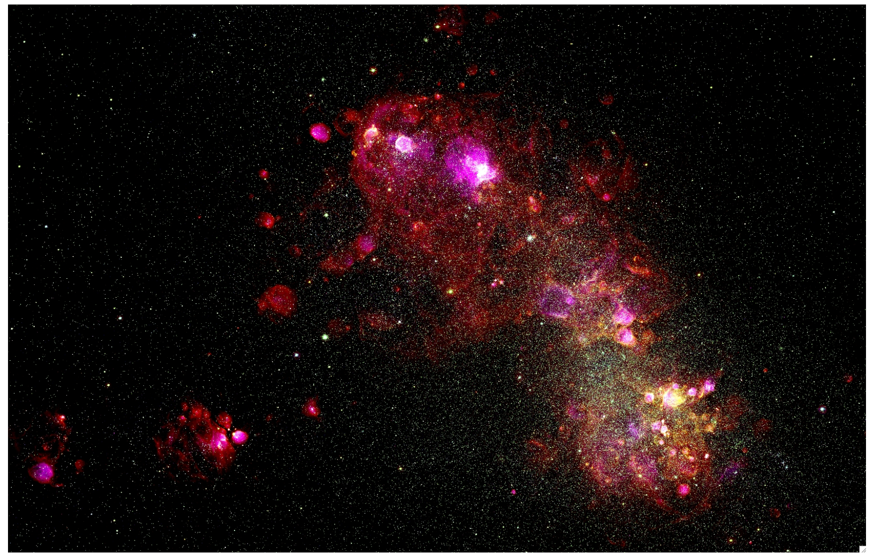
Star Formation at Low Metallicity

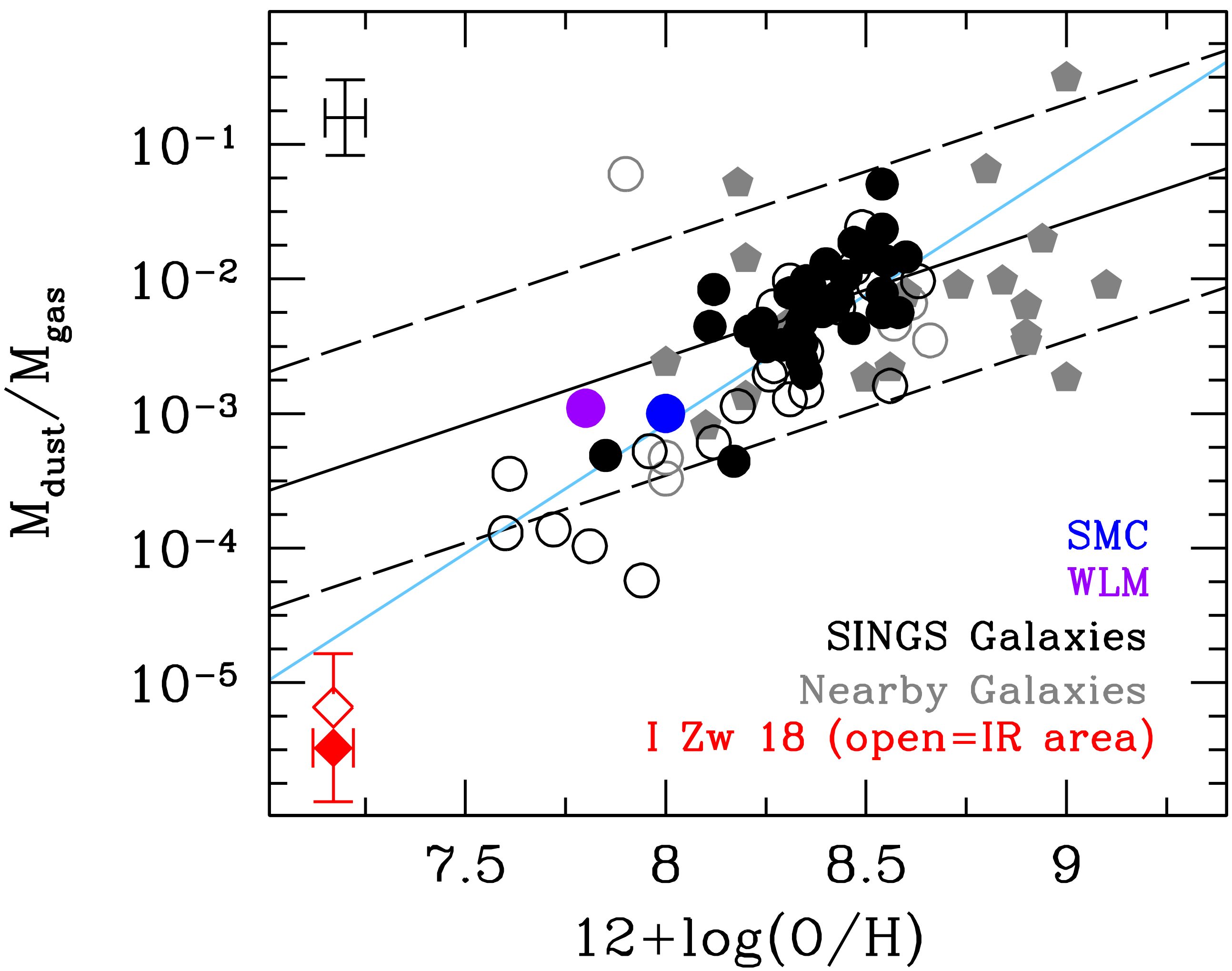



ADAM LEROY (NRAO)

1. Things should be different at low metallicity.
2. Scaling relations: SFR, CO, HI, and stars.
3. PDR Structure: H_2, HI, CII, and CO
4. Molecular clouds at low metallicity.
5. What to look for in the next few years…

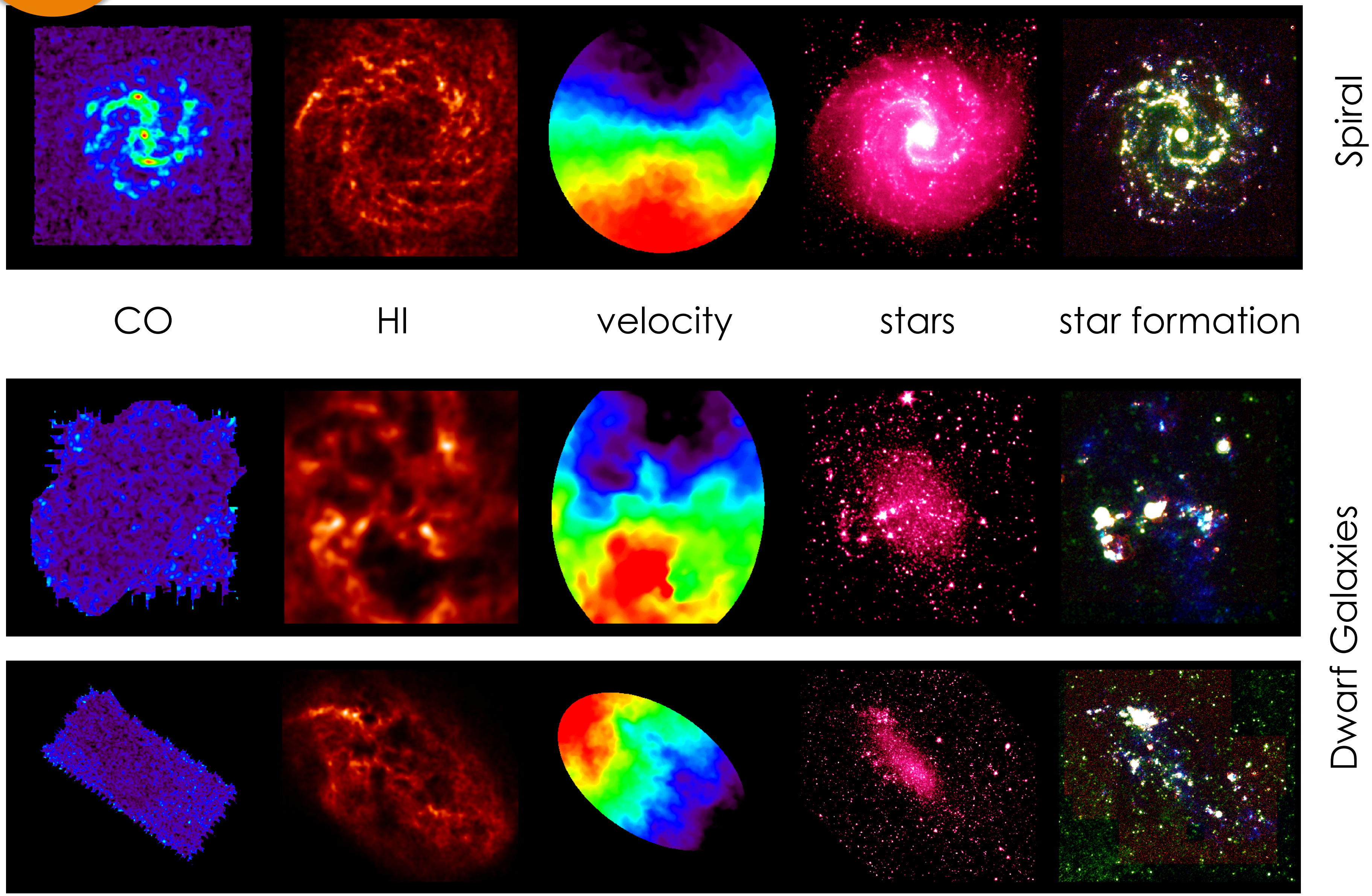
1

Less metals mean less dust.

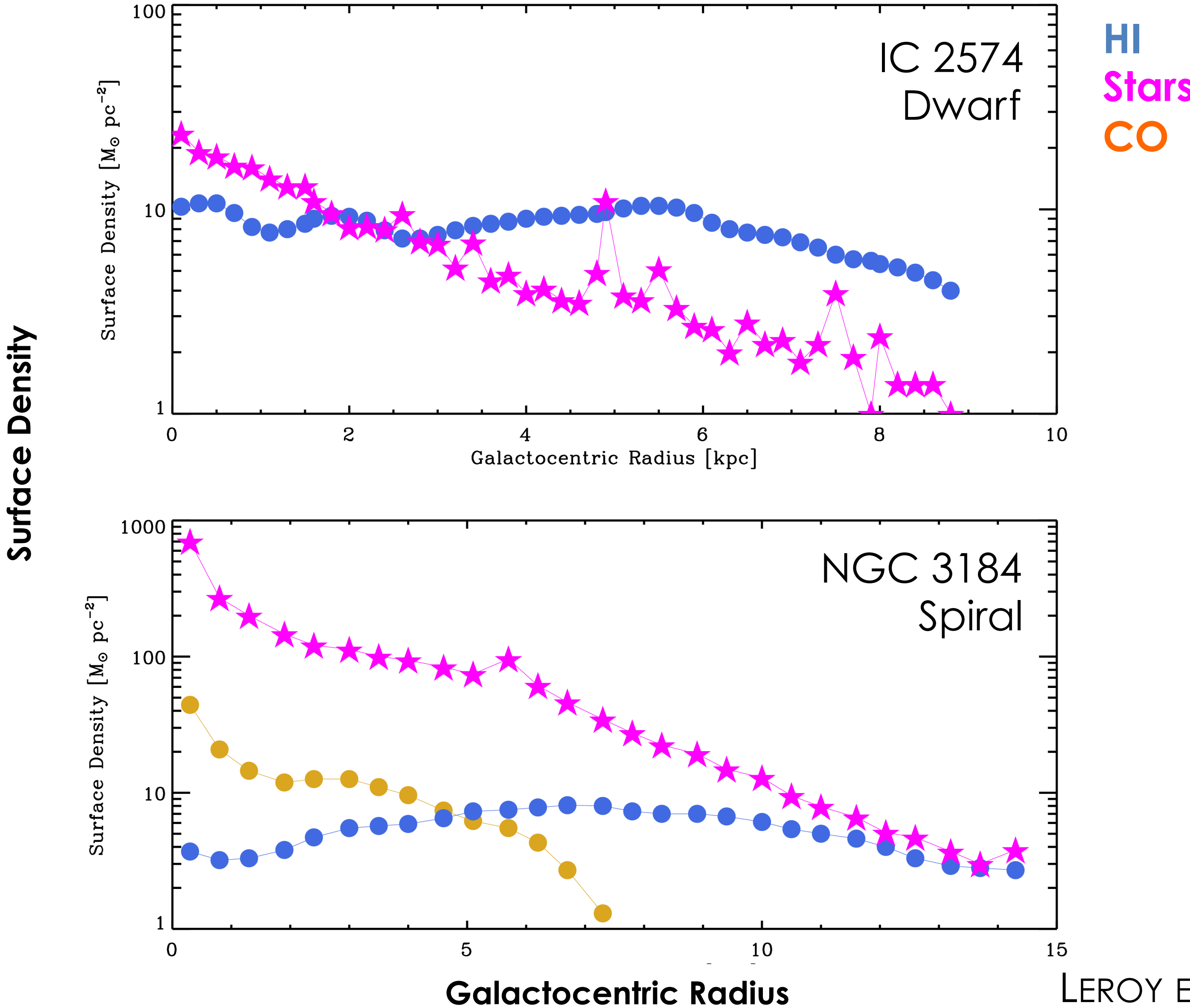


FISHER ET AL. (SUBM.), GALAMETZ ET AL. (2009), DRAINE ET AL. (2007)

