

The Origin of [CII] 158 μ m Emission toward the HII Region Complex S235

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Although the 2P_{3/2}-2P_{1/2} transition of [CII] at 158um is known to be an excellent tracer of active star formation, we still do not have a complete understanding of where within star formation regions the emission originates. Here, we use SOFIA upGREAT observations of [CII] emission toward the HII region complex Sh2-235 (S235) to better understand in detail the origin of [CII] emission. We complement these data with a fully-sampled Green Bank Telescope radio recombination line map tracing the ionized hydrogen gas. About half of the total [CII] emission associated with S235 is spatially coincident with ionized hydrogen gas, although spectroscopic analysis shows little evidence that this emission is coming from the ionized hydrogen volume. Velocity-integrated [CII] intensity is strongly correlated with WISE 12um intensity across the entire complex, indicating that both trace ultra-violet radiation fields. The 22um and radio continuum intensities are only correlated with [CII] intensity in the ionized hydrogen portion of the S235 region and the correlations between the [CII] and molecular gas tracers are poor across the region. We find similar results for emission averaged over a sample of external galaxies, although the strength of the correlations is weaker. Therefore, although many tracers are correlated with the strength of [CII] emission, only WISE 12um emission is correlated on small-scales of the individual HII region S235 and also has a decent correlation at the scale of entire galaxies. Future studies of a larger sample of Galactic HII regions would help to determine whether these results are truly representative.

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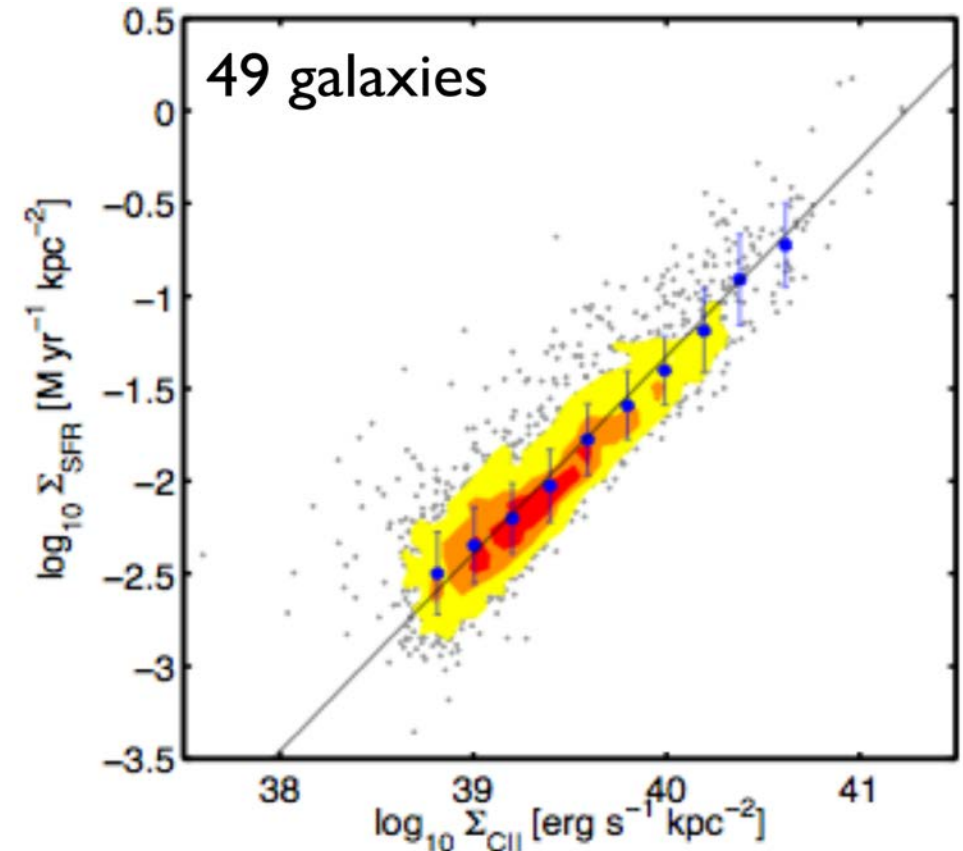
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Motivation

- [CII] $^2P_{3/2} - ^2P_{1/2}$ 158 μm emission known to be a good star formation tracer, but we do not understand in detail *why*
 - Over what spatial scales do the correlations between [CII] and other star formation tracers hold?
- [CII] is the most important cooling line in the Milky Way, and provides 0.1-1% of the total far-infrared emission from galaxies
- [CII] requires a radiation field that can ionize carbon (ionization potential 11.3eV)

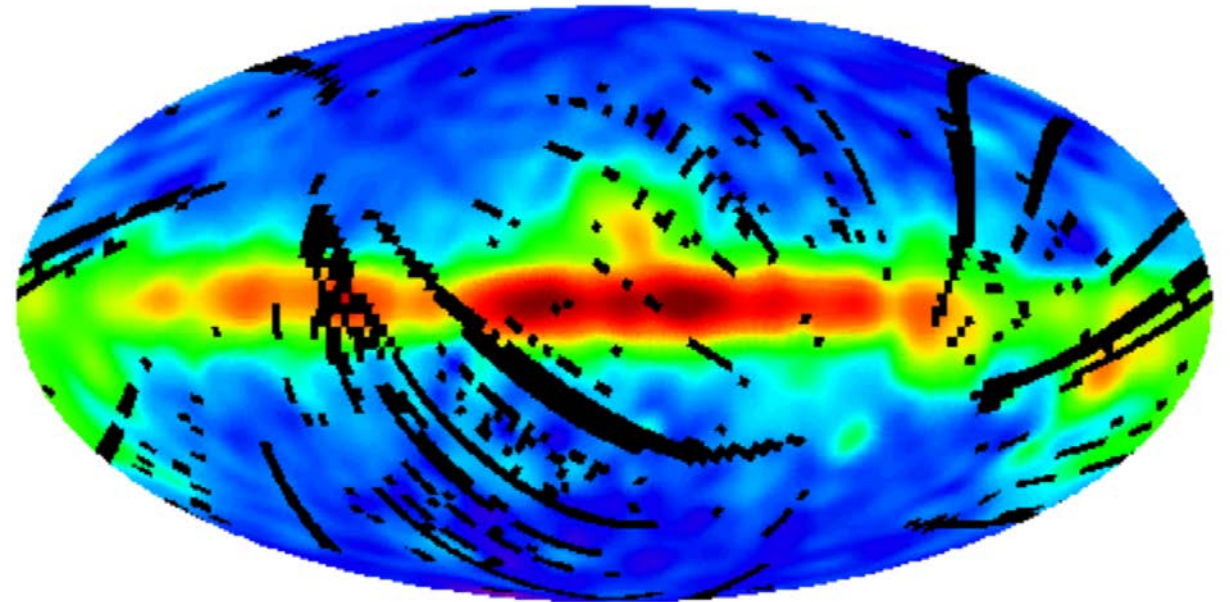


Herrera-Camus et al. (2015)

Large-Scale Distribution of [CII]

- [CII] largely confined to the Galactic plane
 - WIM? (Heiles et al., 1994)
 - CNM? (Bennett et al., 1994)
 - PDRs? (Cubick et al., 2008)
 - What combination?

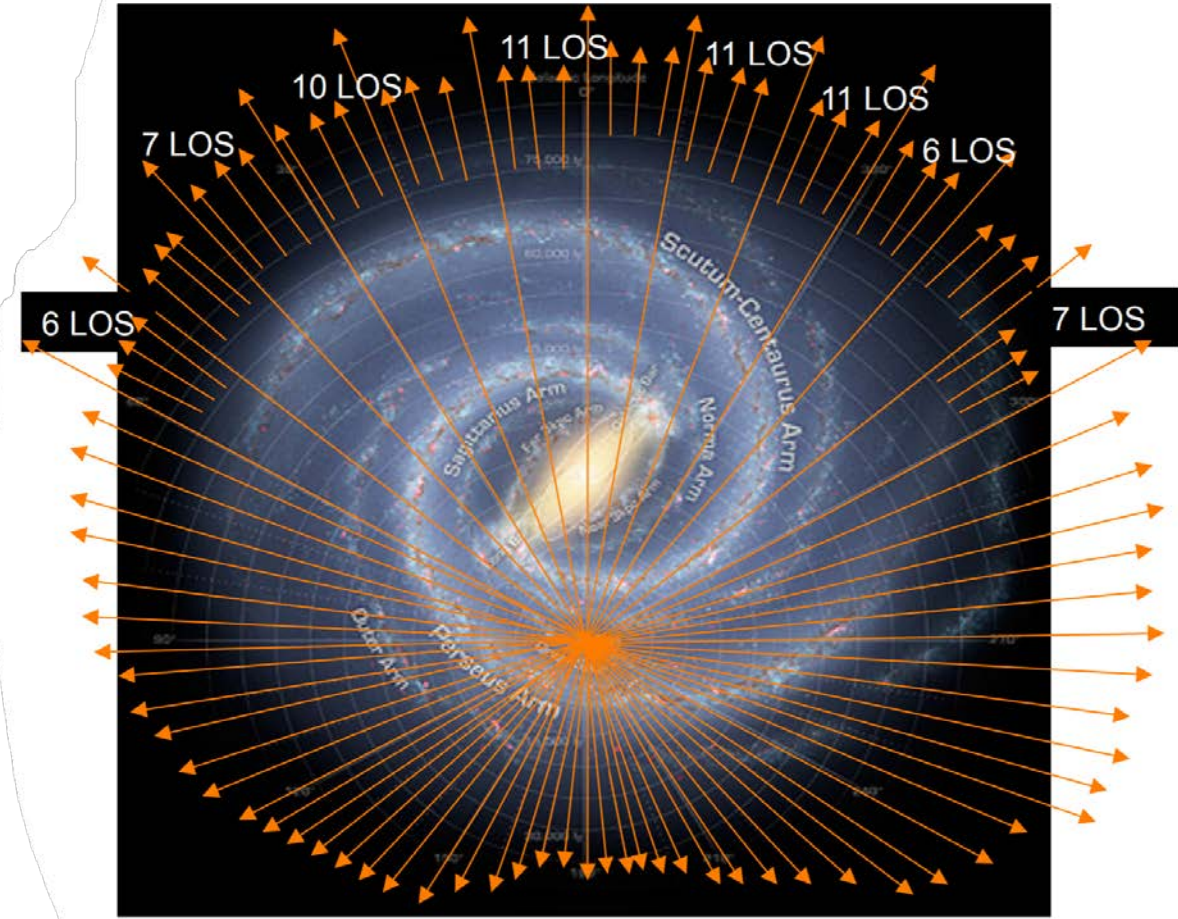
COBE FIRAS 158 μm C⁺ Line Intensity



7 deg angular resolution; 1000 km/sec velocity resolution

Herschel HiFi Got C+ Survey

- Sparsely-sampled [CII] survey in the Galactic plane
- [CII] emission is mostly associated with spiral arms, tracing the envelopes of evolved clouds as well as clouds in the transition between atomic and molecular
- PDRs contribute 47% of the observed emissivity at $b=0$, CNM 20%, ionized gas 4%, and CO-dark H_2 29%



What do individual Star Forming Regions Tell Us?

