Exploring the evolution of GMCs and the state of the ISM with the CANON CO (1-0) survey

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CARMA and **NO**beyama **N**earby Galaxies CO (1-0) Survey (CANON)

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- David Rebolledo – U. Illinois at UC
- Nick Scoville -- Caltech
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GMC evolution and the state of the molecular ISM

- *The state of the molecular ISM*
  - *Cloud evolution from spiral arms to interarm regions*
  - *CO-to-H_2 conversion factor (Xco) → ("going places we don't want to go", M. Heyer)*
  - *Tracing ISM excitation*
  - *GMC velocity dispersions and boundness in galactic centers*
- *Star formation and GMCs (briefly)*
  - *(Correlating offset star formation with GMCs)*
  - *Star formation law*

H_2 proxy: ^{12}CO (1-0)

- J=1-0 transition at 115.2712 GHz, hν/k = 5.5 K

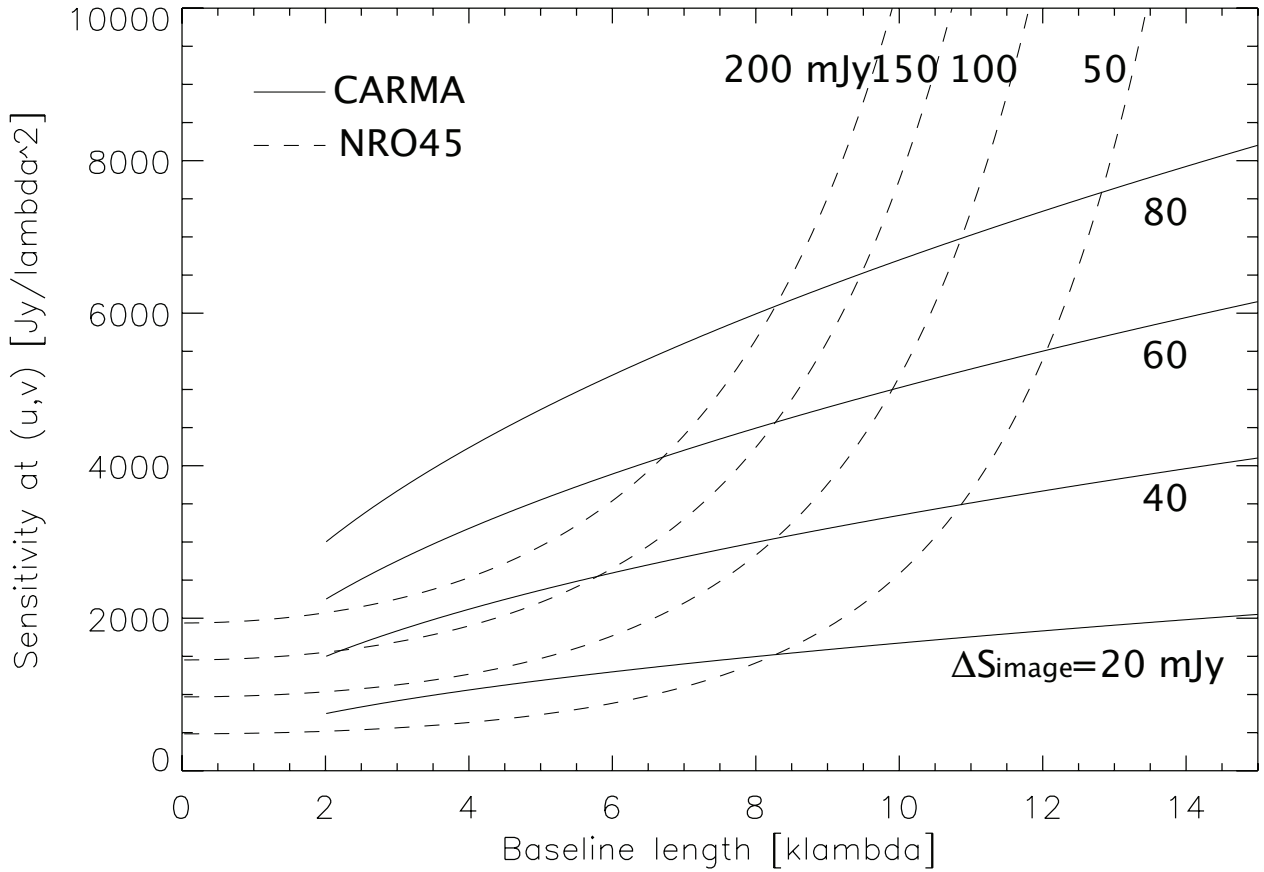
- Critical density given by $n_{H2}=A_{1\text{-}0}/\sigma v \sim 3000$ cm^{-3}
  - But CO (1-0) is optically thick, so n_{crit} reduced by τ
  - $\tau_{CO} \geq \sim 10$ in most GMCs, so critical density for CO (1-0) ≤ 300 cm^{-3}

- Required: well-calibrated CO-to-H2 conversion factor (X_{CO} or α_{CO} in the literature)

Needed:

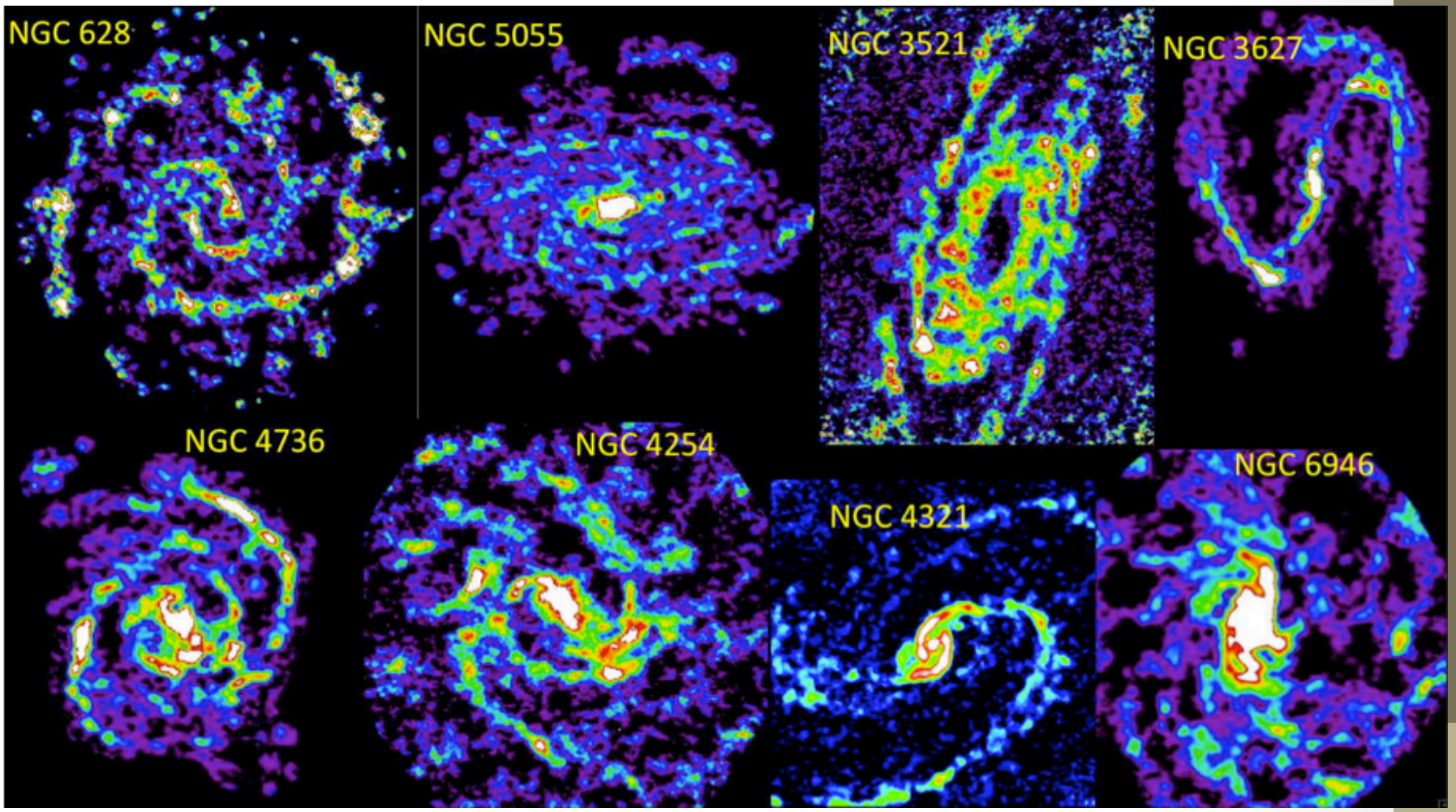
- High resolution CO maps of a representative sample of nearby spiral galaxies, with plenty of available multi-wavelength ancillary data, to quantify:
  - Conversion factor for CO luminosity → H_2 mass (X_{CO})
  - Resolved Kennicutt-Schmidt laws (relating gas to SF)
  - ISM evolution
  - Star formation efficiencies
  - Gas/dust ratios (with the KINGFISH team)
- 29 nearby galaxies in the full sample
  - Chosen from SINGS
  - Dec > 0°, d > 4', SB > 0.5 mJy/sq '' at 160 μm
- Observations
  - Combine NRO 45m and CARMA observations to achieve high image fidelity
  - NRO 45m: OTF mapping of full disks with BEARS (now being upgraded)
  - CARMA: C, D configuration 19-point mosaic mapping of the central regions (2.3')

Sensitivity matching



Koda et al. (2011)

CARMA and **NO**beyama **N**earby-galaxies (CANON) CO (1-0) Survey

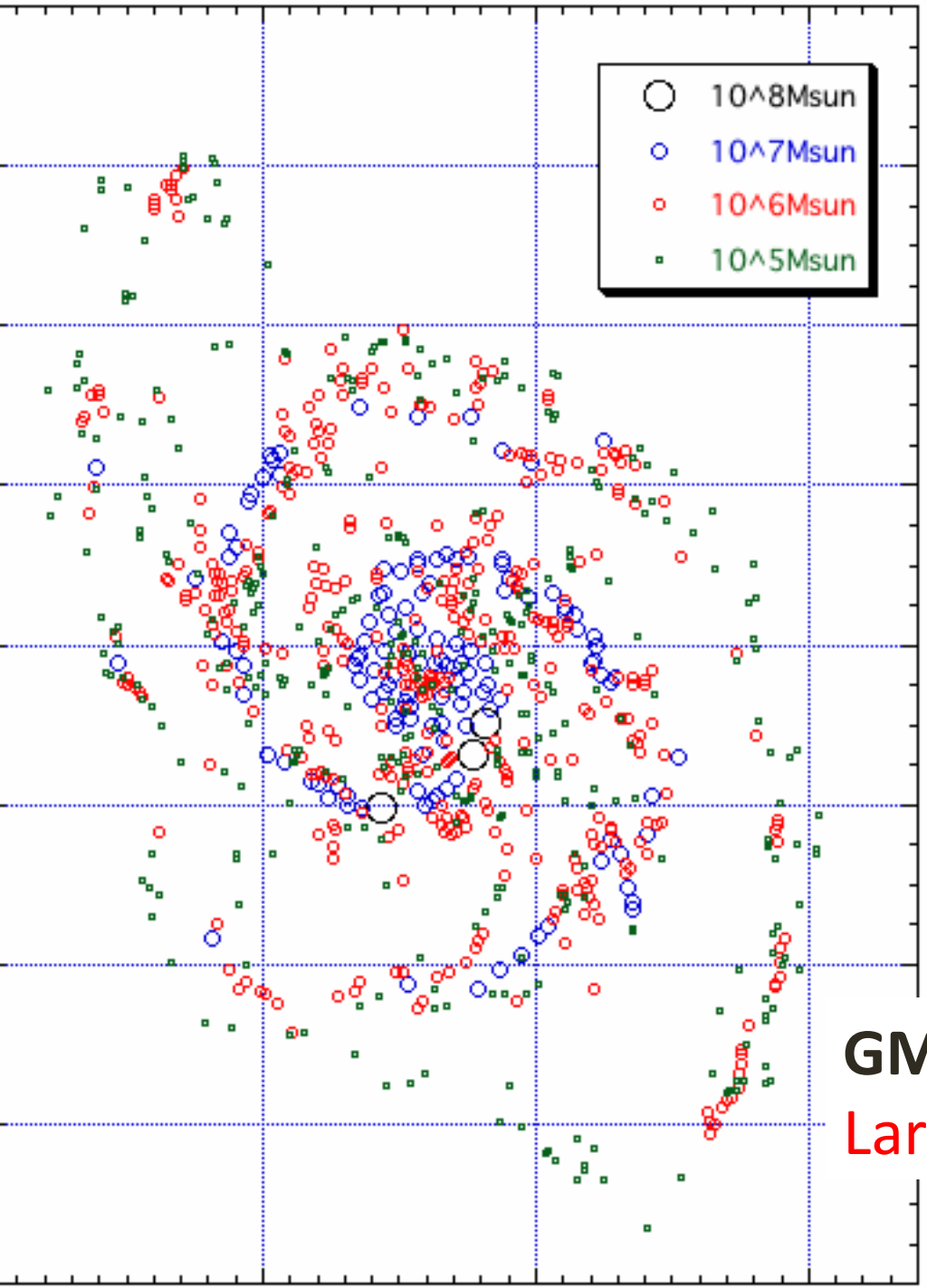


Three times higher sensitivity & resolution (2-3”) compared to BIMA-SONG

Giant Molecular (H_2 + He) Clouds

- GMCs: 10^4 – 10^6 solar masses (GMAs → 10^8)
- Avg. GMC ~40 pc in size
- T~10-20 K
- Average surface density ~ 170 M_{sun}/pc^2
- Self-gravitating (not confined by external pressure)
  - Turbulent linewidths (of CO) ~ few km/s, compared to 0.1 km/s sound speed of gas
- Substructure: cores
- Located in spiral galaxy disks – GMAs coincident with spiral arms, GMCs in arms AND interarm regions

