High Star Formation Efficiency and Low CO-to-H_2 Conversion Factor in Nearby Barred Galaxy Centers

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Background & Motivation

The CO-to-H_2 Conversion Factor (α_{CO})

- Since low-J CO lines are commonly used to trace molecular gas, α_{CO} is central to studying molecular gas and star formation in galaxies.

$$\alpha_{CO} = \frac{M_{mol}}{L_{CO(1-0)}} = \frac{\Sigma_{mol}}{I_{CO(1-0)}} \left(\frac{M_\odot}{K\ km\ s^{-1}\ pc^2}\right), \text{ where } M_{mol} \sim 1.36\, M_{H_2}$$

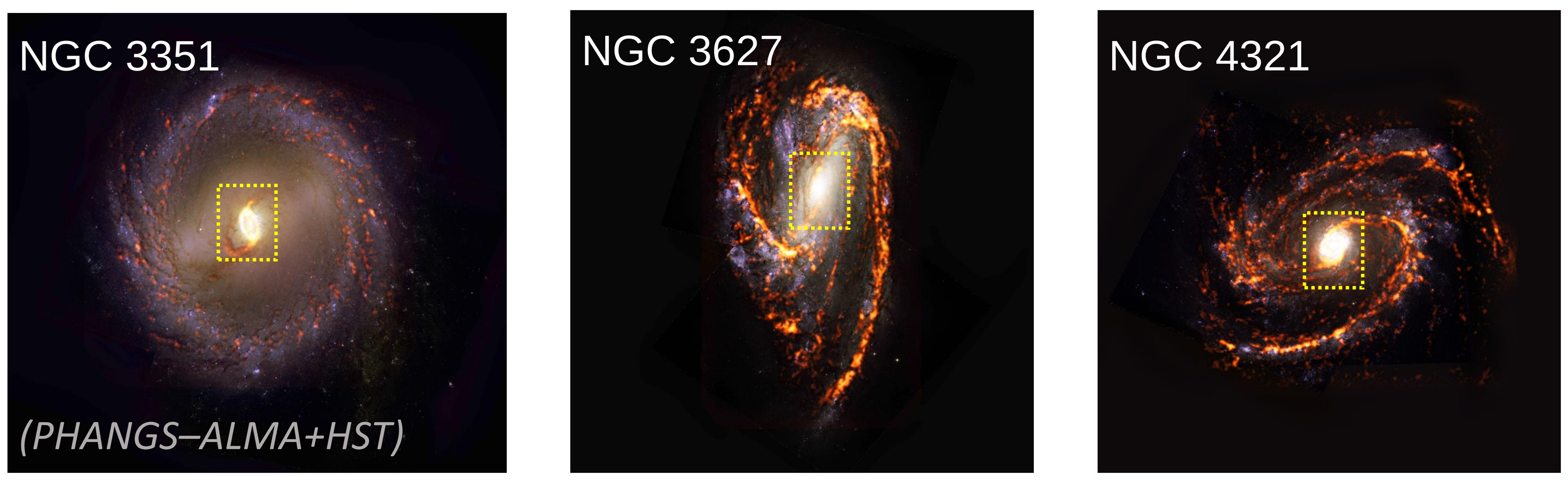
- While most studies assume a constant, Galactic-like α_{CO}, it is known that α_{CO} can vary by orders of magnitude in different environments.
- The variation of α_{CO} causes major uncertainty in current molecular gas measurements, leading to biased star formation efficiencies and various fundamental properties (e.g., virial parameter, free-fall time).

