Revealing the Drivers of CO-to-H_2 Conversion Factor Variation and its Impact on Star Formation Efficiency

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Yu-Hsuan (Eltha) Teng

Collaborators: Karin Sandstrom, Jiayi Sun, Adam Leroy, Alberto Bolatto, I-Da Chiang, Munan Gong, Antonio Usero, Daizhong Liu, Eva Schinnerer, Frank Israel, Diederik Kruijssen, Andreas Schruba, Simon Glover, Ralf Klessen, Miguel Querejeta, Frank Bigiel, Guillermo Blanc, Brent Groves, Erik Rosolowsky, J.-D. Smith, Fabian Walter, *PHANGS Team*

About my research

Star formation and molecular gas in spiral galaxies

- **Dense gas structure and environment** (N_2H^+, HCN, HCO^+…)
  - Filaments and massive star formation in Orion Molecular Cloud *(Teng & Hirano 2020)*
  - Dense gas fraction and star formation efficiency across nearby galaxies *(PHANGS collaboration)*
- **Molecular gas properties and the CO-to-H_2 conversion factor (α_{CO})**
  - Multi-line CO isotopologue modeling in nearby galaxy centers *(Teng et al. 2022)*
  - Identified physical drivers and observational tracers of α_{CO} *(Teng et al. 2023)*
- **Star formation efficiency and stellar feedback**
  - SFE variations across nearby galaxies under new α_{CO} prescriptions *(Teng et al., submitted)* → *arXiv:2310.16037*
  - Systematic study of warm H_2 and stellar feedback in galaxy centers *(Teng et al., in prep)*

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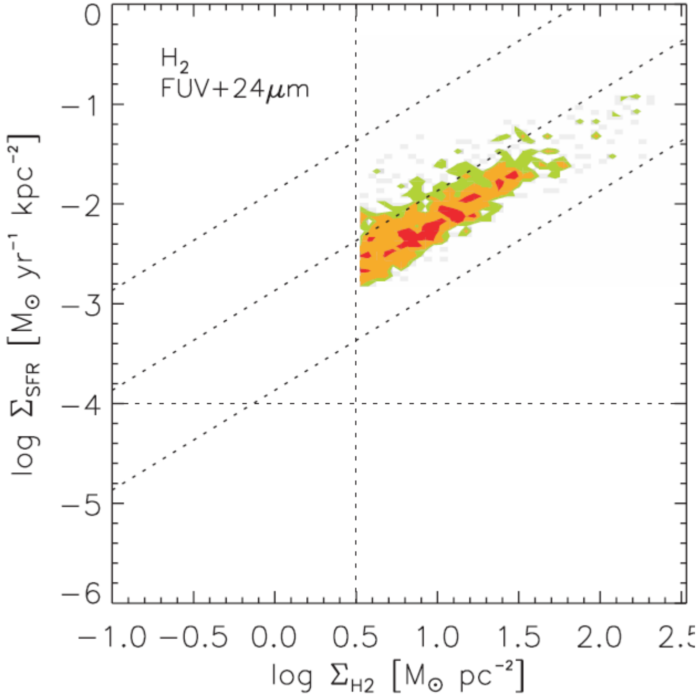
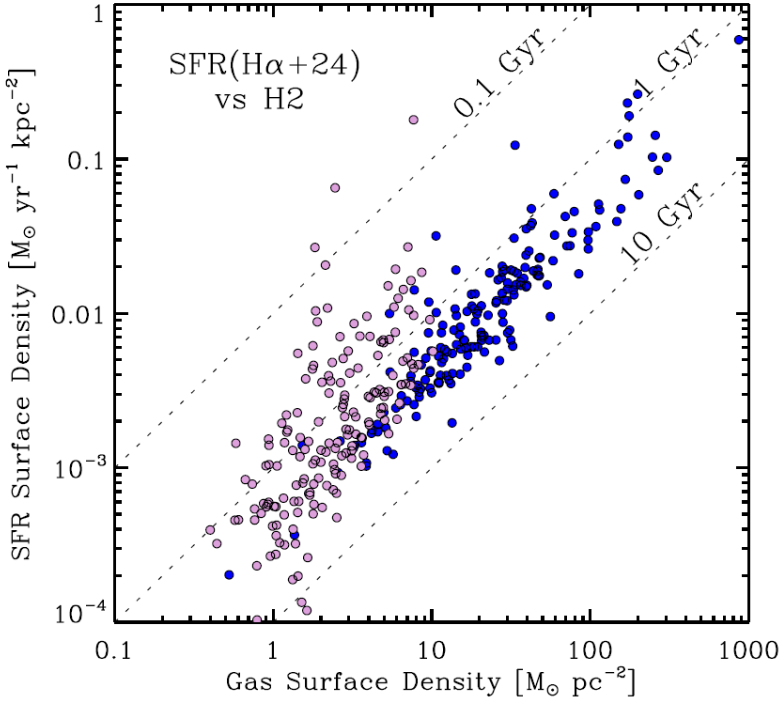
Motivation

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

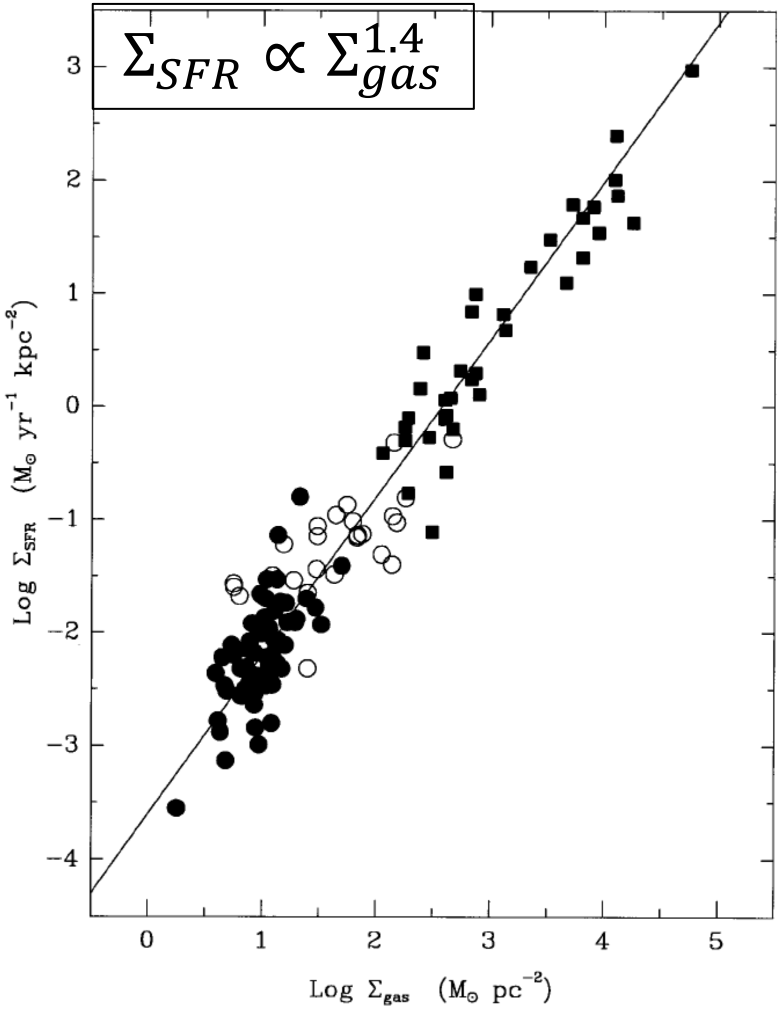
(Bigiel+ 2008)



(Schruba+ 2011)



(Kennicutt 1998)



$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.4}$$

Tracing molecular gas

- Molecular gas mass measurement: convert CO emission to total H_2

  → **CO-to-H_2 conversion factor** $\boldsymbol{\alpha_{\mathrm{CO}} \equiv \frac{M_{\mathrm{mol}}}{L_{\mathrm{CO(1-0)}}} = \frac{\Sigma_{\mathrm{mol}}}{I_{\mathrm{CO(1-0)}}} \left(\frac{\mathrm{M_\odot}}{\mathrm{K\,km\,s^{-1}\,pc^2}}\right)}$

  - Empirical mass-to-light ratio, with $\alpha_{\mathrm{CO}} \sim 4.4$ in MW disk

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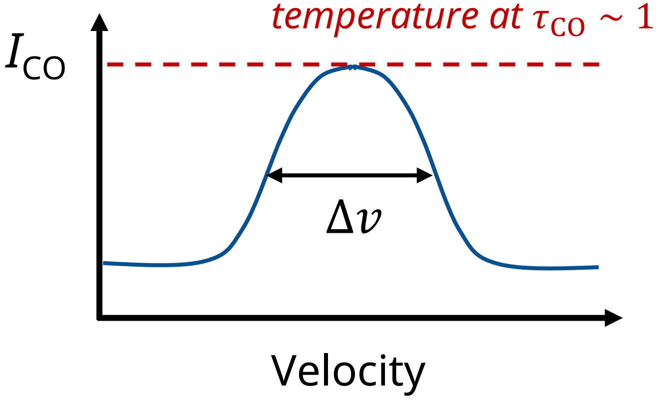
  - Empirical mass-to-light ratio, with $\alpha_{\mathrm{CO}} \sim 4.4$ in MW disk
- But $\boldsymbol{\alpha_{\mathrm{CO}}}$ **varies with molecular gas properties**!
  - metallicity, CO/H_2 abundance
  - density, temperature & velocity dispersion
    - low-*J* CO lines are usually **optically thick**!

    →escaped CO emission due to high velocity dispersion

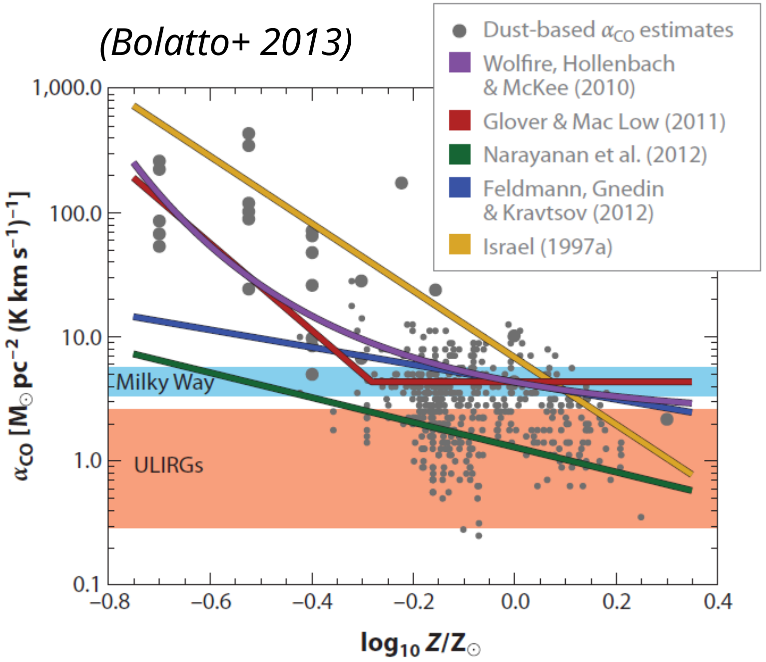


Peak is set by the temperature at $\tau_{\mathrm{CO}} \sim 1$

Regions with different $\alpha_{\mathbf{CO}}$

- 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

(Bolatto+ 2013)



Regions with different α_{CO}

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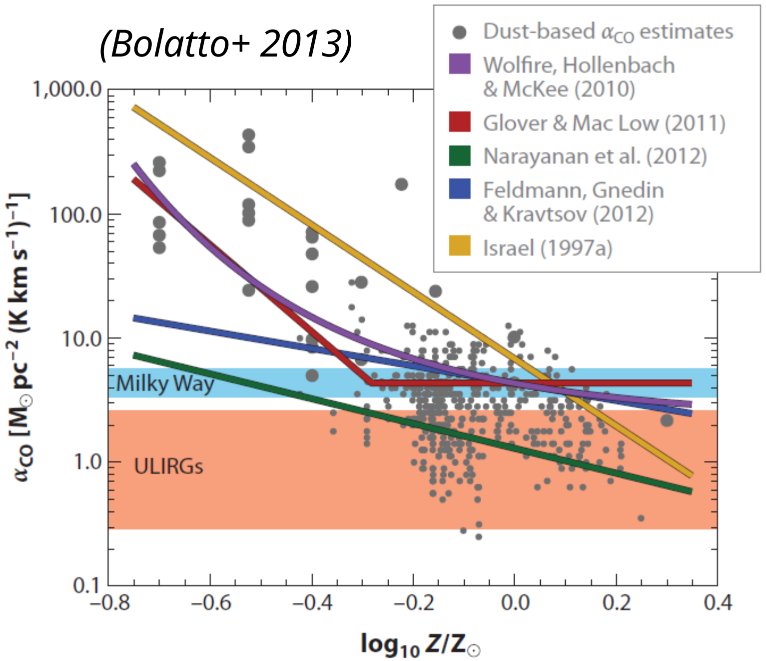
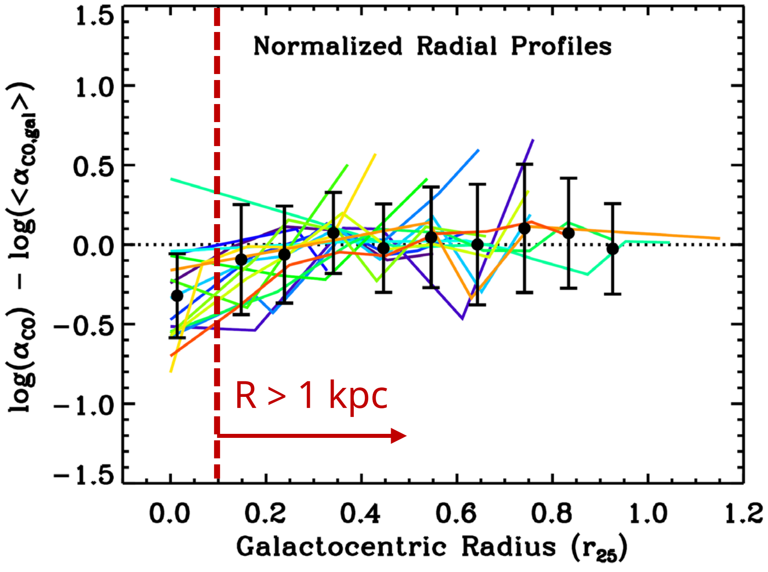
- Galaxy centers
  - α_{CO} in our Galactic Center is 3–10x lower than in the disk
  - ~10x lower α_{CO} found in many **normal galaxy centers**
    - gas concentrations driven by bars and/or spiral arms?
    - higher excitation, turbulence, and/or dynamical process?

    → **emissivity**-dependent terms are important!

(Bolatto+ 2013)



(Sandstrom+ 2013)



Why is $\boldsymbol{\alpha}_{\mathbf{CO}}$ important?

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

→ **$\boldsymbol{\alpha}_{\mathbf{CO}}$ directly impacts star formation properties**

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

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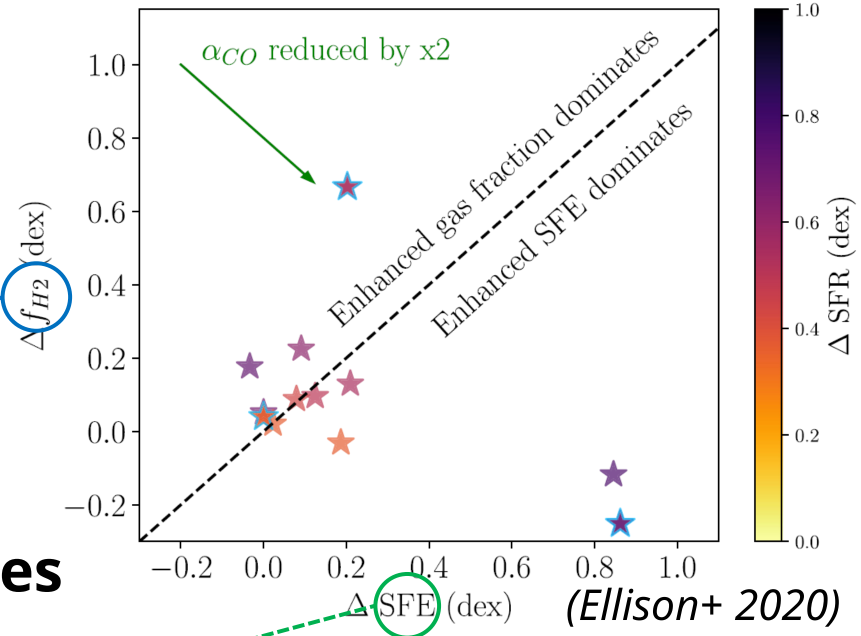

(Ellison+ 2020)

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Why is α_{CO} important?

