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Sterrewacht Leiden

IONIZED CARBON IN THE MAGELLANIC CLOUDS

In collaboration with:
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Y. Okada, and others

Why Ionized Carbon?

Element		Abundance	Ionisation Potential
Hydrogen	^{1}H	1	13.6eV
Helium	^{4}He	0.085	24.6 eV
Carbon	^{12}C	0.00033	11.3 eV
Nitrogen	^{14}N	0.00009	14.5eV
Oxygen	^{16}O	0.00066	13.7 eV

Major ISM Coolant

Diffuse atomic gas (WIM):	[CII], [OI]
Translucent clouds:	[CII], [CI]
Photon-Dominated Regions:	[CII], [OIII]
Dense Molecular Clouds:	CO

Observationally well-suited

* **All in one:**

A single emission line contains essentially all the power emitted

* **Favourable excitation conditions:**

critical temperature 93 K

critical density 3000cm^{-3}

* **Unhampered by interstellar extinction**

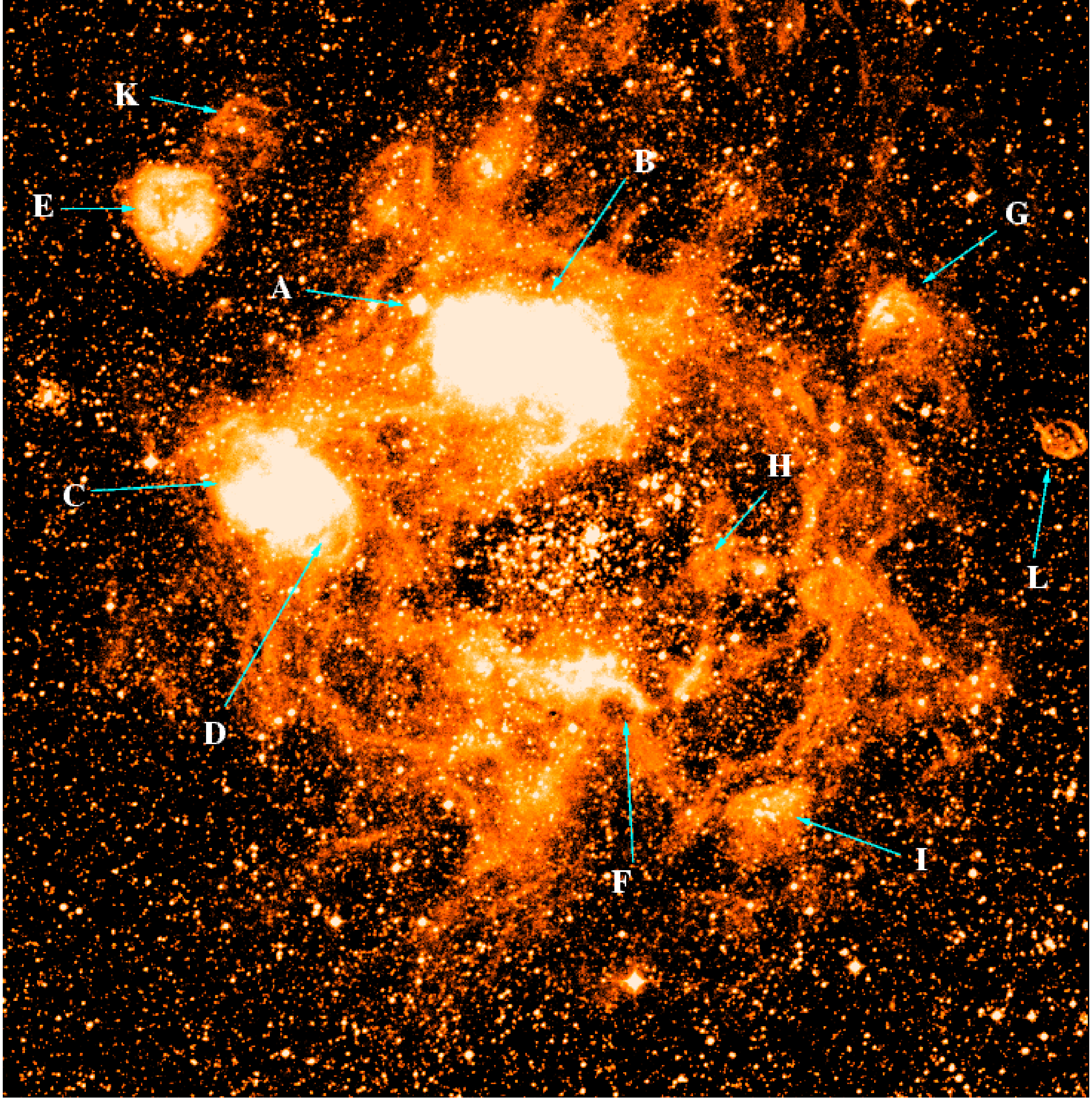
Emission at FIR wavelength 157.7 micron

BUT:

* **only visible from space or stratosphere**

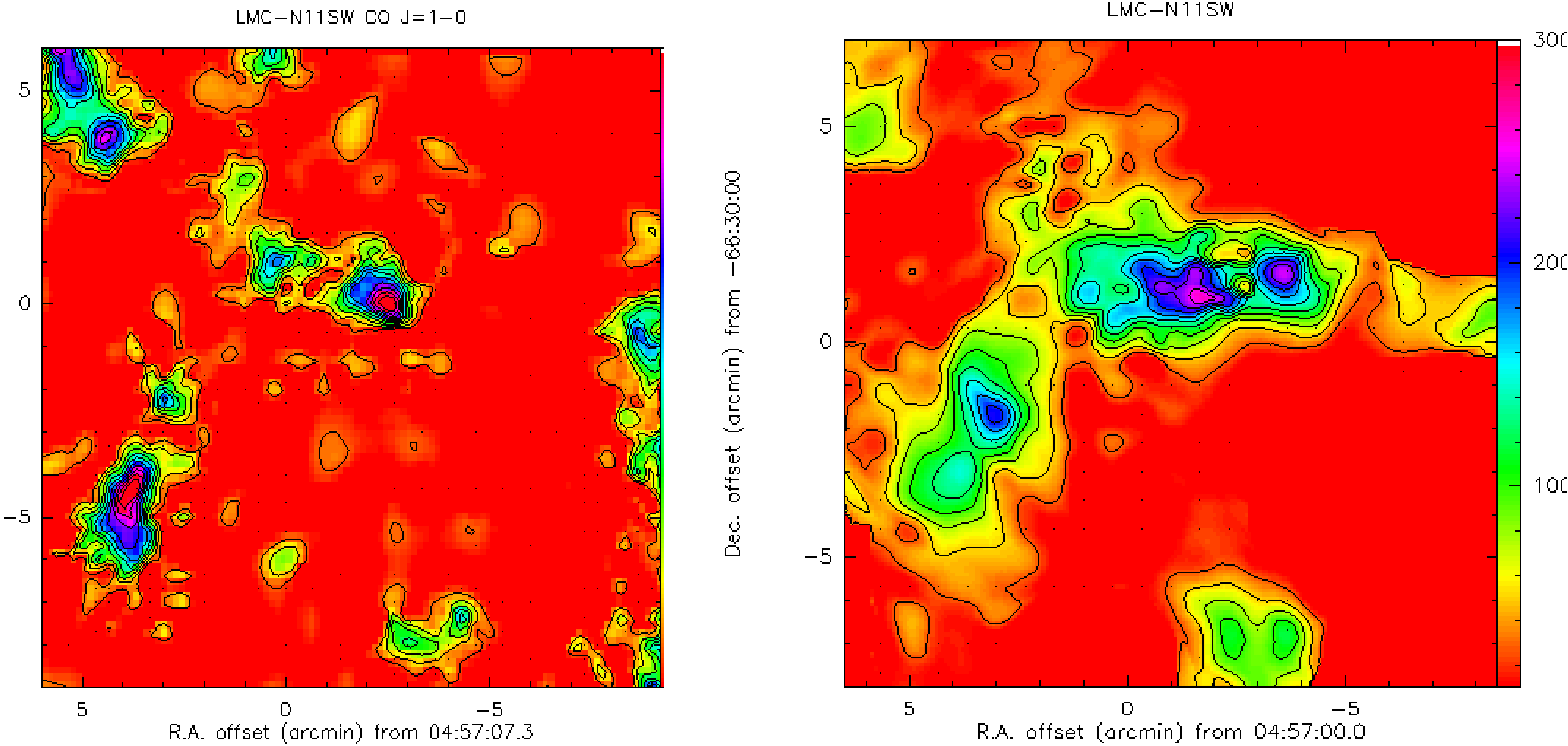
Why Magellanic Clouds?

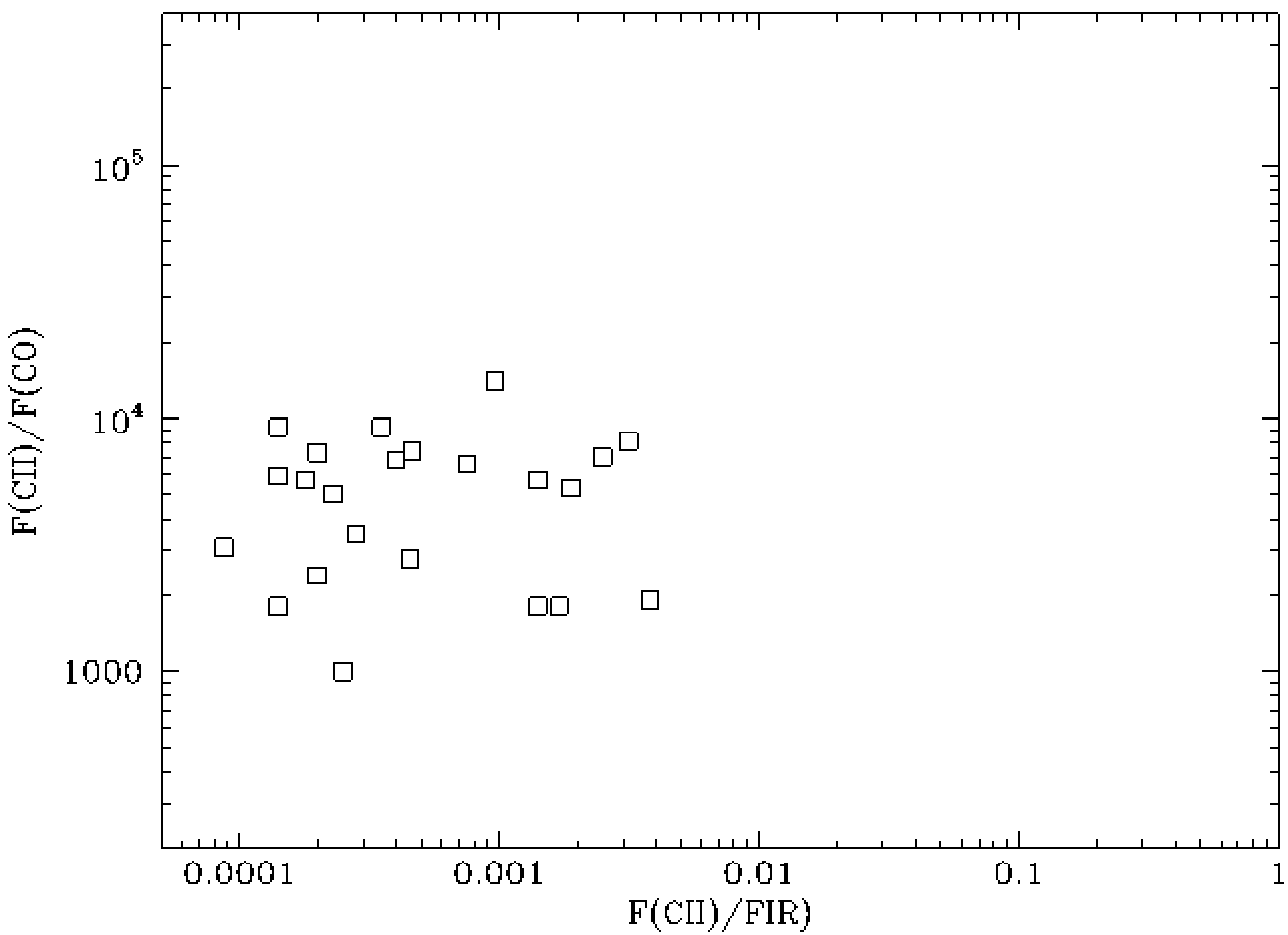
	C	N	O
MW	1	1	1
M33	–	0.2-1.0	0.5-1.5
LMC	0.25	0.10	0.50
N6822	-	0.05	0.45
SMC	0.10	0.06	0.25
IC10	-	0.04	0.40


