Molecular Gas in Primitive Systems:
Lessons from the Local Universe

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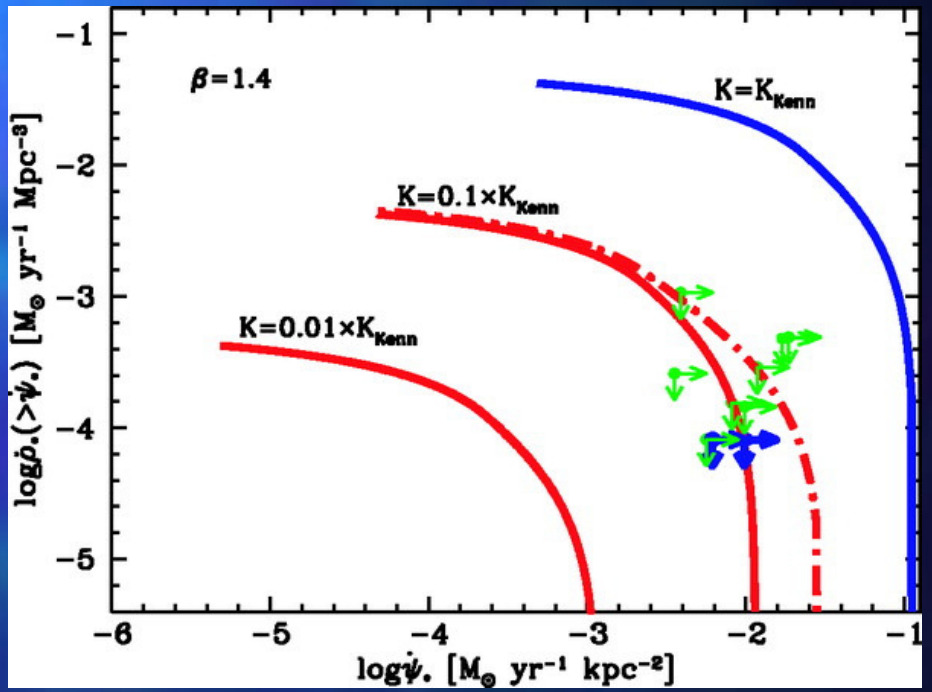
Outline

1. Resolved molecular cloud properties in nearby primitive systems: the extragalactic Larson Laws
2. The Schmidt Law in the Small Magellanic Cloud

How well do we understand the link between gas and star formation?

$HI \rightarrow H_2 \rightarrow$ stars

The Kennicutt-Schmidt law predicts 10 to 30 times more SF than observed in DLAs

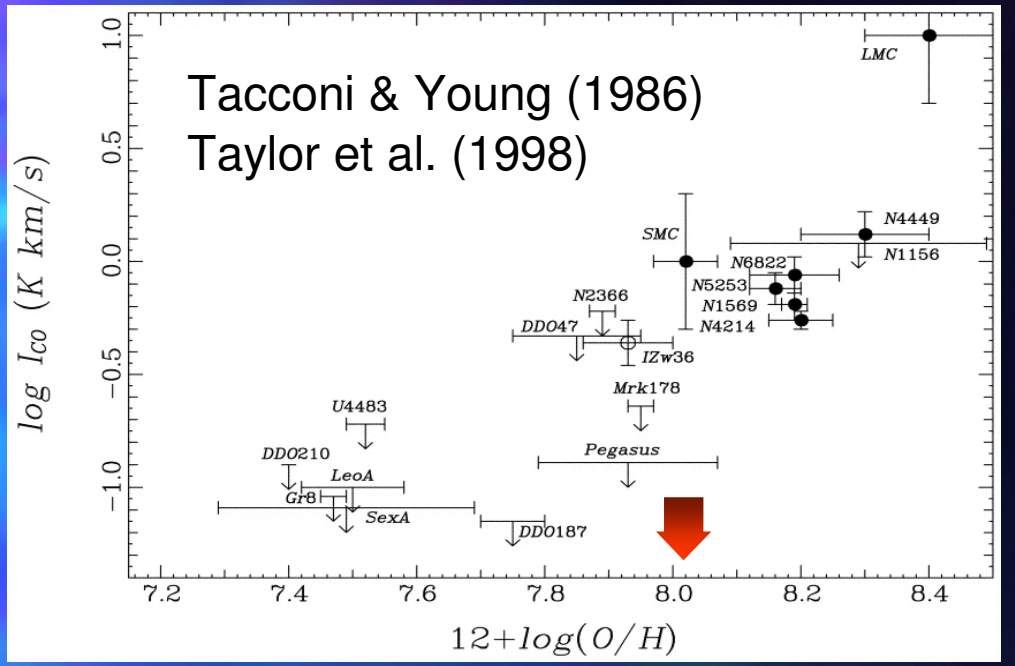


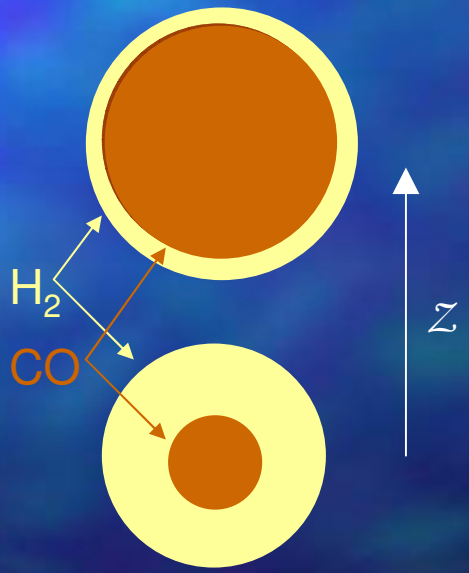
Wolfe & Chen (2006)

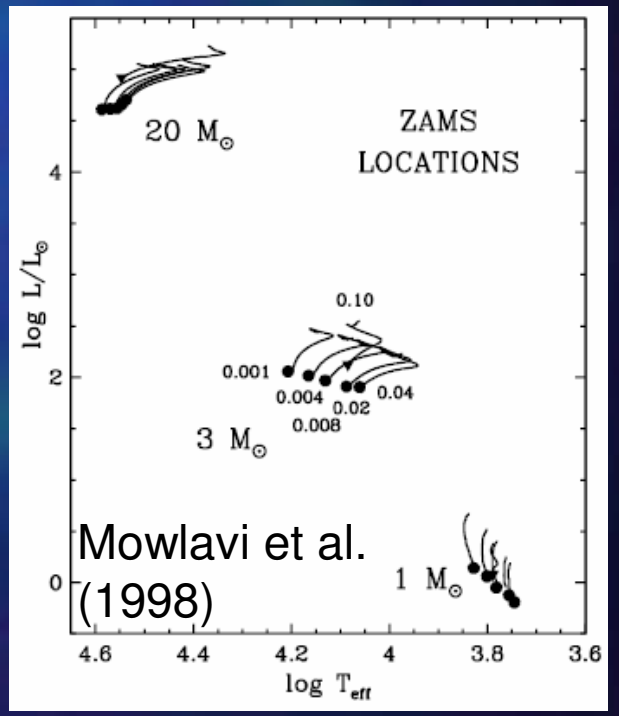
The elusive molecules

- Molecular gas surveys show that HI-rich dwarfs are faint in CO
- Despite active star formation, no galaxies with $Z<1/5\ Z_{\odot}$ are detected in CO
- This is understood as enhanced photo-dissociation of CO, due to diminishing dust UV shielding

