Molecules in (Gas Rich) Dwarf Galaxies

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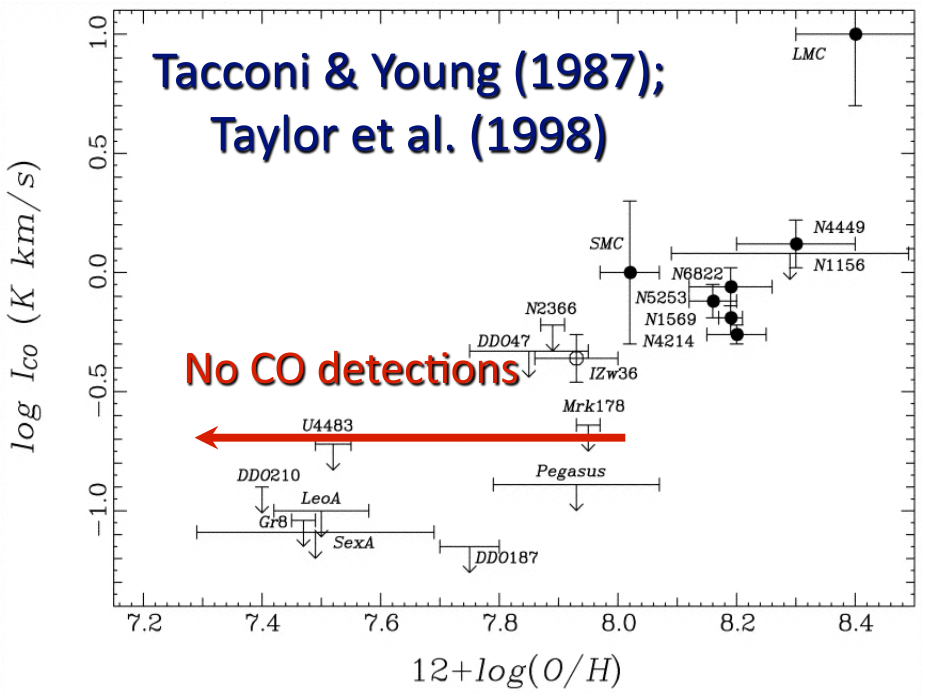
with a lot of help from my friends…

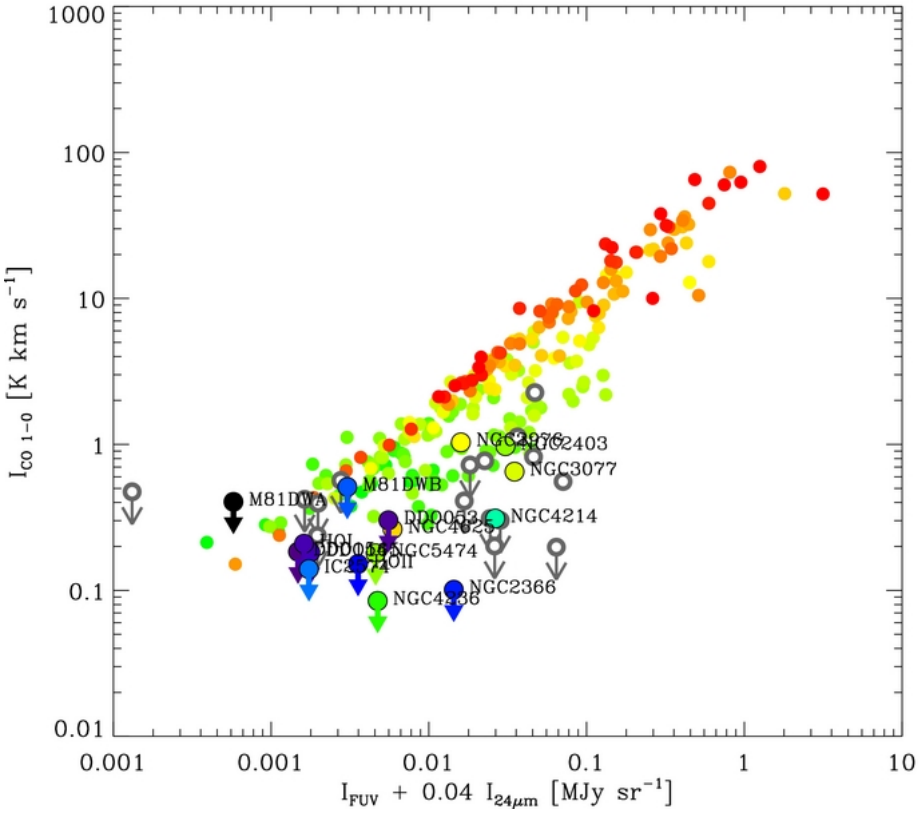
A very short talk…

- Molecules? What molecules?



… and a puzzle

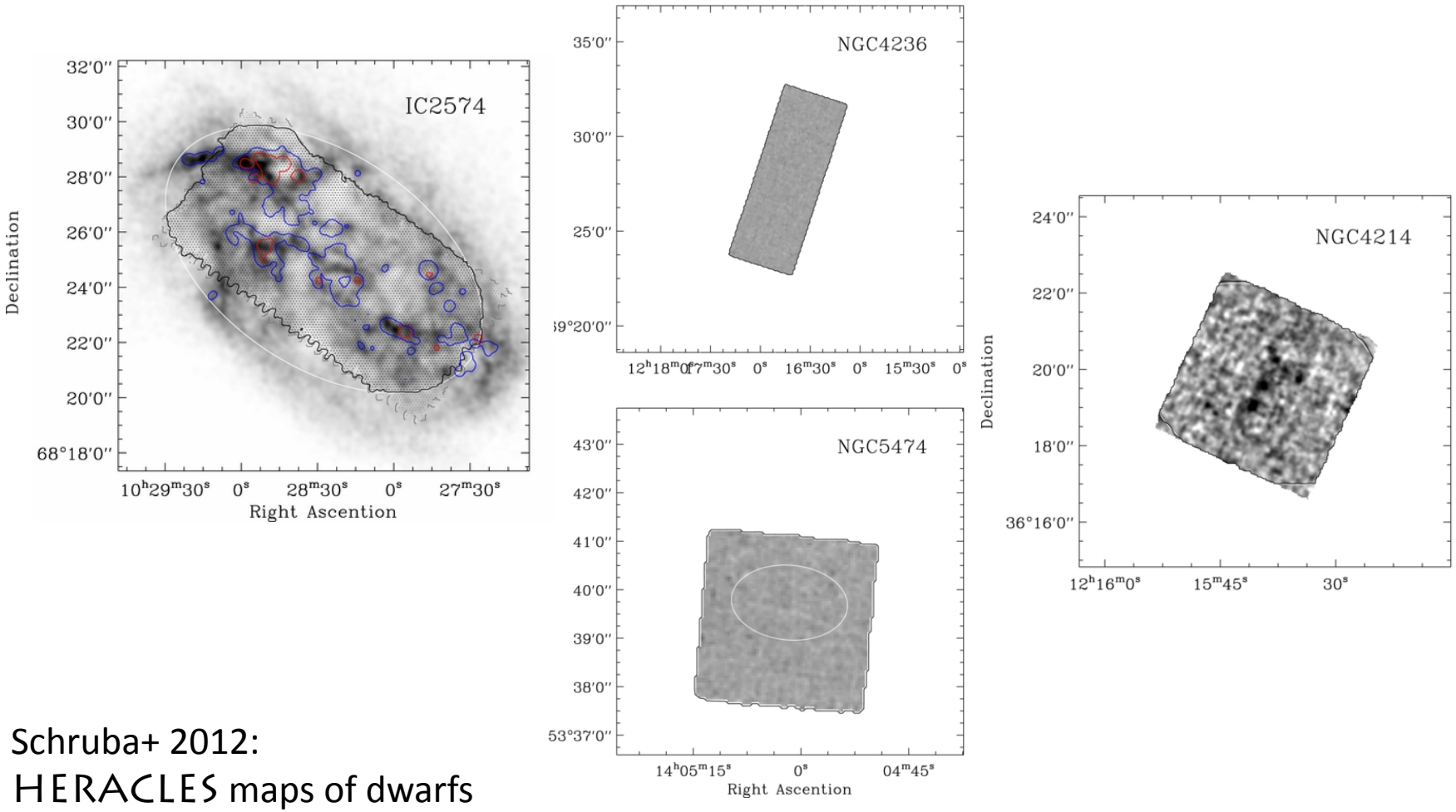
- Too much SF for their CO!
  (remember also Kristen McQuinn's talk)
- Color coding is metallicity



SFR

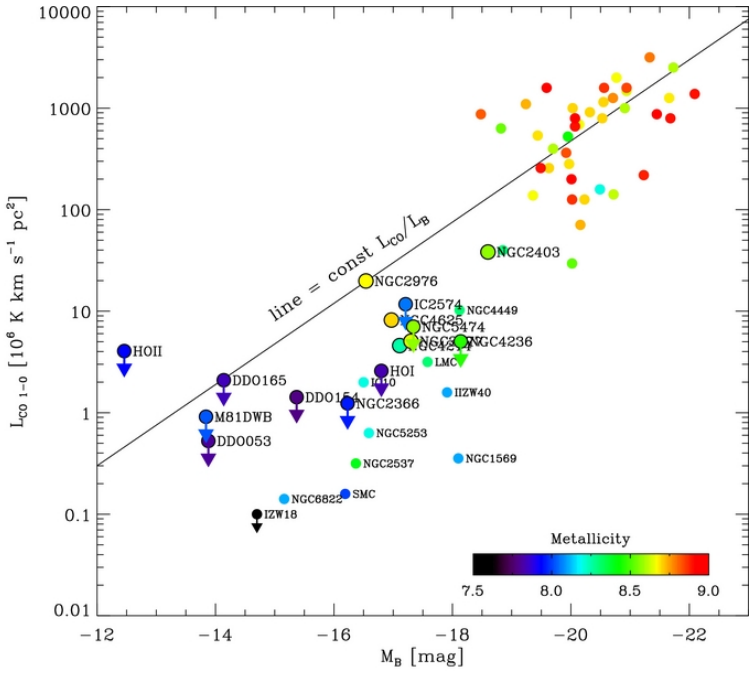
Schruba+ 2012:
HERACLES results

And it is not "old observations"

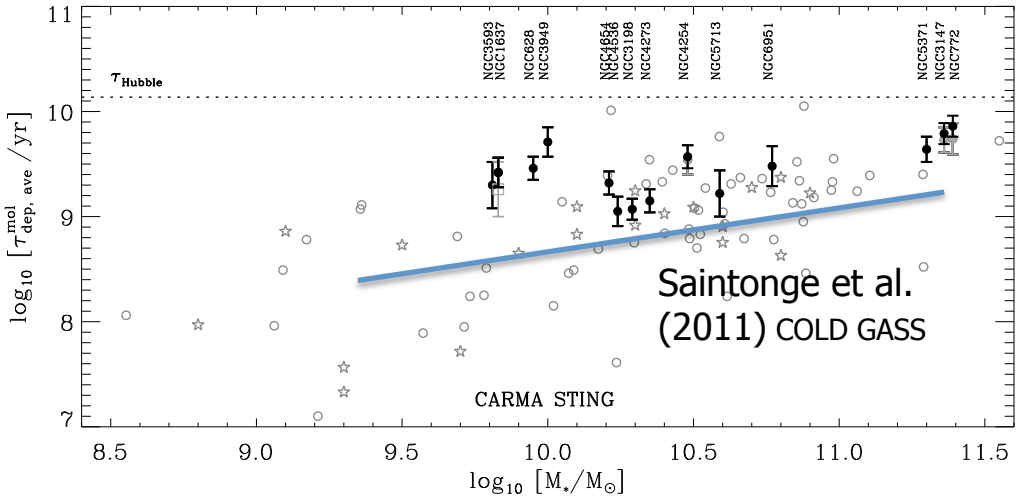


Schruba+ 2012:
HERACLES maps of dwarfs

And it is not "old observations"



