Properties and Star Formation Histories of Intermediate Redshift Dwarf Low-Mass Star-Forming Galaxies

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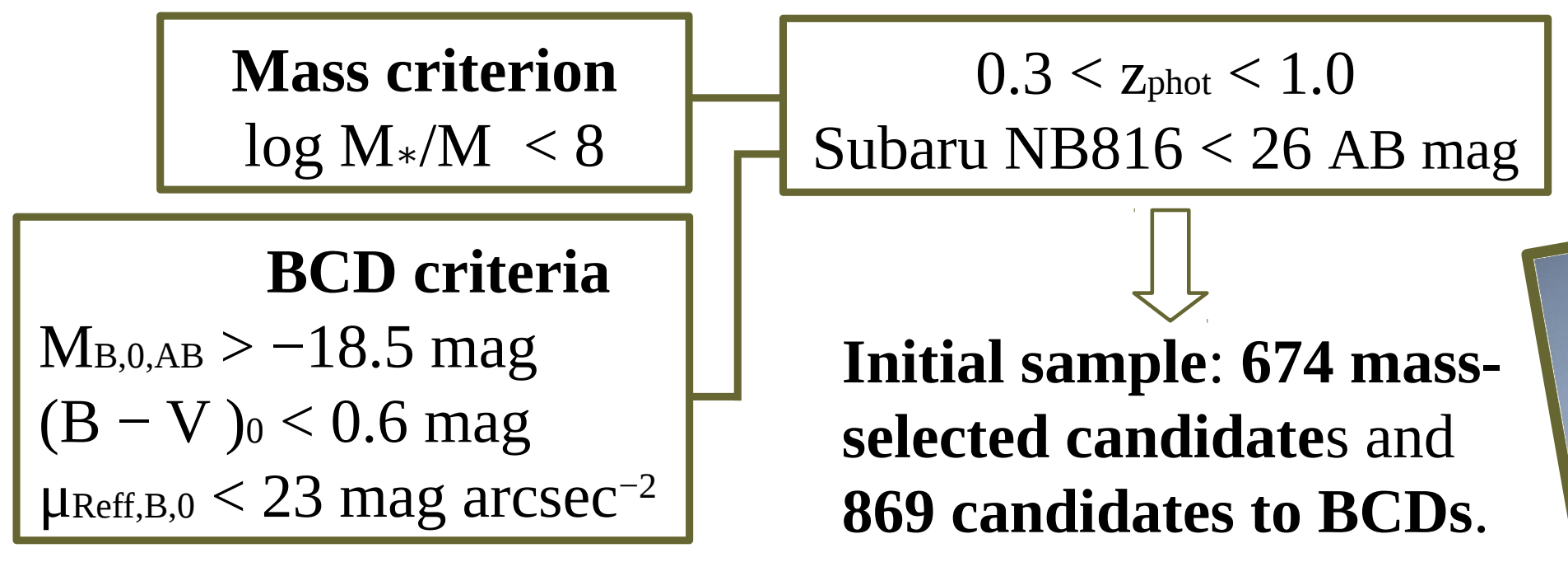
Introduction

The epoch when low-mass star-forming galaxies (LMSFGs) form the bulk of their stellar mass is still uncertain. While some models predict an early formation (e.g., Dekel & Silk, 1986), others favor a delayed scenario until later ages of the Universe (e.g., Kepner+97, Mamon+12). Among dwarfs, LMSFGs turn out to be of special interest for different reasons:

(1) They provide an ideal laboratory for studying star formation (SF) processes. (2) They can be observed at higher redshifts. (3) They resemble the primordial entities in the hierarchical galaxy formation scenario due to their low stellar mass, high gas content, low metallicities, highly excited inter stellar medium (ISM), and active SF. The **main objective** of this work is to **shed light on the formation and evolution of dwarf galaxies**. We aim at reducing the uncertainties in the formation redshift of dwarf galaxies and constraining their star formation histories (SFHs). We use two complementary observational approaches: (1) direct observations of galaxies at different redshifts, and (2) reconstruction of the previous galaxy history from fossil records hidden within their spectral energy distributions (SEDs).

Initial Sample Selection & Data

We select the candidates to dwarf galaxies in a catalog built on the SUBARU-NB816 image of CDFS field. We use preliminary photometric redshifts and stellar masses estimations obtained with **RAINBOW** Software Package (Pérez-González+08, Barro+11a,b), and morphology catalogs by Griffith+12.



Mass criterion
$\log M_*/M < 8$

$0.3 < z_{phot} < 1.0$
Subaru NB816 < 26 AB mag

BCD criteria
$M_{B,0,AB} > -18.5$ mag
$(B-V)_0 < 0.6$ mag
$\mu_{Reff,B,0} < 23$ mag arcsec^{-2}

