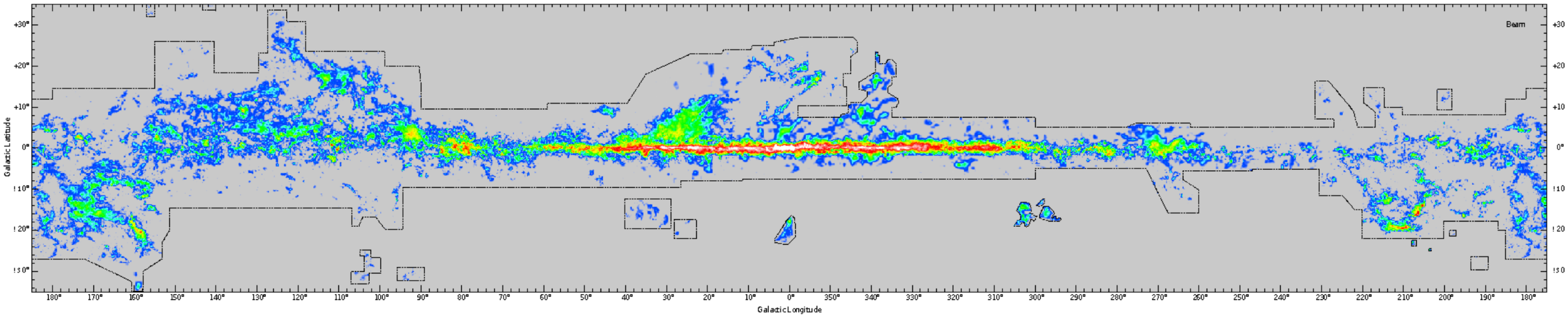
Busch et al. 2019: *arxiv # 1908.04829*

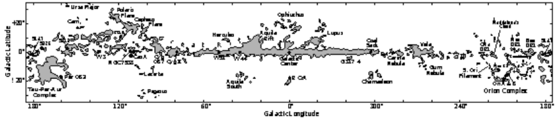
The Physical State of "CO-Dark" Gas in the Perseus Arm

Michael P. Busch
NSF Graduate Fellow
Johns Hopkins University

Collaborators:
Ronald J. Allen (PI, JHU/STScI), David E. Hogg (NRAO), Philip D. Engelke (JHU), David A. Neufeld (JHU), Mark G. Wolfire (UMD)

CO → Molecular Gas





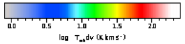


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

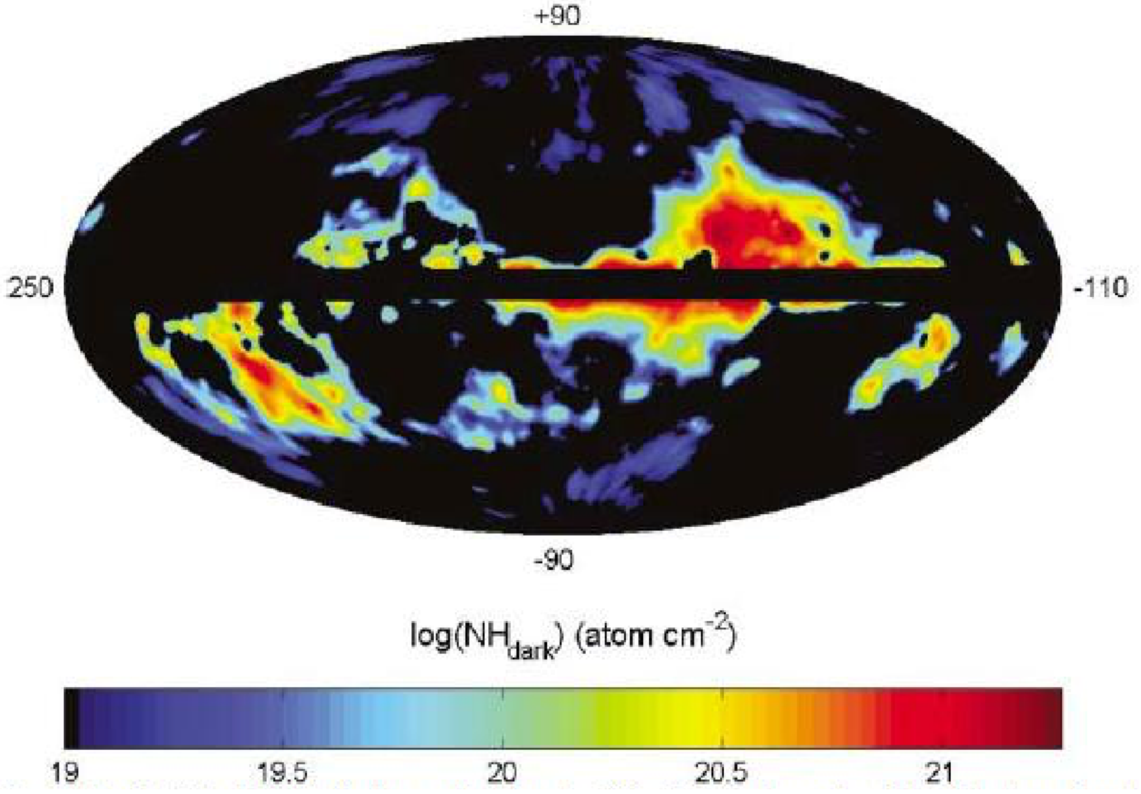
Cfa CO survey -- from Dame et al. (2001) -- δW(CO) ~ 1K

“Dark” Gas Distribution as Traced by Gamma Rays

Grenier et al. 2005:

Gamma rays produced by cosmic rays interacting with gas.

