Cloud-scale Molecular Gas Properties and CO-to-H_2 Conversion Factor Variations in Nearby Galaxy Centers

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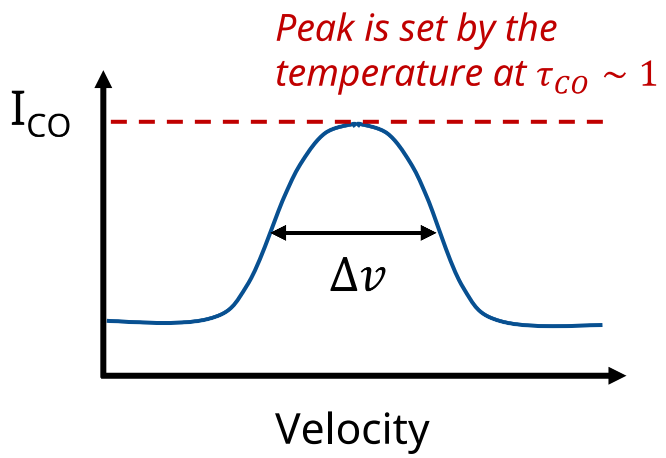
Tracing molecular gas

- Most abundant molecule: H_2
  - lowest energy transition requires >100 K to excite

    → not directly observable in cold molecular gas!

- Second most abundant molecule: CO
  - CO/H_2 abundance ~ 10^{-4}
  - lowest rotational transition can be excited at 5.53 K
  - Low-J CO lines are normally **optically thick**!

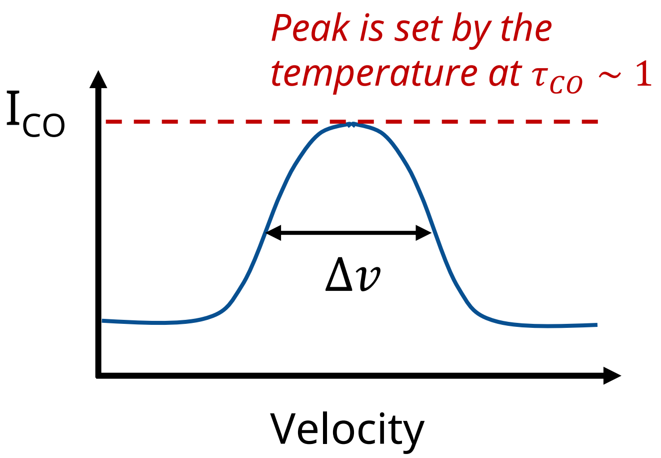
    → escaped CO emission due to high velocity dispersion



CO-to-H_2 conversion factor

- $X_{CO} \equiv \frac{N_{H_2}}{I_{CO(1-0)}} \left(\frac{cm^{-2}}{K\ km\ s^{-1}}\right)$ $\div\ (\mathbf{4.5 \times 10^{19}})$
- $\alpha_{CO} \equiv \frac{M_{mol}}{L_{CO(1-0)}} = \frac{\Sigma_{mol}}{I_{CO(1-0)}} \left(\frac{M_\odot}{K\ km\ s^{-1}\ pc^2}\right)$, where $M_{mol} \sim 1.36\ M_{H_2}$
- An empirically determined mass-to-light ratio
- What affect α_{CO}?
  - temperature and linewidth
  - size-linewidth relation: $\sigma \propto R^{0.5}$ *(Larson 1981, Heyer+ 2009)*

    → turbulent motions in molecular clouds
  - molecular gas properties



Why is α_{CO} important?

- It is the basis of measuring molecular gas, and it is tied to the physical conditions of molecular gas

→ α_{CO} is central to studying the **amount** and **properties** of molecular gas

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

Regions with different α_{CO}

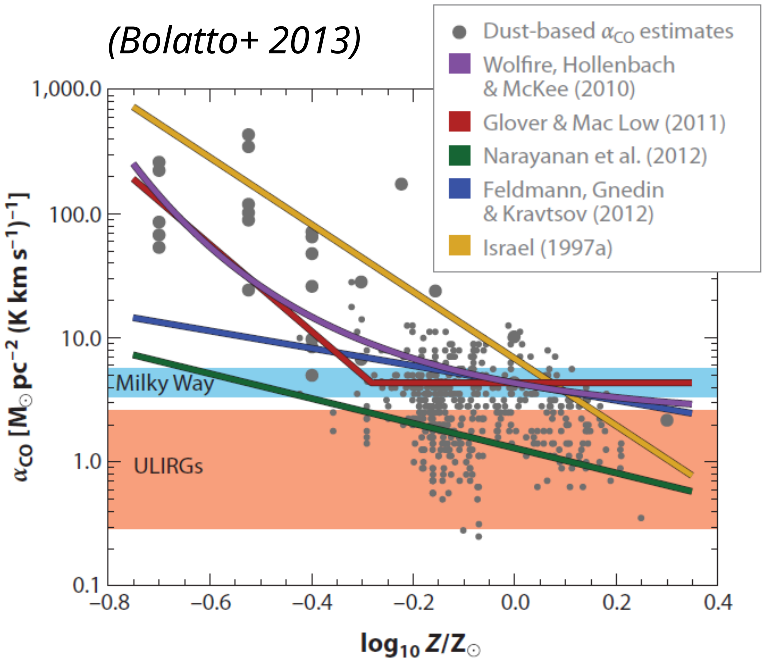
- Low-metallicity galaxies
  - High α_{CO} due to the lack of dust shielding
- (Ultra-)luminous infrared galaxies (U/LIRGs)
  - Many of them are galaxy mergers
  - Gas being warmer, denser, altered dynamics/virial balance
- Galaxy centers
  - α_{CO} in our Galactic Center is 3–10x lower than in the disk
  - low α_{CO} found in the centers of many **barred spiral galaxies**

    → gas concentrations driven by bars and/or spiral arms

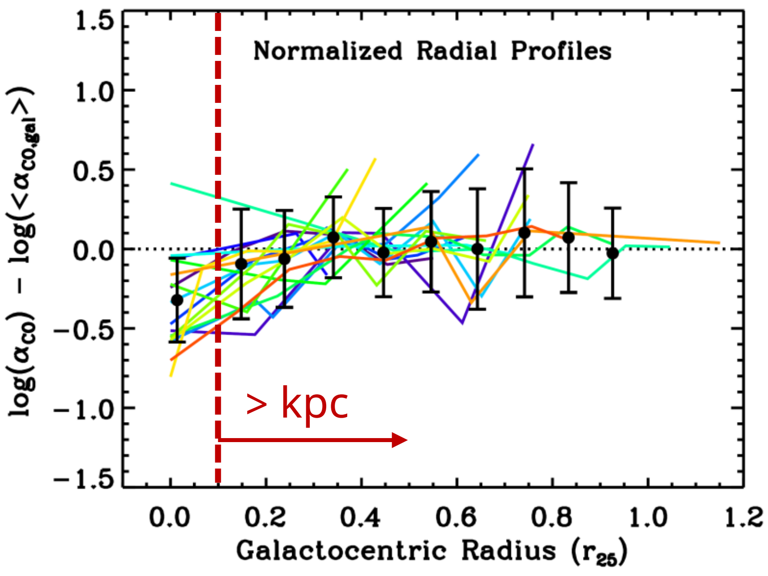
    → frequently host active star formation

    → nuclear starburst, AGN feedback

(Bolatto+ 2013)



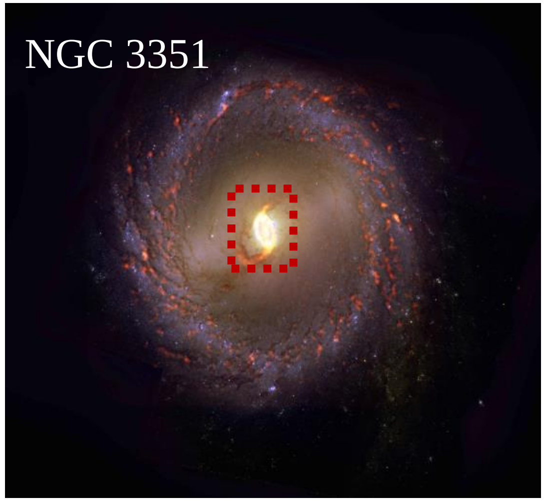
(Sandstrom+ 2013)

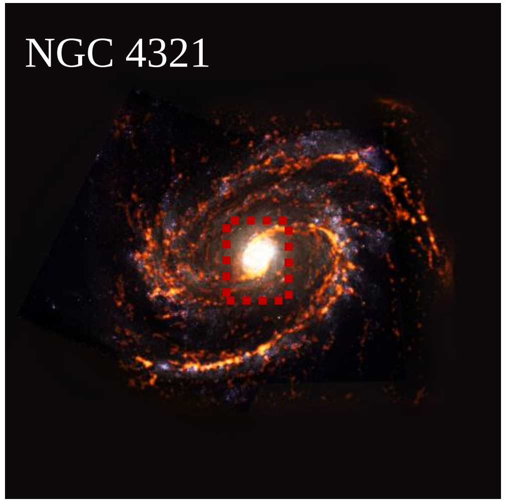


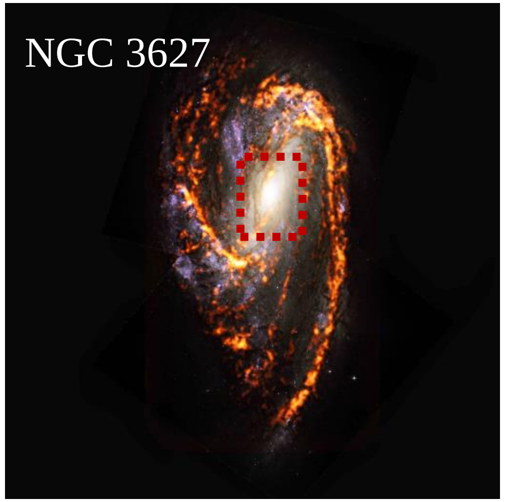
ALMA multi-line observations

- What are the **environmental conditions** in these galaxy centers and what physical processes cause the **variation of α_{CO}**?
- ALMA data of multiple low-*J* CO isotopologues
  - ^{12}CO, ^{13}CO, C^{18}O at *J = 1-0, 2-1, 3-2*
  - NGC 3351, NGC 3627, NGC 4321

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







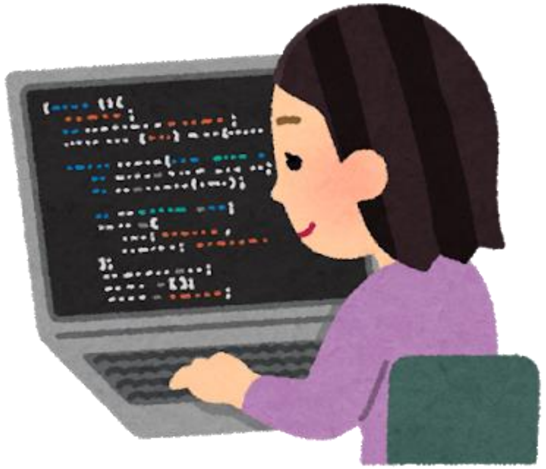
(PHANGS–ALMA+HST)

ApJ paper on NGC 3351

- **Yu-Hsuan Teng**, Karin M. Sandstrom, Jiayi Sun, Adam K. Leroy, L. Clifton Johnson, Alberto D. Bolatto, J. M. Diederik Kruijssen, Andreas Schruba, Antonio Usero, Ashley T. Barnes, Frank Bigiel, Guillermo A. Blanc, Brent Groves, Frank P. Israel, Daizhong Liu, Erik Rosolowsky, Eva Schinnerer, J. D. Smith and Fabian Walter, **"Molecular Gas Properties and CO-to-H_2 Conversion Factors in the Central Kiloparsec of NGC 3351", 2021, *ApJ*, 925, 72**.

