Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Disk-Halo interaction: The molecular clouds in the Galactic center region

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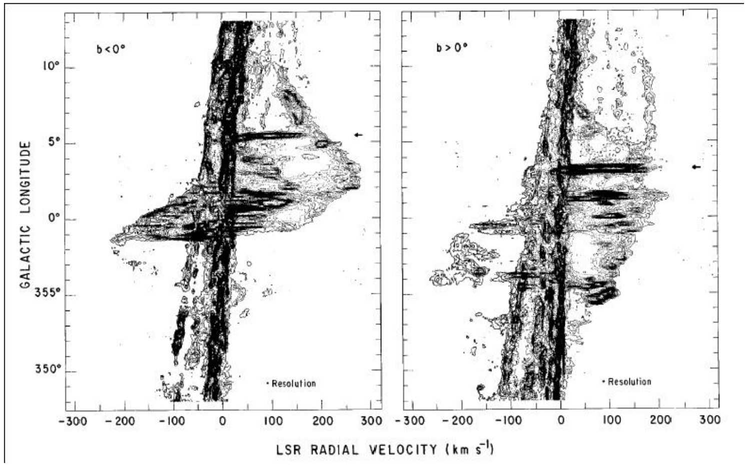
The Galactic center: Feeding and feedback in a normal Galactic nucleus.
October 1st, 2013, Santa Fe New Mexico

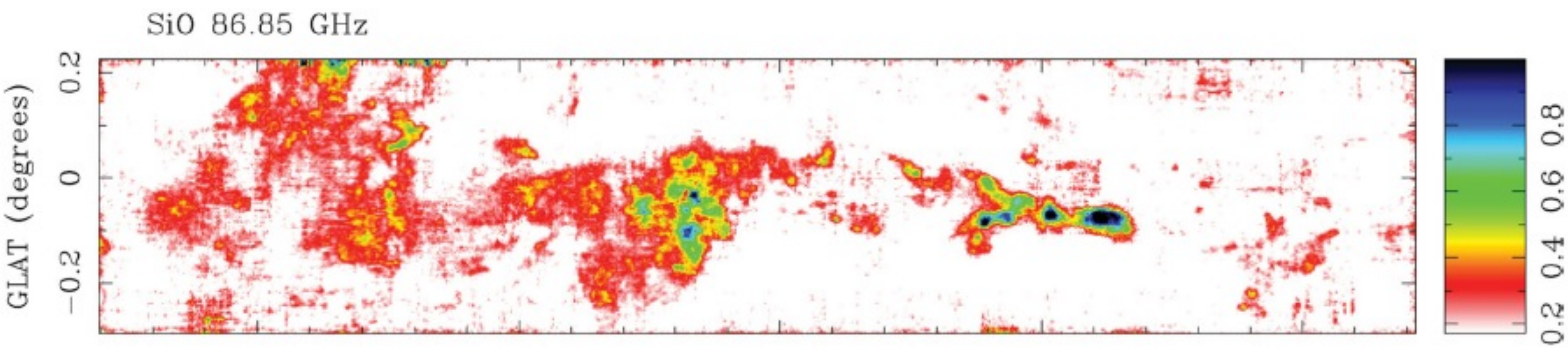
I. Introduction

The molecular clouds in the Galactic center present very different physical and chemical characteristics than the molecular cloud in the disk:

- high kinetic temperatures
- large linewidth
- extended SiO emission



Bitran et al 1997

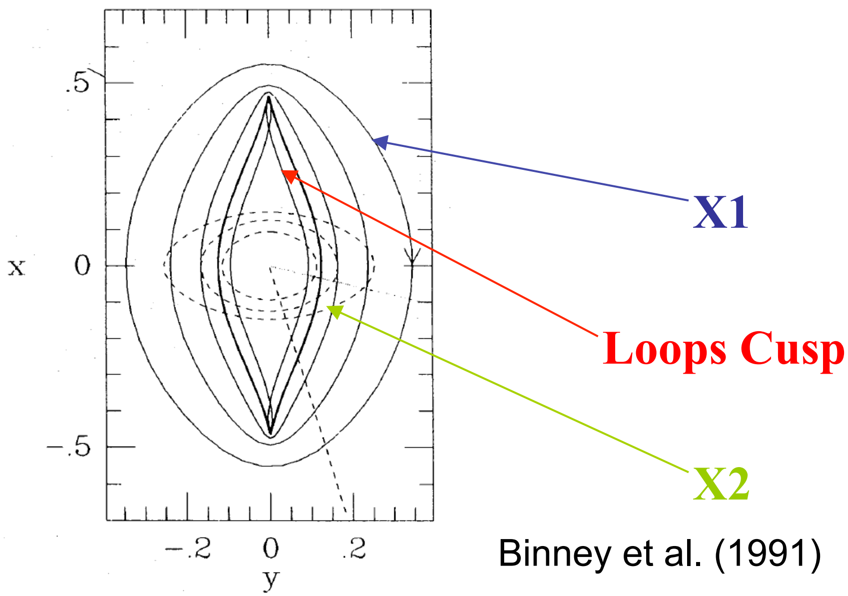


Jones et a.l, 2012

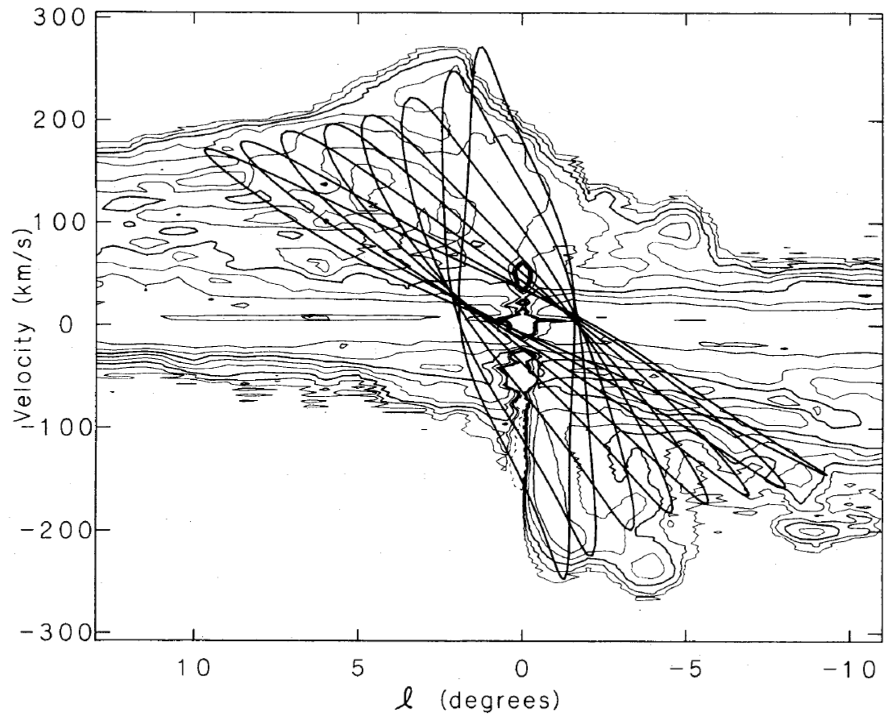
We study two kinds of phenomena occurring in the GC region, and would be responsible for **gas accretion** toward the nuclear region of the Galaxy:

- The barred potential model
- The Giant Molecular Loops (GMLs).