1 Covariant with stellar, gas, kinematic structure.



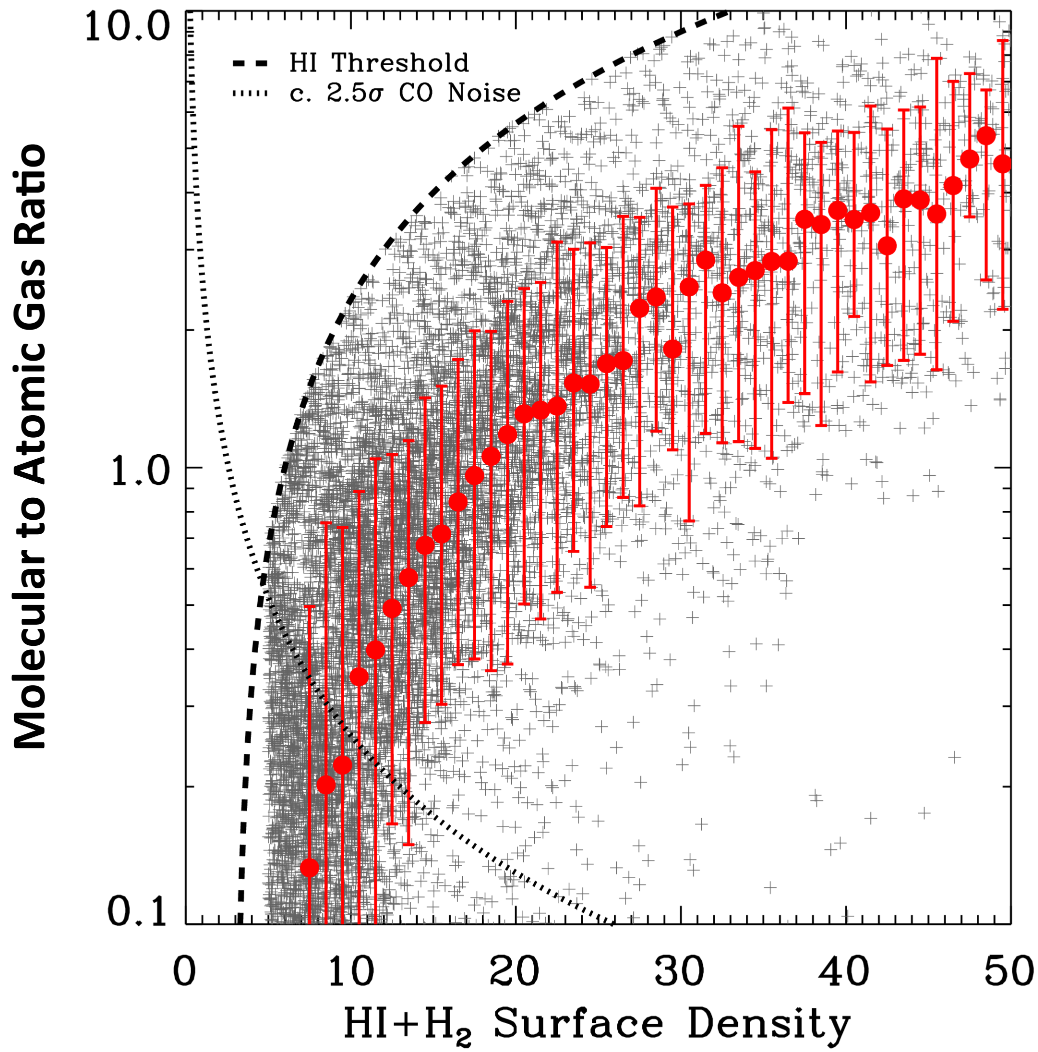
1 Covariant with stellar, gas, kinematic structure.



LEROY ET AL. (2008)

1 Structural differences affect cloud formation.

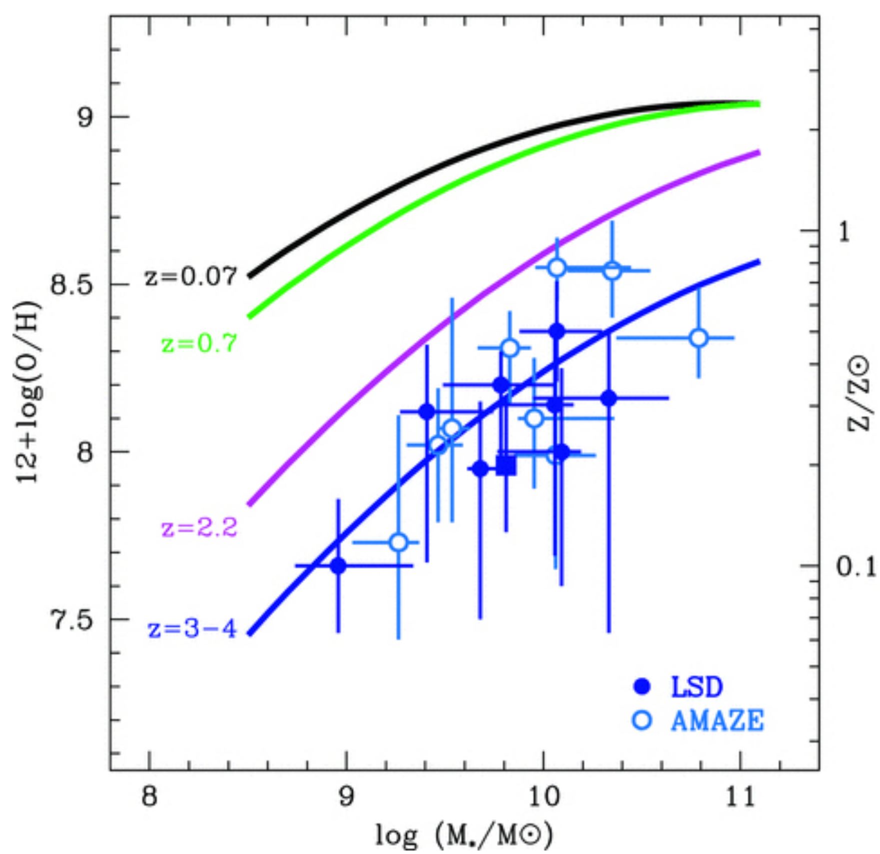
Lower columns mean less molecules



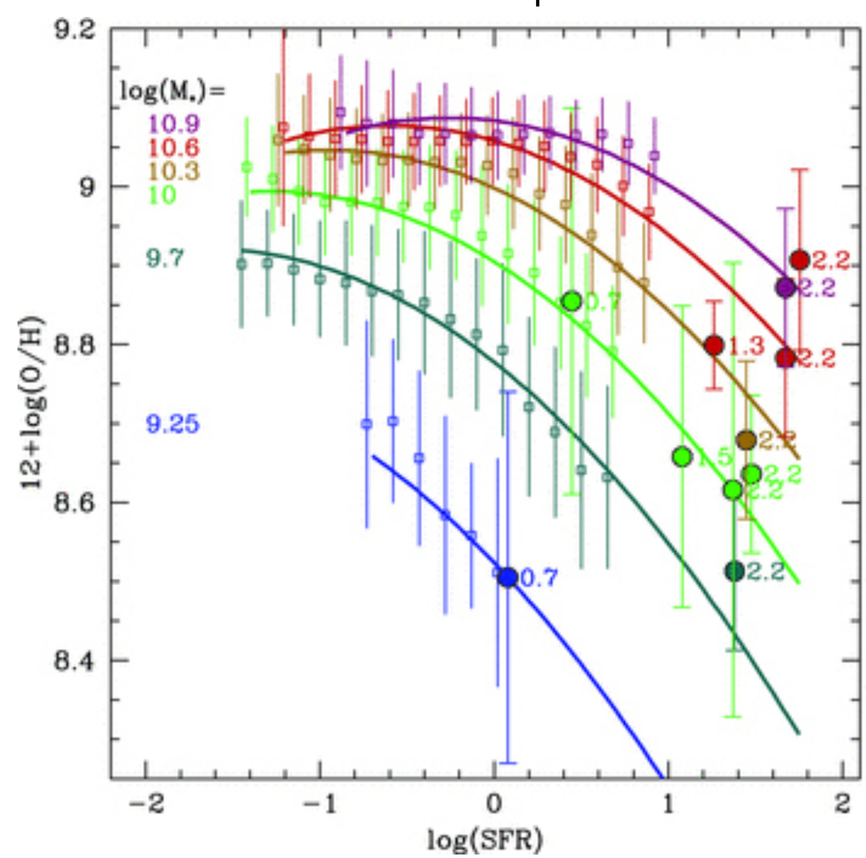
LEROY+KINGFISH IN PREP.

1 Big, high SFR low-metal galaxies (esp. at high z)

Evolution with redshift



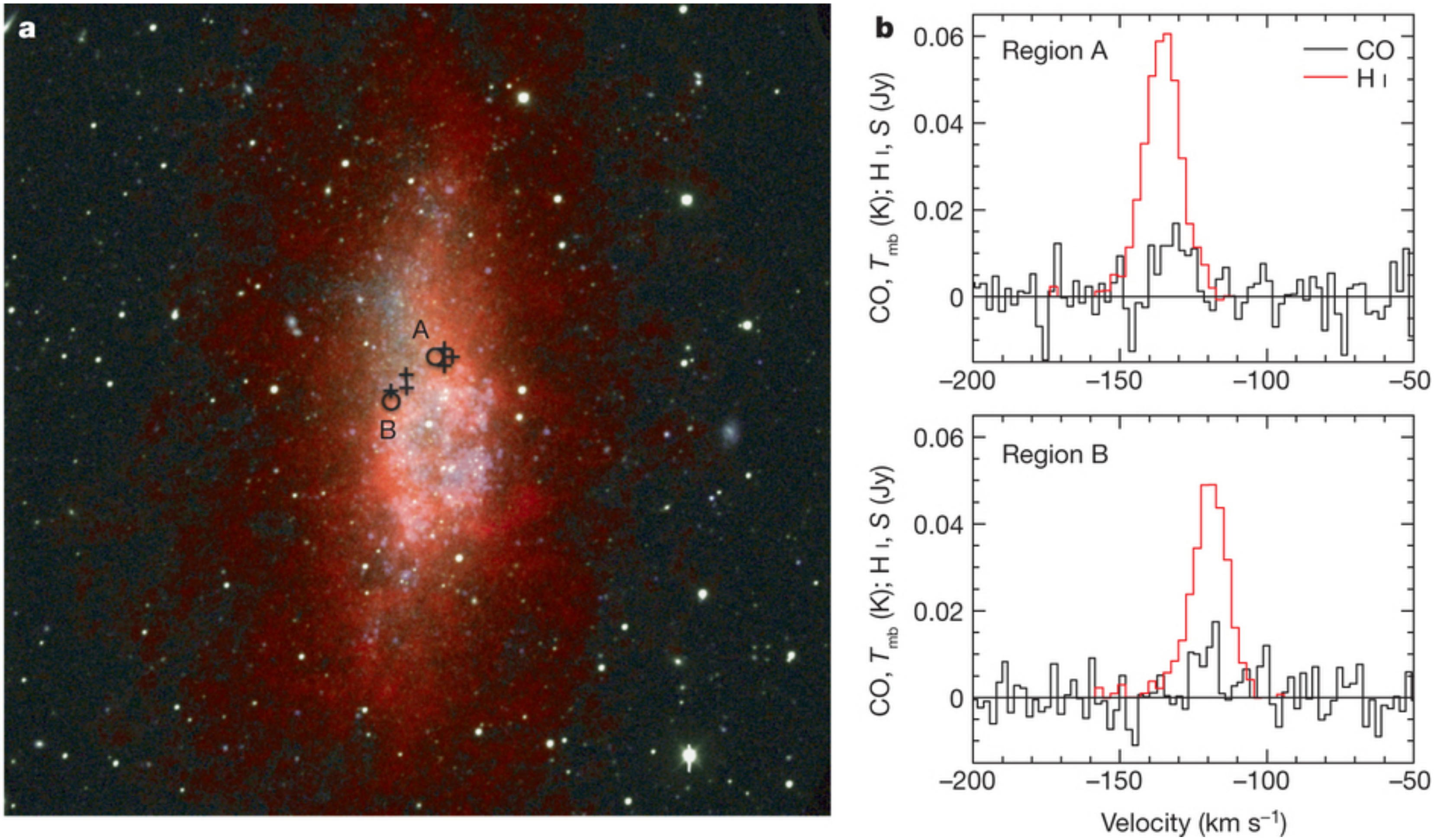
Mass as a third parameter



MANNUCCI ET AL. (2009, 2010)

