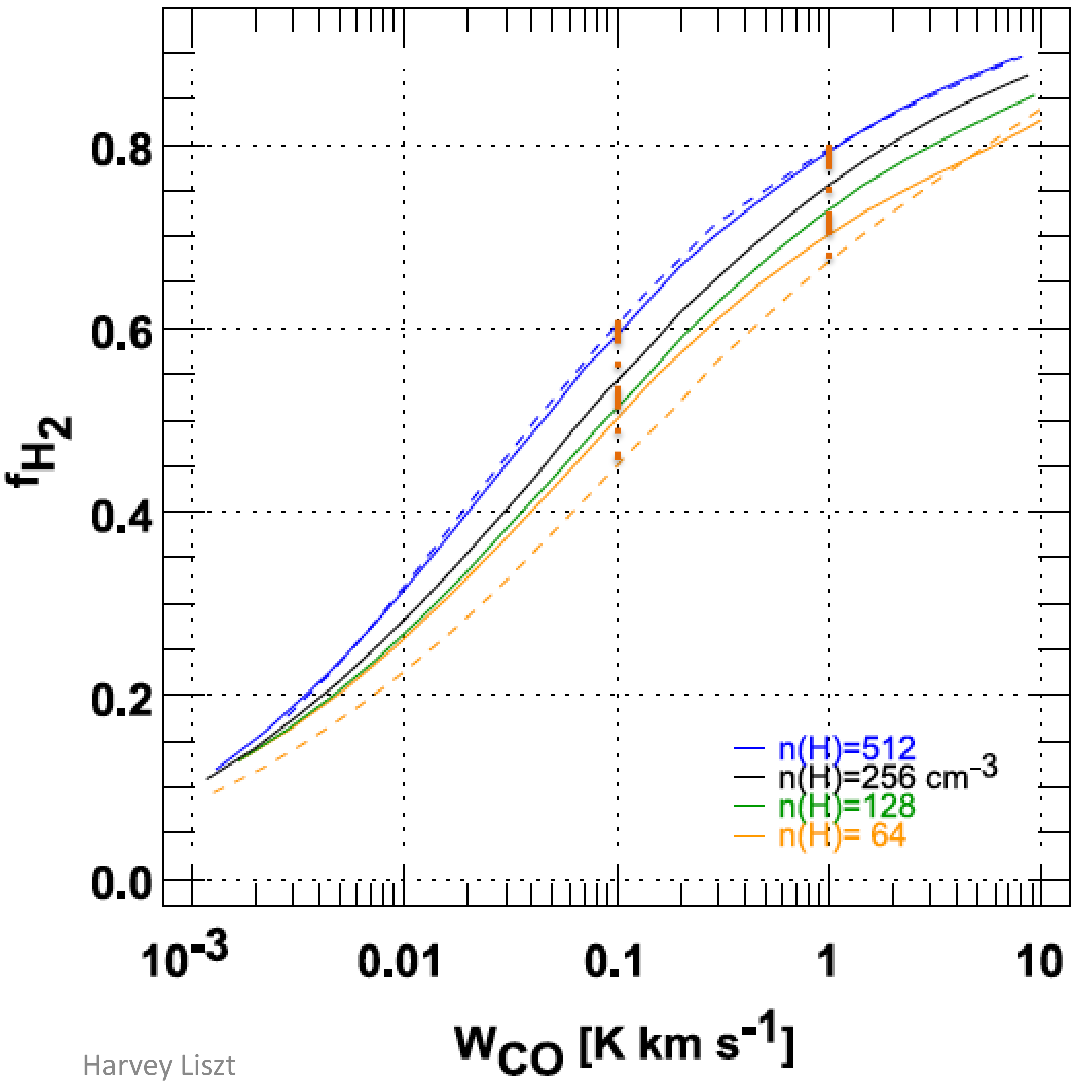
CO emission at typical survey limits W_{CO} = 1 K-km/s is from majority-H_2 gas, f_{H2} ~ 65-80%

CO emission at 10x lower W_{CO} = 0.1 K-km/s is from majority-H_2 gas, f_{H2} ~ 45-60%

Harvey Liszt

Implications for detecting more CO

The Astrophysical Journal, 835:138 (12pp), 2017 February 1



CO emission at typical survey limits W_{CO} = 1 K-km/s is from majority-H_2 gas, f_{H2} ~ 65-80%

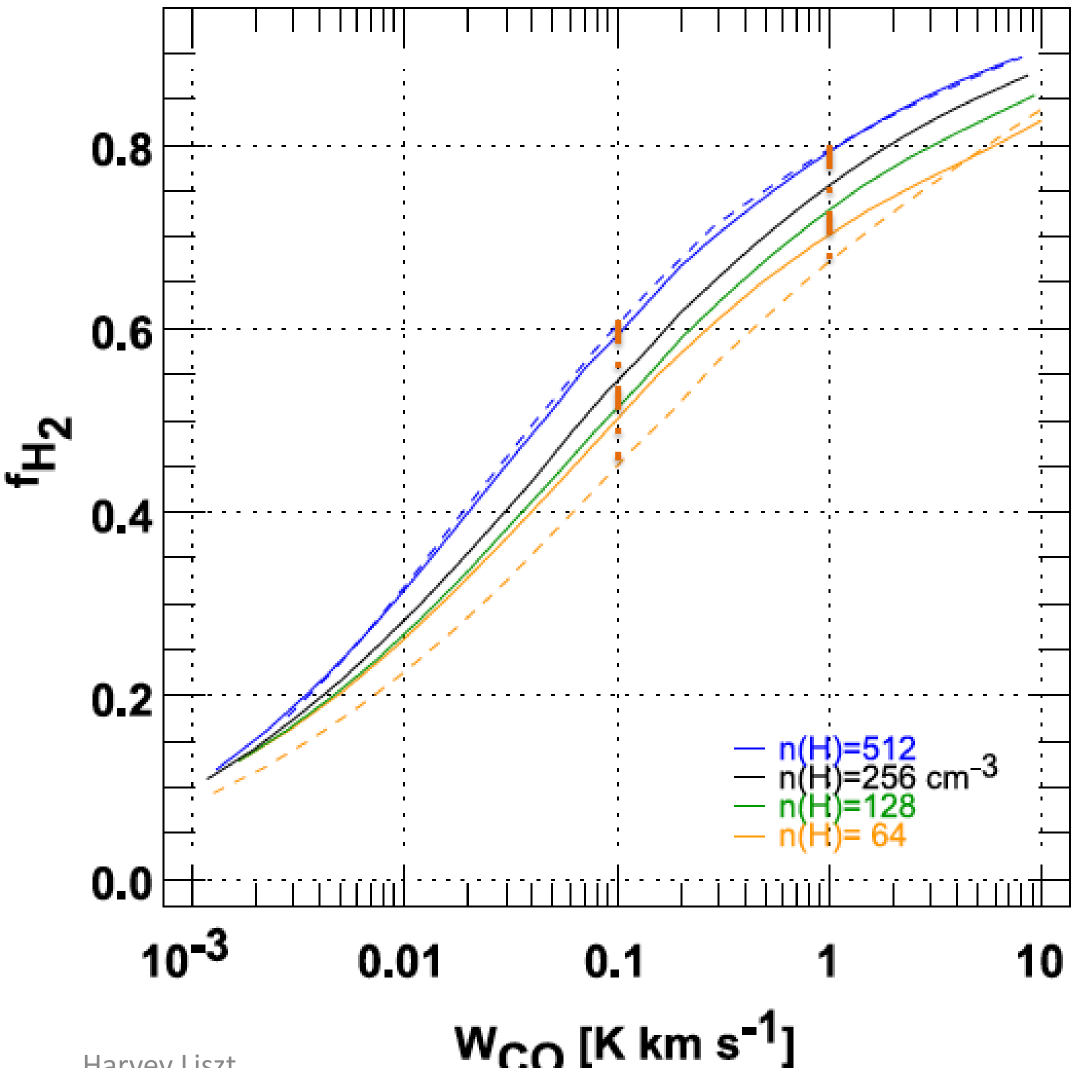
CO emission at 10x lower W_{CO} = 0.1 K-km/s is from majority-H_2 gas, f_{H2} ~ 45-60%

