Investigating the CO-to-H_2 Conversion Factor Variations in Nearby Galaxy Centers

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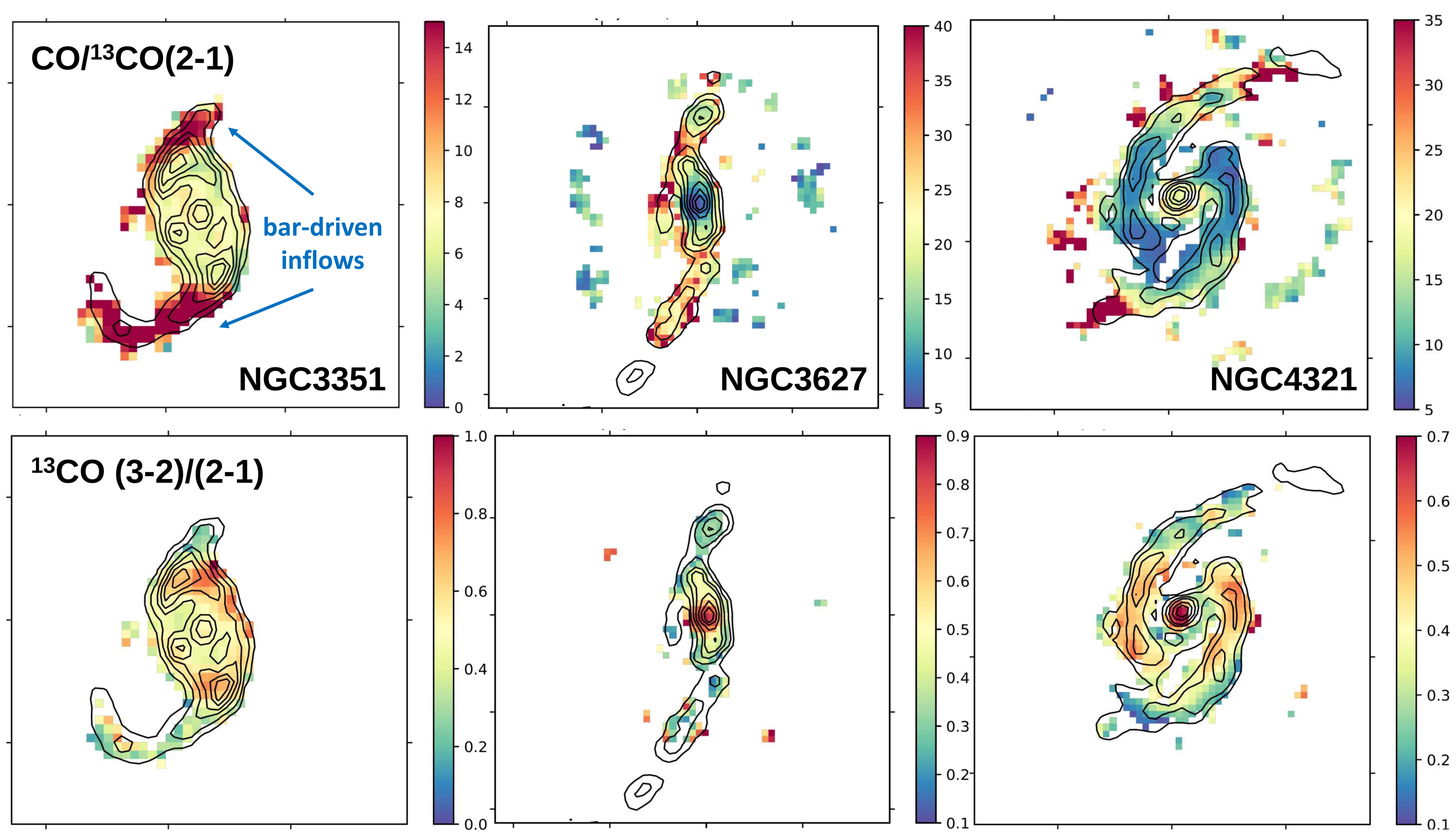
Introduction

Motivation

- Since low-*J* CO lines are commonly used to trace molecular gas, the CO-to-H_2 conversion factor (α_{CO}) is central to studying the amount and properties of molecular gas and star formation.
- 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.
- Many barred galaxy centers, including our Galactic Center, are found to have lower α_{CO} than the typical disk-like value.
- To study the environmental conditions and physical cause of α_{CO} variation in galaxy centers, we target three nearby barred galaxy centers with low α_{CO} revealed by previous kpc-scale observations.

