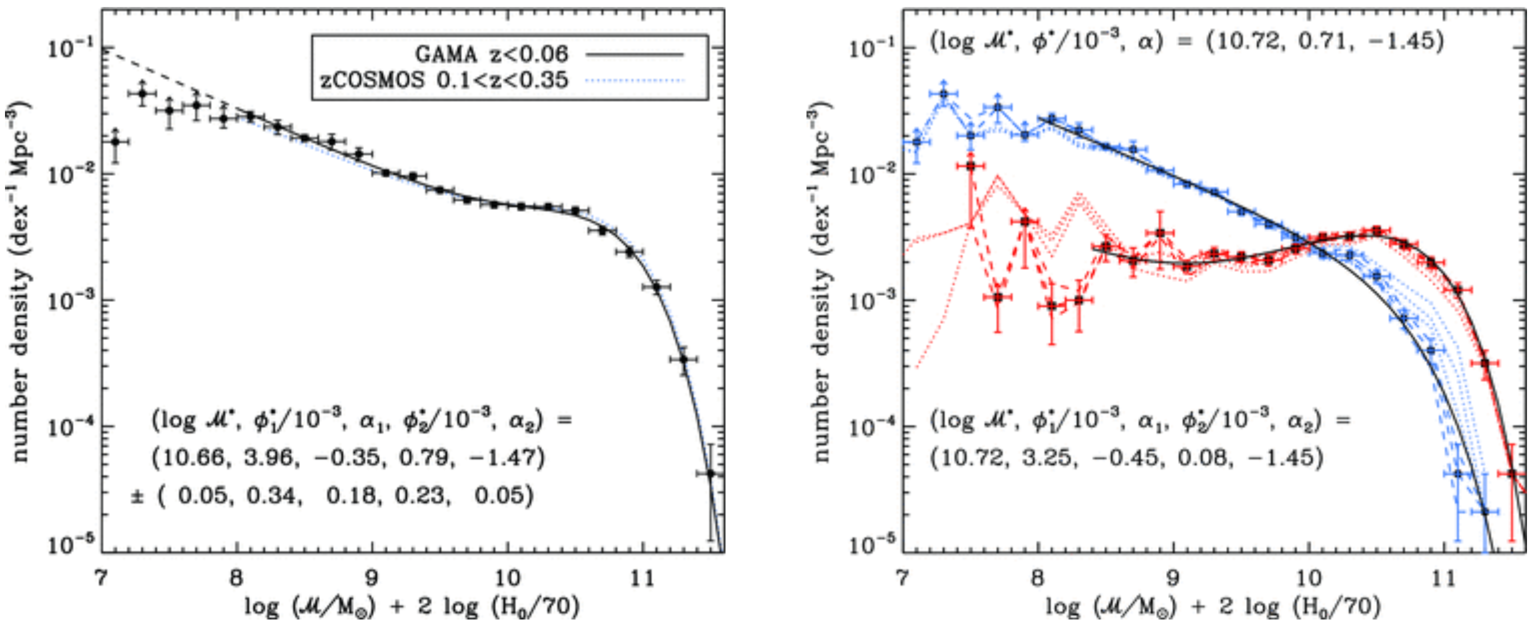
Probing stellar feedback in an extreme low-metallicity starburst

Leslie Hunt (INAF-Osservatorio Astrofisico di Arcetri, Firenze)
with S. Garcia-Burillo (Madrid), V. Casasola (INAF-IRA), P. Caselli (MpE), F. Combes (Paris), C. Henkel (Bonn), R. Maiolino (Cambridge), K. Menten (Bonn), L. Testi (ESO), A. Weiss (Bonn)

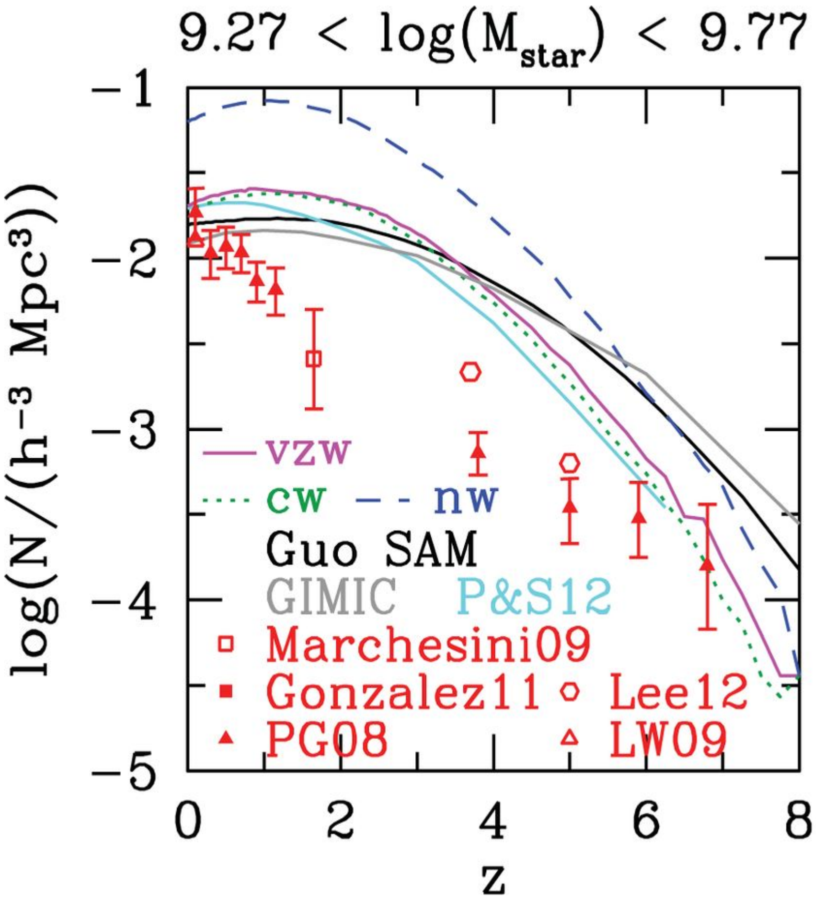
why low-mass dwarf galaxies?



Galaxy stellar mass function from Baldry+ (2012) at z~0-0.4 from the GAMA survey (note double Schechter function with steeper slope α toward lower masses). Right panel shows color-selected red (e.g., "dead") and blue populations separately.

Low-mass star-forming galaxies ($M_{star}<10^{10}\ M_\odot$) are the most abundant in number at z~0, responsible for 15-20% of the mass in stars. They form more stars for their mass (i.e., specific SFR) than higher-mass galaxies at least to z~3 (e.g., Karim+ 2011).

models overestimate numbers of low-mass galaxies



Low-mass bin of galaxy stellar mass function at z~0-6 from Weinmann+ (2012).

For these galaxies ($M_{star}<10^{10}$ $M_{\odot}$), neither semi-analytical models (SAMs) nor cosmological hydrodynamical simulations are able to correctly predict number counts.

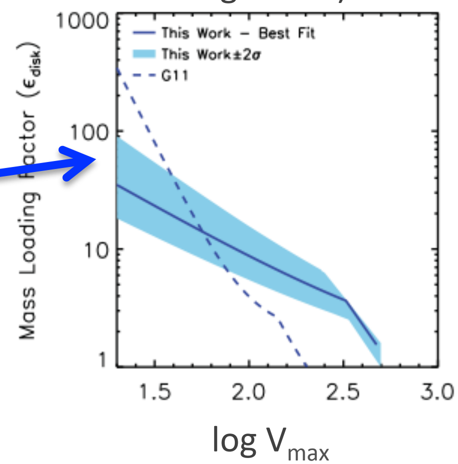
Plot shows SAMs (e.g., Guo+ 2011) compared with observations. The discrepancy between model predictions and observations is already evident at z~0.5, and persists to high redshifts.

