The MALATANG survey: dense gas and star formation in nearby star-forming galaxies

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On behalf of the MALATANG team

JCMT Users Meeting 2022, February 24th-25th

OUTLINE

- Background and Motivation
- The MALATANG survey
  - Science goals
  - Sample and Observations
  - Results
- Summary and Follow-up plans

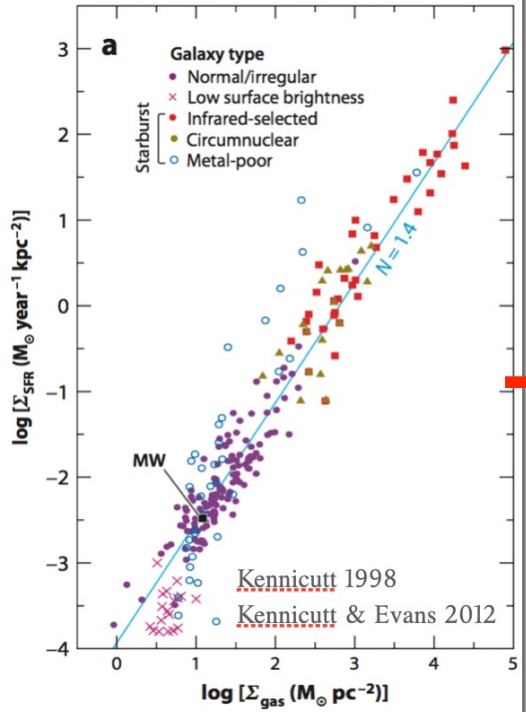
MOTIVATION

Which phases of gas are directly connected to star foramtion?

Scaling relations between gas and SF: $\log L_{IR} = \alpha L'_{gas} + \beta$

Kennicutt-Schmidt law

total gas = HI + H_2

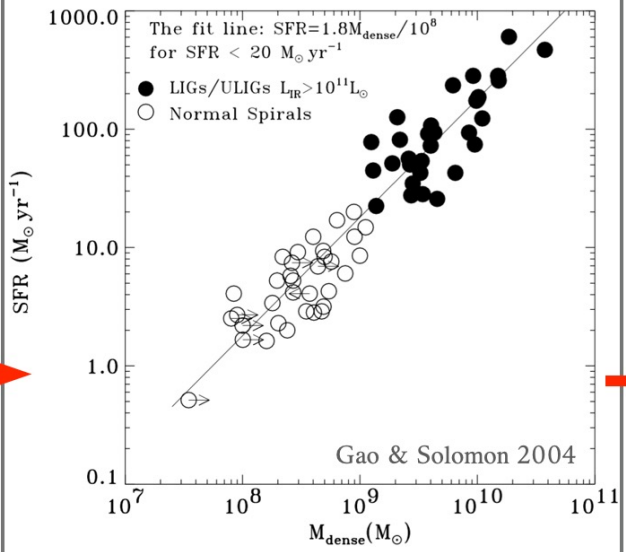


$\Sigma_{SFR} = A\,\Sigma_{gas}^{N} \quad N = 1.40 \pm 0.13$

super-linear slope: non-constant SF efficiency increases with SF rate

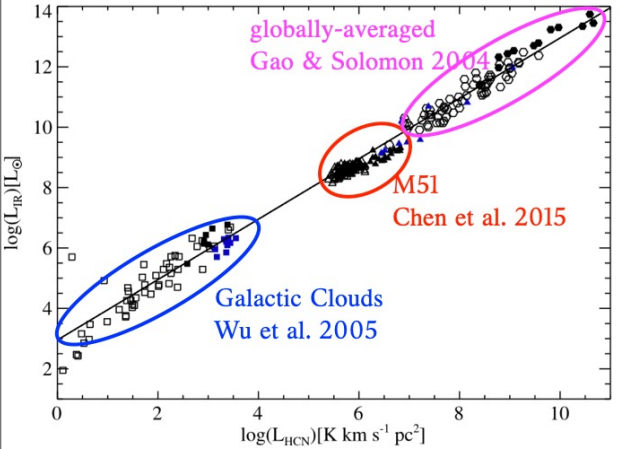
dense gas

(HCN J=1-0, $n_{crit} \sim 3\times10^4$ cm^{-3})

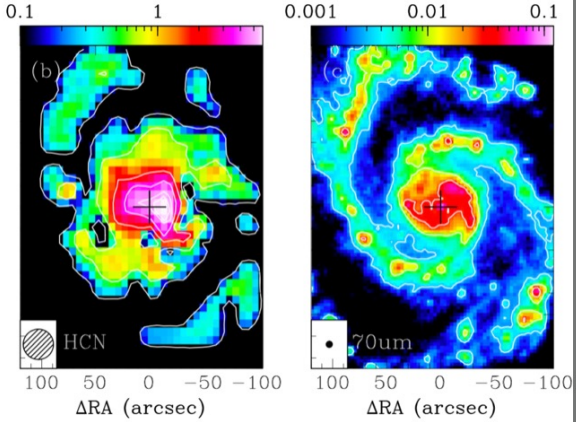


$SFR = 1.8\dot{M}_{dense}/10^8$

linear correlation: constant dense gas SF efficiency in galaxies; the dense molecular gas is directly connected to SF