Very small change in $N(H_2)$ have large effect on W_{CO}

Harvey Liszt

Implications for detecting more CO

The Astrophysical Journal, 835:138 (12pp), 2017 February 1



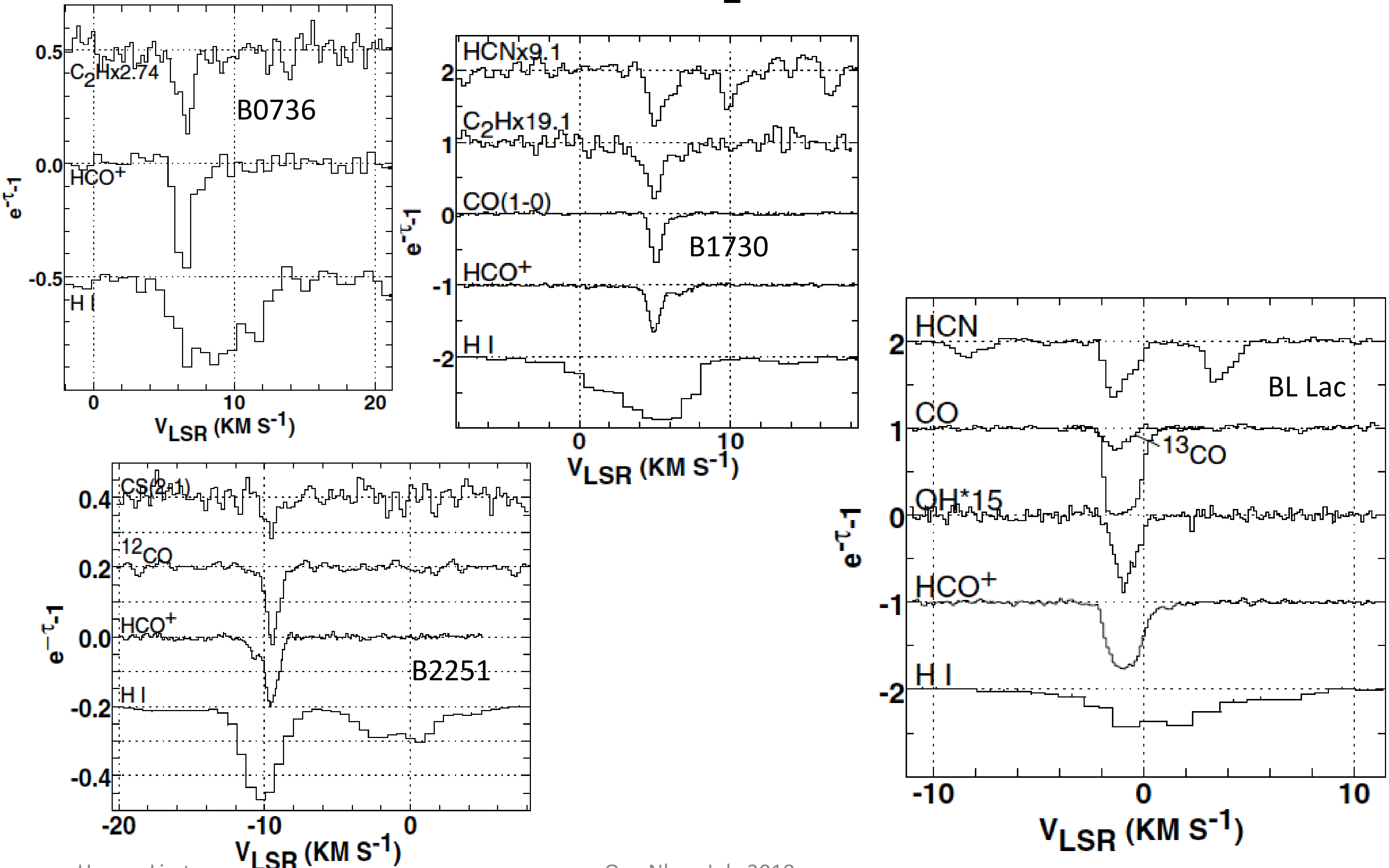
CO emission at typical survey limits W_{CO} = 1 K-km/s is from majority-H_2 gas, f_{H2} ~ 65-80%

CO emission at 10x lower W_{CO} = 0.1 K-km/s is from majority-H_2 gas, f_{H2} ~ 45-60%

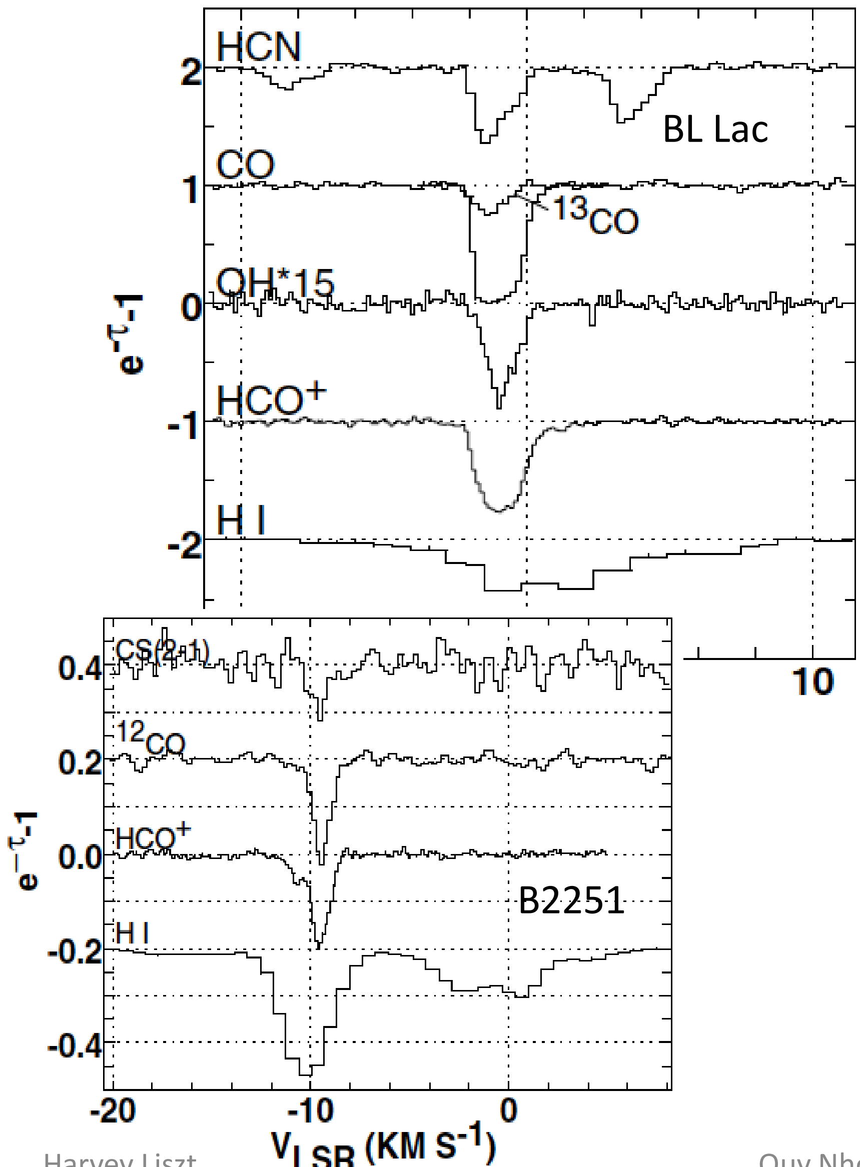
Will only find more CO emission by mapping broad survey beams (4'-8') at 1' resolution + good sampling

