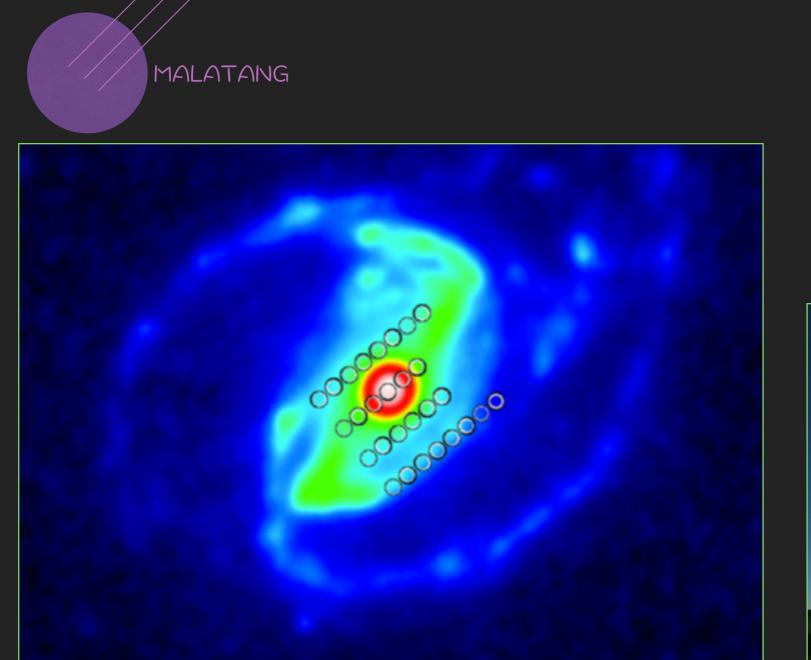
"STIRRING THE POT" – THE MALATANG SURVEY OF DENSE GAS IN NEARBY GALAXIES



THOMAS R. GREVE UNIVERSITY COLLEGE LONDON

ON BEHALF OF THE MALATANG TEAM



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 stArformiNg 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 ~5×10⁶M☉ and scales ~0.2-2.8kpc in other galaxies
- Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations

HARP



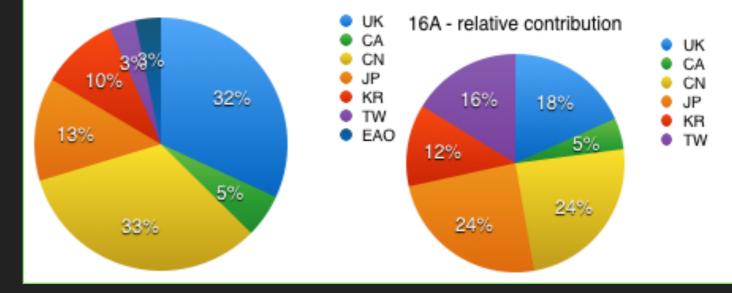
THE TEAM

MALATANG members 91

All JCMT countries represented

Collaborators welcome!

m16al007 - MALATANG



Name	Affiliation	Country	Student	Name	Affiliation	Country	Student	Name	Affiliation	Country	Student
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Christine Wilson	McMaster U.	CA		Tomoka Tosaki	JUEN	JP		Matt Smith	Cardiff U.	UK	
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Jing-Wen Wu	NAOC	CN		Joanna Burgler	NAOJ	JP		George Kelly	UCL	UK	
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Bing Jiang	NJU	CN		Daisuke Iono	NAOJ	JP		Amelie Saintonge	UCL	UK	
Qiu-Sheng Gu	NJU	CN		Quang Nguyen Luong	NAOJ	JP		Richard Tunnard	UCL	UK	Y
Yong Shi	NJU	CN		Sherry Yeh	NAOJ/Subaru	JP		Serena Viti	UCL	UK	
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Richard de Grijs	PKU	CN		Kotaro Kohno	U. Tokyo	JP		Zhi-Yu Zhang	U. Edinburgh	UK	
Luis Ho	PKU	CN		Taehyun Kim	KR KASI	KR		Elias Brinks	U. Hertfordshire	UK	
Jinyi Shangguan	PKU	CN	Y	Yuijin Yang	KASI	KR		Giulio Violino	U. Hertfordshire	UK	Y
Yali Shao	PKU	CN		Hong Soo Park	KASI	KR		kristen Coppin	U. Hertfordshire	UK	
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Yanxia Xie	PKU	CN		Soojong Pak	Kyung Hee U.	KR		Andrew Blain	U. Leicester	UK	
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Dai-Zhong Liu	PMO	CN	Y	Aeree Chung	Yonsei U.	KR		Andrew Rigby	U. Liverpool	UK	Y
Li-Jie Liu	PMO	CN		Bumhyun Lee	Yonsei U.	KR	Y	Dimitra Rigopoulou	U. Oxford	UK	
Qing-Hua Tan	PMO	CN		I-Chenn Chen	NCU	TW		Aprajita Verma	U. Oxford	UK	
Chen-Tao Yang	PMO	CN	Y	Nanase Harada	ASIAA	TW		Mark Sargent	U. Sussex	UK	
Jun-Zhi Wang	SHAO	CN		Satoki Matsushita	ASIAA	TW		Malcolm Currie	EAO	US	
Ting Xiao	SHAO	CN		Anli Tsai	ASIAA/NCU	TW		Sarah Graves	EAO	US	
Cheng Li	Tsinghua U.	CN		Chris Clark	Cardiff U.	UK		Harriet Pearson	EAO	US	
YH. Zhao	UNAO	CN		Timothy Davis	Cardiff U.	UK		Mark G. Rawlings	EAO	US	
Yu-Xin He	XAO	CN	Y	Loretta Dunne	Cardiff U.	UK		Harriet Parsons	EAO	US	
Tao-Tao Fang	XMU	CN		Stephen Eales	Cardiff U.	UK					