1 Molecular gas (CO) very hard to observe.

WLM – first CO detection below 12+log O/H ~ 8.0



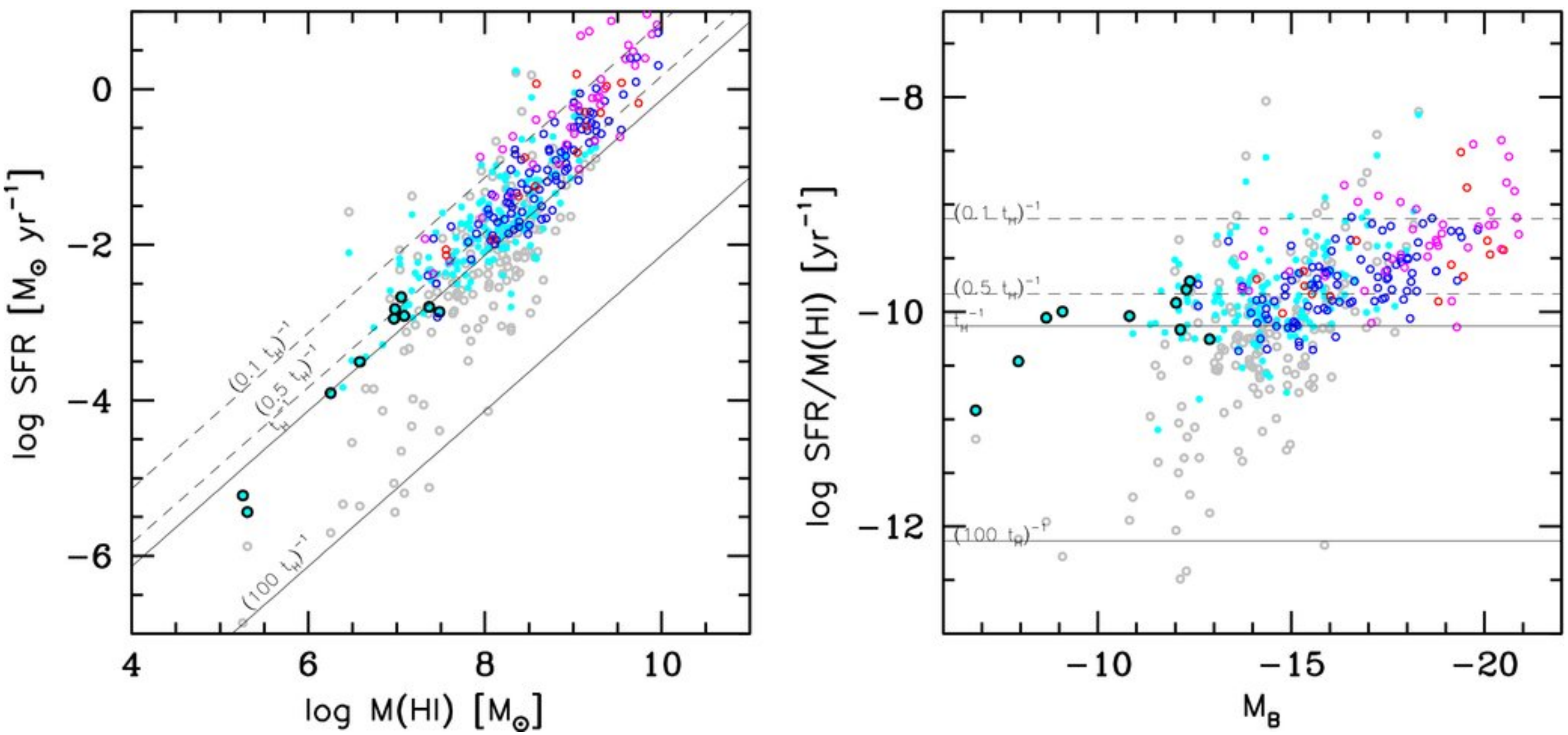
ELMEGREEN ET AL. (2013)

1 Things should be different at low metallicity.

- Low metals mean less dust
- Dust affects visibility of gas (CO), H_2-HI balance
- Z covariant with gas, stellar, kinematic structure
- Column correlates with H_2-HI balance
- SFR as a third parameter / redshift evolution
- CO faint, despite pervasive star formation

2 SFR globally tracks HI, with mass dependence.

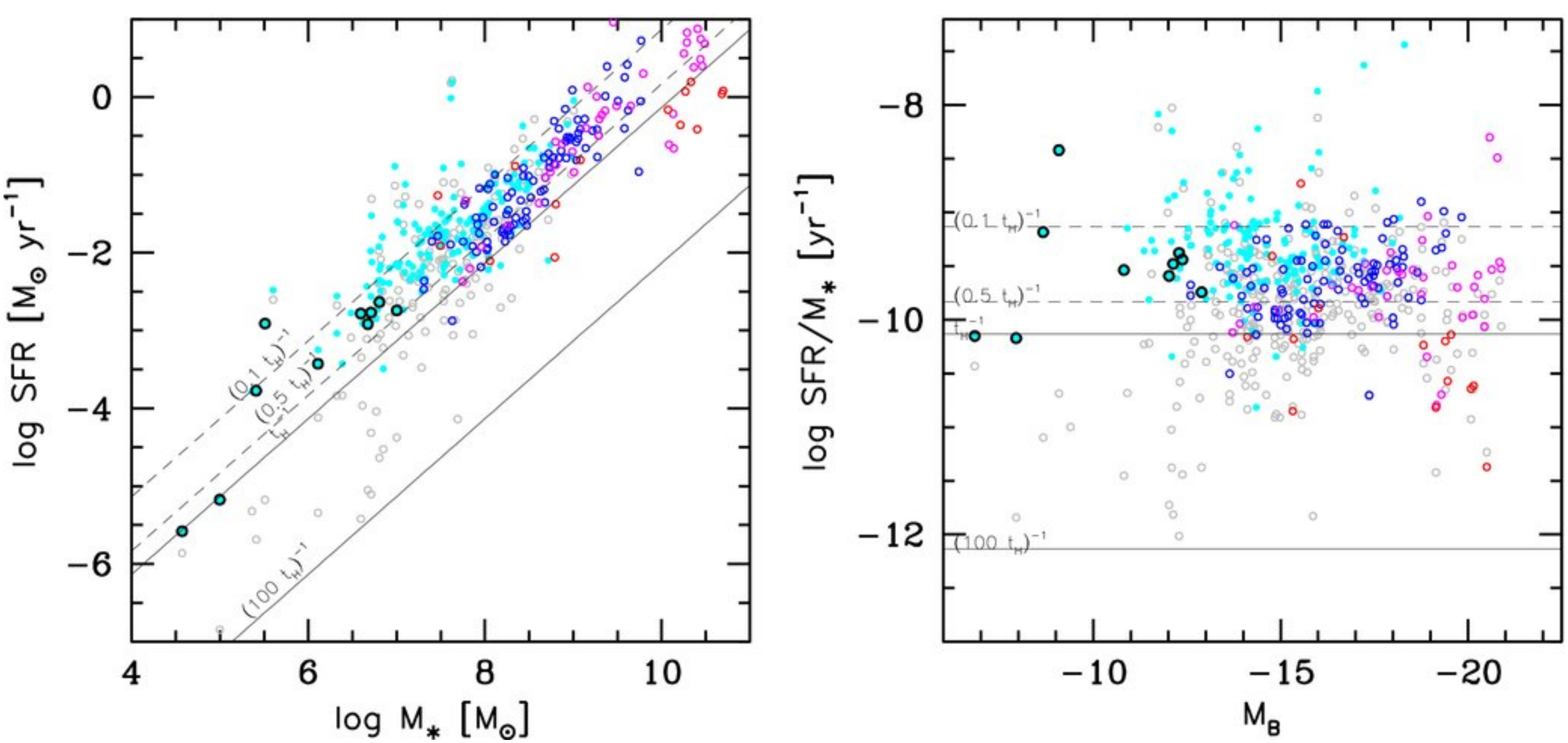
In the local volume SFR tracks HI, t_{dep}~ 1 to 0.1 Hubble times



LEE ET AL. (2009)

2 SFR globally tracks stellar content.

Doubling time <~ ½ Hubble time, less clear slope than HI

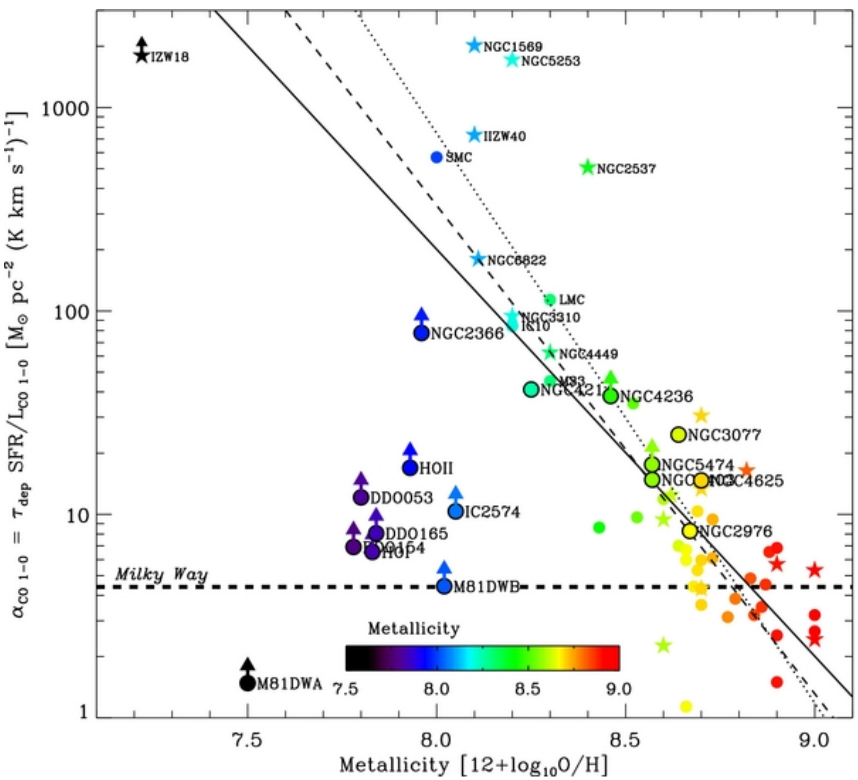


LEE ET AL. (2009)

