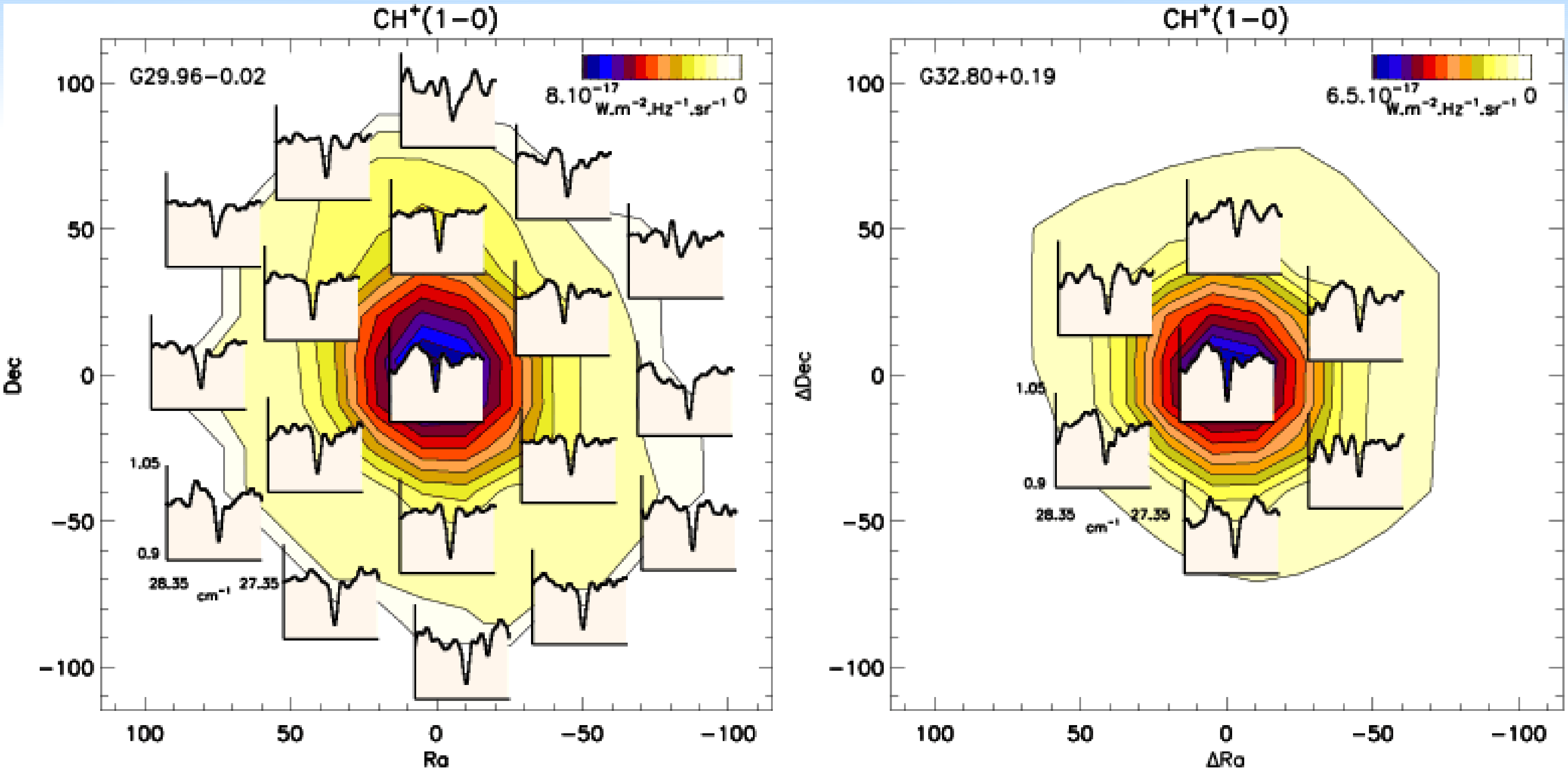
Prospects for high resolution spectroscopy with CCAT



Naylor et al CH^+ with SPIRE

Absorption spectroscopy for CCAT : lessons from Herschel

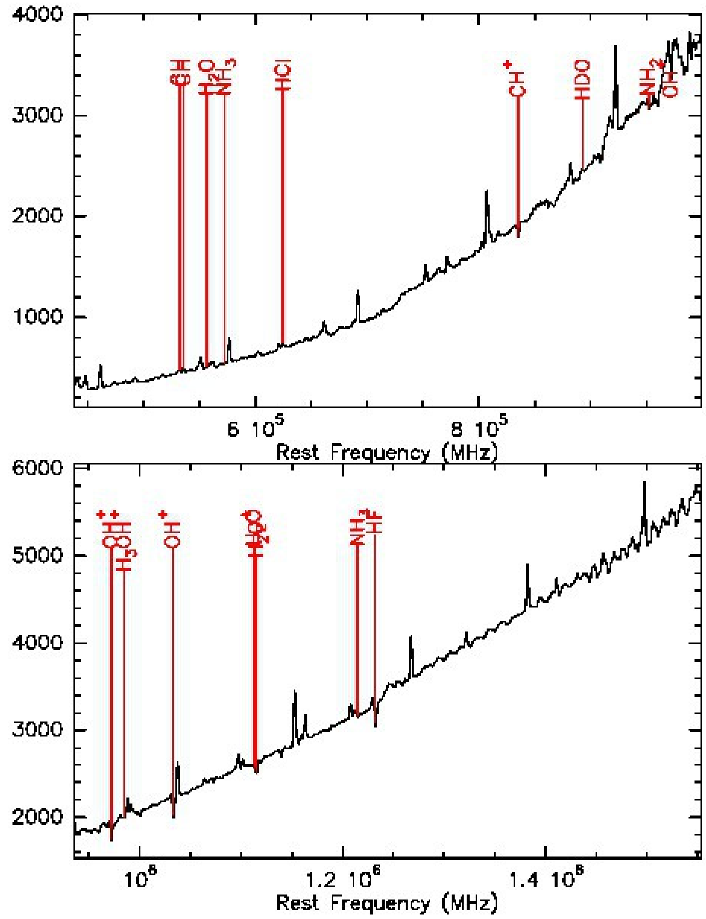
Herschel spectroscopy : medium resolution (SPIRE/ PACS) to high resolution (HIFI)

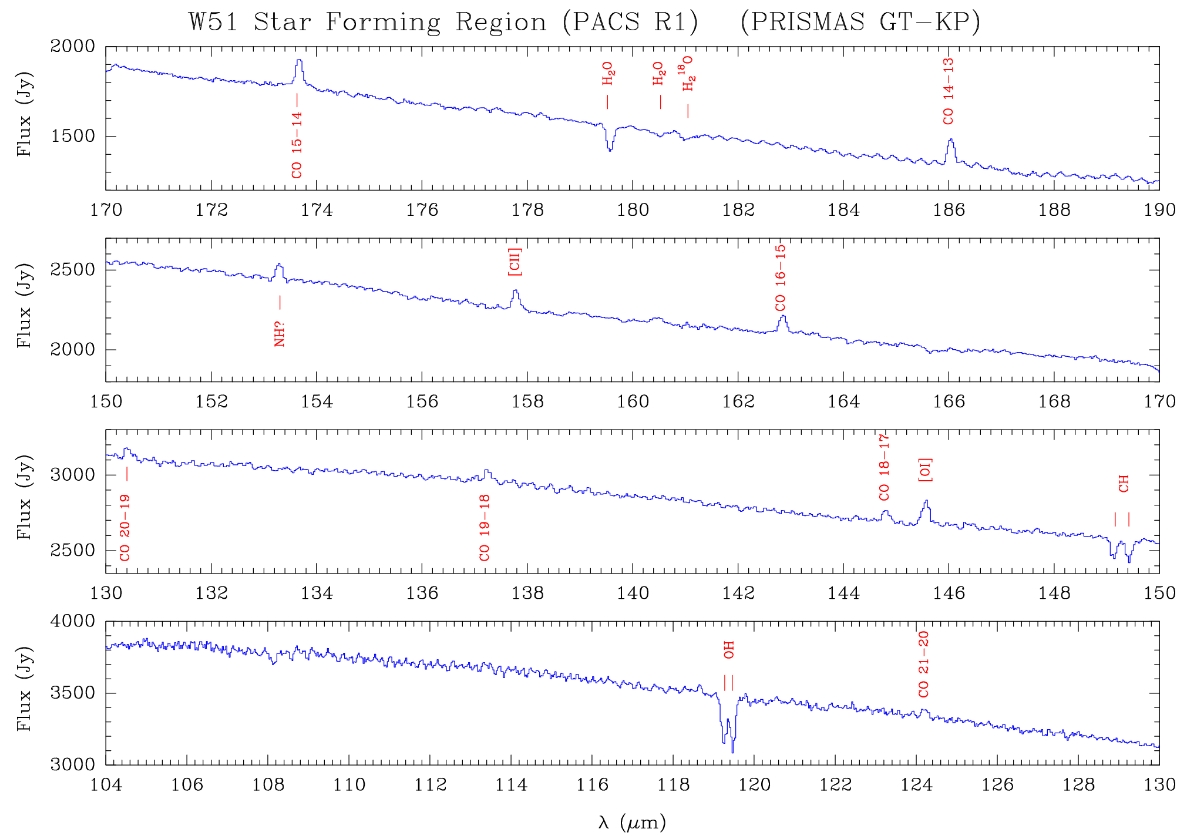
Strong emission lines CO, 13CO, CI, CII, OI, NII, OIII (H_2O, OH)

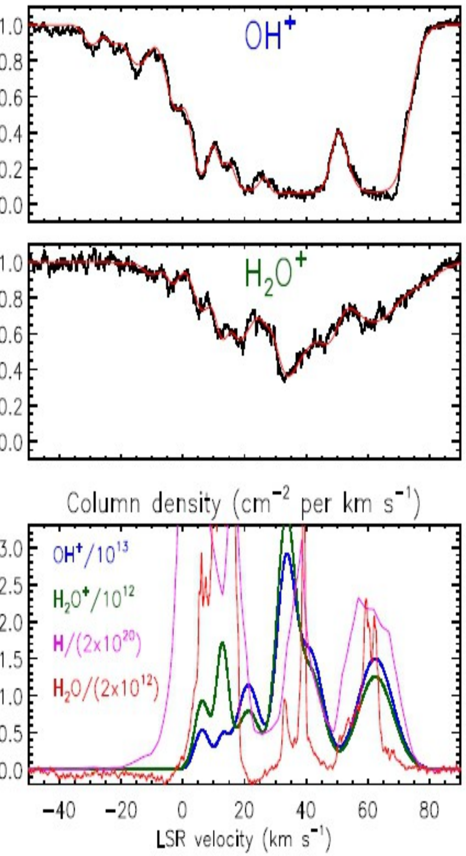
Strong absorption lines, especially ground state hydride lines

