Re-evaluating Star Formation Efficiencies in Nearby Galaxies with a New α_{CO} Prescription

Yu-Hsuan (Eltha) Teng

Postdoc at University of Maryland / PhD from UC San Diego

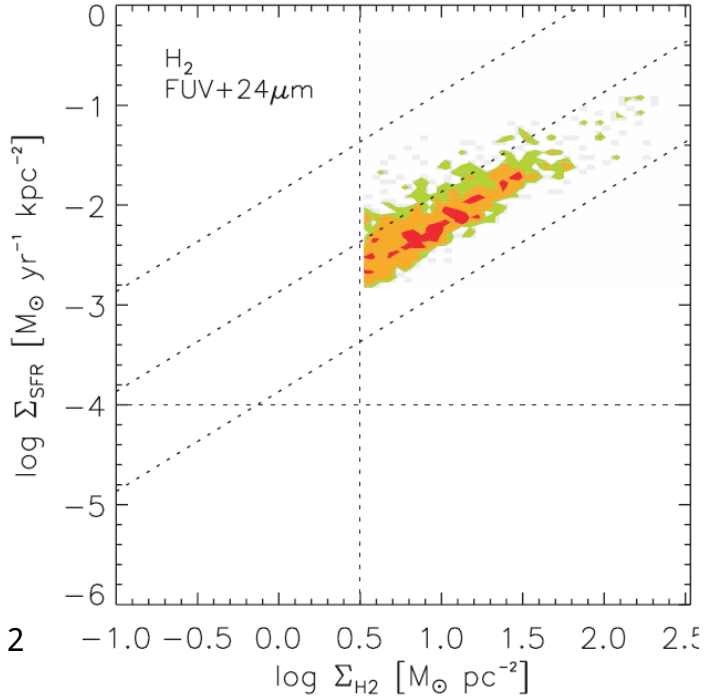
Co-authors: Karin Sandstrom, Jiayi Sun, Adam Leroy, Alberto Bolatto, I-Da Chiang, Antonio Usero, Eve Ostriker, Miguel Querejeta, ..., and

The PHANGS Collaboration

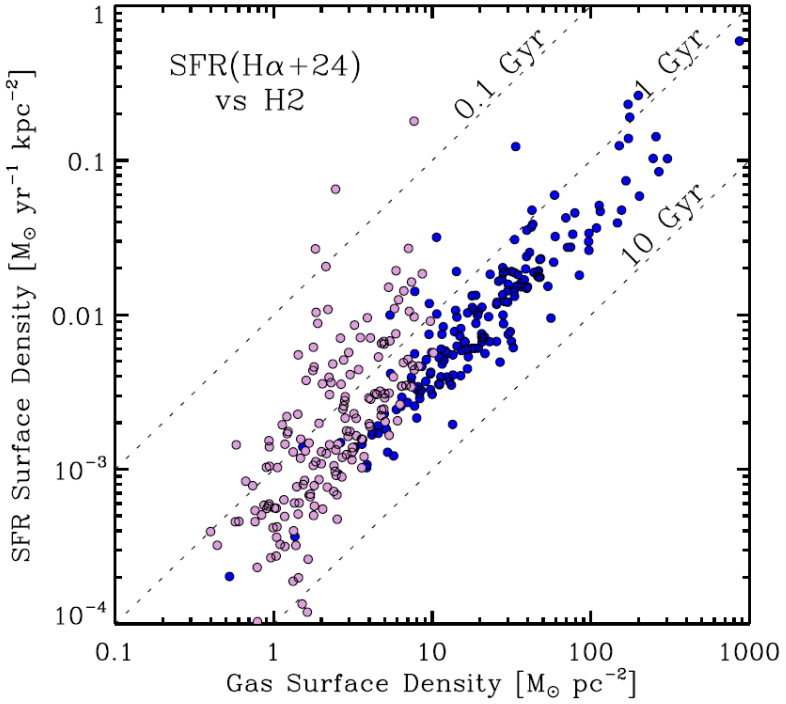
Motivation

- Stars are formed in molecular gas
  - Amount of molecular gas + star formation efficiency
  - molecular Kennicutt-Schmidt relation

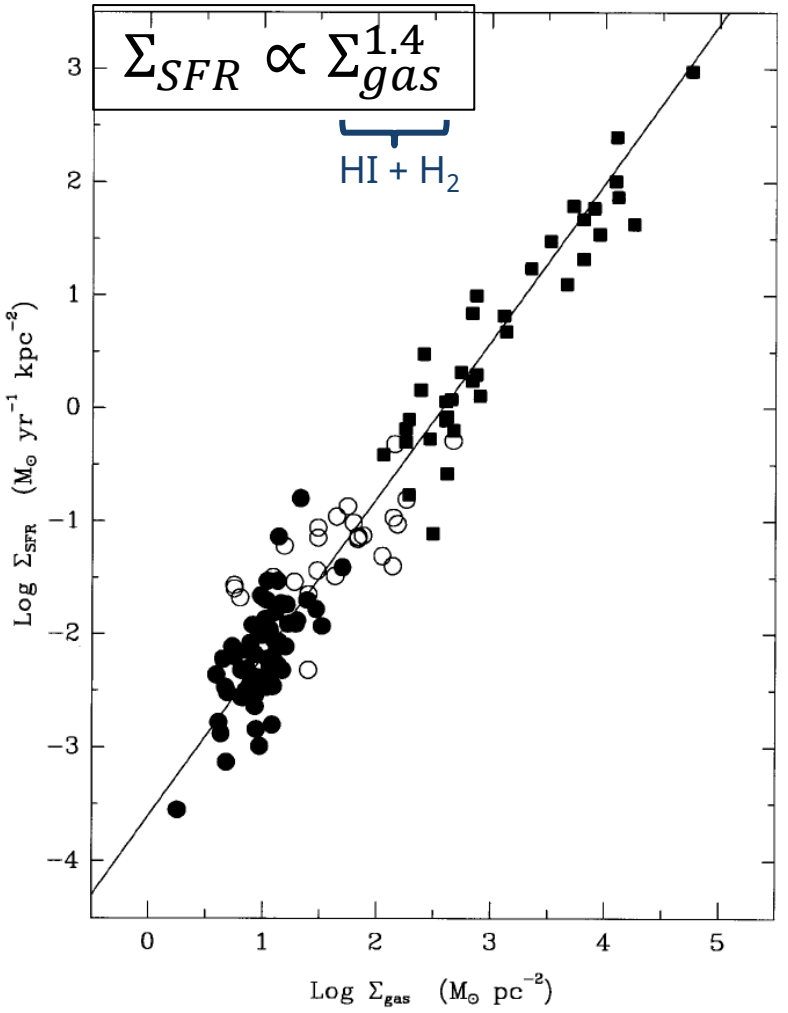
(Bigiel+ 2008)



(Schruba+ 2011)



(Kennicutt 1998)



Challenge: CO-to-H_2 Conversion

- Tracing molecular gas in galaxies

  → **"CO flux to H_2 mass" conversion factor (α_{CO})**

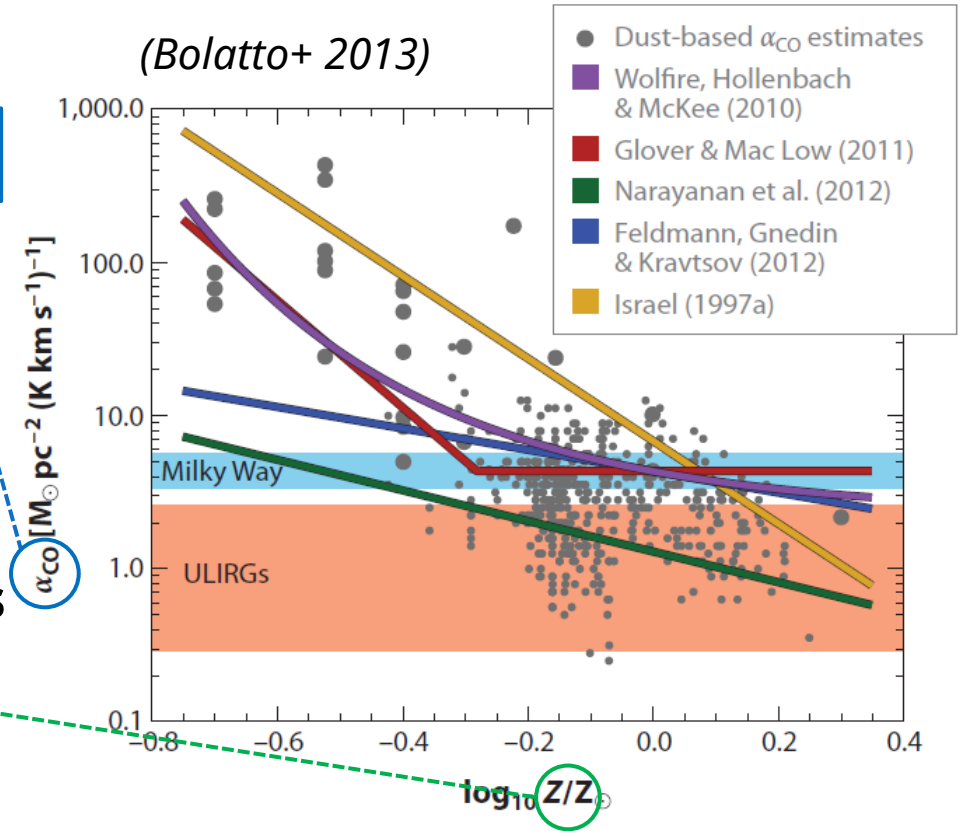
$$\alpha_{\mathrm{CO}} \equiv \frac{M_{H_2}}{L_{\mathrm{CO}(1-0)}} = \frac{\Sigma_{H_2}}{I_{\mathrm{CO}(1-0)}} \left(\frac{\mathrm{M}_\odot}{\mathrm{K\ km\ s^{-1}\ pc^2}} \right) = \text{const ??}$$

Challenge: CO-to-H_2 Conversion

- Tracing molecular gas in galaxies
  - → **"CO flux to H_2 mass" conversion factor (α_{CO})**

$$\alpha_{\mathrm{CO}} \equiv \frac{M_{H_2}}{L_{\mathrm{CO}(1-0)}} = \frac{\Sigma_{H_2}}{I_{\mathrm{CO}(1-0)}} \left(\frac{\mathrm{M}_\odot}{\mathrm{K\ km\ s^{-1}\ pc^2}}\right) \neq \text{const}$$

- Variation of α_{CO} within and between galaxies
  - α_{CO} depends on many **molecular gas properties**
  - → temperature, density, opacity, metallicity …



