(Dense) Molecular Gas & Star Formation in Galaxies

— Results From JCMT Large Program MALATANG

Xue-Jian JIANG (蒋雪健)

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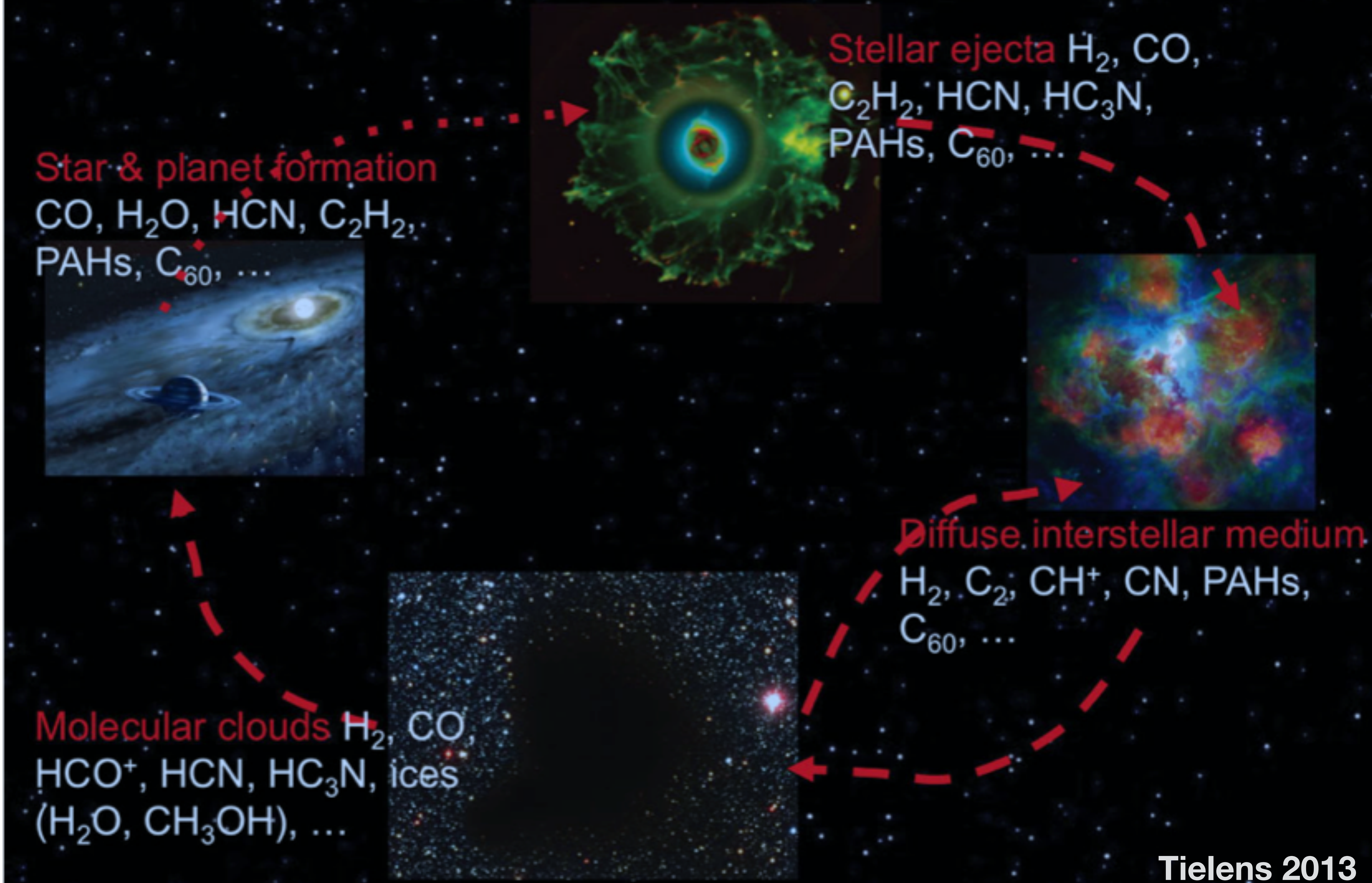
Molecules in the Lifecycle of the ISM



Stellar ejecta H_2, CO, C_2H_2, HCN, HC_3N, PAHs, C_{60}, …

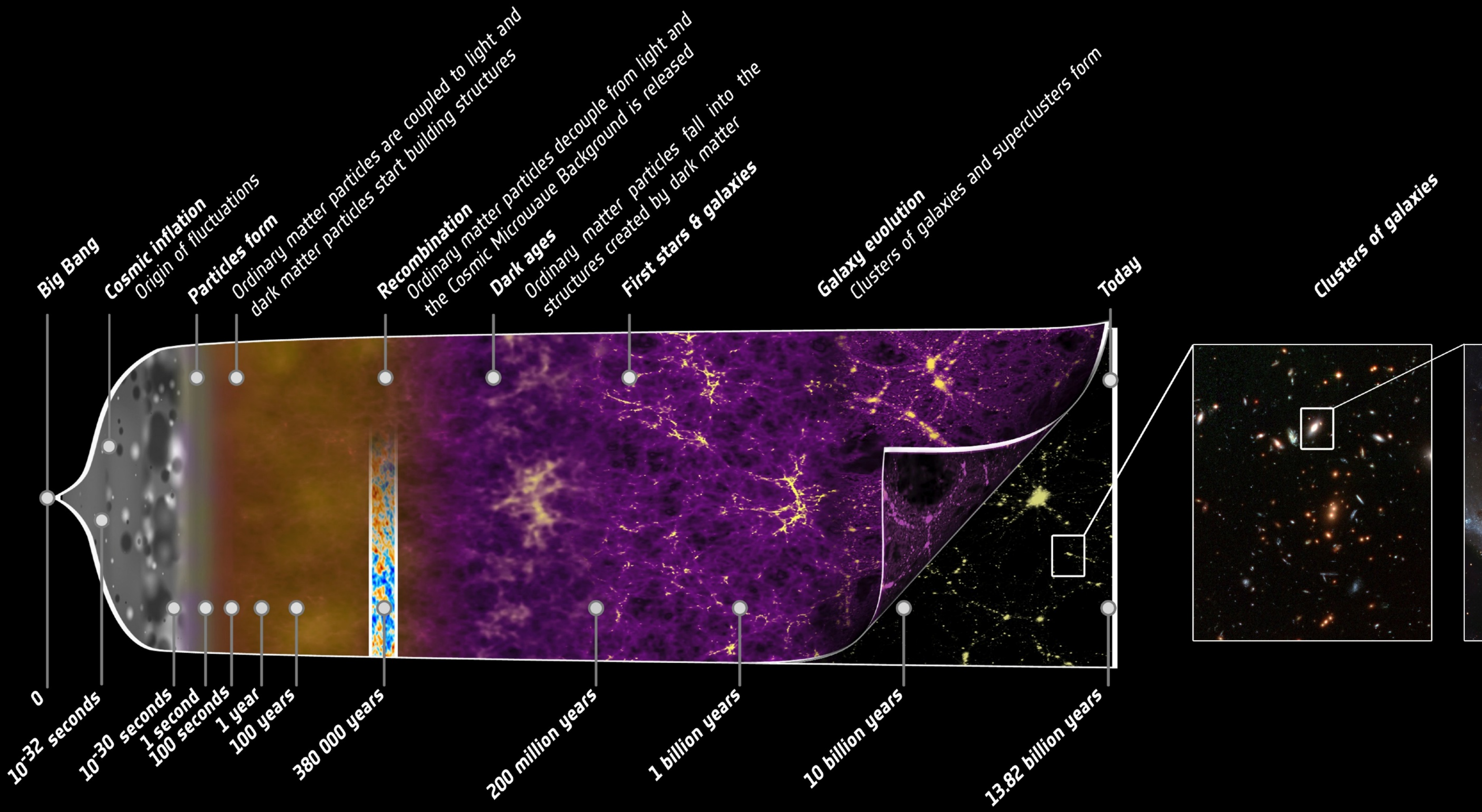
Diffuse interstellar medium H_2, C_2, CH^+, CN, PAHs, C_{60}, …

Molecular clouds H_2, CO, HCO^+, HCN, HC_3N, ices (H_2O, CH_3OH), …

Star & planet formation CO, H_2O, HCN, C_2H_2, PAHs, C_{60}, …

Tielens 2013

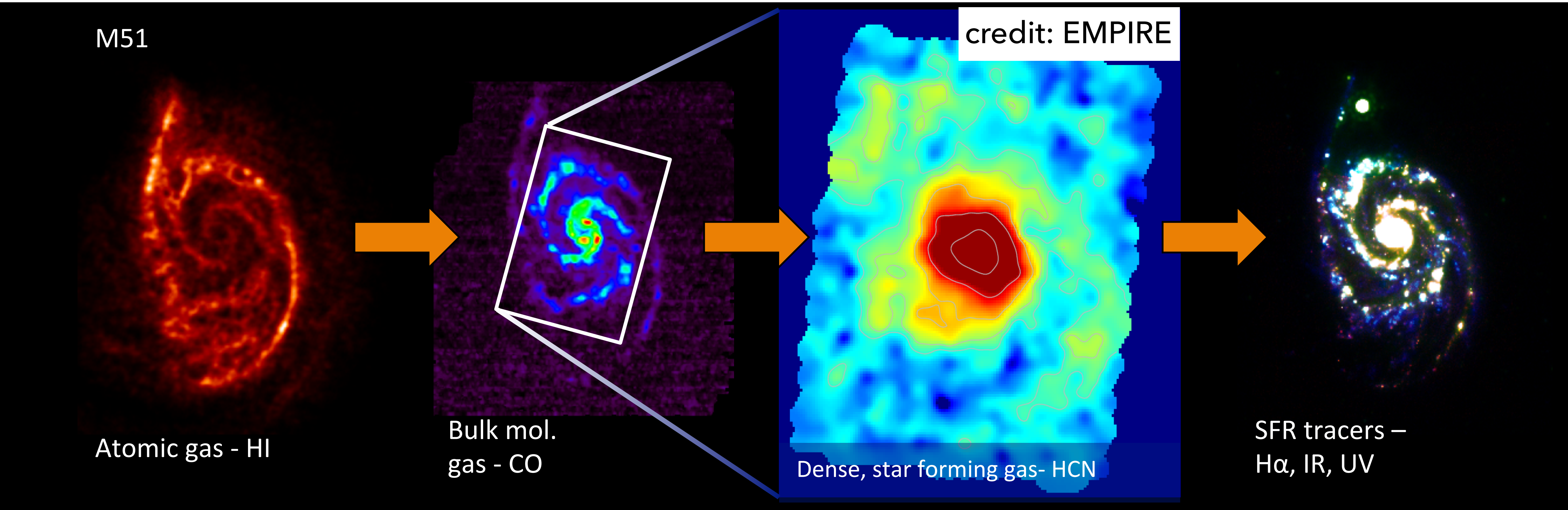
History of Galaxy evolution and star formation



credit: ESA - C. Carreau

Outline

- Molecular gas and Star Formation
- Dense molecular gas – Direct tracer of SF gas
- Recent studies
  - JCMT large program MALATANG
  - MALATANG-II
  - U'u' observations



