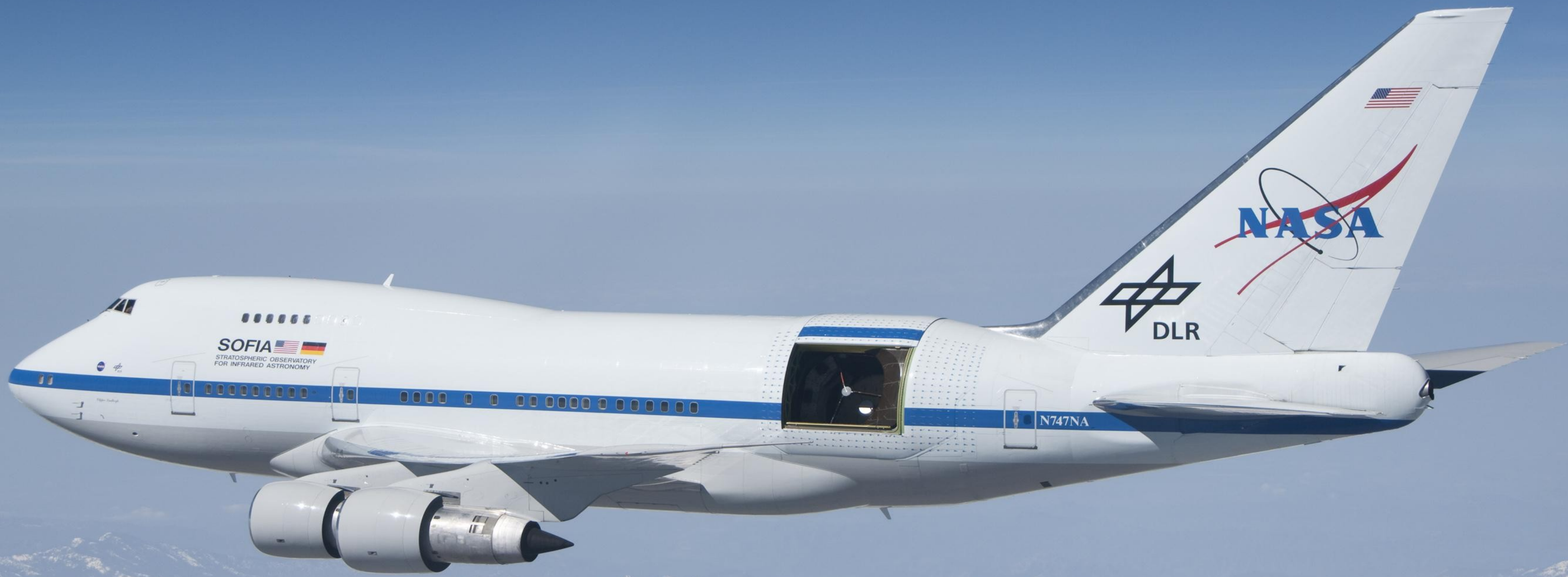
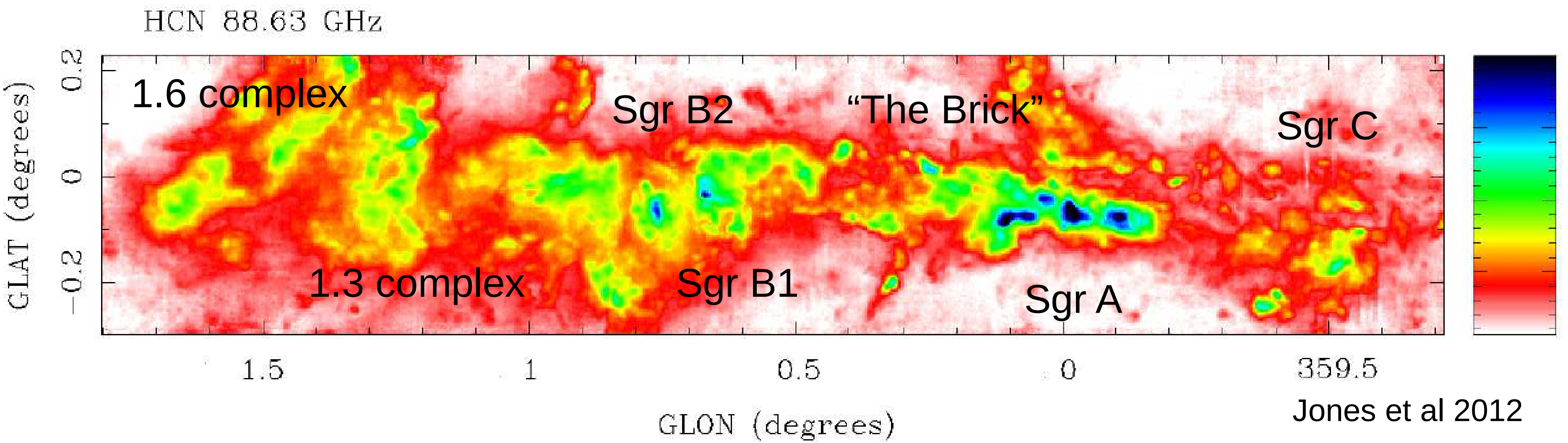
Large scale mapping of the Central Molecular Zone: C^{+} and CO emission



Denise Riquelme, Rolf Güsten, Andrew Harris, Miguel Requena-Torres et al

The CMZ

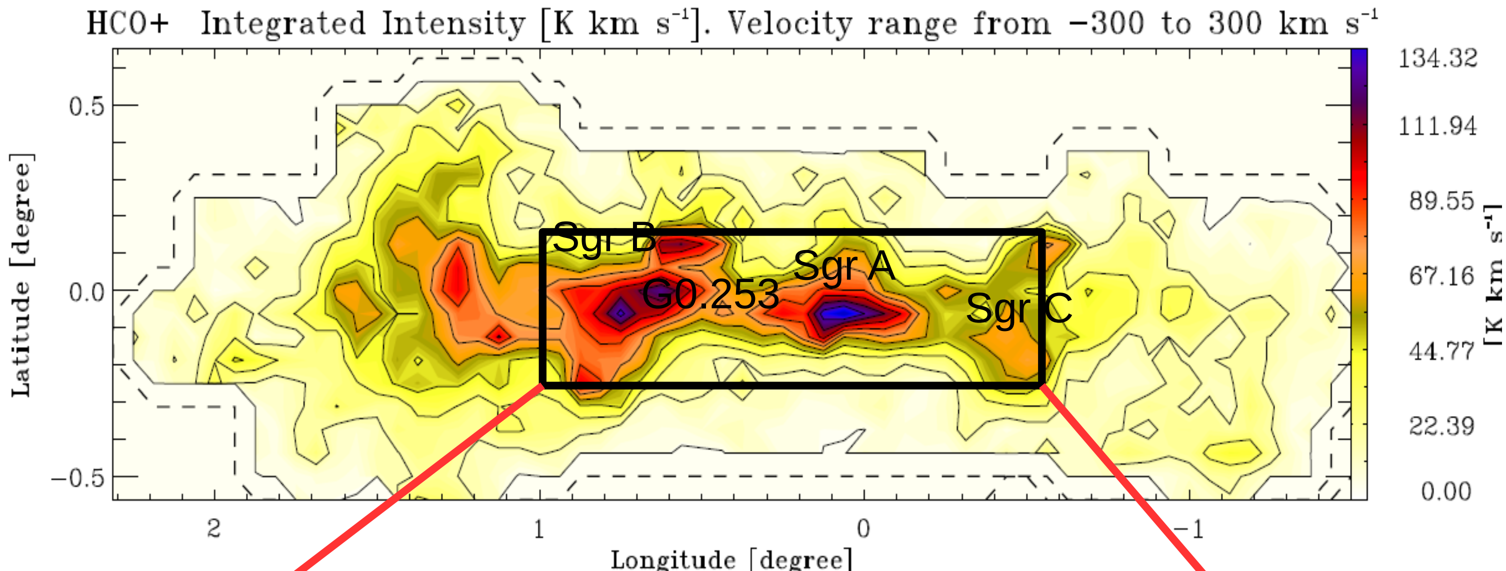


Jones et al 2012

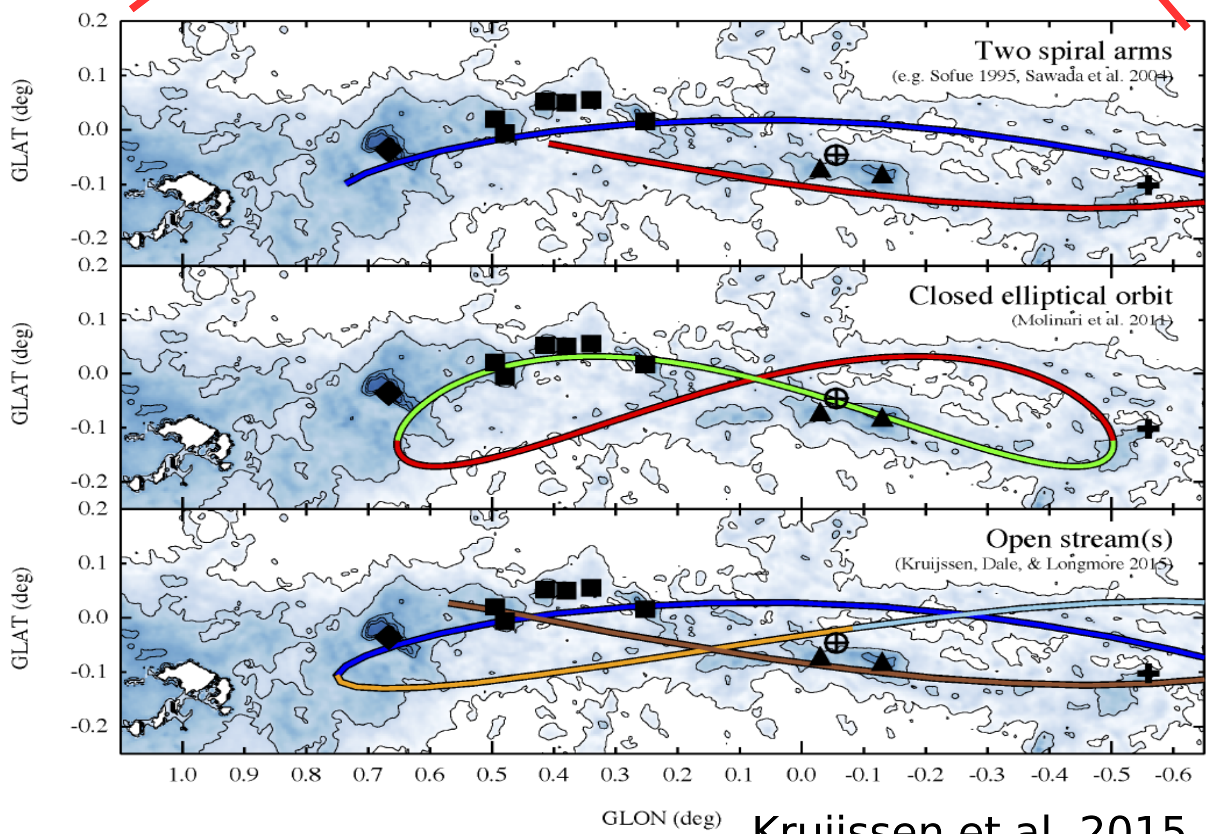
~10 % of the Milky Way's molecular gas, ~ 80 per cent of the dense (>10^3 cm^{-3}) gas. 2-6×10^7 M_o of molecular material (Morris & Serabyn 1996)

