(Dense) Molecular Gas & Star Formation in Galaxies

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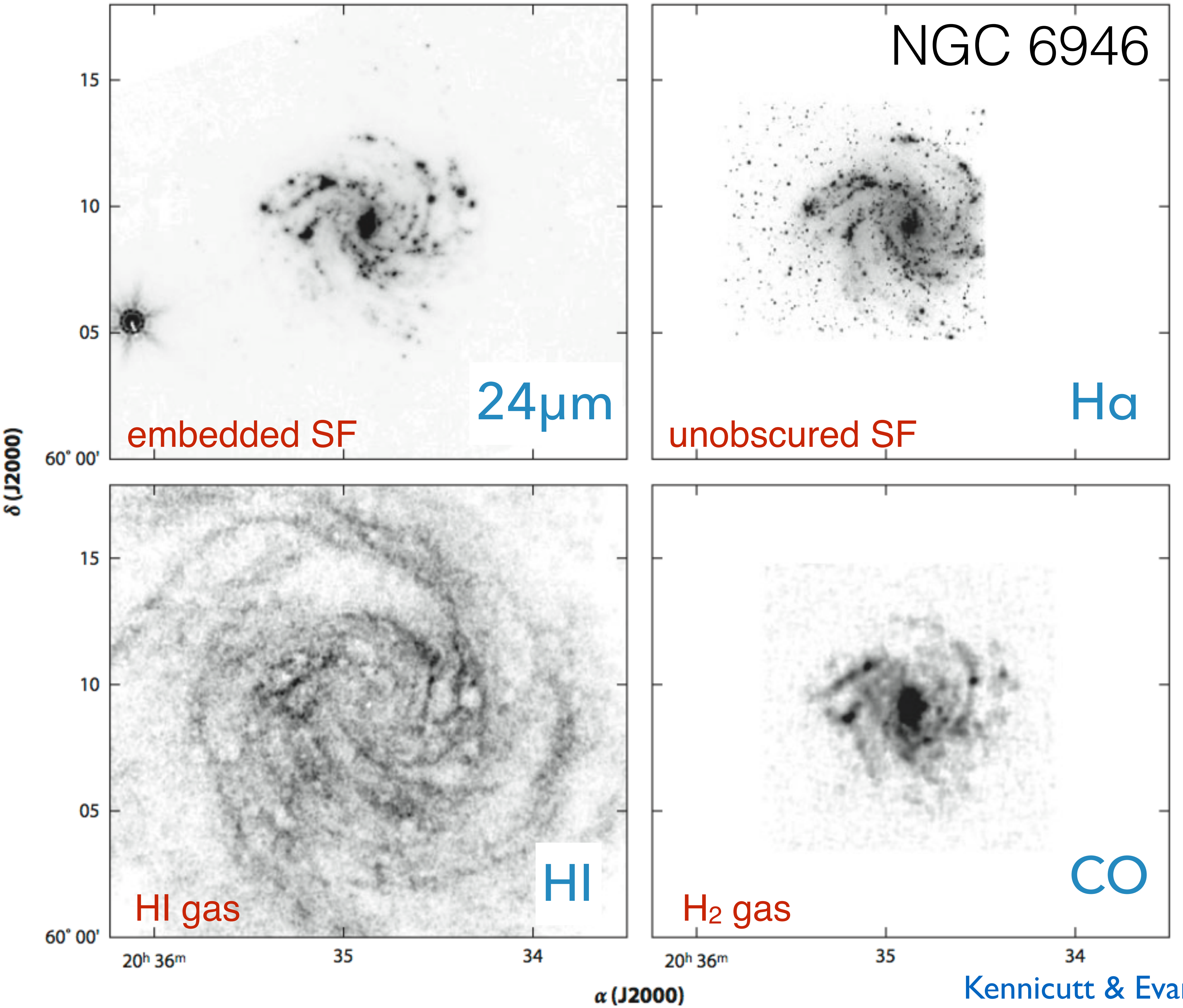
Outline

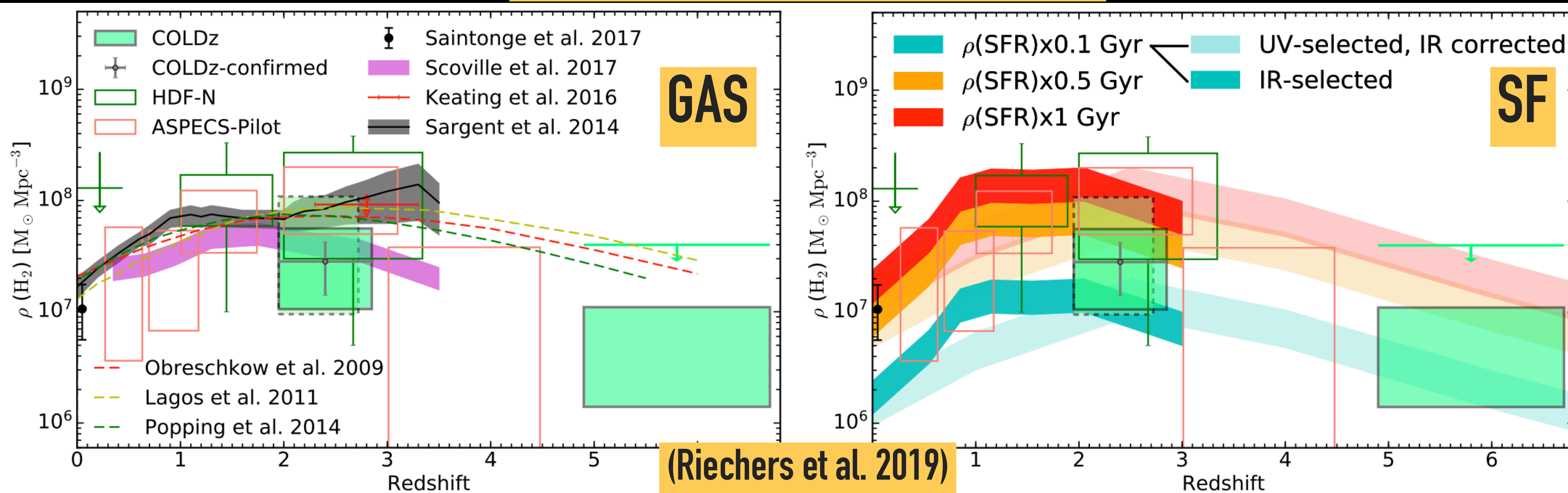
- Motivations:
dense gas as direct tracer of star-forming gas
- JCMT large program (MALATANG)
- Other examples &
Future demands

