Herschel/HIFI Large-Area Velocity-Resolved H_2O Map of Orion:

A Unique Laboratory for Studying the Depth-Dependent Water Abundance in Molecular Clouds

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Harvard-Smithsonian Center for Astrophysics
The Universe Explored by Herschel – October 2013

An ADS search of refereed papers published between 2010 and 2013 with ‘Water’ in the title and `Herschel’ in the abstract returns:

76 refereed papers in ApJ and A&A alone

In most of these papers, the water abundance is inferred by:

1) Determining N(H_2O)

2) Comparing to N(CO) [or N(^{13}CO) or N($C^{18}O$)]

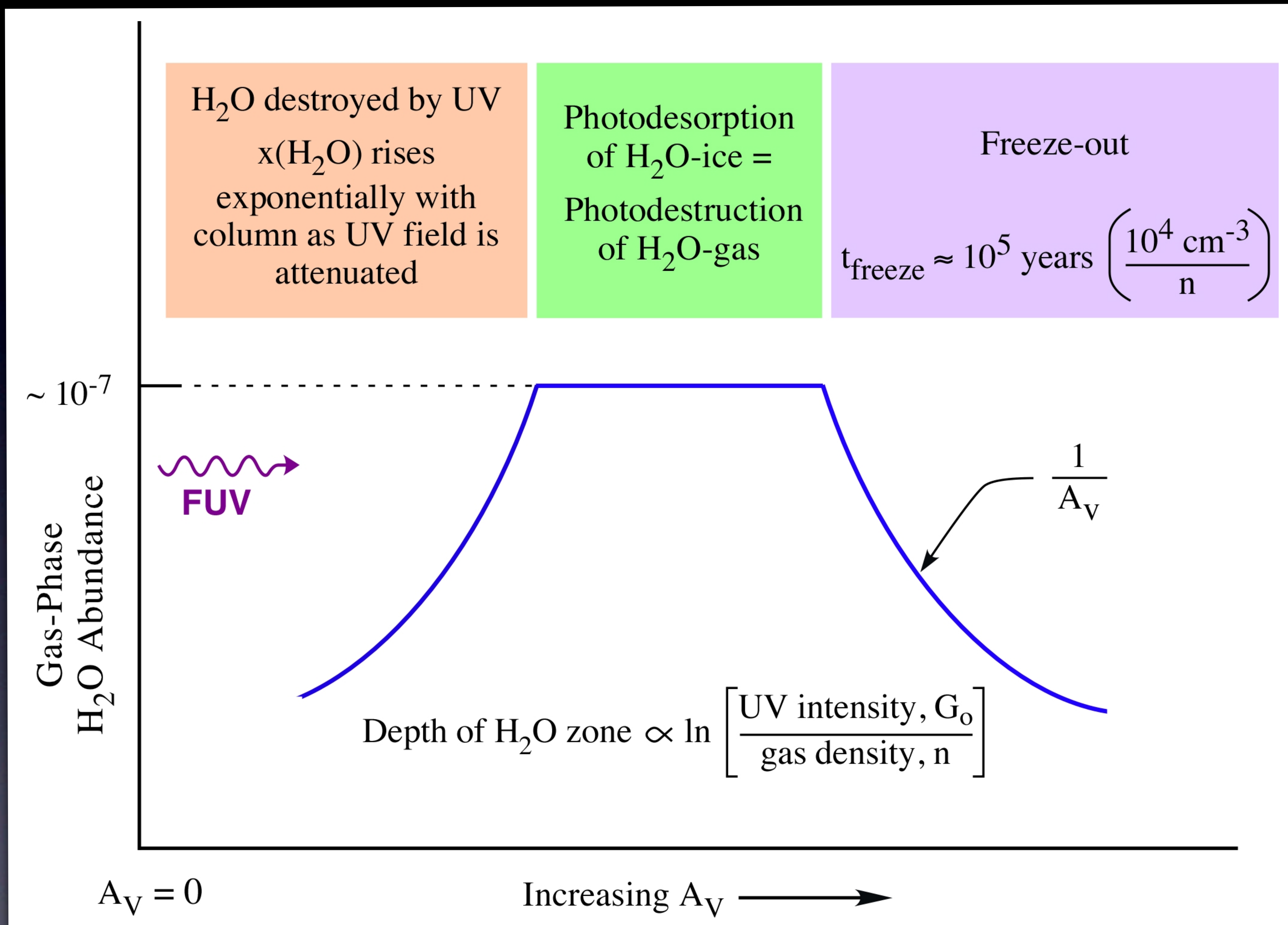
3) Deriving x(H_2O) from N(H_2O) / N(CO) and assumptions about N(CO) / N(H_2)

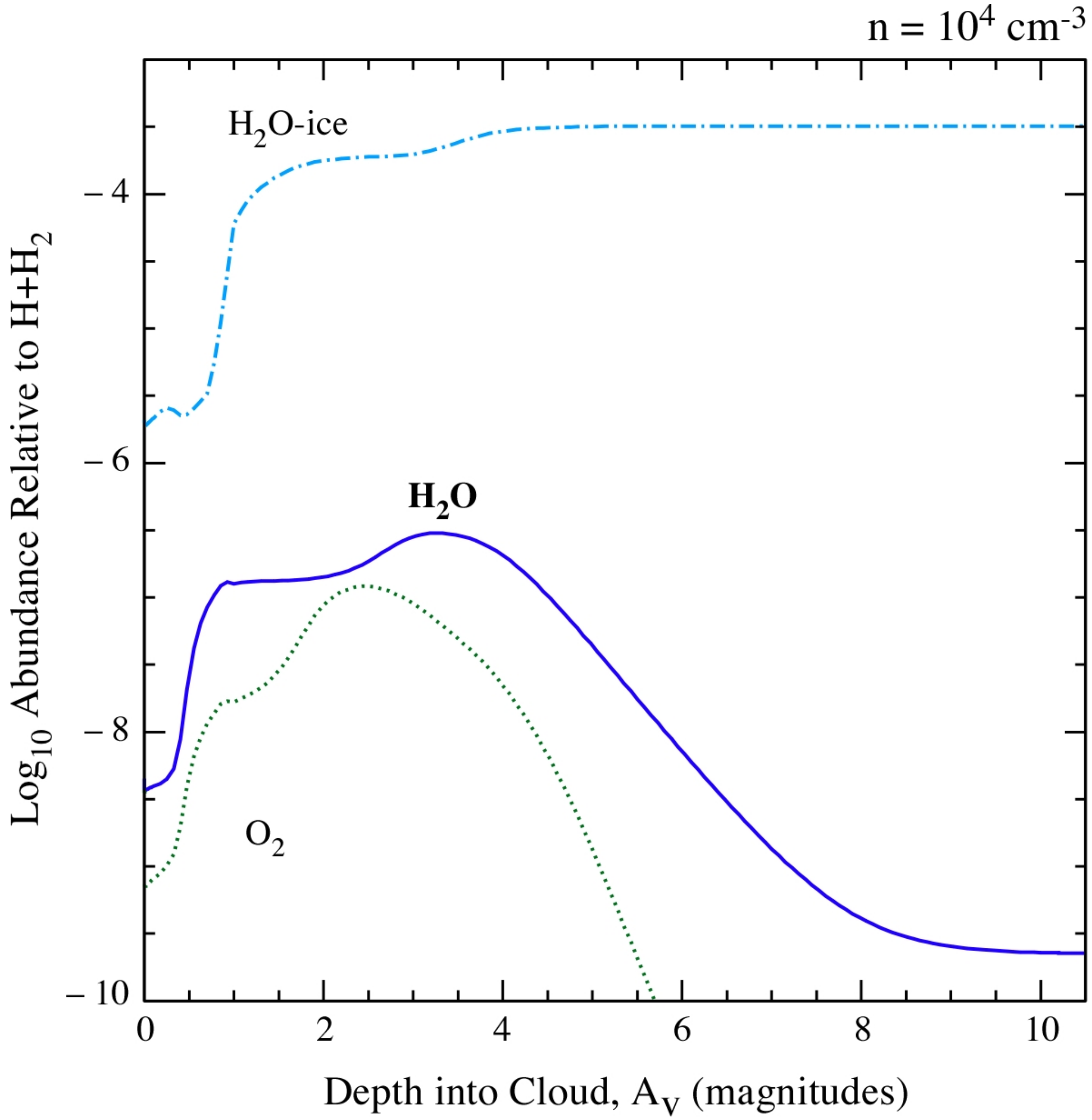
But is this approach observationally supportable, particularly toward dense molecular clouds? No.

Theoretical expectation

- The depth-dependent abundance of water reflects a competition among a number of important but not well-constrained processes, with broad applicability to models of molecular clouds and protoplanetary disks. These processes are believed to be:
  - Rate at which O atoms strike dust grains and combine on their surfaces to form OH and H_2O
  - Rate at which H_2O is removed from grains by FUV photons (photodesorption) and cosmic rays
  - Rate at which H_2O is destroyed by FUV photon (photodissociation)
  - Rate at which H_2O is formed in the gas phase
  - Rate at which H_2O is removed from the gas phase by freeze out
- Models predict this competition will result in a peak in $x(H_2O)$ at $3 \leq A_V \leq 8$ mag. into molecular clouds, depending on G_o and density (cf. Hollenbach et al. 2009).

Schematic Expectation

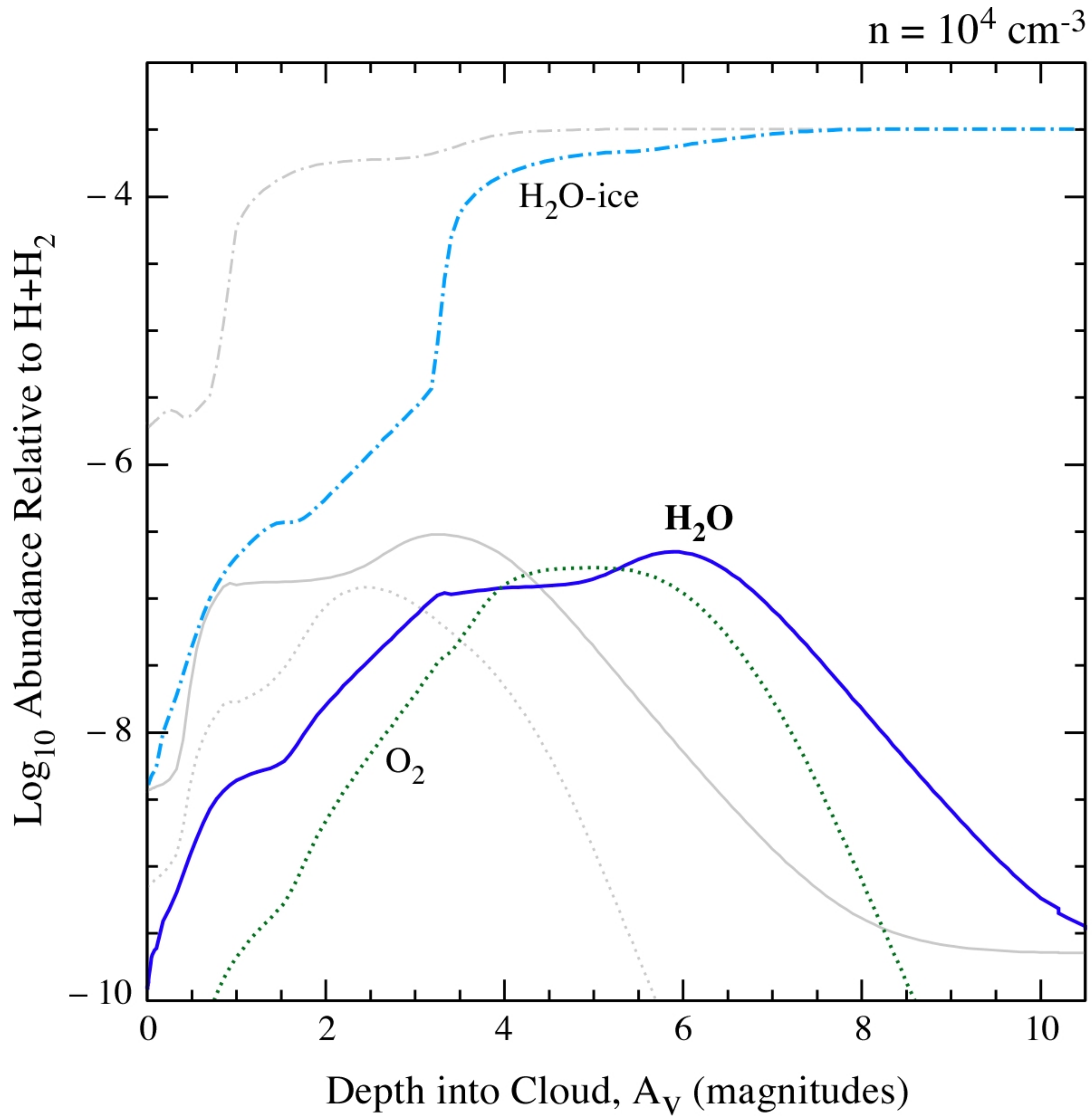




$G_o = 1$

Depth into cloud of H_2O zone $\propto$ ln (G_o/n)

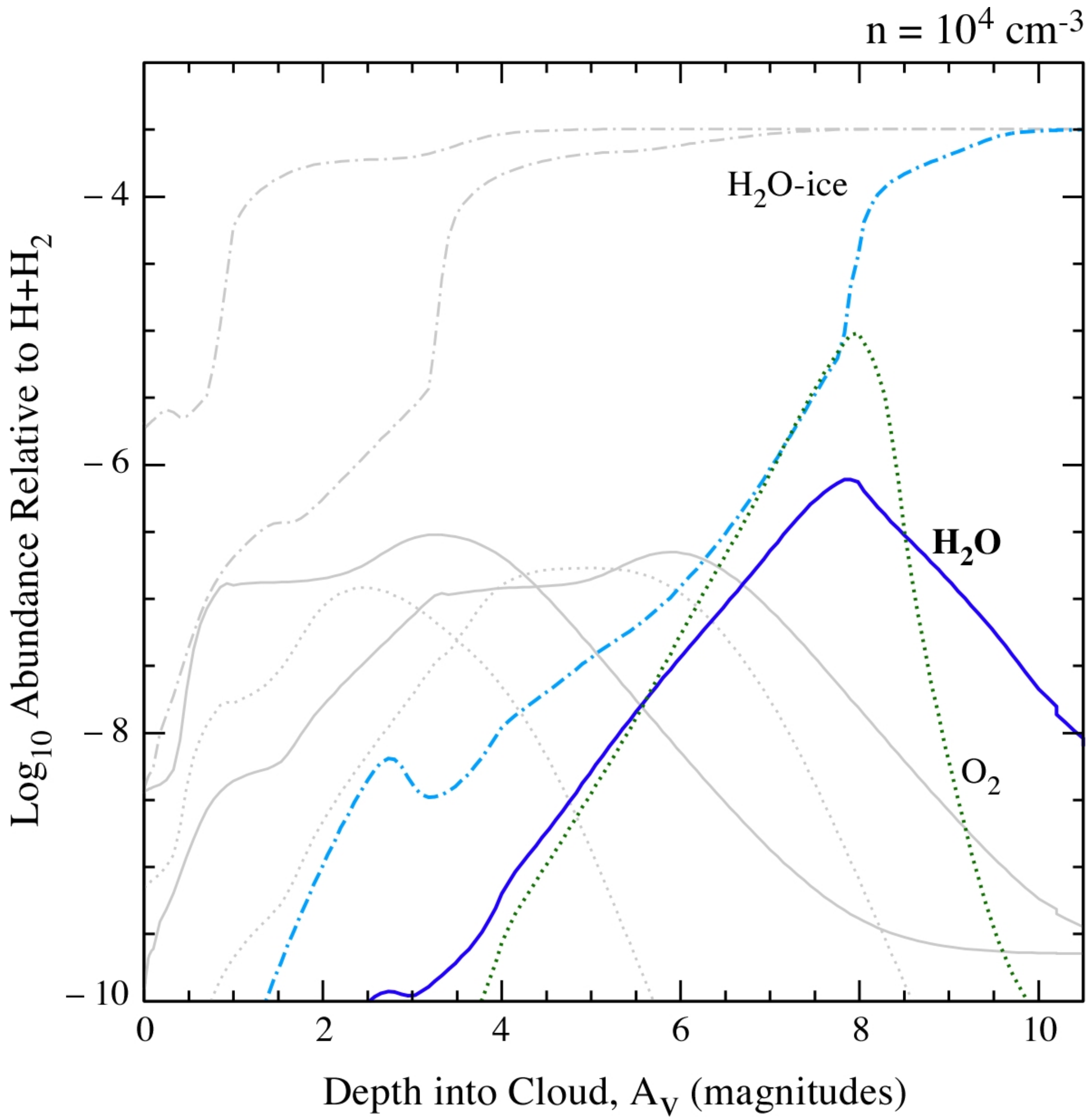
Hollenbach, Kaufman, Bergin & Melnick (2009)



$G_o = 10^2$

Depth into cloud of H_2O zone $\propto$ ln (G_o/n)

Hollenbach, Kaufman, Bergin & Melnick (2009)



$G_o = 10^3$

Depth into cloud of H_2O zone $\propto$ ln (G_o/n)

Hollenbach, Kaufman, Bergin & Melnick (2009)

Theoretical expectation

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- Goal of this study: Subject these predictions to *direct* observational test.

