The ISM at low Z at low z

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Molecules and Dust as Fuel to Star Formation,
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Outline

- Low Metallicity Galaxies
- Where are the Molecules
- How it matters

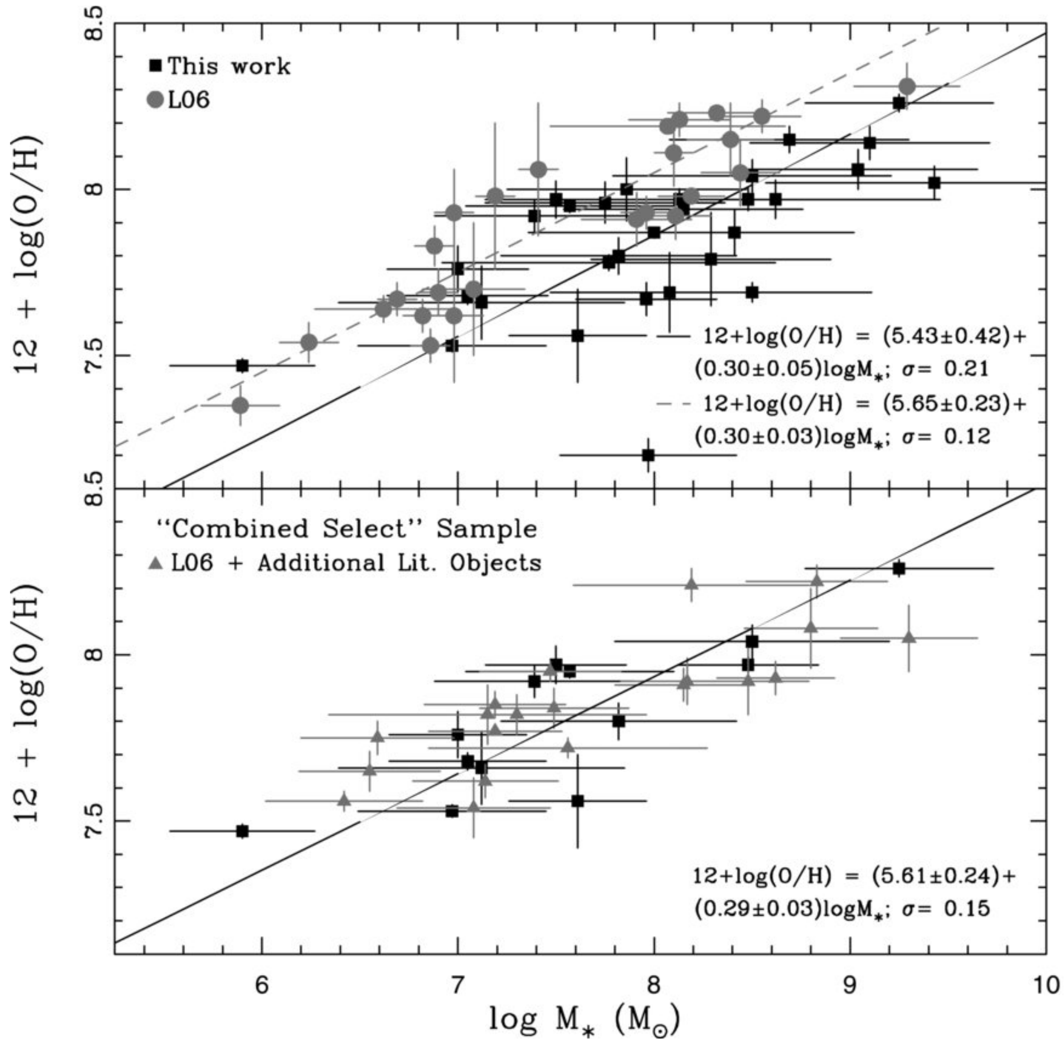
Star Formation at low Z

- Observations of SF gas at low Z in low z galaxies give promise to better understand SF at low Z at high z (but with significant caveats).
- The galaxies of interest are the dwarf irregulars (i.e., not the dSphs).
- The low Z dIs are typically very low mass and typically are found in low density environments.
- The lessons learned may be widely applicable if star formation is predominantly a local process.

Example: Leo P

Leo P, Distance = 1.6 Mpc, discovered in ALFALFA blind HI survey
ISOLATED: 400 kpc from the next nearest dwarf (McQuinn + 2015)

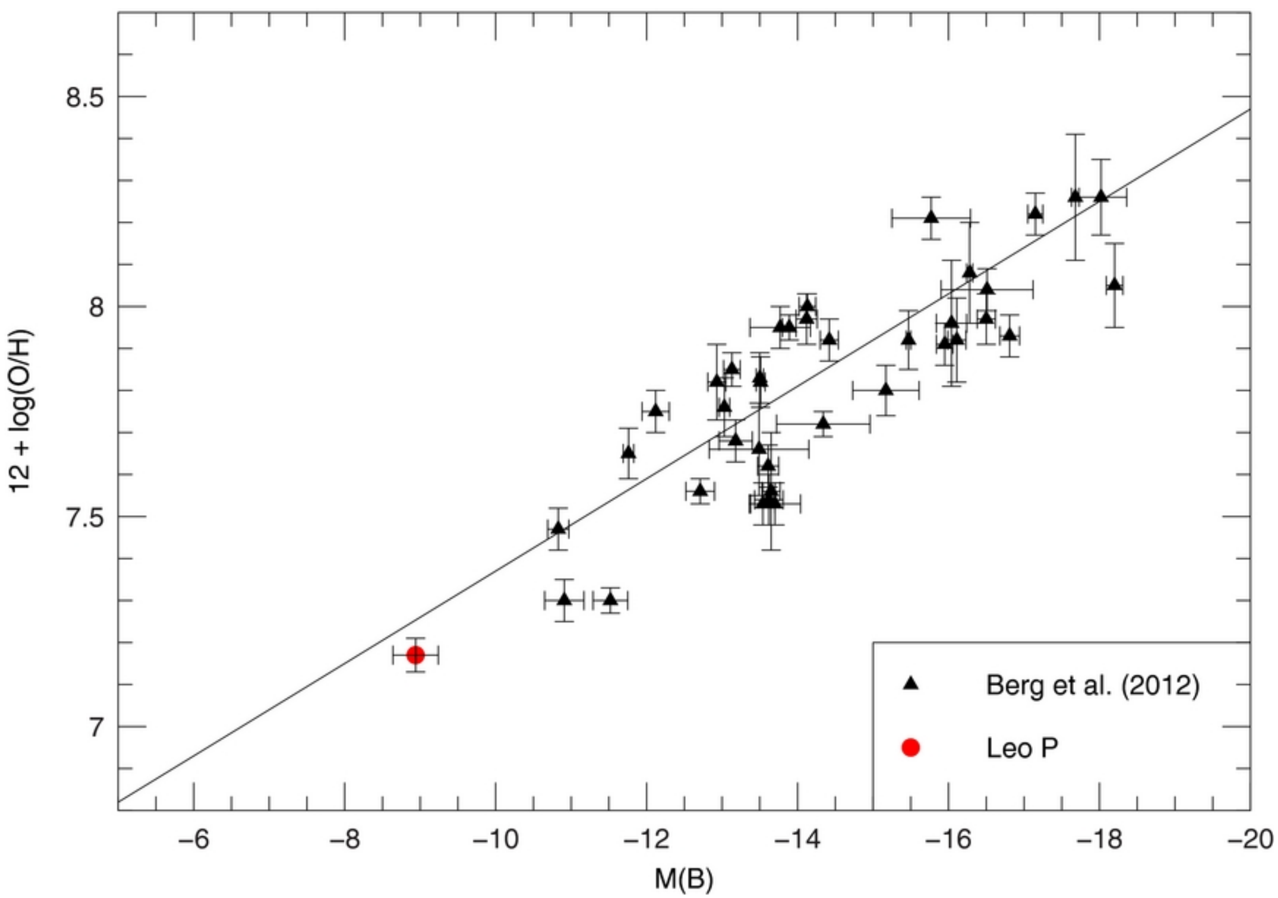
Low Metallicity Dwarfs



From: Berg et al. (2012)

From the Local Volume Legacy Survey, using only galaxies with reliable distances (TRGB or Cepheids) the relationship between stellar mass and ISM metallicity in actively star forming galaxies shows a strong correlation with a very small intrinsic dispersion (0.08 dex in log O/H).