“[Dark gas] surround all the nearby CO clouds and bridge the dense cores to broader atomic clouds, thus providing a key link in the evolution of interstellar clouds.”



OH as a “new” tracer for the Diffuse H2

- OH was the first molecule discovered in radio, (Weinreb, 1963)
  - Emission was only detected in masers.
  - CO was bright and easy to observe -- took over as conventional tracer when discovered.
- The *critical density*--where collisional de-excitation rate equals the spontaneous emission rate, is different for CO and OH (crucial difference is in Einstein A coefficient).
  - For 3-mm CO, n_cr ~ 1000 cm-3
    - Sub-thermally populated in low density clouds, emissivity scales with density
  - For 18-cm OH, n_cr ~ 1 cm-3
    - OH lines will always nearly be thermally populated, ***even in very diffuse H2 gas.*** Emissivity is largely independent of density.
    - Caveat: it’s faint regardless *because* of this difference in Einstein A.

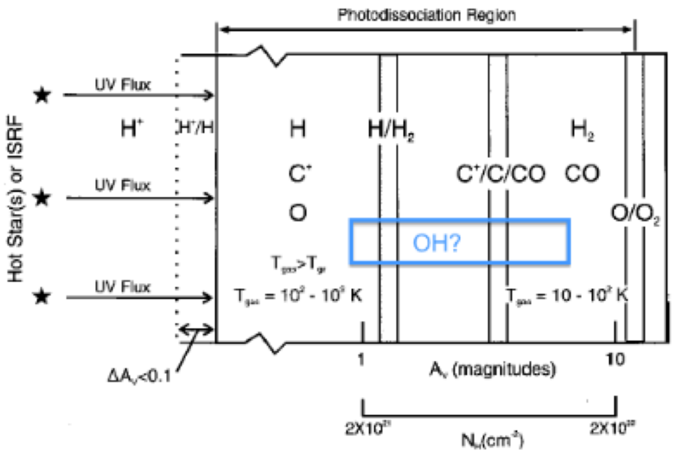
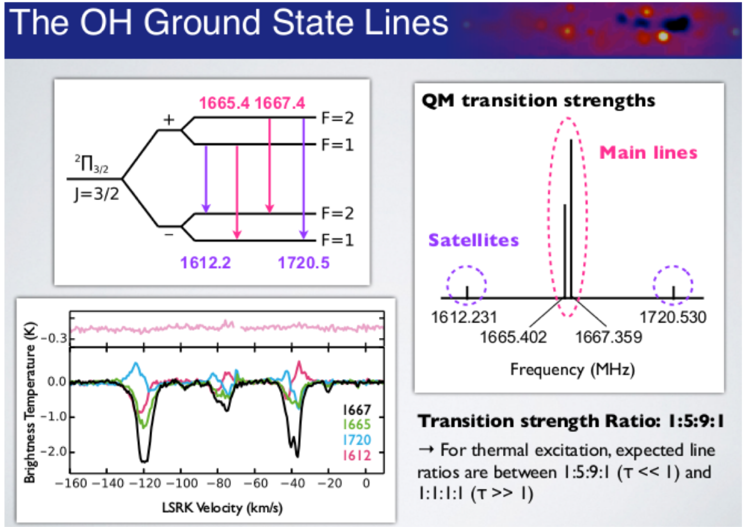


Figure 2. A schematic view of photo-dissociation region (Tielens 2005). It shows the locations of different transition layers. We add the blue pane to indicate the possible location of OH.

Li et al. 2015

Short History of “Normal” OH Emission Surveys

- **Deep Mapping:** Wannier (1993), Barriault (2010), Cotten (2012), Allen (2012, 2015), Busch (2019)
- **Deep Single Pointings:** Tang et al. (2017)
- **Absorption/Emission Pairs:** Liszt & Lucas (1996), Li et al. (2018)



THE STRUCTURE OF DARK MOLECULAR GAS IN THE GALAXY
A Pilot Survey for 18-cm OH Emission Towards $l \approx 105°, b \approx +1°$

