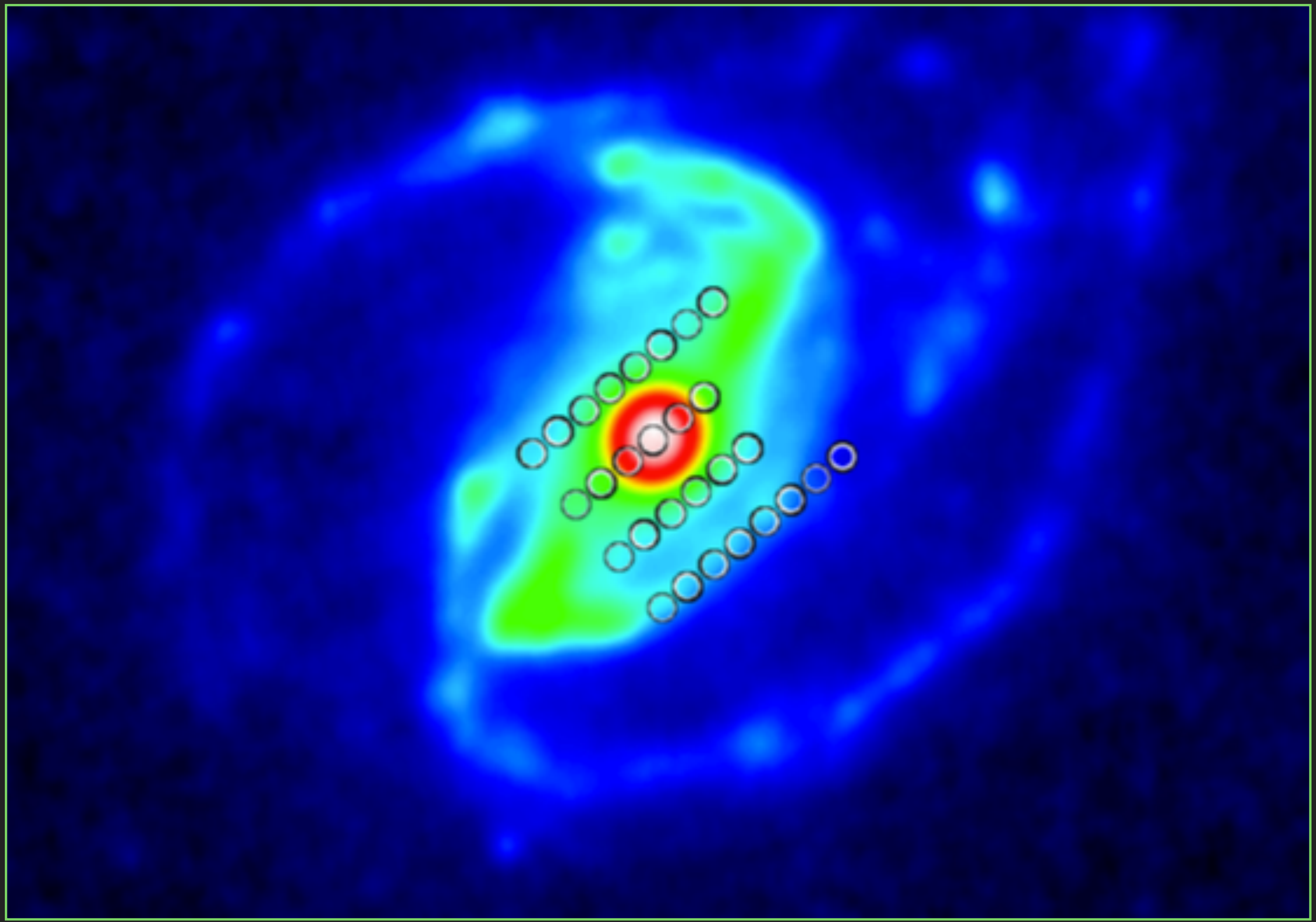
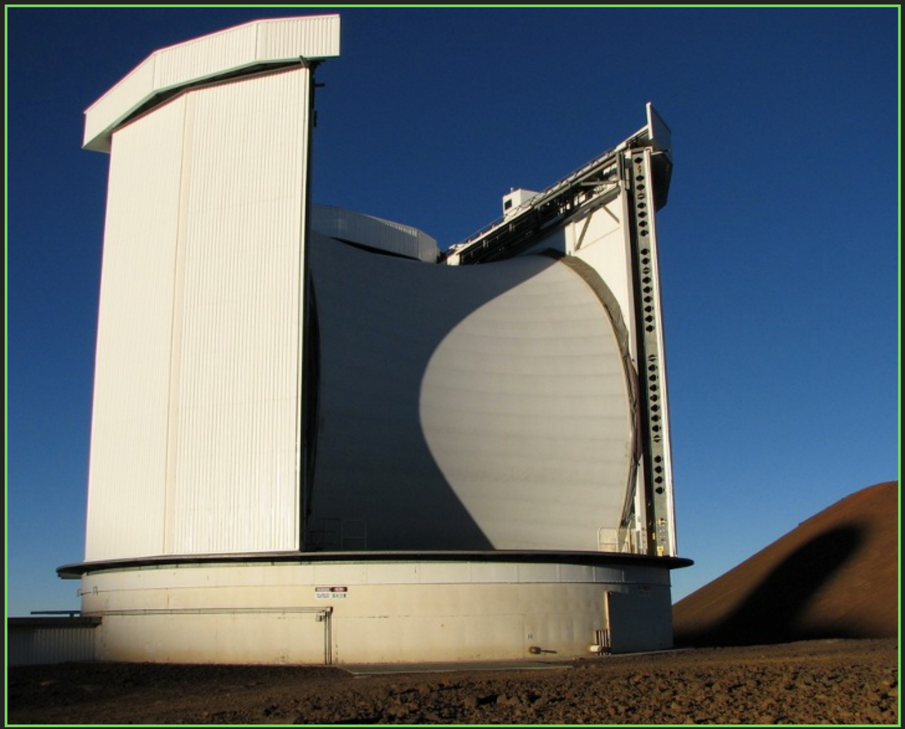
"STIRRING THE POT" – THE MALATANG SURVEY OF DENSE GAS IN NEARBY GALAXIES

MALATANG



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 stAr-formiNg Galaxies

www.eaobservatory.org/jcmt

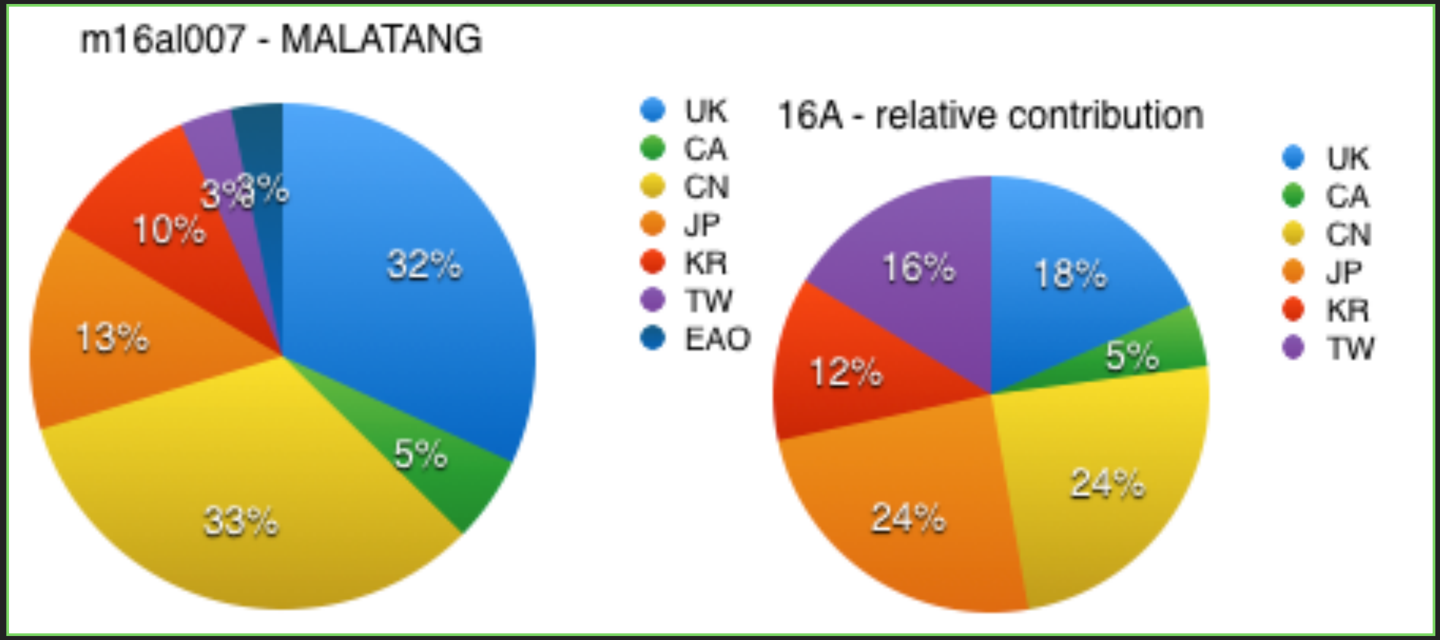
MALATANG IN A NUTSHELL

- 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 $\sim 5\times10^{6} M_{\odot}$ and scales ~0.2-2.8kpc in other galaxies
- Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations

HARP

THE TEAM

- *# MALATANG members 91*
- *All JCMT countries represented*
- *Collaborators welcome!*



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	
Erik Rosolowsky	U. Alberta	CA		Keiichi Maeda	Koyoto University	JP		Stephen Serjeant	Open U.	UK	
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Qian Jiao	NAOC	CN	Y	Yusuke Miyamoto	NAO	JP		John Richer	U. Cambridge	UK	
Xiao-Hu Li	NAOC	CN		Yi-Ping Ao	NAOJ	JP		**Thomas Greve**	UCL	UK	
Jing-Wen Wu	NAOC	CN		Joanna Burgler	NAOJ	JP		George Kelly	UCL	UK	
Hao Chen	NJU	CN		Masa Imanishi	NAOJ	JP		Ilse de Looze	UCL	UK	
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	
Hua Gao	PKU	CN	Y	Joanna Bulger	NAOJ/Subaru	JP		Michal Michalowski	U. Edinburgh	UK	
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	
Siyue Yu	PKU	CN	Y	Hye-In Lee	Kyung Hee U.	KR		Sugata Kaviraj	U. Hertfordshire	UK	
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Yu Gao	PMO	CN		Minjin Kim	KR Kasi	KR		Dave Eden	U. Liverpool	UK	
Xue-Jian Jiang	PMO	CN		Sungeun Kim	Sejong U.	KR		Toby Moore	U. Liverpool	UK	
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	
Y.-H. 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					

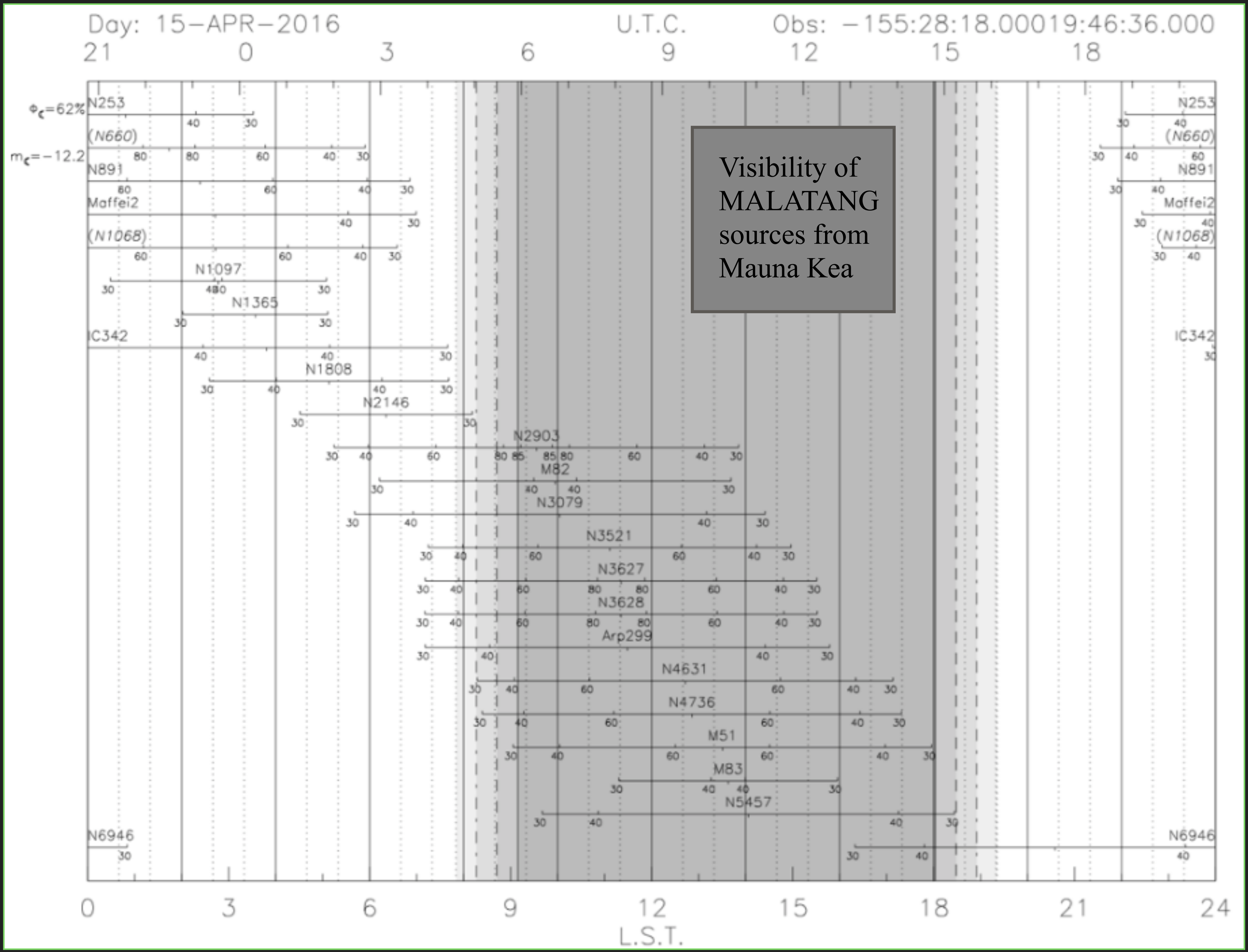
THE SAMPLE

- *S(60μm) > 50 Jy and S(100μm) > 100Jy in RBGS (Sanders+03) and δ > -40º in order to be observable with the JCMT*

- *Total sample size: 23 sources*

N	Source Name	R.A. (J2000)	Decl. (J2000)	Distance (Mpc)	Diameter (arcmin)	$f_{60\mu m}$ (Jy)	$f_{100\mu m}$ (Jy)	$\log L_{\rm fir}$ ($L_{\odot}$)	$\log \Sigma_{SFR}$ ($M_{\odot}{\rm yr}^{-1}{\rm kpc}^{-2}$)
(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

