The *Herschel* spectroscopic view toward Sgr A*

Miriam G. Santa-Maria[α], J. R. Goicoechea[α], J. Cernicharo[α], M. Etxaluze[β], D. Teyssier[γ], M. Gerin[δ], et al.

[α]Instituto de Física Fundamental, Serrano 121-123, Madrid, Spain. e-mail: miriam.g.sm@csic.es javier.r.goicoechea@csic.es

[β]RAL Space, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, UK

[γ]Telespazio Vega UK Ltd. for ESA/ESAC, Urb. Villafranca del Castillo, Villanueva de la Cañada, 28692, Madrid, Spain

[δ]Sorbonne Université, Observatoire de Paris, Université PSL, École Normale Supérieure, CNRS, LERMA, F-75014, Paris, France.

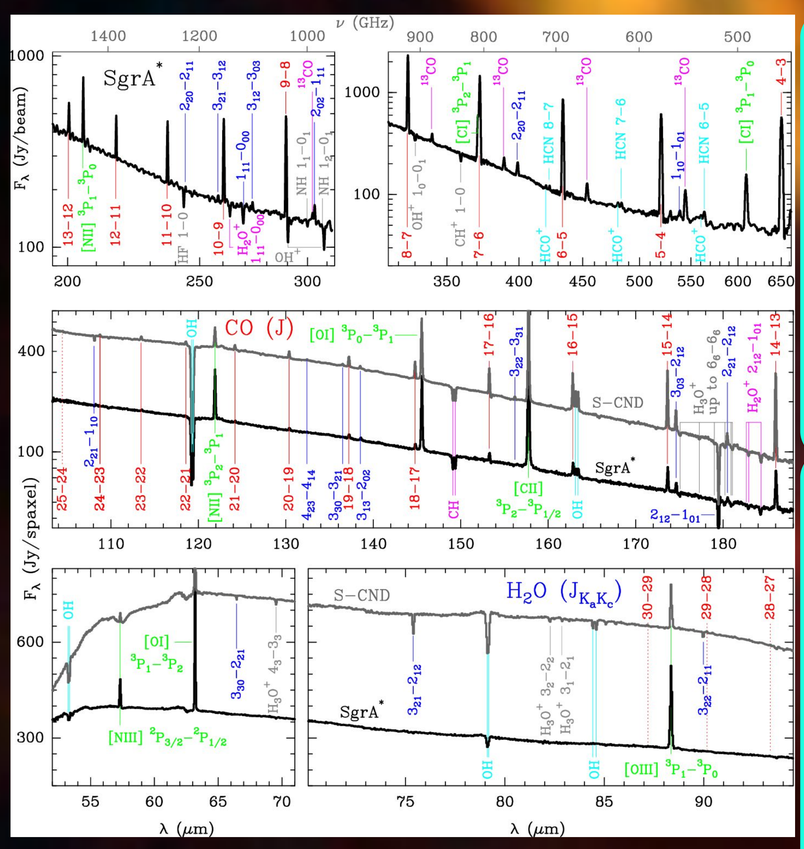
Abstract

Herschel made possible to study the properties of the, not so well constrained, warm molecular gas and dust inside the cavity of the circumnuclear disk (CND; gas in the inner central parsec of the Galaxy). In this communication, we summarize the results of a far-IR spectral scan toward Sgr A* taken with PACS and SPIRE-FTS spectrometers [1], and a velocity-resolved scan (~480-1250 GHz) and [CII] 158 μm line observations carried out with HIFI. The very high spectral resolution (R>10^6) achieved by HIFI allowed us to resolve the velocity structure in the line-of-sight toward the Galactic Center and, for the first time at far-IR wavelengths, the intrinsic molecular emission from the central cavity. We report the presence of high positive-velocity emission (up to about +300 km s^{-1}) detected in the wings of the ^{12}CO J=5-4 to 10-9 lines [2]. This wing component is also seen in H_2O ($1_{1,0}$-$1_{0,1}$), a tracer of hot molecular gas; and in [CII] 158 μm, an univocal tracer of stellar FUV radiation (~6 - 13.6 eV). However, the high velocity wings are not detected in [CI] 492, 806 μm. Later, ALMA images have spatially resolved a collection of ^{12}CO J=3-2 molecular "cloudlets" emitting at the same high positive velocities (v_{LSR}≃+150 to +300 km s^{-1}) inside the central cavity [3]. This work emphasizes the strong synergy between far-IR observations from space and (sub)mm observations with ALMA. Our study adds more quantitative evidence to the existence of high-velocity, warm molecular gas (T_K≃400-2000 K) inside the cavity of the CND and close to Sgr A* (<1pc), the supermassive black hole of the Milky Way.