DIFFERENT PHASES OF ISM

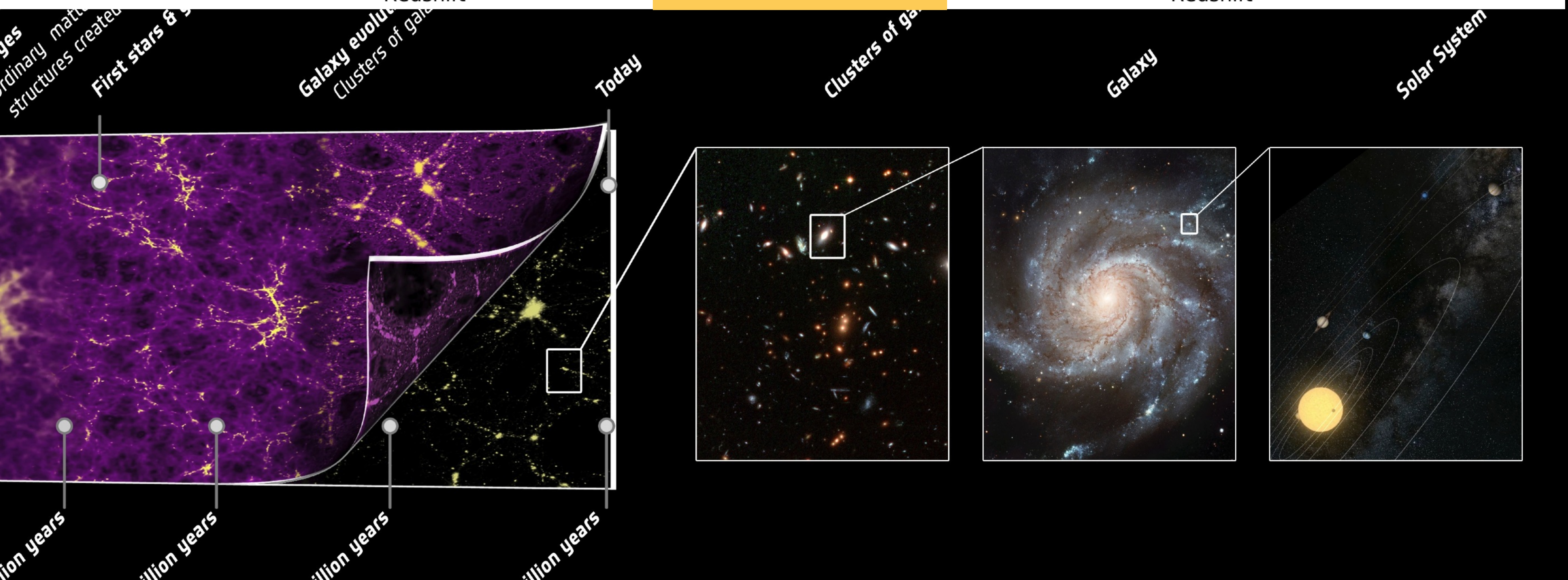


Kennicutt & Evans 2012, ARAA

Molecular gas drives cosmic star formation

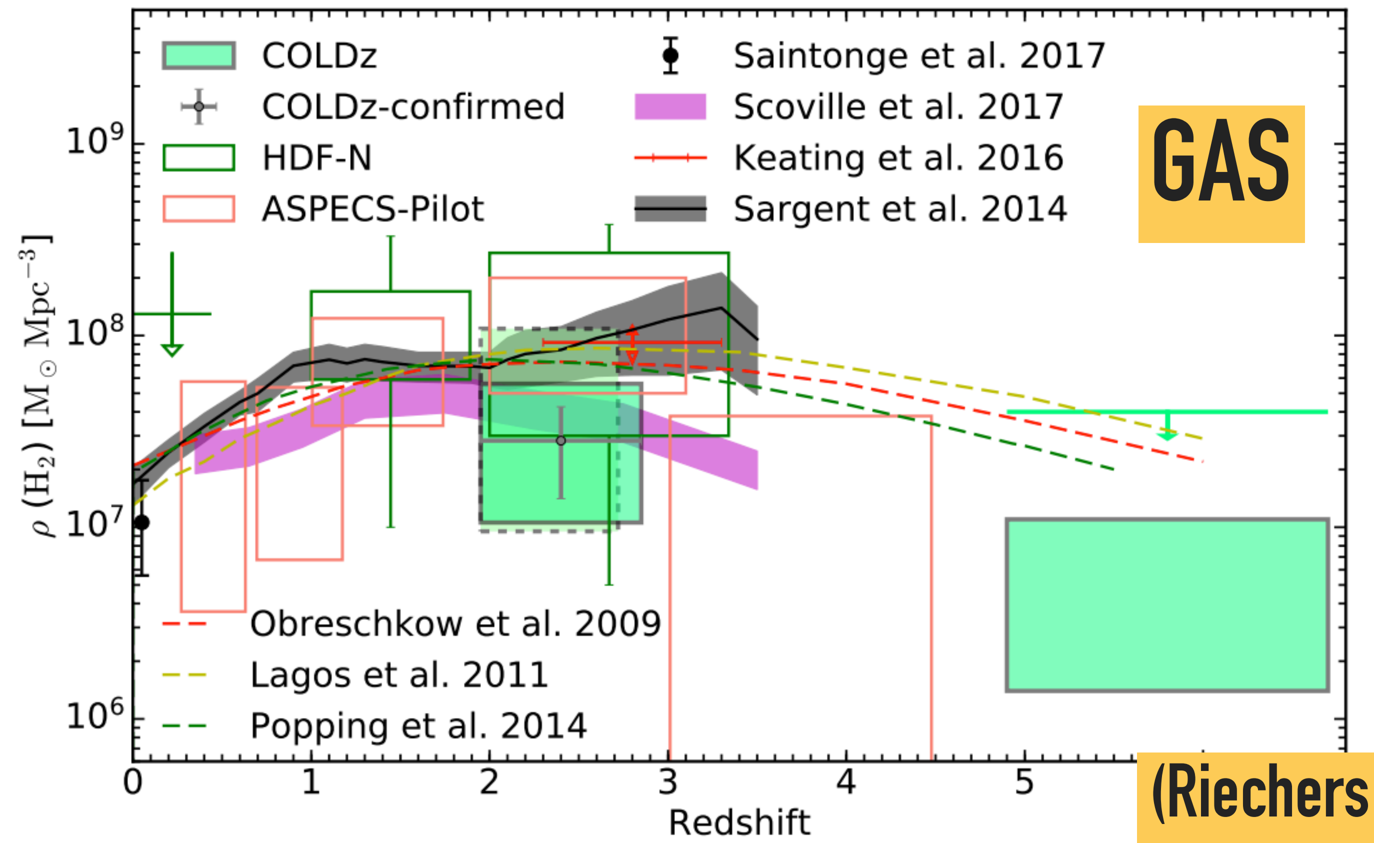


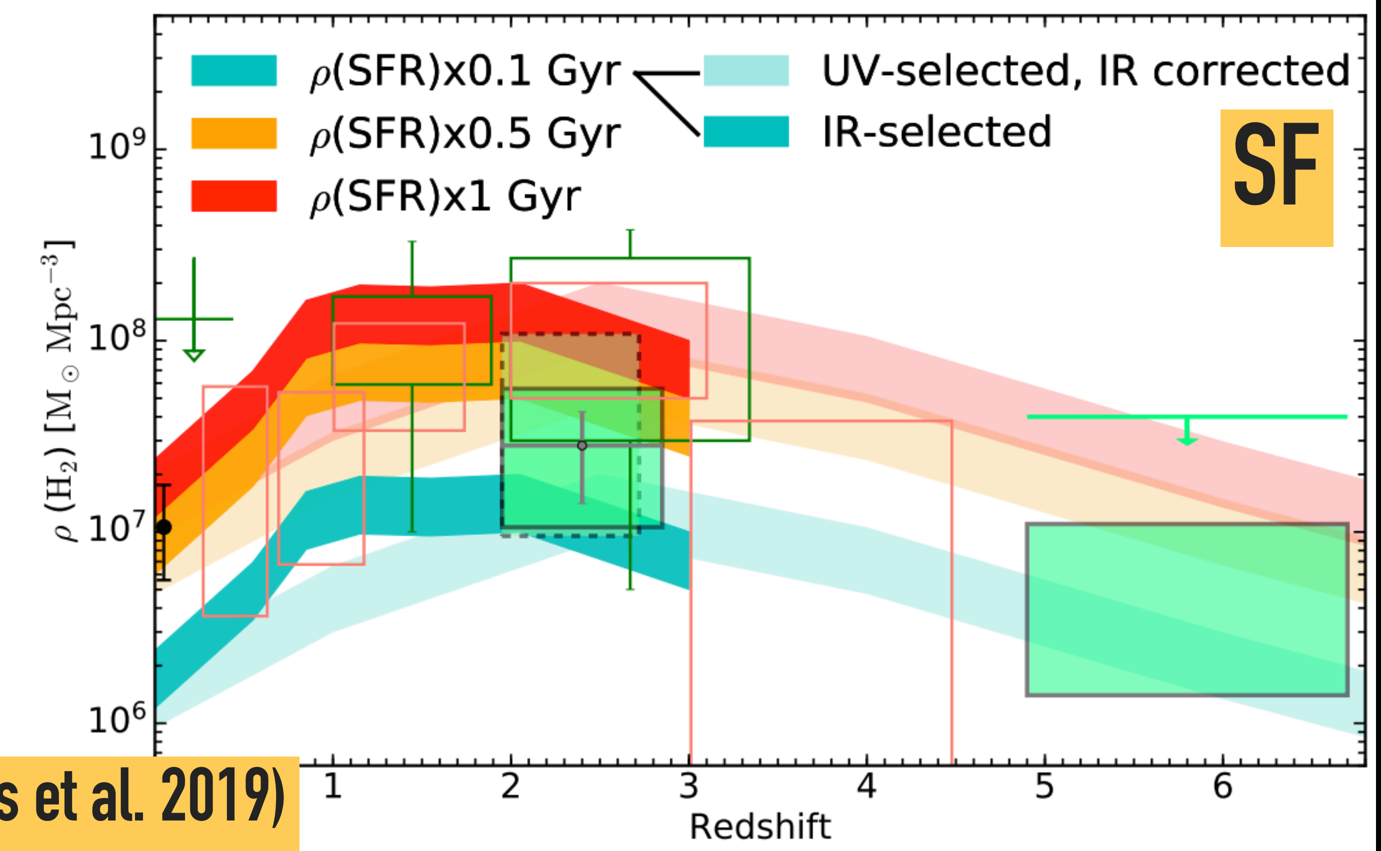
(Riechers et al. 2019)