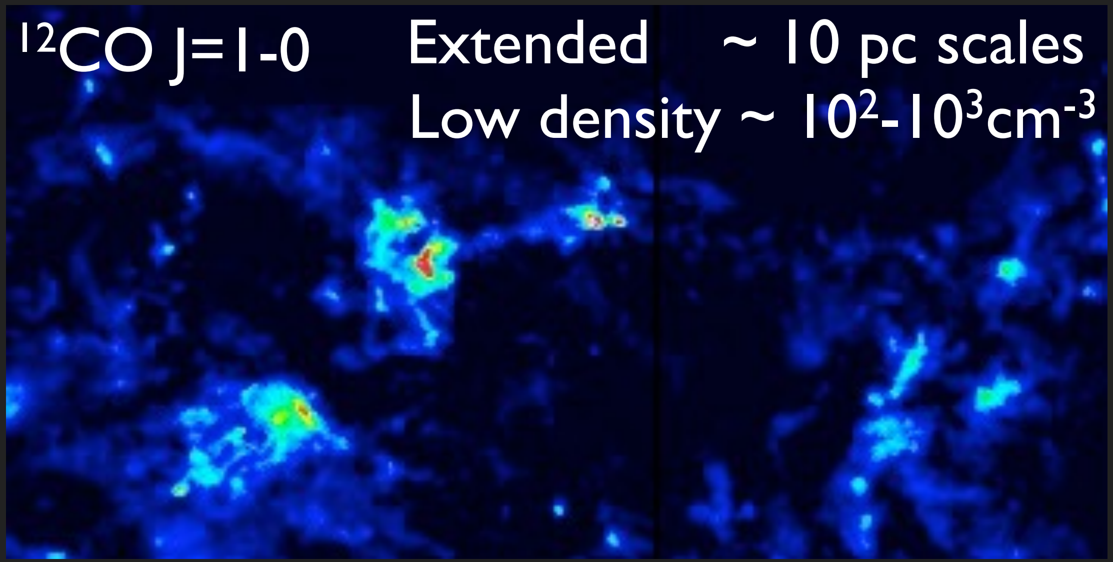
THE SAMPLE

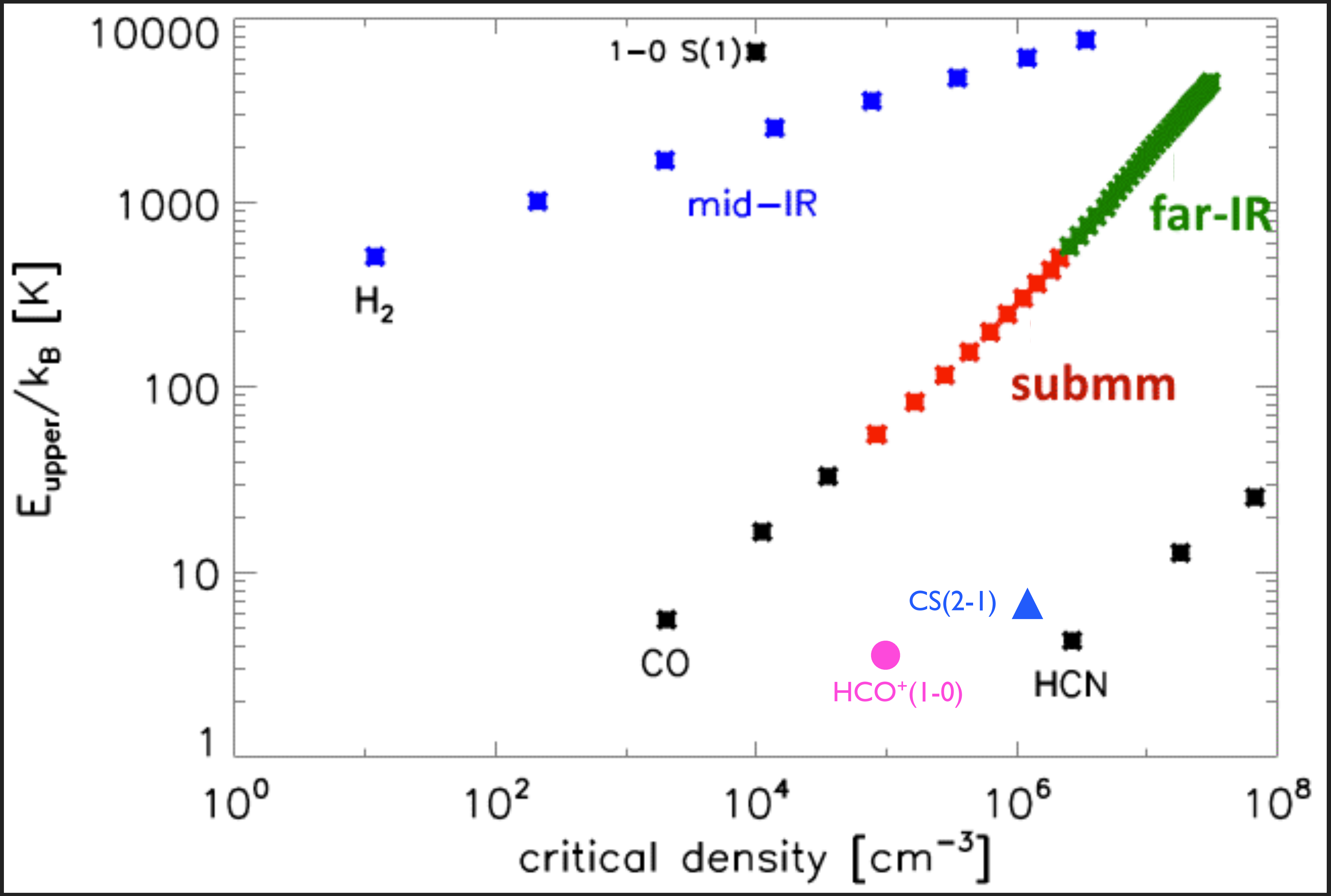

Day: 15–APR–2016
U.T.C.
Obs: –155:28:18.00019:46:36.000
Visibility of MALATANG sources from Mauna Kea
N253
(N660)
N891
Maffei2
(N1068)
N1097
N1365
IC342
N1808
N2146
N2903
M82
N3079
N3521
N3627
N3628
Arp299
N4631
N4736
M51
M83
N5457
N6946
L.S.T.

SCIENCE MOTIVATION

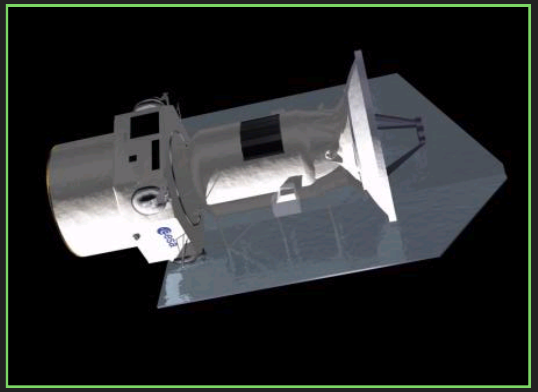
"Star formation" relations: $\log L_{IR} = \alpha L'_{mol} + \beta$

understanding slopes (α) and intercepts (β) for different molecular J-transitions





Herschel

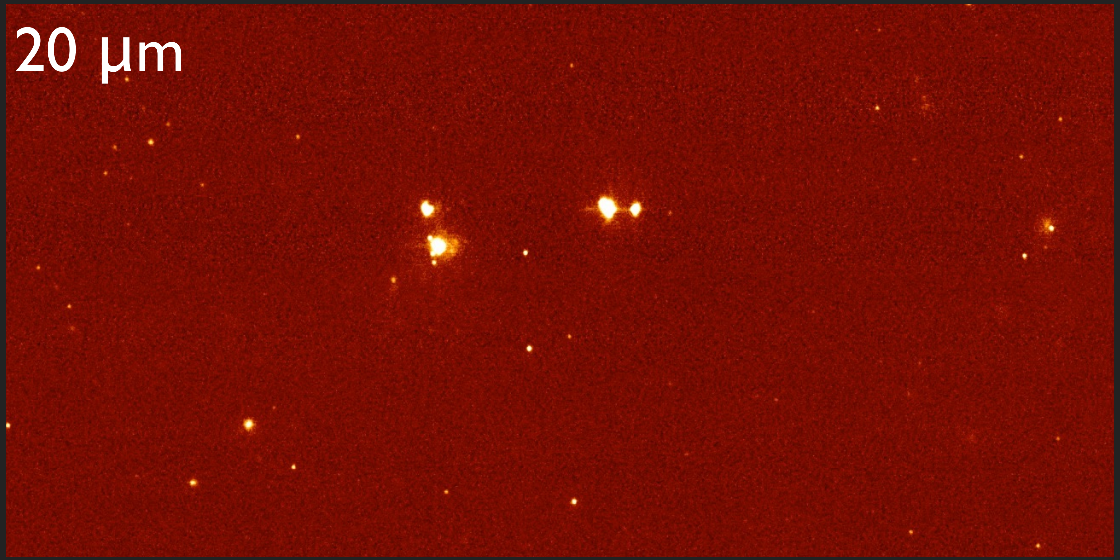


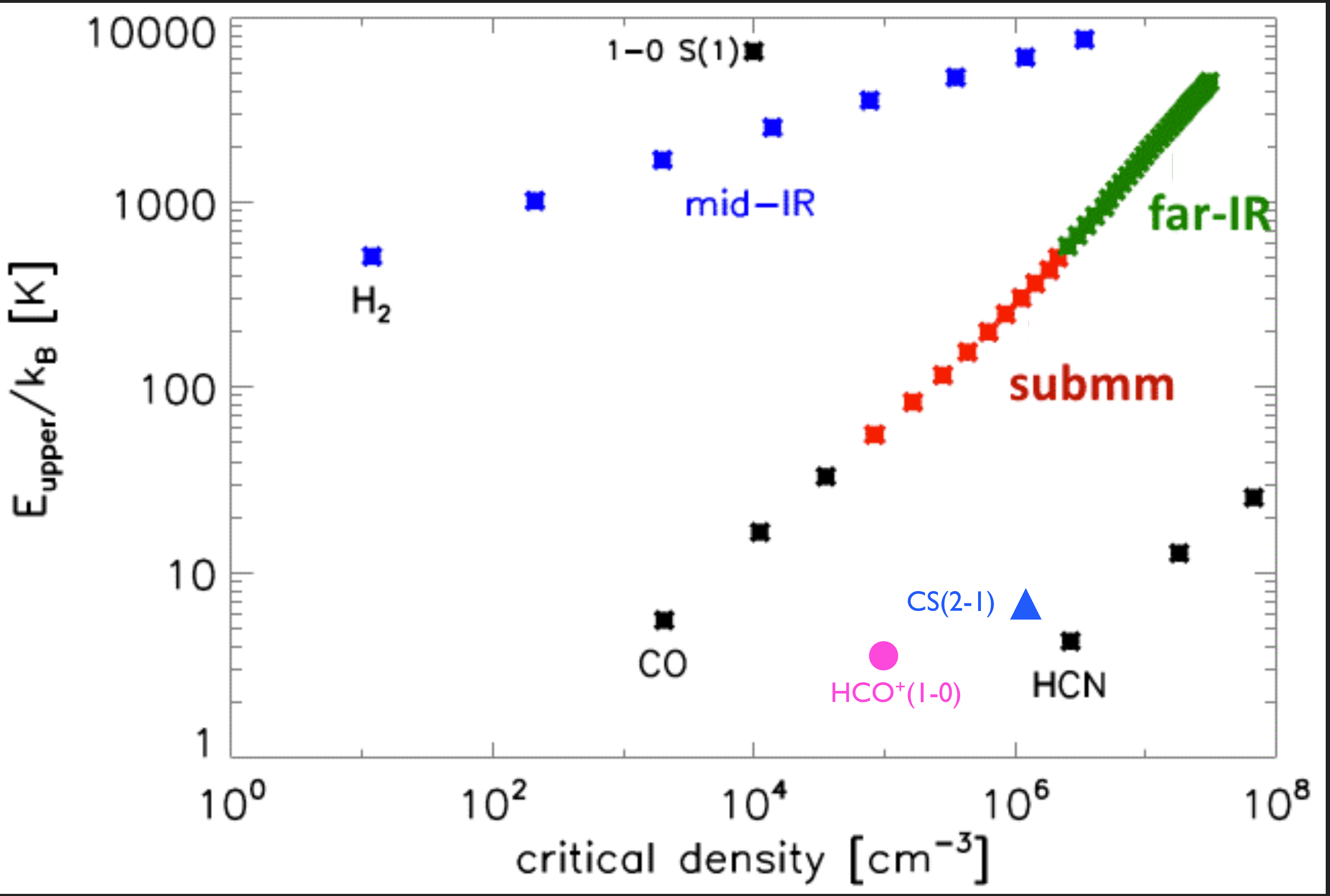
JCMT

SCIENCE MOTIVATION

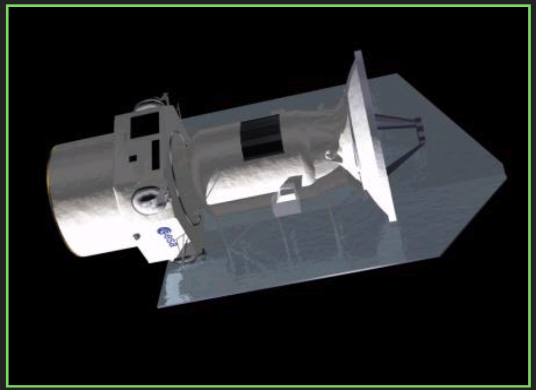
"Star formation" relations: log $L_{IR} = \alpha\, L'_{mol} + \beta$

understanding slopes (α) and intercepts (β) for different molecular J-transitions





Herschel



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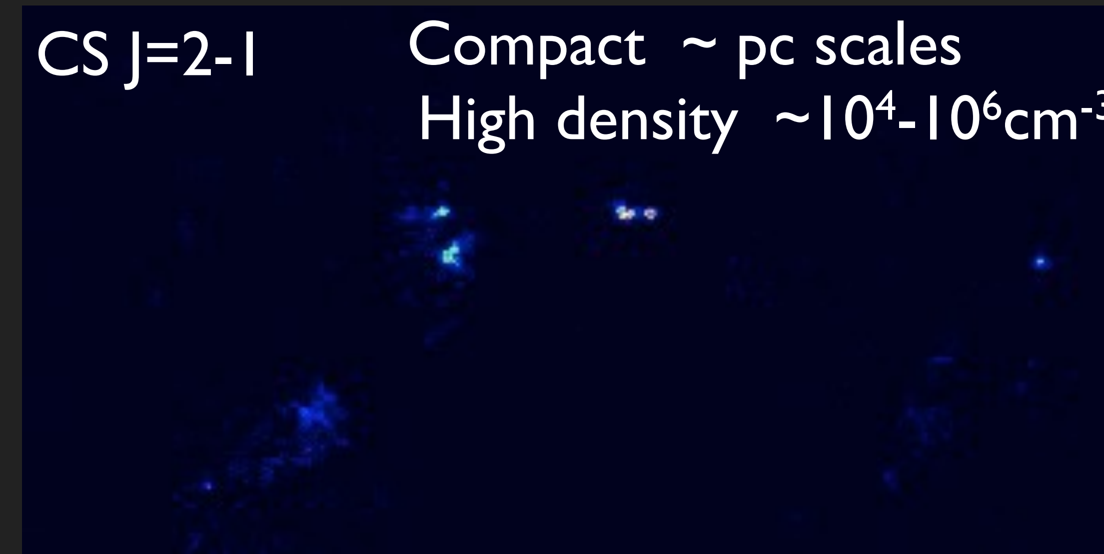