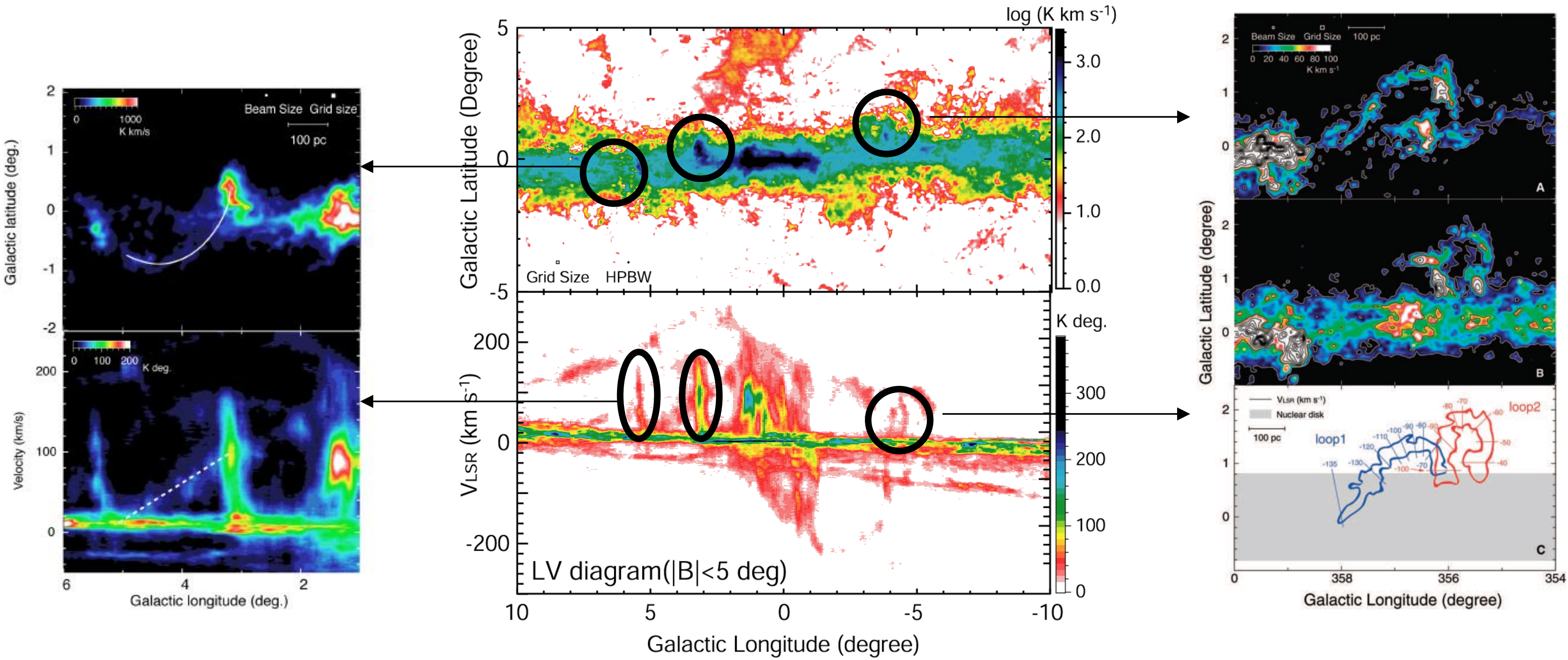
Binney et al. (1991): large-scale gas kinematics in the GC can be accounted for by a **barred galactic potential**, in which there are two major families of orbits inside the bar: the **X1 orbits** parallel to the bar, and the **X2 orbits** orthogonal to it.



Binney et al. (1991)



Fukui et al. (2006) proposed the existence of **giant molecular loops** at the GC formed by a magnetic buoyancy caused by a Parker instability.



According to Fukui's model, the gas of the loops would flow down their sides, along the magnetic field lines, and join with the gas layer of the Galactic plane, generating shock fronts at the **``foot points''** of the loops which is supported by broad velocity features of 40 to 80 km/s.

Outline of this work:

Large scale survey of the GC in SiO (J=2-1,v=0), HCO^+ (J=1-0) and $H^{13}CO^+$ (J=1-0)

↓

Shock Regions

$^{12}C/^{13}C$ isotopic ratio → Trace gas accretion /ejection

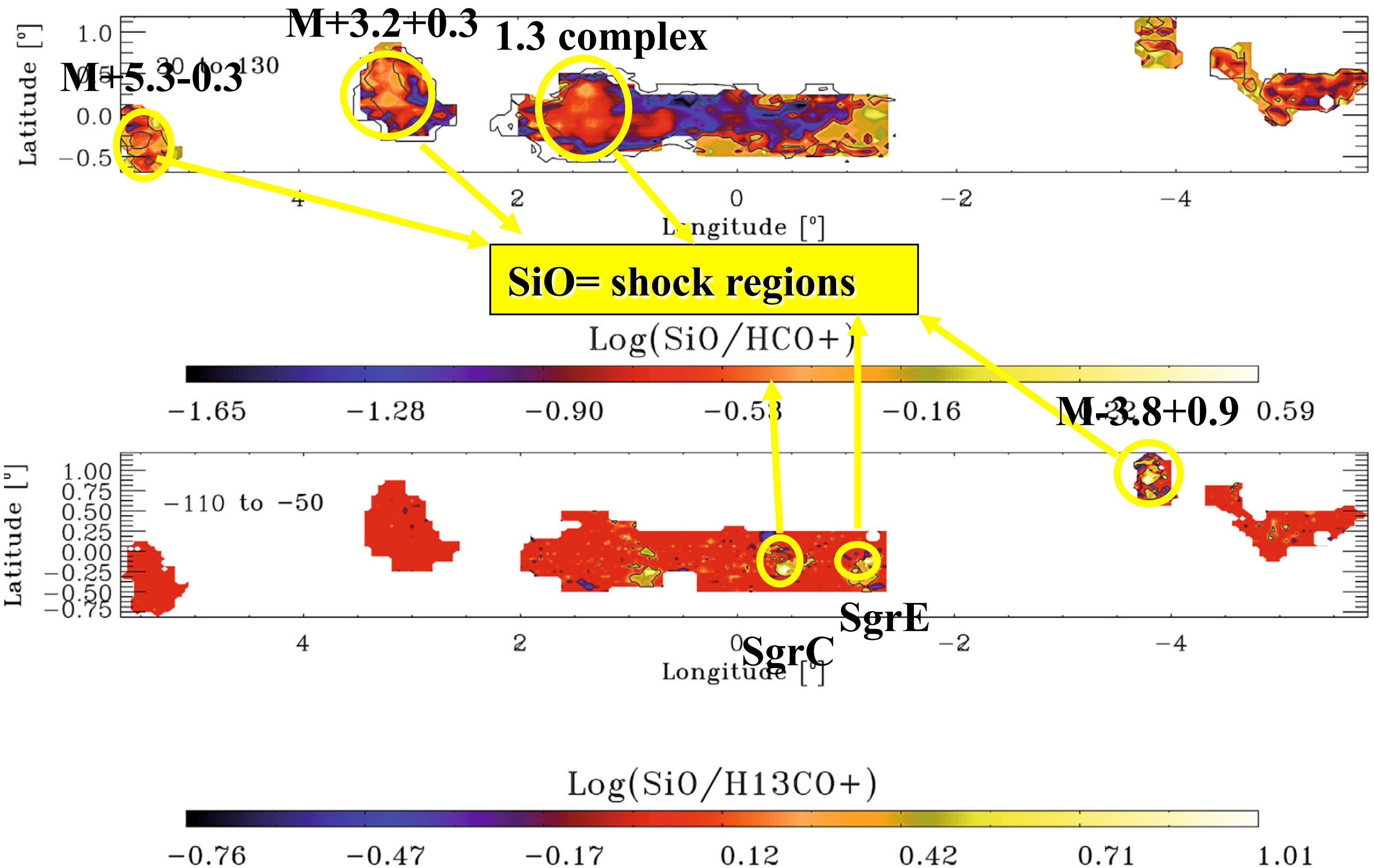
kinetic temperatures → Heating mechanisms, origin of shock, GMLs scenario?

