Evaluation of molecular hydrogen tracers

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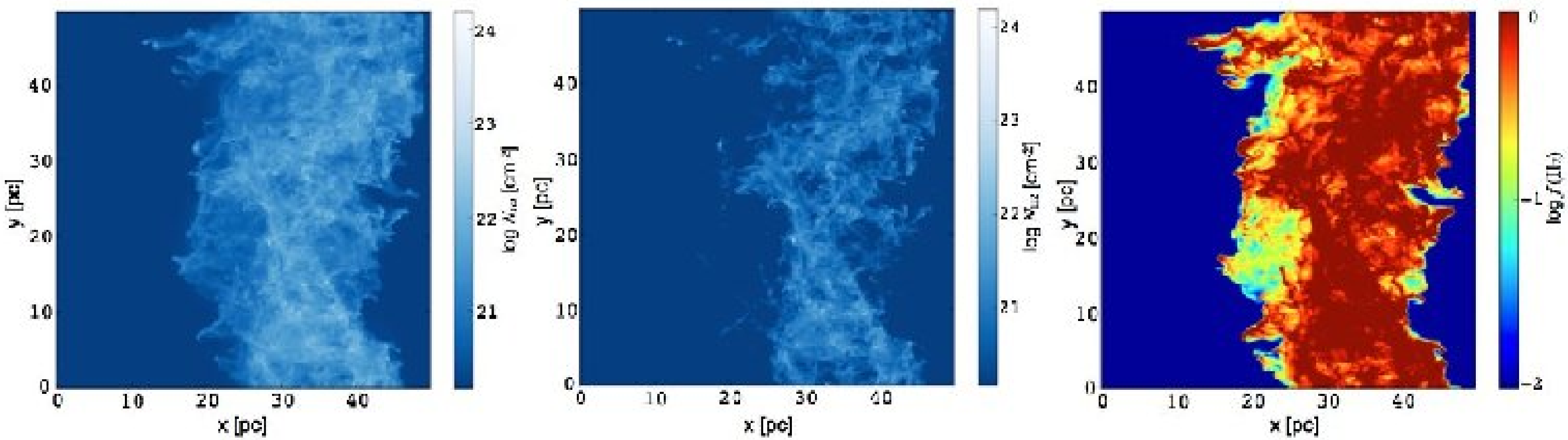
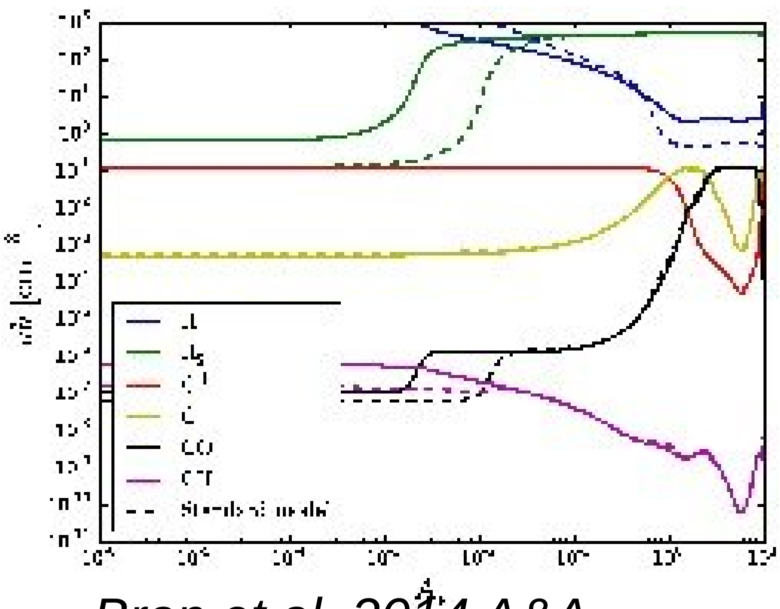
Molecular hydrogen in the diffuse ISM

- Direct H_2 measurements in the UV or the near-IR toward moderately reddened massive stars
- It is interesting to find more species that are well mixed with H_2 and can be used as surrogates over a wider source sample
- Several hydrides have been proposed : CH, HF, OH, H_2O based on direct comparison of column densities and analysis of the chemistry
- Other molecules like HCO^+, CCH can be calibrated relative to the hydrides

Tracing the H_2 fraction



Valdivia et al. 2016 A&A



Bron et al. 2014 A&A

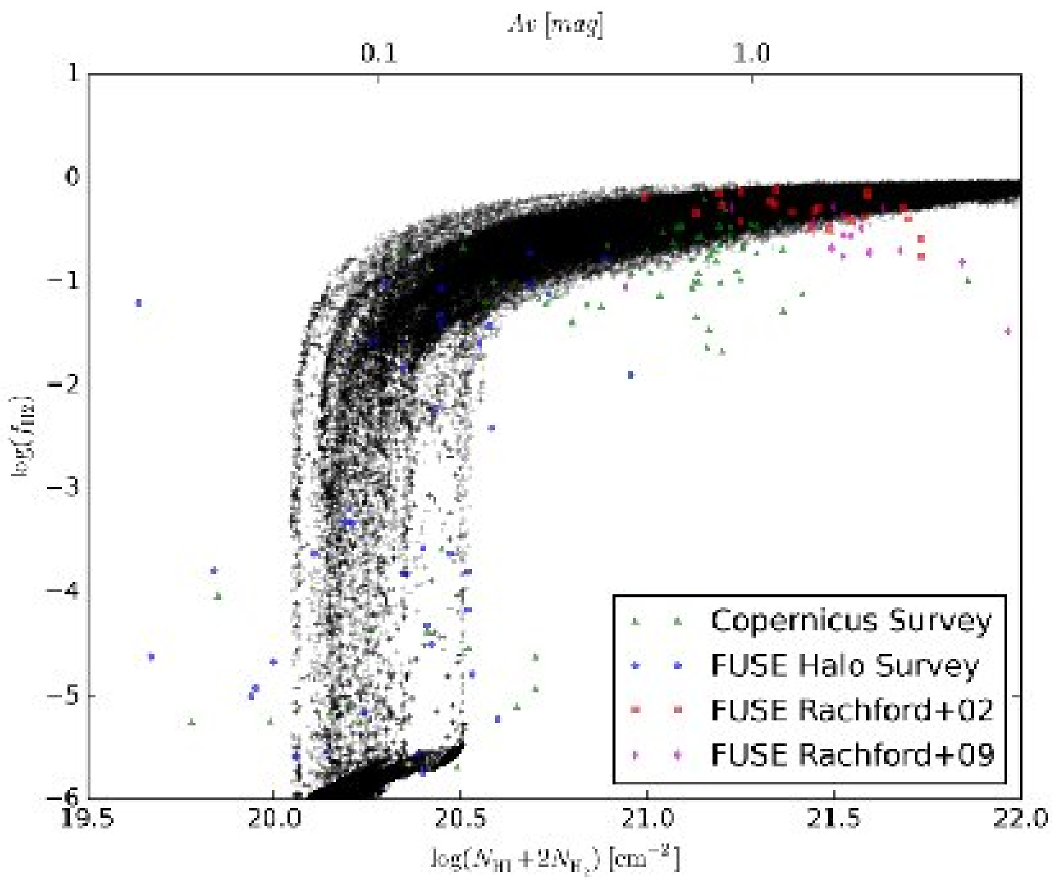
Local value :

$f(H_2) = 2n(H_2)/(n(HI)+2n(H_2))$

Integrated value :

$f(H_2) = 2N(H_2)/(N(HI)+2N(H_2))$

H/H_2 transition



Valdivia et al. 2016 A&A

- Sharp increase of the H_2 fraction near AV ~ 0.1 in G_0 = 1
- When H_2 is detected, the integrated H_2 fraction is already significant (> 0.1) for nearby stars
- CO emission is detected for Av > 0.5 – 1
- Molecule absorption can be detected in regions with no or weak CO emission

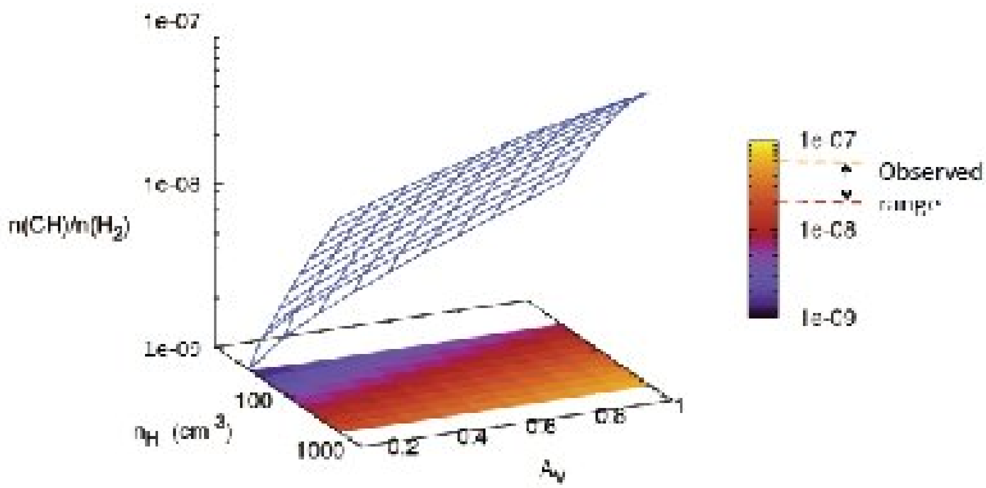
Tracing the H_2 fraction

- Global H_2 tracers = molecules with a nearly constant abundance relative to H_2 (well mixed)

