Ringberg, June 2013

Structure and Organization of the Molecular ISM:

The extragalactic perspective

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with lots of help from R. Xue (UIUC), A. Bolatto (UMD), J. Koda (Stony Brook), A. Hughes (MPIA), E. Rosolowsky (UBC), and many others…

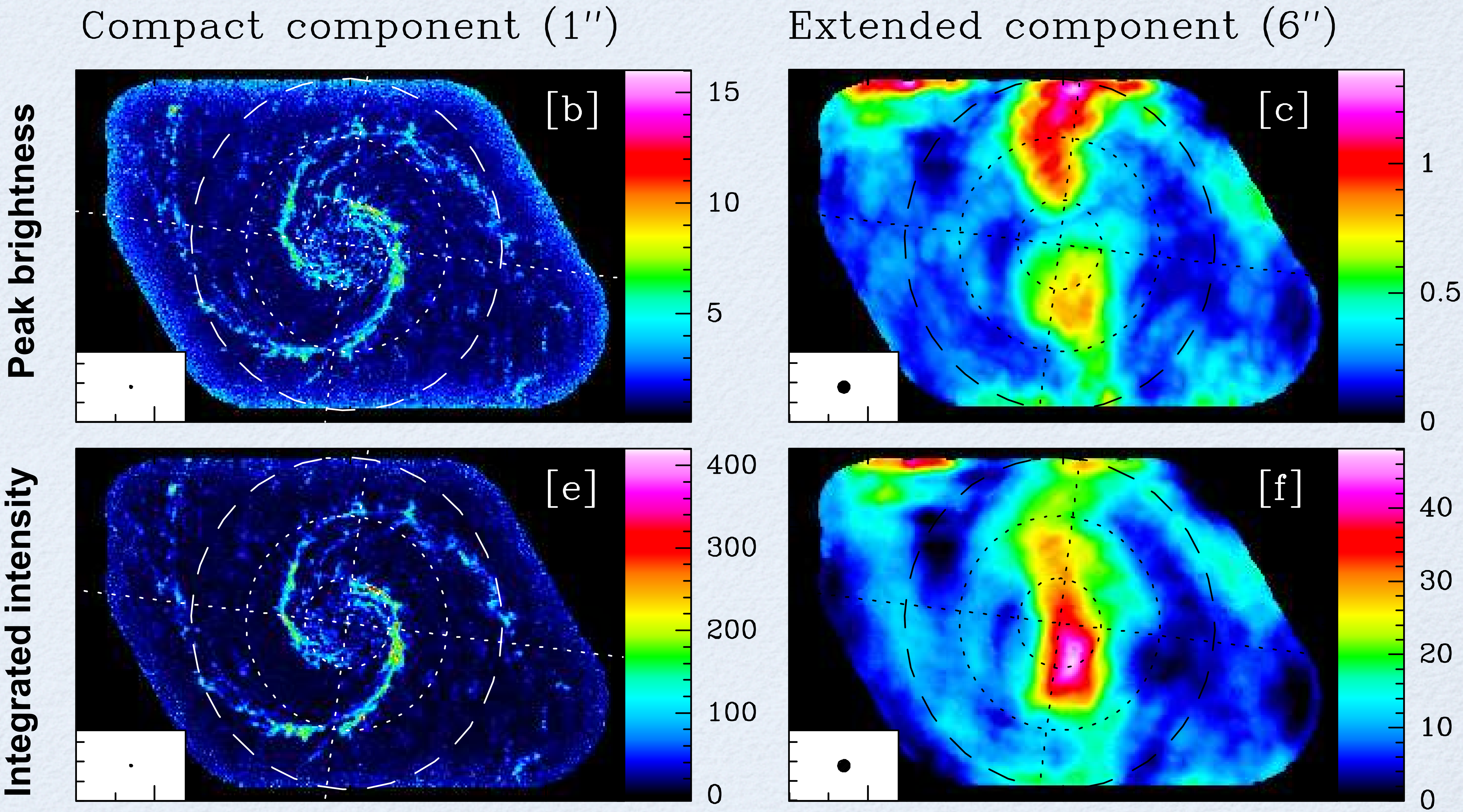
OUTLINE

- Why study the structure of molecular gas?
- The global gas content of galaxies
- Radial distributions and central concentrations
- Azimuthal variations and spiral structure
- Structural decomposition

Motivation

- Molecular gas (at least in our vicinity) is dense, cold, and closely related to star formation.
- This is ***unlike*** atomic gas, which is multiphase (CNM/WNM) under a wide range of conditions.
- Thus non-star-forming HI will tend to be heavily overrepresented in terms of area or volume.
- Main challenges have been sensitivity and resolution: we rely heavily on integrated CO fluxes and have difficulty identifying substructure.
- Even with ALMA we will need to be mindful of short spacings & modeling of excitation, optical depth.

MOTIVATION

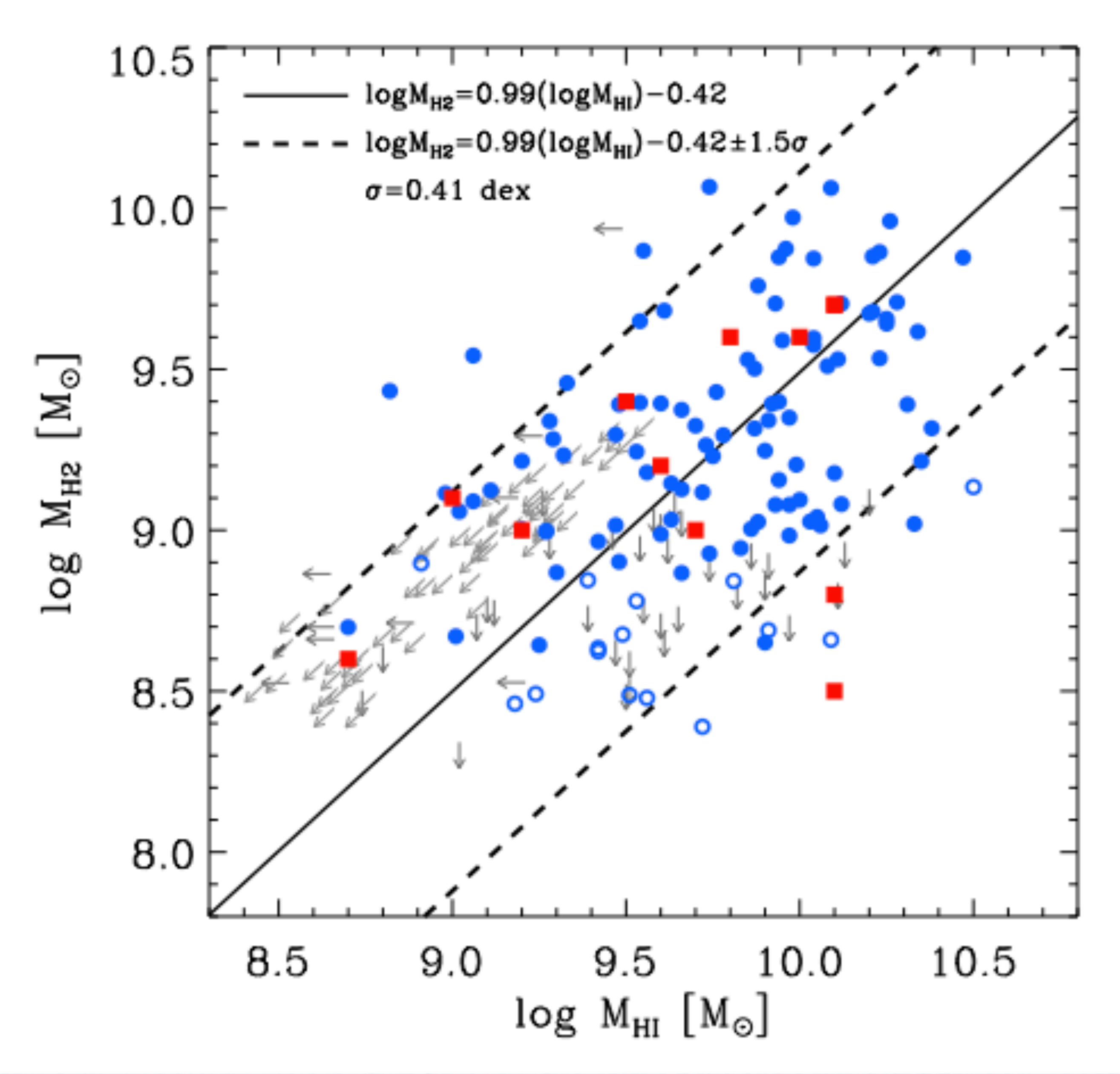


Pety+ 2013

The Molecular ISM: Global Properties

Global Gas Content

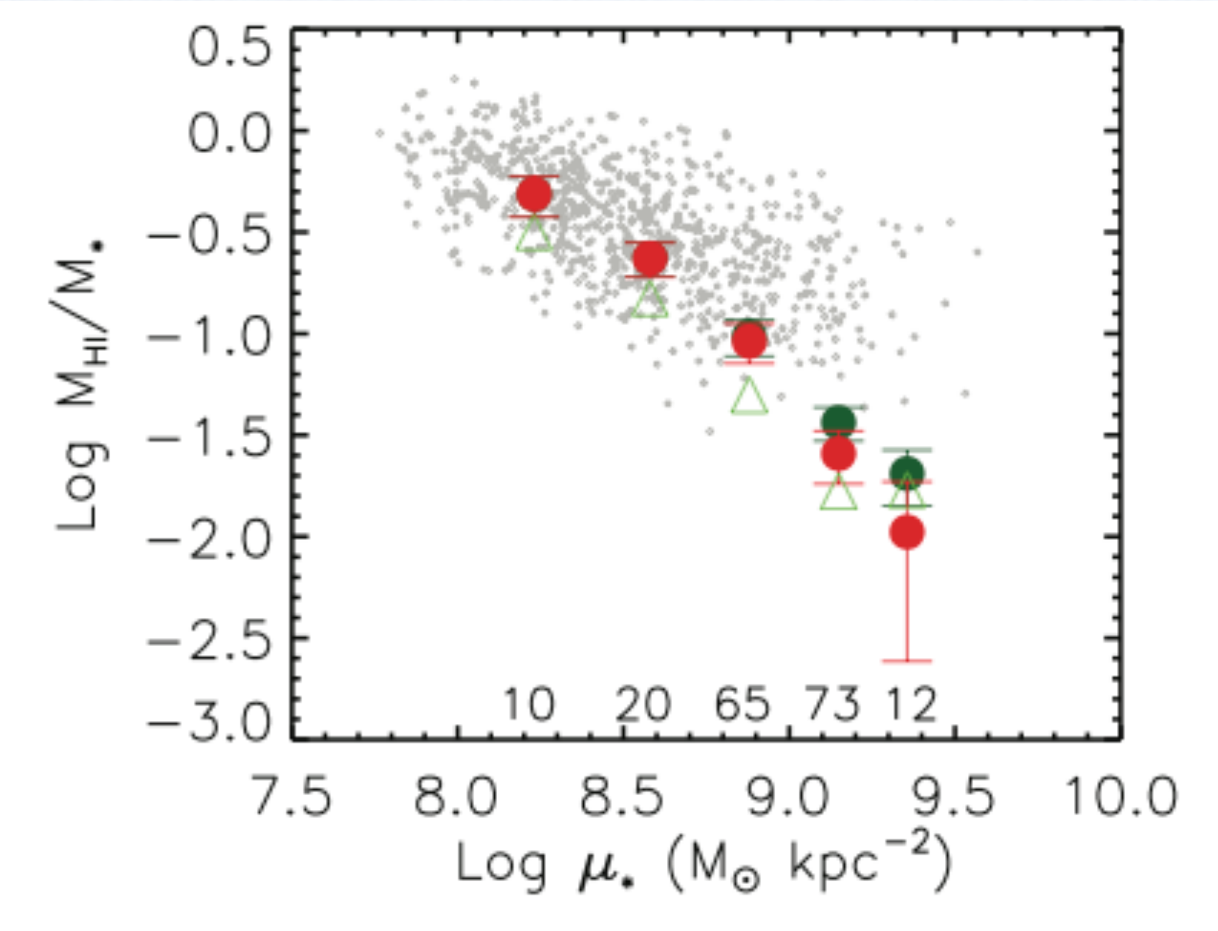
- Based on CO flux measurements with single-dish telescopes
- $M(H_2) \sim 0.3 \times M(HI)$, with large scatter.
- Blue circles: COLD GASS (Saintonge+ 2011).
- Red squares: HERACLES (Leroy+ 2008).



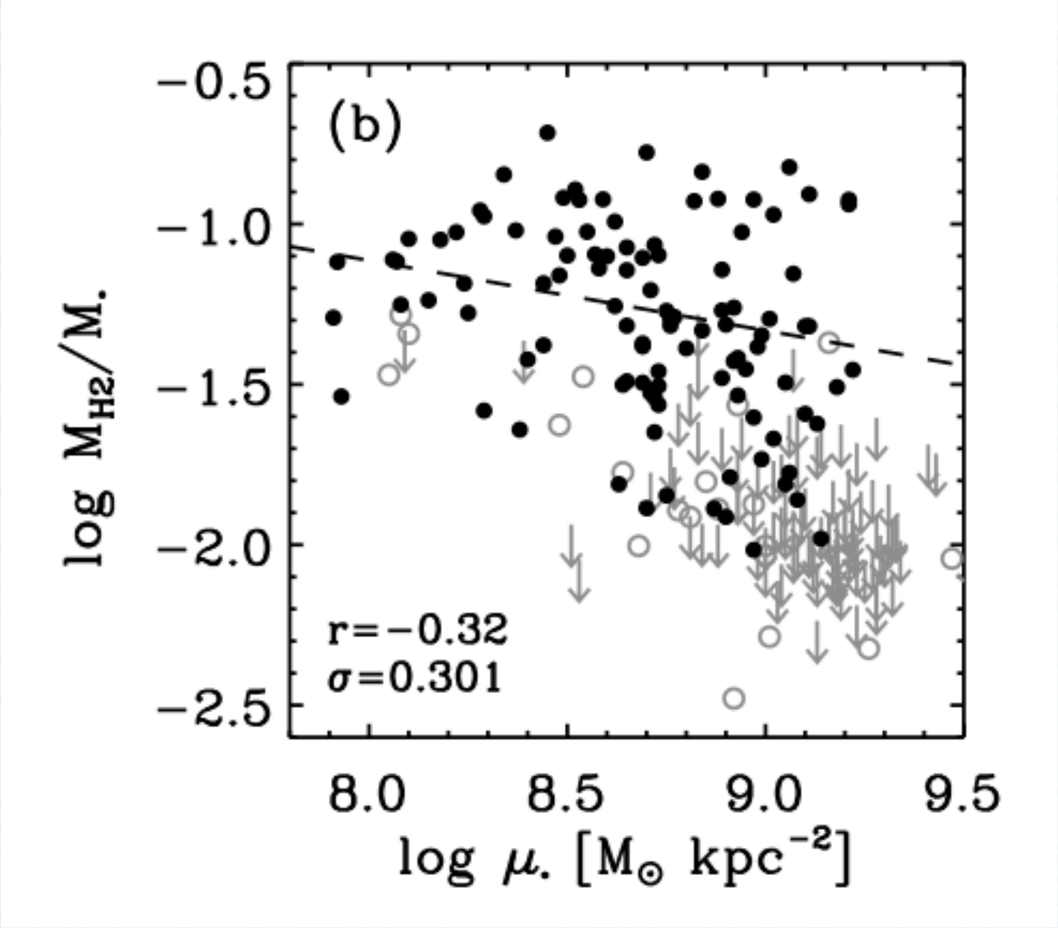
Saintonge+ 2011

GLOBAL GAS CONTENT

- While both f(H_2) and f(HI) decrease with stellar surface density, the trend is far more pronounced for f(HI).
- Note that detectability of H_2 is a strong function of stellar surface density, even if the H_2 fraction, once CO is detected, is not.



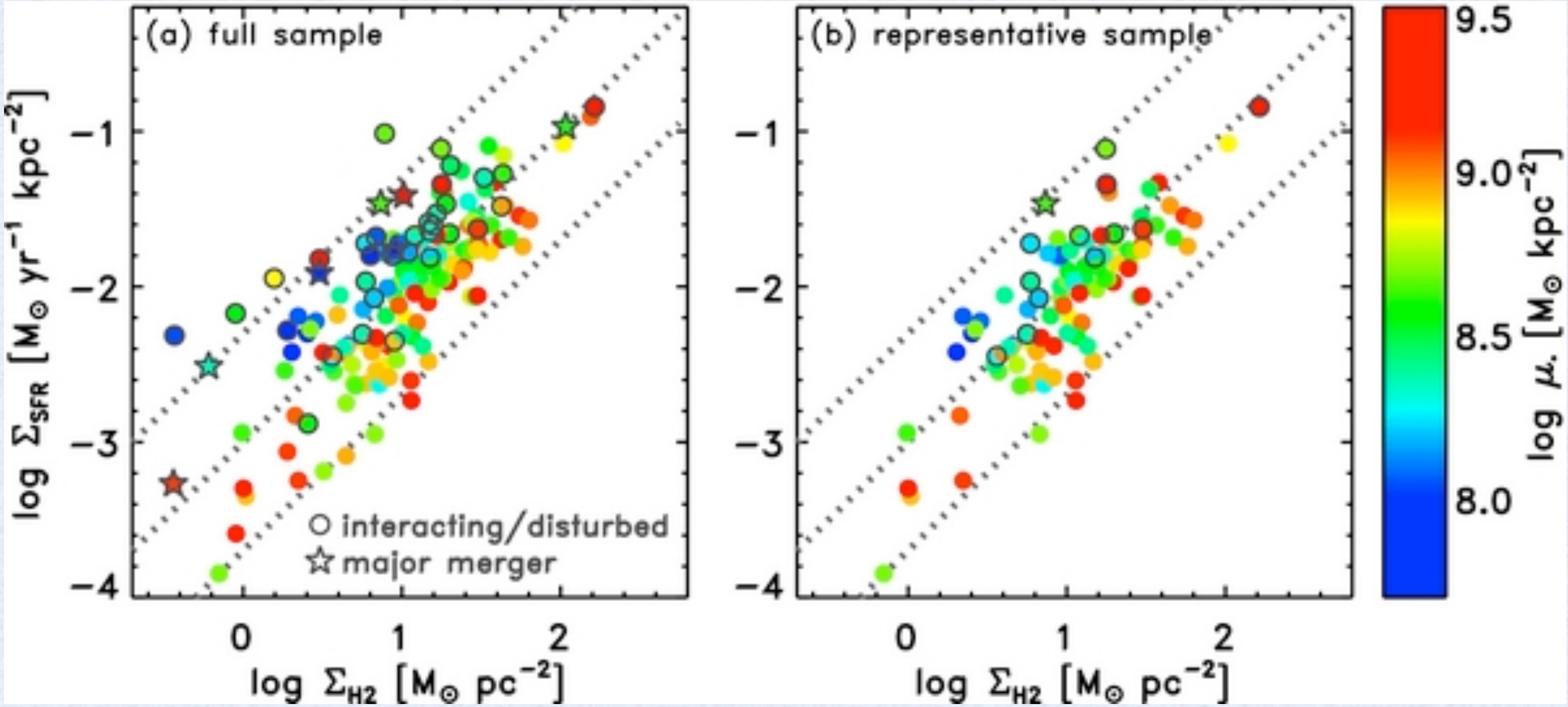
Catinella+ 2010



Saintonge+ 2011

Global Gas Content

- The tendency for high μ_* galaxies to prefer molecular over atomic gas *does **not** imply that they experience more star formation*.
- These galaxies are displaced below the usual Kennicutt-Schmidt relation between H_2 and star formation (Saintonge+ 12).
- Suggests H_2 disks can differ in terms of gravitational instability.