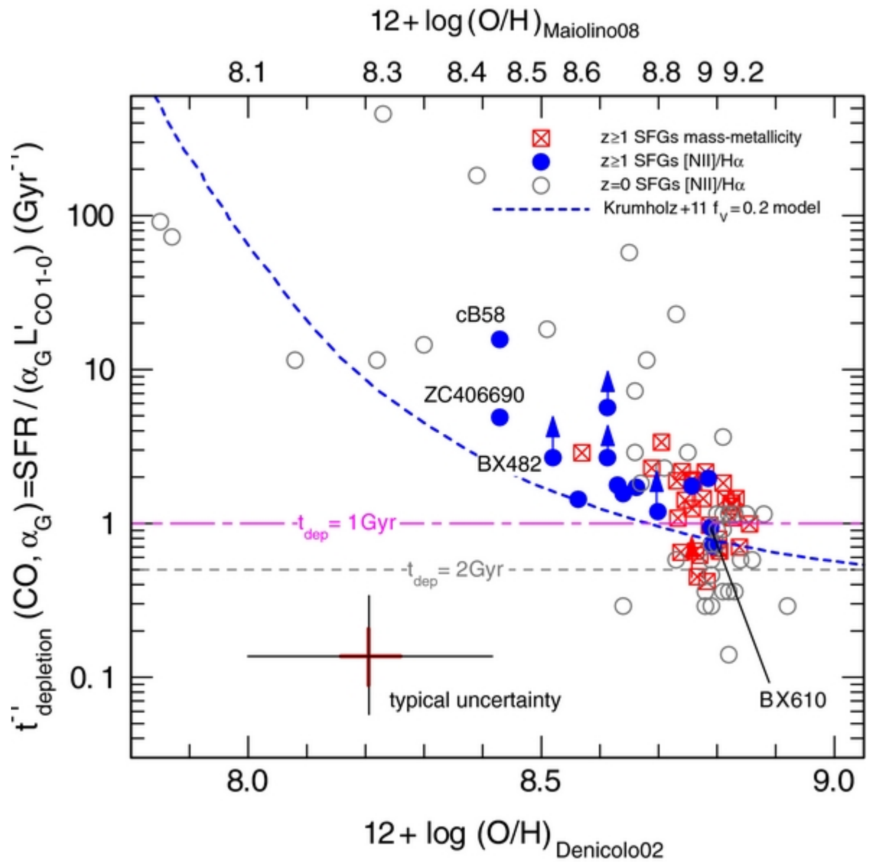
2 SFR/CO increases as metallicity drops

Global ratio SFR/CO sharply increases with dropping Z at high/low z

SFR-to-CO Ratio



SFR-to-CO Ratio

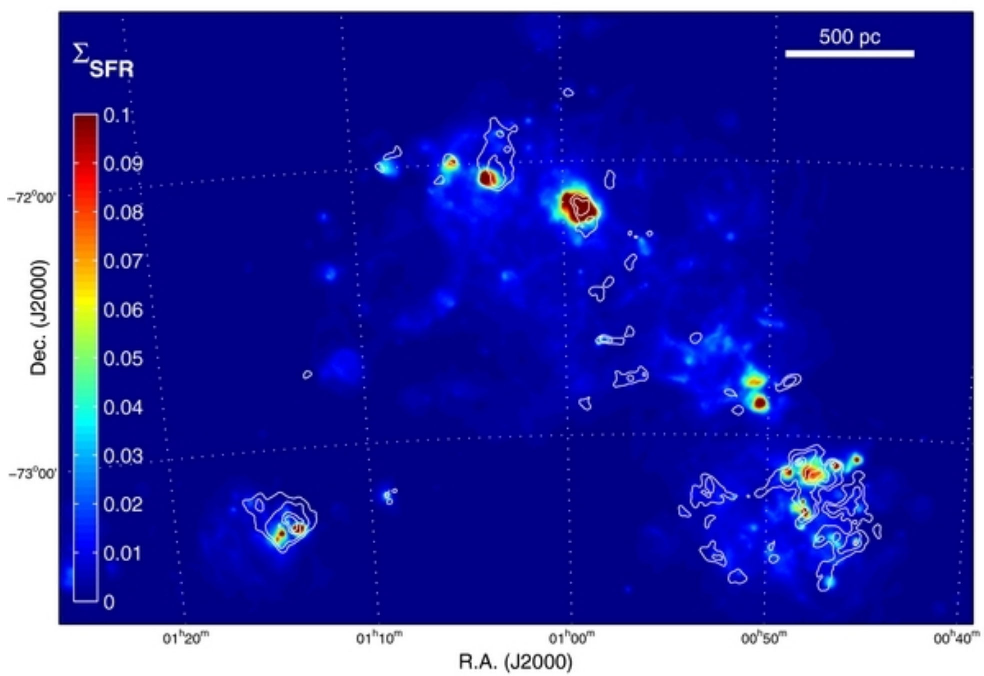


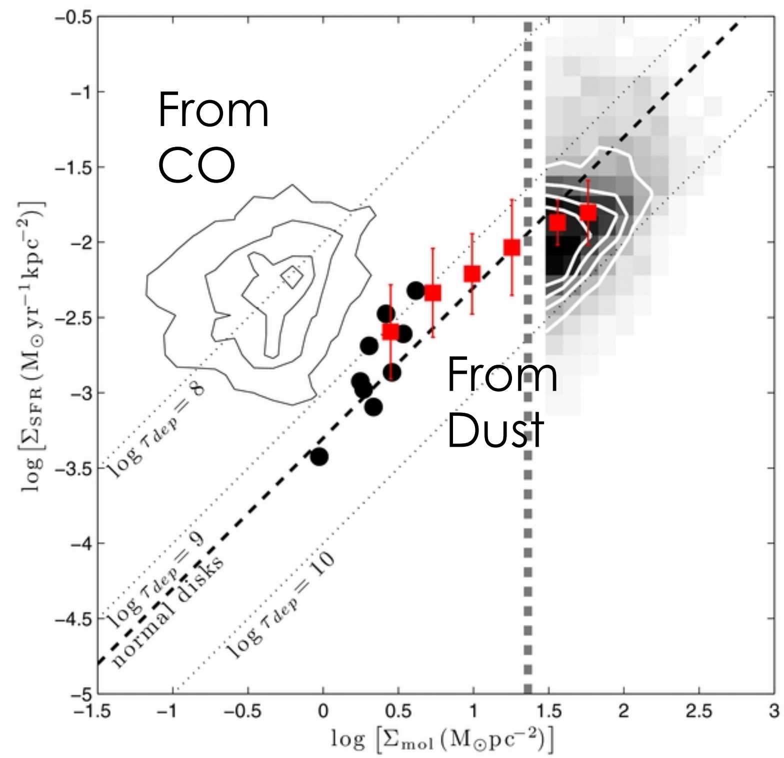
Metallicity (12 + log O/H)

SCHRUBA ET AL. (2012), GENZEL ET AL. (2012)

2 SFR still coincident with H_2, local scaling

Even as ratio changes, SFR and H_2 still show similar distribution.





SFR Surface Density (UV+IR) [M_{sun} yr^{-1} kpc^{-2}]

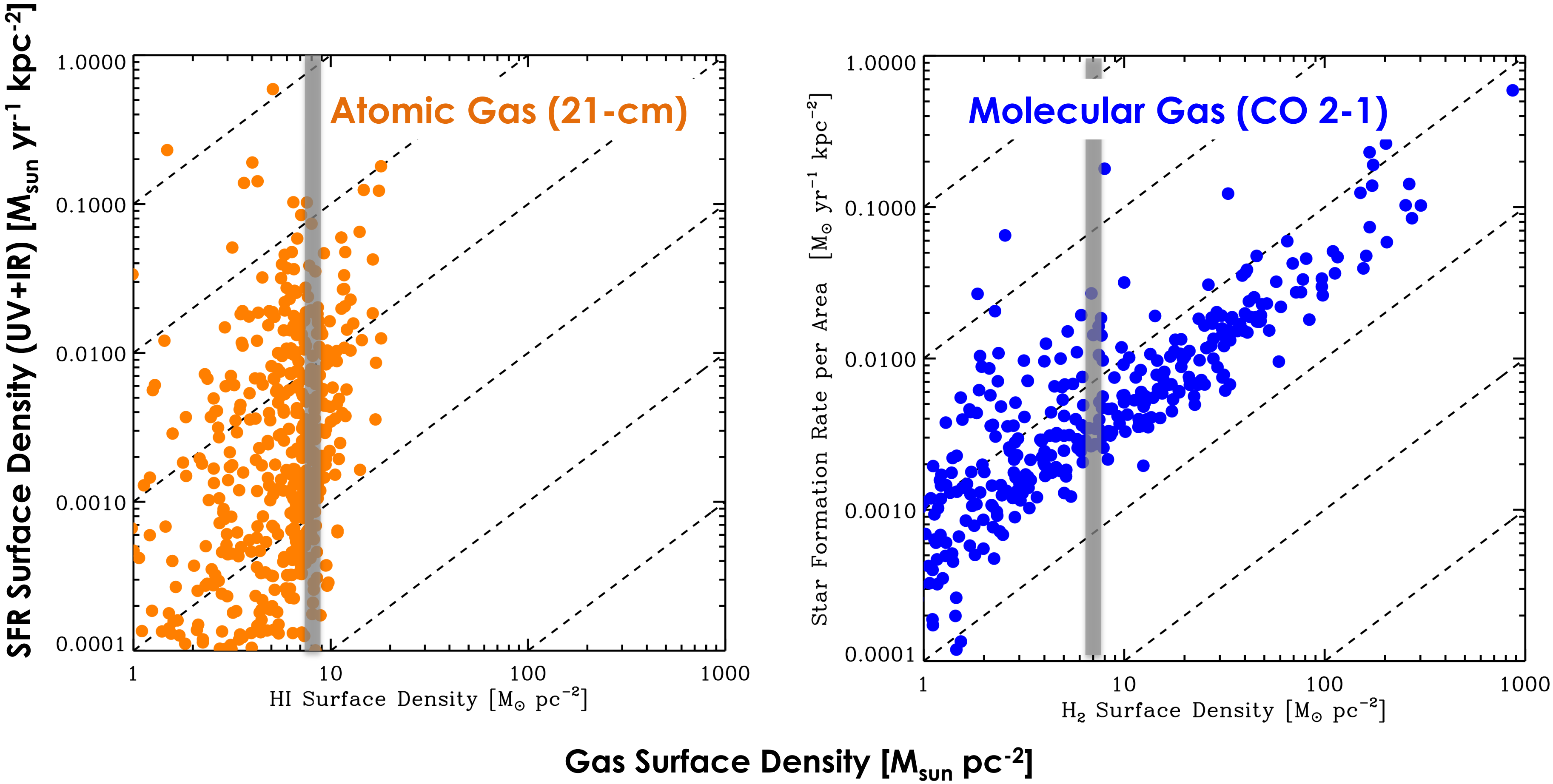
H_2 Surface Density [M_{sun} pc^{-2}]

BOLATTO, LEROY ET AL. (2011), JAMESON, BOLATTO ET AL. (IN PREP.)

2

SFR and CO track in HI dominated regime.

