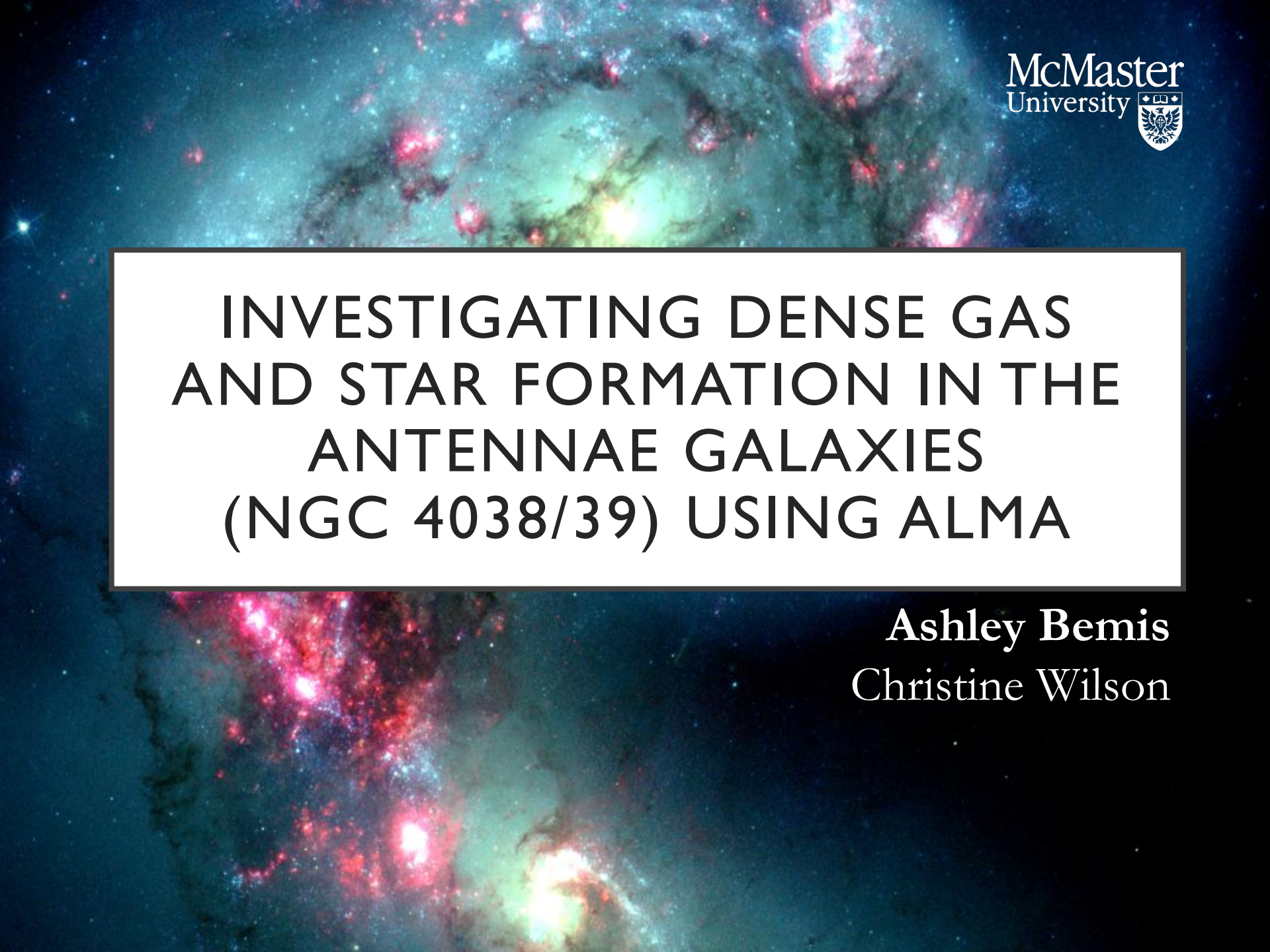


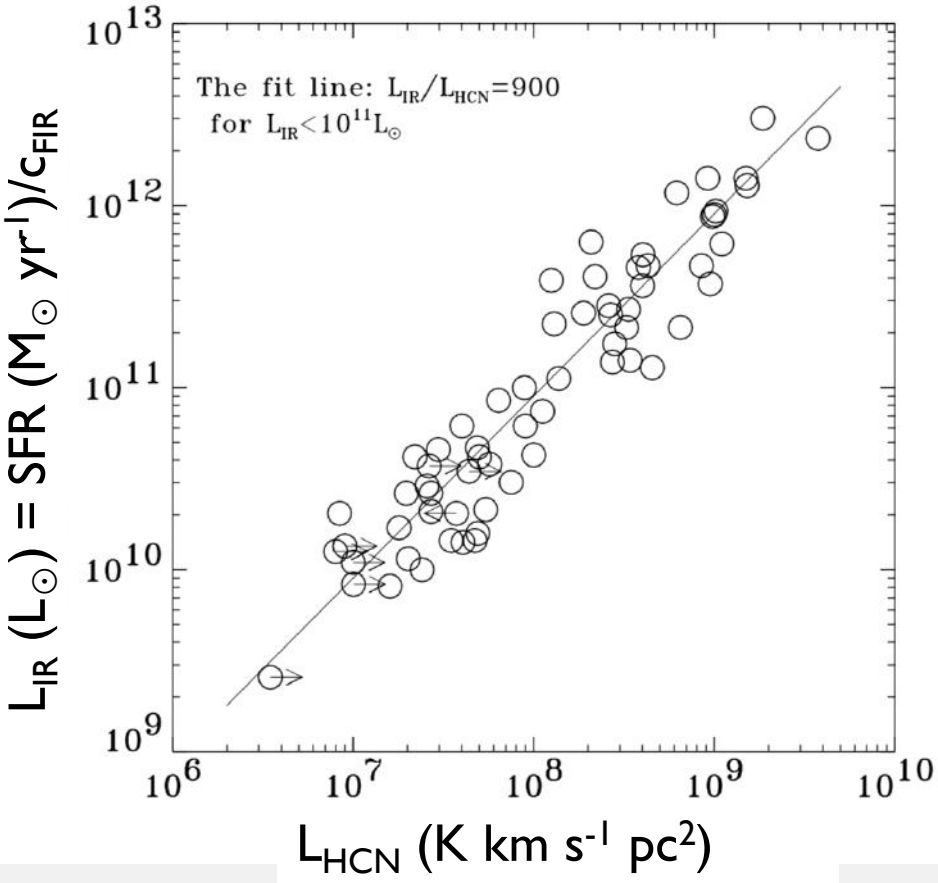
McMaster University

INVESTIGATING DENSE GAS AND STAR FORMATION IN THE ANTENNAE GALAXIES (NGC 4038/39) USING ALMA

Ashley Bemis
Christine Wilson

L_{TIR} – L_{HCN}: LINEAR (GALAXIES)

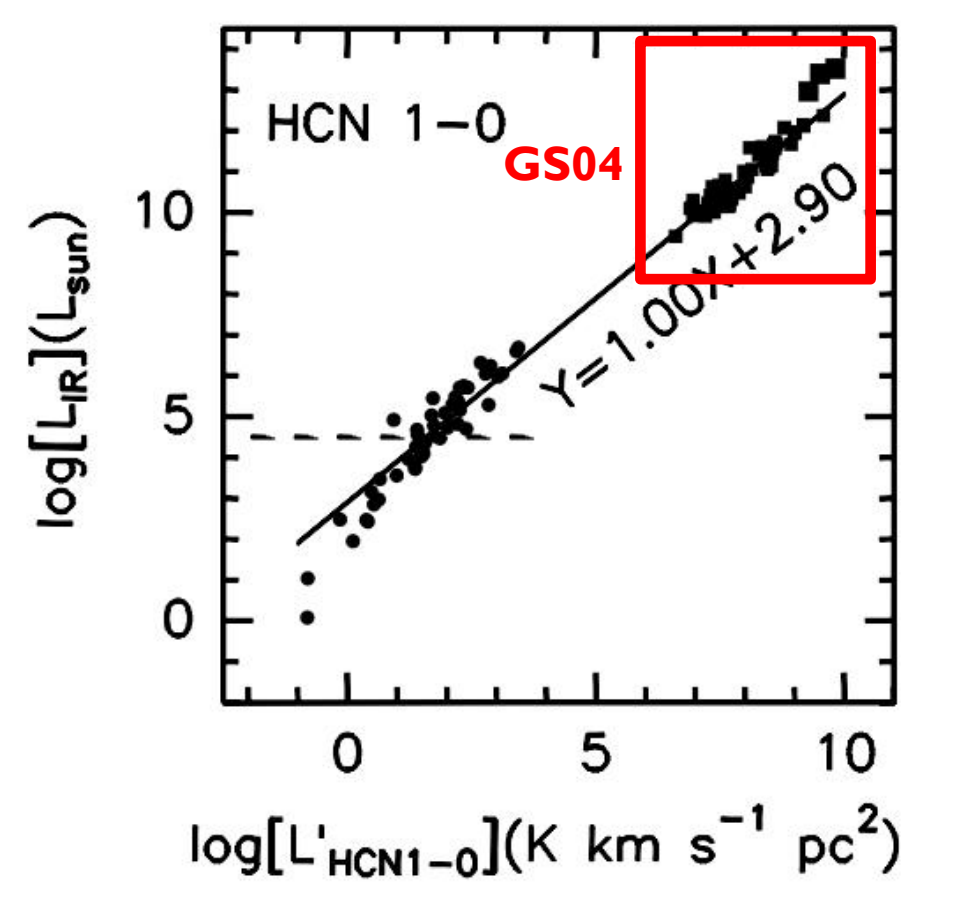
- Gao & Solomon 2004 study of 65 galaxies:
  - SFR traced by infrared luminosity: $L_{IR} \propto$ SFR
  - Dense molecular gas traced by HCN(1-0): $L_{HCN} \propto M_{dense}$
- Show tight linear relationship between SFR and dense gas



Gao & Solomon 2004a

L_{TIR} – L_{HCN}: LINEAR (CLUMPS)

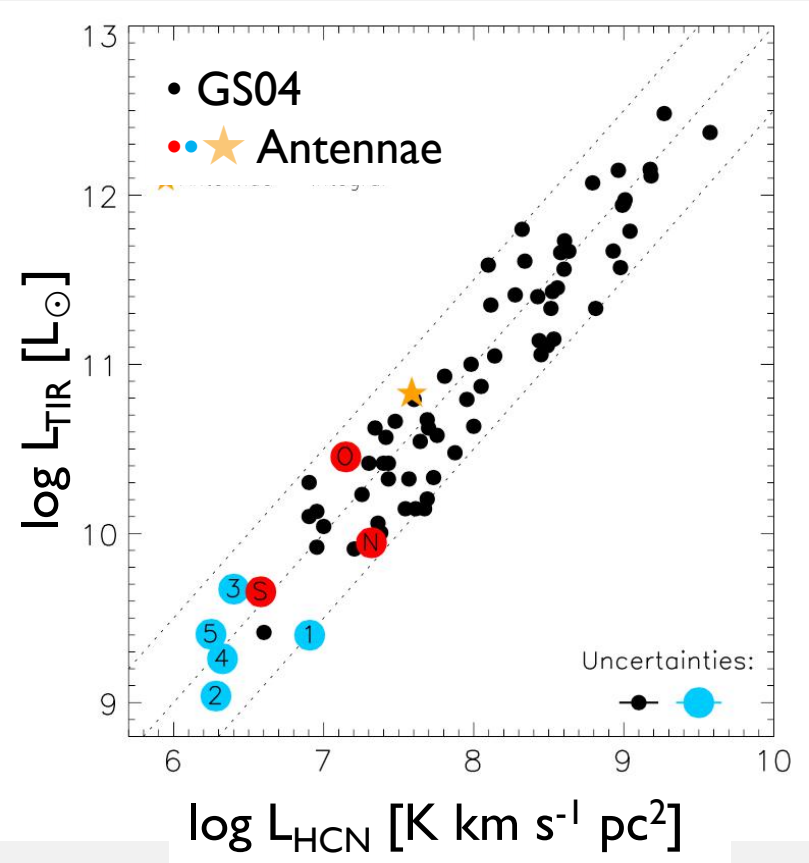
- Relationship extends to MW massive clumps (Wu+2005,2010)
- Sub-galactic scales in between