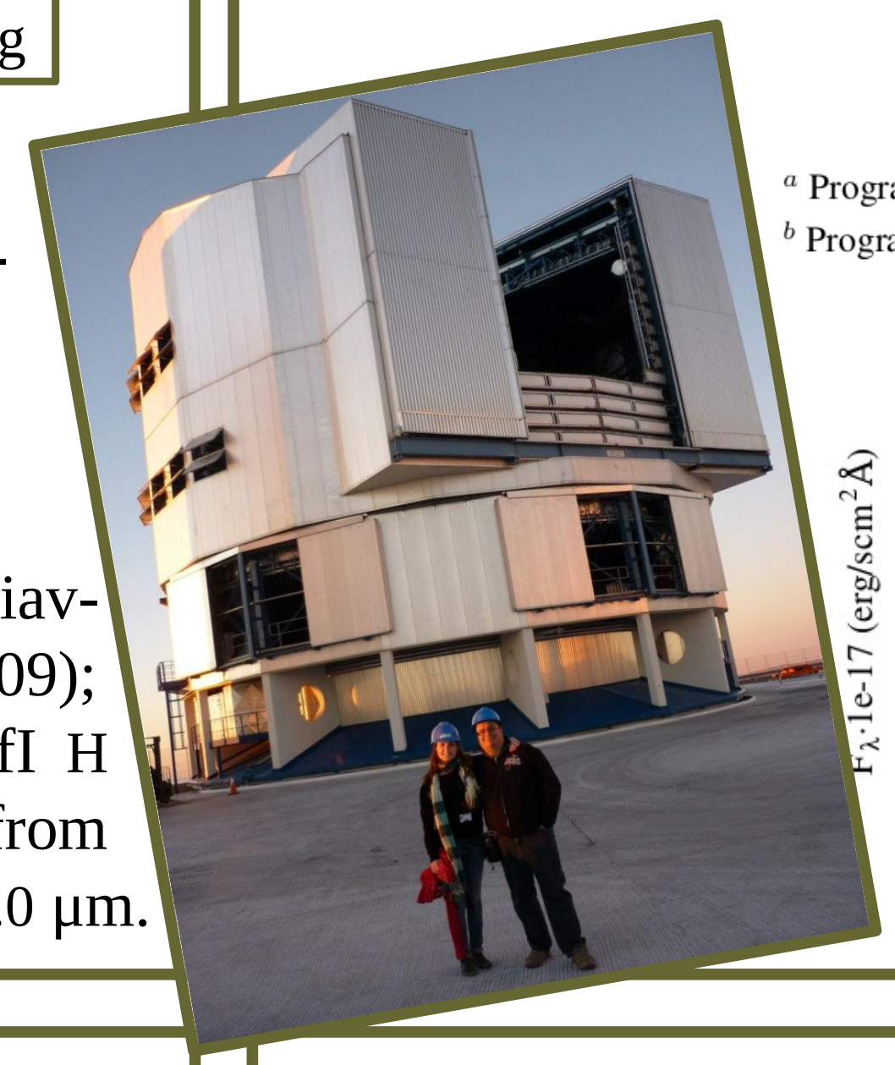
Initial sample: **674 mass-selected candidates** and **869 candidates to BCDs**.

With **RAINBOW** we obtain photometry on 39 bands: HST/ACS b, v, i, z, and VLT/VIMOS U & R from GOODS (Giavalisco+04; Nonino+09); MUSYC (Cardamone+10; Taylor+09); ESO WFI U38, U, B, V, and R (Hildebrandt+06); ESO SofI H (Moy+03); HST/WFC3 F105W, F145W, and F160W from CANDELS (Grogin+11; Koekemoer+11); Spitzer/IRAC 3.6-8.0 µm.

VLT/VIMOS Observations

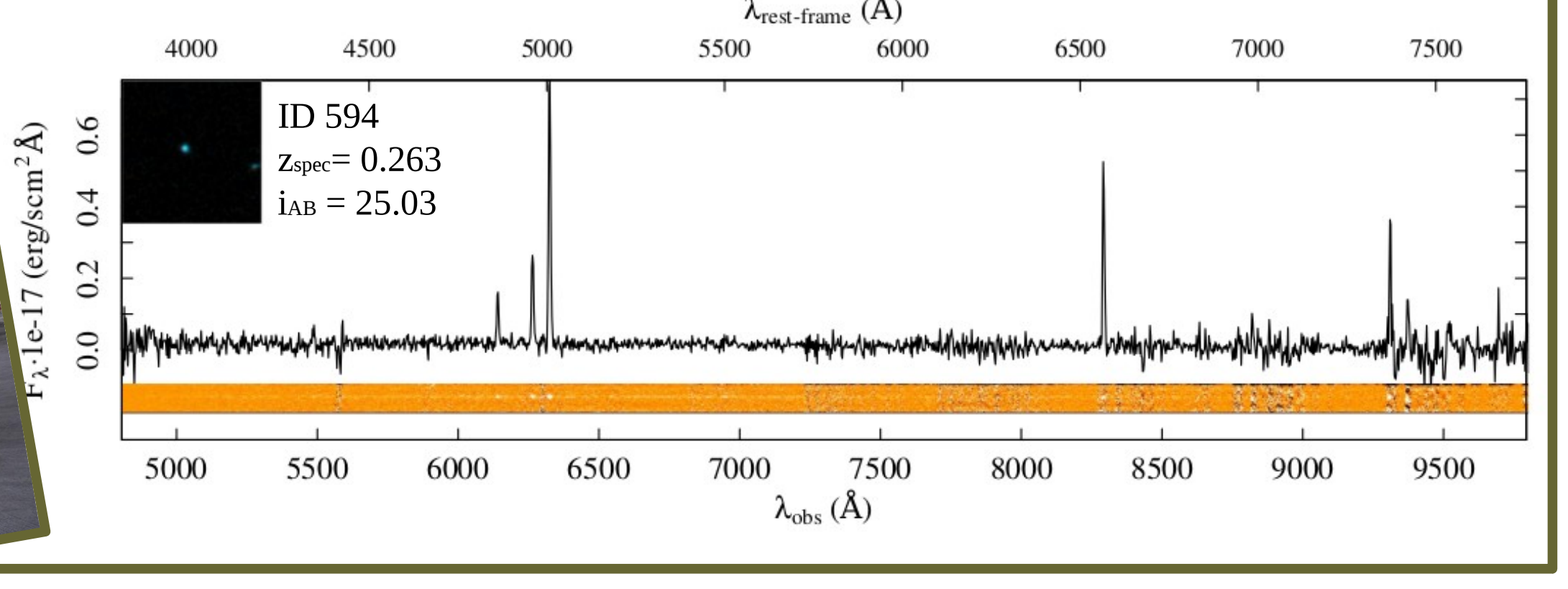
We carry out **2 VIMOS spectroscopy programs**. A total of **3 pointings** with exposure times: **12000s, 9600s, and 13680s**. We observe **327 targets**: 253 candidates to dwarfs and 74 candidates to BCDs. Observations are carried out under excellent atmospheric conditions and seeing values **~0".6 and ~1".2** (first and second program, respectively).

Reduction was carried out with **VIPGI** (Scodeggio+05) and **REDUCEME** (Cardiel, 1999).