α_{CO} in Galaxy Centers

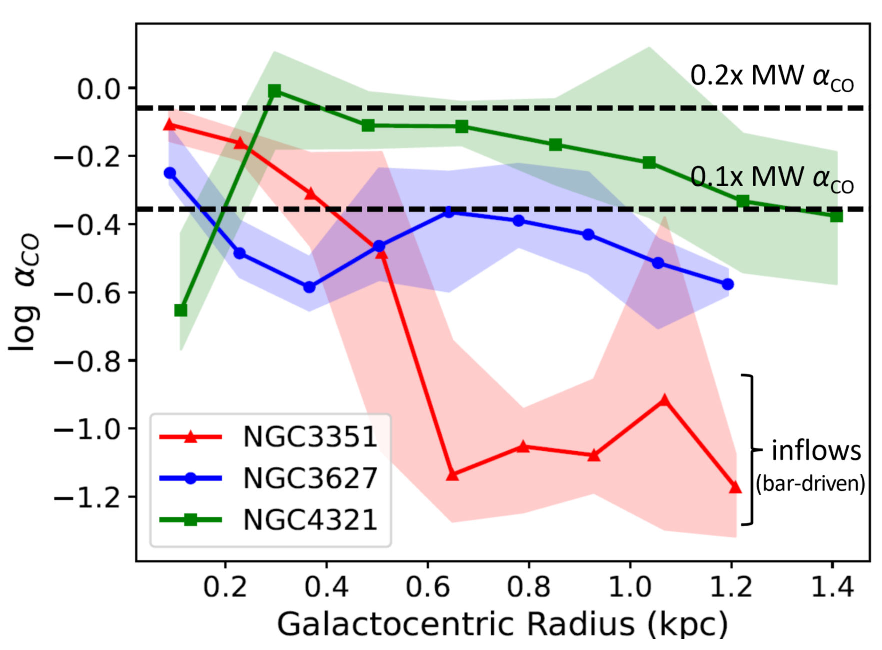
- Many barred galaxy centers, including our Galactic Center, are found to have lower α_{CO} than the standard Galactic disk value.
- The drop of α_{CO} in galaxy centers can be explained by CO emissivity variations due to higher gas temperature and/or lower opacity that originate from intense star formation or the associated gas dynamics.
- There is currently not a α_{CO} prescription that accounts for emissivity variations in galaxy centers. It is challenging, partly because the ways of measuring α_{CO} across nearby galaxies are limited.
- We have developed a new α_{CO} prescription based on our α_{CO} measurements in a set of nearby galaxy centers using dust and CO isotopologue observations.
- We also investigate the impact of current and new prescriptions on the estimation of star formation efficiency in various types of galaxies and galactic nuclei, using the PHANGS-ALMA Large Program dataset.

Measurements

Multi-line CO Isotopologues *(Teng+ 2022, 2023)*



- **ALMA Band 3, 6, 7 observations + multi-line *RADEX* modeling**
  - ^{12}CO(1-0), ^{12}CO(2-1), ^{13}CO(2-1), ^{13}CO(3-2), C^{18}O(2-1), C^{18}O(3-2)
  - Covered the inner ~2 kpc of three barred galaxy centers
  - Matched to 100 pc resolutions for all six lines
  - Modeled gas density, temperature, optical depth, and abundances



+ α_{CO} is 4-15x lower than the standard MW value across all three centers, indicating a 5-10x higher star formation efficiency in their central kpc than using a MW α_{CO}.

+ α_{CO} drops substantially in the bar-driven inflows of NGC 3351 (i.e., $r > 0.5$ kpc).

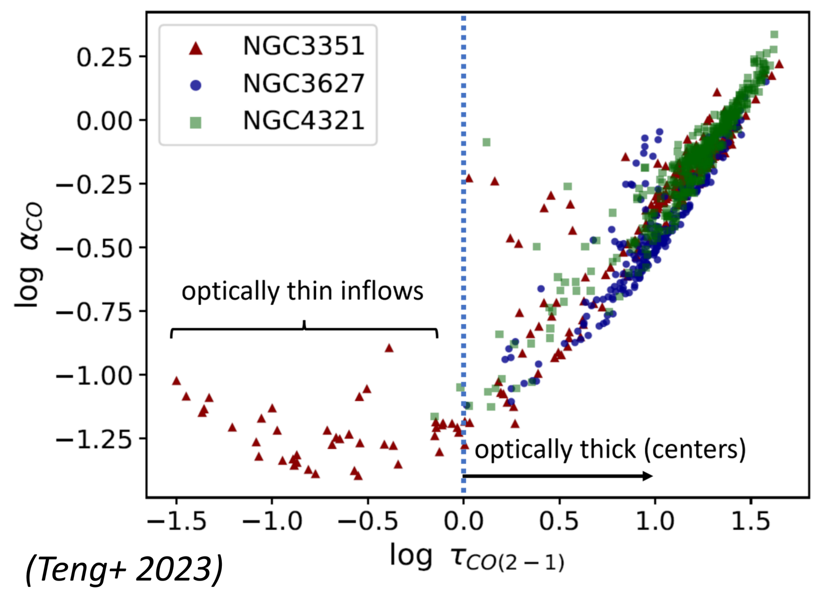
Dust-based α_{CO} Estimates *(Chiang+ 2023 in prep)*