M51

Atomic gas - HI

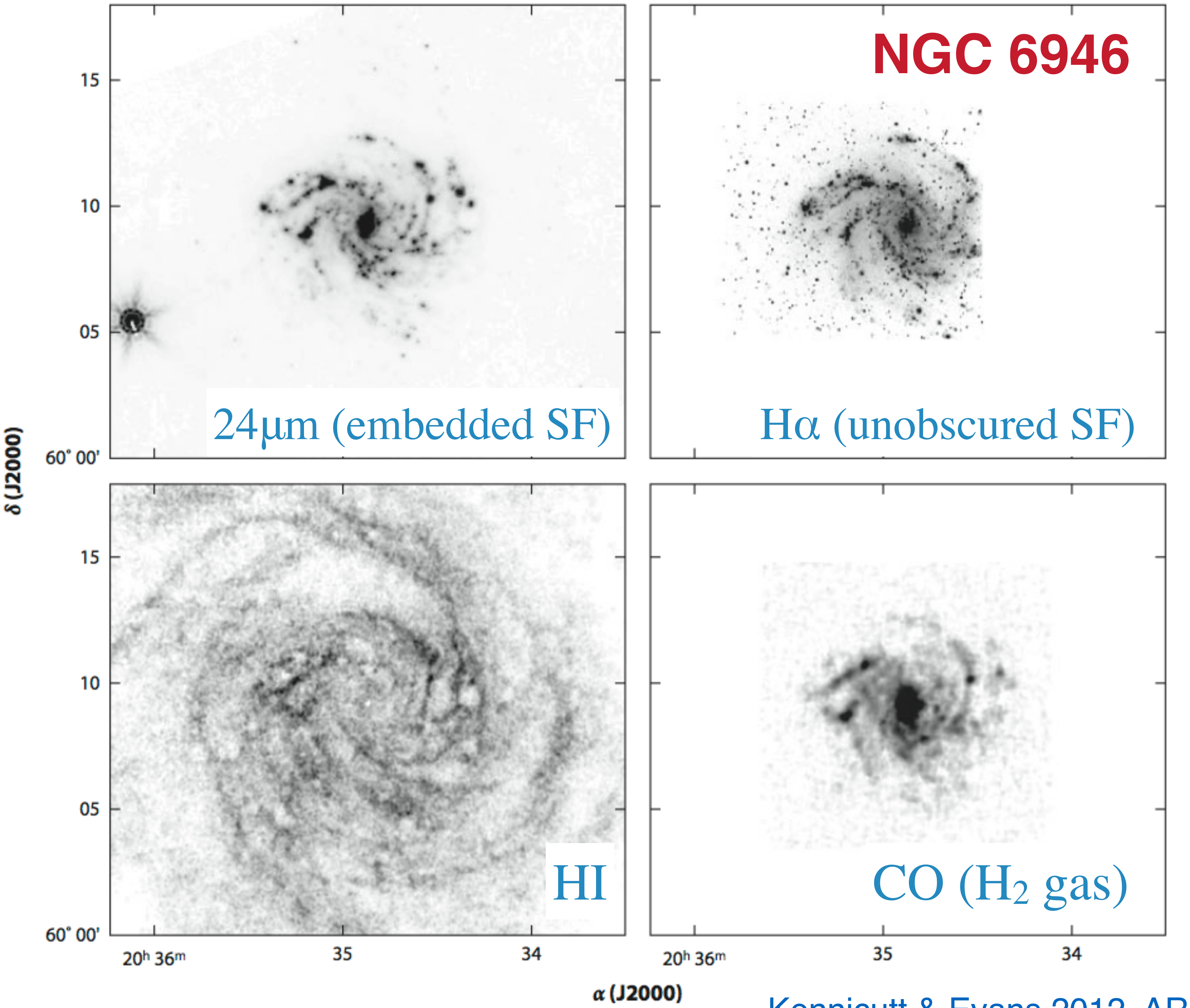
Bulk mol. gas - CO

Dense, star forming gas- HCN

SFR tracers – Hα, IR, UV

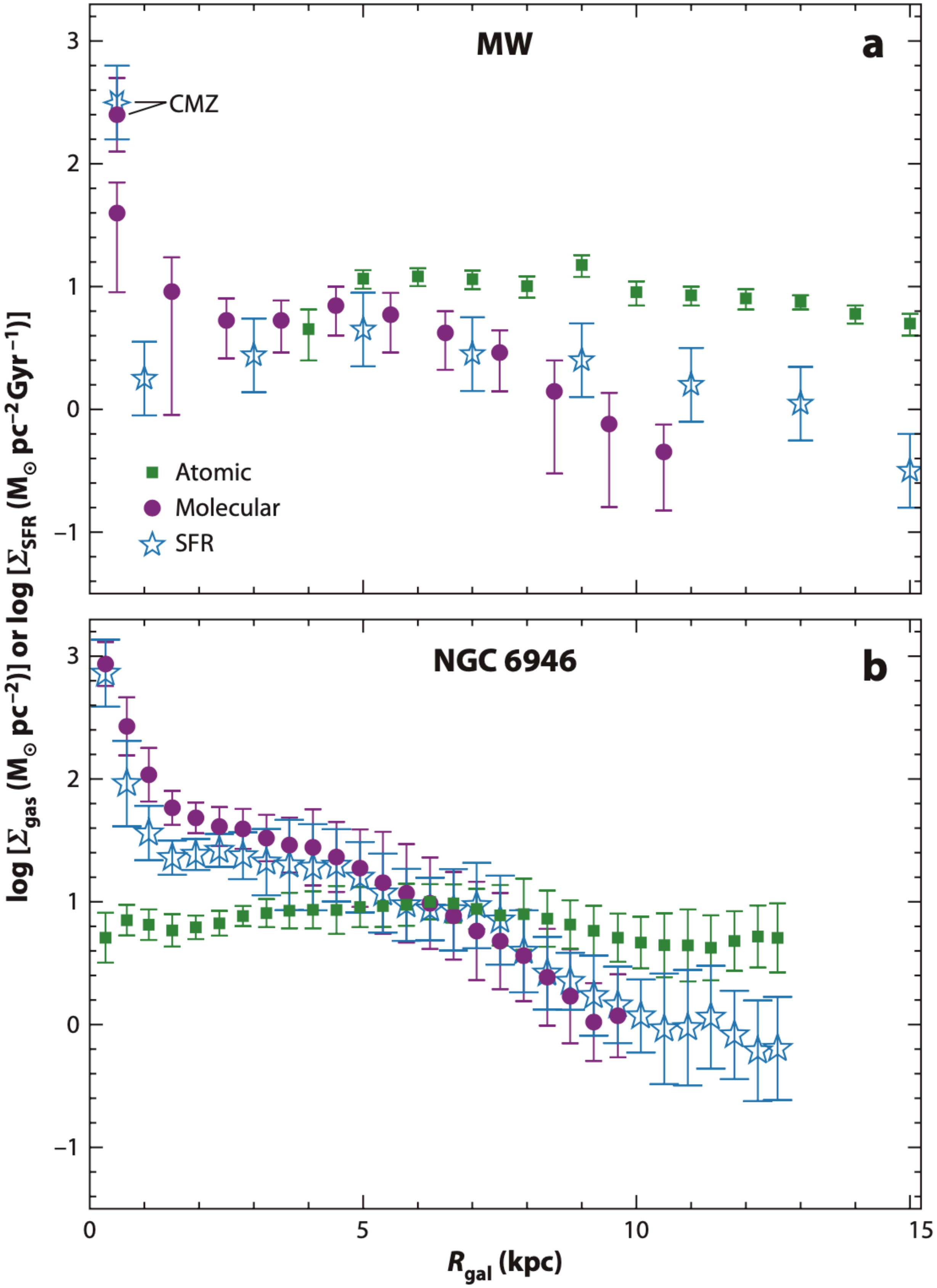
credit: EMPIRE

different phases of ISM

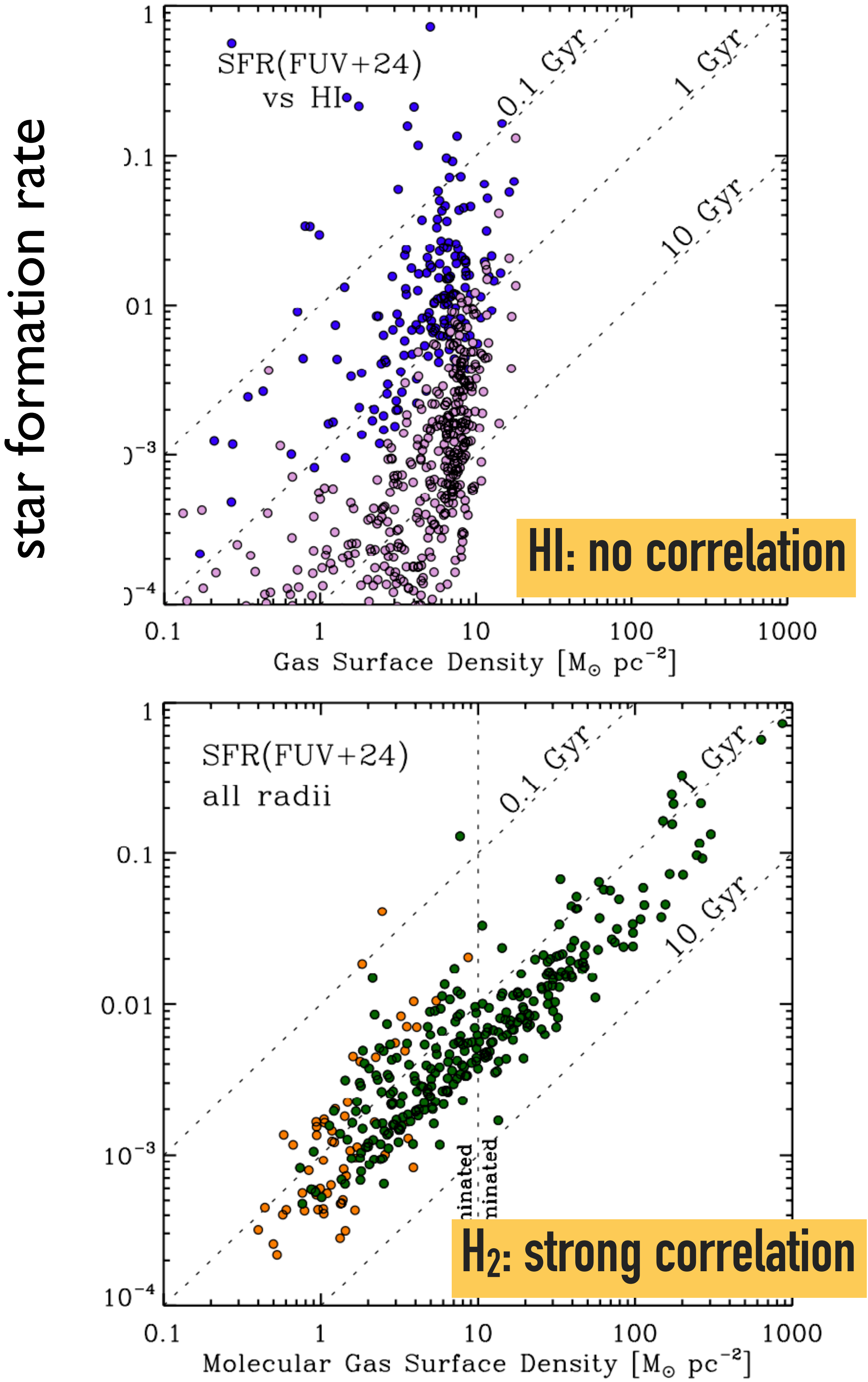


Kennicutt & Evans 2012, ARAA

HI → H$_2$



Kennicutt & Evans 2012

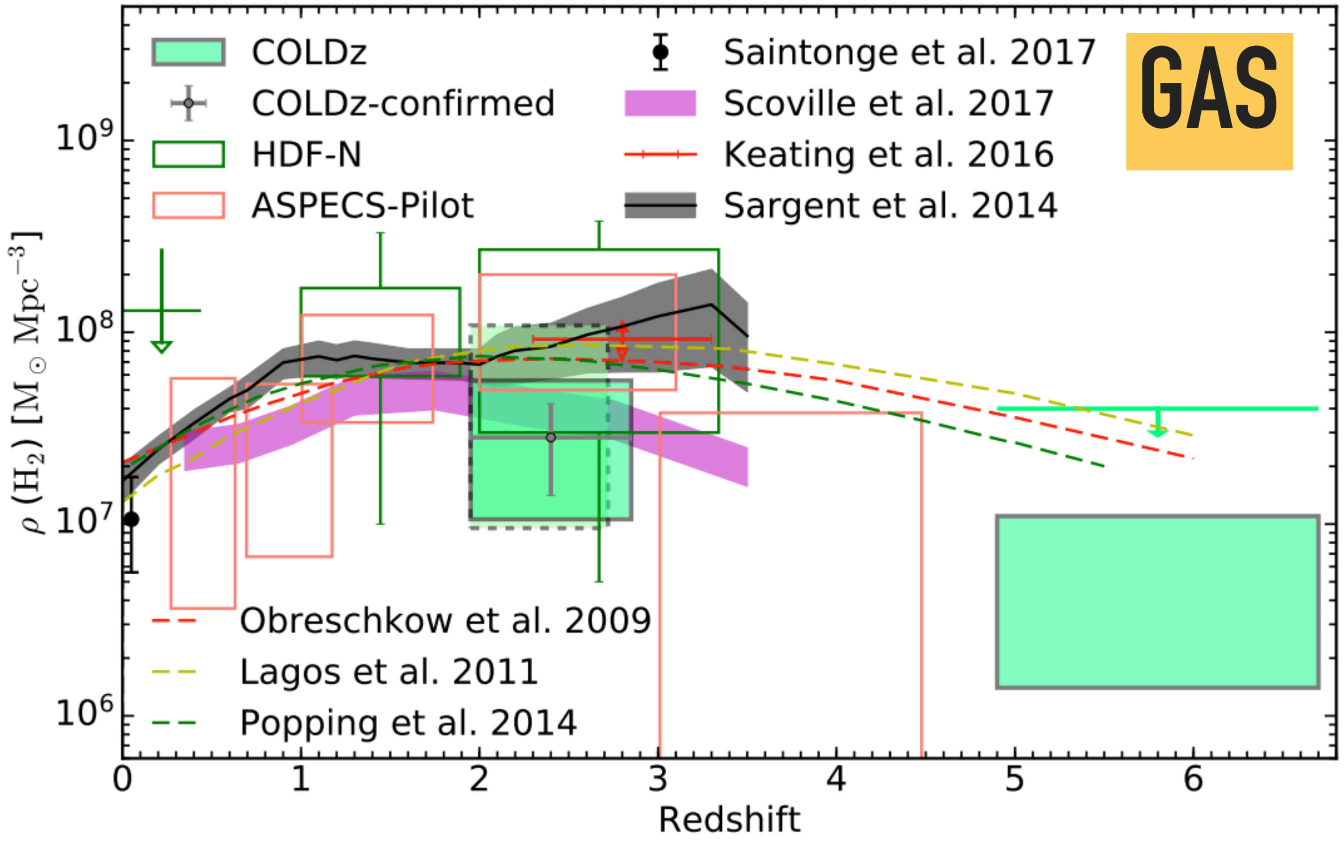


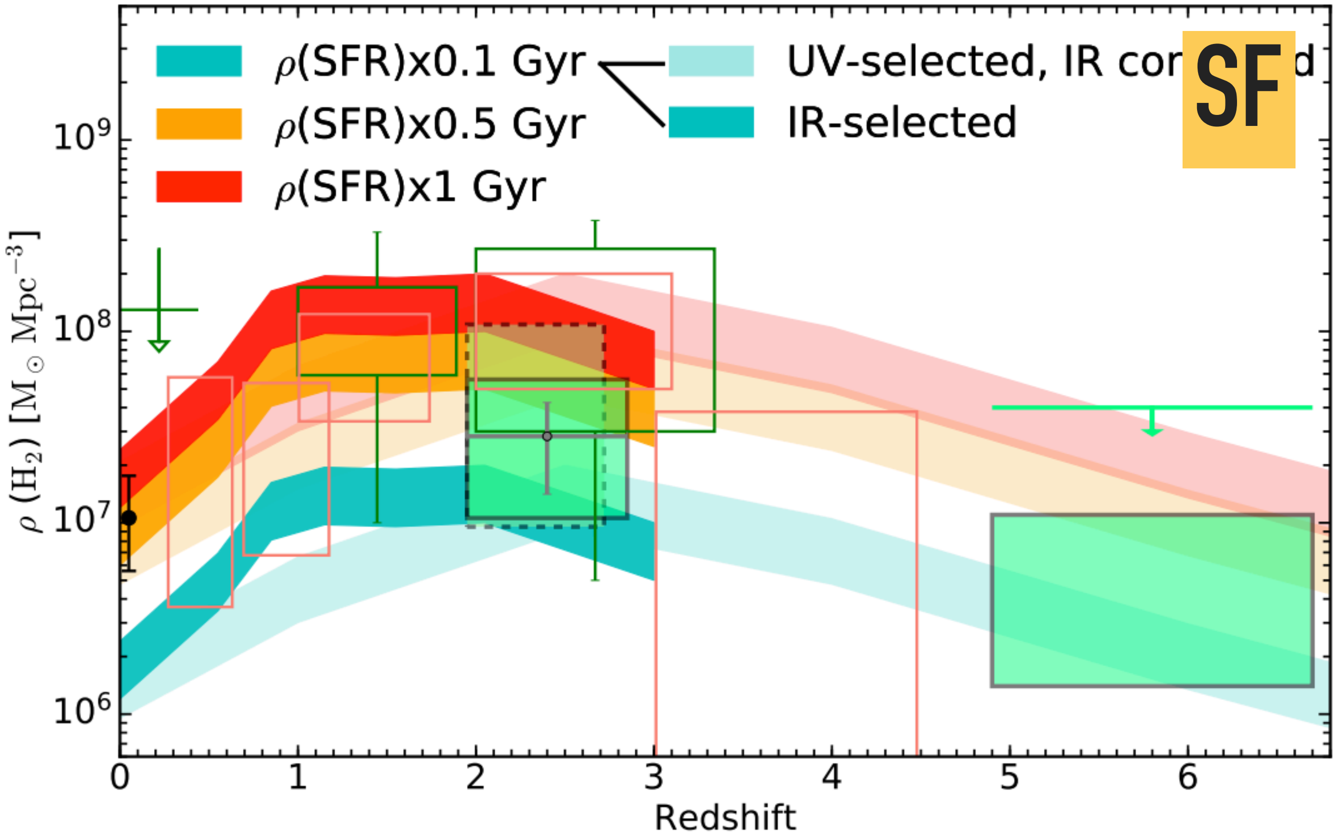
HI: no correlation

H$_2$: strong correlation

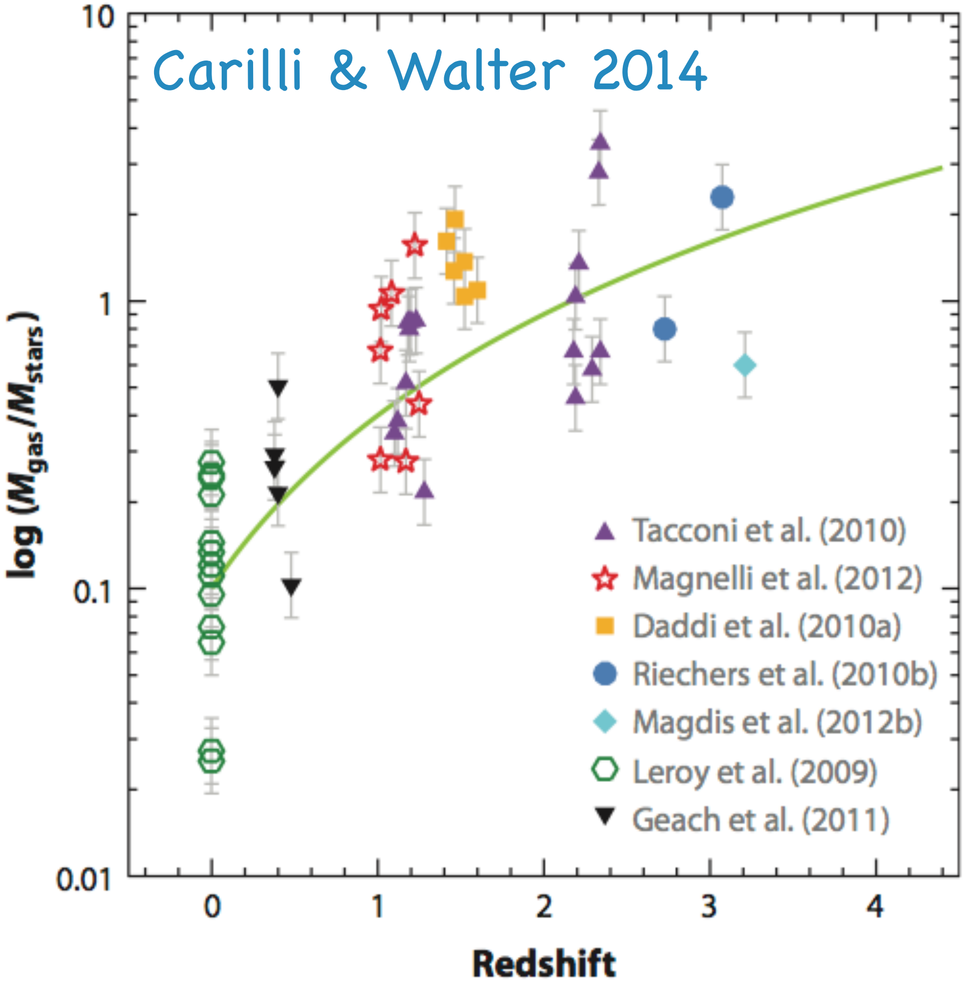
Schruba et al. 2011

Molecular gas drives cosmic star formation





Riechers+ 2019; Bouwens+ 2016;
Madau & Dickinson 2014; Magnelli+ 2013

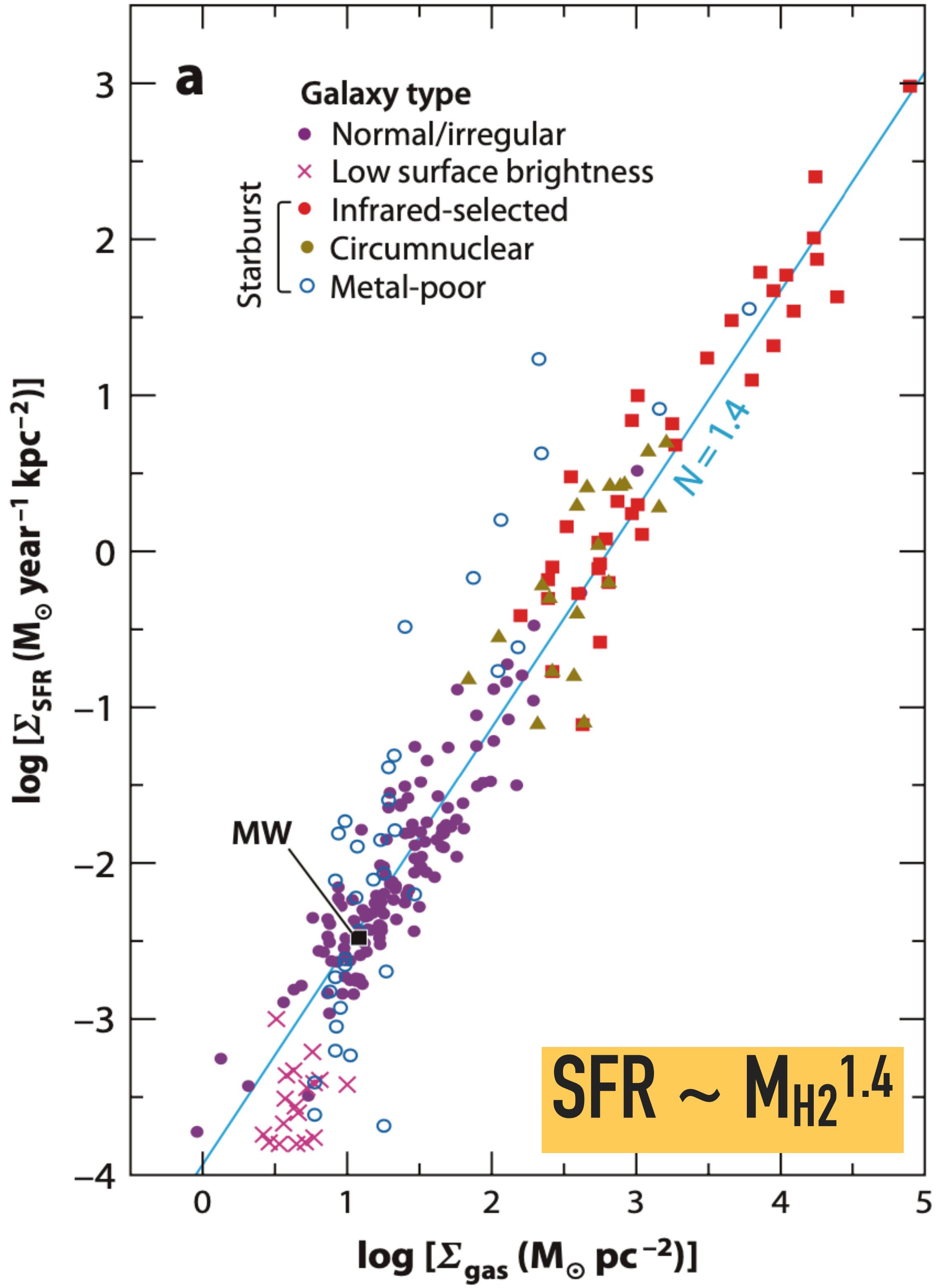


SF galaxy populations ~10 billion years ago were significantly more gas-rich compared to the present day.

the SF history follows the evolution of the molecular gas supply in galaxies.

