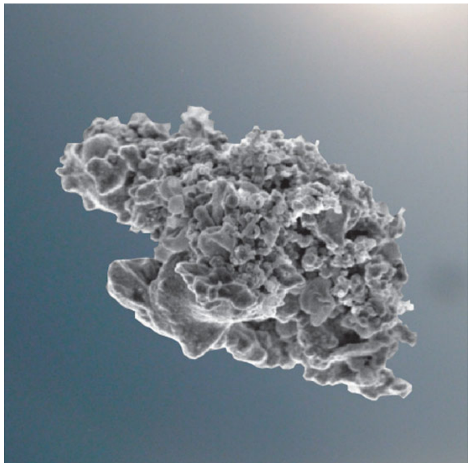
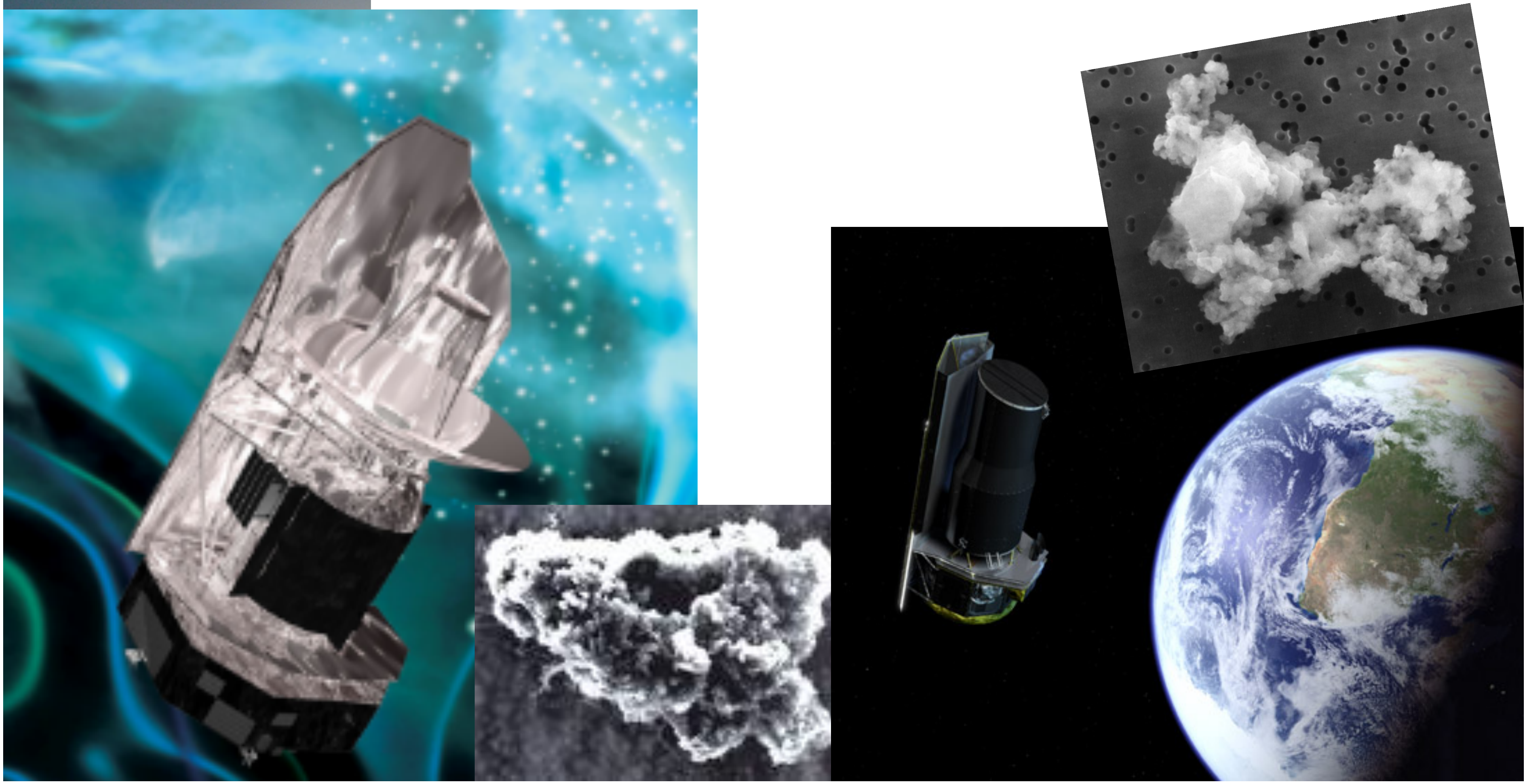


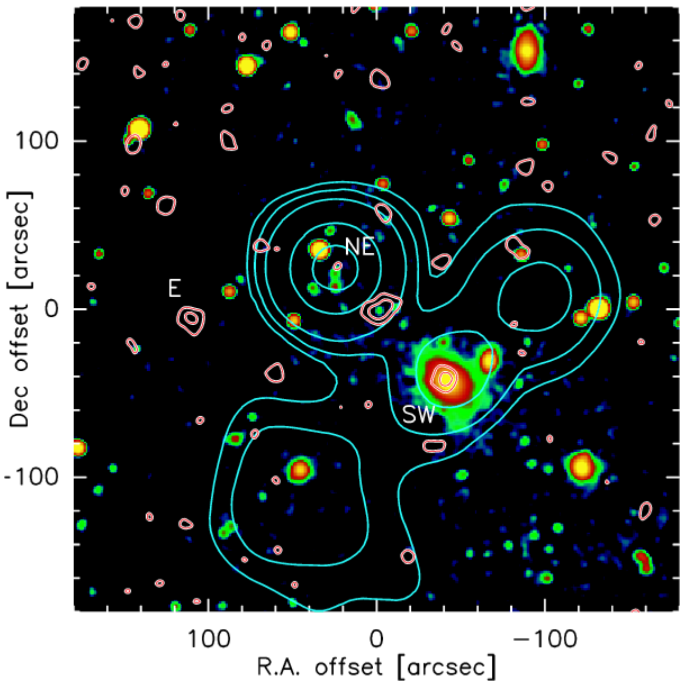
Dust and gas in low-metallicity starbursts

Leslie Hunt (INAF-Osservatorio di Arcetri, Firenze)

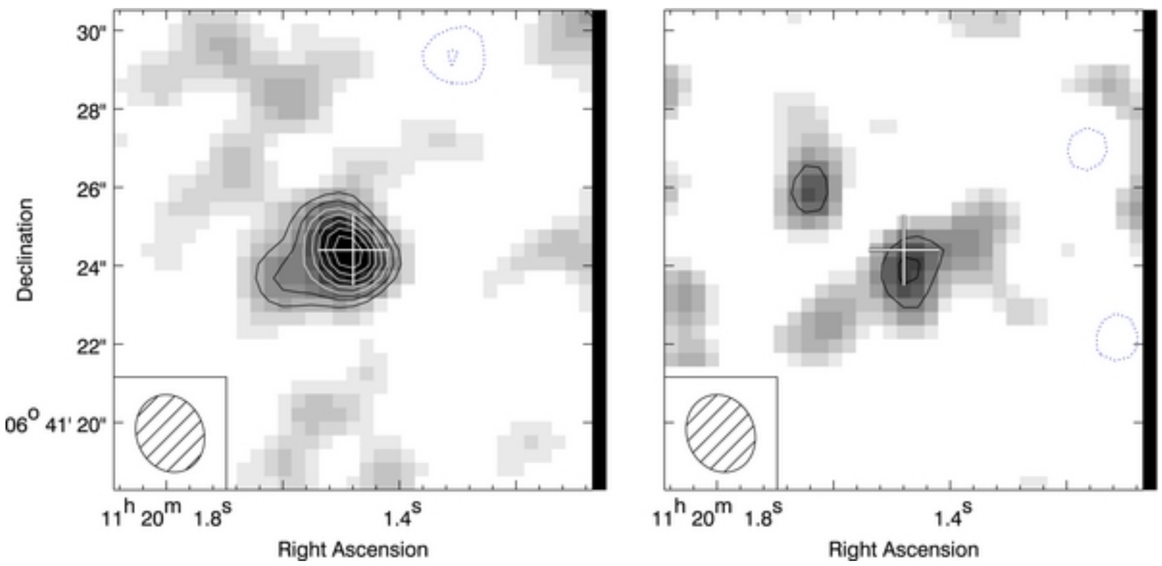


The continuum story

Dust is present at very early times



Field of QSO SDSS J114816.64+525150.3 at z=6.42. Red-white contours 1.2mm MAMBO; blue contours 21cm VLA NVSS. (Bertoldi+ 2003).



Field of QSO ULAS J112001.48+064124.3 at z=7.08. Left panel show [CII], right dust continuum at rest-frame 158 μm (Venemans+ 2012).

~$10^8\, M_\odot$ of dust in a quasar when the universe was ≤ 1 Gyr of age means that the dust production and starburst episode must be very rapid.

Theoretical models suggest that AGB and SNe dust yields are roughly consistent with the observed dust mass, but grain formation within GMCs must also play a role (Valiante+ 2009, 2011; Calura+ 2014).

But how can dust be present in the primordial, metal-free environments prevalent in the early universe?

Exactly how massive starbursts such as that responsible for J1148+5251 and J1120+0641 occur and evolve is not yet clear.

The short interval in which star formation and the ensuing chemical enrichment and dust formation convert a dust-free metal-free environment to a dusty metal-rich one by redshift ~7 is as yet unobserved, and studies of such transitions remain a major observational challenge.

