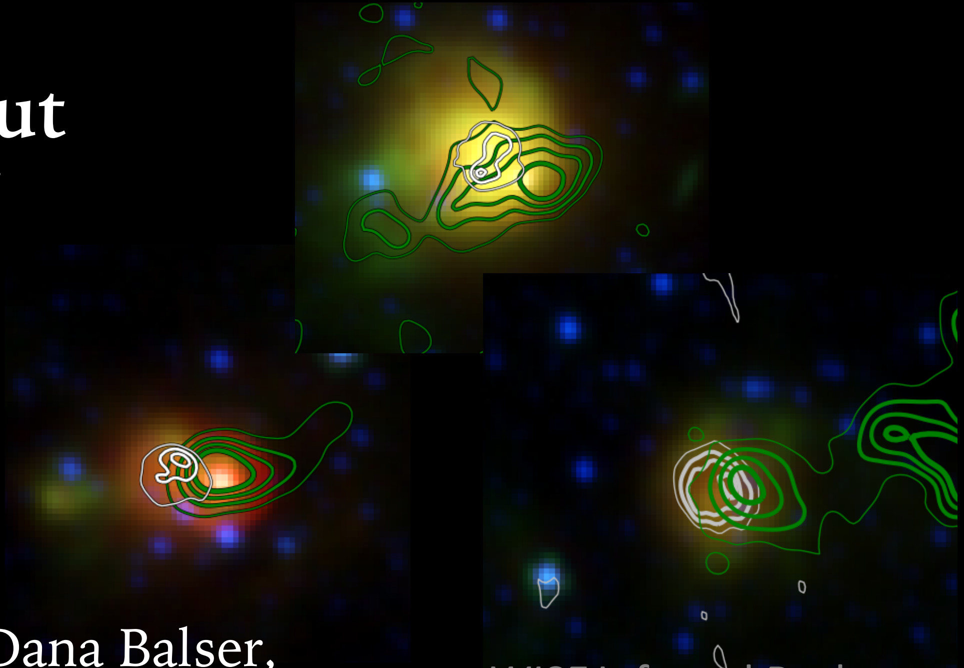
High-Mass Star Formation in the Far Outer Galaxy

Will Armentrout

Postdoctoral Fellow

GREEN BANK OBSERVATORY

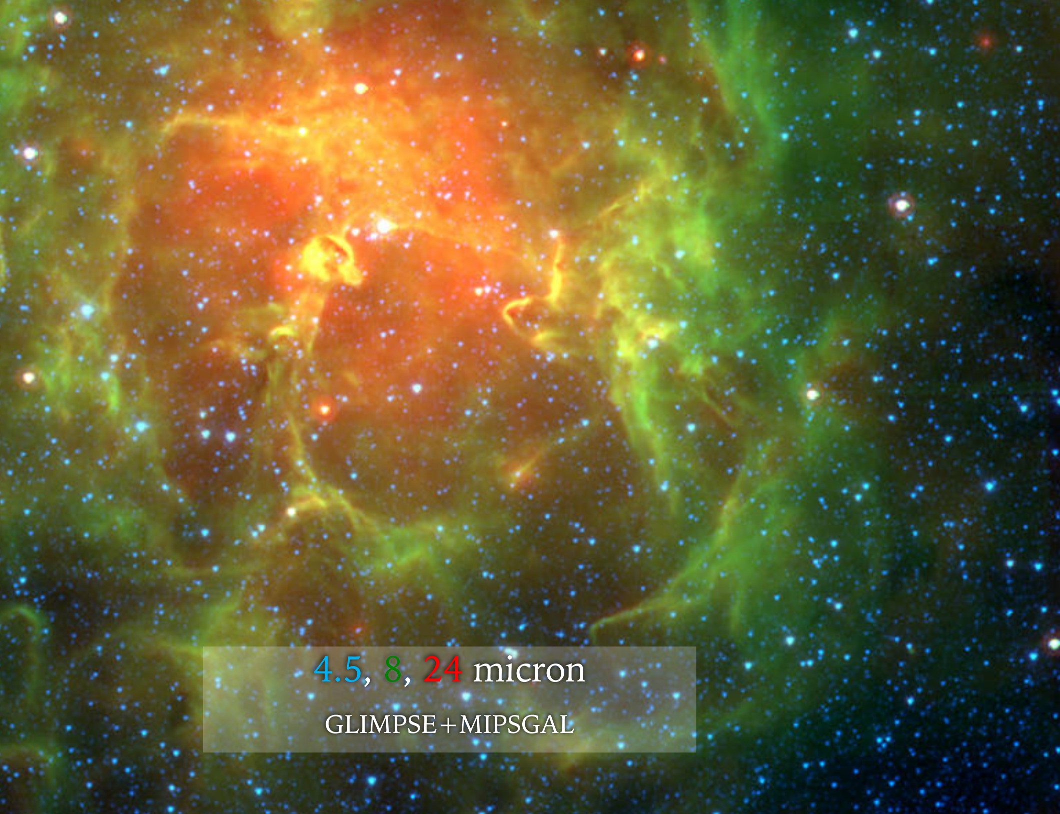


Collaborators on this work:

Loren Anderson, David Frayer, Dana Balser, Tom Bania, Tom Dame, Trey Wenger

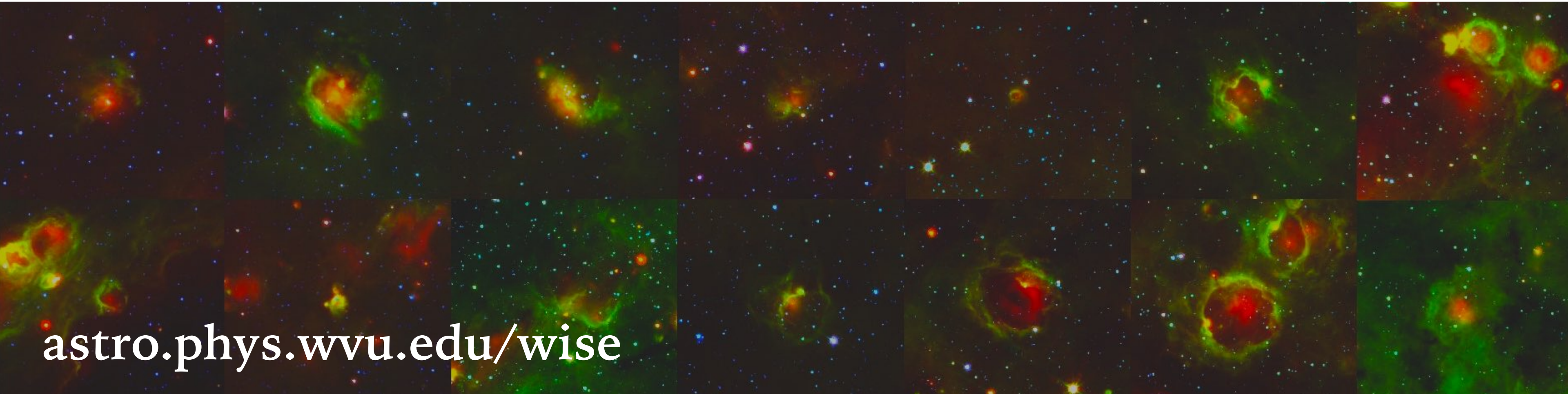
HII Regions as Star Formation Tracers

- Ionized Hydrogen (HII) surrounding high-mass stars
- Can be seen across the Galactic disk from the mid-IR to Radio (bright!)
- Zero-age objects compared to the Milky Way
- Associated molecular gas reservoirs contribute to ongoing star formation

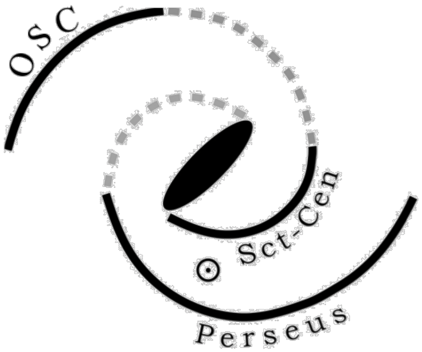


The *WISE* Catalog of Galactic H II Regions

- Contains ~2000 known H II regions and ~6000 candidate H II regions
- Characteristic Infrared Morphology
  - 22 μm core – Hot (≈100 K) small grain emission, traces massive stars
  - 12 μm, diffuse – PAH emission, traces photodissociation regions
- After we determine candidates in IR, we confirm with radio



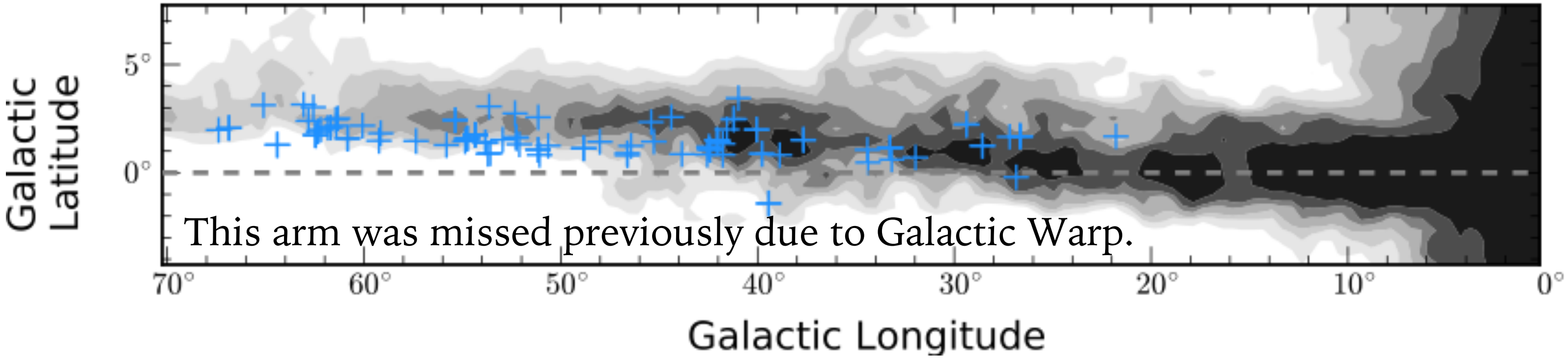
Outer Scutum-Centaurus Arm (OSC)