Wu + 2010

L_{TIR} – L_{HCN}: CASE STUDIES

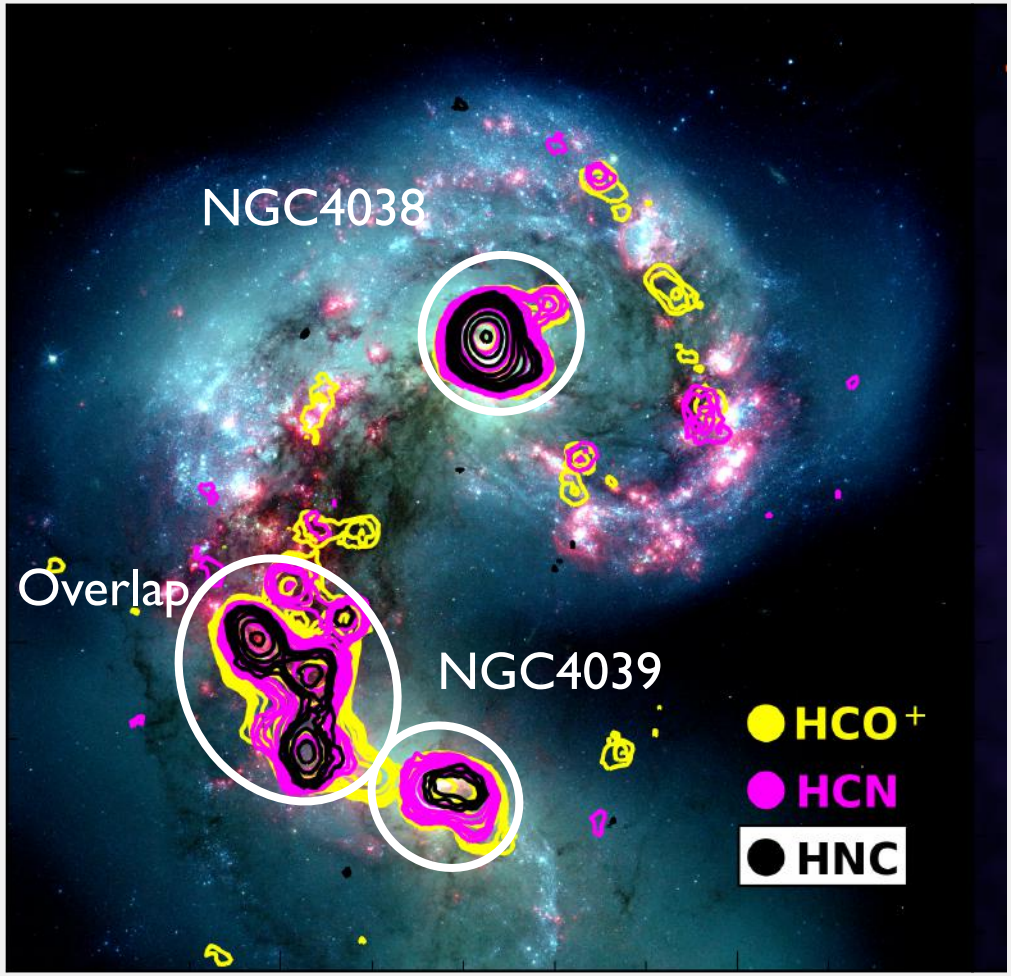
- **Case studies:**
  - Study relationship on a sub-galactic scale
  - Detailed information on (S)GMCs
- Bigiel+2015 use CARMA to study brightest regions in Antennae



Bigiel+2015

THE ANTENNAE: NGC 4038/39

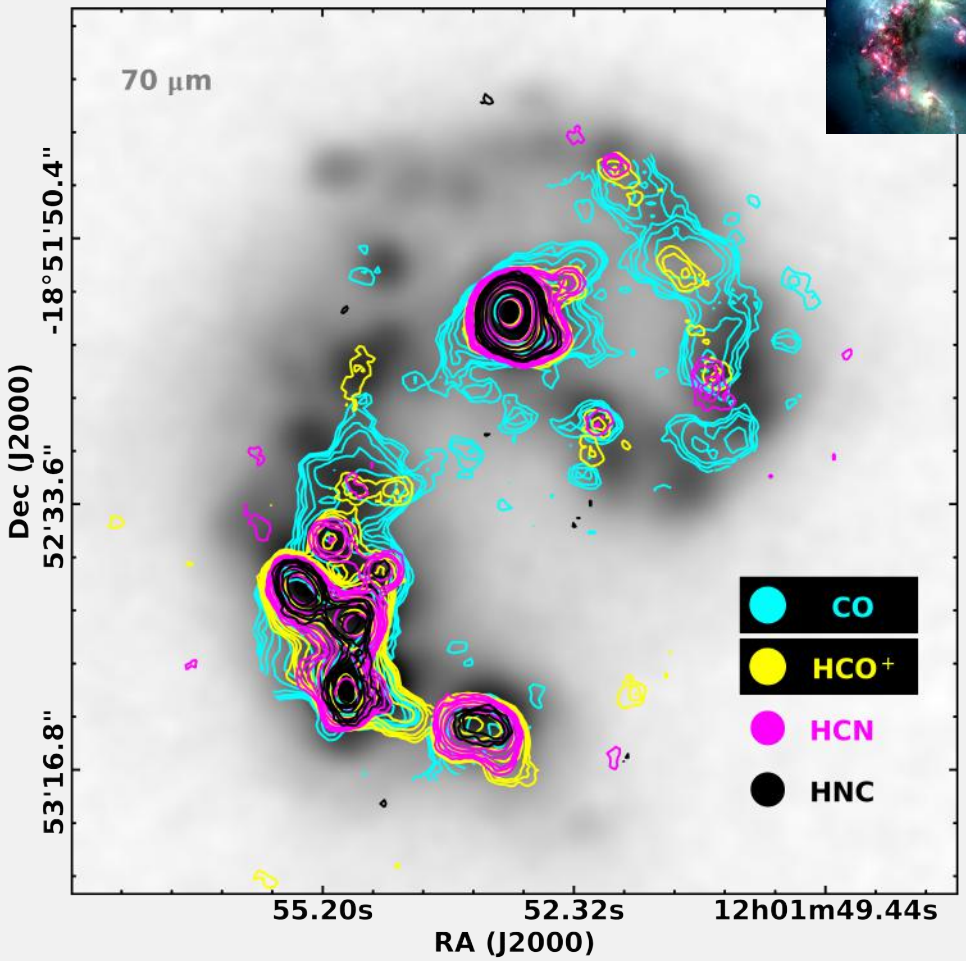
- Nearest pair of interacting/merging galaxies (22 Mpc, Schweizer+2008)
- Burst of star formation in overlap region
- Two nuclei:
  - NGC 4038 (north)
  - NGC 4039 (south)



HST RGB: 658, 500, 435 nm

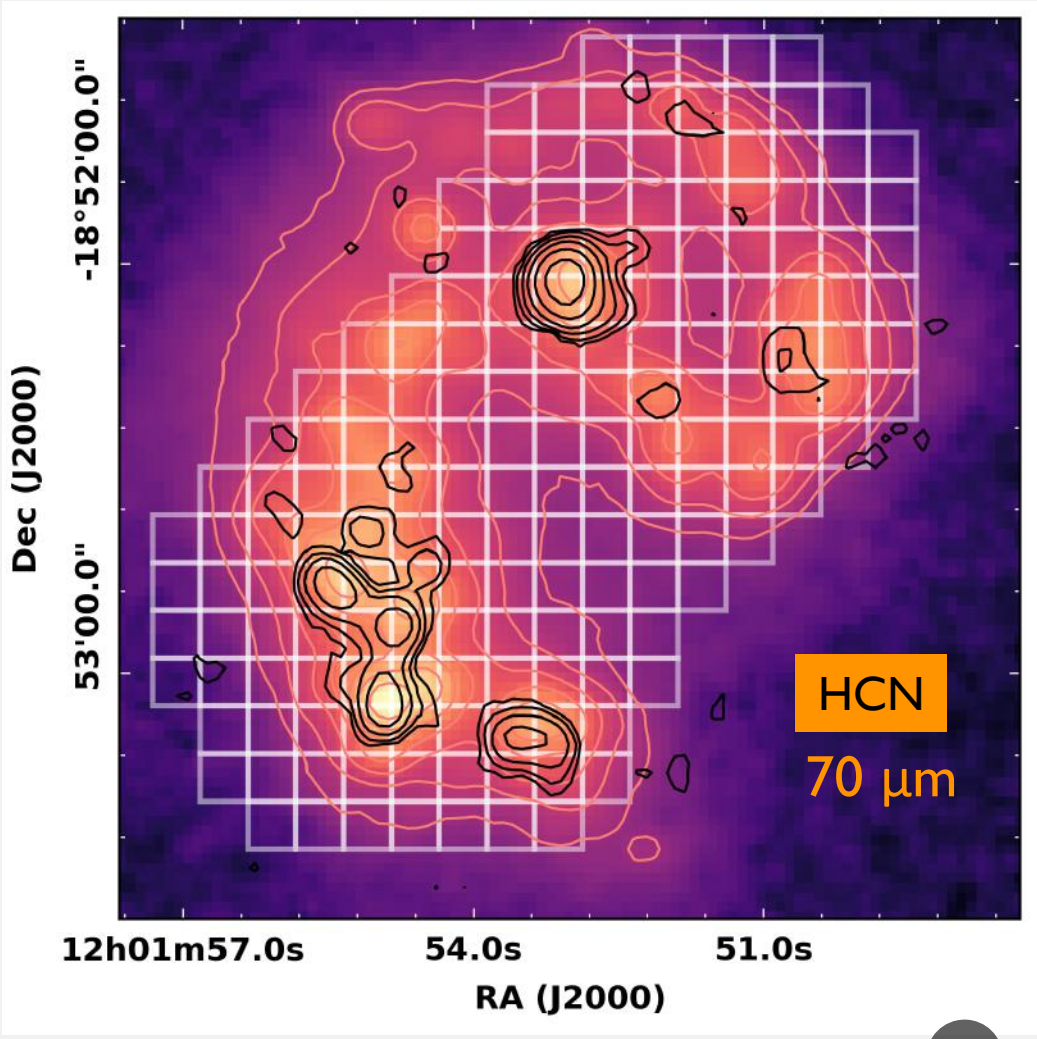
ANTENNAE DATA

- Dense molecular gas (M_{dense}):
  - ALMA HCN(1-0) [magenta]
  - HCO^+ (1-0)
  - HNC (1-0)
- Bulk molecular gas (M_{H2}):
  - OVRO CO(1-0) [cyan] (Wilson+2000)
- SFR tracer:
  - Herschel 70 micron [Grayscale]
  - Convert 70 micron → TIR (Galametz+2013)



1. L_{IR}-L_{HCN} ANTENNAE: "PIXEL BY PIXEL"

- Split into grid of square apertures
- Apertures 7.0x7.0 arcsec
- Take apertures above sensitivity limit



Bemis et al. 2017, in prep.