Schruba+ 2012:
HERACLES results

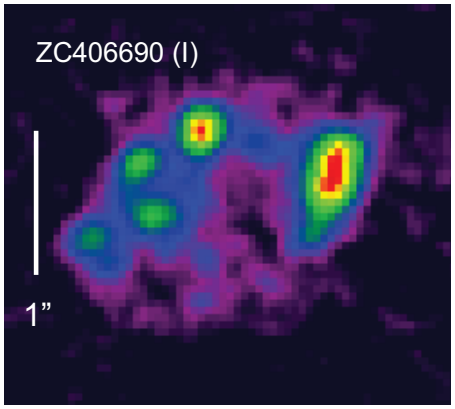


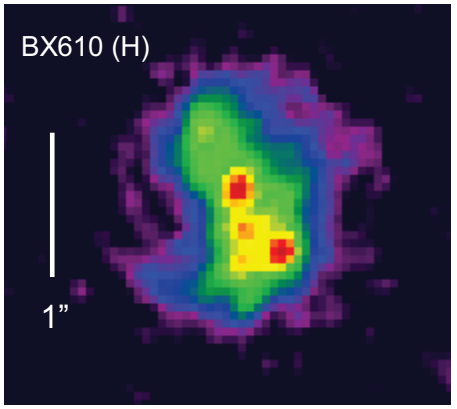
Rahman+ 2011: CARMA
STING + literature

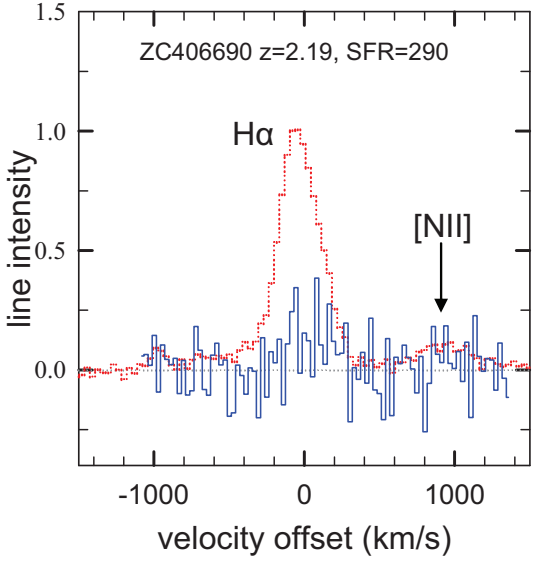
And it's there also at high-z !

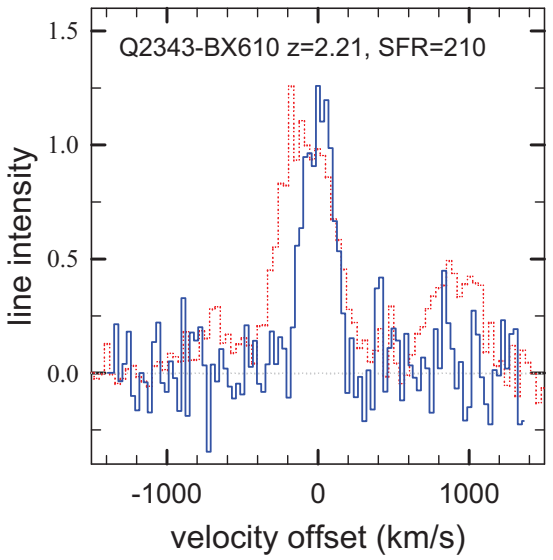
- z~2 glaxies with similar SFR, very different CO and metallicity
- Not dwarfs !!!!
- Likely to become a key issue for "normal" high-z galaxies

Genzel+(2011)









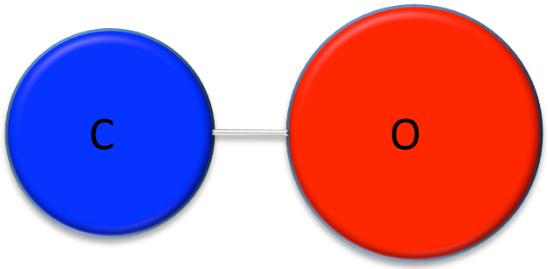
Outline

1. Motivation
2. Theoretical background
3. Resolving the CO into GMCs
4. What we are learning from the Magellanic system
5. Future outlook

2. Theoretical background

- Less CO is not surprising
  - less C and O ⟹ slower CO formation
  - less dust ⟹ faster CO photodissociation
- Why do we care?

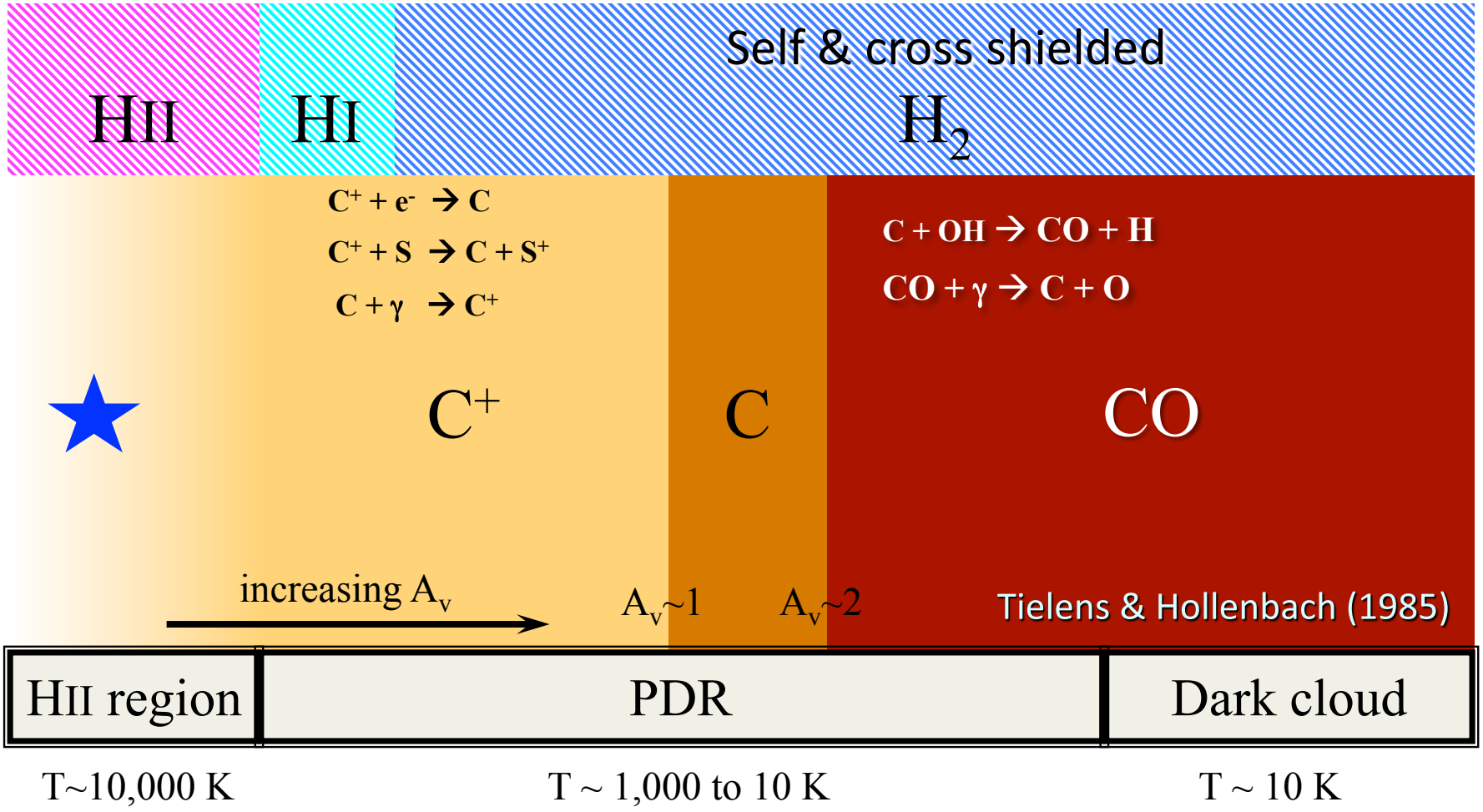
Homonuclear. No permanent dipole. Ground rotational quadrupole transition E/k~510 K



Two most abundant impurities. Chemically favored in dark clouds. Ground dipole transition E/k~5.5 K

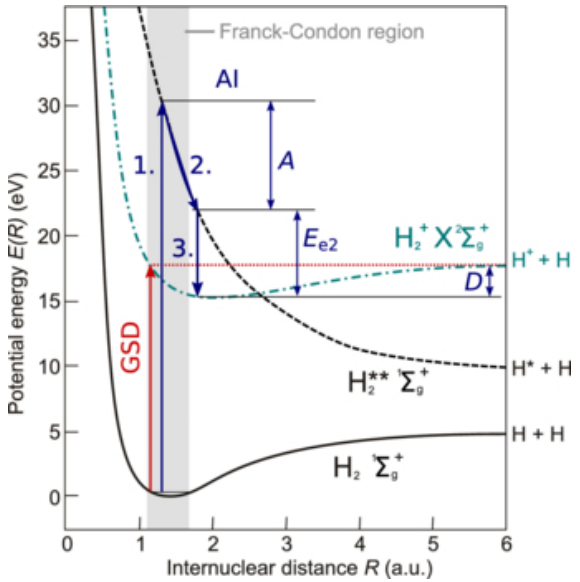
Structure of PDRs

Dust controls UV extinction and physical sizes



H_2 photodissociation

- Photodissociation of H_2 occurs through absorption of Lyman/Werner band photons
- At modest A_V those bands turn optically thick
- This is known as self-shielding
- There is also overlap with HI Ly bands: cross-shielding