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- Tied to physical conditions of molecular gas

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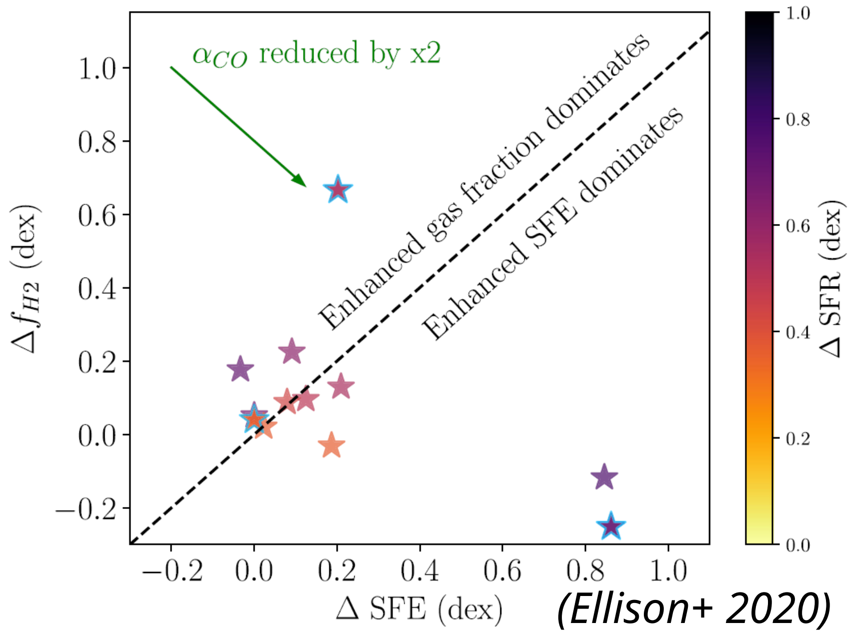

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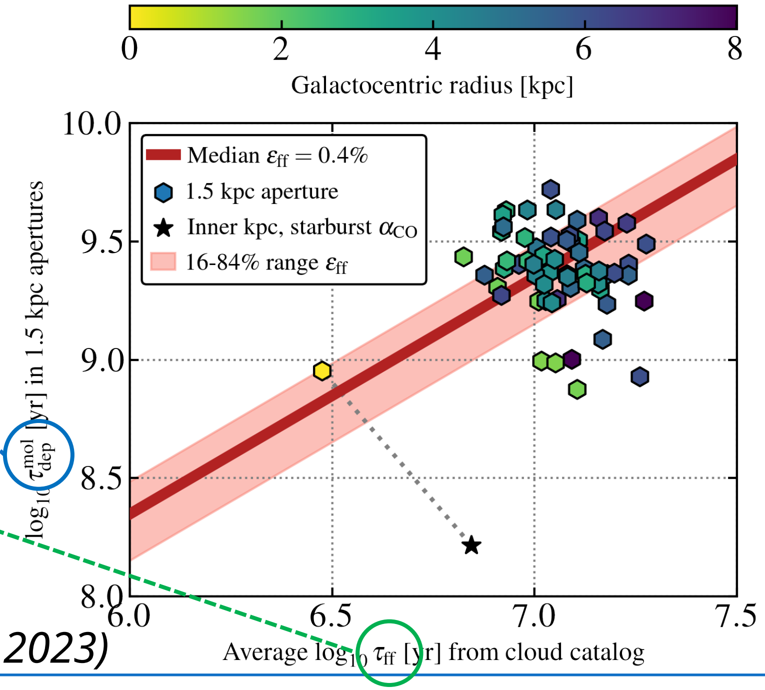

(Querejeta+ 2023)

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

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

Optically thin tracers

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

Gamma-ray emission

- Traces collisions/scattering between cosmic ray and interstellar matter

Virial methods

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

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

- Assumes a constant star formation efficiency

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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

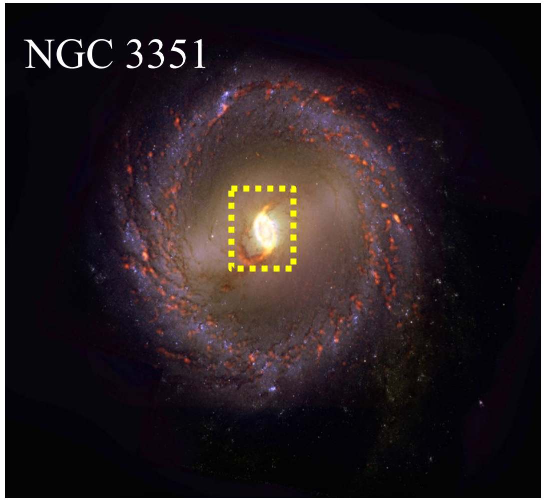
Kennicutt-Schmidt relation – infer Σ_{mol} from the measured Σ_{SFR}

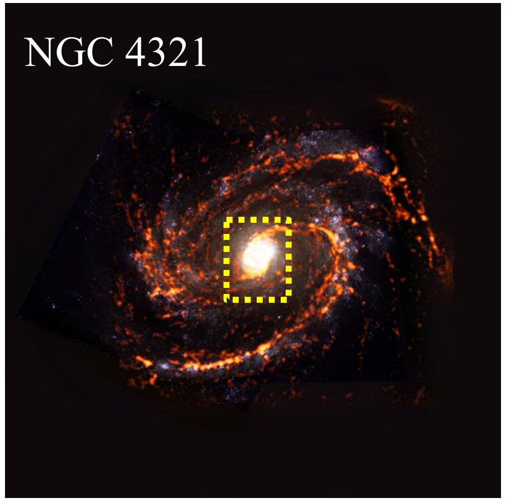
- Assumes a constant star formation efficiency → still under debate

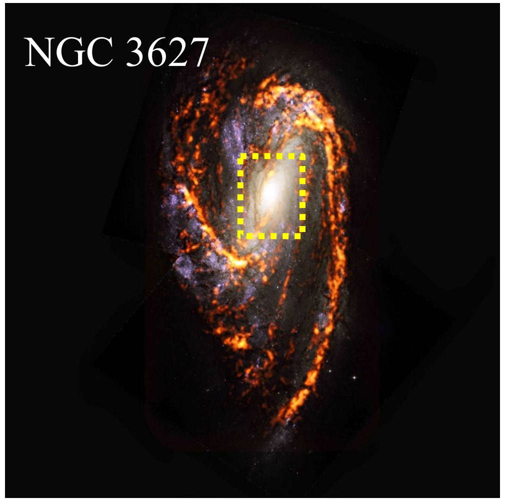
ALMA multi-line observations

- NGC 3351, NGC 3627, NGC 4321
  → nearby **barred spiral galaxies** with **low $\boldsymbol{\alpha_{\mathrm{CO}}}$** 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)







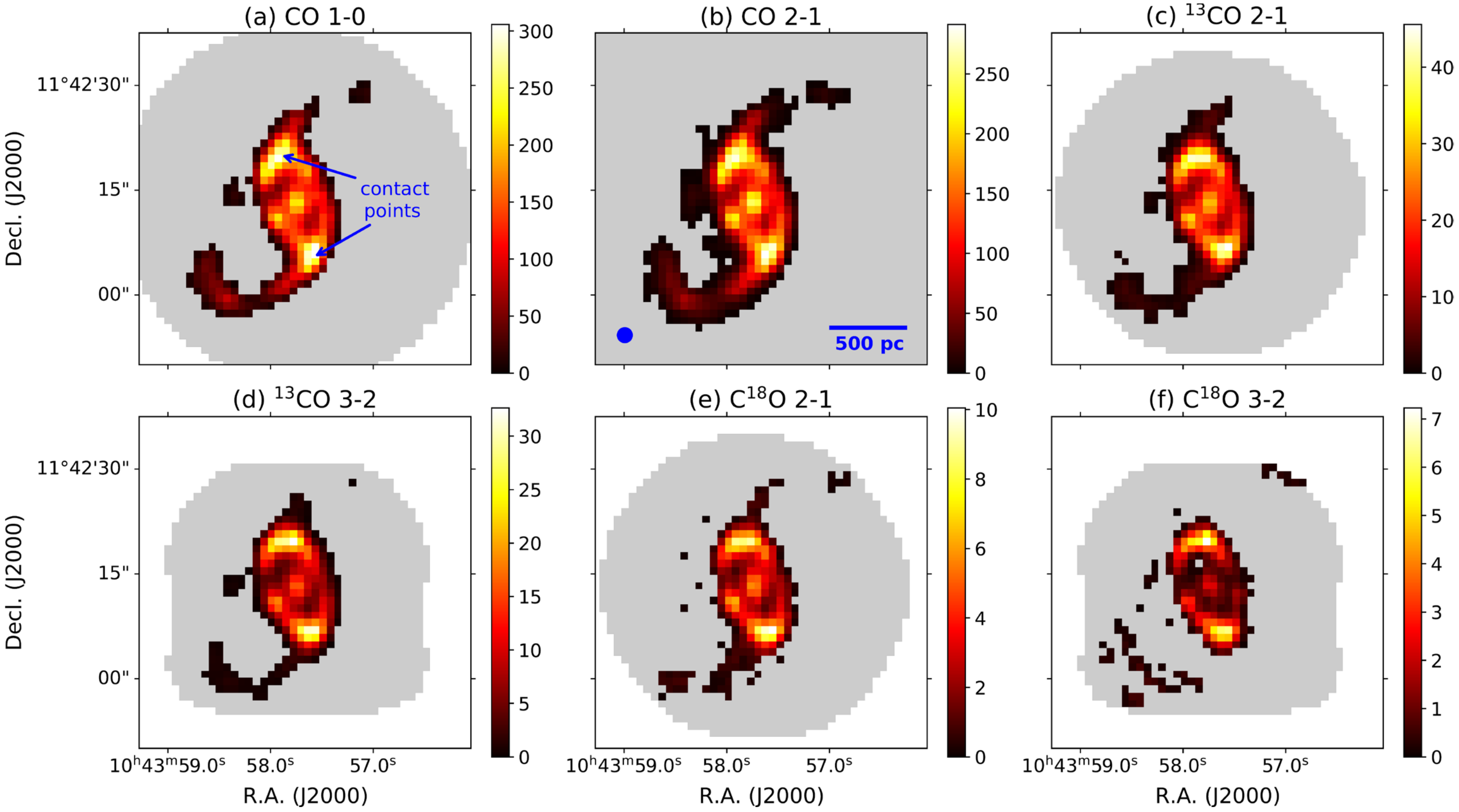
(PHANGS–ALMA+HST)

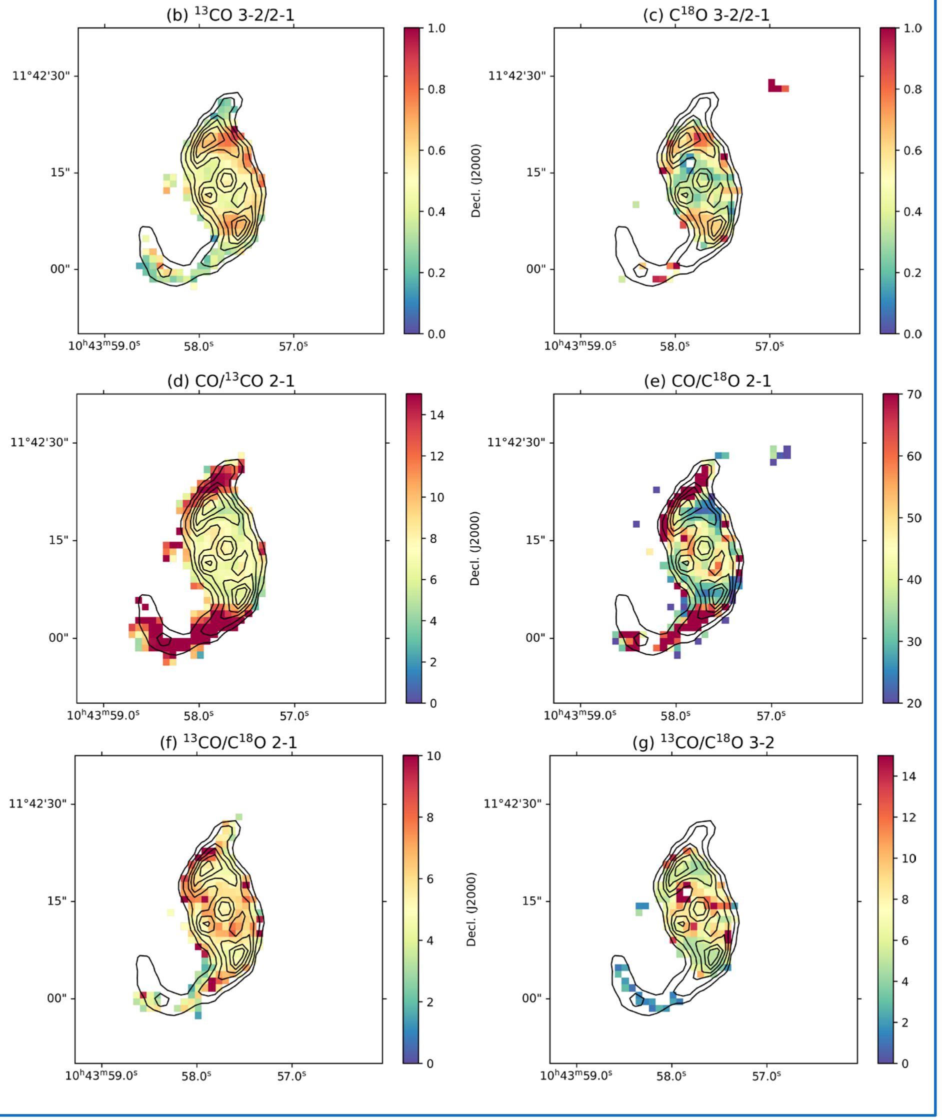
NGC 3351

Line ratios

Moment 0 maps

(Teng+ 2022)





NGC 3351

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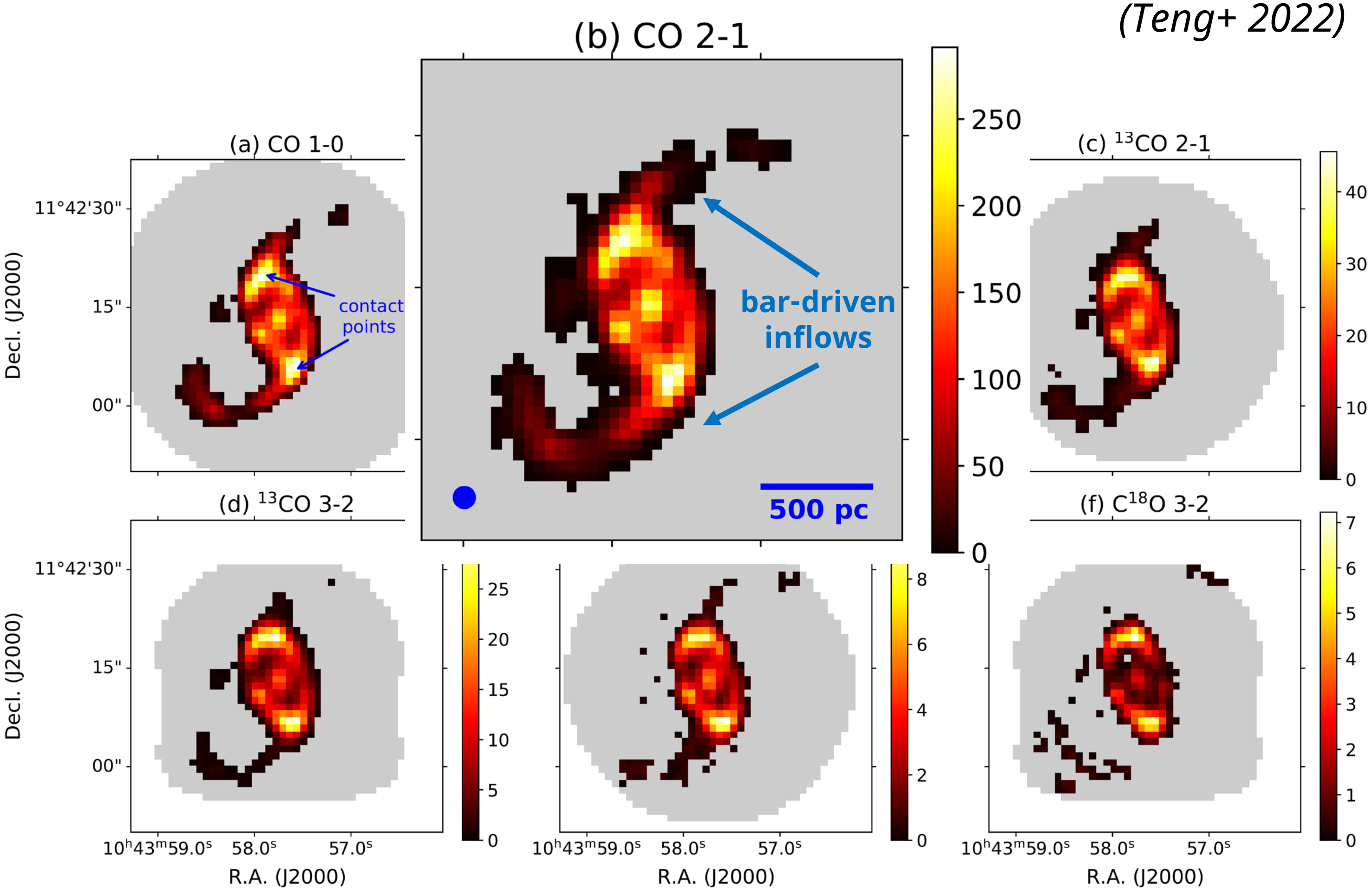

