The Resolved Properties of Extragalactic Giant Molecular Clouds

... or ...

Connecting the Galactic and Extragalactic Scales of Star Formation

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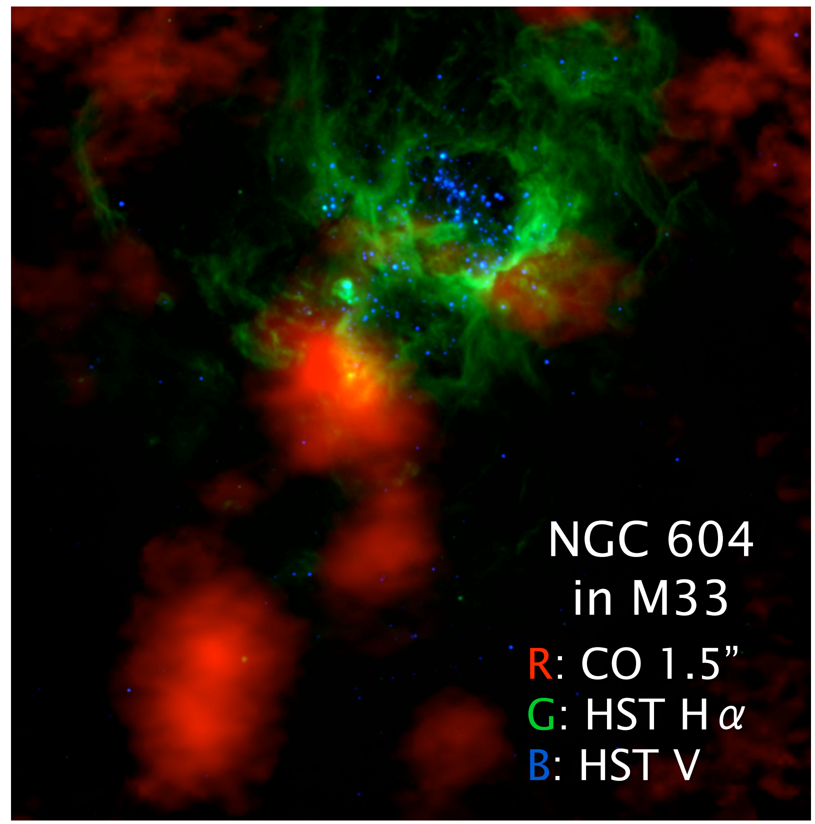
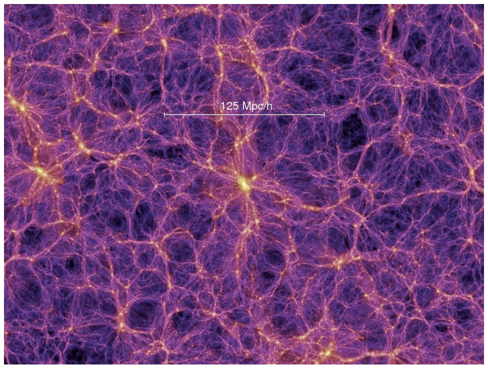
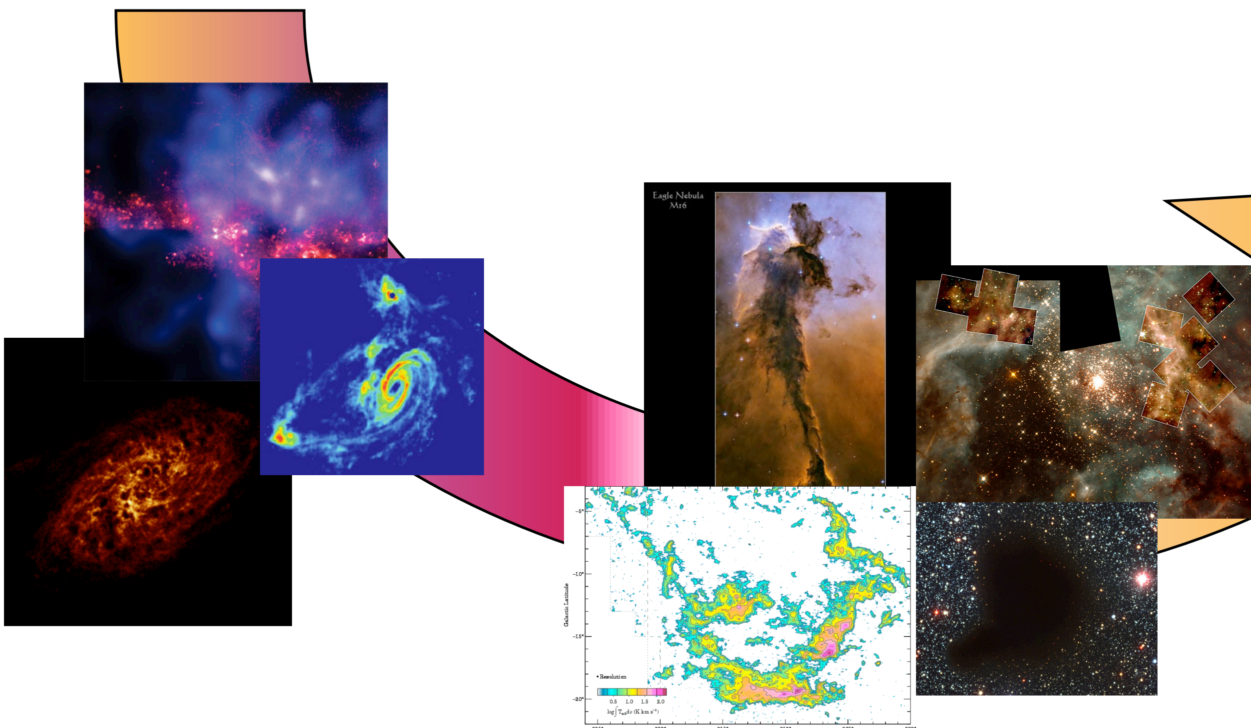
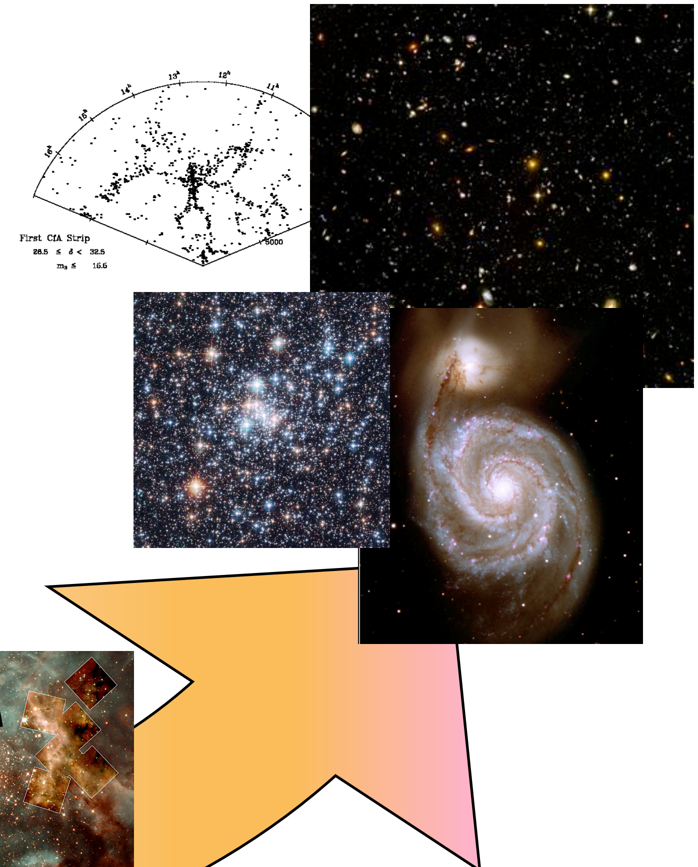


Why GMCs are important:

They mediate the formation of stars from gas, one of the key drivers of galaxy evolution



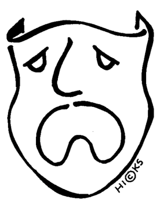




The conversion of gas to stars is at the core of structure formation the direct conversion takes place in GMCs.