Run-Pointing	α [J2000]	δ [J2000]	T_{exp} [s]	# Slits	# Dwarfs	# BCDs[c]
1^a-1	03h32m33.5s	-27°45' 26.3"	14400	119	94	25
1^a-2	03h32m22.8s	-27°51' 09.5"	14400	119	99	20
2^b-3	03h32m33.5s	-27°45' 26.3"	13680	92	60	32

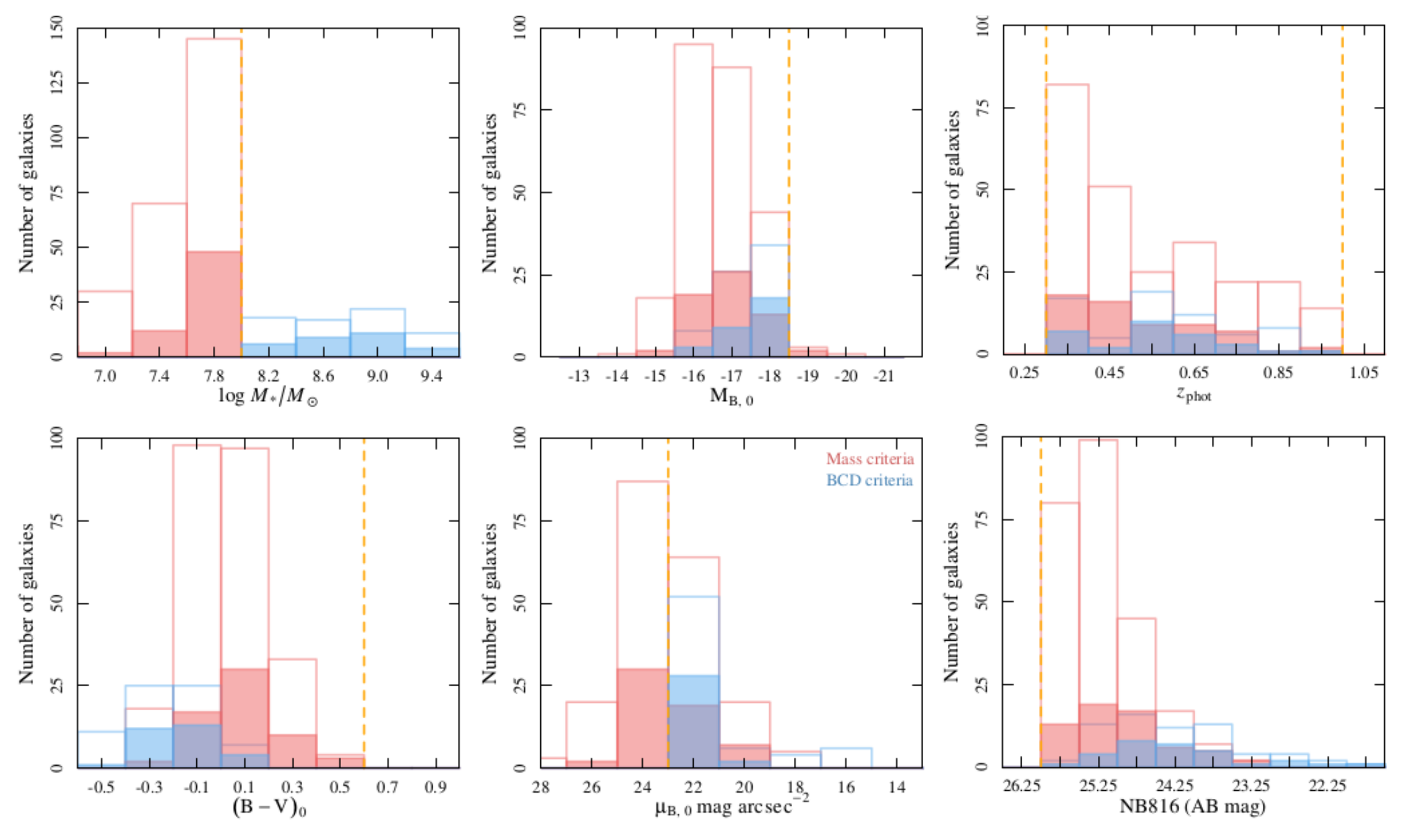
[a] Program 088.A-0321.
[b] Program 090.A-0858.

