Molecular Cloud Evolution & (Massive) Star Formation in Galactic Dynamics

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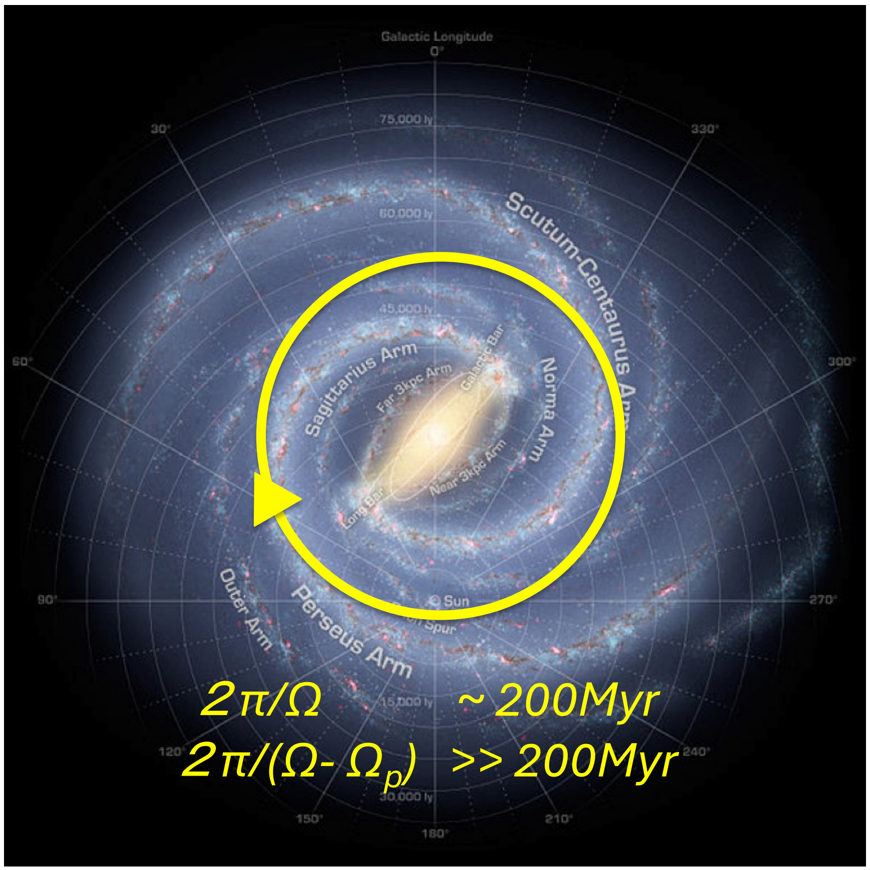
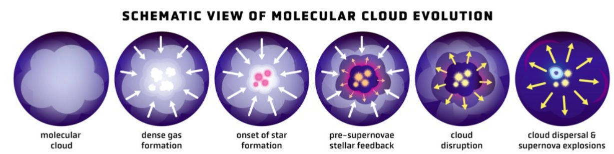
Cloud Lifecycle in Large-Scale Galactic Context



<u>Cloud lifetime</u>

<u>~5-30 Myr</u>

Form and *die* at the same location



→ All phases at all places
→ *No galaxy-scale* pattern

<u>~>100 Myr</u>

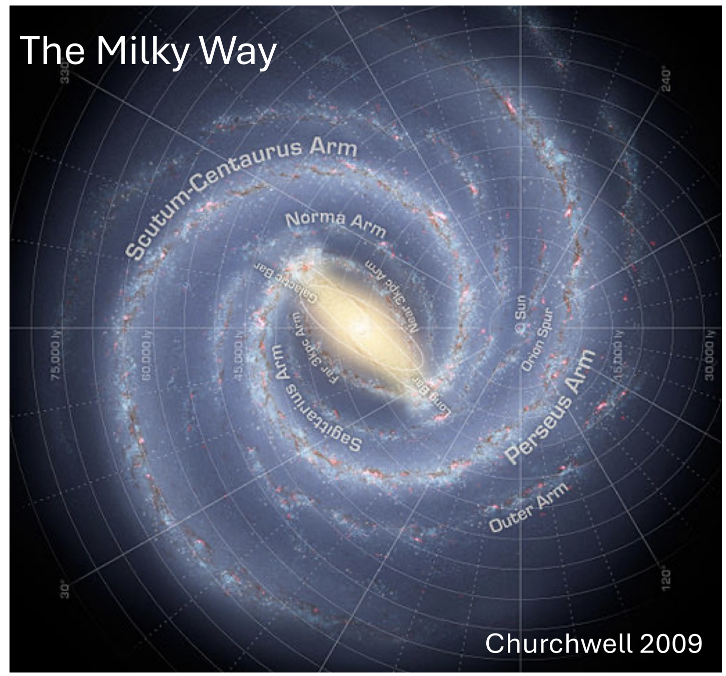
Form, *move, and evolve* around the disk

→ Correlate with galactic structures
→ Galaxy-scale pattern

This Talk: Galaxy-Scale Variations in M83 (the closest MW-analog)