3 mm line mapping of M-3.8+0.9 → morphology, chemical composition and the kinematics of the shocked gas

II.Large Scale survey of the Galactic center region in SiO (J=2-1, v=0), HCO$^+$ (J=1-0) and H^{13}CO$^+$ (J=1-0)

NANTEN 4m telescope $-5^o.75 < l < 5^o.6$; $-0^o.7 < b < 1^o.3$

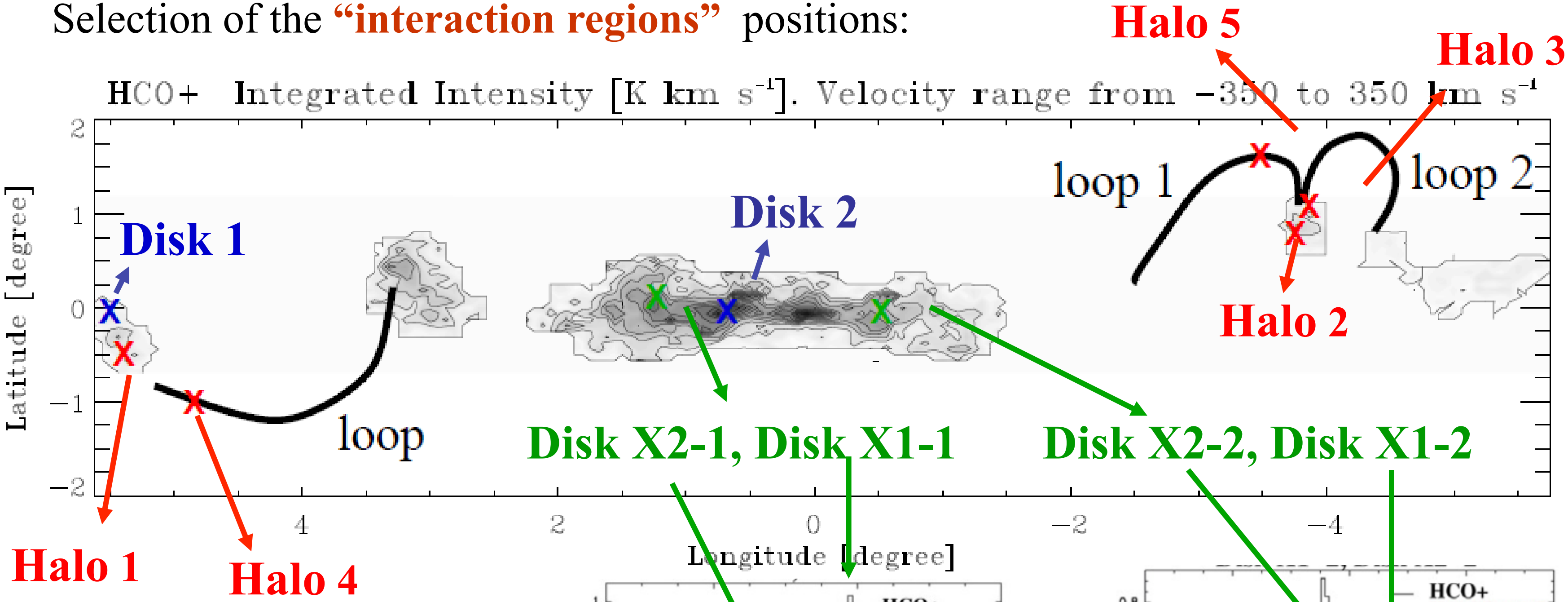
Integrated intensity ratio

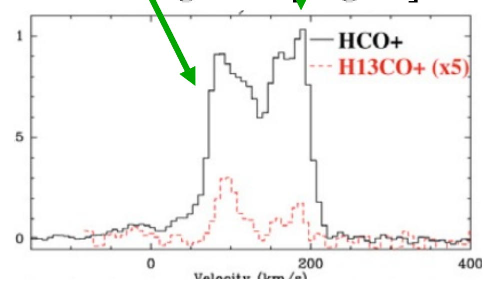


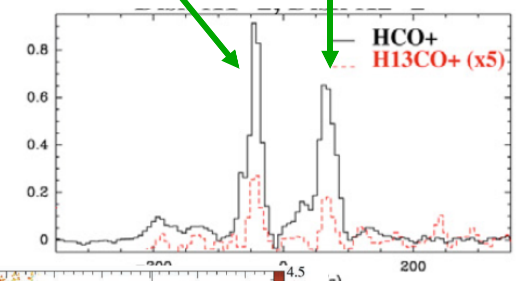
Data cubes available at http://www.das.uchile.cl/galcendata

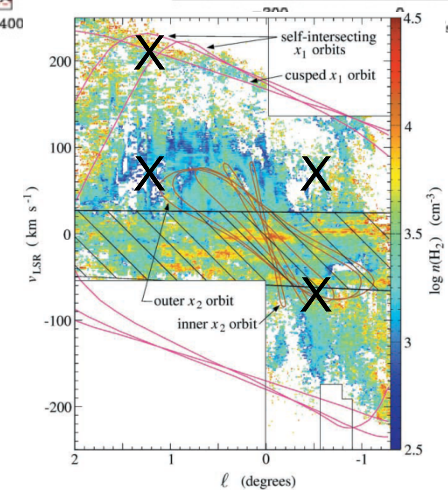
Riquelme, et al 2010b, *A&A*, 523, A45

Selection of the **"interaction regions"** positions:









Halo: high altitude clouds found in the GML (**"disk-halo interaction"**)

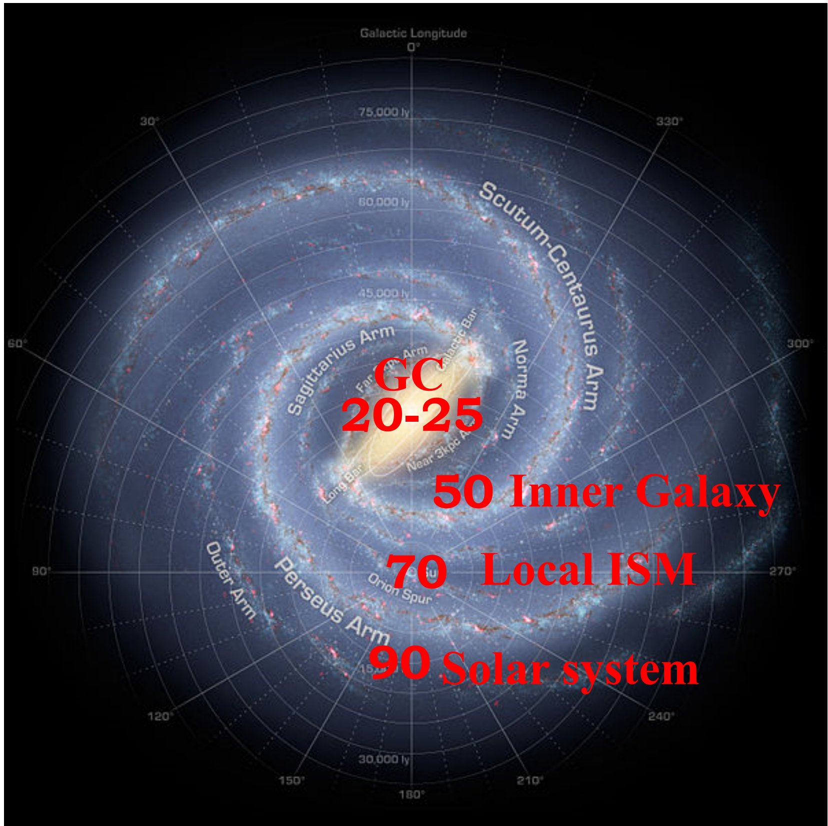
Disk X1, Disk X2: positions at X1-X2 orbits interaction. Two main kinematical components, one associated to the X1 orbits and the other to the X2 orbits