Ronald J. Allen

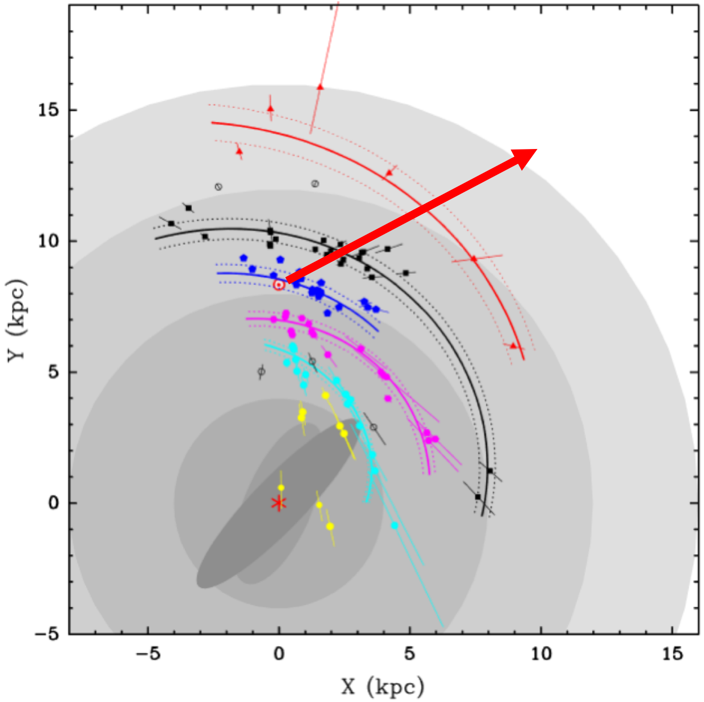
Variations in profile structure on scales of 0.5°

3.2 kpc. The grid spacing in the present OH data therefore corresponds to a linear scale of ≈ 28 pc, sufficient to resolve broad structure in a giant molecular cloud, but too coarse to resolve core structures in such clouds. In order to compare the OH molecular clouds with the more familiar CO molecular clouds, it will be necessary to map selected OH features on a finer grid, perhaps even down to the Nyquist interval of the GBT beam.

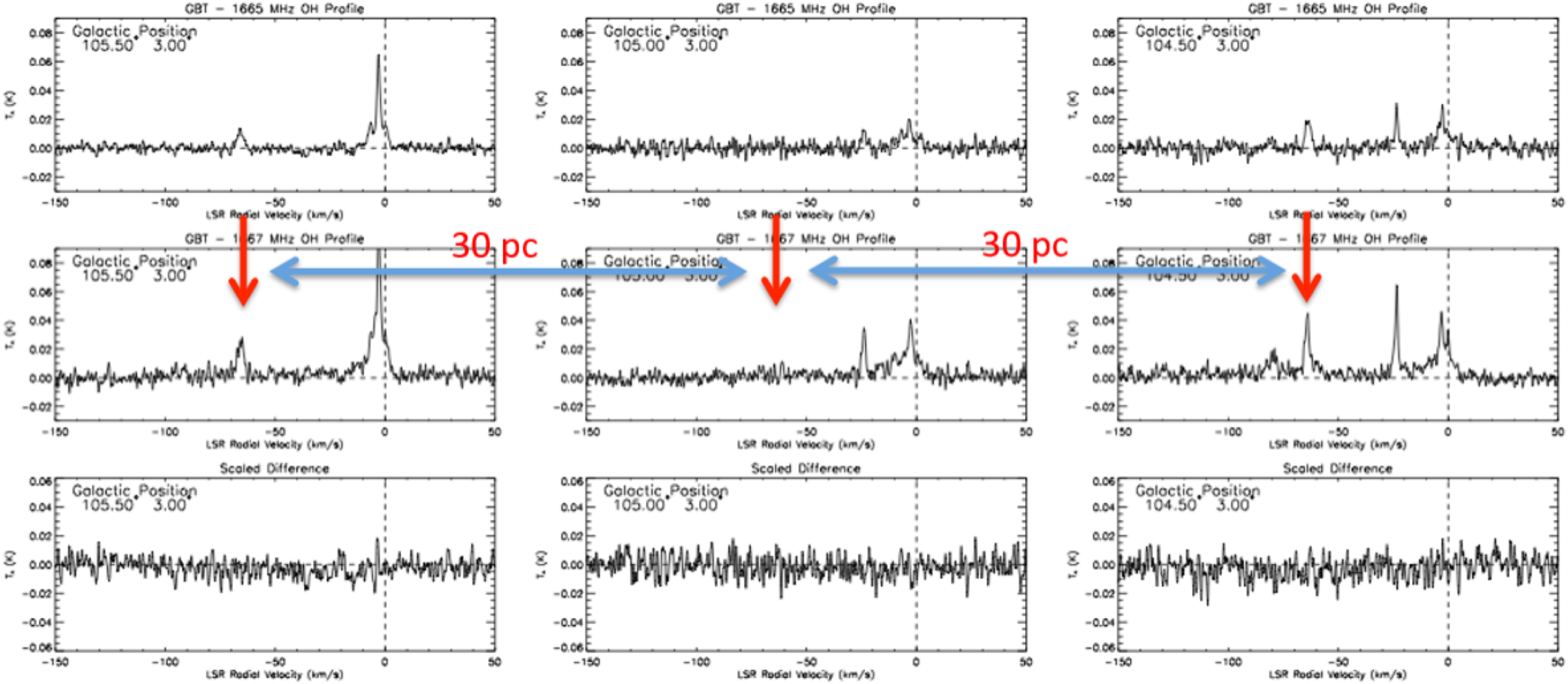
Motivation for this work
- Busch et al. 2019

The Outer Galaxy works well for OH emission surveys!

