ICRR seminar
June 14th, 2012

The Resolved Kennicutt-Schmidt Law in Nearby Galaxies

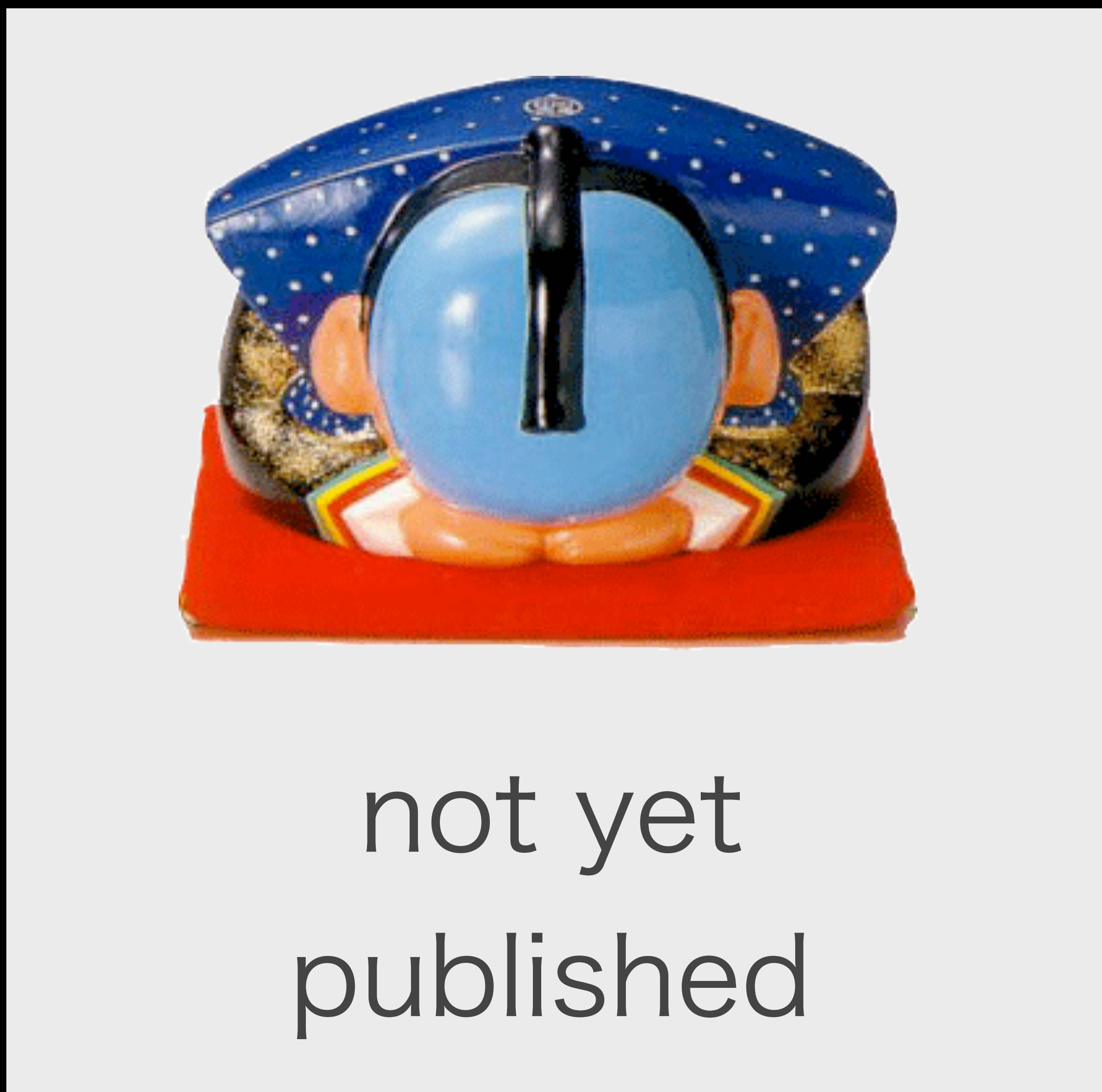
Rieko Momose[1,2,3]

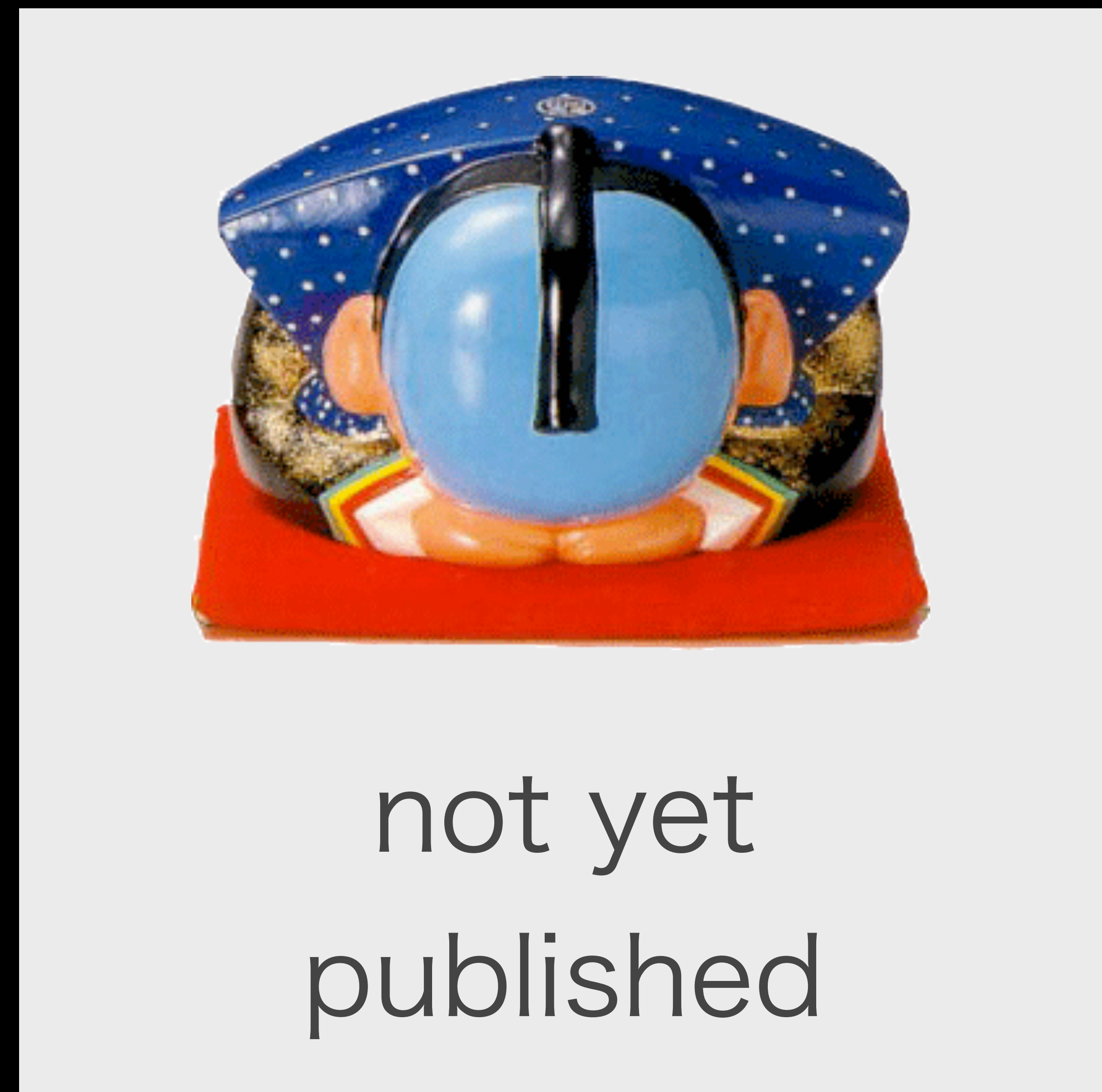
Sachiko K. Okumura[2,4], Jin Koda[5], Robert C. Kennicutt, Jr[6], Jennifer Donovan Meyer[5], Daniela Calzetti[7], Guilin Liu[7,8], Fumi Egusa[9], Nick Scoville[10], Tsuyoshi Sawada[2], Nario Kuno[11]

1. ICRR, University of Tokyo, 2. University of Tokyo, 3. Chile/NAOJ, 4. Japan Woman's University, 5. Stony Brook University, 6. University of Cambridge, 7. University of Massachusetts, 8. Johns Hopkins University, 9. JAXA, 10. Caltech, 11. NRO/NAOJ