- Pabst et al. (2017, 2019); study of Orion B
- Goicoechea et al. (2015); study of OMC1 in Orion
- Graf et al. (2012); study of NGC2024 in Orion B

- Tiwari et al. (2018); study of M8 (Trifid Nebula)

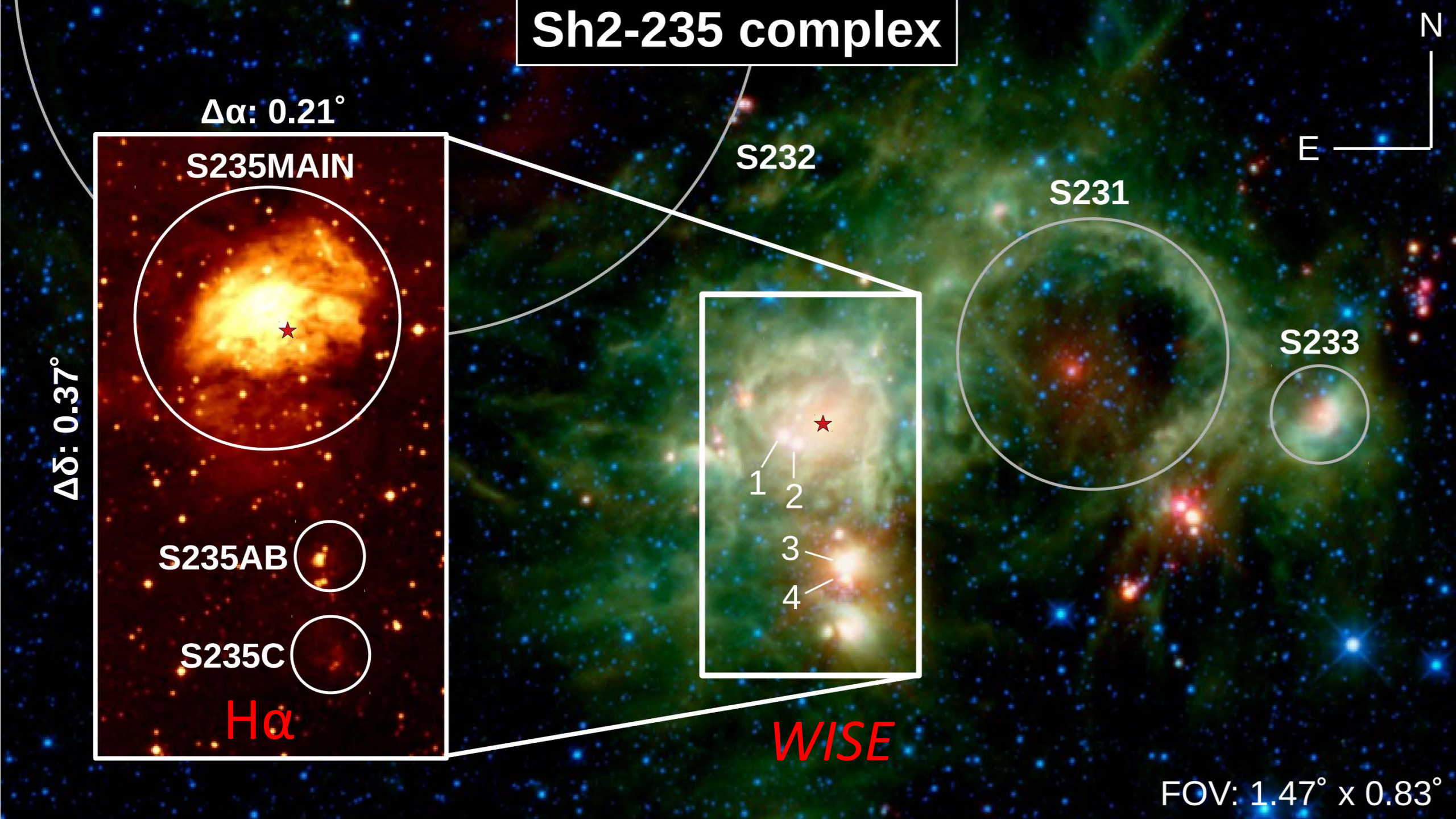
- Schneider et al. (2018), Simon et al. (2012); study of Sharpless 106

These studies support [CII] emission arising from photodissociation regions (PDRs) around HII regions

Motivation for S235

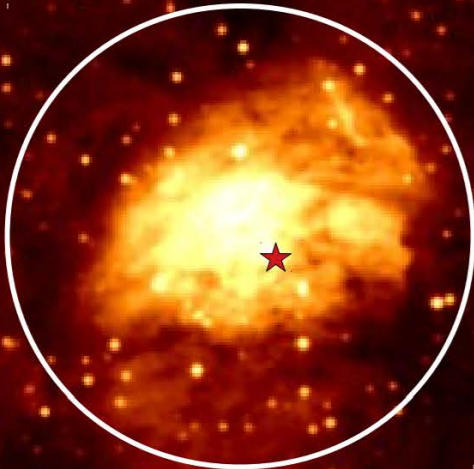
- The detailed study of one typical HII region complex may help us to understand the origin of [CII] emission
- The Sharpless 235 region is a good target because it is angularly large but not too large to map ($\sim 10'$), nearby, and bright, but otherwise is a typical Galactic HII region
 - Should be representative of the overall Galactic HII region population
 - Has two younger associated HII regions, and so can begin to examine age-effects to the relationships

Sh2-235 complex



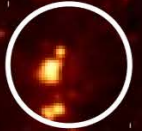
$\Delta\alpha: 0.21^\circ$

S235MAIN



$\Delta\delta: 0.37^\circ$

S235AB



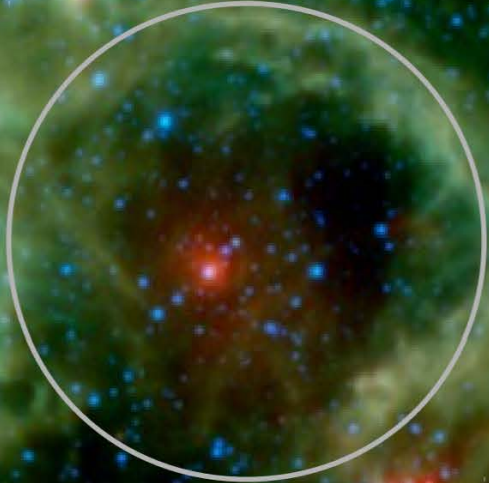
S235C



H α

S232

S231



S233



- 1
- 2
- 3
- 4

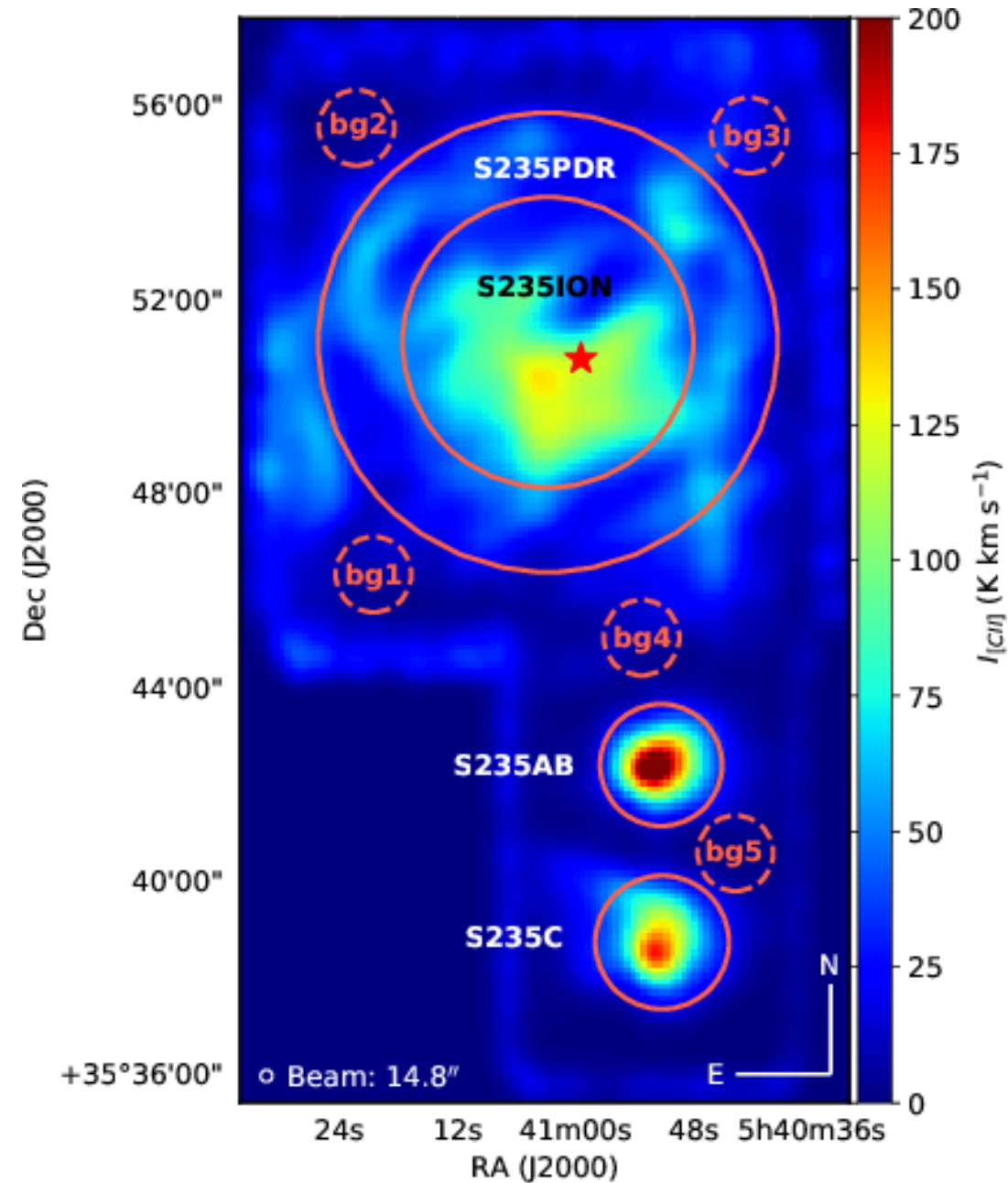
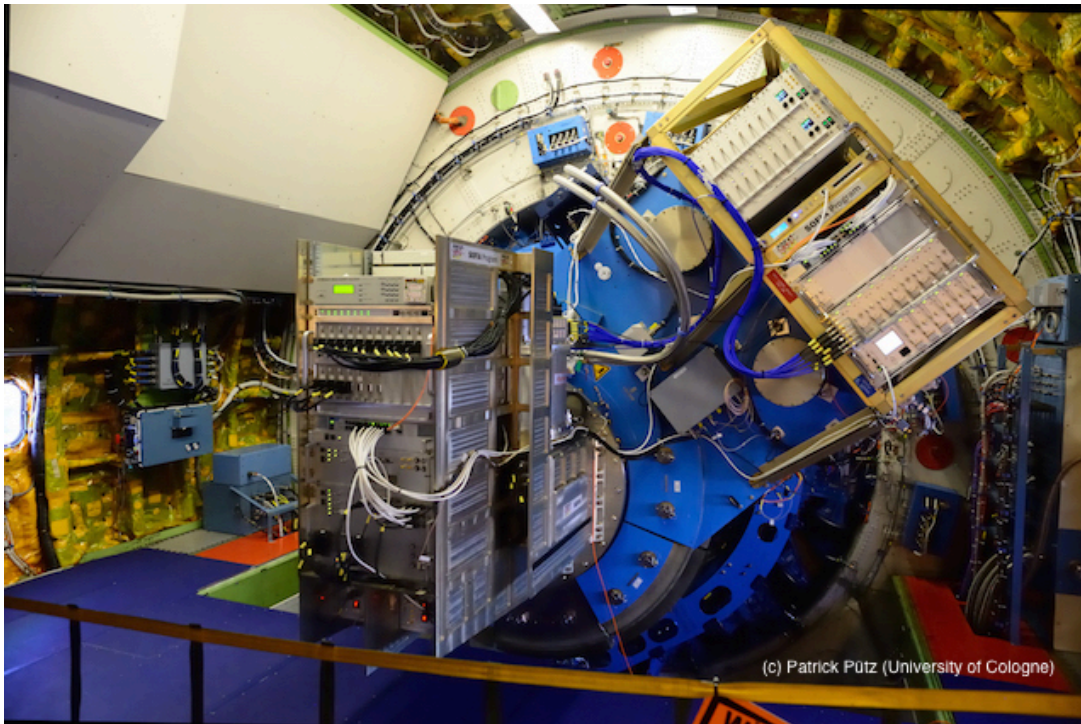
WISE

FOV: 1.47° x 0.83°

SOFIA [CII] Data

158 μm [CII] OTF Map, 15'' resolution

Single-pixel 205 μm [NII] map over same area



Ancillary Data: WISE

12 μm (left)