Mass/Metallicity Relationship

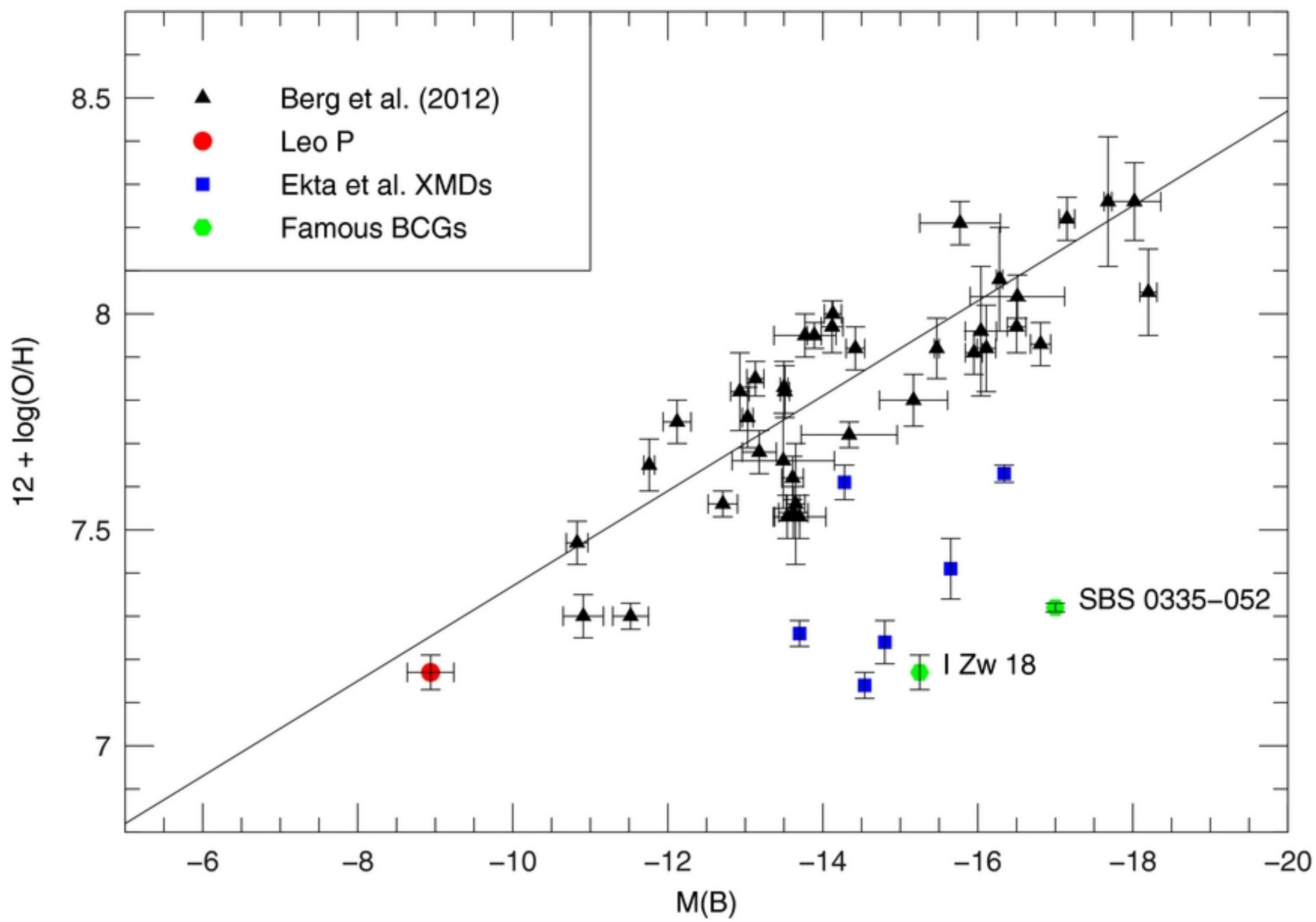


EDS et al. (2013)

Because of the small dispersion, the L/Z relationship is a great predictor of O/H in dwarfs.

Leo P was discovered by the Arecibo ALFALFA blind HI survey.

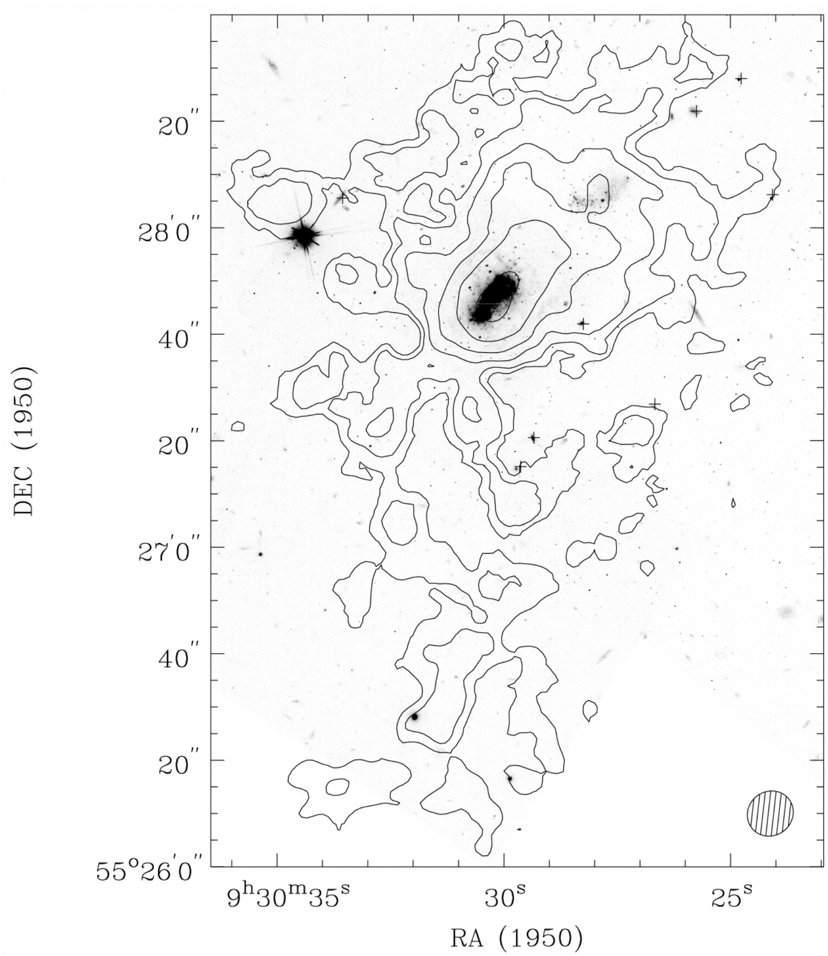
Dwarfs: Mass/Metallicity Relationship

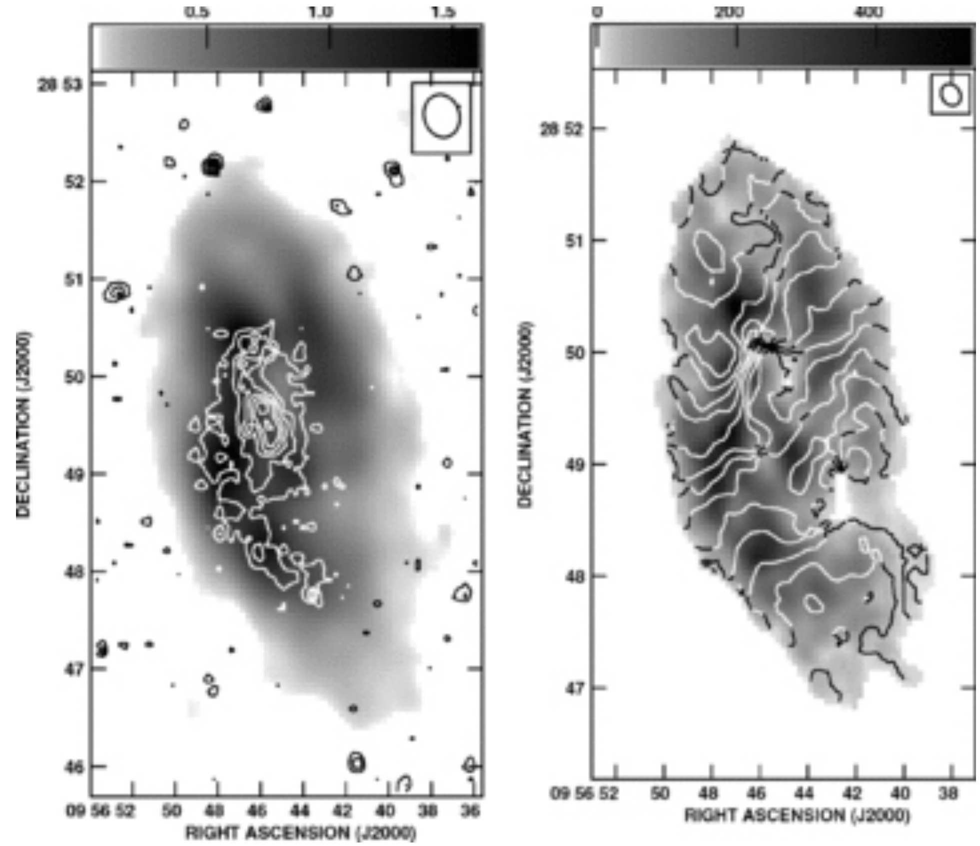


From HI imaging Ekta et al. (2006+) show that the high luminosity, low abundance outliers exhibit evidence of recent interactions, explaining both the elevated SFRs and the low Z due to recent infall of pristine gas.

EDS et al. (2013)

Dwarfs: Mass/Metallicity Relationship





HI imaging of IZw18 (van Zee+ 1998) and DDO 68 (Ekta+ 2008) showing that the high luminosity, low abundance outliers have very disturbed HI morphologies.