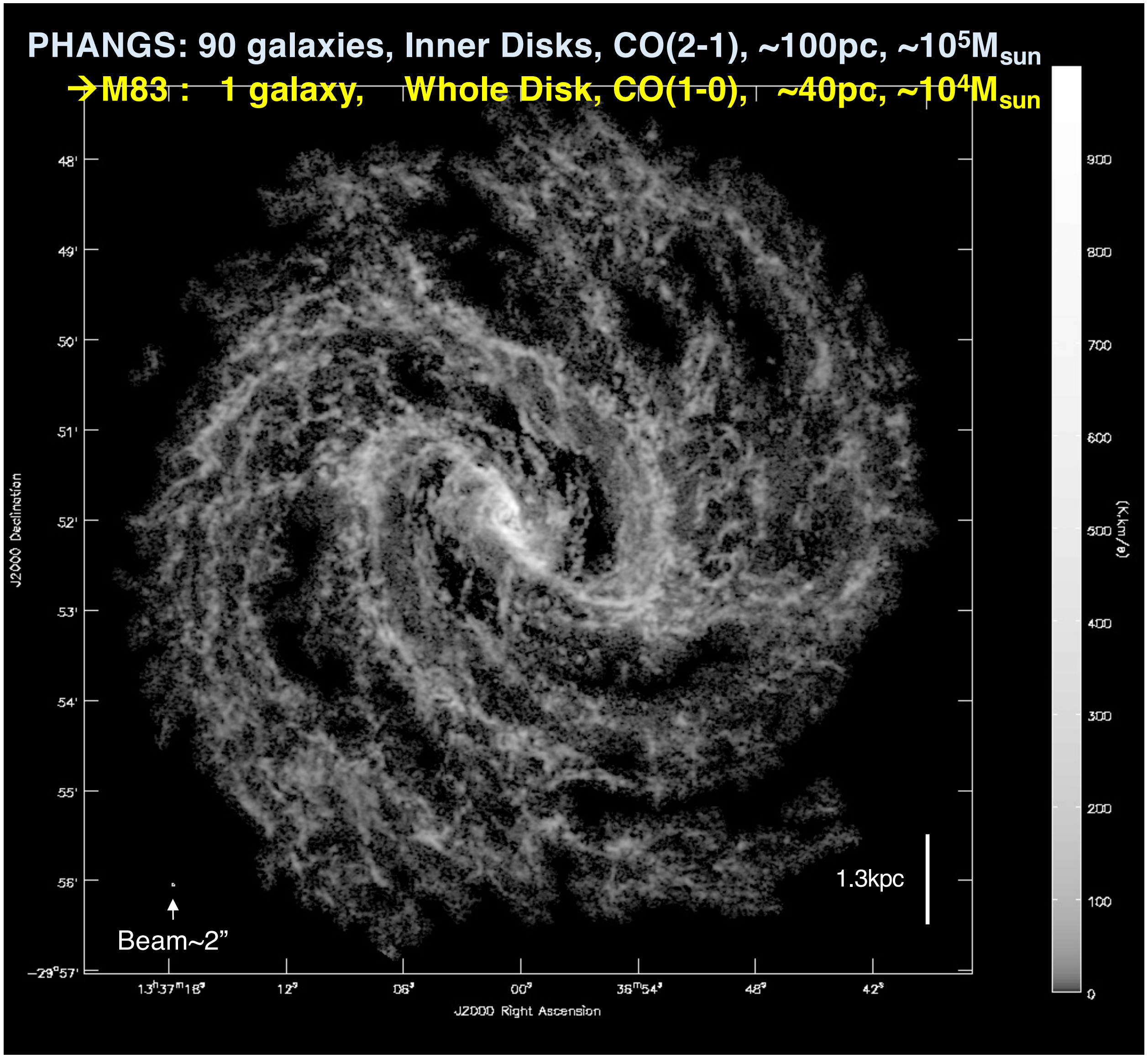
- **The CO 2-1/1-0 ratio (R_{21}):** low → high excitation from interarm to spiral arms
- **Cloud properties:** Unbound in interarm → Bound in spiral arms.

→ Molecular gas/cloud evolution synchronized with galactic dynamics



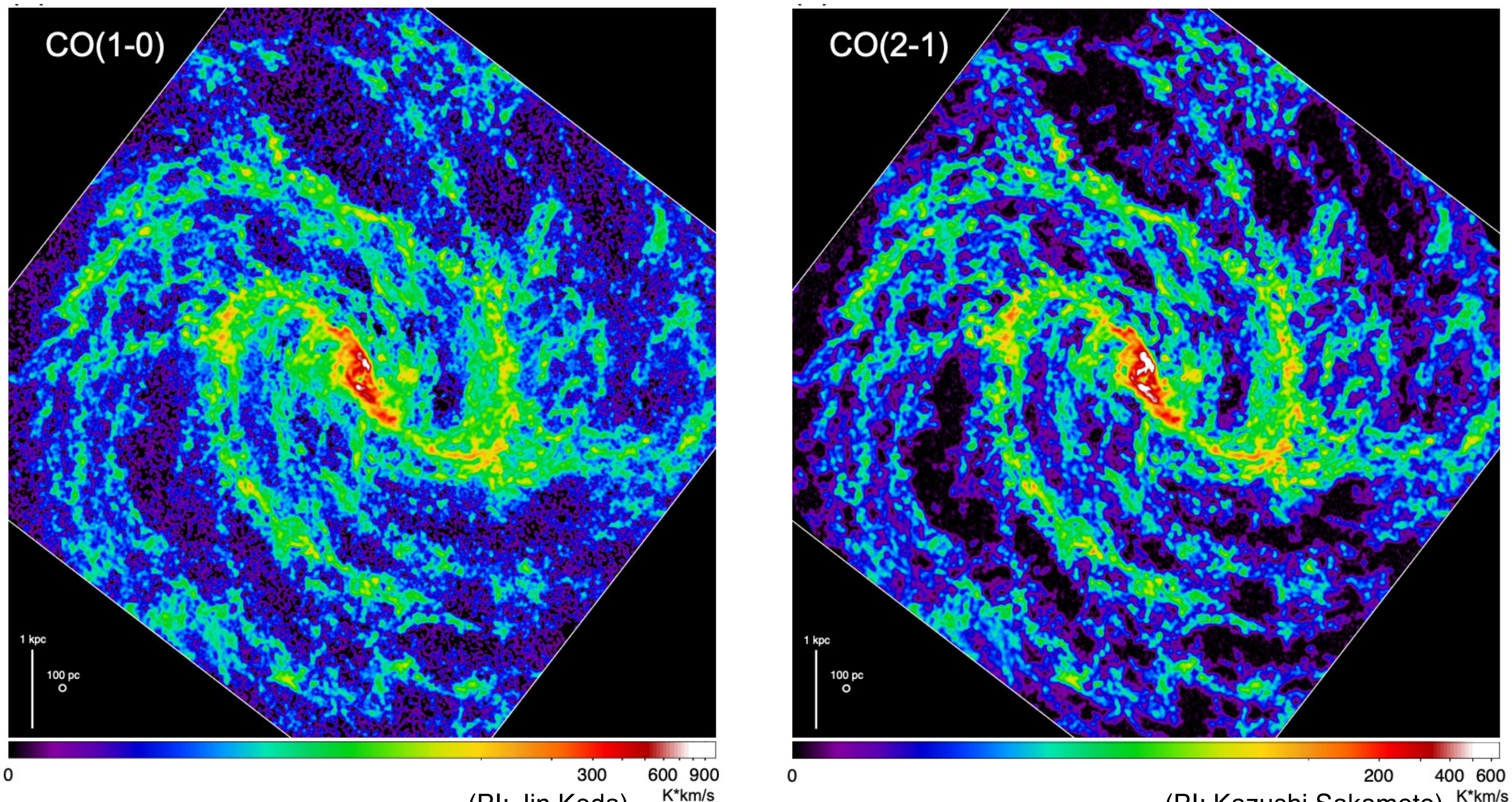
M83 CO(1-0)

ALMA 12m+7m+TP
jointly-imaged with MIRIAD



Koda et al. 2023

CO(1-0) more extended: CO(2-1) more concentrated



(PI: Jin Koda)

(PI: Kazushi Sakamoto)