Cloud associated with Carina Nebula



GMC Distribution in M51

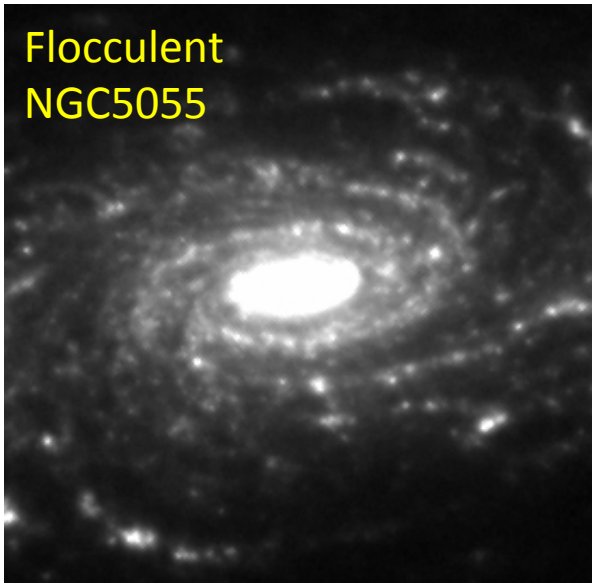
- Giant Molecular Clouds
  - GMC: $10^{5\text{-}6}$ M_{sun}
  - Both in spiral arms and interarm
- Giant Molecular Associations
  - GMA: $10^{7\text{-}8}$ M_{sun}
  - Only in spiral arms

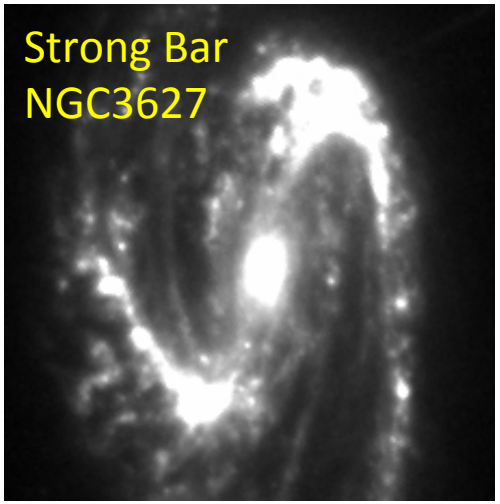
GMC evolution

Large (arm) → Small (interarm)

Koda et al. 2009

GMC Distribution and Structure

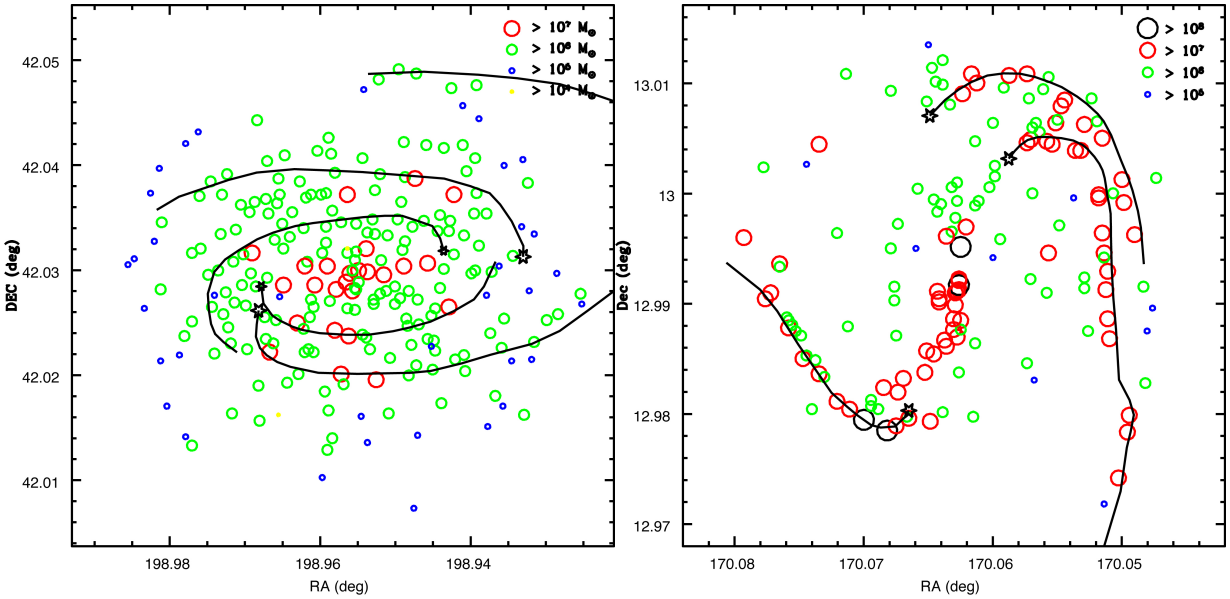




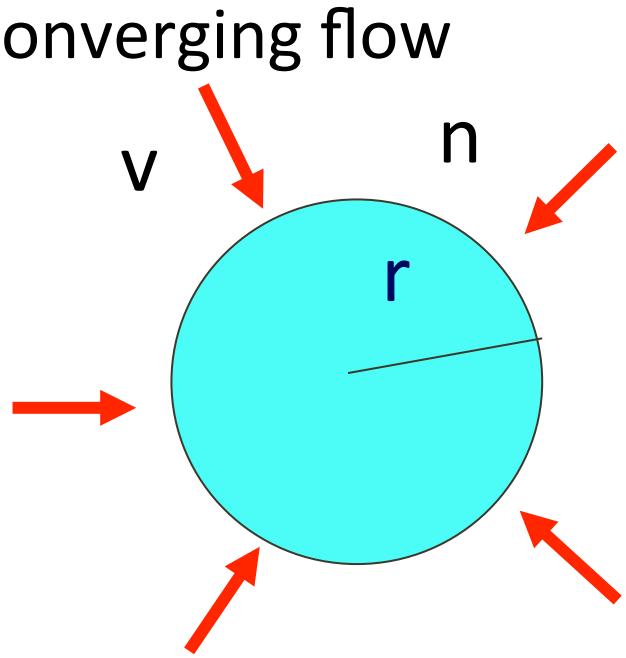
GMC evolution

Large (arm) →

Small (interarm)



In-situ GMC Formation – No!



v: converging velocity

n: density of ambient gas

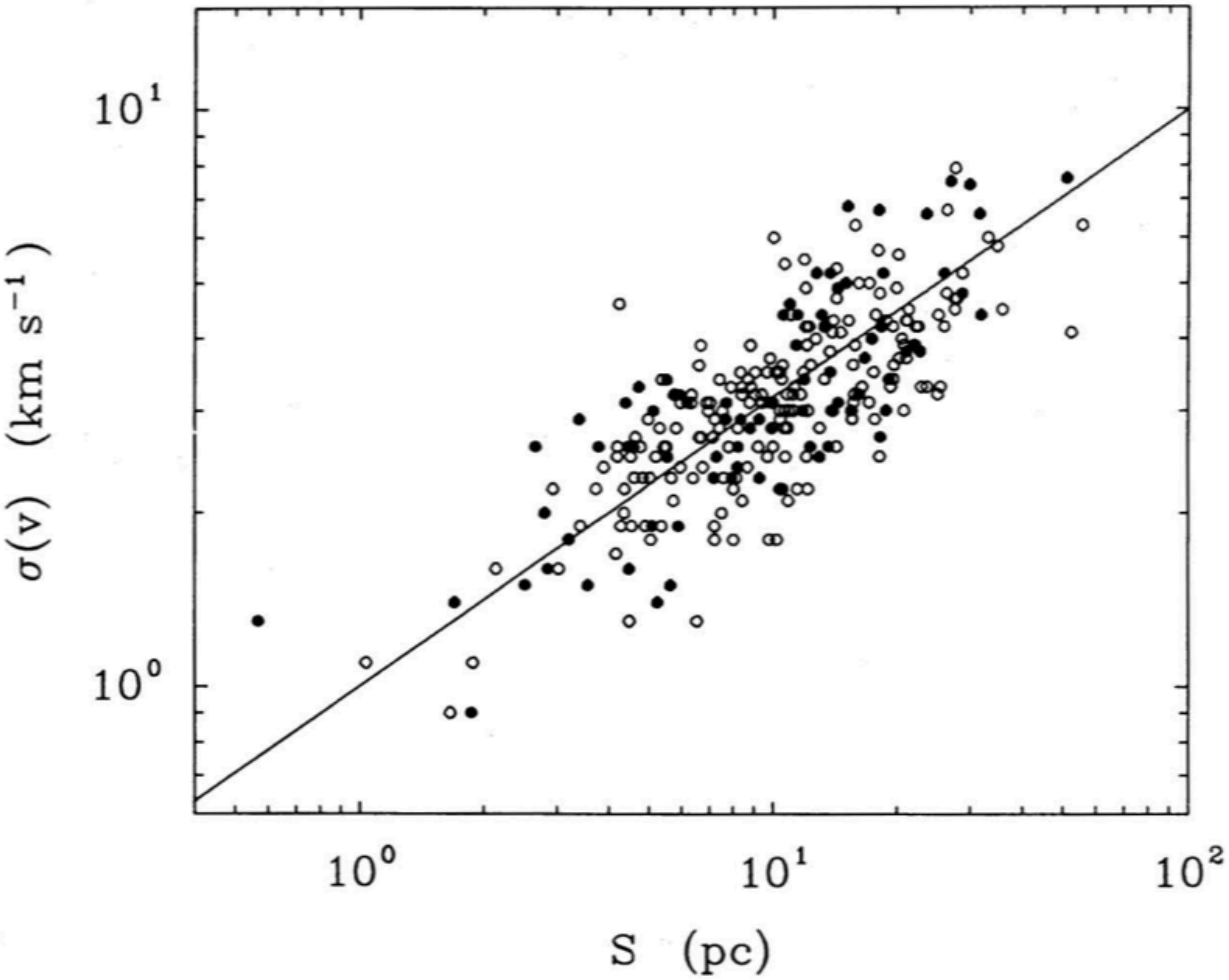
r: radius of region

$$\dot{M}_{in} = 4\pi r^2 m_H n v$$

$$M_{in} = 3\times10^3 M_{sun}\left(\frac{r}{10\,pc}\right)^2\left(\frac{n}{1cm^{-3}}\right)\left(\frac{v}{10km/s}\right)\left(\frac{t}{10^7\,yr}\right)$$