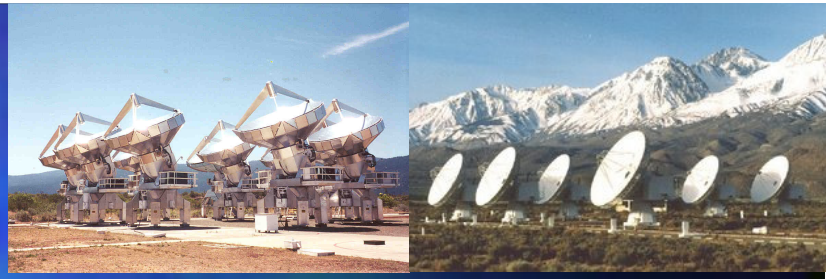
Maloney & Black (1988); Bolatto et al. (1999); Röllig et al. (2006)

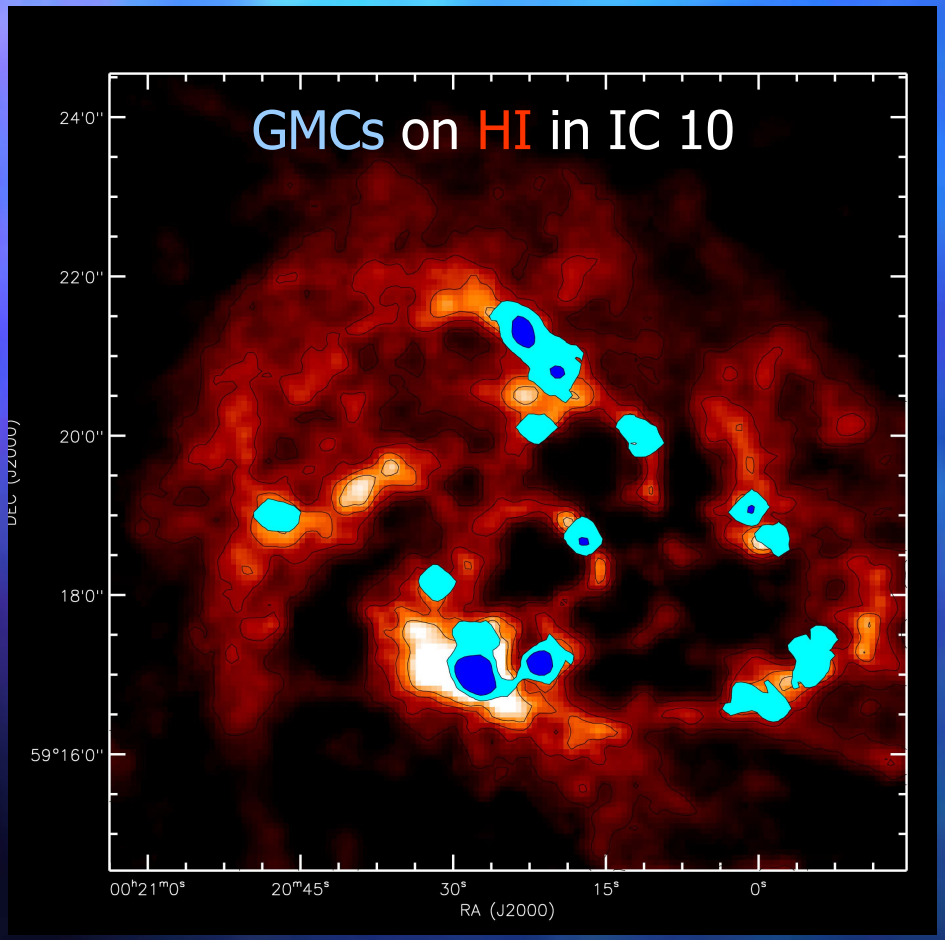






GMCs in dwarf galaxies



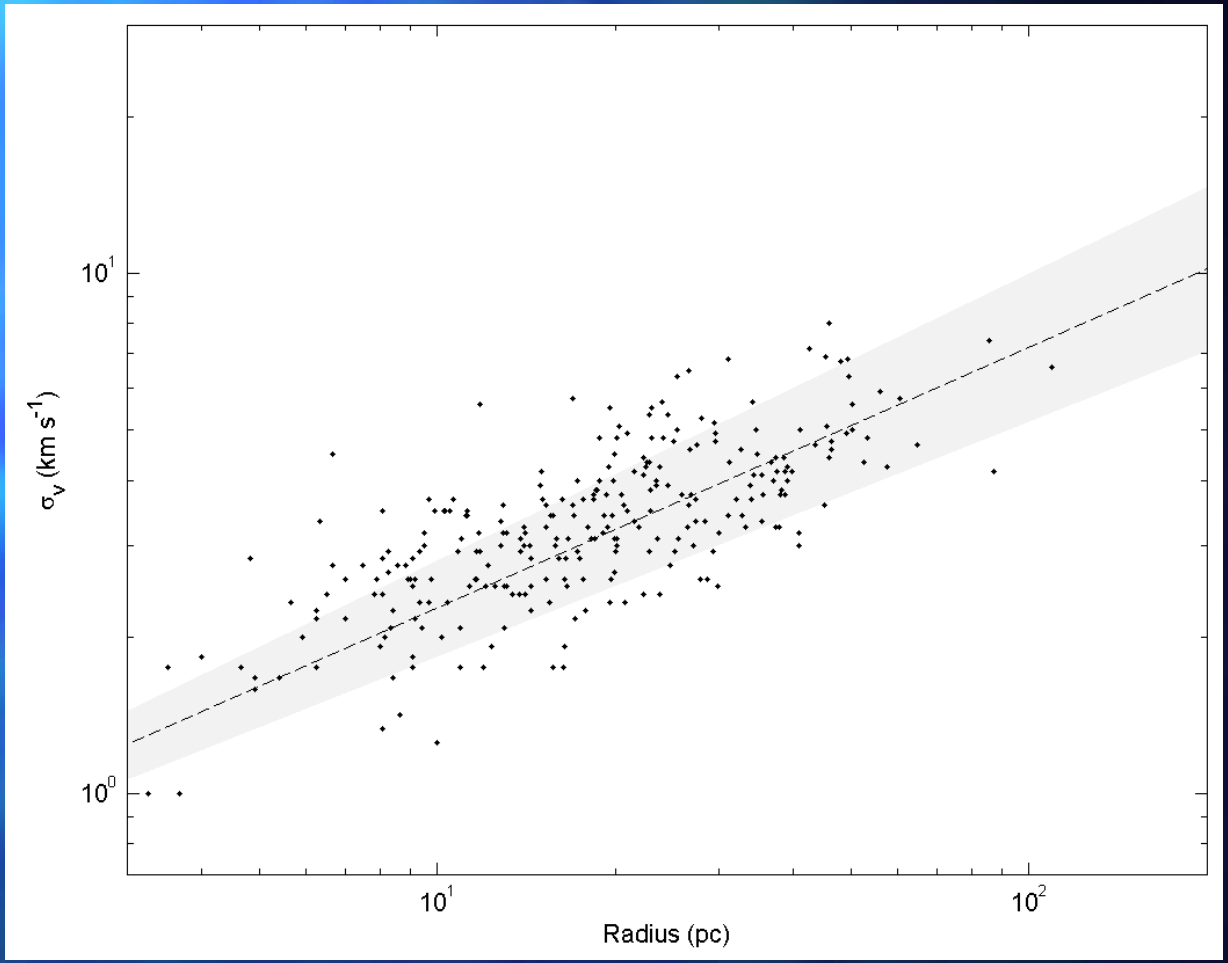


Leroy, Bolatto, Walter, & Blitz (2006)