To test these predictions, need:

- Method that distinguishes between molecules that exist preferentially near cloud surfaces and those that are distributed throughout the cloud
- Favorable source – geometry, spatial extent, line strengths
- Mix of molecular species whose depth-dependent abundance spans the range from surface tracers to volume tracers
- Transitions that are optically thin

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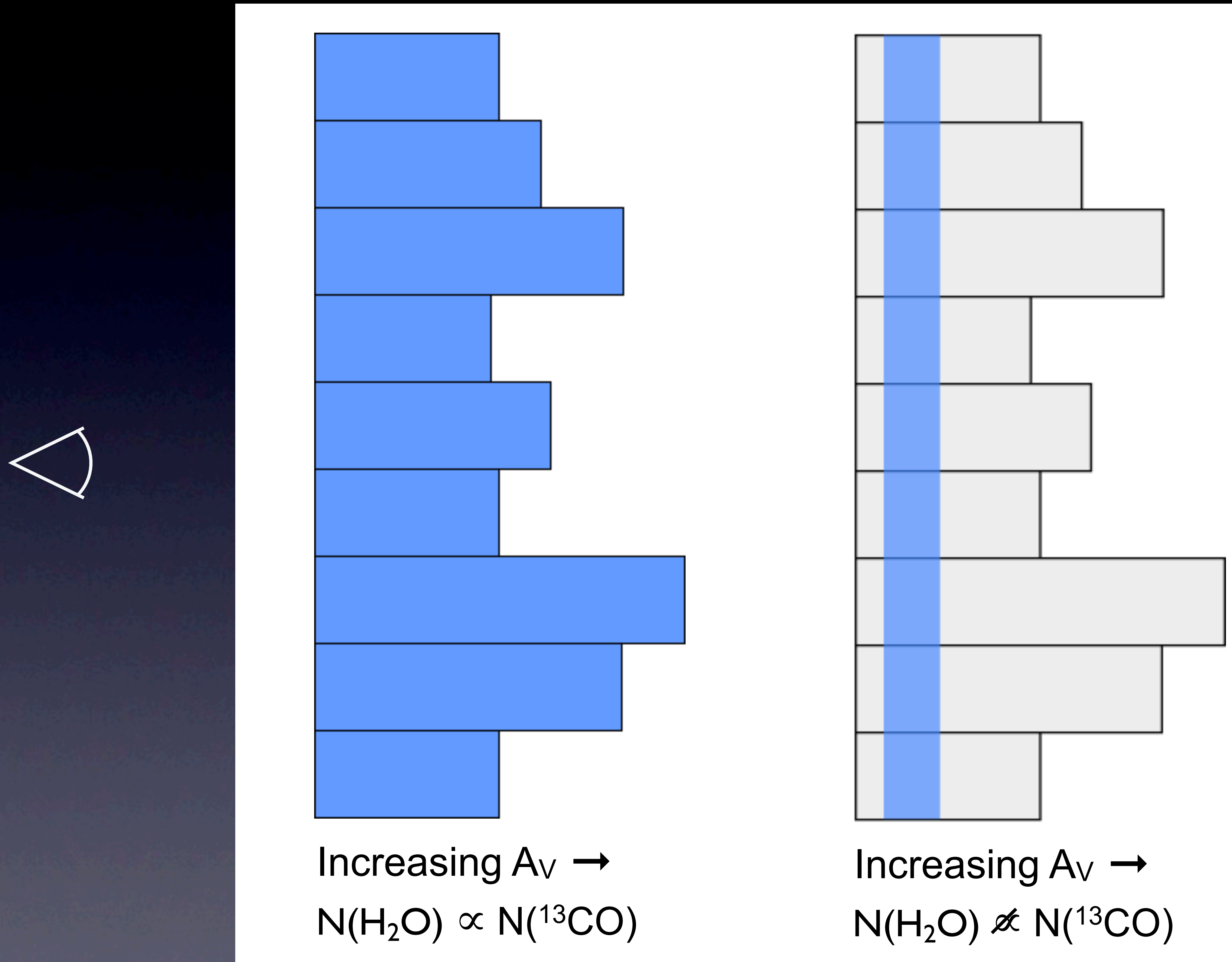
H_2O Line Flux $\propto$ $n(H_2) \cdot N(H_2O)$



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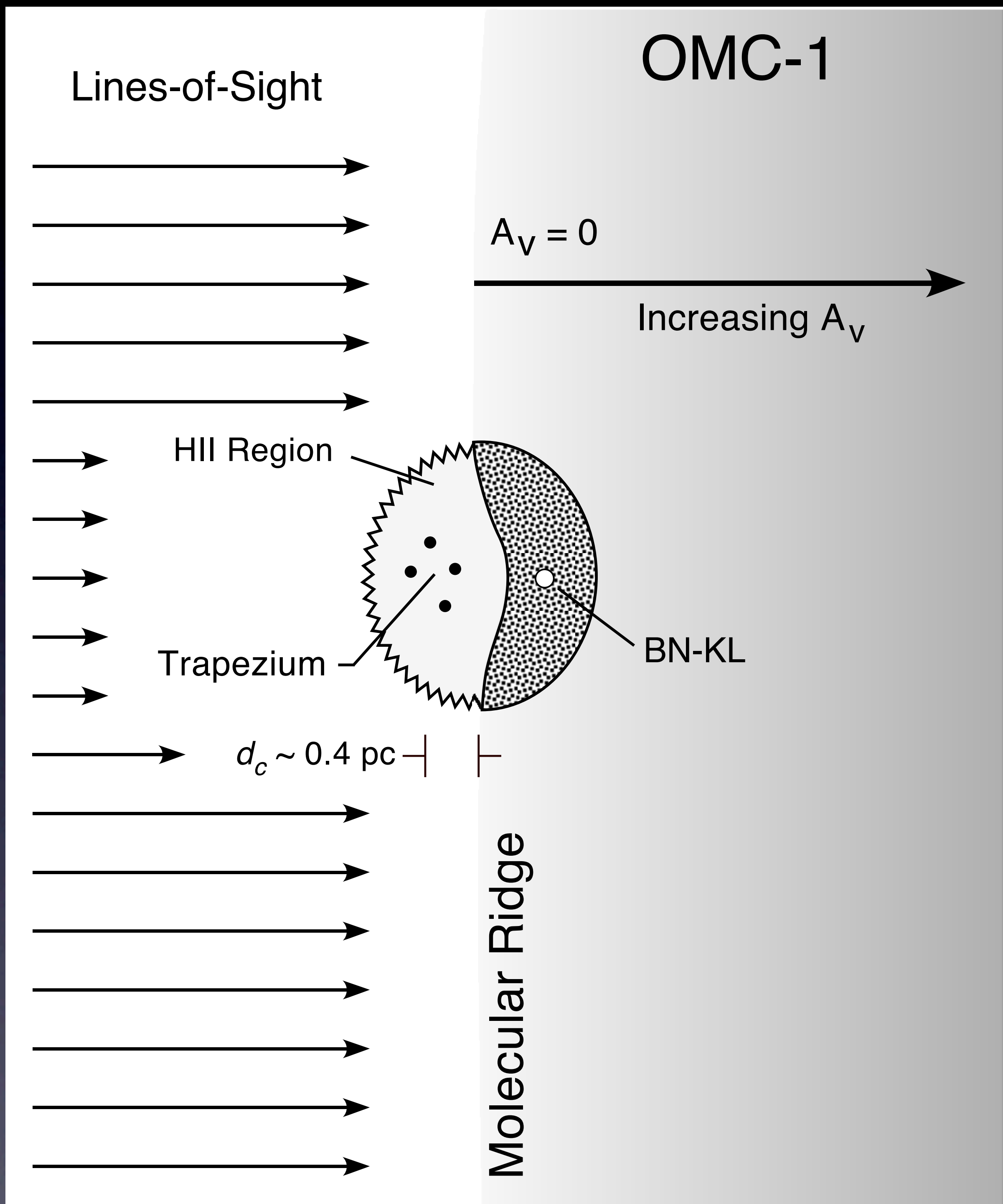
Face-On Orion Molecular Ridge is an Excellent Lab



- It presents a face-on geometry to us, so each beam pointing samples an independent gas column from $A_V = 0$ into the cloud.
- It's extended: 10′-15′ East-West and ~30′ North and > 60′ South of BN/KL, allowing for > 2000 HIFI 557 GHz H_2O map positions.
- The line emission is strong, allowing for relatively high SNR spectra to be obtained over most of the extended region.
- Because the Ridge gas is warm (~25 - 40 K), CO freeze out is not a concern.

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FCRAO Spectral Maps

Species	Transition	Energy Above Gnd State (E_u/k)	Rest Frequency (GHz)	FCRAO FWHM Beamsize (arcsec)
C_2H	N=1-0 J=1/2-1/2	4.20 K	87.402[a]	56
HCN	J=1-0	4.25 K	88.632[a]	55
N_2H^+	J=1-0	4.47 K	93.174[a]	52
$C^{18}O$	J=1-0	5.27 K	109.782	46
^{13}CO	J=1-0	5.29 K	110.201	46
CN	N=1-0 J=3/2-1/2	5.45 K	113.491[a]	46
^{12}CO	J=1-0	5.53 K	115.271	45

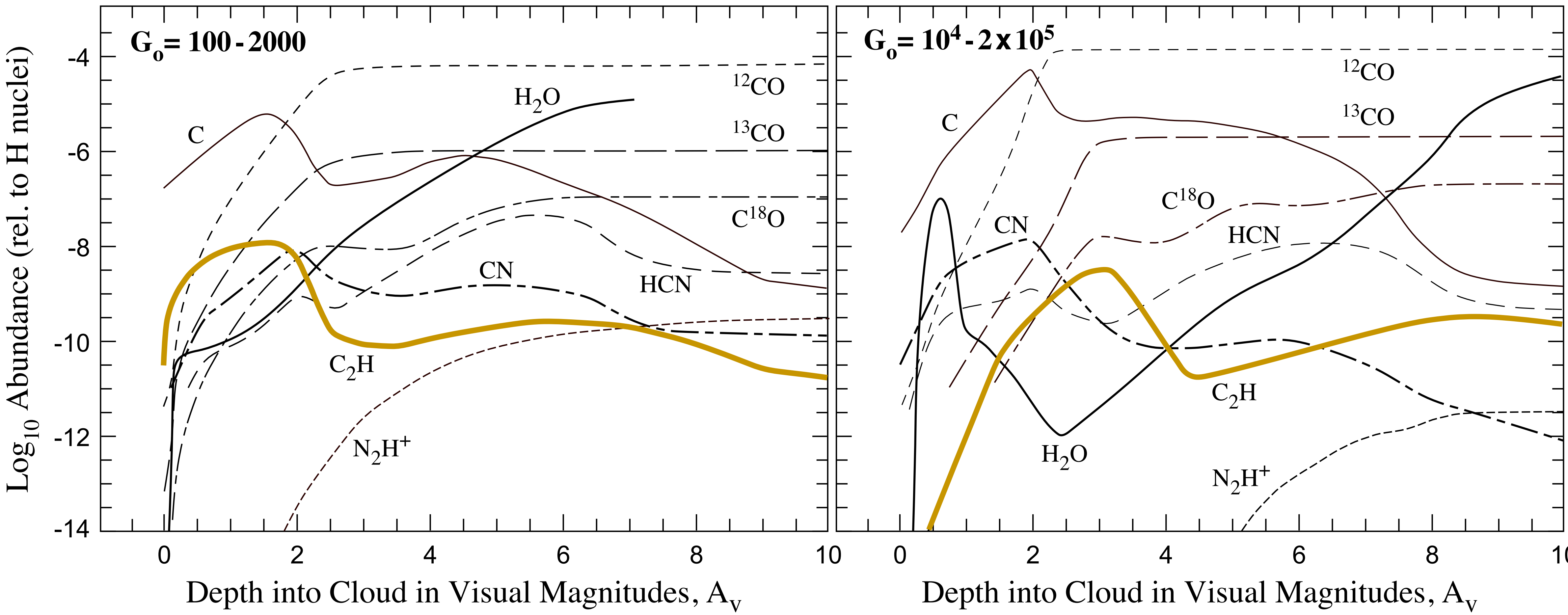
[a] Rest frequency of the strongest hyperfine component.

All maps are fully sampled (obtained via OTF mapping)

Summary of Herschel / HIFI H_2O and NH_3 Observations

Frequency:	557 GHz (o-H_2O, LSB)
	572 GHz (o-NH_3, USB)
Total Map Time:	5 hrs. 11 min.
HIFI:	Band 1b
Operation Mode:	OTF – Position Switch (Full-Beam Spacing)
T_{sys} H-Pol:	80.4 – 80.9 K
T_{sys} V-Pol:	93.2 – 94.7 K
Observing Time:	11.84 s per position (4 scans total, 2 per pol.)
No. of Spatial Positions:	**2220**
Data Reduction:	HIPE 10, Class, IDL

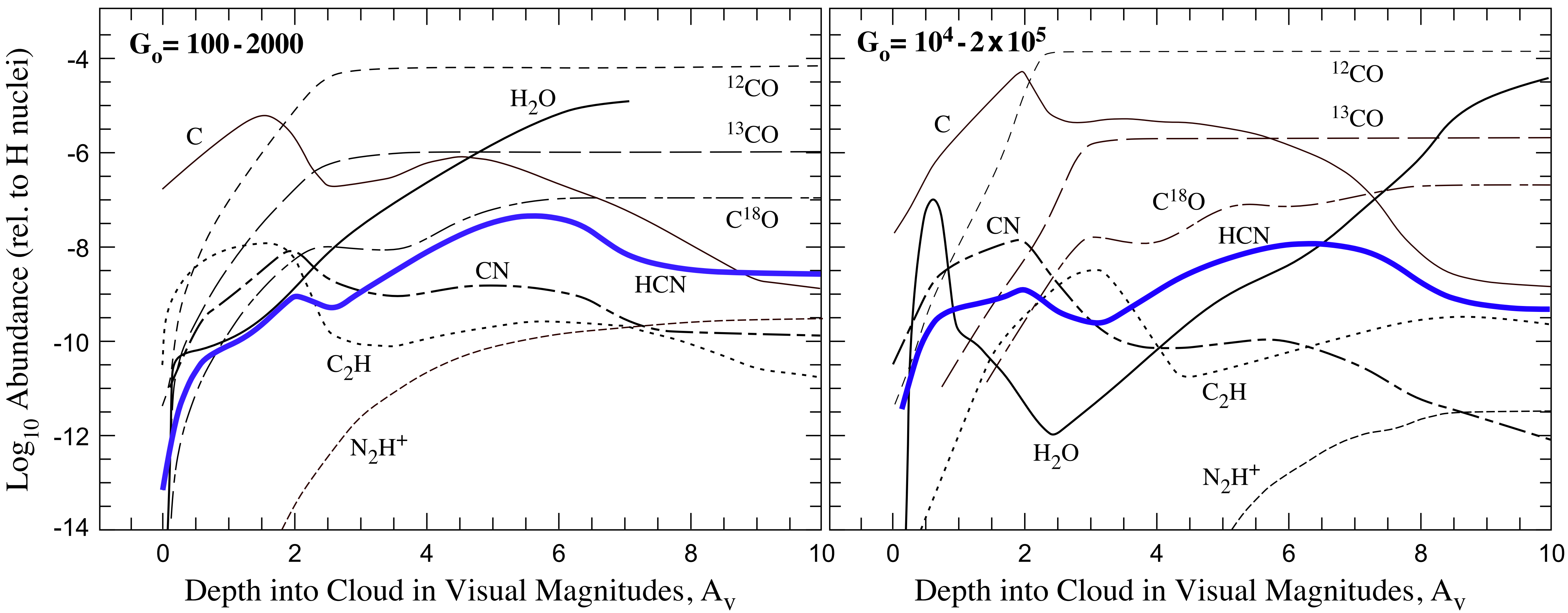
C_2H



CN, HCN	Boger & Sternberg (2005)	C, ^{12}CO, CN, HCN	Boger & Sternberg (2005)
C, C_2H, N_2H^+	Morata & Herbst (2008)	C_2H	Morata & Herbst (2008)
^{12}CO, ^{13}CO, C^{18}O, H_2O	Jansen et al. (1995)	^{13}CO, C^{18}O	Jansen et al. (1995)
		H_2O, N_2H^+	Sternberg & Dalgarno (1995)

NOTE: Predicted H_2O abundance profile does not include the effects of freeze out.