Extension of the Scutum-Centaurus Arm in 1st Quadrant

Boundary for high-mass SF within the Milky Way

Mean Solar Distance ~21 kpc
Galactocentric Radius ~15 kpc



Integrated HI from the LAB Survey – Figure 1 from Armentrout et al. 2017

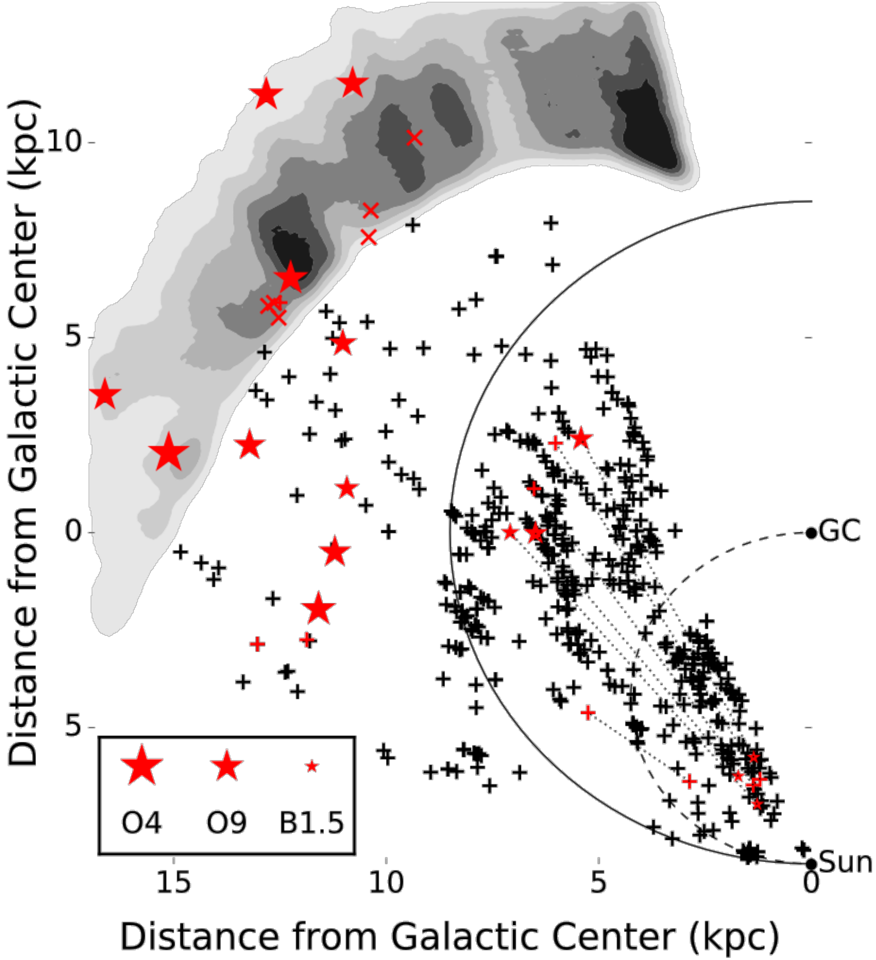


Figure 5 from Armentrout et al. 2017
with Integrated HI in Grayscale

Face-On Map

(First Quadrant)

17 Detected OSC HII Regions

Red targets observed in Armentrout+ 2017. **Black** from known HII region catalog (Anderson+ 2015).

Largest Heliocentric Radii of any HII Regions Discovered within the Milky Way

Stellar types as early as O4 ($\sim$60 $M_\odot$)

Expectations for Outer Galaxy Star Formation

Star formation in the outer Galaxy could be similar to that of a much younger Milky Way (or galaxies like the Large Magellanic Cloud)

- **Lower Gas Densities**
- **Lower Metallicity Environment**

From Balser et al. 2011/2015

$12 + \log(O/H) =$	> 8.9	at the Galactic Center (GC)
	8.54	at the Solar orbit
	8.29	at 15 kpc from GC

- **Higher Molecular Gas Conversion Factor** (CO-to-H_2, X_{CO})

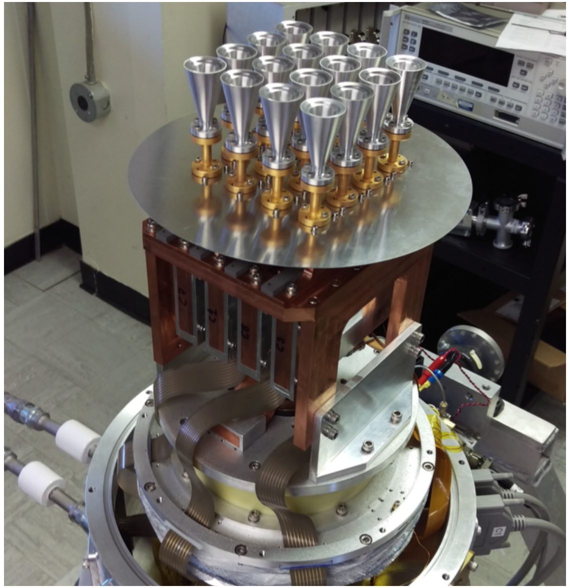
Observing and Reduction Plan

1. Map the thermal continuum and molecular gas (^{13}CO/HCN/HCO+) from **all known OSC HII regions** with the Green Bank Telescope.
2. Characterize the total molecular gas (from ^{13}CO) and the dense gas clumps (from HCN/HCO+) of outer Galaxy star forming regions.

GOAL : Constrain the efficiency of star formation in the outer Galaxy.

- Compare stellar component and molecular gas reservoirs of outer and inner Galaxy samples.
  radio continuum ➞ ionizing radiation ➞ stellar content   molecular lines ➞ gas content
- Map out to ~15 kpc from Galactic Center (Complementary sample to EMPIRE Survey, etc. which detects HCN and HCO+ out to galactocentric radii of ~10 kpc in other Galaxies.)

Molecular Gas Maps of OSC HII Regions



16 pixel Argus Array, GBT

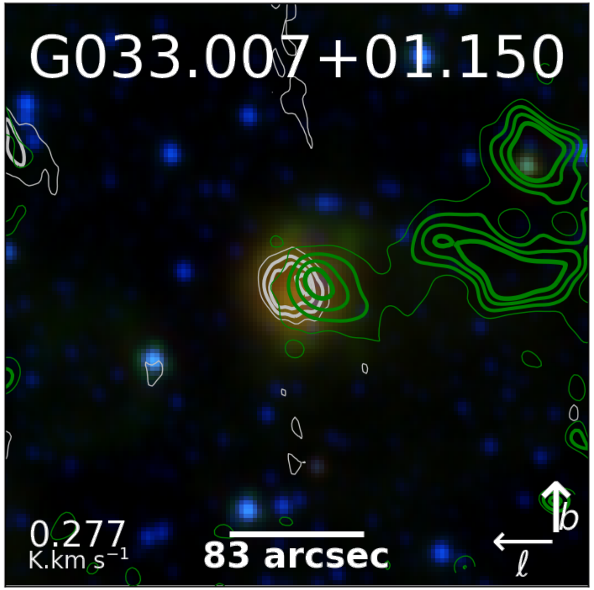
This work tunes to ^{13}CO, HCN, HCO+, & 7 other lines

16-element Argus Array
Green Bank Telescope

Operates from 74-116 GHz

Currently ~1000 hours of available Argus time per year

(Project underway to enable daytime high frequency observations)

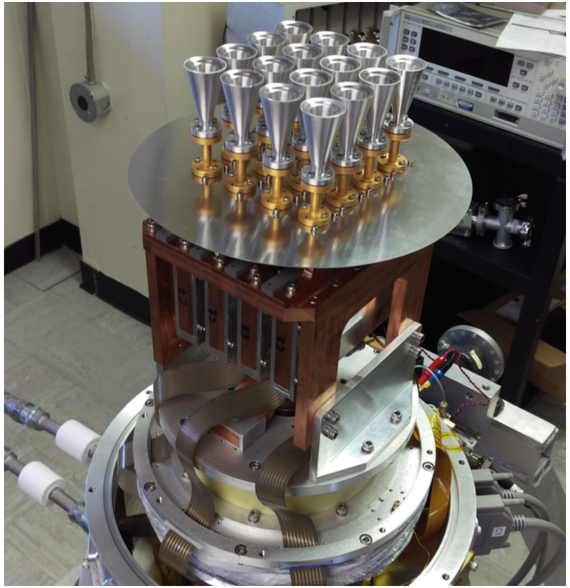


^{13}CO Contours in Green

VLA Contours in Grey (10 GHz Continuum)