Sgr A* and the central cavity

- Galactic center: d ≃ 8.5 kpc, hundred times closest galactic nuclei, high spatial resolution studies.
- Central Cavity: innermost pc of the Galaxy.
  hosts a supermassive black hole, nuclear stellar cluster and streamers of ionized gas
  Unique environment for our understanding of galactic nuclei and galactic evolution.
- Unique laboratory for ISM in extreme conditions:
  - Intense UV fields and winds from massive stars
  - Shocks
  - Strong gravitational shears
  - Complicated orbital motions
- The presence of molecular gas inside the cavity of the Circumnuclear Disk (CND) was originally not expected, because of the hostile conditions inside the cavity.
- Radio interfometers (VLA, ALMA): high-resolution spectral images of the molecular gas emission.

PACS+SPIRE spectra toward Sgr A* and the CND



Top panel: SPIRE-FTS spectrum toward Sgr A*. Middle and bottom panels: PACS spectra toward Sgr A* and the CND. Flux density units are Jy spaxel^{-1} for PACS and Jy beam^{-1} for SPIRE.

The FIR spectrum toward Sgr A*

-Strong emission:
+ [OIII], [OI], [CII], [NIII], and [CI]
+ high-J CO rotational lines:
  central cavity: up to J=24-23
  CND: up to J=30-29
+ mid-J HCN and HCO^+.

-Ground-state absorption lines:
+ light hydrides: HF, CH, NH
+ ions: OH^+, H_2O^+, CH^+
+ rot. excited lines: H_2O, OH, H_3O^+

Herschel & CO rot ladder

Most of the luminosity emitted by molecular gas heated by shocks or illuminated by strong FUV fields is radiated in mid-J and high-J lines at sub-mm and FIR, inaccessible to ground-based telescopes.

Observations of the CO rot ladder are critical tools to determine the heating mechanisms and nature of the molecular gas in the GC.

Herschel/HIFI toward Sgr A*: High Positive Velocity Wings (HPVW)

HIFI high resolution allowed us to spectrally resolve complicated line profiles and independently study various velocity components toward the GC.

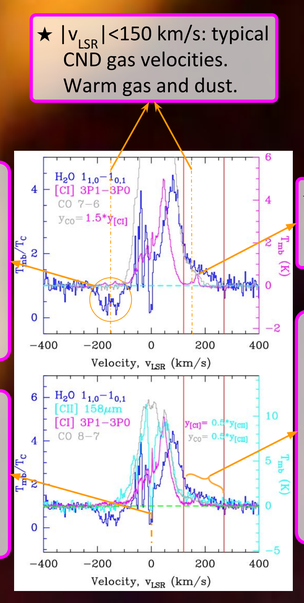
★ $|v_{LSR}|$<150 km/s: typical CND gas velocities. Warm gas and dust.

