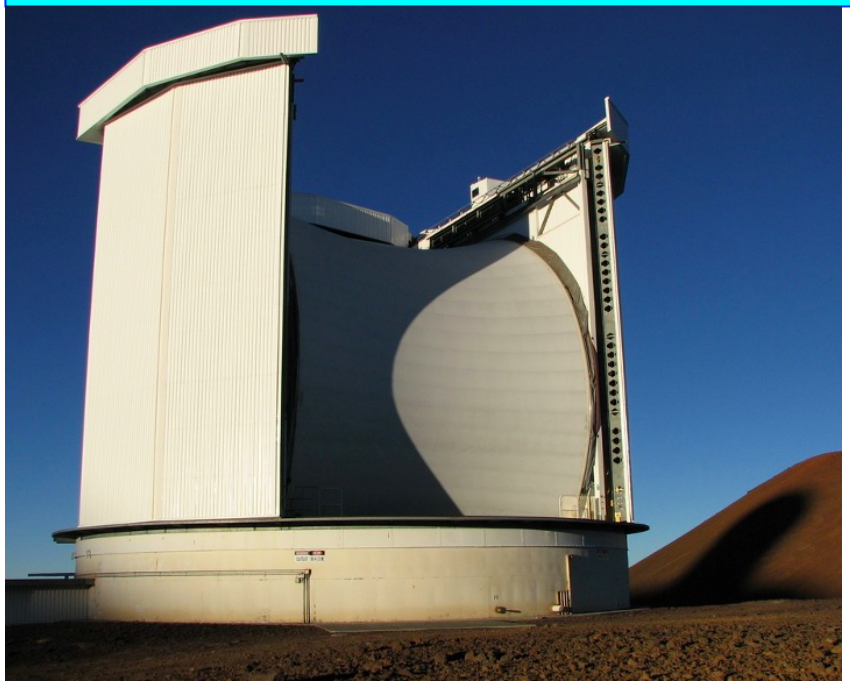
"STIRRING THE POT" – THE MALATANG SURVEY OF DENSE GAS IN NEARBY GALAXIES



Yu GAO (高煜) (>90 team members)
Purple Mnt. Obs

1 Chen, Gao & Braine+2015/7 ApJ (1612.00459***)***; 2 Liu,D., Gao & Isaak+2015 ApJL (1504.05897); 3 Liu,L., Gao & Greve 2015 ApJ (1502.08001); ***4 Zhang, Gao & Henkel+2014 ApJL***

MALATANG

Gastronomical meaning:

A common type of Chinese street food, especially popular in Beijing It originated in Sichuan, but it differs mainly from the Sichuanese version in that the Sichuanese version is more similar to what in northern China would be described as hot pot.

Astronomical meaning:

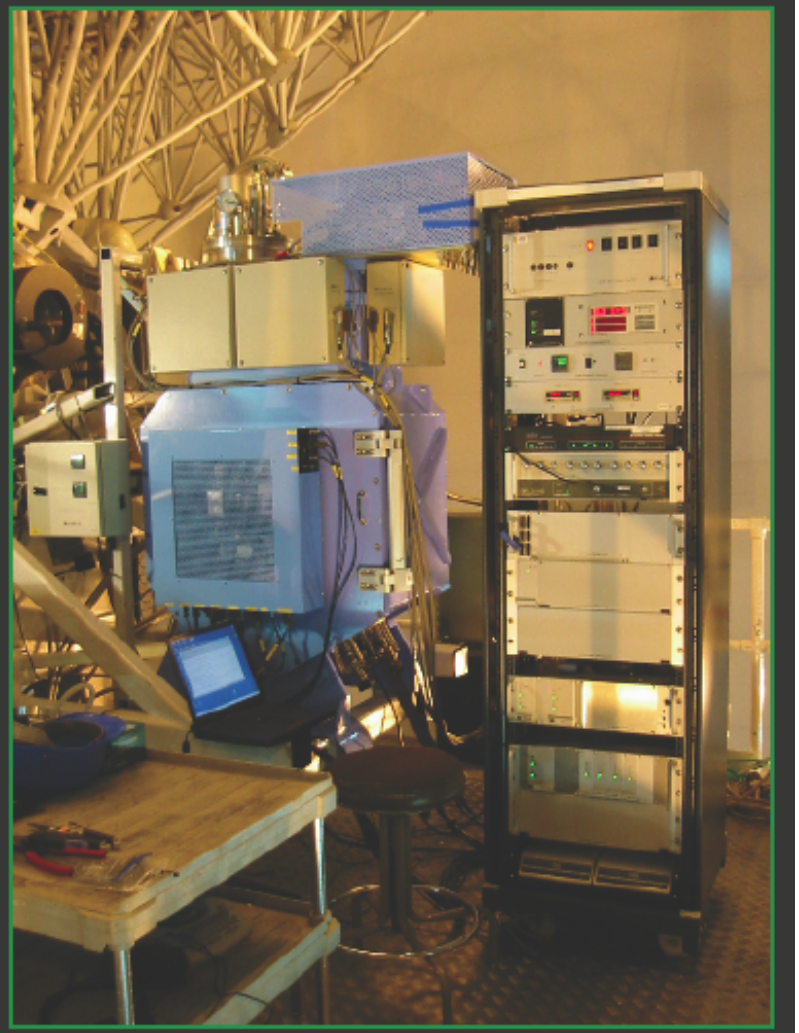
MALATANG = MApping the dense moLecular gAs in The strongest stAr-formiNg Galaxies

www.eaobservatory.org/jcmt

MALATANG IN A NUTSHELL

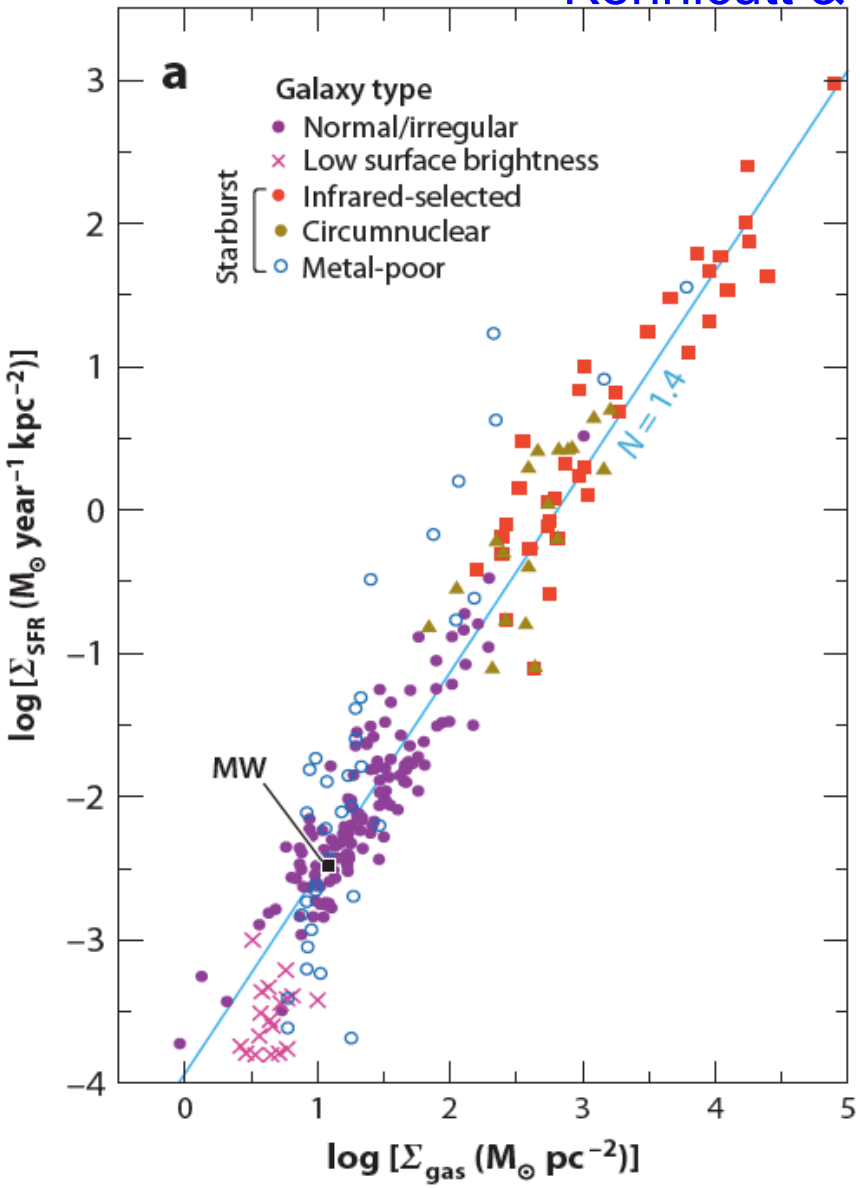
- *A 390hr campaign on the JCMT using the HARP array to map HCN and HCO+ J=4-3 in 23 of the nearest and IR-brightest galaxies beyond the Local Group*
- *First attempt at systematically map the distribution of dense gas out to large galactocentric distances in a statistically significant sample*
- *Explore the dense gas vs. star formation relationship down to gas masses of ~5×$10^6 M_\odot$ and scales ~0.2-2.8kpc in other galaxies*
- *Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations*