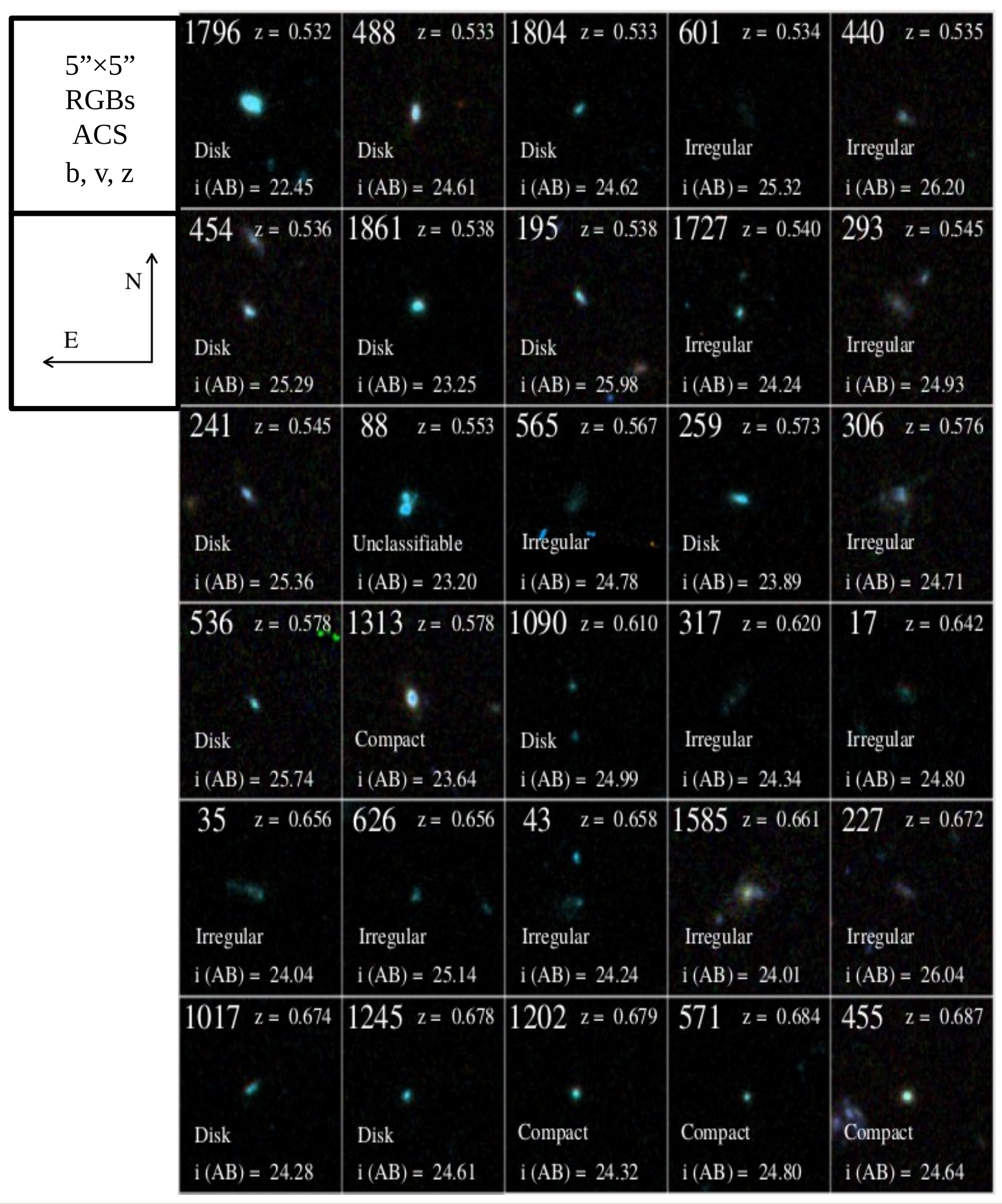


Spectroscopic Sample

We obtain **reliable spectroscopic redshifts** and **emission lines measurements** (e.g., [OII]λλ3727, Hβ, and [OIII]λλ4959,5007) for a representative subsample of **94 galaxies** (solid histograms) out of the 327 galaxies observed (open histograms).

Our analysis is limited to these spectroscopically confirmed galaxies. This biases our sample towards **star-forming galaxies**.



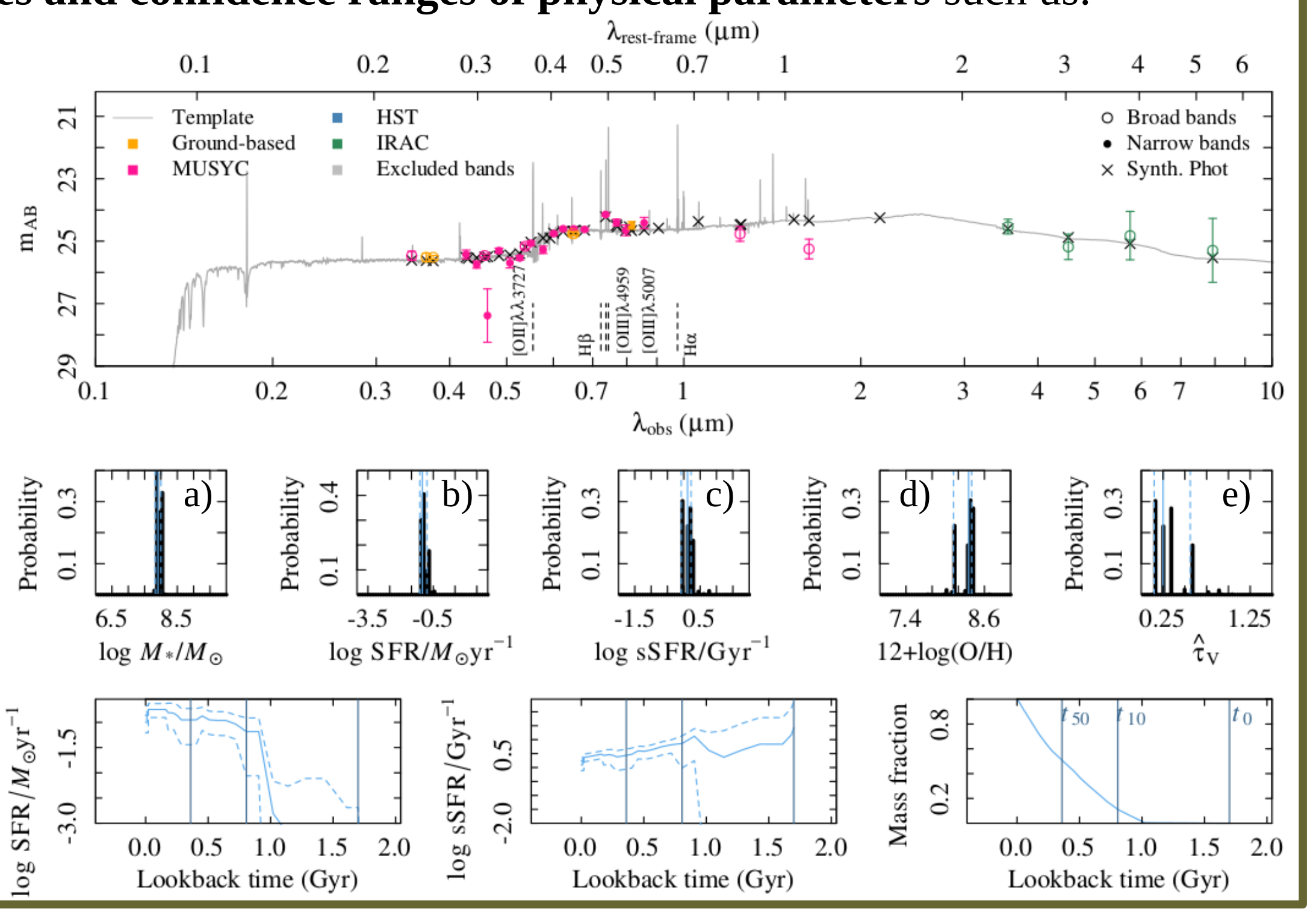


SED-fitting

We use the **Bayessian methodology developed by Pacifici et al. (2012)** to obtain **SED-fits for 91 galaxies**. This tool (1) consistently combines photometric (broadband) and spectroscopic (equivalent widths of emission lines) data, and (2) uses physically motivated SFHs with non-uniform variations of the star formation rate (SFR) as a function of time, to provide **best estimates and confidence ranges of physical parameters** such us:

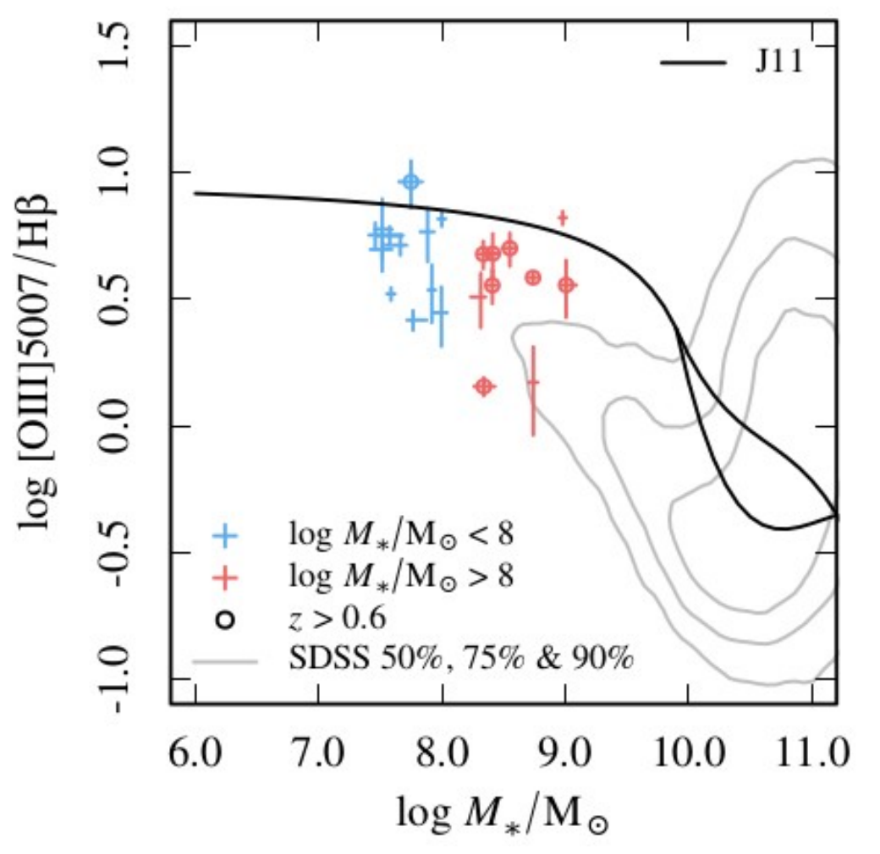
a) **Stellar mass**.
b) **SFR**.
c) **Specific SFR**.
d) Gas-phase **oxygen abundance**.
e) Total effective V-band absorption **optical depth of the dust**.

It also provides a **best-estimate SFH** for each galaxy.



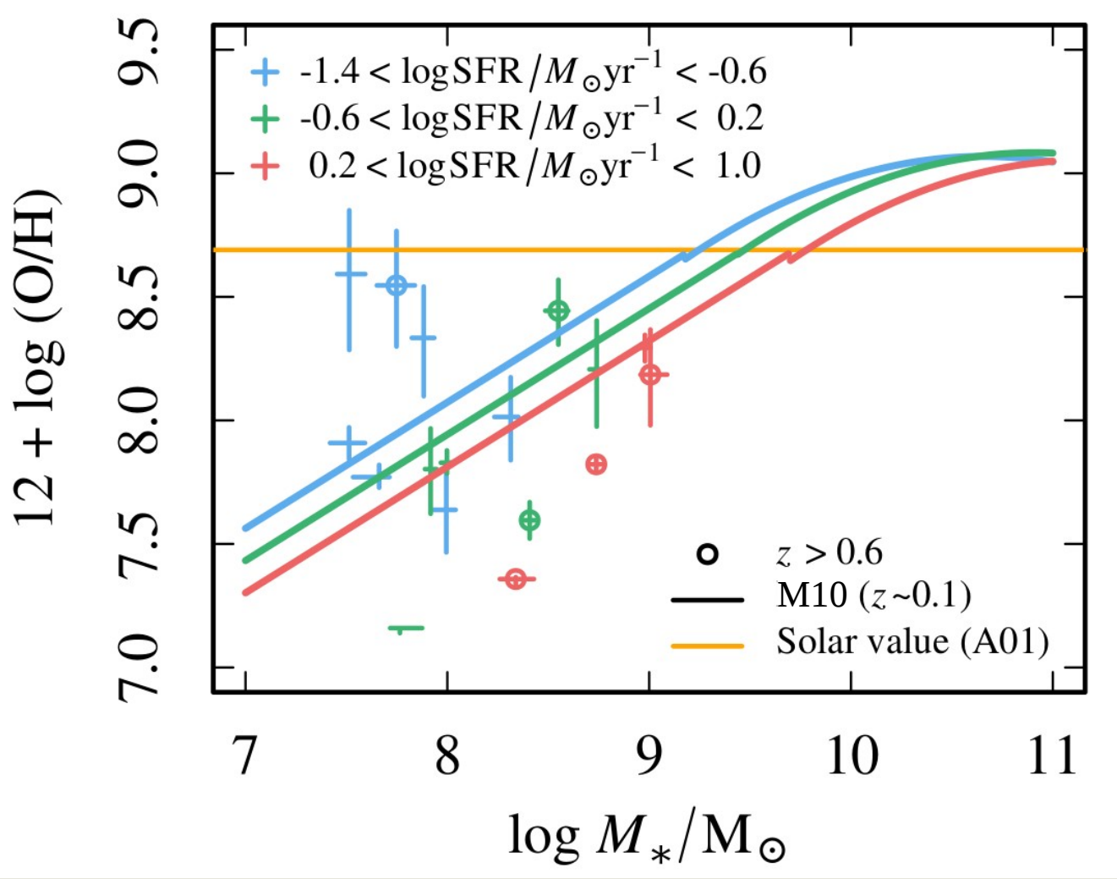
Physical properties (I)