To find more H_2, do more absorption work.

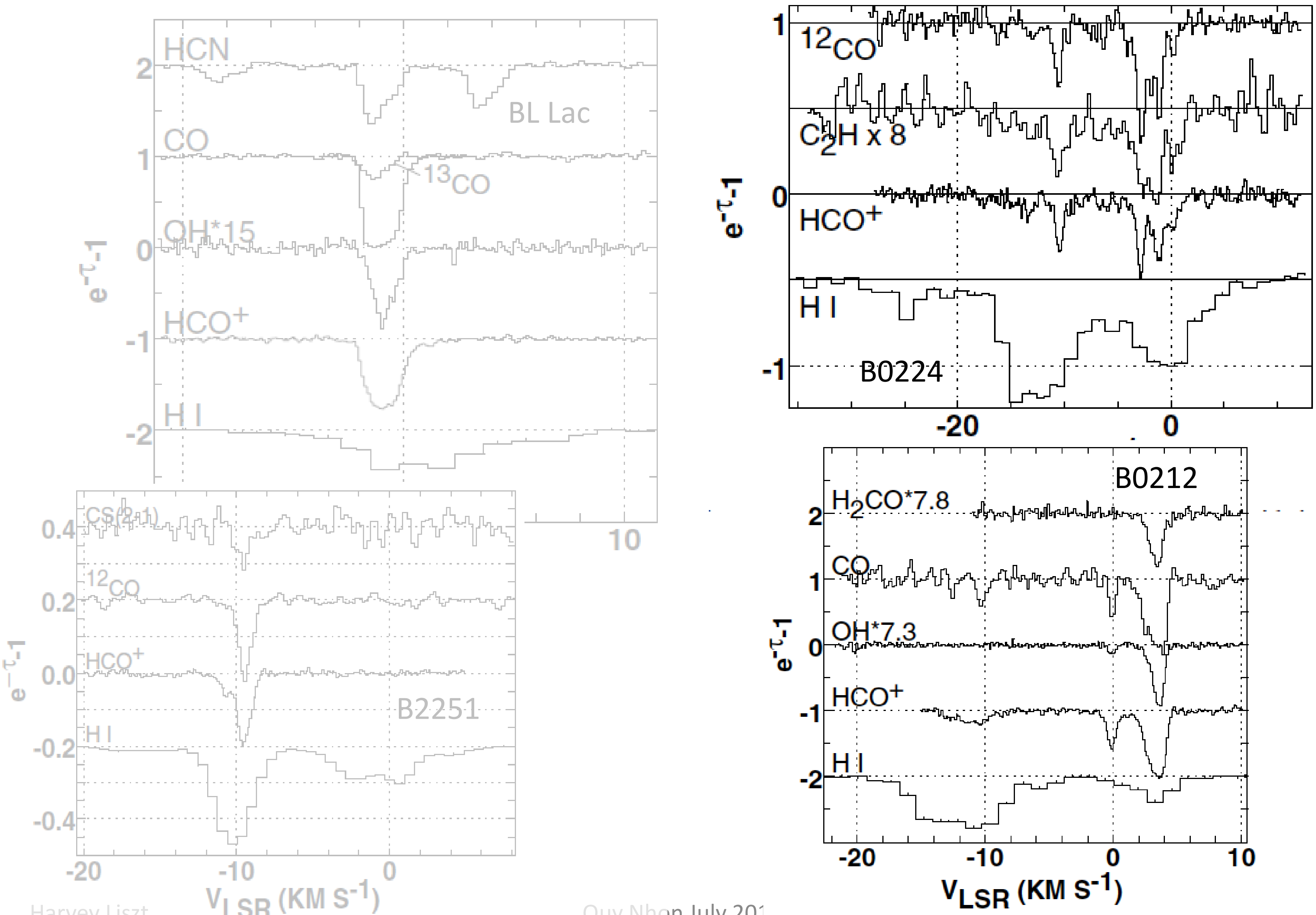
H I absorption as H_2 surrogate - ‘Yes’