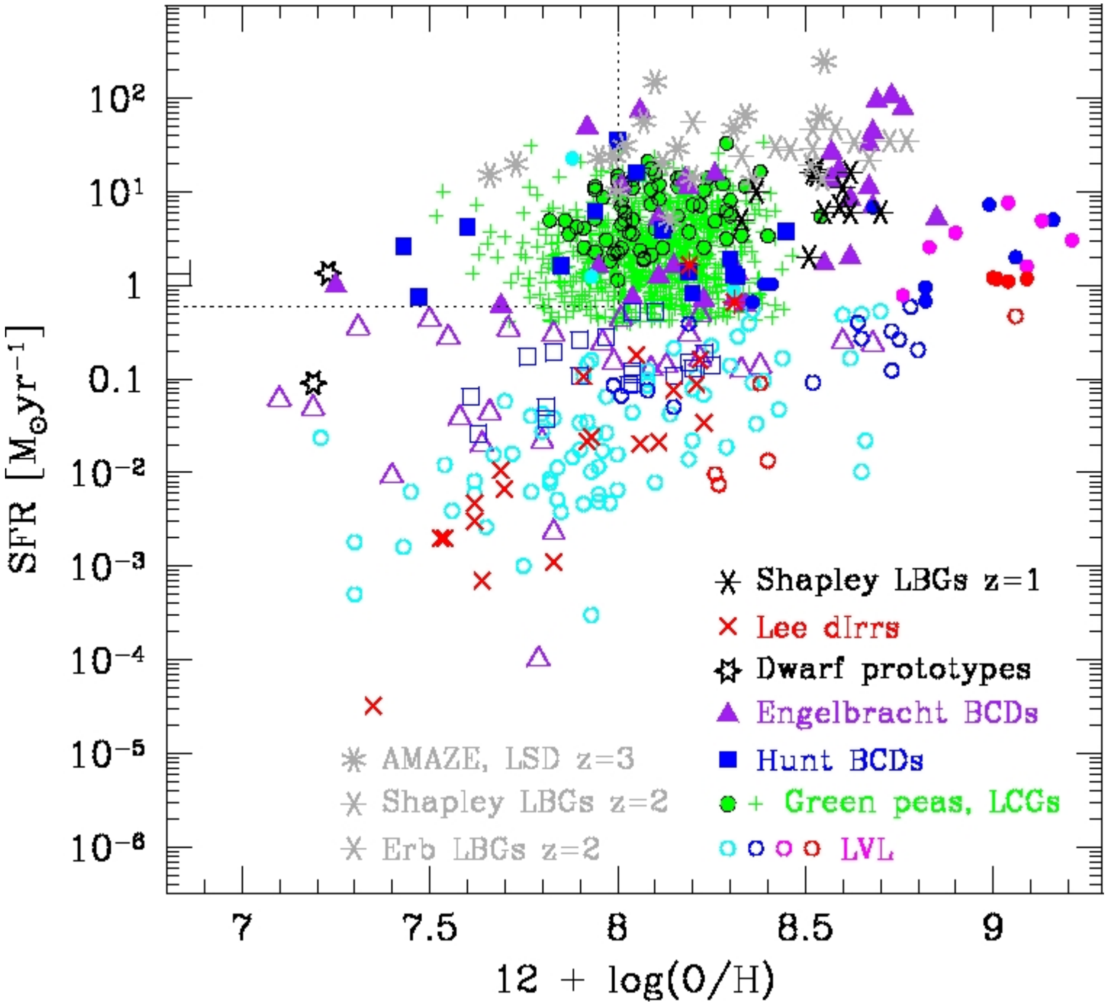
A local approach to a cosmological problem

If we can study the properties of a metal-poor ISM and its constituents locally, we may be able to better understand the high-redshift transition from metal-free Population III stars to the chemically evolved massive galaxies typical of the current epoch.

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, they can provide a unique window on the transition from a metal-free ISM to a metal-rich one.

But metallicity is generally correlated with SFR so we need to choose carefully in order to optimize the analogy with high-redshift starbursts.



(Taken from Hunt+ 2012).

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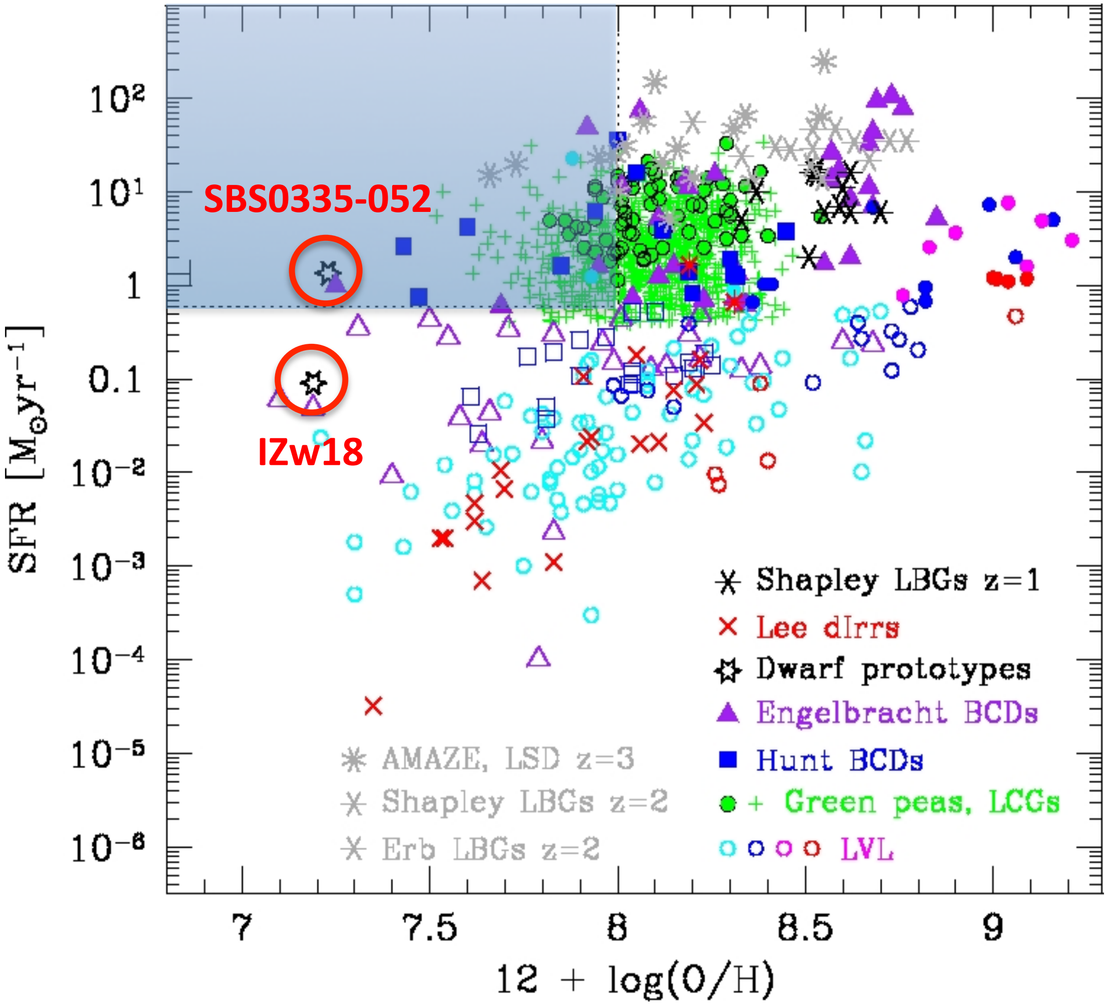


(Taken from Hunt+ 2012).

Dust in I Zw 18

12+log(O/H) = 7.17, ~1/30 $Z_{\odot}$

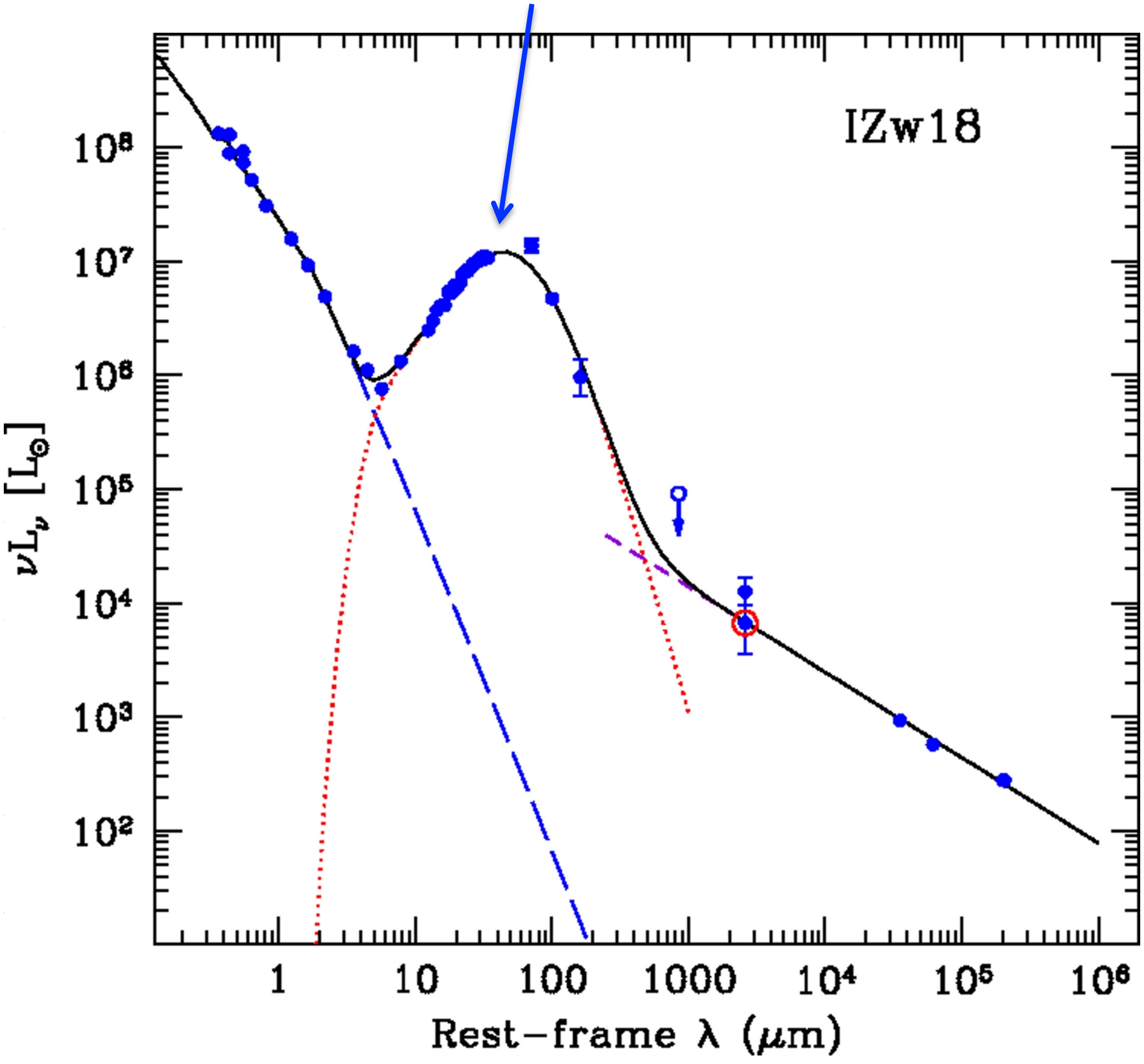
SFR = 0.1 $M_{\odot}$ /yr

(Hunt+ 2005)

Stellar mass ~1.4 x 10^6 $M_{\odot}$ (Fumagalli+ 2010)

Best-fit DUSTY model (cocoon of dust surrounding central star cluster, Ivezic & Elitzur 1997) gives a dust mass 3.4 x 10^2 $M_{\odot}$

The dust type that gives the best fit is primordial supernovae grains (Schneider & Bianchi 2007) with no silicates!