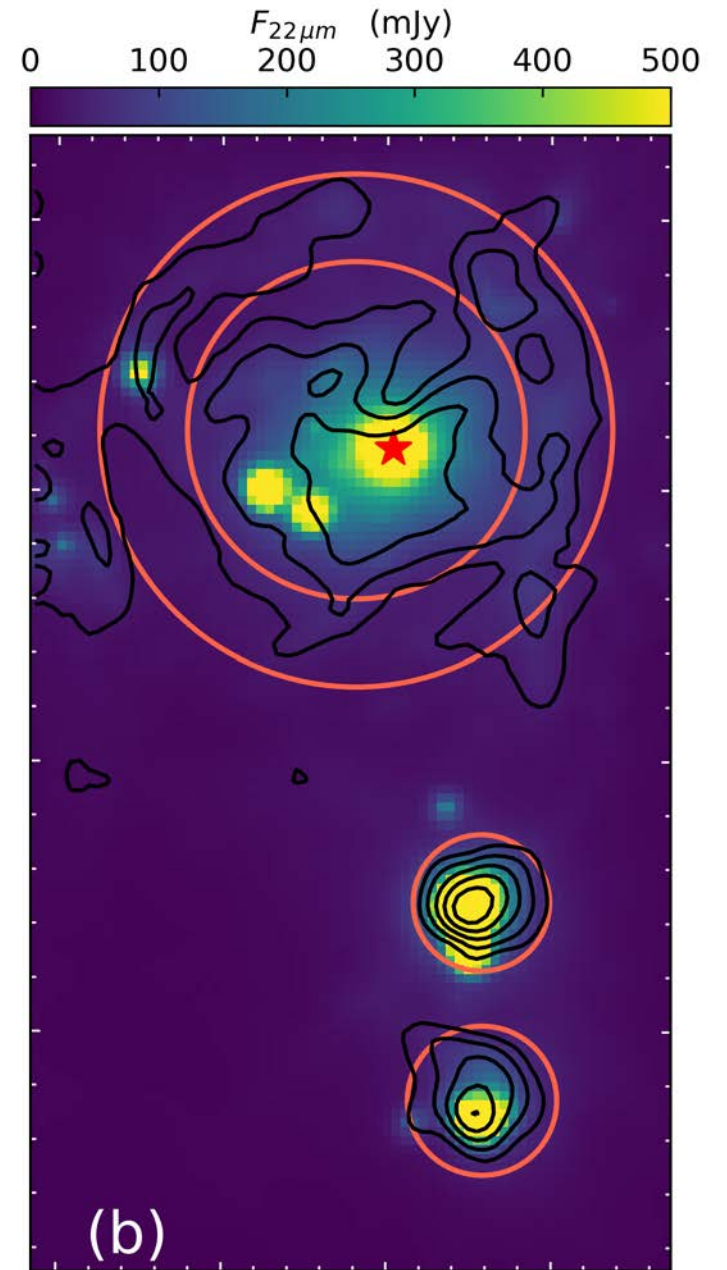
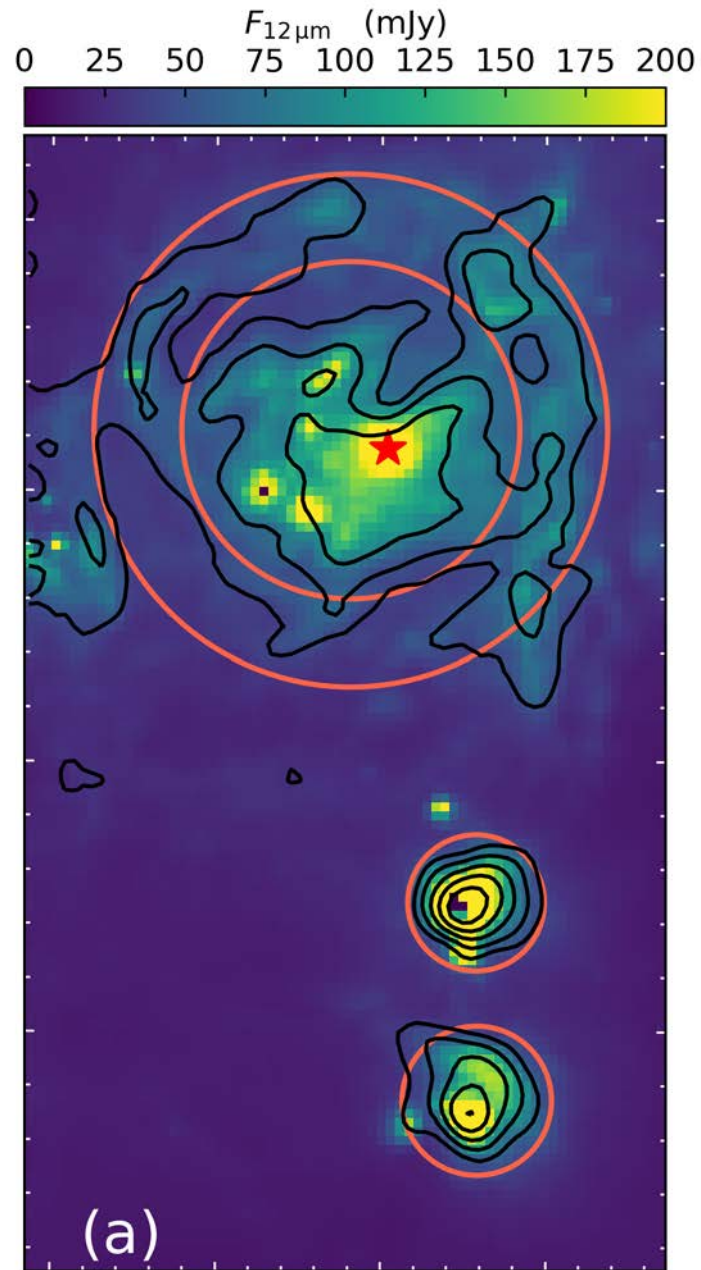
22 μm (right)

6'' resolution (12 μm)

12'' resolution (22 μm)

Traces PAH (12 μm) and
hot dust (22 μm)

Contours are [CII]
integrated Intensity

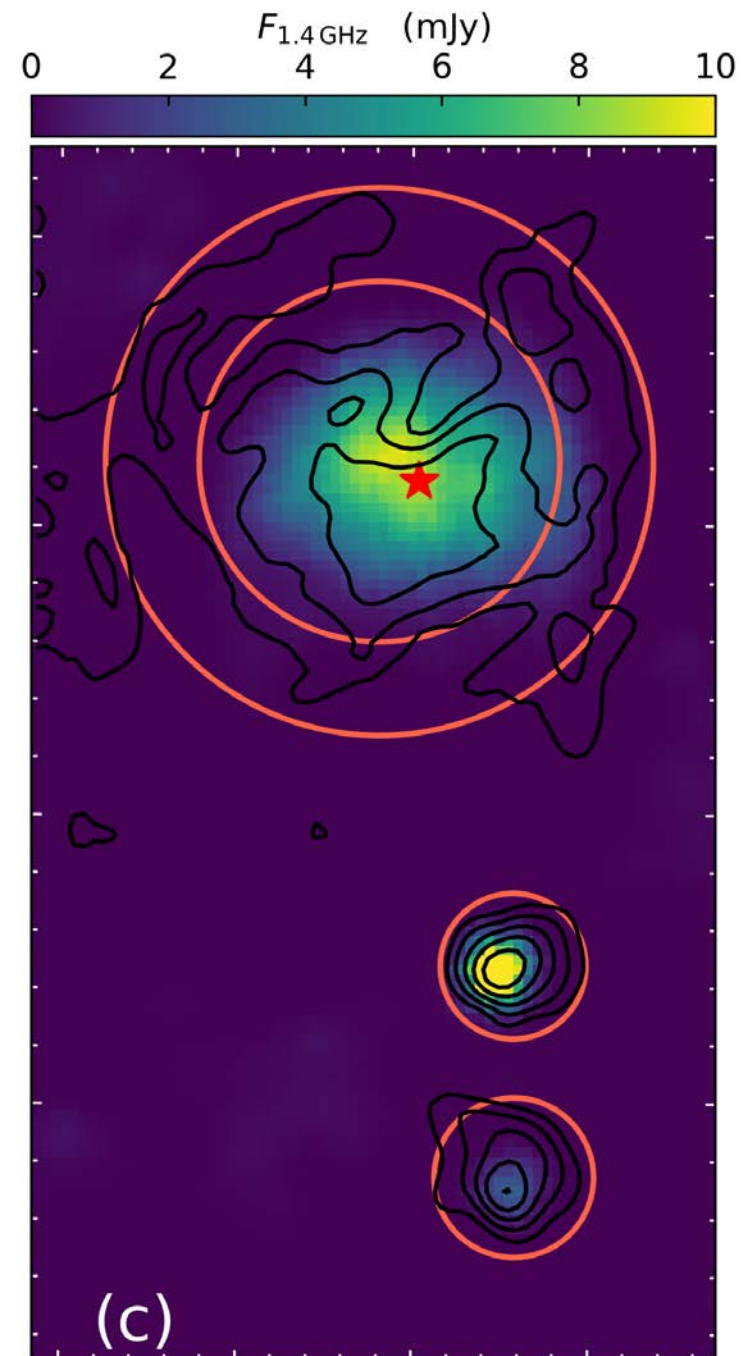


Ancillary Data:

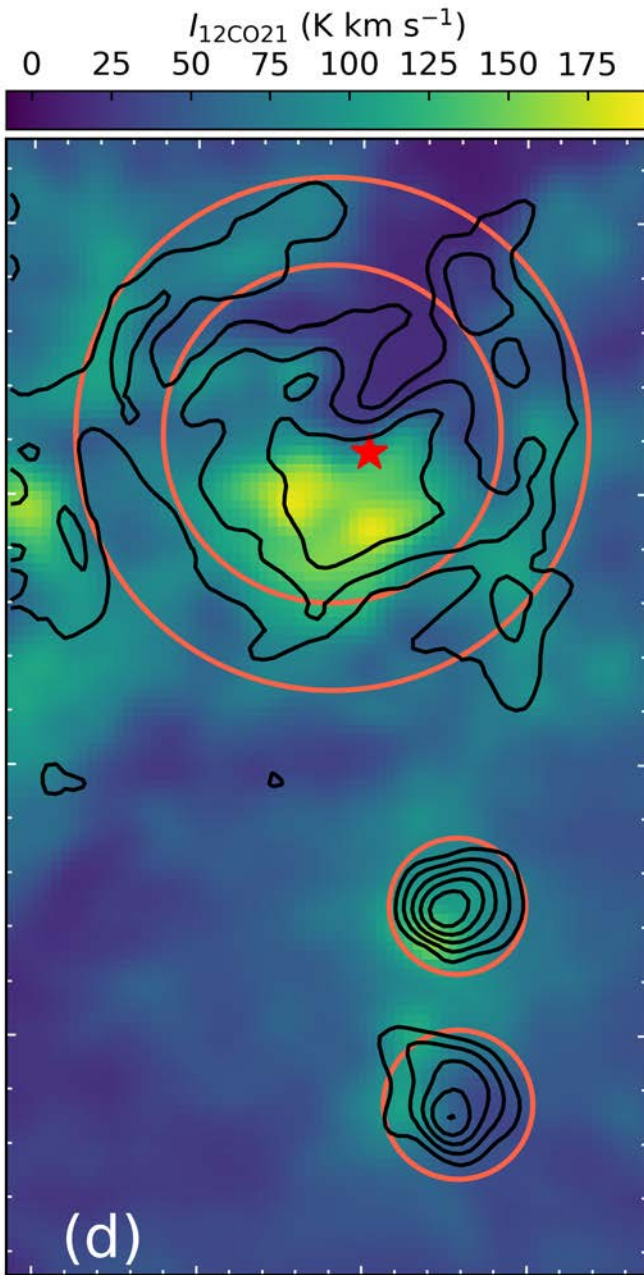
NVSS 1.4 GHz continuum

45'' resolution. Does not
recover all extended emission

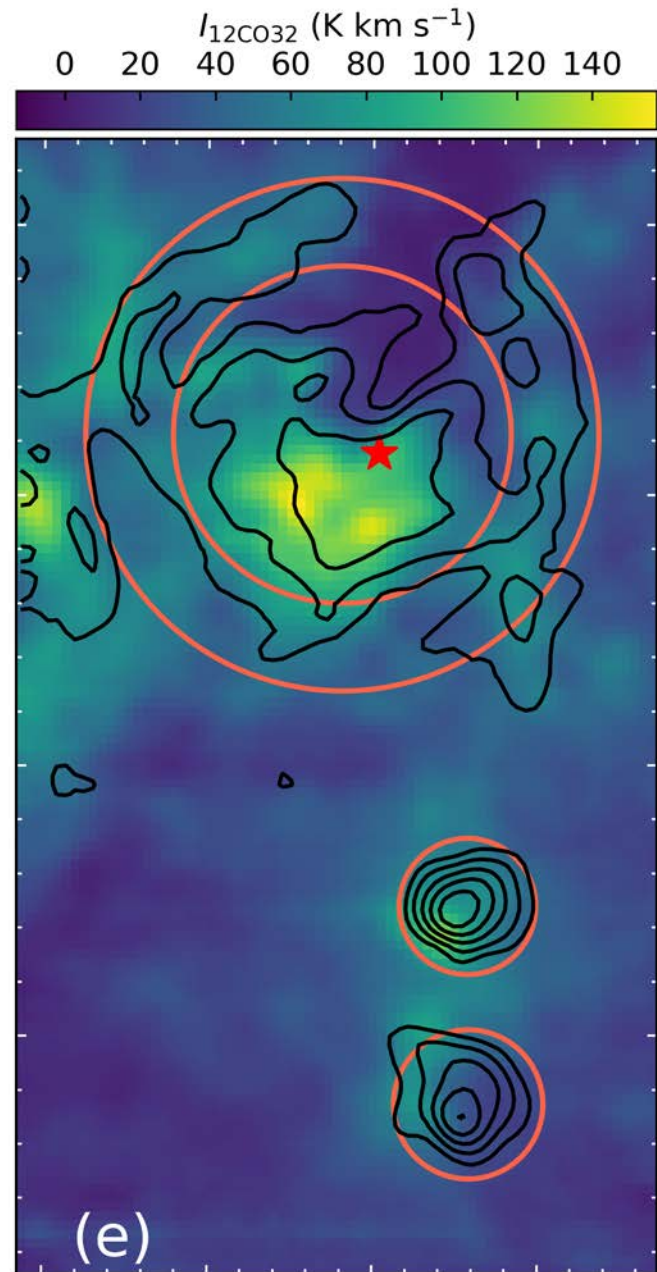
Traces free-free emission from
the plasma



