

SOFIA-upGREAT spectroscopic imaging of the $158\mu\text{m}$ [C II] spectral line of the Galactic center's Sgr B region

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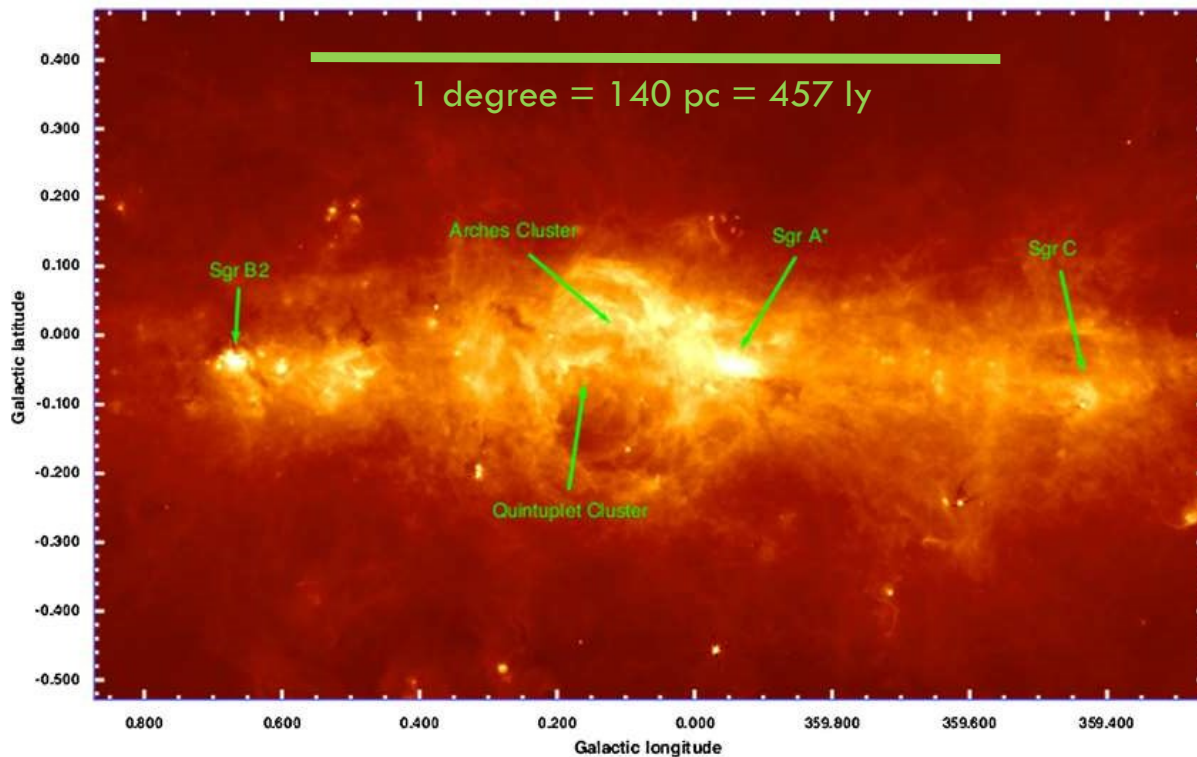
Image credit: NASA



Outline

- Overview and introduction
- Structure
 - Intensity
 - Velocity
- C^+ is from both PDRs and HII regions
- SgrB2(M) and the other cores are invisible in [C II]
- Summary

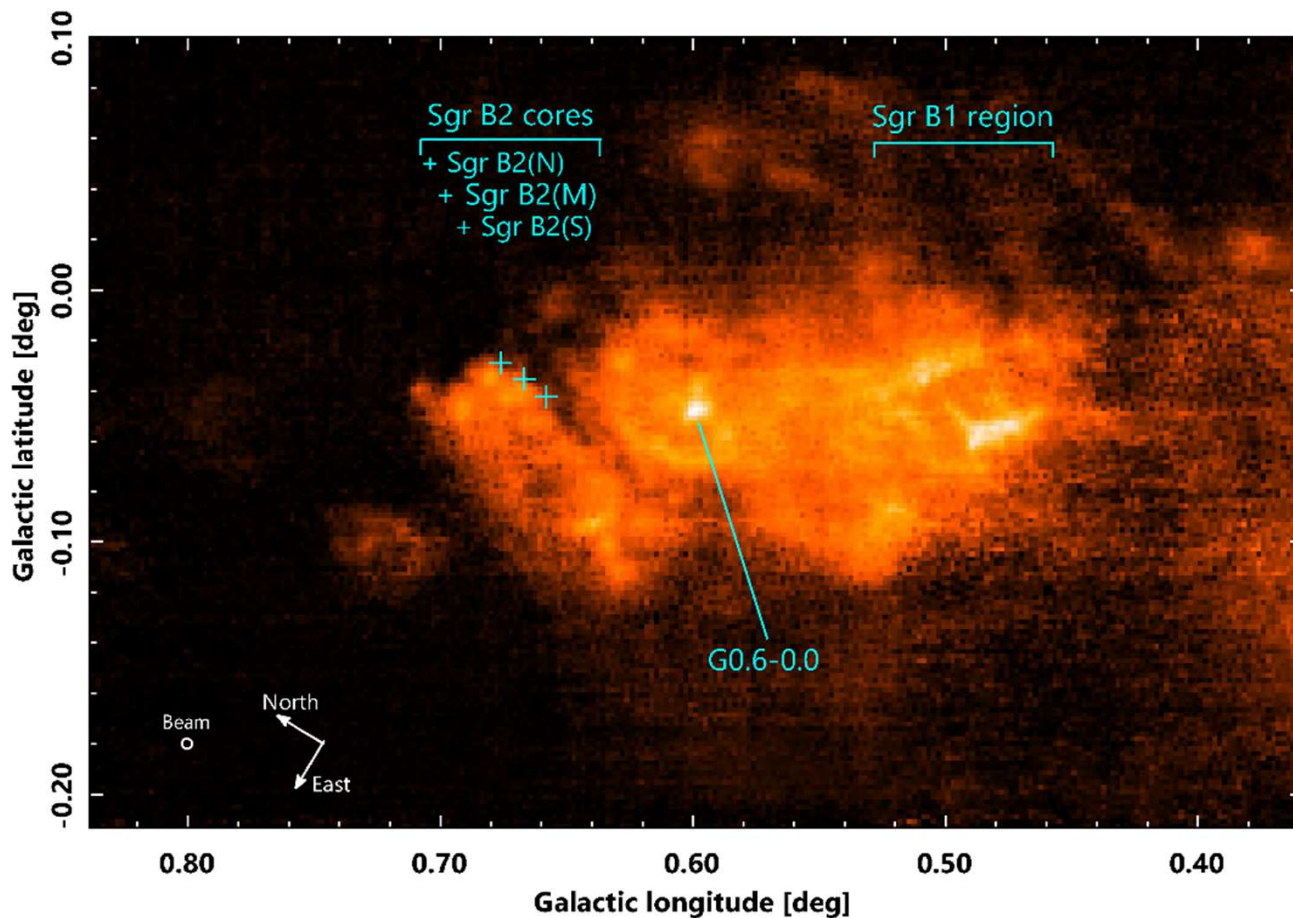
Joint German-US project to image the Galaxy's Central Molecular Zone in ionized carbon (C^+)