Take home message:

The CO-bright portions of extragalactic giant molecular clouds are almost identical to those of Galactic giant molecular clouds**.*



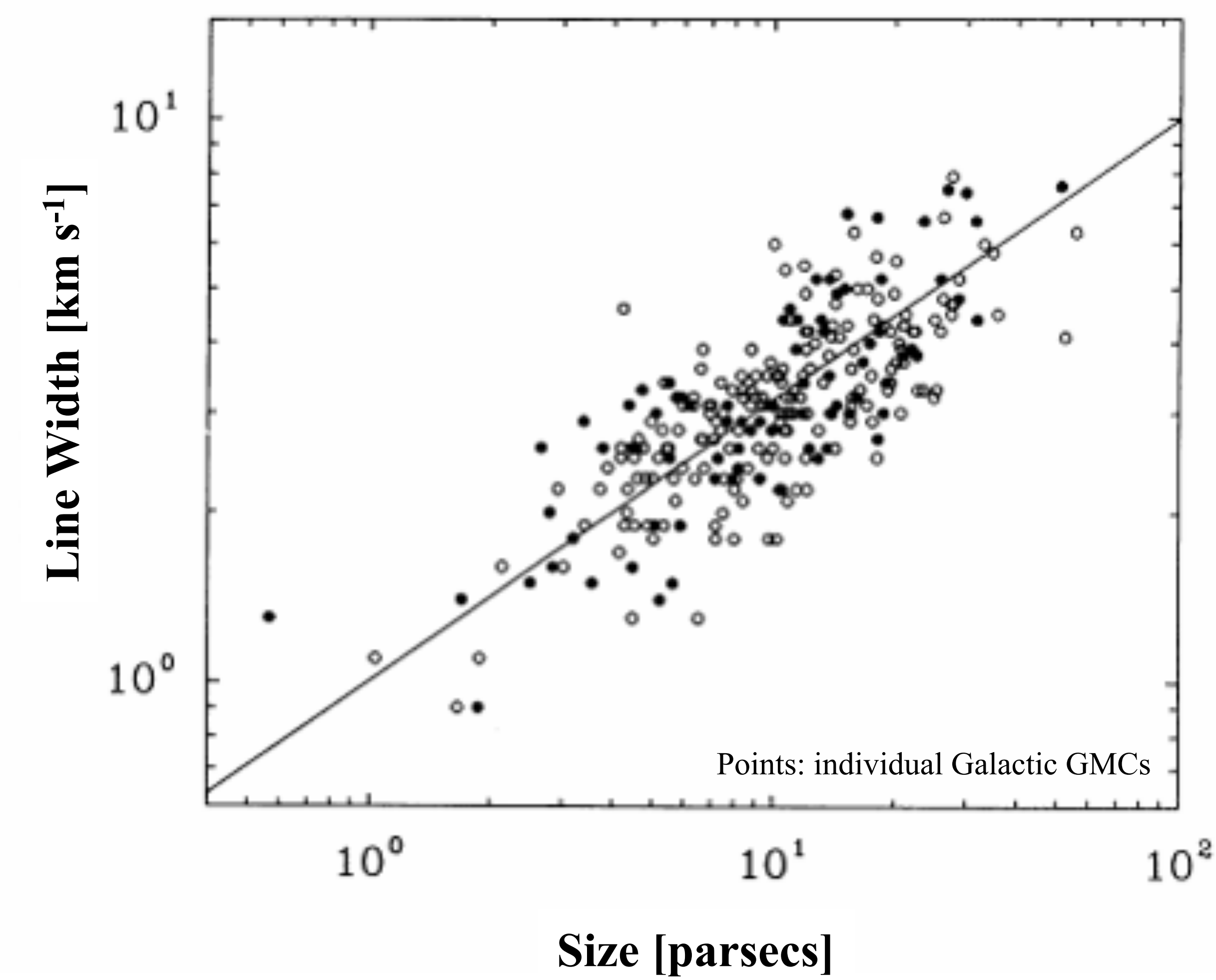
But CO tells only part of the story, particularly in the Small Magellanic Cloud. Dust suggests extended reservoirs of H_2 untraced by CO at very low metallicity.

* Details matter.
** Claims verified for non-starburst galaxies only.
*** Past performance is not necessarily indicative of future results.

Background: GMC scaling relations in the MW

CO

"Size-Line Width Relation"



Solomon+ 87

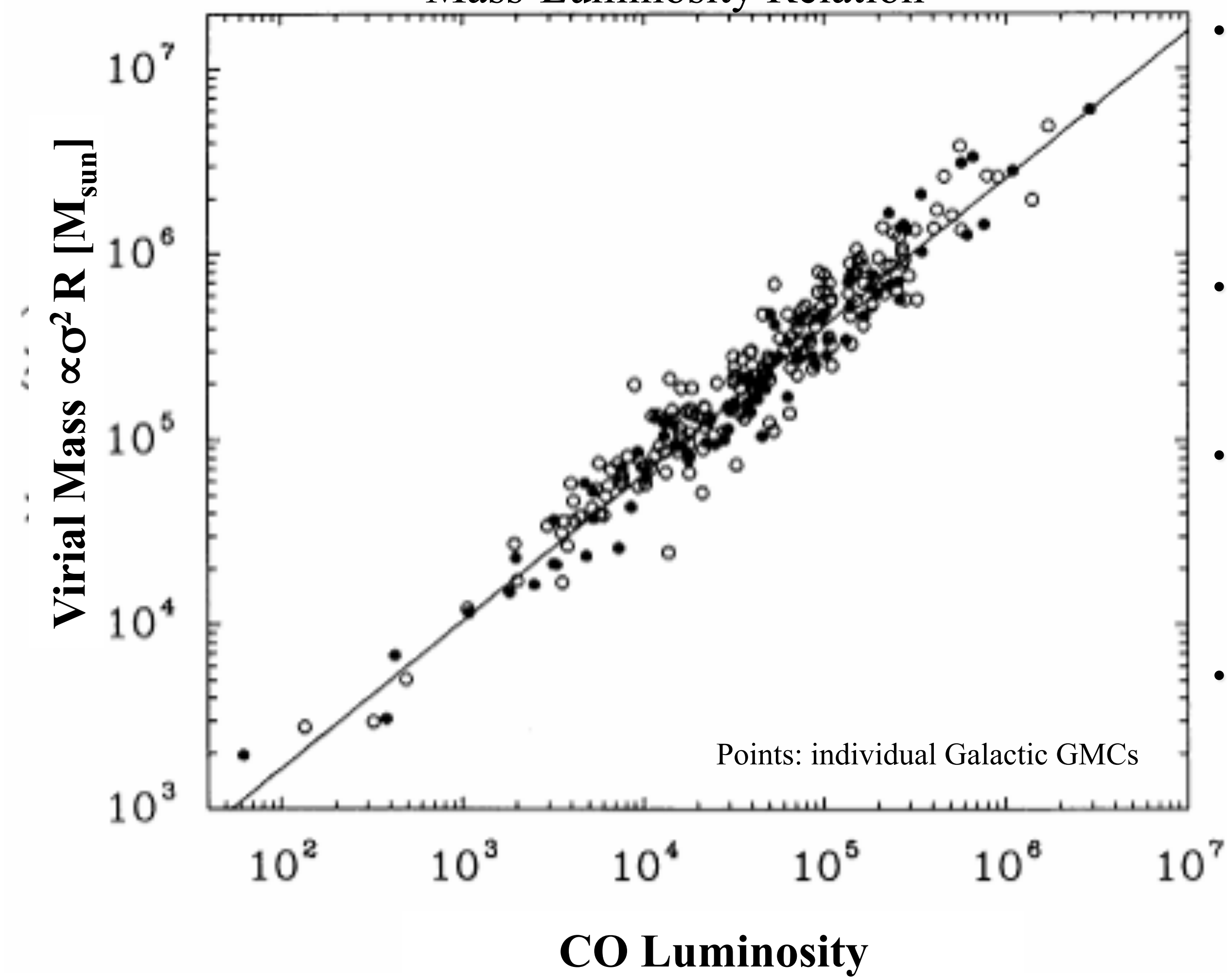
- *Recognized by Larson 79, 81 and attributed to Kolmogorov turbulence.*
- *Today attributed to compressible, shock-dominated supersonic (Burger's) turbulence.*
- *In Milky Way:* $\sigma = 0.72\ R_{pc}^{0.5}$ *km/s*
- *Coefficient related to surface density:*

  with $M_{vir} \sim R\sigma^2 \Rightarrow$ $\Sigma = M/R^2 \sim const$
- *In Milky Way:* $\Sigma \sim 170\ M_{sun}/pc^2$
- *But see recent work by Heyer et al. (2008)!*

Background: GMC scaling relations in the MW

CO

“Mass-Luminosity Relation”



Solomon+ 87

- *Luminosity-line width and luminosity-size relations yield mass-luminosity relation*
- *Milky Way:* $M_{vir} = 39\ L_{co}^{0.8}\ M_{sun}$
- *Quasi-linearity gives rise to* X_{co}*, the CO-to-*H_2 *conversion factor*
- *In the MW, virial, γ-ray, and dust continuum values of* X_{co} *are consistent*

What We Did…

CO

Compiled new and literature observations of GMCs:

- *BIMA, OVRO, PdBI, and SEST*

- *spatial resolution 7-120 pc.*

- *metallicity to ~ 1/5 to solar.*

- *two orders in galaxy mass.*

Analyzed these data in a consistent manner:

-CPROPS *(Rosolowsky & Leroy 06)*

TABLE 2
GALAXY PROPERTIES

Galaxy	Morph.	Dist.	M_B	Met.	Ref.
IC 10	Irr/BCD	0.95	−16.7	8.2	6
NGC 185	dSph/dE3	0.63	−14.7	8.2	1
NGC 205	E5	0.85	−15.9	8.6	1
SMC	Sm	0.061	−16.7	8.02	7
LMC	Sm	0.052	−18.0	8.43	7
NGC 1569	Irr	2.2	−17.3	8.19	2
NGC 2976	Sc	3.45	−17.4	8.7	3
NGC 3077	Irr	3.9	−17.5	8.7	3
NGC 4214	Irr	2.94	−17.2	8.23	4
NGC 4449	Irr	3.9	−18.0	8.32	5
NGC 4605	Sc	4.26	−17.9	8.7	3
Disk Galaxies					
Milky Way	SB	0.008	−21.4	8.7	8
M31	Sb	0.79	−21.1	8.7	10
M33	Scd	0.84	−18.9	8.4	9

"The Resolved Properties of Extragalactic GMCs"
Bolatto, Leroy, Rosolowsky, Walter, Blitz, 2008, ApJ,in press.

