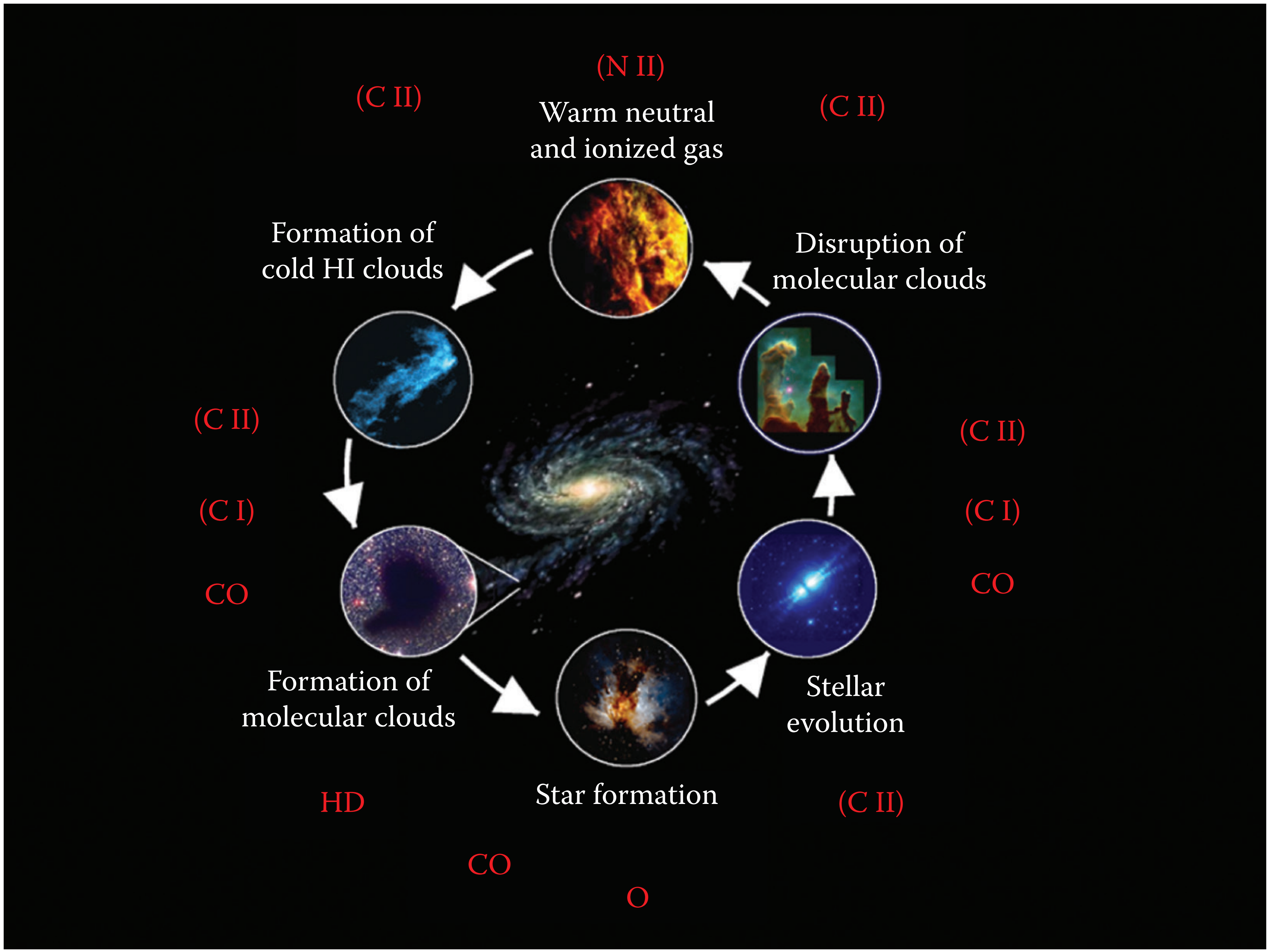
[N II] 1.46 THz Line Galactic Plane Survey

Umemoto, T. (NRO)

南極天文ワークショップ（極地研）　2018年9月12日

Lifecycle of the ISM



Walker (2016)

Atomic and molecular lines at THz

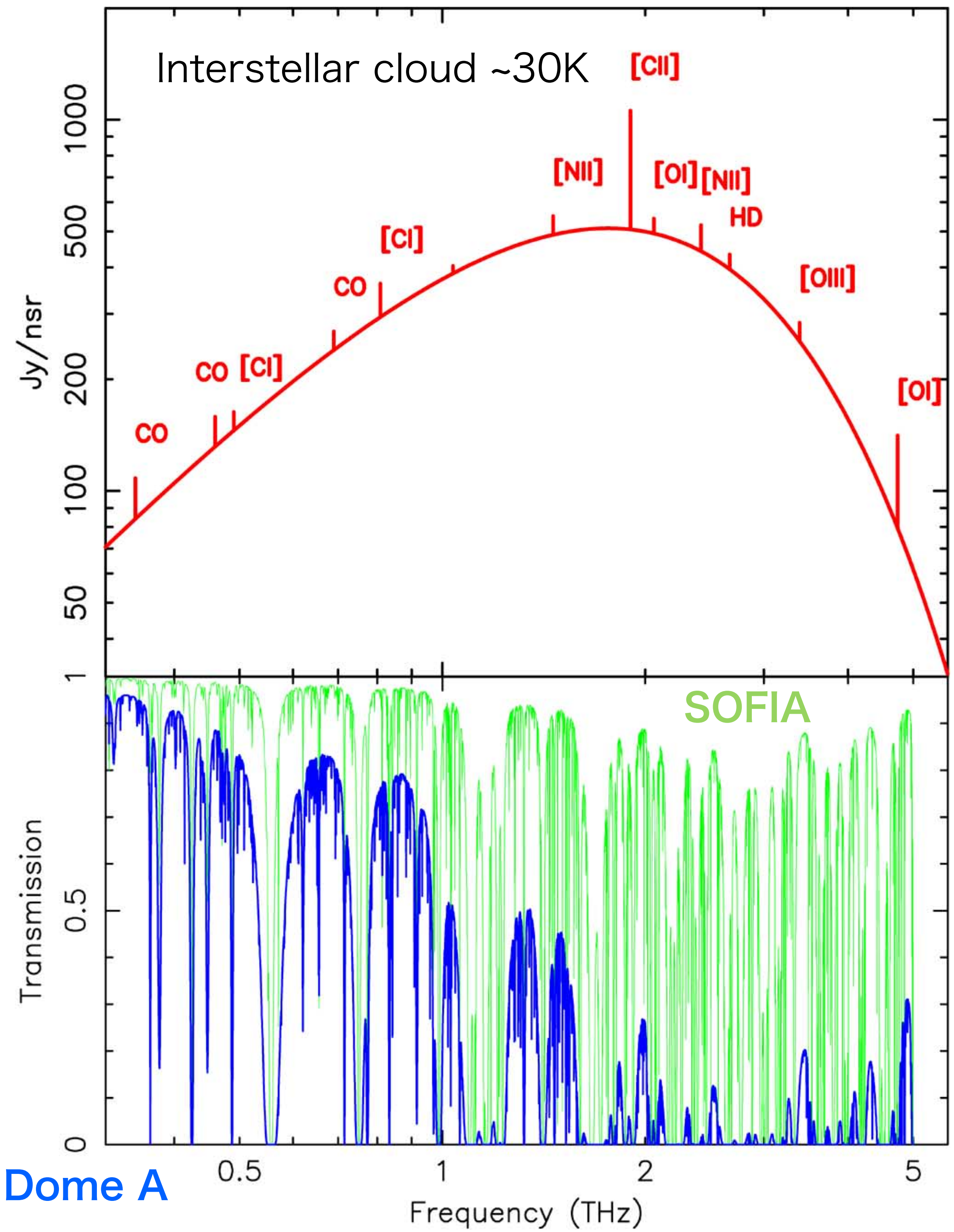
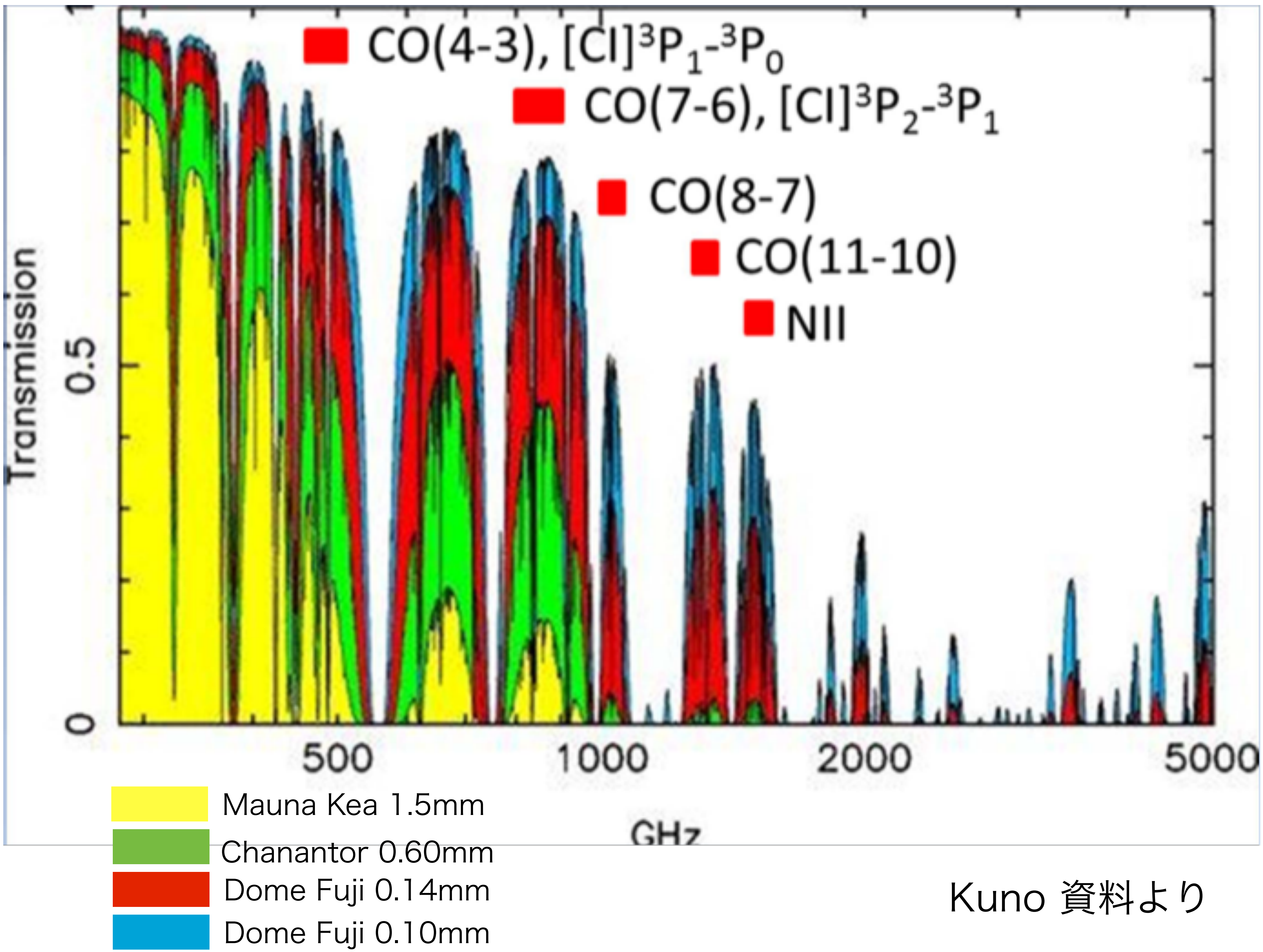


TABLE I
SAMPLE OF IMPORTANT THz LINES

Species	Freq (THz)	Typical Ground[a]	Best Ground[a]	Airborne[a]
C	0.492, 0.809	Y	Y	Y
CH	0.532, 0.536	N	Y	Y
H_2O	0.557, 1.113	N	N	N
HCl	0.635	Y	Y	Y
D_2H^+	0.692	Y	Y	Y
CO	1.037-1.497	N	Y	Y
CH^+	0.835	M	M	Y
OH^+	0.909	M	Y	Y
NH_2	0.953	M	Y	Y
NH	0.974	N	M	Y
NH^+	1.013	N	Y	Y
H_2O^+	1.115	N	N	N
HF	1.232	N	N	Y
H_2D^+	1.370	N	Y	Y
N^+	1.461	N	Y	Y
OH	1.835, 1.838	N	M	Y
H_2O_2	1.846	N	N	N
C^+	1.901	N	M	Y
O	2.060, 4.746	N	M/N	Y
HD	2.675	N	N	Y
O^{++}	3.394	N	M	Y

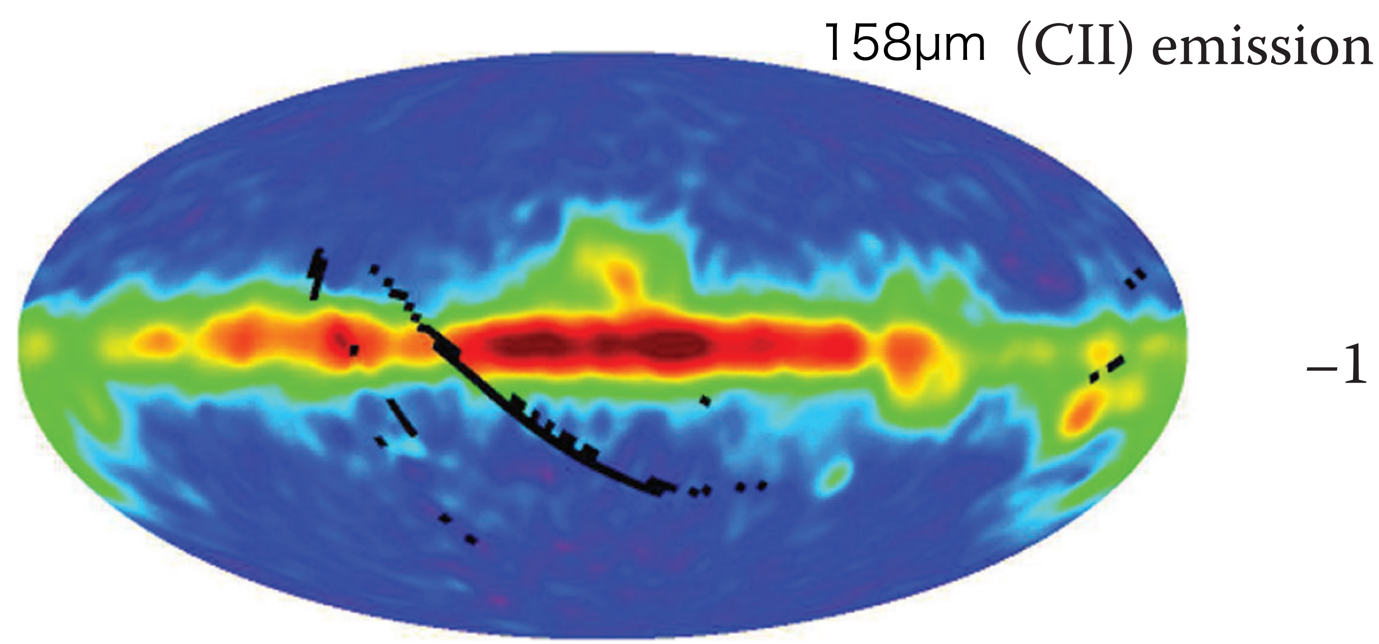
Kulesa (2011)