Herschel-SPIRE far-IR (70 μ m) image showing energy deposition from young stars in giant molecular clouds (Molinari+2011)

- Our Galactic center is 8 kpc (26,000 ly) away; SOFIA/GREAT sees structure at 0.6 pc (2 ly) resolution in the C^+ spectral line
- C^+ traces regions where radiation ionizes carbon atoms and may destroy molecules: a key component of the interstellar medium
- Questions: why do stars form where they do in the CMZ? How does gas flow through the CMZ? How does gas reach the central black hole?
- A large collaborative project with US, German, and instrument consortium observing time: Güsten & Harris PIs
- A lasting legacy from SOFIA

upGREAT image of [C II] toward SgrB



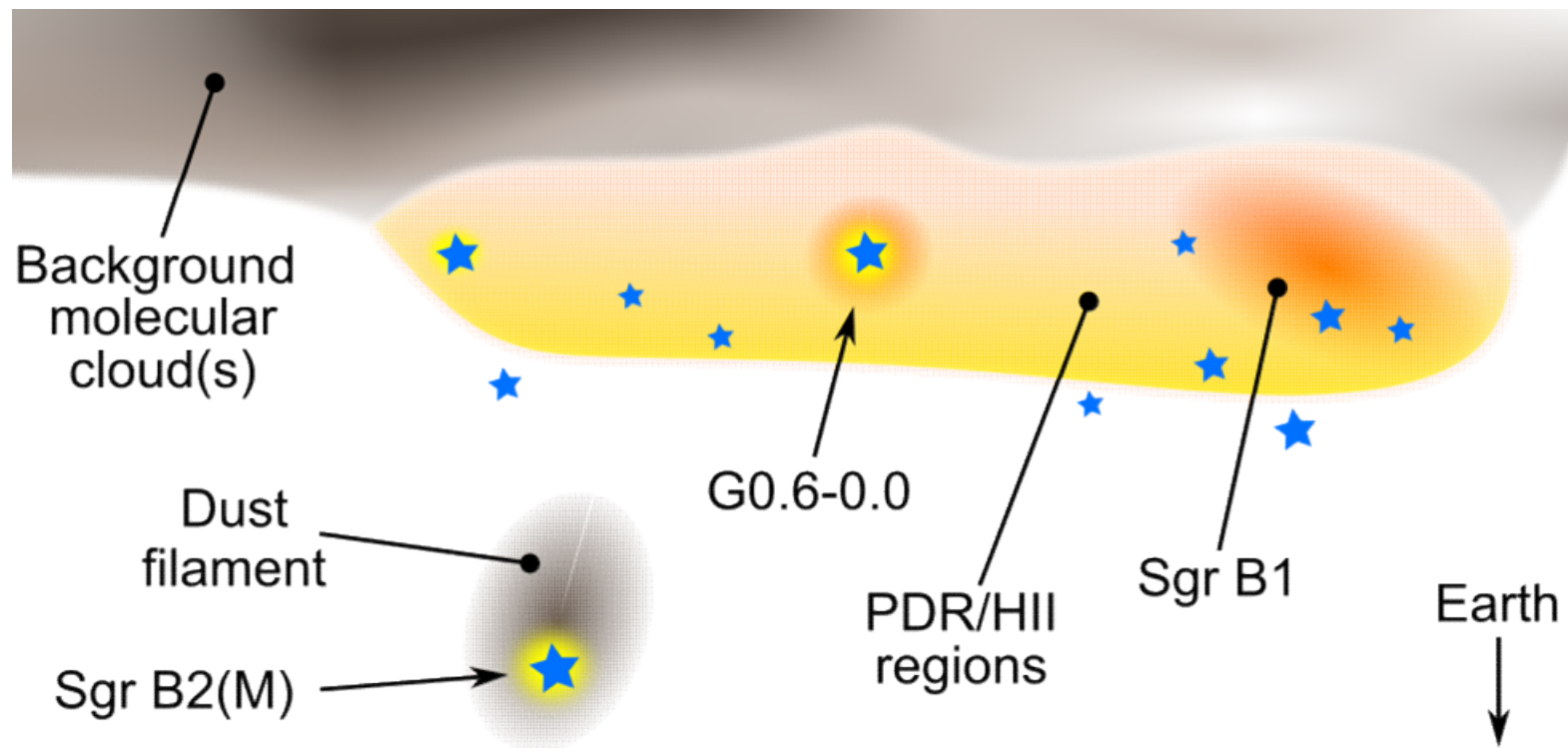
67 x 45 pc field

0.55 pc, 1 km/s resolutions
(~12,700 spectra with 200
velocity channels each)

Image from 6 of 18 “tiles”
from CMZ mapping project

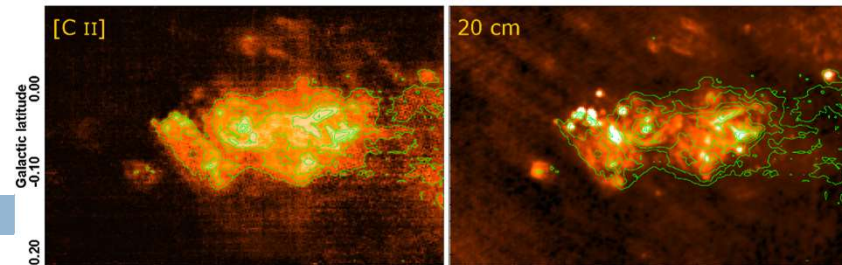
Data obtained during multiple
New Zealand flights

Structure of the SgrB region



Distributions

SOFIA
Harris+21

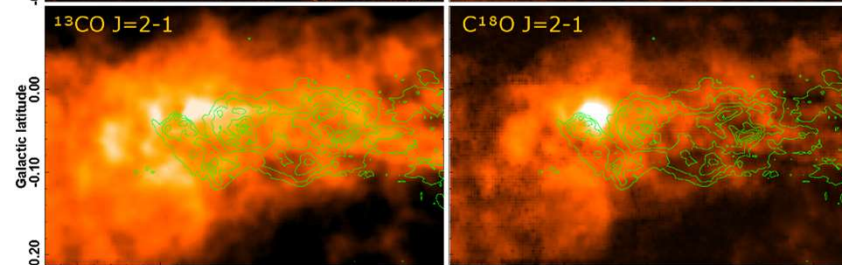


VLA
Lang+10

^{13}CO , C^{18}O , $160\ \mu\text{m}$ are all more extended than $[\text{C II}]$, $20\ \text{cm}$, $70\ \mu\text{m}$