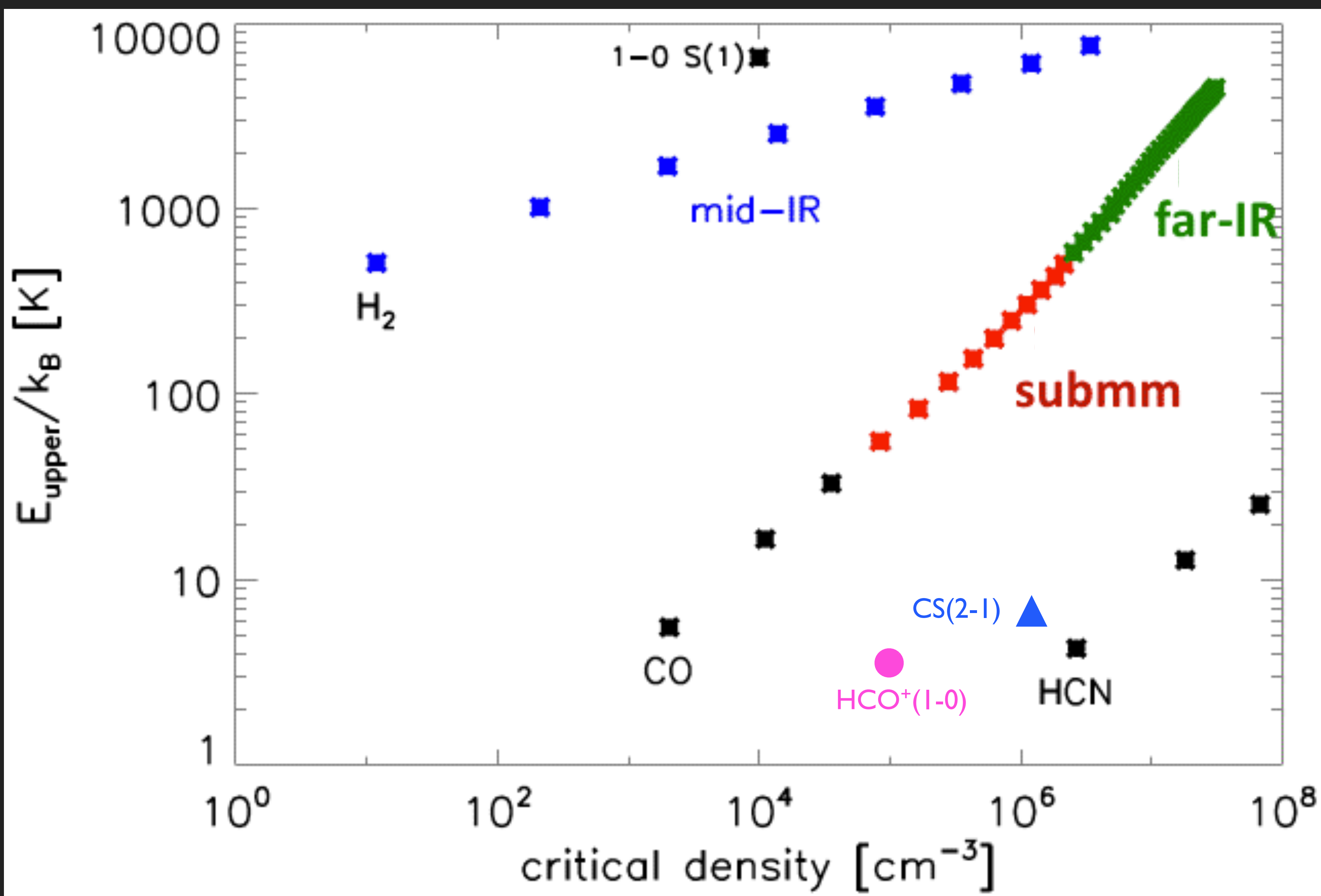

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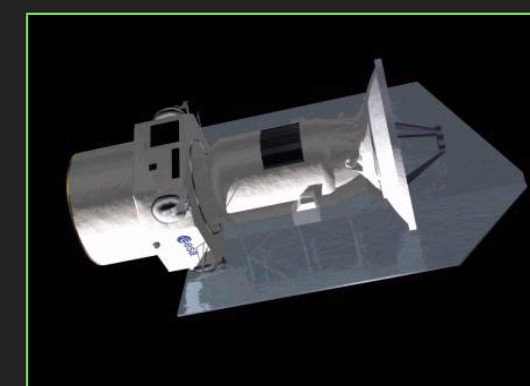
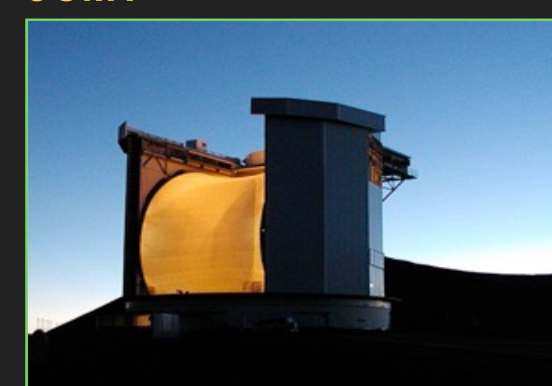


JCMT

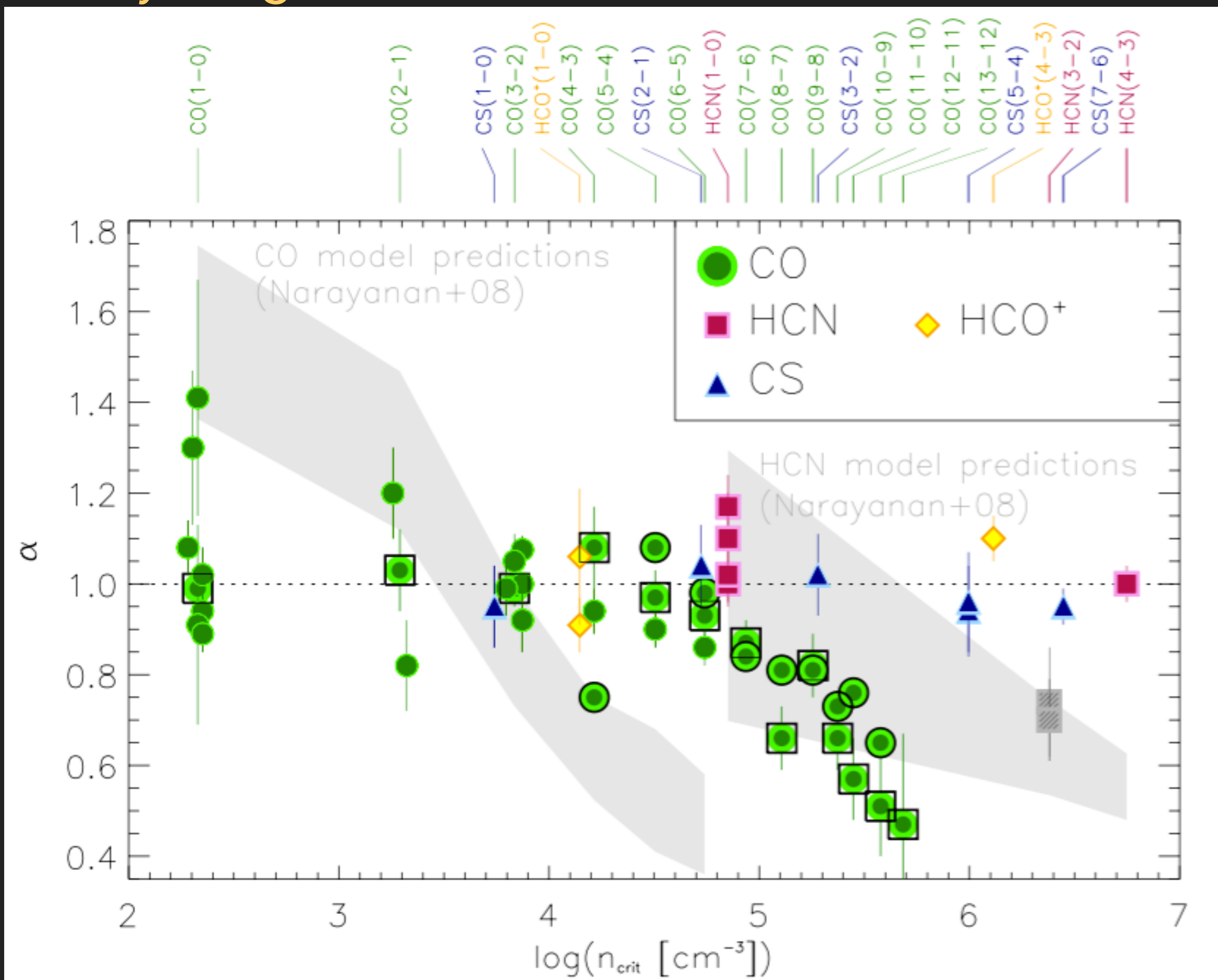


SCIENCE MOTIVATION

"Star formation" relations: $\log L_{IR} = \alpha\, L'_{mol} + \beta$

understanding slopes (α) and intercepts (β) for different molecular J-transitions

Galaxy-integrated α vs. n_{crit}



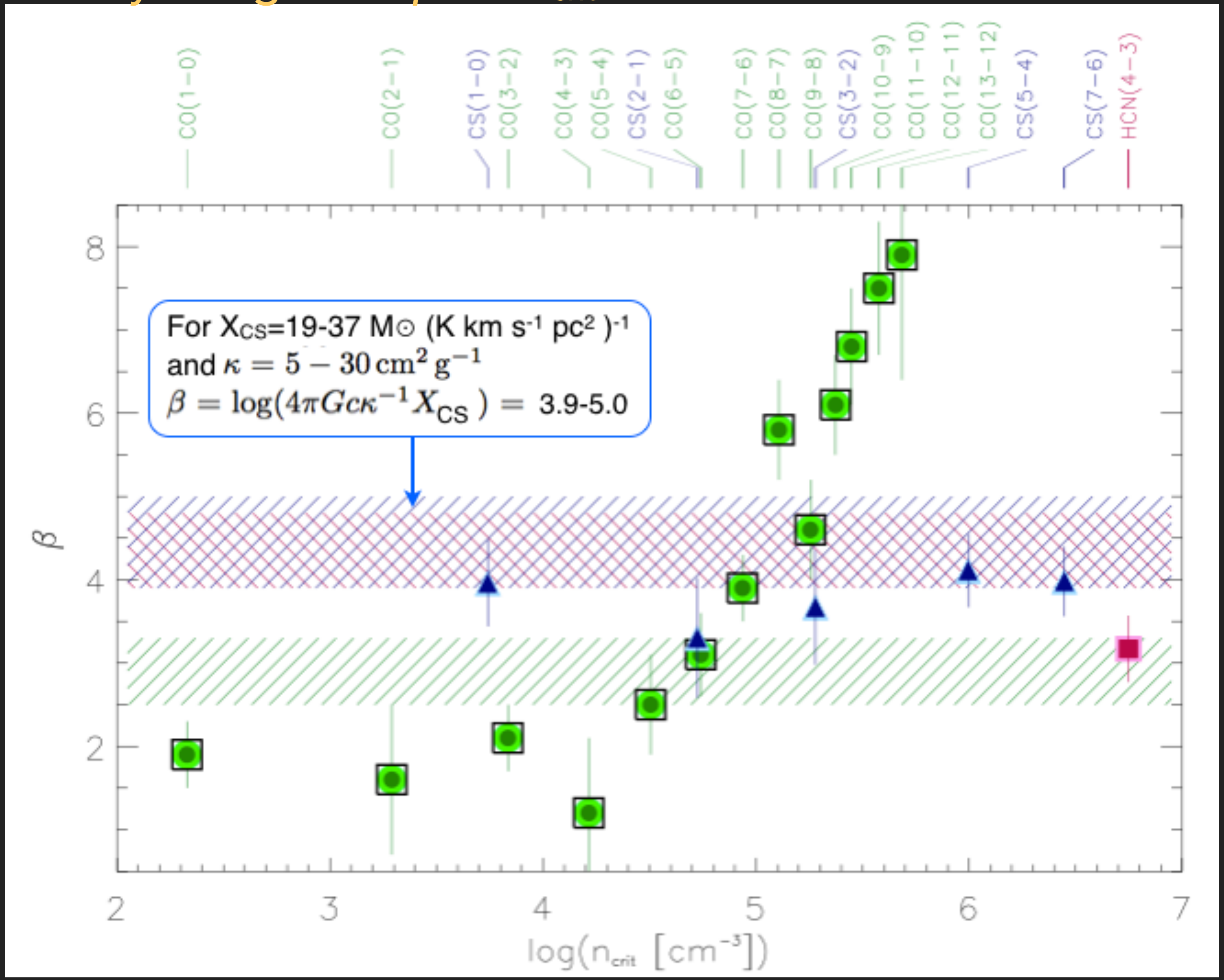
Transition	$n_{\rm crit}$ [cm^{-3}]	E_J/k_B [K]
CO(1 − 0)	4.4×10^2	5.53
CO(2 − 1)	3.6×10^3	16.60
CO(3 − 2)	1.3×10^4	33.19
CO(4 − 3)	3.0×10^4	55.32
CO(5 − 4)	5.9×10^4	82.97
CO(6 − 5)	1.0×10^5	116.16
CO(7 − 6)	1.5×10^5	154.87
HCN(1 − 0)	1.7×10^5	4.25
HCN(2 − 1)	1.6×10^6	12.76
HCN(3 − 2)	5.2×10^6	25.52
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

SCIENCE MOTIVATION

"Star formation" relations: log L_{IR} = α L'_{mol} + β

understanding slopes (α) and intercepts (β) for different molecular J-transitions