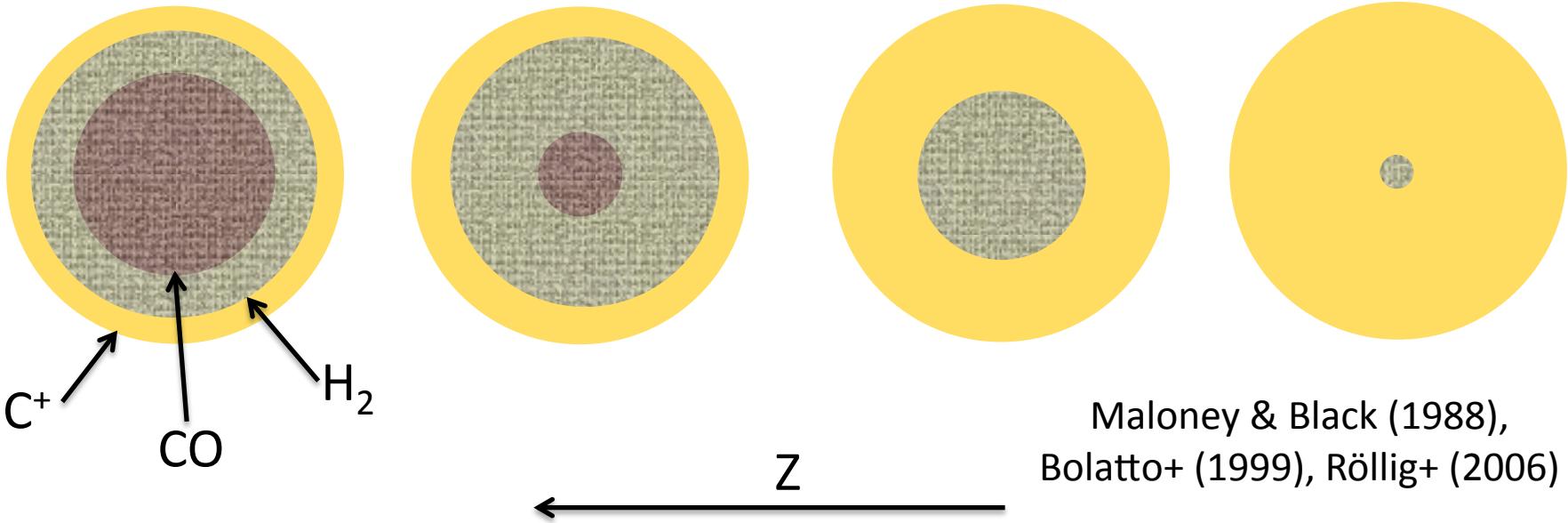


"A diatomic molecule is one with one atom too many"

– Arthur Schawlow

Metallicity effects

- As metallicity and dust-to-gas ratios decrease, A_V~1 moves deeper into clumps of constant column density
- CO disappears when A_V<2 through a clump, but H_2 exists to much lower extinctions
- The relative amount of CO and H_2 is set by the distribution of column densities in the ISM

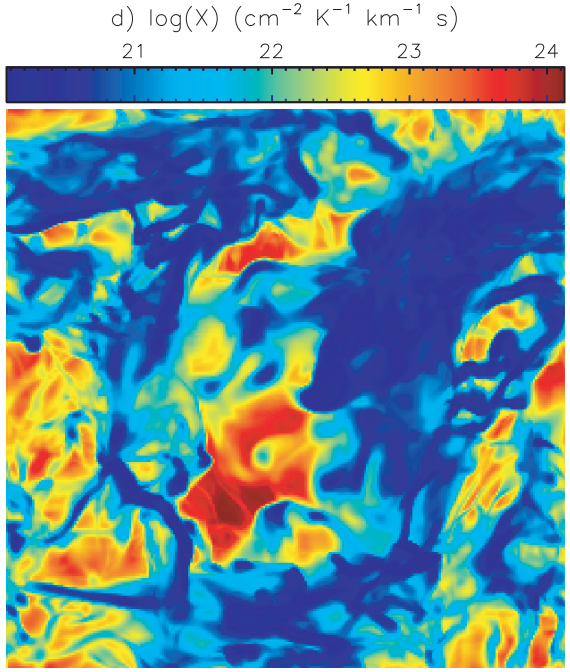


Maloney & Black (1988), Bolatto+ (1999), Röllig+ (2006)

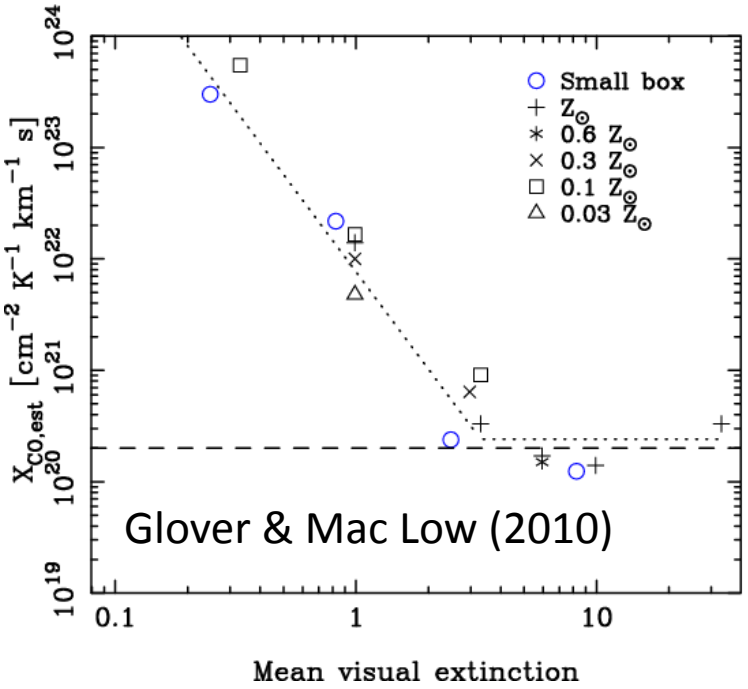
Gas in a box: CO-to-H_2

Simulations of time-dependent chemistry in a turbulent box, illuminated by UV, probing a range of metallicities

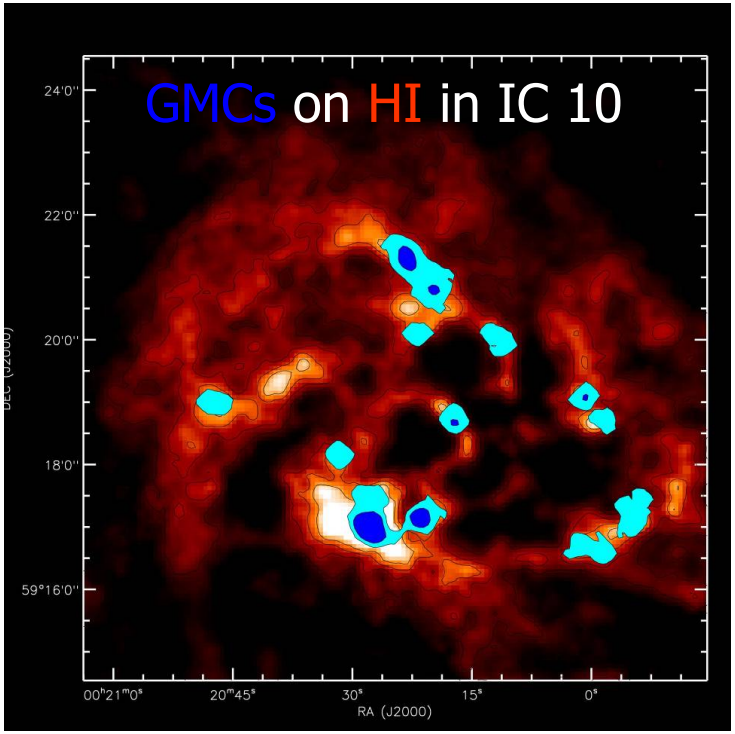
- The CO-to-H_2 conversion, X_{CO} , depends mostly on A_V, and only indirectly (through the dust-to-gas ratio) on metallicity
- Corollary: X_{CO} is due to the combined effect of the N(H) PDF and the DGR(Z)



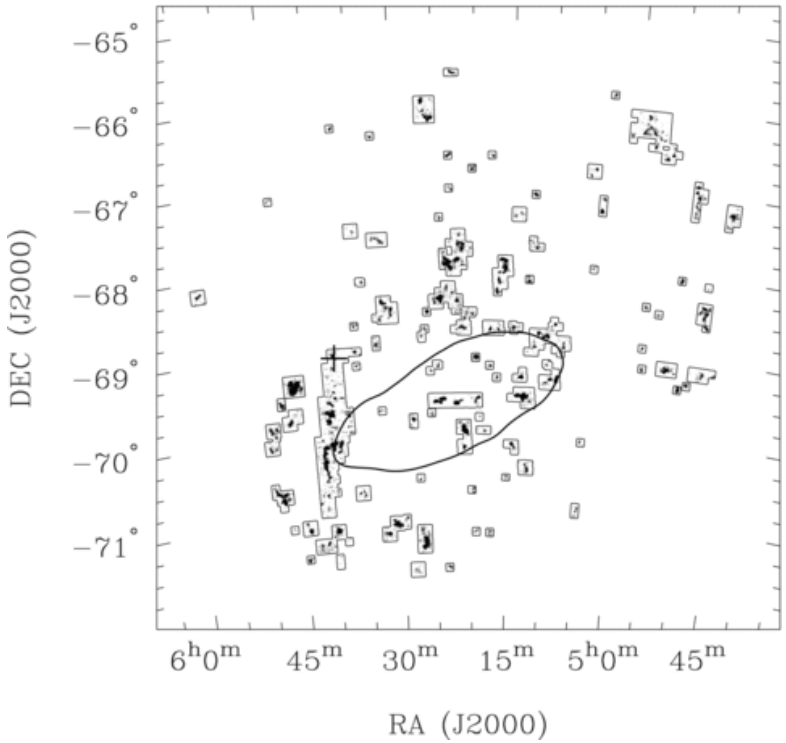
Shetty+(2011a,b); see also Wolfire+(2010), Feldmann+ (2011)