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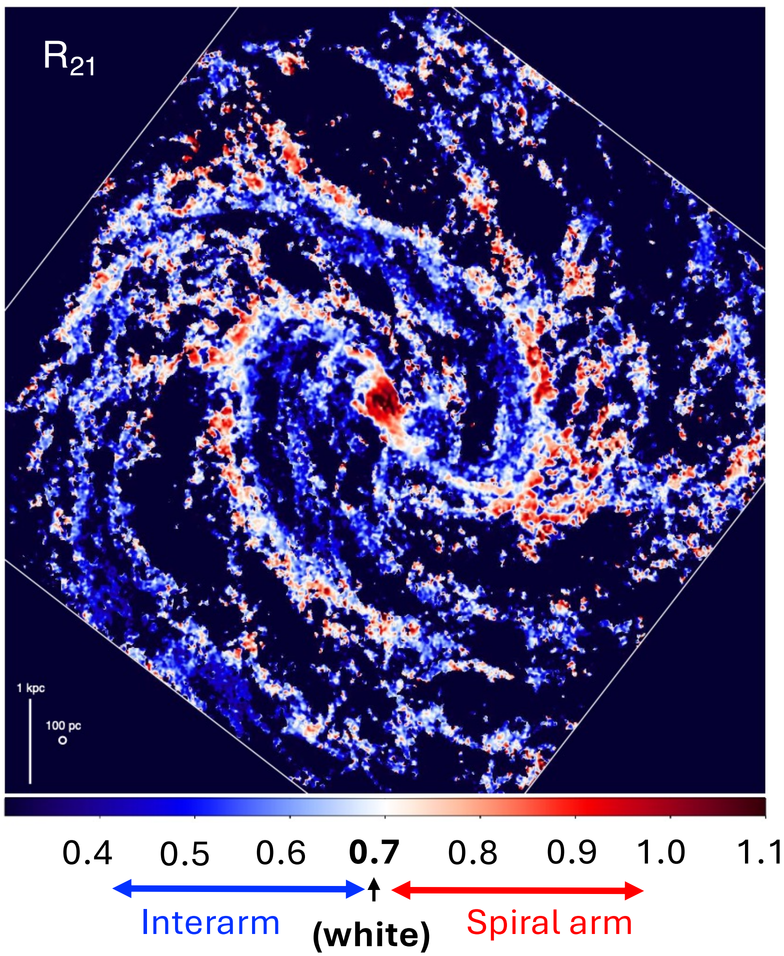
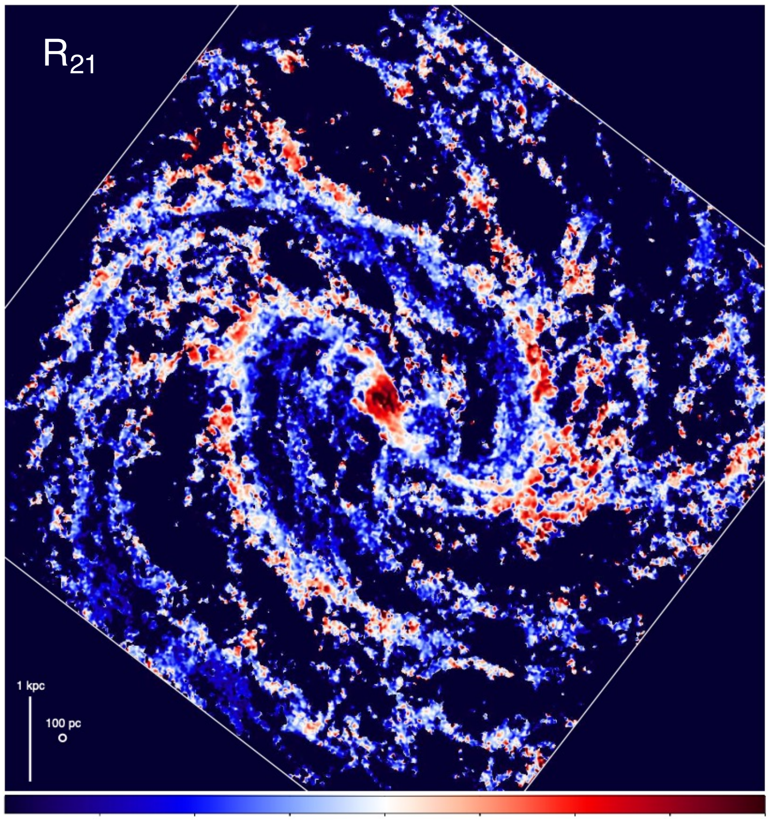
R_{21} = CO 2-1/1-0 Line Ratio: Large-Scale Variations



R_{21} <0.7 in interarm regions
↔ R_{21} >0.7 in spiral arms

Koda et al. 2025

Interarm↔Arm: x2-3 changes around typical (n_{H2}, T_{kin})



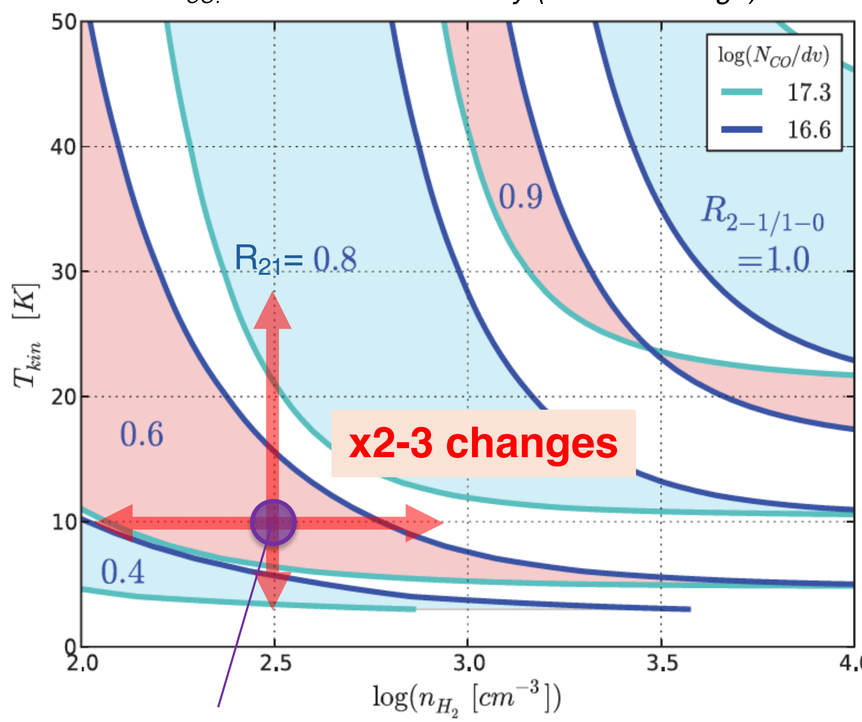
0.4 0.5 0.6 **0.7** 0.8 0.9 1.0 1.1

Interarm **(white)** Spiral arm

Koda et al. 2025

Large Velocity Gradient (LVG) Calculation

$N_{CO.}$ … CO column density (fixed in a range)