α_{CO} in ~40 nearby galaxies at 2 kpc resolution, using measurements of dust and atomic gas surface densities (Σ_{dust}, Σ_{atom}), CO integrated intensity (I_{CO}), metallicity (Z), and assuming dust-to-metals ratio (D/M).

$$\alpha_{CO} = (\Sigma_{gas} - \Sigma_{atom})/I_{CO(1-0)}\ , \text{ where } \Sigma_{gas} = \frac{\Sigma_{dust}}{\left(\frac{Z}{1-Z}\right)(D/M)}$$

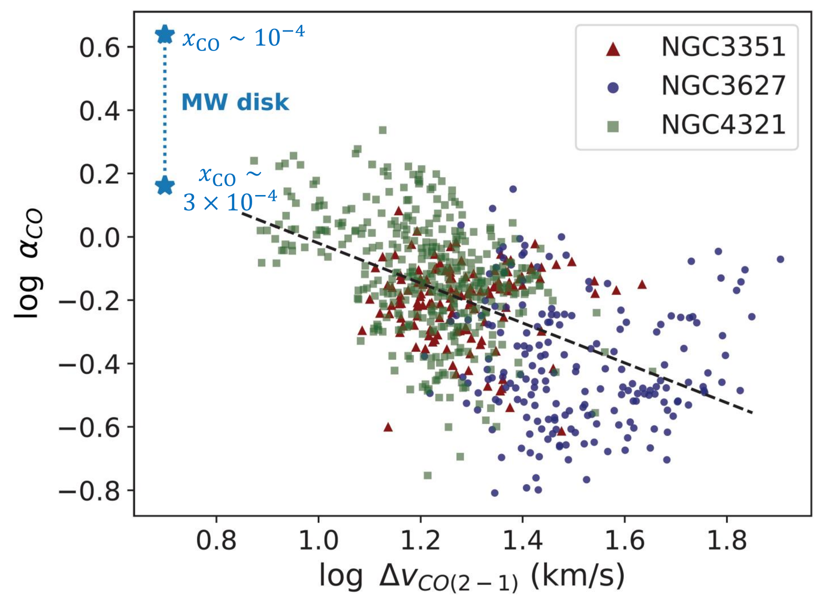
Results

The Drivers and Tracers of α_{CO} in Barred Centers *(Teng+ 2023)*



(Teng+ 2023)

+ We found a strong, positive correlation between α_{CO} and ^{12}CO optical depth (τ_{CO}) across all three barred centers where CO emission is optically thick. This relation can explain ~80% of the observed α_{CO} variation, implying that **τ_{CO} is the primary driver of α_{CO} in these barred centers.**



