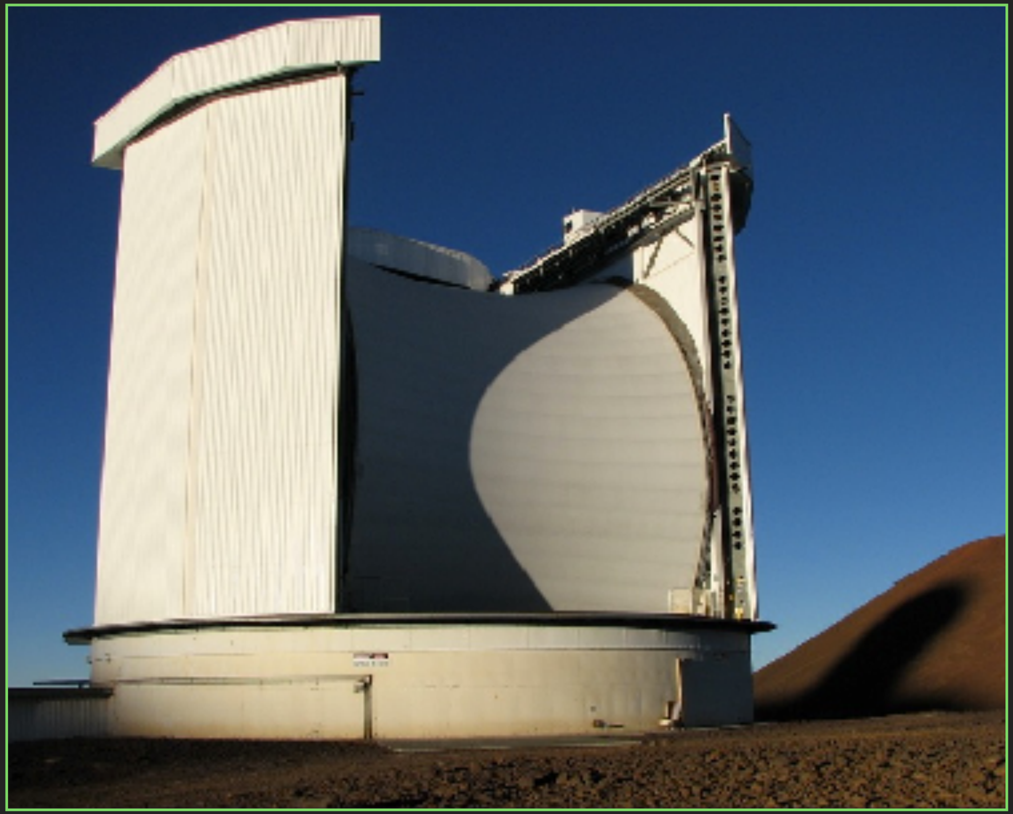
MALATANG

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

www.eaobservatory.org/jcmt

On behalf of the MALATANG team:

THOMAS R. GREVE
UNIVERSITY COLLEGE LONDON



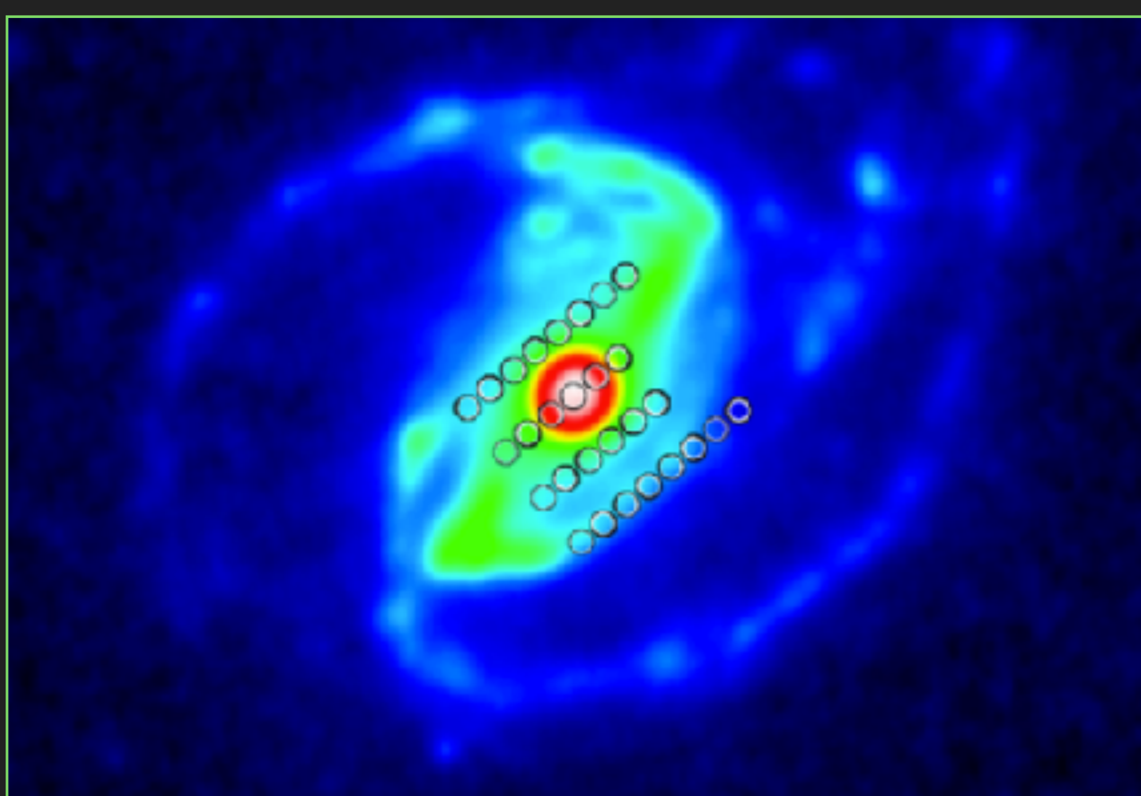
Seoul National University, Feb 1st 2018

SCIENCE MOTIVATION

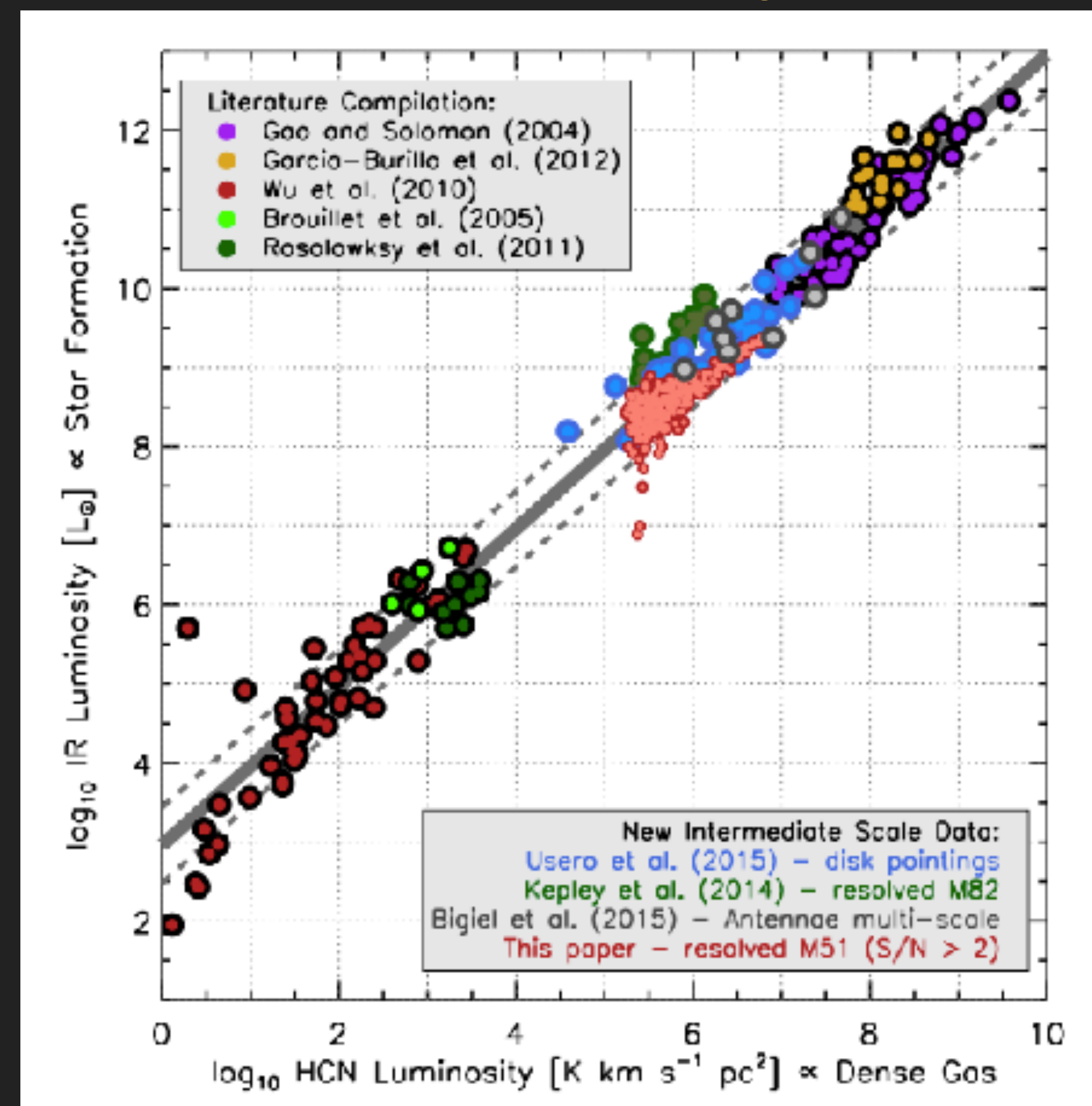
Exploring star formation as a function of physical scale, environment and gas density

Goals:

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



HCN(1-0) in M51 Bigiel et al. (2016)



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Star formation relations

Theorists

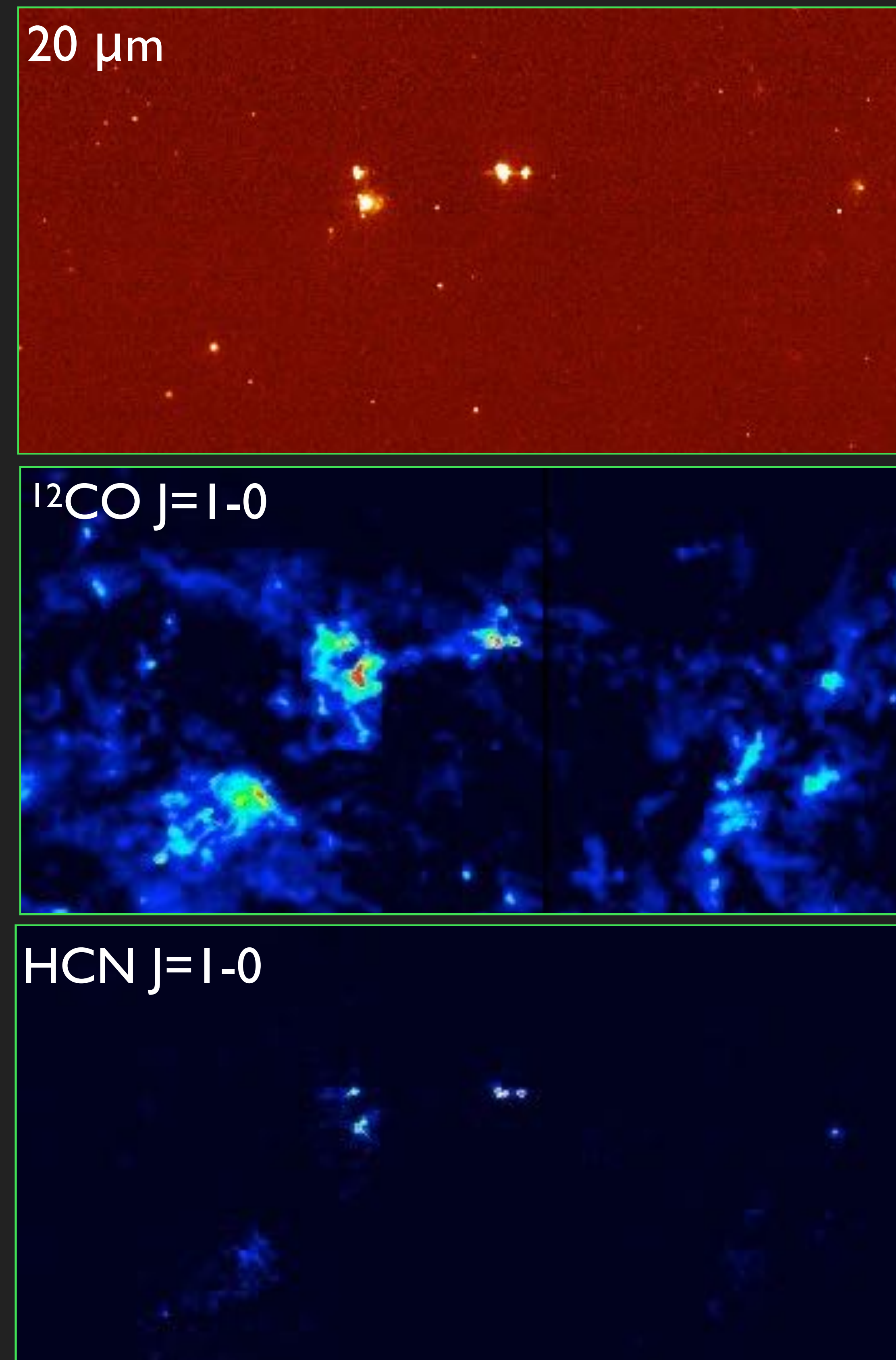
$$SFR = \frac{M_{\rm dense}}{\tau_{\rm ff}} \times \epsilon_{\rm ff}$$