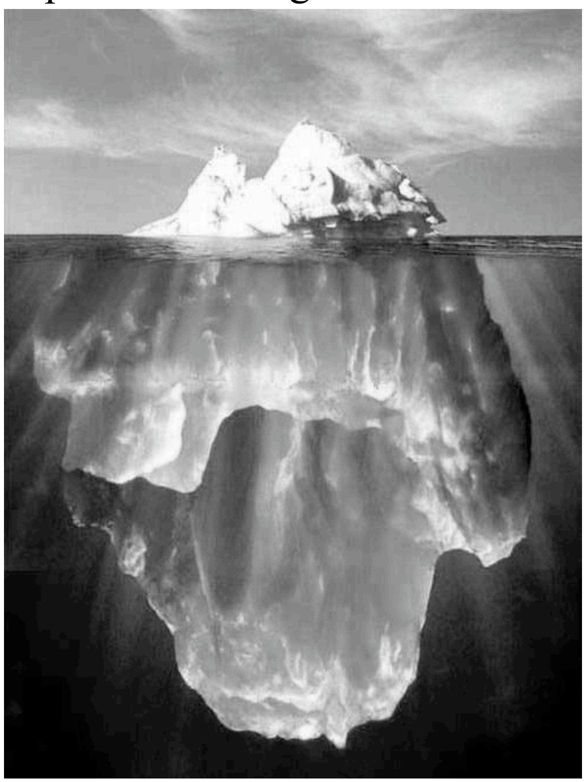
Measuring Extragalactic GMC Properties

CO

Comparing heterogeneous data sets among galaxies is made challenging by biases due to …

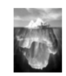
<u>Finite Sensitivity</u>

"Tip of the iceberg in a sea of noise"



<u>Finite Resolution</u>

Other galaxies are very far away



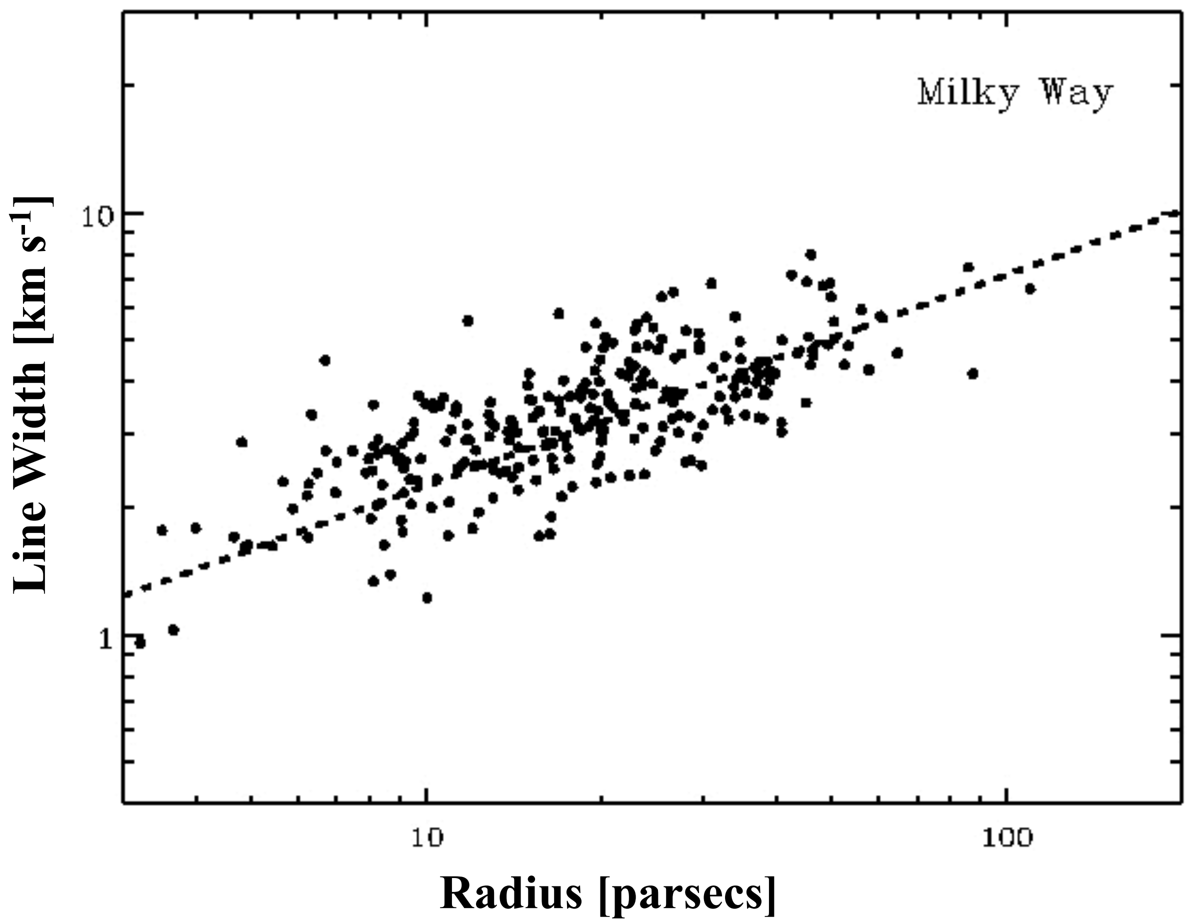
An attempt to systematically correct for these biases: **CPROPS** (Rosolowsky & Leroy 06)

