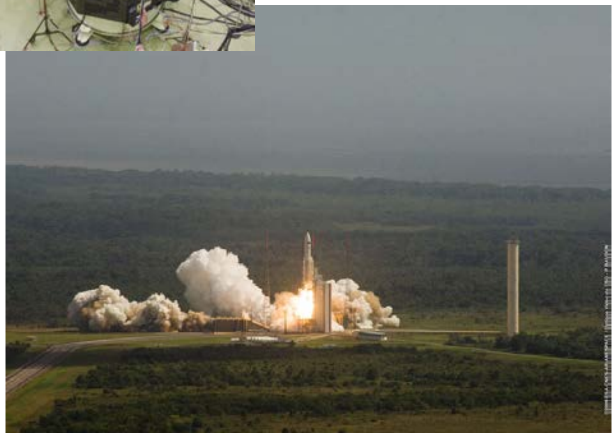
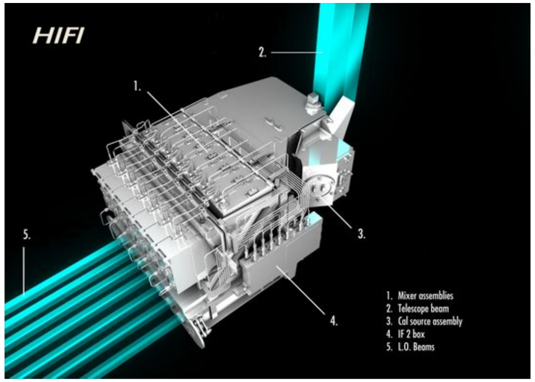


# "Interstellar hydrides with Herschel: from the 20th to the 21th century"




Maryvonne Gerin

# Designing the mission : spectroscopy

- T.G. Phillips in ESA, From Ground-Based to Space-Borne Sub-mm Astronomy p 221-228 (SEE N91-21986 13-89)

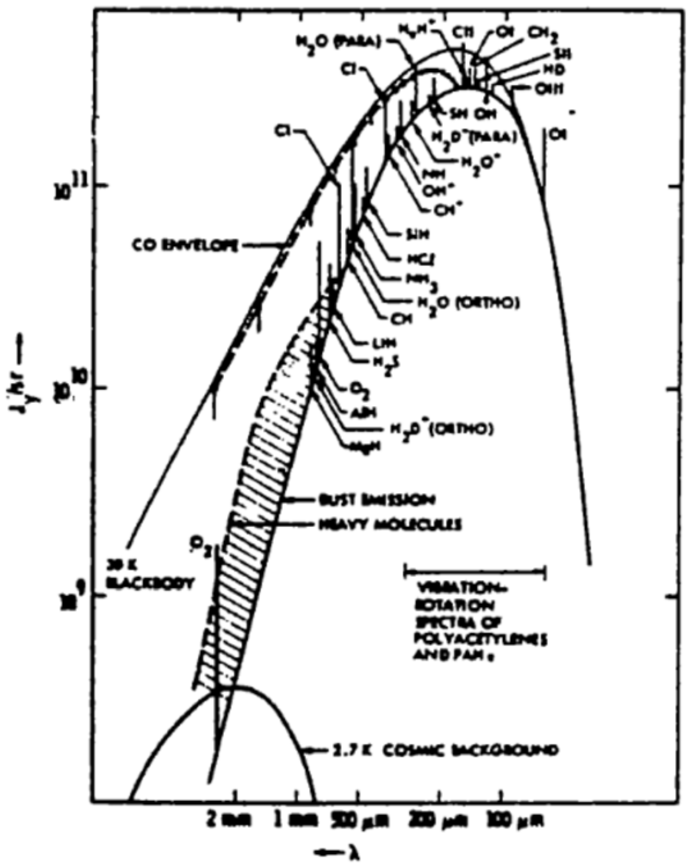


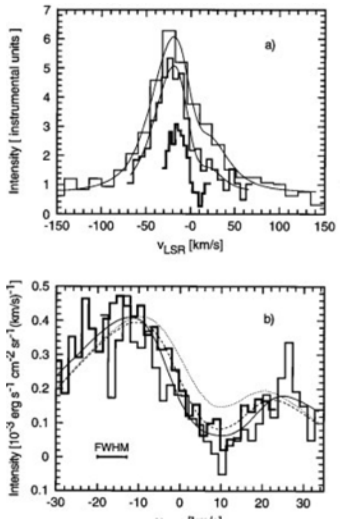

Figure 3. The anticipated spectrum of a 30K, dense interstellar cloud, showing the dust spectrum, heavy and light molecule rotation spectra and atomic fine-structure lines.

# Fine structure lines : ISO & KAO before Herschel & SOFIA

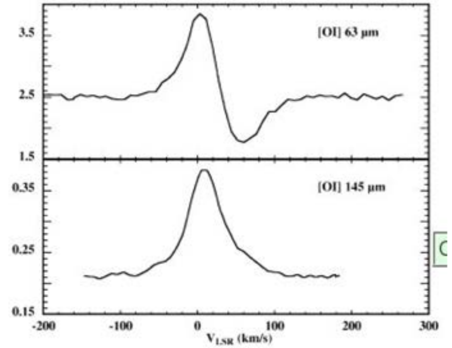
- KAO : [OI] in DR21 *(Poglitsch et al. 1997)*
- ISO : SgrB2, W49 at “high” spectral resolution (FP) *(Vastel et al. 2000, Lis et al. 2001)* :

- Detection of absorption in [CII] and [OI] 63µm
- Limited velocity resolution → Difficulty in determining the opacity and for disentangling narrow and features

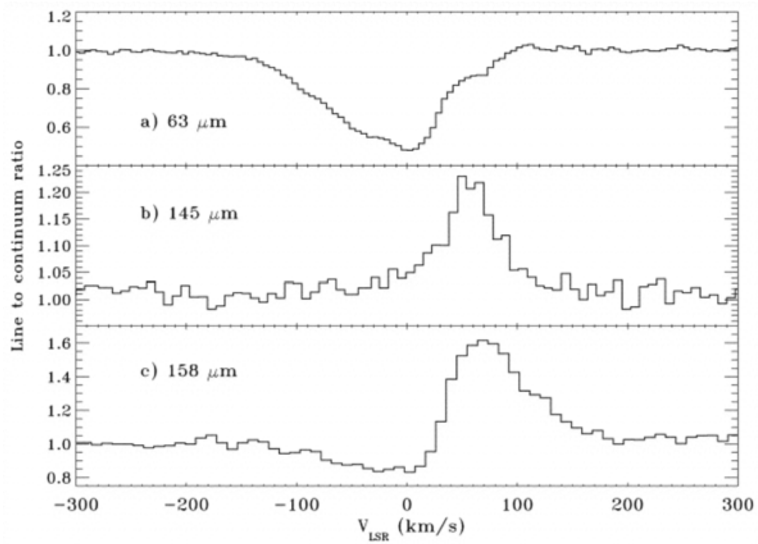
**KAO : DR21**



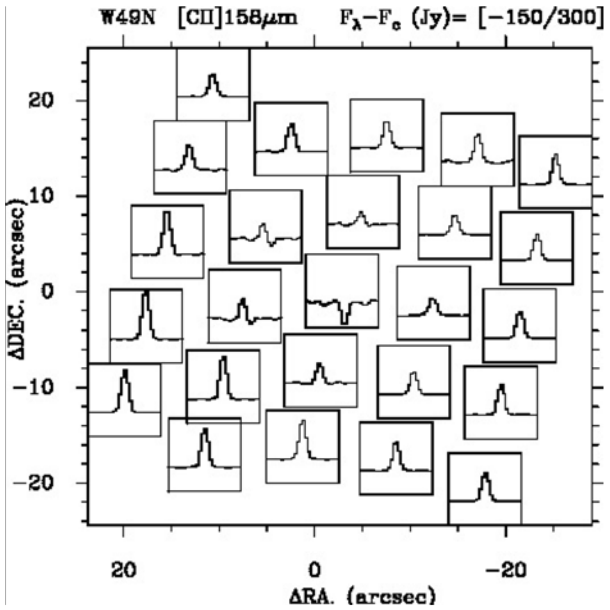

**ISO : W49N**



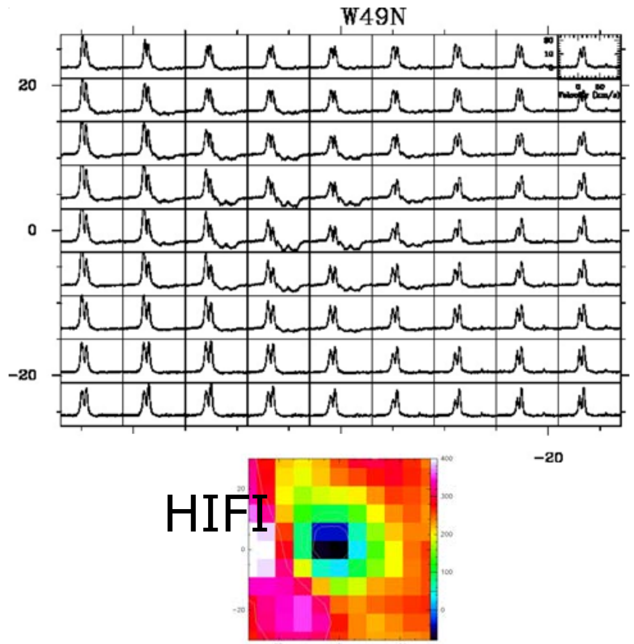

**ISO : SgrB2**

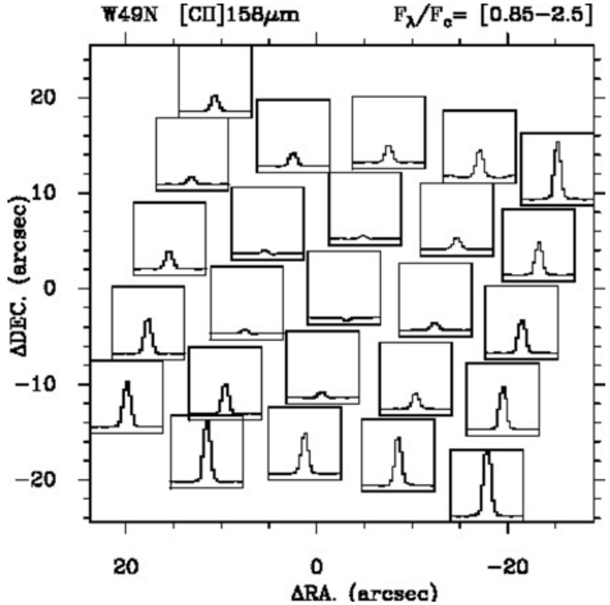


# [CII] with HIFI & PACS towards W49N




Line Flux



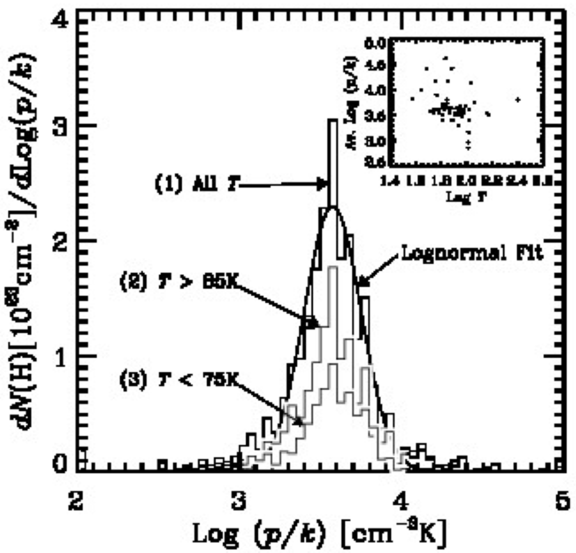




Line/continuum ratio

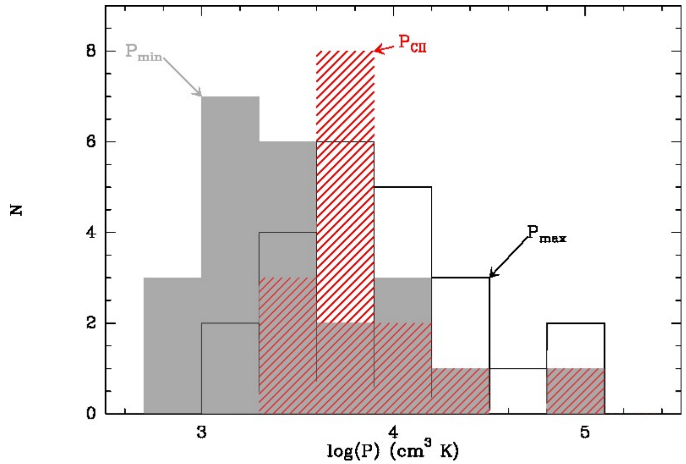
- HIFI : Load chop observations with “ref” position 1.5° OFF the Galactic plane
- PACS : Chopped with 6' OFF. Correction for OFF contamination
- Complex line profiles with prominent absorption from foreground gas
- PACS with low spectral resolution : absorption in the central pixel → can contribute to the [CII] deficit ?