WISE Infrared Background

Molecular Gas Maps of OSC HII Regions



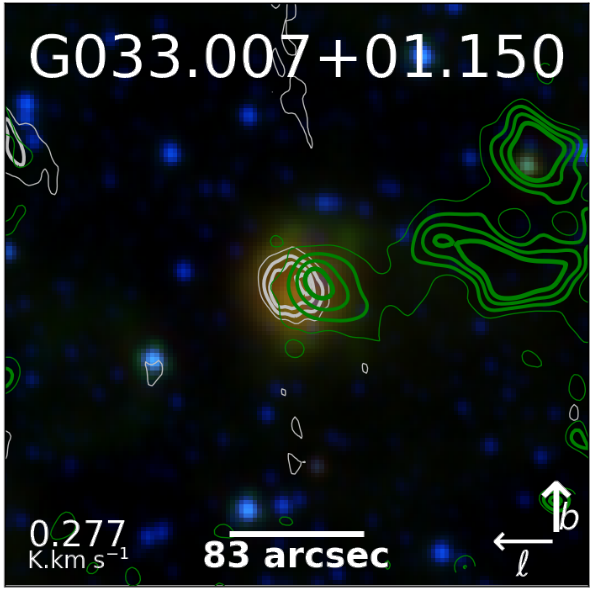
16 pixel Argus Array, GBT

This work tunes to ^{13}CO, HCN, HCO+, & 7 other lines

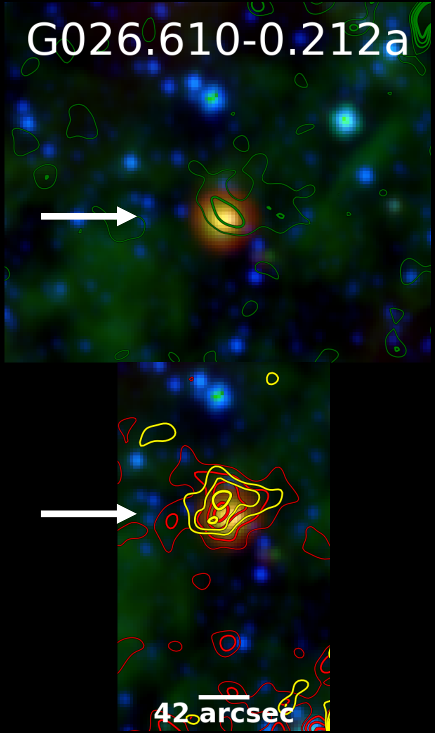
5 arcmin x 5 arcmin
(Daisy Scans)
25 minutes per map
RMS ~0.5 K /~0.1 K • km s^{-1}
7 arcsec resolution at 110 GHz

>65% of OSC HII regions had ^{13}CO detections, covering a wide range of molecular cloud masses
(11/17)

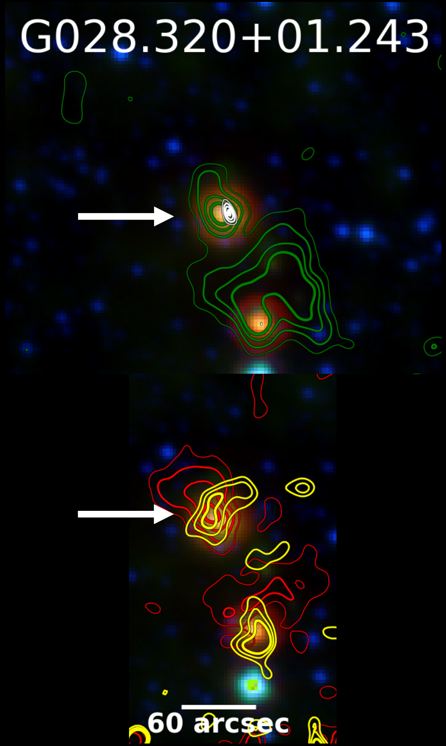
100% of OSC HII regions (so far) had dense gas (HCN, HCO+) detections
(6/6)



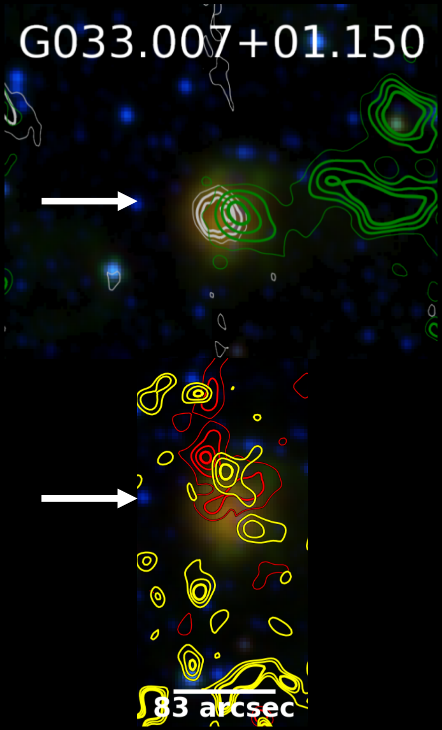
^{13}CO Contours in Green
VLA Contours in Grey (10 GHz Continuum)
WISE Infrared Background



$\mathrm{Log}(N_{Ly}) = 49.1$ (O5.5)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.6$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.4$
$M_{Dense}/M_{mol} = 5.3\%$