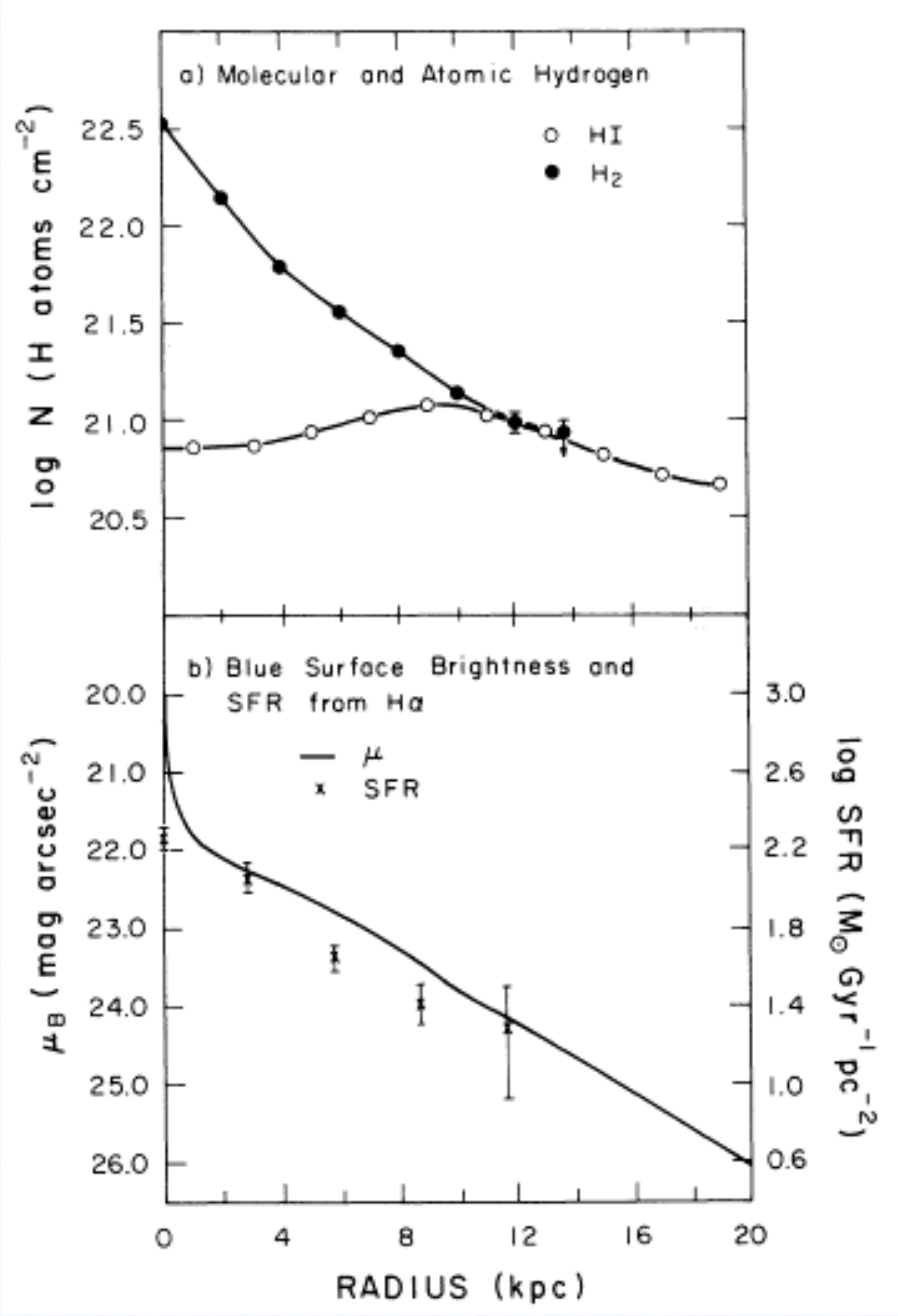


Saintonge+ 2012

The Molecular ISM: Radial Distribution

Radial Distributions

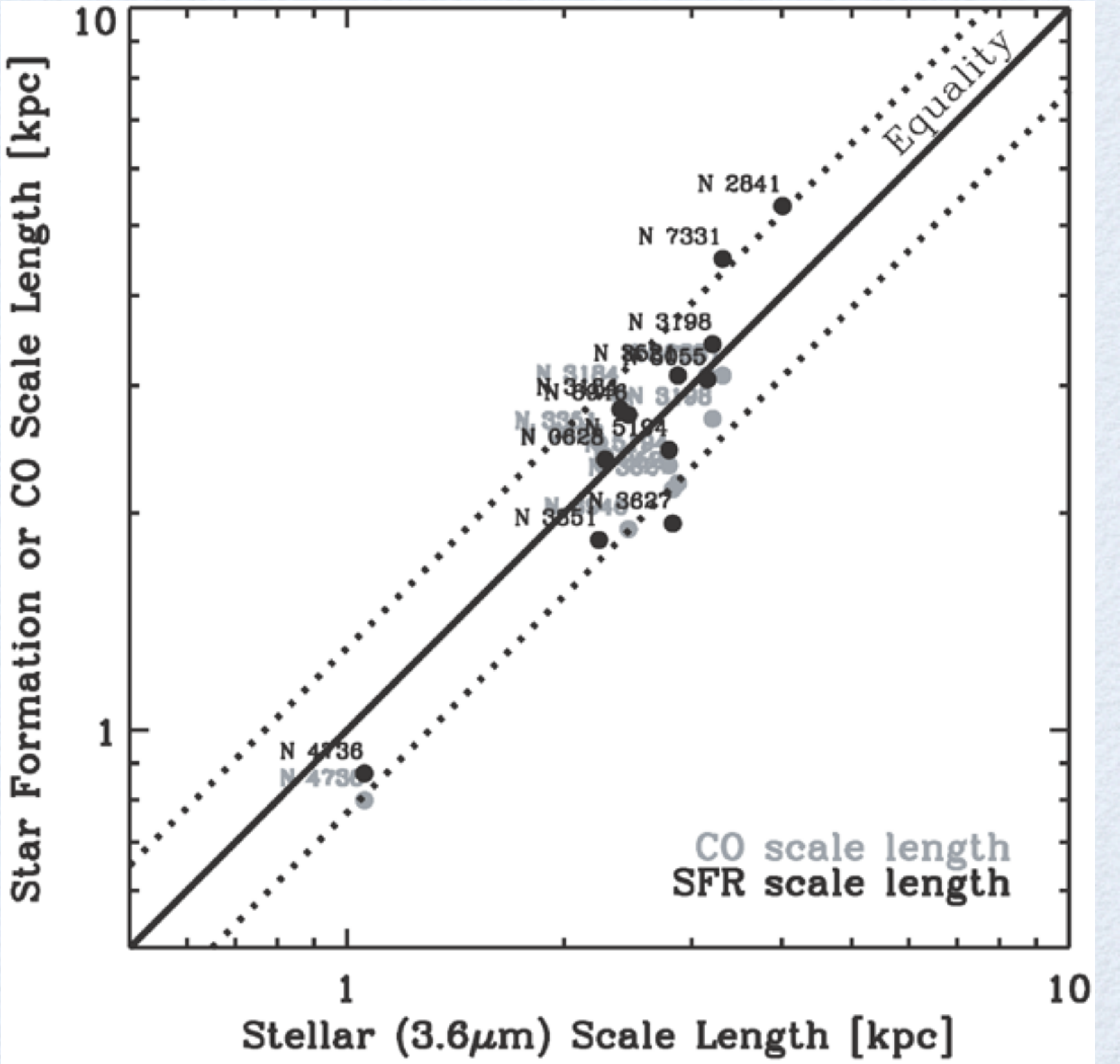
- Early work in the 1980's (typically major axis profiles) showed that the radial CO distribution traces the stellar disk well in the nearest face-on galaxies.



NGC 6946 by Tacconi & Young 1986

Radial Distributions

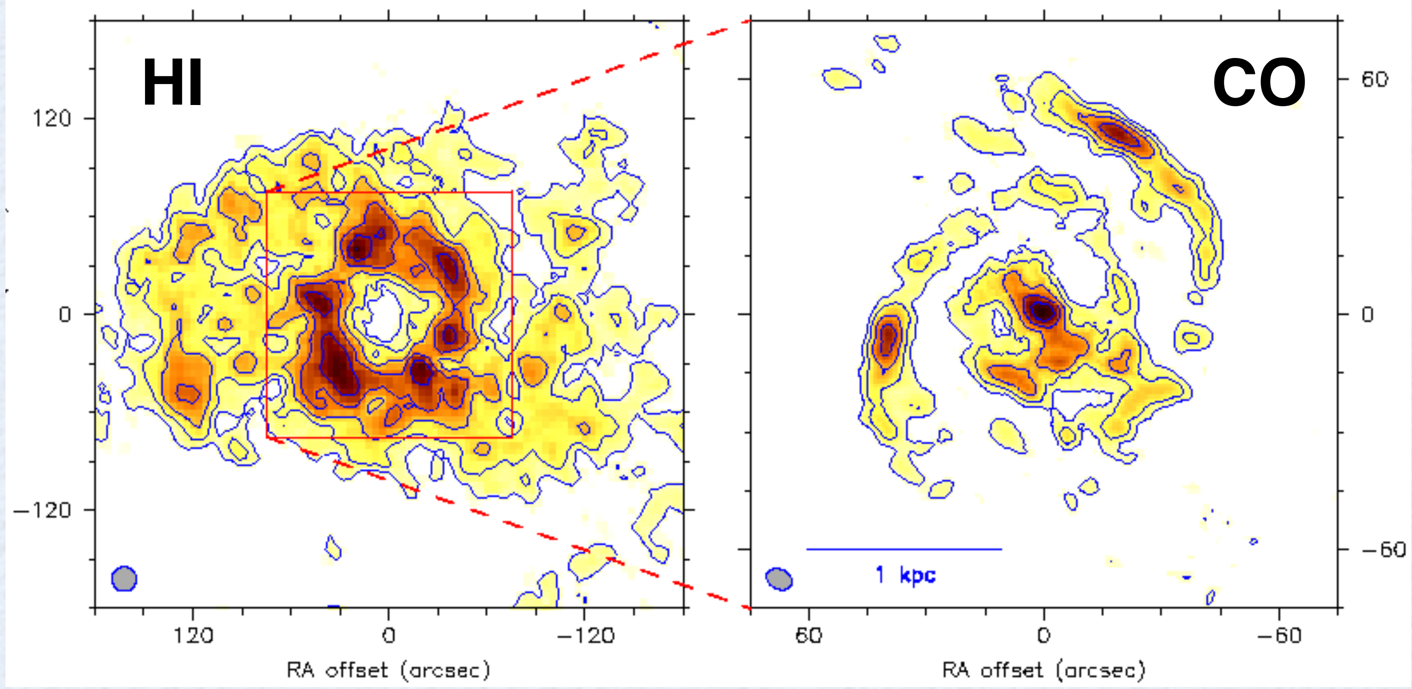
- Early work in the 1980's (typically major axis profiles) showed that the radial CO distribution traces the stellar disk well in the nearest face-on galaxies.
- Confirmed by many later studies, most recently by full-disk CO(2-1) mapping with the IRAM 30m HERA receiver (Leroy+ 2008).



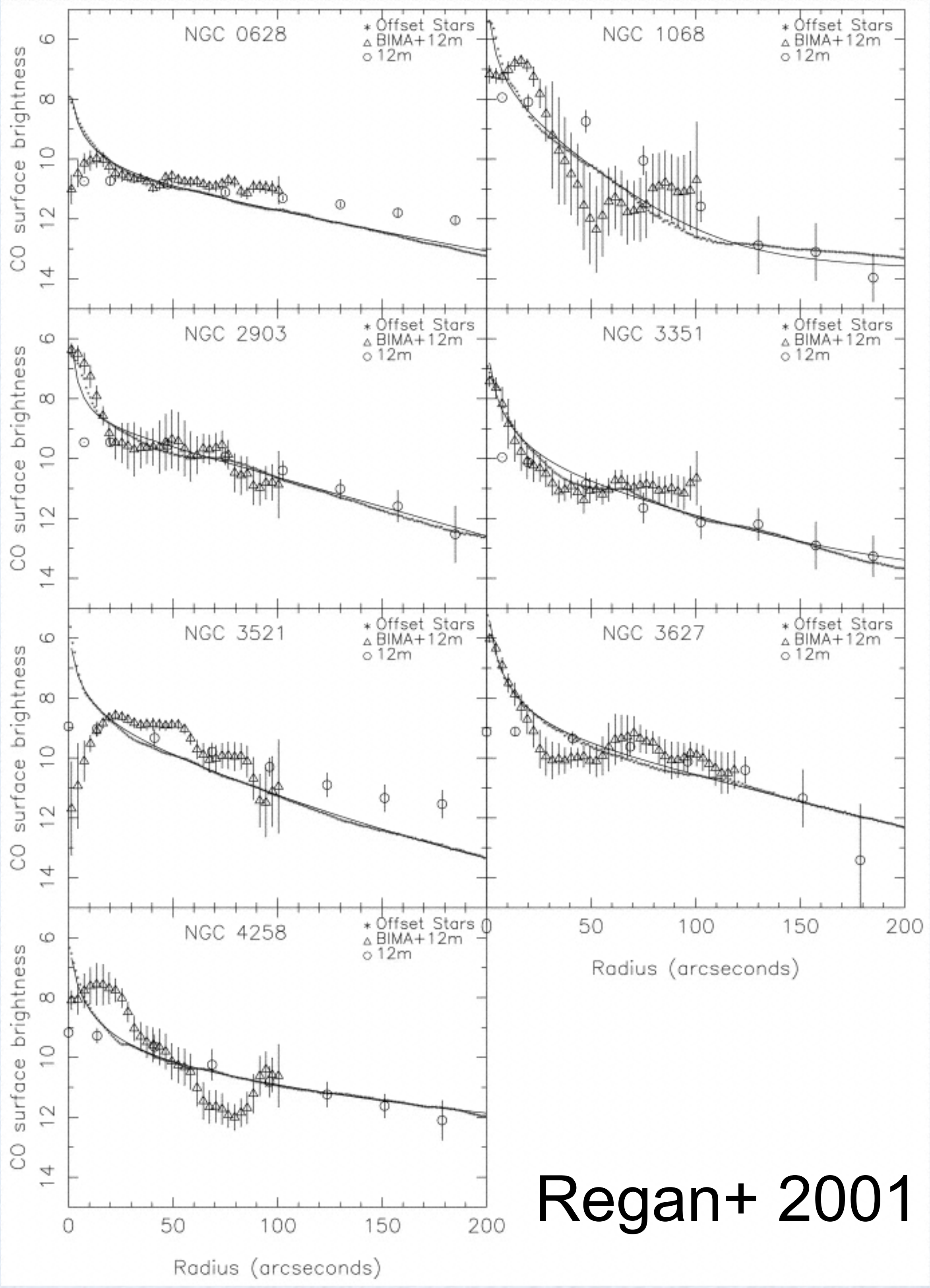
Leroy+ 2008

Radial distributions

- Radio interferometric studies like BIMA SONG have been key to resolving central CO concentrations ("bulges") as well as depressions ("central holes").