SED peaks at ~70μm

SED fitting with DUSTY models from Hunt + (2014); Spitzer data from Wu+ 2007, Herschel data from Herrera-Camus + 2012, Remy-Ruyer+ 2013, 3mm from Leroy+ 2007.

Dust extinction measured from SBS0035-052 SED

12+log(O/H) = 7.23

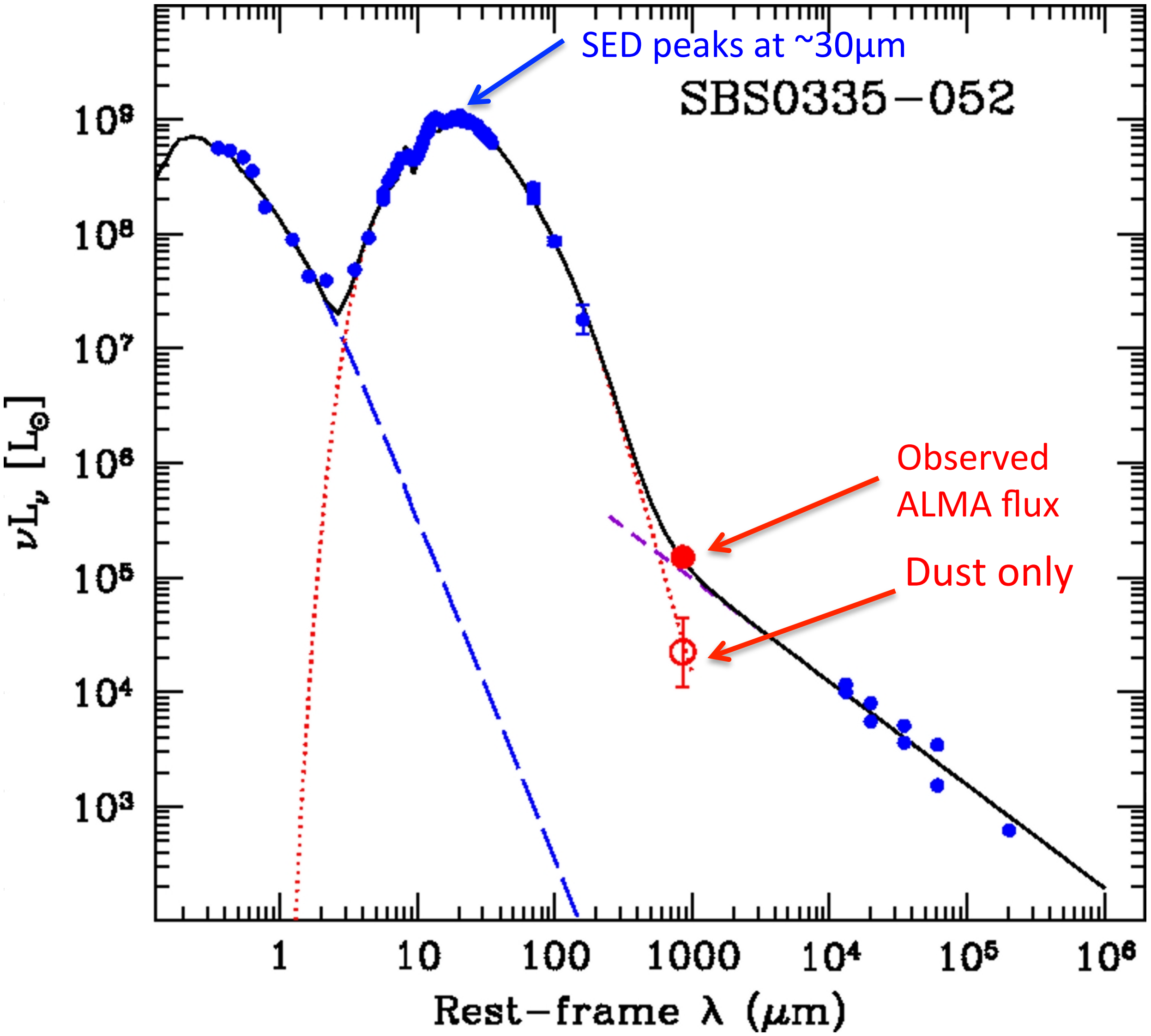
SFR = 1 $M_\odot$ /yr
(Hunt+ 2004)

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

A_V ~ 12 mag from silicate absorption feature at 9.7µm (Houck + 2004), consistent with Brα/Brγ (Hunt+ 2001).

SED fitting with DUSTY (as for I Zw 18) gives dust masses of ~3.8 x 10^4 $M_\odot$

Silicate dust, unlike IZw18!



SED peaks at ~30µm

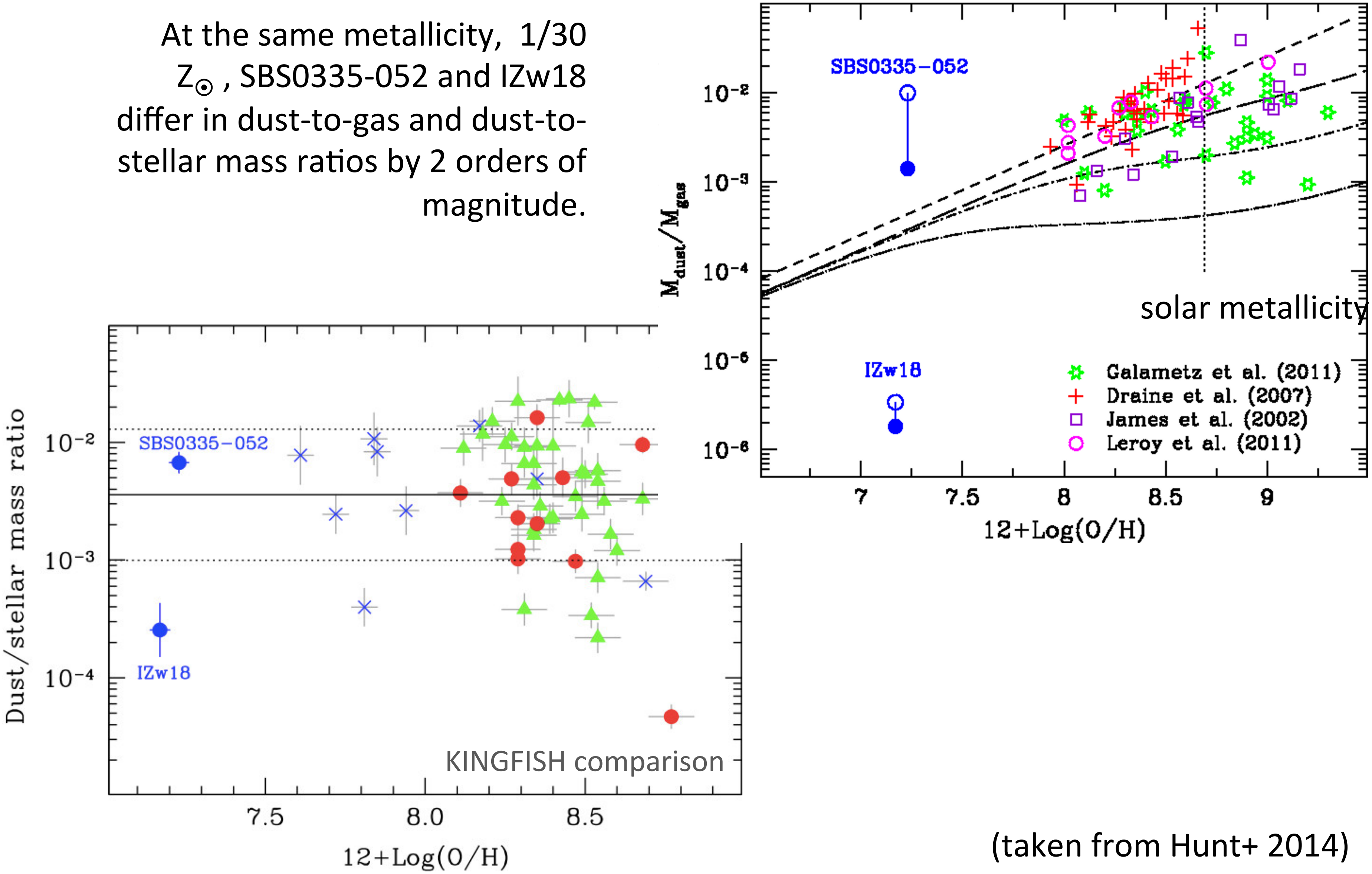
Observed ALMA flux

Dust only

SED from Hunt+ (2014)

Dust 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.



solar metallicity

KINGFISH comparison

(taken from Hunt+ 2014)

Beyond “local cosmology”

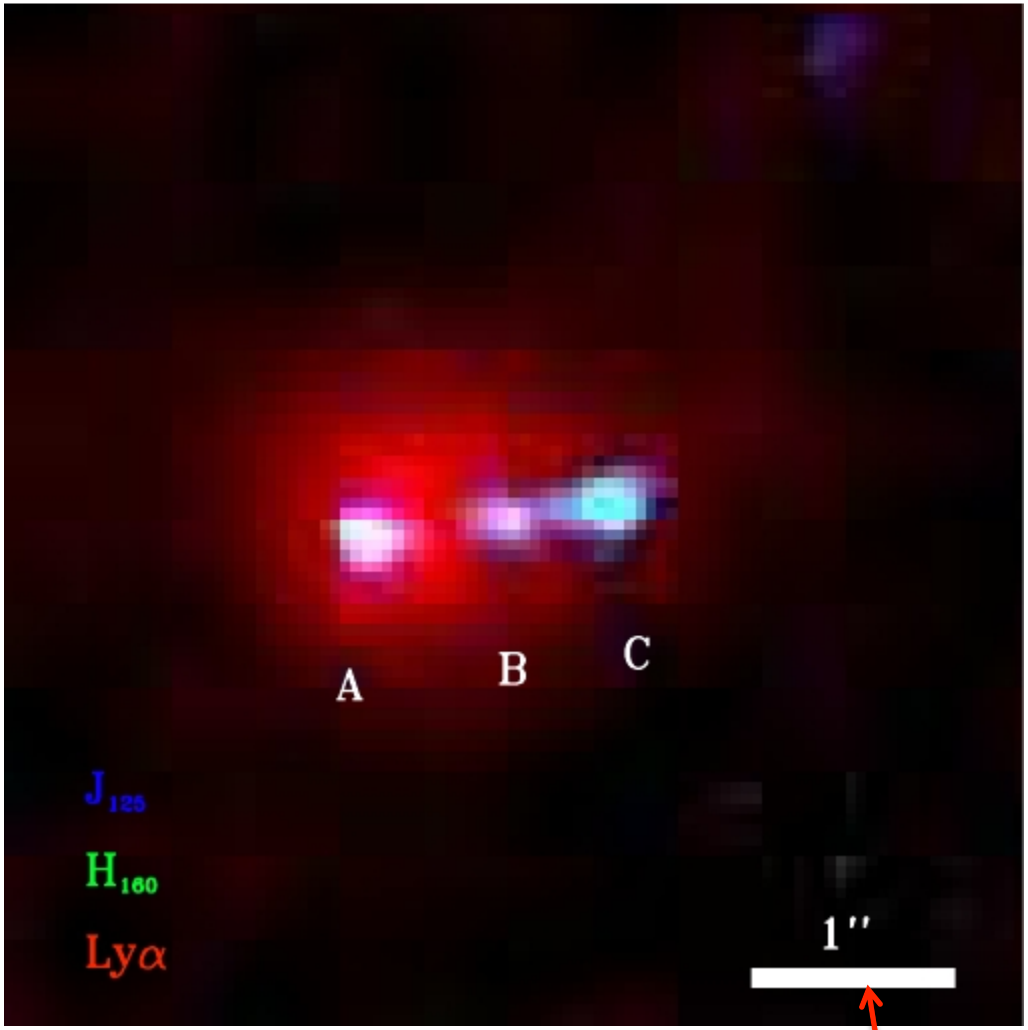
Himiko, a Lyman α emitter (LAE) at $z=6.6$