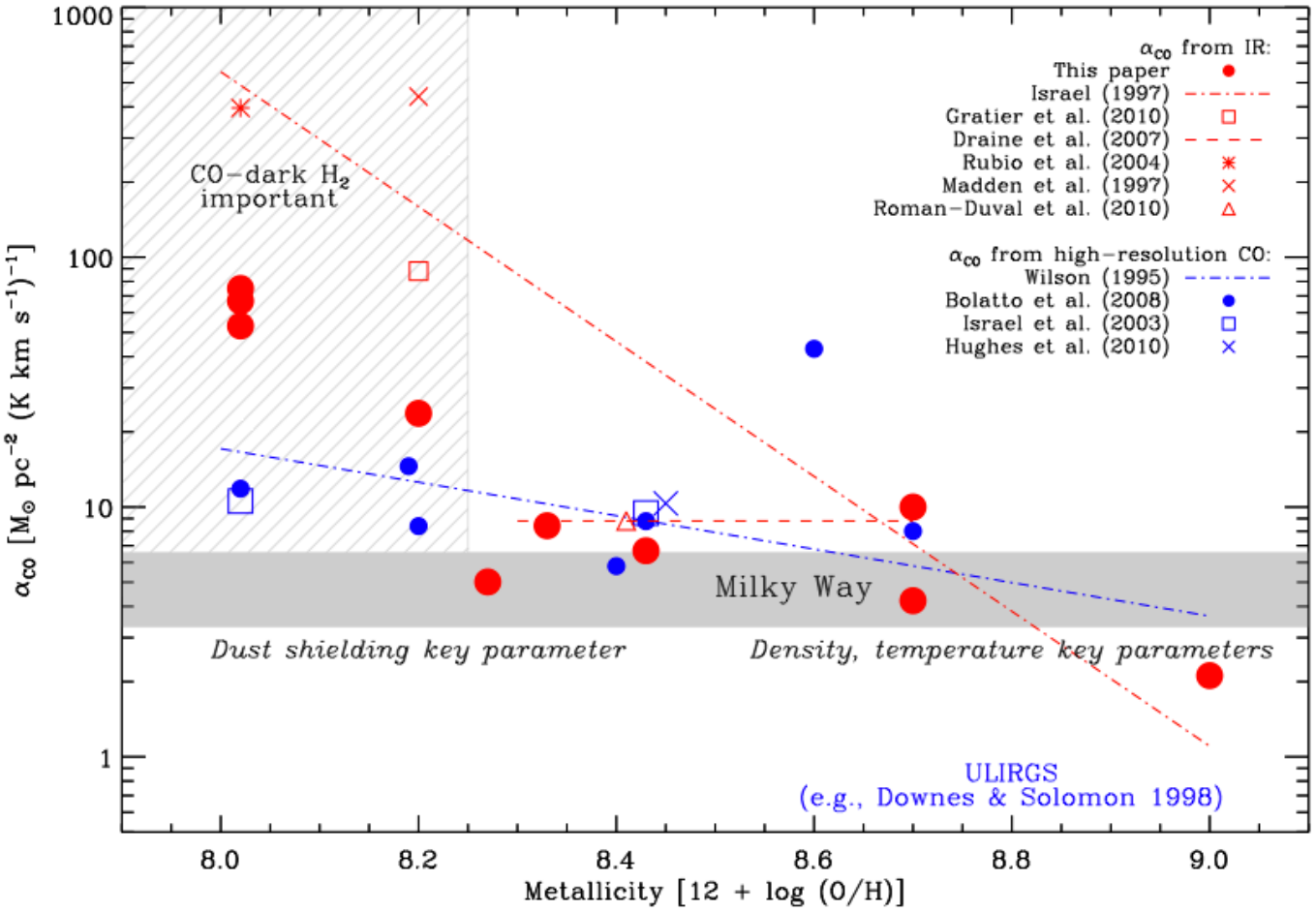
Very difficult to accumulate 10 $^{5\text{-}6}$ Msun in a small volume.

Milky Way GMC population



Solomon et al. (1987)

Extragalactic GMC populations

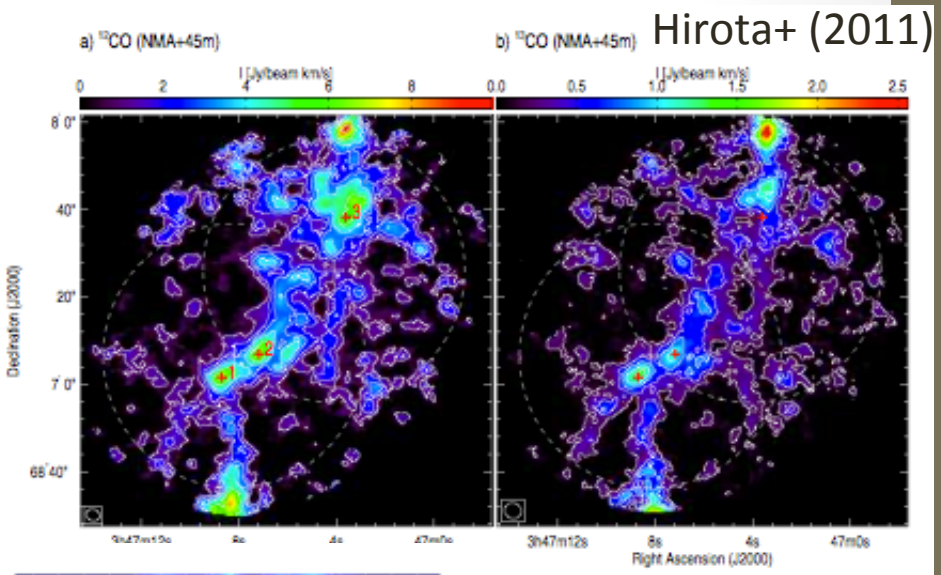


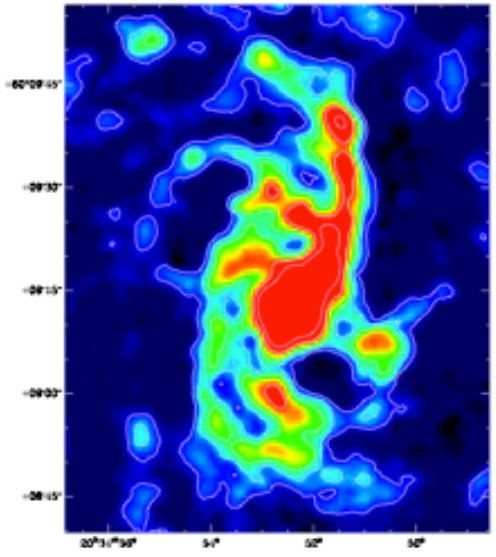
Leroy+ (2011)

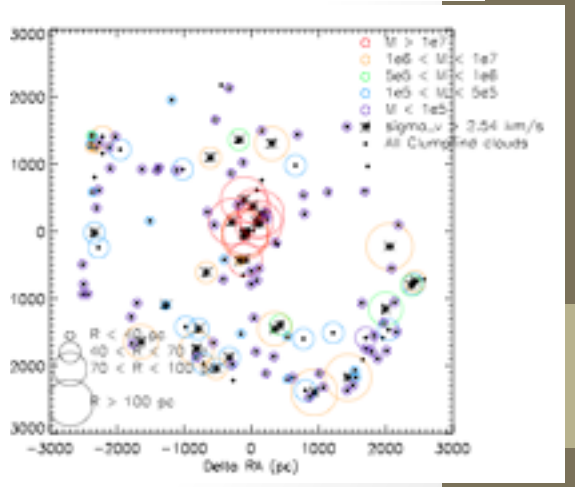
Extragalactic GMC populations

- Low metallicity GMCs have dominated resolvable observations → X_{CO} measurements of Galactic GMCs have been our best guess for everything else
- How similar are Milky Way GMCs to other galaxies' GMCs?
- GMCs in larger spirals are starting to appear…
- But recent BIMA-SONG survey of nearby spirals has resolution 300-400 pc, not enough to resolve typical (or large) Milky Way GMCs

IC 342, Hirota+ (2011)