Challenge: CO-to-H_2 Conversion

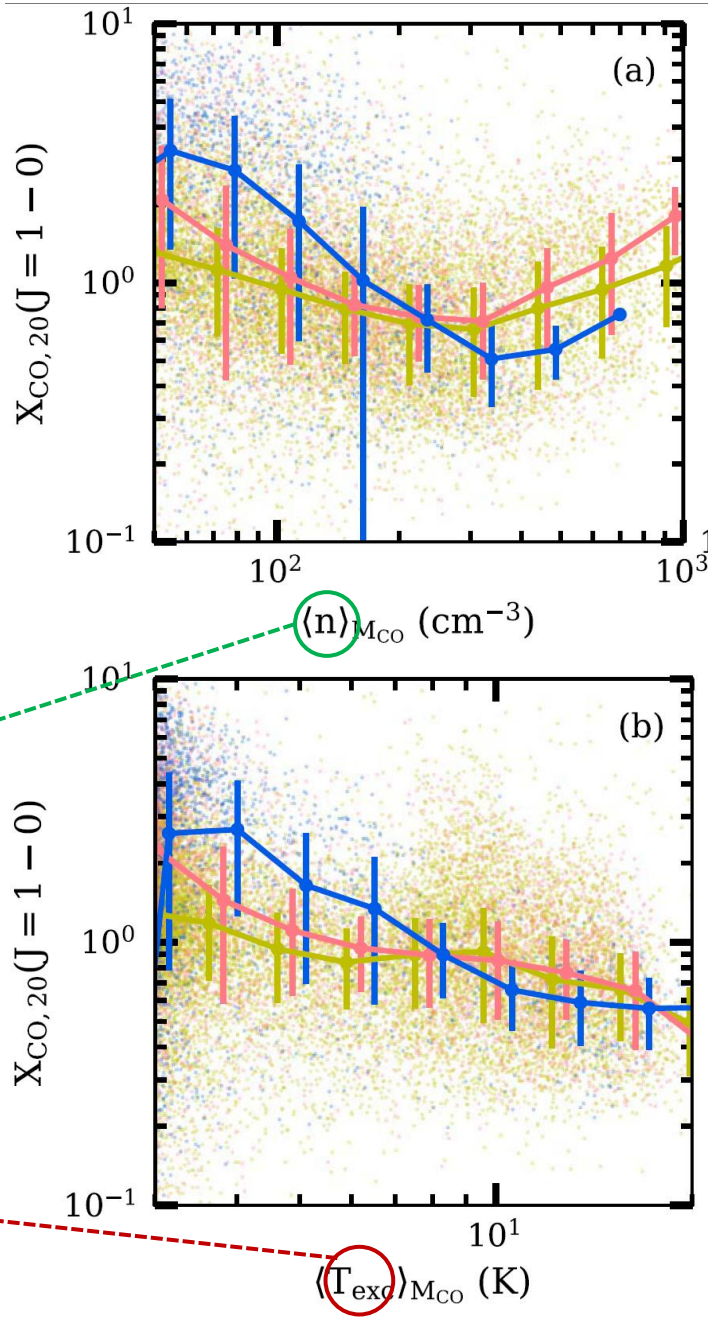
- Tracing molecular gas in galaxies

  → **"CO flux to H_2 mass" conversion factor (α_{CO})**

$$\alpha_{\mathrm{CO}} \equiv \frac{M_{H_2}}{L_{\mathrm{CO}(1-0)}} = \frac{\Sigma_{H_2}}{I_{\mathrm{CO}(1-0)}} \left(\frac{\mathrm{M}_\odot}{\mathrm{K\ km\ s^{-1}\ pc^2}}\right) \neq \text{const}$$

- Variation of α_{CO} within and between galaxies
  - α_{CO} depends on many **molecular gas properties**

  → temperature, density, opacity, metallicity …



(Gong+ 2020)

Impact of α_{CO} variations

- Variation of α_{CO} within and between galaxies
  - Dependence on molecular gas properties

  → temperature, density, opacity, metallicity …

- **α_{CO} impacts every physical quantities inferred from M_{mol}**
  - star formation efficiency (gas depletion time^{-1}) = SFR / M_{mol} $\propto \alpha_{CO}^{-1}$
  - virial parameter, turbulent pressure, cloud free-fall time… → all related to $M_{mol} \propto \alpha_{CO}$

Impact of α_{CO} variations

- Variation of α_{CO} within and between galaxies
  - Dependence on molecular gas properties

  → temperature, density, opacity, metallicity …

  → Which physical conditions contribute the most to α_{CO} variation?

- **α_{CO} impacts every physical quantities inferred from M_{mol}**
  - star formation efficiency (gas depletion time^{-1}) = SFR / M_{mol} $\propto \alpha_{CO}^{-1}$
  - virial parameter, turbulent pressure, cloud free-fall time… → all related to $M_{mol} \propto \alpha_{CO}$

  → How would correcting for α_{CO} systematically impact these SF properties?

Impact of α_{CO} variations

- Variation of α_{CO} within and between galaxies
  - Dependence on molecular gas properties

  → temperature, density, opacity, metallicity …

  → Which physical conditions contribute the most to α_{CO} variation?

- **α_{CO} impacts every physical quantities inferred from M_{mol}**
  - star formation efficiency (gas depletion time^{-1}) = SFR / M_{mol} $\propto \alpha_{CO}^{-1}$
  - virial parameter, turbulent pressure, cloud free-fall time… → all related to $M_{mol} \propto \alpha_{CO}$

  → How would correcting for α_{CO} systematically impact these SF properties?

Identify **observables** that can trace the main driver and thus α_{CO}

A good α_{CO} prescription

Multi-line analysis with ALMA

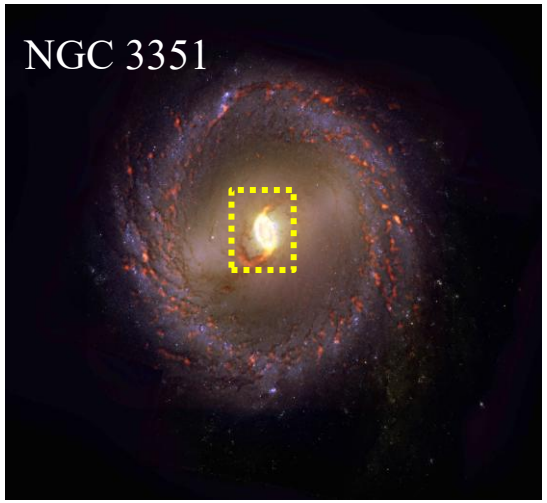
(Teng+ 2022, 2023)

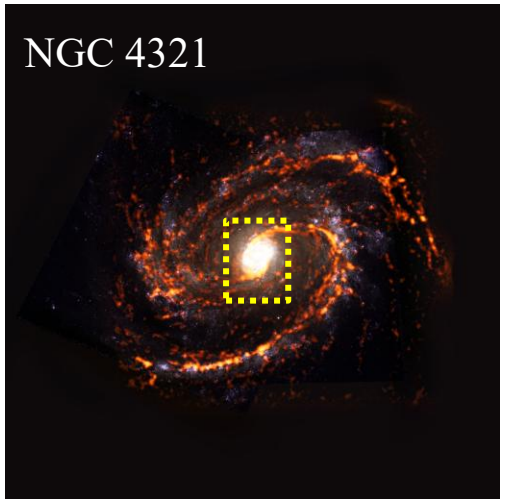
- NGC 3351, NGC 3627, NGC 4321

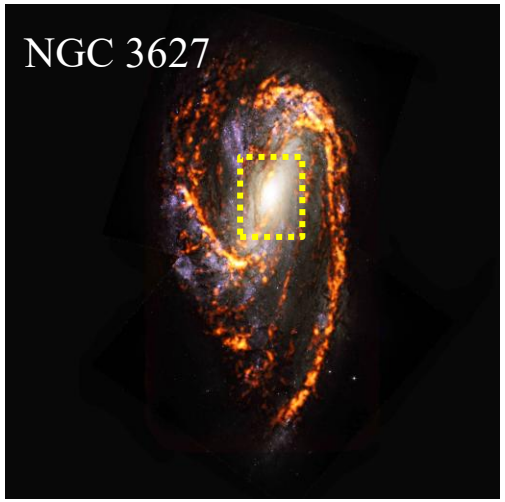
  → nearby **barred spiral galaxies** with **low α_{CO}** in the central kpc

  (e.g., Sandstrom+ 2013, Israel 2020)

- ALMA Band 3, 6, 7
  - Multi-line CO isotopologues
    - **^{12}CO** (1-0) and (2-1)
    - **^{13}CO** (2-1) and (3-2)
    - **C^{18}O** (2-1) and (3-2)
  - central ~2 kpc regions
  - angular resolution: 2'' (~100 pc)







(PHANGS–ALMA+HST)

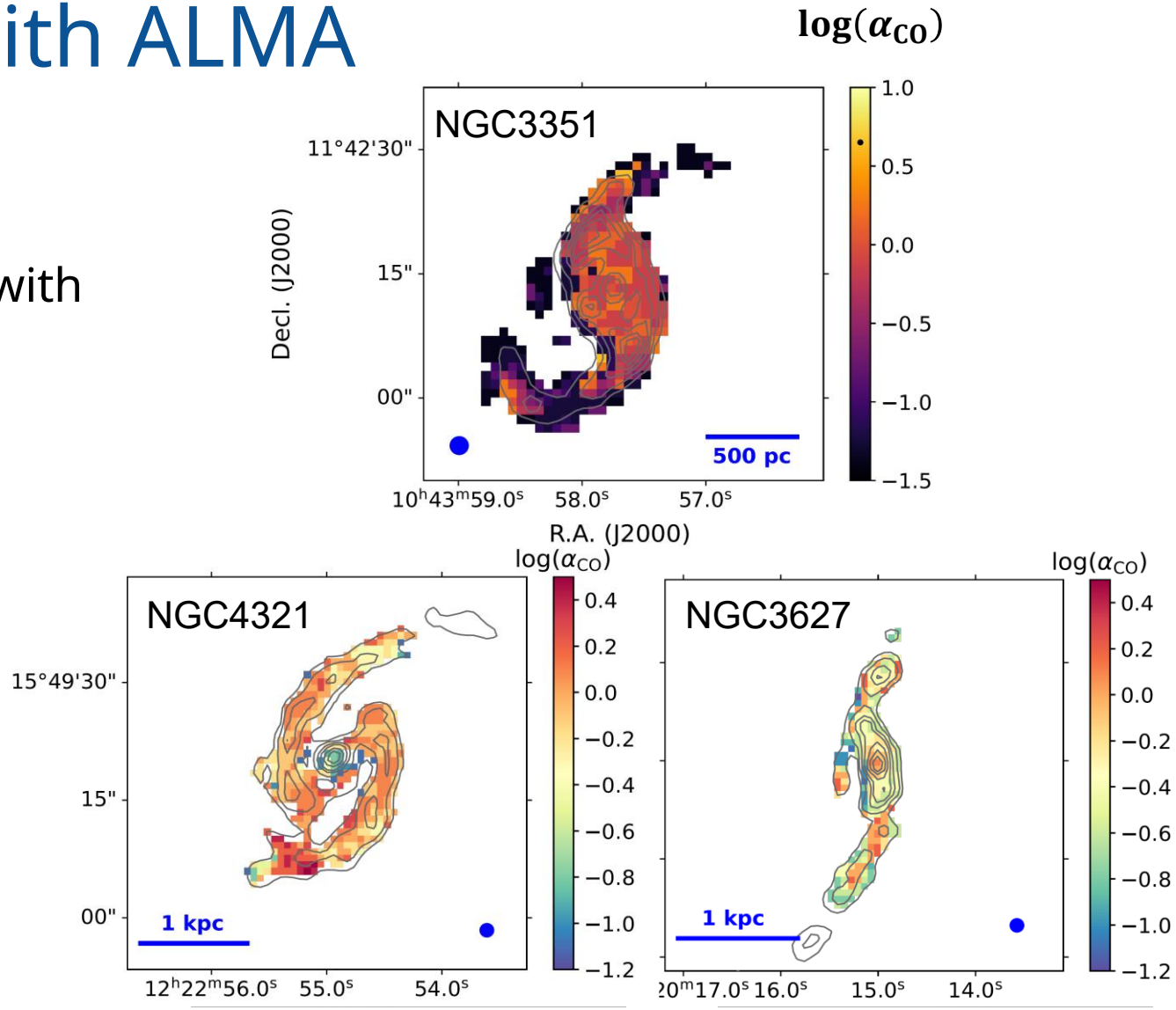
Modeling method & details: *Teng+ 2022, 2023*
Code: github.com/ElthaTeng/multiline-bayesian-modeling