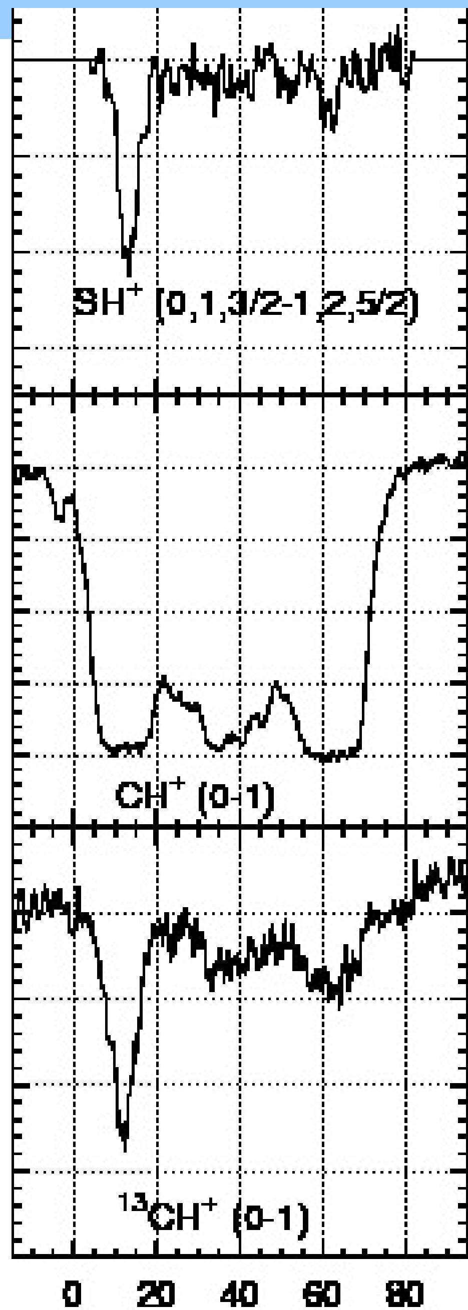
Many weaker features (emission & absorption)

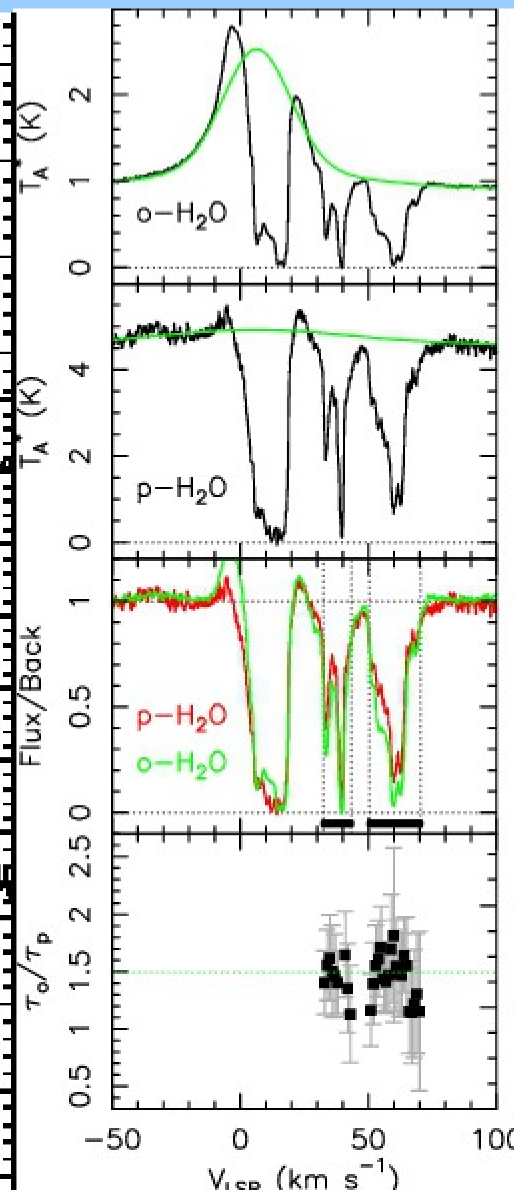
Examples :I the line of sights to W49N

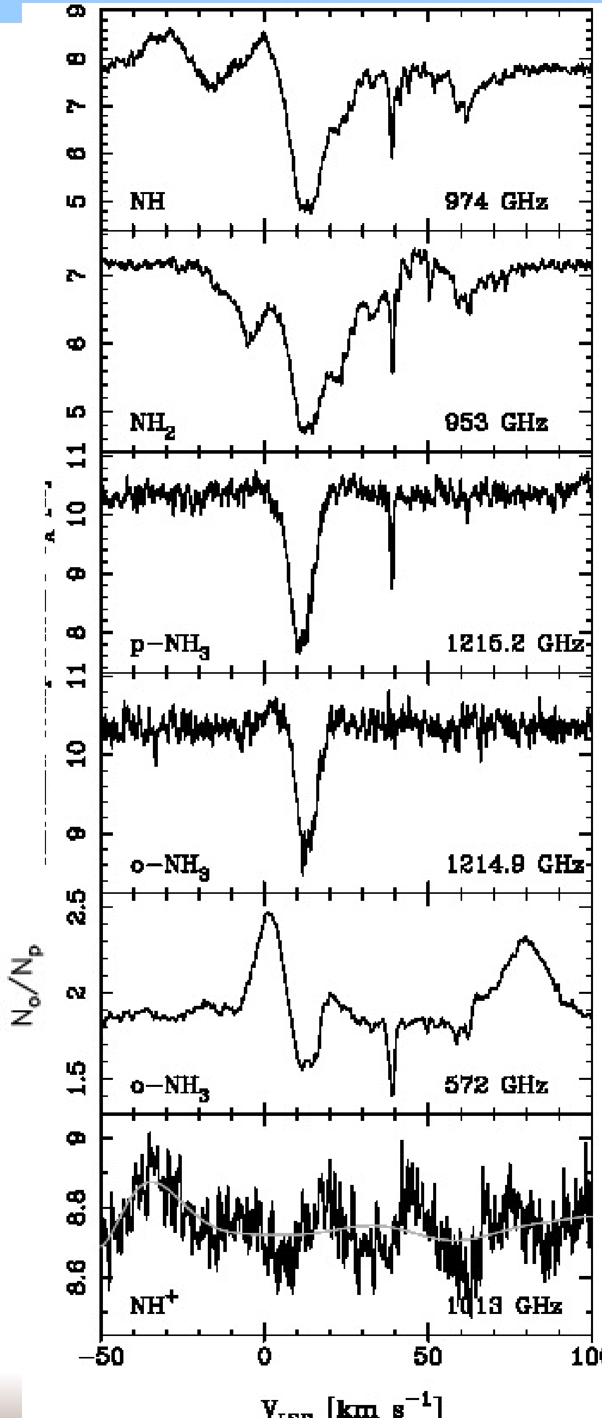





OH+
H2O+
Column density (cm-2 per km s-1)
OH+/10^13
H2O+/10^12
H/(2x10^20)
H2O/(2x10^12)
LSR velocity (km s-1)


SH+ [0,1,3/2-1,2,5/2]
CH+ (0-1)
13CH+ (0-1)


T*A (K)
o-H2O
p-H2O
Flux/Back
p-H2O
o-H2O
τo/τp
No/Np
VLSR (km s-1)

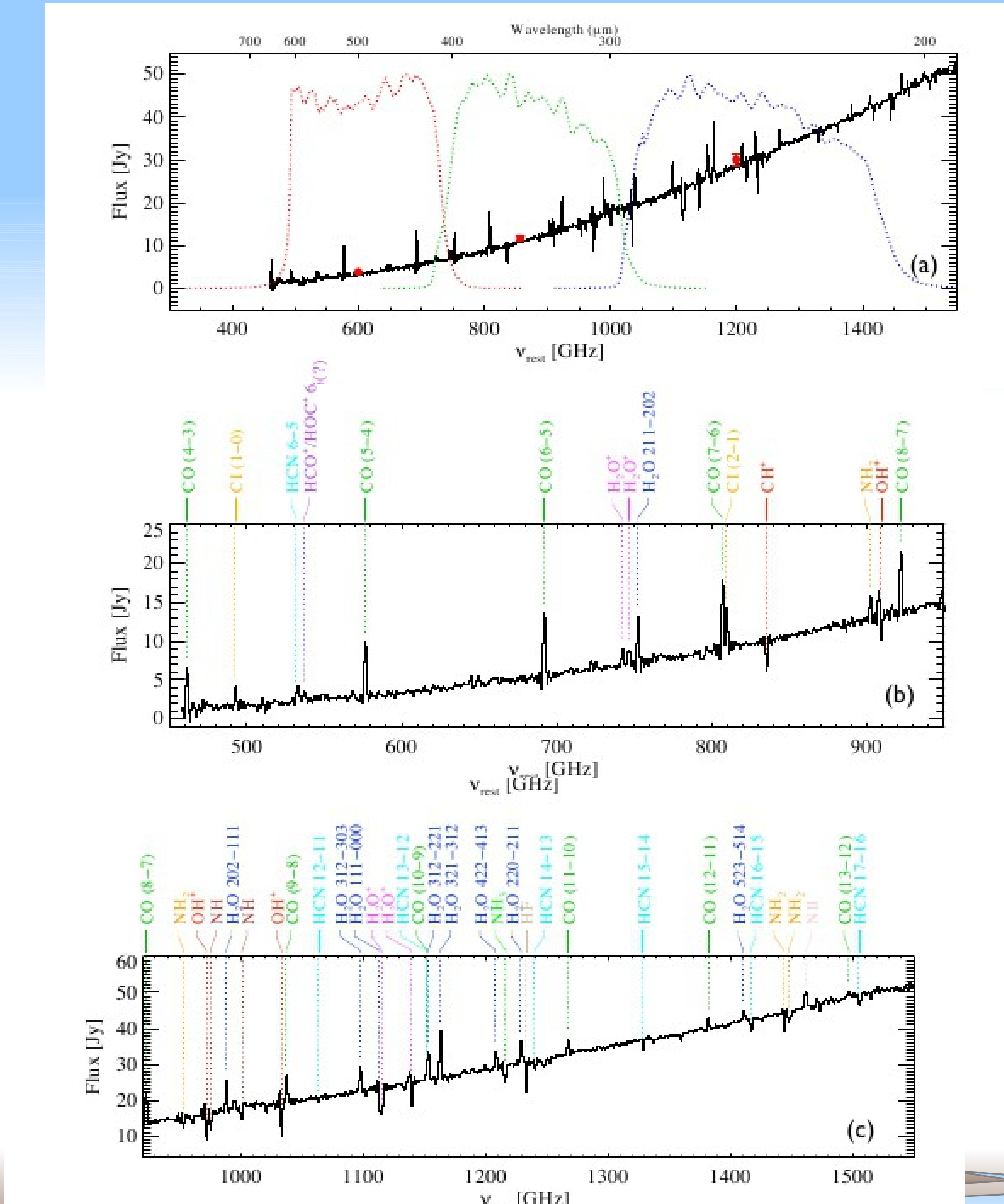

NH 974 GHz
NH2 953 GHz
p-NH3 1215.2 GHz
o-NH3 1214.9 GHz
o-NH3 572 GHz
NH+ 1013 GHz
VLSR [km s-1]