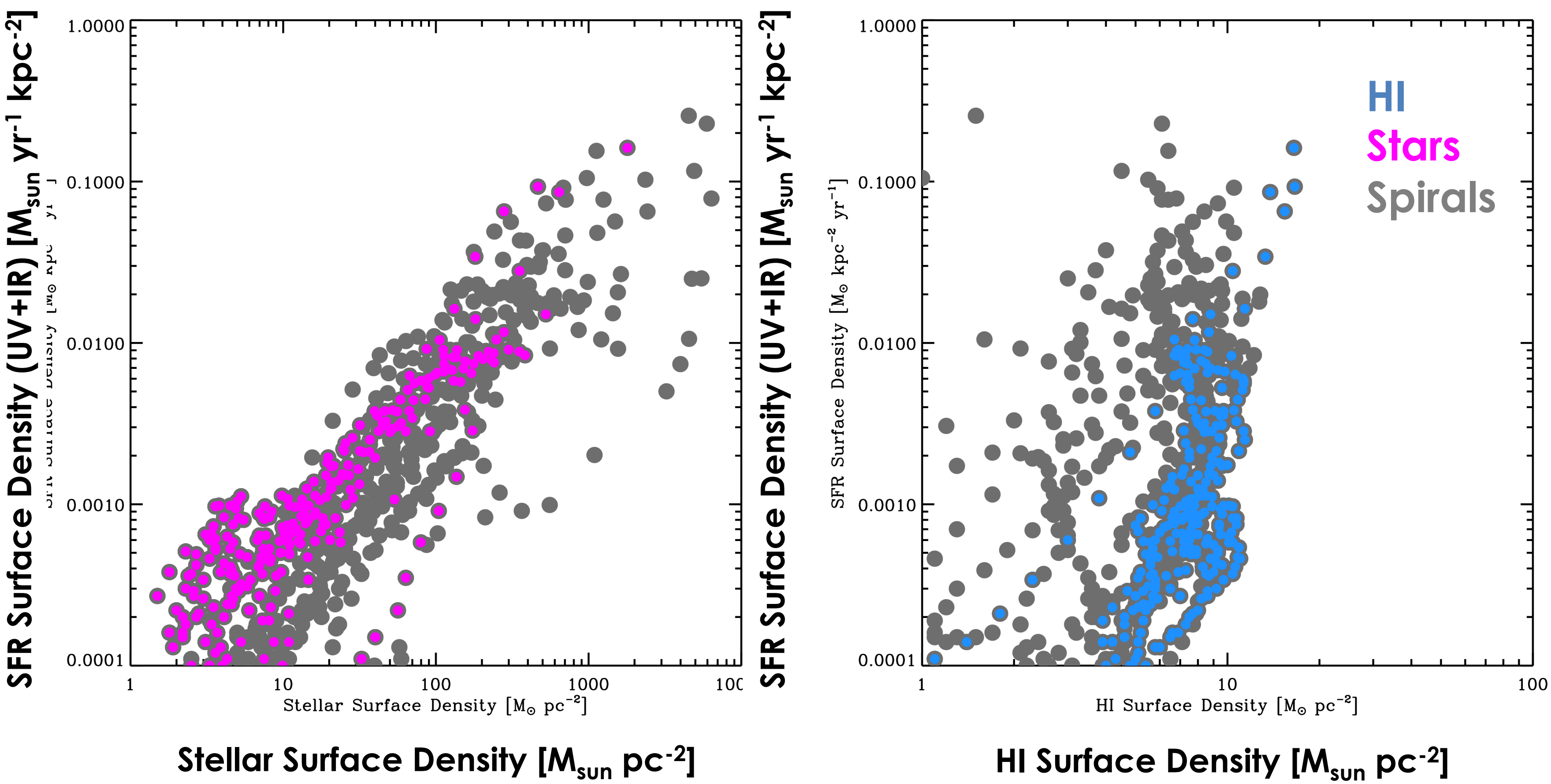
More generally, SFR still tracks molecular gas in HI-dominated regions.



SCHRUBA ET AL. (2011)

2 SFR tracks older stars in nearby dwarf galaxies.

Dwarfs in color, spirals in gray



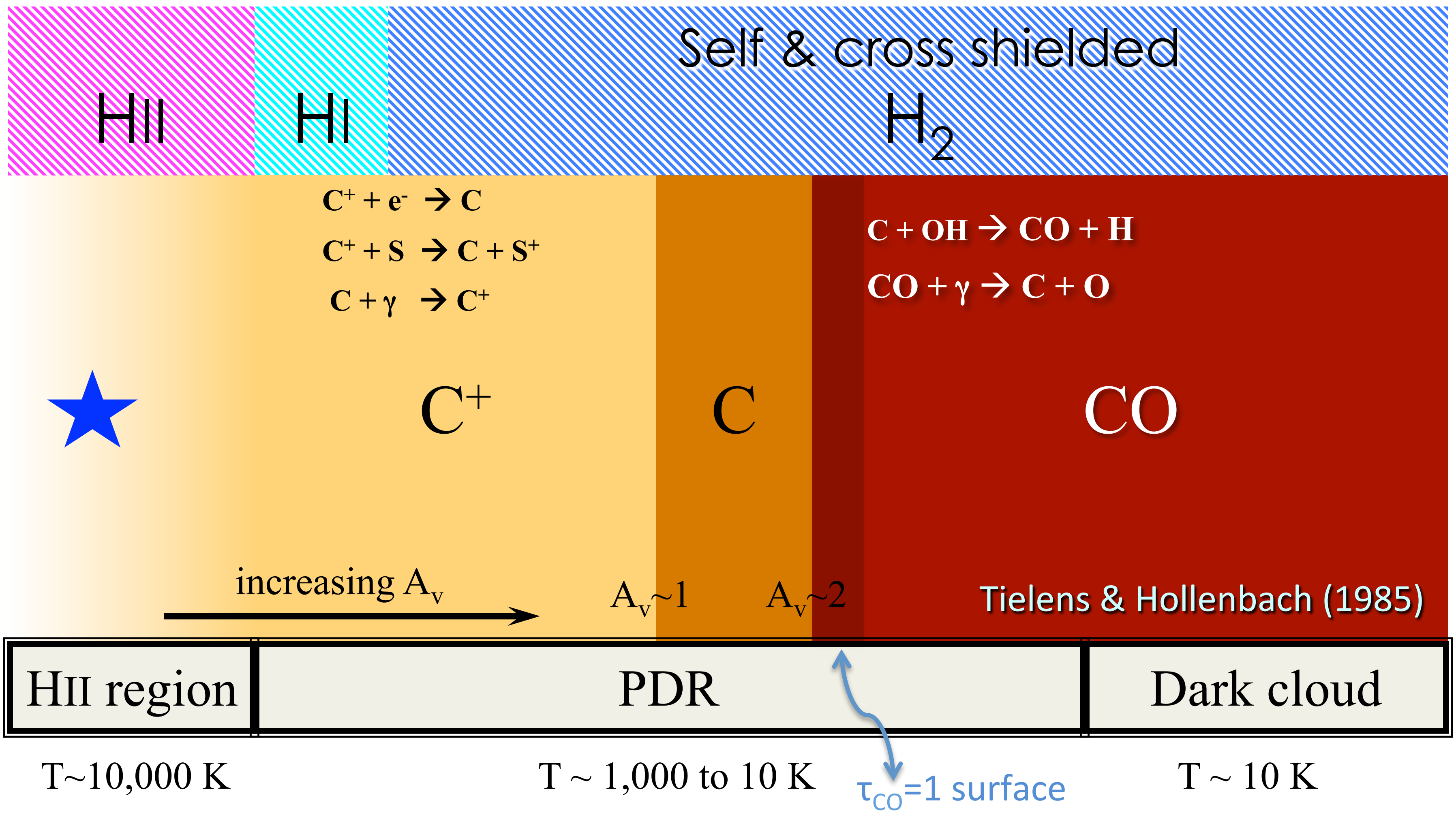
HUNTER ET AL. (1998), LEROY ET AL. (2008)

2 Scaling relations: SFR, CO, HI, and stars.

- Global SFR tracks HI (with some slope)
- Global SFR tracks stellar content
- SFR/CO increases with dropping metallicity
- SFR still associated with CO where HI dominates
- SFR broadly occurs where there are stars

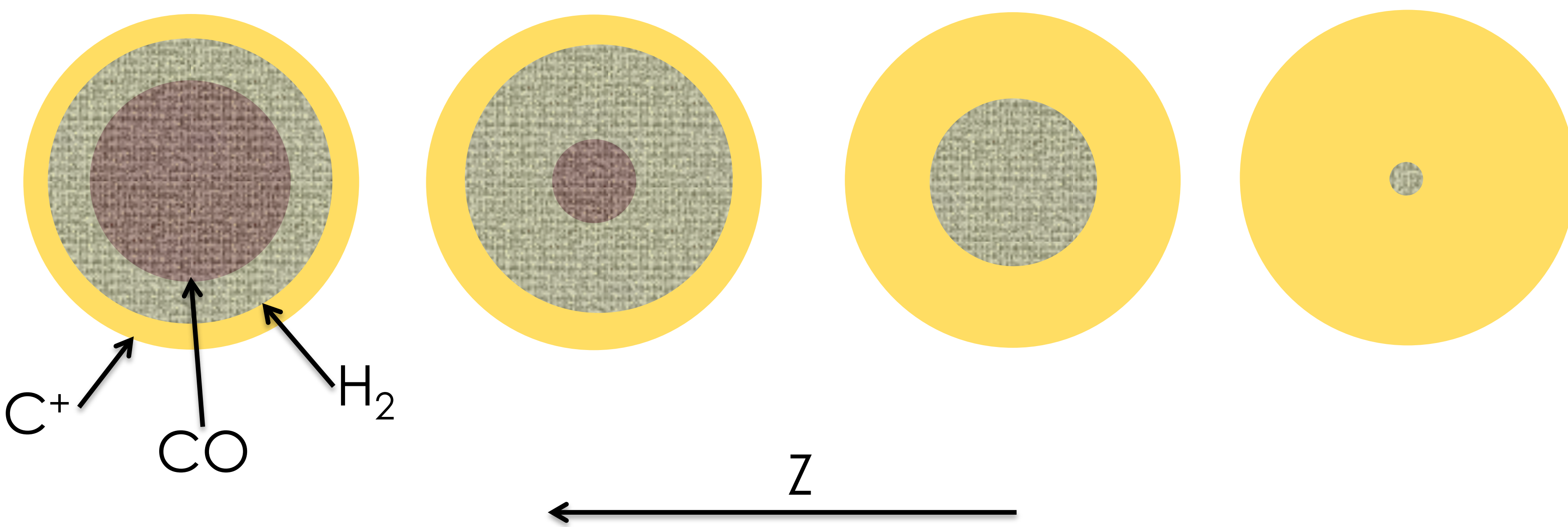
3 PDR Structure: H_2, HI, CII, and CO

Dust controls UV extinction and physical sizes of regions



3 CO and H_2 surfaces shrink with decreasing Z

Dropping metallicity pushes H_2 in, CO in even faster

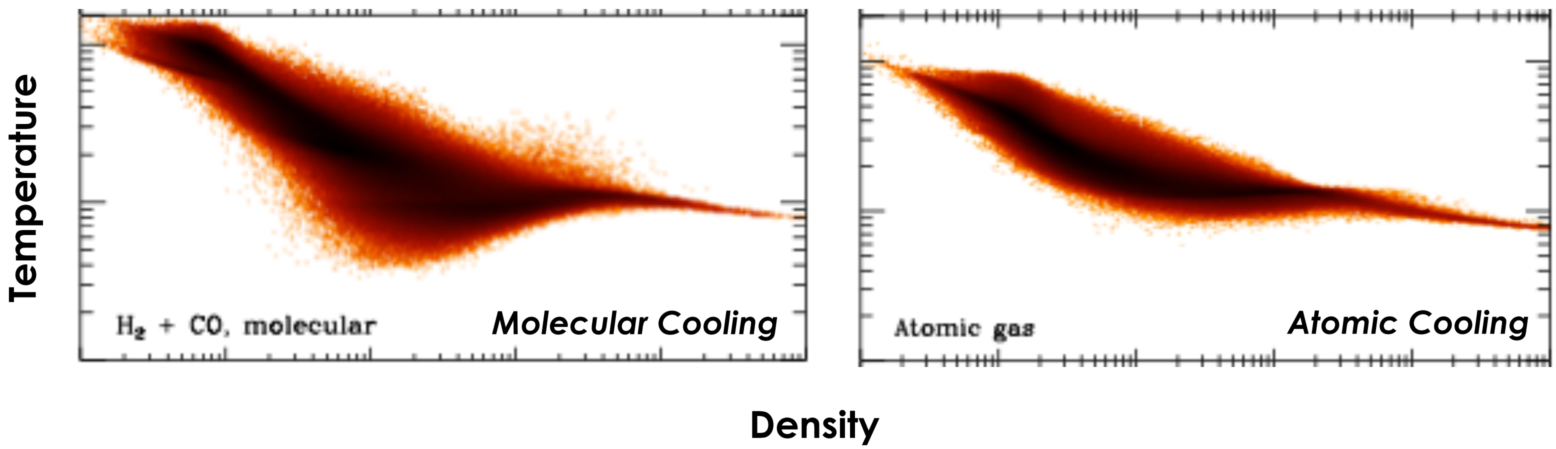


MALONEY & BLACK (1988), BOLATTO+ (1999), RÖLLIG+ (2006), BOLATTO+ (2013)