The Size-Line Width Relation in Galaxies

CO

Milky Way

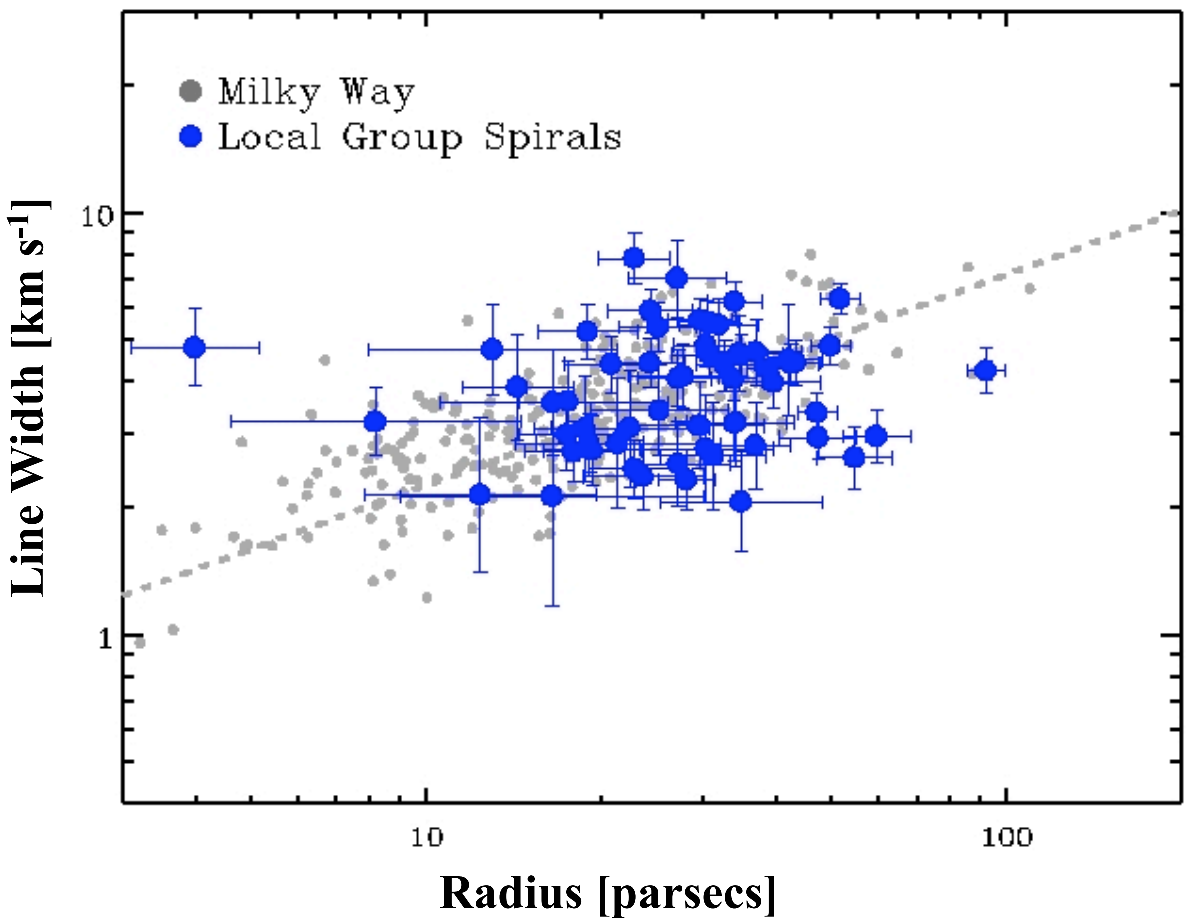
Solomon+ 87



Solomon+ 87

The Size-Line Width Relation in Galaxies

CO



Milky Way

Solomon+ 87

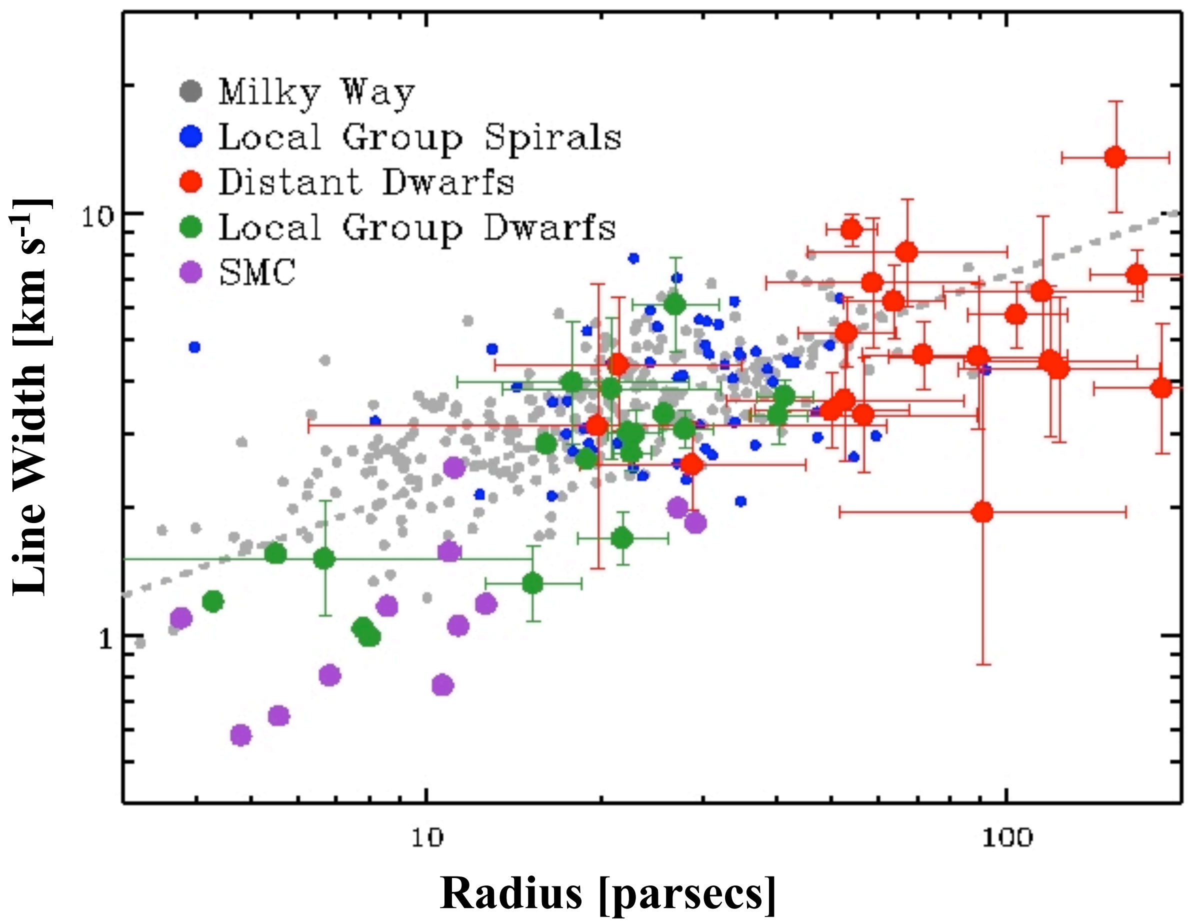
Local Group Spirals

M31 & M33

Rosolowsky+ 03, Rosolowsky 07

The Size-Line Width Relation in Galaxies

CO



Milky Way

Solomon+ 87

Local Group Spirals

M31 & M33

Dwarfs outside the Local Group

NGC 1569, 2976, 3077, 4214, 4449, 4605

Local Group dwarfs

IC 10, LMC, NGC 185, NGC 205

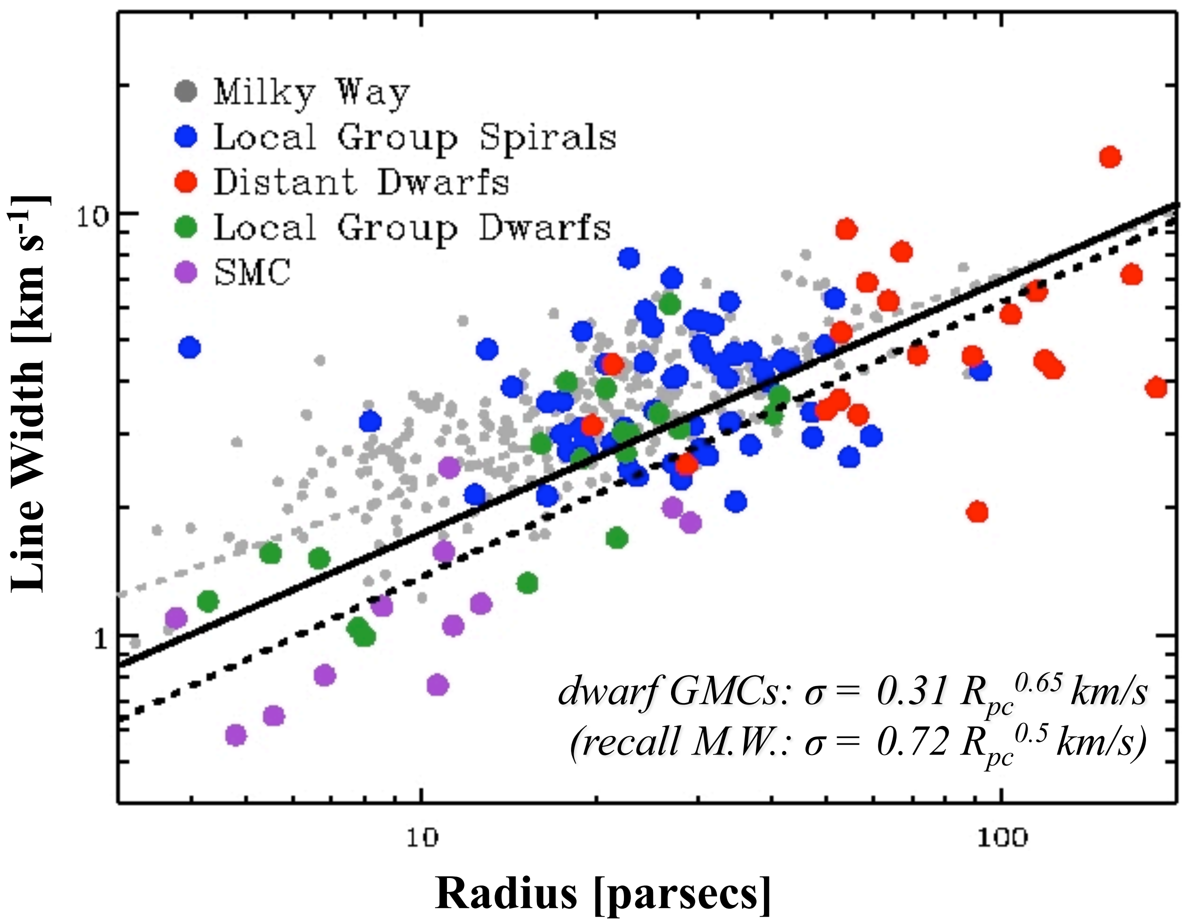
SMC

N83, LIRS36, LIRS49

Taylor+ 99, Walter+ 01, 03; Leroy+ 06, Young+ 01; Bolatto+ 03, Rubio+ 93 (SEST K.P.)

The Size-Line Width Relation in Galaxies

CO



Dwarfs fairly consistent with both Milky Way and local group spirals:

- for $\sigma \sim R^{0.5}$, $\Sigma_{dwarf} \sim 85\ M_{sun}/pc^2$

Worst outliers (factor ~ 2): small clouds in SMC:

- low surface density?

- increased B-field? (e.g. Bot+ 07)

- clouds not virialized?

Main conclusion: agreement in CO-based GMC props…

(recall o.o.m. discrepancies in integrated properties).

Luminosity-Virial Mass Relation

CO

(one version of other independent Larson's Law)

We find $M_{vir} \sim L_{CO}$ *…*

- Solomon (MW): $M_{vir} \sim L_{CO}^{0.8}$

CO-to-H2 factor roughly as MW if GMCs are virialized…

SMC falls on Galactic line.