K
E
B
G
A
C
H
L
D
F
I

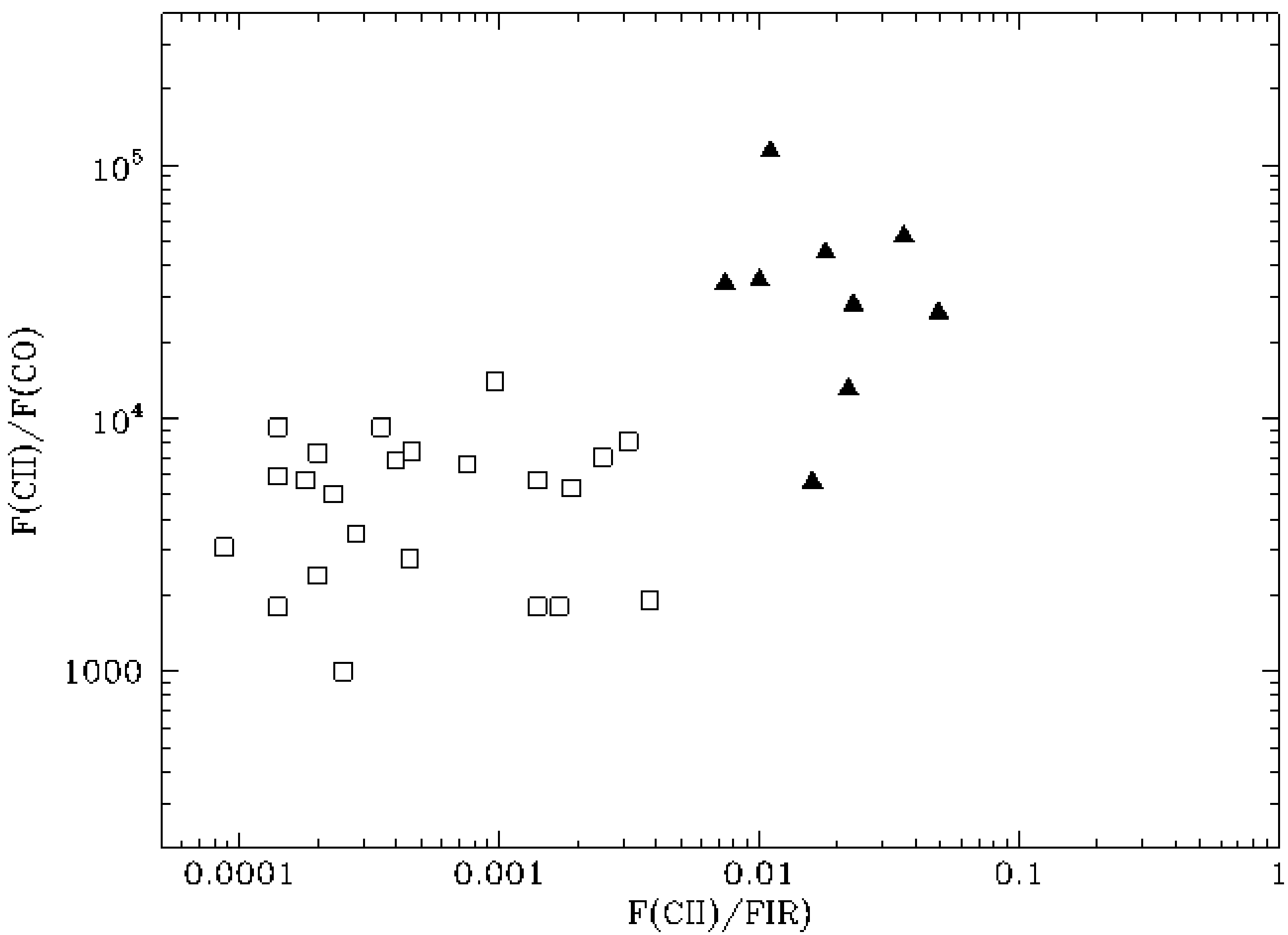
SEST CO and KAO [CII] maps

resolution one arcmin = 16 pc (Israel & Maloney 2011)

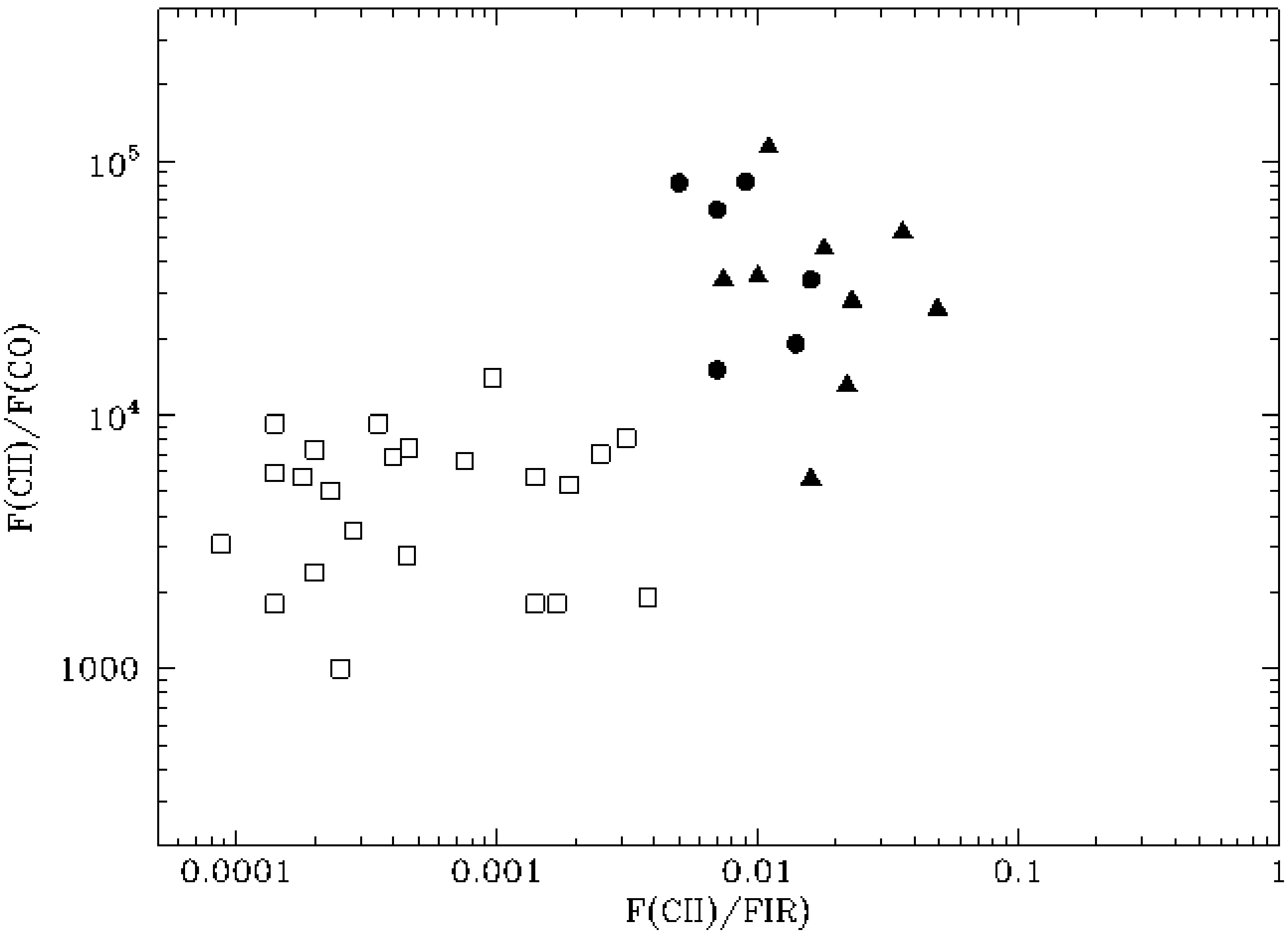




F(CII)/F(CO)
10^5
10^4
1000
0.0001
0.001
0.01
0.1
1
F(CII)/FIR



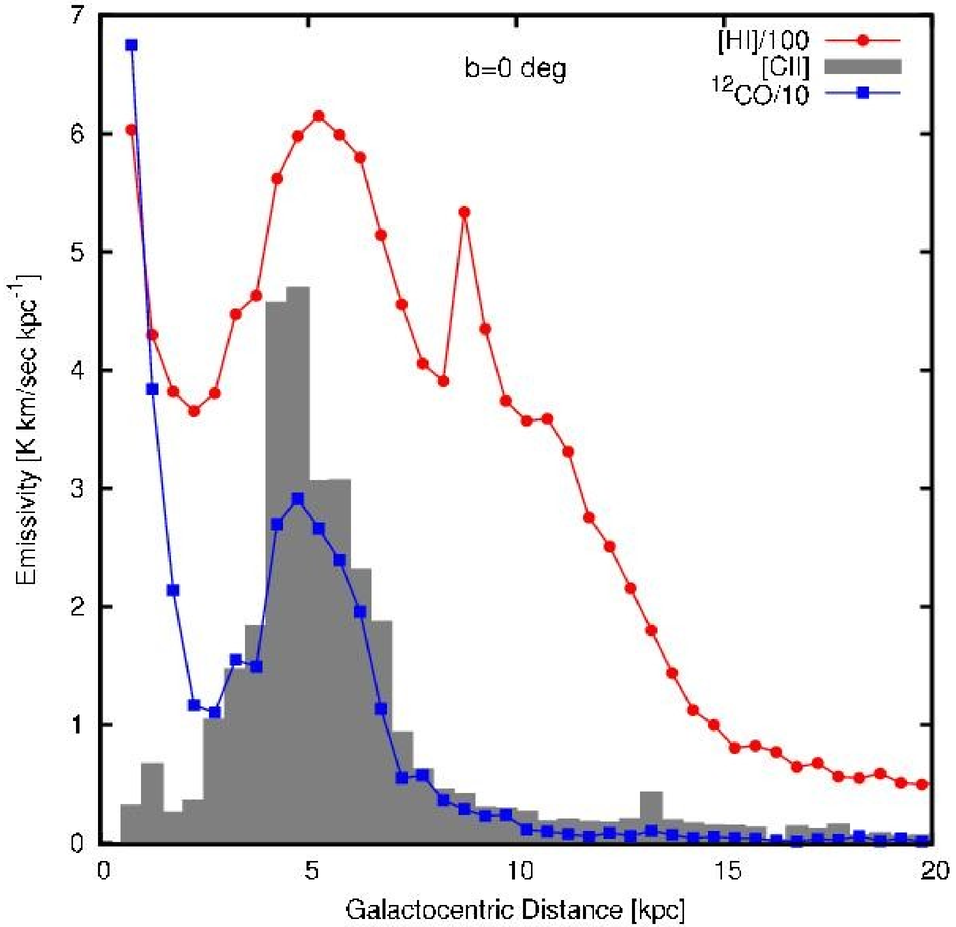
10^5
10^4
1000
F(CII)/F(CO)
0.0001
0.001
0.01
0.1
1
F(CII)/FIR