HARP

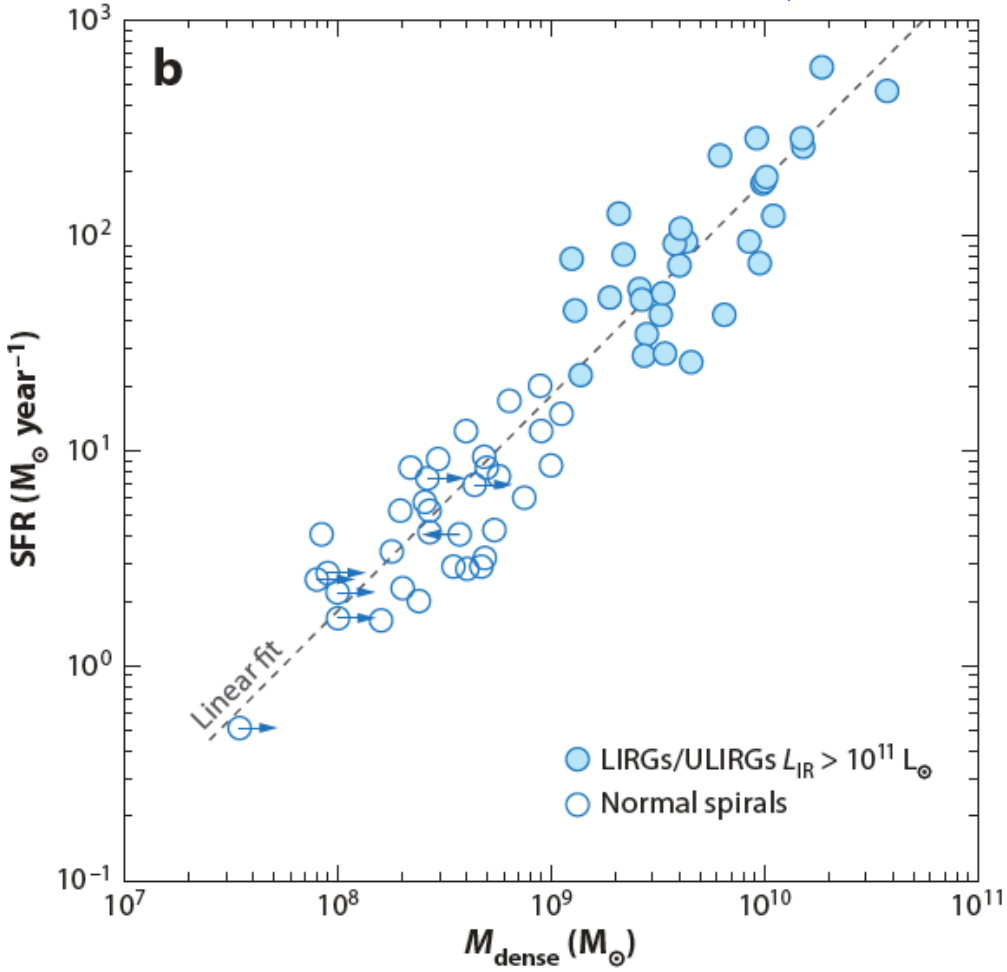


Motivation

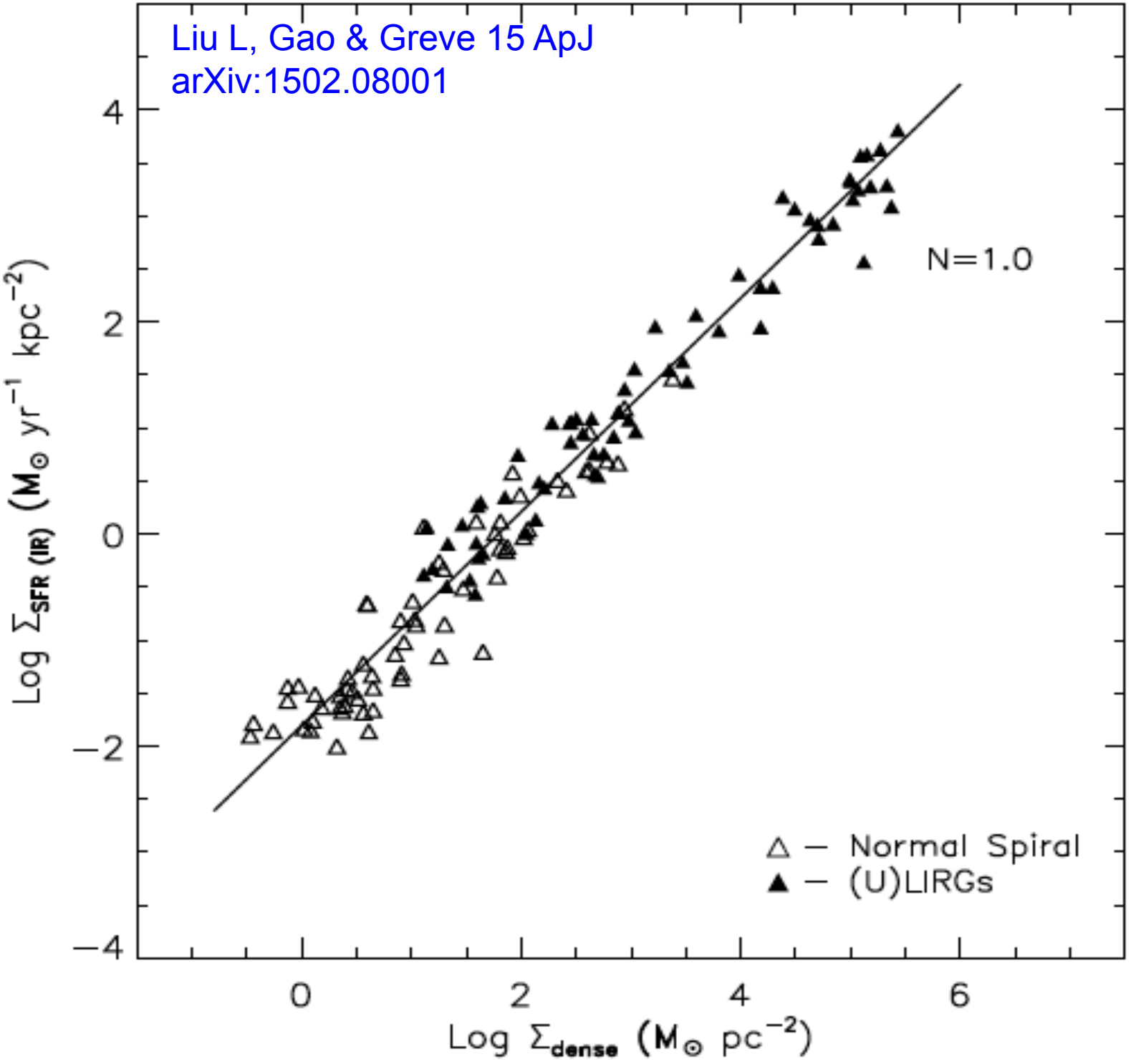
Kennicutt & Evans 2012, ARAA

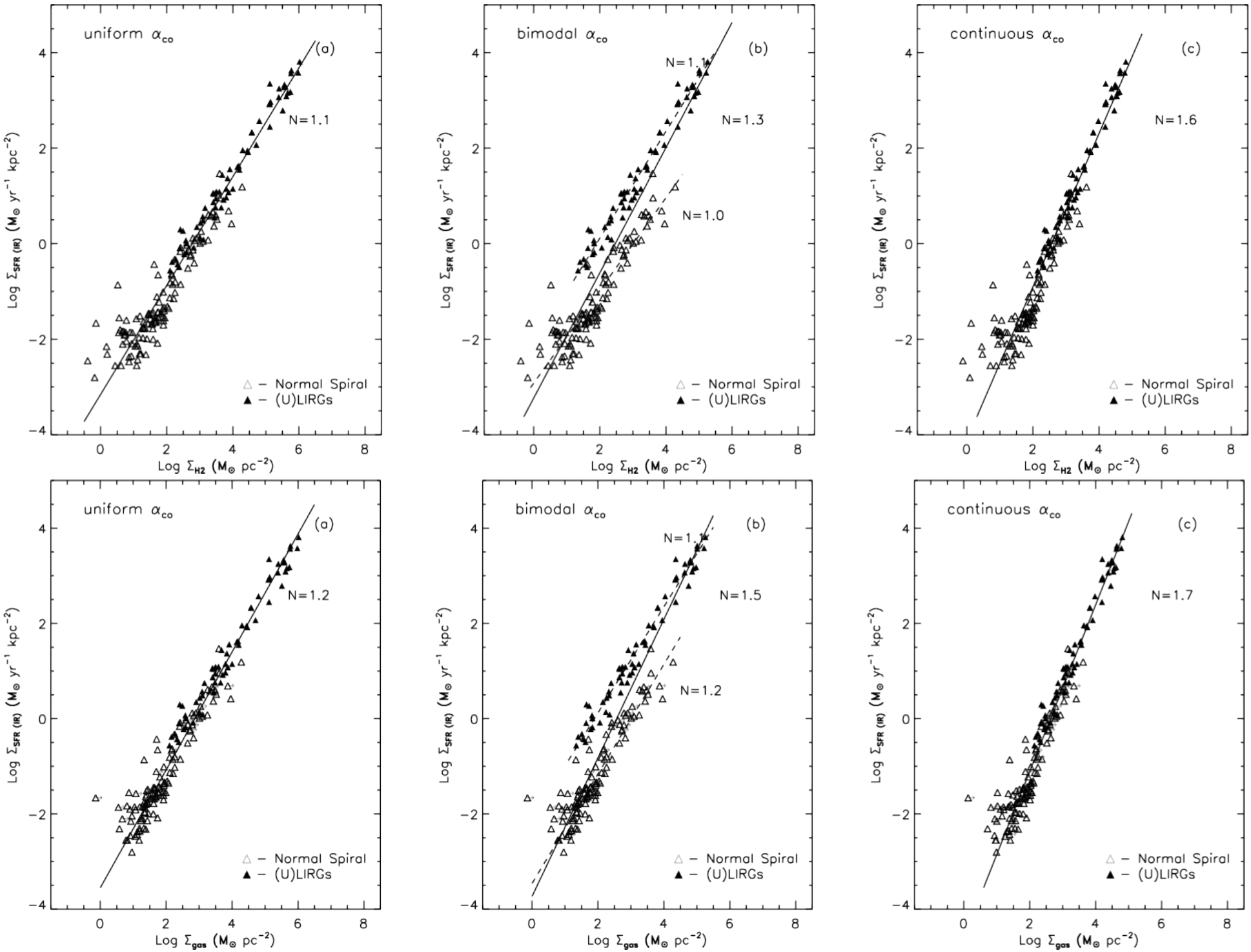


Gao & Solomon 2004a,b

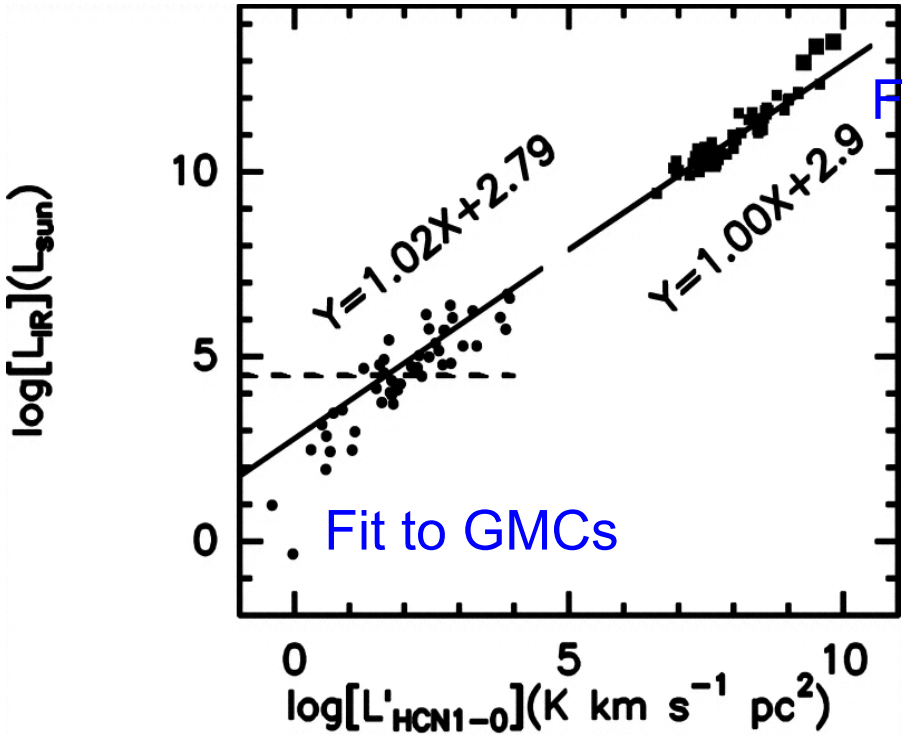


Disk-average [SFR~ density(HI+H2)^1.4]

