Breakdown of Kennicutt-Schmidt Law at Giant Molecular Cloud Scales

Sachiko Onodera (Meisei University, Japan),
NRO MAGiC project team, FUGIN project team

Outline of Today's Talk

- Resolved Kennicutt-Schmidt law in nearby galaxies
  - NRO M33 All-disk survey of Giant Molecular Clouds project (MAGiC)
  - Breakdown of the K-S law in M33 at GMC scale
  - Reason for the breakdown
  - Star formation relation derived from other tracers of star formation rate and gas
- Resolved star formation relation in the Milky Way
  - Preliminary result from NRO galactic-plane CO survey project (FUGIN)

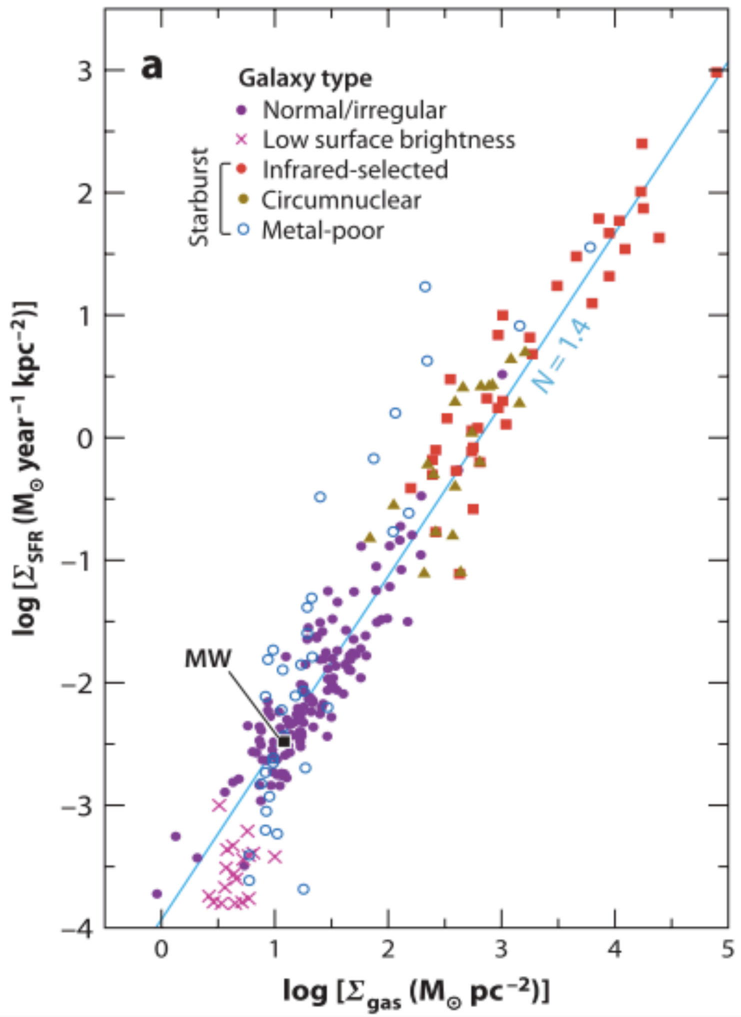
Introduction: Molecular Gas and Star Formation in Nearby Galaxies

- Kennicutt-Schmidt law

Global correlation between gas mass and star formation rate (SFR) in galaxies ($\Sigma_{SFR} \propto \Sigma_{gas}^{N}$)

N~1.4 (Kennicutt 1998, Kennicutt & Evans 2012)

Large-scale studies provide essential information on the relation between large-scale properties of galaxies and star formation



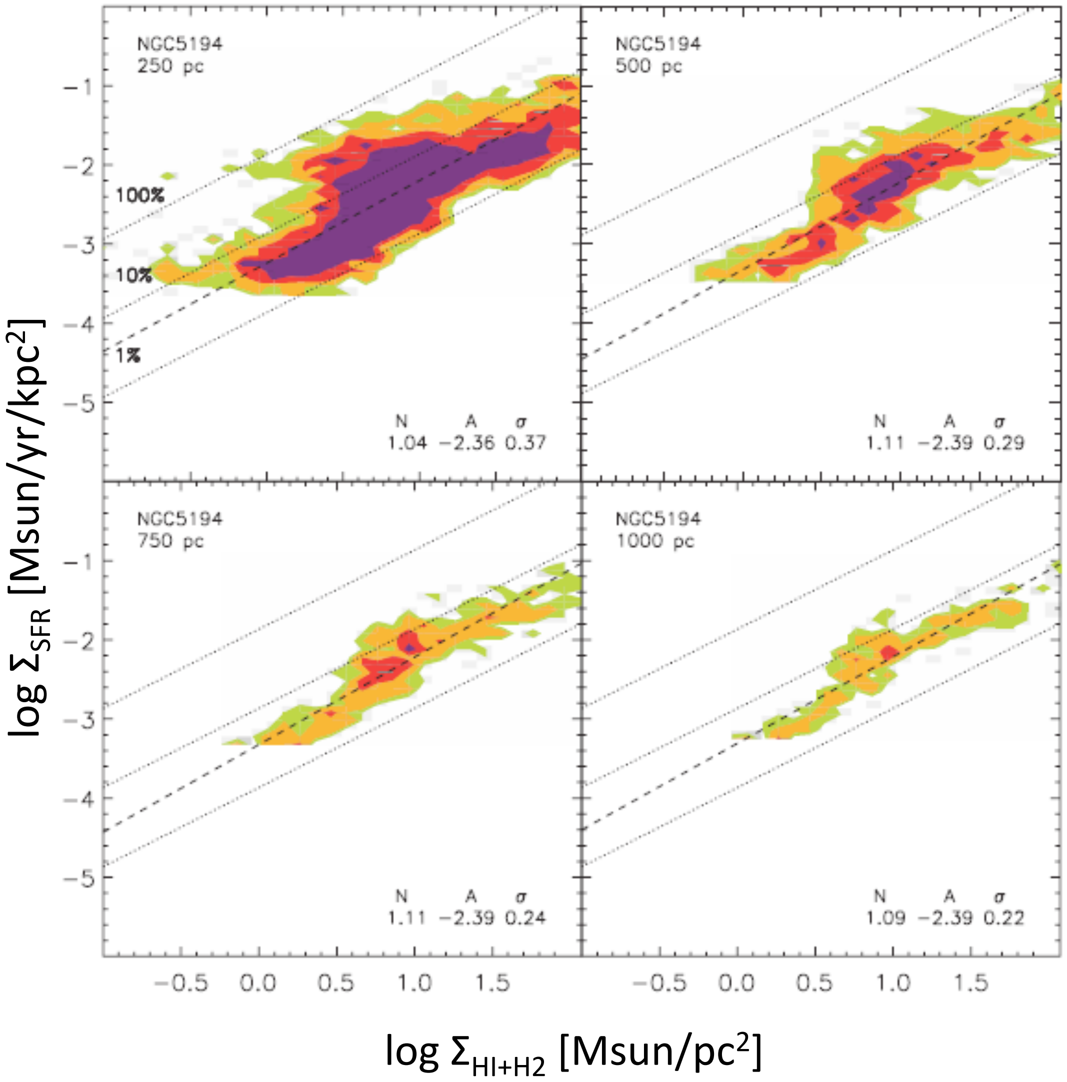
Kennicutt & Evans 2012

Resolved Kennicutt-Schmidt Law

The process of converting gas into stars occurs on a smaller scale, within molecular clouds.

- How is this correlation connected to each star-forming region?
- To which scale does this correlation hold?