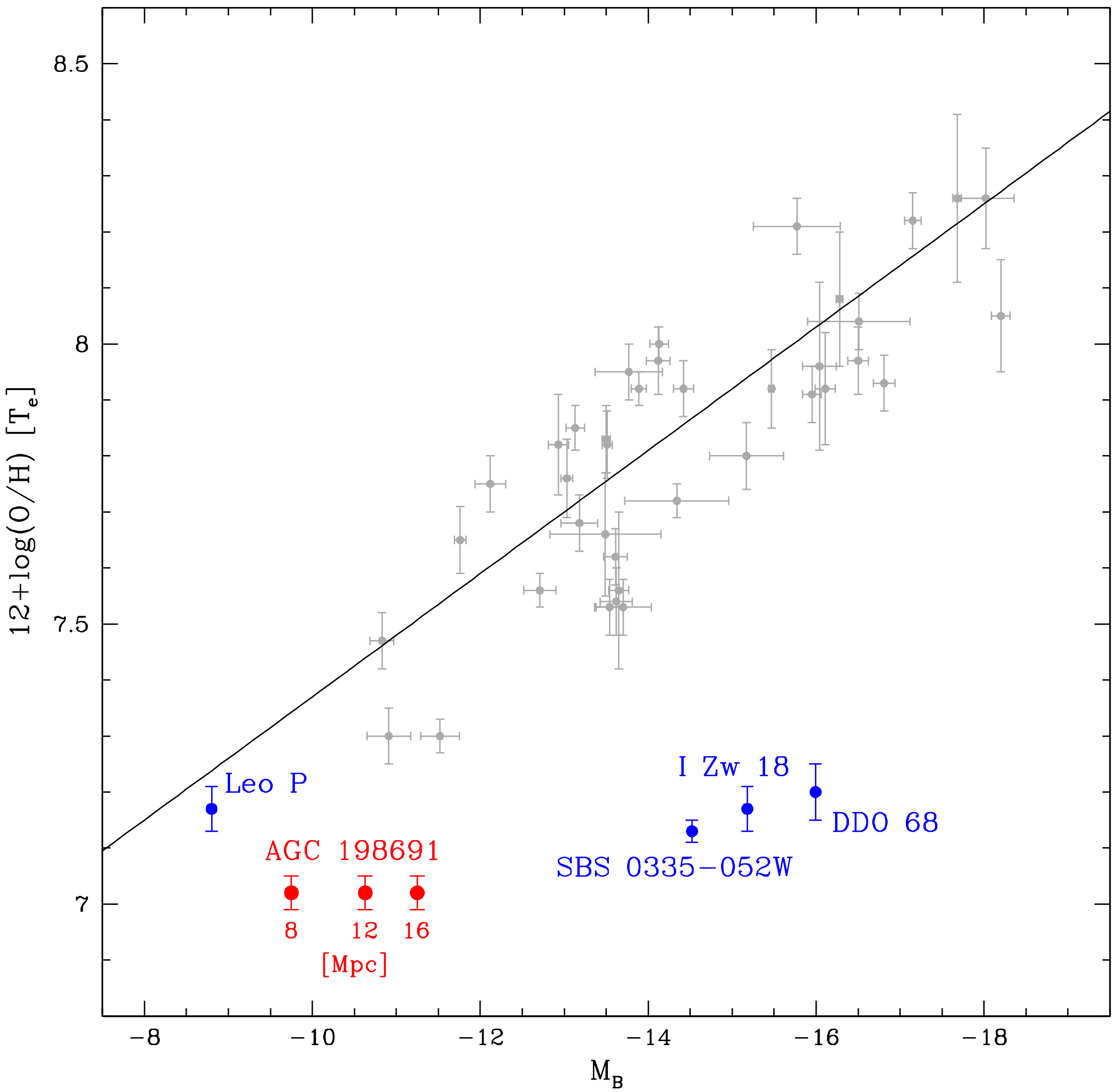
Dwarfs: Mass/Metallicity Relationship

- Paradox:
- Low luminosity dwarfs are the most common galaxies
- Extremely metal-poor galaxies are very rare
- Solution: High surface brightness star formation events are very rare in extremely low mass galaxies

Finding Low Metallicity dIs

- Low mass galaxies are low surface brightness.
- => SDSS is not a promising place to search.
- Very rare in SDSS spectral catalog; search for blue diffuse dwarfs (James et al. 2015)
- HI blind surveys (e.g., ALFALFA) are successful (e.g., AGC 198691) and hold promise
- Future low surface brightness optical surveys will be successful

Mass/Metallicity Relationship



Because of the small dispersion, the L/Z relationship is a great predictor of O/H in dwarfs.

Hirschauer et al. (2016)

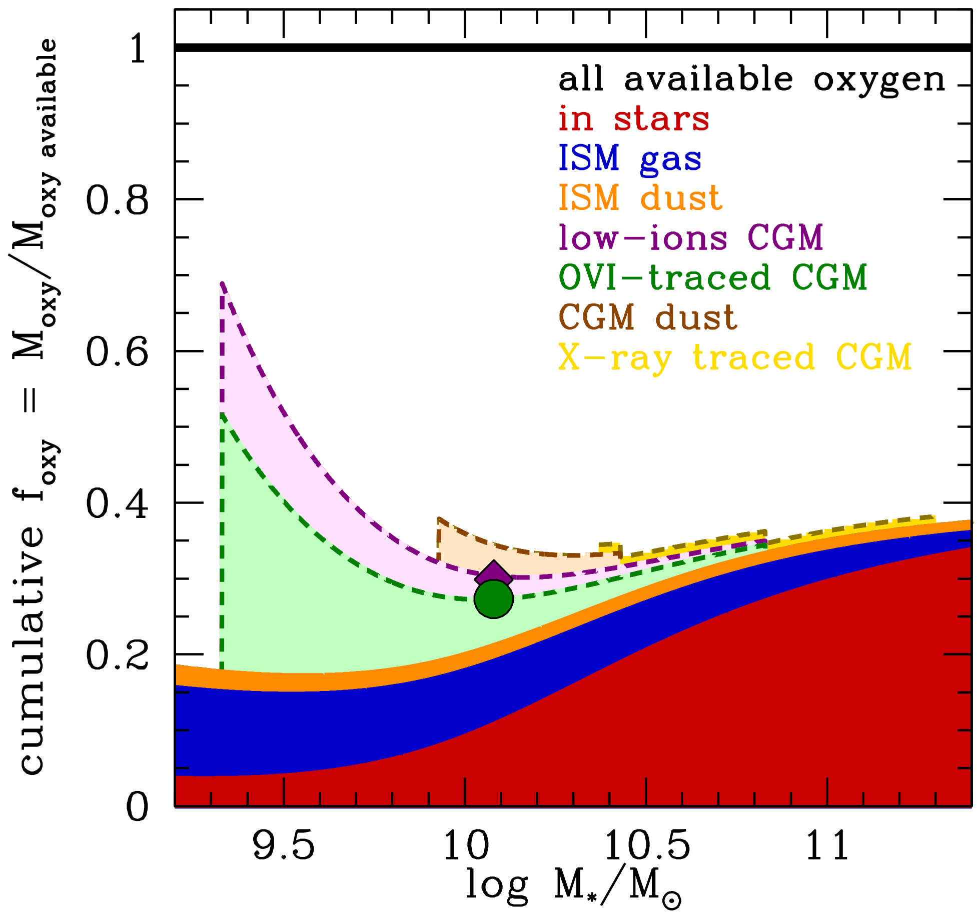
Dwarfs: Metallicity Dispersion

- Very little evidence of measurable oxygen abundance dispersions in low luminosity dwarfs.
- Kobulnicky et al. (1996+) detailed studies of NGC 4214, NGC 4449 searched for enrichment from SNe and WR stars and found none.
- Because of the nearly solid body rotation, pollution should be long lived. Absence of dispersion implies enrichment happens globally through cooling of a well-mixed, hot phase.

Why low Z?

- Low Z implies either inefficient production of metals (SF) or inefficient retention of metals (winds). High gas mass fractions and low effective yields imply both are important (Dalcanton 2007).
- Very interesting result from Peeples+ (2014) that oxygen retained is roughly independent of galaxy mass
- In Leo P, ~4% of oxygen is retained (McQuinn+ 2016)

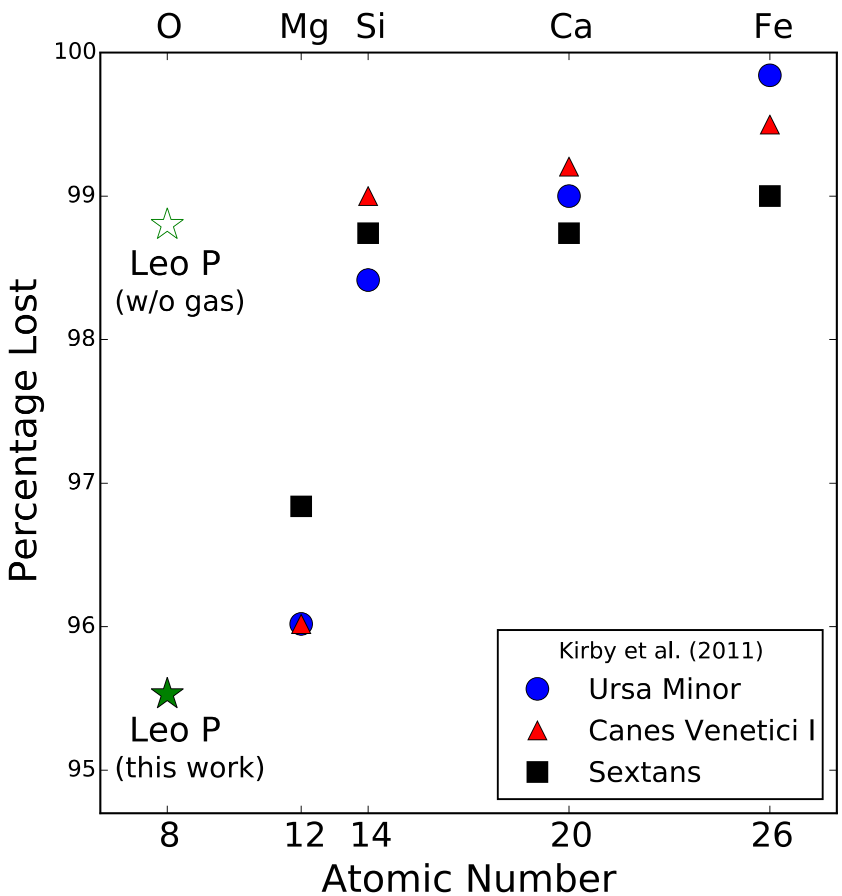
Metals: Accounting and Loss



An accounting of where the oxygen ends up as a function of mass. The surprising thing is the relatively flat total in stars +gas+dust as a function of mass (Peeples+2014).