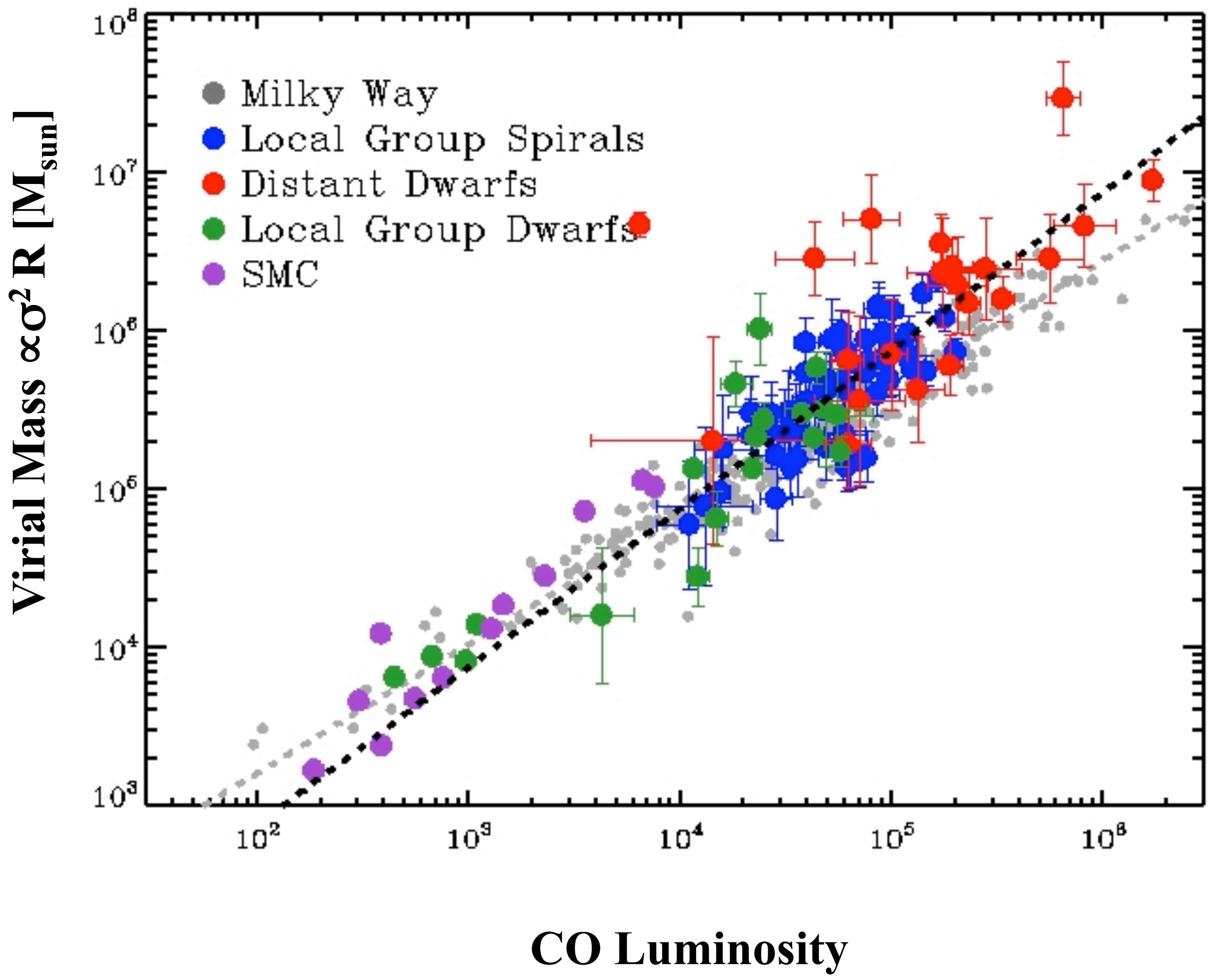
Other scaling relations:

L_{CO} *vs.* R

L_{CO} *vs.* σ

M_{vir} *vs.* R

follow from these two.



The CO-to-H_2 Conversion Factor

CO

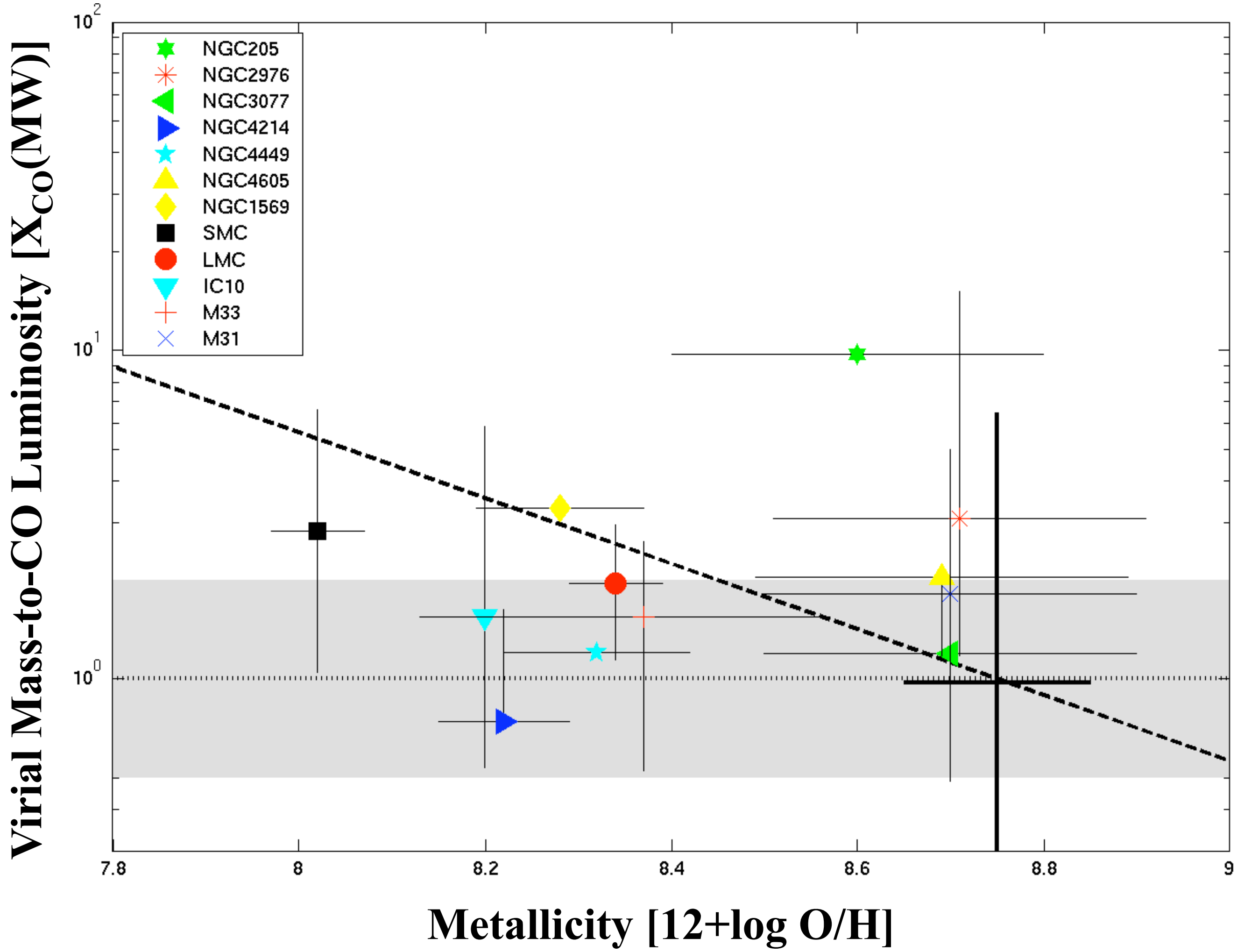
Ratio of virial mass to CO luminosity vs. metallicity.

- X_{CO} *for virialized clouds.*

No strong trend.

SMC completely compatible with MW clouds and Solomon (0.8) slope…

- *i.e.,* $M_{vir}/L_{CO} \sim L_{CO}^{-0.2}$



Photoionization-regulated star formation?

CO

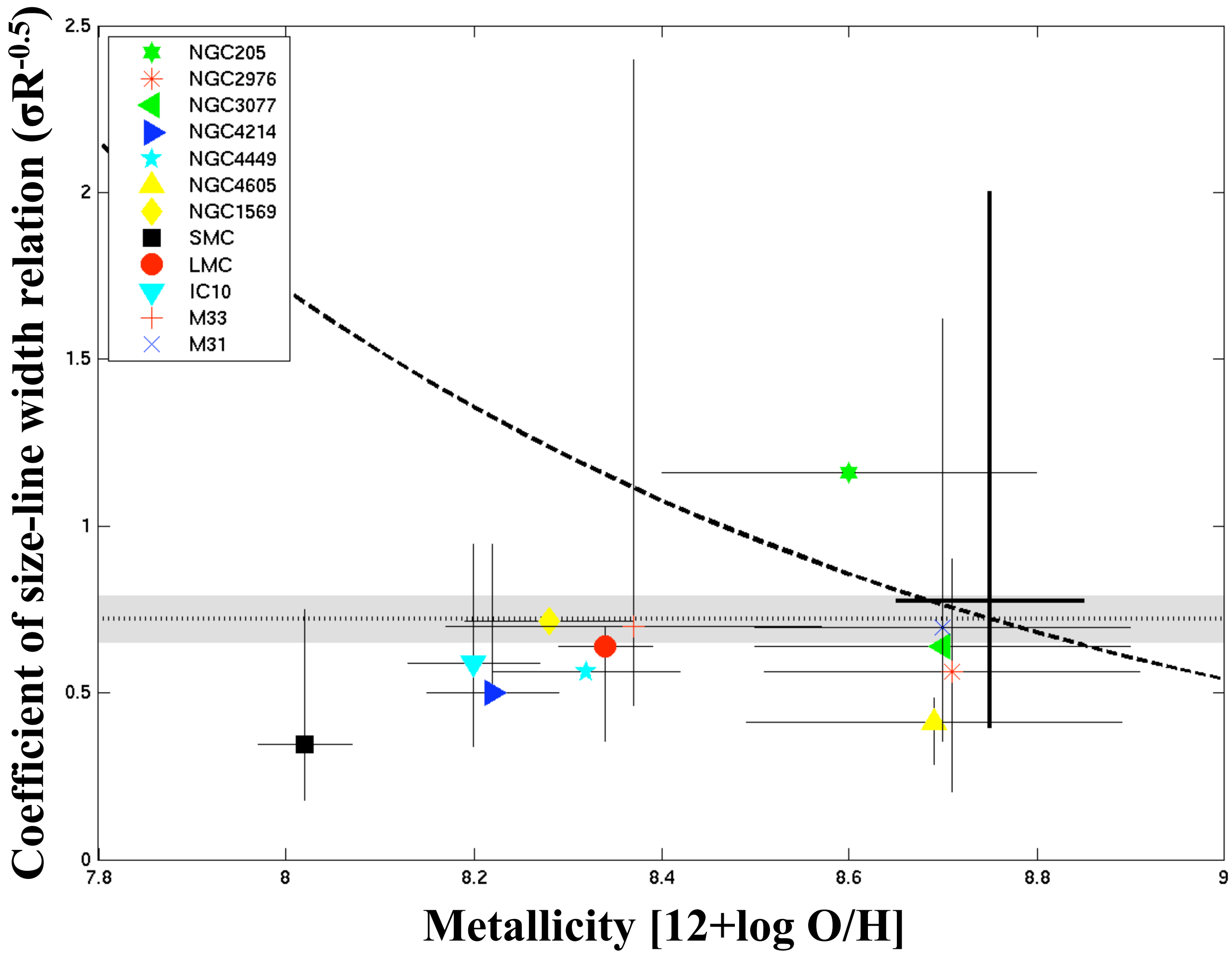
Star forming clouds need similar extinctions at their centers to decouple from magnetic support and collapse (McKee 1989)