- We can resolve individual GMCs only in nearby dwarf galaxies
  - R~10 – 50 pc
  - GMCs are frequently found along HI filaments
  - Limited by S/N and resolution
- Consistent extragalactic GMC properties require correcting for observational biases
- Poorly done in the literature (see Rosolowsky & Leroy 2006)

The size-linewidth relation

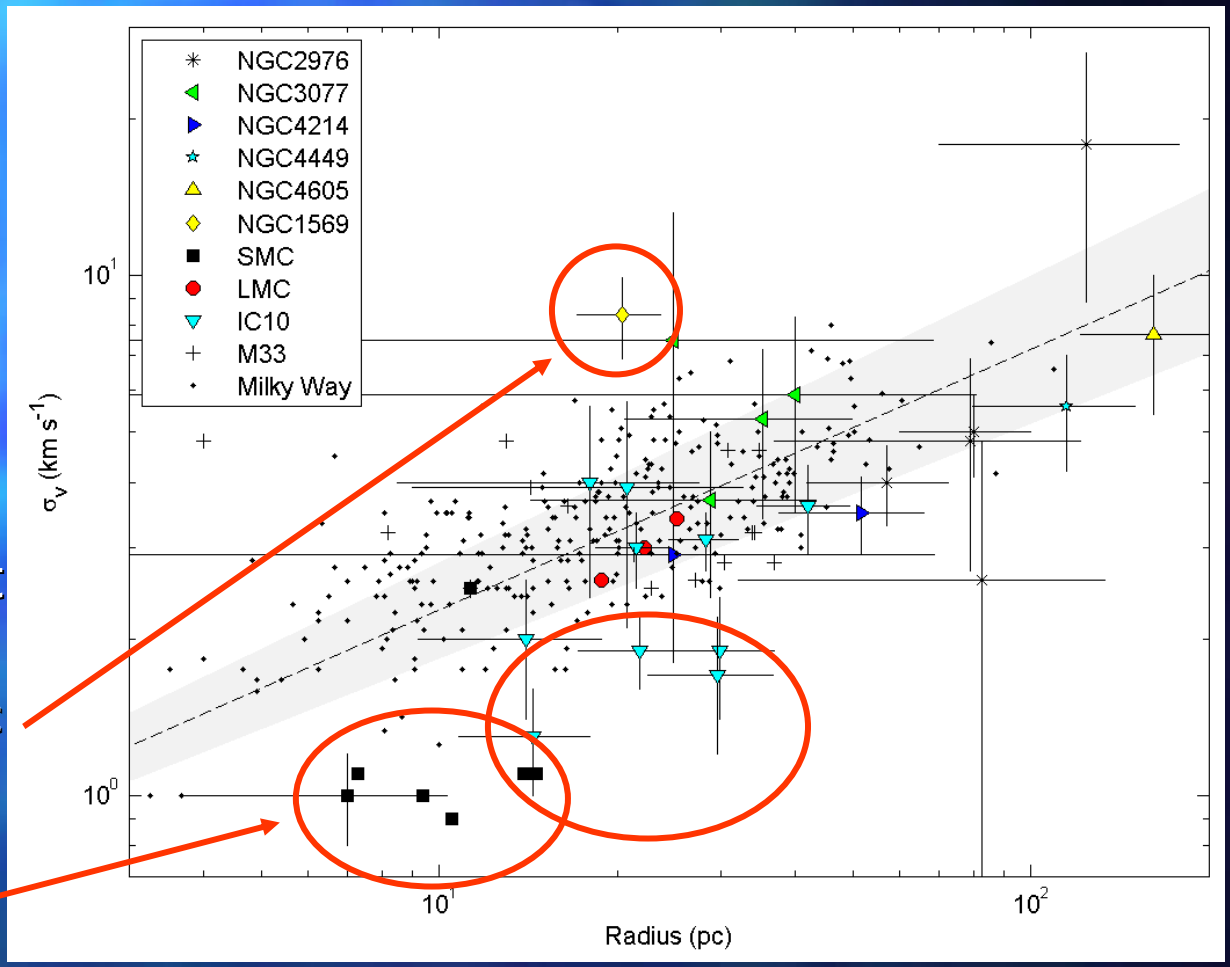
- Maintained by frequent turbulent energy injection on large scales (MRI, SNe, gravo-thermal instability)
- $\sigma = 0.72\ R^{0.5}$



Milky Way sample by Solomon et al. 1987

The size-linewidth relation

- Maintained by frequent turbulent energy injection on large scales (MRI, SNe, gravo-thermal instability)
- $\sigma=0.72\ R^{0.5}$
- If virial equilibrium is assumed $M\sim R\sigma^2$, $\Sigma_{H2} \sim 170\ M_o/pc^2$ for all galaxies!
- Three galaxies seem not quite consistent:
  - NGC 1569, problematic data
  - SMC and IC10, 50-100% under the standard relation
- Density? Magnetic field? Not in equilibrium?