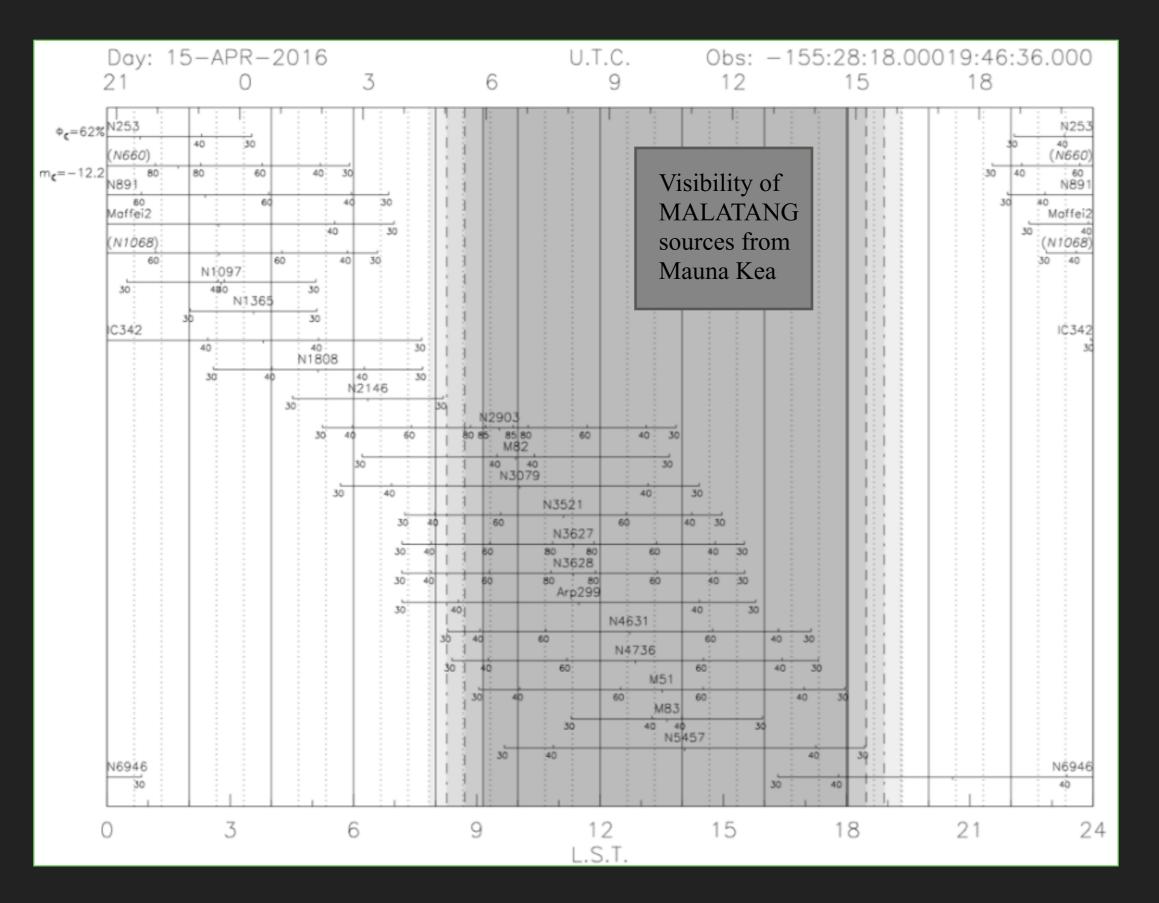
THE SAMPLE

S($60\mu m$) > 50 Jy and S($100\mu m$) > 100Jy in RBGS (Sanders+03) and δ > -40° in order to be observable with the JCMT

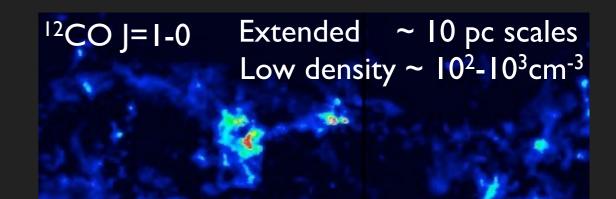
Total sample size: 23 sources

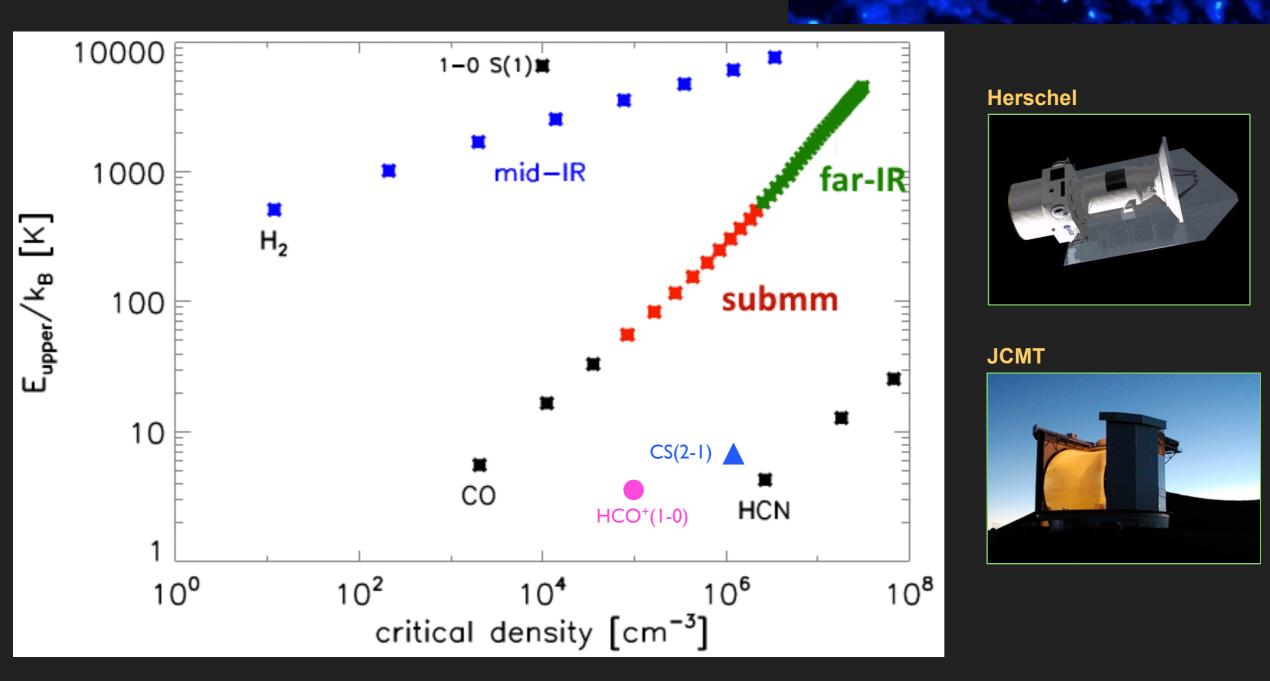
Ν	Source Name	R.A.	Decl.	Distance	Diameter	<i>f</i> 60µm	<i>f</i> 100µm	logL _{fir}	$\log \Sigma_{SFR}$
		(J2000)	(J2000)	(Mpc)	(arcmin)	(Jy)	(Jy)	(L_{\odot})	$(M_{\odot} \mathrm{yr}^{-1} \mathrm{kpc}^{-2})$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	*NGC 253	00 47 33.1	-25 17 18	2.5	27.5×6.8	967.81	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

THE SAMPLE

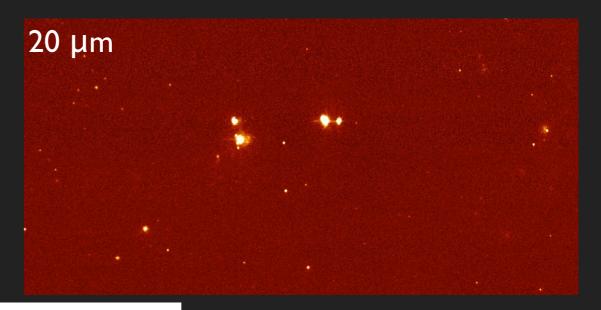


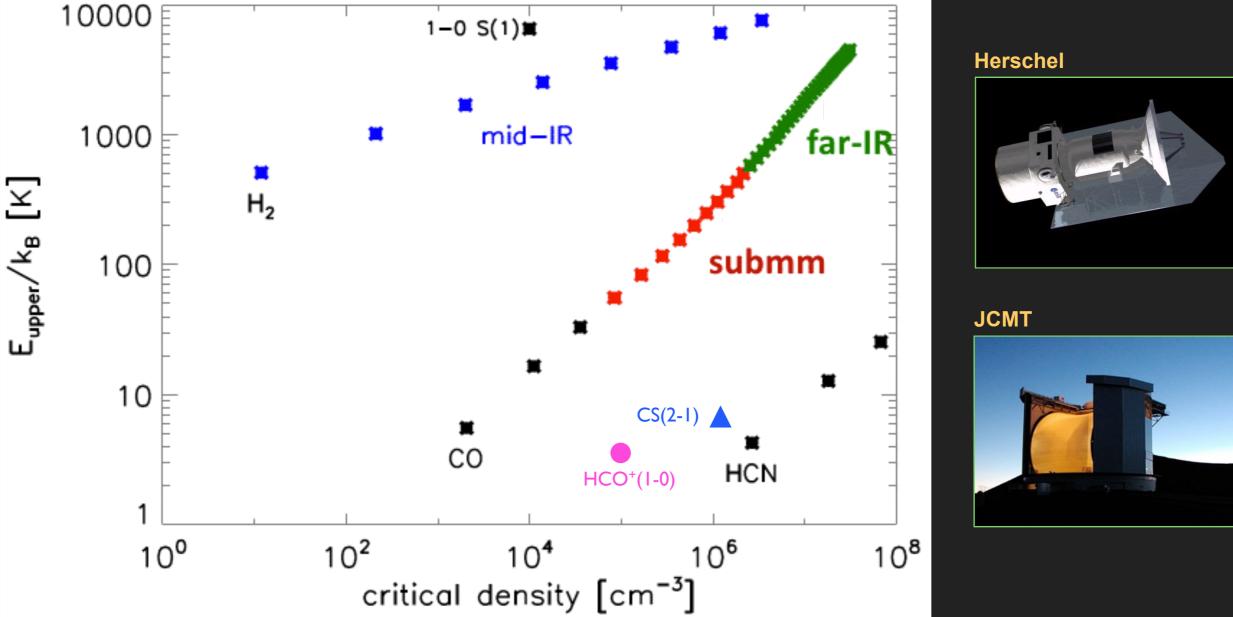
"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$ understanding slopes (a) and intercepts (β) for different molecular J-transitions



