Extending the Latest CO-to-H_2 Conversion Factor Prescriptions

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Jiayi Sun, I-Da Chiang, …, and *The PHANGS Team*

Variable CO-to-H_2 Conversion

- Tracing molecular gas in galaxies: CO observation

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

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

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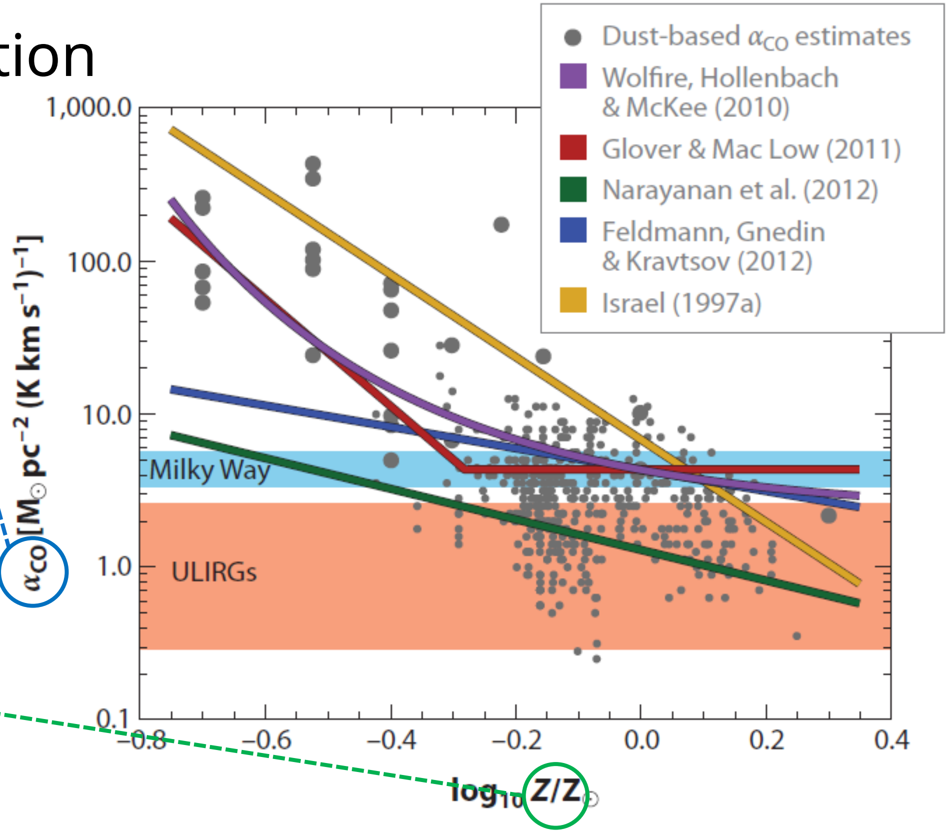
- Variation of α_{CO} within and between galaxies
  - α_{CO} depends on many **molecular gas properties**

    → temperature, density, opacity, metallicity ...



(Bolatto et al. 2013)

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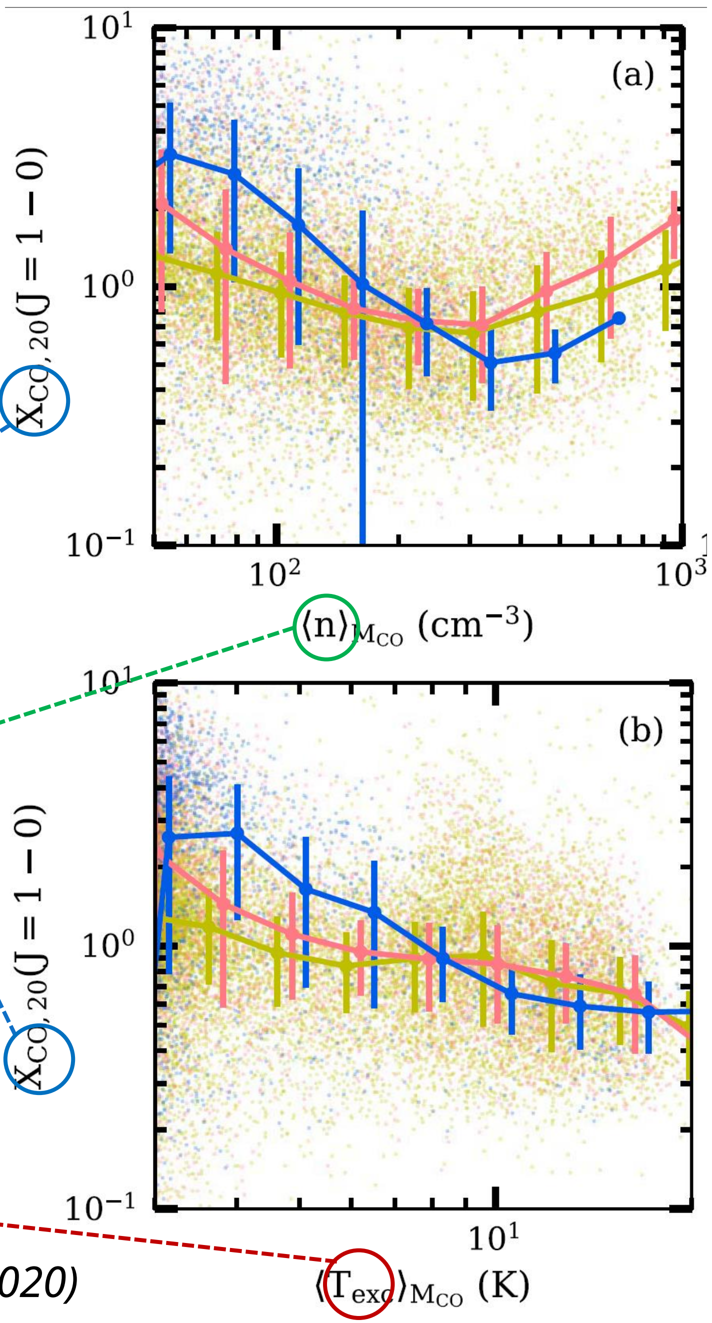

(Gong et al. 2020)

Recent α_{CO} Prescriptions

- Pure **metallicity** dependent
  - $\alpha_{\mathrm{CO}} \propto (Z/Z_{\odot})^{-\gamma}$, where $\gamma \sim 1.3 - 2.0$

  (Genzel+2012, Hunt+2015, Amorin+2016, Accurso+2017, Madden+2020)

- **CO emissivity** dependent
  - CO velocity dispersion: $\alpha_{\mathrm{CO}} \propto \Delta v_{\mathrm{CO}}^{-\gamma}$, where $\gamma = 0.6 - 0.8$ *(Teng+2023, 2024)*
  - Stellar mass surface density: $\alpha_{\mathrm{CO}} \propto \Sigma_{*}^{-\gamma}$, where $\gamma = 0.2 - 0.5$

    (Bolatto+2013, Chiang+2024, Schinnerer & Leroy 2024)
  - Other: CO intensity *(Narayanan+2012, Gong+2020)*, SFR *(Renaud+2019)*, multi-CO line ratios *(Gong+2020, Teng+2023)*, gas clumpiness *(Ramambason+2023)*, …

- Uncertainty (σ) > 0.2-0.3 dex for most prescriptions

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- Pure **metallicity** dependent
  - $\alpha_{\rm CO} \propto (Z/Z_\odot)^{-\gamma}$, where $\gamma \sim 1.3 - 2.0$ → Not accounting for CO emissivity, can be biased

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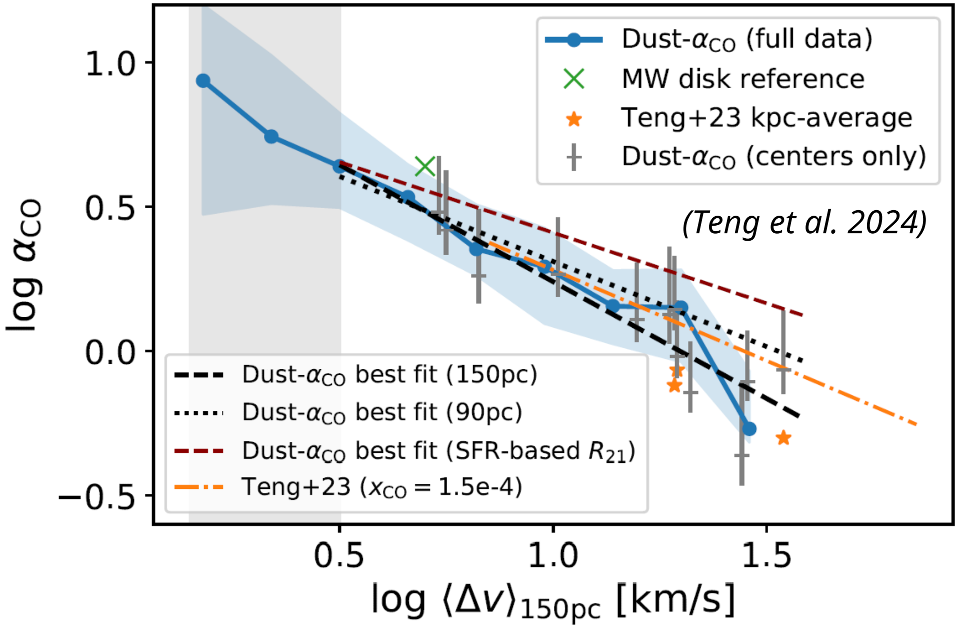
- **CO emissivity** dependent
  - CO velocity dispersion: $\alpha_{\rm CO} \propto \Delta v_{\rm CO}^{-\gamma}$, where $\gamma = 0.6 - 0.8$ *(Teng+2023, 2024)* → Need high-res, but low uncertainty!
  - Stellar mass surface density: $\alpha_{\rm CO} \propto \Sigma_*^{-\gamma}$, where $\gamma = 0.2 - 0.5$ → Higher uncertainty and need multi-band observations

    (Bolatto+2013, Chiang+2024, Schinnerer & Leroy 2024)
  - Other: CO intensity *(Narayanan+2012, Gong+2020)*, SFR *(Renaud+2019)*, multi-CO line ratios *(Gong+2020, Teng+2023)*, gas clumpiness *(Ramambason+2023)*, ... → Limited sample or less widely tested
- Uncertainty (σ) > 0.2-0.3 dex for most prescriptions

A new Δv-based α_{CO} prescription *(Teng et PHANGS 2024)*

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

1. Verified across barred and non-barred galaxies from centers out to $R_{\mathrm{gal}} \sim 10$ kpc
2. Smallest scatter among current α_{CO} prescriptions (σ~0.1 dex) → tracing CO opacity *(Teng+2023)*
3. Requires only CO data; already includes metallicity effects (at least for PHANGS-like galaxies)



