Maryvonne Gerin

PRISMAS

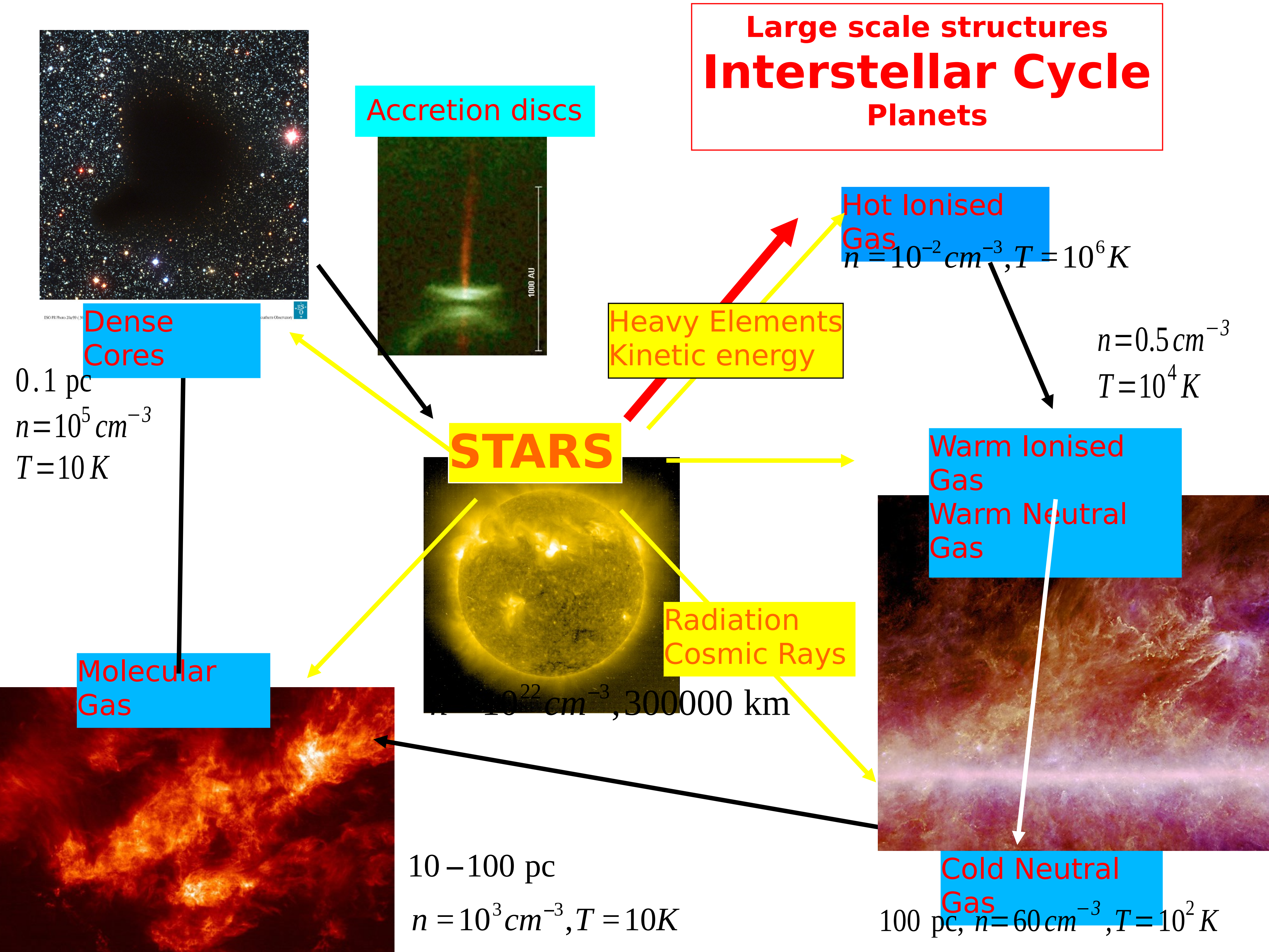
PRobing InterStellar Molecules with Absorption line Studies

Sounding the diffuse ISM with *Herschel*/HIFI

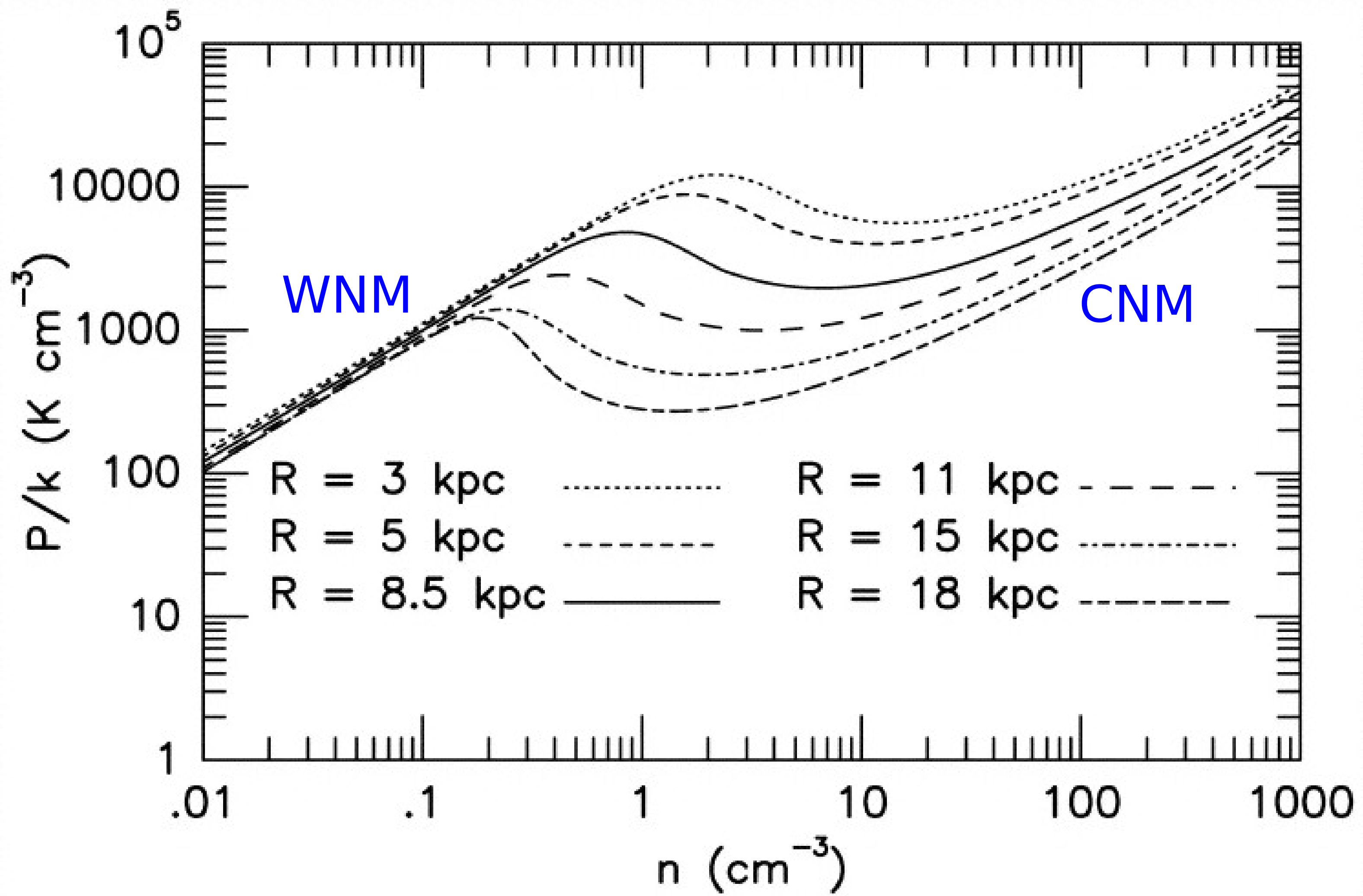
[CII] absorption and emission across the Galactic Plane

ANR SCHISM

- The diffuse ISM is present everywhere in the Galaxy
- It is an important segment of the ISM life cycle.
- It dominates the mass of neutral gas.


Large scale structures
Interstellar Cycle
Planets
Accretion discs
1000 AU
Hot Ionised Gas
$n=10^{-2}cm^{-3}, T=10^{6}K$
Dense Cores
0.1 pc
$n=10^{5}cm^{-3}$
$T=10\,K$
Heavy Elements
Kinetic energy
$n=0.5\,cm^{-3}$
$T=10^{4}K$
STARS
Warm Ionised Gas
Warm Neutral Gas
Radiation
Cosmic Rays
$n=10^{22}cm^{-3}$, 300000 km
Molecular Gas
10 – 100 pc
$n=10^{3}cm^{-3}, T=10K$
Cold Neutral Gas
100 pc, $n=60\,cm^{-3}, T=10^{2}K$

The 2-phase structure of the diffuse neutral gas

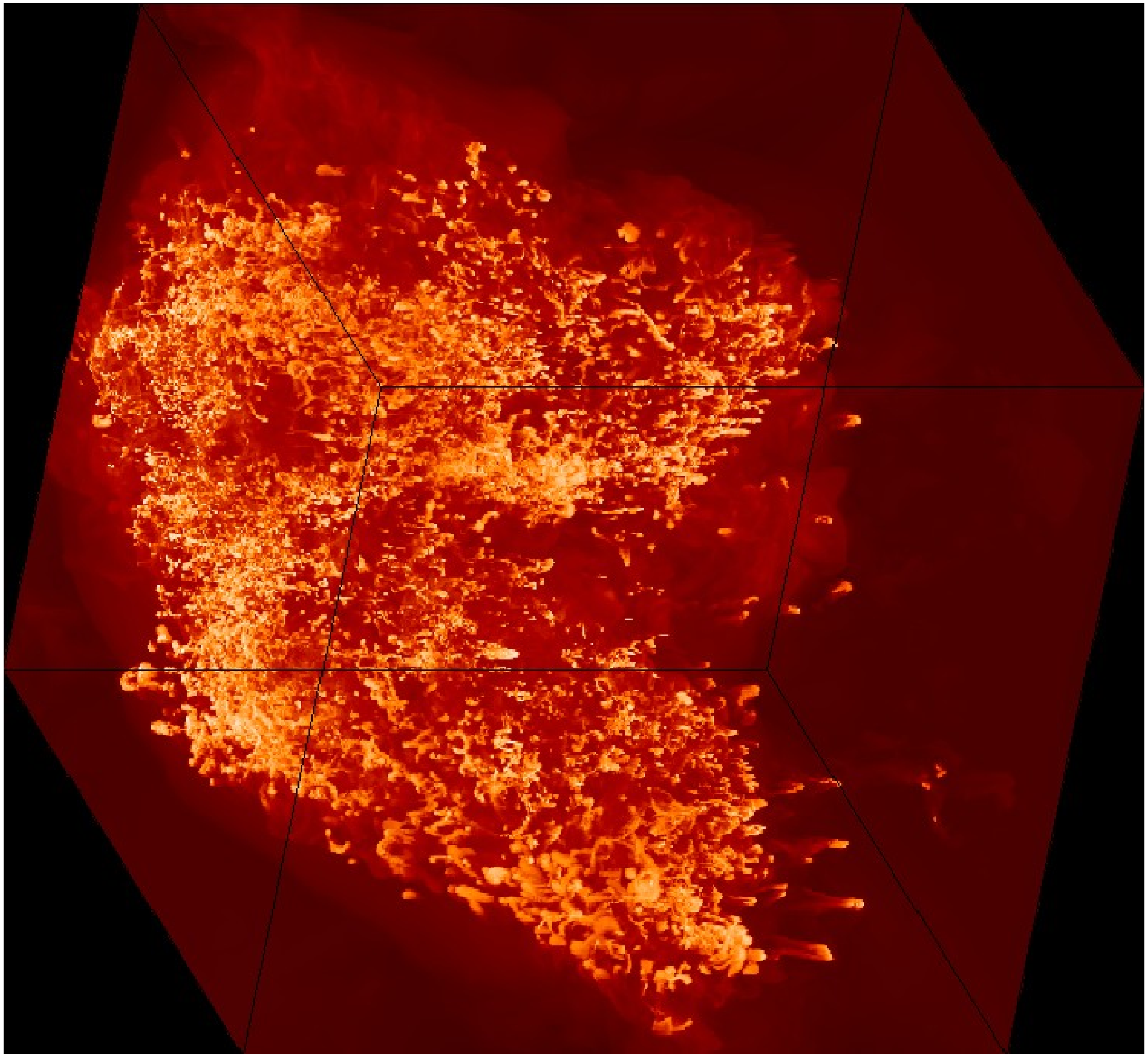


Wolfire et al. 2003

Open issues

- Properties of the ISM phases : densities, pressure and variations with environments
- Structure and geometry both at small scale and at large scale of the phases, filling factors
- Relative fractions of CNM & WNM, and of ionized gas