HCN



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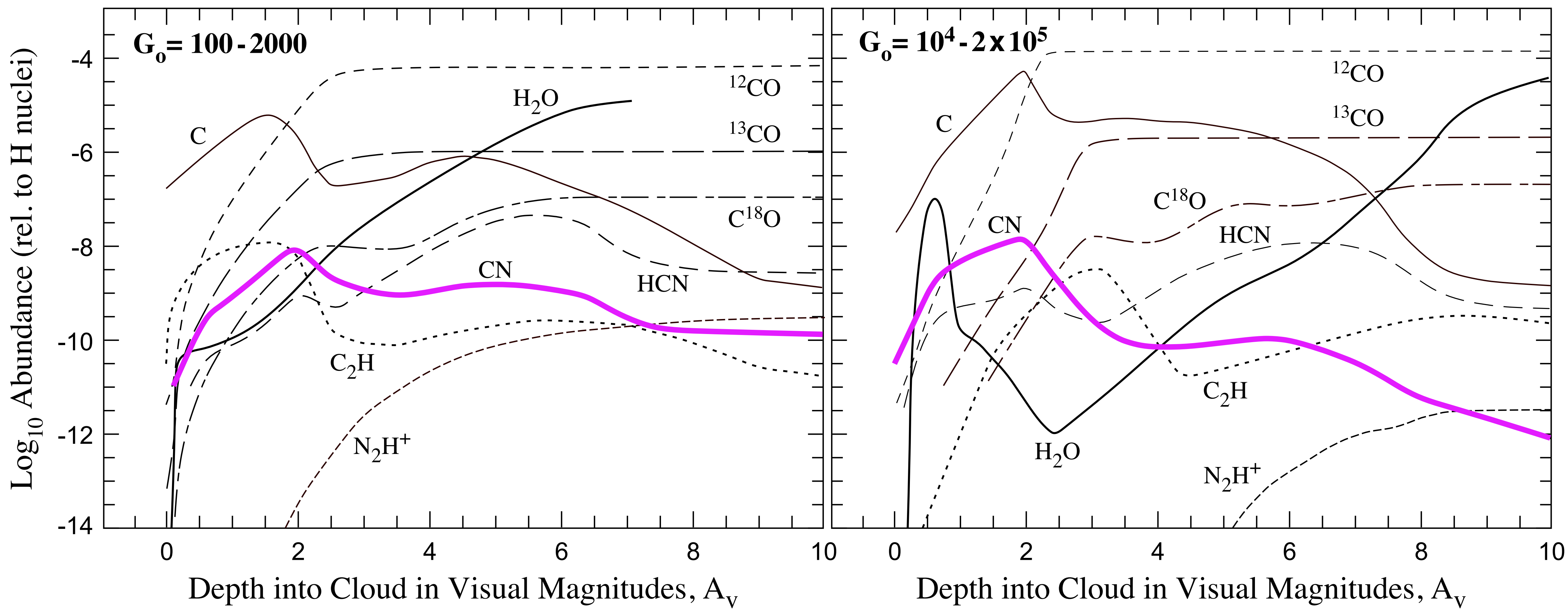
CN



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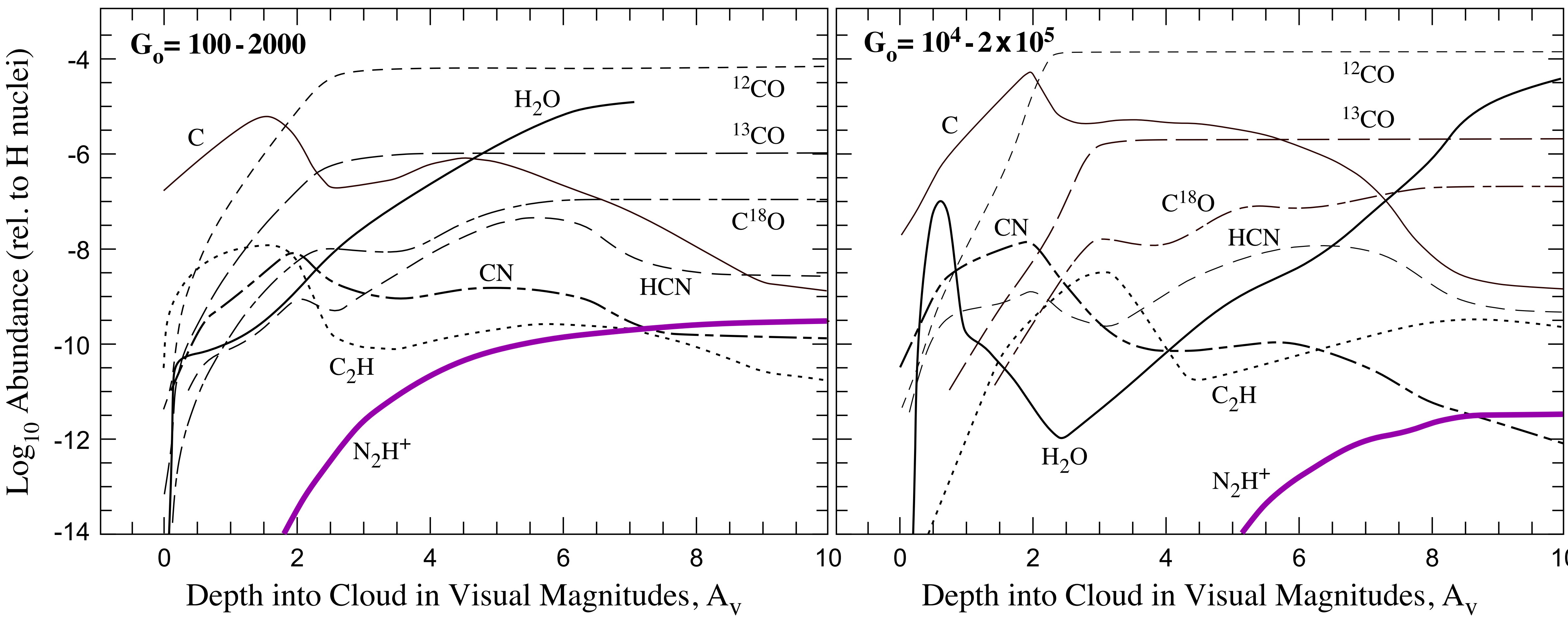
N_2H^+



CN, HCN	Boger & Sternberg (2005)
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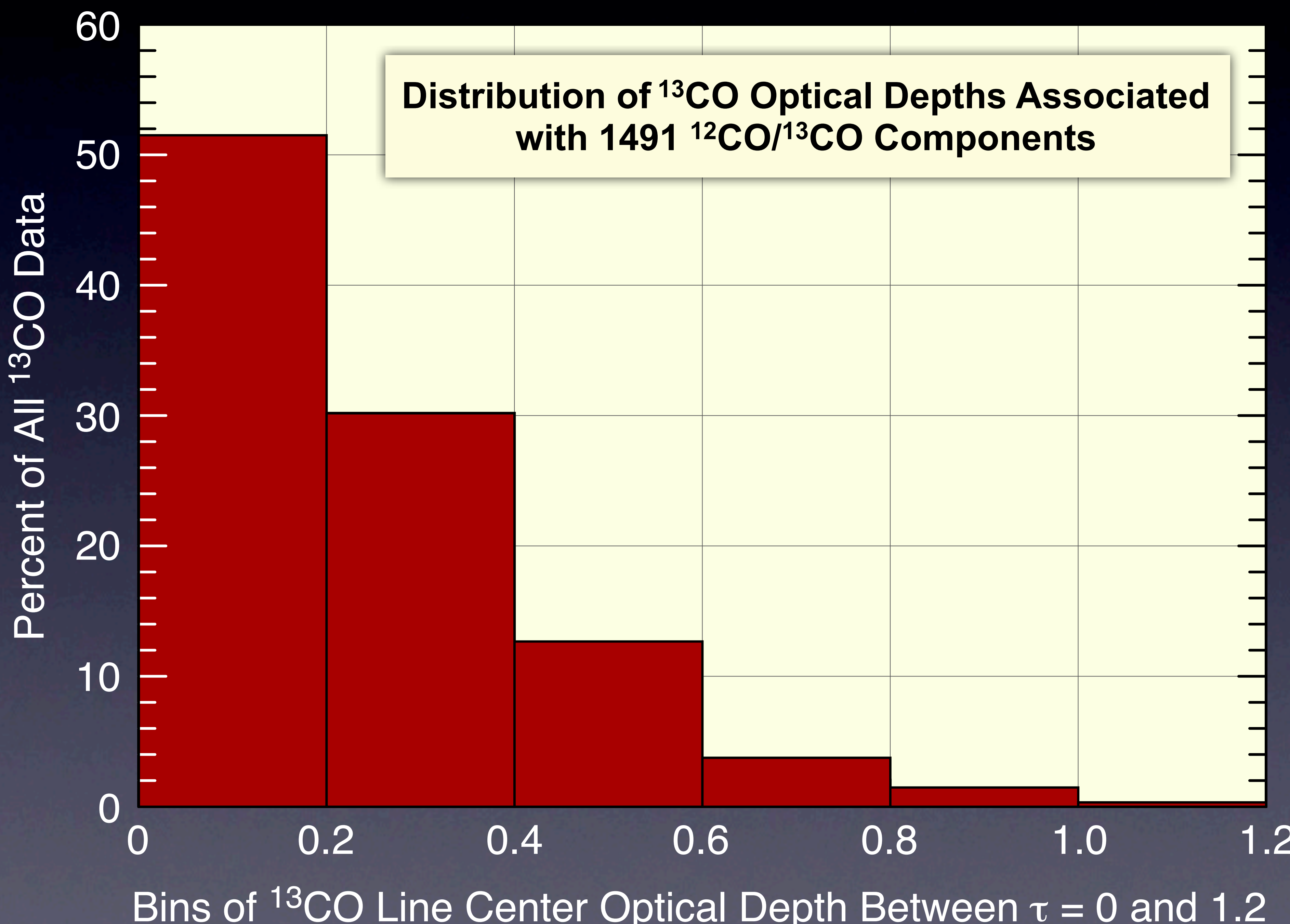
^{13}CO *J*=1-0 line center optical depth is derived from the brightness temps. of the ^{12}CO ^{13}CO *J*=1-0 transitions



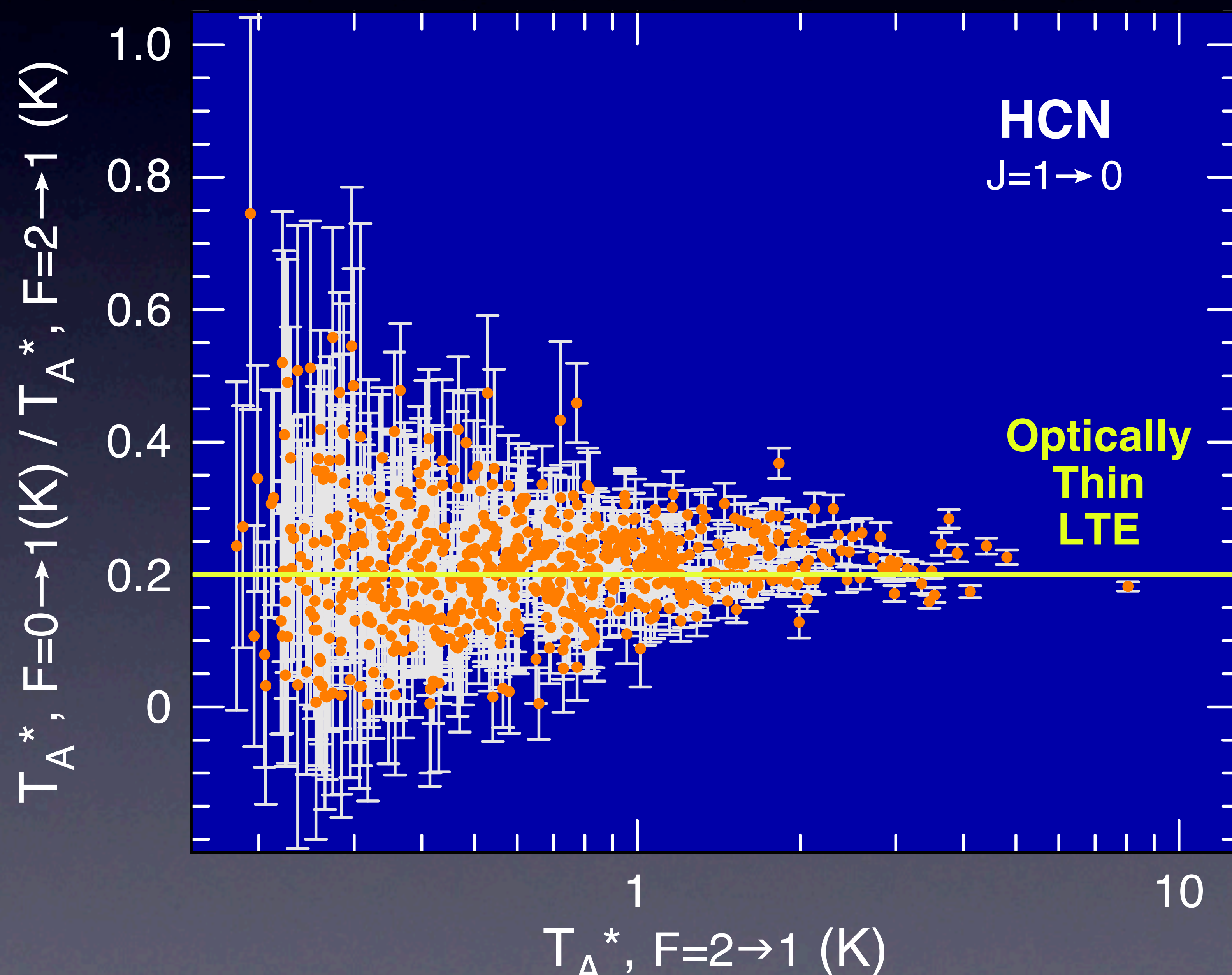
> 99% of the ^{13}CO velocity components have $\tau \leq 1$