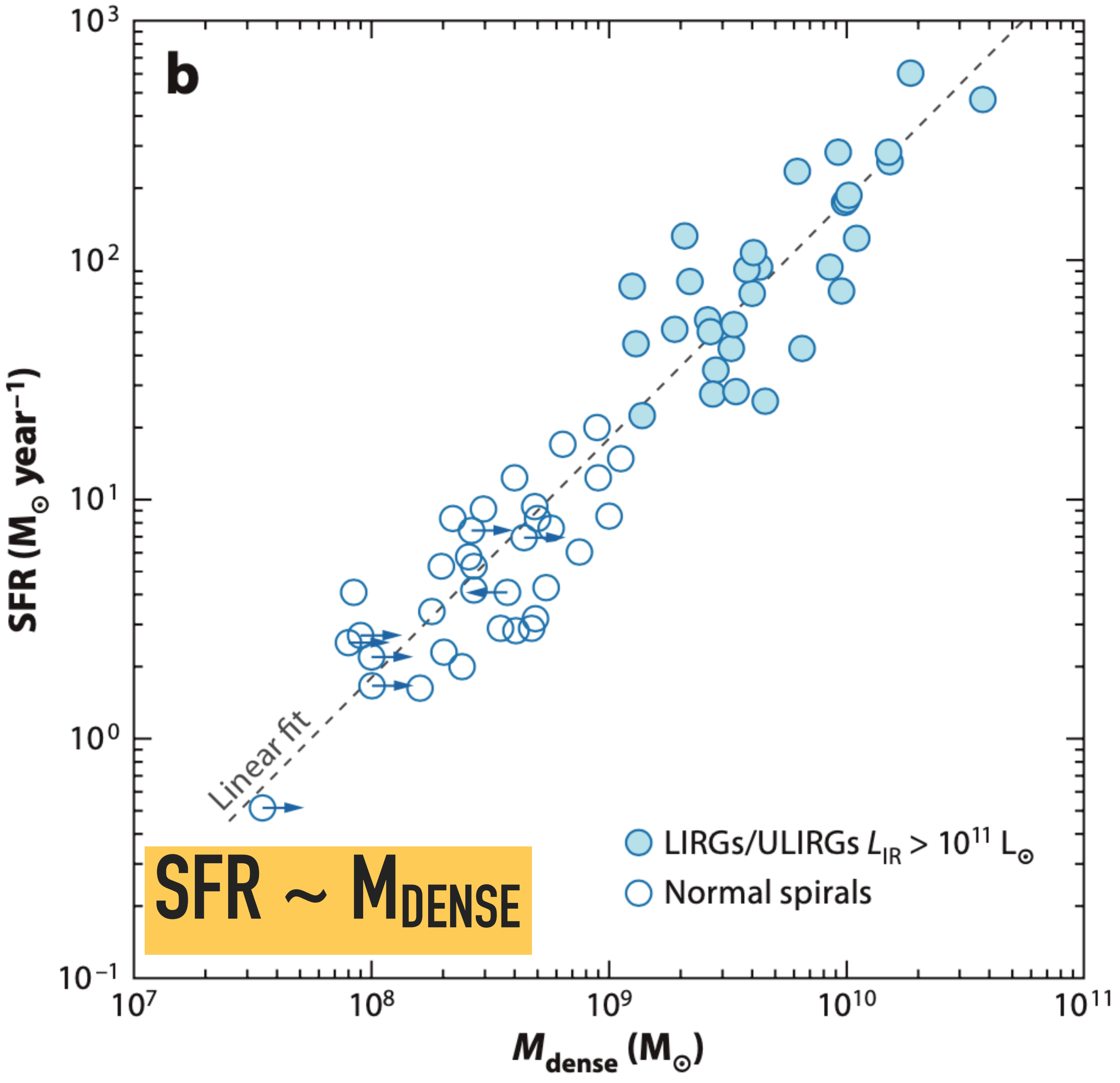
1. the SF history follows the evolution of the molecular gas supply in galaxies.

Star Formation “laws”



$SFR \sim M_{H2}^{1.4}$

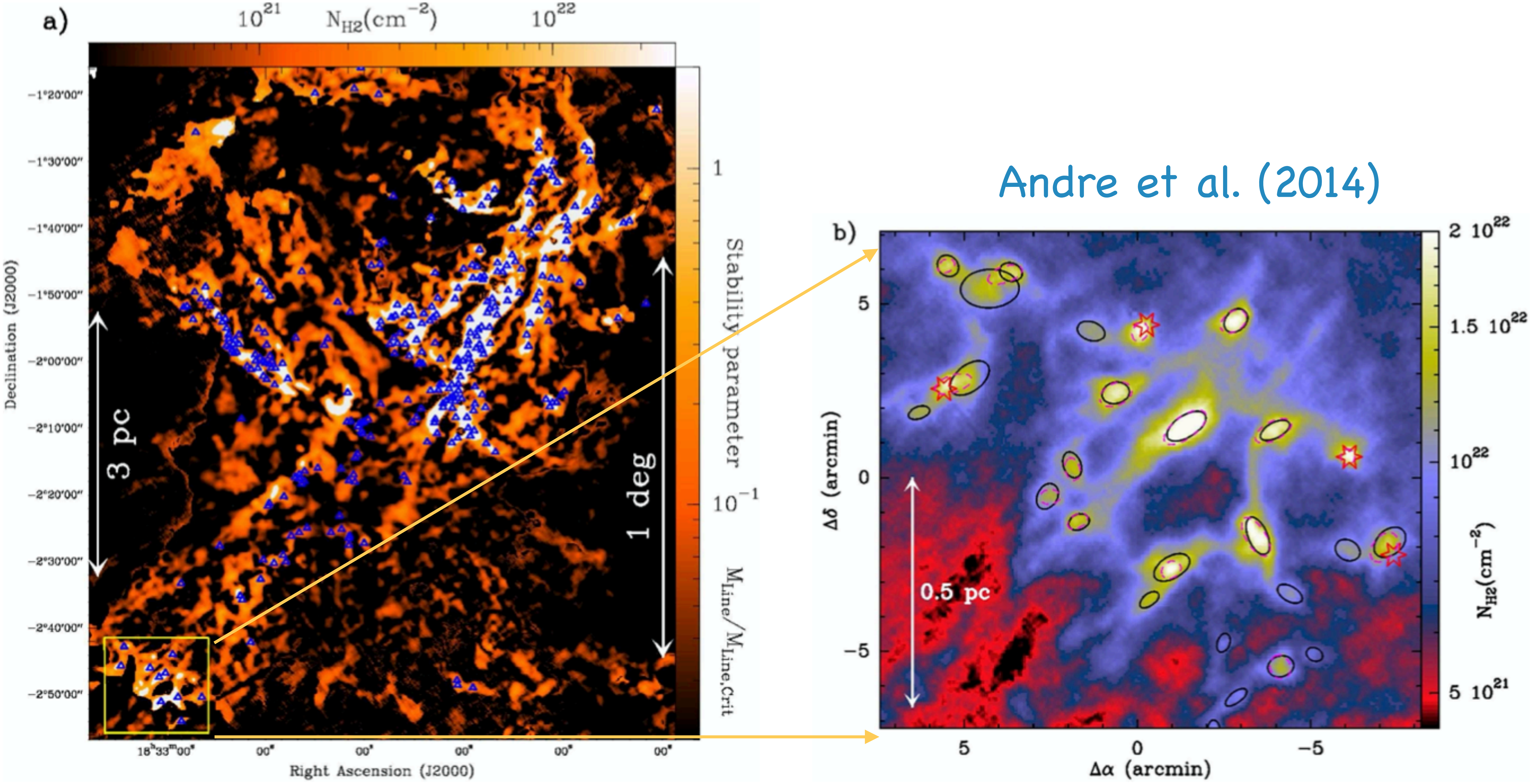
Kennicutt & Evans 2012



$SFR \sim M_{DENSE}$

Gao & Solomon 2004a,b

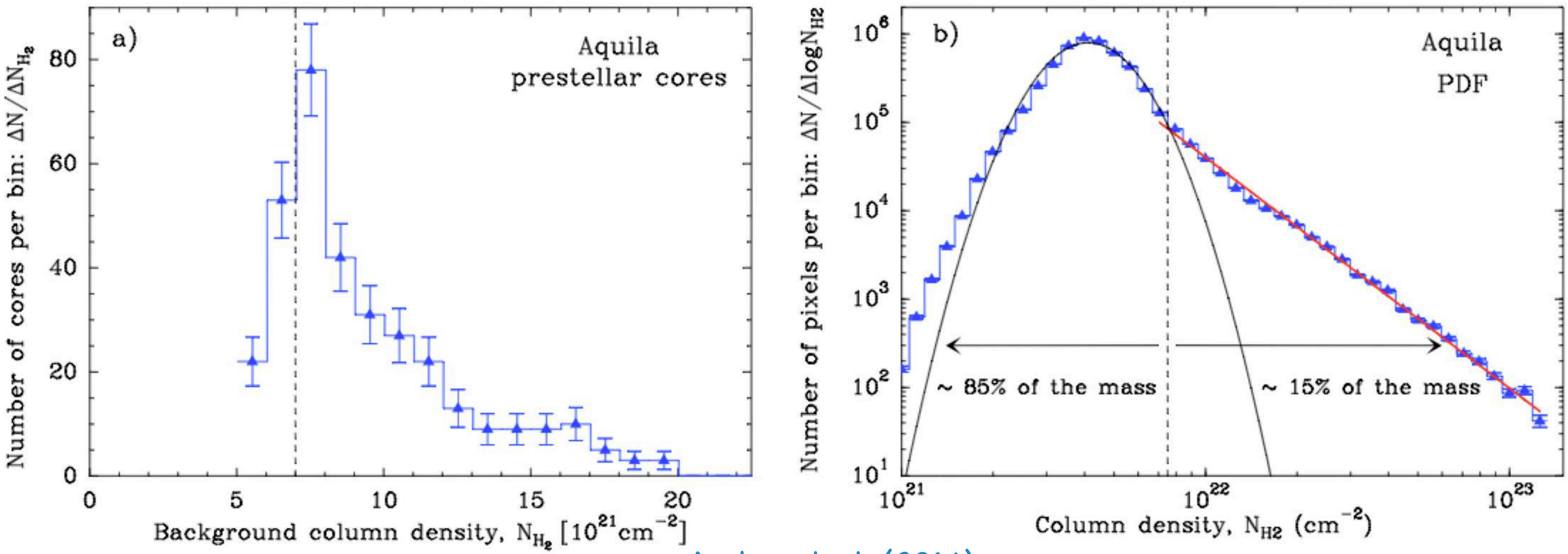
NOT any molecular gas . . .



Andre et al. (2014)

- prestellar and protostellar cores are closely related to high density regions.

new stars formed in high density regions

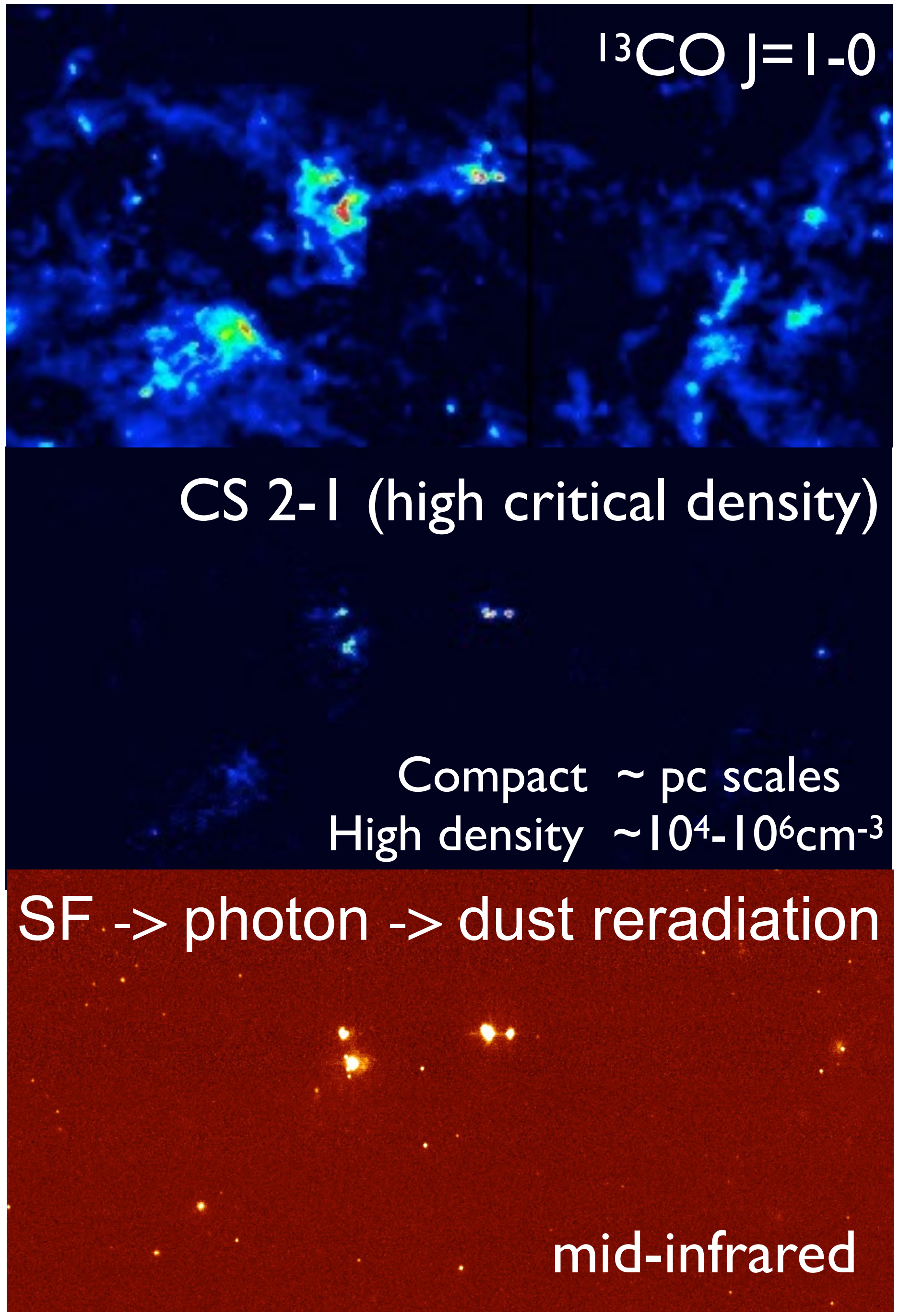


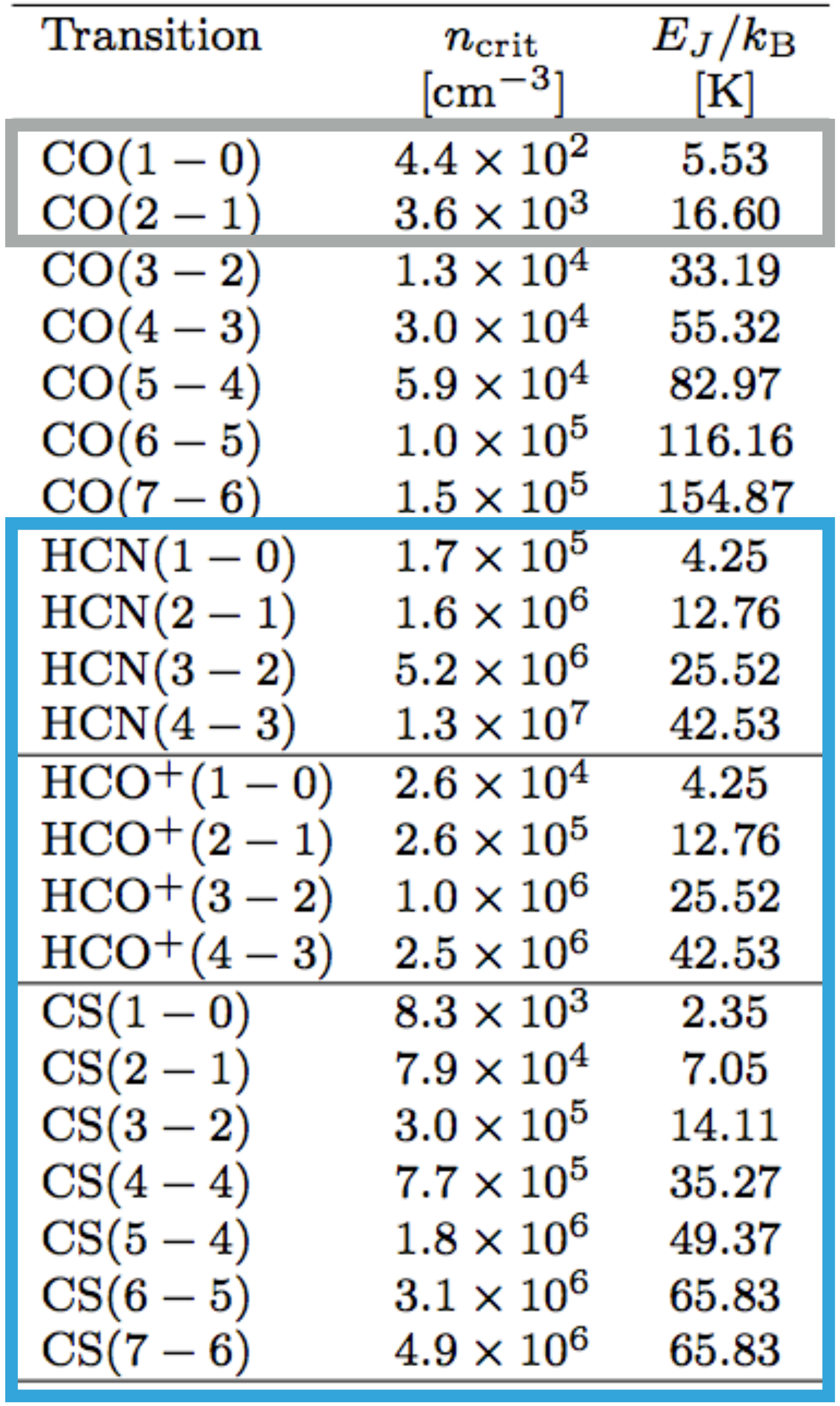
Andre et al. (2014)

- **90%** cores in dense regions
- only a small fraction of the total gas mass (~**15%** in the case of Aquila) is above the column density threshold.
- only filaments with $M_{\mathrm{line}} > M_{\mathrm{line,crit}}$ are able to fragment into self-gravitating cores. (N_{H2} threshold ~ 7 x 10^{21} cm^{-2}, or a number density $\boldsymbol{n_{\mathrm{H2}}}$ ~ **2×10^4 cm^{-3}**)