Models : a 3D view

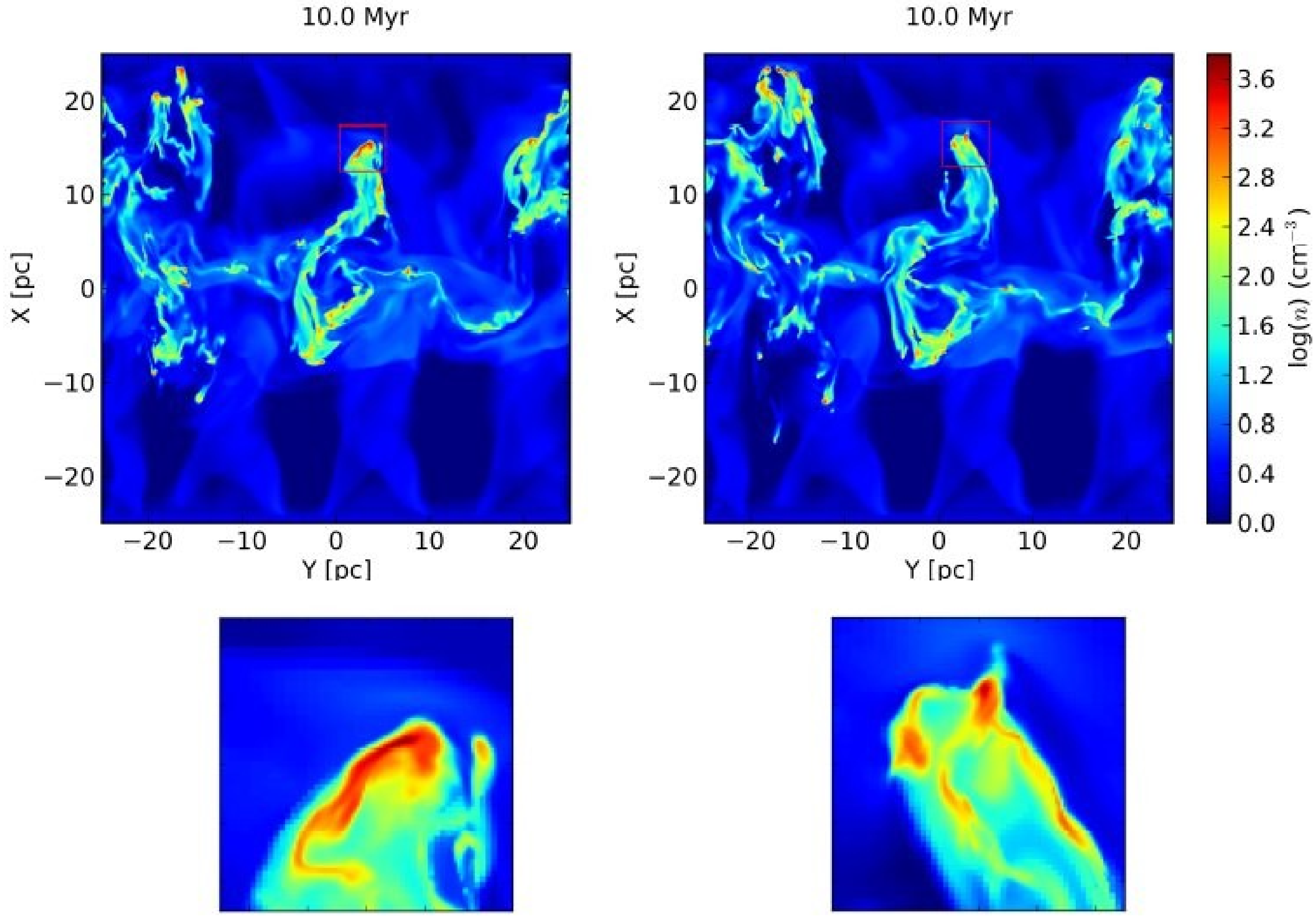


MHD simulation (RAMSES code)

Max density $n>1000\ cm^{-3}$
min density $n \sim$ few cm^{-3}

Audit & Henebelle'10

Impact of extinction calculation on the small scale structure



Including the extinction of the FUV radiation field leads to more structures at high density

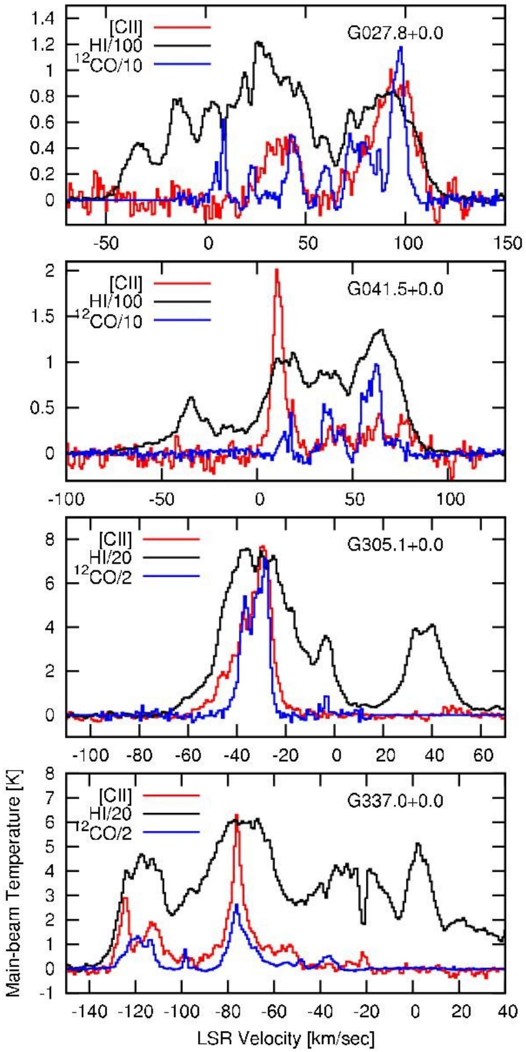
(*Valdivia & Hennebelle '14)*

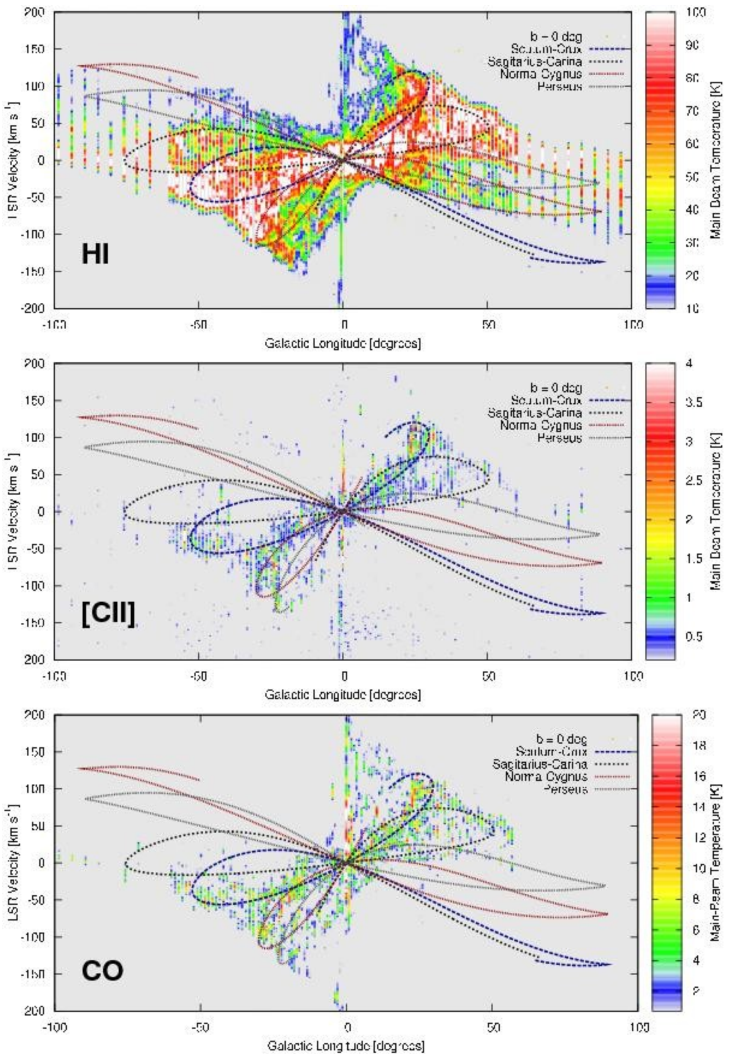
The GotC+ *Herschel* survey (Langer, Pineda, Goldsmith, Velusamy et al.)

C$^+$ 158μm fine structure line Galactic plane survey with *Herschel*

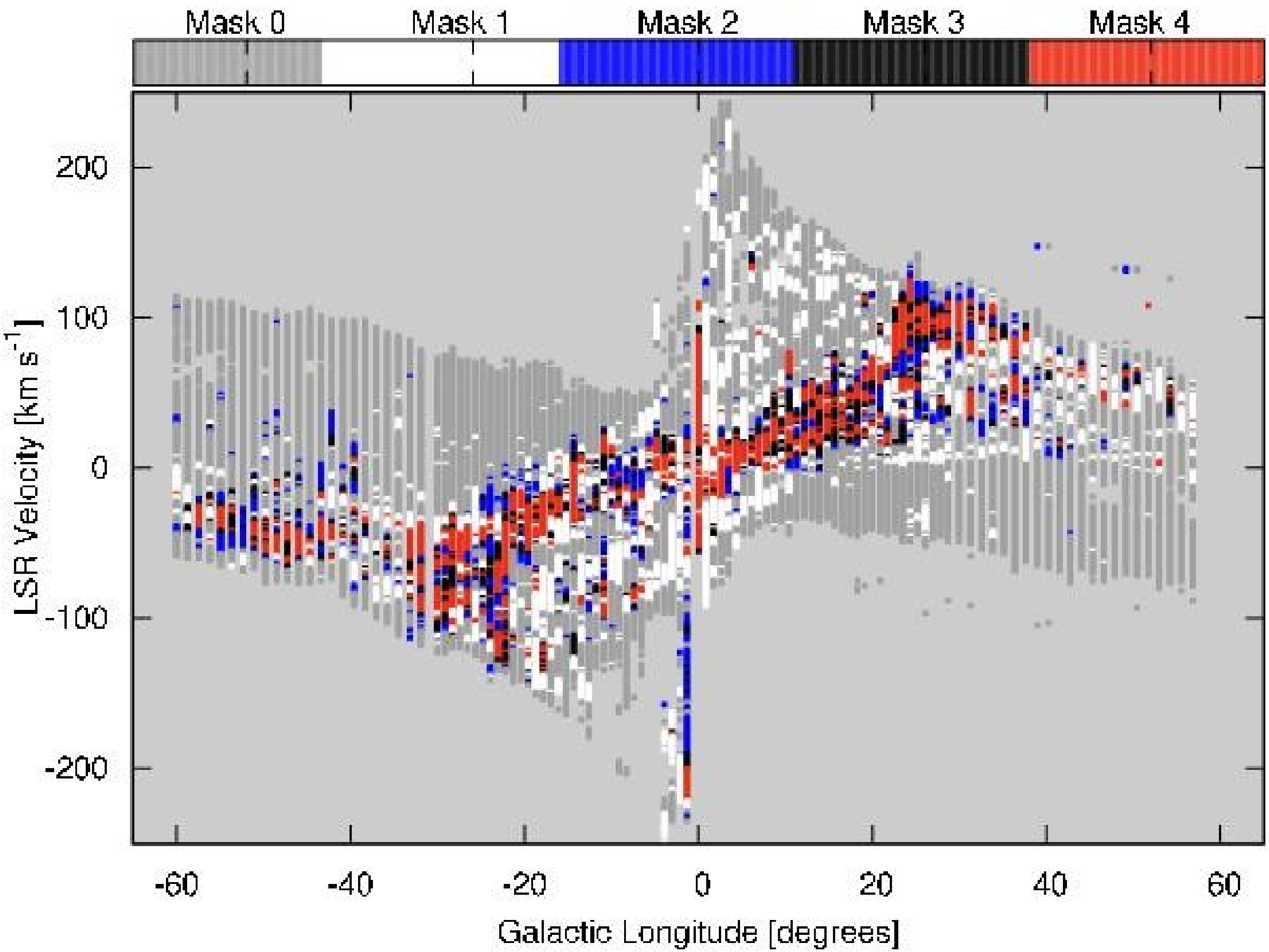
Complemented with ground based data for CO & HI

Separation of the [CII] emission from the different phases





Mask 0 : HI
Mask 1 : HI & CO
Mask 2 : HI & CII, no CO
Mask 3 : HI & CII & CO
Mask 4 : HI & CII & CO & 13CO

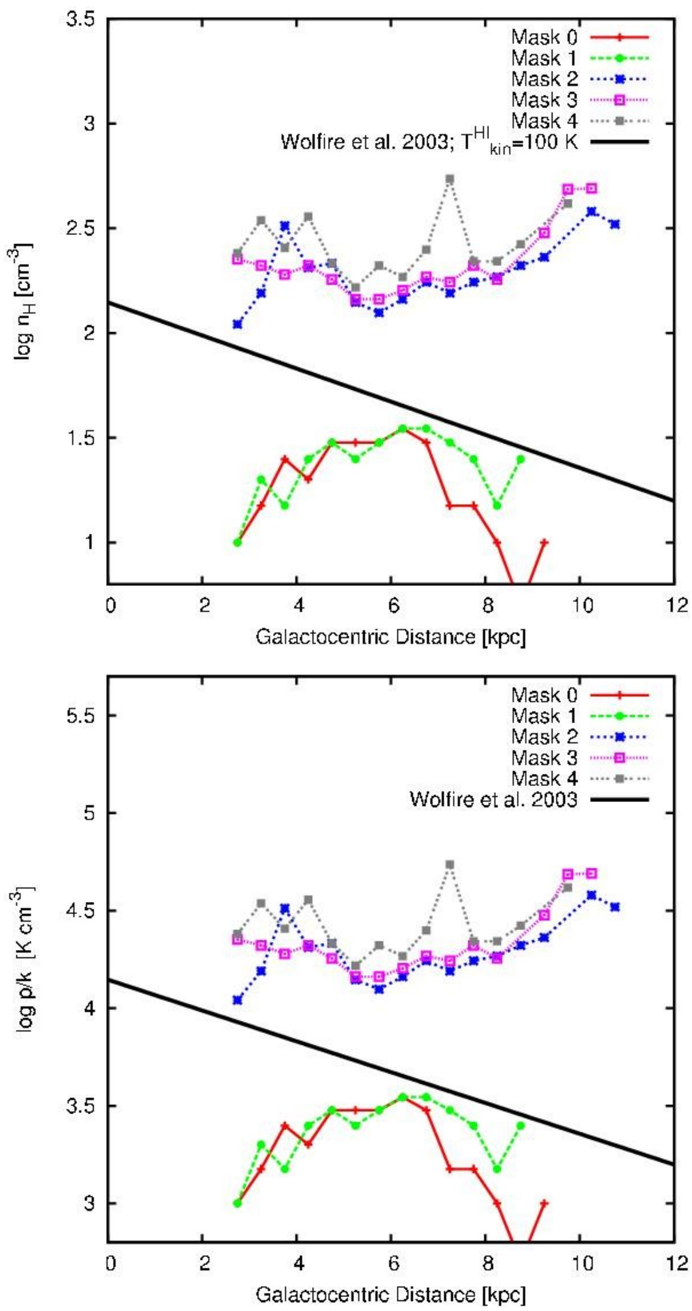


Position velocity maps of the different types of regions defined in Sect. 4.1 at b = 0°. Mask 0 (grey) represents velocity components with only H i detected, Mask 1 (white) are components with only H i and CO detected, Mask 2 (blue) components with only H i and [C ii], Mask 3 (black) components with H i, [C ii], and CO, and Mask 4 (red) components wit H i, [C ii], 12CO, and 13CO.