Given the Mass-Excitation diagram (Juneau+11) of our sample, we can affirm that **the nature of the source of the emission lines we identify in our sample is SF** rather than AGN activity.



To derive the oxygen **abundance** we use the ***R23*** method (Pagel+79), and the calibration by Kewley and Dopita (2002) and Kobulnicky and Kewley (2004). We use the method as described in Kewley and Ellison (2008), and the low metallicity branch expressions. We obtain **12+log(O/H)∼7.16-8.59**, i.e., **very low metallicities ∼1-1/34 $Z_⊙$** (solar value by Allende Prieto+01), consistent with works such as Henry+13. We do not find a clear correlation between metallicity and stellar mass.

The **Fundamental Metallicity Relation** (Mannucci+10; Lara-López+10) is thought to suggest that there is an interplay between SF and gas inflows leading to an **inverse correlation between SFR and metallicity**. We find hints of the same trend for our sample of LMSFGs.

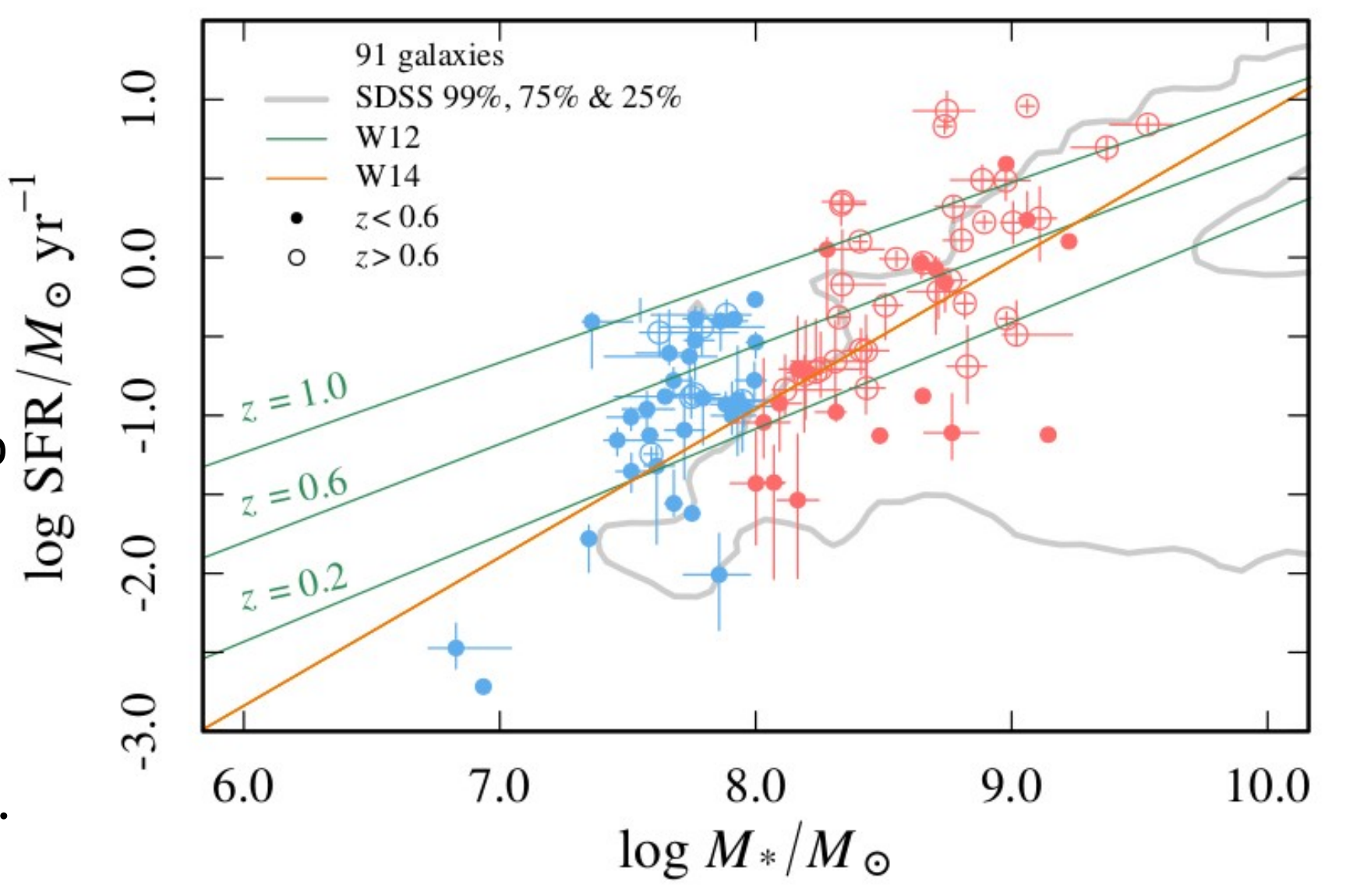


We only find **3 candidates to extremely metal-deficient galaxy** following the definition by Guseva et al. 2015.

Physical properties (II)

Stellar masses span **from 10^7 $M_⊙$ to $10^{9.5}$ $M_⊙$**. SFRs span a wide 3 dex range varying within **$\log SFR/M_⊙\ yr^{-1} \sim -2.8$–$0.8$** . sSFRs span between **$\log sSFR \sim -10.2$–-7.8 yr^{-1}**. These values are similar to previous studies of low-mass galaxies (e.g., Brinchmann+04; Bauer+05; Salim+07; Amorín+12; Atek+14).