CONTENTS

ABSTRACT



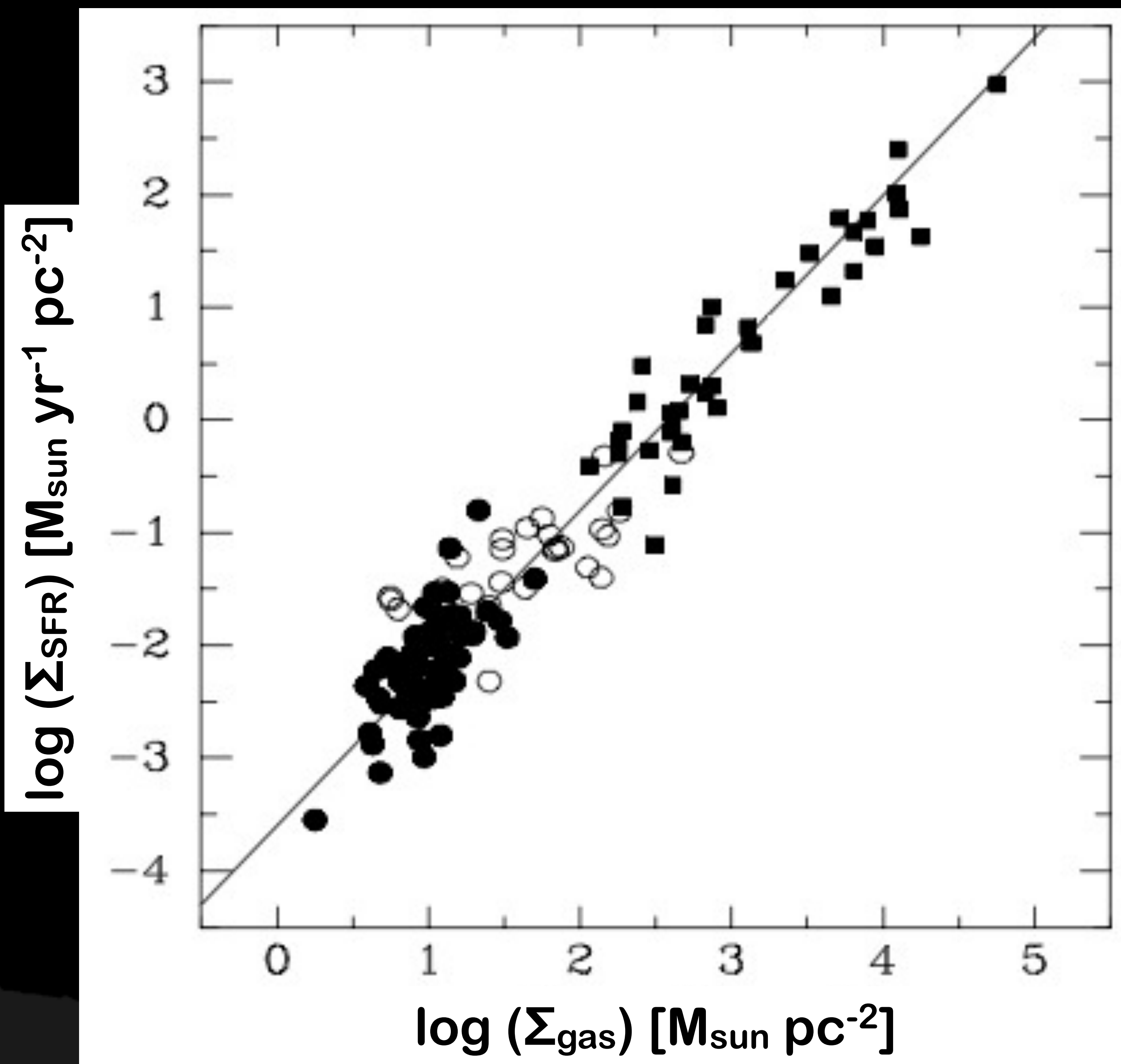


We obtain super-linear slope of the K-S law on 500 pc from 10 galaxies

Star formation mechanism indicated by the K-S law is little different among structures

1. INTRODUCTION

The Kennicutt-Schmidt Law



- Power law correlation between SFR and gas density (Schmidt 59)

$$\Sigma_{\rm SFR} = A\Sigma_g^N,$$

- Observationally, the index has been estimated among galaxies (Kennicutt 98; following)
  - N = 1.2 -- 1.8

※ Star Formation Rate (SFR)
The amount of gas mass converted to stars per unit time [M$_\odot$/yr]

Physical Predictions From The K-S Law

- Star formation would be regulated by some physically motivated time scale

$$\Sigma_{\rm SFR} = \epsilon_{\rm tphy} \frac{\Sigma_{\rm gas}}{t_{\rm phy}},$$

$$\Sigma_{\rm SFR} \propto \epsilon_{\rm tphy}\ \Sigma_{\rm gas}^{1-m} = \epsilon_{\rm tphy}\ \Sigma_{\rm gas}^{N},$$

N = 1

- Constant star formation at fixed time scale

$$\mathrm{SFR} = \frac{\rho_{\rm gas}}{t_{\rm SF}}.$$

$$\Sigma_{\rm SFR} = \epsilon \Sigma_{\rm gas},$$

N > 1

- Star formation at a free-fall time scale ($t_{\rm ff}$)

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G \rho_{\rm gas}}}.$$

$$\Sigma_{\rm SFR} = \epsilon_{\rm ff} \frac{\Sigma_{\rm gas}}{t_{\rm ff}} \propto \Sigma_{\rm gas}^{1.5},$$

N = 1.5

- Star formation regulated by collision time scale

$$t_{\rm cc} = \frac{\lambda}{v} = \frac{h m_{\rm GMC}}{\sqrt{2}\ \Sigma_{\rm gas}\ a^2\ \pi v}$$

$$\lambda_{\rm mfp} = \frac{1}{\sqrt{2} N D},$$

$$\Sigma_{\rm SFR} = \epsilon_{\rm cc} \frac{\Sigma_{\rm gas}}{t_{\rm cc}} \propto \Sigma_{\rm gas}^{2}.$$

N = 2

Physical Predictions From The K-S Law

In order to understand the mechanism of star formation, estimating the index of the K-S law is important

N = 1

- Constant star formation at fixed time scale

$$\mathrm{SFR} = \frac{\rho_{\mathrm{gas}}}{t_{\mathrm{SF}}}.$$

$$\Sigma_{\mathrm{SFR}} = \epsilon \Sigma_{\mathrm{gas}},$$

N > 1

- Star formation at a free-fall time scale (t_{ff})

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32 G \rho_{\mathrm{gas}}}}.$$

$$\Sigma_{\mathrm{SFR}} = \epsilon_{\mathrm{ff}} \frac{\Sigma_{\mathrm{gas}}}{t_{\mathrm{ff}}} \propto \Sigma_{\mathrm{gas}}^{1.5},$$

N = 1.5

- Star formation regulated by collision time scale

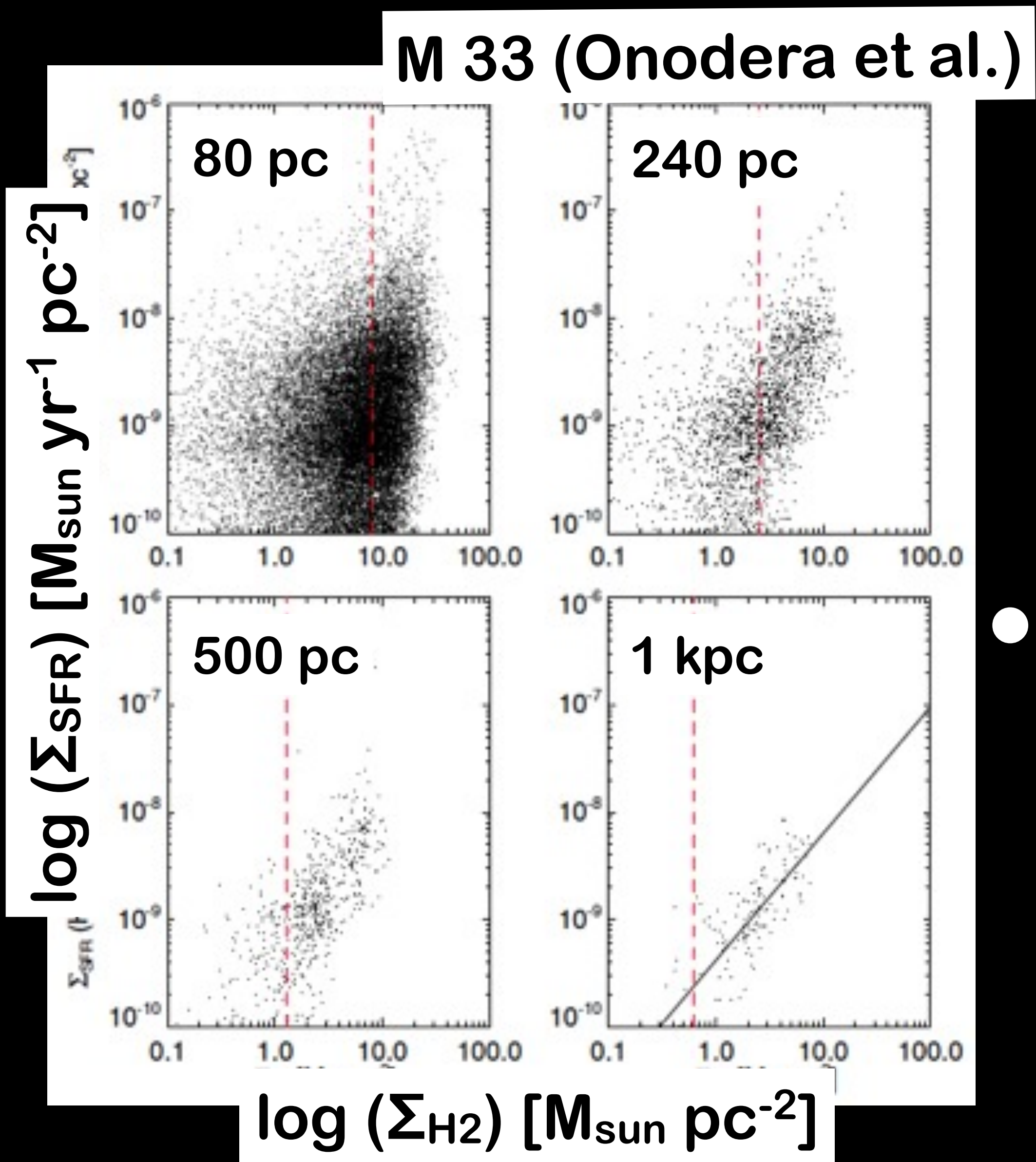
$$t_{\mathrm{cc}} = \frac{\lambda}{v} = \frac{h m_{\mathrm{GMC}}}{\sqrt{2}\, \Sigma_{\mathrm{gas}}\, a^2\, \pi v}$$