credit: ESA - C. Carreau

Molecular gas drives cosmic star formation





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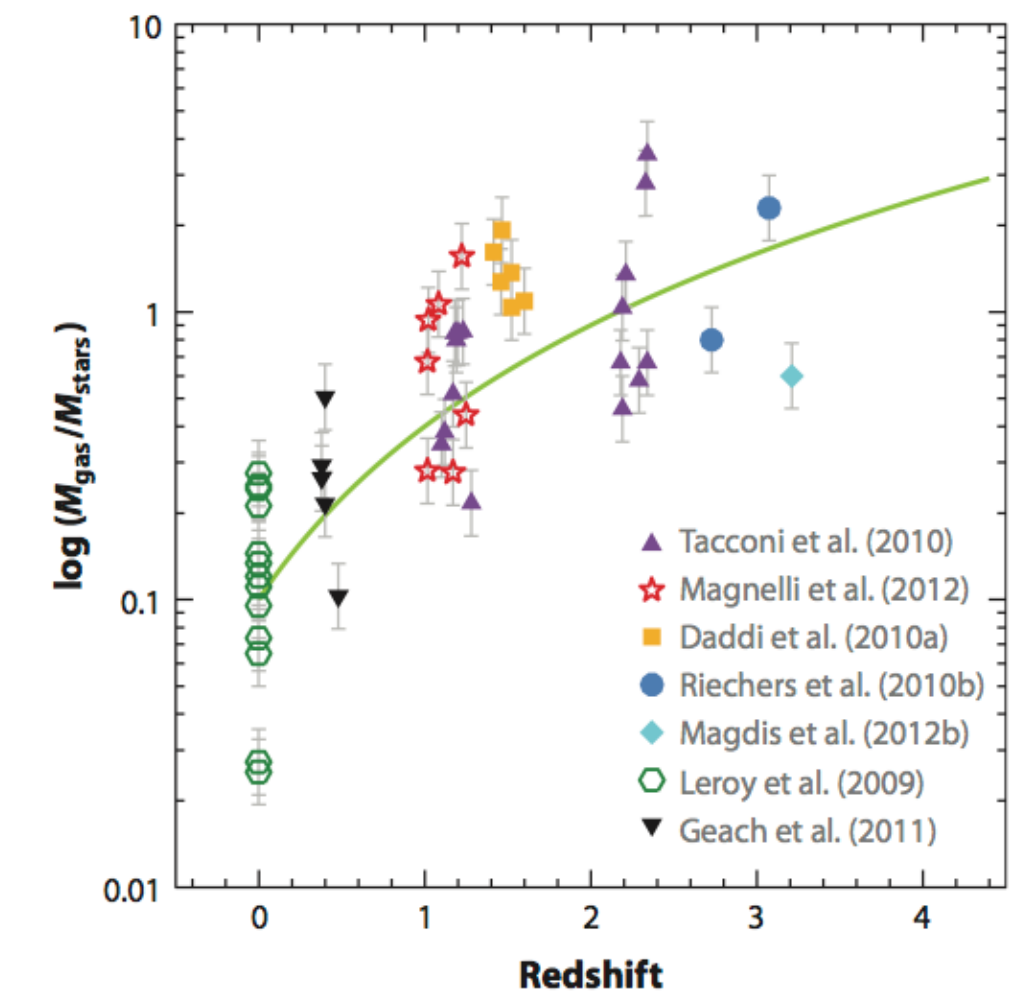
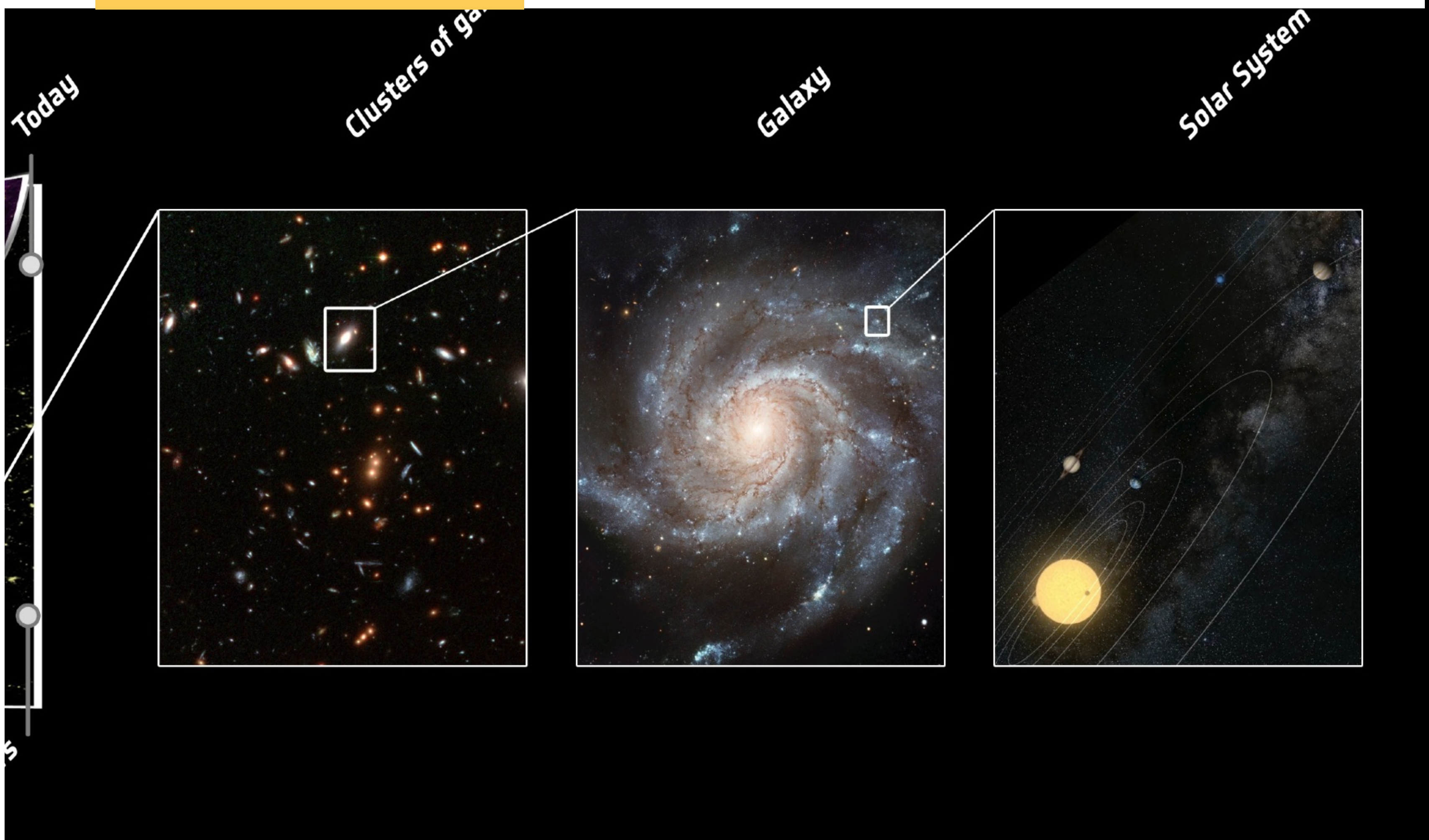