The star formation rate is 10-100 lower than expected for the huge amount of dense gas and dust contained in this region (Yusef-Zadeh et al. 2009; Immer et al. 2012; Longmore et al. 2013; Kruijssen & Longmore 2013)

CMZ have different properties from "normal" (i.e. spiral arm) clouds:
much denser (n ~ 10^4 cm^{-3} vs. 10^2 cm^{-3}),
much warmer (60 K < T < 120 K vs. 10–20 K),
much more turbulent (v ~ 10 – 20 km/s vs. a few km/s)
widespread emission of shock tracer (SiO, HNCO, CH_3OH)



Star formation is confined here, and may be related to the orbital-streams dynamics of the gas



The bulk of the gas is found at velocities -100 < v < 120 km/s Known as 100 pc ring (Molinari et al. 2011)

Kruijssen et al, 2015. Henshaw et al, 2016

How the dense gas is collected at the Galactic center ?

Why the large clouds are distributed as they are?

Why the star formation is low at the GC?

Why stars are formed in some places but no others?

How is the 3-D distribution of the CMZ structures?

Can turbulence alone explain the high kinetic temperatures and the high velocity dispersion observed in the Galactic center?

Panoramic view of the Central Molecular Zone

Constructing a full and large scale chemical inventory of the CMZ

APEX

Unveil dense atomic gas missing from molecular emission with a [CII] and [OI] large scale mapping of the CMZ

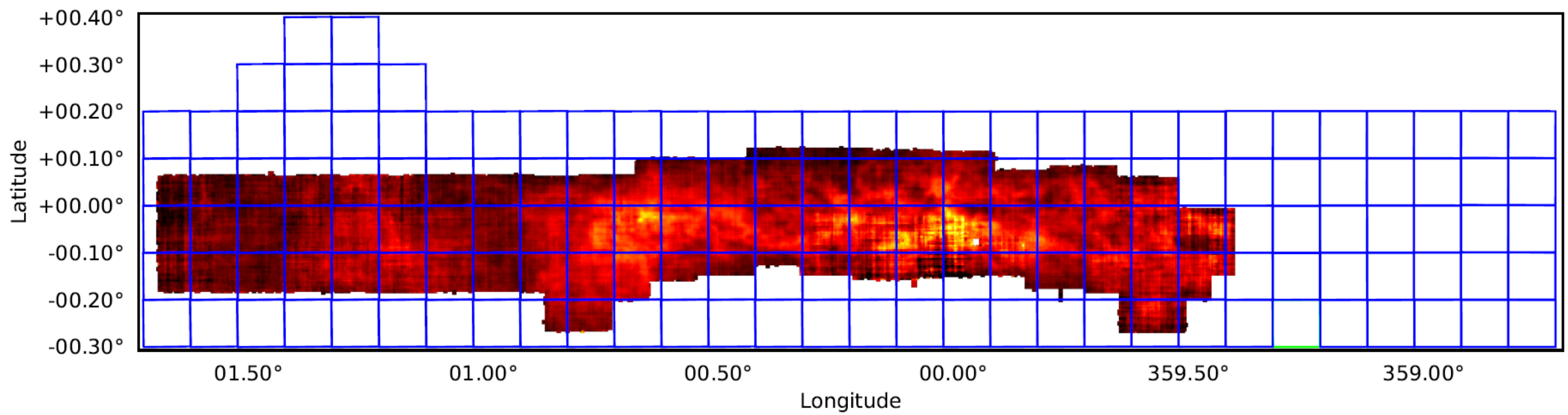
SOFIA

Observations:

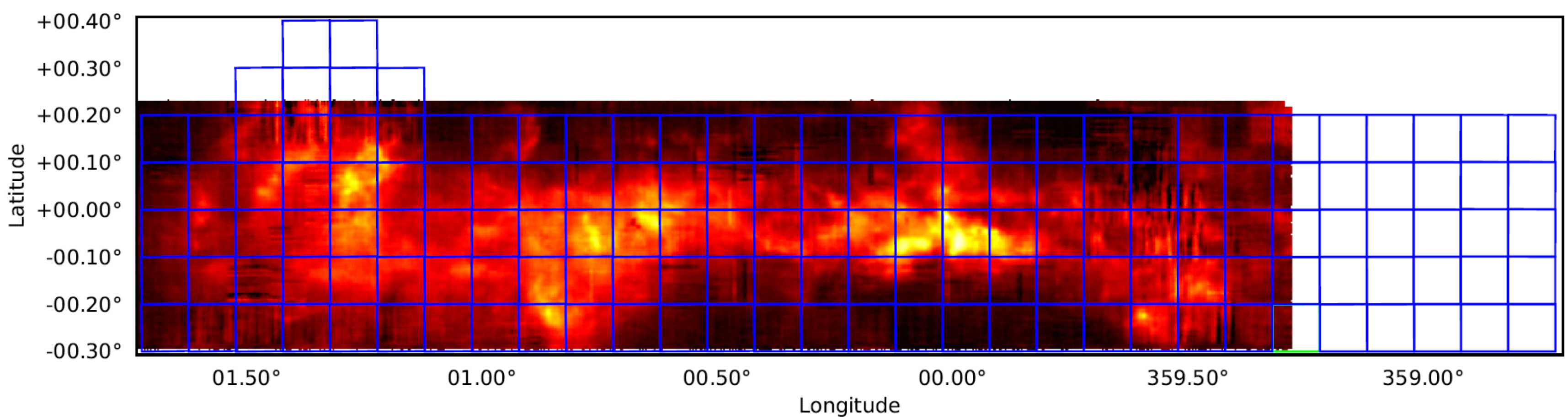
March 2017 – August 2019

PI230 receiver: 2SB dual polarization, 8 GHz per sideband = 32 GHz!
Backends: FFTS4G
156 tiles, 6'x6', 27 min each tile, one scanning direction
12 off-positions ~16 min each
Total time ~73 hours!