Motivation: ISM & Star-formation

tracing dense gas —— the direct fuel of SF



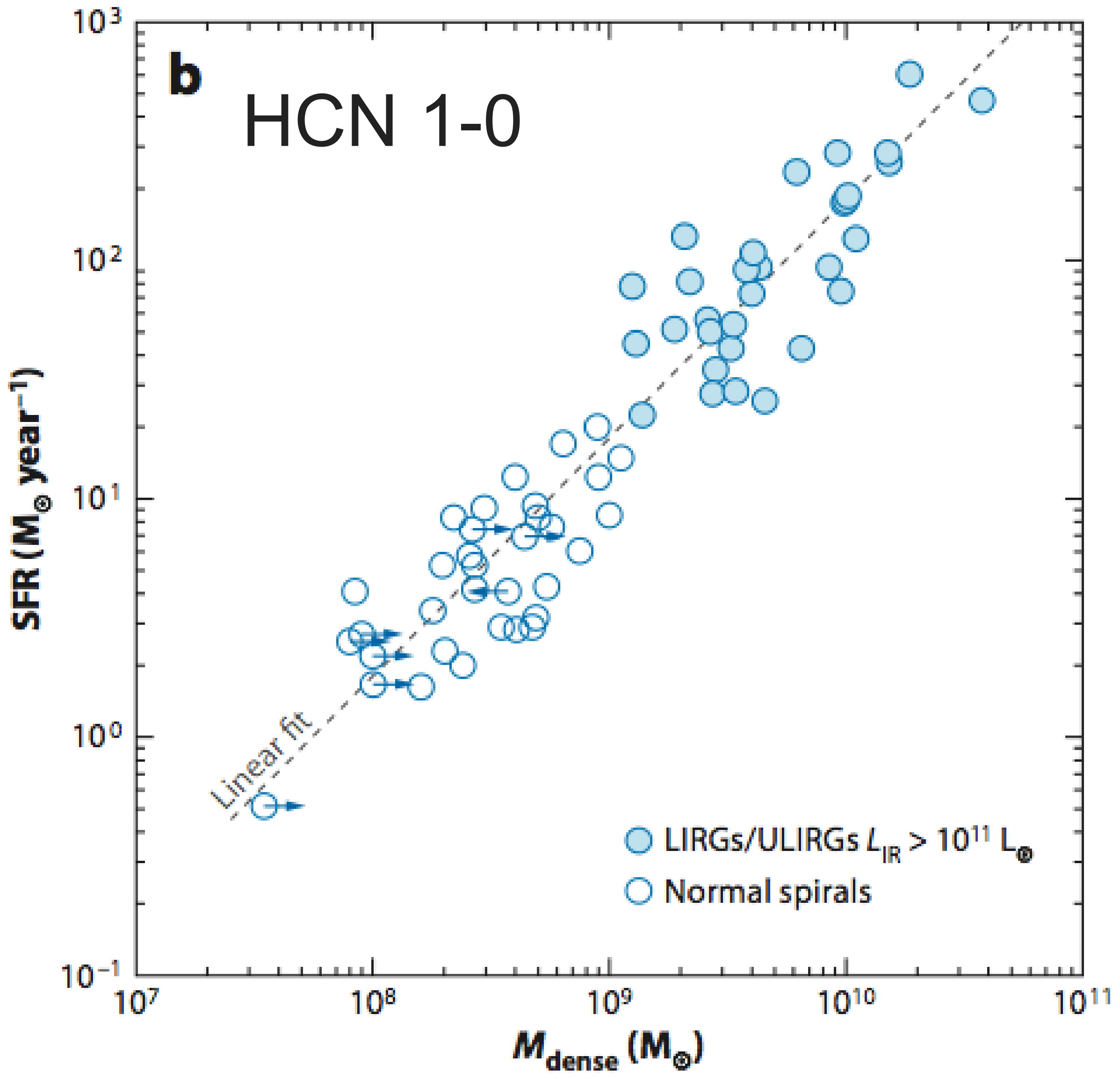


Transition	$n_{\rm crit}$ [cm^{-3}]	$E_J/k_{\rm B}$ [K]
CO(1 – 0)	4.4×10^2	5.53
CO(2 – 1)	3.6×10^3	16.60
CO(3 – 2)	1.3×10^4	33.19
CO(4 – 3)	3.0×10^4	55.32
CO(5 – 4)	5.9×10^4	82.97
CO(6 – 5)	1.0×10^5	116.16
CO(7 – 6)	1.5×10^5	154.87
HCN(1 – 0)	1.7×10^5	4.25
HCN(2 – 1)	1.6×10^6	12.76
HCN(3 – 2)	5.2×10^6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

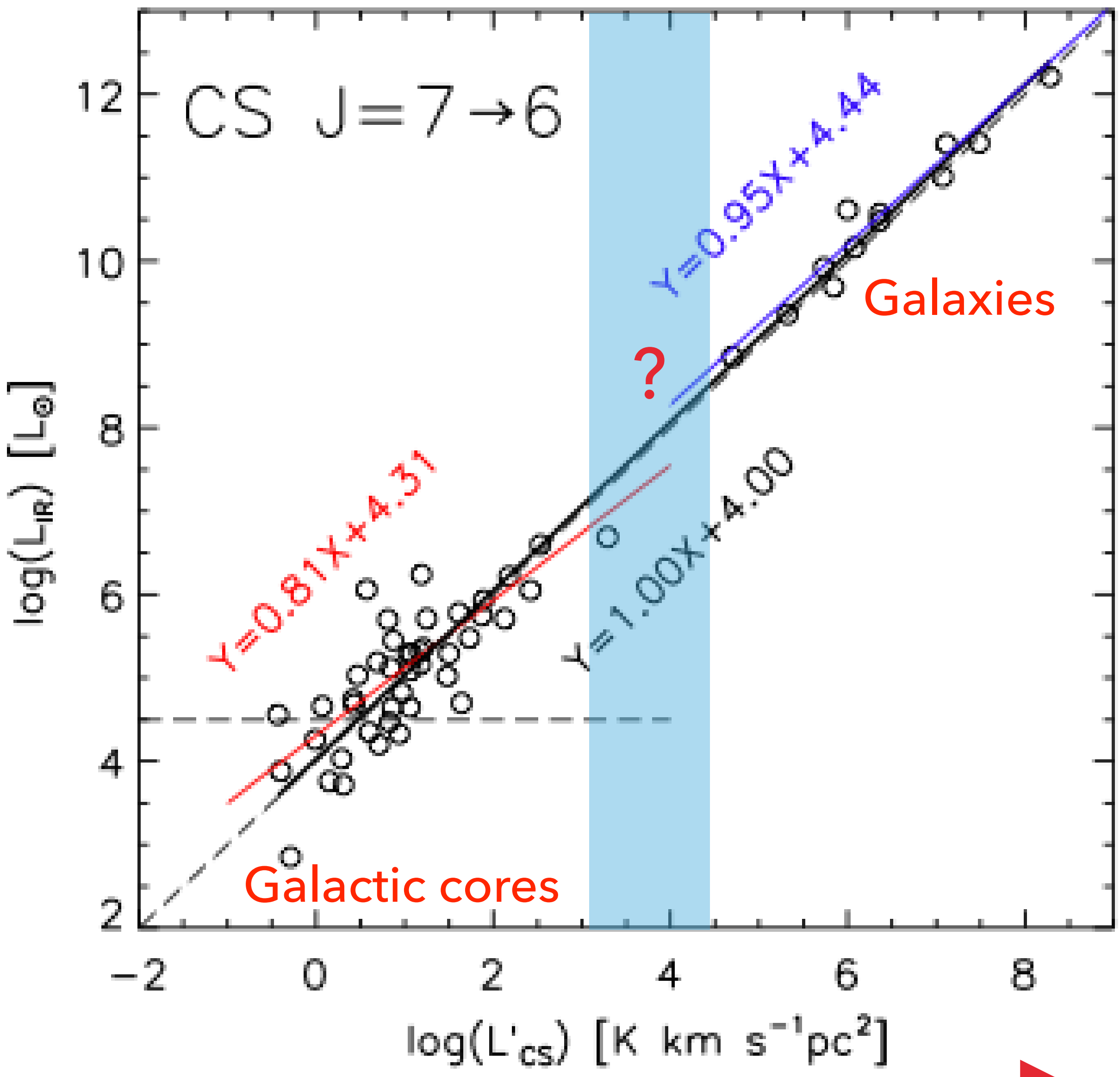
Star Formation relations

SFR

Gao & Solomon 2004a,b



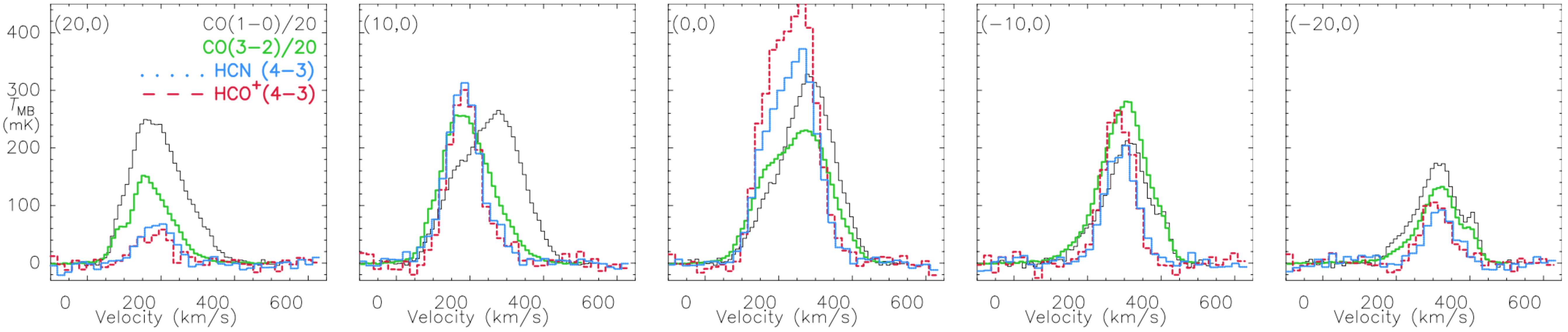
Zhang et al. 2014; Wu et al. 2005



Dense gas mass

Questions to address

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



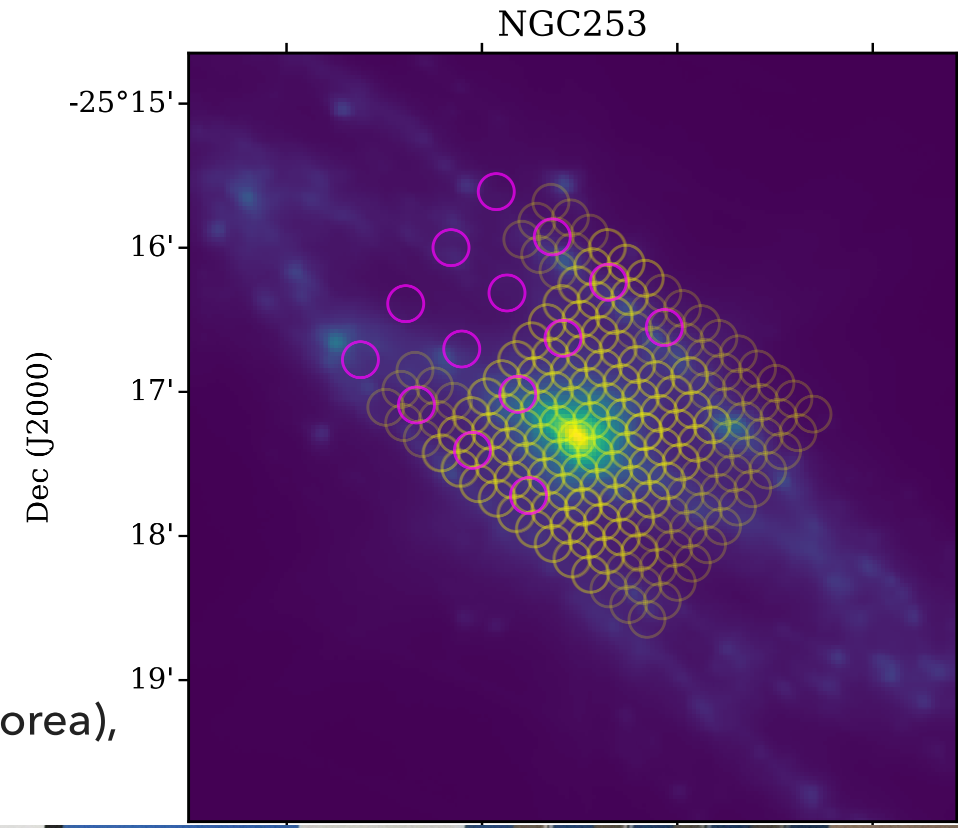
JCMT LARGE PROGRAM: MALATANG

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:

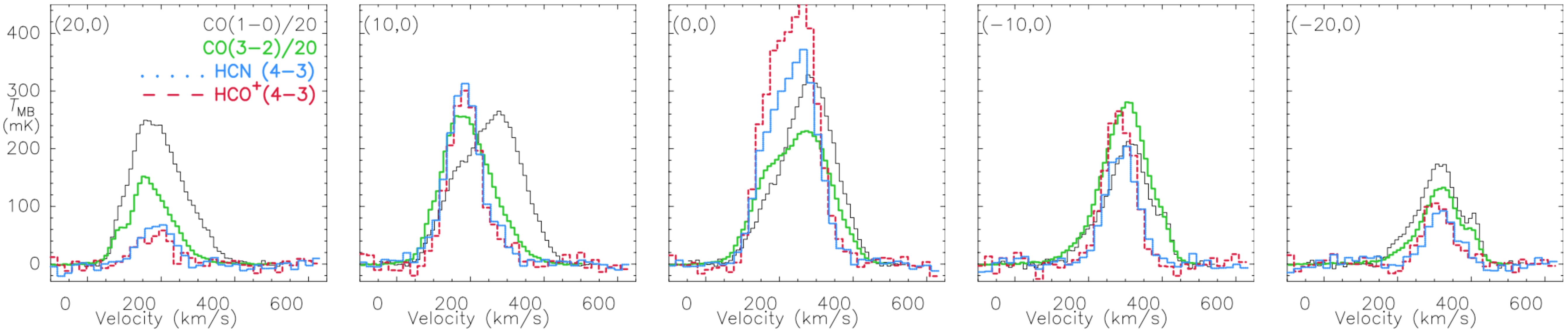
- Resolved dense gas SF relations
- Intermediate (sub-kpc) scales/luminosities
- Radial distribution of dense gas and SF efficiency



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.

MALATANG RESULTS

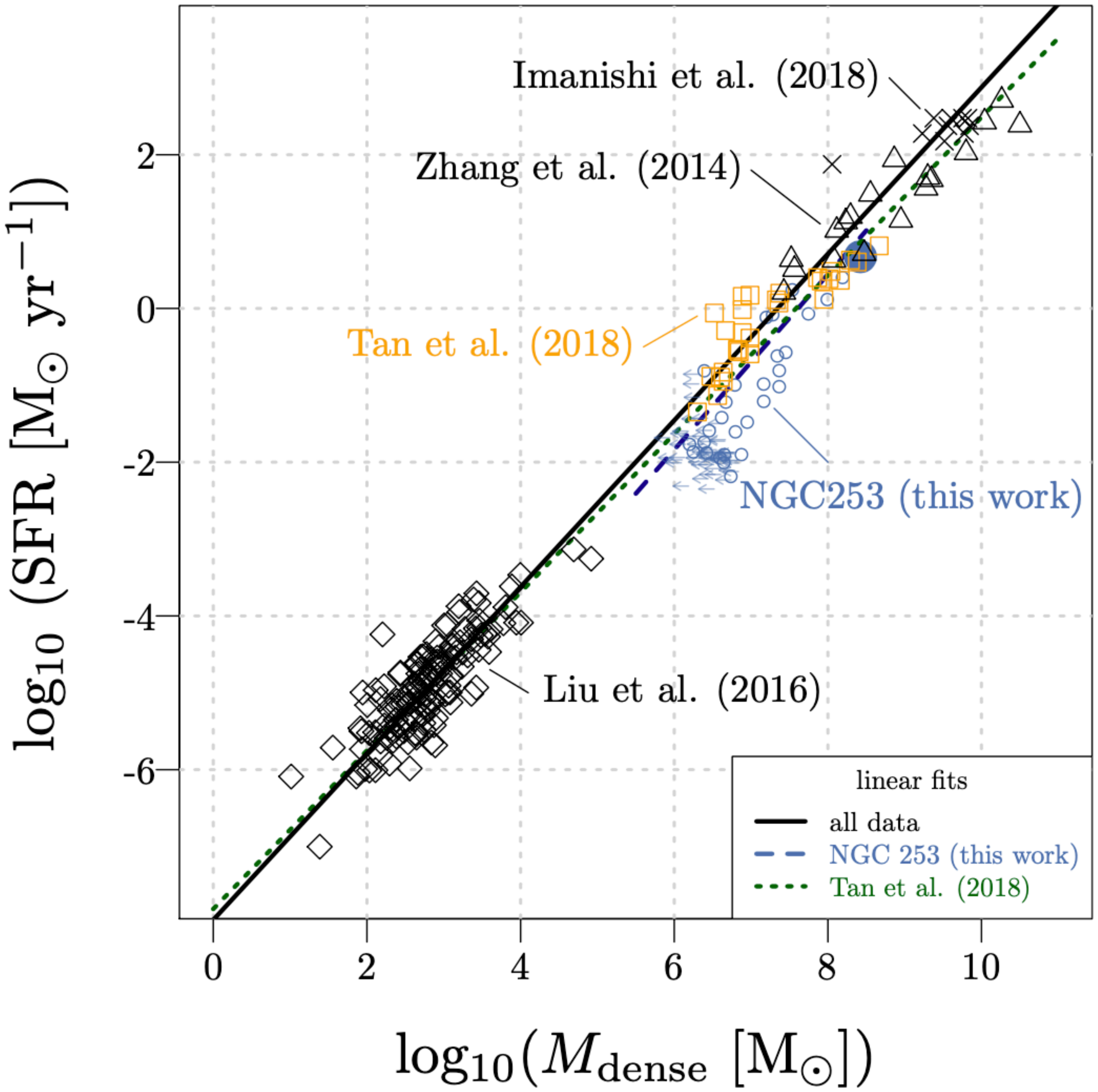
- SF law (Tan et al. 2018)
- NGC 253 (Jiang et al. submitted)
  - CO(3-2)/(1-0)
  - f_{dense} (HCN/CO) and $\mathrm{SFE}_{\mathrm{dense}}$ (SFR/HCN)
  - the role of stellar component ?