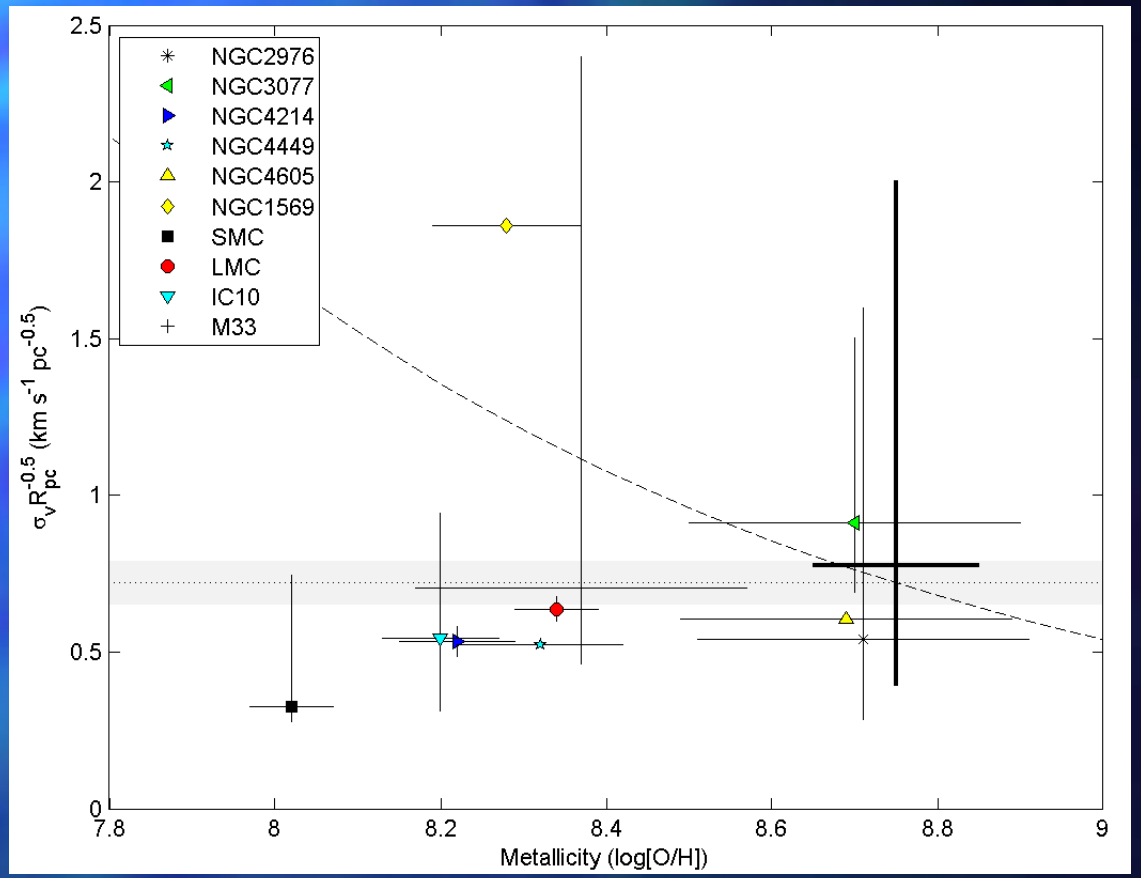
Milky Way sample by Solomon et al. 1987

Photoionization-regulated star formation ?

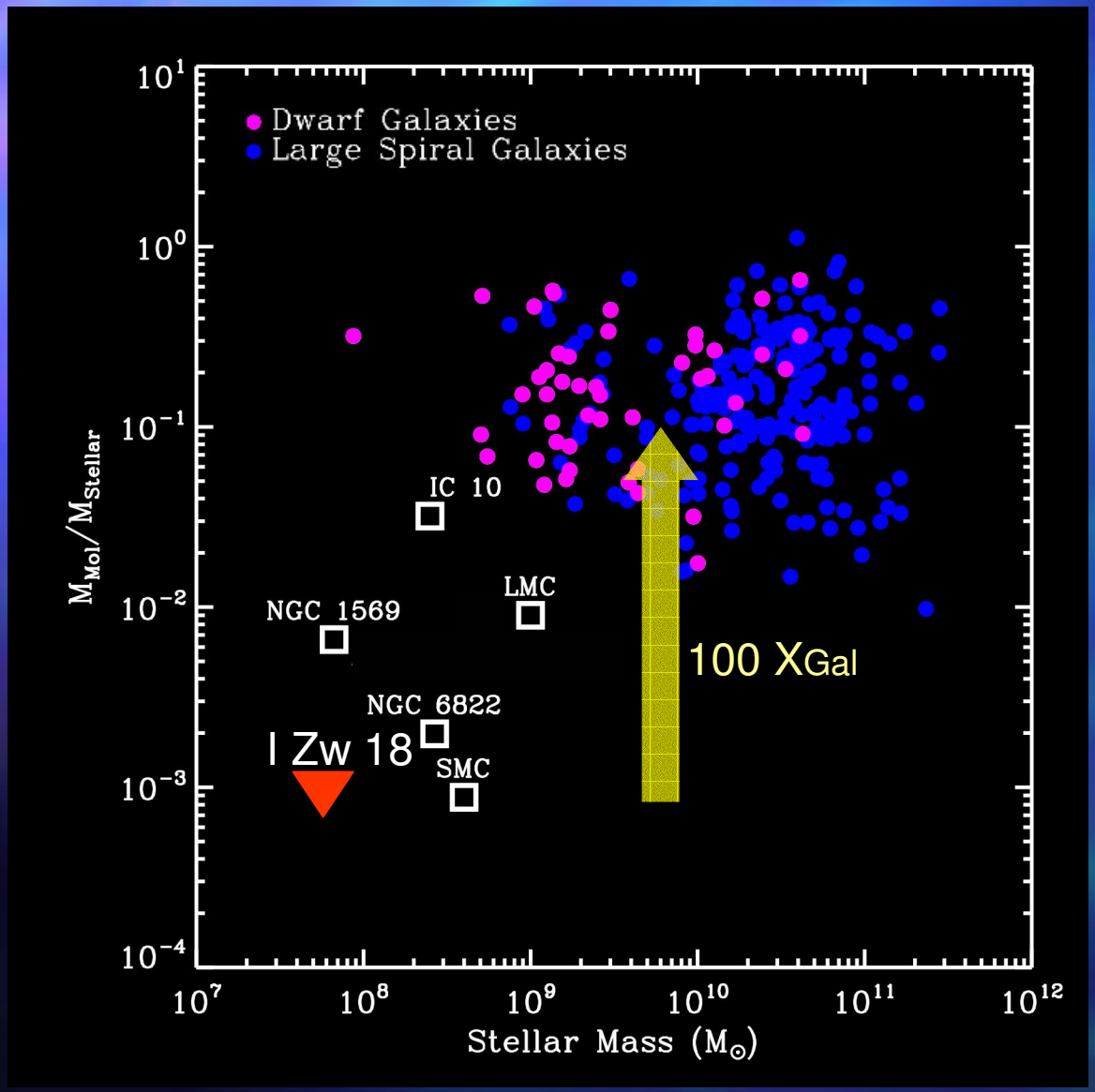
- Star forming clouds need similar extinctions at their centers to decouple from magnetic support and collapse (McKee 1989)
- Theory predicts