$$\lambda_{\mathrm{mfp}} = \frac{1}{\sqrt{2} N D},$$

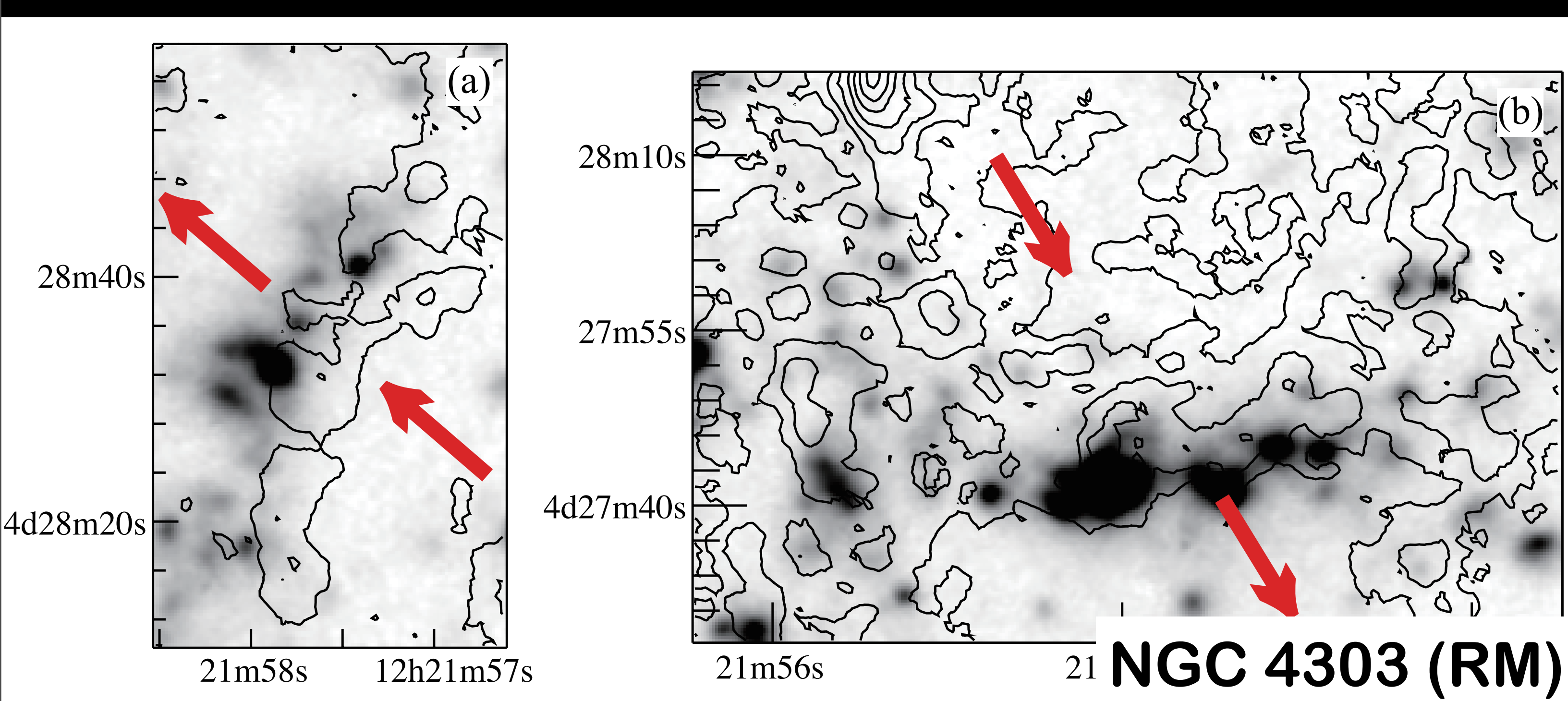
$$\Sigma_{\mathrm{SFR}} = \epsilon_{\mathrm{cc}} \frac{\Sigma_{\mathrm{gas}}}{t_{\mathrm{cc}}} \propto \Sigma_{\mathrm{gas}}^{2}.$$

N = 2

Recent Study of The K-S Law 1



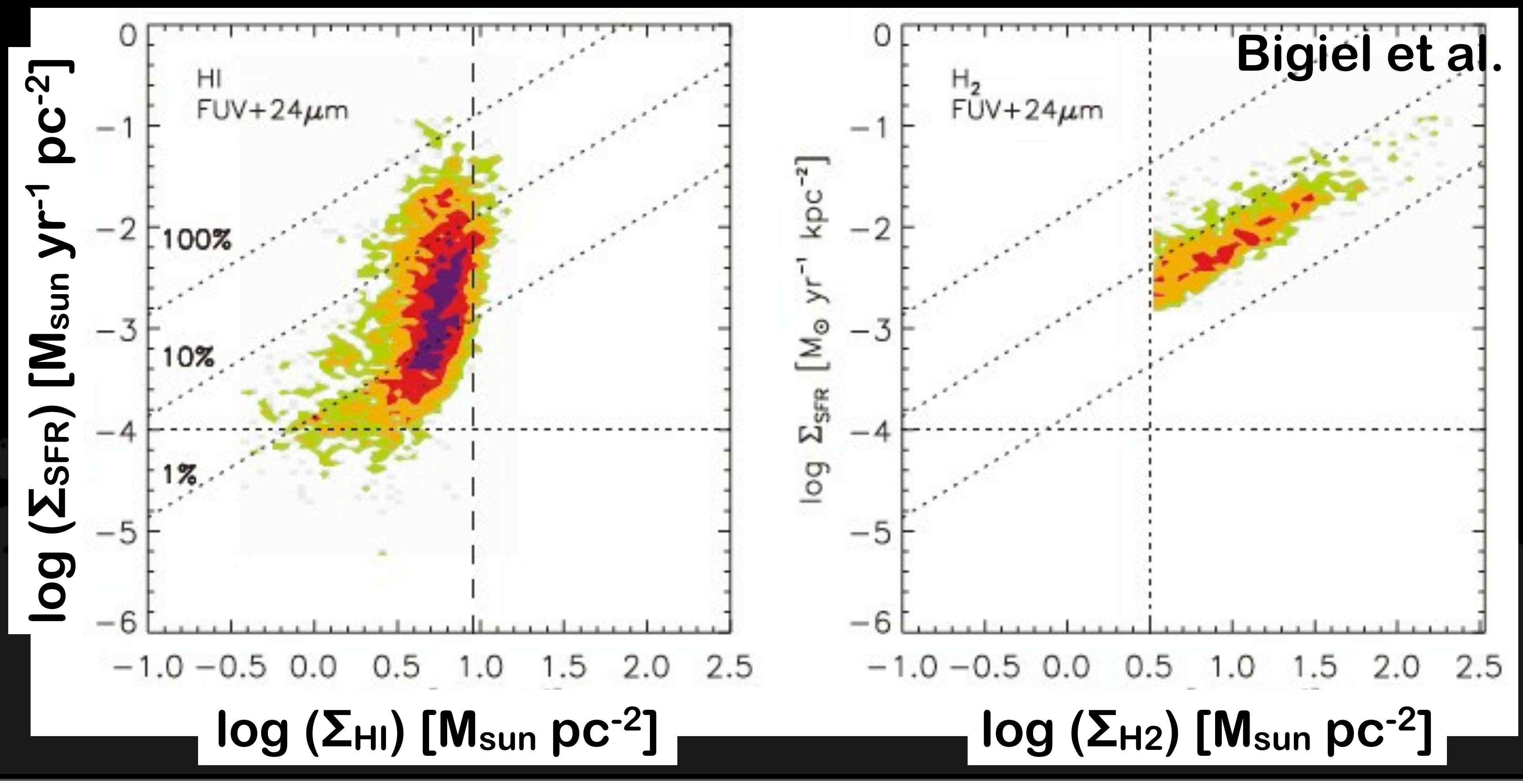
- The K-S law studies are shifting those of obtained within a galaxy
  - NGC 5194 (M 51): ~ 500 pc (e.g. Kennicutt et al. 07; Blanc et al. 09)
  - M 33: 80-200 pc: poor--break down (Verley et al. 10; Onodera et al. 10)



The mechanism of triggering star formation operates at a scale smaller than 500 pc.

Recent Study of The K-S Law 2

- Statistical study of K-S law on sub-kpc scale (Bigiel et al. 08)
  - Molecular gas is dominant above 10 $M_\odot$ pc^{-2}
  - The correlation between Σ_{SFR} and Σ_{H2} is N ~ 1



Remaining Problem And Motivations

✳ Resolved K-S law

- The K-S law traced by CO(J=1-0) breaks down on GMC scale (< 100 pc), but holds on 500 pc
- The index of N ~ 1 becomes standard value of the K-S law
  - No study of the K-S law on sub-kpc scale using CO(J=1-0) line among several galaxies
  - Little study to estimate accurate SFR

✳ Motivation

- Studying the K-S law on 500 pc scale using CO(J=1-0) line as a tracer of the amount of molecular gas to 10 nearby galaxies
  - We resolve galactic structures and study the K-S law to each structure