Himiko, discovered by Ouchi+ (2009), is a triple L* galaxy system with extended Lyman α emission. Each clump is ≤ 2 kpc in diameter.

This galaxy would also be regarded as a Lyman-break galaxy (LBG) because of its extremely red i'-z' > 2.1 (e.g., Bouwens+ 2011).

Its combined stellar mass of ~1.5×10^{10} $M_\odot$ and its SFR of ~100 $M_\odot$ yr^{-1} make it a (mild) starburst with specific SFR ~7×10^{-9} yr^{-1}.

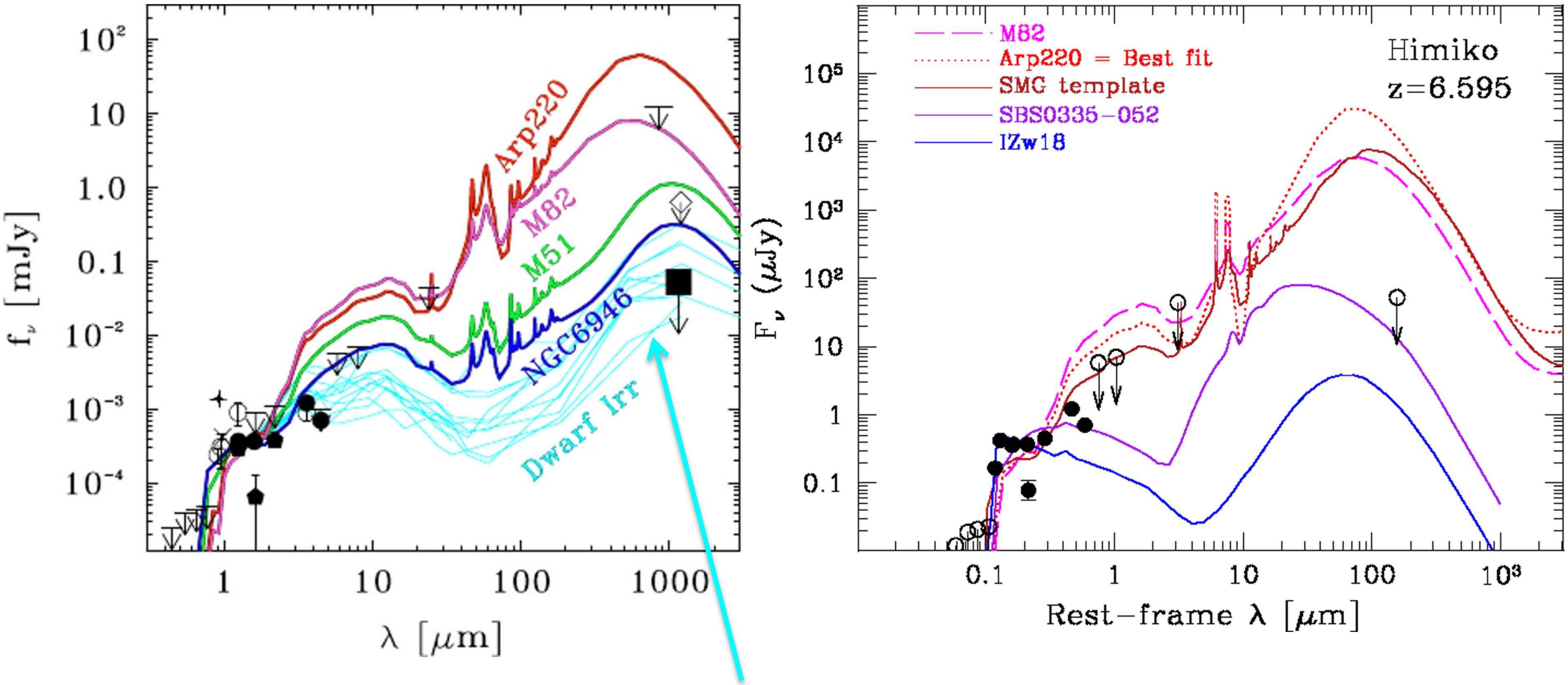
From ALMA rest-frame 160µm non-detection, Ouchi+ (2013) conclude that Himiko is a very low-metallicity near-primordial galaxy with little dust.



(taken from Ouchi+ 2013)

5.5 kpc

Himiko’s spectral energy distribution (SED)



Himiko SED from Ouchi+ (2013). Dwarf irregular SEDs from Dale+ (2007), other galaxies from Silva+ (1998). The SEDs for IZw18 and SBS0335-052 are from Hunt+ (2014) and shown previously. All SEDs normalized to Himiko’s rest-frame optical emission.

Observationally, can we characterize dust at high z?

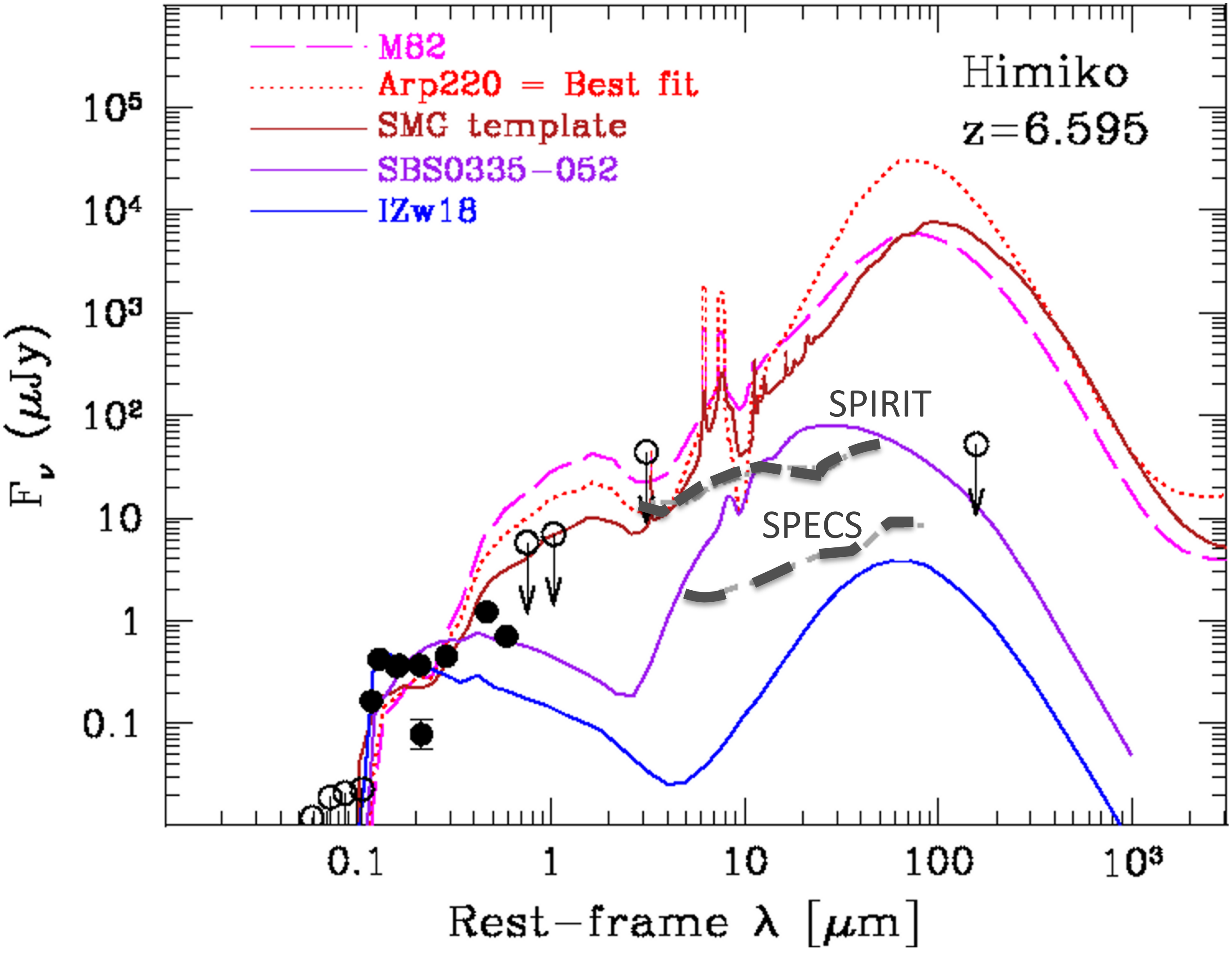
- ✓ SEDs of metal-poor starbursts in the Local Universe peak at shorter wavelengths than most other galaxies. They are also clumpy and do not have a typical stellar disk or bulge. It could be that Himiko behaves more like SBS0335-052 or IZw18 than more quiescent dwarf irregular galaxies.

- ✓ Thus, at high z need long-wavelength coverage at good sensitivity to adequately sample the SED peak, a necessary condition to accurately measure dust mass (and IR luminosity).

- ✓ But because high-z galaxies (like local low-metallicity starbursts) tend to be clumpy, need sub-arcsec spatial resolution to localize the dust emission and better separate it from contamination by free-free emission. Good spatial resolution will also ensure that we can map the dust and investigate the effects of (stellar) feedback on the ISM.

