GOT C+ Survey of [CII] 158 μm Emission: Atomic to Molecular Cloud Transitions in the Inner Galaxy

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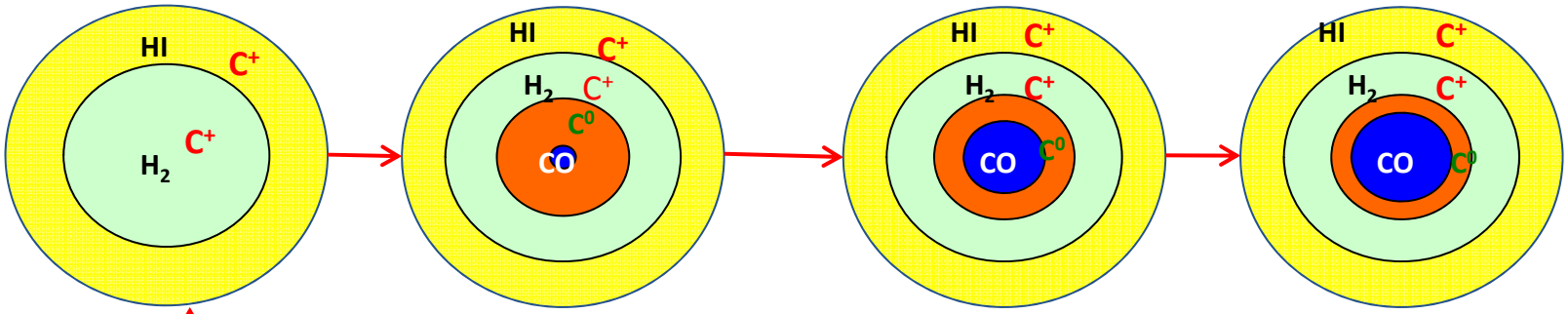
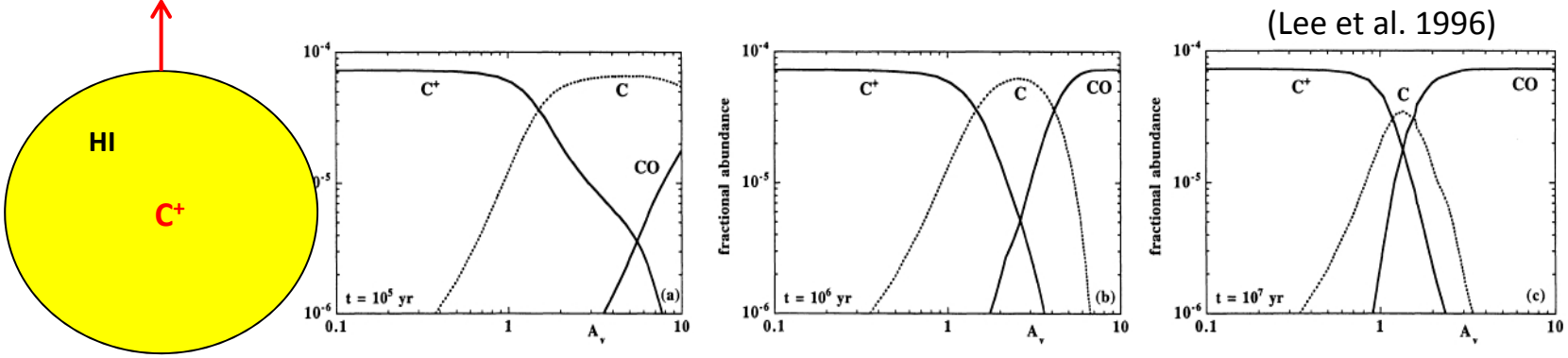
Outline

- Why Survey [CII]?
  - Cloud evolution:
    - » C^+ to CI, CO transition
    - » HI to H_2 transition
- HIFI GOT C+ survey of Galactic Plane:
  - Spectrally resolved [CII] data
  - Ancillary HI, ^{12}CO, ^{13}CO and $C^{18}O$ data
  - [CII] clouds: data base
- C^+ as diagnostic of "dark-H_2 gas"
- Galactic distribution of [CII] emission