W49N

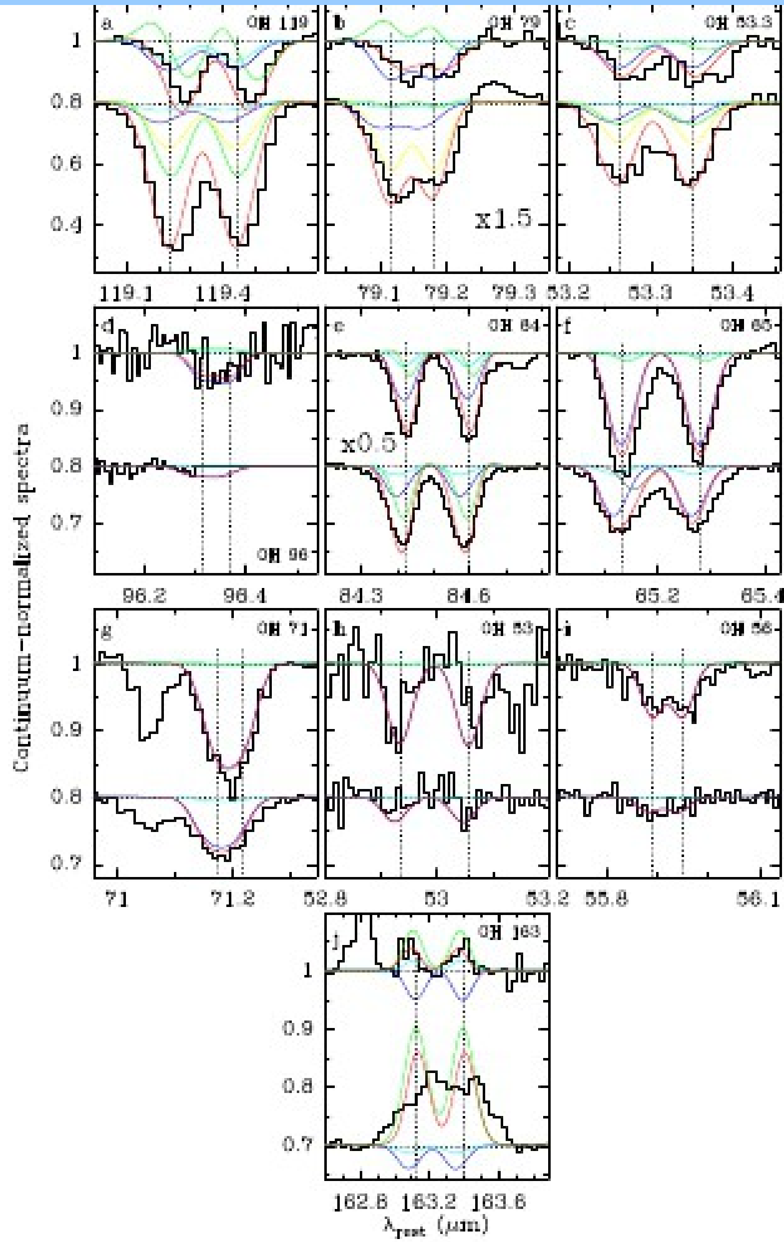
Examples : II Arp220 & N4418

- Submillimeter and FIR spectrum dominated by absorption (Sturm et al, Gonzalez-Alfonso et al)
- Ground state & high energy lines of H_2O, OH, HCN
- reactive ions (OH^+, H_2O^+, CH^+)
- Difference with Mrk 231 : same lines but emission

- Broad & complex line profiles : OH, H2O tracers of energetic phenomena : massive outflows, winds
- High critical density : extremely dense and hot gas , FIR excitation => neighborhood of AGN ?



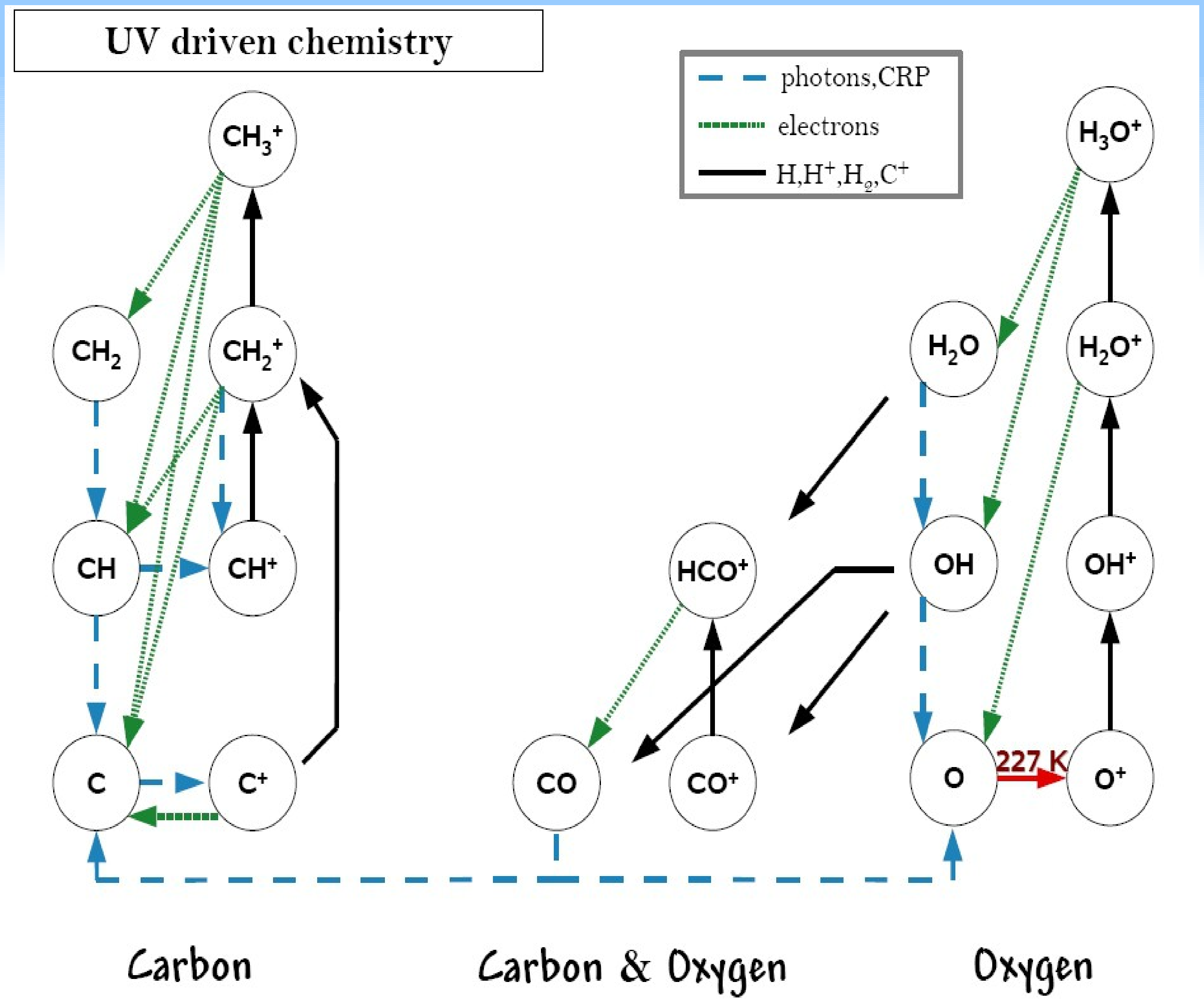
Arp 220
Spire
Rangwala et al



Arp 220 & NGC4418
OH, H_2O, HCN
absorption in excited states (Eu > 500K)
Gonzalez-Alfonso et al

Also HCO^+(4-3) P-Cyg profiles with SMA (0.3", Sakamoto)

Hydrides

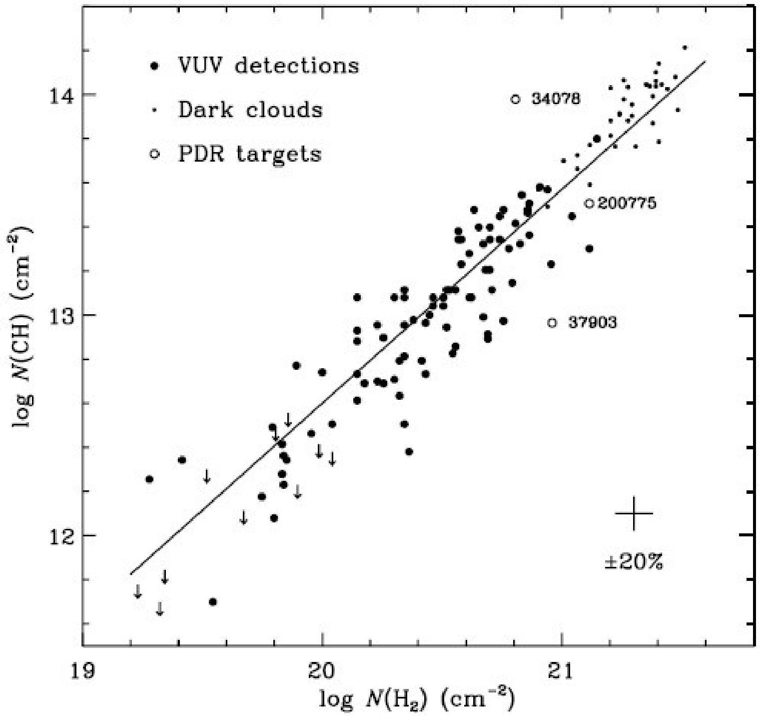


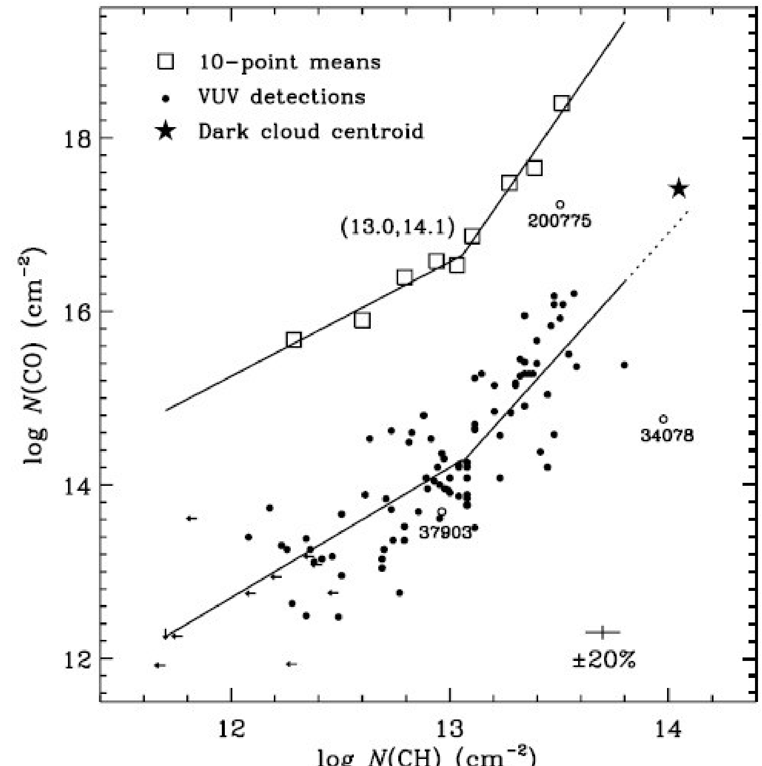
- built in the first chemical steps starting from atomic gas