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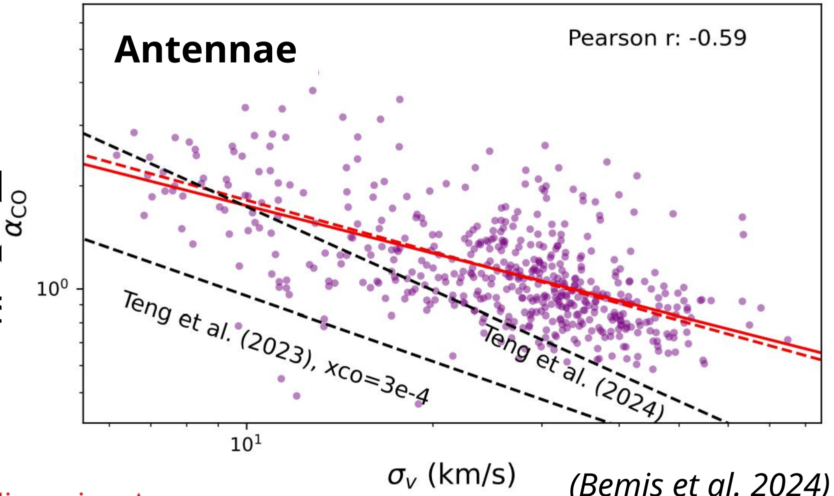
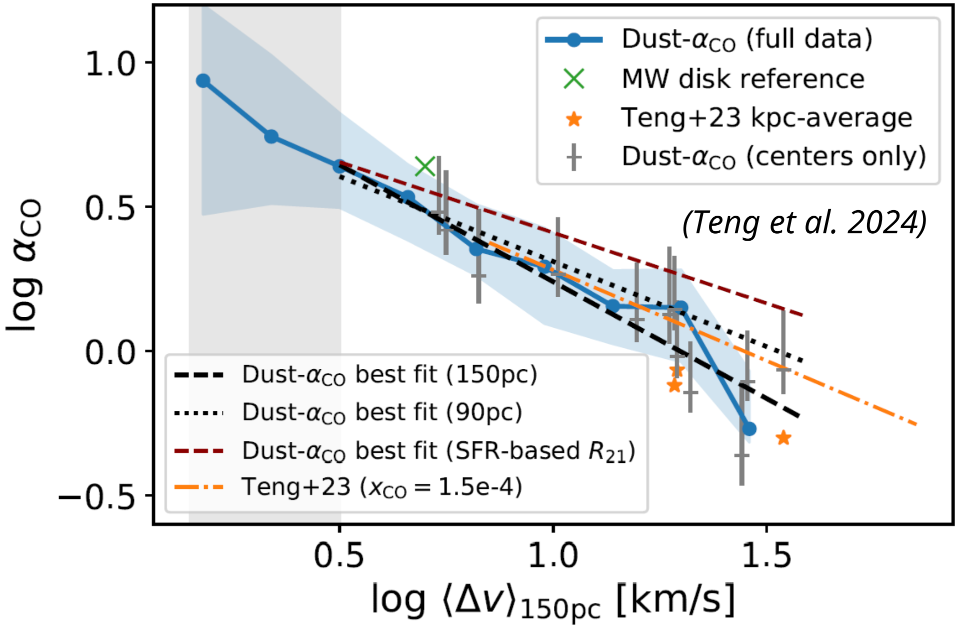
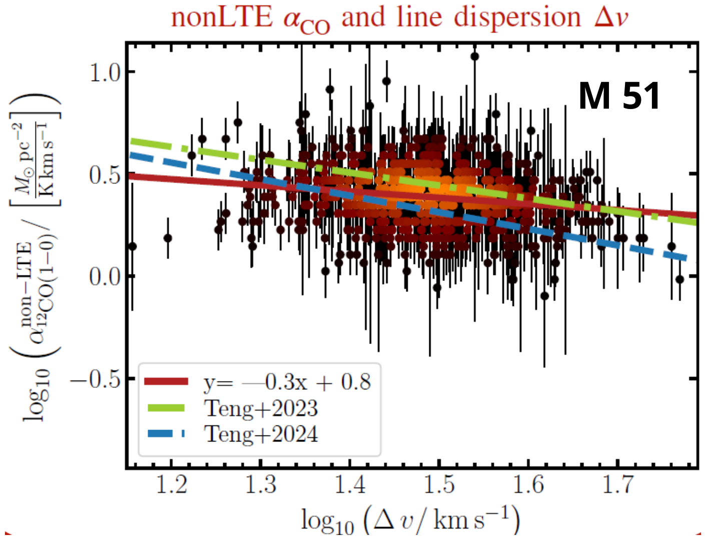
(He et al. 2024)

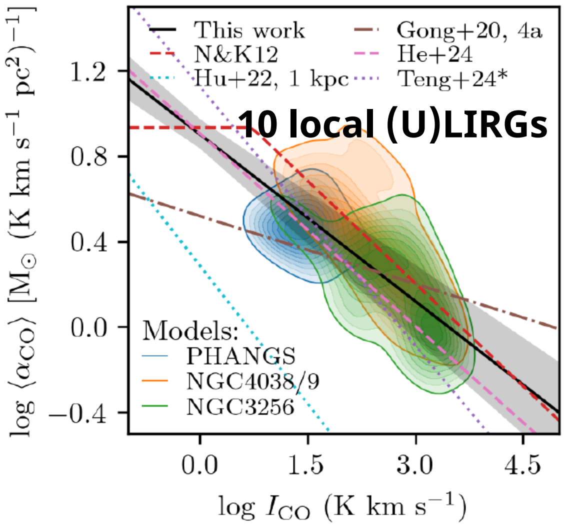




(den Brok et al. 2025)



(Bemis et al. 2024)



Kpc-scale Δv also works!

- Clear $\alpha_{\mathrm{CO}} - \Delta v$ trend using Δv from ~100 pc to 2 kpc resolutions

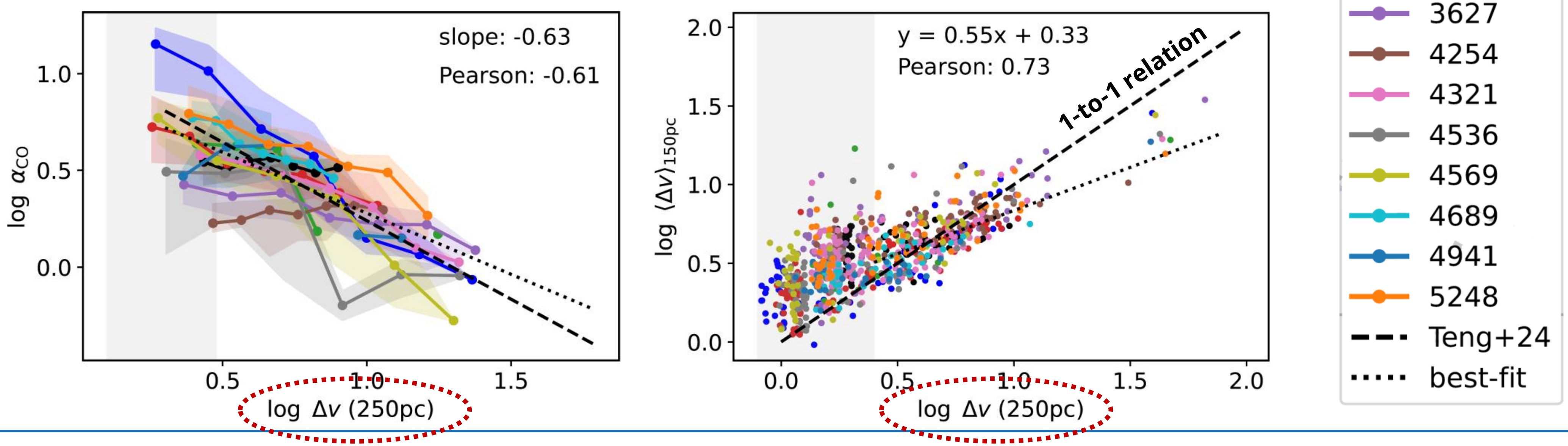
  → Δv-based α_{CO} prescription is generalizable to kpc-resolution data !

- 150-pc Δv strongly correlates with Δv from sub-kpc to kpc scales

  → low-res Δv can trace 150 pc-scale Δv well !

- After removing galaxy rotation, we find that kpc-averaged $\Delta v_{150\mathrm{pc}}$ still contribute to 40-70% of $\Delta v_{1\mathrm{kpc}}$ even in galaxy centers!

(Teng et al. in prep)



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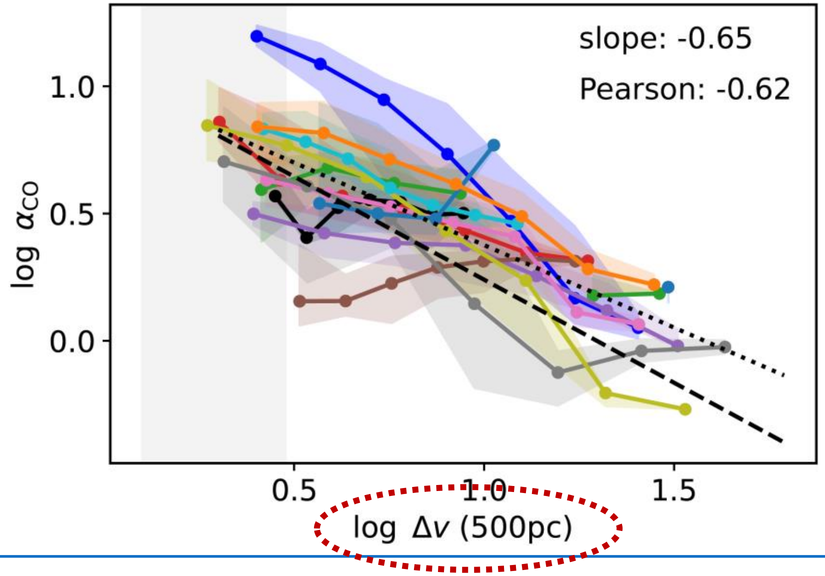

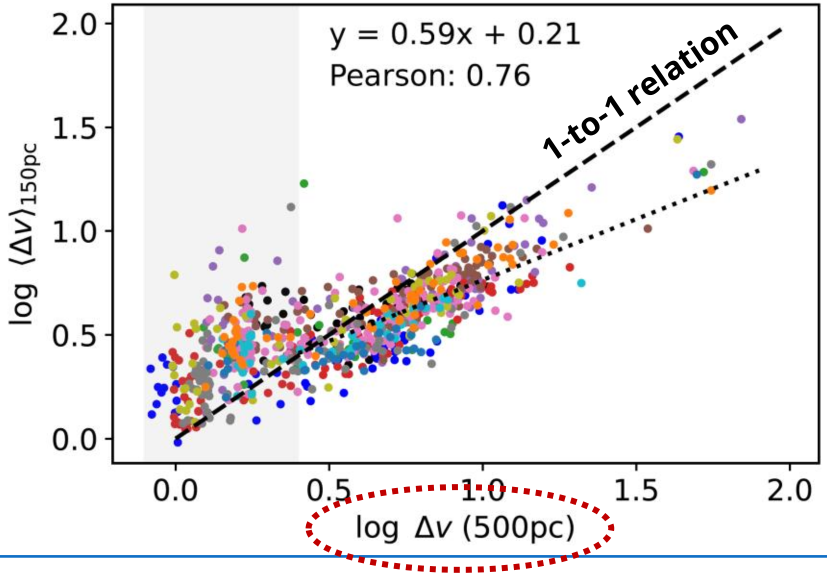

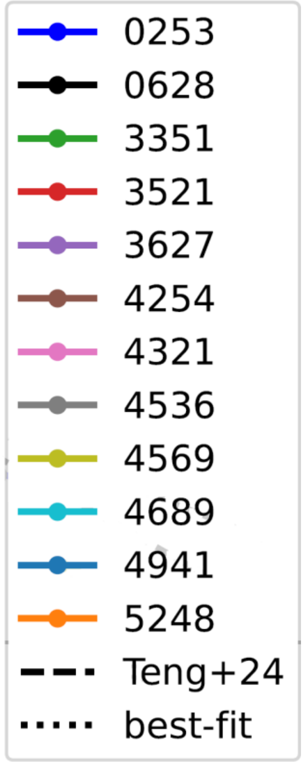

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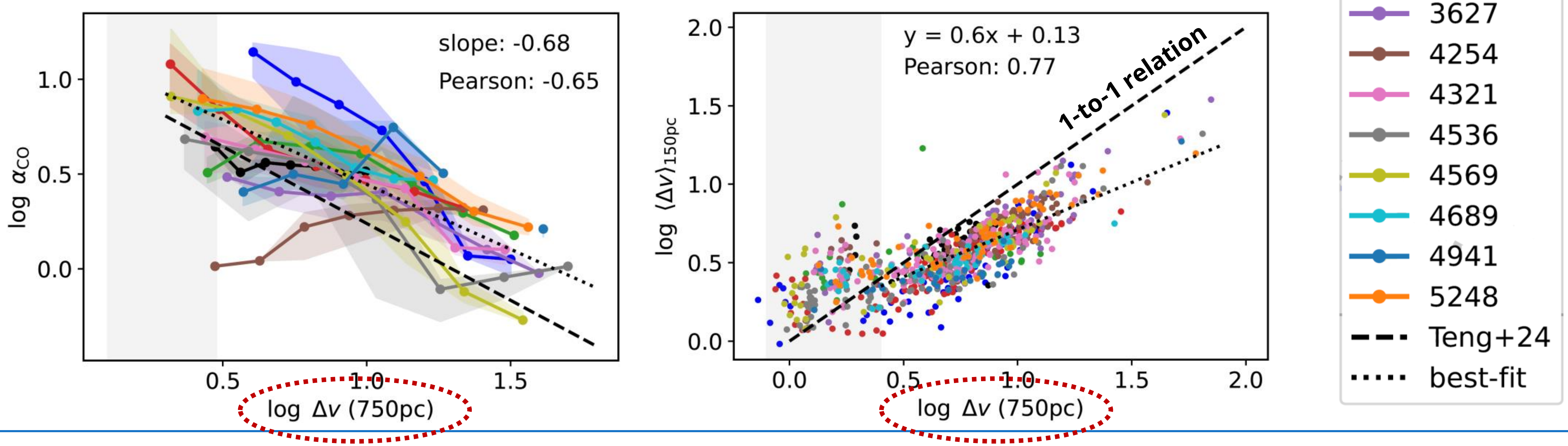