Galaxy-integrated β vs. n_{crit}



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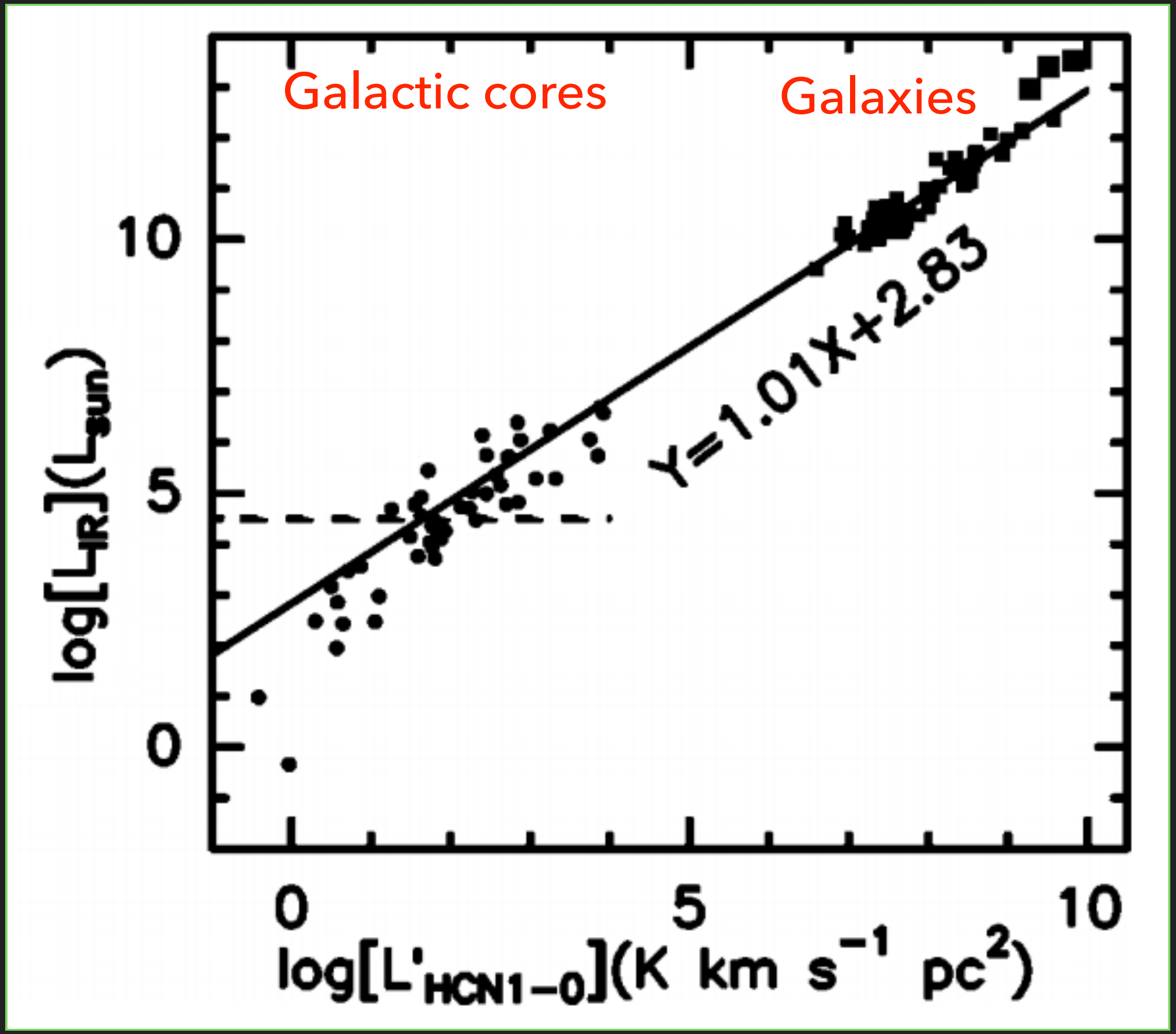
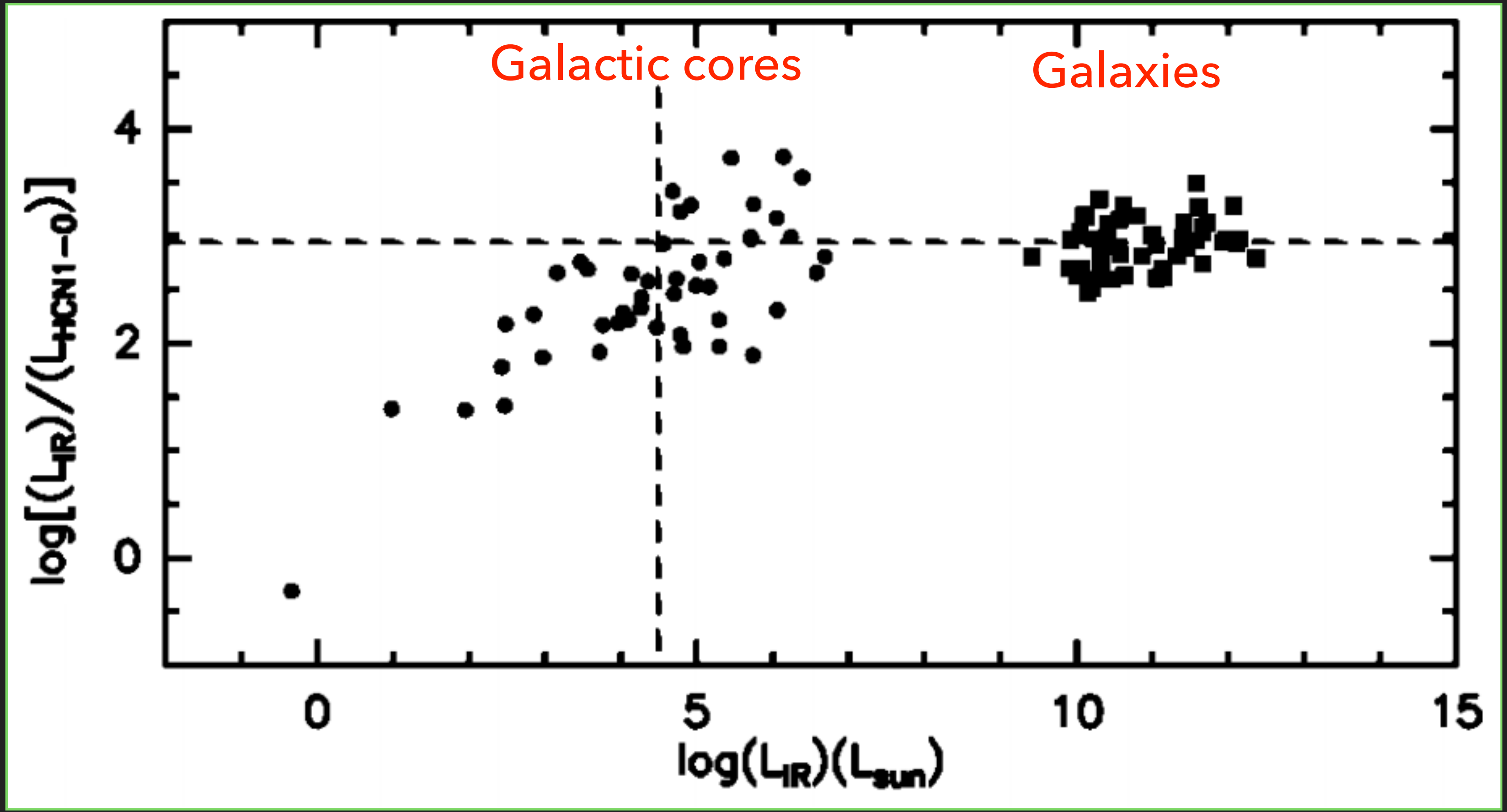
SCIENCE GOALS

- *Resolved dense gas star formation relations*





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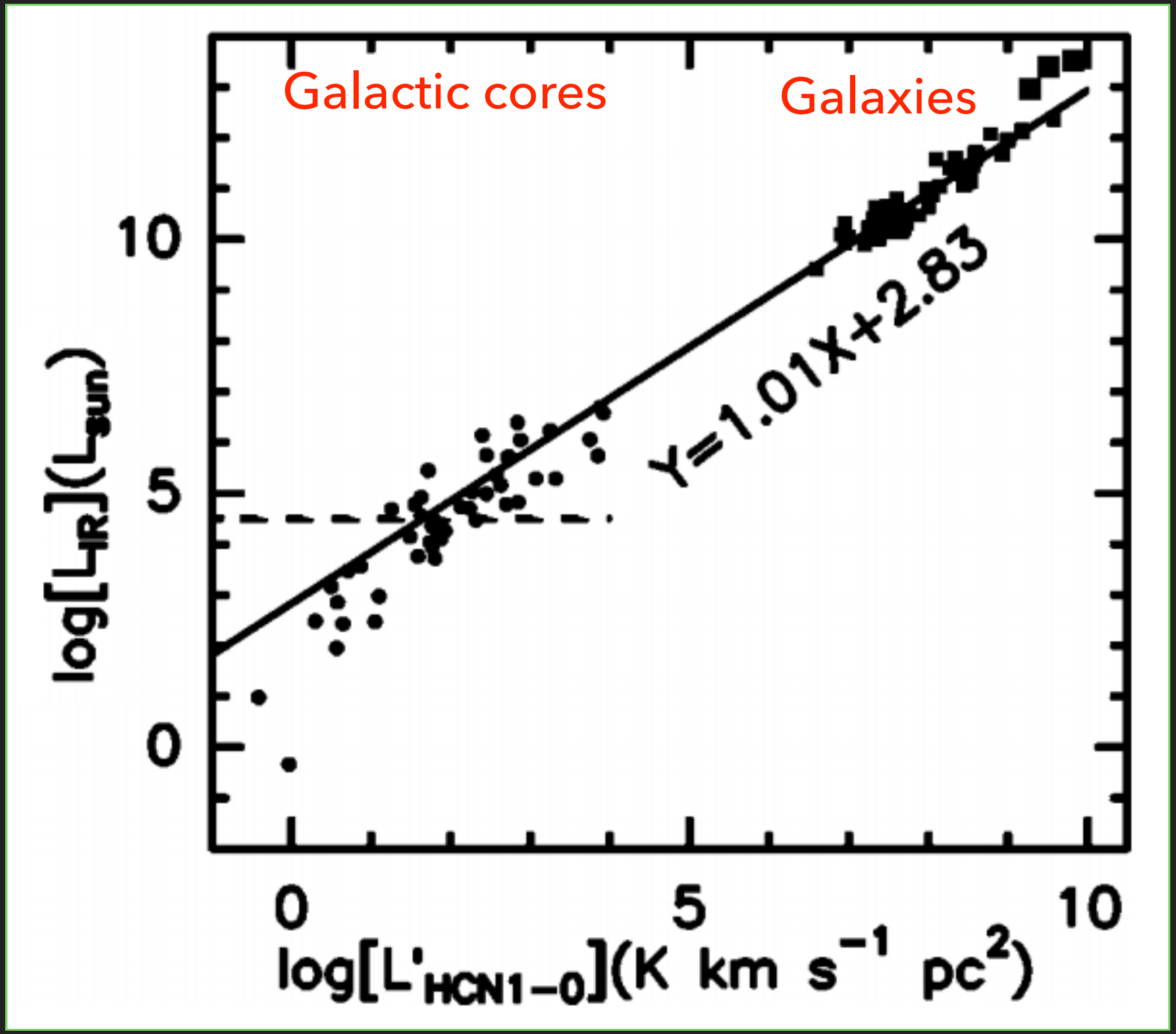
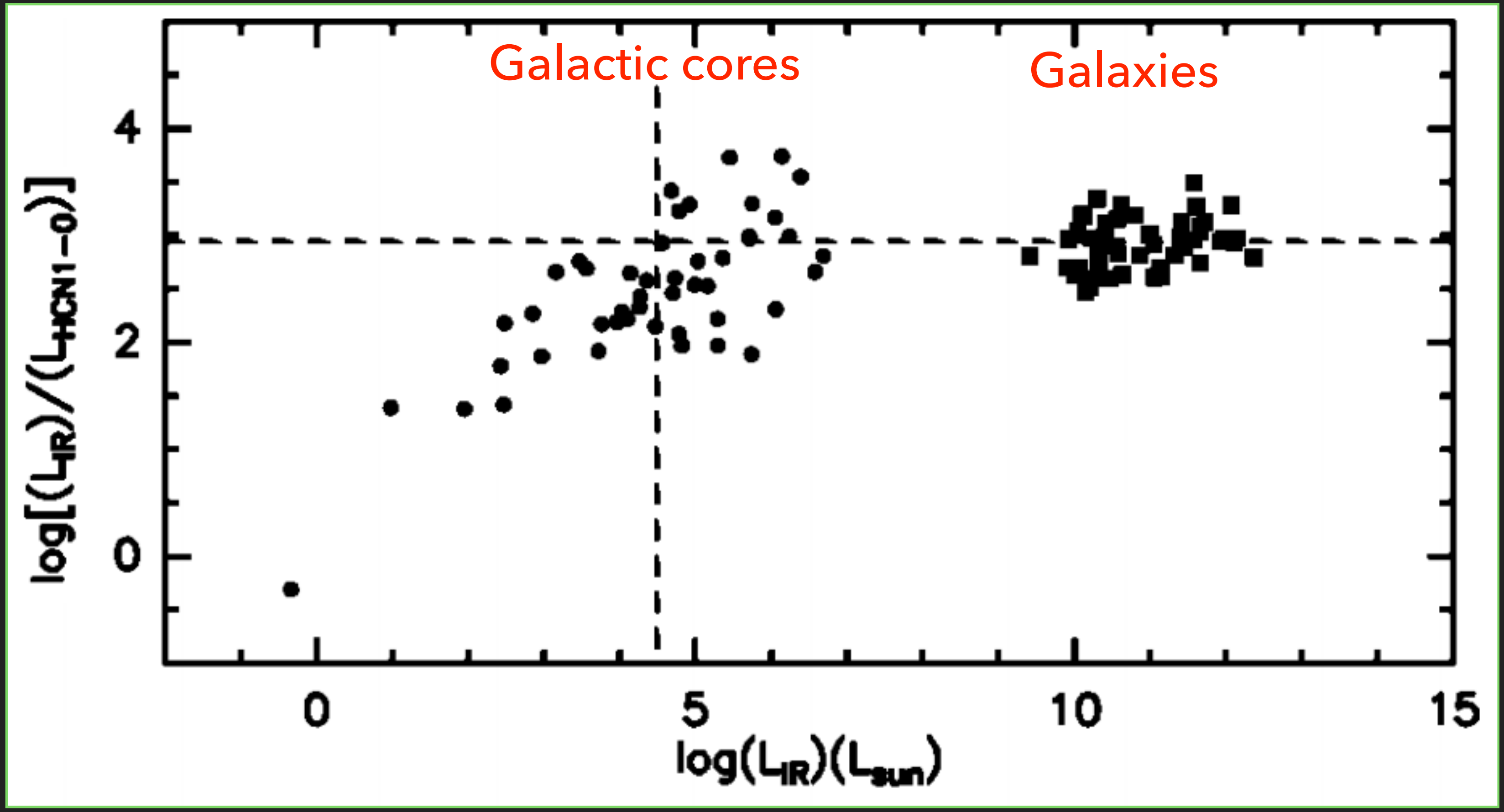
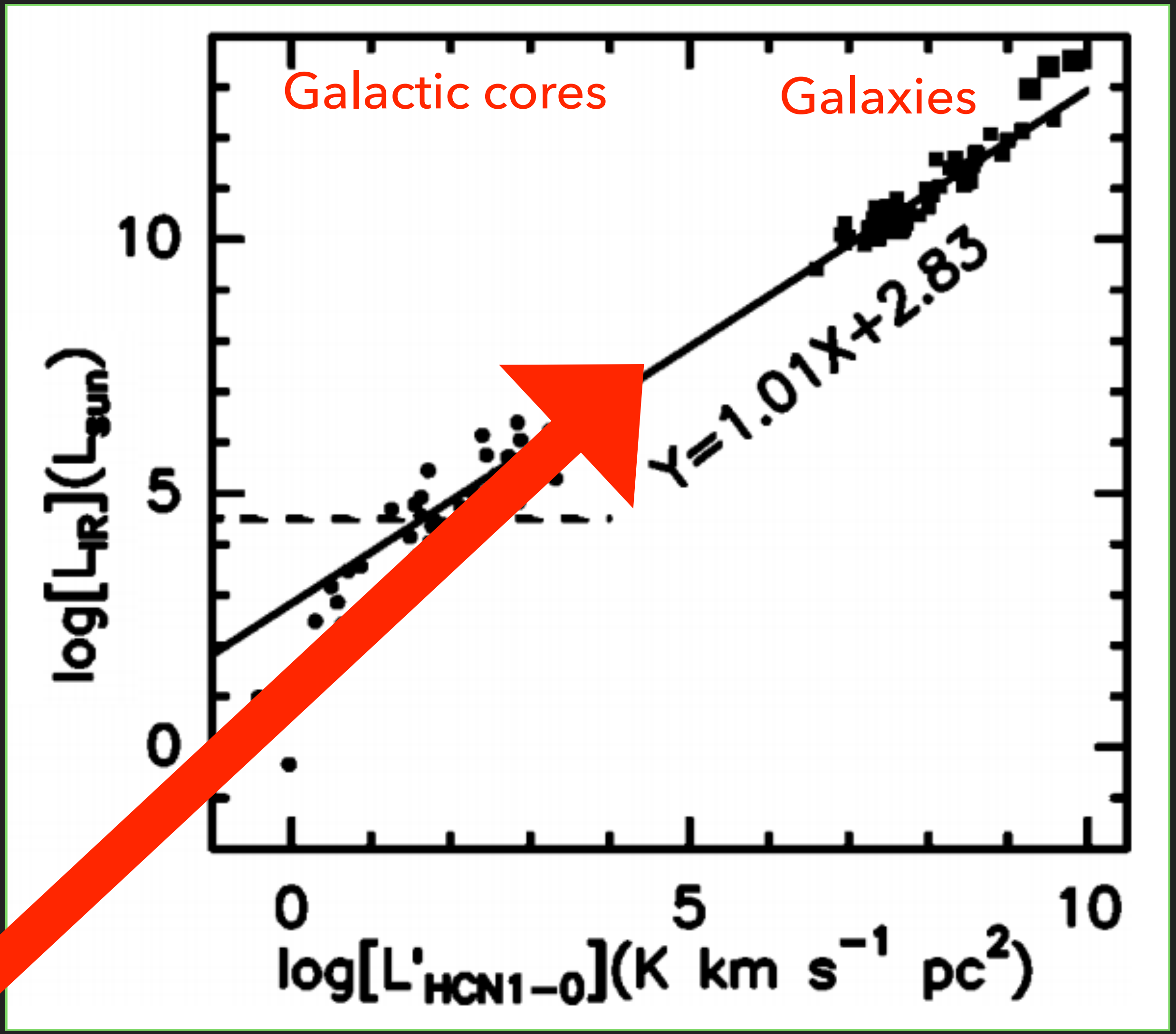
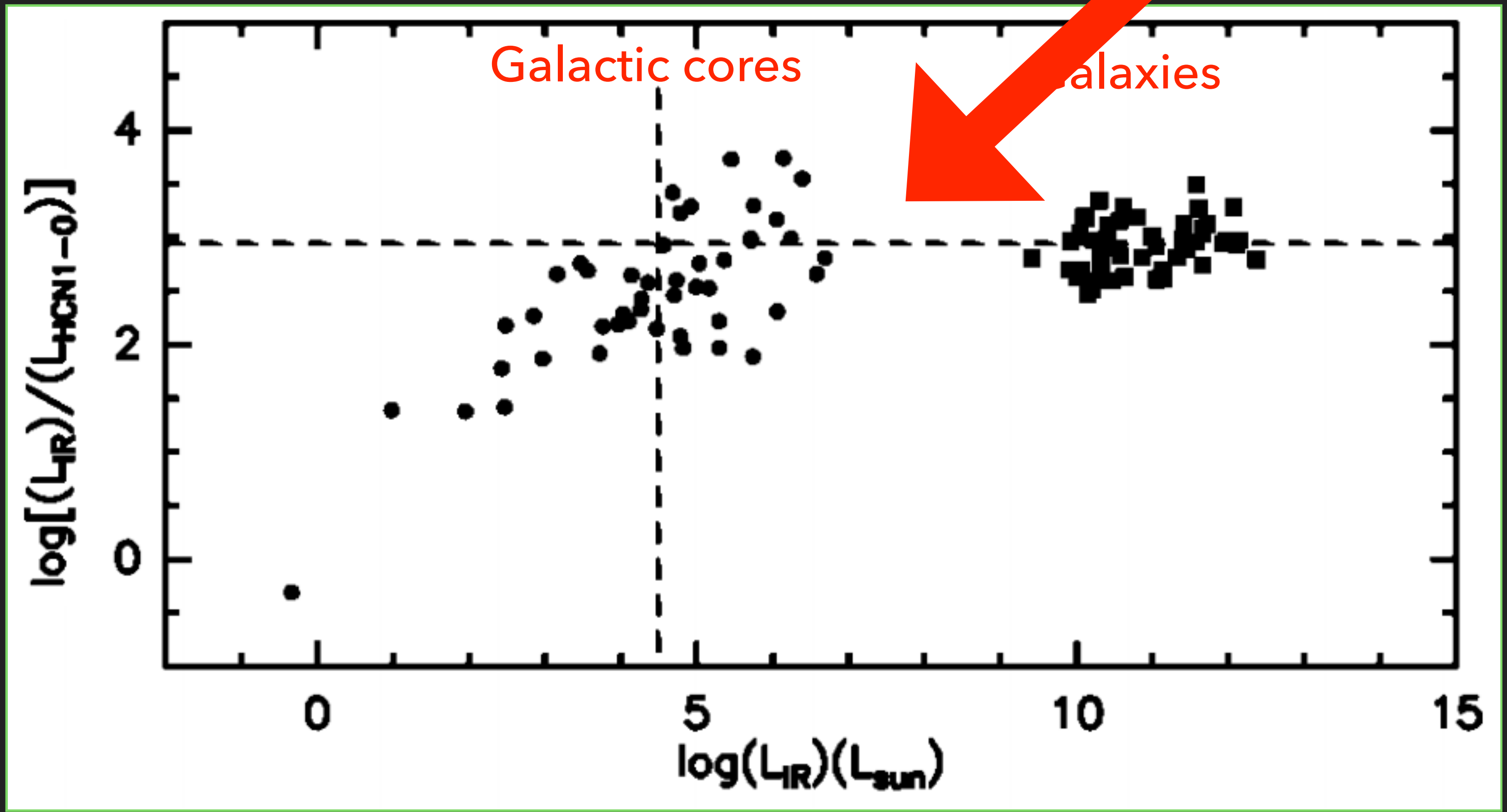




