6th Galaxy Evolution Workshop
@ Kavli IPMU
Jun. 6, 2019

COMING
CO Multi-line Imaging of Nearby Galaxies

Hokkaido University Founded 1876

CO(J = 2–1)/CO(J = 1–0) ratio in nearby galaxies

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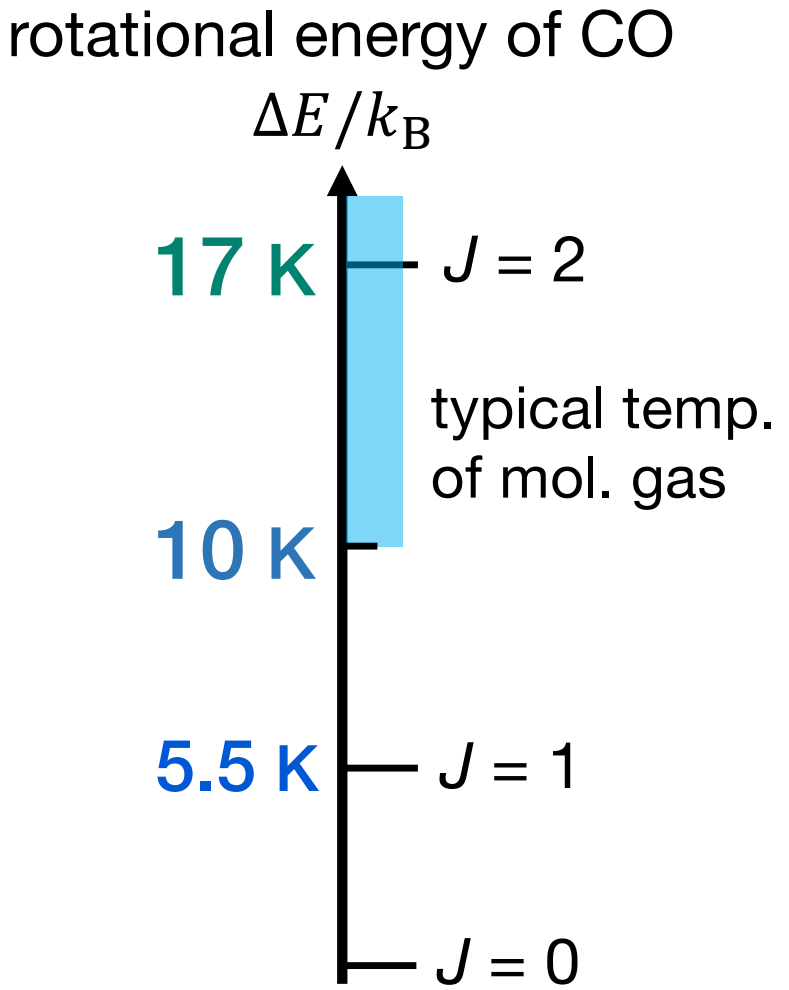
& COMING members

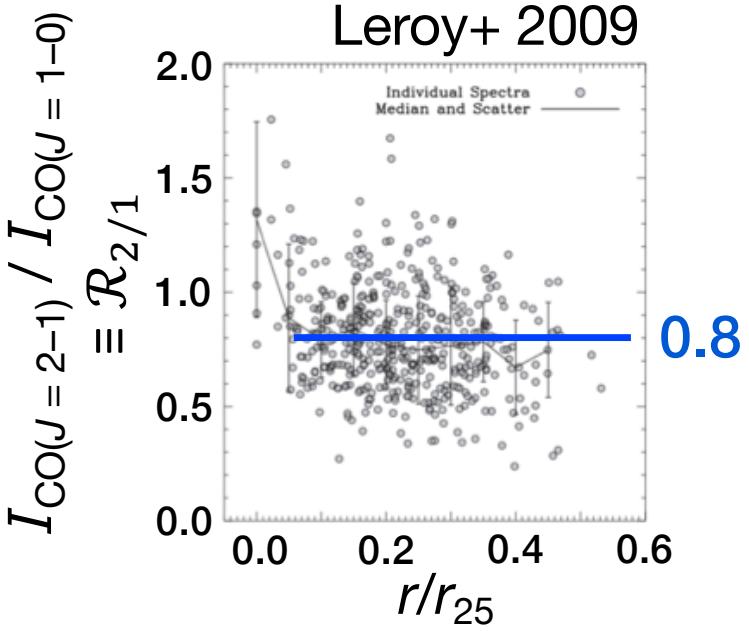
CO transitions and their energy levels

- CO $J = 1$ level: well excited thanks to low energy
- CO($J = 1$–0): most used tracer of **cold** molecular gas
- CO $J = 2$ level: higher level by 10 K than $J = 1$
- CO($J = 2$–1): traces **warmer** or **denser** molecular gas?

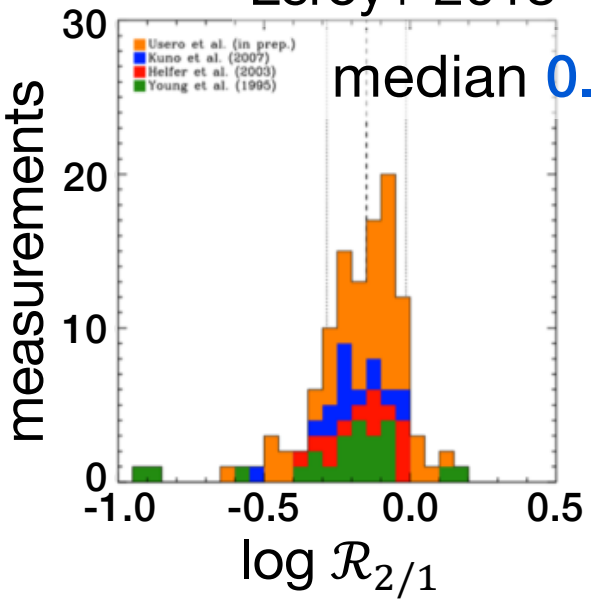


CO(*J* = 2–1) as a proxy of CO(*J* = 1–0)?

Leroy+ 2009



Leroy+ 2013



✓ median of $\mathcal{R}_{2/1}$:
~ 0.7 in several galaxies

$$\Sigma_{\rm mol} = \cos i\, \alpha_{\rm CO}\, I_{\rm CO(J=1-0)}$$
$$= \cos i\, \alpha_{\rm CO}\, \frac{I_{\rm CO(J=2-1)}}{\mathcal{R}_{2/1}}$$

✓ when $\sum_{\rm mol}$ is derived from CO(*J* = 2–1) $\mathcal{R}_{2/1}$ is assumed as **const. (0.7) !!**

✓ $\mathcal{R}_{2/1}$ **depends on** excitation of CO…

Data of the CO lines

COMING
CO Multi-line Imaging of Nearby Galaxies

CO(J = 1–0)

- COMING (Sorai+ 2019)
- Nobeyama CO Atlas of Nearby Spiral Galaxies (Kuno+ 2007)

CO(J = 2–1)