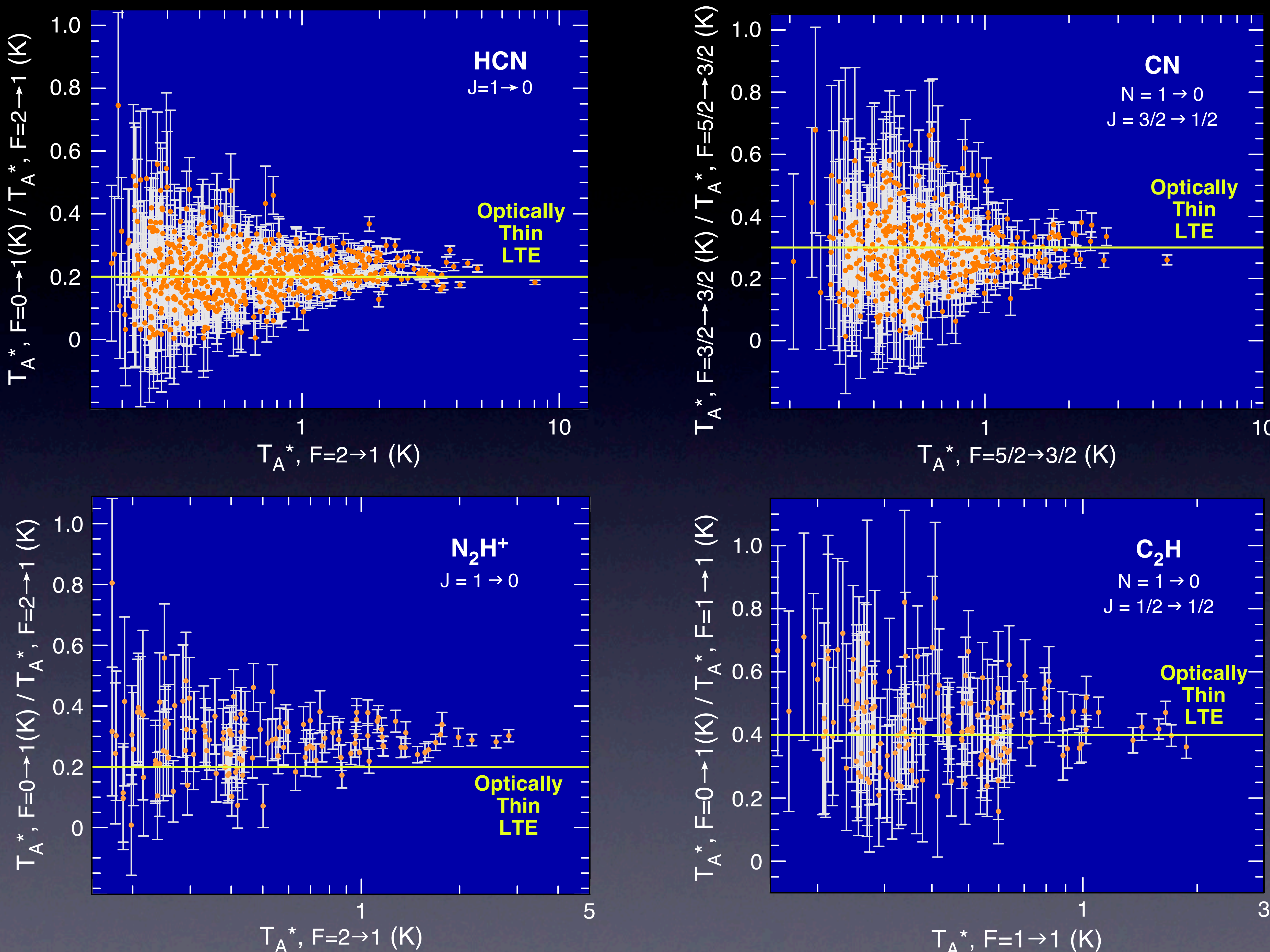
Hyperfine intensity ratio is sensitive to optical depth

For HCN:

The F=2→1 is the strongest HFS component and F=0→1 the weakest.

If these components are *optically thin and in LTE*, the ratio is 0.20.




HCN
J=1→0
Optically Thin LTE
T_A^*, F=0→1(K) / T_A^*, F=2→1 (K)
T_A^*, F=2→1 (K)
CN
N = 1 → 0
J = 3/2 → 1/2
Optically Thin LTE
T_A^*, F=3/2→3/2 (K) / T_A^*, F=5/2→3/2 (K)
T_A^*, F=5/2→3/2 (K)
N_2H^+
J = 1 → 0
Optically Thin LTE
T_A^*, F=0→1(K) / T_A^*, F=2→1 (K)
T_A^*, F=2→1 (K)
C_2H
N = 1 → 0
J = 1/2 → 1/2
Optically Thin LTE
T_A^*, F=0→1(K) / T_A^*, F=1→1 (K)
T_A^*, F=1→1 (K)

H_2O and NH_3 optical depths:

- The H_2O and NH_3 emission from the quiescent gas is weak.

- The critical densities at 25 K are:

H_2O	9.7×10^7 cm^{-3}
NH_3	3.6×10^7 cm^{-3}

which is $\gg$ the density of the extended Orion Molecular Ridge

- Emission in such high critical density transitions should be "effectively" optically thin.

I.e., the emission should increase linearly with column density.

The Observations

FCRAO Map

^{13}CO J=1-0

110.201 GHz

E_u/k = 5.3 K

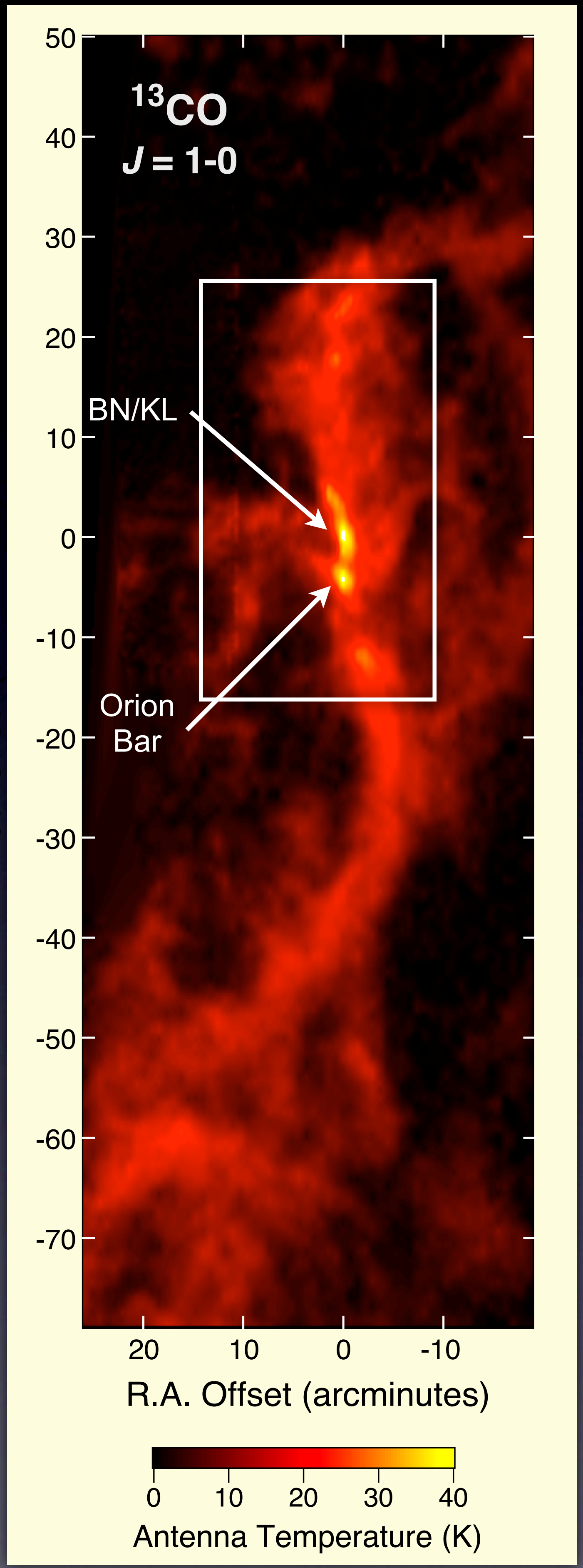
46″ Beam

Offsets relative to:

R.A. = $05^h\ 35^m\ 14.5^s$

Dec. = -05° 22′ 37″

(J2000)



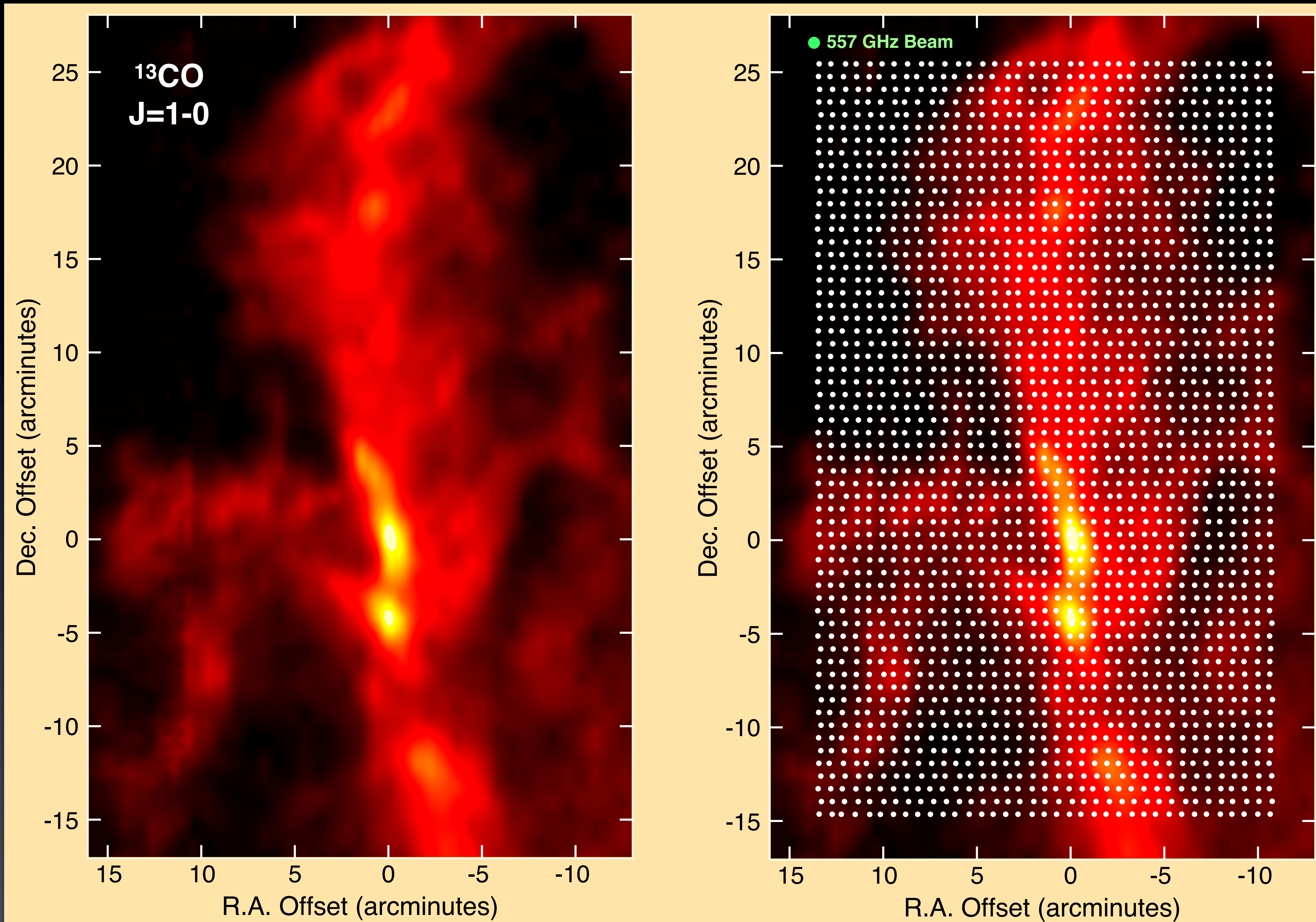
H_2O

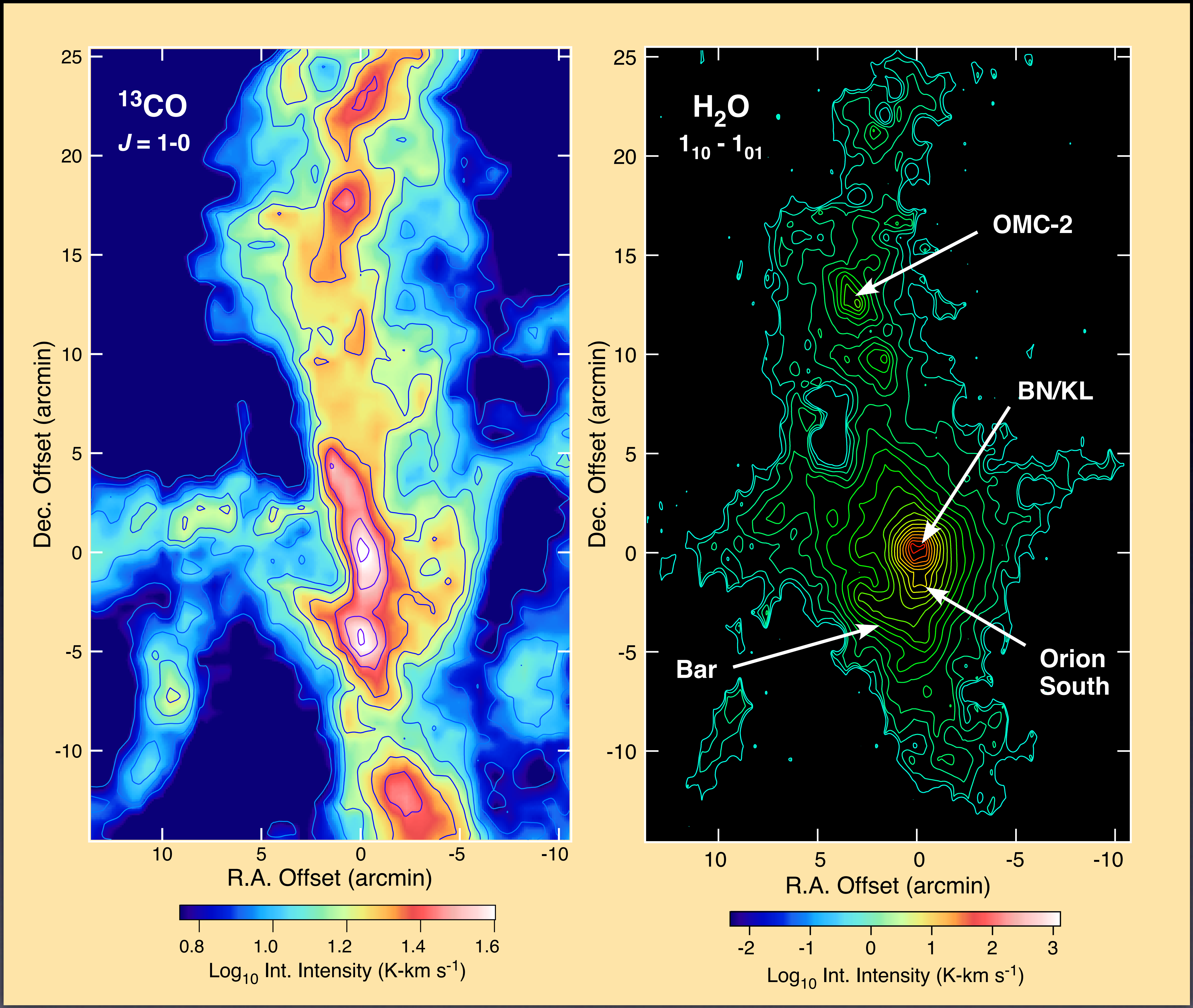
556.936 GHz 1_{10} - 1_{01}

Map Area:

25′ x 40′

Observed 557 GHz Spatial Positions

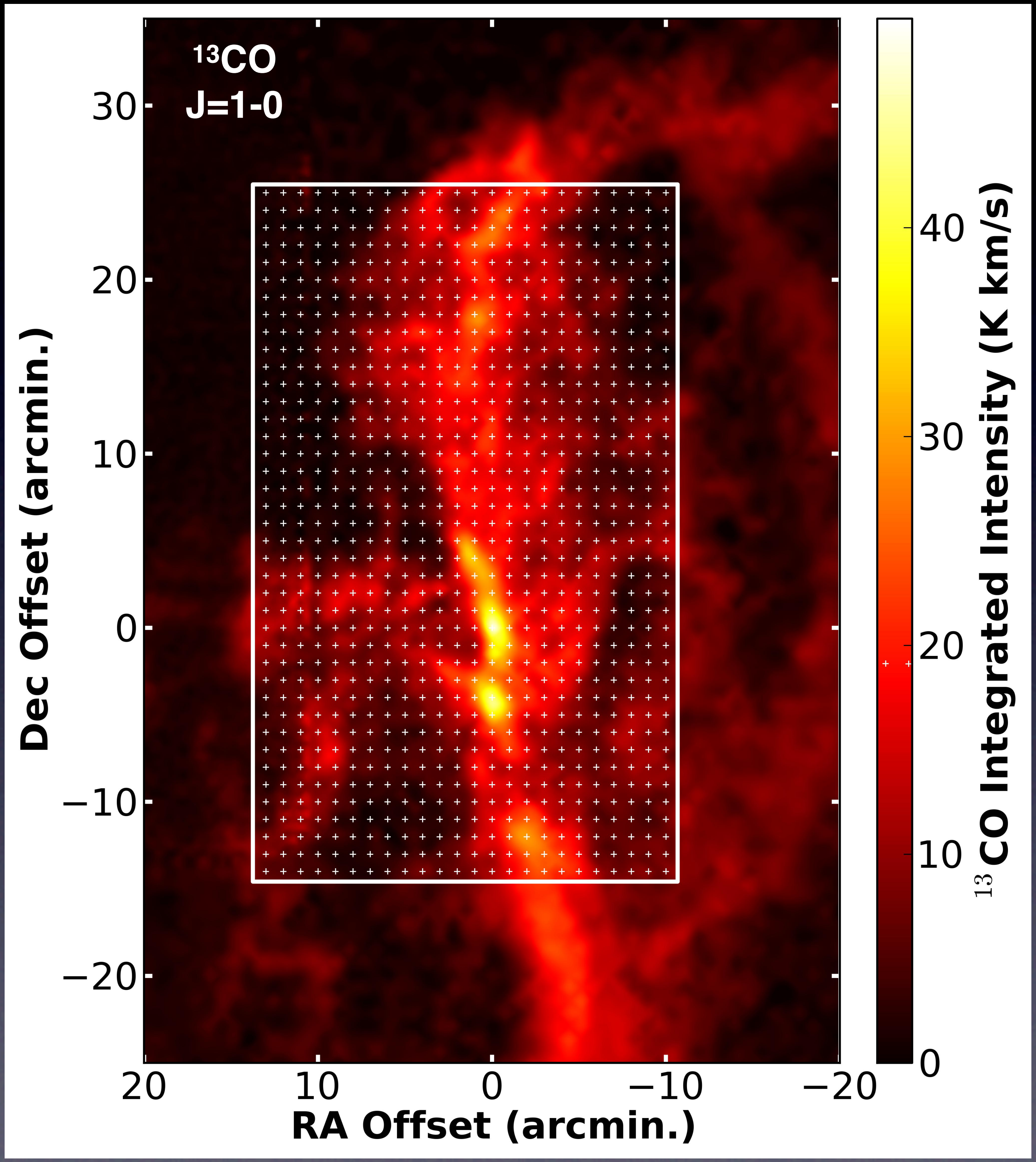




^{13}CO
$J = 1\text{-}0$
25
20
15
10
5
0
-5
-10
Dec. Offset (arcmin)
10
5
0
-5
-10
R.A. Offset (arcmin)
0.8
1.0
1.2
1.4
1.6
Log_{10} Int. Intensity (K-km s^{-1})
H_2O
$1_{10} - 1_{01}$
OMC-2
BN/KL
Bar
Orion South
25
20
15
10
5
0
-5
-10
Dec. Offset (arcmin)
10
5
0
-5
-10
R.A. Offset (arcmin)
-2
-1
0
1
2
3
Log_{10} Int. Intensity (K-km s^{-1})

Data Reduction

HIFI and FCRAO Data Reduction



HIFI and FCRAO maps have been regridded on the same 1′ grid with 1′ (FWHM) circular beams using a Gaussian kernel.

# of Regridded Positions: 960

HIFI and FCRAO Data Reduction

In addition:

- To compute τ (^{13}CO, J=1-0) and N(^{13}CO), use was made of the ^{12}CO and ^{13}CO J=1-0 emission measured by FCRAO, with each ^{13}CO spectrum fit with between 1 and 4 Gaussian profiles in order to isolate spectrally distinct velocity components.

- The visual extinction along each line of sight is based on the work of Ripple et al. (2013) who used 2MASS infrared stellar photometry measurements of the Orion A and Orion B molecular clouds, along with ^{12}CO and ^{13}CO J=1-0 emission, to establish the relation between N(^{13}CO) to A_V, including the Herschel/HIFI water map region.

  ∴ Each spatial position is characterized by a single value of N(^{13}CO) and A_V, and between 1 and 4 values of τ (^{13}CO, J=1-0)

- The integrated intensity (K km s^{-1}) for each species toward each spatial position was obtained through direct integration of each spectrum over the velocity range defined by the ^{13}CO emission.

Constraints

- To ensure the analysis isn't affected by spatial positions containing molecular emission not from the face-on PDR, the area within the red rectangle was excluded from the analysis:
  - 2′ north, west and 3′ east of BN/K (shock emission)
  - 5′ south of BN/KL (shock emission + Orion South + Orion Bar)
- In addition, other lines of sight exhibiting broad line emission – e.g., OMC-2 – were either excluded or, where clearly present, only the narrow components were used.

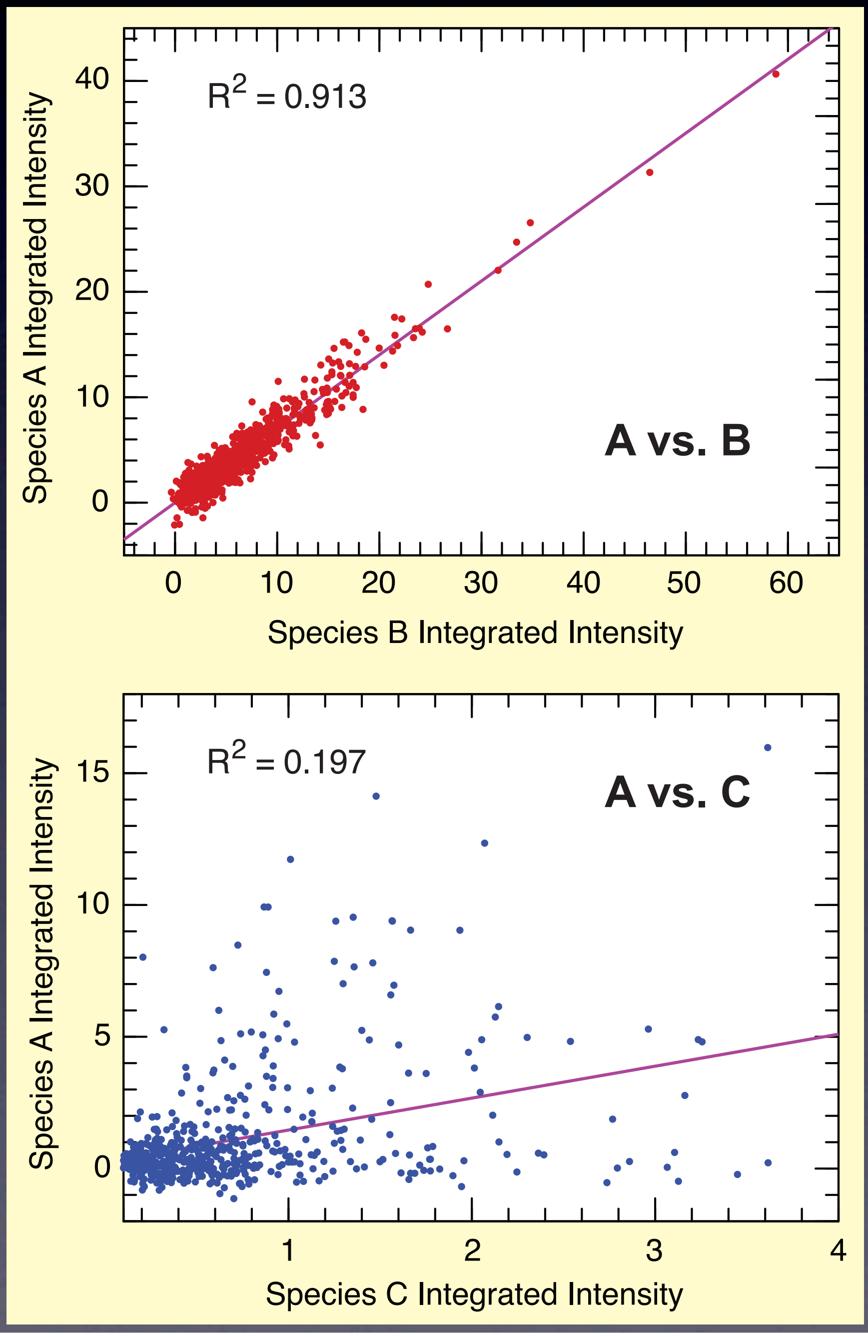
Results 1: Principal Component Analysis (PCA)

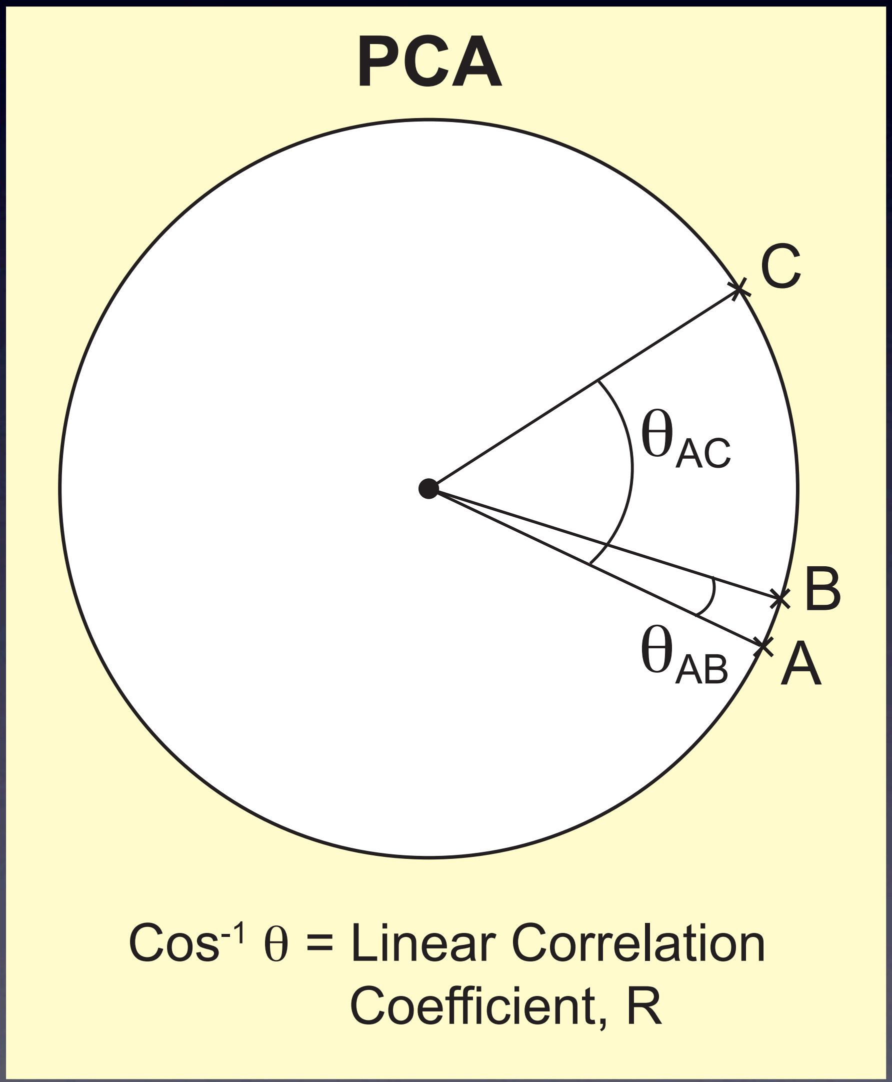
A technique used to highlight similarities and differences in a large and complex dataset

Principal Component Analysis

PCA's goal is to find, among linear combinations of the data variables, a sequence of orthogonal, or completely uncorrelated, factors that most efficiently explain the differences in the data.

The degree of clustering of the vectors is a measure of their correlation.





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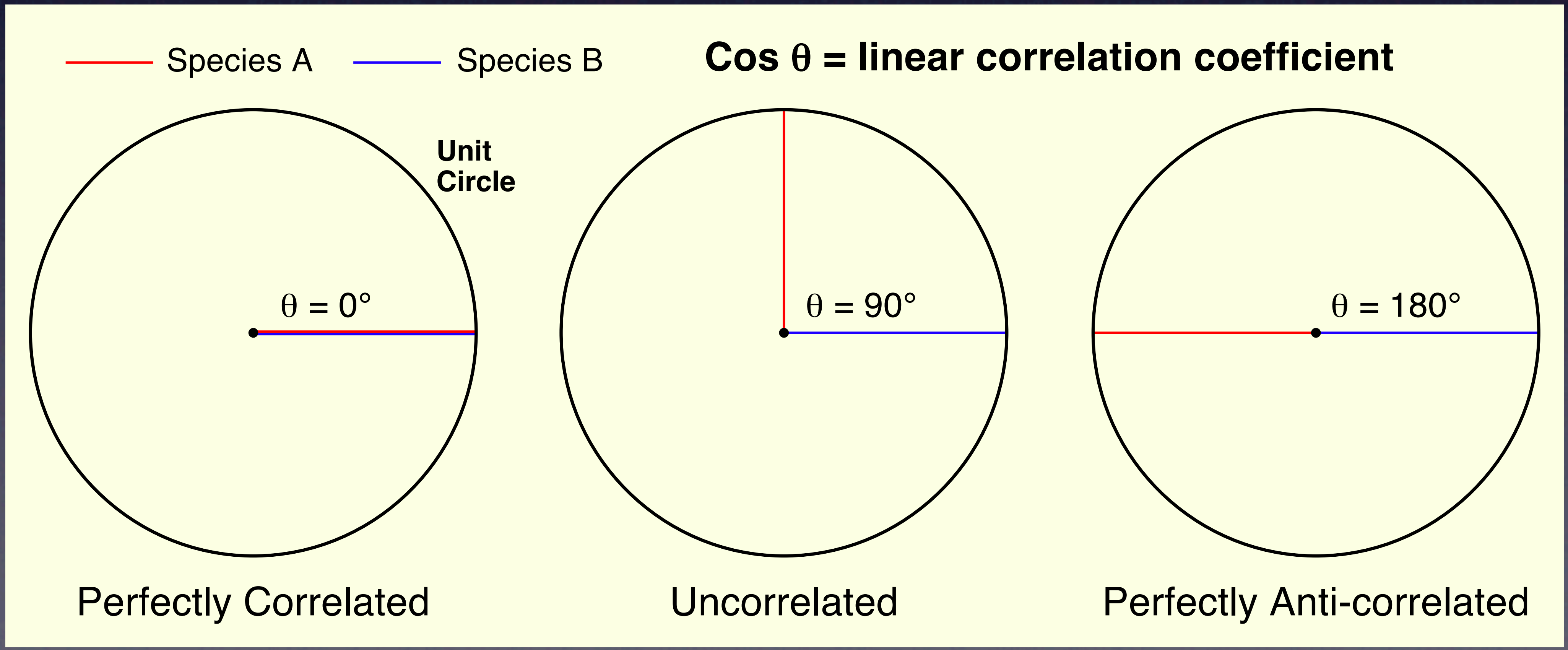
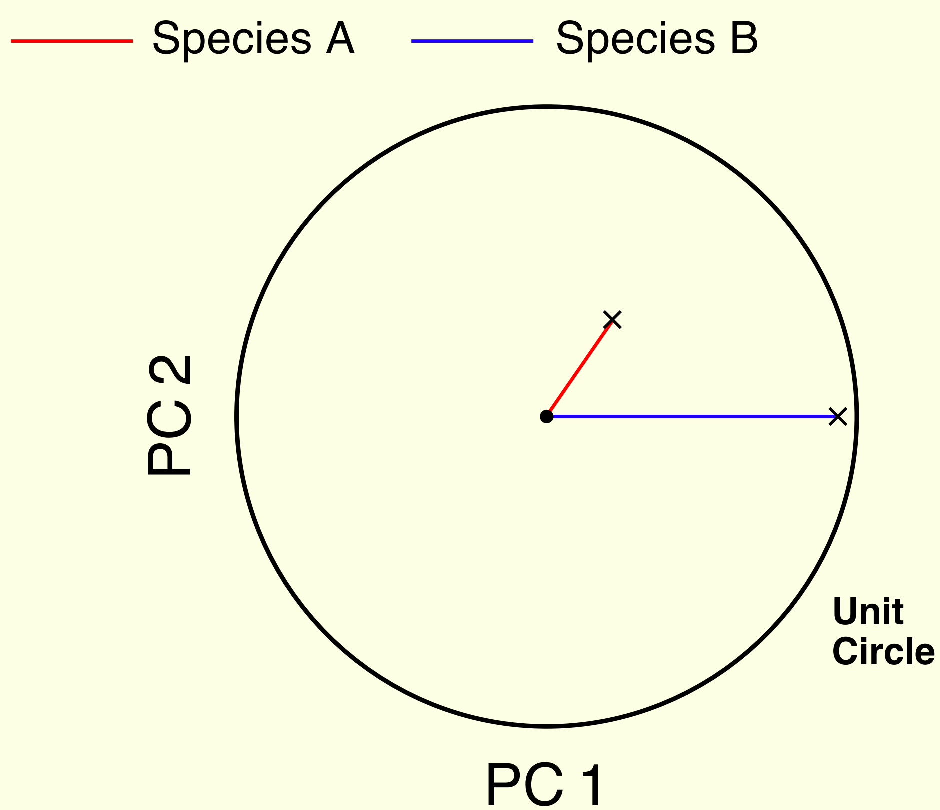
To ensure that the analysis gives equal weighting to each line – versus allowing the brightest lines to dominate the analysis – the integrated intensities for each spectral line have been mean subtracted and divided by the standard deviation.