Atomic and molecular lines at THz

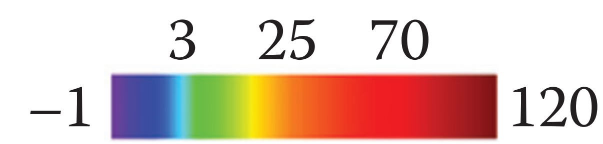


Kuno 資料より

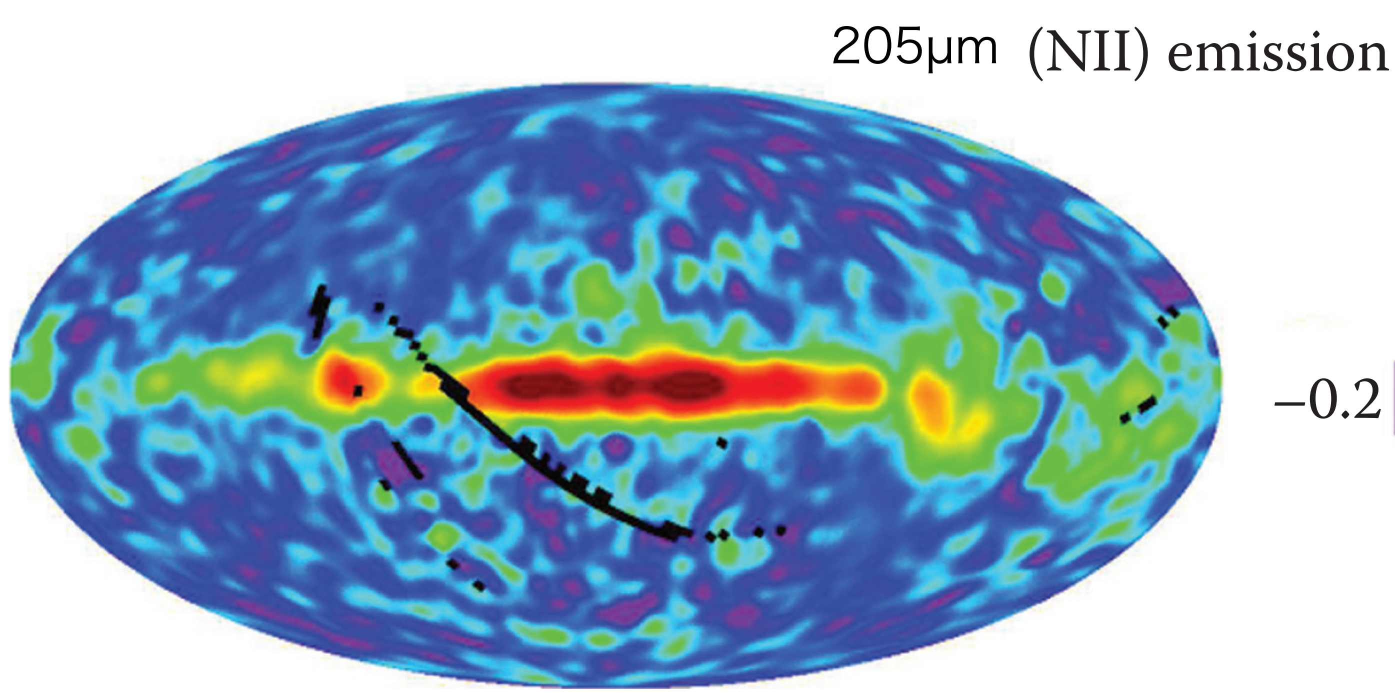
COBE/FIRAS maps of [C II] & [N II]



- All sky survey with a special resolution of 7° & a velocity resolution of 1000km/s



- [C II] line is the dominant cooling line of the ISM at ~0.3% of infrared continuum



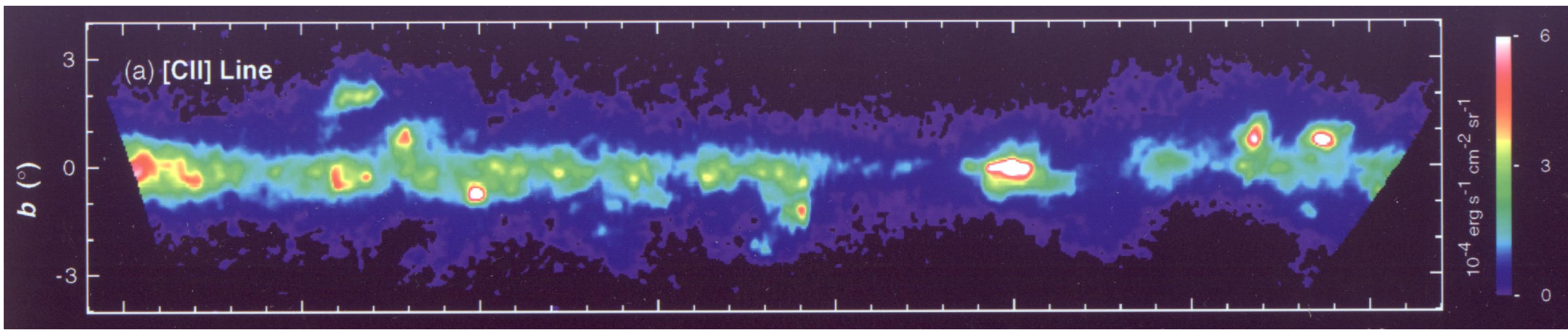
- [N II] & [C I] are less intense by a factor of 10 & 100

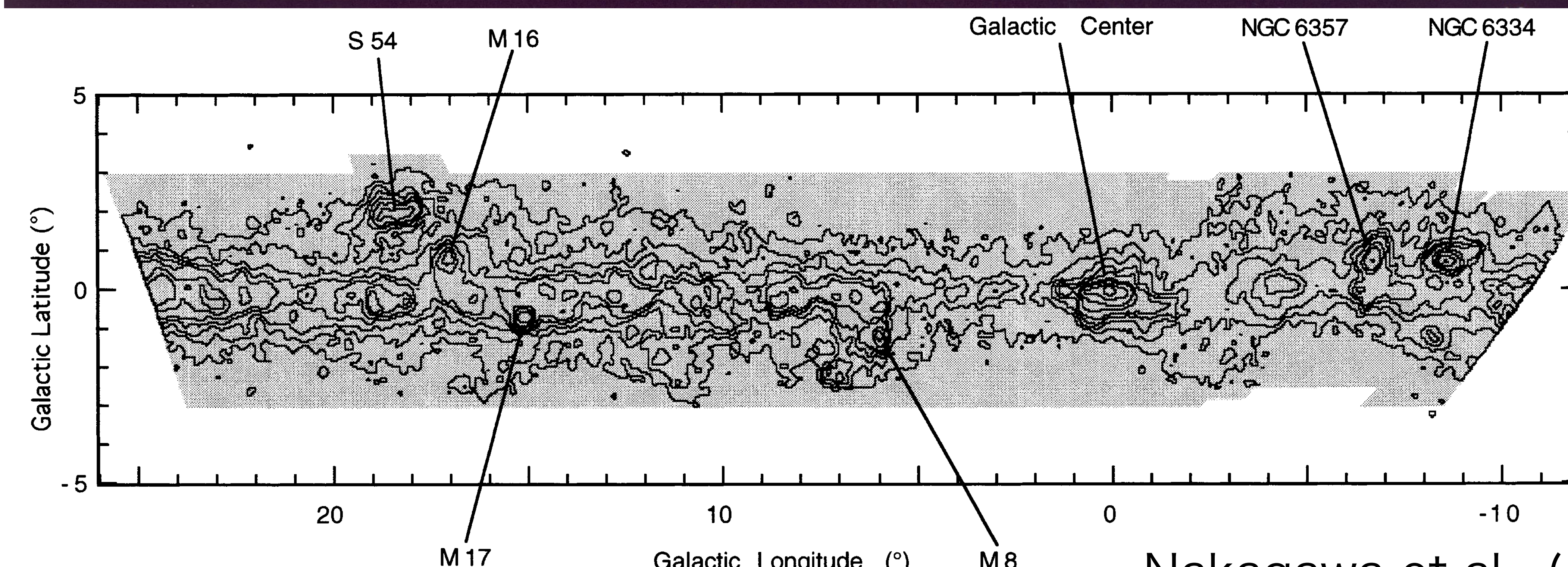
- [N II] line will appear at strongly ionized regions --> by comparing [C II] &[N II], determine if [C II] is arising from ionized or neutral gas

Fixsen, Bennett, & Mather (1999)

[C II] Galactic Plane Survey by BICE

- Balloon-borne Infrared Carbon Explorer
  - 15' angular resolution & 175 km/s velocity resolution



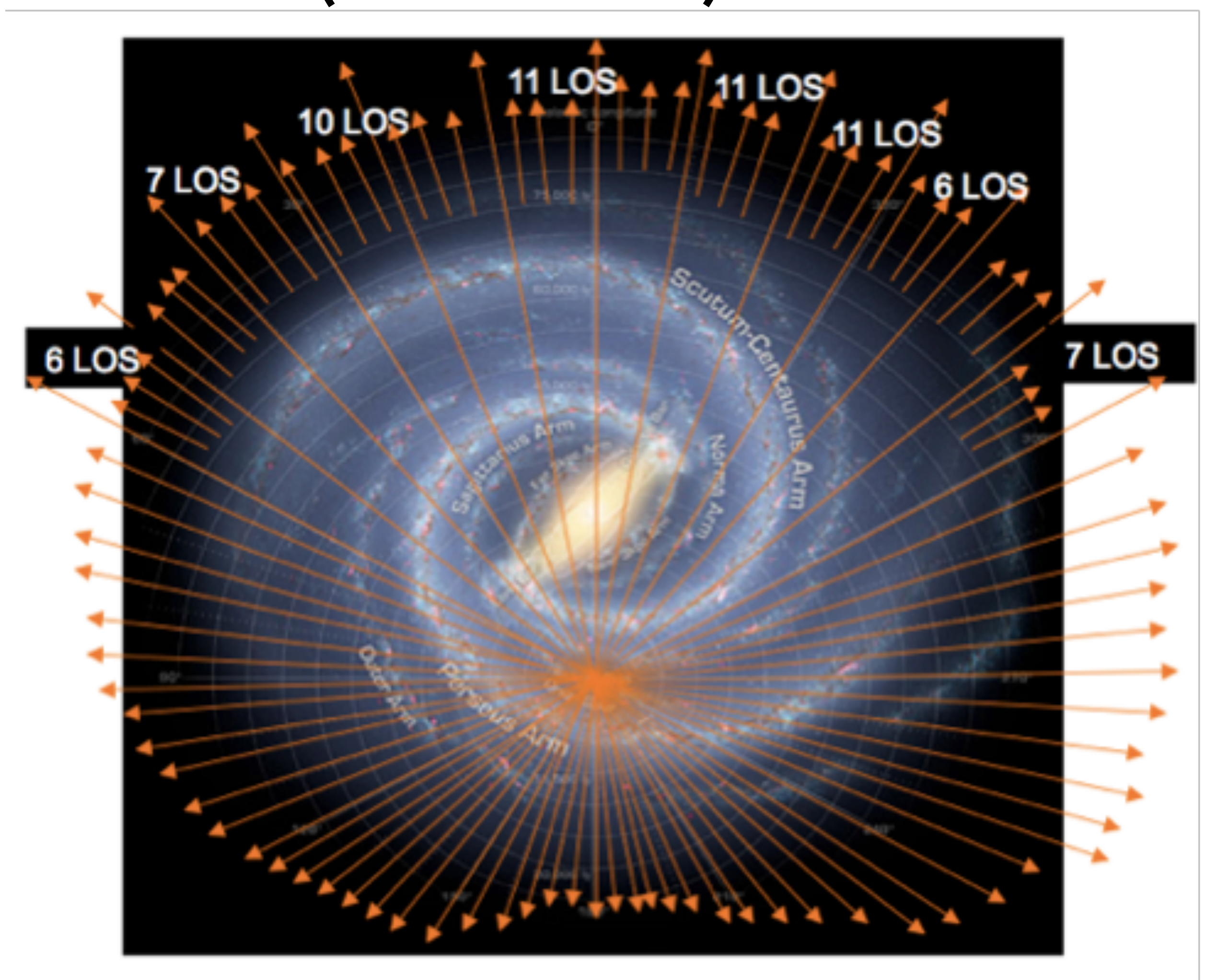


Nakagawa et al. (1998)

FIG. 8.—Far-infrared [C II] line intensity contour map obtained by BICE with a spatial resolution of 15′. Contour levels are 0.3, 0.6, 1, 1.5, 2, 3, 4, 6, and 9 × 10^{-4} ergs s^{-1} cm^{-2} sr^{-1}. The shading shows the observed area. Representative bright sources are labeled.

Herschel [C II] Galactic plane survey

- Galactic Observations of Terahertz C+ (GOT C+)

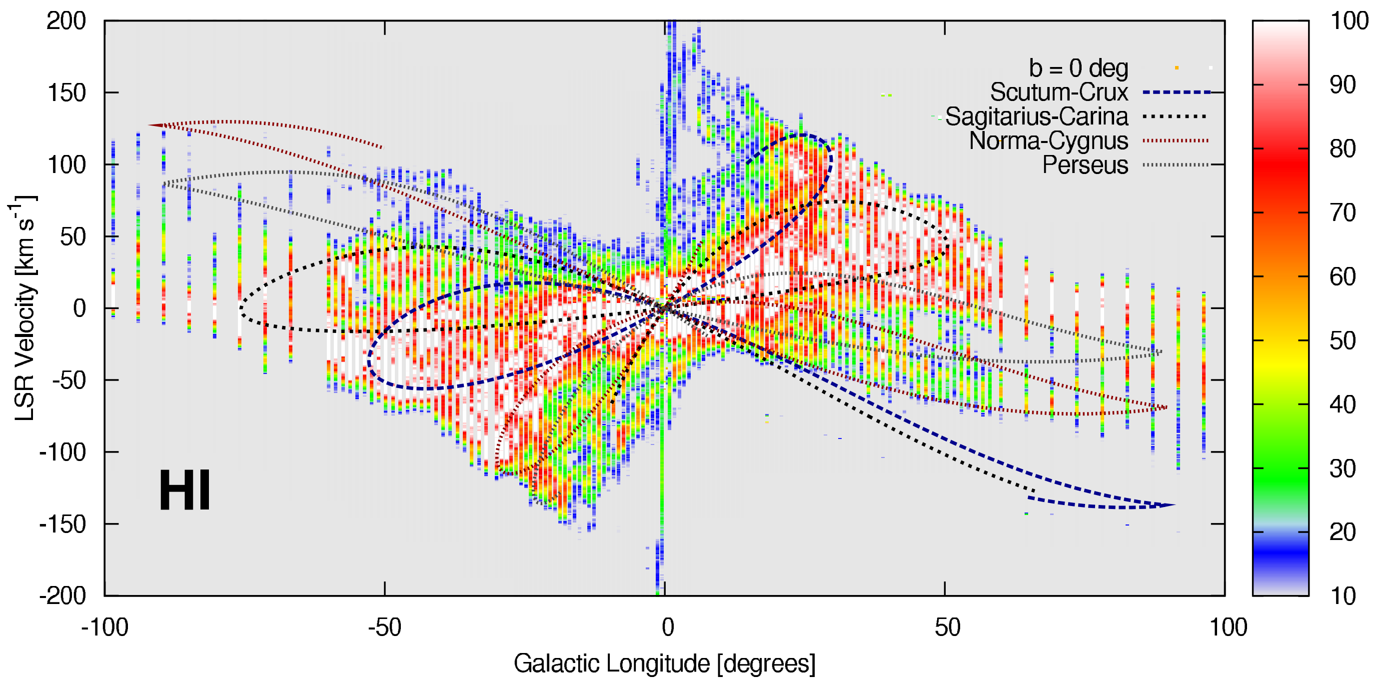


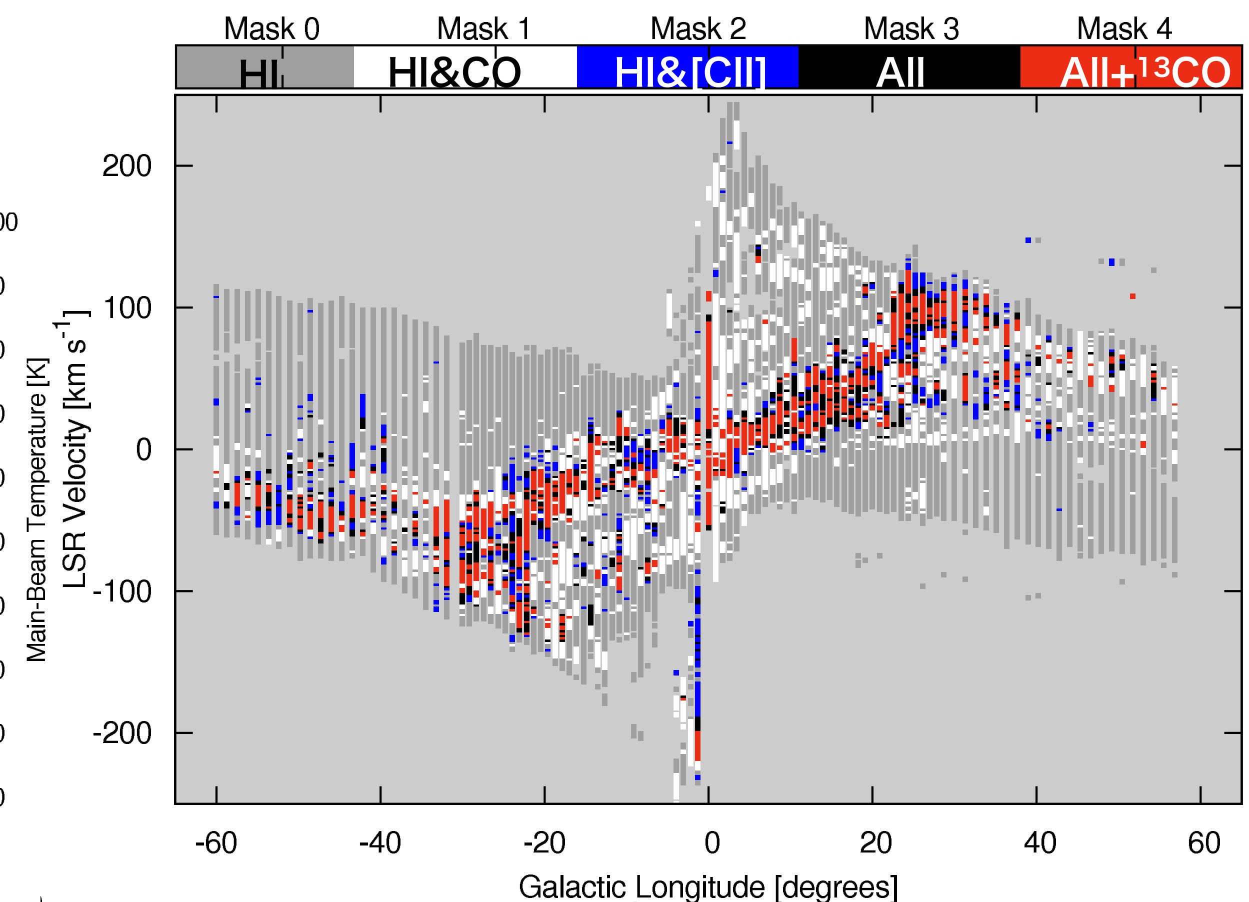
- [C II] survey by Herschel(3.5m)/ HIFI with 12” angular resolution & 0.1 km/s velocity resolution
- 452 LOSs volume-weighted sample of the Galactic plane
- Every 0.87° (|l|<60°), 1.3° (30°< |l| <60°), 4.5° (60°< |l| <90°), and 4.5° to 13.5°(|l| >90°)
- b=0°, ±0.5°, and ±1.0°, ±2.0 (|l| >90°)