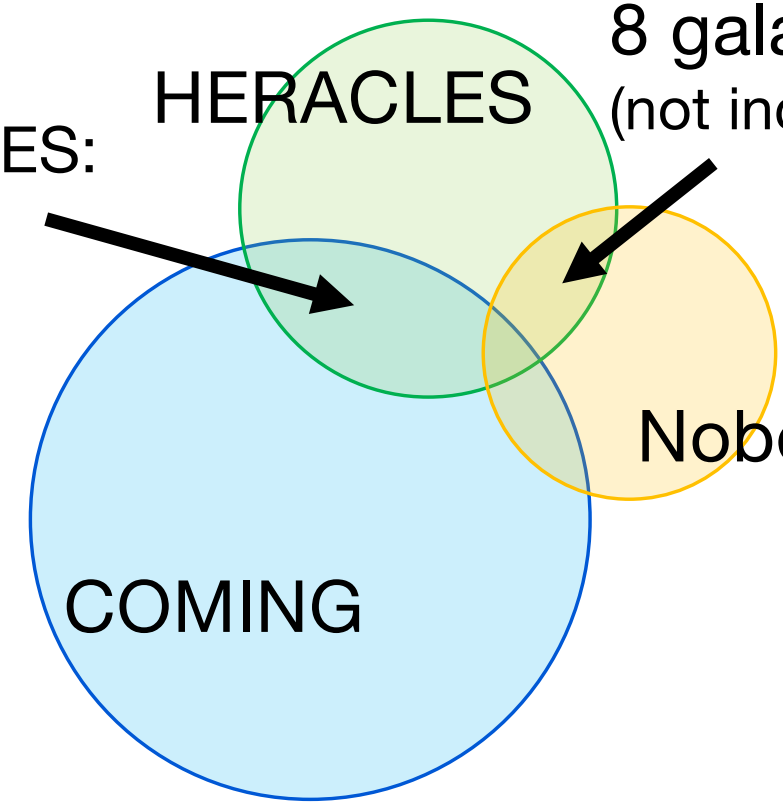
(DiVertiCimes/IRAM)

- HERACLES (Leroy+ 2009)

Sample

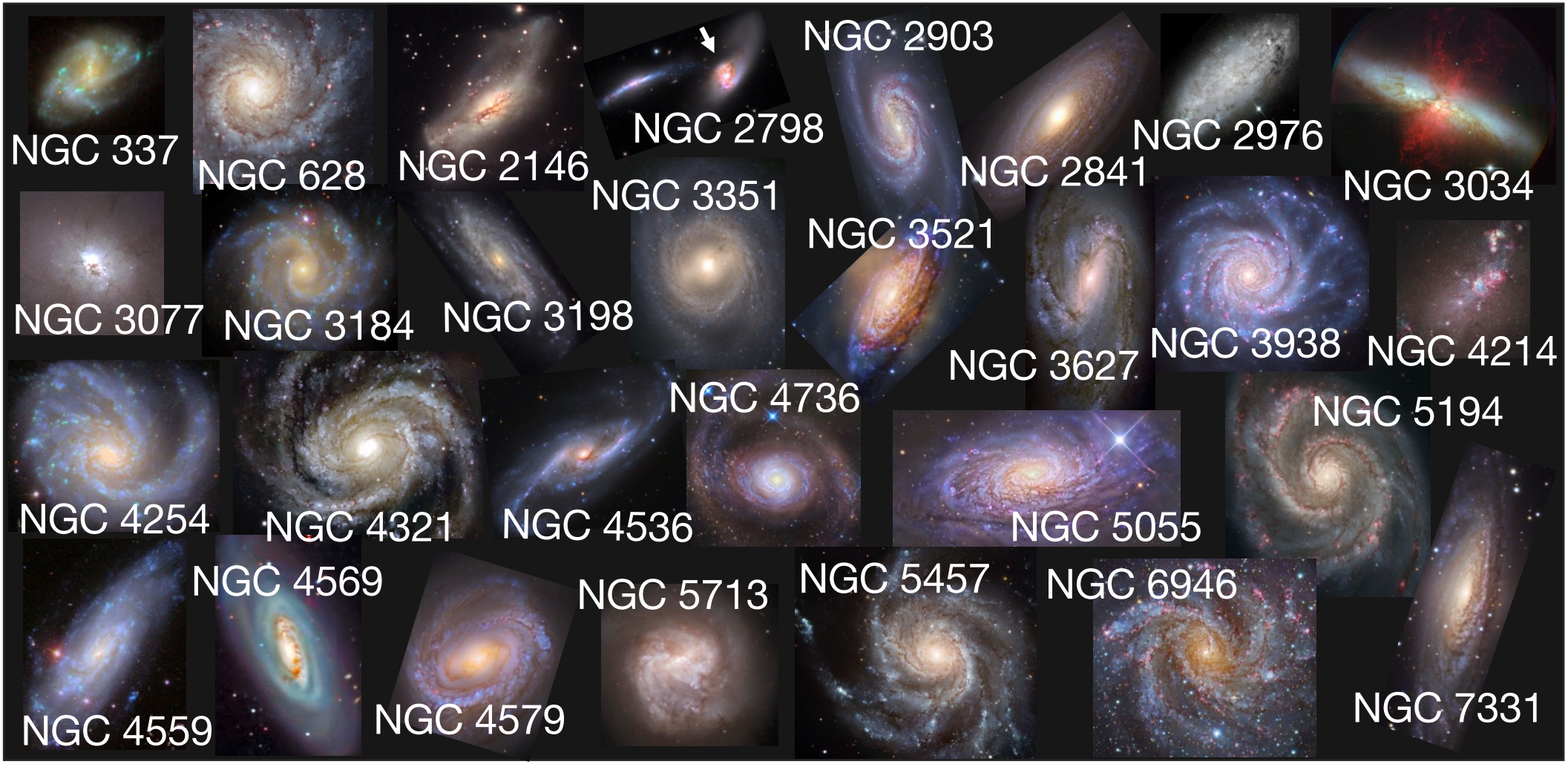
CO Atlas ∩ HERACLES:
8 galaxies
(not including COMING samples)