3 PDR Structure: H_2, HI, CII, and CO

Being atomic and not molecular doesn't prohibit cold gas

Physical conditions similar with molecular and atomic cooling

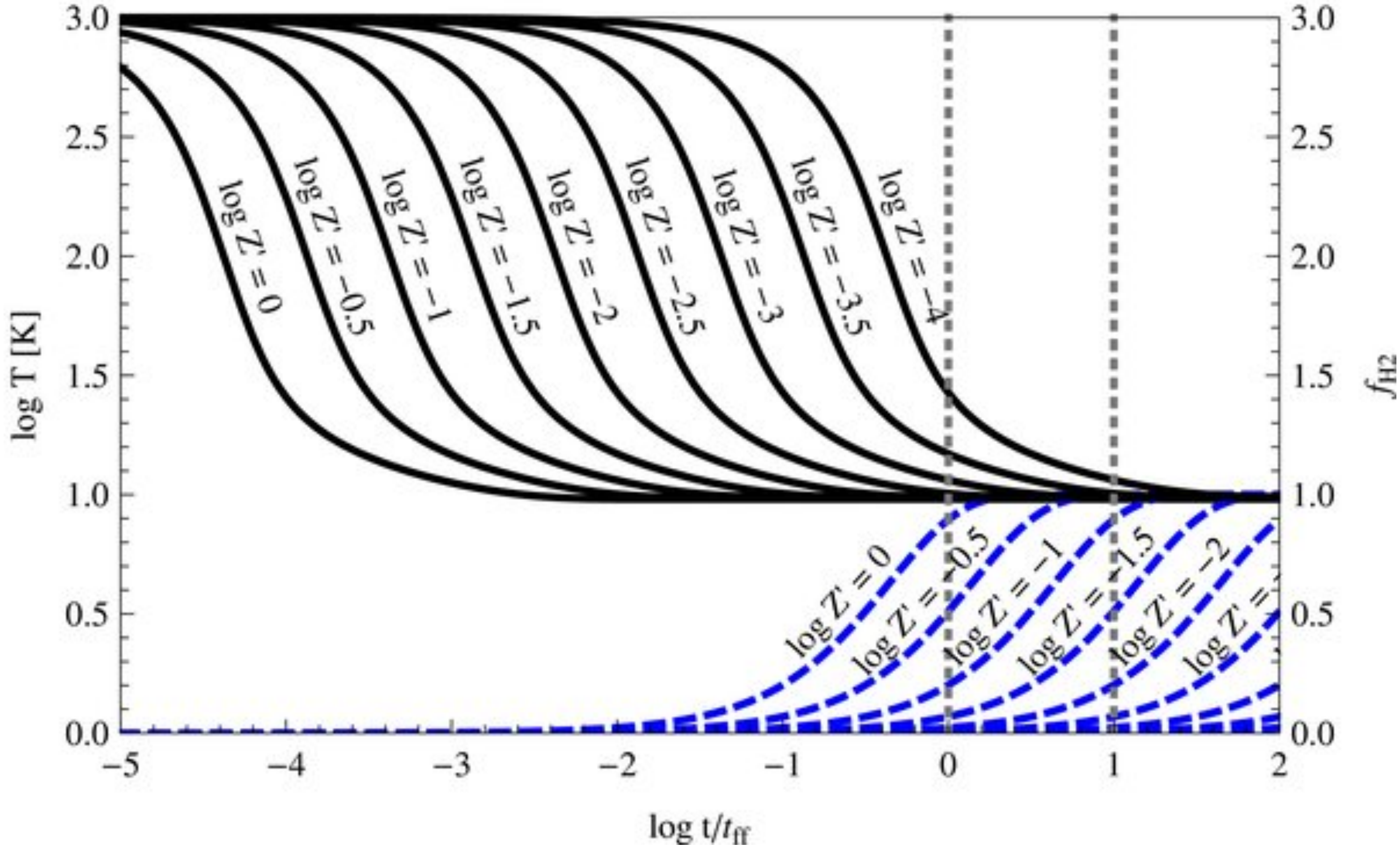


GLOVER & CLARK (2010, 2012)

3

Stars can form before molecules pervade

At low enough metallicity, stars may form before molecules dominate



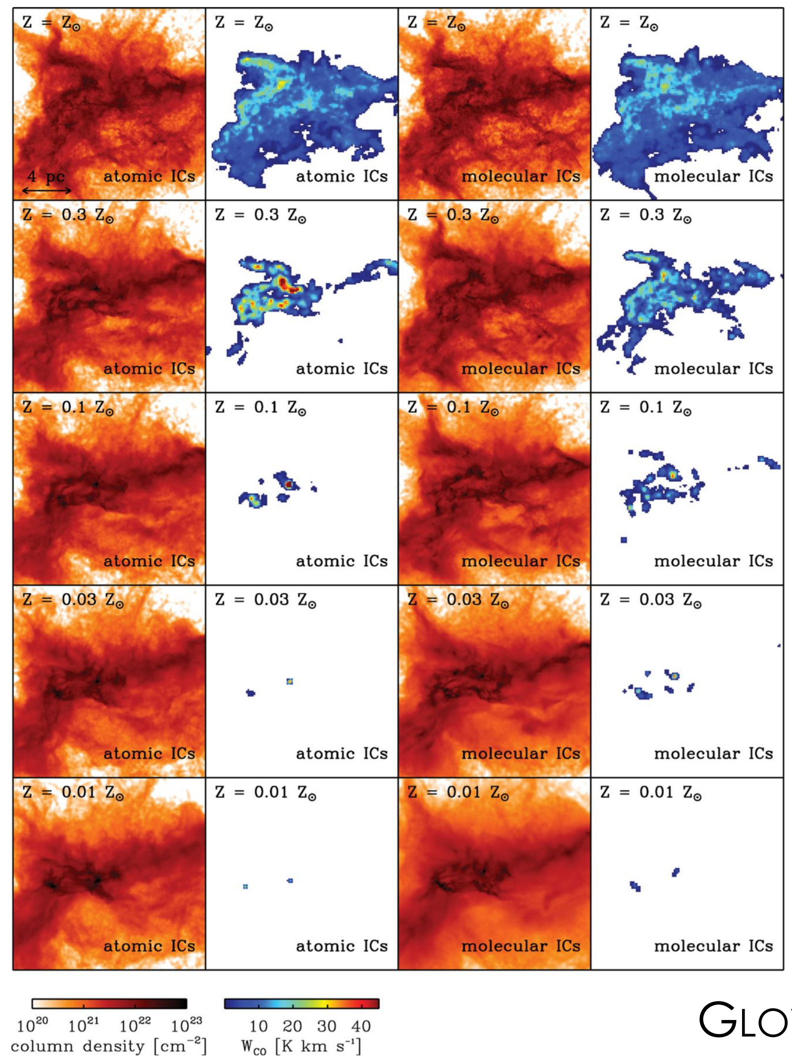
Temperature

Time (in free fall times)

KRUMHOLZ (2012)

3 PDR structure confuses CO observations

Observing these effects complicated by our tracers.

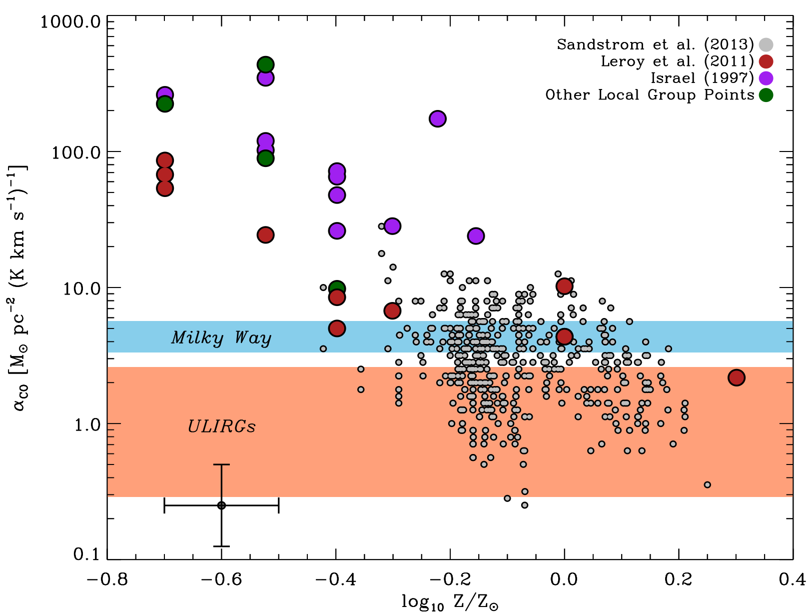


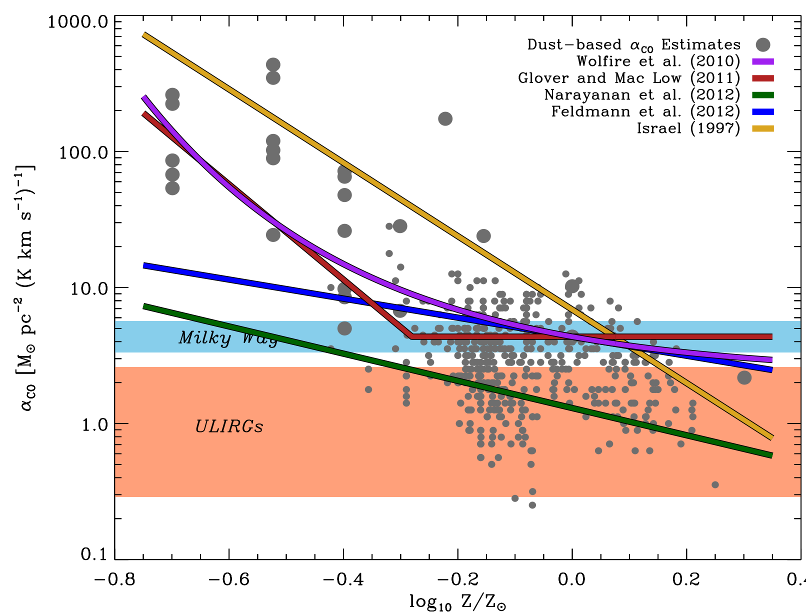
GLOVER & CLARK (2012)

3 PDR structure confuses CO observations

Shielding with constant surface density (Wolfire et al. 2010)

$$\sim 1.5 \exp\left(\frac{-0.4}{DGR' \, \Sigma_{100}}\right)$$





BOLATTO, WOLFIRE, & LEROY (2013), SANDSTROM ET AL. (2012)