- at the root of interstellar chemistry

- Diagnostics of physical / chemical processes

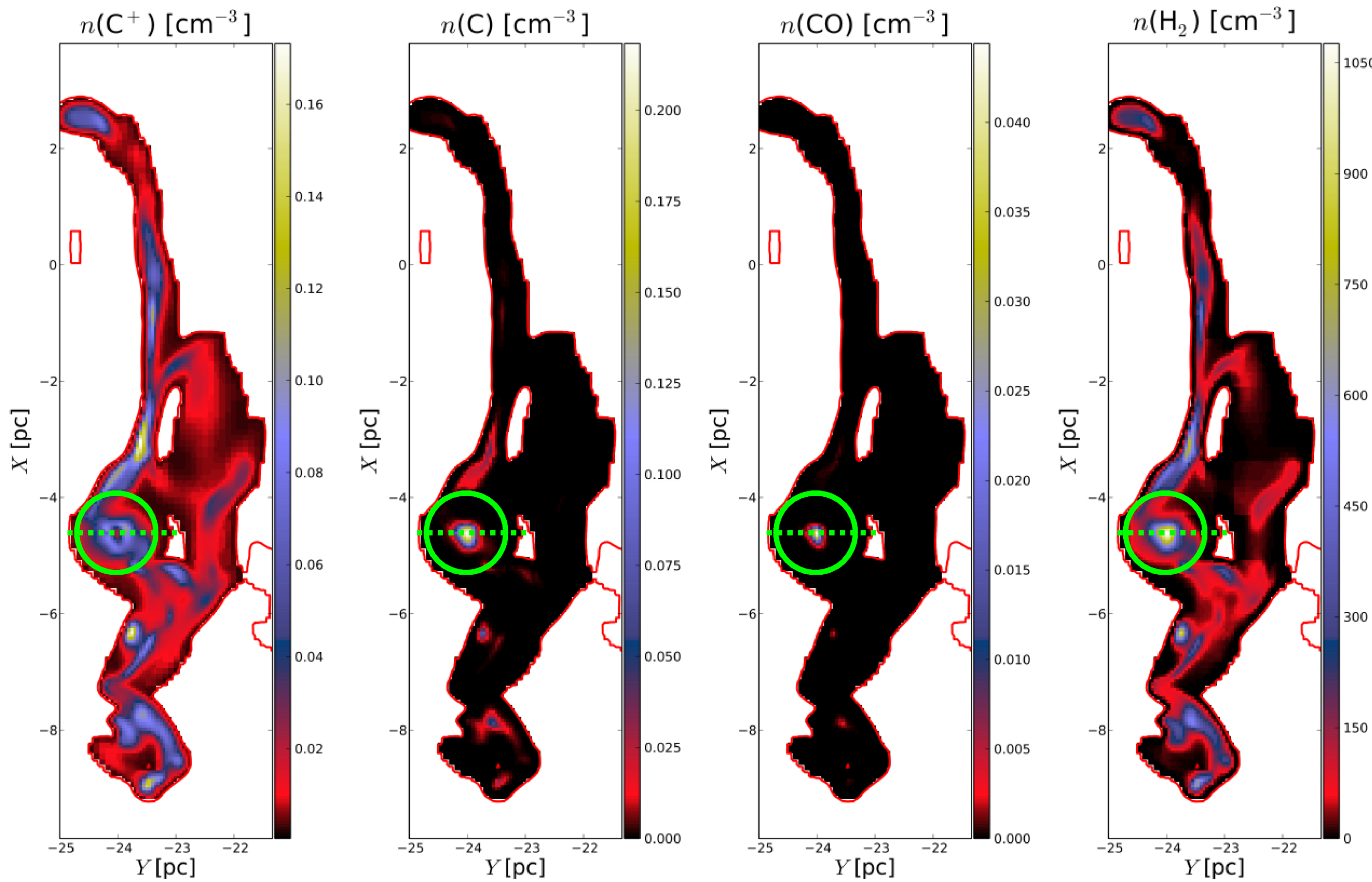
Hydrides as diagnostics : H_2 column density

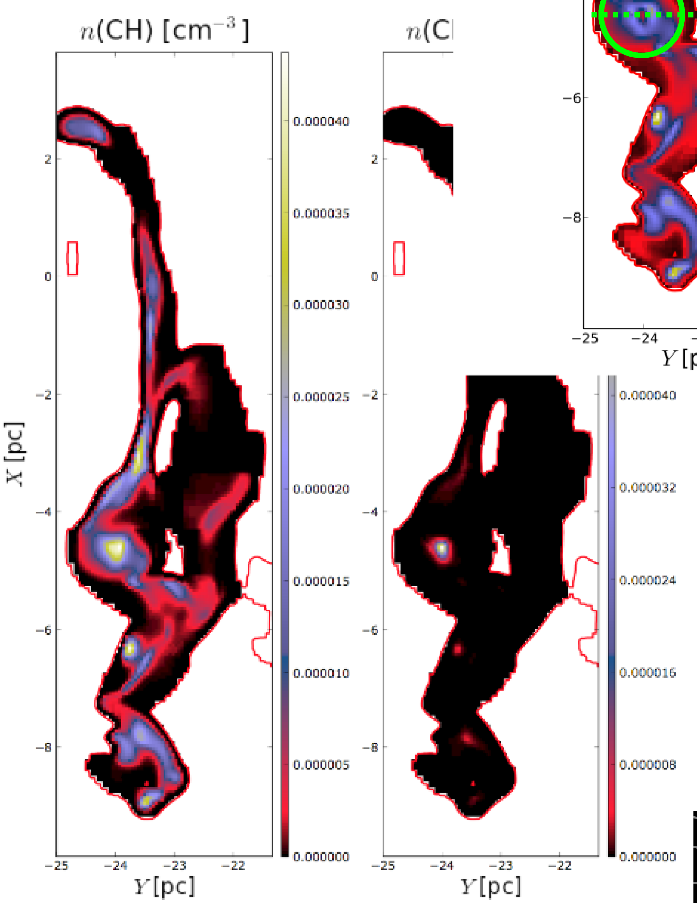




CH (Visible) scales with H_2 (FUV) ($CH/H_2 \sim 3.5\ 10^{-8}$)

Sheffer et al 2008



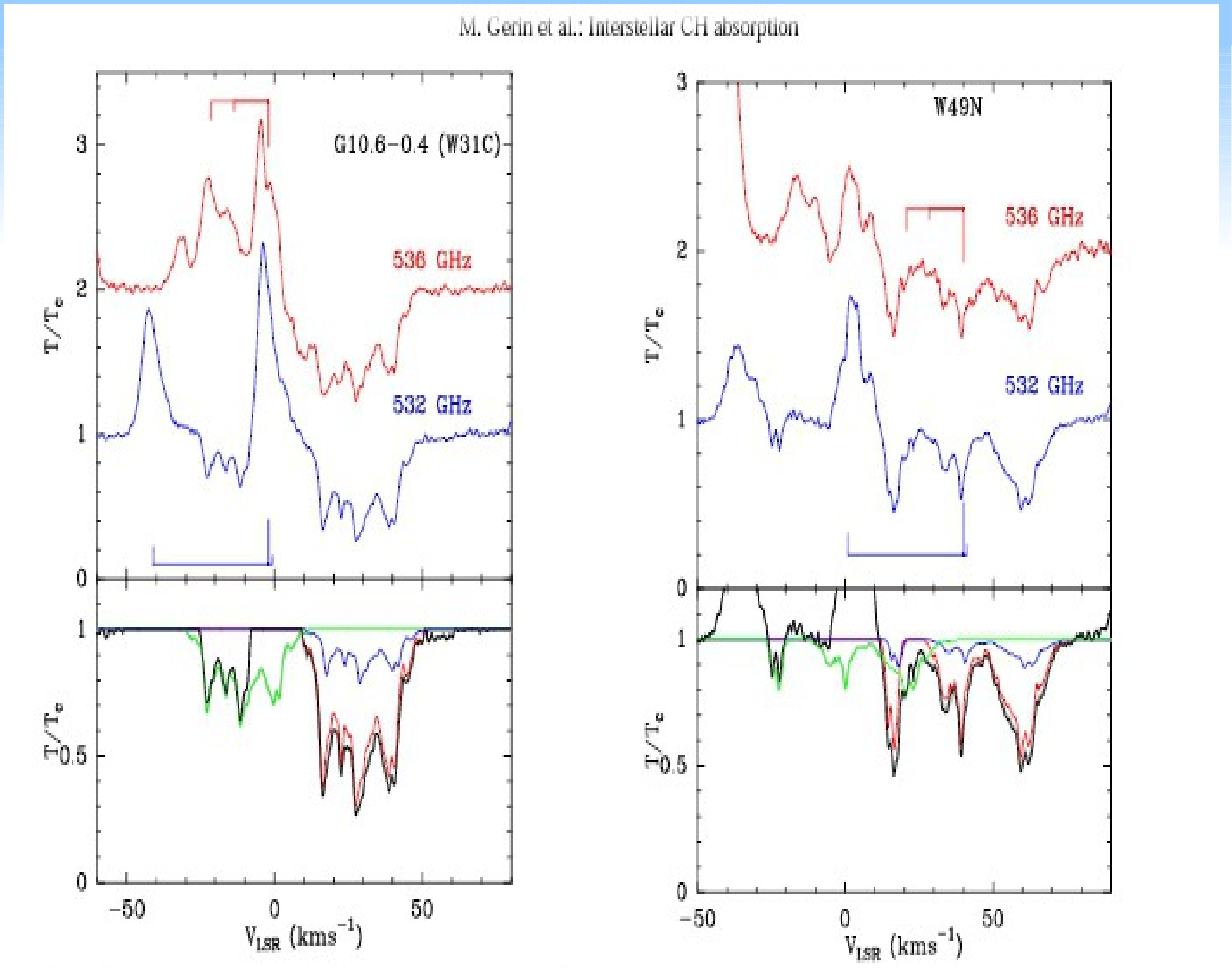


Levrier et al in prep

Methylidyne CH

- CH ground state triplet at 532 & 536 GHz.
- Other triplet 2THz
- Lines not saturated but complex profiles
- Combination of emission & absorption
- N(CH) ~ few 10^{14} cm^{-2}
- CH & HF consistent with $CH/H_2 \sim 3.5\ 10^{-8}$ derived from UV/visible