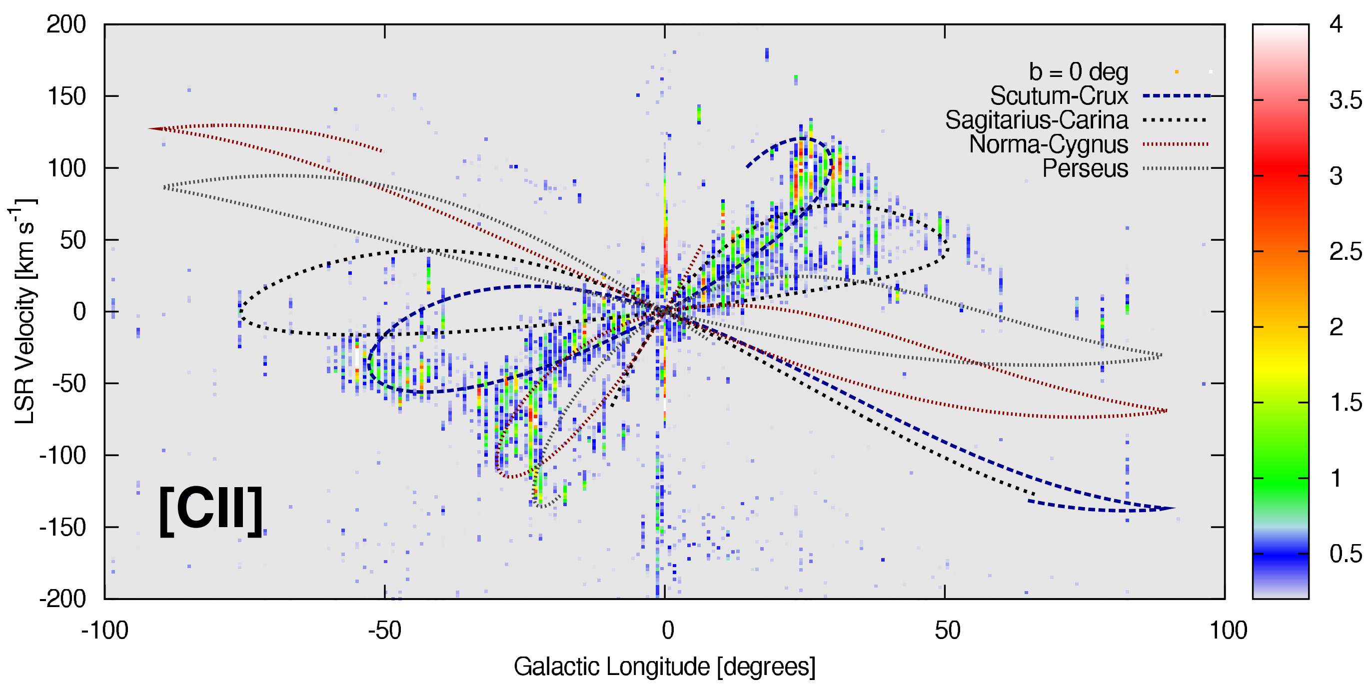
Langer et al. (2010), Pineda et al. (2013), Langer et al. (2014)

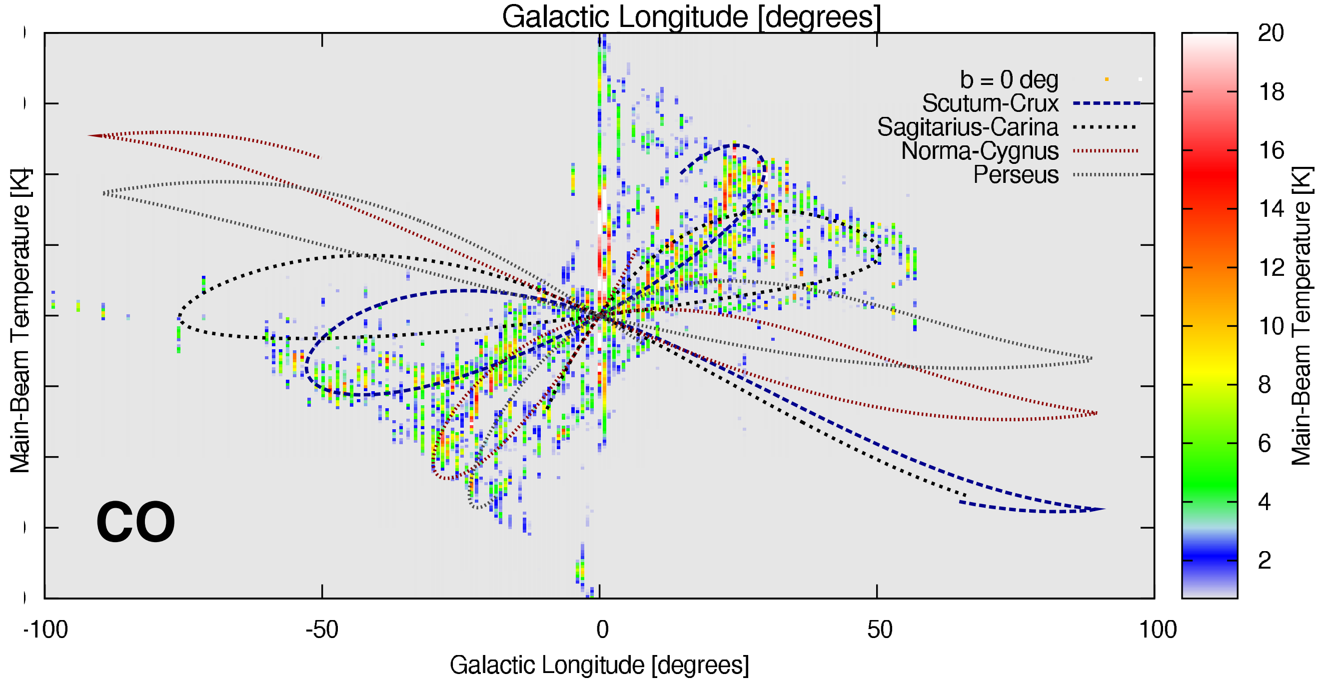
Herschel [C II] Galactic plane survey

- P-V maps at b=0°





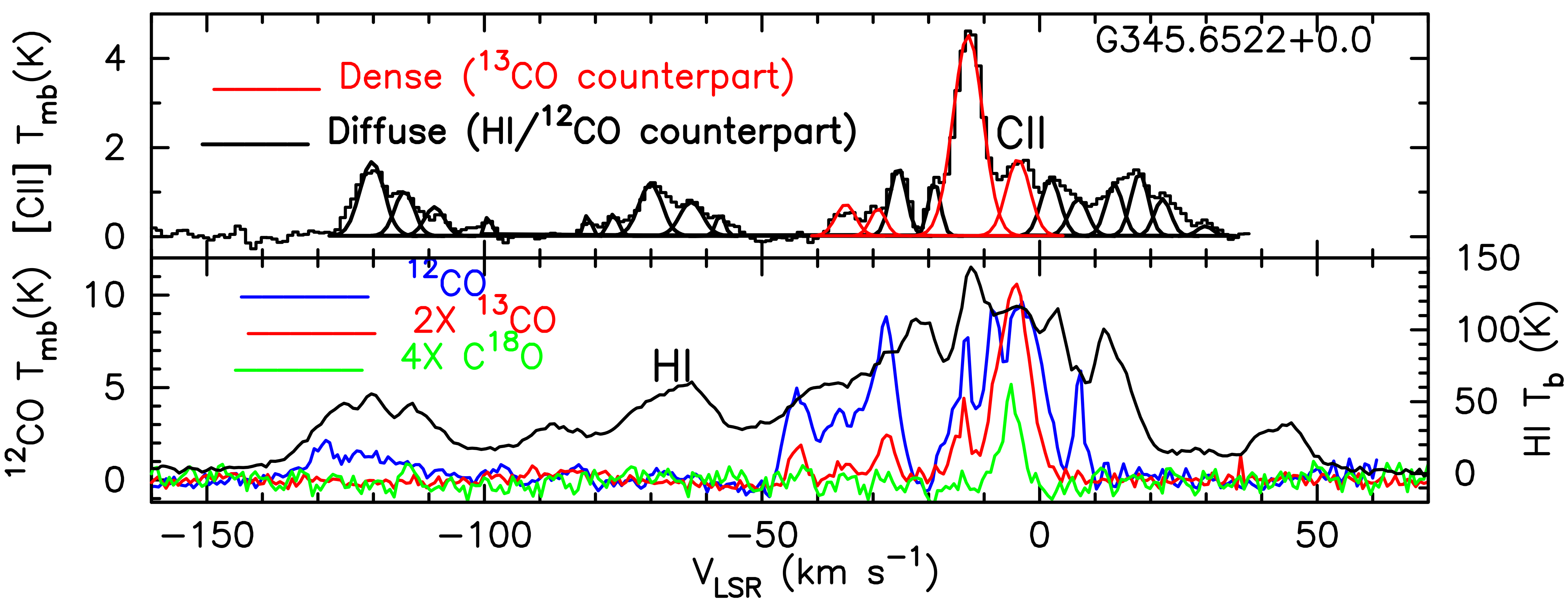




Pineda et al. (2013)

Herschel [C II] Galactic plane survey

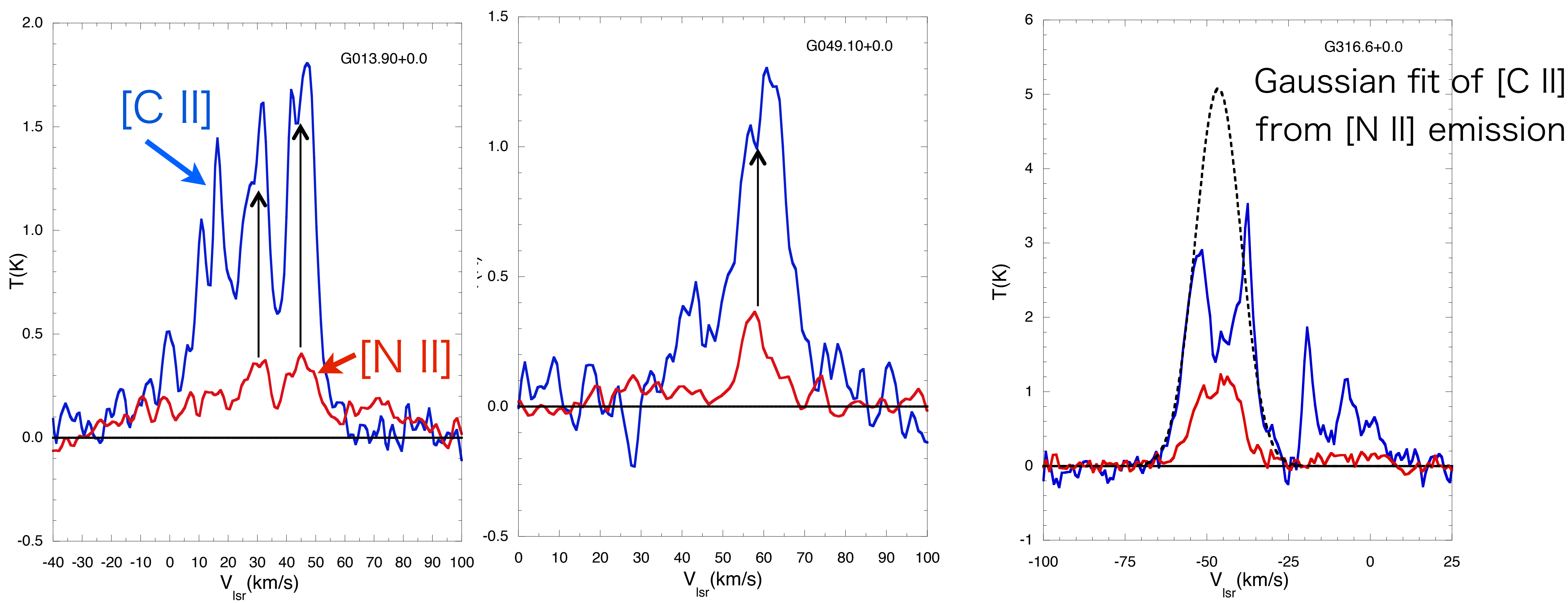
- ISM components in the Galactic plane
  - Combining HI, [C II], and CO data
  - [C II] emission comes from PDRs(~47%), “CO-dark” cloud (~28%), cold atomic gas(~21%) and ionized gas(~4%)
  - HI is mostly CNM in the inner Galaxy, but WNM in the outer Galaxy



Langer et al. (2010), Pineda et al. (2013), Langer et al. (2014)

[C II] and [N II] by Herschel/HIFI

- [N II] emission to the GOT C+
  - Can separate the contributions from highly ionized and weakly ionized gas to the [C II] emission
  - [C II] emission arising from strong sources of [N II] emission is frequently absorbed by foreground gas --> **underestimate** highly ionized gas by only [C II] observations



Langer, Goldsmith & Pineda (2016)

[N II] Galactic Plane Survey

FUGIN Project

(Umemoto et al. 2017 PASJ, 69,78)

- Using multi-beam receiver FOREST, OTF mapping of the Galactic plane in ^{12}CO, ^{13}CO, $C^{18}O$(J=1-0), simultaneously