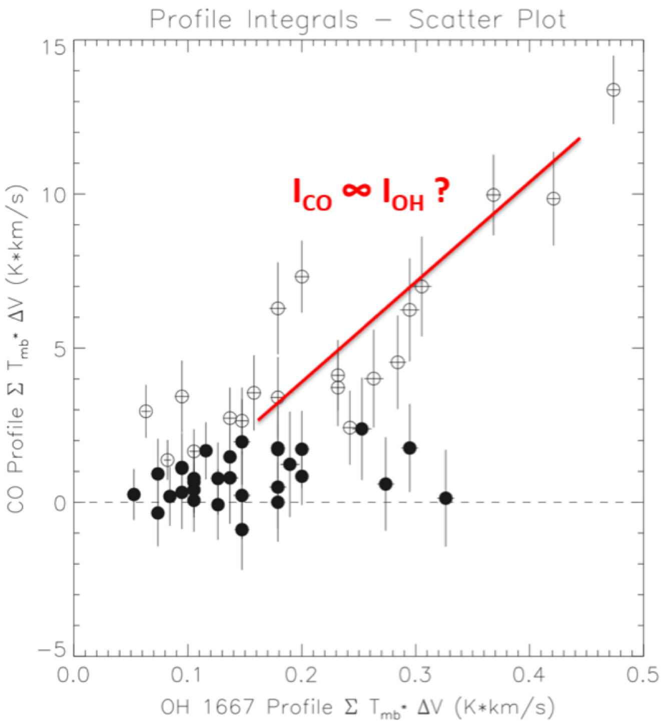
- Differential Galactic rotation separates spectral features in V along the LOS:
  - Local gas: V_LSR ~ 0 km/s
  - Inter-Arm gas: V_LSR ~ 0 km/s
  - Perseus Arm: V_LSR ~ -65 km/s
  - Outer Arm: V_LSR ~ -100 km/s
- **Lack of near/far kinematic distance ambiguity** in the Outer Galaxy.
- **The continuum background is much lower than pointing towards the Inner Galaxy… (~3.5 K)**.
  - For the low excitation temperature of OH (~5K, Engelke & Allen 2018), this is crucial!
  - Dawson et al. 2014 & SPLASH survey did not detect extended OH towards Inner Galaxy
- Distances to known precisely via VLBI parallax measurements (Reid et al 2014, Choi et al. 2014, Reid et al 2018) → ***allows accurate spatial mapping***.

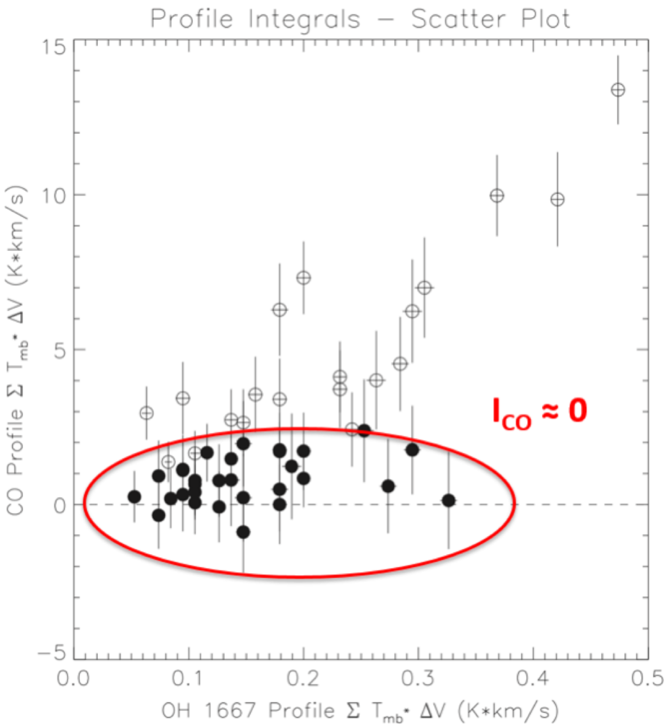


Spatially Resolving Dark Gas (Allen 2015)



Results from Allen 2015 OH Survey:





Allen, Hogg, & Engelke (2015)