$$SFE = \frac{SFR}{M_{\rm dense}} = \frac{\epsilon_{\rm ff}}{\tau_{\rm ff}}$$

Observer

$$L_{\rm IR} = 10^{\beta} L_{\rm line}^{\alpha}$$

$$\frac{L_{\rm IR}}{L_{\rm line}} = 10^{\beta} L_{\rm line}^{\alpha-1}$$



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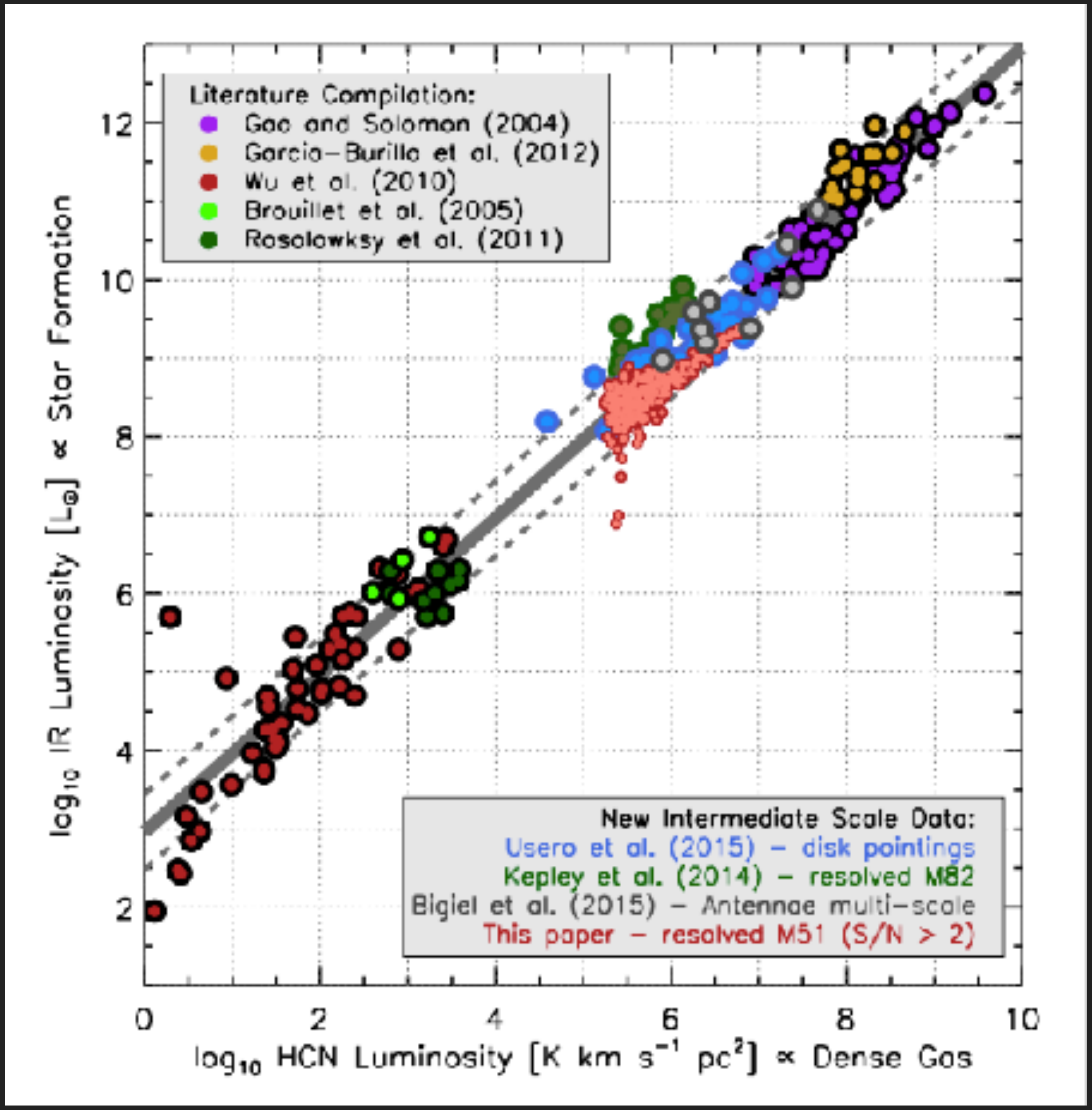

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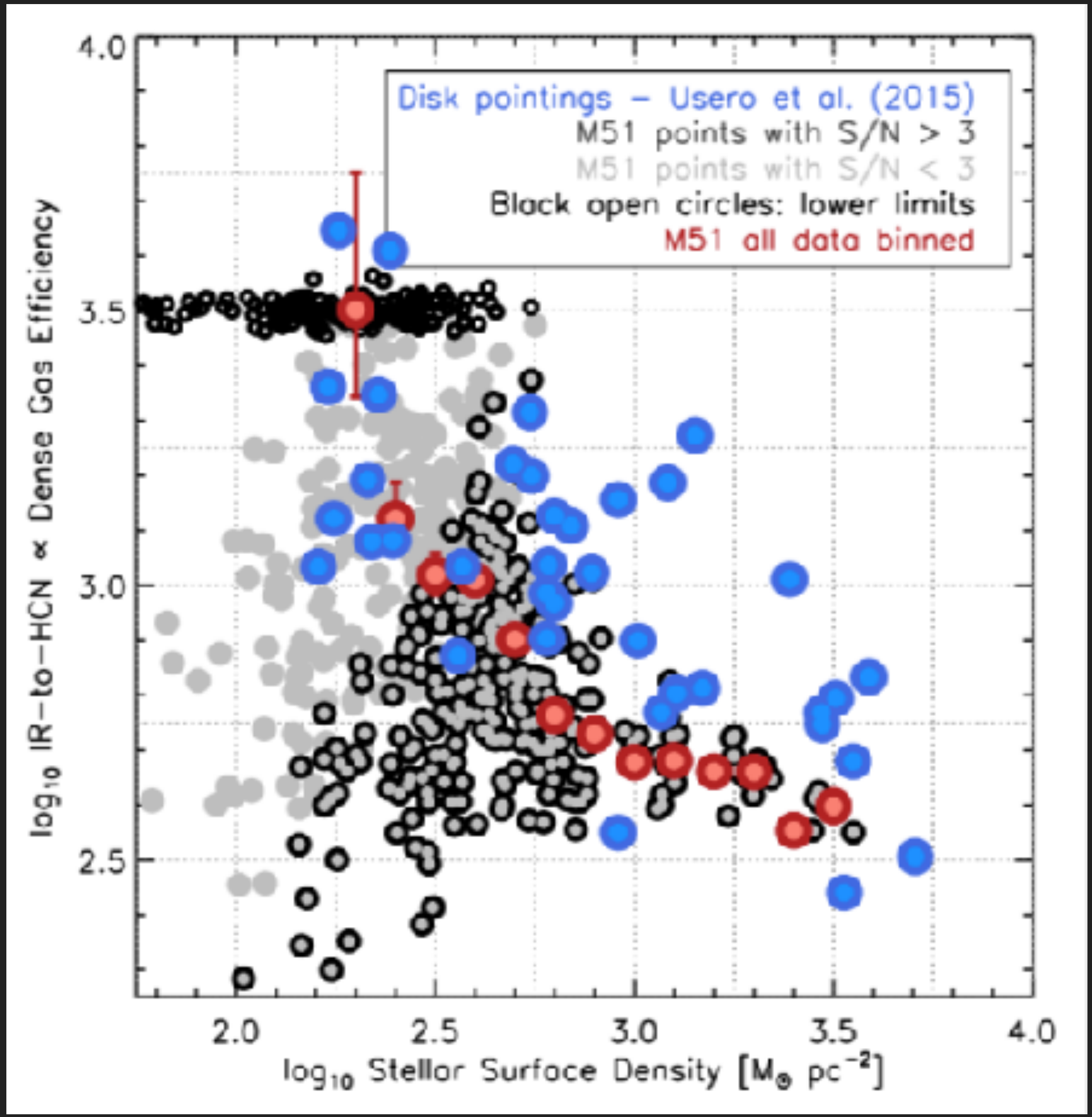

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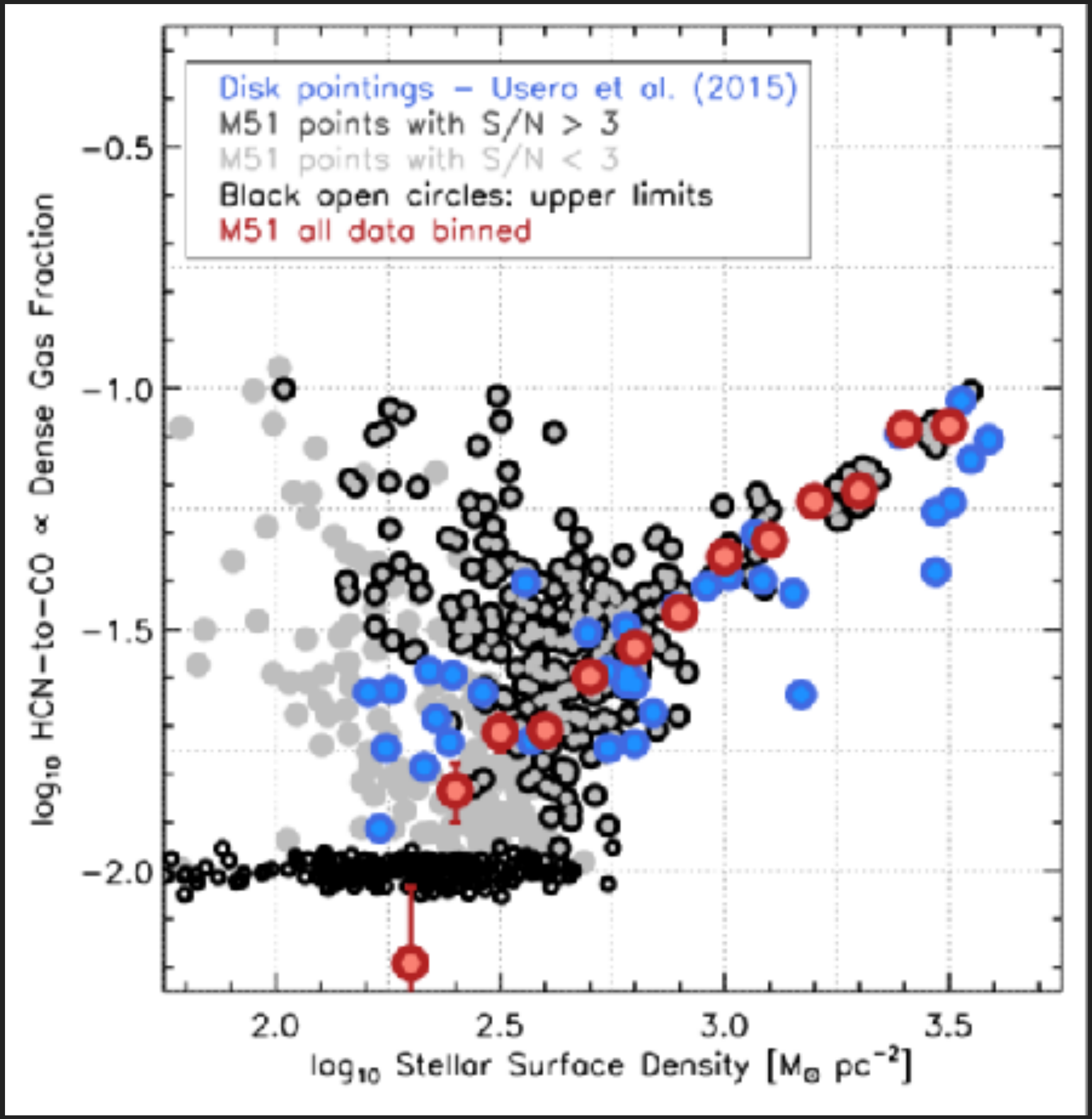

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- Feedback effects (e.g., radiation pressure)?
- Environment (pressure, turbulence)
- Mechanical heating

Observer

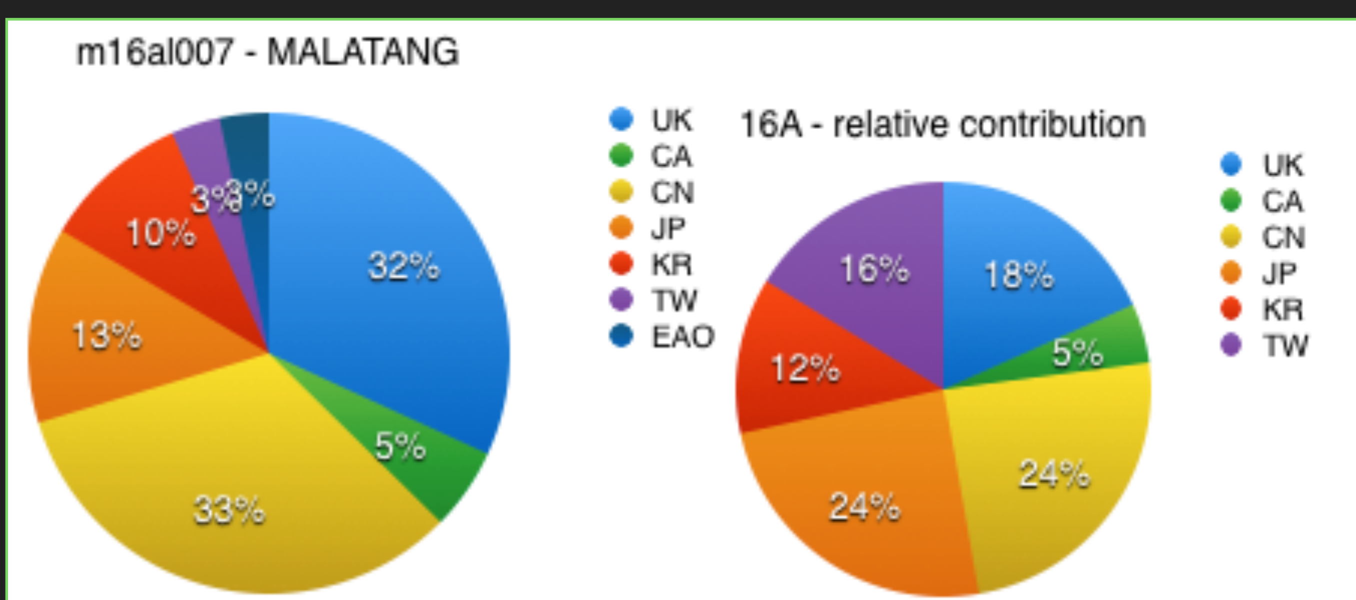
$$L_{\rm IR} = 10^{\beta} L_{\rm line}^{\alpha}$$

$$\frac{L_{\rm IR}}{L_{\rm line}} = 10^{\beta} L_{\rm line}^{\alpha-1}$$

- What densities do HCN/HCO+ J=1-0 really probe (e- coll. excitation)?
- Excitation effects (mid-IR pumping)
- PDR vs. XDR chemistry
- Fractionisation
- Mechanical, CR, X-ray heating
- HCN self-absorption in ULIRGs