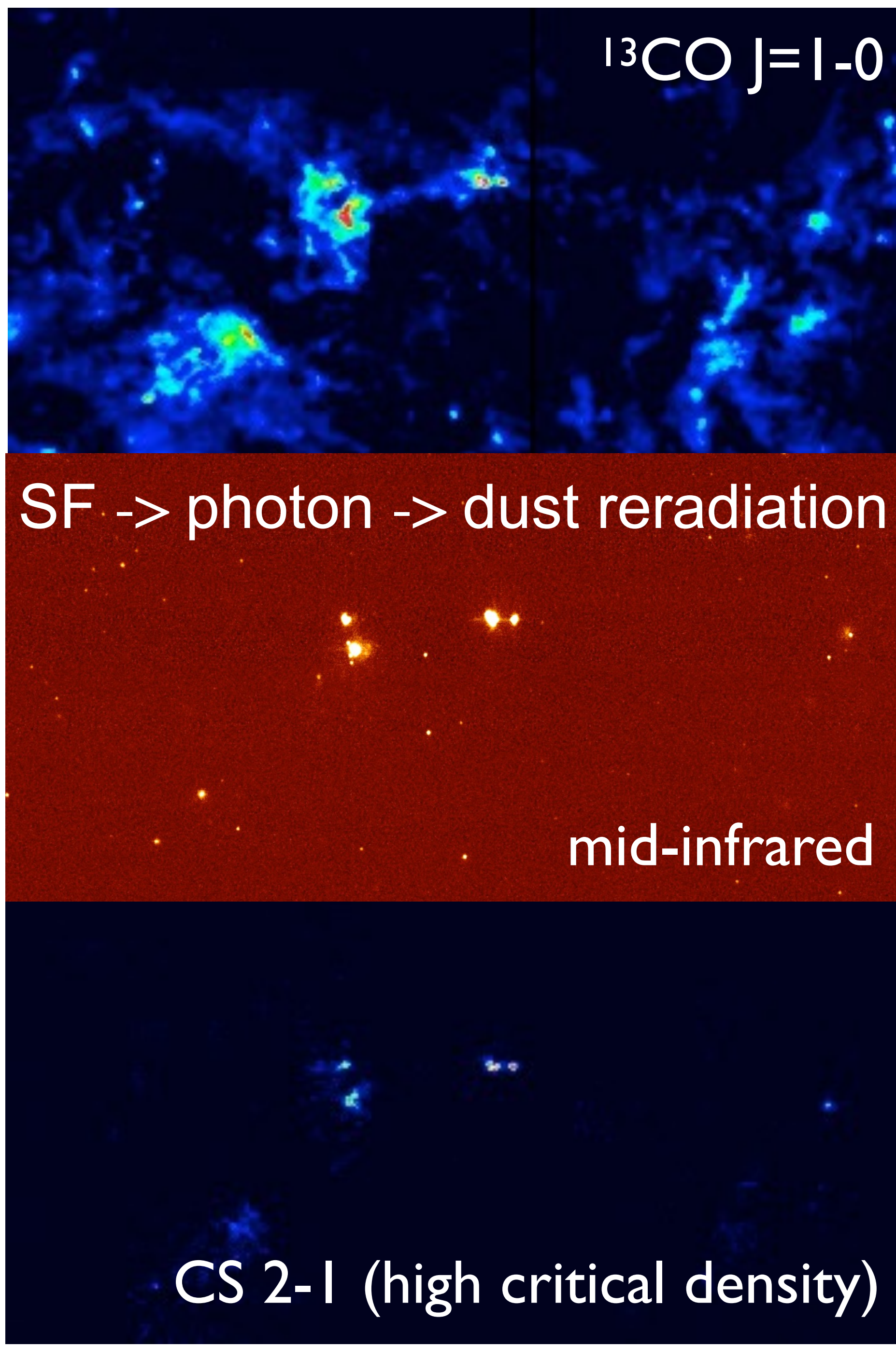
CARILLI & WALTER 2014



credit: ESA - C. Carreau

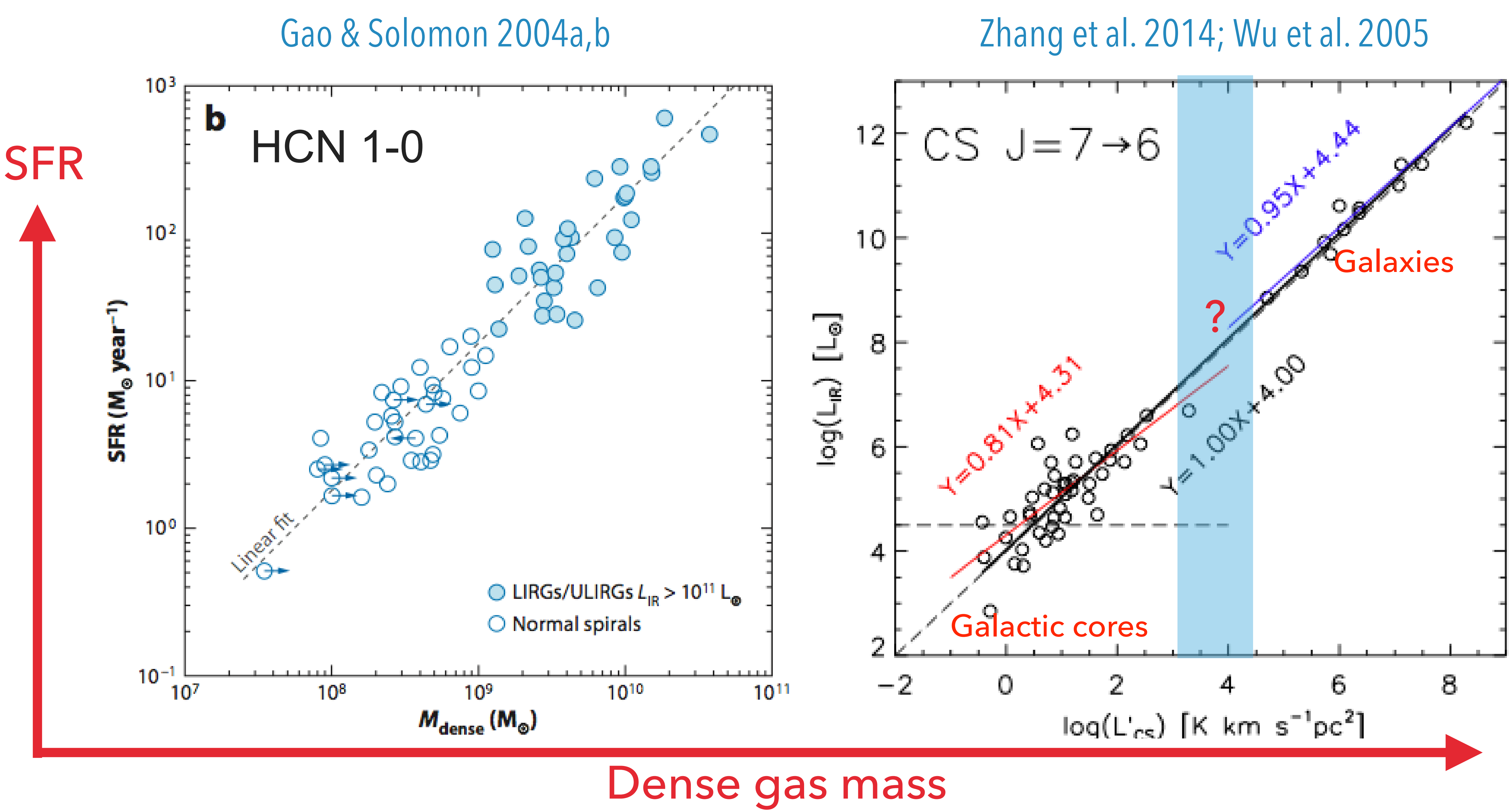
Motivation: ISM & Star-formation

tracing dense gas — the direct fuel of SF



Transition	$n_{\rm crit}$ [cm^{-3}]	$E_J/k_{\rm B}$ [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

Star Formation relations



QUESTIONS TO ADDRESS

- Different environments: nuclear, arm, disk?
- Connection between local clouds and galaxies?
- Consistency and differences between tracers?

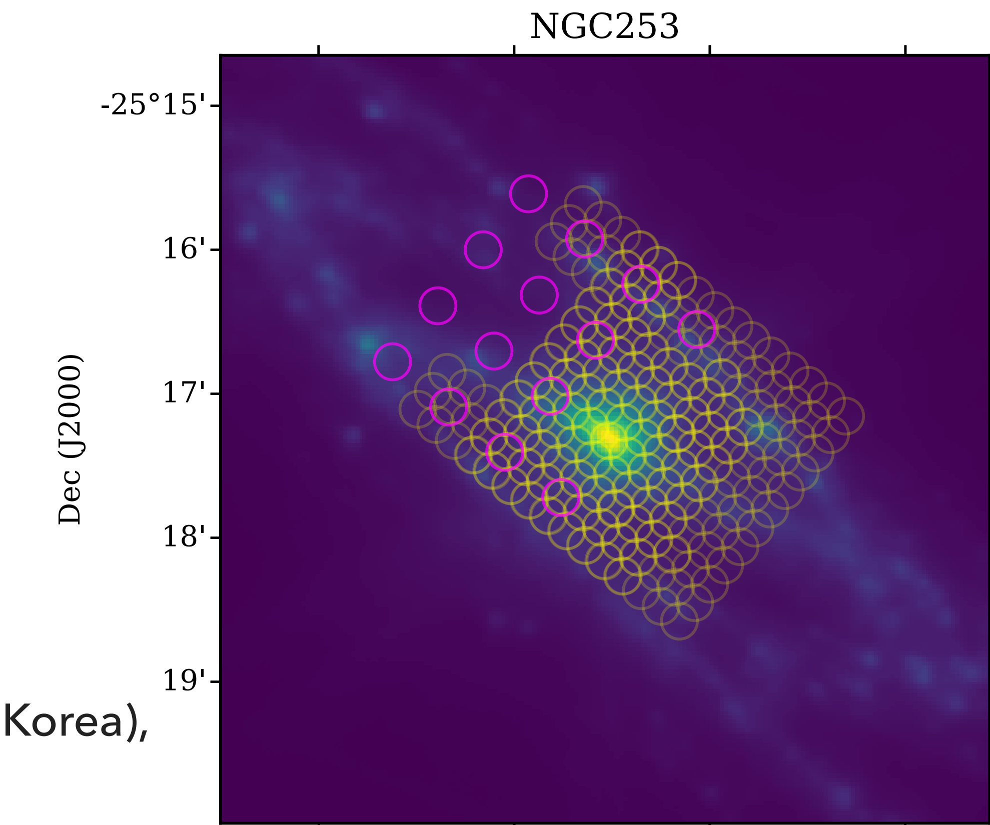
JCMT LARGE PROGRAM: MALATANG

Mapping the Dense moLecular gAs in the sTrongest stAr-formiNg Galaxies

- HCN 4-3 and HCO^+ 4-3 survey toward 22 IR-bright galaxies
- 390 hours (Nov. 2015 – Jul. 2017)

Significance:

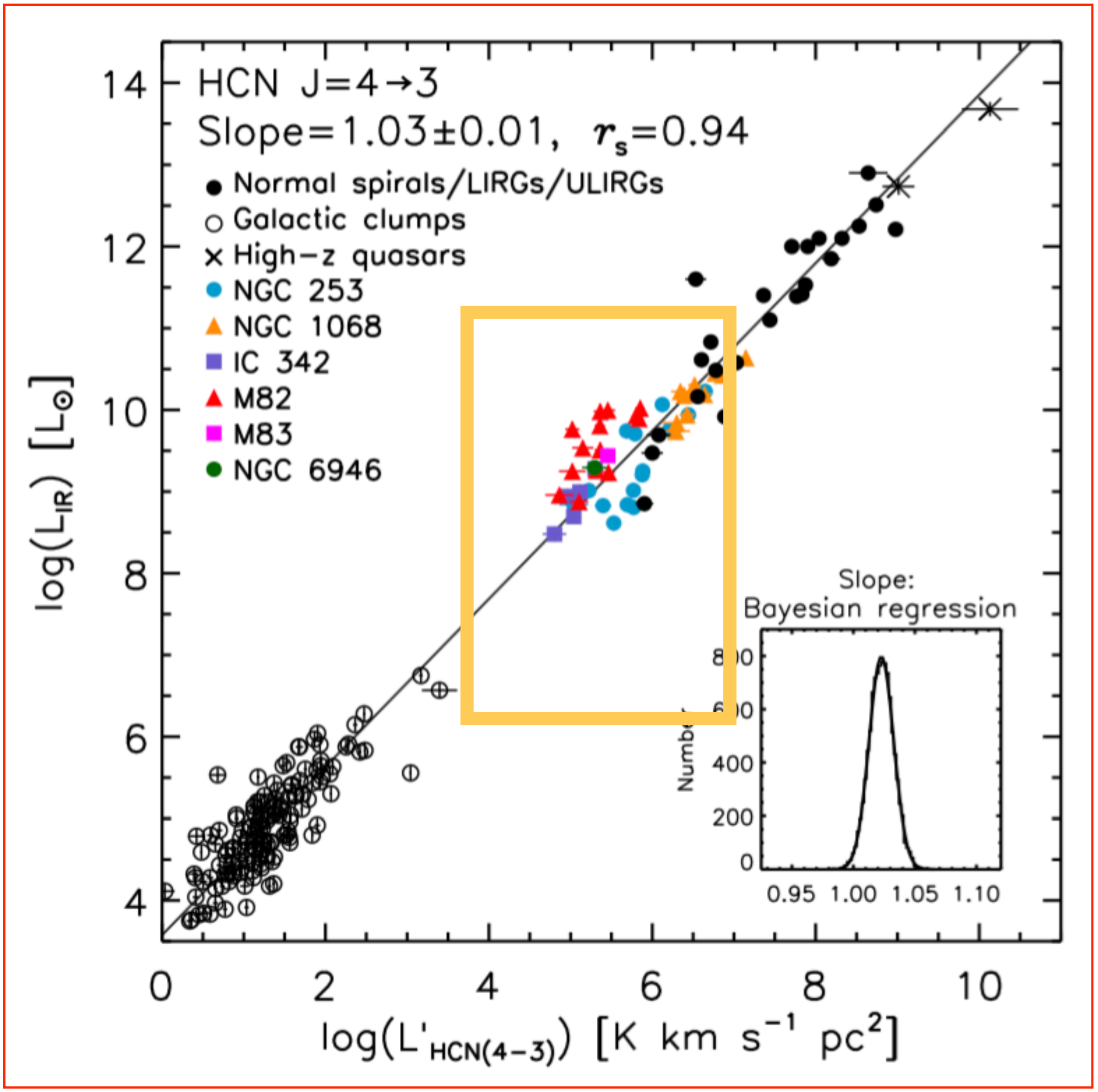
- Resolved dense gas SF relations
- Intermediate (sub-kpc) scales/luminosities
- Radial distribution of dense gas and SF efficiency