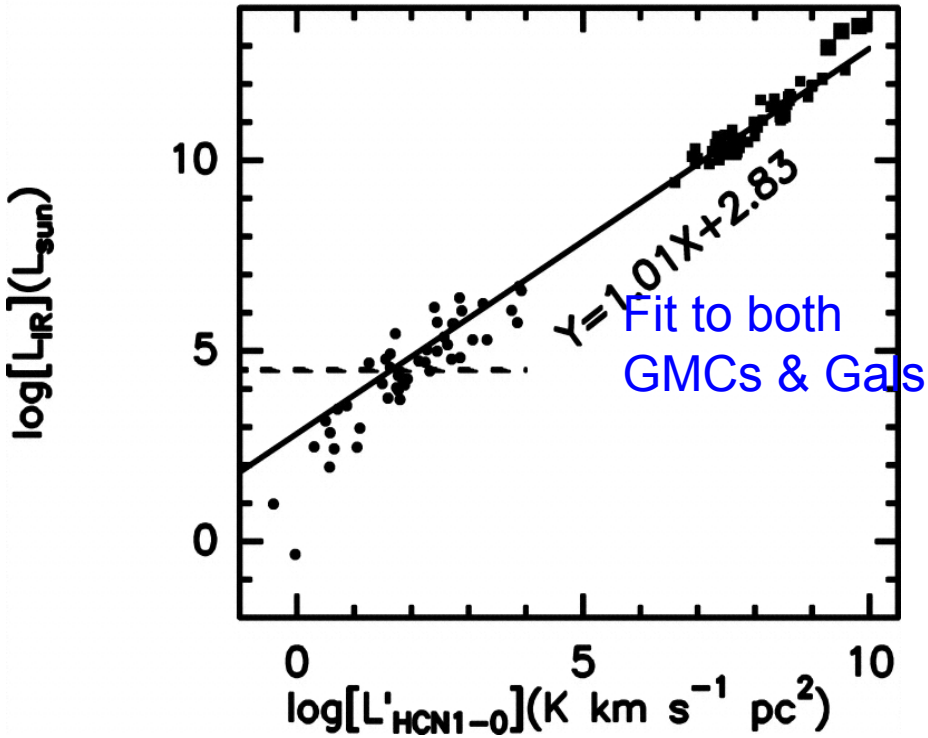

Liu L, Gao & Greve 15 ApJ
arXiv:1502.08001
N=1.0
△ — Normal Spiral
▲ — (U)LIRGs
Log $\Sigma_{SFR\ (IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{dense} ($M_\odot$ pc^{-2})
4
2
0
−2
−4
0
2
4
6

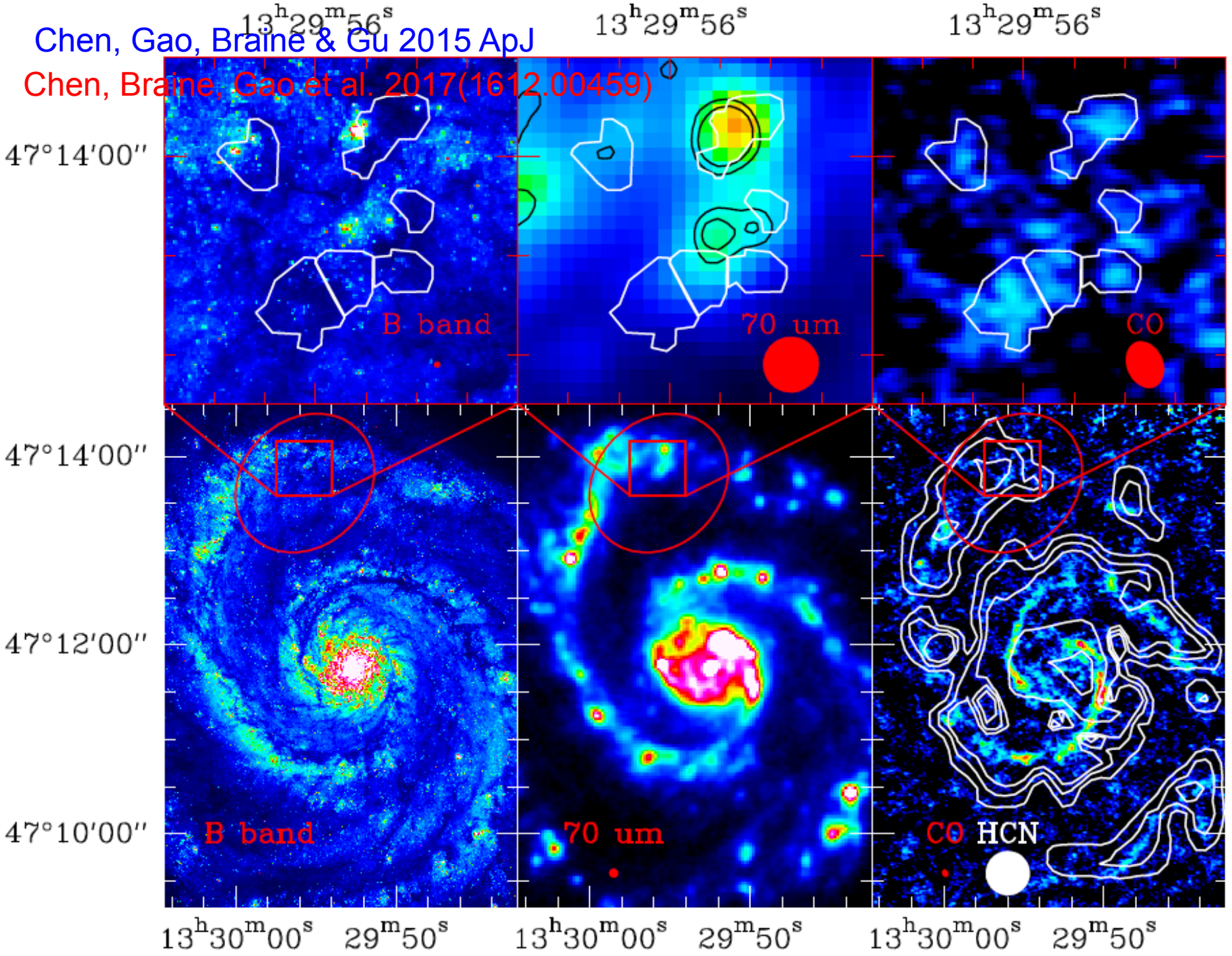

uniform α_{co}
(a)
N=1.1
bimodal α_{co}
(b)
N=1.3
N=1.0
continuous α_{co}
(c)
N=1.6
△ – Normal Spiral
▲ – (U)LIRGs
Log $\Sigma_{SFR\ (IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{H2} ($M_\odot$ pc^{-2})
uniform α_{co}
(a)
N=1.2
bimodal α_{co}
(b)
N=1.5
N=1.2
continuous α_{co}
(c)
N=1.7
△ – Normal Spiral
▲ – (U)LIRGs
Log $\Sigma_{SFR\ (IR)}$ ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{gas} ($M_\odot$ pc^{-2})