MALATANG IN A NUTSHELL

- *A 390hr (band 3) JCMT/HARP campaign to map HCN and HCO+ J=4-3 in 23 nearby IR-bright galaxies*
- *Systematically explore the dense gas vs. star formation relationship on scales ~0.2-2.8kpc across nuclear vs. disk environments*
- *MALATANG membership: 97*
- *All JCMT partners represented*
- *Observations completed!*



HARP

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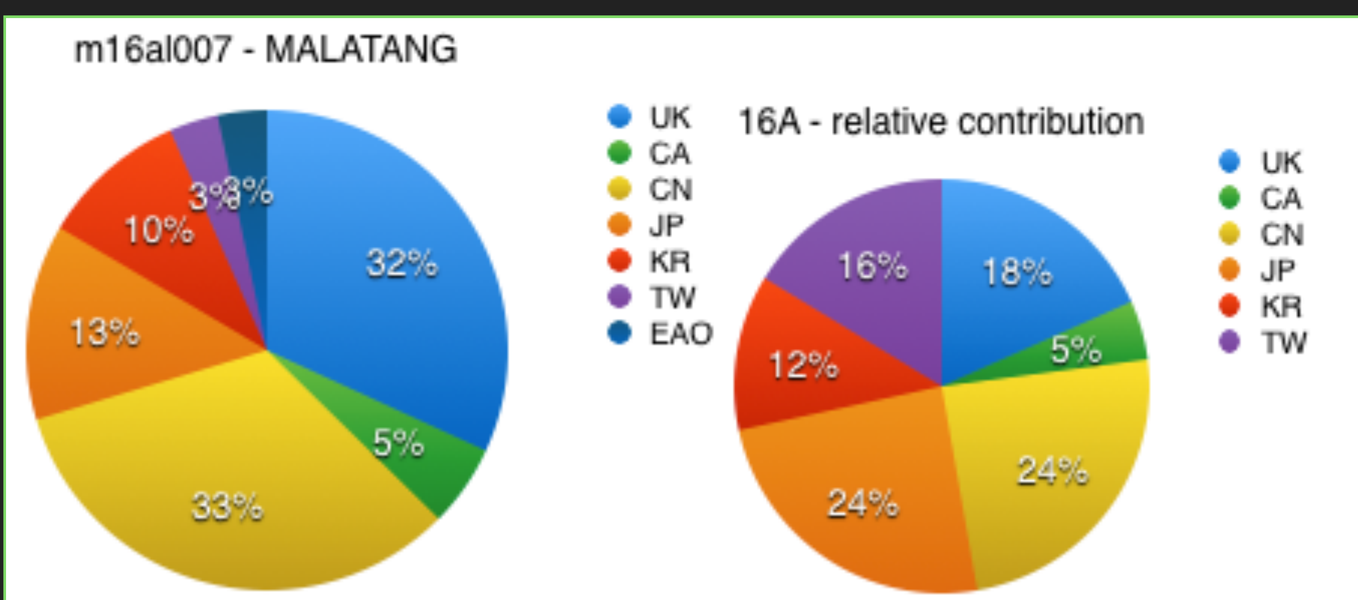


Why HCN and HCO^+ J=4-3?

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

MALATANG IN CONTEXT

- *HERACLES (Leroy et al.):*
  - *HERA/IRAM-30m CO(2-1) maps of ~30 nearby disk galaxies*
  - *~20″ resolution (FWHM)*
  - *About 10 sources overlap with MALATANG*

- *Kepley et al. (2014) :*
  - *GBT/W-receiver HCN/HCO+(1-0) on-the-fly maps of M82*
  - *Overlap with MALATANG*
  - *~9″ resolution (FWHM)*

- *EMPIRE (Bigiel et al.):*
  - *EMIR/IRAM-30m HCN/HCO+(1-0) on-the-fly maps of 9 nearby galaxies*
  - *No overlap with MALATANG*

- *MALATANG:*
  - *JCMT/HARP HCN/HCO+(4-3) maps of ~23 nearby disk galaxies*
  - *Tracing truly high density, star-forming gas*

SAMPLE

MALATANG

23 of the nearest and IR-brightest galaxies beyond the Local Group

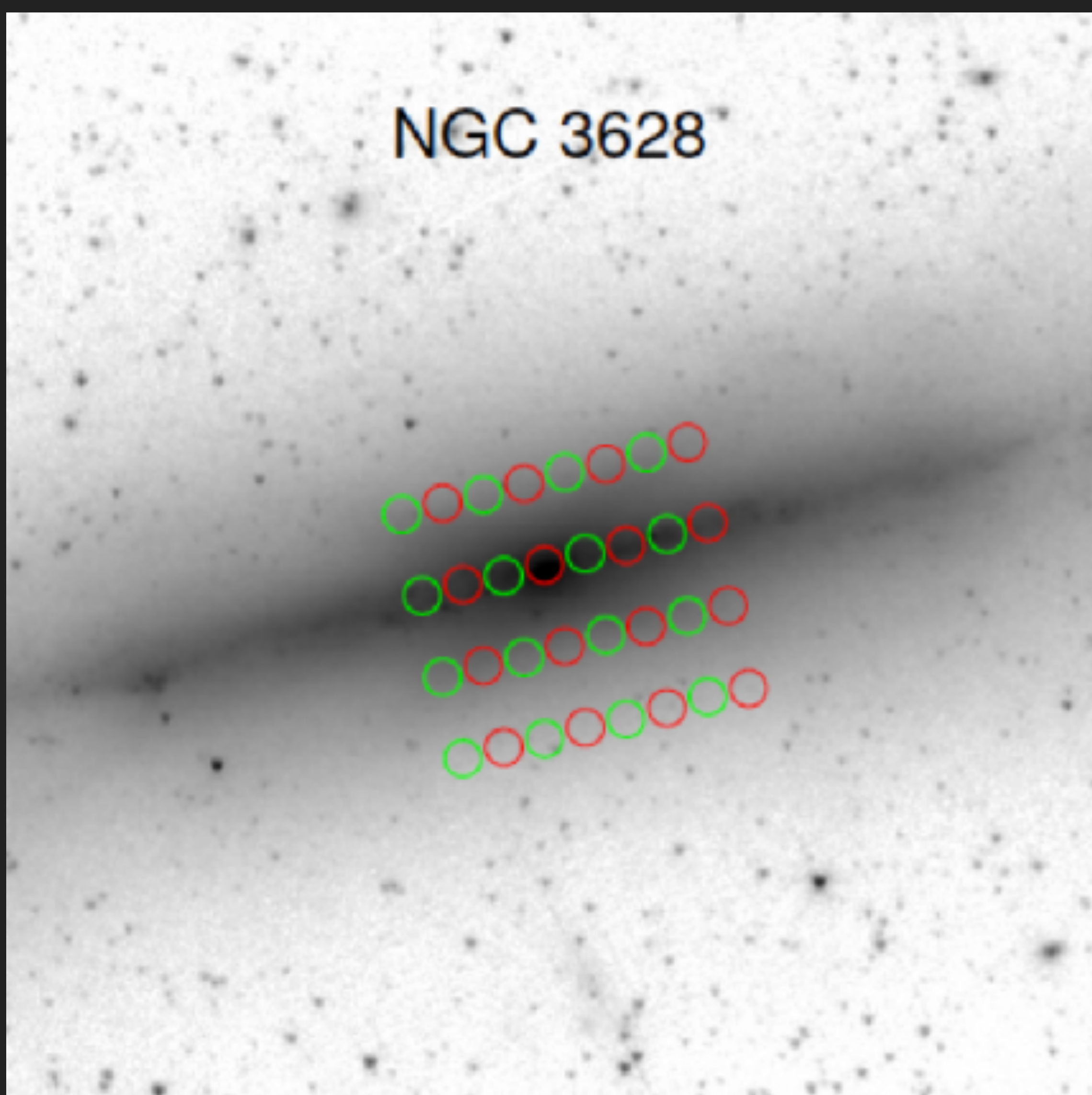
Criteria:

- *IR-bright (f_{60um} > 50Jy and f_{100um} > 100Jy) from RGBS*
- *JCMT observable (δ > -40°)*
- *Nearby (2.5-54Mpc)*
- *Normal, starburst and AGN galaxies*
- *Herschel data*

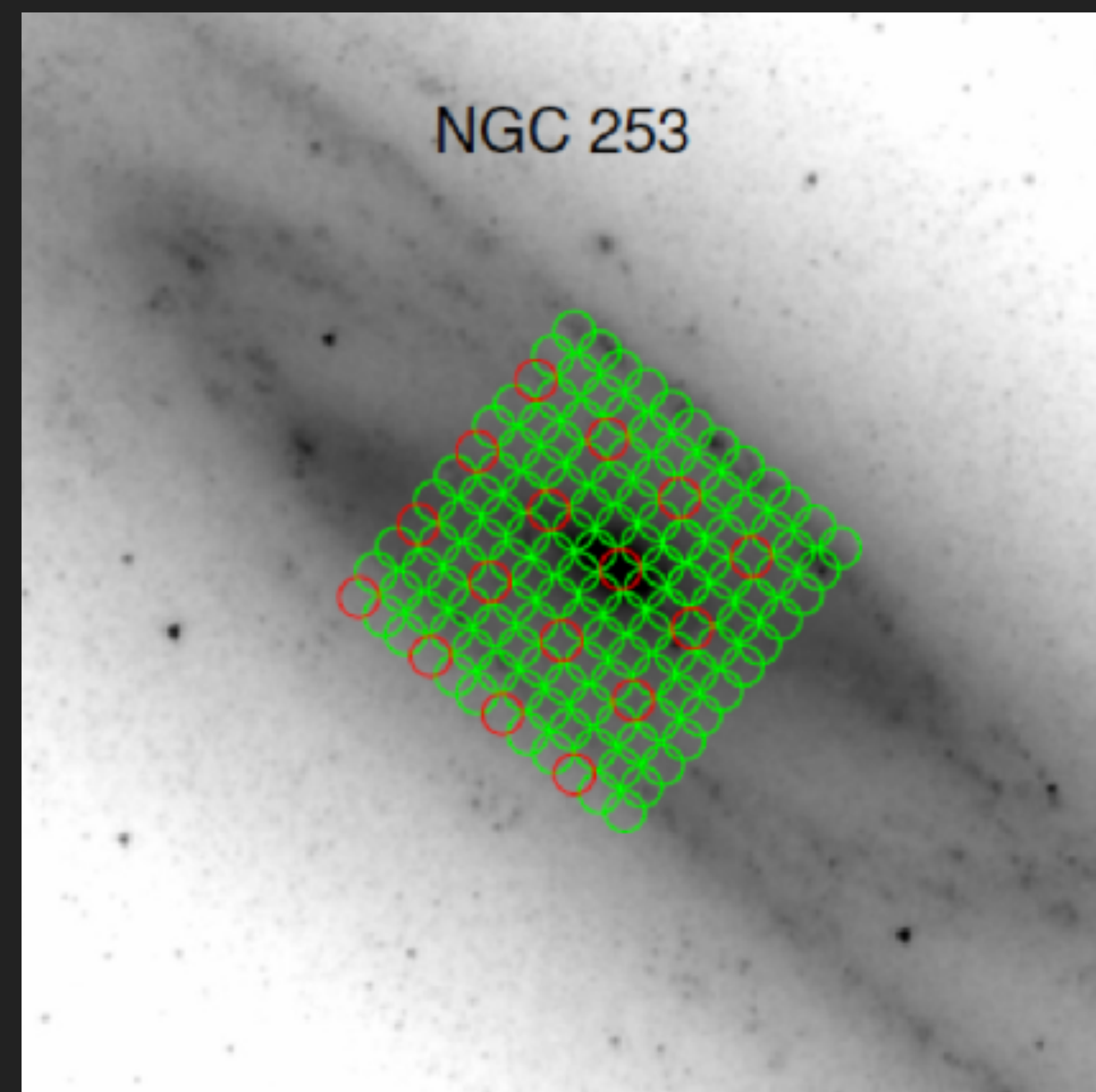
N (1)	Source Name (2)	R.A. (J2000) (3)	Decl. (J2000) (4)	Distance (Mpc) (5)	Diameter (arcmin) (6)	$f_{60\mu m}$ (Jy) (7)	$f_{100\mu m}$ (Jy) (8)	$\log L_{\rm fir}$ ($L_\odot$) (9)	$\log\Sigma_{SFR}$ ($M_\odot {\rm yr}^{-1}{\rm kpc}^{-2}$) (10)
1	***NGC 253**	00 47 33.1	−25 17 18	2.5	27.5×6.8	967.81	1288.15	10.29	0.05
2	*NGC 660	01 43 02.4	13 38 42	14.0	8.3×3.2	65.52	114.74	10.38	0.37
3	*NGC 891	02 22 33.4	42 20 57	10.0	13.5×2.5	66.46	172.23	10.18	-1.76
4	Maffei 2	02 41 55.0	59 36 15	2.8	5.82×1.57	135	225	10.00	0.42
5	***NGC 1068**[a]	02 42 40.7	−00 00 48	16.7	7.1×6.0	196.37	257.37	10.89	1.92
6	NGC 1097	02 46 19.0	−30 16 30	16.4	9.3×6.3	53.35	104.79	10.59	-0.08
7	*NGC 1365[a]	03 33 36.4	−36 08 25	20.8	11.2×6.2	94.31	165.67	10.86	0.55
8	***IC 342**	03 46 48.5	68 05 47	3.7	21.4×20.9	180.80	391.66	10.01	-2
9	NGC 1808[a]	05 07 42.3	−37 30 47	10.5	6.5×3.9	105.55	141.76	10.55	0.61
10	*NGC 2146	06 18 37.7	78 21 25	15.2	6.0×3.4	146.69	194.05	10.93	0.44
11	*NGC 2903	09 32 10.1	21 30 03	6.2	12.6×6.0	60.54	130.43	10.05	-1.22
12	*M82[b]	09 55 52.7	69 40 46	3.5	11.2×4.3	1480.42	1373.69	10.61	1.05
13	*NGC 3079	10 01 57.8	55 40 47	16.2	7.9×1.4	50.67	104.69	10.65	-0.4
14	NGC 3521	11 05 48.6	−00 02 09	8.2	11.0×5.1	49.19	121.76	9.84	-1.55
15	*NGC 3627	11 20 14.9	12 59 30	8.1	9.1×4.2	66.31	136.56	10.24	-1.43
16	*NGC 3628	11 20 17.0	13 35 23	9.6	14.8×3.0	54.80	105.76	10.14	-0.85
17	Arp 299	11 28 30.4	58 34 10	54.1	...	113.05	111.42	11.74	0.3
18	*NGC 4631	12 42 08.0	32 32 29	8.1	15.5×2.7	85.40	160.08	10.10	-1.9
19	NGC 4736	12 50 53.0	41 07 14	4.8	11.2×9.1	71.54	120.69	9.59	-1.01
20	M51	13 29 52.7	47 11 43	7.6	11.2×6.9	97.42	221.21	10.31	-1.78
21	***M83**	13 37 00.9	−29 51 56	3.7	12.9×11.5	265.84	524.09	9.94	-1.44
22	NGC 5457	14 03 12.5	54 20 56	5.2	28.8×26.9	88.04	252.84	10.13	-2.14
23	***NGC 6946**	20 34 52.3	60 09 14	5.5	11.5×9.8	129.78	290.69	10.01	-1.68