Bigiel et al. 2008



<u>Observational Difficulty</u>

Most galaxies are too far to resolve each star-forming region because of our resolution limit

→ close galaxies

M33 All-disk survey of Giant Molecular Clouds (NRO MAGiC)

- Local group galaxy
- Close to our Galaxy (D = 840 kpc) each GMC can be resolved (NRO 45m resolution : 20"~ 80 pc)

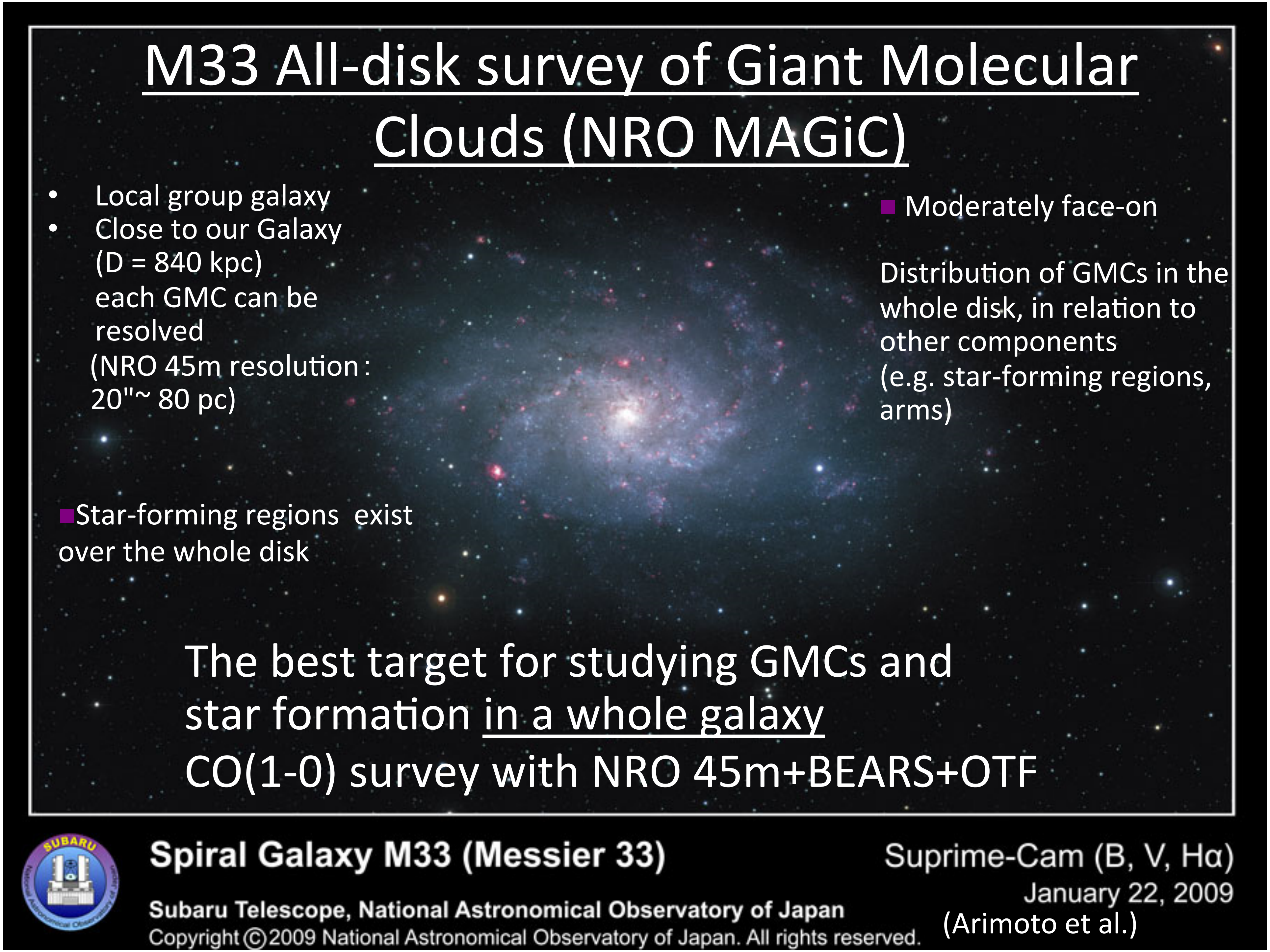
■ Moderately face-on

Distribution of GMCs in the whole disk, in relation to other components (e.g. star-forming regions, arms)