★ -180 km/s: high negative vel. gas clouds
★ -135 km/s: near side expanding molecular ring (EMR)

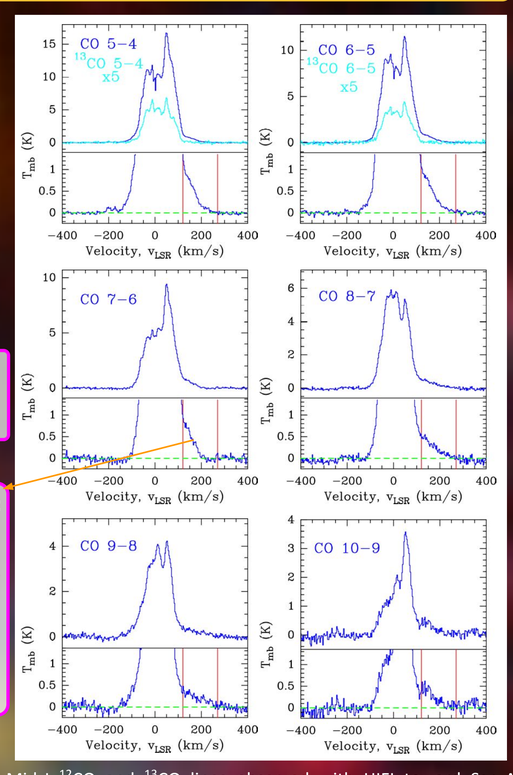
★ +0 km/s: local diffuse clouds in Galactic arms, & clouds in the inner hundreds pc GC.

★ +165 km/s: EMR's back side. Cold & diffuse gas.

★ +120 → +270 km/s: high positive-vel. gas emission.
- [CII]158μm: FUV stellar photons
- H_2O: high temp.
- mid-J CO: warm molecular gas



HIFI multi-line detection toward Sgr A*.



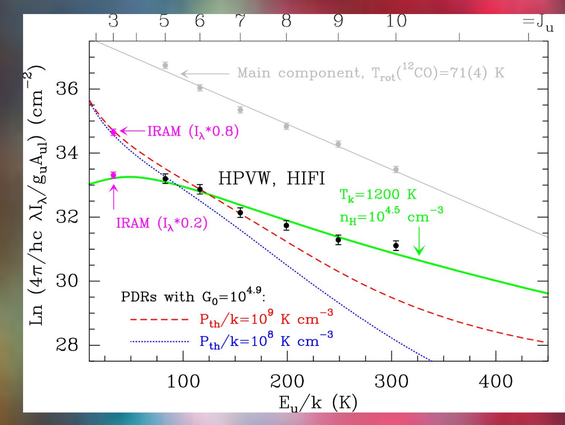
Mid-J ^{12}CO and ^{13}CO lines observed with HIFI toward Sgr A*. The 2 red vertical lines (+120 and +270 km s^{-1}) -> HPVW emission.

Physical conditions in the central cavity

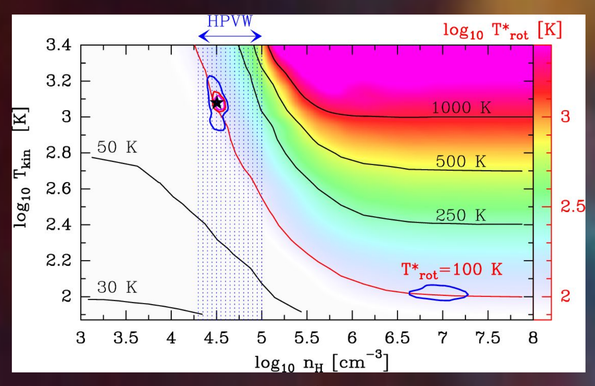
With HIFI we spectrally resolve the HPVW emission in several rotationally excited CO lines.

Emision comp.	T_{rot} [K]	N(^{12}CO) [cm^{-2}]	r^2
main comp.	71±4	(6±1)x10^{17}	0.986
HPVW	101±12	(1.9±0.4)x10^{16}	0.946

HPVW comp: higher degree of excitation.
Main comp: dominated by emission from the CND.



Observed CO intensities of the main and HPVW components toward Sgr A* translated to rotational population diagrams. The green curve shows the best isothermal non-LTE model. The red and blue dashed curves show predictions of PDR models with G_0 = $10^{4.9}$ and ζ_{CR} = 10^{-15} s^{-1} (line intensities multiplied by 0.04)



CO rotational temperatures obtained from isothermal non-LTE models. The red curve shows the parameter space that reproduces the observed T_{rot} of the HPVW component. The blue-shaded area shows the estimated gas density of the high-velocity cloudlets detected by ALMA [3].