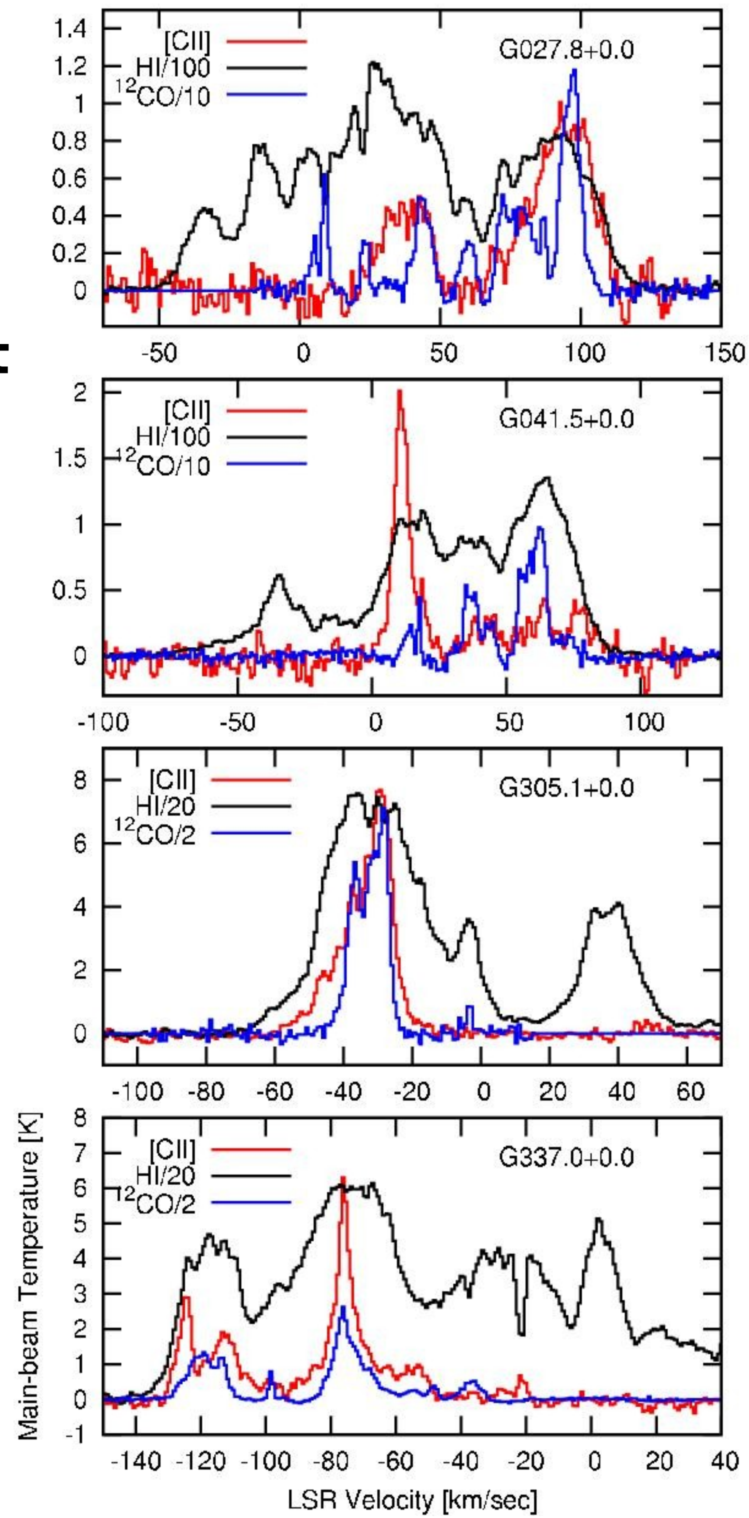

F(CII)/F(CO)
10^5
10^4
1000
0.0001
0.001
0.01
0.1
1
F(CII)/FIR

Herschel HIFI

GOTC+ MWW [CII] Survey

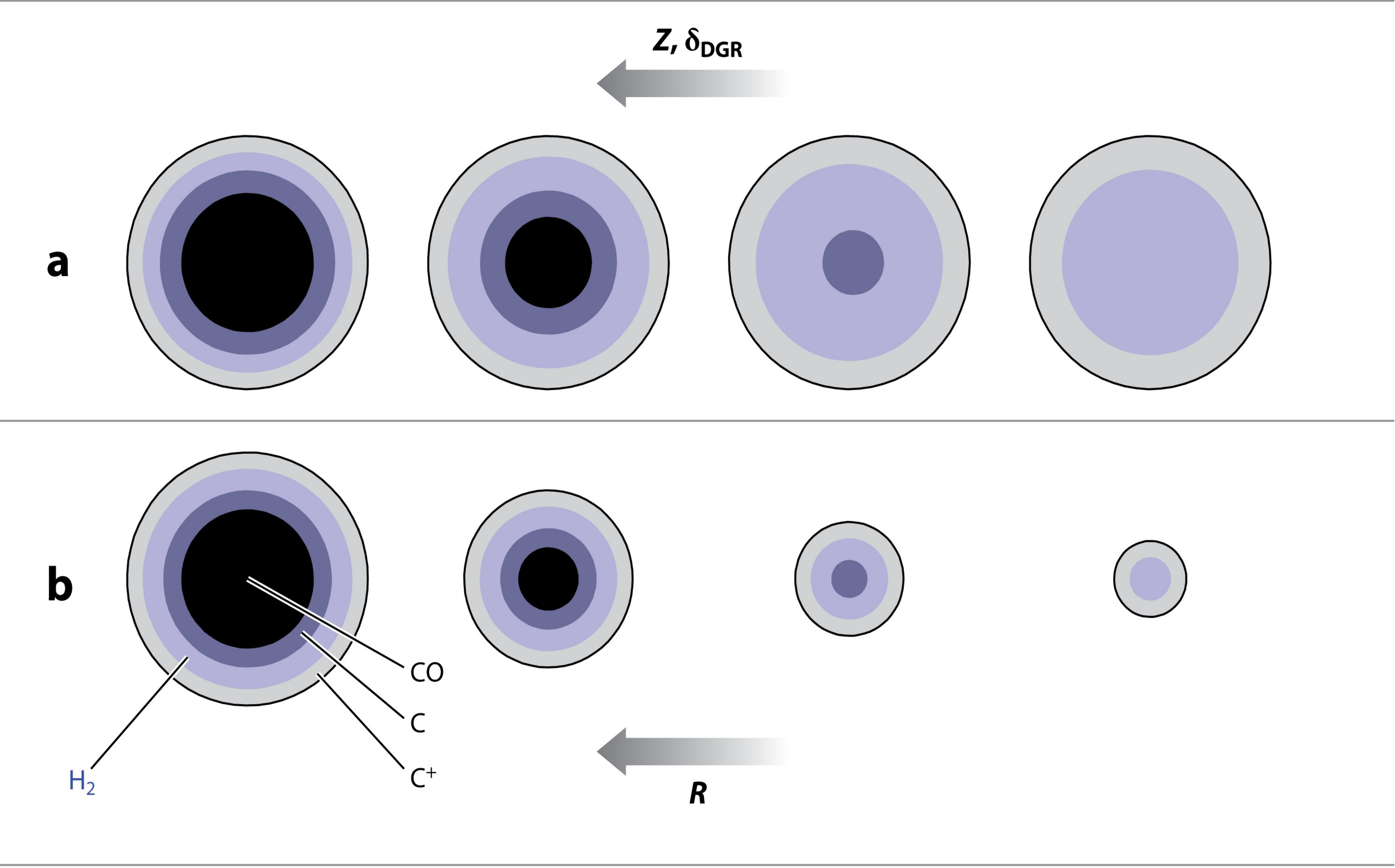
Langer, Pineda, Velusamy, Goldsmit





No single reliable tracer of H_2 mass

- Other abundant molecules: CO (optically thick, need ^{13}CO as well)
- Dust continuum emission (FIR SED) (dust properties poorly known)
-
- CO-related atomic lines: [CI], [CII] (very few lines)



Bolatto AD, et al. 2013.
Annu. Rev. Astron. Astrophys. 51:207–68

Make use of total carbon

C^+, C^o, CO relations depend on environment and heating mechanism

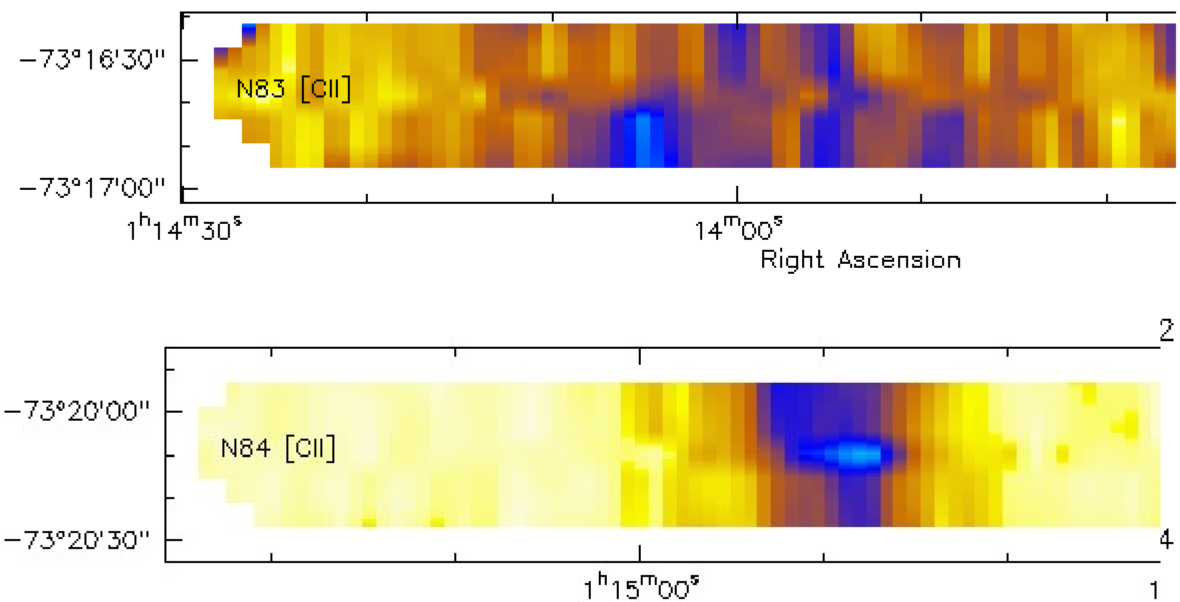
Consider all three together:
Combine emission in all CO, [CI], [CII] transitions to define physical conditions
e.g. LVG analysis

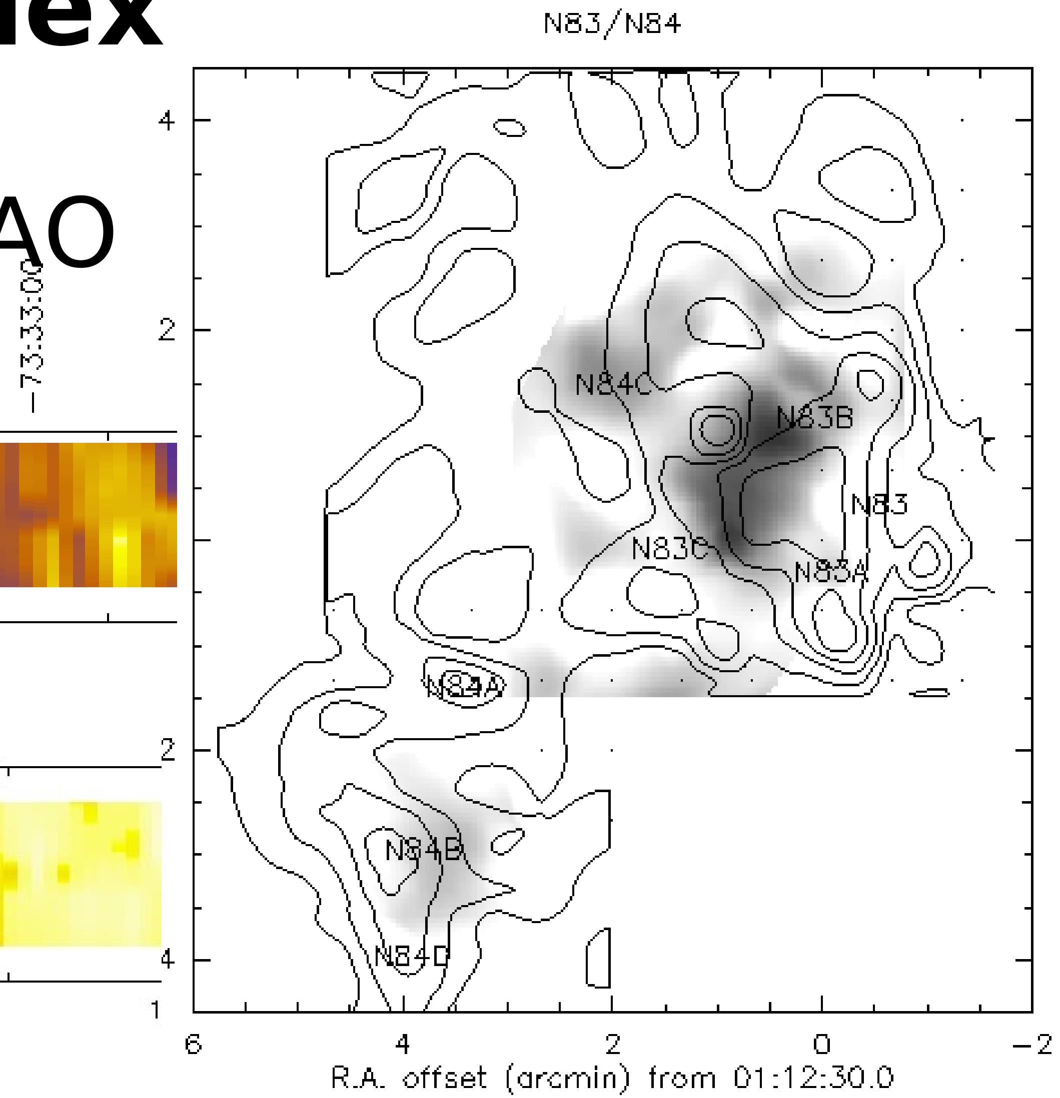
For mass, also need [C]/[H] abundance and C depletion factor