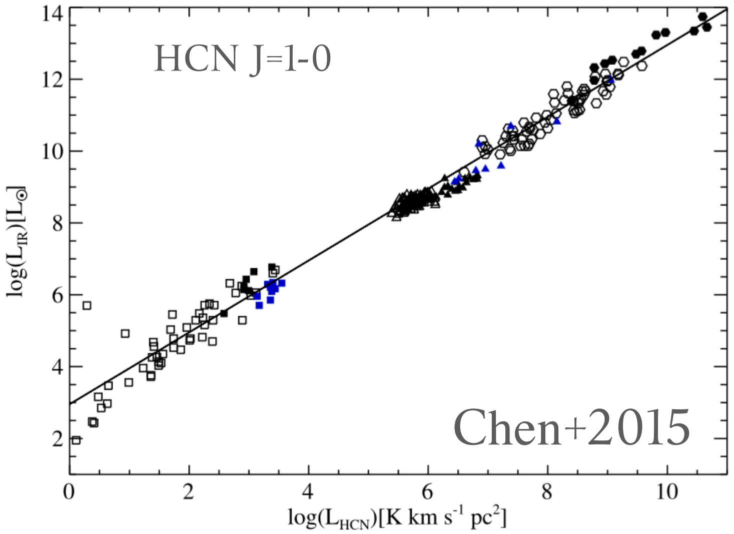
results (1) SF relation

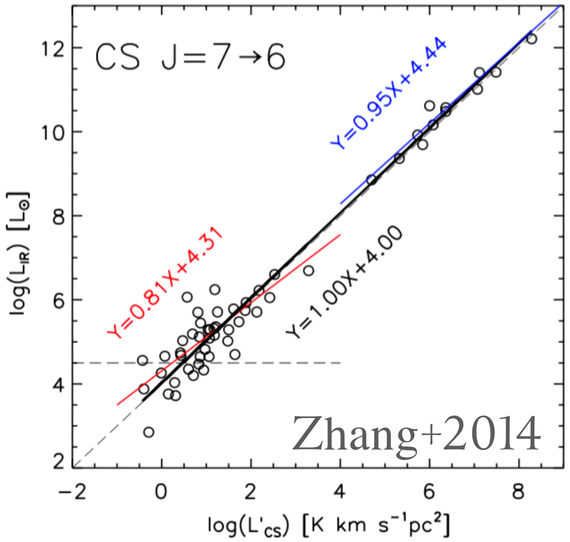
- linear correlations hold for all densities >10^4 cm^{-3}
- Bridge the gap between extragalactic (galaxy-integrated) and Galactic (single clouds) observations

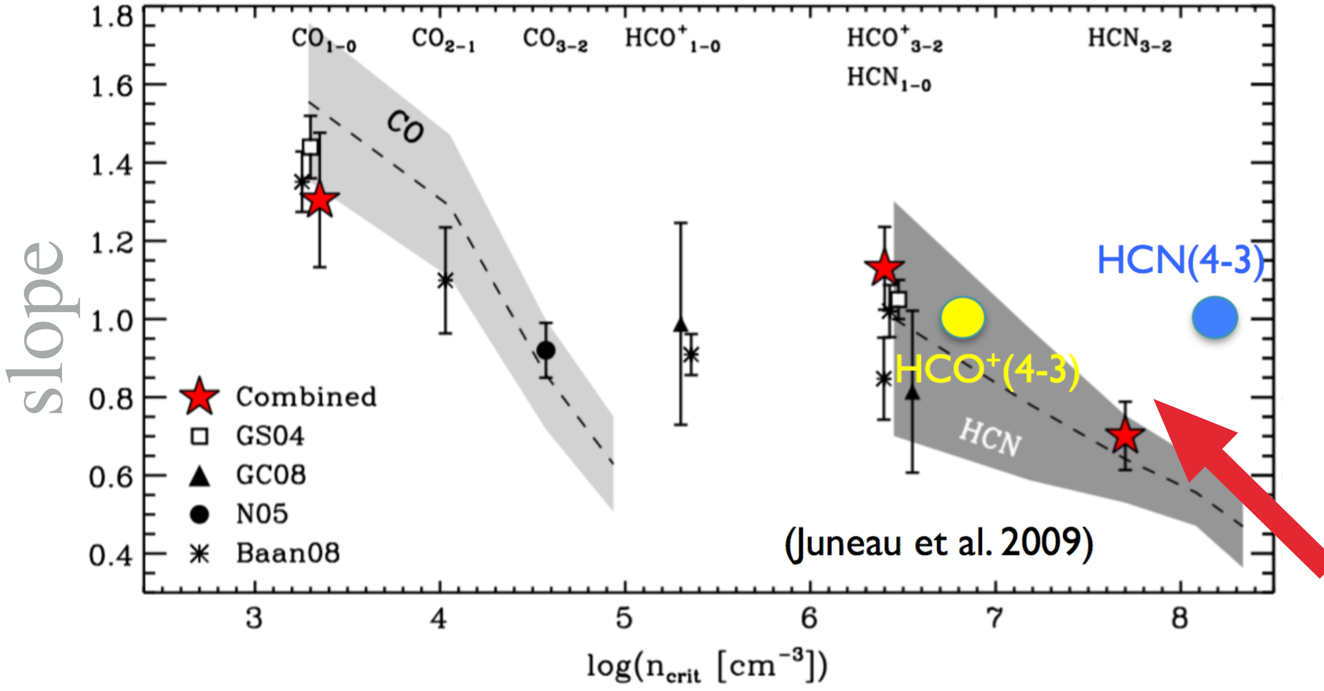
➤ linear correlations hold for all densities >10^4 cm^{-3}!



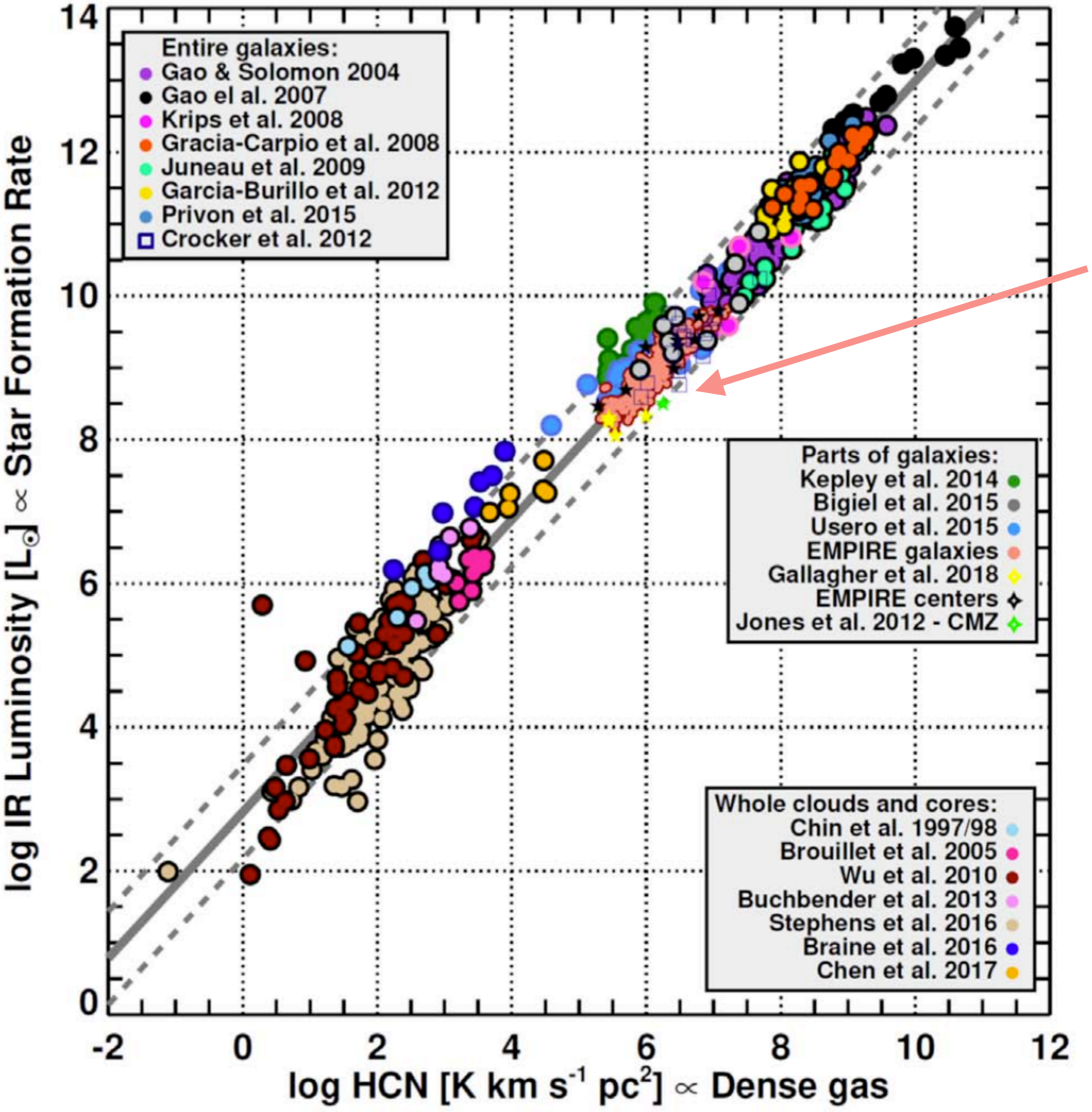
Jiang et al. (submitted)







bridging the gap in the universal dense-gas SF law.



EMPIRE

(30-m large program)

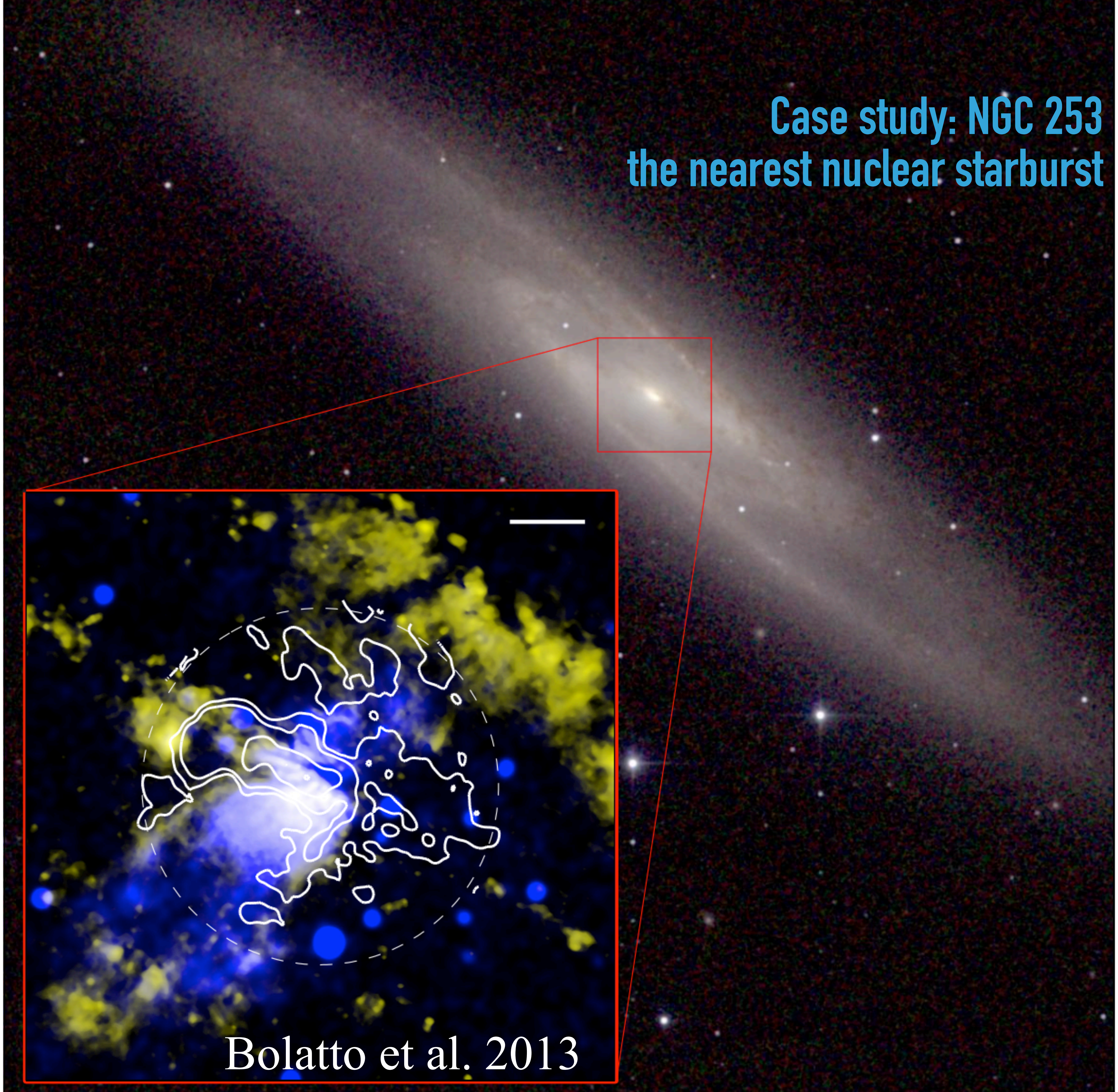
Jiménez-Donaire et al. 2019

- ~ 440 h
- nine galaxies
- an instantaneous bandwidth of 15.6 GHz

1. **the SF history follows the evolution of the molecular gas supply in galaxies.**