The GBT One Square Degree (OSD) Survey

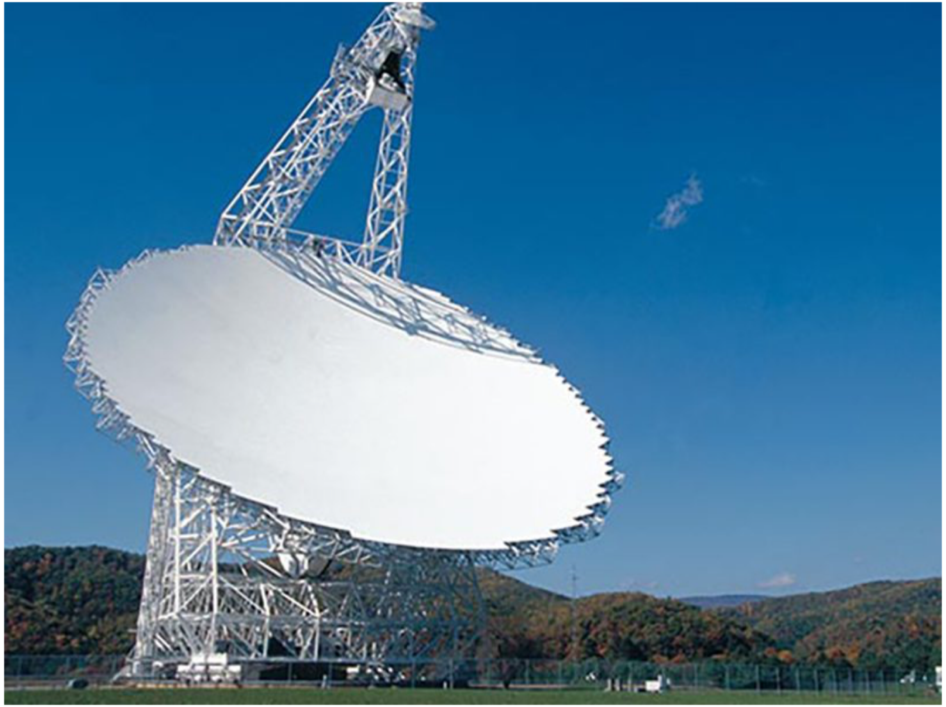
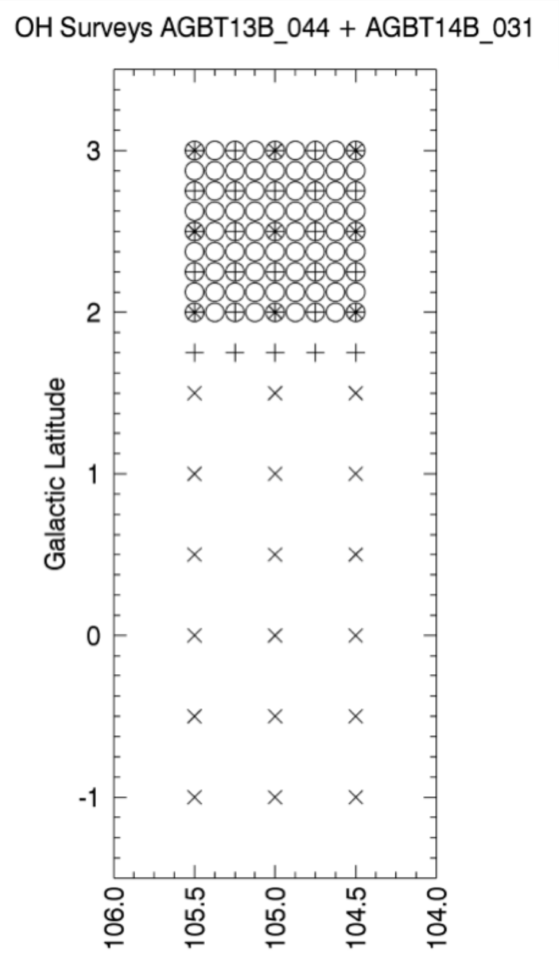
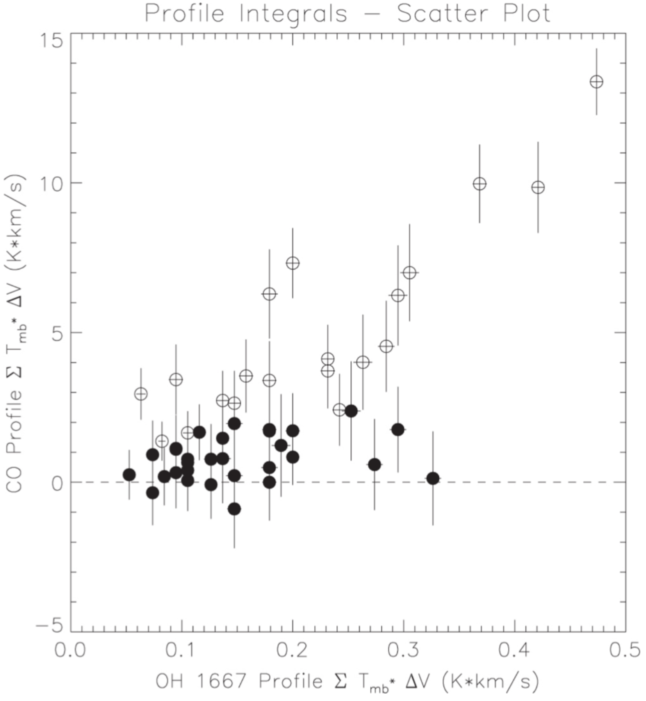