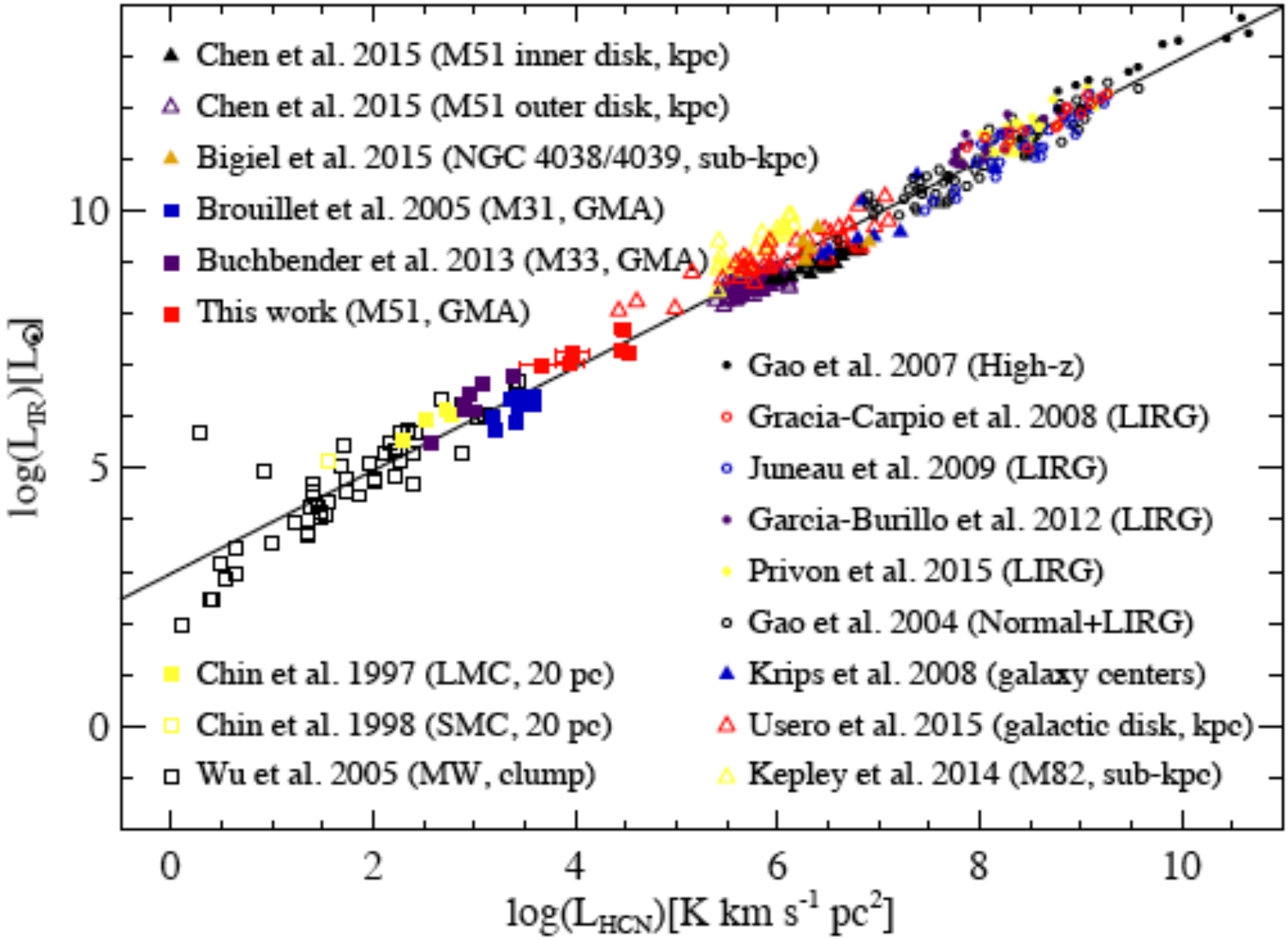
Wu, Evans, Gao et al. 2005 ApJL

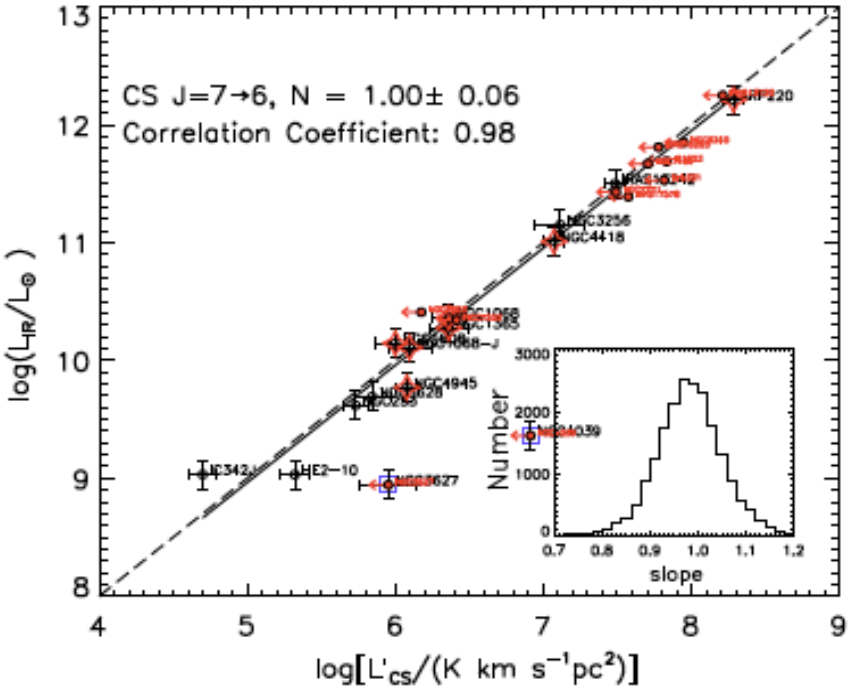


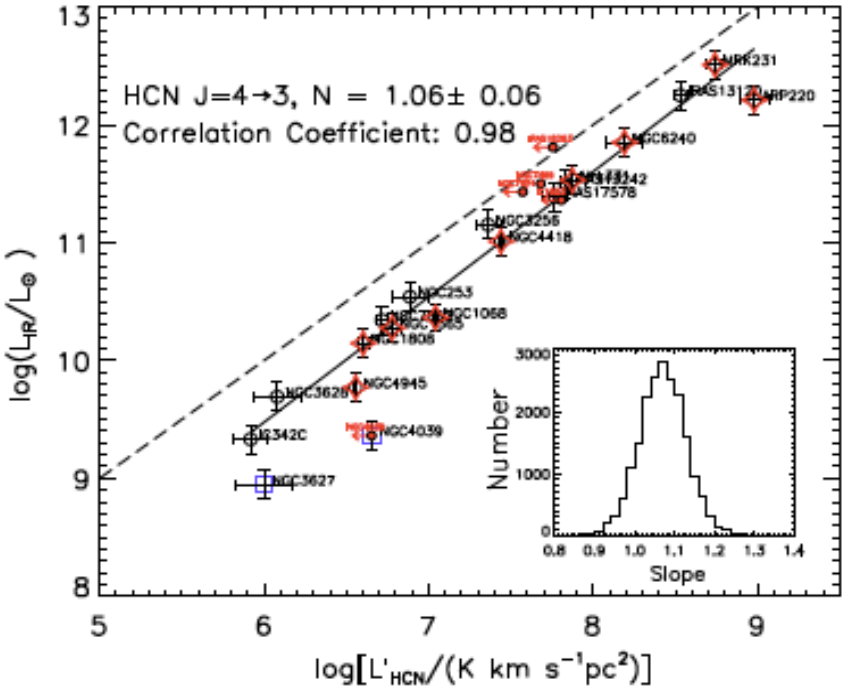
Wu+2010



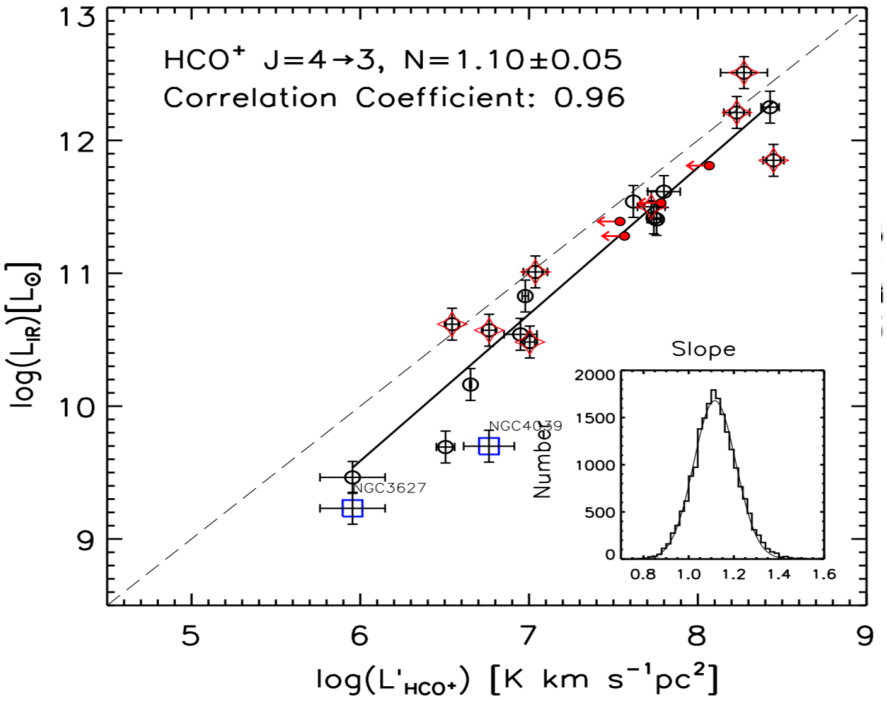

Chen, Gao, Braine & Gu 2015 ApJ
Chen, Braine, Gao et al. 2017(1612.00459)
13h29m56s
13h29m56s
13h29m56s
47°14′00″
47°14′00″
47°12′00″
47°10′00″
B band
70 um
CO
B band
70 um
CO HCN
13h30m00s 29m50s
13h30m00s 29m50s
13h30m00s 29m50s

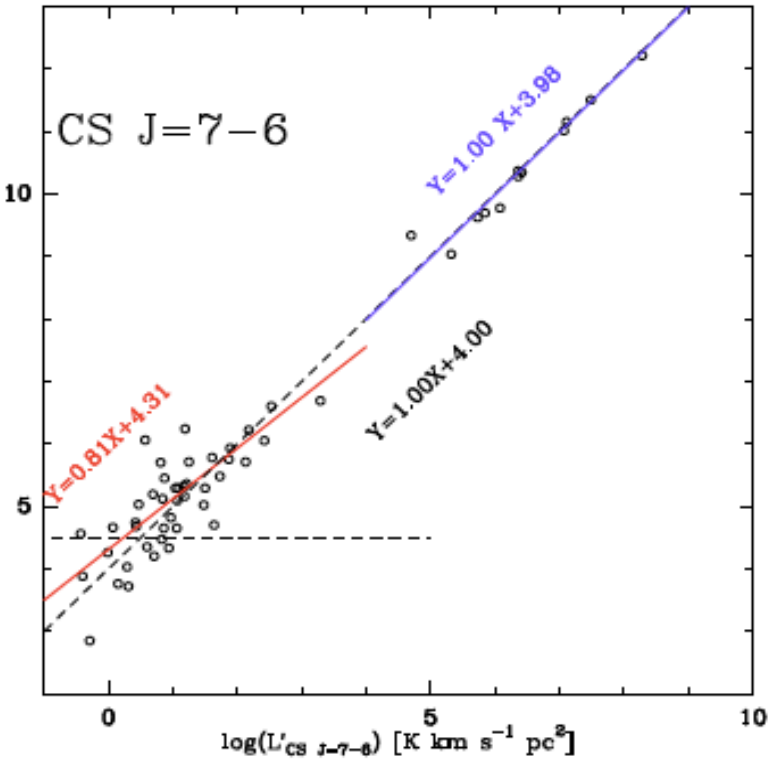

Chen et al. 2015 (M51 inner disk, kpc)
Chen et al. 2015 (M51 outer disk, kpc)
Bigiel et al. 2015 (NGC 4038/4039, sub-kpc)
Brouillet et al. 2005 (M31, GMA)
Buchbender et al. 2013 (M33, GMA)
This work (M51, GMA)
Gao et al. 2007 (High-z)
Gracia-Carpio et al. 2008 (LIRG)
Juneau et al. 2009 (LIRG)
Garcia-Burillo et al. 2012 (LIRG)
Privon et al. 2015 (LIRG)
Gao et al. 2004 (Normal+LIRG)
Krips et al. 2008 (galaxy centers)
Usero et al. 2015 (galactic disk, kpc)
Kepley et al. 2014 (M82, sub-kpc)
Chin et al. 1997 (LMC, 20 pc)
Chin et al. 1998 (SMC, 20 pc)
Wu et al. 2005 (MW, clump)
log(L_IR)[L_⊙]
log(L_HCN)[K km s^-1 pc^2]
0
5
10
0
2
4
6
8
10