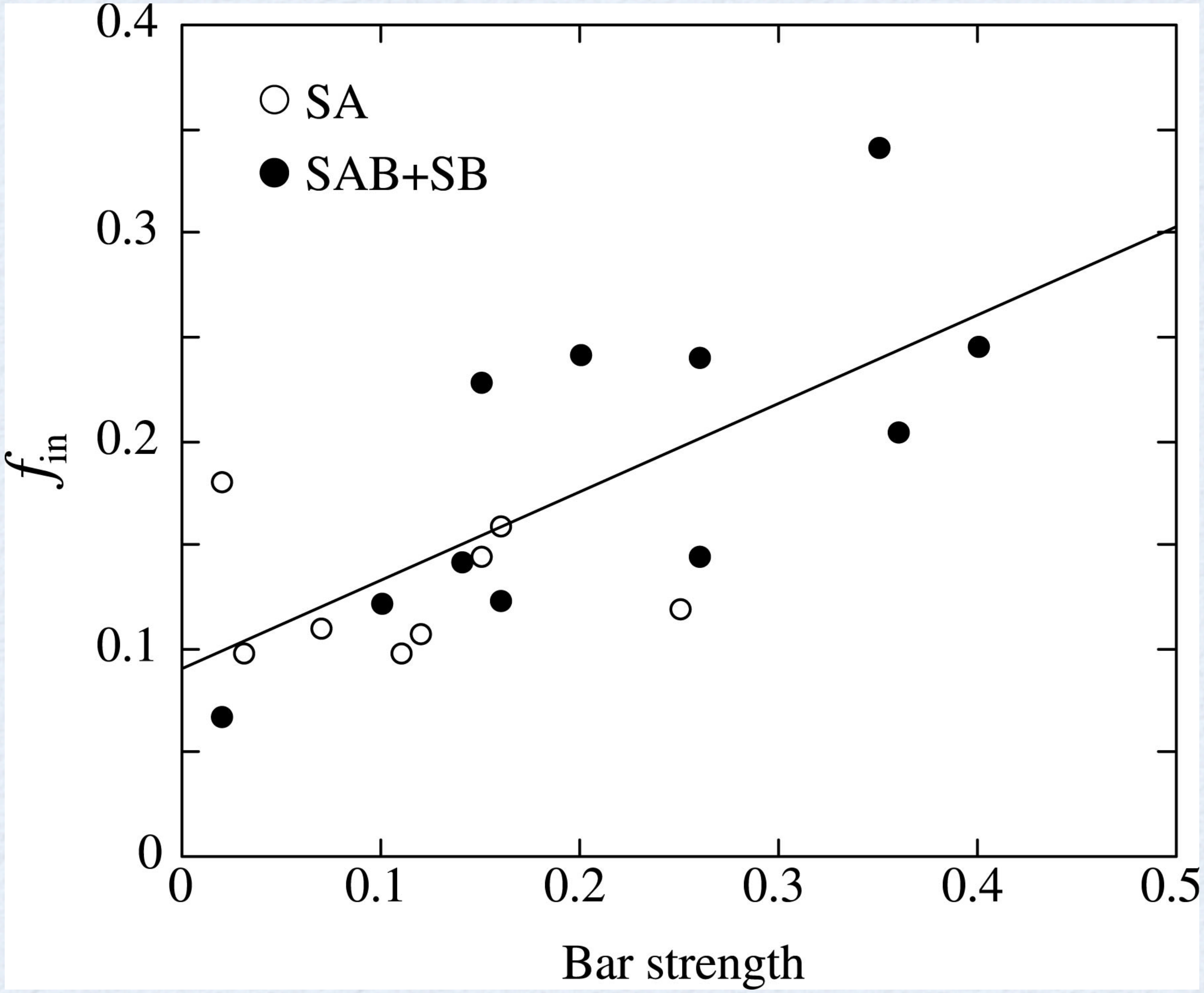
NGC 4736 by Wong & Blitz 2000



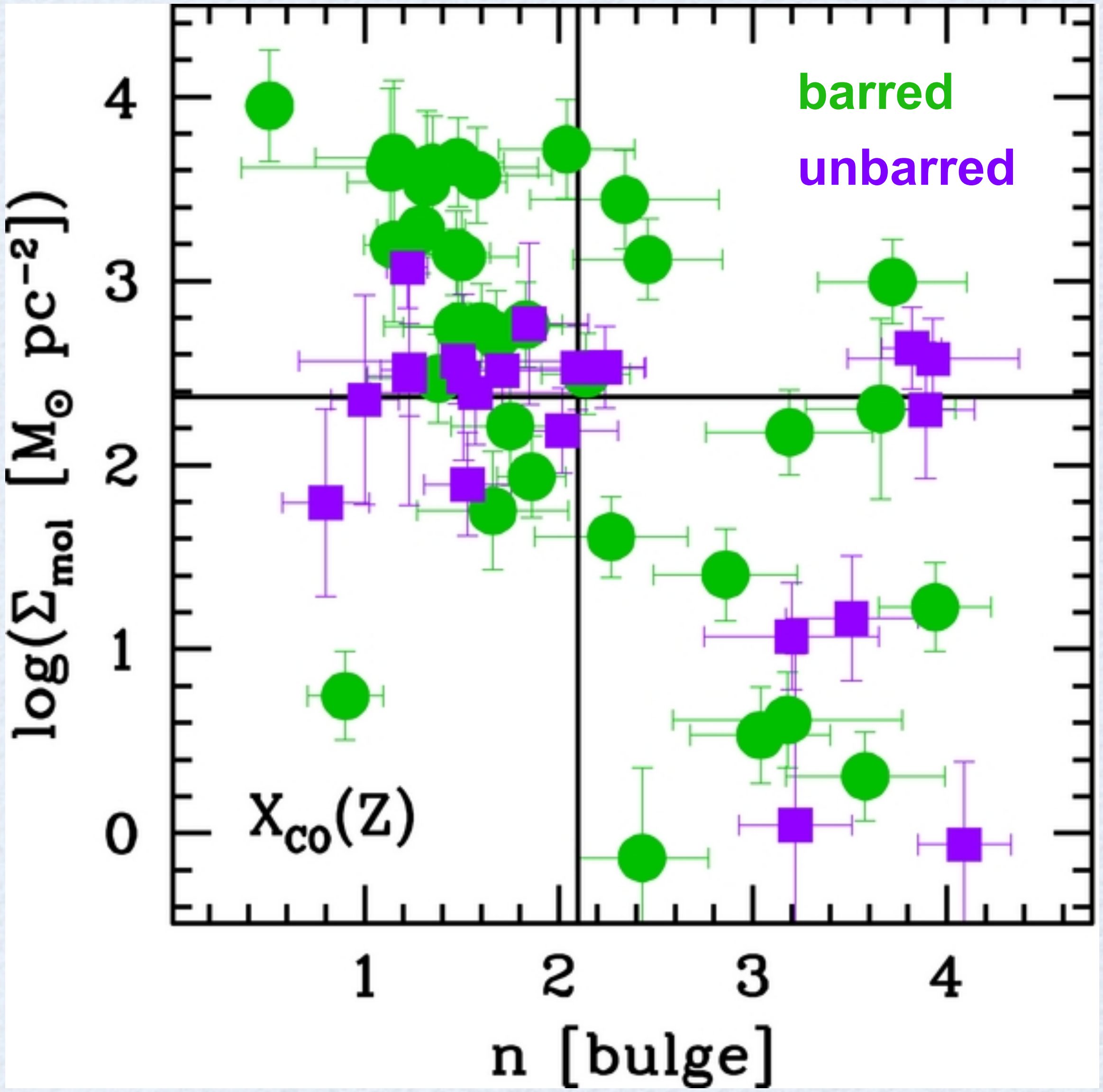
Regan+ 2001

Radial distributions

- Bars appear to concentrate CO towards the centers of galaxies, leading(?) to formation of low Sersic index "pseudobulges".



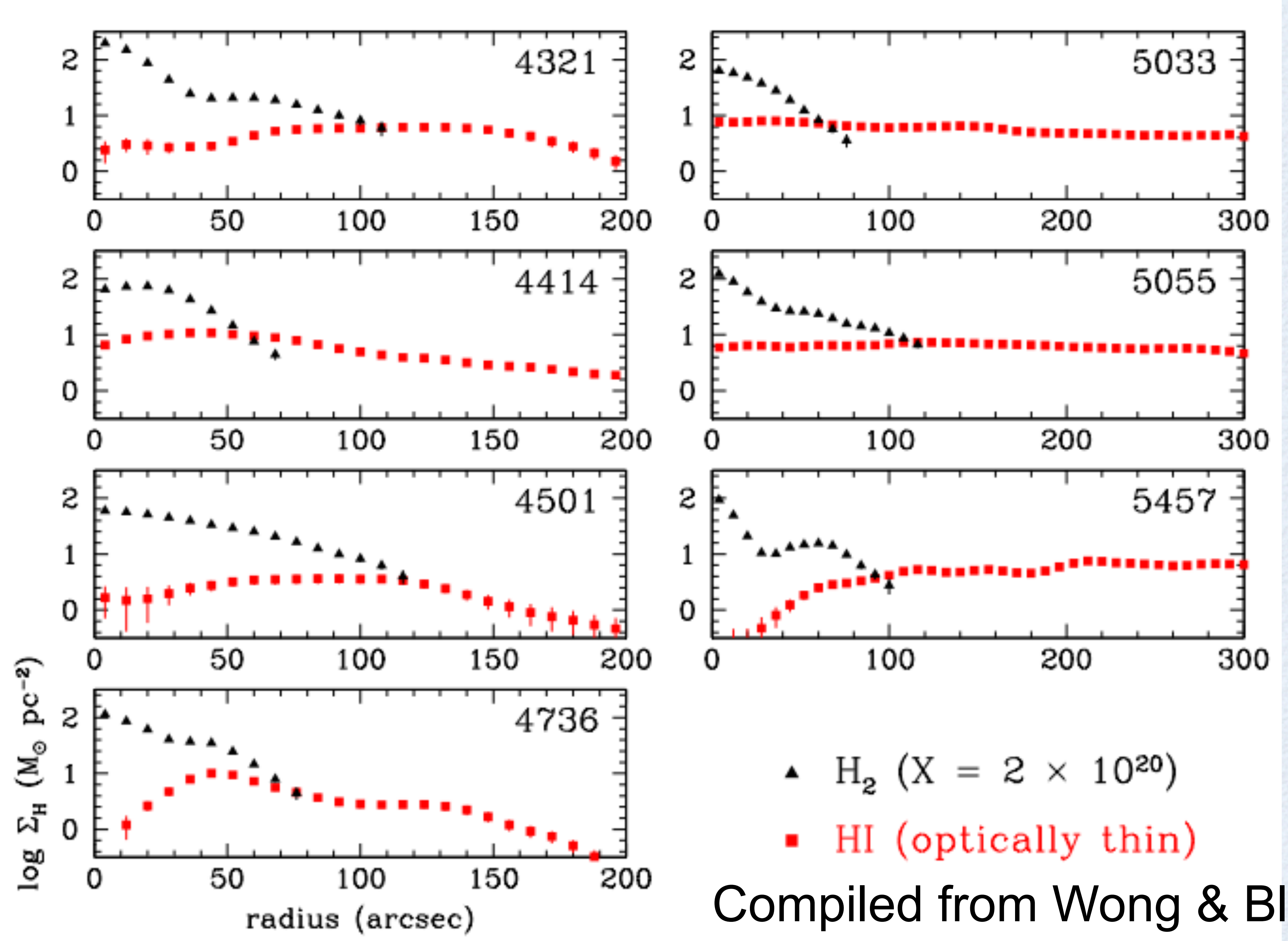
Kuno+ 2007



Fisher+ 2013

Radial distributions

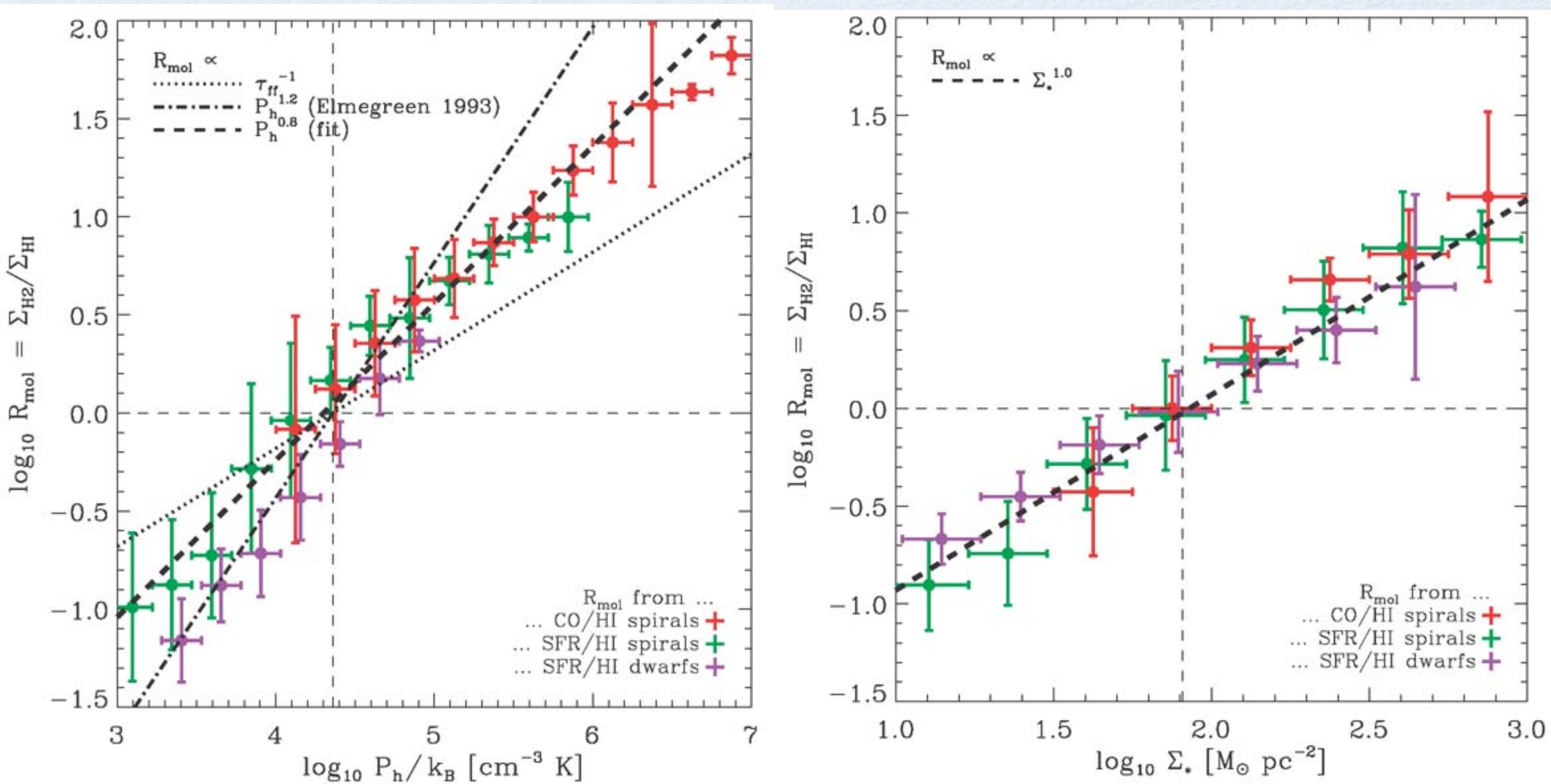
- "Central holes" appear to be more common in HI than in CO.



Compiled from Wong & Blitz 2002

Radial distributions

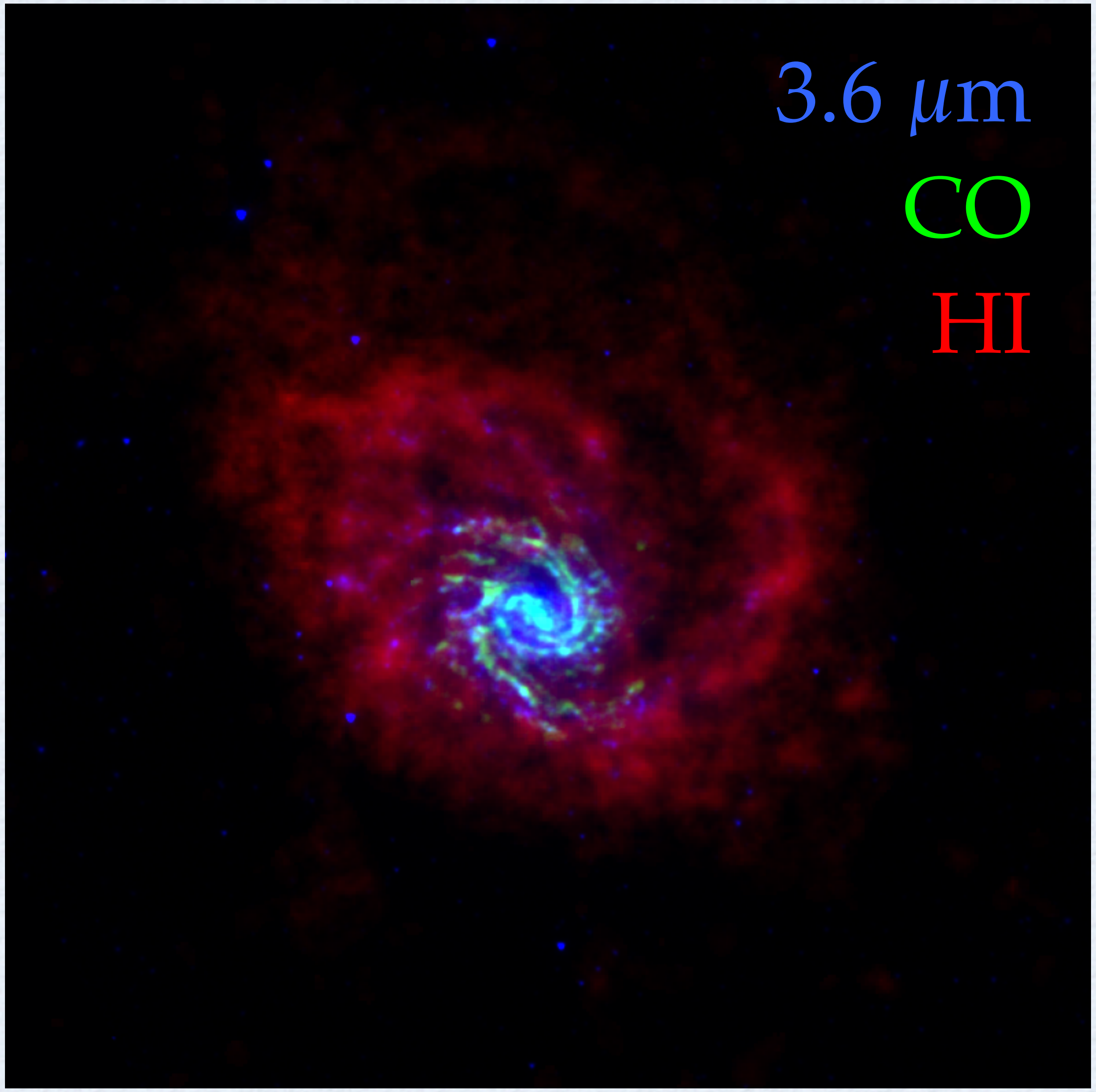
- The (dimensionless!) quantity $R_{mol} = \Sigma_{H_2} / \Sigma_{HI}$ correlates with Σ_*.

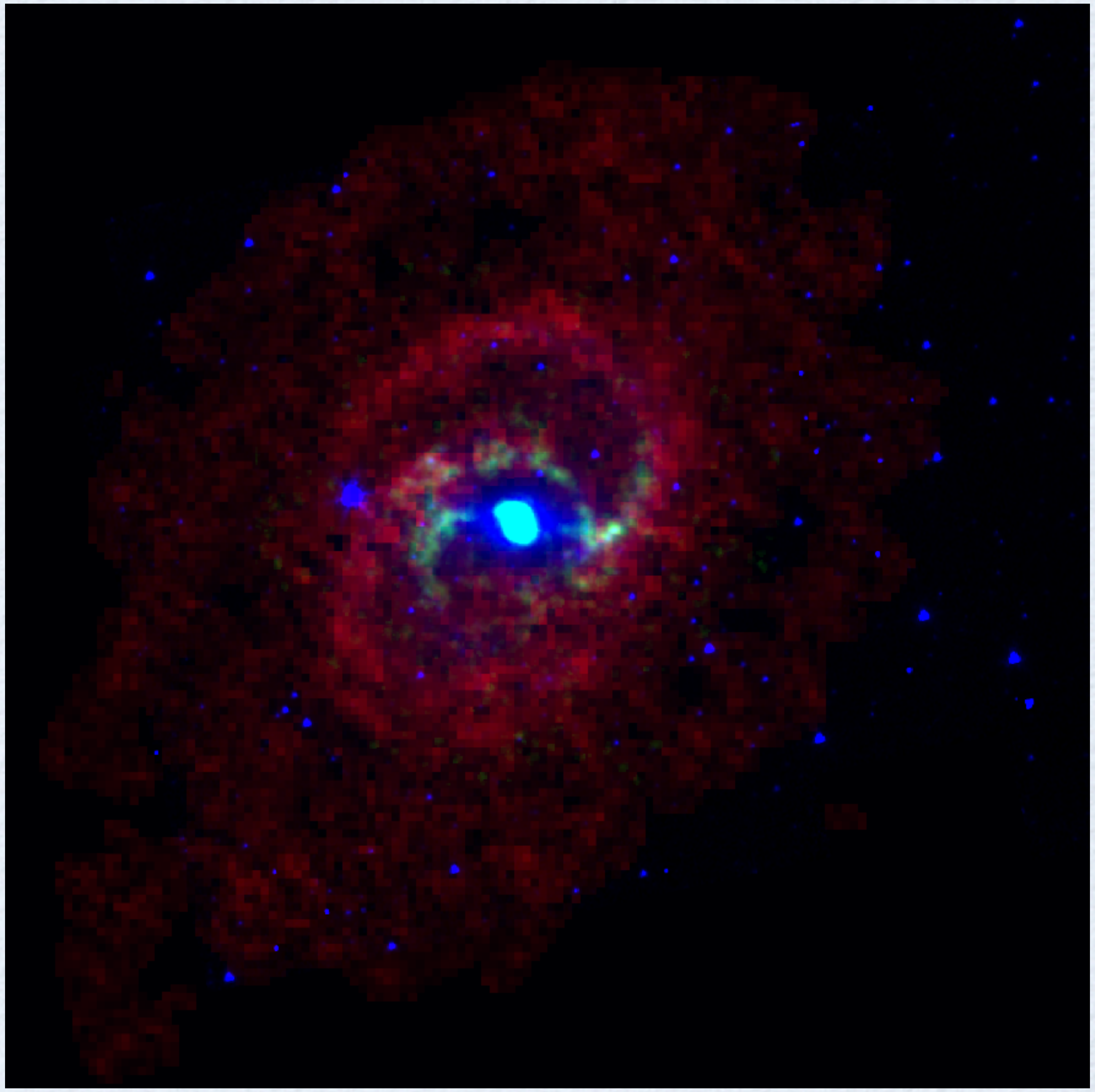


Leroy+ 2008

HI to H_2 Transition

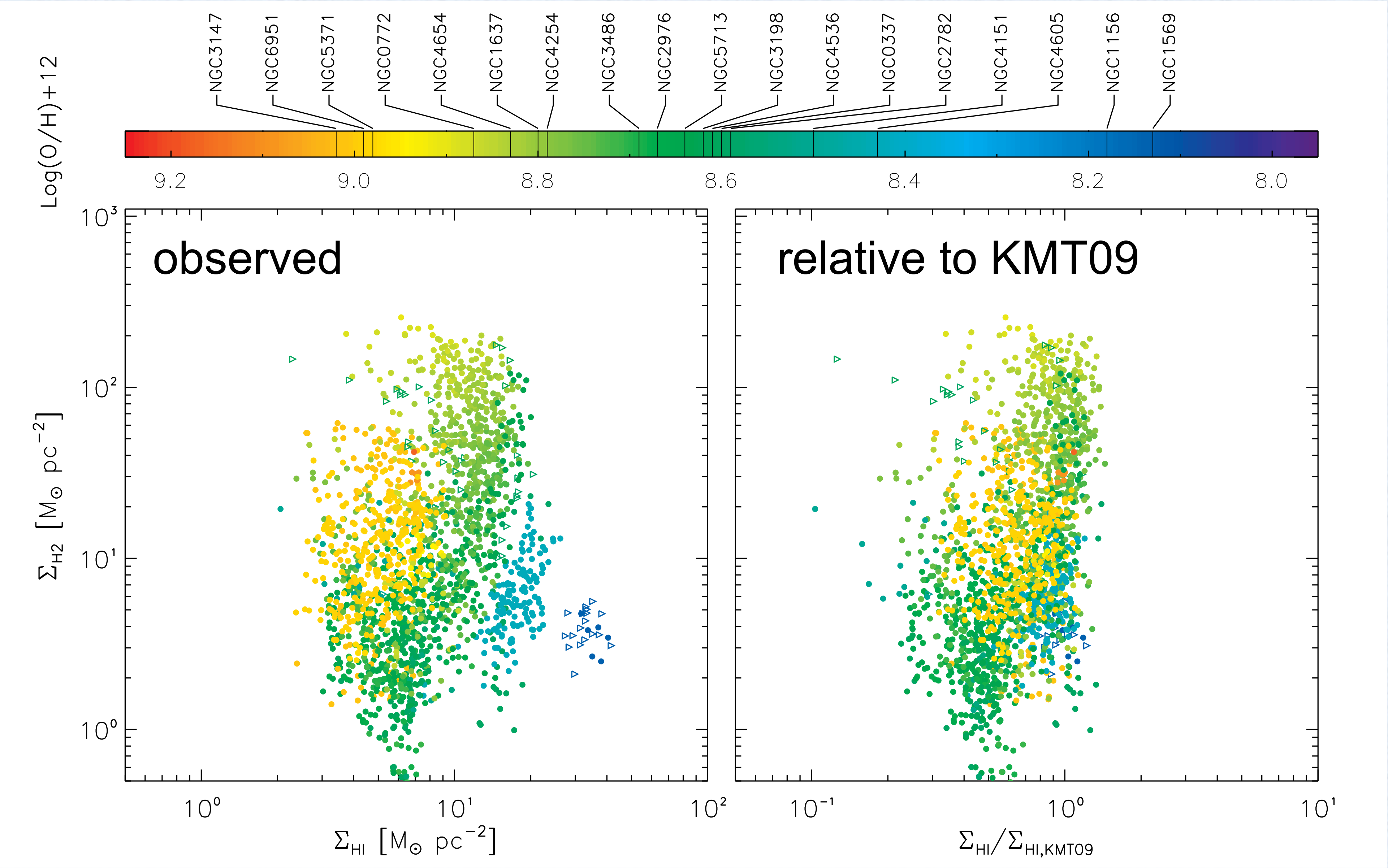
- A clue to the origin of the $R_{mol} - \Sigma_*$ correlation comes from pixel by pixel comparison of CO, HI, and 3.6 μm maps in the CARMA STING project (R. Xue, PhD thesis).