SCIENCE GOALS

- *Resolved dense gas star formation relations*
- *Intermediate scales/luminosities*

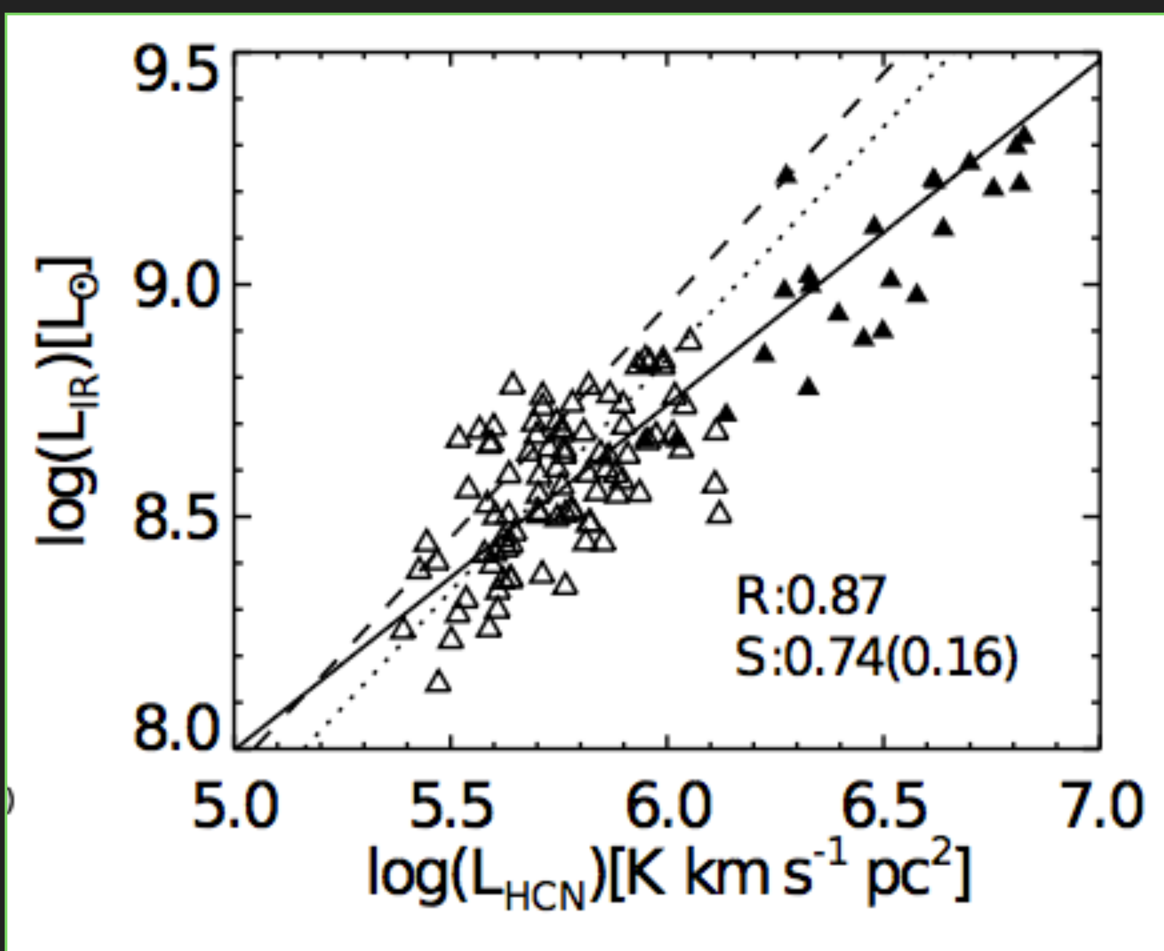


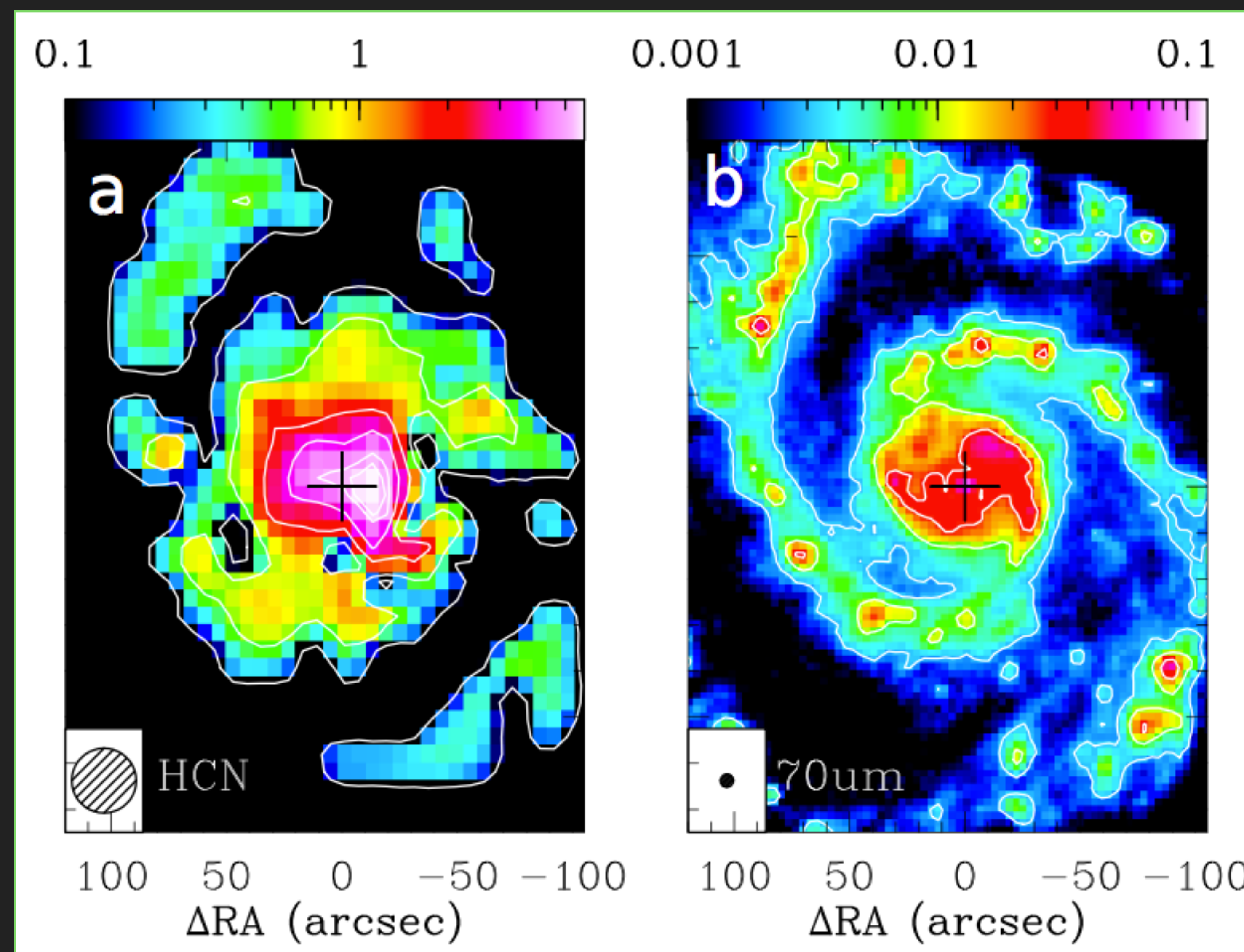


SCIENCE GOALS

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

IRAM 30m/HERA: HCN(1-0) Chen et al. (2015)