Observations

- **ALMA Band 3, 6, 7 observations**
  - CO(1-0), CO(2-1), ^{13}CO(2-1), ^{13}CO(3-2), C^{18}O(2-1), C^{18}O(3-2)
- **Targets—**NGC 3351, NGC 3627, NGC 4321
  - Observed area: inner ~2 kpc region
  - Angular resolution: matched to $2''$ (~100 pc)
- **Line ratios—**sensitive to excitation/abundance/opacity conditions
  - Masking: S/N > 3 in either lines and 12-m flux recover rate > 70%
  - Overlaid contours: CO(2-1) integrated intensity



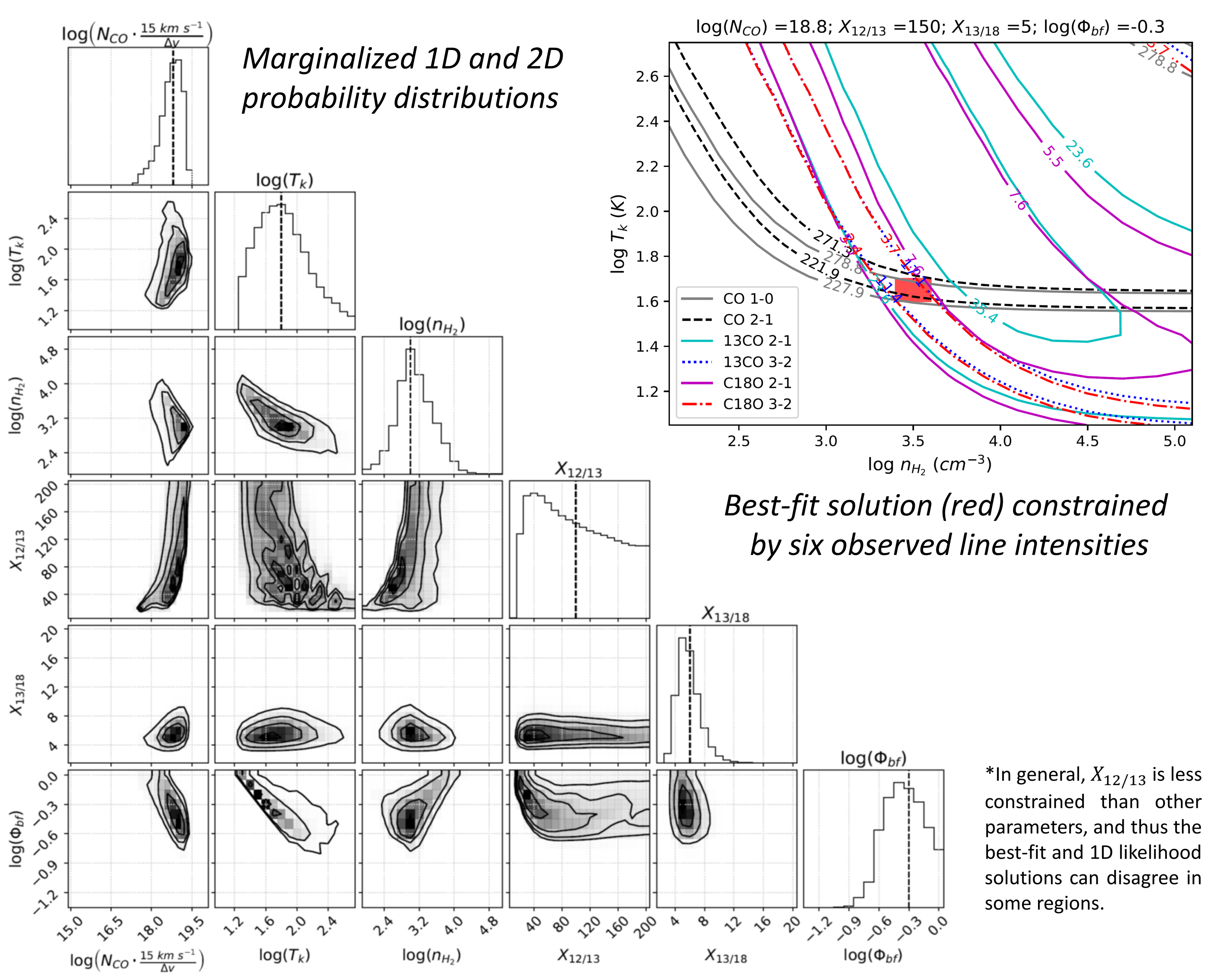
Multi-line Bayesian Modeling

Molecular Gas Properties

We use *RADEX*, a **non-LTE radiative transfer** code, to model intensity of all six lines under various combination of CO column density per line width ($N_{CO}/\Delta v$), kinetic temperature (T_k), H_2 volume density (n_{H_2}), CO/^{13}CO ($X_{12/13}$)* and ^{13}CO/C^{18}O abundances ($X_{13/18}$), and beam-filling factor (Φ_{bf}).