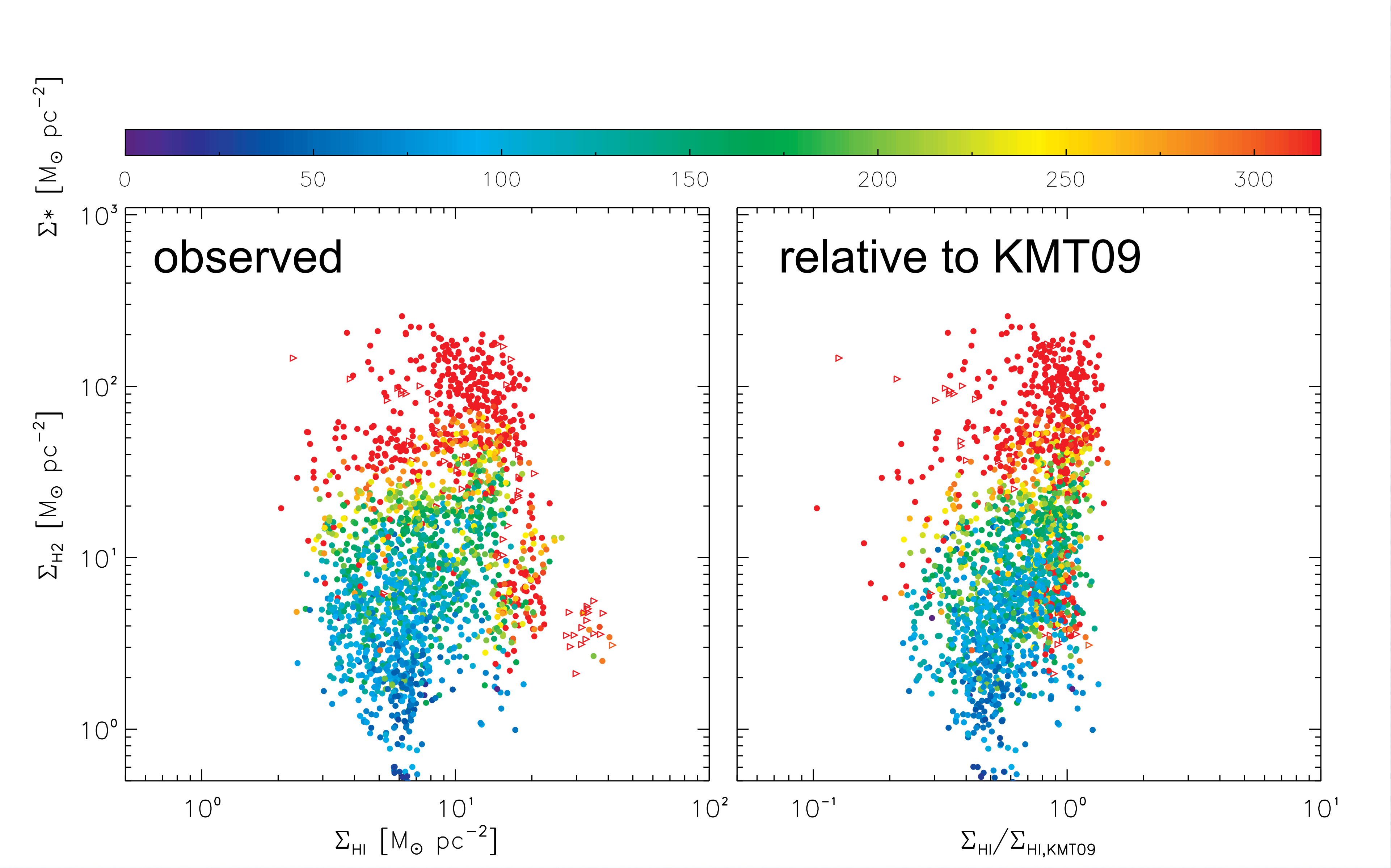
HI TO H_2 TRANSITION

- In the regime where CO is detected, Σ_{HI} is confined to a narrow range of values that is metallicity dependent, as predicted by self-shielding models (Krumholz+ 2009).



HI TO H_2 TRANSITION

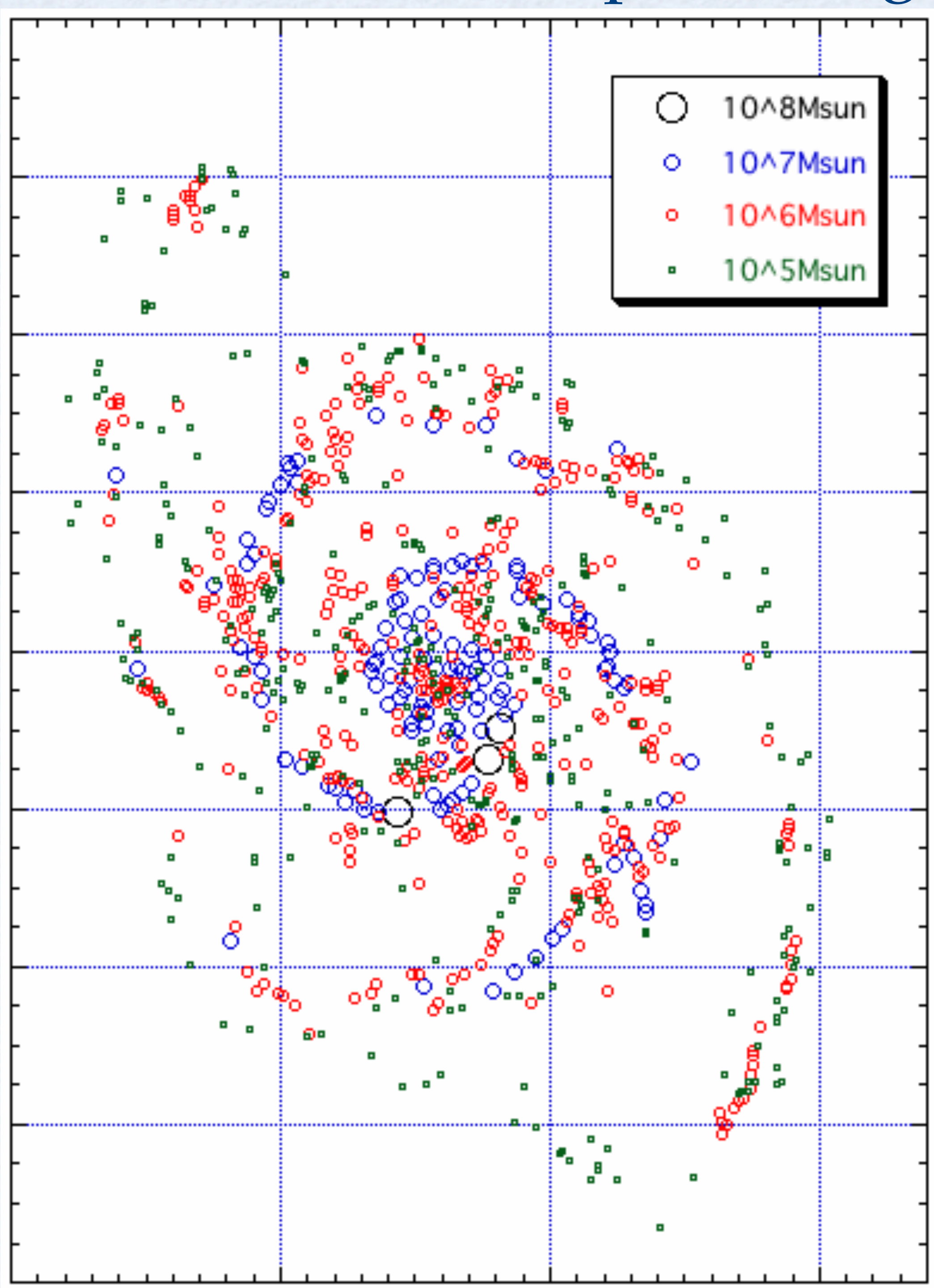
- Σ_{H_2} on the other hand correlates strongly with Σ_*. This suggests that H_2 supply is regulated by the stellar disk, either directly (e.g. stellar mass loss) or indirectly (e.g., gravitational instability).

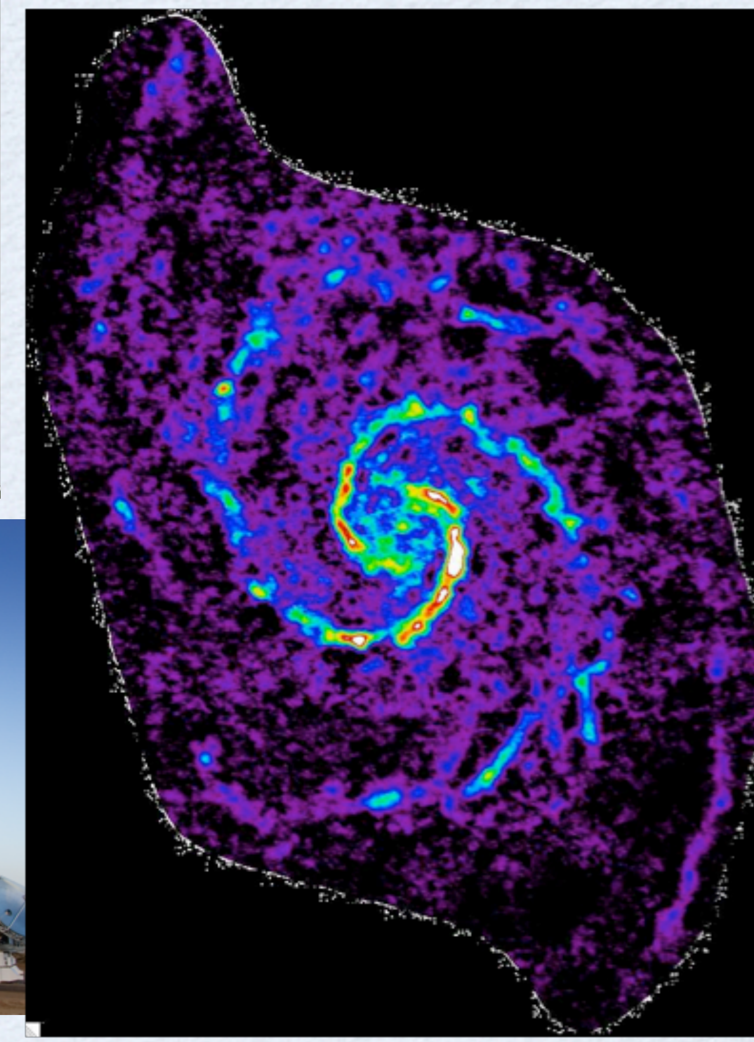


The Molecular ISM: Azimuthal Distribution

AZIMUTHAL STRUCTURE

- Gaseous spiral arms appear to be places where GMCs congregate into massive complexes ("giant molecular associations").

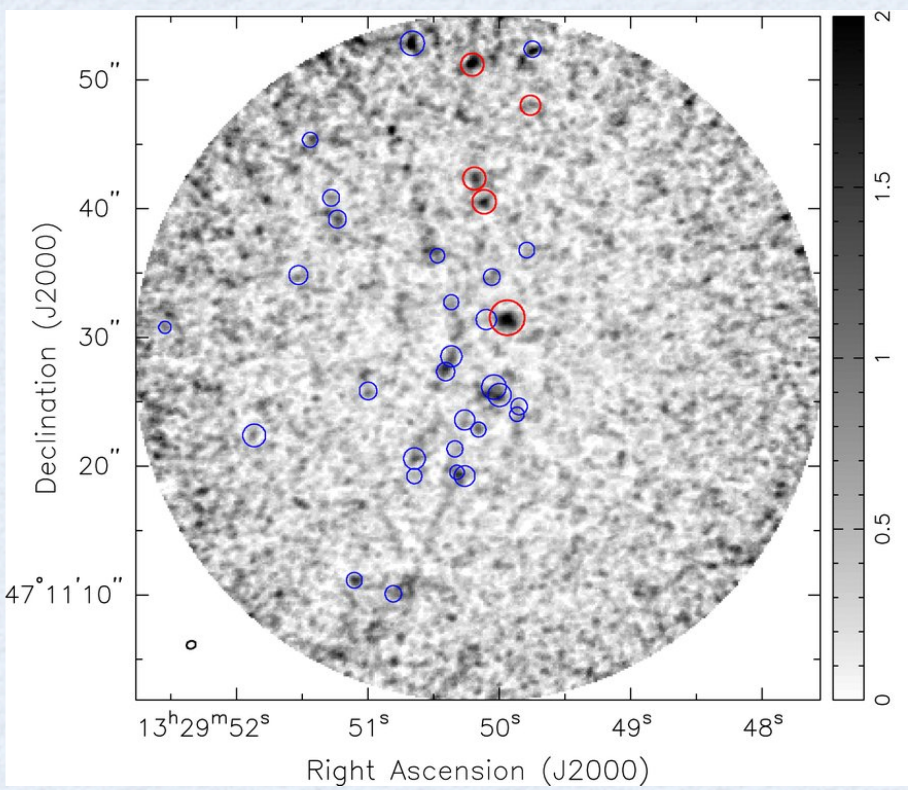


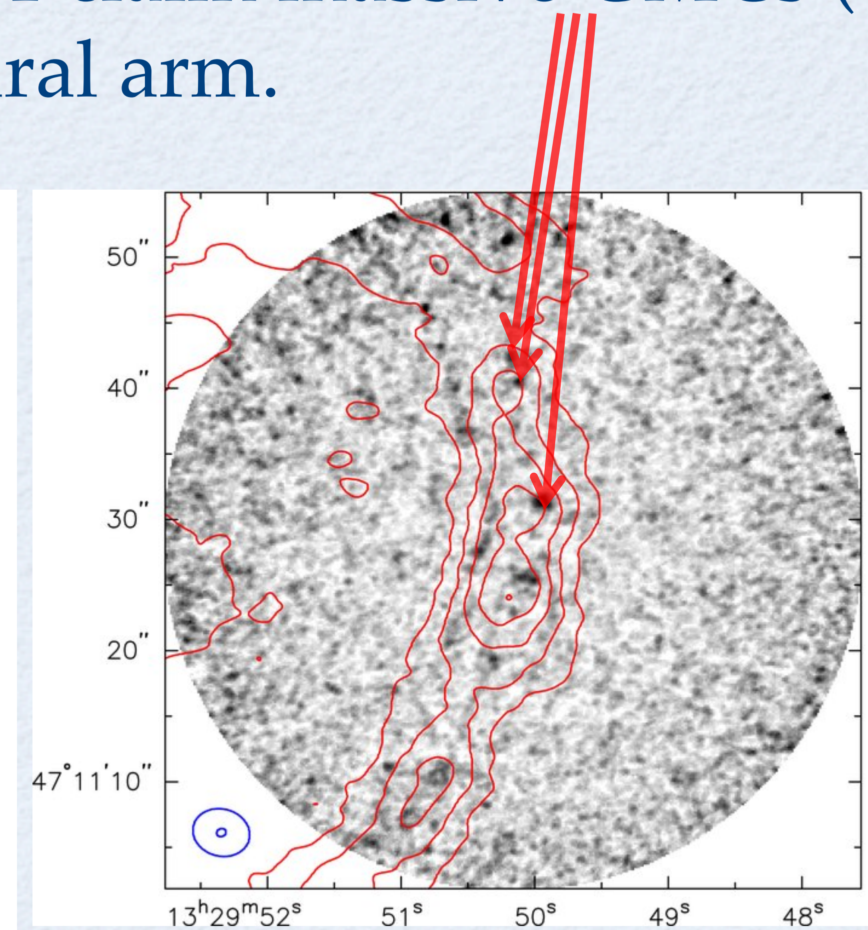


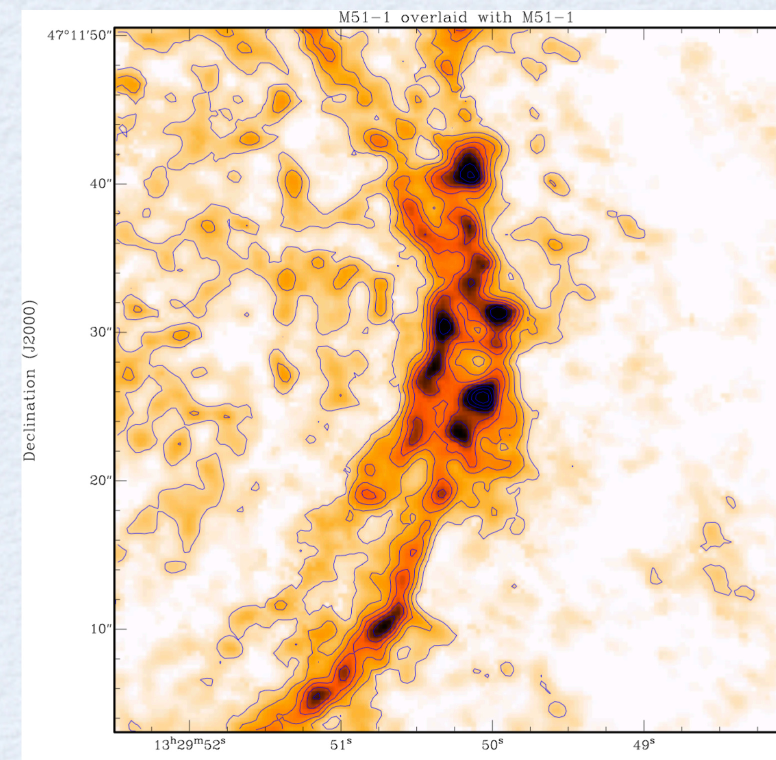
M51 by Koda+ 2009

Azimuthal Structure

- Interpreting azimuthal "offsets," though useful for estimating evolutionary time scales, is fraught with difficulty.
- In M 51, Egusa+ 2011 claim massive GMCs (circled red) are shifted west of the main spiral arm.