■Star-forming regions exist over the whole disk

The best target for studying GMCs and star formation <u>in a whole galaxy</u>

CO(1-0) survey with NRO 45m+BEARS+OTF

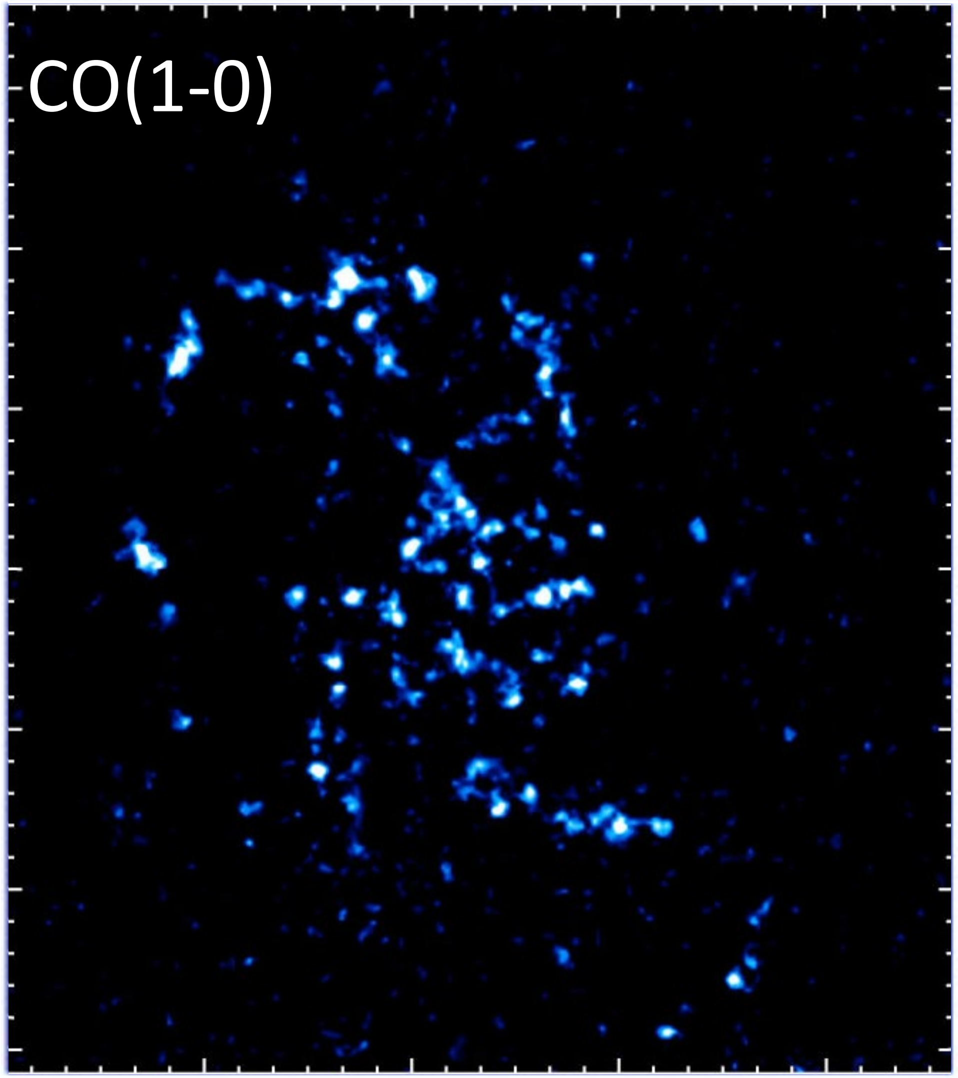


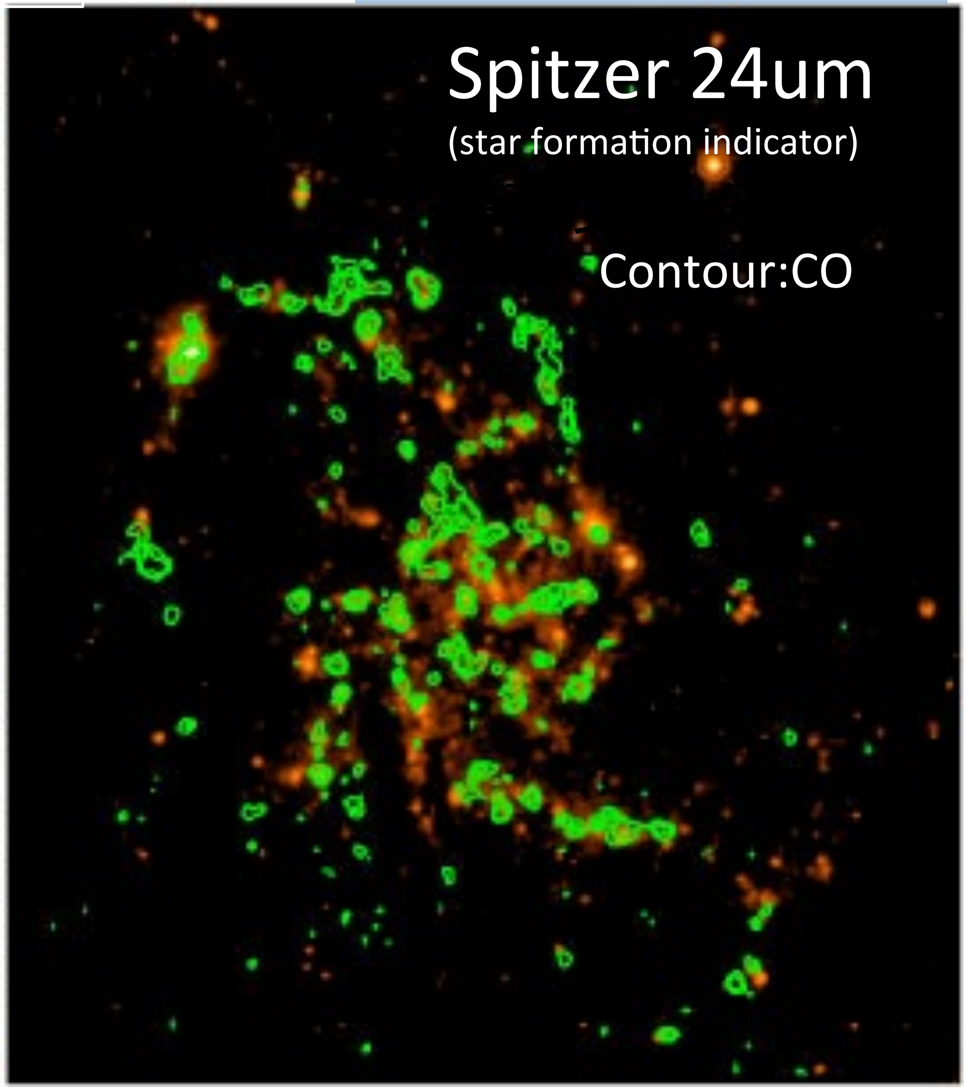
(Arimoto et al.)

Variety of Molecular Gas and Star Formation

Data cube available on NRO website!

K-S law is broken at some scales





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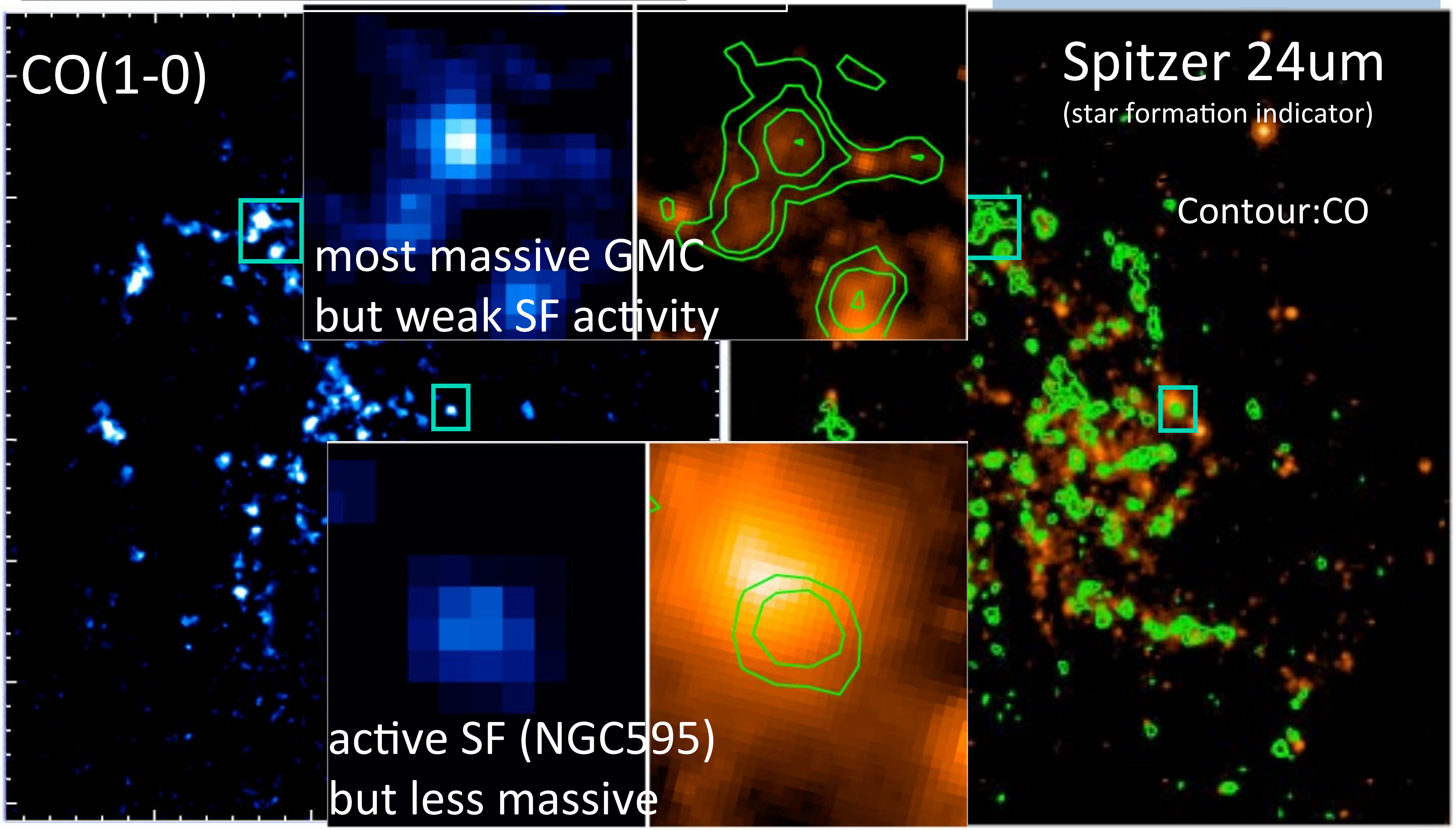
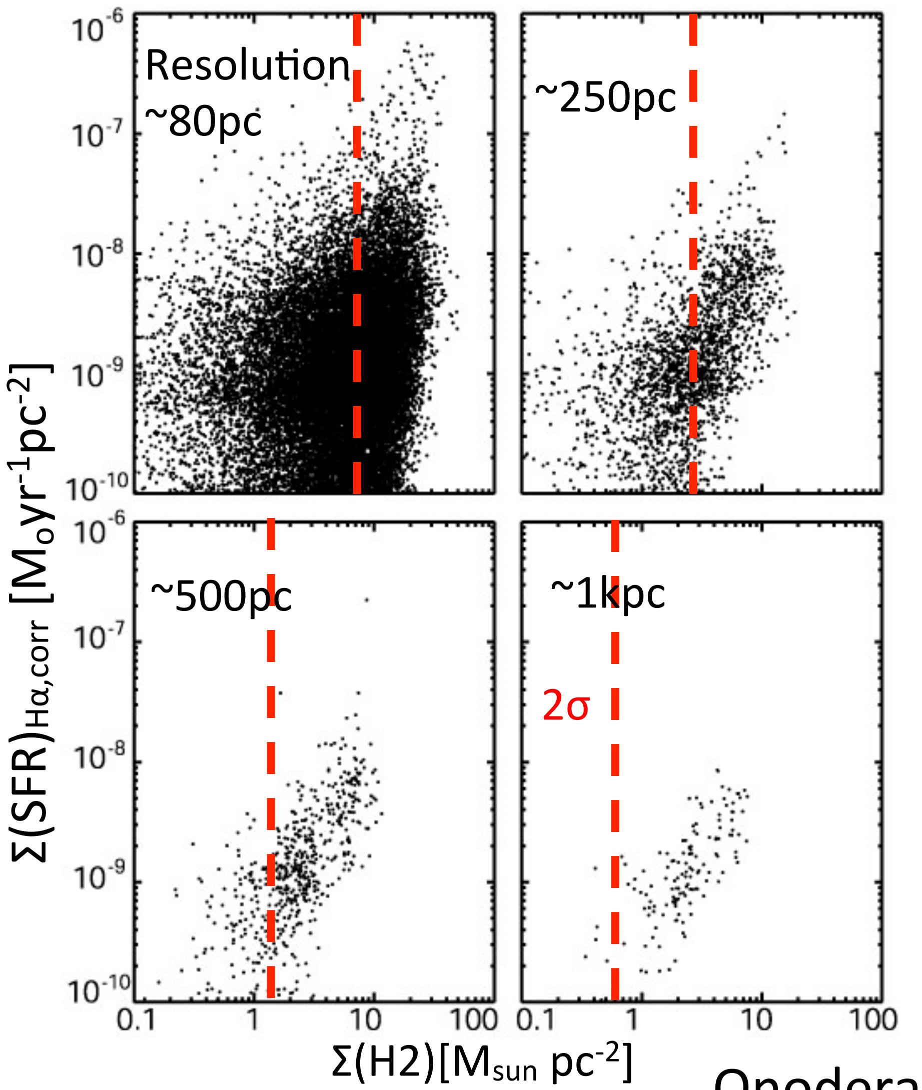