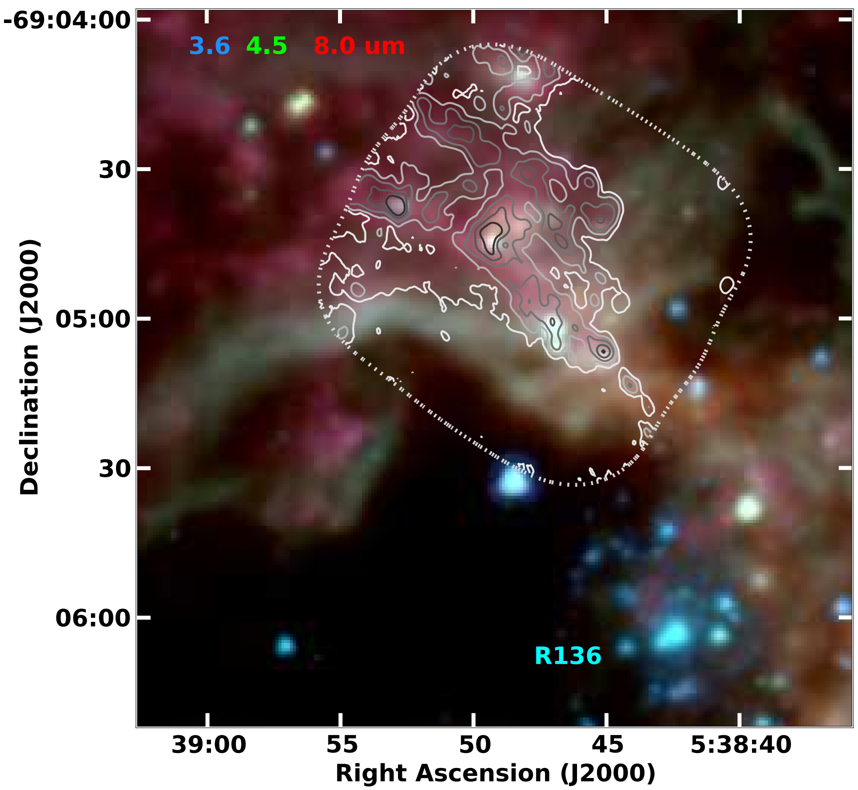
3

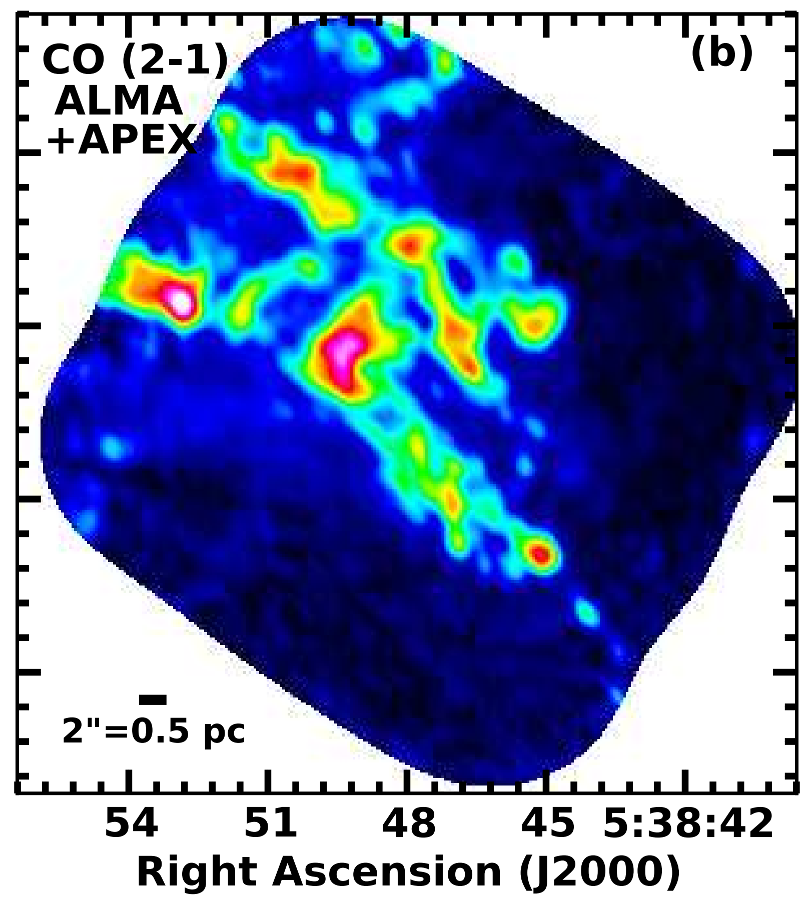
PDR Structure: H_2, HI, CII, and CO

- Dust abundance affects PDR structure
- Relative sizes of H_2, HI, CO, CII regions change
- HI can cool to star forming temperatures
- Conversion factor remains a challenging issue
- α_{CO} and f_{mol} hard to disentangle observationally

4 Molecular clouds at low metallicity.

Less diffuse emission, individual clumps (100-1000 M_{sun}) resolved.

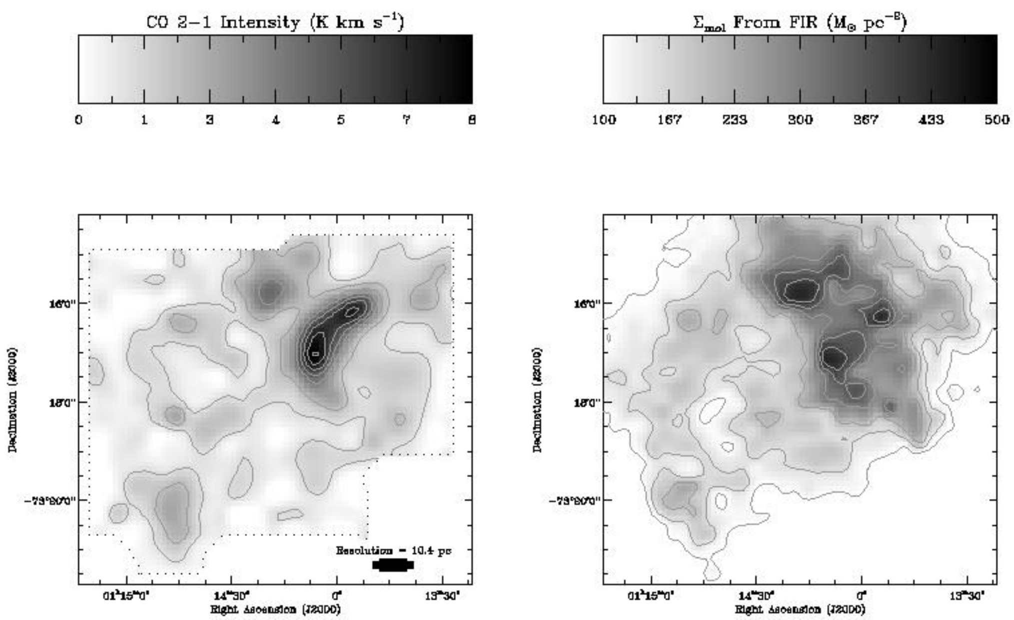




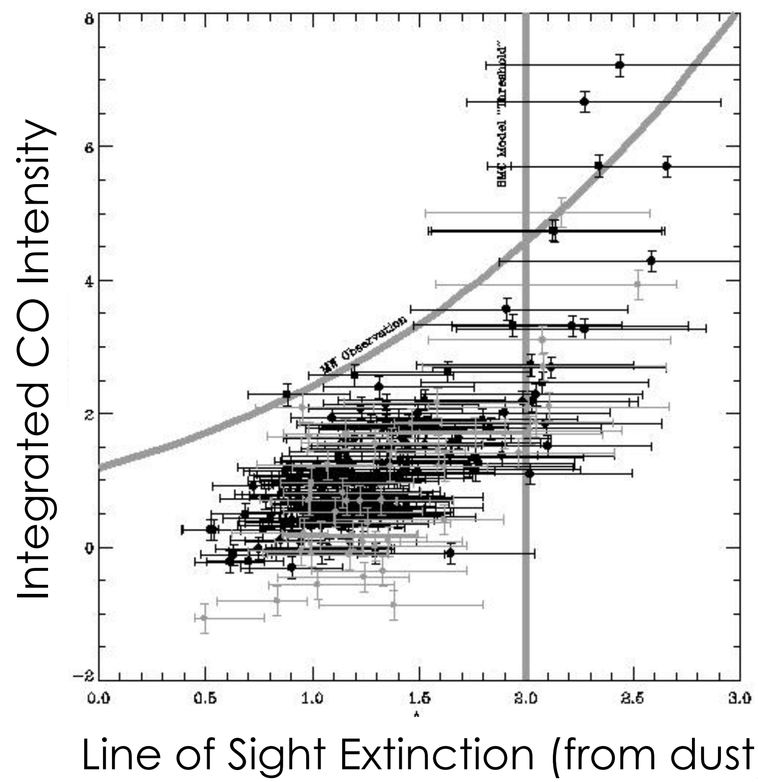
INDEBETOUW ET AL. (SUBMITTED)

4 Molecular clouds at low metallicity.

Possible to resolve PDR structure comparing dust, CO, HI, A_V



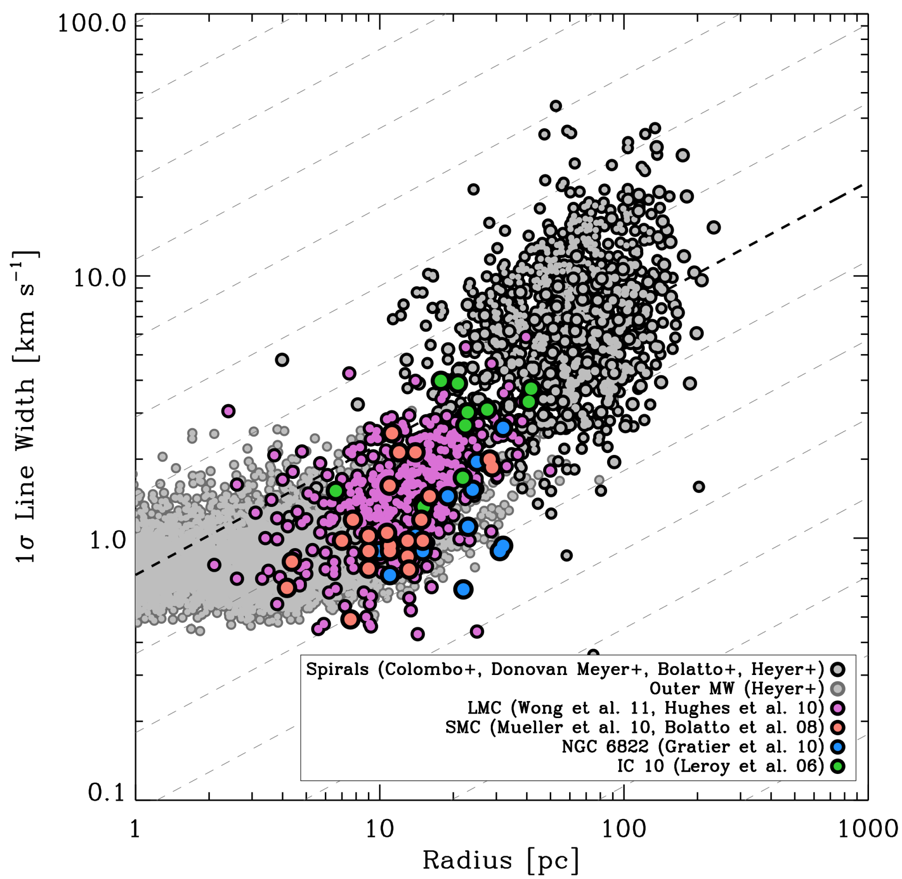
Independent line of sights



LEROY ET AL. (2009), ROMAN-DUVAL ET AL. (2010), ROMAN-DUVAL ET AL. (IN PREP)

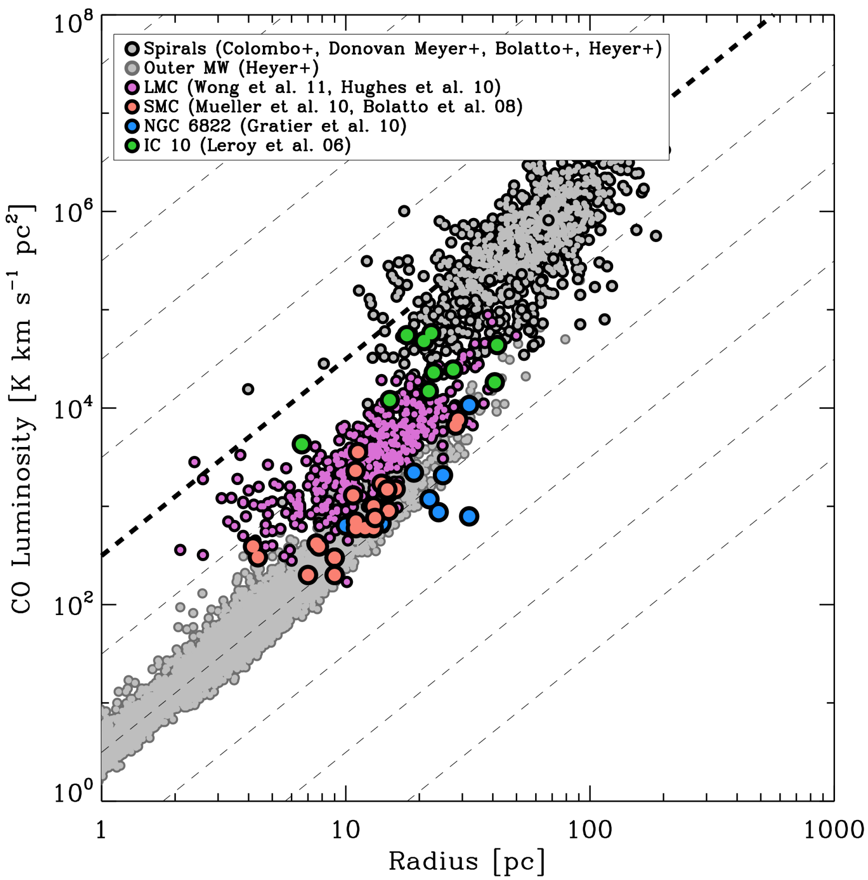
4 Molecular clouds at low metallicity.