OBSERVATIONS

- *16 edge-on galaxies*
- *Grid mode along major axis*



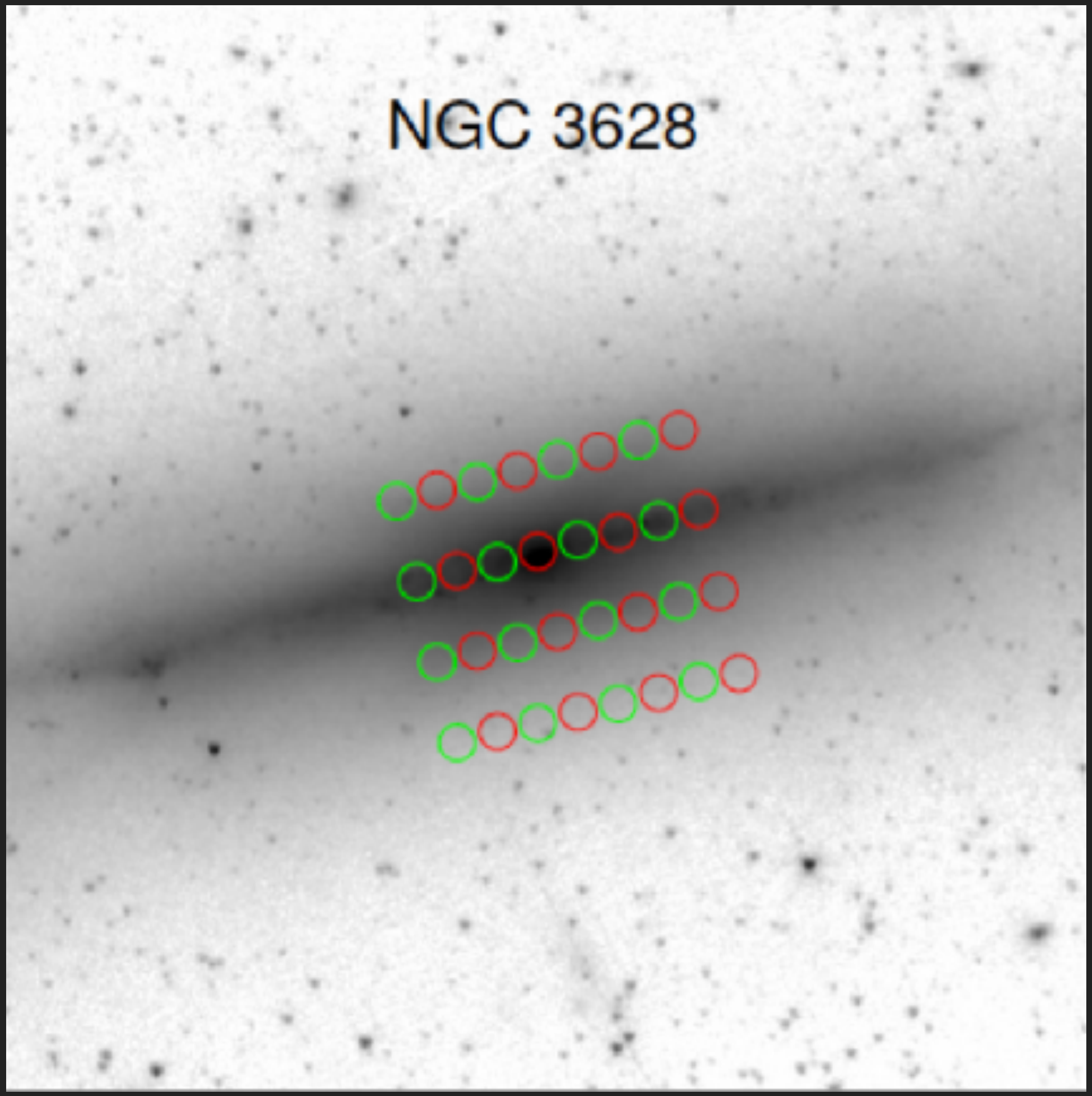
- *7 face-on/large galaxies*
- *Jiggle maps of 2′x2′ central region*



OBSERVATIONS DONE!

MALATANG

- *16 edge-on galaxies*
- *Grid mode along major axis*



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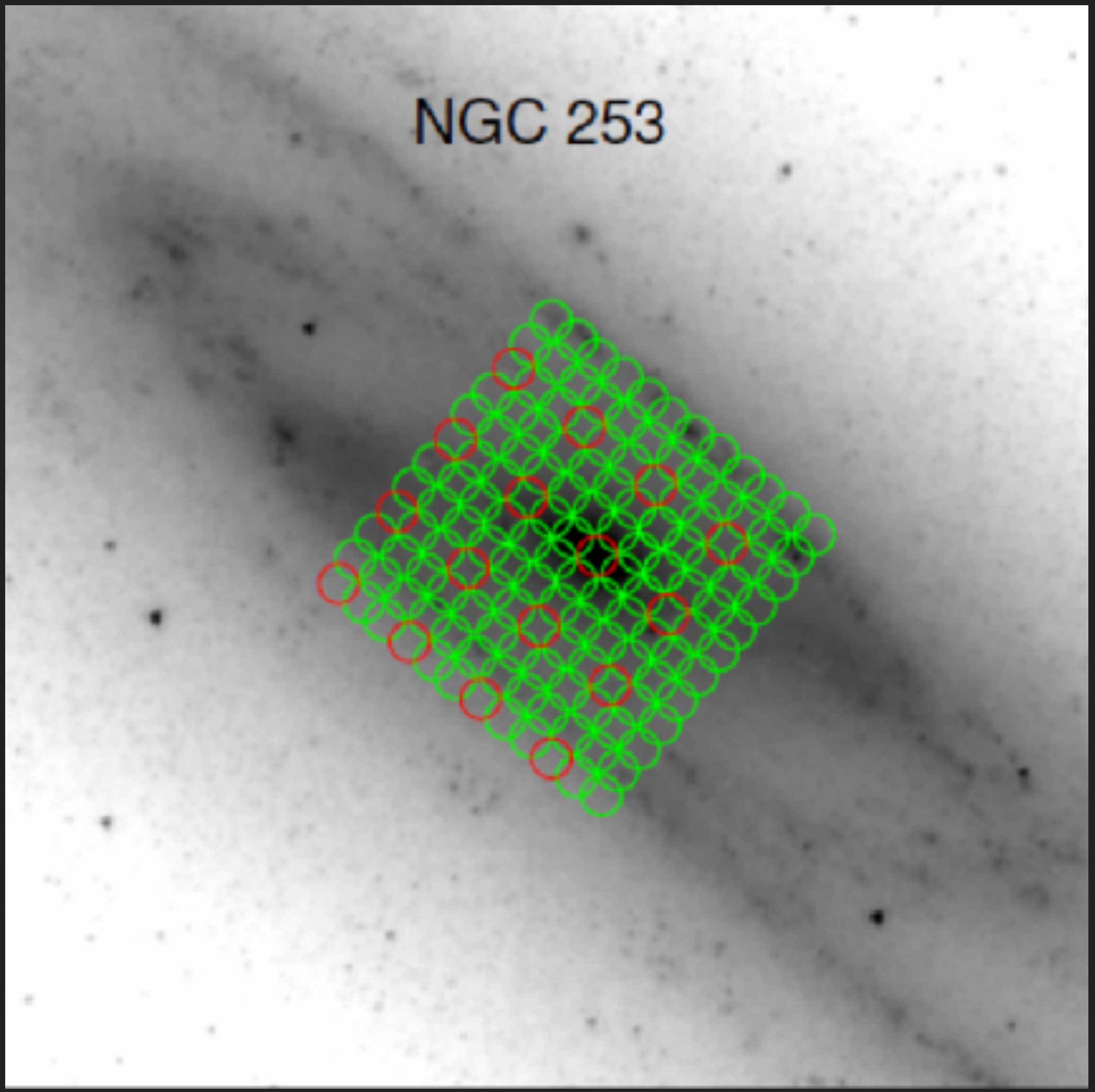
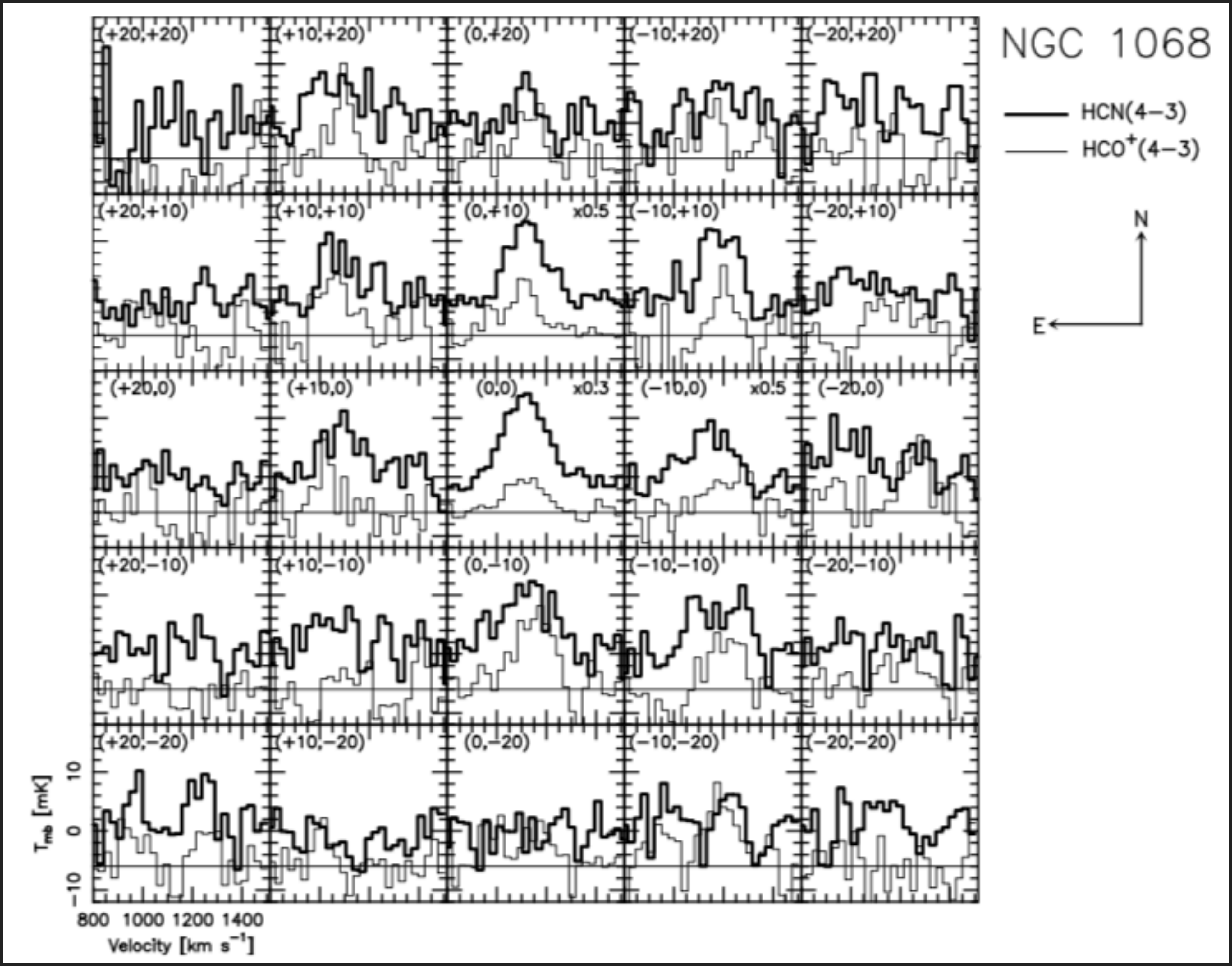