$[\text{C II}]$, $20\ \text{cm}$, $70\ \mu\text{m}$ have similar distributions

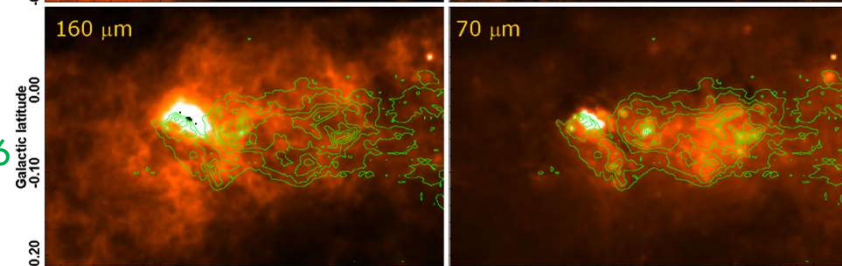
APEX
Riquelme+



APEX
Riquelme+

^{13}CO , C^{18}O , $160\ \mu\text{m}$ emphasize a very bright compact source associated with the SgrB2 star-forming cores

Herschel
Molinari+16

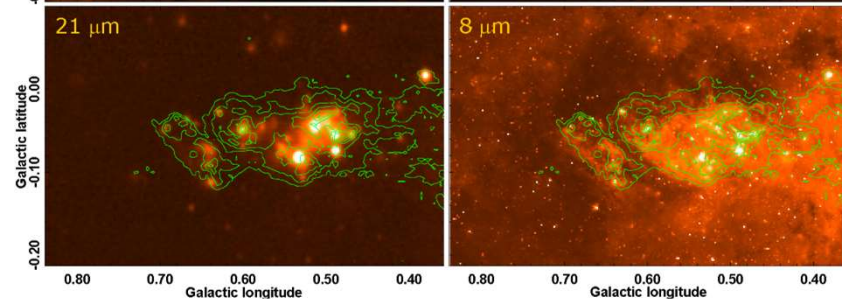


Herschel
Molinari+16

$21\ \mu\text{m}$ is dominated by point sources

$8\ \mu\text{m}$ and $20\ \text{cm}$ are a mix of extended and point source emission; $8\ \mu\text{m}$ also shows a lot of emission and absorption from the Galactic plane