3. Resolving the CO distributions

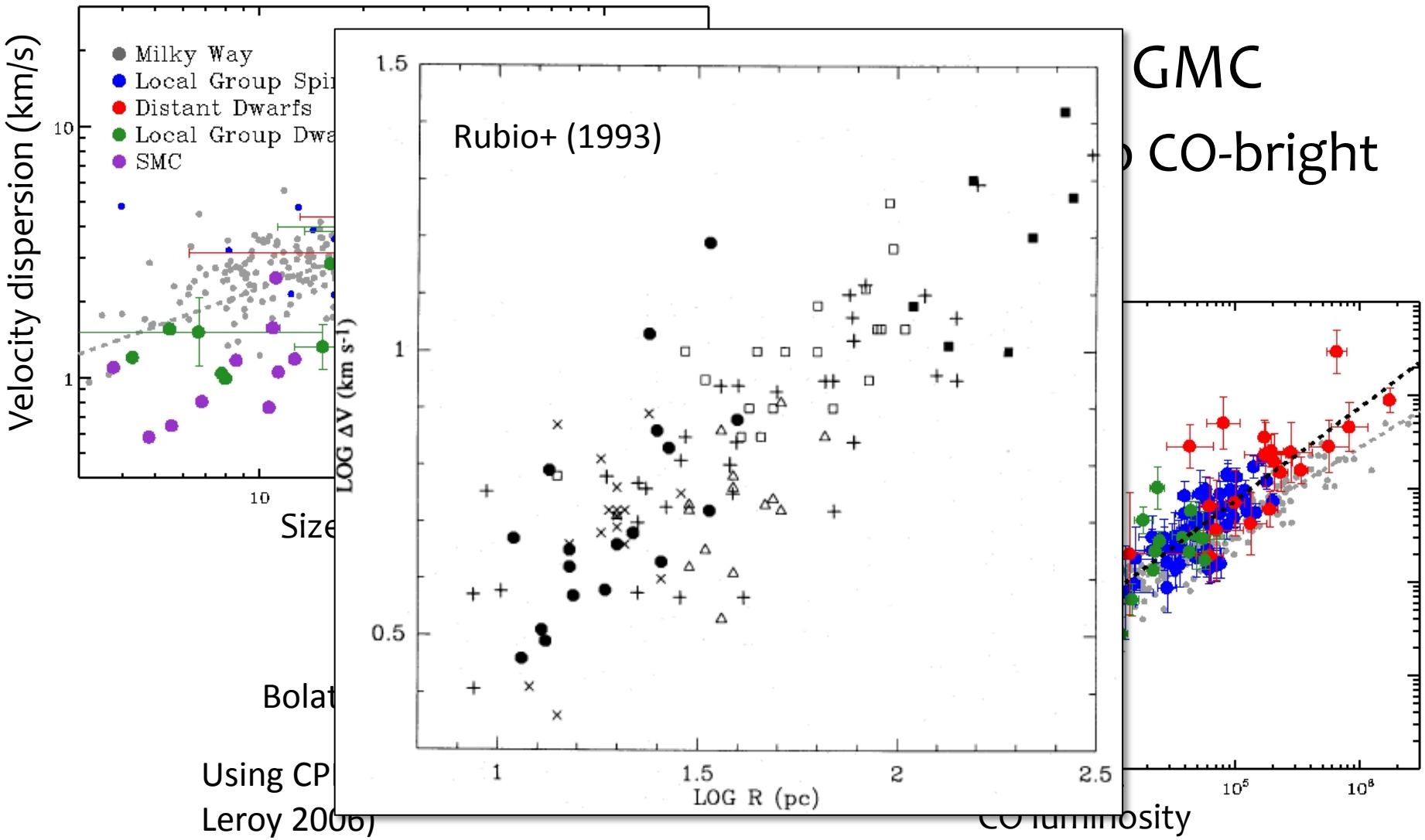


Leroy+ (2006)
GMCs in IC 10 using BIMA

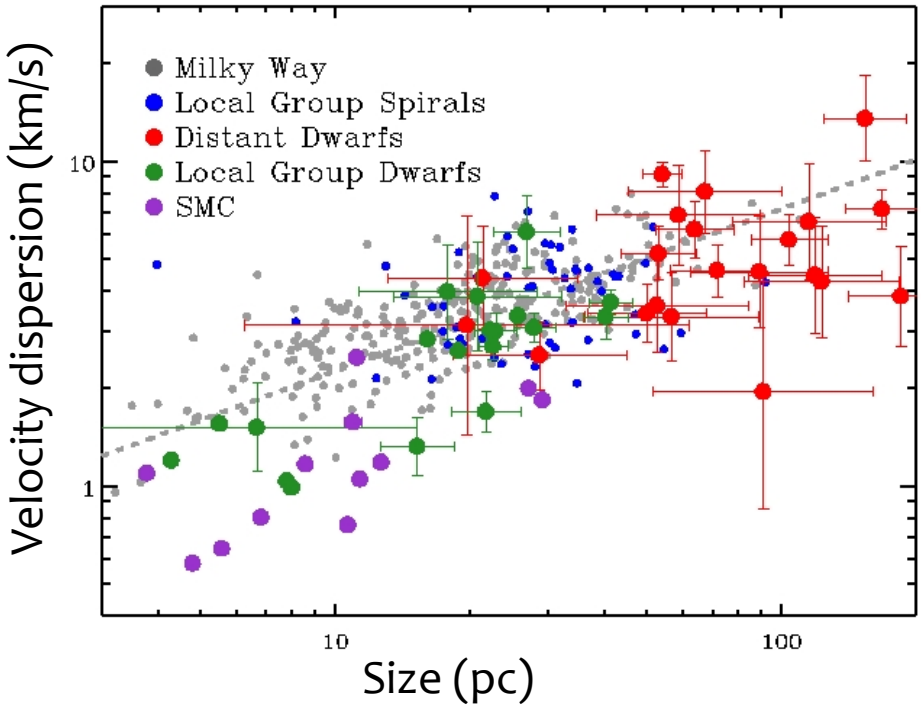


Hughes+ (2010)
GMCS in the LMC using Mopra
See also NANTEN (Fukui+ 2006)
and SEST KP (Israel+ 1993)

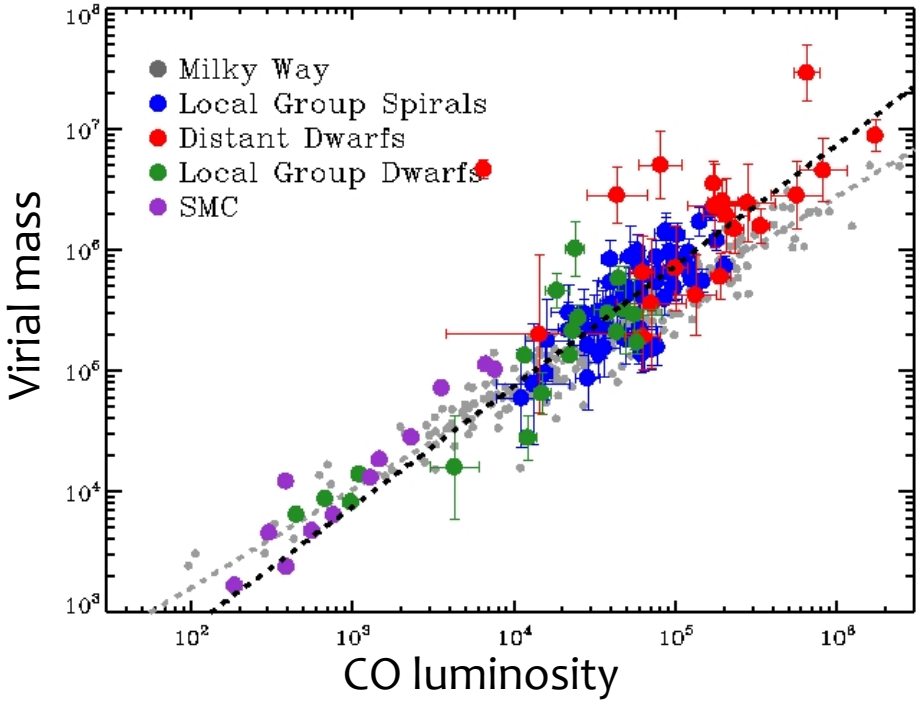
Larson's laws



Larson's laws



- A GMC is a GMC
  - Applies to CO-bright material

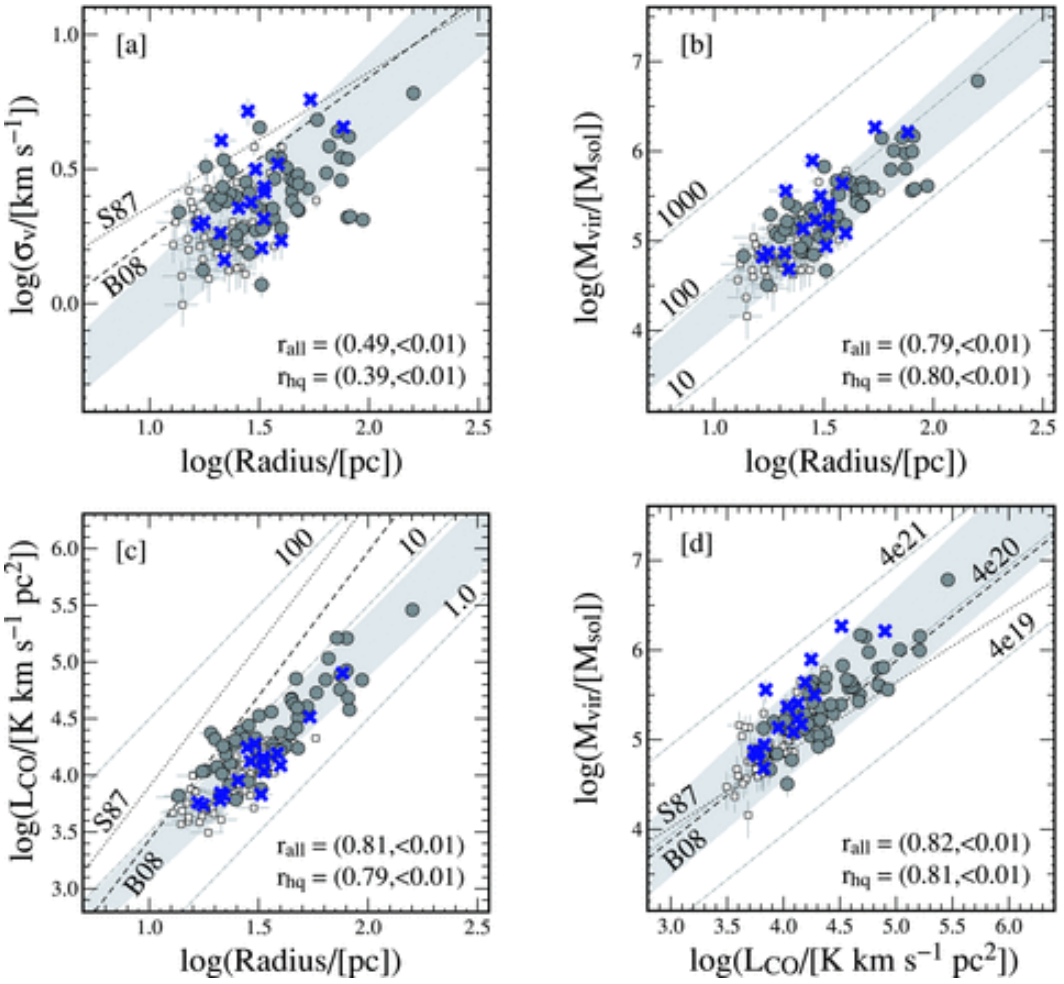


Bolatto+ (2008)

Using CPROPS (Rosolowsky & Leroy 2006)

MAGMA results

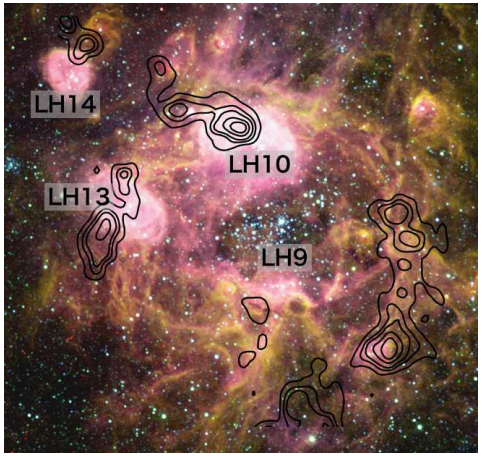
- General agreement with previous results
- Despite general faintness, once the CO distribution is resolved to a few pc, the GMC properties are similar