ESA image

[CII] Tracks Interstellar Cloud Evolution



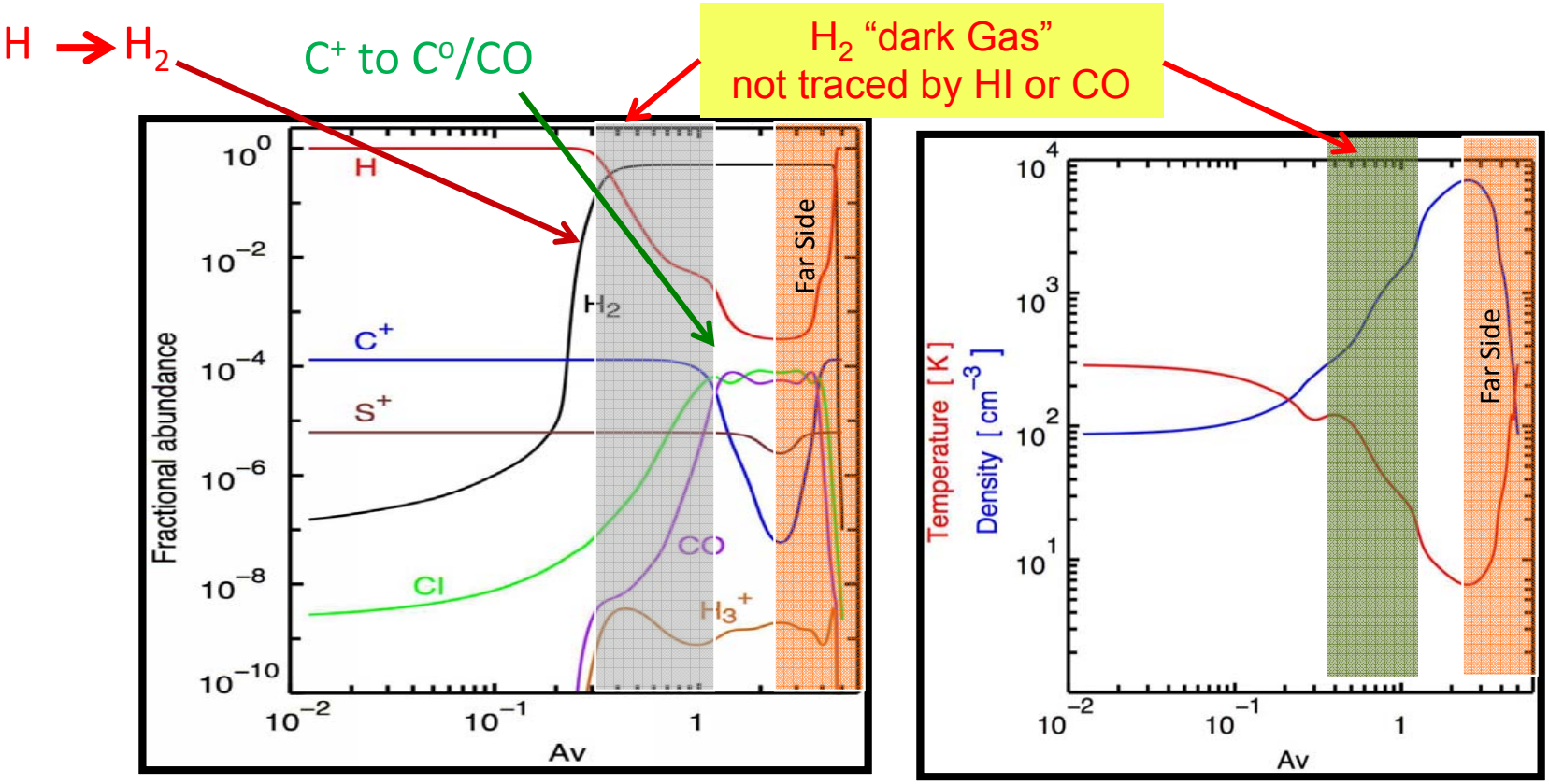


(Lee et al. 1996)

- Carbon exits mostly as C^+
- Transition Clouds
  - H_2 & C^+,
  - Some C^o & CO But no ^{13}CO
  - [CII] ➔ warm, dense H_2
- Dense Molecular Clouds
  - ^{12}CO & ^{13}CO; some $C^{18}O$

- ➢ Models estimate about 30% H_2 gas in the transition layers which is not traced by CO (Wolfire et al. 2010).
- ➢ HIFI [CII] detections of C^+/H_2 layers (Velusamy et al. 2010; Langer et al. 2010)

How much H_2 gas is missed by CO?



— FUV (I_0 ~ 50) (finite slab - both sides illuminated) & P ~2 x10^4 K cm^{-3}

» n(HI) ~ 50 - 100 cm^{-3} , T_{kin} ~ 100 to 200K

» n (H_2,CII) ~ 2-8 x10^2 cm^{-3} & T_{kin} ~ 50 – 100K

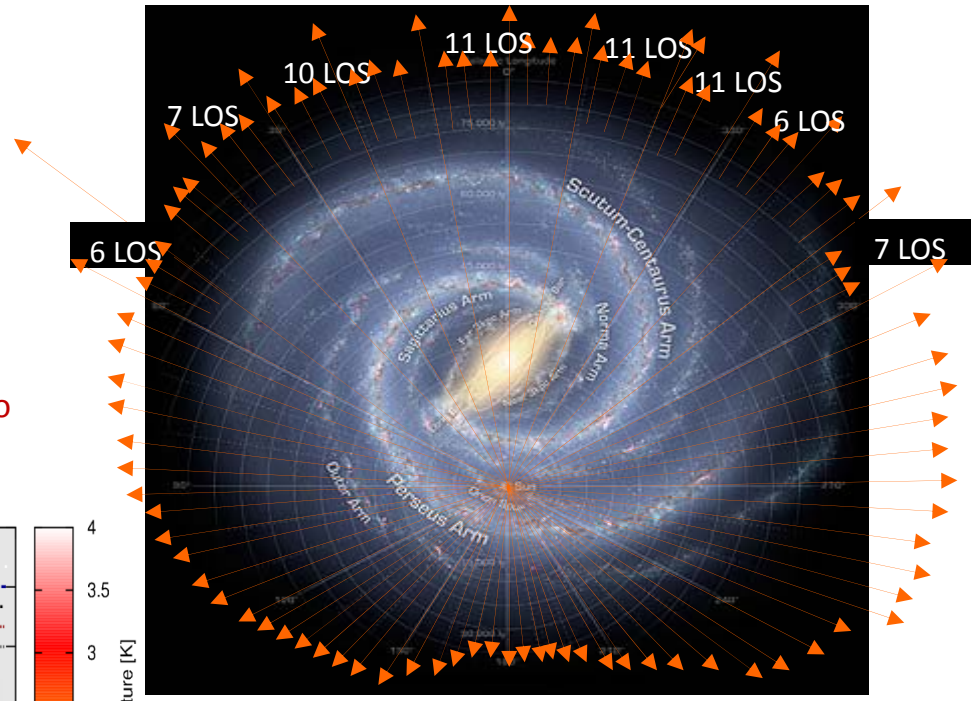
– [CII] intensity ➔ a measure of A_v up to C^+/CO transition