According to Weinmann+ (2012) the problem is in the **treatment of SFR**, namely **too efficient** at low masses. **Treatment of stellar feedback!**

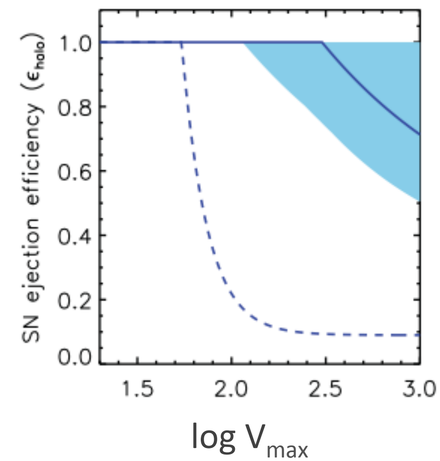
models with revised feedback recipes are better

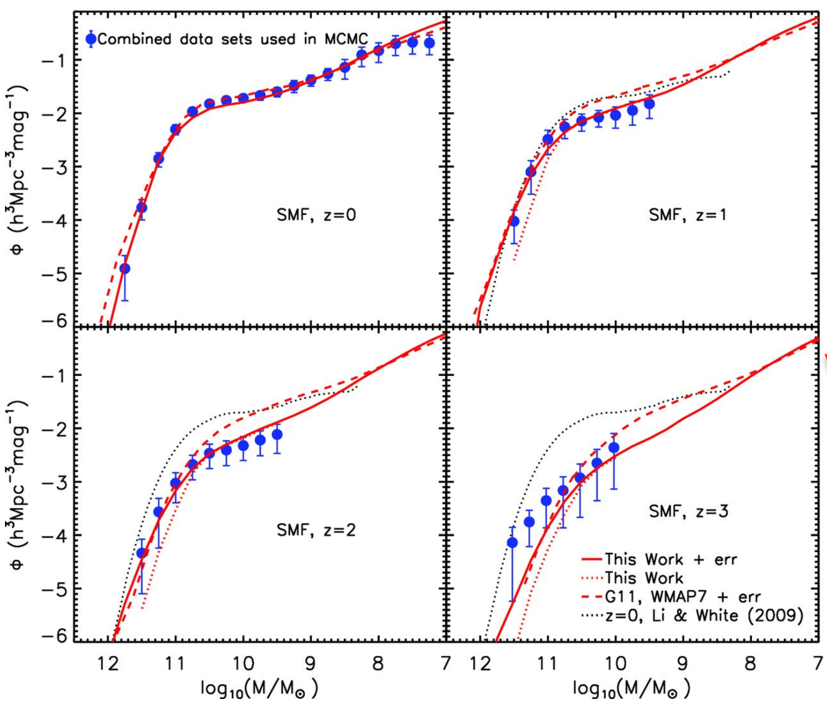
More recent models (Henriques+ 2013) improve the original Munich simulations (Guo+ 2011) by incorporating modified treatment of stellar feedback.

disk heating efficiency w.r.t. SFR (mass loading factor)



fraction of SN energy for gas heating/ejection





Increased efficiencies (above) suppress low-mass galaxies at early times, but high mass return ensures that such galaxies form later, consistently with observations at z~0. Slight (factor 2) residual overabundance of models remains at z~2 (Henriques+ 2013).

the importance of feedback

Over the last few years, feedback from accreting black holes or from massive stars and supernovae (SNe) has become a cornerstone of our understanding of galaxy evolution.

Feedback shapes the:

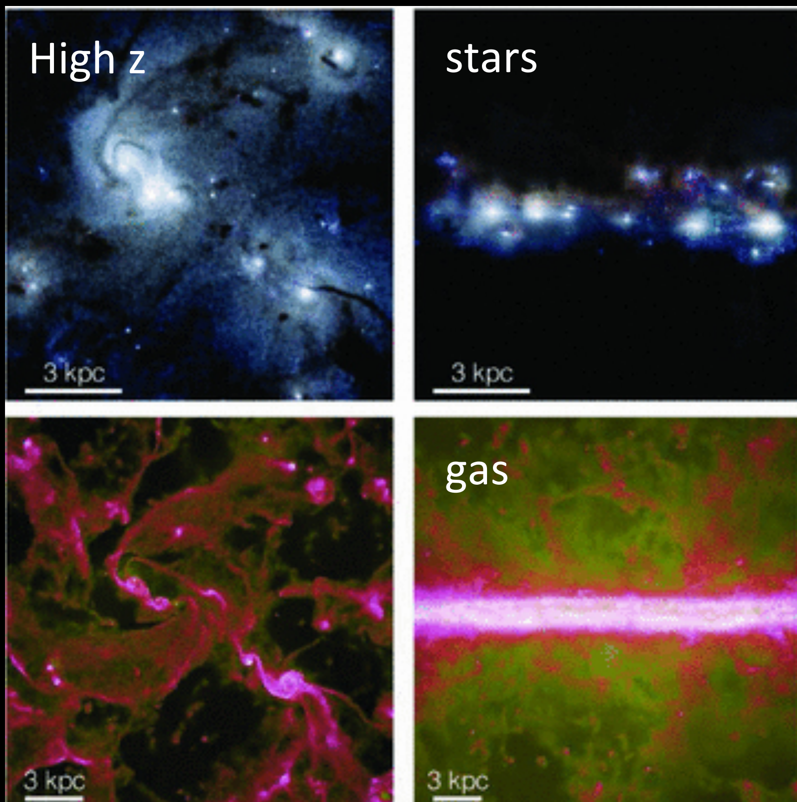
star-formation history of the universe (Schaye+ 2010),

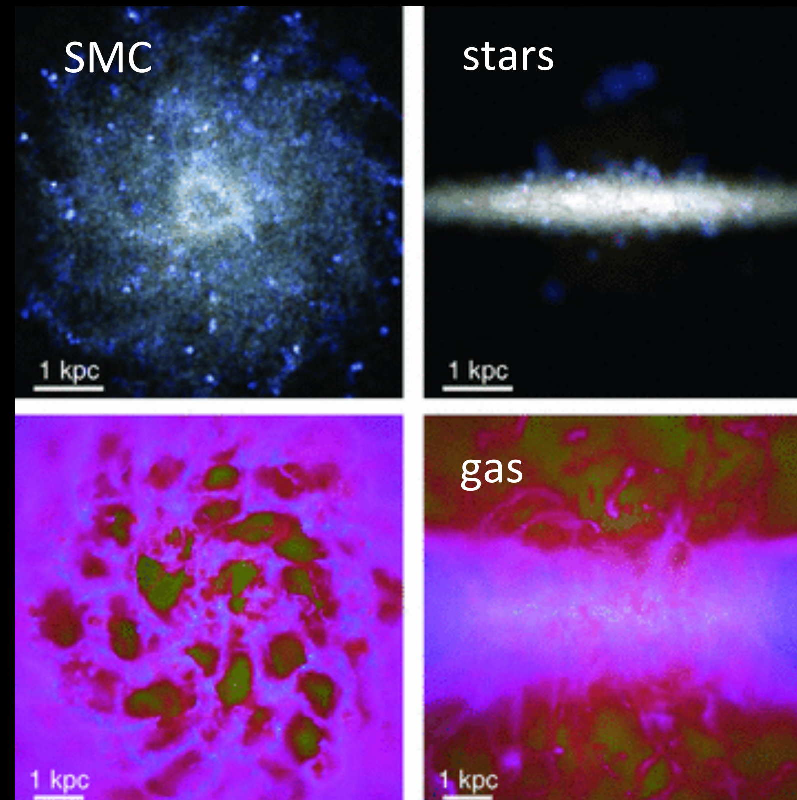
mass-metallicity relation (e.g., Tremonti+ 2004; Mannucci+ 2010, 2011; Dave'+ 2011, 2012), and

luminosity functions and colors of galaxies (Somerville+ 1999).

However, even before the onset of SNe, **massive stars** provide significant feedback through deposition of energy and momentum into the interstellar medium (ISM). **Dust is a crucial aspect** of this process because radiation pressure from interaction of photons with dust grains works to hydrodynamically couple dust and gas (e.g., Murray+ 2005; Hopkins+ 2011), thus producing **momentum-driven winds** which successfully explain a wide variety of galaxy properties (Hopkins+ 2012).

feedback also shapes the ISM





Massive z~2-4 starburst disk with SFR>100 $M_{\odot}yr^{-1}$. Gravitational collapse forms massive kpc-scale star cluster complexes responsible for the clumpy morphology. Violent outflows are present which maintain a thick gas disk and disrupt clumps.