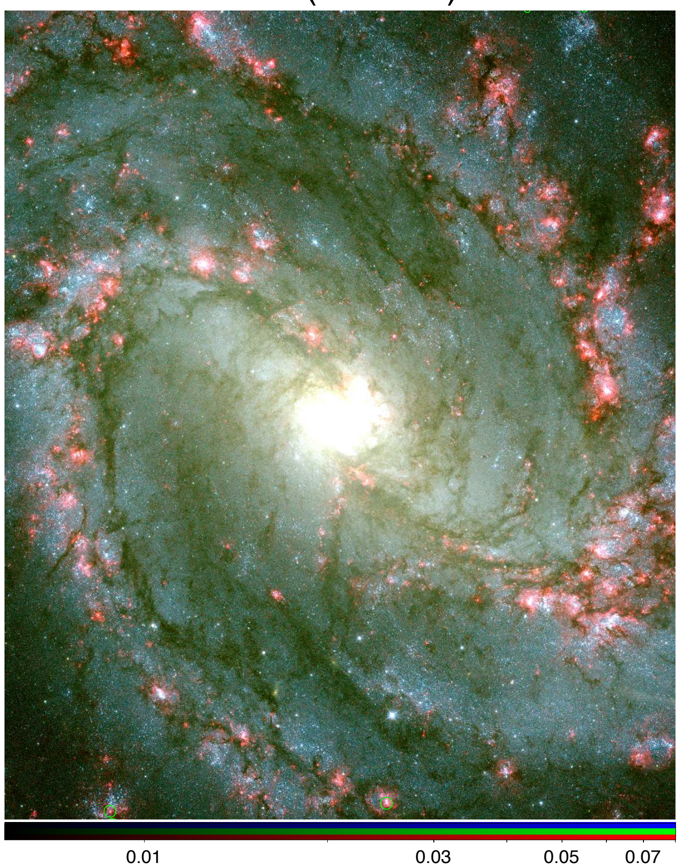
Typical Galactic cloud (Scoville & Sanders 1987)

(n_{H2}, T_{kin}) ~ (300 cm^{-3}, 10K)

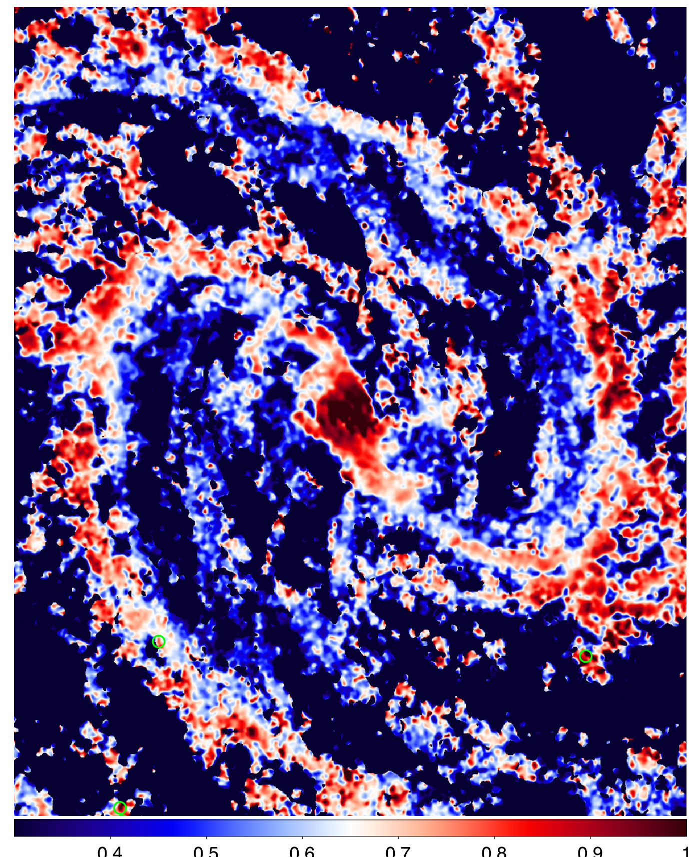
Koda et al. 2012

What controls the gas condition?: Feedback? Galactic Dynamics?

HST (red=Hα)



R_{21} = CO 2-1/1-0

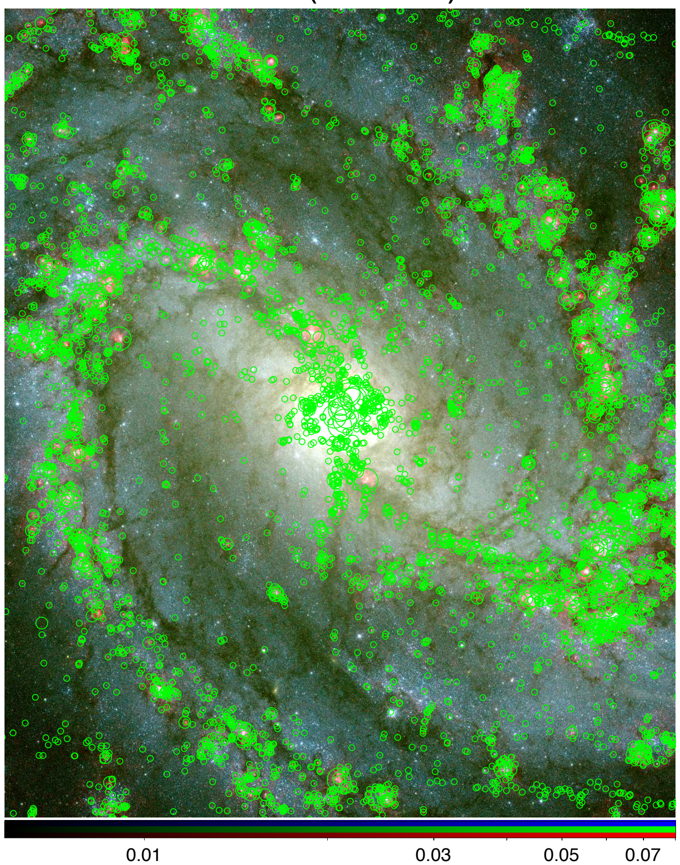


Koda et al. 2025

5.7x7.0 kpc^2

Separate Inside/Outside HII Regions → HII Region Mask

HST (red=Hα)



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Method: HST Hα + SExtractor

Detection Limit: $L_{H\alpha}$~>10^{35} erg/s

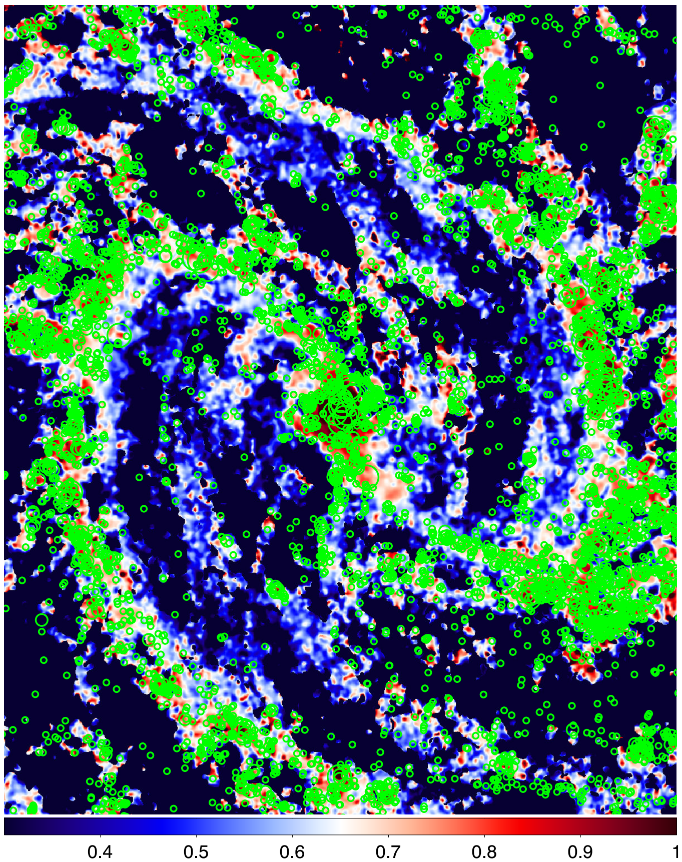
(The Orion Nebula ~7×10^{36})