SPECTRA

MALATANG



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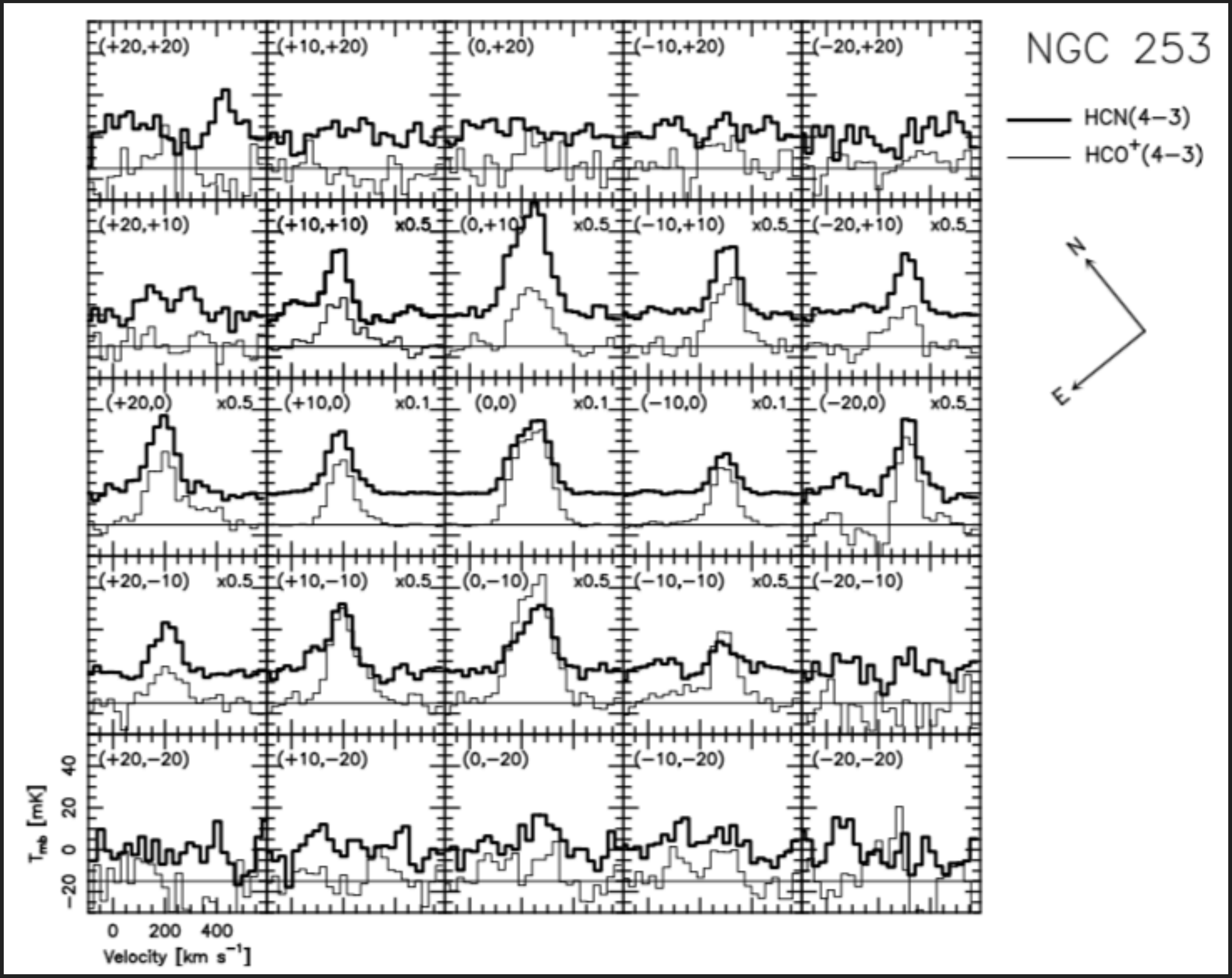
NGC 253
HCN(4−3)
HCO+(4−3)
N
E
(+20,+20)
(+10,+20)
(0,+20)
(−10,+20)
(−20,+20)
(+20,+10)
(+10,+10) x0.5
(0,+10) x0.5
(−10,+10) x0.5
(−20,+10) x0.5
(+20,0) x0.5
(+10,0) x0.1
(0,0) x0.1
(−10,0) x0.1
(−20,0) x0.5
(+20,−10) x0.5
(+10,−10) x0.5
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(−10,−10) x0.5
(−20,−10)
(+20,−20)
(+10,−20)
(0,−20)
(−10,−20)
(−20,−20)
Tmb [mK]
−20 0 20 40
0 200 400
Velocity [km s−1]

PAPERS - STATUS

MALATANG

- Last MTR: 9 papers proposed
- 1 accepted
- 2 submissions in 2018
- 2 under construction
- 3 halted

- Use this meeting to brainstorm new ideas
- Annouce a new call for MALATANG paper ideas

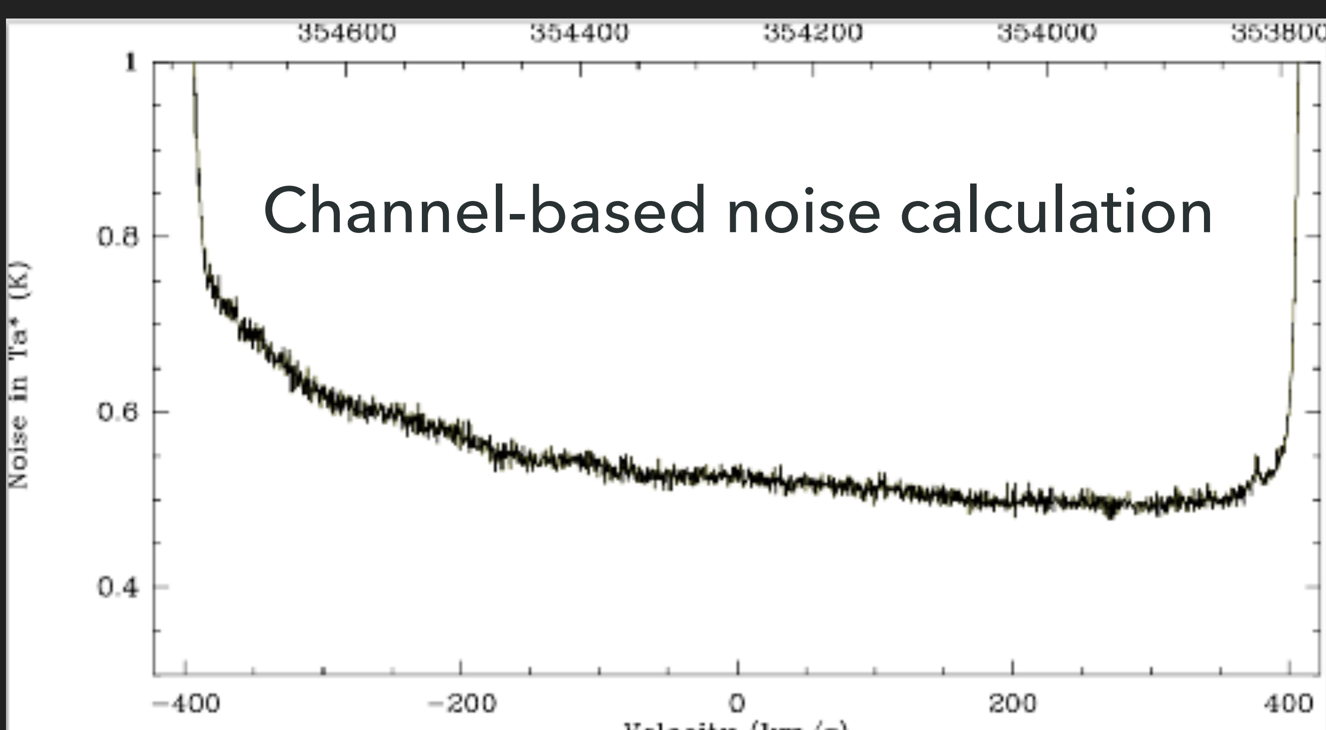
PAPER I *Survey & DR paper (Zhang et al., in prep)*

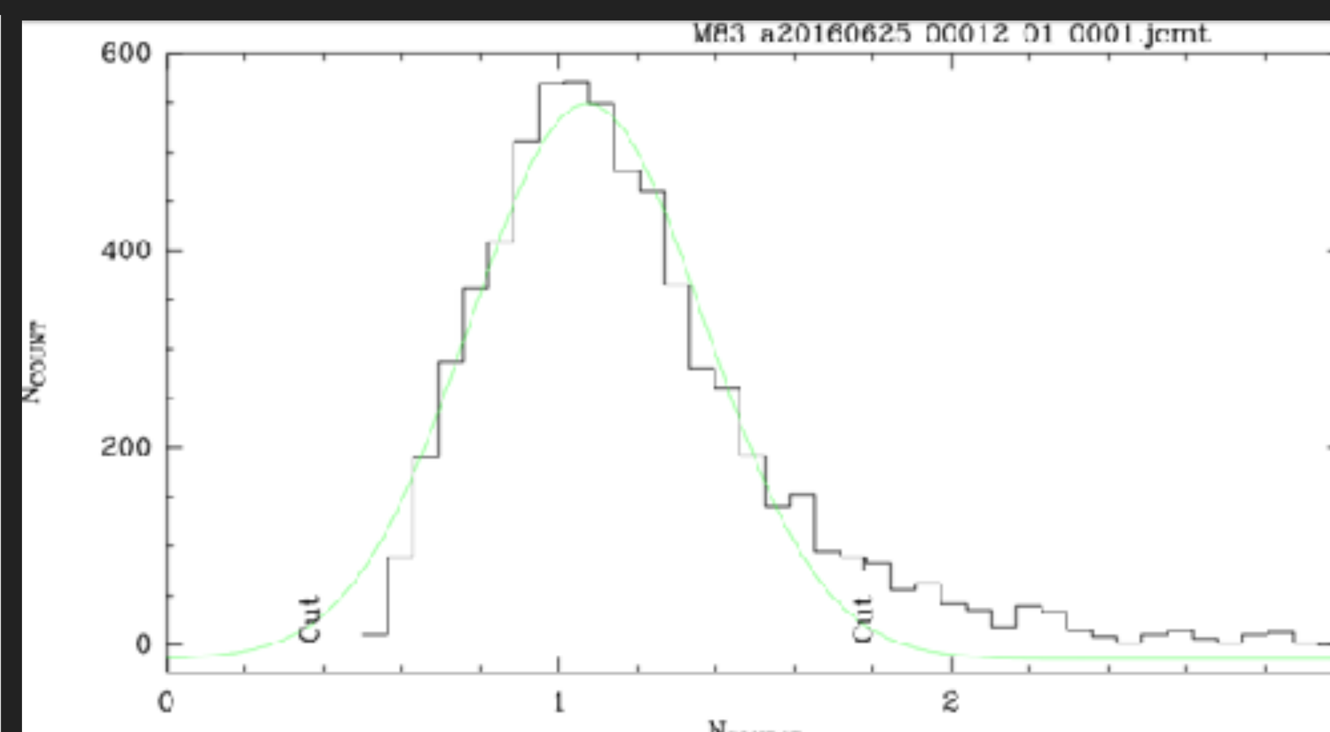
MALATANG-DR:

- Gildas/CLASS based
- Independent from ORAC-DR
- Important consistency check

Features:

- Converts raw HARP data to sdf-format (CLASS readable)
- Sophisticated quality-assessment of each receptor sub-scan –> 'goodnes'
- Optimised for weak/broad lines
- Channel-based noise calculation