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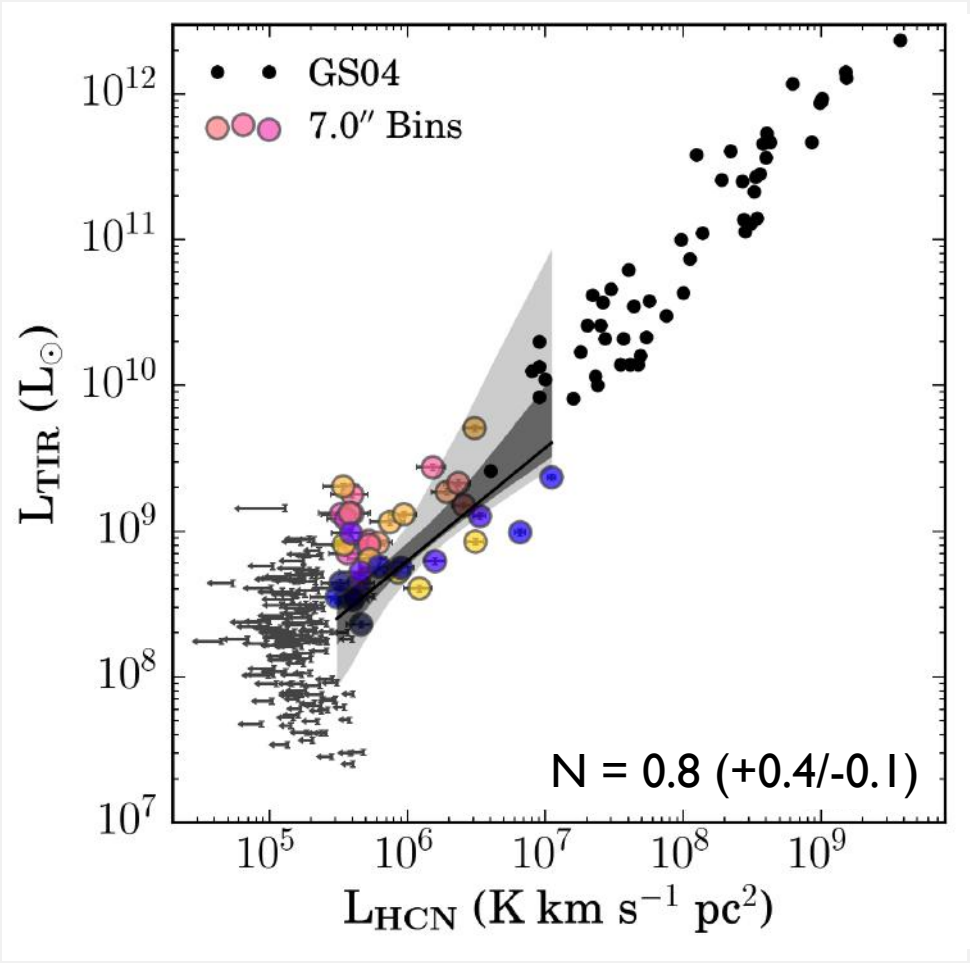
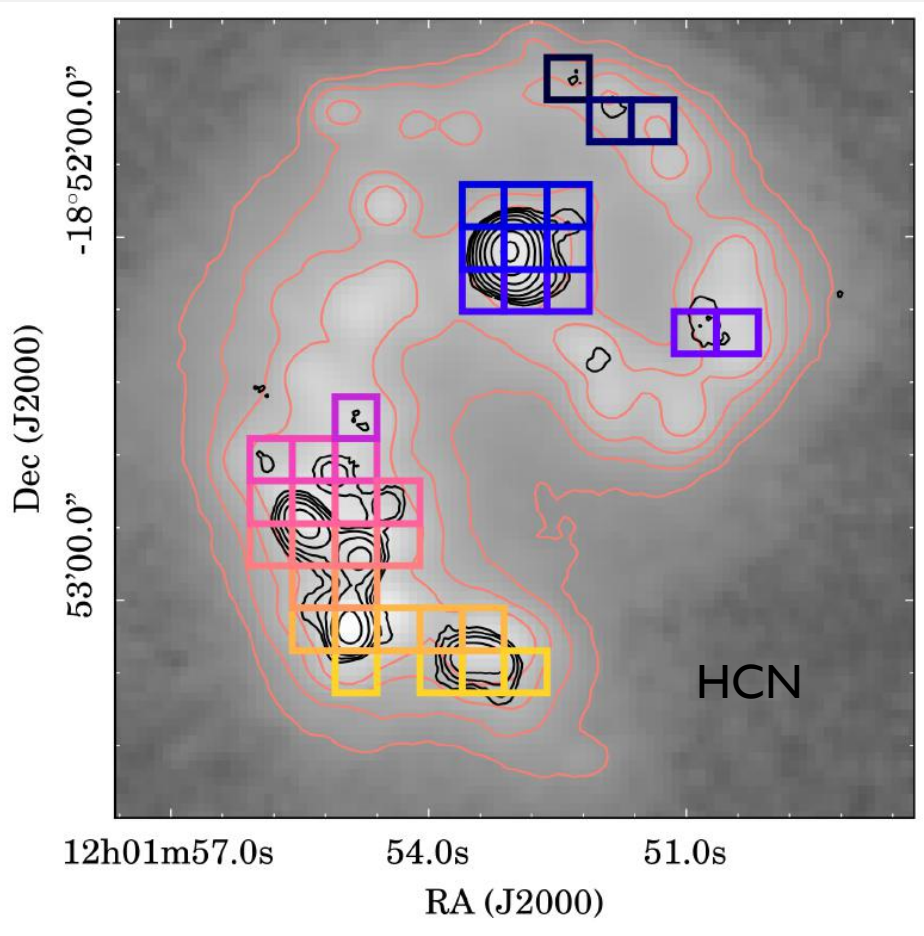
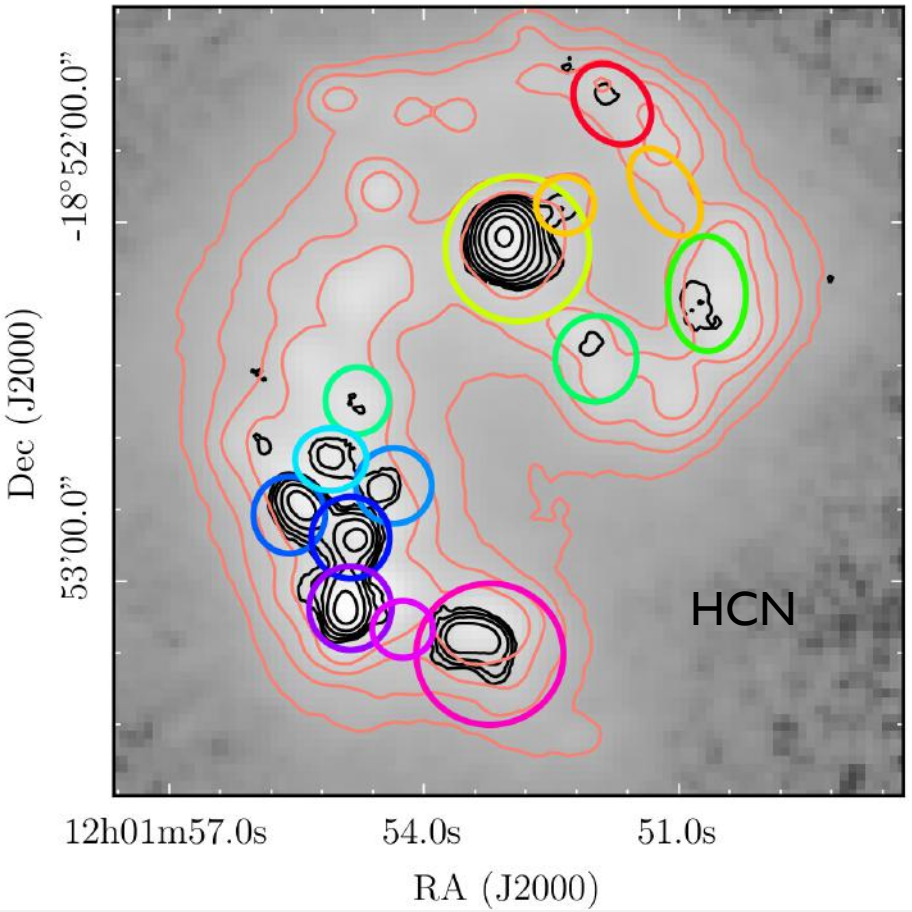




Bemis et al. 2017, in prep.

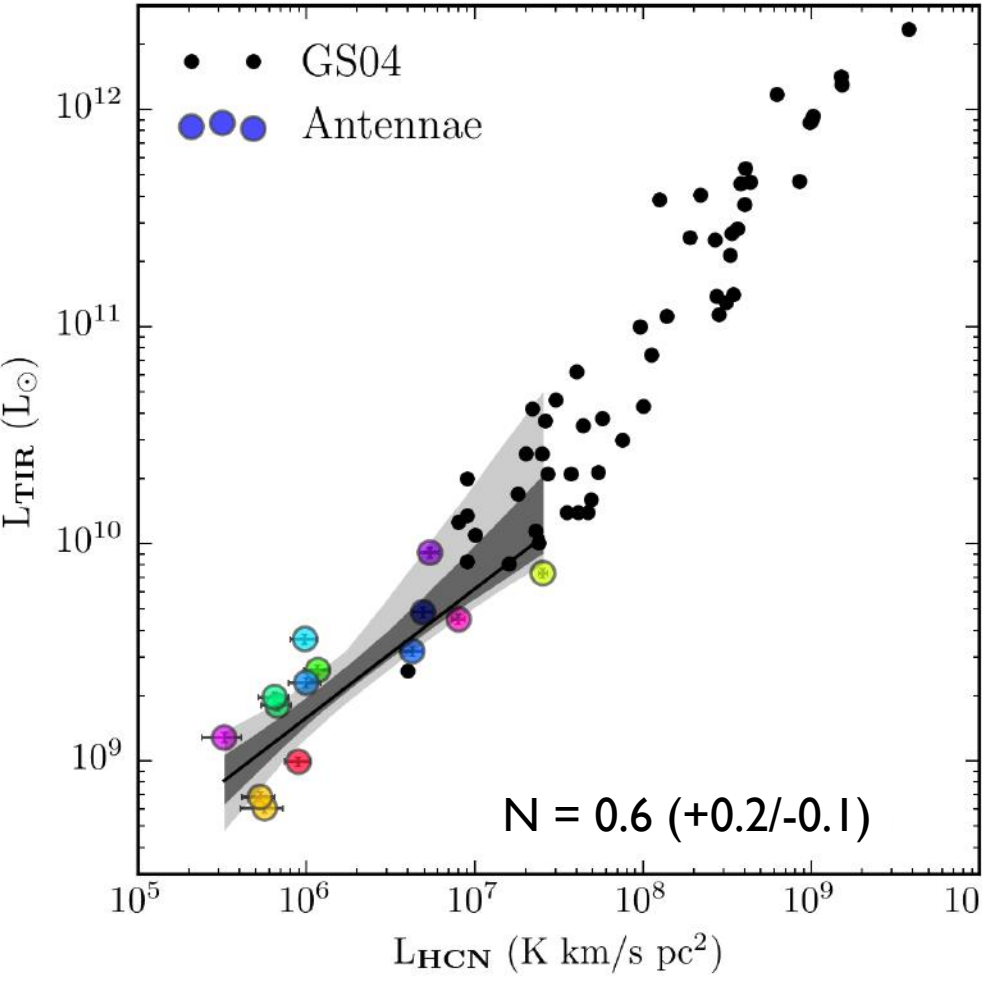
2. L_{IR}-L_{HCN} ANTENNAE: ELLIPTICAL APERTURES