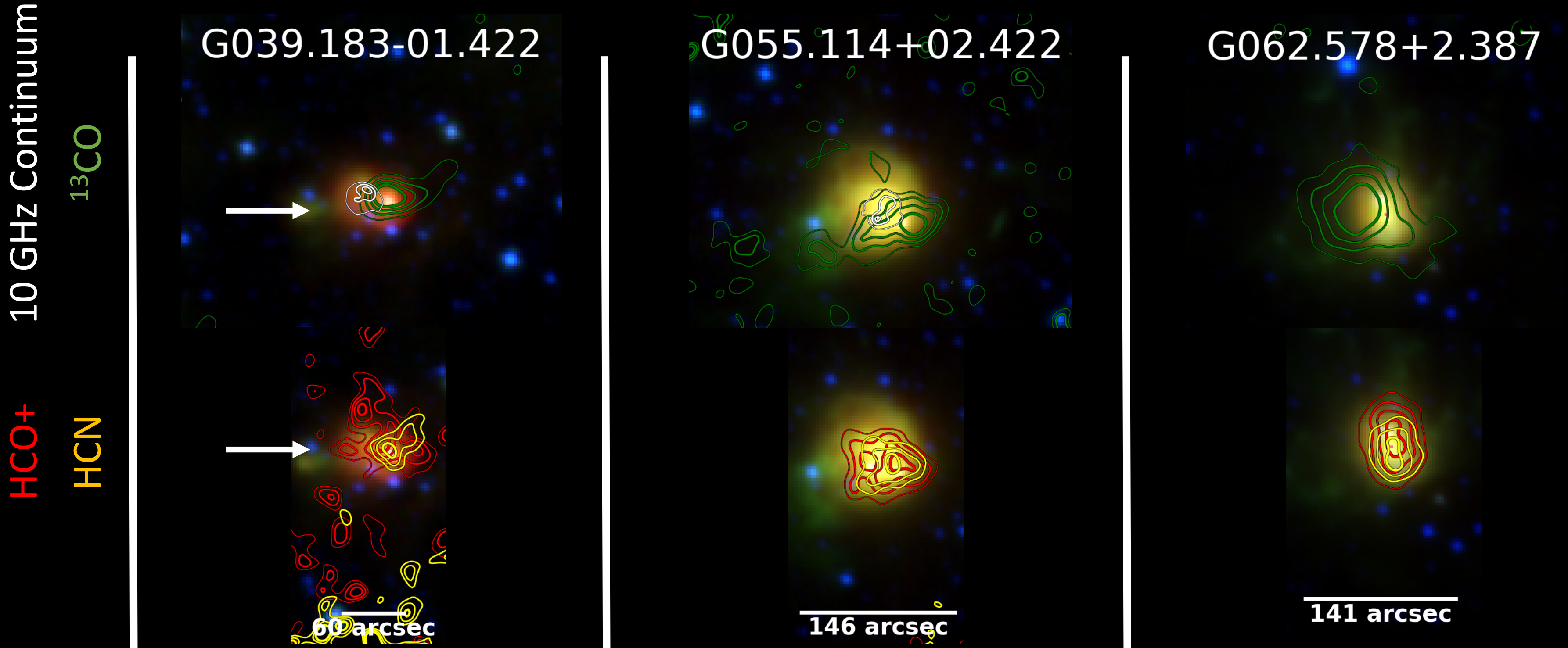


$\mathrm{Log}(N_{Ly}) = 48.2$ (O8)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.7$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.5$
$M_{Dense}/M_{mol} = 5.7\%$



$\mathrm{Log}(N_{Ly}) = 48.2$ (O8)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.8$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.5$
$M_{Dense}/M_{mol} = 4.8\%$

GREEN BANK OBSERVATORY



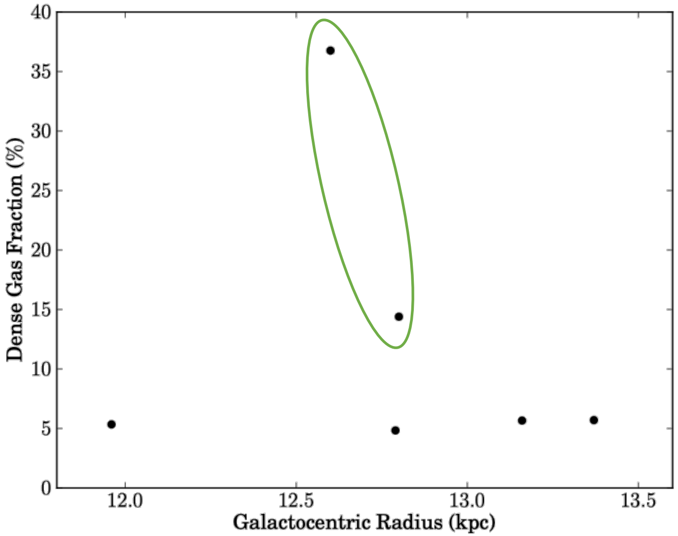
$\mathrm{Log}(N_{Ly}) = 48.3$ (O8)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.2$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.0$
$M_{Dense}/M_{mol} = 5.7\%$

$\mathrm{Log}(N_{Ly}) = 49.4$ (O4)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.0$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.5$
$M_{Dense}/M_{mol} = 36.8\%$

$\mathrm{Log}(N_{Ly}) = 49.2$ (O5.5)
$\mathrm{Log}(M_{Mol}/M_{\odot}) = 5.6$
$\mathrm{Log}(M_{Dense}/M_{\odot}) = 4.8$
$M_{Dense}/M_{mol} = 14.4\%$