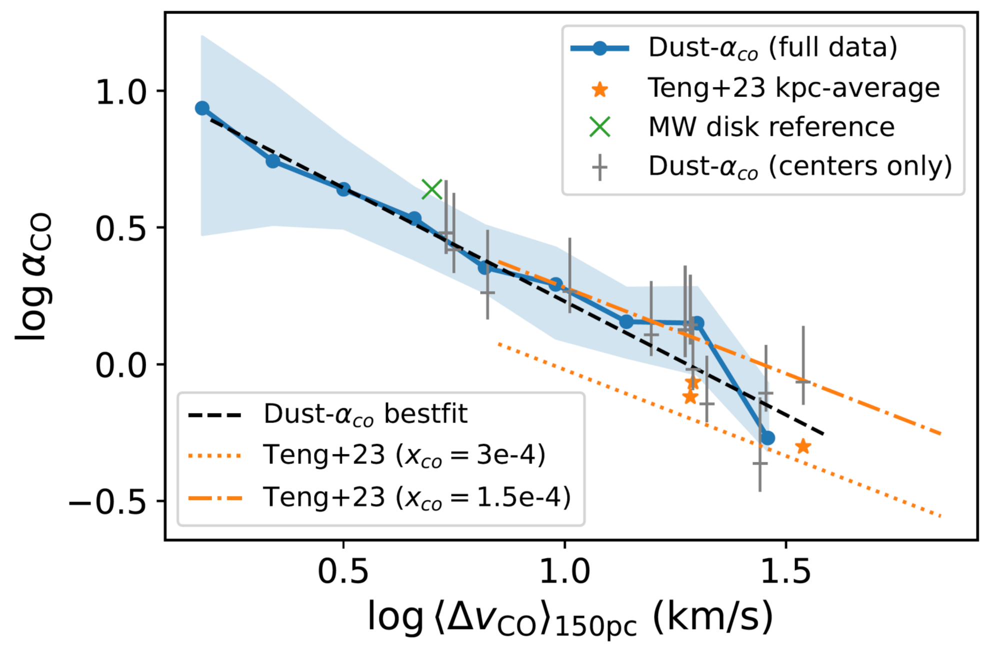
+ Assuming a CO/H_2 abundance (x_{CO}) of 3e-4, we found a clear trend of α_{CO} decreasing with the observed CO(2-1) line width. The trend extrapolates well to the standard MW disk value. These suggest that **velocity dispersion mainly traces τ_{CO} changes, and thus it can be a useful indicator for predicting α_{CO}.**

A New α_{CO} Prescription Capturing Emissivity Effects

A similar anti-correlation of α_{CO} and Δv_{CO} is also seen in 2-kpc resolution measurements of α_{CO} (from *Chiang+ 2023 in prep*) with kpc-averaged $\Delta v_{CO(2-1)}$ measured at 150 pc scales (from *Sun+ 2022*). This includes **12 barred and non-barred galaxies** out to R ~10 kpc.

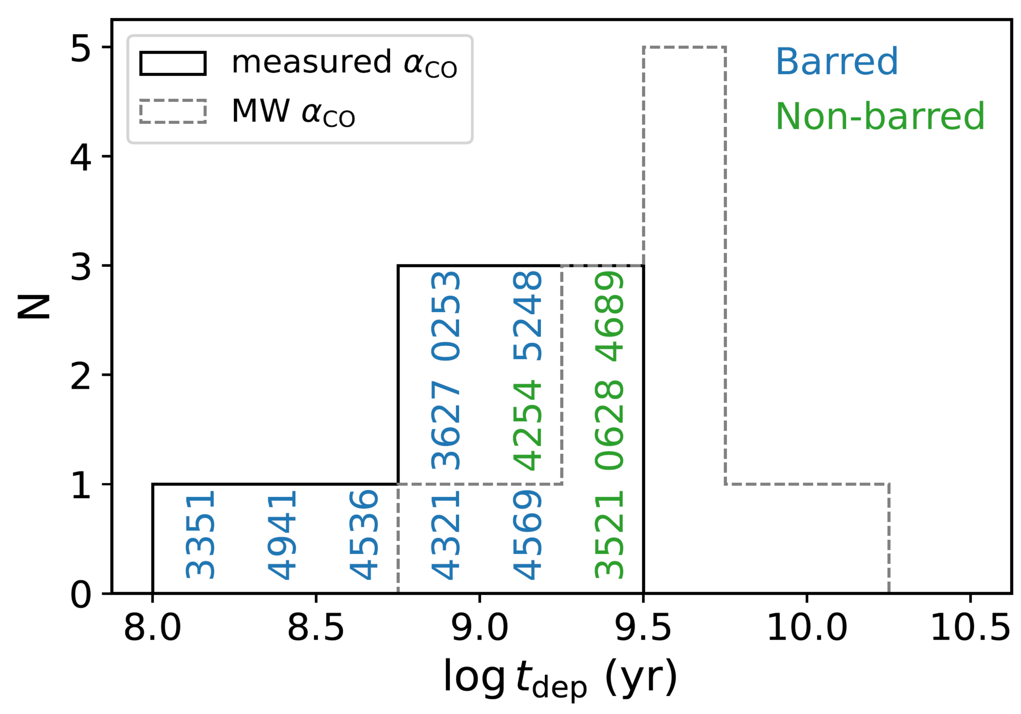
$$\log \alpha_{CO} = -0.83 \log\langle\Delta v_{CO}\rangle_{150pc} + 1.06$$

The dust-based α_{CO} across 12 galaxies shows a strong anti-correlation with the mean velocity dispersion, which is in close agreement with our prediction based on barred galaxy centers. This supports that velocity dispersion can be used to trace optical depth and α_{CO} variations in galaxy centers.