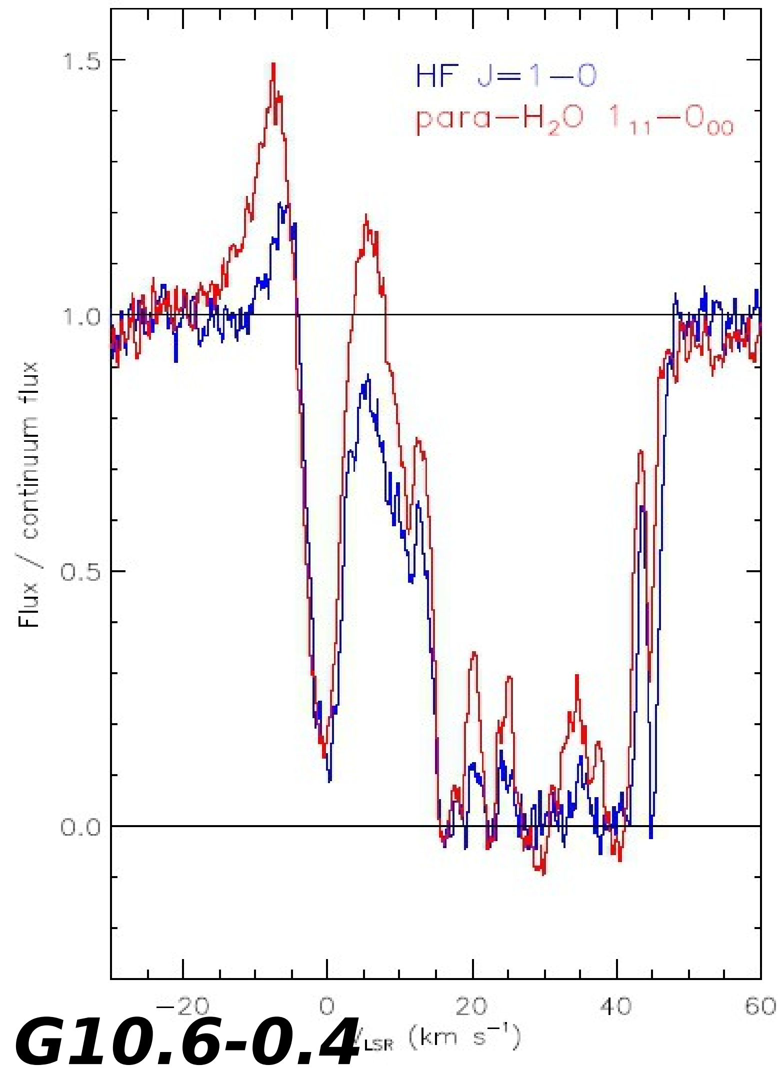
$\tau(CH) \sim N(H_2)/10^{21}$



- *Gerin et al A&A 521*

Hydrogen fluoride HF

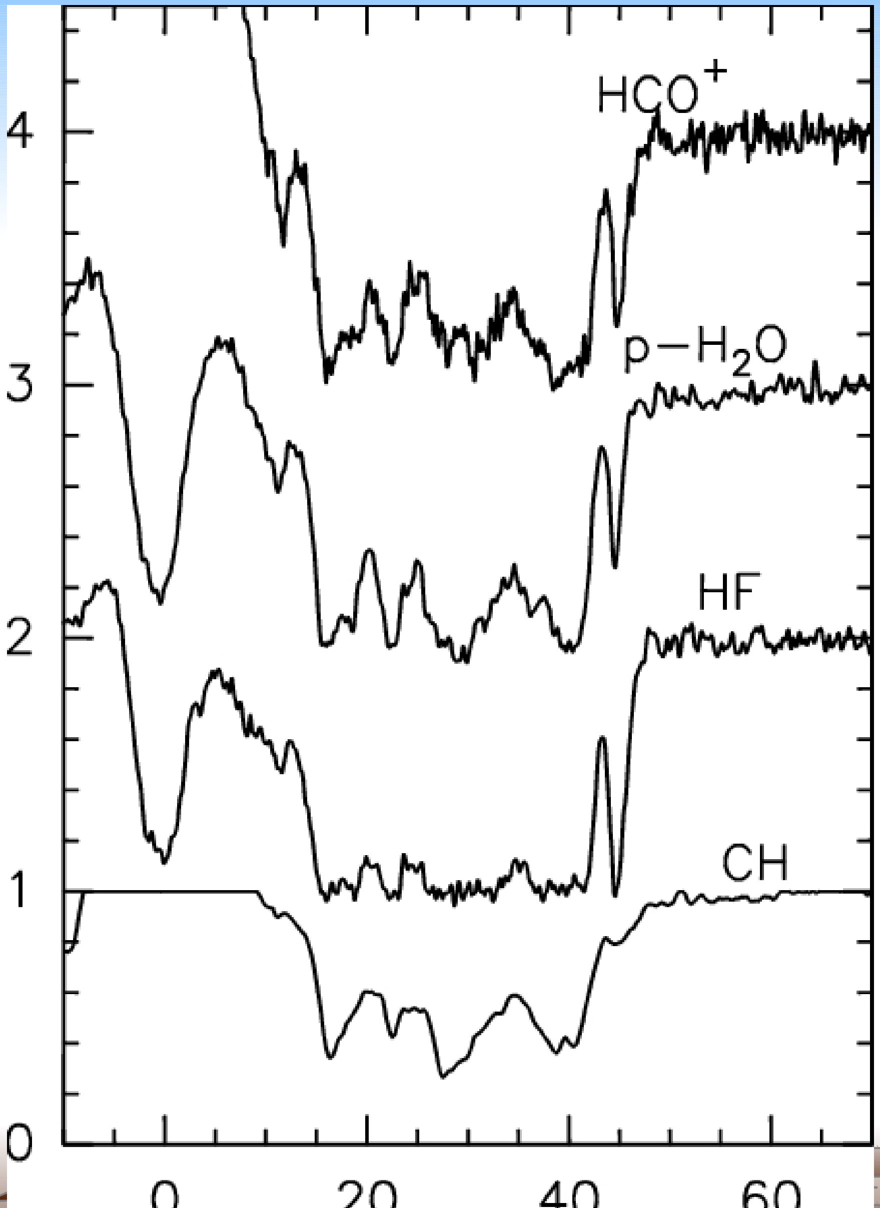
- Fluorine reacts with H_2, making HF
- (Neufeld et al)
- = > HF uses all the gas phase F
- => HF reveals H_2
- => HF is present as soon as H_2 is present, even in clouds with no detectable CO or H_2O.
- => $\tau(HF) > \tau(p\text{-}H_2O)$

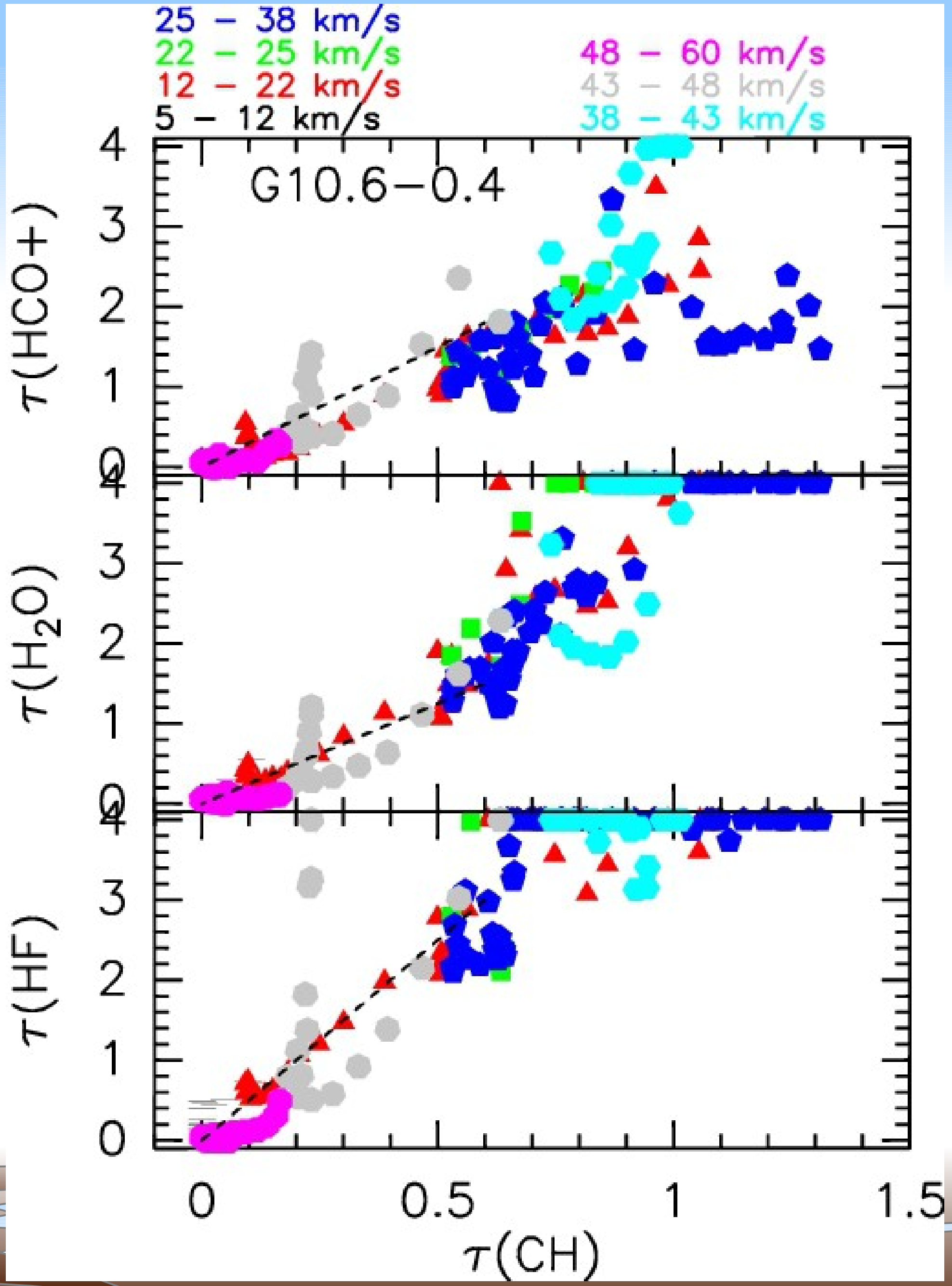


$\tau(HF) \sim N(H_2)/10^{20}$ (dv = 1 km/s)

- ***G10.6-0.4***
- ***Neufeld et al 2010a A&A 5***

CH : relation with other molecules : linear scaling => constant abundance ratio





Hydrides as diagnostics : ζ cosmic ray ionization rate

Cosmic rays : ionization source for H and H_2 in neutral gas

The charge can be transferred to molecular ions.