Photo: NRAO/GBO

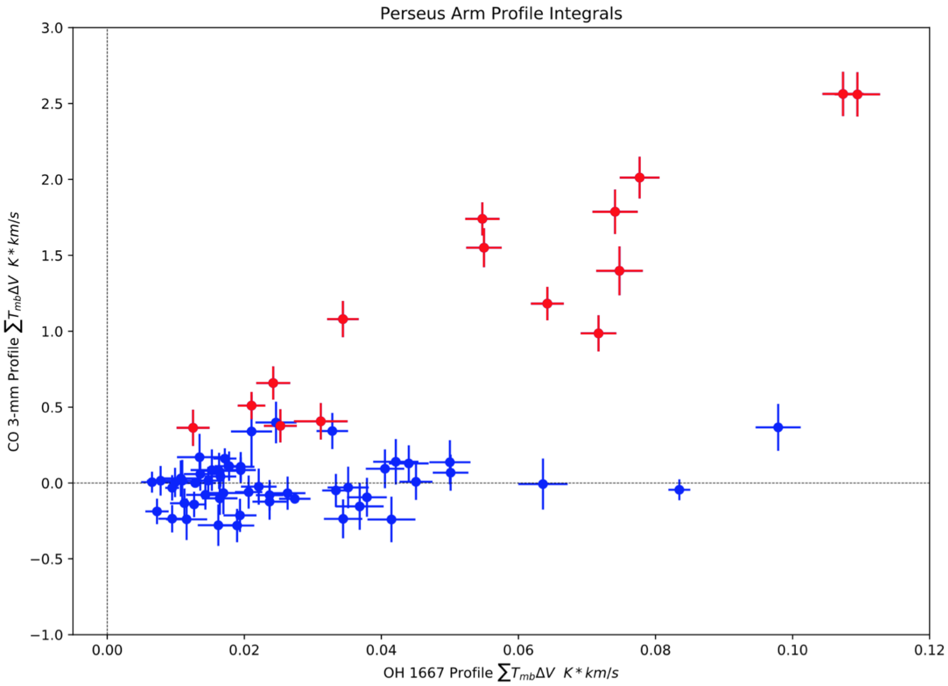


Large Scale (Pilot) vs Small Scale (OSD)

Allen et al. 2015 (Paper I.)

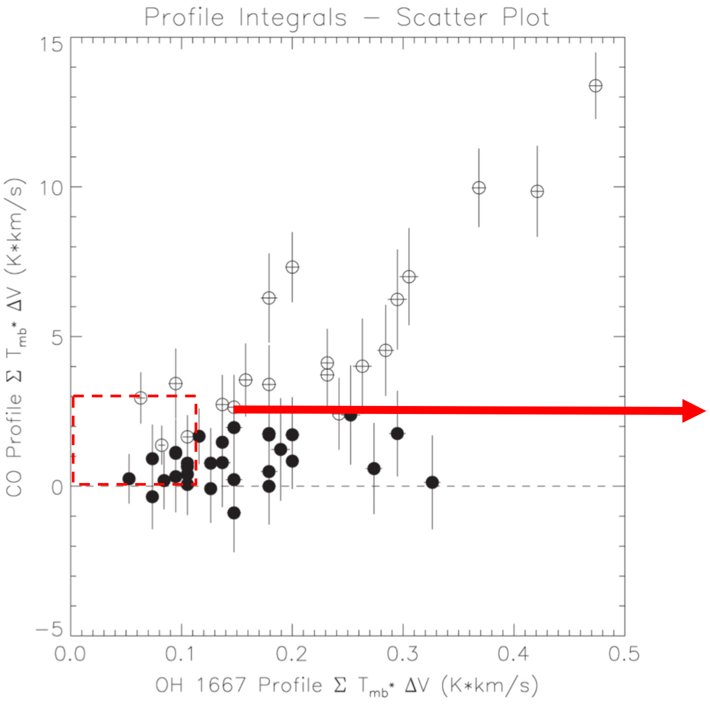


Busch et al. 2019 (Paper II.)