Physical conditions of the different components compared with models from Wolfire et al. (2003)

Limited sensitivity for the diffuse gas with low excitation conditions

Mask 0 : HI
Mask 1 : HI & CO
Mask 2 : HI & CII, no CO
Mask 3 : HI & CII & CO
Mask 4 : HI & CII & CO & 13CO



Why absorption spectroscopy

- The only way to sound gas of low excitation
- Sensitivity limited by accuracy on the continuum, access to low column density features
- Accurate measurement of line profiles and opacities -> better measurement of column densities
- Easy comparison of different species

BUT

- Little information on spatial structure except for extended continuum emission
- Comparison of lines at very different frequencies (eg mm and FIR) not obvious because of different continuum emission processes (HII region vs dust) therefore different background source structure

PRISMAS

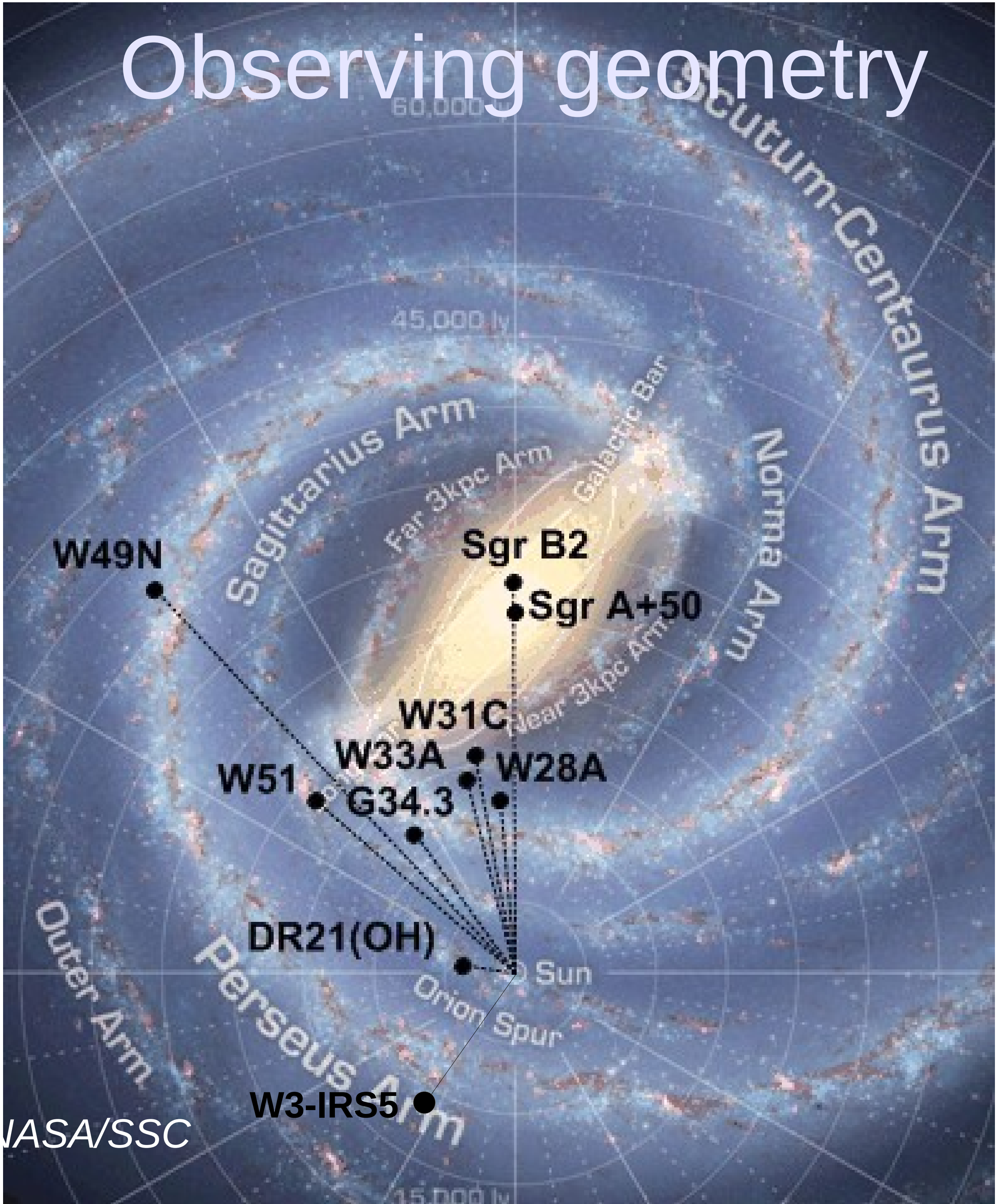
PRobing InterStellar Molecules with Absorption line Studies

- Excellent sensitivity down to the same range of column density as visible spectroscopy for molecules in common (e.g. CH and CH^+) => probe diffuse and translucent gas with Av few mag in the FIR spectral range.
- 8 background sources

Targeted species for absorption

- C — CH, ^{13}CH, CH^+, $^{13}CH^+$, CH_2 , C_3 C, C^+
- N — NH, NH_2, NH_3 (o & p), $^{15}NH_3$, ND, NH_2D, NH^+ , N^+
- O — OH^+,H_2O^+ (o & p),H_3O^+, H_2O (o & p), $H_2{}^{18}O$, HDO, D_2O
- F — HF, DF
- Cl — HCl, HCl^+ , H_2Cl^+
- S — SH^+
- Ar — ArH^+

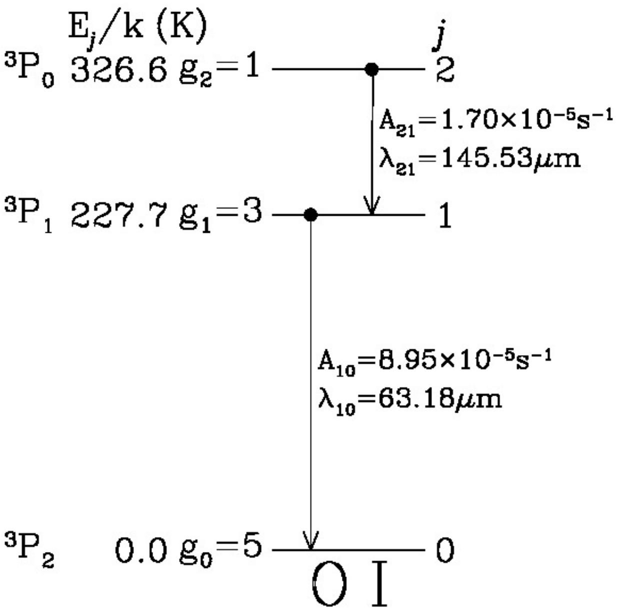
Observing geometry



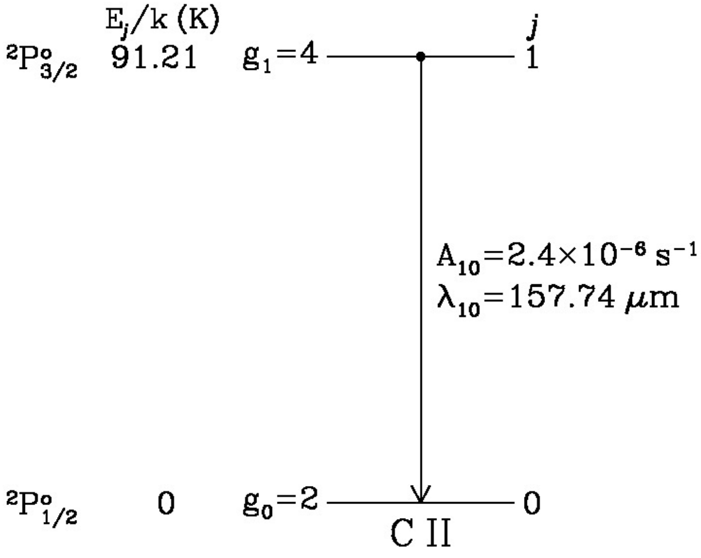
Massive star forming regions as background sources

Fine structure lines
[CII], [OI], [CI], [NII]

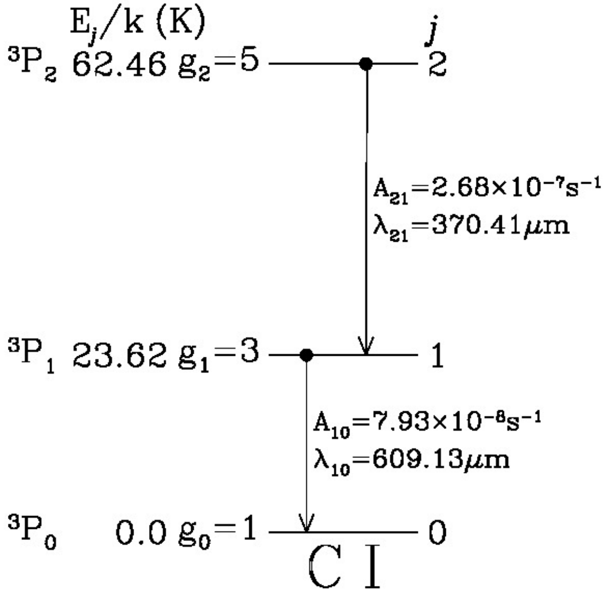
[OI]



[CII]



[CI]

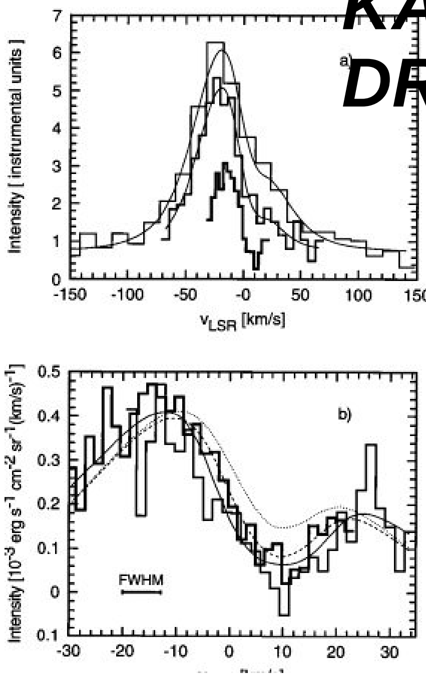


Fine structure lines : previous observations

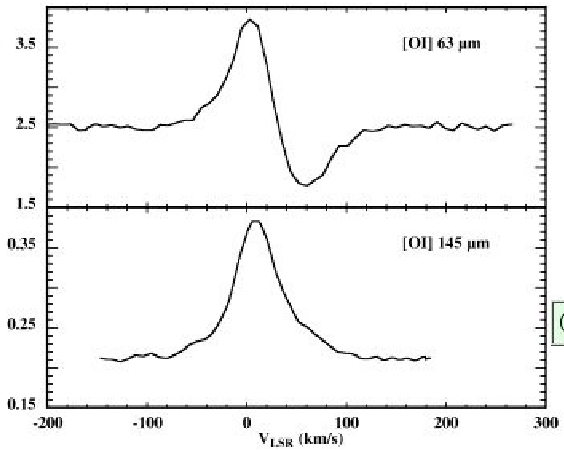
- [OI] in DR21 *(Poglitsch et al. 1997)*
- SgrB2, W49 with ISO high spectral resolution (FP) *(Vastel et al. 2000, Lis et al. 2001)* :

Detection of absorption in [CII] and [OI] 63µm
Limited velocity resolution → Difficulty in accounting for the absorption by HI/CNM + H_2/CO.
Contribution from warm phases ?