COMING ∩ HERACLES:
21 galaxies

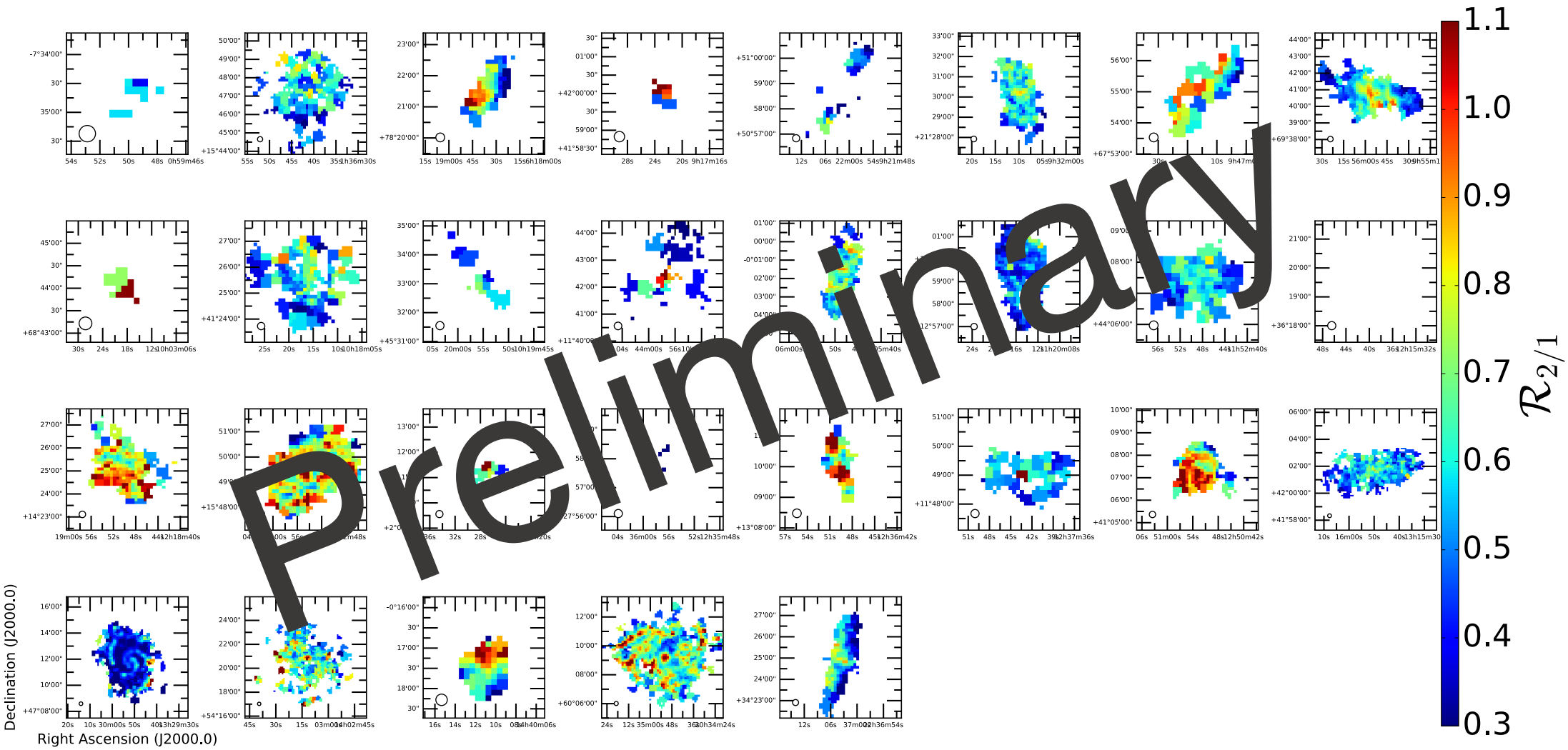


total sample: 29 galaxies

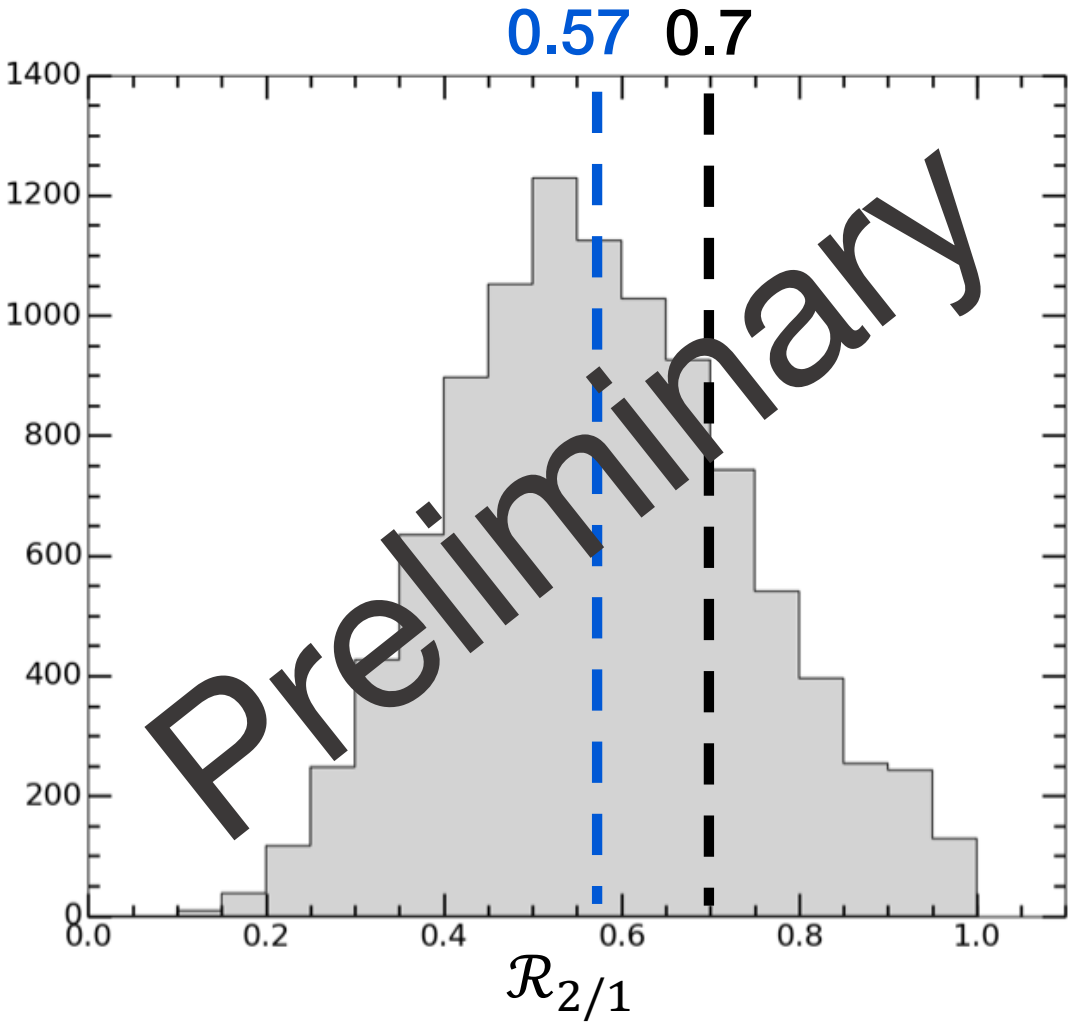
Sample


NGC 337
NGC 628
NGC 2146
NGC 2903
NGC 2798
NGC 2976
NGC 2841
NGC 3034
NGC 3351
NGC 3521
NGC 3077
NGC 3184
NGC 3198
NGC 3938
NGC 4214
NGC 3627
NGC 4736
NGC 5194
NGC 4254
NGC 4321
NGC 4536
NGC 5055
NGC 4569
NGC 5713
NGC 5457
NGC 6946
NGC 4559
NGC 4579
NGC 7331