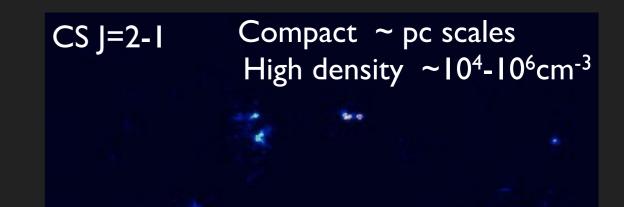


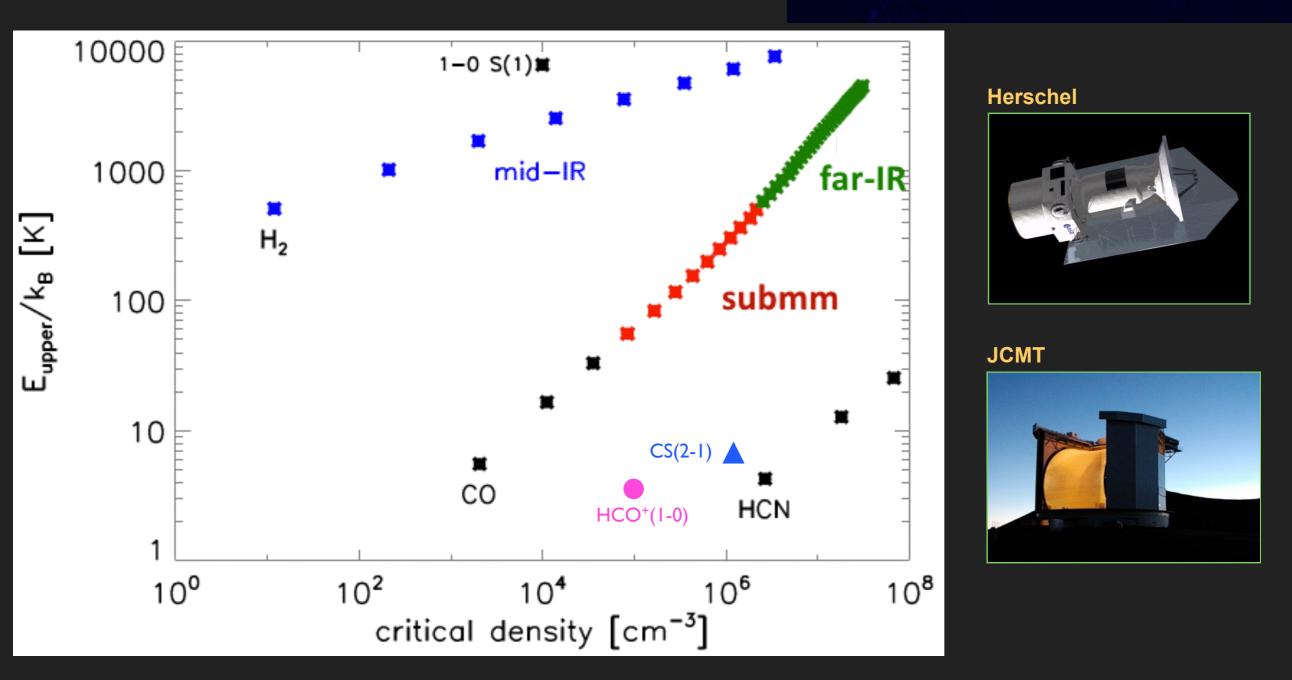
"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$ understanding slopes (a) and intercepts (β) for different molecular J-transitions





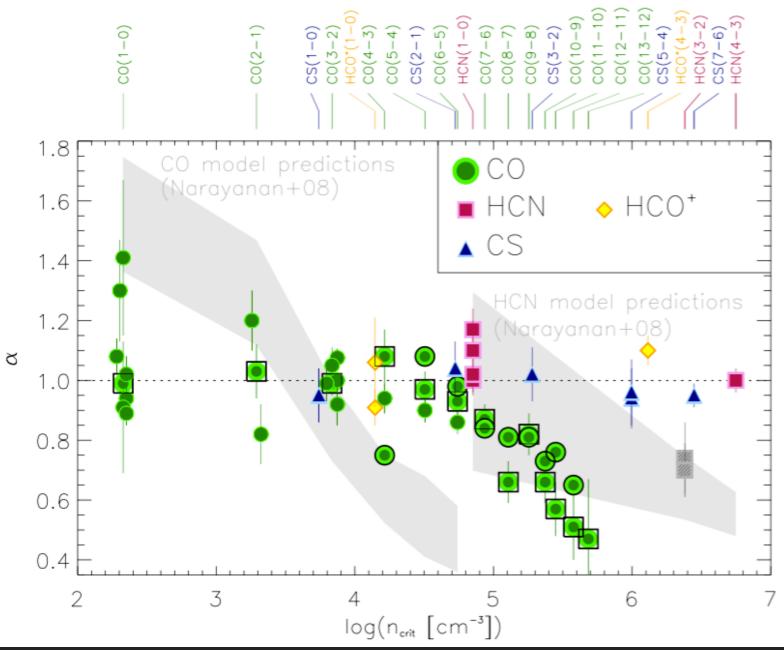
"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$ understanding slopes (a) and intercepts (β) for different molecular J-transitions





"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$ understanding slopes (a) and intercepts (β) for different molecular J-transitions