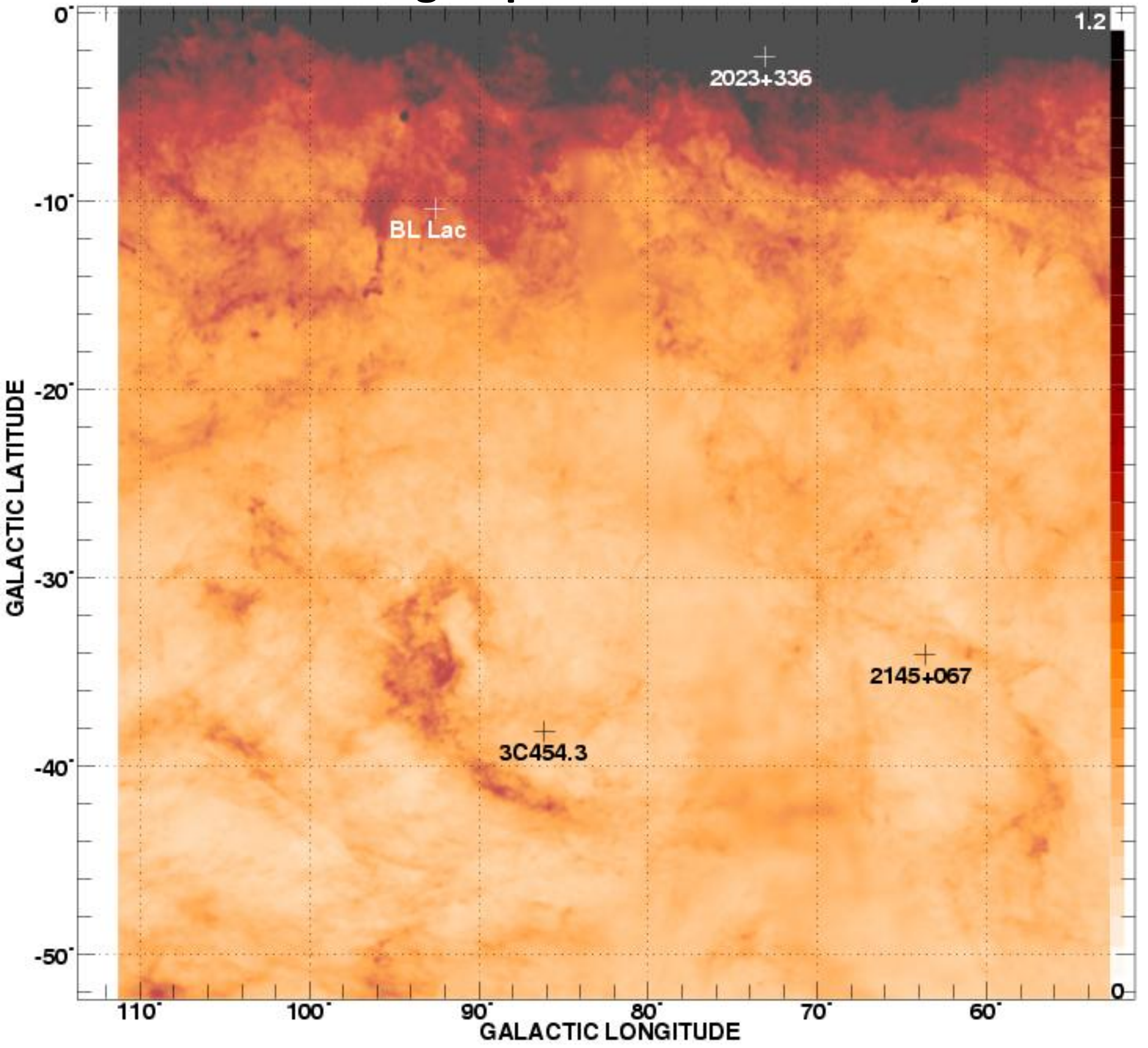
H I absorption as H_2 surrogate - 'Yes'



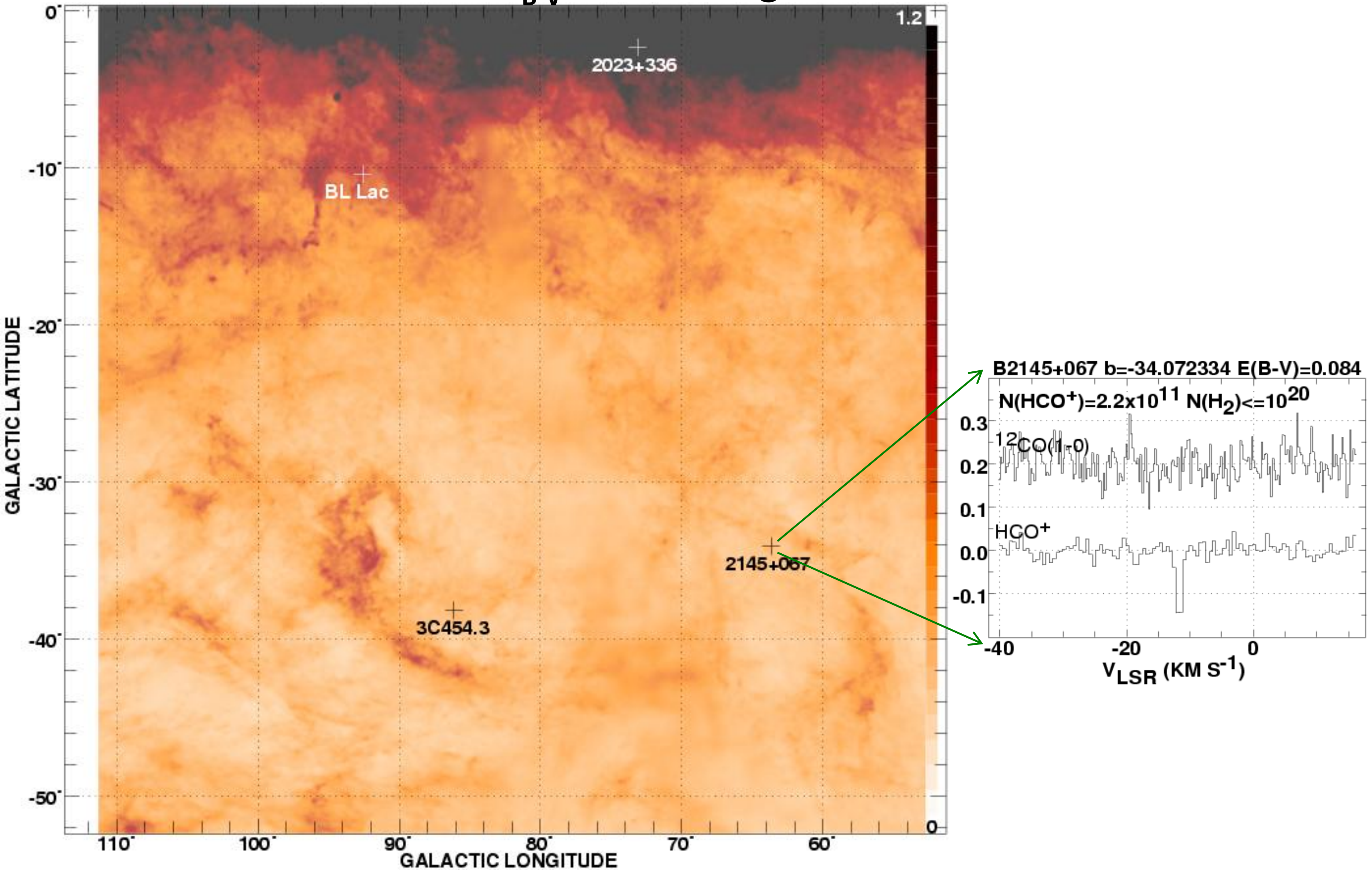
H I absorption as H_2 surrogate - NO!