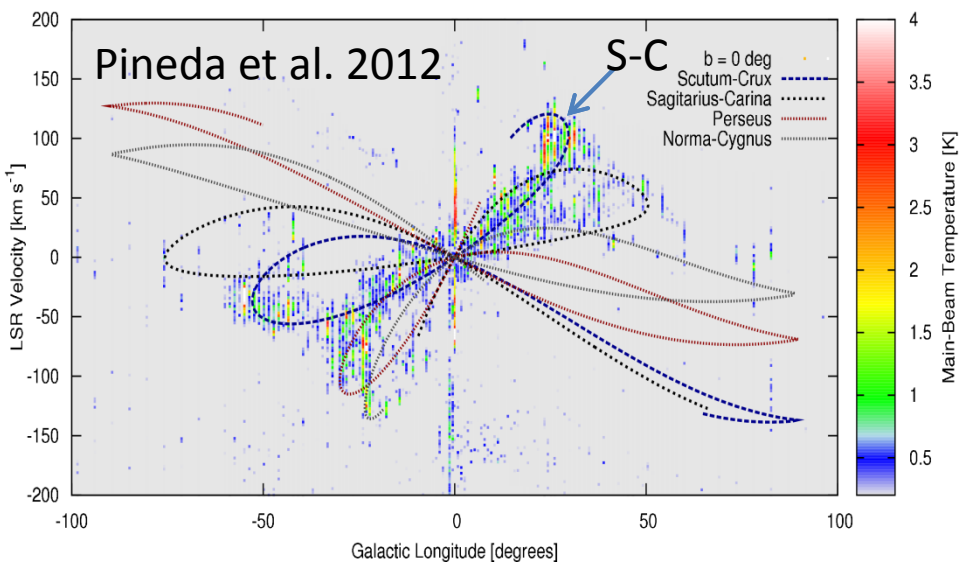
– Chemical pathways ➔ useful constraint on FUV & CR ionization rate

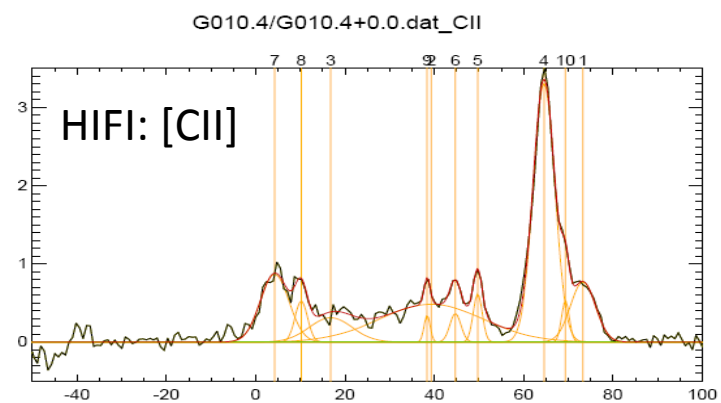
GOT C+ [CII] 1.9 THz Survey

Herschel OT Key project (PI: Langer)

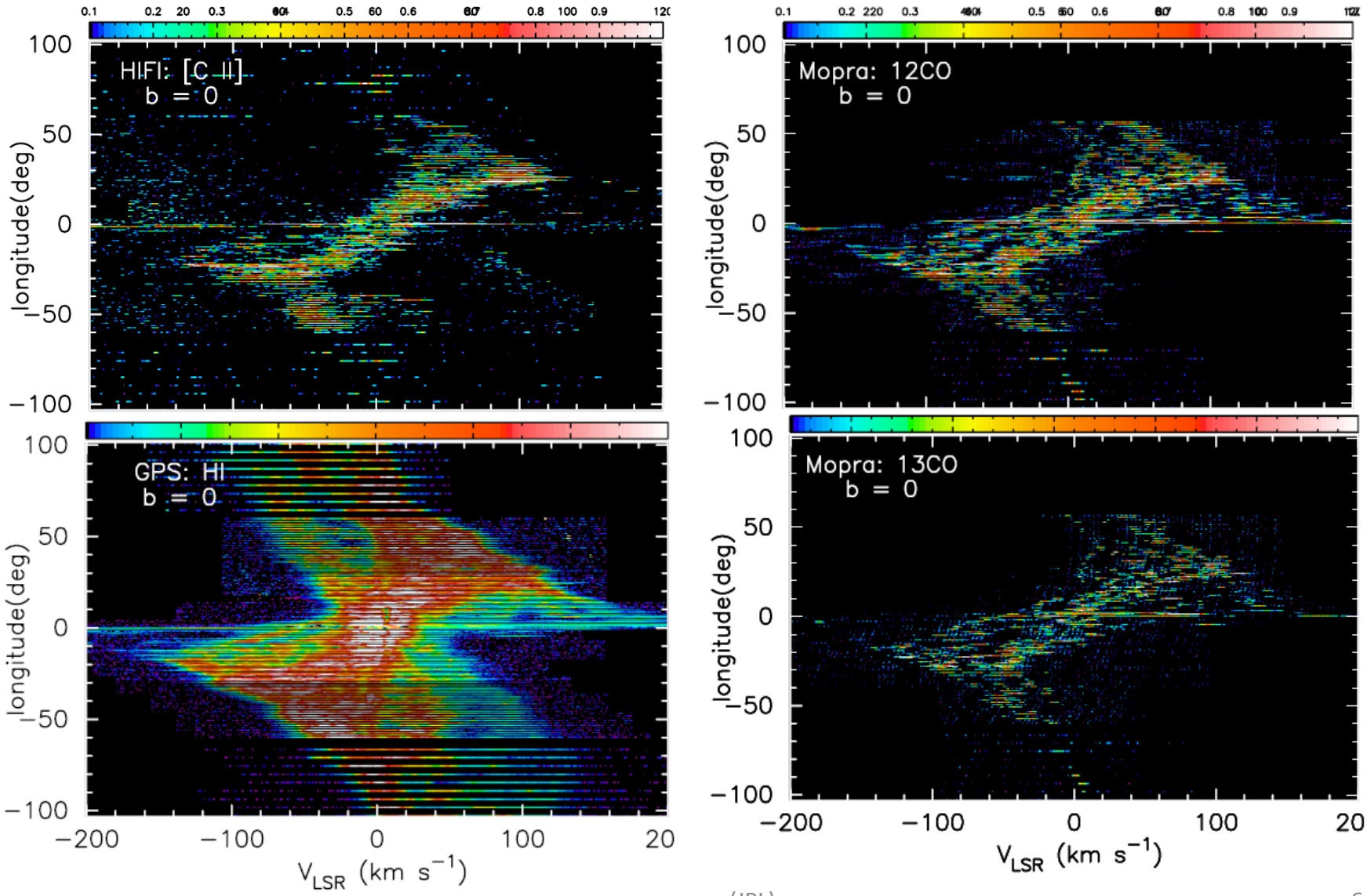
- HIFI pointed observations
- systematic , unbiased sample of ≈ 500 LOSs in the disk
- volume weighted: concentrated towards inner Galaxy
- sample each *l* at *b* = 0°, ± 0.5° & ±1°