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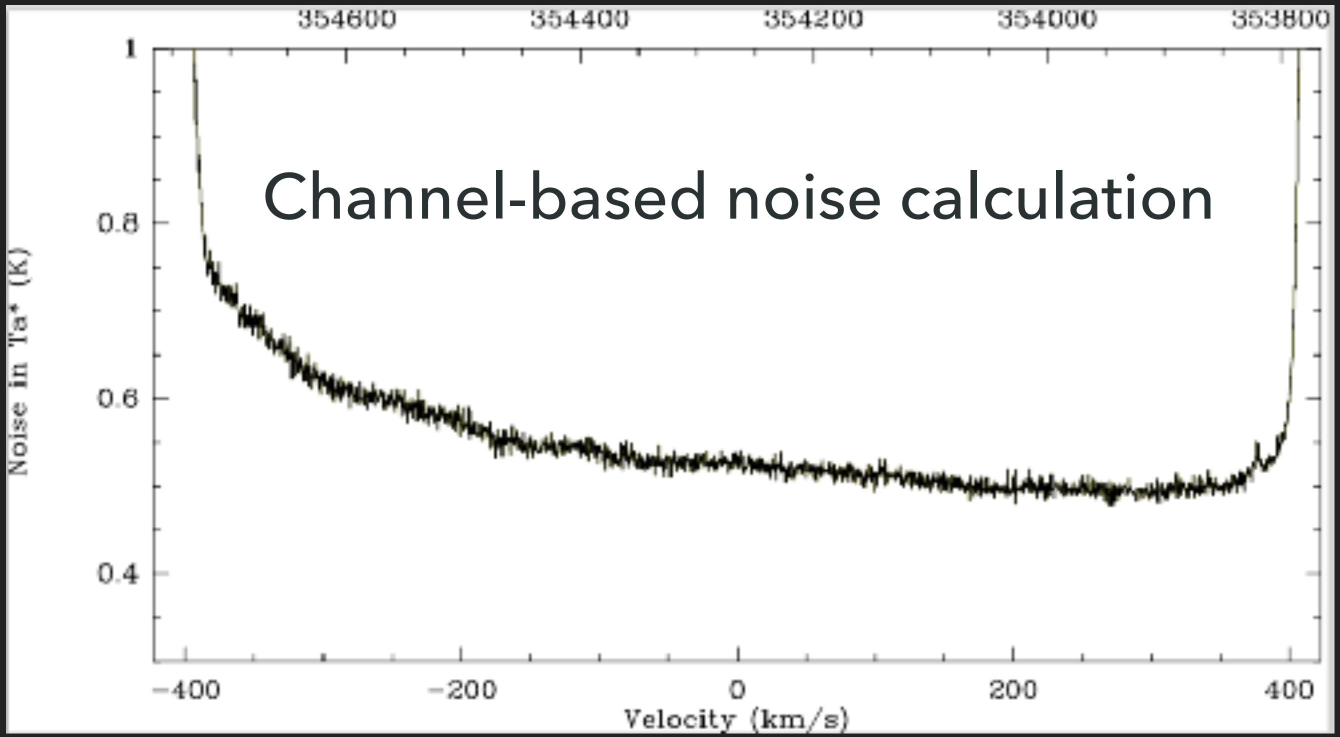

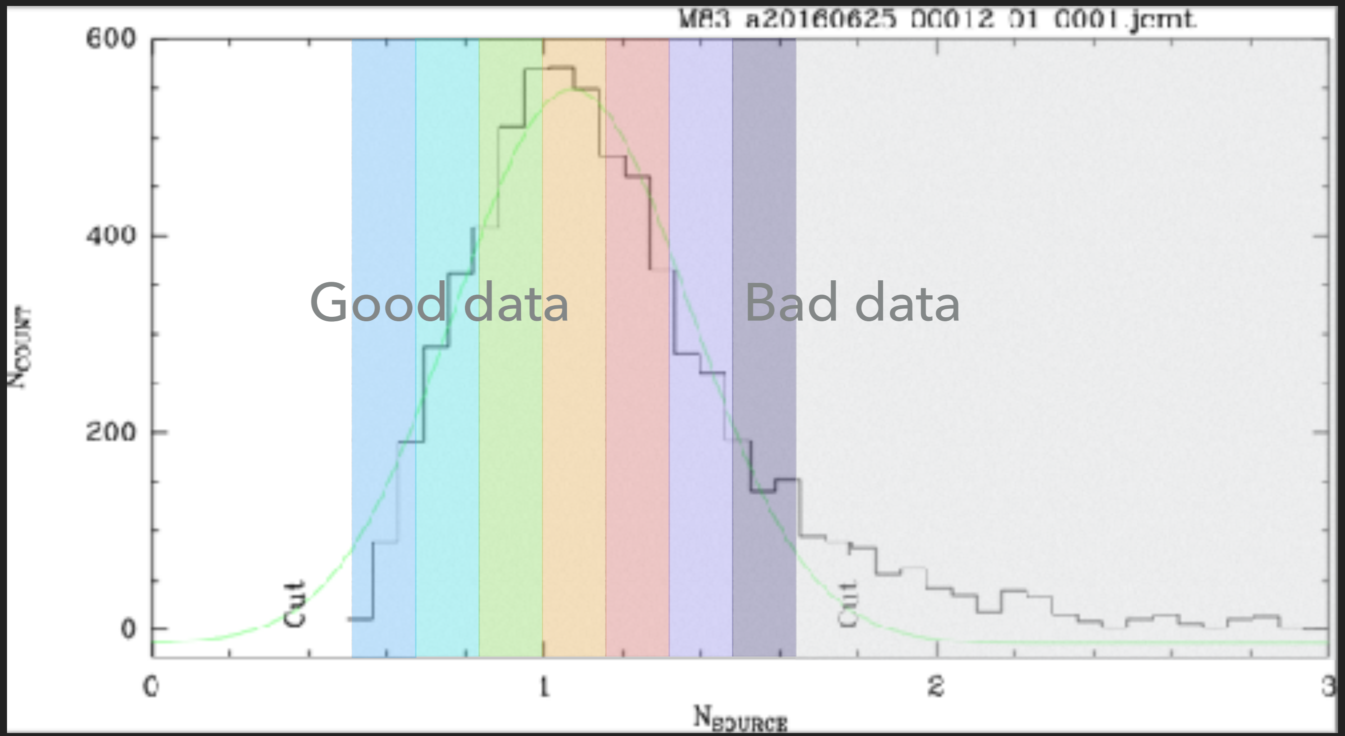

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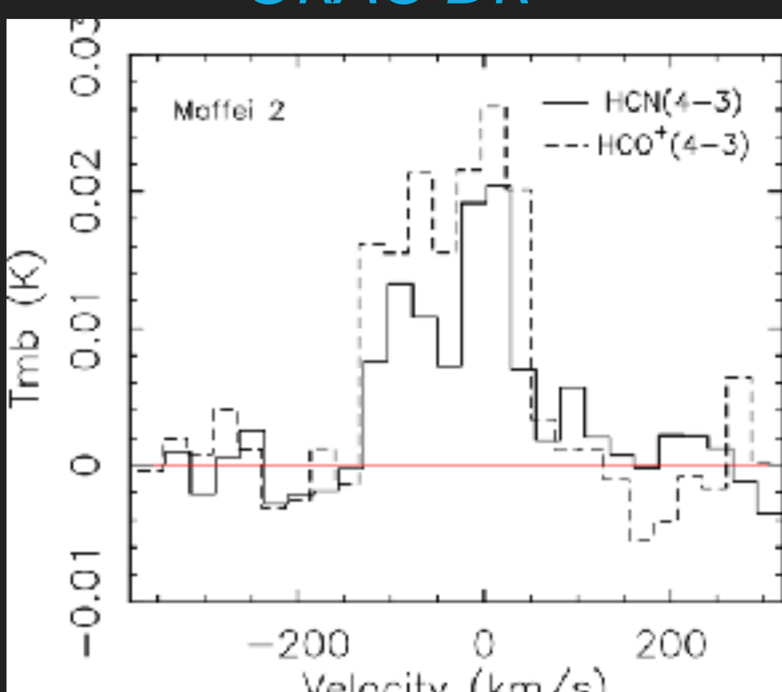
ORAC-DR



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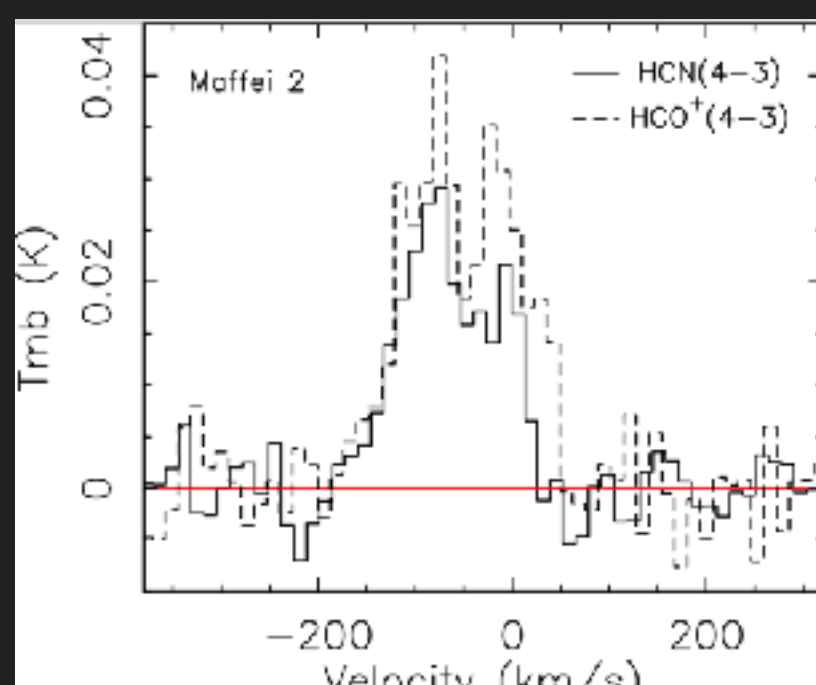
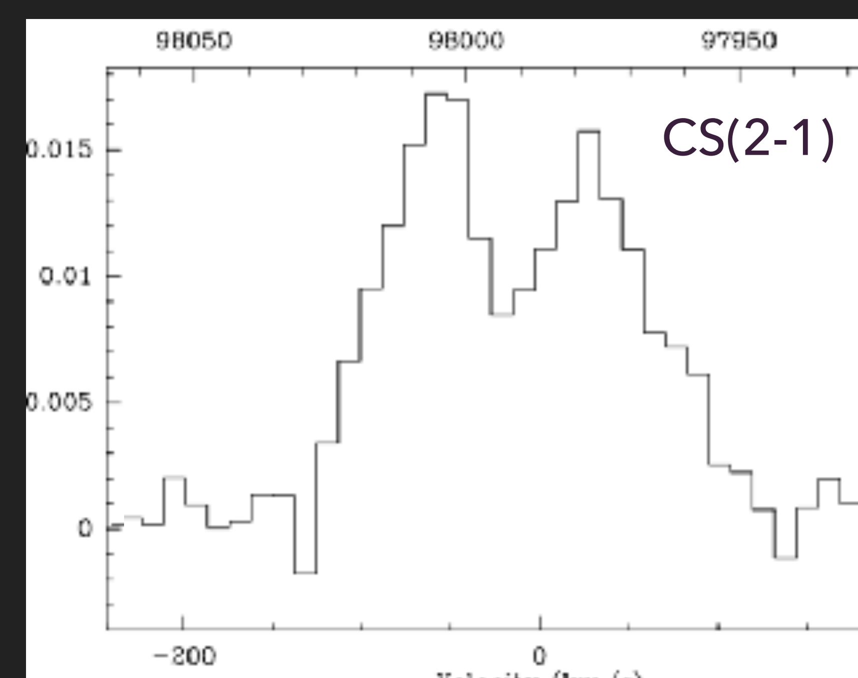


IRAM 30m

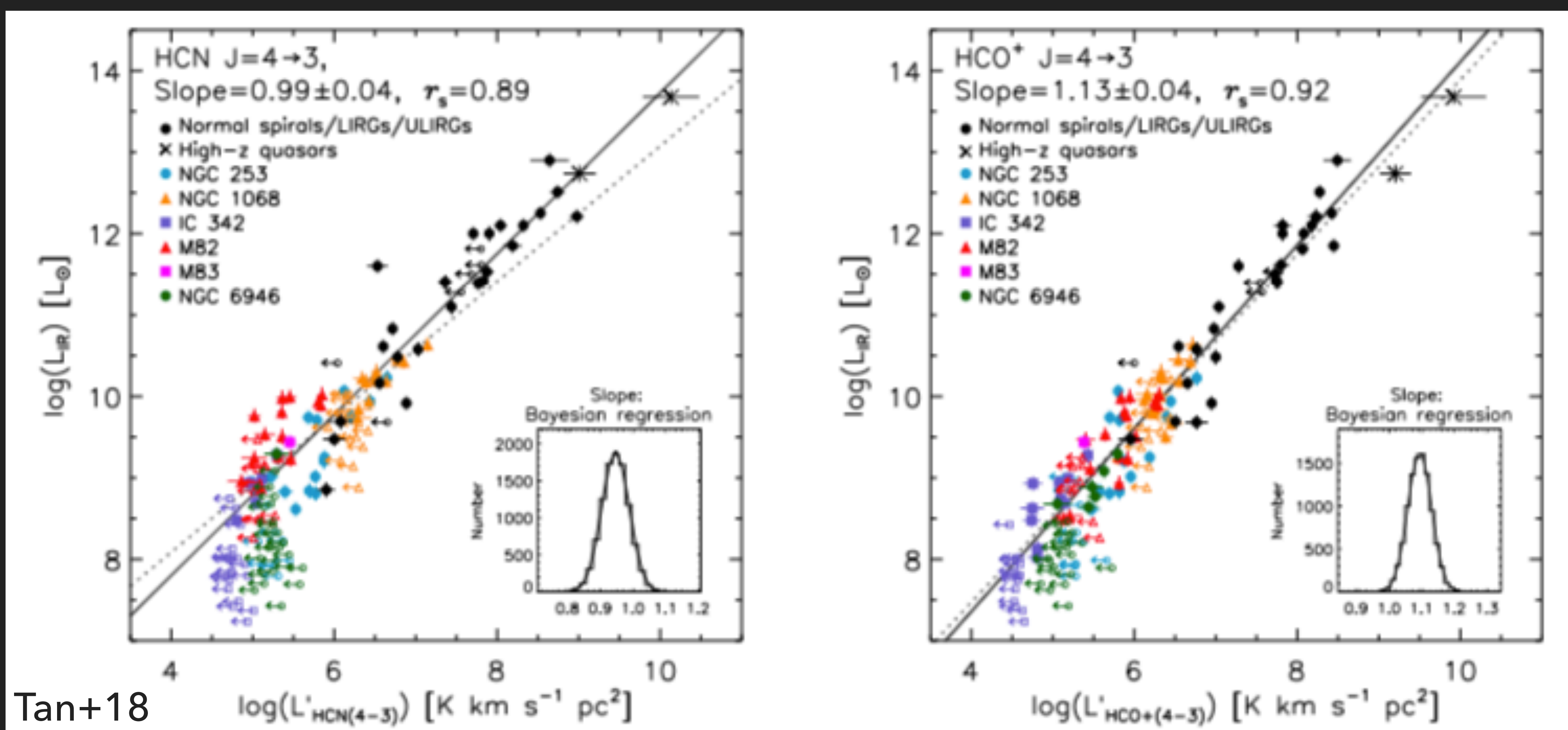


PAPER II

L_{gas}-L_{IR} on sub-kpc scales (Tan et al., accepted)