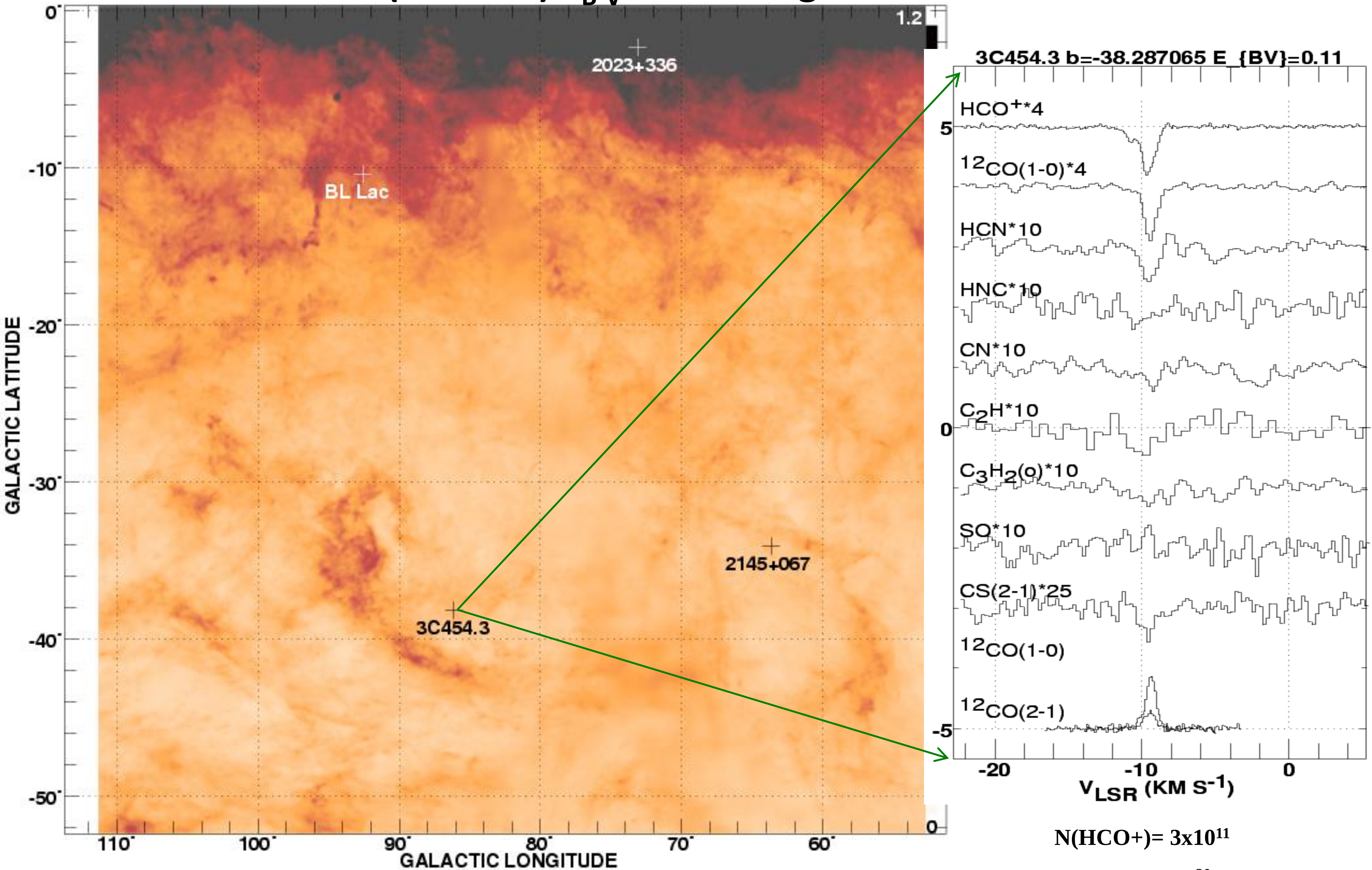
A glimpse of the chemistry



B2145-067 E_{B-V} = 0.084 mag



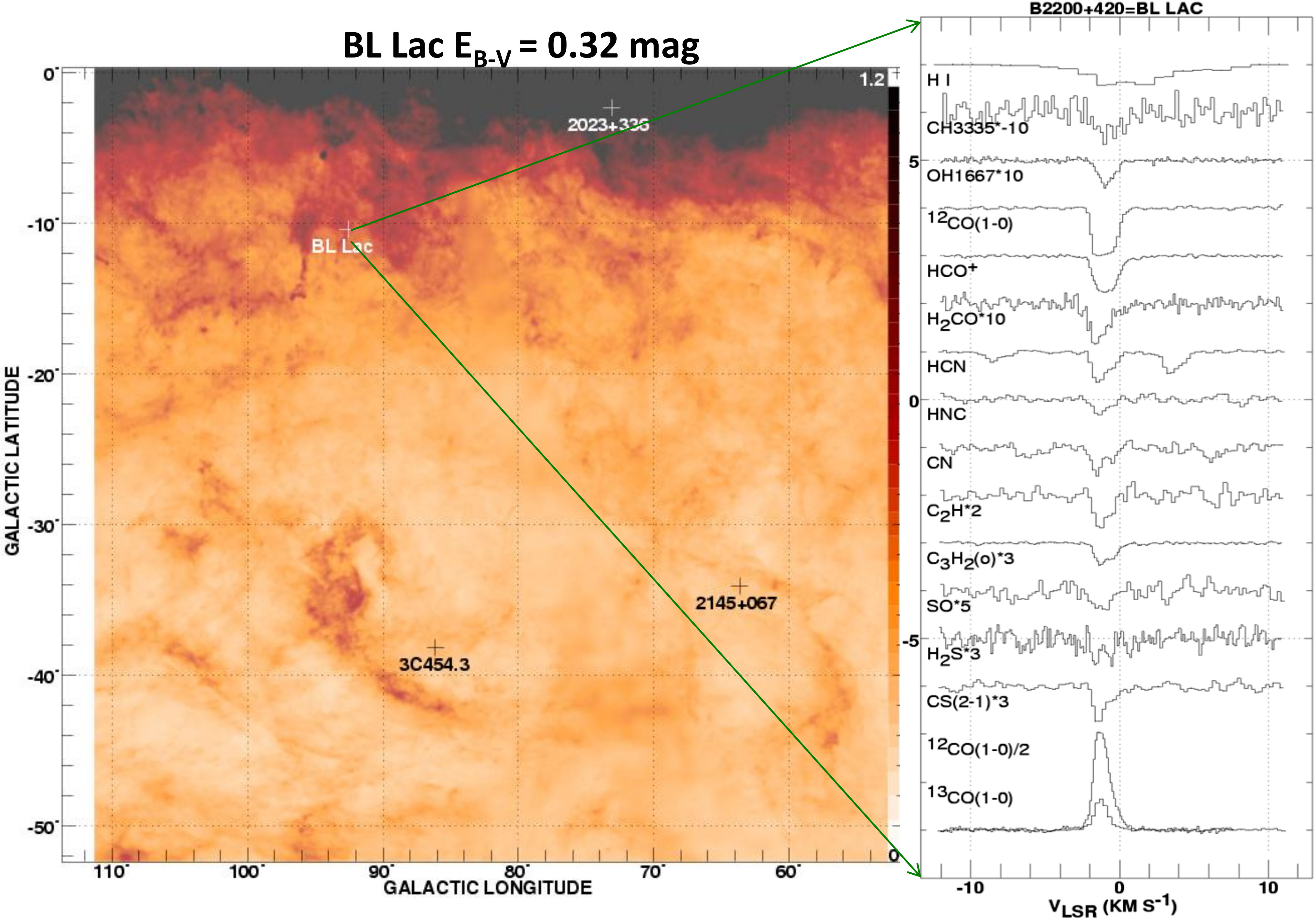
B2251 (3C454.3) E_{B-V} = 0.11 mag



N(HCO+)= $3x10^{11}$