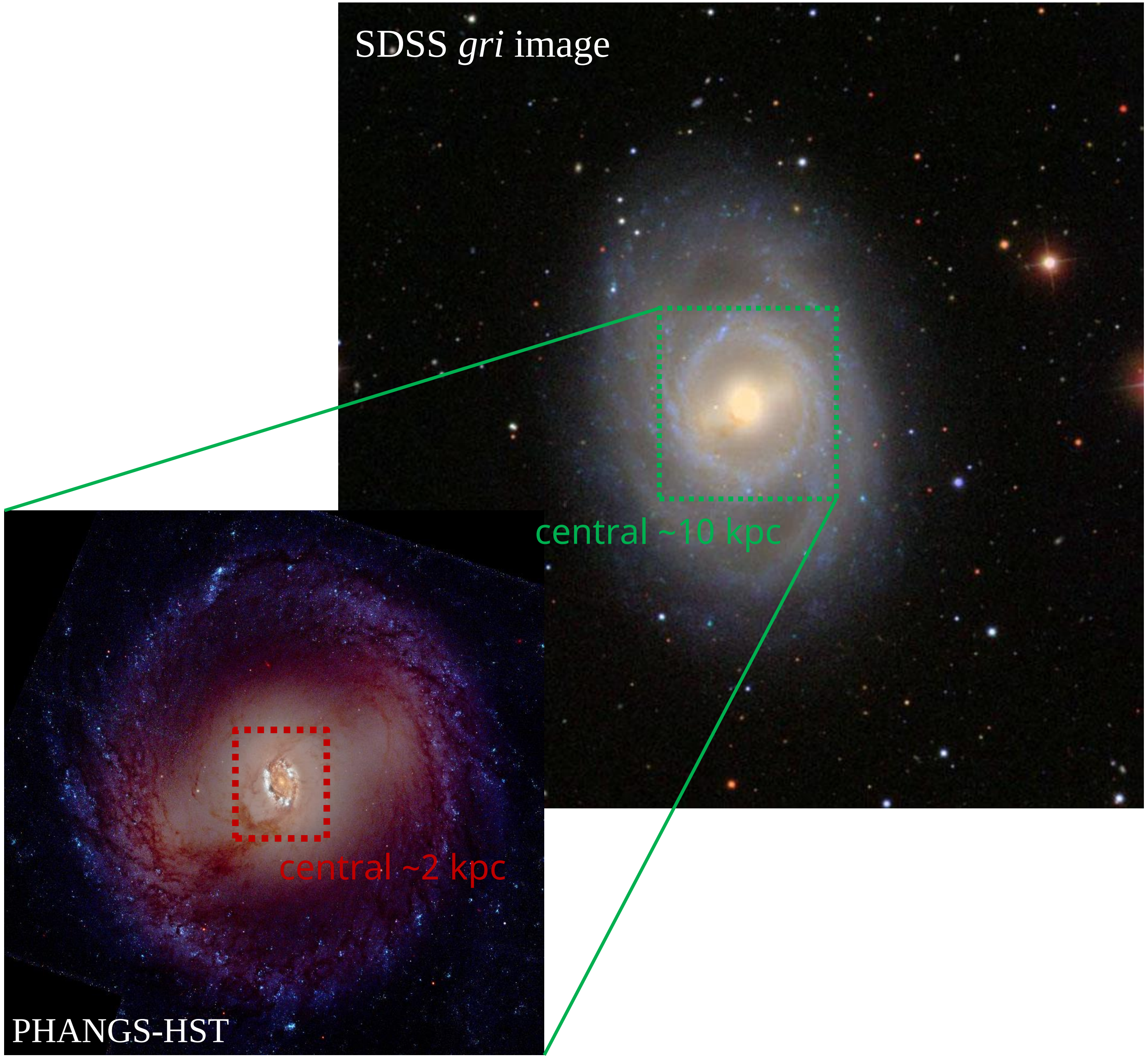
- https://arxiv.org/abs/2111.05844

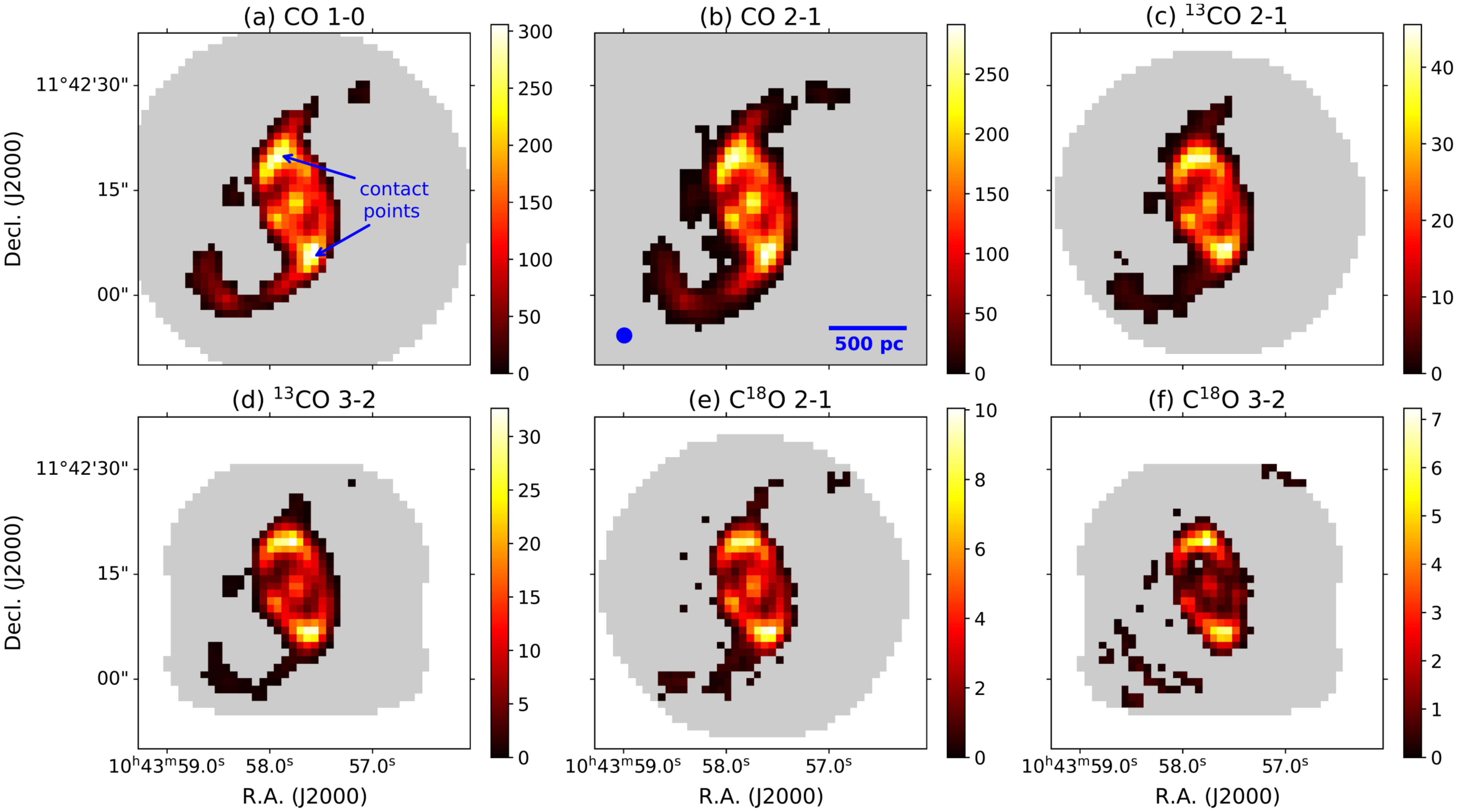
- https://github.com/ElthaTeng/multiline-ngc3351



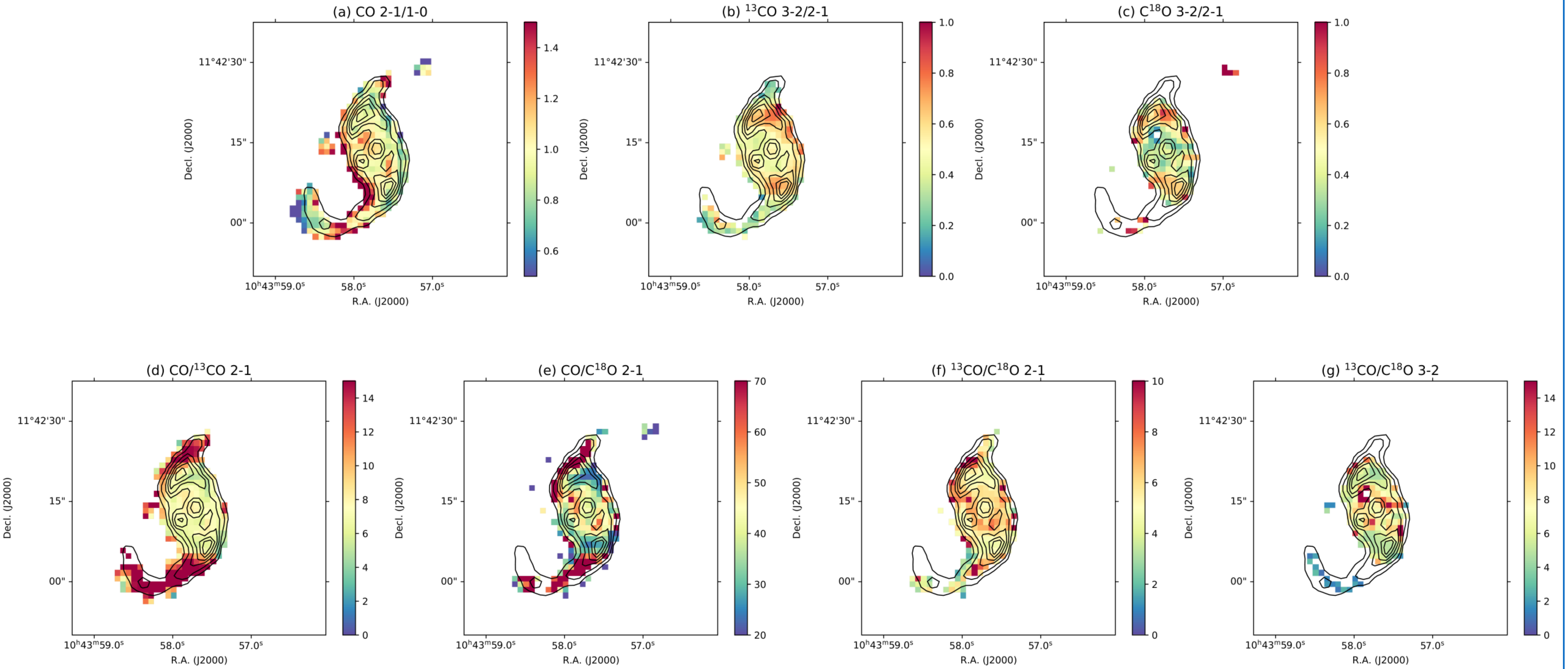
Observations

- NGC 3351 (M95)
  - Distance: 10.0 Mpc
  - Type: SBb
  - circumnuclear star-forming ring
- ALMA Band 3, 6, 7
  - central ~2 kpc region
  - angular resolution: 2.1'' (~100 pc)
  - CO isotopologues
    - ^{12}CO (1-0) and (2-1)
    - ^{13}CO (2-1) and (3-2)
    - C^{18}O (2-1) and (3-2)