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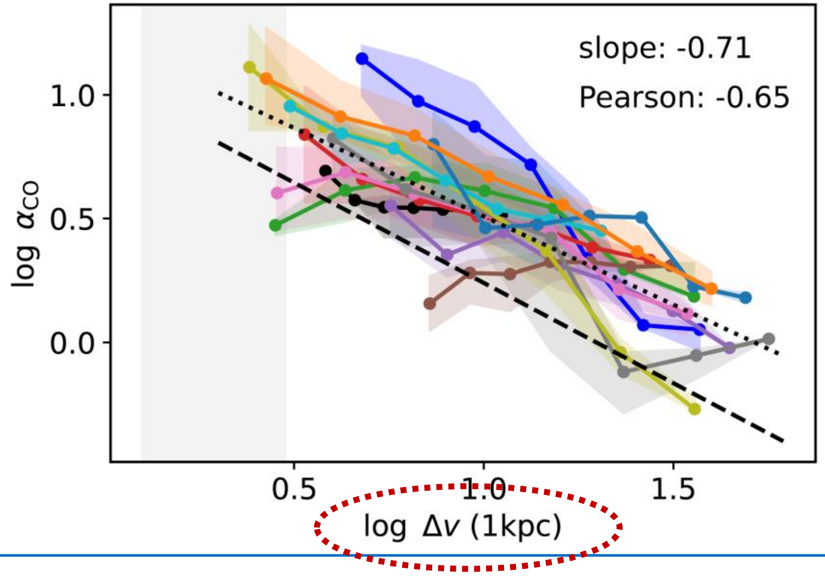

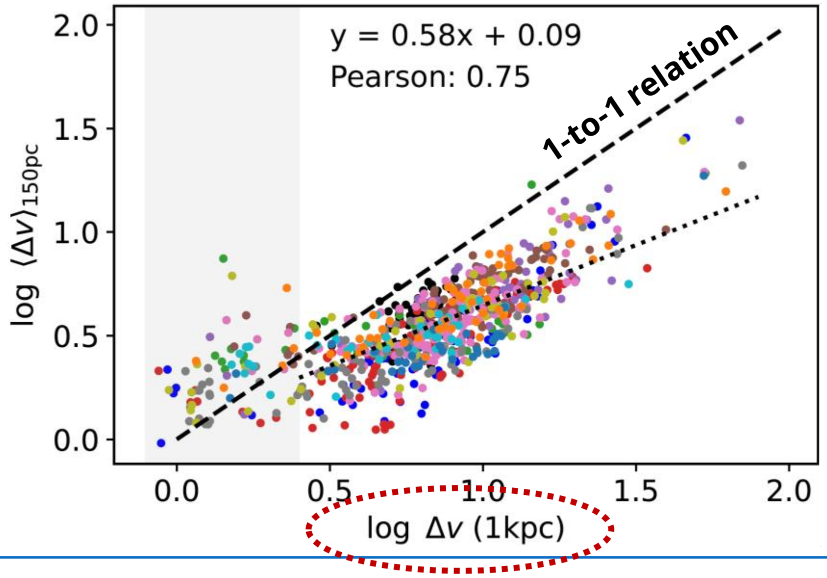

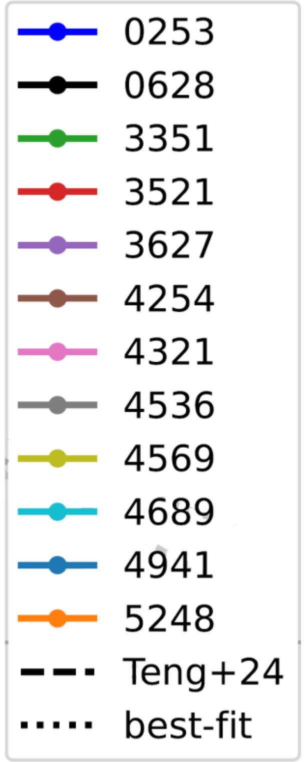

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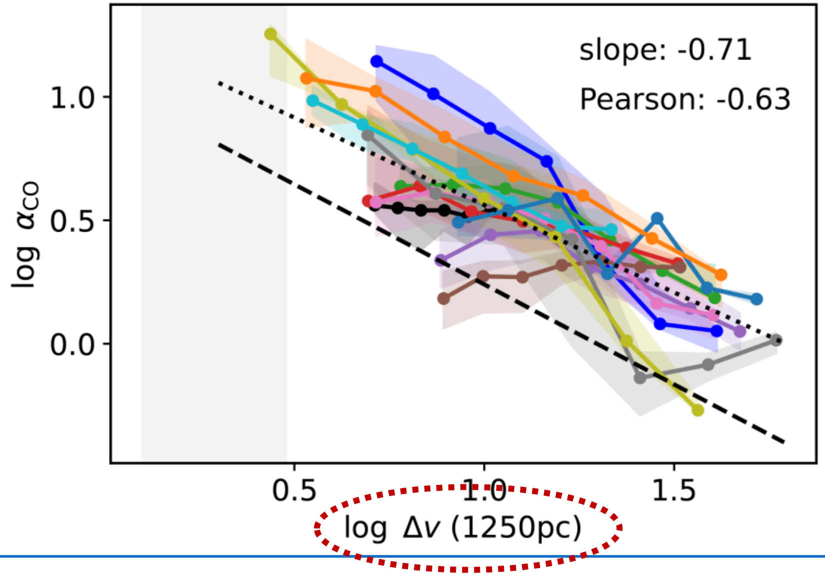

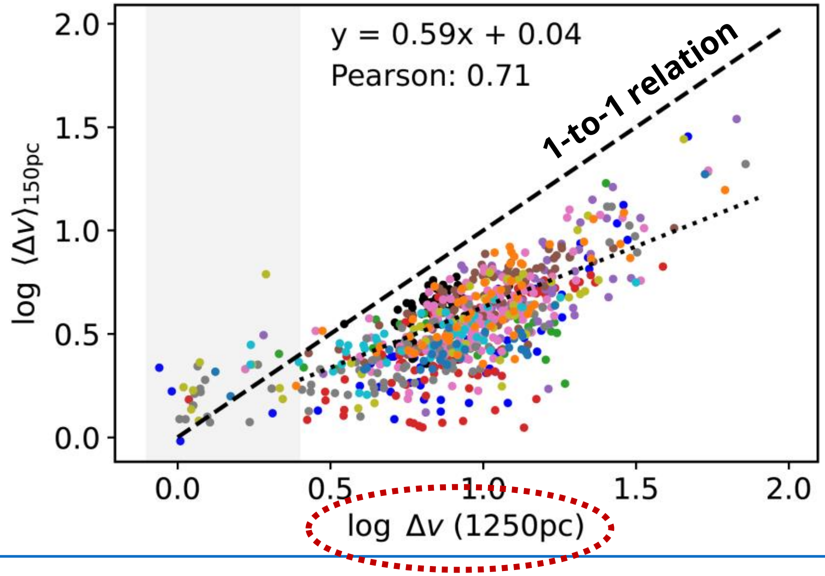

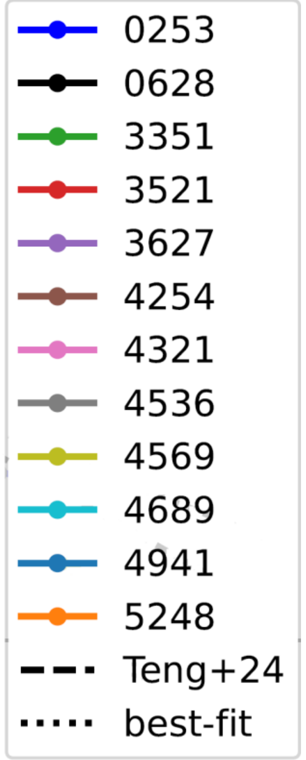

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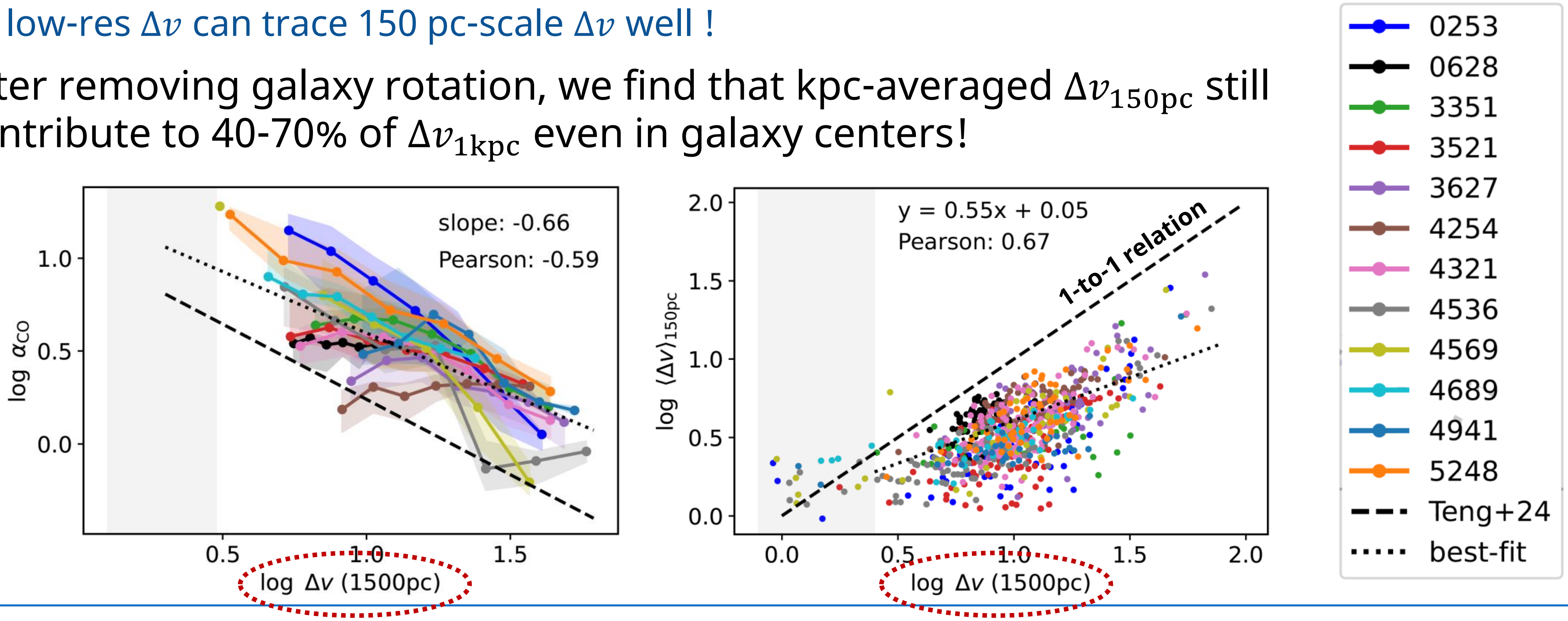

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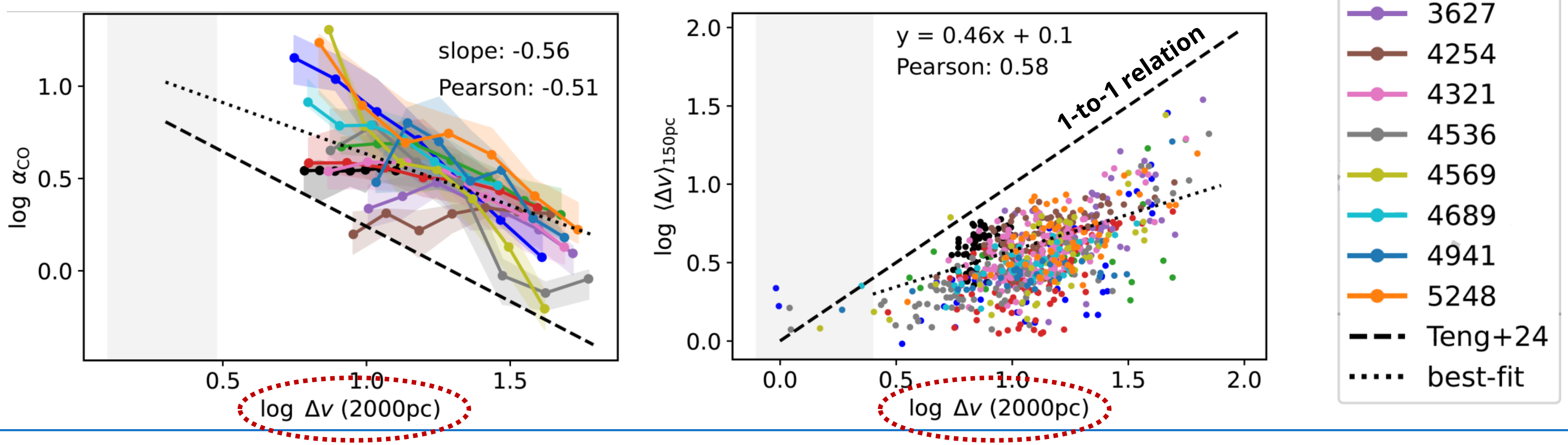