On a pixel-by-pixel basis, we study the **marginalized probability distribution** of each parameter using Bayesian likelihood analysis. We also derive the best-fit solution that gives highest likelihood in the full 6-D model grid.

Below shows an example for one bright pixel in the inner arms of NGC 4321.



Best-fit solution (red) constrained by six observed line intensities

*In general, $X_{12/13}$ is less constrained than other parameters, and thus the best-fit and 1D likelihood solutions can disagree in some regions.

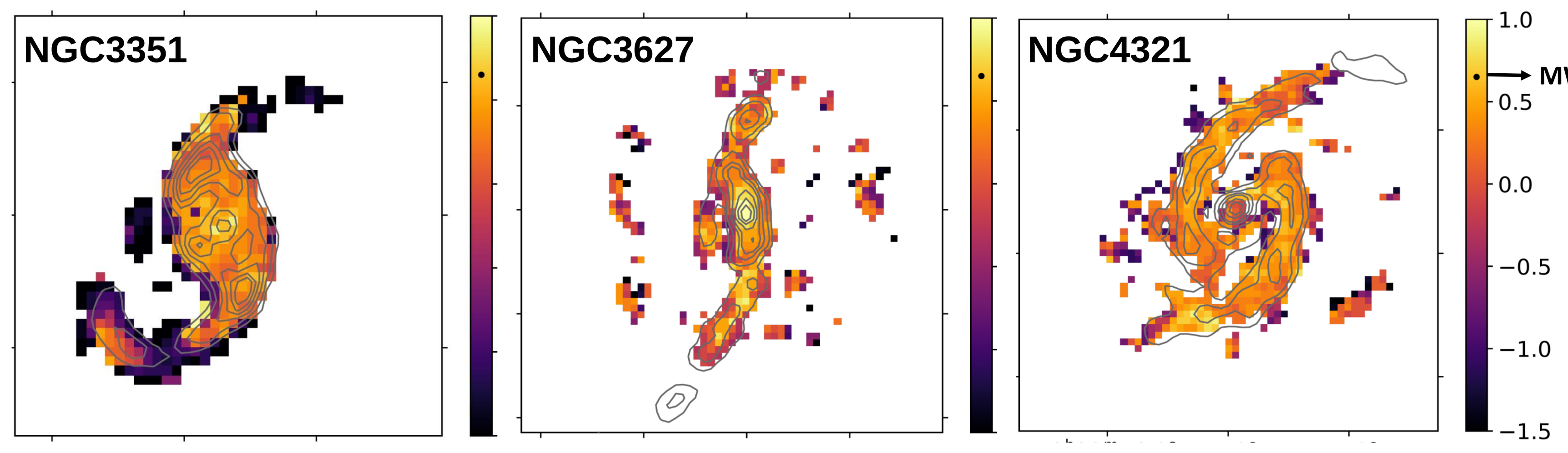
Conversion Factor Variations

Our modeling also allows us to derive the marginalized likelihood of α_{CO} for each pixel via the following equation:

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

where x_{CO} is the CO/H_2 abundance ratio (assumed at a starburst value of 3×10^{-4}), and A is the area relevant to the conversion between I_{CO} and L_{CO}.