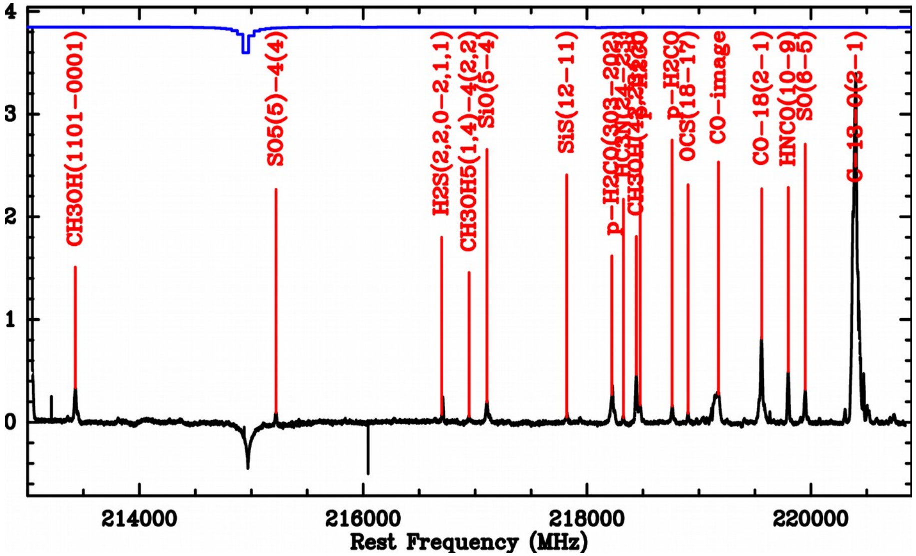
^{13}CO (2-1) Ginsburg et al 2016

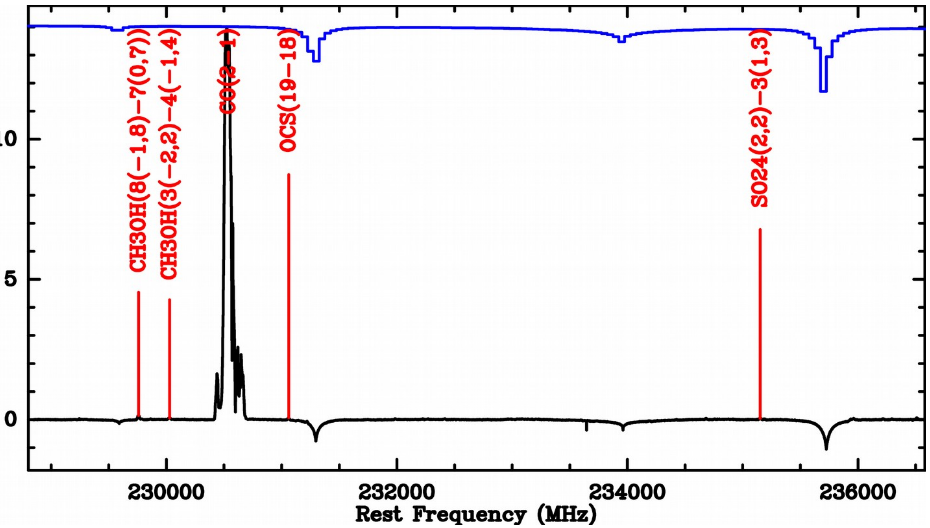


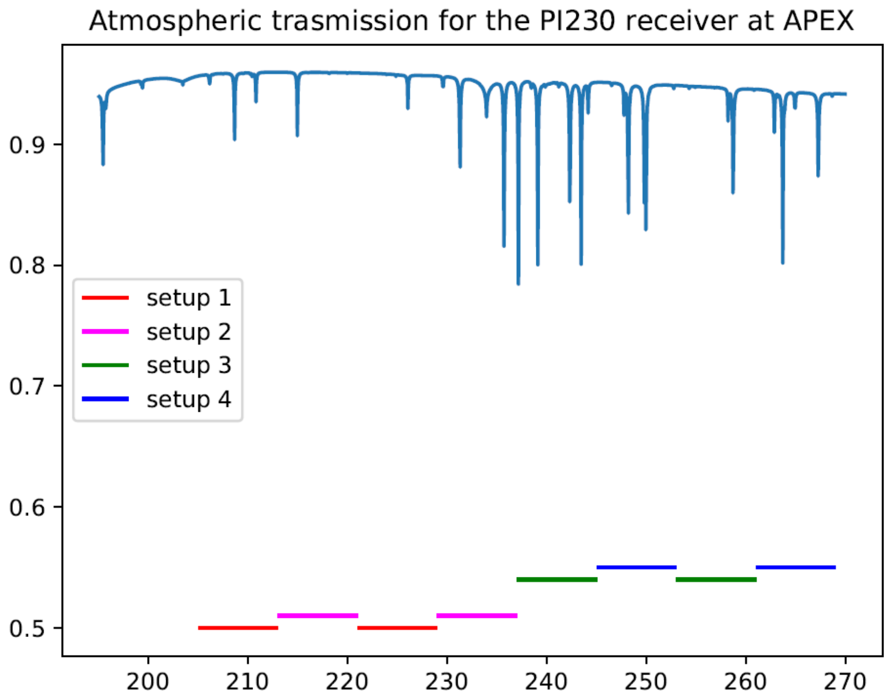
HCN (1-0) Jones et al 2012

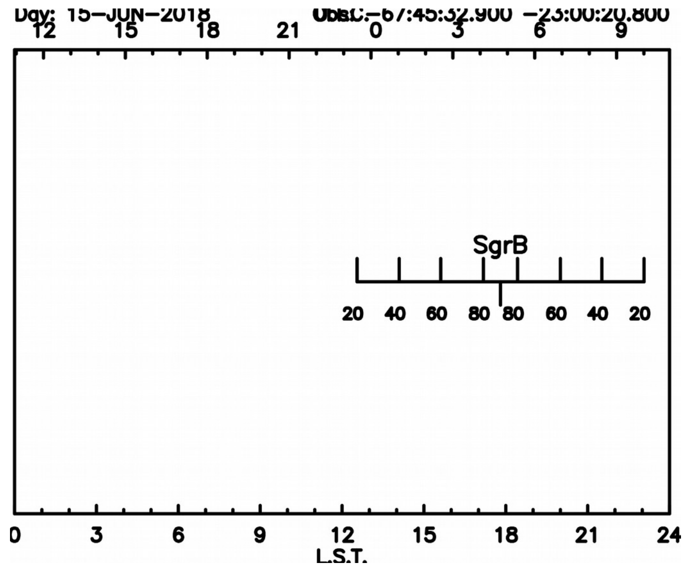


Tunning frequency 218.8 GHz. Frequency range: 213.0-220.8 GHz and 228.8-236.6 GHz
Instantaneous bandwidth of 15.6 GHz!



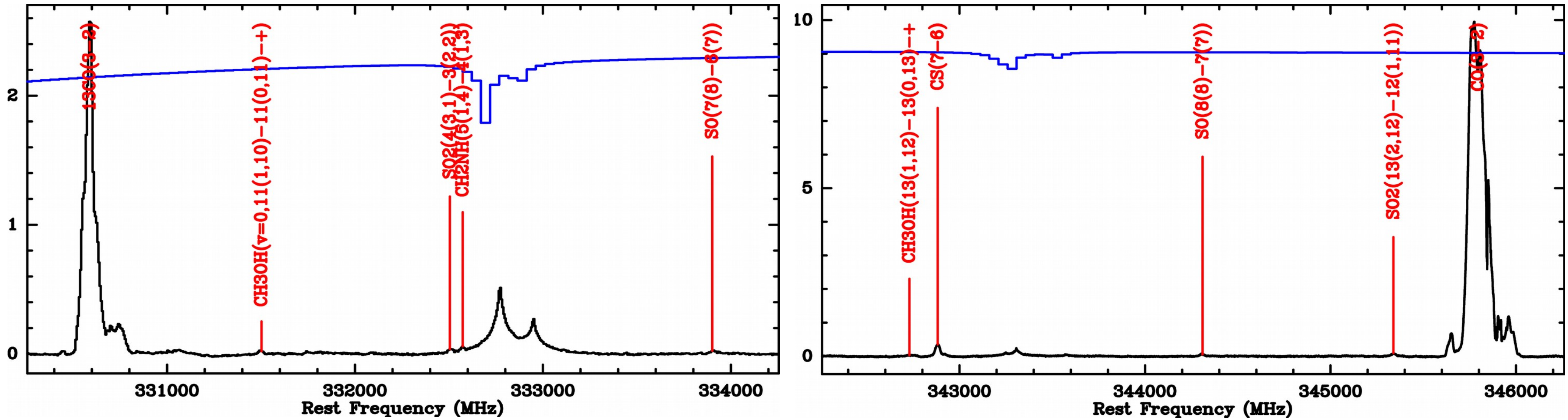


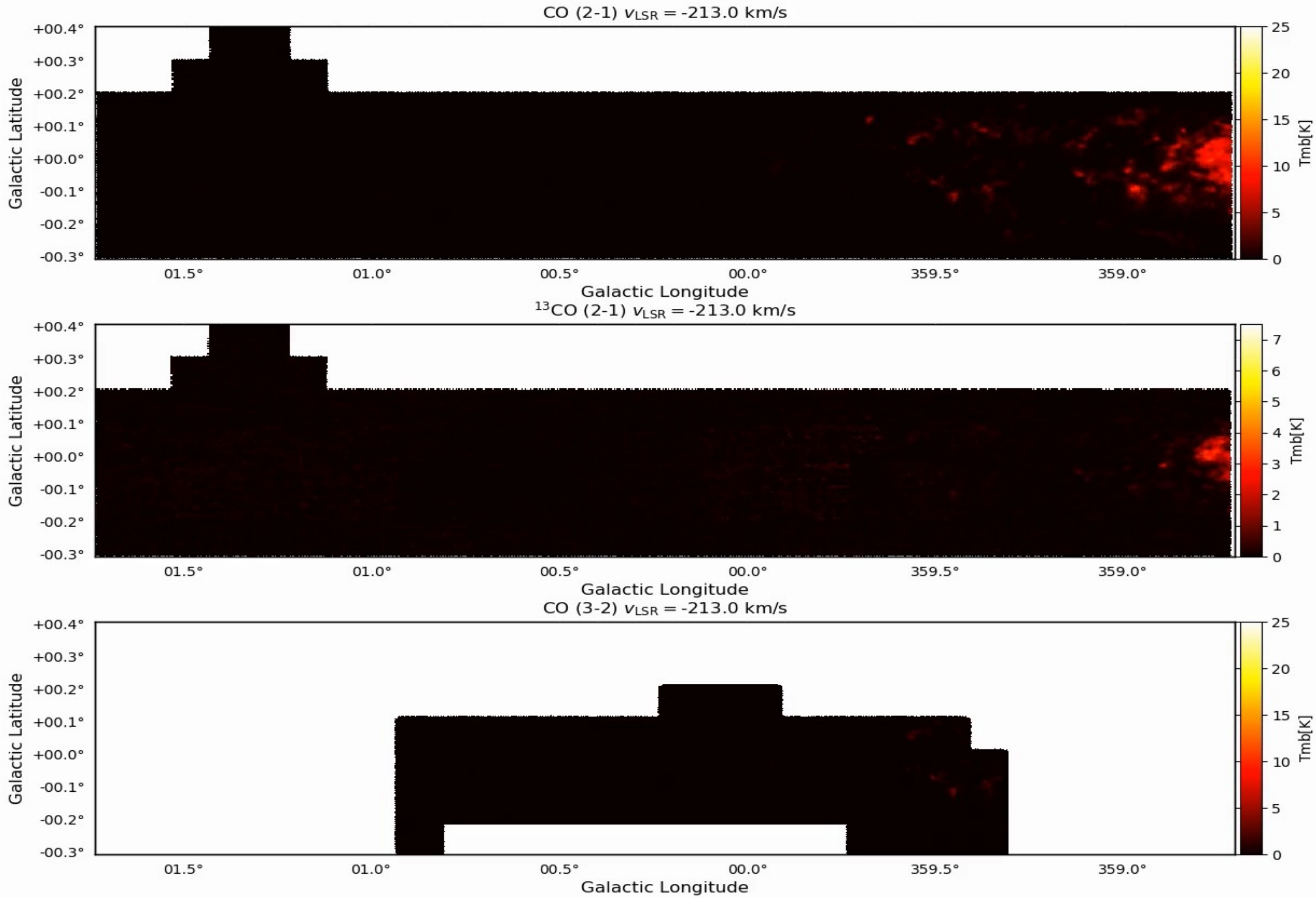




LASMA receiver: 7 pixel hexagonal array, single polarization, 2SB, 4 GHz per sideband
Backends: FFTS4G
56 tiles, 6’x6’, 30 min each tile, both scanning directions plus references 60 hours!

Tunning frequency: 344.19 GHz. Frequency range: 330.19-334.19 GHz and 342.19-346.19 GHz.
Instantaneous bandwidth of 8 GHz!