To what scale is the Kennicutt-Schmidt law valid?



the surface density of molecular gas mass vs SFR in a high resolution (~80pc)

- Correlations are evident in 1kpc, 500pc
- Become looser with higher resolution, and finally breaks down (dispersion over ~four orders of magnigude)

Schruba+ (2010), Boquien+ (2015) which used UV, Hα, MIR, &FIR have shown the similar results

⇒GMC scale (~80pc) is where the K-S law becomes invalid

Onodera et al. 2010

Reasons for breakdown of the K-S law at GMC scales

- Drift of clusters from their parent clouds
- Stochasticity effects on the estimation of SFR
- Different evolutionary stages of GMCs

Reason for breakdown of the K-S law at GMC scales

- Drift of clusters from their parent clouds
  - In Milky Way, young clusters recede from their parent GMCs with v>10km/s (Leisawitz+ 1989)
  - the separation between them is expected to be ~100pc at a cluster age of 10Myr

  ⇒ comparable to our resolution of 80pc

⇒ However, it cannot explain some star forming regions without associated GMCs nor GMCs without associated star forming regions

Reason for breakdown of the K-S law at GMC scales

- Stochasticity effects on the estimation of SFR
  - due to small sampling at high spatial resolutions
  - IMF is not fully populated when smaller regions that contain only a few stars in clusters are sampled.
  - Thus, in regions with weaker extinction-corrected Hα emission, this effect may lead to significant scatters in the estimated Σ(SFR).
  - Assuming $T \sim 10^4$ K and $n_e \sim 100 cm^{-3}$ in HII regions, the ionizing photon flux is $Q(H0) = 7.3\times10^{11} L(H\alpha)_{corr}\ s^{-1}$ (Kennicutt 1988; Brocklehurst 1971).
  - $\Sigma(SFR) = 10^{-9}$ Msun $yr^{-1}\ pc^{-2}$

    ⇒ $L(H\alpha)_{corr} = 6.6\times10^{35}\ erg\ s^{-1}$ within the 80 pc beam

    ⇒ Total ionizing photon flux : $Q(H0) = 4.9\times10^{48}\ s^{-1}$.

Stochasticity effects on the estimation of SFR

– The ratio of the error in Q(H0) to the mean value, σ[Q(H0)]/Q(H0), is ~10 $M^{-1/2}$ (M:cluster mass)(Cervino et al. 2002)

⇒ the cluster mass required to produce the ionizing flux is 50∼ 5×10^4 Msun, which results in σ[Q(H0)]/Q(H0) ≈ 1 to 0.04.

- In summary, the error due to the effect of stochasticity at Σ(SFR) = 10^{-9} Msun yr^{-1} pc^{-2} is 0.04–1×10^{-9} Msun yr^{-1} pc^{-2} in the 80 pc scale.
- The error decreases with higher Σ(SFR) and lower spatial resolutions.

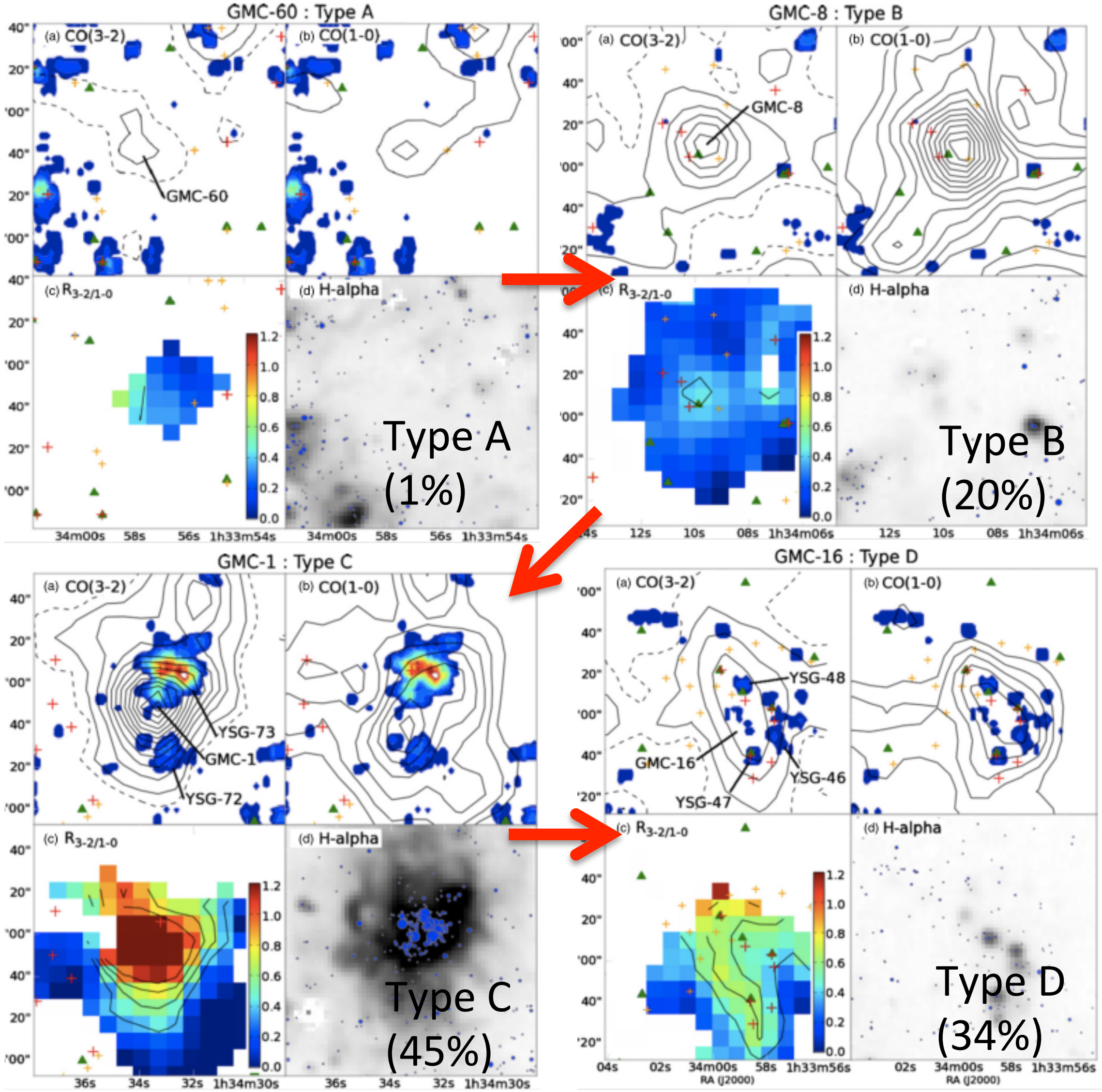
Although the error is significant at smaller Σ(SFR) at the 80 pc resolution, it cannot explain the scatter of over four orders of magnitude in Σ(SFR).