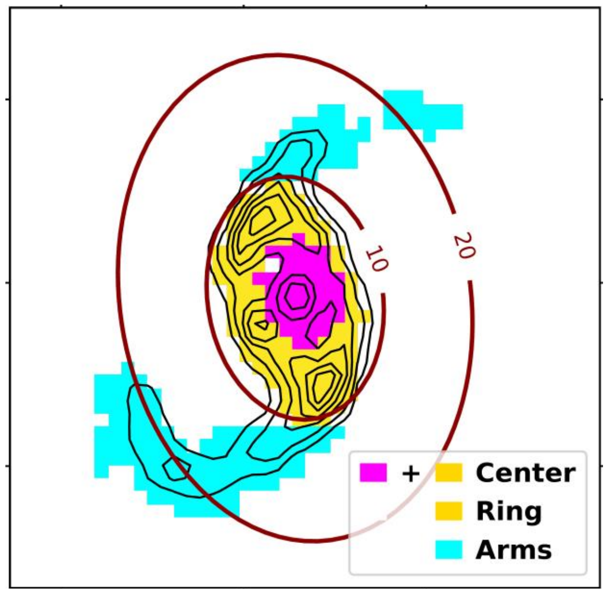
(a) CO 1-0
(b) CO 2-1
(c) ^{13}CO 2-1
(d) ^{13}CO 3-2
(e) C^{18}O 2-1
(f) C^{18}O 3-2
contact
points
500 pc
Decl. (J2000)
R.A. (J2000)
11°42'30"
15"
00"
10^{h}43^{m}59.0^s
58.0^s
57.0^s


(a) CO 2-1/1-0
(b) ^{13}CO 3-2/2-1
(c) C^{18}O 3-2/2-1
(d) CO/^{13}CO 2-1
(e) CO/C^{18}O 2-1
(f) ^{13}CO/C^{18}O 2-1
(g) ^{13}CO/C^{18}O 3-2
11°42'30"
15"
00"
Decl. (J2000)
10^{h}43^{m}59.0^s
58.0^s
57.0^s
R.A. (J2000)

Multi-line modeling

- 6D integrated flux models using RADEX *(van der Tak+ 2007)*
  - $\frac{N_{CO}}{\Delta v}$: CO column density per linewidth ($cm^{-2}\ km^{-1}\ s$)
    - relevant for radiative transfer, determines optical depths
  - n_{H_2}: H_2 volume density (cm^{-3})
  - T_k : kinetic temperature (K)
  - $X_{12/13}$: $^{12}CO/^{13}CO$ abundance ratio
  - $X_{13/18}$: $^{13}CO/C^{18}O$ abundance ratio
  - Φ_{bf}: beam-filling factor
    - beam dilution effect, ranges from 0 to 1.
- Pixel-by-pixel + regional (stacking) analysis

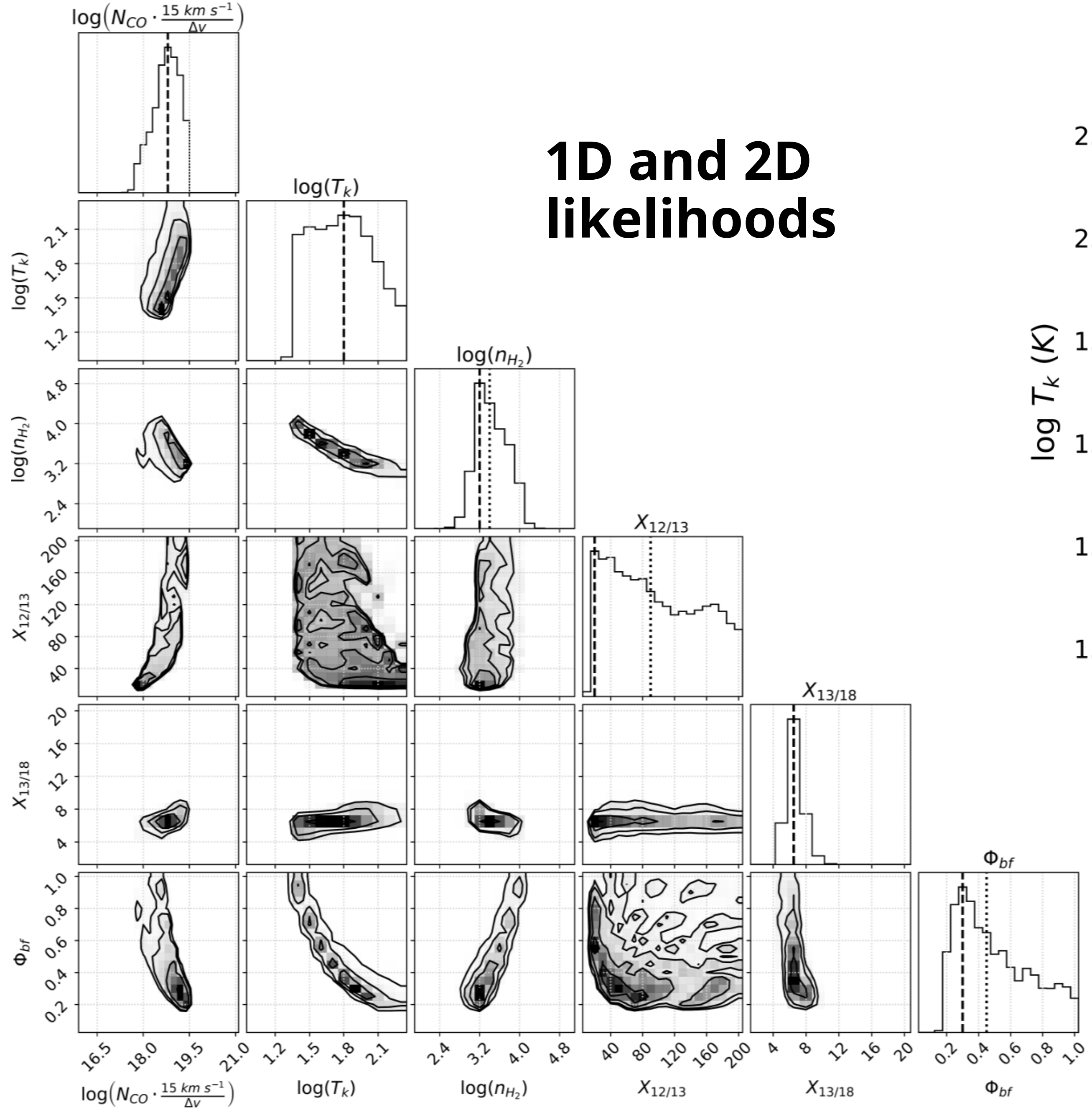
Definition of regions



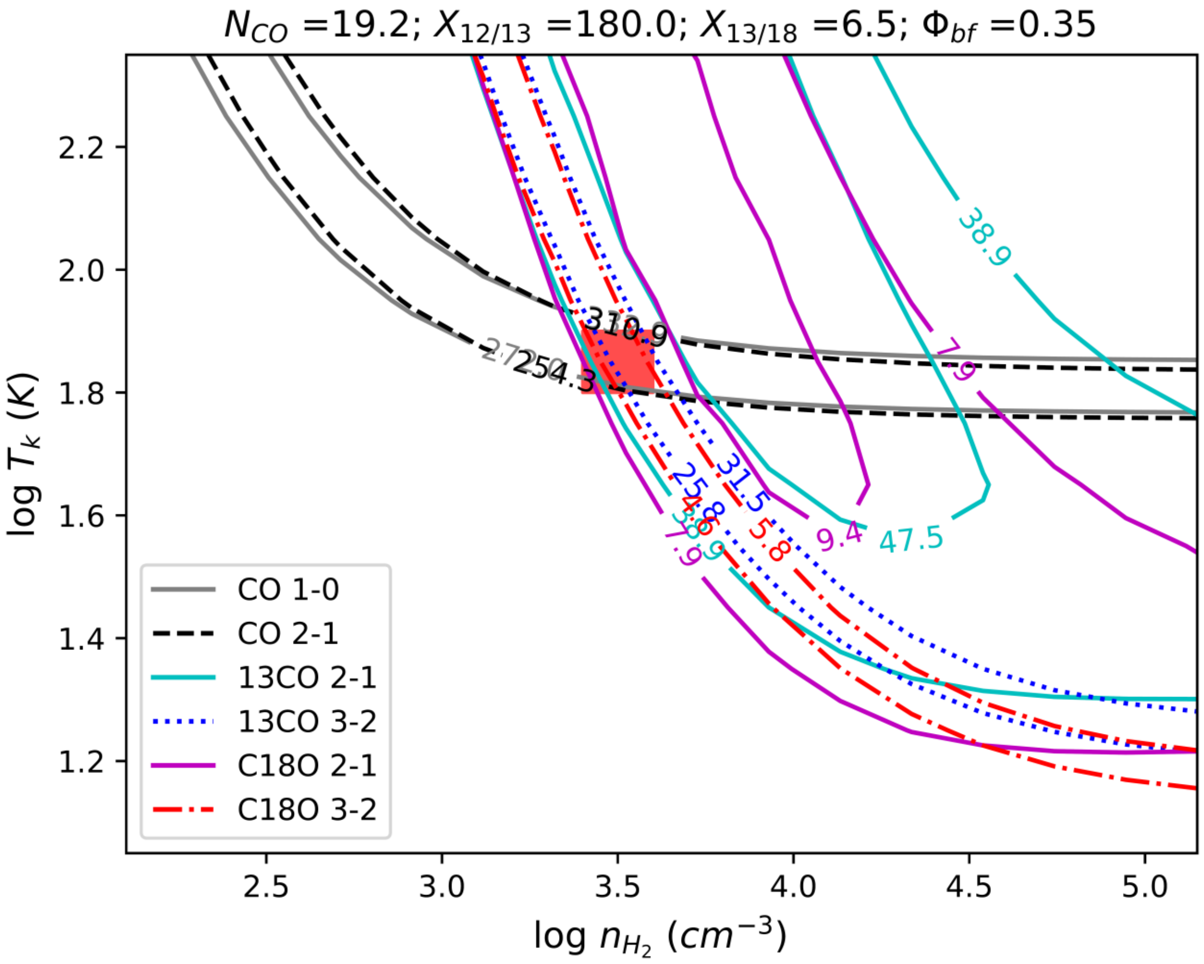
Multi-line modeling

- Best-fit solution and probability distribution for each pixel/region
  - $\chi^2 = \sum_{i=1}^{6} \left(\frac{F_i^{mod} - F_i^{obs}}{\sigma_i} \right)^2$ → $P = \frac{e^{-\chi^2/2}}{\prod_{i=1}^{6} \sqrt{2\pi\sigma_i^2}}$
  - Flux uncertainties: $\sigma = \sqrt{\sigma_{noise}^2 + \sigma_{cal}^2}$ where $\sigma_{cal} \sim 10\%\ I_{CO}$
  - Physical constraint: line-of-sight path length
    - $\ell_{los} = N_{CO}\left(\sqrt{\Phi_{bf}}\, n_{H_2}\, x_{CO}\right)^{-1} < 100$ pc