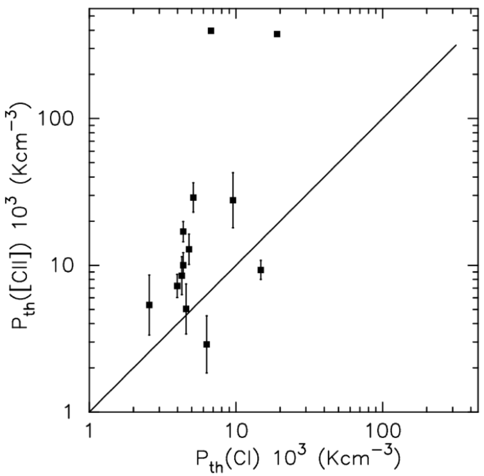
# Determination of the diffuse gas pressure distribution

From FUV : *Jenkins & Tripp 2011*




From FIR with Herschel : *Gerin+2015, Velusamy+2017*

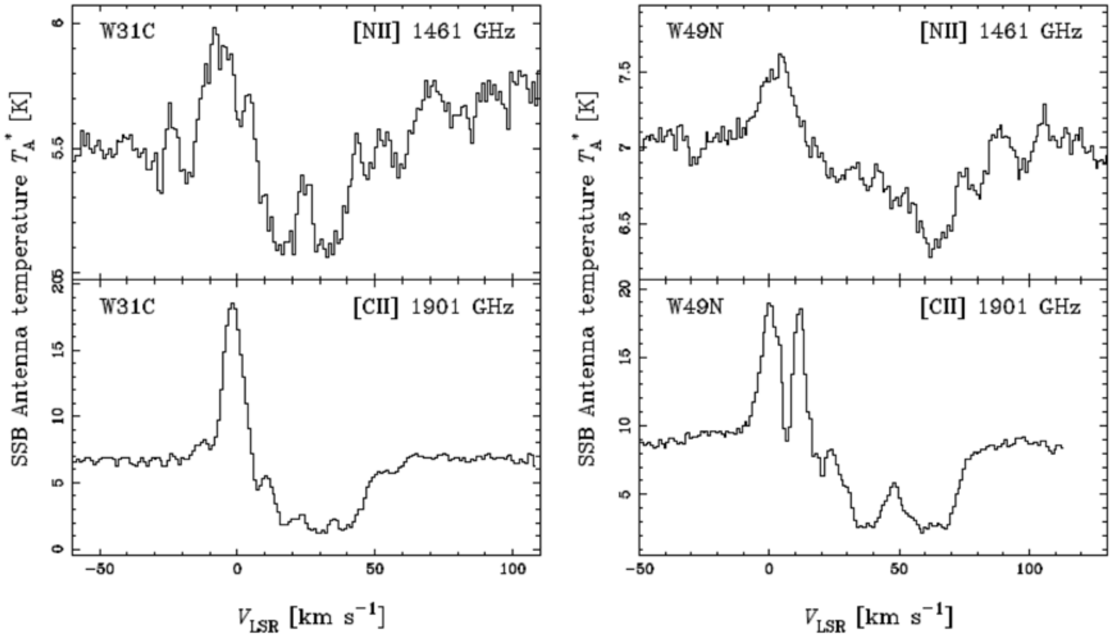



Median pressure : log(p) = 3.58 +/- 0.175
p ~ nT ~ 3800 Kcm$^{-3}$
within a factor 1.5

Variation of pressure with Galactic radius : 6900 Kcm$^{-3}$
At the mean Galactic radius of 5 kpc
Good agreement for the same sources

# $N^+$ absorption as a tracer of the WIM



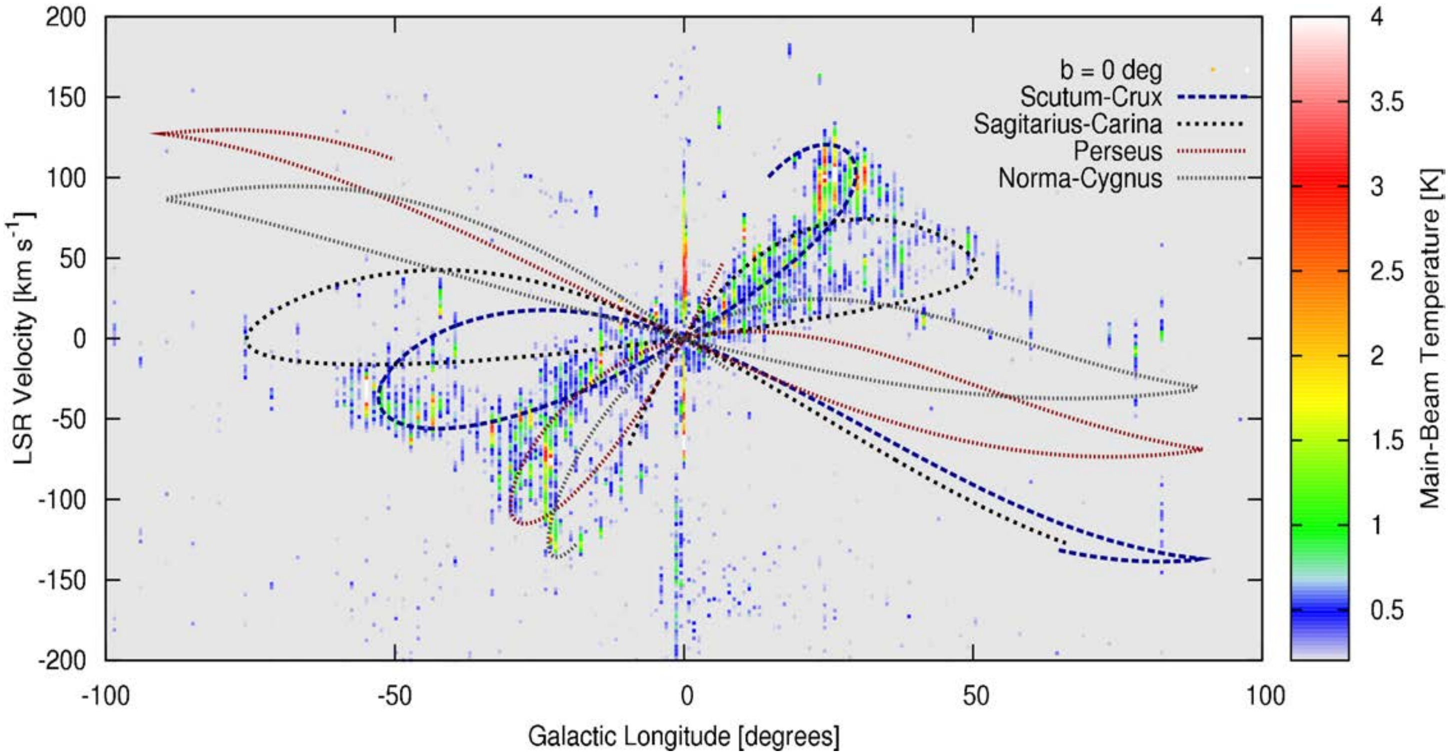

*Persson+ 2014*

$N(N^+) \sim 1.5\ 10^{17}\ cm^{-2}$ - $N(C^+)/N(N^+) \sim 40$

Diffuse ionized gas with $n(H^+) \sim 0.1 – 0.3\ cm^{-3}$ and T ~ 8 000 K → Warm Ionized Medium (WIM)

C/N ~ 3 – 4 ; → about 10% of the $C^+$ absorption is associated with the WIM

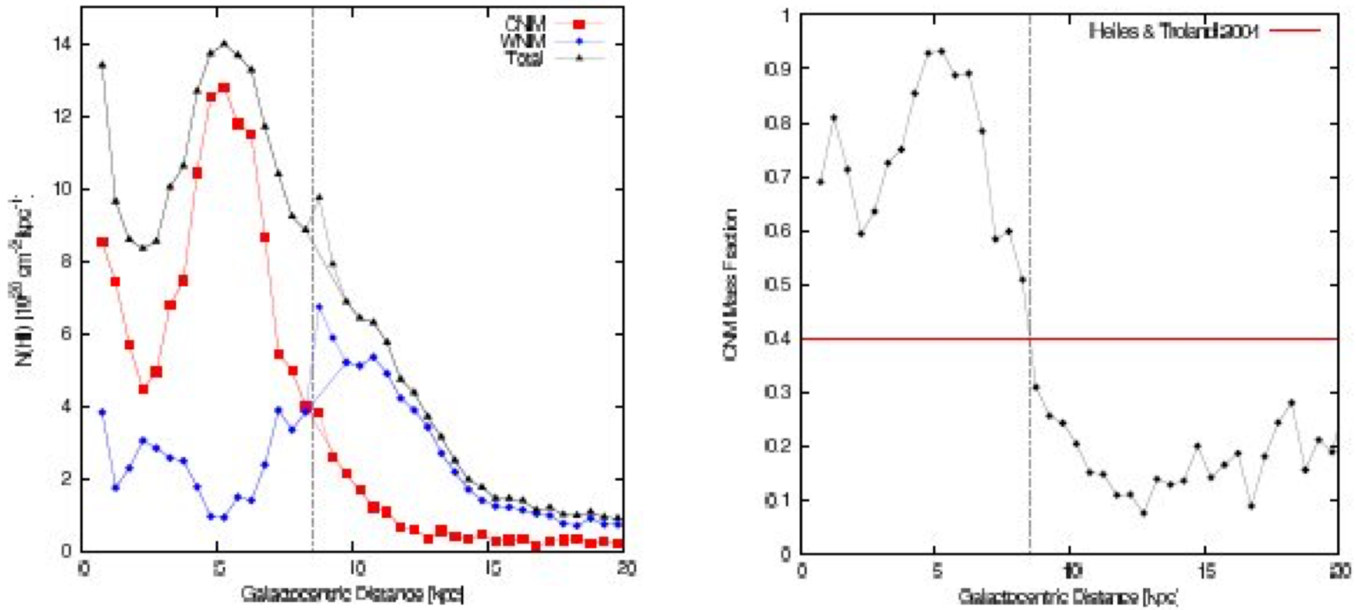
# GOT C+ [CII] Distribution in the Milky Way