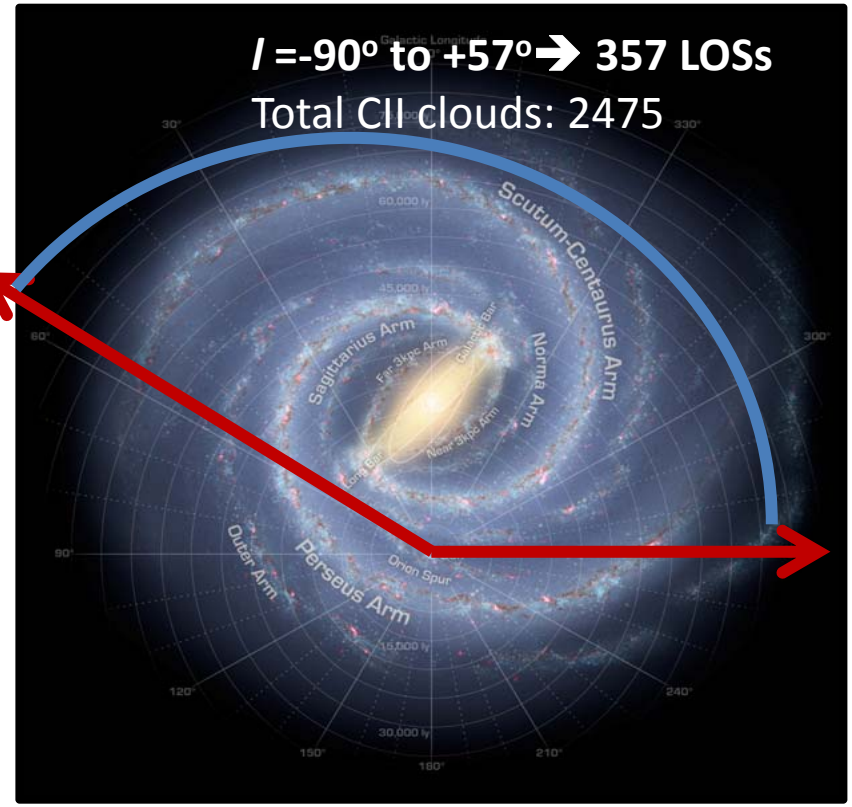
Spectra based extraction using GOT C+ Survey Data



GOT C+ data base: [CII] clouds

- Gaussian fit velocity-resolved spectra
- [CII], HI, ^{12}CO & ^{13}CO data at all LOSs
  - — most LOSs have $C^{18}O$ data
- Total 2580 [CII] clouds in GOT C+ survey
- Within inner Galaxy *l*=-90° to +57°

— Analyze [CII] clouds with narrow (< 10 km/s) line-width



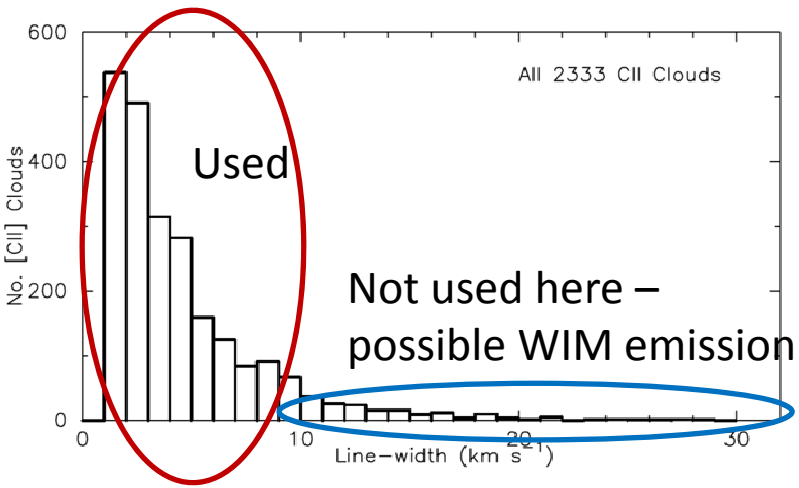
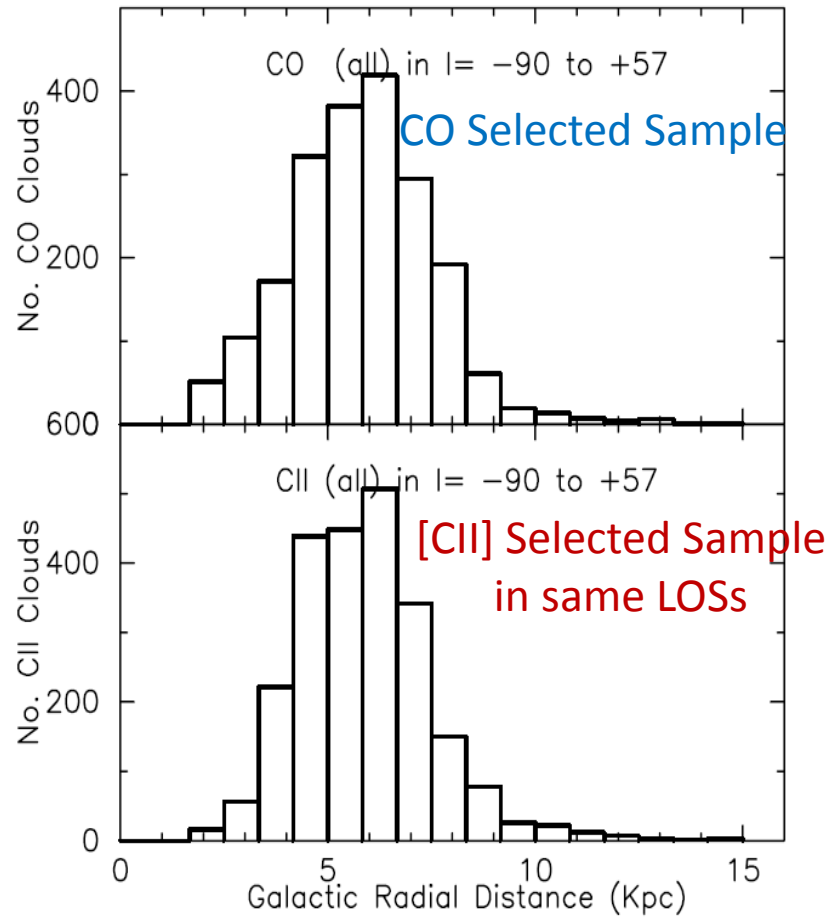