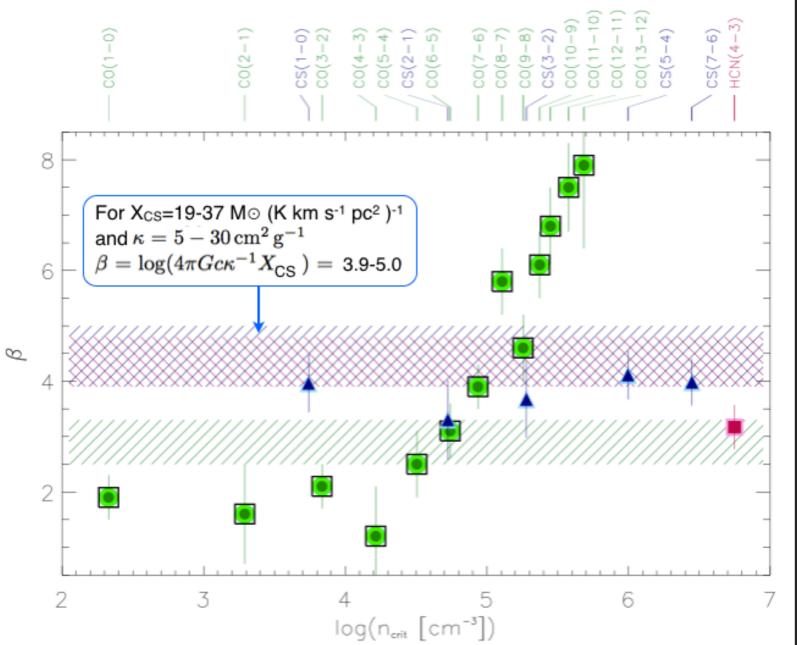
Galaxy-integrated a vs. n_{crit}



Transition	$n_{ m crit}$	$E_J/k_{ m B}$
	$[\mathrm{cm}^{-3}]$	[K]
CO(1-0)	4.4×10^{2}	5.53
$\dot{O(2-1)}$	$3.6 imes10^3$	16.60
CO(3-2)	$1.3 imes 10^4$	33.19
CO(4-3)	$3.0 imes 10^4$	55.32
CO(5-4)	$5.9 imes 10^4$	82.97
CO(6-5)	$1.0 imes 10^5$	116.16
CO(7-6)	$1.5 imes 10^5$	154.87
HCN(1-0)	1.7×10^{5}	4.25
HCN(2-1)	$1.6 imes 10^6$	12.76
HCN(3-2)	$5.2 imes 10^6$	25.52
HCN(4-3)	$1.3 imes 10^7$	42.53
$HCO^{+}(1-0)$	$2.6 imes10^4$	4.25
$HCO^{+}(2-1)$	$2.6 imes10^5$	12.76
$HCO^{+}(3-2)$	$1.0 imes 10^6$	25.52
$HCO^{+}(4-3)$	$2.5 imes 10^6$	42.53
CS(1-0)	$8.3 imes10^3$	2.35
CS(2-1)	$7.9 imes10^4$	7.05
CS(3-2)	$3.0 imes10^5$	14.11
CS(4-4)	$7.7 imes 10^5$	35.27
CS(5-4)	1.8×10^6	49.37
CS(6-5)	3.1×10^6	65.83
CS(7-6)	$4.9 imes 10^6$	65.83

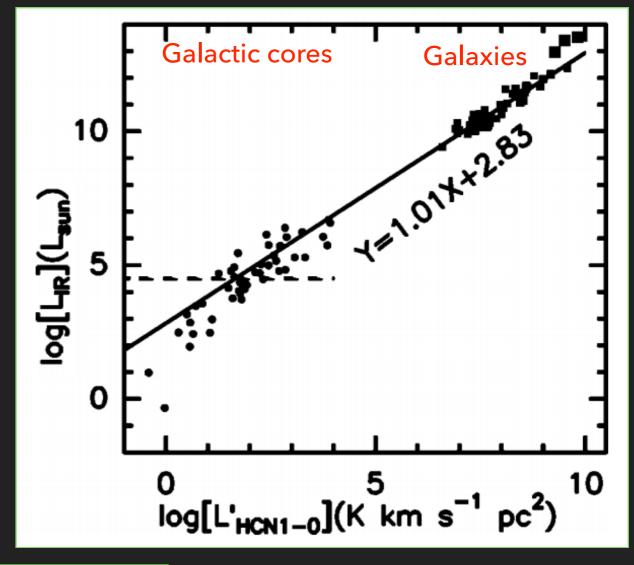
"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$ understanding slopes (a) and intercepts (β) for different molecular J-transitions

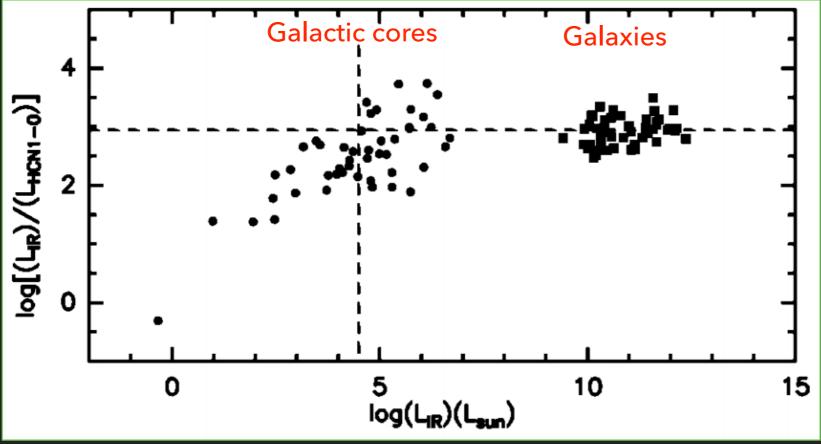
Galaxy-integrated β vs. n_{crit}



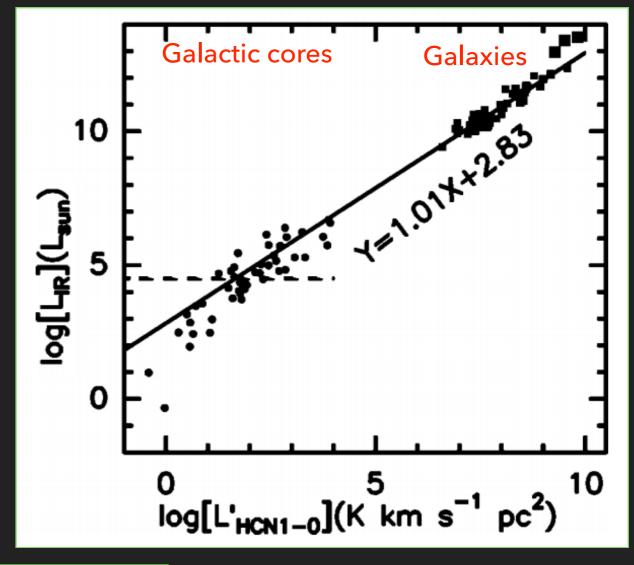
$n_{ m crit}$	$E_J/k_{ m B}$
$[\mathrm{cm}^{-3}]$	[K]
4.4×10^2	5.53
$3.6 imes10^3$	16.60
$1.3 imes 10^4$	33.19
$3.0 imes10^4$	55.32
$5.9 imes10^4$	82.97
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1.5×10^5	154.87
1.7×10^{5}	4.25
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$5.2 imes 10^6$	25.52
$1.3 imes 10^7$	42.53
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$3.0 imes10^5$	14.11
7.7×10^{5}	35.27
1.8×10^{6}	49.37
3.1×10^{6}	65.83
4.9×10^{6}	65.83
	$\begin{array}{c} 4.4 \times 10^2 \\ 3.6 \times 10^3 \\ 1.3 \times 10^4 \\ 3.0 \times 10^4 \\ 5.9 \times 10^4 \\ 1.0 \times 10^5 \\ 1.5 \times 10^5 \\ 1.5 \times 10^5 \\ 1.6 \times 10^6 \\ 5.2 \times 10^6 \\ 1.3 \times 10^7 \\ 2.6 \times 10^4 \\ 2.6 \times 10^5 \\ 1.0 \times 10^6 \\ 2.5 \times 10^6 \\ 1.0 \times 10^6 \\ 8.3 \times 10^3 \\ 7.9 \times 10^4 \\ 3.0 \times 10^5 \\ 7.7 \times 10^5 \\ 1.8 \times 10^6 \\ 3.1 \times 10^6 \end{array}$