Theory predicts

$$\sigma = 0.72\ (A_V/7.5\ \delta_{gr})^{0.5}\ R^{0.5}$$

Measurements show no evidence of that trend

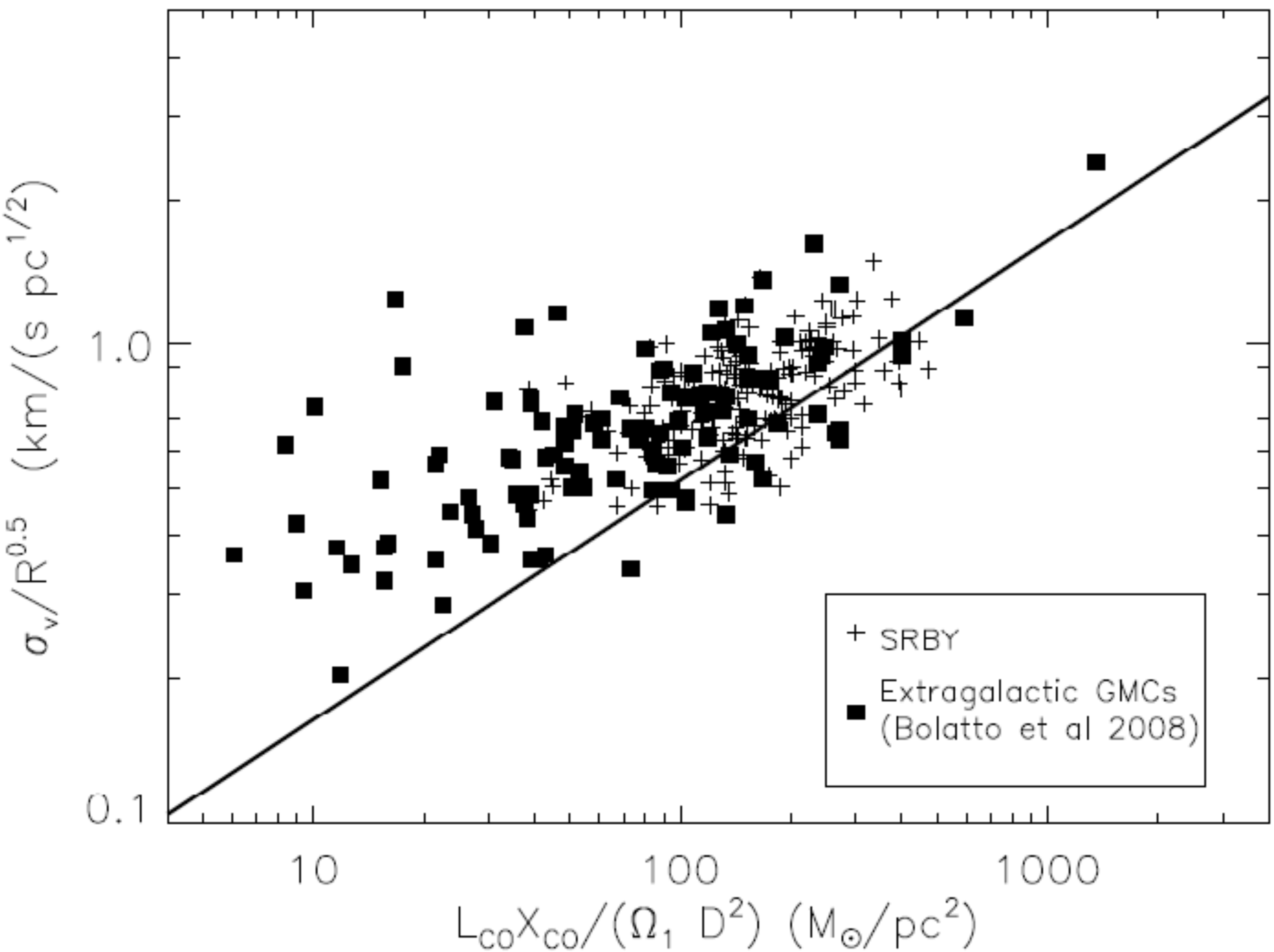
Caveats: are we reaching the relevant scales? Is the prediction overly simplistic?



Recent developments: Σ may not be constant

CO

Heyer et al. (2008) using GRS survey

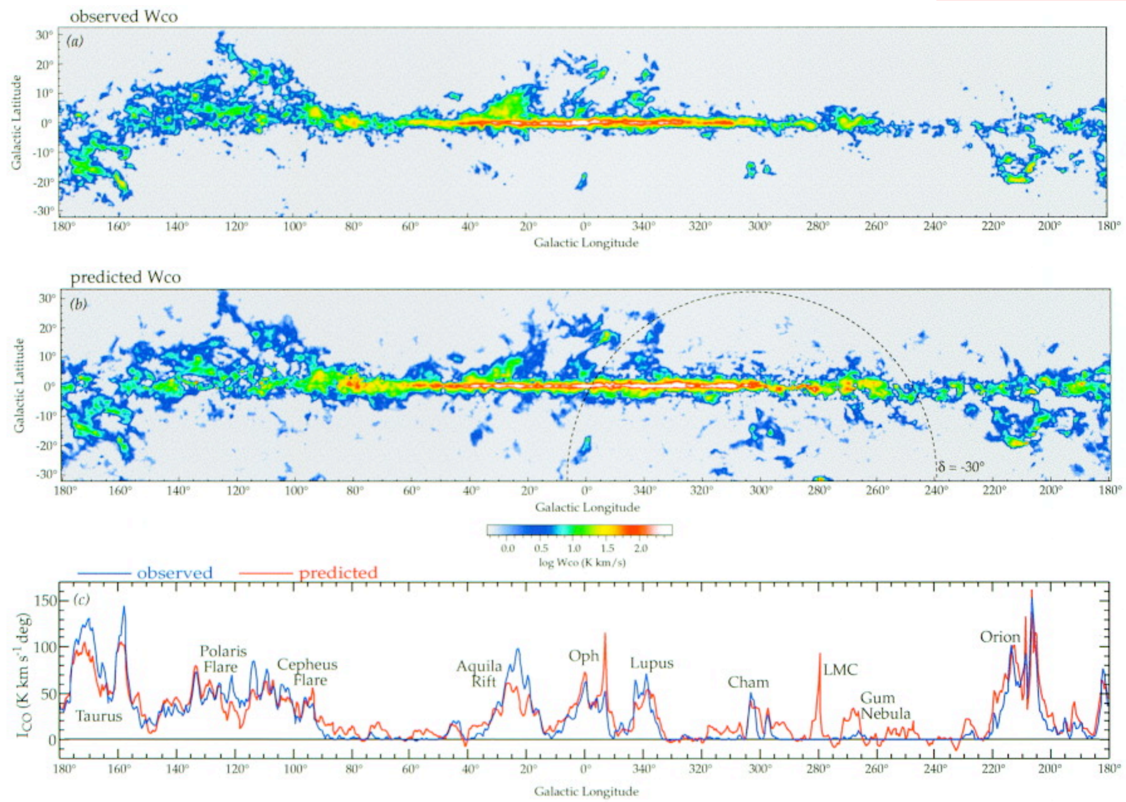


Background: A Different Way to Trace H_2

FIR

CO is expected to be biased at low z. FIR dust emission offers another view.