Cloud populations extend GMCs into diffuse MW gas



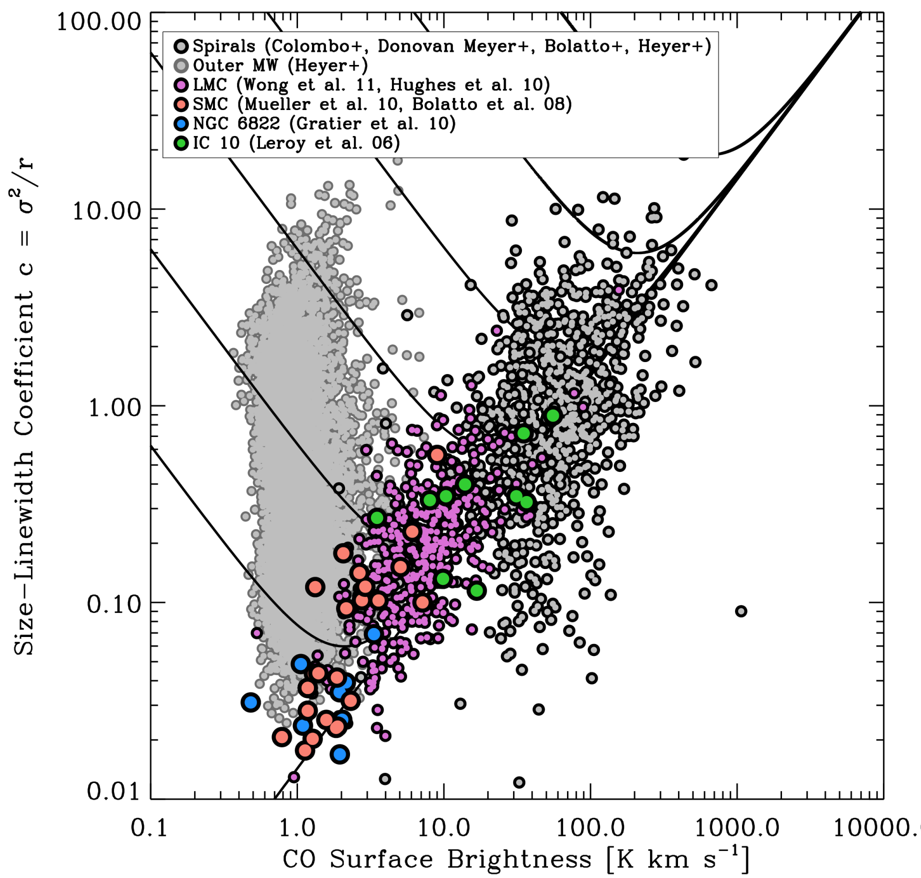
4 Molecular clouds at low metallicity.

Surface brightness lower at low metallicty



4 Molecular clouds at low metallicity.

Mostly consistent with lower surface density, still bound clouds



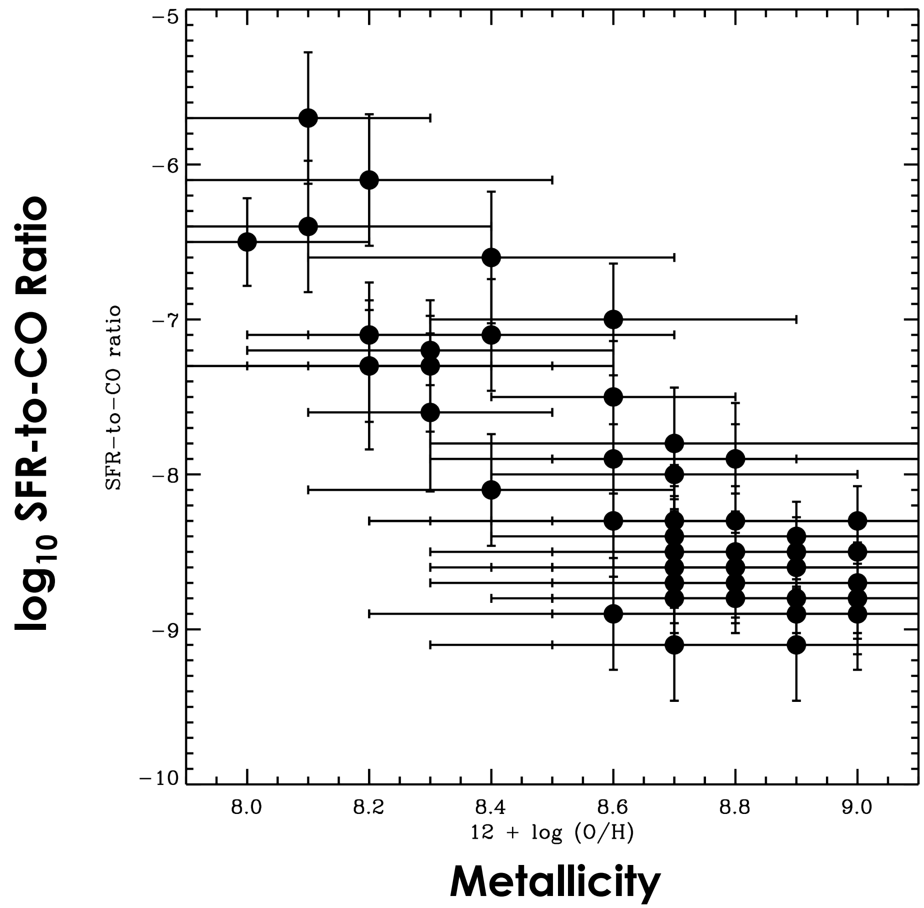
4 Molecular clouds at low metallicity.

- ALMA resolves pc-scale clumps near 30 Dor
- Resolved dust-based H_2 and CO show PDR
- Low-z Local Group clouds extend spiral scalings
- Lower CO surface brightness
- Consistent with bound, low surface density clouds

5 What to look for next…

5 Statistics, populations in SFR/CO

So far we have bright, low hanging fruit
Robust samples across a range of redshifts…

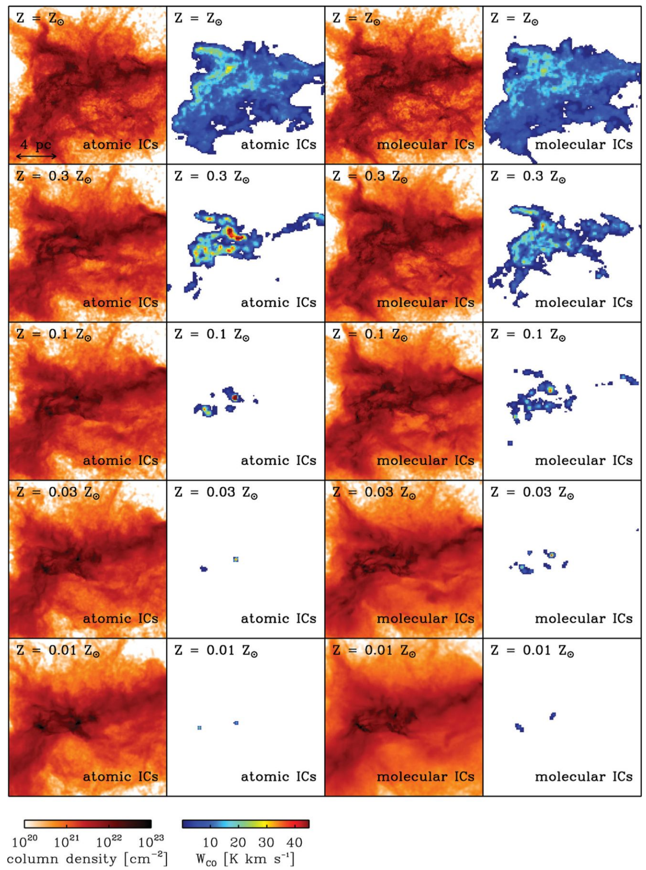


KRUMHOLZ, LEROY, AND MCKEE (2011), SCHRUBA ET AL. (2012), GENZEL ET AL. (2012)

5

Resolve, overconstrain clouds

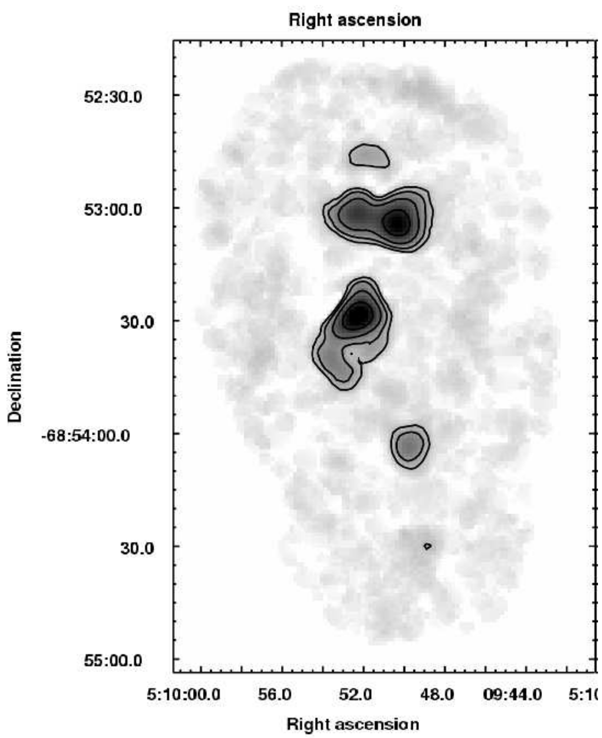
Combining CII, dust, CO, HI at high resolution
"Milky Way" view of low metallicity clouds…



INDEBETOUW ET AL. (SUBM.), ROMAN-DUVAL ET AL. (IN PREP)

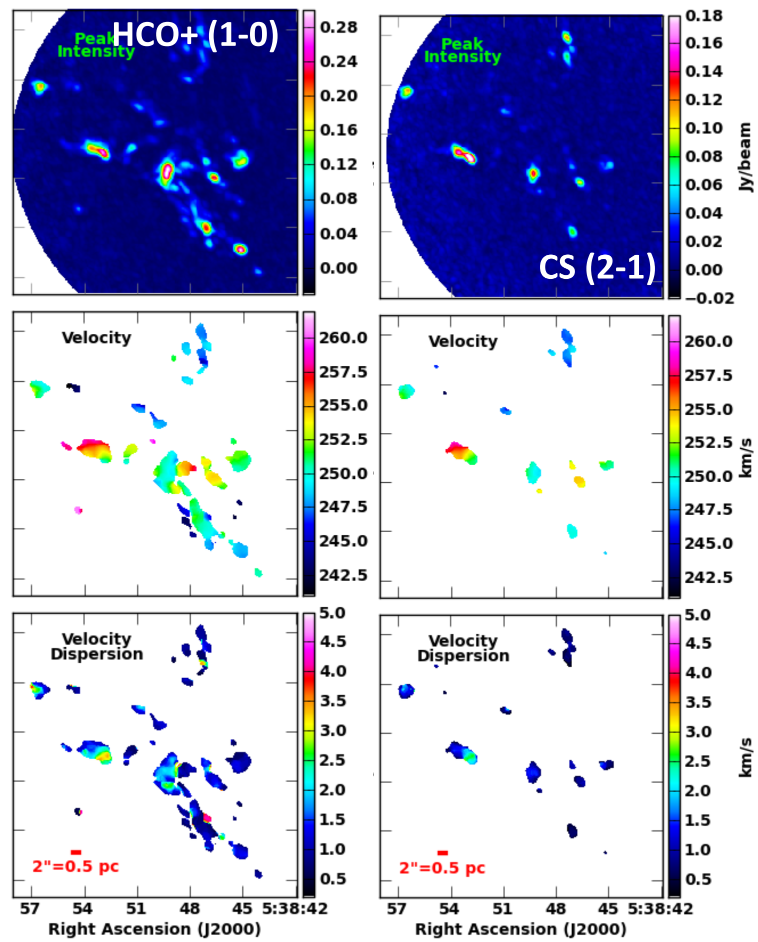
5 Beyond CO at low metallicity

Molecules beyond CO have been challenging beyond the LMC…
Physical conditions, dense gas fraction at low metallicity



HCO+ in the LMC:

SEALE, OTT, WONG, ET AL. (2012)



Brogan et al. (in pre.)