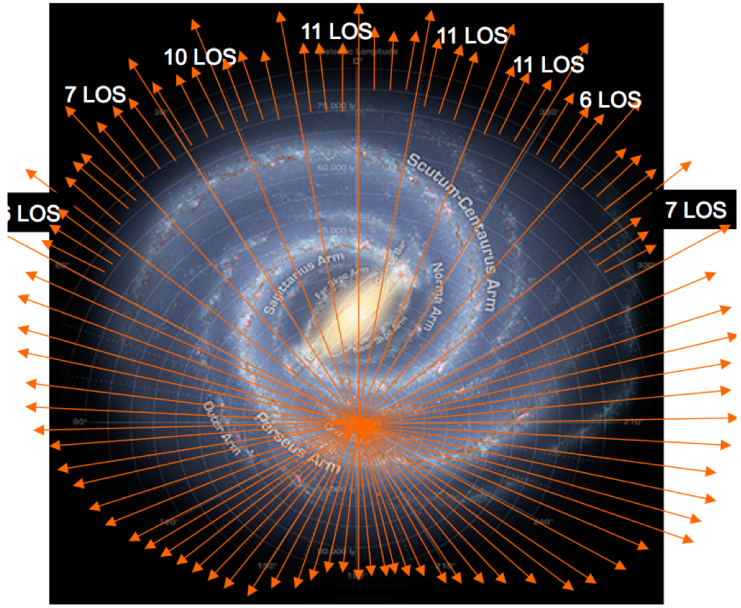



*Goldsmith, Langer, Pineda, Velusamy+*

# The CNM/WNM fraction from Herschel GotC+ survey

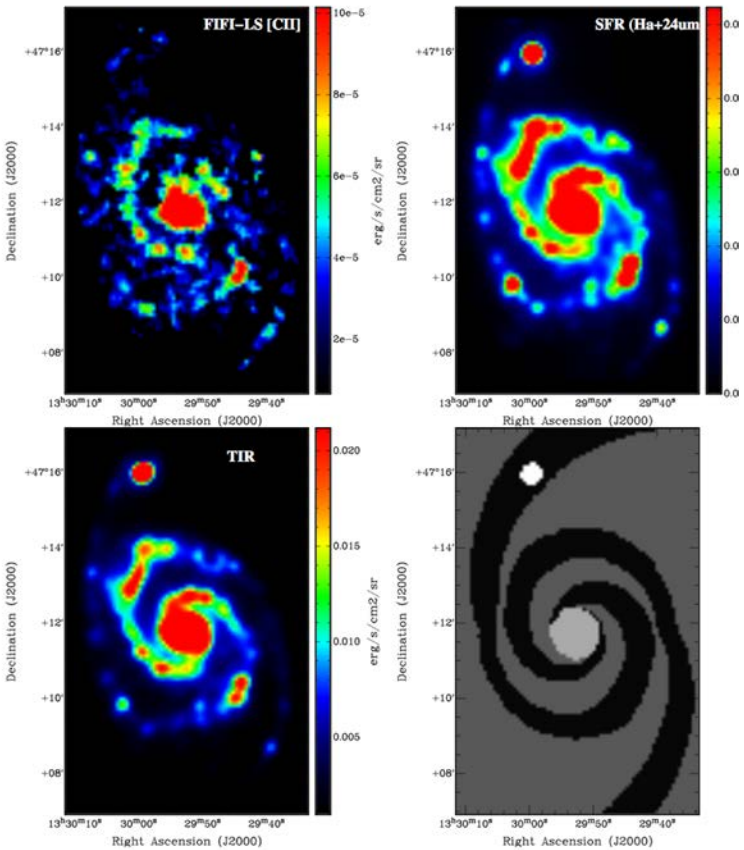
Pineda, Langer, Velusamy, and Goldsmith: A *Herschel* [C II] Galactic Plane Survey



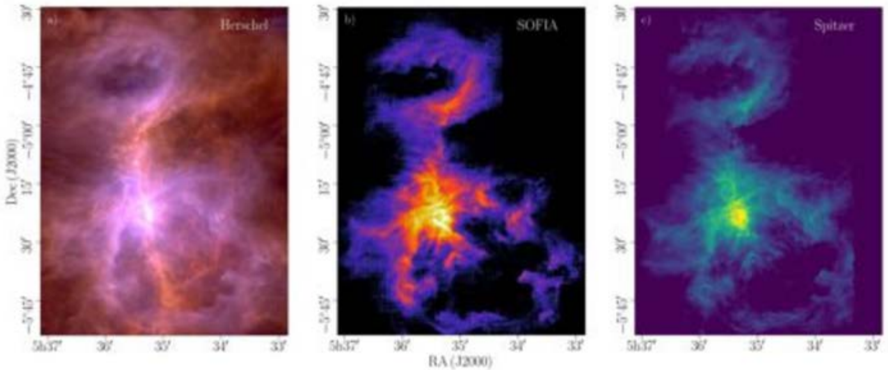



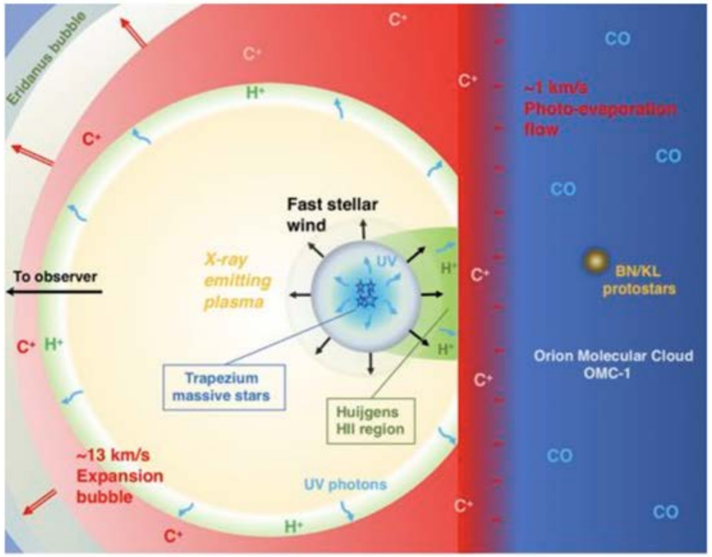

[CII] fine structure line at 158 µm is the main coolant of the CNM.

The Comparison of HI and [CII] emission enables the separation of the CNM and WNM




Pineda+2018
[CII] in M51




Pabst+2019
[CII] in Orion / L1630

Large scale [CII] maps :
Star formation rate
Feedback effect from massive stars

# Preparation for Herschel/HIFI observations : molecules

1/ Choosing the species :
- Hydrides from the main elements (C, N, O)
- Hydrides with specific properties (F, Cl)

2/ Choose the targets :
- Use SWAS & ODIN + VLA subset of strong FIR sources with known foreground absorption

3/ Define the observations :
- Expected abundances from models ?
- **Constant sensititivity : S/N = 100 on continuum**
- Frequencies & line strengths ? Ask spectroscopists

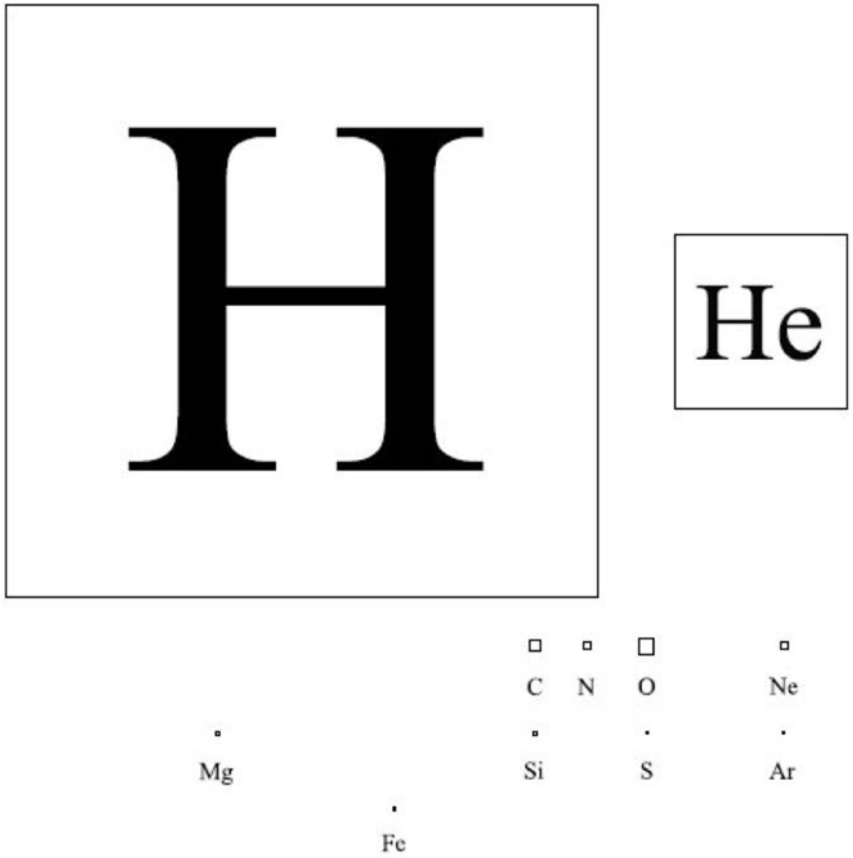


Figure 4.1 "The Astronomer's Periodic Table".

*The Astronomer's Periodic Table ; B. Mc Call*

**Table 1 Main astrophysical hydrides[a)]**

| Formula | Name | Spectral domain[b)] | Ref. |
|---|---|---|---|
| $H_2$ | Molecular Hydrogen | UV-Visible, IR, FIR | Carruthers (1970b) |
| $H_3^+$ | Protonated molecular hydrogen | IR | Geballe & Oka (1996) |
| CH | Methylidyne | UV-Visible, (sub)mm, cm | Swings & Rosenfeld (1937) |
| $CH_2$ | Methylene | FIR, (sub)mm | Hollis, Jewell & Lovas (1995) |
| $CH_3$ | Methyl | IR | Feuchtgruber et al. (2000) |
| $CH_4$ | Methane | IR | Lacy et al. (1991) |
| $CH^+$ | Methylidynium | UV-Visible, FIR, (sub)mm | Douglas & Herzberg (1941) |
| $CH_3^+$ | Methylium | IR, (sub)mm | Roueff et al. (2013)[c] |
| NH | Imidogen | UV-Visible, (sub)mm | Meyer & Roth (1991) |
| $NH_2$ | Amidogen | (sub)mm | van Dishoeck et al. (1993) |
| $NH_3$ | Ammonia | (sub)mm, cm | Cheung et al. (1968) |
| $NH_4^+$ | Ammonium | (sub)mm | Cernicharo et al. (2013)[d)] |
| OH | Hydroxyl radical | UV-Visible, FIR, cm | Weinreb et al. (1963) |
| $H_2O$ | Water | FIR, (sub)mm, cm | Cheung et al. (1969) |
| $OH^+$ | Hydroxylium | UV-Visible, (sub)mm | Wyrowski et al. (2010) |
| $H_2O^+$ | Oxidaniumyl | UV-Visible, (sub)mm | Ossenkopf et al. (2010) |
| $H_3O^+$ | Hydronium | FIR, (sub)mm | Phillips, van Dishoeck & Keene (1992) |
| HF | Hydrogen fluoride | FIR | Neufeld et al. (1997) |
| SH | Mercapto radical | UV-visible, FIR | Neufeld et al. (2012) |
| $H_2S$ | Hydrogen sulfide | (sub)mm | Thaddeus et al. (1972) |
| $SH^+$ | Sulfanylium | (sub)mm | Benz et al. (2010); Menten et al. (2011) |
| HCl | Hydrogen chloride | UV-visible, (sub)mm | Blake, Keene & Phillips (1985) |
| $HCl^+$ | Chloroniumyl | FIR | De Luca et al. (2012) |
| $H_2Cl^+$ | Chloronium | (sub)mm | Lis et al. (2010a) |
| $ArH^+$ | Argonium | (sub)mm | Barlow et al. (2013) |

[a)]Adapted from The Astrochymist (www.astrochymist.org); [b)] The corresponding wavelength ranges are : UV-Visible 100 – 1000nm, IR : 1 – 20 $\mu$m, FIR 20 – 300 $\mu$m ; (sub)mm 0.3 – 4 mm; cm 1 - 20 cm; [c)] A tentative detection of the isotopologue $CH_2D^+$ is reported; [d)] The detection of the isotopologue $NH_3D^+$ is reported.