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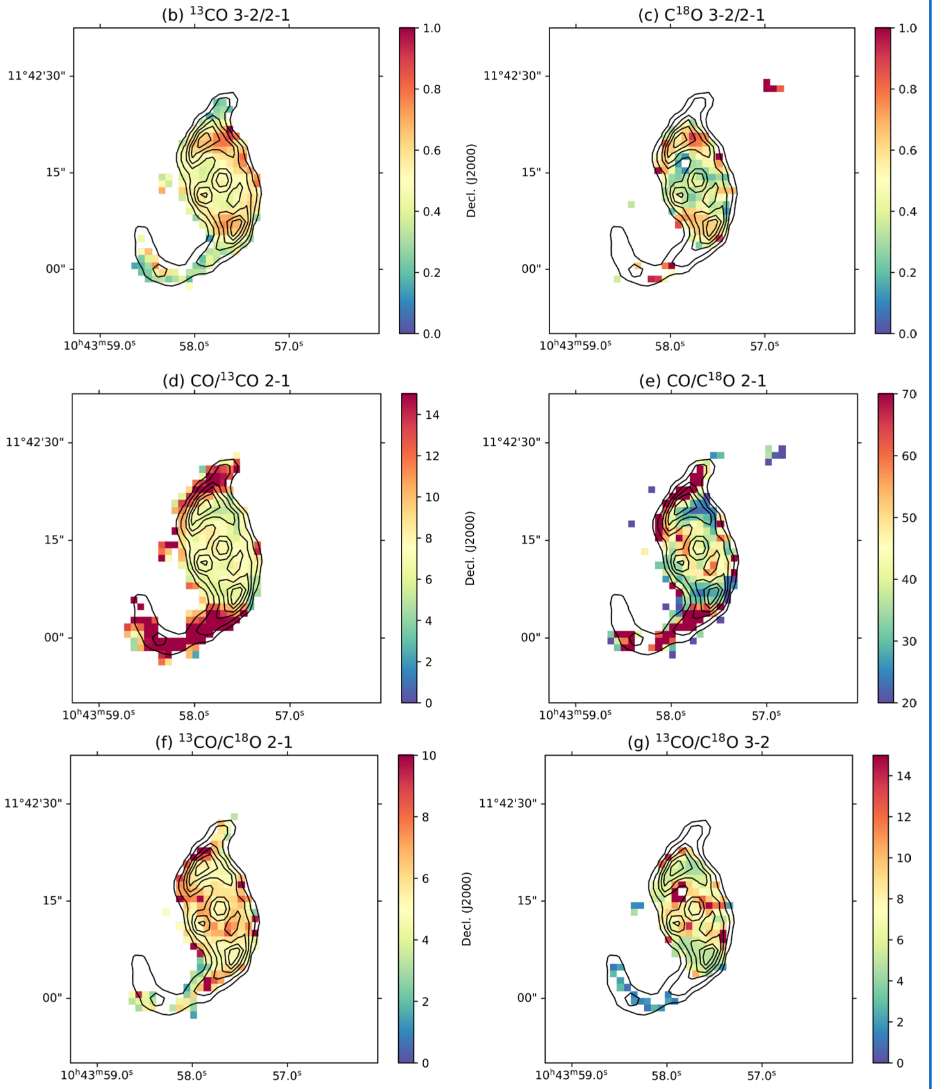

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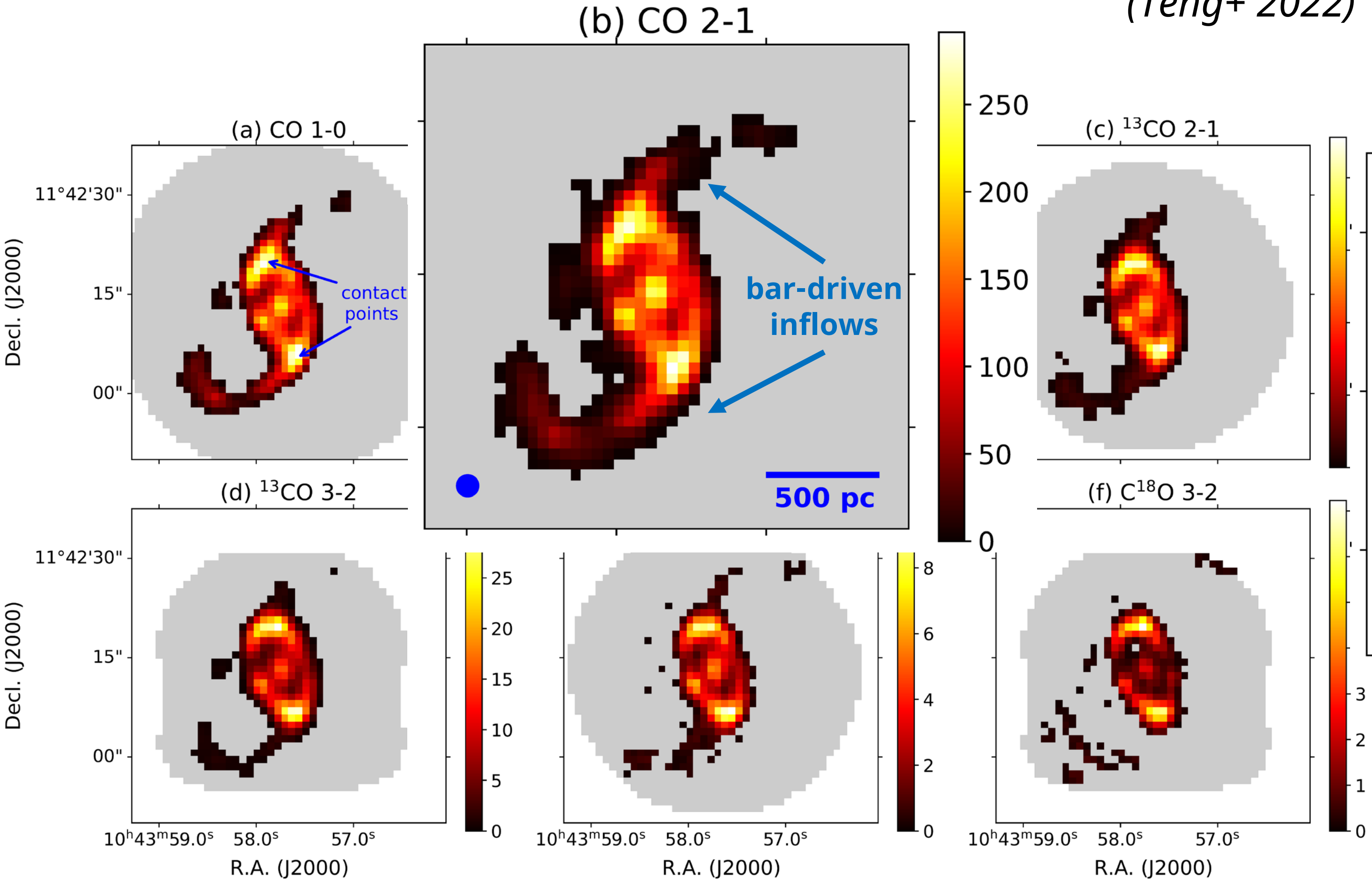

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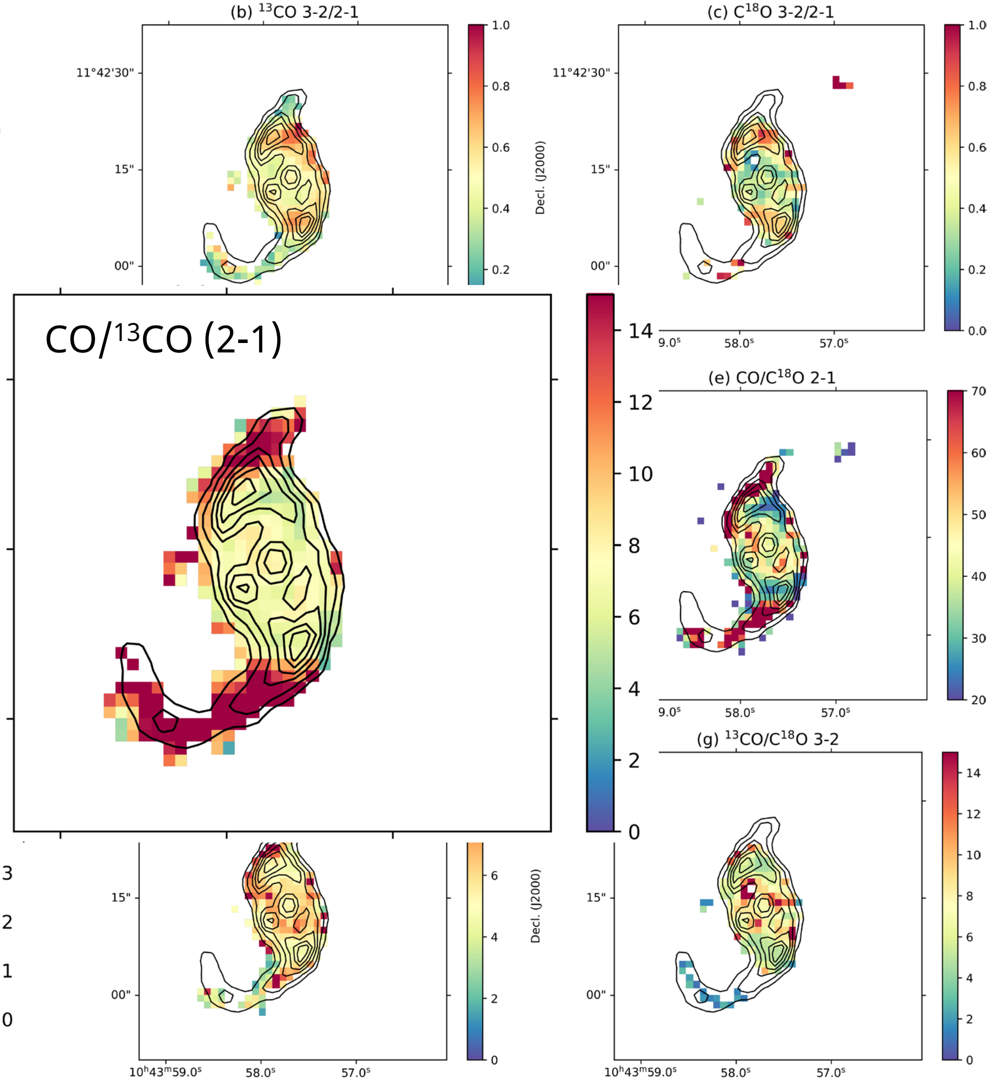
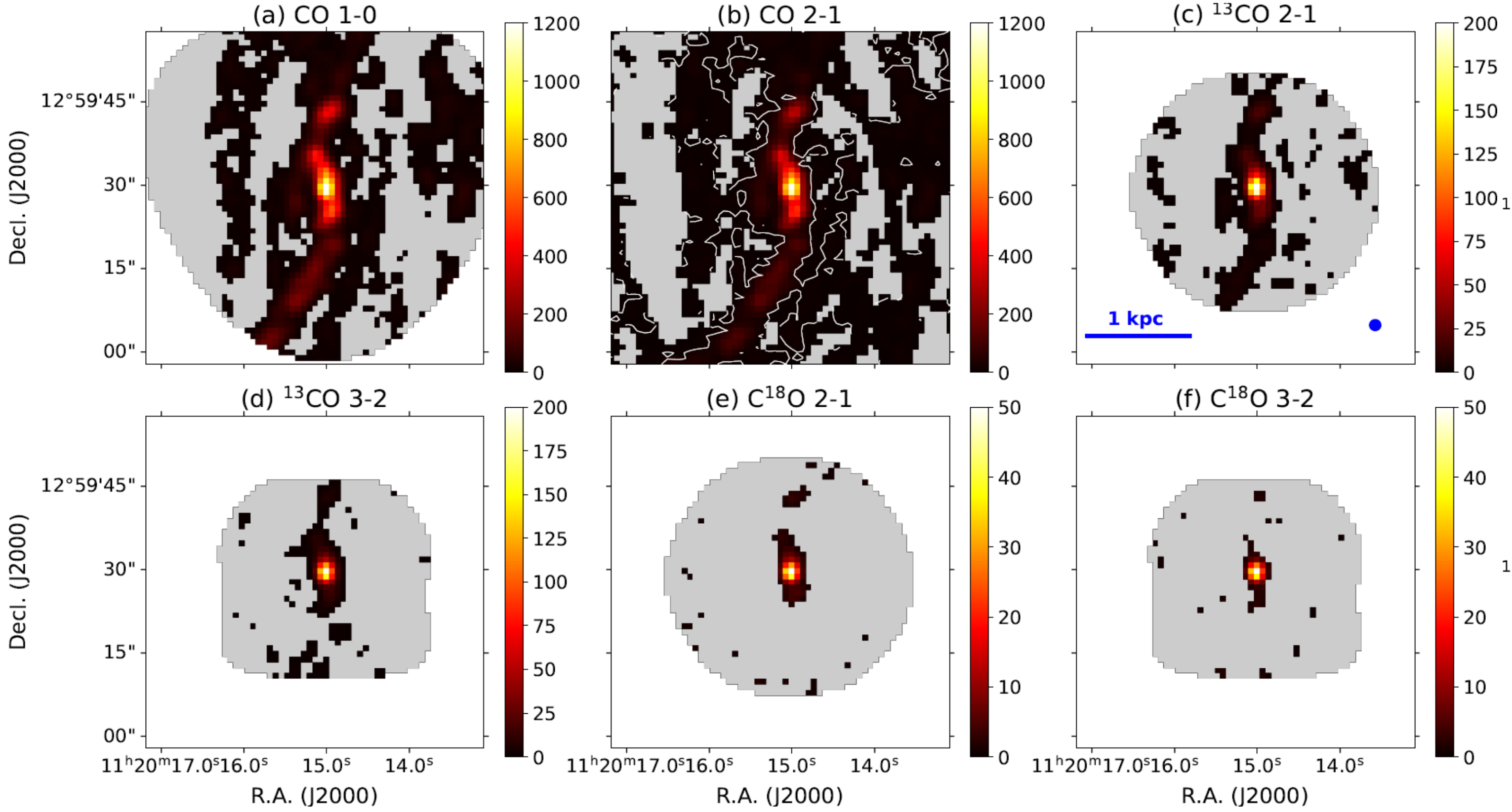


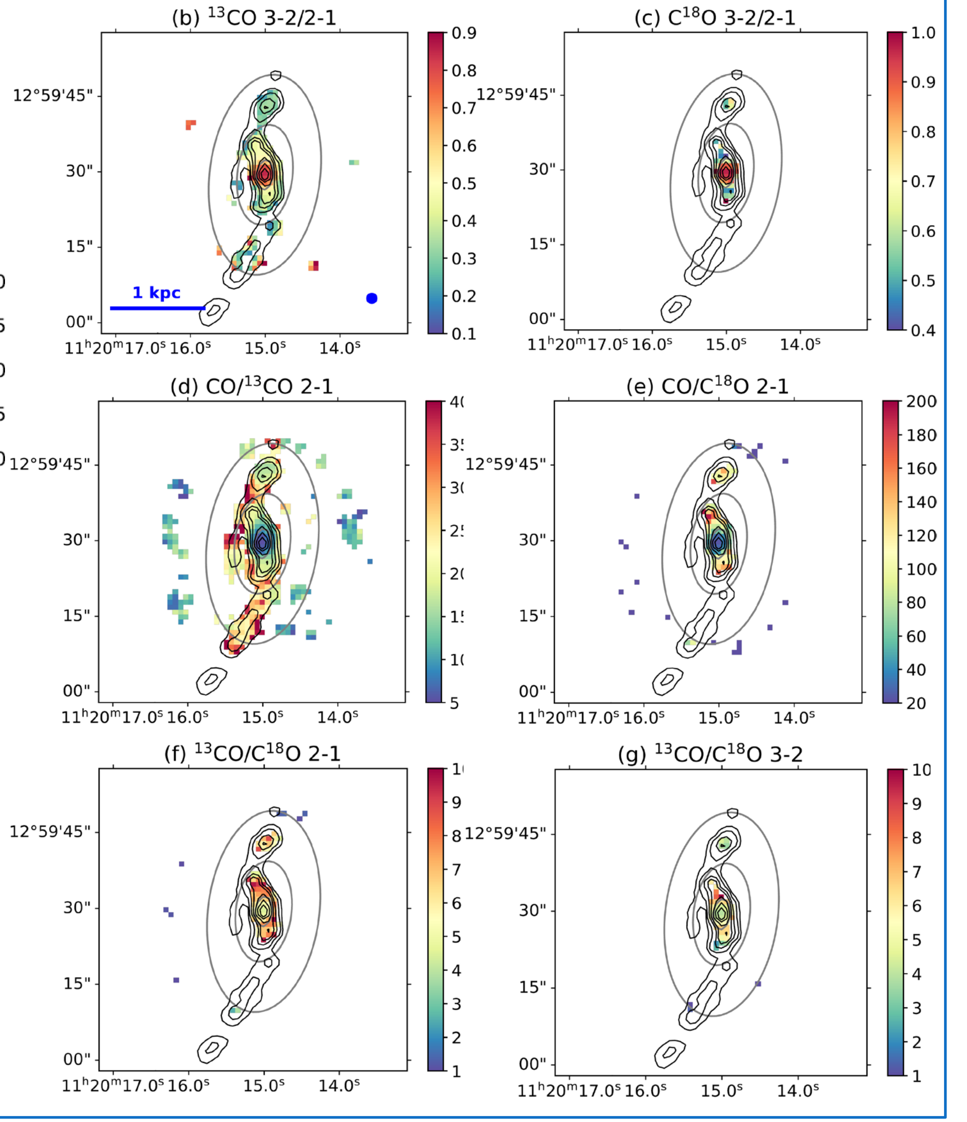
NGC 3627

Line ratios

(Teng+ 2023)