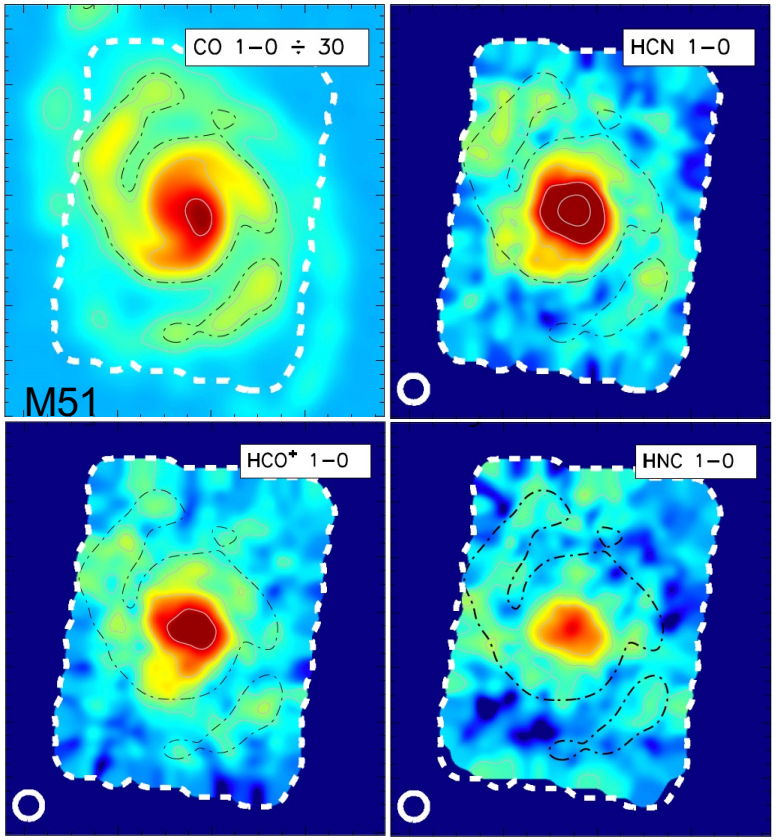
M51: HCN J=1-0 vs. PACS 70μm



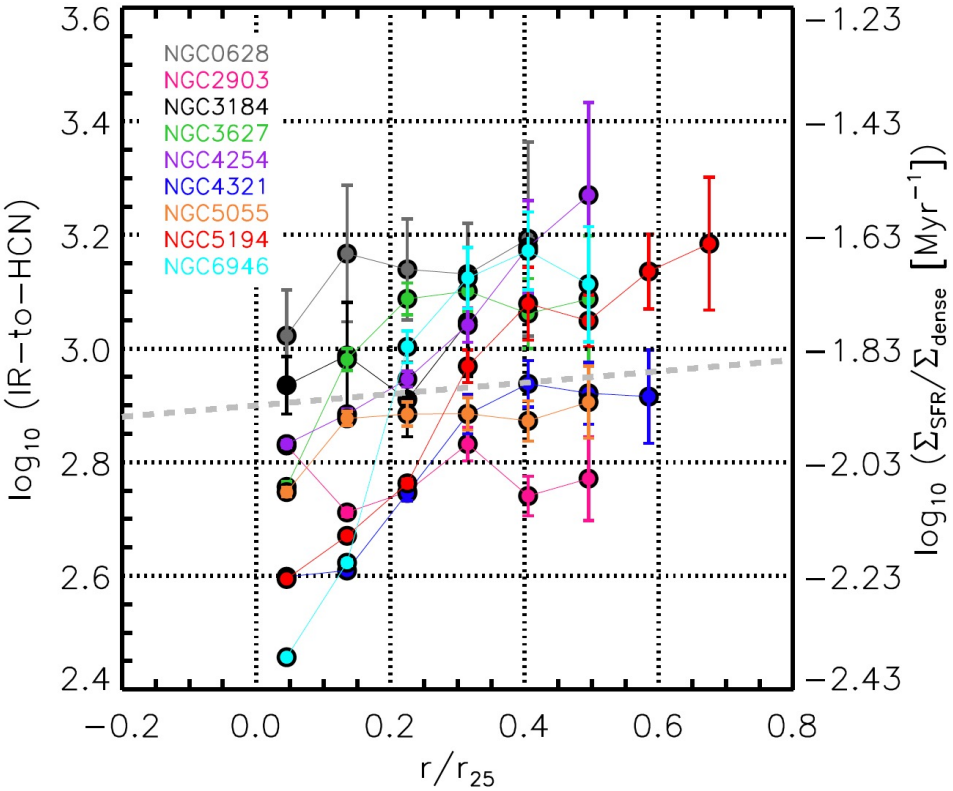
Chen, Gao et al. (2015)

MOTIVATION Whether dense gas forms stars is sensitive to the local environment?

IRAM 30m – EMPIRE (3-4mm dense gas tracers)



Bigiel et al. 2016

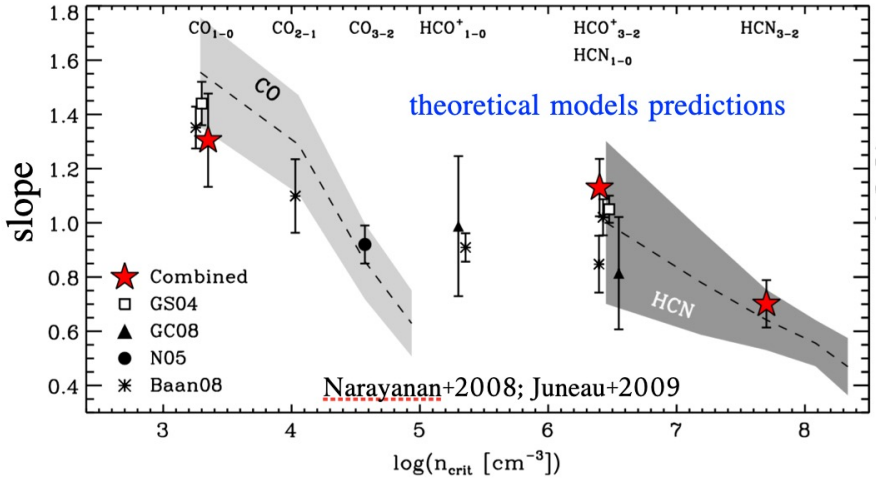


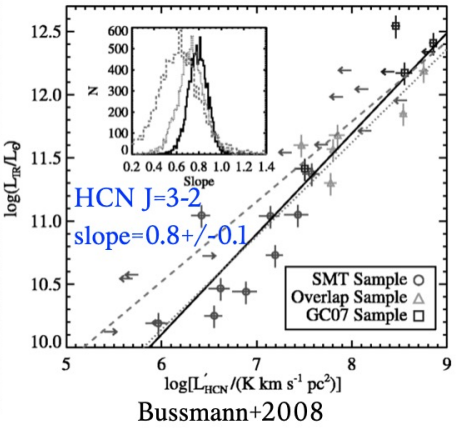
Jimenez-Donaire et al. 2019
(see also Usero et al. 2015)

- The conditions in a galaxy disk set the gas density distribution and that the dense gas traced by HCN shows an environment-dependent relation to star formation

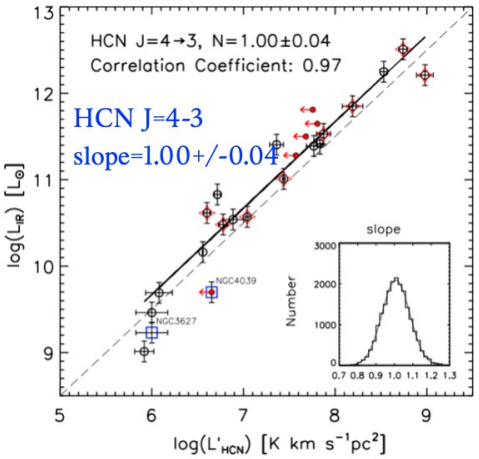
MOTIVATION How the gas properties affect their ability to form stars?

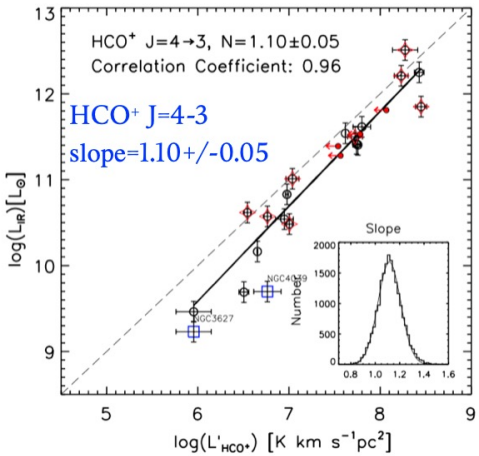
Slope of log(L_{IR})-log(L'gas) vs. molecular line critical densities

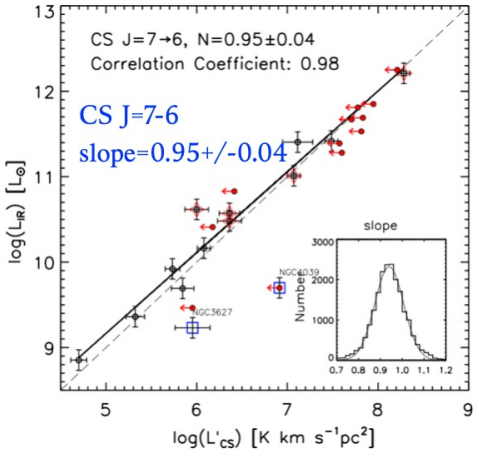




Transition	n_{crit} [cm^{-3}]	E_J/k_B [K]
$CO(1-0)$	4.4×10^2	5.53
$CO(2-1)$	3.6×10^3	16.60
$CO(3-2)$	1.3×10^4	33.19
$CO(4-3)$	3.0×10^4	55.32
$CO(5-4)$	5.9×10^4	82.97
$CO(6-5)$	1.0×10^5	116.16
$CO(7-6)$	1.5×10^5	154.87
$HCN(1-0)$	1.7×10^5	4.25
$HCN(2-1)$	1.6×10^6	12.76
$HCN(3-2)$	5.2×10^6	25.52
$HCN(4-3)$	1.3×10^7	42.53
$HCO^+(1-0)$	2.6×10^4	4.25
$HCO^+(2-1)$	2.6×10^5	12.76
$HCO^+(3-2)$	1.0×10^6	25.52
$HCO^+(4-3)$	2.5×10^6	42.53
$CS(1-0)$	8.3×10^3	2.35
$CS(2-1)$	7.9×10^4	7.05
$CS(3-2)$	3.0×10^5	14.11
$CS(4-4)$	7.7×10^5	35.27
$CS(5-4)$	1.8×10^6	49.37
$CS(6-5)$	3.1×10^6	65.83
$CS(7-6)$	4.9×10^6	65.83







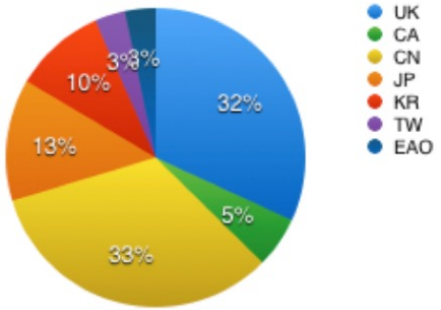
Zhang, Gao et al. (2014)