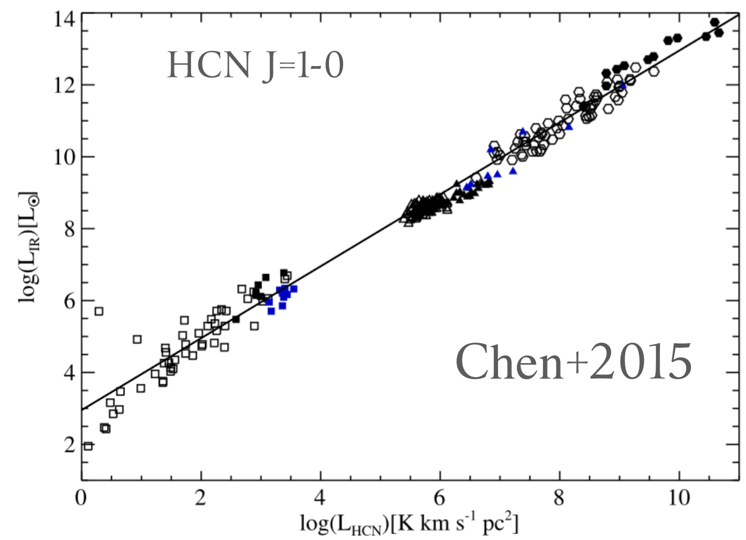
PI: Yu Gao (CN), Thomas Greve (UK) & Zhiyu Zhang (Germany)
co-I: Satoki Matsushita (Taiwan), Kotaro Kohno(Japan), Aeree Chung(South Korea), Christine Wilson (Canada), Qinghua Tan et al.

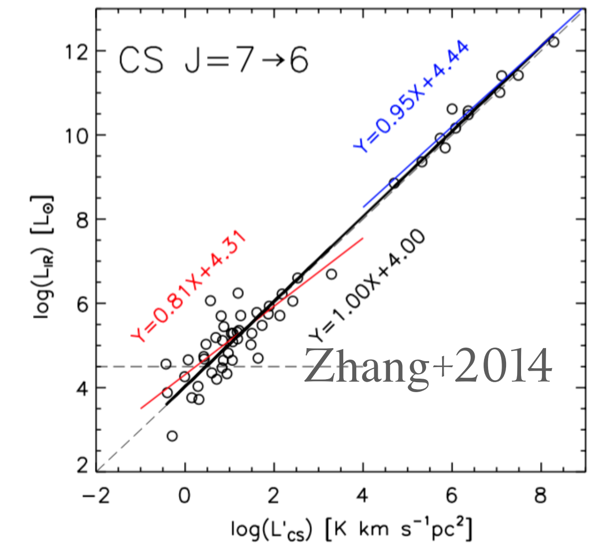
RESULTS (1) SF RELATION

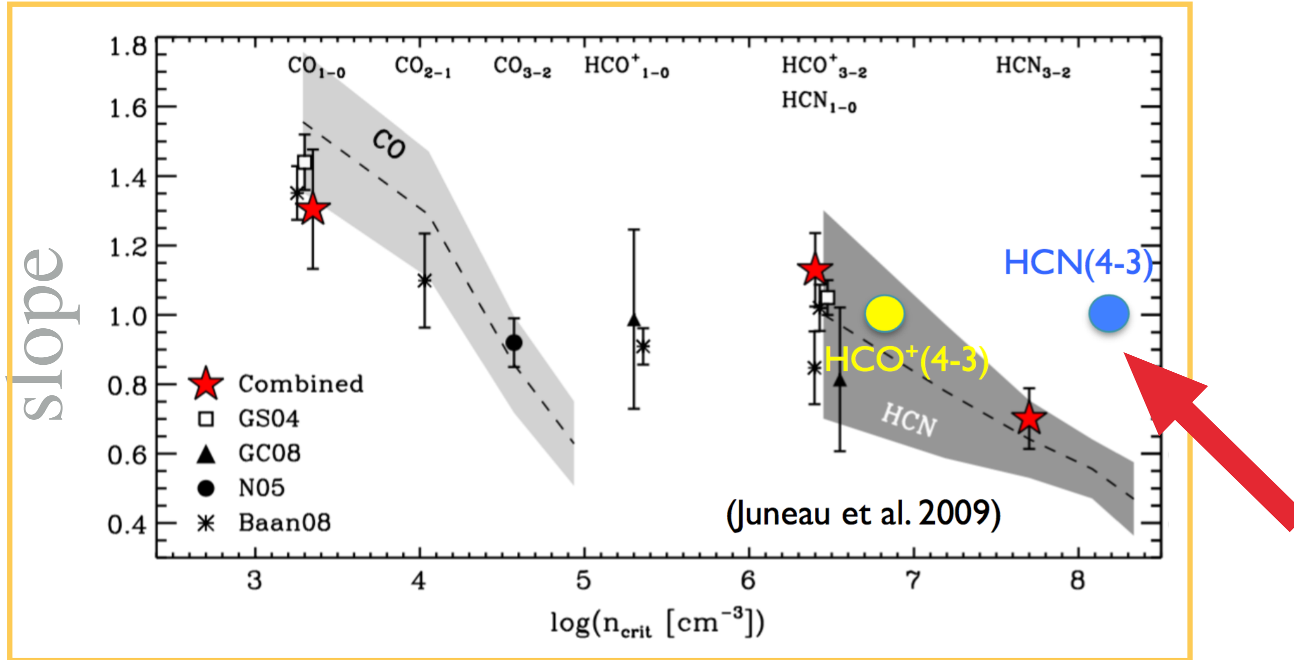
- linear correlations hold for all densities >10^4 cm^{-3}!
- Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations



Tan et al. (2018)