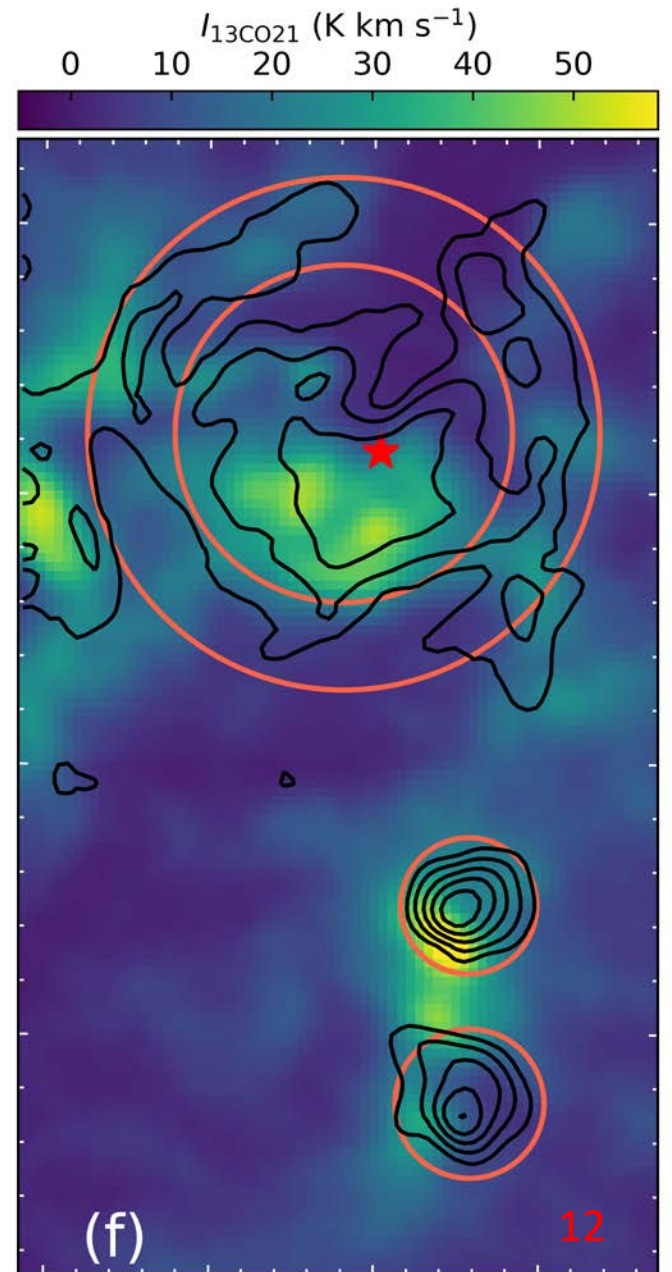
Ancillary Data: ^{12}CO 2-1



^{12}CO 3-2



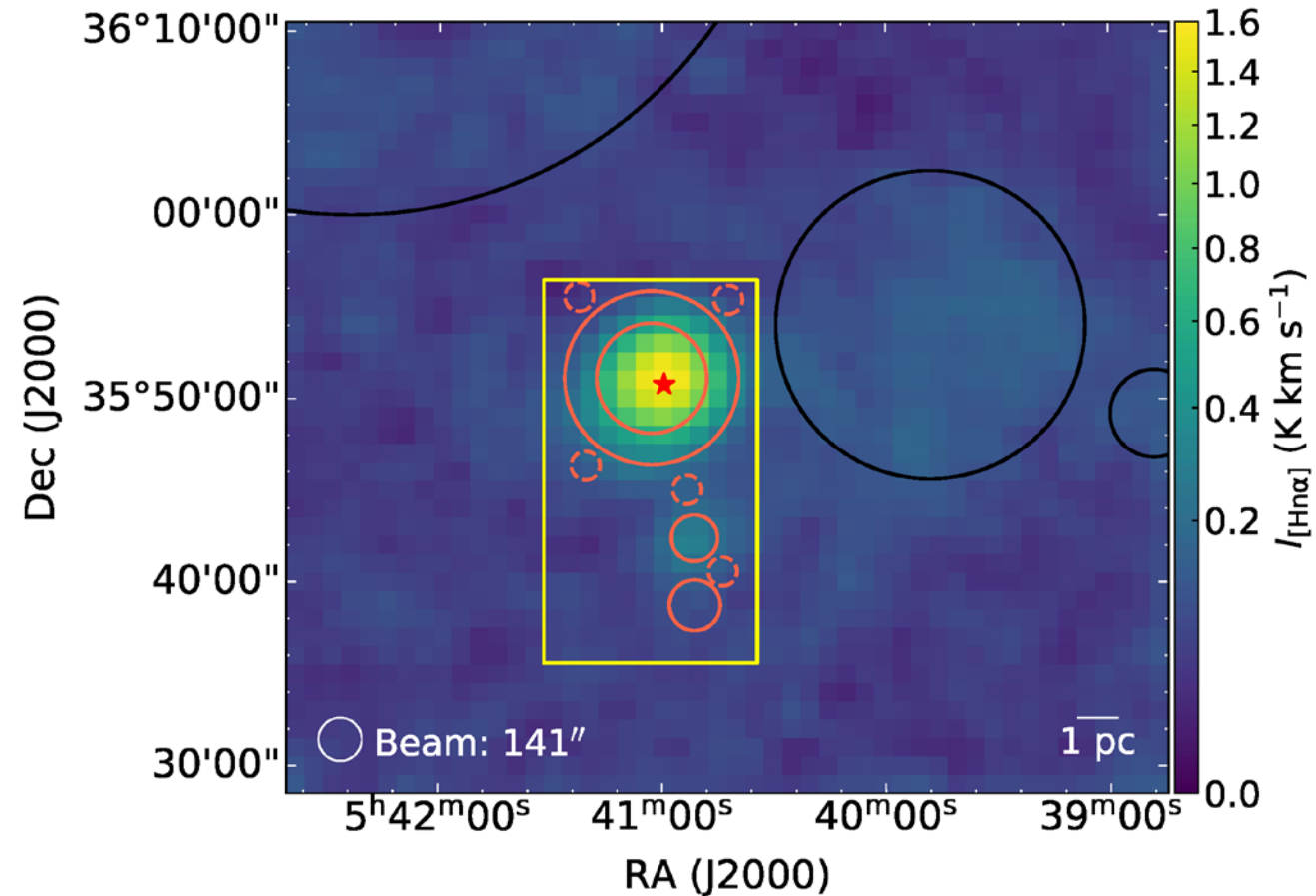
^{13}CO 2-1 (Bieging et al., 2016)



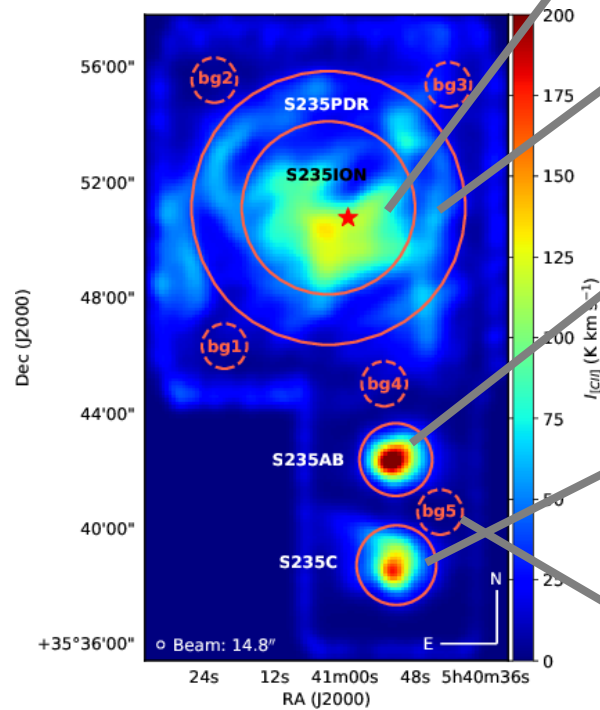
Green Bank Telescope Radio Recombination Lines (RRLs)

Resolution $\sim 2'$

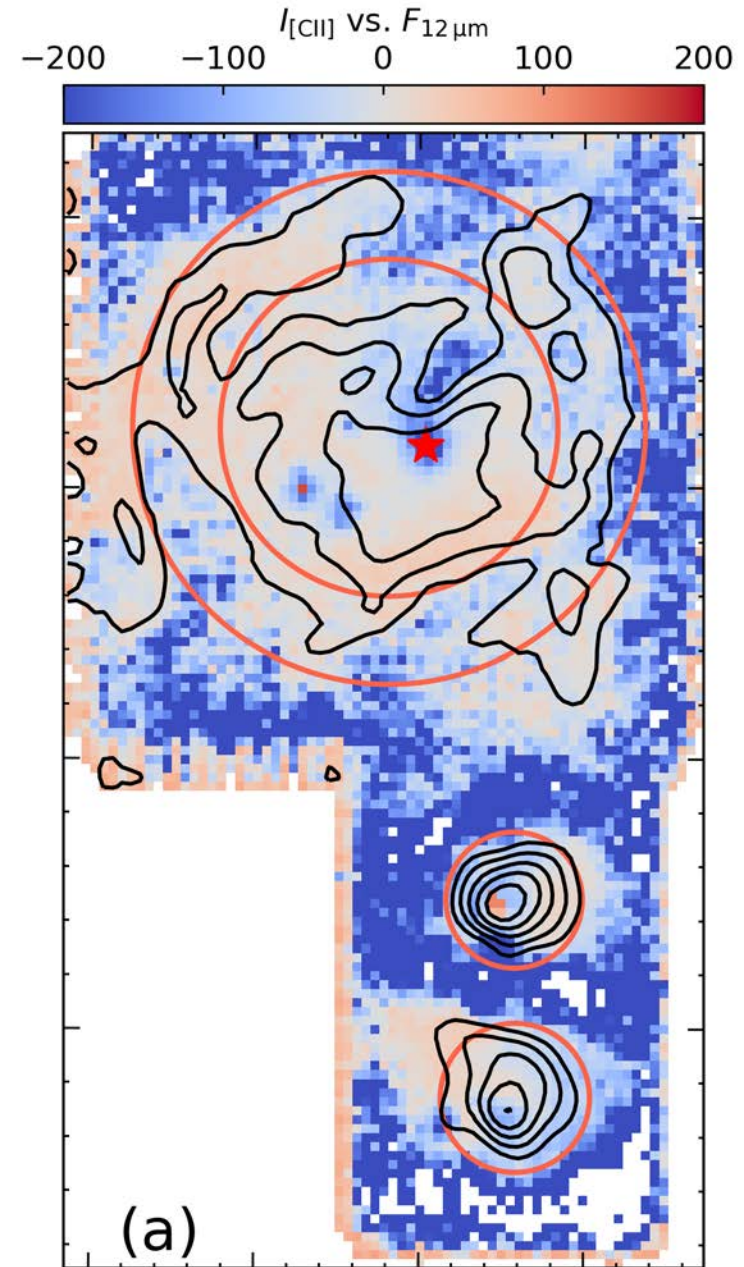
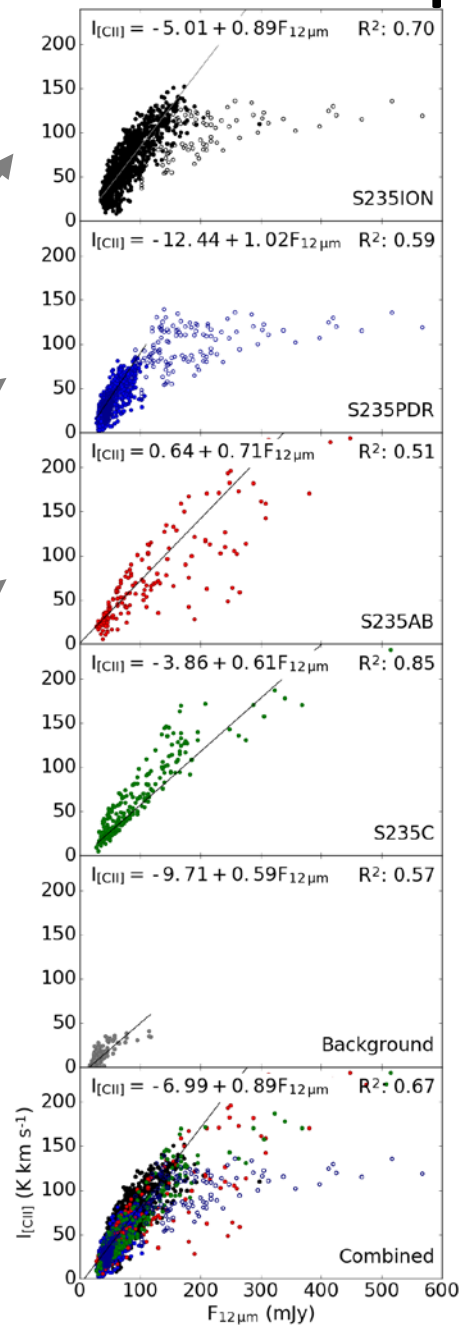
Primarily traces ionized
Hydrogen, but also detects
ionized carbon