Moment 0 maps

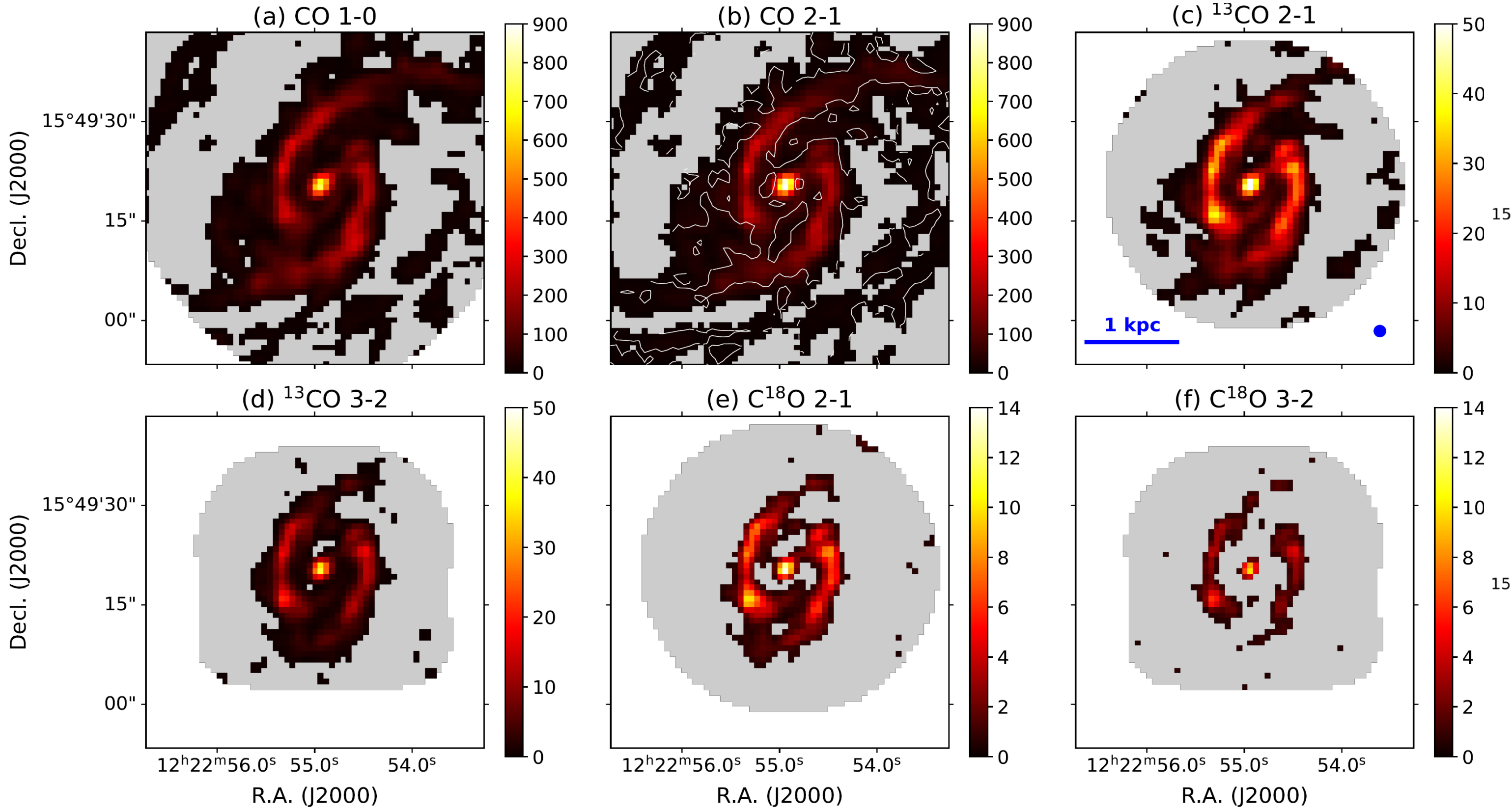




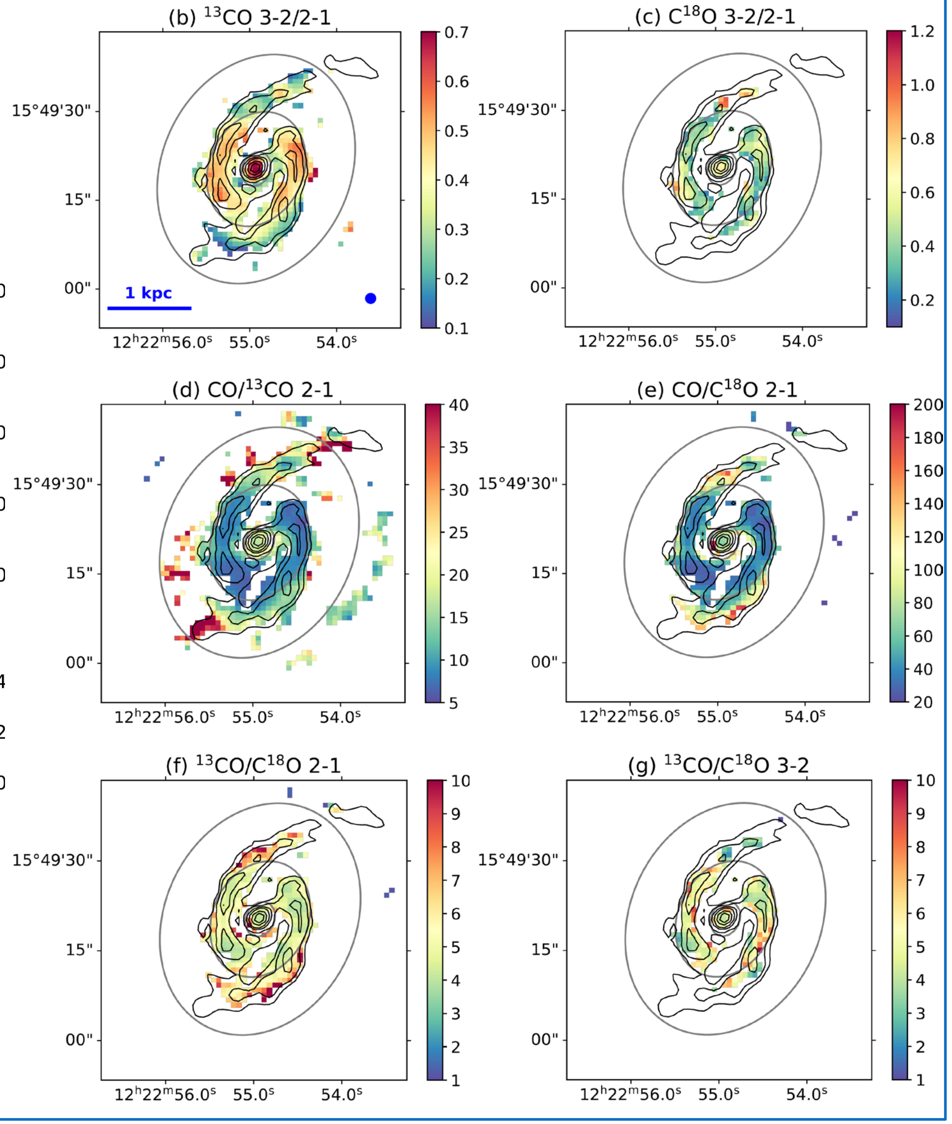
NGC 4321

Moment 0 maps

(Teng+ 2023)

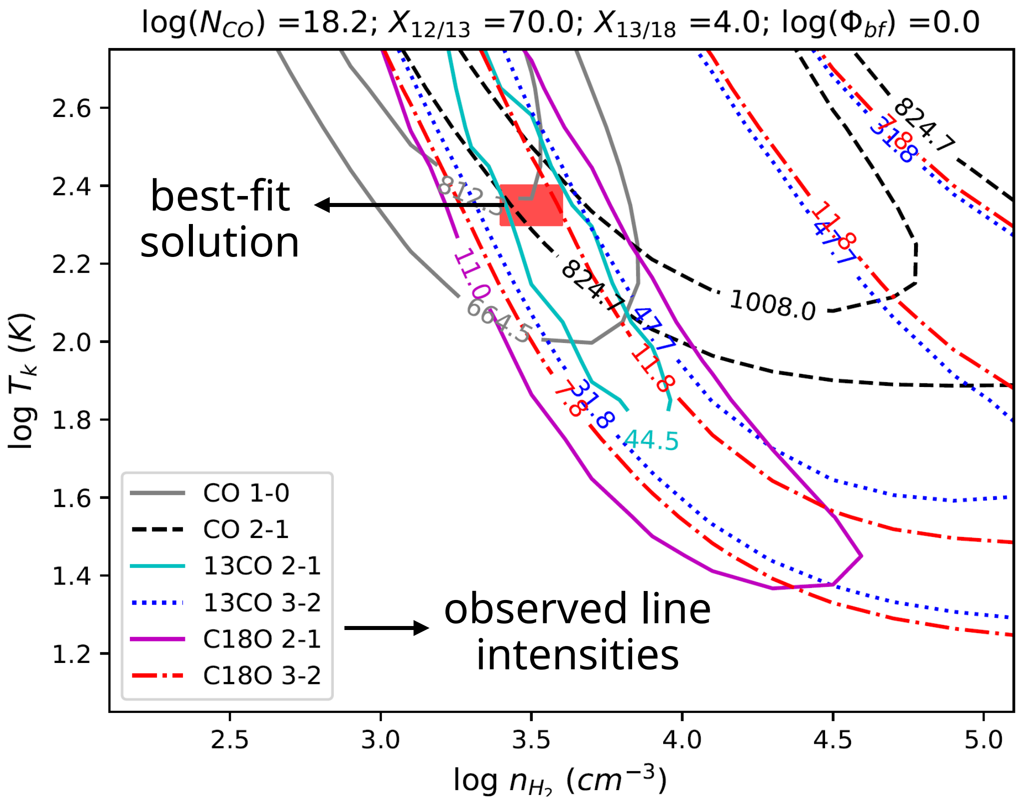


Line ratios



Multi-line modeling

non-LTE radiative transfer + Bayesian likelihoods



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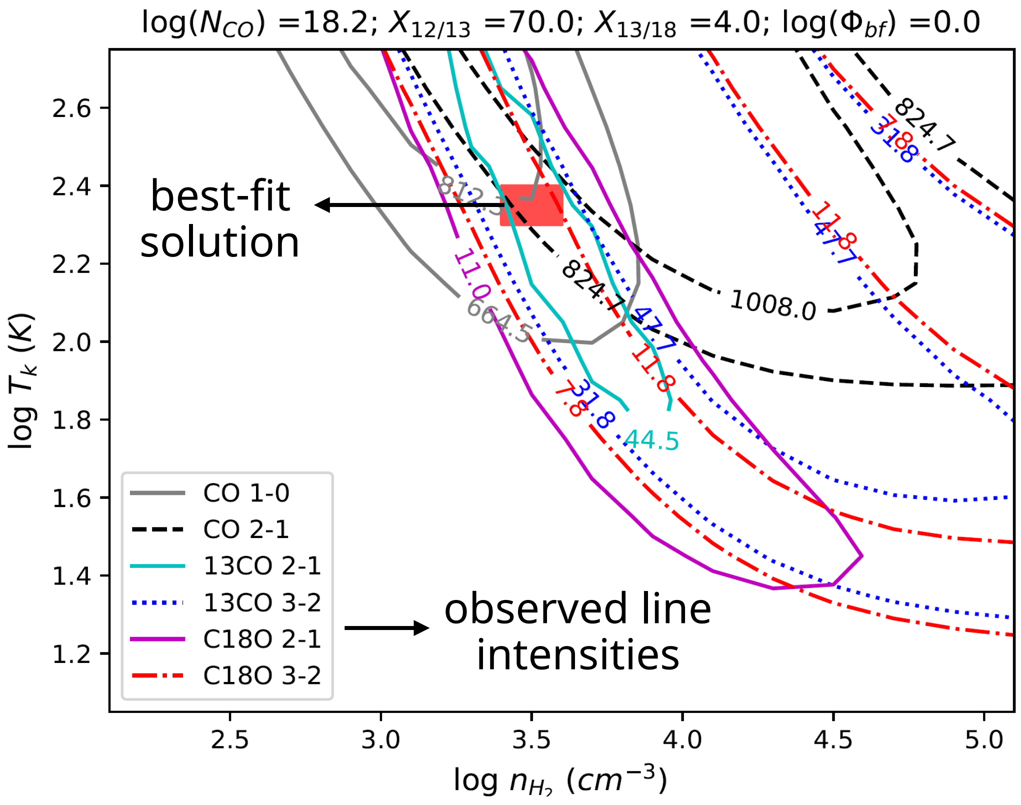
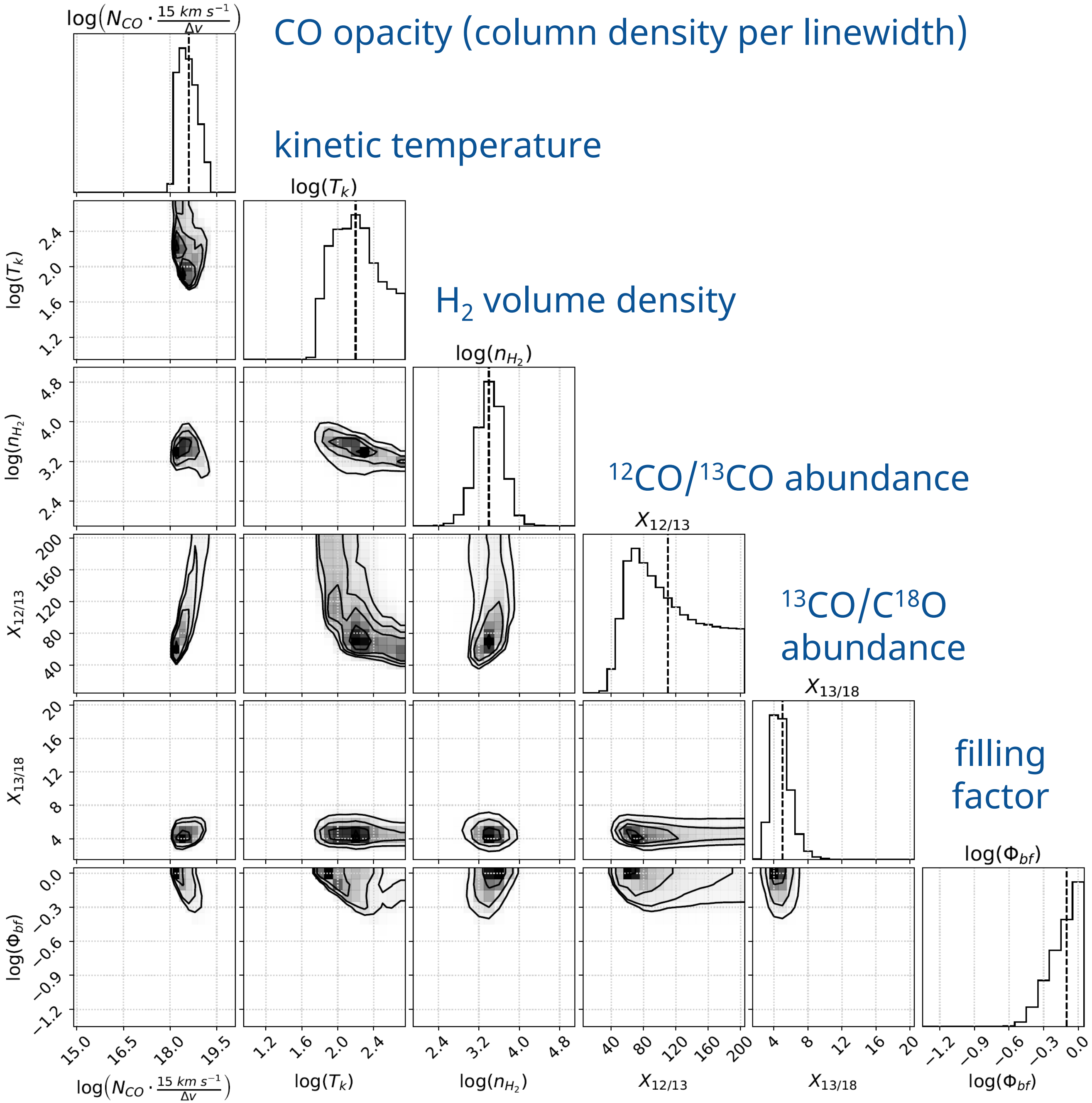


best-fit solution

observed line intensities



CO opacity (column density per linewidth)