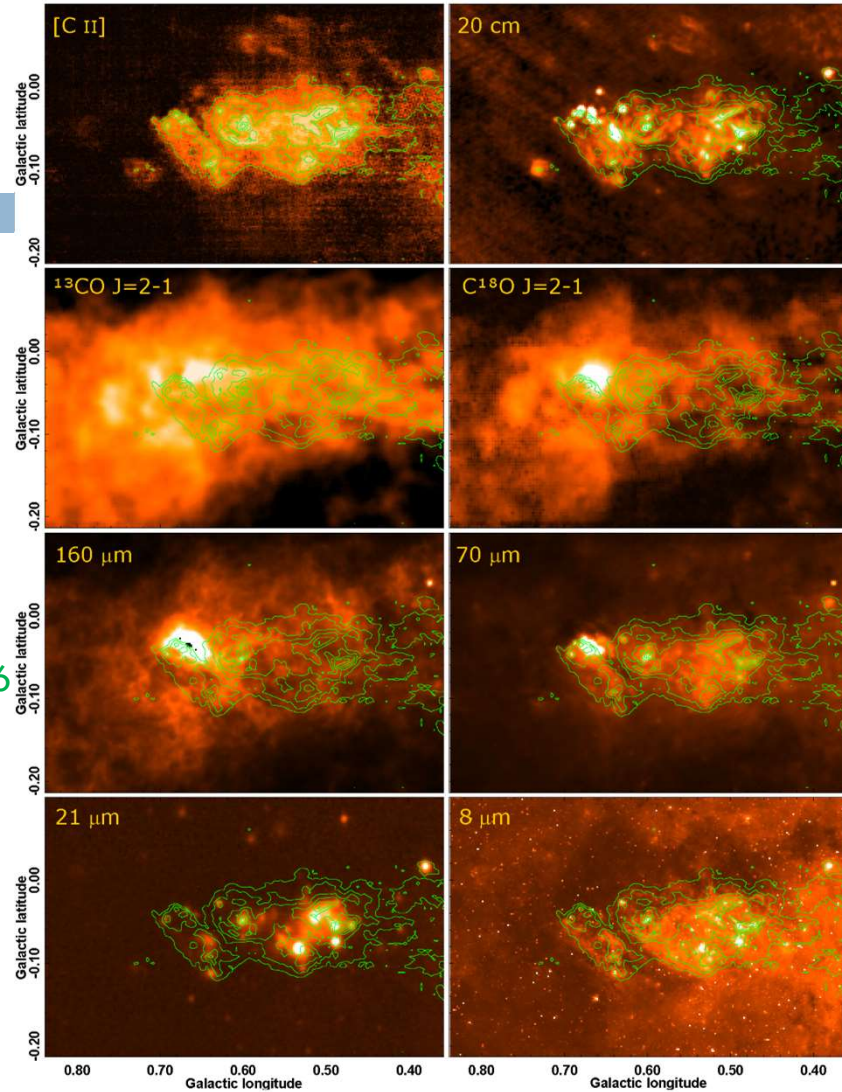
MSX
Price+01



Spitzer
Stolovoy+06

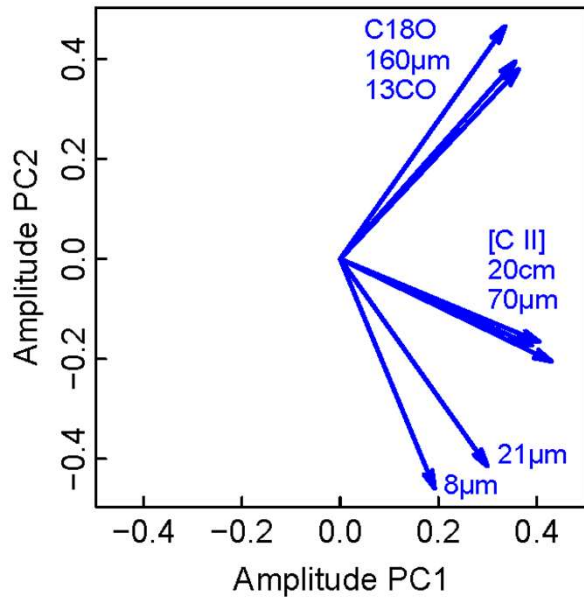
Distributions

SOFIA
Harris+21



VLA
Lang+10

PCA image decomposition



APEX
Riquelme+

APEX
Riquelme+

Herschel
Molinari+16

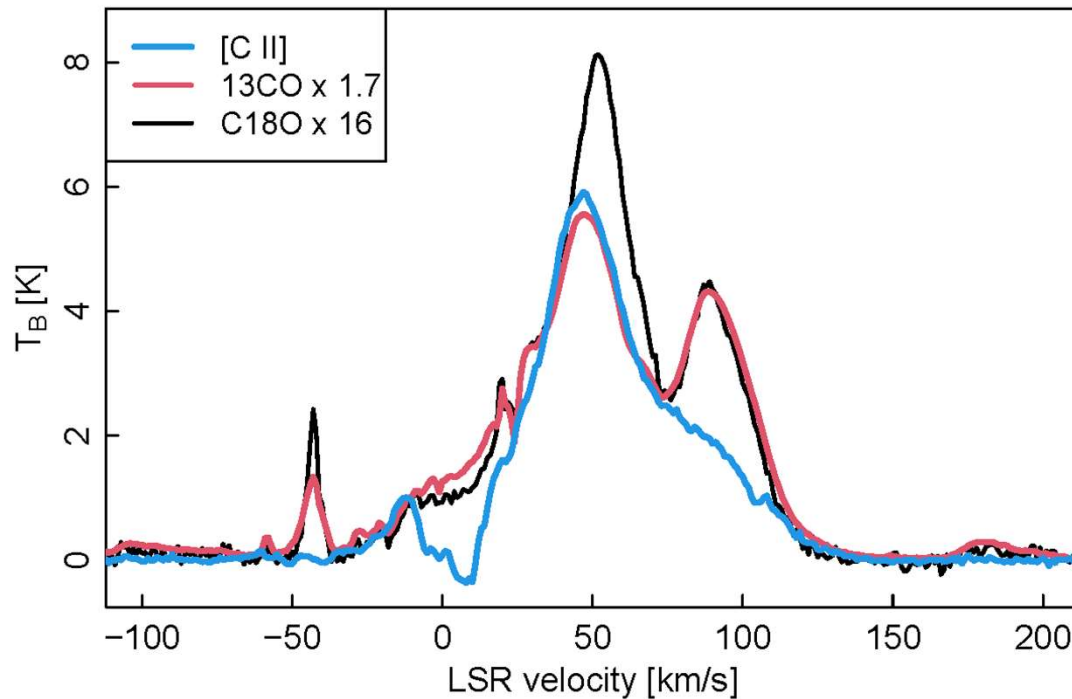
Herschel
Molinari+16

MSX
Price+01

Spitzer
Stolovoy+06

Spectroscopy

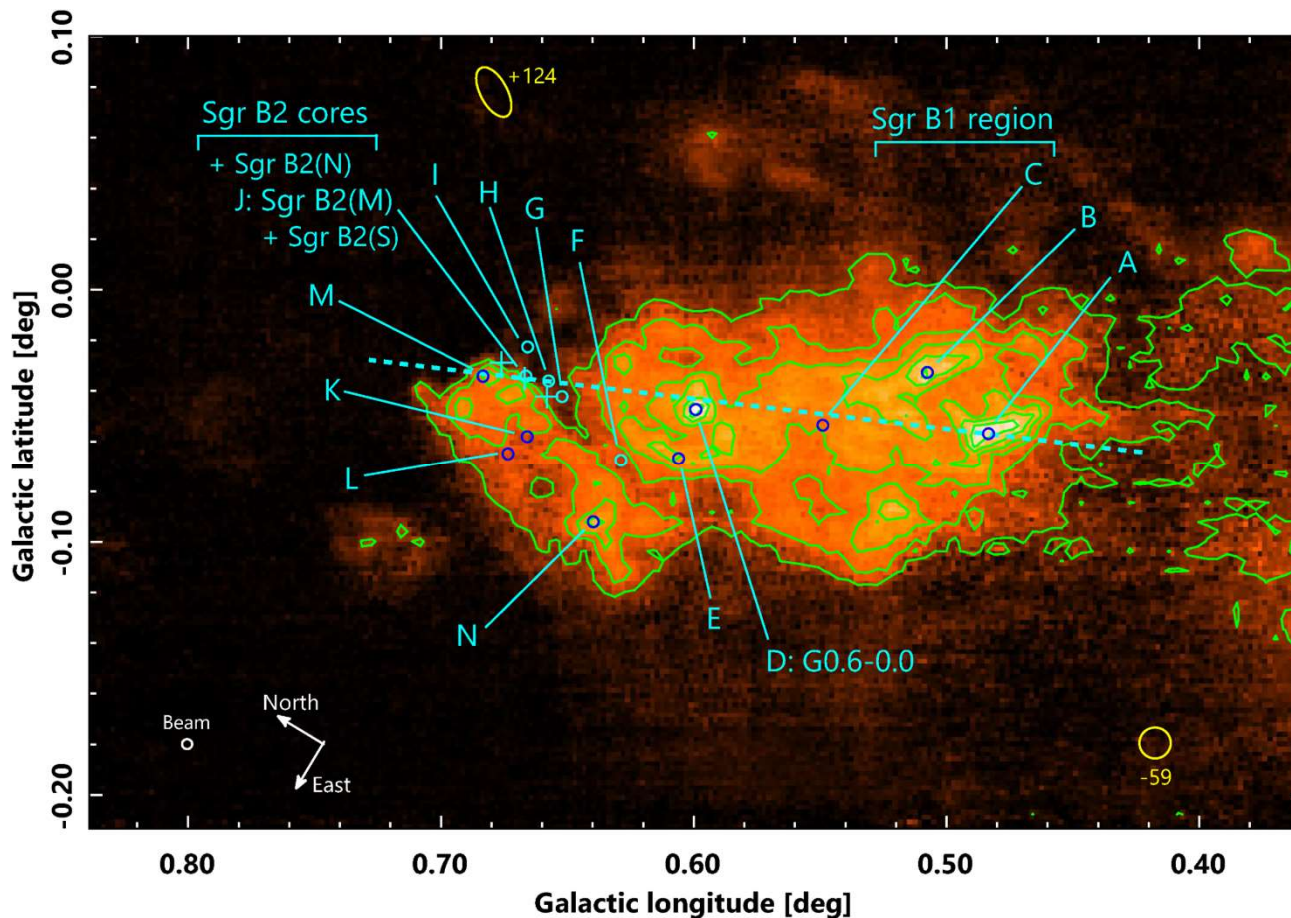
Area-averaged spectra from SgrB's [C II] body



Velocity-resolved spectroscopy identifies physically separate components and tracks kinematics