- ✓ Comparison of dust emission with UV+optical extinction curves measured with similar spatial scales will be crucial to understand dust at high z.

SPIRIT or SPECS could do the job



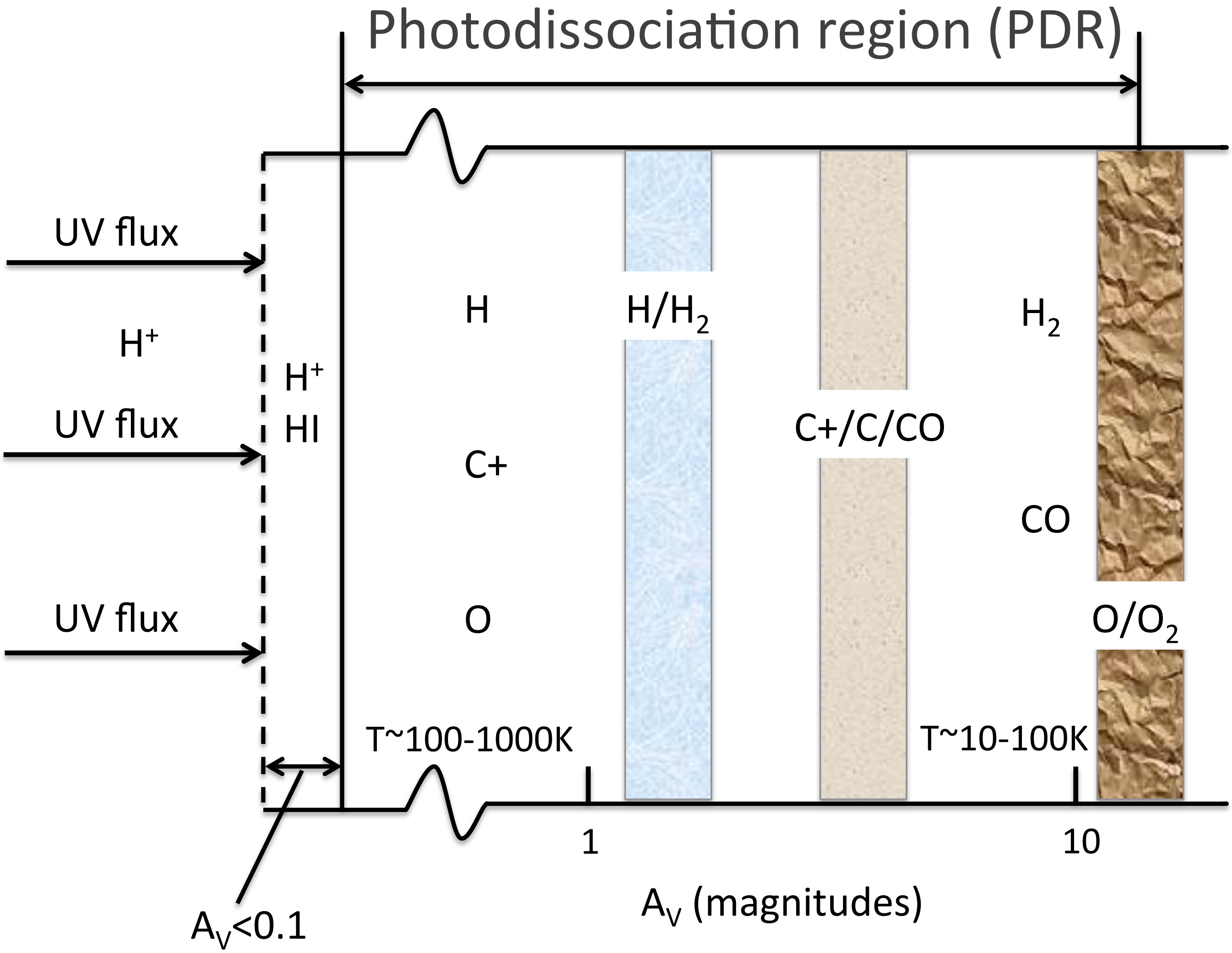
Probing dust content at the epoch of reionization

- ✓ Dust (together with H_2 and fine-structure lines) plays a fundamental role for gas cooling in pristine environments and governs the fragmentation at high redshift which leads to star formation and the transition from Population III to Pop. II (that occurs at $10^{-4} – 10^{-5}\ Z_{\odot}$, Omukai+ 2005; Schneider+ 2006, 2012; Clark+ 2008; Dopcke+ 2011, 2013)).

- ✓ The presence of dust at z>5 may establish a molecular ISM through formation of H_2 on dust grains (Latif+ 2012, Vallini+ 2012). Even at very low metallicity, high dust optical depths can result in a run-away mode of SF (Hiroshita & Hunt 2004).

- ✓ Dust properties and production processes in the low $Z/Z_{\odot}$ high-z universe can only be studied through studies of dust emission, better still if combined with well-determined extinction curves. Extrapolating SBS0335-052 (L_{IR}/M_{dust}) to Himiko at z~6.6 implies that SPECS could measure dust masses as low as a few times $10^6\ M_{\odot}$ (roughly 100 times lower than ALMA).

The carbon story
(CO-dark H_2 gas)



Photodissociation region (PDR)

UV flux

H^+

UV flux

UV flux

H^+
HI

H

C+

O

H/H_2

C+/C/CO

H_2

CO

O/O_2

T~100-1000K

T~10-100K

1

10

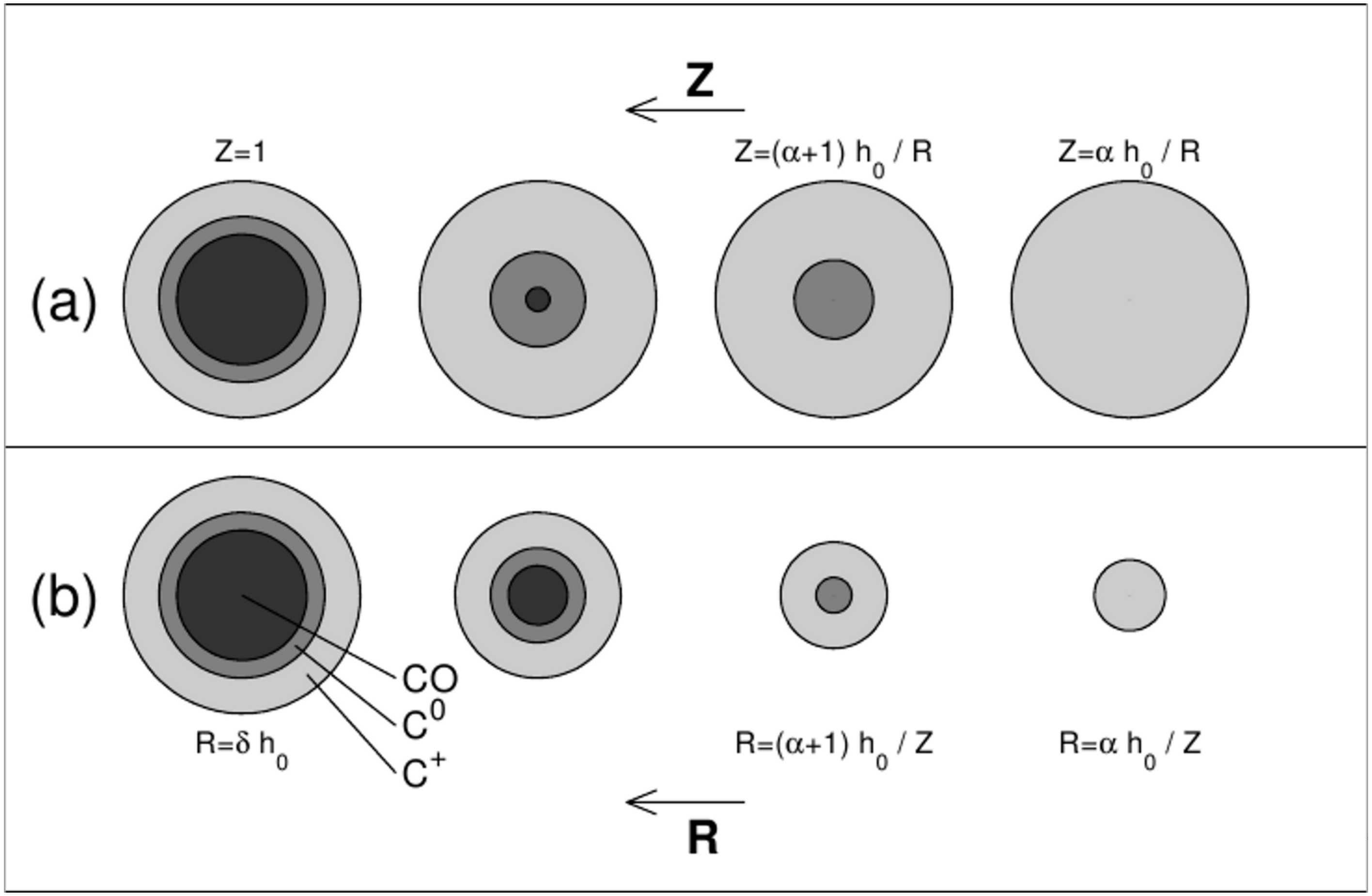
A_V (magnitudes)

$A_V<0.1$

(adapted from Wolfire & Kaufman 2011)