$\sigma = 0.72\ (Av/7.5\ d_{gr})^{-0.5}\ R^{-0.5}$

- Measurements show no evidence for that trend



Star formation and molecular gas



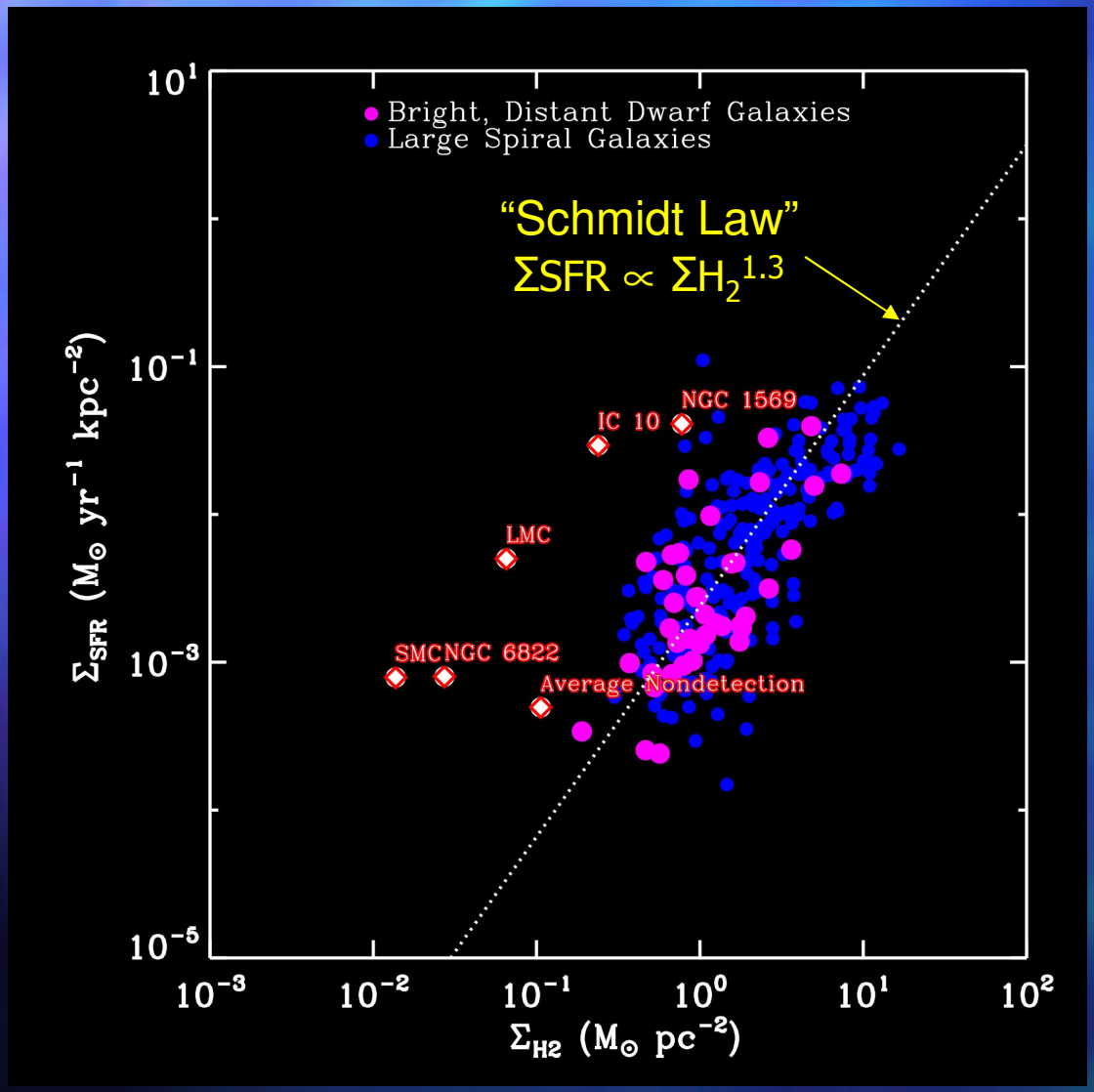
- Very nearby, "SMC-like", dwarfs show much less H_2 per stellar mass than massive systems
- These dwarfs are not just scaled down versions of larger galaxies:

1. The $M_{mol} - M_*$ relation is changing
2. M_{mol} accounting problem: need larger Xco

   N_{H_2} = Xco Ico

Leroy, Bolatto, Simon, & Blitz (2005); Leroy, Walter, Bolatto, et al. (2007)

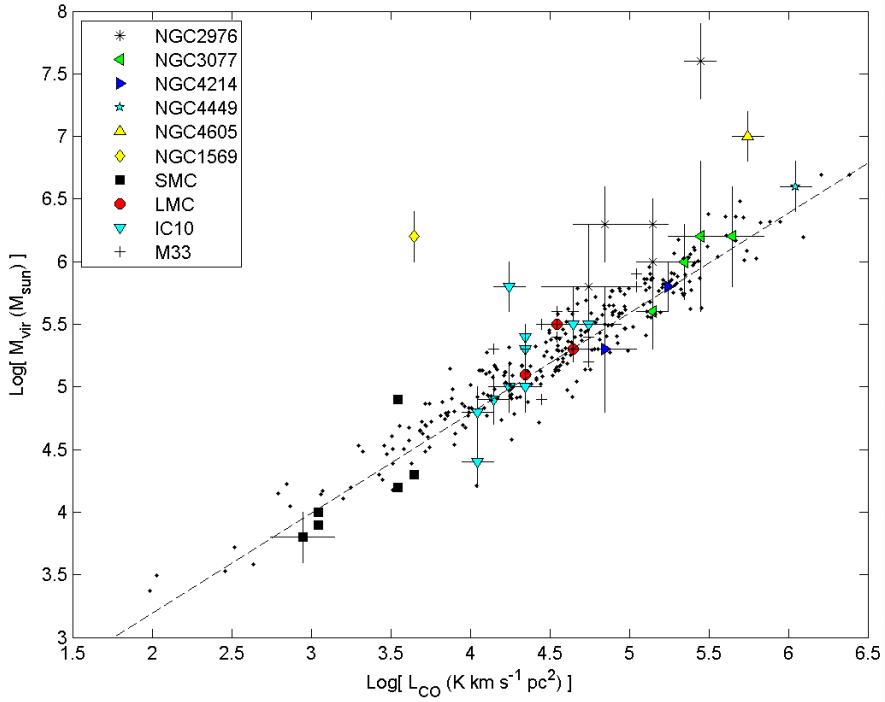
Star formation and molecular gas content

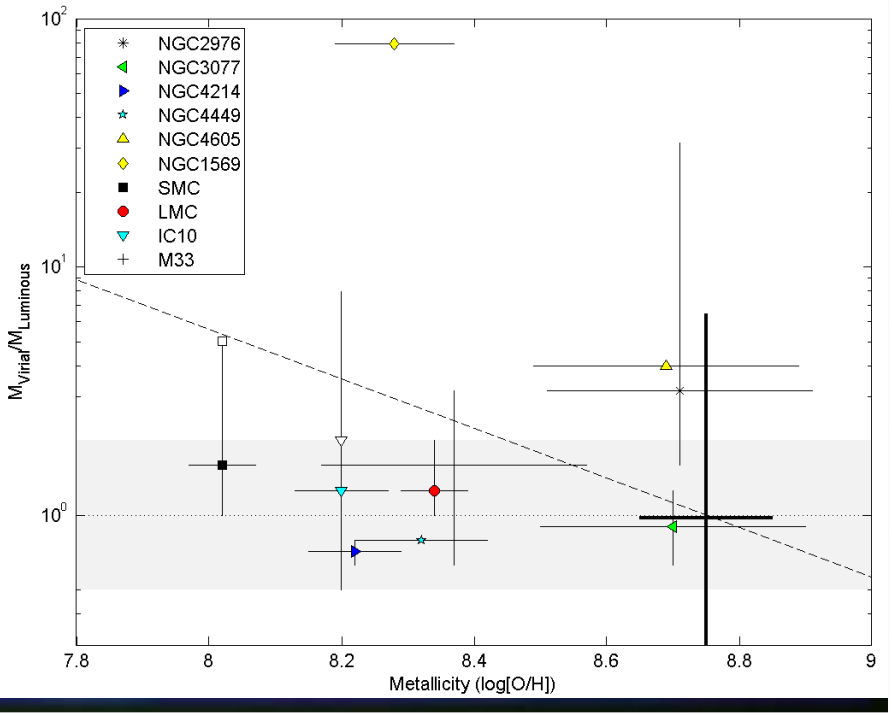


- "Massive" dwarfs look like larger galaxies with Galactic Xco
- "SMC-like" dwarfs are again clearly outside the correlation

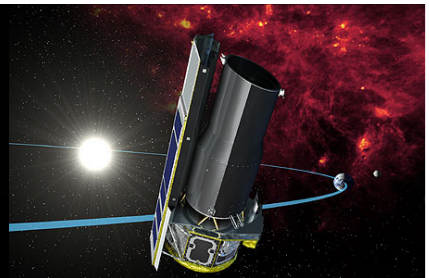
Unchanging Xco?