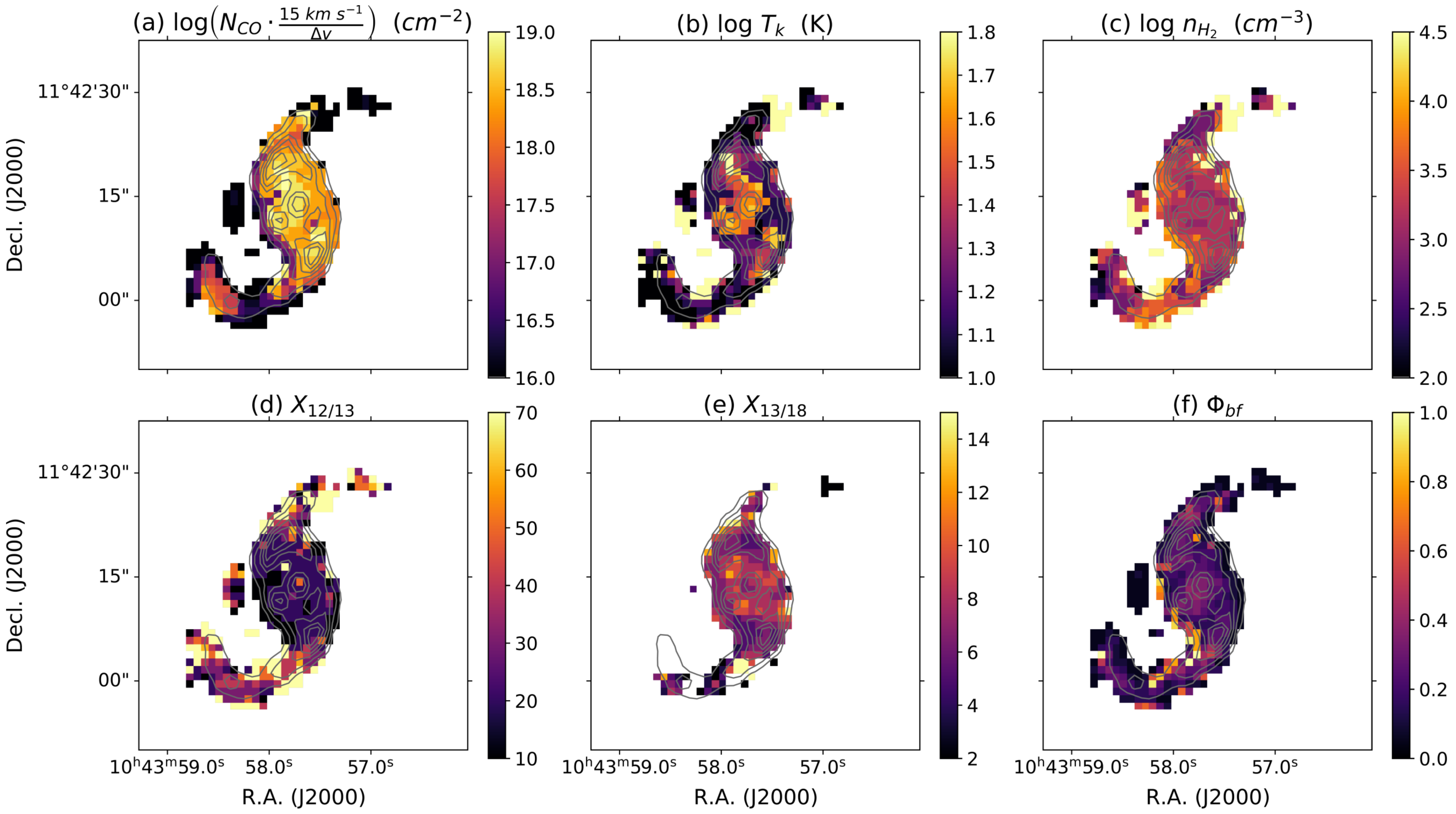
    → scale height for molecular gas in disk galaxies ~ 100 pc



1D and 2D likelihoods



best-fit parameter set

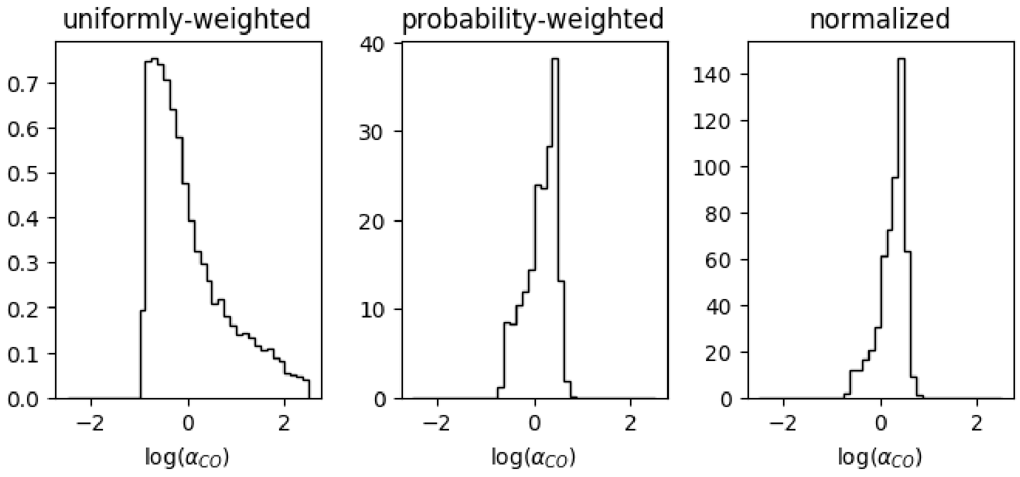


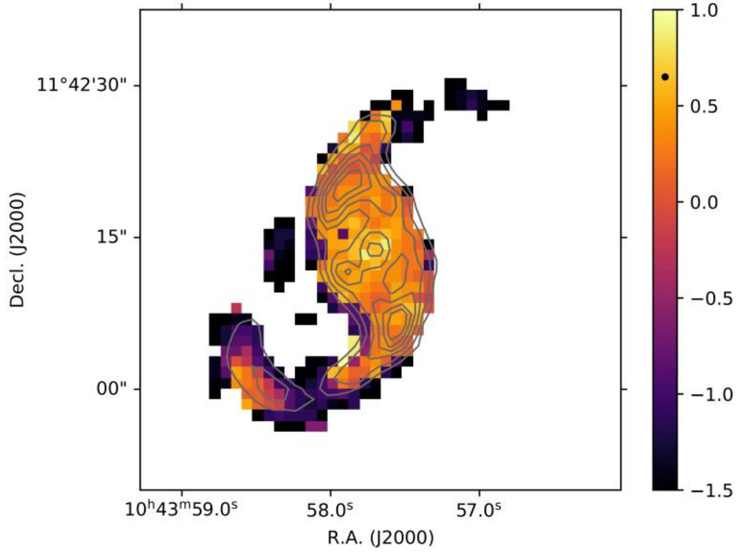
(a) $\log\left(N_{CO}\cdot\frac{15\ km\ s^{-1}}{\Delta v}\right)$ (cm^{-2})
(b) $\log T_k$ (K)
(c) $\log n_{H_2}$ (cm^{-3})
(d) $X_{12/13}$
(e) $X_{13/18}$
(f) Φ_{bf}
Decl. (J2000)
R.A. (J2000)
11°42'30"
15"
00"
$10^h43^m59.0^s$
58.0^s
57.0^s

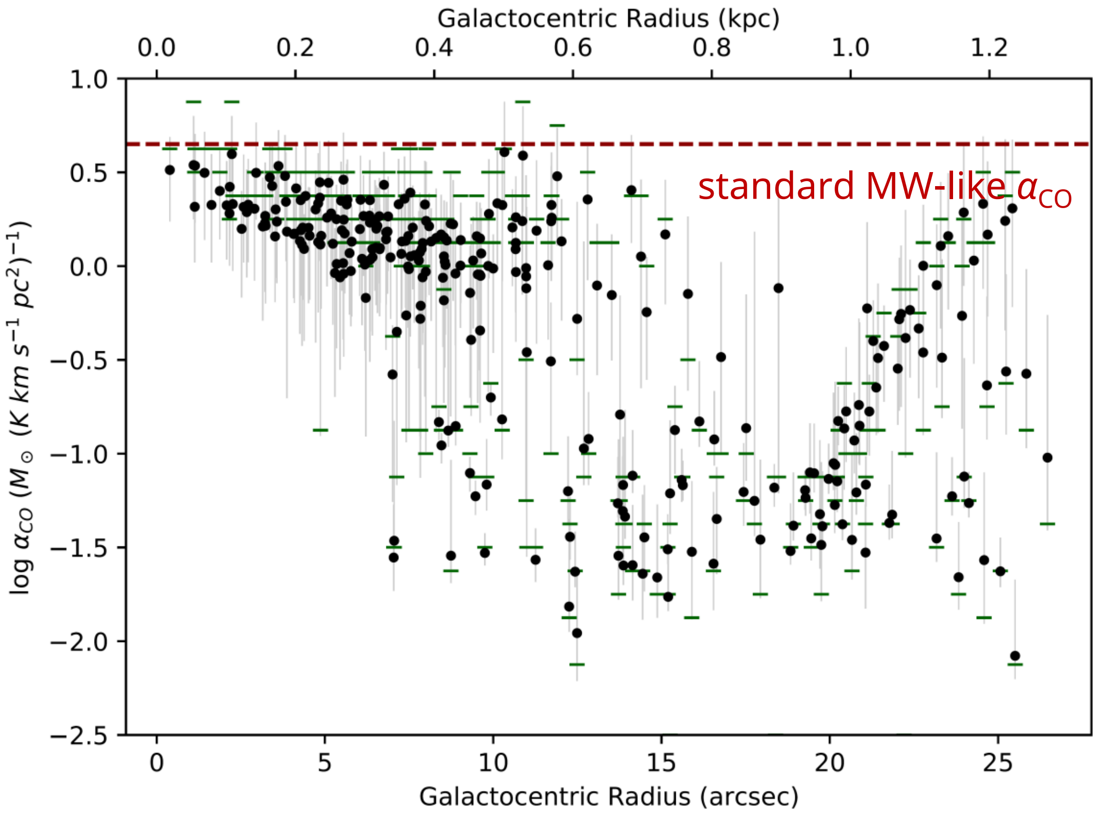
Marginalized α_{CO} likelihood

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

$$= \frac{1.4\ m_{H_2}(M_\odot)\ N_{CO}(cm^{-2})\ \Phi_{bf}\ A(cm^2)}{x_{CO}\ I_{CO(1-0)}(K\ km\ s^{-1})\ A\ (pc^2)}$$