| Element | Ionization Potential (eV) | **Endothermicity (Kelvin equivalent = $\Delta E/k_B$) for** | | | **Driver** |
|---|---|---|---|---|---|
| | | $X + H_2 \rightarrow XH + H$ | $X^+ + H_2 \rightarrow XH^+ + H$ | $X + H_3^+ \rightarrow XH^+ + H_2$ | |
| He | 24.587 | No reaction | Exothermic, but primary channel is to $He + H + H^+$ | 29000 | |
| C | 11.260 | 11000 | 4300 | | Warm gas |
| N | 14.534 | 15000 | 230 | 10000 | Cosmic rays |
| O | 13.618 | 920 | | | Warm gas or cosmic rays |
| F | 17.423 | | | 10000 | None needed |
| Ne | 21.564 | No reaction | Exothermic, but primary channel is to $Ne + H + H^+$ | 27000 | |
| Si | 8.152 | 17000 | 15000 | | Warm gas |
| P | 10.487 | 19000 | 13000 | | Warm gas |
| S | 10.360 | 10000 | 10000 | | Warm gas |
| Cl | 12.968 | 515 | | | UV with hν > 12.97 eV |
| Ar | 15.760 | No reaction | | 6400 | Cosmic rays |

*Gerin, Neufeld & Goicoechea ARAA 2016*

PRISMAS
PRobing InterStellar Molecules with Absorption line Studies

HEXOS
Herschel HIFI Observations of Extraordinary Objects
The Orion and Sagittarius B2 Star-Forming Regions

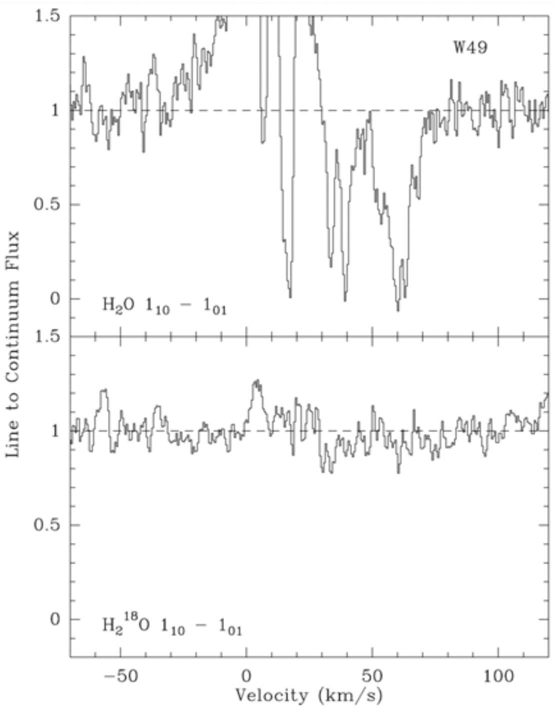
# Warm And Dense ISM

| | |
|---|---|
| He | $HeH^+$ |
| C | $CH$, $^{13}CH$, $CH^+$, $^{13}CH^+$, $CH_2$ , $CH_3$ *$CH_3^+$*, $CH_2D^+$, $CH_4$ , C, $C^+$ |
| N | NH, *$^{15}NH$* $NH_2$, $NH_3$ (o & p), $^{15}NH_3$, ND, $NH_2D$, $ND_2H$, $ND_3$, $NH_3D^+$, *$NH^+$* , $N^+$ |
| O | $OH^+$, $H_2O^+$ (o & p), $H_3O^+$, $H_2O$ (o & p), $H_2{}^{18}O$, HDO, $D_2O$, OD |
| F | HF, *DF* |
| Cl | HCl, $HCl^+$ , $H_2Cl^+$ |
| S | SH, $H_2S$, $SH^+$ |
| Ar | $ArH^+$ |

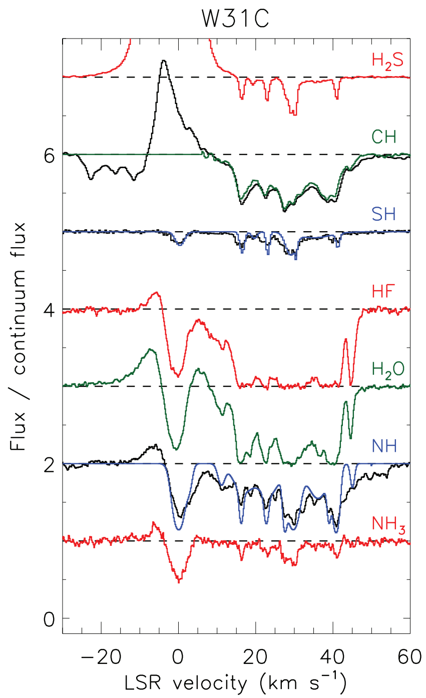
ISO
Herschel new detection
Herschel observations
SOFIA new detection
ALMA
Other telescopes
*No detection yet*

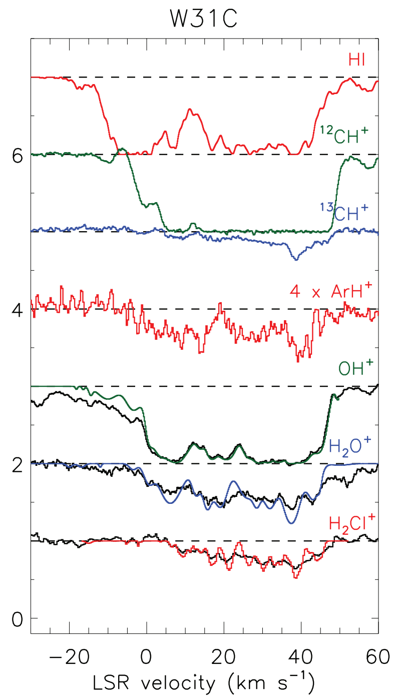
# Molecular absorption profiles : from SWAS & ODIN to Herschel & SOFIA

**W31C**



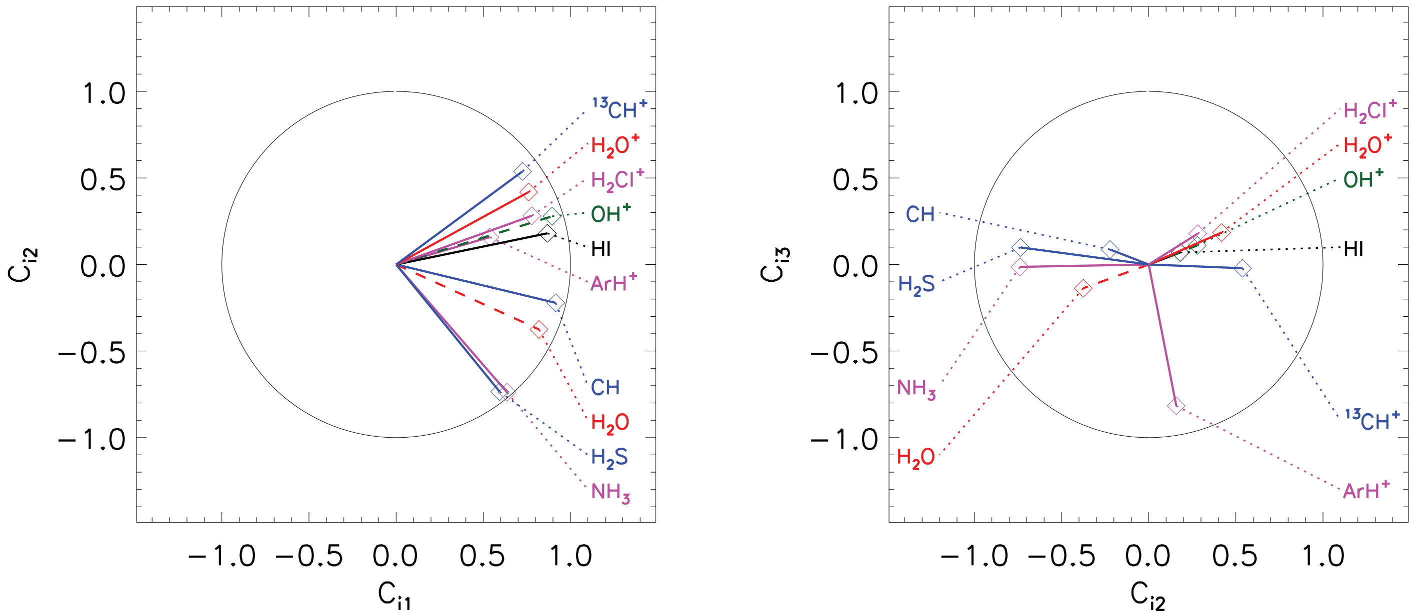

*Plume+ 2004*




*Gerin,Neufeld, Goicoechea*
*ARAA 2016*

# PCA analysis of hydride absorption spectra




Separation of different families :

- "HI" : ions like $CH^+$, $OH^+$ & $H_2O^+$. Gas with a low fraction of hydrogen in $H_2$
- CH & $H_2O$ for diffuse molecular gas : trace the $H_2$ column density
- $H_2S$ & $NH_3$ molecular gas with lower filling factor (higher density). Similar behavior as CN & HNC

*Gerin, Neufeld & Goicoechea 2016 ARAA*

# Tracing the $H_2$ fraction

Local value

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

$\neq$

Integrated value

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

- Global 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
  - Abundance uncertainty ≤ factor of 2
  - Characteristic scales probed are ~ few pc for local sight-lines, up to ~ 100pc for Galactic Plane sources
  - Averaging effect along the line of sight → better accuracy for long sightlines

- Local $H_2$ tracers = species with enhanced abundance in a special range of $H_2$ fraction :
  - molecular ions formed and destroyed by $H_2$ reach a peak abundance at a given $f(H_2)$ (which may depend on the conditions) (e.g. $OH^+$, $H_2O^+$, $ArH^+$)
  - Trace only the gas close to this optimum $f(H_2)$
  - The local $H_2$ fraction may therefore be different from the global value

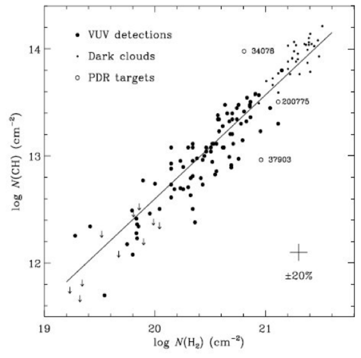
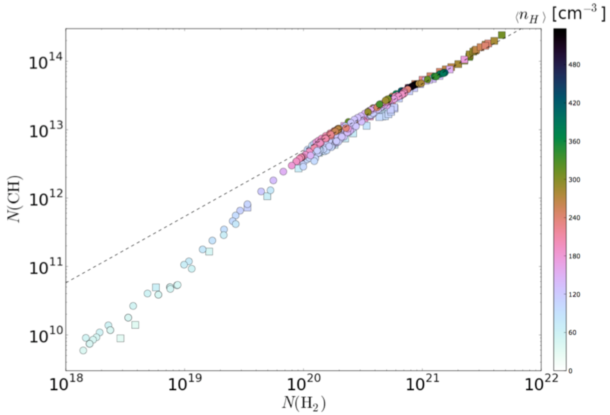
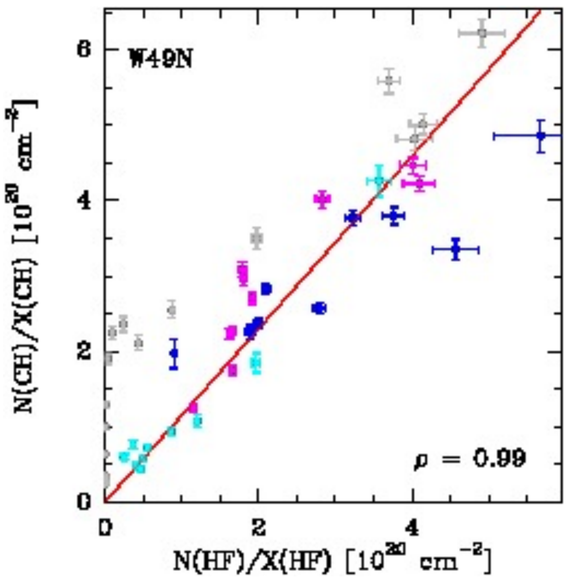