Principal Component Analysis

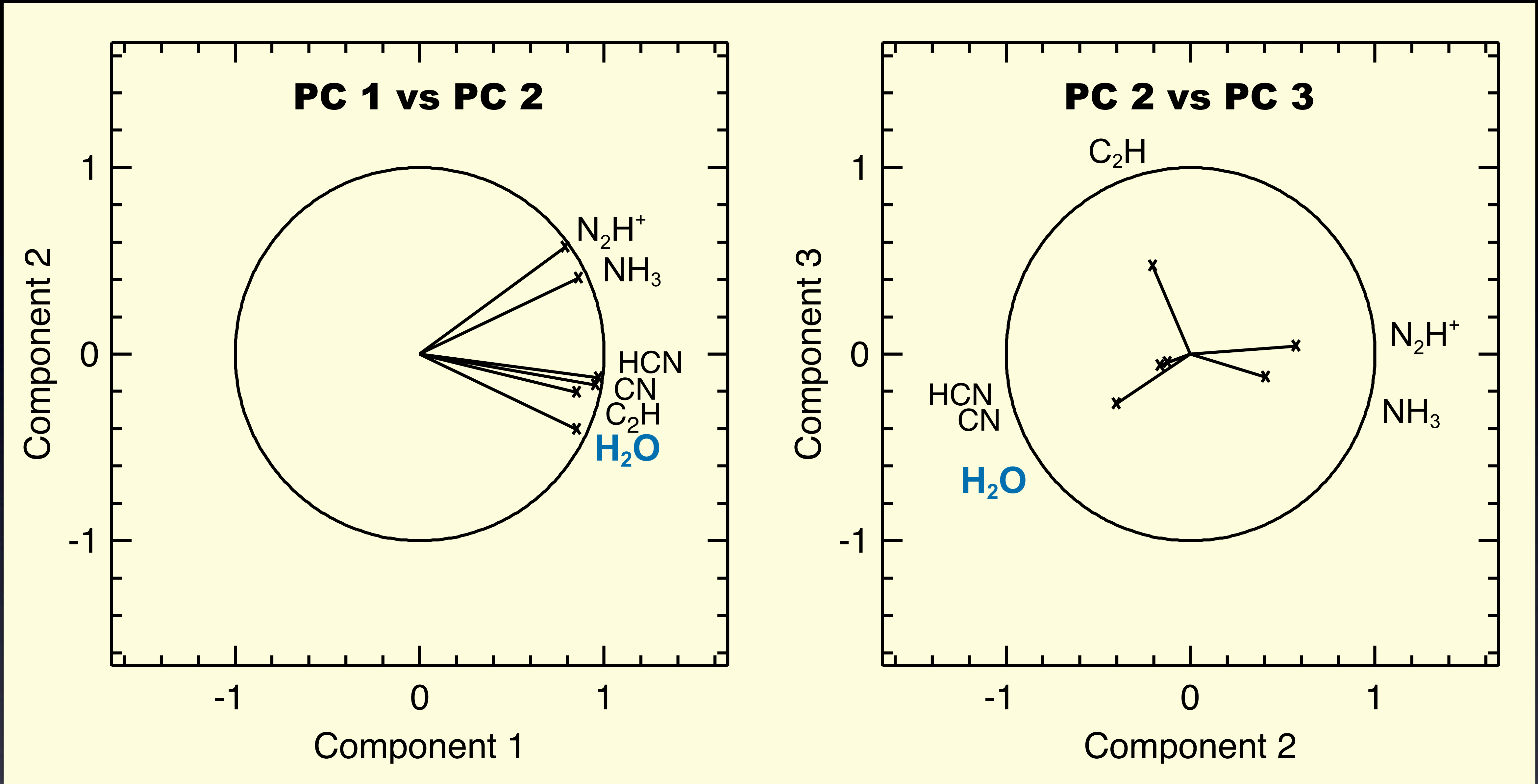
Because the Principal Components (PCs) are normalized, the proximity of the points to the circle of unit radius is a measure of the degree to which any two PCs contain almost all of the variance in the data.



The variance in the Species B data is much better described by Principal Components 1 and 2 than the variance in Species A.

Principal Component Analysis

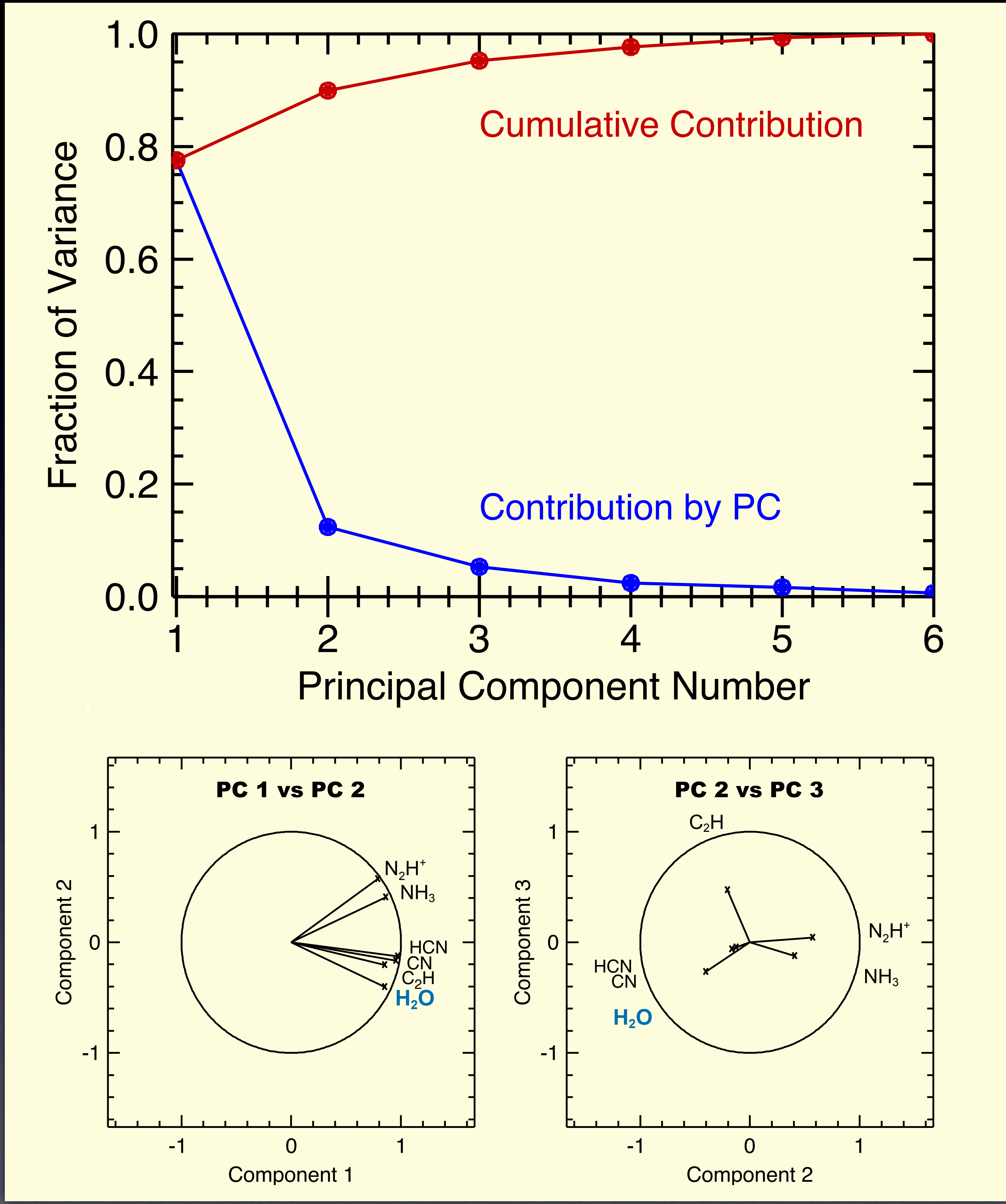
Based on 834 spatial positions toward which at least ^{13}CO was detected



⇒ PCA shows that H_2O is highly correlated with HCN, C_2H, CN, but not with the NH_3 and N_2H^+. However, PCA doesn't directly establish where H_2O lies within the cloud.

Principal Component Analysis

90% of the total variance between all 6 species is accounted for with PCs 1 and 2, and 95% of the total variance is accounted for with the addition of PC 3.



Results 2: Ratio of Species

Determining where water (and other species) lie within molecular clouds

Ratio of Species

Once we know:

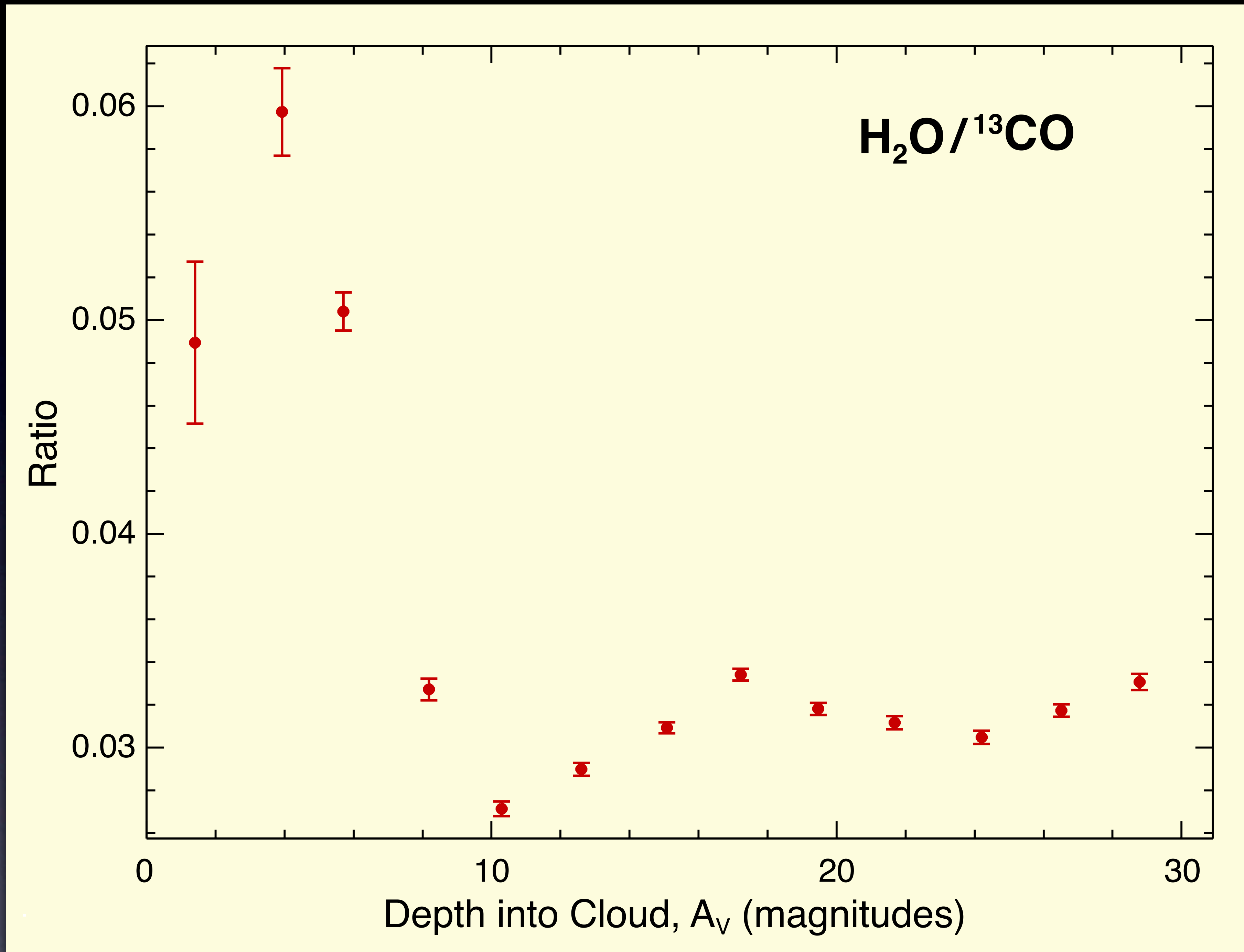
- A_V associated with each spatial position
- The lines are optically thin

and with 640 spatial positions toward which H_2O was detected, it's possible to construct:

- Ratios of integrated intensities at each spatial position and for each associated A_V

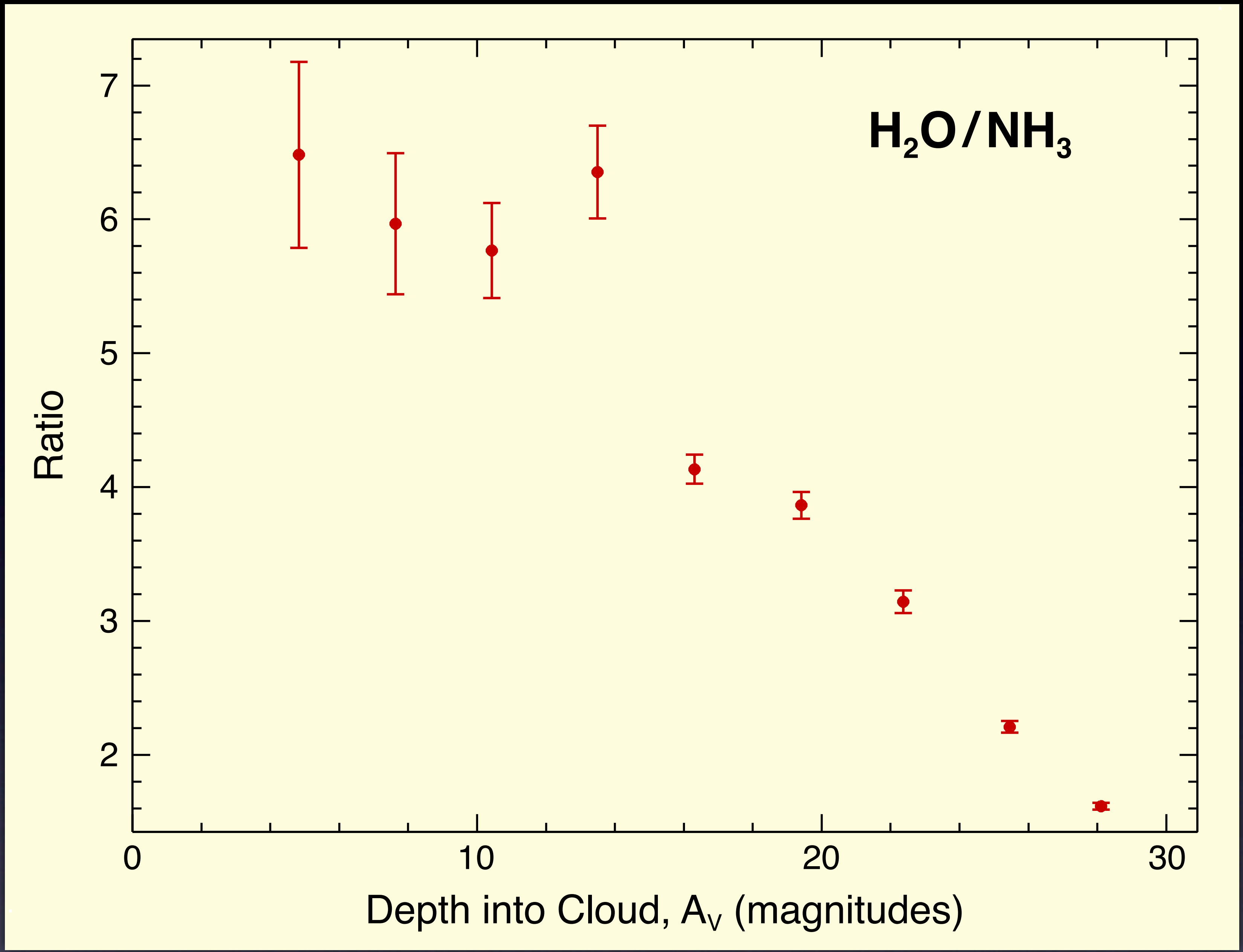
Taking these 100's of ratios and averaging them within bins of A_V for clarity then yields...