CO (2-1) v_{LSR} = -213.0 km/s
^{13}CO (2-1) v_{LSR} = -213.0 km/s
CO (3-2) v_{LSR} = -213.0 km/s
Galactic Latitude
Galactic Longitude
Tmb[K]
+00.4° +00.3° +00.2° +00.1° +00.0° -00.1° -00.2° -00.3°
01.5° 01.0° 00.5° 00.0° 359.5° 359.0°
0 5 10 15 20 25
0 1 2 3 4 5 6 7

SOFIA

CII mapping of the CMZ

We plan to produce a velocity resolved C^+ datacube of the complete CMZ at subparsec resolution (0.6 pc)

C^+ has a ground state energy of 91 K, excitation by soft UV with energy 11.3 eV, and excitation by collisions with electrons, HI and H_2

C^+ traces the warm ionized medium, the warm and cold diffuse atomic medium and the warm and dense molecular gas.

C^+ is generally the dominant gas coolant line from galaxies.

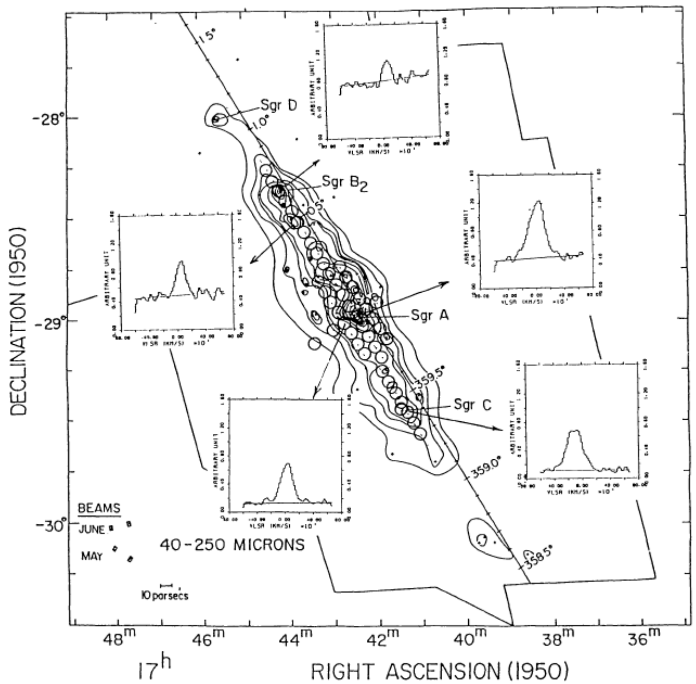
Previous works show that the line traces a combination of dense gas at the edges of molecular clouds (tracing young star formation revealed by PDRs on nearby molecular clouds) and more distributed “CO-dark” gas missing from molecular emission.

C^+ will provide a measure of the dense atomic gas and will complement the existing atomic, molecular, and dust data on the CMZ

C$^+$ observations of the CMZ

Lugten et al 1986 — Observations of CII towards Sgr A using the 94 cm telescope onboard the NASA Kuiper Airborne Observatory. ~50” beam size, velocity resolution of 33-50 km/s

Okuda et al 1989 — Fabry-Perot spectometer onboard a balloon telescope.
Balloon telescope has an apperture of 50 cm and 3.6’ beam size.
Spectral resolution is 120 km/s. 45 point across the CG



Okuda et al, 1989

Bennett et al 1994 — COBE FIRAS

Nakagawa et al 1998 — Ballon-borne Infrared Carbon Explorer (BICE)

Strong and wideaspread C$^+$ emission, but spectrally not resolved

Herschel Space Observatory was possible to map spectrally resolved CII in the CMZ using the Heterodyne Instrument in the far-Infrared (HIFI)

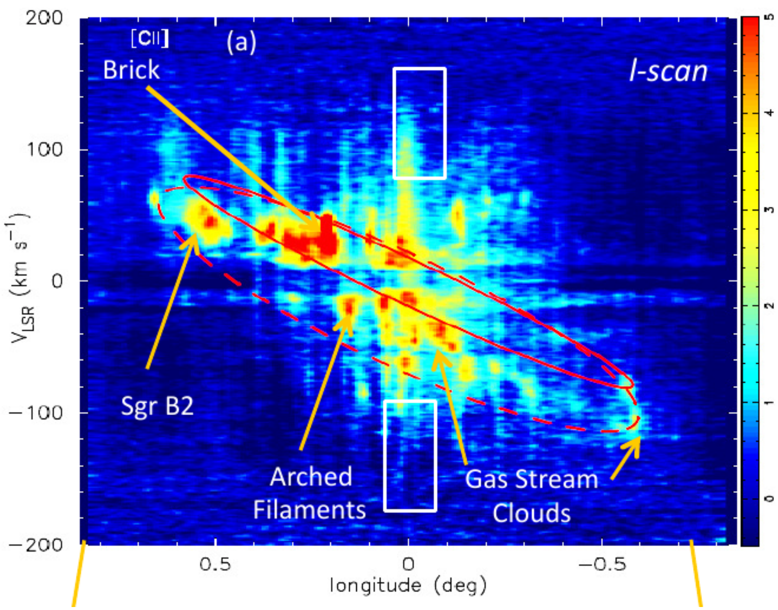
HEXGAL programme (Güsten 2007)

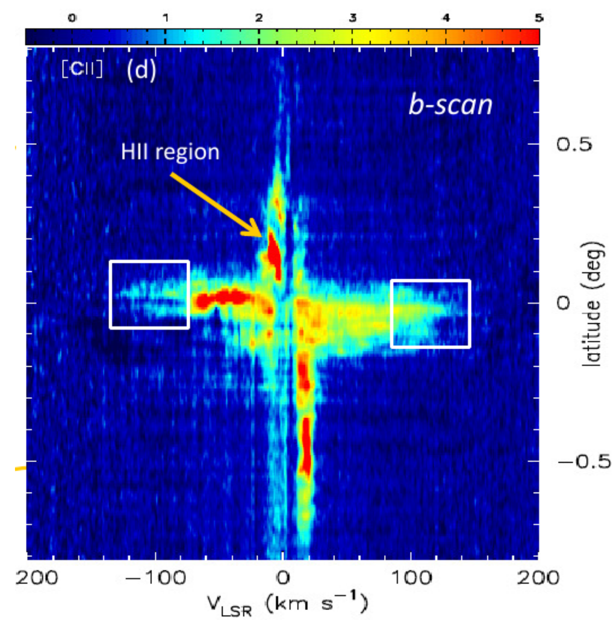
Map of Sgr A region (Garcia et al, 2015, 2016)

Galactic Observations of Terahertz C^+ (GOT C^+ , Langer et al 2010, Pineda et al 2013, Langer 2017)

Two strip scans of 1.6° across (l,b)=(0,0)

Langer et al, 2017





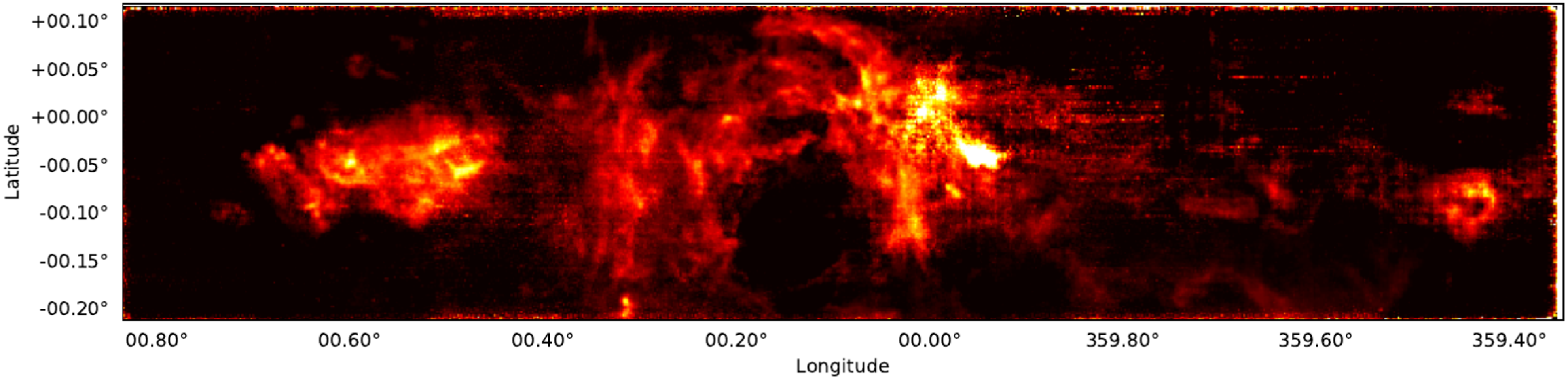
Small beam at 1.9 THz (12”) and single pixel, not possible to map large areas

Joint German-US project to image the Galaxy's Central Molecular Zone in ionized carbon (C^+)