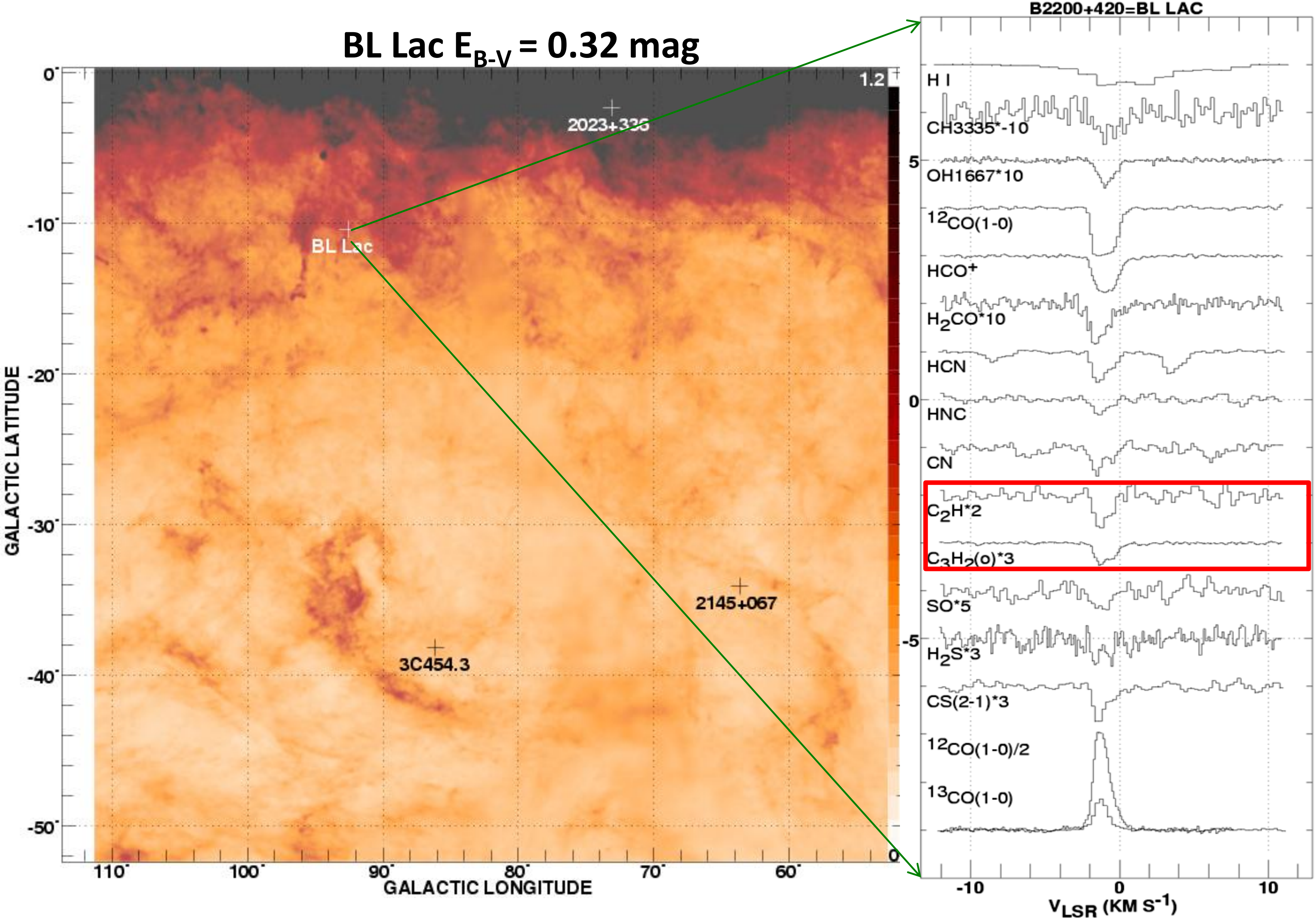
N(H_2)~ $1.5x10^{20}$

BL Lac E_{B-V} = 0.32 mag



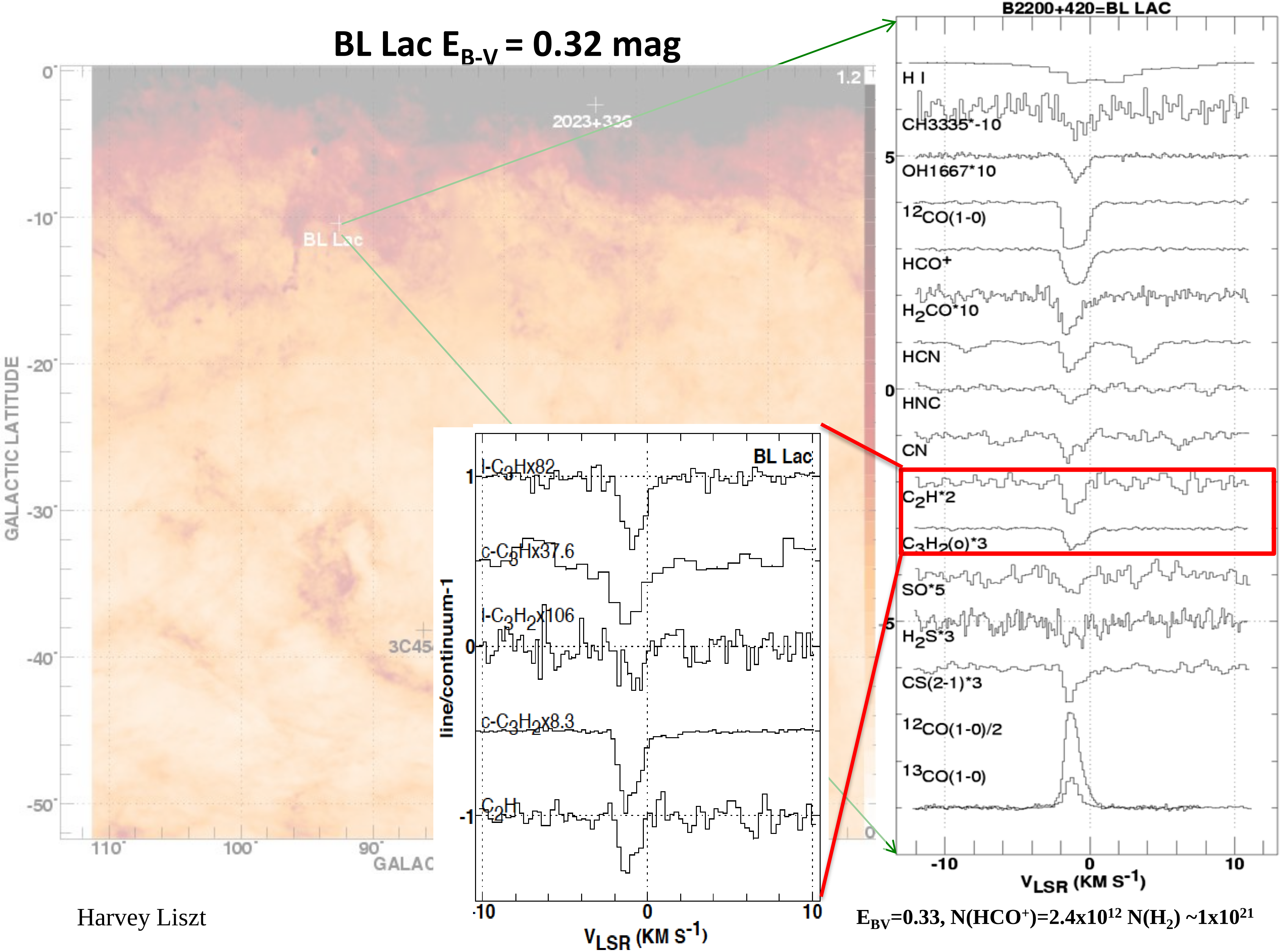
Harvey Liszt Quy Nhon July 2018 **E_{BV}=0.33, N(HCO^+)=2.4x10^{12} N(H_2) ~1x10^{21}**