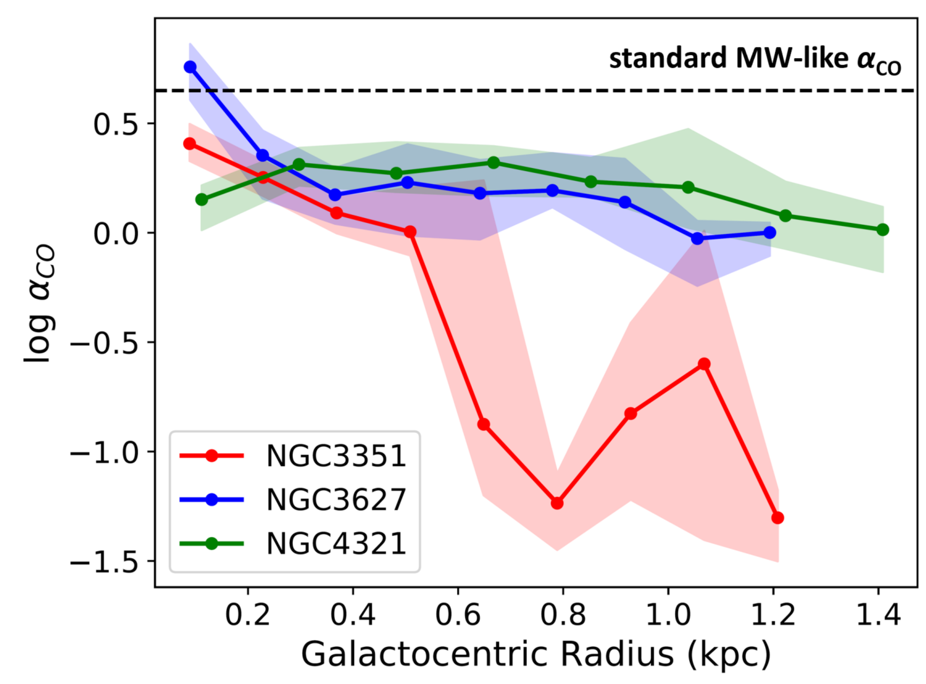
By extracting the maximum 1D likelihood solutions and iterating over the pixels, we obtain spatial distribution of α_{CO} at ~100 pc scales:



+ Almost all pixels across our observed regions have **α_{CO} lower than the standard MW value**.

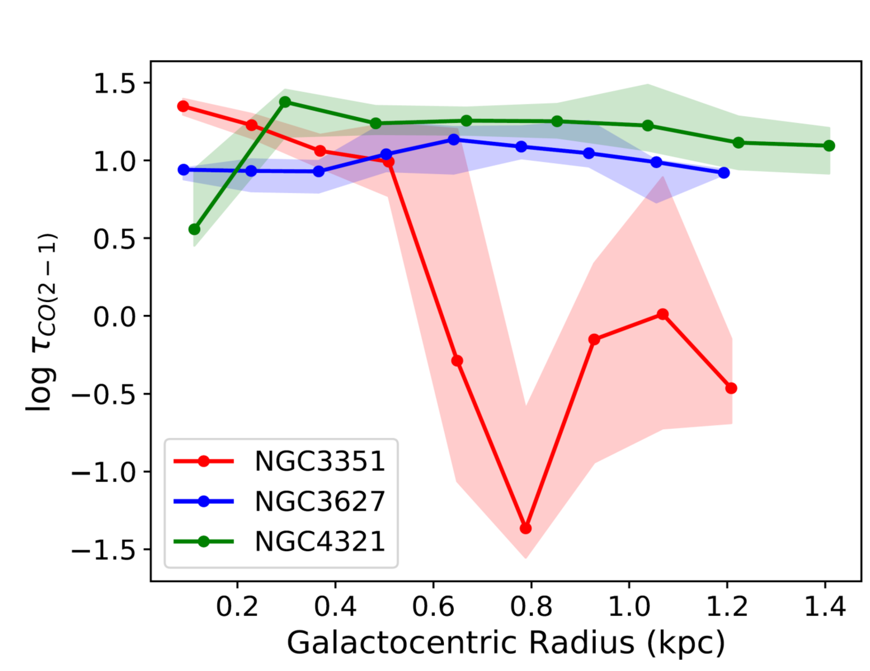
+ A decreasing α_{CO} trend with radius starting from r~0.5 kpc is consistently seen. Also, α_{CO} in NGC 3351 drops significantly at $r > 0.5$ kpc which corresponds to the **bar-driven inflows**.

+ The nuclei ($r < 0.2$ kpc) of these galaxies show diverse α_{CO} trends.