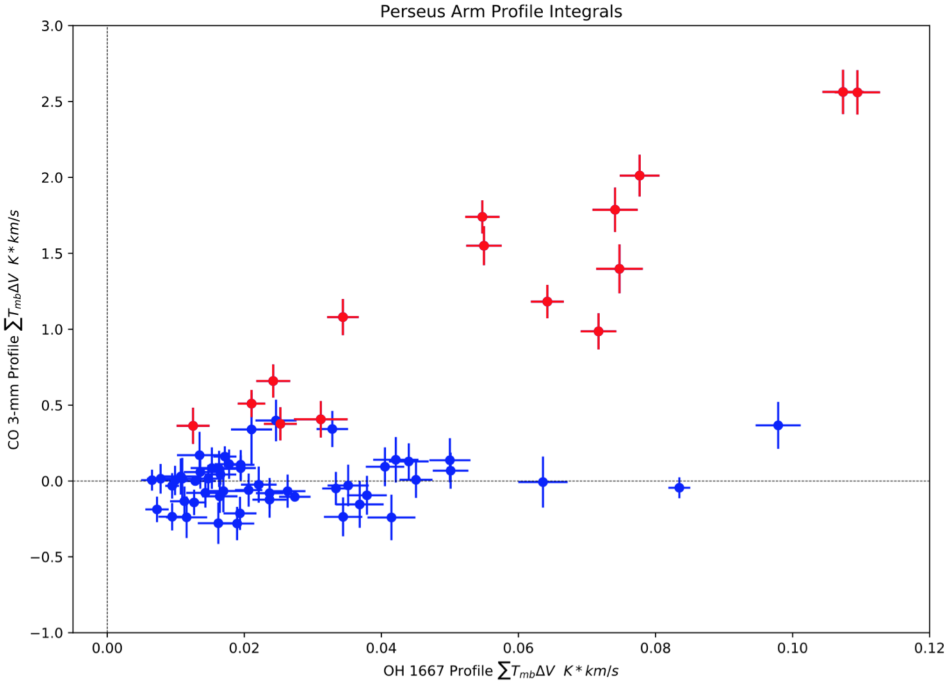


Large Scale (Pilot) vs Small Scale (OSD)

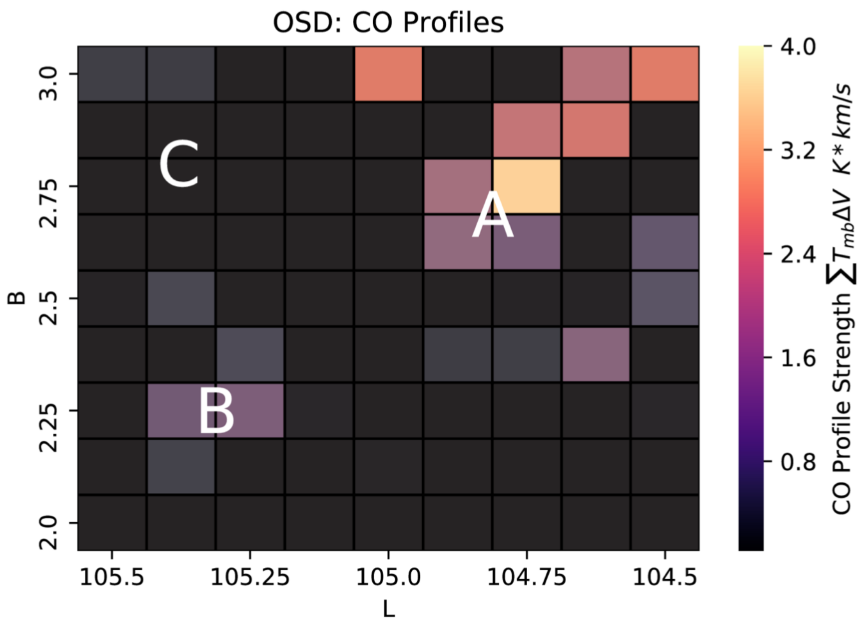
All OH Features in Spectra

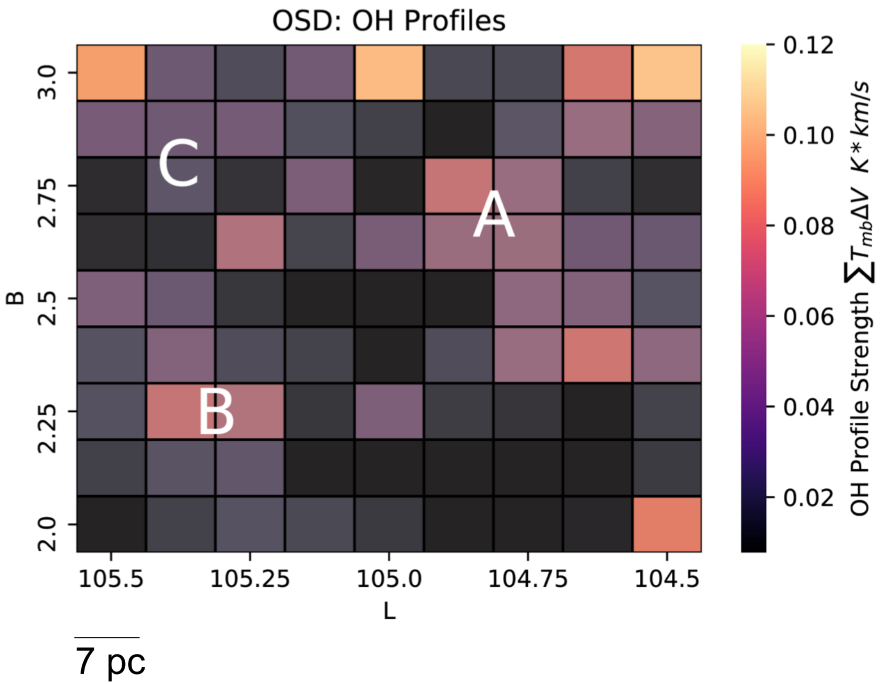


The Perseus Arm feature.