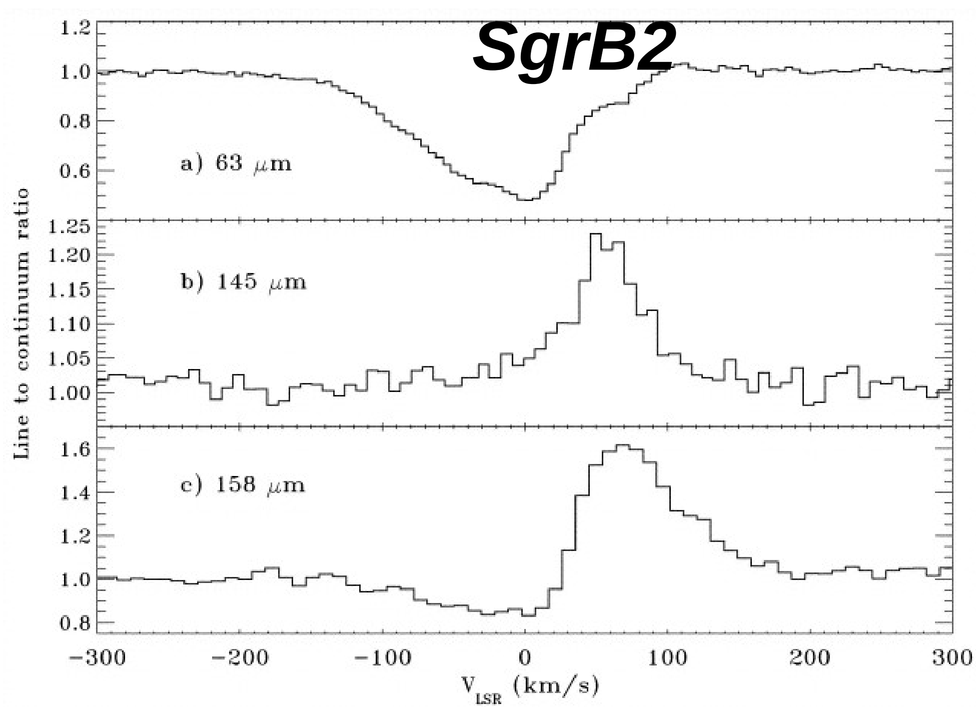
KAO DR21)



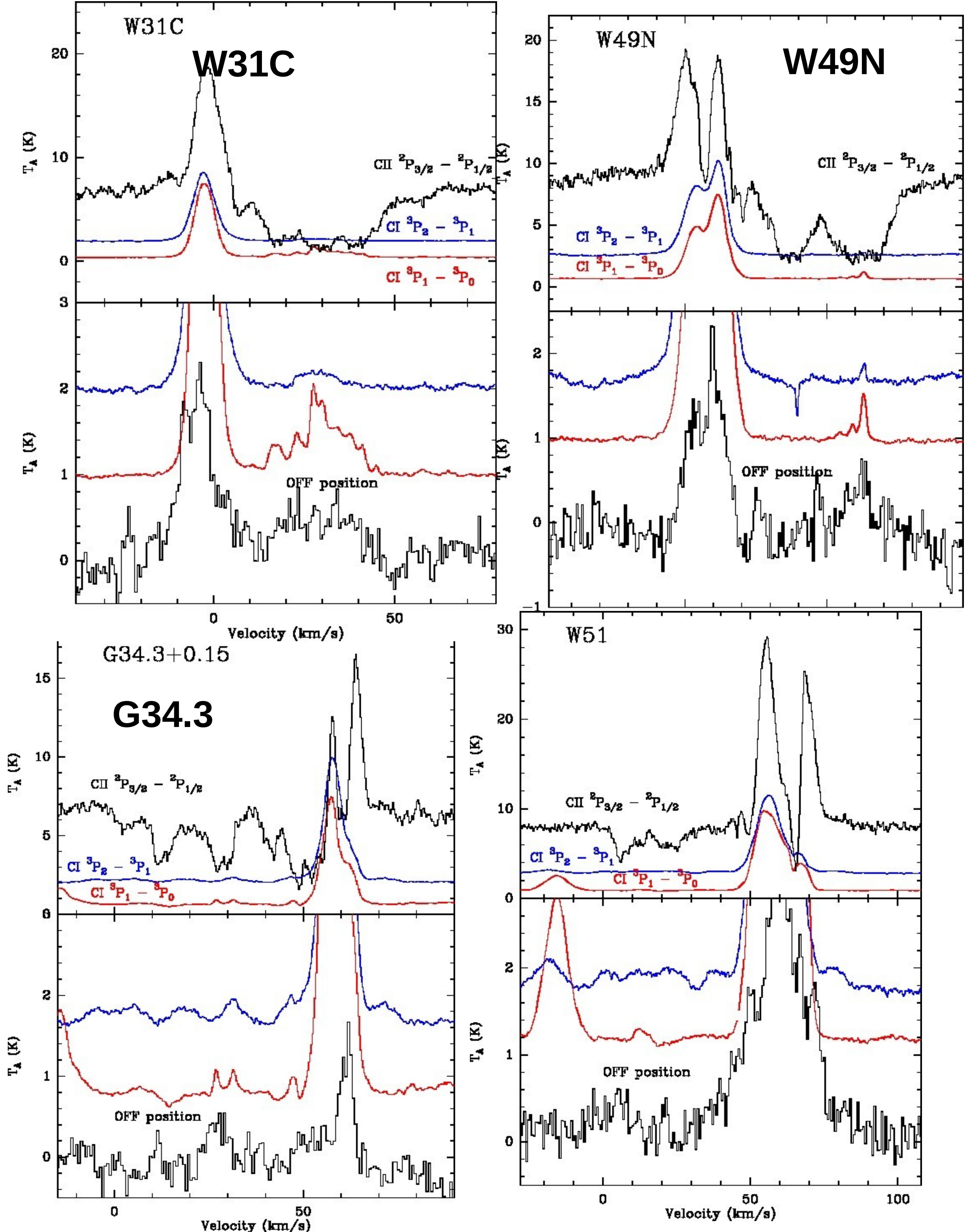
ISO W49N



ISO SgrB2



HIFI [CII] & [CI] spectra

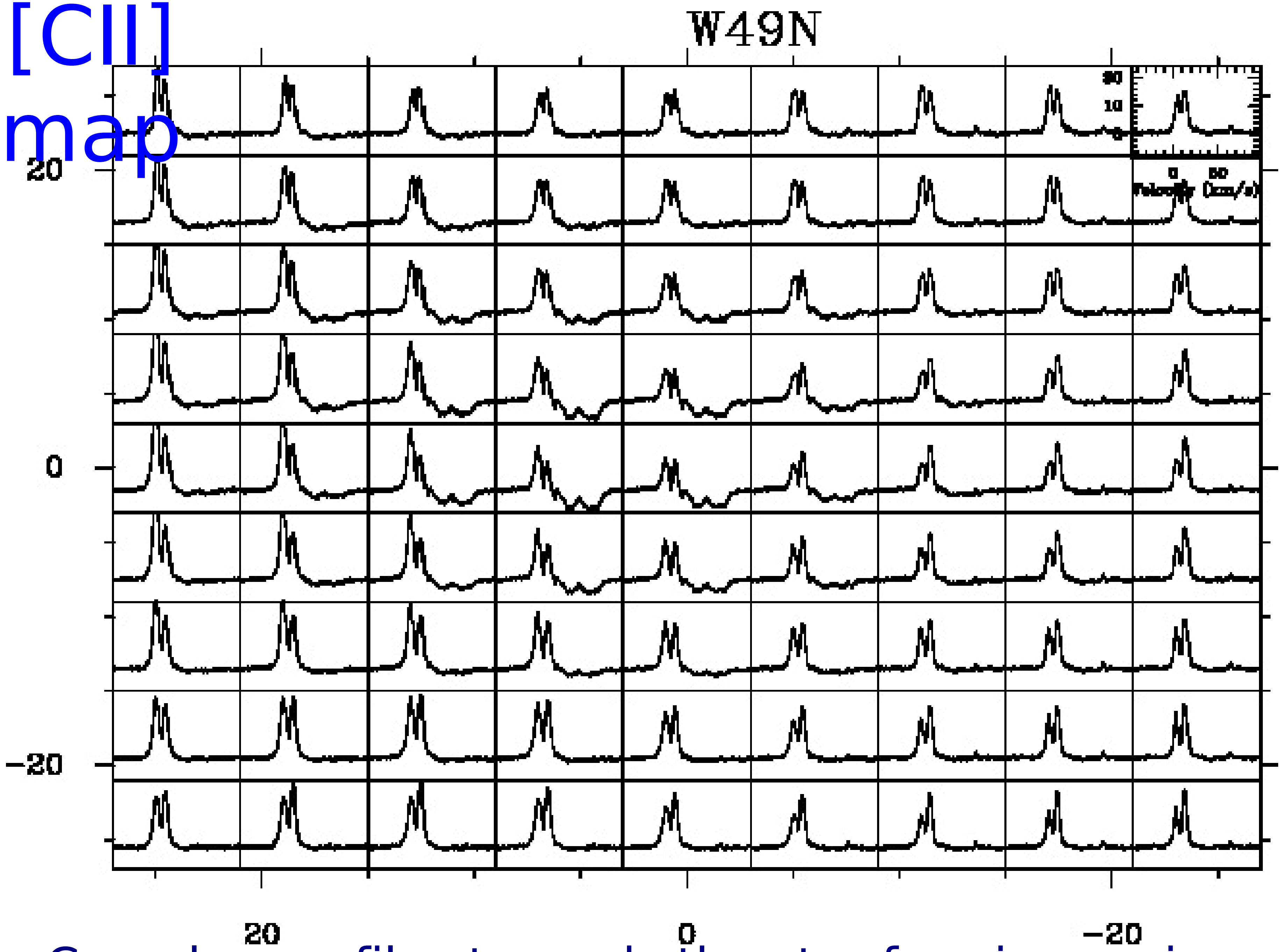


- Deep [CII] absorption & complex profile of the background source.
- Load chop with distant references combined with DBS data
- Weak emission at the OFF position T~ 0.5K

- Weak CI emission from foreground with [CI] 1-0/ [CI] 2-1 ~ 2 - 6

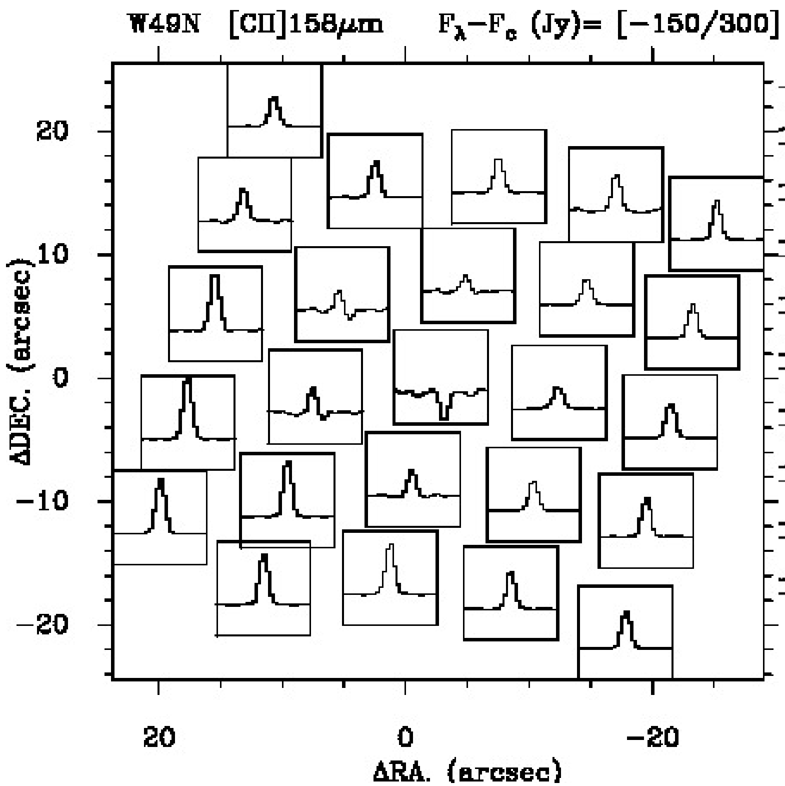
Gerin et al, 2014

[CII] map

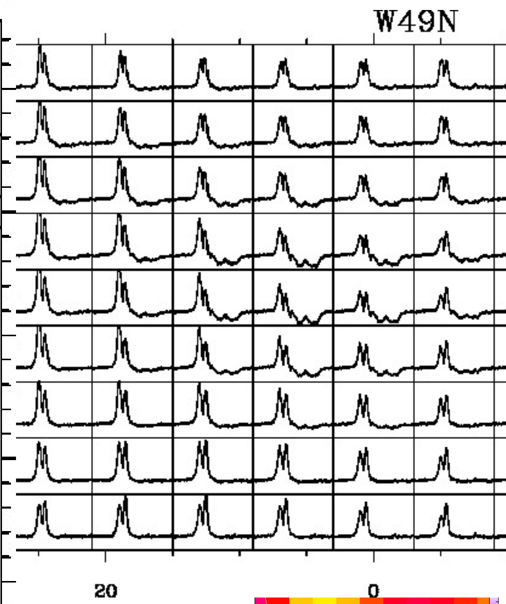


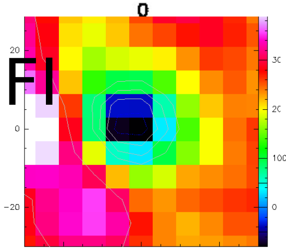
Complex profiles towards the star forming regions (outflows, self-absorption)

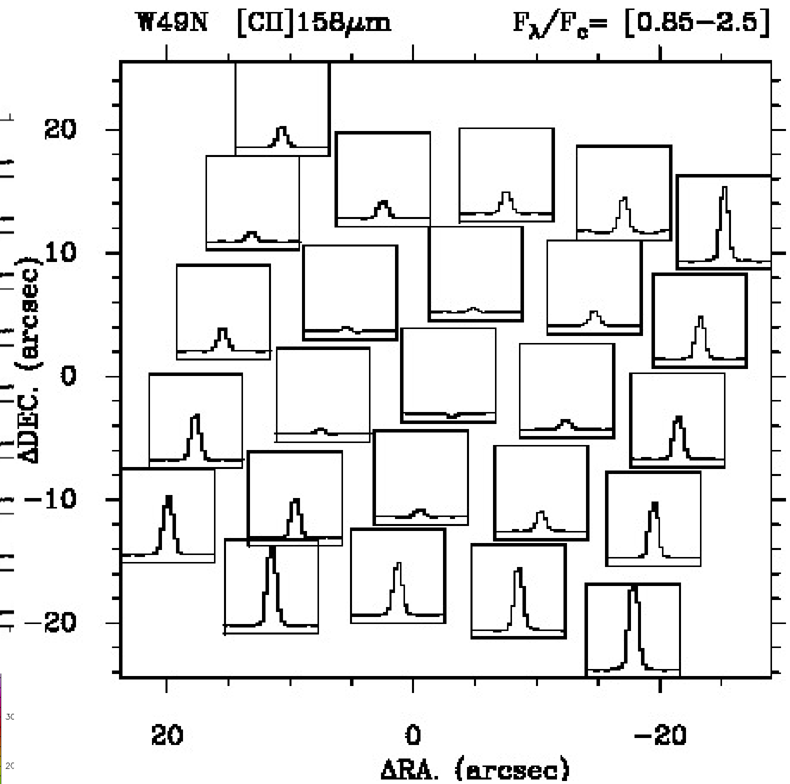
[CII] (1.9 THz – HIFI/PACS)