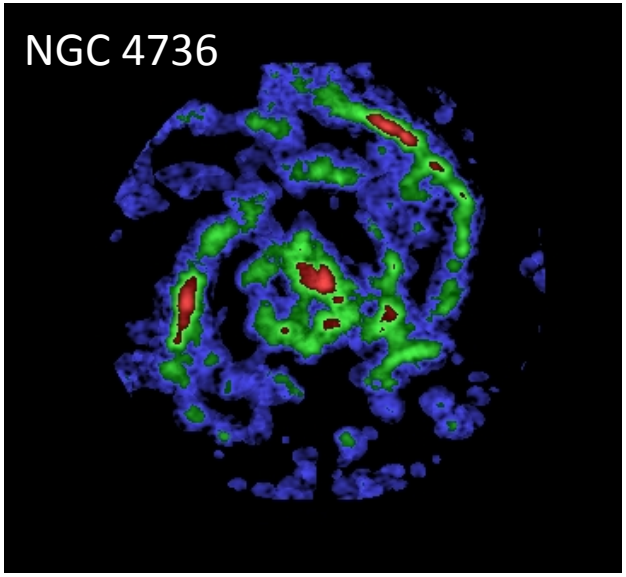


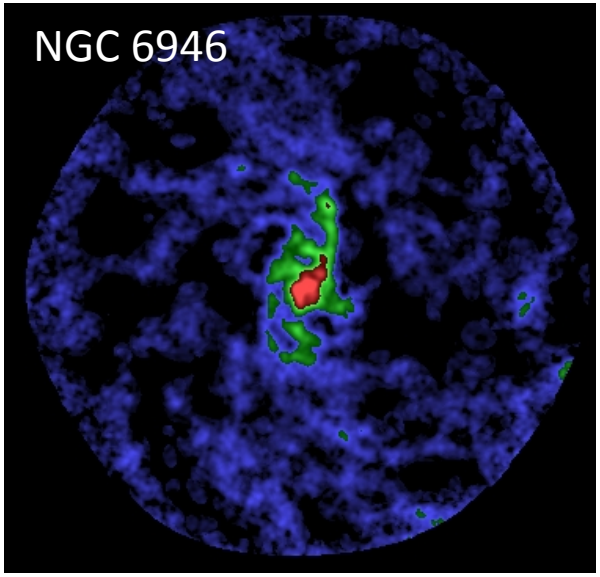


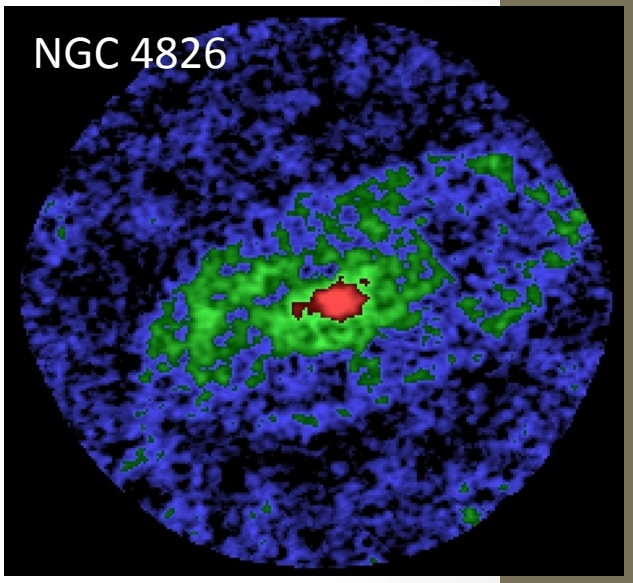


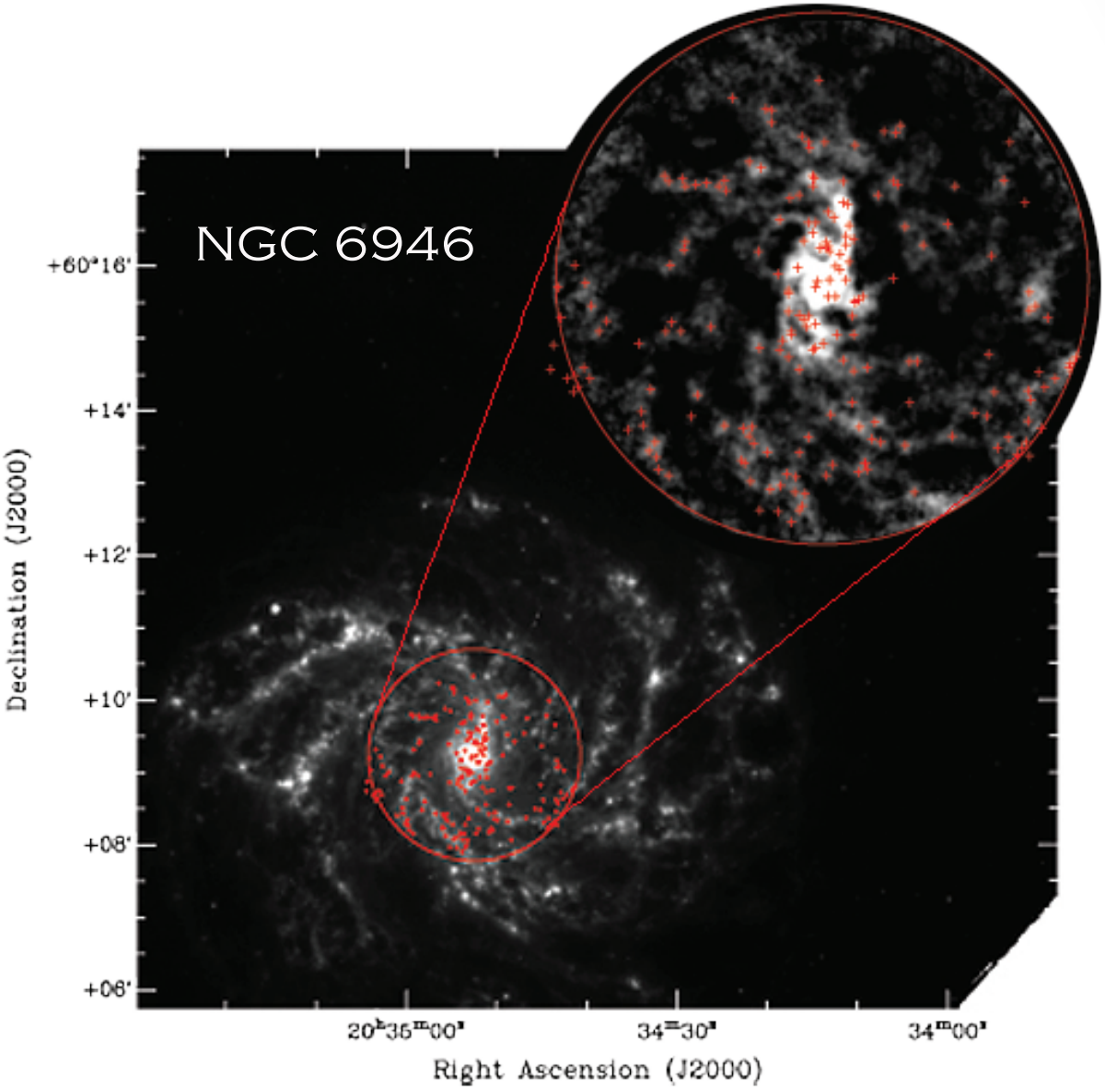
NGC 6946, DM+ (2012)

Best resolved nearby galaxies in CANON

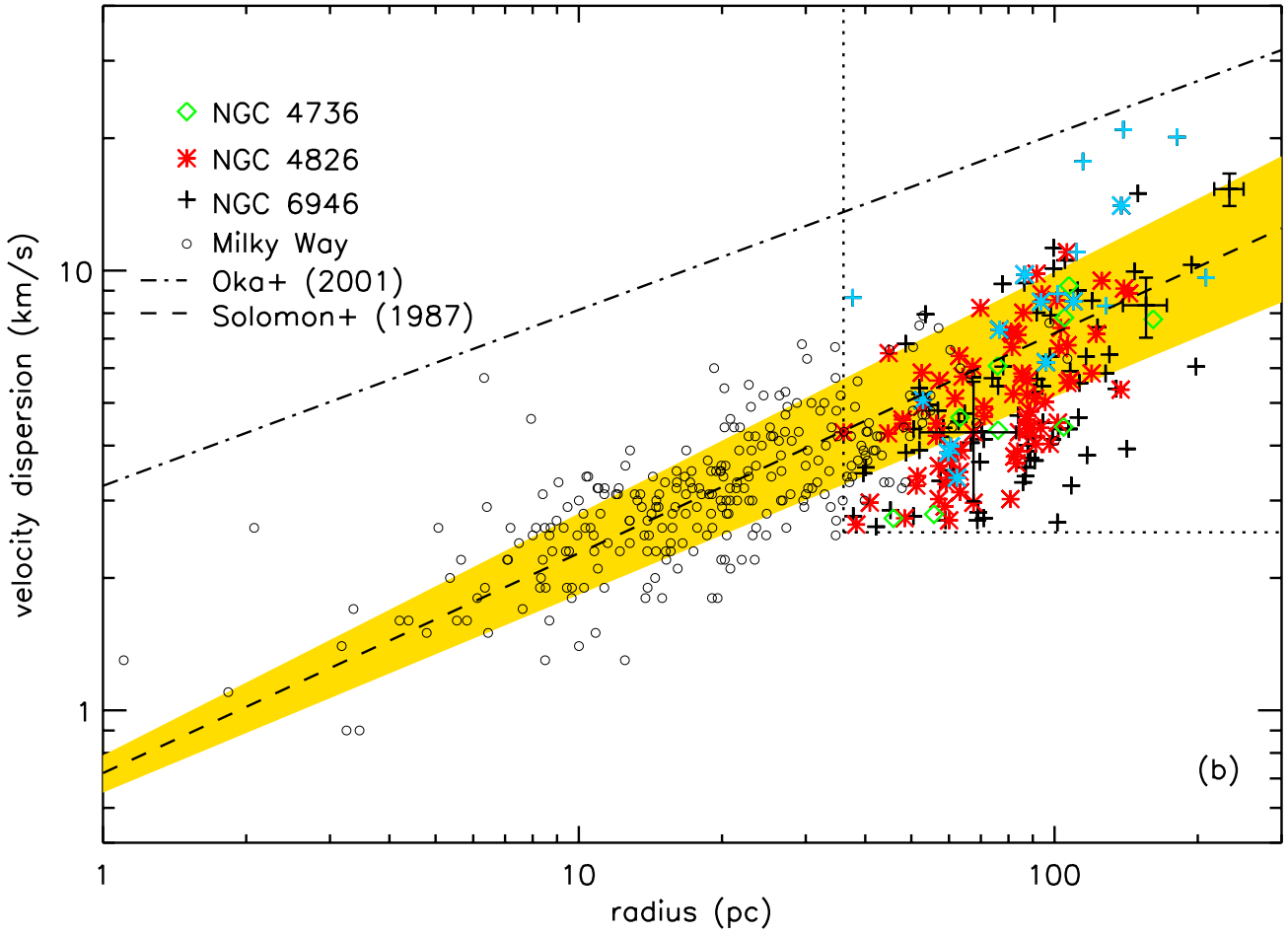






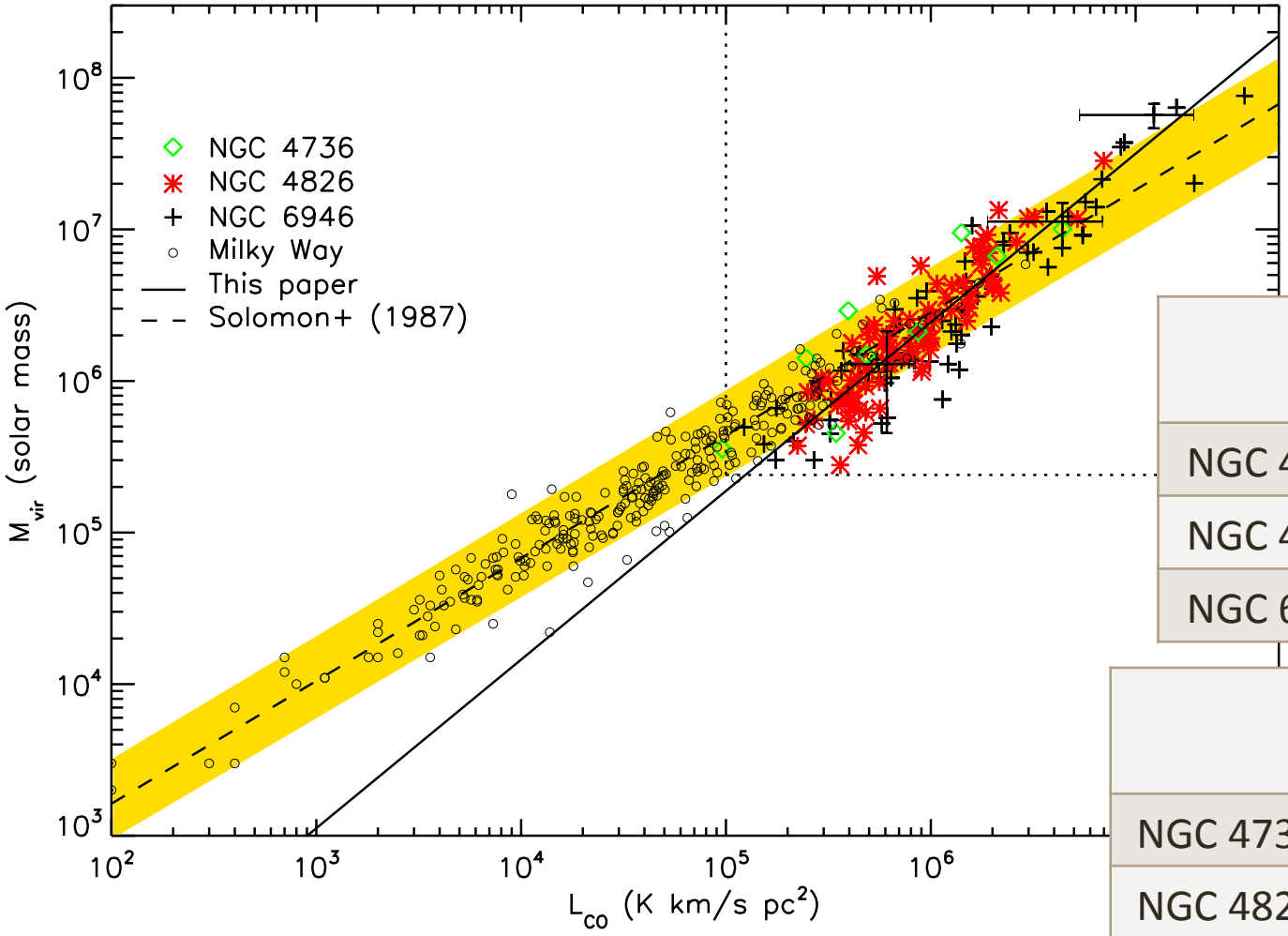

NGC 6946
+60°16'
+14'
+12'
+10'
+08'
+06'
Declination (J2000)
20h35m00s
34m30s
34m00s
Right Ascension (J2000)

GMCs in nearby galaxies



JDM+12, JDM+13

CO-to-H_2 conversion factors

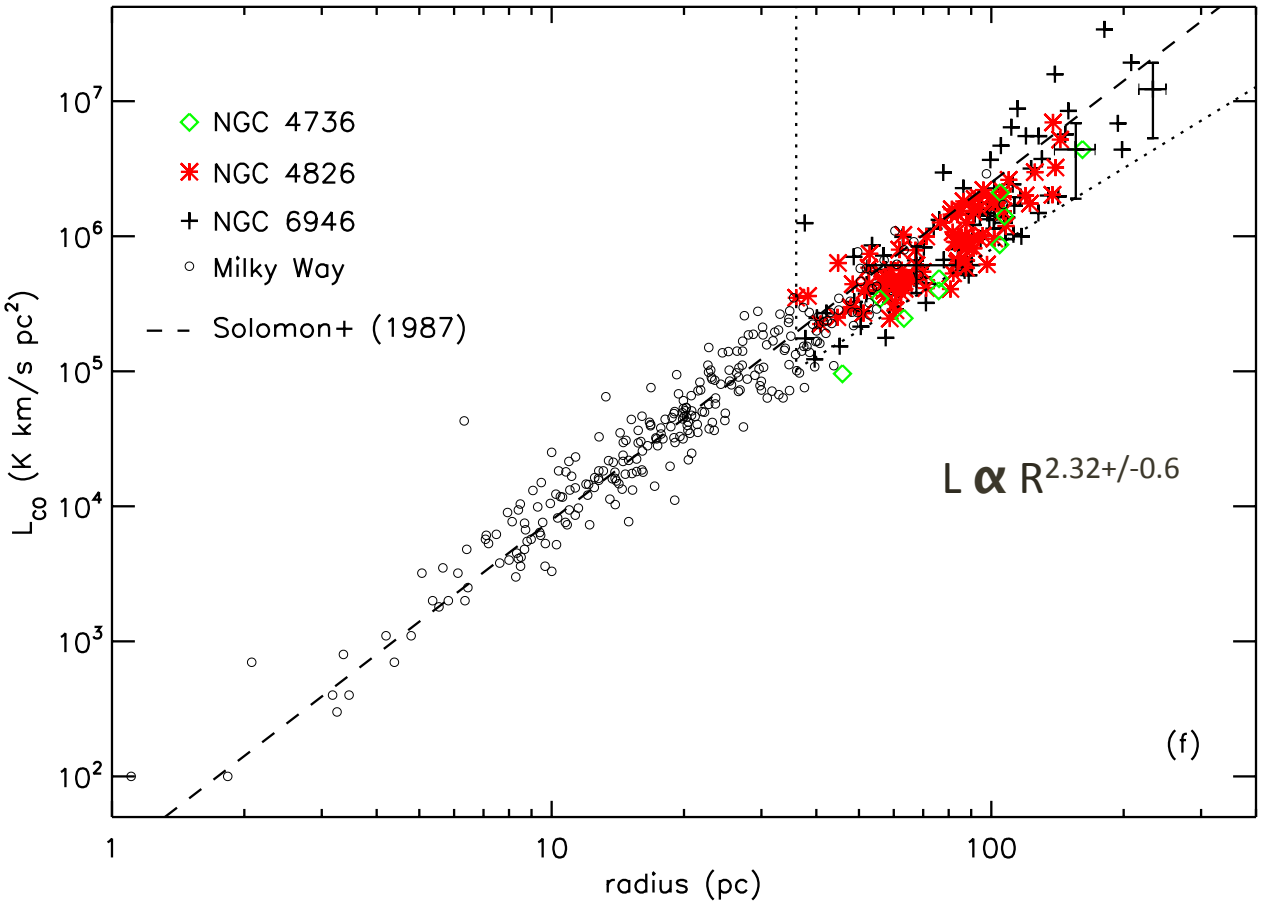


	Avg. Σ (M_{sun}/pc^2)
NGC 4736	120
NGC 4826	140
NGC 6946	170

	Avg. X_{co} (cm^{-2} / (K km/s))
NGC 4736	1.83 x 10^{20}
NGC 4826	1.27 x 10^{20}
NGC 6946	1.15 x 10^{20}