$\mathcal{R}_{2/1}$ maps of the sample



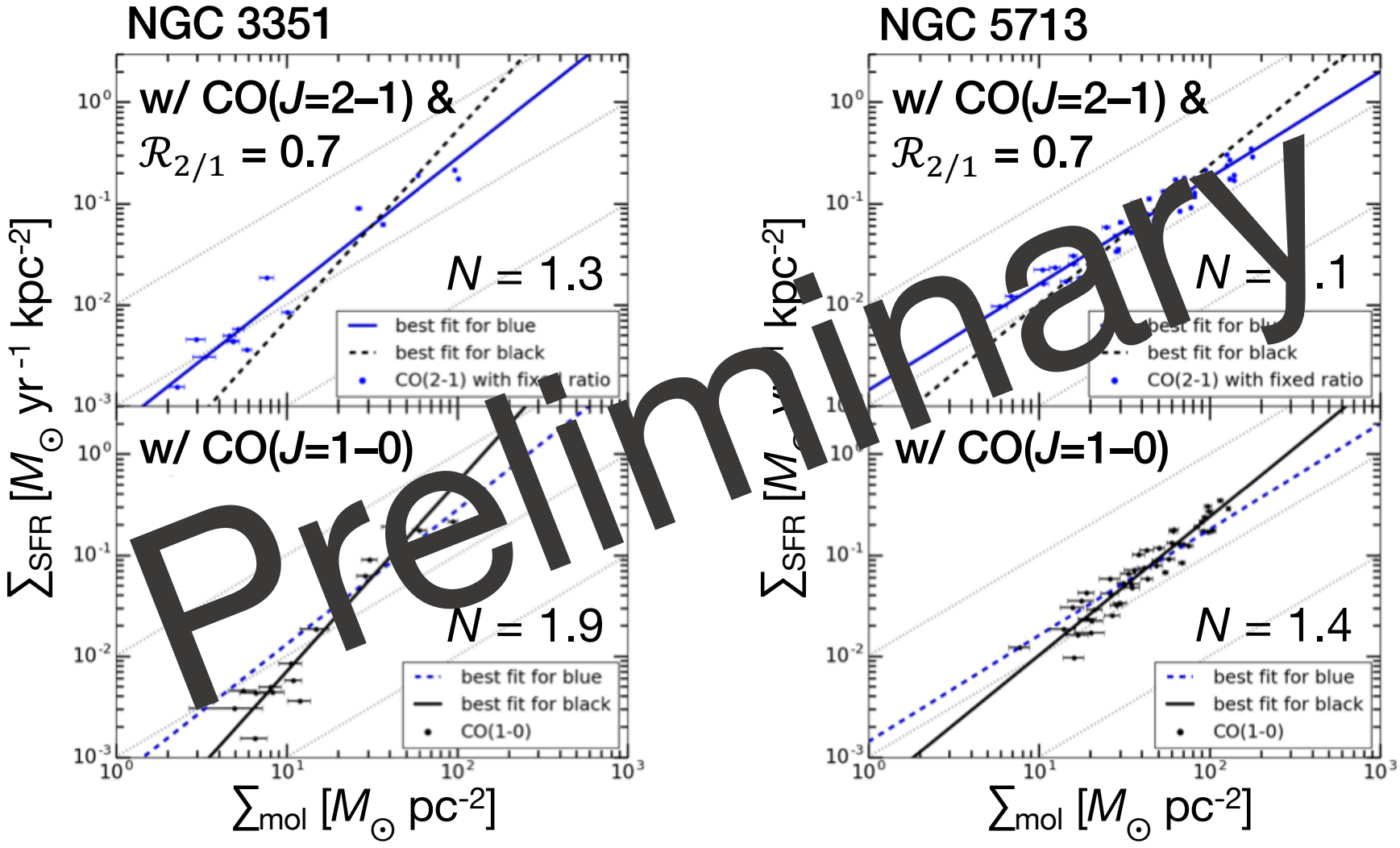
Histogram of $\mathcal{R}_{2/1}$



✓ $\mathcal{R}_{2/1}$ = 0.7 is **rather larger**

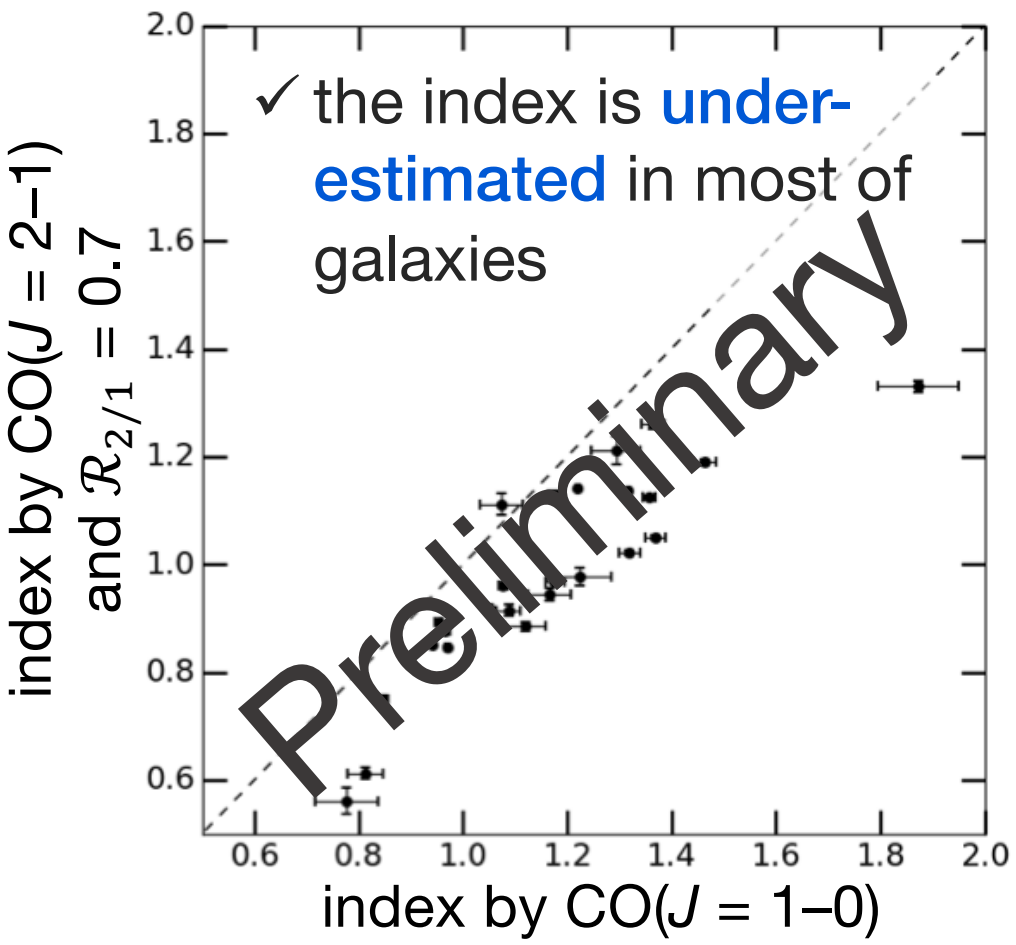
- median = 0.57
- weighted mean = 0.62
- std. dev. = 0.20