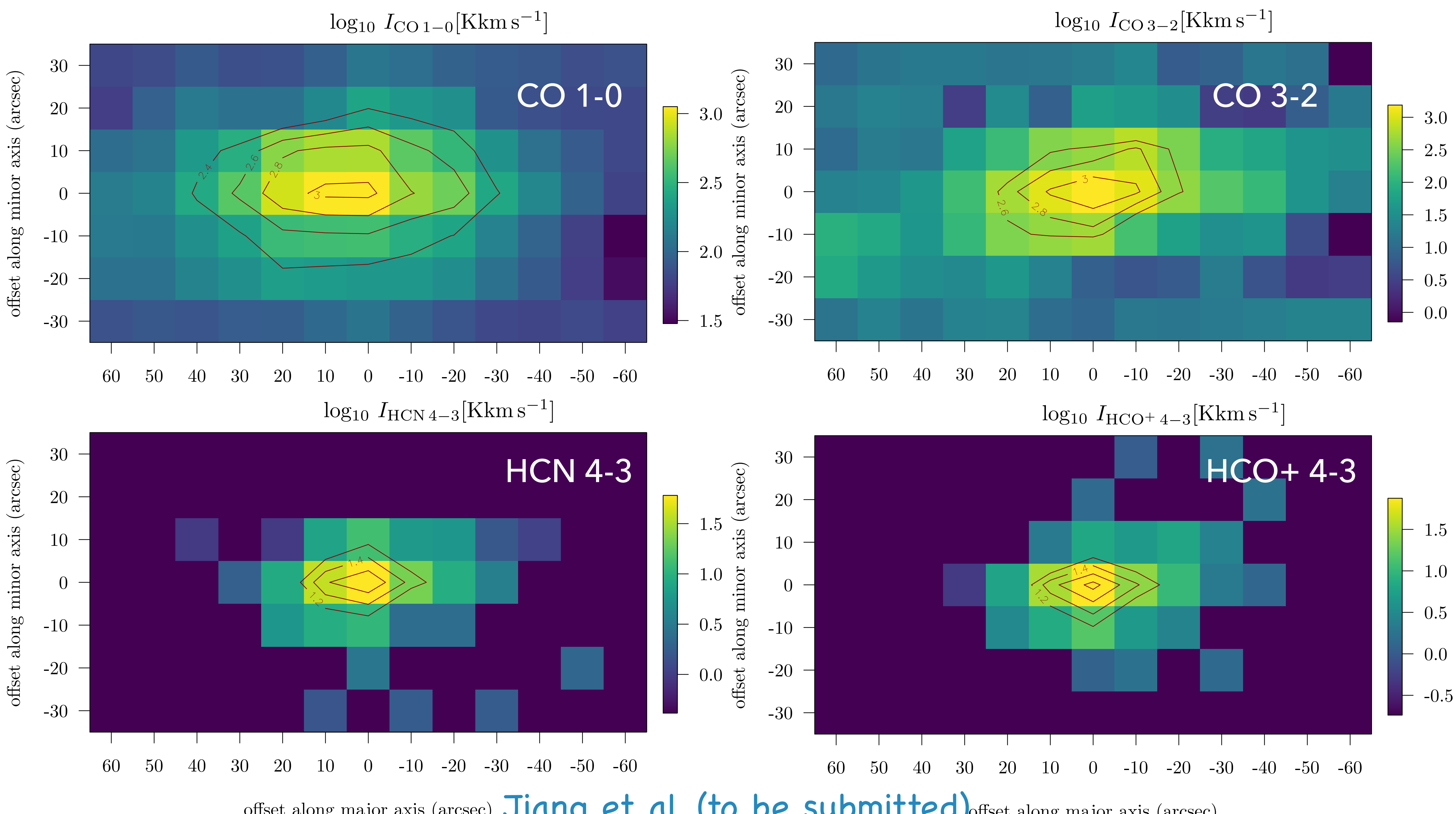




RESULTS (2): NGC 253

DENSE GAS IS CONCENTRATED

			concentration index
	r_{90}	r_{50}	r_{90}/r_{50}
stellar	0.69 (0.08)	0.30 (0.12)	2.28 (0.92)
CO 1-0	0.6 (0.03)	0.31(0.05	1.94 (0.34)
CO 3-2	0.29 (0.06)	0.09(0.08)	3.36 (3.32)
L_{IR}	0.44 (0.15)	0.11 (0.25)	3.86 (8.54)
HCN 4-3	0.17 (0.27)	…	…
HCO+ 4-3	0.32 (0.26)	…	…



Jiang et al. (to be submitted)

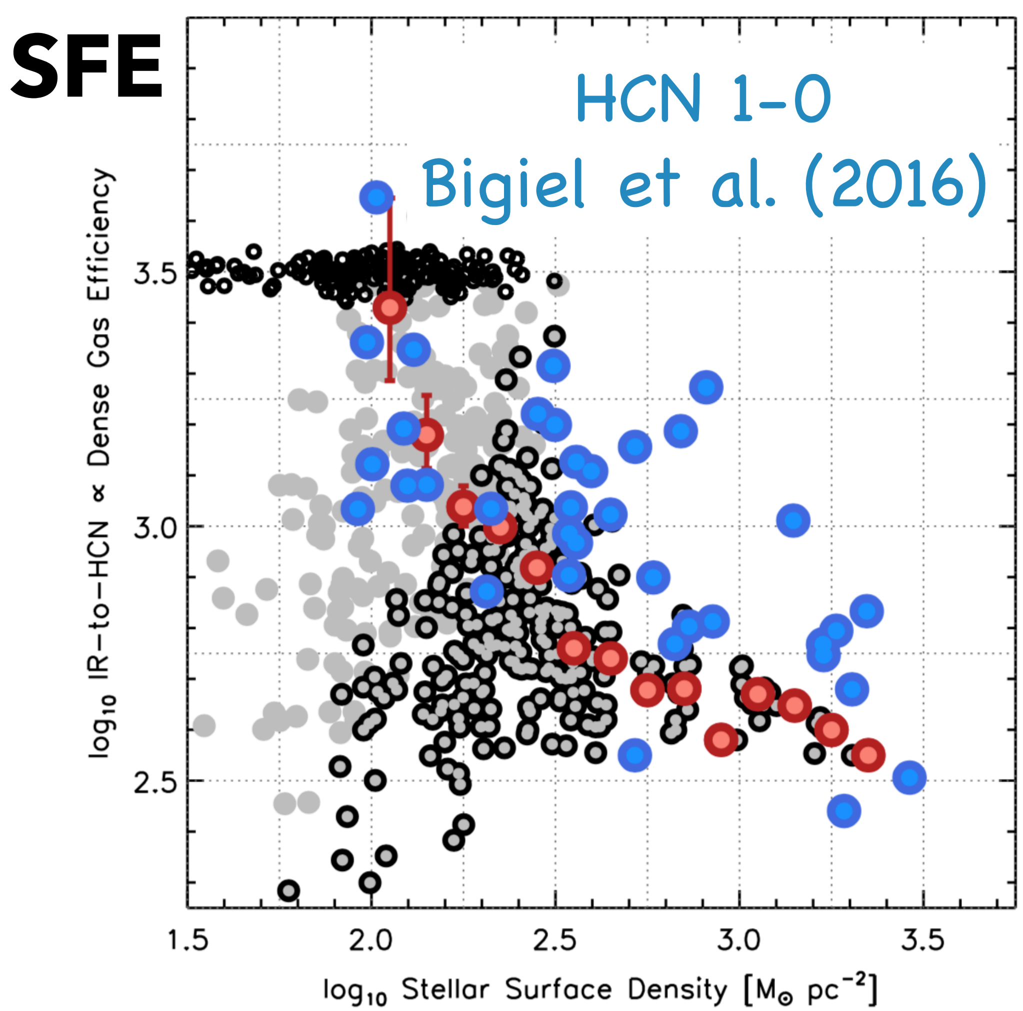
RESULTS (3) NGC 253

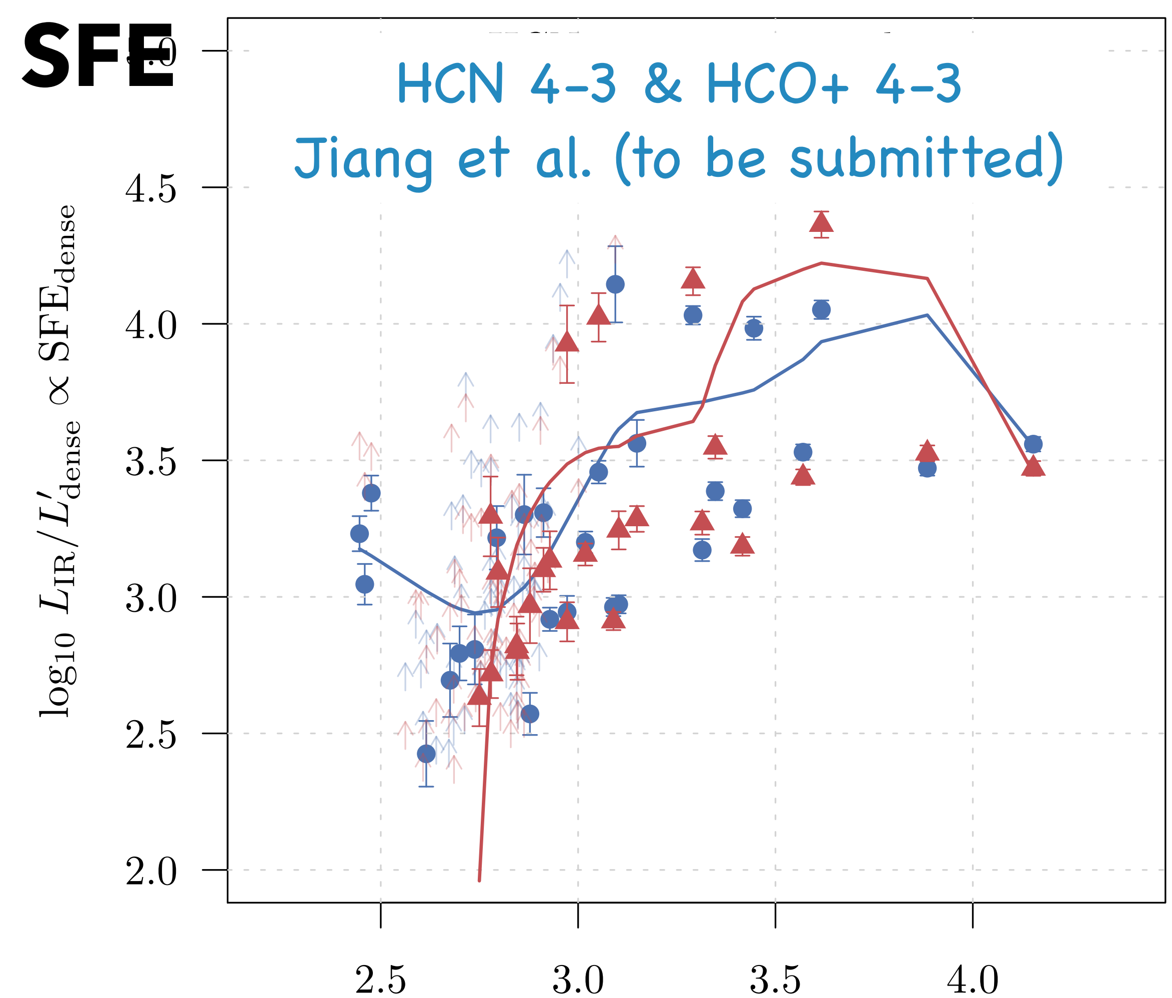
relation to stellar feedback?

for different transitions, stellar feedback has different effect?