  CH, HF, OH, H_2O, HCO^+ , CCH

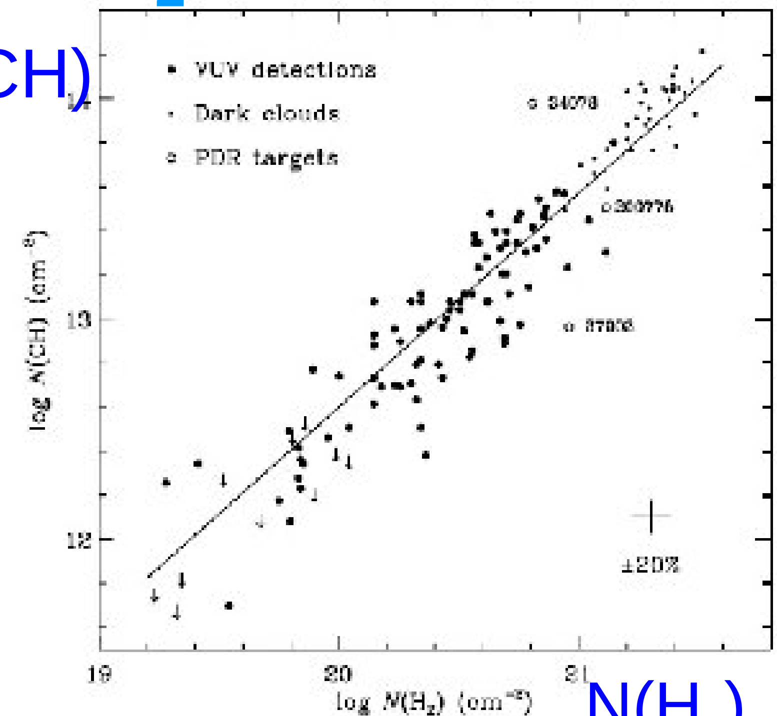
  - Provide the integrated H_2 column along the line of sight for each velocity feature
  - Characteristic scales probed are ~ few pc for local sight-lines, up to ~ 100pc for Galactic Plane sources
  - Averaging effect along the line of sight
- Local H_2 tracers = species with enhanced abundance in a special range of H_2 fraction

CH as a tracer of H_2



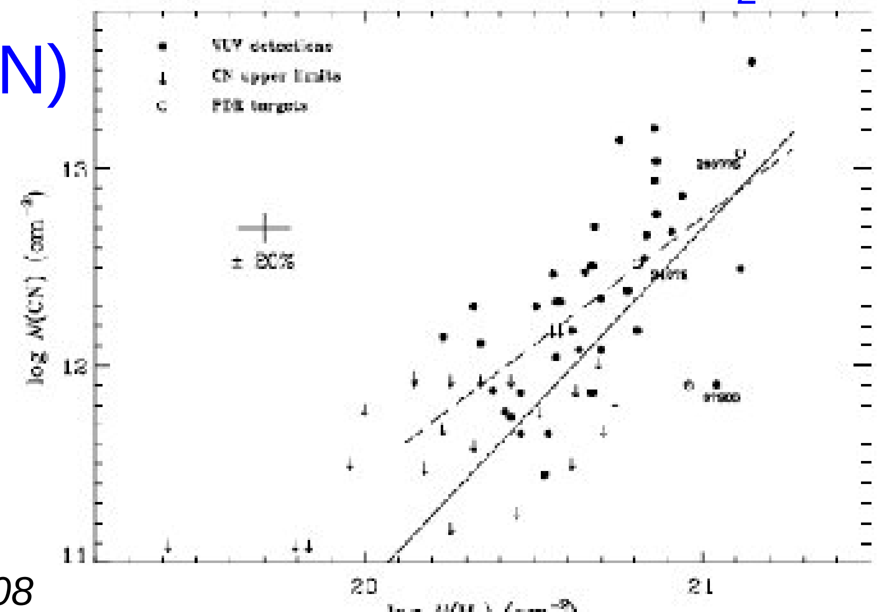
courtesy B Godard using the Meudon PDR code

N(CH)



N(H_2)

N(CN)



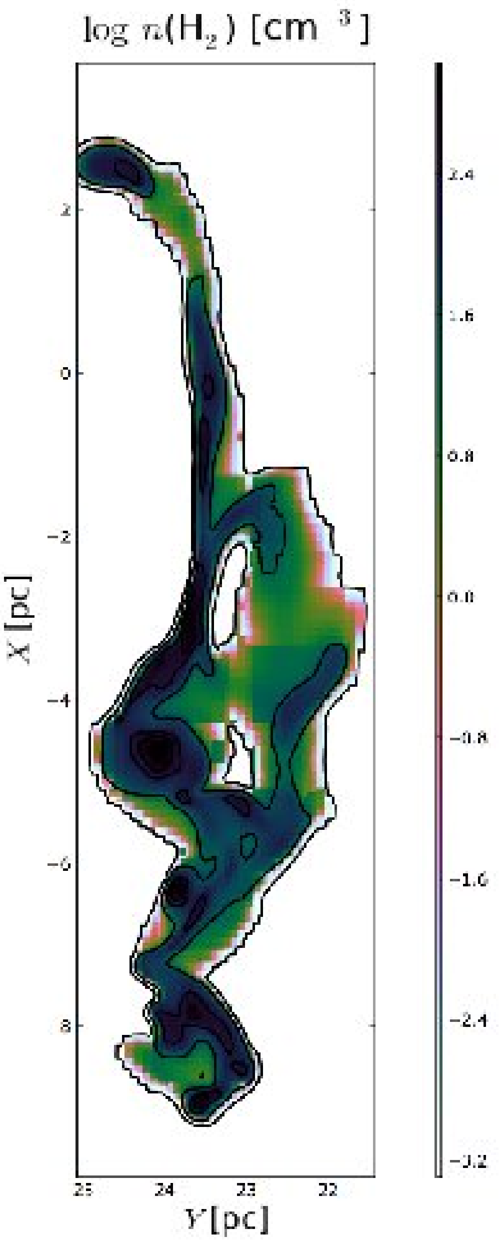
Sheffer et al. 2008

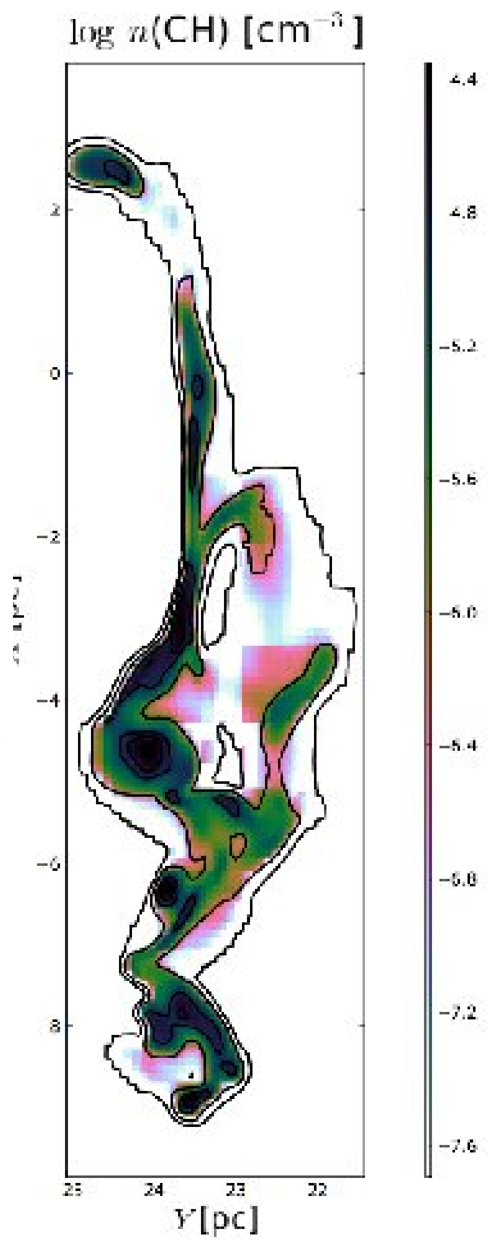
- CH is well correlated with H_2 with a scatter