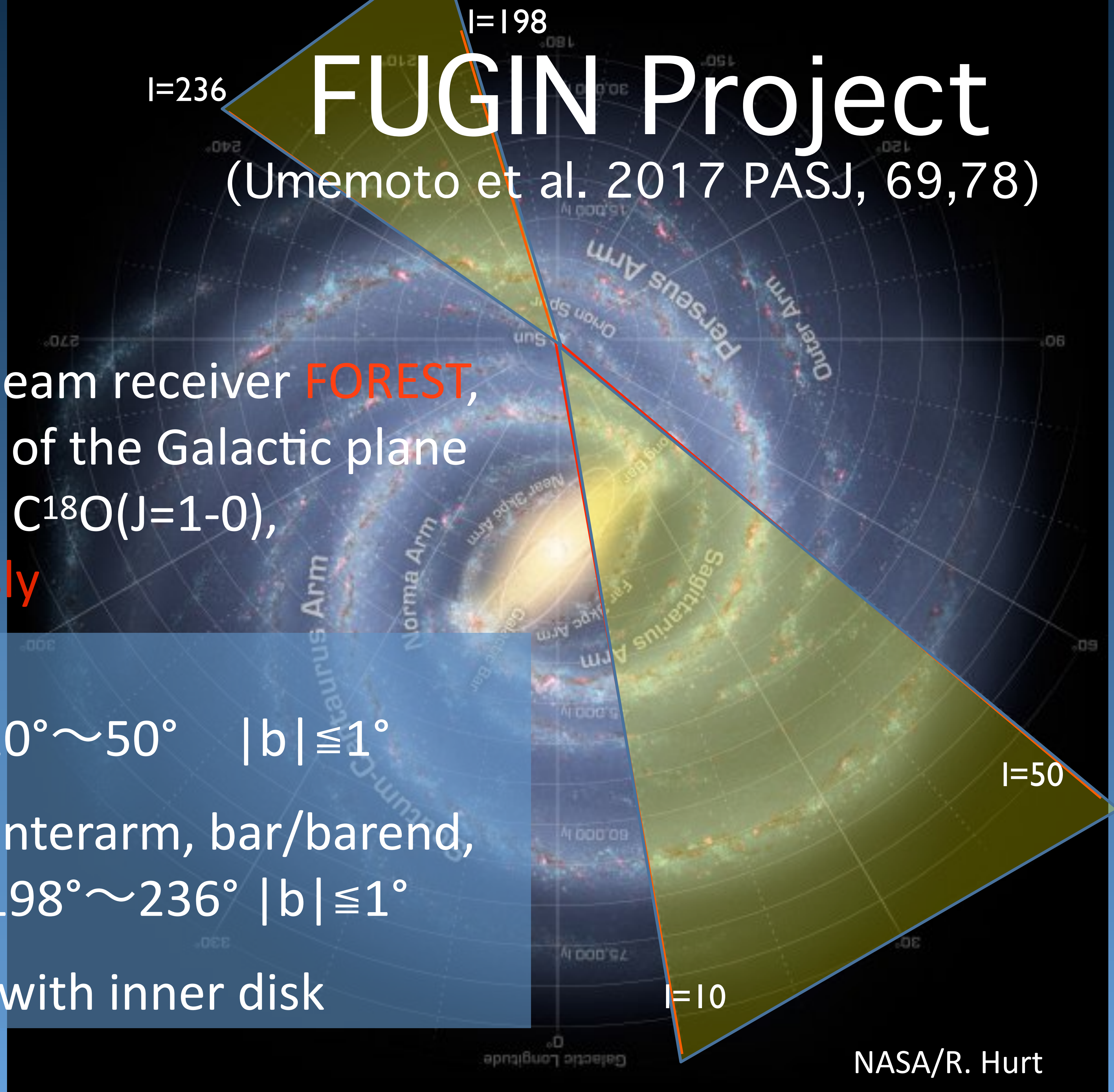
Mapping area:

inner disk: l = 10°～50°　|b|≦1°

Spiral arms, interarm, bar/barend,

outer disk: l = 198°～236° |b|≦1°

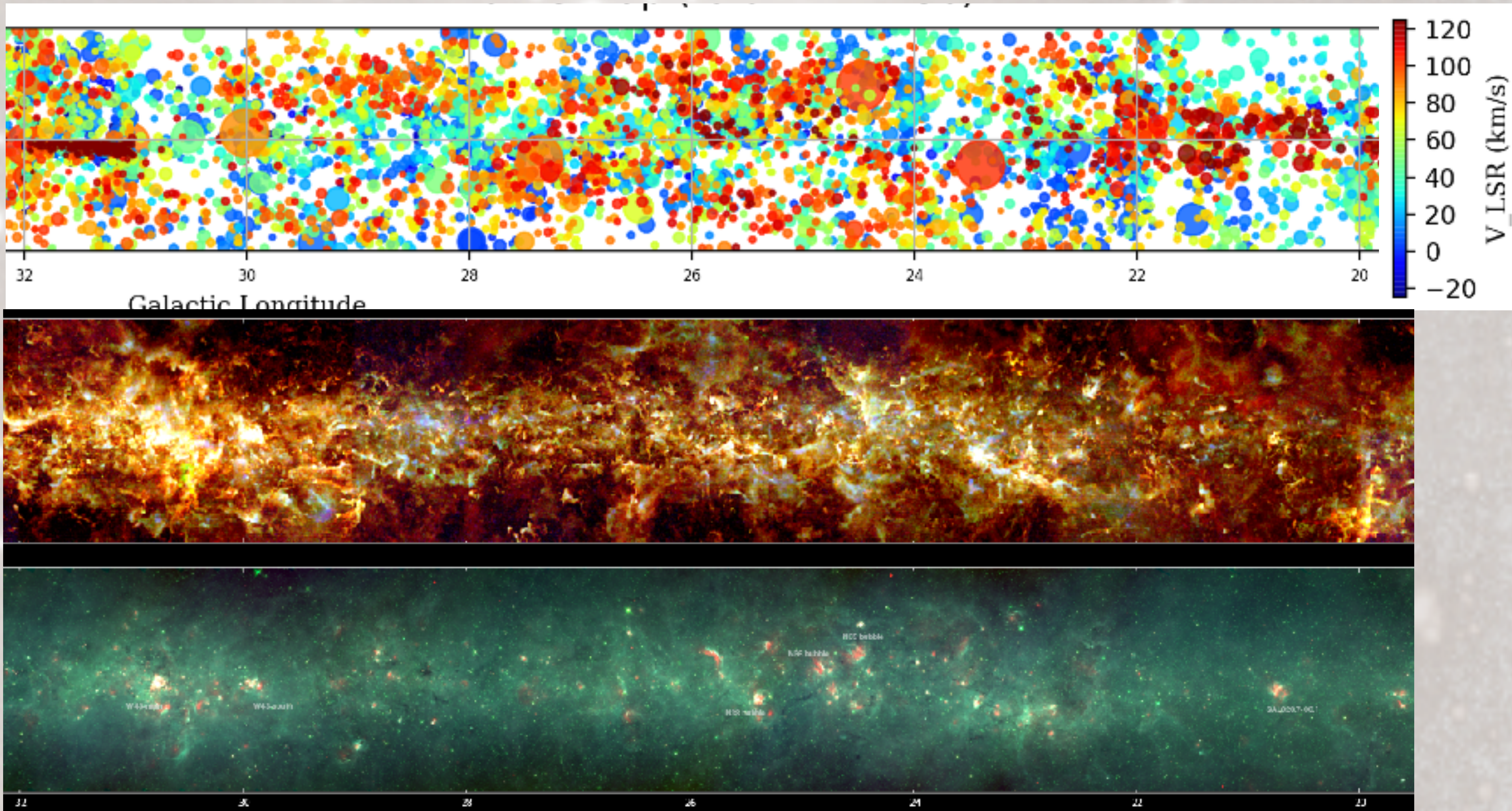
Comparison with inner disk

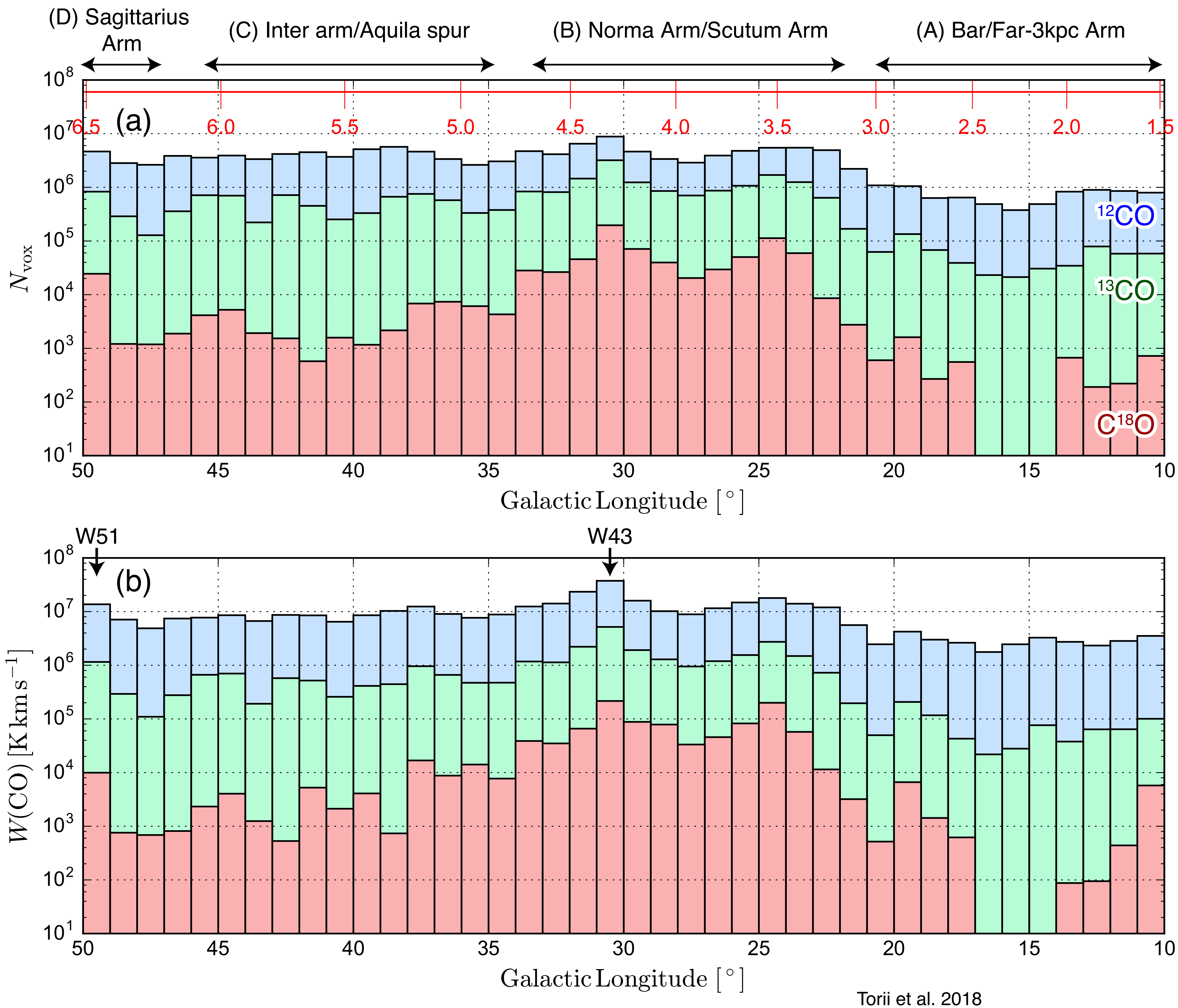


NASA/R. Hurt

01 Molecular Cloud Identification

Identified Strunctures by Dendrogram (Fujita et al. in prep.)

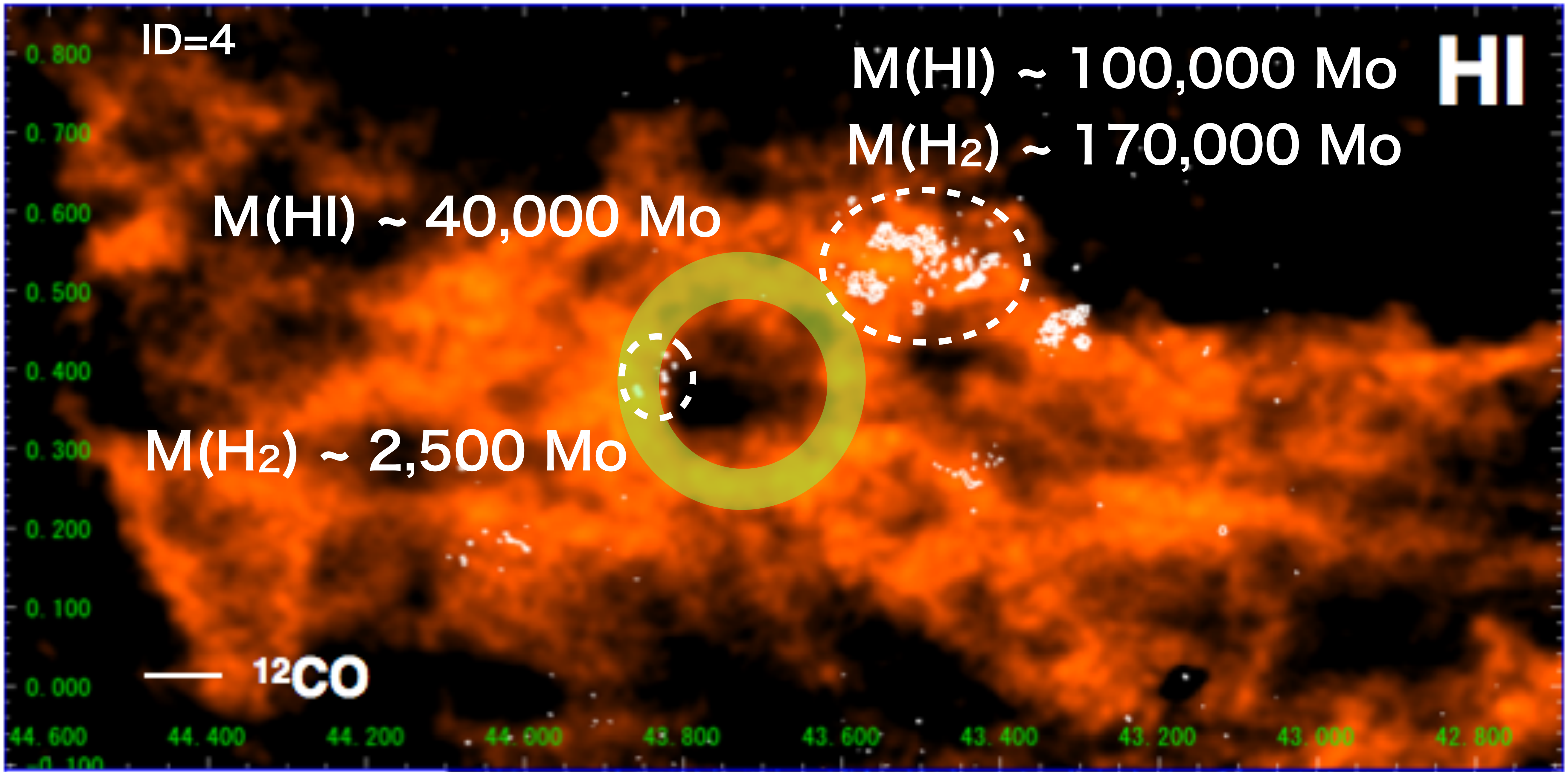




(D) Sagittarius Arm
(C) Inter arm/Aquila spur
(B) Norma Arm/Scutum Arm
(A) Bar/Far-3kpc Arm
(a)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
^{12}CO
^{13}CO
C^{18}O
$N_{\rm vox}$
Galactic Longitude [°]
W51
W43
(b)
W(CO) [K km s^{-1}]
Galactic Longitude [°]
Torii et al. 2018