Table: GOT C+ [CII] Clouds: *l* =-90° to +57°

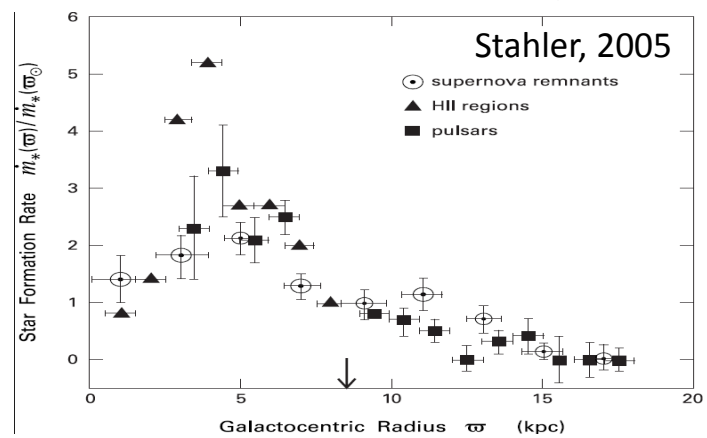
	Type	total	b=0°	b=±0.5°	b=±1.0°
No. LOS	--	357	119	119	119
[CII] clouds with No CO	Diffuse: HI/H_2	374	150	130	94
^{12}CO	Transition	672	242	239	191
^{13}CO	Dense	694	393	200	101
$C^{18}O$	Bright PDRs	384	214	128	42

GOT C+ [CII], CO clouds

- [CII], CO clouds extracted on the same LOSs by Gaussian fit velocity-resolved spectra
- Use LSR velocity to infer the R_G for each [CII] cloud
- [CII] clouds have slightly narrower distribution in R_g
- Not all [CII] clouds have CO
  - 20% in [CII] selected sample do not have any CO emission
  - 20% in CO selected sample do not have any CO emission

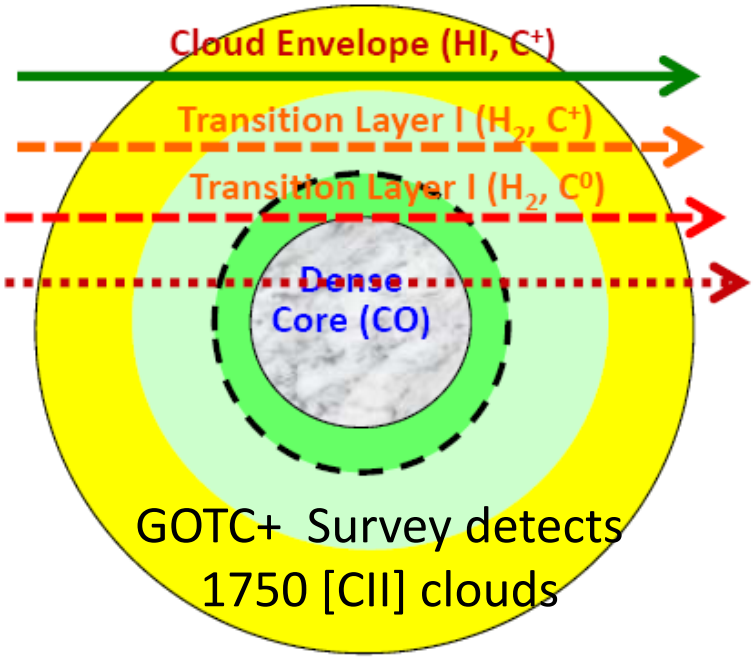


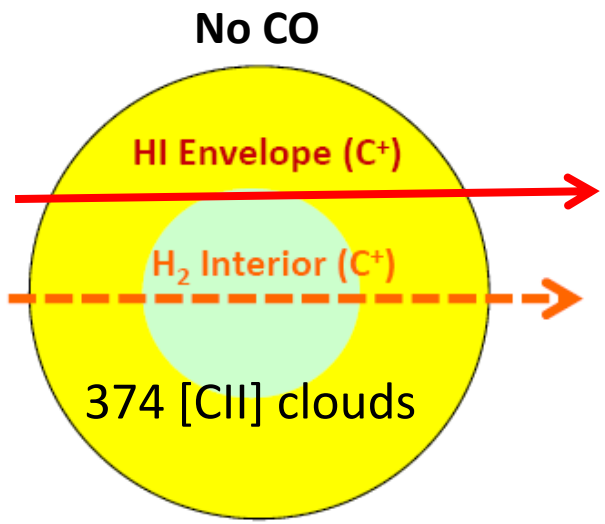
➔ [CII] cloud distribution follows Star formation rate