Multi-line analysis with ALMA

(Teng+ 2022, 2023)

- NGC 3351, NGC 3627, NGC 4321
  → nearby **barred spiral galaxies** with **low α_{CO}** in the central kpc
  (e.g., Sandstrom+ 2013, Israel 2020)

- ALMA Band 3, 6, 7
  - Multi-line CO isotopologues
    - **^{12}CO** (1-0) and (2-1)
    - **^{13}CO** (2-1) and (3-2)
    - **C^{18}O** (2-1) and (3-2)
  - central ~2 kpc regions
  - angular resolution: 2'' (~100 pc)



CO opacity (column density per linewidth)

kinetic temperature

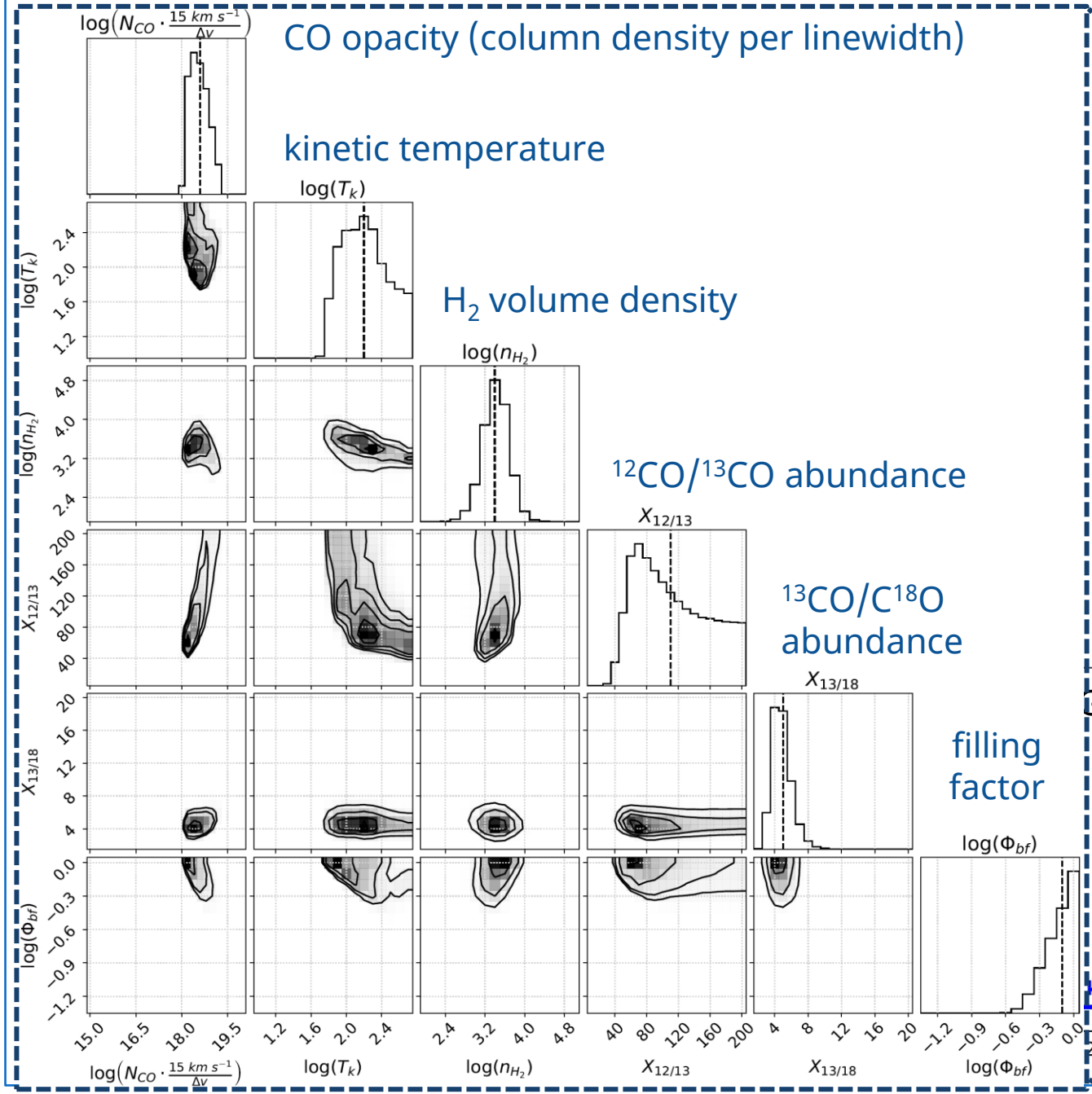
H_2 volume density

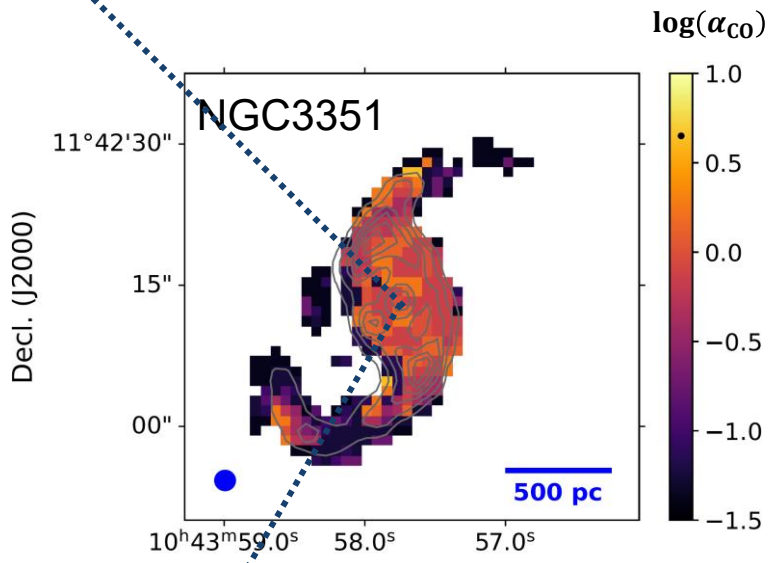
$^{12}CO/^{13}CO$ abundance

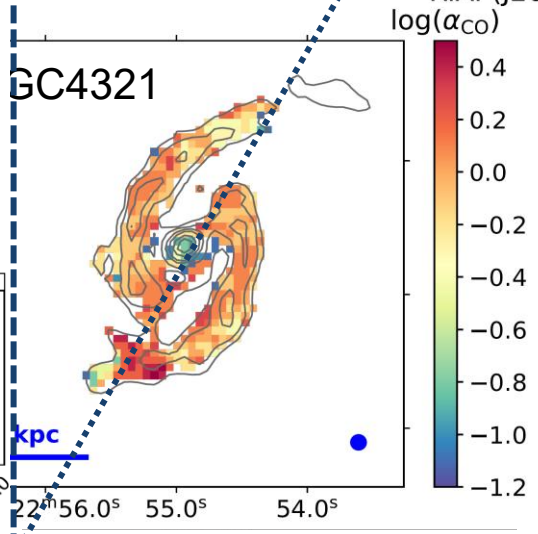
$^{13}CO/C^{18}O$ abundance

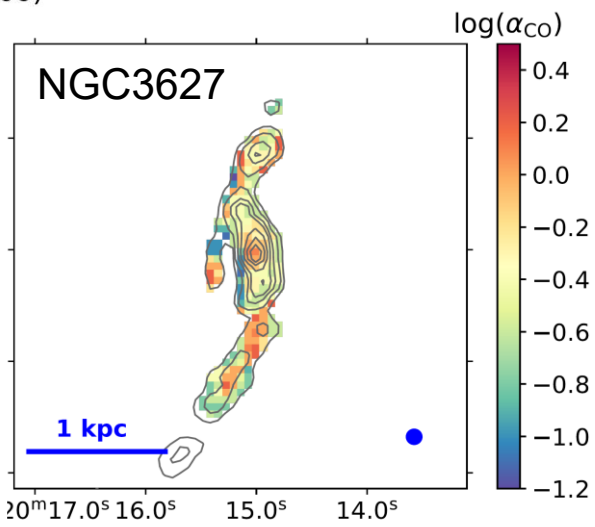
filling factor

Modeling method & details: *Teng+ 2022, 2023*
Code: github.com/ElthaTeng/multiline-bayesian-modeling