Evolutions of GMCs in M33

Different evolutionary stages in M33 using CO(3-2)

- Type A : no sign of massive SF
- Type B : only with relatively small HII regions
- Type C: with both HII regions & young (<10 Myr) stellar groups
- Type D: with both HII regions & relatively old (10–30 Myr) stellar groups

the dispersion in the K-S law is largely due to variations in the evolutionary stage of the GMCs

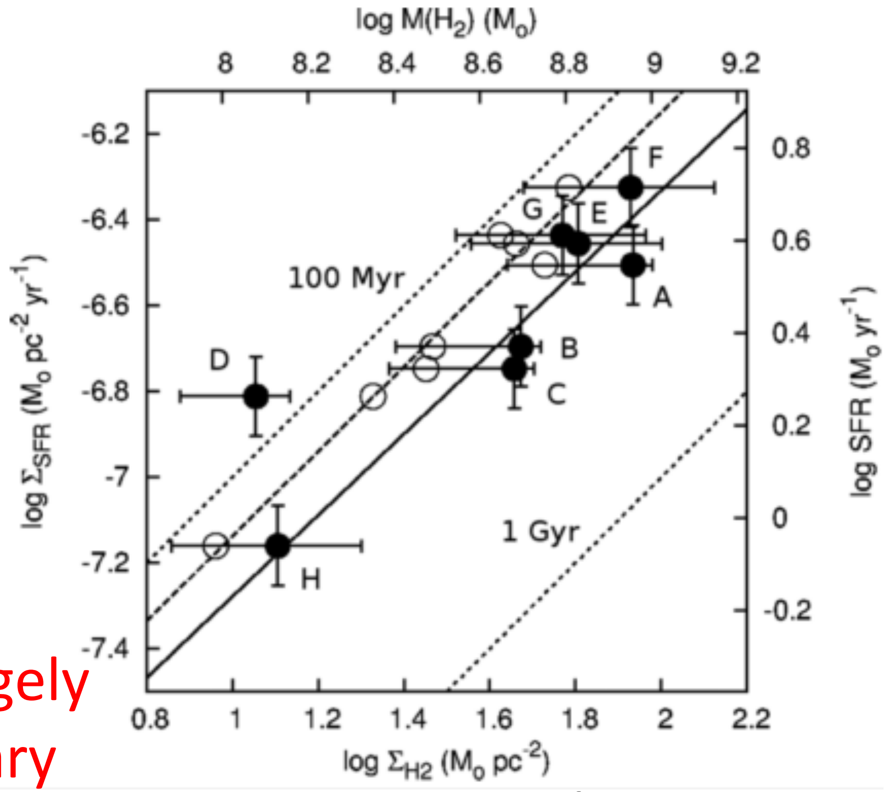


Miura et al. 2012

K-S law at matched age in Taffy I

- Taffy I: interacting galaxy that experienced a direct collision only ~20Myr ago
- Ages of the SF blobs estimated from Paα Equivalent width
- Ages of all blobs except for region B and region D: ~7Myr
  Region D : <3.5Myr
- The dispersion σ of correlation:
  14% (constant conversion factor)
  25% (different conversion factor)
  excluding region D
- at the same resolution (700pc)
  σ=50% (M51), 27% (NGC 3521)
  (Liu et al. 2011)
  43% (M33: 500pc resolution)
  (Onodera et al. 2010)

the dispersion in the K-S law is largely due to variations in the evolutionary stage of GMCs

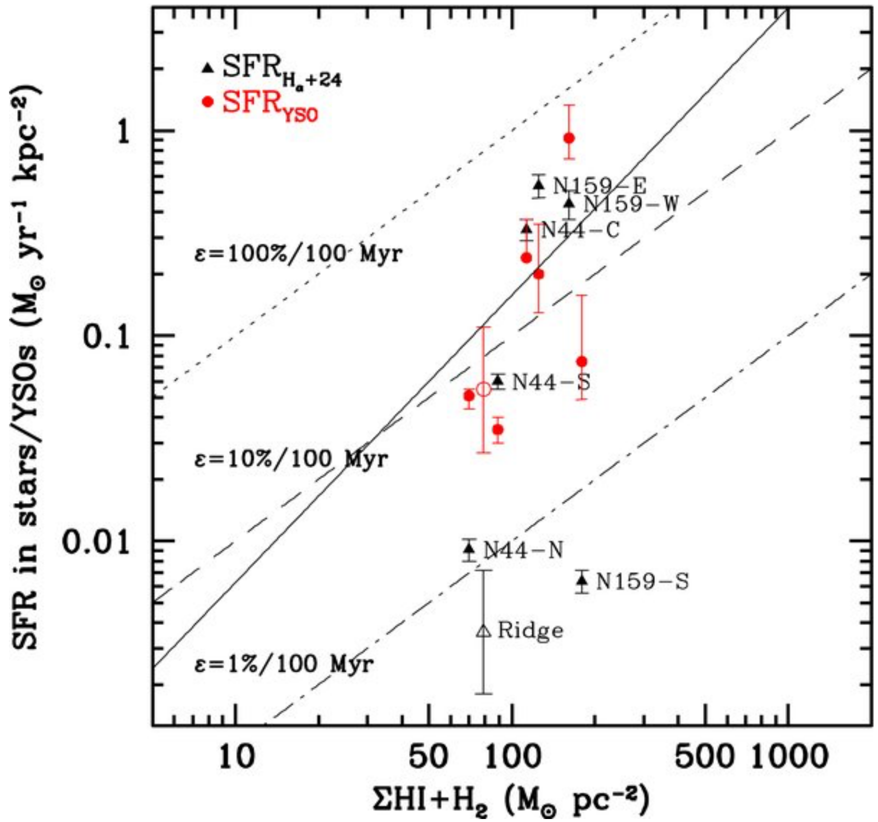


Komugi et al. 2012

K-S law using YSO as SFR tracer in Large Magellanic Cloud

- the relation between Σ(SFR) & Σ(HI+H2) in LMC for six GMCs
- large scatter in Σ(SFR) derived from Hα+24um ～ two orders of magnitude
- the Σ(HI+H2) lies within a factor of two
- scatter in Σ(SFR) derived from YSO ～an order of magnitude

⇒YSO: a better tracer of SFR



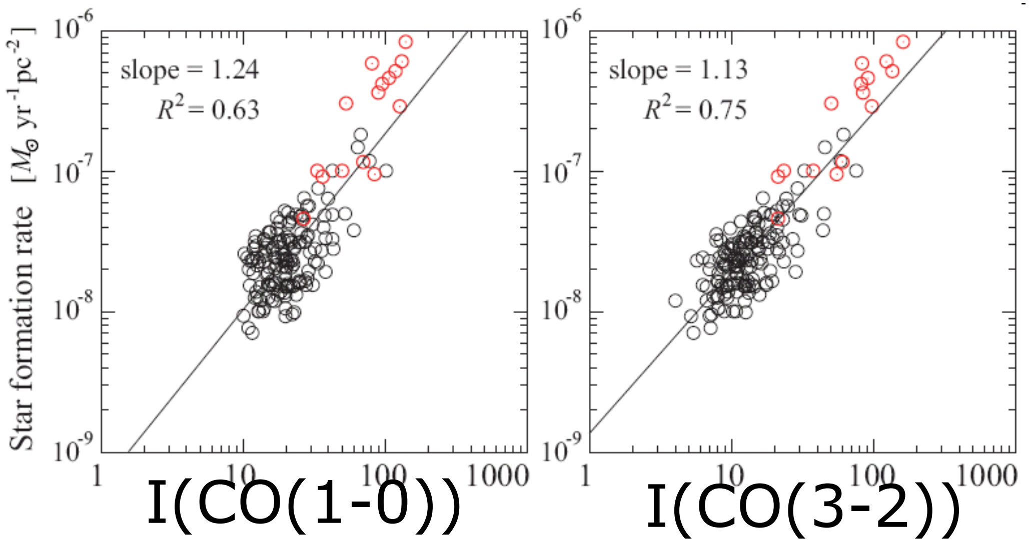
Chen et al. 2010

Previous Studies: CO(3-2)-SFR correlations in Nearby Galaxies (See also Michiyama's poster)