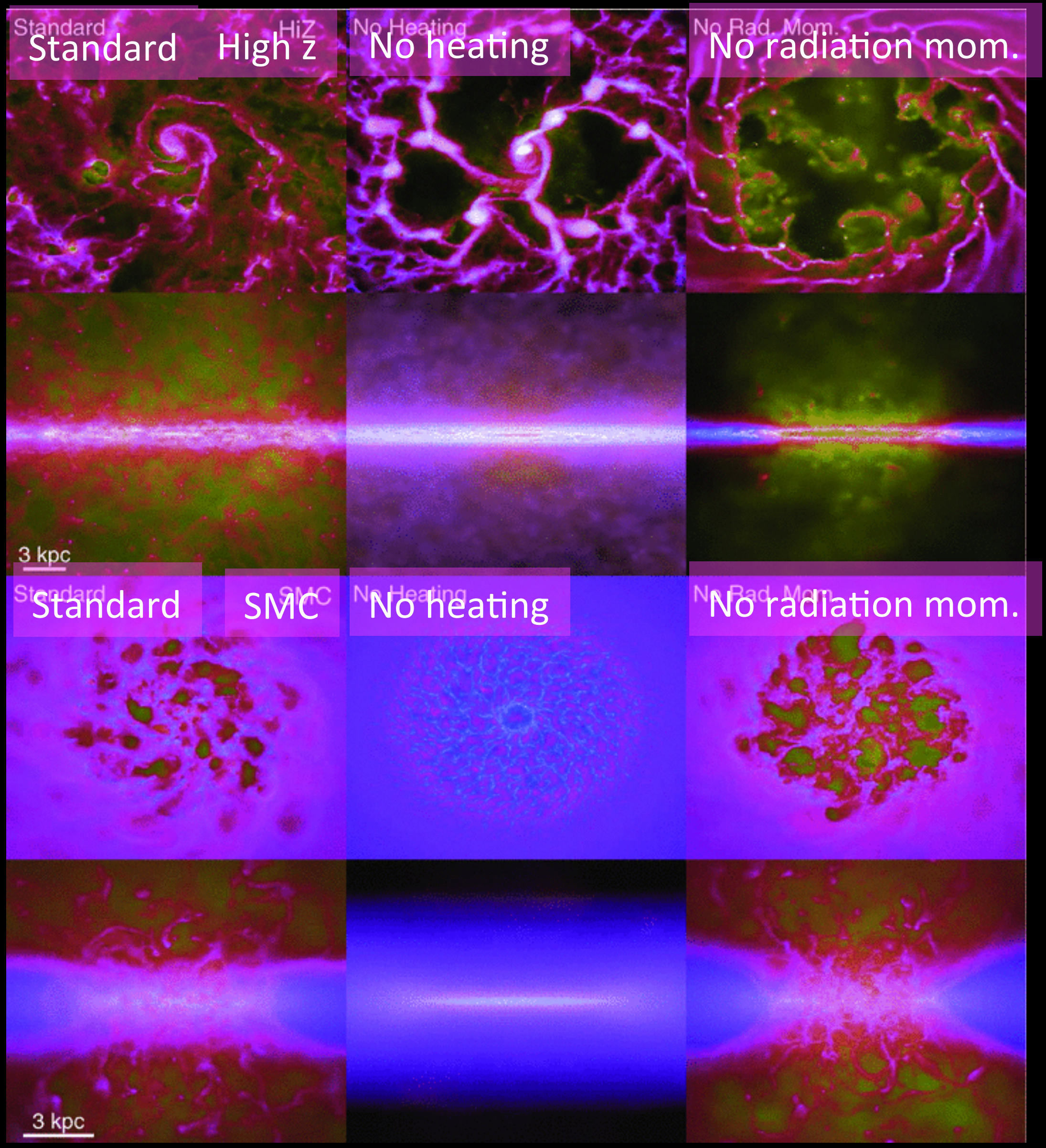
Same but for an SMC analog with SFR>0.1 $M_{\odot}yr^{-1}$. Morphology is typical of a dwarf irregular, with a thick disk mostly of ionized gas. Despite low SFR, a wind is plainly evident with a mix of warm/cool entrained material. Taken from Hopkins+ 2012.

feedback efficiency depends on mass

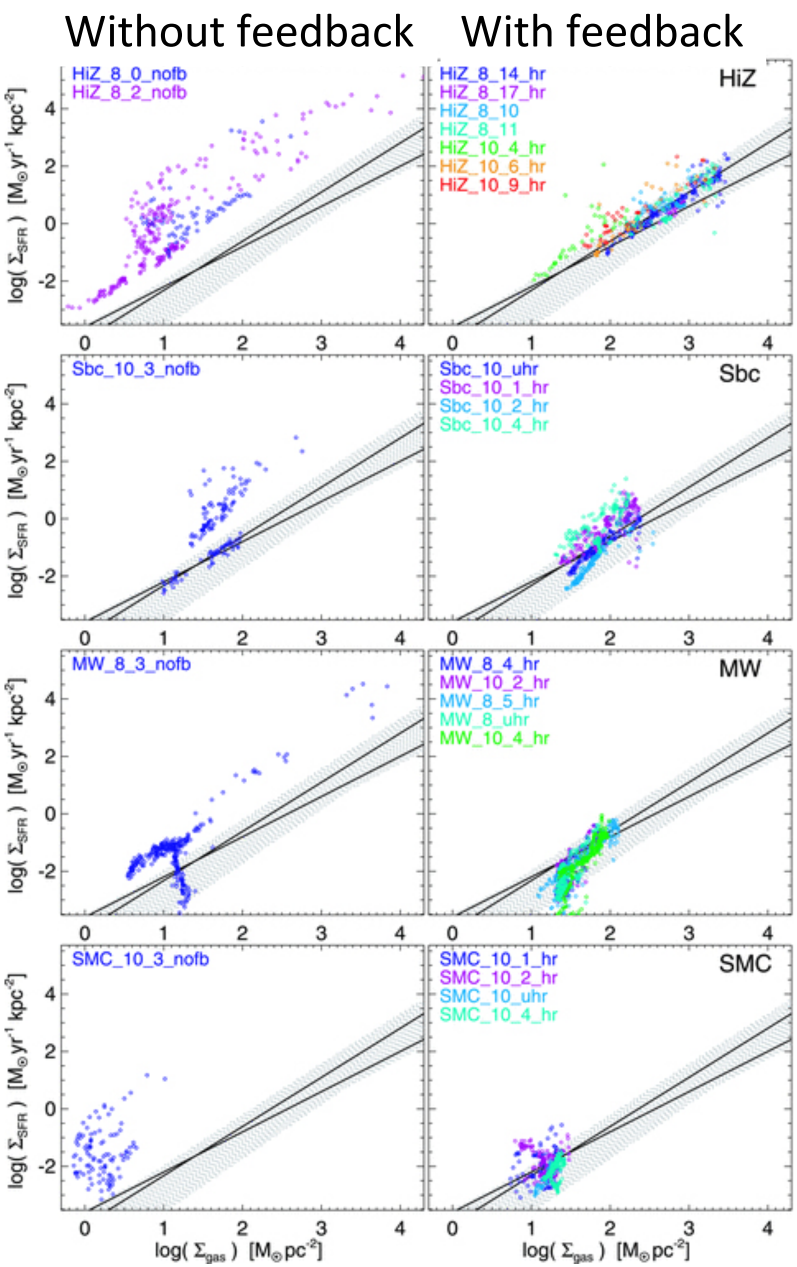
Middle panel shows heating disabled (including energy injection from SNe, shocked stellar winds, and photoionization). Right panel shows no radiation pressure.

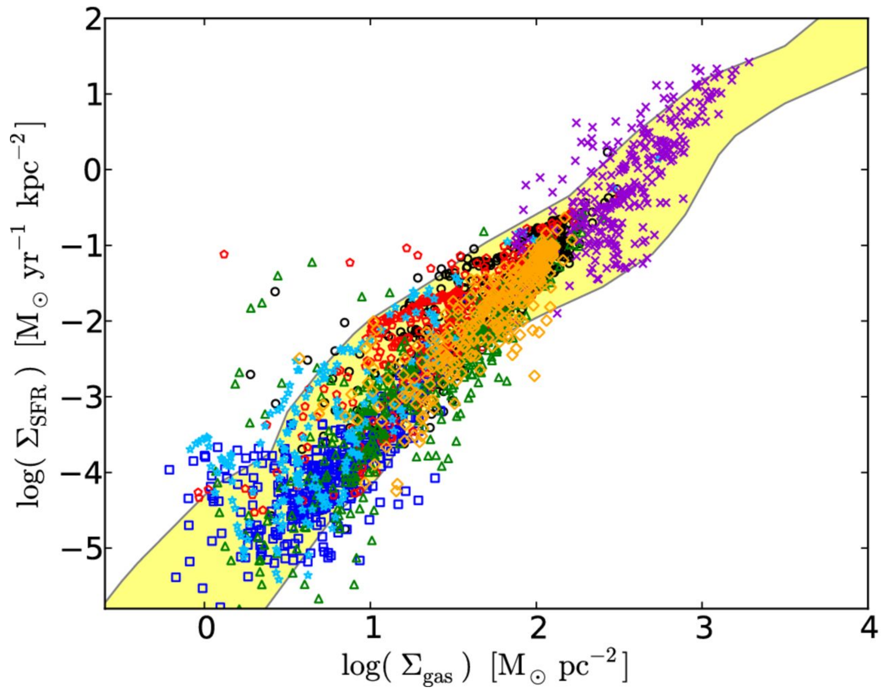
In the high-z case, without heating, the hot-gas filling factor is greatly reduced, but the global morphology is similar; without radiation pressure, the individual GMCs collapse without limit. In the SMC case, there is no wind without heating, but without radiation pressure, the wind and disk thickness are unaltered.