Line Flux




HIFI

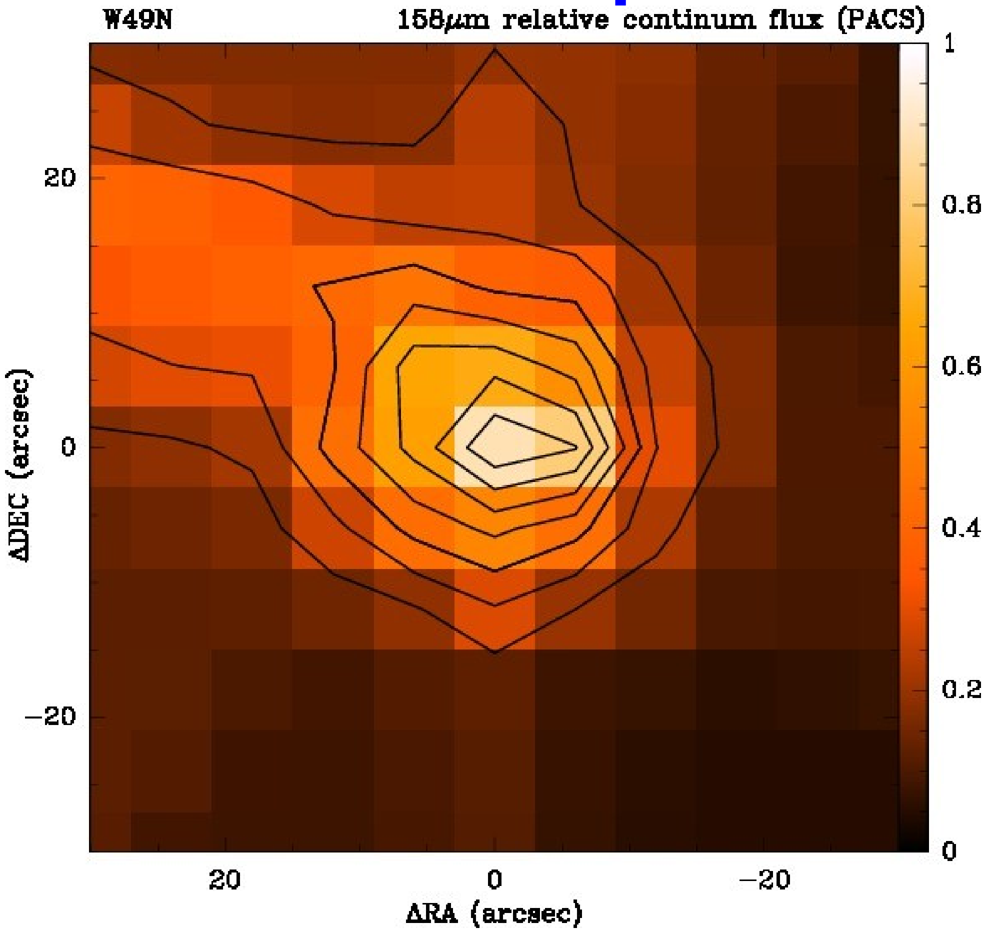


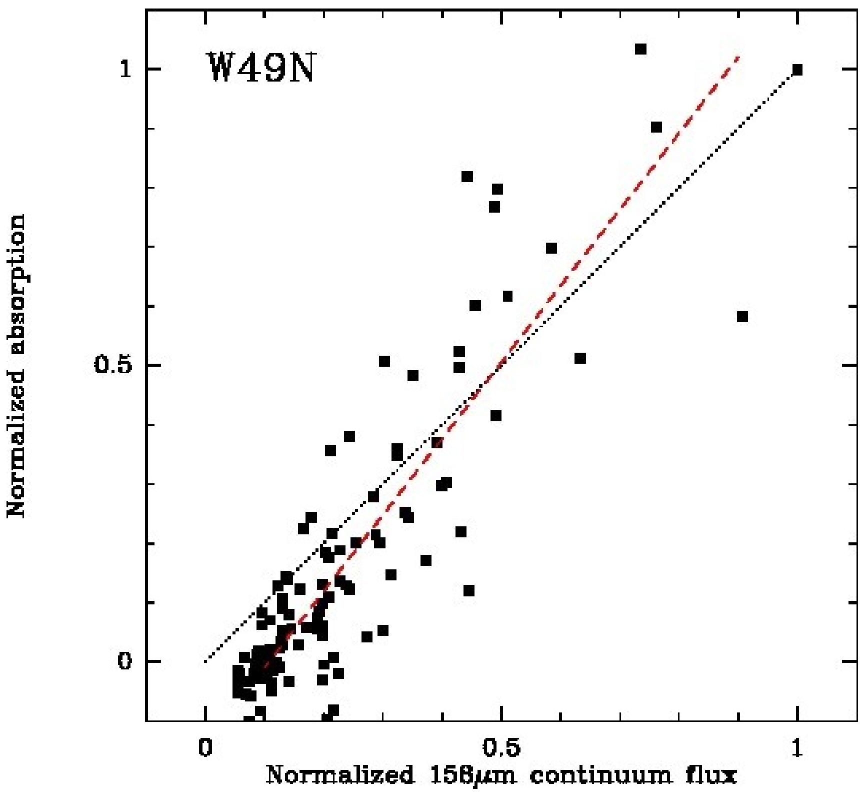
Line/continuum ratio

HIFI : Load chop observations with “ref” position 1.5° OFF the Galactic plane
PACS : Chopped with 6' OFF. Correction for OFF contamination
Strong absorption from foreground gas

PACS with low spectral resolution : absorption or low Line/continuum for bright continuum sources → [CII] deficit ?

[CII] absorption – structure





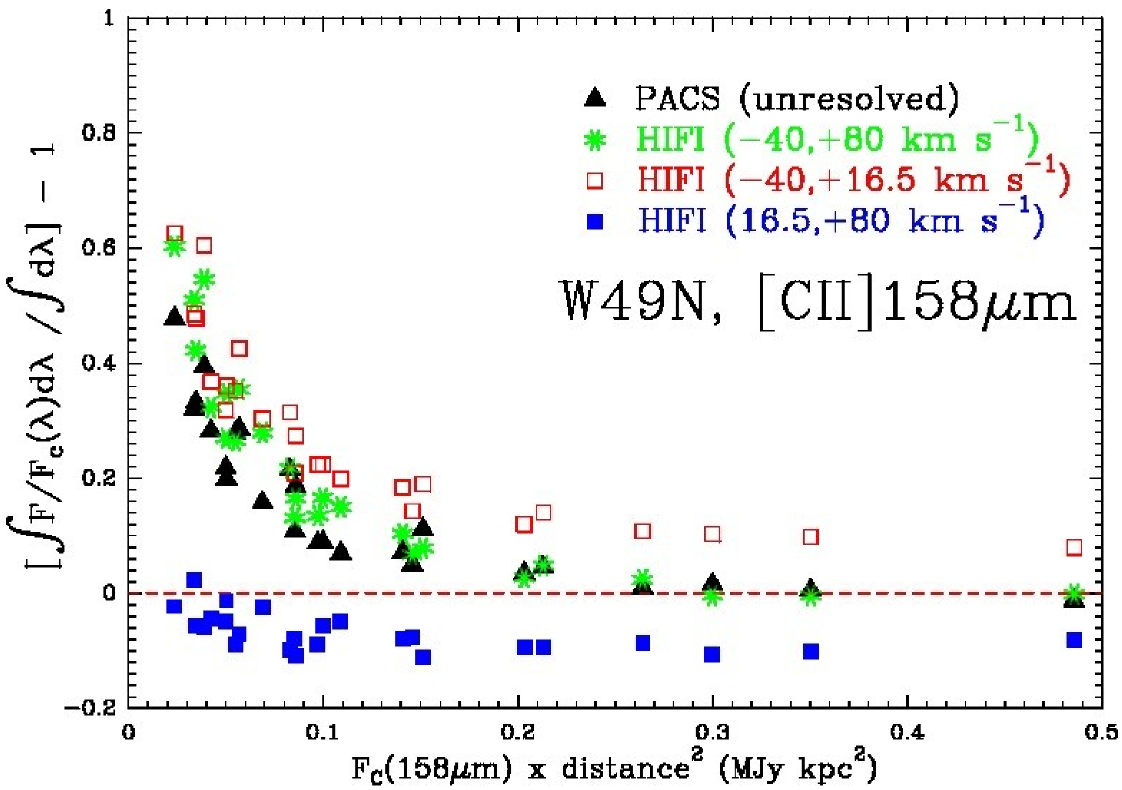
Comparison with PACS continuum “map” :
Extended absorption from the foreground gas.
The depth of the absorption scales with the continuum
Behaves as a ~ constant opacity foreground.
Nearly uniform foreground

The impact of spectral resolution & the "CII deficit"

Good agreement between PACS & HIFI

Low spectral resolution : line of sight absorption leads to canceling of the source emission.

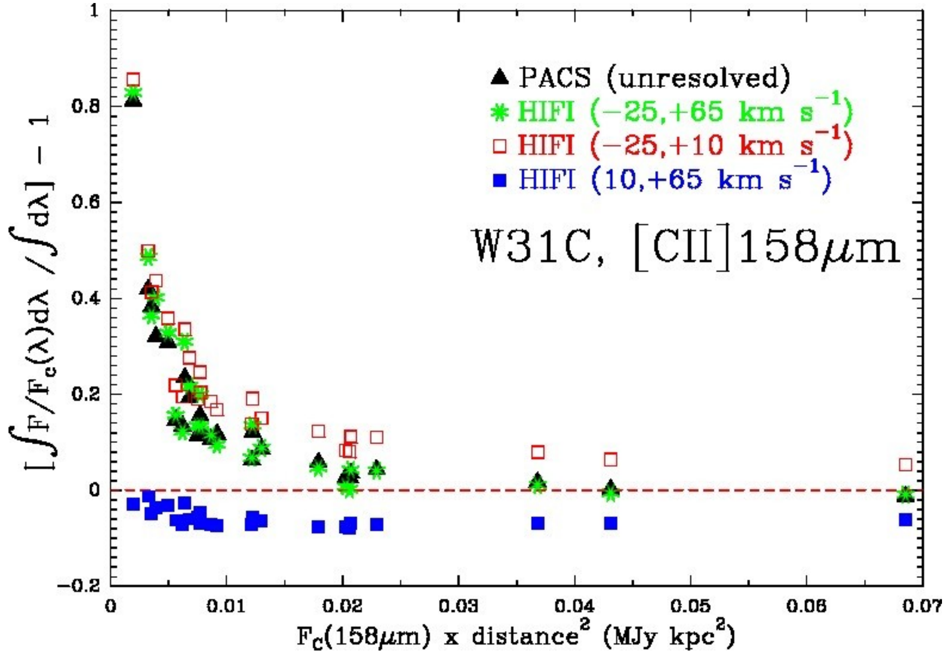
Decrease of [CII]/FIR towards the FIR peak : from **2×10^{-3} to ~ 3×10^{-4}** similar to ultra luminous IR galaxies