Broad lines, two main components at +50 and +90 km/s

Spectral line mapping

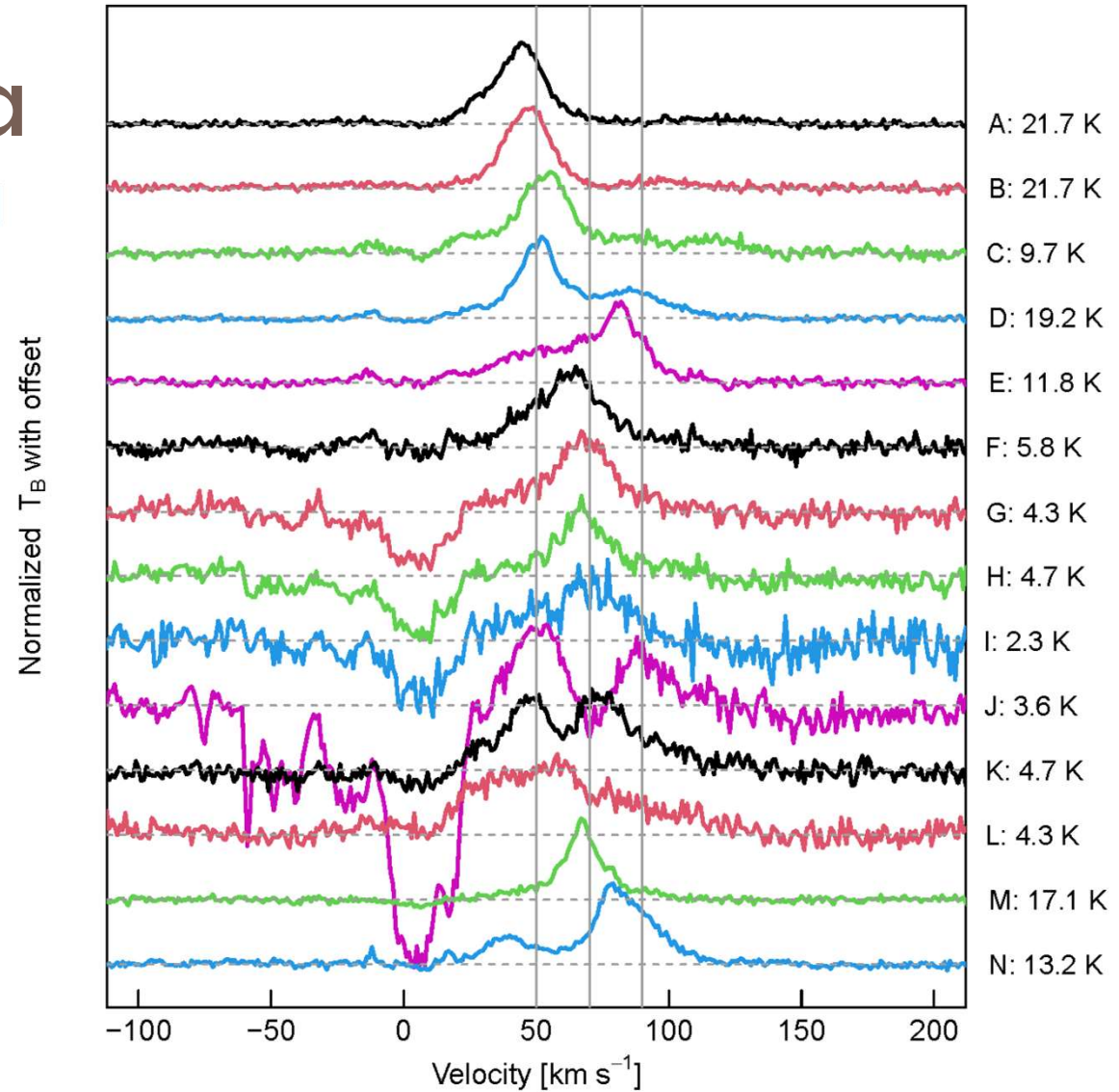


The SgrB data cube contains
~12,700 spectra with 200
velocity channels each

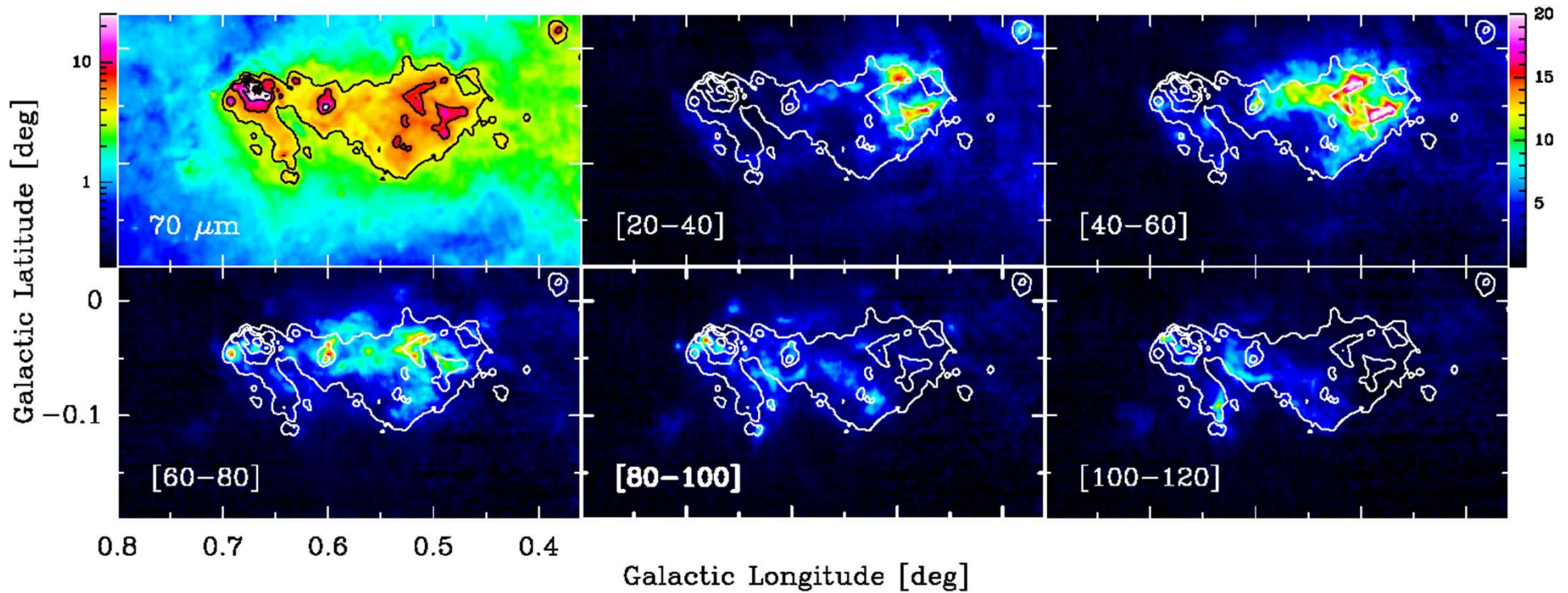
Many different ways to look at
the data