Taken from Hopkins+ 2012.



gas scaling relations shaped by feedback





Without stellar feedback, SFR surface densities of Schmidt-Kennicutt (SK) relation are in excess of observations by factors of 100 to 10^4 (Hopkins + 2011).

Recent simulations confirm that the yellow observed range (above) is well predicted by models with feedback. The emergent SK law ends up with 2% efficiency (Hopkins+ 2014).

lack of observational constraints

Despite their success, a problem of this latest generation of models of galaxy evolution with feedback is that there are few observational constraints for stellar feedback occurring in low-mass metal-poor dwarf galaxies (although see Lopez+ 2011, 2014 for LMC, SMC HII region analyses).

This is an especially important consideration for simulations of chemically unenriched, primordial galaxies, during the **brief transition phase of their evolution between a pristine metal-free ISM and one that has been polluted by rapid star formation** (Wise+ 2012).

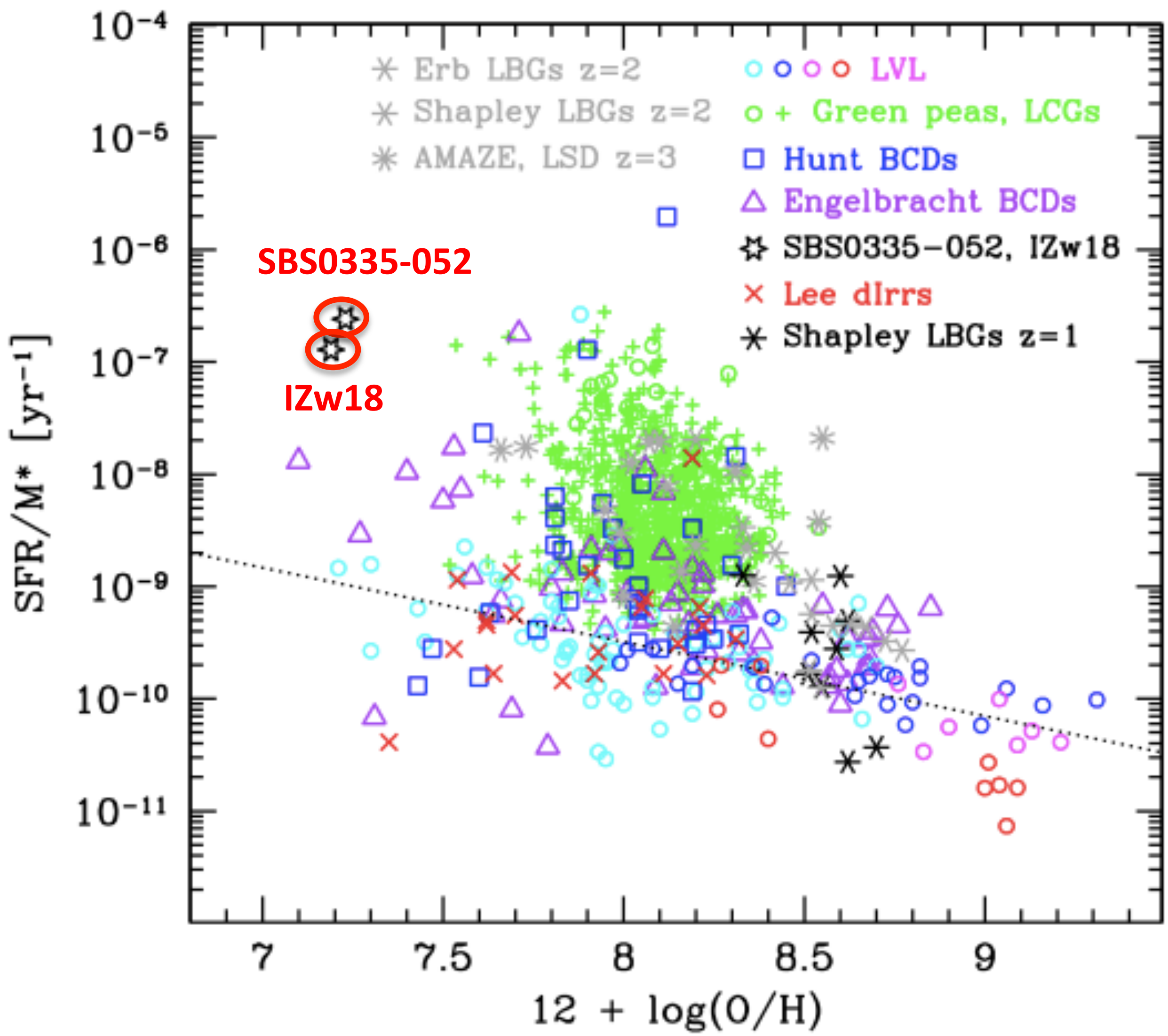
The star-formation rate (SFR), stellar mass, gas-mass fraction, and dust opacity all regulate the ability of feedback to disrupt the ISM, **but low-mass galaxies are usually assumed to be of low column density with dust content depending exclusively on ISM metallicity** (e.g., Murray+ 2005; Hopkins+ 2010, 2012; Faucher-Giguere+ 2013). **However, our Cycle 0 ALMA observations have shown these assumptions to be incorrect.**

results from ALMA Cycle 0

metal-poor starbursts in the local universe

Locally, star-forming dwarf galaxies are much more metal poor than galaxies observed so far at high redshift. Hence, unique window on the transition from a metal-free ISM to a metal-rich one.

Metallicity is correlated with specific SFR (sSFR) locally so need to optimize the analogy with high-redshift starbursts. Selection effects important.



(adapted from Hunt+ 2012)

SBS 0335-052, an extreme metal-poor starburst

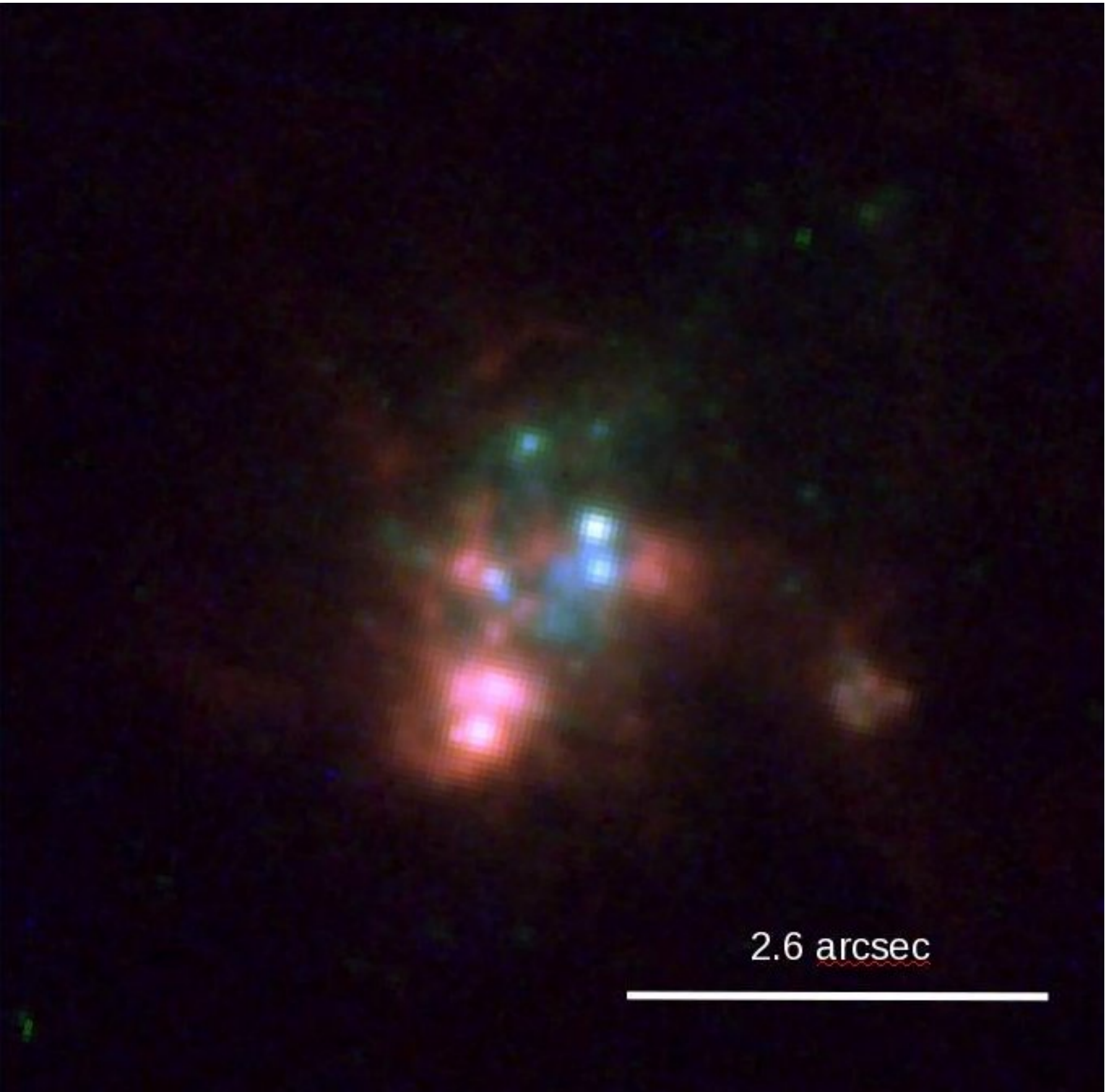


Figure from Reines, Johnson, Hunt (2008).