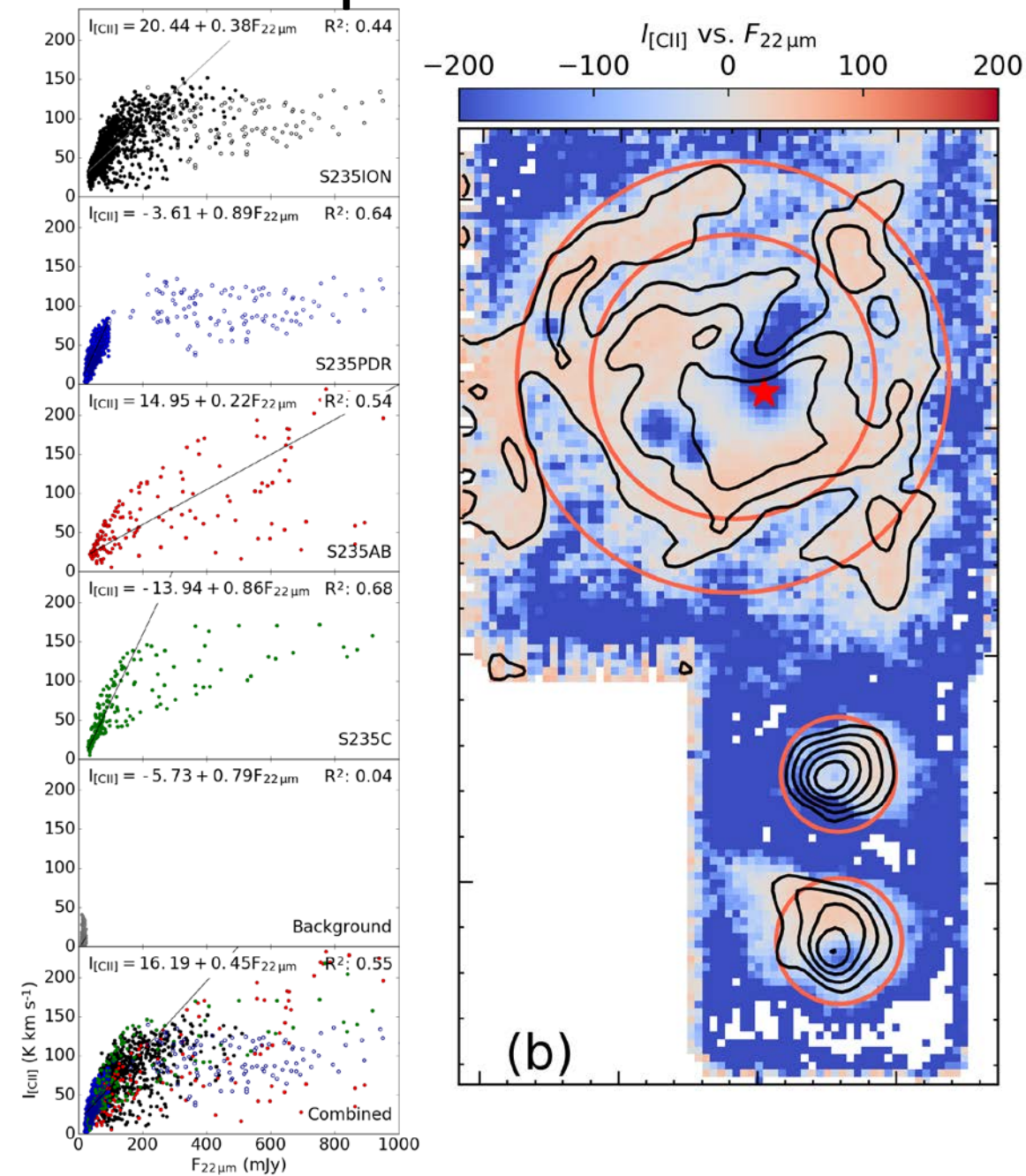
Pixel-by-pixel correlation plots and ratio maps



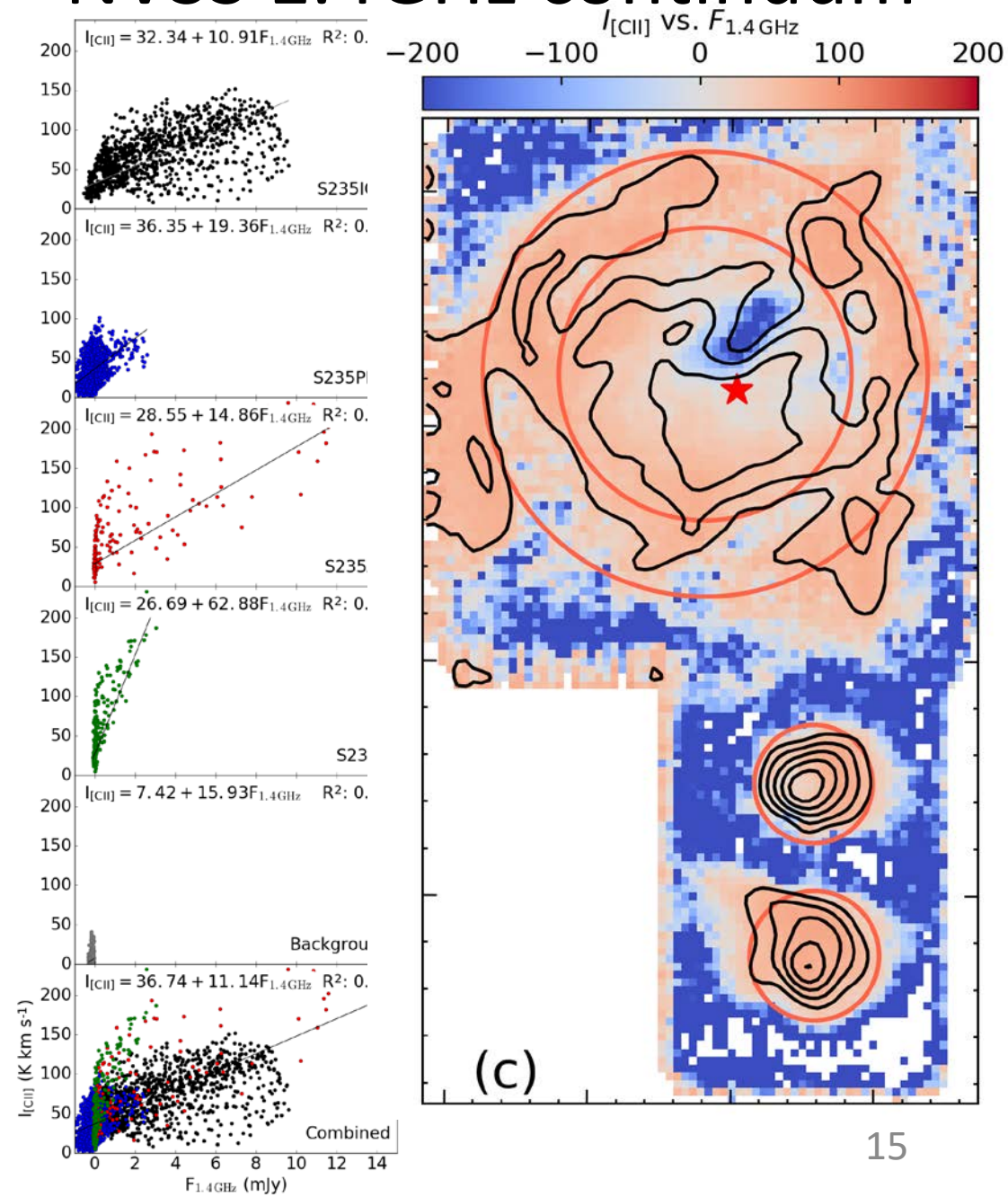
WISE 12 μm



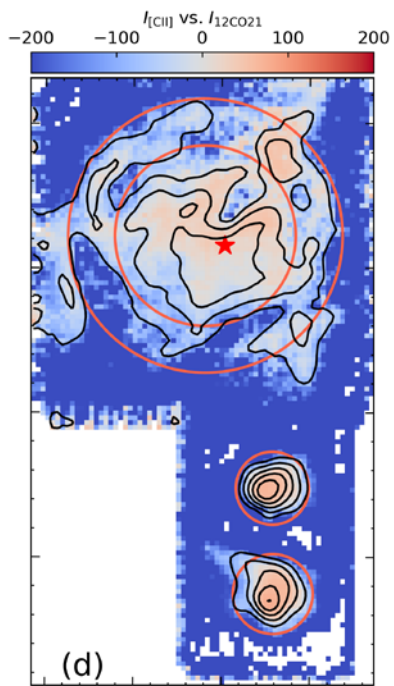
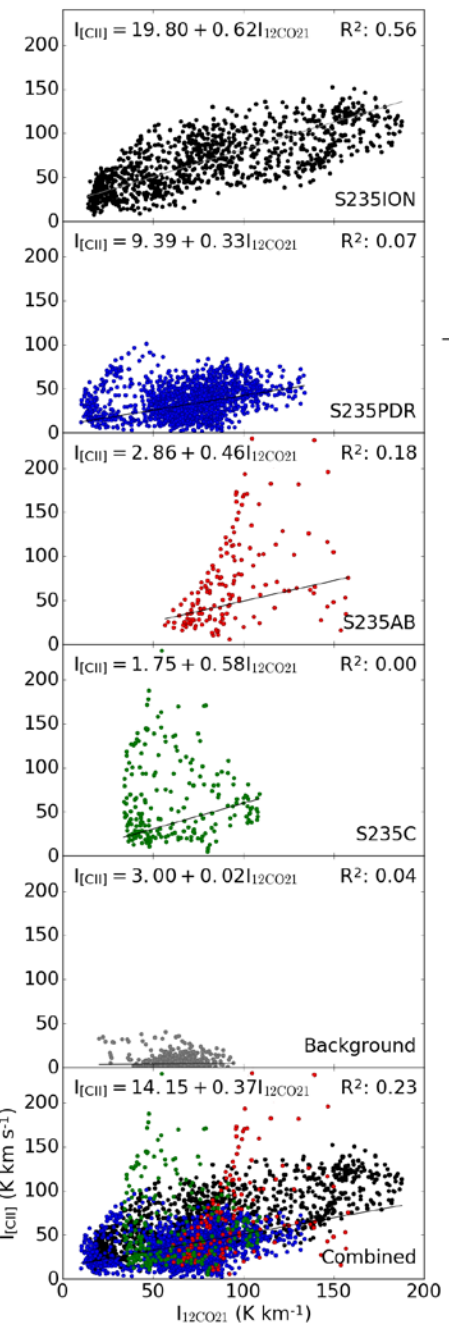
WISE 22 μ m



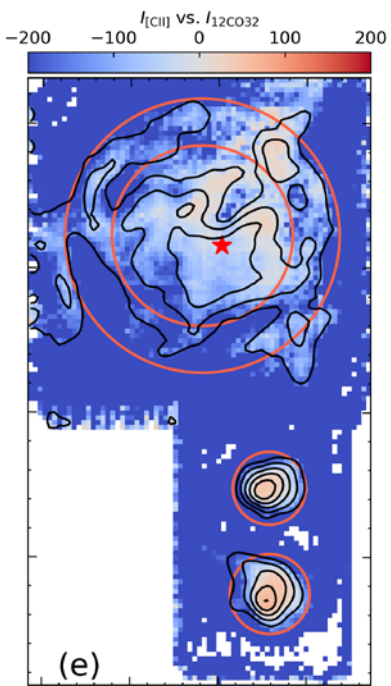
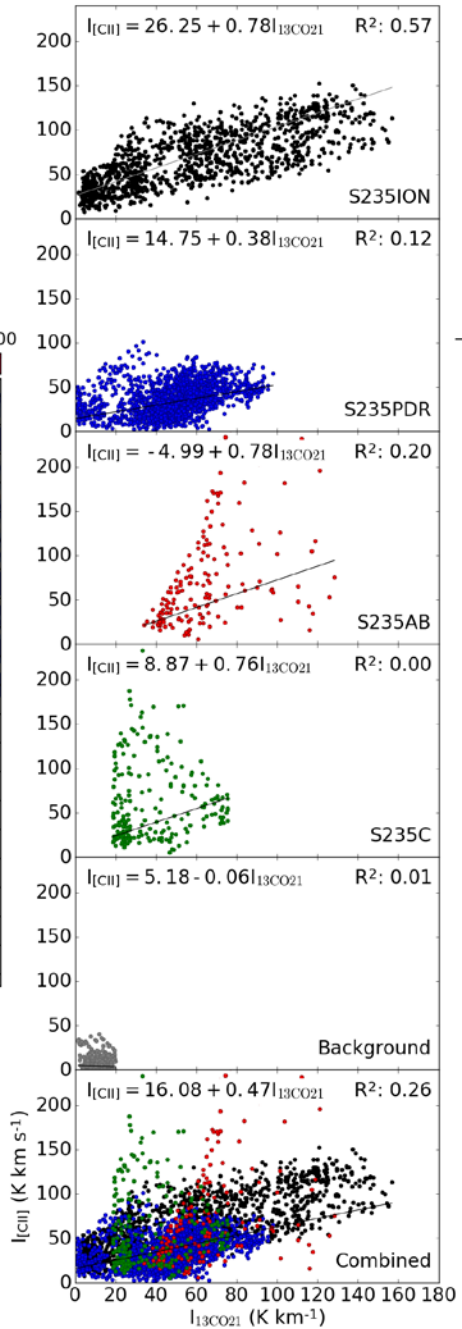
NVSS 1.4GHz continuum