Sample spectra

Data from interesting and representative positions

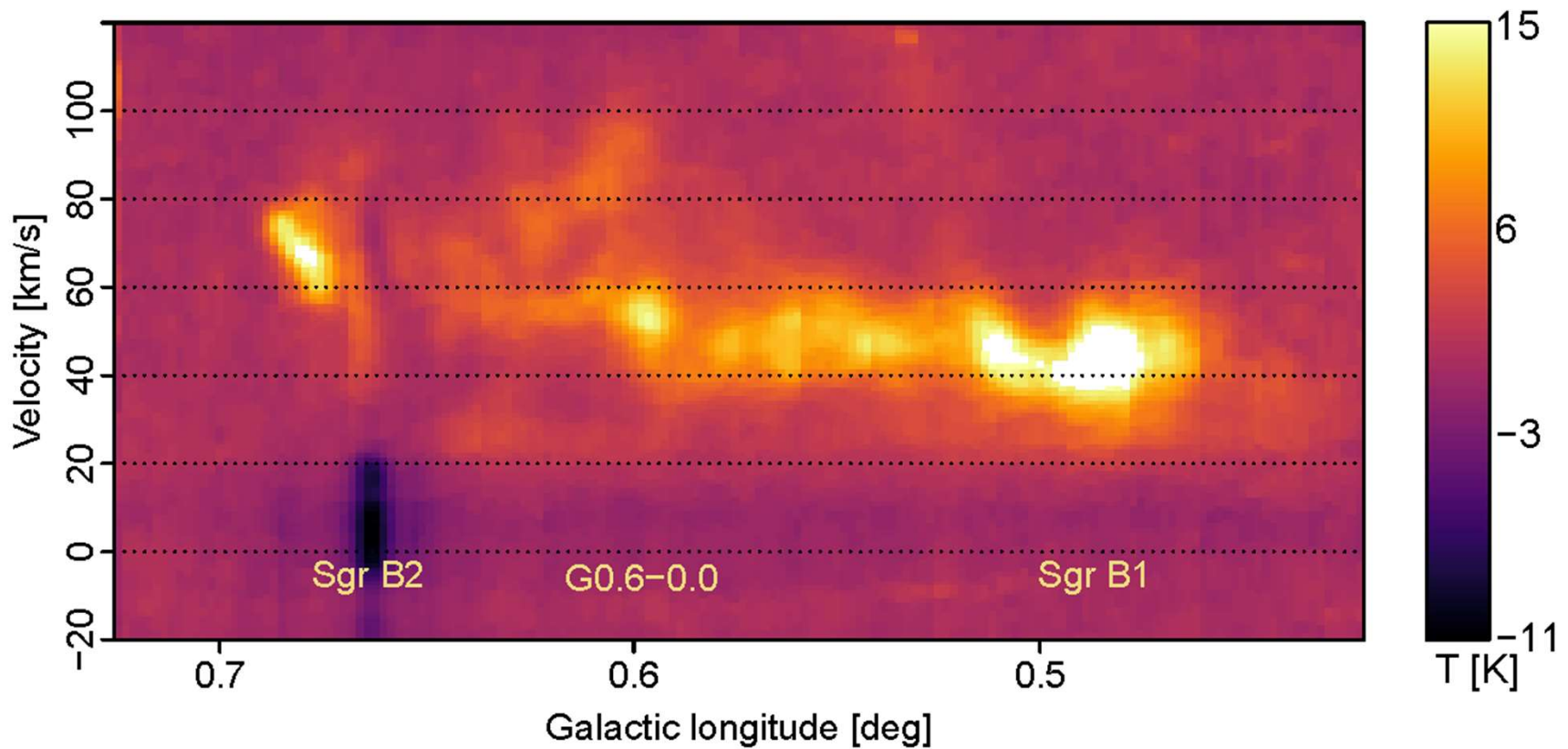


[C II] velocity channel maps

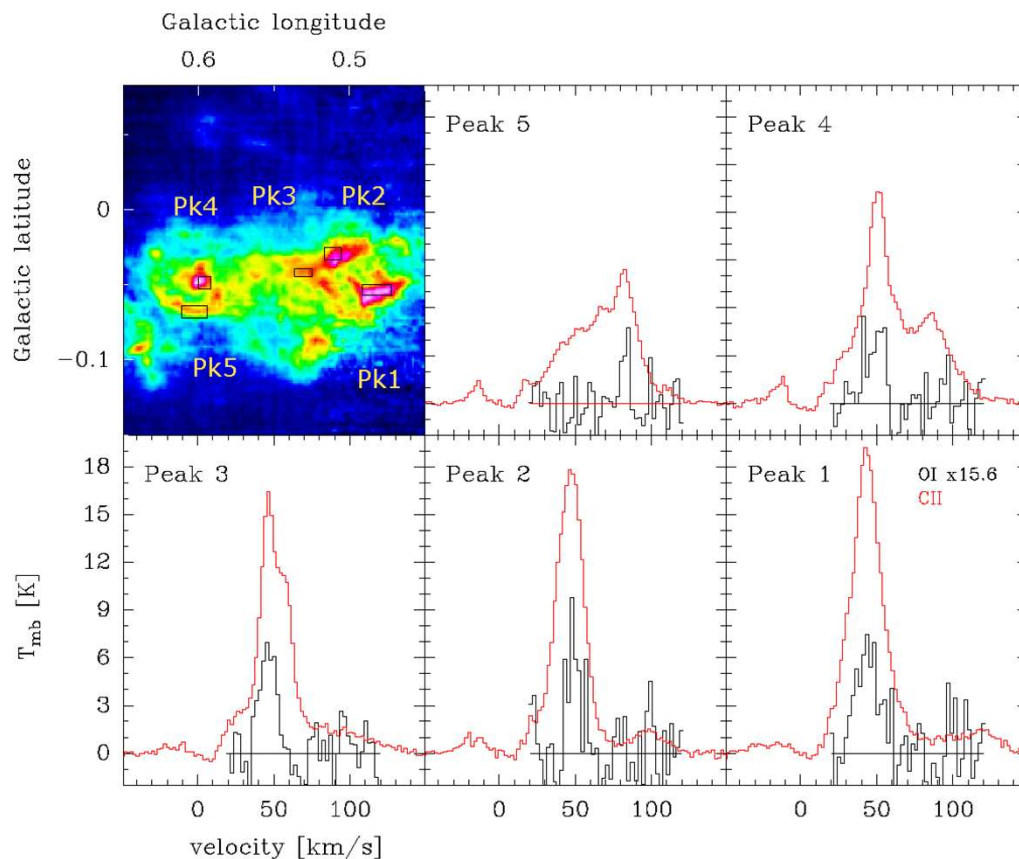


70 μm continuum from Molinari+16

Position-velocity diagram for SgrB



upGREAT velocity-resolved 63 μm [O I]