JDM+12, JDM+13

GMCs in nearby galaxies

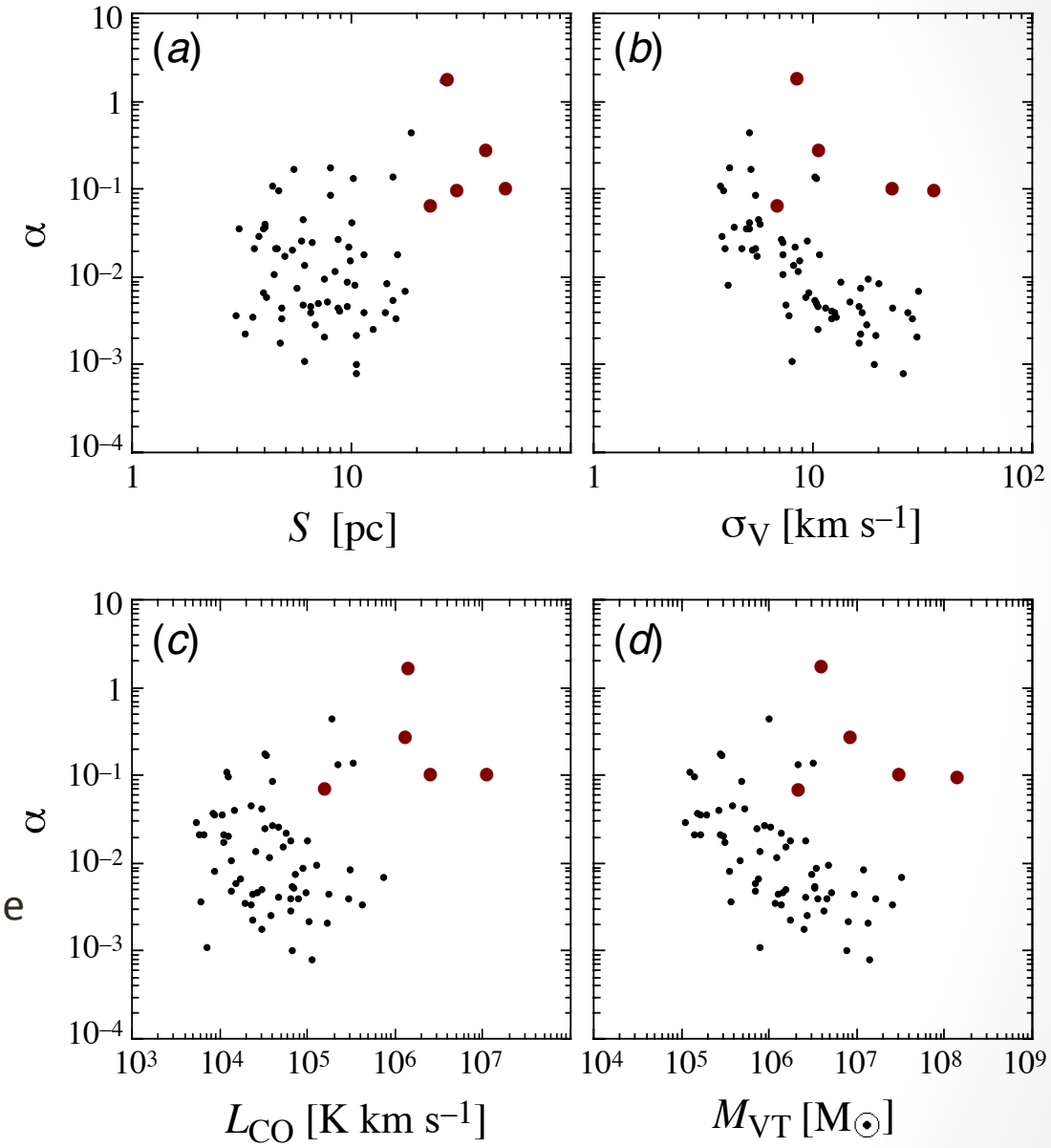


JDM+12, JDM+13

- Galactic center clouds

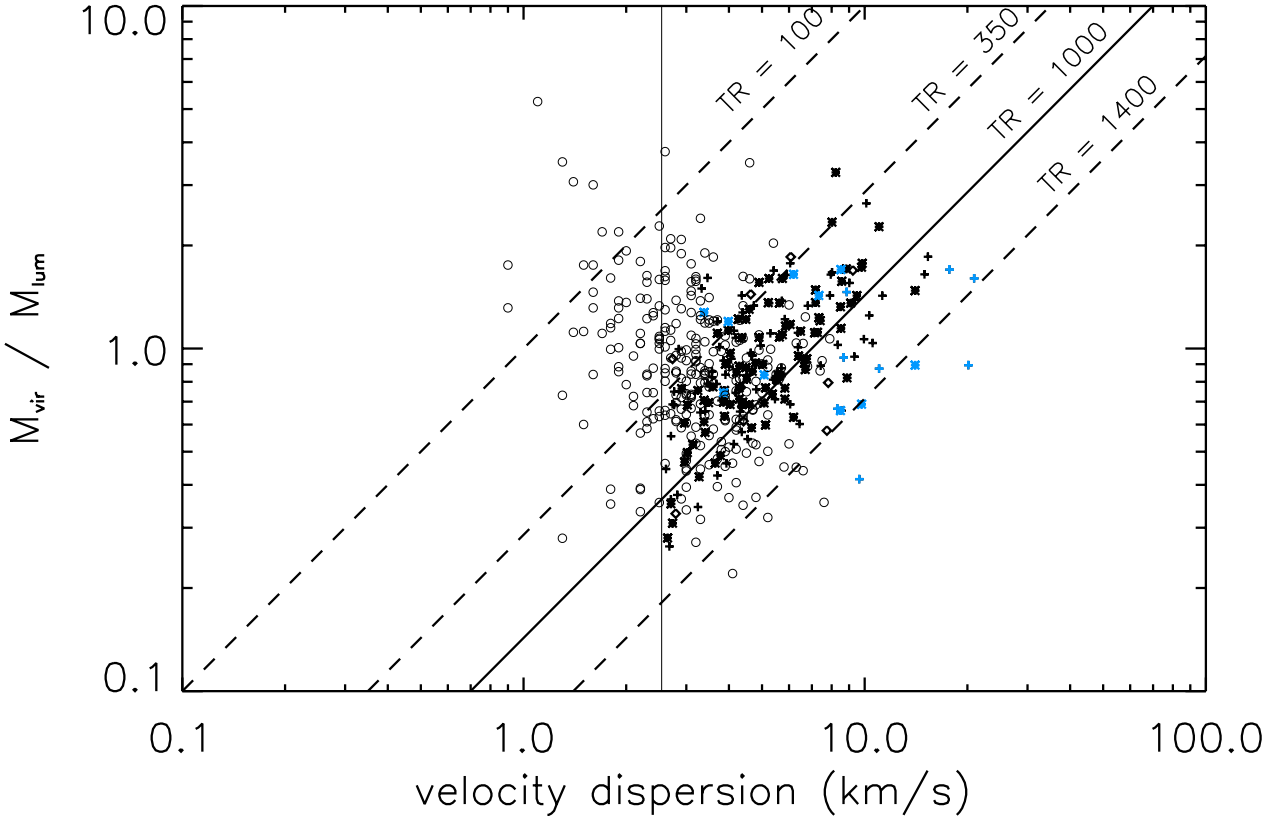
stable

unstable



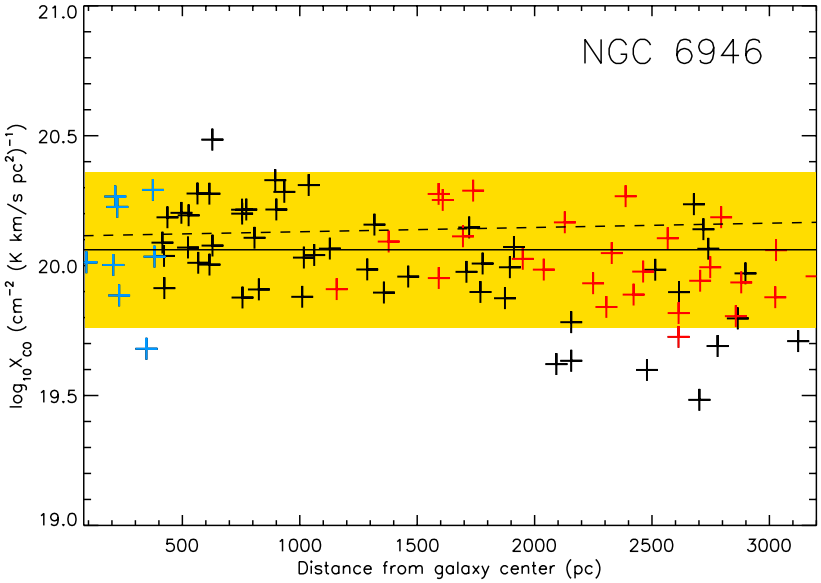
Oka+ (2001)

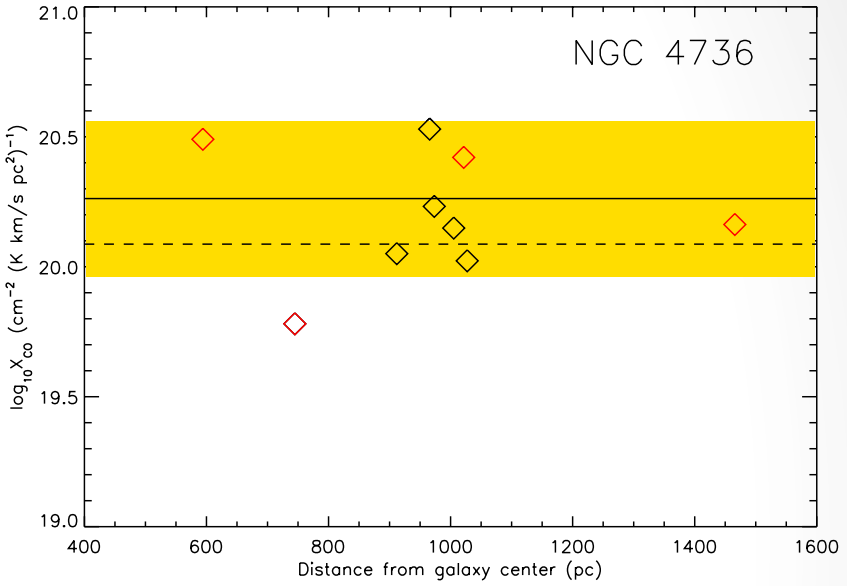
Cloud stability and velocity dispersion

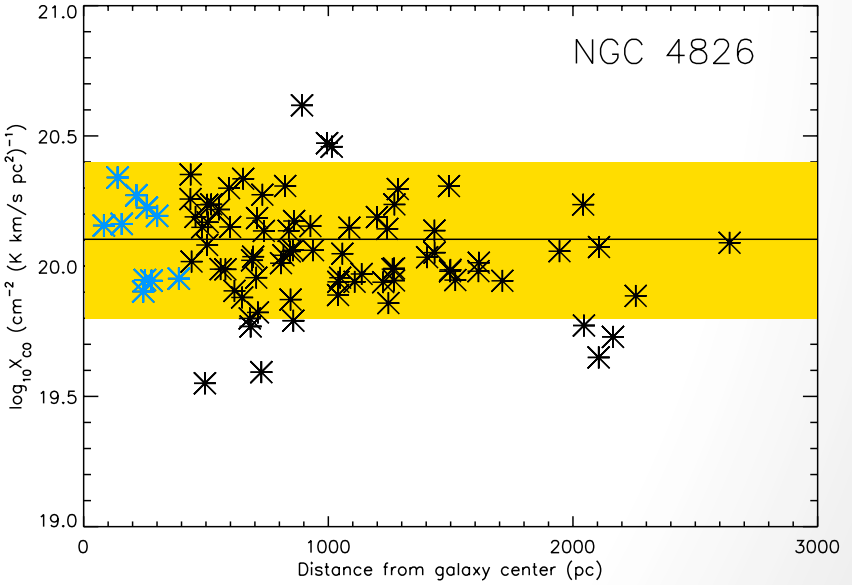


JDM+ (2013)