Disk : not associated to neither the GMLs nor the locations of the orbits interaction

III.Tracing gas accretion in the Galactic center using the $^{12}C/^{13}C$ isotopic ratio

- ^{12}C should be formed in first generation, metal-poor massive star, on rapid time scale, ^{13}C should be produced primarily via CNO processing of ^{12}C seeds from earlier stellar generation, on a lower time scale in low and intermediate mass stars or novae (Meyer 1994,Wilson & Matteucci 1992, Prantzos et al., 1996).
- The $^{12}C/^{13}C$ isotopic ratio shows, therefore, the relative degree of primary to secondary processing in stars.

Gradient with galactocentric distance (e.g. Wilson 1999): from 80-90 in the solar neighborhood, 70 in the local ISM, 50 in the inner Galaxy (4 Kpc), 20-25 in the GC.

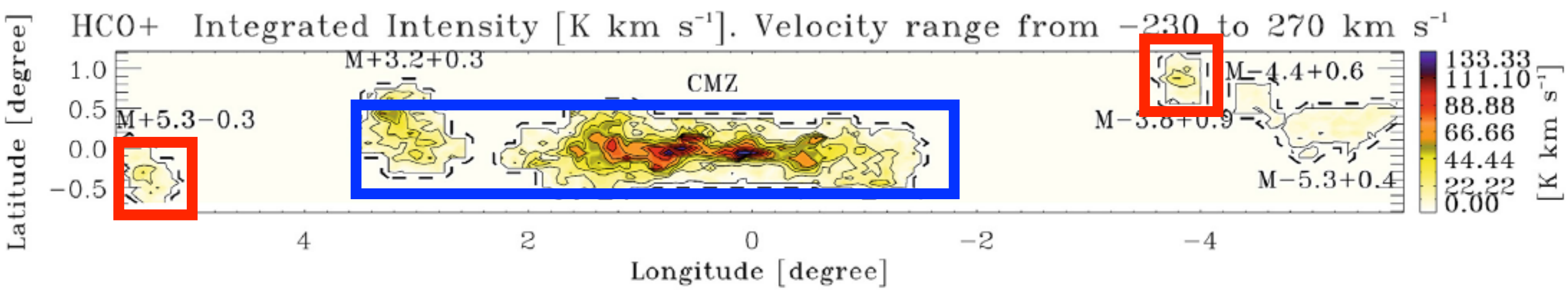


The $^{12}C/^{13}C$ isotopic ratio is well established in the GC.

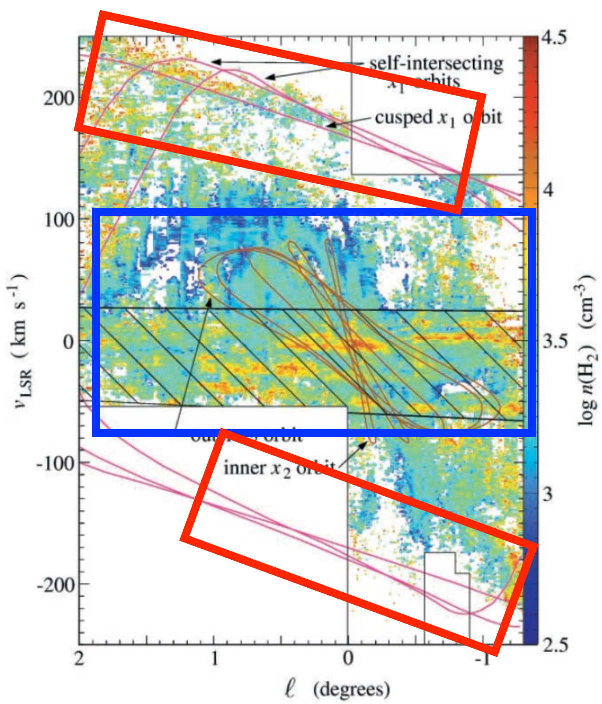
Very processed gas

$^{12}C/^{13}C \sim 20$ -25

$^{12}C/^{13}C$?



However, this ratio is, so far, unknown in the high velocity components (X1 orbits) and in the high latitude regions (GMLs).



This work: HCO^+, $H^{13}CO^+$, HNC, $HN^{13}C$, HCN, $H^{13}CN$, to measure the $^{12}C/^{13}C$ isotopic ratio.

Only one transition. This is a **lower limit** to the actual **$^{12}C/^{13}C$ isotopic ratio**

Source	Velocity Component LSR [km s^{-1}]	Velocity Range [km s^{-1}]	$HCO^+/H^{13}CO^+$ ratio of $\int T_A^* dv$
Halo 1	100	[50, 190]	45.5± 5.4
	87	[50, 97]	≥73.9
	117	[97,135]	32 ± 3.7
	144	[135,190]	39.1±24.7
Halo 2		…20]	73.1±36.5
	le…	…70]	≥34.4
	rig…	…20]	53.2±26.1
Halo 3		…30]	38 ±5.0
	le…	…80]	54.2 ±37.7
	cen…	…30]	35.7 ±4.0
Halo 4		…50]	28.3 ±5.4
		…10]	29.2 ±7.5
	rig…	…50]	≥10.6
Halo 5		…40]	13.8 ±5.0
Disk X1-1		…0]	56 ± 6.4
	le…	…0]	57.2 ± 7.5
	rig…	…0]	54.4 ± 11
Disk X2-1	95	[50,140]	29 ± 1.6
	left wing	[50,92]	32.4 ± 3.7
	right wing	[92,140]	27.3 ± 1.7
Disk X1-2	67	[0,100]	42.1± 8.0
Disk X2-2	−43	[−80,−20]	21.7 ±1.9
Disk 1	66	[35,105]	14.0 ±2.8
	central peak	[35,70]	16.4 ±4.6
	right wing	[70,105]	11.6 ±3.4
Disk 2	left wing	[0, 43]	≥29.1
	55	[43, 97]	4.1 ± 0.1
	right wing	[97,135]	16.1 ± 2.3

The high isotopic ratio found by us in the foot point confirm the GMLs scenario!

➤ $^{12}C/^{13}C$

4-32 in Disk, Disk-X2

consistent with previous studies

>40 in Halo, Disk-X1

different degree of nuclear processing

consistent with the accretion of the gas from the halo and from the outskirts of the Galactic disk.

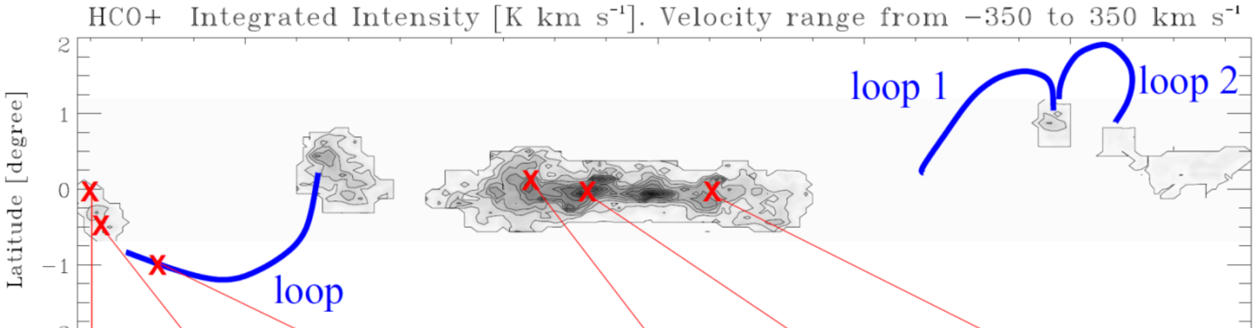
Fresh non-processed gas… accreted from elsewhere!!!!