Sgr B region mapped (cycle 5; PI: A. Harris, R. Güsten) in NZ 2017

Sgr A region cycle 6. PI: A. Harris

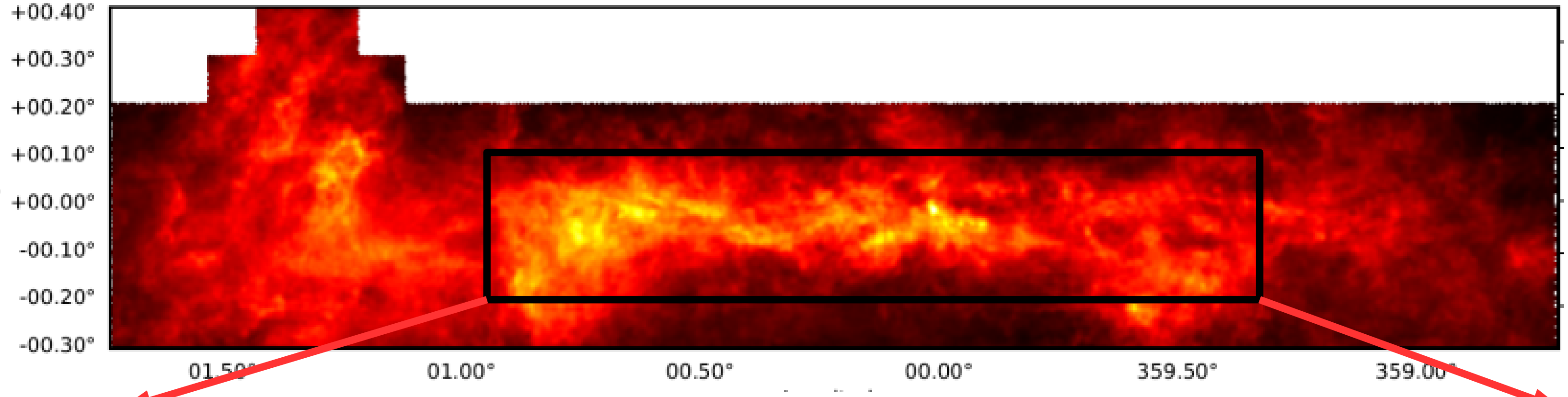
Sgr C region cycle 6. PI: D. Riquelme



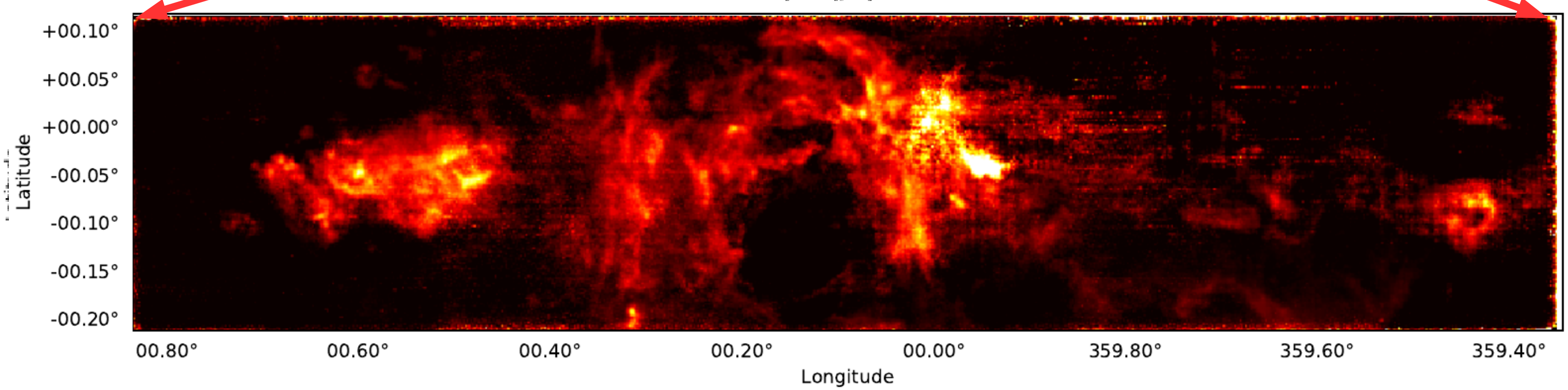
32.3 Hours of observation:
- 12.5 hrs German OT
- 6.1 hrs US OT
- 13.7 hrs GT

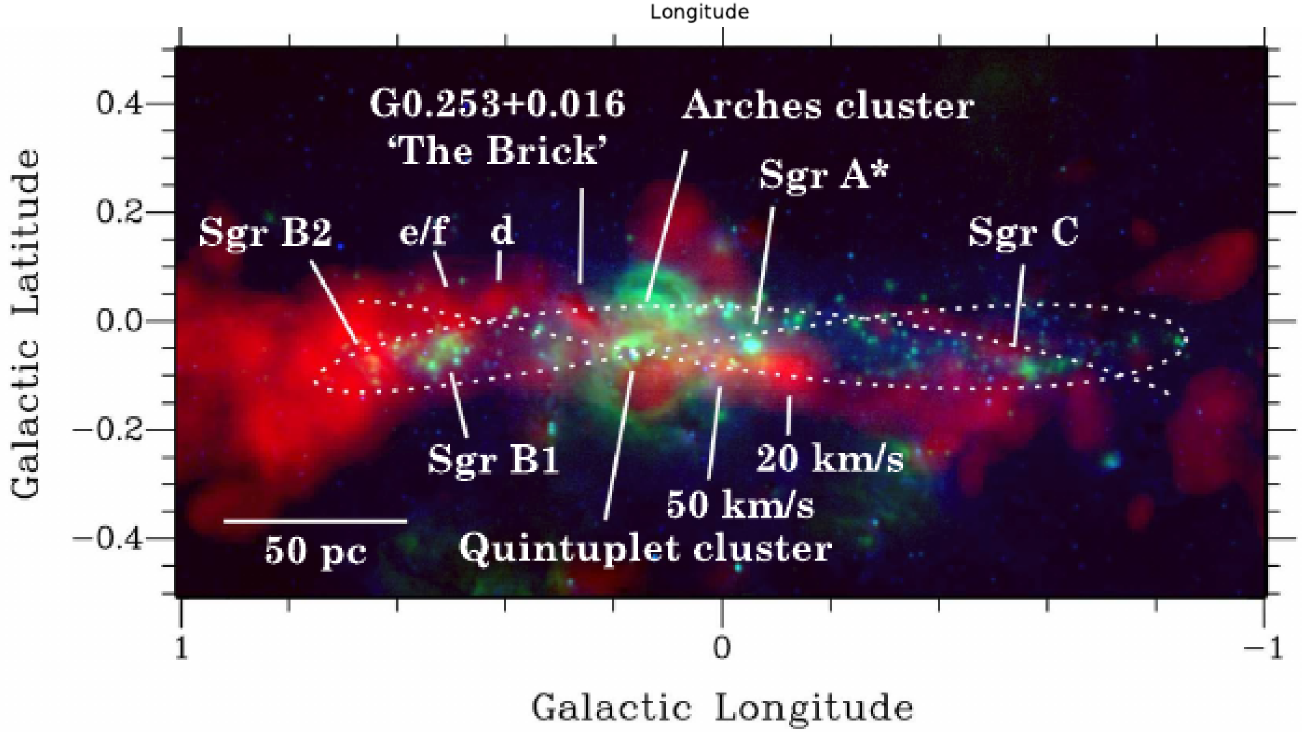
<u>A lasting legacy from SOFIA</u>

CO (2-1)

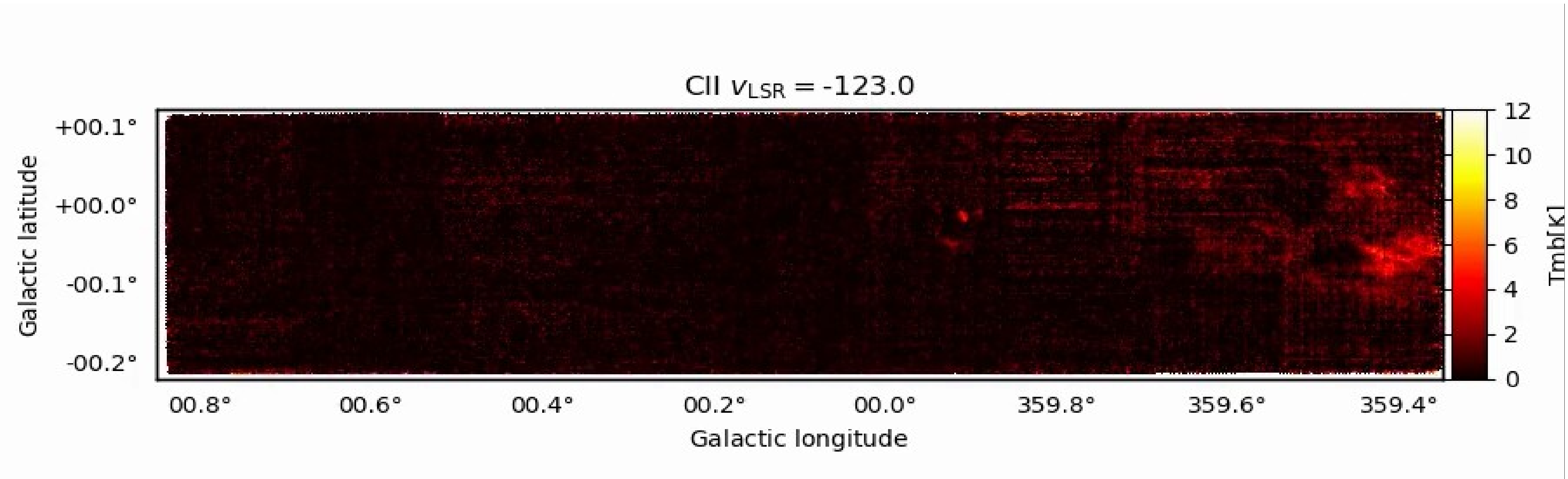


CII

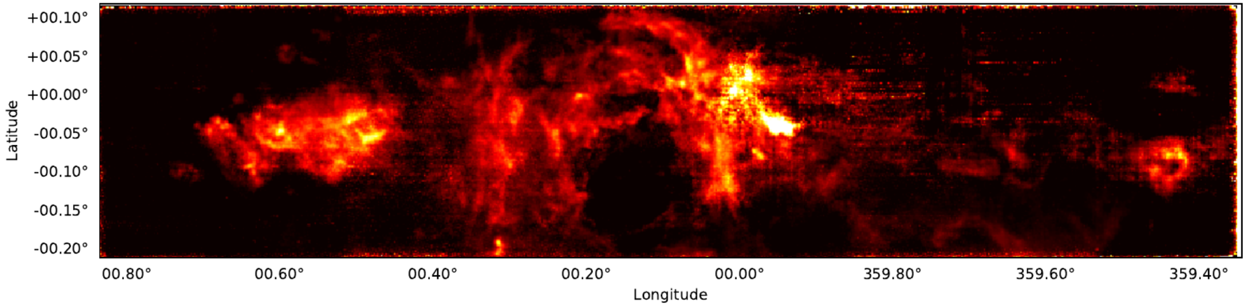


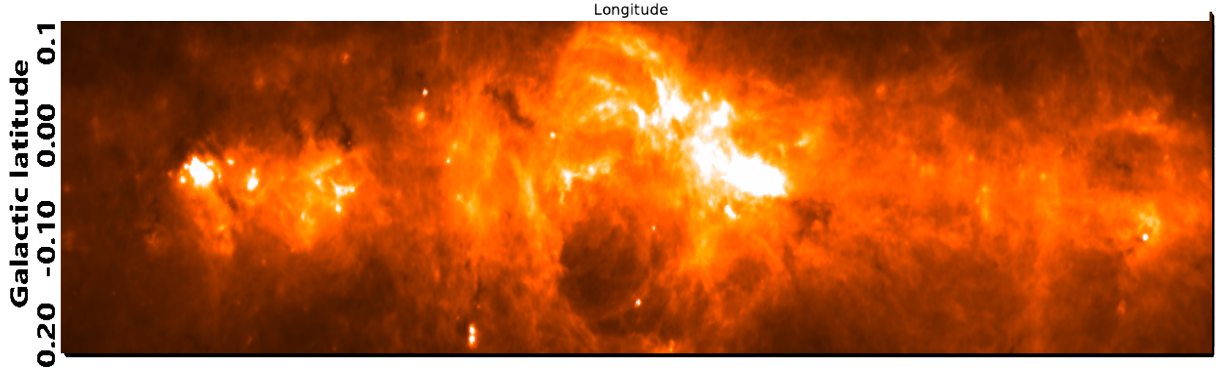


Three-colour composite reference image, with $NH_3(1, 1)$ in red, MSX 21.3 μm in green, and MSX 8.3 μm in blue. Figure from Kruijssen et al 2015