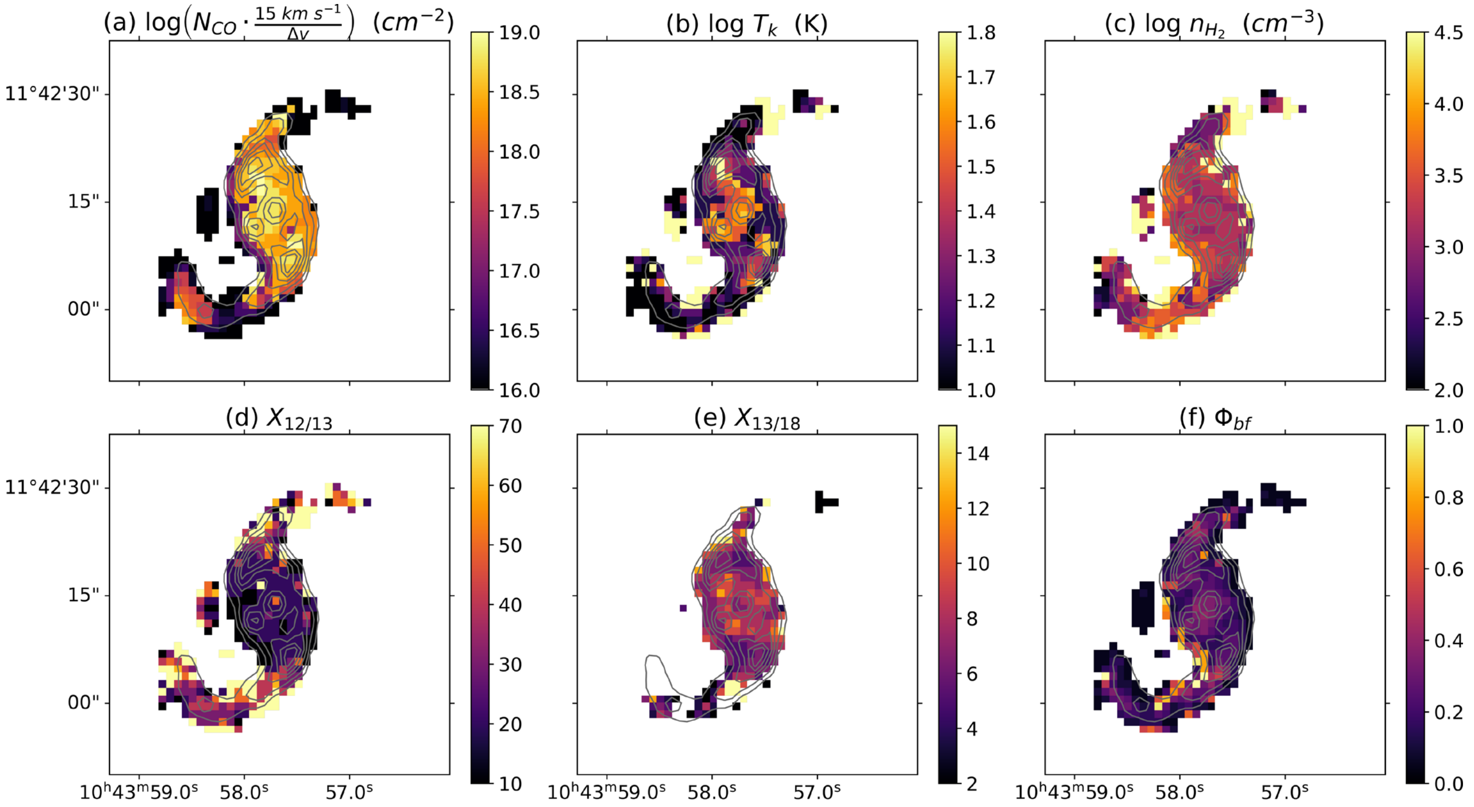
kinetic temperature

H_2 volume density

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

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

filling factor


(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}
11°42'30"
15"
00"
10h43m59.0s
58.0s
57.0s
19.0
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0.2
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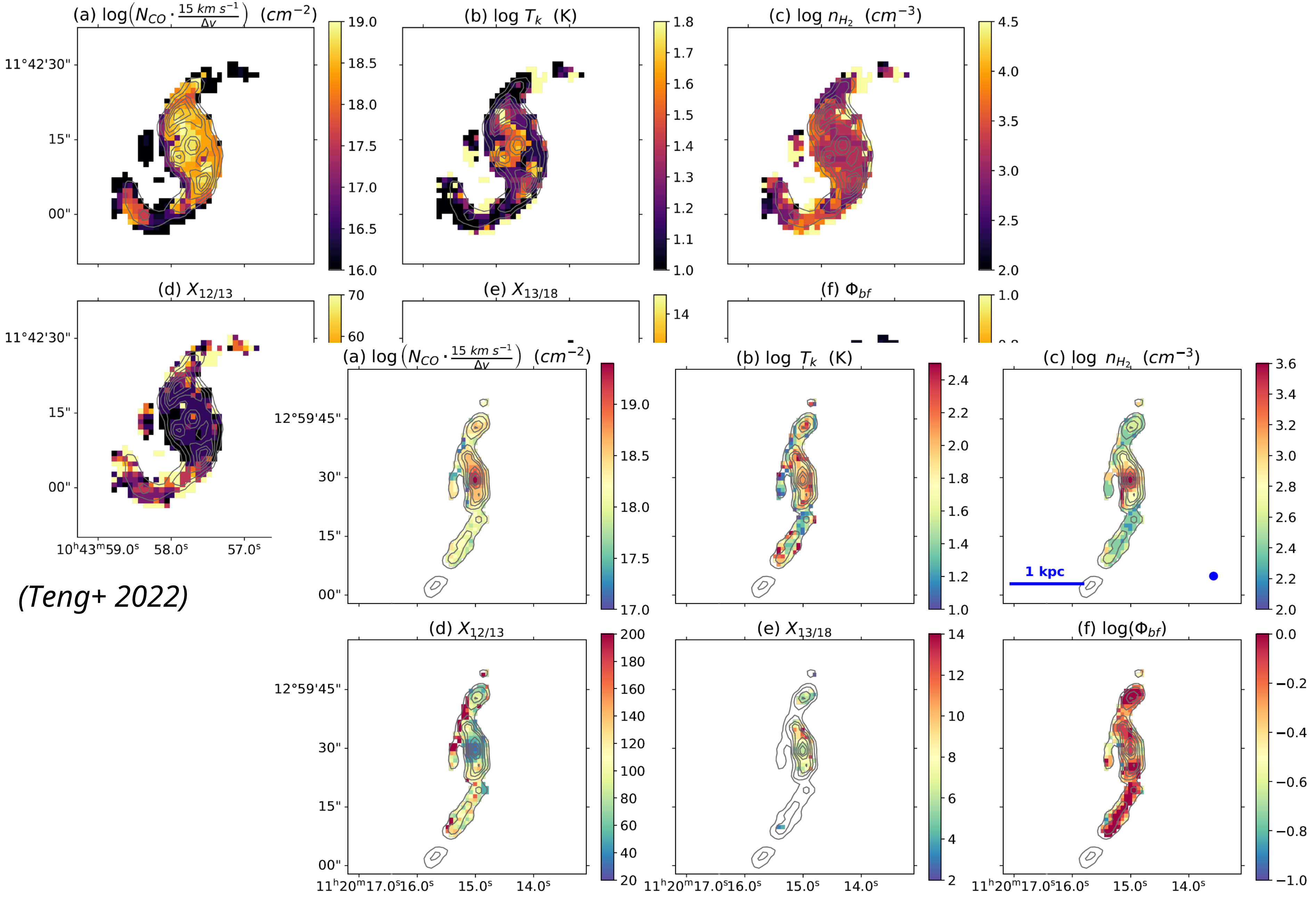
(Teng+ 2022)



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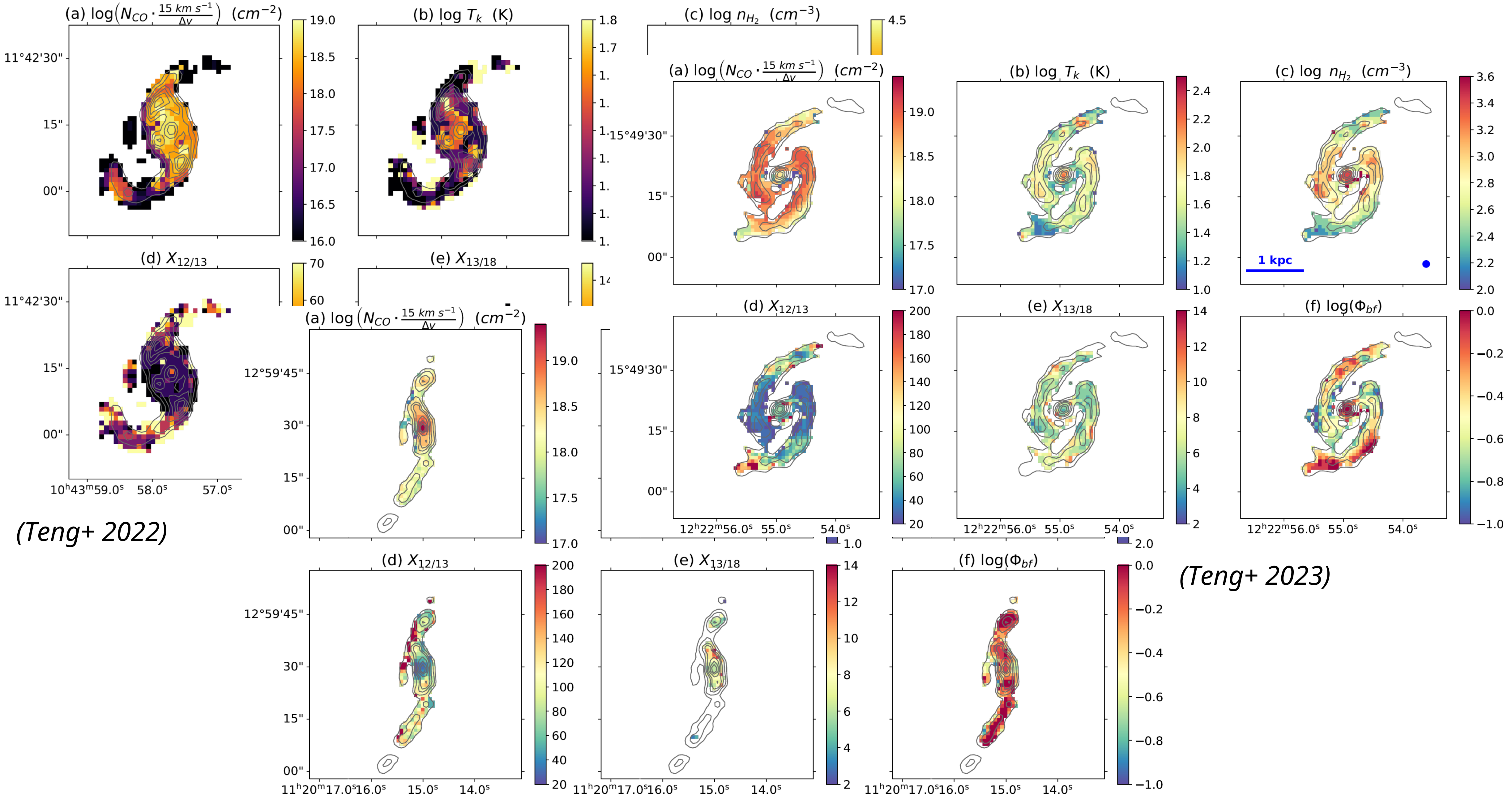

(Teng+ 2022)

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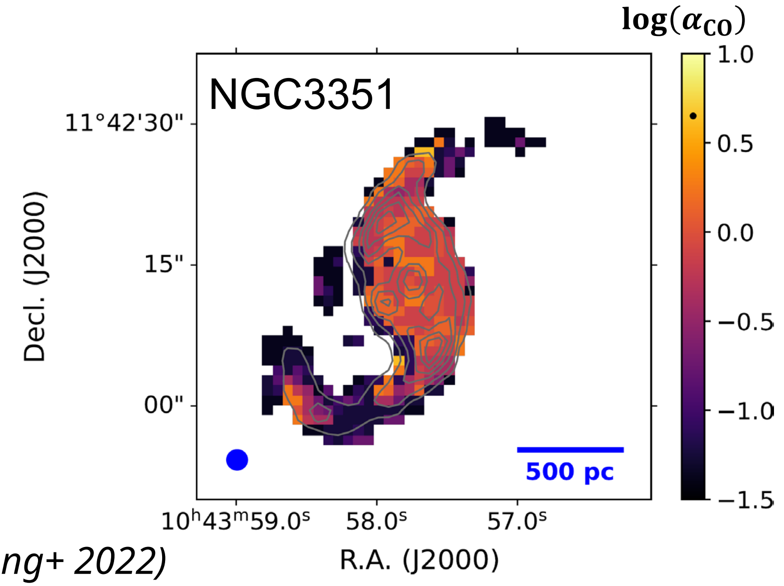
$\alpha_{\rm CO}$ distribution

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

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



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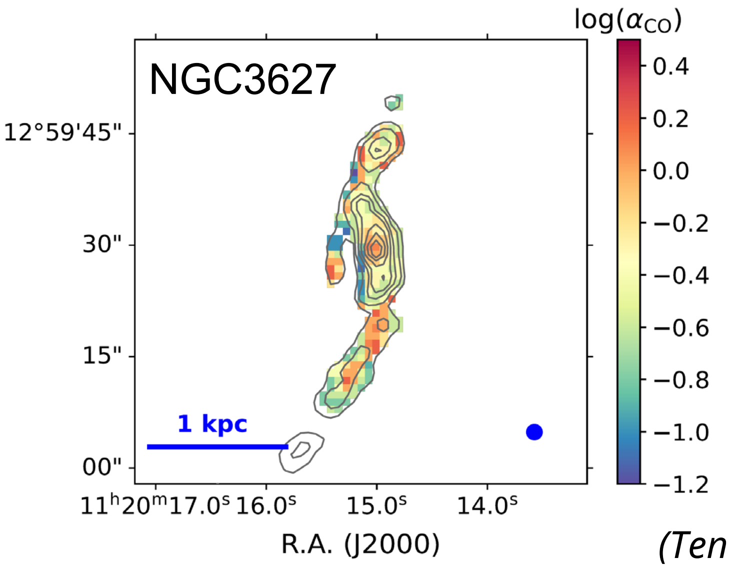