Radial "profiles"

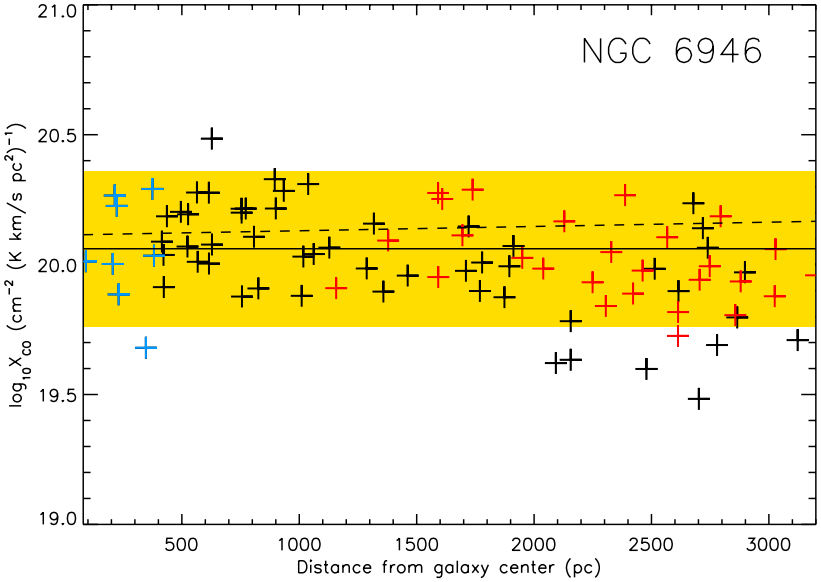


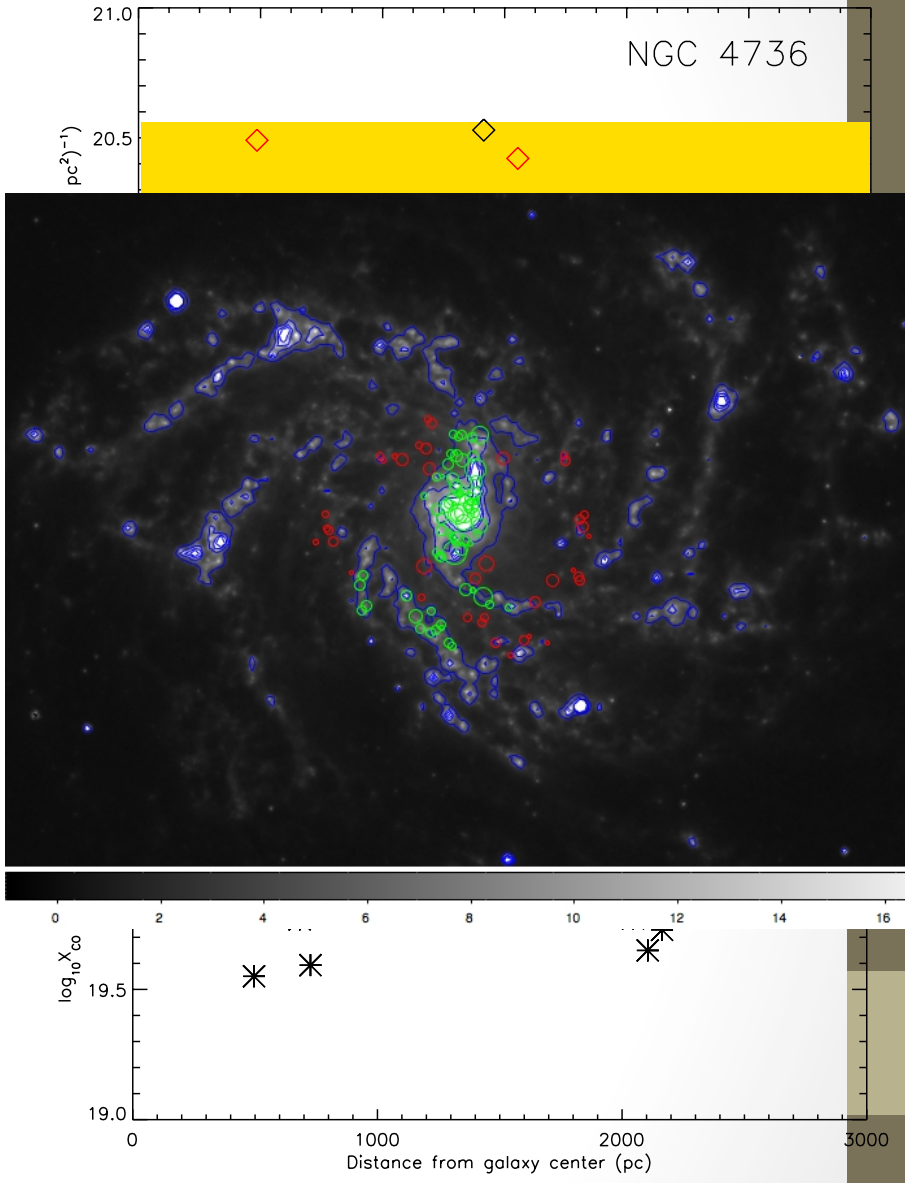




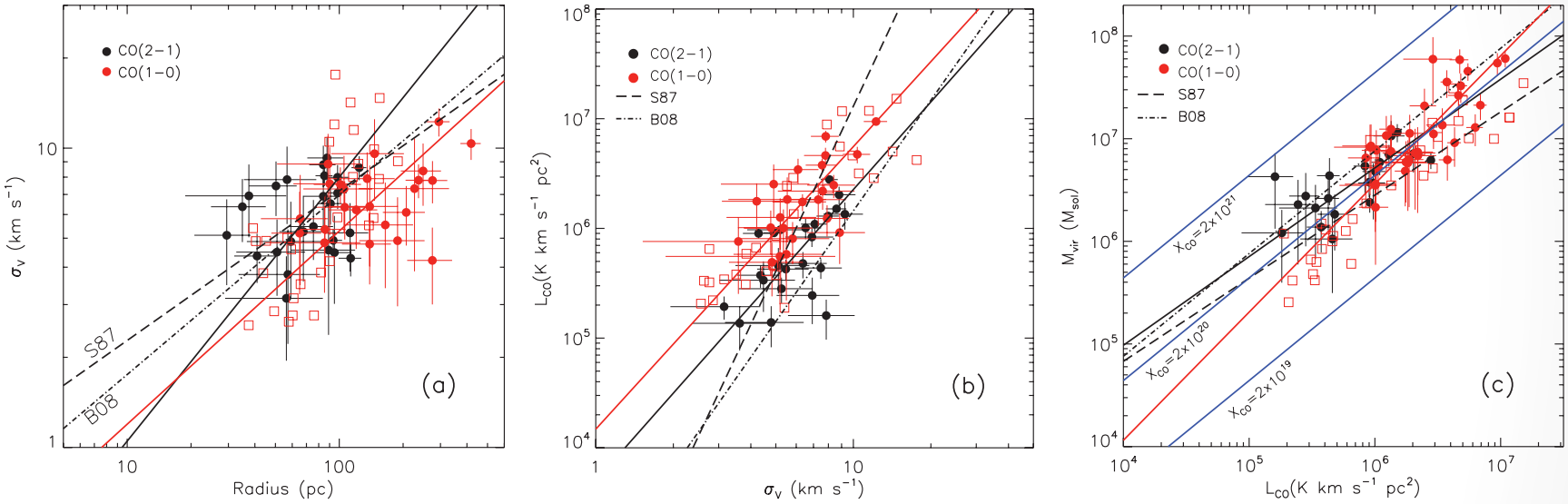
JDM+ (2013)

Radial “profiles”



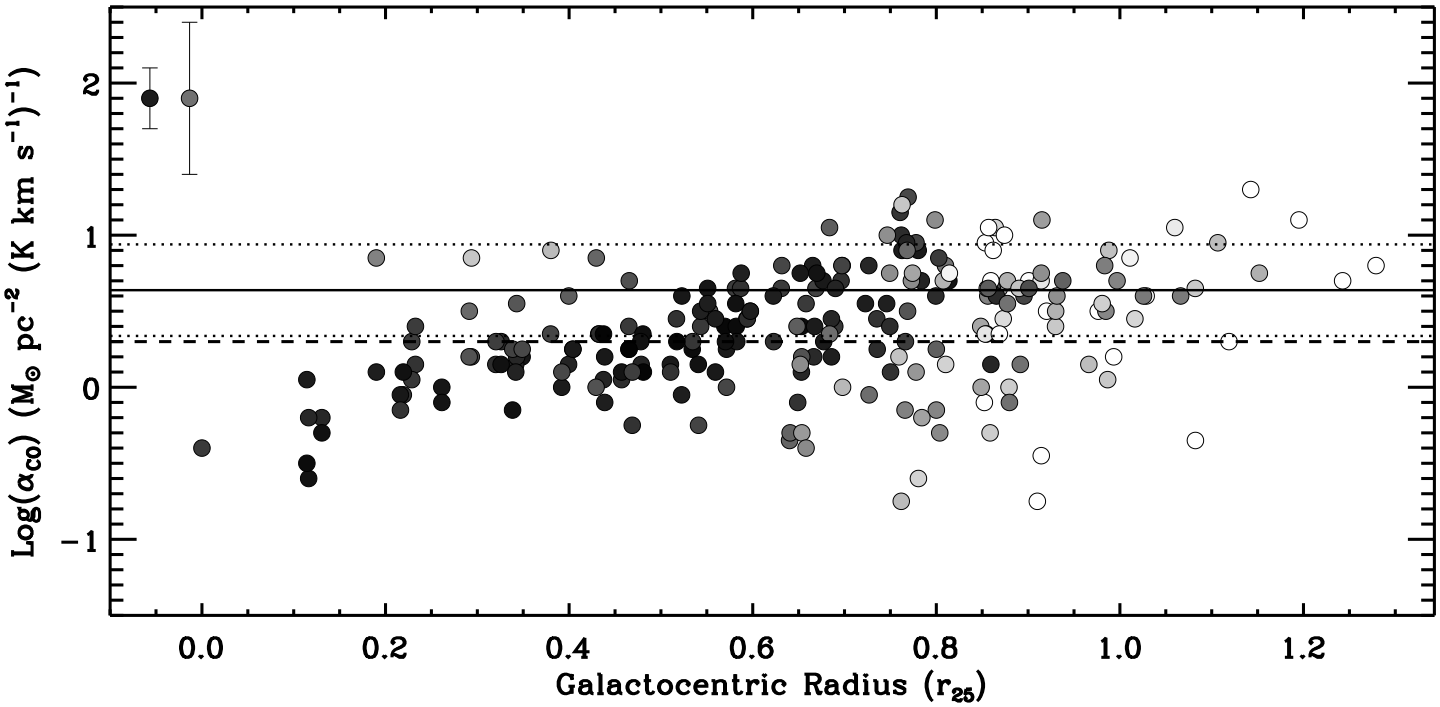


Outer disk of NGC 6946



Rebolledo+ (2012)