2. **bridging the gap in the universal dense-gas SF law.**

Case study: NGC 253
the nearest nuclear starburst

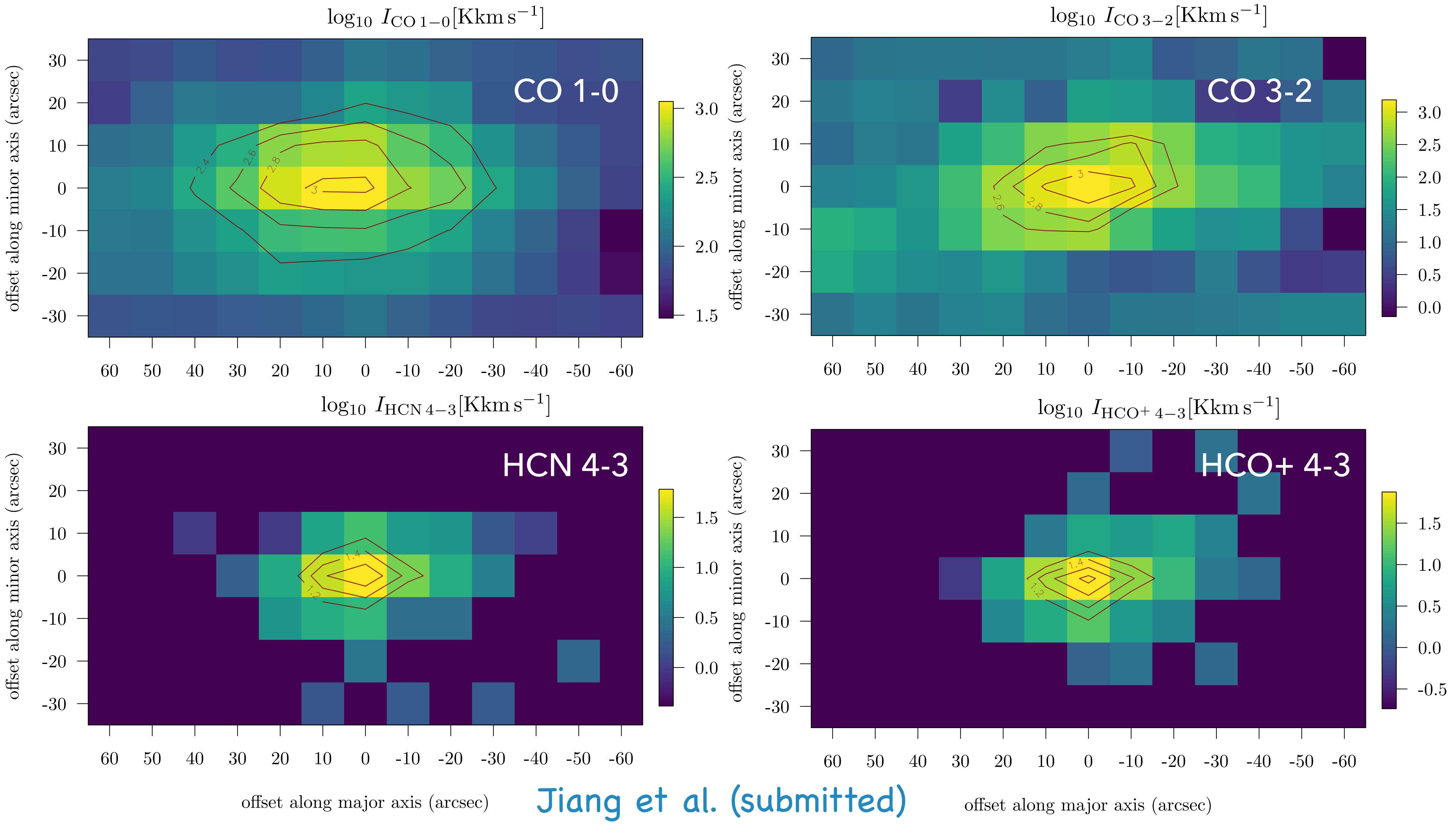


Bolatto et al. 2013

(2) NGC 253

dense gas distribution is compact

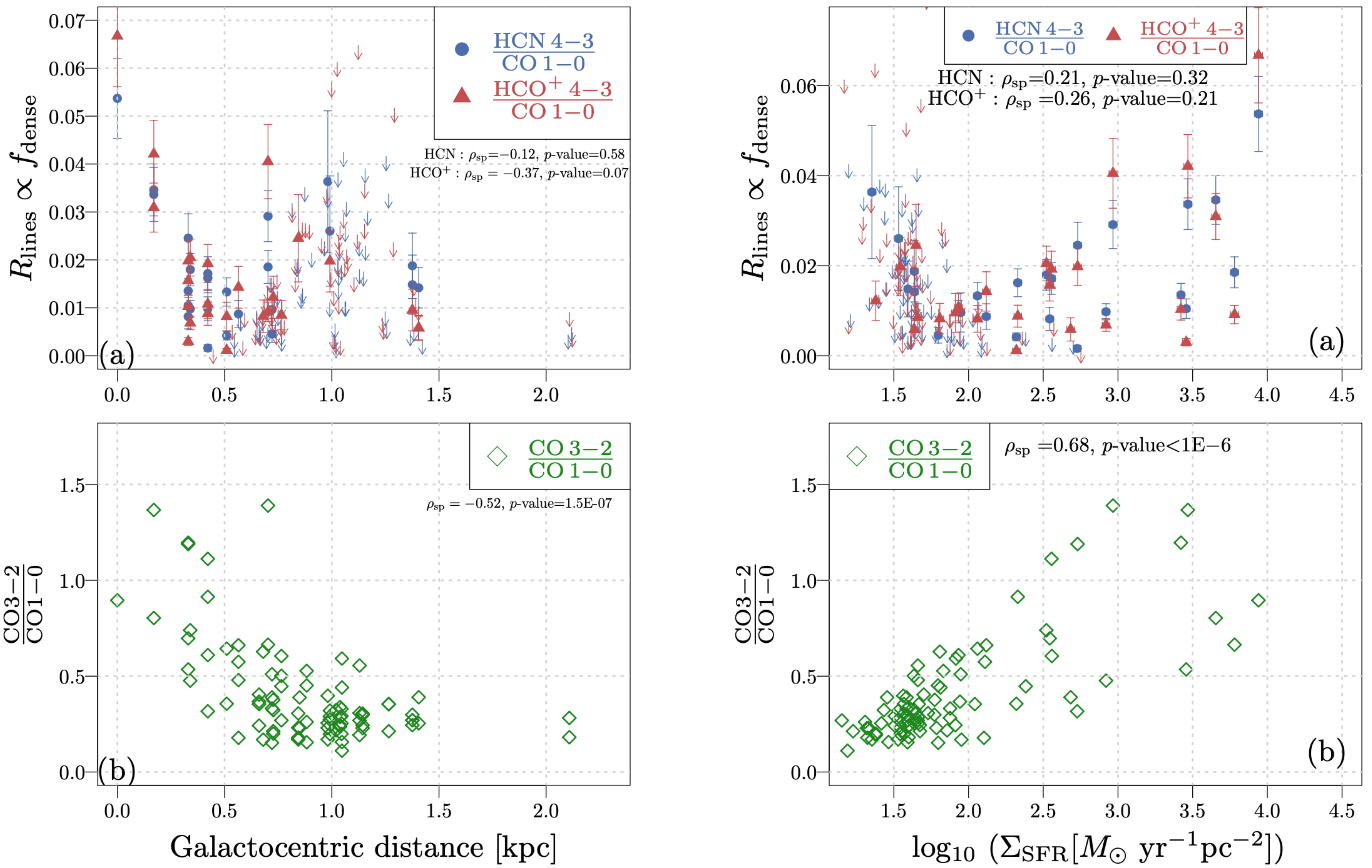
	r_{90}	r_{50}	concentration index r_{90}/r_{50}
stellar	0.87 (0.13)	0.37 (0.04)	2.36 (0.44)
CO 1-0	0.78 (0.15)	0.38 (0.05)	2.07 (0.48)
CO 3-2	0.68 (0.07)	0.30 (0.01)	2.26 (0.27)
L_{IR}	0.68 (0.12)	0.33 (0.02)	2.06 (0.39)
HCN 4-3	0.58 (0.15)	0.14 (0.01)	4.00 (1.10)
HCO+ 4-3	0.54 (0.18)	0.10 (0.01)	5.29 (1.91)



Jiang et al. (submitted)

(3) line ratio variation

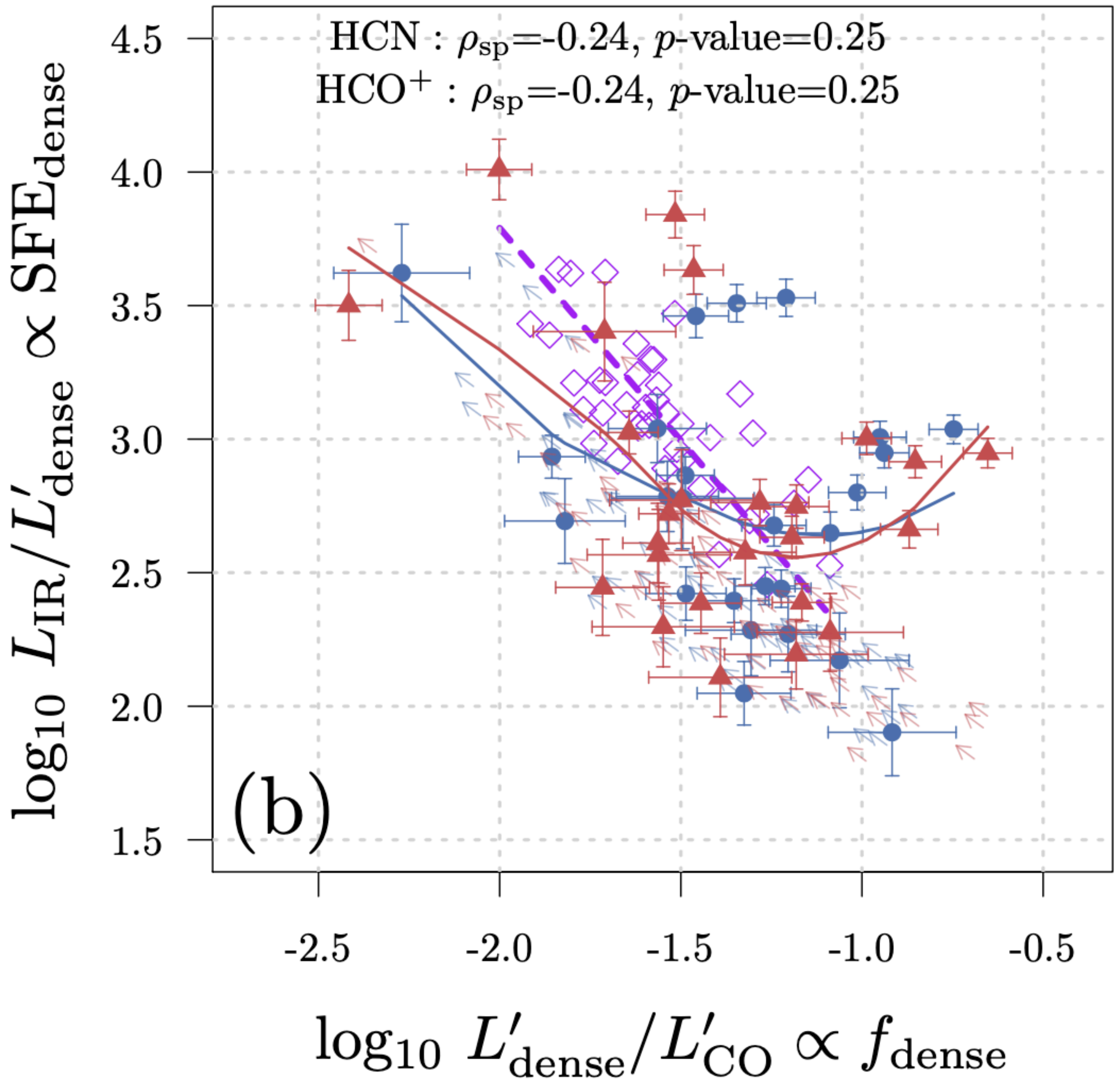
Jiang et al. (submitted)

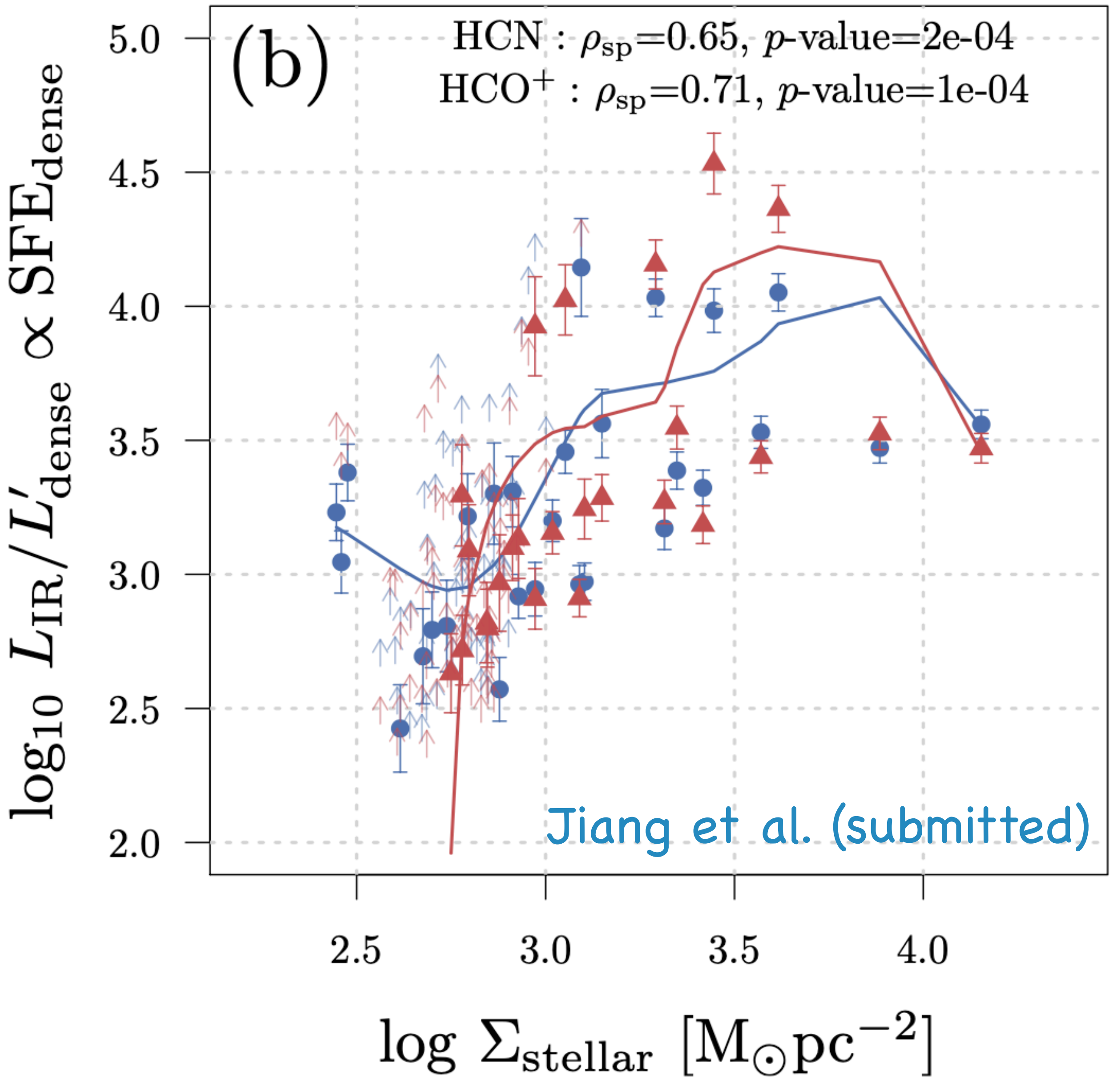


CO ratio is dependent on environment

cautious about using CO 3-2 to estimate H_2

(4) SFE variation (SFR / HCN)





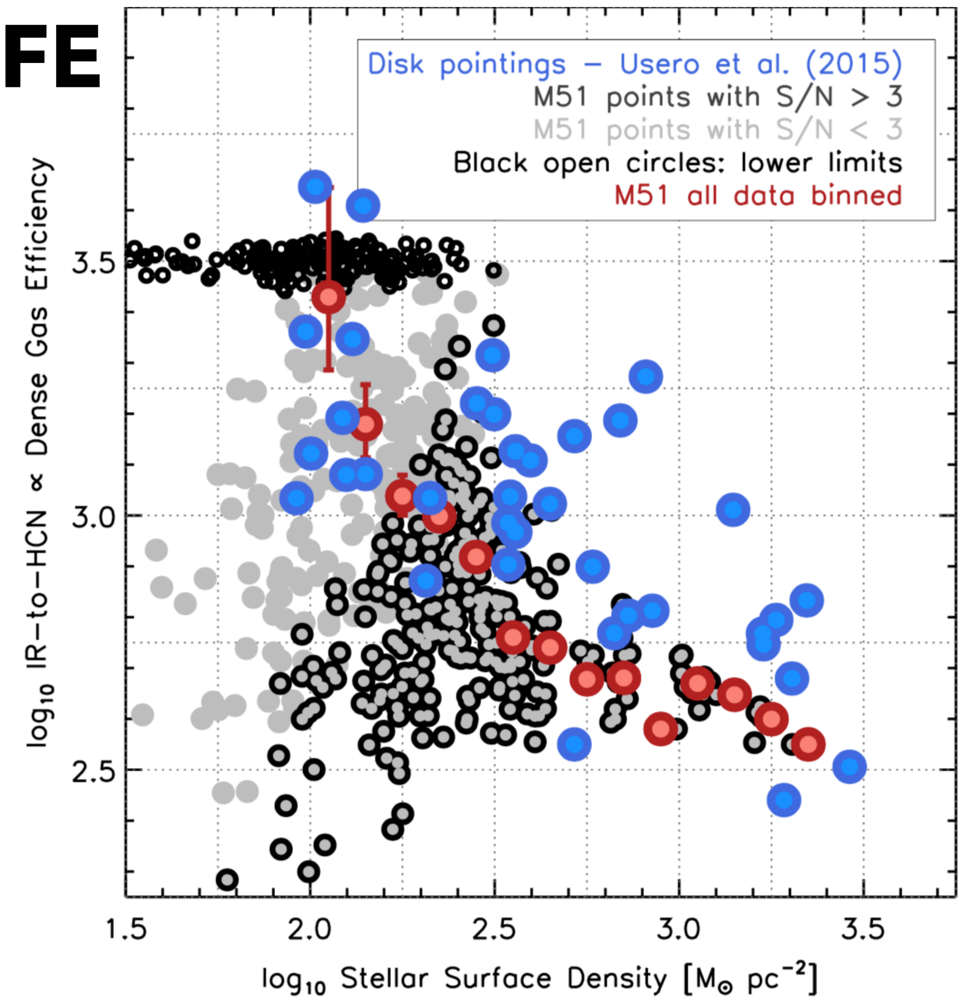
Jiang et al. (submitted)

- high $f_{\rm dense}$ ➔ high SFE ?
- high $\Sigma_{\rm stellar}$ ➔ high SFE

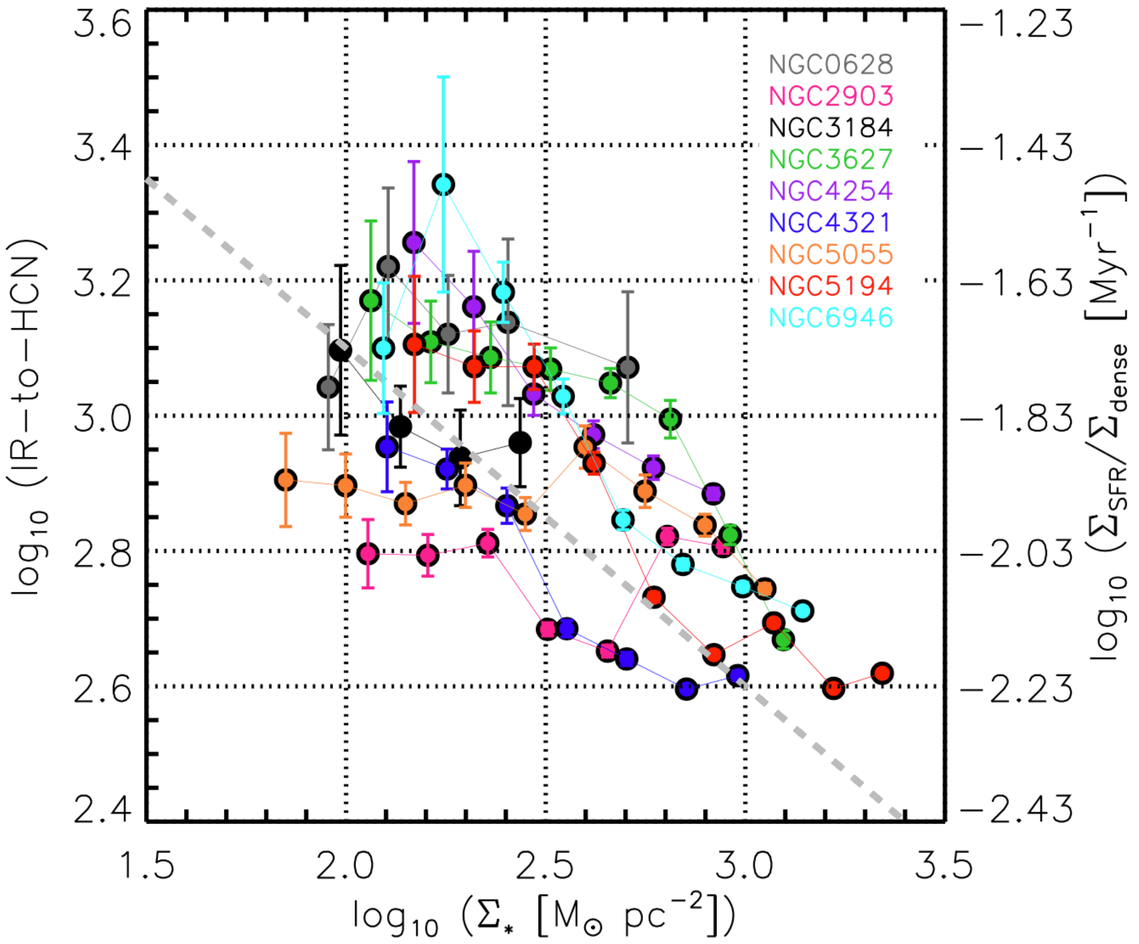
SFE vs. $\Sigma_{\mathrm{stellar}}$: inconsistent with results using HCN 1-0

- lower IR/HCN10 in higher $\Sigma_{\mathrm{stellar}}$

SFE



Bigiel et al. (2016)