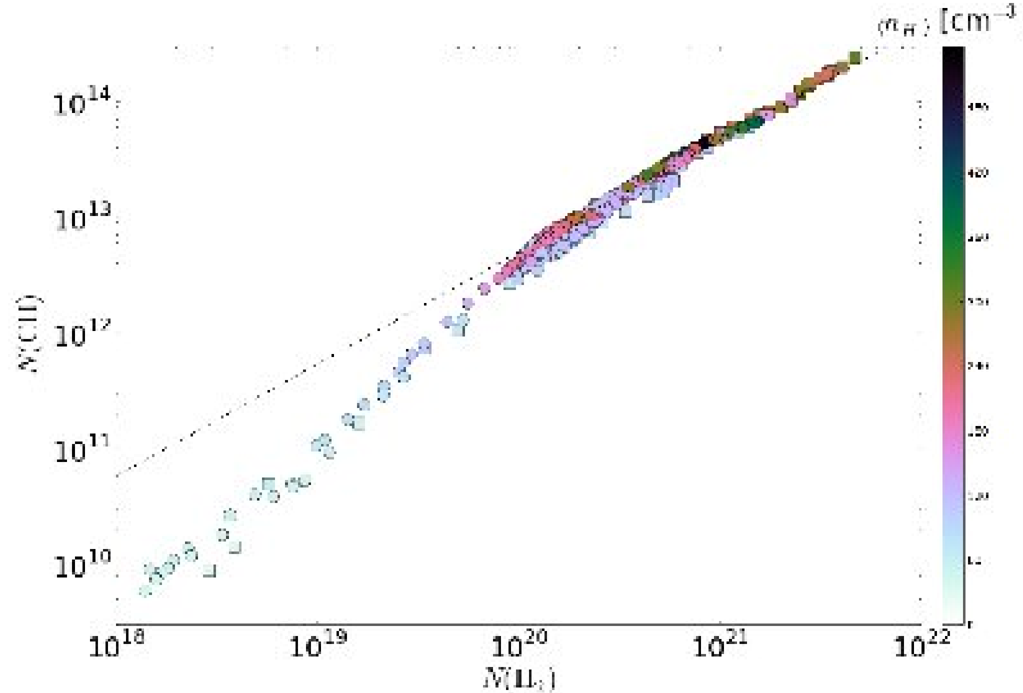
  $N(CH)/N(H_2) \sim 3.6\ 10^{-8}$

- Other species like CN show non linear correlations

H_2 **CH**





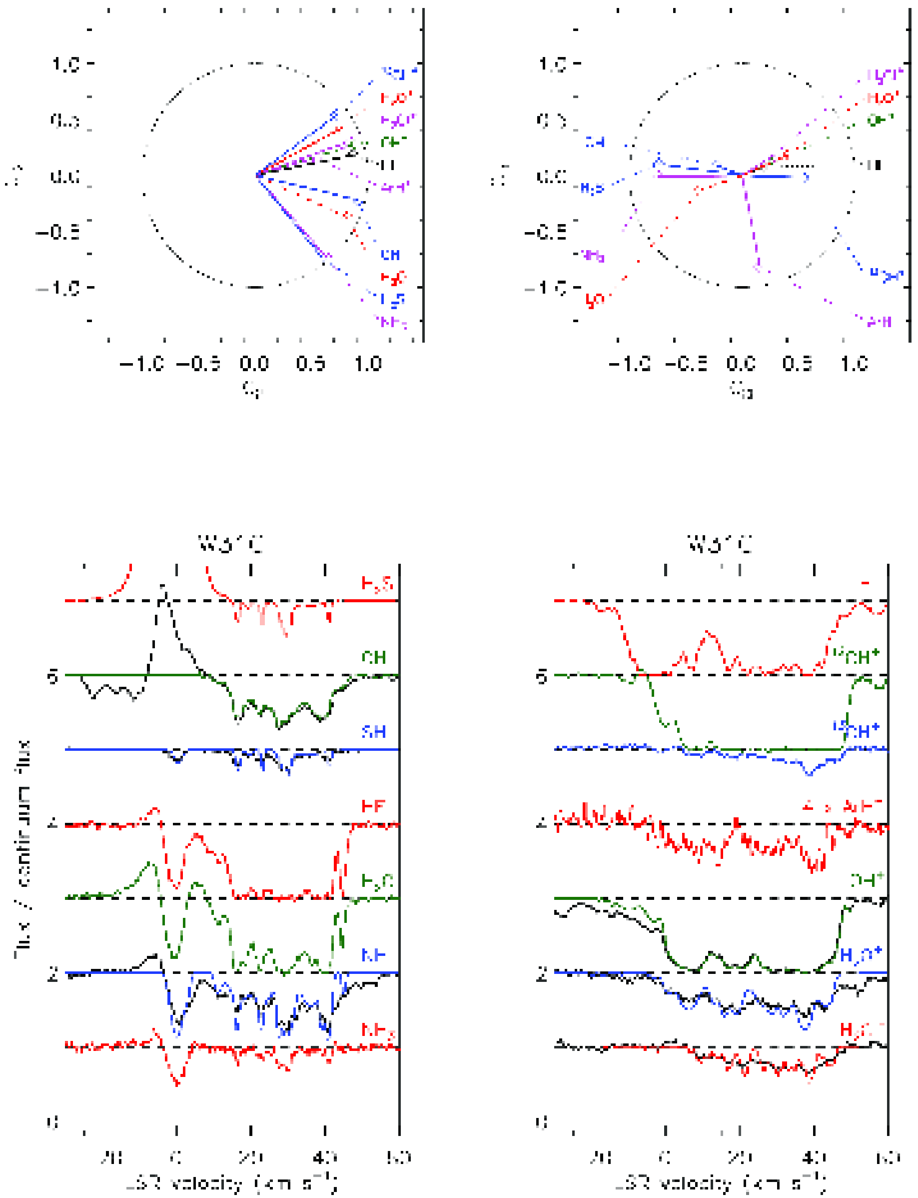


PDR model as post-processing of a MHD simulation

The CH/H_2 correlation is well reproduced for $n > 100$ cm^{-3}

Levrier et al. 2012

PCA analysis of hydride absorption spectra



Separation of different families :

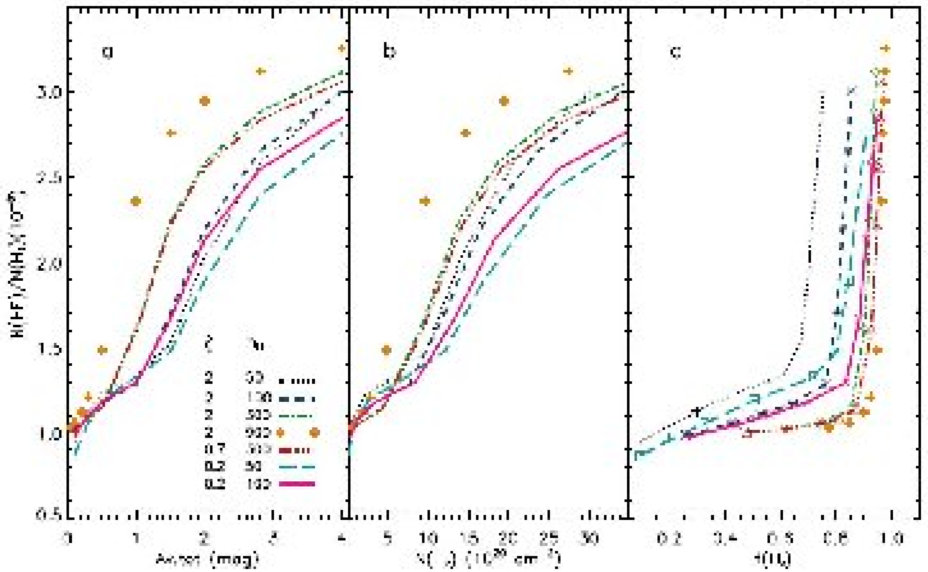
- “HI” : ions like CH^+, OH^+ & H_2O^+
- CH & H_2O diffuse molecular gas
- H_2S & NH_3 molecular gas with lower filling factor (higher density). Similar behavior as CN

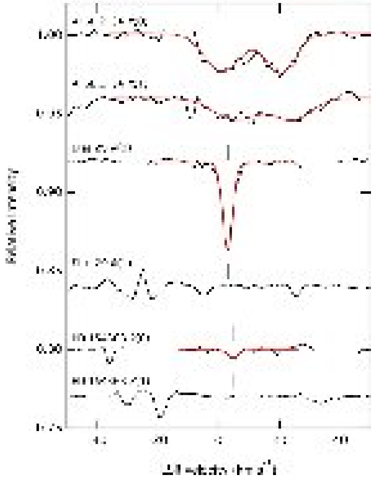
Gerin, Neufeld & Goicoechea 2016 ARAA

Neutral hydrides as H_2 tracers : CH, HF OH & H_2O

- Additional species with different sensitivity to the H_2 column
- HF is formed in the exothermic reaction $F + H_2$:
- Destroyed by photons and by reaction with C^+ (producing CF^+)
- HF/H_2 scales as ~ 2xF/H
- Direct comparison :