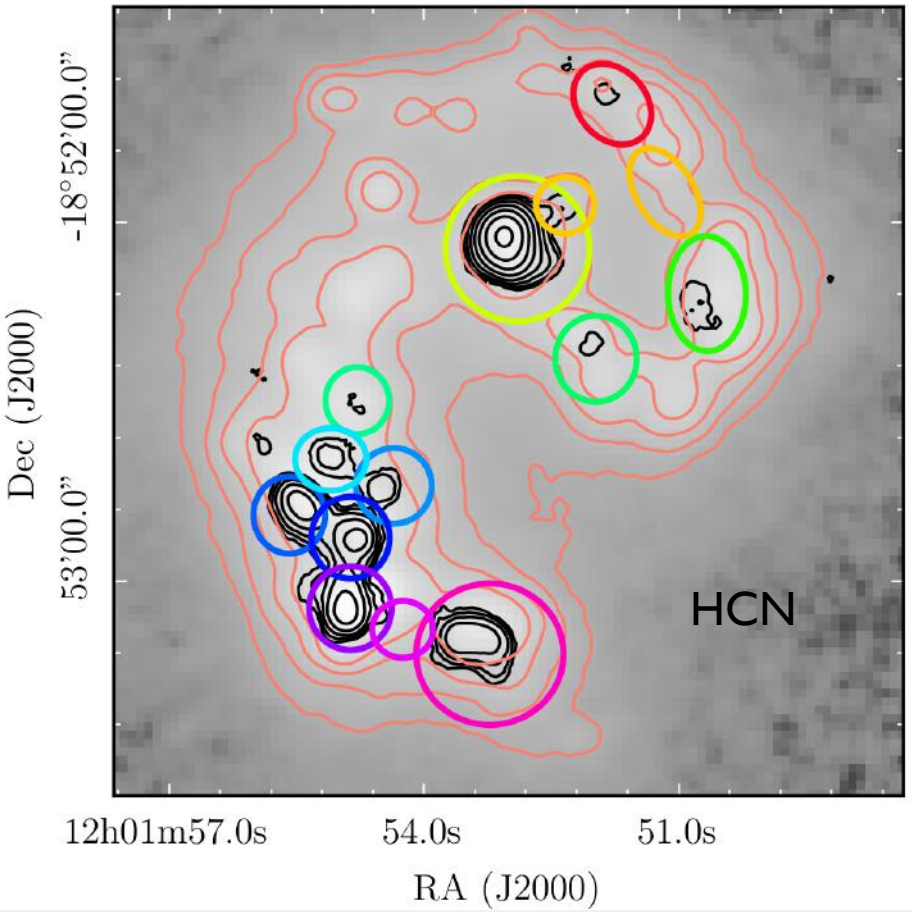
- Selected apertures around clumps identified by CPROPS (Rosolowsky & Leroy 2006, 2011)
- Sizes of apertures vary with extent of emission



Bemis et al. 2017, in prep.

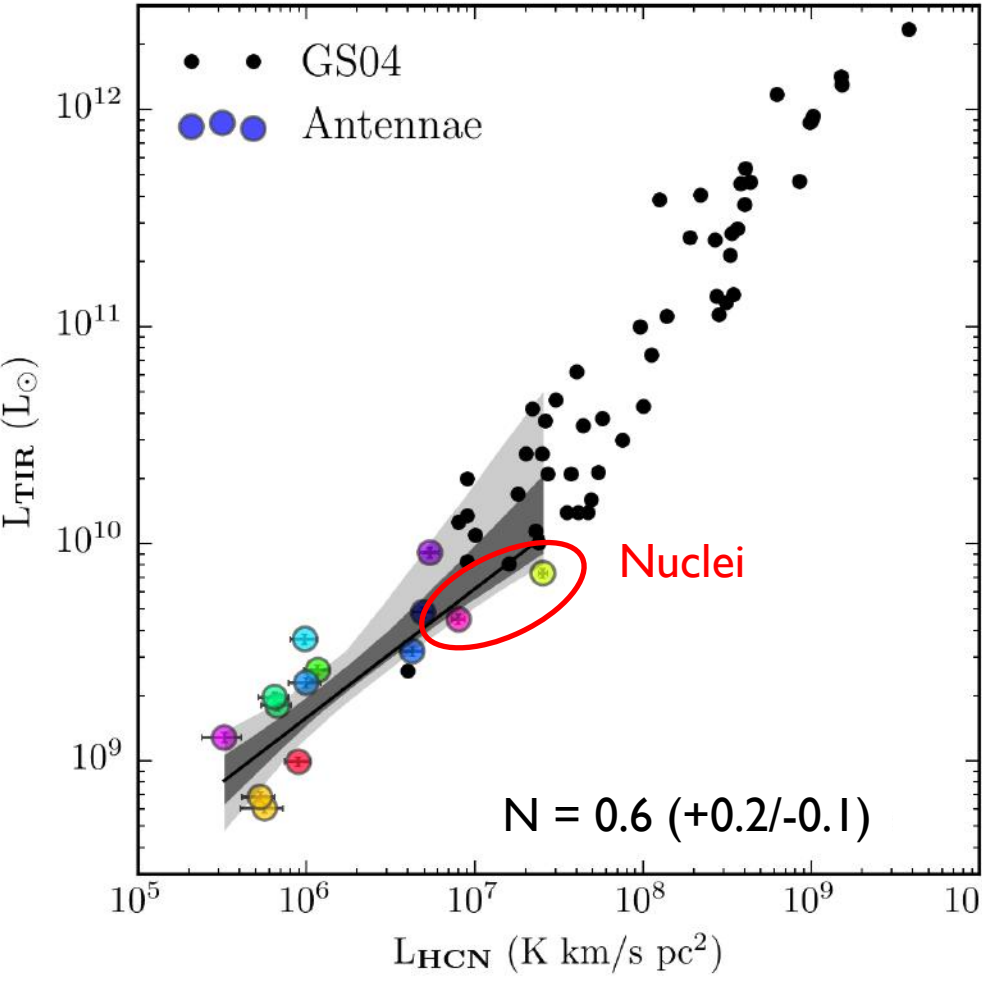
RESULTS: $L_{TIR} - L_{HCN}$

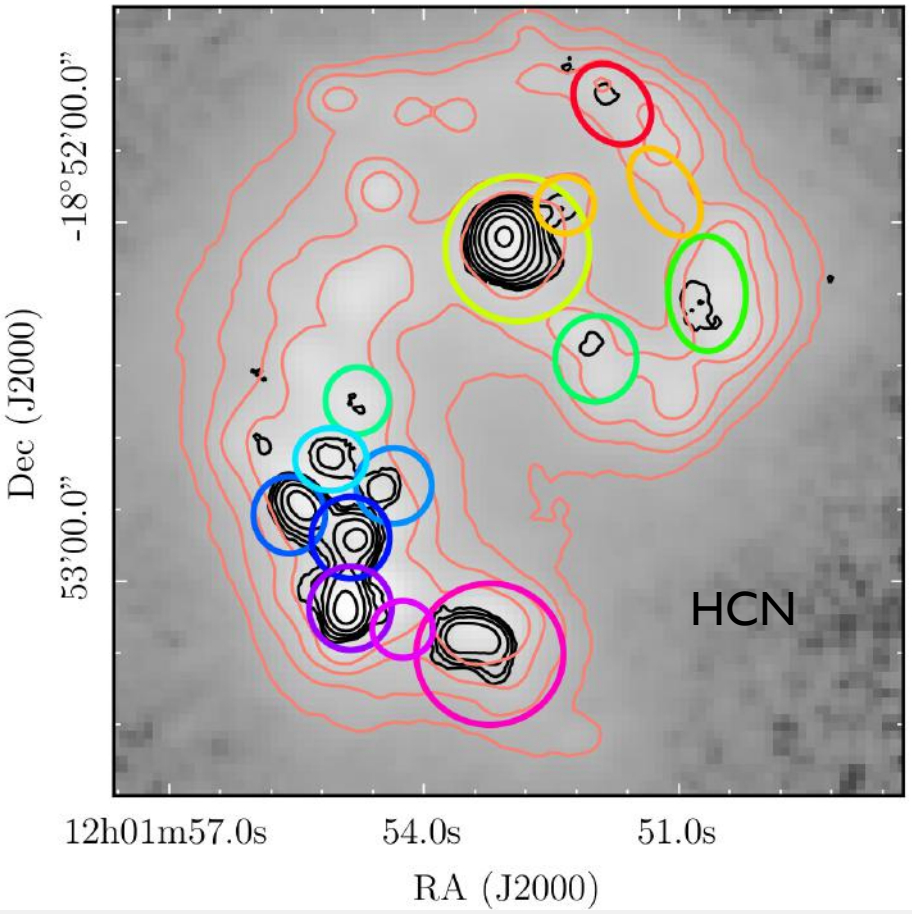




Bemis et al. 2017, in prep.