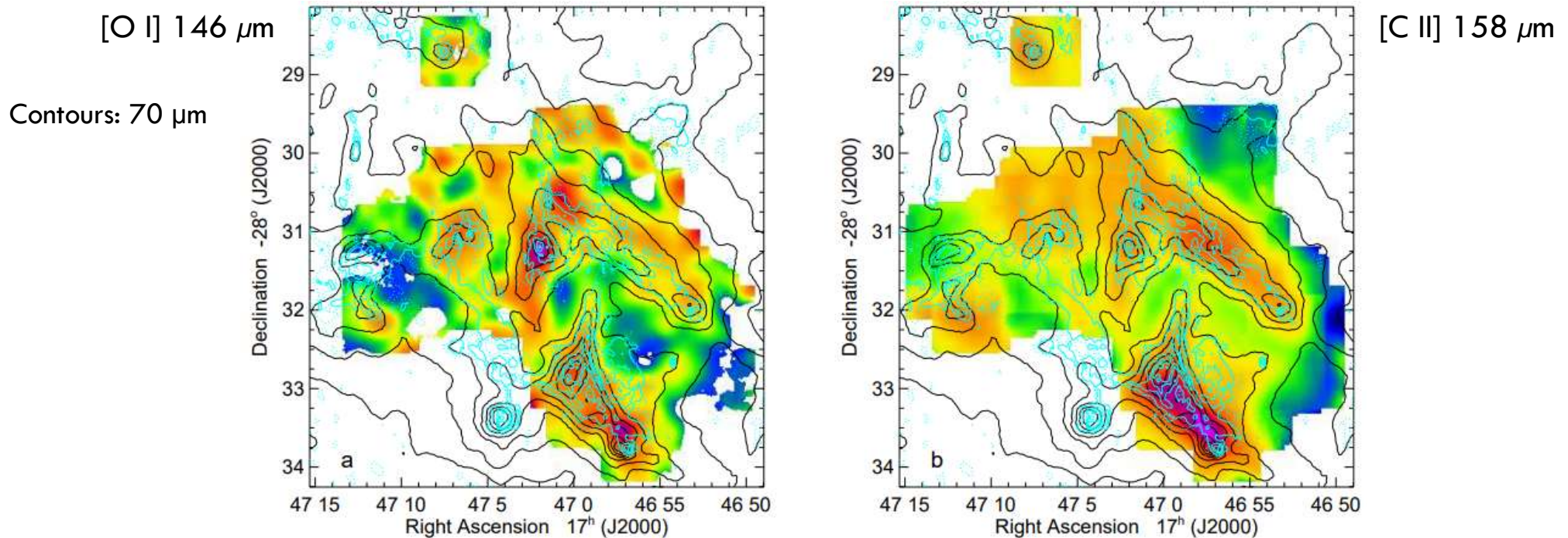


Ground-state 63 μm [O I] is strong at [C II] peaks

$$I[\text{O I}]/I[\text{C II}] \sim 0.3$$

Goicoechea+04 detected [O I] throughout the Sgr B2 region in the large ISO beam, proposed origin in widespread PDRs. Also found $I[\text{O I}]/I[\text{C II}] \sim 0.3$

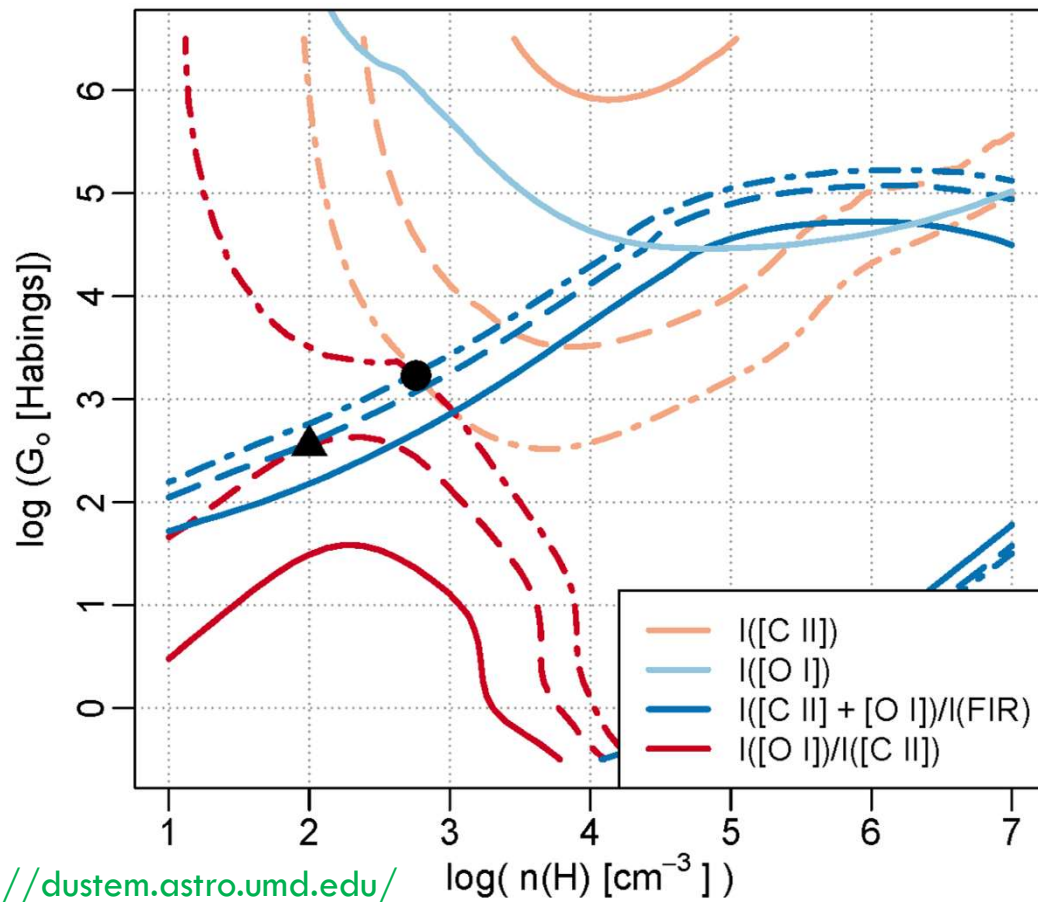
FIFI-LS images of Sgr B1 in [O I] and [C II]



Plenty of neutral gas, evidence for widespread PDRs

Simpson+2021

PDR modeling with PDRtoolbox



We constrain models with absolute intensities and ratios of upGREAT [C II] and [O I], Herschel 70 μm FIR intensity

FIR is from 70 μm , since 160 μm probes mainly cooler background

Solid lines: unmodified numbers, no convergence (lines don't cross). Dashed line/triangle: 58% of [C II] in HII regions; dashed-dot/circle, 76% in HII region

Low-density PDR, in any case, in agreement with Simpson+21

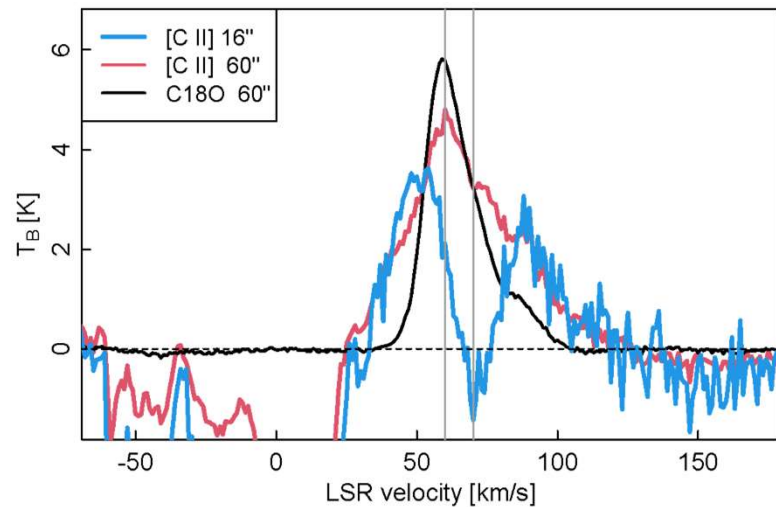
As usual, [O I] 63 μm , 145 μm are problems, and don't converge on a simple model