- The luminosity-virial mass relation is entirely compatible with that of the Galaxy (Solomon et al. 1987)
- No marked trend with galaxy metallicity in the ratio of virial to luminous mass
- Does this mean that star formation is much more efficient for "SMC-like" dwarfs?





The "classical dust" continuum from MIPS



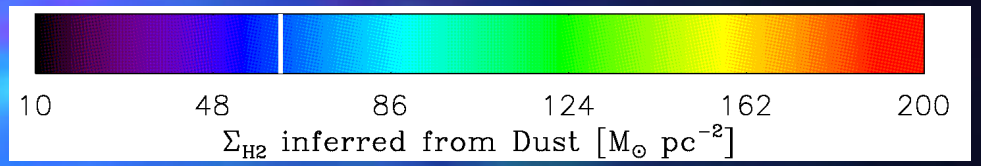
Spitzer Survey of the Small Magellanic Cloud

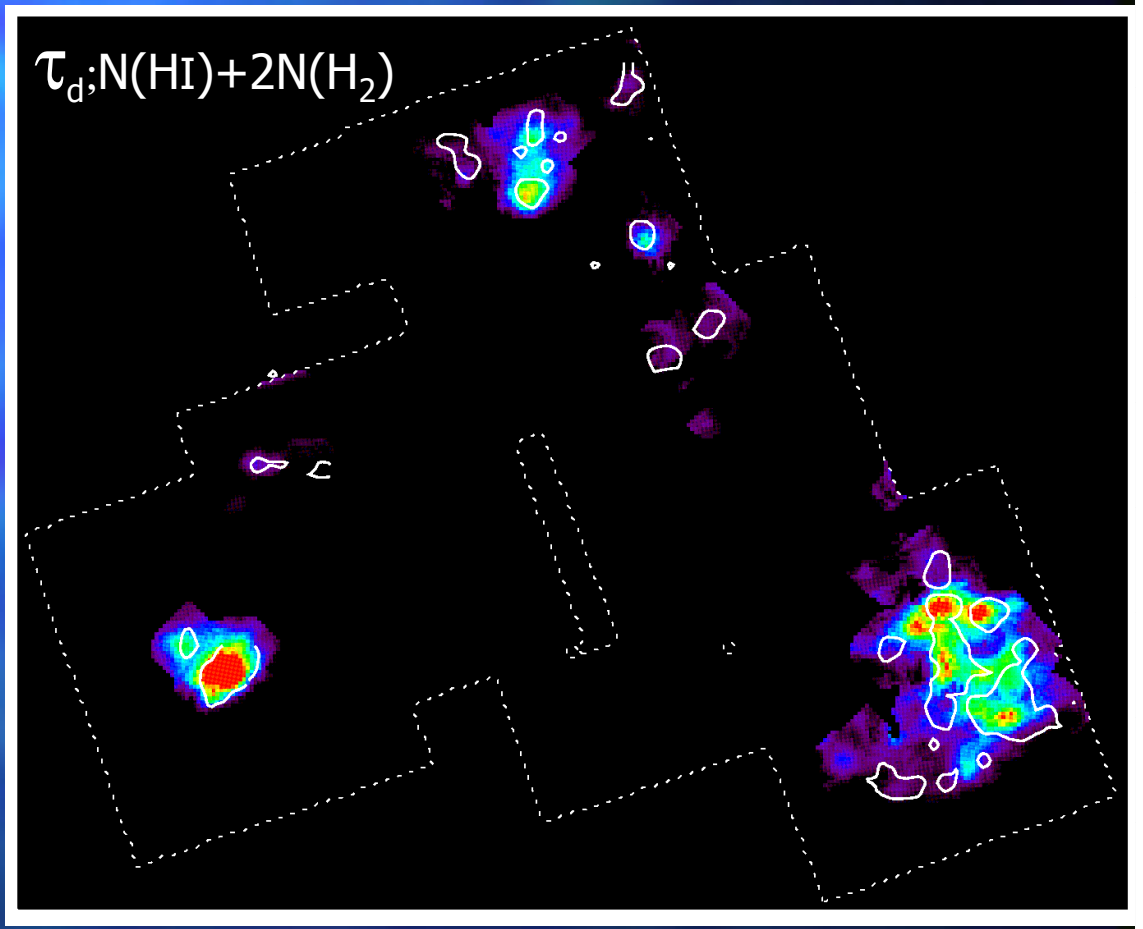
24 um = Blue
70 um = Green
160 um = Red

Obtaining an H_2 map from the FIR

- Used 100 and 160 um to avoid influence of stochastic heating
- More than one temperature component. Used Dale & Helou (2000) models
- DGR determined locally
  - DGR_{AVE}~1:900, DGR_{BAR}~1:800, DGR_{WING}~1:1200
- M_{H2}~3x10^7 M_{sun} total molecular mass, compared to M_{HI}~2x10^8 M_{sun}