CII v_{LSR} = -123.0
+00.1°
+00.0°
-00.1°
-00.2°
Galactic latitude
00.8°
00.6°
00.4°
00.2°
00.0°
359.8°
359.6°
359.4°
Galactic longitude
12
10
8
6
4
2
0
Tmb[K]

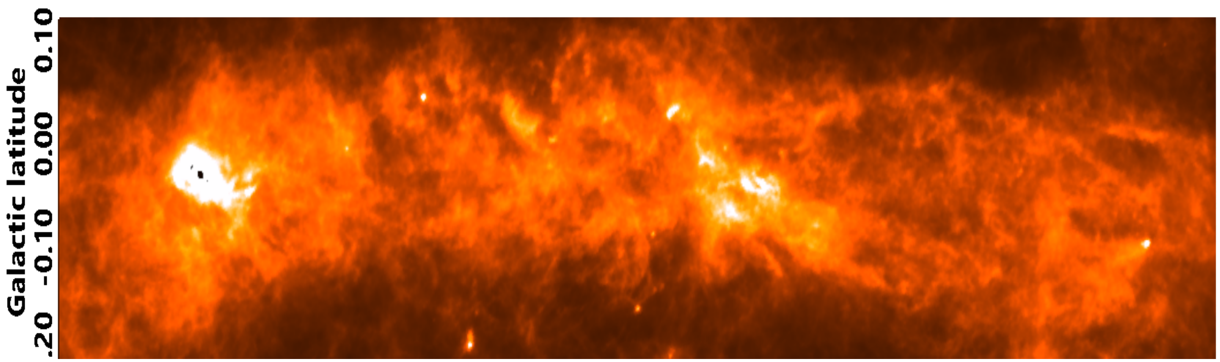
The correlation between C^+ and the 70 microns indicates that both are tracing ambient UV light and the radiation field is soft to produce C^+ without further ionization of the C-atoms





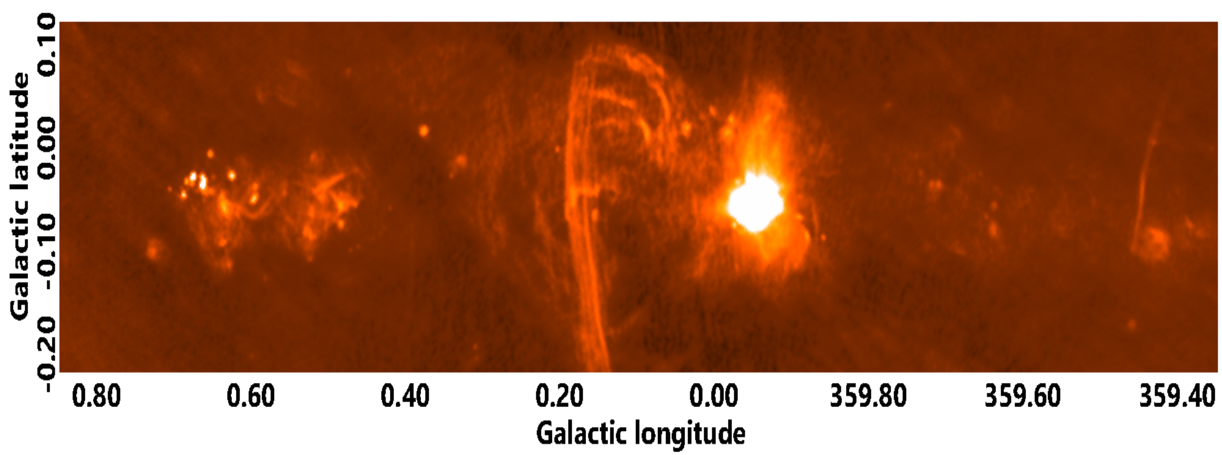
70 µm

Herschel



160 µm

Herschel



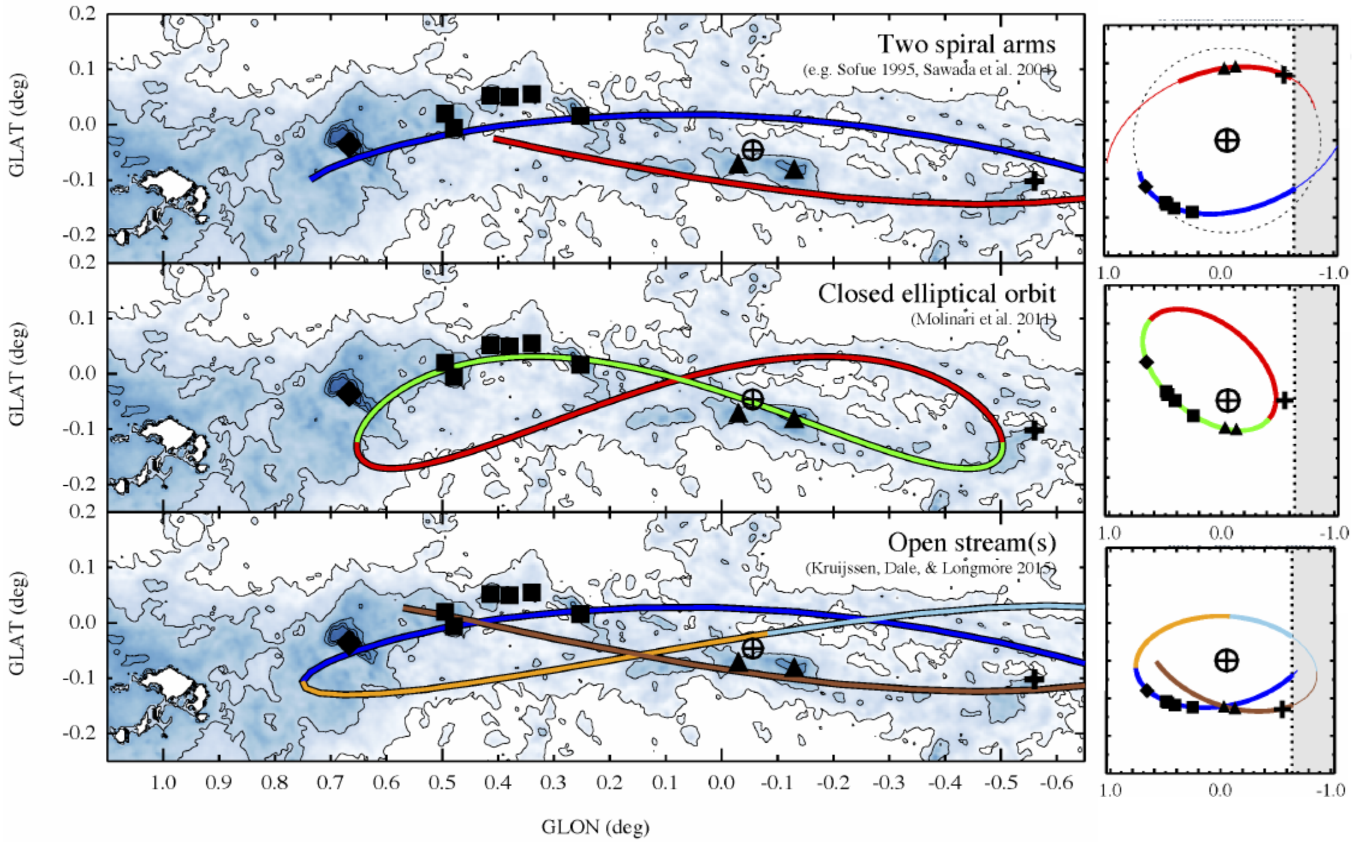
20 cm

Lang et al 2010

What's next?:
Science!

1. Study flows at larger scale in the Galactic center

Kinematics and dynamics of the CMZ
Towards a 3-D characterization of the CMZ



Henshaw et al, 2016

Mostly molecular data have provided constrain to the model.
C^+ traces a combination of dense star forming gas at the UV illuminated edges of molecular clouds and CO-dark gas that may have been expelled by star formation or may condense to form molecular clouds. The C+ mapping will help to complete the physical picture of material on these streams.

Apply the Spectral Clustering for Interstellar Molecular Emission Segmentation (SCIMES) (D. Colombo et al, 2015) to separate structures and study the flows of gas in the GC.

We will characterize the gas in the 100 pc stream, which contains the well known star forming clouds Sgr B, Sgr A and Sgr C, and the gas at high velocity, which is likely for gas accretion towards the GC.

With this analysis, we will be able to construct a complete picture of the flows of gas from higher longitudes towards the Galactic center and also to smaller scales of the CND.