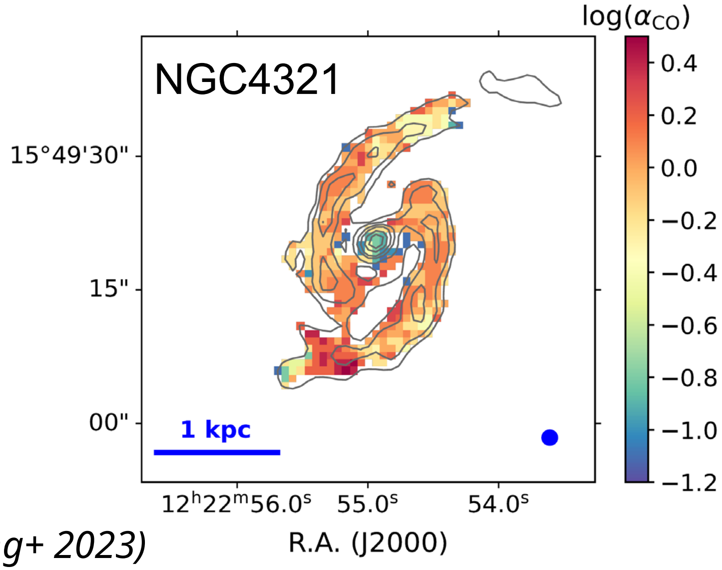

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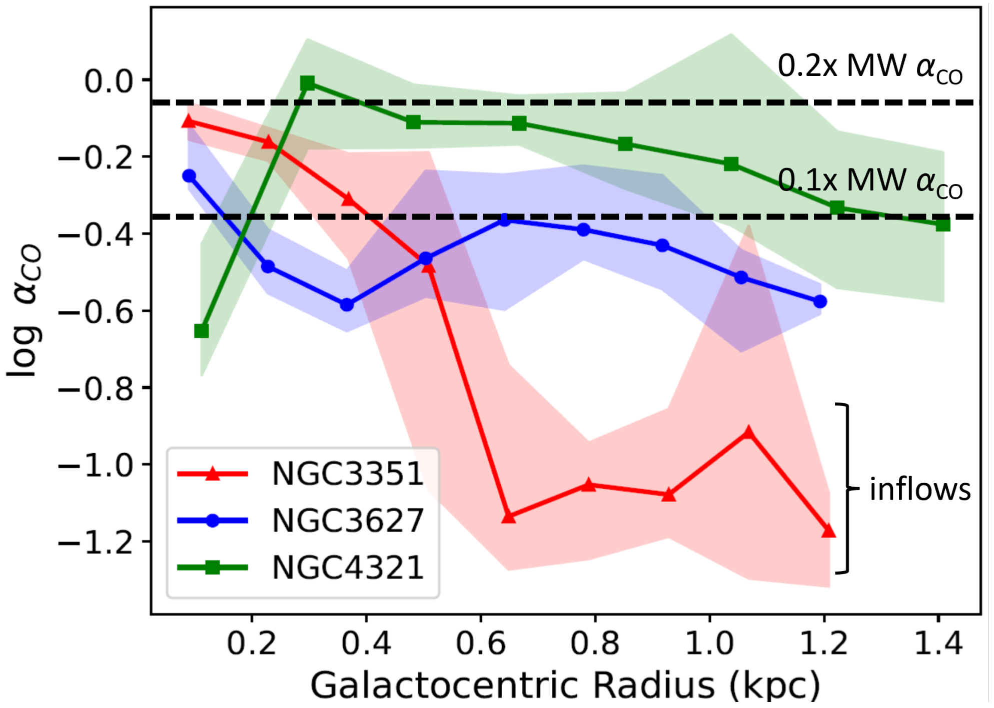
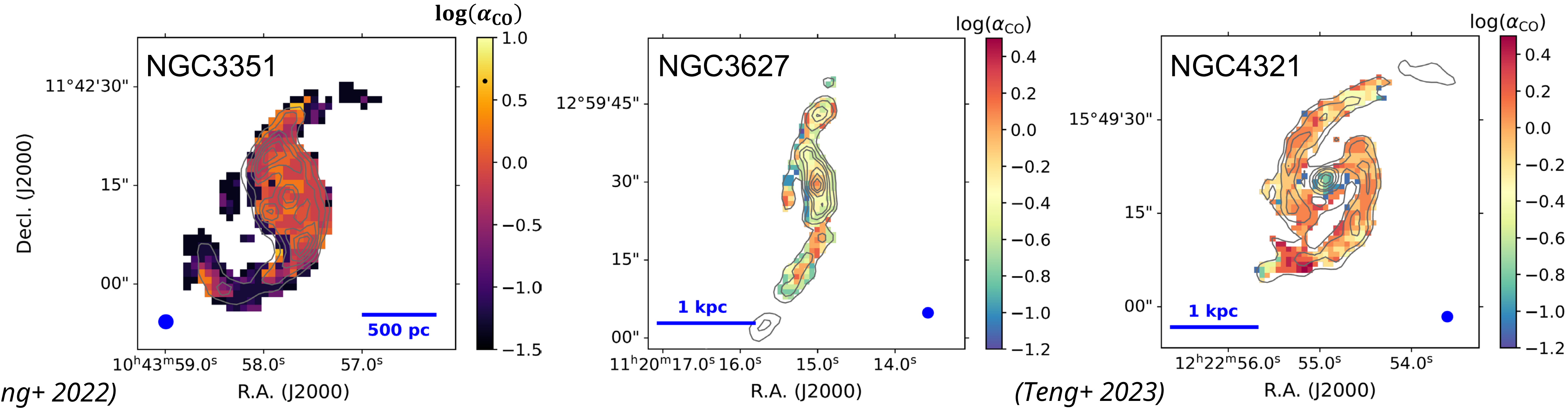




(Teng+ 2022)

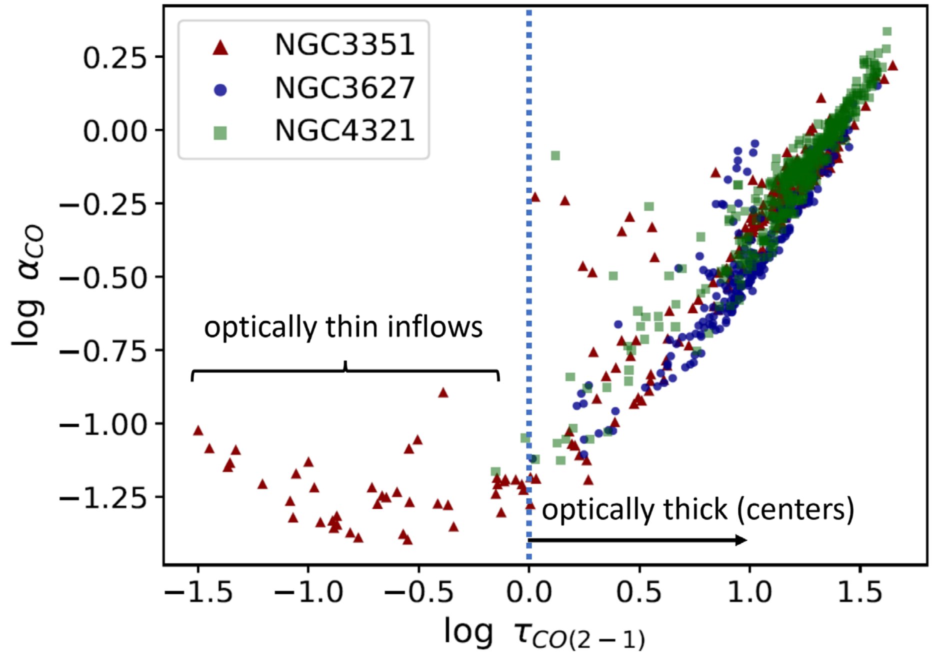
(Teng+ 2023)

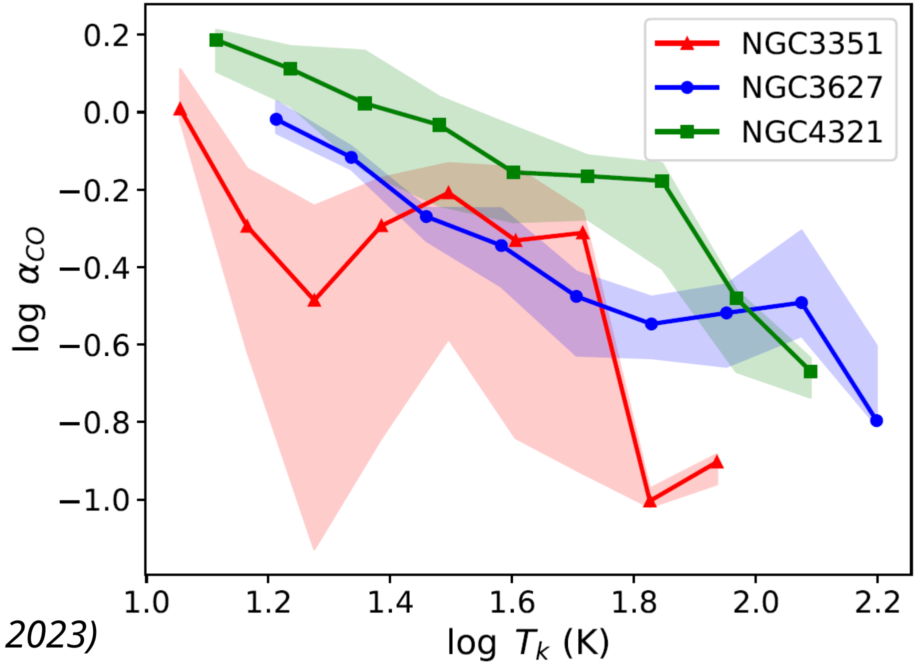
Physical drivers of α_{CO}

- 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%)

→ $$\log\left[\frac{\alpha_{\mathrm{CO}}}{\mathrm{M}_\odot/(\mathrm{K\ km\ s^{-1}\ pc^2})}\right] = 0.78\log[\tau_{\mathrm{CO(2-1)}}] - 0.18\log\left(\frac{T_\mathrm{k}}{\mathrm{K}}\right) - 0.84$$

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

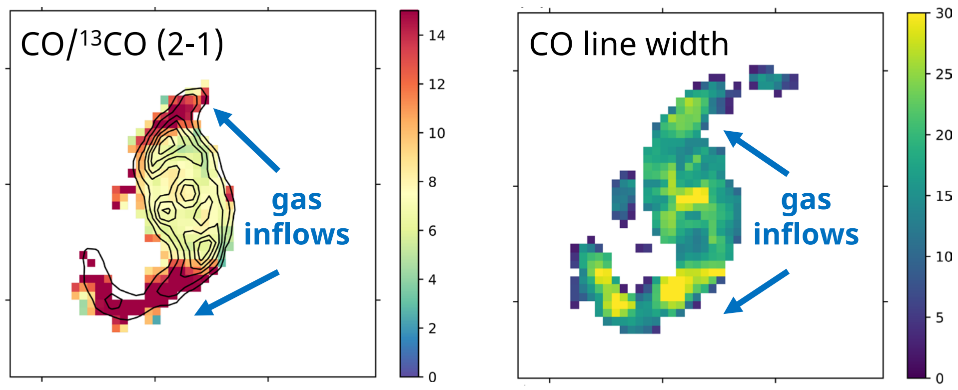




(Teng+ 2023)

Potential α_{CO} tracers

- 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



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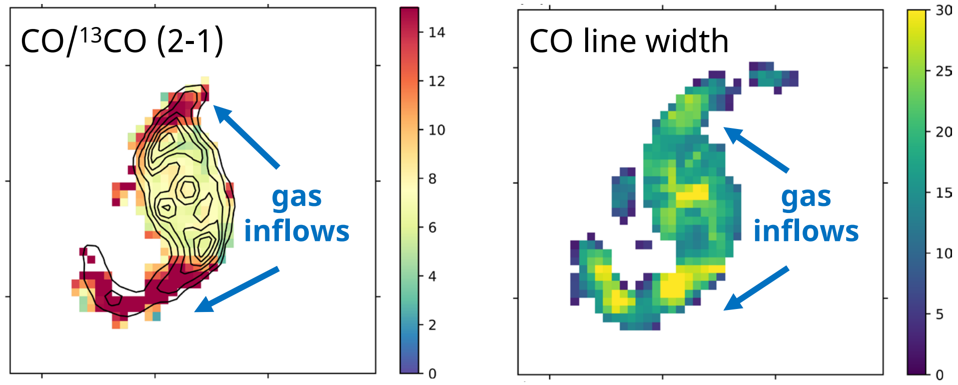
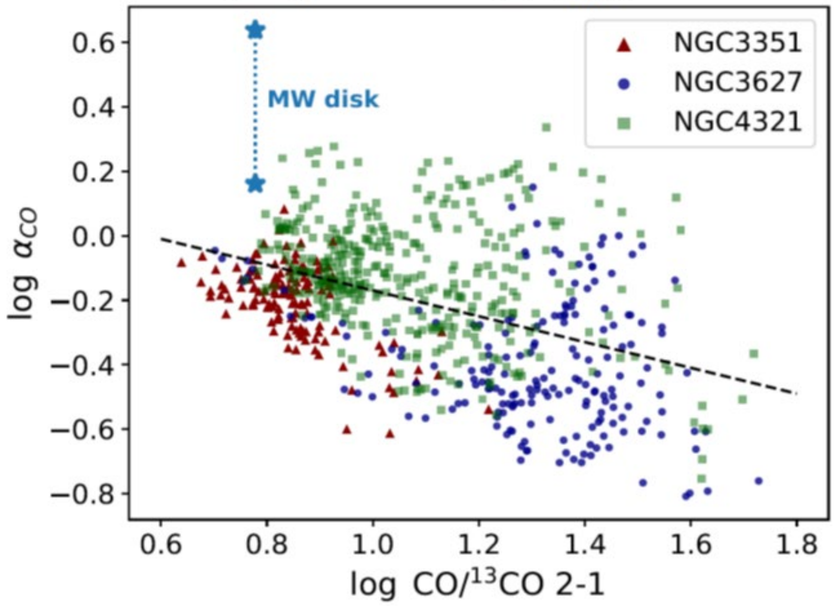


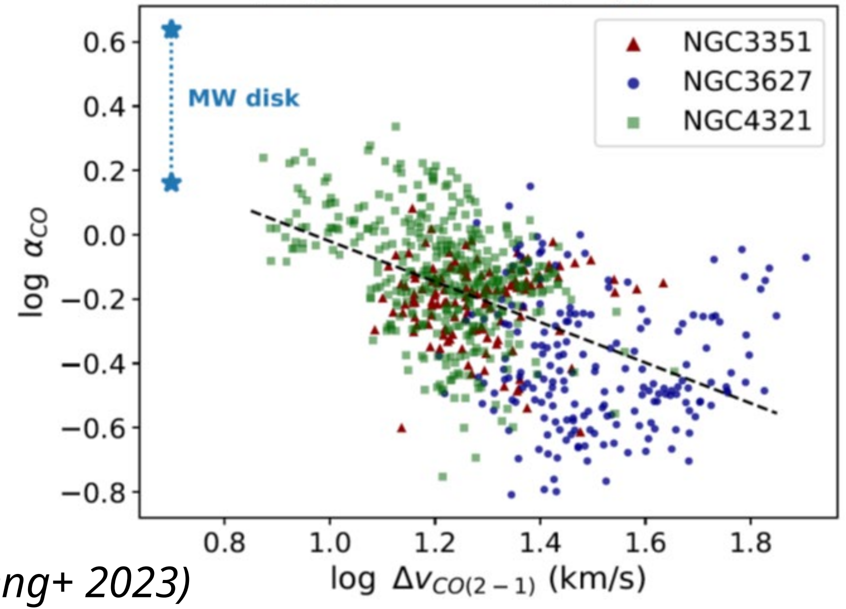
(Teng+ 2022)

- 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 $\tau_{\mathrm{CO}} \propto N_{\mathrm{CO}}/\Delta v$

$$\log(\alpha_{\mathrm{CO}}) = -0.4\log(R_{12/13}) + 0.23$$



$$\log(\alpha_{CO}) = -0.63\log(\Delta v_{\mathrm{CO}}) + 0.61$$

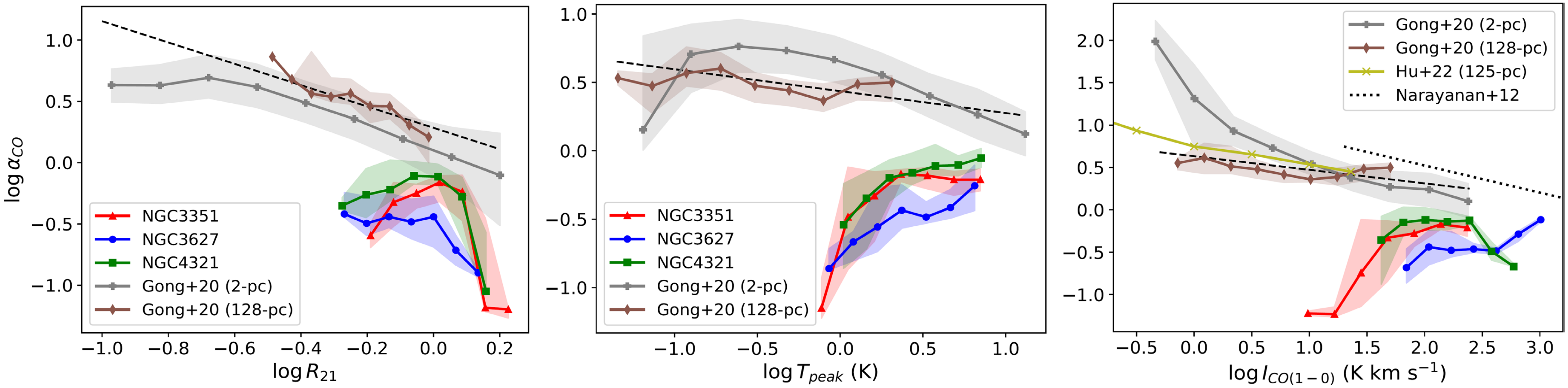


(Teng+ 2023)

Compare with simulations

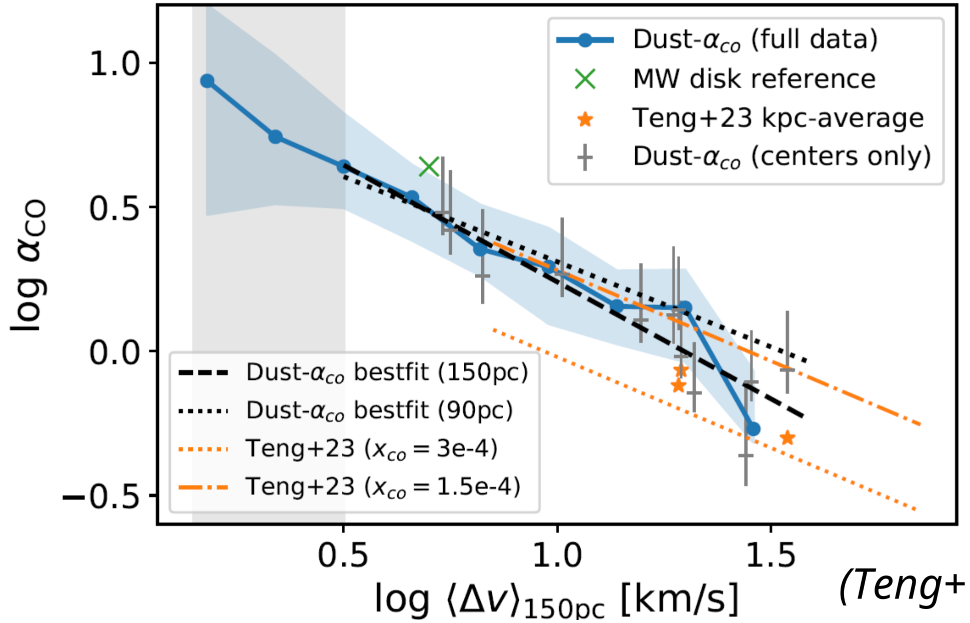
- (M)HD simulation of galaxy/ISM at pc-scales *(Narayanan+ 2012, Gong+ 2020, Hu+ 2022)*
- Focus on Galactic disk-like or low metallicity environments
- Overestimate α_{CO} in galaxy centers
  → Gas inflows & turbulence effects are important!