SMC Wing
N83/N84 Complex

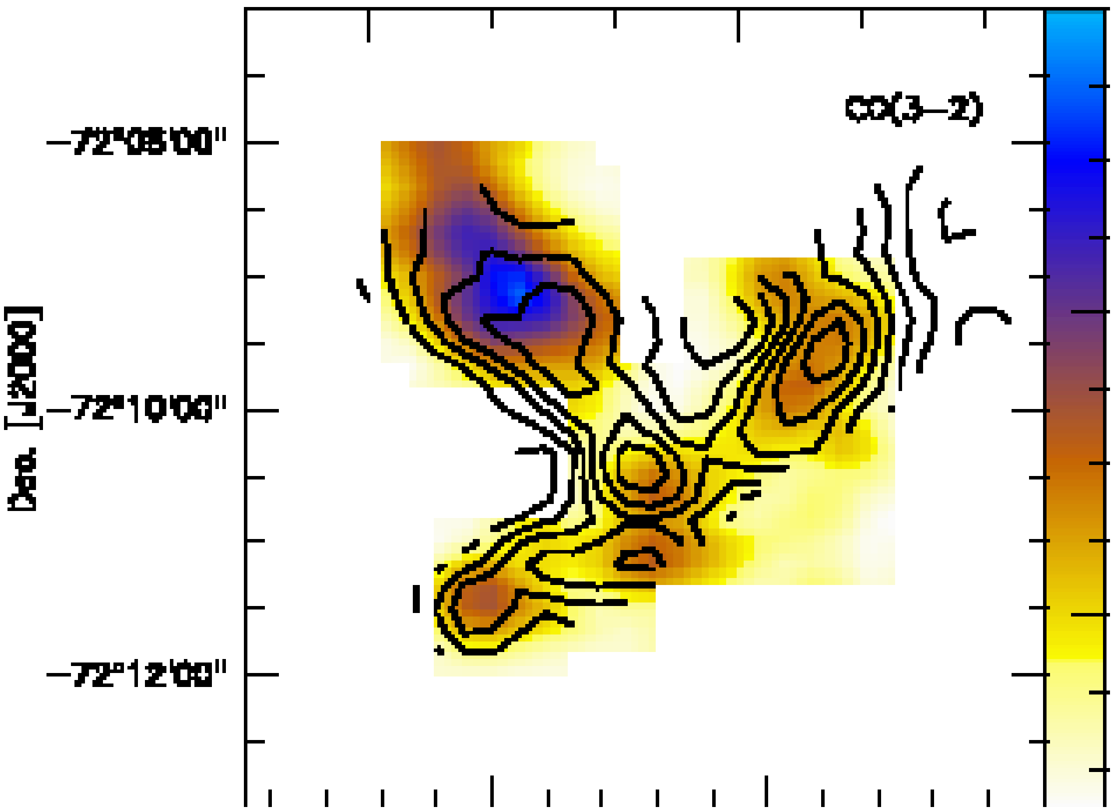
KAO

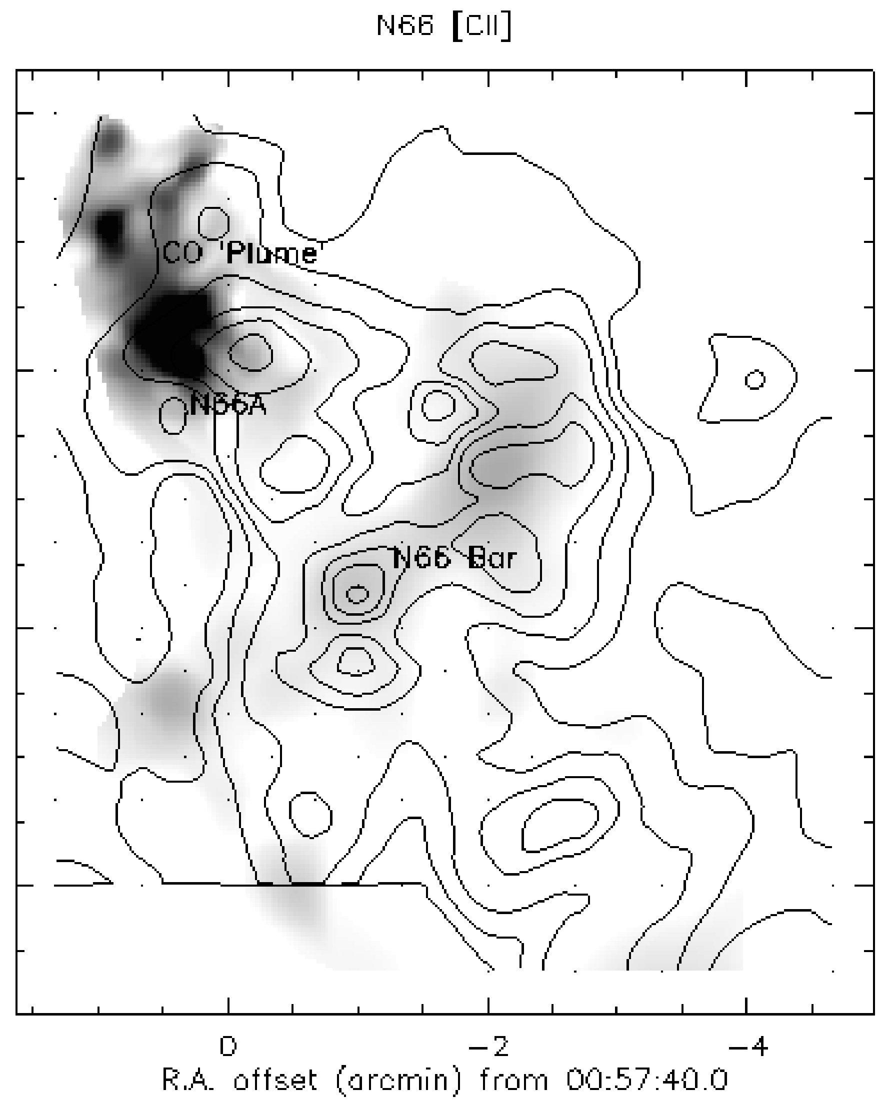
Herschel HIFI





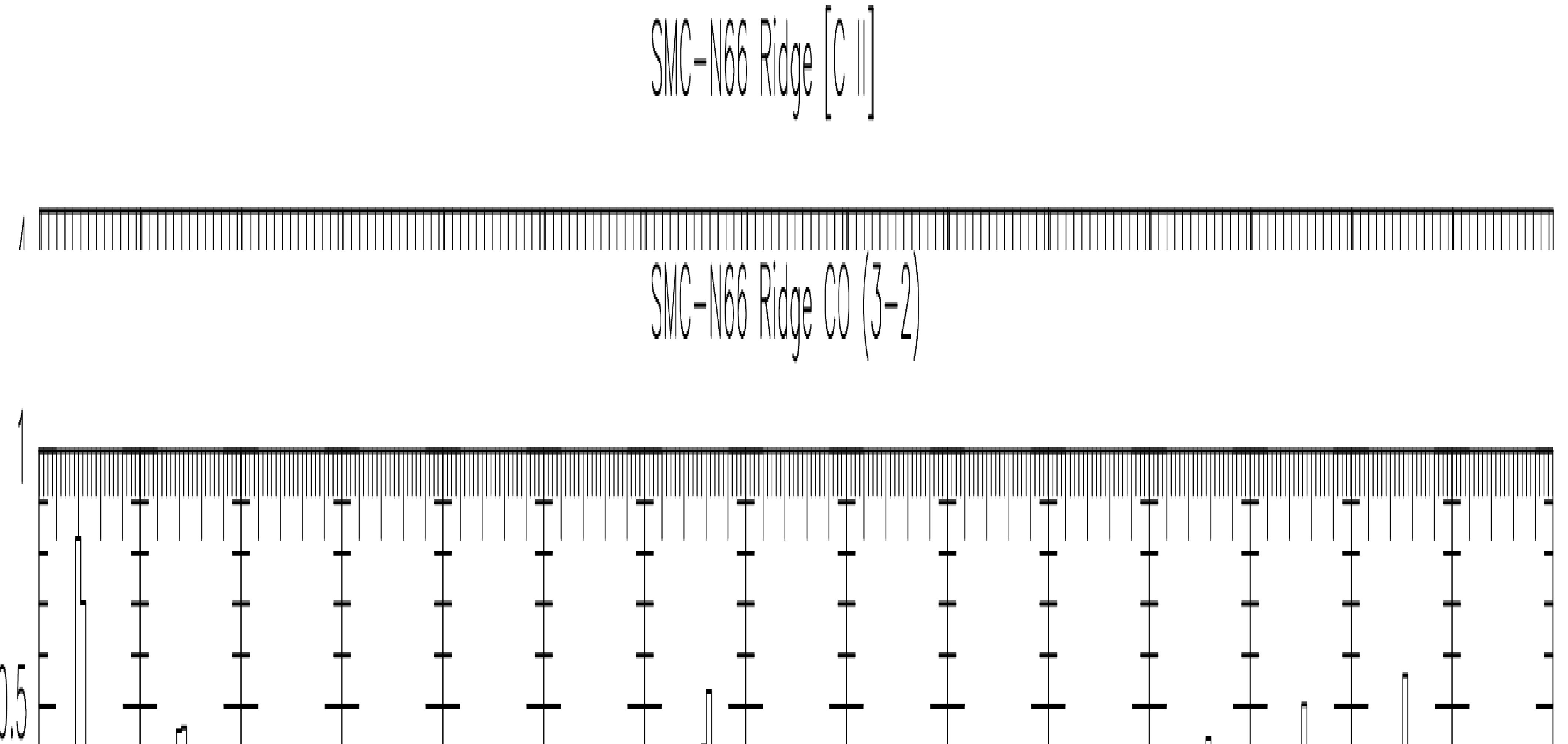
SMC-N66 [CII] SOFIA vs KAO



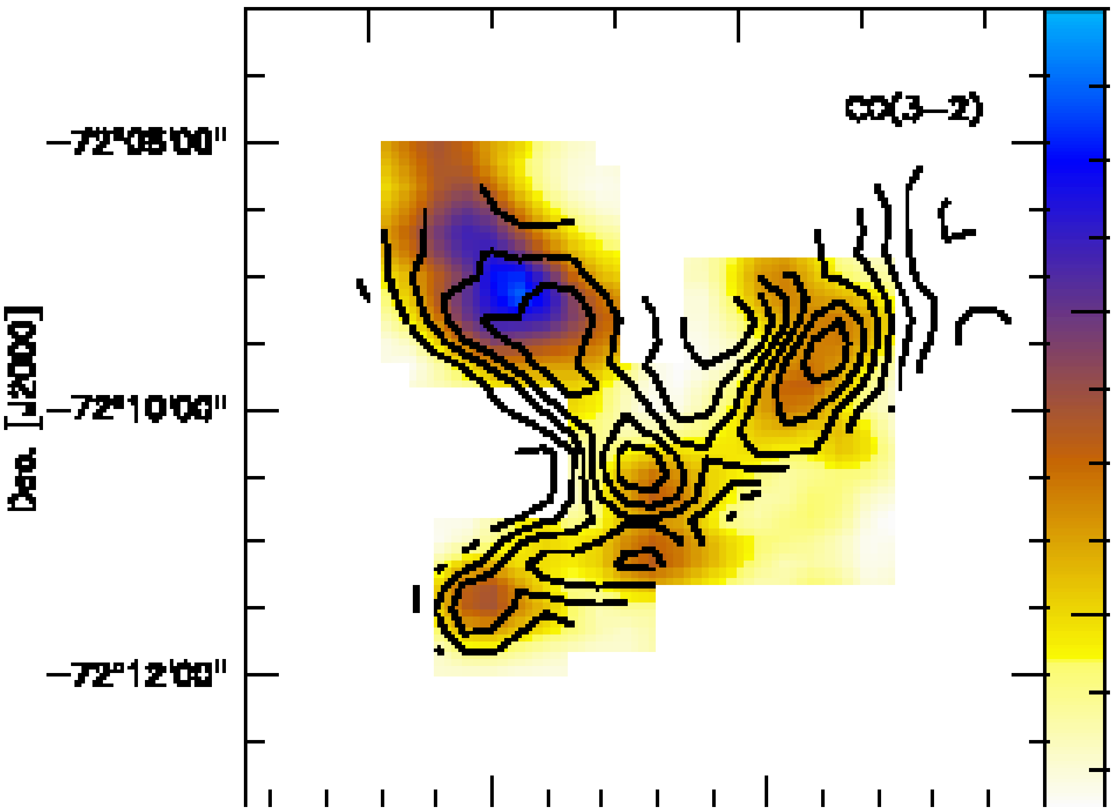


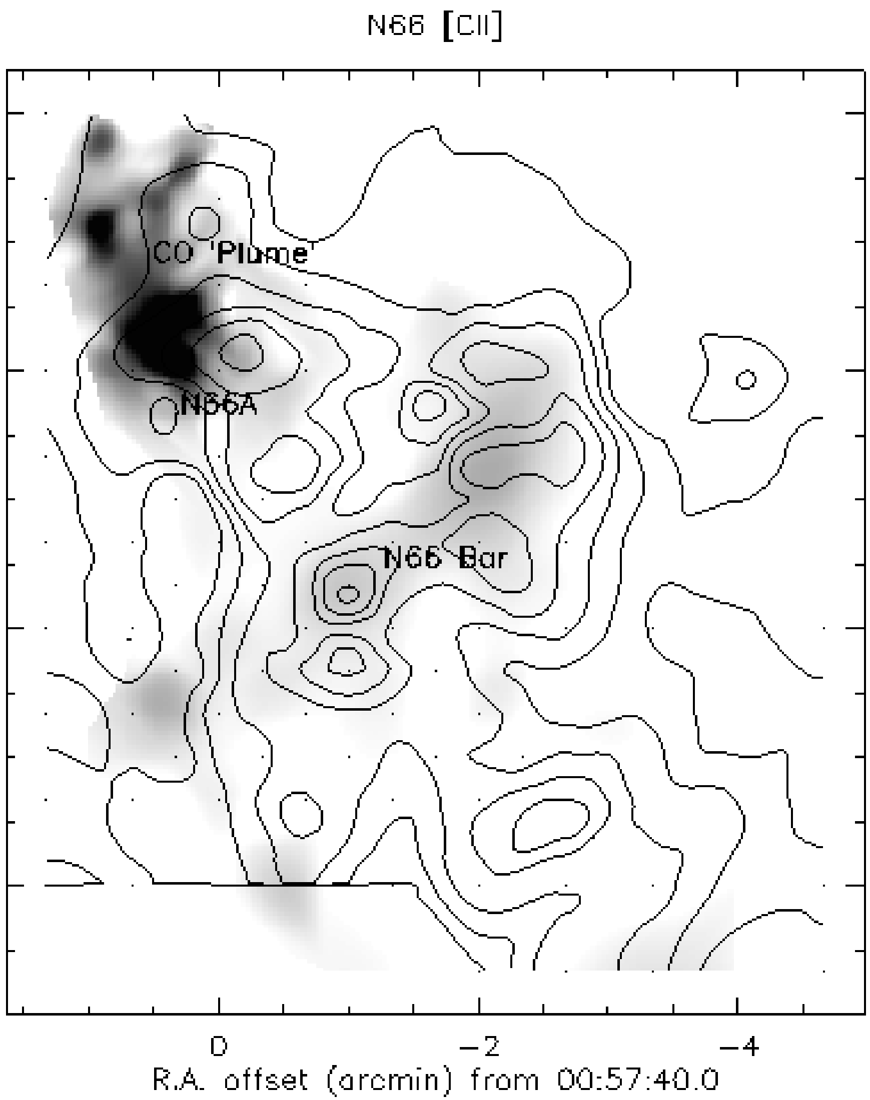
SMC-N66

SOFIA GREAT & APEX-FLASH