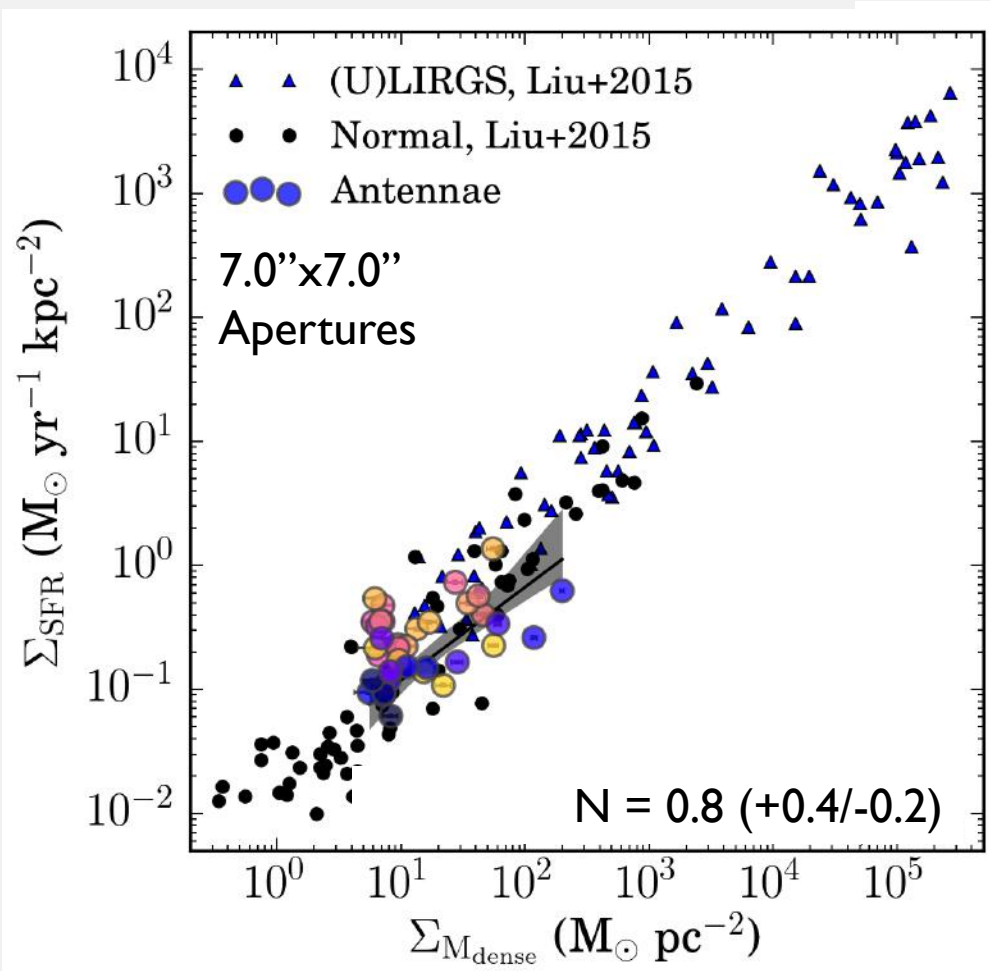
RESULTS: L_{TIR} – L_{HCN}

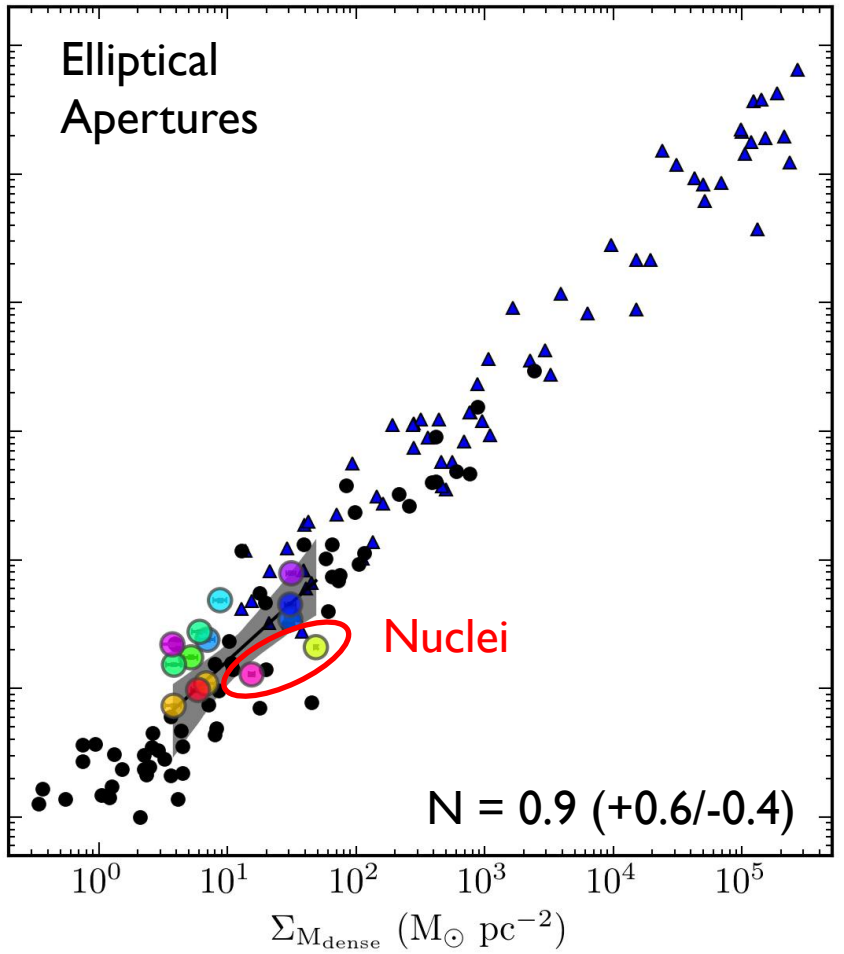




Bemis et al. 2017, in prep.

RESULTS: $\Sigma_{SFR} - \Sigma_{M,DENSE}$

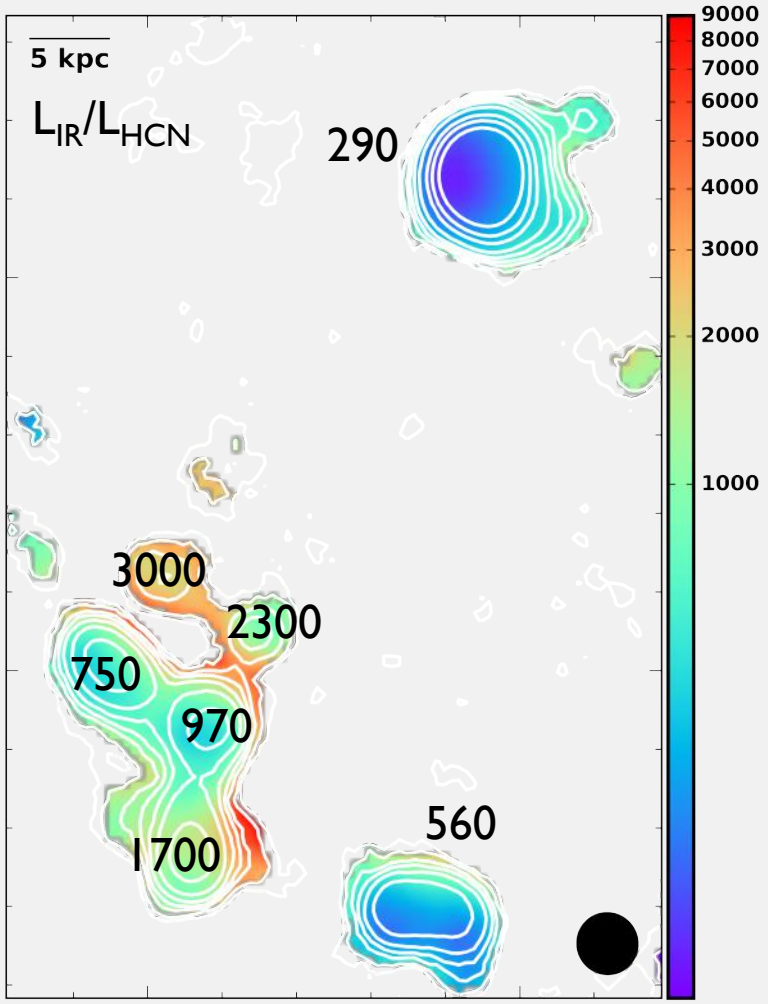




Bemis et al. 2017, in prep.

STAR FORMATION EFFICIENCY OF DENSE GAS

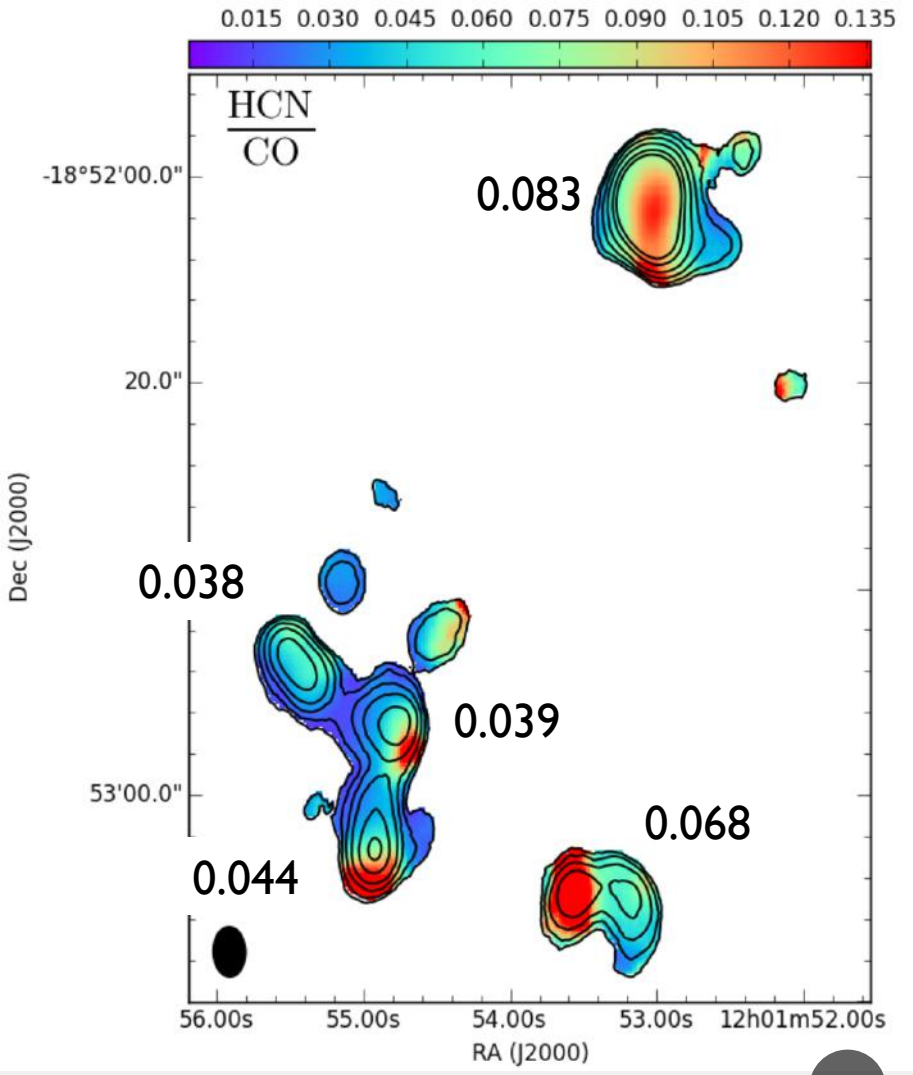
- L_{TIR}/L_{HCN} = lower in nuclei than in overlap
  - N4038 ~ 290 $L_\odot$ / K km/s pc^2
  - N4039 ~ 560 $L_\odot$ / K km/s pc^2
  - Average ~ 1800 $L_\odot$ / K km/s pc^2
- L_{TIR}/L_{HCN} = Star forming efficiency of dense gas, SFE_{dense}
- Nuclei lower L_{TIR}/L_{HCN}, despite higher L_{HCN}/L_{HCO}



Bemis et al. 2017, in prep.

DENSE GAS FRACTION

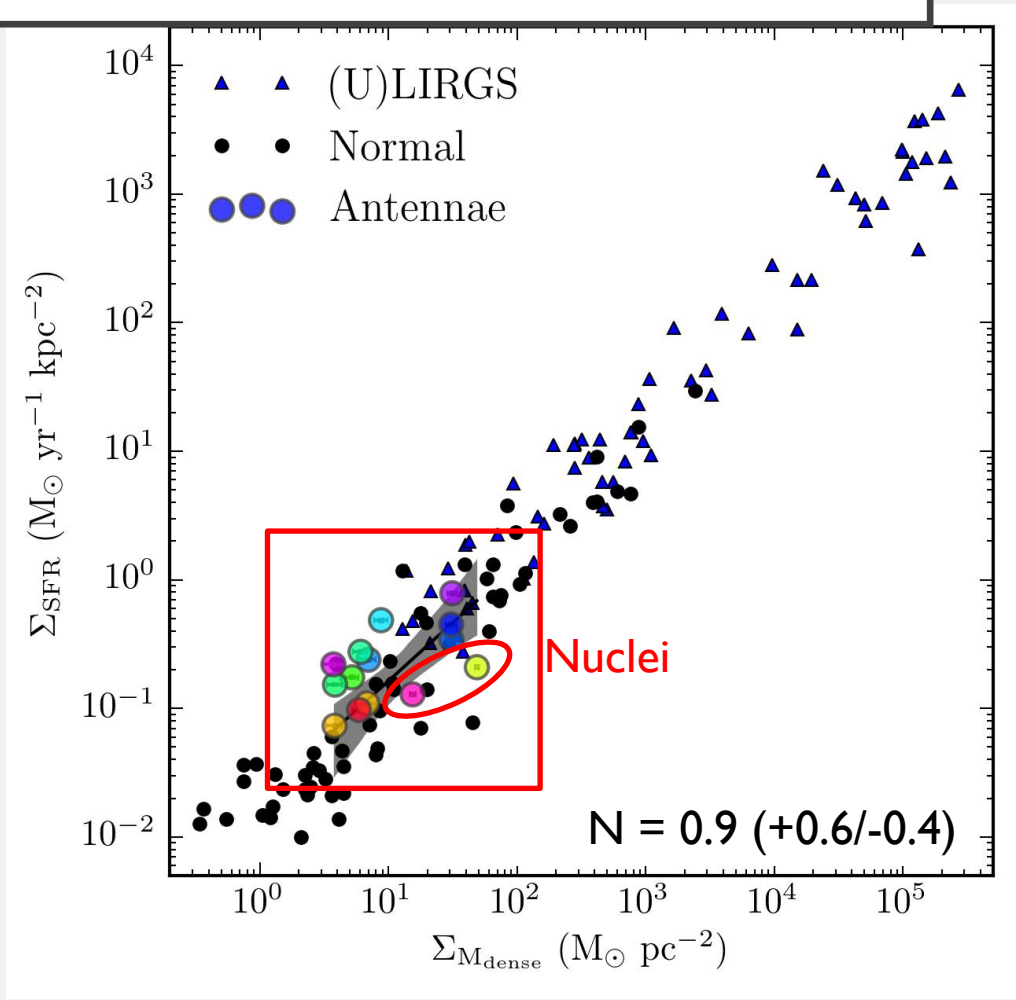
- Nuclear regions show enhancement in HCN emission relative to CO (Schirm+2016)
- L_{HCN}/L_{CO} = dense gas fraction, f_{dense}



Schirm + 2016

WHAT PHYSICS DRIVES THIS VARIATION IN L_{IR}-L_{HCN} RELATIONSHIP?