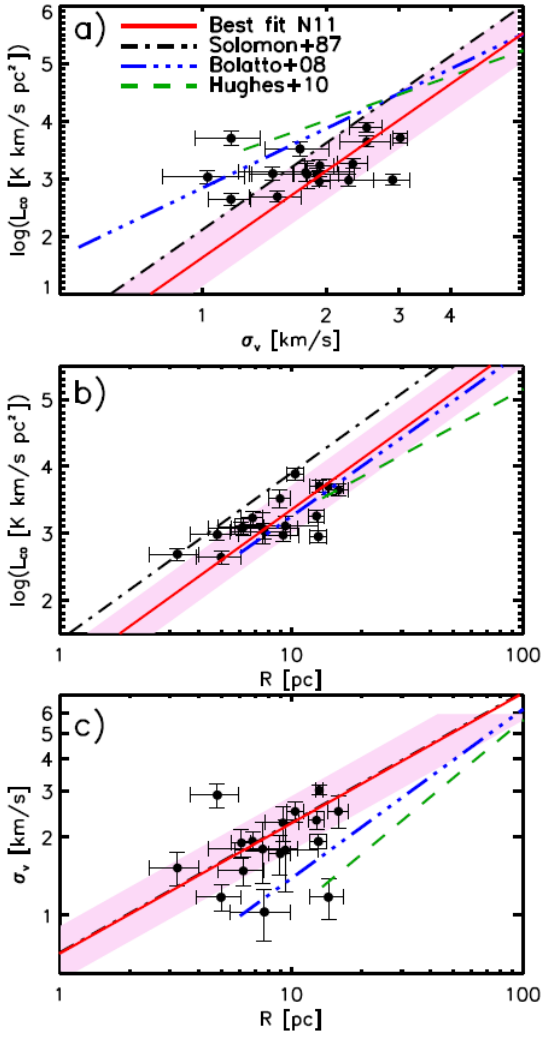
Hughes+ (2010)

N11 results

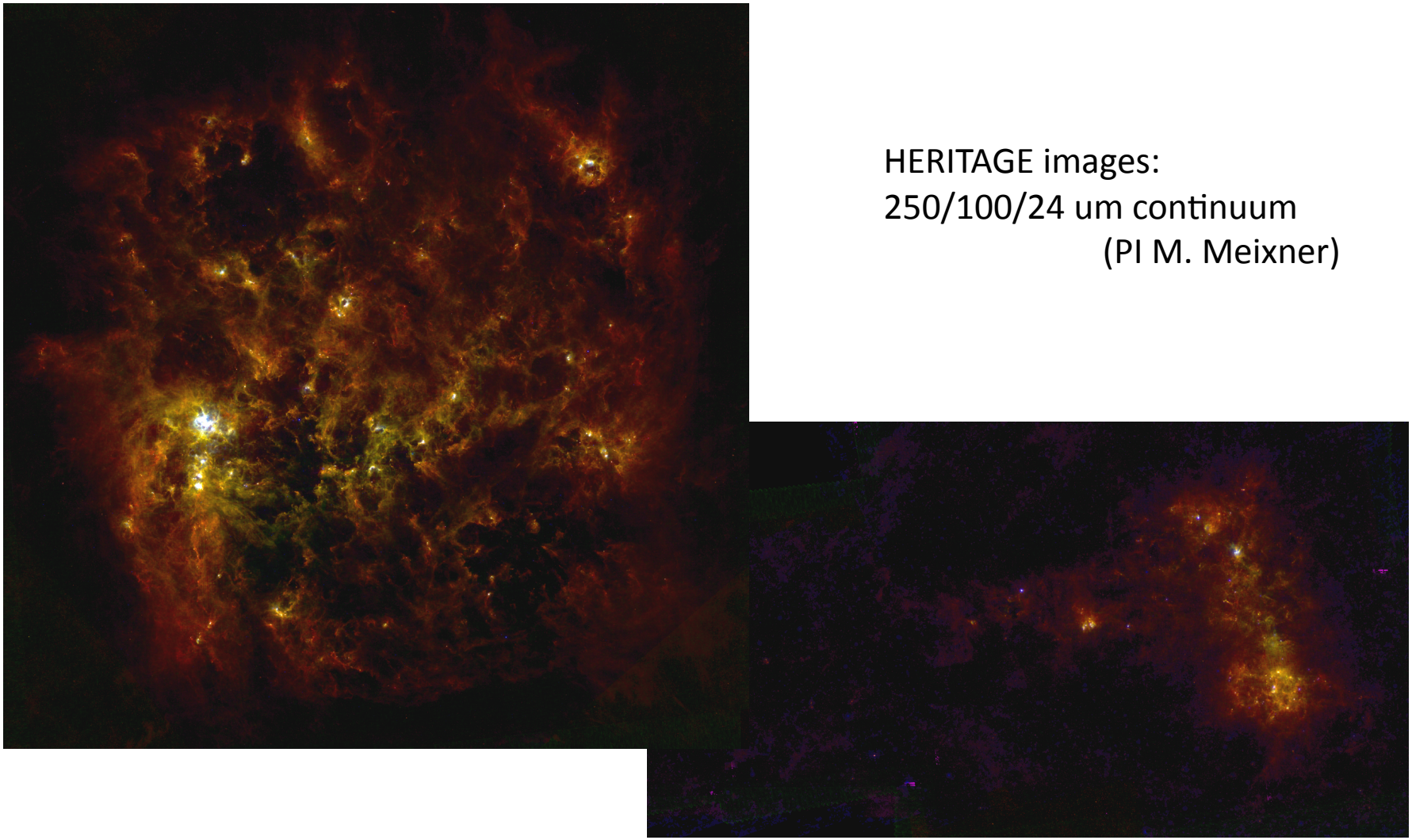
- General agreement with previous results
- Despite general faintness, once the CO distribution is resolved to a few pc, the GMC properties are similar



N11 in the LMC;
C. Herrera+ (submitted)

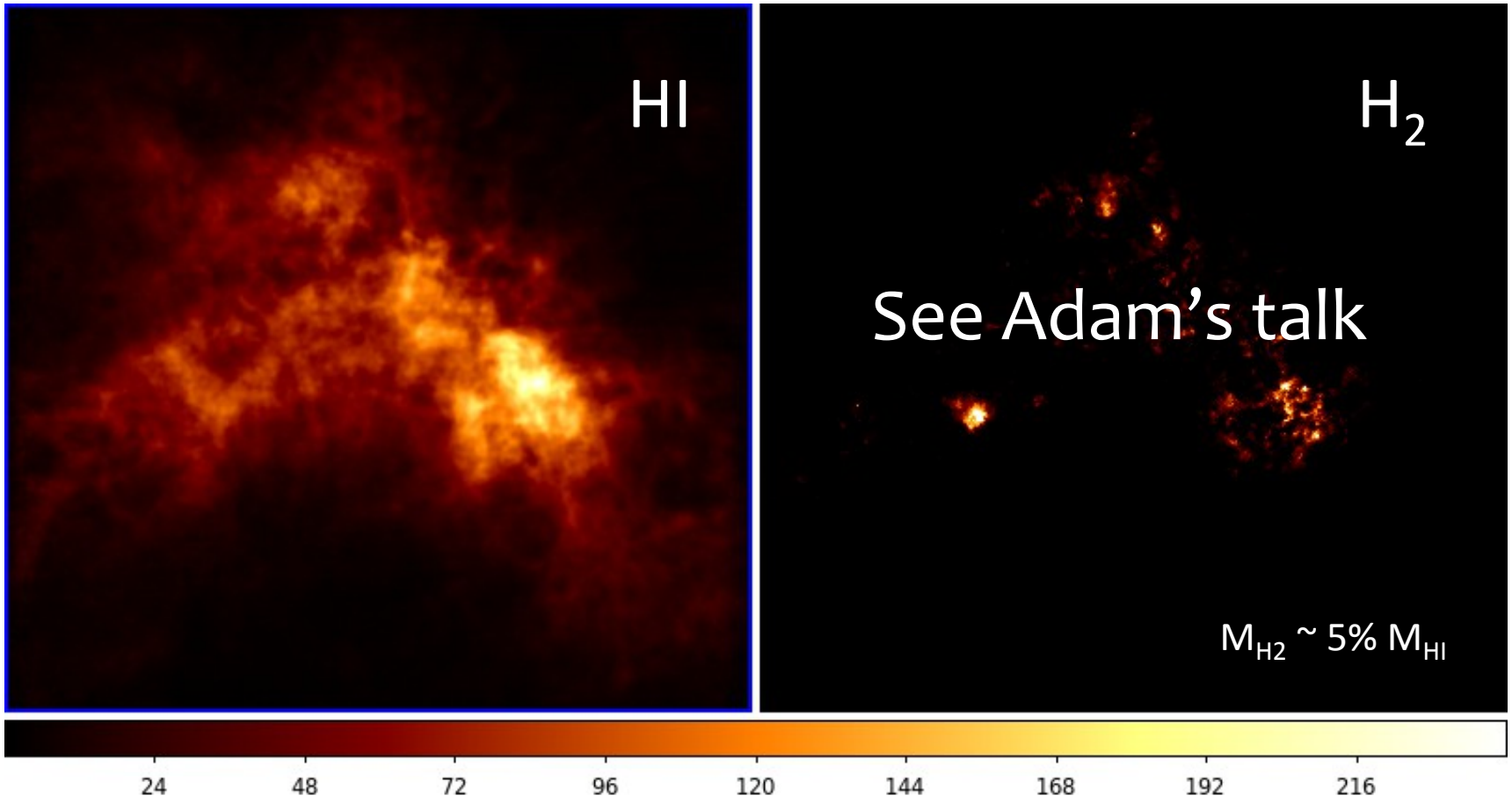


4. Molecules in the Magellanic Clouds



HERITAGE images:
250/100/24 um continuum
(PI M. Meixner)