MALATANG

https://www.eao.hawaii.edu/MALATANG

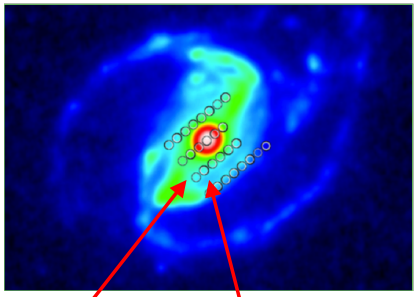
MApping the dense moLecular gAs in The strongest stAr-formiNg Galaxies

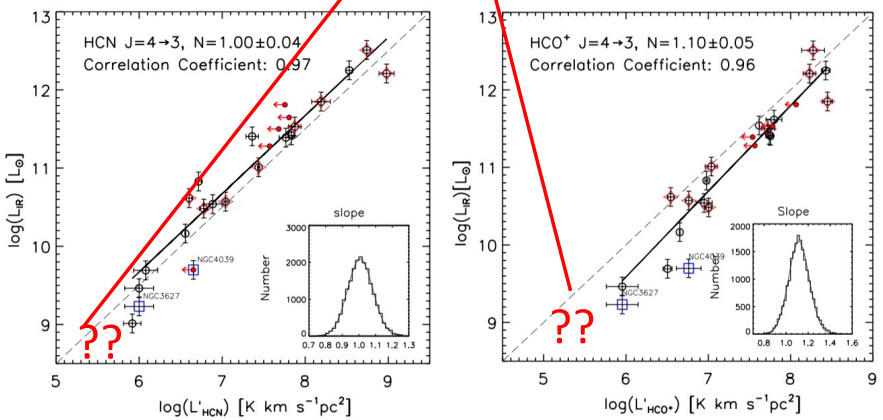
- JCMT Large Program – M16AL007 & M20AL022 (~40% complete)
- PIs: Yu Gao, Zhiyu Zhang, Thomas Greve
- A 400+400 hours (band 3 to 4) campaign on the JCMT using the HARP array to map HCN & HCO^+ J=4-3 in 28 of the nearest and IR-brightest galaxies beyond the local group
- First attempt at systematically map the distribution of dense gas out to large galactocentric distances in a statistically significant sample



SCIENCE GOALS

- Resolved dense gas star formation relations
- Intermediate scales/luminosities
- Different environments: nuclear vs. disk
- Radial distribution of dense gas and SF efficiency
- Dense gas excitation as a function of environment

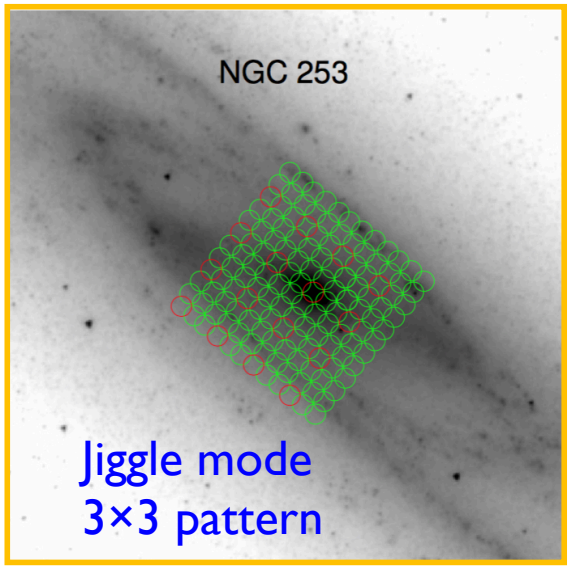




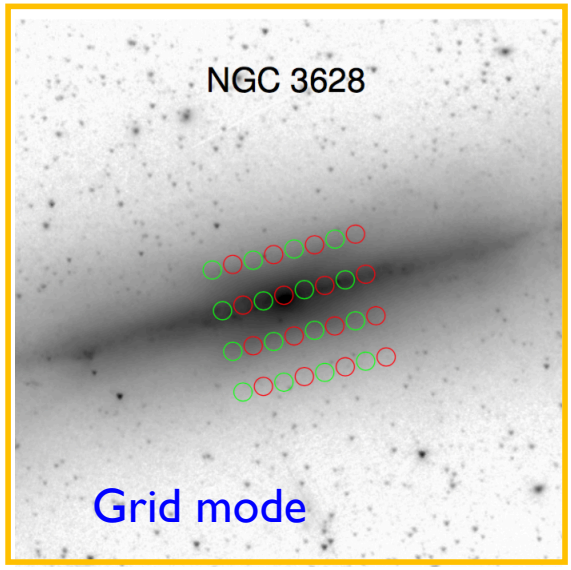
SAMPLE & OBSERVATIONS

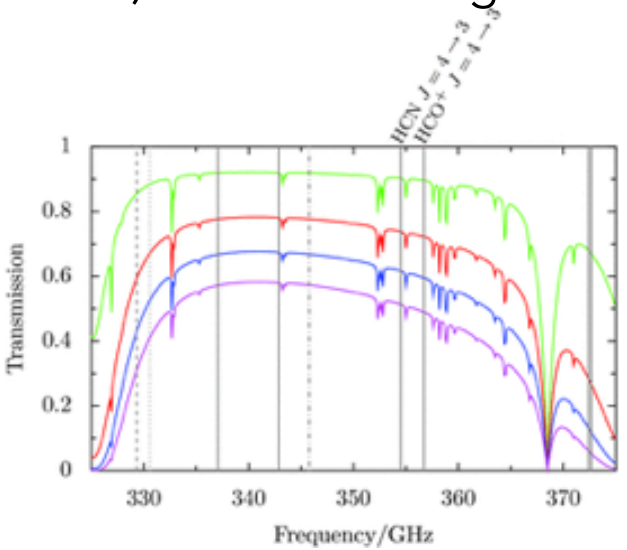
- S(60μm)>50 Jy and S(100μm)>100 Jy in RBGS(Sanders+03) and **δ**>-40 deg
- In total 28 IR bright nearby galaxies