- Is $L_{HCN} \sim M_{dense}$ constant? Probably not.
- CO conversion factor varies with environment, different types of galaxies (Bolatto+ 2013)
- Evidence X_{HCN} lower in (U)LIRGs (Graciá-Carpio 2008)



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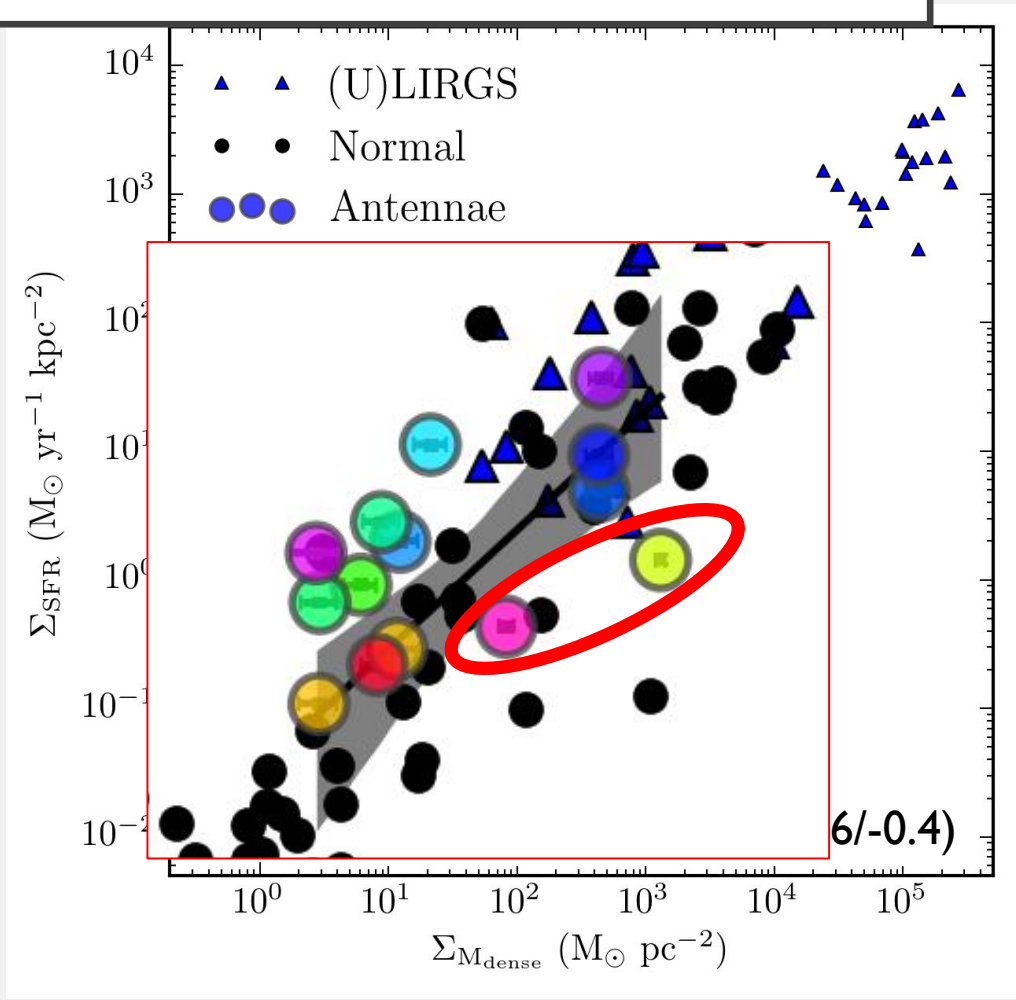
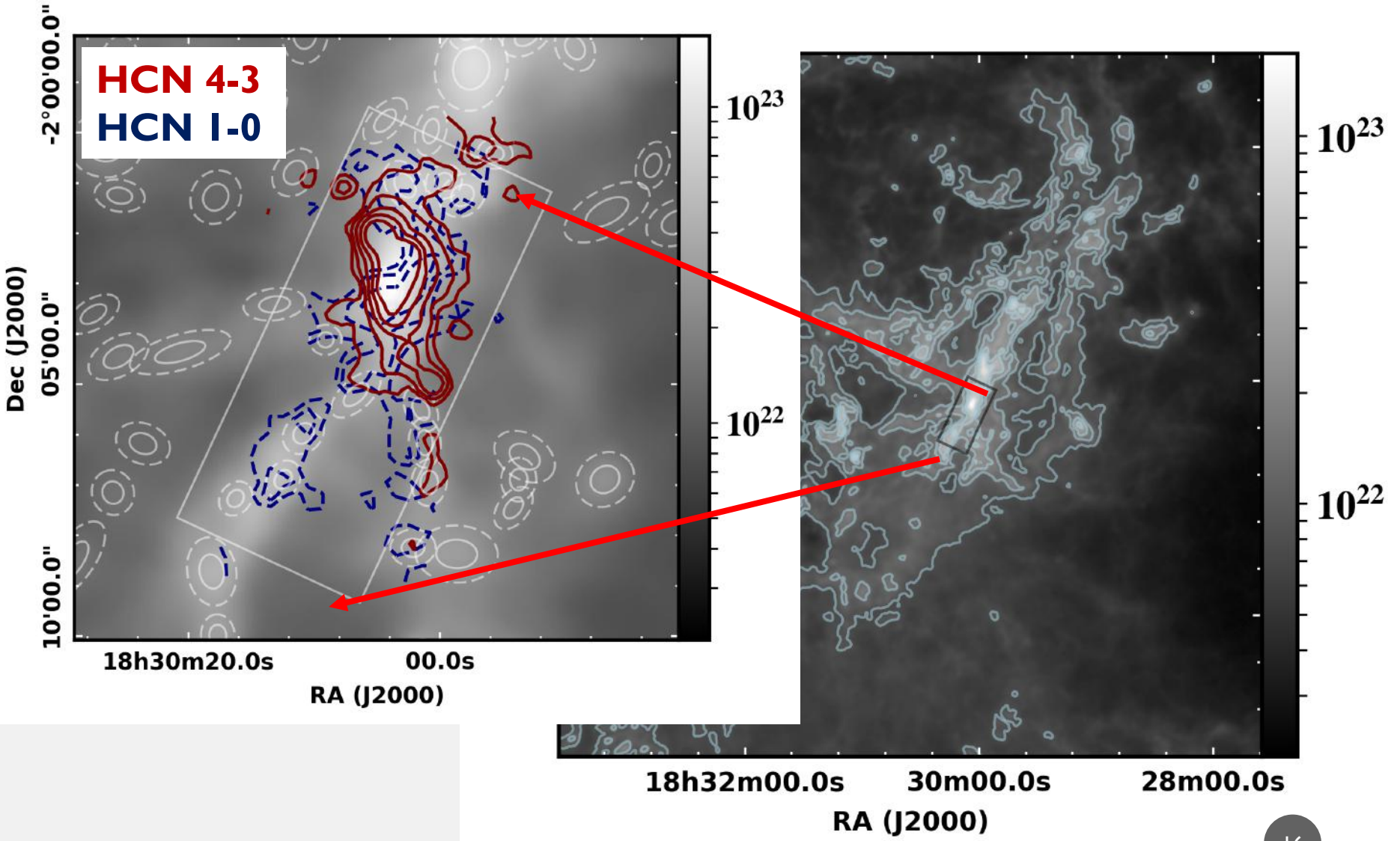


HOW DO WE TEST THE L_{HCN}-M_{DENSE} RELATIONSHIP?

1. **Extragalactic Studies:** multi-line excitation analyses to derive density, temp., abundances
2. **Galactic Studies:** Can compare independent tracers of mass (e.g. dust mass) with L_{HCN}!