Dust to gas ratio (DGR) and Xco

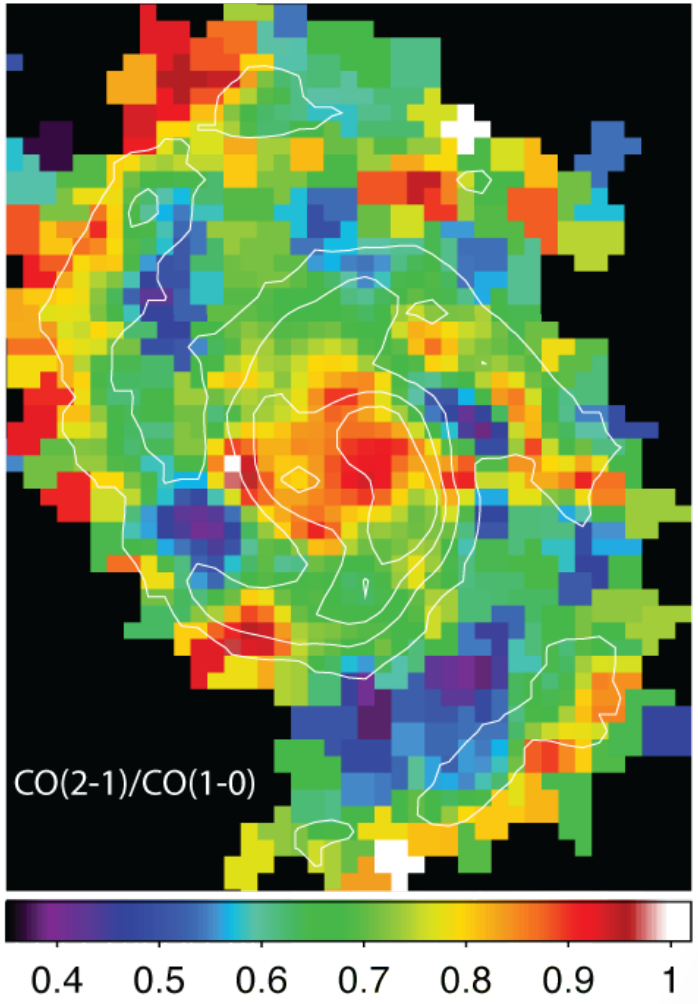


$$\Sigma_{\rm dust} = {\rm DGR}\,(1.36\Sigma_{\rm HI} + \alpha_{\rm CO} I_{\rm CO})$$

Sandstrom+12

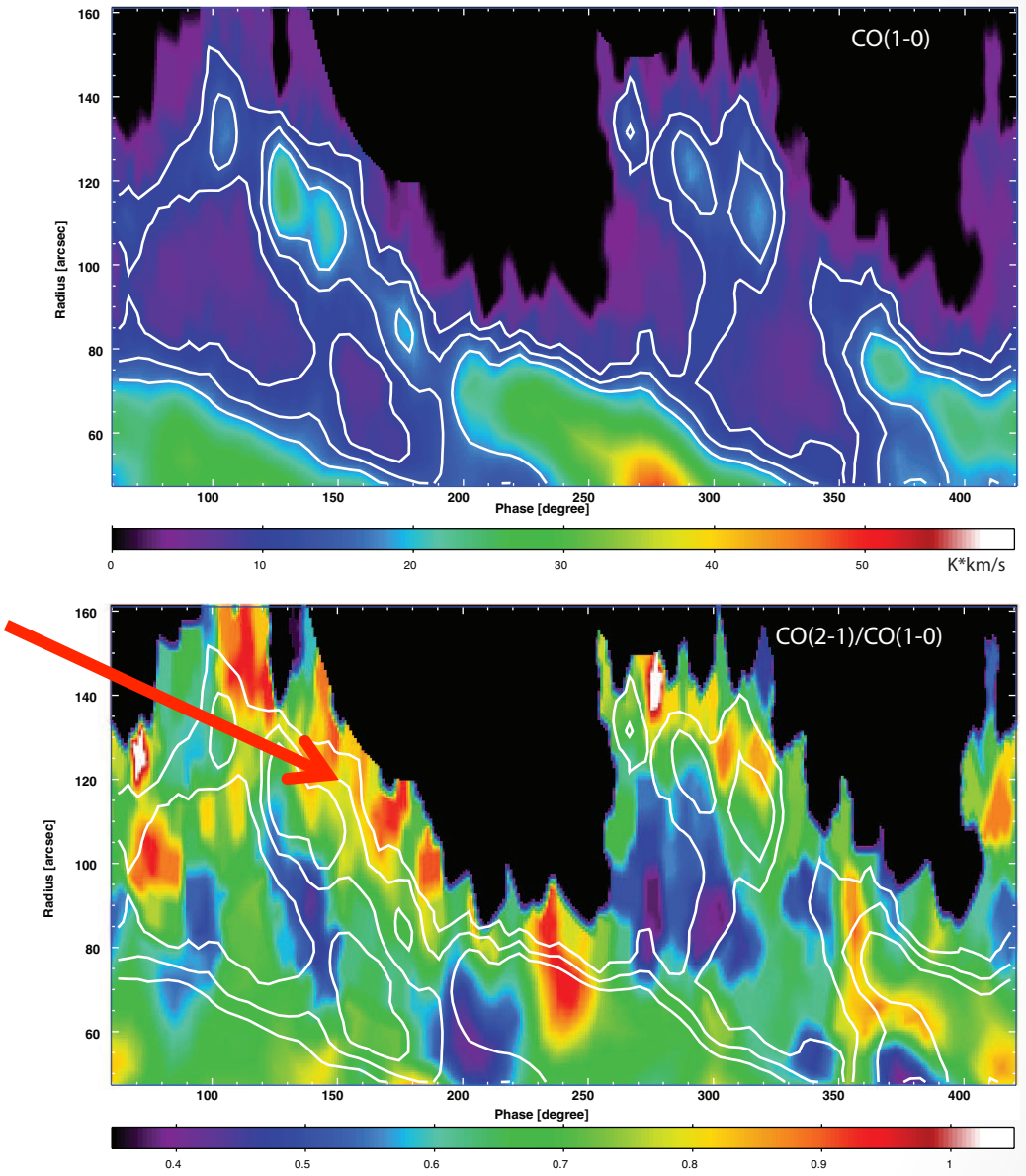
CO (2-1)/CO (1-0)

- Spiral arms
  - High ratio ~ 0.8-1.0
- Interarm regions
  - Low ratio ~ 0.4-0.6
- Central 2.5kpc
  - High ratio ~ 0.8-1.0

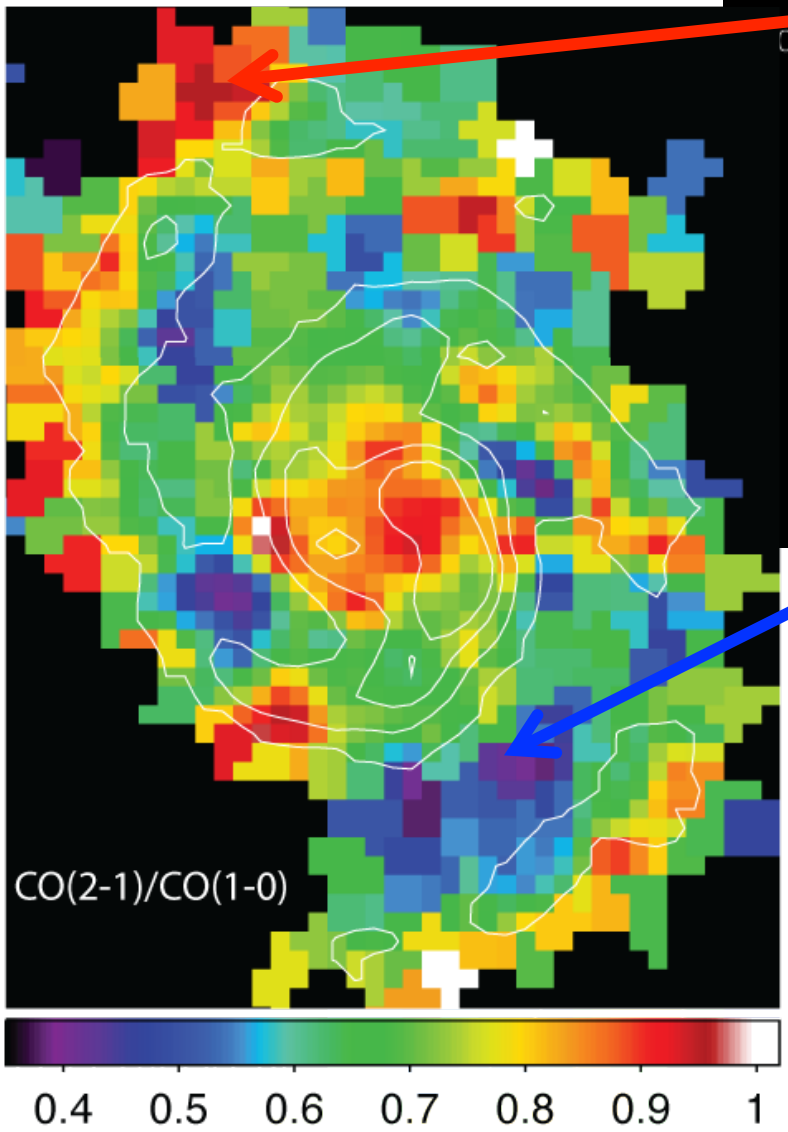


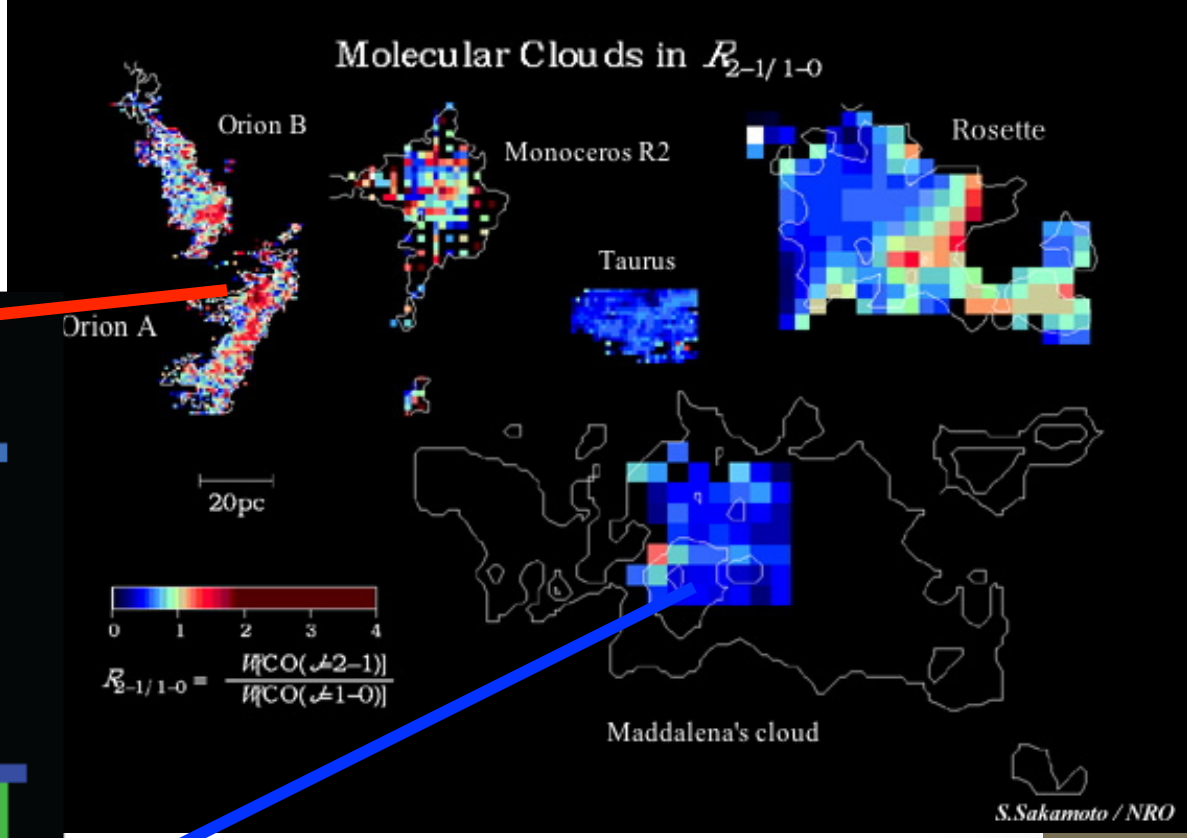
Koda+ (2012)