2. Account for the CO-dark gas in the Galactic center

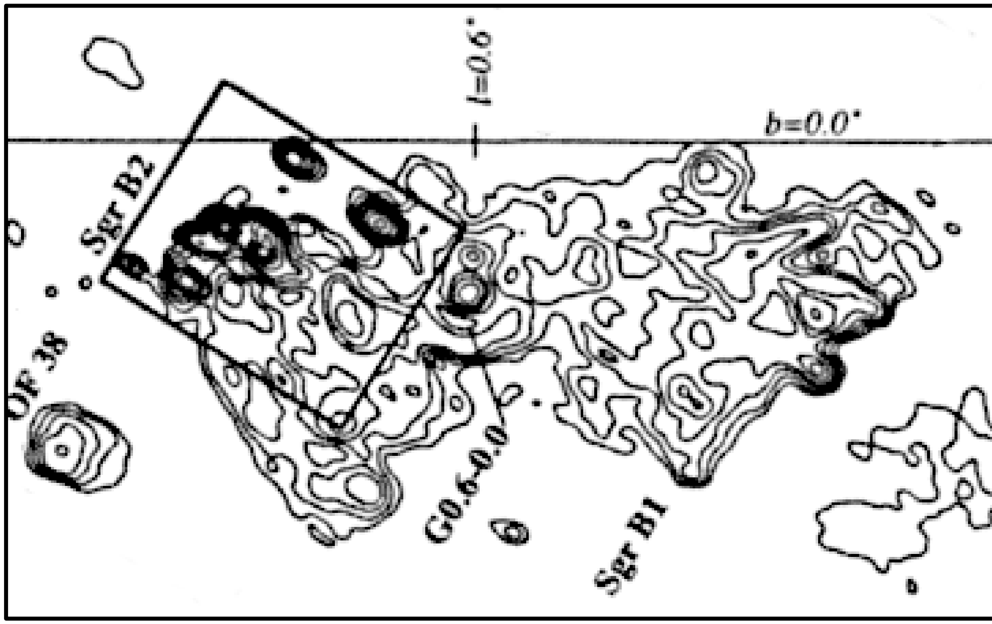
The mass of the molecular clouds has traditionally been traced using CO observations, but the column density from the cloud exterior to the location where hydrogen becomes molecular is smaller than the required to C become molecular in the form of CO. In the outer parts of the clouds there is a fraction of H_2 associated with C^+ and C instead of CO

The CO-dark gas could be as large as the 30% (from the two stripes observations in Langer et al 2017)

We will use our large-scale CO (2–1) map from APEX to identify the CO-bright gas and mask associated [C II] emission in space and velocity

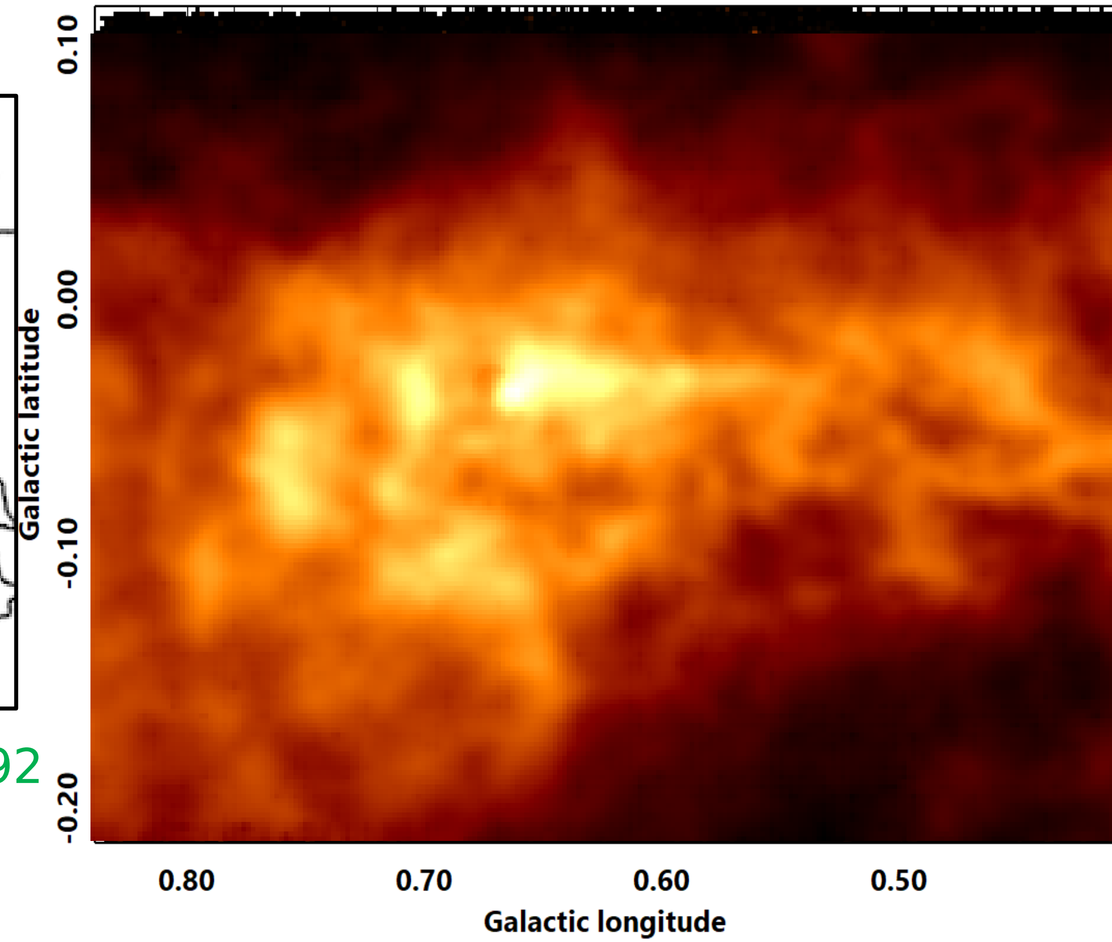
3. Detailed study towards the key regions

Sgr B region (Harris et al, in prep)