(Usero et al. 2015, Bigiel et al. 2016, Gallagher et al. 2018a)

similar discussion in the CMZ (Central Molecular Zone):
Kauffmann et al. 2013, 2017; Kruijssen et al. 2014; Rathborne et al. 2015)





stellar surface density

FOLLOW-UP PLAN

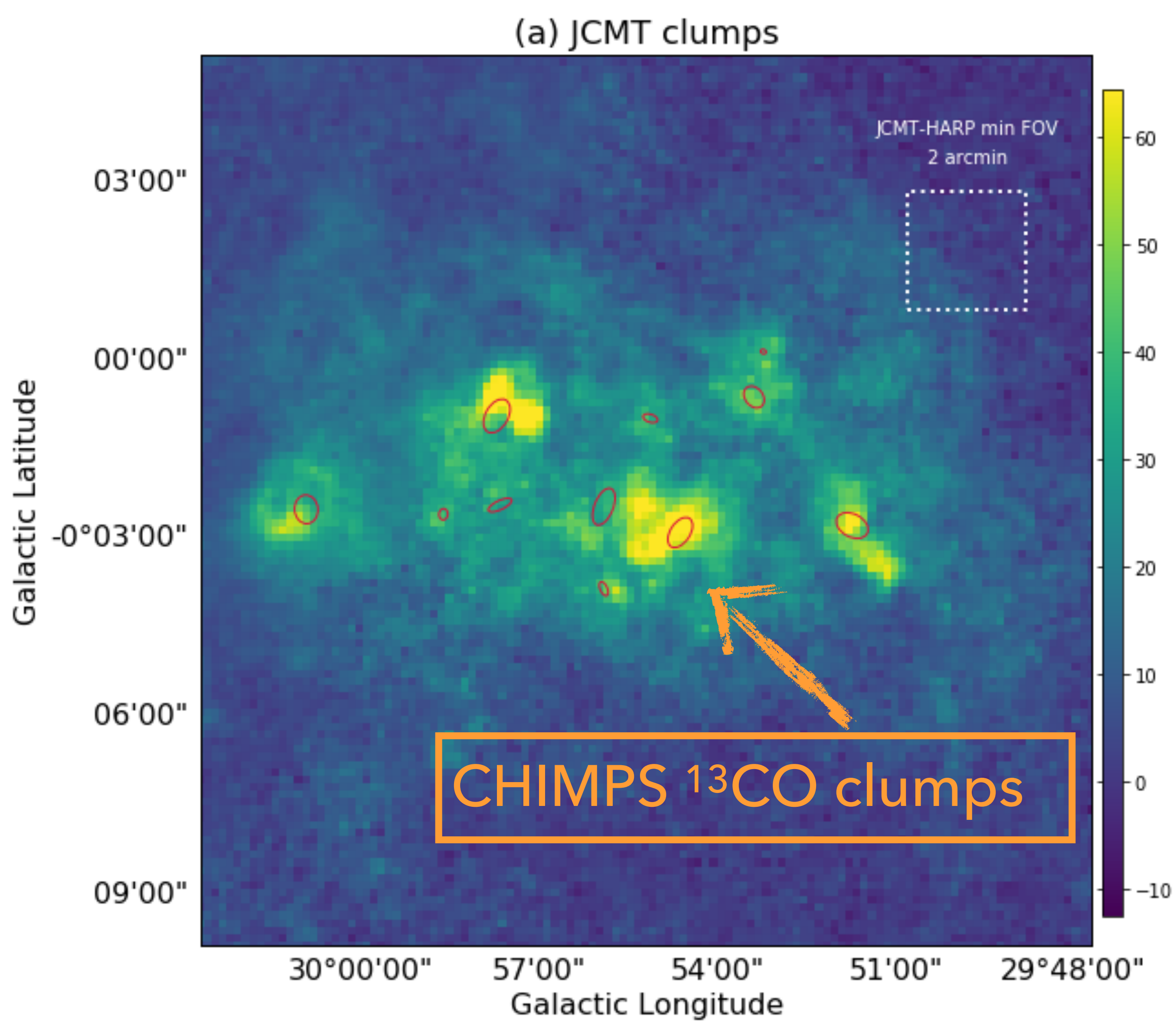
HCN & HCO+ (3–2), AND LARGER SAMPLE

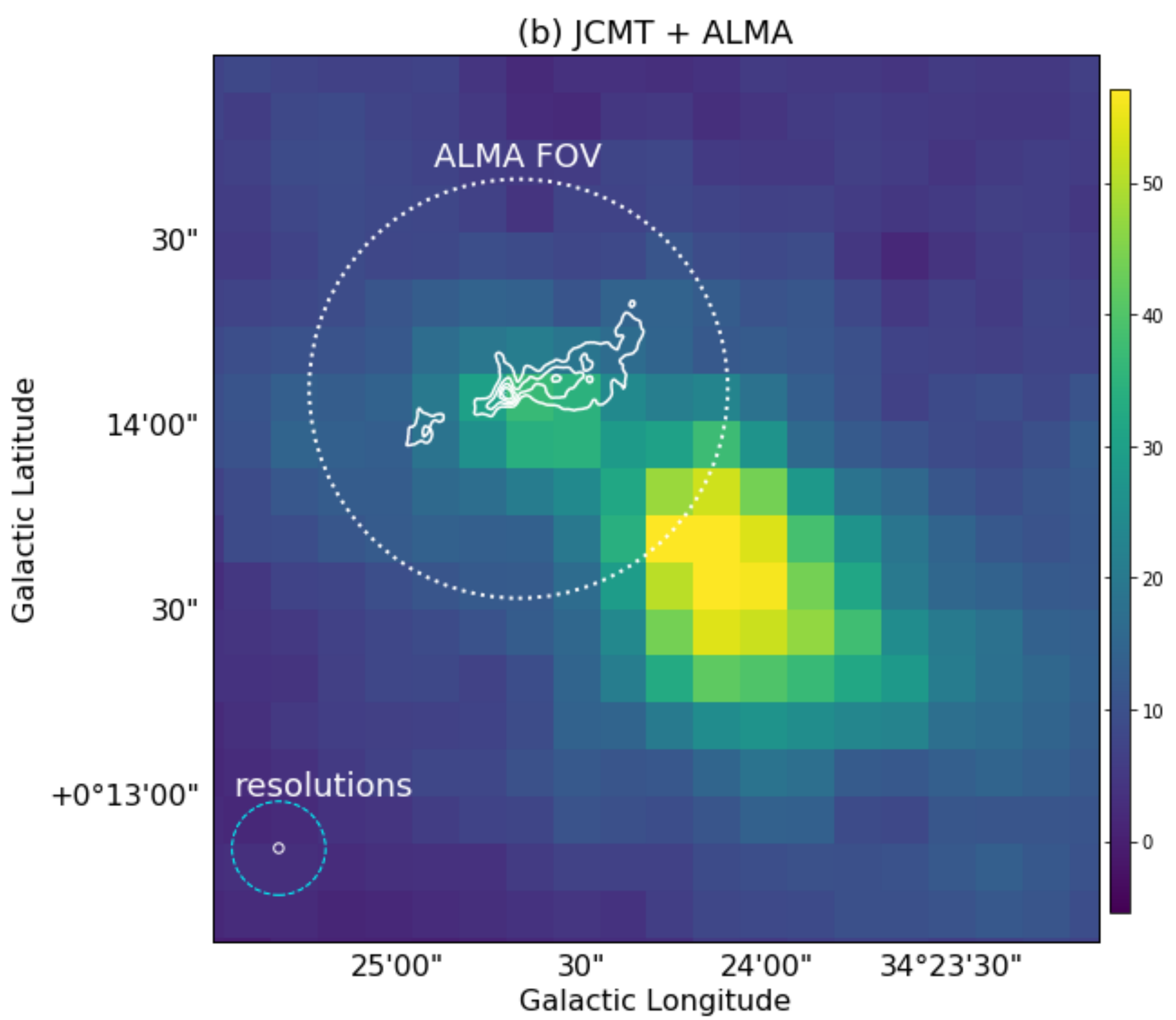
- multi-*J* will better constraint SF properties
- new JCMT observations: M16AP028: 38 hrs; M19AP004: 50 hrs Scuba2 data (M16BP098)
- many available in archive →
- ALMA archive can enlarge the sample to southern sky

N	Name	RA J2000	DEC J2000	HCN 3-2 archive	HCO+ 3-2 archive
1	NGC 1808	05 07 42.3	−37 30 47	no	no
2	NGC 3521	11 05 48.6	−00 02 09	no	no
3	NGC 4631	12 42 08.0	32 32 29	no	no
4	NGC 4736	12 50 53.0	41 07 14	no	no
5	NGC 5457	14 03 12.5	54 20 56	no	no
6	M51	13 29 52.7	47 11 43	no	no
7	NGC 2146	06 18 37.7	78 21 25	yes	no
8	NGC 3628	11 20 17.0	13 35 23	yes	no
9	NGC 253	00 47 33.1	−25 17 18	yes	yes
10	NGC 660	01 43 02.4	13 38 42	yes	yes
11	NGC 891	02 22 33.4	42 20 57	yes	yes
12	Maffei 2	02 41 55.0	59 36 15	yes	yes
13	NGC 1068	02 42 40.7	−00 00 48	yes	yes
14	IC 342	03 46 48.5	68 05 47	yes	yes
15	NGC 2903	09 32 10.1	21 30 03	yes	yes
16	M82	09 55 52.7	69 40 46	yes	yes
17	NGC 3079	10 01 57.8	55 40 47	yes	yes
18	NGC 3627	11 20 14.9	12 59 30	yes	yes
19	Arp 299	11 28 30.4	58 34 10	yes	yes
20	M83	13 37 00.9	−29 51 56	yes	yes
21	NGC 6946	20 34 52.3	60 09 14	yes	yes