PDR structure changes at low metallicity

← increasing metallicity, constant cloud radius

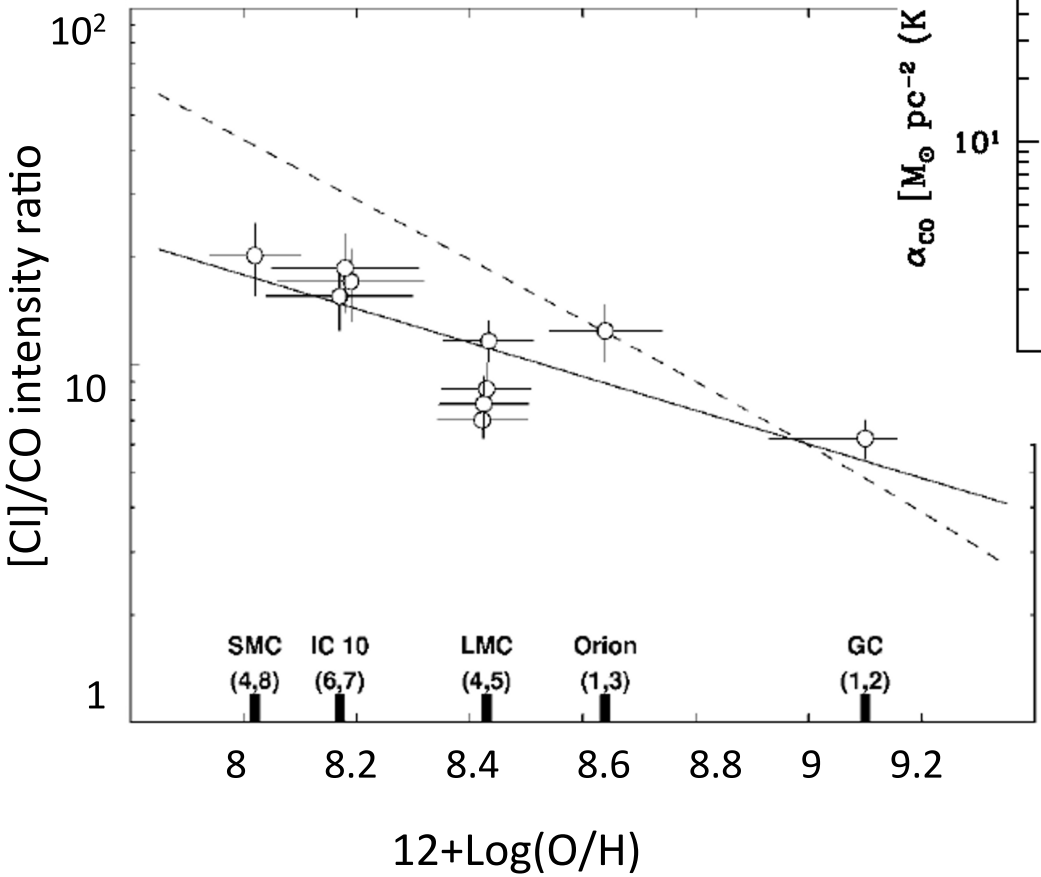


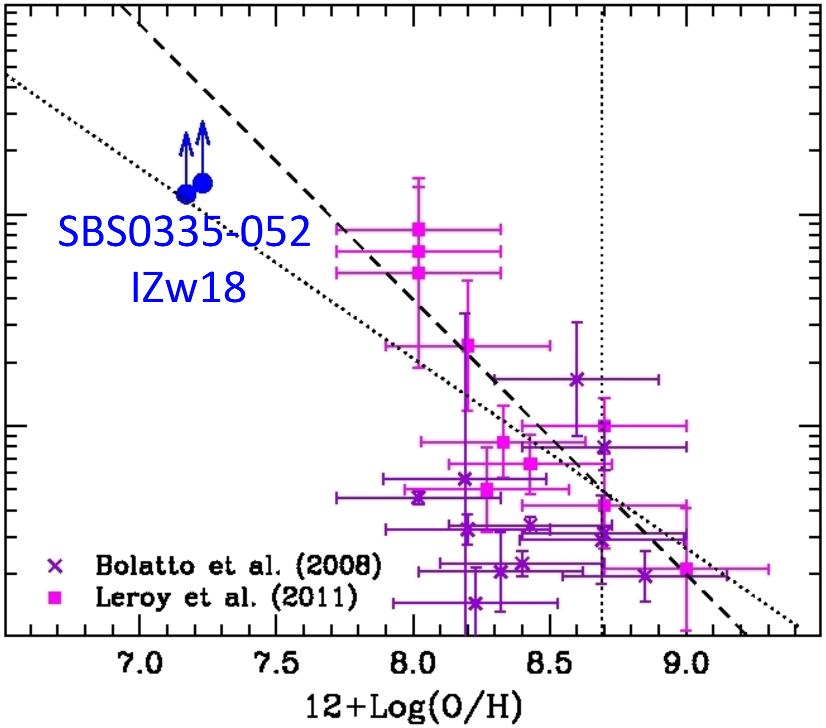
← increasing radius, constant metallicity

(taken from Bolatto+ 1999)

CO-dark H_2 gas prevalent at low metallicity

CO-H_2 mass conversion factor α and ratio of atomic carbon [CI] ($^3P_1$-$^3P_0$, 610μm) to CO(1-0) both larger at low metal abundance



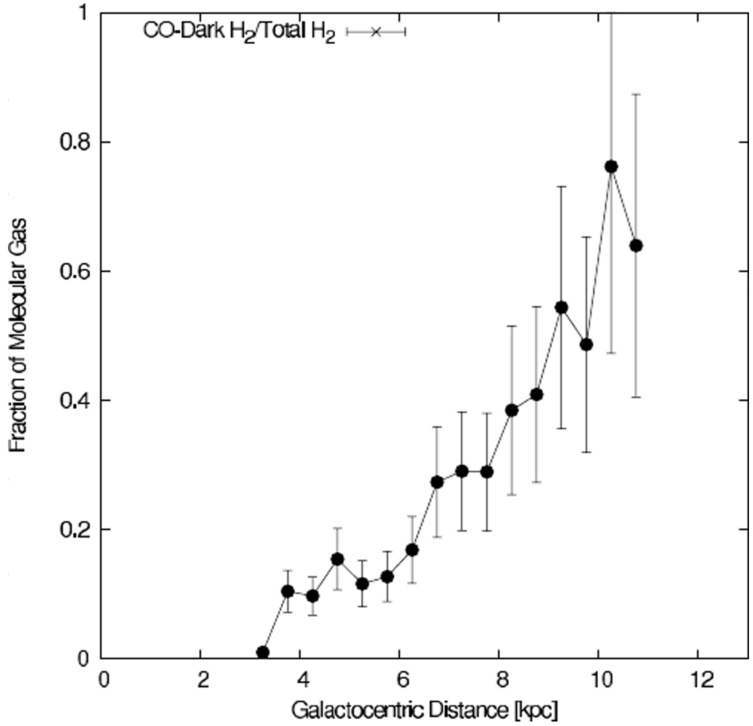


[CI] ($^3P_2$-$^3P_1$, 370μm) is typically 2-10 times stronger than [CI](1-0) but difficult to observe from the ground at z=0 (Band 10, ALMA).

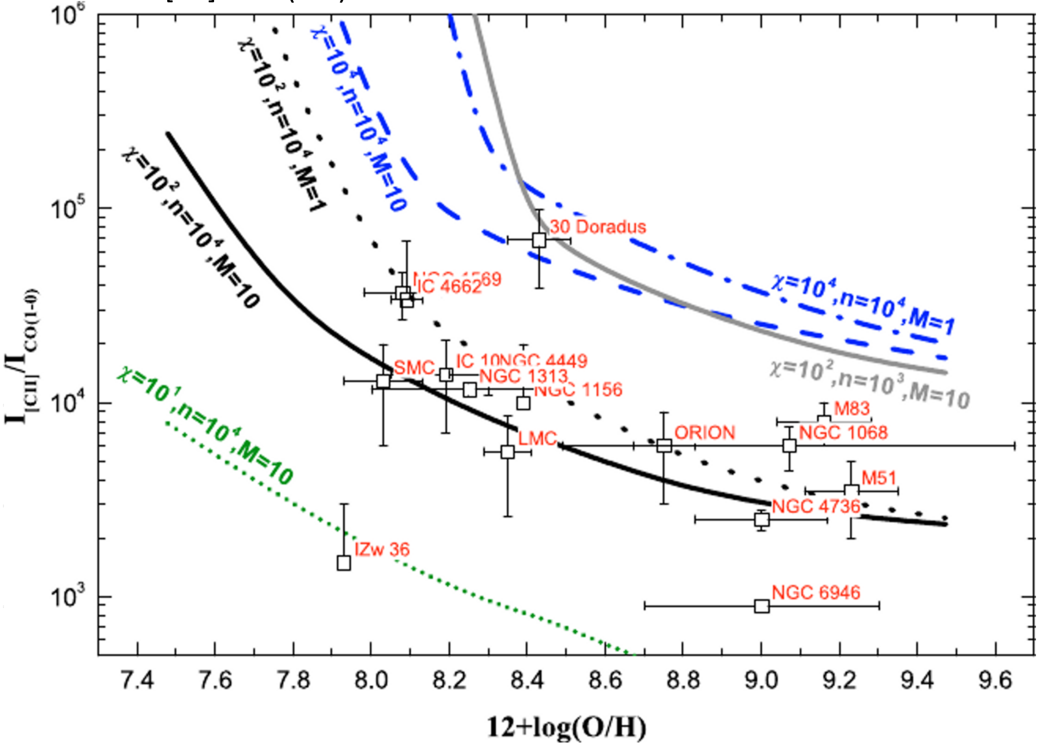
(Bolatto+ 2000, Hunt+ 2014)

CO-dark H_2 gas traced also by C+

Radial variation of Milky Way fraction of CO-dark H_2 gas (GOT C+ Pineda+ 2013)



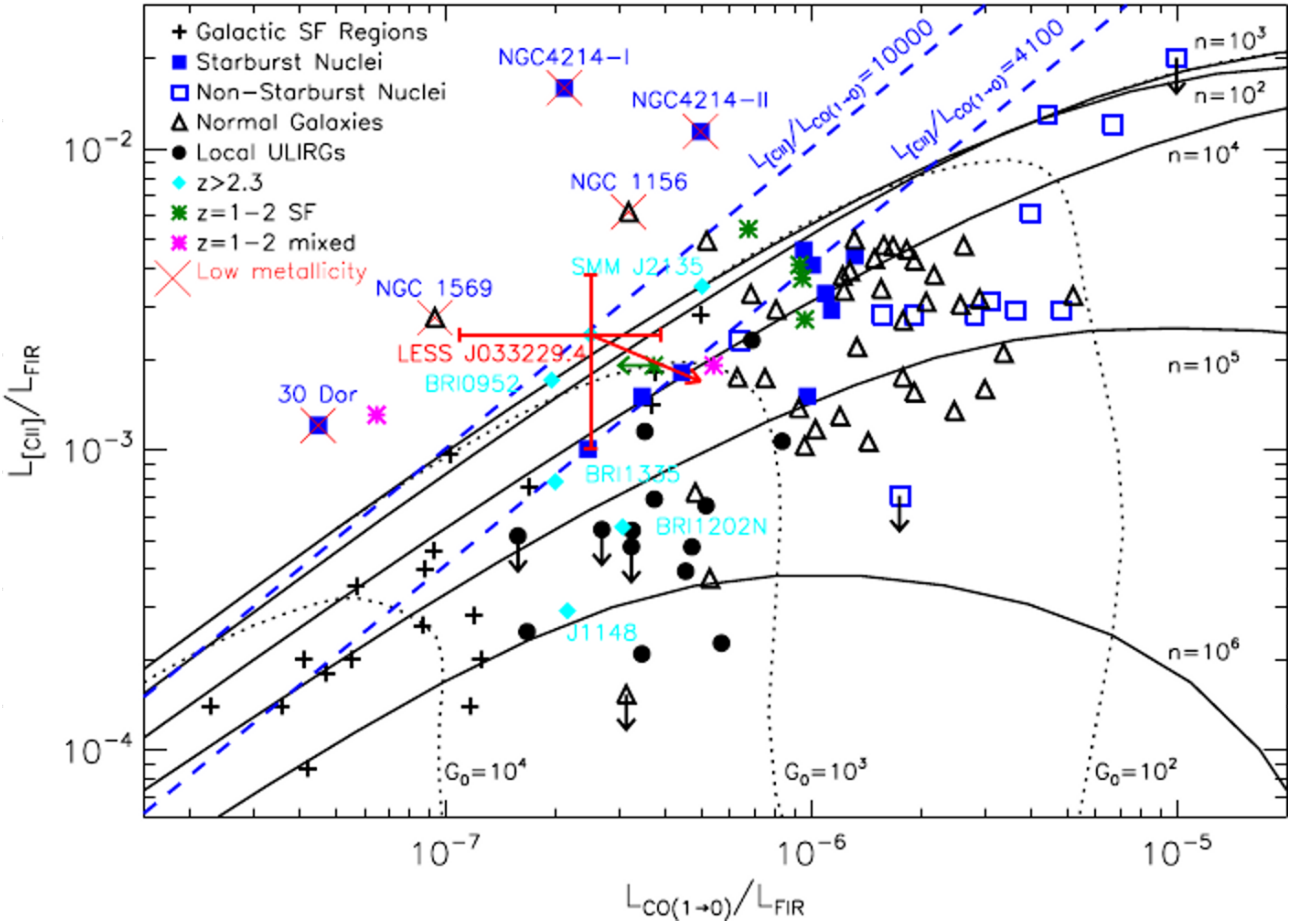
$I_{[CII]}/I_{CO(1-0)}$ vs. metallicity (Roellig+ 2006)