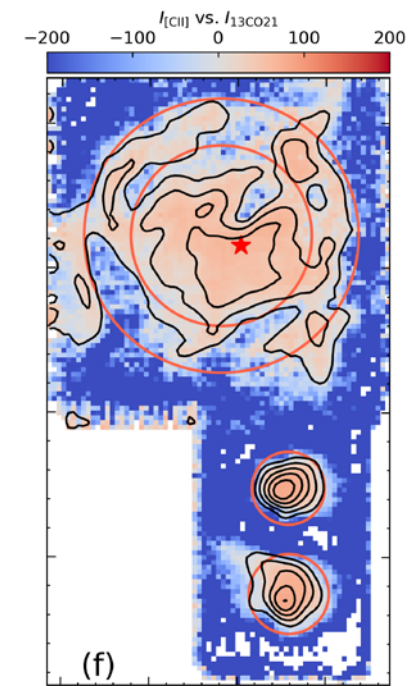
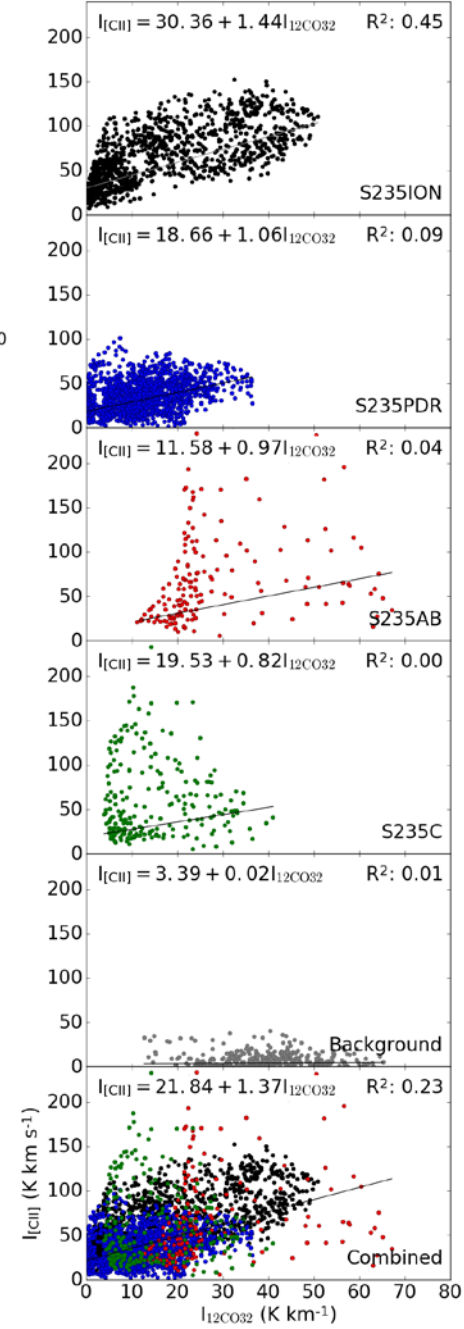
^{12}CO 2-1



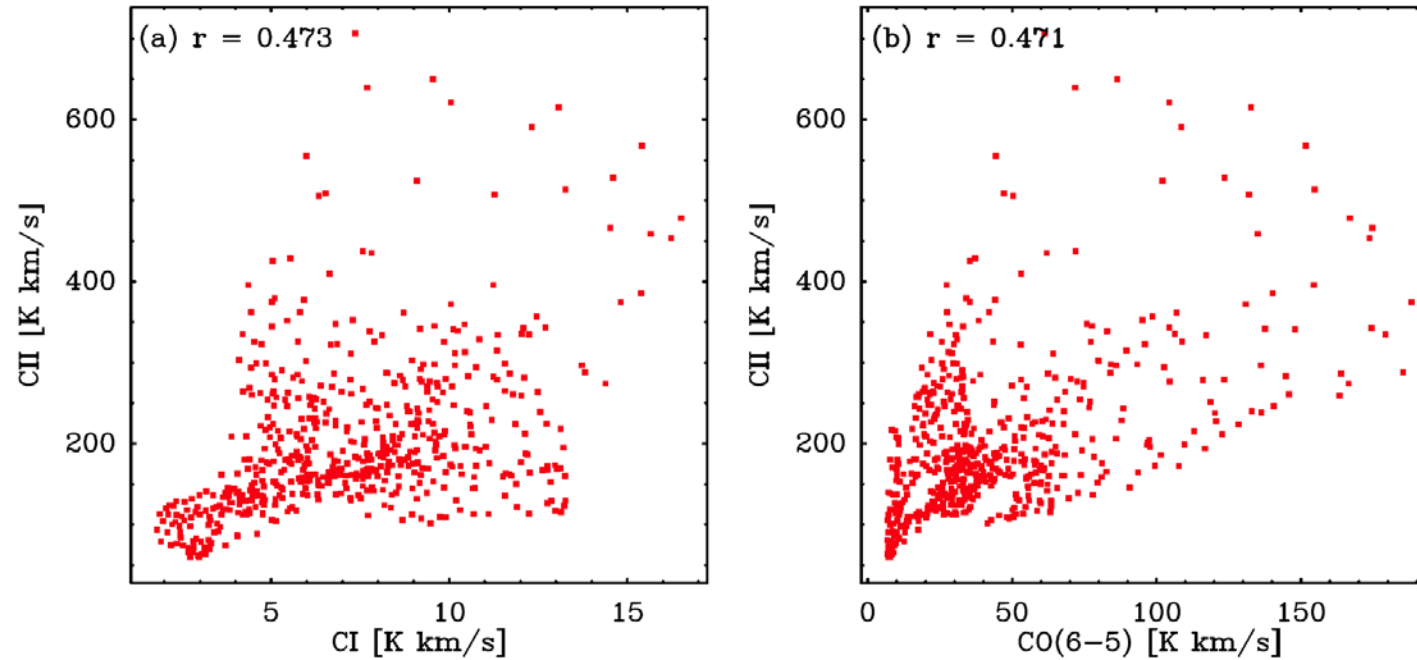
^{13}CO 2-1



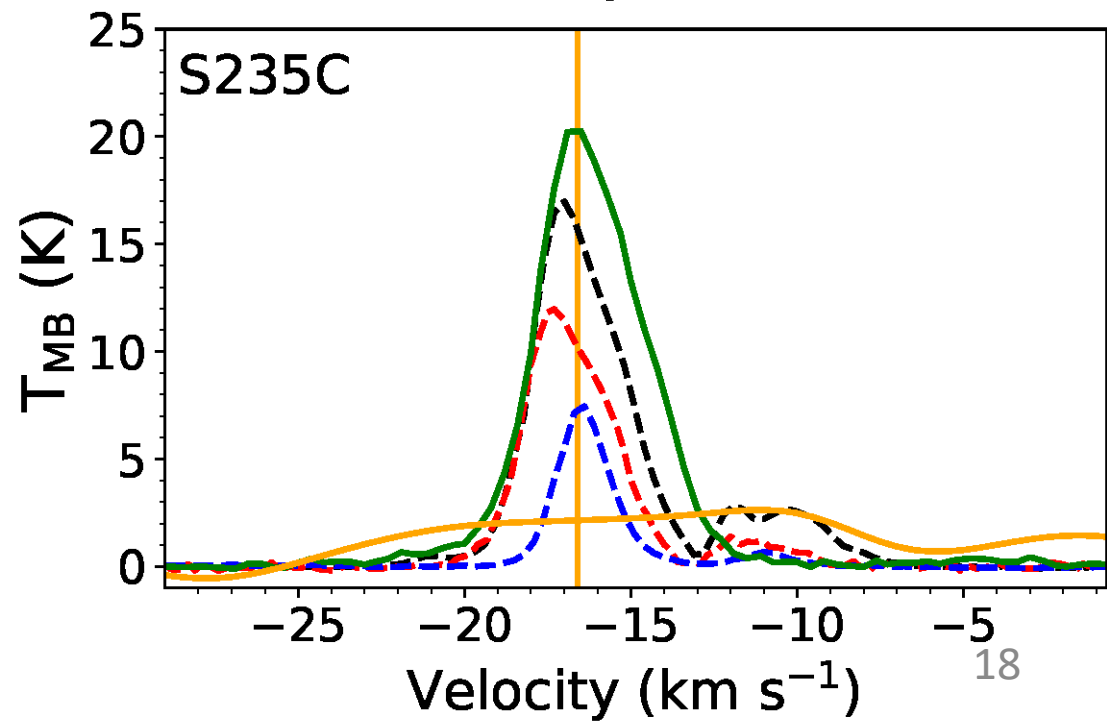
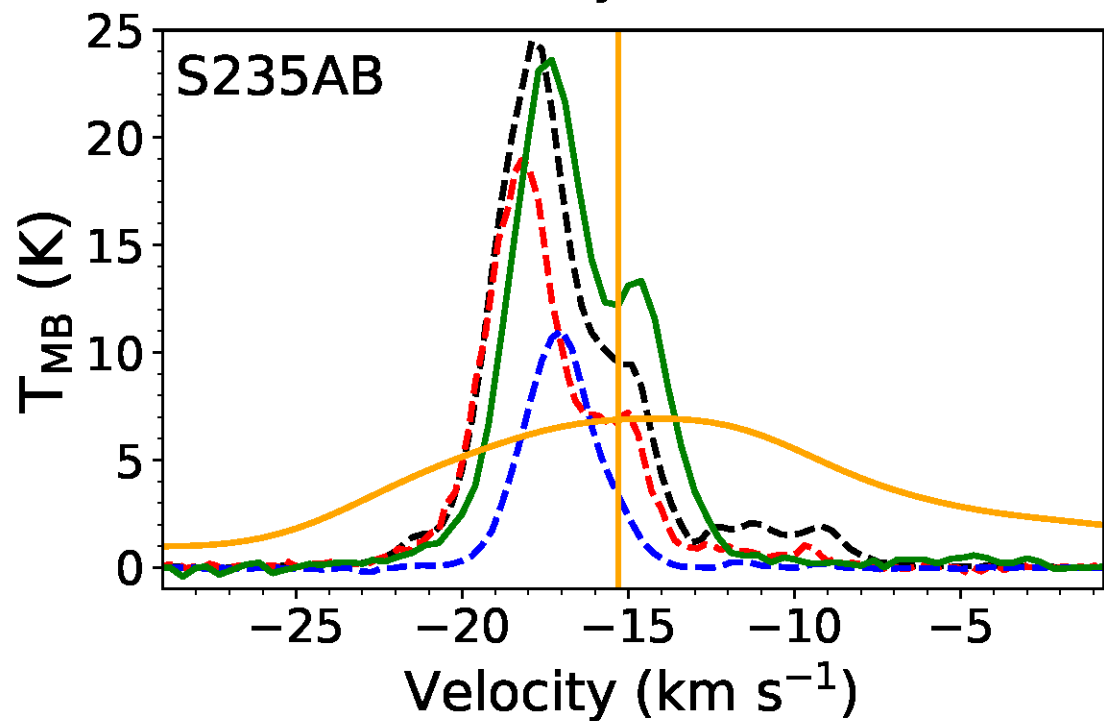
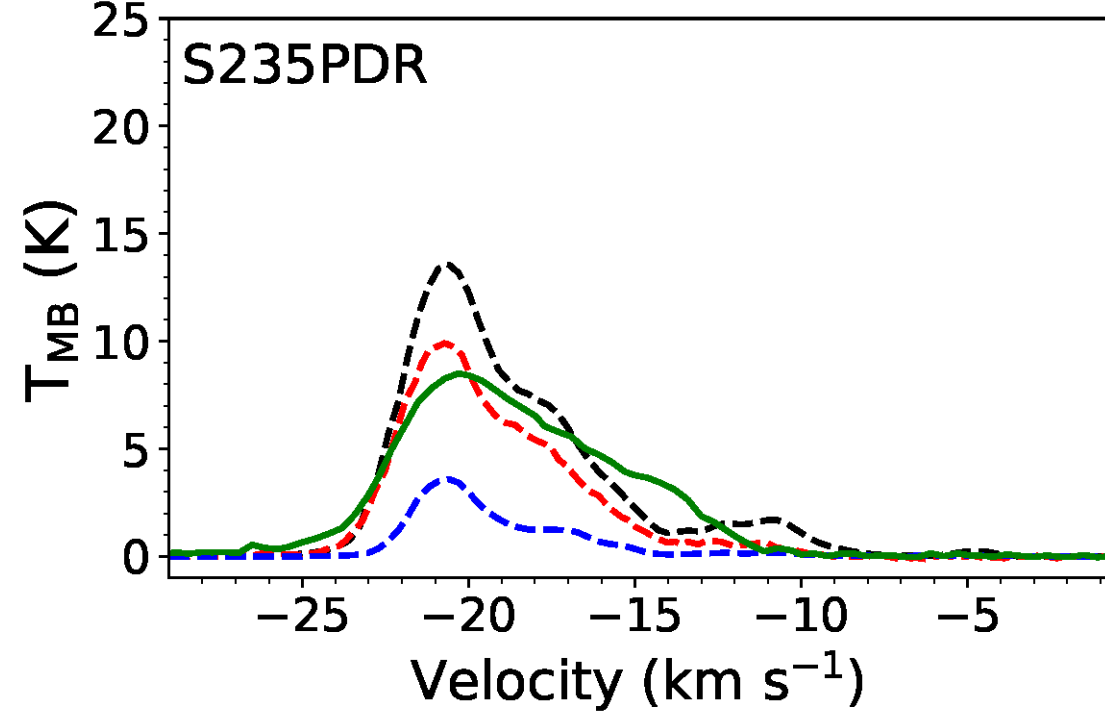
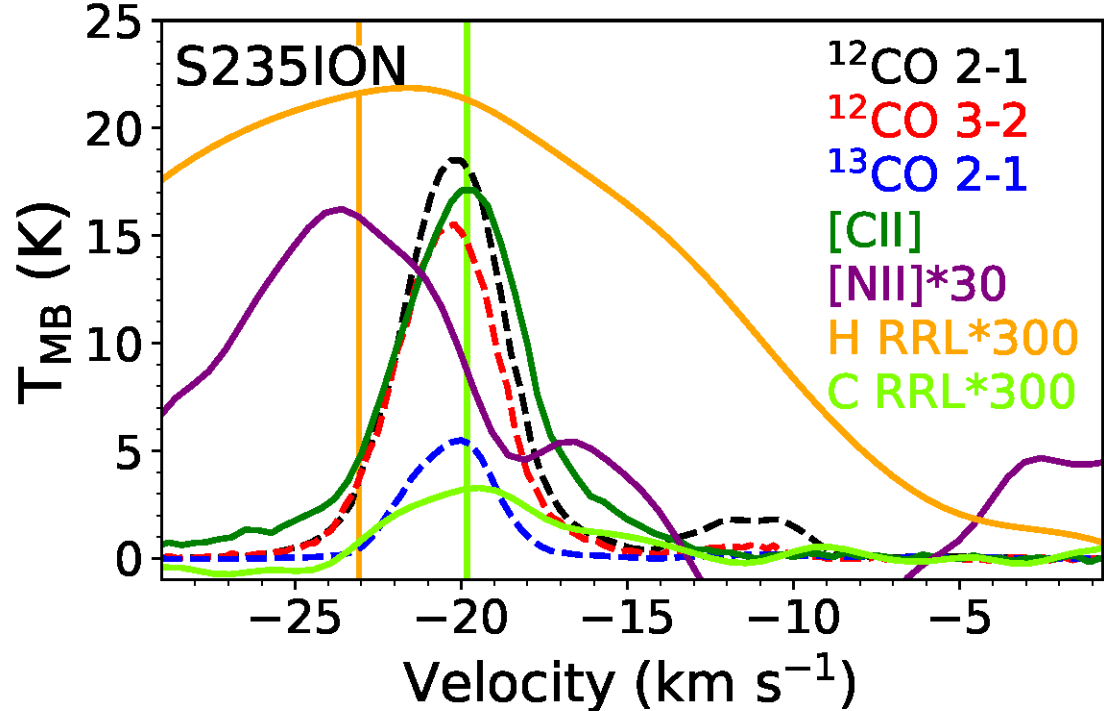
^{12}CO 3-2