More Extensions…

- Testing other prescriptions:
  - α_{CO} dependence on the ^{12}CO/^{13}CO line ratios is also found at 100 pc scales

    (Teng+ 2023, He+ 2024, den Brok+ 2025)

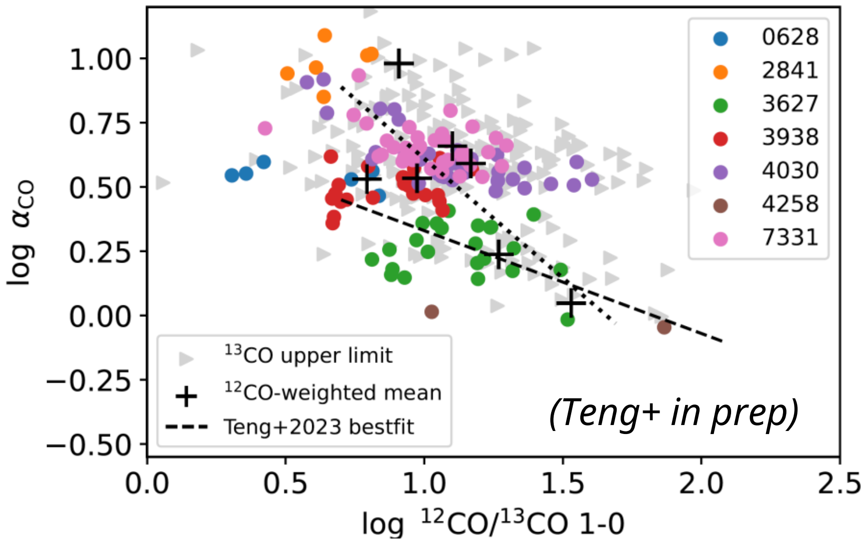
  → likely also work for kpc resolutions ?

- Expanding on different galaxy populations:
  - **GBT-EDGE CO(1-0) survey** *(Teng, Bolatto+ in prep)*

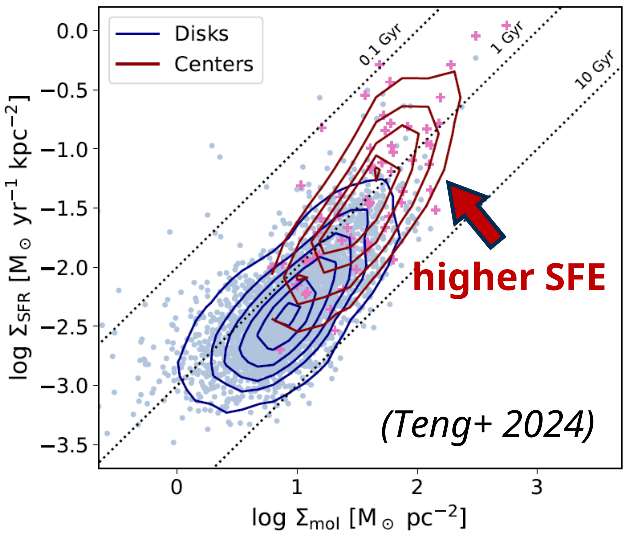
  → 150 galaxies sampling SFR from 0.01 to 10 $M_{\odot}/\mathrm{yr}$

  → SFE variations and systematic impacts from α_{CO} ?

data from current kpc-scale CO survey



Change of KS relation using Δv-based α_{CO} across 66 PHANGS galaxies



GBT-EDGE → ?

THANK YOU!

Calibrating on the PHANGS sample, we proposed a new α_{CO} prescription as a function of CO velocity dispersion, which predicts α_{CO} within 0.1 dex uncertainty.

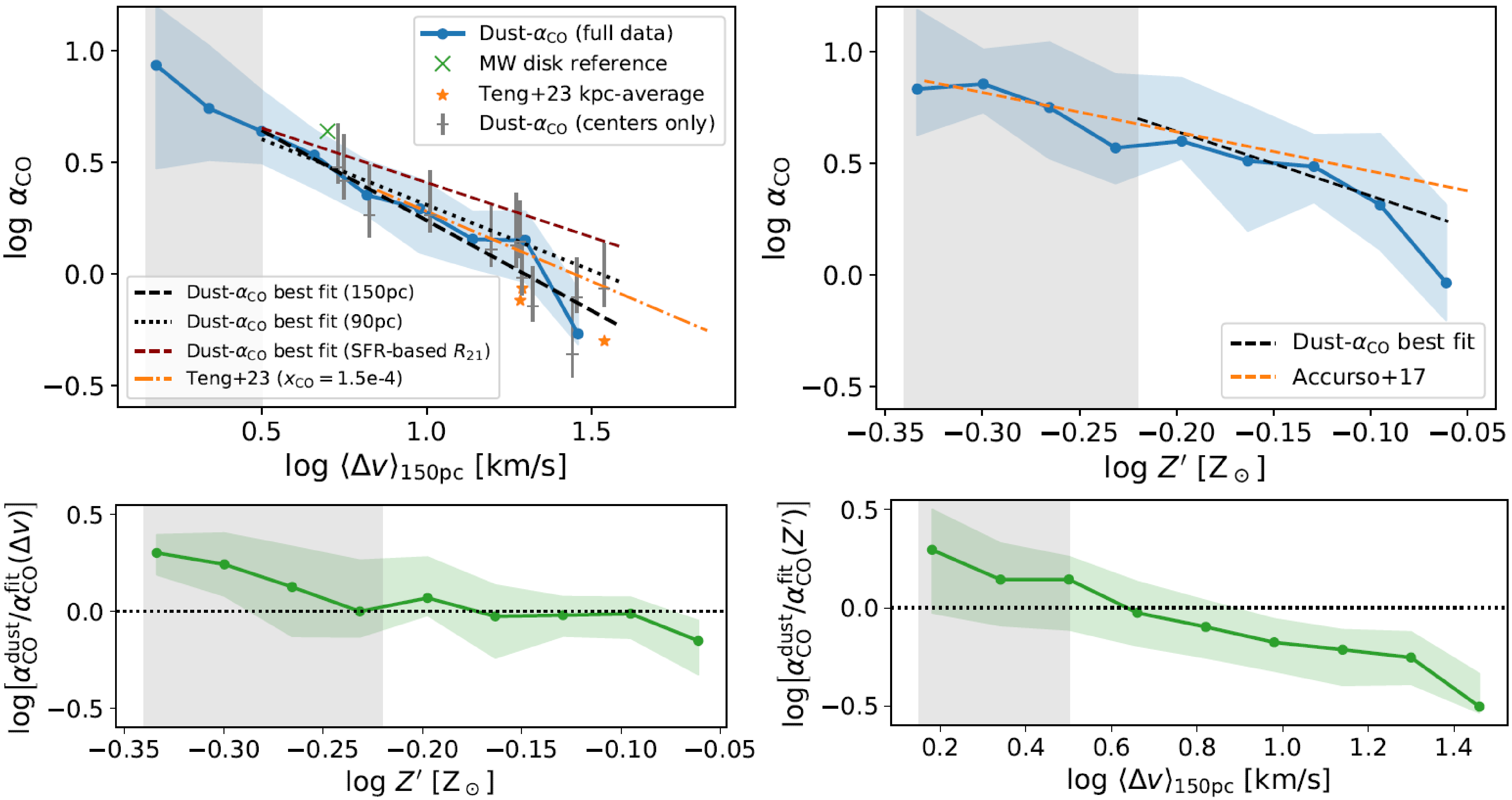
The prescription works best with high-res (< 150 pc) Δv_{CO}, but it can also extend well to kpc-scale data due to strong correlations with Δv_{CO} at lower resolutions.






Contact me: Eltha Teng   yhteng@umd.edu   https://elthateng.github.io/

Most relevant paper: **Y.-H. Teng** et al. 2024, *ApJ*, 961, 42



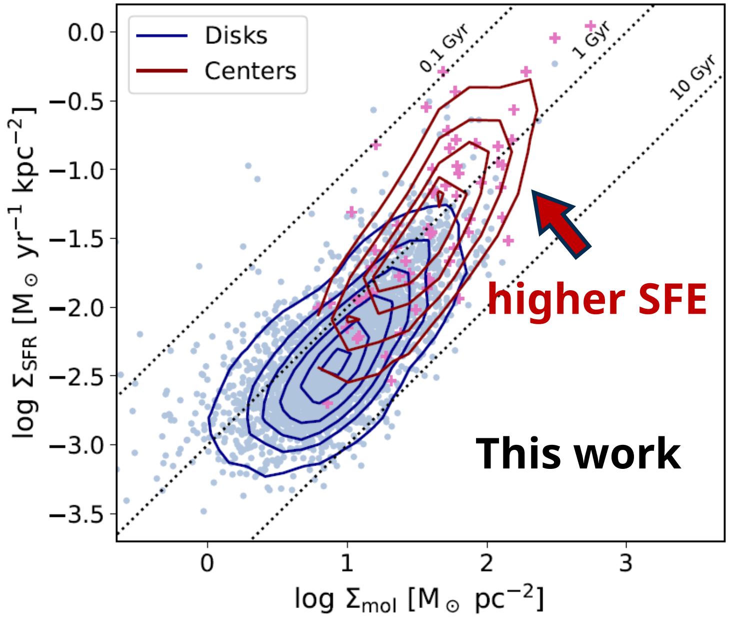
Dust-α_{CO} (full data)
MW disk reference
Teng+23 kpc-average
Dust-α_{CO} (centers only)
Dust-α_{CO} best fit (150pc)
Dust-α_{CO} best fit (90pc)
Dust-α_{CO} best fit (SFR-based R_{21})
Teng+23 ($x_{CO} = 1.5$e-4)
log α_{CO}
log $\langle \Delta v \rangle_{150pc}$ [km/s]
Dust-α_{CO} best fit
Accurso+17
log Z' [$Z_\odot$]
log[$\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(\Delta v)$]
log[$\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(Z')$]

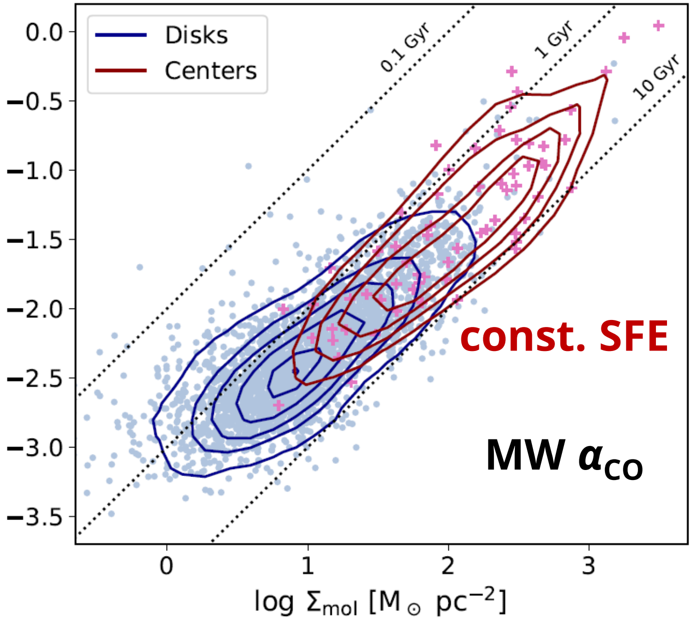
(Teng+ 2024)

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
  - $\boldsymbol{\Sigma_{mol}}$ **overestimated** by ~5x in galaxy centers with MW α_{CO}