Ratio of Species



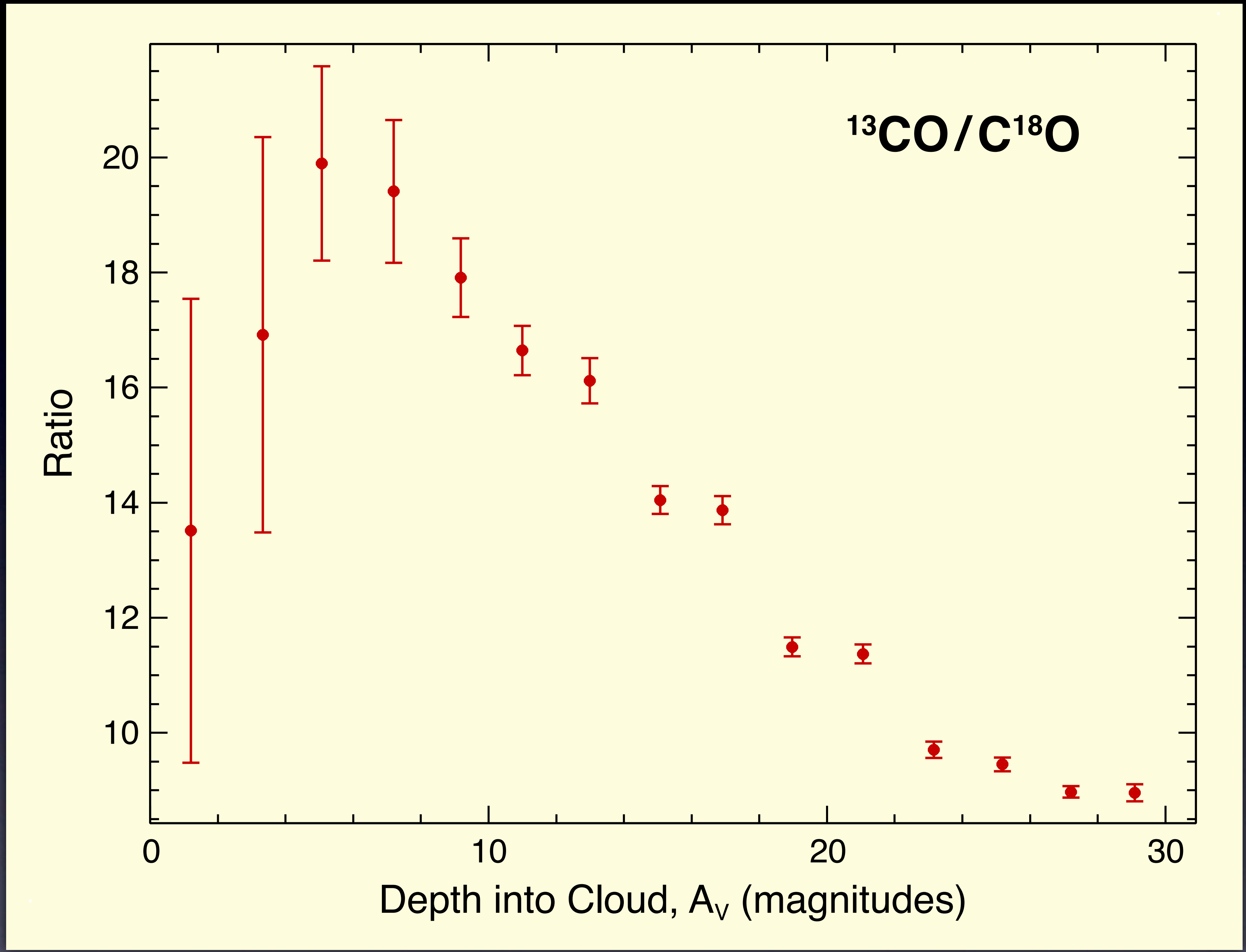
⇒ Confirms that H_2O peaks near the cloud surface, as predicted

Ratio of Species



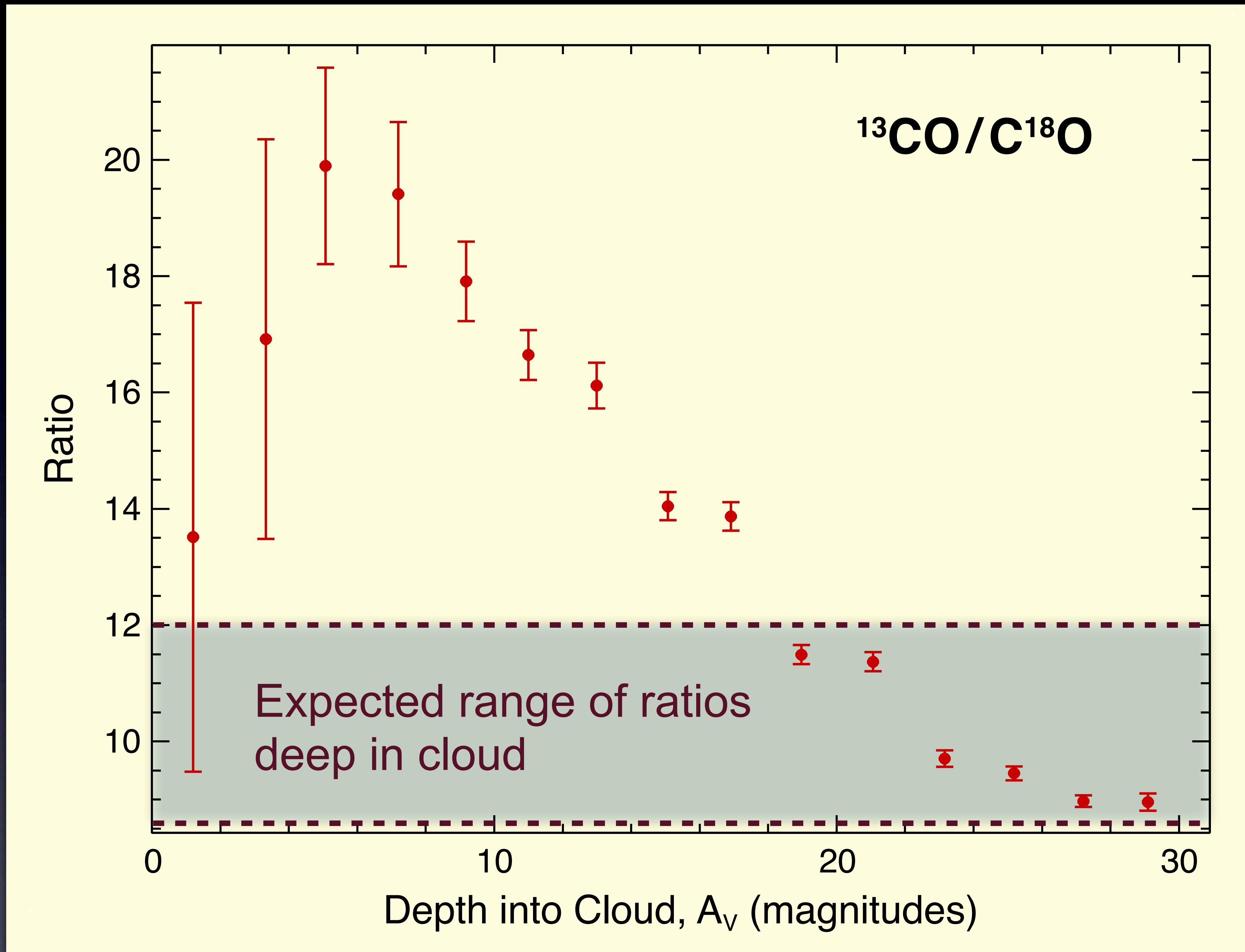
⇒ Rise in the H_2O emission is not due to excitation effects since E_u/k for the H_2O and NH_3 transitions are nearly the same – 26.7K and 27.5K, respectively (and $n_{cr} > 10^7$ cm^{-3} for both)

Ratio of Species



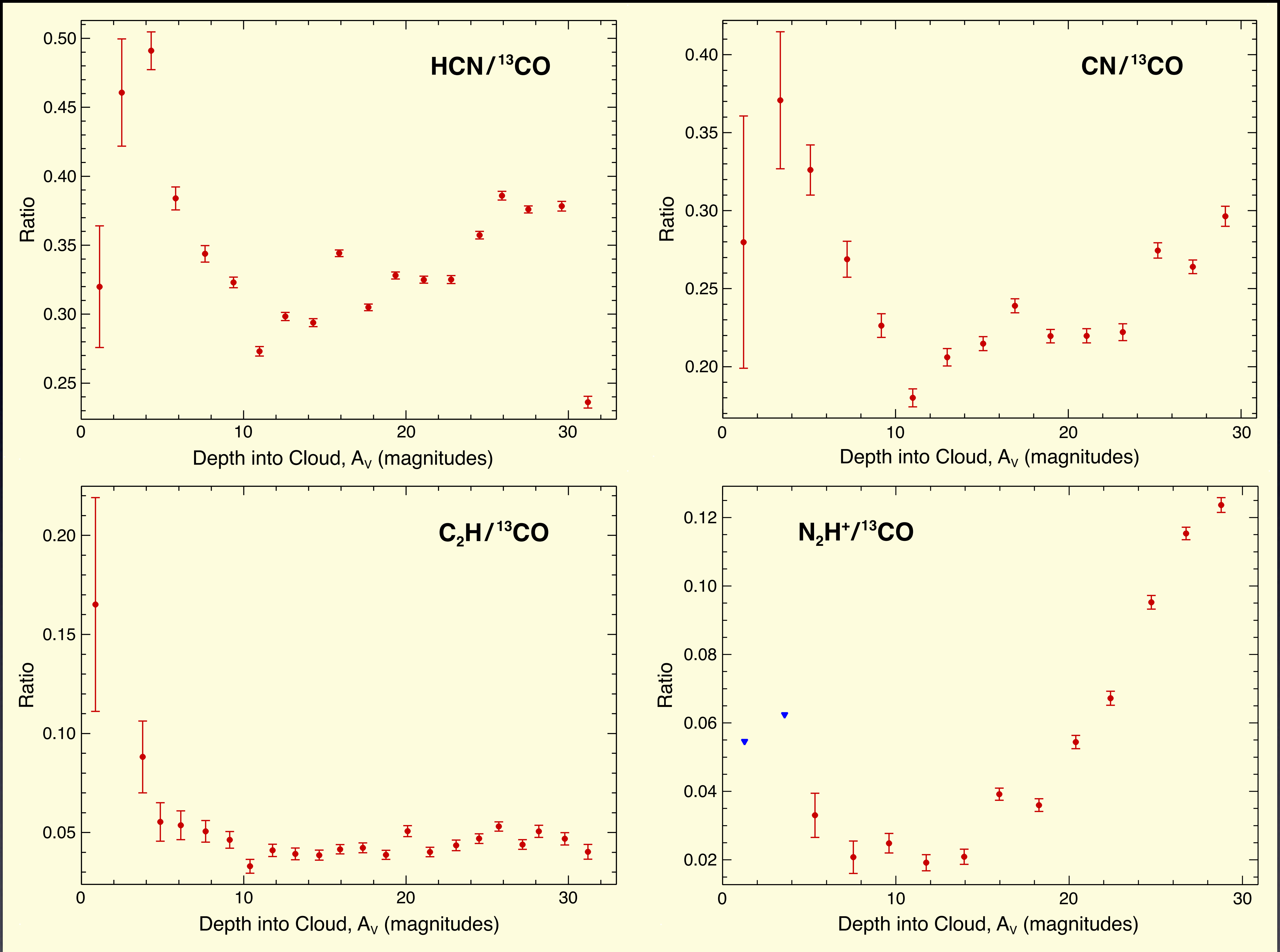
⇒ Technique produces the rise in the $^{13}CO/C^{18}O$ ratio expected based on the relative self-shielding of these isotopologues

Ratio of Species



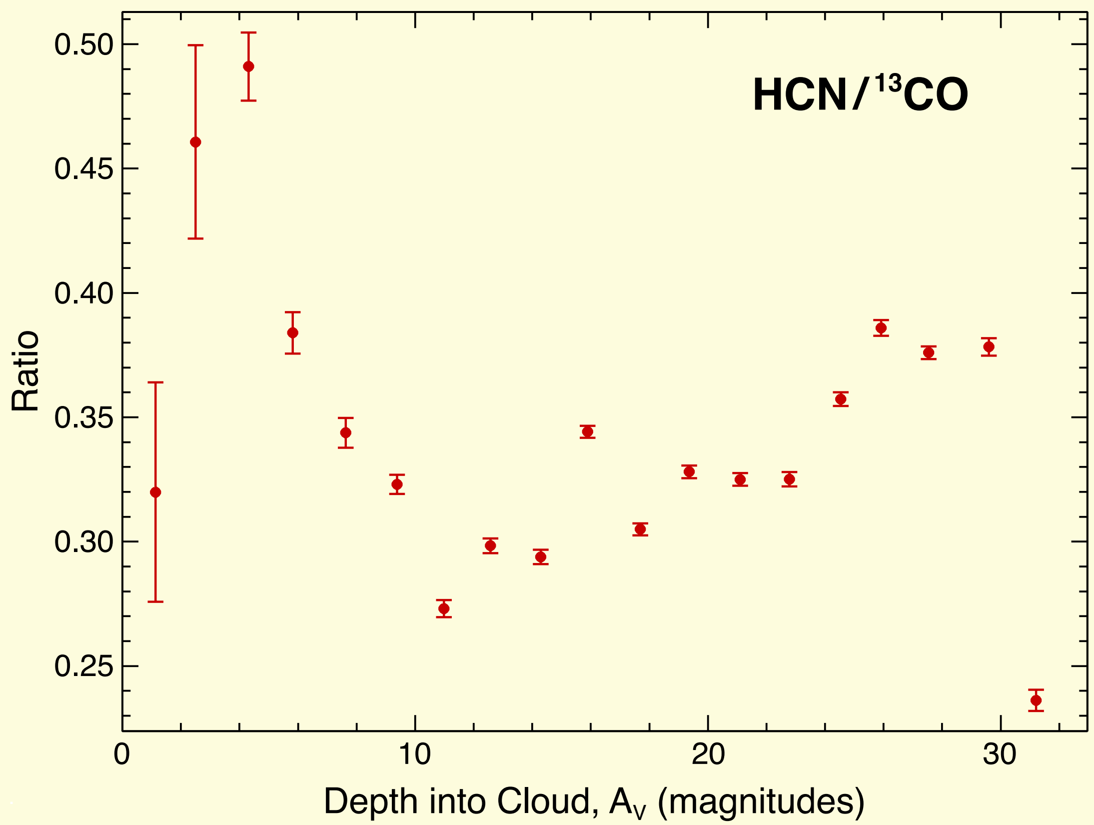
⇒ and the ratio of 8-12 predicted deep in the cloud based on the measured $^{13}C/^{12}C$ and $^{16}O/^{18}O$ ratios