Mask: enclose relatively large are around HII region

$L_{H\alpha}$ > 10^{38} erg/s → D_{circle} = 200 pc
$10^{37\text{-}38}$ erg/s → = 100 pc
< 10^{37} erg/s → = 50 pc

R_{21}: Pushed to >0.7 by Dynamics and to ~0.8-1.0 by Feedback

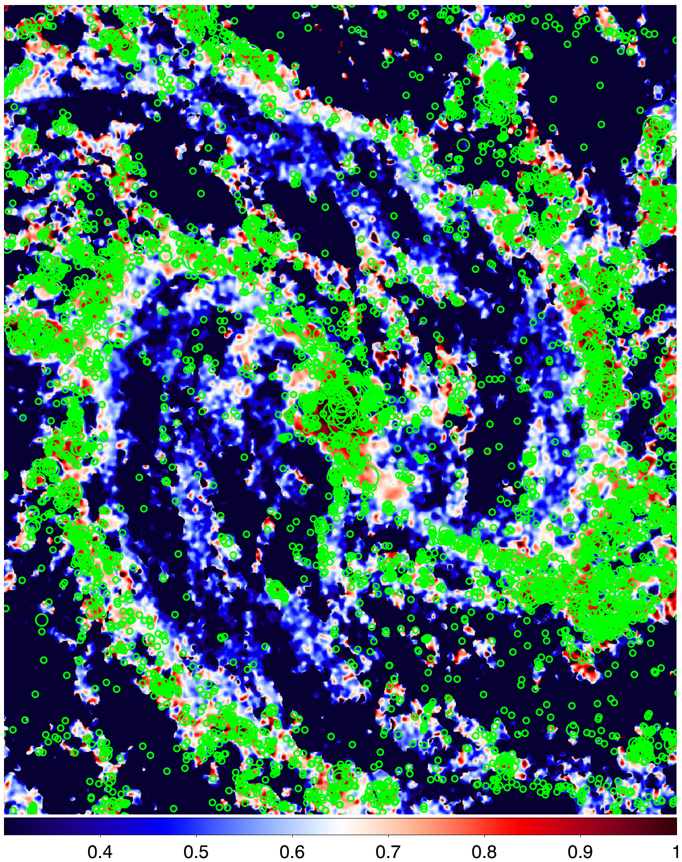
R_{21} .. *See* outside HII region mask



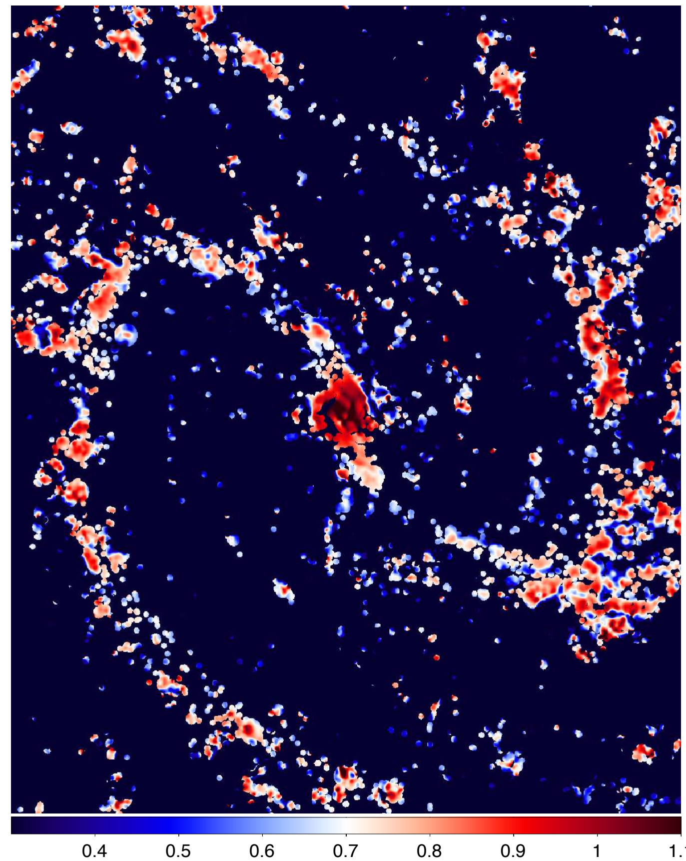
Koda et al. 2025

R_{21}: Pushed to >0.7 by Dynamics and to ~0.8-1.0 by Feedback

R_{21} .. *See* outside HII region mask



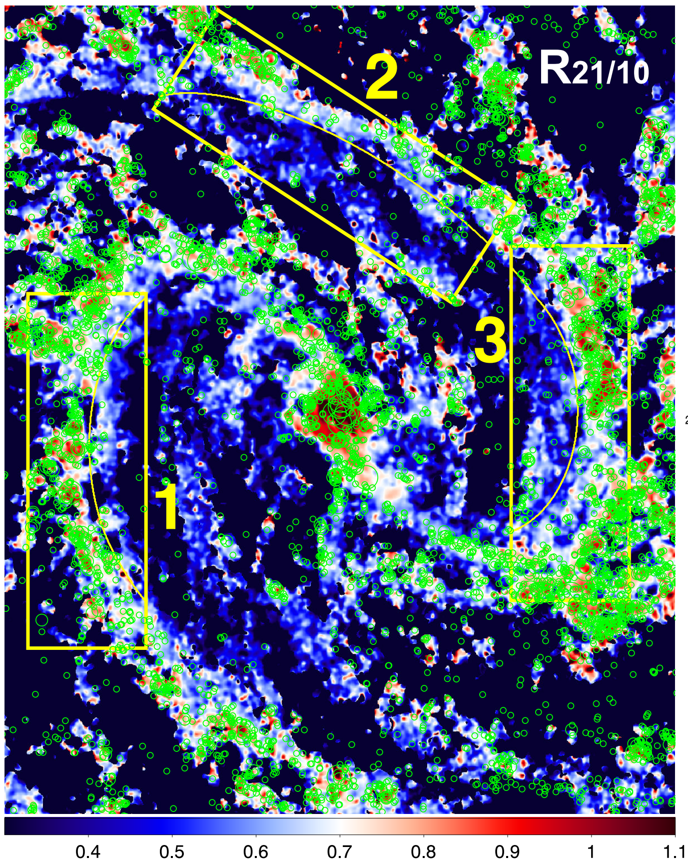