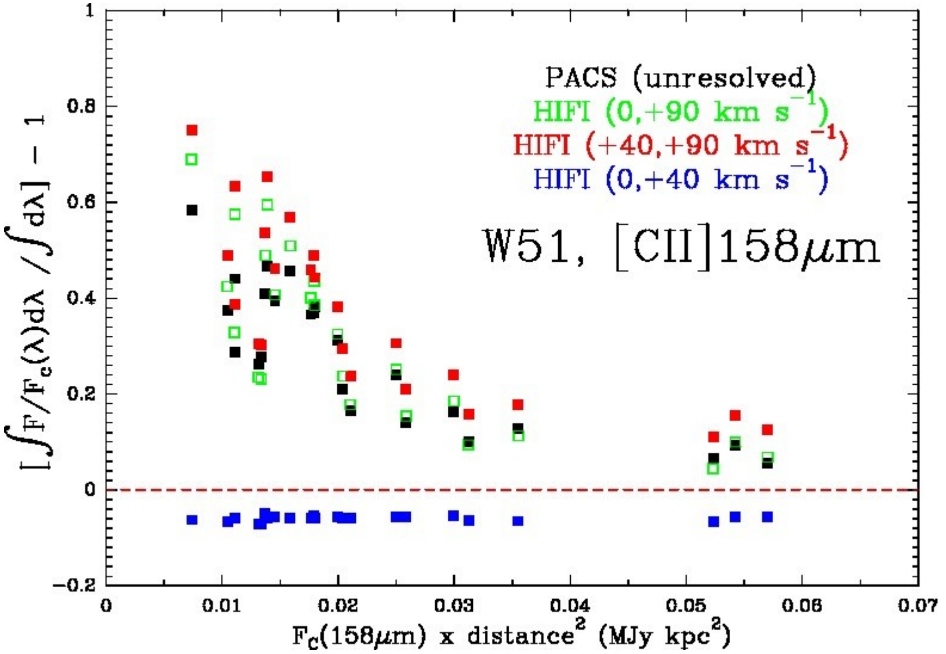


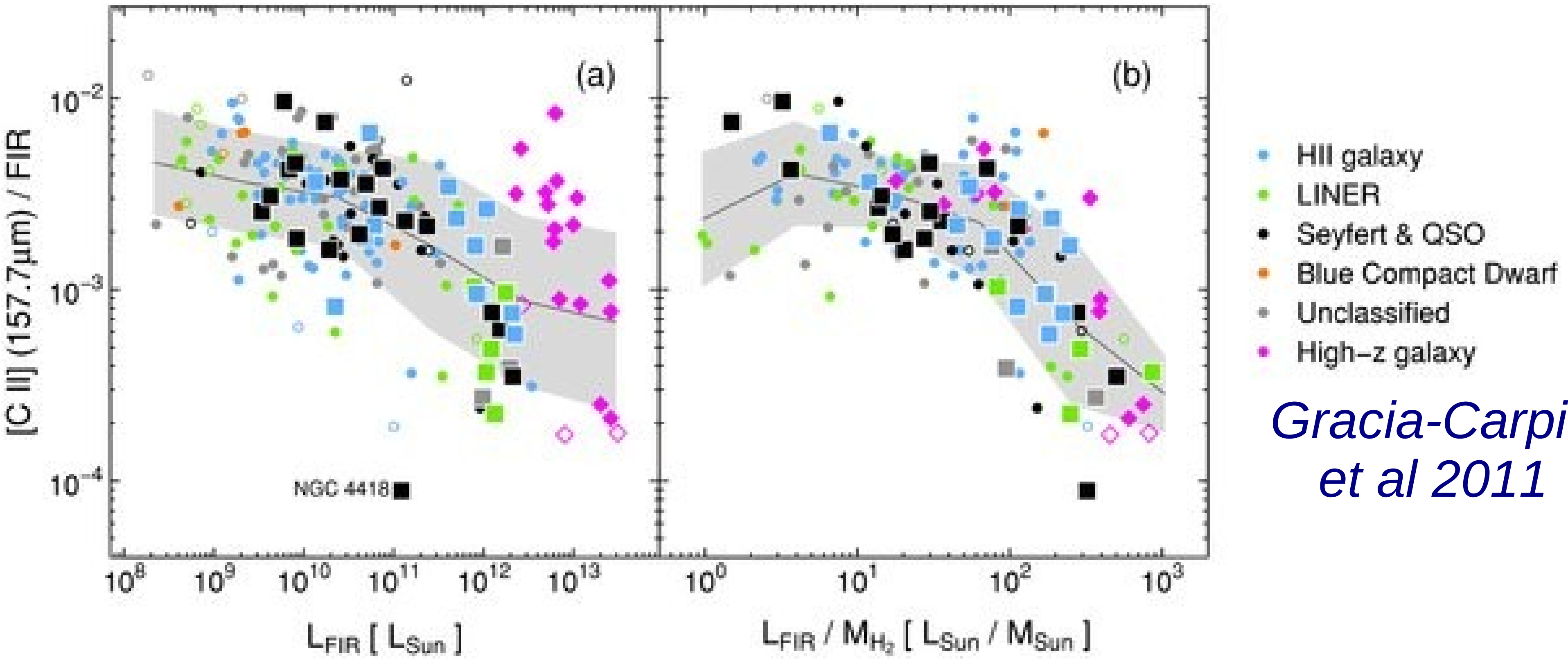
$$I_{rel}(CII) = \frac{\int \frac{F(\lambda)}{F_c(\lambda)} d\lambda}{\int d\lambda} - 1 .$$

$$\frac{L([CII])}{L_{FIR}} \sim 3.1 \pm 0.35 \times 10^{-3} I_{rel}(CII) .$$

Other sources





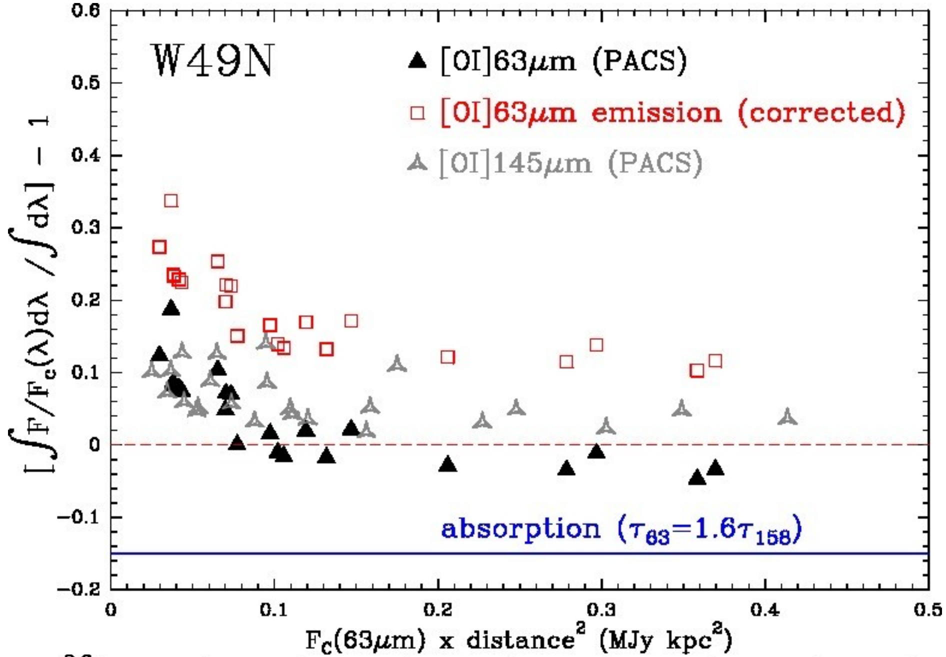


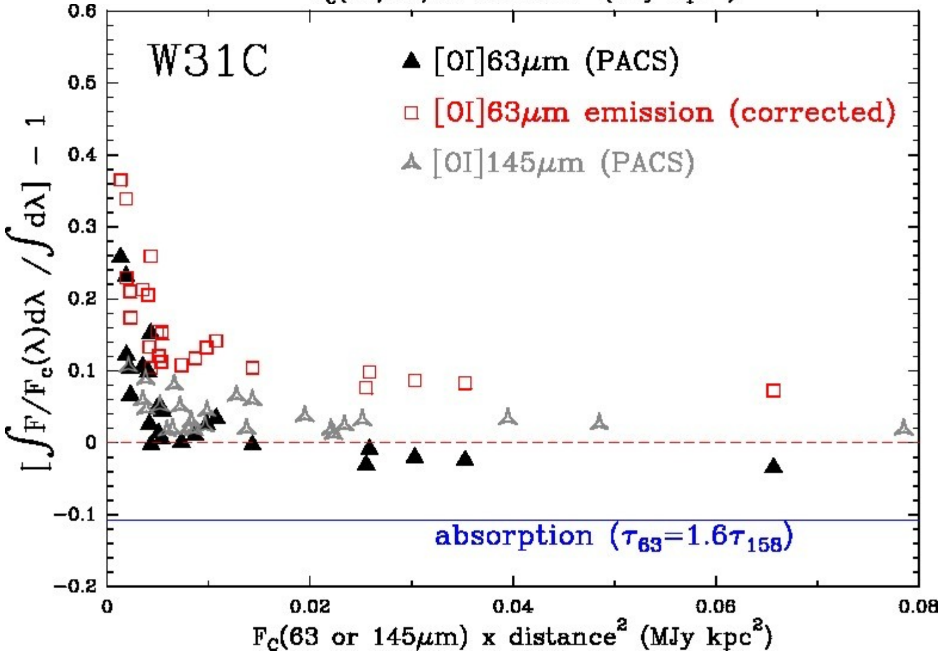
Gracia-Carpio et al 2011

- HI absorption in NGC4418 (*Costaglia et al 2013*)
- Expected dimming of the [CII] signal → -0.04 & -0.11 for the 2 velocity components
- Move NGC4418 from ~10^{-4} up to ~ 1.5 x 10^{-4}

[OI] lines

$^3P_2 - {}^3P_1$: 63 µm
$^3P_1 - {}^3P_0$: 145 µm





$$\frac{L(OI_{63})}{L_{FIR}} \sim 10^{-3} I_{rel}(OI_{63}) \text{ and } \frac{L(OI_{145})}{L_{FIR}} \sim 3.1\times10^{-3} I_{rel}(OI_{145}).$$

tau(OI_63) ~ 1.6 tau(CII) with standard ISM abundances
→ Stronger effect for 63µm line
Confirmed by SOFIA observations (*e.g. Leurini et al. '15*)

The 145 µm line is not strongly affected by absorption
Same behavior of decreasing line emission with increasing continuum, but shallower slope

Correction using [CII] ;
Next step : SOFIA high spectral resolution data.

CII excitation

$^2P_{3/2}$-$^2P_{3/2}$ 1900 GHz
Eu ~ 91 K
A = 2.32 10^{-6} s^{-1}

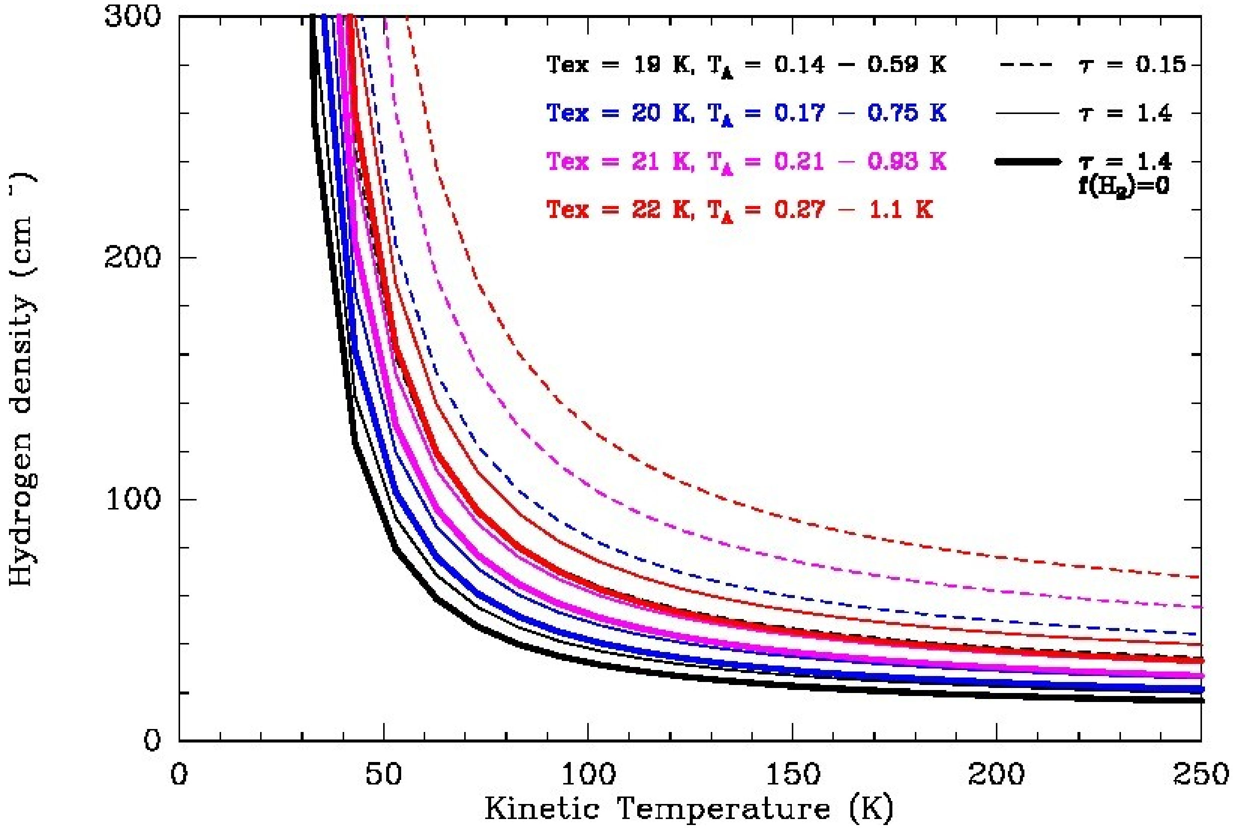
CNM conditions :
collisional excitation by H, H_2, He and electrons

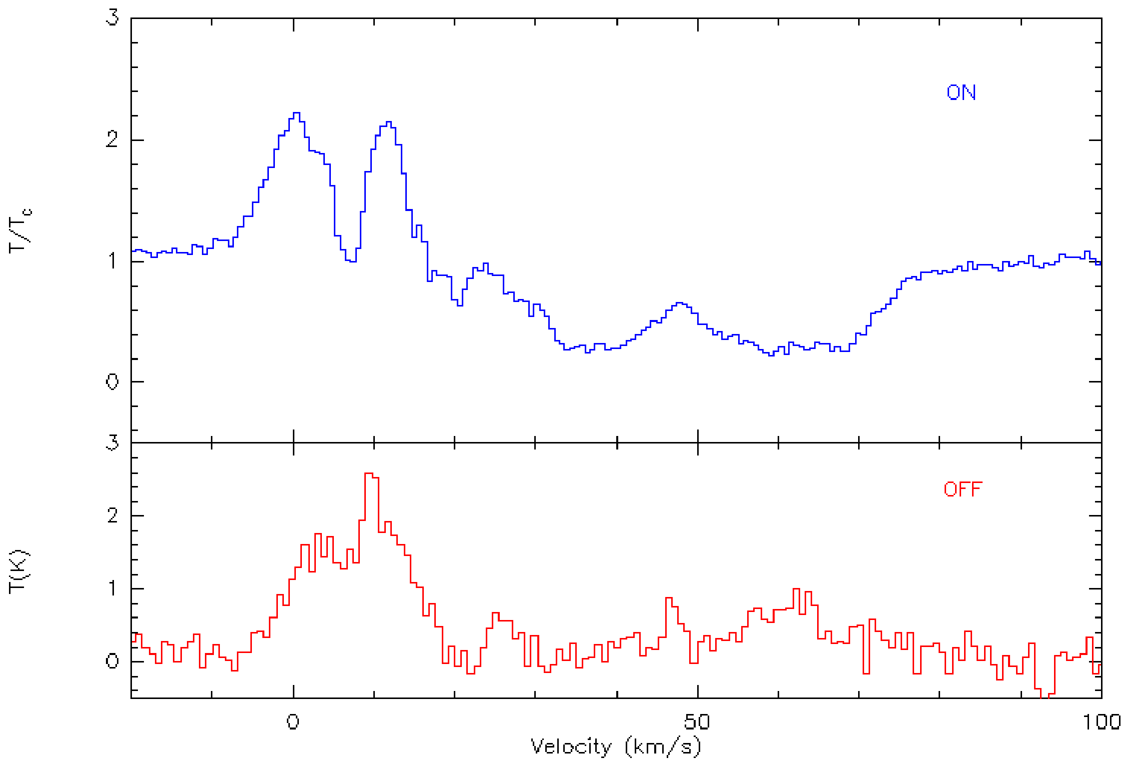
Moderate excitation → Most of the population in the ground state