Remarkably similar to the MW and other large spirals

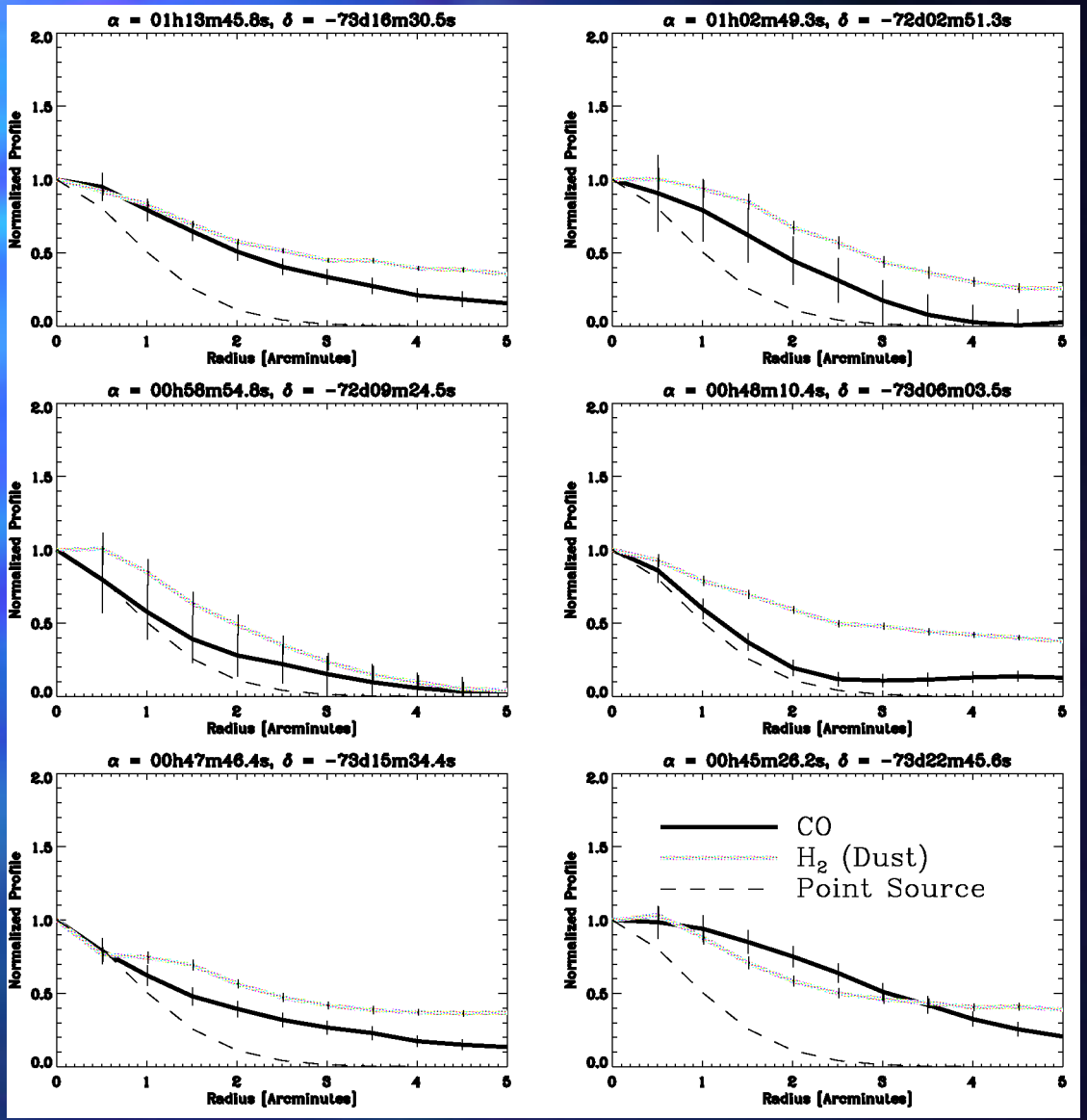




Leroy, Bolatto, et al. (2007)

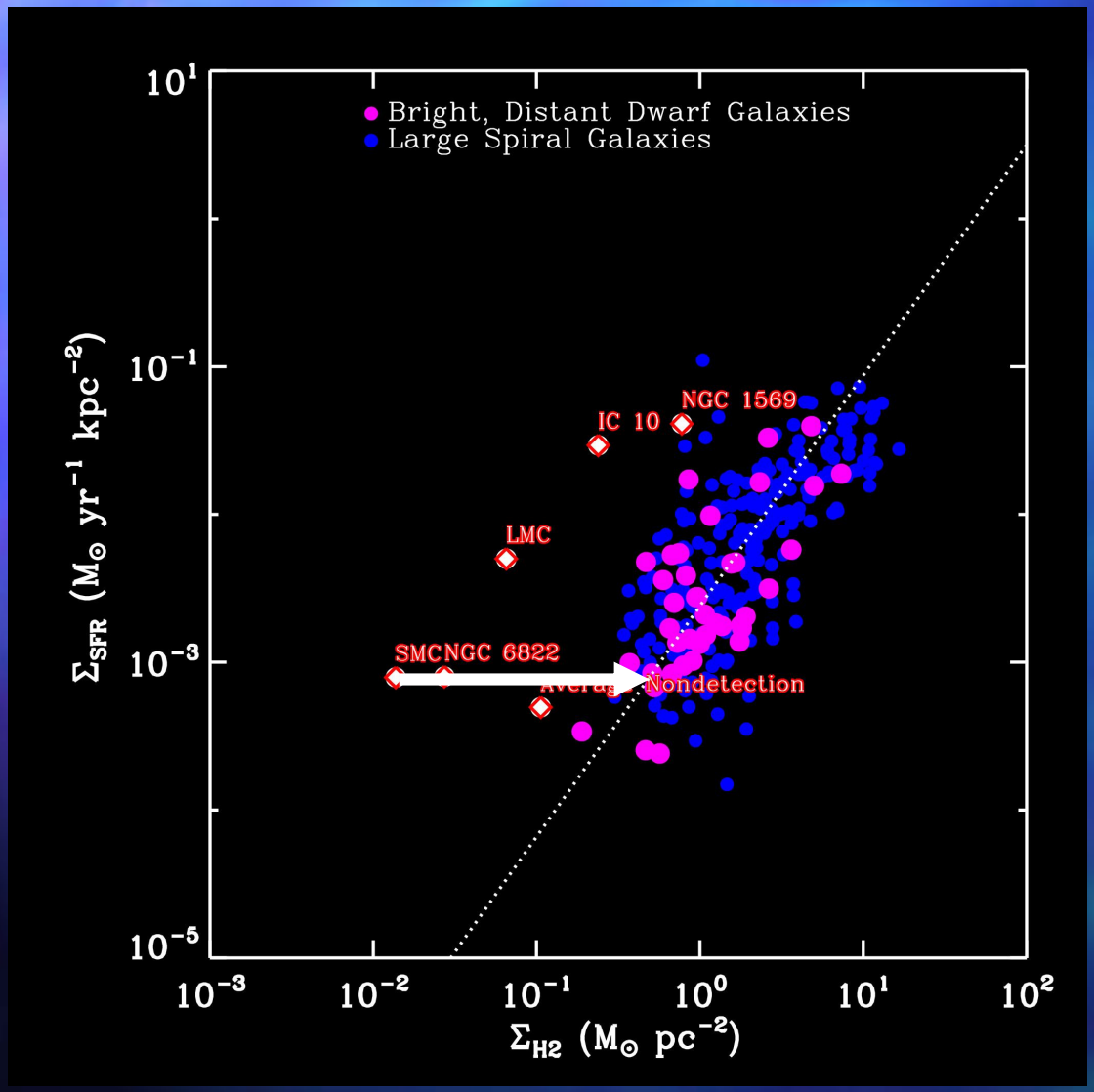
CO and H_2 profiles

- H_2 is 30% more extended than CO
- Surface densities are similar to MW
  - Considerably lower than predictions from photoionization-regulated star formation theory:
    - Expect 500-3000 M_{sun}/pc^2 (A_v~4-8)
    - Find 180 M_{sun}/pc^2 (A_v~1-2)
- Systematically smaller/clumpier clouds could rescue the theory



Leroy, Bolatto, et al. (2007)