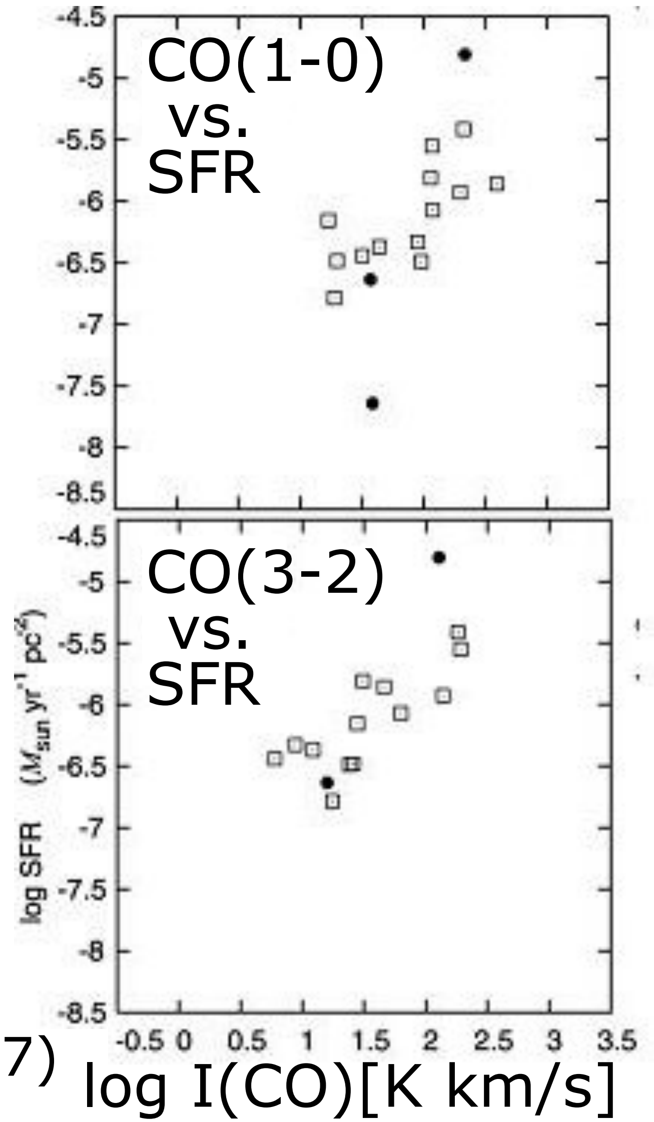
Nearby galactic centers

In 500pc~kpc resolution
CO(3-2) intensity: slightly better correlation with SFR than CO(1-0)

M83 disk&center

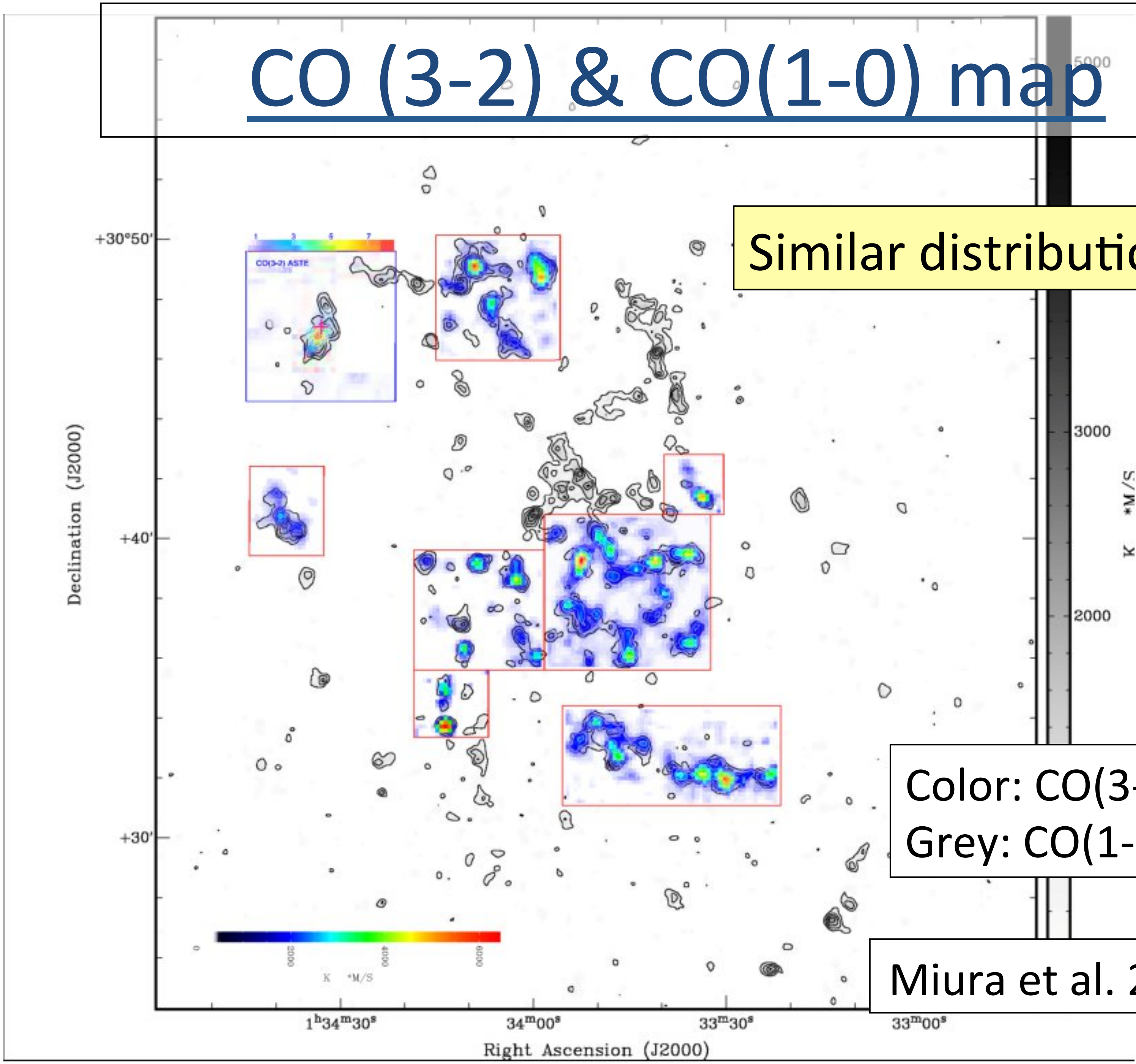


(Muraoka+ 2009)



(Komugi+ 2007)