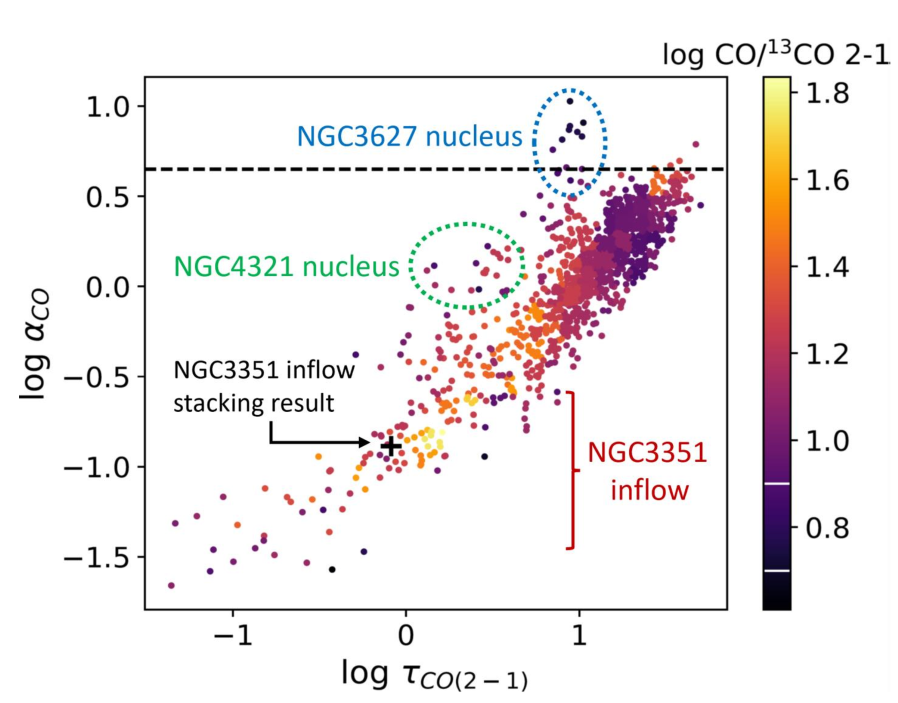


Discussion

α_{CO} Dependence and Observational Tracers



The modeled **CO optical depth** (τ_{CO}) shows a similar radial trend as α_{CO}, indicating a strong α_{CO} dependence with τ_{CO}. Thus, increased velocity dispersion and lower surface density in the inflows of NGC 3351 can explain the substantially lower α_{CO}. Moreover, the enhanced CO/^{13}CO (2-1) ratio observed in the inflows suggests more **escaped CO emission** due to lower τ_{CO}, which could lead to such low α_{CO} values.



A clear, positive correlation of α_{CO} with τ_{CO} is seen in all three galaxy centers, while α_{CO} tend to be higher in the dense and warm nuclei. The bar-driven inflow of NGC 3351 has lower α_{CO} and τ_{CO}. Within our observed regions, the **CO/^{13}CO (2-1) ratio mainly traces τ_{CO}, and thus it may be useful in predicting α_{CO} variation in galaxy centers**.

Comparison with Literature

- From a theoretical perspective, α_{CO} is expected to be approximately proportional to $\tau_{CO}/(1-e^{-\tau_{CO}})$ for thermalized, optically thick emission [5]. This could explain the positive correlation seen between α_{CO} and τ_{CO}.
- Using dust-based α_{CO} [6] with single-dish CO observations at ~1.5 kpc resolutions, anti-correlation of α_{CO} with CO/^{13}CO (1-0) ratio was observed across the disks of some starburst galaxies, but not in normal galaxies [2].
- While temperature has been reported as an important driver of α_{CO} variation in theoretical and simulation studies [1,3,4], our results show that there is not a simple relationship in α_{CO} and T_k.
- The intensity-weighted α_{CO} over our observed regions agree with dust-based results at ~$40''$ resolution [6] after beam matching.

References

[1] Bolatto et al., 2013, ARA&A, 51, 207
[2] Cormier et al., 2018, MNRAS, 475, 3909
[3] Gong et al., 2020, ApJ, 903, 142
[4] Narayanan et al., 2012, MNRAS, 421, 3127
[5] Papadopoulos et al., 2012, ApJ, 751, 10
[6] Sandstrom et al., 2013, 777, 5
[7] Teng et al., 2022, ApJ, 925, 72
[8] Teng et al., 2022, in prep