17A JCMT HCN 4-3 OBS OF AQUILA

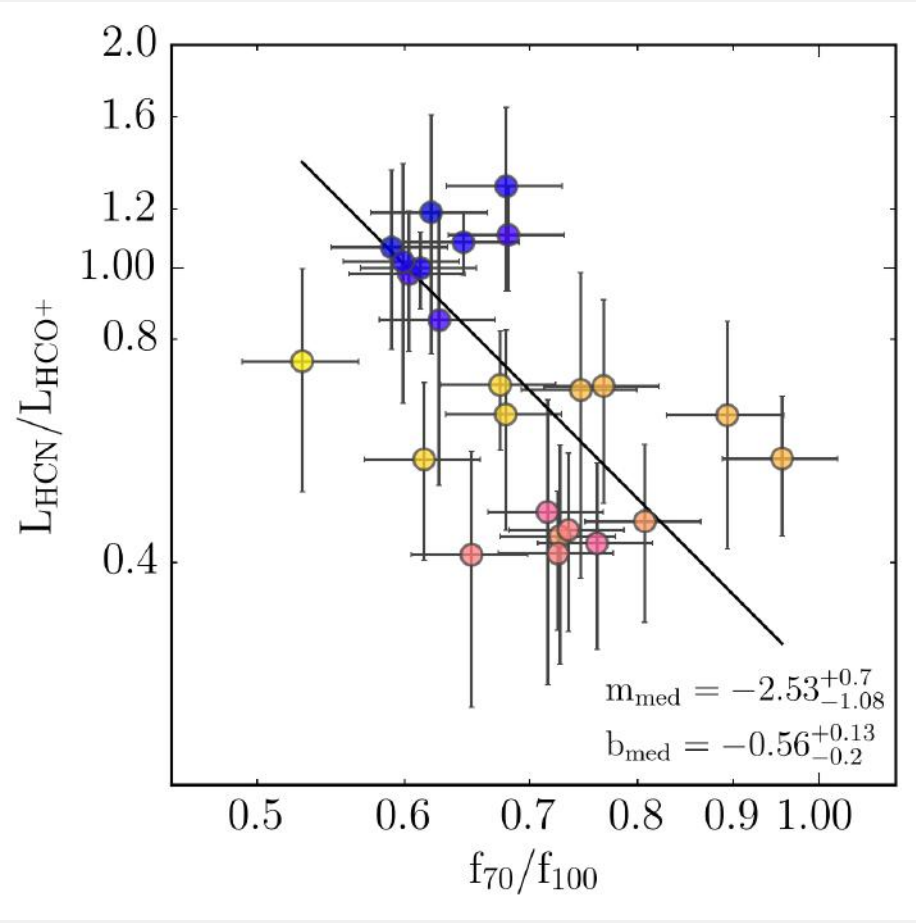


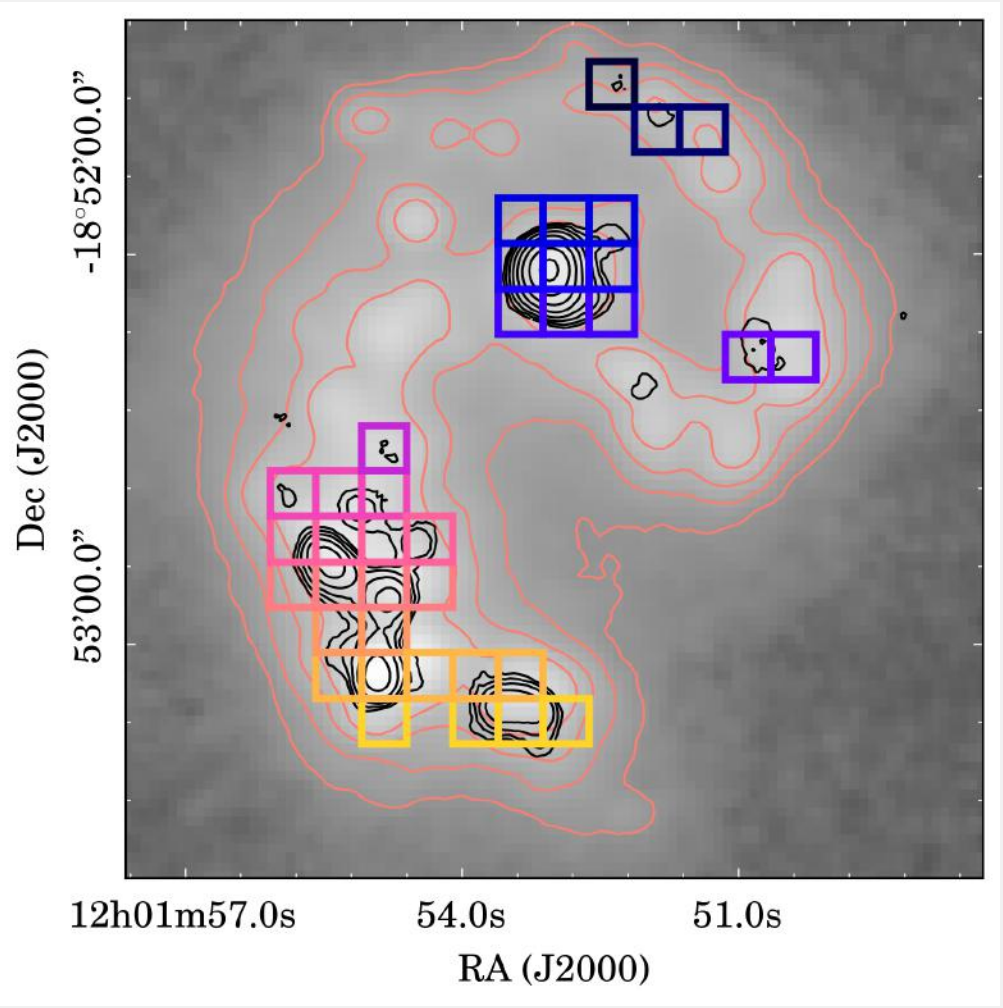
HGBS column density map, Könyves+2015

CONCLUSIONS & FUTURE WORK

- Regions of Antennae system extend the Gao & Solomon (2004) sample in the Pixel by Pixel analysis
- Antennae system appears sublinear analysis over "individual" sources
- Nuclei appear to have lower SFE_{dense} – possible biases in our observational tracers?
- $L_{HCN} \neq M_{dense}$?:
  - Higher HCN abundance?
  - Excitation effects?
- **More Work:**
  - Antennae: do multi-line excitation analyses to derive density, temp., abundances,
  - Perform analysis on other extragalactic systems
  - Galactic work: Compare independent tracers of mass (e.g. dust mass) with L_{HCN}!

VARIATIONS WITH DUST TEMPERATURE





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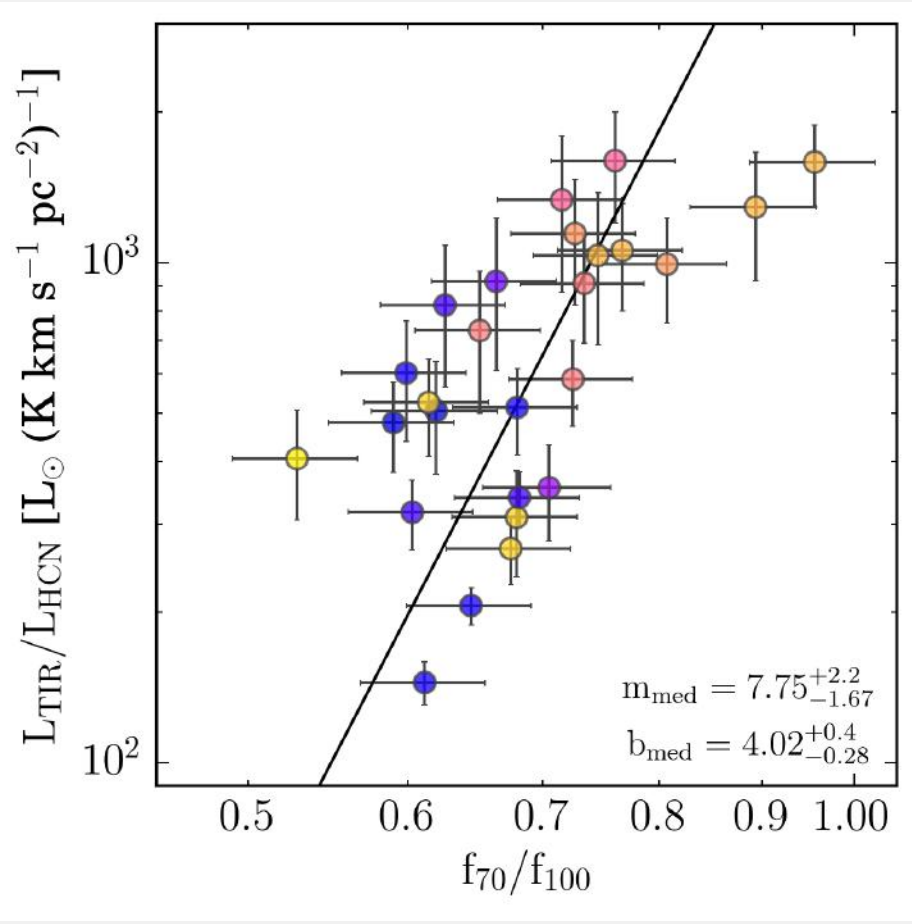
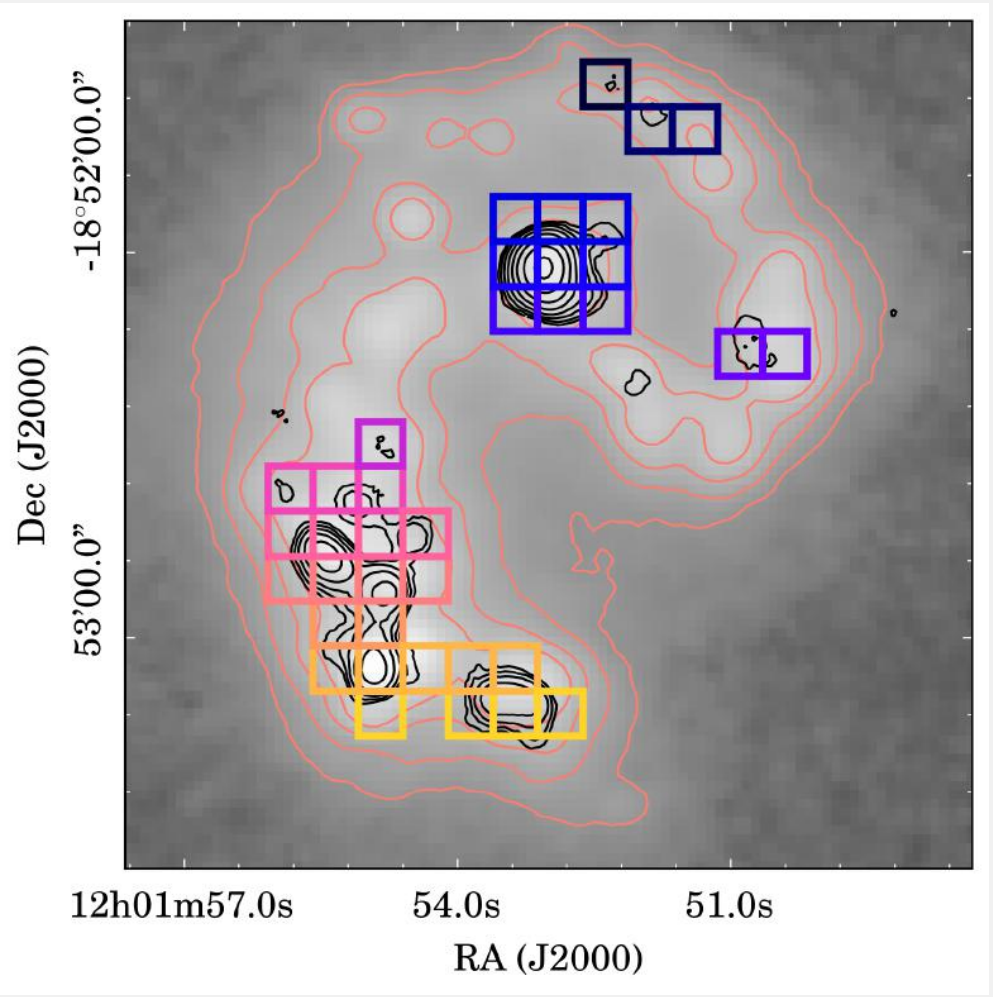
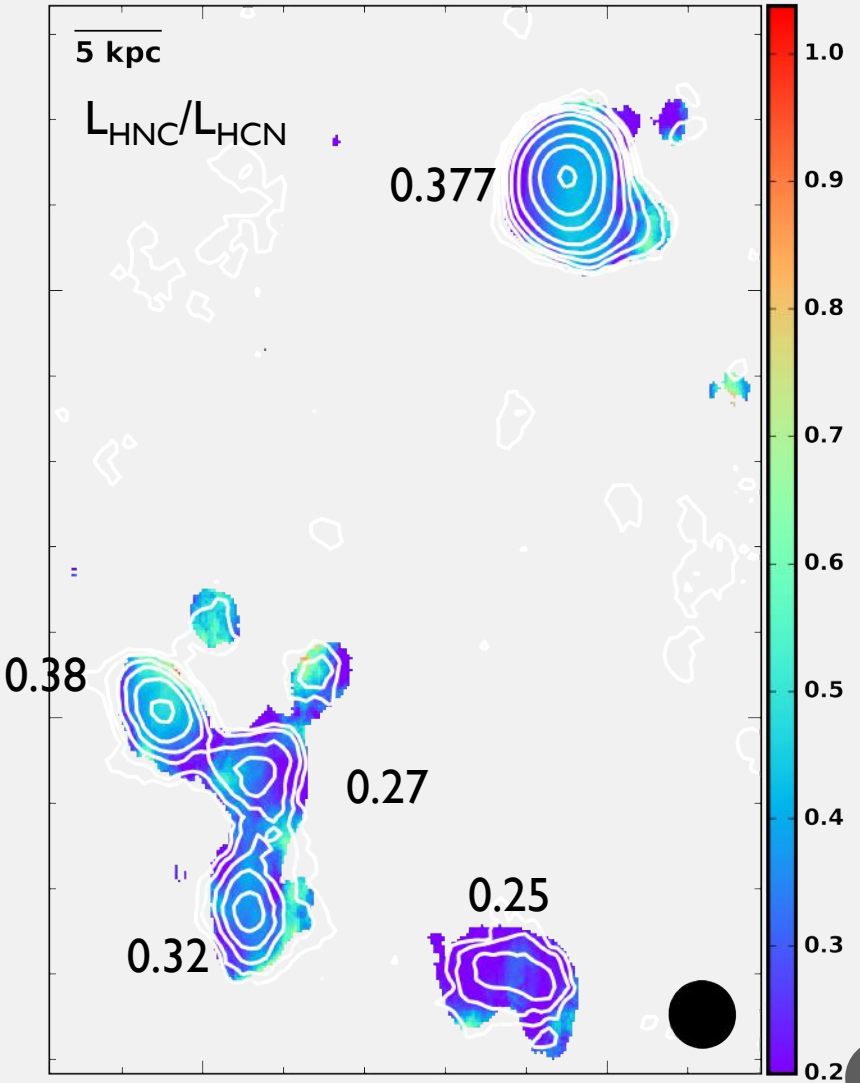