The abundance scales with **ζ**

$$H_2^+ + H_2 \rightarrow H_3^+$$

$$H^+ + O \rightarrow O^+ \quad ; \quad O^+ + H_2 \rightarrow OH^+ + H$$

$$OH^+ + H_2 \rightarrow H_2O^+ + H \; ; \quad H_2O^+ + H_2 \rightarrow H_3O^+ + H$$

OH^+, H_2O^+, H_3O^+

=> Analytic expression (Neufeld et al 2010 & in prep)

$n(OH^+)/n(H_2O^+) = 0.64 + 0.12\,(T/300K)^{-0.5}/f(H_2)$

$OH^+/H_2O^+ > 4$

=> **OH^+ mostly in atomic gas with a small fraction of H_2 (< 10%)**

$OH^+/H \sim 3 \times 10^{-8}$ $H_2O^+/H \sim 3 \times 10^{-9}$

O+ formed by charge transfer between O and H^+

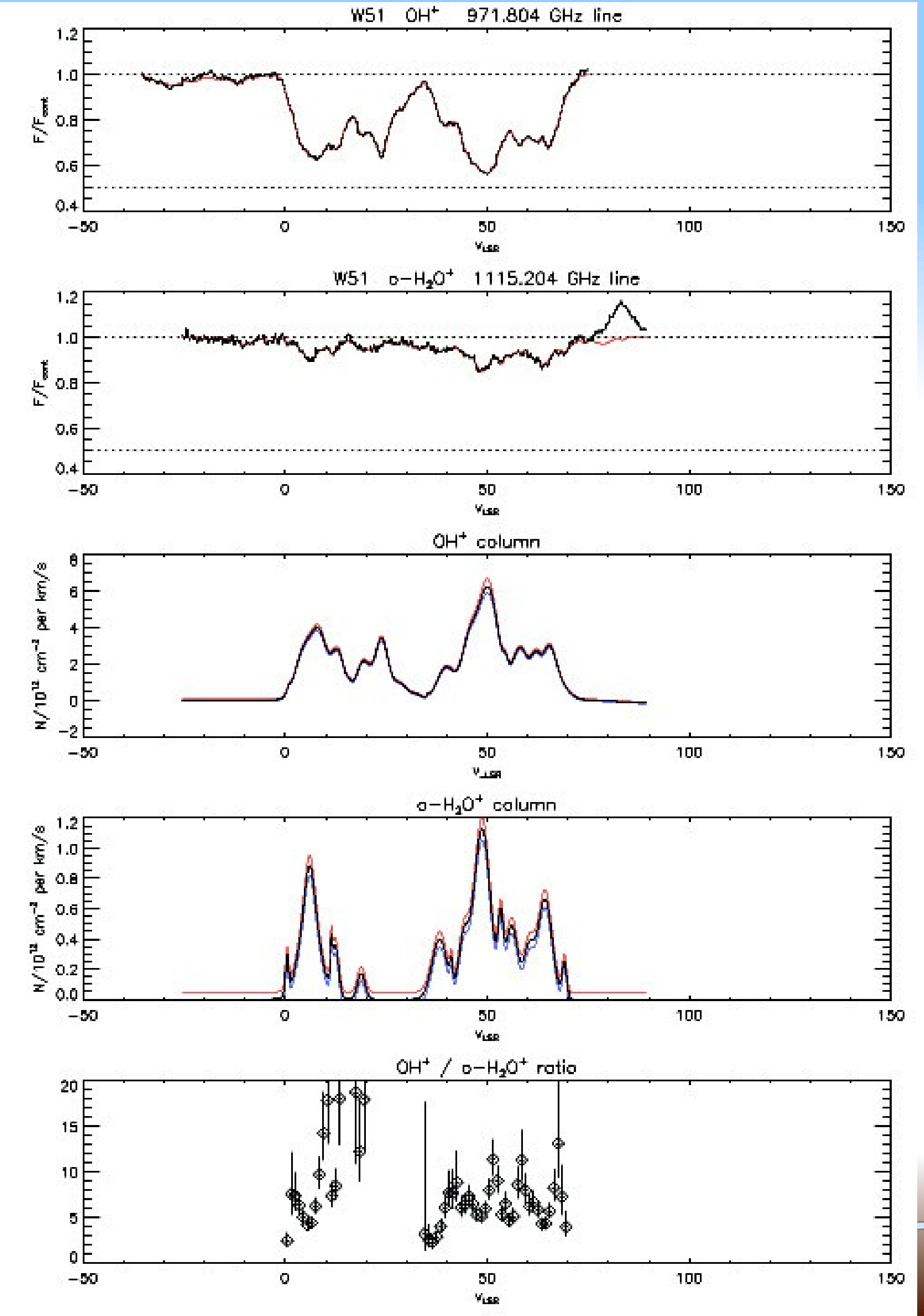
=> **OH^+ & H_2O^+ sensitive to ζ , the ionization rate due to cosmic rays $\zeta(H) = 0.6 – 2.4\ 10^{-16}\ s^{-1}$**

- The OH^+/H_2O^+ ratio traces the H_2 fraction in gas where it is measured
  - Typical values ~ 5 indicate clouds that are primarily ATOMIC

- The OH^+ abundance probes the cosmic ray ionization rate
  - Typical values indicate cosmic ray ionization rates ~ 10^{-16} s^{-1} per H atom

As for HF, the sideband gain ratio is critical when the optical depth is large. Here, the existence of hyperfine structure can provide valuable constraints.

Recent results from W51 are shown at the right (Neufeld et al. in preparation)



Hydrides as diagnostics : turbulence

CH^+ & SH^+ : Reactive ions formed in endothermic reactions with H_2 with several 1000 K.

Need an energy source for activating the reaction
==> dissipative regions of turbulence exhibit the right properties : heating + ion-neutral drift
=> efficient formation of CH^+ and SH^+ & consequences for the diffuse medium chemistry.

==> Alternative : Intense FUV or X-ray radiation in dense molecular gas.

Hydride as diagnostics : abundances and chemical evolution

HCl, H_2Cl^+ and HCl^+ have ground state transitions in the submillimeter => Simultaneous observations of ^{35}Cl and ^{37}Cl

Also

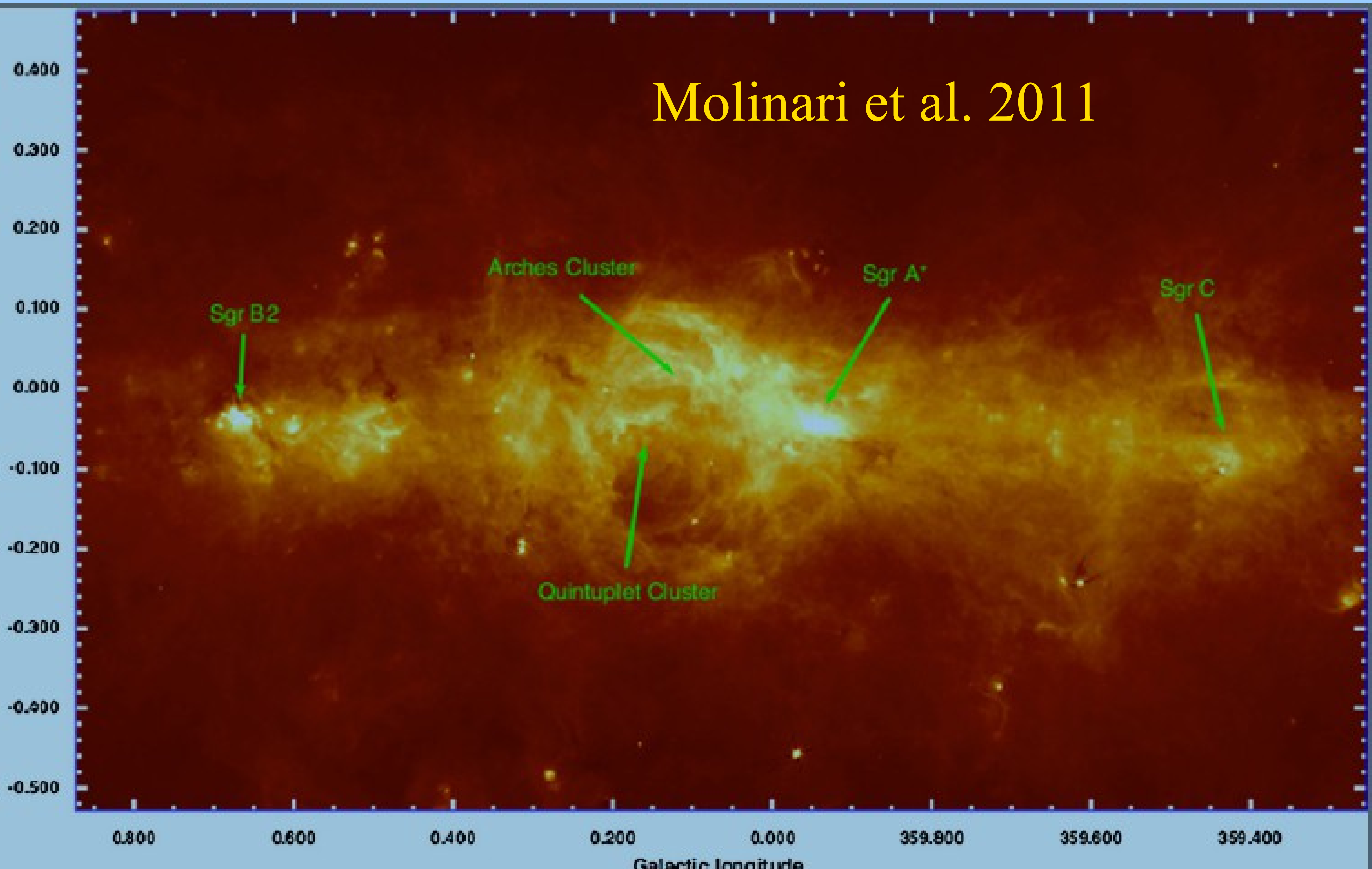
$^{12}CH^+$ & $^{13}CH^+$

H_2O, HDO, $H_2{}^{18}O$ ...

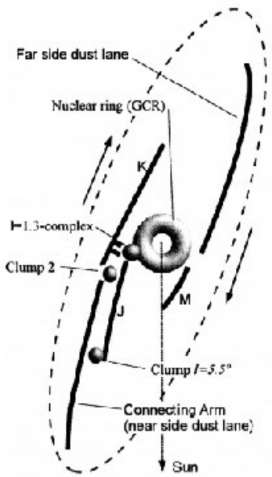
Prospects for CCAT : I The Galactic Center