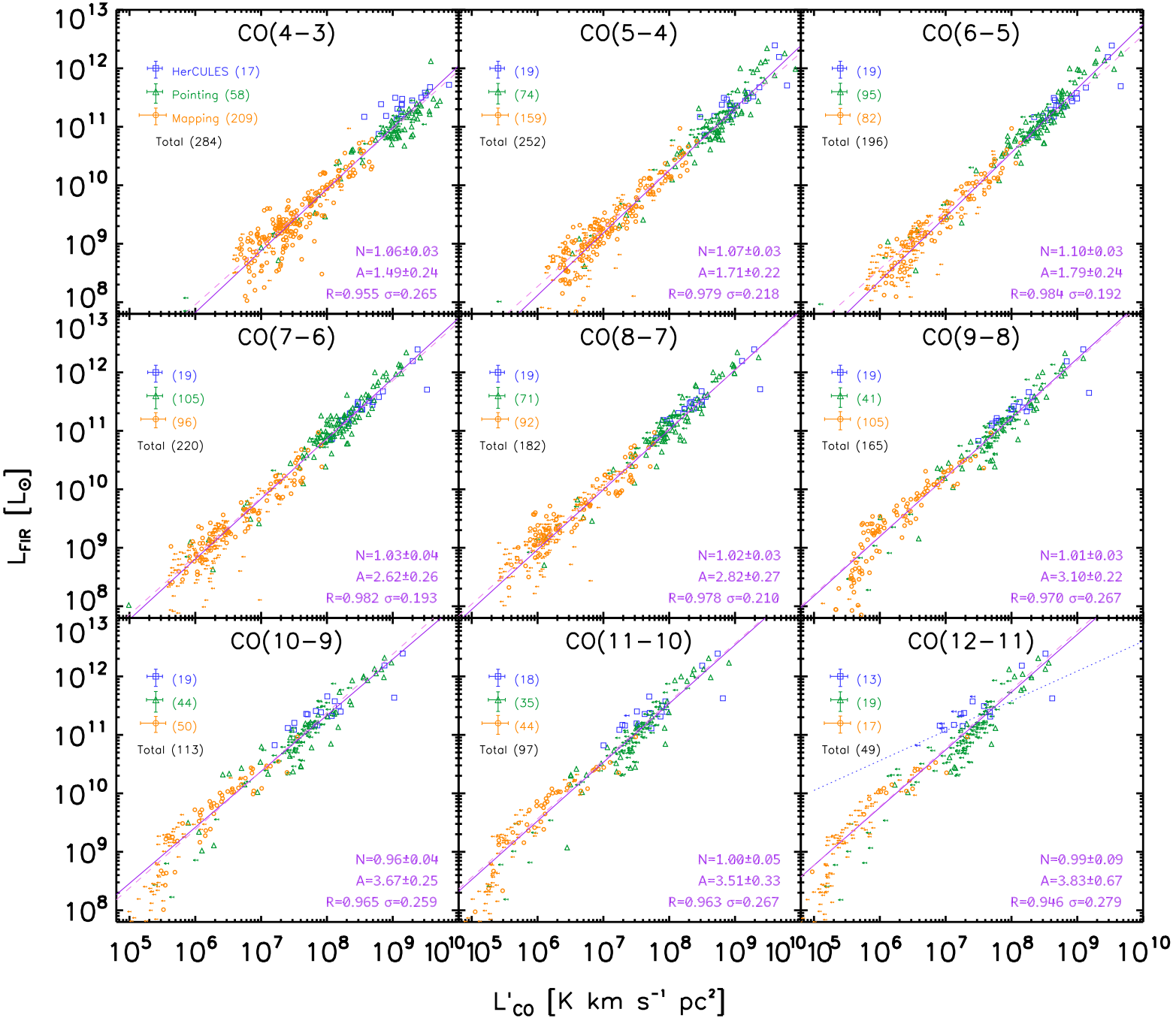




Zhang, Gao, Henkel et al. 2014







All are not far from linear
– dense gas law

CO J~6-8 are the tightest
– best SF tracer

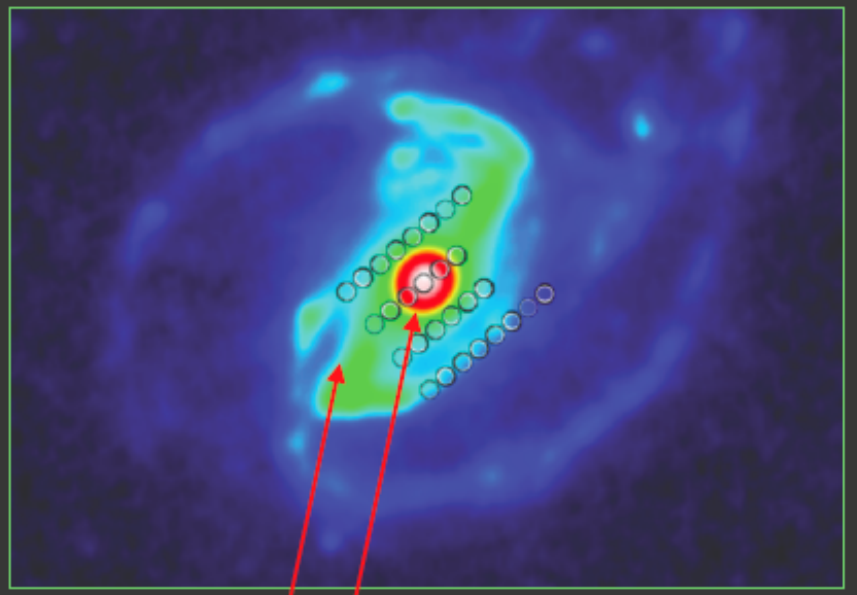
Slightly super-linear at J≤6 – K-S law

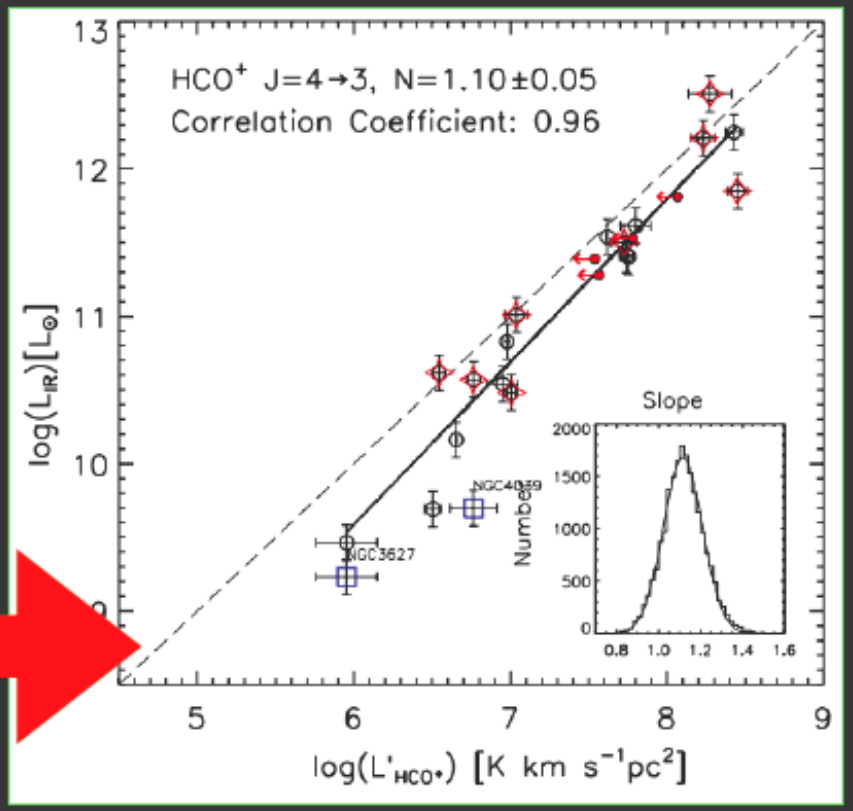
High-J CO better tracers dense gas!

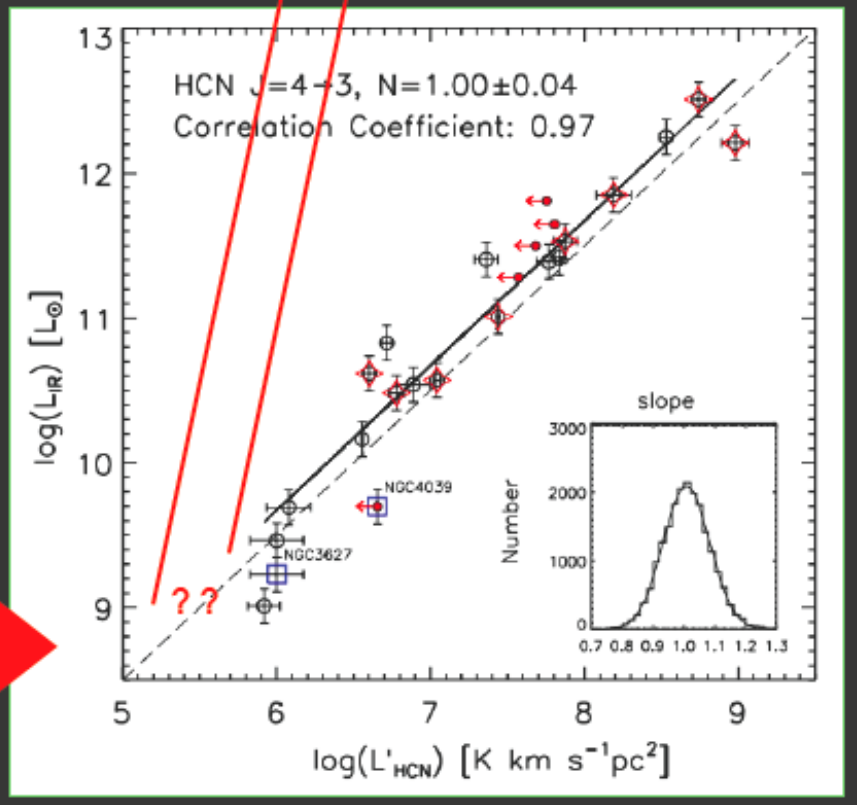
D. Liu, Gao, Isaak, et al. 2015

SCIENCE GOALS

- *Resolved dense gas star formation relations*
- *Intermediate scales/luminosities*
- *Different environments: nuclear vs. disk*
- *Radial distribution of dense gas and SF efficiency*