M8: Tiwari et al. (2018)

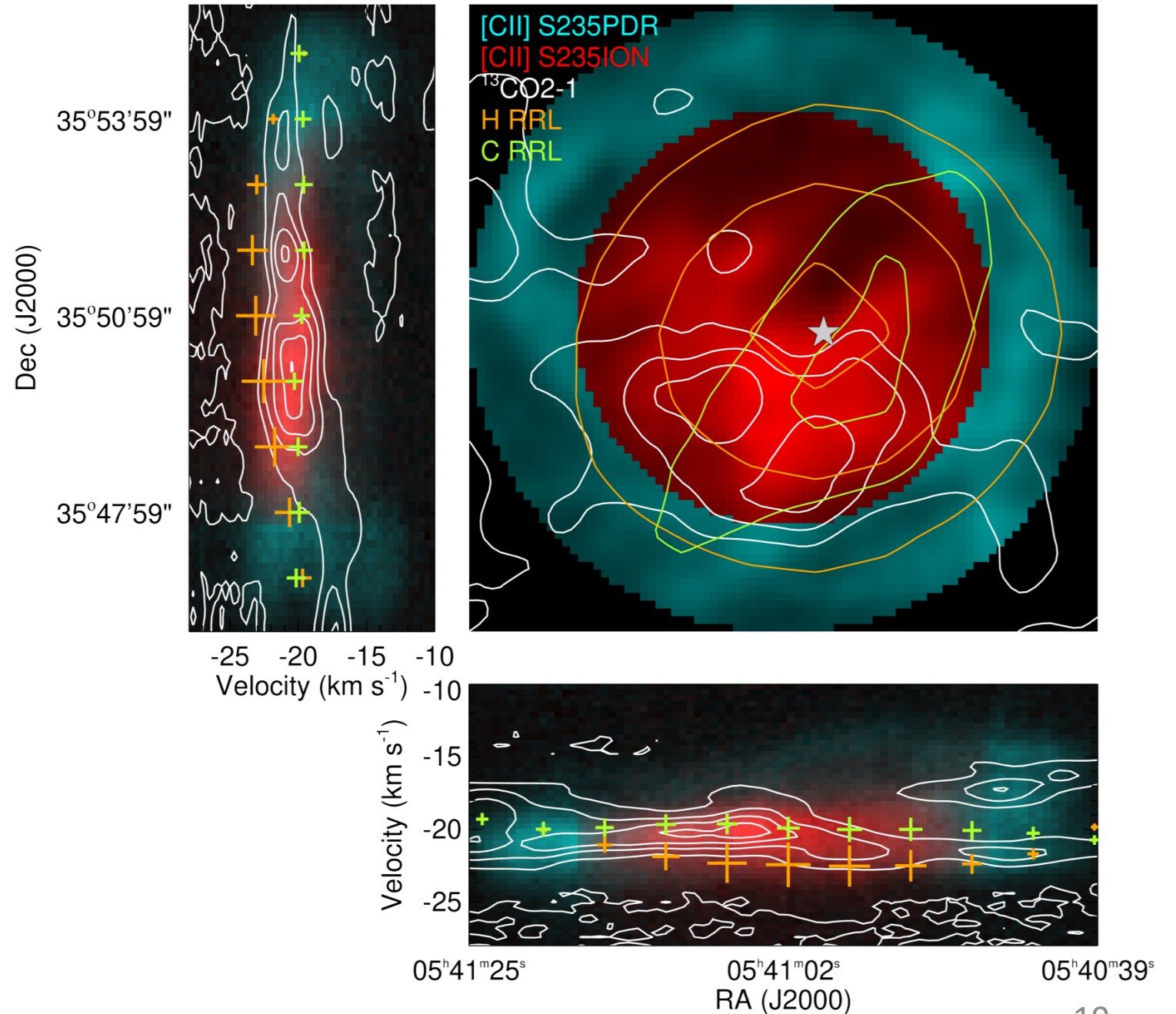


SOFIA [CI] & [CII] poorly correlated, as are CO 6-5 and [CII]



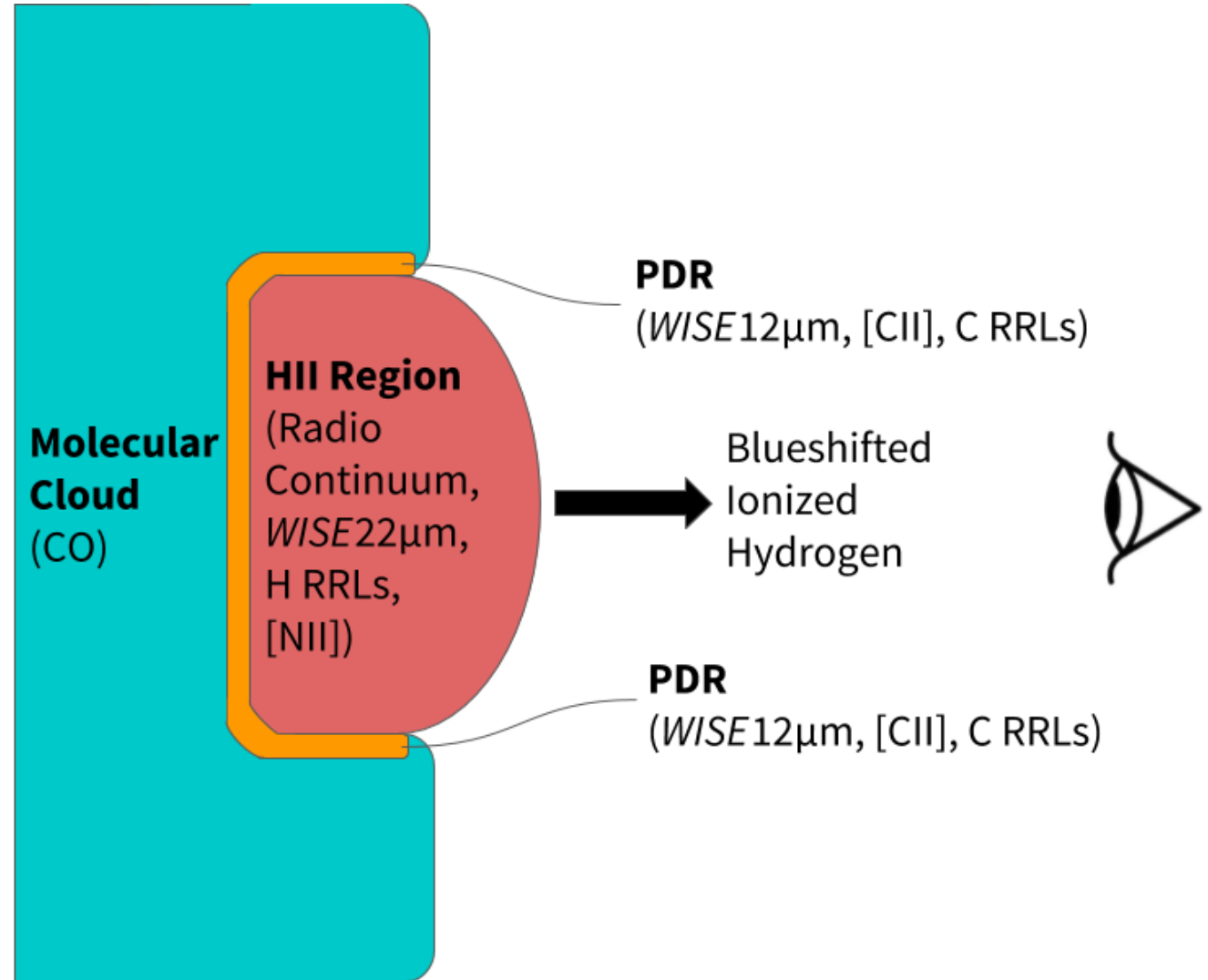
Position-velocity

- Red and cyan are [CII] from ionized and PDR regions
- CO (white) and C RRLs (green) in agreement
- CO (white) and H RRLs (orange) not in agreement