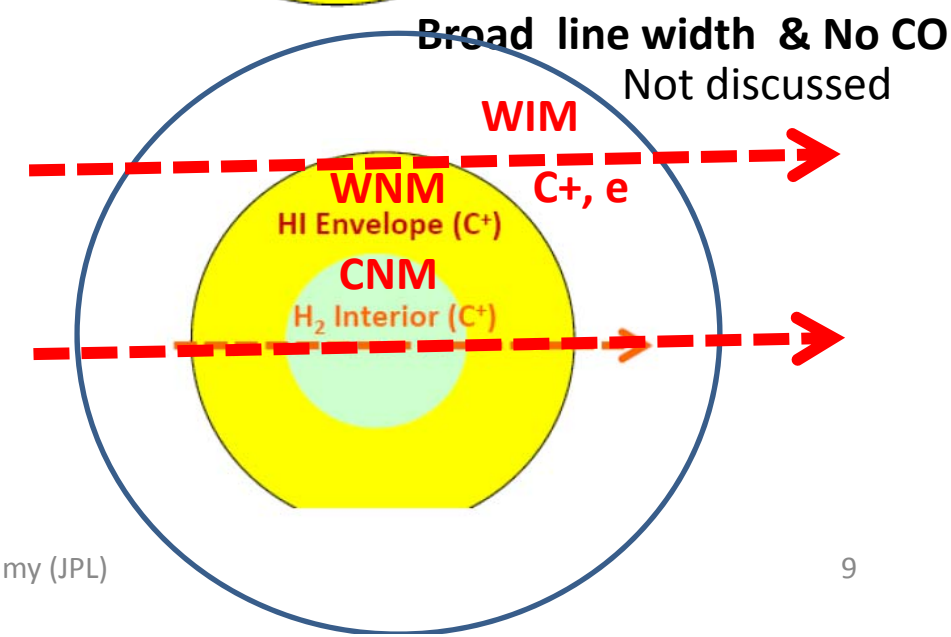


Statistical analysis of [CII] in clouds -1

What is observed by single LOS?



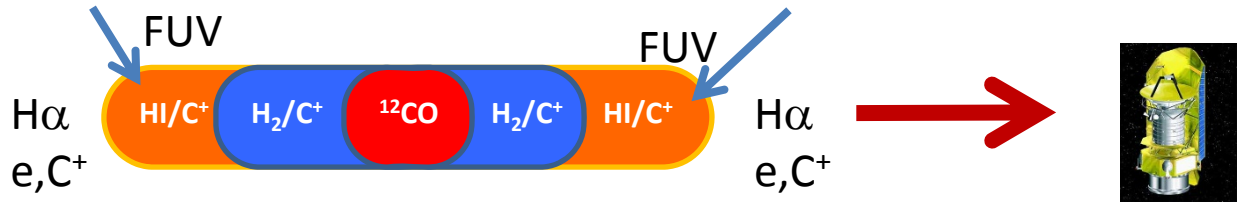




➔ The large number of clouds (>2000) in our sample allows meaningful statistical analysis of cloud properties.

- Beam sizes:
  - [CII] 12”
  - HI 60” -150“
  - CO 33“

Statistical analysis of [CII] in clouds -2



$I(CII) = I(CII,e) + I(CII,HI) + I(CII,H_2)$

$N(HI) \alpha I(HI)$

$I(CII)_{HI} = f(n_{HI},T_K)\, N(HI)\, x(C^+)$

(f = excitation of C^+)

[CII] sensitive to (n,T) or P

Excess [CII] intensity in H_2 layer

$I(CII)_{H2} = I(CII) - I(CII)_{HI}$

$N(C^+)_{H2} = f(n_{H2},T_K)^{-1}\, I(CII)_{H2}$

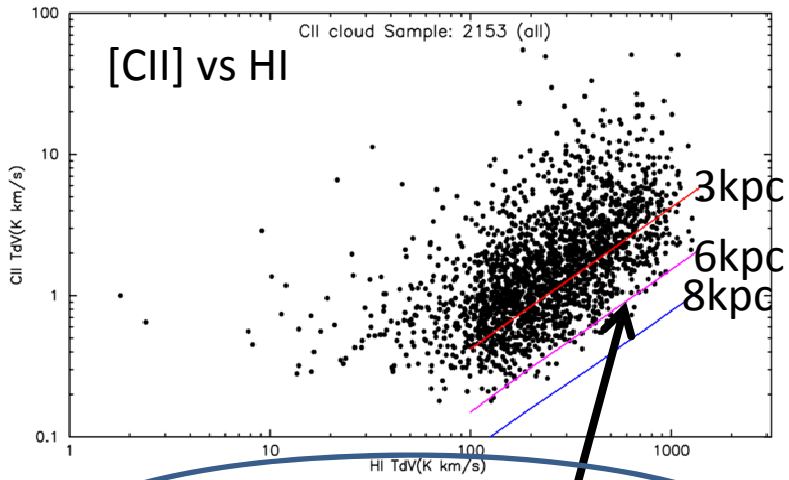
$N(H_2)_{C+} = N(C^+)_{H2}/x(C^+)_{H2}$

- Use LSR velocity to infer the R_G for each [CII] cloud
- Use [CII] line width ➔ integrated intensities: I(CII), I(HI), I(12CO)
- Use galactic model: Pressure $P(R_G)$
  - n(HI),T(HI)
  - $N(H_2)$, $T(H_2)$
  - Metalicity gradient: $x(C^+)$

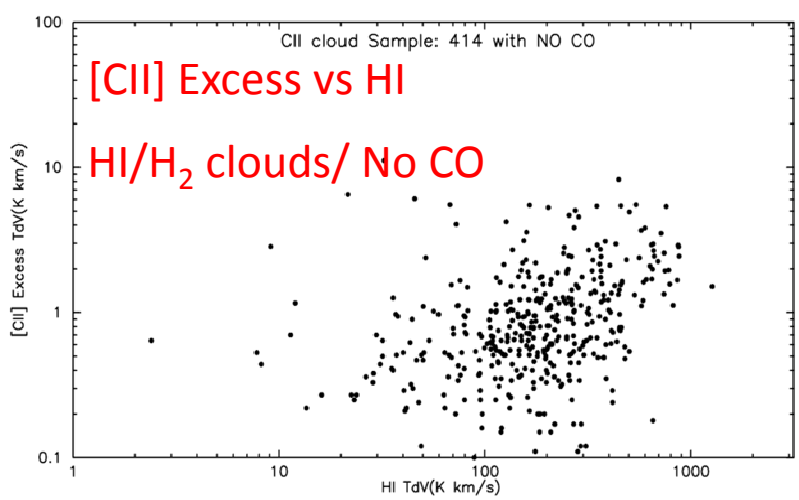
Langer, (2010, 2011) & Velusamy, et al. (2010, 2011)