Riquelme et al, 2010a, *A&A*, 523, A51

IV.Kinetic temperature in the Disk-Halo connection region

NH_3 (1,1) to (6,6) using 100m Effelsberg telescope towards the 6 visible positions.

IRAM 30m telescope: SiO (2-1), CS(3-2), (2-1), $C^{34}S$(2-1), HNCO (10-9), ^{13}CO (1-0), $C^{18}O$ (1-0)



only one (warm) T_{kin} regime (>90 K) at the halo (foot points and top of the loop).

Two T_{kin} regimes (~ 150 K and ~ 40 K) for the CMZ and in the standard GC gas

Source	Cloud number	Low temperature T_{kin} [K]	Low temperature $n(H_2)$ 10^4 cm^{-3}	High temperature T_{kin} [K]	High temperature $n(H_2)$ 10^4 cm^{-3}	Single temperature from p-NH_3 T_{kin} [K]	Single temperature from p-NH_3 $n(H_2)$ 10^4 cm^{-3}
Halo 1	1					>115	<1.00
	2					>90	$8.49^{5.63}_{4.08}$
	3					>135	$1.58^{1.72}_{1.23}$
Halo 2	1						$1.26^{1.56}_{0.98}$
	2						<2.51
Halo 3	1						$1.50^{2.05}_{0.09}$
	2						$3.55^{2.76}_{1.96}$
Halo 4	1					95	$2.75^{2.54}_{1.49}$
Halo 5	1						$7.47^{5.11}_{3.18}$
Disk X1-1	1	38	$13.0^{8.21}_{5.05}$	>300[a]	$3.55^{2.56}_{1.66}$		
Disk X2-1	1	38	$5.62^{4.38}_{3.11}$	100	$2.70^{2.73}_{1.90}$		
Disk X1-2	1	52	$13.3^{8.09}_{5.34}$	215	$5.62^{3.88}_{2.46}$		
Disk X2-2	1	28	$14.1^{8.88}_{5.98}$	95	$6.20^{5.02}_{2.95}$		
Disk 1	1	23	<1.12	>154[b]	<0.16		
	2	38	$4.57^{3.84}_{2.33}$	>82[b]	$2.51^{2.40}_{1.55}$		
Disk 2	1	68	$4.97^{3.94}_{2.40}$	200	$2.47^{2.00}_{1.35}$		
	2					> 145	$2.51^{2.50}_{2.41}$
	3	50	$15.8^{9.27}_{6.94}$	80	$11.6^{8.32}_{5.32}$		

High kinetic temperatures in all the observed positions

Is the heating mechanism in the GMLs very efficient?, or Is the cooling in the CMZ more effective than in the halo positions?

Riquelme et al., 2013, A&A, 549A, 36R

Is the cooling in the CMZ more effective than in the halo positions.?

Molecular clouds cool down by the collisional excitation of molecules and atoms followed by the radiative emission of this energy from the cloud (Hollenbach 1988).

Goldsmith & Langer (1978), velocity gradient of 1 km s^{-1} pc^{-1}, T=10-60 K.

Neufeld & Kaufman (1993), Neufeld (1995), derived radiative cooling rates ($10 \leq T_{kin} \leq 2500$ K), and stated that the dominant coolants are CO, H_2, O, H_2O.

Le Bourlot et al. (1999) derived the cooling rate by H_2 ($100 \leq T_{kin} \leq 10^4$ K; $1 \leq n(H_2) \leq 10^8$ cm^{-3})

Gas-dust coupling :

$$\Lambda_{gd} = 2.4 \times 10^{-33} T_g^{1/2} (T_g - T_d) n^2(H_2) \ \text{erg s}^{-1} \text{ cm}^{-3}$$

Goldsmith & Langer (1978)

		Goldsmith & Langer	Neufeld	Le Bourlot	Gas-dust coupling
Source	a	$\Lambda_{total}^{b,e}$	$\Lambda_{total}^{c,e}$	$\Lambda_{H_2}^{d,e}$	Λ_{gd}^{d}
Halo 1	1		14.0	0.78	0.018
Halo 1	2		242	4.36	0.86
Halo 1	3		46.8	31.4	0.057
Halo 2	1		21.6	0.015	0.028
Halo 2	2		13.3	0.82	0.016
Halo 3	1		30.7	1.3	0.039
Halo 3	2		136	3.1	0.22
Halo 4	1		44.9	1.4	0.10
Halo 5	1		210	3.9	0.74
Disk X1	1	1.5	36.7		0.081
			534	261	0.79
Disk X2	1	1.5	12.7		0.015
			48.5	1.2	0.11
Disk X1	2	3.6	101		0.51
			746	112	1.3
Disk X2	2	0.60	16.5		0.57
			150	3.3	0.51
Disk 1	1	0.071	1.26		0.005
			1.37	0.51	0.001
Disk 1	2	0.28	25.8		0.010
			45.1		0.064
Disk 2	1	1.3	48.6		0.17
			179	34	0.23
Disk 2	2		55.8	8.1	0.16
Disk 2	3	3.2	86.8		0.60
			224		1.3

Is the heating mechanism in the GMLs very efficient?

High T_{kin} through the GC. Therefore the heating mechanism should apply for the gas in the entire GC region, with little effect on the dust.

The dissipation of mechanical turbulence through shocks

$$\Gamma_{\rm turb} \approx 3.5 \times 10^{-28} v_{\rm t}^3 n_{\rm H} \left(\frac{1\ {\rm pc}}{R_{\rm c}}\right) {\rm erg\ s^{-1}\ cm^{-3}}$$

Black 1987

Ion-slip heating: **??**

$$\Gamma_{is} = \frac{B^4}{32\pi^2 R^2 x_i n_n^2 \mu_{in} \sigma_{in}(v_n)} \ {\rm erg\ s^{-1} cm^{-3}}$$

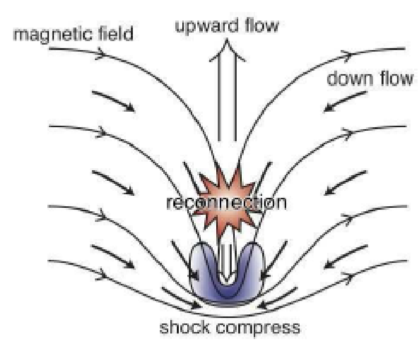
Scalo 1977

Cosmic rays heating: Require a cosmic rate ionization rate (ζ) of one or two orders of magnitude than the Galactic value of $10^{-17} s^{-1}$, which is indeed possible! (Yusef-Zadeh et al. (2007); Goto et al. (2008) estimate an ζ of $10^{-15} s^{-1}$) It cannot be ruled out.