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



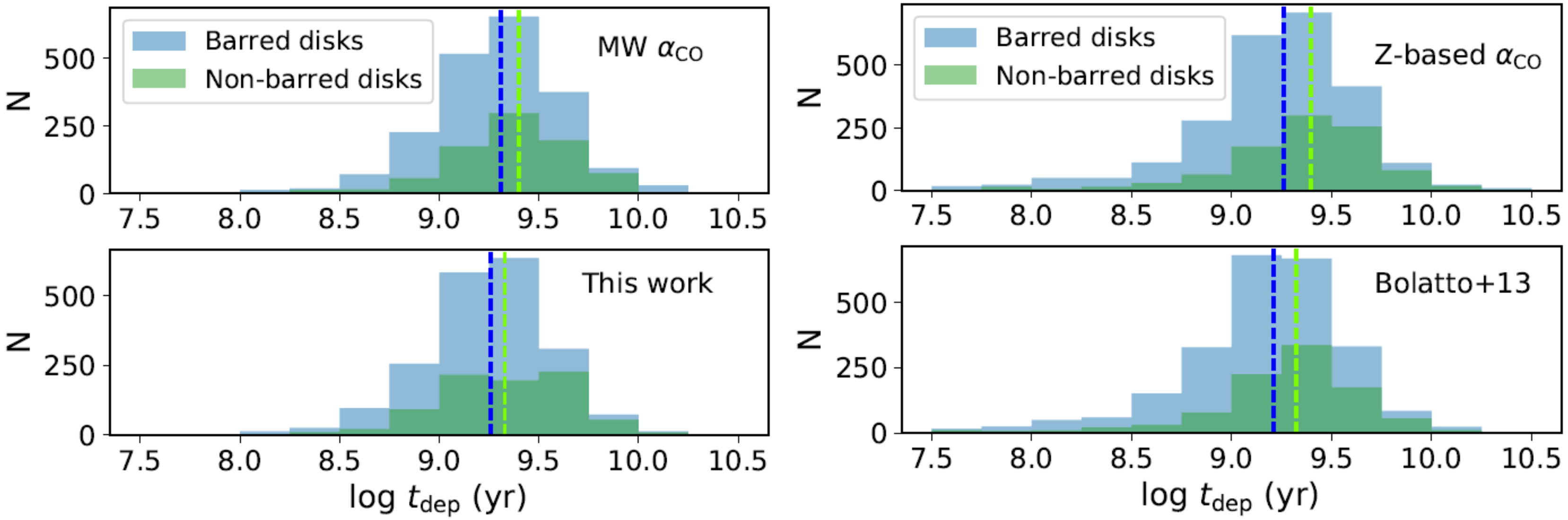


(Teng+ 2024)

Barred vs. non-barred galaxies

- Compare gas depletion time (SFE^{-1}) using different $\alpha_{\rm CO}$ 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**

Disks



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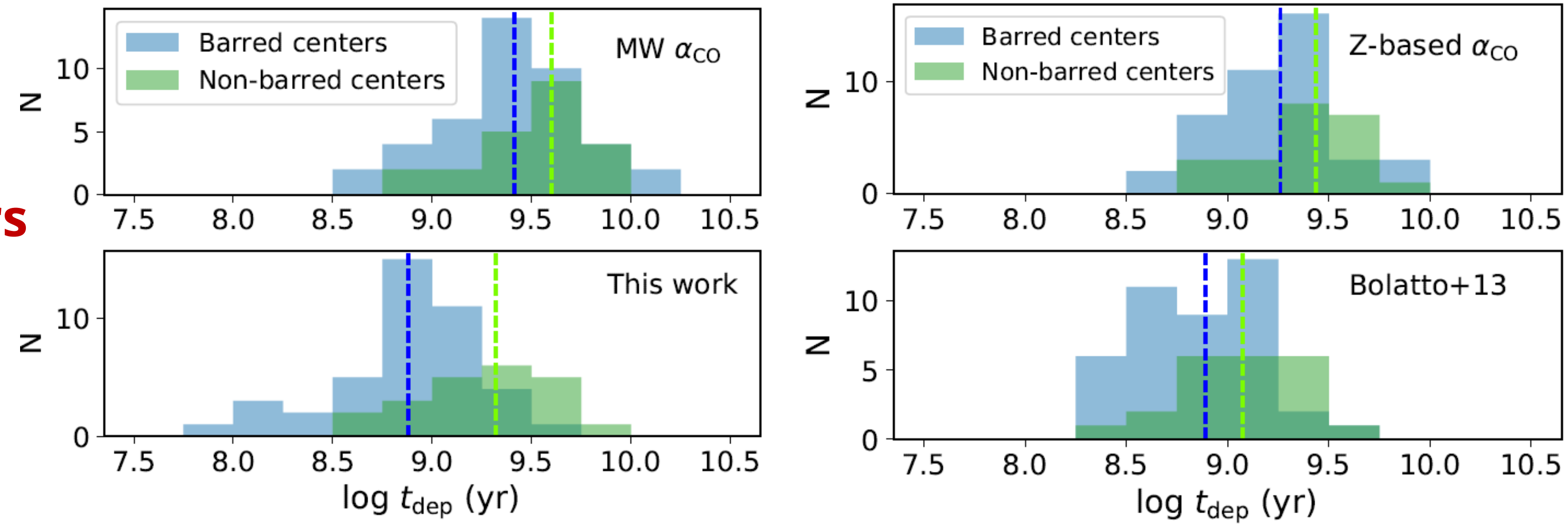
Centers



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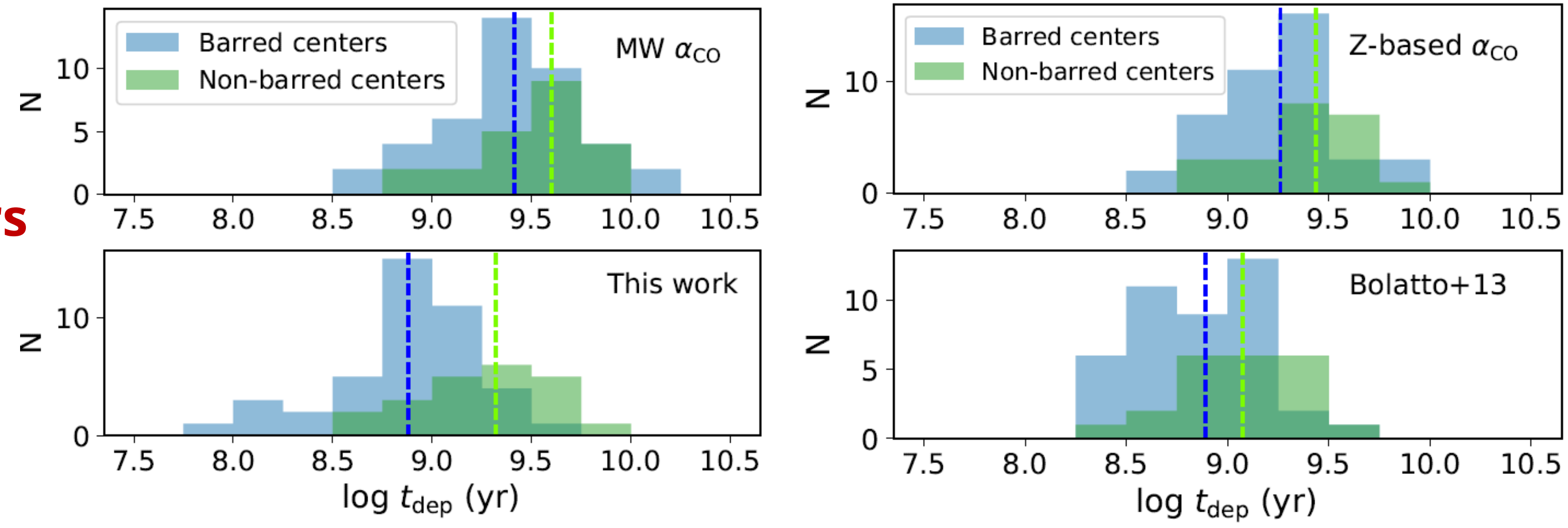

MW $\alpha_{\rm CO}$:

const.

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

(Teng+ 2024)

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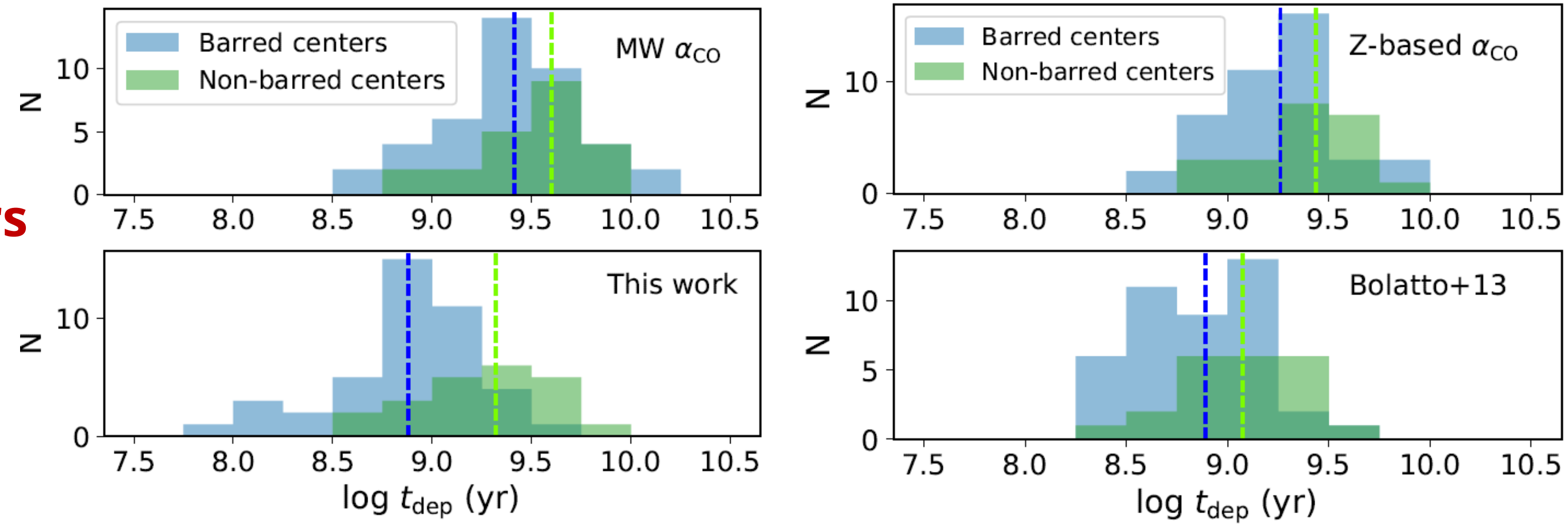

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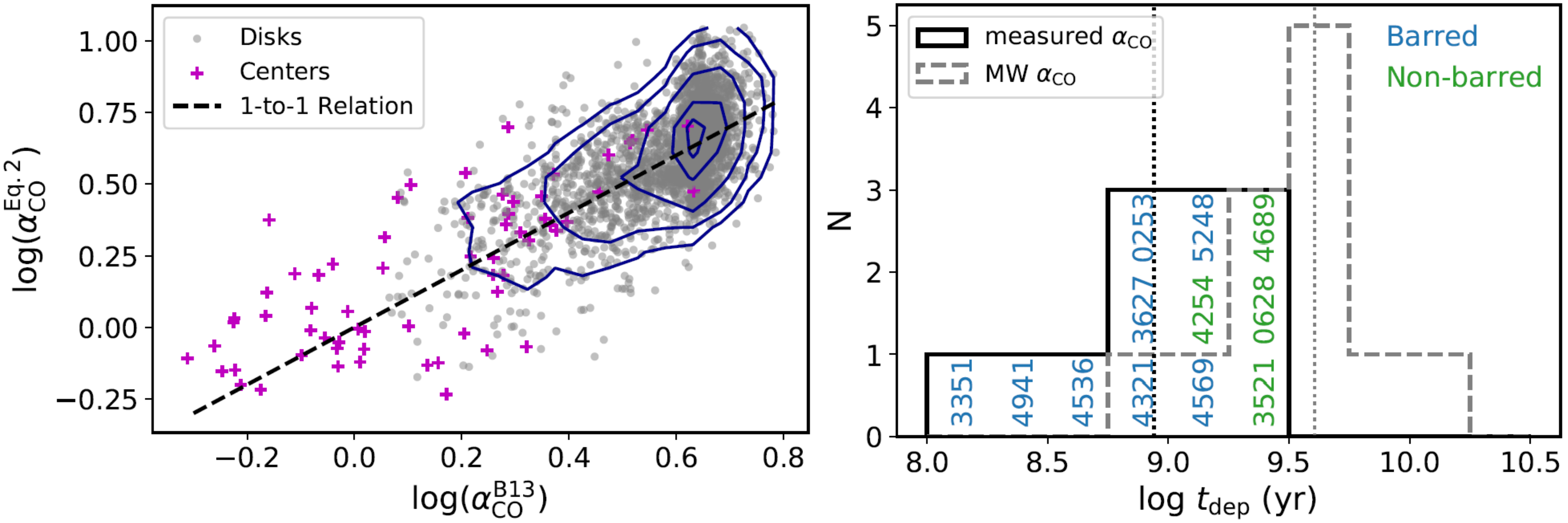
const.