FOLLOW-UP POTENTIALS:
CONNECT GALACTIC AND EXTRAGALACTIC STUDIES

- the large FOV of JCMT and the high resolution of ALMA (or SMA) are great complement to each other



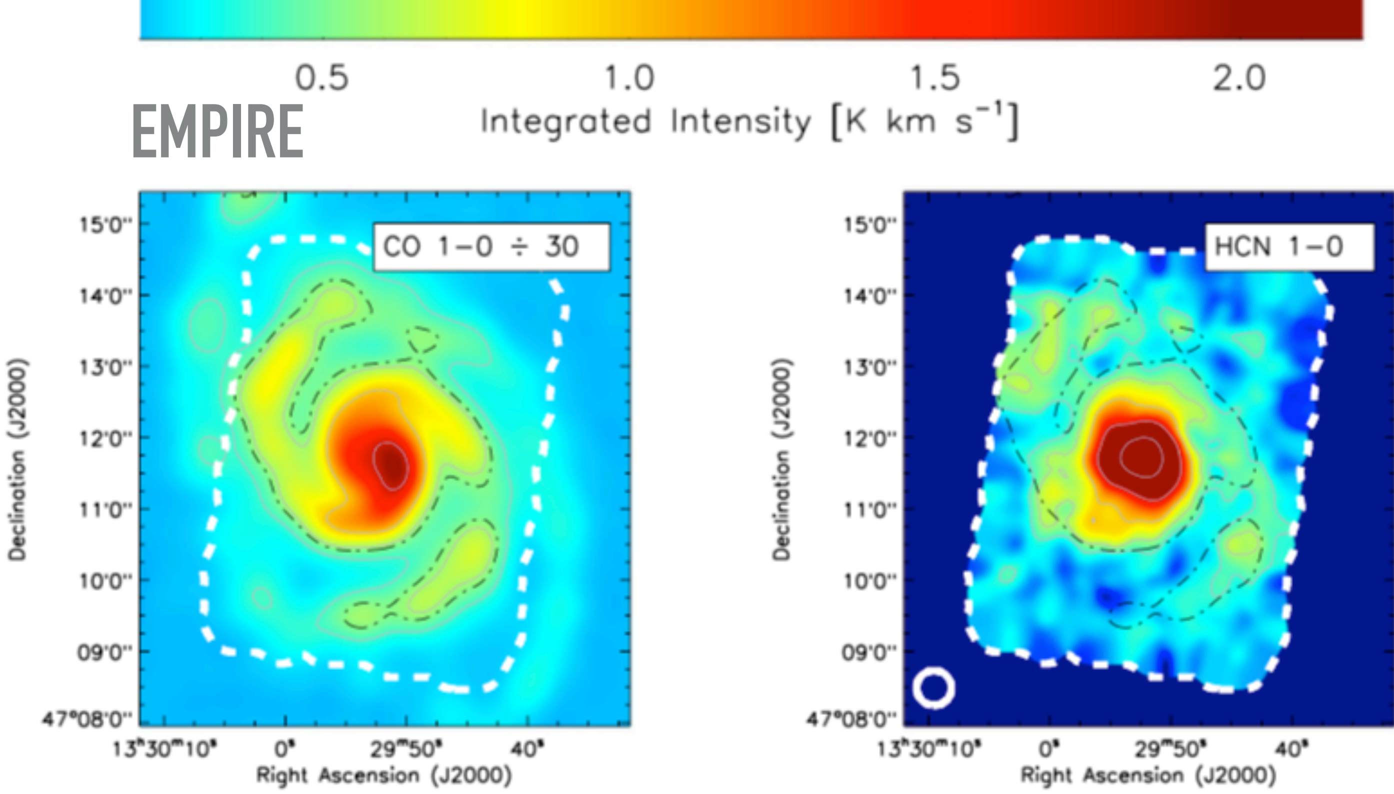


RESEARCH SUMMARY

- MALATANG focuses on sub-kpc scale
- Exploring the effect of stellar feedback.

DEMANDS (DREAMS)

EXAMPLES

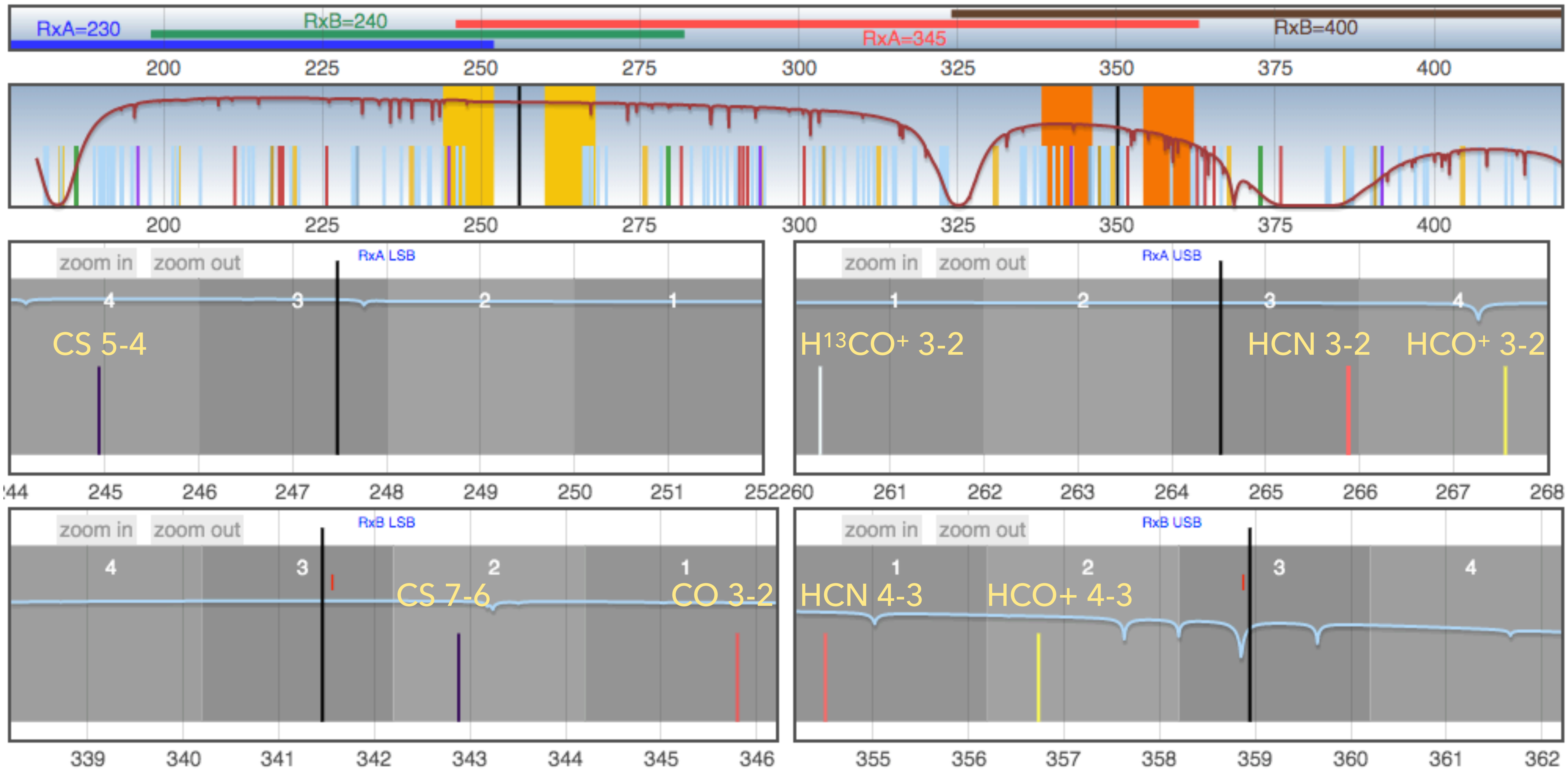


- M51: EMPIRE (30m, Bigiel et al. 2016)
  89 GHz, 75h, RMS: ~15 mJy, 4'x6'
- NGC253: (MALATANG – JCMT)
  354 GHz, 20 h, RMS: ~ 100 mJy, 2'x2' covered
- NGC253: ALMA (16 antennas)
  100 GHz,, 3-point and 7-point mosaic, 1.5' covered (Meier+ 2015, Leroy+ 2015)
- NGC1068 ALMA (18 – 27 antennas)
  2h, 11-field mosaic in band 7 and 1-point in band 9 (García-Burillo+ 2014, Viti+2014)
- ULIRGs (45 antennas)
  z=0.05 ~ 0.15 (HCN 3-2, 1 mJy, Imanishi et al. 2019)

HIGH SENSITIVITY AND RESOLUTION !

WIDE BAND !

- **wide band !**
  higher SNR,
  higher efficiency
  more accurate line ratios
- many physical/chemical properties embedded
  isotopes, shocks, temperatures …
  (Zhang et al. 2018, nature)



similar upgrade for JCMT as the SMA?

DATA ARCHIVE

- data growing faster than community
- “data mining” more challenging
- need data center in China?

SUMMARY OF DREAMS

- Wide band (and stable baseline)
- high sensitivity (large dish)
- large FOV (heterodyne array)
- urgent need of fast archive access