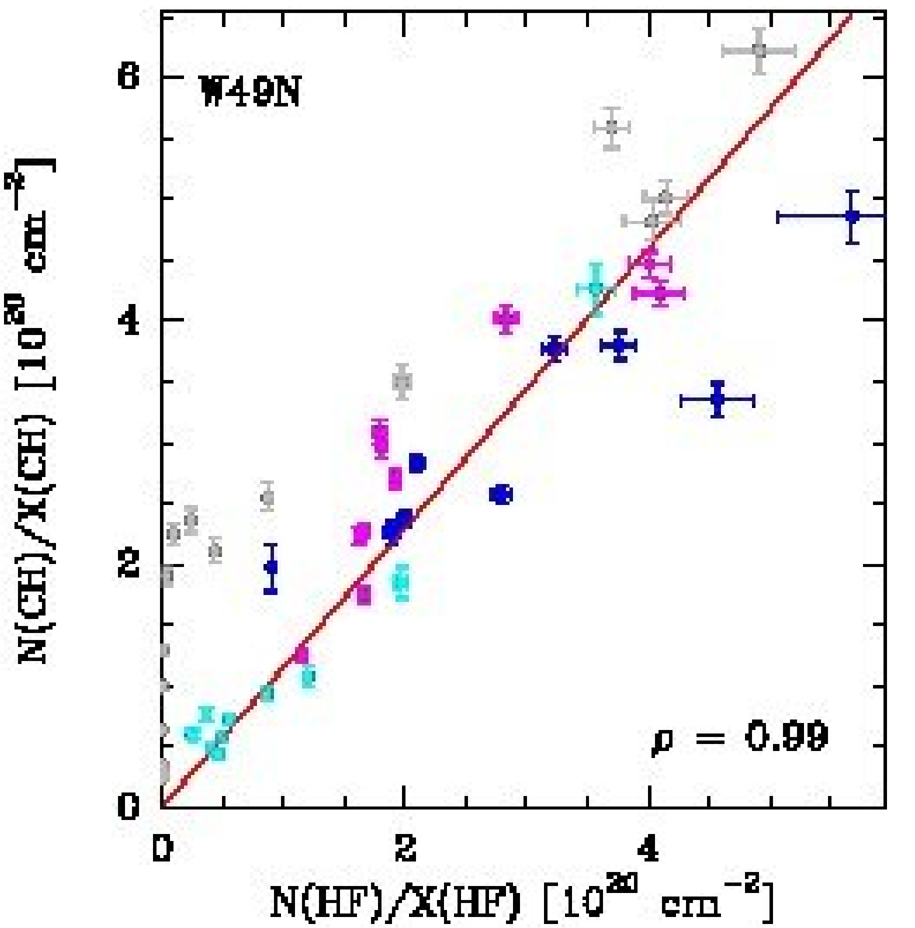
  $HF/H_2 \sim 0.5 – 1.1 \times 10^{-8}$ Consistent with models at moderate $f(H_2)$

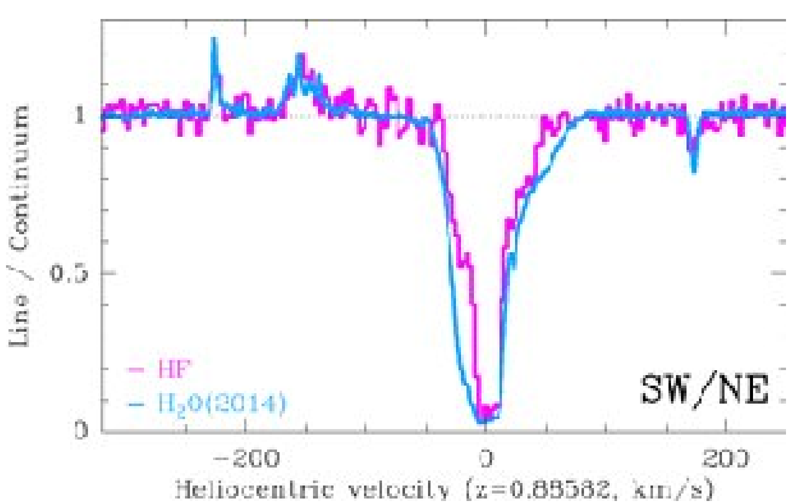




Talk by R. Monje

Indriolo et al. 2013, Sonnentrucker et al. 2015





CH & HF

N(HF) / N(CH) ~ 0.4

Using CH/H_2 = 3.6 10^{-8}

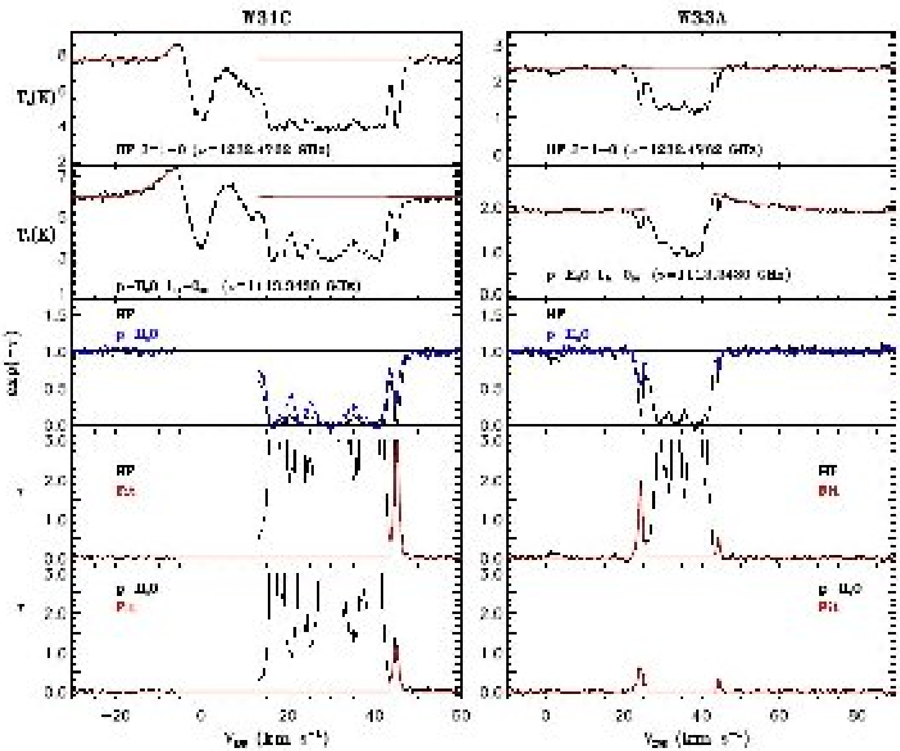
HF/H_2 ~ 0.6 – 2.4x10^{-8}

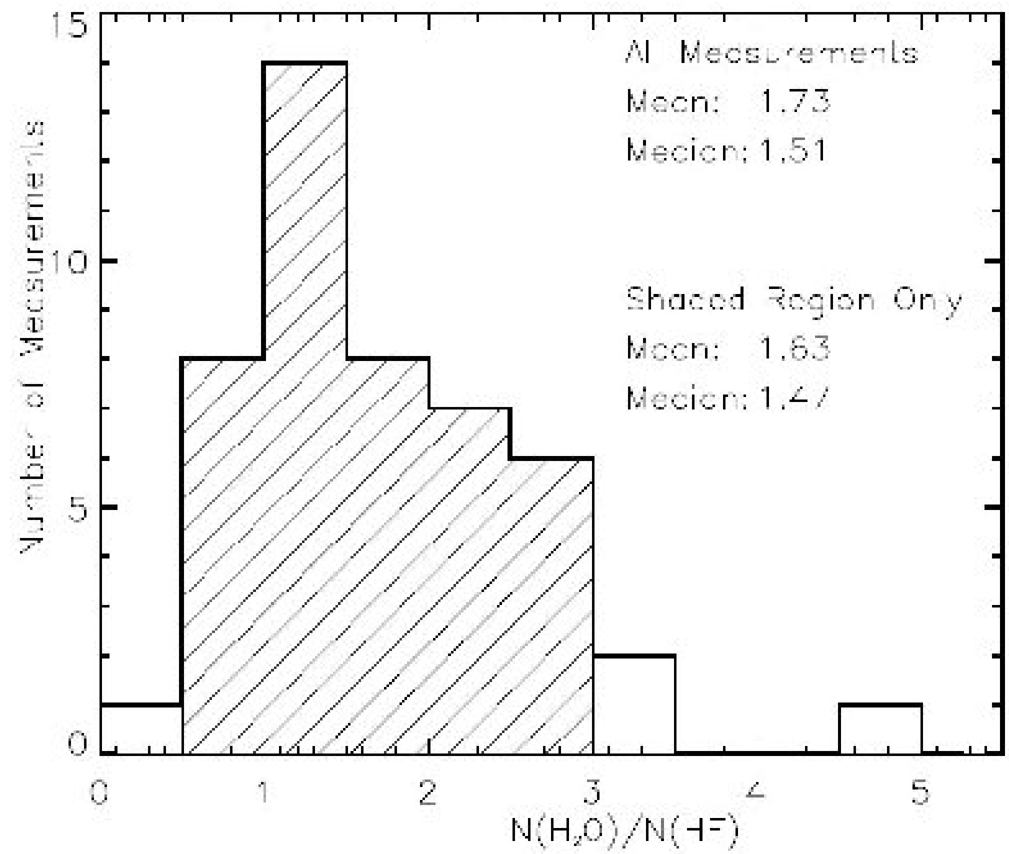
consistent with models & direct measurement