[CII] ($^2P_{3/2}$-$^2P_{1/2}$), one of the main coolants of the ISM [and > 20 times brighter than CI(1-0)], is a valuable indicator of CO-dark molecular gas at low metallicity.

C+ observed in high-z star-forming galaxies

(LESS galaxy z=4.8)

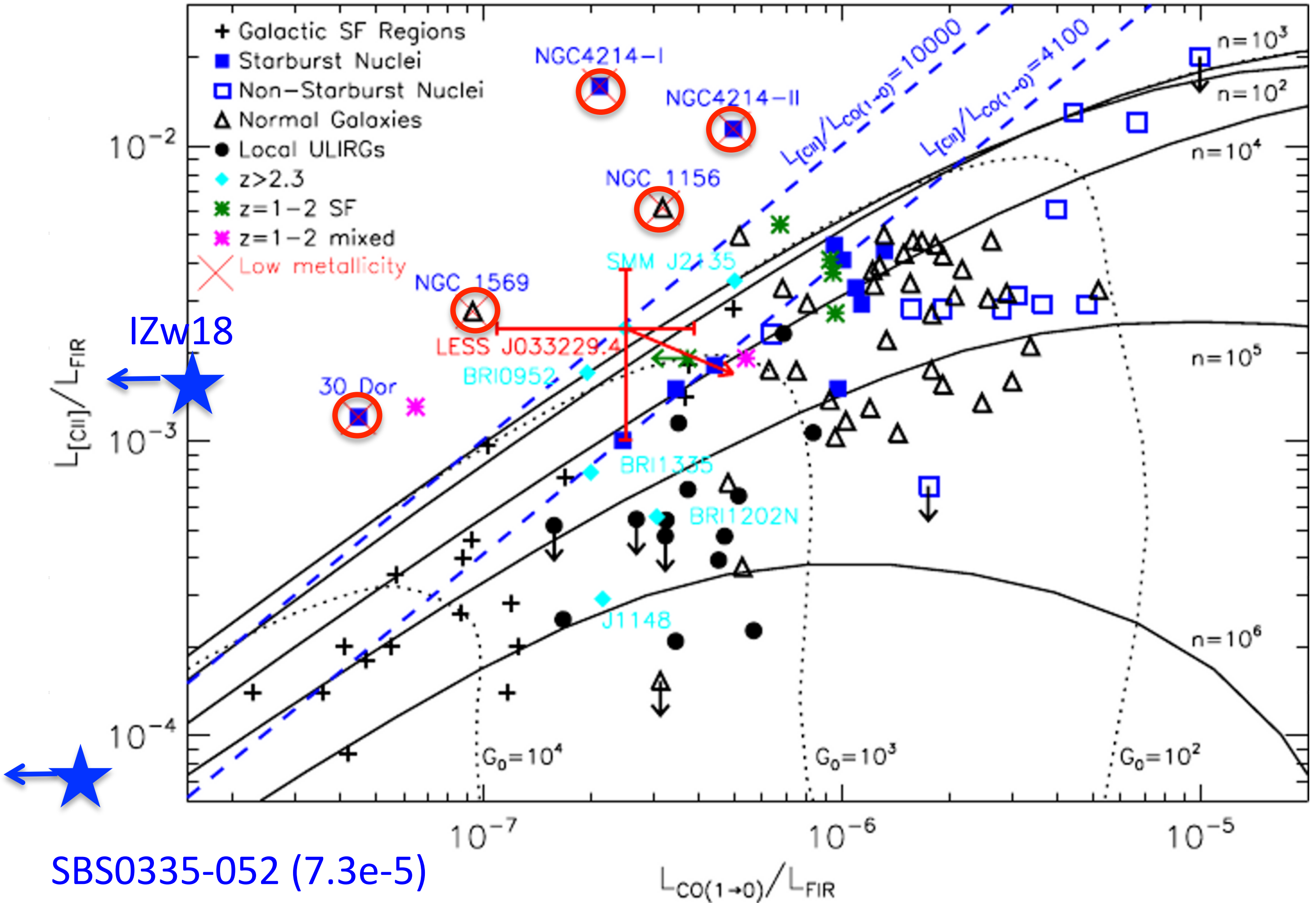


$L_{[CII]}/L_{FIR}$ vs. $L_{CO(1-0)}/L_{FIR}$ powerful diagnostic because ratios sensitive to gas density n and incident FUV flux G_0.

(taken from de Breuck+ 2011)

C+ observed in high-z star-forming galaxies

(LESS galaxy z=4.8)

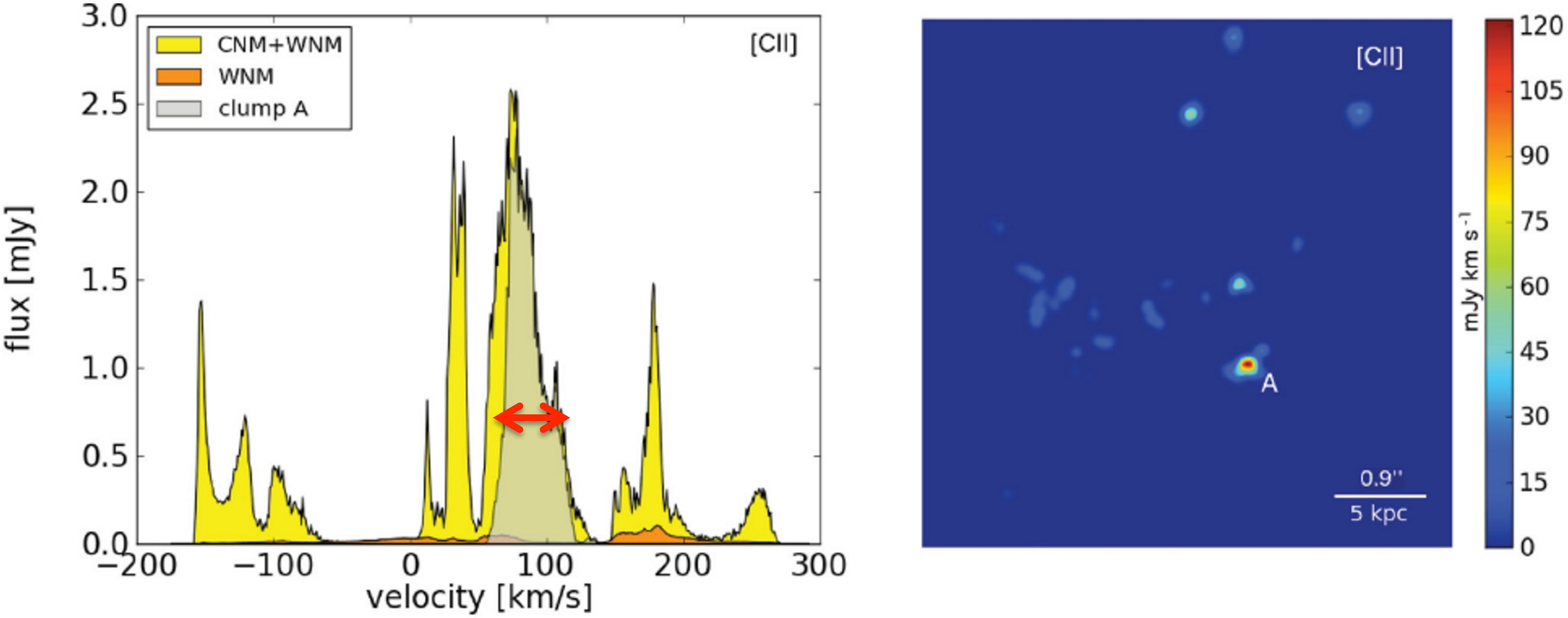


$L_{[CII]}/L_{FIR}$ vs. $L_{CO(1\text{-}0)}/L_{FIR}$ powerful diagnostic because ratios sensitive to gas density n and incident FUV flux G_0.

Low metallicity galaxies also have excess [CII]/FIR, but see SBS0335-052

(taken from de Breuck+ 2011, [CII] fluxes from K. Croxall, priv. comm.)