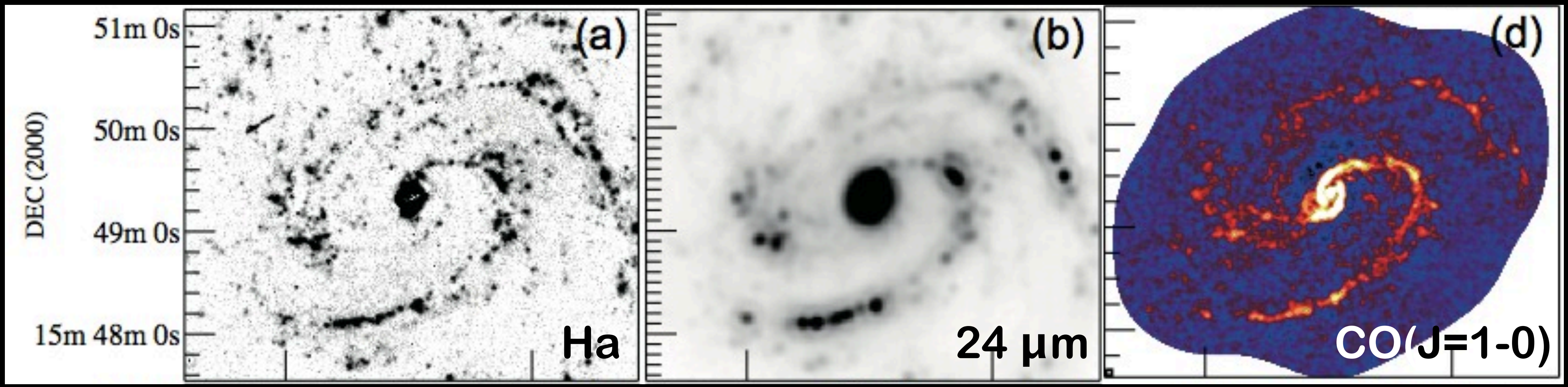
2. OBSERVATIONS & METHODS

Target of The Study

- Nearby disk galaxies which have relatively face-on viewing

NAME	Distance (Mpc)	V_{LSR} (km/s)	Hubble Type	i (deg)	P.A. (deg)
NGC 3521	10.1	801	SABbc	64	163
NGC 3627	9.38	727	SABb	65	173
NGC 4254	16.5	2407	SAc	-30	24
NGC 4303	16.1	1556	SABbc	28	312
NGC 4321	14.32	1571	SABbc	32	30
NGC 4736	5.2	308	SAab	36	105
NGC 4826	7.48	408	SAab	-59	115
NGC 5055	7.8	484	SAbc	56	105
NGC 5194	7.62	463	SABbc *	20	163
NGC 6946	6.8	50	SABcd	32	53

Methodology of The Study



- Re-gridding Σ_{SFR} and Σ_{H2} data to 500 pc scale
  - Σ_{H2} : CO(J=1-0) data
  - Σ_{SFR} : Ha + 24um data
- We compare pixel-by-pixel of both Σ_{SFR} and Σ_{H2} data, and plot each data point in the K-S law plot
- Fitting the linear regression to the correlation

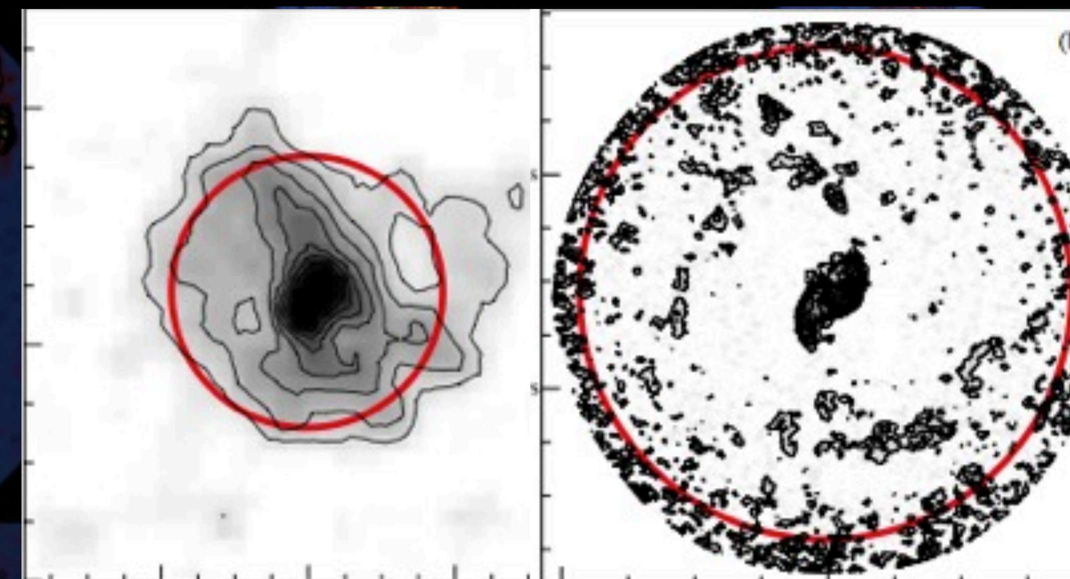
Observations

- We observed CO(J=1-0) line by NRO45 and CARMA as a part of CANON survey
  - ✳ NGC 4303 by Momose et al. 10
  - ✳ NGC 5194 by Koda et al. 09

※ CANON = CARMA and NOBEYAMA Nearby-galaxies CO survey

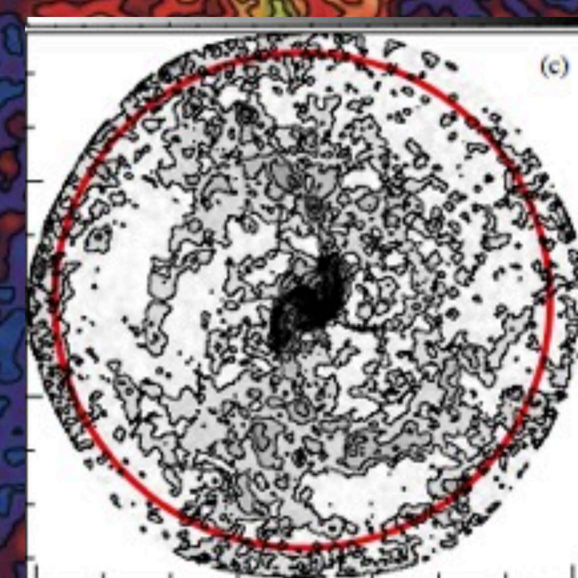
Data Combining

- We require the high spatial resolution data without missing flux
- Combining the data observed by single-dish and interferometer can recover the total flux with high spatial resolution

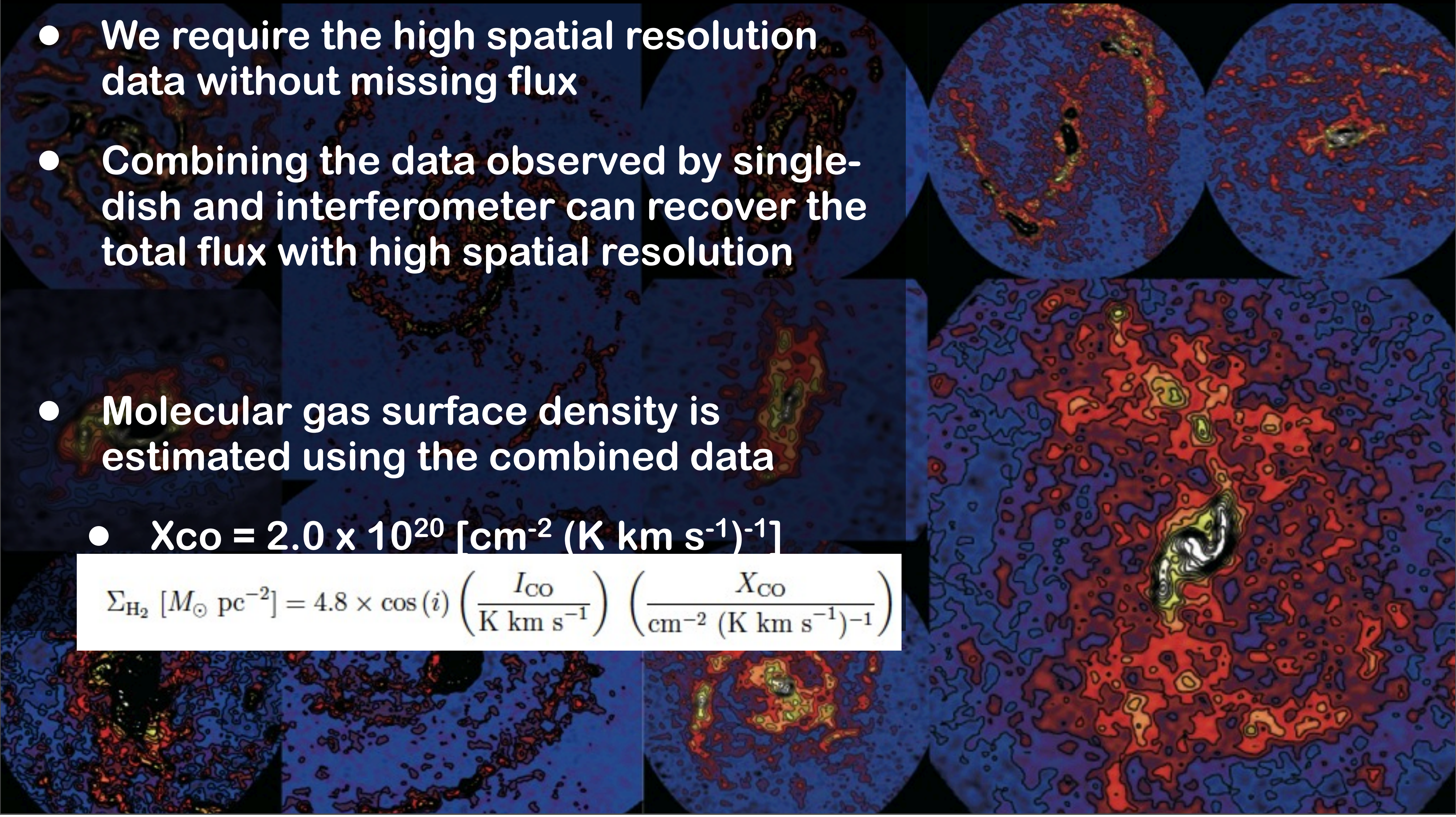


- Molecular gas surface density is estimated using the combined data
  - Xco = 2.0 x 10^{20} [cm^{-2} (K km s^{-1})$^{-1}$]

$$\Sigma_{H_2}\ [M_\odot\ \mathrm{pc}^{-2}] = 4.8 \times \cos(i) \left(\frac{I_{CO}}{\mathrm{K\ km\ s^{-1}}}\right) \left(\frac{X_{CO}}{\mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}}\right)$$