Talk by R. Monje

Wiesemeyer et al. 2016, Godard et al. 2012
Emprechtinger et al. 2012, Kawaguchi et al. 2016

Herschel Observations of HF & H_2O





$N(H_2O) = 4\ N(p\text{-}H_2O)$

$N(H_2O) / N(HF) \sim 1.5$; with a real scatter

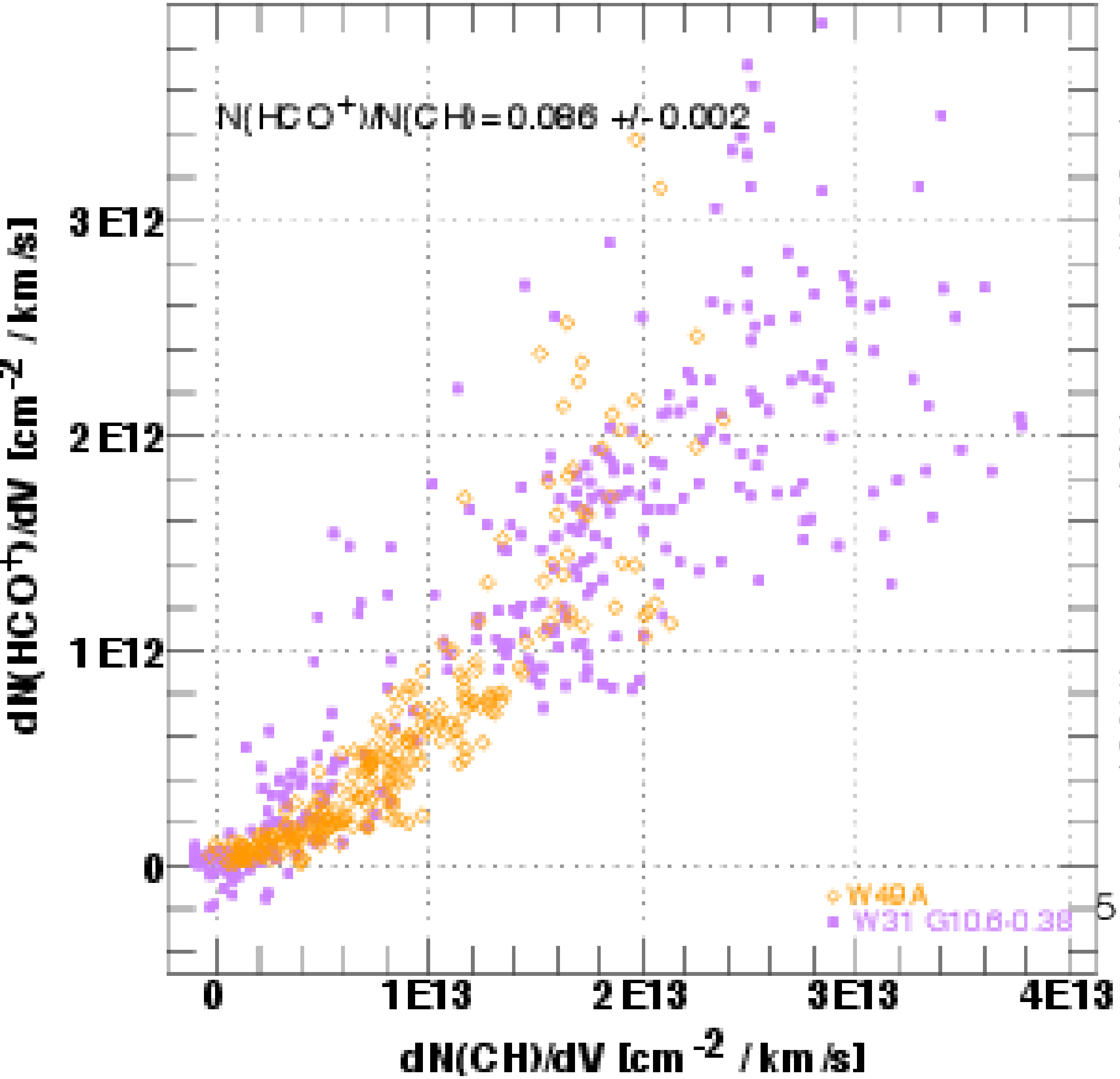
$N(H_2O)/N(H_2) \sim 2.2\ 10^{-8}$

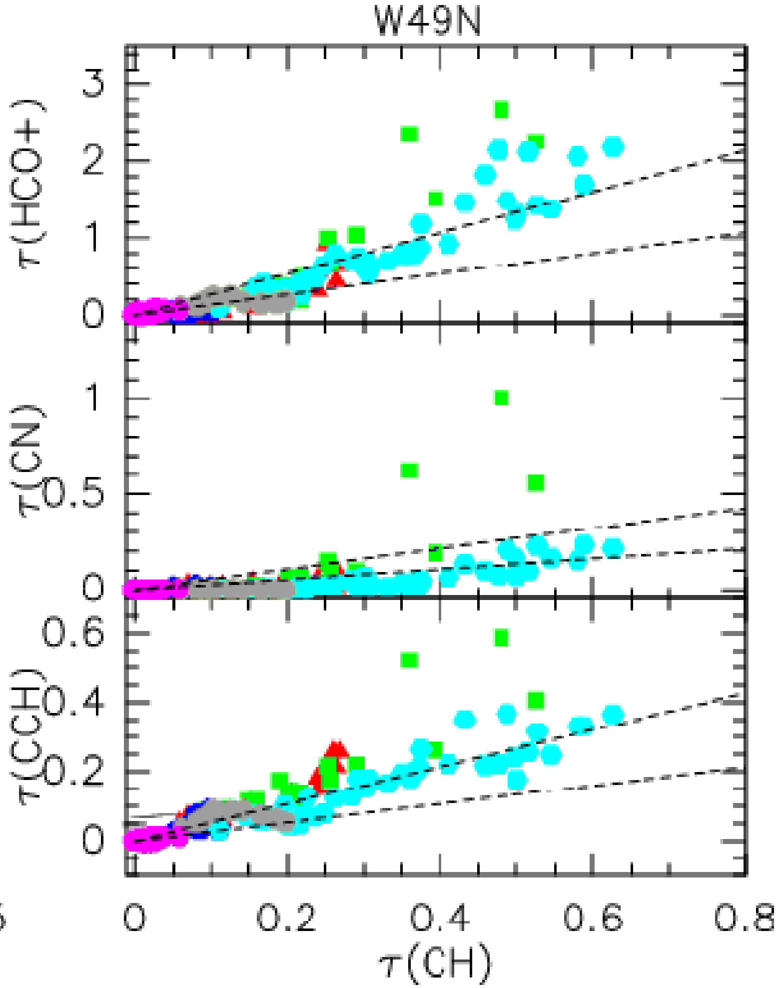
Sonnentrucker et al. 2015

Secondary tracers

- Hydride submillimeter lines are good tracers but relatively difficult to access
- Hydride lines in the cm domain are very weak
- It is interesting to use other species with strong absorption lines at lower frequencies (~ 100GHz) where the sky is more transparent : **HCO^+, CCH**