Back again to the Molecular Schmidt Law



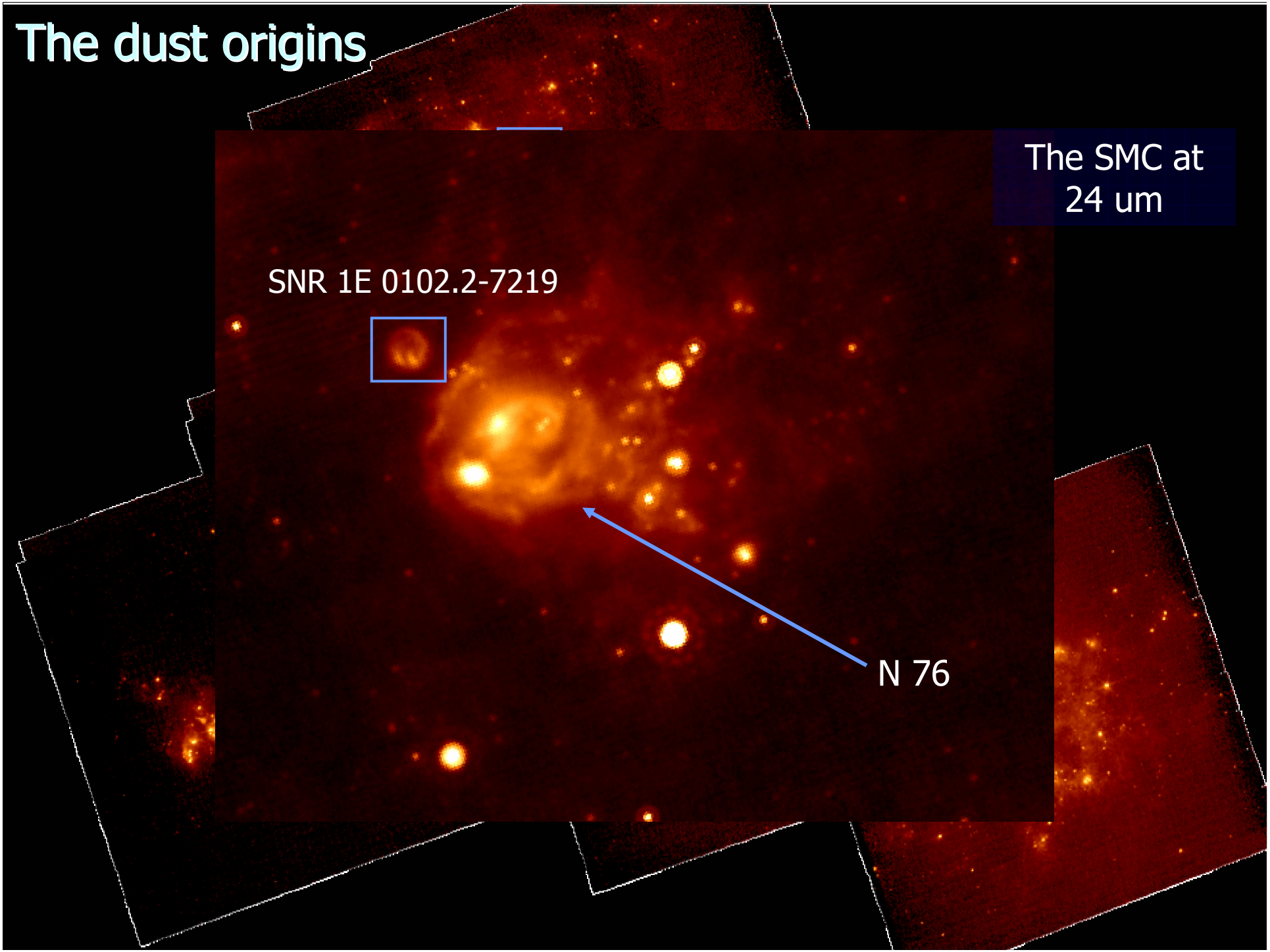
- Conundrum: "SMC-like" dwarfs have anomalously high SFR for their CO content
- Virial CO properties are very similar
- Dust results point to a x50 increase to Xco in the SMC
- Extra H_2 is in cloud envelopes

Despite differences in metallicity and rotational properties, there is no evidence for a change in the "Molecular Schmidt Law" for small galaxies

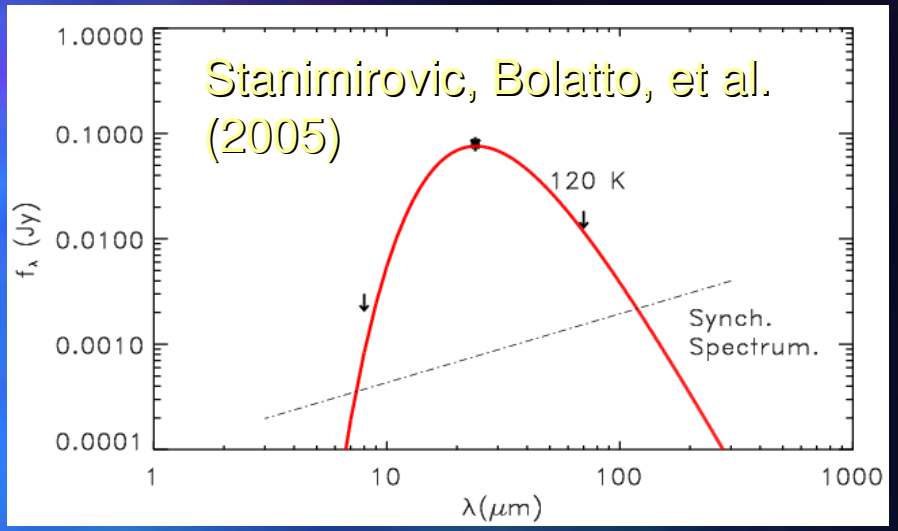
Conclusions

- Larson Laws in small, low metallicity dwarf galaxies are very similar to the Milky Way
  - Is this the foundation for an invariant IMF?
- Dust continuum studies suggest that the CO cores in these primitive galaxies are surrounded by large H_2 envelopes, and there is a wealth of molecular gas not traced by CO
- Once this is taken into account, these galaxies will likely fall on the molecular Schmidt Law
- Many problems for photoionization-regulated star formation theory
  - No increase in velocity dispersion for decreasing metallicity
  - No increase in Σ for decreasing metallicity
  - How can gas invisible in CO partake in star formation?

The dust origins



SNR and dust production



- O-rich, type Ib/c, age~1000-2000 yr
- Progenitor: M>20 M_{sun}, rich in O, Ne, and Mg
- For dust mixed in SNR expect T~130 K (Dwek 1987)
  - Our data is consistent with T_{dust}~120 K
- Models predict 0.08 to 0.3 M_{sun} of dust produced per SN (Dwek & Scalo 1980; Todini & Ferrara 2001; Morgan & Edmunds 2003)
  - We measure M_{dust} ~ 3 to 8$3 10^{-4}$ M_{sun}
  - Consistent with other SNR results (e.g., Cas A; Hines et al. 2004; Krause et al. 2004)
  - Given SN rate, SN account for 0.1% of dust in SMC (but see Sugerman et al. 2006)

Thanks!

Thanks to Edvige, Simone, Raffaella, and the rest of the organizers for a wonderful experience

A tutti grazie!

Caveats

- Linearity of the MIPS 160 um detectors
  - Checked against DIRBE
- Systematic differences in dust properties or DGR between "molecular" and "reference" regions
  - Large spatial scales
  - Works for the MW (Dame et al. 2001)
- Missing cold dust