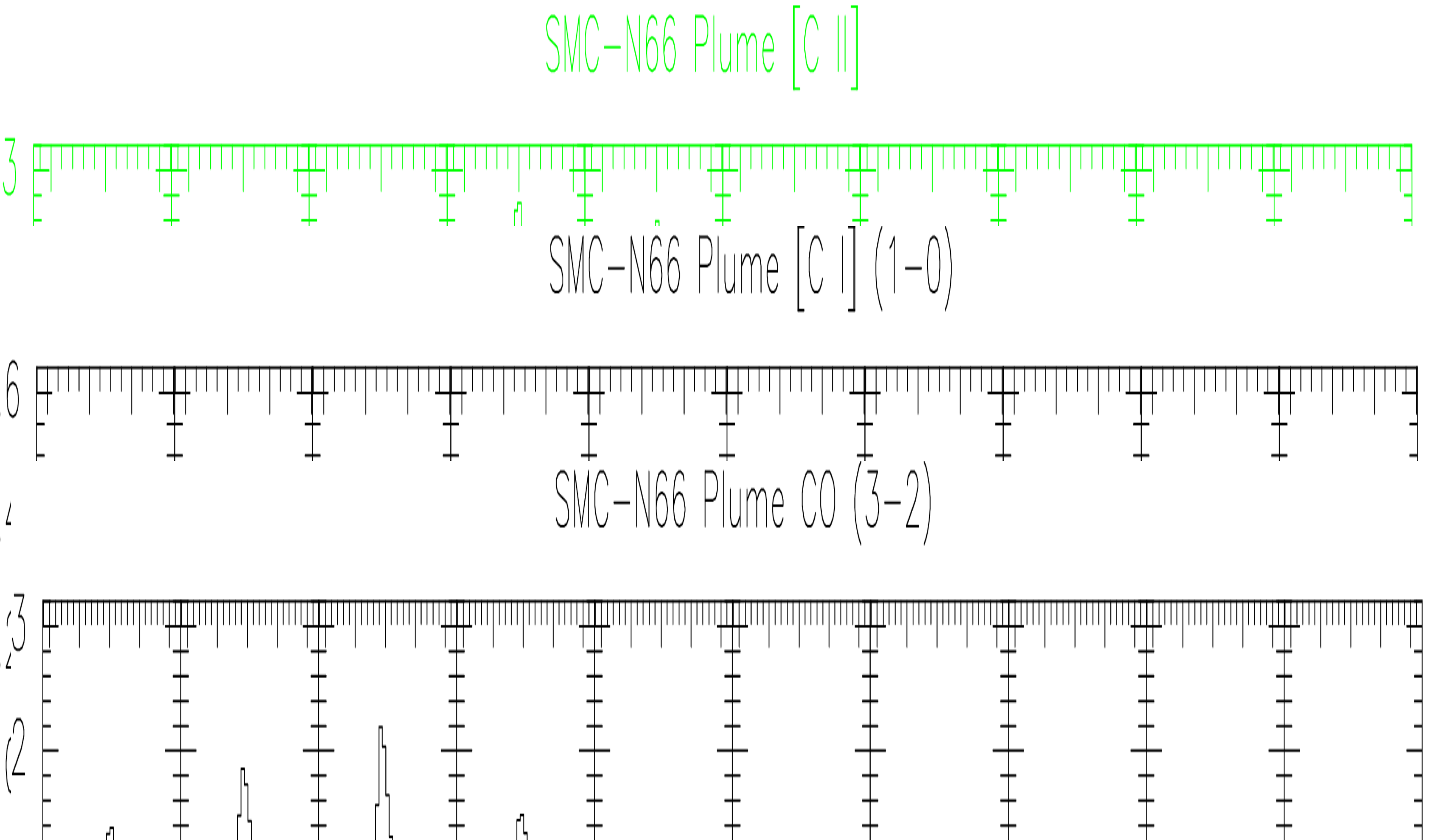


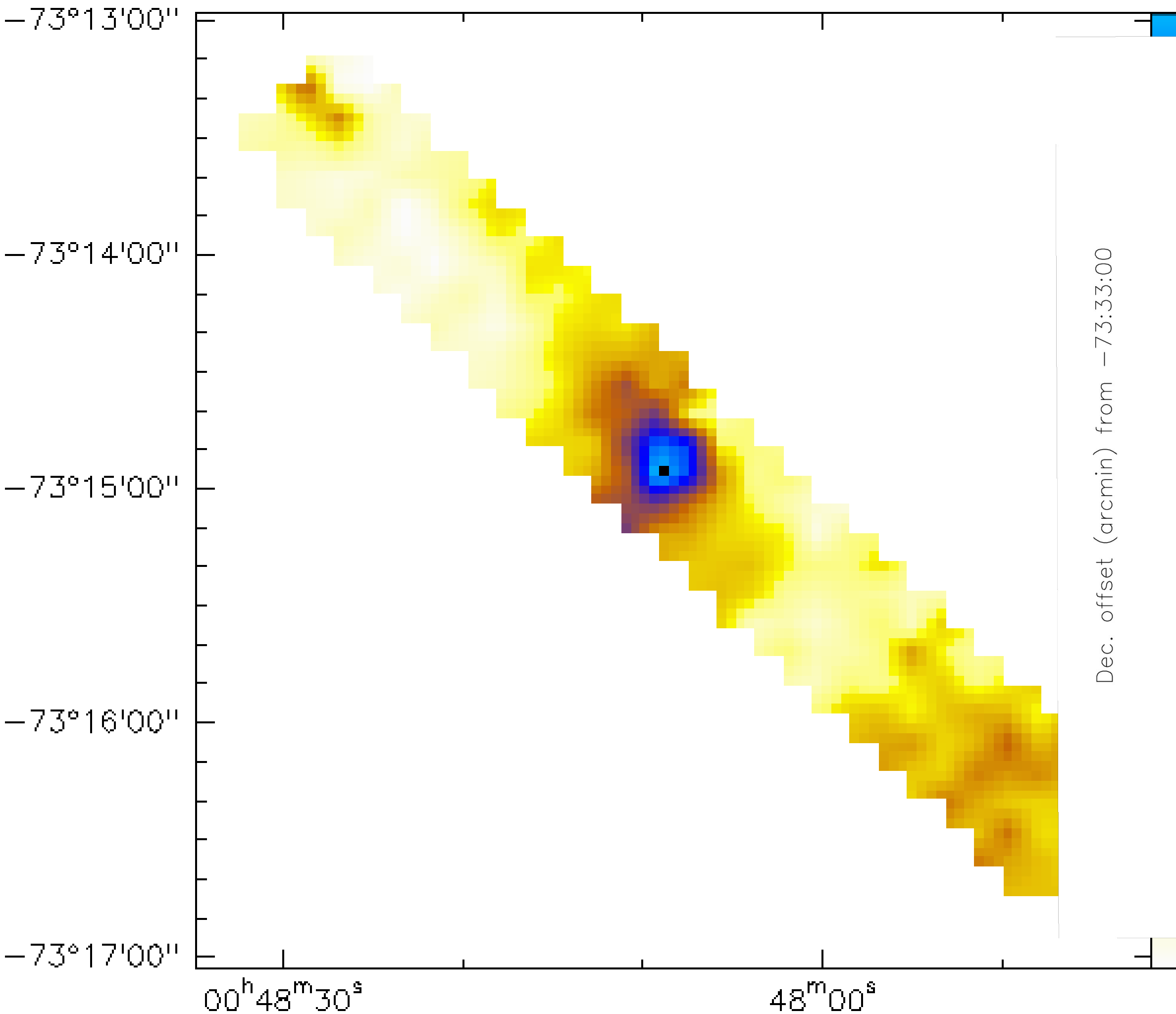
SMC-N66 [CII] SOFIA vs KAO

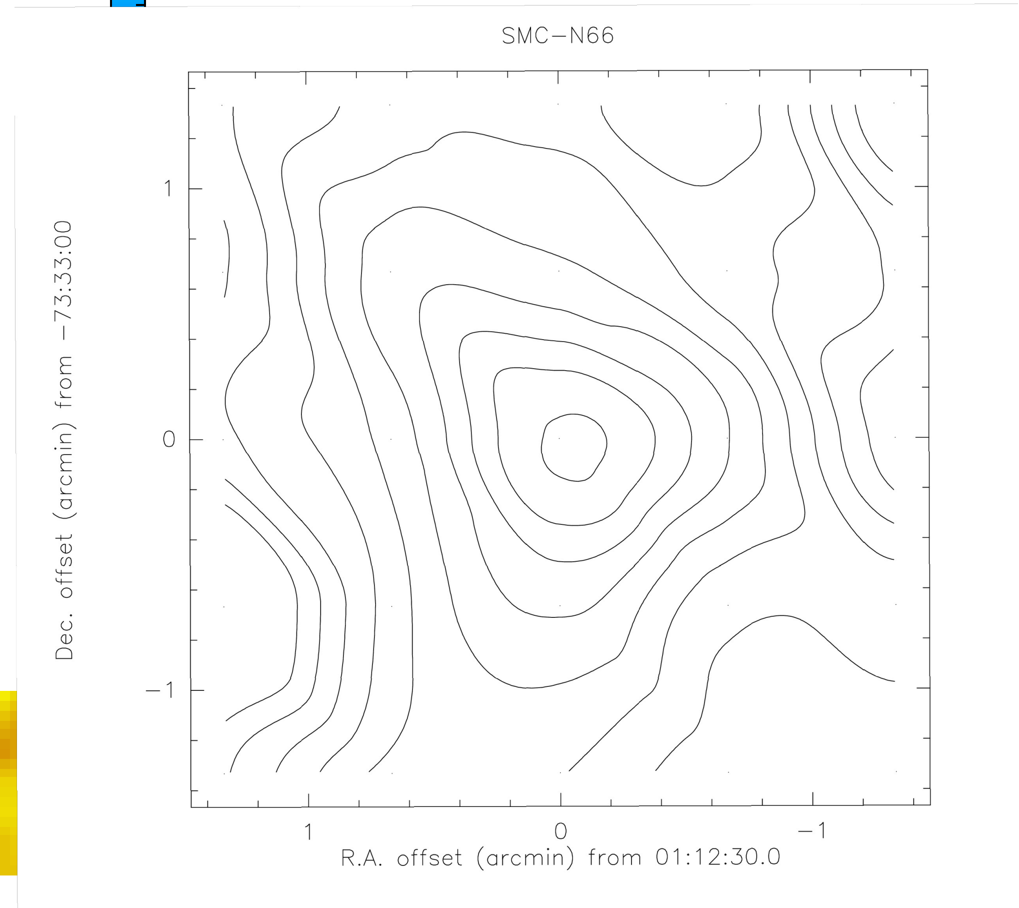




SMC-N66



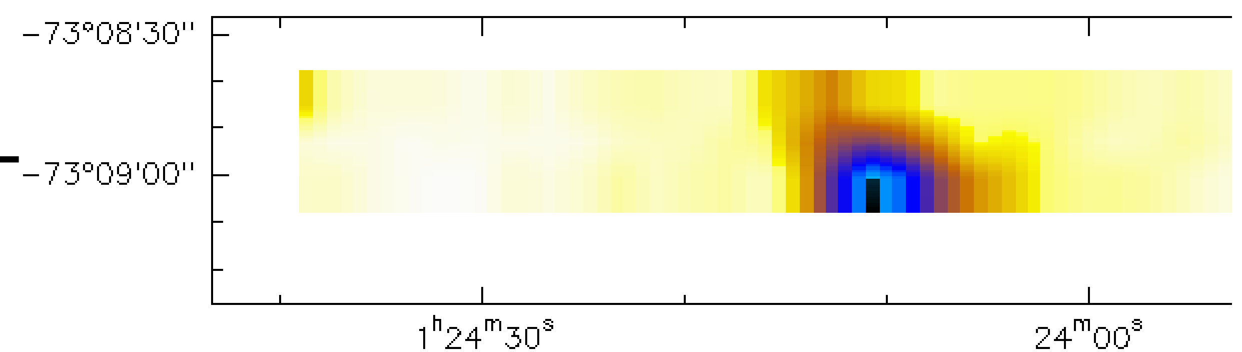




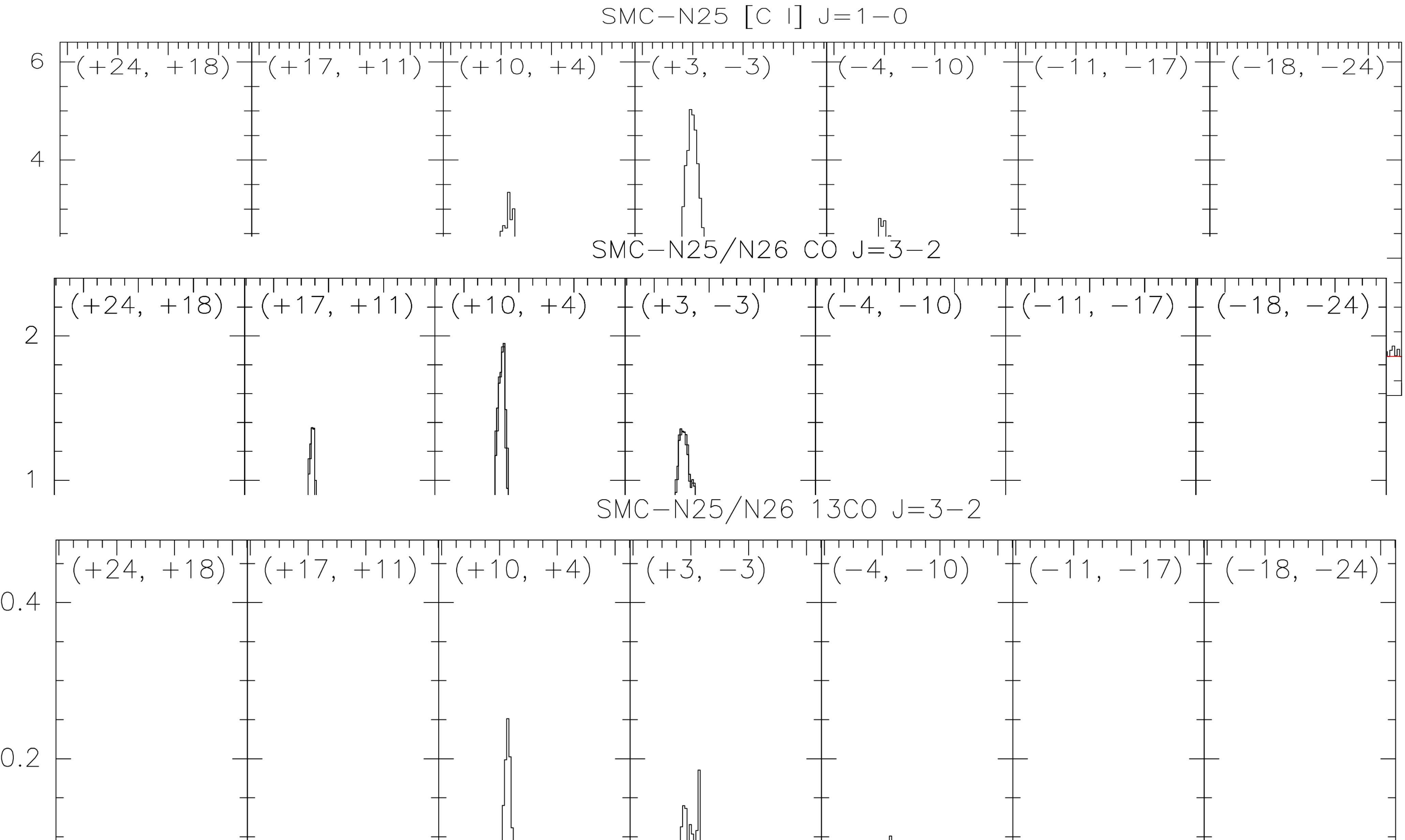
SMC N25 [CII]

SOFIA
GREAT

SMC N88 [CII]

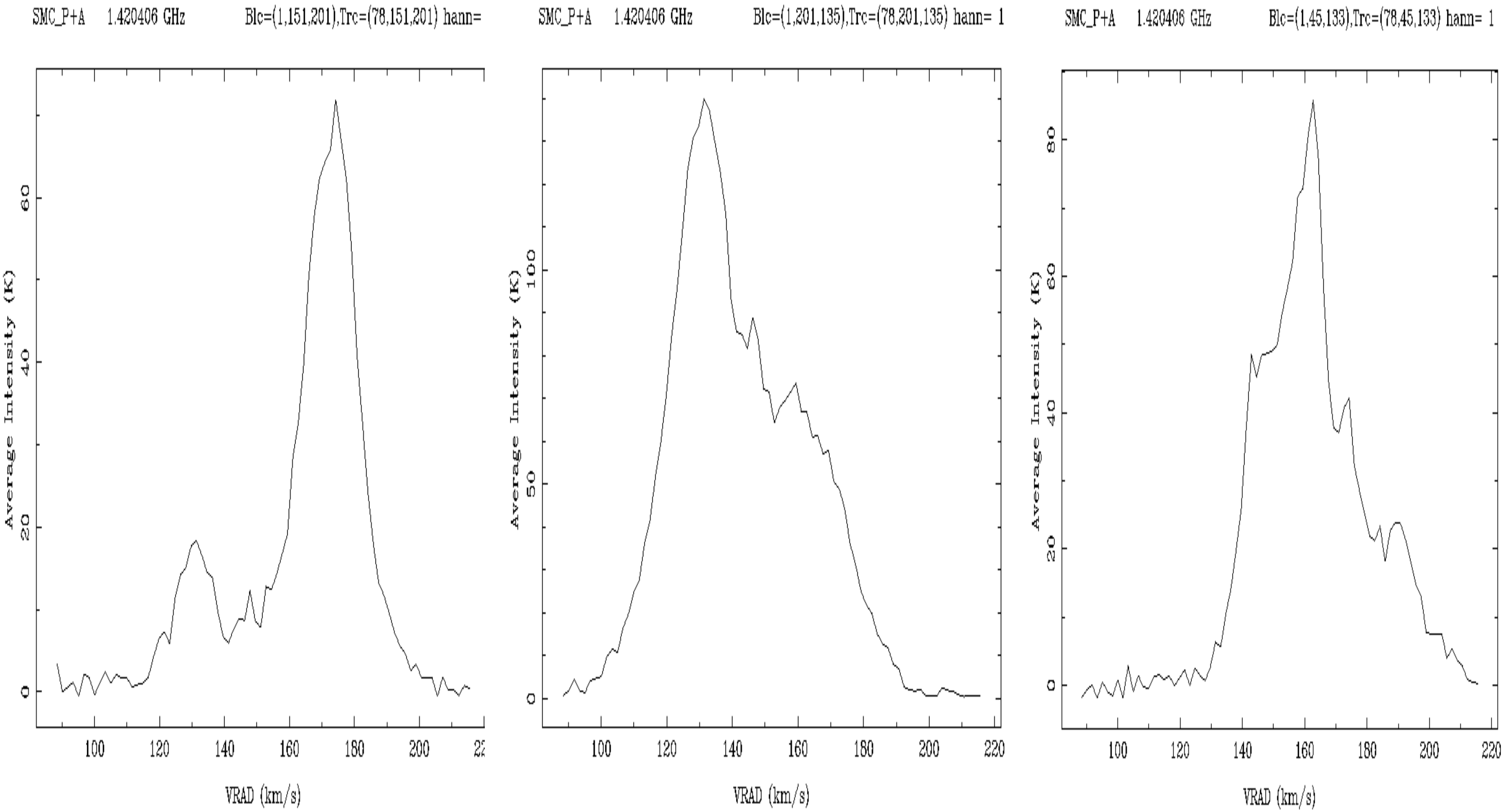


SMC-N25


SMC−N25 [C I] J=1−0
(+24, +18)
(+17, +11)
(+10, +4)
(+3, −3)
(−4, −10)
(−11, −17)
(−18, −24)
6
4
SMC−N25/N26 CO J=3−2
(+24, +18)
(+17, +11)
(+10, +4)
(+3, −3)
(−4, −10)
(−11, −17)
(−18, −24)
2
1
SMC−N25/N26 13CO J=3−2
(+24, +18)
(+17, +11)
(+10, +4)
(+3, −3)
(−4, −10)
(−11, −17)
(−18, −24)
0.4
0.2