This blue compact dwarf hosts six Super Star Clusters (SSCs), distributed over ~700 pc (2.6”).

Most of the SF takes place in the two southernmost SSCs, which together host ~10000 O stars. SSCs unresolved at HST/ACS resolution (<~ 30 pc).

12+log(O/H) = 7.23

SFR = 1 $M_\odot$ /yr
(Hunt+ 2004)

Stellar mass ~10^7 $M_\odot$
(Reines+ 2008, Fumagalli+ 2010)

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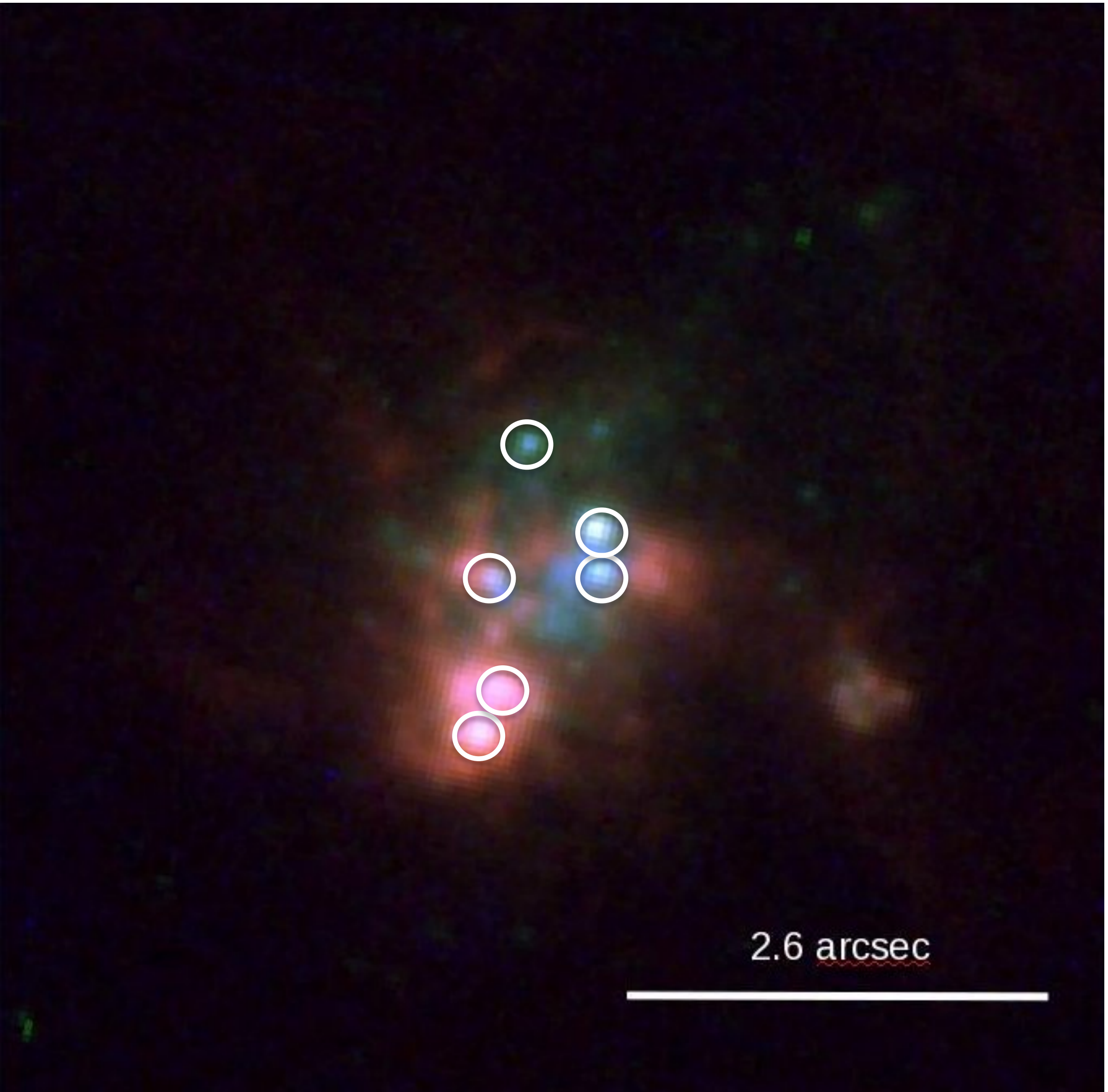

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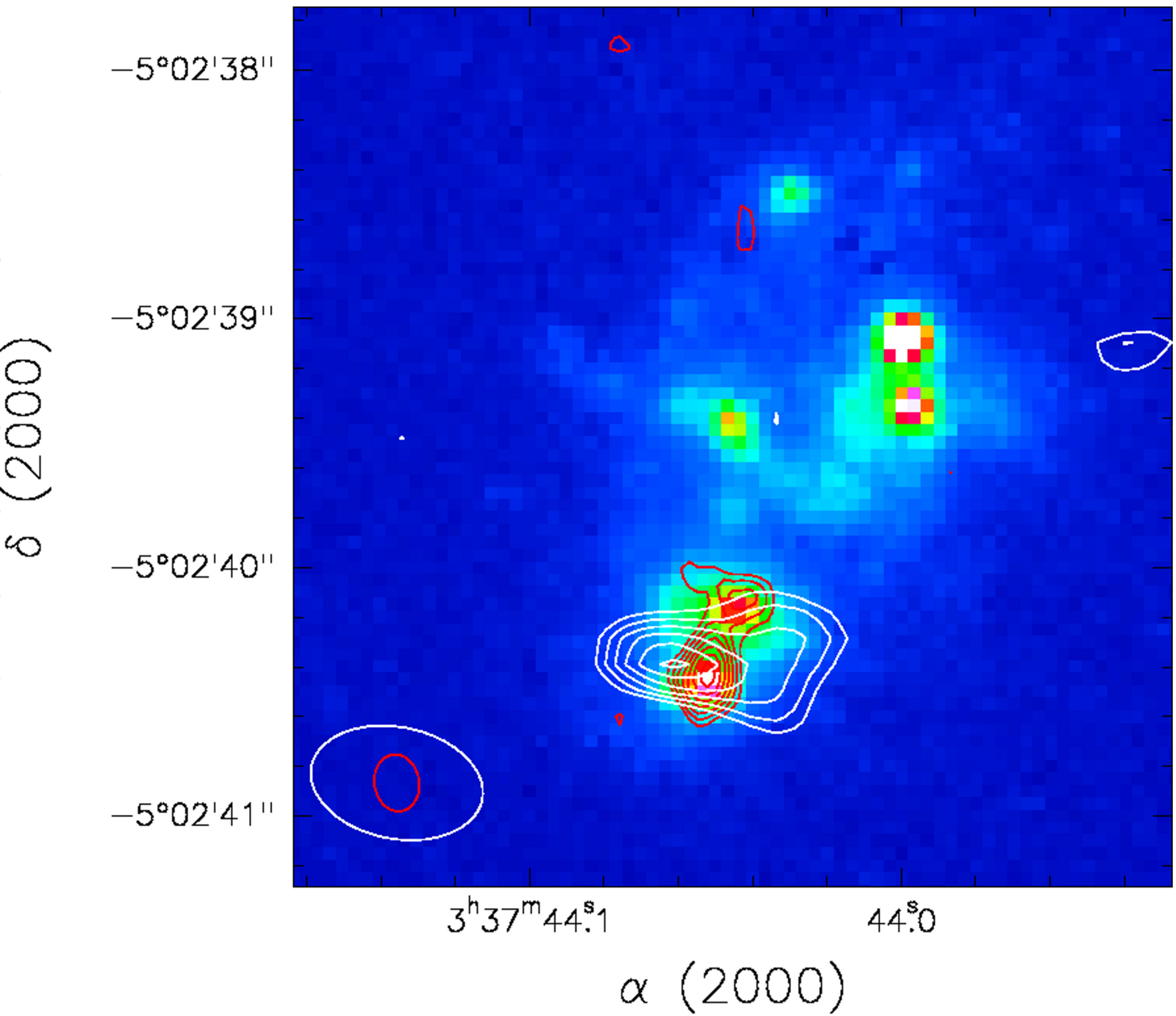
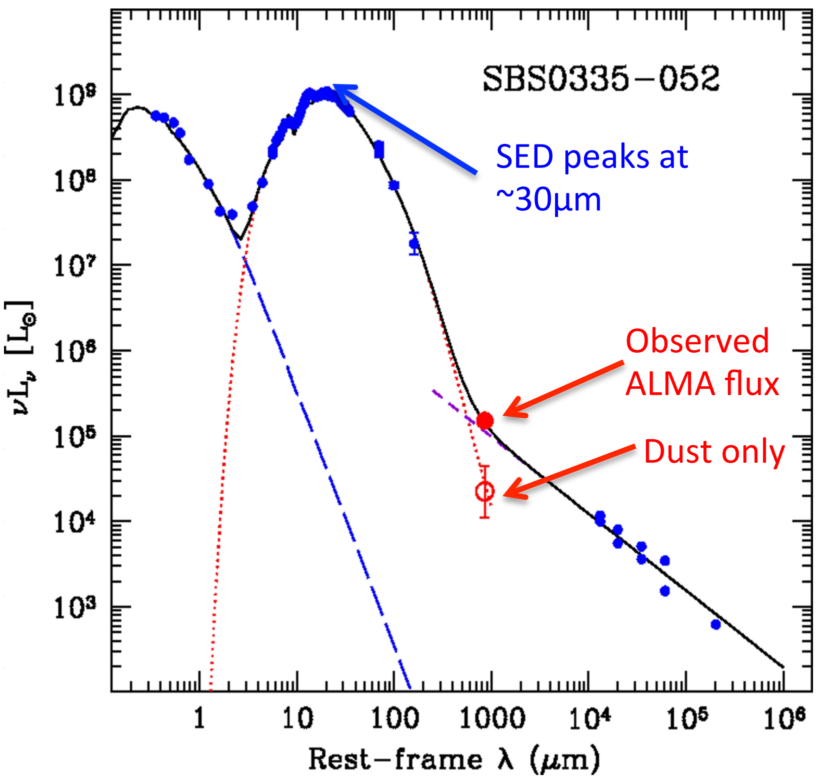