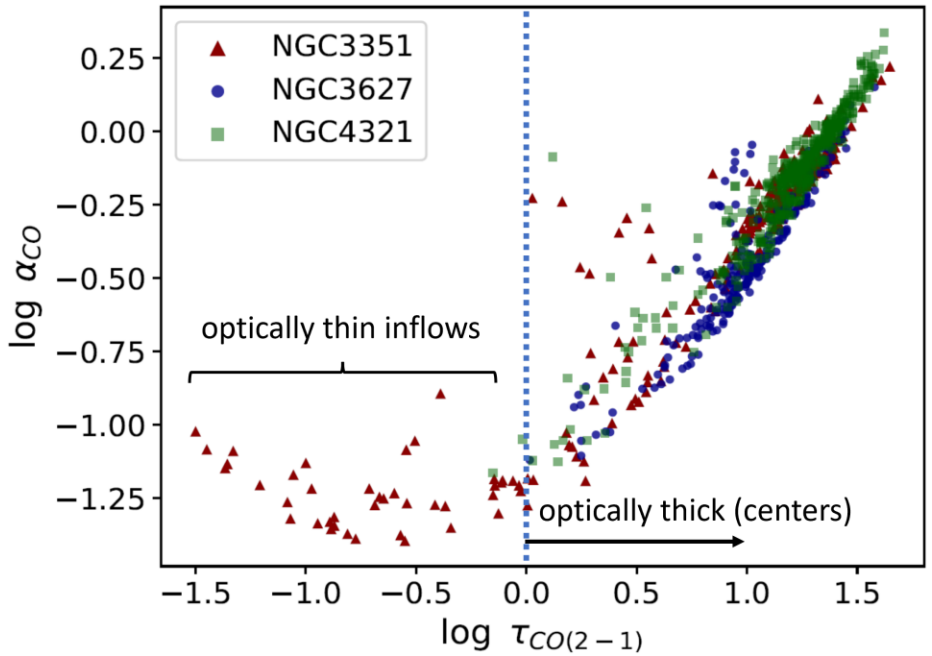
Physical drivers of α_{CO}

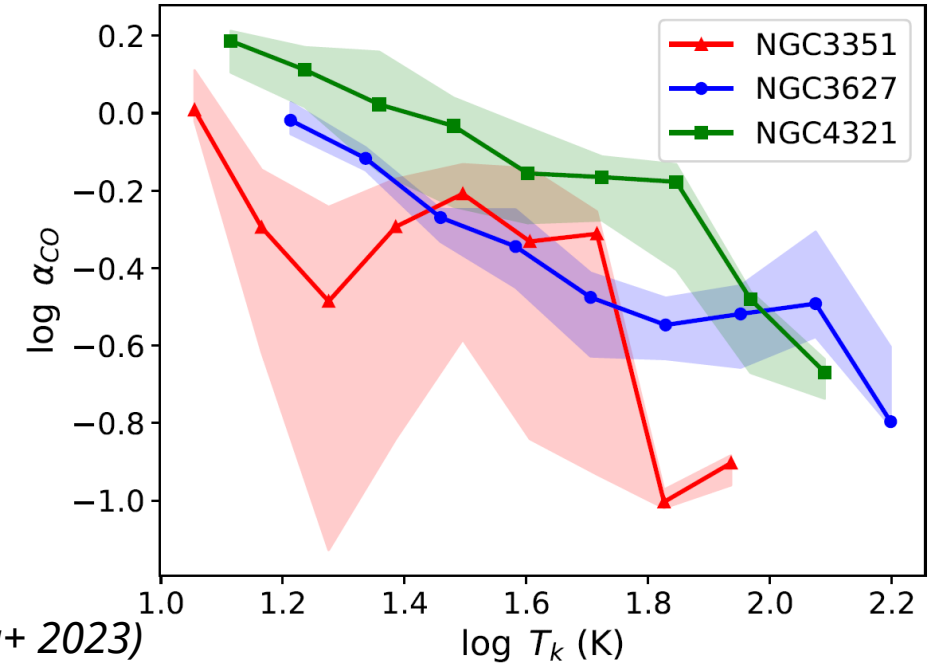
- Strong correlation between α_{CO} and CO optical depth τ_{CO} in optically thick regions (~80%)
- To the second order, α_{CO} anti-correlates with gas temperature T_k (~20%)

→ $$\log\left[\frac{\alpha_{CO}}{M_\odot/(K\ km\ s^{-1}\ pc^2)}\right]$$

$$= 0.78\log[\tau_{CO(2-1)}] - 0.18\log\left(\frac{T_k}{K}\right) - 0.84$$

- Next step: observational tracers for α_{CO}?

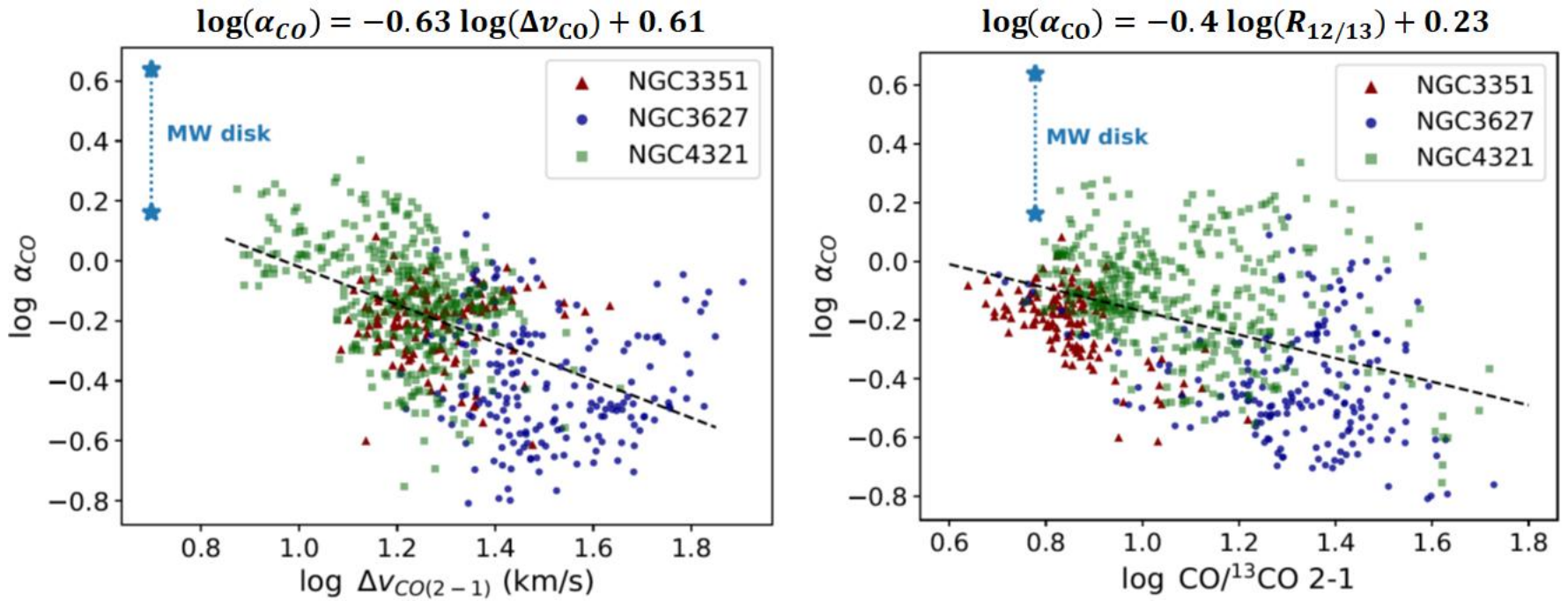




(Teng+ 2023)

Observational tracers of α_{CO}

- Higher **velocity dispersion** in these galaxy centers decreases τ_{CO} and thus lowers $\alpha_{CO,}$ as $\tau_{CO} \propto N_{CO}/\Delta v$
- The **CO/^{13}CO (2-1) ratio** mainly reflects τ_{CO}, as CO is optically thick while ^{13}CO is optically thin, and [CO/^{13}CO] ~ constant



(Teng+ 2023)

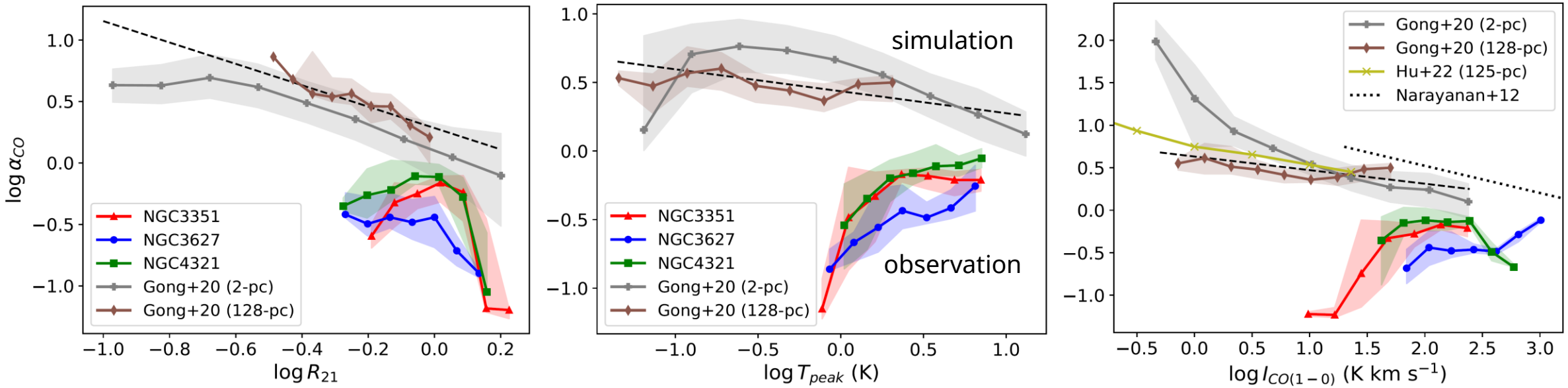
Compare with simulations

- (M)HD simulation of galaxy/ISM at pc-scales *(Narayanan+ 2012, Gong+ 2020, Hu+ 2022)*

  → current simulations tend to overestimate α_{CO} in galaxy centers

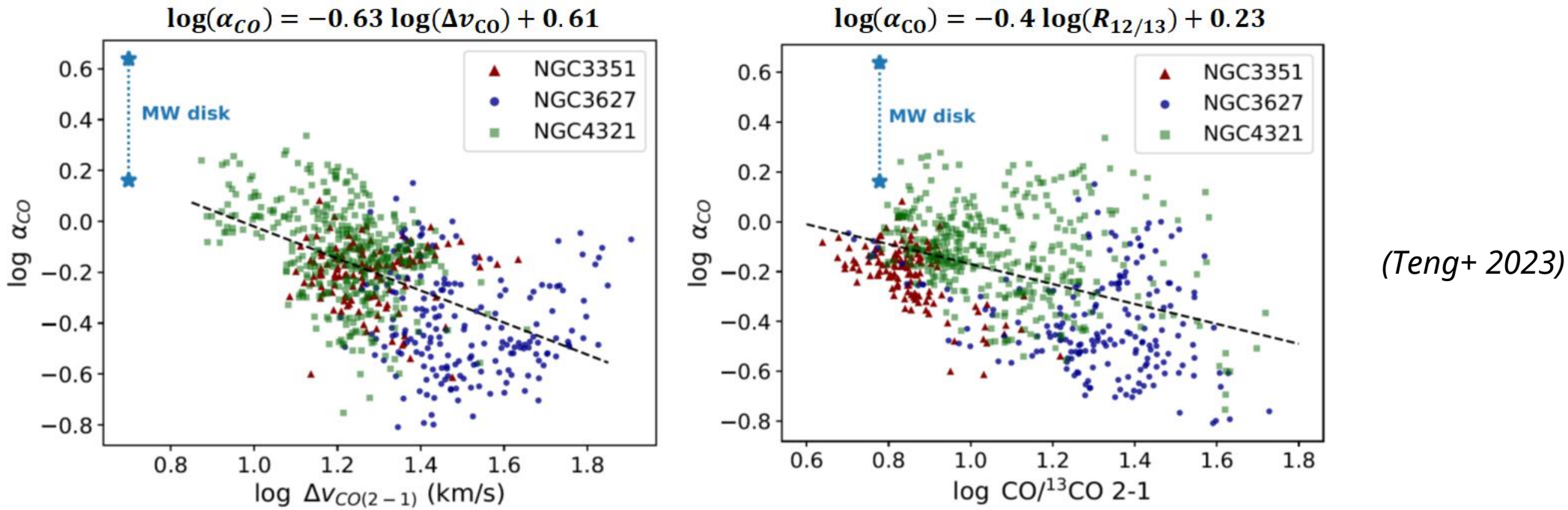
  → **gas inflows** & **turbulence effects** should have significant contributions to α_{CO}!