However, and **probably due to our selection criteria, we reach lower values of SFR (i.e., sSFR) for the same masses**. **These values place the galaxies in the final sample on the SF main sequence (SF-MS) found by Whitaker+12 and Whitaker+14**. The dispersion of our data could be suggesting that besides "normal" star-forming galaxies (galaxies that belong to the star formation main sequence, SF-MS), **in our sample we include a fraction of galaxies with a SF anomaly, either starbursts or SF deficient systems**. This could be a consequence of our selection criteria, in which initially, we do not favor a particular SF level.



Star Formation Histories

Final samples:
- **LMSFGs**: 31 galaxies with **$\log M_*/M_⊙ \le 8$**
- **Secondary**: 43 galaxies with **$\log M_*/M_⊙ > 8$**

Redshift range $0.3 < z_{spec} < 0.9$.

Stellar mass assembly milestones :
- **t_0:** Lookback time at the **onset of SF.**
- **t_{10}:** Lookback time when a galaxy forms the **10% of the final stellar mass.**
- **t_{50}:** Lookback time when a galaxy forms the **50% of the current stellar mass.**

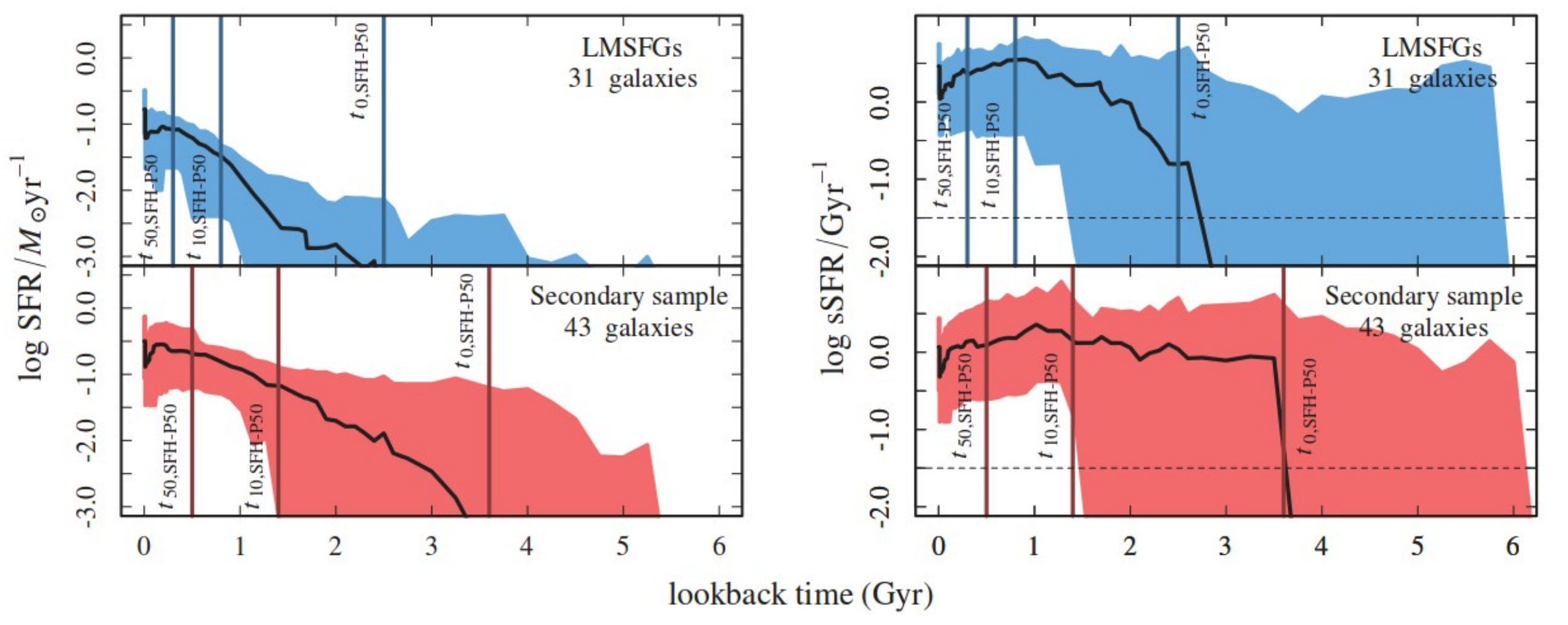
We combine individual SFHs in order to identify general trends: (1) We normalize the individual SFHs to the median stellar mass of the corresponding subsample. (2) We set each SFH to a common reference system, $t_z = 0$. (3) We co-add the individual SFHs and for each step in lookback time we derive median (50% of the distribution, SFH-P50) and confidence ranges (16% and 84% of the distribution, SFH-P16 and SFH-P84, respectively) of the SFRs. We refer to the path defined by the median along the lookback time as SFH-P50. We use SFH-P16 and SFH-P84 for the paths outlined by the percentiles 16th and 84th, respectively. We use a similar approach to obtain the median sSFR history (sSFRH). (4) Consecutively, we characterize these composite SFHs using the milestones.

The galaxies in both our final subsamples appear to have formed a large fraction of their stellar mass (90%) recently (a 0.5–1.8 Gyr period prior the observation). This is in agreement with the work by Leitner+12. Given our reference system is t_z , this means that at any redshift low-mass galaxies appear to be intrinsically "young" objects, in agreement with the downsizing cosmological trend (Cowie+96). More massive galaxies tend to present longer SFHs.