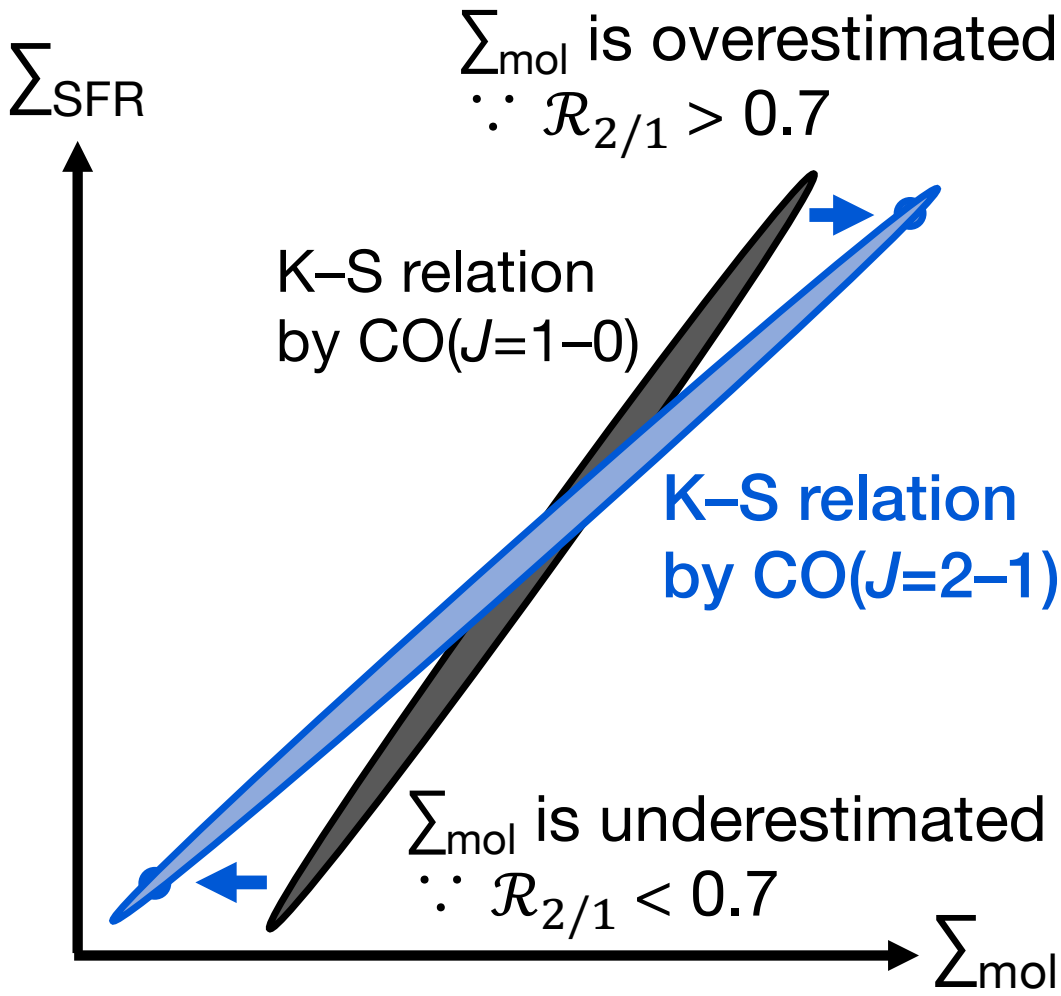
Effects on the Kennicutt–Schmidt relation