SCIENCE GOALS

- *Resolved dense gas star formation relations*
- *Intermediate scales/luminosities*
- *Different environments: nuclear vs. disk*
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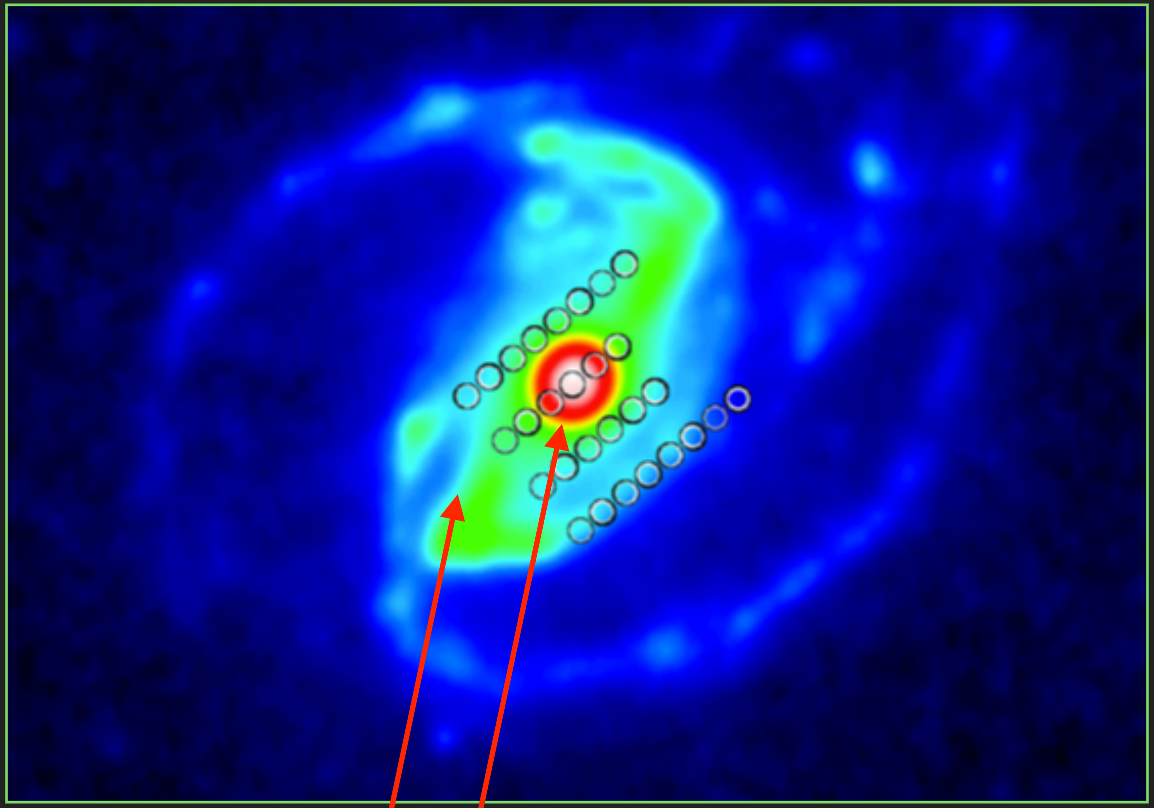
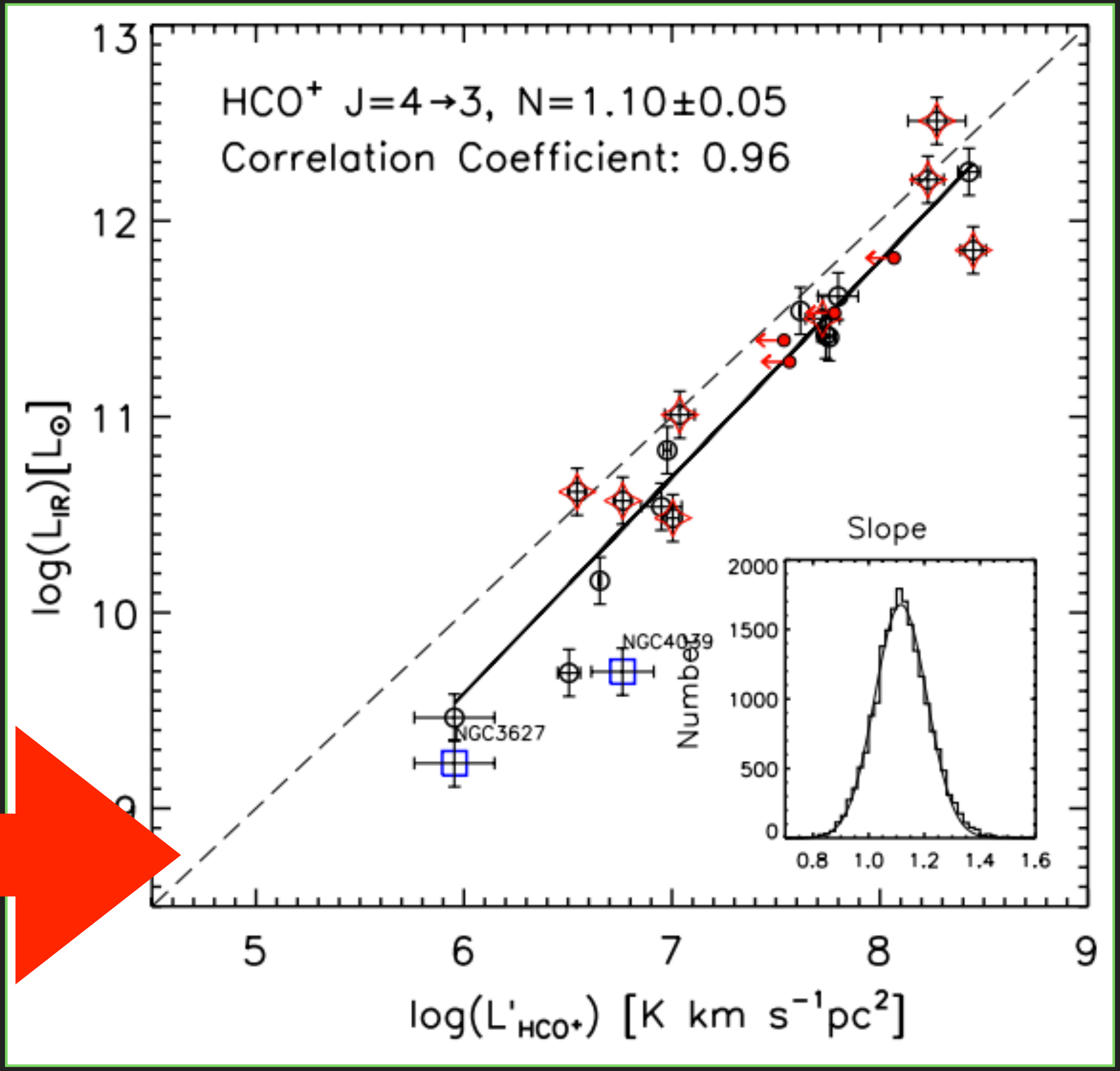
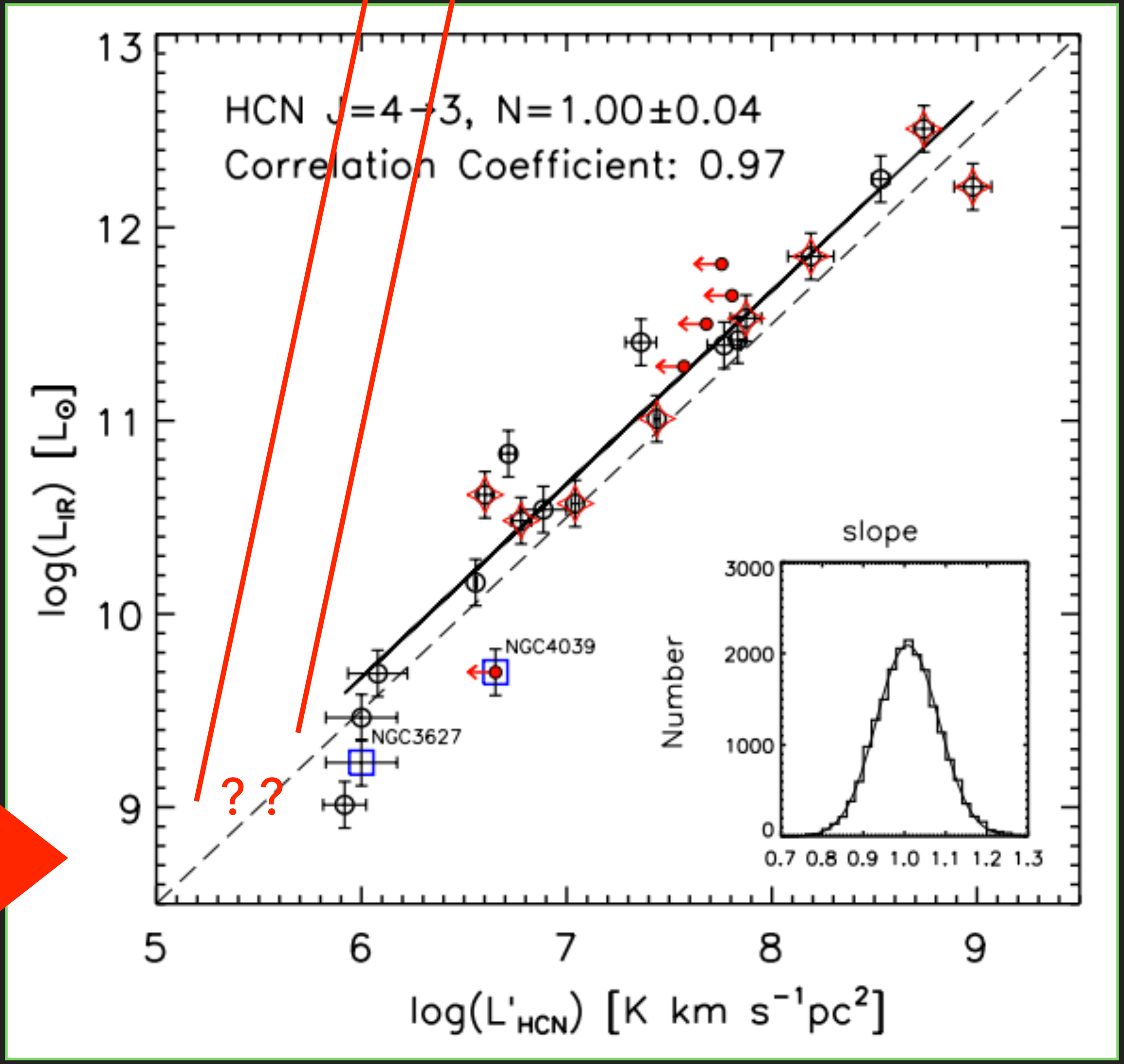
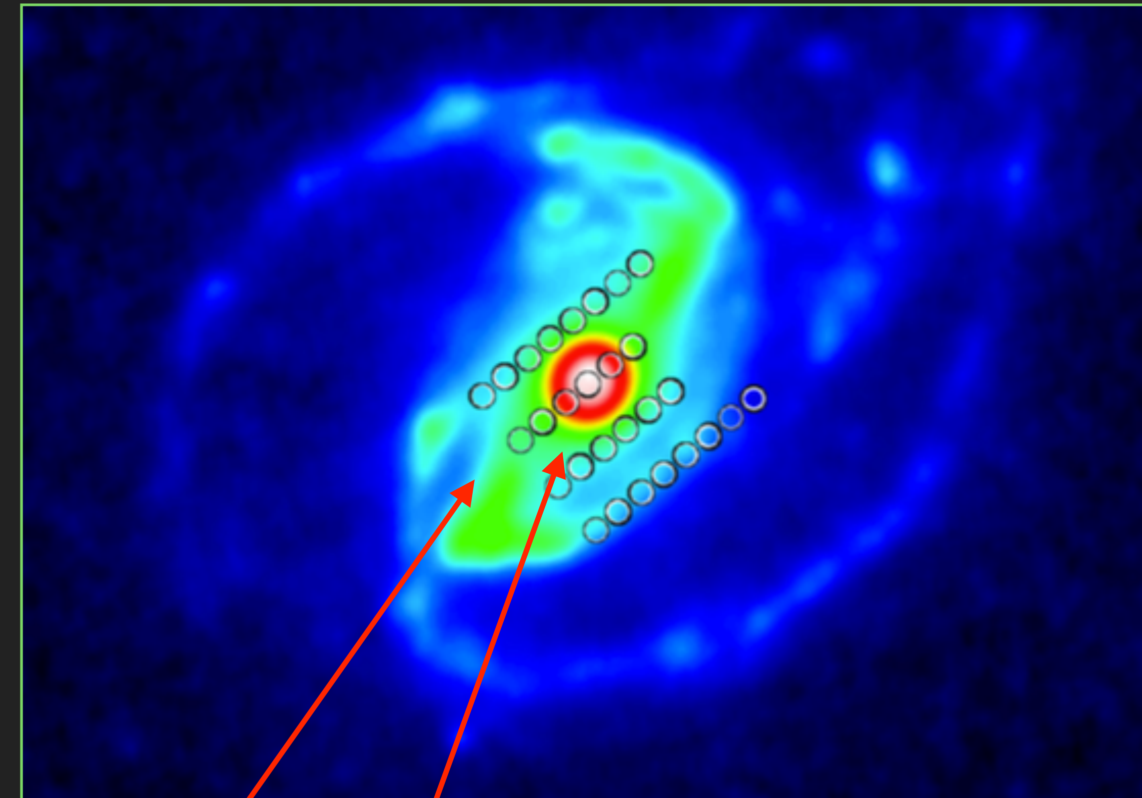