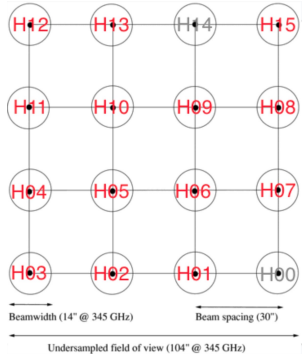
Face-on/large galaxies



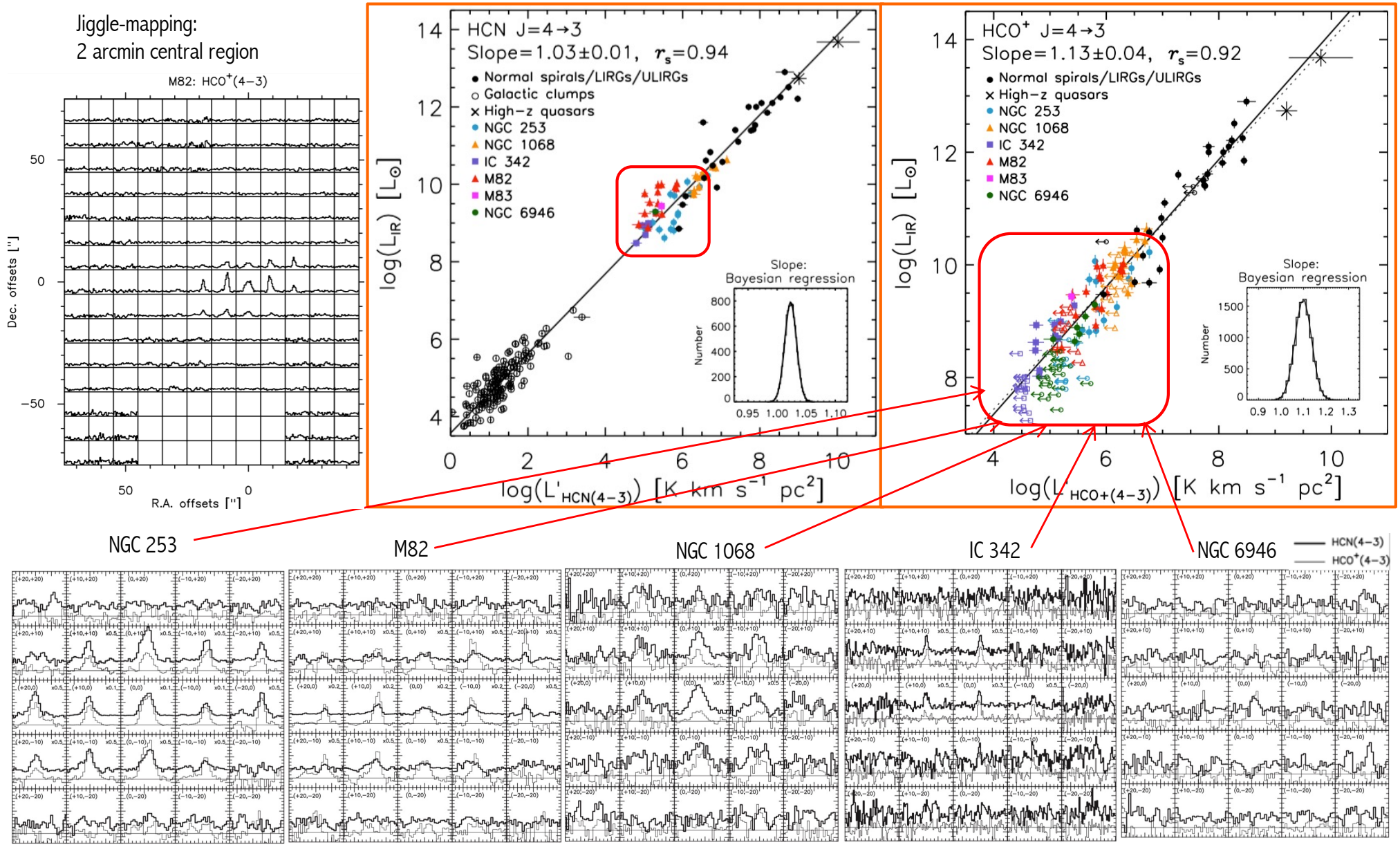
Edge-on galaxies







The MALATANG Survey: the Lgas-L_{IR} correlation on sub-kpc scale in six nearby star-forming galaxies (Tan et al. 2018)



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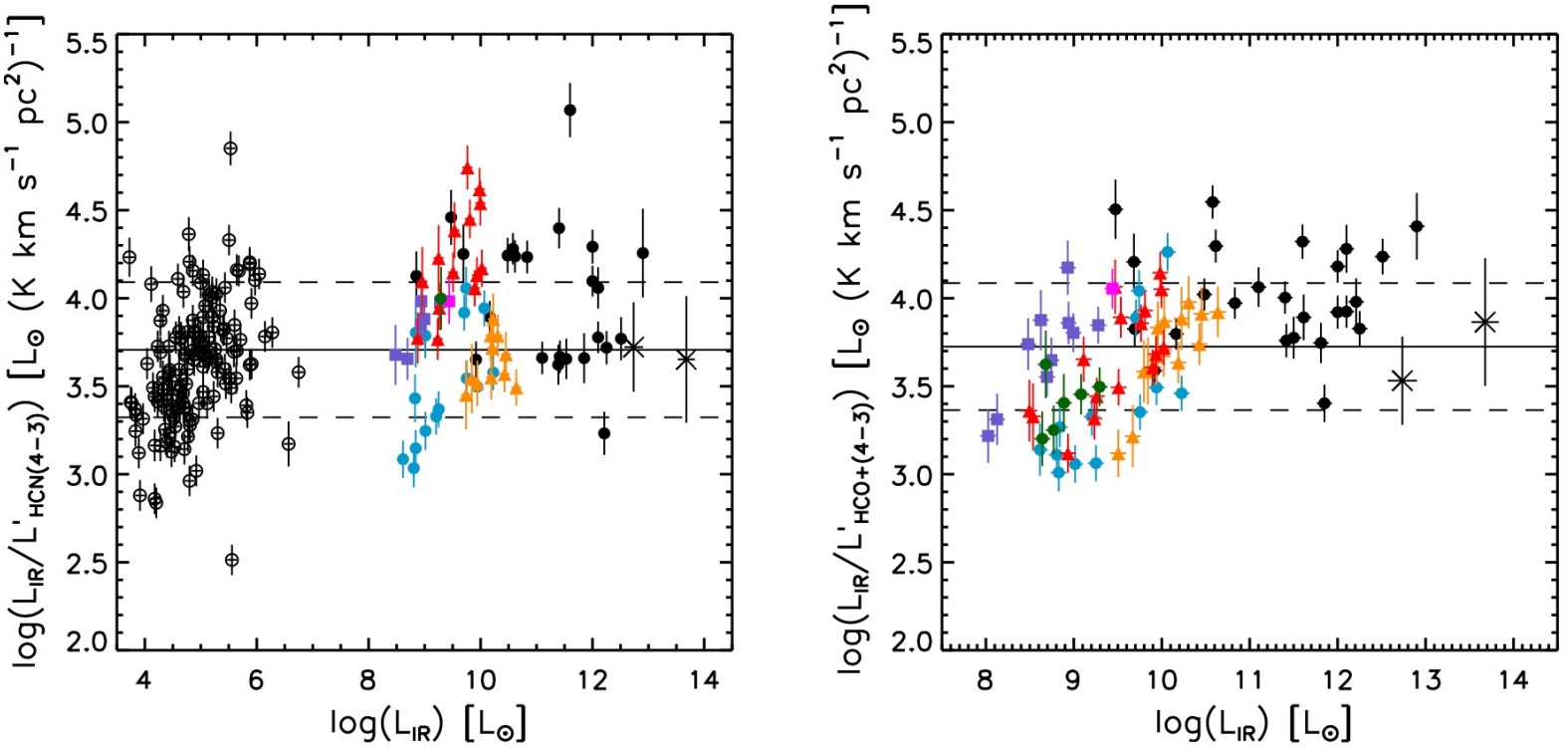
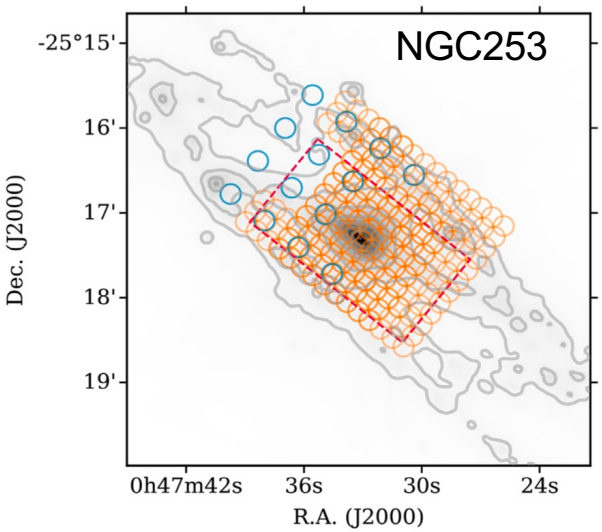
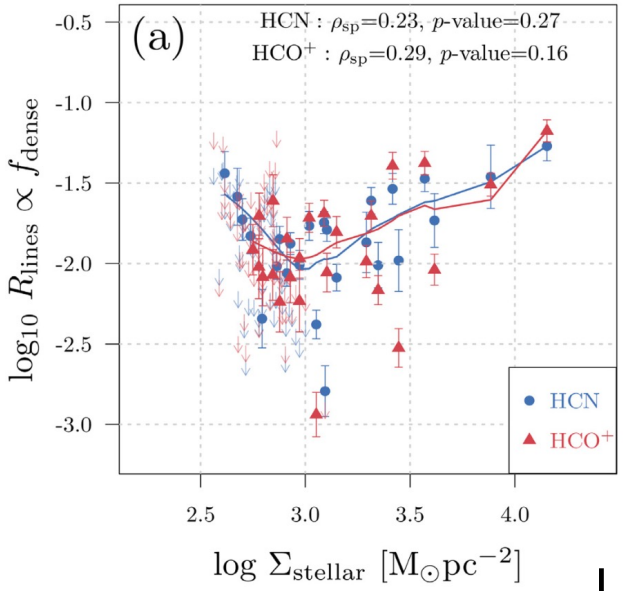