R_{21} .. Inside HII region mask



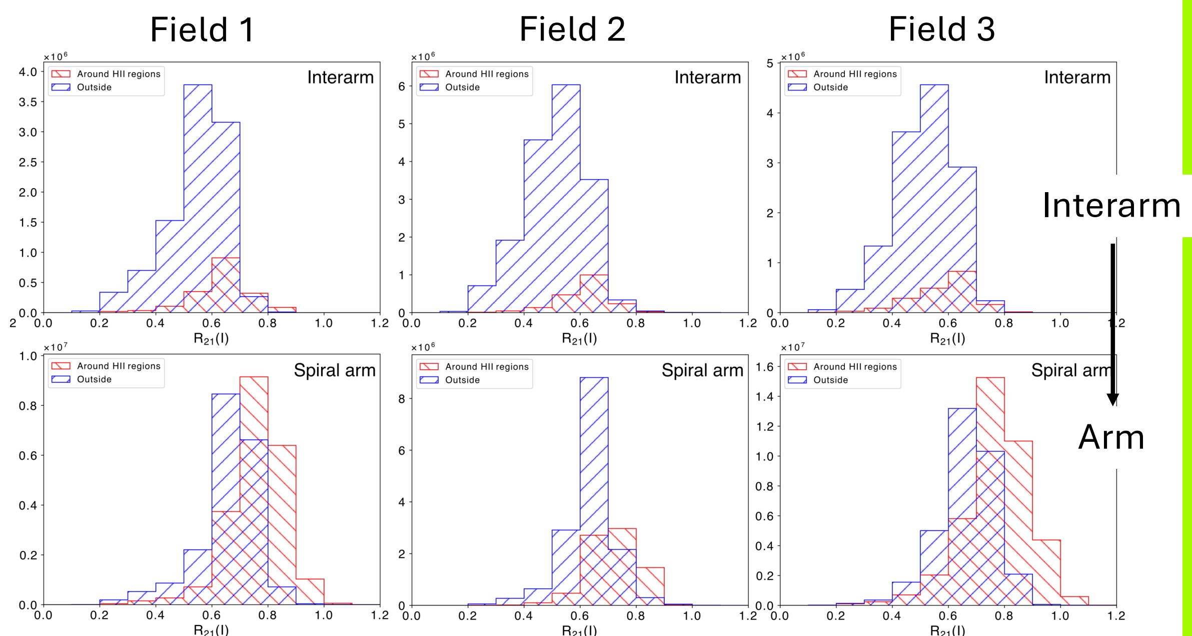
Koda et al. 2025

Causality unclear: dense/warm → SF? *or* Feedback → dense/warm?

R_{21}: Pushed to >0.7 by Dynamics and to ~0.8-1.0 by Feedback



Histograms of R_{21} = CO 2-1/1-0

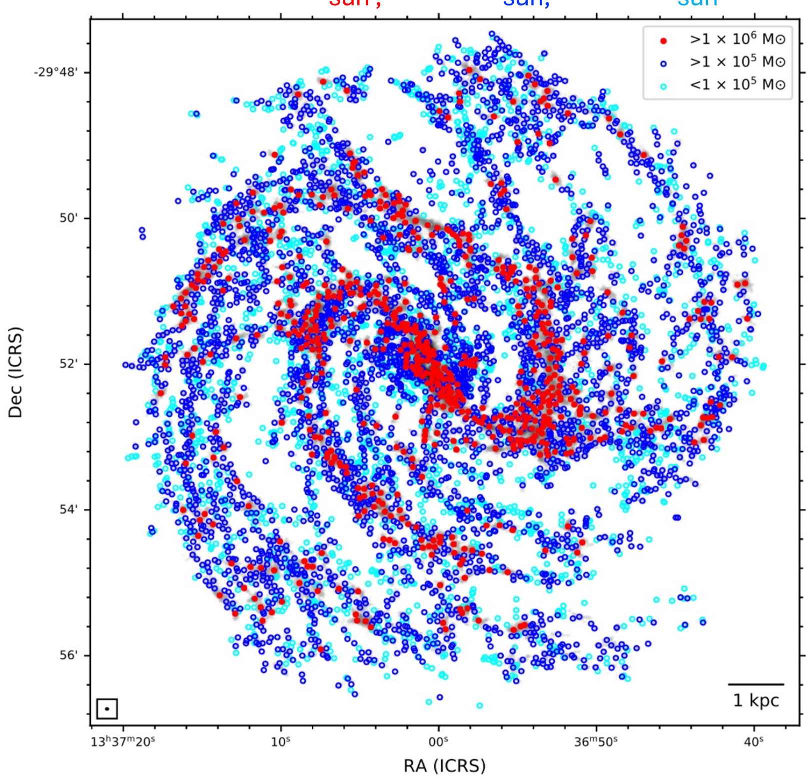


Outside HII Regions Around HII Regions

Molecular Cloud Evolution: 93% of CO emission identified as clouds

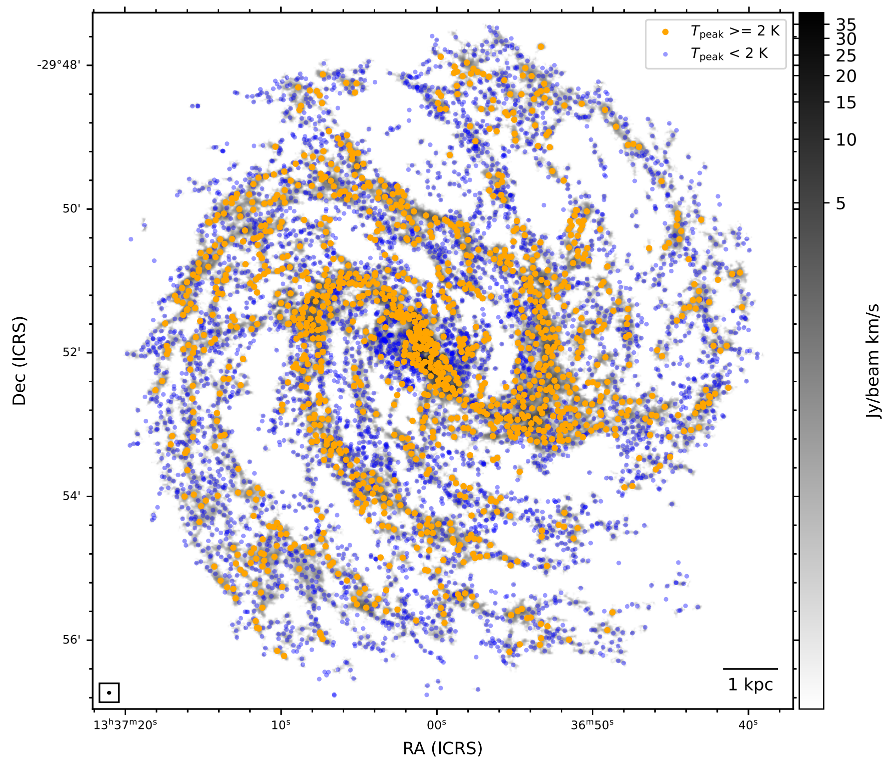
$M_{lum} = \alpha_{CO} L_{CO}$ (α_{CO} = const.)