If Leo P is representative, there is a decrease to lower masses, but not a dramatic one.

Metals: Accounting and Loss



McQuinn et al. (2016)

A comparison of the heavy elements produced by supernovae and the heavy elements retained in stars in dSphs shows almost complete loss (Kirby+ 2013).

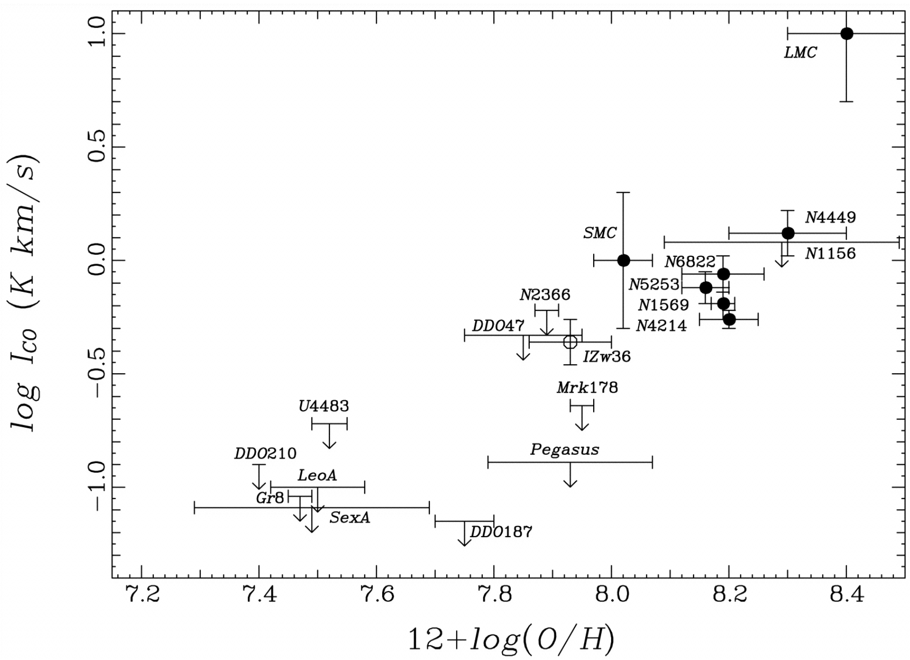
But if external forces were responsible for the quenching, the accounting is off. The similarly low mass Leo P shows a higher retention fraction.

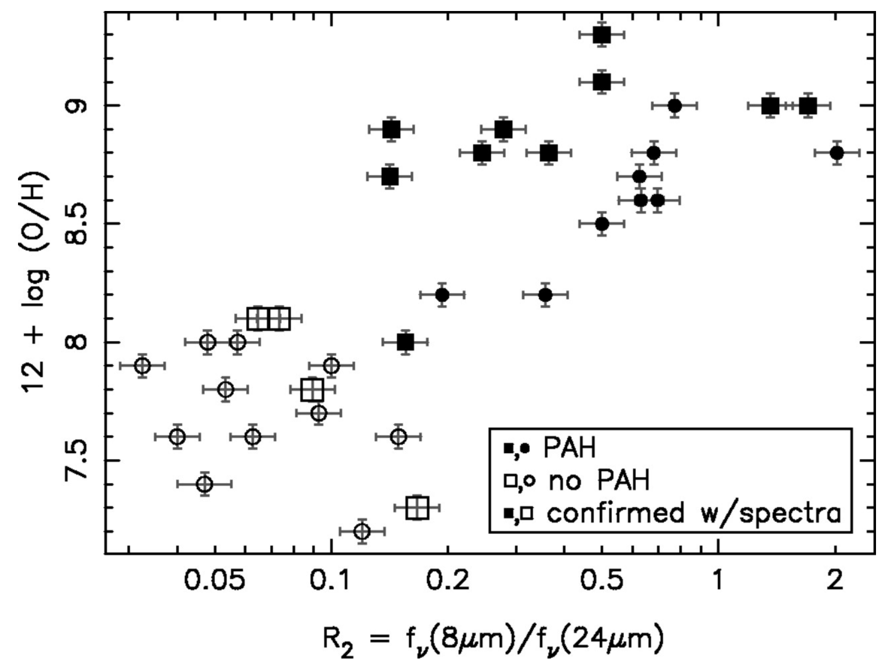
The Low Metallicity ISM:

Observing the molecular gas at low metallicity is a challenge.

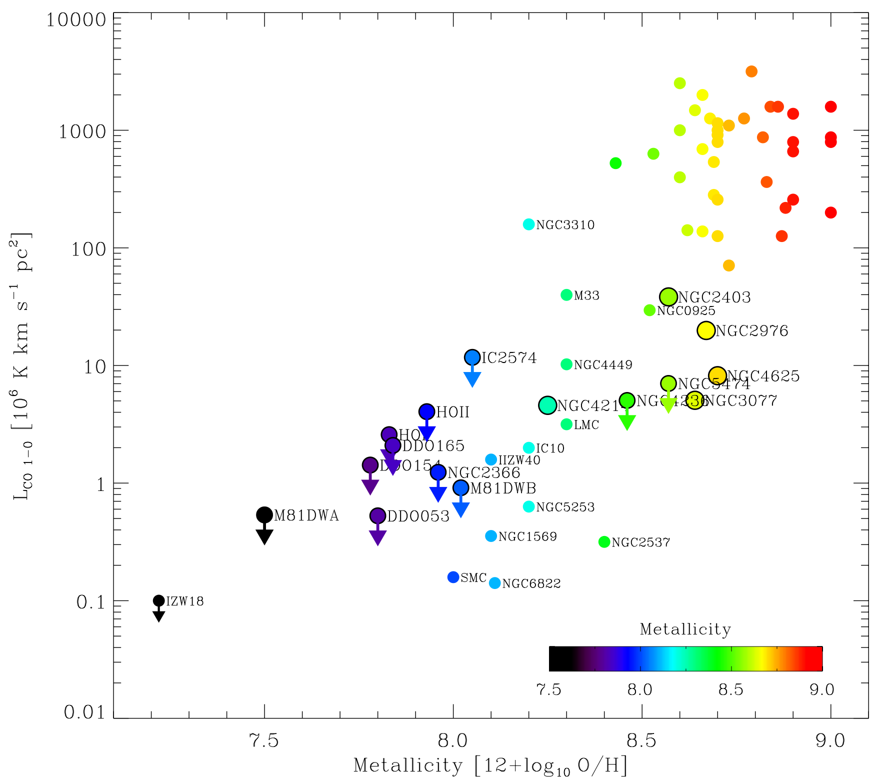
Theoretically, the very character of the ISM changes at low metallicity (e.g., Spaans & Norman 1997).

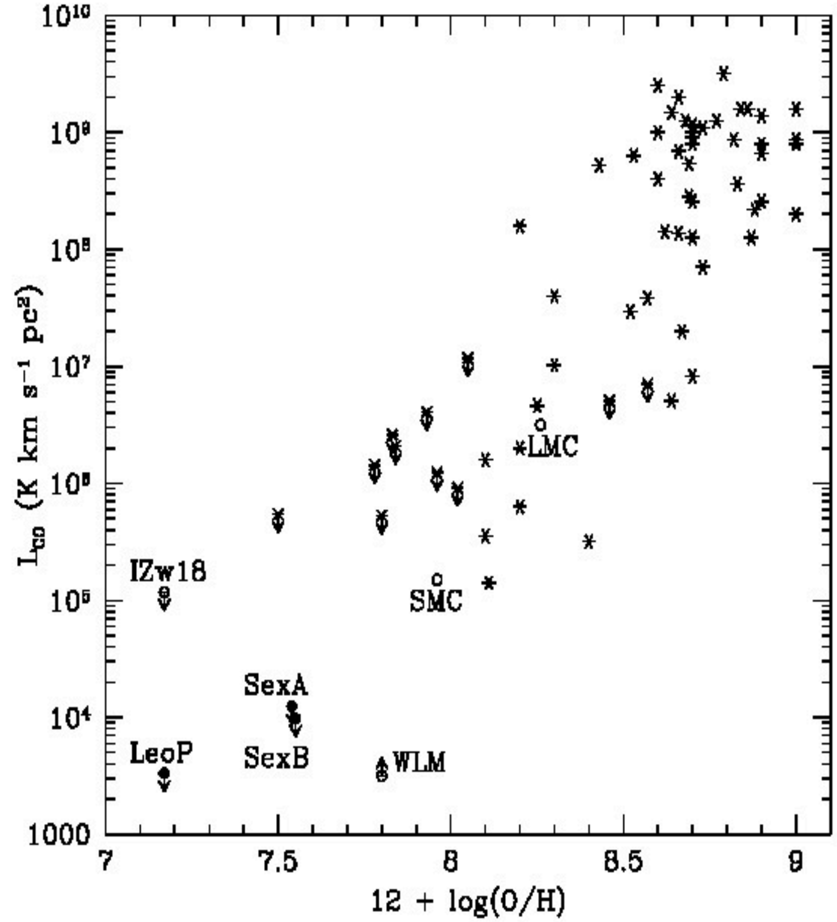
This is supported by observations showing a relative lack of CO emission (e.g., Taylor et al. 1998, Leroy et al. 2005) and a relative lack of PAH emission (Engelbracht et al. 2005, Jackson et al. 2006).