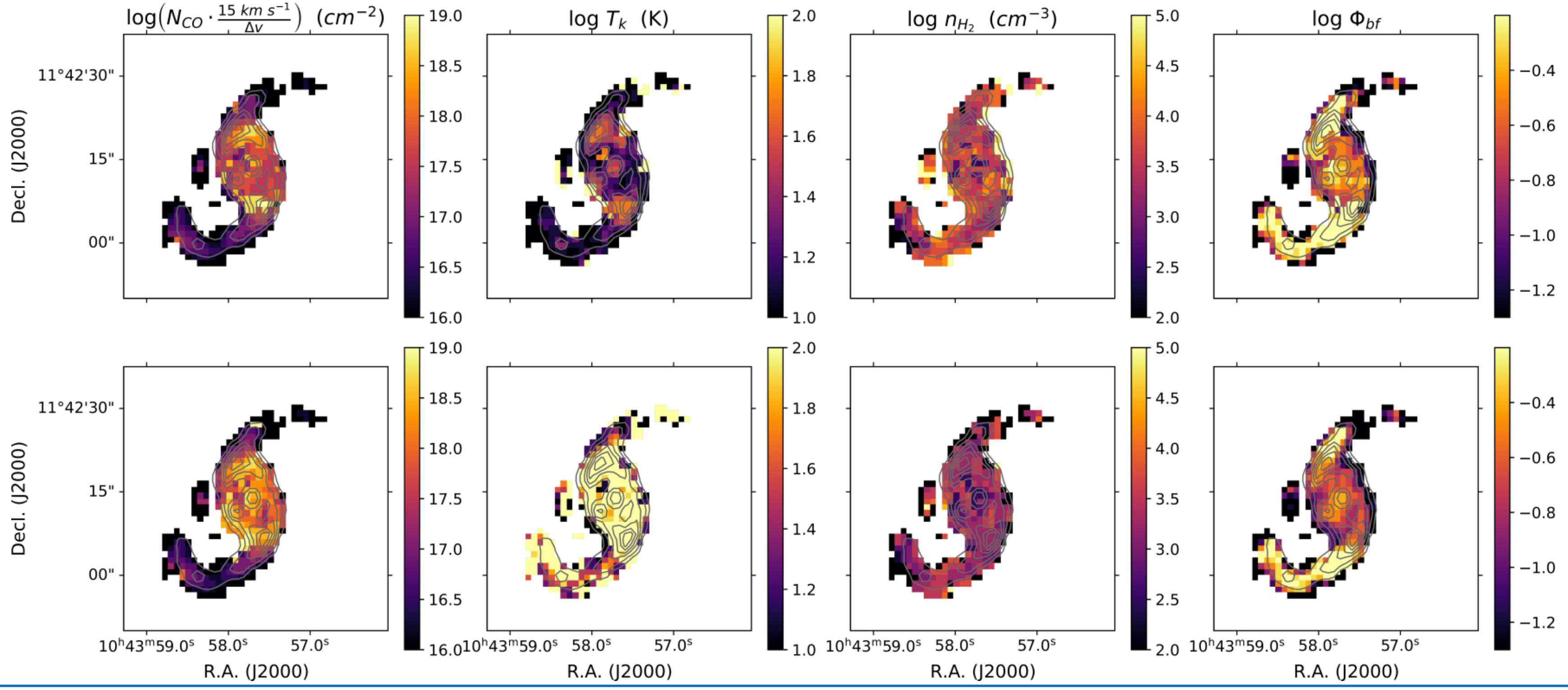






Two-component modeling

- 8D integrated flux models
  - $X_{12/13} = 25, \;\; X_{13/18} = 8$ based on one-component results
  - Axes: $\left(\frac{N_{CO}}{\Delta v}, n_{H_2}, T_k, \Phi_{bf}\right) \times 2$



Similar to the one-component result

< 0.5 dex difference between two phases

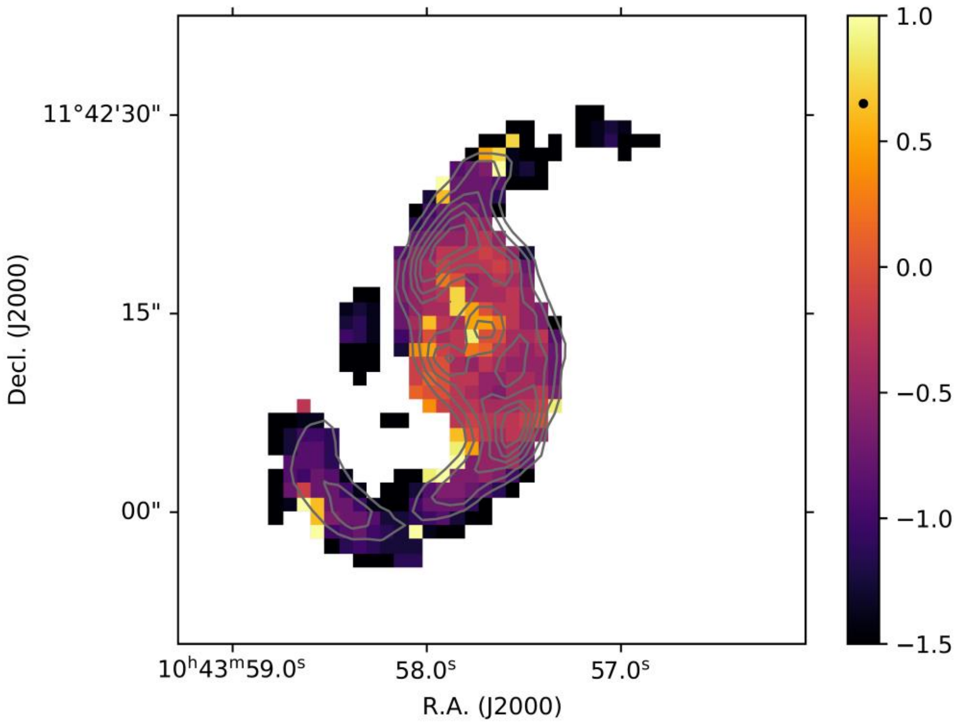
Secondary component with $T_k \sim 100$ K

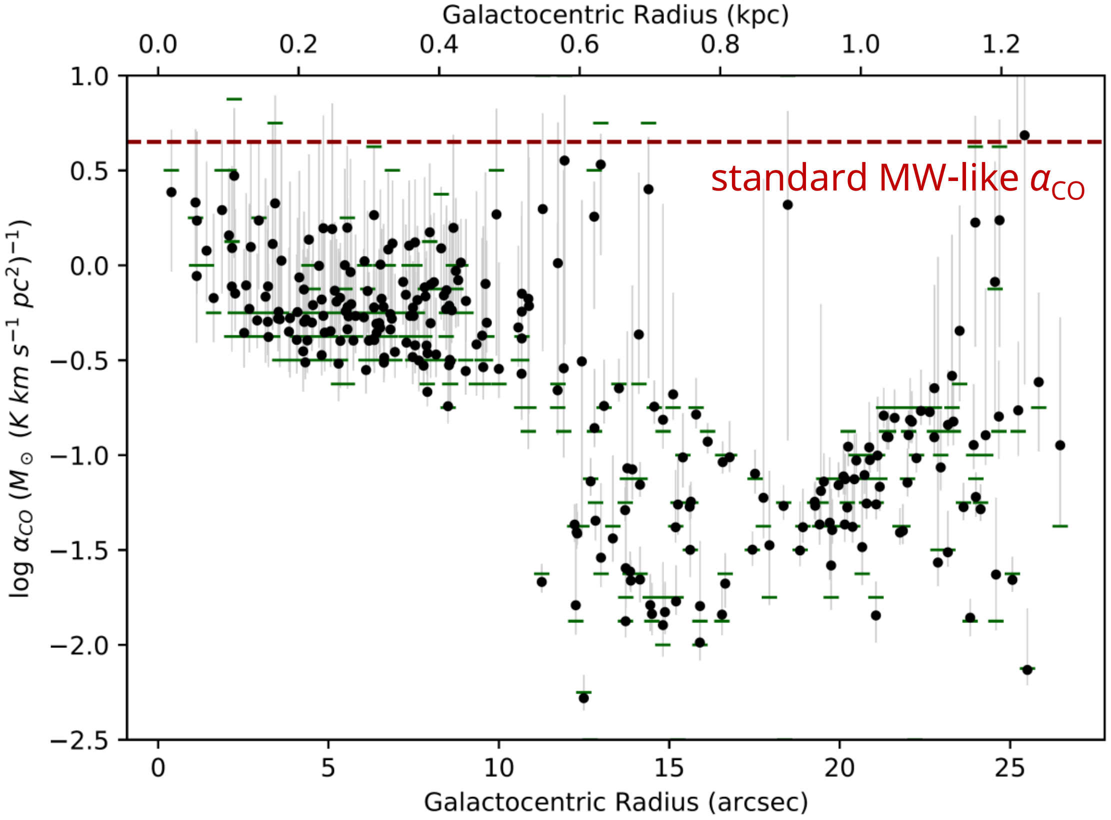
α_{CO} distribution

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

$$= \frac{1.4\ m_{H_2}(M_{\odot})\ N_{CO}(cm^{-2})\ \Phi_{bf}\ A(cm^2)}{x_{CO}\ I_{CO(1-0)}(K\ km\ s^{-1})\ A\ (pc^2)}$$

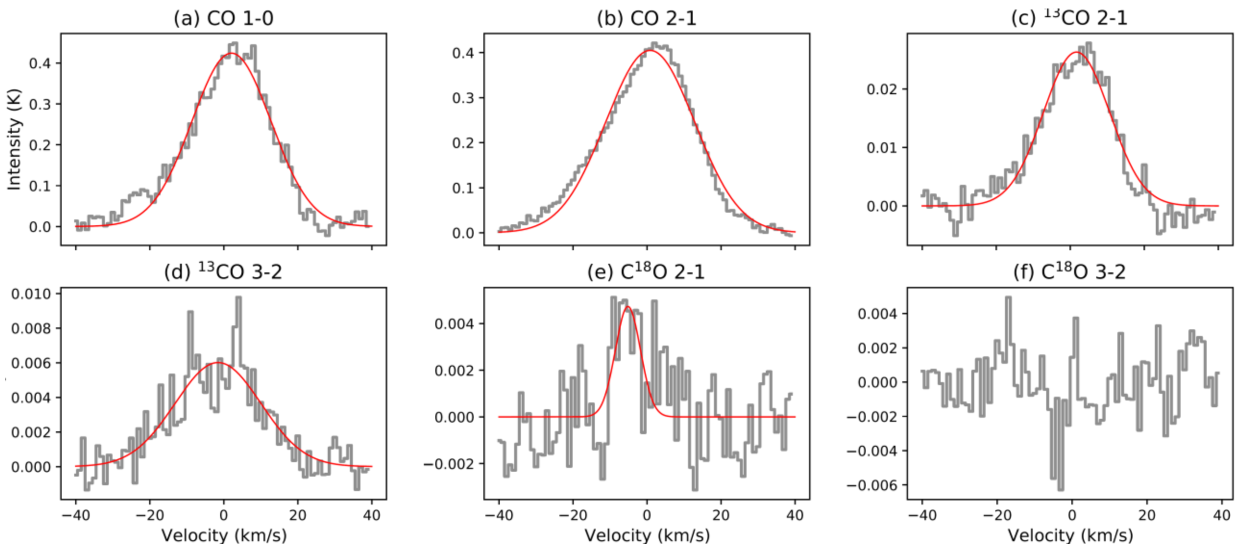
$\alpha_{CO,avg} \sim 1.11 \pm 0.09$, similar to our one-component result and previous dust-based estimation by *Sandstrom+13*