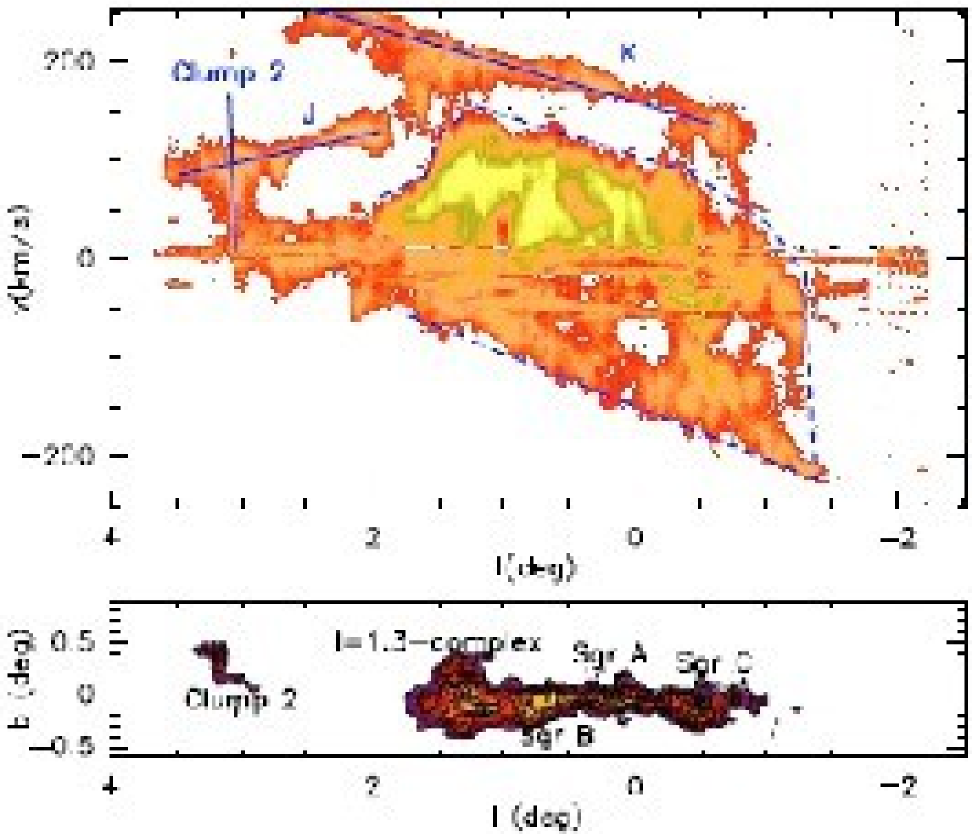
- The most nearby Galactic nucleus
- Active (massive) star formation (i.e. the Arches cluster)
- Massive black hole
- Energetic radiation (X-ray, cosmic rays, γ rays, positrons, etc.) + strong variability (flares, echoes)
- Gas dynamics : bar structure
- Magnetic field

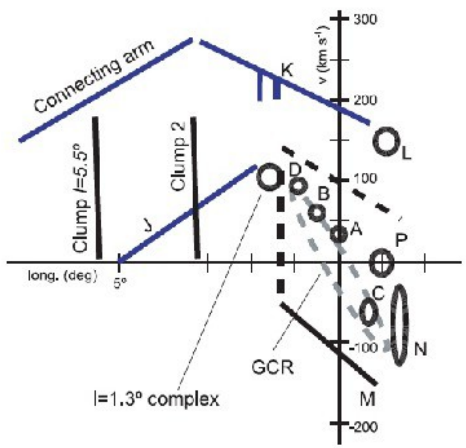
=> Laboratory for star formation in starburst galaxies



Molinari et al. 2011
Arches Cluster
Sgr A*
Sgr C
Sgr B2
Quintuplet Cluster
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
0.800
0.600
0.400
0.200
0.000
359.800
359.600
359.400
Galactic longitude







Rodriguez-Fernadez

2006, 2008

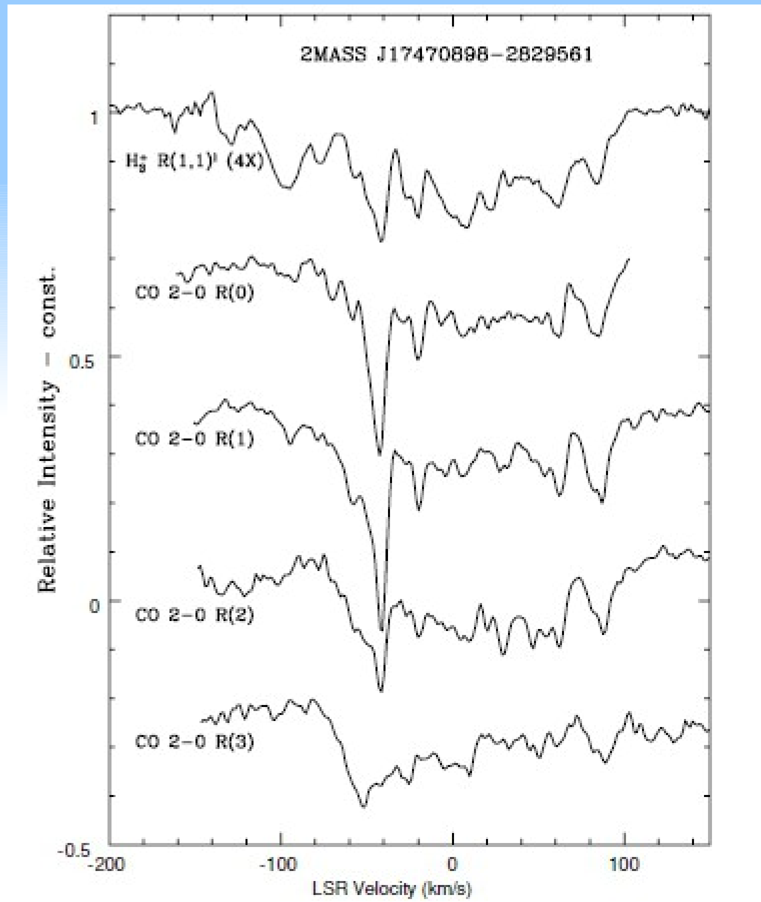
Galactic center open issues

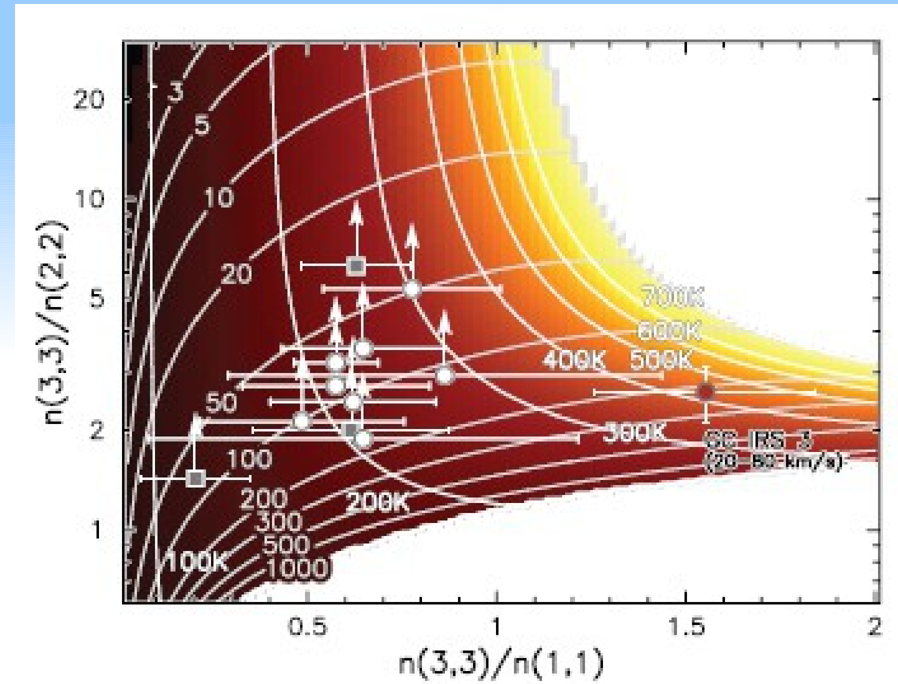
ISM phases :

- Massive GMCs with warm gas and cold dust (shock heated ?)
- Warm diffuse gas traced by H3+ absorption
- Hot bubbles

Relative distribution of the stars and gas phases, filling factors ? Heating sources ?
Role of cosmic rays, X-rays & γ rays ?
Relation to Galactic structure and feedback

H_3^+ in the central molecular zone,



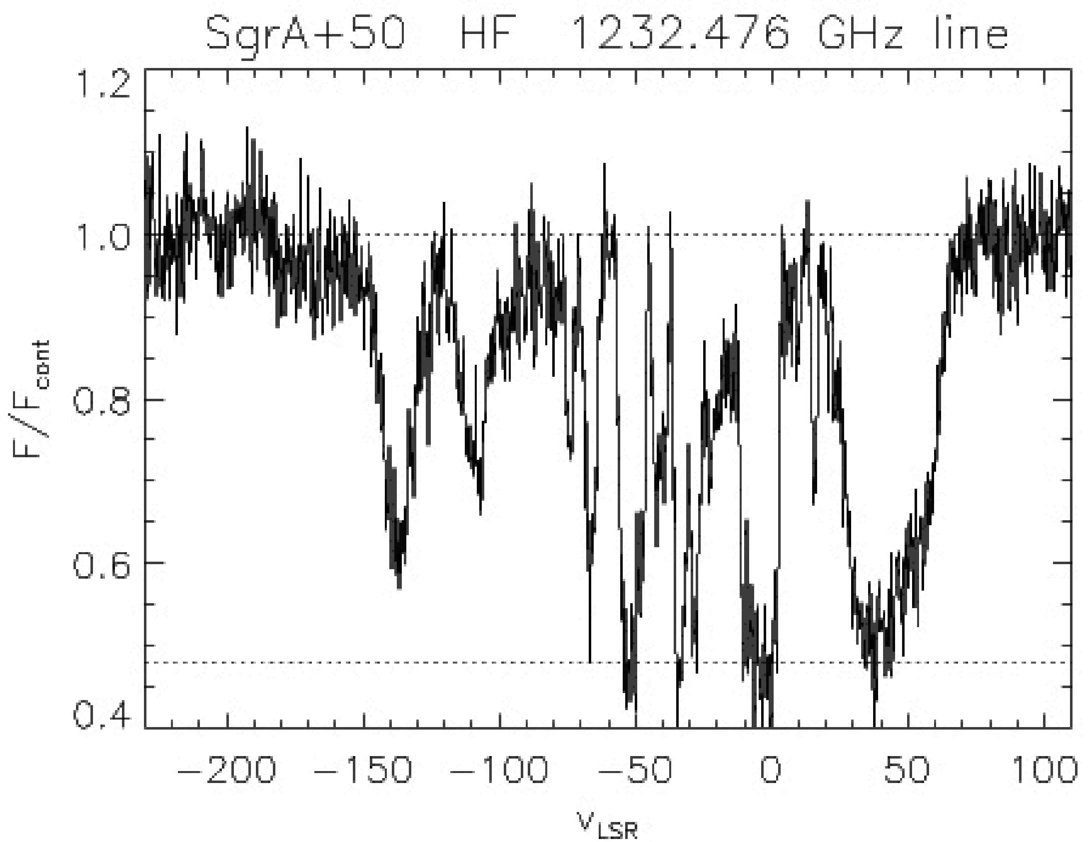


Geballe & Oka, Goto et al.