Source	a	T_{kin} [K]	$n(H_2)$ [$\times 10^4$ cm^{-3}]	Λ_{total} [b,e]	Λ_{total} [c,e]	Λ_{H_2} [d,e]	Λ_{gd} [d]	Γ_{turb} [e]
Halo 1	1	115	1.00		14.0	0.78	0.018	27.5
Halo 1	2	90	8.49		242	4.36	0.86	58.4
Halo 1	3	135	1.58		46.8	31.4	0.057	12.9
Halo 2	1	113	1.26		21.6	0.015	0.028	31
Halo 2	2	113	0.97		13.3	0.82	0.016	16.5
Halo 3	1	113	1.50		30.7	1.3	0.039	62.6
Halo 3	2	113	3.55		136	3.1	0.22	178
Halo 4	1	95	2.75		44.9	1.4	0.10	41
Halo 5	1	95	7.47		210	3.9	0.74	51.4
Disk X1	1	38	13.0	1.5	36.7		0.081	849
		300	3.55		534	261	0.79	232
Disk X2	1	38	5.62	1.5	12.7		0.015	234
		100	2.70		48.5	1.2	0.11	113
Disk X1	2	52	13.3	3.6	101		0.51	76.3
		215	5.62		746	112	1.3	32.2
Disk X2	2	28	14.1	0.60	16.5		0.57	158
		95	6.20		150	3.3	0.51	69.4
Disk 1	1	23	1.12	0.071	1.26		0.005	5.29
		154	0.16		1.37	0.51	0.001	0.76
Disk 1	2	38	4.57	0.28	25.8		0.010	31.4
		82	2.51		45.1		0.064	17.3
Disk 2	1	68	4.97	1.3	48.6		0.17	250
		200	2.47		179	34	0.23	124
Disk 2	2	145	2.51		55.8	8.1	0.16	32.5
Disk 2	3	50	15.8	3.2	86.8		0.60	129
		80	11.6		224		1.3	94.7

Probably none of the mechanism discussed would be the responsible of the lack of the low temperature component observed in the halo positions. An extra heating input would be required ???

Torii et al 2010 propose that gas in the foot point is heated by C-shock and that the warmest region of the foot points is additionally heated by magnetic reconnection or by upward flowing gas bounced by the narrow neck in the foot point. This effect would provide an extra heating of $\Gamma \sim 3.9\text{–}7.8 \times 10^{-21}$ erg cm^{-3} s^{-1}.



Neglegible!

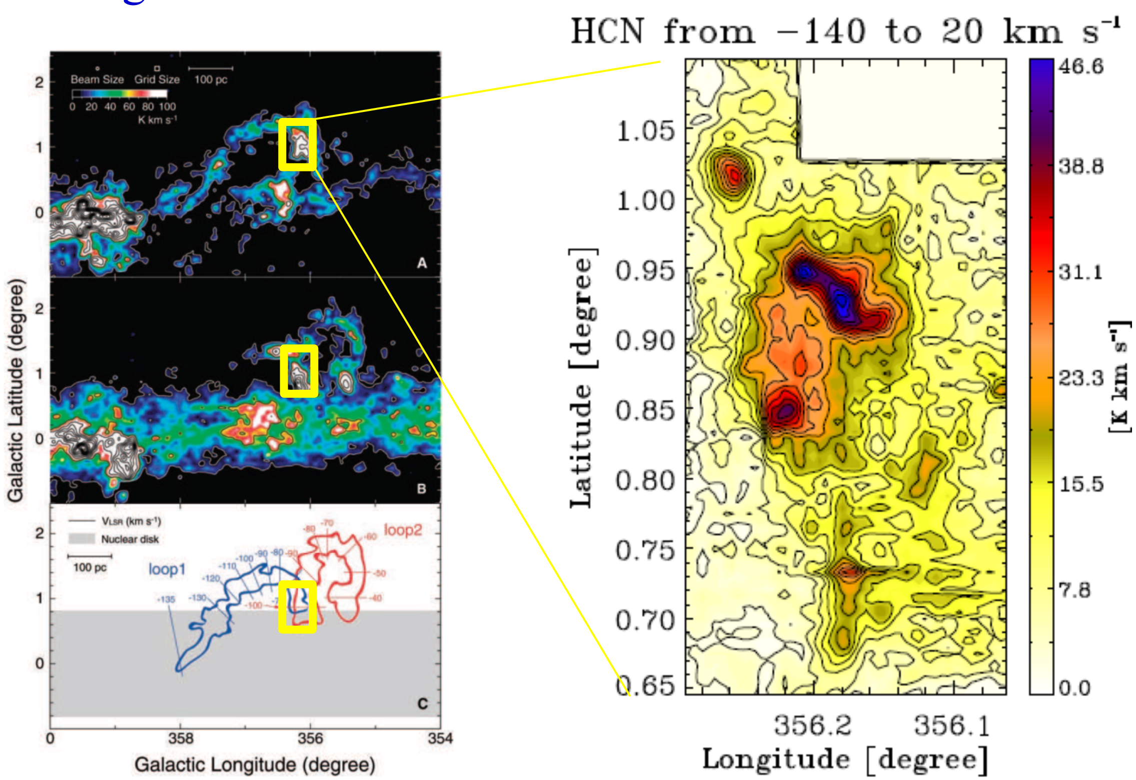
We need exhaustive studies of the Foot point of the GMLs!!!

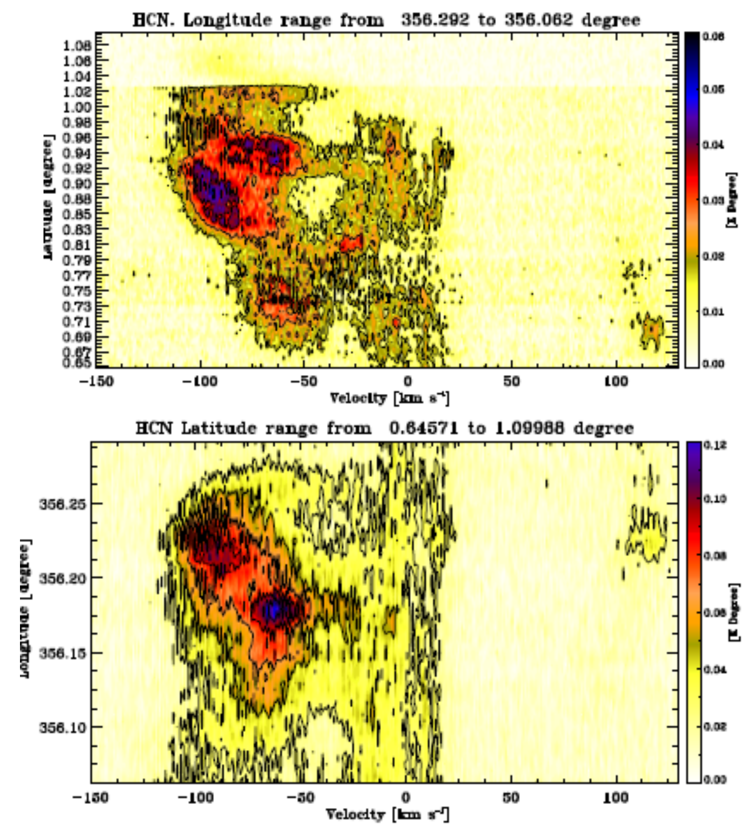
V. The missing key: a complete study of the foot points of the GMLs

To reveal the morphology, chemical composition and the kinematics of the shocked gas in the foot points of the giant molecular loops