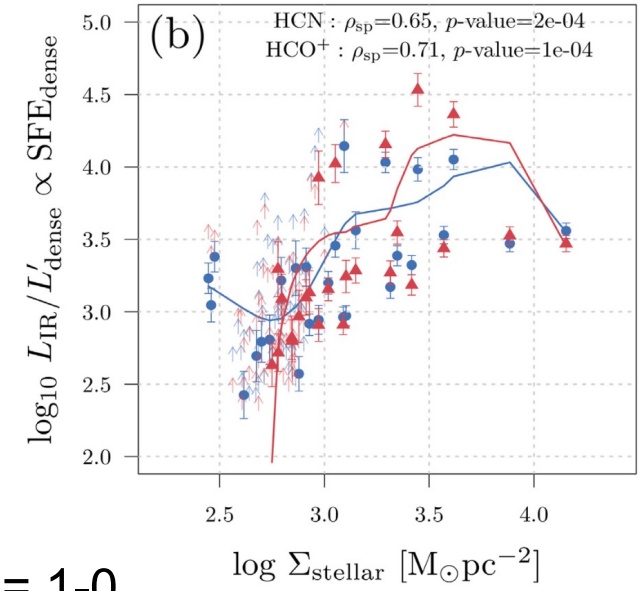
- The mean L_{IR}/L_{dense} ratio appears to vary little across the whole population of sample galaxies
- Significant scatter in L_{IR}/L_{dense} ratio (~0.36 dex for whole galaxies)
- L_{IR}/L_{dense} increases with L_{IR} for individual spatially resolved galalxies

The MALATANG Survey: dense gas and star formation from high transition HCN and HCO^+ maps of NGC 253 (Jiang et al. 2020)