(Teng+ 2023)



A new Δv-based α_{CO} prescription

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



(Teng+ submitted)

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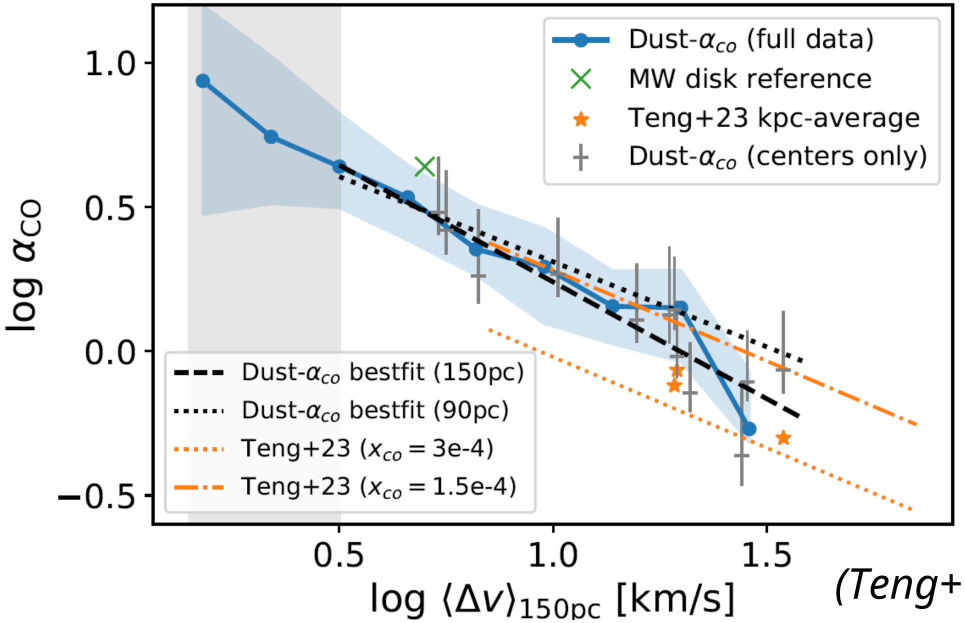
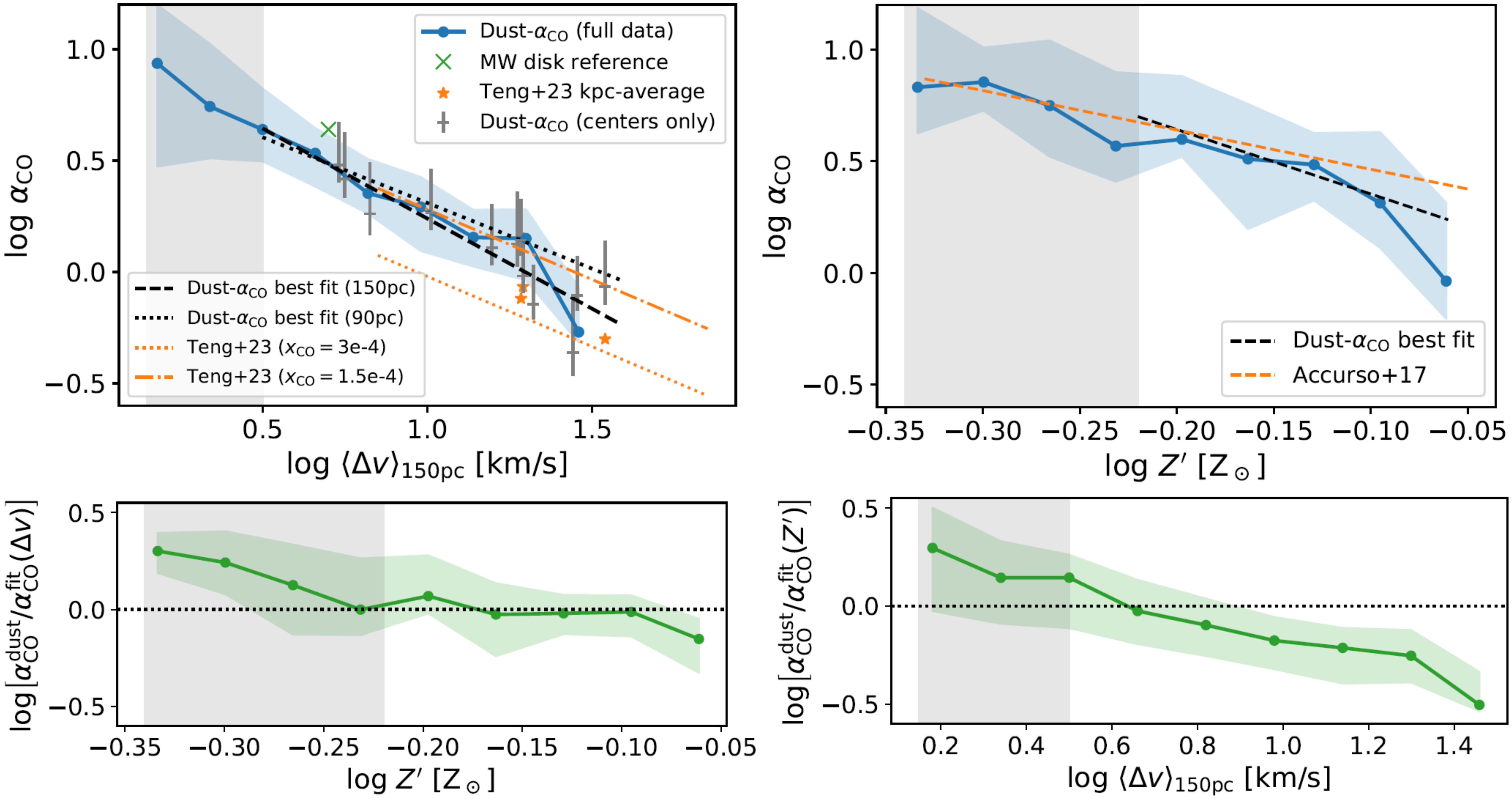


(Teng+ submitted)

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

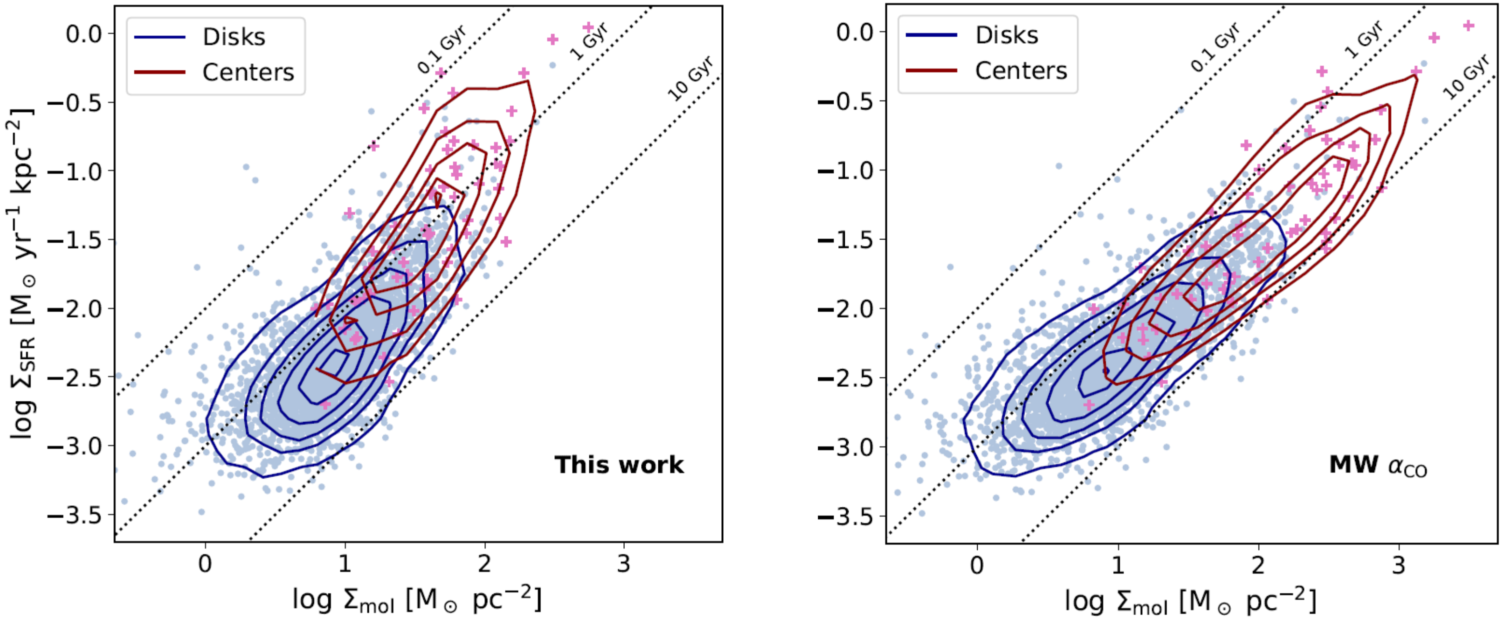
1. Least scatter among existing α_{CO} prescriptions (σ~0.1 dex)
2. Closest connection to the physics of α_{CO} (i.e., optical depth variation)
3. Requires only CO observations


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)
Teng+23 ($x_{CO} = 3e\text{-}4$)
Teng+23 ($x_{CO} = 1.5e\text{-}4$)
log α_{CO}
1.0
0.5
0.0
−0.5
0.5
1.0
1.5
log $\langle \Delta v \rangle_{150pc}$ [km/s]
Dust-α_{CO} best fit
Accurso+17
log α_{CO}
1.0
0.5
0.0
−0.5
−0.35
−0.30
−0.25
−0.20
−0.15
−0.10
−0.05
log Z' [$Z_\odot$]
log$[\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(\Delta v)]$
0.5
0.0
−0.5
−0.35
−0.30
−0.25
−0.20
−0.15
−0.10
−0.05
log Z' [$Z_\odot$]
log$[\alpha_{CO}^{dust}/\alpha_{CO}^{fit}(Z')]$
0.5
0.0
−0.5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
log $\langle \Delta v \rangle_{150pc}$ [km/s]

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}

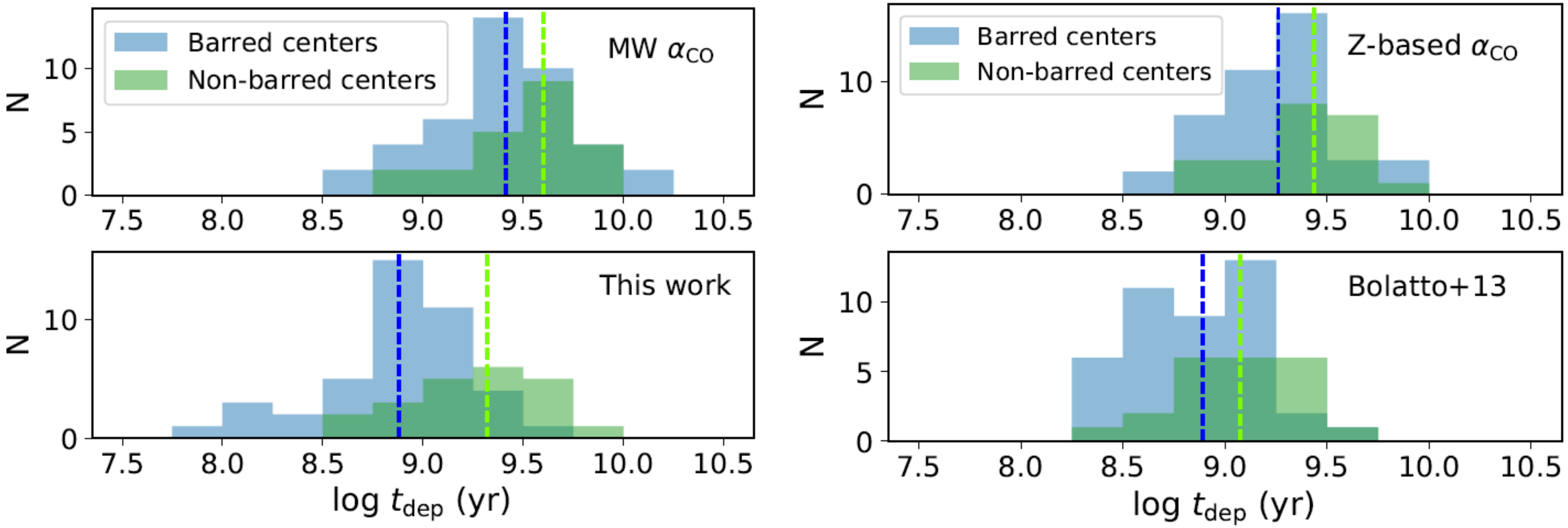
→ choice of α_{CO} greatly affects our understanding of galactic-scale star formation!