BL Lac E_{B-V} = 0.32 mag



E_{BV}=0.33, N(HCO^+)=2.4x10^{12} N(H_2) ~1x10^{21}

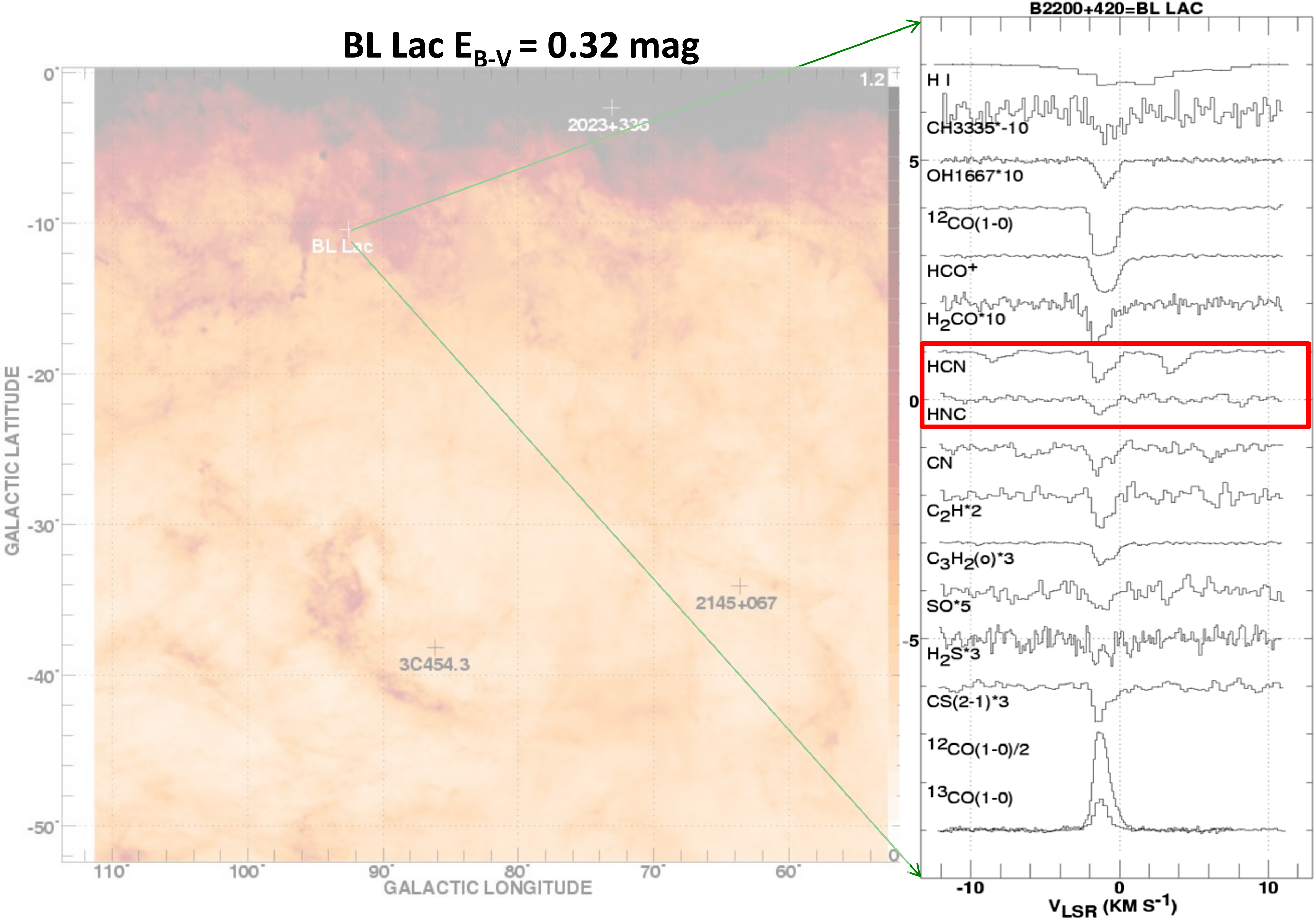
BL Lac E_{B-V} = 0.32 mag



Harvey Liszt

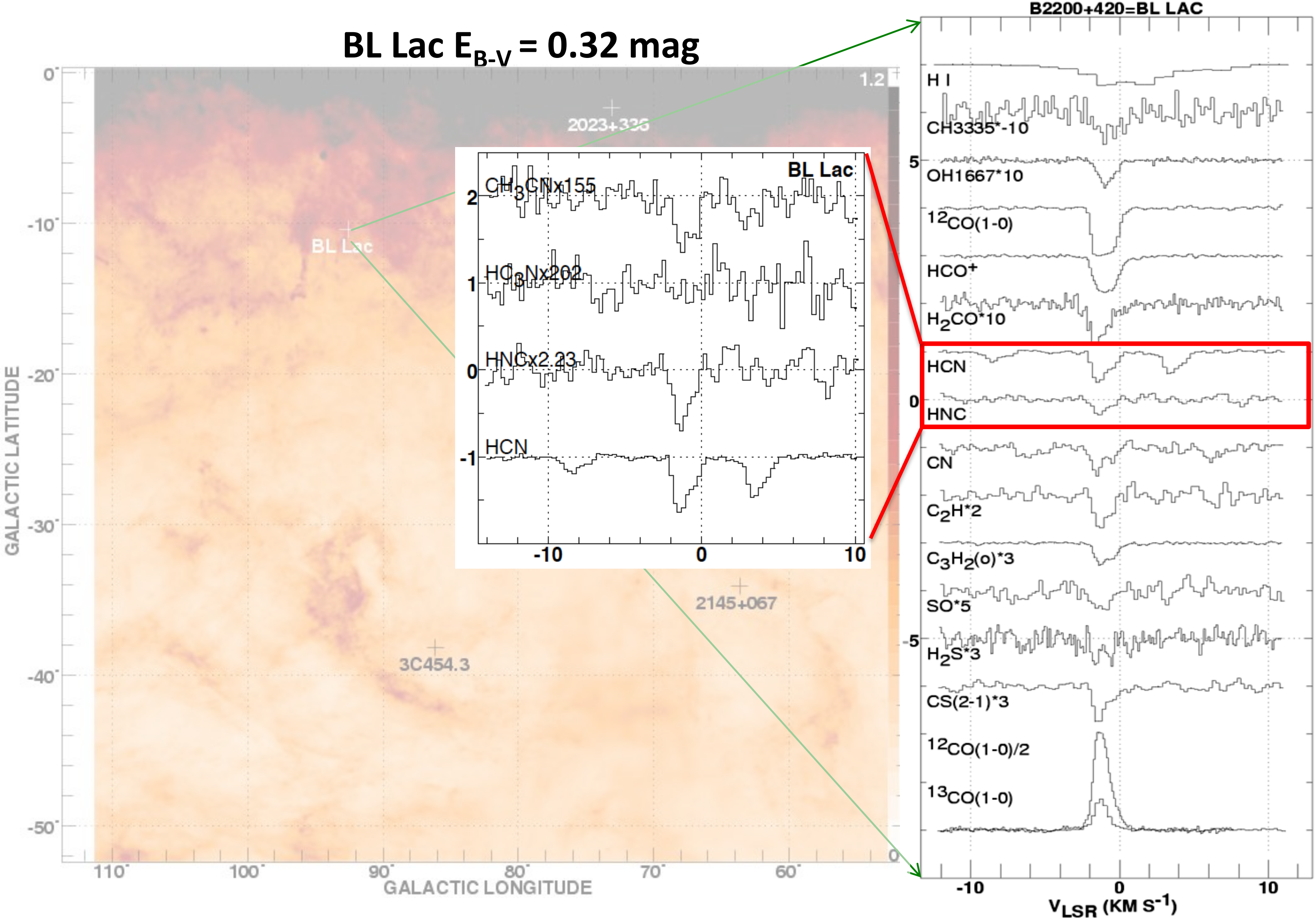
E_{BV}=0.33, N(HCO^+)=2.4x10^{12} N(H_2) ~1x10^{21}