Left: Lack of CO detections below 12+log(O/H) = 8.0 (Taylor et al. 1998)
Right: Lack of PAH detections below 12+log(O/H) = 8.0 (Engelbracht et al. 2005)



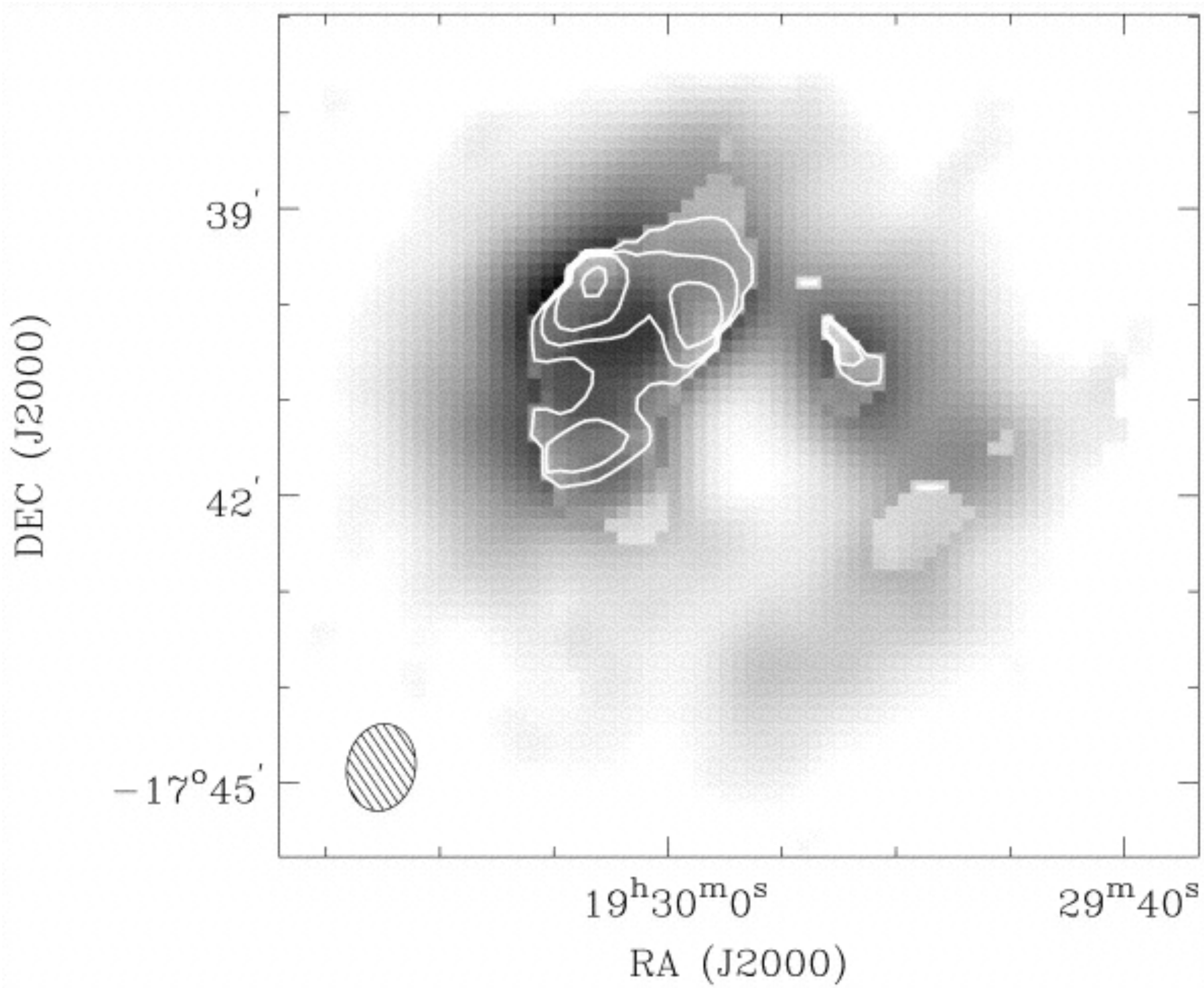


Left: Lack of CO detections below 12+log(O/H) = 8.0 (Schruba et al. 2012)
Right: An ALMA CO detection at 12+log(O/H) = 7.8 (Elmegreen et al. 2013), and CARMA non-detections at lower metallicities (Warren et al. 2015)