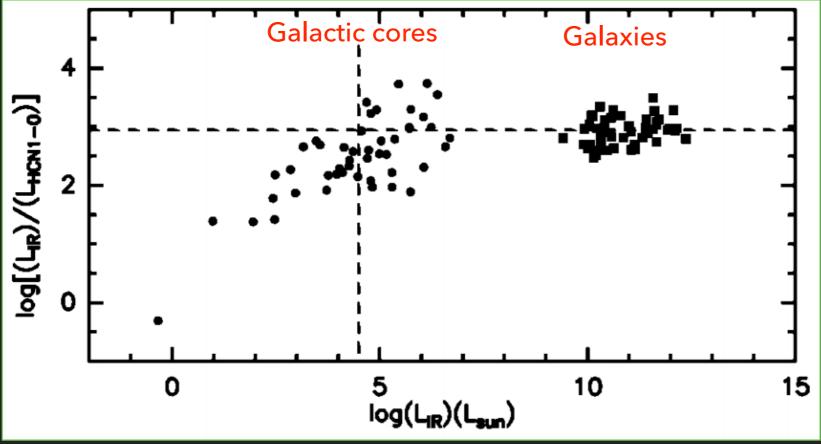
Resolved dense gas star formation relations





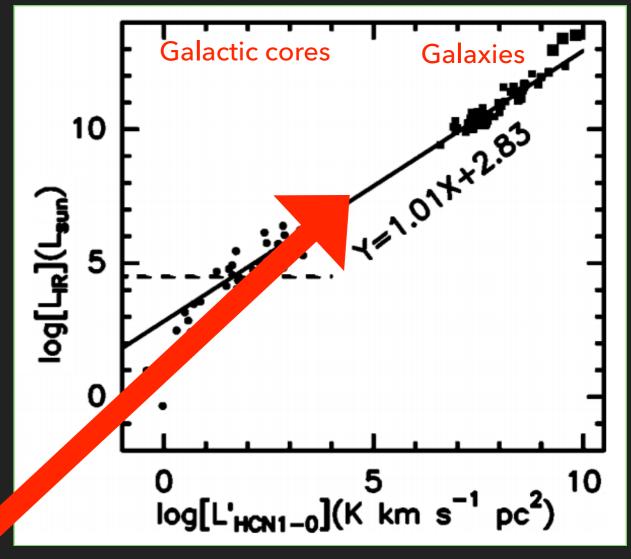
Resolved dense gas star formation relations

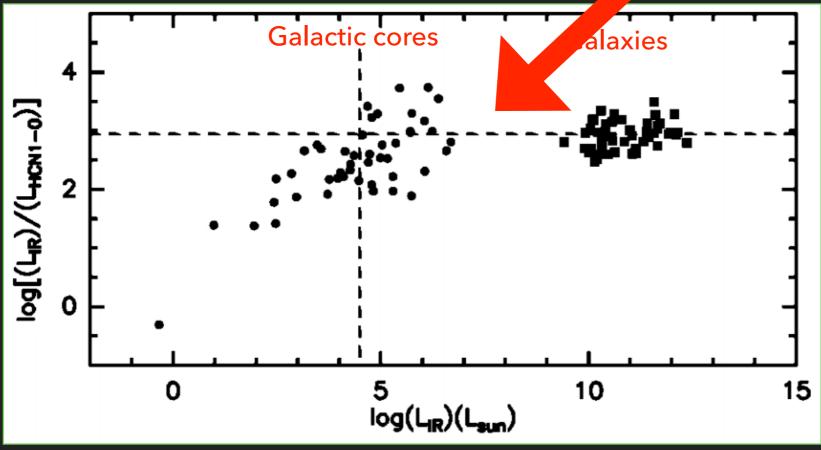




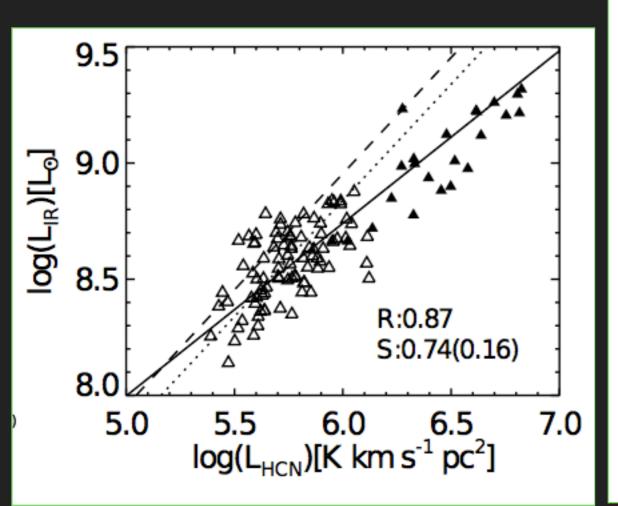
Resolved dense gas star formation relations

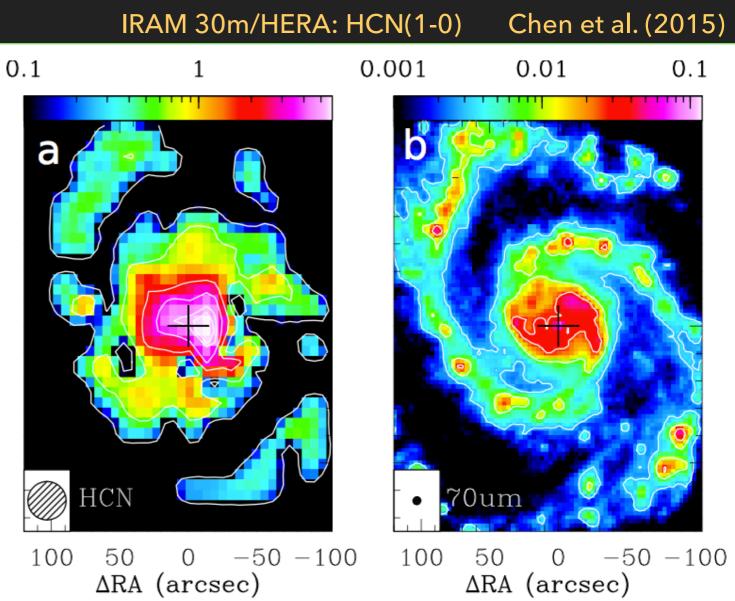
Intermediate scales/luminosities





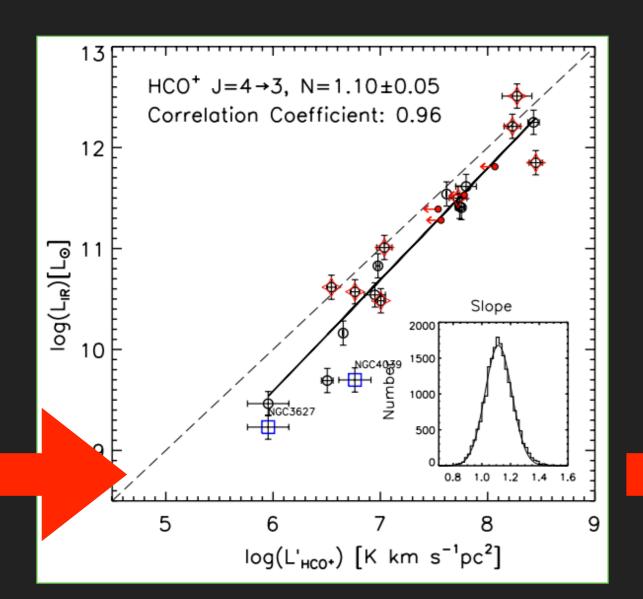
- Resolved dense gas star formation relations
- Intermediate scales/luminosities
- Different environments: nuclear vs. disk
- Radial distribution of dense gas and SF efficiency