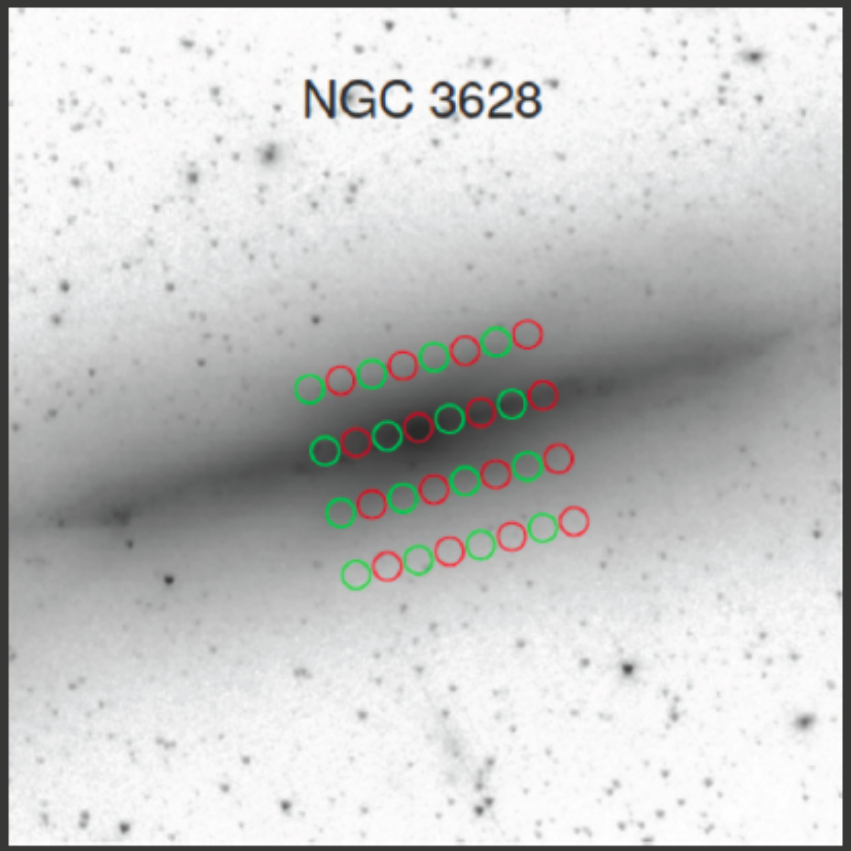




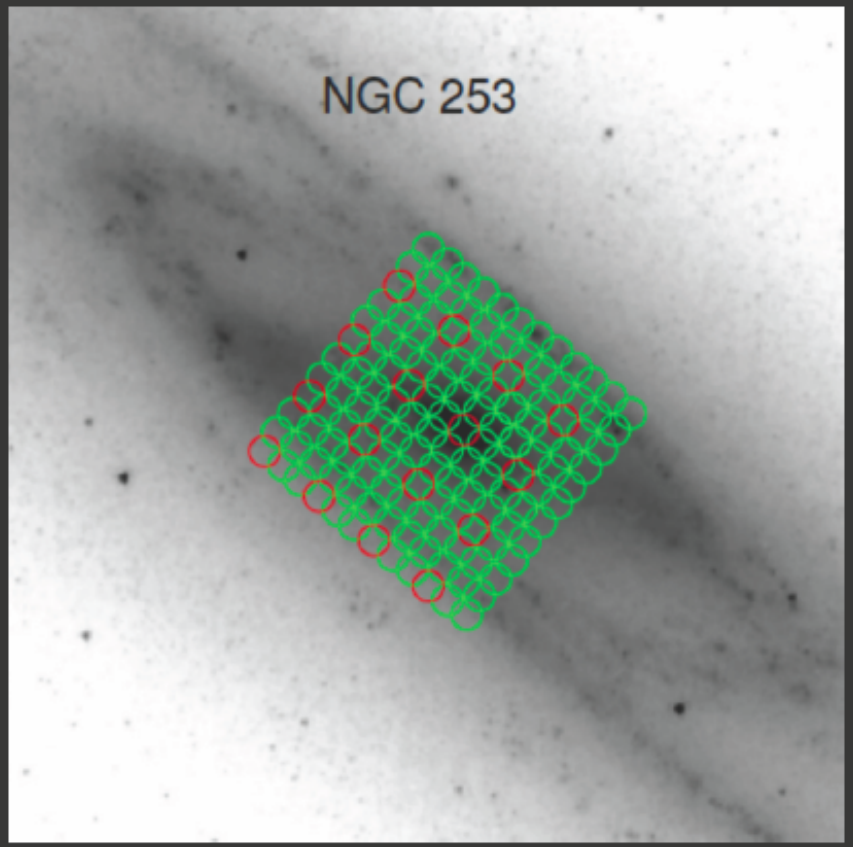


SCAN PATTERNS

- *Grid mode*
- *Mostly for edge-on galaxies*

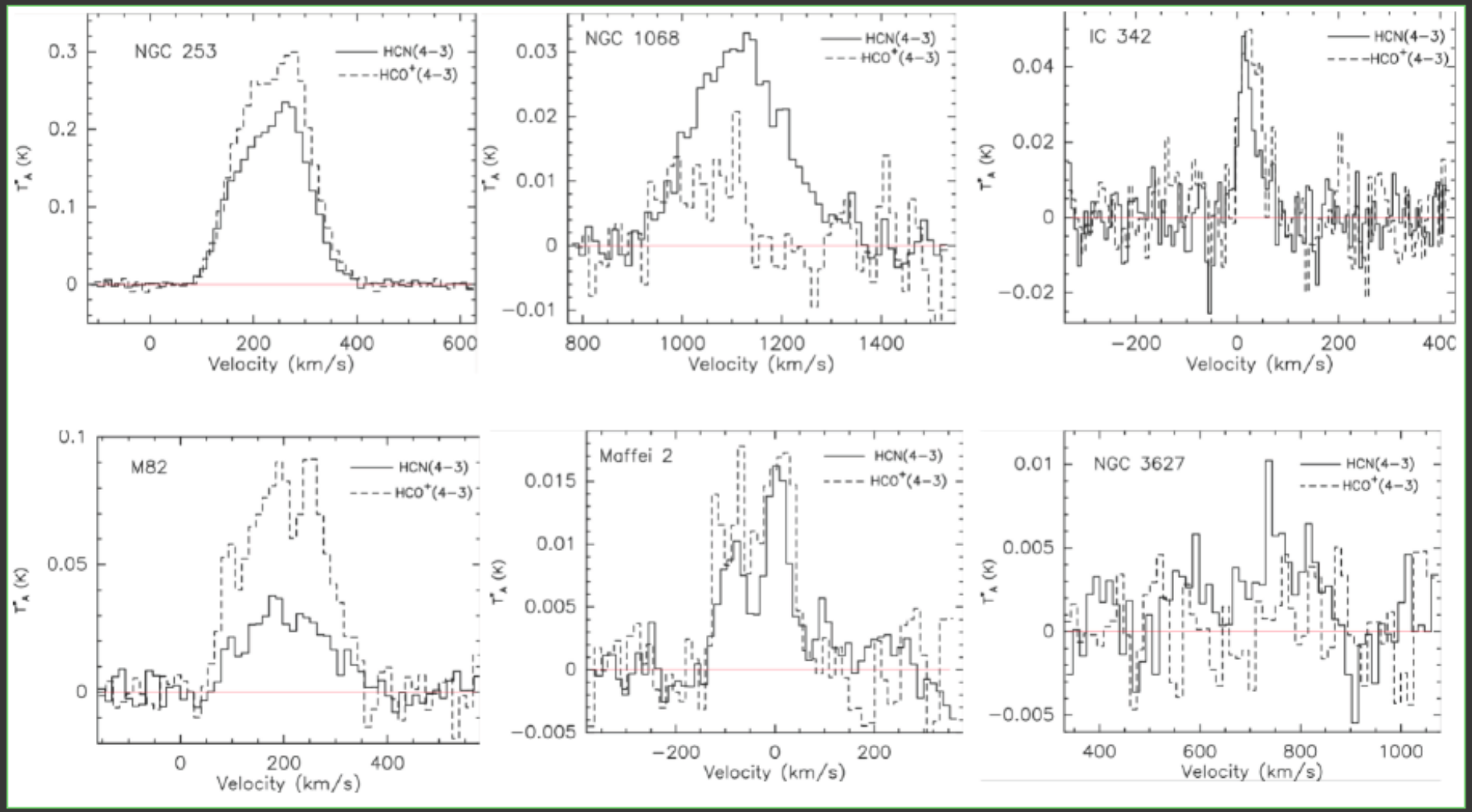


- *Jiggle mode*
- *Mostly for face-on/large galaxies*



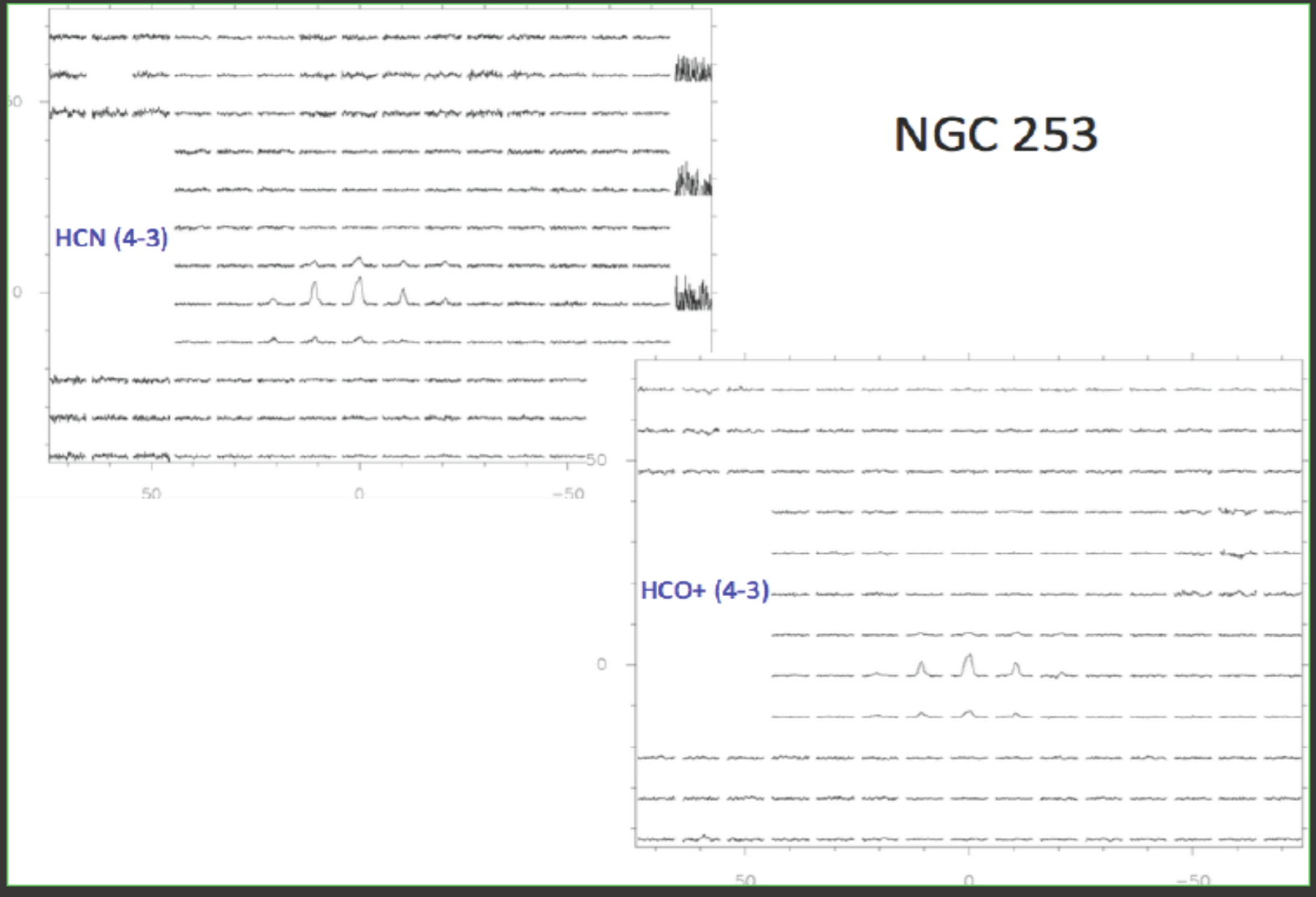
FIRST DATA – SPECTRA