$> 10^6$ M_{sun}, $10^{5\text{-}6}$ M_{sun}, $< 10^5$ M_{sun}



$T_p = peak\ surface\ brightness\ (temperature)$

>2K, <2K



Massive to less massive (1) between arm and interarm (2) from the inner to outer disk

Hirota et al. 2024

More Massive, Denser, More Bound

Virial Parameter: $\alpha_{vir} \propto \dfrac{M_{vir}}{M_{lum}} \propto \dfrac{R\sigma_v^2}{\alpha_{CO} L_{CO}}$ $< 1\sim2$ – gravitationally–bound

T_p>2K clouds

Massive (>$4\times10^5 M_{sun}$)

More-bound

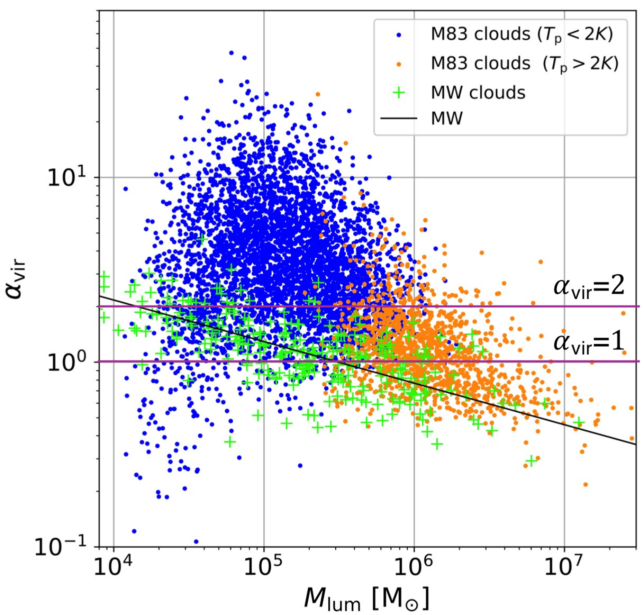
T_p<2K clouds

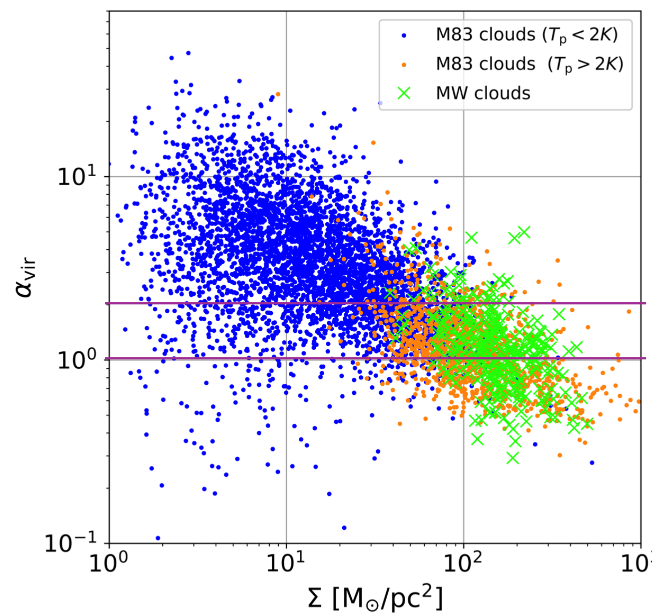
Less massive (<$4\times10^5 M_{sun}$)

Less-bound

MW clouds

Solomon et al. 1987

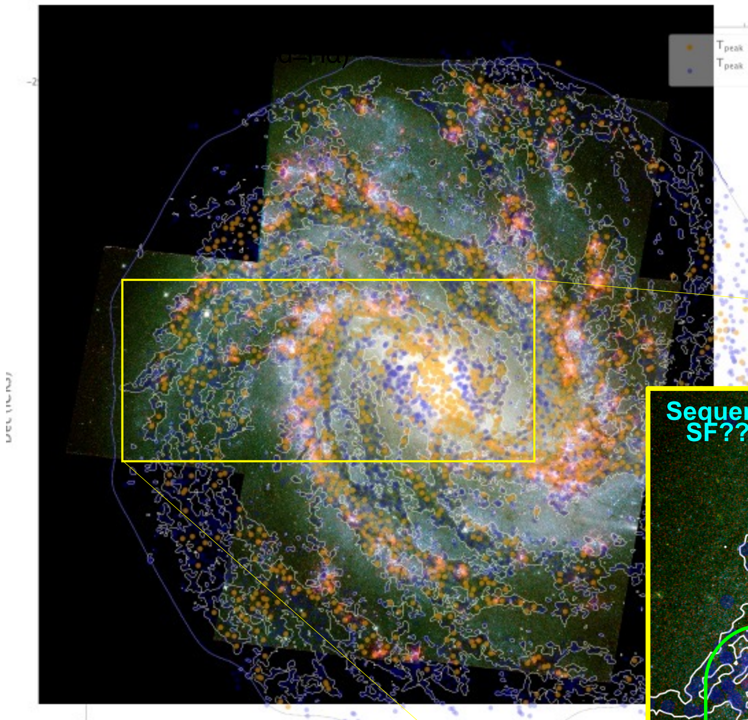




Some clouds (structures) may be unbound. Scale-dependence.
Should we move away from the "molecular cloud" paradigm?