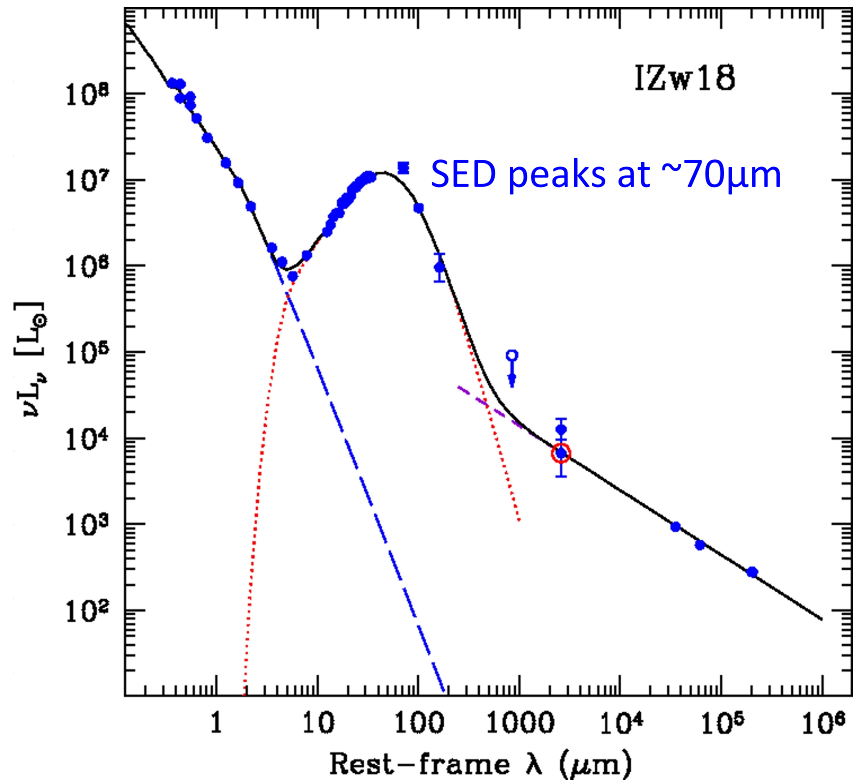
ALMA Band 7 (345 GHz, 857 μm) in white contours, overlaid on ACS F555M image of SBS0335-052. Red contours show VLA 3.6 cm image (Johnson, Hunt, Reines 2009). Resolution 0.6”, 160 pc resolution.

The ALMA 870 μm emission is extended, but the elliptical beam shape precludes conclusions about dust+free-free outflow.

(Hunt+ 2014)

dust extinction measured from SBS0035-052 SED





A_V ~ 12 mag from silicate absorption feature at 9.7µm (Houck+ 2004), consistent with Brα/Brγ (Hunt+ 2001). SED fitting with DUSTY model (cocoon of dust surrounding central star cluster, Ivezic & Elitzur 1997) gives **dust mass of ~3.8 x 10^4 $M_\odot$**

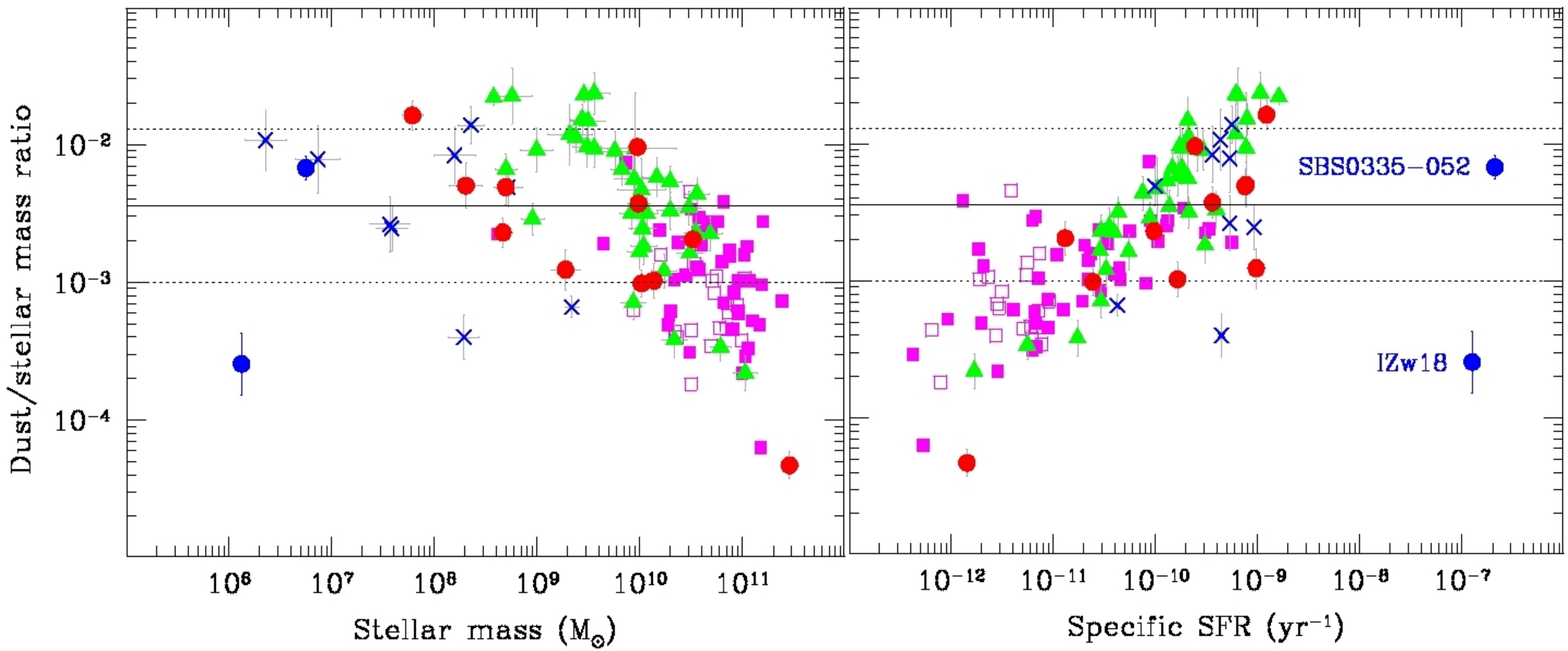
Silicate dust, unlike IZw18!