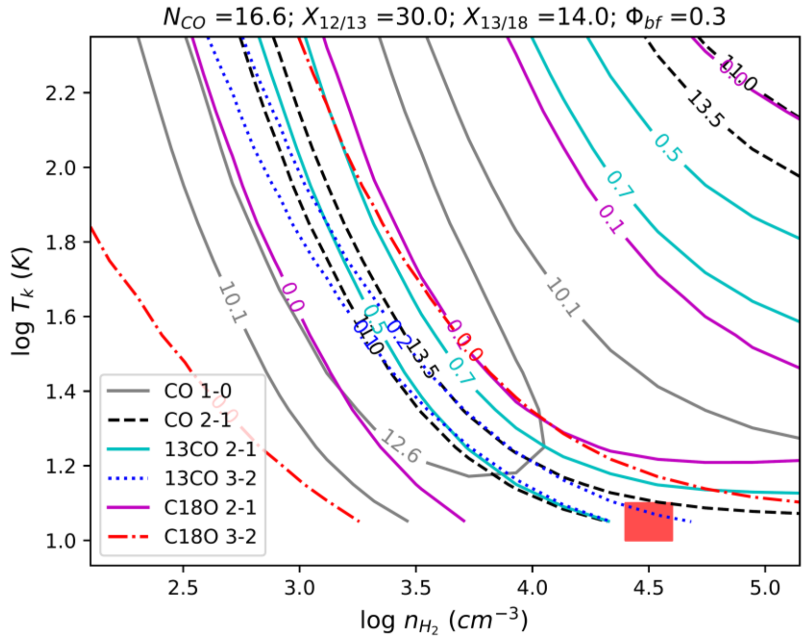


α_{CO} in the inflow arms

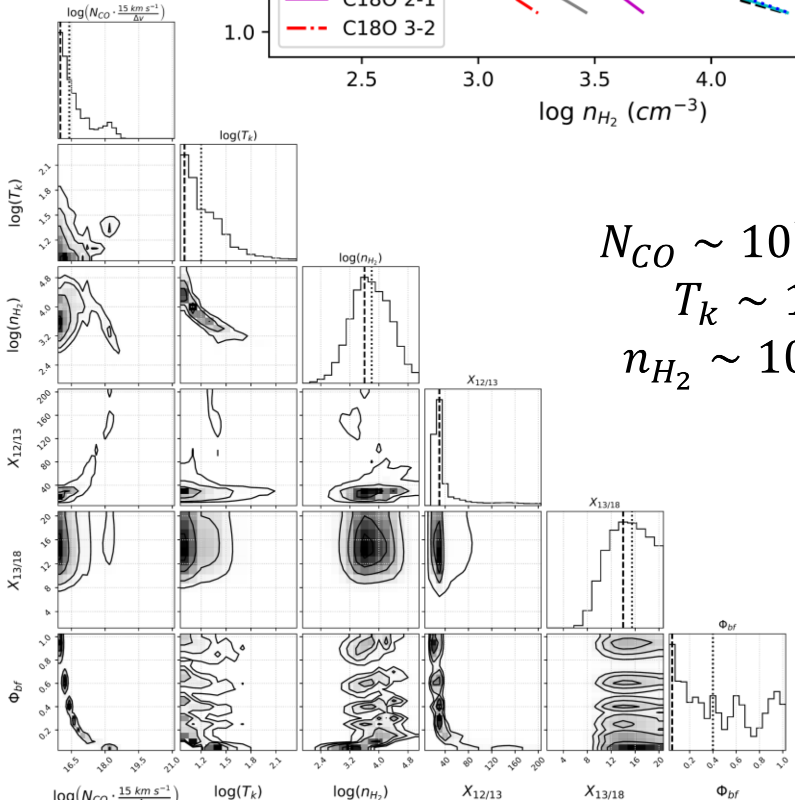
averaged spectra



best-fit



prob



$$N_{CO} \sim 10^{16}\ cm^{-2}$$
$$T_k \sim 10\ K$$
$$n_{H_2} \sim 10^4\ cm^{-3}$$

$$\alpha_{CO,avg} \sim 0.01 - 0.1$$

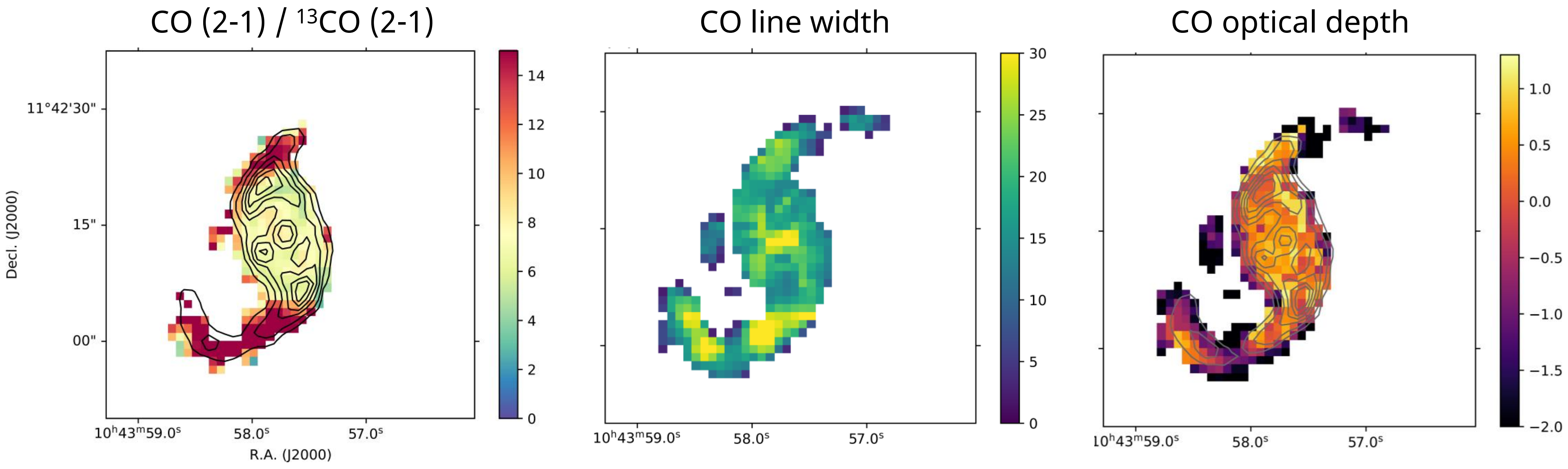
→ an order of magnitude lower than center

→ match well with pixel-based results

Discussion

- α_{CO} substantially lower in the inflow arms
  - Higher CO/^{13}CO line ratios → more CO emission
    - → Higher $X_{12/13}$ abundance?
    - → Lower CO optical depth?
  - Turbulence / shear → higher velocity dispersion

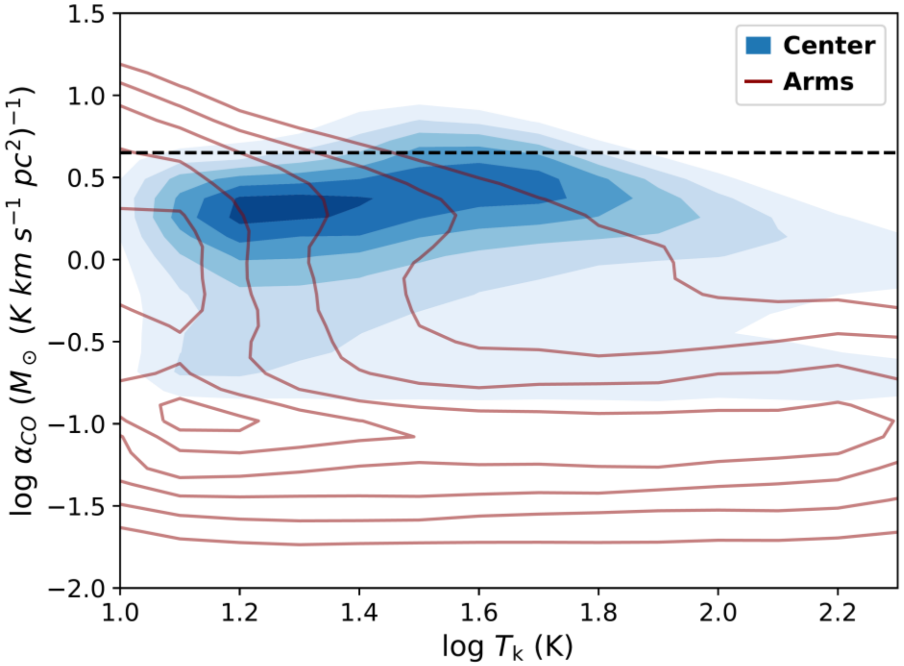
→ escaped CO emission due to low CO optical depth



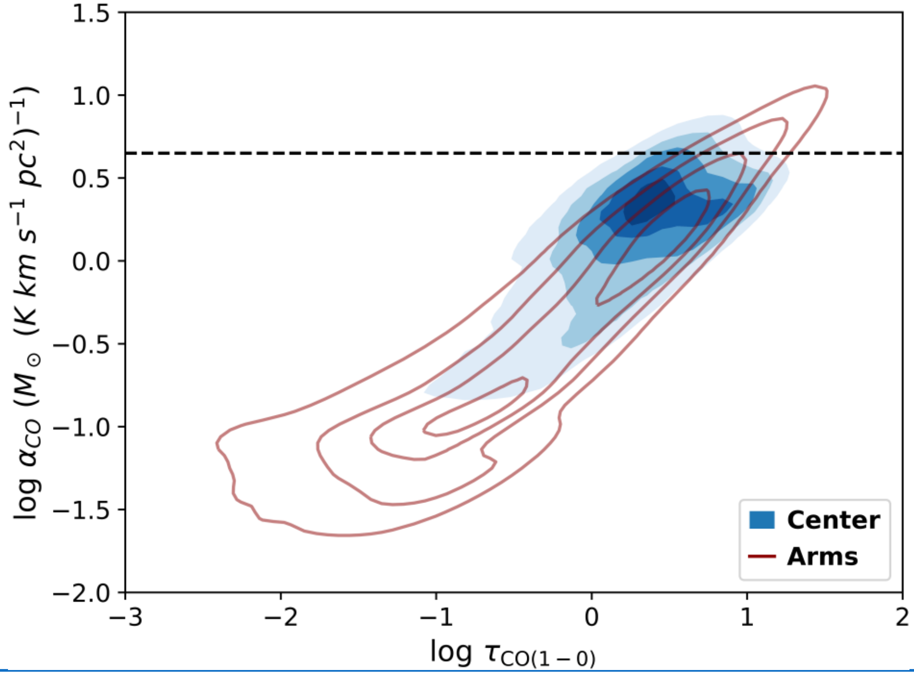
Discussion

- Lower-than-Galactic α_{CO} in the center/ring
  - α_{CO} correlation with temperature or optical depth
  - Higher velocity dispersion in barred galaxy centers than in the disks *(Sun+ 2018, 2020)*

α_{CO} vs. T_k



α_{CO} vs. τ_{CO}



standard MW-like α_{CO}

Discussion

- No clear variation in CO isotopic abundances
  - $X_{12/13} \sim 20 - 30$
  - $X_{13/18} \sim \begin{cases} 6-8, & \text{ring and nucleus} \\ 8-10, & \text{gaps inbetween} \end{cases}$