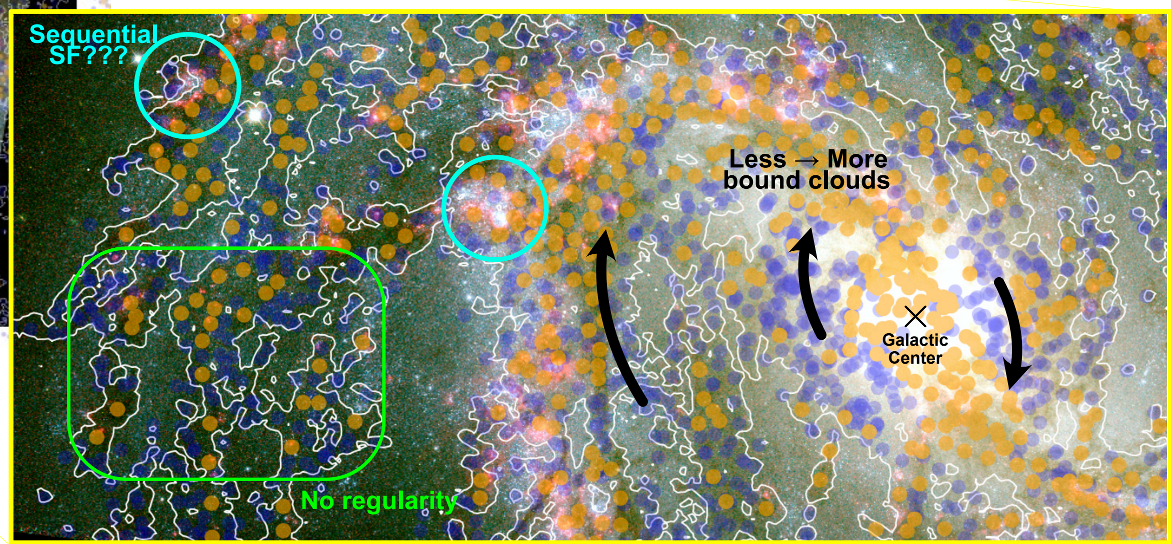
Hirota et al. 2024

Cloud Evolutionary Sequence in Galactic Dynamics



Inner disk:
Interarm: Less-bound → Arms: More-bound

Outer disk:
Random, Irregular



T_p>2K clouds: *Massive, More-bound*
T_p<2K clouds: *Less massive, Less-bound*

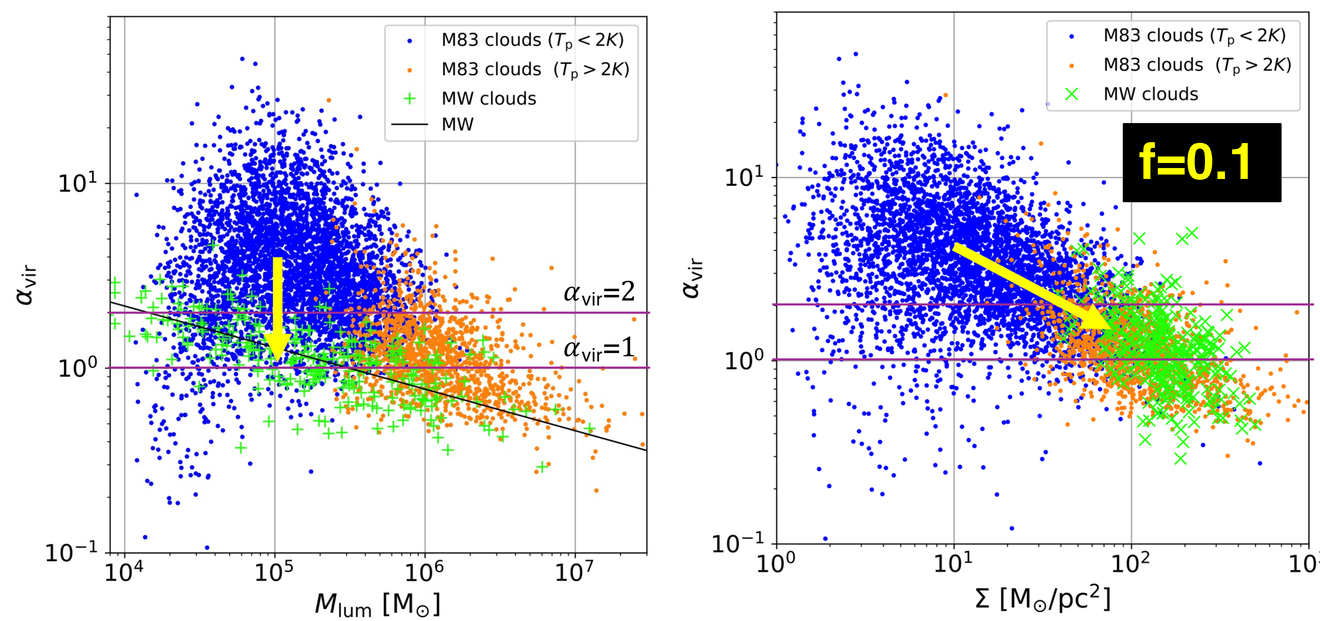
Hirota et al. 2024

Caveat on Cloud Analysis: Beam Filling Factor

T_p=2K roughly separates (likely) resolved and (likely) unresolved clouds

Beam filling factor

$$f = \frac{\Omega_{cloud}}{\Omega_{beam}}$$



Corrections

Radius: $R \propto f^{1/2}$

Surface density: $\Sigma \propto f^{-1}$

Virial parameter: $\alpha_{vir} \propto f^{1/2}$

The sequence could potentially be an artifact due to insufficient resolution.
Need 20-pc resolution to resolve smallest clouds.

Hirota et al. 2024

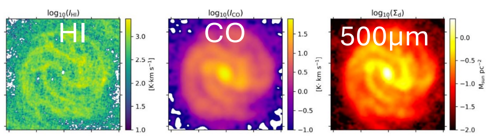
AD: Students' work

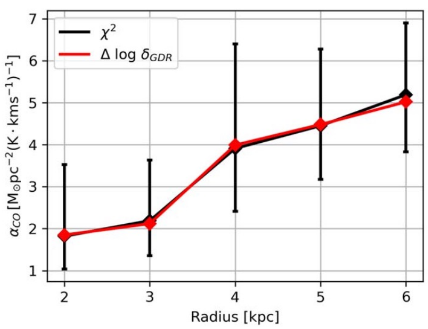
Radial increase in α_{CO} (Xco)

Amanda Lee et al. 2024

[Radial increase in α_{CO}]

- Derived by the dust-based method



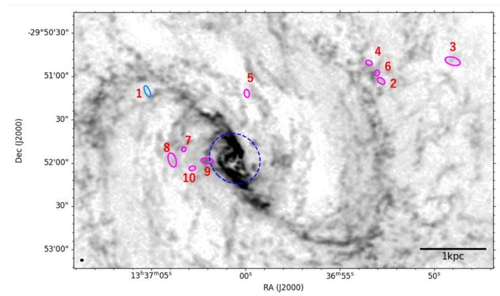


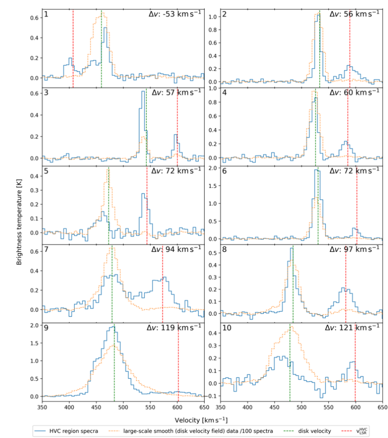
Explained by

- *Radial variations in cloud population*

Molecular High-Velocity Clouds

Nagata et al. 2025
(ApJ, accepted; arXiv:2505.12757)





[10 HVCs]

>50km/s from disk

R~30-80 pc
M~10^5 M_{sun}
σ_V~3-20km/s

Mostly (9/10) in positive velocity
Too heavy to lift up from the disk by SNe
→ *(Likely) infalling gas*

Summary: Dynamically-Driven Molecular Gas/Cloud Evolution

- **ALMA CO obs. of M83 at 40pc resolution** – the closest MW-analog (*d*=4.5Mpc)
- **The CO 2-1/1-0 ratio (R_{21}) shows large-scale variations - Solid**

  The gas becomes denser/warmer from interarm to spiral arms *even without* (massive) star formation
- **Cloud properties evolve in synch with galactic structure & dynamics - Likely**

  Less-bound in interarms → more-bound in spiral arms.

→ Molecular gas/cloud evolution synchronized with galactic dynamics (rotation timescales)