- *Traces the total gas (HI + H2) column.*
- *Probably better, at least 'differently biased.'*
- *In the Galaxy, matches Gamma Ray and CO results well.*
- *In the SMC, IRAS suggests much more H_2 than seen from CO (Israel 1997).*



Dame, Hartmann, and Thaddeus (2001)

Method:

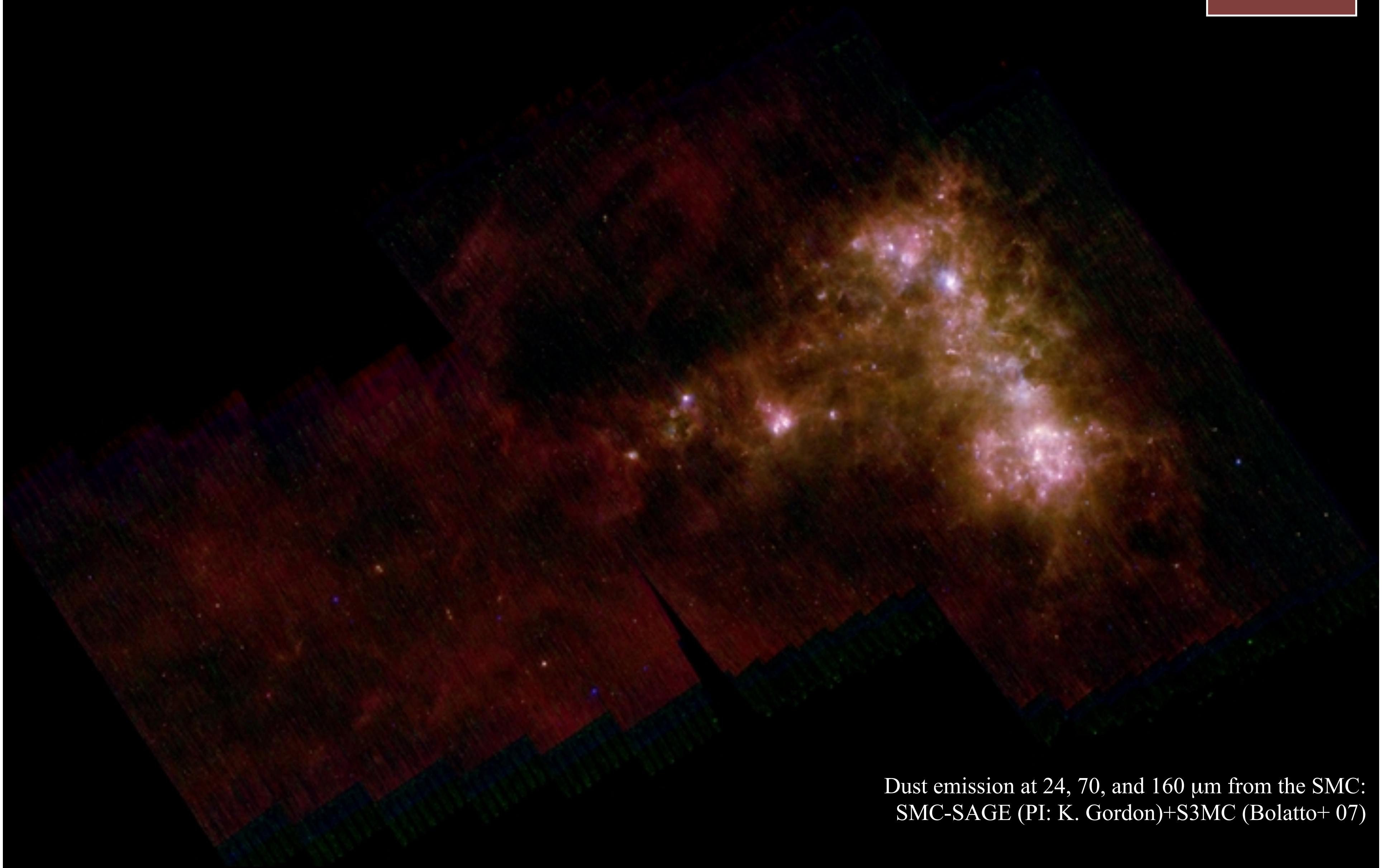
$$\Sigma_{H2} = (\Sigma_{dust} \times DGR^{-1}) - \Sigma_{HI}$$

*Estimate the **dust surface density** using FIR emission at 100 & 160 microns (need two bands to make a temperature estimate).*

*Measure the **dust-to-gas ratio** from the ratio of dust to atomic gas away from the molecular line emission but near enough to calibrate out galactic variations.*

*From the beautiful ATCA+Parkes HI map by Stanimirovic et al. (1999), the distribution of **atomic gas** is known.*

FIR



Dust emission at 24, 70, and 160 μm from the SMC:
SMC-SAGE (PI: K. Gordon)+S3MC (Bolatto+ 07)

The Spitzer view of H_2 in the SMC at 70 pc

FIR

Use 100 and 160 um to model τ_{dust}

Use τ_{dust}~N(HI)+2N(H_2)

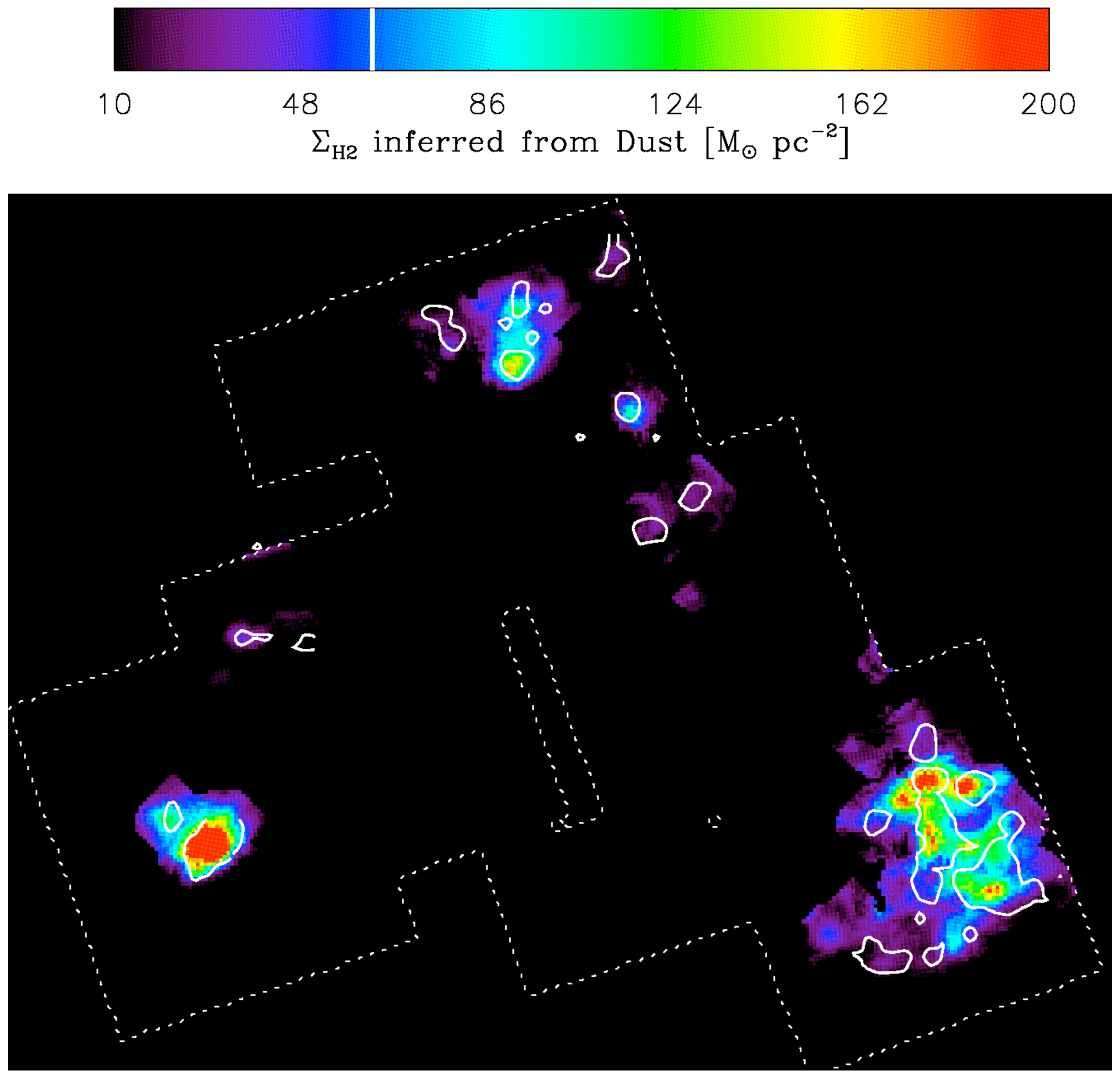
Determine DGR locally

M_{H2}~3x10^7 M_{sun} total molecular mass, compared to M_{HI}~2x10^8 M_{sun}

This means Xco~30-60 times Galactic!

Furthermore, Σ_{FIR}~180 M_o/pc^2 , while Σ_{VIR}~45 M_o/pc^2 !