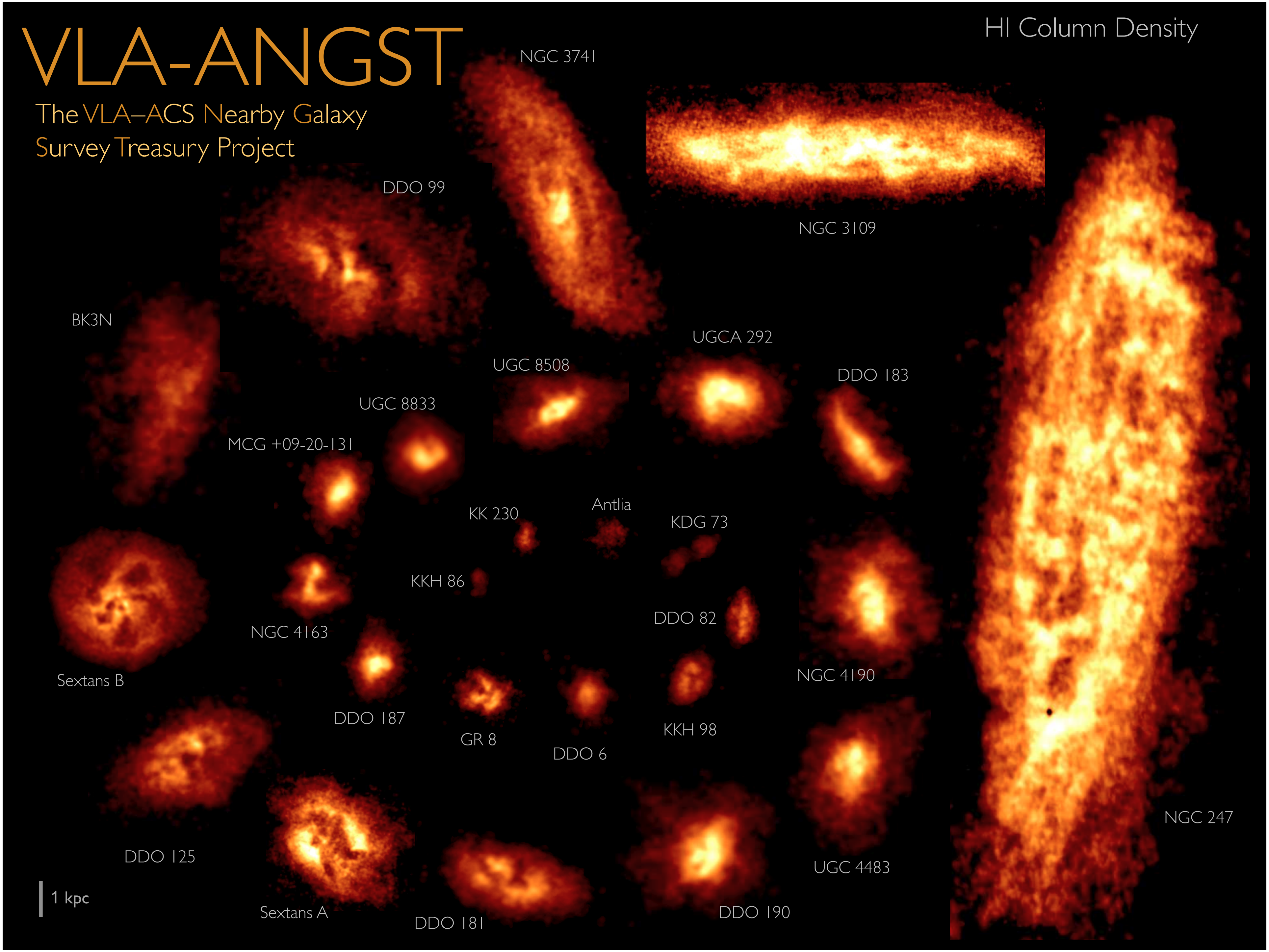
Tracing H_2 at Low Metallicity

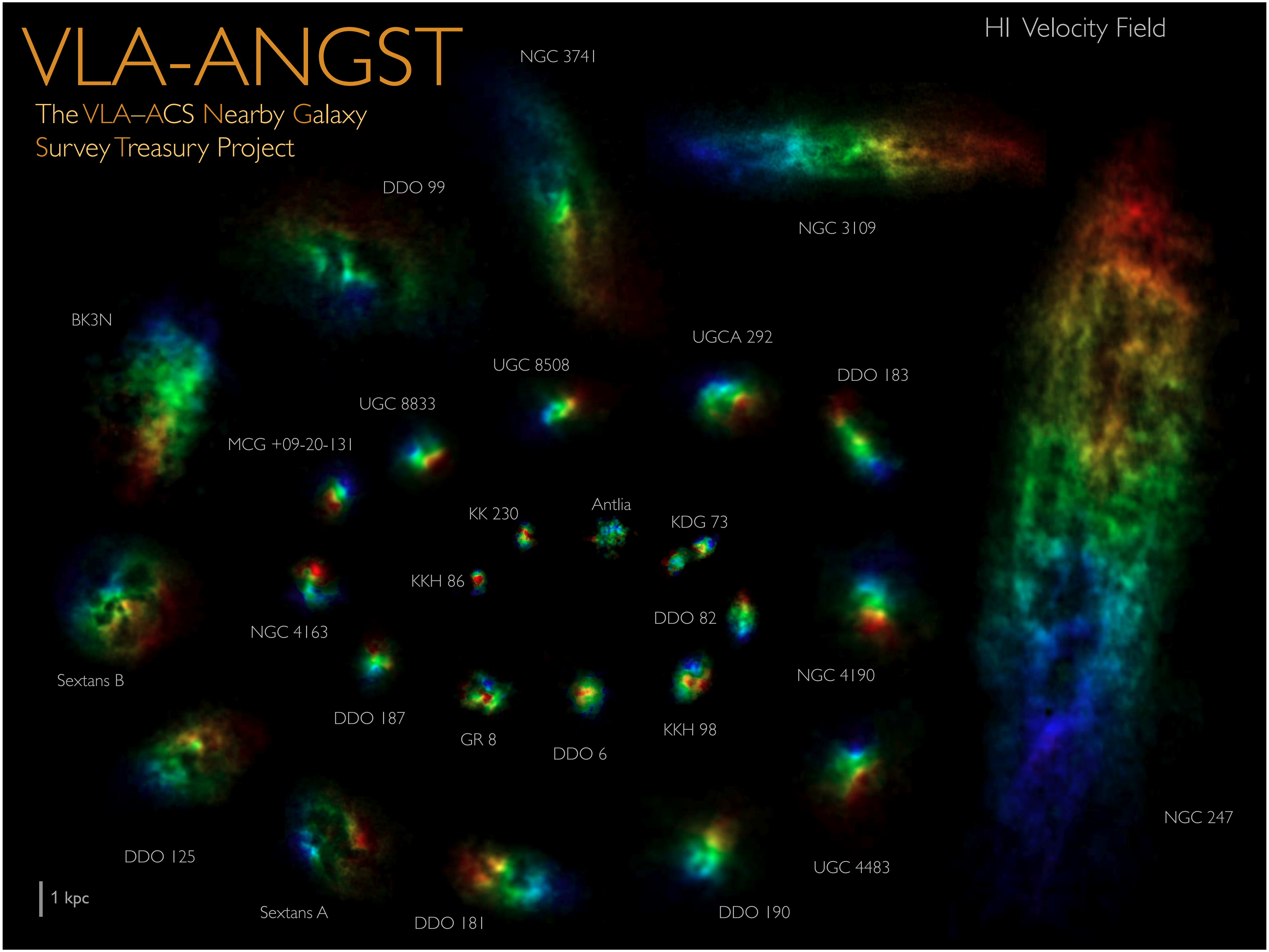
One potential method for tracing the molecular component is to identify "cold" HI emission a la Young et al. (1997), Begum et al. (2006), de Blok & Walter (2006), Ianjamasimanana et al. (2012), Warren et al. (2012).

Typically HI spectra show two components, a broad component associated with the warm ISM and a narrow component associated with the cold ISM. Does the cold ISM trace the molecular H?



HI in Sag DIG showing both broad and narrow components from Young et al. (1997) study.


VLA-ANGST
The VLA–ACS Nearby Galaxy Survey Treasury Project
HI Column Density
NGC 3741
NGC 3109
DDO 99
BK3N
UGCA 292
UGC 8508
DDO 183
UGC 8833
MCG +09-20-131
KK 230
Antlia
KDG 73
KKH 86
DDO 82
NGC 4163
Sextans B
NGC 4190
DDO 187
GR 8
DDO 6
KKH 98
NGC 247
DDO 125
UGC 4483
1 kpc
Sextans A
DDO 181
DDO 190


VLA-ANGST
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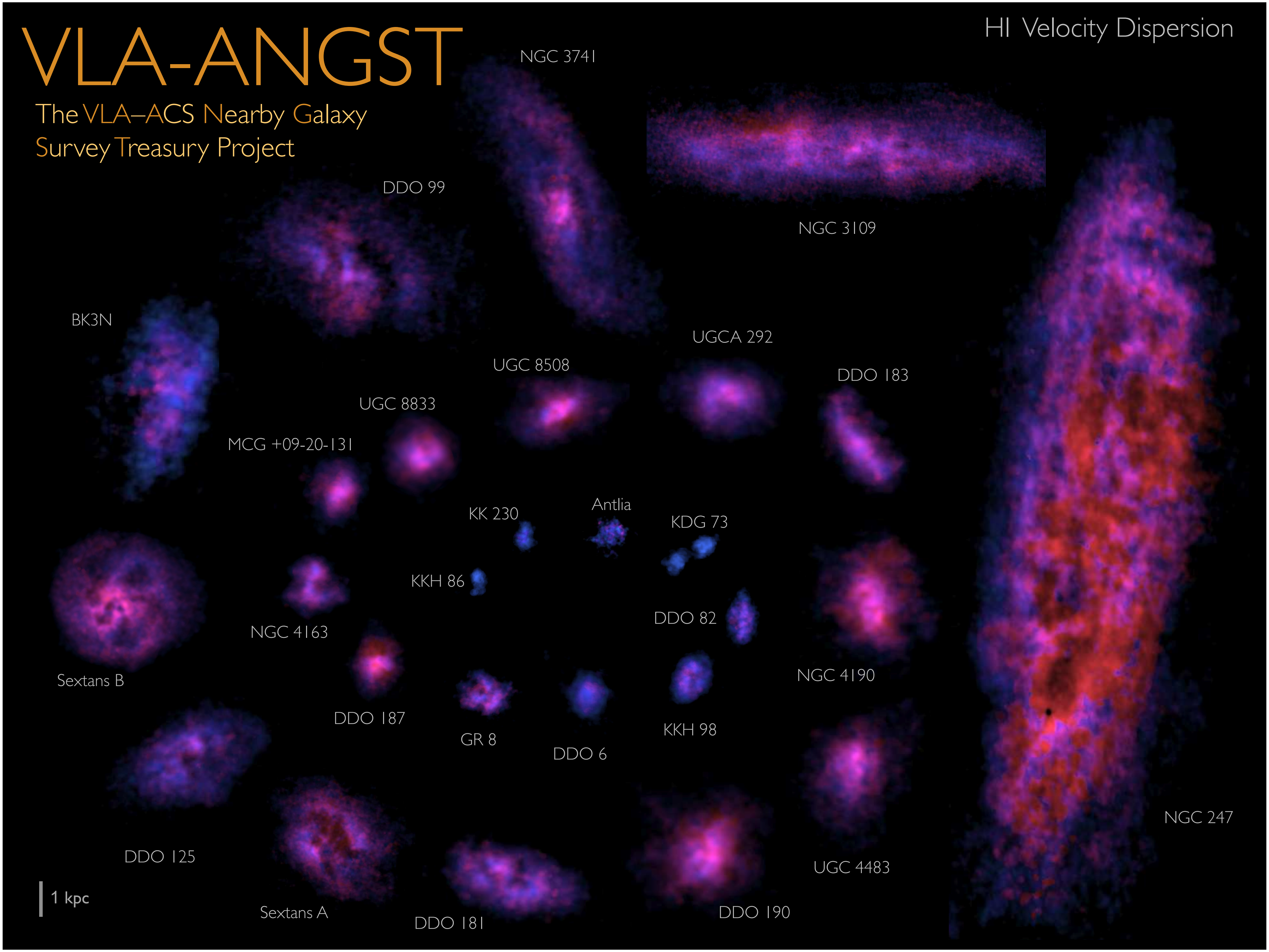