(Teng+ 2023)



Observational tracers of α_{CO}

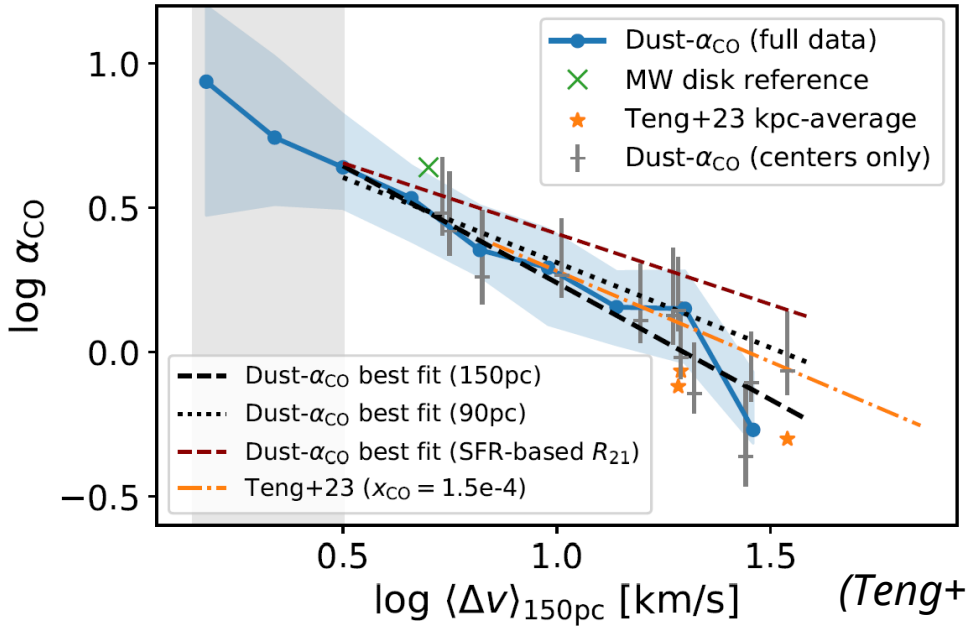
- Higher **velocity dispersion** in these galaxy centers decreases τ_{CO} and thus lowers $\alpha_{CO,}$ as $\tau_{CO} \propto N_{CO}/\Delta v$
- The **CO/^{13}CO (2-1) ratio** mainly reflects τ_{CO}, as CO is optically thick while ^{13}CO is optically thin, and [CO/^{13}CO] ~ constant



(Teng+ 2023)

A new Δv-based $\alpha_{\rm CO}$ prescription

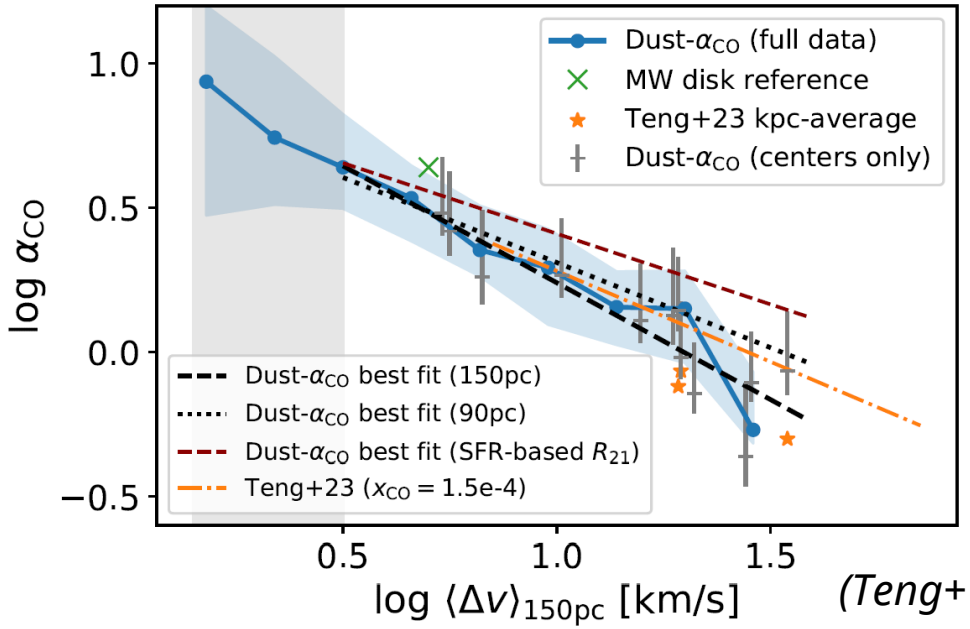
- We have found consistent $\alpha_{\rm CO}$– Δv dependence across more galaxies!
  - **12 barred and non-barred galaxies out to $R_{\rm gal} \sim 10$ kpc**
  - Dust-based $\alpha_{\rm CO}$ measurements at 2-kpc resolution *(Chiang+ 2024)*
  - Kpc-averaged Δv measured at 90/150-pc scale from PHANGS *(Sun+ 2022)*



(Teng+ 2024)

A new Δv-based $\alpha_{\rm CO}$ prescription

- We have found consistent $\alpha_{\rm CO}$– Δv dependence across more galaxies!
  - **12 barred and non-barred galaxies out to $R_{\rm gal} \sim 10$ kpc**
  - Dust-based $\alpha_{\rm CO}$ measurements at 2-kpc resolution *(Chiang+ 2024)*
  - Kpc-averaged Δv measured at 90/150-pc scale from PHANGS *(Sun+ 2022)*



(Teng+ 2024)

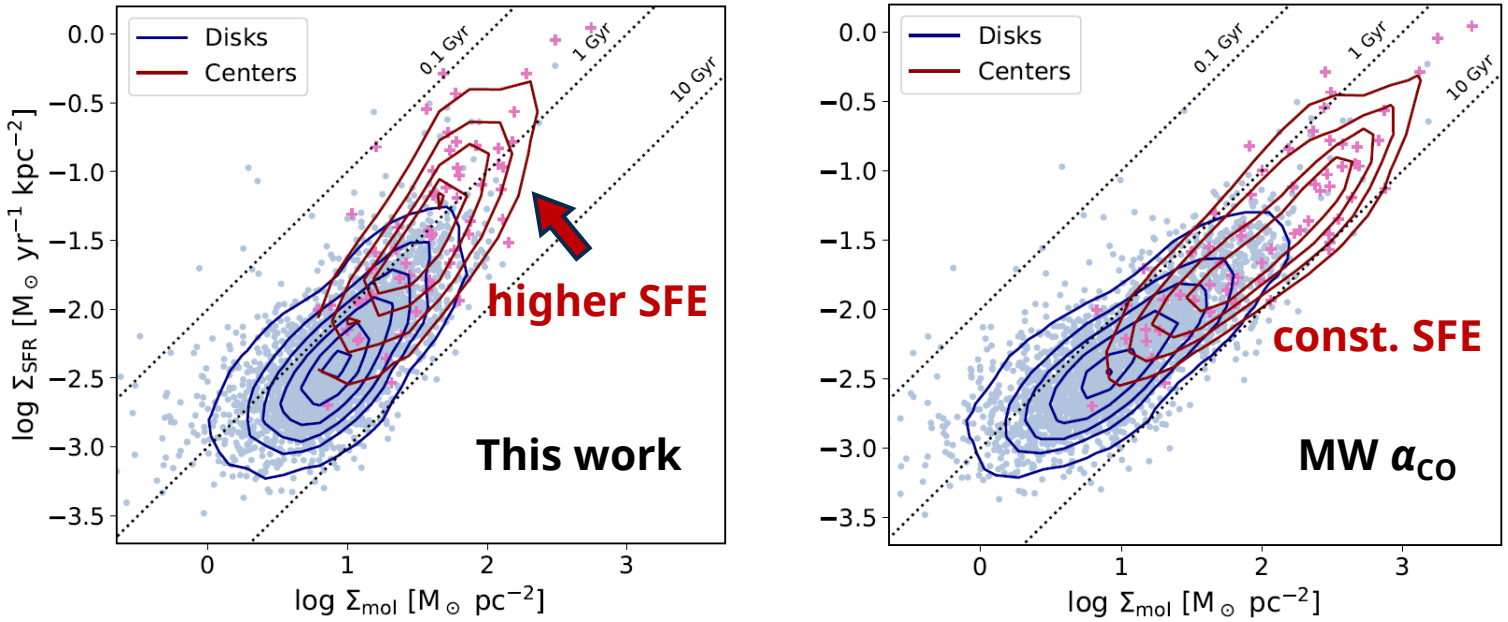
$$\log\left[\frac{\alpha_{\rm CO}}{\rm M_\odot/(K\,km\,s^{-1}\,pc^2)}\right] = -0.81\log\left(\frac{\langle\Delta v\rangle_{150\rm pc}}{\rm km\,s^{-1}}\right) + 1.05$$

1. Least scatter among existing $\alpha_{\rm CO}$ prescriptions (σ~0.1 dex)
2. Closest connection to the physics of $\alpha_{\rm CO}$ (i.e., optical depth variation)
3. Recently also verified in Antennae and M51 (*He+ 2024, den Brok+ submitted*)

Impact on star formation efficiency

- Tested on 65 galaxies from PHANGS, and compared to MW α_{CO}:
  - **Enhanced SFE** towards galaxy centers and high-Σ_{mol} regions
  - **Σ_{mol} overestimated** by ~5x in galaxy centers with MW α_{CO}

  → choice of α_{CO} greatly affects our understanding of galactic-scale star formation!

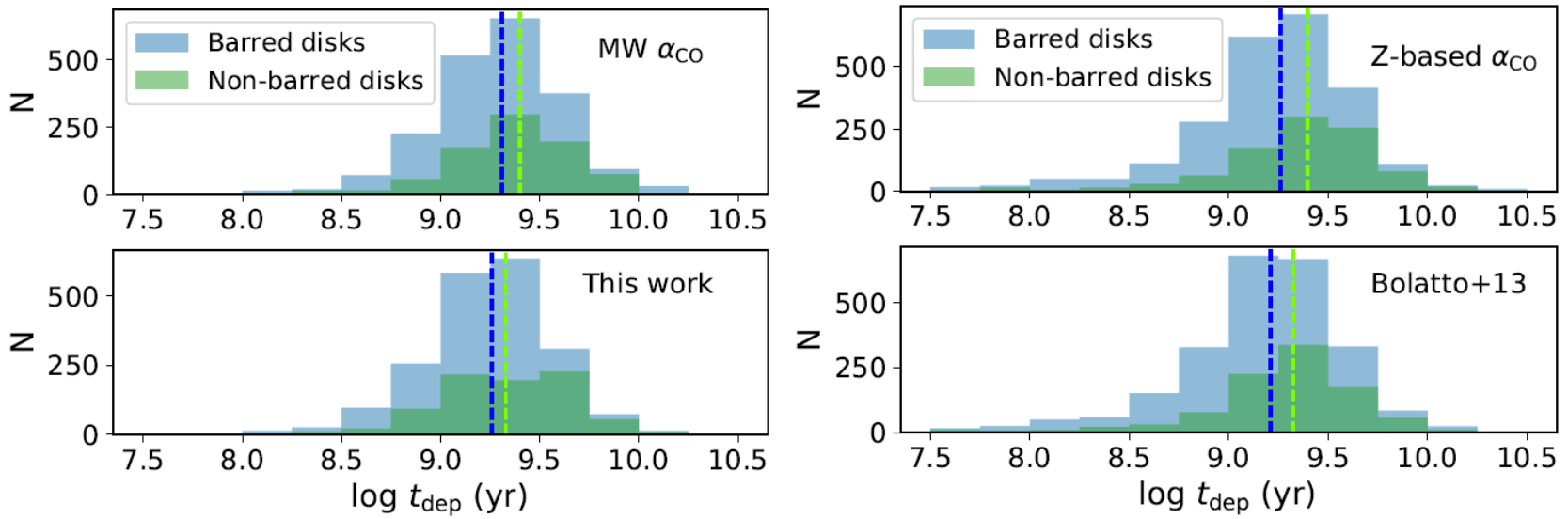


(Teng+ 2024)