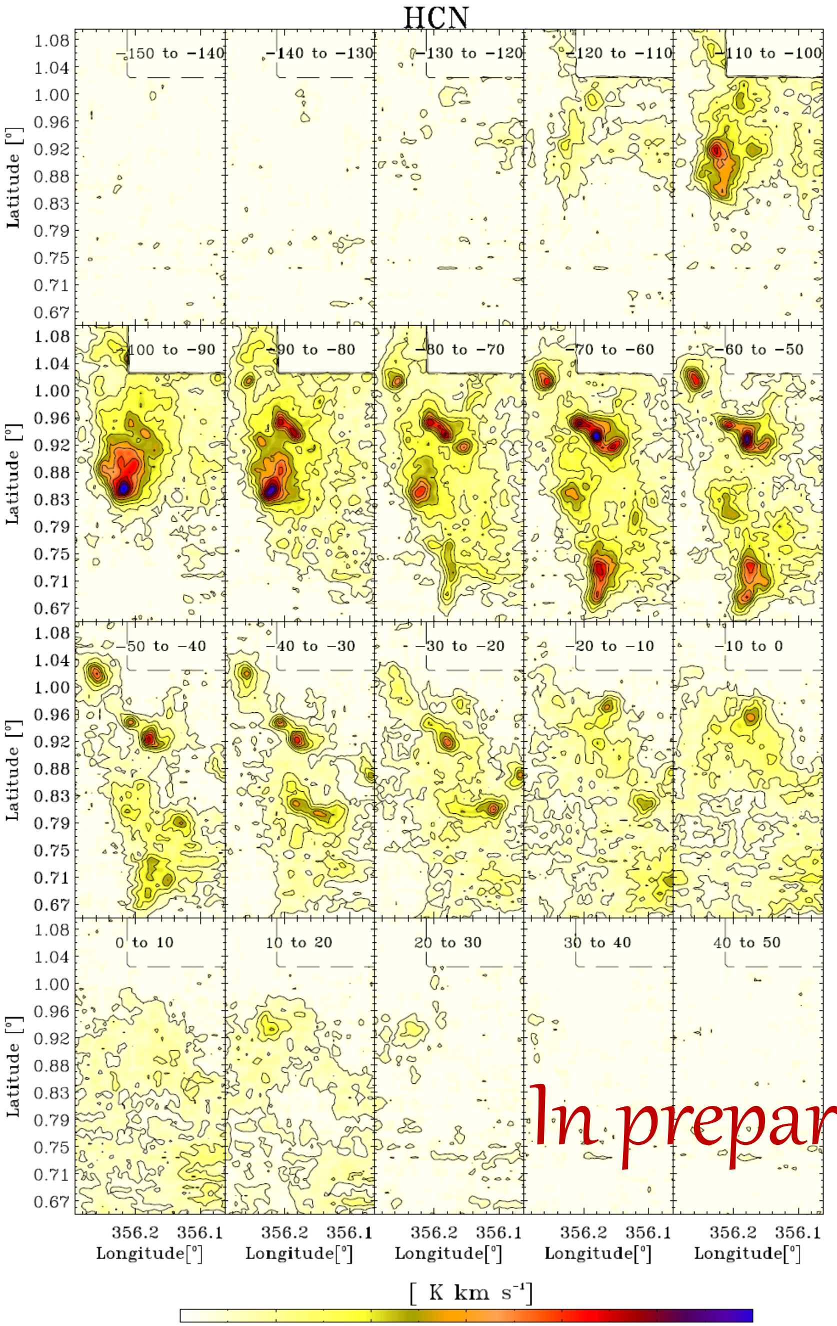
3 mm line mapping using the 22m Mopra telescope of the foot points of the GMLs placed at M-3.8+0.9 molecular (85.275 to 93.555 GHz, and 95.585 to 103.866 GHz)

SiO, SO, HCN, $H^{13}CN$, HNC, $HN^{13}C$, HCO^+, $H^{13}CO^+$, N_2H^+, HNCO, HC_3N, CH_3CN, ^{13}CS among others