~1/30 $Z_\odot$, SFR = 0.1 $M_\odot$ /yr (Hunt+ 2005); stellar mass ~1.4 x 10^6 $M_\odot$ (Fumagalli+ 2010)

Best-fit DUSTY model (as for SBS0035-052) gives a **dust mass 3.4 x 10^2 $M_\odot$**. Best-fit dust is primordial supernovae grains (Schneider & Bianchi 2007) with no silicates!

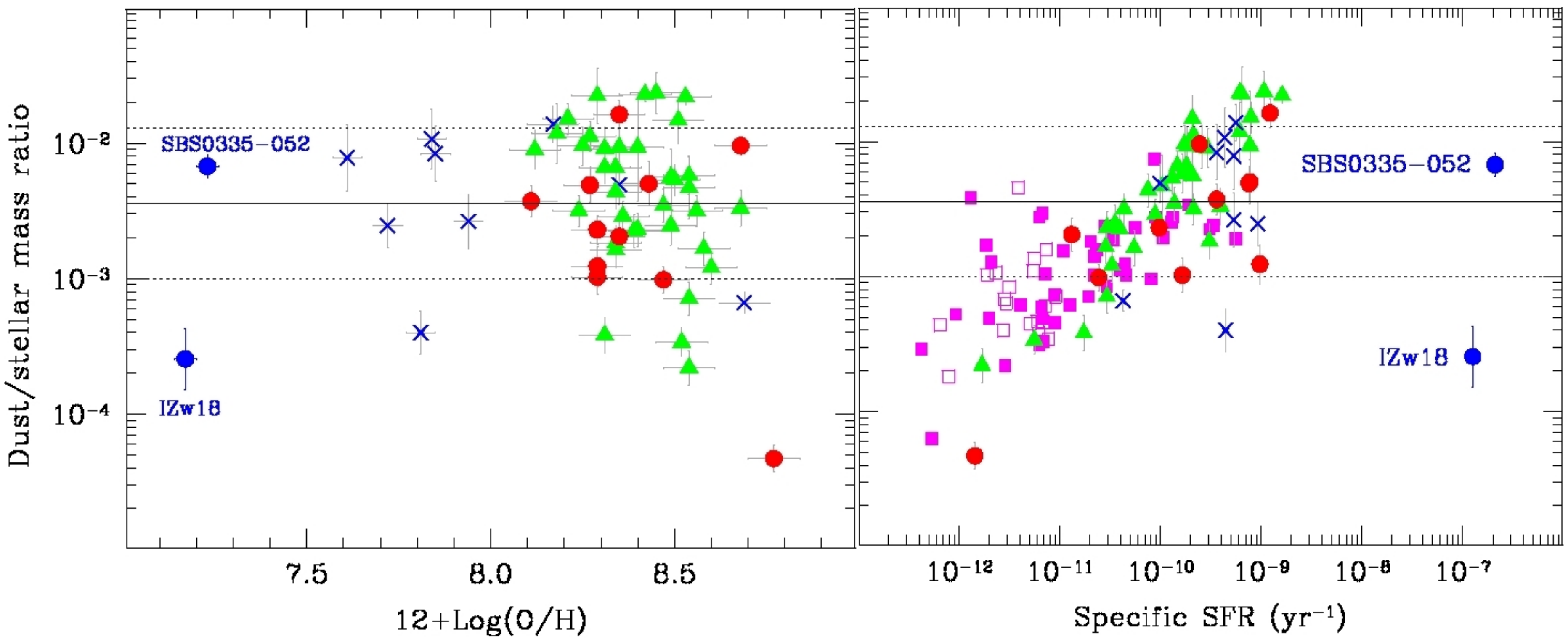
(from Hunt+ 2014)

dust (to stars) content not constant with metallicity



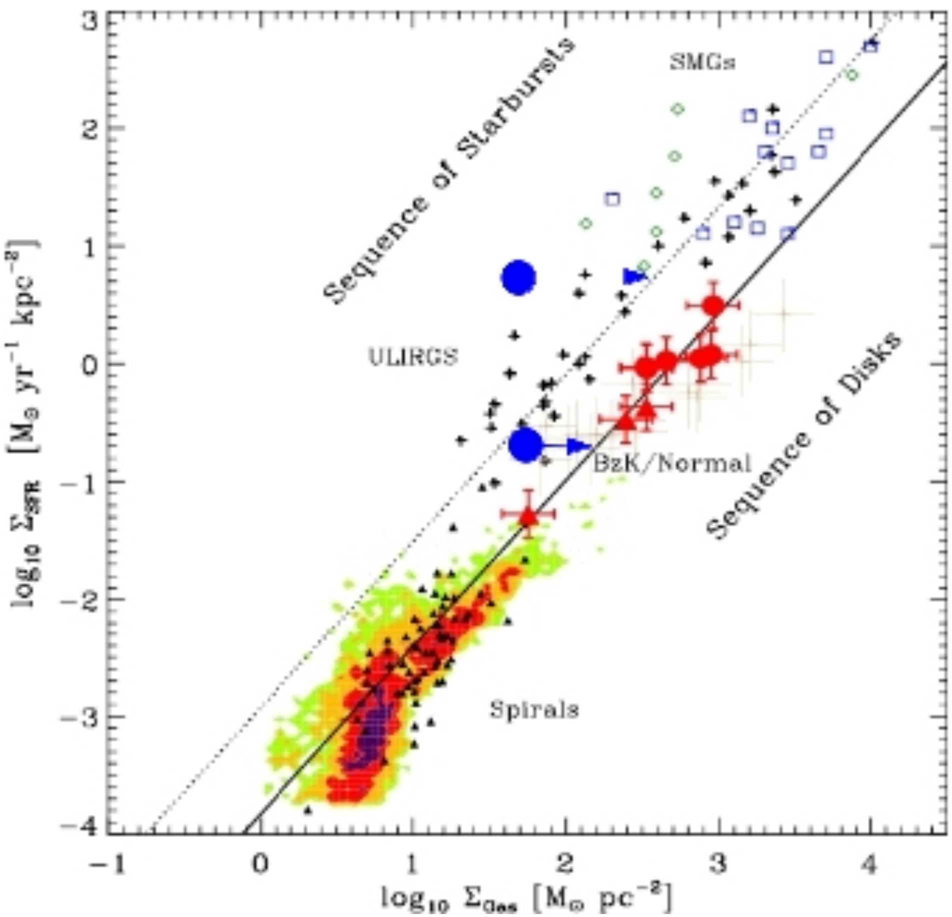
At the same metallicity, 1/30 $Z_{\odot}$, SBS0335-052 and IZw18 differ in dust-to-gas and dust-to-stellar mass ratios by 2 orders of magnitude.

dust (to stars) content not constant with metallicity

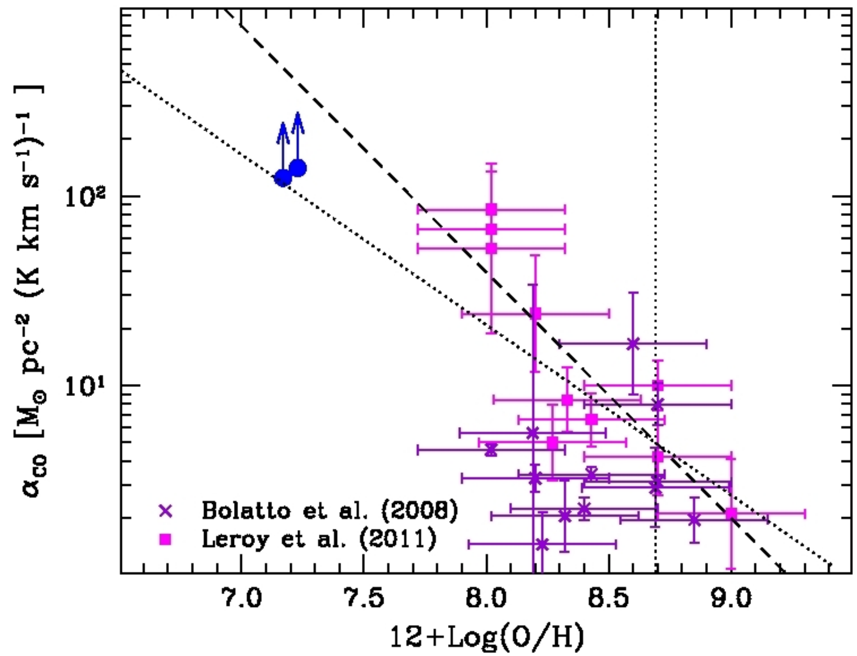


At the same metallicity, 1/30 $Z_\odot$, SBS0335-052 and IZw18 differ in dust-to-gas and dust-to-stellar mass ratios by 2 orders of magnitude.