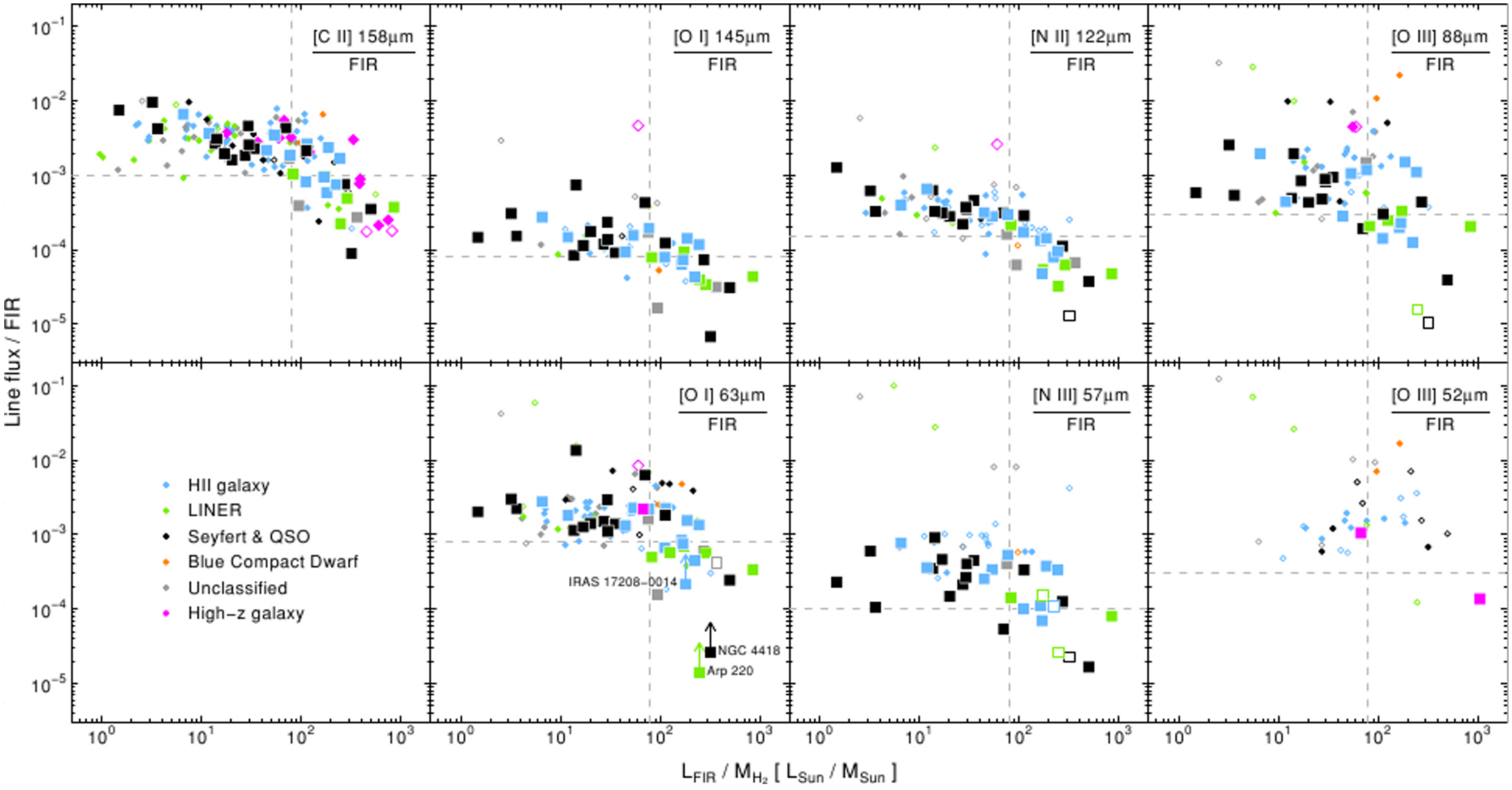
Line width ~ 50 km/s
Displacement from systemic velocity ~100 km/s



However, subgrid multiphase models of ISM in z~6 galaxies predict highly clumped [CII] clouds (< 3 kpc) and that [CII] virtually disappears at low O/H because of decreased cooling and disappearance of the CNM (Vallini+ 2013)

What about oxygen?

Deficits for most of the FIR fine-structure lines but maybe less for [OI]63μm

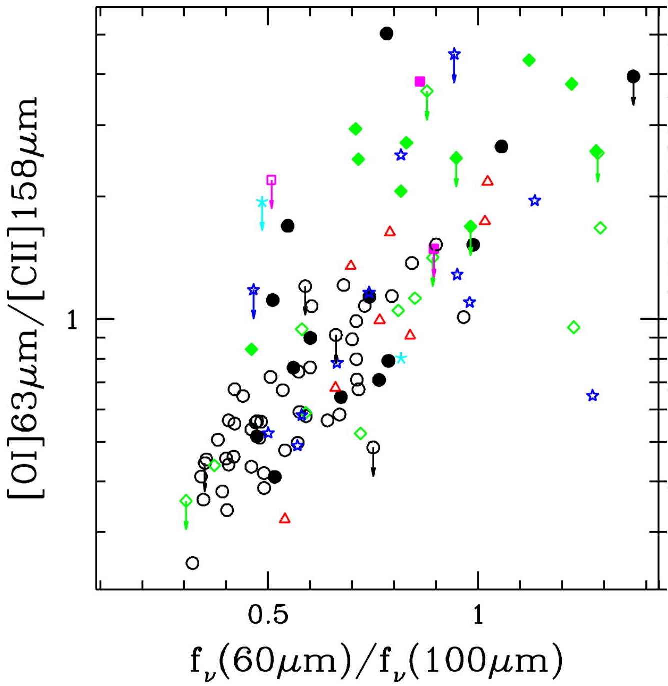


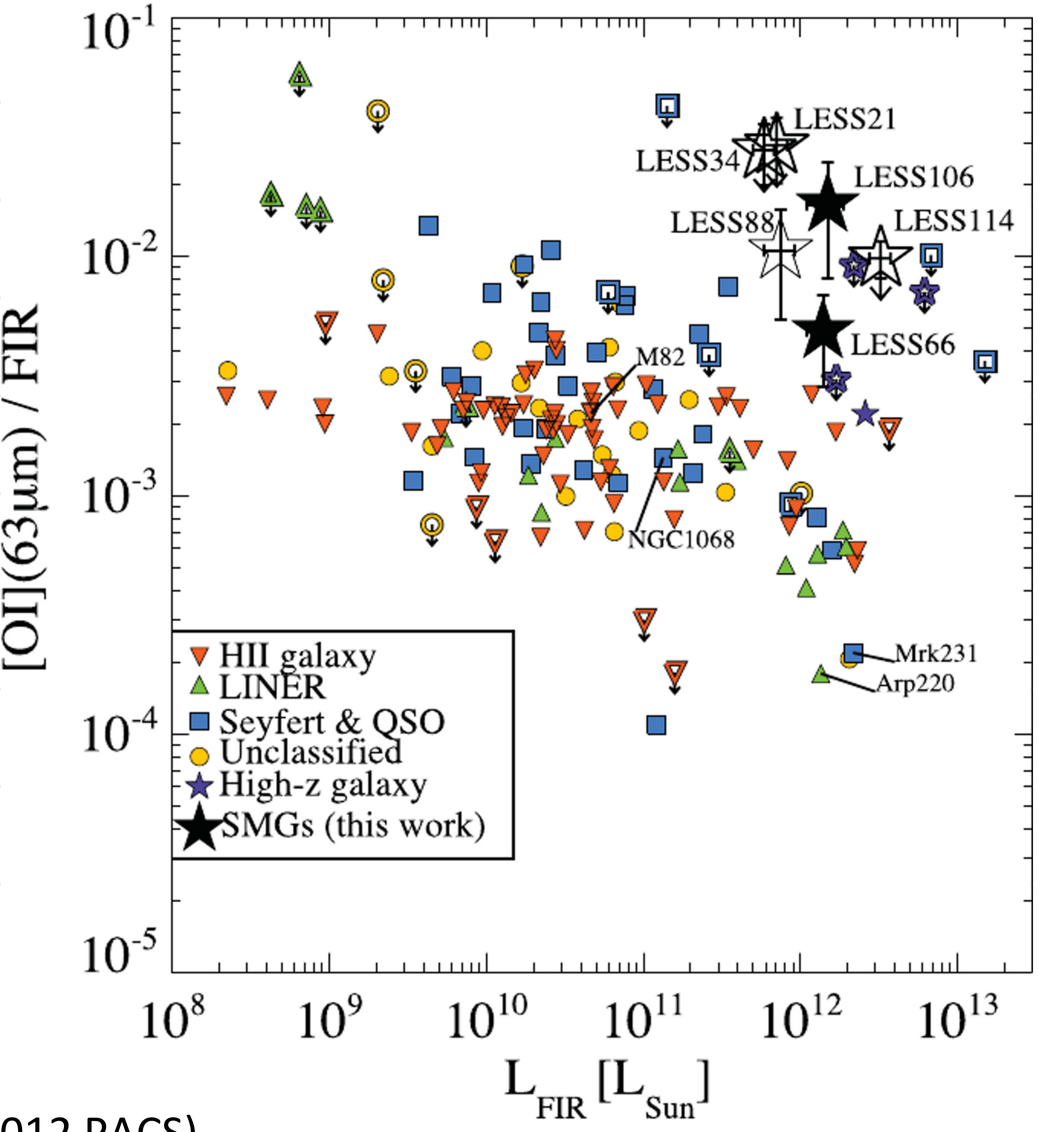
The deficits at high L_{FIR}/M_{H2} (and maybe for SBS0335-052) could be due to high ionization parameter (Abel+2009).

(from Gracia-Carpio+ 2011)

In dense PDRs, [OI] supplants [CII] as primary coolant

Critical density n_{cr} of [OI]63µm ~ 10^6 cm^{-3} while n_{cr} [CII] ~ 3e3 cm^{-3}.





(from Brauher+ 2008 ISO, Coppin+ 2012 PACS)

Constraining ISM physics in pristine environments

✓ The behavior of the two brightest ISM cooling lines, [CII] and [OI], changes dramatically with metallicity. Up to now, it is very difficult to probe these transitions in faint, metal-poor objects especially in the local Universe (integrated fluxes ~ 1e-18 W m^{-2}).

✓ Critical densities of CO(1-0) and CI lines are both $n_{cr} \sim 10^3$ cm^{-3}, thus transitions probably arise from the same volume. The 3P fine-structure system of cool atomic carbon forms a simple 3-level system, thus detection of both optically thin lines, CI(1-0), CI(2-1) can be used to derive excitation temperature, neutral C column density, and mass, without additional information (e.g., Weiss+ 2003, Walter+ 2011). The detection of both transitions has been reported in only a few galaxies to date, and in conjunction with ALMA, the technique can be used up to high redshifts.

Atomic carbon will be a powerful diagnostic for low-metallicity galaxies.

Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	60 – 4000 for [CI] to $z \leq 5$
Angular resolution	arcsec	<0.1 to resolve z~7 clumpy structures
Spectral resolution, $(\lambda/\Delta\lambda)$	dimensionless	6000 to resolve 50 km/s
Continuum sensitivity	μJy	1−5
Spectral line sensitivity	10^{-19} W m^{-2}	at least 0.1 (10^{-20} W m^{-2})
Instantaneous FoV	arcmin	1-5 for metal-poor dwarfs at z=0; 0.5 for high z
Number of target fields	dimensionless	N/A
Field of Regard	sr	4π