GREEN BANK OBSERVATORY

Molecular Gas Maps of OSC HII Regions

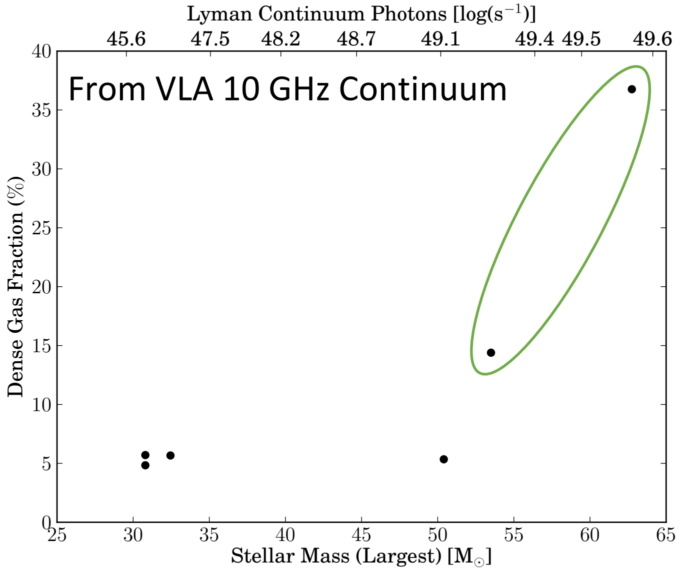


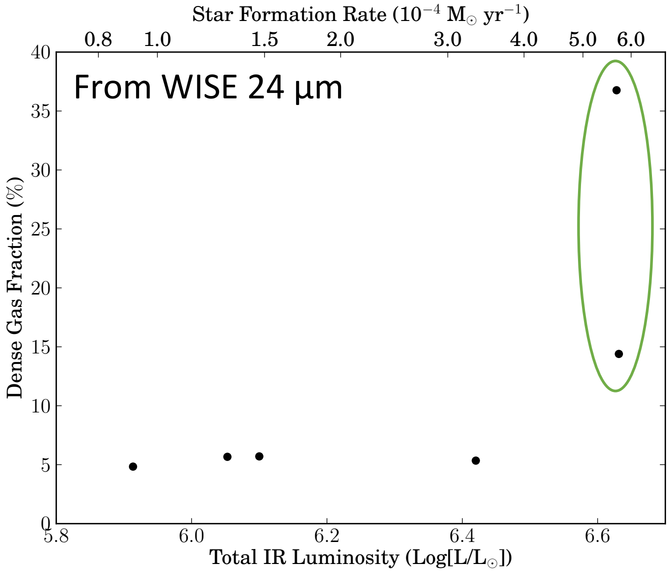
The outliers are actively star forming. These are our highest luminosity regions.

Most regions in our survey range have a dense gas fraction of 5%.

- Battisti & Heyer (2018) found typical dense gas fraction of 7% of Milky Way clouds.
- Jimenez-Donaire et al. (2019) found the dense gas fraction in EMPIRE galaxies decreased with R_{Gal}, out to their limit of 10 kpc.
- Our “average” cloud has a dense gas fraction of 5%, but it’s still a small sample.

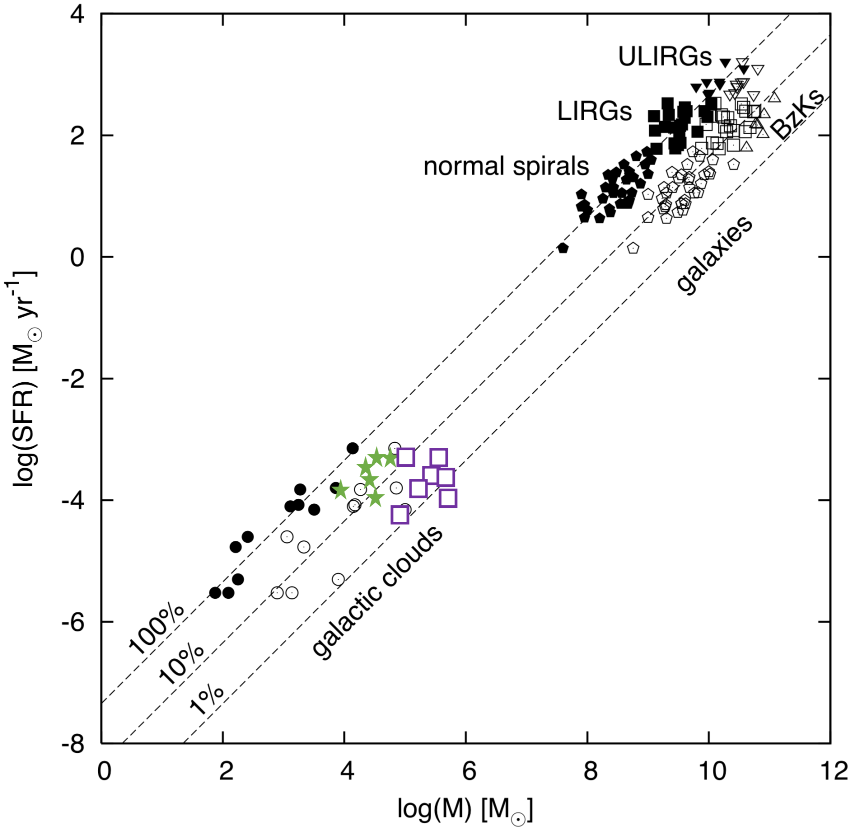
Molecular Gas Maps of OSC HII Regions





- Highest luminosity regions have higher dense gas fractions.
- The ionizing sources could be:
  - Stripping away the diffuse molecular gas, leaving dense, star forming cores intact
  - Heating the regions and exciting HCN (this has been seen in the centers of ULIRGS)

Molecular Gas Maps of OSC HII Regions



Gao and Solomon relationship reproduced from Lada et al. 2012

Green Stars –
Dense Gas, traced by HCN

Purple Squares –
Total Molecular Gas, traced by ^{13}CO

SFR calculated from *WISE* 24 μm (Cluver+ 2017) using the *WISE* Catalog of Galactic HII Regions (Anderson+ 2014)

Molecular masses from our ^{13}CO and HCN observations using Lada+ 2012 prescription

High-Mass Star Formation in the Far Outer Galaxy

Star formation in the outer Galaxy could be similar to that of a much younger Milky Way (or lower metallicity galaxies like the Large Magellanic Cloud). It can also serve as a pattern for star formation on the outskirts of nearby galaxies.

The OSC contains stellar types as early as O4, Molecular cloud masses ranging from 10^5 - 10^6 $M_\odot$. Dense gas tracers have been detected in all targets so far observed. *(Observations ongoing)*

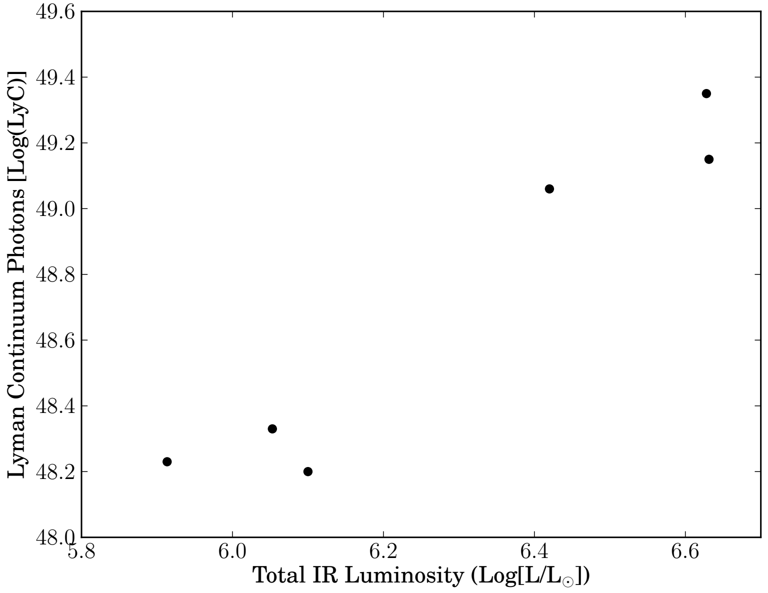
Dense gas ratio is flat beyond R_{Gal} = 10 kpc (5%), with the exception of the most active star forming regions (log[LyC] > 49), where the ratio was increased by a factor of ~7 (ratio of 37%).