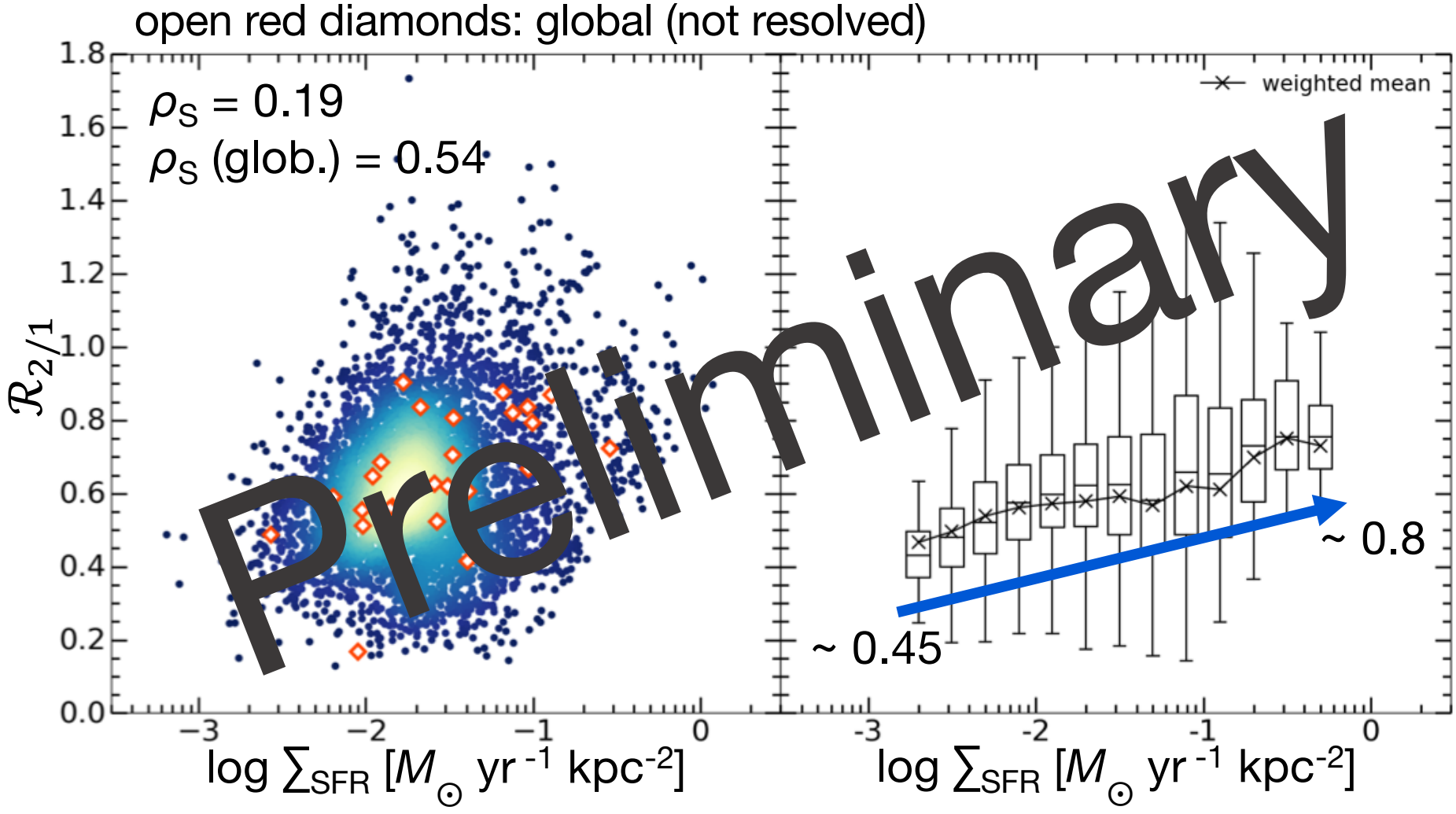
Preliminary

Effects on the K–S relation

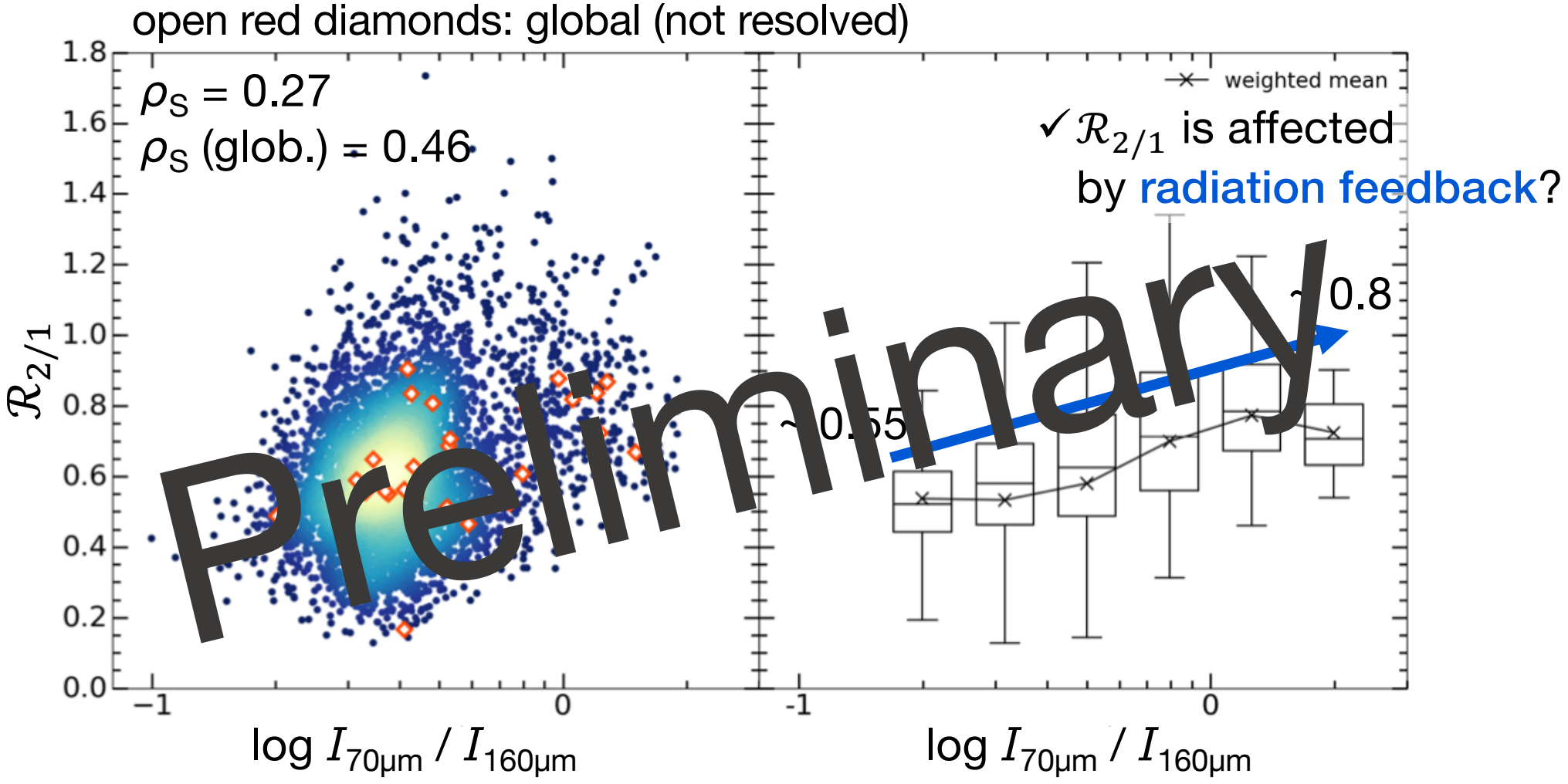




Correlations of $\mathcal{R}_{2/1}$ and basic quantities – $\sum_{SFR}$

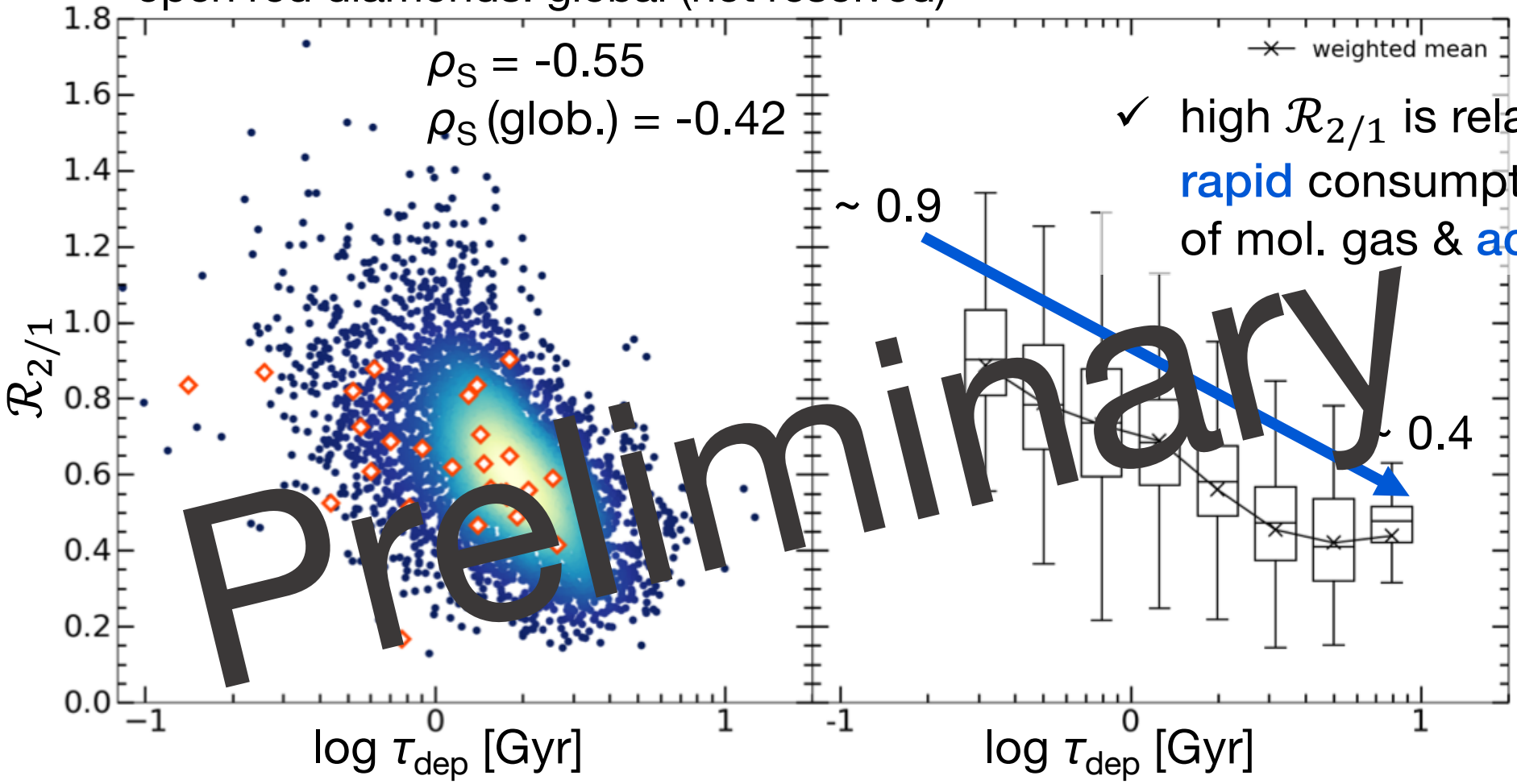


Correlations of $\mathcal{R}_{2/1}$ and basic quantities – IR color



Correlations of $\mathcal{R}_{2/1}$ and basic quantities – $\tau_{\rm dep}$

open red diamonds: global (not resolved)



✓ high $\mathcal{R}_{2/1}$ is related to **rapid** consumption of mol. gas & **active** SF

Preliminary

Conclusions

- The assumption of the constant $\mathcal{R}_{2/1}$ (≡ $I_{\mathrm{CO}(J\,=\,2\text{–}1)}$ / $I_{\mathrm{CO}(J\,=\,1\text{–}0)}$) of 0.7 is no longer **valid**
- The index of the K-S relation is **underestimated** if $\mathcal{R}_{2/1}$ is assumed as 0.7
- $\mathcal{R}_{2/1}$ would be influenced by **radiation feedback** from stars

✓ CO(*J* = 2–1)/CO(*J* = 1–0) ratio should not be assumed as a constant!!

Appendix

Why our median is less than 0.7?