Data Combining



- We require the high spatial resolution data without missing flux
- Combining the data observed by single-dish and interferometer can recover the total flux with high spatial resolution
- Molecular gas surface density is estimated using the combined data
  - $X_{CO} = 2.0 \times 10^{20}$ [cm^{-2} (K km s^{-1})$^{-1}$]

$$\Sigma_{\mathrm{H_2}}\ [M_\odot\ \mathrm{pc}^{-2}] = 4.8 \times \cos(i) \left(\frac{I_{\mathrm{CO}}}{\mathrm{K\ km\ s^{-1}}}\right) \left(\frac{X_{\mathrm{CO}}}{\mathrm{cm^{-2}\ (K\ km\ s^{-1})^{-1}}}\right)$$

Estimating SFR

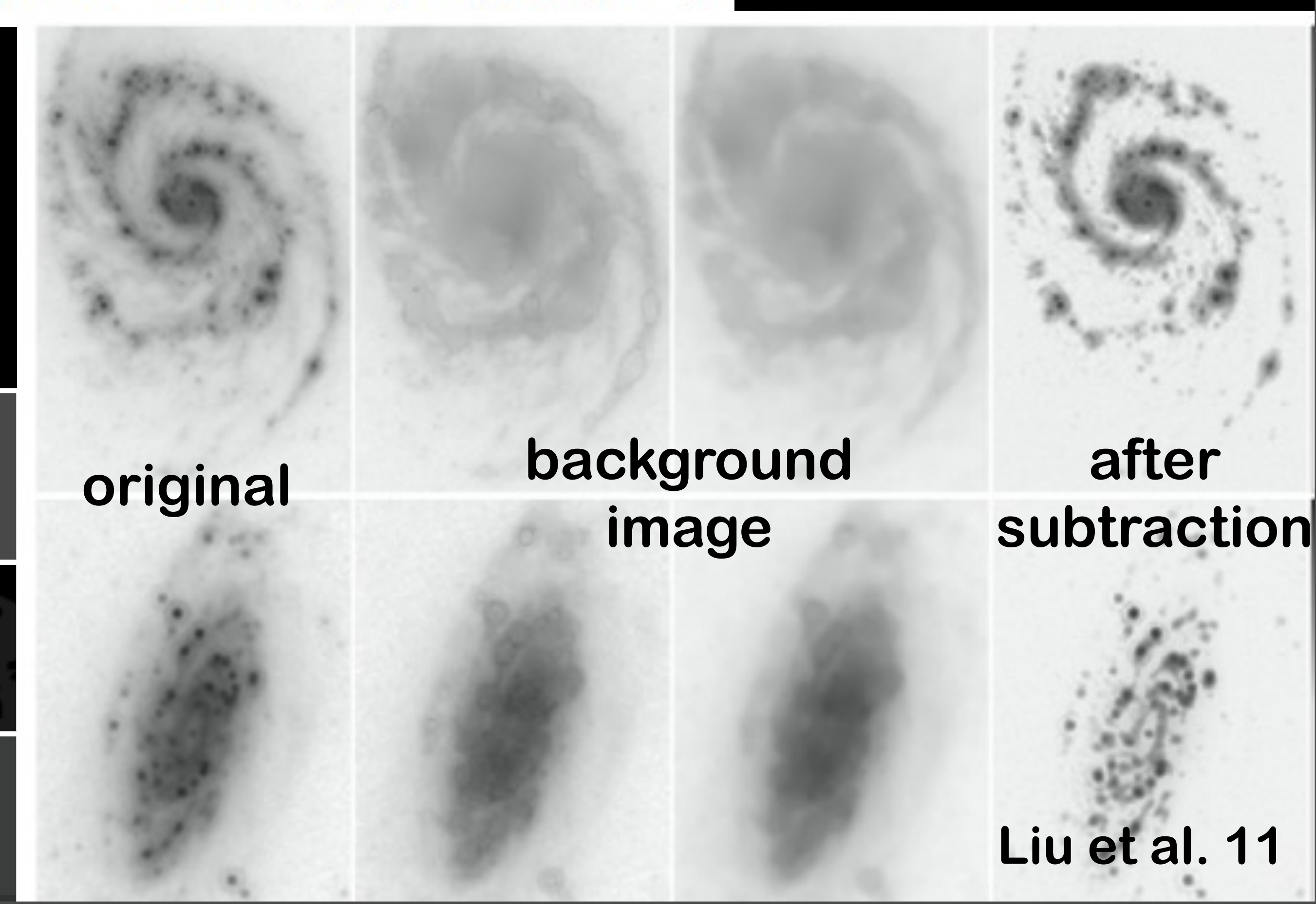
- We can estimate SFR counting emission from young stars and assuming IMF
    - Ha and 24um images are used to estimate SFR (Kennicutt 98; Calzetti et al. 07)

$$
\begin{aligned}
\mathrm{SFR}\ [M_{\odot}\mathrm{yr}^{-1}] &= 7.9\times10^{-42}\ L(\mathrm{H}\alpha)_{\mathrm{corr}}\ [\mathrm{erg\ s}^{-1}] \\
&= 7.9\times10^{-42}\ \{L(\mathrm{H}\alpha)_{\mathrm{obs}} + (0.031\pm0.006)L(24\mu\mathrm{m})\}\ [\mathrm{erg\ s}^{-1}]
\end{aligned}
$$

- We carried out diffuse ionized gas (DIG) subtractions

Diffuse Ionized Gas

	local	not young stars	fraction
Ha	leak emission	ionized by hot old stars	30-50 % of total L_{Ha}
24um	---	dust heated by old stars	20-80 % of total f_{24um}



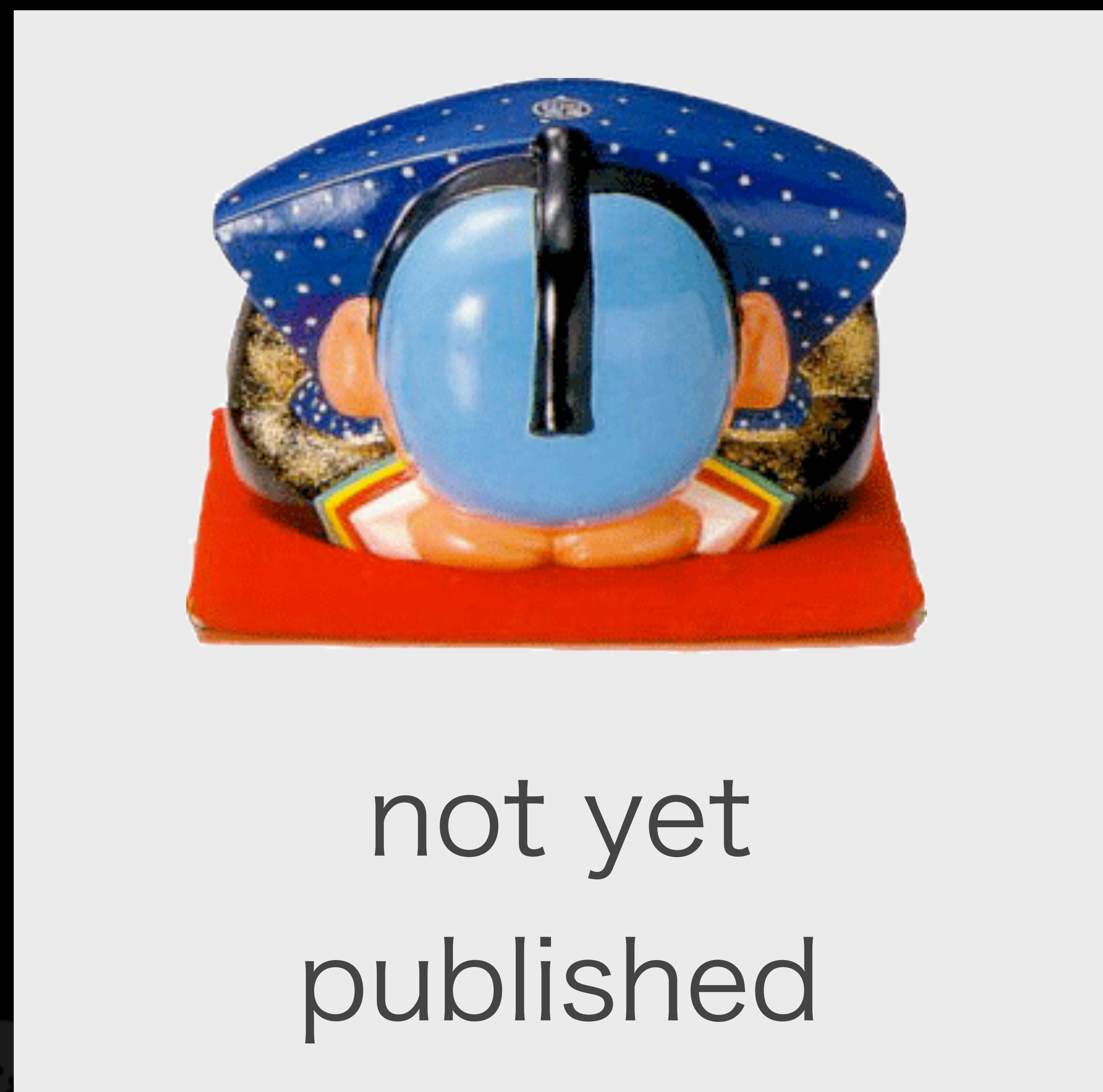
3. RESULTS & DISCUSSIONS

3.1 GLOBAL K-S LAW

3.2 STRUCTURAL K-S LAW

3.1
GLOBAL K-S LAW FROM ALL GALAXIES

The K-S Law
From All 10 galaxies



We obtain super-linear slope of the K-S law on 500 pc

- We obtain the index of
  - N = 1.75±0.09 (DIG subtracted) on 500 pc
  - N = 1.26±0.03 on 750 pc