Wolfire et al. (2003)

Statistical analysis of [CII] in clouds -3



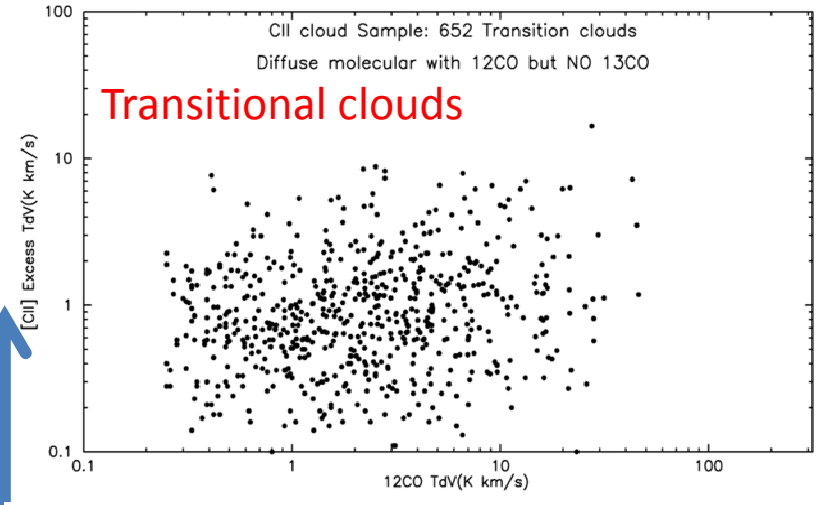
Estimated I(CII) for [n(HI),T(HI)] at R_G given by $P \sim 1.4e4 \exp(-R_G/5.5)$

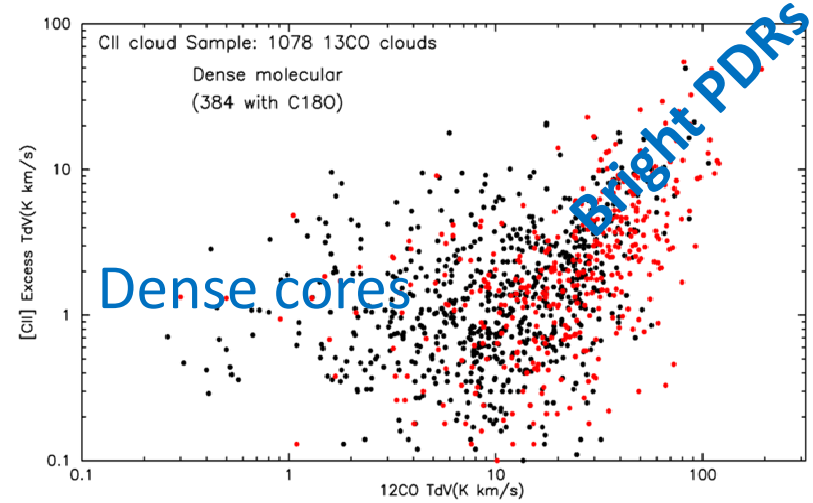


$N(H_2)$ in C+/H2C

N(HI)