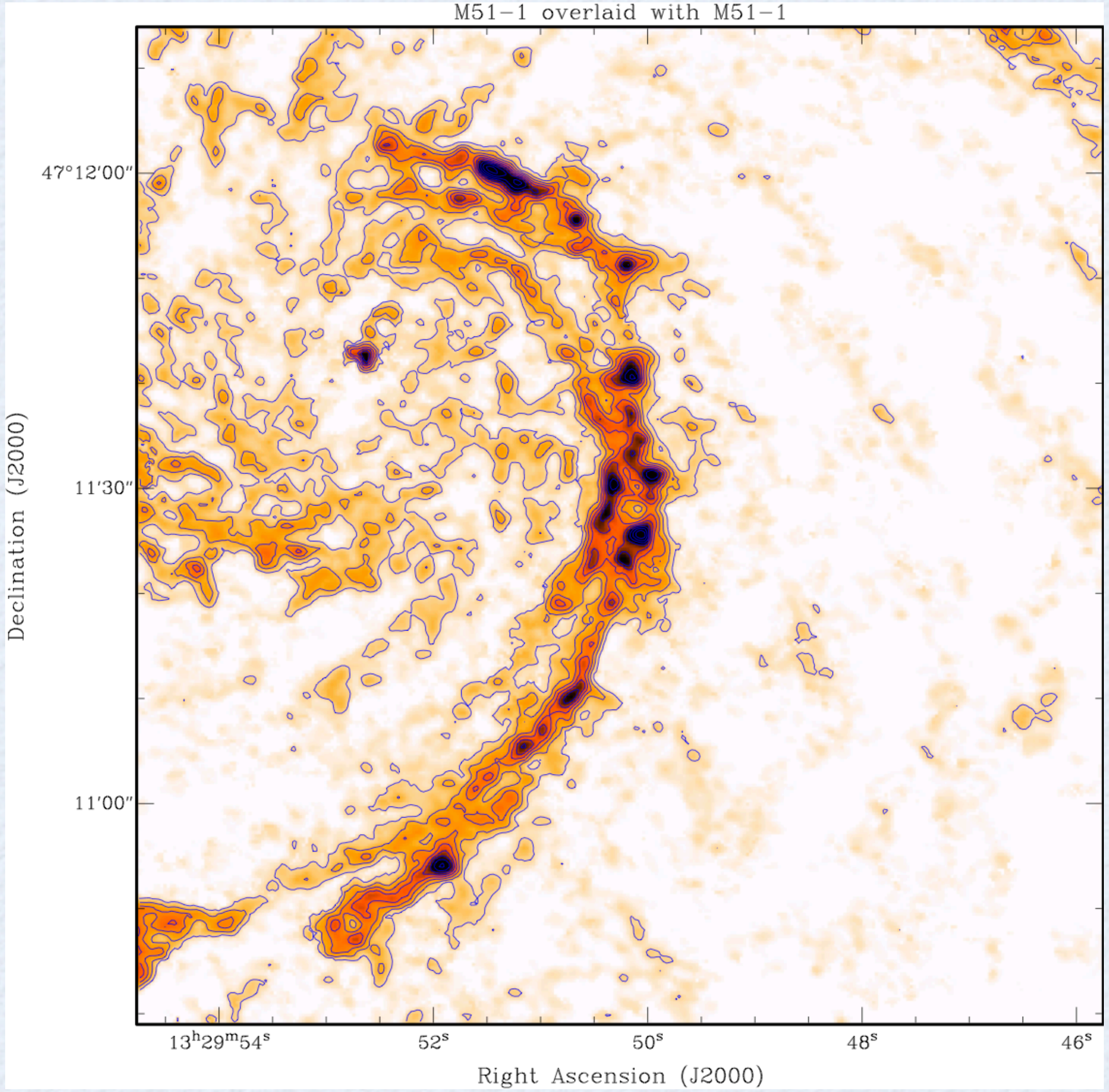


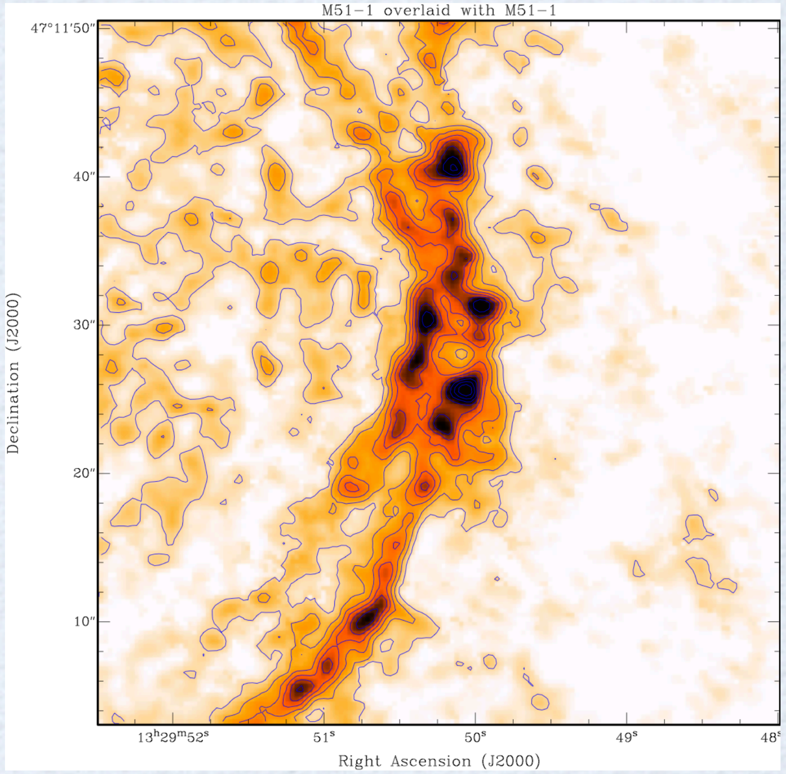
Egusa+ 2011

PAWS data from Schinnerer+ 2013

Azimuthal Structure

- It's also easy to confuse radial with azimuthal structure.
- Apparent lack of CO west of the arm may be mainly a radial trend.

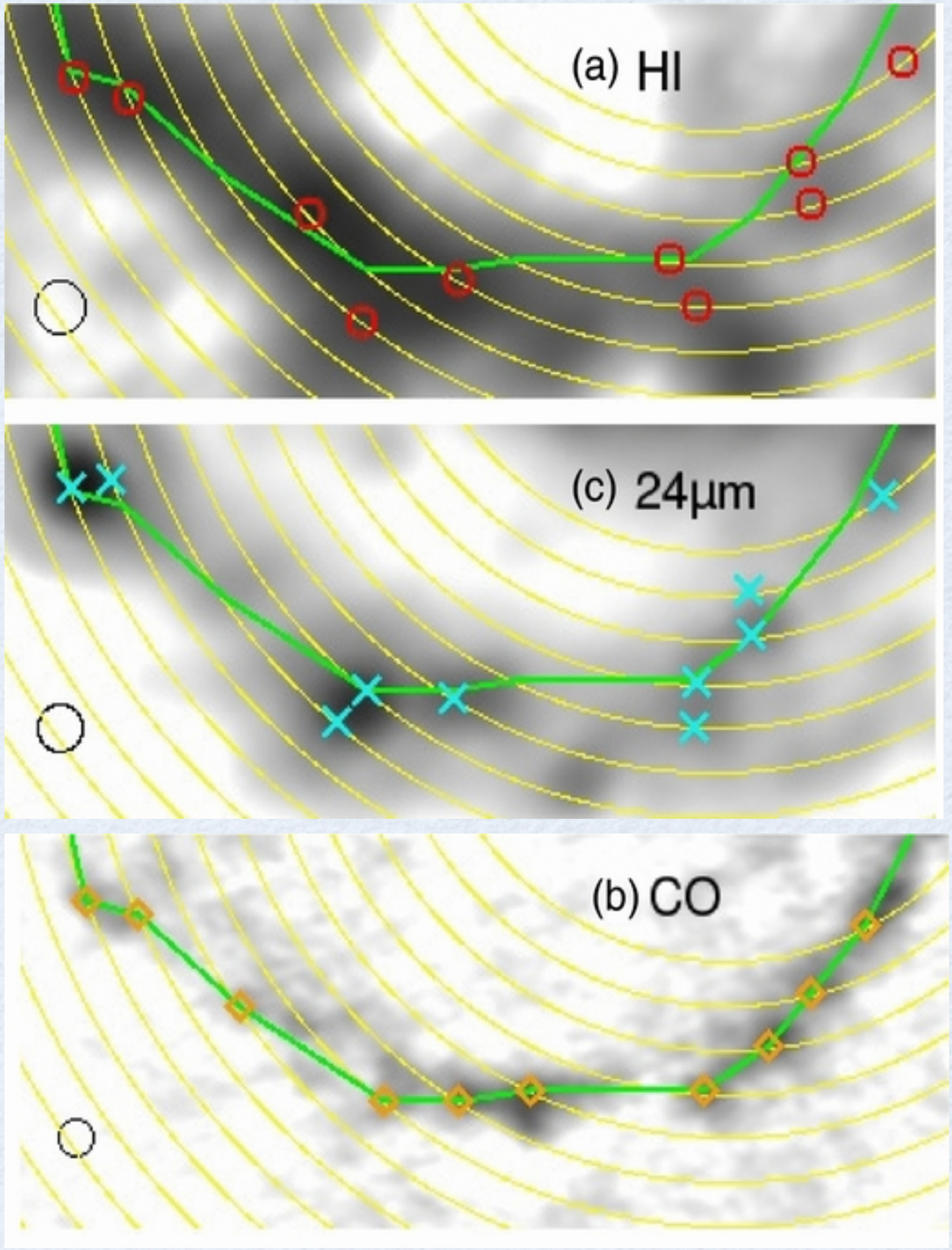




PAWS data from Schinnerer+ 2013

Azimuthal structure

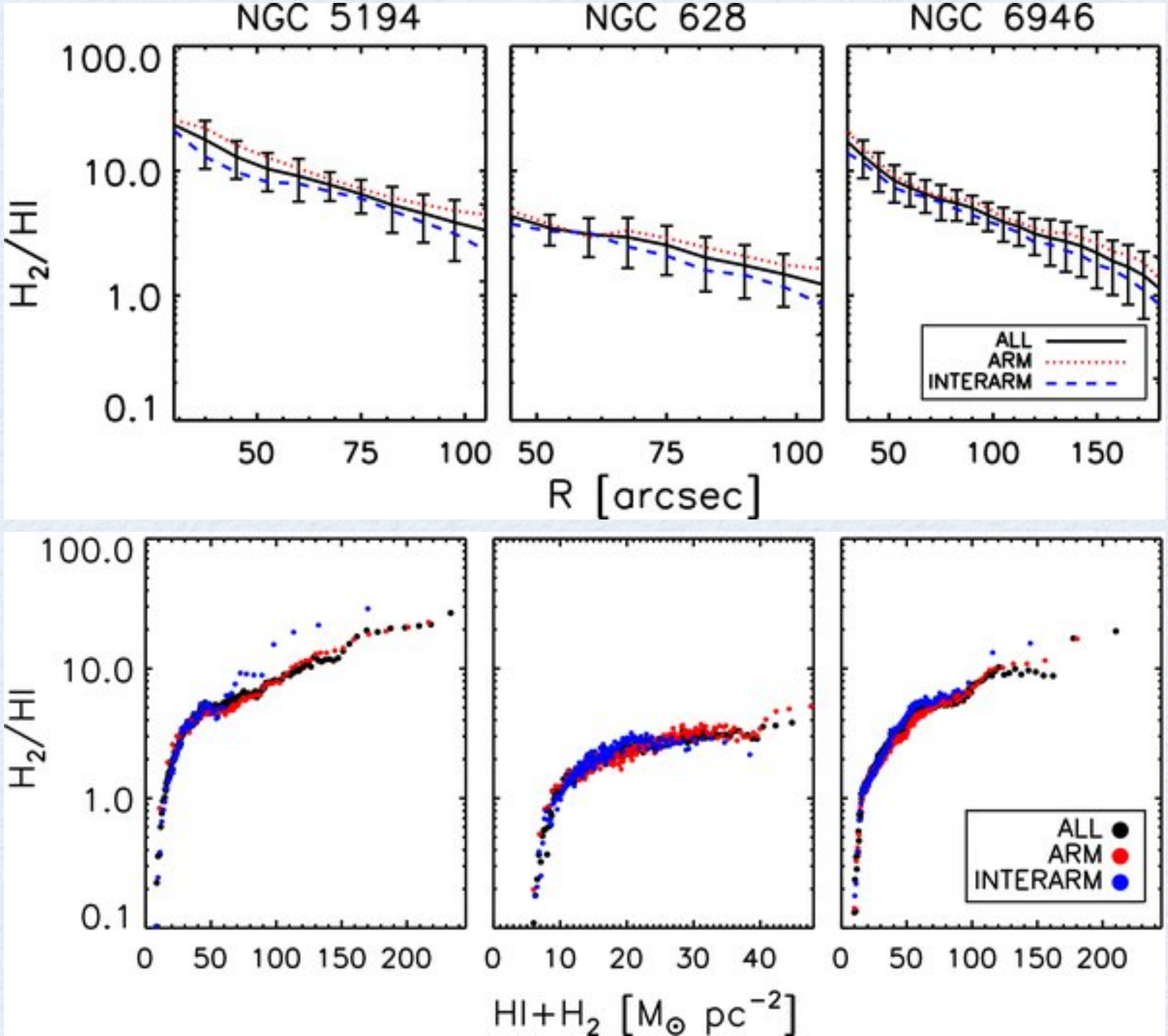
- Inferences about evolution depend on tracers used
- In M 51, HI is mainly a dissociation product of H_2 (Louie+ 2013).
- To what extent is dust or CO emission tracing the gas density vs. radiative heating from young stars?
- Effect of variable extinction on UV and optical SFR tracers (e.g. Hα)



Louie+ 2013

AZIMUTHAL STRUCTURE

- Foyle+ 2010 find that H_2/HI ratio slightly enhanced in spiral arms, but this is probably just an effect of higher gas density in arms.