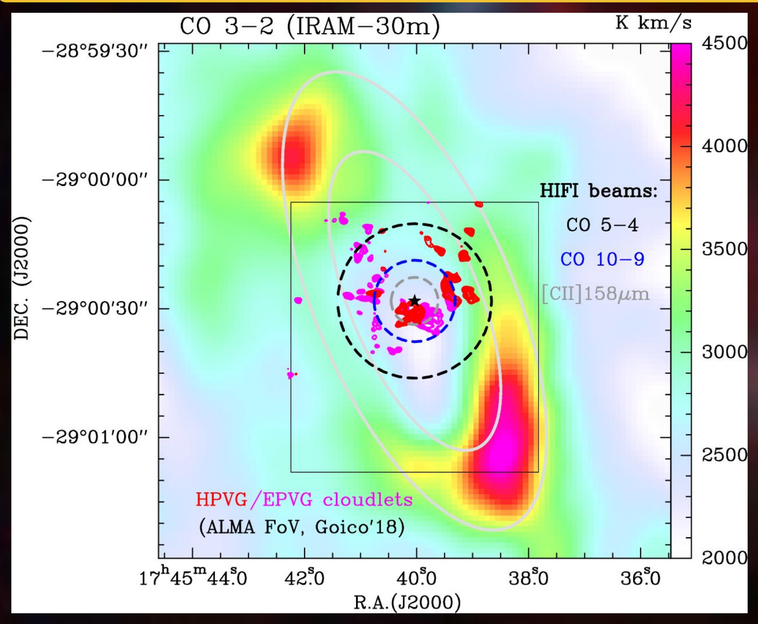
Non-local, non-LTE CO excitation models

Our best fit: T_k≃1200 K, n_H≃$10^{4.5}$cm^{-3}

Excitation subthermal (densities <10^7cm^{-3})

A more accurate solution require to observe and spectrally resolve higher J CO lines.

Synergies between Herschel ALMA and IRAM 30m.



CO J= 3-2 integrated intensity map of the inner 2' of the Galaxy obtained with the IRAM 30m telescope -> emission from the CND.
The square box: field of view observed by ALMA in CO J=3-2 -> high positive-velocity cloudlets inside the cavity [3].
The gray curves: representative orbits CND with 1.5 and 2.3 pc de-projected radii.
The black, blue, and gray dashed circles centered at Sgr A* (black star) show HIFI's HPBWs at multiple frequencies (from ~11'' to ~40'').

Can molecular gas exist inside the central cavity, close to Sgr A*?

The high angular resolution of ALMA and the high spectral resolution of HIFI in the submm have done possible to study the molecular gas inside the cavity.

At |v|>150 km/s, ^{12}CO emission show gas at high positive-velocity, in J=3-2 line with ALMA and mid-Js with HIFI.

Conclusions

- In the central cavity (< 1 pc):
  - Our observations add quantitative evidence to the existence of high-velocity, hot molecular cloudlets inside the cavity of the CND and close to Sgr A* (<1 pc).
  - [CII] 158 μm wing emission: presence of FUV illumination.
  - The neutral atomic and molecular gas (n_H~10^{4-5} cm^{-3}): heated by UV photons (G_0>10^4)
- PDRs alone cannot drive the heating of the high positive velocity component. FUV-irradiated shocks likely dominate the heating of the hot molecular gas.
- Hot molecular gas mass: 10-60 $M_\odot$ in the inner 1.5 pc of the Galaxy (X(CO)=2·10^{-5} -> A_V≃0.5 mag)

References

[1] Goicoechea, J. R., et al. 2013 ApJ 769 L13
[2] Goicoechea, J. R., et al. 2018 A&A 616 L1
[3] Goicoechea, J. R., et al. 2018 A&A 618 A35

Background image credit: ALMA (ESO/NAOJ/NRAO)/ J. R. Goicoechea (Instituto de Física Fundamental, CSIC, Spain)