Discussion 1
Physical Predictions

- Star formation would be regulated by some physically motivated time scale

$$\Sigma_{\rm SFR} = \epsilon_{\rm tphy} \frac{\Sigma_{\rm gas}}{t_{\rm phy}},$$

$$\Sigma_{\rm SFR} \propto \epsilon_{\rm tphy}\ \Sigma_{\rm gas}^{1-m} = \epsilon_{\rm tphy}\ \Sigma_{\rm gas}^{N},$$

~100 pc

N = 1

- Constant star formation at fixed time scale

$$\mathrm{SFR} = \frac{\rho_{\rm gas}}{t_{\rm SF}}.$$

$$\Sigma_{\rm SFR} = \epsilon \Sigma_{\rm gas},$$

N > 1

- Star formation at a free-fall time scale (t_{ff})

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G \rho_{\rm gas}}}.$$

$$\Sigma_{\rm SFR} = \epsilon_{\rm ff} \frac{\Sigma_{\rm gas}}{t_{\rm ff}} \propto \Sigma_{\rm gas}^{1.5},$$

N = 1.5

- Star formation regulated by collision time scale

$$t_{\rm cc} = \frac{\lambda}{v} = \frac{h m_{\rm GMC}}{\sqrt{2}\ \Sigma_{\rm gas}\ a^2\ \pi v}$$

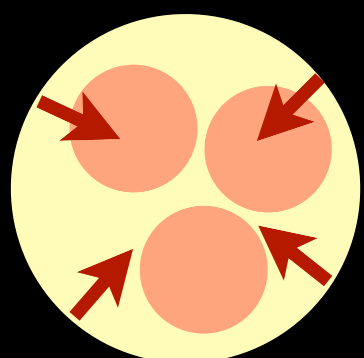
$$\lambda_{\rm mfp} = \frac{1}{\sqrt{2} N D},$$

$$\Sigma_{\rm SFR} = \epsilon_{\rm cc} \frac{\Sigma_{\rm gas}}{t_{\rm cc}} \propto \Sigma_{\rm gas}^{2}.$$

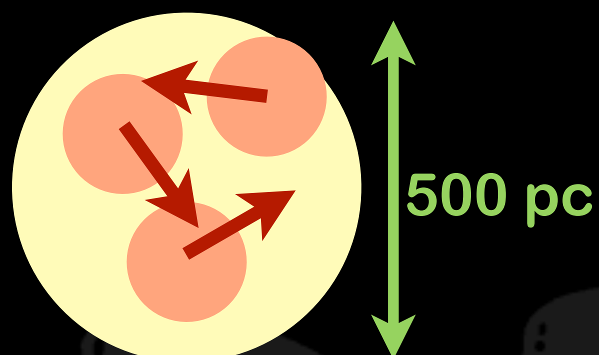
N = 2

Discussion 1
Physical Predictions on 500 pc

N = 1.5



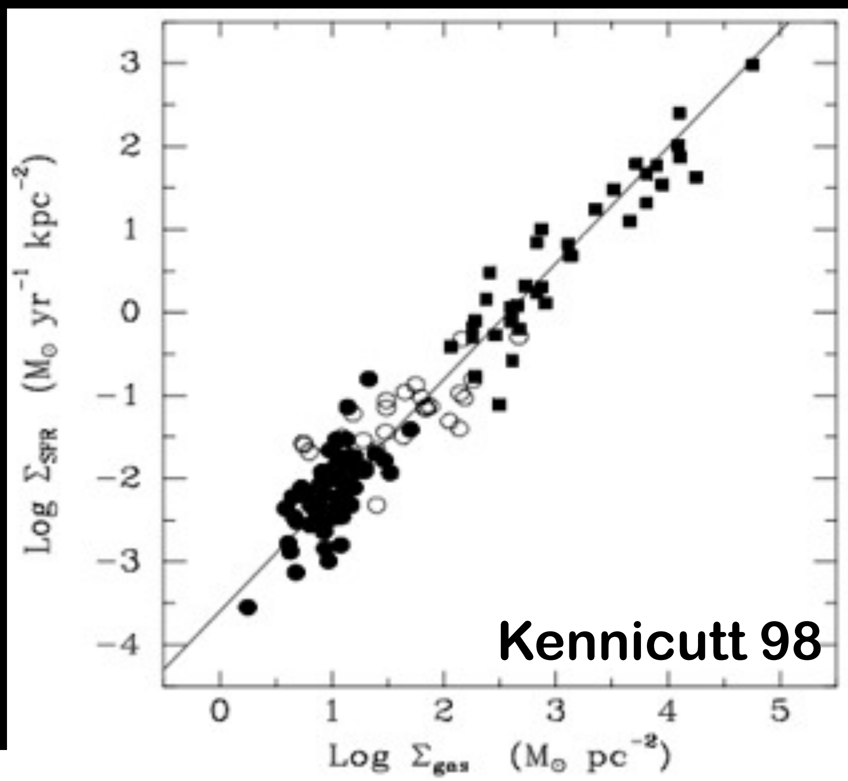
N = 2

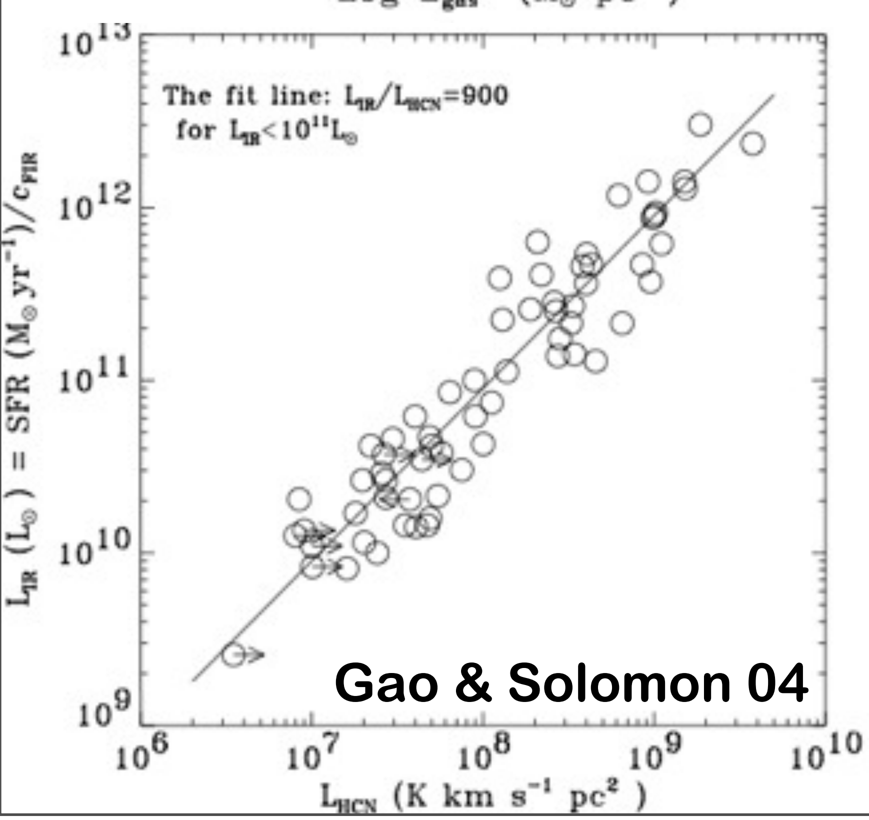


- Within a 500 pc, there may be some GMCs to form stars
- N > 1
  - Existence of molecular gas is not enough to form clouds which will bear stars
    - Self-gravity of molecular gas
    - Cloud-cloud collision
    - Mixture of both

Any mechanism is required for triggering star formation on 500 pc scale

Discussion 2
Gas Tracers and The Index





The relation between the amount of molecular gas and SFR (e.g. Kennicutt 07; Liu et al. 11; This study)

- N > 1
  - ✳ The relation between the molecular gas which can form stars and SFR

The relation between dense gas and SFR (e.g. Gao & Solomon 04; Komugi et al. 07; Iono et al. 09)

- N ~ 1
  - ✳ The relation between star-forming cores and SFR

Line	n_{crit} [cm^{-3}]
CO (J=1-0)	3 x 10^2
HCN (J=1-0)	~ 10^{5-6}
CO (J=3-2)	~ 10^4
CO (J=2-1)	~ 10^3