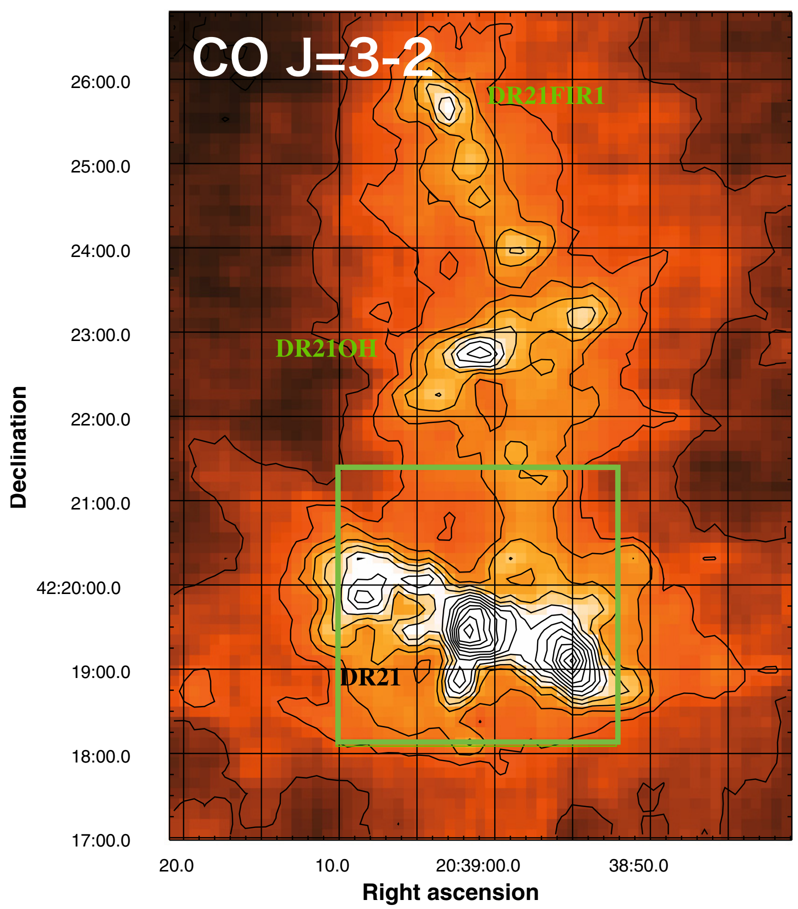
HI and H_2 mass

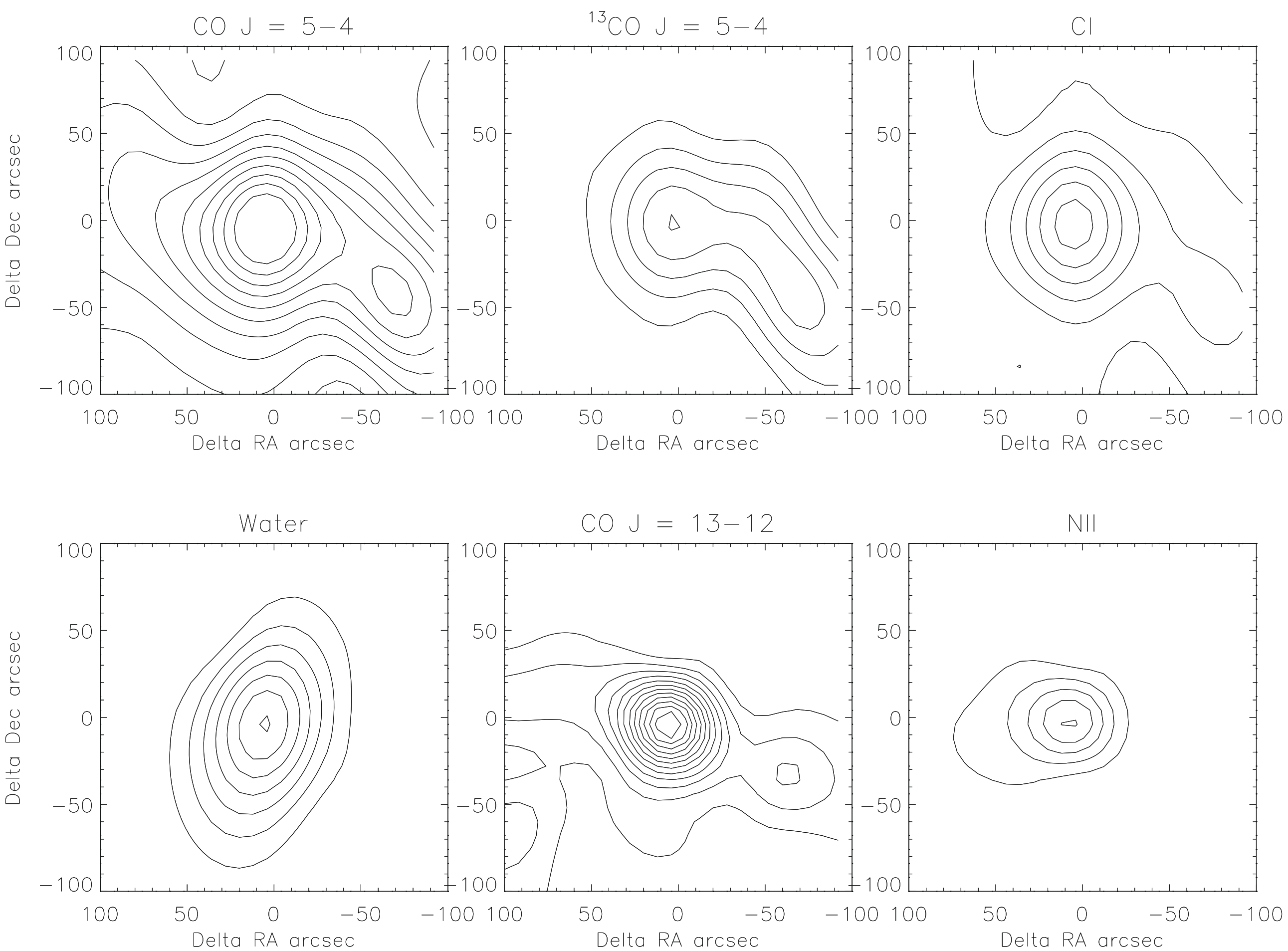
- FUGIN CO clouds identified with the DENDROGRAM



Herschel-SPIRE of DR21

- Herschel-SPIRE spectroscopy
  - 196-671μm (CO, ^{13}CO, HCO^+, H_2O, [C I], [NII]) $\lambda / \Delta \lambda = 1000$
  - [N II] 205μm <--> [C II]157 : n_{crit} = 46 cm^{-3}, Te=8000K
  - [N II] emission to the east coincides with a hole in the excited H_2, indicate a cavity of ionized gas

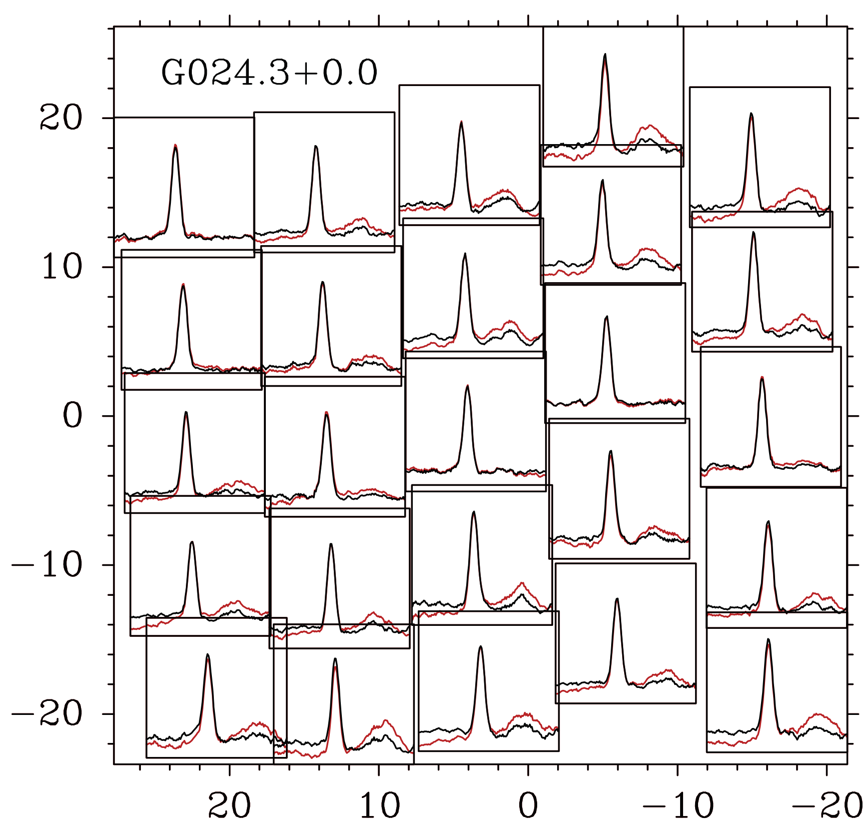


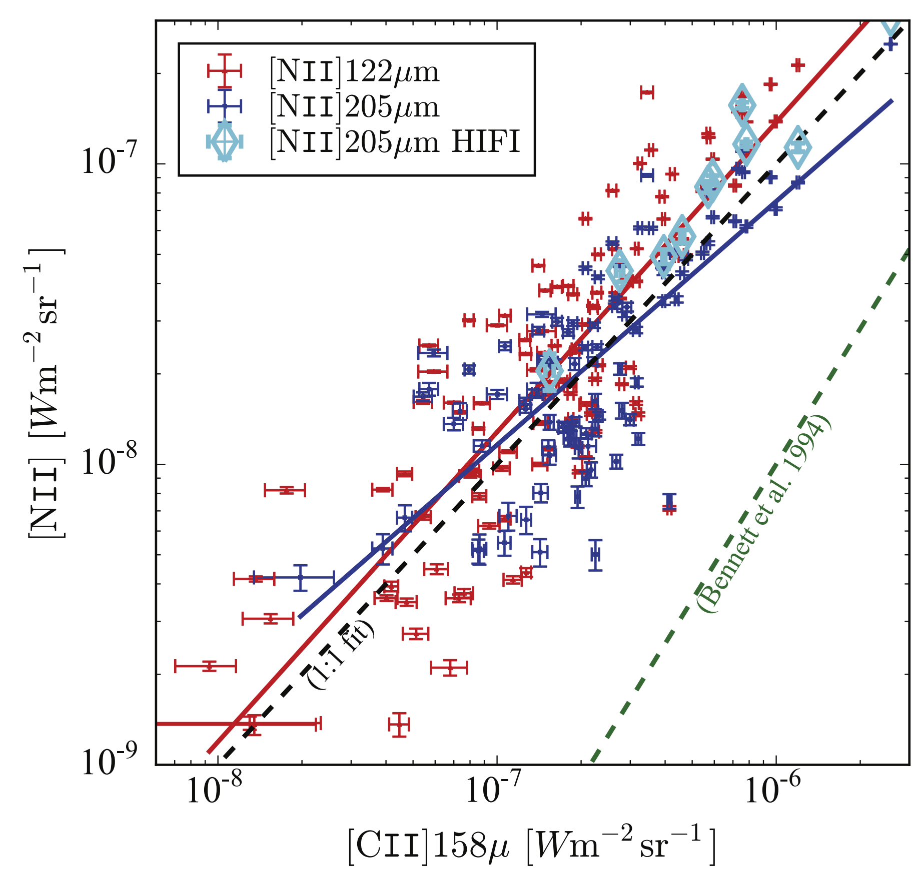


White et al. (2010)

Herschel [N II] Galactic plane survey

- [N II] at 122 & 205 μm with PACS(5x5)
  - 149 LOSs selected from GOT C+, 10”(122um),15”(205μm)
  - Bothe lines are detected in the range -60°≤ l ≤60°
  - [N II] emission highly correlated with that of [C II]
  - High electron density--> extended envelopes of H II regions, and low-filling factor high-density fluctuations of WIM





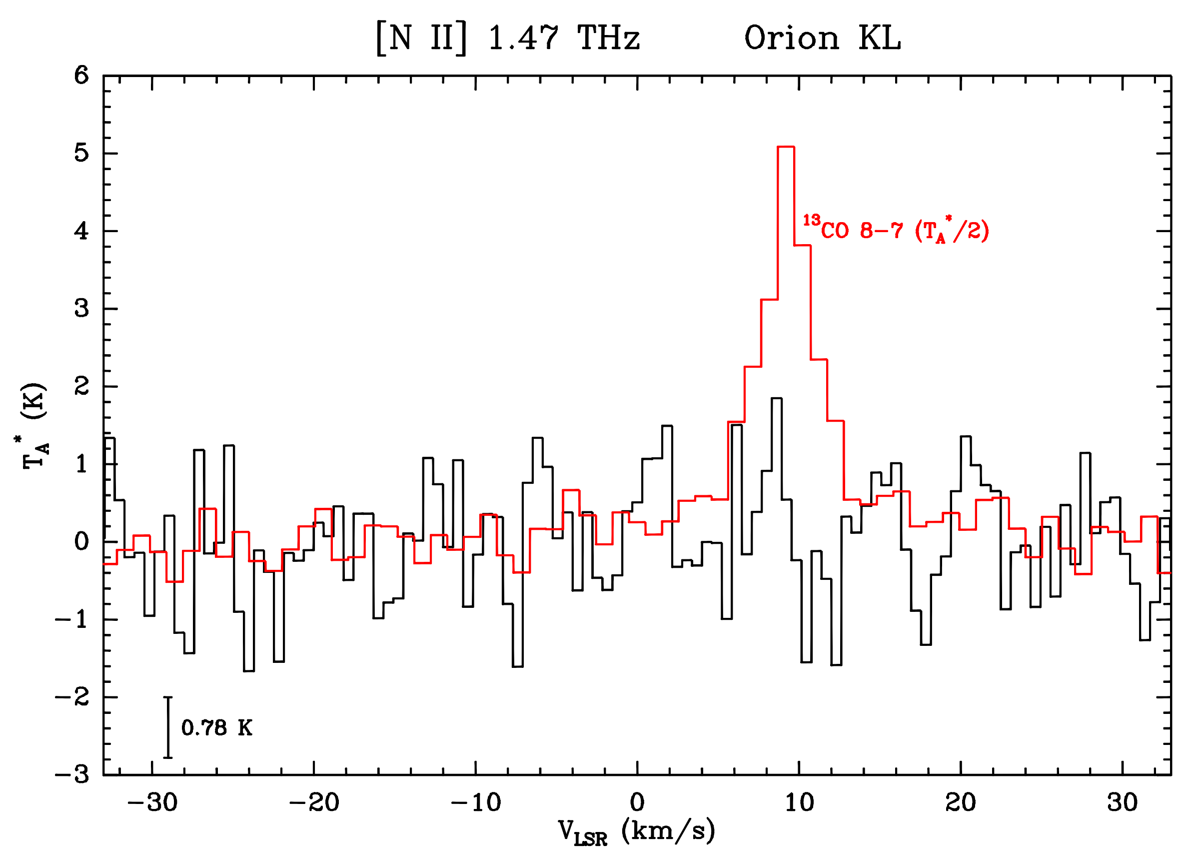
Goldsmith et al. (2015)

[N II] 1.46 THz Galactic plane survey

- [N II] emission line
  - [N II] line will appear at **strongly ionized** regions --> by comparing [C II] &[N II] maps, it is possible to determine if [C II] is arising from **ionized or neutral** gas
  - [C II] emission is frequently **absorbed** by foreground gas --> underestimate highly ionized gas by only [C II] observations
  - An **excellent probe** of star formation rate (**SFR**) and infrared dust luminosity (**L_{IR}**) (Zhao et al. 2013) because the [N II] is less contaminated from the emission of older star due to an ionization potential higher than hydrogen
- [N II] 1.46 THz Galactic plane survey @S.P.
  - **Wide area mapping of the Milky Way --> evolutionary process of interstellar medium not only neutral gas but also ionized gas**

THz Telescopes on the ground

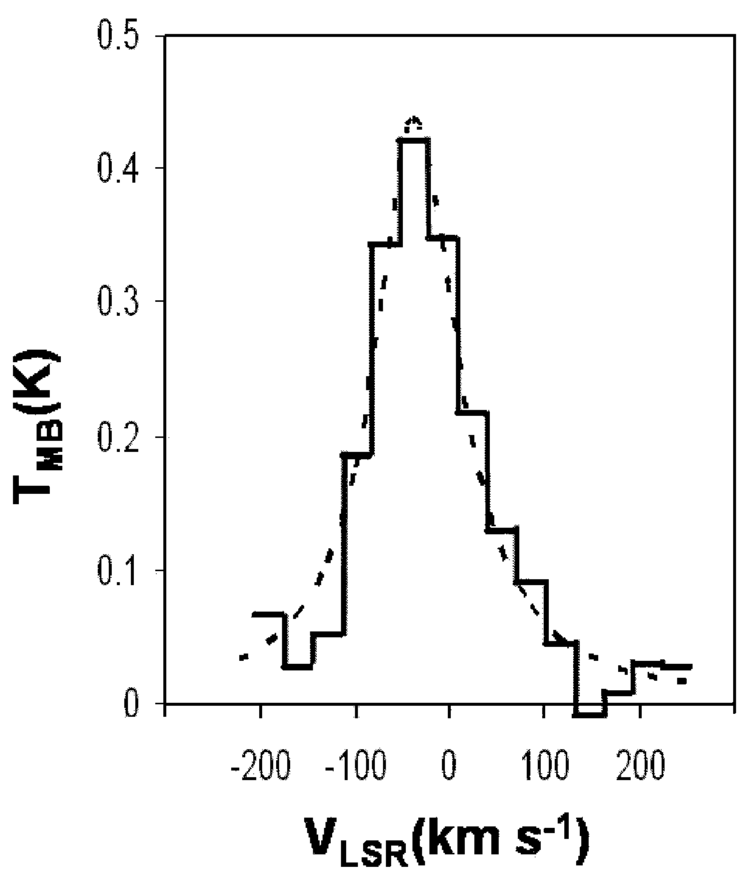
- Receiver Lab Telescope (80cm) (SAO)
  - Ground-base at 5525m , 40 km north of ALMA
  - 1~2 THz (^{12}CO, ^{13}CO, [C I] 809GHz, [NII] 1.46THz)
  - did not detect [N II] emission at Ori KL<--> 5K expected from [C II]/[N II] by COBE
  - --> different filling factor of two lines trace gas