CO (3-2) & CO(1-0) map

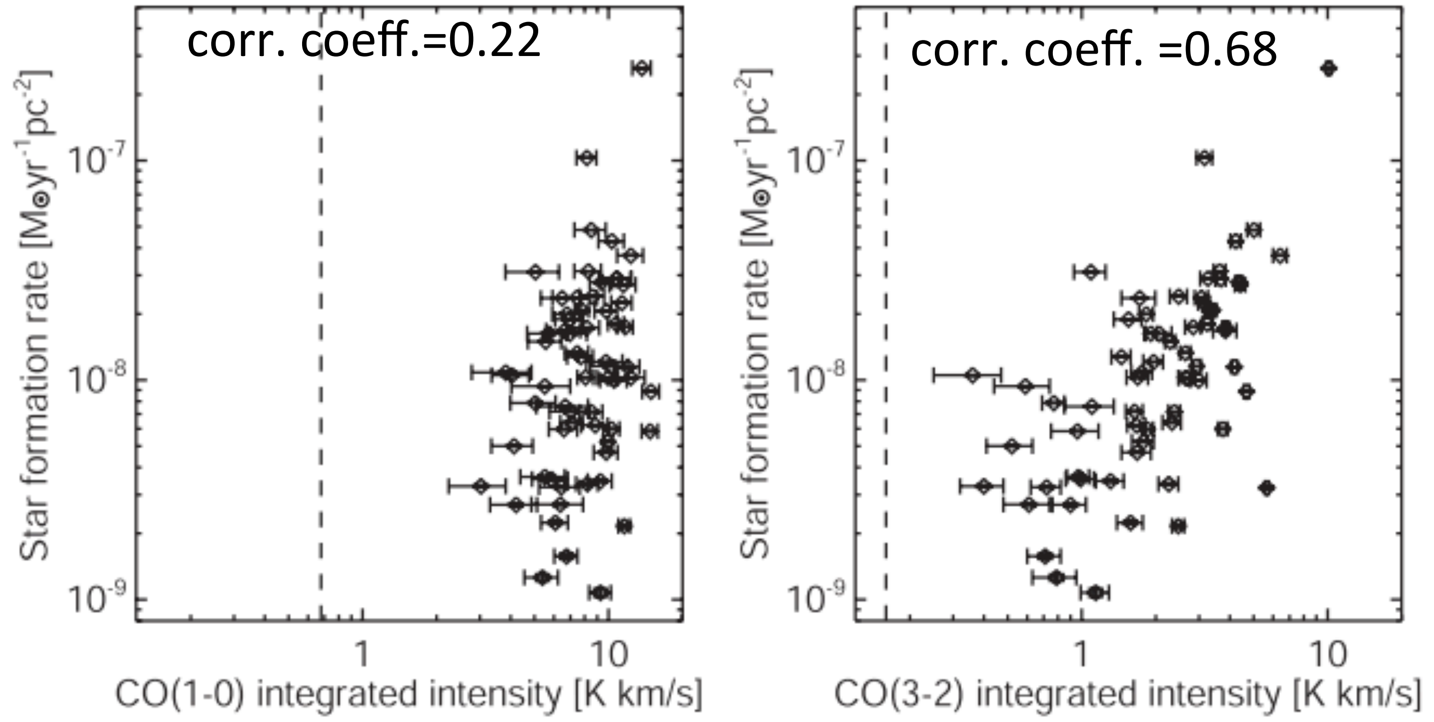


Similar distribution

Color: CO(3-2)
Grey: CO(1-0)

Miura et al. 2014

SFR vs. CO(1-0), CO(3-2) in GMCs



Onodera+ 2012

- No correlation is found between I(CO 1-0) &Σ(SFR) <u>in GMC scales</u>
- I(CO 3-2) -Σ(SFR) correlation (already known in kpc-scale) is valid down to GMC scales

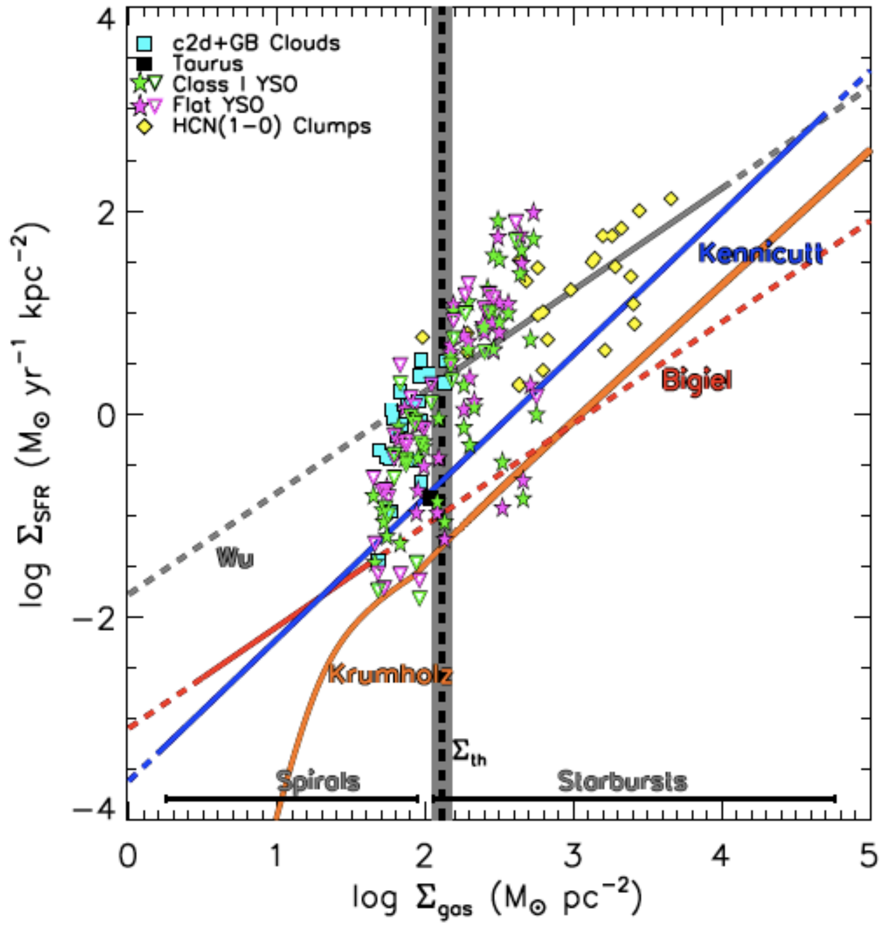
⇒ Star formation is closely associated with the warm and dense regions traced by CO(3-2) line, <u>also in each GMC</u>

Star formation relations in the Milky Way

- Spitzer c2d ＆ Gould's Belt survey
  20 low-mass star-forming molecular clouds
- Av map →Σ_{gas}
- YSO number density→Σ_{SFR}
- resolution: size of molecular clouds (～3pc on average)
- index is superlinear: largely different from that of the extragalactic K-S law（N=1～1.4）

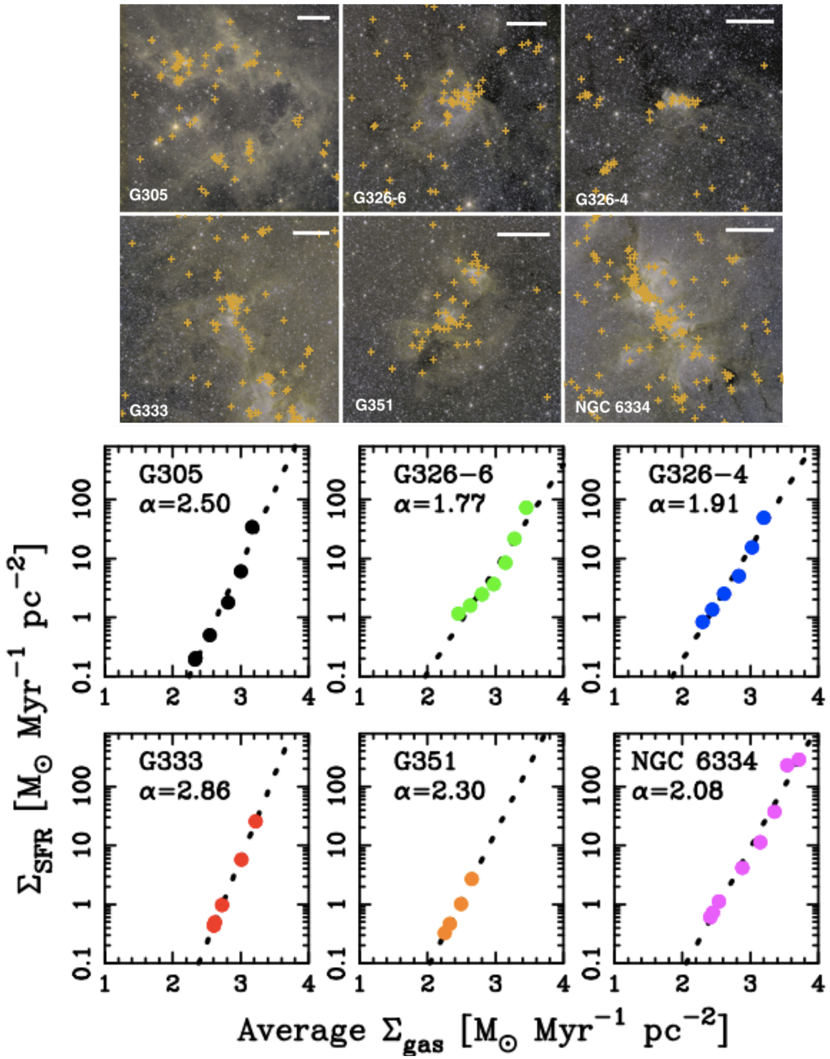
→ star-forming threshold in gas surface density of ～100Msun pc^{-2} ?