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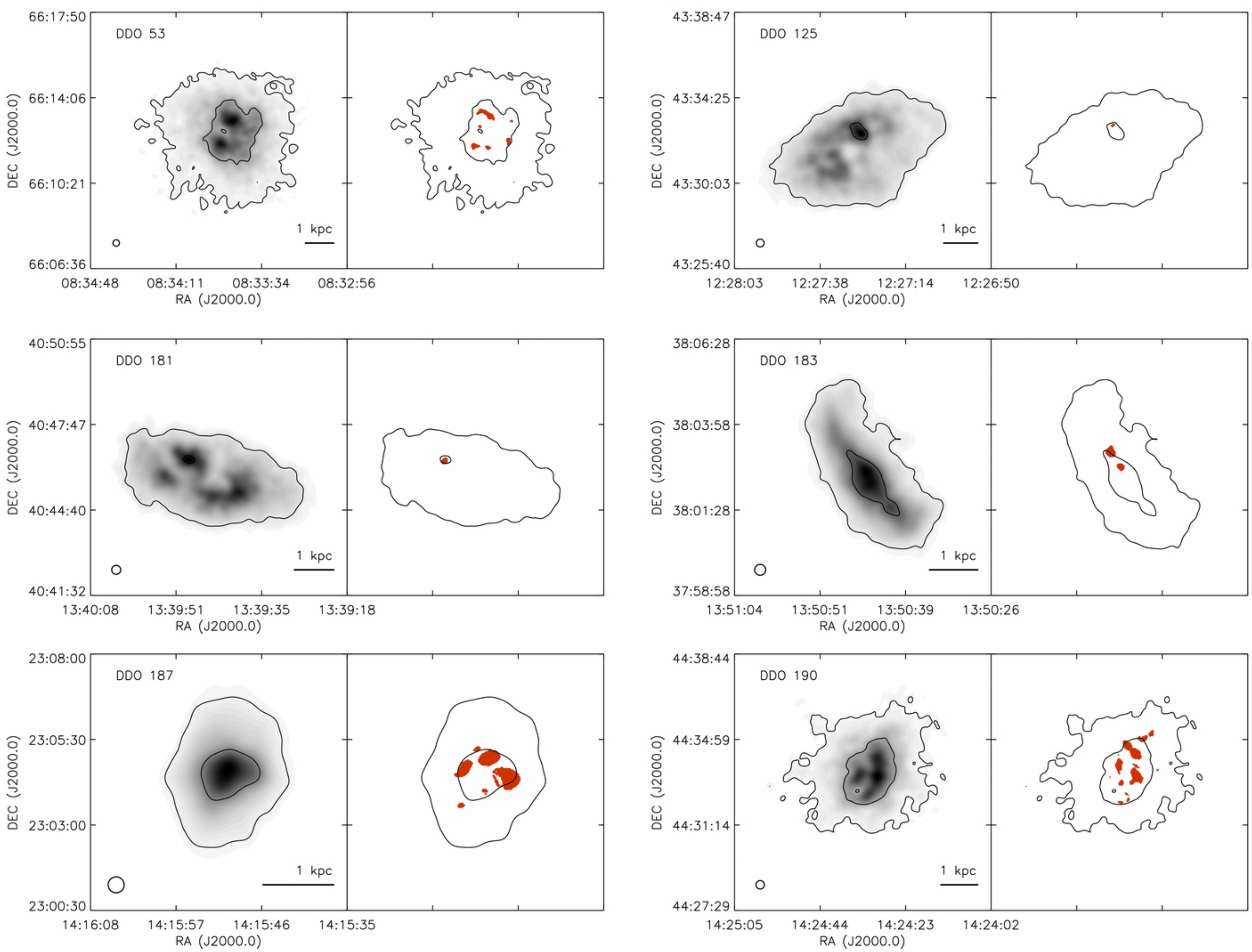
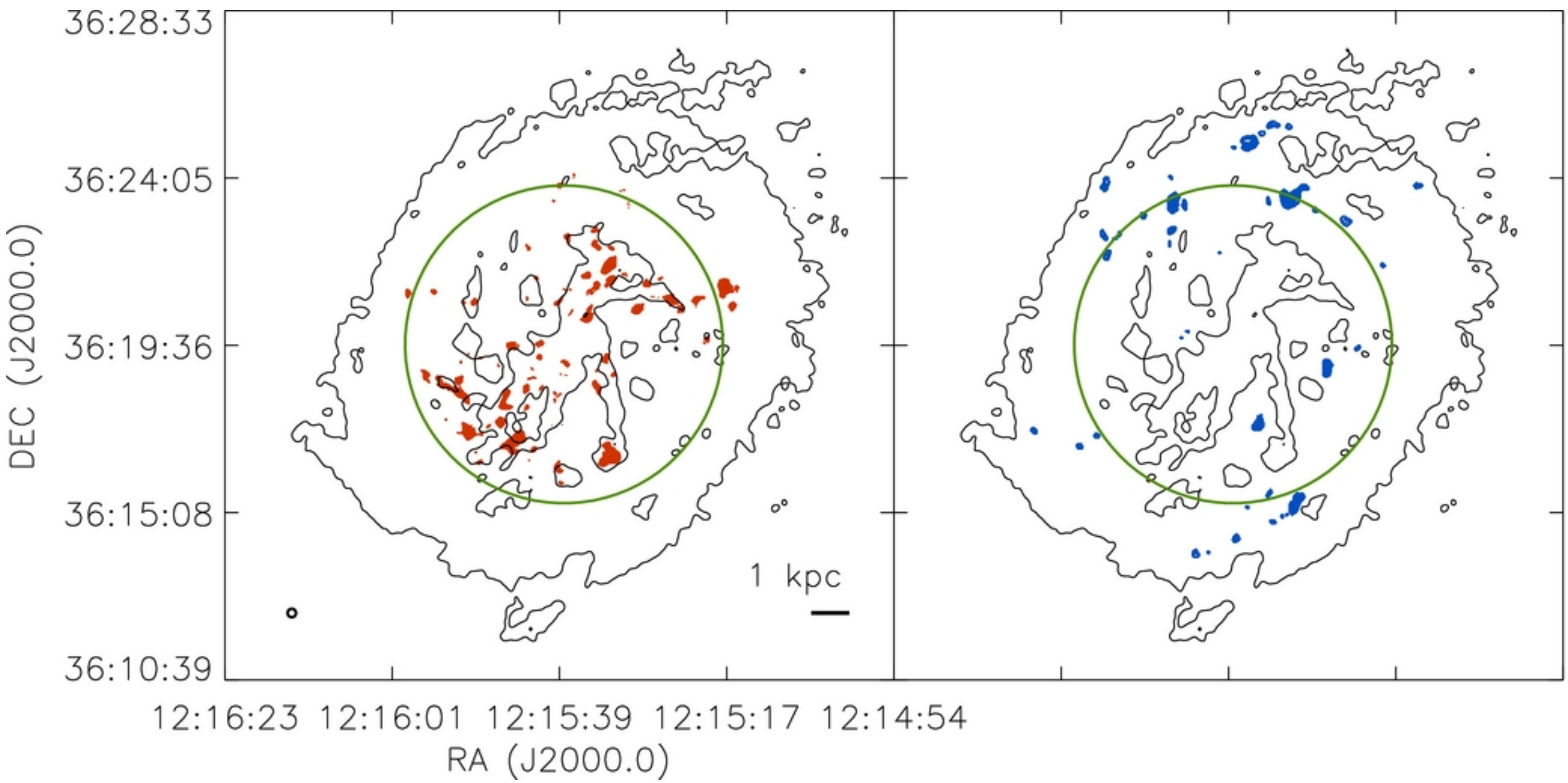
Tracing H_2 at Low Metallicity

- Using VLA HI observations of low mass galaxies from THINGS and VLA/ANGST, Warren et al. (2012) found:
- Cold H I is found in 23 of 27 (~85%) galaxies
- The cold H I contributes ~20% of the total line-of-sight flux when found with warm H I.
- Spectra best fit by a single Gaussian, but dominated by cold H I emission, are found primarily beyond the optical radius of the host galaxy.
- The cold H I is typically found in localized regions and is generally not coincident with the very highest surface density peaks of the global H I distribution.
- The lower limit for the mass fraction of cold-to-total H I gas is only a few percent in each galaxy.



Locating cold HI in low mass star forming galaxies (Warren et al. 2012)



Locating cold HI from double Gaussian profiles (left) and single Gaussian profiles (right) in the low mass star forming galaxy NGC 4214. (Warren et al. 2012)