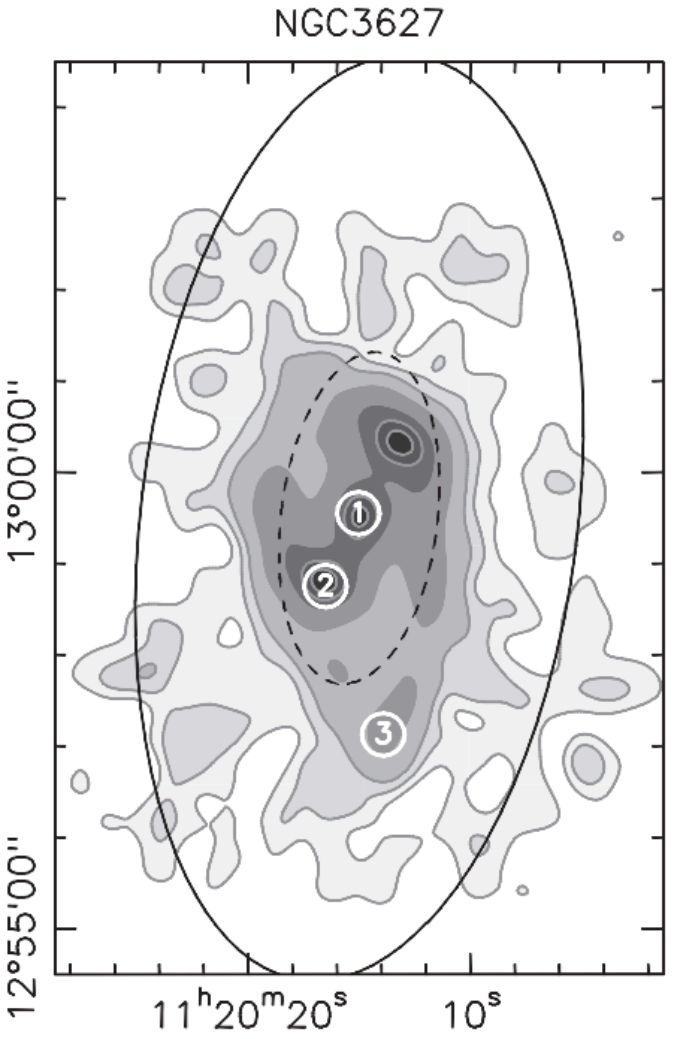
Observed regions of Usero+ 2015:
only positions where **CO(J = 2–1) is strong**

Not the entire disk of galaxies

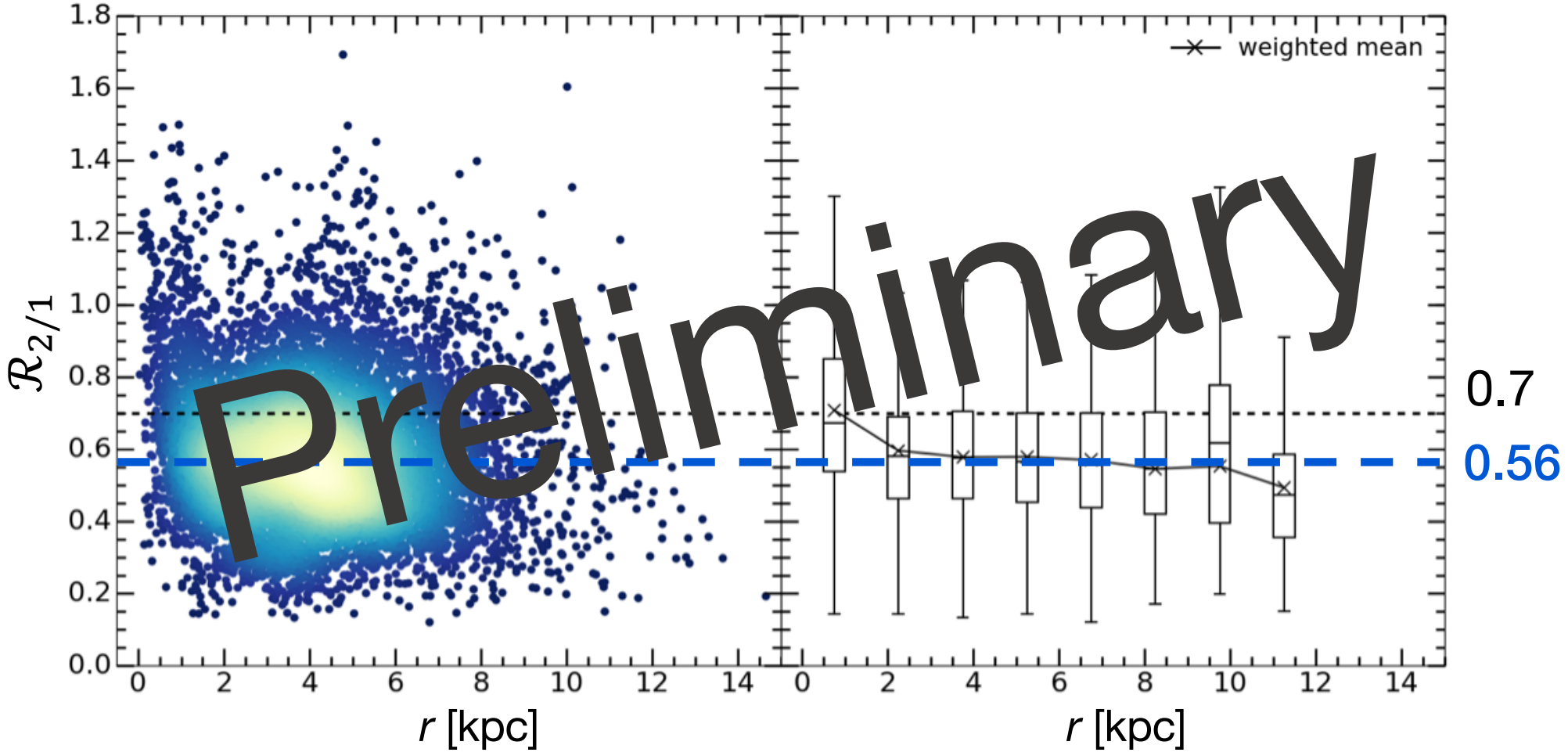
The obs. points usually include the center