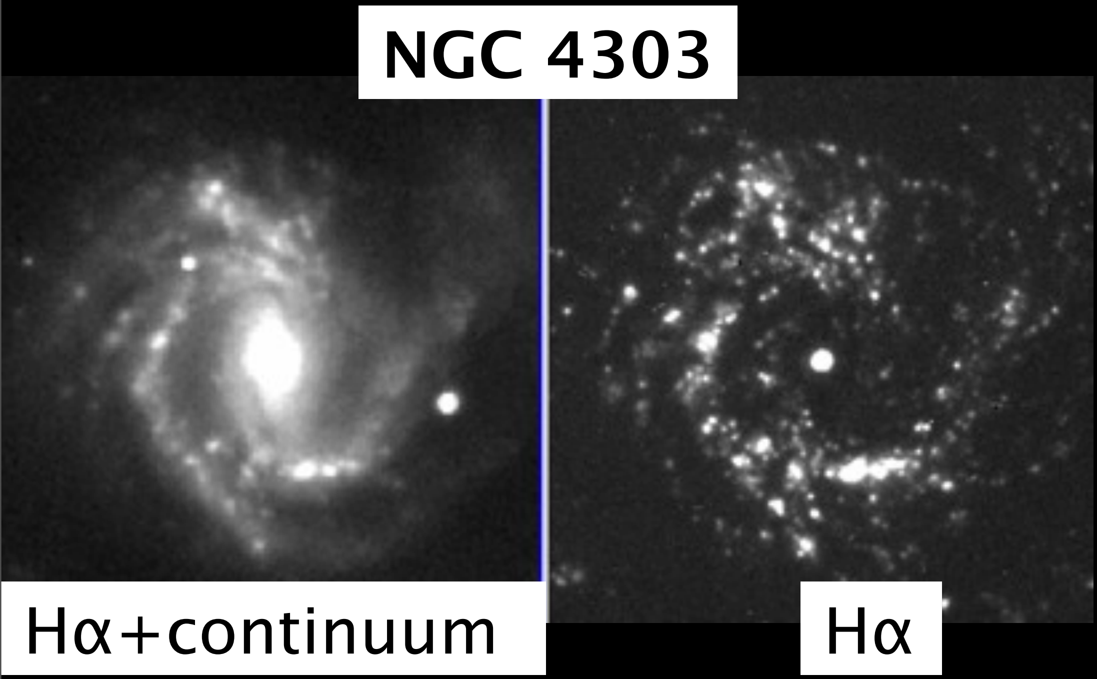
CO(J=1-0) is a best tracer to understand SF mechanism

Summary 1

- We estimate the K-S law index by estimating accurate SFR and molecular gas surface density from CO(J=1-0)
- The K-S law on 500 pc shows the super-linear slope with N = 1.75.
- Some trigger mechanisms, such as self-gravity of molecular gas or cloud-cloud collision or mixture of them are necessary for forming stars.
- The correlation between SFR and amount of the molecular gas traced by CO(J=1-0) can indicate the mechanism of star formation rather than the correlation seen by dense gas tracers

3.2
STRUCTURAL K-S LAW WITHIN A GALAXY

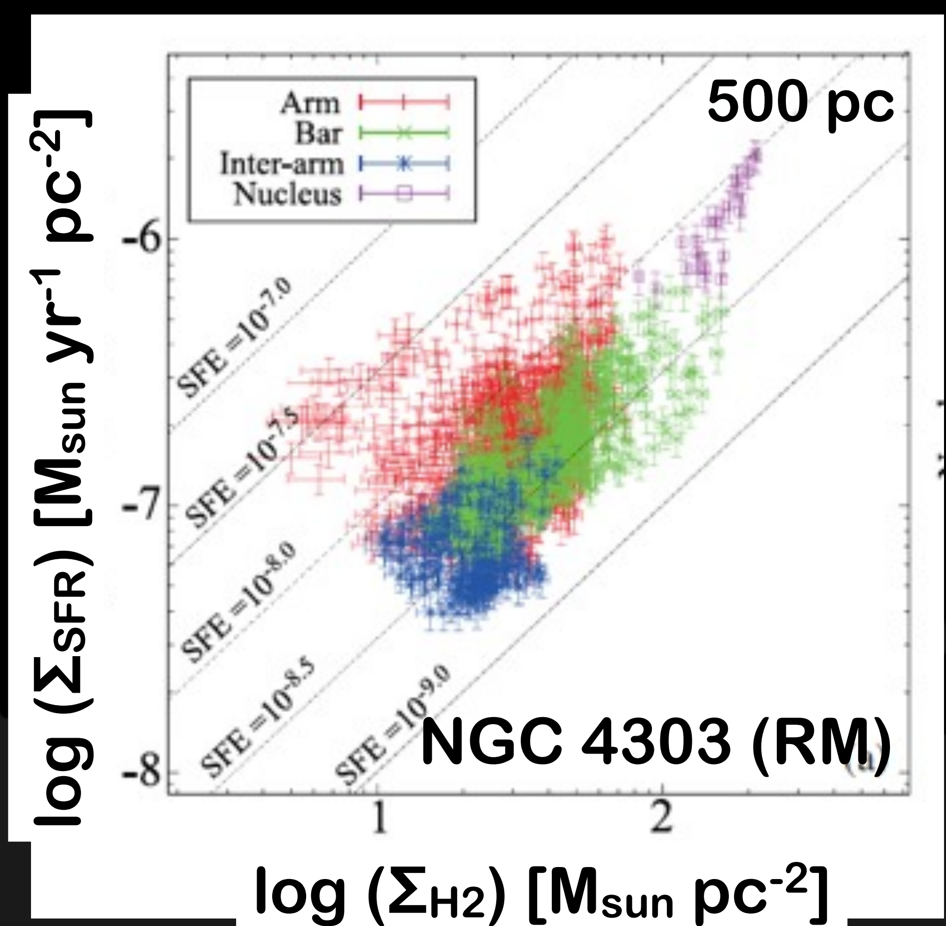
Star Formation Within A Galaxy



We confirmed the difference of SFE depending on galactic structures (Momose et al. 10)

- Active star formation in the spiral arms
- Star formation is suppressed in the bar

- Galactic dynamics (e.g. galactic shock, shear in the bar) would regulate star formation (e.g. Downes et al. 96; Sheth et al. 02, 04)



※ Star Formation Efficiency (SFE)
The ratio of SFR to gas mass [/yr]

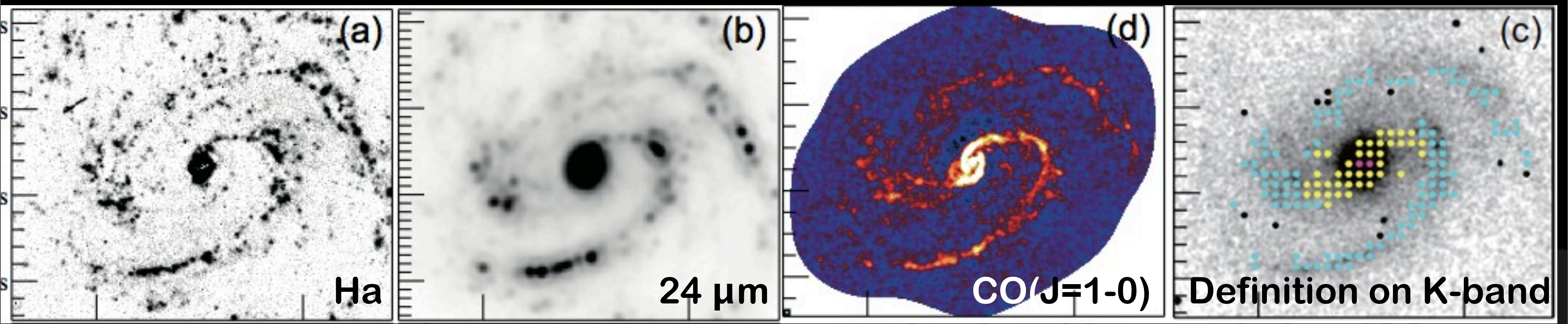
Definition of Galactic Structures

- We divide all regions of a galaxy to the nucleus, spiral arms, bar and other regions where is including inter-arm region

Nucleus: central 500 pc around the dynamical center

Bar: estimate using IRAF

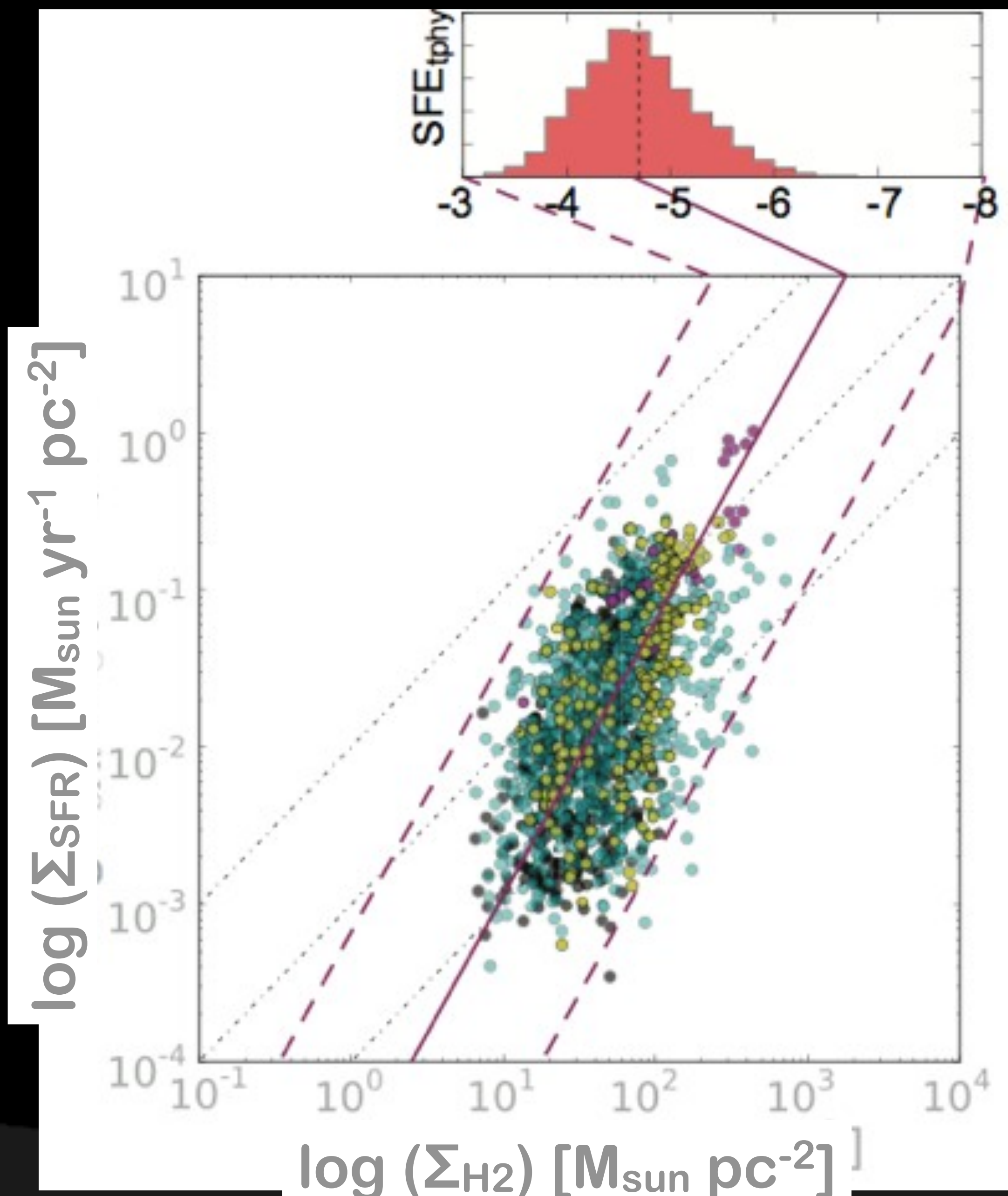
Spiral Arms/Other: estimated using GALFIT