use Schmidt-Kennicutt relation to estimate H_2



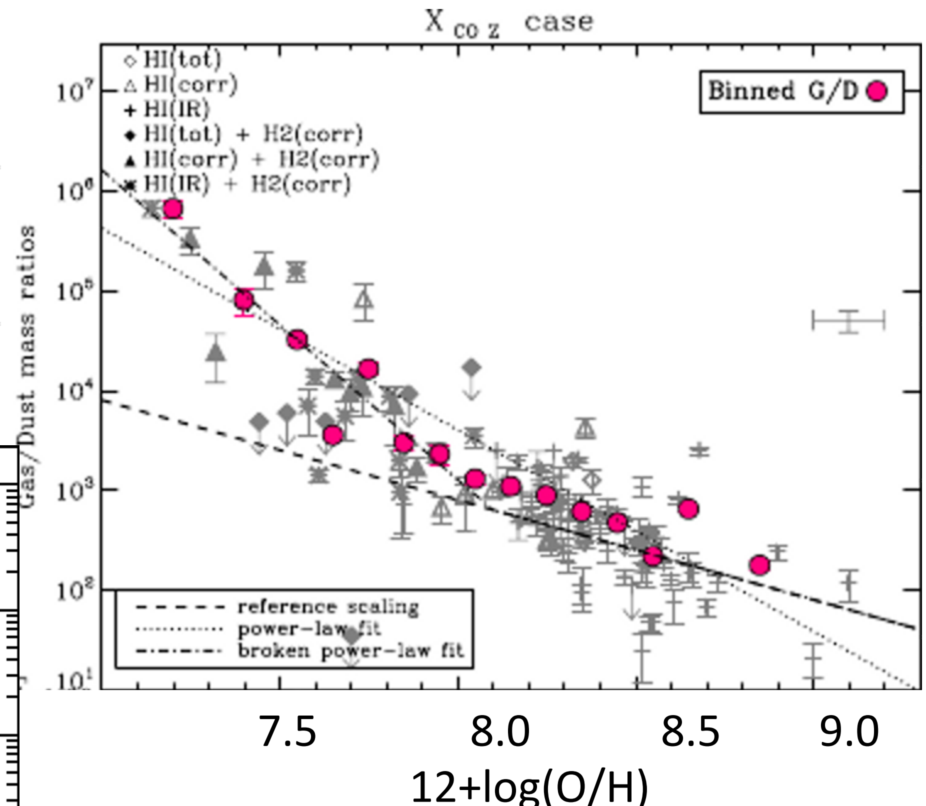
(from Daddi+ 2010, see Hunt+ 2014)



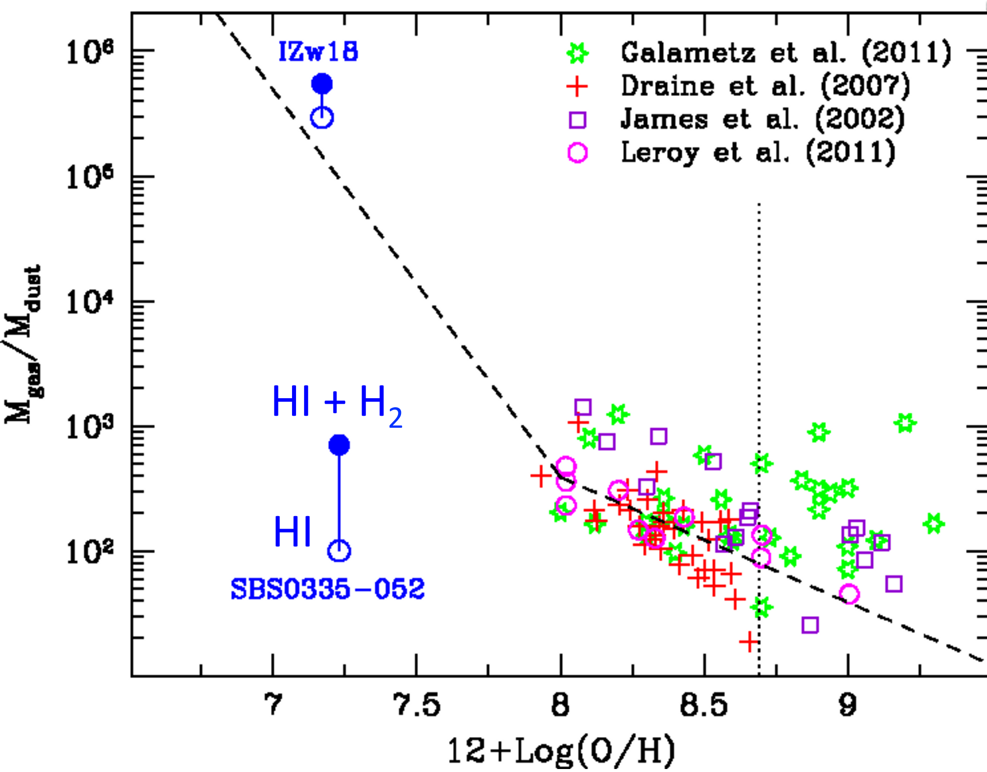
Making arbitrary assumption that SBS0335-052 should follow the "starburst sequence" and IZw18 the "sequence of disks", we can constrain the H_2 mass conversion factor α_{CO}. SBS0335-052 from CO(3-2) (Hunt+ 2014), IZw18 CO(1-0) (Leroy+ 2007).

dust (to gas) content not constant with metallicity

At the same metallicity, 3% $Z_\odot$, SBS0335-052 and IZw18 differ in dust-to-gas and dust-to-stellar mass ratios by 2 orders of magnitude.



(Remy-Ruyer+ 2014)



(Hunt+ 2014)

proposed Cycle 2 ALMA observations to map the dust in SBS0335-052 (proposal ranked B, 0-10%)

Band 9 (435 µm), 0.2 arcsec

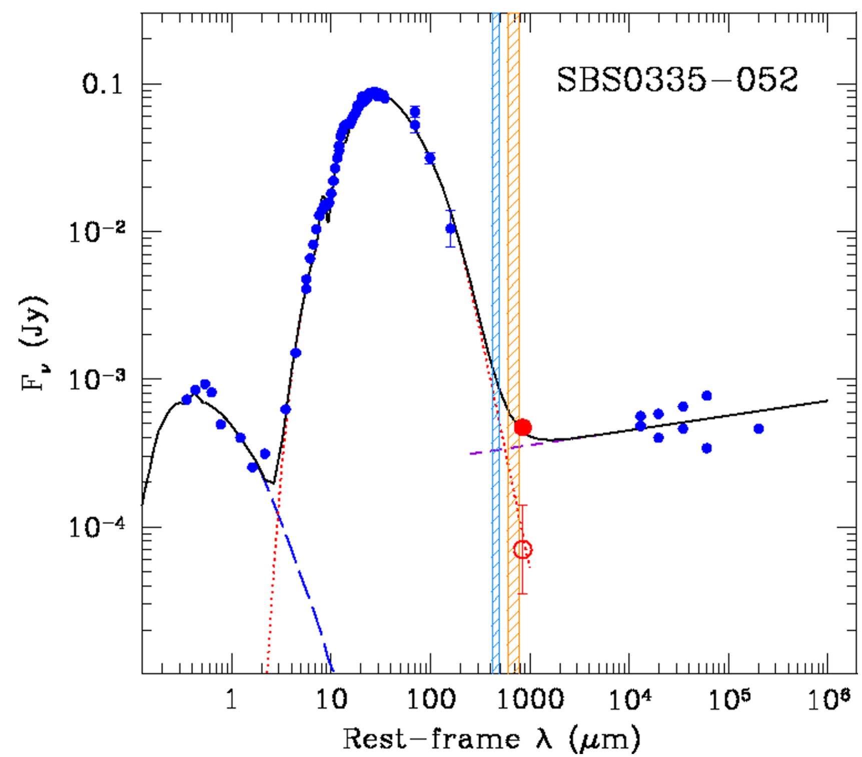
With cm observations at same resolution, we will **map the dust in SBS0335-052 at 55 pc resolution** in order to address the following (CO(6-5) obtained *a gratis*):

What is the effect of feedback from massive stellar winds on the dust distribution?

How clumpy is the metal-poor dust? (must be clumpy otherwise would see no optical emission)

How do galaxy counterparts of damped Lyα systems appear close up? (SBS0335-052 shows P-Cygni absorption features around Lyα, corresponding to a terminal wind velocity of ~500 km s^{-1} (Thuan & Izotov 1997))

What is the interplay between dust and ionized gas in a metal-poor starburst?



Band 9 is the only ALMA band where dust emission dominates. Note Band 8 and previous Band 7 observations.