N(C^+) ~ 1.4 10^{17} ∫τ(CII)dv

N(HI) ~ 10^{21} ∫τ(CII)dv

for C/H = 1.4 10^{-4}





[CII] Excitation

Typical level of the diffuse CII emission ~ 0.5K & opacity from absorption : τ ~ 1 → **Tex ~ 20.5K**

Most of the C^+ ions are in the ground state (~ 98%) → Absorption

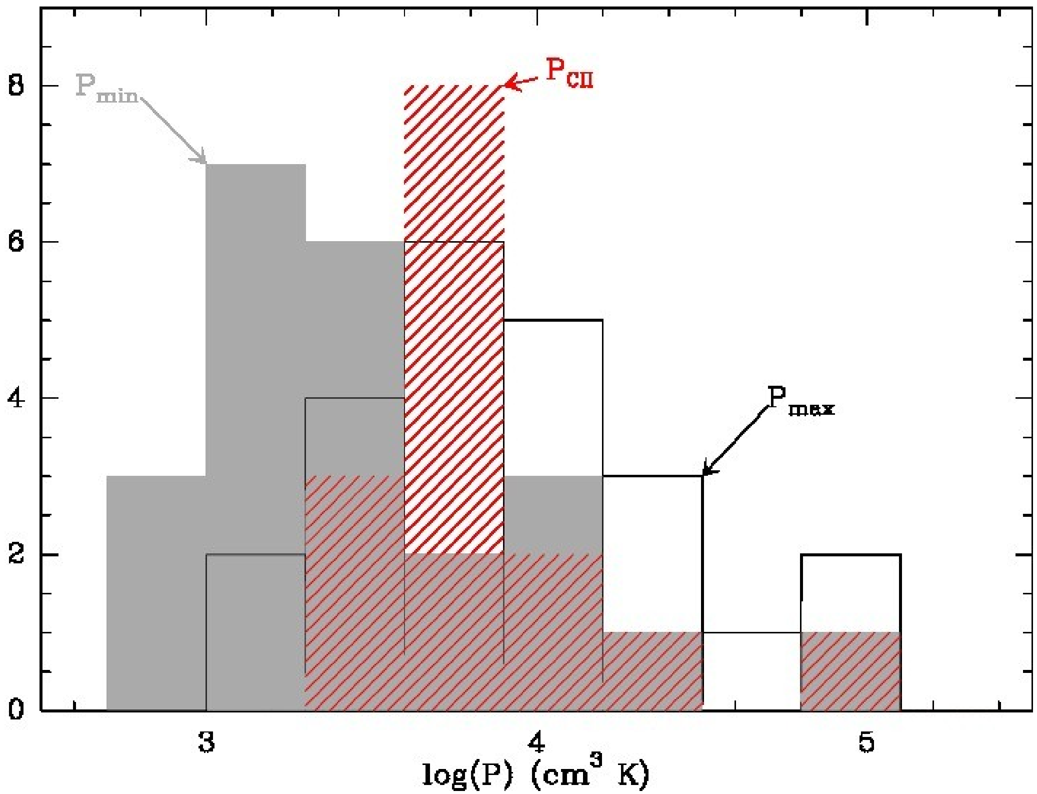
Excitation conditions consistent with diffuse gas

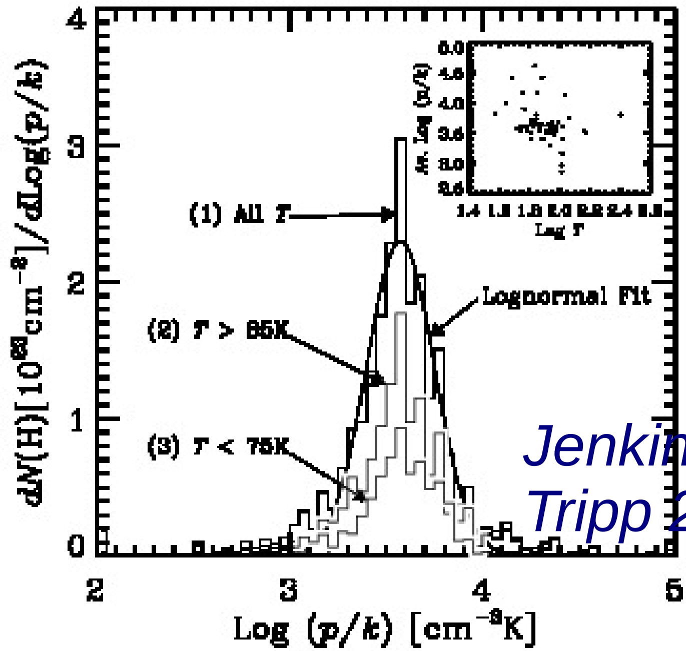
T ~ 100 K (from HI), n ~ 40 – 80 cm^{-3} ; median value 60 cm^{-3}

p/k_B ~ 3800 – 22000 Kcm^{-3} median : 5900 Kcm^{-3}

The gas detected in absorption is the CNM

CI excitation



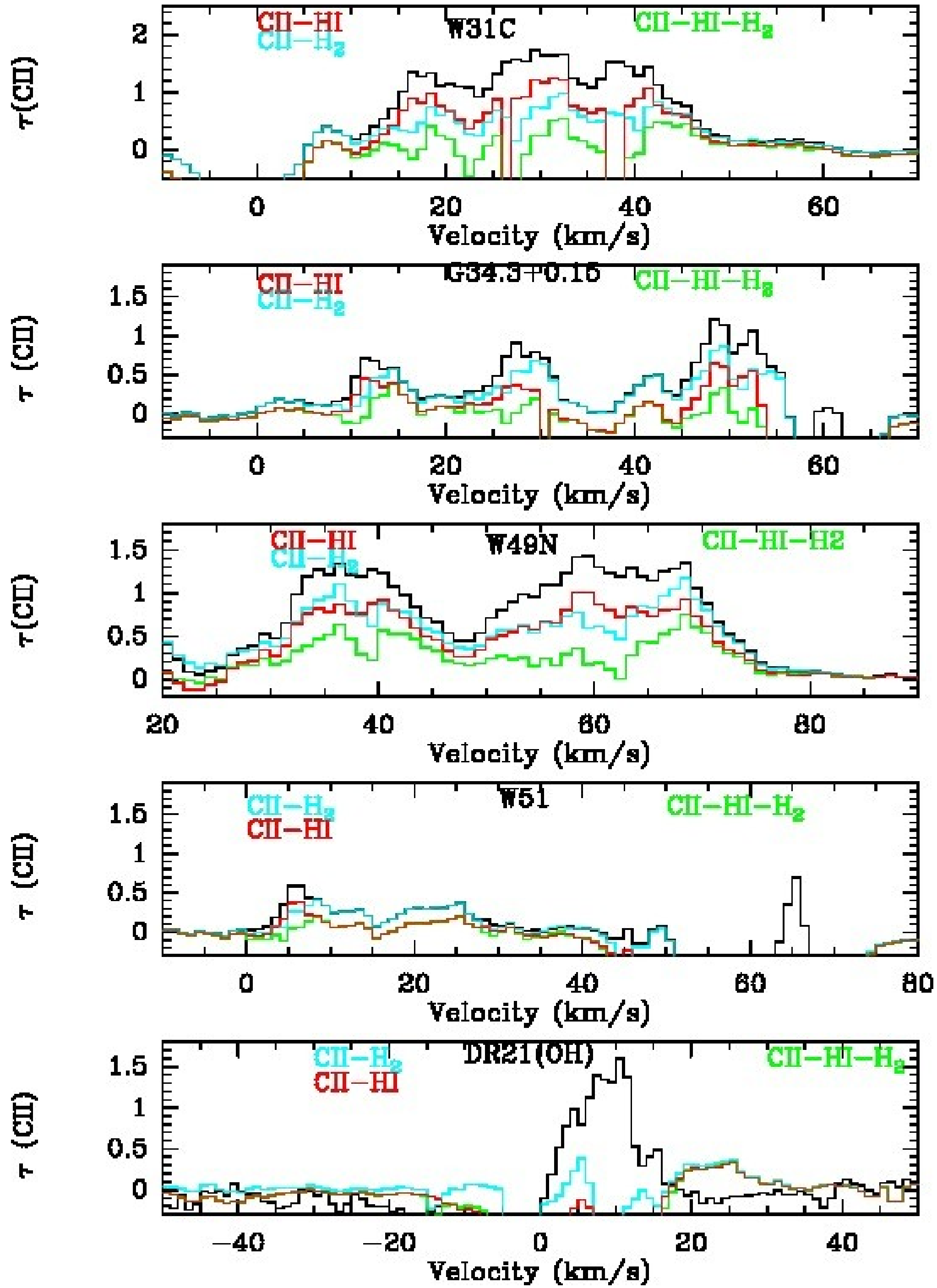


Jenkins & Tripp 2011

CNM conditions : collisional excitation by H, H_2, He & electrons

$N(C)/N(C^+)$ ~ 6% (1 – 28%) → All carbon in C+

We derive a pressure range for each velocity component : low pressures (**few 10^3 Kcm^{-3}**) except for a subset of high pressure (> 10^4 Kcm^{-3})



H_2 fraction

Use CH & HF as tracers of diffuse H_2

21cm absorption for HI

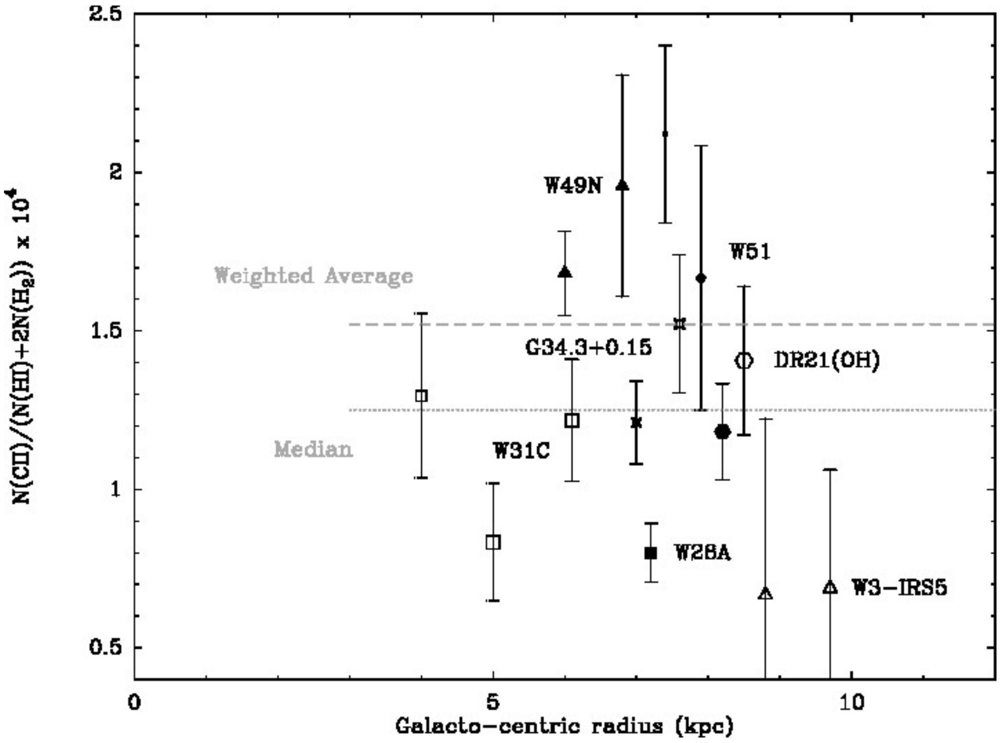
[CII] absorption is associated with diffuse gas with both HI & H_2

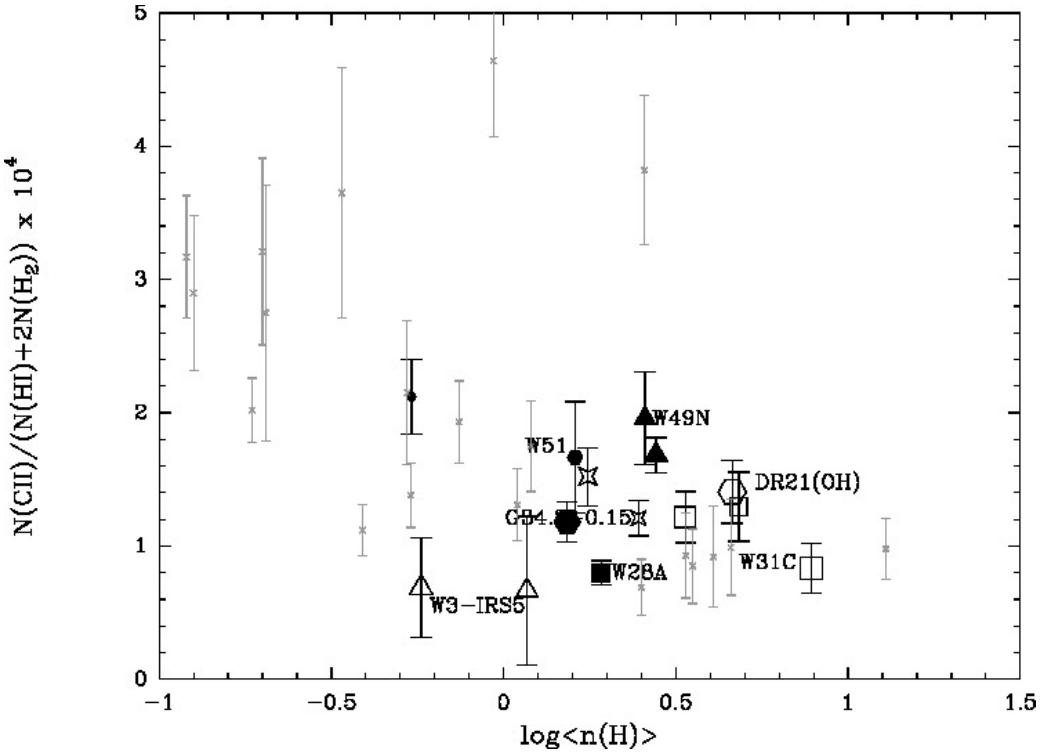
Fraction of H in molecular form

$f(H_2)$: ~ 5 to 75 %

(Godard et al. 2012, Sonnentrucker et al. '15)

C^+ abundance





- Nearly constant C^+ abundance as a function of Galacto-centric radius : **$C^+/H \sim 1.5\ 10^{-4}$**
- Good overall agreement of C^+ abundance as compared with HST measurements
- Good overall agreement of H_2 column densities derived from CH & HF

Filling factors

Using the Galactic rotation curve

- The velocity profile provides the path length along the line of sight ***L*** (~ few kpc)

Typical velocity gradient 1 km/s for 100pc

- Using HI & molecules for diffuse H_2 to derive $\boldsymbol{N(H_{tot})}$, and knowing the density **n** and the fraction of hydrogen in H_2 $\boldsymbol{f(H_2)}$

The CNM path along the same line of sight :

$$\boldsymbol{s = N(H_{tot})/n} \sim \text{few tens of pc (6 – 130 pc)}$$

- Filling factor of CNM:

$$\boldsymbol{f = s/L : 1 – 13\% \text{ (median 2.5 \%)}}$$

Statistical meaning : individual structures are not resolved.