BL Lac E_{B-V} = 0.32 mag



E_{BV}=0.33, N(HCO^+)=2.4×10^{12} N(H_2) ~1×10^{21}

BL Lac E_{B-V} = 0.32 mag



E_{BV}=0.33, N(HCO^+)=2.4x10^{12} N(H_2) ~1x10^{21}

What's next

- Finding the molecular gas
  - Are current estimates of $\langle n_H \rangle$ and molecular fraction correct?
  - Is so much of the local molecular gas really diffuse?

What's next

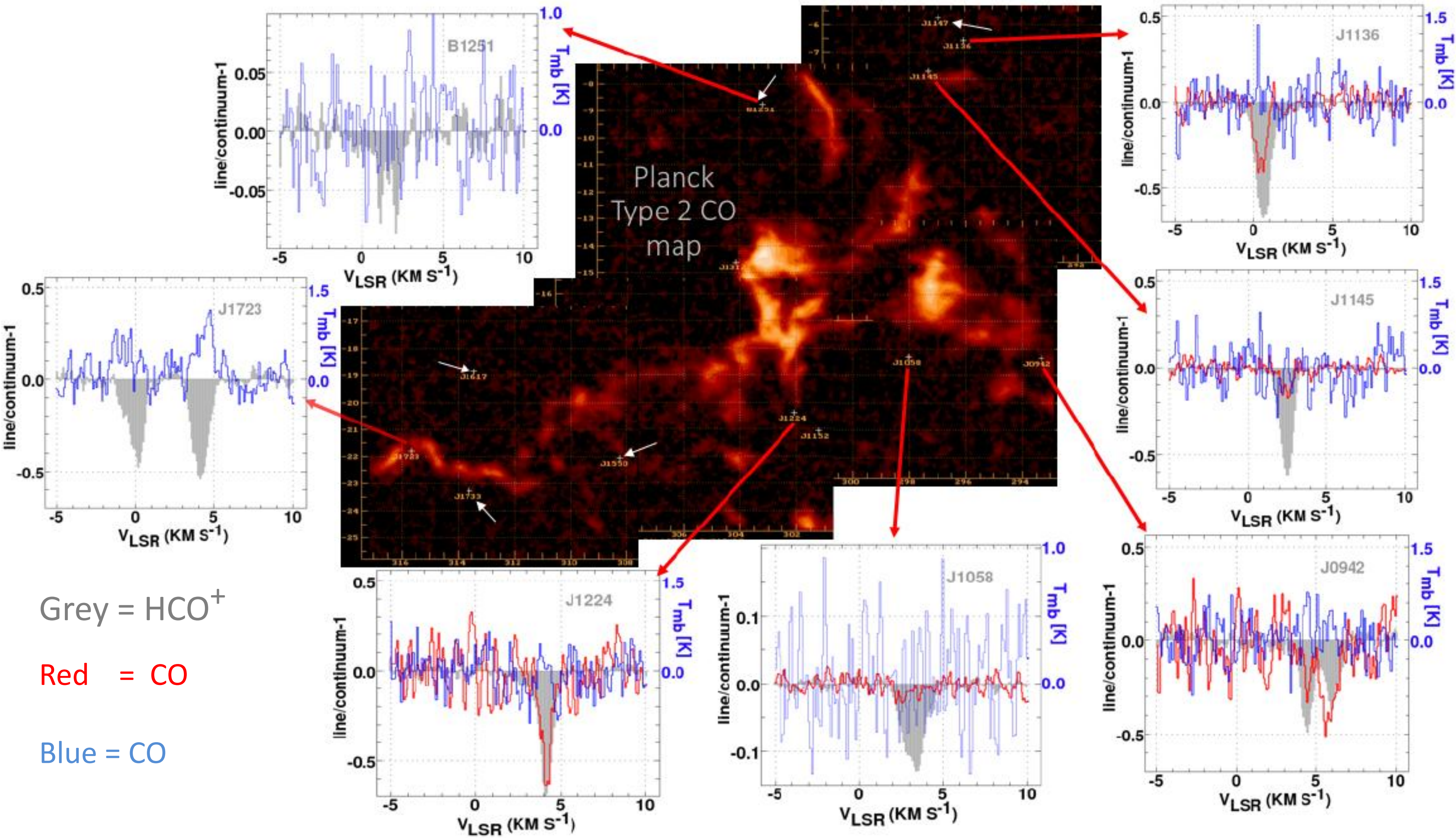
- Finding the molecular gas
  - Are current estimates of <n_H> and molecular fraction correct?
  - Is so much of the local molecular gas really diffuse?
  - Large scale opportunistic absorption line tomography
    - Surveys of ALMA calibrators
    - Correlation w/features of known distance (a la R. Lallement et al)

What's next

- Finding the molecular gas
  - Are current estimates of <n_H> and molecular fraction correct?
  - Is so much of the local molecular gas really diffuse?
  - Large scale opportunistic absorption line tomography
    - Surveys of ALMA calibrators
    - Correlation w/features of known distance (a la R. Lallement et al)
  - Targeted searches for the host of DNM missing in emission
    - Absorption line observations in specific regions

DNM in Chamaeleon

Gerin, Grenier, Liszt 2018



Grey = HCO^+

Red = CO

Blue = CO

What's next

- Characterizing the diffuse molecular gas
  - Establishing the chemical complement of diffuse gas
    - Connection with DIBS? PAH?
  - Exploring chemical origins in diffuse molecular gas
    - Chemistry not in equilibrium with thermodynamics of mean pressure
    - Turbulence driving molecular ion chemistry to form HCO^+ and CO
      - TDR models (Godard et al 2014, A&A, 570A, 27)
  - Characterizing the role of chemistry in shaping the CO sky
    - How much of the CO signal is from diffuse gas?

OK, thanks for listening