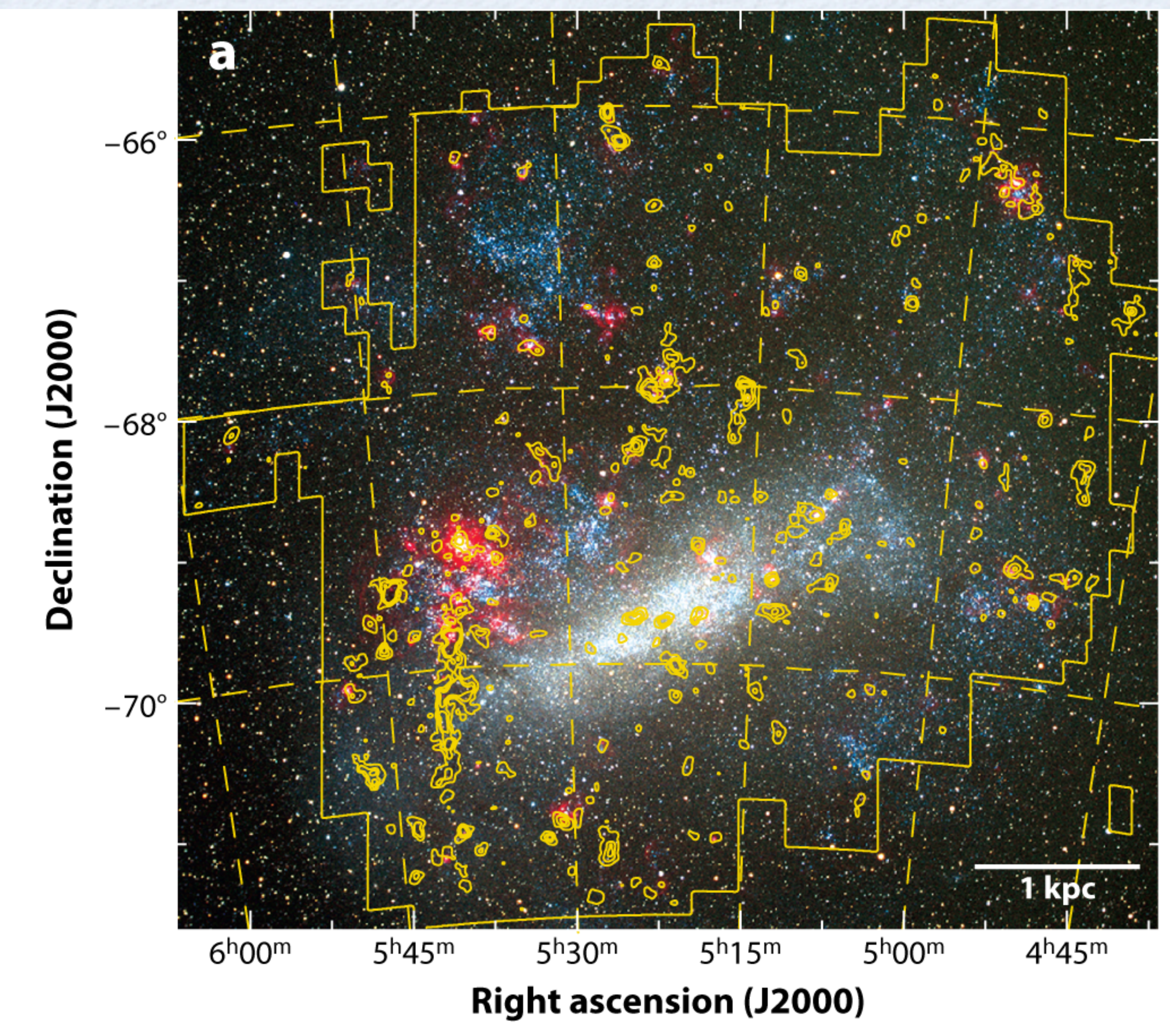


Foyle+ 2010

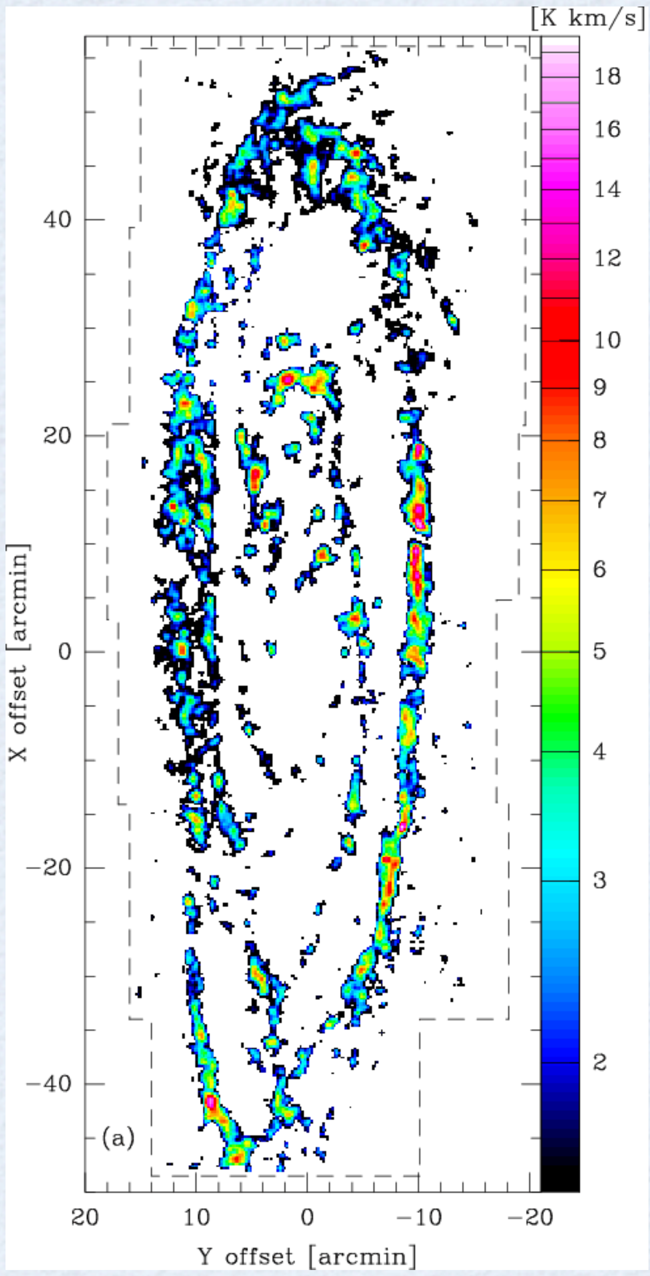
The Molecular ISM: Cloudy Structure

IDENTIFYING GMC'S

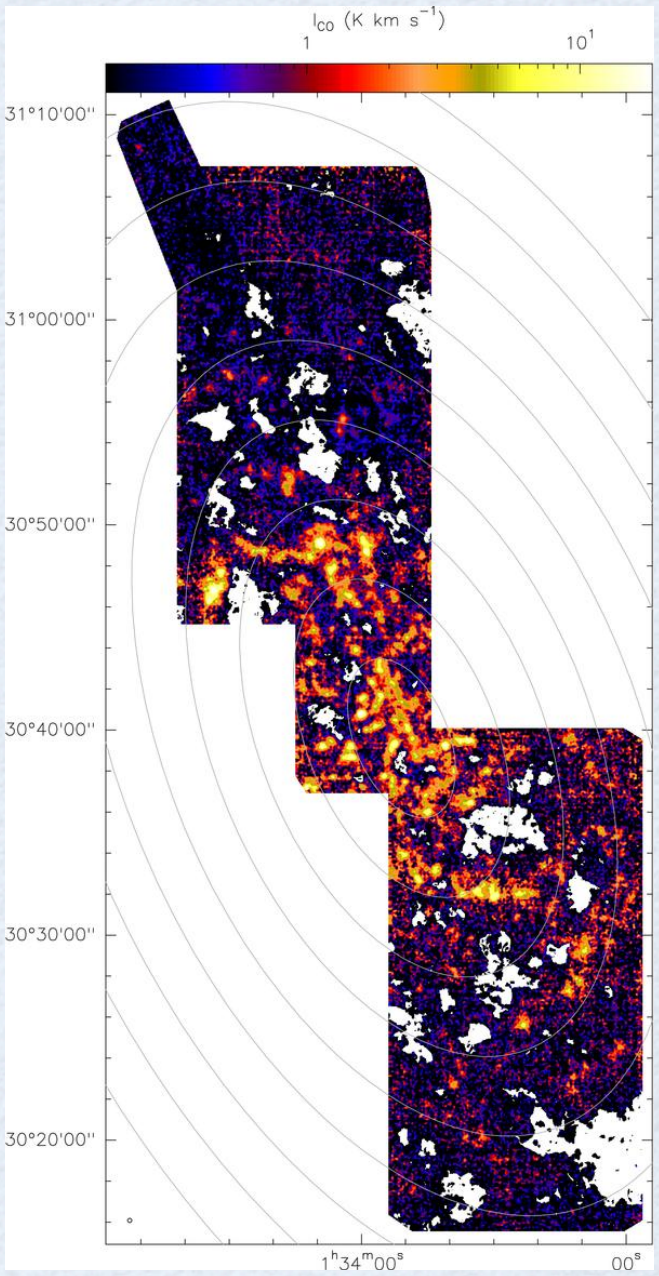
- Spatially resolved CO maps of the nearest galaxies, including the LMC, M 31, and M 33, invite structural decomposition.



LMC: Fukui+ 2008



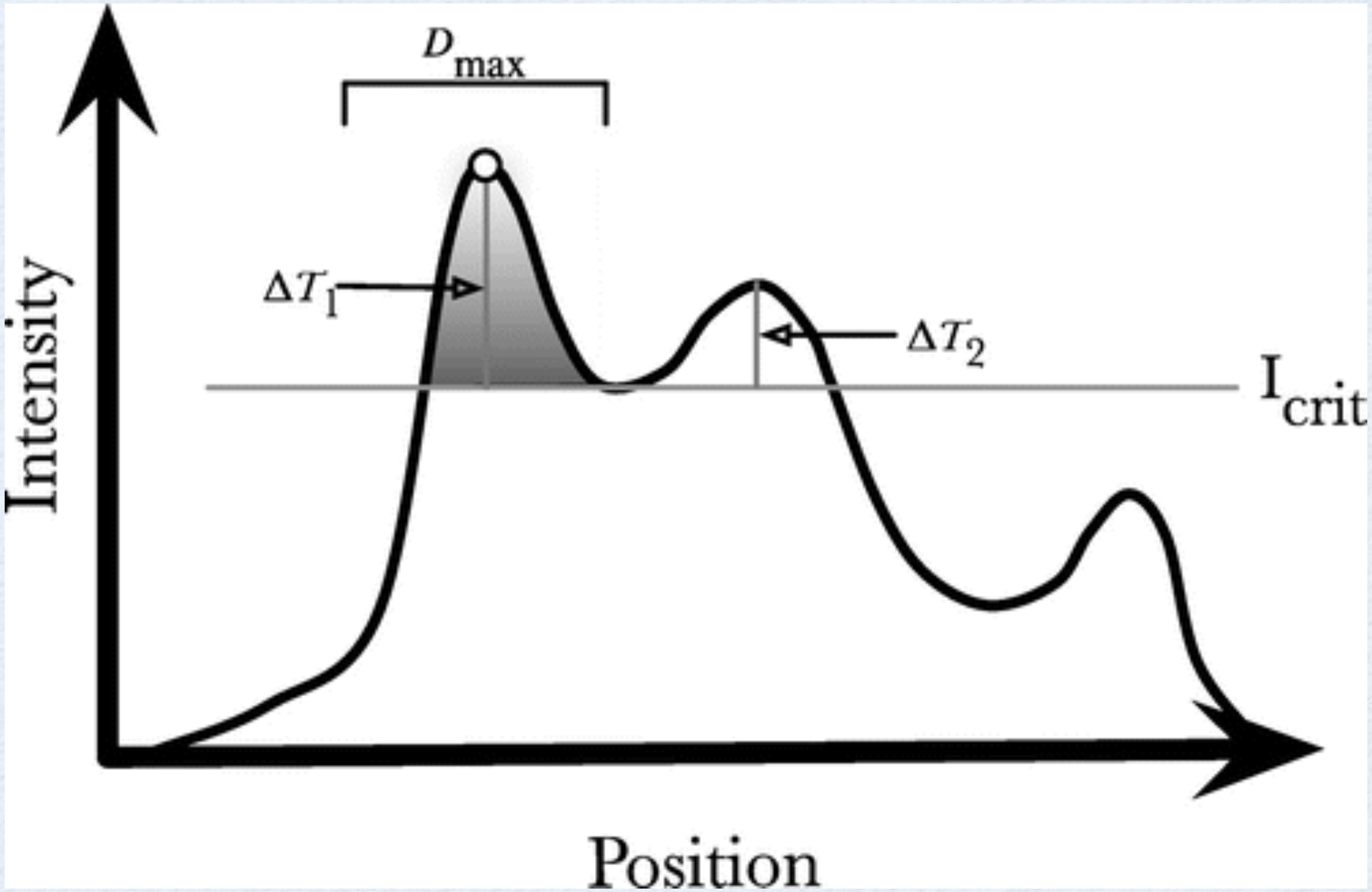
M31: Nieten+ 2006



M33: Gratier+ 2010

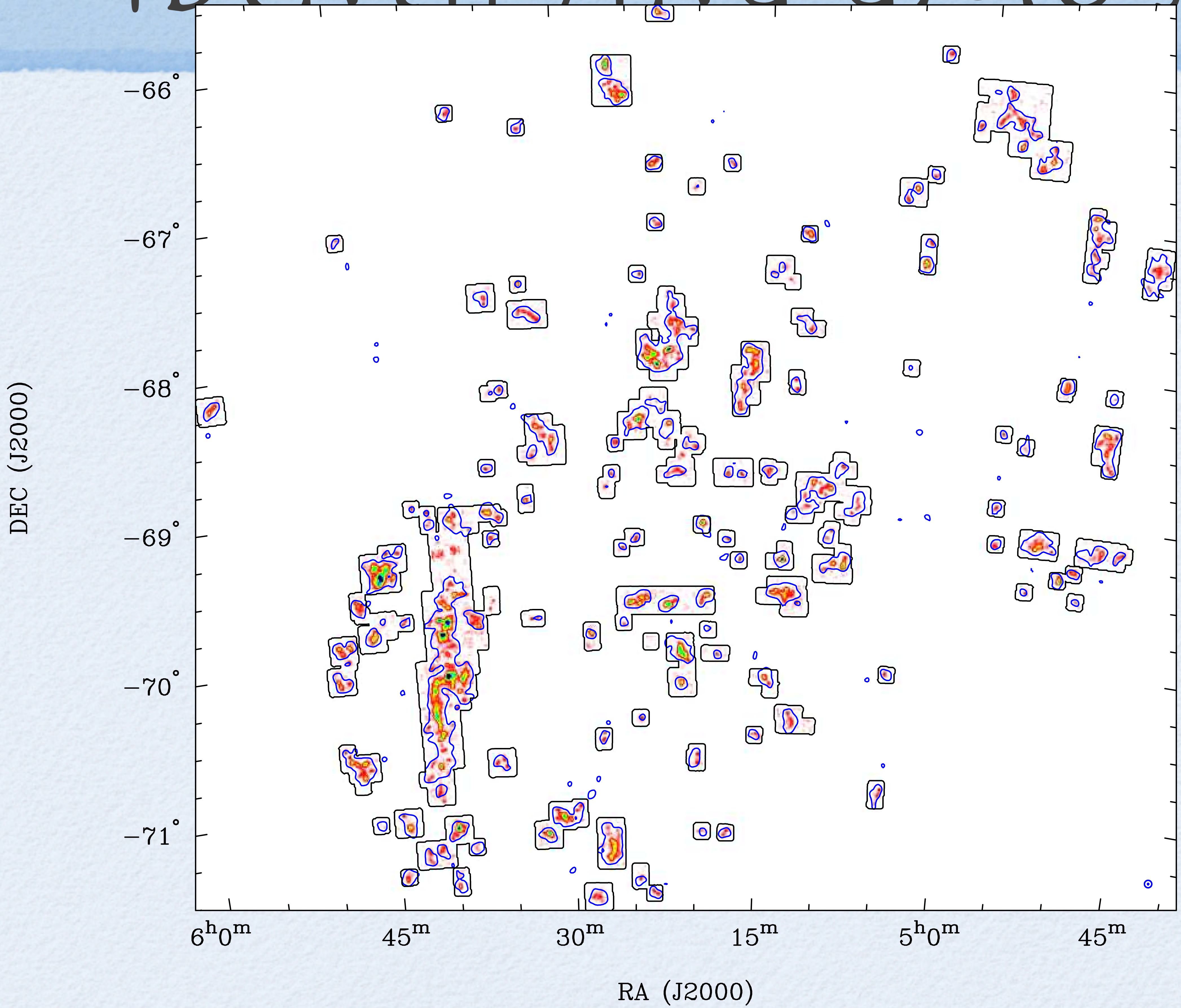
IDENTIFYING GMC'S

- GMCs can be identified as peaks in the CO distribution that
  - are sufficiently far from other peaks in position-velocity space and
  - have sufficient area and contrast above the merge level I_{crit} that they are unlikely to be noise fluctuations.