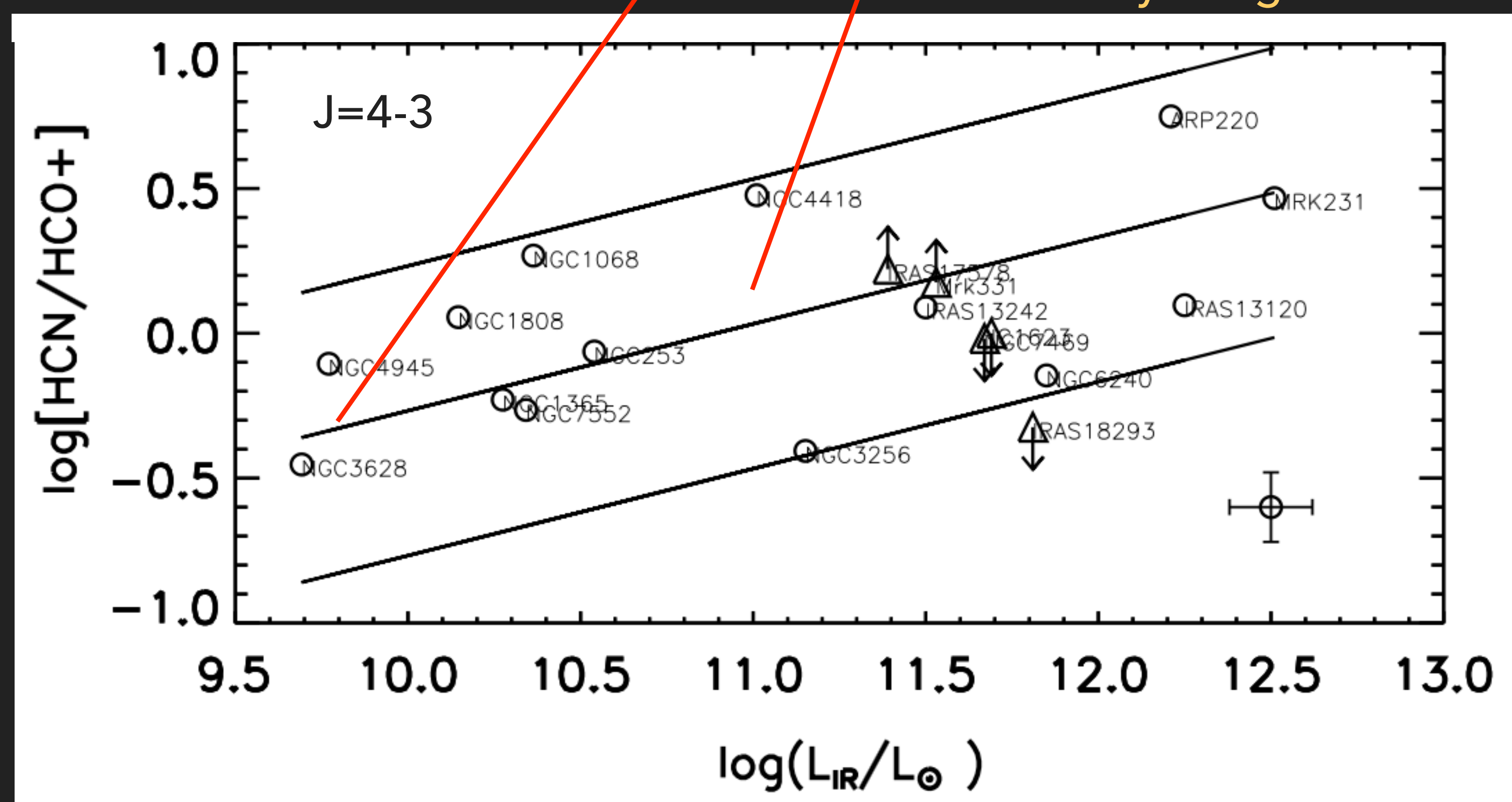


SCIENCE GOALS

- *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*

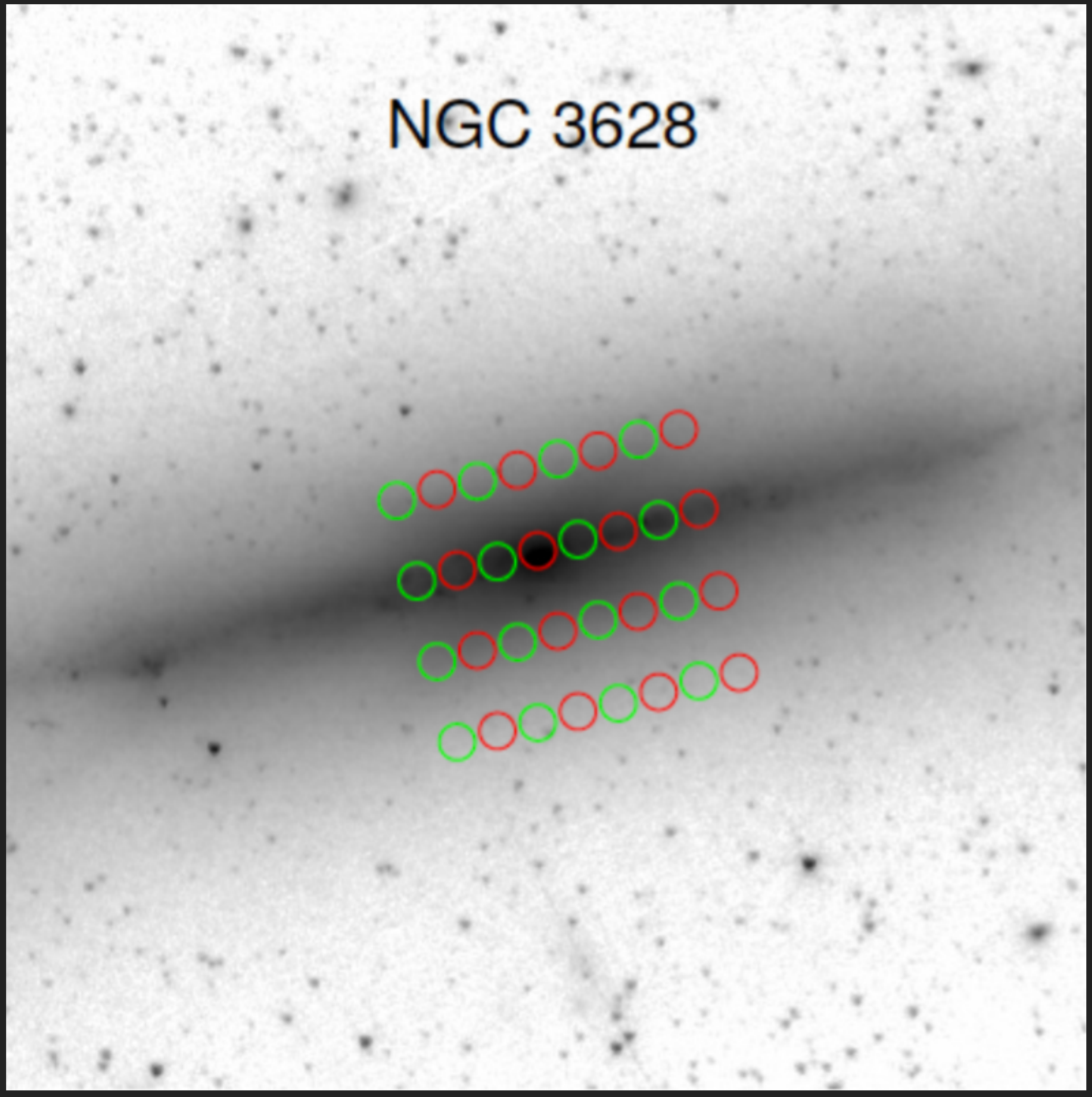


Galaxy-integrated ratios

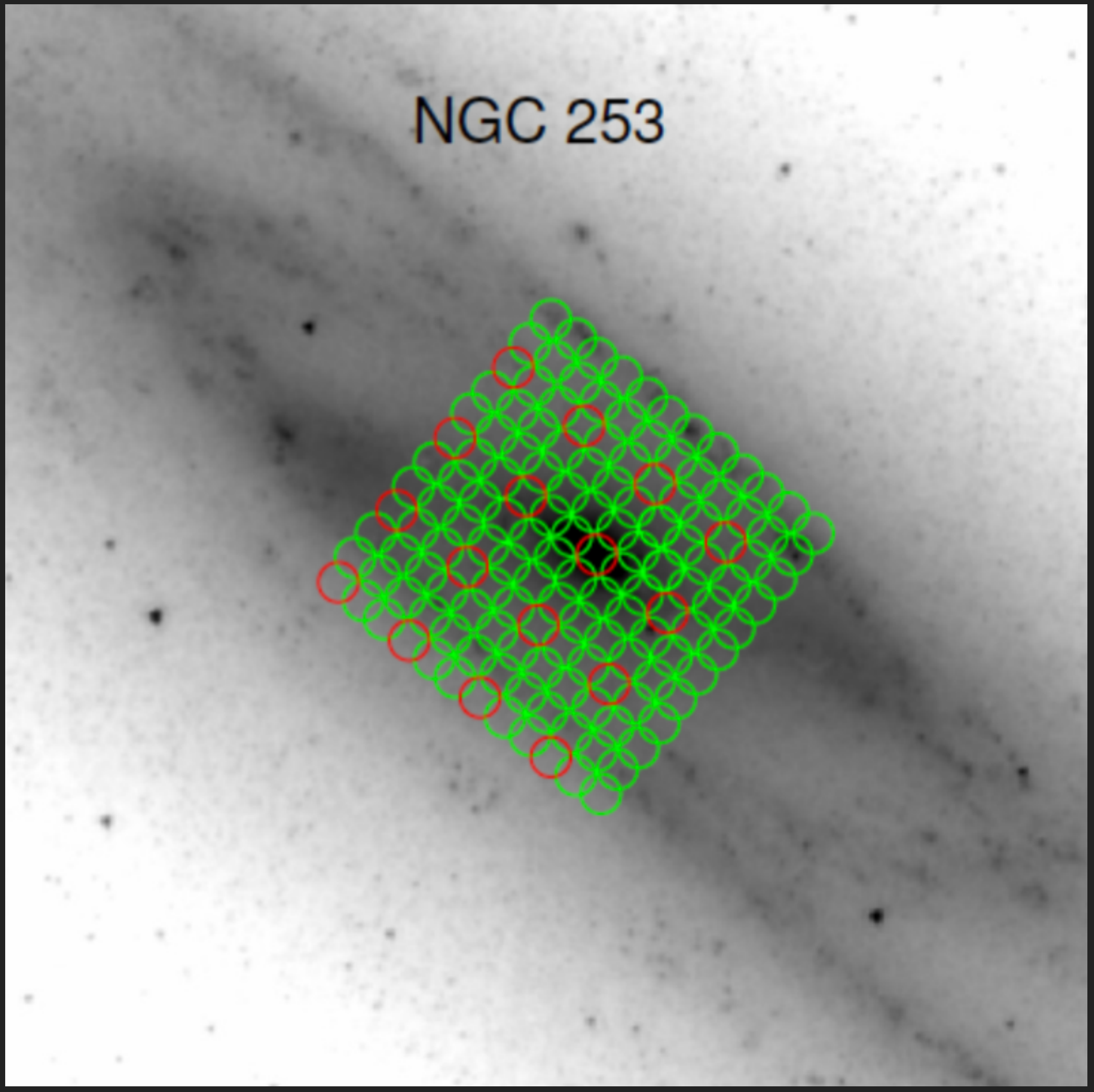


SCAN PATTERNS

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

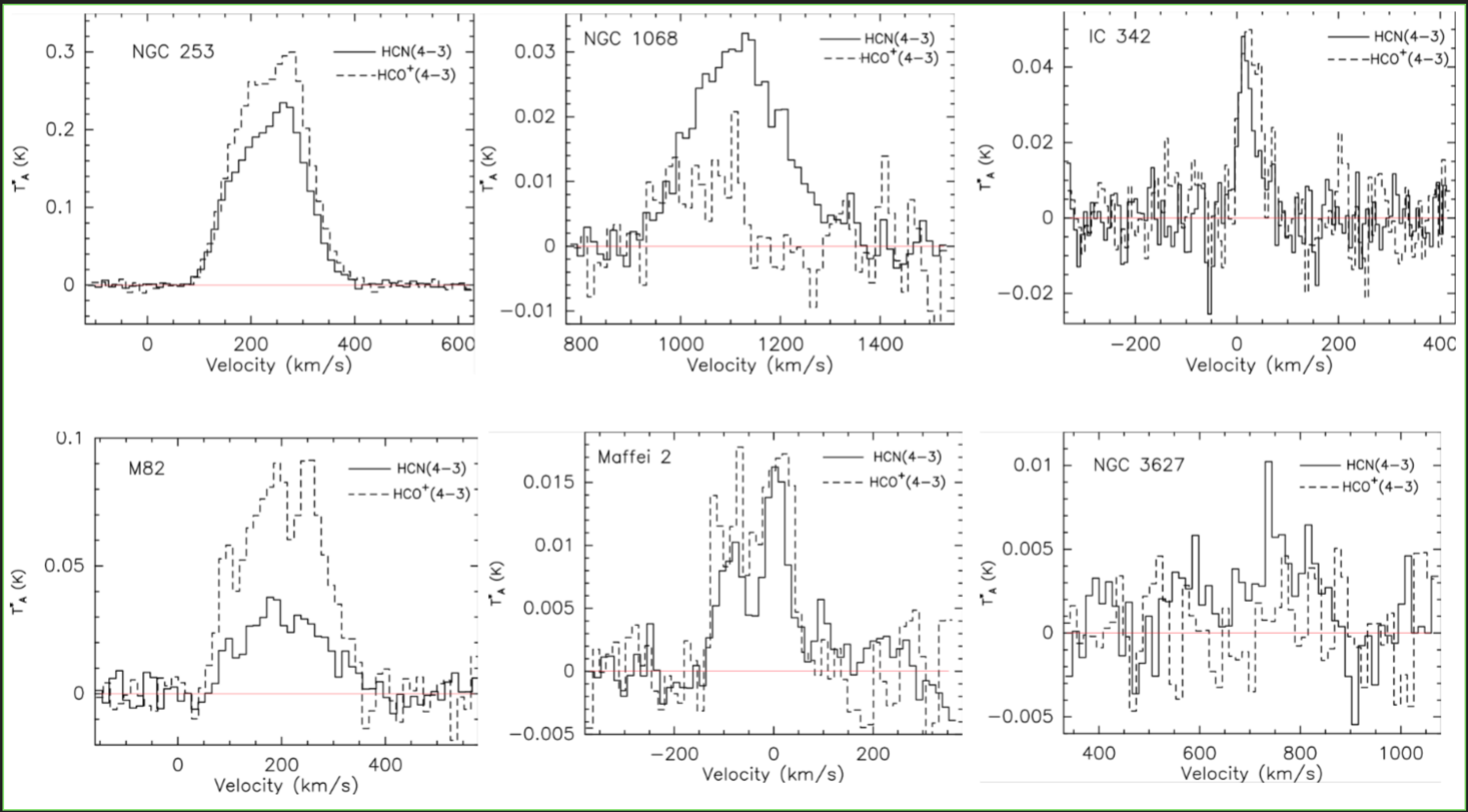


- *Jiggle mode*
- *Mostly for face-on/large galaxies*



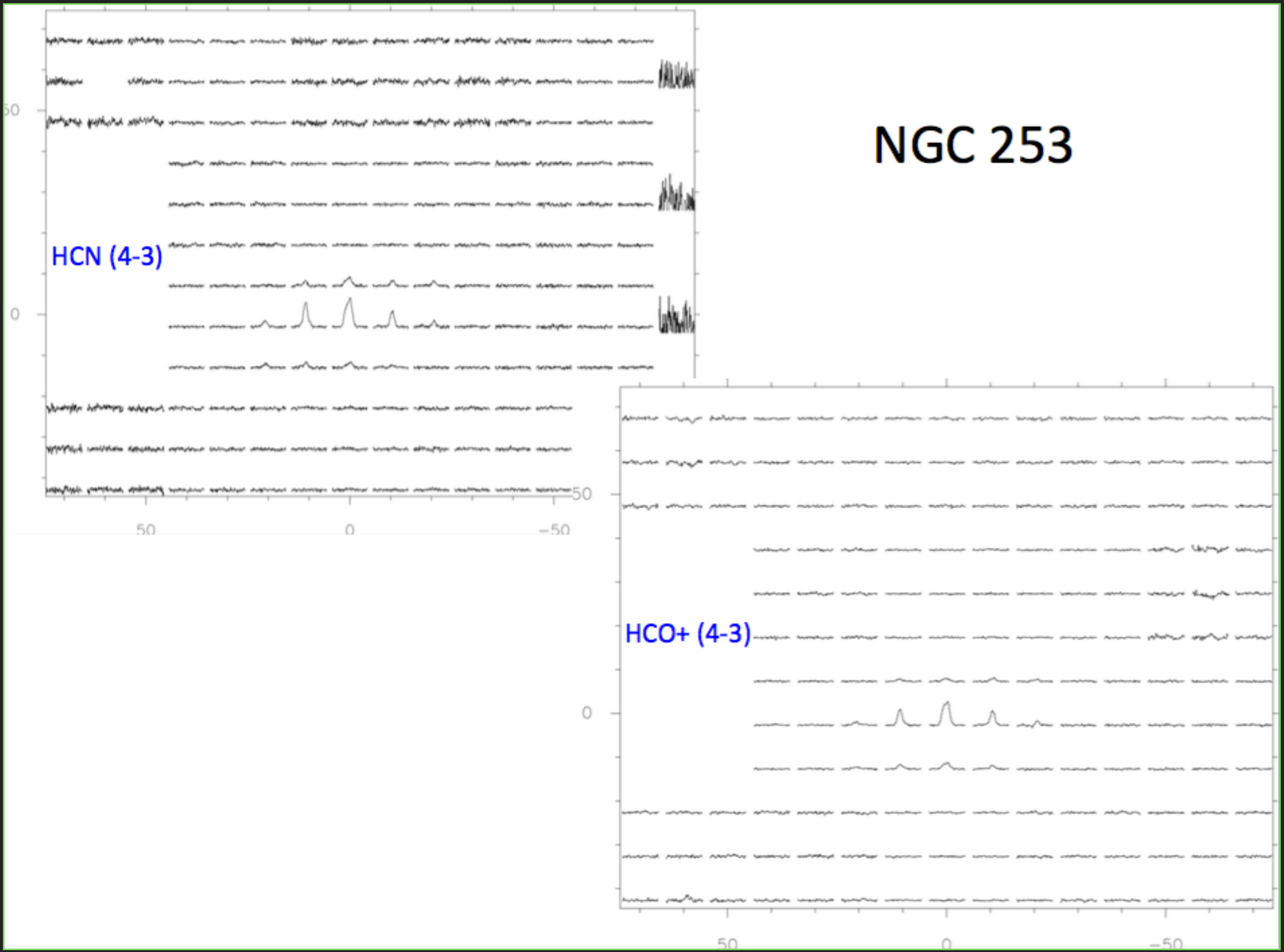
FIRST DATA – SPECTRA

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



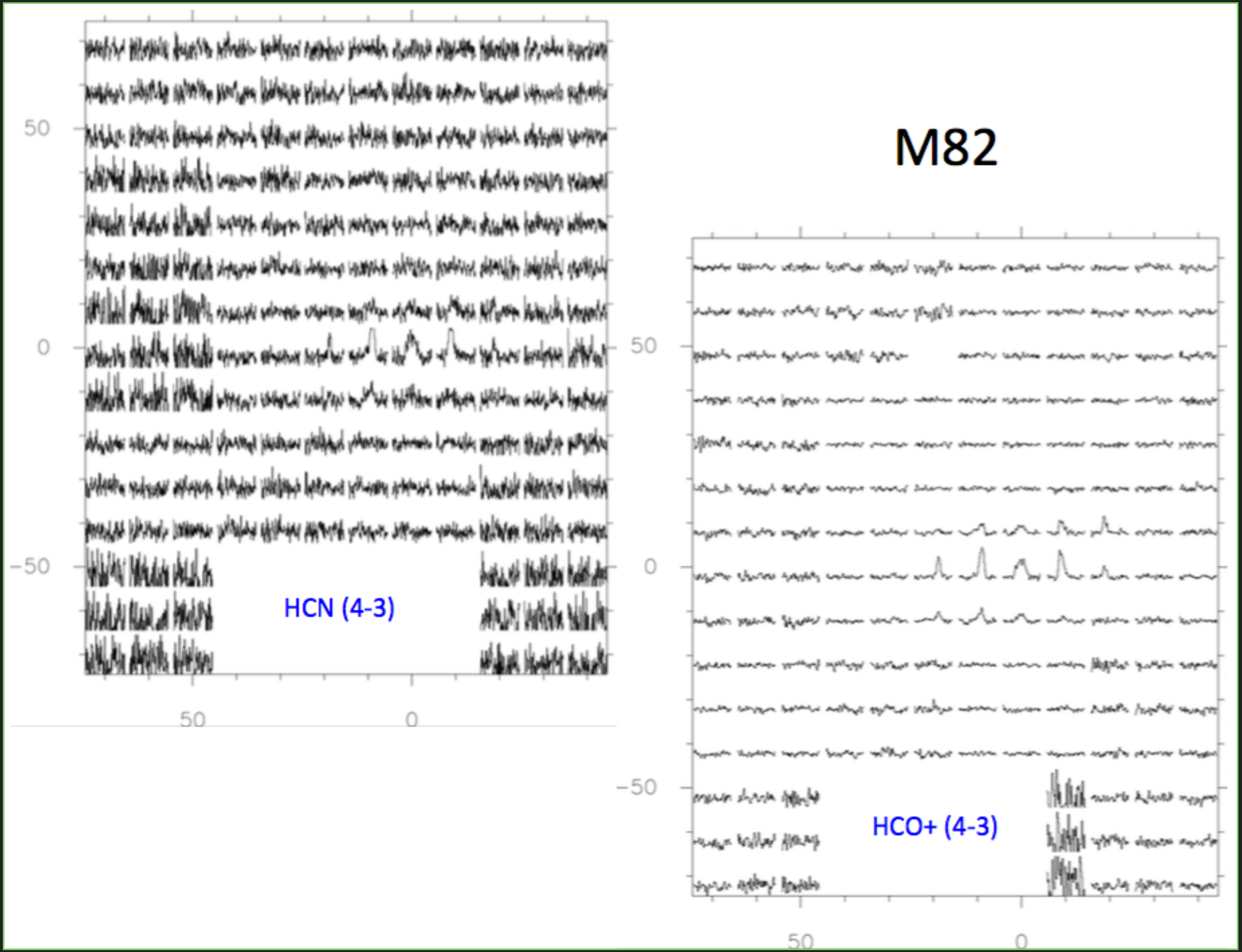
FIRST DATA – SPECTRA

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



FIRST DATA – SPECTRA

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



FIRST DATA – SUMMARY

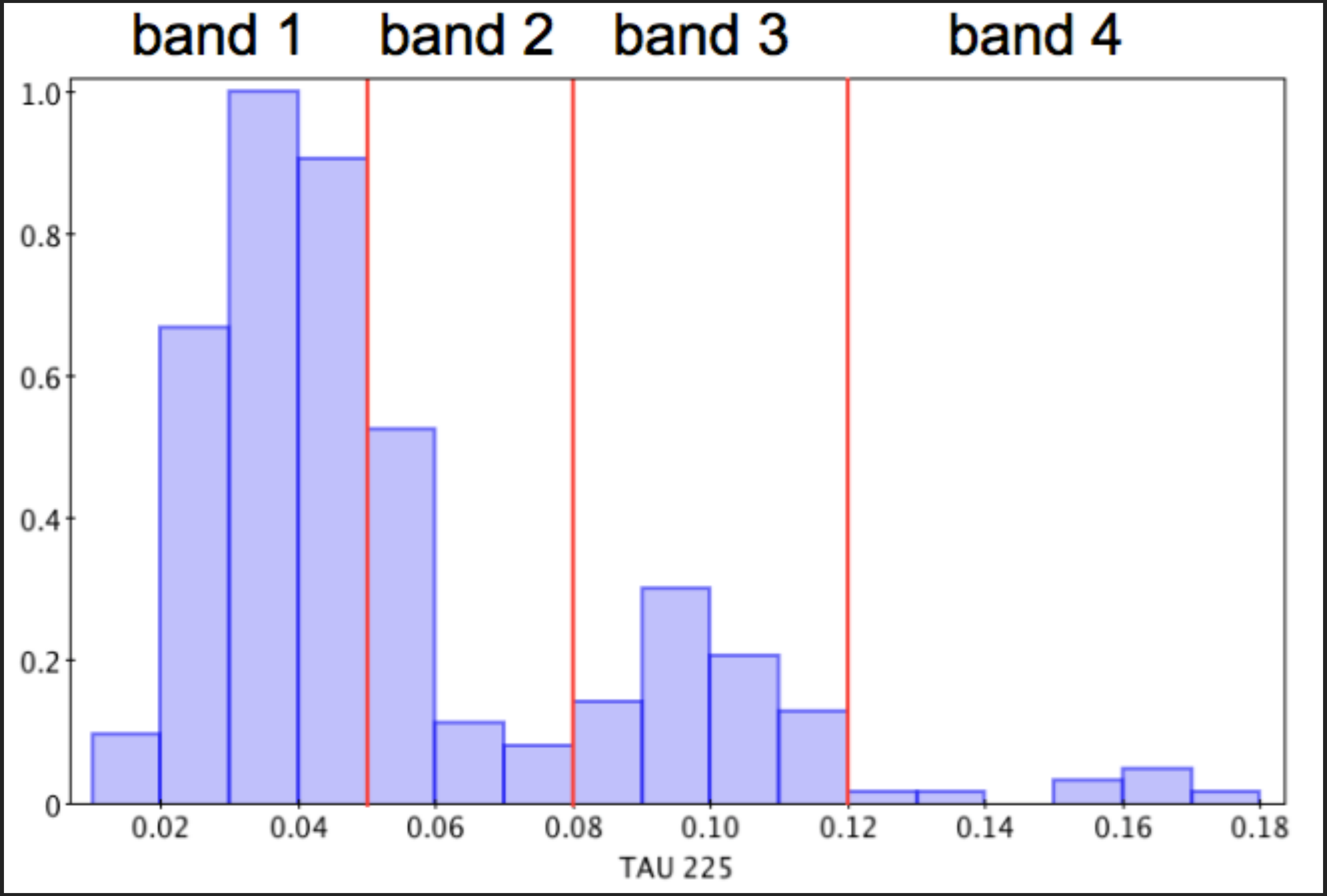
Name	Molecule	Obs_mode	Int_time (hours)	Tau(225 GHz)	Tau_median	$T_A^{*\,a}$ _peak (K)	RMS[b] (mK)
NGC 253	HCN (4-3)	Jiggle	2.36	0.018-0.042	0.022	0.23	4.1 (6.6 km s^{-1})
	HCO^+ (4-3)	Jiggle	1.67	0.033-0.037	0.036	0.30	6.9 (6.6 km s^{-1})
NGC 660	HCN (4-3)	Grid	0.83	0.046-0.048	0.047	0.012	3.9 (13.2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

[a] The line peak intensity measured in the central position of galaxies.