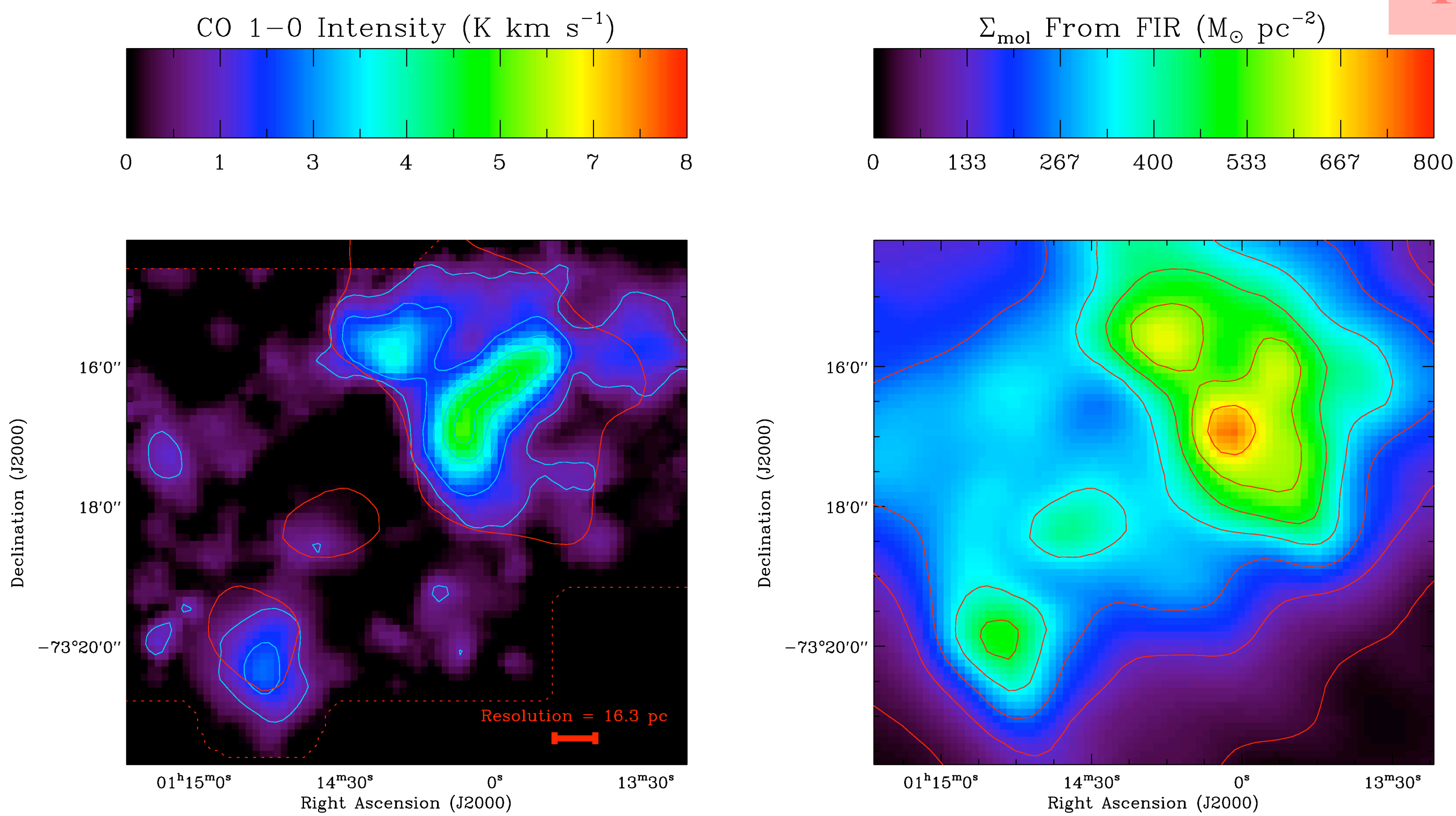
The H_2 we find places the SMC squarely into the <u>molecular</u> Schmidt law



Leroy, Bolatto, et al. (2007) using NANTEN CO

What happens at higher resolution?

FIR



We work out a "VSG-corrected" emissivity in the large scales, and assume it in the small scales

We map the CO and H_2 distribution at 15 pc scales

CO emission is seen only at Av>1.6, Σ~350 M_o/pc^2

How do we put together this picture with the kinematic studies?

Leroy, Bolatto, et al. (2008, in prep.)

Metallicity and Cloud Structure in the SMC

CO FIR

CO-emiting GMCs are just the peaks of the H_2 distribution in the SMC.

GMC internal kinematics (and so M_{vir}) sample only the potential of this CO-emitting volume.

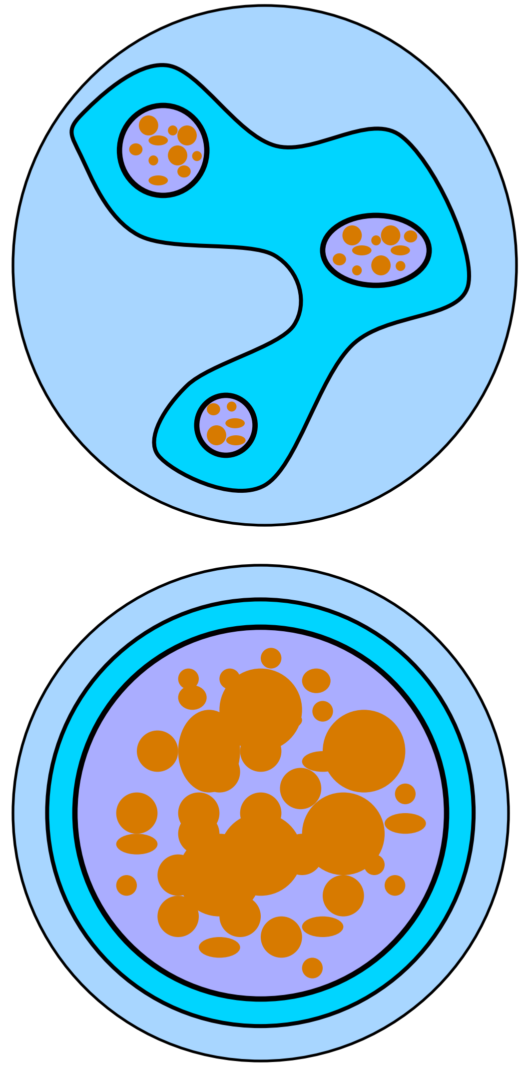
- hence low X_{CO} from CO.

There are large envelopes containing most of the mass surrounding these peaks

- hence large mass of H_2 (FIR).

This gas lacks the extinction to form CO.

- hence large H_2 (FIR) / CO



SMC

outer disks?

Milky Way

Israel et al. (1987); Maloney & Black (1988)
Elmegreen (1989); Rubio et al. (1993)

Metallicity and Cloud Structure in the SMC

CO FIR

Consistent with cloud-cloud dispersion

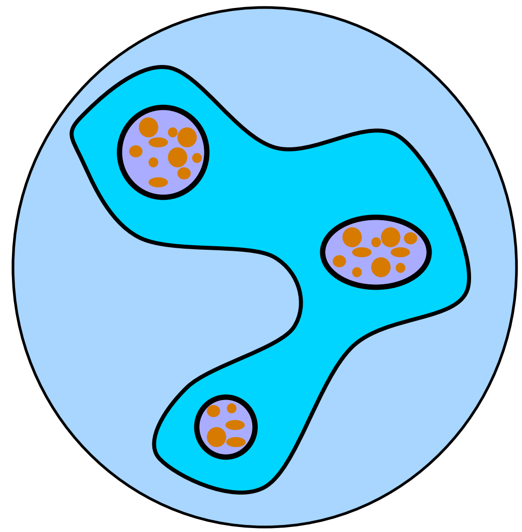
(e.g., NANTEN virial mass results)

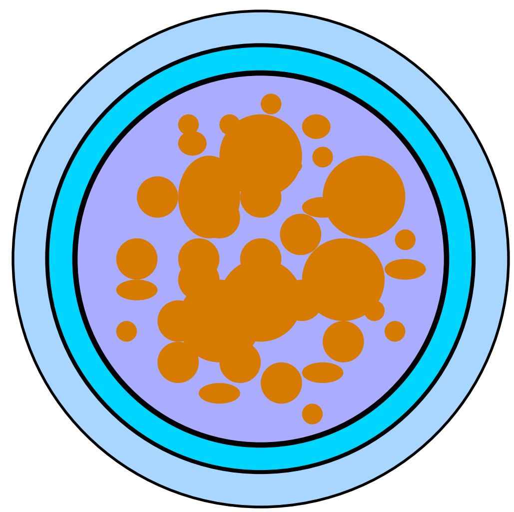
In MW parts of clouds follow Larson's Laws

Heyer & Brunt 04, Rosolowsky+ 08, Wong+ 08

Requires H_2 self-shielding to be important at metallicity ~ 1/5 solar

Low-A_V, CO-free gas somehow participates in star formation… but in local (MW) clouds SF also restricted to densest parts of clouds.





Israel et al. (1987); Maloney & Black (1988)
Elmegreen (1989); Rubio et al. (1993)

Summary

- *The CO-bright parts of extragalactic GMCs show remarkable similarities:*
  - *Larson relations are universal*
  - *Surface densities are similar to MW (Σ~85 M_{sun}/pc^2)*
  - *Virial mass-CO Luminosity relation is similar too:*
    X_{CO} approximately Galactic ***inside resolved GMCs***
- *Nevertheless metallicity plays a role:*
  large, low-A_V molecular envelopes are invisible in CO in the SMC
- ***We really need ALMA to expand these studies beyond the immediate vicinity of the Milky Way***
  - *Clouds in starbursts and mergers?*
  - *The outskirts of galaxies?*
  - *Dense portions of molecular clouds?*
  - *Submm dust emission at high resolution?*

A systematic sampling of the blue sequence