HI and H_2 at ⅕ Solar metallicity

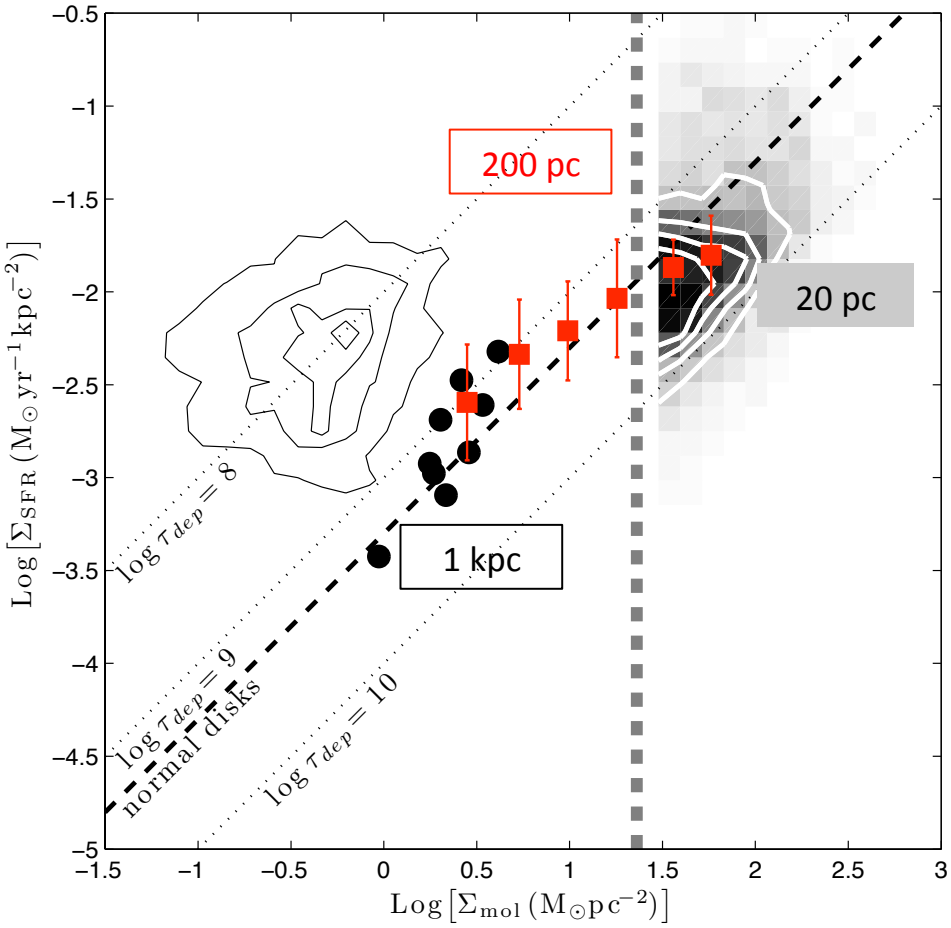


Surface densities in $M_\odot/pc^2$

HI: STANIMIROVIC ET AL. 2000
H2: BOLATTO ET AL. 2011

Relation between H_2 and Star Formation

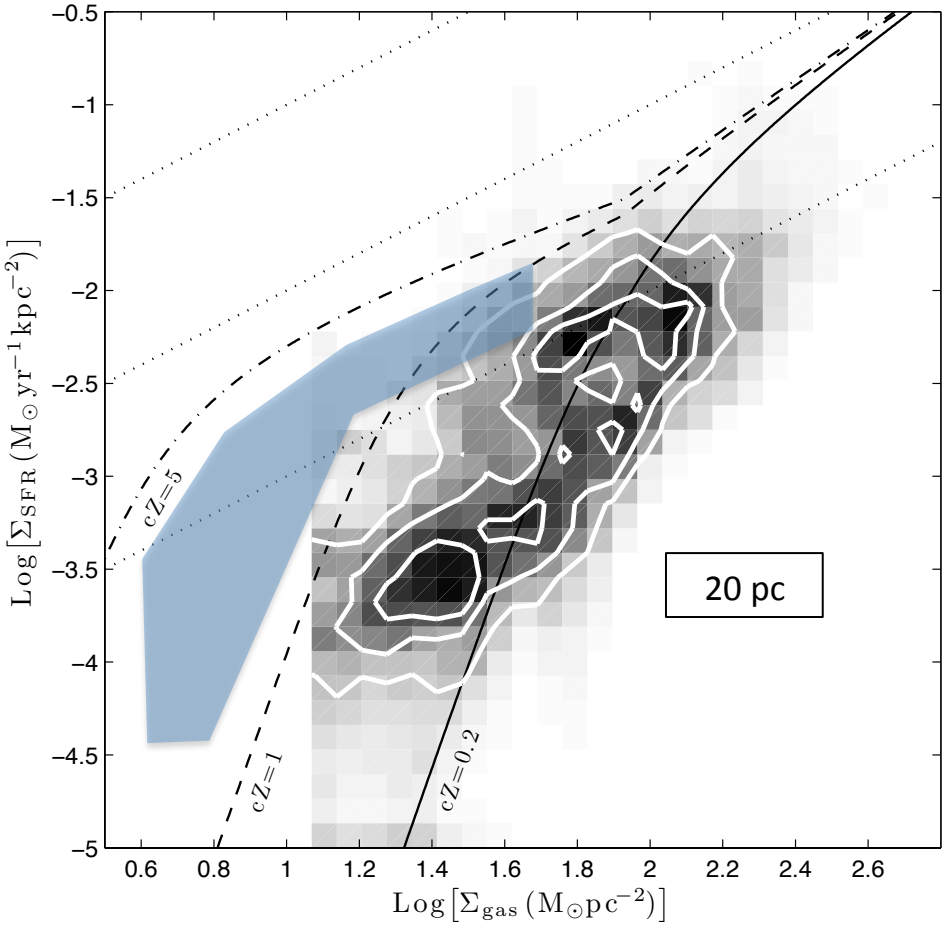
- Looks just like the high metallicity version
- No major metallicity effects
- Except for the CO intensity



BOLATTO ET AL. (2011)

The SFL for all gas

- Caveat: geometry (G. Besla's talk)
- The SMC is clearly displaced toward substantially higher surface densities
  - -a lot of HI but little corresponding SF
- Need larger gas column to attain the Av necessary for HI to H_2 transition
- Direct impact on galaxy simulations, interpretation of results (e.g., Wolfe & Chen 2006)
- Ooverall good agreement with the KMT09 track for Z=0.2



Bolatto et al. (2011)

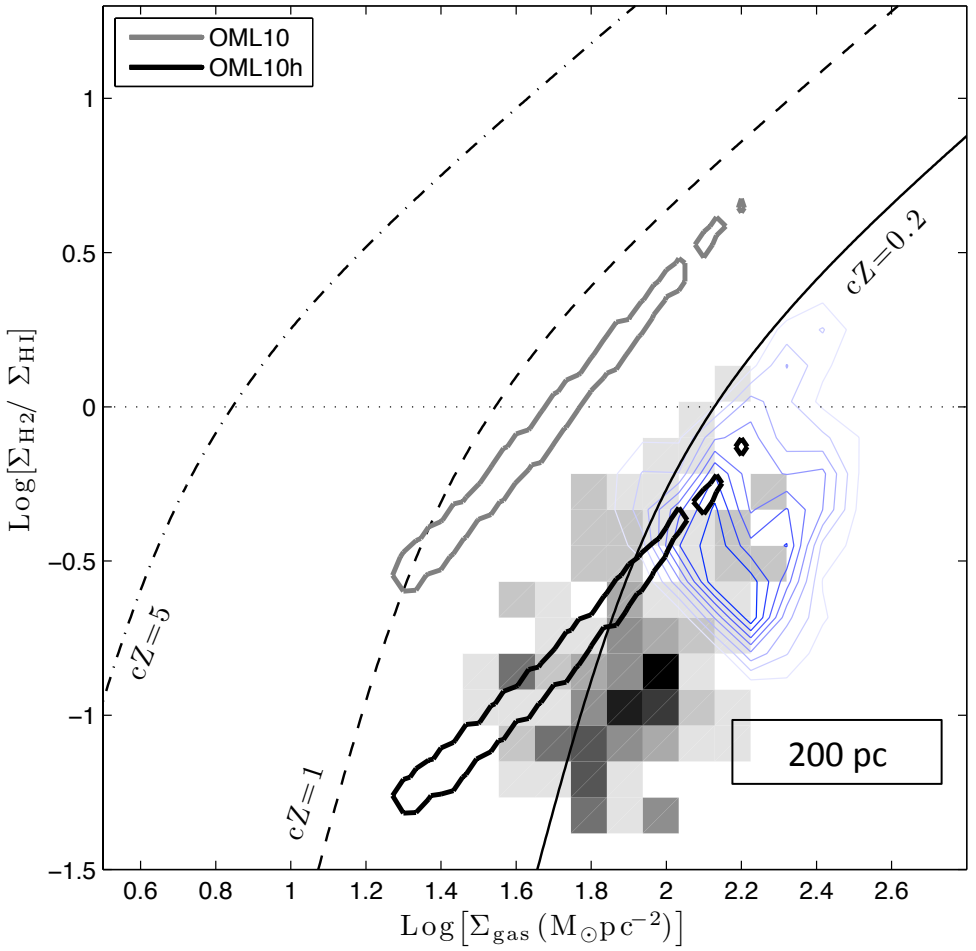
The models

- Krumholz, McKee, & Tumlinson (2009)
  - Gas in photodissociation equilibrium with radiation field, generated by conversion of H_2 into stars at a rate of a few % per free-fall timescale
- Ostriker, McKee, & Leroy (2010)
  - Gas in two-phase thermodynamic equilibrium determined by pressure balance (from gravity) and heating rate from conversion of dense phase into stars with a timescale of 2 Gyr
  - In a modified version, we introduced a metallicity dependency in the radiation field reflecting the increase in the escape of FUV from dense SF regions due to lower dust-to-gas ratios

It is possible to understand it…

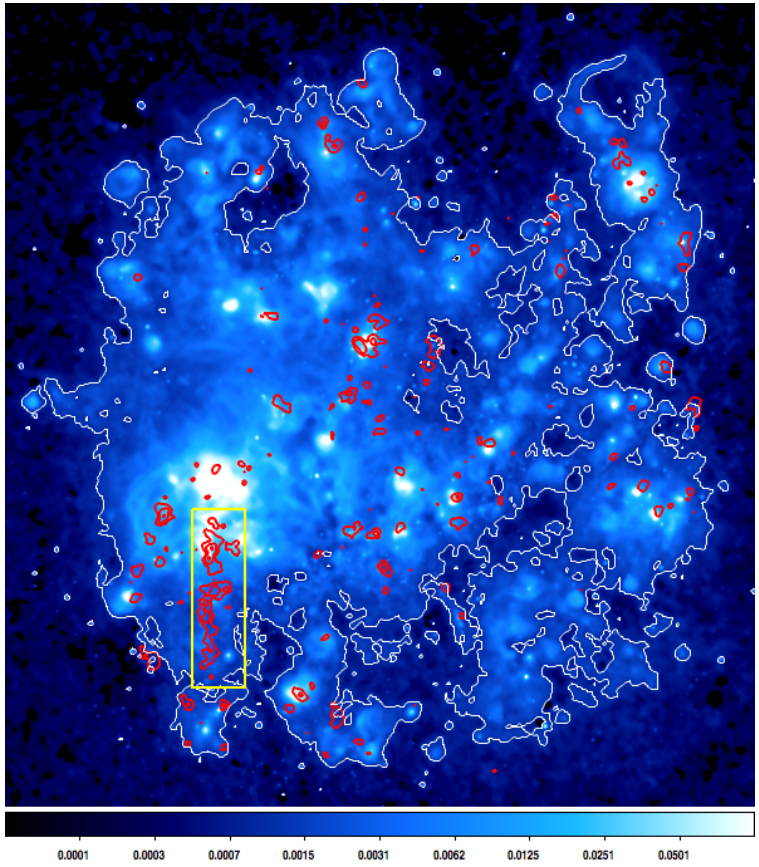
- …in terms of more than one model

- If we combine KMT09 and OML10, we can compute HI in "dense" phase
  - very reasonable agreement with CNM measurements of 15%