Implications for Star Formation Efficiency *(Teng+ 2023 in prep)*

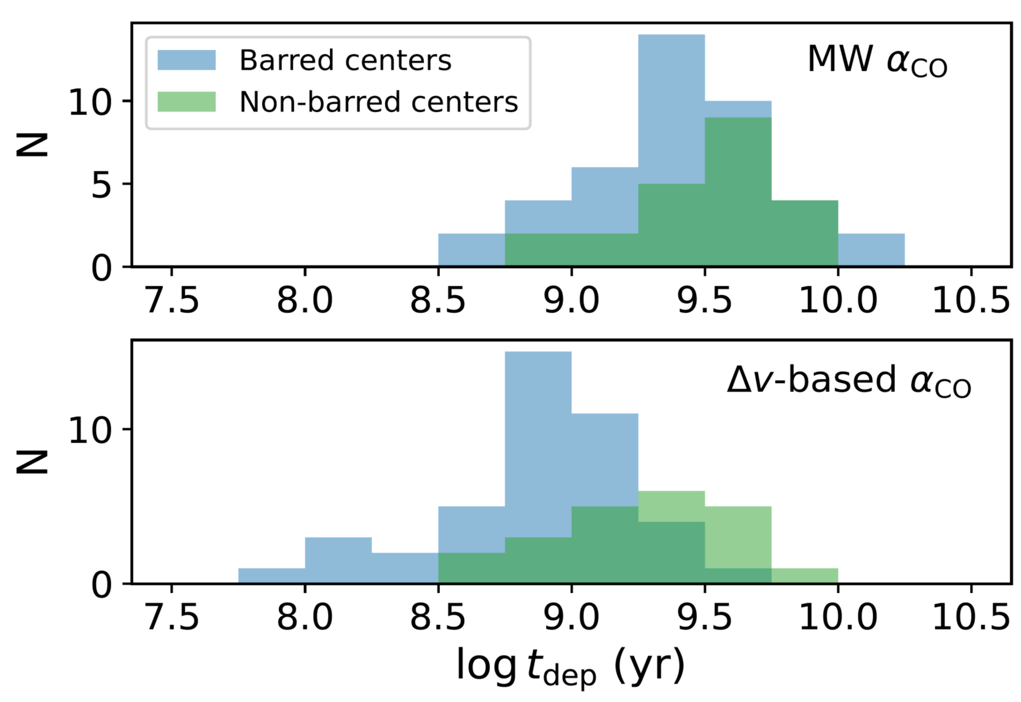
The derived molecular gas depletion time (t_{dep}) in 12 galaxy centers, using measured α_{CO} via dust and CO isotopologues vs. MW α_{CO}:



A clear separation in t_{dep} is found between barred and non-barred galaxy centers, suggesting **high star formation efficiency in barred centers.**

Using the measured α_{CO}, t_{dep} in the central 1.5 kpc of these galaxies are on average 4-5x lower than using a MW α_{CO}.

A similar comparison of the derived t_{dep} in 64 galaxy centers from the PHANGS-ALMA sample, applying our Δv-based α_{CO} prescription:



Our prescription reveals that barred centers have distinctly higher star formation efficiency than non-barred centers, while **using the MW α_{CO} obscures such difference.**

With the MW α_{CO}, star formation efficiencies in barred galaxy centers are overall underestimated by a factor of 3-4.

References

[1] Bolatto et al., 2013, ARA&A, 51, 207
[2] Chiang, I-D. et al., 2023, in prep
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[5] Sun et al., 2022, AJ, 164, 43
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[7] Teng et al., 2023, ApJ, arXiv:2304.04732
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