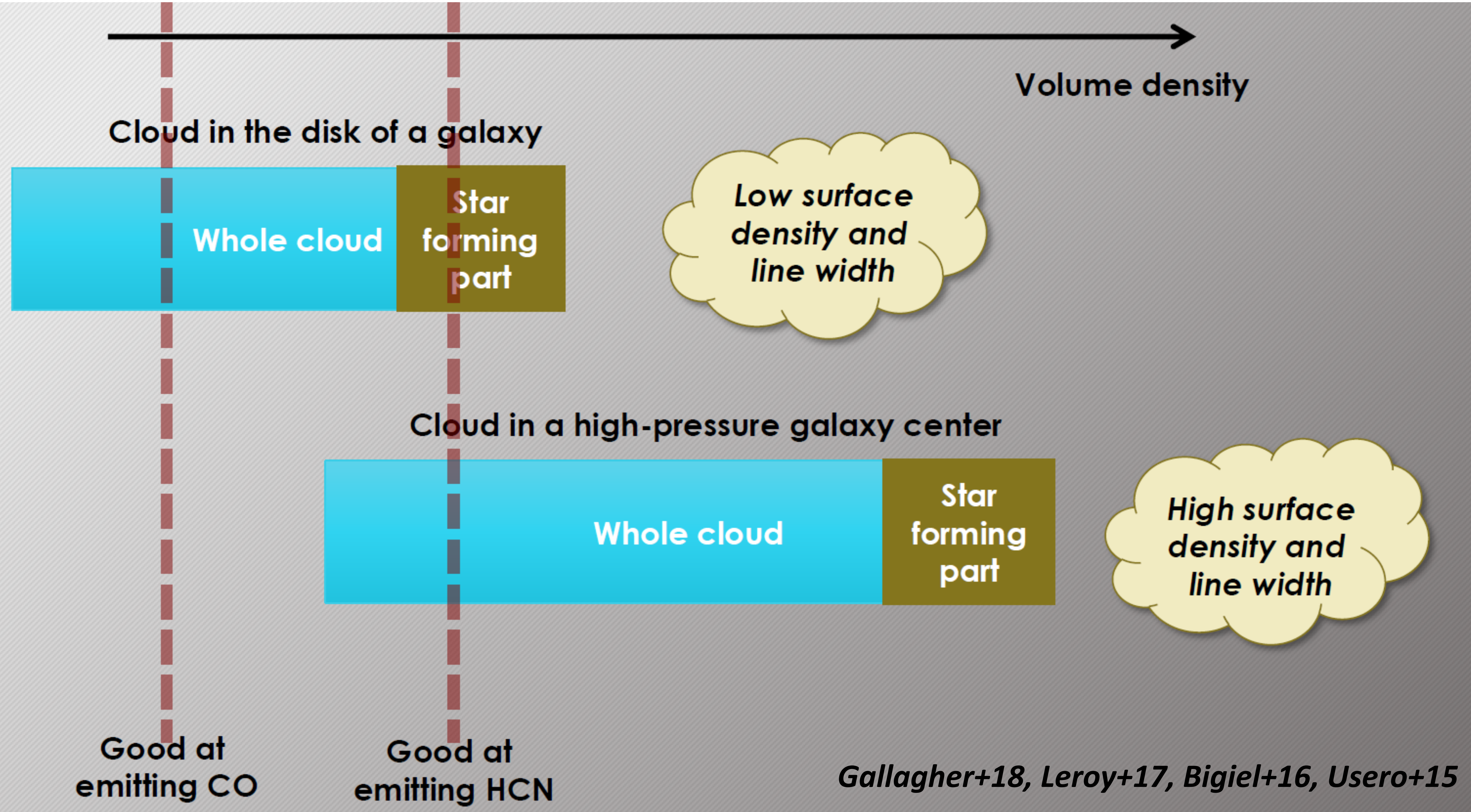
Jiménez-Donaire et al. 2019

stellar surface density

from Jiménez-Donaire's talk

Possible interpretation?

This appears to lead to a context-dependent role for the gas that emits in HCN and similar lines, evidenced by the changing IR-to-line ratios with environment.



Volume density

Cloud in the disk of a galaxy

Whole cloud

Star forming part

Low surface density and line width

Cloud in a high-pressure galaxy center

Whole cloud

Star forming part

High surface density and line width

Good at emitting CO

Good at emitting HCN

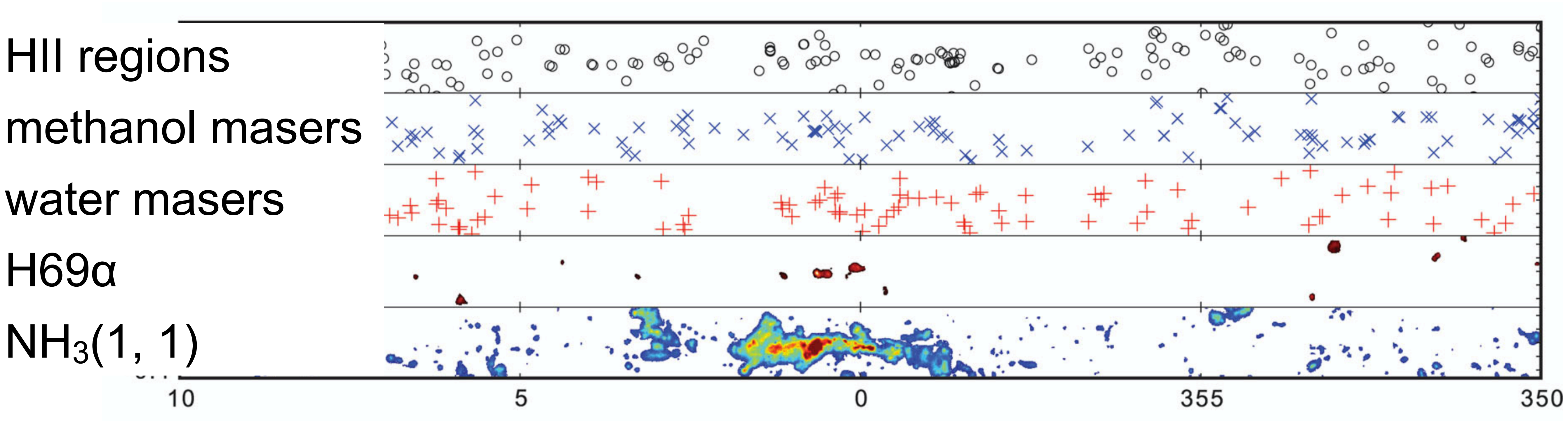
Gallagher+18, Leroy+17, Bigiel+16, Usero+15

Similar behavior in the Central Molecular Zone:

‘regular’ SF but strong dense gas emission -> low SFR/dense-gas ratio (SFE_{dense})

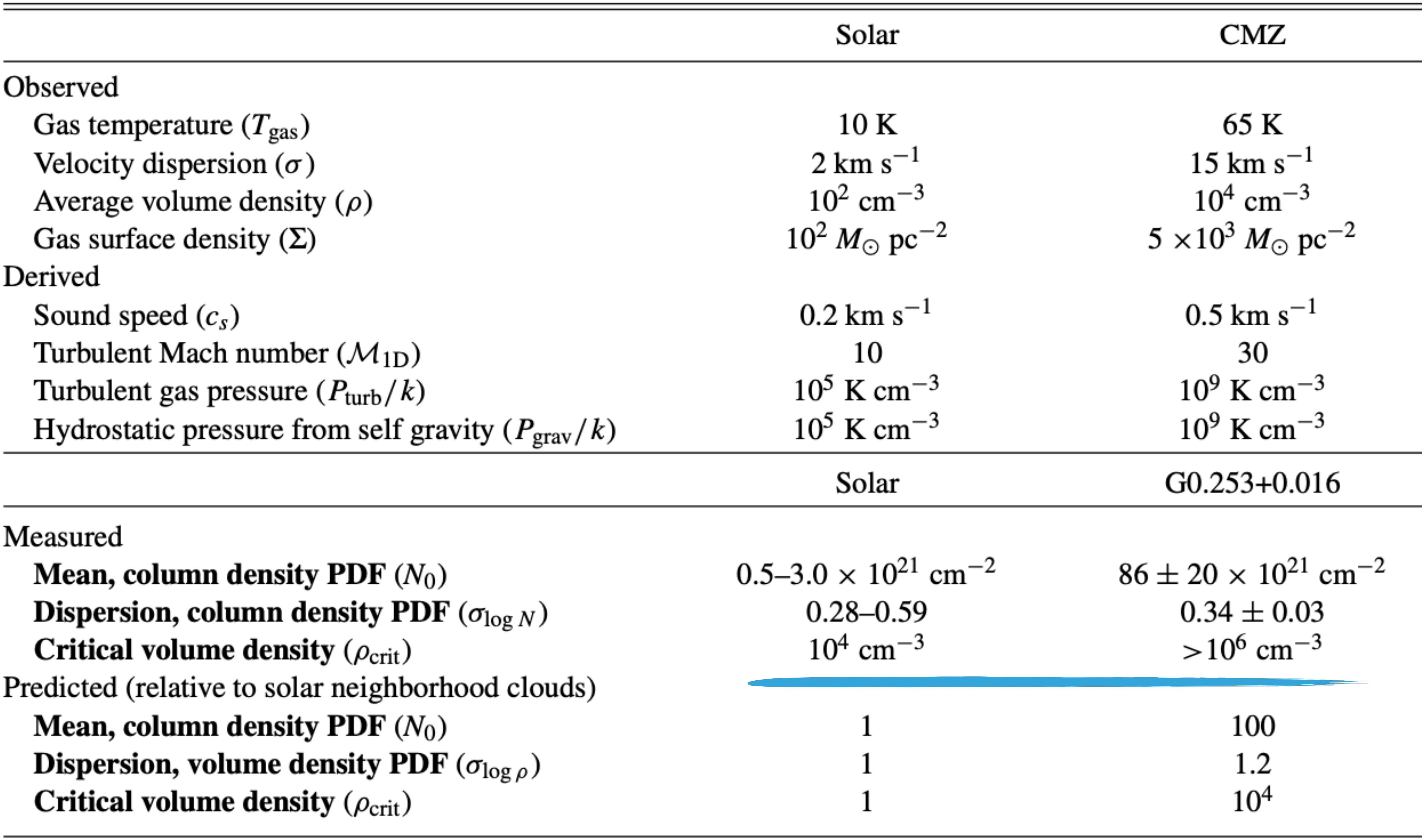
(Usero et al. 2015, Bigiel et al. 2016, Gallagher et al. 2018a)

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



Longmore et al. 2013

comparing solar neighborhood to the CMZ

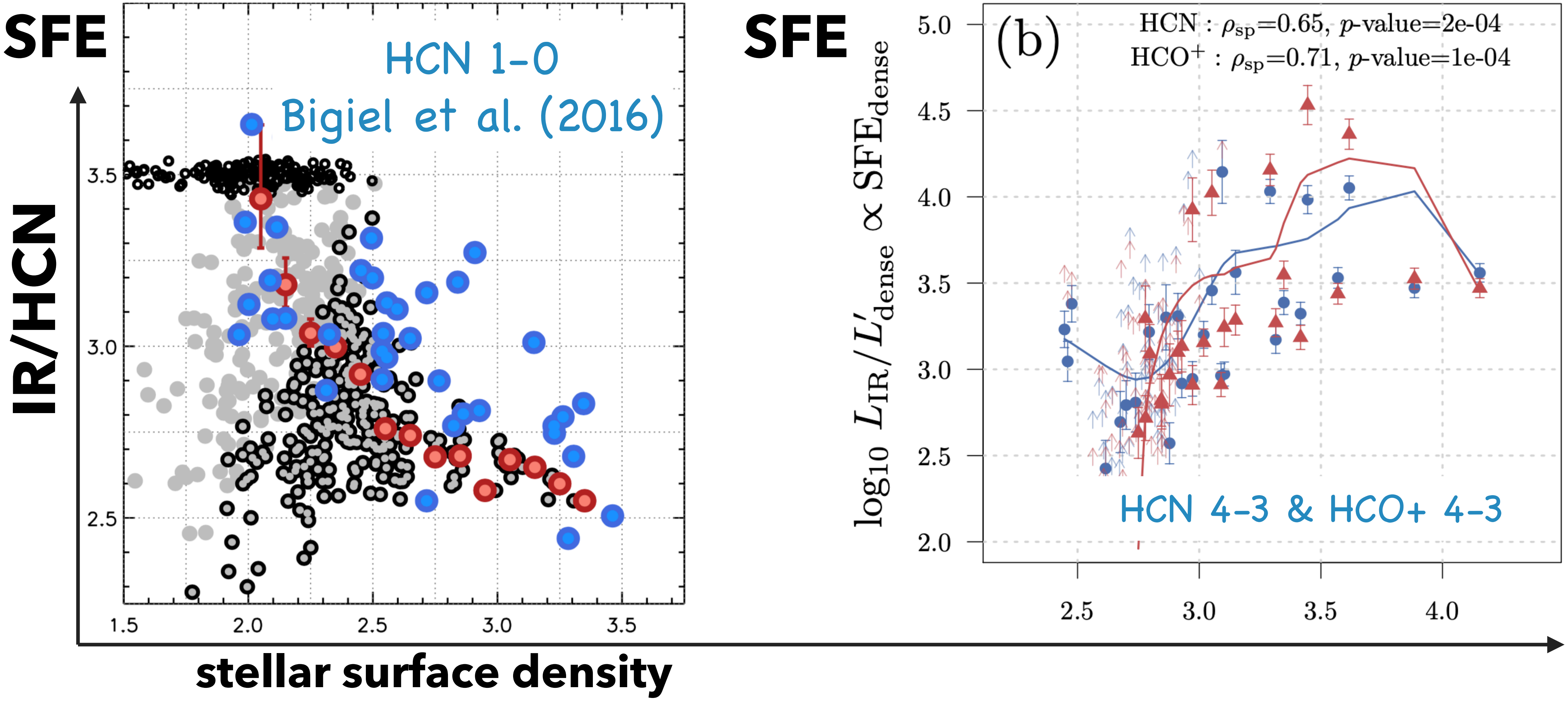


	Solar	CMZ
Observed		
Gas temperature (T_{gas})	10 K	65 K
Velocity dispersion (σ)	2 km s^{-1}	15 km s^{-1}
Average volume density (ρ)	10^2 cm^{-3}	10^4 cm^{-3}
Gas surface density (Σ)	10^2 $M_\odot$ pc^{-2}	5×10^3 $M_\odot$ pc^{-2}
Derived		
Sound speed (c_s)	0.2 km s^{-1}	0.5 km s^{-1}
Turbulent Mach number ($\mathcal{M}_{\mathrm{1D}}$)	10	30
Turbulent gas pressure (P_{turb}/k)	10^5 K cm^{-3}	10^9 K cm^{-3}
Hydrostatic pressure from self gravity (P_{grav}/k)	10^5 K cm^{-3}	10^9 K cm^{-3}
	Solar	G0.253+0.016
Measured		
Mean, column density PDF (N_0)	0.5–3.0 × 10^{21} cm^{-2}	$86 \pm 20 \times 10^{21}$ cm^{-2}
Dispersion, column density PDF ($\sigma_{\log N}$)	0.28–0.59	0.34 ± 0.03
Critical volume density (ρ_{crit})	10^4 cm^{-3}	$>10^6$ cm^{-3}
Predicted (relative to solar neighborhood clouds)		
Mean, column density PDF (N_0)	1	100
Dispersion, volume density PDF ($\sigma_{\log \rho}$)	1	1.2
Critical volume density (ρ_{crit})	1	10^4

Rathborne et al. 2014

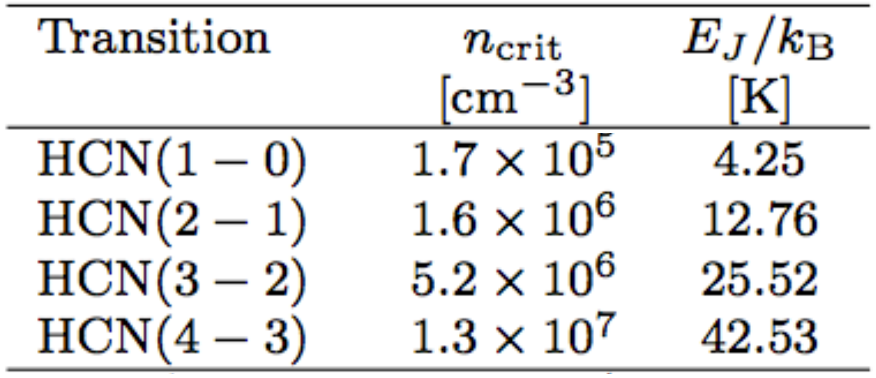
Different relation with stellar feedback?