High line ratio gas leads spiral arms



$R_{2\text{-}1/1\text{-}0}$



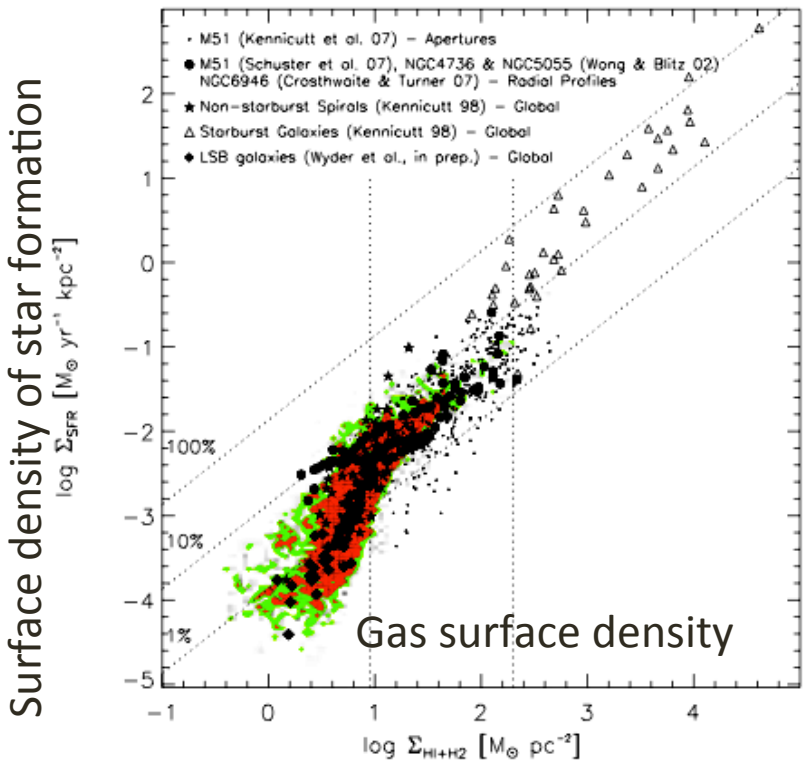


- Interarm -- dormant, less star forming GMCs
- Spiral arms – actively star forming GMCs

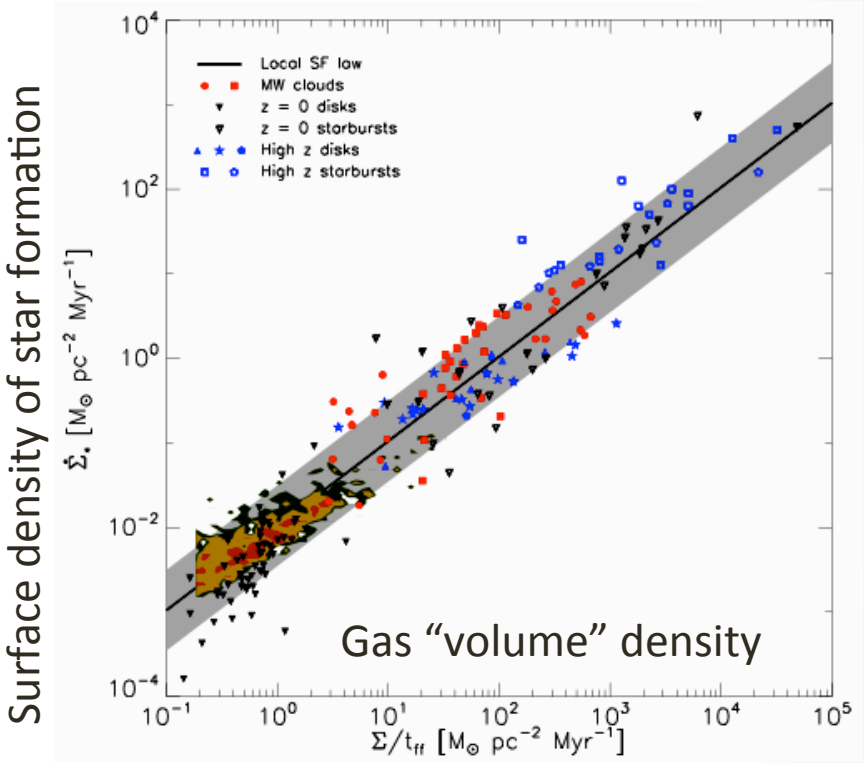
Koda+ (2012)

A quick word about star formation…

Schmidt-Kennicutt relation



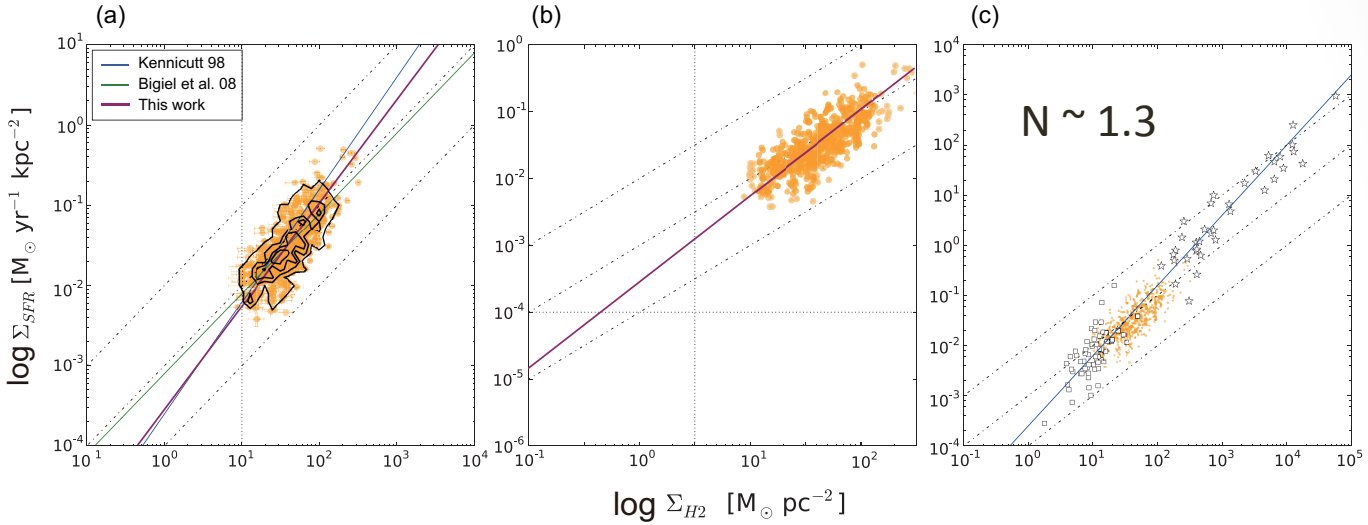
Bigiel+ (2008)



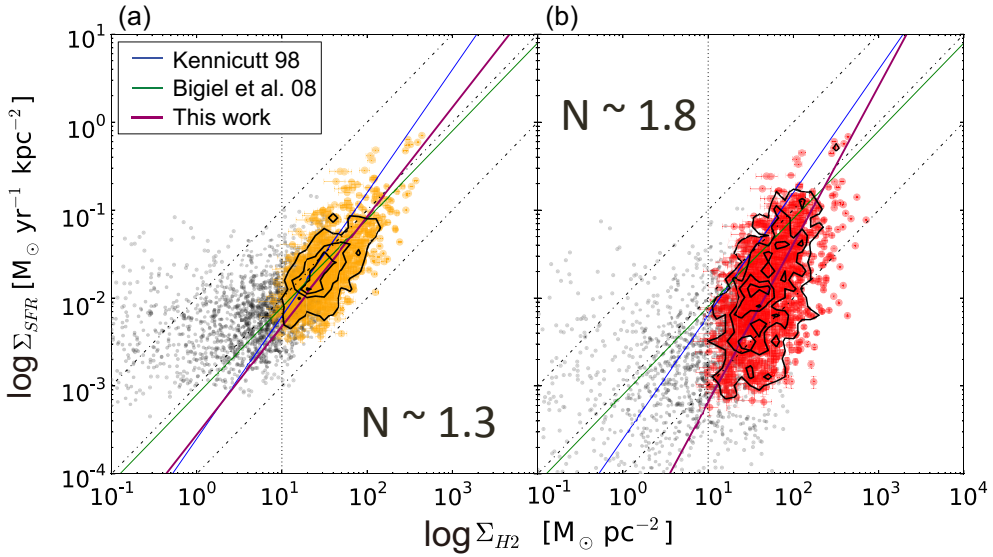
Krumholz+ (2011)

CO (1-0) vs. star formation

750 pc scale

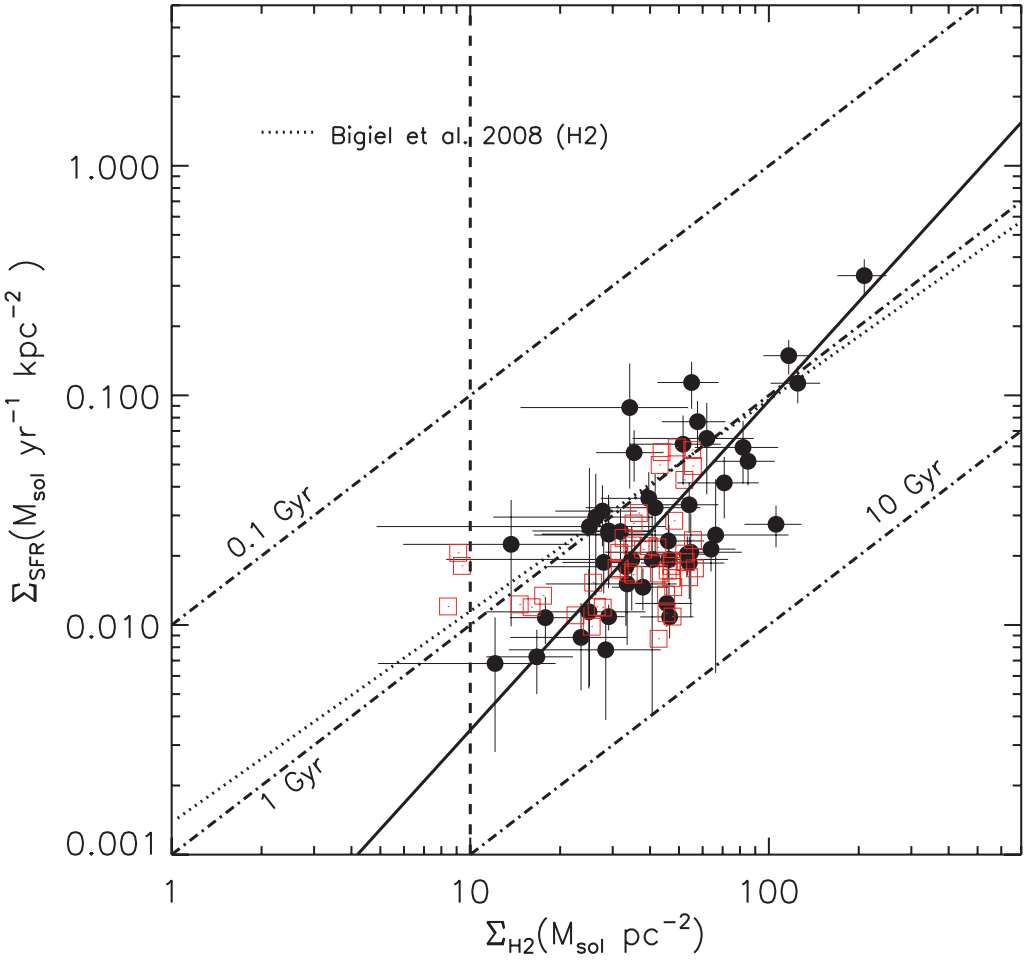


500 pc scale



Momose+ (2013), accepted

Star formation in the outer disk of NGC 6946



Rebolledo+ (2012)

Summary

- Our CARMA+NRO survey of nearby galaxies enables resolved measurements of GMCs in galaxies outside of the Local Group
  - GMCs are similar with X_{co} within a factor of 2 of the MW value
  - No dependence on environment or radius is observed

- The excitation state of the gas, traced by CO(2-1)/CO(1-0) ratio, is higher on the leading edges of spiral arms (0.8-1.0) than in the interarm regions (0.4-0.6) in M51
  - Average over whole disks is ~0.7, but varies with environment
  - Has implications for constraints of Xco and DGR using CO(2-1)

- Star formation law consistent with slope N = 1.3