Future Work: **(1)** Finish mapping dense gas from the OSC sample.
(2) Compare to representative inner Galaxy sample to trace radial trends.

Will Armentrout
warmentr@nrao.edu

Postdoctoral Fellow
Green Bank Observatory

Molecular Gas Maps of OSC HII Regions



Total infrared luminosity scales with 10 GHz radio continuum (thermal).

Deriving Underlying Stellar Population

$$L_\nu = 4\pi\ 10^{-26} \left[\frac{D}{\mathrm{m}}\right]^2 \left[\frac{S_{int}}{\mathrm{Jy}}\right] [\mathrm{W\ Hz^{-1}}] \qquad (3)$$

$$N_{Ly} = 6.3\times10^{52} \left[\frac{T_e}{10^4\ \mathrm{K}}\right]^{-0.45} \left[\frac{\nu}{\mathrm{GHz}}\right]^{0.1} \left[\frac{L_\nu}{10^{20}\ \mathrm{W\ Hz^{-1}}}\right] [\mathrm{s^{-1}}] \qquad (4)$$

Table 4. Single-Star H II Region Parameters

Spectral Type	$\mathrm{Log_{10}(N_{Ly})}$ ($\mathrm{s^{-1}}$) Smith	Martins	Spectral Type	$\mathrm{Log_{10}(N_{Ly})}$ ($\mathrm{s^{-1}}$) Smith	Martins
B1.5	**46.10**	–	O7.5	48.70	**48.44**
B1	**46.50**	–	O7	49.00	**48.63**
B0.5	**47.00**	–	O6.5	–	**48.80**
B0	**47.40**	–	O6	–	**48.96**
O9.5	–	**47.56**	O5.5	–	**49.11**
O9	47.90	**47.90**	O5	49.20	**49.26**
O8.5	–	**48.10**	O4	49.40	**49.47**
O8	48.50	**48.29**	O3	49.50	**49.63**

Armentrout et al. (2017)

Balser 2011 – Metallicity Structure of Milky Way

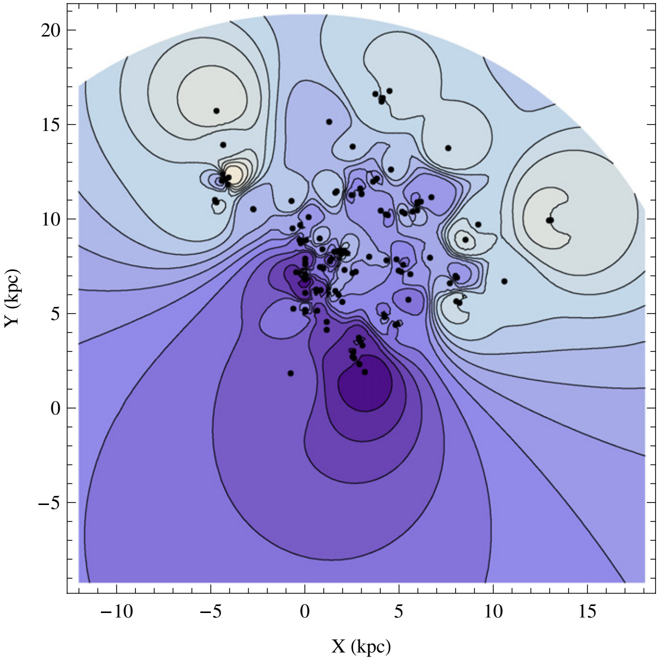


Figure 7. Image of the Galactic distribution of nebular electron temperatures produced from the discrete H II regions located between Galactic azimuth 330° and 60° for the Green Bank Sample (110 sources). The image was generated by using Shepard's method with $\alpha = 5$ (see the text). The contours range between 6400 and 11,200 K at intervals of 400 K. The darker shades are lower temperatures. The orientation is the same as in Figure 1 with the Galactic Center located at ($x = 0$, $y = 0$) and the Sun at 8.5 kpc above the Galactic Center at zero azimuth. The points indicate the location of the discrete H II regions.