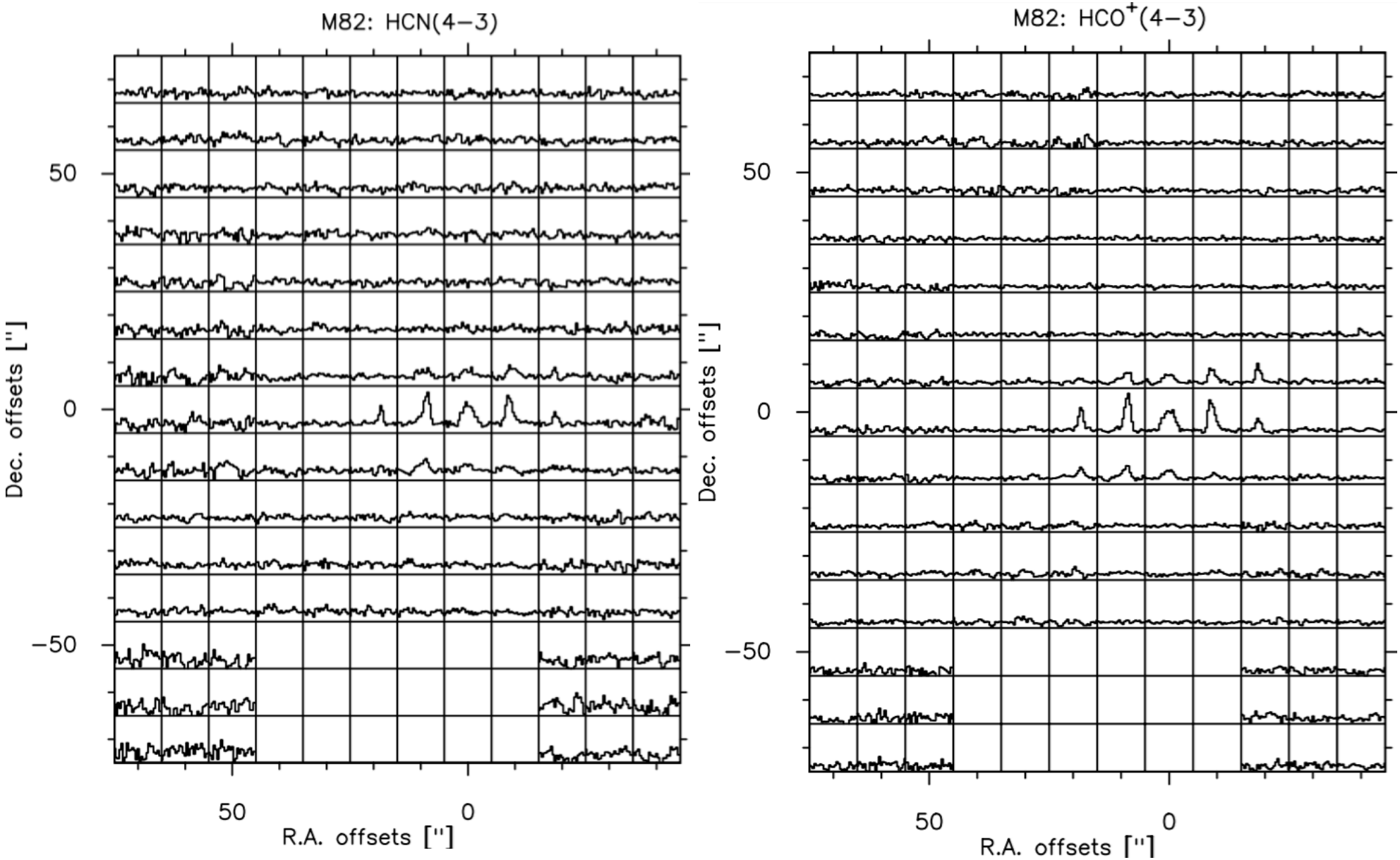
- *HCN and HCO^+ J=4-3 (central pointings). Strong detections*
- *HCO^+ often stronger than HCN*

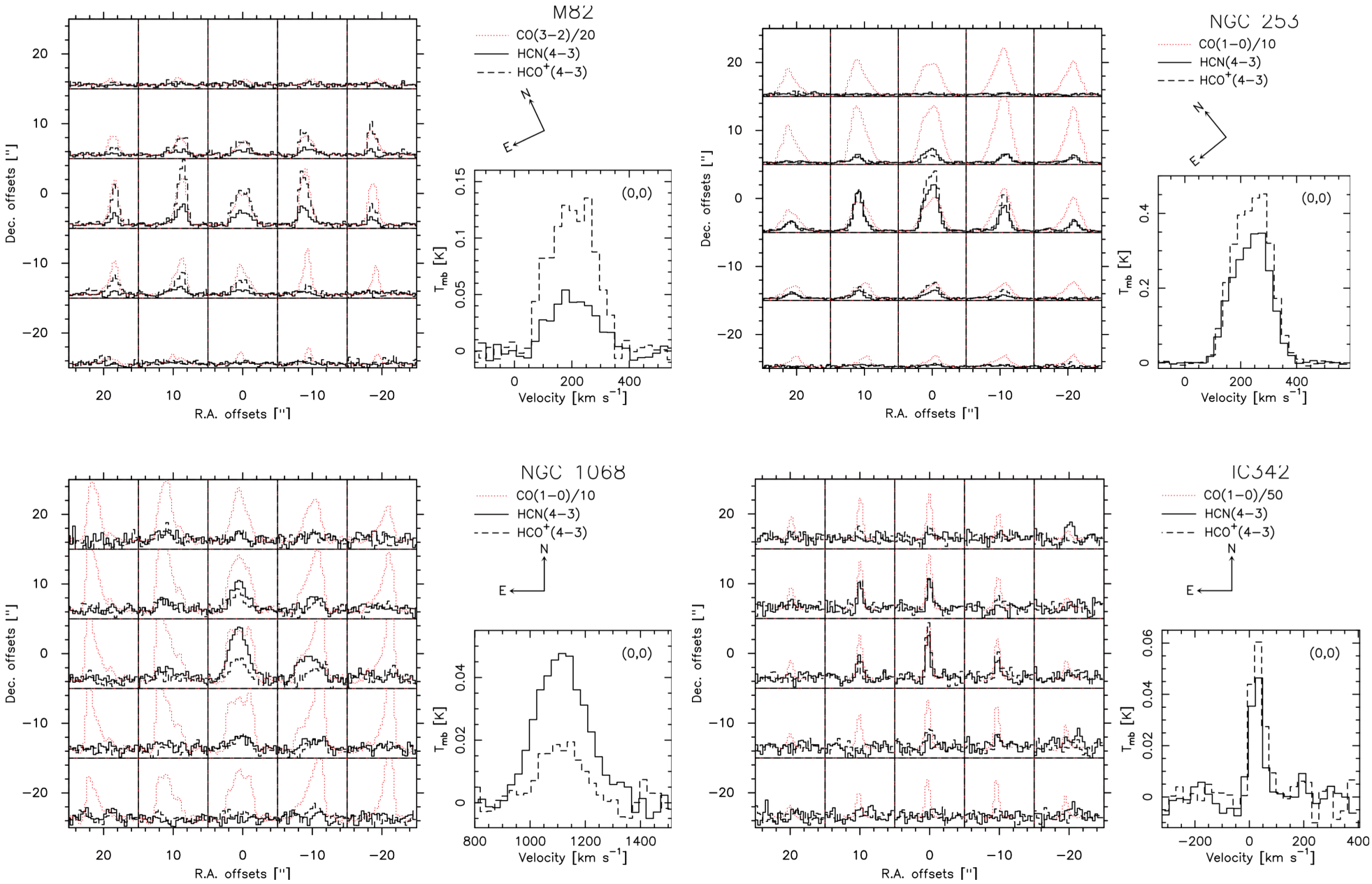


FIRST DATA – SPECTRA

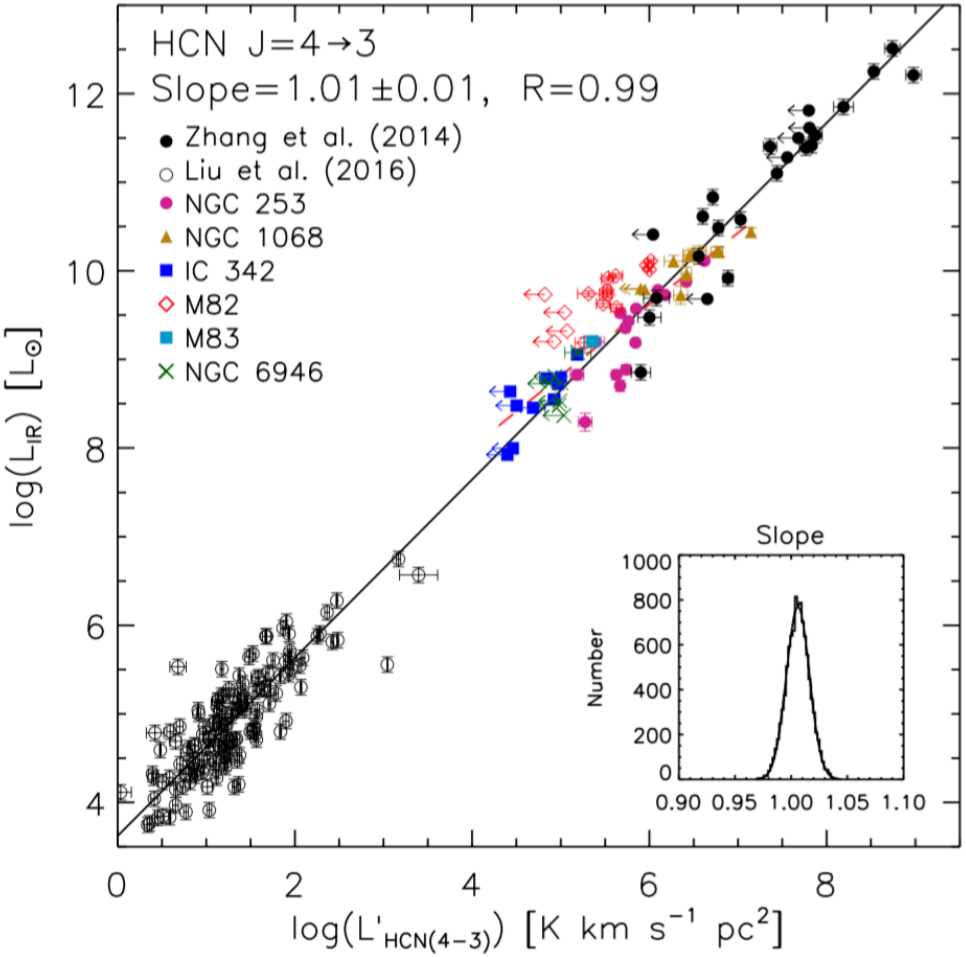
- *HCN and HCO^+ J=4-3 (off centre pointings). Lines are weaker*