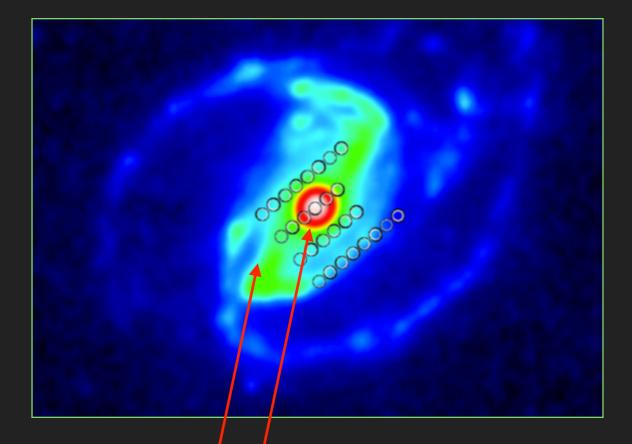


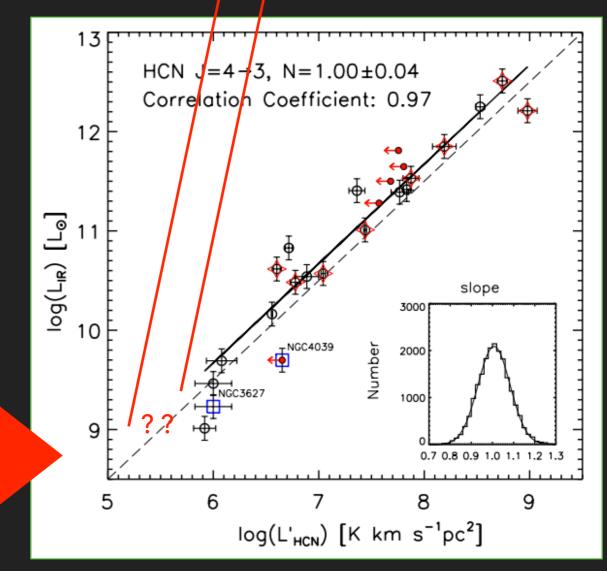


Resolved dense gas star formation relations

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

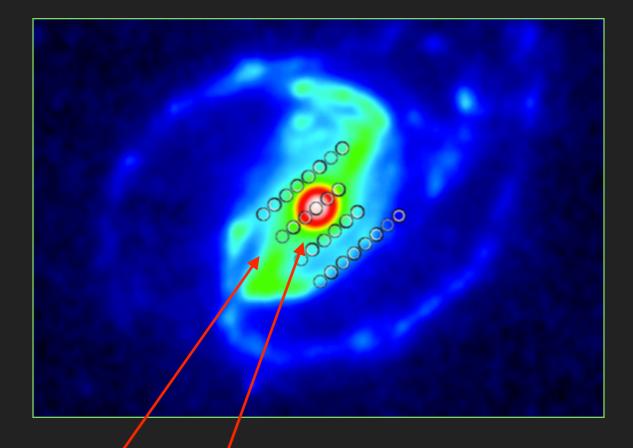




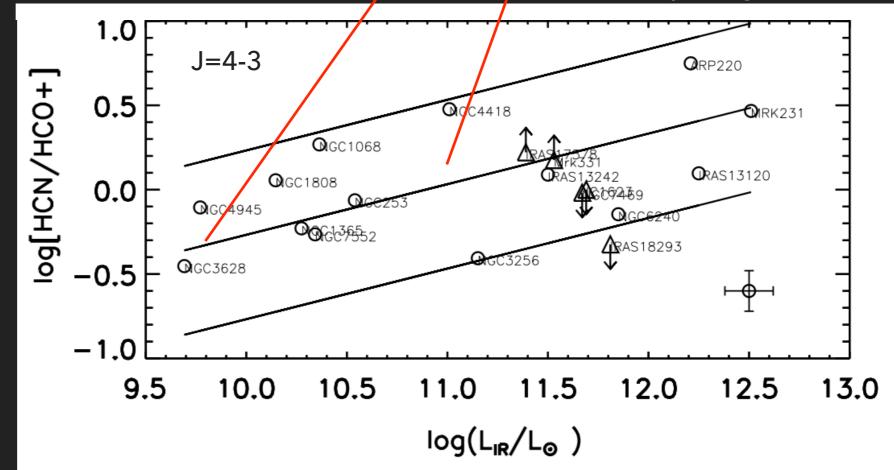


Resolved dense gas star formation relations

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



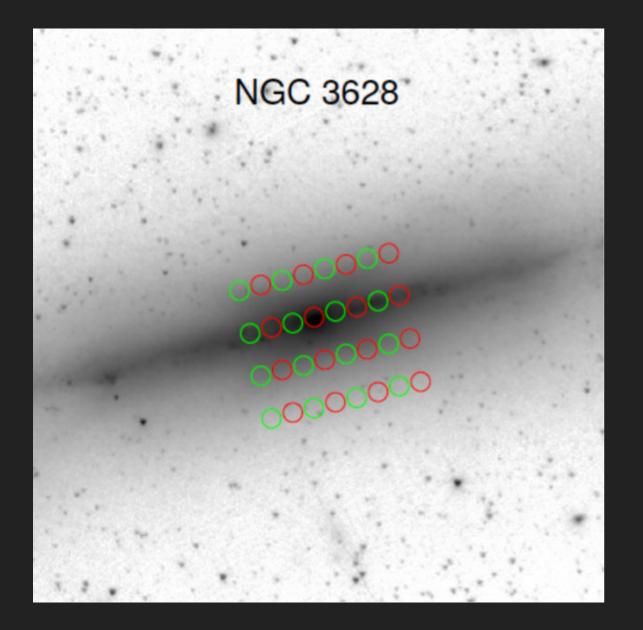
Galaxy-integrated ratios



SCAN PATTERNS

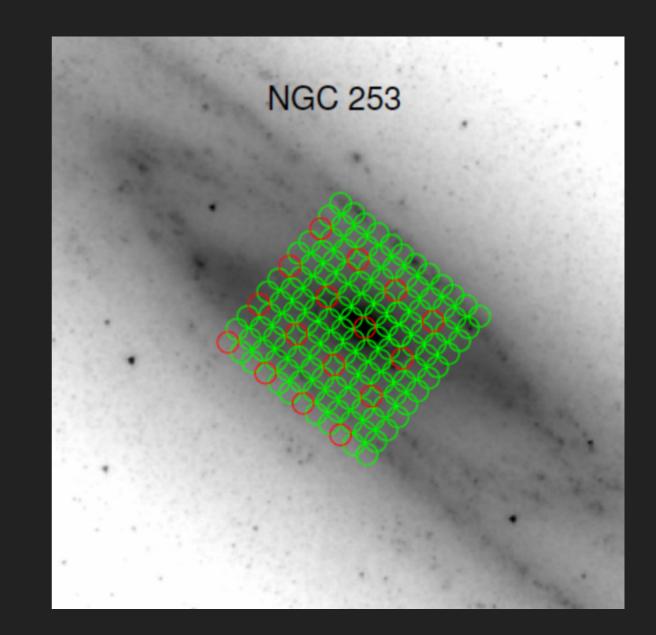
Grid mode

Mostly for edge-on galaxies



Jiggle mode

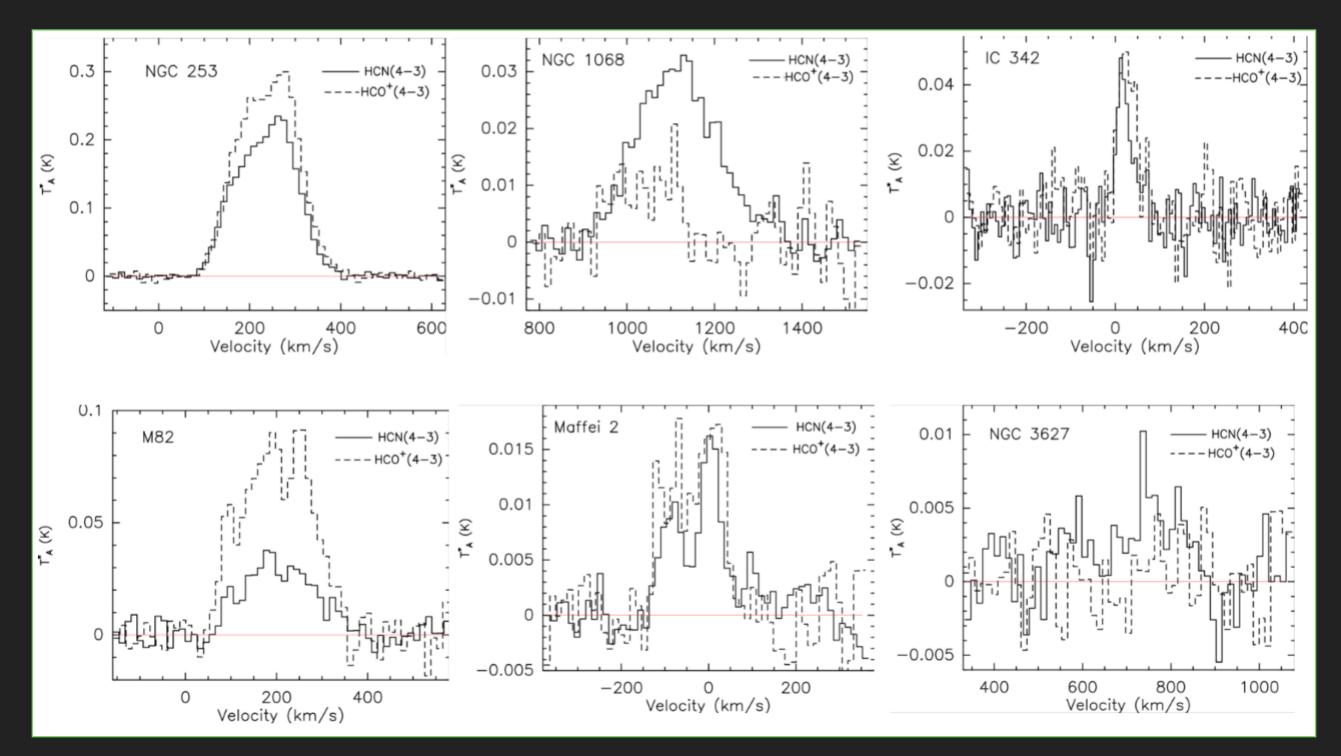
Mostly for face-on/large galaxies



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

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- 0 - 0	HCN (4-3) "			имерлити, кладивати, обрадцили, одороции имелитик бластити, обрадалися издерация имеатица: работатик окрудирал отосполого имеатица: содистик серектра отосполого алустации, имеалиций собратира		I		i i i	
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FIRST DATA – SPECTRA

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

-50

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FIRST DATA – SUMMARY

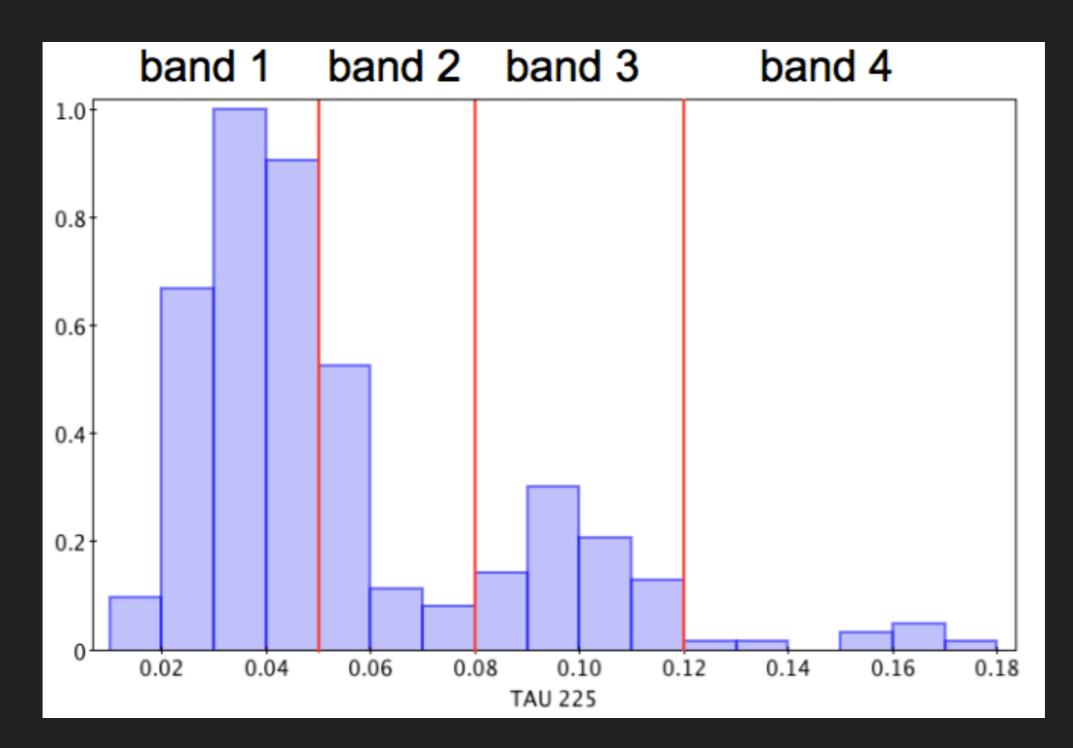
Name	Molecule	Obs_mode	Int_time (hours)	Tau(225 GHz)	Tau_median	T _A ^a ₋peak (K)	RMS ^b (mK)
NGC 253	HCN (4-3)	Jiggle	2.36	0.018-0.042	0.022	0.23	$4.1 \ (6.6 \ \mathrm{km \ s^{-1}})$
	HCO^{+} (4-3)	Jiggle	1.67	0.033-0.037	0.036	0.30	$6.9 (6.6 \text{ km s}^{-1})$
NGC 660	HCN (4-3)	Grid	0.83	0.046-0.048	0.047	0.012	$3.9 (13.2 \text{ km s}^{-1})$