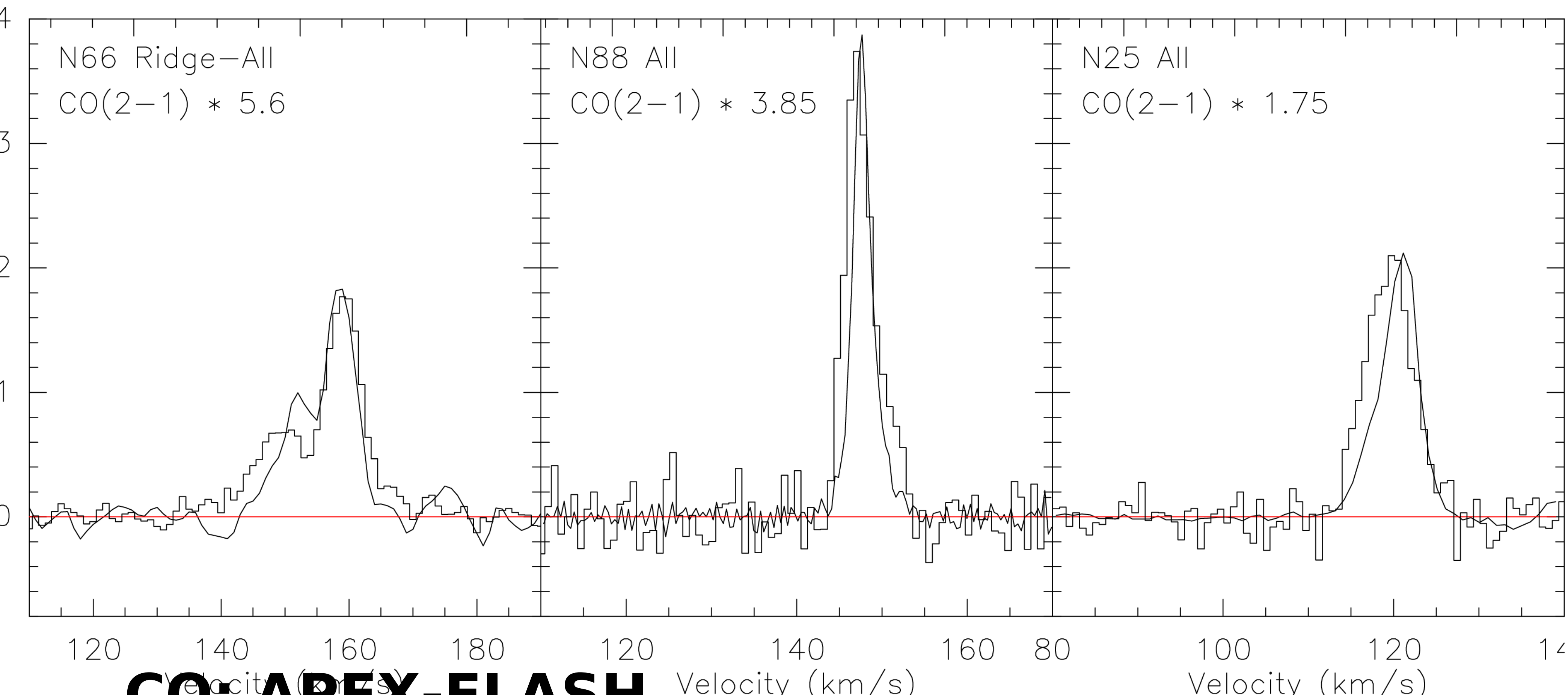
SMC HI in N66, N25, N88

very wide emission ~ 80 km/s



ATCA

SMC: Comparison [CII] and CO



CO: APEX-FLASH

[CII]: SOFIA-GREAT

OBSERVATIONAL SUMMARY [CII] SMC

1. **compact**/ bright vs **extended**/diffuse [**CII**] **emission**: 40% : 60%

2. bright [**CII**] **distribution** follows CO

3. [**CII**] **profile shapes** very similar to CO profile shapes; slightly greater width

4. [**CII**] **fluxes** anti-correlate with CO fluxes

5. [**CI**] **fluxes** correlate with CO fluxes

CONCLUSIONS SMC 1

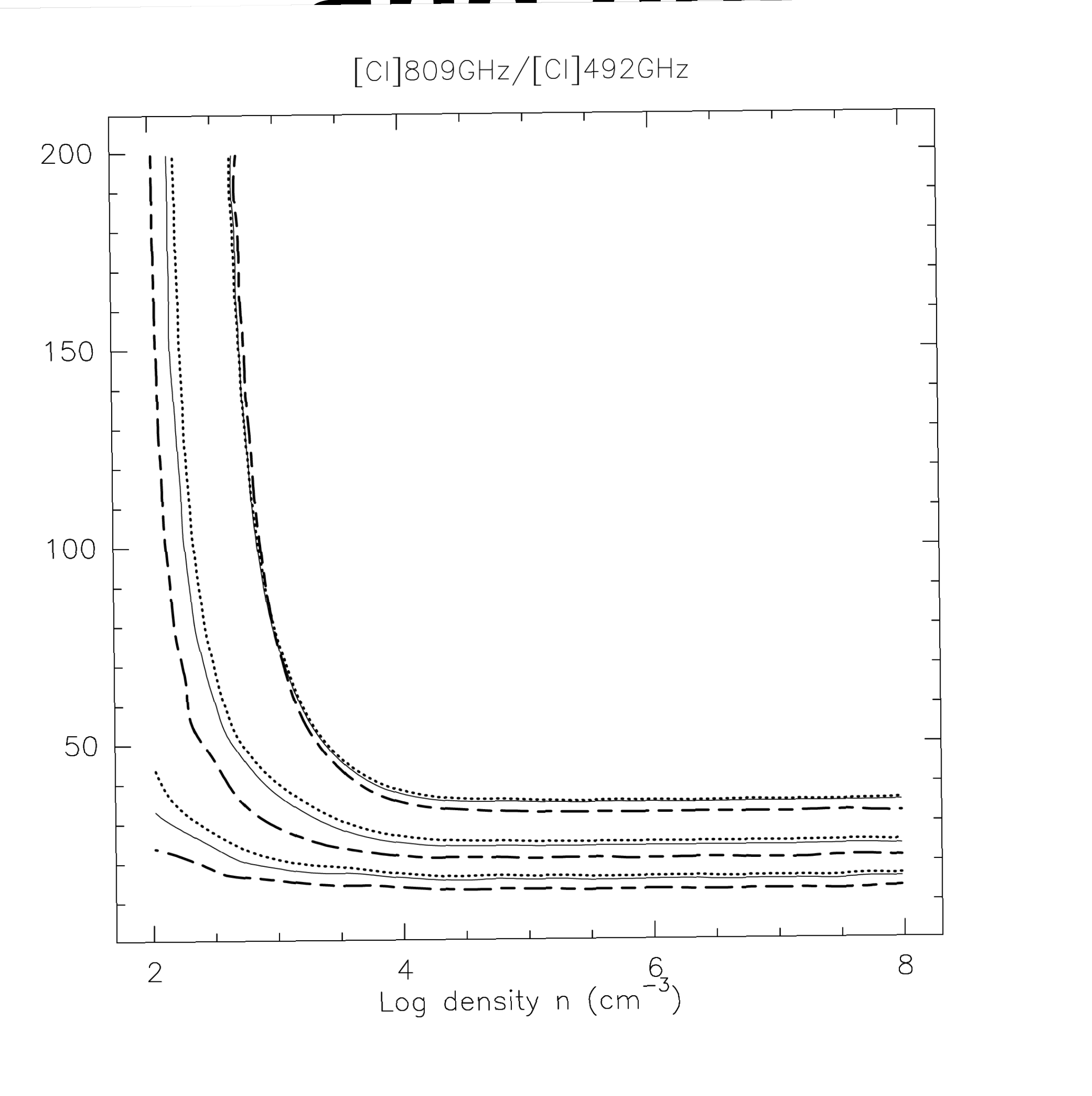
Molecular gas tracers:

	N66+N25+N88	N25+N88
CO	20 +/-10 %	8 +/- 4 %
[CI]	10 +/- 5 %	4 +/- 1 %
[CII]	70 +/-20 %	88 +/-13 %

CONCLUSIONS SMC 2

* CO-dark H_2 gas is 80% - 95% of all gas
* [CII] best tracer of H_2 column density need [CI] and CO for quantitative result
* Molecular gas traced by CO, by [CI] and by [CII] occupy same volume
* Expanding molecular ring in N66 better traced by [CII] than by CO
* Small sample, huge bias! Need more SMC fields ....
* Also LMC to define metalicity effects ...

C, CO ladders very degenerate and don't cut the cake



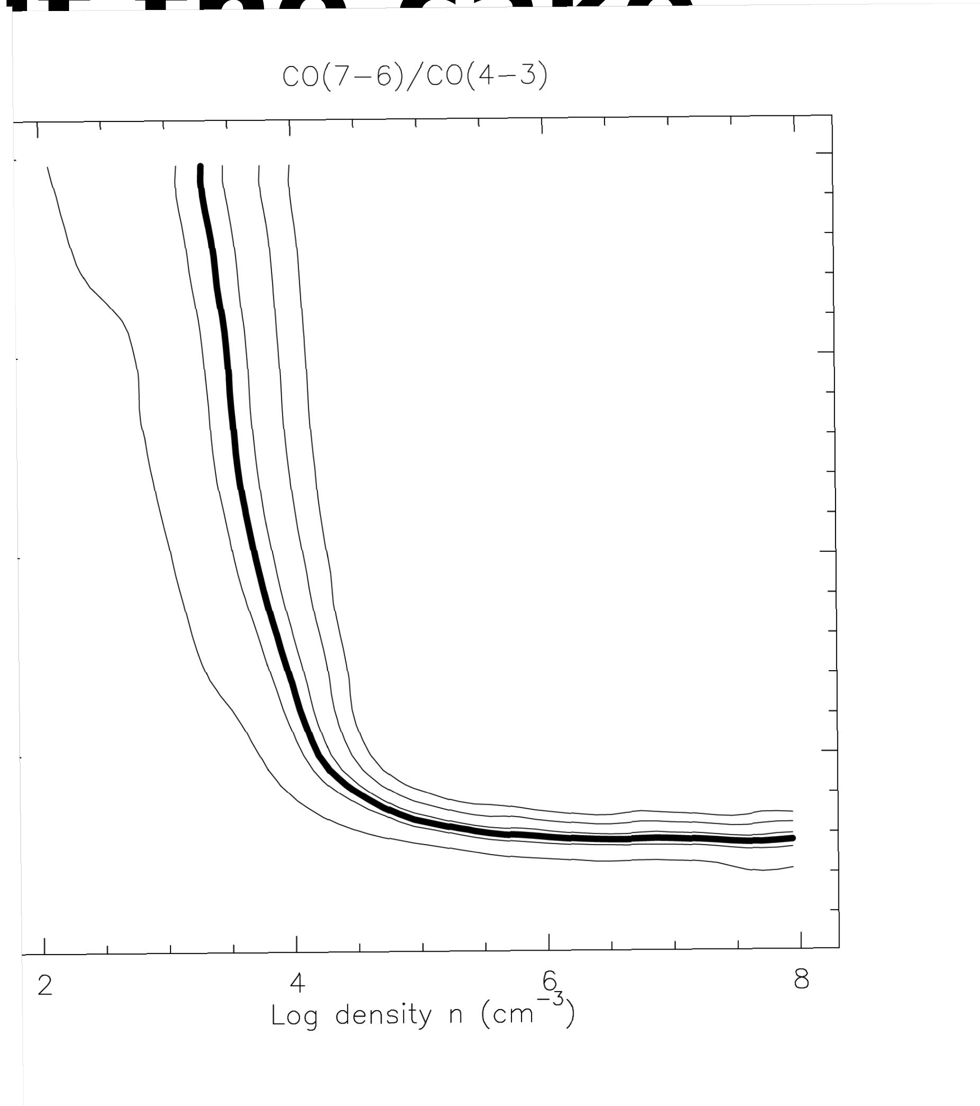


Figure 7 from Leroy et al 2011

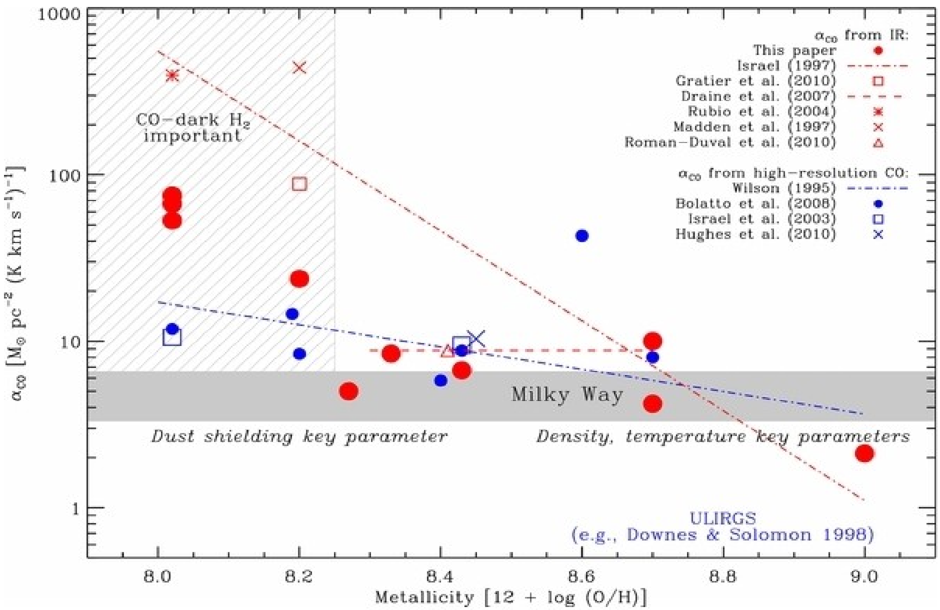
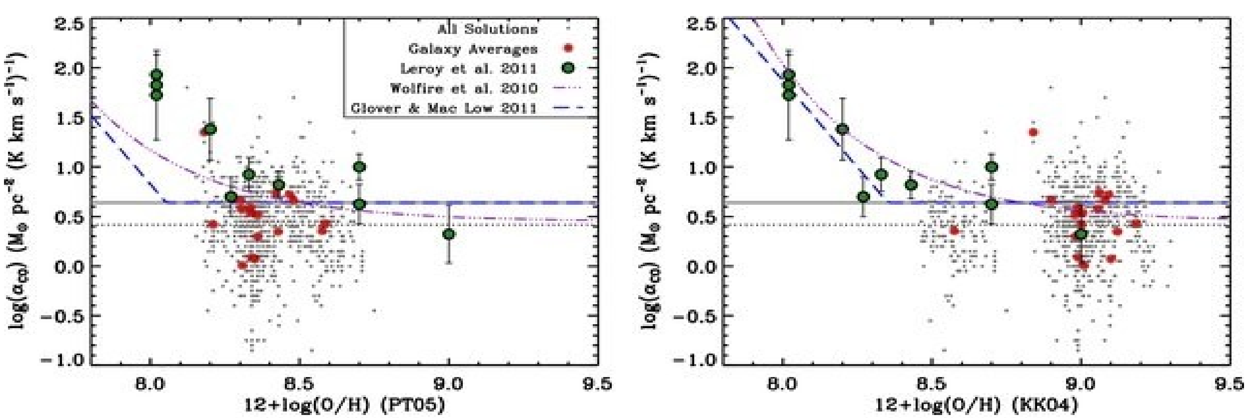