Spatially Resolving Dark Gas (OSD)



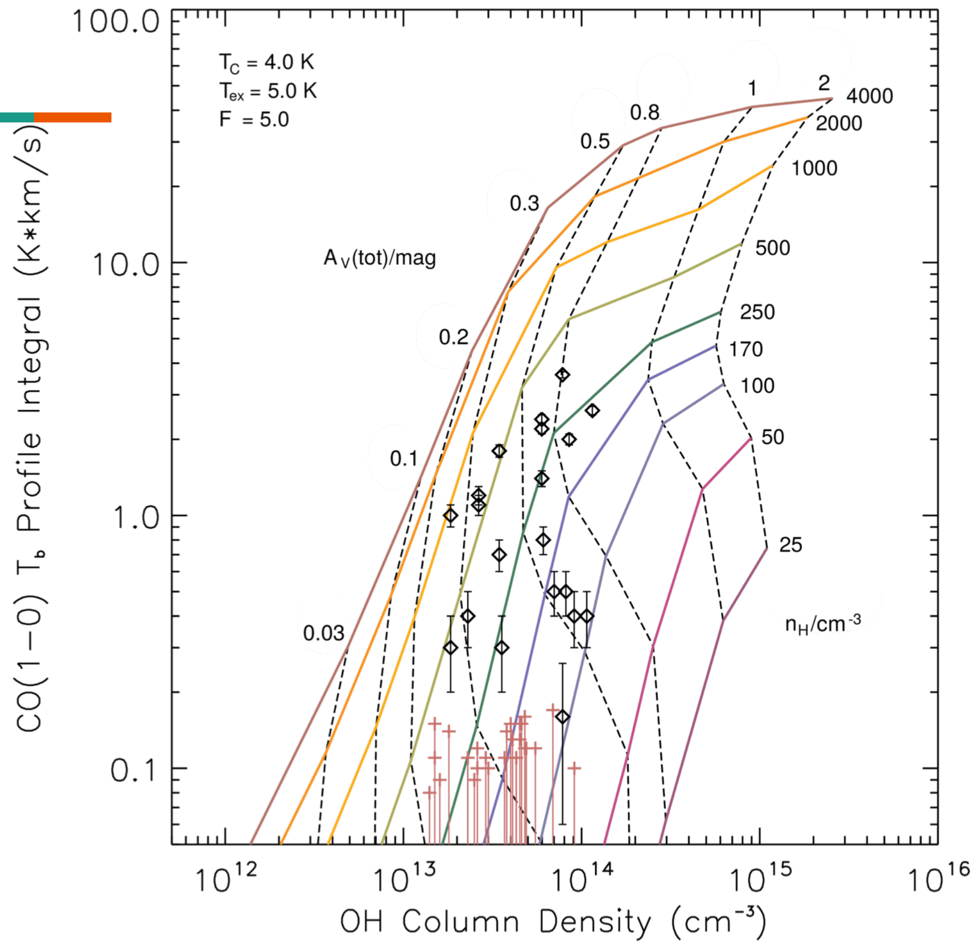


A: CO core surrounded by OH emission.
B: Smaller CO clump surrounded by OH emission.
C: Region devoid of CO but ubiquitous OH emission!

63 pc x 63 pc survey.

Busch et al. 2019, *arxiv # 1908.04829*

Physical State of the 'CO-Dark' Gas:



- Diffuse Cloud Models -- Hollenbach et al. 2012, Neufeld & Wolfire 2016
- Assuming Draine ISRF field.
- Incredibly detailed:
  - ~ 70 molecular abundances
  - ~ 300 chemical reactions
  - ~ large number of heating and cooling mechanisms.
- Caveat(s):
  - Lacking geometry
  - No turbulent dissipation or heating in small pockets of gas along the LOS.

Busch et al. 2019

Summary

Table 1. Volume Density Results for Molecular Gas in the One Square Degree Survey.

T_C (K)	T_{ex}^{67} (K)	F	CO-Bright Mean Volume Density (cm^{-3})	CO-Dark Mean Volume Density (cm^{-3})
4.0	5.0	5.0	400 ± 70	$< 210 \pm 20$
5.0	6.0	6.0	280 ± 40	$< 200 \pm 20$
5.0	5.5	11	160 ± 15	$< 120 \pm 10$

OH emission appears to be morphologically consistent with the description of Dark Gas by Gamma Rays (Grenier et al. 2005.)

- Sensitive measurements of OH can reveal extended OH surrounding CO molecular clouds by many pc.
- As long as the gas maintains a high molecular fraction--OH is a good candidate tracer of the Diffuse H2.
- We observe a volume density effect responsible for the lack of CO emission and ubiquitous OH emission.
  - In low density molecular gas, collisions with H2 dominate--CO is mainly subthermal and emissivity is sensitive to volume density.
- **The OSD is a dense OH survey that we can directly compare to previous CO surveys.**
  - We can trace Dark Gas spatially using OH, which is spatially decoupled from CO emission.
  - ~90% detectable OH emission, ~25% detectable CO emission.
  - We need more data (bigger than 1 degree, ~ 100x100pc) to resolve dark gas features.

Other DMG Tracers:

- Visit our poster in the lobby on current OH efforts to trace diffuse H_2 structure and kinematics!
- Stick around after lunch for a talk regarding C^+ by Suzanne Madden.
- A poster on HF Observations with HIFI by Umit Kavak et al.
- A poster on Simulations of H_2 by Sarah Nickerson
    - ~ About half of H_2 lays in diffuse gas and is hard to observe.