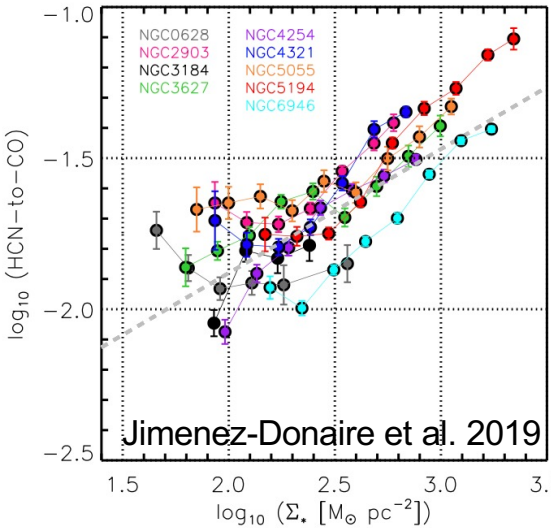
J = 4-3

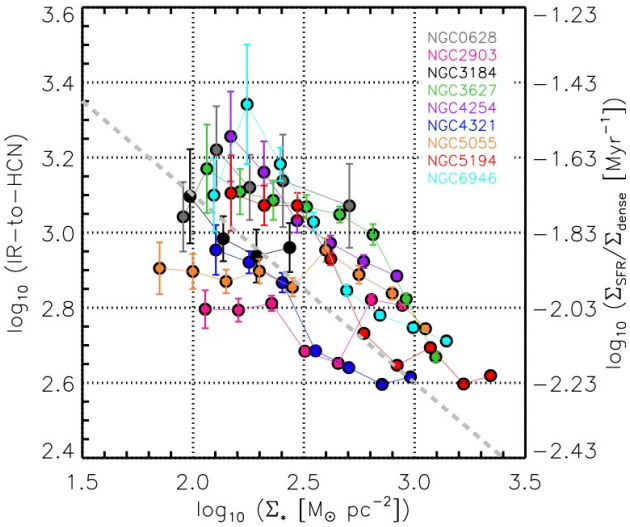






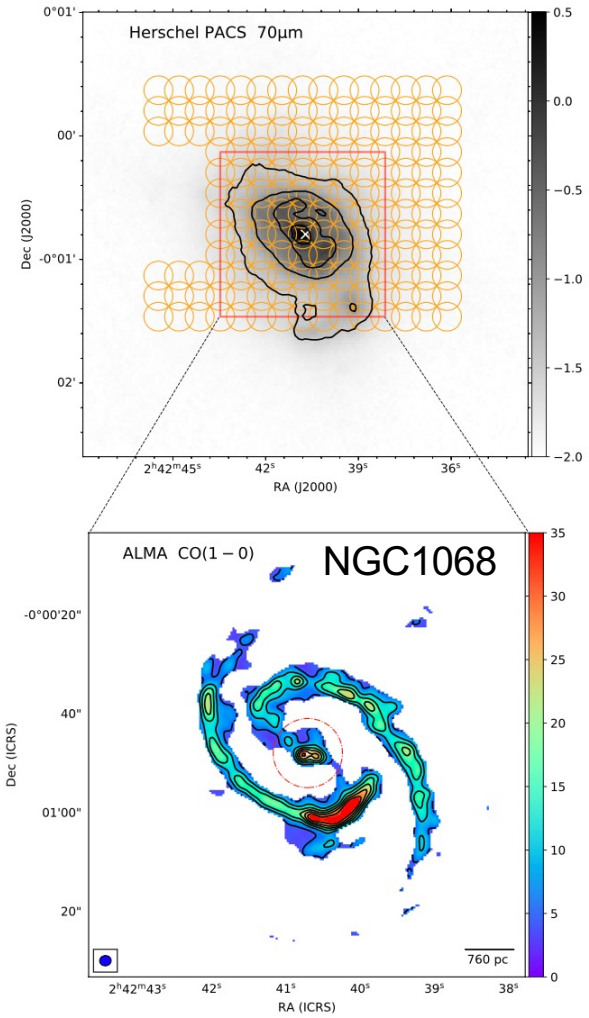
J = 1-0

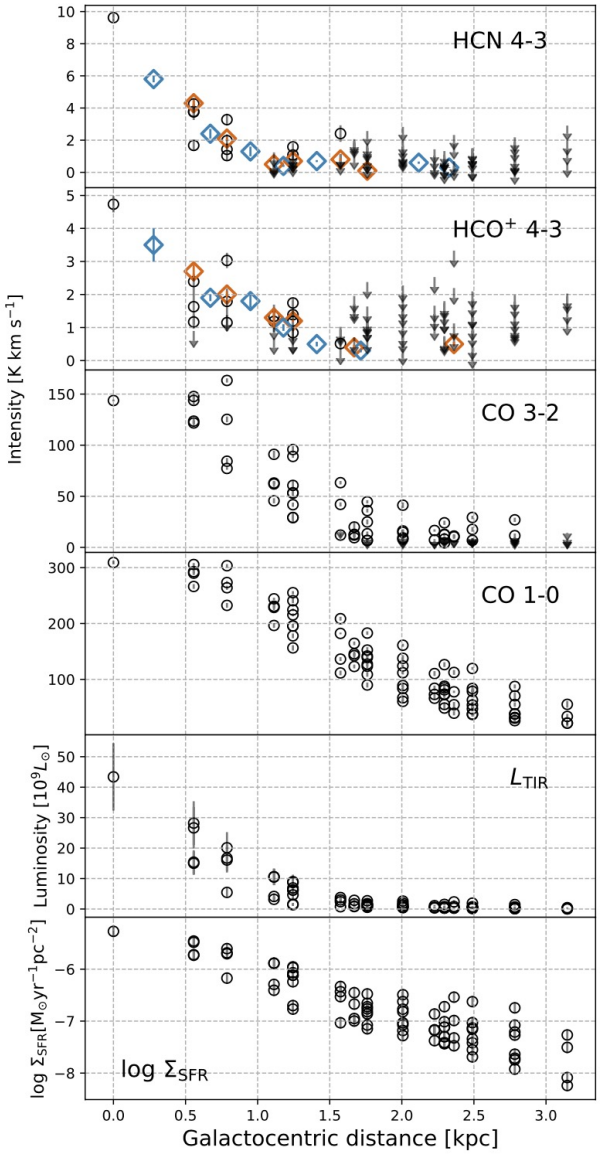


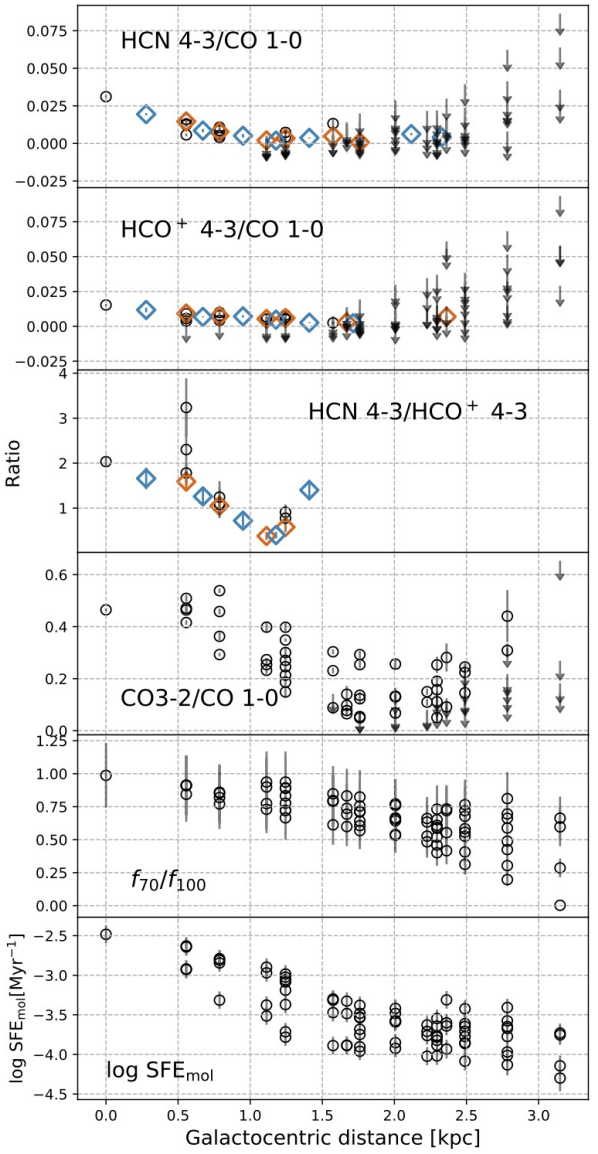


- SFE_{dense} increases with higher stellar surface density, inconsistent with the results using HCN J=1-0 data
- The existing stellar components might have different effects on the high-J HCN and HCO^+

The MALATANG Survey: dense gas and star formation in NGC 1068 (Lin et al. 2022, submitted)