MALATANG

- 6 sources with jiggle maps
- Linear LIR-Ldense fit over many decades
- But systematic offsets on resolved scales



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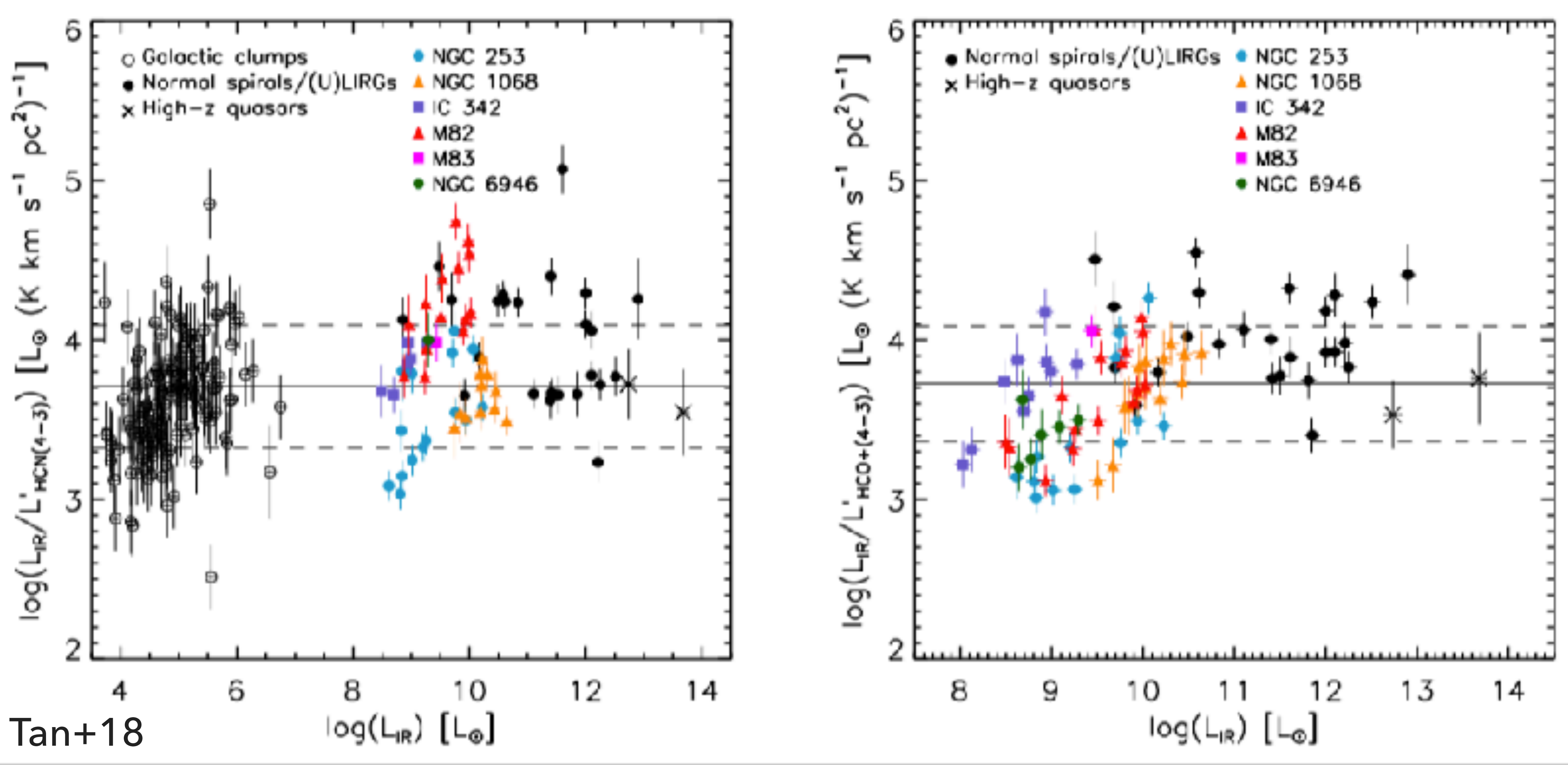

Tan+18

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L_{gas}-L_{IR} on sub-kpc scales (Tan et al., accepted)

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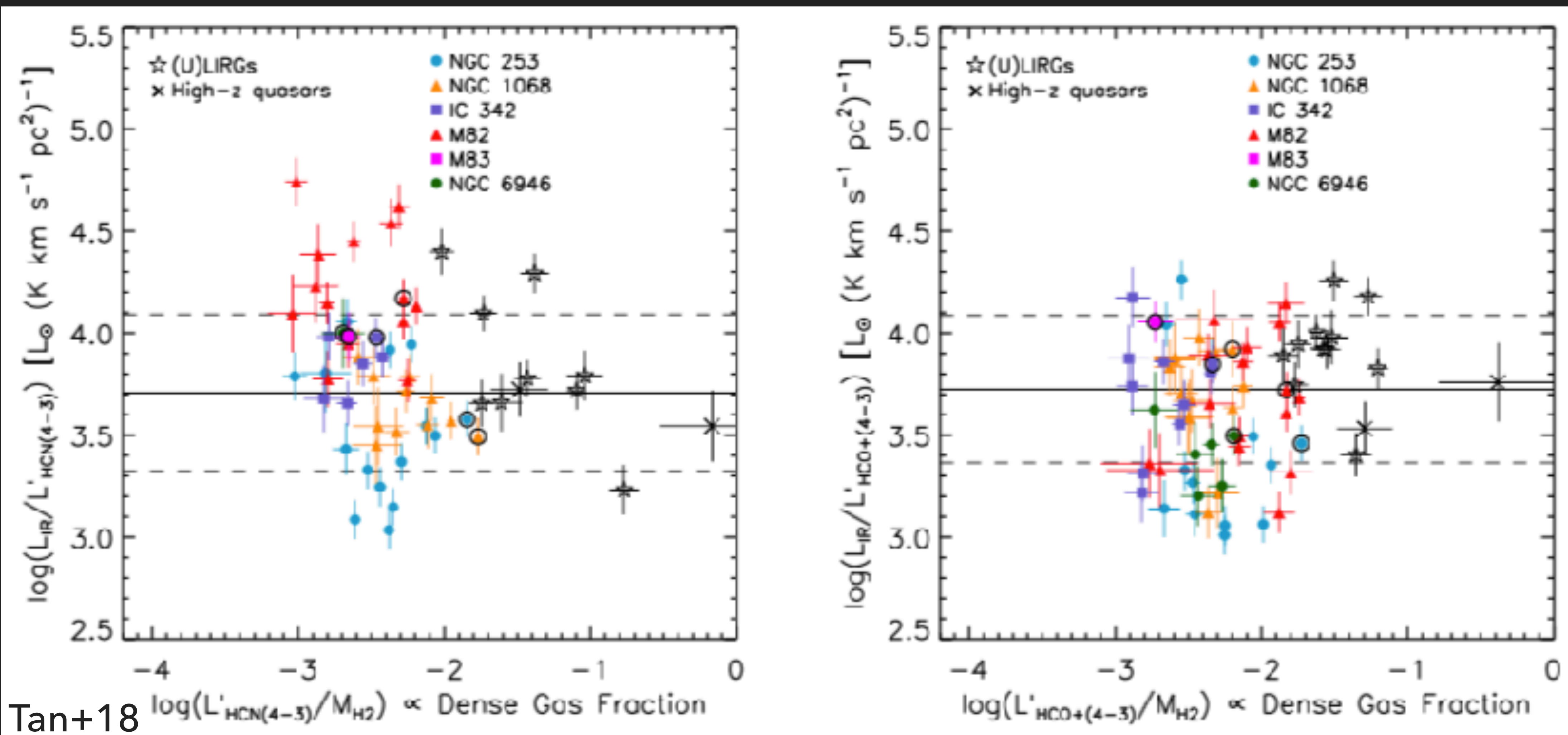
- Linear LIR-Ldense fit over many decades
- But systematic offsets on resolved scales
- L_{IR}/L_{dense} - L_{IR} trends on sub-kpc scales
- L_{IR}/L_{dense} no clear trend with dense gas fraction - but systematic offsets seen



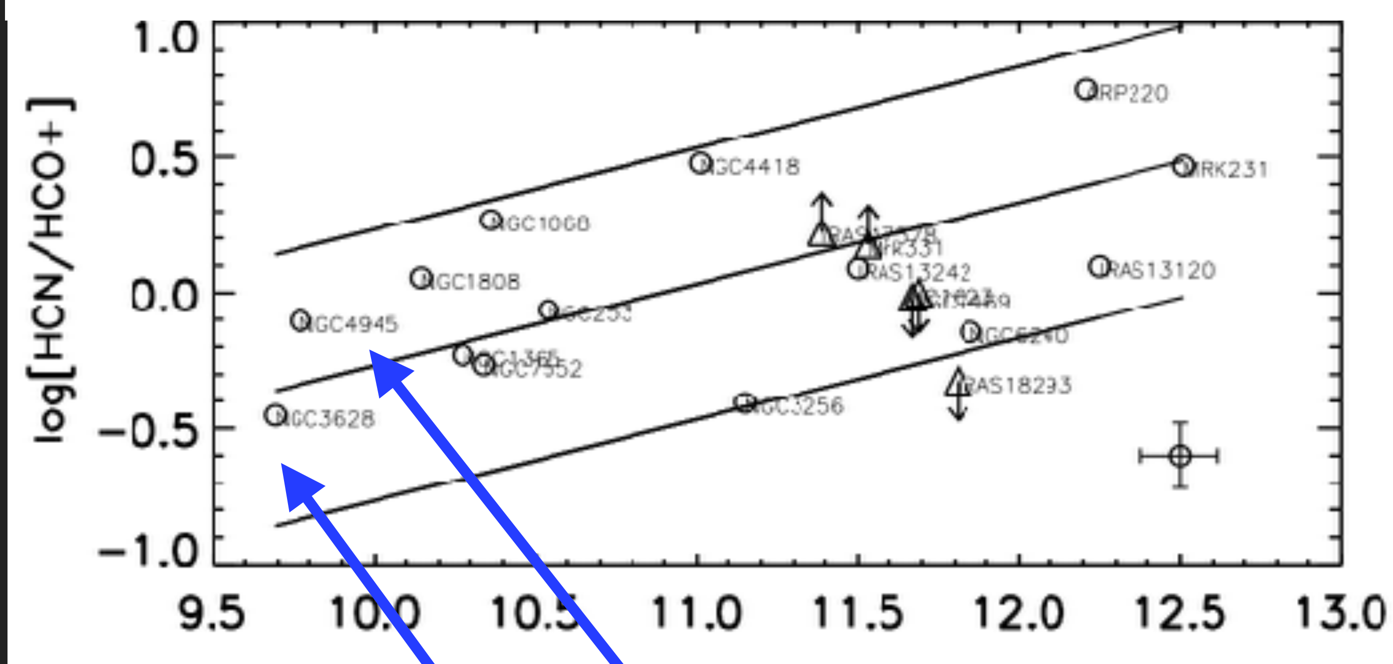
Tan+18

PAPER III

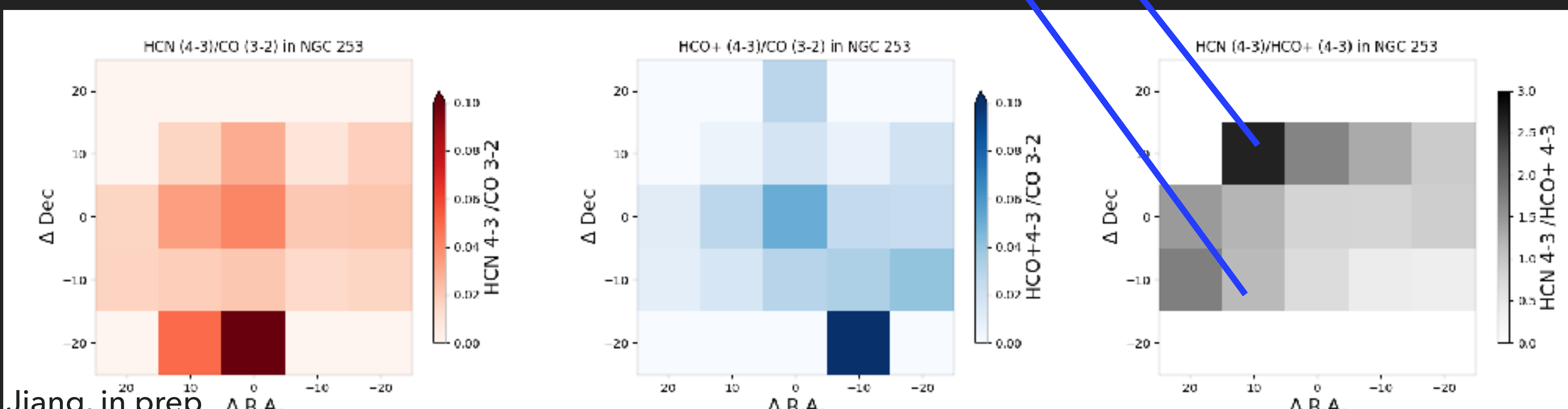
Dense gas exctiation vs environment (Jiang et al., in prep)

MALATANG

- Large variations in HCN/HCO+
- Radial HCN/HCO+ and CO(3-2) profiles
- Radial SFE, f_{dense} profiles
- L_{IR} dependence?
- Density variations?