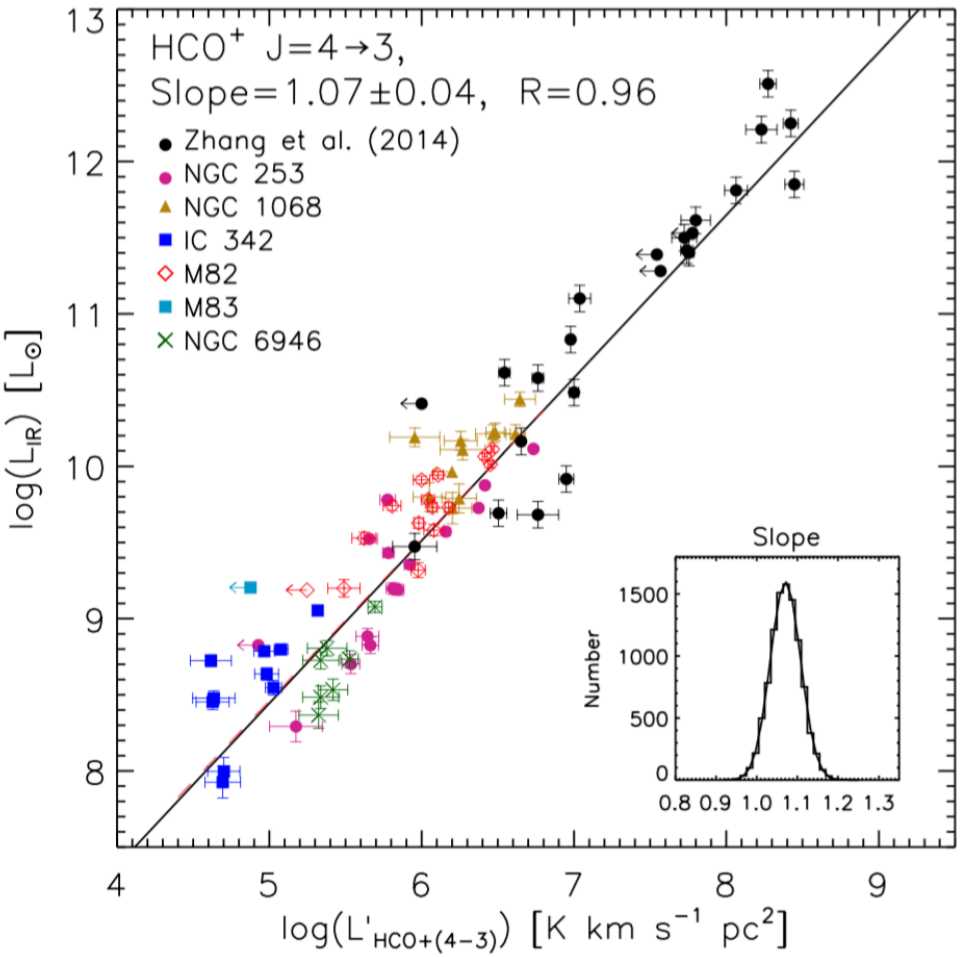

M82: HCN(4−3)
M82: HCO+(4−3)
50
0
−50
Dec. offsets ['']
50
0
R.A. offsets ['']


M82
CO(3–2)/20
HCN(4–3)
HCO+(4–3)
N
E
(0,0)
Tmb [K]
Velocity [km s−1]
Dec. offsets ["]
R.A. offsets ["]
NGC 253
CO(1–0)/10
HCN(4–3)
HCO+(4–3)
N
E
(0,0)
Tmb [K]
Velocity [km s−1]
Dec. offsets ["]
R.A. offsets ["]
NGC 1068
CO(1–0)/10
HCN(4–3)
HCO+(4–3)
N
E
(0,0)
Tmb [K]
Velocity [km s−1]
Dec. offsets ["]
R.A. offsets ["]
IC342
CO(1–0)/50
HCN(4–3)
HCO+(4–3)
N
E
(0,0)
Tmb [K]
Velocity [km s−1]
Dec. offsets ["]
R.A. offsets ["]

L_{IR} vs. $L'_{HCN(4-3)}$



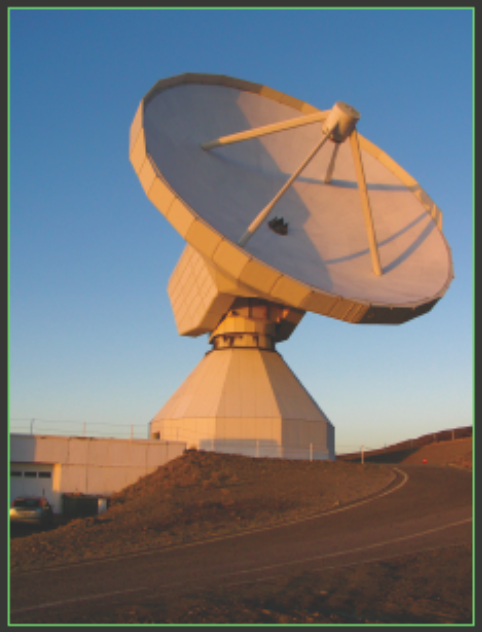
L_{IR} vs. $L'_{HCO+(4-3)}$



SYNERGY & FOLLOW-UP

- *Observations:*
  - *JCMT SCUBA-2 and HARP CO(3-2) follow-up*
  - *High resolution ALMA and NOEMA maps*
  - *Herschel Archive: high-J CO data*
  - *IRAM-30m continuum (NIKA, 2mm) and line (HERA, J=2-1)*
  - *APEX (high-J lines)*

IRAM



ALMA

PAPER PLAN

- *Paper I: MALATANG Survey description and first results*
- *Paper II: First resolved HCN/HCO$^+$ J=4-3 vs. IR relations for a significant fraction of sample.*
- *Paper III: Stacking of spectra of weak/non-detections. Explore HCN/HCO+ vs. IR relations in outskirts of galaxies*
- *Paper IV: Explore radial distribution of dense gas fraction in galaxies. Gas depletion time-scales as a function of galactocentric distance*
- *Paper V: Connecting MALATANG to Herschel+SCUBA-2 maps, concomitance between dense gas and dust heating*
- *Paper VI: Including HI data and connecting the atomic gas phase with the dense gas. Radial distributions.*
- *Paper VII: SPH + radiative transfer modelling.*

2016

2018

And more…

THANK YOU

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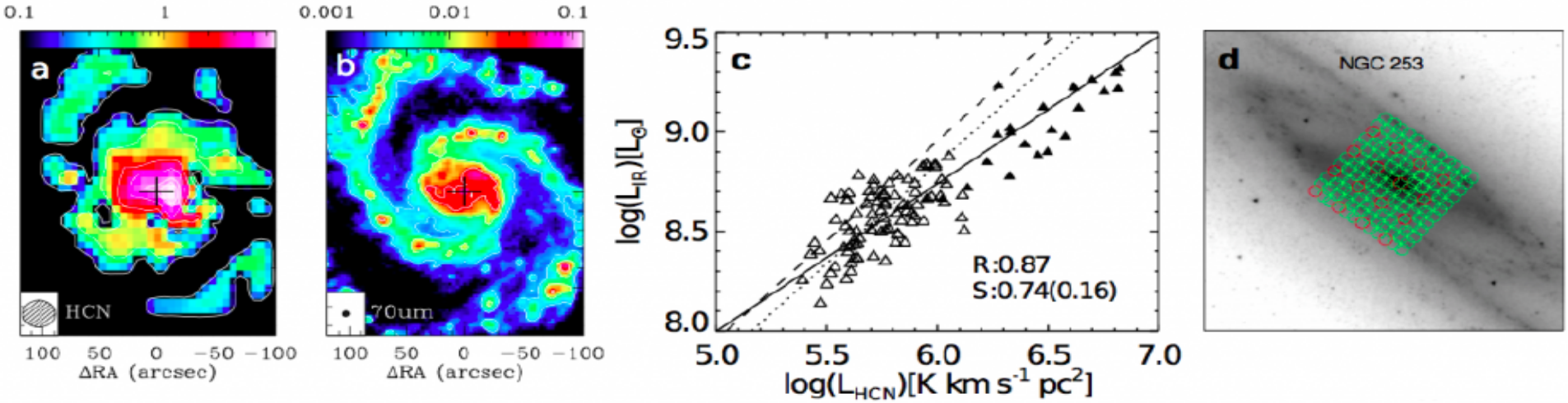
Satoki Matsushita; Aeree Chung;
Erik Rosolowsky; Kohno Kotaro



MALATANG in a nutshell: here illustrated by a study of M51 (Chen et el 2015). a) Moment 0 map of the HCN J= 1 – 0 emission towards M 51 (contours at: 0.1, 0.6, 1.9, 3.4, 4.9, 5.4 K km/s on the Tmb scale). b) Herschel/PACS 70 μm image tracing the IR dust continuum (contours at: 3, 9, 27, 81 mJy/pixel. c) The resolved $L_{IR} - L'_{HCNJ=1-0}$ relation observed towards M 51, with each symbol representing a region ~1 kpc in size. The solid and dashed lines show the best log-linear fits to the nuclear (filled triangles) and disk (open triangles) regions combined and to the disk regions only, respectively. The combined correlation is seen to be shallower than the galaxy-integrated linear relation observed by Gao & Solomon (2004) (illustrated by the dashed line). d) Schematic of a HARP-B jiggle mode observations of a MALATANG target (NGC 253). With a beam spacing of 1000 , the shown 3 x 3 jiggle pattern will result in fully sampled HCN and HCO+ J = 4 -3 maps that probe dense molecular gas across a range of environments, from inter-arm regions to the central starburst nuclei.