(Teng+ submitted)

Barred vs. non-barred centers

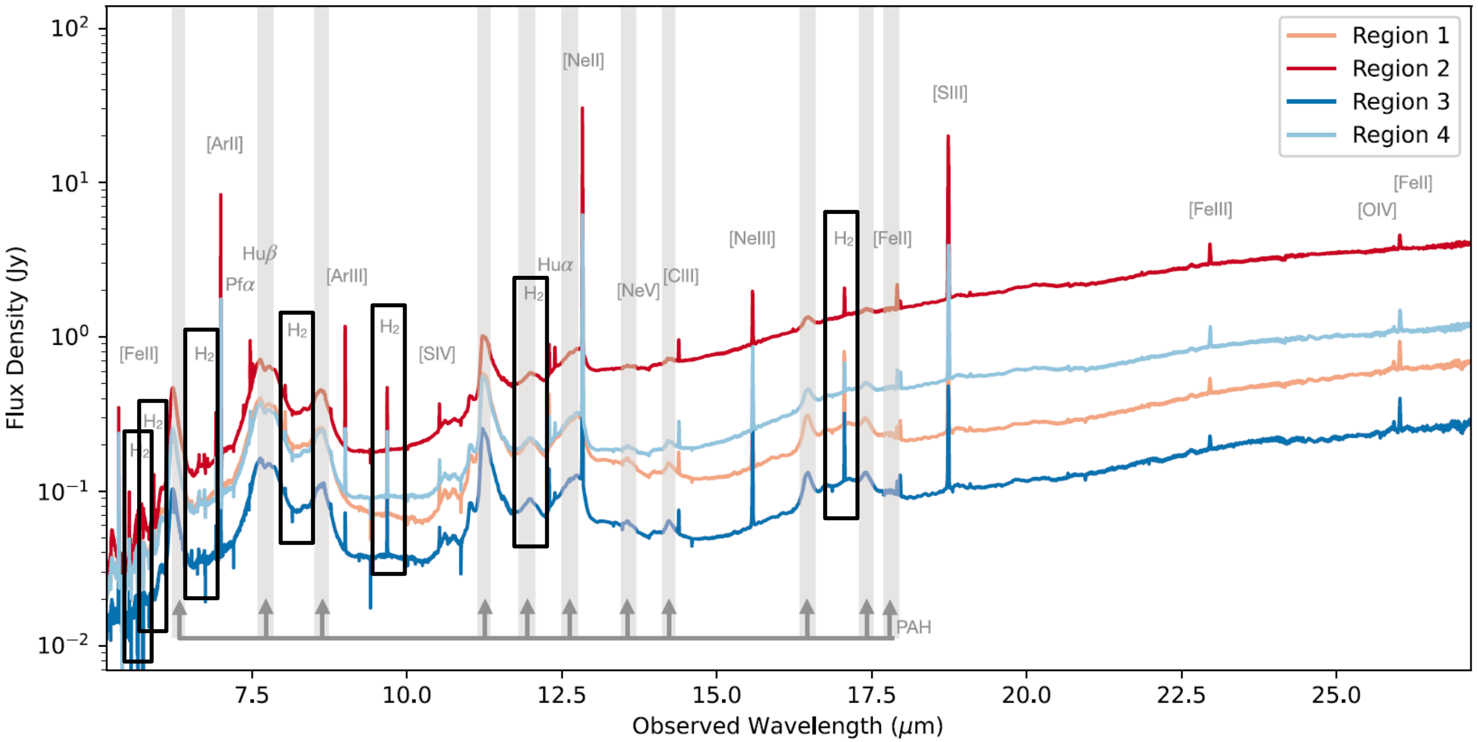
- Derived molecular gas depletion time using different $\alpha_{\rm CO}$ prescriptions:
  - Both MW and Z-based $\alpha_{\rm CO}$ result in 3-5x longer $t_{\rm dep}$ in galaxy centers overall
  - Bolatto+13 $\alpha_{\rm CO}$ predicts short $t_{\rm dep}$ in galaxy centers similar to our average
  - **Only our prescription reveals ~3x shorter $t_{\rm dep}$ in barred galaxy centers**



(Teng+ submitted)

Future work

- Drivers of SFE variations
  - gas structure, density, dynamical effects (from e.g., bars, turbulence, shocks)
  - JWST revealing warm H_2 gas and embedded SF

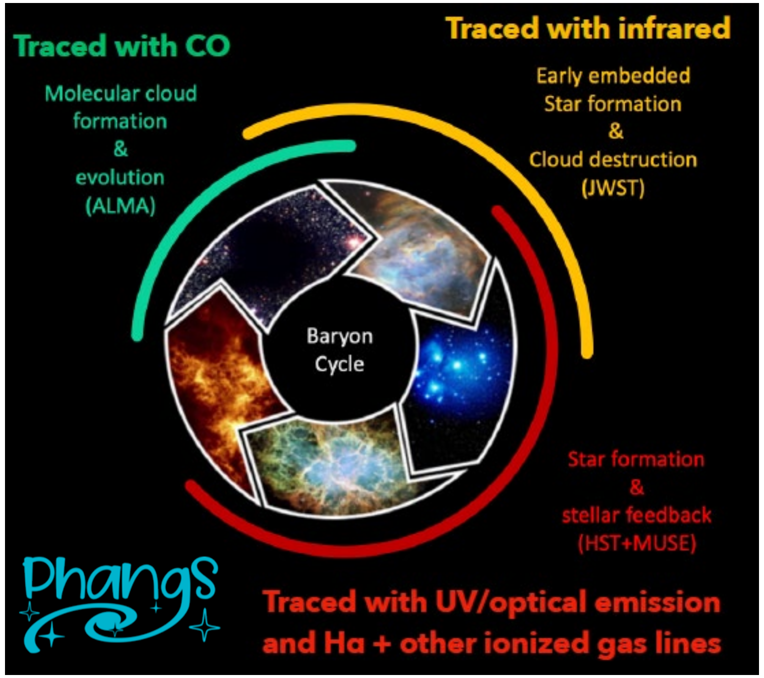


7 H_2 rotational lines well detected in M83 center with JWST MIRI!

(Hernandez+ 2023)

Future work

- Drivers of SFE variations
  - gas structure, density, dynamical effects (from e.g., bars, turbulence, shocks)
  - JWST revealing warm H_2 gas and embedded SF
- Impact on other cloud/SF properties
  - SFE per cloud free-fall or orbital time scales
  - virial parameter, turbulent pressure, ISM equilibrium



credit: K. Kreckel

Future work

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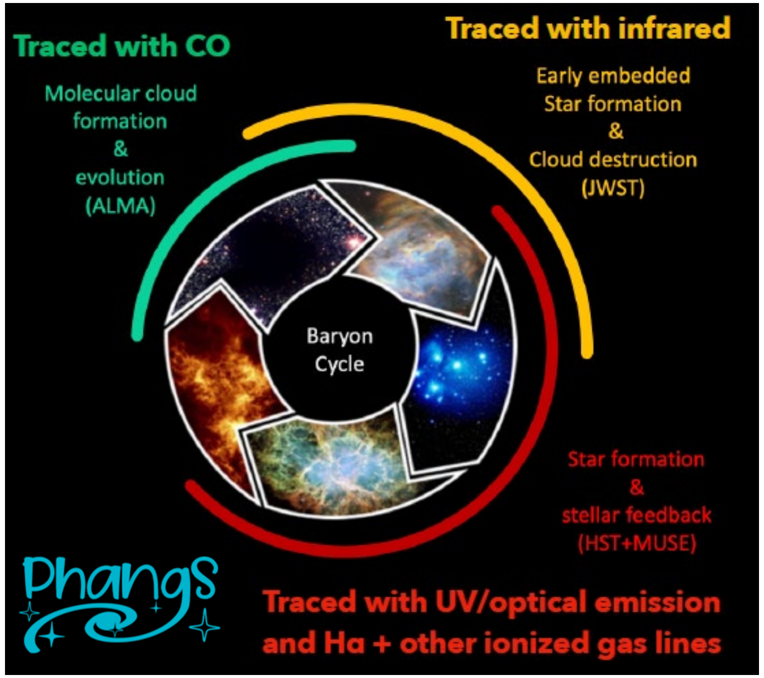
- Impact on other cloud/SF properties
  - SFE per cloud free-fall or orbital time scales
  - virial parameter, turbulent pressure, ISM equilibrium
- α_{CO} calibration based on various line ratios
  - ^{12}CO/^{13}CO dependence also tracing CO opacity

  → similar dependence seen in mergers!

  → ^{13}CO line mapping across active/normal galaxies
  - CO 2-1/1-0 ratio tracing temperature effect



credit: K. Kreckel

THANK YOU!

Lower α_{CO} in galaxy centers

5-15x lower α_{CO} than MW disk

New tracers for α_{CO}

velocity dispersion & CO/^{13}CO ratio

Main drivers of α_{CO}

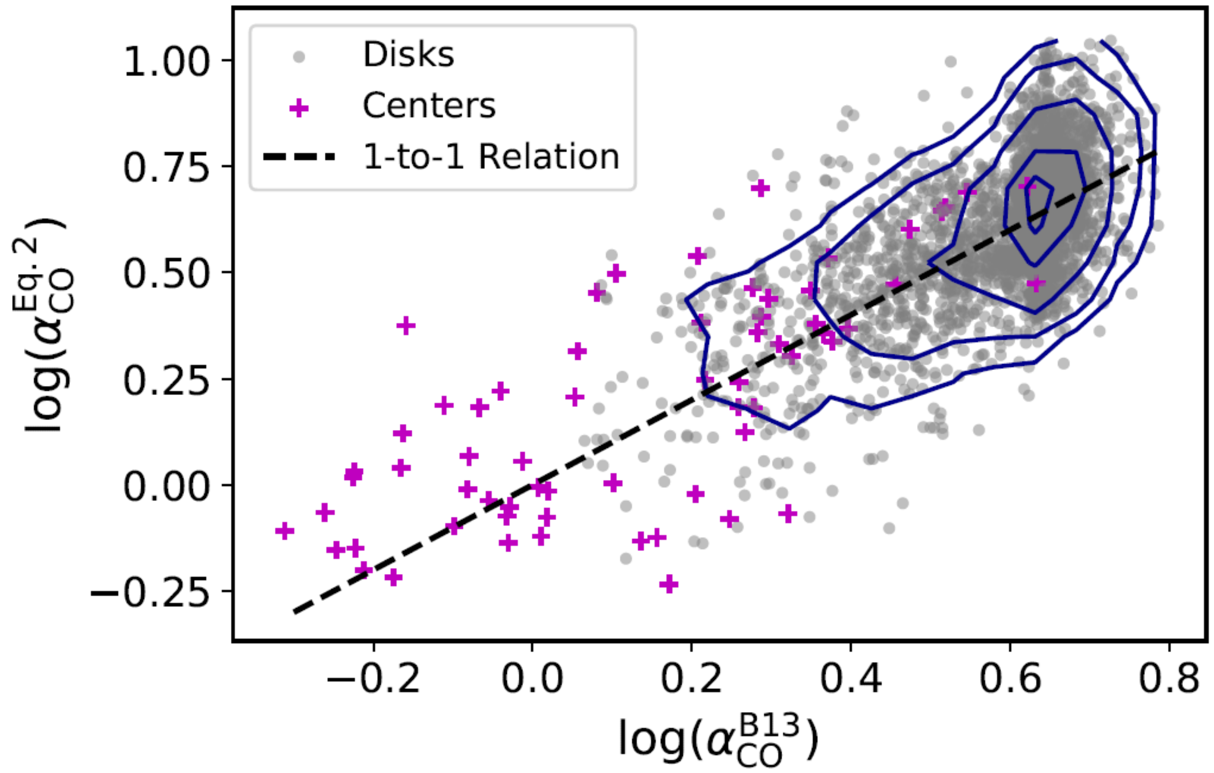
CO optical depth & gas temperature

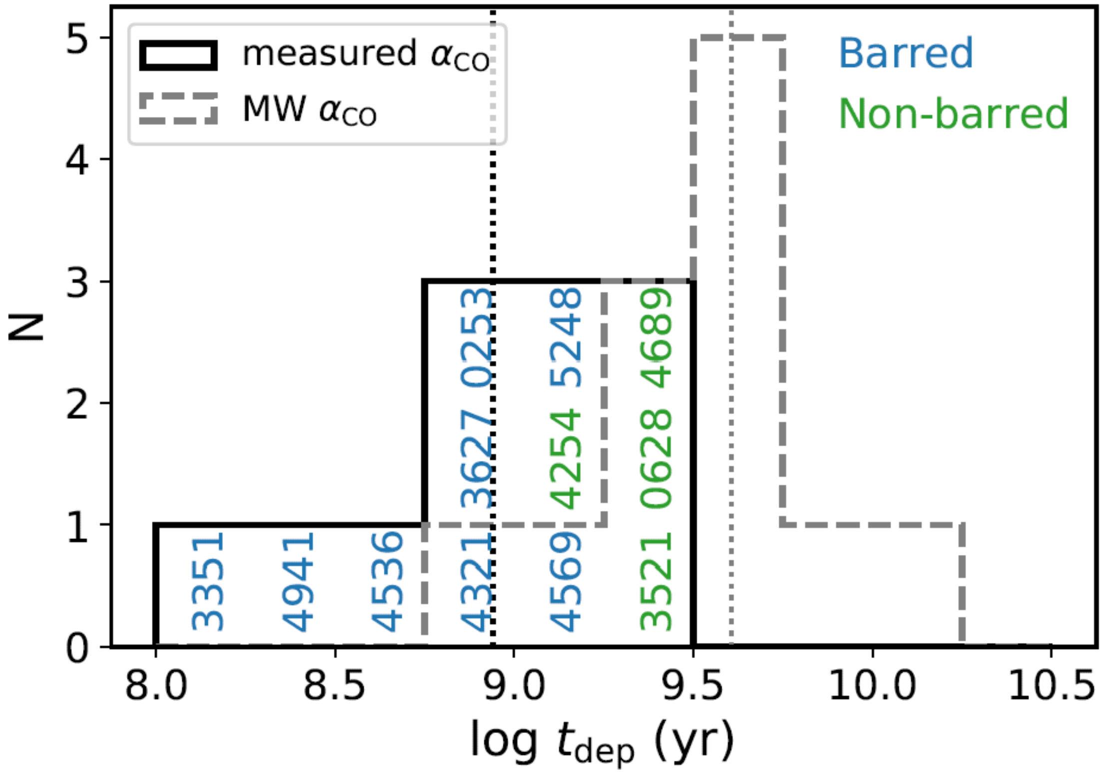
Enhanced SFE in barred centers

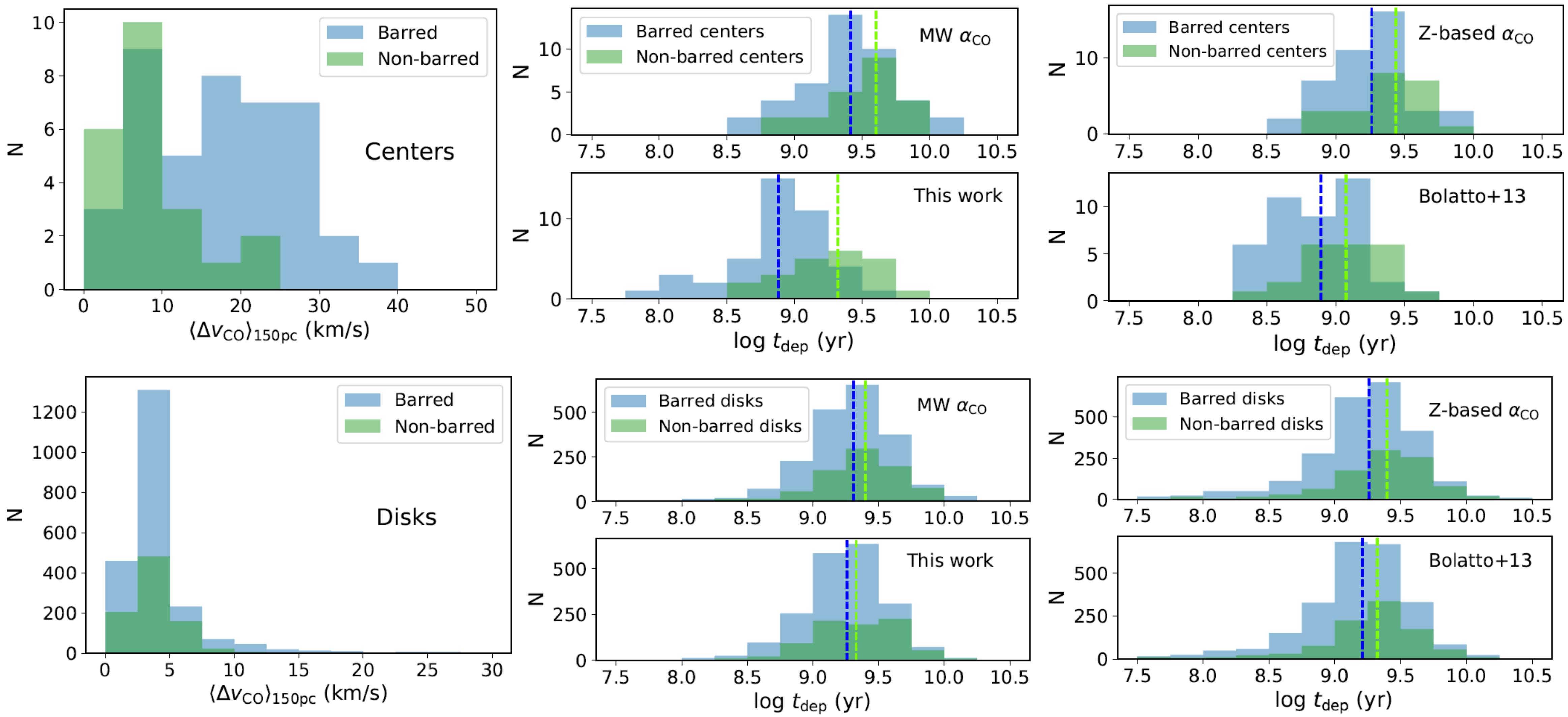
revealed with our new, Δv-based α_{CO}

Contact me: yuteng@ucsd.edu https://elthateng.github.io/

Papers: Teng et al. 2022, ***ApJ***, 925, 72; Teng et al. 2023, ***ApJ***, 950, 119; Teng et al. 2023, ***arXiv:2310.16037***


Disks
Centers
1-to-1 Relation
1.00
0.75
0.50
0.25
0.00
−0.25
$\log(\alpha_{\rm CO}^{\rm Eq.\,2})$
−0.2
0.0
0.2
0.4
0.6
0.8
$\log(\alpha_{\rm CO}^{\rm B13})$


measured $\alpha_{\rm CO}$
MW $\alpha_{\rm CO}$
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 $t_{\rm dep}$ (yr)


Barred
Non-barred
Centers
N
⟨Δv_CO⟩_150pc (km/s)
Barred centers
Non-barred centers
MW α_CO
Z-based α_CO
This work
Bolatto+13
log t_dep (yr)
Barred
Non-barred
Disks
N
⟨Δv_CO⟩_150pc (km/s)
Barred disks
Non-barred disks
MW α_CO
Z-based α_CO
This work
Bolatto+13
log t_dep (yr)
7.5
8.0
8.5
9.0
9.5
10.0
10.5