(Teng+ 2024)



Disks
Centers
1-to-1 Relation
1.00
0.75
0.50
0.25
0.00
−0.25
−0.2
0.0
0.2
0.4
0.6
0.8
$\log(\alpha_{CO}^{Eq.2})$
$\log(\alpha_{CO}^{B13})$
measured α_{CO}
MW α_{CO}
Barred
Non-barred
3351
4941
4536
4321
3627
0253
4569
5248
4254
3521
0628
4689
N
0
1
2
3
4
5
8.0
8.5
9.0
9.5
10.0
10.5
$\log t_{dep}$ (yr)

(Teng+ 2024)

Measuring $\boldsymbol{\alpha_{\mathrm{CO}}}$

Estimate the total molecular gas mass and then compare with CO emission

Optically thin tracers

- *CO isotopologues* – require knowledge of density, temperature, and isotopic abundances
- *Dust* – require assumptions on dust-to-gas ratios

Gamma-ray emission

- Traces collisions/scattering between cosmic ray and interstellar matter

  → low sensitivity, only possible in the Local Group

Virial methods

- Use the size and line width to derive the virial mass ($M_{vir} \propto \sigma^2 R/G$)

  → requires cloud-scale resolution & clouds likely not virialized

Kennicutt-Schmidt relation – infer Σ_{mol} from the measured Σ_{SFR}

- Assumes a constant star formation efficiency → empirical relation under debate

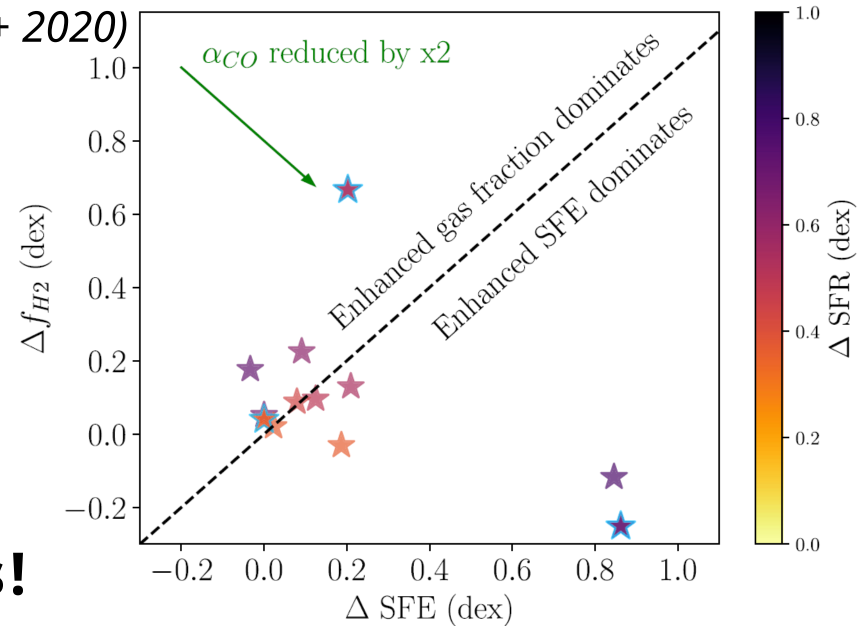
Why is α_{CO} important?

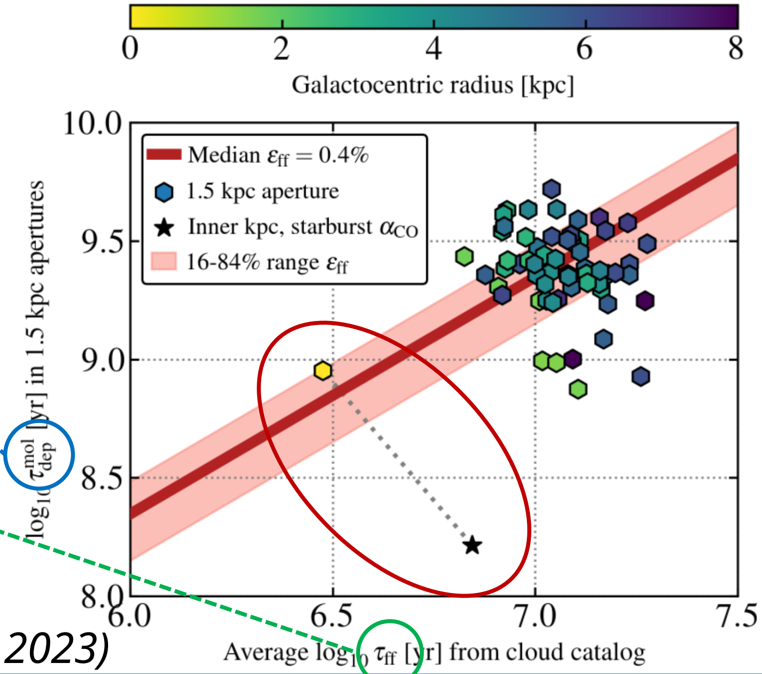
- Basis of measuring molecular gas mass
- Tied to physical conditions of molecular gas

→ **α_{CO} impacts many star formation properties!**

- Virial parameter $\alpha_{\mathrm{vir}} \equiv \frac{2T}{U} \propto \frac{\sigma^2}{M_{\mathrm{mol}}}$
- Star formation efficiency $\varepsilon_{\mathrm{eff}}$ = SFR / M_{mol}
- Gas depletion time $\boxed{\tau_{\mathrm{dep}} = 1/\ \varepsilon_{\mathrm{eff}} = M_{\mathrm{mol}}\ /\ \mathrm{SFR}}$
- Cloud free-fall time $\boxed{\tau_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho_0}}}$, where $\rho_0 \propto \frac{M_{\mathrm{mol}}}{R^3}$
- Turbulence pressure $P_{\mathrm{turb}} = \rho\sigma^2 \sim \frac{M_{\mathrm{mol}}\,\sigma^2}{2R}$

(Ellison+ 2020)





(Querejeta+ 2023)

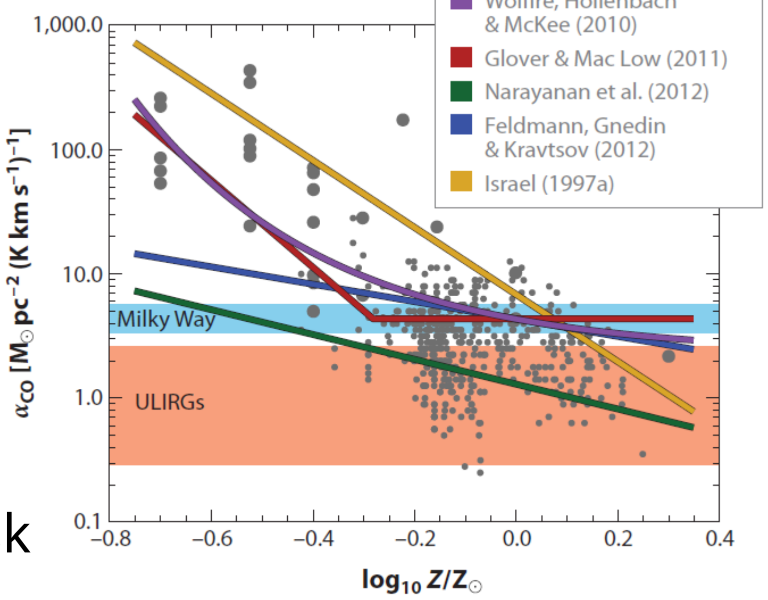
Inferring molecular gas mass

- Most abundant molecule: H_2
  - Tracing cold molecular gas: CO emission
  - → **"CO flux to H_2 mass" conversion factor (α_{CO})**

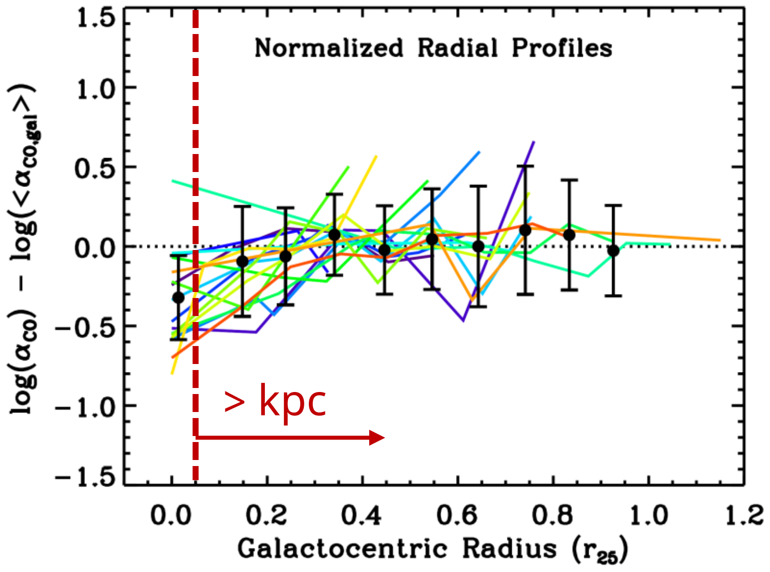
$$\alpha_{\rm CO} \equiv \frac{M_{H_2}}{L_{\rm CO(1-0)}} = \frac{\Sigma_{H_2}}{I_{\rm CO(1-0)}} \left(\frac{\rm M_\odot}{\rm K\ km\ s^{-1}\ pc^2}\right) \sim 4.4 \text{ in MW disk}$$

- Variation of α_{CO} within and between galaxies
  - Dependence on **gas physical properties**
    - temperature, density, opacity, metallicity …
  - Low α_{CO} found in many **normal galaxy centers**
    - gas concentrations driven by bars and/or spiral arms?
    - higher excitation, turbulence, and/or dynamical process?
  - → **emissivity**-dependent terms are important!

(Bolatto+ 2013)



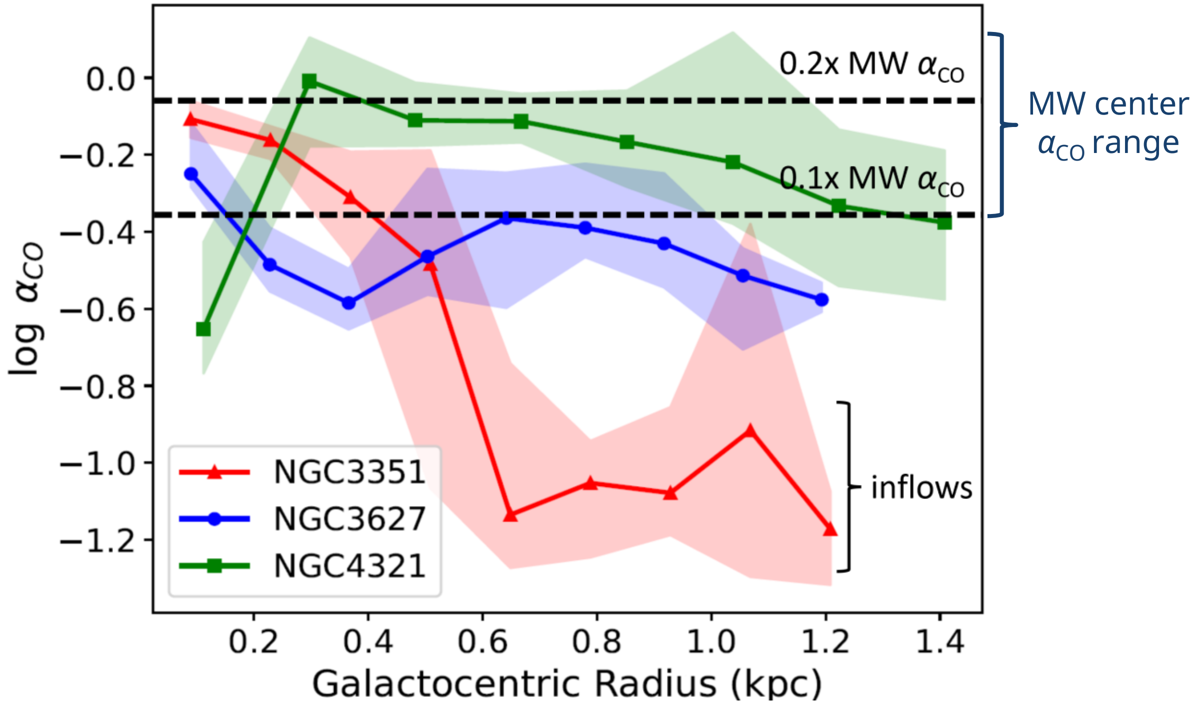
(Sandstrom+ 2013)