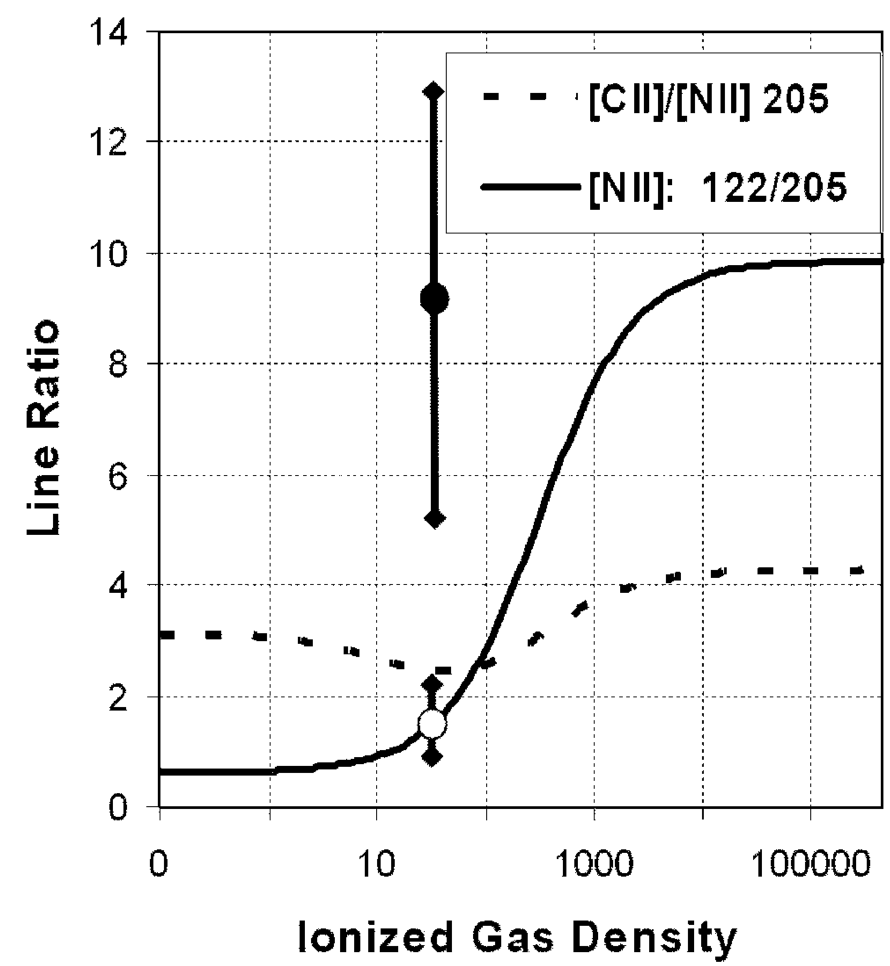
Marrone et al. (2005)

Detection of 205μm [N II] from Ground

- AST/RO at South Pole (1.7m)
  - The first detection of 205μm [N II] line from ground-base
  - [N II] emission reveals the fraction of [C II] emission arises from the ionized gas and the neutral ISM
  - **27% of [C II] arises from the low-density ionized gas but 73% from the neutral ISM!**

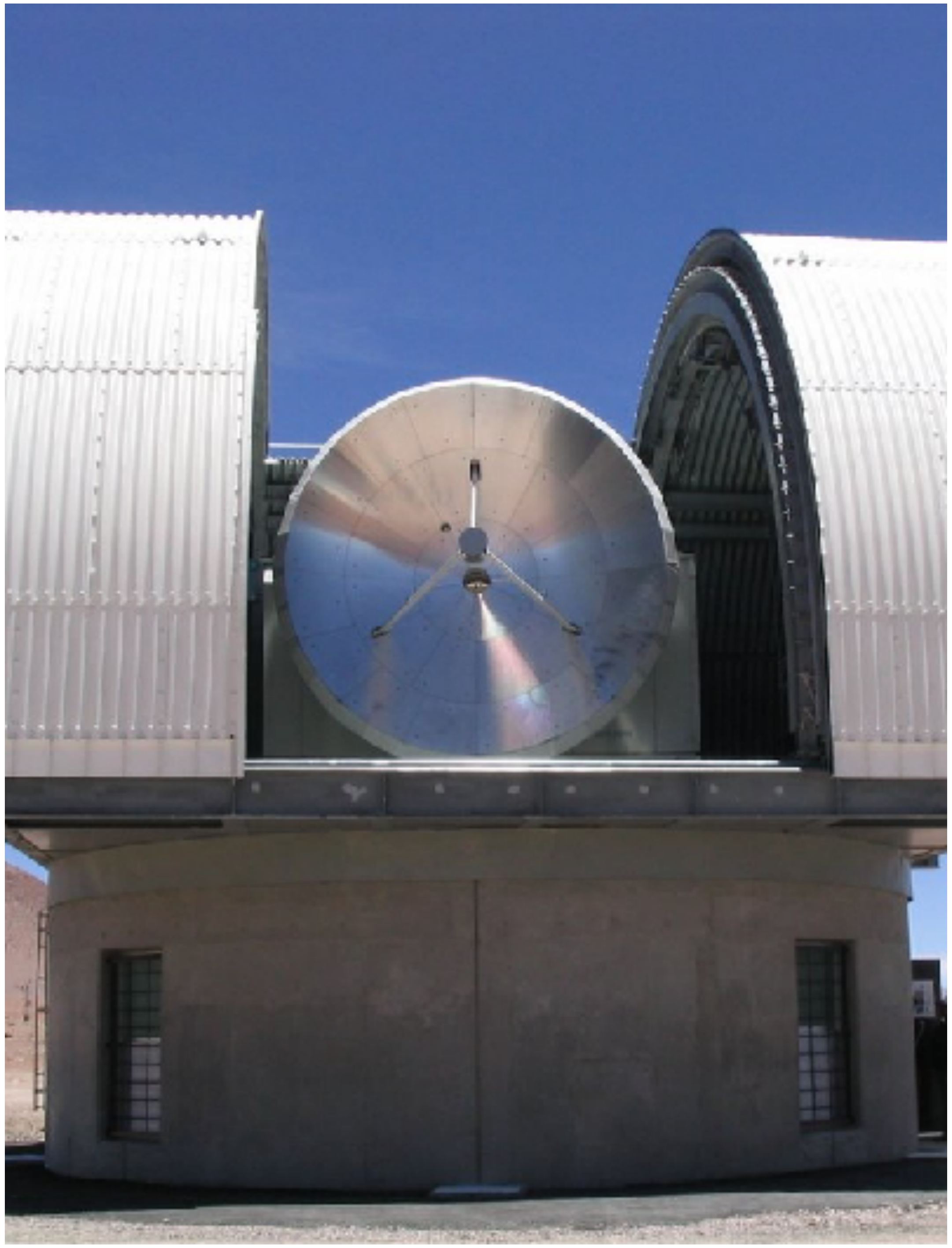


[N II] emission from Carina nebular
with velocity resolution of 60 km/s



Oberst et al. (2006)

Small Telescope Designed as Survey



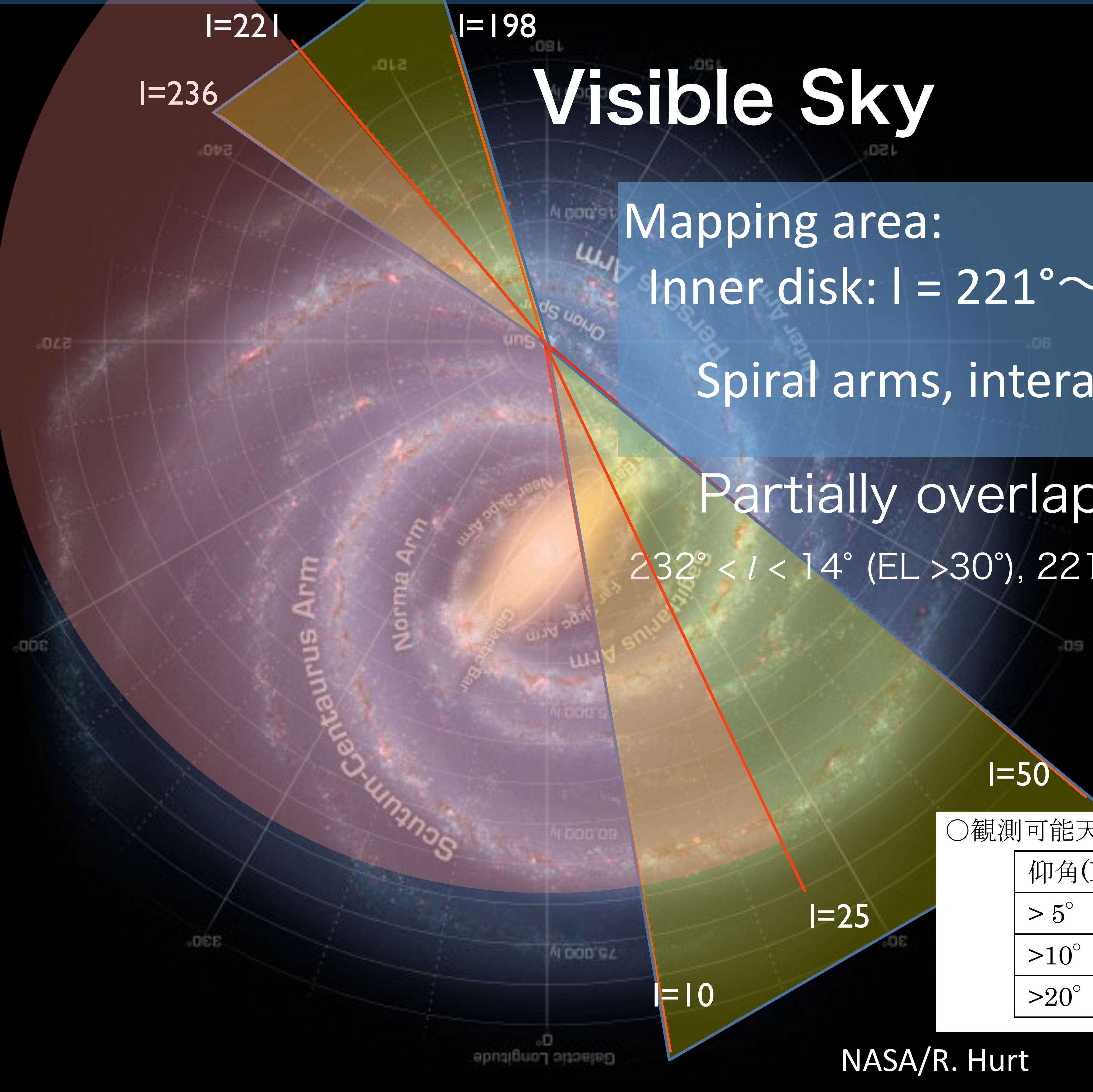
NANTEN II (4m)

- Diameter: 3-6 m
- Surface accuracy: < 20μm
  - For the detection of 205μm [N II] line from ground-base, < 10μm?
- Wide field heterodyne receiver camera
  - For wide area mapping, 100-250 multi-beam receiver

Angular resolution

GHz	3m	4m	6m
460	55”	41”	27”
850	29”	22”	15”
1500	17”	13”	8.5”

Visible Sky



Mapping area:

Inner disk: l = 221°〜25° |b|≦1°

Spiral arms, interarm, bar, G.C.

Partially overlap FUGIN area

232° < l < 14° (EL >30°), 221° < l < 25° (EL>20°)

○観測可能天域（@新ドームふじ）

仰角(EL)	赤緯(Decl.)
> 5°	<+8°
>10°	<+3°
>20°	<−7°

NASA/R. Hurt

Survey with Small Telescope

- [N II] 1.46THz Galactic plane survey
  - [N II] emission reveals the fraction of [C II] emission arises from the ionized gas and the neutral ISM
  - [C I] 809GHz observation when the weather is not good
  - Mapping area: l = 221°- 25° (EL>20°), $|b| \leq 1°$ ($|b| \leq 2°$)
  - 20" grid, $\Delta T(5\sigma)$=0.76K, 10x10 beams —> 20,000h (OTF)
    >> more low noise receiver and more beams (or smaller D)

Freq. band (GHz)	Freq. range (GHz)	Lines	Beam	Sensitivity (5σ) (τ=10min, Δv=1km/s)	Angular Resolution (D=4m)
460	385-540	CO (J=4-3), [C I] $^3P_1$-$^3P_0$	250	0.054 K	41.3"
650	575-735	HCl, D_2H^+	250	0.092 K	28.5"
850	775-965	CO (J=7-6), [C I] $^3P_2$-$^3P_1$	250	0.14 K	21.7"
1000	1000-1060	CO (J=8-7), NH^+	100	0.35 K	18.7'
1300	1250-1380	CO (J=11-10), H^2D^+	100	0.47 K	14.2"
1500	1450-1550	[N II]	100	0.76 K*	12.7"

(*:Tsys=6000K) From Kuno's document

Survey with ~~Small Telescope~~

- [N II] 1.46THz Galactic plane survey
  - [N II] emission reveals the fraction of [C II] emission arises from the ionized gas and the neutral ISM
  - [C I] 809GHz observation when the weather is not good
  - Mapping area: l = 221°- 25° (EL>20°) some strip scans
  - 20" grid, ΔT(5σ)=0.76K, 10x10 beams —> 55h (OTF)/strip >> some strip scans at latitude b

Freq. band (GHz)	Freq. range (GHz)	Lines	Beam	Sensitivity (5σ) (τ=10min, Δv=1km/s)	~~Angular Resolution (D=4m)~~
460	385-540	CO (J=4-3), [C I] $^3P_1$-$^3P_0$	250	0.054 K	~~41.3"~~
650	575-735	HCl, D_2H^+	250	0.092 K	~~28.5"~~
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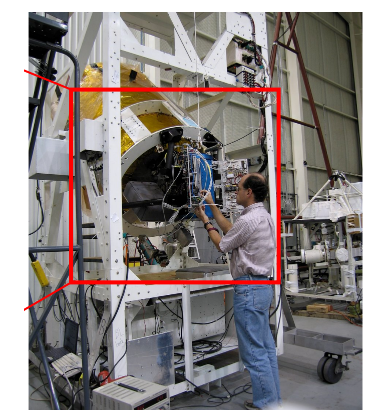
1300	1250-1380	CO (J=11-10), H^2D^+	100	0.47 K	~~14.2"~~
1500	1450-1550	[N II]	100	0.76 K*	~~12.7"~~

(*:Tsys=6000K) From Kuno's document

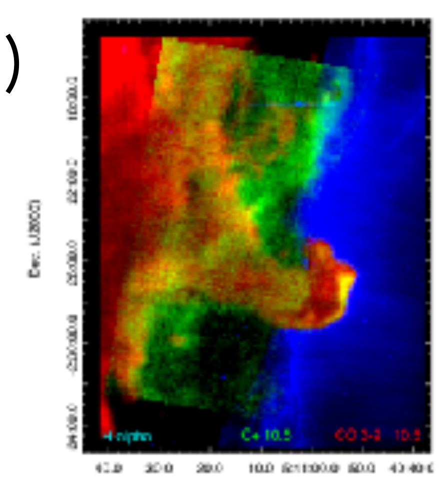
THz Survey Telescopes

- FIRSPEX (~1m) (Rigopoulou et al. 2015)
  - Small satellite from LEO by ESA and CAS(China)
  - [C II] 1.9THz, [NII] 1.46THz, [C I] 809GHz, CO(6-5) 690 GHz

- STO (80cm) (Walker et al. 2016)
  - The Stratospheric TeraHertz Observatory by Balloon
  - [C II] 1.9THz and [NII] 1.46THz at 1 arcmin. angular resolution



- SOFIA(2.5m)/GREAT (Young et al. 2012)
  - GREAT: 60–240μm (Heyminck et al. 2012)
  - 1.25~5 THz ([N II] 1.46THz, [C II] 1.90THz, [O I] 2.06, 4.74THz)



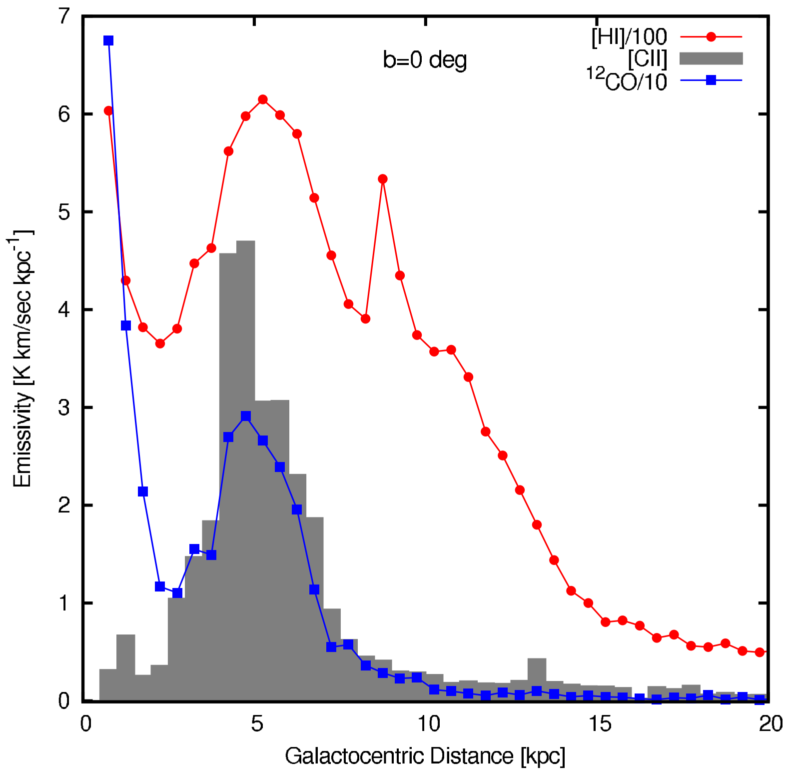
Hα, [C II}], CO(3-2)

Summary

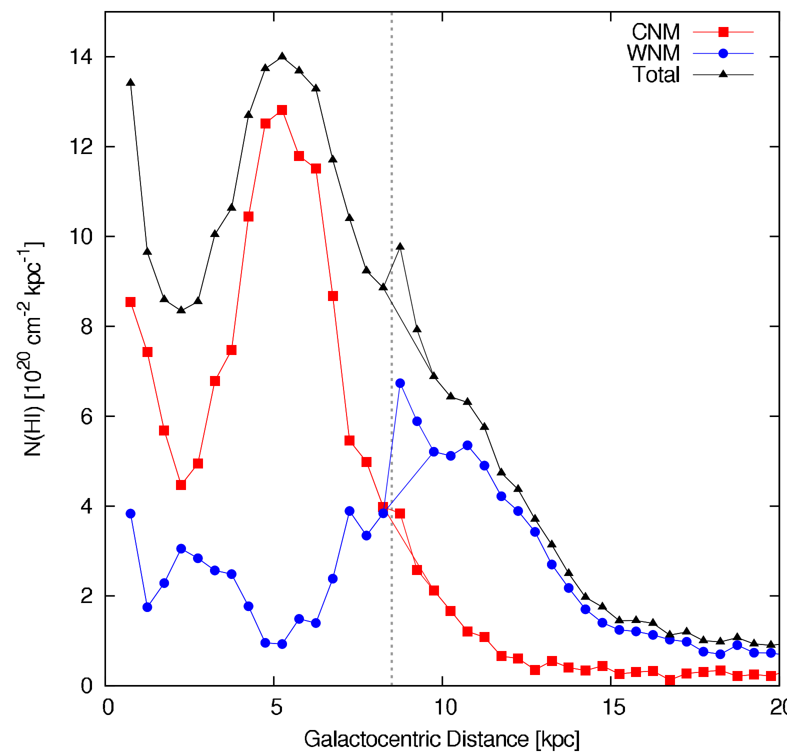
- To understand the evolutionary process of interstellar medium not only **neutral gas** but also i**onized gas**, the observations of **atomic lines at THz** are critical.
- [N II] is an **excellent probe** of star formation rate (**SFR**) and infrared dust luminosity (**L_{IR}**), and [N II] emission reveals the fraction of [C II] emission arises from the **ionized** gas and the **neutral** ISM.
- So I would like to propose the [N II] 1.46THz Galactic plane survey with the heterodyne receiver camera at South Pole. There is difficulty to survey entire the Milky Way, but it is good to observe the limited area (strips) or the latitude direction.