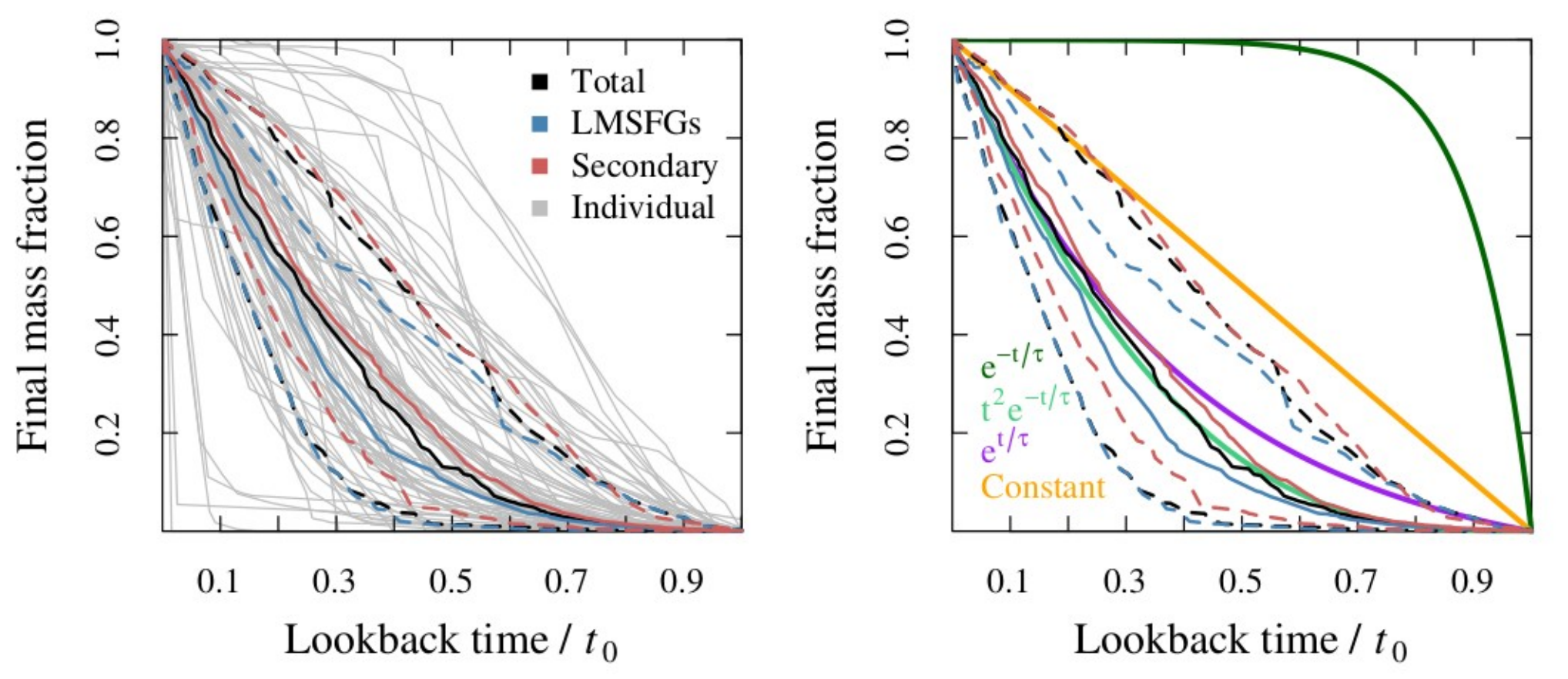
Sample	SFH-P50		
	t_0	t_{10}	t_{50}
(1)	(2)	(3)	(4)
LMSFGs	2.5±0.4	0.8±0.1	0.3±0.0
Secondary	3.6±0.3	1.4±0.3	0.5±0.1

Sample	SFH-P16		
	t_0	t_{10}	t_{50}
(1)	(5)	(6)	(7)
LMSFGs	1.3±0.2	0.5±0.2	0.3±0.1
Secondary	1.7±0.3	0.9±0.1	0.4±0.1

Sample	SFH-P84		
	t_0	t_{10}	t_{50}
(1)	(8)	(9)	(10)
LMSFGs	5.0±1.0	1.8±1.0	0.5±0.1
Secondary	5.9±0.7	3.4±0.7	0.8±0.2



We plot the fraction of final stellar mass against the fraction of the total length of each individual SFH, and compare the average of the different subsamples (LMSFGs, Secondary) with simple parametric SFHs. While constant and exponentially increasing seem compatible with the average SFHs, we can see that **exponentially decreasing SFHs are not representative of our sample**.



Conclusions (Rodríguez-Muñoz et al. 2015 & Rodríguez-Muñoz et al. in prep.)

1) We obtain SFRs and stellar masses consistent with the SF-MS over 2 dex in stellar mass. The large dispersion displayed by our data suggests that our mass selection criterion includes in the sample galaxies with a wide range of properties.
2) Intermediate redshift dwarf SF galaxies present high excited ISM, and low metallicities (∼1-1/34 $Z_⊙$) resembling the population of galaxies in the primitive universe.
3) The median SFH of our sample of LMSFGs suggests that 90% of the stellar mass observed is formed in a 0.5–1.8 Gyr period prior the observation. Our results reinforce the idea of a recent stellar-mass formation for LMSFGs at intermediate redshifts, in agreement with the downsizing cosmological frame (Cowie+96).
4) Despite the fact the SFH of dwarf galaxies is predicted to be dominated by stochastic processes, we find an average SFH compatible with delayed decreasing exponentials and incompatible with typical τ -models.

References

Allende Prieto+01 (A01); Amorín+12; Atek+14; Barro+11a; Barro+11b; Bauer+05; Brinchmann+04; Cardamone+10; Cardiel, 1999; Cowie+96; Dekel & Silk, 1986; Giavalisco+04; Griffith+12; Grogin+11; Henry+13; Hildebrandt+06; Juneau+11, Kartaltepe+14; Kepner+97; Kewley & Dopita, 2002; Kewley & Ellison, 2008; Kobulnicky & Kewley, 2004; Koekemoer+11; Leitner,12; Mamon+12; Mannucci+10 (M10); Moy+03; Nonino+09; Pacifici+12; Pagel+79; Phillips+97; Pérez-González+08; Salim+07;
Scodeggio+05; Taylor+09;
Whitaker+12 (W12);
Whitaker+14 (W14).