→ ~ Milky Way center values (*Milam+05*, *Areal+18*)

- Both our one- and two-component models predict
  - a dominant gas phase with $n_{H_2} \sim 2 - 3 \times 10^3$ cm^{-3}
  - higher temperature of $T_k \sim 30 - 60$ K near the nucleus and contact points

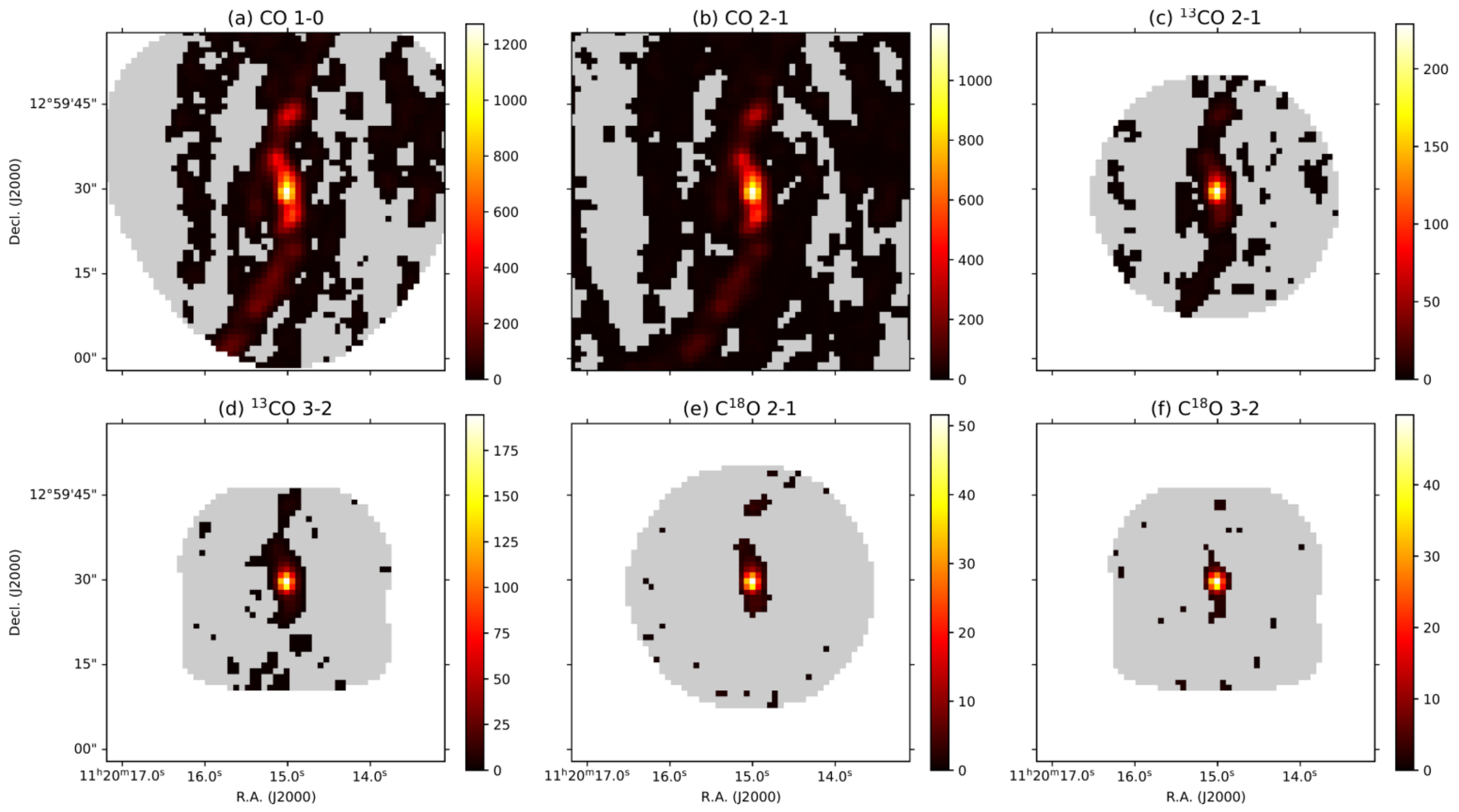
→ similar to the density and temperature structure in the Milky Way's Central Molecular Zone

- a gas weighted mean α_{CO} of ~1.5 $M_\odot$ $(K\ km\ s^{-1}\ pc^{-2})^{-1}$

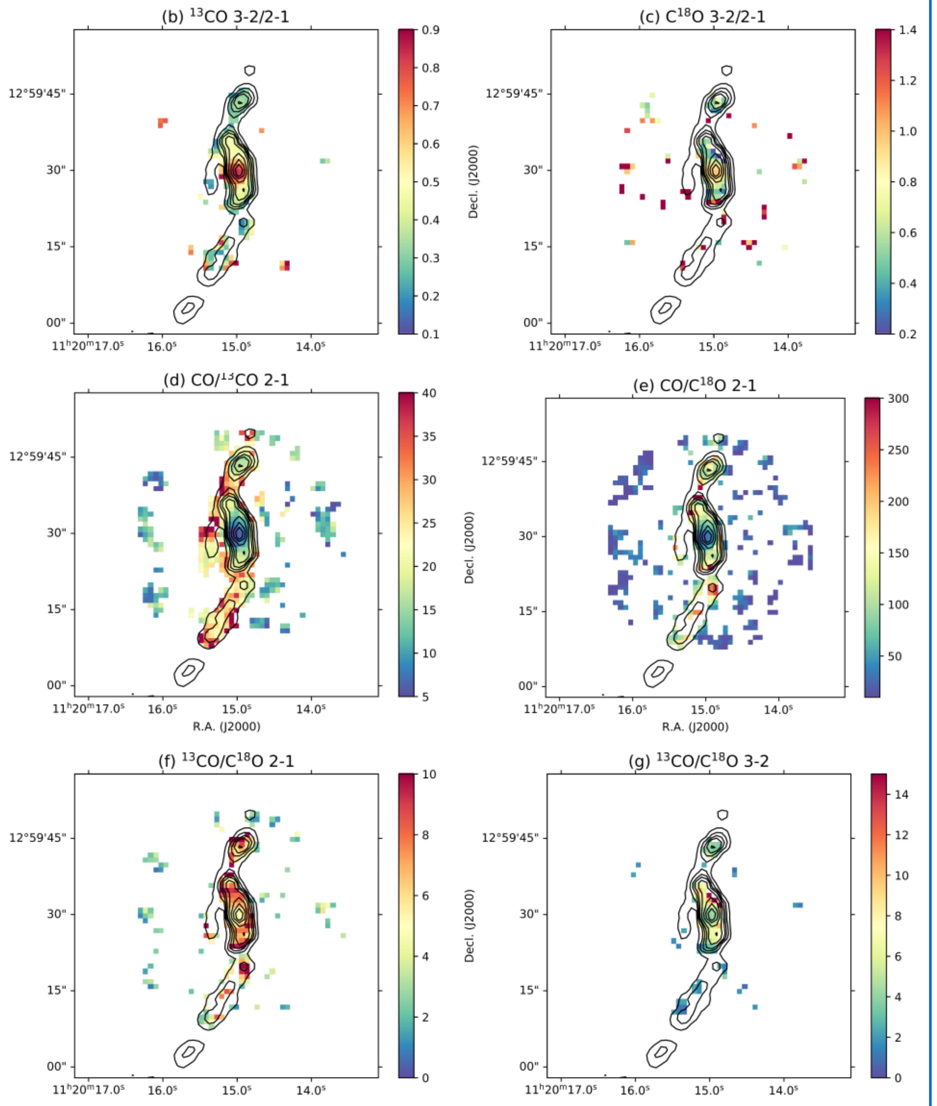
→ consistent with the mean $\alpha_{CO(2\text{-}1)}$ ~ 1 ± 0.4 determined by *Sandstrom+13* based on dust modeling at a 40'' scale