Critical density: n_c(HCN43) 100 times higher than n_c (HCN10)

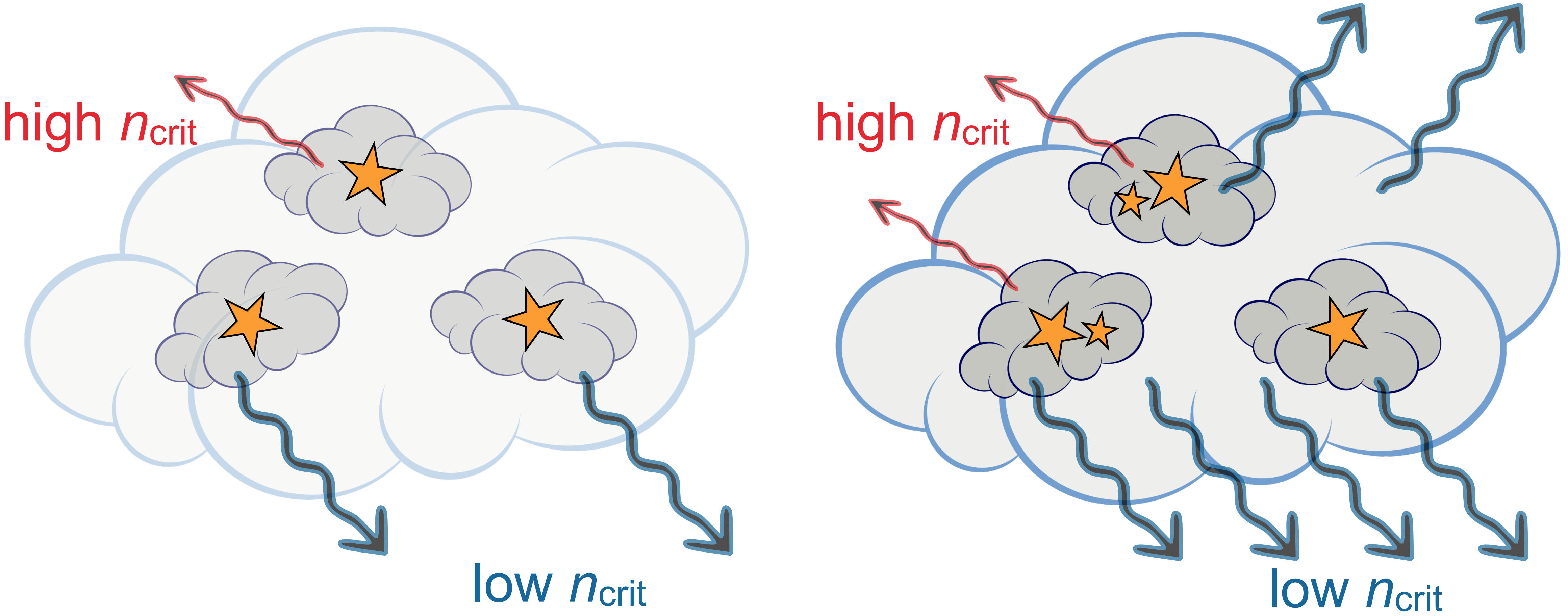


Stellar components affect gas density and SF activity!

gas density and “contrast”



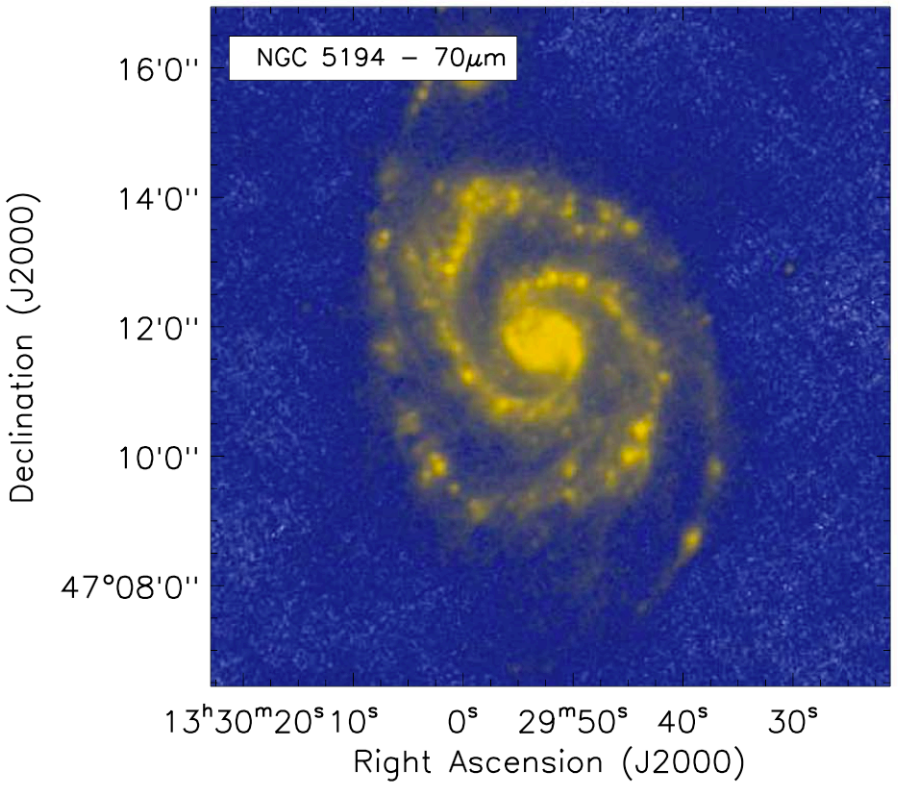
Transition	$n_{\rm crit}$ [cm^{-3}]	$E_J/k_{\rm B}$ [K]
HCN$(1-0)$	1.7×10^5	4.25
HCN$(2-1)$	1.6×10^6	12.76
HCN$(3-2)$	5.2×10^6	25.52
HCN$(4-3)$	1.3×10^7	42.53

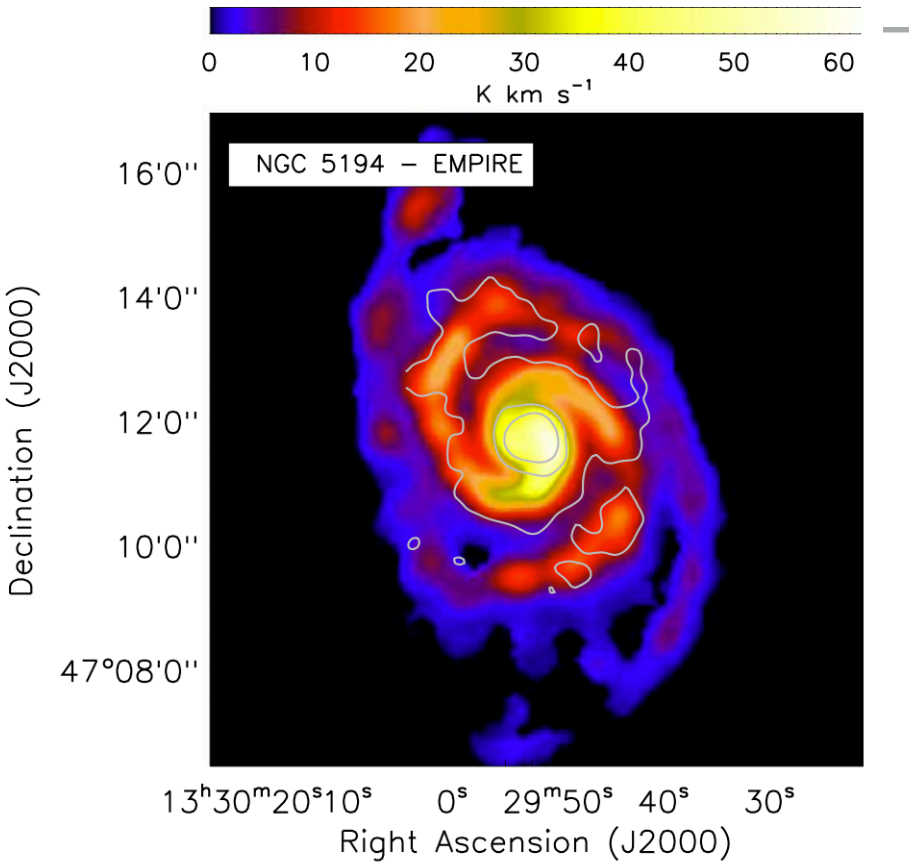


- higher ***n*, *Σ*, *p*, *I***$_{\rm HCN1-0}$ …
- lower SF efficiency (SFR / LHCN10)

1. the SF history follows the evolution of the molecular gas supply in galaxies.
2. Bridging the gap in the universal dense-gas SF law.
3. Stellar components affect gas density and SF activity!

JCMT large program: MALATANG-II





Galaxy	Scanned Field (arcmin^2)
NGC 628	4.0 × 4.0
NGC 2903	2.0 × 3.5
NGC 3184	3.0 × 3.0
NGC 3627	2.5 × 4.0
NGC 4254	3.0 × 3.0
NGC 4321	4.0 × 2.5
NGC 5055	6.0 × 3.0
NGC 5194	4.2 × 5.7
NGC 6946	4.5 × 6.5

+ Maffei 2

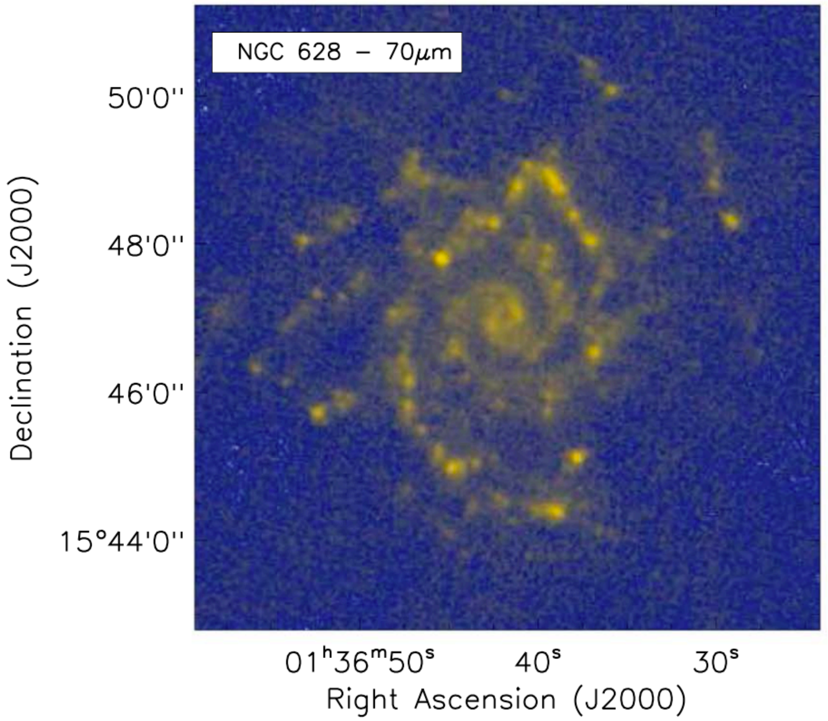
+ M83

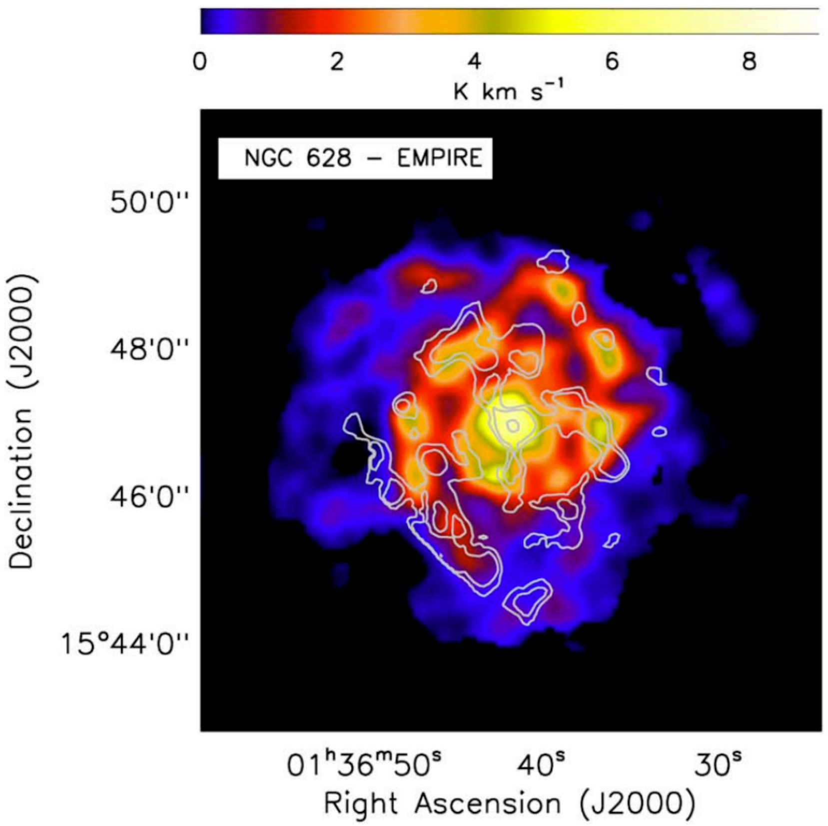
- synergy with the **EMPIRE** 30-m survey
- HCN 1-0 and 4-3

Main Spectral Lines Covered by Our EMIR Setups

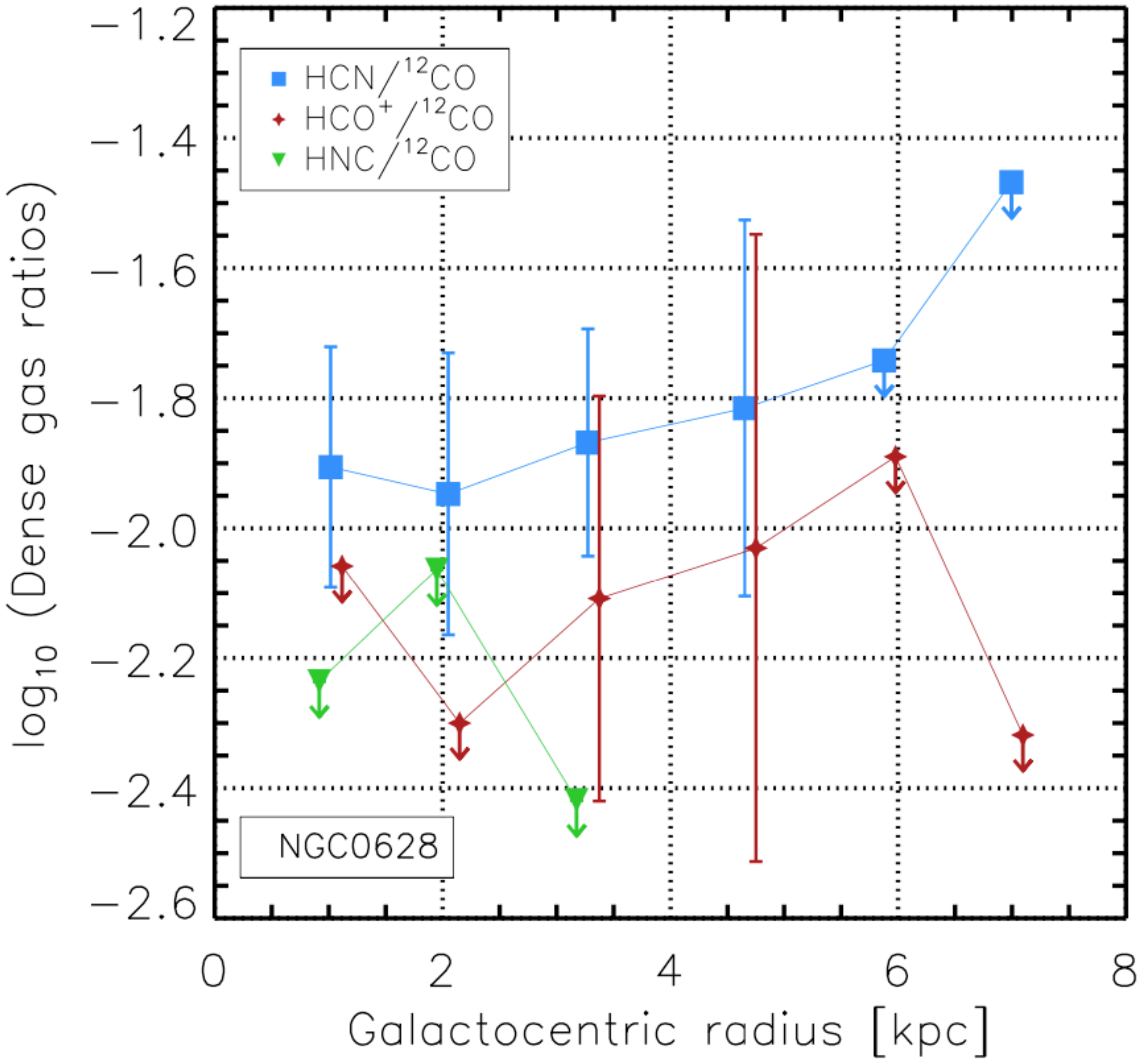
Species	$\nu_{\rm rest}$ (GHz)	$E_{\rm up}$[a] (K)	$n_{\rm crit}$[a] (cm^{-3})	Beam Size[b] ('')
SiO 2–1[c]	86.45	6.25	1×10^5	34.04
C_2H 1–0	87.32	4.19	1×10^5	33.86
HNCO 4–3	87.93	10.55	1×10^4	33.63
HCN 1–0	88.63	4.25	2×10^5	33.36
HCO^+ 1–0	89.19	4.28	3×10^4	33.15
HNC 1–0	90.66	4.35	1×10^5	32.61
N_2H^+ 1–0	93.20	4.47	4×10^4	31.73
$C^{18}O$ 1–0[d]	109.78	5.27	4×10^2	26.83
HNCO 5–4	109.90	15.8	1×10^7	26.70
^{13}CO 1–0[d]	110.20	5.29	4×10^2	26.13
^{12}CO 1–0	115.27	5.53	4×10^2	25.65

JCMT large program: MALATANG-II





example: NGC628 shows an abnormal HCN_{1-0}/CO profile



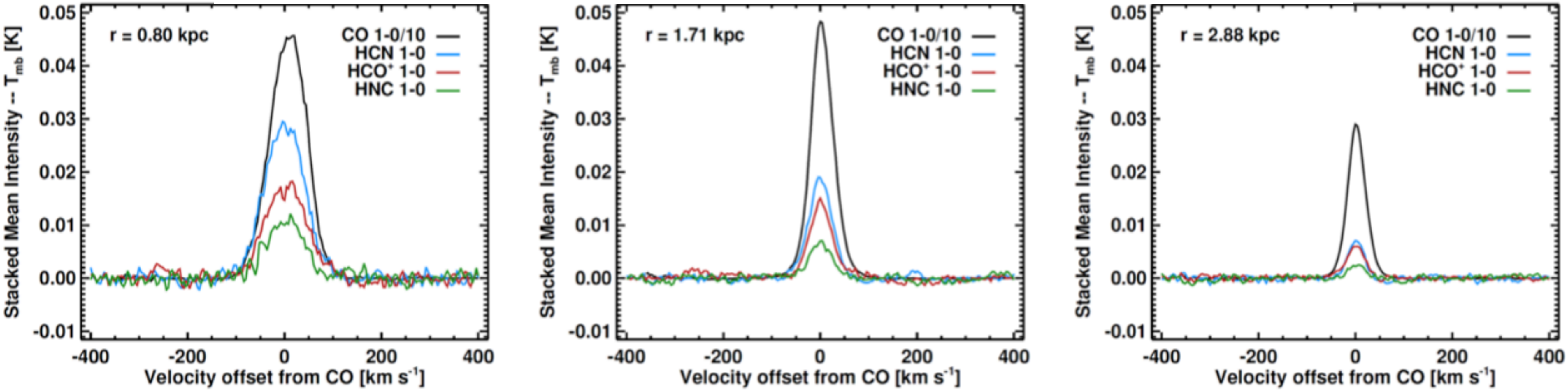
Follow-up plans

HCN & HCO+ (3-2)

- multi-*J* will better constraint SF properties
- compare Galactic clouds with external galaxies
- many available in archive

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

HCN 1-0 from 30-m (Jiménez-Donaire et al. 2019)



- In the galaxy center:
  HCN 3-2/1-0 (in T_{mb}) ~ 0.5

1. **the SF history follows the evolution of the molecular gas supply in galaxies.**

2. **Bridging the gap in the universal dense-gas SF law.**

3. **Stellar components affect gas density and SF activity!**

4. **multi-*J* observation can reveal (*T*, *n*) information.**