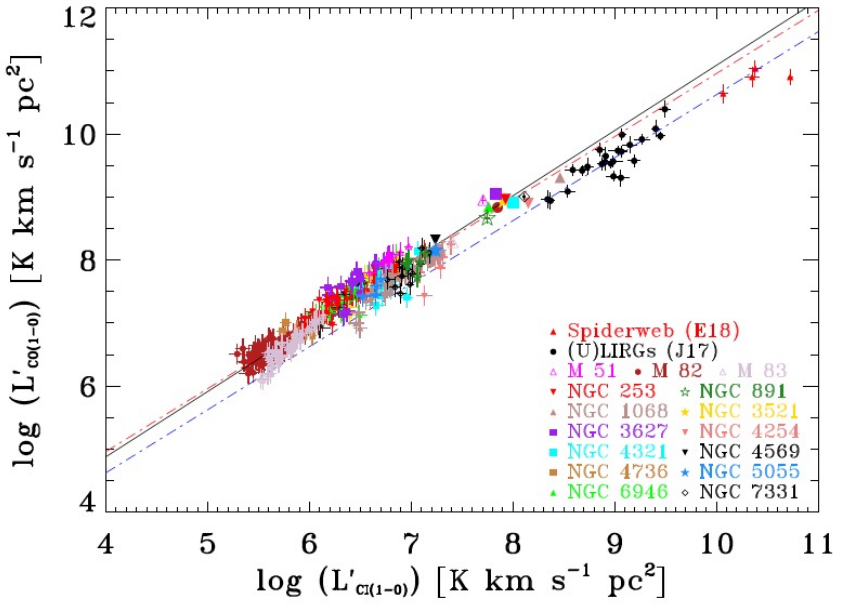


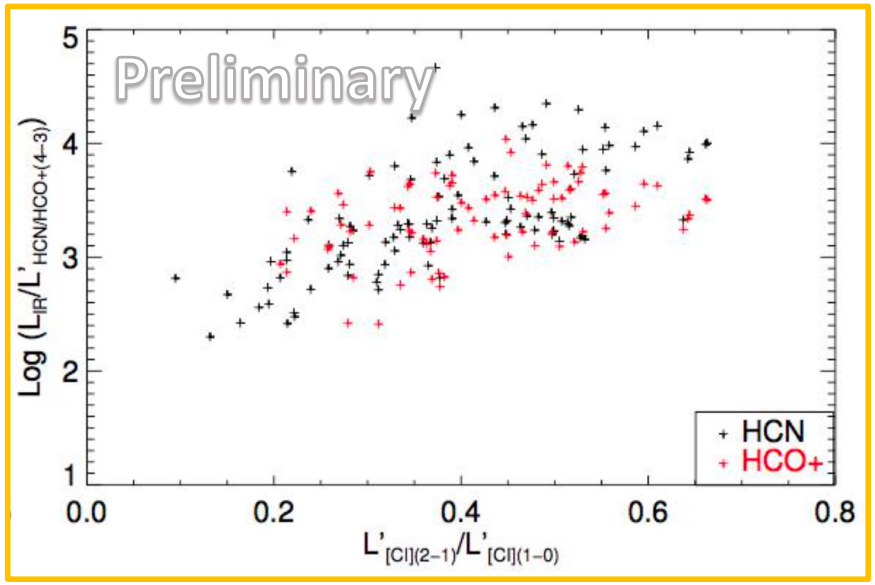


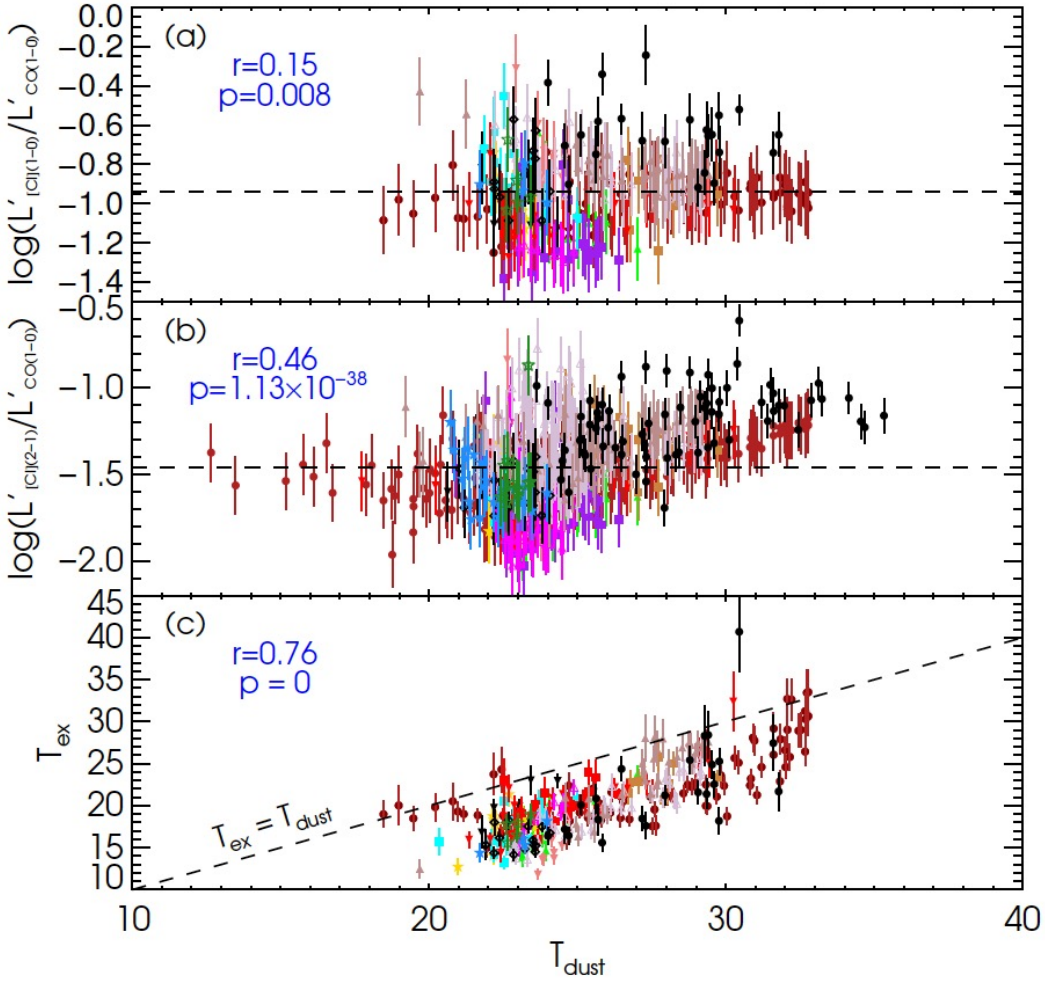


The relationship between SFE_{dense} and [CI] excitation

(Jiao et al., in prep.)

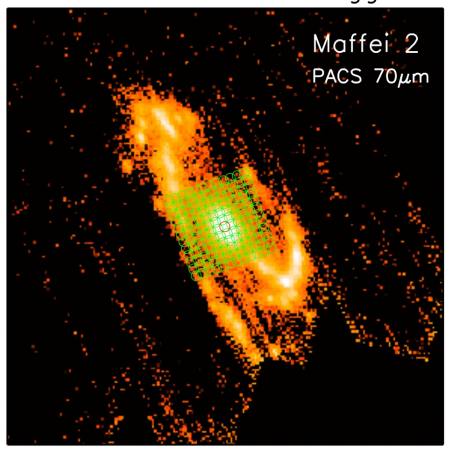


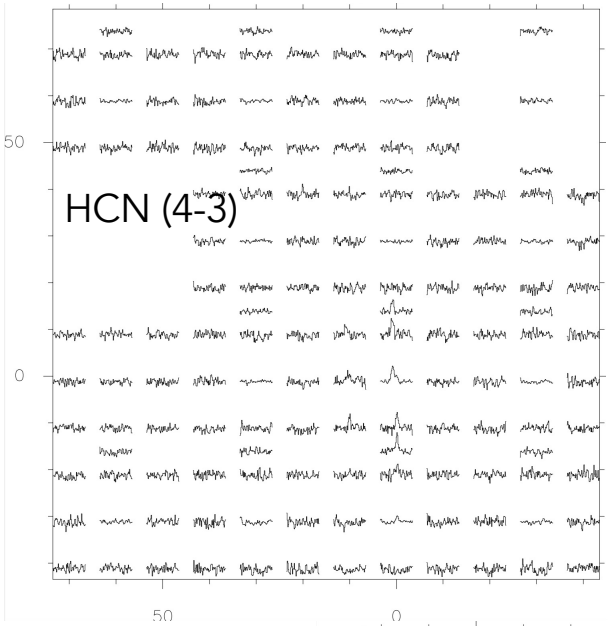


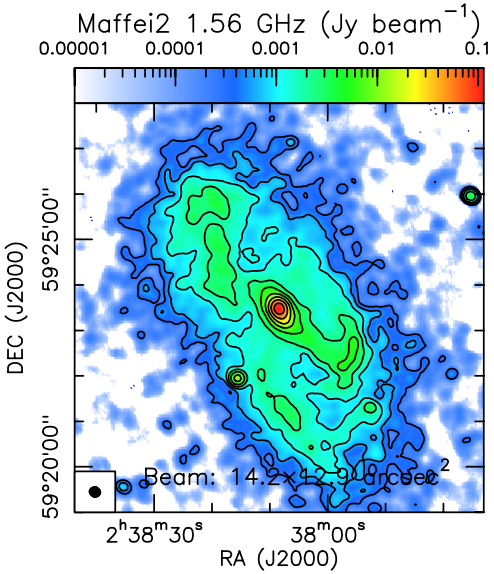


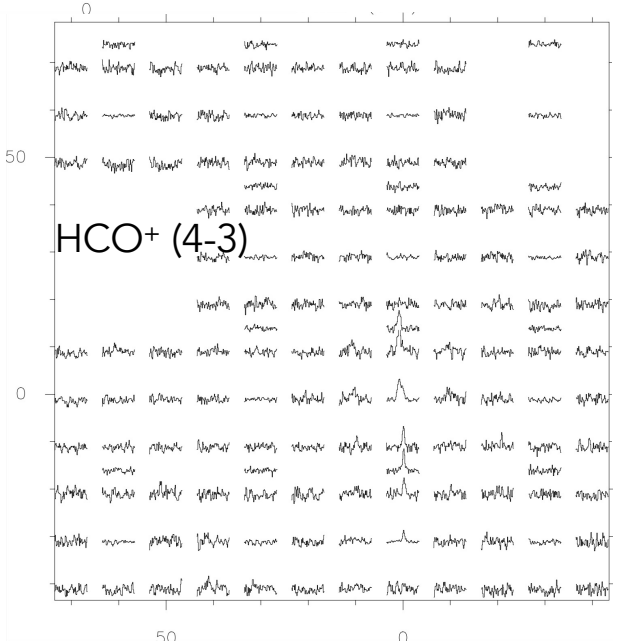
Jiao et al. 2017, 2019

The relationships between dense gas, infrared emission, and radio conitnuum on sub-kpc scale in galaxies (Tan et al. in prep.)