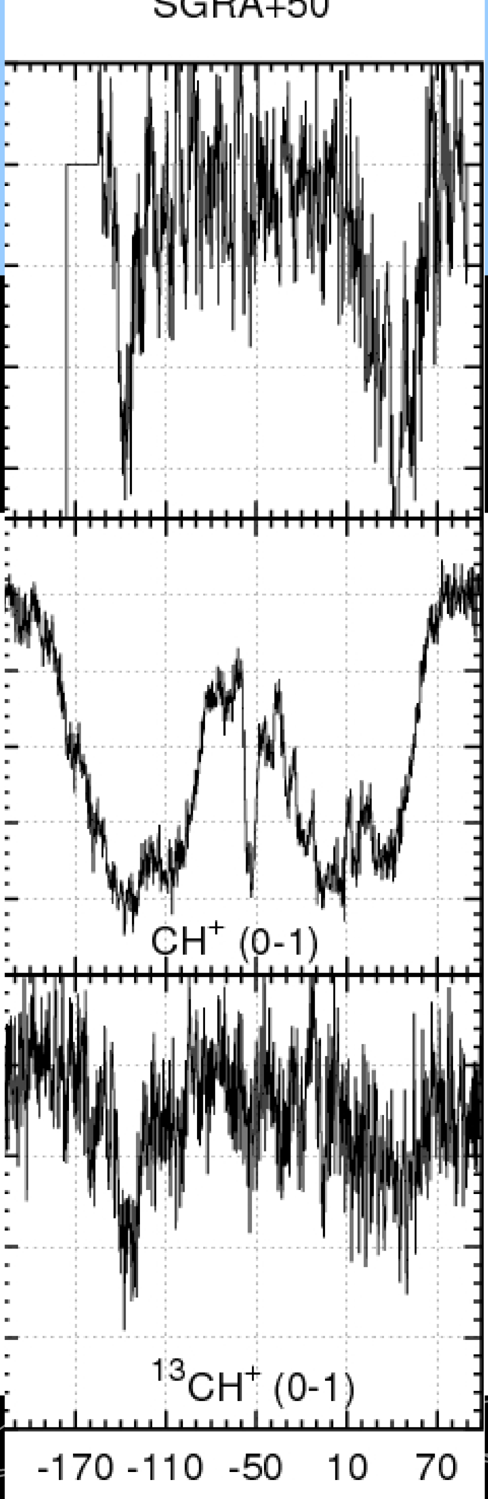
Low density 50 – 100 cm^{-3} , High Temp ~ 250 K
High ζ ~ 10^{-15} s^{-1}

Interstellar hydrides in absorption toward bright continuum sources in the Galactic Center

Recent spectrum toward the Sgr A +50 km/s cloud shows a spectacular absorption line spectrum with absorption detectable over an LSR velocity range of over 200 km/s

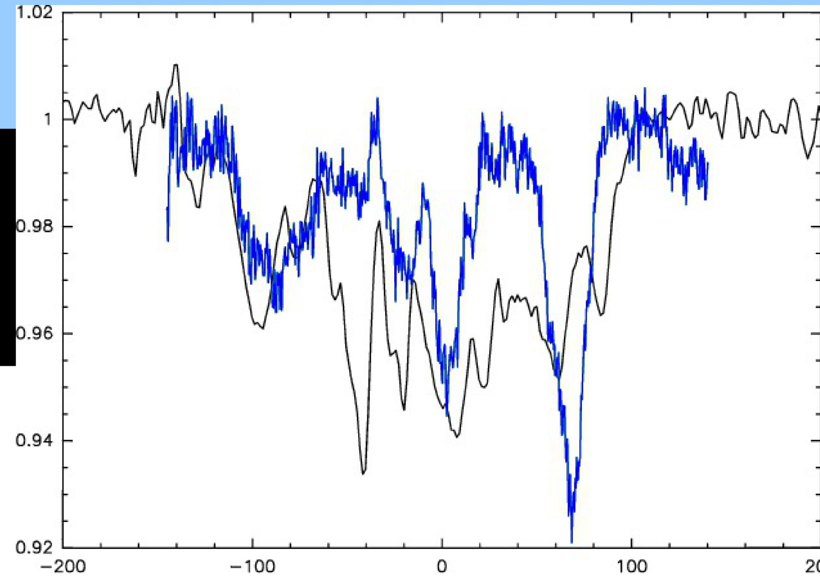


Sonnentrucker, Neufeld, Phillips et al. in preparation



Godard et al.
Submitted

Falgarone in prep



Broad absorption from CH^+, $^{13}CH^+$, SH^+,OH^+ ..
Likely tracing the same gas as H_3^+.

Galactic Center with CCAT

Maps of molecular emission lines trace the GMCs

Extended dust emission => Maps of absorption lines using the cold dust emission as background. Structure & physical conditions of the warm diffuse gas + variability in relation with SgrA* activity (eg Terrier et al. 2010)

So far few H_3^+ data (limited by number of stars)

CCAT can perform surveys of OH^+, $^{13}CH^+$, SH^+,H_2O^+ .H_2Cl^+, HDO, ...

Needs high spectral resolution (km/s)

Perspectives for CCAT : starburst & active galaxies

- Winds and energetic phenomena => broad absorption lines & P-Cygni profiles. OH, H_2O
- Radiation diagnostics associated to AGN vicinity (eg NGC1068, Centarus A) , OH^+ ?
- Search for absorption from excited lines (HCN, HCO^+)

- Diffuse ISM in external regions (for edge-on systems)

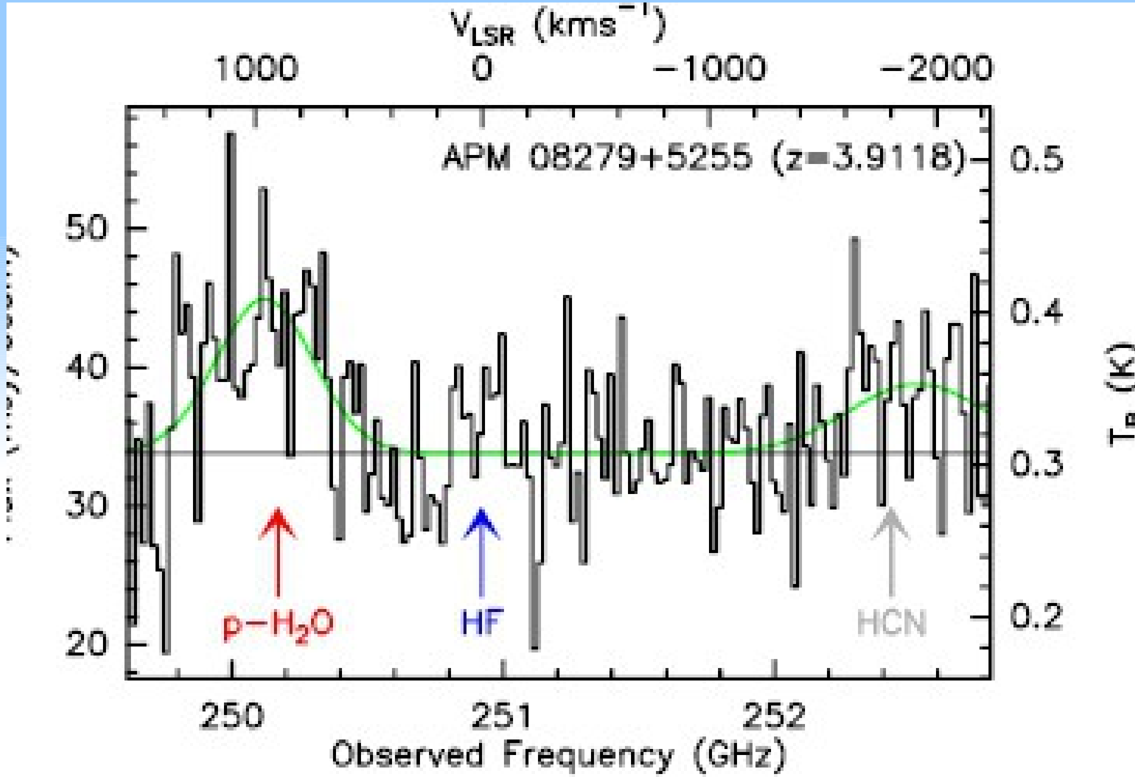
=> Medium spectral resolution, good sensitivity

Perspectives for CCAT : distant universe

• Molecular lines offer sensitive probes of ISM content : gas mass, gas density, energetics, ionization rate, ionization fraction, etc.

• Molecule excitation → CMB temperature

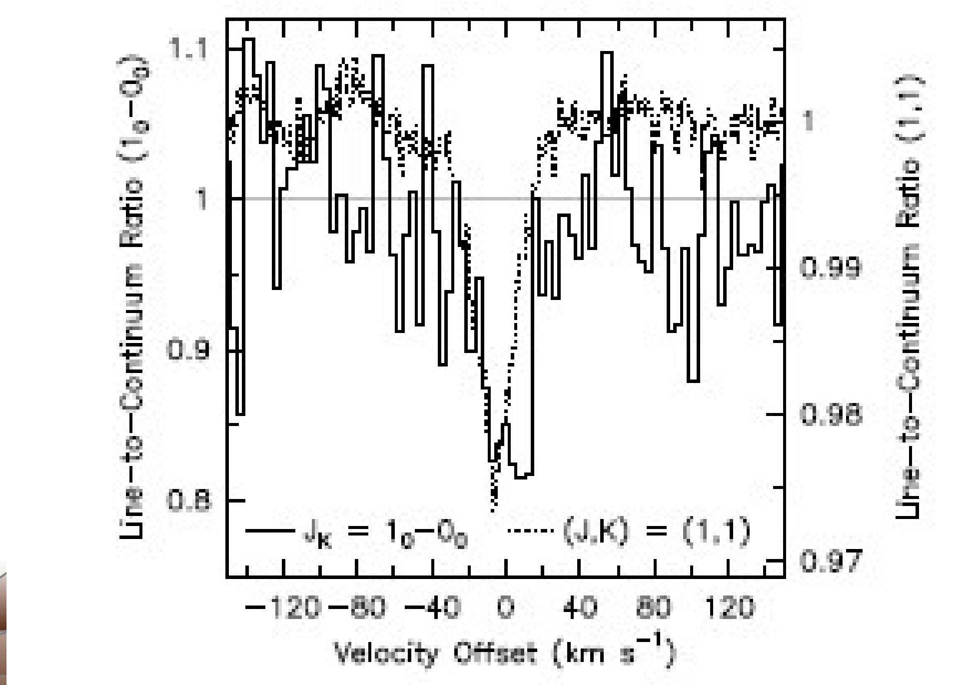
• new spectral lines => new possibilities of testing possible drifts of fundamental constants
(eg comparison of NH_3 rotational and inversion lines is sensitive to me/mp Henkel et al 2010), also H_3O^+



APM 08279+5255

Neufeld et al 2011& Bradford et al with Z-spec

- No HF (nucleosynthesis ?)
- Strong H_2O emission



PKS1830-2822

Menten et al APEX

H_2O & NH_3 absorption

ALMA + CCAT ?

Recommended lines for absorption studies

Local objects : $z = 0$

Hydrides :

H_2S, p-NH_2, p-H_2O^+, HCl, H_2Cl^+, SH^+, $^{13}CH^+$, HDO, OH^+

Other interesting species

CI, HCO^+, HOC^+ CN, CCH, c-C_3H_2,HCN, HNC, H_2CO , CS, SO,

High redshift ($z > 0.1$)

More hydride lines :

OH, CH, H_2O, NH, $NH_{2,}$$NH_3$, HF, HCl^+, CH^+, o-H_2O^+, H_3O^+

Other species : C_3, excited HCO^+, HCN …

Fine structure lines : CII, OI