Figure 15 from Sandstrom et al. 2013



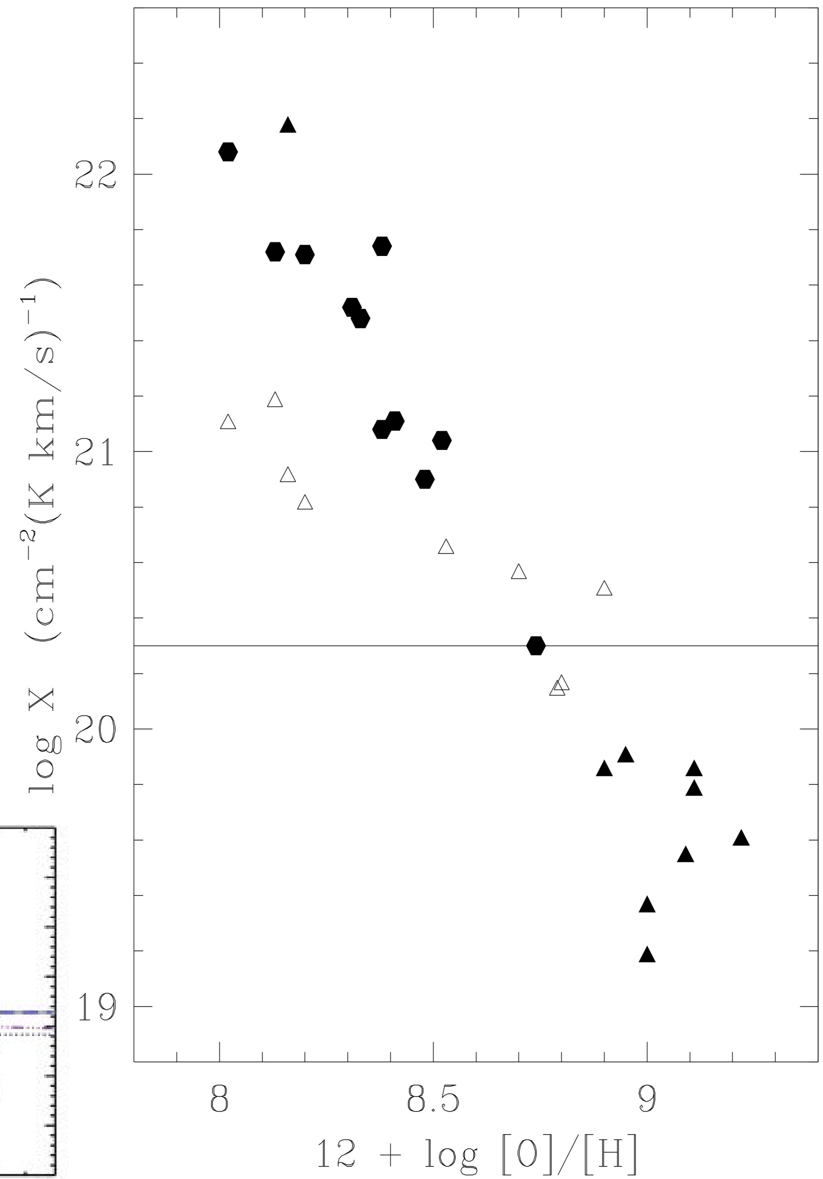


Figure 2 from Israel 2000

CONCLUSIONS SMC 2

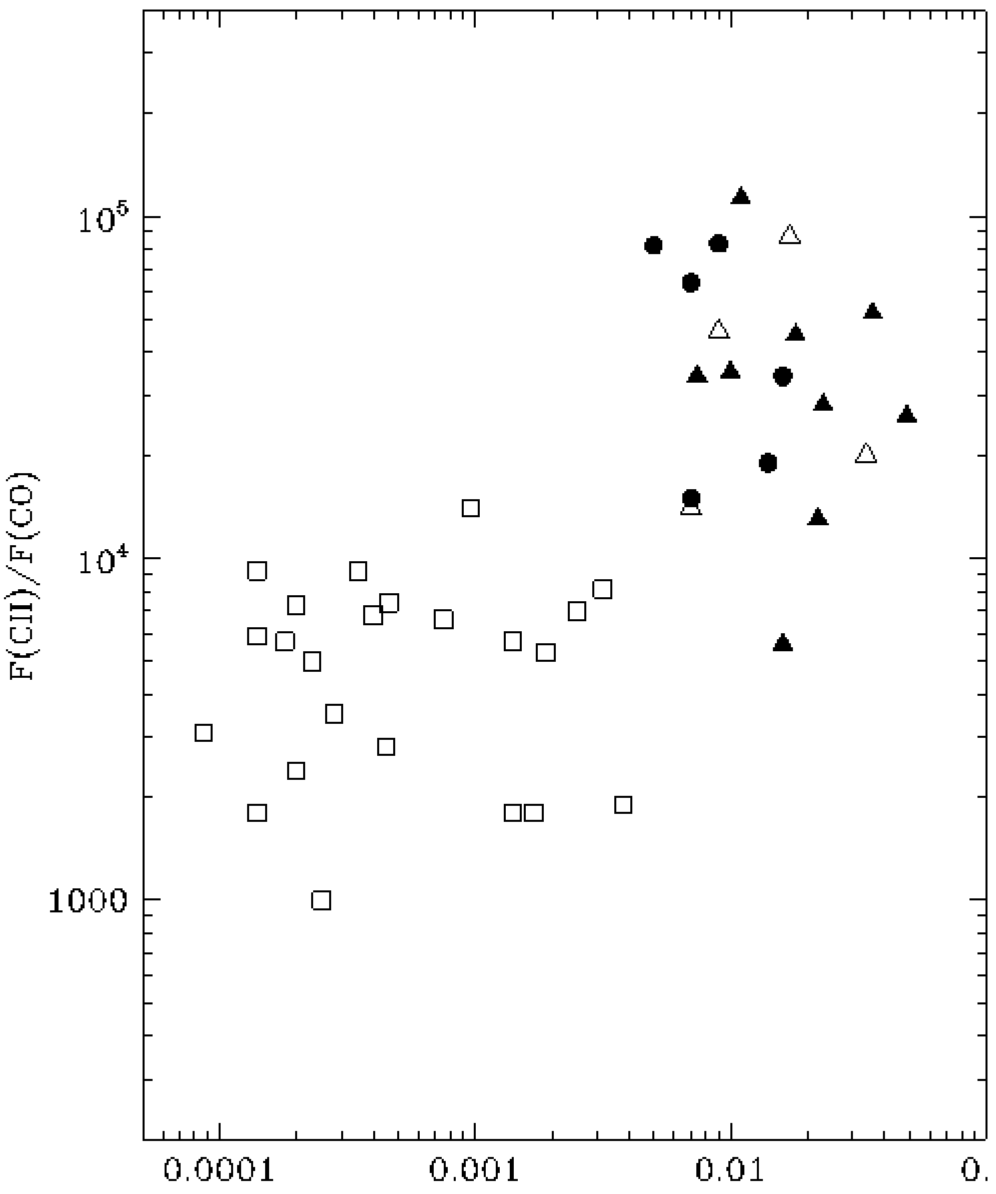
*. CO-dark H_2 gas is 80% - 95% of all gas

* [CII] is by far the best tracer of H_2 column densities – but we need [CI] and CO to establish this quantitatively

* Molecular gas traced by CO, by [CI] and by [CII] well-mixedl

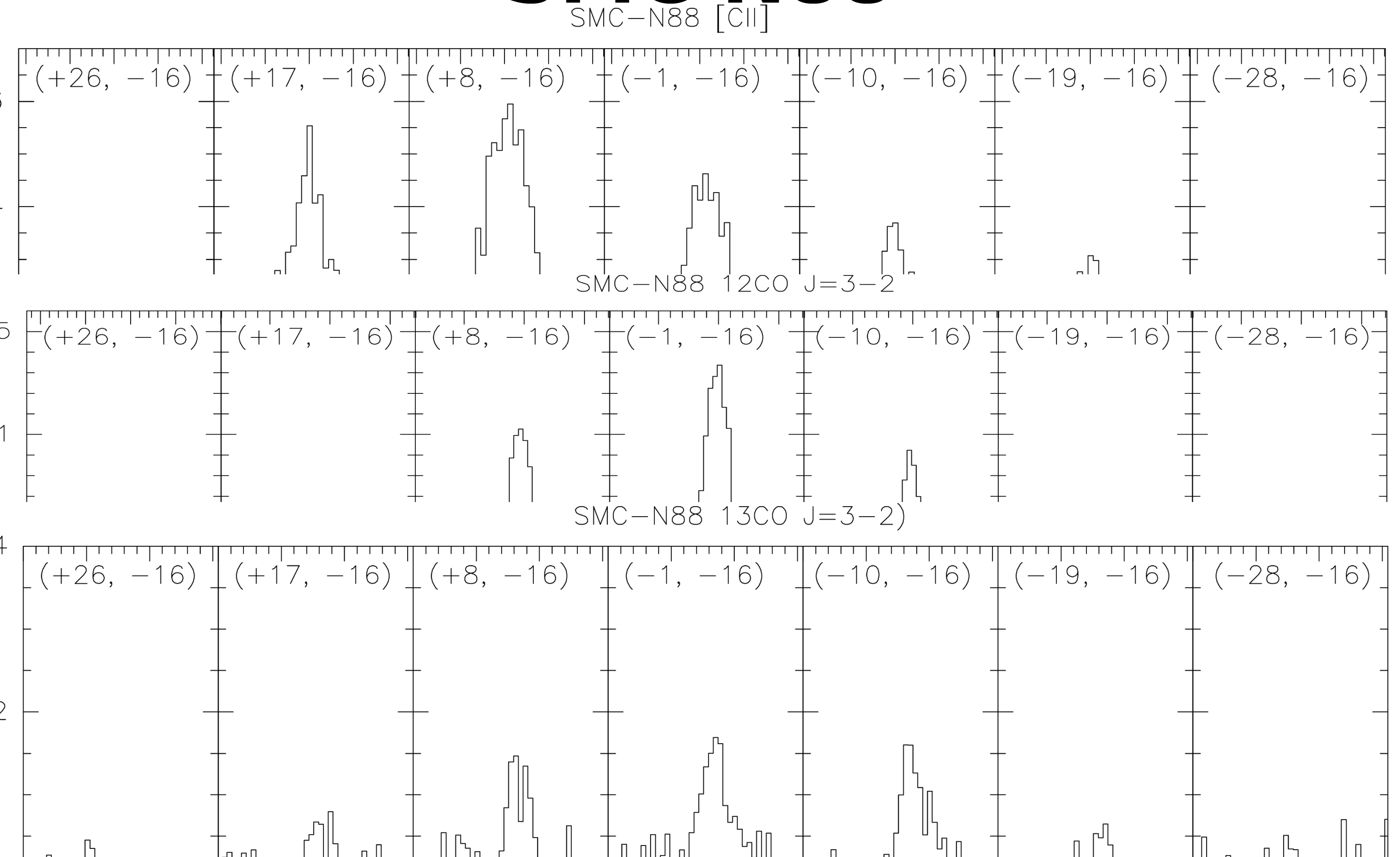
4. Expanding molecular ring in N66

5. Small sample, huge bias!



10^5
10^4
1000
0.0001
0.001
0.01
0.1
F(CII)/FIR
F(CII)/F(CO)

SMC-N88


SMC−N88 [CII]
(+26, −16)
(+17, −16)
(+8, −16)
(−1, −16)
(−10, −16)
(−19, −16)
(−28, −16)
SMC−N88 12CO J=3−2
(+26, −16)
(+17, −16)
(+8, −16)
(−1, −16)
(−10, −16)
(−19, −16)
(−28, −16)
SMC−N88 13CO J=3−2)
(+26, −16)
(+17, −16)
(+8, −16)
(−1, −16)
(−10, −16)
(−19, −16)
(−28, −16)