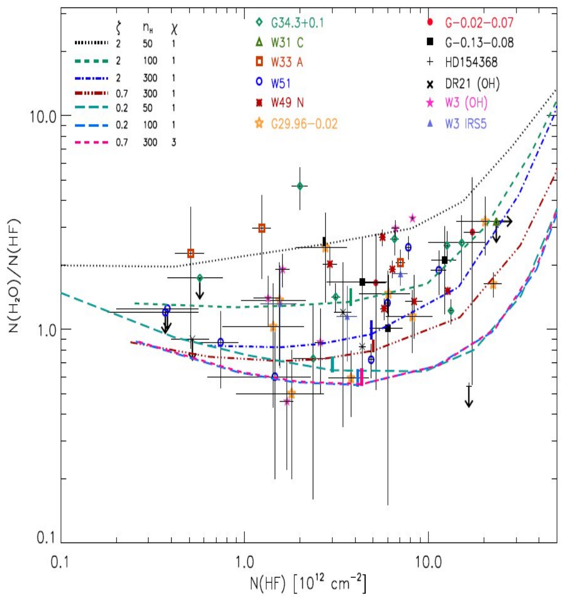

Fig. 8.—CH column density shown to have a linear correlation with $N(H_2)$, characterized by a single slope of $0.97 \pm 0.07$. The optical data fit is seen to match the Mattila (1986) dark cloud extension of the CH vs. $H_2$ relationship. The abundance ratio $CH/H_2$ is constant at $3.5 \times 10^{-8}$.




# CH , HF & $H_2O$

- HF : formed exothermically in the F + $H_2$ reaction → HF tracks $H_2$
- CH is shown from observations and models to track $H_2$ with a. constant abundance $CH/H_2$= 3.6 $10^{-8}$



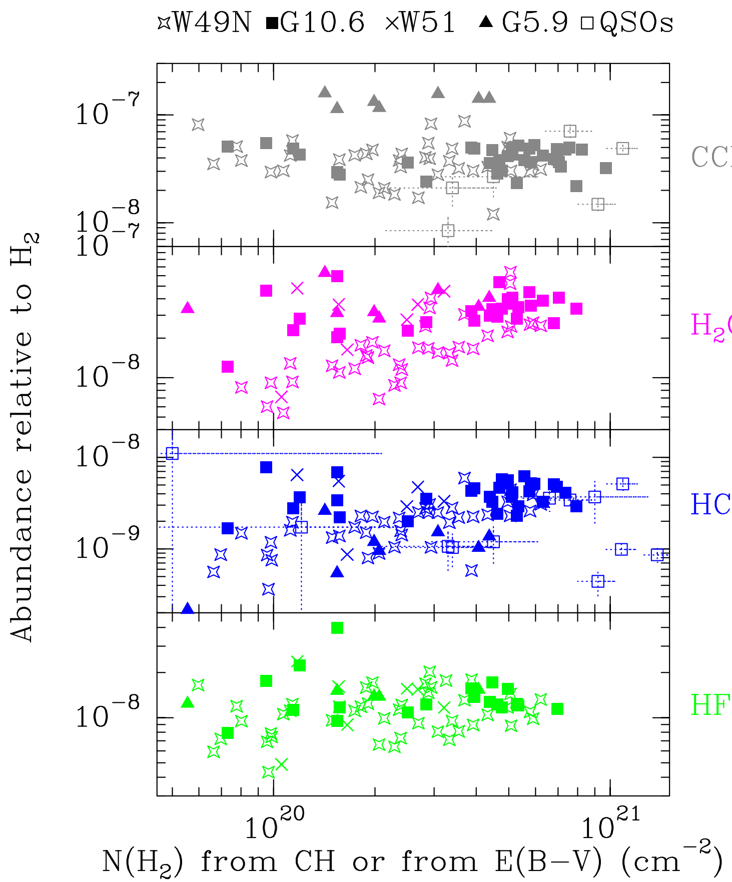

N(HF) / N(CH) ~ 0.4 → $HF/H_2$~ 0.6 – 2.4x$10^{-8}$
$H_2O$/HF ~2 → H2O/H2 ~ 2.5x$10^{-8}$

Consistent with chemical models & direct measurement towards stars

**Good understanding of the chemistry**
**Molecular probes of the $H/H_2$ transition**

*Neufeld+2010, Flagey+2013, Tziniti+2014, Sonnentrucker+2015, Wiesemeyer+ 2016, Godard+ 2012 Emprechtinger+ 2012, Levrier+2012, Sheffer+2008*

# Other Molecules tracing $H_2$




**CCH**
$4.4x10^{-8}$ (0,15 dex)

**H2O**
**2.7 $10^{-8}$ (0.20 dex)**

**HCO+**
**3.1 $10^{-9}$ (0.21 dex)**

**HF**
**1.2 $10^{-8}$ (0.14dex)**

- Species with strong absorption lines at lower frequencies (~ 100GHz) where the sky is more transparent : **$HCO^+$, CCH, HOC+, CF+**
- Nearly constant abundances over a decade in N(H2) with a real dispersion (0.2 dex or a factor 1.6)
- Includes the regime of CO-dark H2 with N(H2) ~ $5x10^{20}$ $cm^{-2}$
- Choice of species to cover a range in N(H2) :

*HF is the most sensitive probe in the THz domain*
*$HCO^+$ is the most sensitive probe in the mm domain*
*$HCO^+$ , p-$H_2O$ & OH (THz) probe the same range of $H_2$ columns*
*CH & CCH allow to reach higher $H_2$ columns where $HCO^+$ is saturated*

*Gerin+2018*

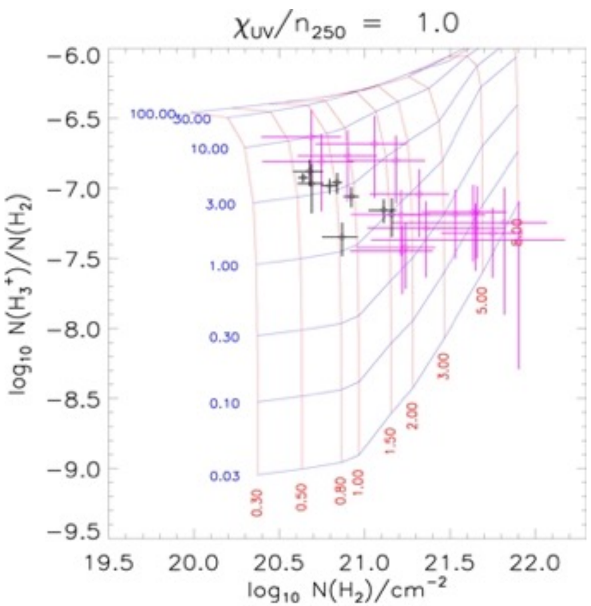
# Determination of the Cosmic Ray ionization rate

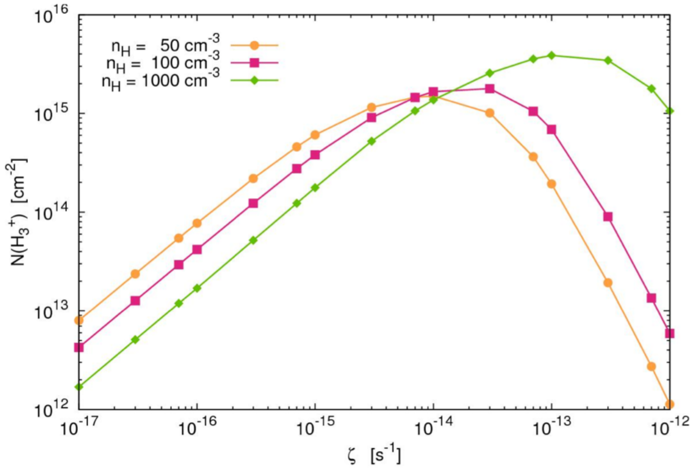
Molecular ions formed by CR-induced ionization of

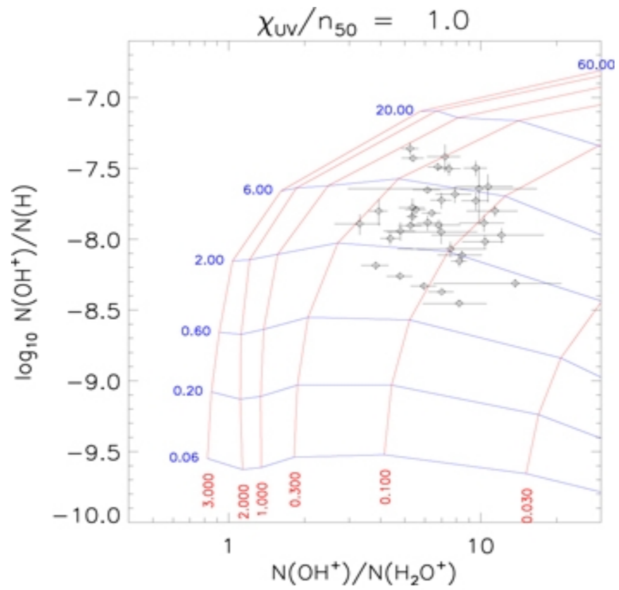
$H_2$ : $H_3^+$

H : $OH^+$, $H_2O^+$, $H_3O^+$

Ar : $ArH^+$



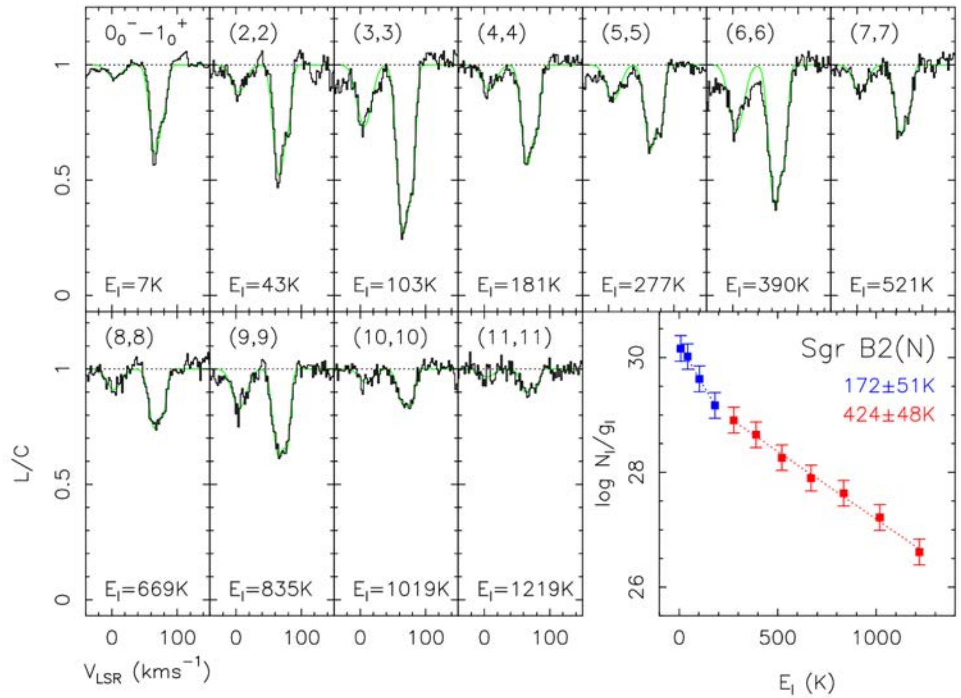

New probes of CRIR ; Higher value in diffuse gas than in dense & cold clouds

$\zeta(H) = (2.3+/-0.6) \times 10^{-16}\ s^{-1}$ ($H_2$) ; $\zeta(H)/n_{50} = (4.6+/-0.5) \times 10^{-16} s^{-1}$ (H clouds)