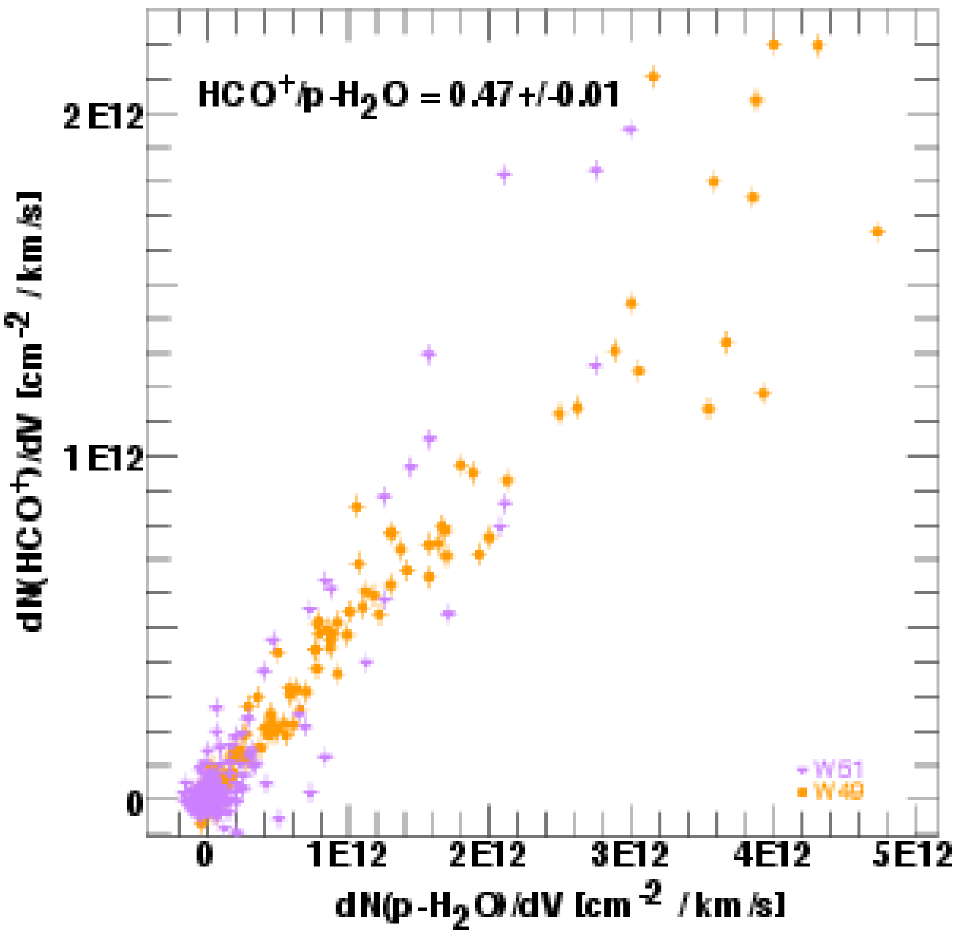
Comparisons with CH

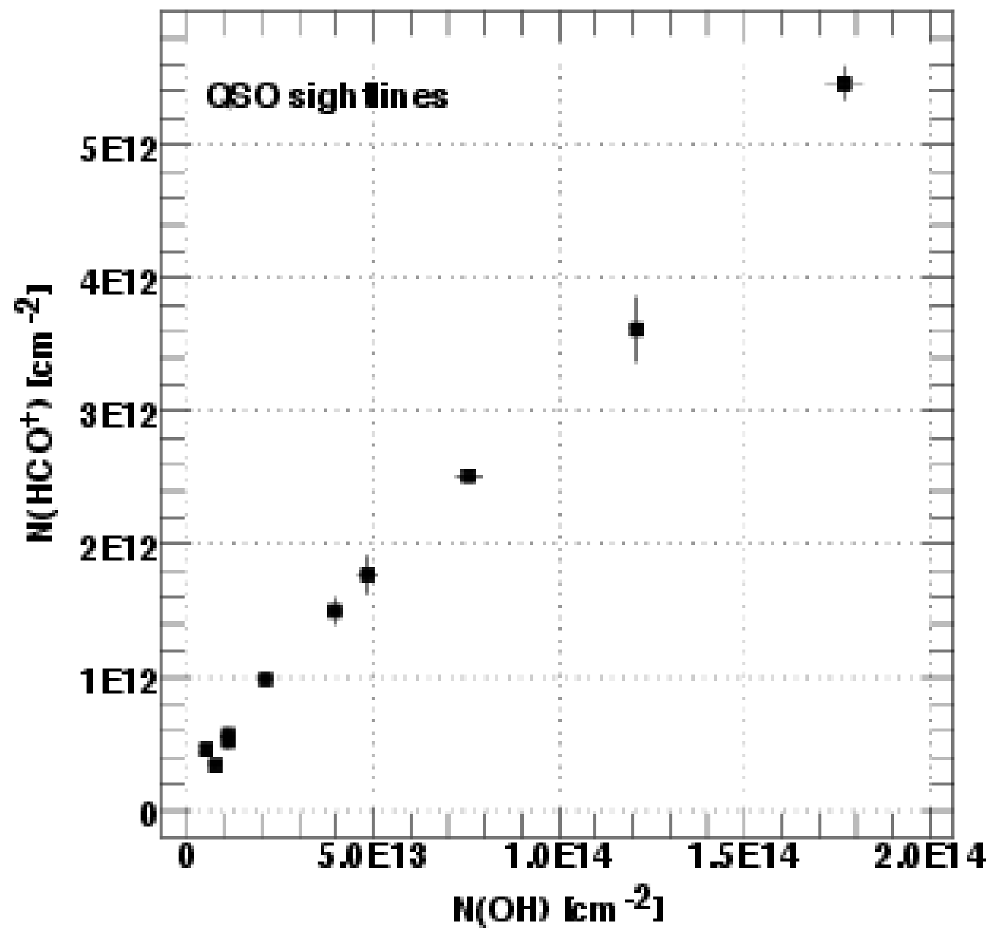




Gerin et al. 2010, Liszt 2017

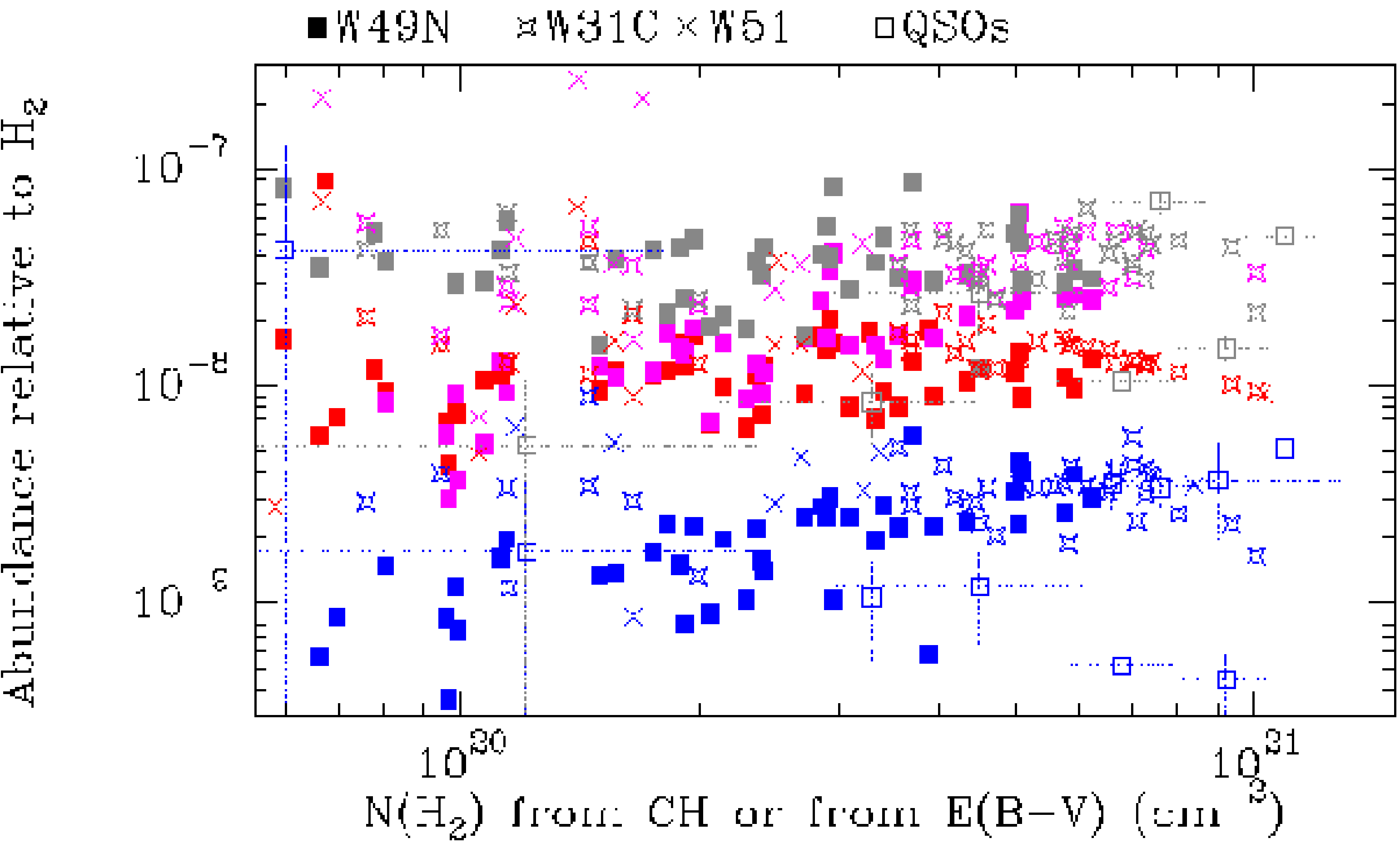
Comparison with H_2O & OH





Liszt 2017, Lucas & Liszt 1996

Abundances relative to H_2



CCH $4.1\ 10^{-8}$ (0.14 dex)