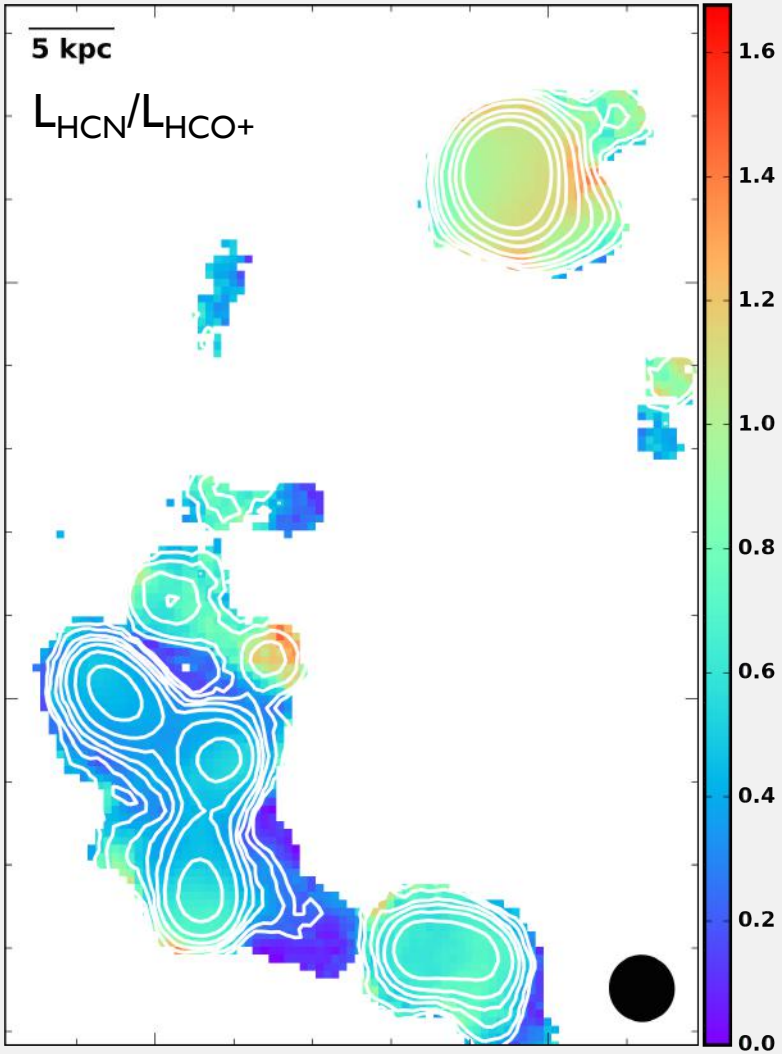
MECHANICAL HEATING

- Exchange reaction:
  H + HNC ←→ H + HCN
- L_{HNC}/L_{HCN} ratio indicates temperature, mechanical heating
- L_{HNC}/L_{HCN}:
  - higher in N4038 (~0.377)
  - lower in N4039 (~0.25) (Schirm + 2016)



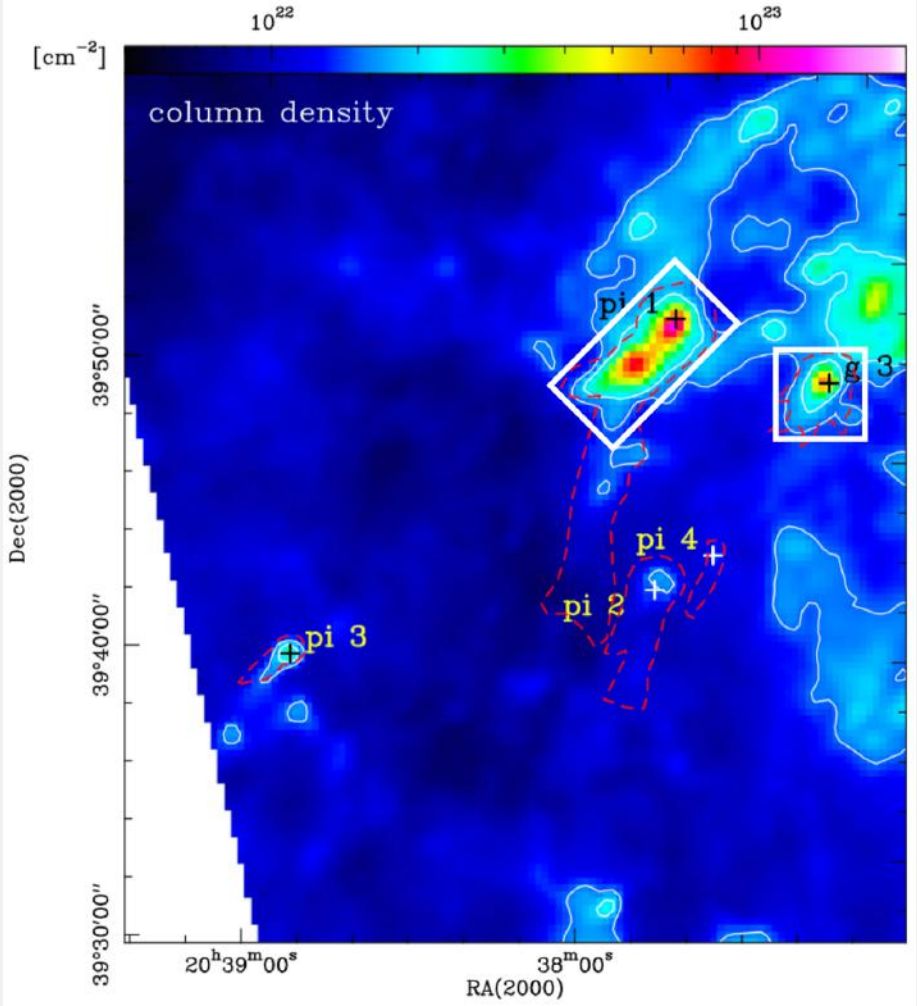
IONIZATION FRACTION & SF GAS

- HCO^+ sensitive to ionization fraction
- HCO^+ abundance reduced in SF and highly turbulent gas



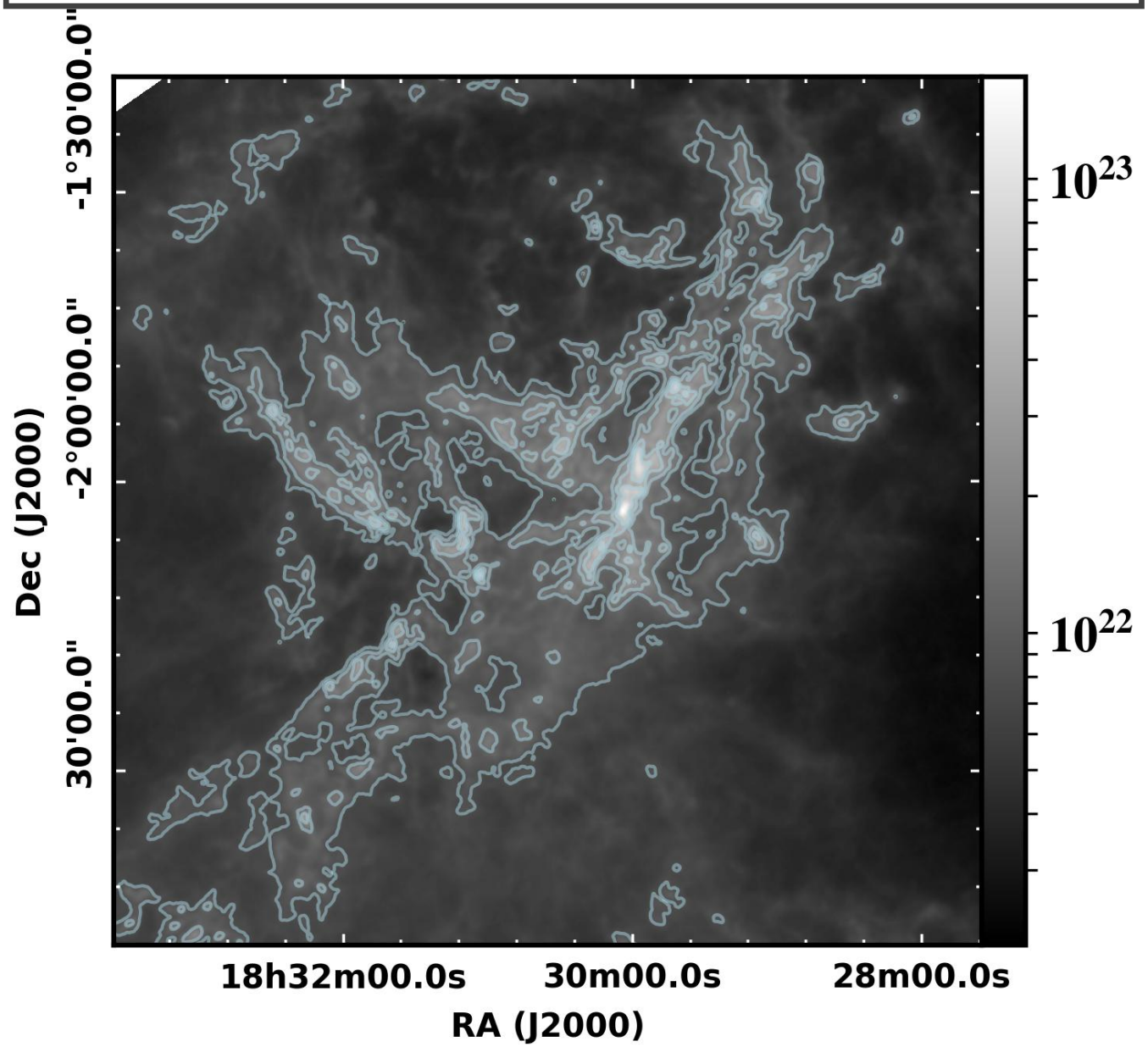
CONSTRAINING L_{HCN}-M_{DENSE} IN THE MW

- Observations of HCN 4-3 in Galactic GMCs
- Sources with accurate dust column density maps – HGBS / HOBYS
  - Cygnus X
  - Aquila



Cygnus X, Schneider+2016

AQUILA-SERPENS



CHECKING FOR BIASES: SFR