NGC 891	HCN (4-3)	Grid	2.50	0.049-0.091	0.051	0.01	$2.3 (13.2 \text{ km s}^{-1})$
Maffei 2	HCN (4-3)	Grid	5.00	0.031-0.184	0.040	0.016	$1.8 (13.2 \text{ km s}^{-1})$
	HCO^{+} (4-3)	Grid	3.48	0.096-0.113	0.099	0.018	$3.0 (13.1 \text{ km s}^{-1})$
NGC 1068	HCN (4-3)	Jiggle	2.92	0.025 - 0.049	0.041	0.032	$2.2 (13.2 \text{ km s}^{-1})$
	HCO^{+} (4-3)	Jiggle	1.67	0.034 - 0.052	0.044	0.015	$5.8 (13.1 \text{ km s}^{-1})$
NGC 1097	HCN (4-3)	Grid	2.08	0.022 - 0.073	0.024		$3.2 \ (26.4 \ \mathrm{km \ s^{-1}})$
NGC 1365	HCN (4-3)	Grid	0.83	0.024 - 0.024	0.024		$7.4 (13.2 \text{ km s}^{-1})$
IC 342	HCN (4-3)	Jiggle	2.50	0.030 - 0.081	0.039	0.05	$7.2 \ (6.6 \ \mathrm{km \ s^{-1}})$
	HCO ⁺ (4-3)	Jiggle	3.38	0.024 - 0.162	0.087	0.05	$8.4 \ (6.6 \ \mathrm{km \ s^{-1}})$
NGC 1808	HCN (4-3)	Grid	0.83	0.062 - 0.065	0.064	0.01	$3.1 \ (26.4 \ \mathrm{km \ s^{-1}})$
NGC 2146	HCN (4-3)	Grid	0.83	0.138 - 0.165	0.152		
NGC 2903	HCN (4-3)	Grid	4.38	0.047 - 0.109	0.090	0.0025	$1.3 \ (26.4 \ \mathrm{km \ s^{-1}})$
M82	HCN (4-3)	Jiggle	2.50	0.017 - 0.042	0.032	0.035	$4.7 \ (13.2 \ \mathrm{km \ s^{-1}})$
	HCO ⁺ (4-3)	Jiggle	1.68	0.047 - 0.053	0.049	0.09	$7.1 \ (13.1 \ \mathrm{km \ s^{-1}})$
NGC 3627	HCN (4-3)	Grid	3.33	0.060-0.110	0.103	0.007	$2.4 \ (13.2 \ \mathrm{km \ s^{-1}})$
	HCO ⁺ (4-3)	Grid	3.17	0.092-0.100	0.094		$2.5 \; (13.1 \; \mathrm{km \; s^{-1}})$
NGC 3628	HCN (4-3)	Grid	4.11	0.046 - 0.120	0.089	0.012	$1.9 \; (13.2 \; \mathrm{km \; s^{-1}})$
Arp 299	HCN (4-3)	Grid	3.33	0.050 - 0.065	0.056	0.006	$1.3 \ (13.2 \ \mathrm{km \ s^{-1}})$

^aThe line peak intensity measured in the central position of galaxies.