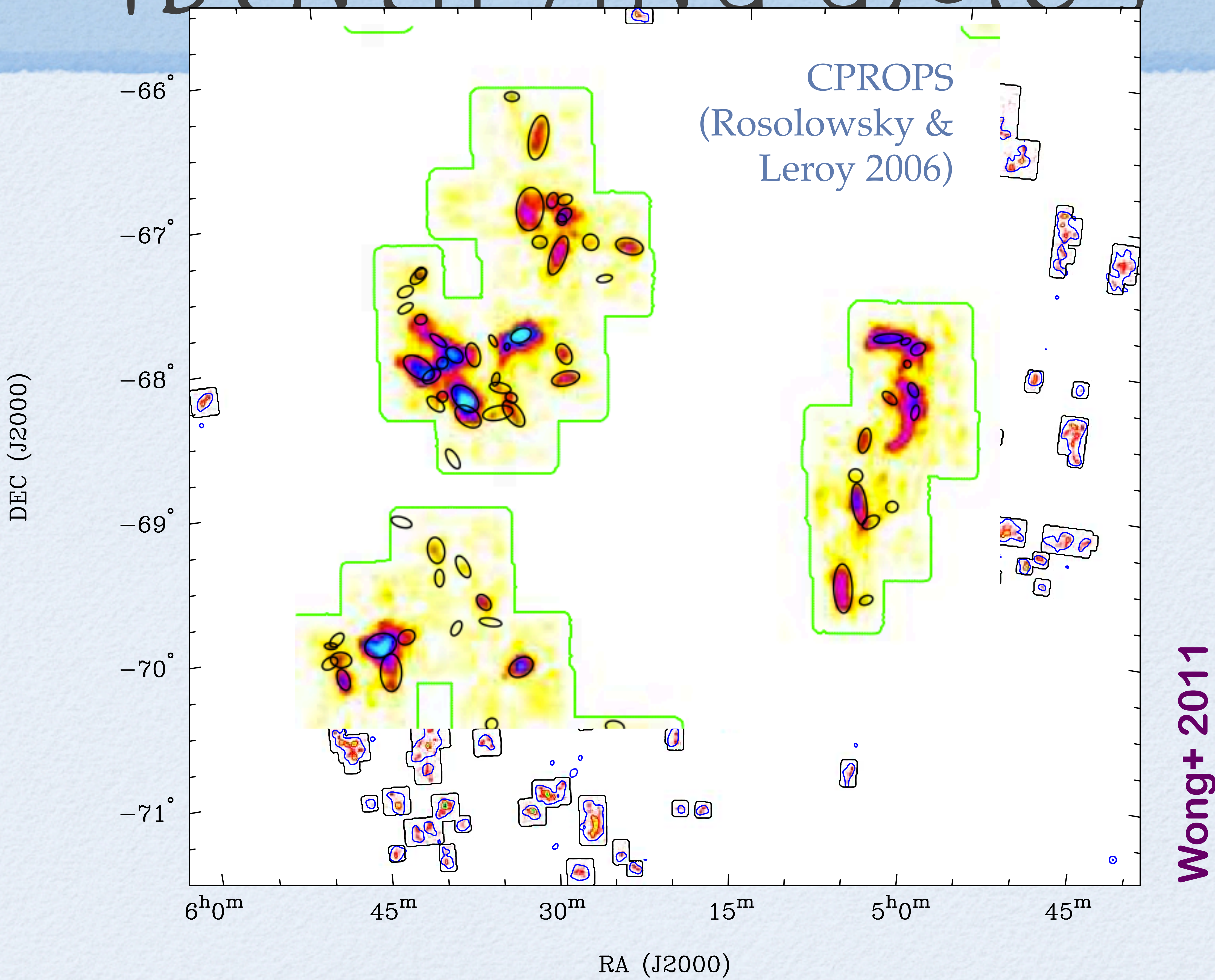
Rosolowsky+ 2008

IDENTIFYING GMC'S



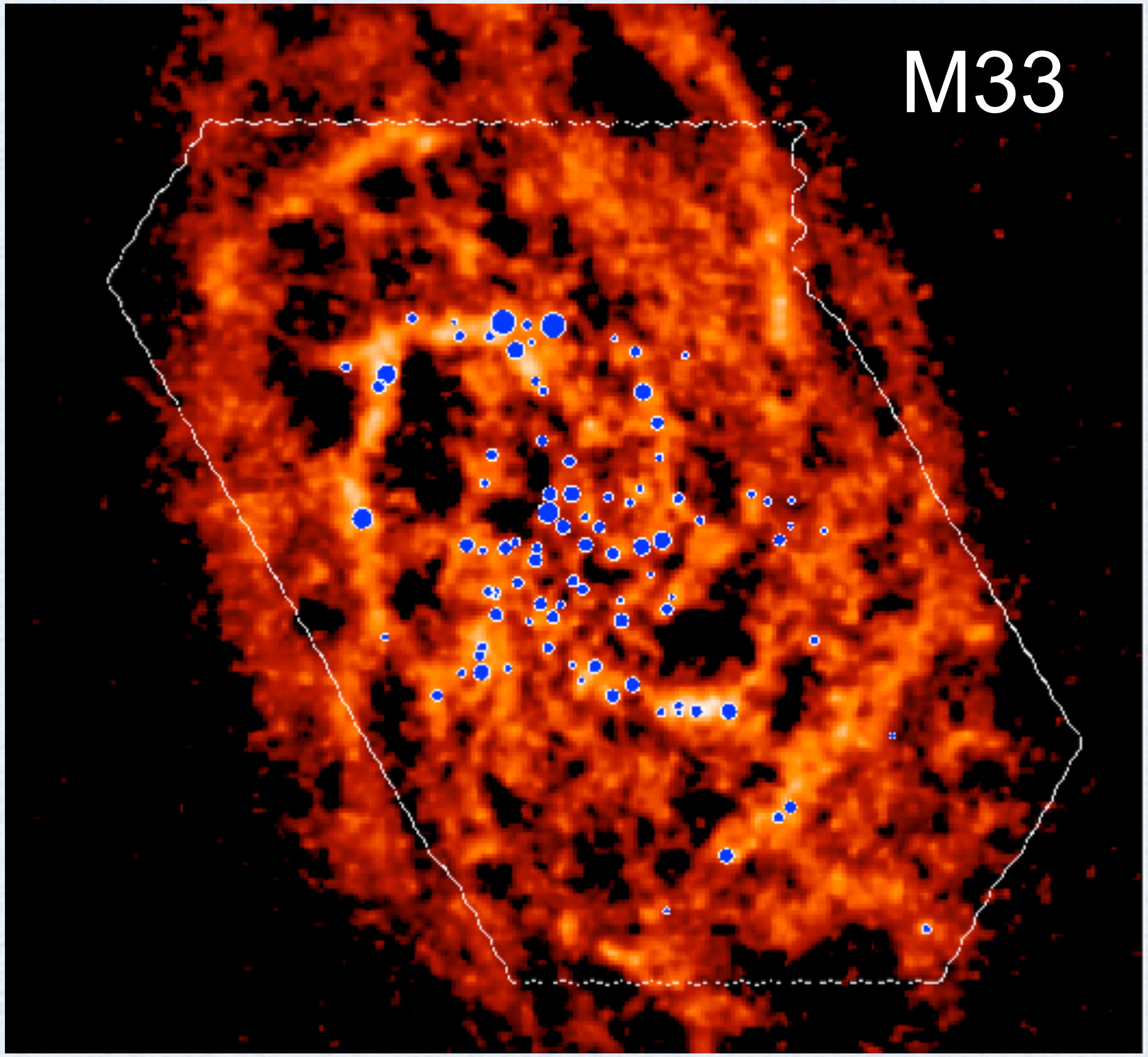
Wong+ 2011

Identifying GMC's

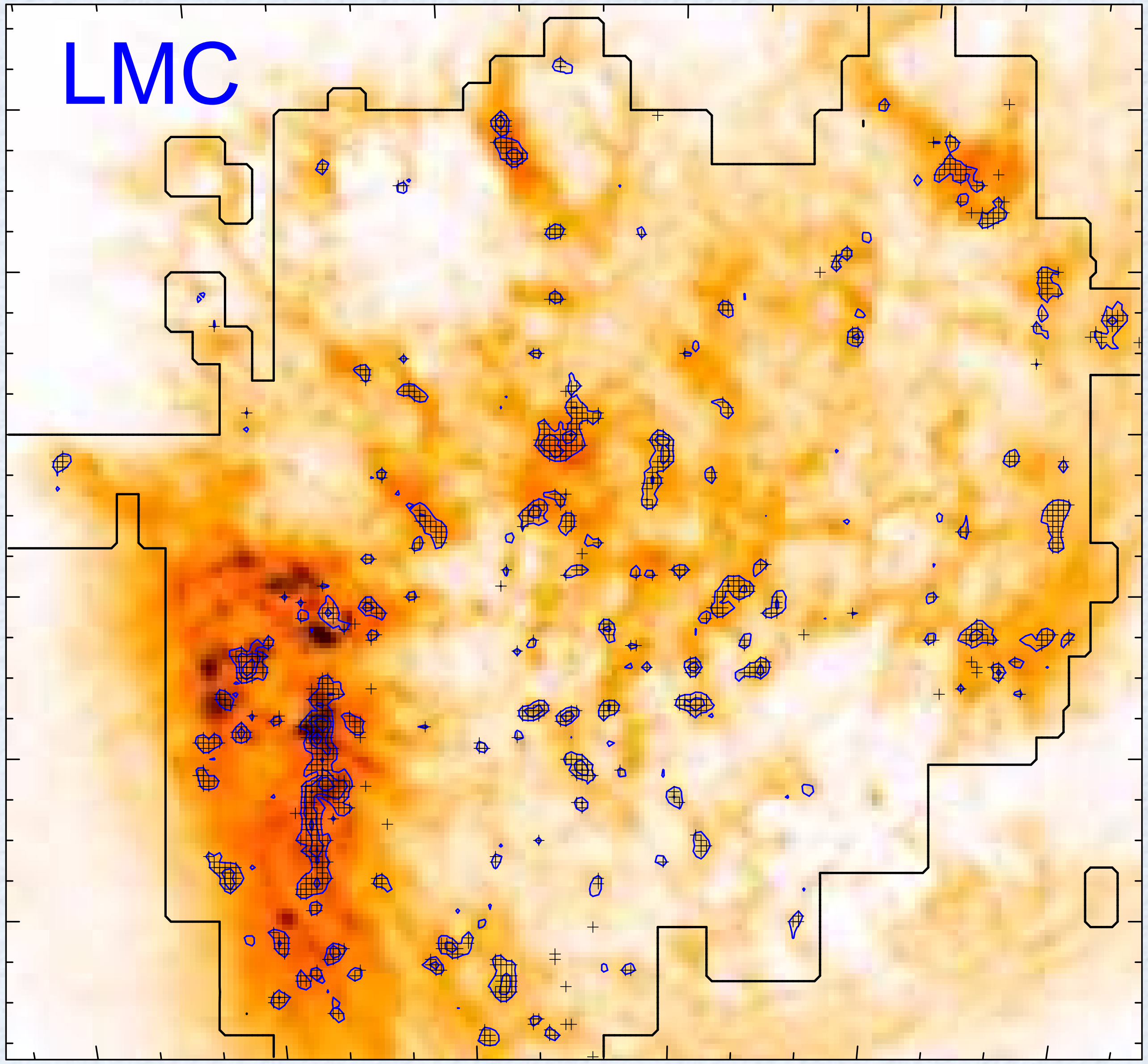


Association with HI

- In HI-dominated galaxies, GMCs are exclusively found in regions of high HI column density, again consistent with self-shielding models.



Engargiola+ 2003



Wong+ 2009

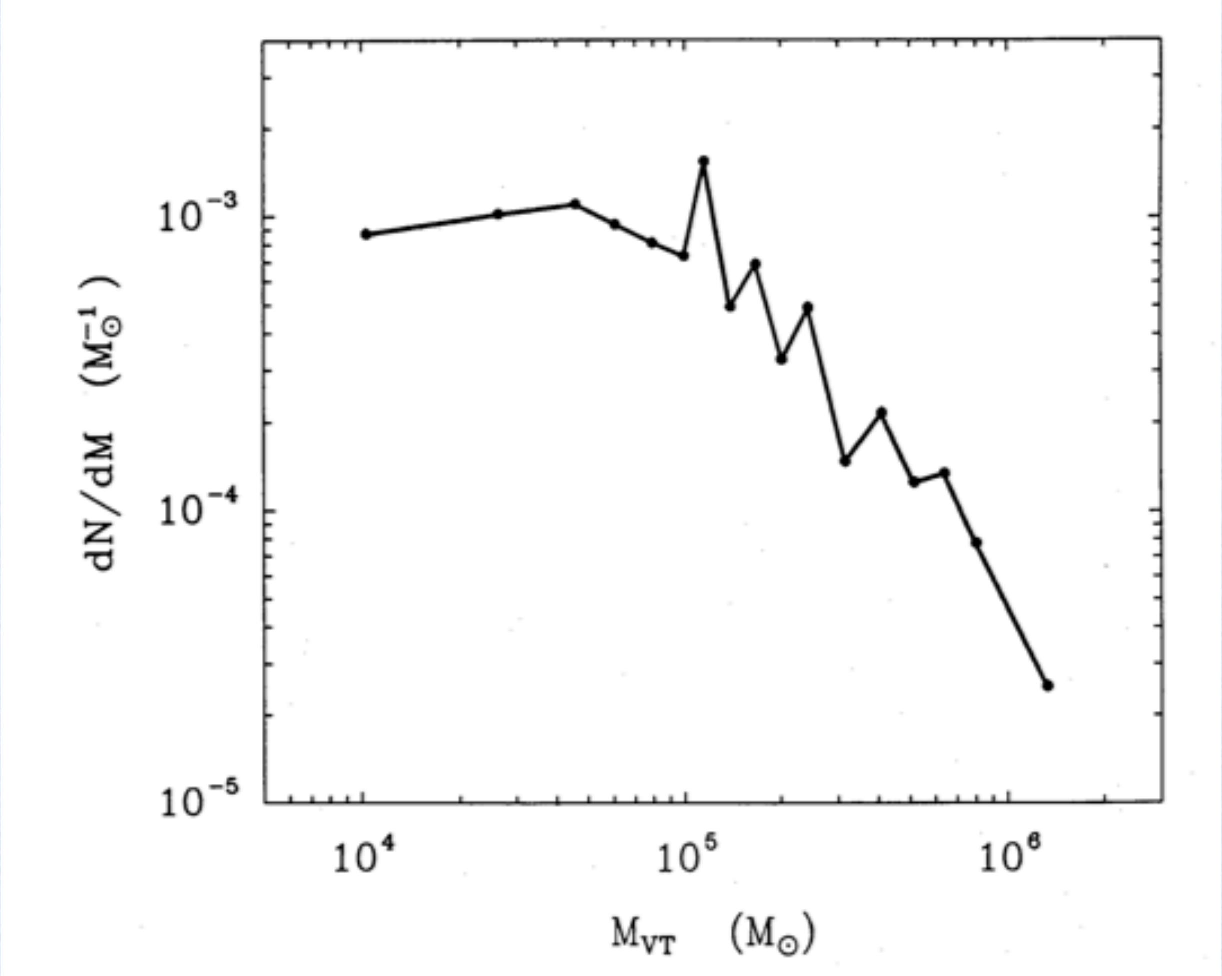
GMC Mass Spectrum

$$\frac{dN}{dM} \propto M^{\beta}$$

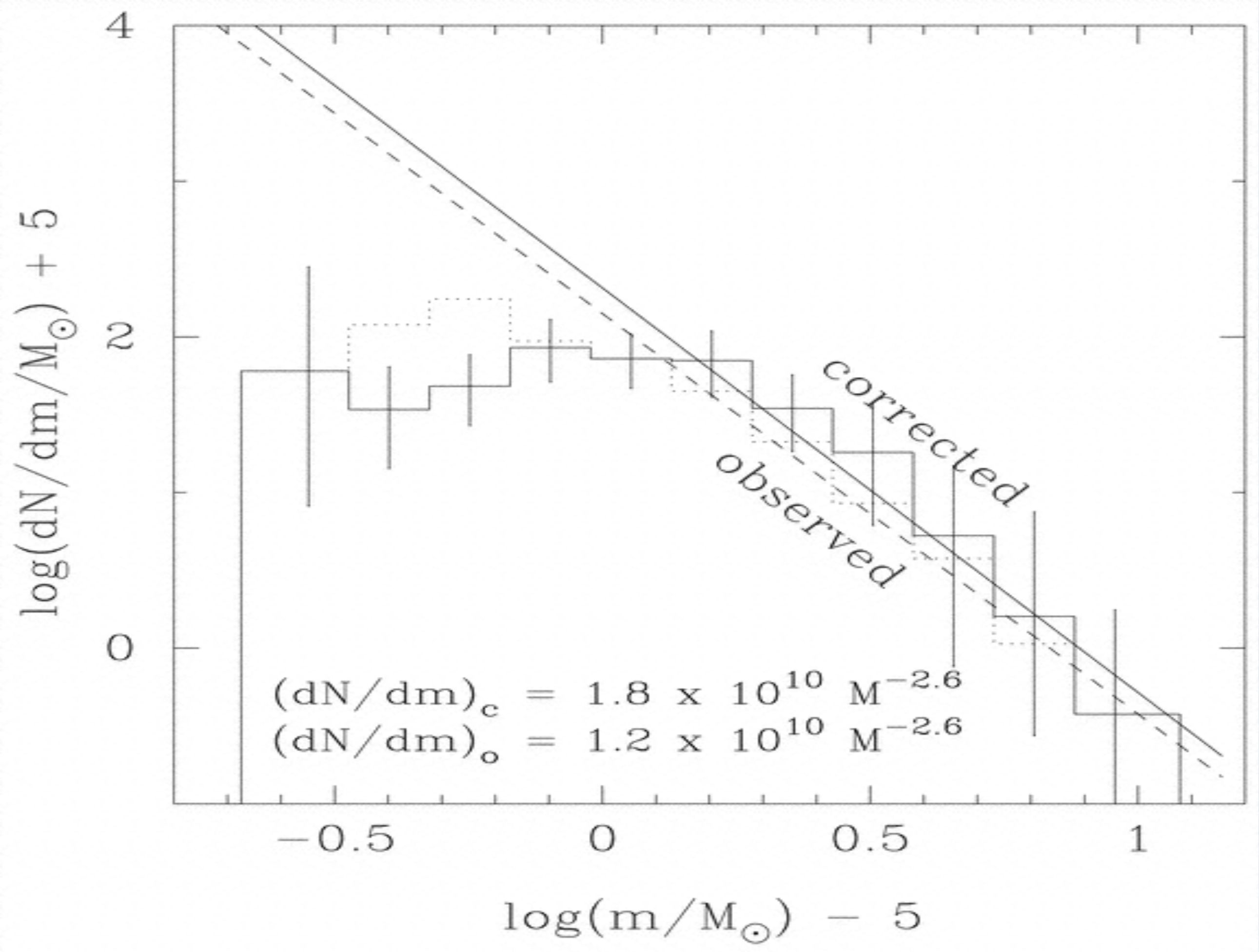
$\beta > -2$ Majority of mass in high-mass clouds.

$\beta < -2$ Majority of mass in low-mass clouds.

MW: β = –1.5 (Solomon+ 87)



M33: β = –2.6 (Engargiola+ 03)

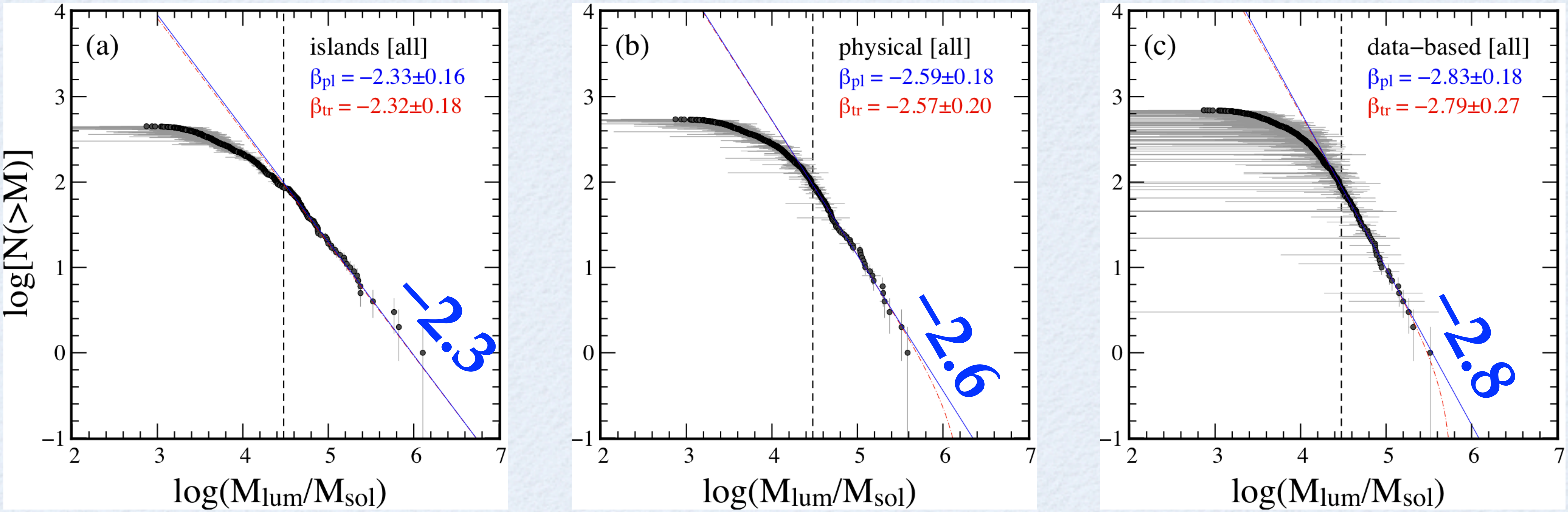


Mass Spectrum: LMC

Max. contiguous <R> = 13.5 pc

"GMC-like" <R> = 12.3 pc

Resolution limited <R> = 11.2 pc

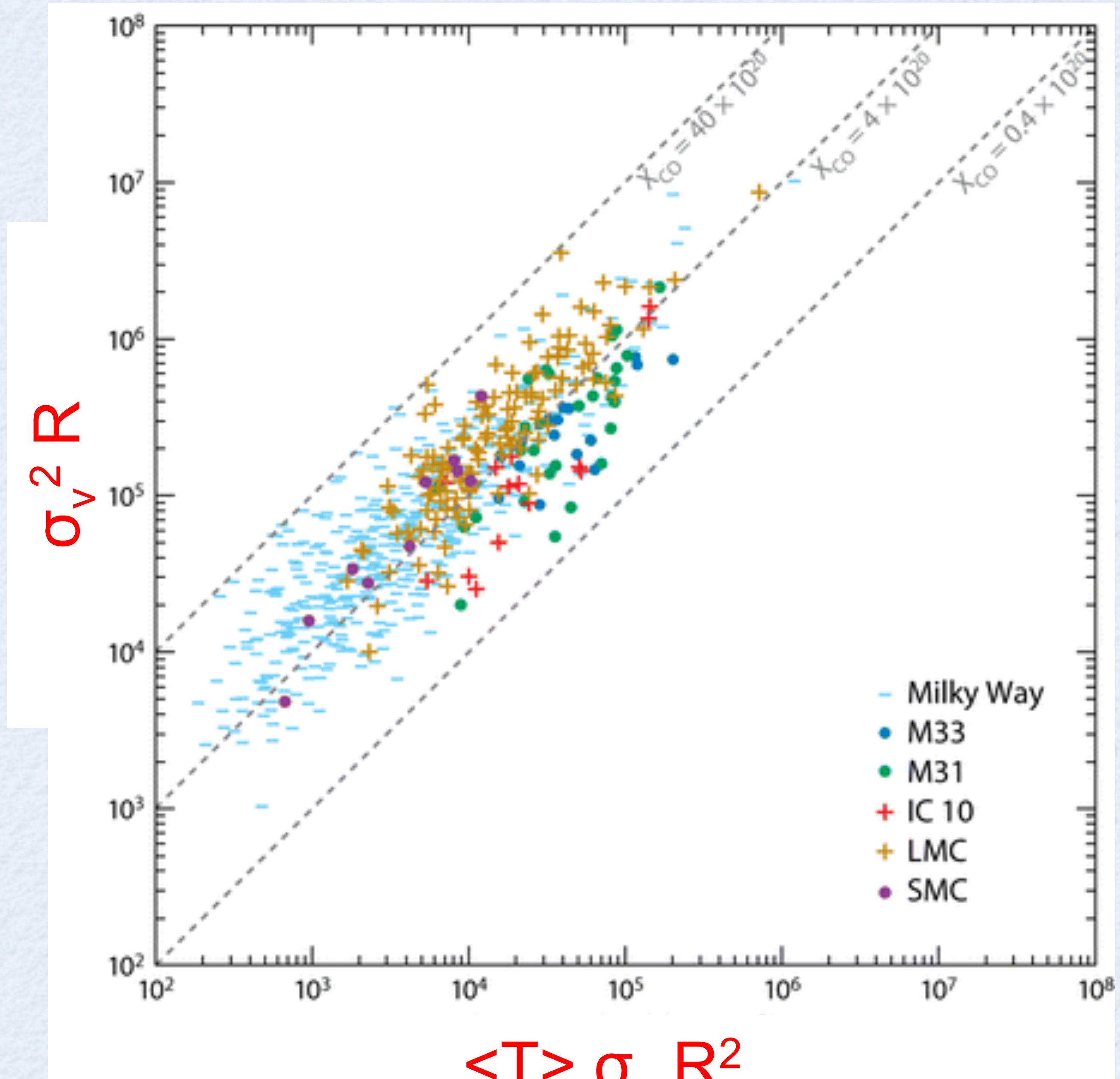


Further decomposition tends to steepen cloud mass function (as expected), but even largest contiguous structures have slope < –2.