Heiderman et al. 2010



Star formation relations in the Milky Way

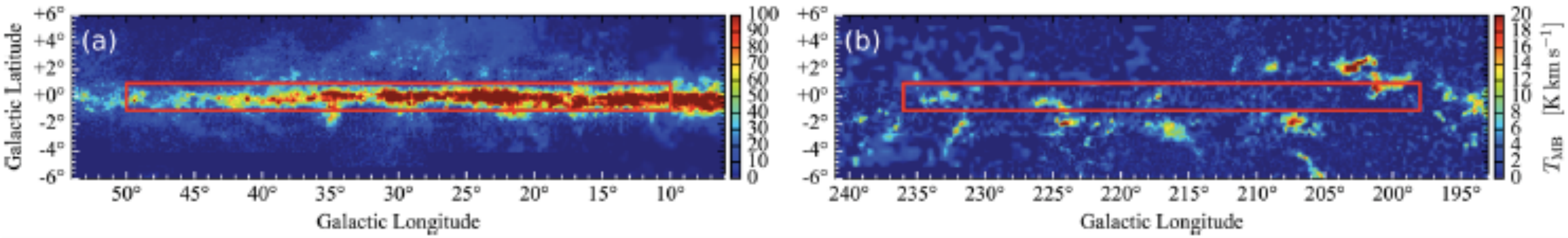
Willis et al. 2015



Six high-mass star-forming molecular clouds

- class I YSO number→Σ_{SFR}
- Herschel FIR→Av→Σ_{gas}
- Single power law in each cloud but N is different among clouds
- N is also superlinear even in Σ_{gas}>100Msun pc^{-2}

FOREST Unbiased Galactic plane Imaging survey with the Nobeyama 45 m telescope (FUGIN project)



Red square: observational regions, color map:CfA survey CO map by Dame+ (2001)

- unbiased CO line mapping of the Galactic Plane (2014~2017)
- 10°< l < 50°, |b|< 1° (80 deg^2) and 198°< l <236°, |b|< 1°(76 deg^2)
- spiral arms (Perseus, Sagittarius, Scutum, and Norma arms), bar
- ^{12}CO, ^{13}CO, and C^{18}O (J=1–0) lines, simultaneously
- new multi-beam receiver, FOREST, on the Nobeyama 45m telescope
- angular resolution of the final map: 20″ (^{12}CO), 21″ (^{13}CO & C^{18}O)

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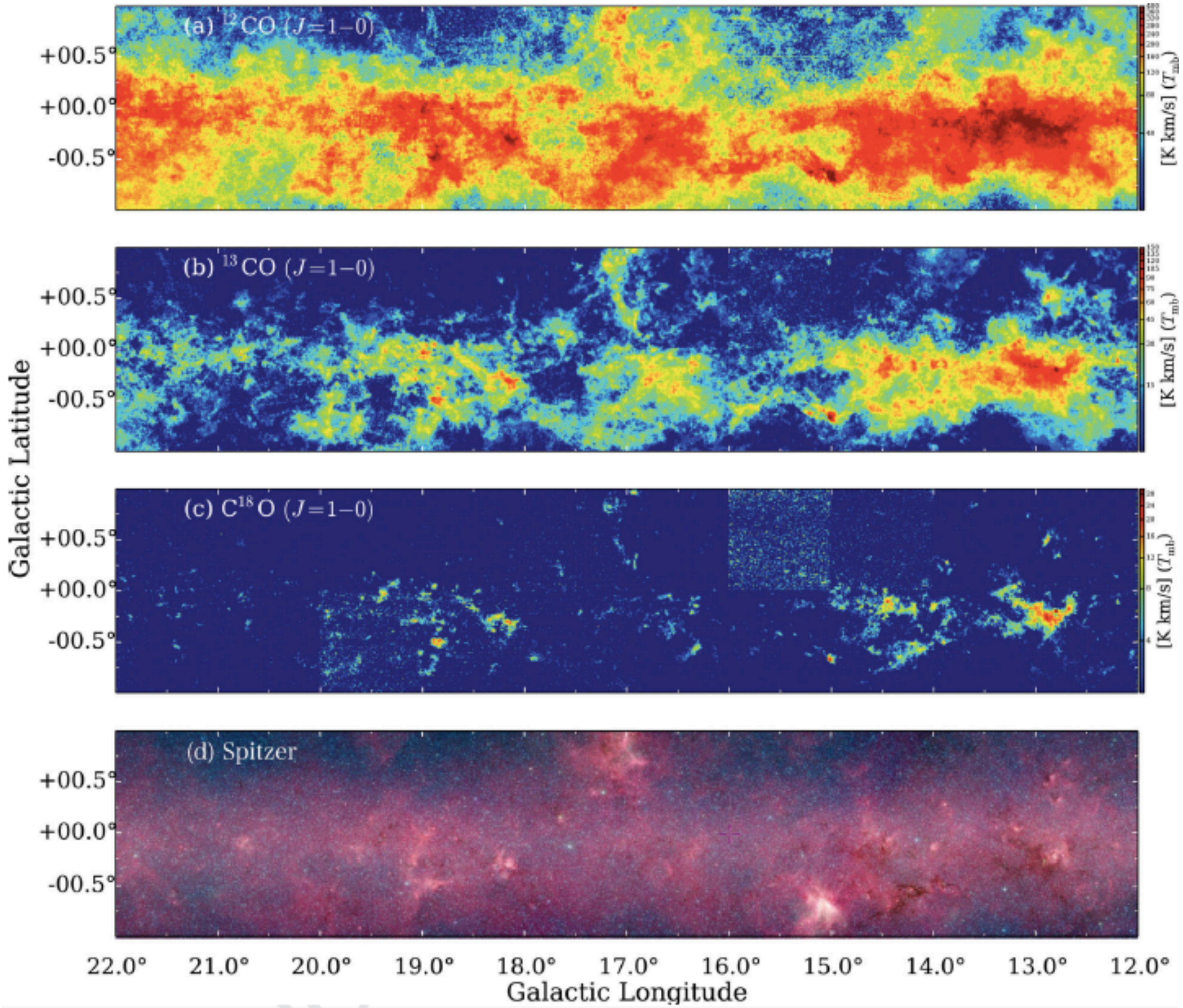

^{12}CO
total molecular gas
diffuse regions
～10^2 cm^{-3}

^{13}CO & C^{18}O
denser and optically
thinner molecular gas
～10^3 to 10^4 cm^{-3}

Umemoto et al. 2017

Preliminary Results in M17 Region

confidential

Comparison with previous results

confidential

Summary

- The "classical" K-S relation between Σ(SFR) derived from Hα, IR and UV and $\Sigma(H_2)$ derived from CO breaks down at the GMC scale
  - Drift of newborn stars from the parent clouds and stochasticity effects on the estimation of SFR are not large enough to explain the dispersion
  - Different evolutionary stages of GMCs are the main reason