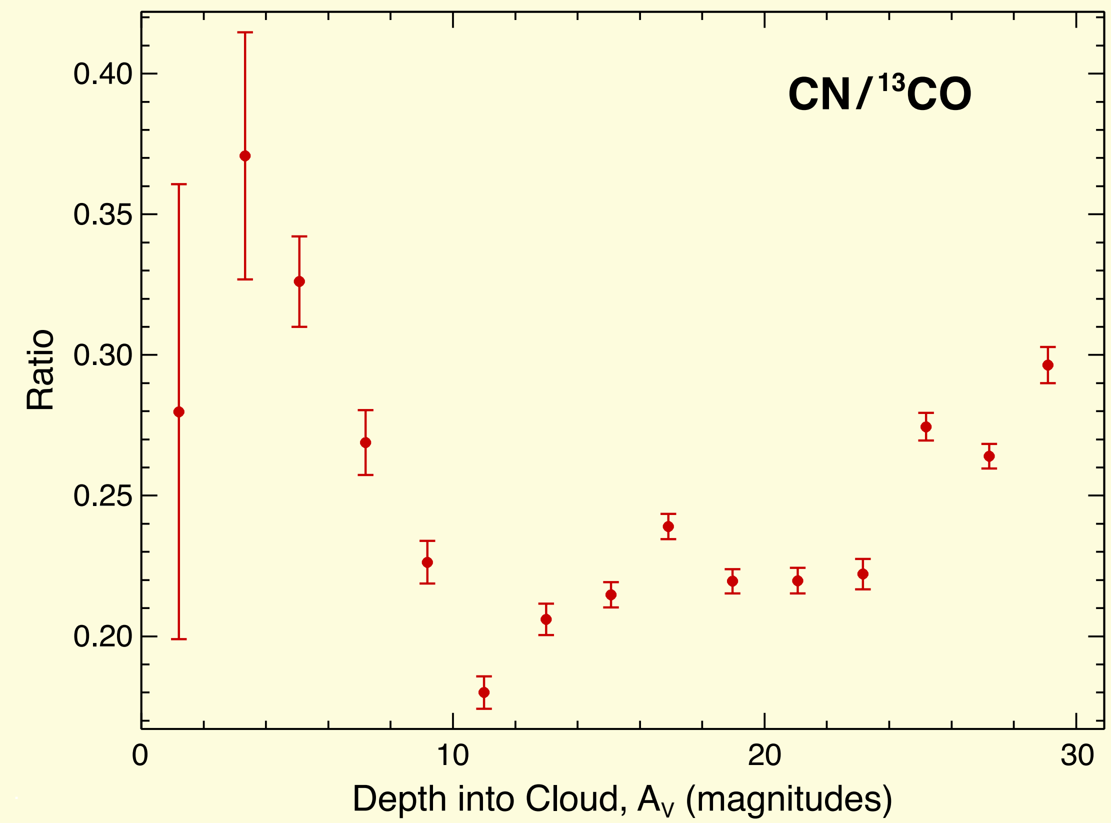
Ratio of Species

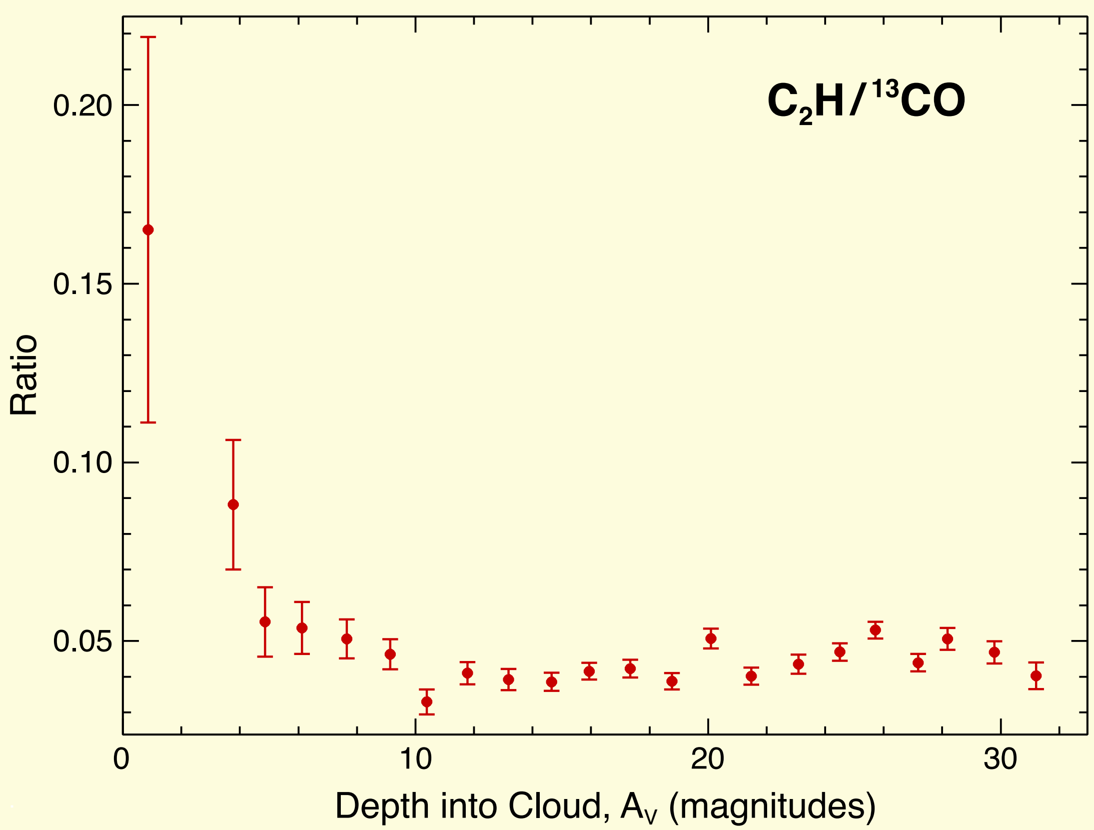


Monday, March 24, 2014

Ratio of Species

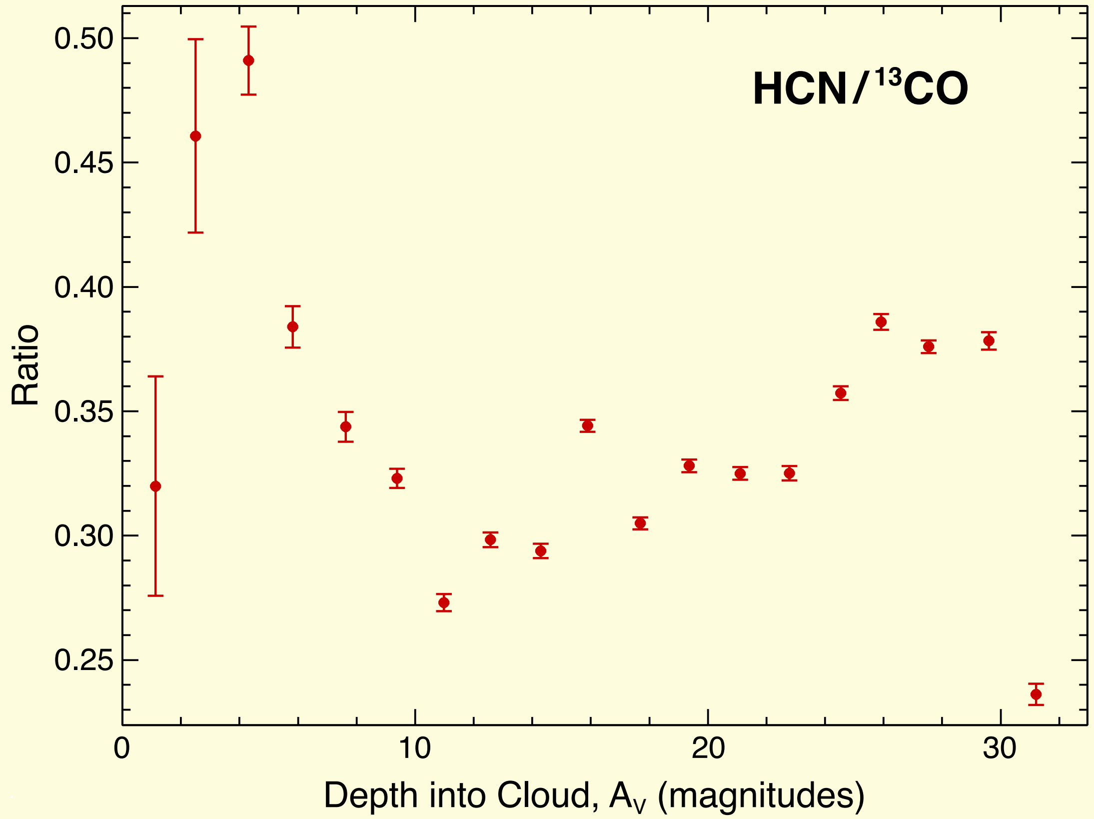


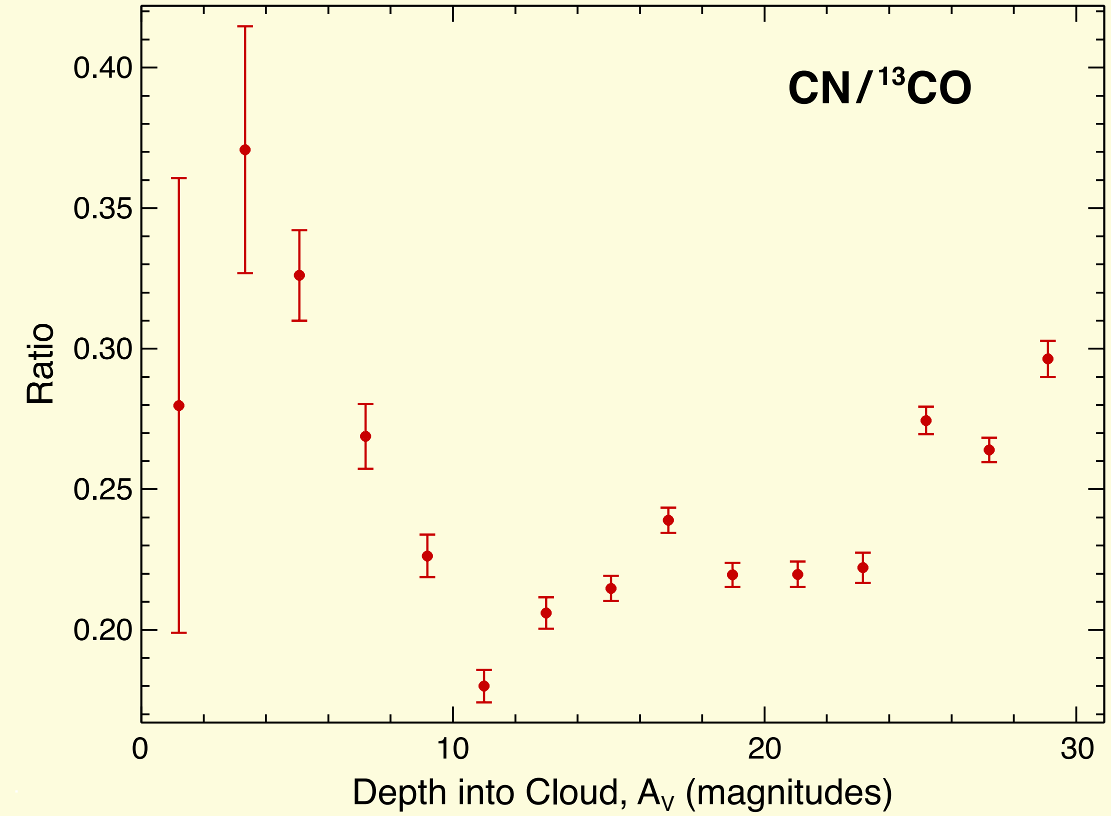




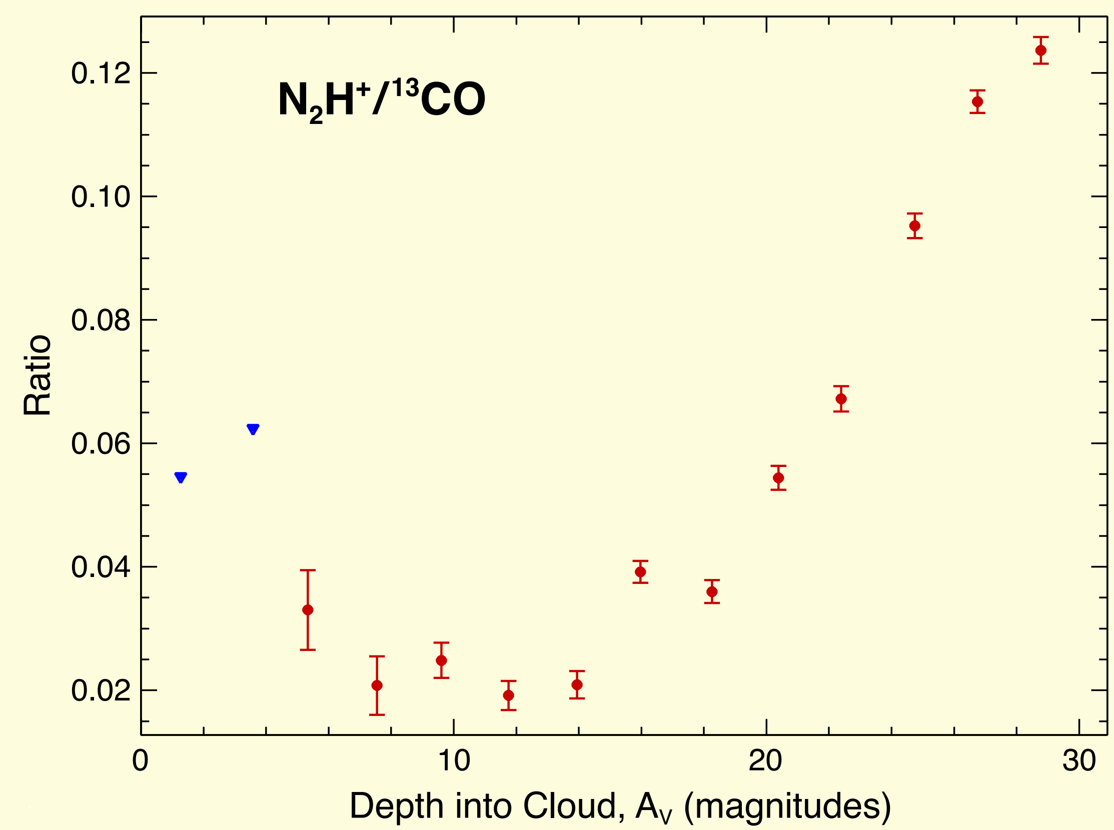
$\Rightarrow$ Shows rise in HCN, CN and C_2H emission toward the cloud surface, as predicted by PDR models.

Ratio of Species





⇒ Shows rise in N_2H^+ emission deep into the cloud, as predicted by chemical models.



Summary

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- Herschel/HIFI was used to obtain 2220 fully-sampled spectra toward the face-on Orion Molecular Ridge over a 25′ x 40′ area in the 1_{10}-1_{01} 557 GHz line.
- These data were combined with fully-sampled maps obtained with FCRAO in low-lying transitions of ^{13}CO, $C^{18}O$, HCN, CN, C_2H, and N_2H^+ to determine *observationally* the depth-dependent distribution of gas-phase water within quiescent molecular gas.
- The maps, which were obtained with beam sizes ranging from 40″ to 56″, were spatially resampled to 1′ beams on a common 1′ spatial grid, resulting in 960 spectra for each species (or 6720 spectra, total).
- Principal Component Analysis reveals a strong correlation between H_2O and the surface tracers HCN, CN, and C_2H and no significant correlation with the volume tracers NH_3 and N_2H^+.
- Integrated intensity ratios are in broad agreement with PDR and cloud chemical models. Comparison with ^{13}CO and NH_3 shows a relative rise in H_2O integrated intensities at low A_v (not due to excitation effects)

➜ Measures of the integrated intensities of H_2O and 6 other species provides direct evidence that the water vapor abundance peaks near the surfaces of dense clouds.