H_2O $2.8\ 10^{-8}$ (0.22 dex)

HF $1.2\ 10^{-8}$ (0.17dex)

HCO^+ $2.8\ 10^{-9}$ (0.18 dex)

$N(H_2)$ is derived from N(CH) with $CH/H_2 = 3.6\ 10^{-8}$ for Galactic plane sight-lines or from E(B-V) & N(HI) for QSO sight-lines

Searching for diffuse H_2 : some numbers

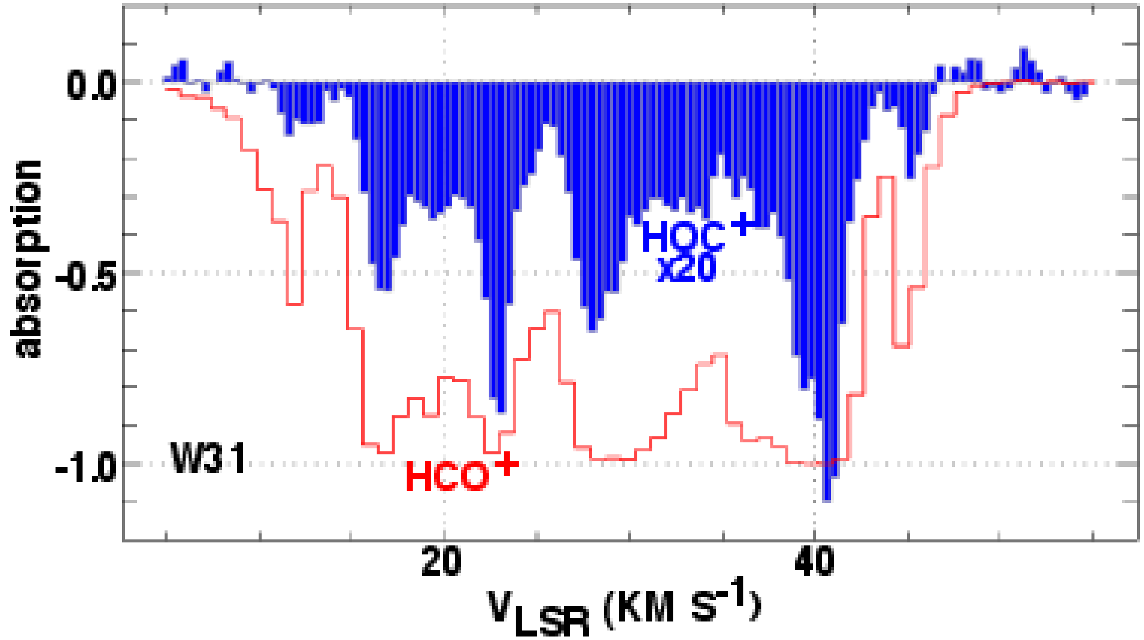
Use a combination of species to probe a wide range of column densities

	HF 1-0	p-H2O 111-000	CH	HCO+ 1-0	HOC+ 1-0	CCH	OH
Freq (GHz)	1232.5	1113.3	532.76	89.189	89.487	87.317	2510
N/∫τdv cm^{-2}/kms^{-1}	2.4E12	2.33E12	3.64E13	1.12E12	2.15E12	6.53E13	2.5E13
$N(H_2)$/∫τdv cm^{-2}/kms^{-1}	1.9E20	3.3E20	1.0E21	4.0E20	7.1E22	1.6E21	2.5E20

HCO^+ is the most sensitive probe in the mm domain

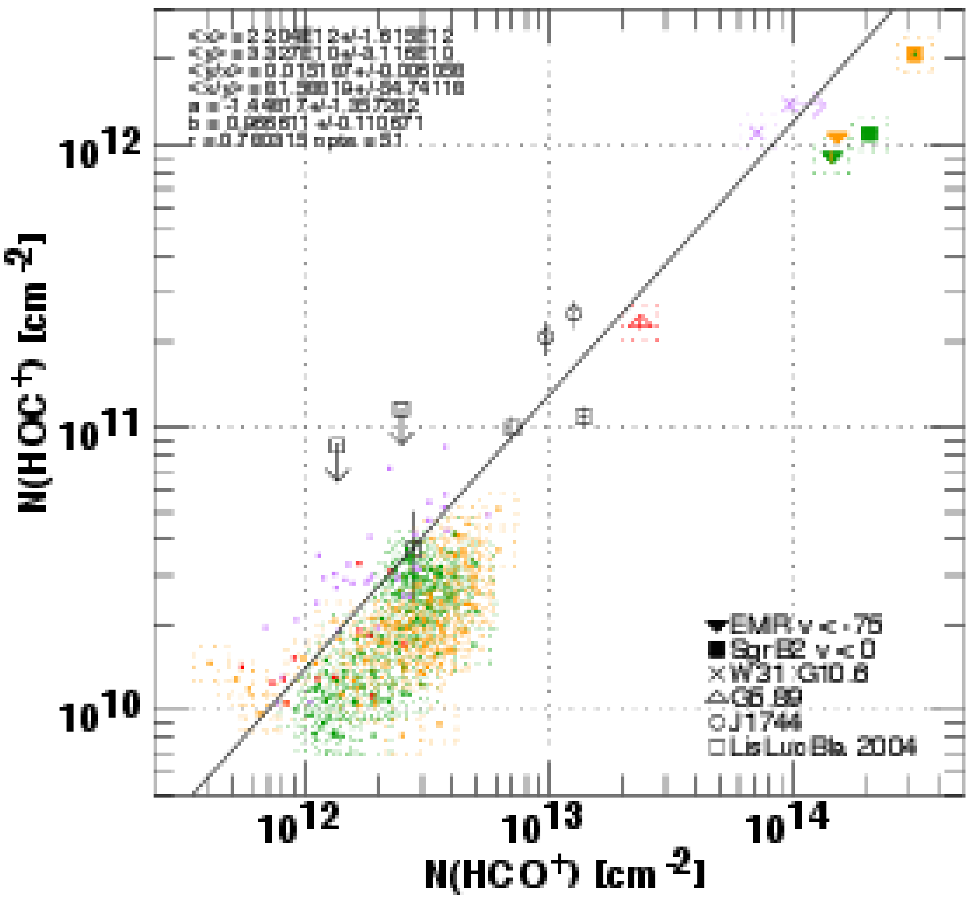
HCO+ and p-H_2O probe the same range of H_2 columns

Investigating the chemistry : comparing the ions HOC^+ & HCO^+



$C^+ + H_2O \rightarrow HCO^+ \& HOC^+$

- Destruction by e- (both) and by H_2 (HOC^+)
- Additional production routes for HCO^+ through e.g. CH_3^+
- Fairly constant abundance ratio of 0.01