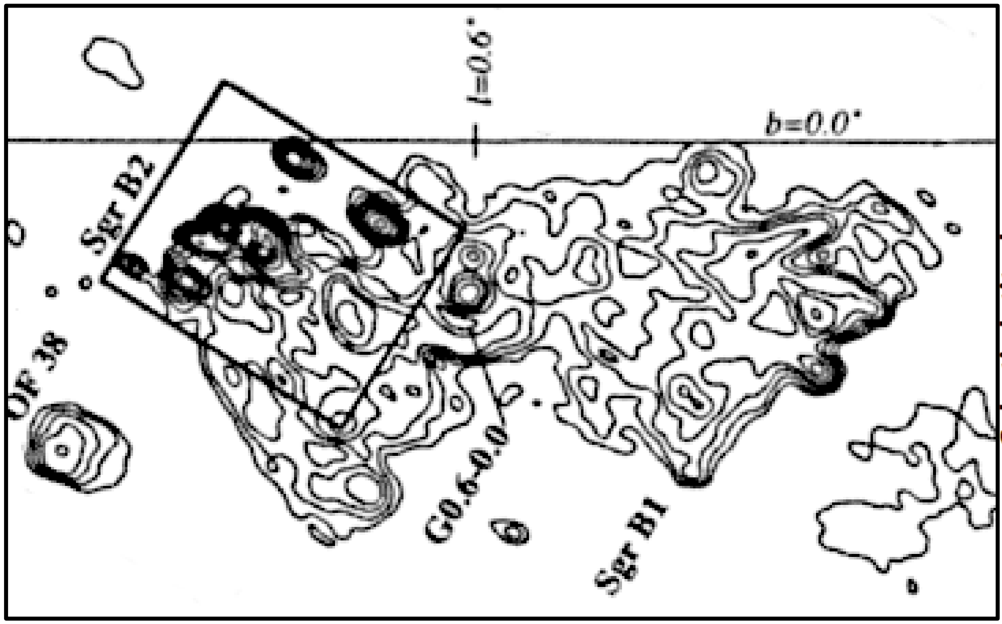
20 cm

Mehringer et al 1992



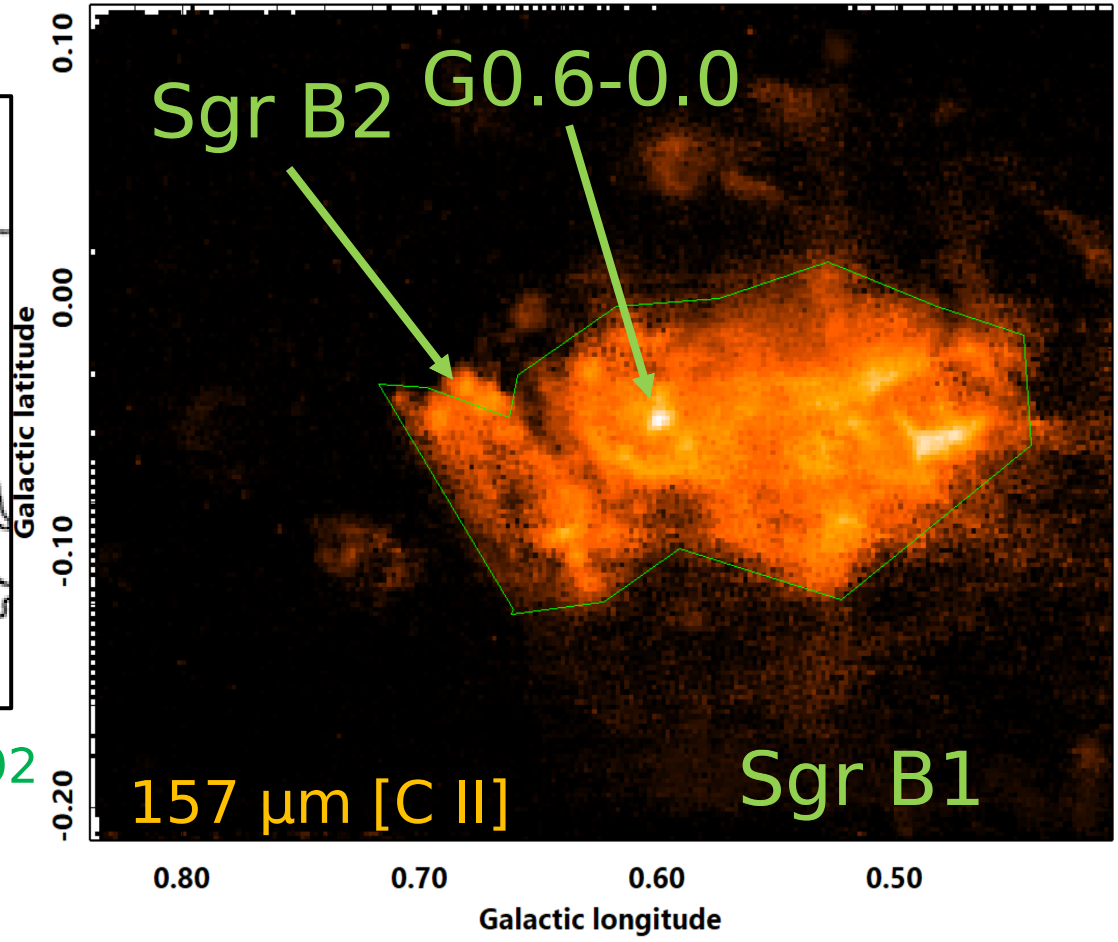
^{13}CO (2-1) emission

Sgr B region



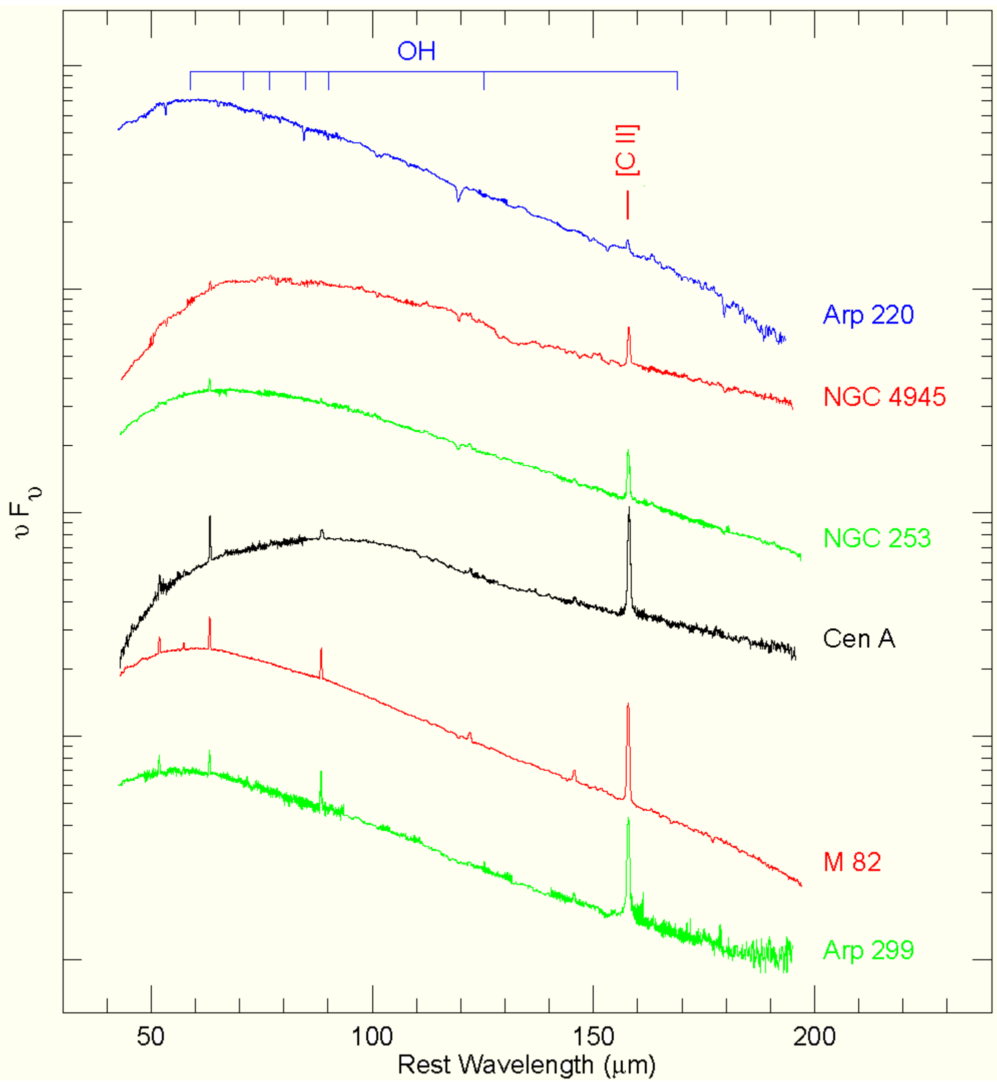
20 cm

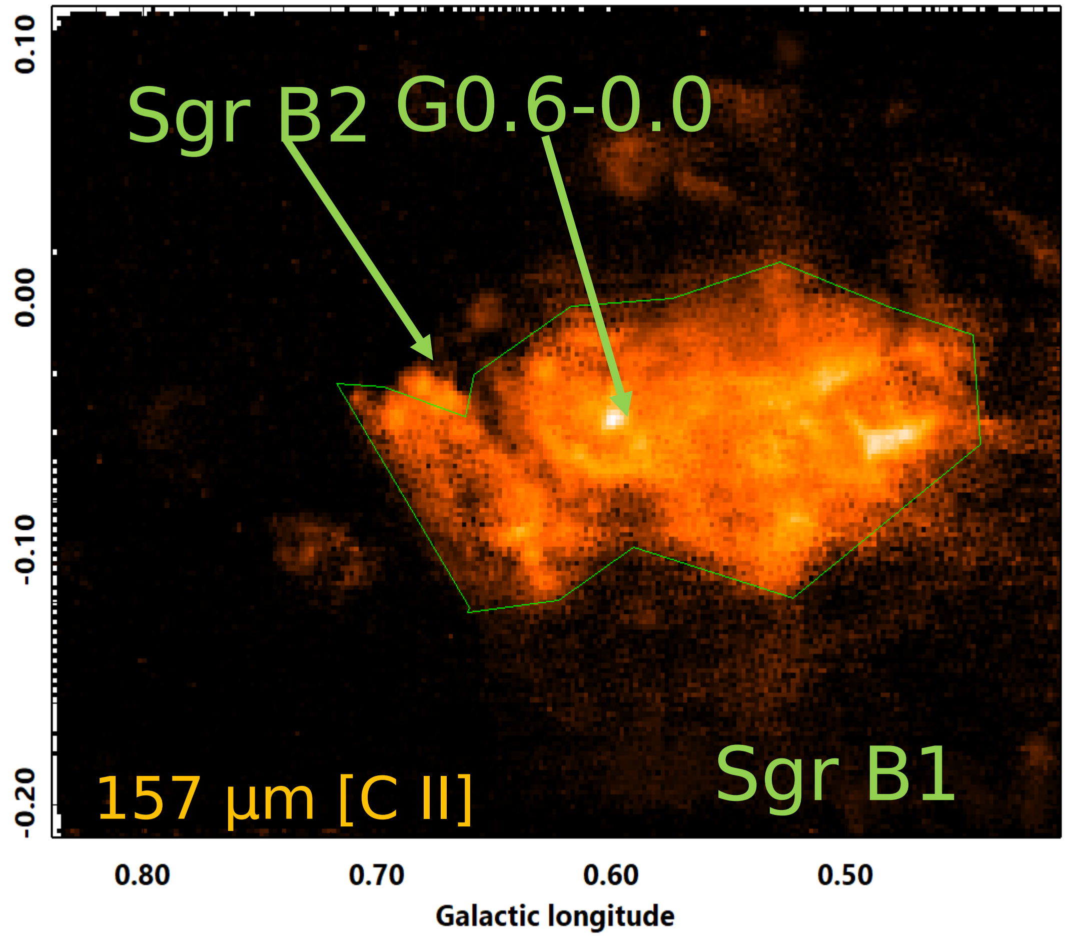
Mehringer et al 1992



3. Detailed study towards the key regions

Sgr B region





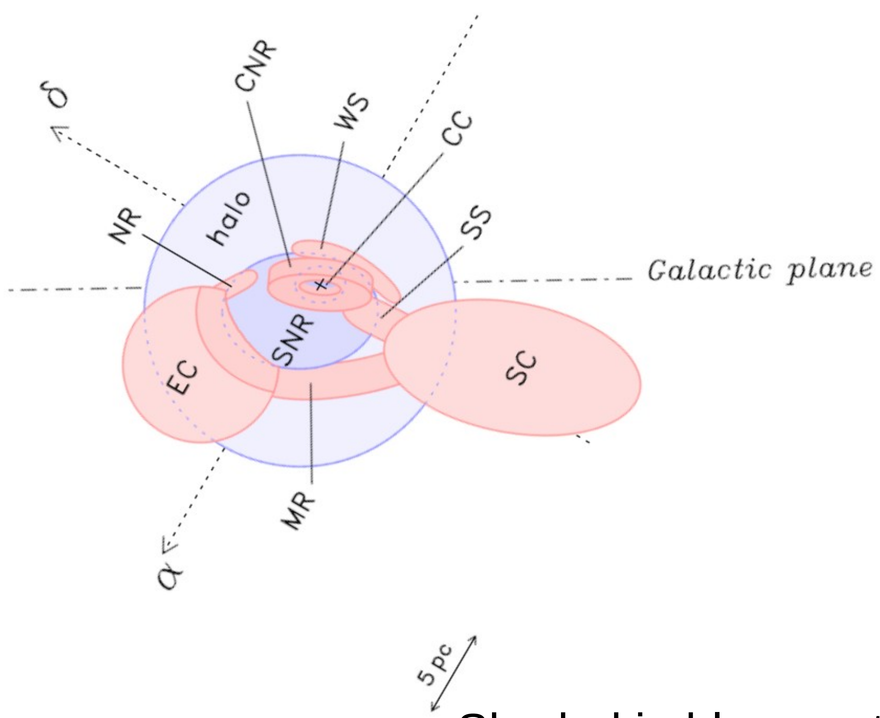
Fischer et al. 1999

More to come

Sgr A region (Harris et al, in prep)

This is a very rich region with several features and different phenomena. Sgr A host a supermassive black hole surrounded by a Circunnuclear disk, host star clusters (the Arches and the Quintuplet) and several thermal and non-thermal filaments.

See Erick’s talk!



Shaded in blue are the diffuse, mostly ionized components.
Shadded in red are the molecular components.
Ferriere 2012

Sgr C region (Riquelme et al, in prep)

This huge molecular complex is located at the negative-longitude side of the CMZ, where there is less molecular material overall.

SgrC has a large variety of physical phenomena:

- HII region accompanied by nonthermal filament (Lang et al., 2010)
- A high mass star formation site with an outflow (Forster & Caswell, 2000)
- High velocity gas with forbidden velocities according to Galactic rotation (Tanaka et al., 2013, Riquelme et al, 2010, 2013).

These properties make it a critical place to study star formation/suppression within the Galactic center and gas accretion toward the CMZ.


Thanks!