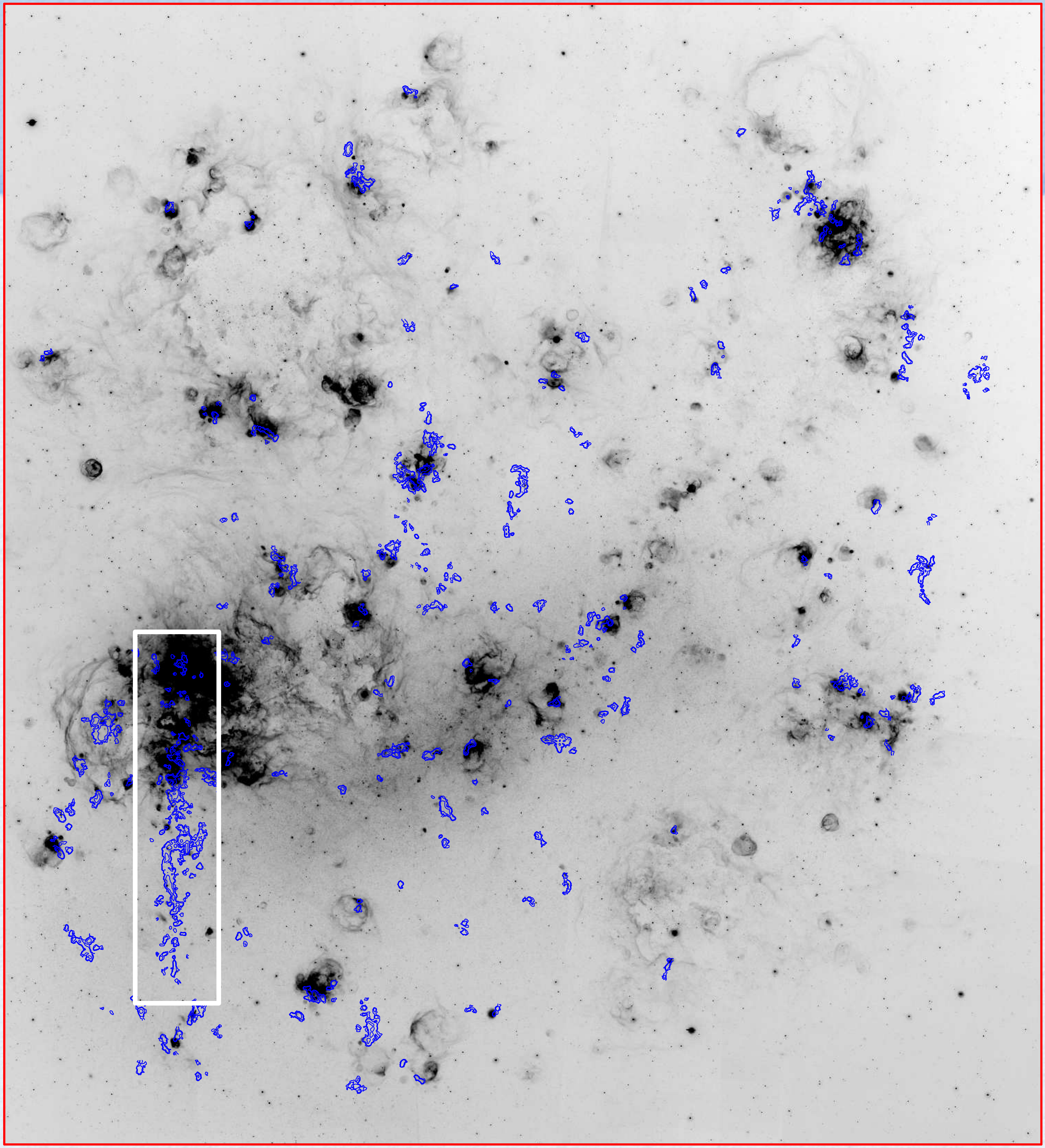
Caveat: are we missing low surface brightness emission?

Virial Equilibrium?

- **The observed correlation of virial mass with CO luminosity does not necessarily require that GMCs be virialized.**

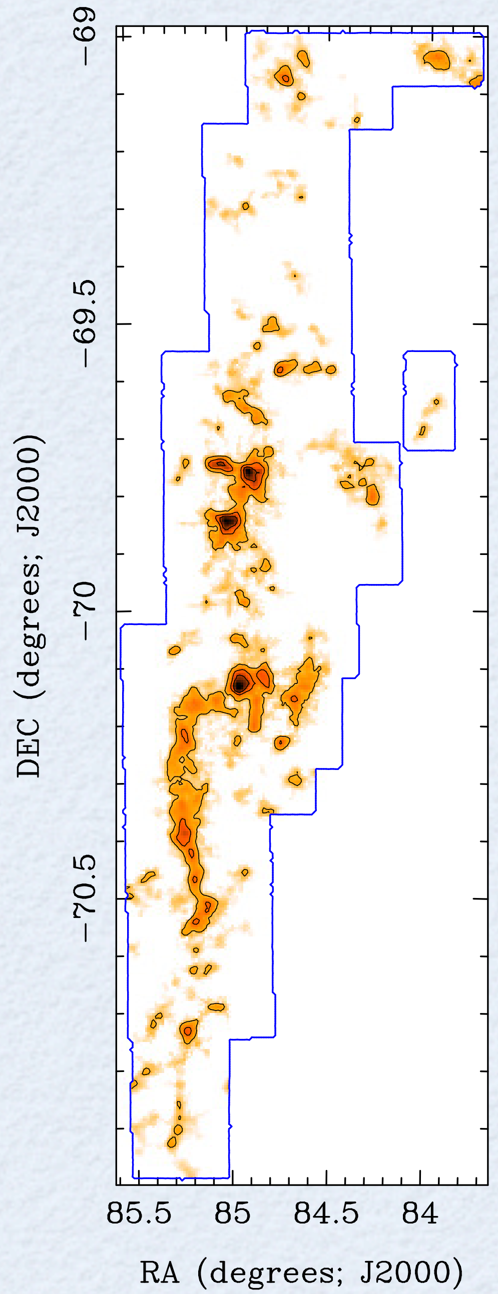


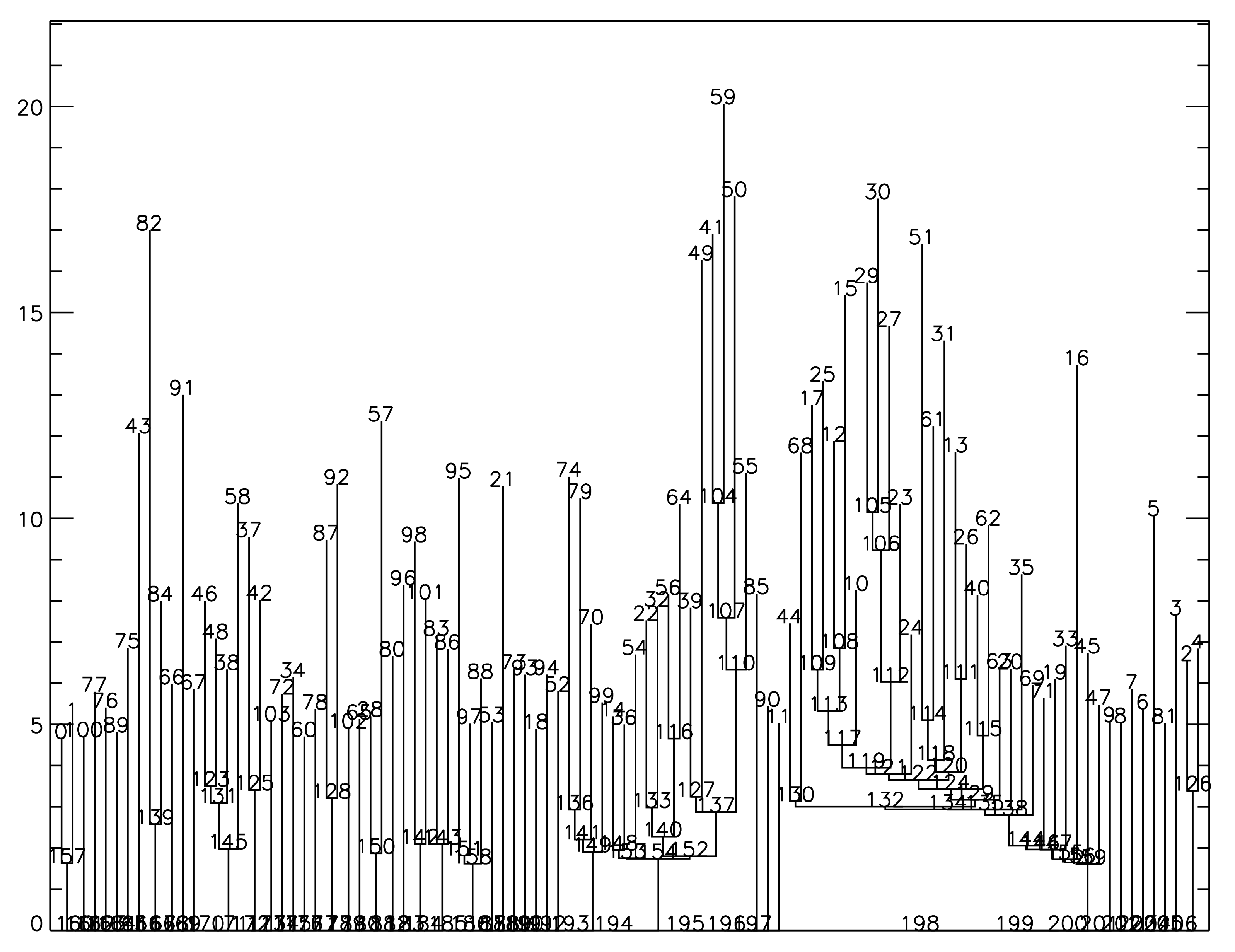
Fukui Y, Kawamura A. 2010.
Annu. Rev. Astron. Astrophys. 48:547–80



Dendrograms

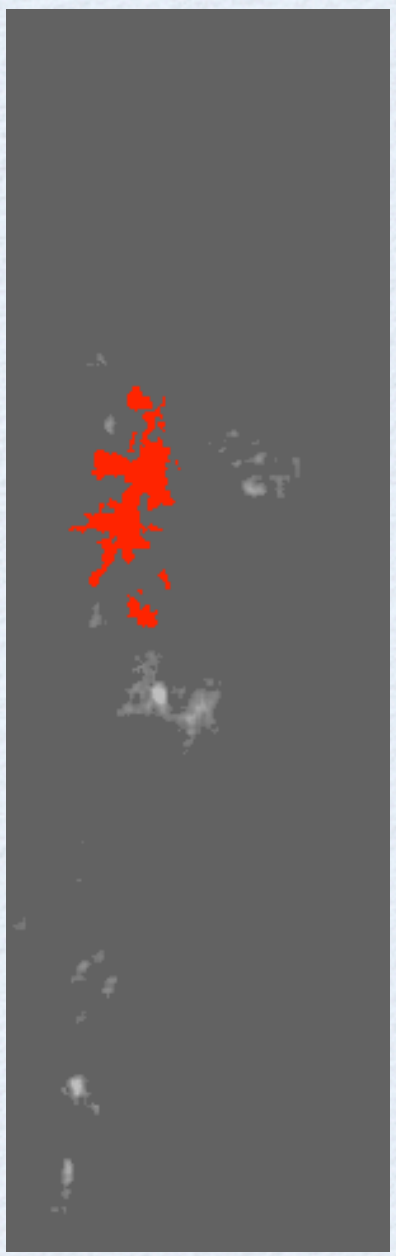
- If a molecular "intercloud" medium exists, one expects to see multiple narrow peaks superposed on a few broad ones. This can be visualized using a cluster tree ("dendrogram").

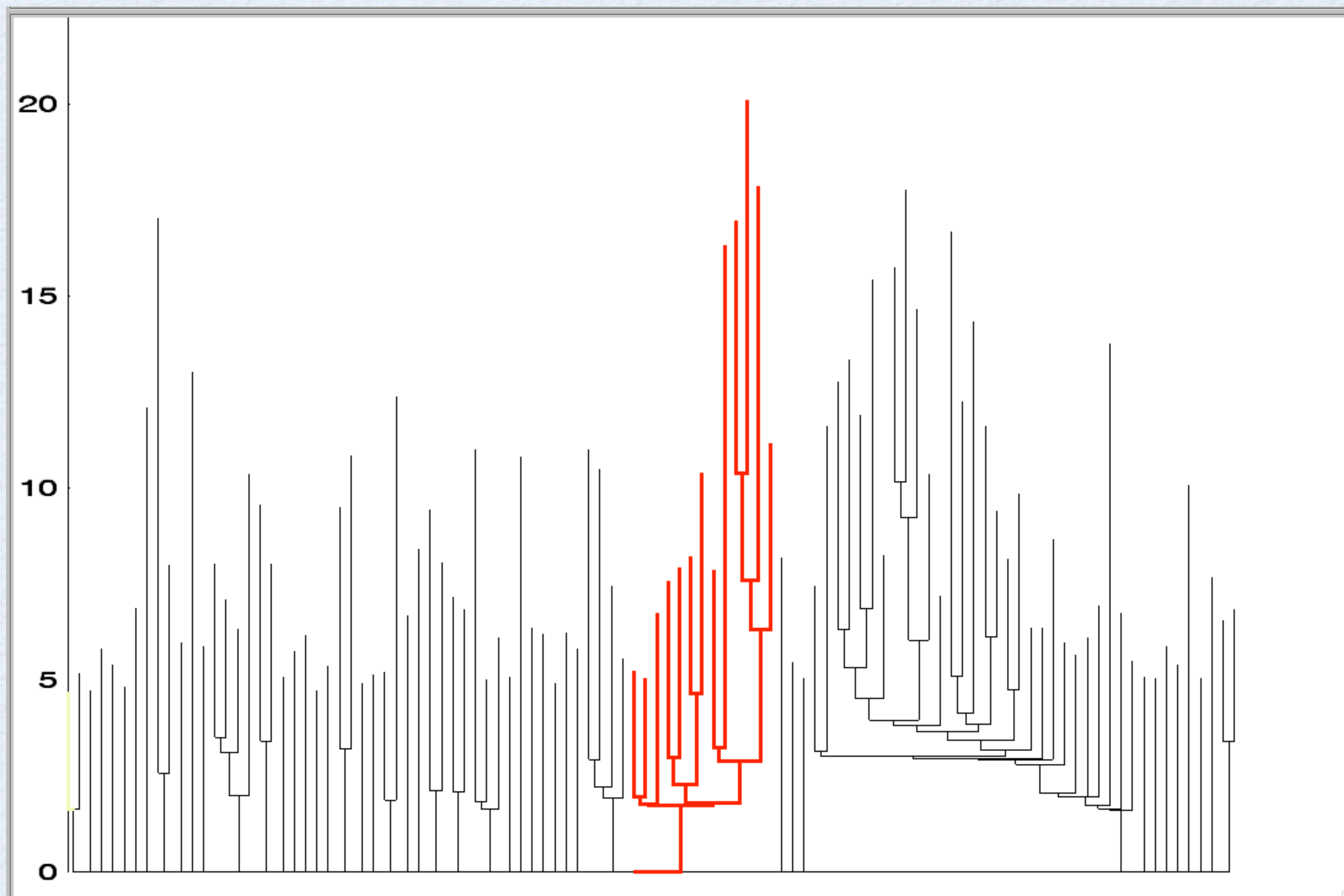




Dendrograms

- Example of applying the code of Rosolowsky+ (2008) to the eastern "Molecular Ridge" in the LMC.





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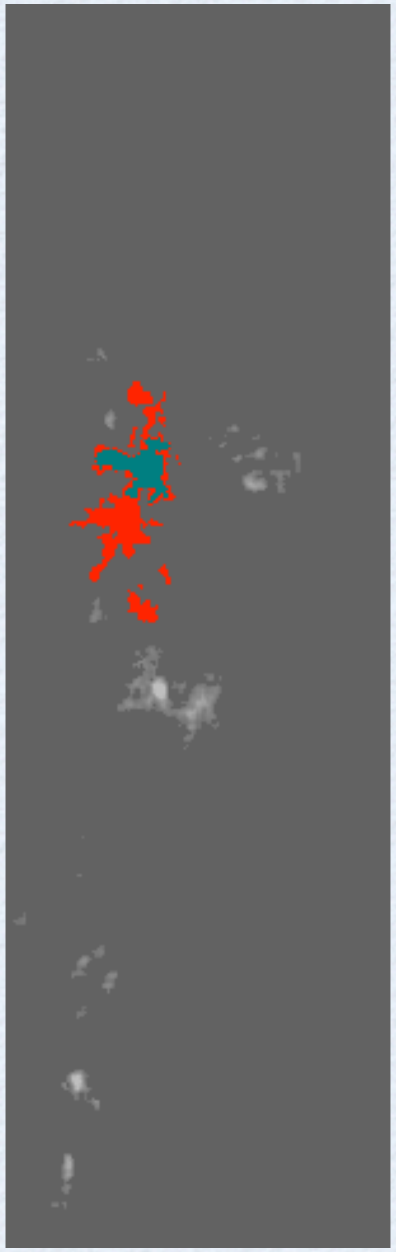

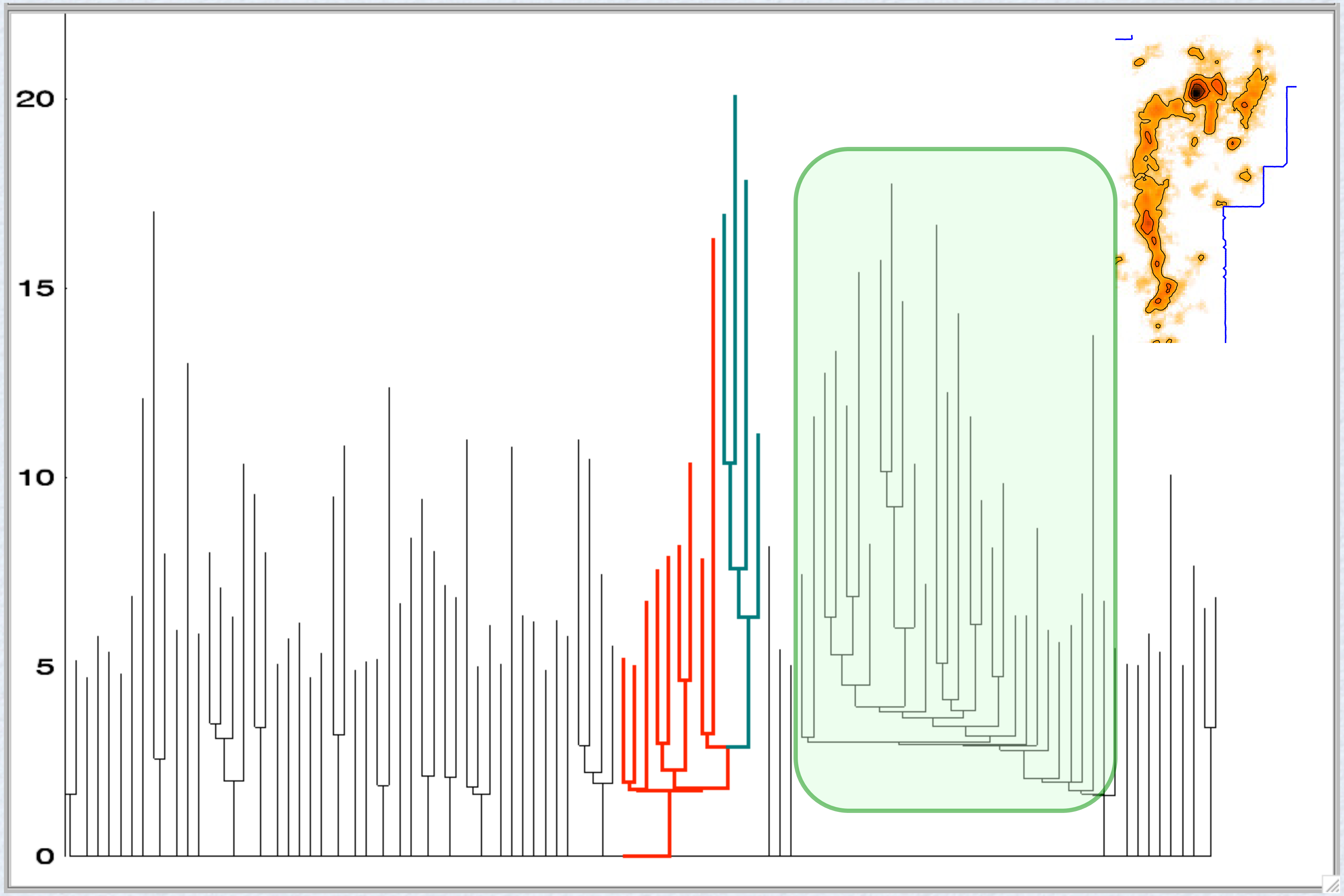

SUMMARY

- H_2 preferentially occurs in regions of high gas and high stellar surface density, leading to radial distributions and total masses distinct from HI.
- Characterizing the life cycle of GMCs remains difficult because ages and causality difficult to establish.
- We are starting to obtain censuses of GMCs in the nearest galaxies along with rough property measurements (size, line width, luminosity).
- CO clouds in the LMC appear generally discrete with an excess of small clouds, though more sensitive data will be needed to confirm this.