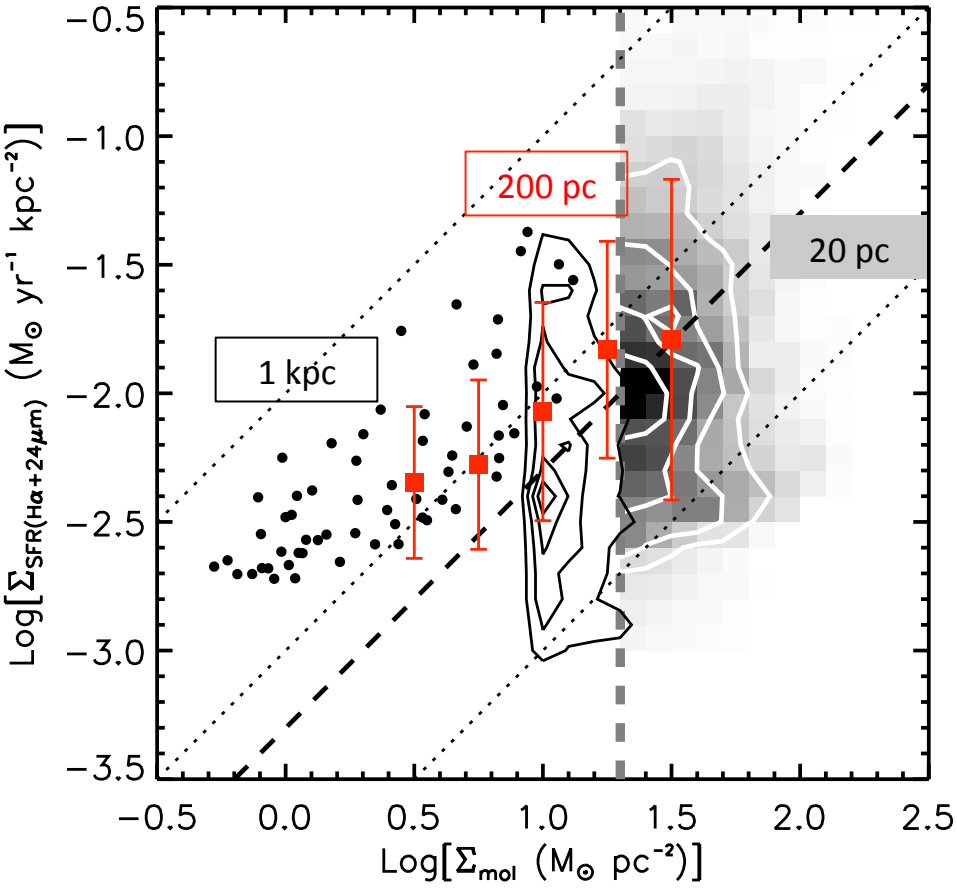


Bolatto et al. (2011)

Work in progress: the LMC



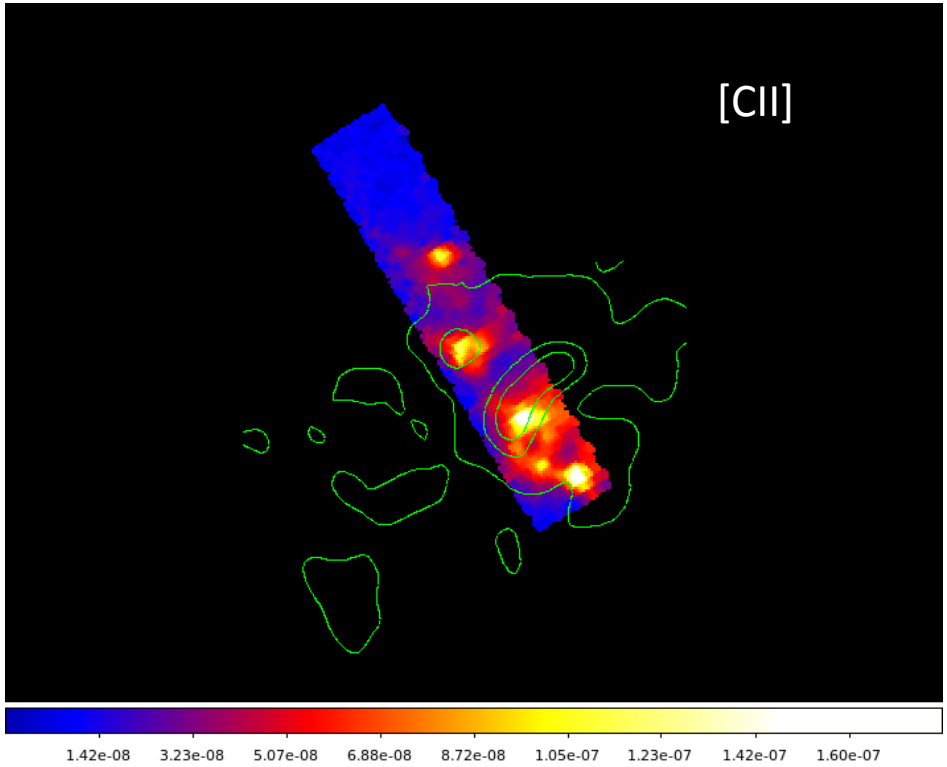
HA WITH CO CONTOURS



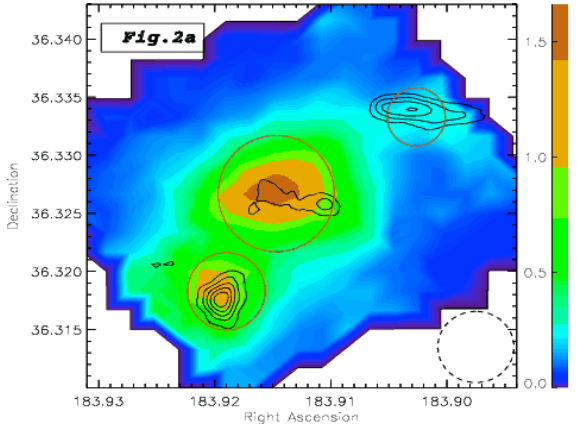
JAMESON ET AL. (IN PREP)

5. What's next?

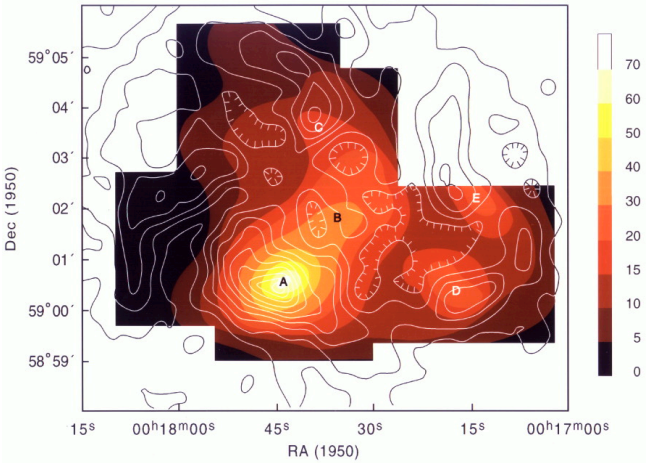
HERSCHEL PACS spectroscopy in the SMC:
6 regions, several lines



See talk later today by V. Le Boutellier

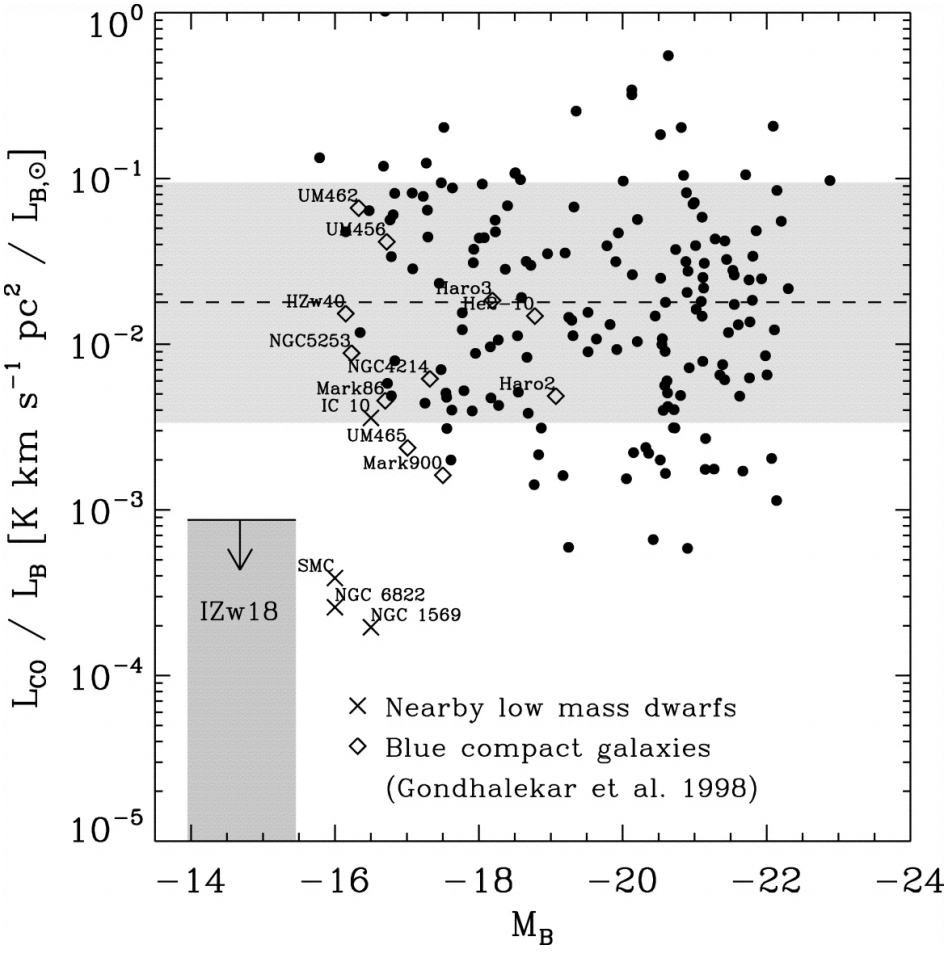


NGC4214; Cormier+(2010)



IC 10; Madden+(1997)

Perspectives for CO

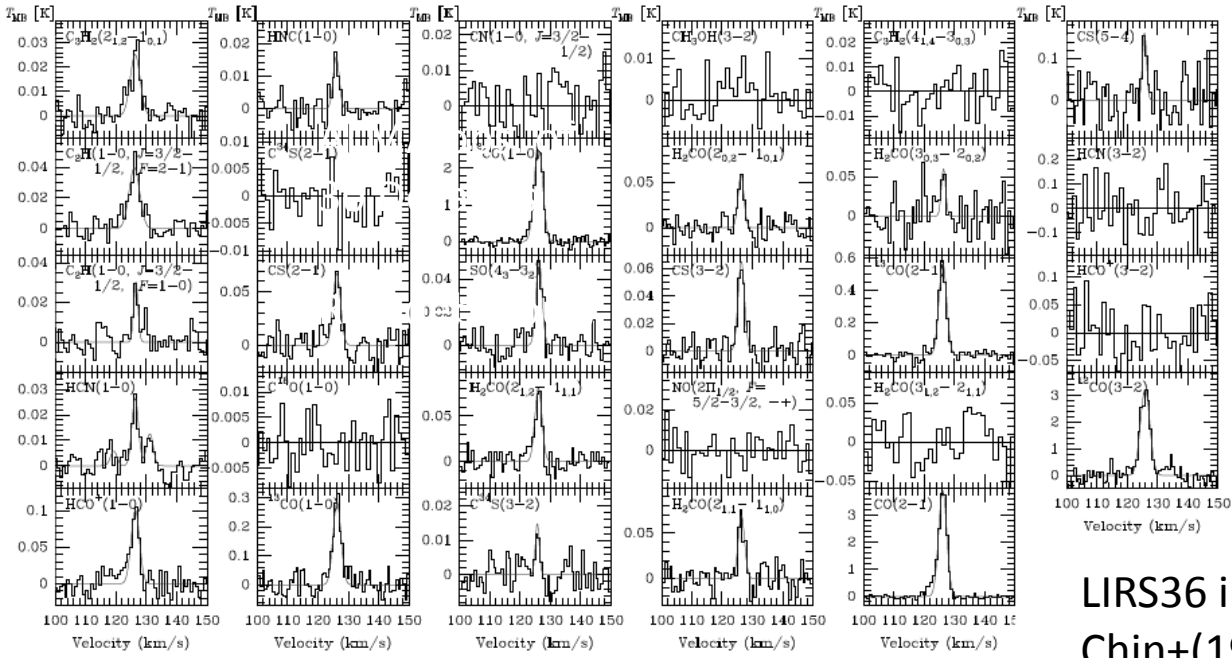


Leroy+ (2007)
also Herrera+ (2012)

ALMA:
L. Hunt SBS0335 project

Other molecules?