Star Formation in Each Structure

not yet
published

The Variation of Star Formation Activities



- We define SFE$_{tphy}$ as following:
  - ✳ Efficiency toward the averaging star formation mechanism given area

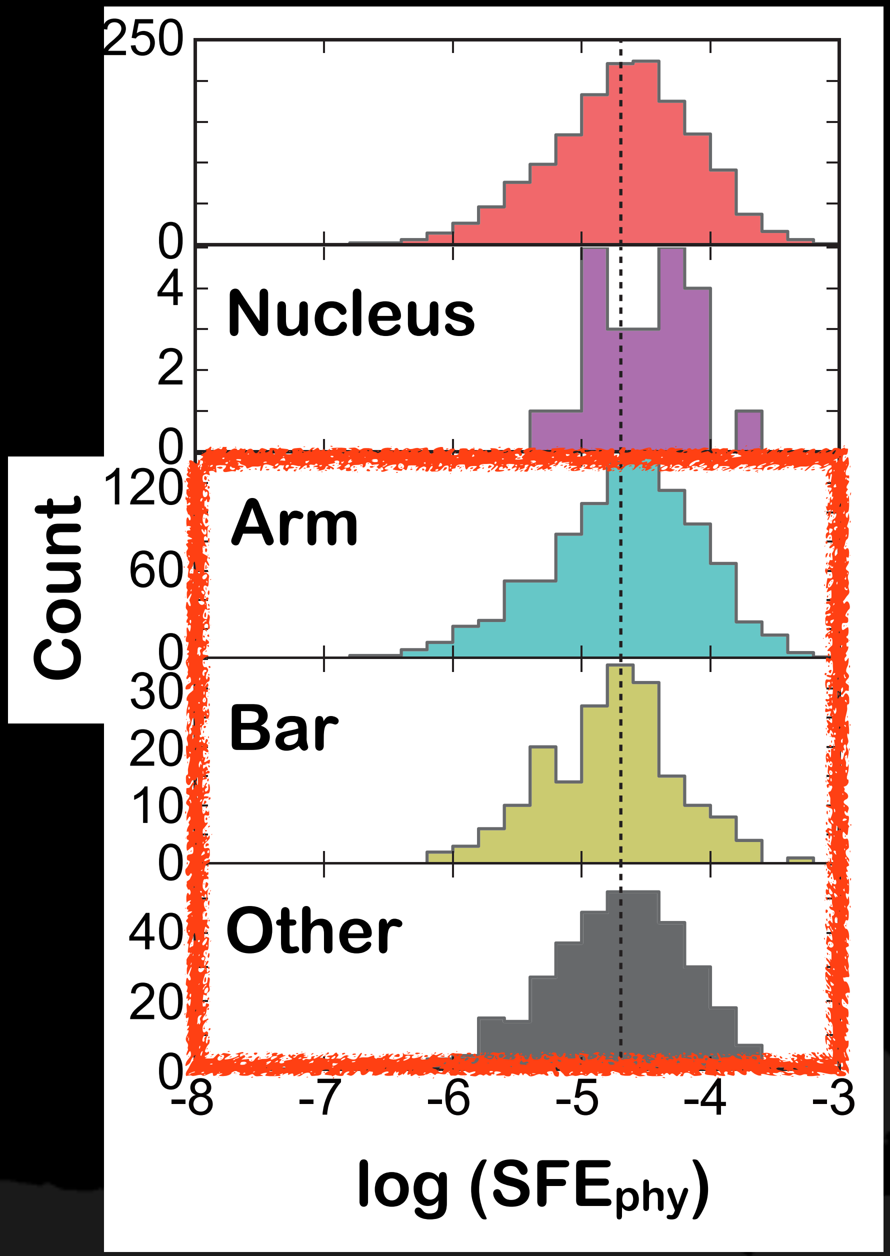
$$\Sigma_{\rm SFR} = \epsilon_{\rm tphy} \frac{\Sigma_{\rm gas}}{t_{\rm phy}},$$

$$\Sigma_{\rm SFR} \propto \epsilon_{\rm tphy}\, \Sigma_{\rm gas}^{1-m} = \epsilon_{\rm tphy}\, \Sigma_{\rm gas}^{N},$$

$$\mathrm{SFE_{tphy}} = \frac{\Sigma_{\rm SFR}\ [M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}]}{\Sigma_{\rm H2}^{N}\ [M_\odot\ \mathrm{pc}^{-2}]^{N}}.$$

N = 1.75

The Variation of Star Formation Activities



- We compare peak and distribution of the SFE_{tphy}s
  - Scatter: the nucleus is smaller than rest of structures
  - Peak: little different
- The SFE_{tphy}s are little different among structures from all galaxies
  - Averaging mechanism of star formation can be the same
  - The nucleus may be different than rest of structures

Summary 2

- We compare the K-S law for each structure of a galaxy -- the nucleus, bar, spiral arms and other region
- Averaging structures from all sample galaxy show the little difference of star formation mechanism
    - Star formation mechanism may be different from other structures of a galaxy

4. SUMMARY

Summary

Aim & Method

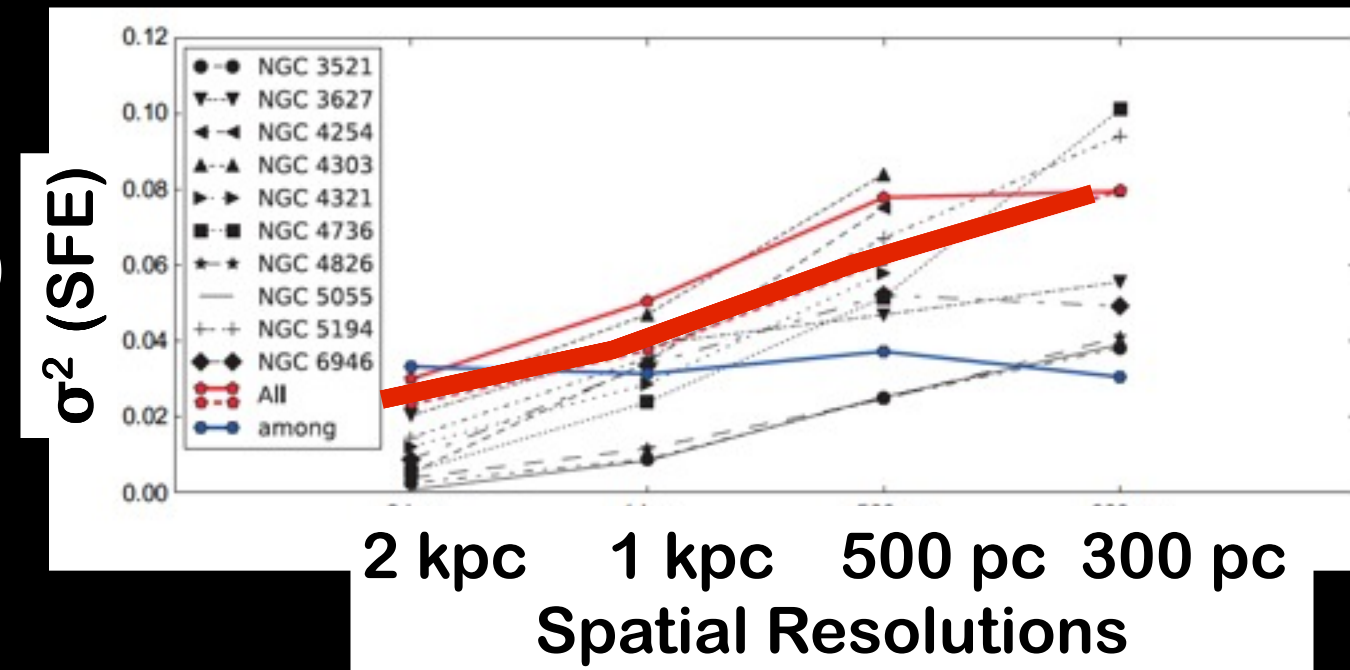
- We study the K-S law on 500 pc scale among nearby 10 galaxies
- In order to estimate the amount of molecular gas and SFR accurately,
  - we combined CO(J=1-0) data observed by CARMA and NRO45, respectively
  - we subtracted DIG from Ha and 24um images

Result & Discussion

- We obtained the super-linear slope of the K-S law (N = 1.75)
  - Star formation can be induced by some trigger mechanism
  - The correlation between SFR and bulk of molecular gas traced by CO(J=1-0) can show the mechanism of star formation
- Self-gravity of molecular gas is a main mechanism for star formation in each structure of a galaxy

Future Works

- Bulk gas vs SFR
  - Global K-S law --> N > 1 (~ 1.5)
  - Resolved K-S law --> N > 1
  - GMC scale --> break-down



Which scale causes break-down of the K-S law?