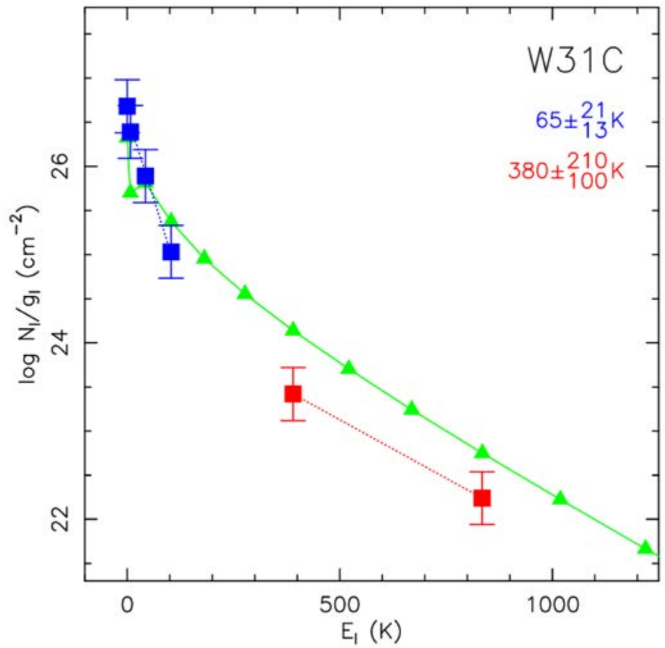
*Neufeld & Wolfire 2017, Le Petit+2016*

# The surprise of $H_3O^+$

*SgrB2(N)*




*W31C*

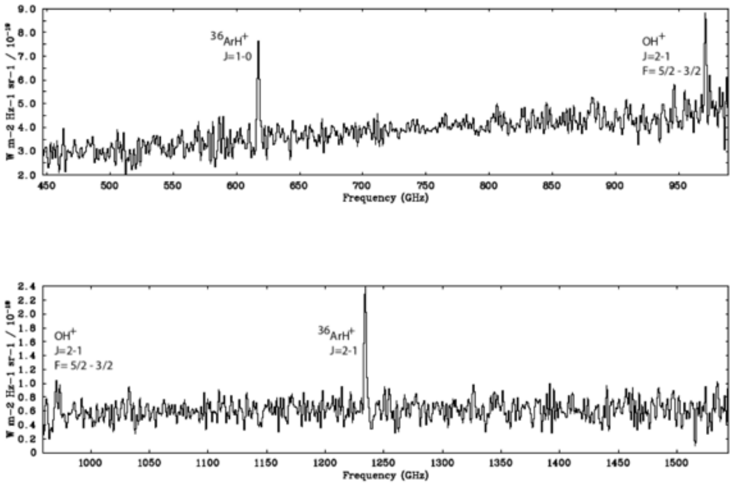


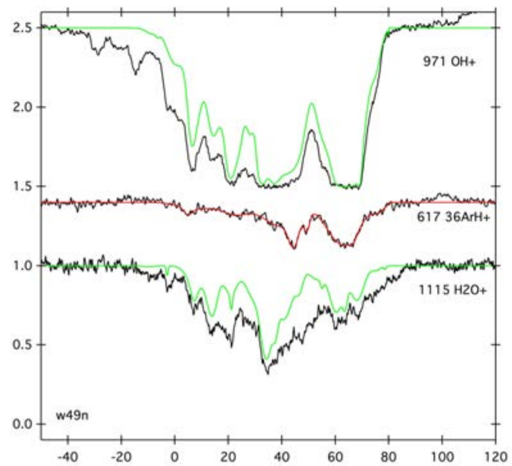

$H_3O^+$ absorption in metastable states : Hot $H_3O^+$ !

Different behavior from other ions & neutrals : Chemical pumping of the metastable stables at the molecule formation & slow relaxation

*Lis +2014*

# The surprise of $ArH^+$

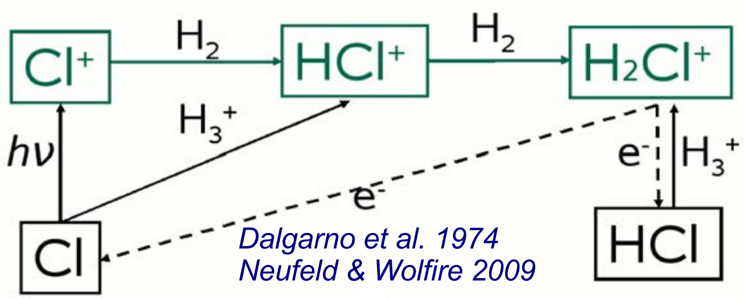


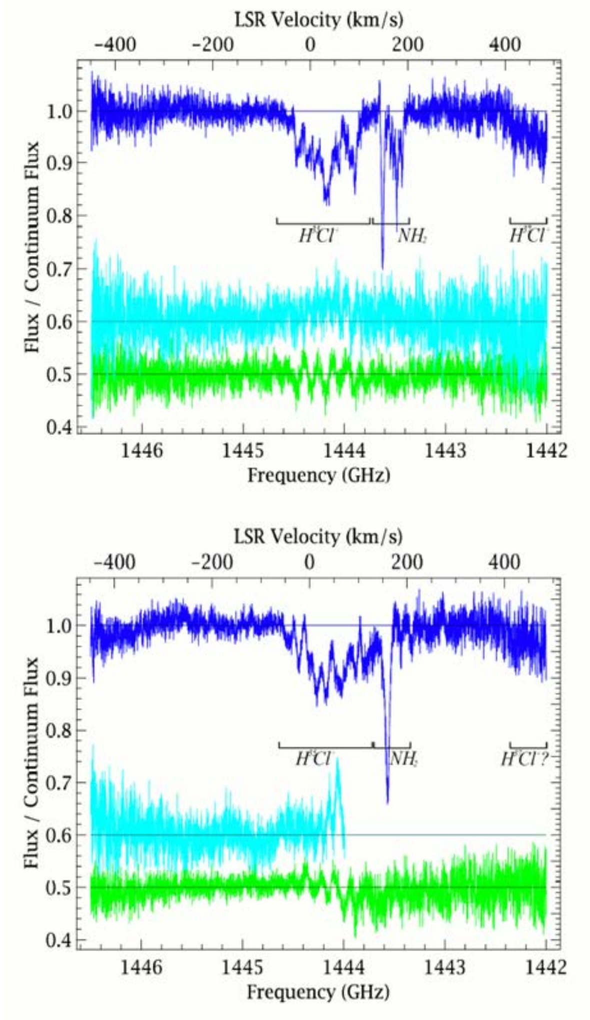




- U line in HIFI & PACS spectra → Identified as $ArH^+$
- Specific chemistry : $ArH^+$ abundance maximum when $f(H_2) \sim 10^{-4}$ to $10^{-3}$
- $ArH^+$ abundance relative to H ~ $10^{-10}$ to $10^{-9}$
- Now detected at high redshift

Barlow et al. 2013, Schilke et al. 2014

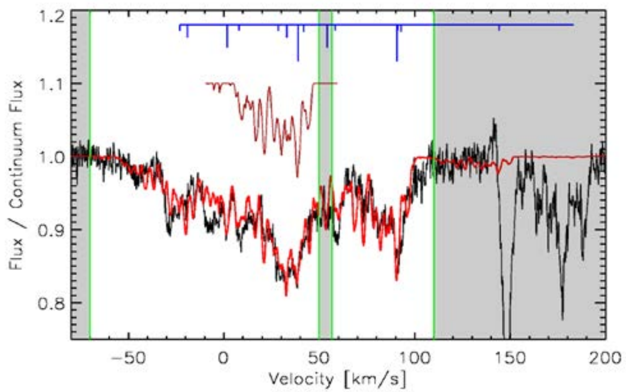
# Cl chemistry in the ISM : an illustration of the collaboration between spectroscopy, models & observations



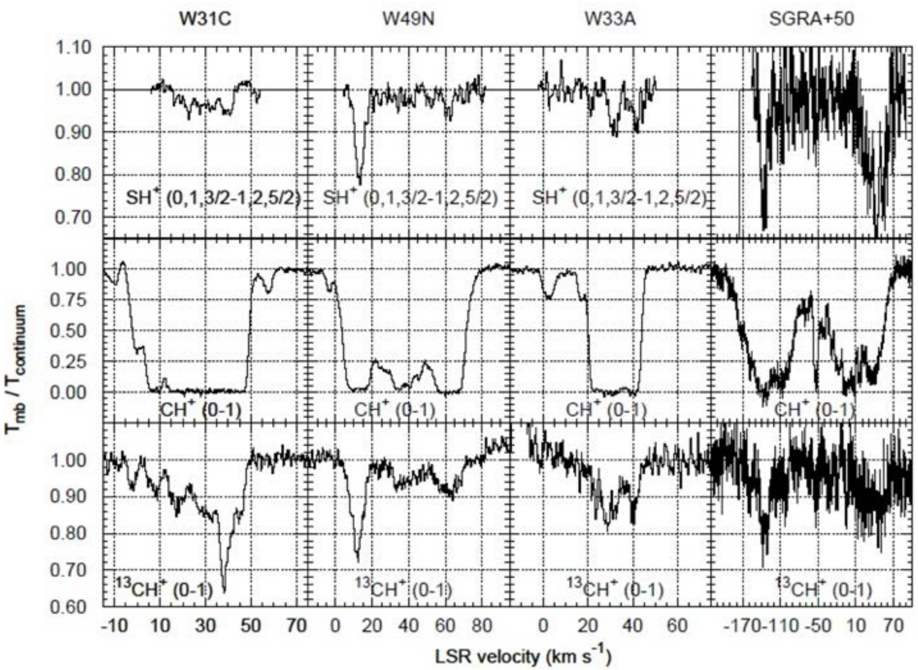

HCl in the ISM discovered in 1985 *(Blake et al 1985)*

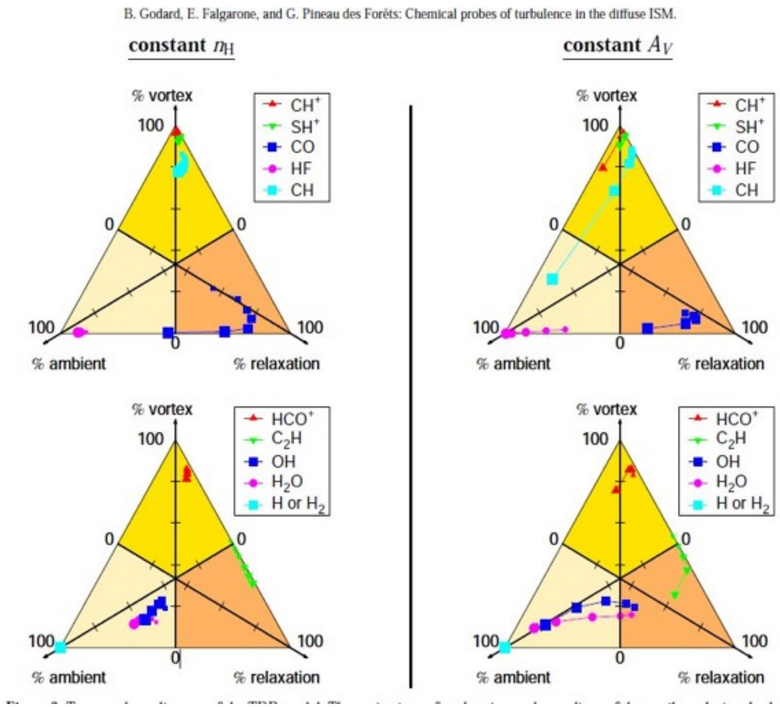
*Herschel/HIFI* discovery of $H_2Cl^+$ *(Lis et al. 2010)* and $HCl^+$ *(De Luca et al. 2012).*