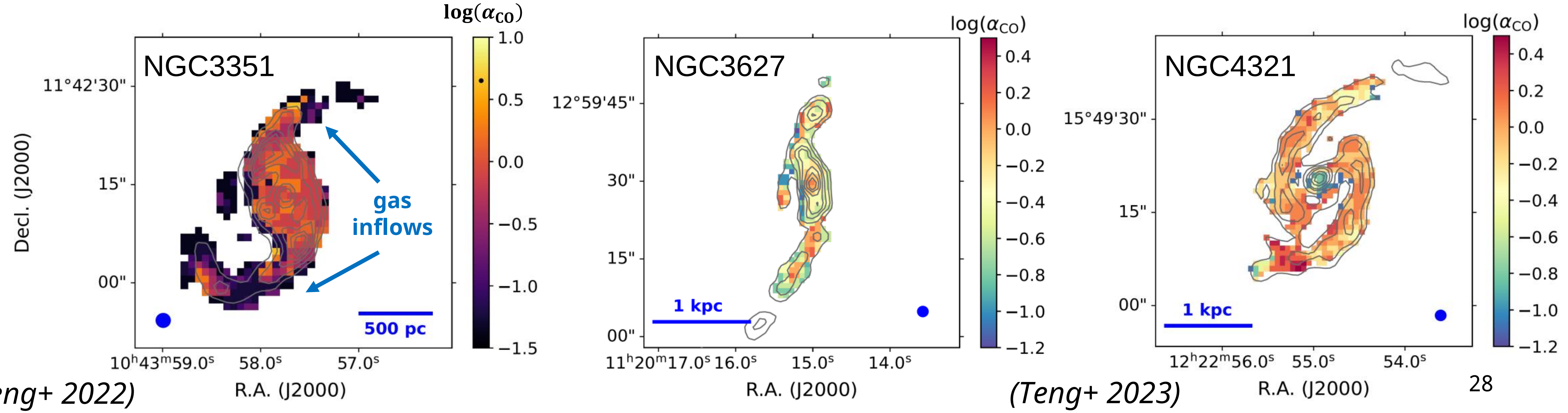


α_{CO} distribution

$$\alpha_{\mathrm{CO}} = \frac{M_{\mathrm{mol}}}{L_{\mathrm{CO(1-0)}}}\left(\frac{\mathrm{M_\odot}}{\mathrm{K\ km\ s^{-1}\ pc^2}}\right)$$

$$= \frac{1.36\, m_{\mathrm{H_2}}(\mathrm{M_\odot})\, N_{\mathrm{CO}}(\mathrm{cm^{-2}})\, \Phi_{\mathrm{bf}}\, A(\mathrm{cm^2})}{I_{\mathrm{CO(1-0)}}(\mathrm{K\ km\ s^{-1}})\, A\,(\mathrm{pc^2})} \cdot \frac{3\times10^{-4}}{x_{\mathrm{CO}}}$$





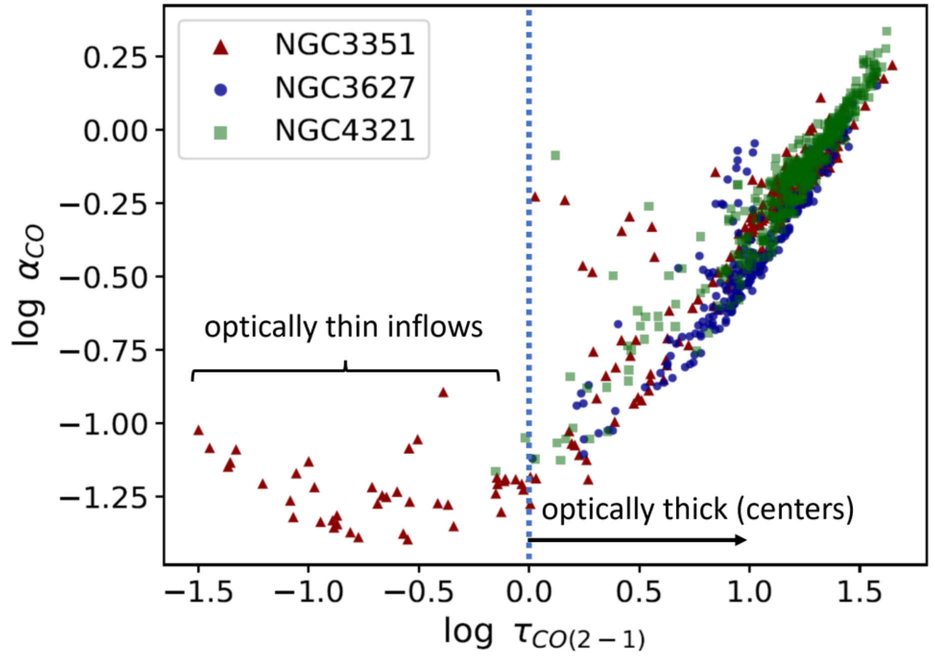
(Teng+ 2022) (Teng+ 2023)

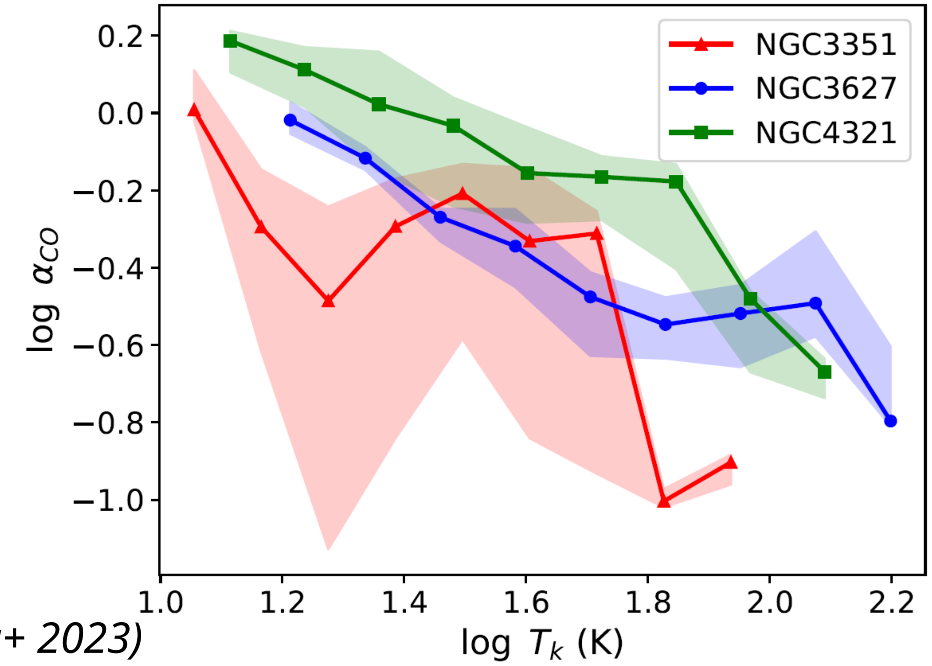
Physical drivers of α_{CO}

- 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%)

$$\rightarrow \log\left[\frac{\alpha_{CO}}{M_\odot/(K\ km\ s^{-1}\ pc^2)}\right] = 0.78 \log[\tau_{CO(2-1)}] - 0.18 \log\left(\frac{T_k}{K}\right) - 0.84$$

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

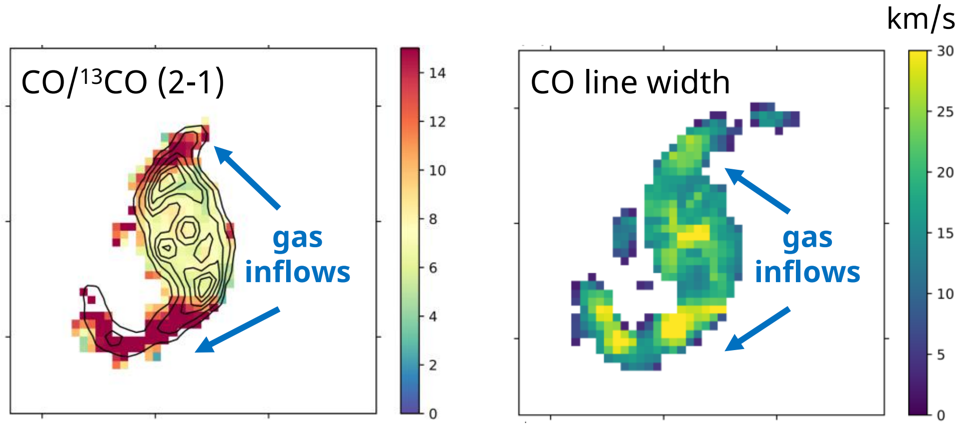




(Teng+ 2023)

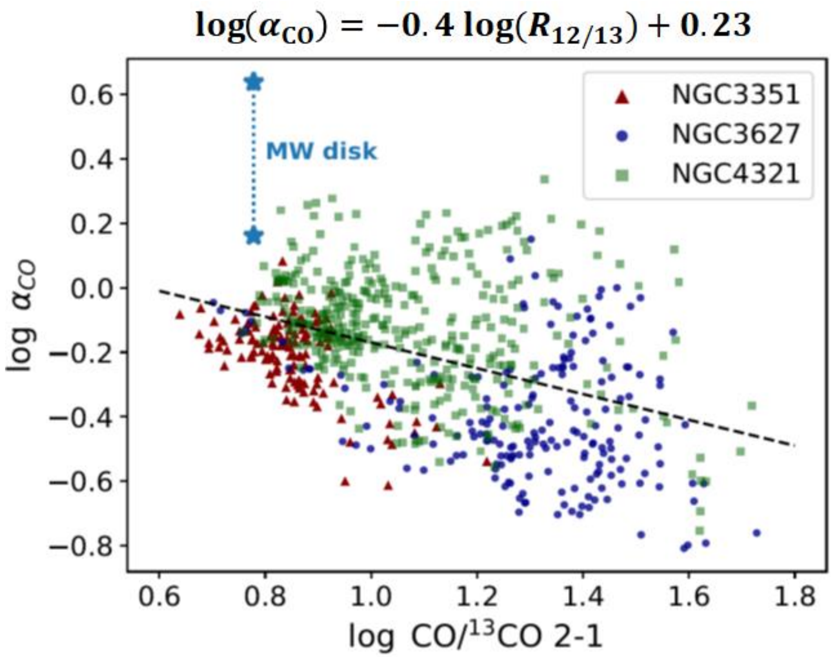
Observational tracers of α_{CO}

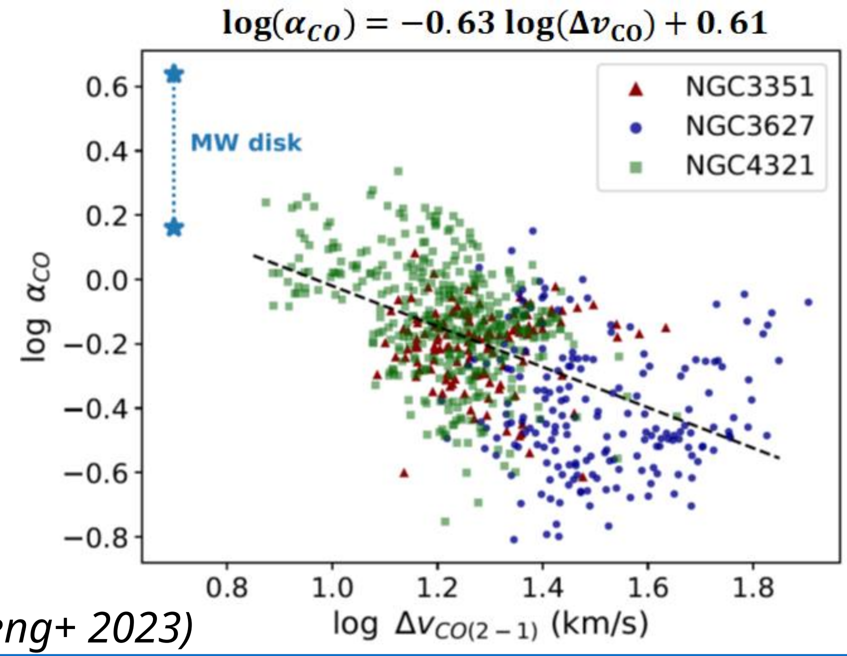
- Low α_{CO} and τ_{CO} in NGC 3351 inflows
  - escaped CO emission due to very low τ_{CO}
  - increased CO/^{13}CO line ratio and line width