Barred vs. non-barred galaxies

- Compare gas depletion time (SFE^{-1}) using different α_{CO} prescriptions:
  - All prescriptions lead to similar t_{dep} distribution across **galaxy disks**
  - Both MW and Z-based α_{CO} result in 3-5x longer t_{dep} in **galaxy centers** overall
  - Bolatto+13 α_{CO} predicts shorter t_{dep} in general, similar to our centers average
  - **Only our prescription reveals ~3x shorter t_{dep} in barred galaxy centers**

Disks

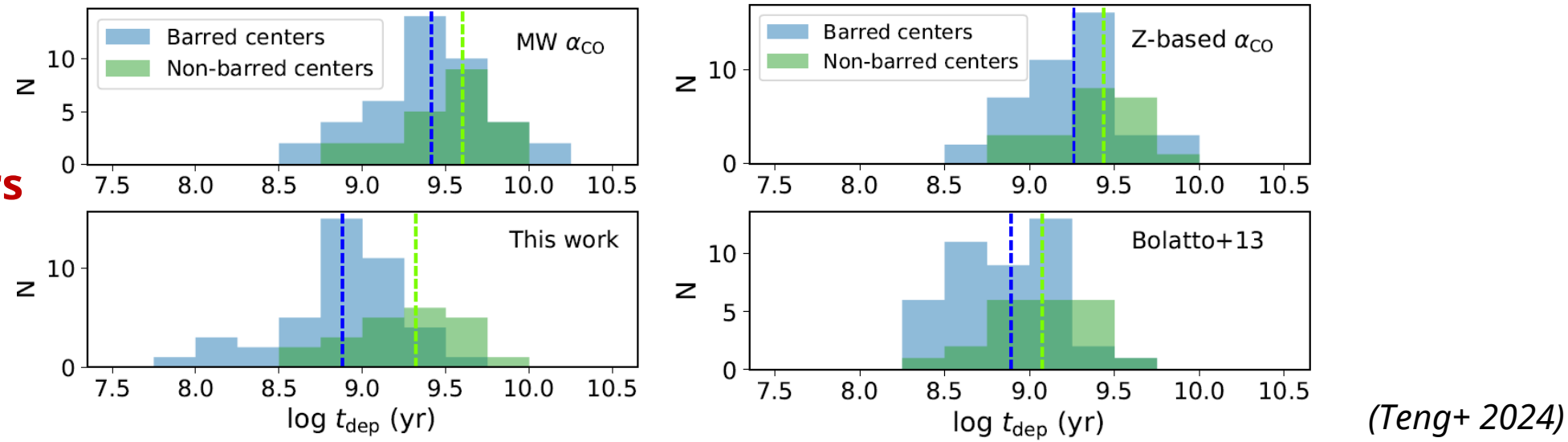


(Teng+ 2024)

Barred vs. non-barred galaxies

- Compare gas depletion time (SFE^{-1}) using different $\alpha_{\rm CO}$ prescriptions:
  - All prescriptions lead to similar $t_{\rm dep}$ distribution across **galaxy disks**
  - Both MW and Z-based $\alpha_{\rm CO}$ result in 3-5x longer $t_{\rm dep}$ in **galaxy centers** overall
  - Bolatto+13 $\alpha_{\rm CO}$ predicts shorter $t_{\rm dep}$ in general, similar to our centers average
  - **Only our prescription reveals ~3x shorter $t_{\rm dep}$ in barred galaxy centers**

Centers

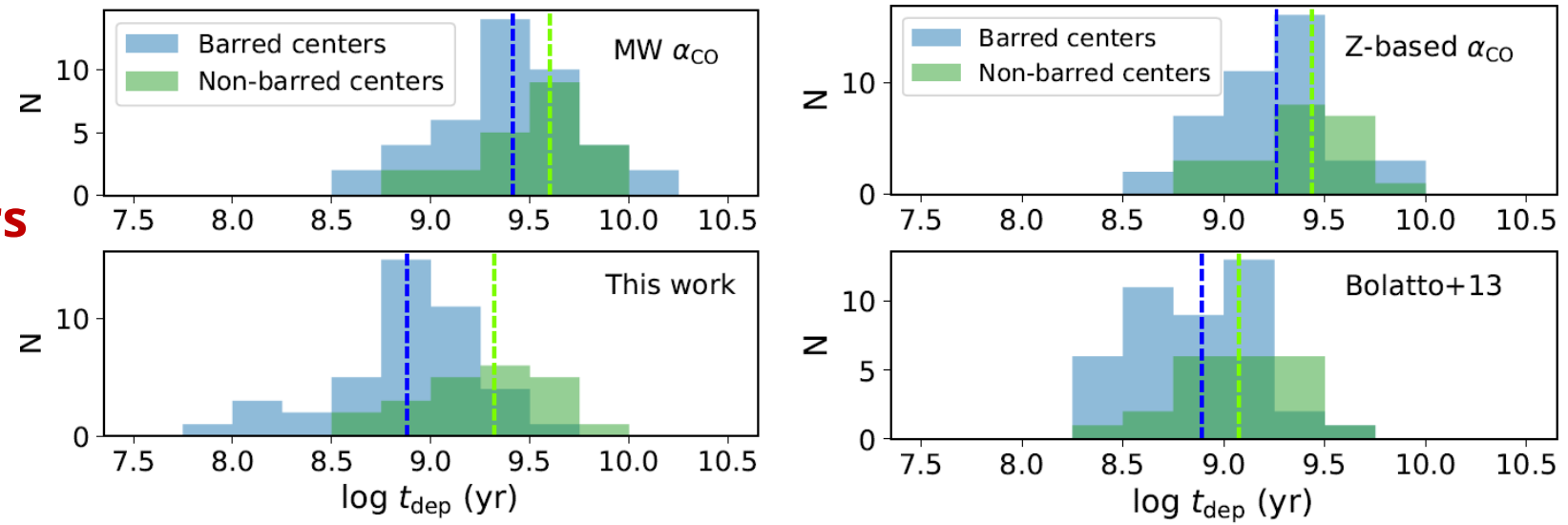


(Teng+ 2024)

Barred vs. non-barred galaxies

- Compare gas depletion time (SFE^{-1}) using different $\alpha_{\rm CO}$ prescriptions:
  - All prescriptions lead to similar $t_{\rm dep}$ distribution across **galaxy disks**
  - Both MW and Z-based $\alpha_{\rm CO}$ result in 3-5x longer $t_{\rm dep}$ in **galaxy centers** overall
  - Bolatto+13 $\alpha_{\rm CO}$ predicts shorter $t_{\rm dep}$ in general, similar to our centers average
  - **Only our prescription reveals ~3x shorter $t_{\rm dep}$ in barred galaxy centers**

Centers



MW $\alpha_{\rm CO}$:

const.

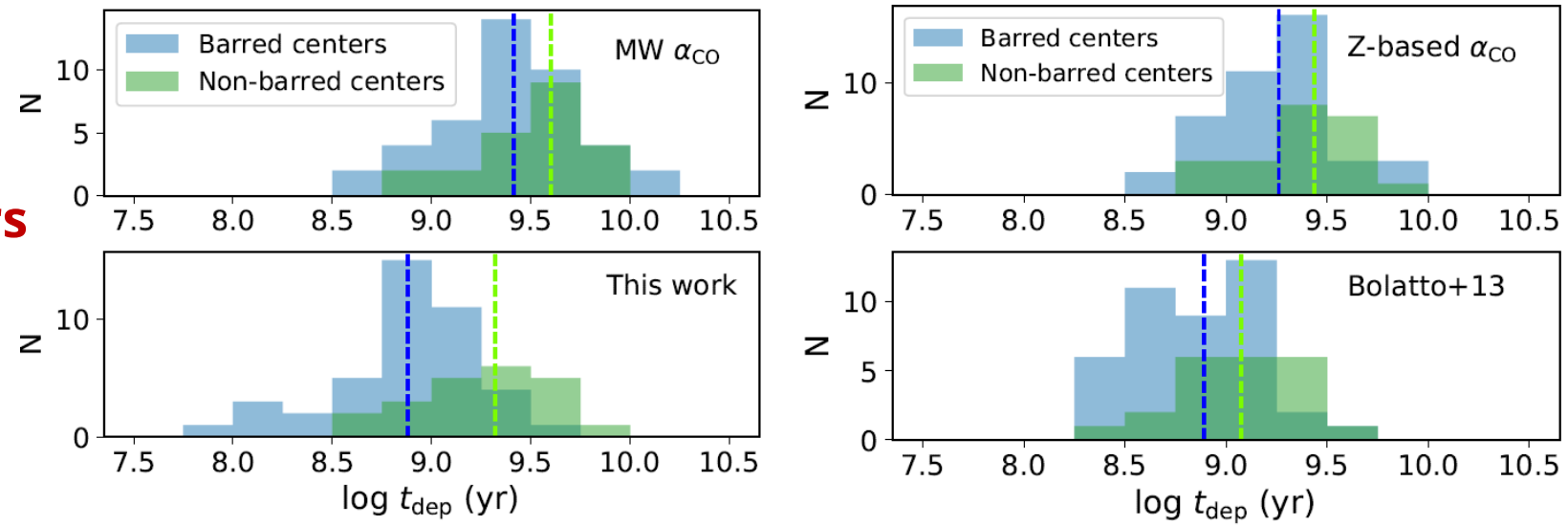
$$\mathrm{SFE} = \frac{\mathrm{SFR}}{M_{\rm mol}}$$

(Teng+ 2024)

Barred vs. non-barred galaxies

- Compare gas depletion time (SFE^{-1}) using different α_{CO} prescriptions:
  - All prescriptions lead to similar t_{dep} distribution across **galaxy disks**
  - Both MW and Z-based α_{CO} result in 3-5x longer t_{dep} in **galaxy centers** overall
  - Bolatto+13 α_{CO} predicts shorter t_{dep} in general, similar to our centers average
  - **Only our prescription reveals ~3x shorter t_{dep} in barred galaxy centers**

Centers



Our α_{CO} :

$$\uparrow SFE = \frac{SFR}{M_{mol}} \uparrow$$

const.