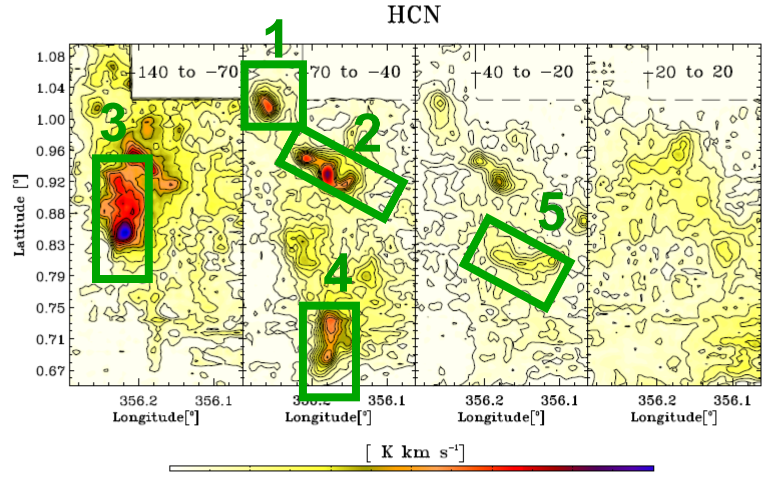


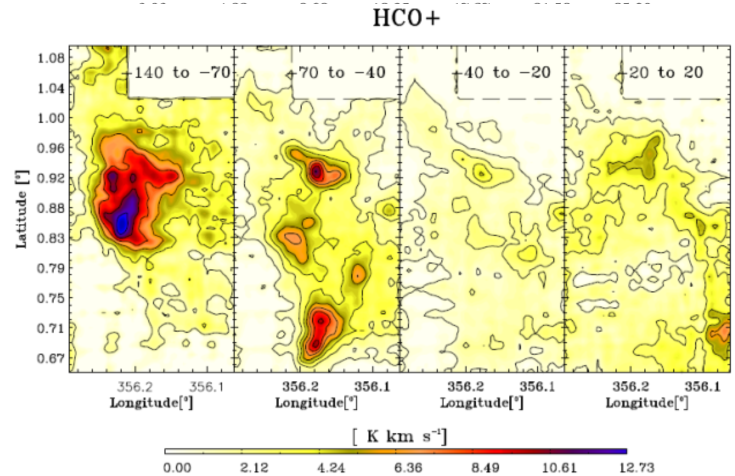


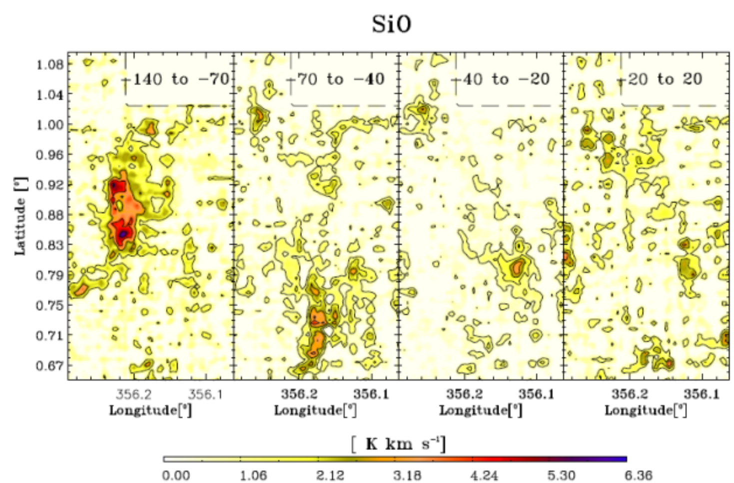
Morphology and kinematics

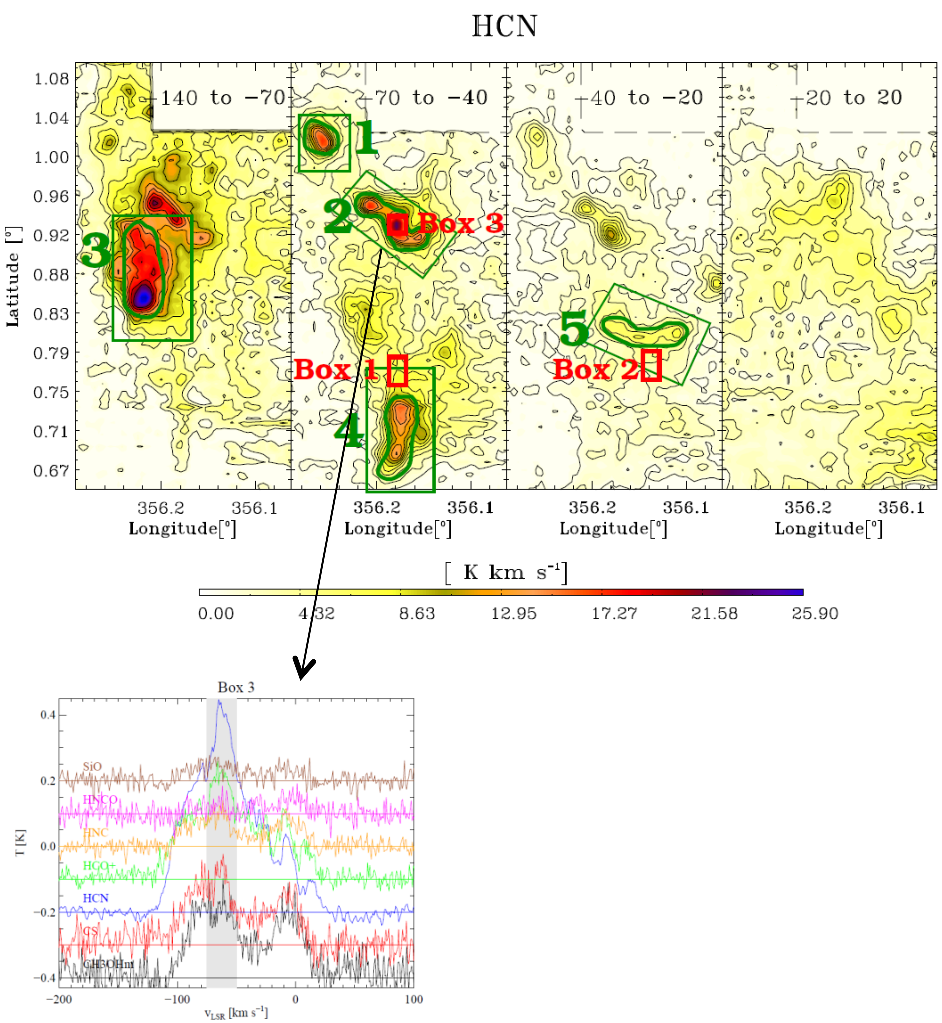


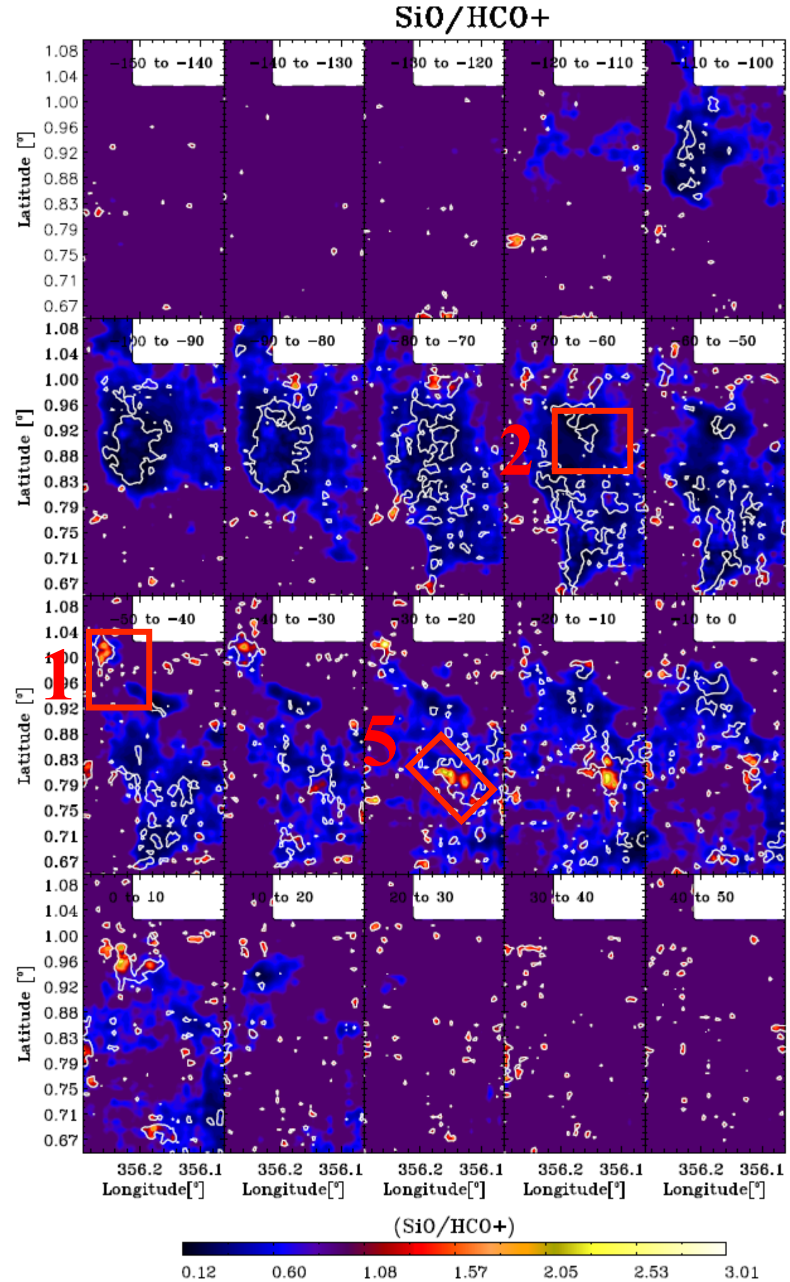
In preparation!











There are differences up to a factor 25 between the region where the HCO^+ dominate in the complex 2, and where the SiO dominates in the complex 5 and in complex

In preparation!

VI.Summary

We have studied the molecular clouds in the Galactic center region, with special emphasis in the zones where these molecular clouds interact with matter coming from the disk, and from high latitude clouds in the halo of the Galaxy (disk-halo interaction).

- From the large scale survey of the GC region in the molecular lines HCO^+ (J=1-0), $H^{13}CO^+$ (J=1-0), and SiO (J=2-1) we identify **shock regions** as traced by the enhancements of the SiO emission with respect to HCO^+.

The interaction regions were studied using the **$^{12}C/^{13}C$** isotopic ratio to **trace gas** accretion.

- We determined lower limits to the $^{12}C/^{13}C$ isotopic ratio. We found **high isotopic ratios** toward the **halo** positions **(> 40 to > 70)** and **X1-X2 orbit** interactions **(> 42 to > 56)**, which is consistent with accretion of the gas from the halo and from the outskirts of the Galactic disk.

- From metastable inversion transitions NH_3, we derive **high T_{kin}** for all observed positions. **Two T_{kin}** regimes for gas in the **CMZ** and for gas in the disk, and **one T_{kin}** component for the gas in the **GMLs**. Using other molecular tracer (SiO, HNCO, CS, ^{13}CO, $C^{18}O$) we propose that the **heating mechanism** for the studied positions in this work is **shock**.

- 3mm line mapping towards the foot points of the GMLs will reveal important clues about this features.