[CII] Excess vs ^{12}CO





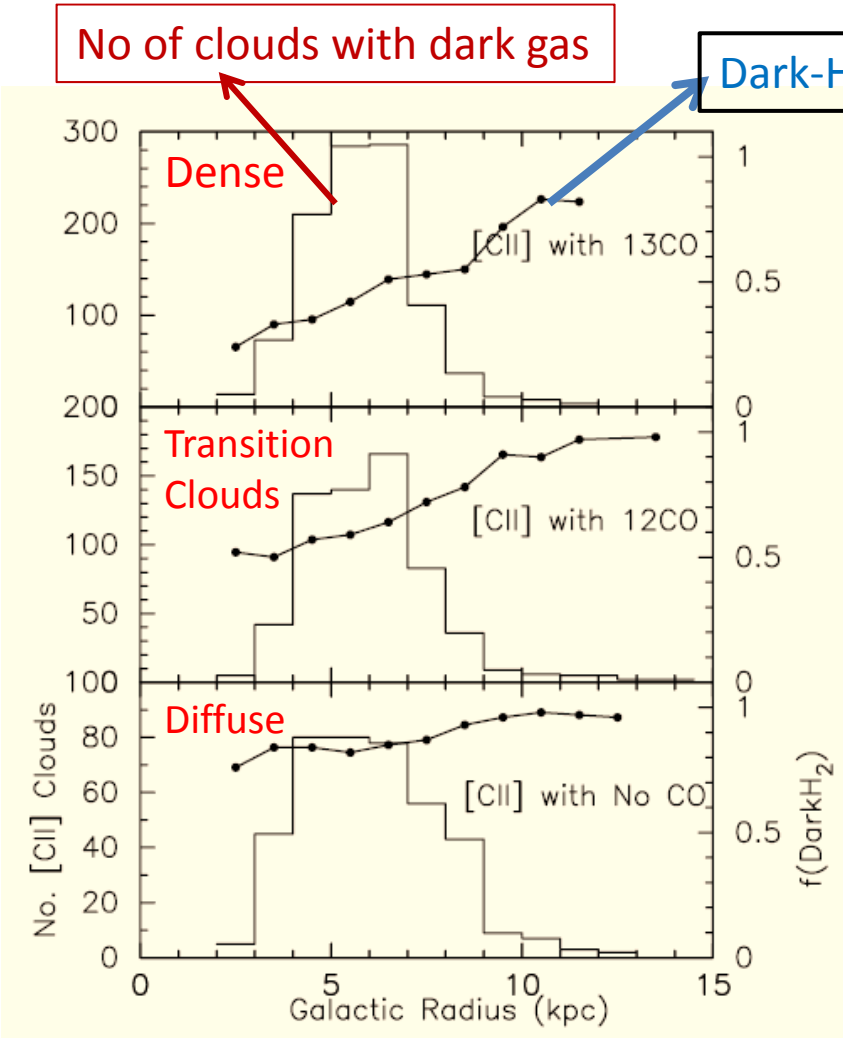
$N(H_2)$ in C+/CO transition

$N(H_2)$ traced by CO

"Dark-H_2 Gas" Mass Fraction

- Use excess I(CII) to estimate $N(H_2)_{CII}$
  - $I(CII)_{H2} = I(CII)_{tot} - I(CII)_{HI}$

$$f = \frac{M(H_2)_{CII}}{M(HI) + M(H_2)_{CII} + M(H_2)_{CO}}$$

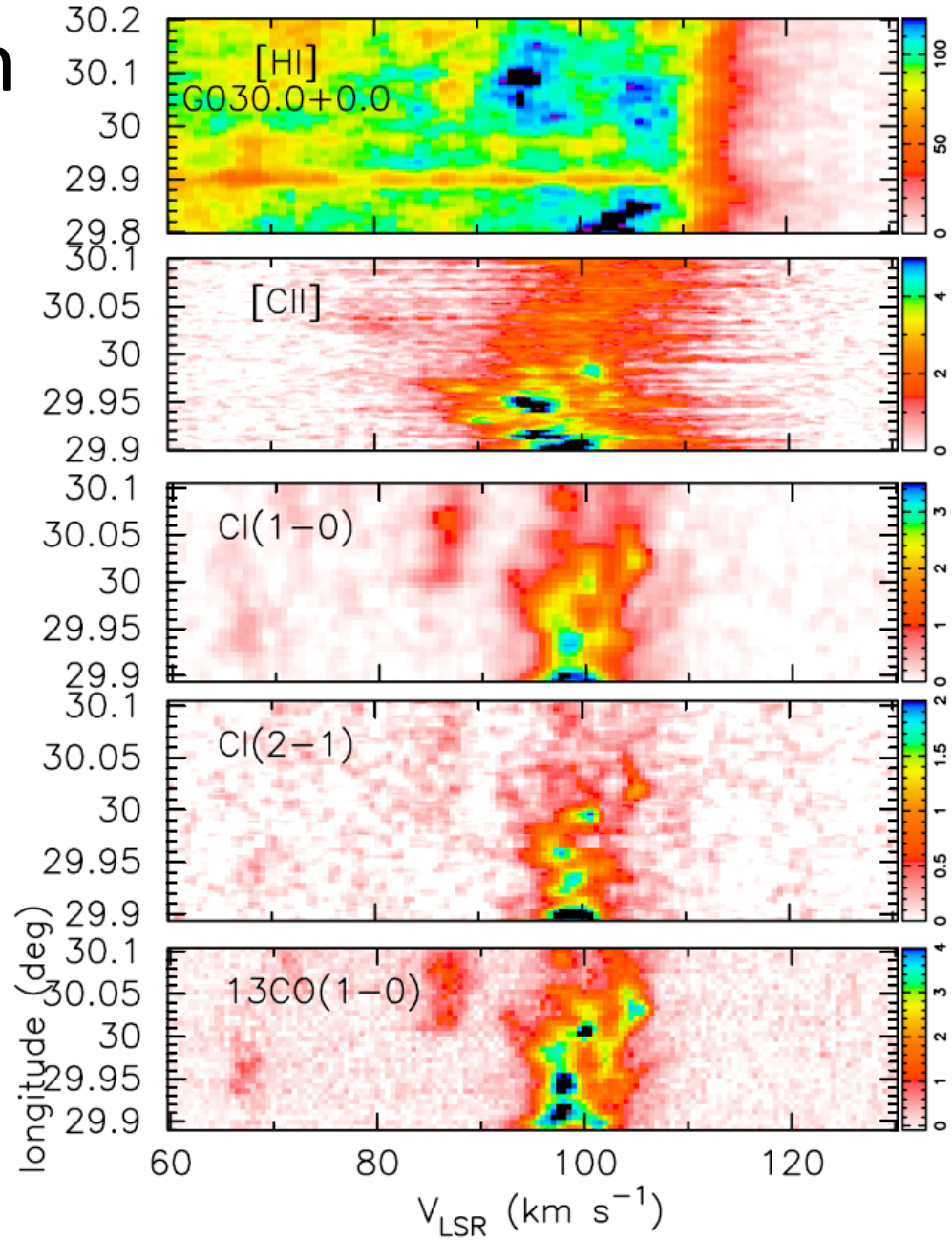


- increase of mass fraction $f(H_2)$ with R_G is a consequence of the gradient in $x(C^+)$
- low metalicity
  - deeper penetration of FUV into cloud
  - larger C^+ emitting envelope
  - small CO core.

➔ Need detailed modeling using data in the C^o/CO transition from [CI] and mid-J CO

There is more from HIFI mapping……

12 arcmin



Spatially [CII] traces

- CNM traced by CO & CI
- a spatially and spectrally diffused broad component associated with WNM/WIM

Summary

- GOT C+ survey of Galactic [CII] emission provides a large sample of "C^+-clouds" (>2000) and new details on the distribution and characteristics of the cloud transitions in the ISM
- C^+ emission in these clouds trace the dark-H_2 gas in the C^+/CO transition
- GOT C+ results on the global distribution of [CII] clouds is consistent with tracing the FUV and star formation in the Galactic disk.
- More to follow in Herschel OT1 & OT2 observations
- The GOTC+ [CII] data will be released through HSC