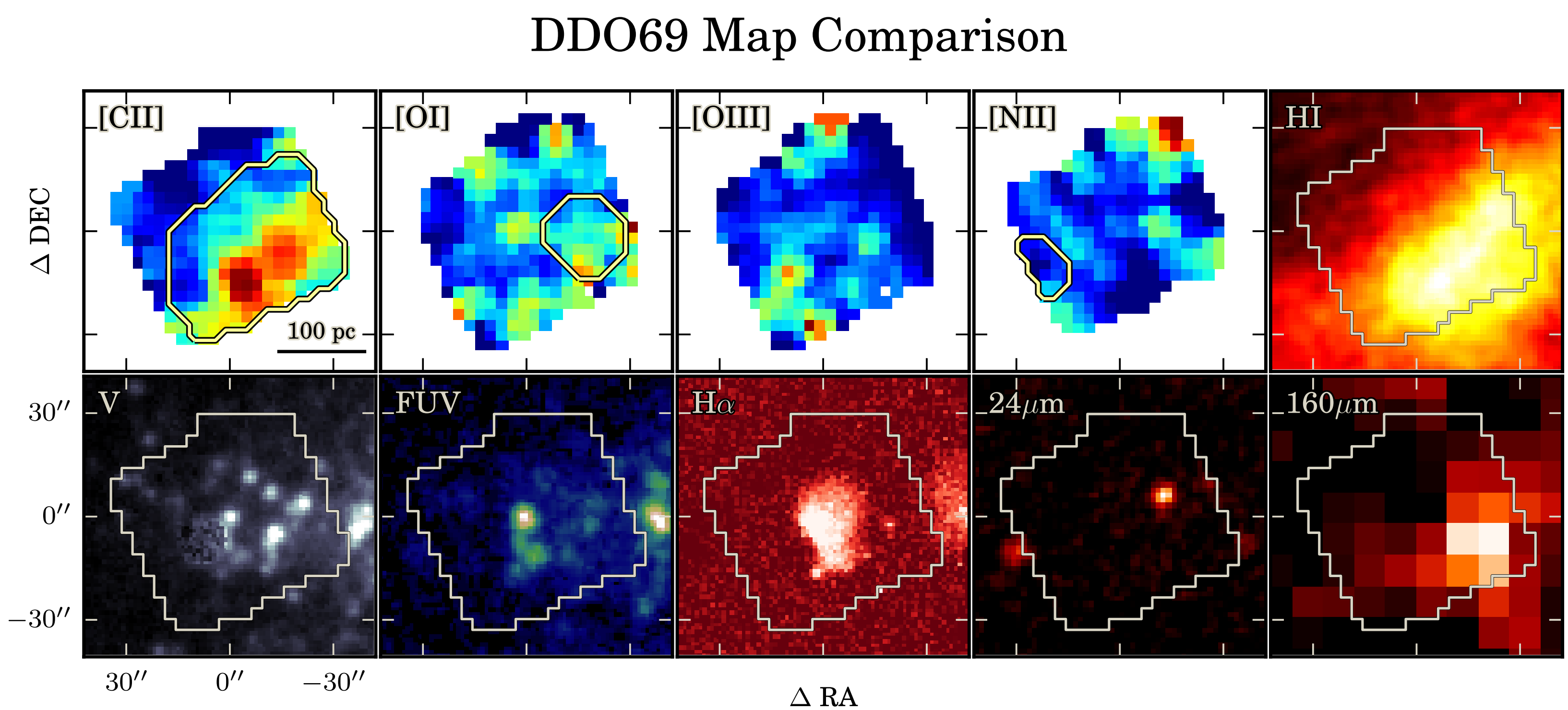
Finding H_2 at Low Metallicity

- (1) CO – not promising, even with Alma
- (2) direct H_2 observations – not promising
- (3) cold HI – indirect
- (4) C^+ emission – indirect
- (5) dust emission – indirect

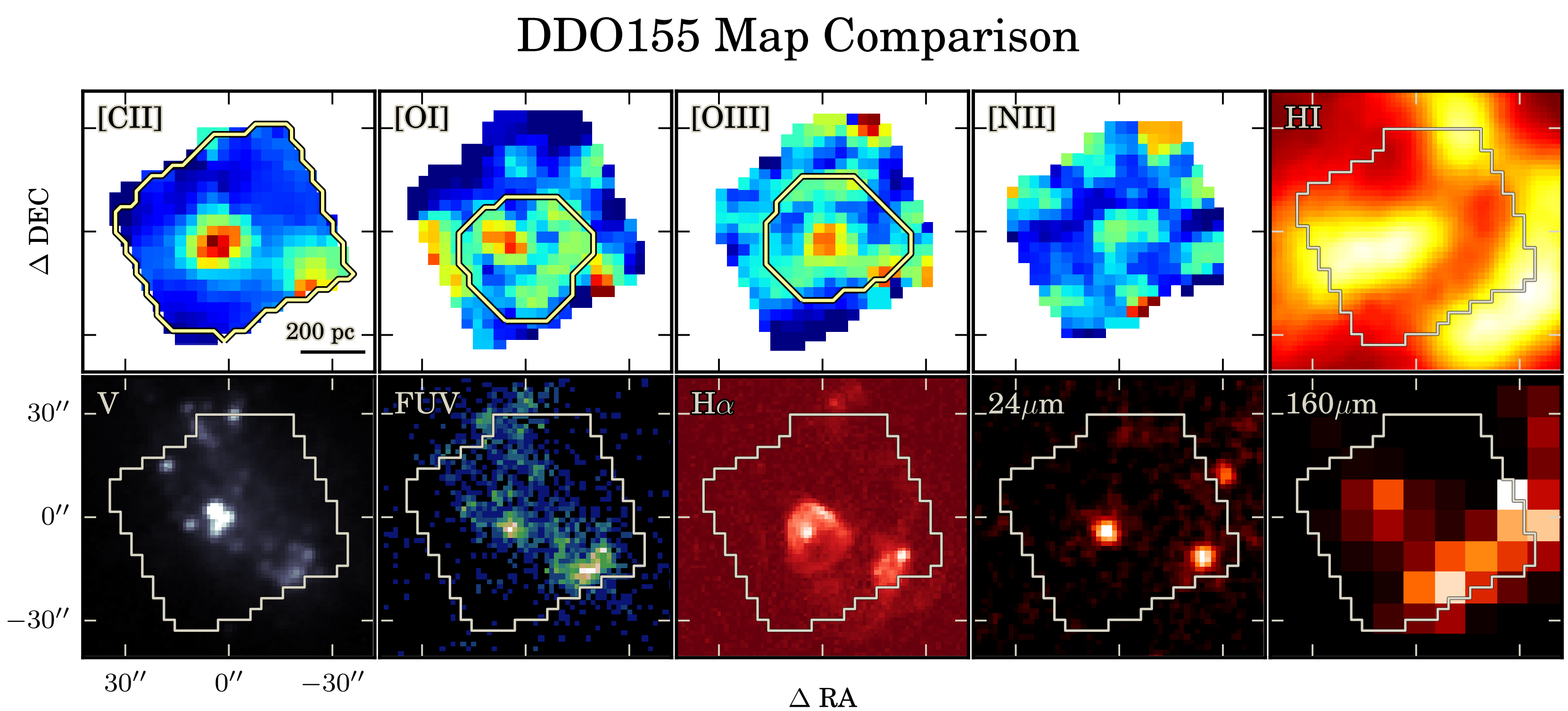
Finding H_2 at Low Metallicity

"We favor a self-consistent use of dust, an optically thin tracer of gas, as the currently most mature methodology to robustly estimate molecular mass at low metallicity."

Bolatto et al. (2013)



Herschel Far-IR spectroscopic imaging of a nearby dwarf galaxy compared with emission at other wavelengths. (Cigan et al. 2016)



Herschel Far-IR spectroscopic imaging of a nearby dwarf galaxy compared with emission at other wavelengths. (Cigan et al. 2016)

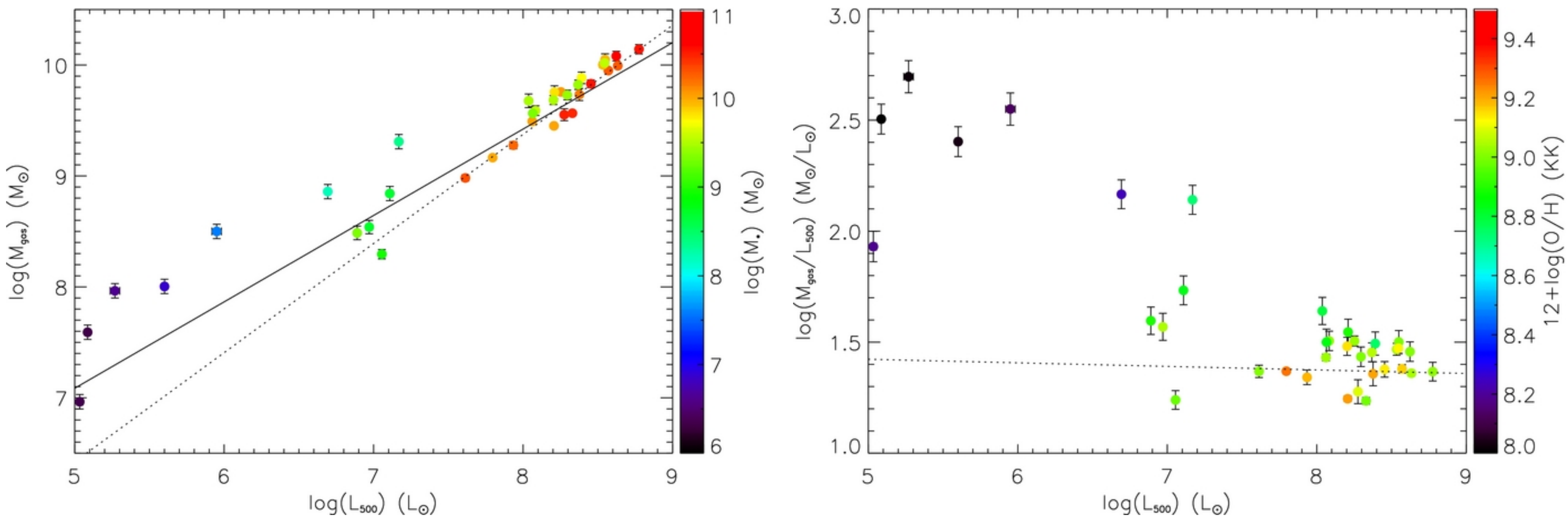
Finding H_2 at Low Metallicity

A definitive study will require a combination of spatially resolved observations.

For example, combining high resolution HI with a dust map allows an estimate of the H_2 column. If this corresponds to narrow HI and/or C^+ emission, then these observable tracers can be calibrated as functions of Z and SFR.

How it Matters

Maybe it doesn't?



From Groves+(2015)

How it Matters

I think a better understanding of the relationship between H2 and SF at low Z as a function of metallicity provides interesting challenges for modelers and would make interpretation of observations of unresolved galaxies more credible.

I think that spatially resolved studies of nearby systems are the most promising opportunity for this challenge.