(Teng+ 2024)

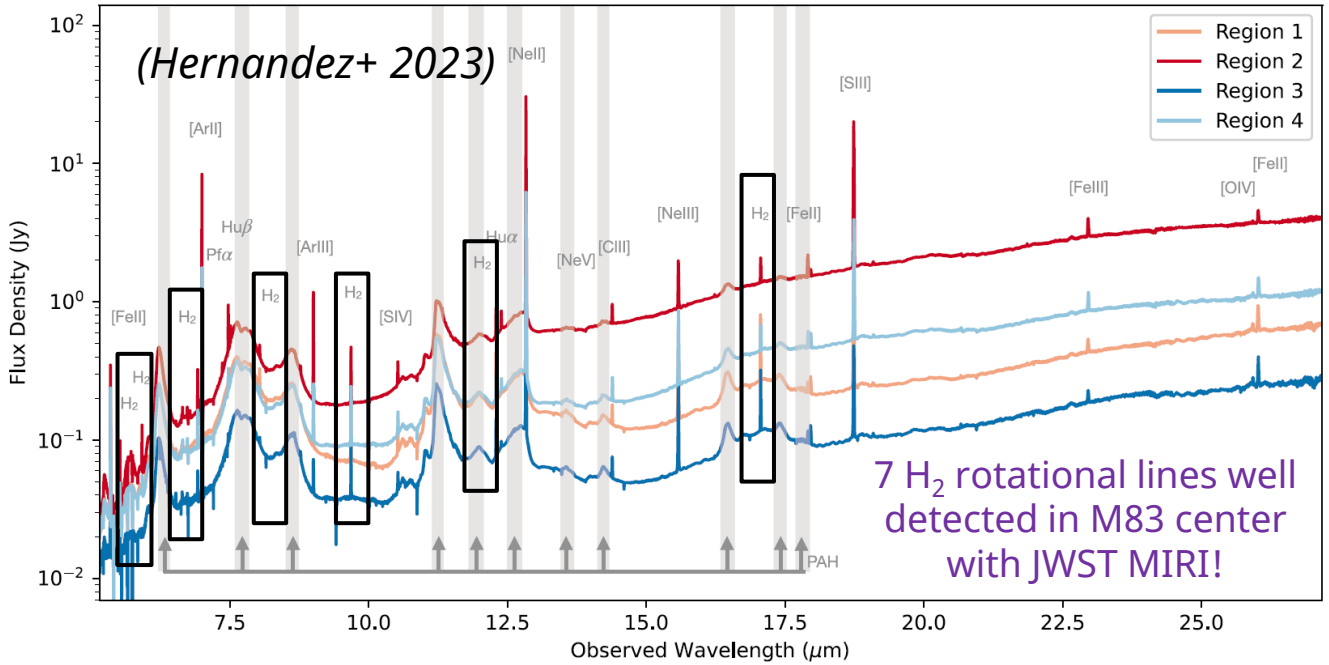
Future directions

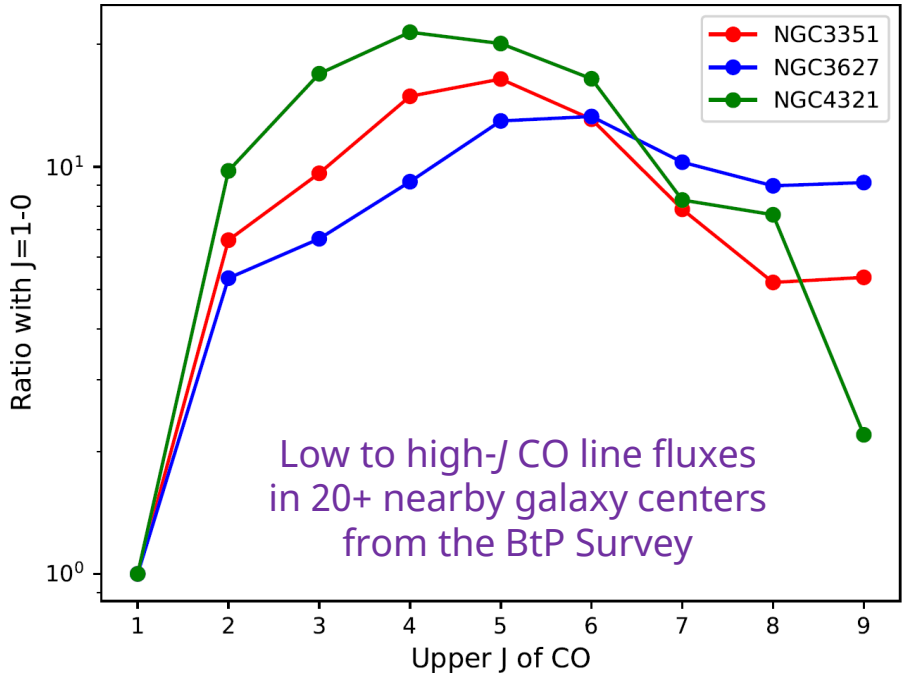
- What is driving the increase of SFE in barred galaxy centers?

  1) **JWST**: warm H_2 gas and embedded SF → impact of **stellar feedback** on SFE?

  2) High-*J* CO ladder and H_2 line modeling across 20+ nearby galaxy centers

(Teng+ in prep)





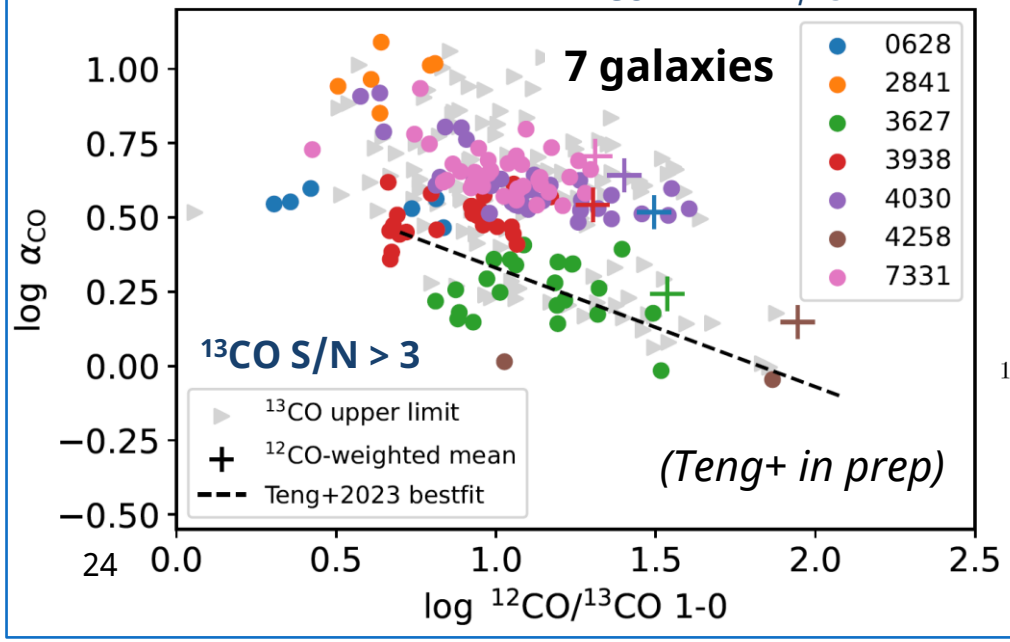
Future directions

- Examine α_{CO} dependence on $^{12}CO/^{13}CO$ line ratio across large sample

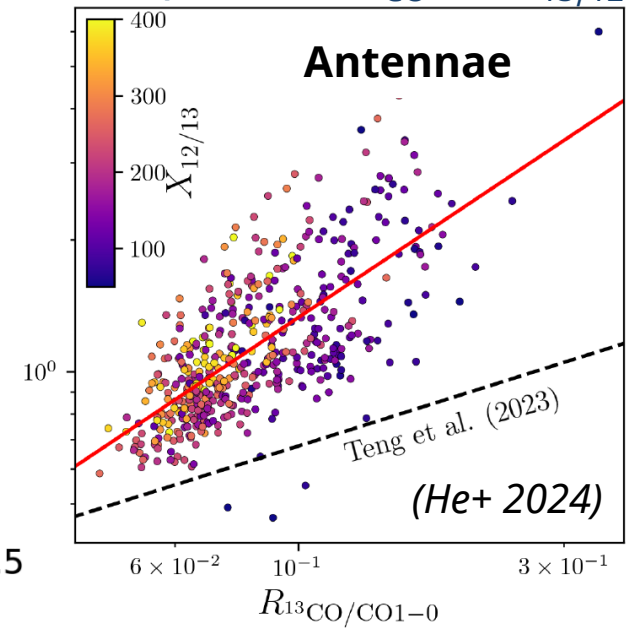
  → Is opacity the only key driver of α_{CO}? A better α_{CO} prescription for kpc-scale studies?

  → **ALMA, ngVLA**: high-resolution & sensitive $^{12}CO/^{13}CO$ maps; α_{CO} for high-z galaxies

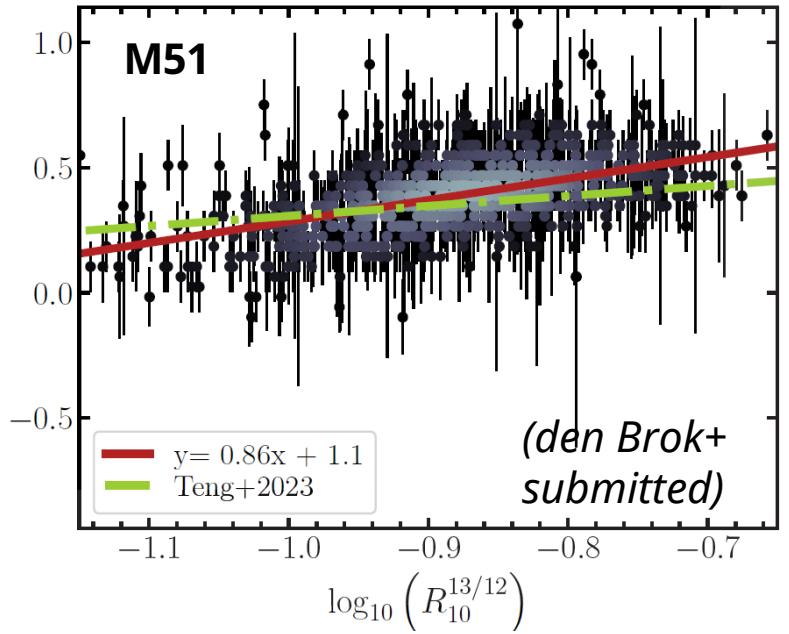
kpc-scale α_{CO} vs. $R_{12/13}$



150 pc-scale α_{CO} vs. $R_{13/12}$



170 pc-scale α_{CO} vs. $R_{13/12}$



THANK YOU!

Low α_{CO} in galaxy centers
5-15x lower α_{CO} than MW disk

New observational tracers for α_{CO}
velocity dispersion & CO/^{13}CO ratio

Main physical drivers of α_{CO}
CO optical depth & gas temperature

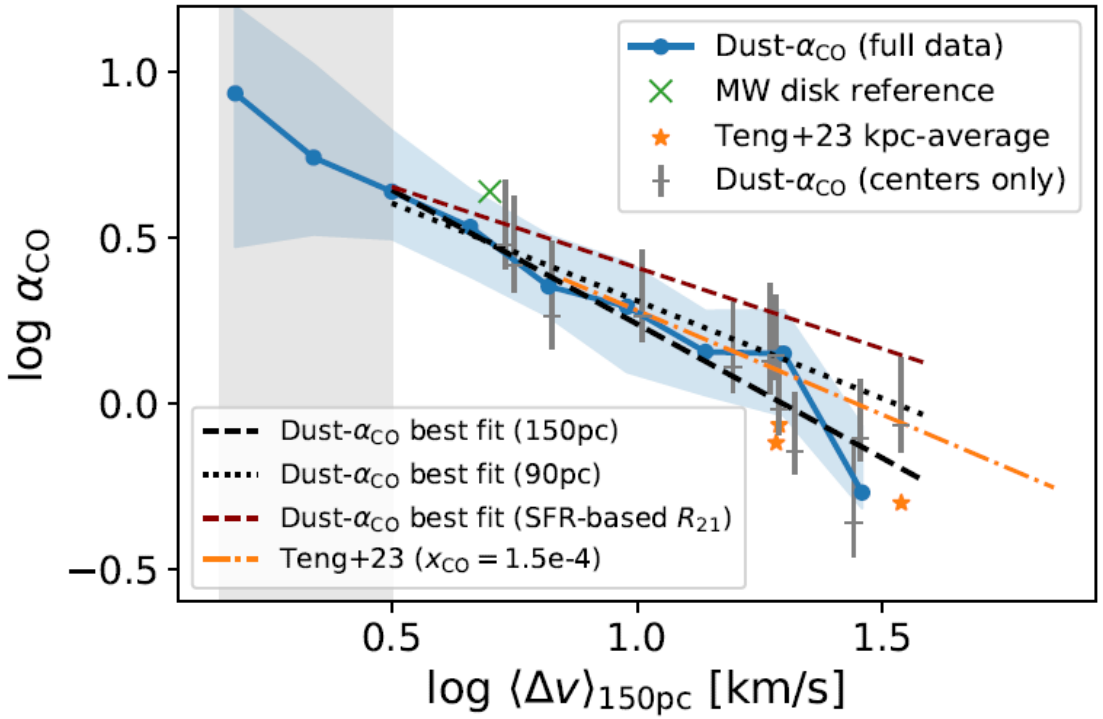
Enhanced SFE in barred centers
revealed with our new, Δv-based α_{CO}