Radial Distribution of ISM

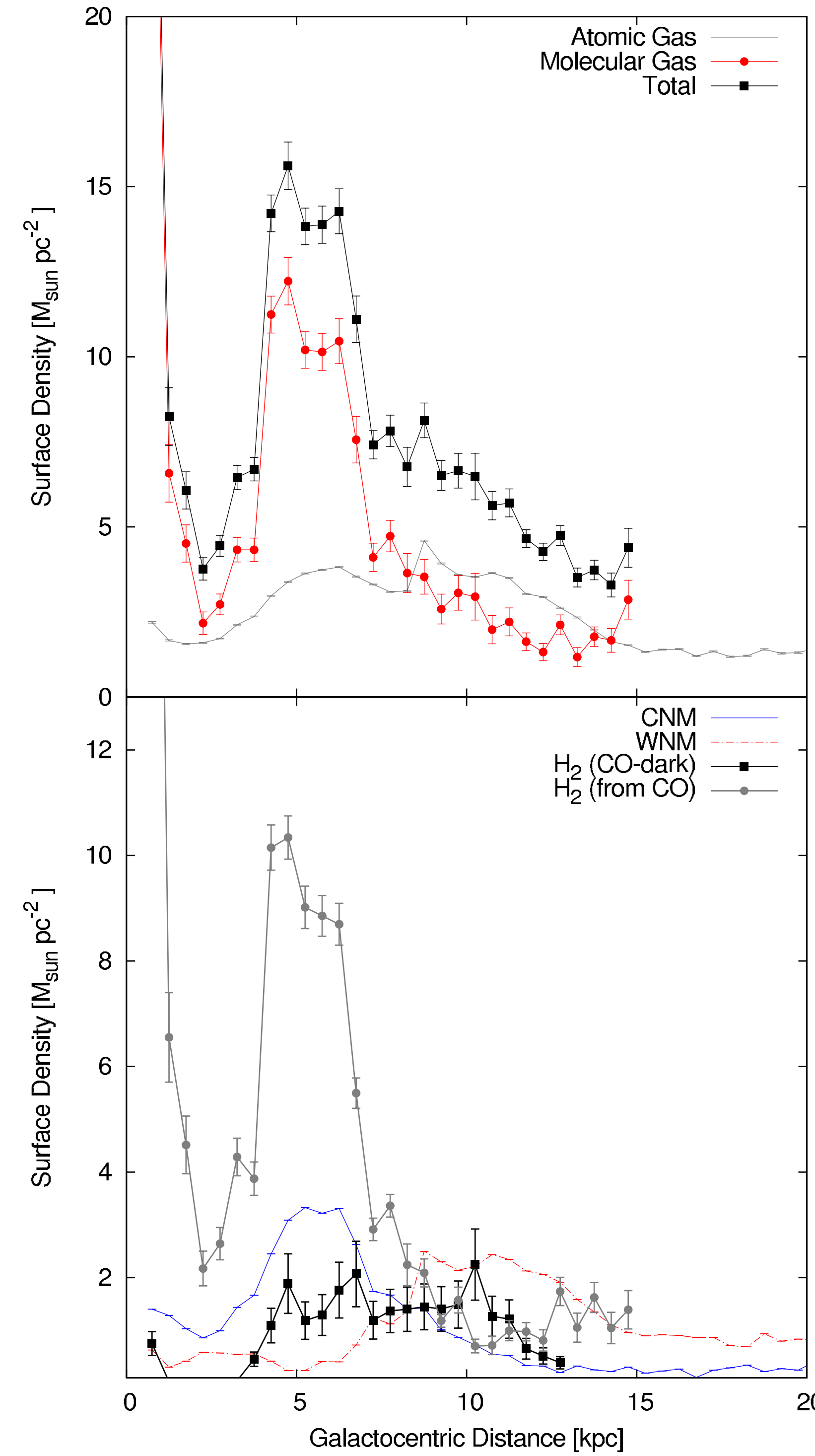
Pineda et al. (2011)



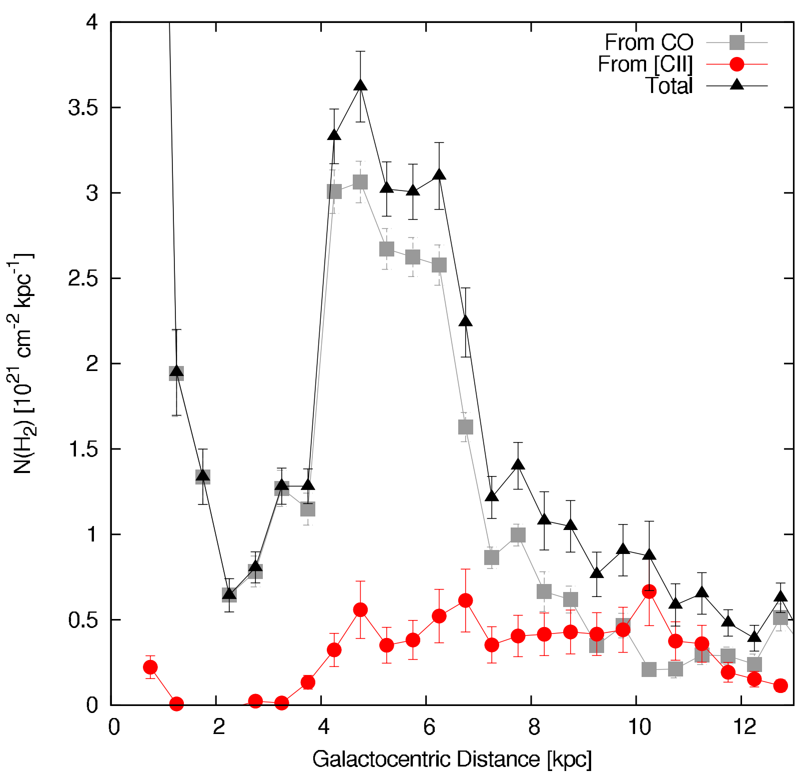
Radial distribution of [C II], H I, and 12CO at b=0



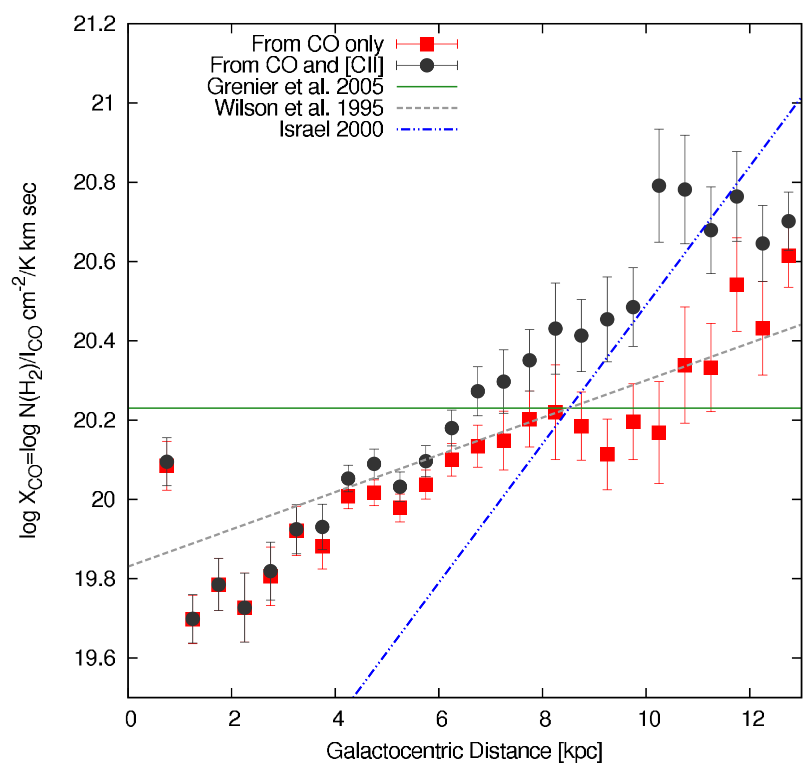
Radial distribution of CNM and WNM



Radial distribution of surface density of hydrogen in the Galactic plane



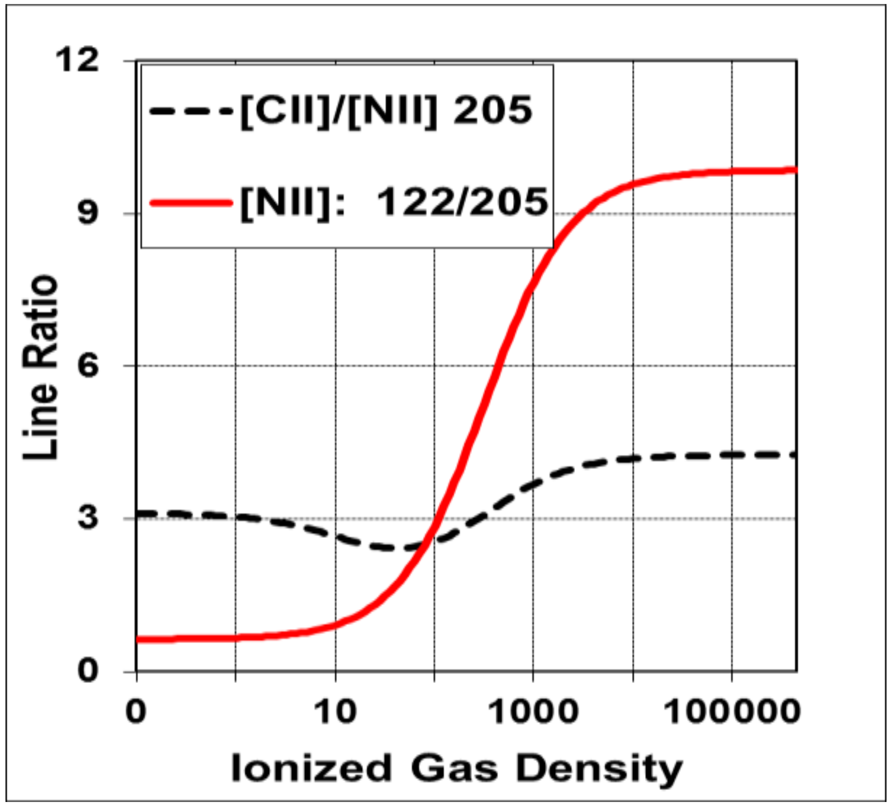
Radial distribution H2 column density



Radial distribution of CO-to-H2 confession factor

Diffuse Gas Density

- [N II]$_{122\mu m}$/[N II]$_{205\mu m}$ line ratio
  - [C II] 158μm/[N II] 205μm line ratio indicates [C II] emission arising in ionized gas (insensitive gas density)
  - [N II] 122μm/[N II] 205μm can be used as an effective density tracer between 20 and 2000cm^{-3} (Stacey 2011)



Stacey et al. (2011)

[N II] as Probe of SFR and L_{IR}

- [N II] emission line
  - An **excellent probe** of star formation rate (**SFR**) and infrared dust luminosity (**L_{IR}**) (Zhao et al. 2013) because the [N II] is less contaminated from the emission of older star due to an ionization potential higher than hydrogen.
  - Therefore, **$L_{[N\,II]}$** may be a more accurate indicator of **SFR** the the more conventional L_{IR} -derived estimates.

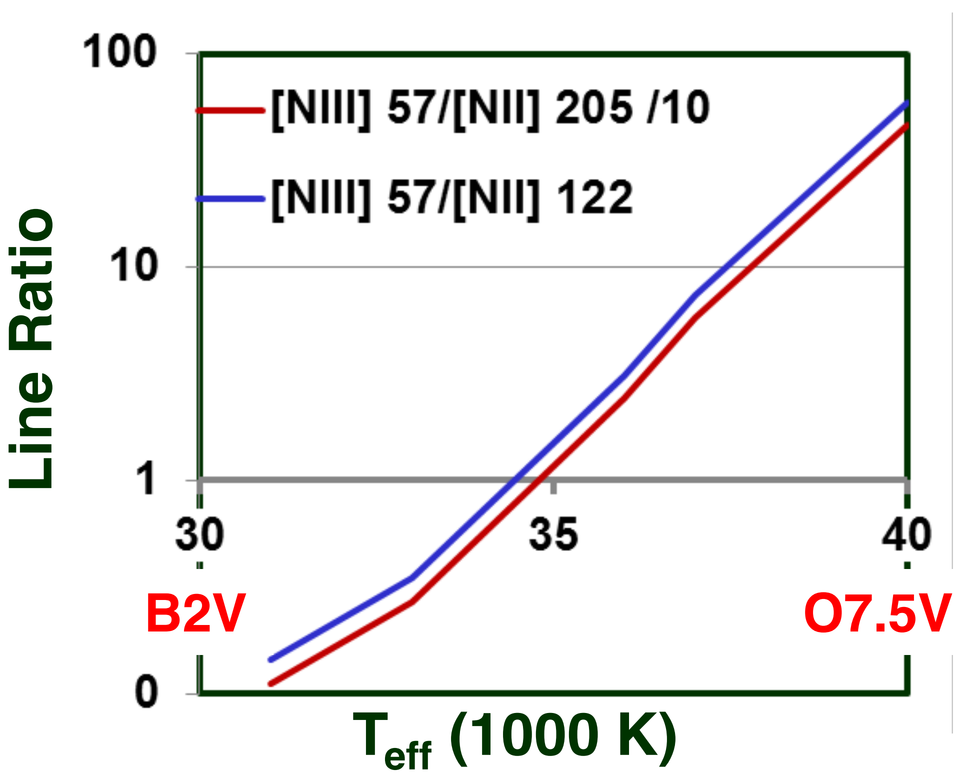
$$\log \mathrm{SFR} = (-5.31 \pm 0.32) + (0.95 \pm 0.05) \log L_{[\mathrm{NII}]}$$

$$\log L_{\mathrm{IR}} = (4.51 \pm 0.32) + (0.95 \pm 0.05) \log L_{[\mathrm{NII}]}$$