[b] rms 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

▷ *18 galaxies observed to date*

Time allocated to project: 390h0m0s in tau range [0.05,0.20]
Time remaining on project: 293h6m0s
Completion 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

galaxy	Molecule	time
Arp299	HCN	3.3
	HCO+	0.8
IC342	HCN	2.5
	HCO+	3.4
M82	HCN	2.5
	HCO+	1.7
maffei2	HCN	5.0
	HCO+	3.5
NGC1068	HCN	3.1
	HCO+	2.3
NGC1097	HCN	5.1
NGC1365	HCN	1.2
NGC1808	HCN	2.9
	HCO+	3.3
NGC2146	HCN	2.5
NGC253	HCN	2.4
	HCO+	1.7
NGC2903	HCN	6.2
	HCO+	2.6
NGC3079	HCN	2.1
NGC3521	HCN	2.4
NGC3627	HCN	3.3
	HCO+	3.2
NGC3628	HCN	4.1
	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

2016

- *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.*

2018

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)*

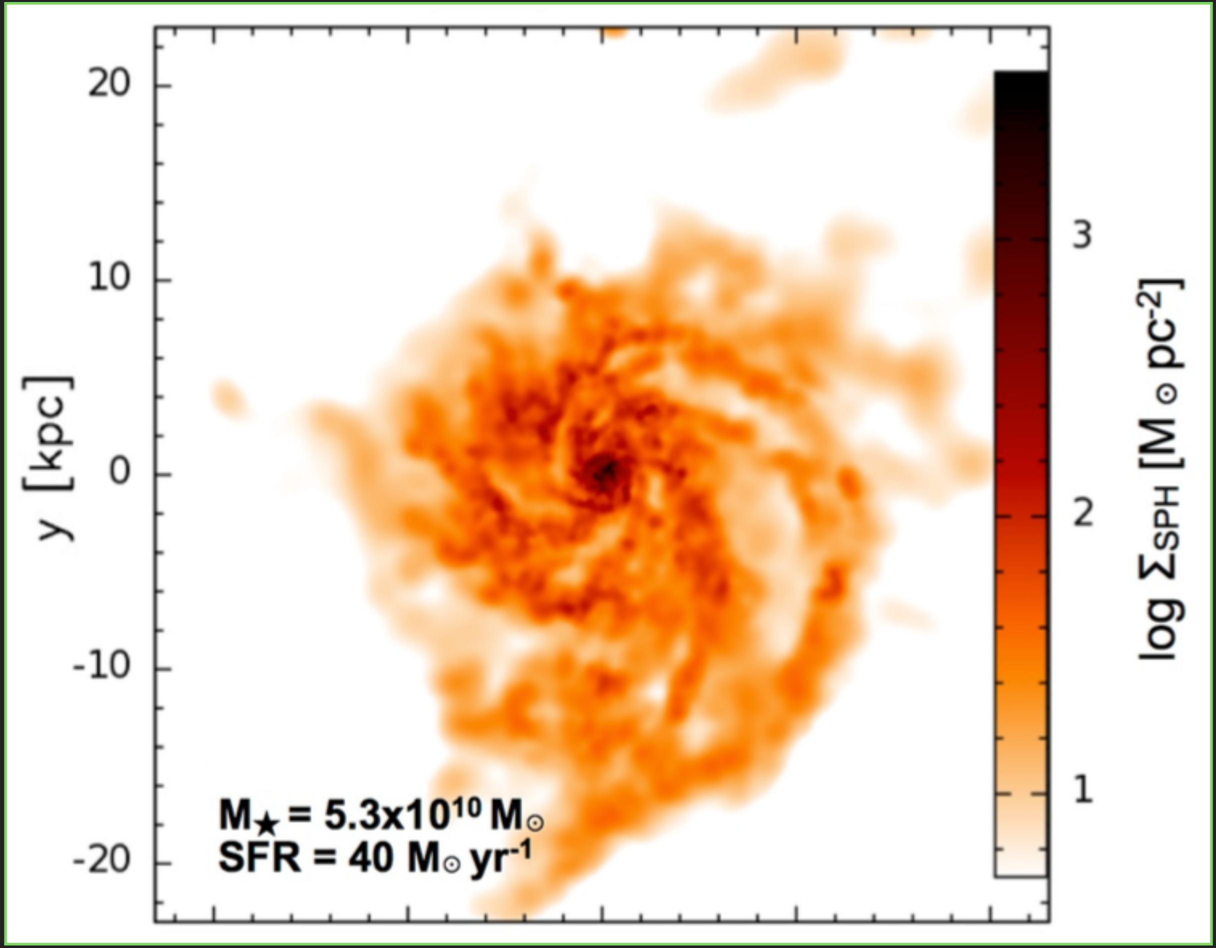
IRAM

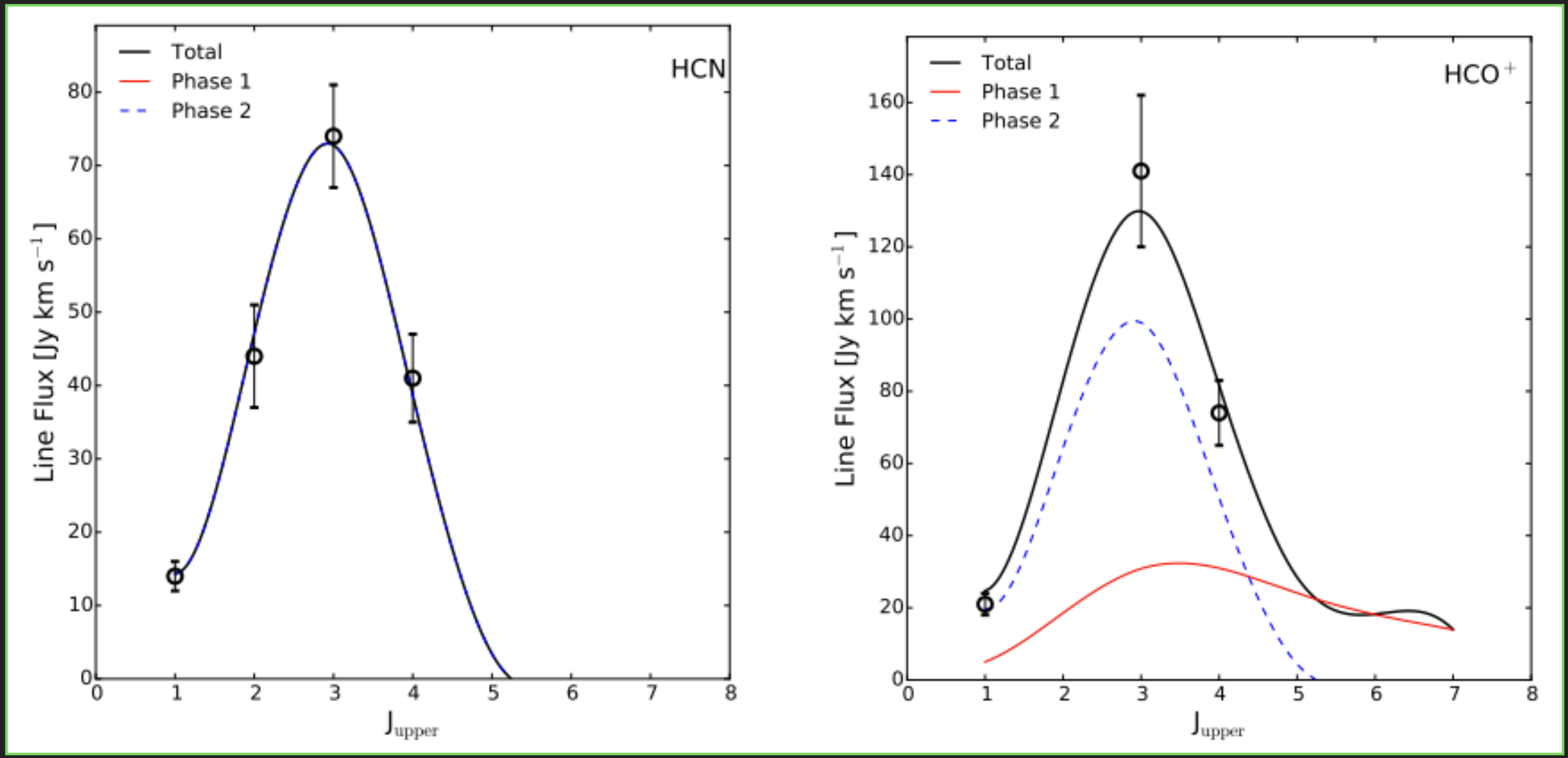
ALMA

SYNERGY & FOLLOW-UP

- *Modelling:*
  - *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*

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





LVG modelling of HCN and HCO$^+$

Tunnard et al. (2015)

THANK YOU

MALATANG

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www.eaobservatory.org/jcmt