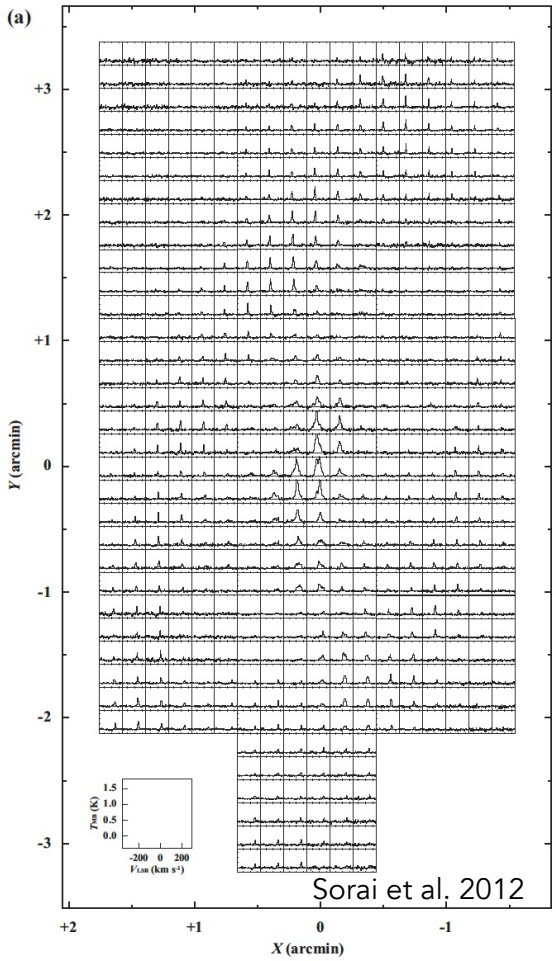








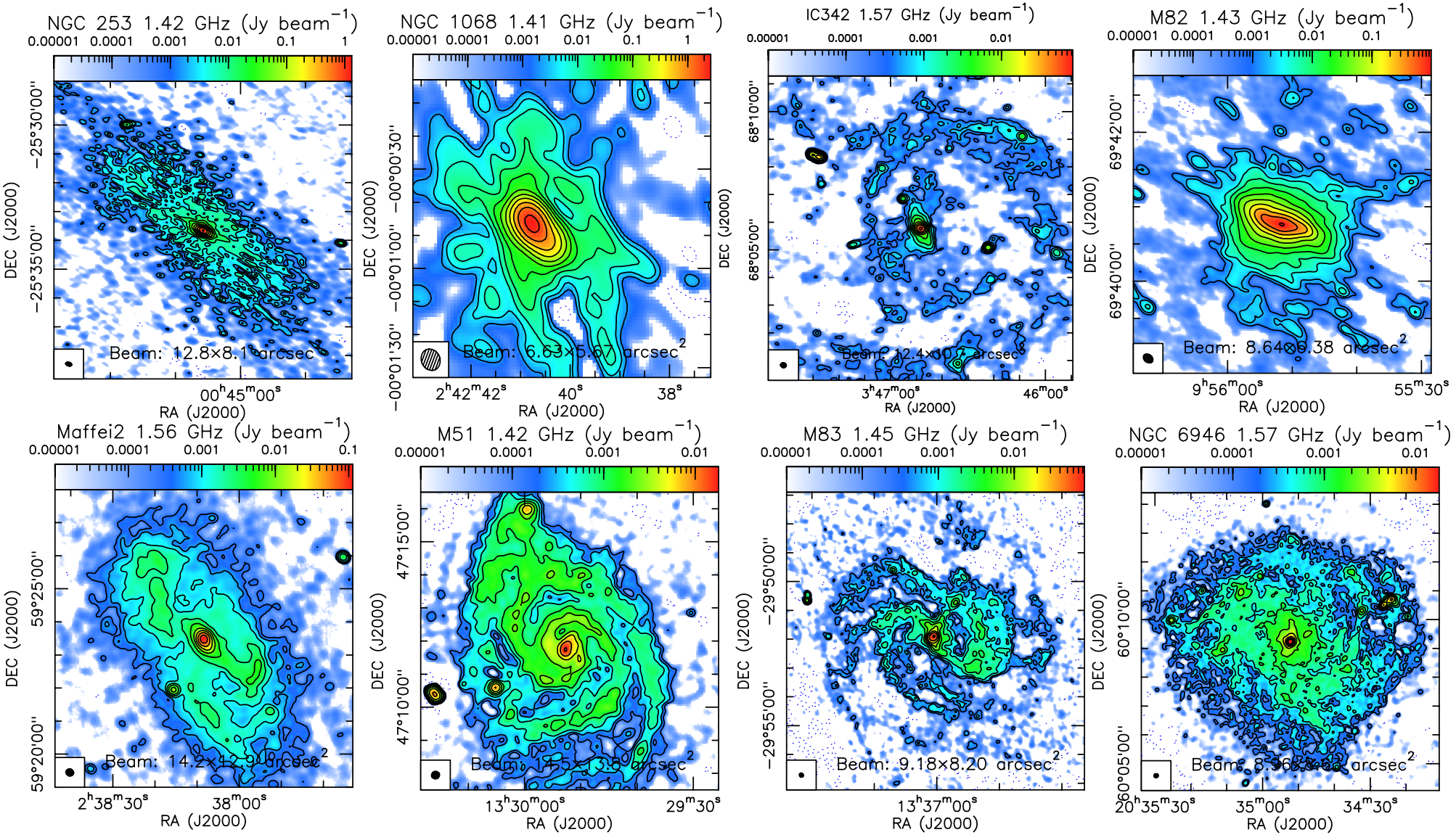
NRO45m: CO (1-0)



Sorai et al. 2012

The relationships between dense gas, infrared emission, and radio conitnuum on sub-kpc scale in galaxies (Tan et al. in prep.)

VLA L-band Radio Continuum



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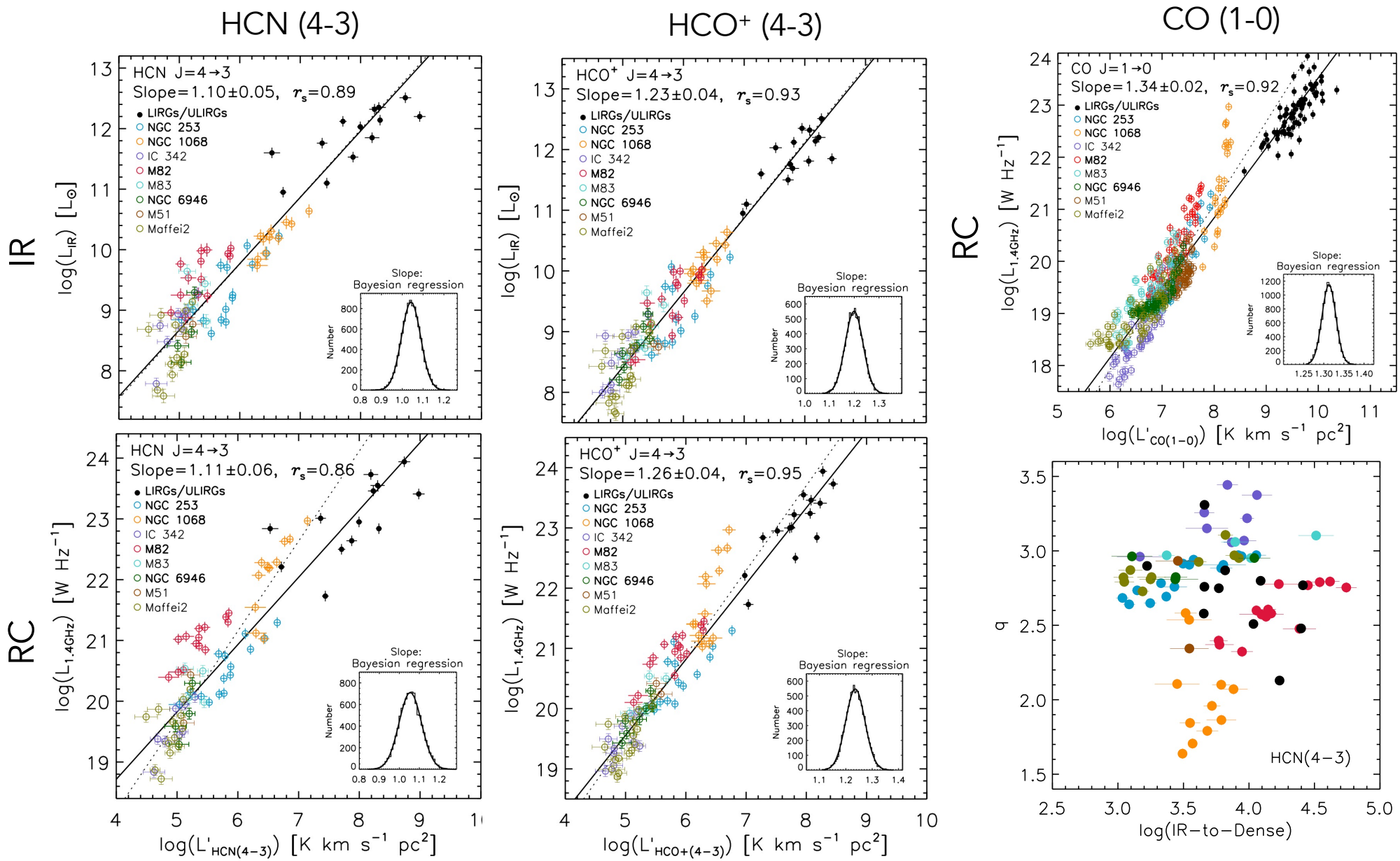

SUMMARY

- Dense gas and star formation in spatially resolved galaxies at sub-kpc scale
  - linear correlation, extend the relaiton to an intermediate luminosity regime
  - systematic variations of SFE_{dense} with L_{IR} within individual galaxies
- Detailed studies on NGC 253 and NGC 1068
  - SFE_{dense} traced by high-J HCN/HCO^+ increases with higher stellar surface density, inconsistent with the results based on HCN J=1-0
- The relationship between SFE_{dense} and [CI] excitaiton
- Relationships between dense gas, star formation, and radio continuum
  - tight correlation between dense gas and RC
  - a rising trend for IR/RC as a function of SFE_{dense}, IR-RC relation may have a dependency on the local environment

FOLLOW-UP PLANS

- Observations
  - JCMT SCUBA-2 & HCN/HCO^+ J=3-2
  - High resolution SMA/ALMA maps
  - Herschel archive: high-J CO, [CI] data
  - APEX high-J HCN/HCO^+/CS lines
- Modelling:
  - LVG & PDR modelling of SF regions
  - reproducing observed relations and line ratio

Thank you!