↓

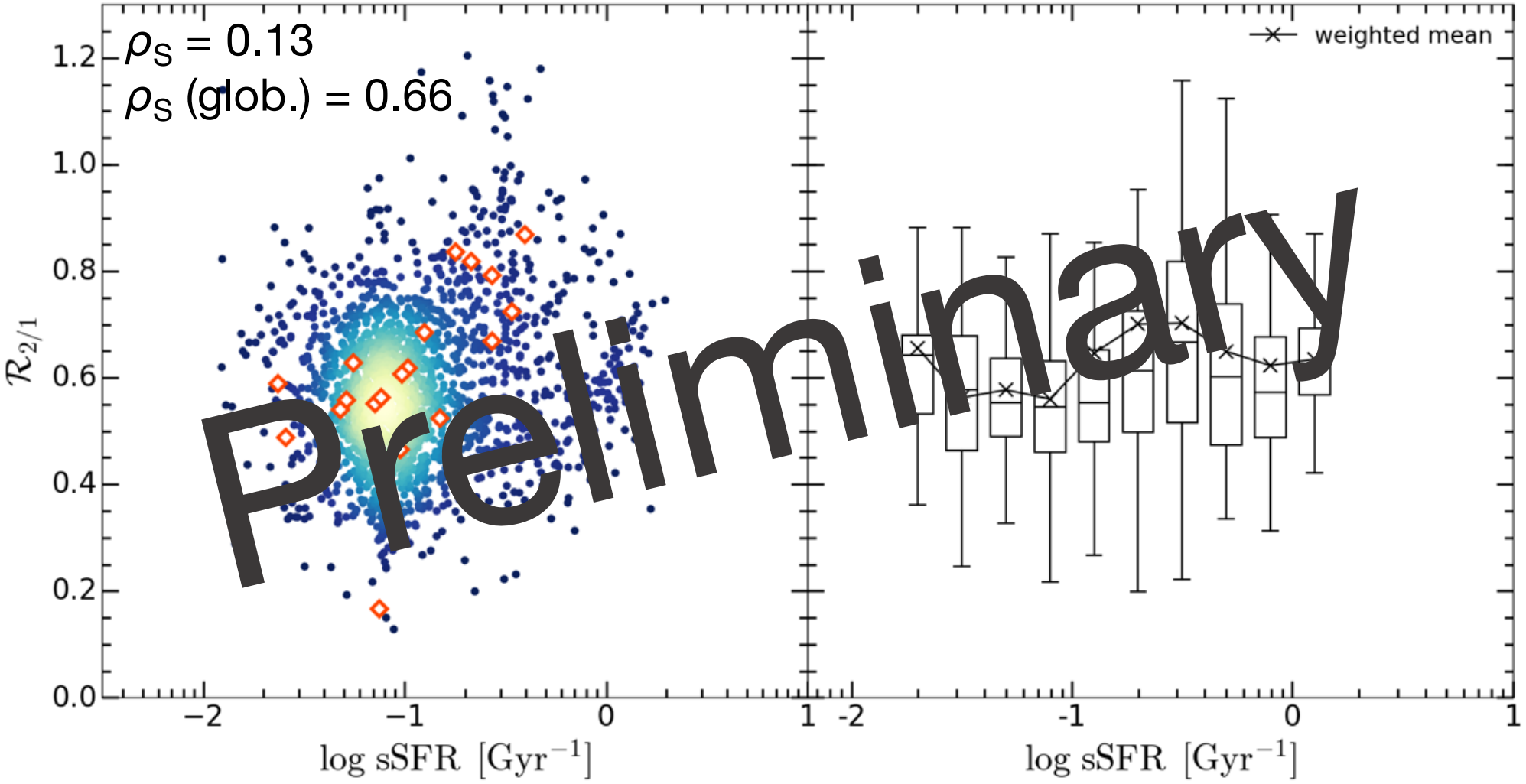
The obs. position selection would bias large $\mathcal{R}_{2/1}$



Radial distribution of $\mathcal{R}_{2/1}$



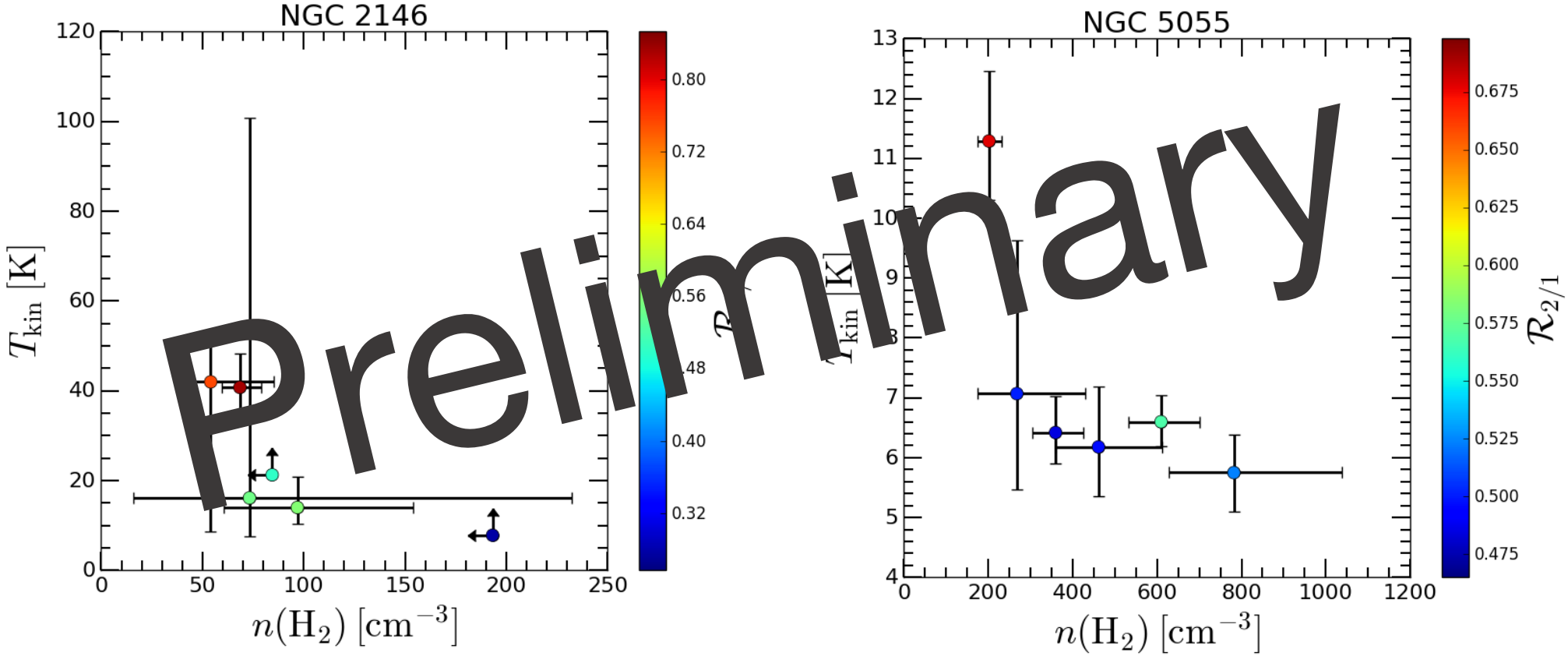
Correlations of $\mathcal{R}_{2/1}$ and basic quantities – sSFR



$\mathcal{R}_{2/1}$ and density, temperature of mol. gas

✓ $\mathcal{R}_{2/1}$ is more sensitive to temp.?

(I will increase samples)



n(H$_2$) and $T_{\rm kin}$ are derived from CO(1–0), CO(2–1) & ^{13}CO(1–0)

Variations of $\mathcal{R}_{2/1}$ and $X_{\rm CO}$

$$X_{\rm CO} \propto \frac{\sqrt{n(\rm H_2)}}{T_{\rm kin}}$$ (e.g., Solomon+ 1987)

$n(\rm H_2)$ ↗ → $X_{\rm CO}$ ↗ & $R_{2/1}$ ↗

$T_{\rm kin}$ ↗ → $X_{\rm CO}$ ↘ & $R_{2/1}$ ↗

metallicity Z ↘ → $X_{\rm CO}$ ↗ & $R_{2/1}$ ↗

(e.g., Bolatto+ 2013, Penaloza+ 2018)

velocity disp. σ_V ↗ → $X_{\rm CO}$ ↘ & $R_{2/1}$ ↘

(e.g., Watanabe+ 2011, Sorai+ 2012)

$$\sum_{\rm mol} = I_{\rm CO(\mathit{J}=1–0)} \times \alpha_{\rm CO}$$
$$= I_{\rm CO(\mathit{J}=2–1)} \times \alpha_{\rm CO} / R_{2/1}$$

effect of high $n(\rm H_2)$, large σ_V and low Z:

variations of $X_{\rm CO}$ and $R_{2/1}$ **will be canceled**

effect of high $T_{\rm kin}$:

variations of $X_{\rm CO}$ and $R_{2/1}$ **will be amplified**

→ more underestimated mol. gas mass