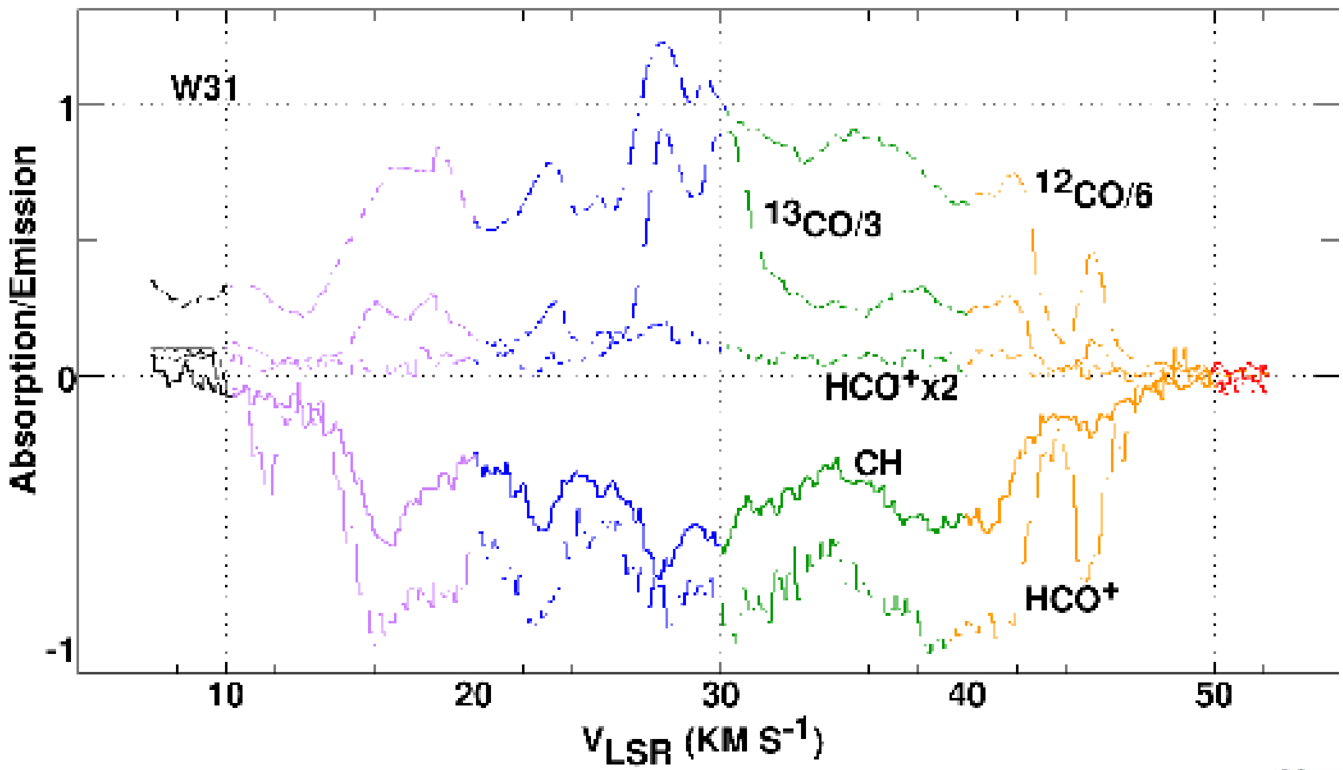
Conclusions

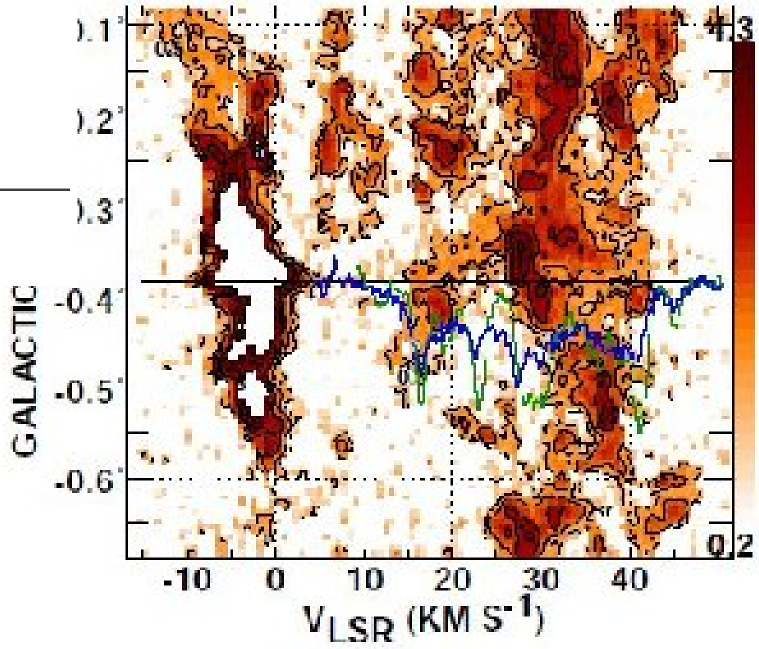
- Good tracers of diffuse H_2 with an abundance scatter of ~ 0.15 dex (factor of 1.4) CH; HF, p-H_2O, HCO^+, CCH , OH, ...
- Abundances are ~ constant in the Galactic Plane but variations are expected with metallicity, FUV radiation field, CR ionization rate … The Galactic Center region may be different !
- Probe these species over a wider range of conditions. Direct observations of H_2 in the IR ?
- Continue to investigate the chemistry, e.g. the tight correlation between OH, H_2O and HCO^+ in the context of coupled dynamical/chemical models

CO in diffuse clouds

- CO is one of the main tracer of molecular gas, through the J= 1-0 line at 115.27 GHz. At large scales (> pc)
  - $N(H_2)$ (cm^{-2})= X_{CO} ICO $(Kkms^{-1})$ with X_{CO} the CO to H_2 conversion factor.
  - $X_{CO} \sim 2 \times 10^{20}$ cm^{-2} /Kkm/s
- It is not easy to separate “diffuse CO” from “dense CO” because the J=1-0 line is easily excited in warm diffuse gas even if the CO abundance is relatively low (10^{-6} to 10^{-5} relative to $H_{2,}$ N(CO) > 10^{15} cm^{-2})
- In low Av regions, CO formation is driven by turbulence. ***See B Godard talk***

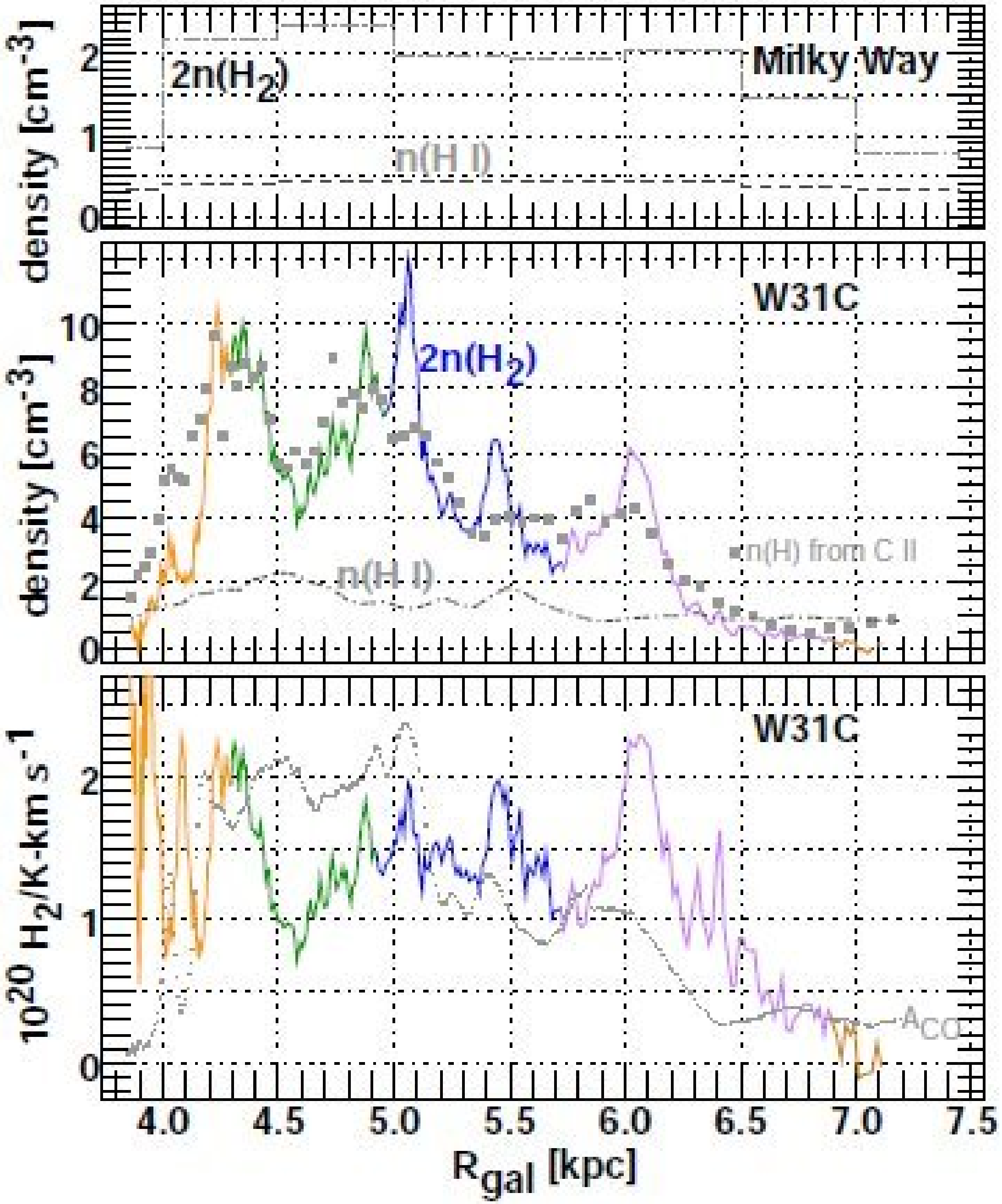
Calibration of CO/H_2 across the Galactic plane : the W31C example





Use CH to derive N(H_2) &
compare with I_{CO}

Liszt & Gerin,2016



- X_{CO} **~ 1 – 2 10**^{20} $cm^2/Kkms^{-1}$
- Consistent with other determinations
- Density of the diffuse molecular gas :

  n(H) ~ 130 cm^{-3}
- Volumne filling factor ~ 3%