^brms noise level measured at a spectral resolution listed in the parenthesis.

WEATHER CONDITIONS

Most of the data have been taken in Band 1 and 2!



CURRENT STATUS

Time allocated to project:390h0m0s in tau range [0.05,0.20]Time remaining on project:293h6m0sCompletion rate:24%

Click here to remote eavesdrop

Project: M16AL007

Observations were acquired on the following dates:

2015-11-28 (1.15 hours) click on date to retrieve data 2015-11-29 (4.65 hours) click on date to retrieve data 2015-11-30 (4.70 hours) click on date to retrieve data 2015-12-01 (4.65 hours) click on date to retrieve data 2015-12-02 (4.80 hours) click on date to retrieve data 2015-12-06 (3.30 hours) click on date to retrieve data 2015-12-10 (4.70 hours) click on date to retrieve data 2015-12-11 (1.05 hours) click on date to retrieve data 2015-12-12 (7.30 hours) click on date to retrieve data 2015-12-13 (13.05 hours) click on date to retrieve data 2015-12-16 (3.95 hours) click on date to retrieve data 2015-12-20 (0.95 hours) click on date to retrieve data 2015-12-21 (1.25 hours) click on date to retrieve data 2015-12-23 (4.15 hours) click on date to retrieve data 2015-12-24 (9.35 hours) click on date to retrieve data 2015-12-30 (1.45 hours) click on date to retrieve data 2015-12-31 (0.95 hours) click on date to retrieve data 2016-01-19 (2.40 hours) click on date to retrieve data 2016-02-02 (no science data charged) 2016-02-03 (no science data charged) 2016-02-04 (no science data charged) 2016-02-07 (1.15 hours) click on date to retrieve data 2016-02-10 (9.10 hours) click on date to retrieve data 2016-02-11 (8.85 hours) click on date to retrieve data 2016-02-22 (1.00 hours) click on date to retrieve data 2016-02-23 (1.10 hours) click on date to retrieve data 2016-02-24 (1.05 hours) click on date to retrieve data 2016-02-25 (1.05 hours) click on date to retrieve data 2016-03-02 (1.00 hours) click on date to retrieve data 2016-03-03 (1.05 hours) click on date to retrieve data 2016-03-04 (1.05 hours) click on date to retrieve data

18 galaxies observed to date

galaxy	Molecule	time	
Am200	HCN	3.3	
Arp299	HCO+	0.8	
10242	HCN	2.5	
IC342	HCO+	3.4	
M82	HCN	2.5	
IVIOZ	HCO+	1.7	
moffei?	HCN	5.0	
maffei2	HCO+	3.5	
NICC1069	HCN	3.1	
NGC1068	HCO+	2.3	
NGC1097	HCN	5.1	
NGC1365	HCN	1.2	
NCC1909	HCN	2.9	
NGC1808	HCO+	3.3	
NGC2146	HCN	2.5	
NGC253	HCN 2.4	2.4	
NGC203	HCO+	1.7	
NGC2002	HCN	6.2	
NGC2903	HCO+	2.6	
NGC3079	HCN	2.1	
NGC3521	HCN	2.4	
NGC2627	HCN	3.3	
NGC3627	HCO+	3.2	
NGC3628	HCN	4.1	
11903020	HCO+	3.3	
NGC4736	HCN	3.3	
NGC660	HCN	0.8	
NGC891	HCN	2.5	
NGC4631		0.0	
M51		0.0	
M83		0.0	
NGC5457		0.0	
NGC6946		0.0	

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.

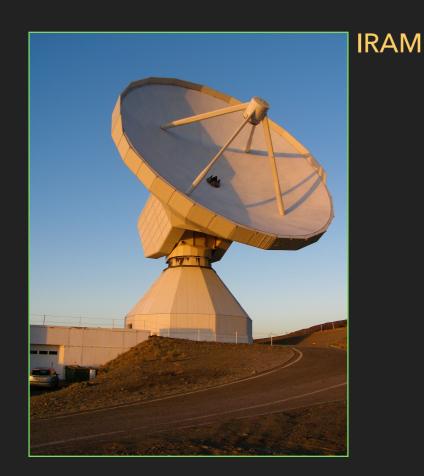
2016

And more...

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)





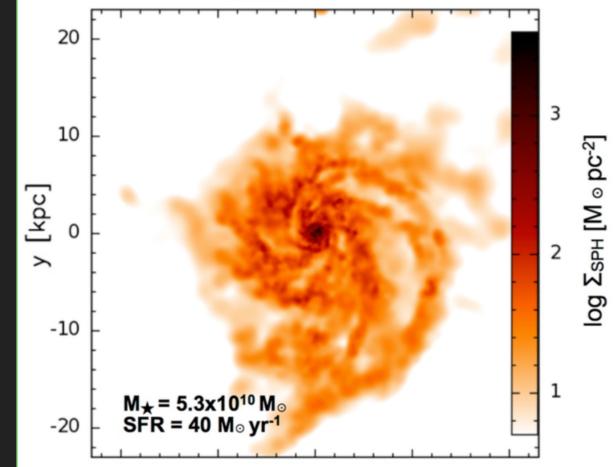
ALMA

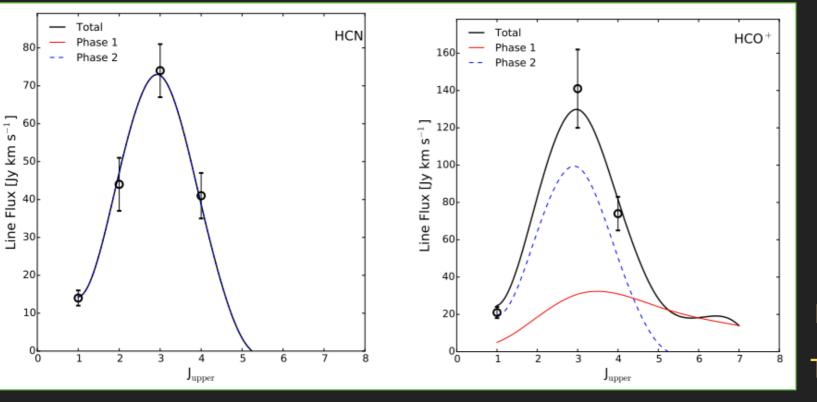
SYNERGY & FOLLOW-UP

Modelling:

 s^{-1}]

- LVG and PDR modelling of SF regions characterising their physical/chemical conditions
- Galaxy-wide SPH + RT transfer modelling of HCN and HCO+ lines
- Reproducing observed relations and line ratios





LVG modelling of HCN and HCO⁺ Tunnard et al. (2015)

SPH + RT simulation: Olsen et al. (2016)

THANK YOU

MALATANG

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