- Not impossible, but heroic
- ALMA!!



LIRS36 in the SMC; Chin+(1999)

Other molecules?

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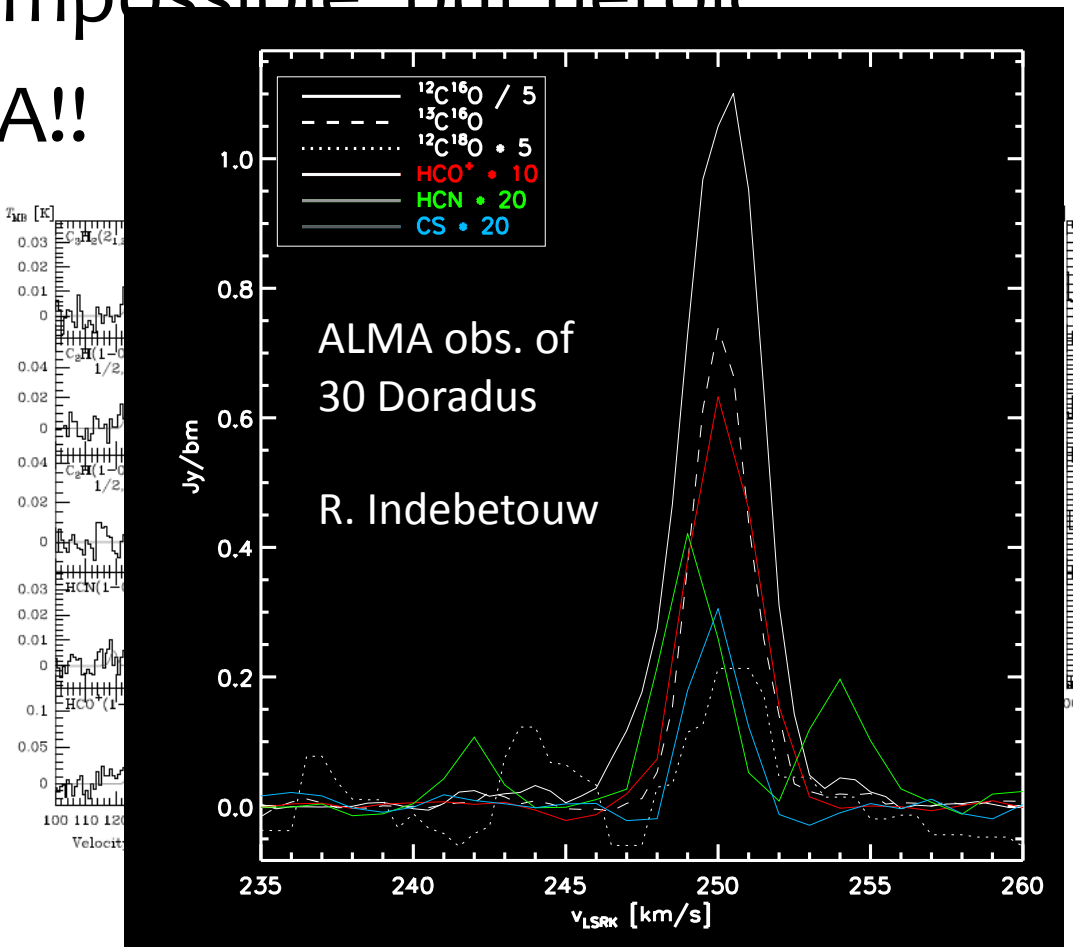
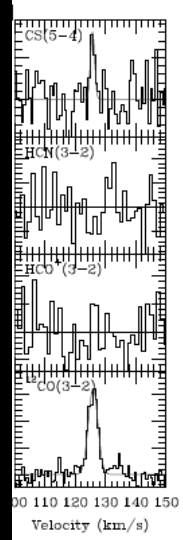
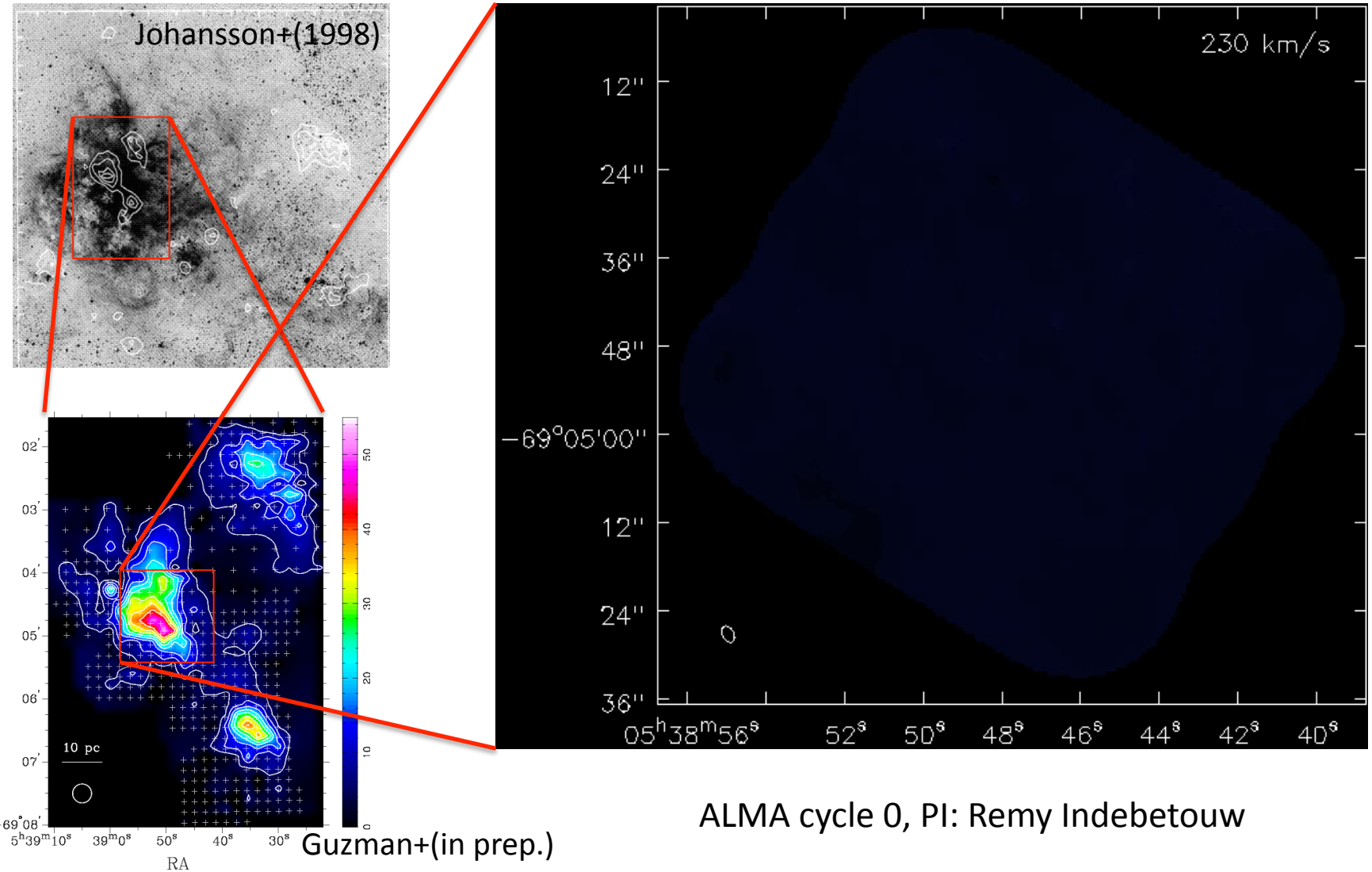




LIRS36 in the SMC;
Chin+(1999)

ALMA CO in 30 Doradus



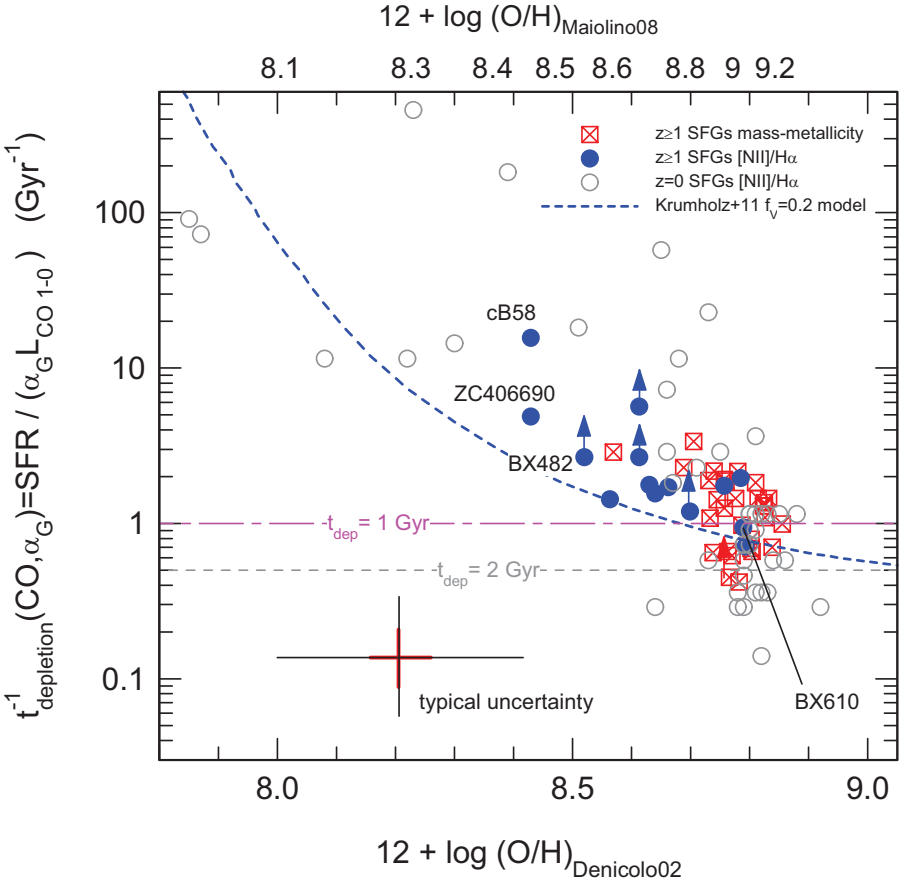
Guzman+(in prep.)

ALMA cycle 0, PI: Remy Indebetouw

Back to high-z

- Local dwarfs can really help understand key problems related to galaxy evolution

  (although they may not be analogs of anything)
- Short τ_{dep} or X_{CO}?
- Is H_2 necessary for star formation? Is CO?



Genzel+(2011); Krumholz+(2011)

Conclusions

- Plenty of H2 molecules!
  - most likely explanation
  - dearth of molecular tracers
  - but ALMA should be able to detect them
- Work on dwarf galaxies is crucial to understand the low metallicity ISM

- It wasn't such a short talk after all…