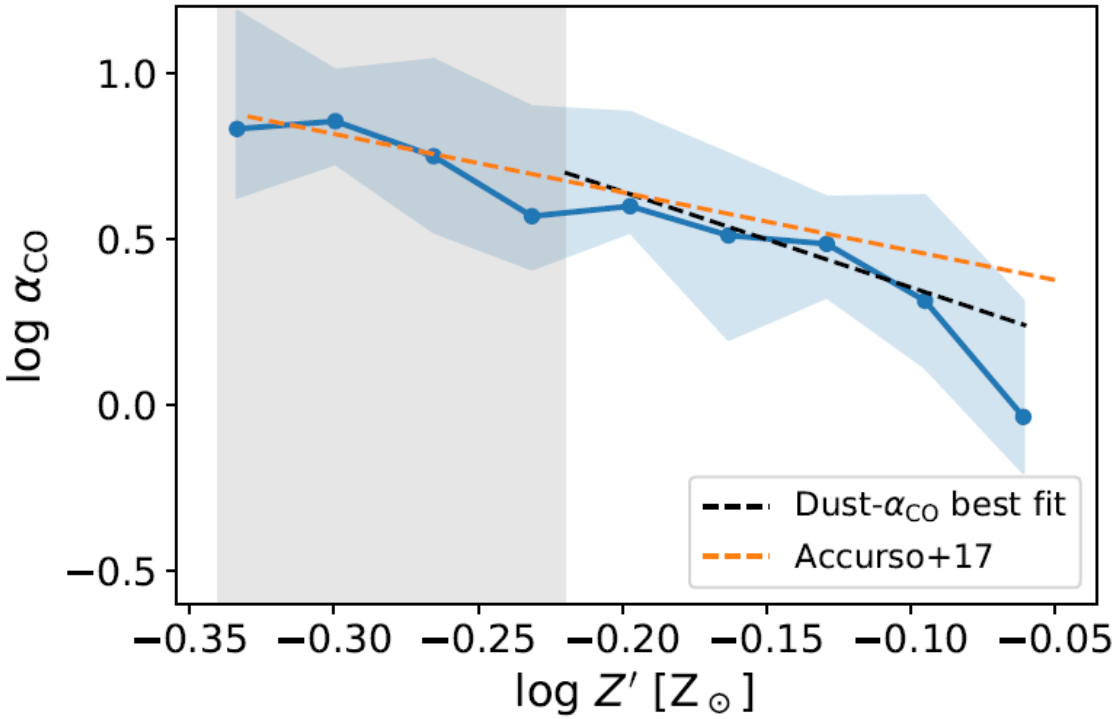


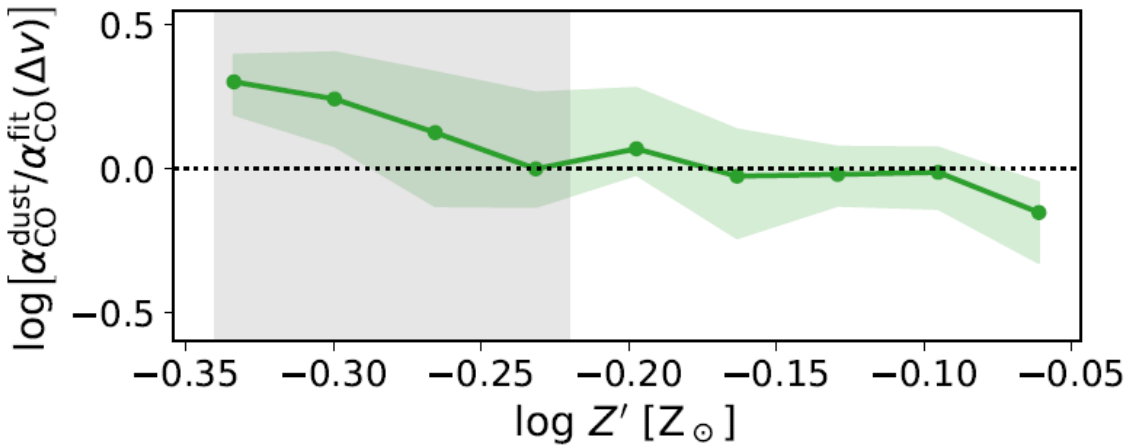


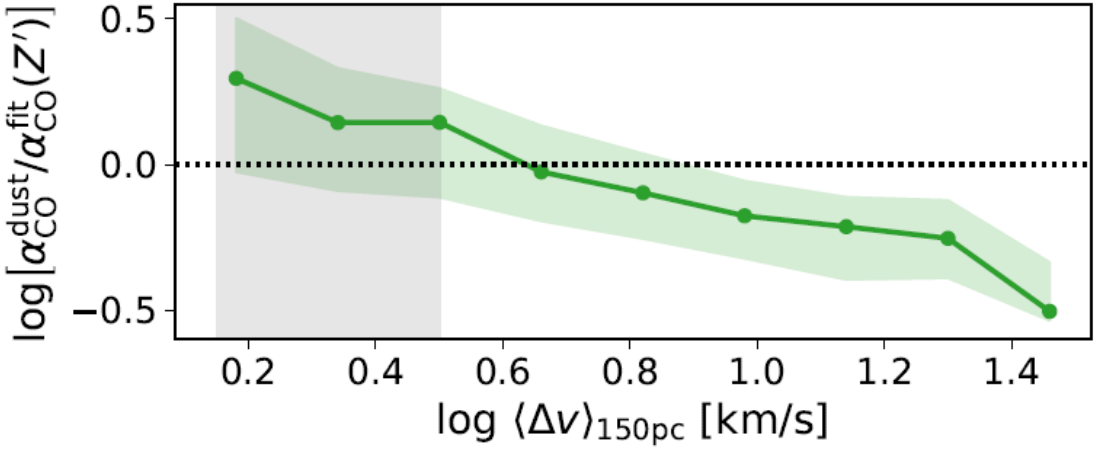

Contact me: elthateng@gmail.com https://elthateng.github.io/

Papers: **Y.-H. Teng** et al. 2022, *ApJ*, 925, 72; **Y.-H. Teng** et al. 2023, *ApJ*, 950, 119; **Y.-H. Teng** et al. 2024, *ApJ*, 961, 42


Dust-α_{CO} (full data)
MW disk reference
Teng+23 kpc-average
Dust-α_{CO} (centers only)
Dust-α_{CO} best fit (150pc)
Dust-α_{CO} best fit (90pc)
Dust-α_{CO} best fit (SFR-based R_{21})
Teng+23 (x_{CO} = 1.5e-4)
log α_{CO}
log $\langle \Delta v \rangle_{150pc}$ [km/s]


Dust-α_{CO} best fit
Accurso+17
log α_{CO}
log Z' [$Z_\odot$]

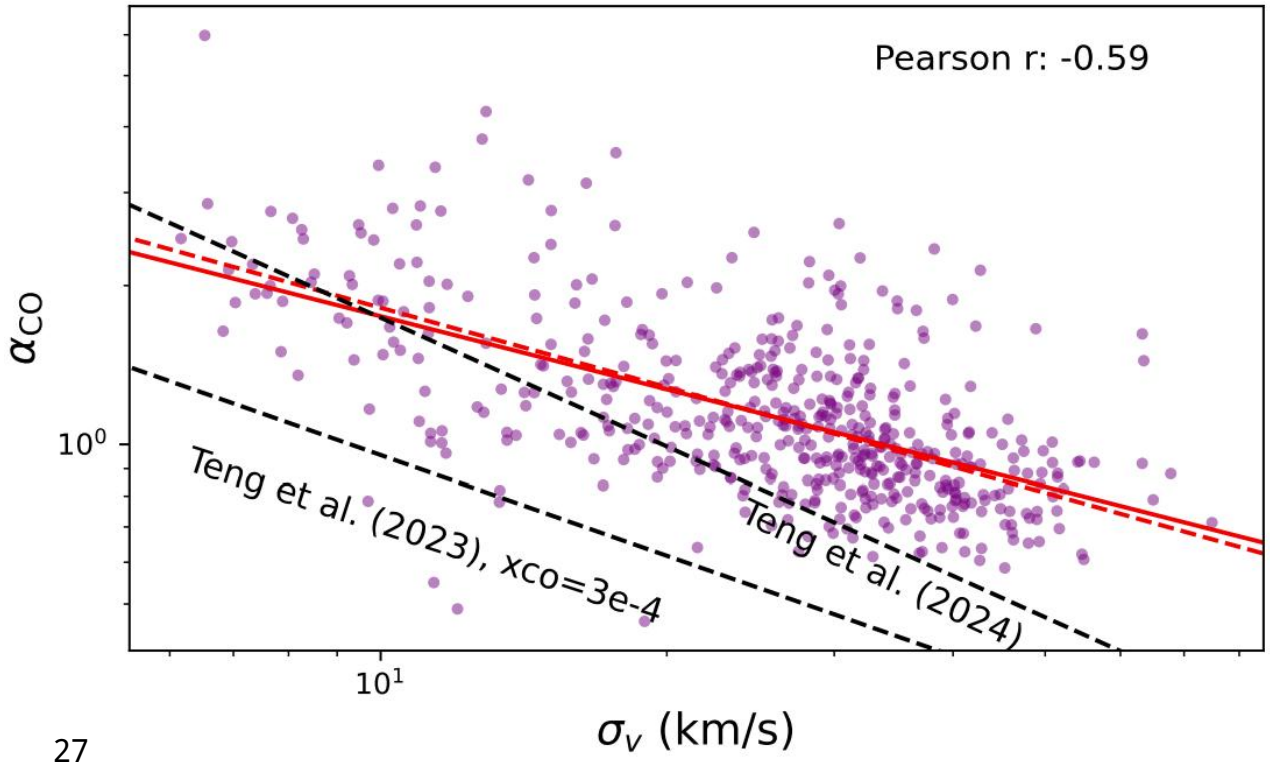

log $[\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(\Delta v)]$
log Z' [$Z_\odot$]


log $[\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(Z')]$
log $\langle \Delta v \rangle_{150pc}$ [km/s]

(Teng+ 2024)

Further tests on the $\alpha_{CO} - \Delta v$ prescription

Antennae *(He, Wilson+ 2024 in press)*



M51 *(den Brok+ submitted)*