Cooling rate

C^+ cooling rate :

$$\Lambda(C^+) = \frac{h\nu A_{ul} g_u e^{-\frac{h\nu}{k_B T_{ex}}}}{Q(T_{ex})} \frac{N(C^+)}{N_{tot}(H)} .$$

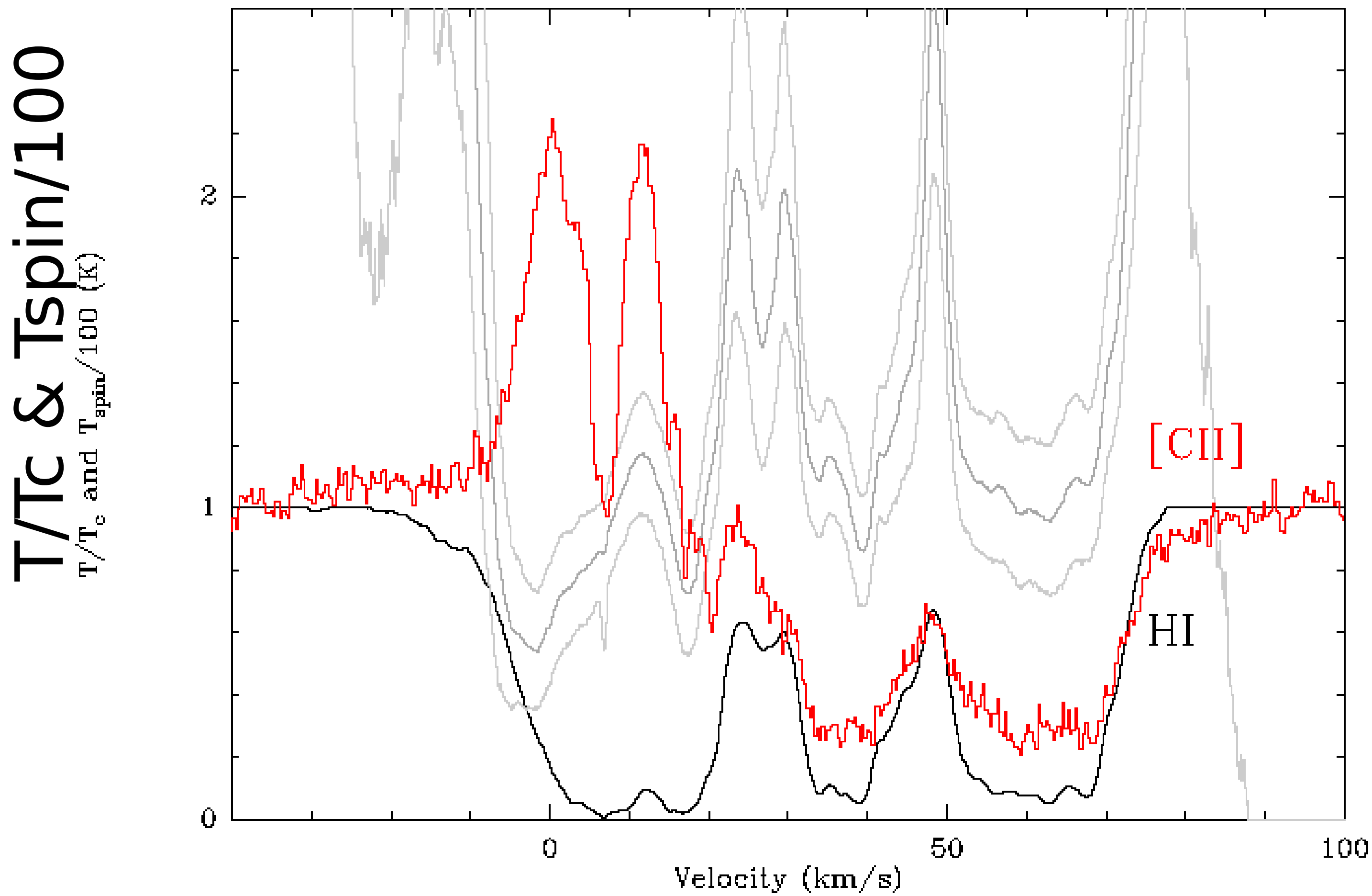
Derived from the measured Tex.

$$\Lambda(C^+) = 9 \times 10^{-26} \frac{x_C}{1.4 \times 10^{-4}} \, ergs^{-1} H^{-1} .$$

3 – 5 times higher than the local cooling rate *(Lehner et al. 2004)*

Consistent with a small increase of the radiation field / Heating rate in the inner Galaxy, as modelled by *Wolfire et al. '03*

Warm phases



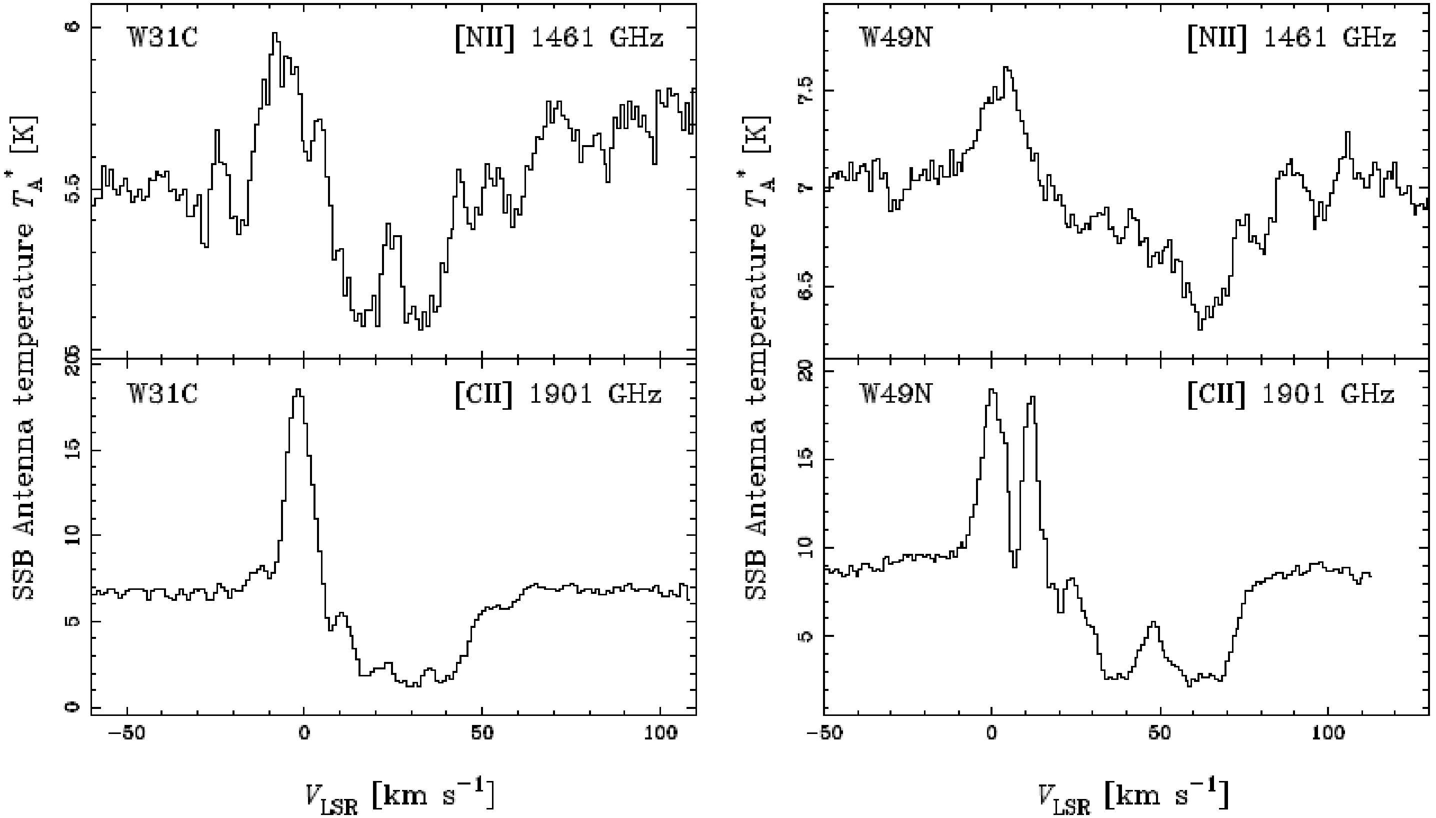
CII emission from the WIM (Velusamy et al) → CII absorption from WIM / WNM ?

Excess absorption in high Tspin regions (JVLA data Winkel & Menten in prep)

Excess C^+ column density from the combination of HI (CNM) and H_2 (from CH)

Consistent with ~ 5 – 10 % of the total C^+ and a filling factor of the warm phases ~ 1

N^+ absorption as a tracer of the WIM (*Persson et al. 2014*)



N^+ fine structure line at 205 µm

1461 GHz

$N(N^+) \sim 1.5\ 10^{17}$ 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 ;

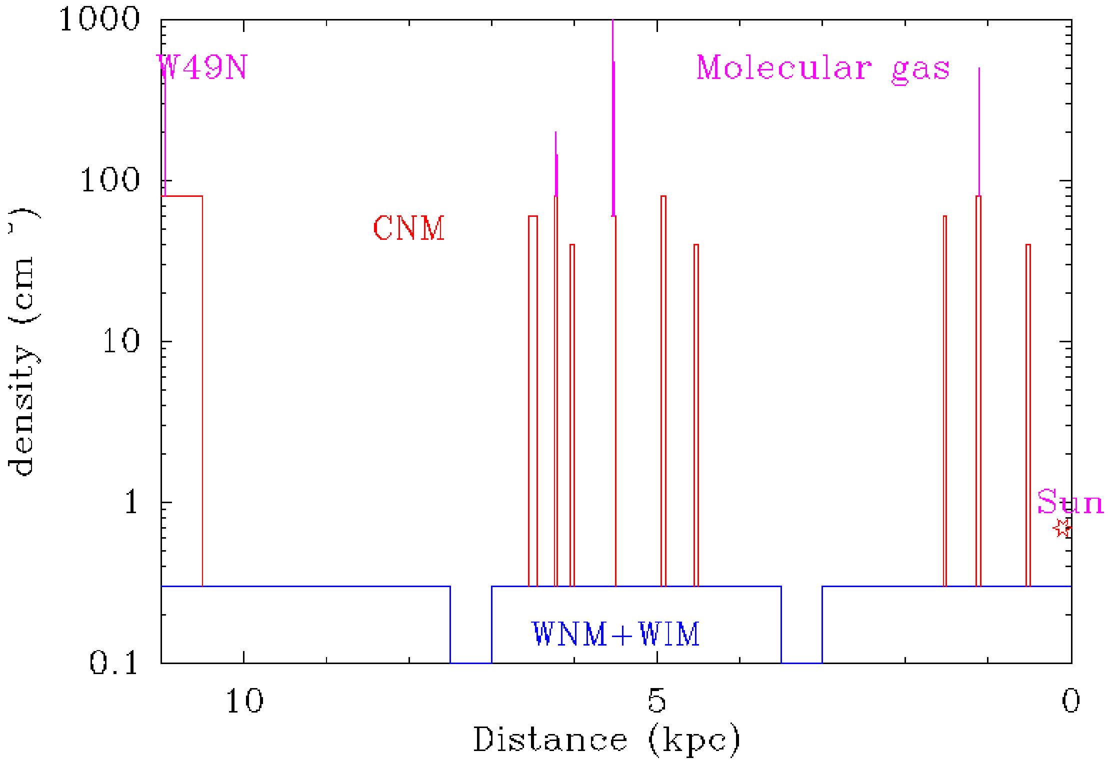
→ Warm Ionized Medium (WIM)

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

Tomography along the line of sight to W49N

Thanks to *Herschel*, we have good tracers of the total gas column density : HI abs → CNM; CH & HF → H_2, CII → H_tot

We can determine the fraction of H in H_2 the gas density & pressure (using T from HI) & connect CNM and molecular gas.



- CNM contribution to the column density > 85%
- CNM pressure ~ 6000 Kcm^{-3}
- CNM Filling factor along the line of sight ~ 2.5 %
- Higher density regions from NH_3 , CN , (300 – 1000cm^{-3})
- OH^+ trace the CNM interfaces with low H_2 fraction

- Most of the volume is filled by the warm phases (> 50%)

Future Prospects

SOFIA : [CII], [OI] heterodyne spectra

From the ground, use molecules tracing the diffuse gas, combining absorption & emission

- HCO^+
- HOC^+
- CF^+
- CCH

Formed from C^+