(Teng+ 2022)

- The CO/^{13}CO (2-1) ratio mainly reflects τ_{CO}
- Higher velocity dispersion in barred galaxy centers decreases τ_{CO} and thus α_{CO}, since $\tau_{CO} \propto N_{CO}/\Delta v$





(Teng+ 2023)

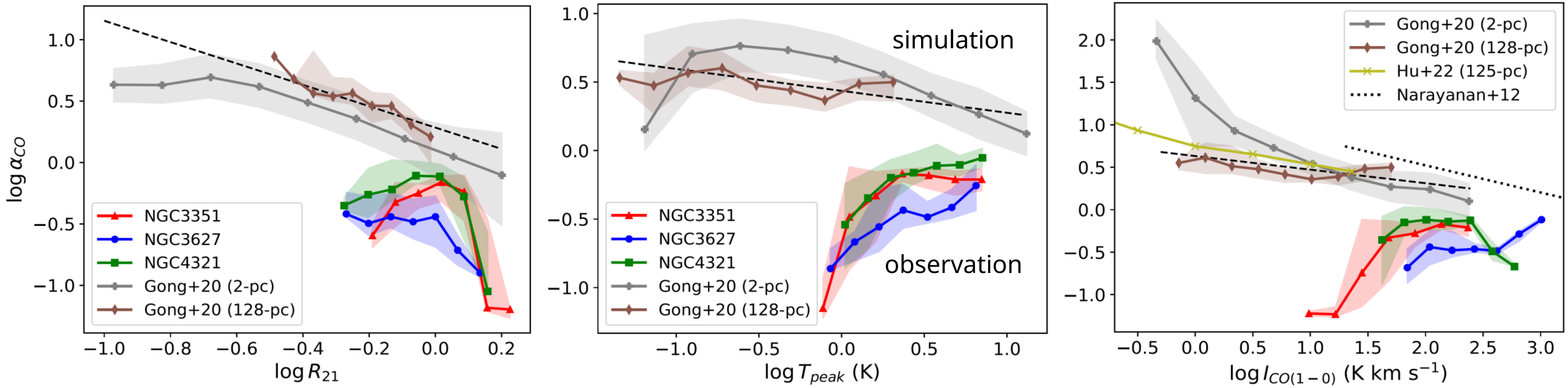
Compare with simulations

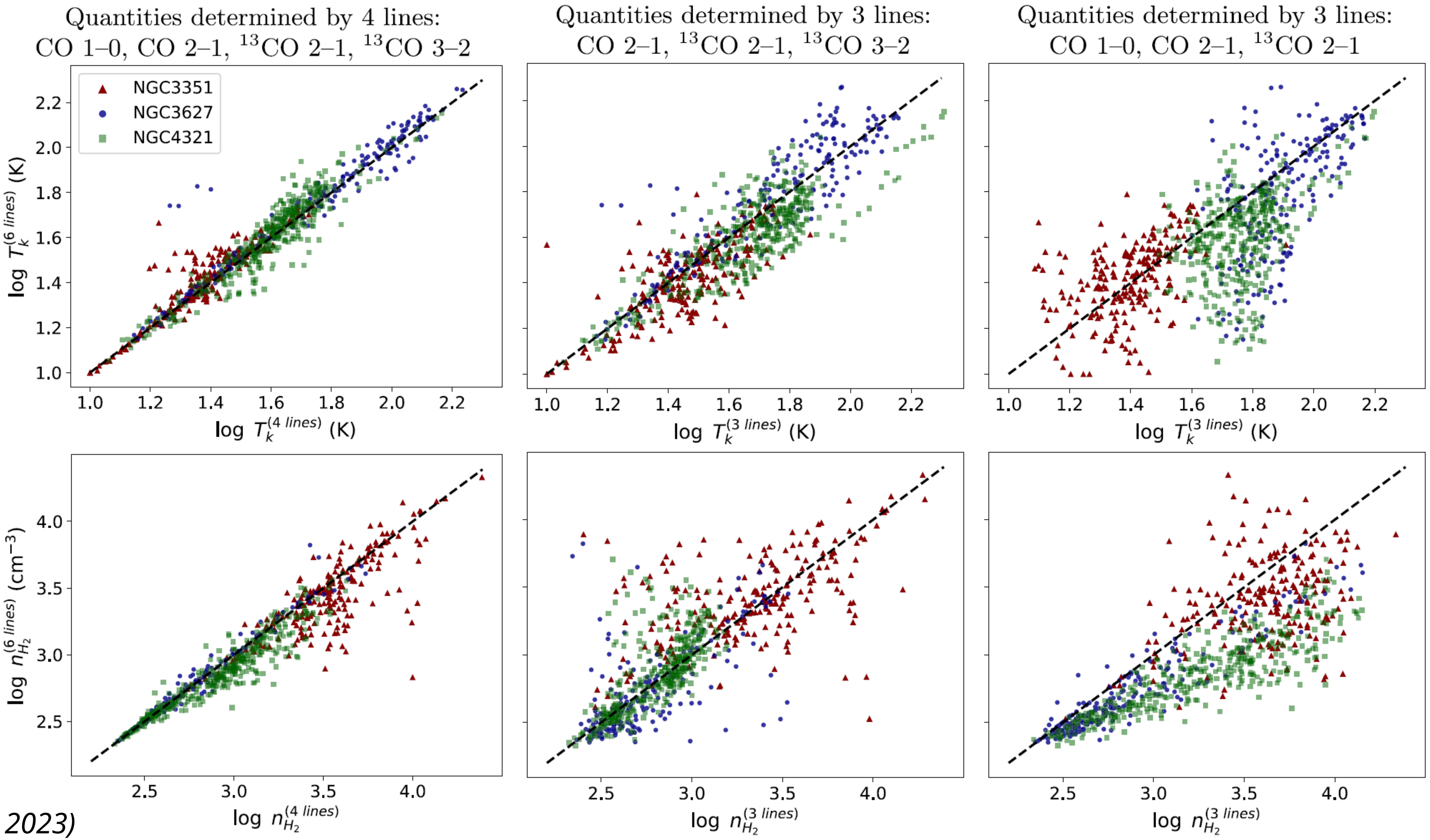
- (M)HD simulation of galaxy/ISM at pc-scales *(Narayanan+ 2012, Gong+ 2020, Hu+ 2022)*

  → current simulations tend to overestimate $\alpha_{\rm CO}$ in galaxy centers

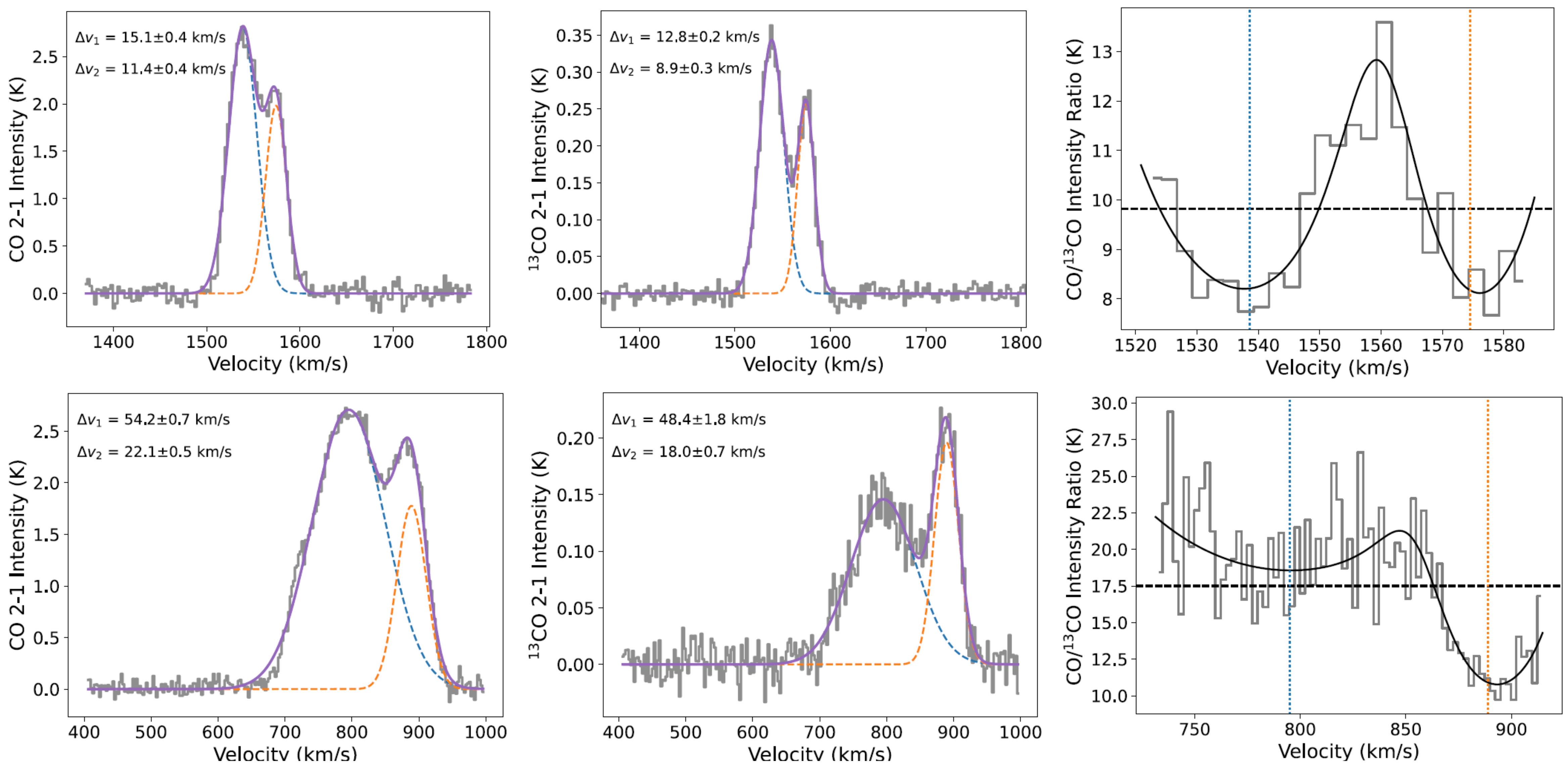
  → **gas inflows** & **turbulence effects** should have significant contributions to $\alpha_{\rm CO}$!

(Teng+ 2023)




Quantities determined by 4 lines:
CO 1–0, CO 2–1, ^{13}CO 2–1, ^{13}CO 3–2
Quantities determined by 3 lines:
CO 2–1, ^{13}CO 2–1, ^{13}CO 3–2
Quantities determined by 3 lines:
CO 1–0, CO 2–1, ^{13}CO 2–1
NGC3351
NGC3627
NGC4321
log $T_k^{(6\ lines)}$ (K)
log $T_k^{(4\ lines)}$ (K)
log $T_k^{(3\ lines)}$ (K)
log $n_{H_2}^{(6\ lines)}$ (cm^{-3})
log $n_{H_2}^{(4\ lines)}$
log $n_{H_2}^{(3\ lines)}$

(Teng+ 2023)



Δv_1 = 15.1±0.4 km/s
Δv_2 = 11.4±0.4 km/s
CO 2-1 Intensity (K)
Velocity (km/s)
Δv_1 = 12.8±0.2 km/s
Δv_2 = 8.9±0.3 km/s
^{13}CO 2-1 Intensity (K)
Velocity (km/s)
CO/^{13}CO Intensity Ratio (K)
Velocity (km/s)
Δv_1 = 54.2±0.7 km/s
Δv_2 = 22.1±0.5 km/s
CO 2-1 Intensity (K)
Velocity (km/s)
Δv_1 = 48.4±1.8 km/s
Δv_2 = 18.0±0.7 km/s
^{13}CO 2-1 Intensity (K)
Velocity (km/s)
CO/^{13}CO Intensity Ratio (K)
Velocity (km/s)

(Teng+ 2023)