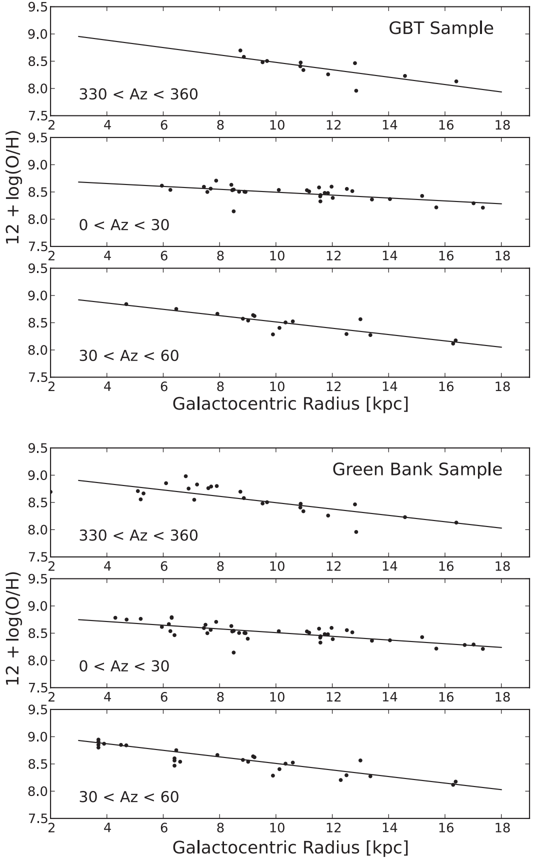
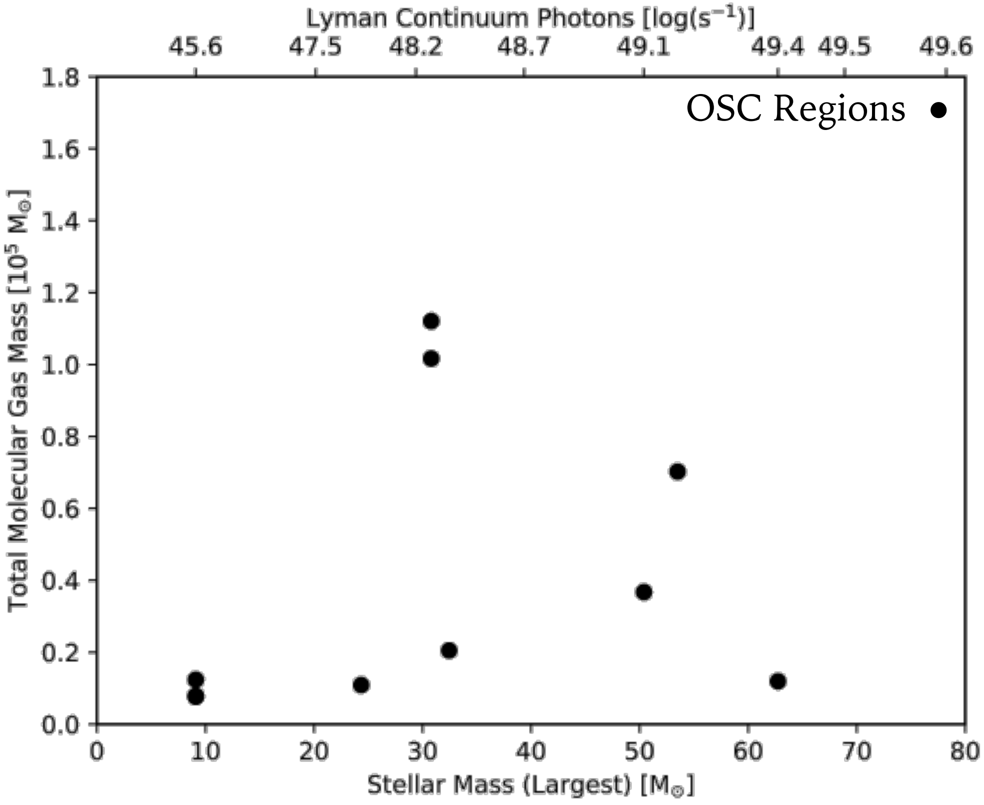


Figure 8. O/H abundance ratio radial gradient for the GBT Sample (top) and the Green Bank Sample (bottom). Only quality factor values of C and better for both line and continuum data are included. The solid lines are linear least-squares fits to the data. Top panel: $330° < Az < 360°$. Middle panel: $0° < Az < 30°$. Bottom panel: $30° < Az < 60°$.

Molecular Gas Maps of OSC HII Regions



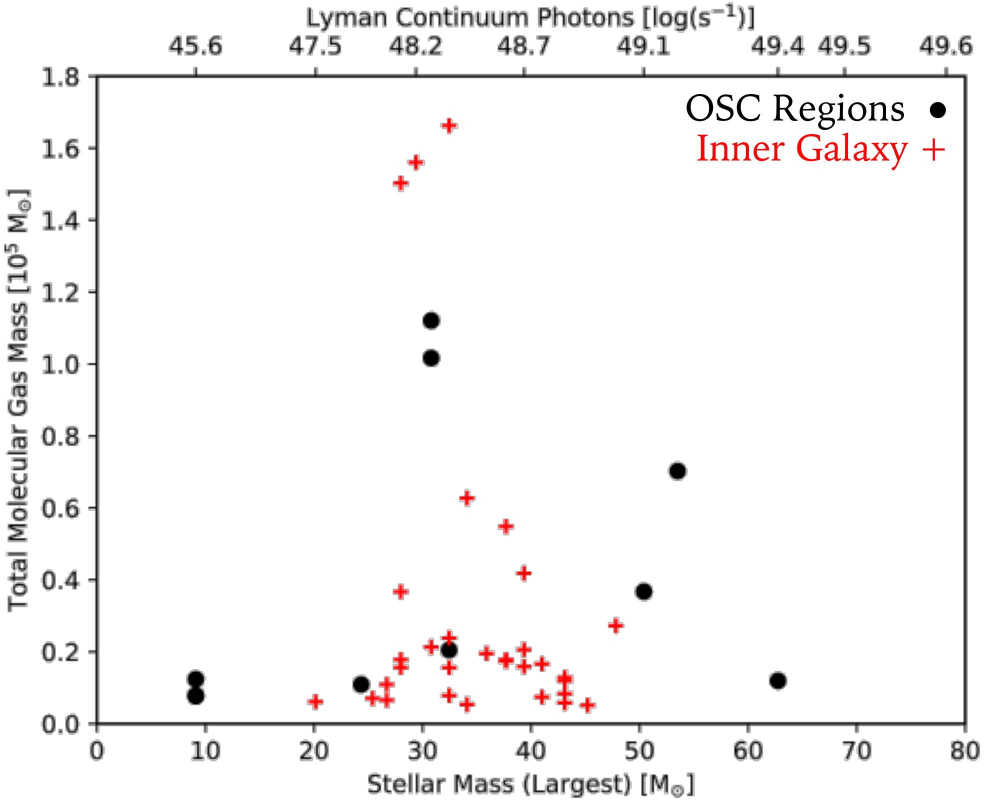
X-Axis : Lyman Continuum Photons / Stellar Mass from VLA radio continuum observations

Y-Axis : Total Molecular Gas Mass from GBT ^{13}CO observations

$X_{13CO} = 10 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$

OSC Molecular gas mass is likely an underestimate, since X_{CO} should be higher in outer Galaxy (with lower metallicity)

Molecular Gas Maps of OSC HII Regions



X-Axis : Lyman Continuum Photons / Stellar Mass from VLA radio continuum observations

Y-Axis : Total Molecular Gas Mass from GBT ^{13}CO observations

$X_{13CO} = 10 \times 10^{20}\ cm^{-2}\ (K\ km\ s^{-1})^{-1}$

OSC Molecular gas mass is likely an underestimate, since X_{CO} should be higher in outer Galaxy (with lower metallicity)

Inner Galaxy sample from Anderson+ 2008 using BU-FCRAO Galactic Ring Survey