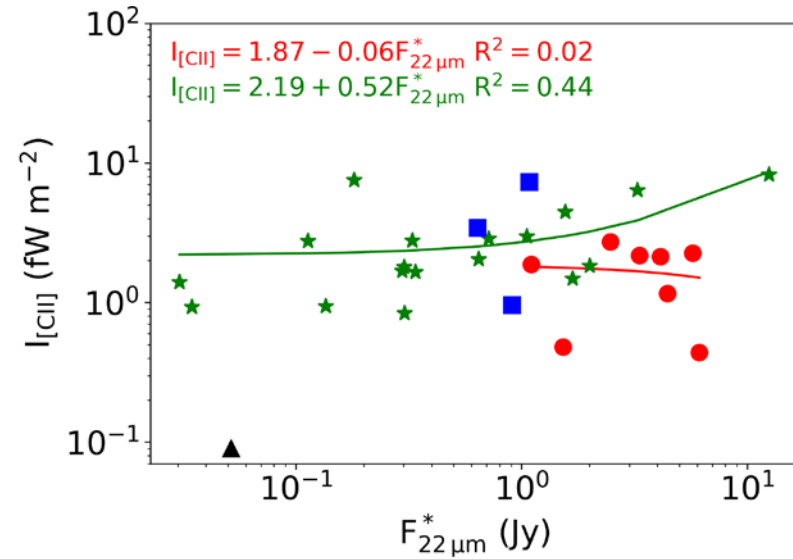
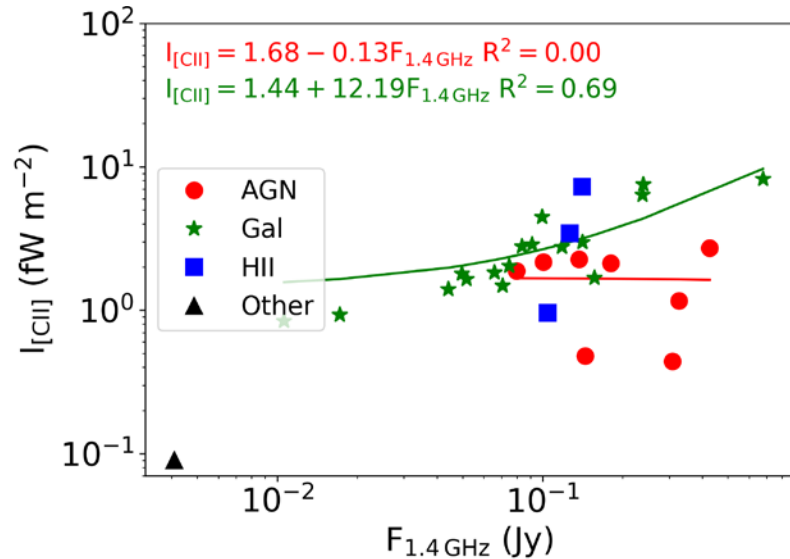
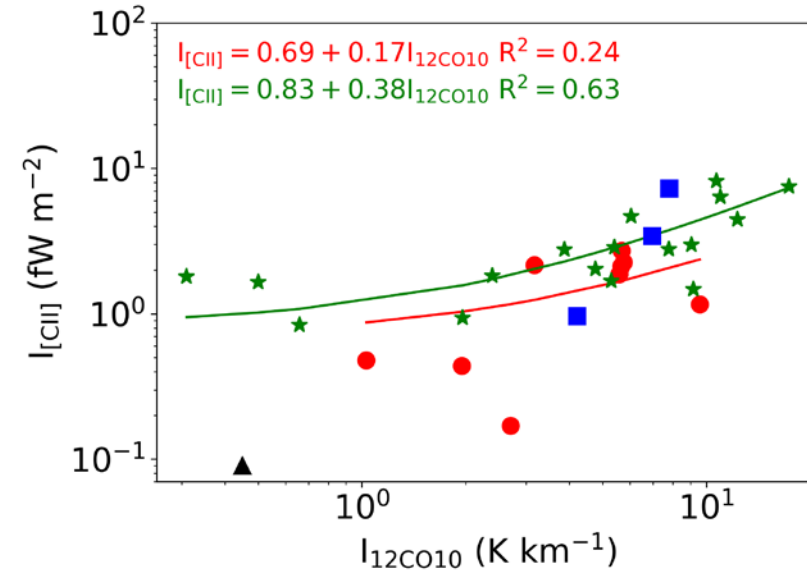
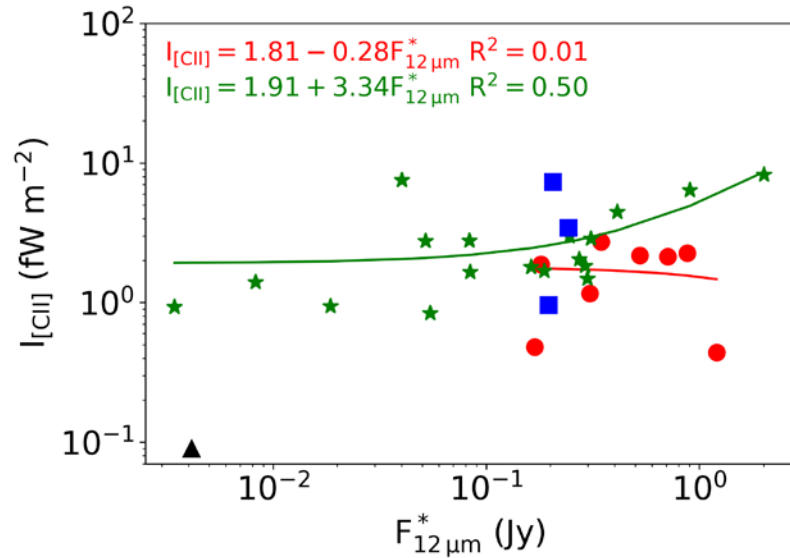


A Model

- [CII] & *WISE* 12 μ m, [CII] & C RRLs strongly correlated
 - 12 μ m emission comes from PAHs in the PDR, as do C RRLs.
We propose the [CII] also comes from the PDR
- Radio continuum, *WISE* 22 μ m, H RRLs, and [NII] centrally concentrated, blueshifted with respect to [CII]
 - **Little evidence of [CII] coming from the ionized hydrogen volume**



What do these relations look like for galaxies?

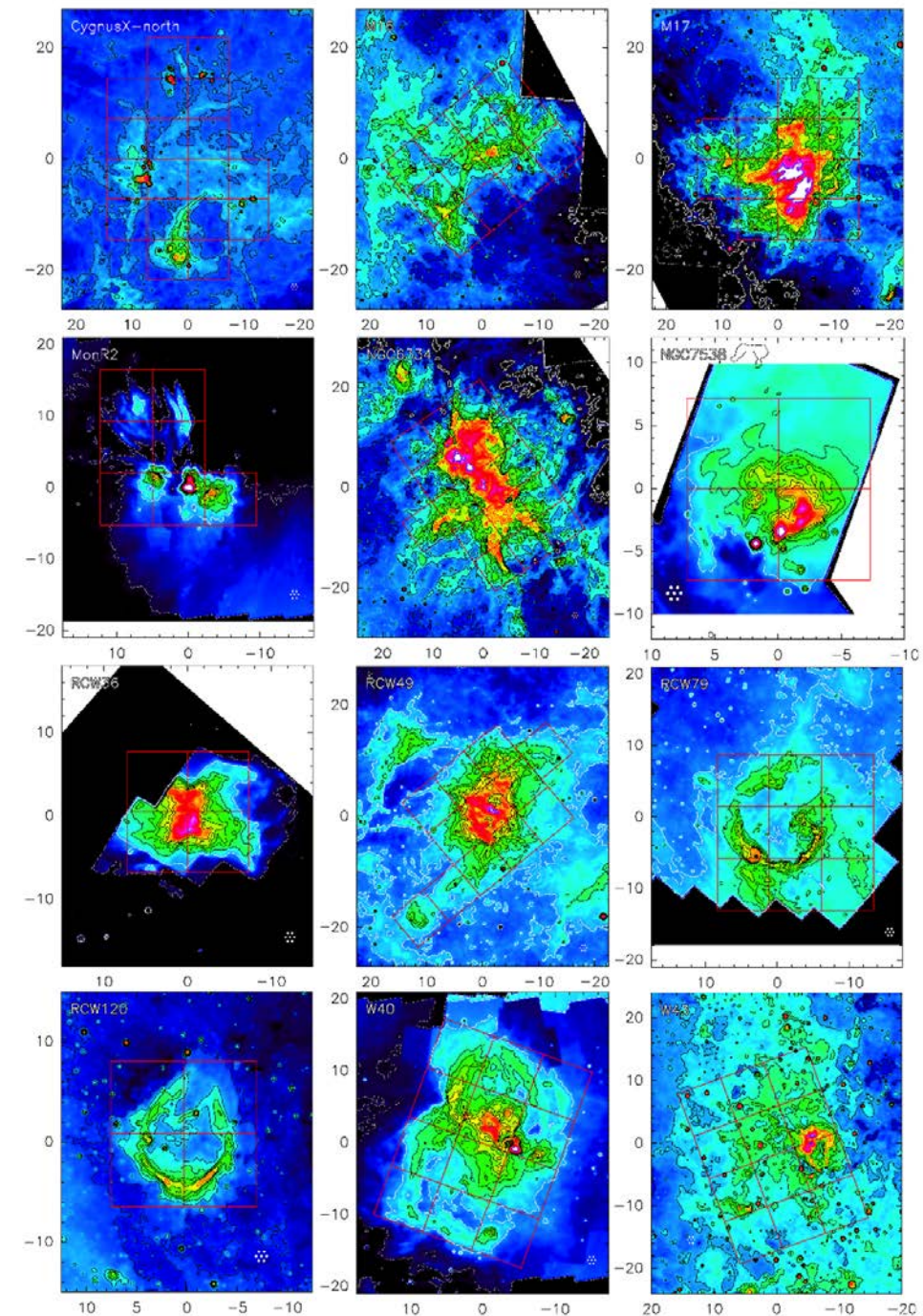


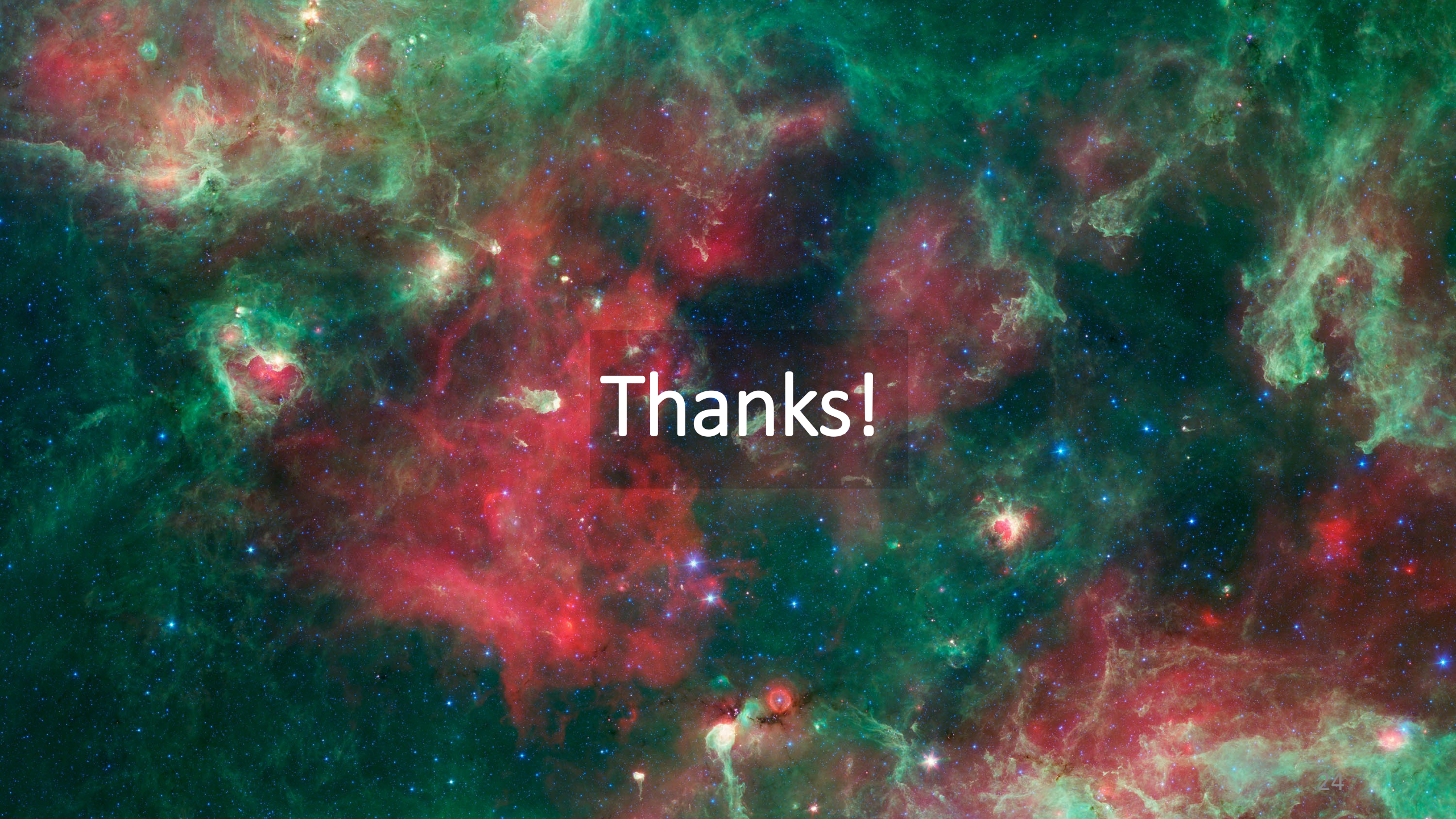
Conclusions

- [CII] emission strongly correlated with *WISE* 12 μ m emission across entire S235 complex, but not strongly correlated with CO
 - [CII] comes from the S235 PDR; little evidence that significant [CII] emission comes from the ionized hydrogen volume
- Implies that extragalactic correlation between [CII] and other star forming tracers holds only at larger scales
- Future studies of a larger sample of Galactic HII regions would help to determine whether these results are truly representative.

SOFIA Feedback Large Program

- Will study the interaction of massive stars with their environment in 12 sources that span a range in stellar characteristics
- Quantify the mechanical energy injection and radiative heating efficiency
- Quantify the relationship between star formation activity and energy injection and the negative and positive feedback processes involved, link that to other measures of activity on scales of individual massive stars, of small stellar groups, and star clusters.





Thanks!