Initial Results – NGC 3627

Moment 0 maps

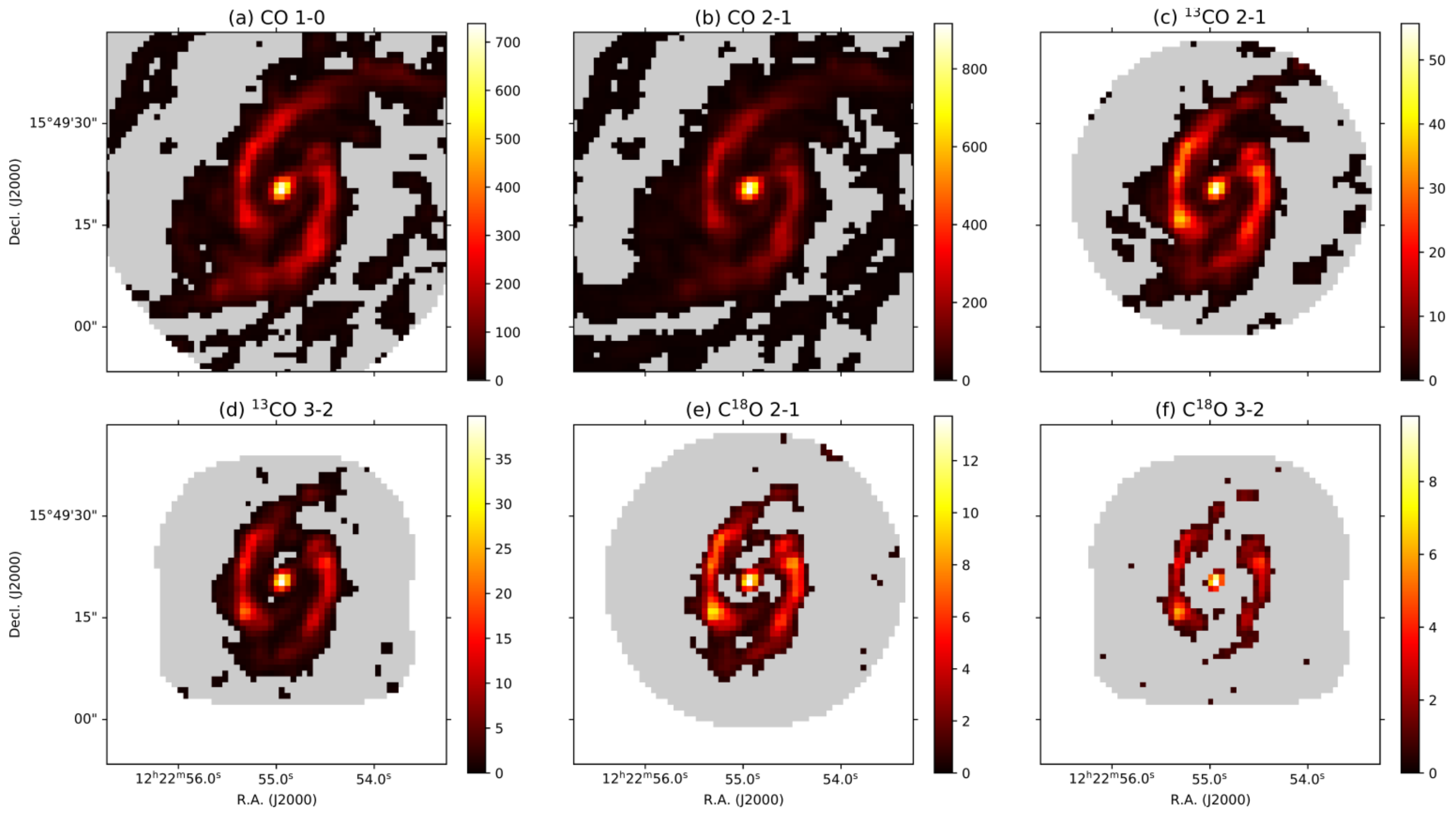


Line ratios

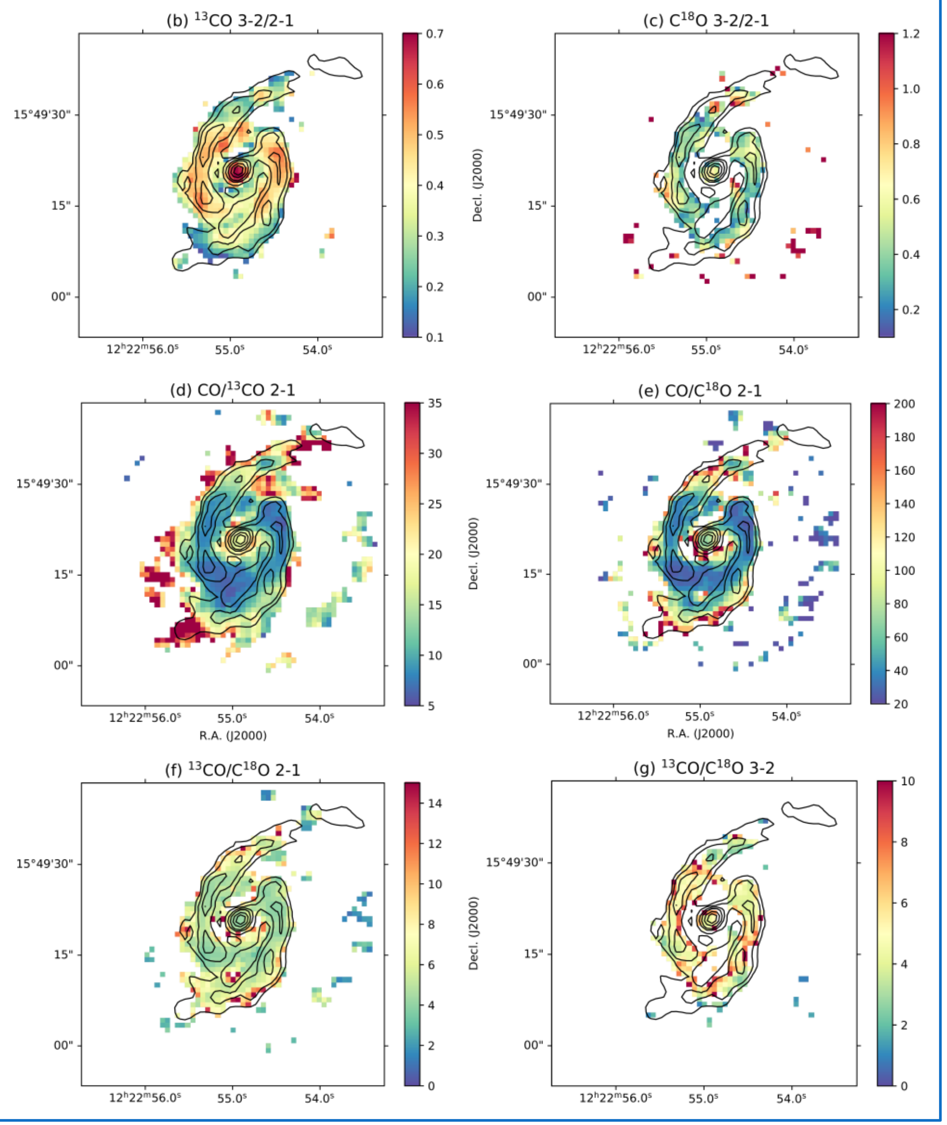


Initial Results – NGC 4321

Moment 0 maps



Line ratios

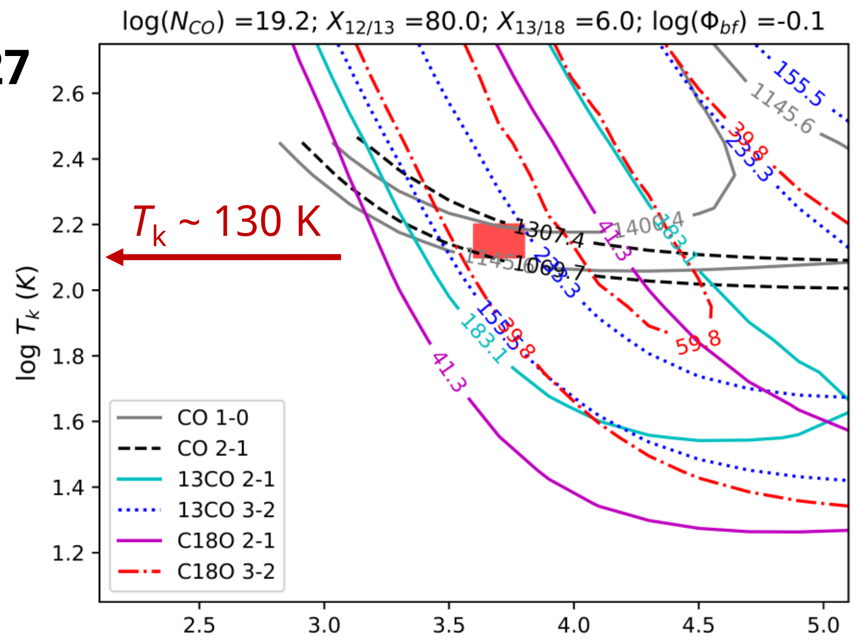


Initial results – modeling

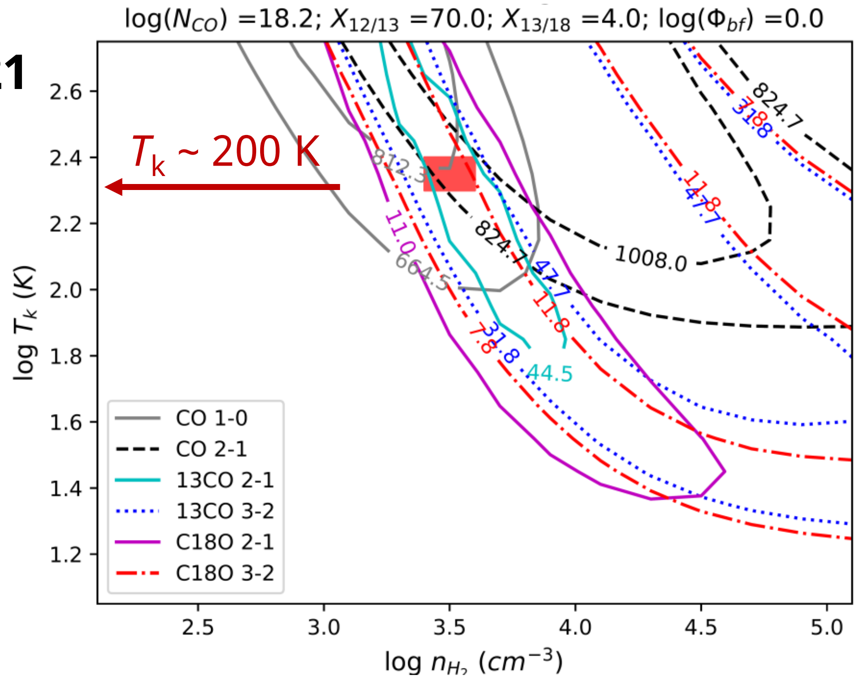
- The inner ~300 pc nuclei of both galaxies
  - Best-fit solutions match well with 1DMax, except for less-constrained $X_{12/13}$ in the marginalized 1D likelihood distributions
  - $T_k > 100$ K → AGN? More active SF?
  - $n_{H2} > 3 \times 10^3$ cm^{-3} in both nuclei

    → 2-10x higher than the arms
  - $N_{CO} > 10^{19}$ cm^{-2} in the NGC 3627 nucleus

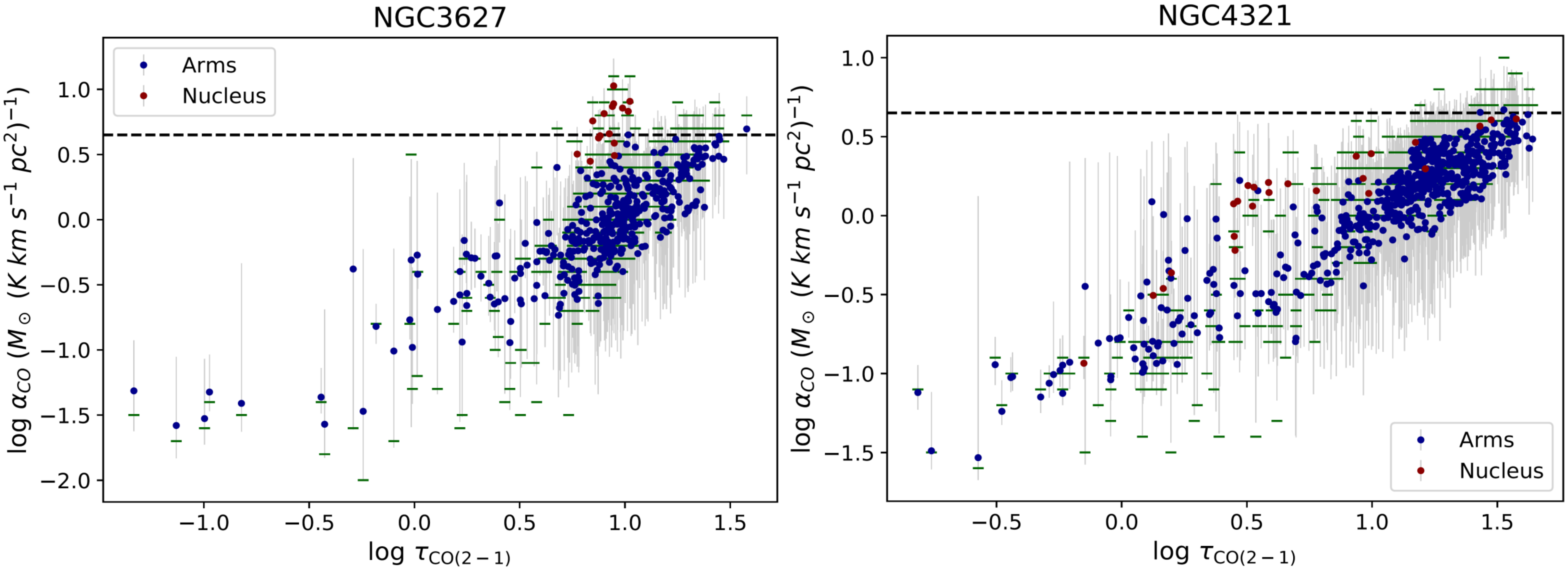
NGC 3627



NGC 4321



Initial results – α_{CO} vs. τ_{CO}



THANK YOU!

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https://elthateng.github.io/

Paper: **Teng+2022, *ApJ*, 925, 72**