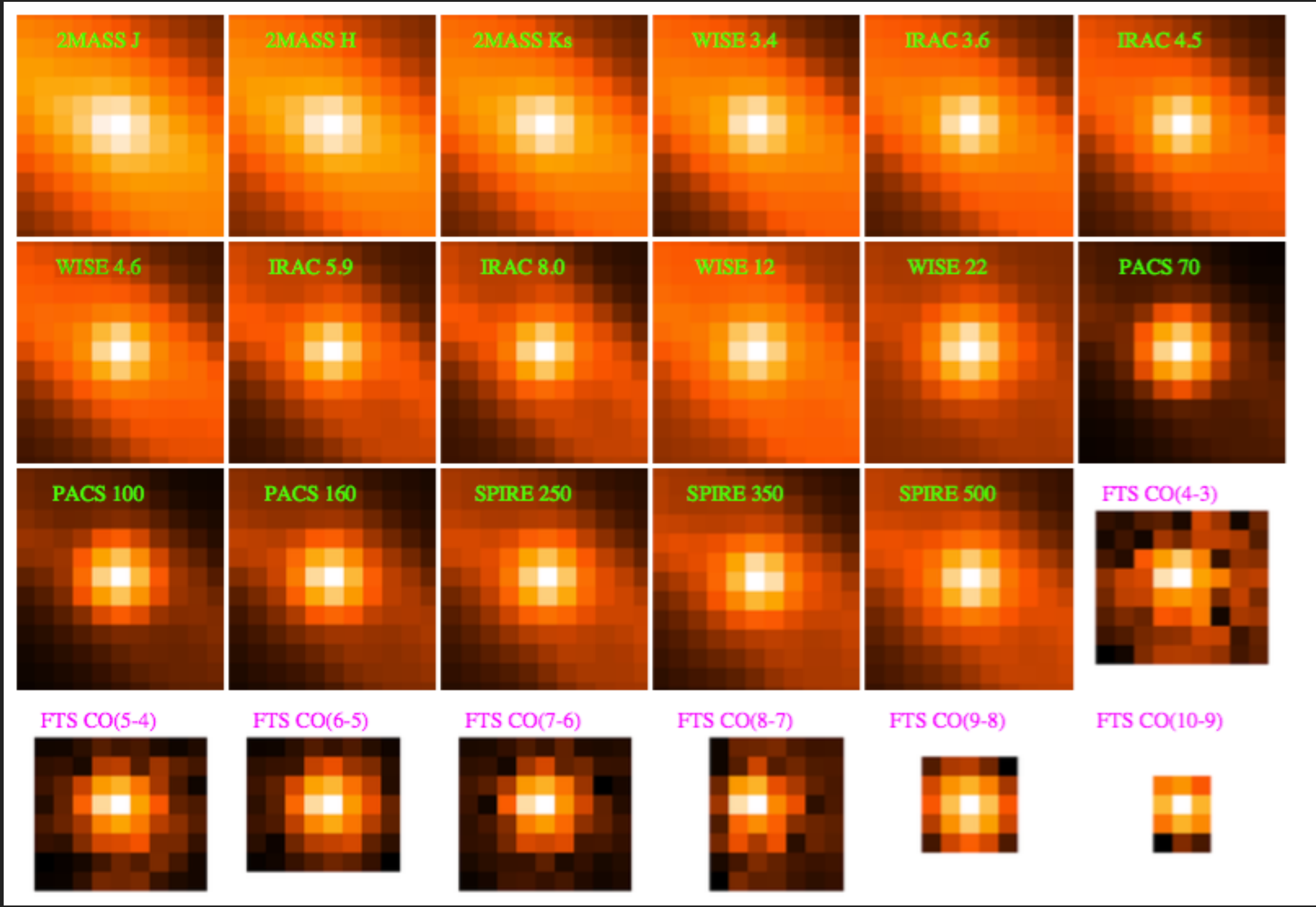
Zhang+13



Jiang, in prep

PAPER IV *Liu et al., in prep*

- Pixel-to-pixel comparison of SPIRE-FTS high-J CO and HCN/HCO+
- Pixel-to-pixel LVG modelling
- Distributed L_{IR} (SFR)



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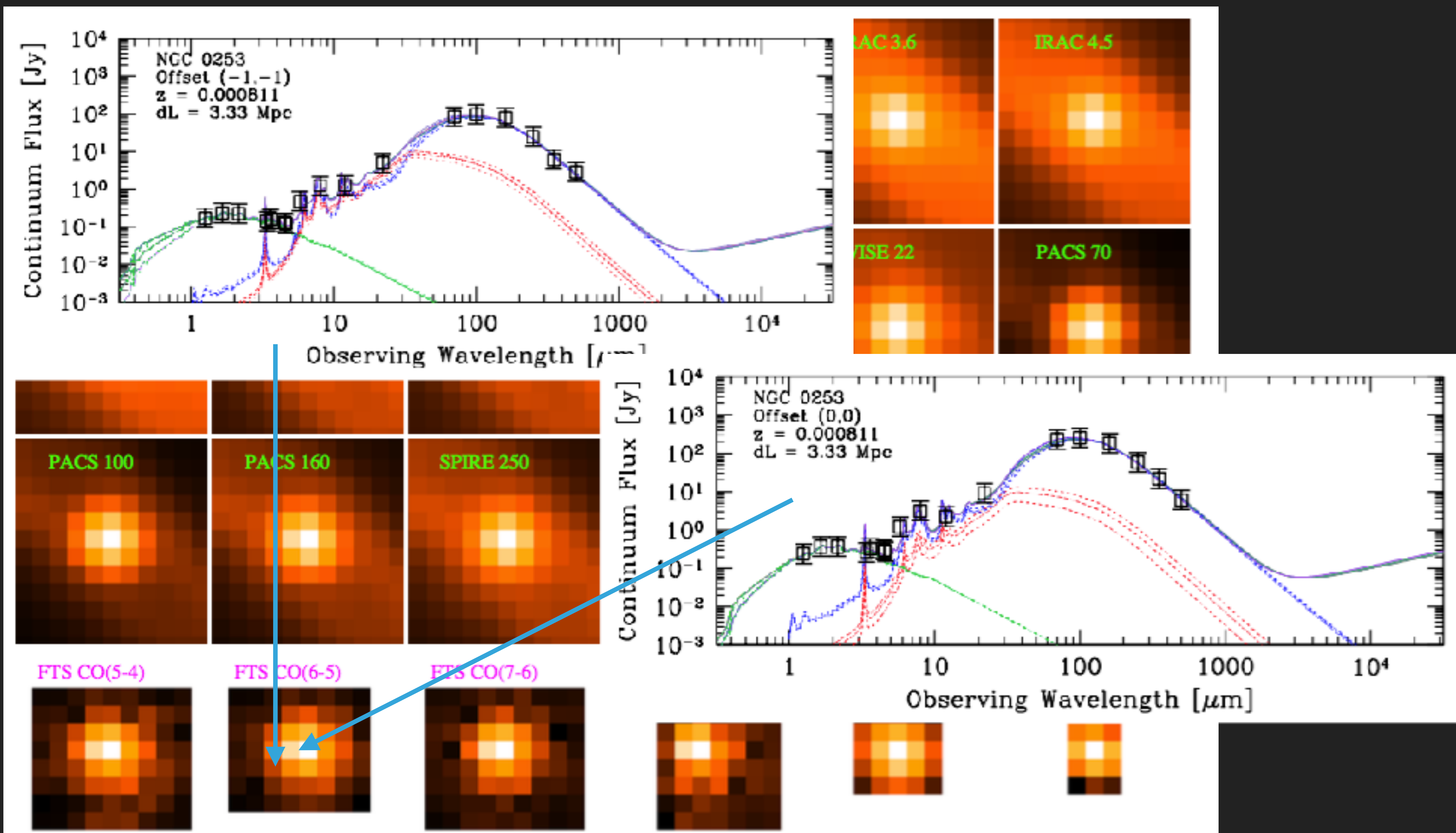


FOLLOW-UP WORK

Continuum Observations:

- *JCMT SCUBA-2 maps of MALATANG sources* ✓

  M18AP056: NGC1365, IC342, MAFFEI2, NGC1068

- *IRAM-30m NIKA2 maps @ 2mm*

Band	Number of KIDs	Wavelength	Bandwidth	NEFD	HPBW	FoV
NIKA2 2 mm/150 GHz	1020	2.00 mm	125-170 GHz	20 mJy*s$^{1/2}$	18"	6.5'
NIKA2 1 mm/260 GHz	2x1140	1.15 mm	240-280 GHz	30 mJy*s$^{1/2}$	12"	6.5'

- *APEX ArTeMIS 350micron maps (raster/spiral mode maps or on-the-fly mode). Beam 8.5" (so ~3× better than Herschel)*

  ~50% of MALATANG sources are observablee with APEX

  2′×2′ ArTeMIS map, 1hr integration:

Good weather pwv =0.2 mm	Poor weather pwv =0.8 mm	Average weather pwv =0.5 mm
41.9 mJy/beam	119.2 mJy/beam	71.6 mJy/beam

FOLLOW-UP WORK

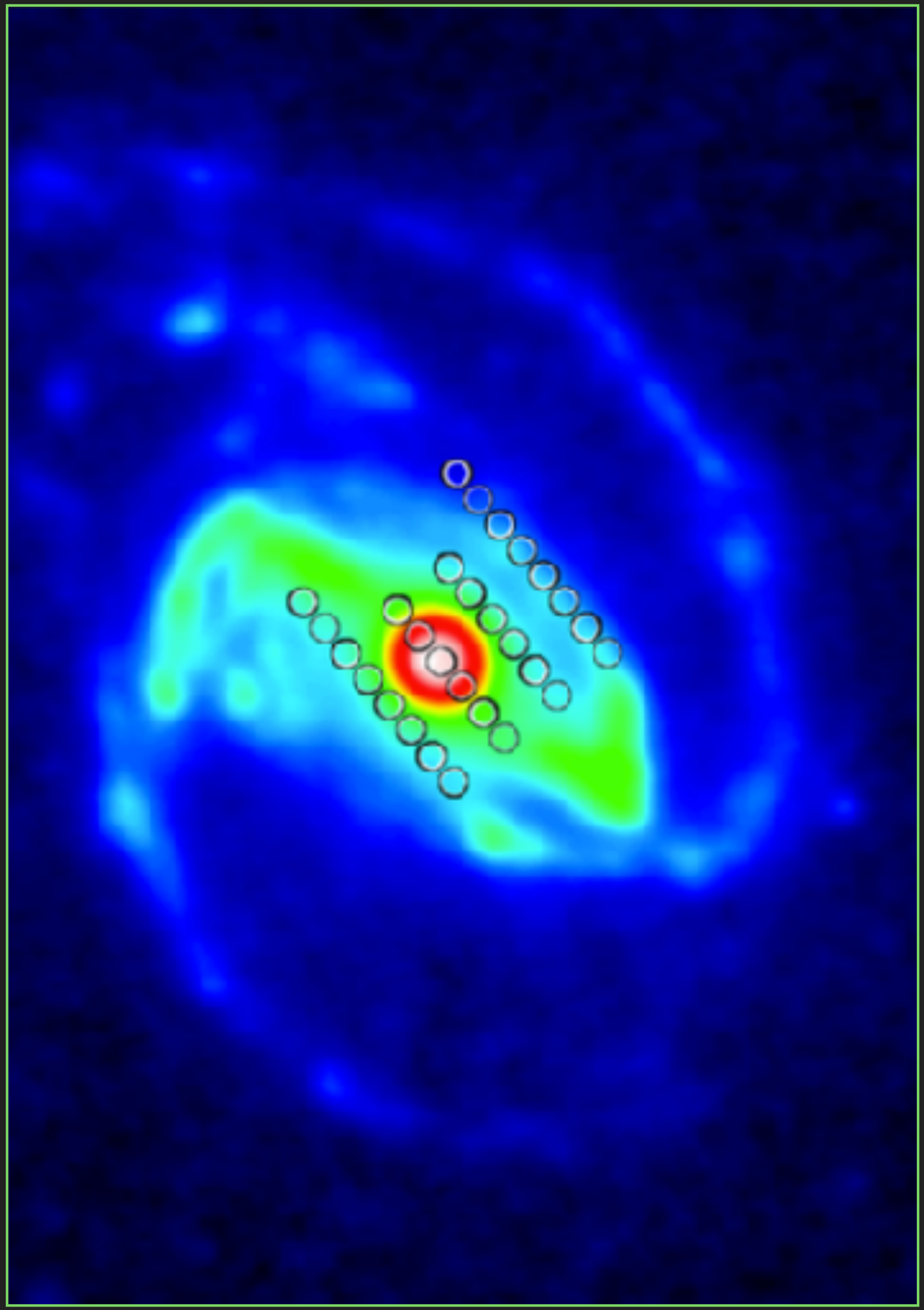
Heterodyne Observations:

- *JCMT HARP CO(3-2) follow-up*
- *IRAM-30m (HERA, EMIR)*
- *Nobeyama 45m*
- *GBT*
- *High resolution ALMA, NOEMA and SMA maps*
- *APEX (high-J lines)*

Nobeyama 45m

SUMMARY

- *MALATANG observing is done!*
- *Careful data reduction*
    - *Developed an independent DR pipeline*
    - *Final data-products*
    - *Off-nuclear HCN/HCO+ lines weaker than anticipated*
- *3 MALATANG papers accepted by the end of 2018*
    - *Survey & DR paper*
    - *Dense gas relation on sub-kpc scales, first results from 6 jiggle maps*
    - *Radial HCN/HCO+ excitation*
- *More papers and follow-up proposals in the works*



THANK YOU

MALATANG