<http://dustem.astro.umd.edu/>

[C II] is from PDRs and HII regions

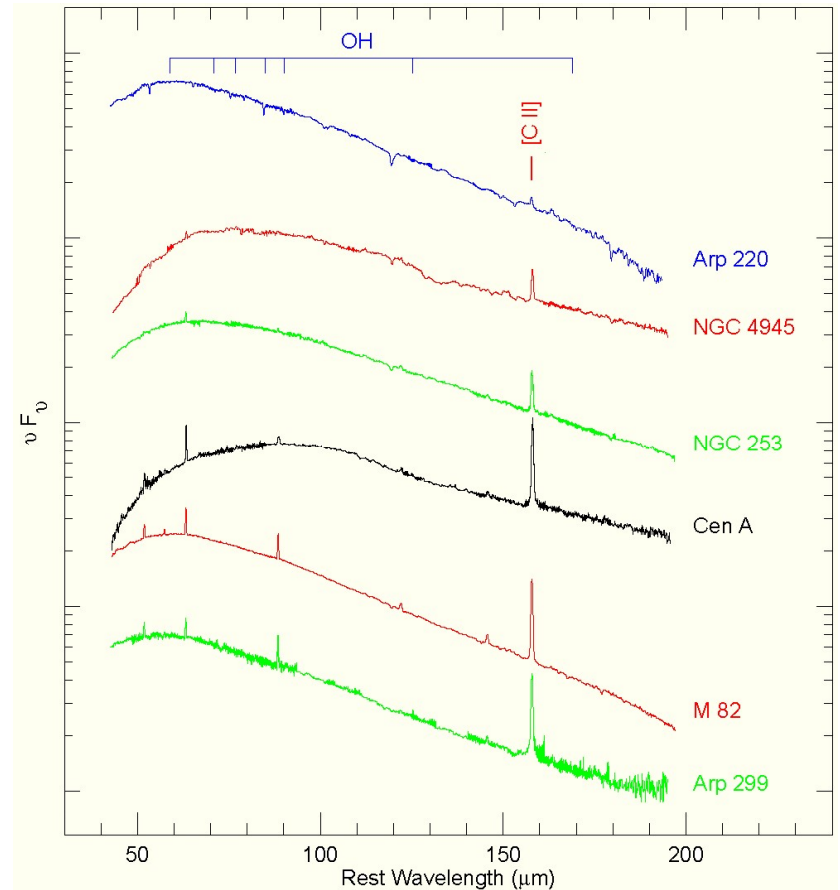
- Estimates for columns and masses
 - $N(\text{C}^+) = 1.2 \times 10^{18} \text{ cm}^{-2} \Rightarrow m(\text{C}^+) = 50 M_{\odot}$
 - $N(\text{H}+2\text{H}_2) = 3.9 \times 10^{21} \text{ cm}^{-2} \Rightarrow m(\text{H}+2\text{H}_2) = 1.4 \times 10^4 M_{\odot}$
 - $N(\text{H}^+) = 1.9 \times 10^{21} \text{ cm}^{-2} \Rightarrow m(\text{H}^+) = 5.7 \times 10^3 M_{\odot}$ (20 cm free-free from Lang+20)
 - $N(\text{H}^+)/N(\text{H}) \sim 0.5$
- PDR modeling implies 58% to 76% of [C II] is from PDRs
- Both are in approximate agreement, both agree with typical values from other galactic nuclei

Sgr B2(M): Nearly invisible in C⁺



Provides a detailed look at the correspondence between compact, high luminosity star formation and [C II] in a galactic nucleus

A local example of the ULIRG “C⁺ deficit?”



Summary

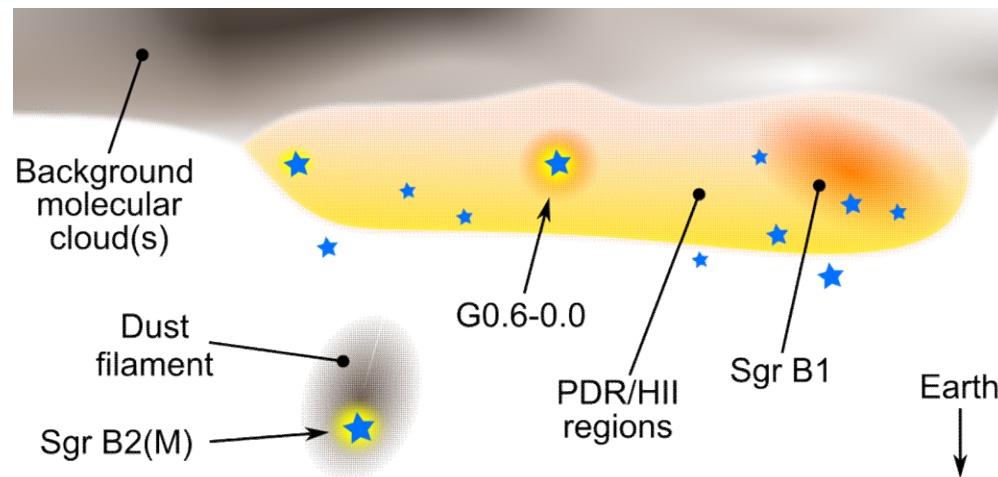
- SgrB is a major contributor to the entire Galactic center's [C II] luminosity: 12% of total from 6% of area
- SgrB is a ~ 35 pc long structure, continuous in velocity and extent, that encompasses SgrB1, G0.6-0.0, and SgrB2
- 160 μm continuum and CO are more extended than [C II]. This, along with the lack of [C II] self-absorption, indicates that the [C II] is on the near side of a large molecular cloud or clouds

Summary

- [C II] and 70 μm continuum share nearly identical spatial distributions, and 20 cm free-free is similar. All are excellent tracers of young stars
- PDR modeling indicates that about 50-75% of the [C II] flux is from H II regions, in agreement with other modeling in other luminous galactic nuclei
- Emission is from well-mixed PDRs and H II regions across the region, indicating that distributed star formation is common across SgrB

Summary

- SgrB2(M) is in front of the SgrB emission, and despite its high luminosity, is invisible in [C II] except in absorption against its FIR continuum. This is a promising region to study the “C⁺ deficit” found in luminous galactic nuclei
- Deduced structure



All this and more, including discussion of uncertainties and information related to orbital triggers for star formation in the Sgr B2 cores, in:

SOFIA-upGREAT imaging spectroscopy of the [C II] 158 μm fine structure line of the Sgr B region in the Galactic center

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<https://arxiv.org/pdf/2107.14495.pdf>

ApJ, in press