*De Luca+2012*

# Two Reactive ions : $CH^+$ and $SH^+$



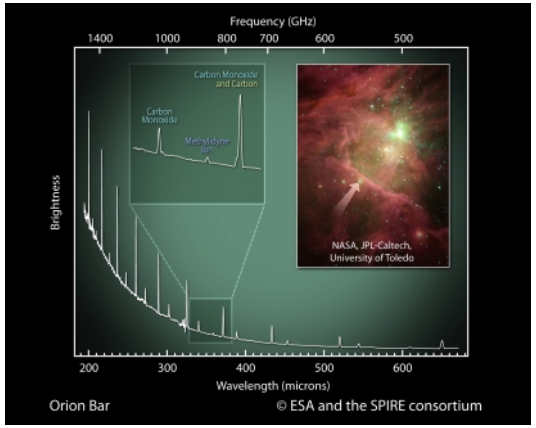



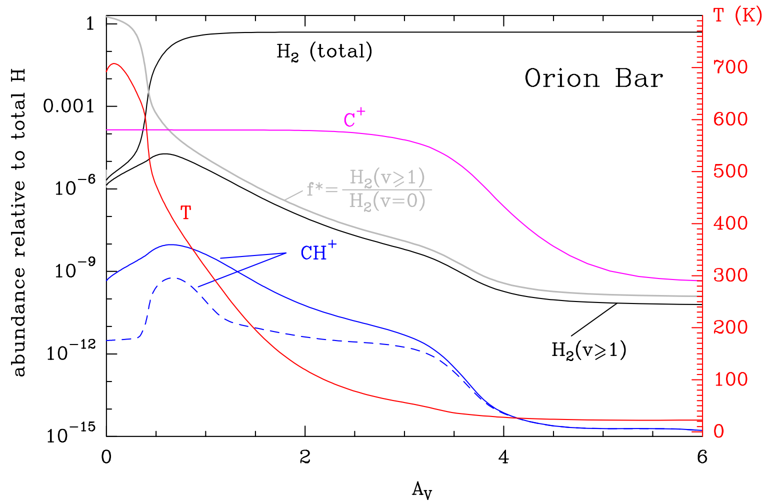

Endothermic formation pathway ($C^+ + H_2 \rightarrow CH^+ + H$ $\Delta E$ 4300K) : use the energy of ion-neutral velocity drift for enhancing the formation in diffuse gas

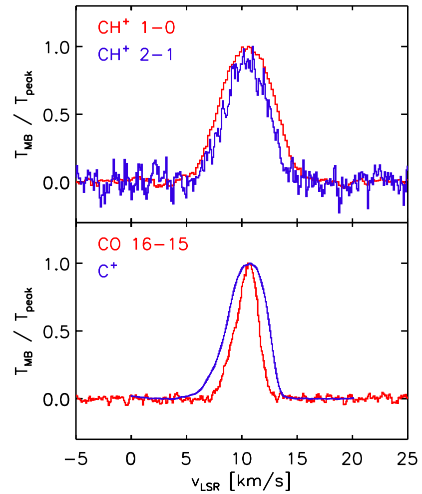
Diagnostic of turbulence properties

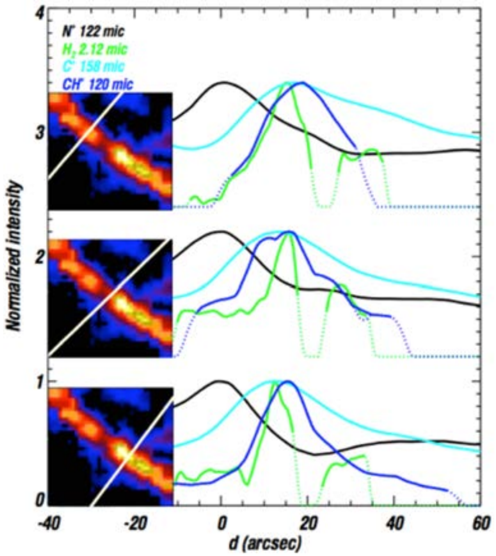
*Godard+2012,2014*

# The surprise of detecting extended $CH^+$ emission




$CH^+$ in PDRs : Efficient formation with vibrationally excited $H_2$

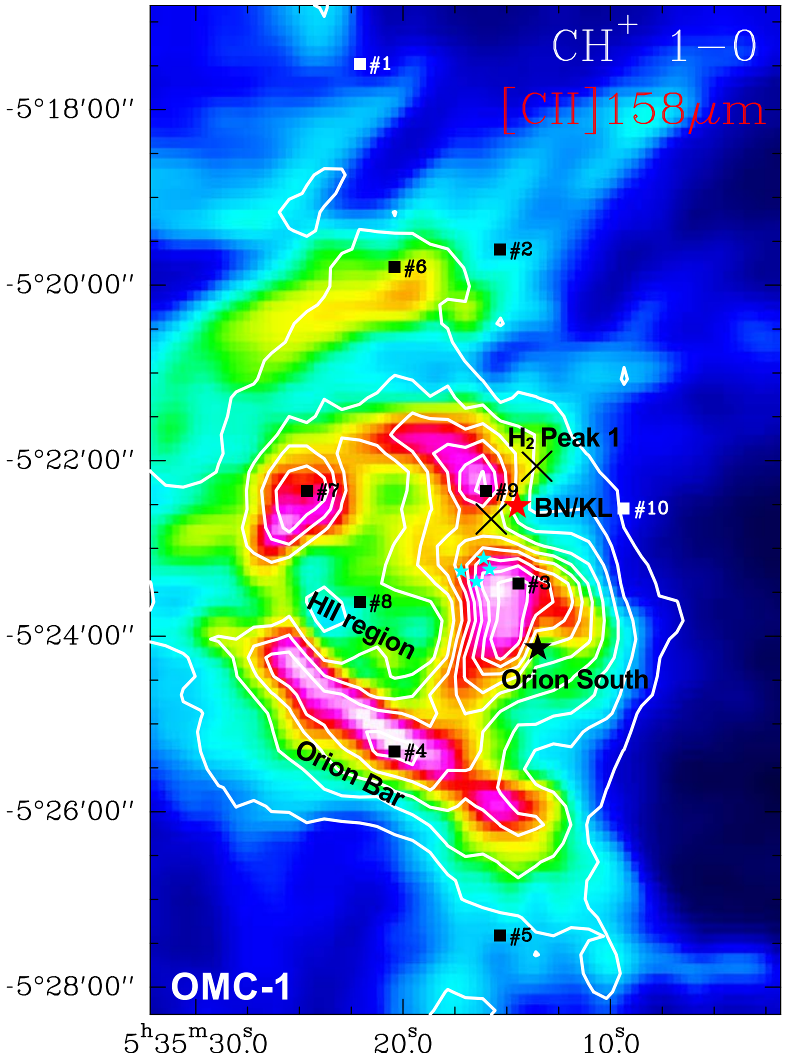
Other possibility : irradiated Shocks

*Agundez+2010, Parikka+2017*

# Tracers of UV irradiated molecular cloud surfaces

$CH^+$ and $C^+$
emission show similar
spatial
Distributions

The reaction with vib
excited $H_2$ is efficient at
large scales !