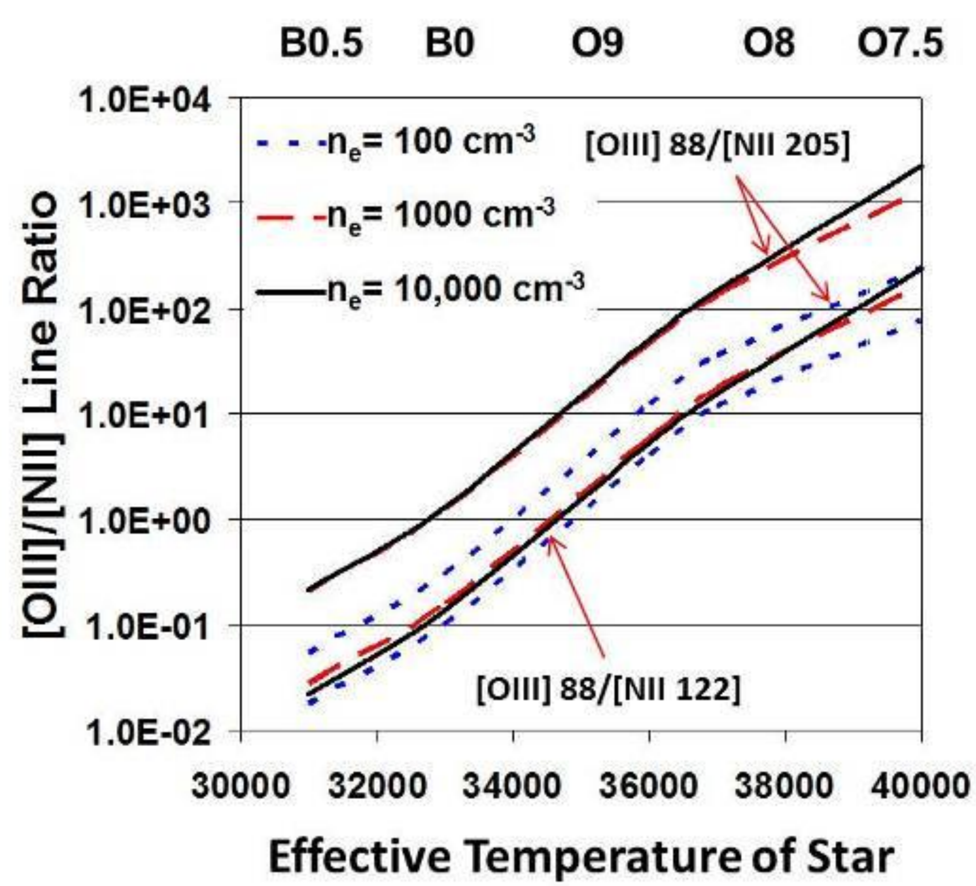
where
SFR = star formation rate ($M_{\odot}$ yr^{-1})
$L_{[\mathrm{NII}]}$ = luminosity of [NII] line ($L_{\odot}$)
L_{IR} = luminosity of dust in IR ($L_{\odot}$)

Spectral Classification of Ionizing Star

- [N III]$_{57\mu m}$/[N II]$_{205\mu m}$ line ratio
  - To probe the effective surface temperature, T_{eff}, and spectral type of ionizing stars (B_2V -$O_{7.5}V$)
- Multiple [O II]/[N II] line ratios
  - To constrain the spectral type of ionizing start for wide range of electron densities, n_e

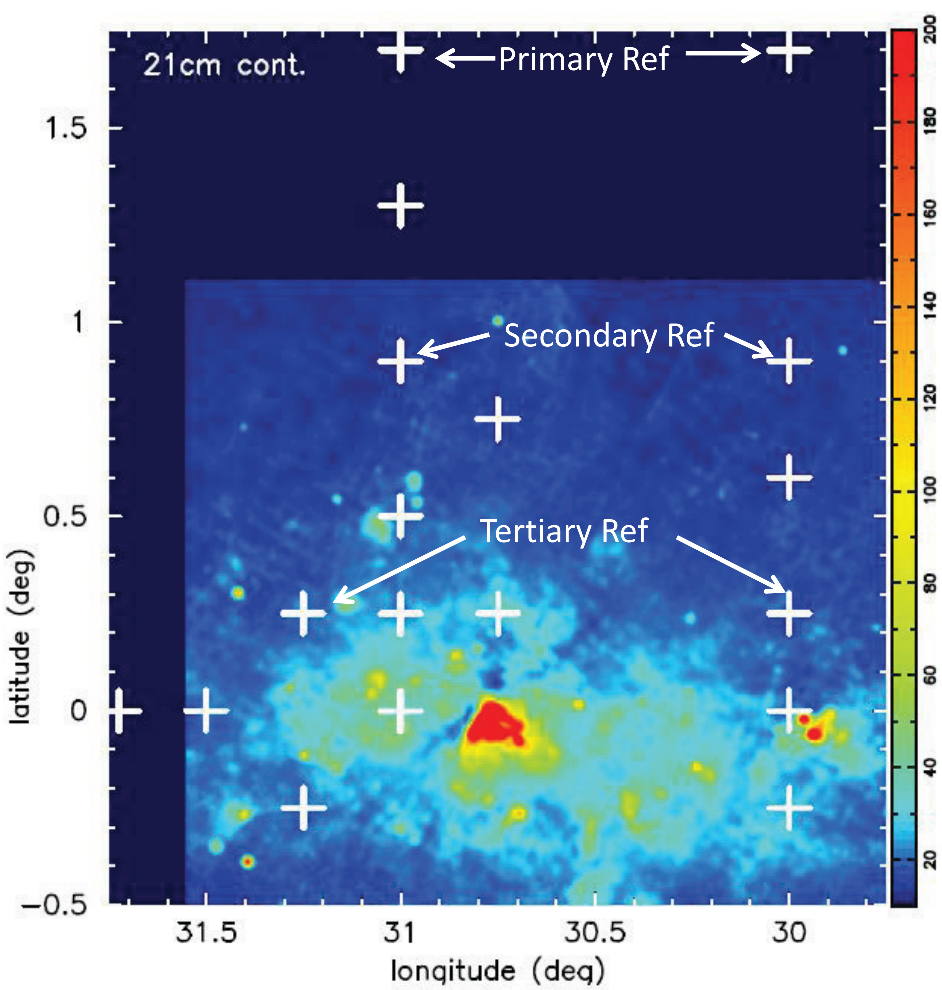


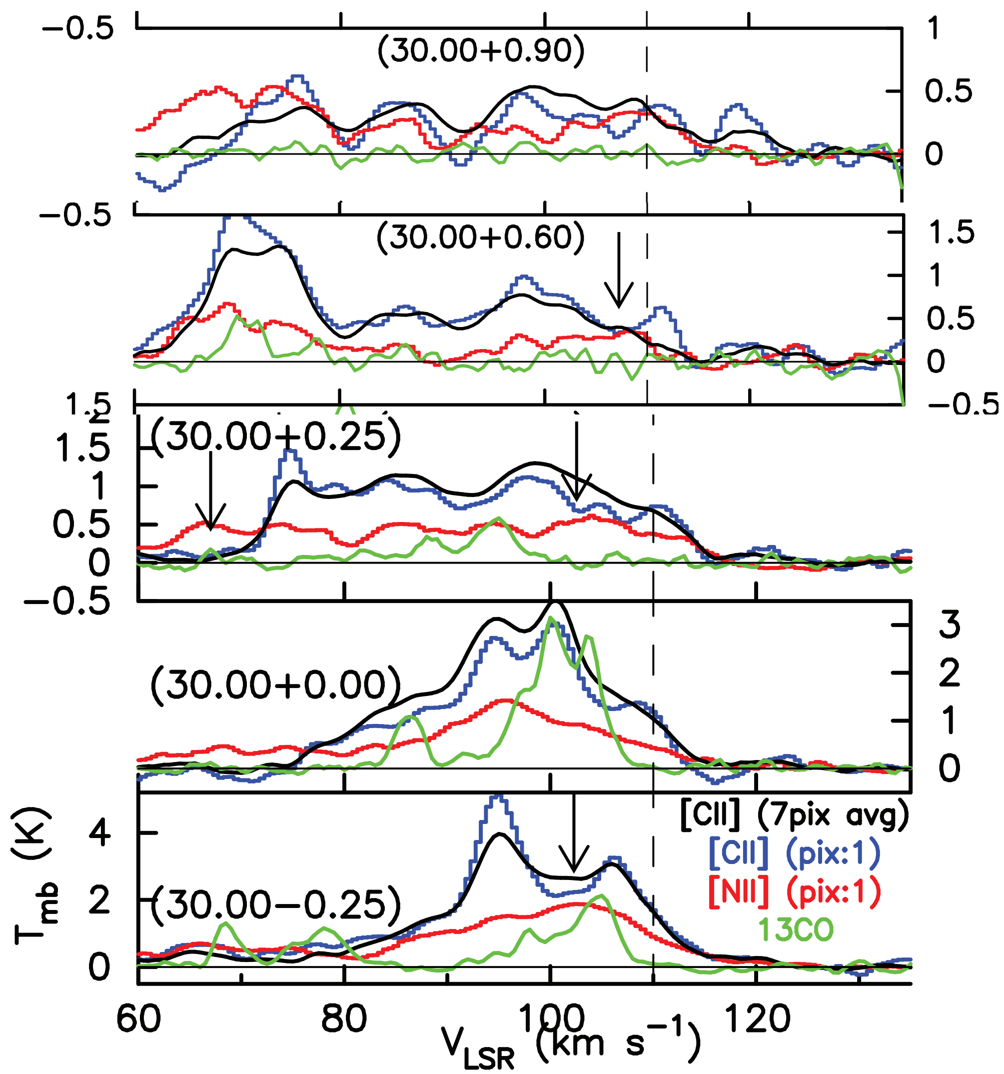
Stacey et al. (2011)



Ionized Gas in the Scutum Arm

- [C II]158μm & [N II]205μm obs. by SOFIA
  - Highly ionized gas of the WIM at the inner edge of the Scutum arm tangency sampled along18 LOS (l=30.0-31.75°)
  - Strong [N II] emission throughout the Scutum tangency and decreases exponentially with latitude with a scale height~55pc

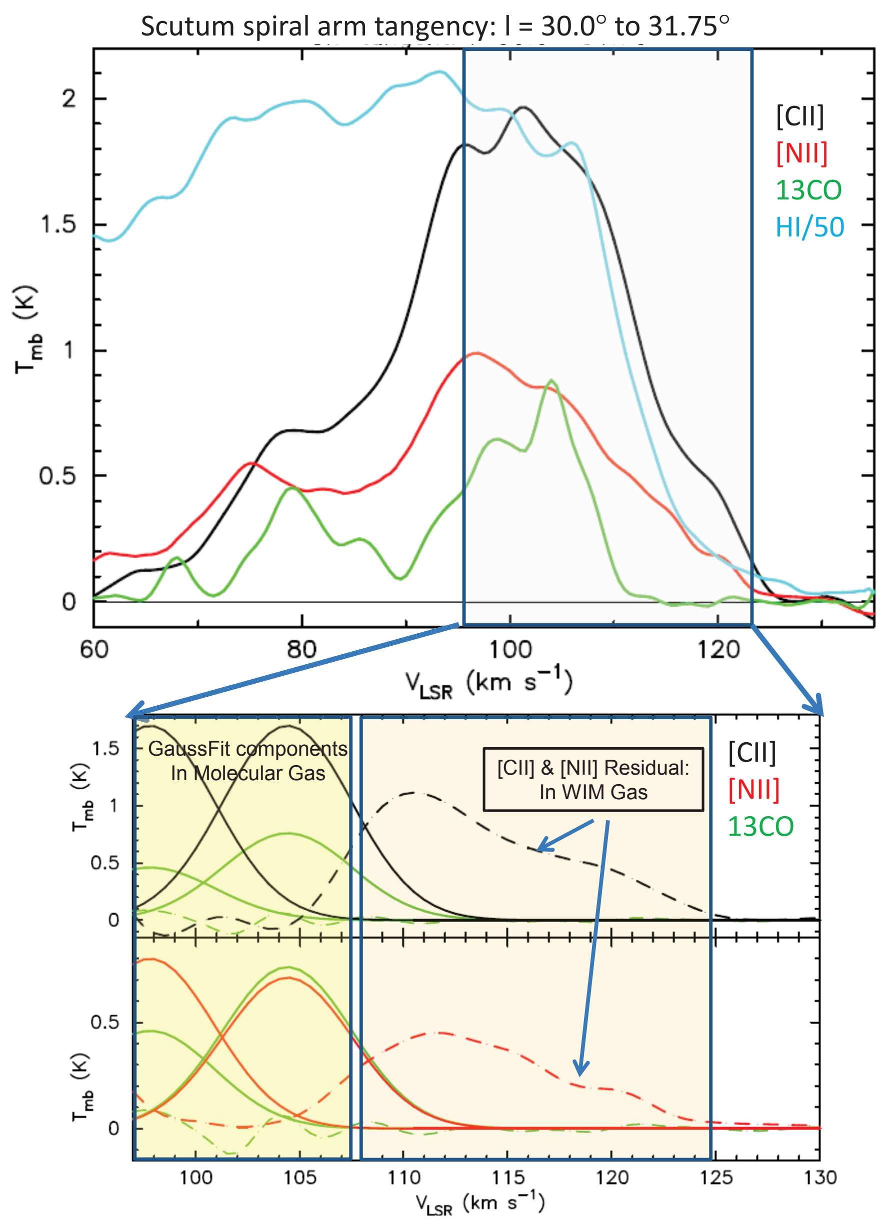


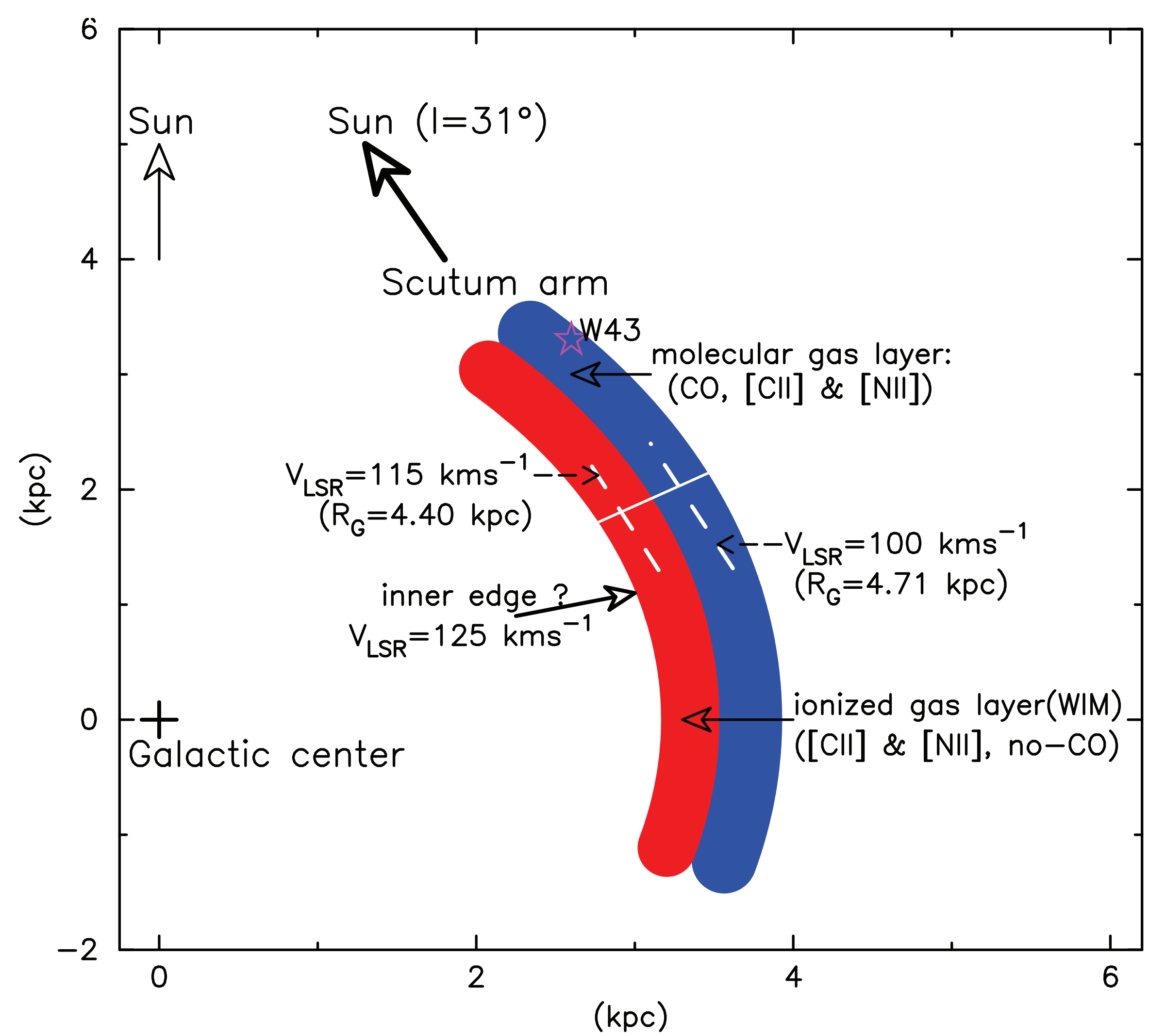


Langer et al. (2017)

Ionized Gas in the Scutum Arm

- There is highly ionized gas within the arm with 1-20 times electron density of the interarm WIM
- [N II] emission arises from shock compression layers of the WIM, accelerated by the gravitational potential of the arm





Langer et al. (2017)