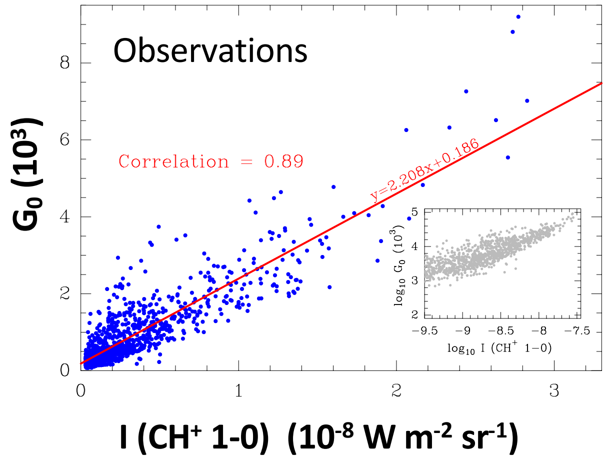

$CH^+$ 1-0 @ 835 GHz

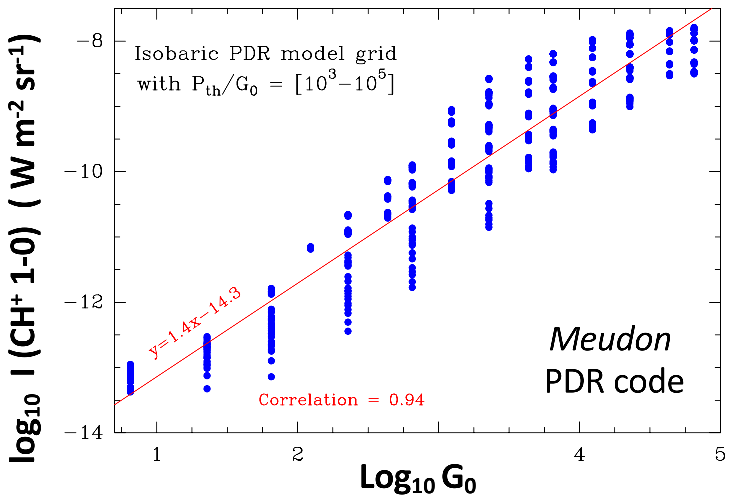
[CII] @ 1.9 THz

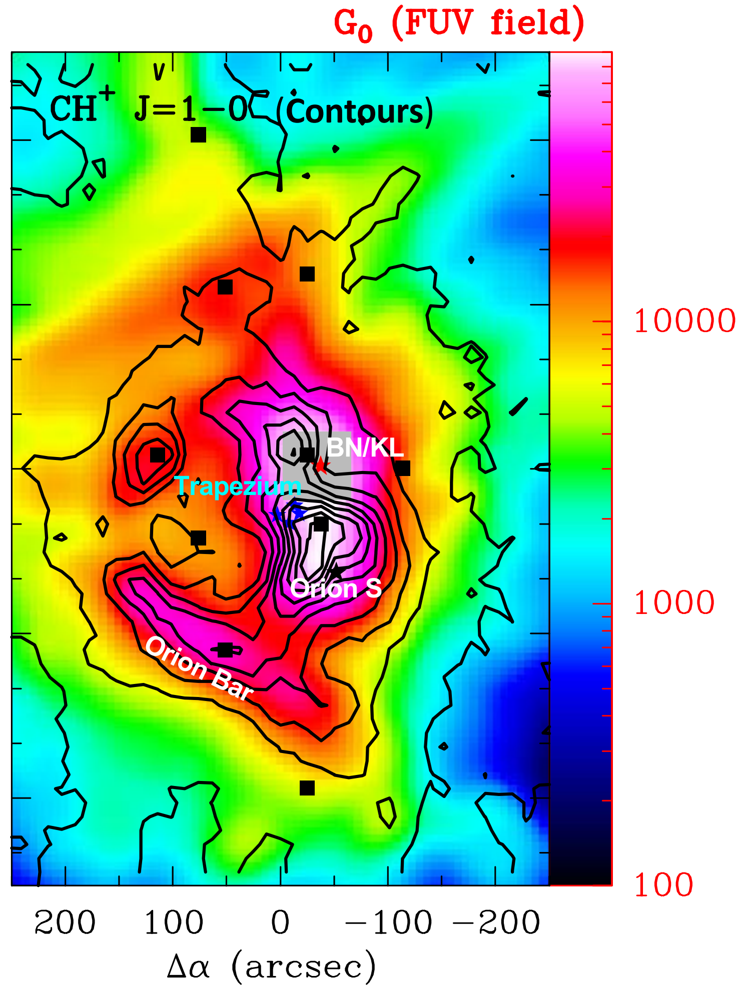
Herschel / HIFI

Morris+16
Goicoechea+15,19

# $CH^+$ $J$=1-0 emission scales with $G_0$ in OMC-1

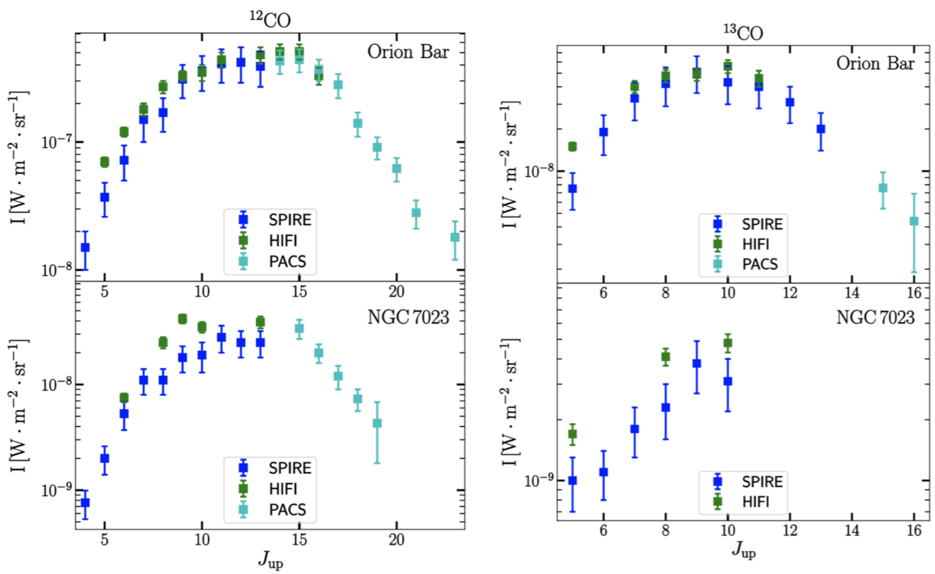


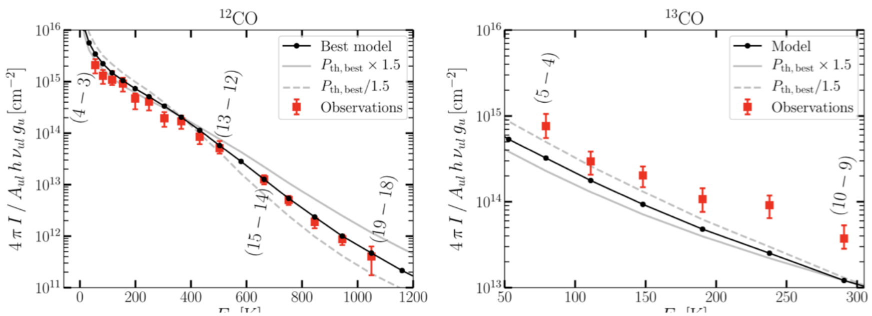



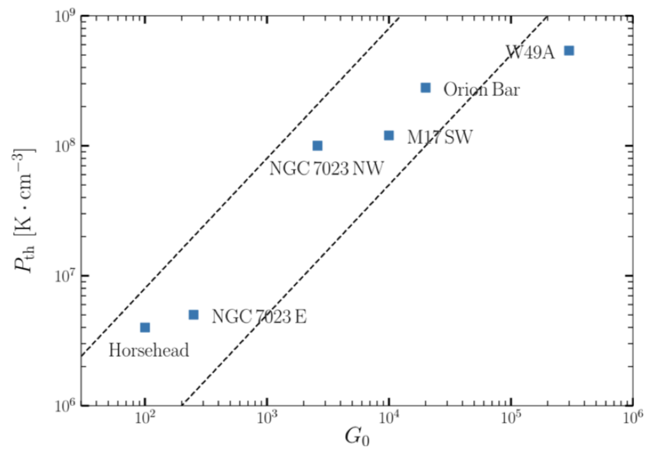




Goicoechea+15,19

# Detecting the full CO spectral line energy distribution




Orion Bar : Good fit with constant pressure PDR model, with detailed accounting of the heating processes

The maximum pressure scales with G0

*Joblin+2018*

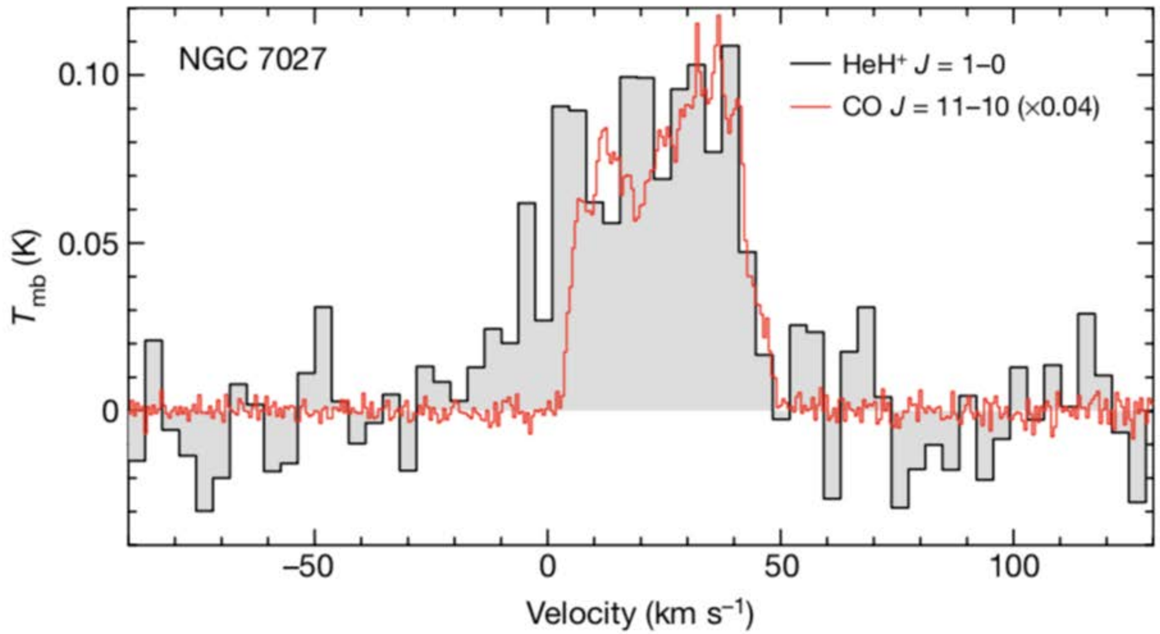
# A new hydride : $HeH^+$ in NGC 7027

- Evidence for efficient radiative association
- HeH+ is the starting point of chemistry in the Early universe (with a somewhat different chemical network)

$$He^+ + H \rightarrow HeH^+ + h\nu$$

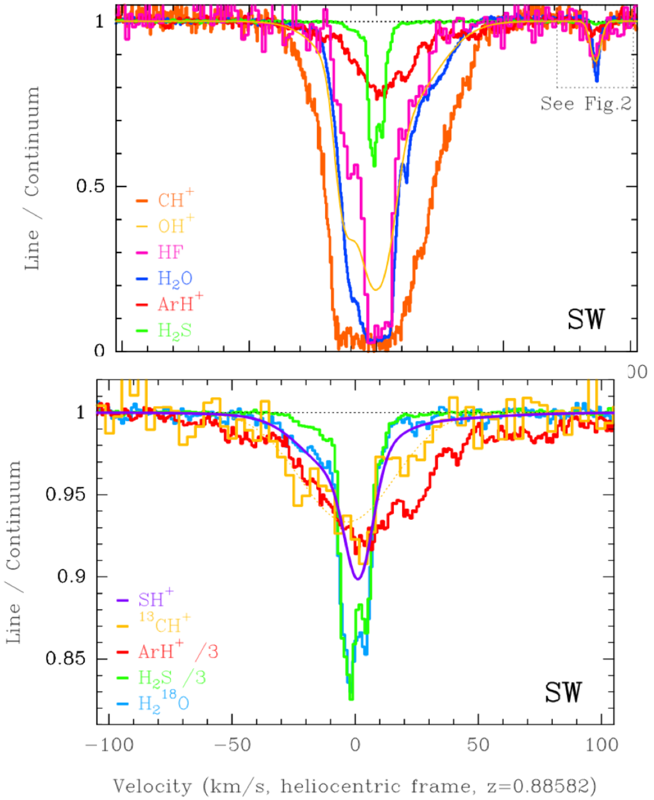
$$HeH^+ + e^- \rightarrow He + H$$

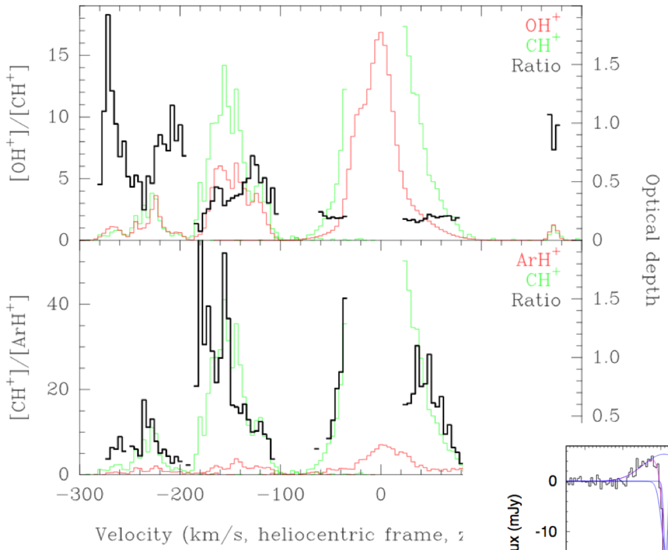
$$HeH^+ + H \rightarrow H_2^+ + He$$

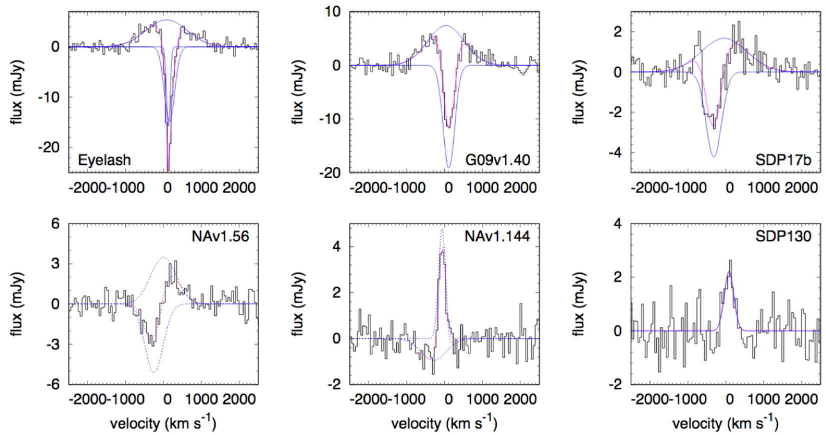



Güsten+ 19

# Hydrides at High redshift : use ALMA & NOEMA




Muller+2017, Falgarone+2017

# A lot of Challenges for Models :

- ISM Chemistry : CI ; $C^+$/C/CO transition ; $CH^+$ & $SH^+$
- PDR physics : explaining the CO SLED and the relationship between G0 and Pressure
- Understanding Feedback processes for galaxy evolution
- Understanding the intricacy of ISM phases : toward GUSTO
- Cosmic Rays origin and propagation

# General remarks

- Early preparation :
  - Laboratory work (spectroscopy, molecular processes, dust properties ..
  - Theory (collisional cross sections, reactivity ;  ..)
  - Source Models : PDR, MHD, radiative transfer
  - Use archives + ground based observations
- Many surprises :
  - do not trust models at 100%
  - Systematic approach in observations (limit in S/N ; broad spectral coverage) as in guaranteed time allows to open the discovery space
- Legacy for the future : unique wavelength coverage & range of spectral resolution

**ESA Voyage2050 FIR workshop : Paris June 14th**

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