The instructions manual of the first galaxies: extreme emission line galaxies at low redshift

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CEFCA

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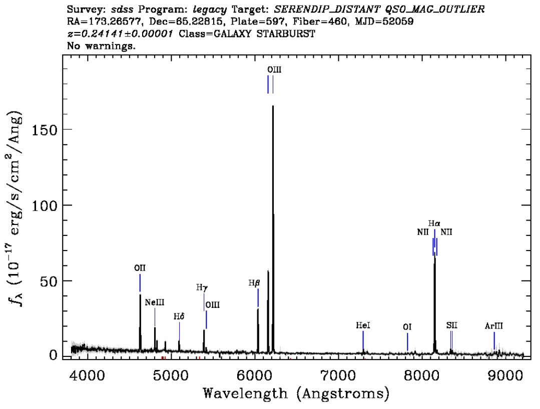
Summary

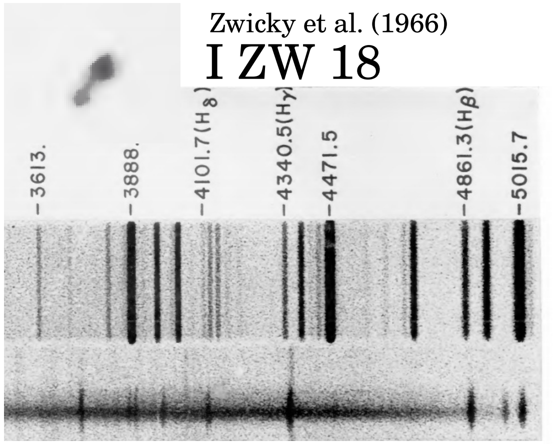
- 1. Introduction and motivation
- 2. Detection of extreme emission line galaxies at z<0.06 in the multifilter J-PLUS survey
  - Sample selection
  - Context
  - Photometric results
- 3. Follow-up analysis
  - Spectroscopy
    - Comparison with other analogs and high-z objects
  - Further analysis
- 4. Conclusions

Introduction

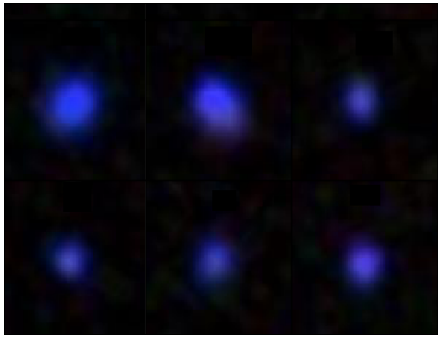
- From the 1960s, many surveys have uncovered strongly star-forming galaxies in the nearby Universe (HII galaxies, BCDs...)
- In the past 15 years, more and more extreme samples of galaxies have been identified
  - z~0.3 Green Peas (Cardamone et al. 2009)
  - z~0 Blueberry Galaxies (Yang et al. 2017)
  - Higher-z EELGs (Amorín et al. 2015, Sanders et al. 2020)
- These samples share some properties with typical galaxies at high redshift
  - Compact morphology
  - Strong emission lines
  - Low metallicity
- Are they truly analogs of galaxies in the epoch of reionization?
  - A few studies in the past years pointed in that direction (i.e. Izotov et al. 2021)
  - The first JWST spectra showed striking similarities between the z>7 galaxies and low-z analogs (e.g. Schaerer et al. 2022)
- **Analyzing in detail the properties of enough local EELGs can help uncover the nature of the first galaxies in the history of the Universe**

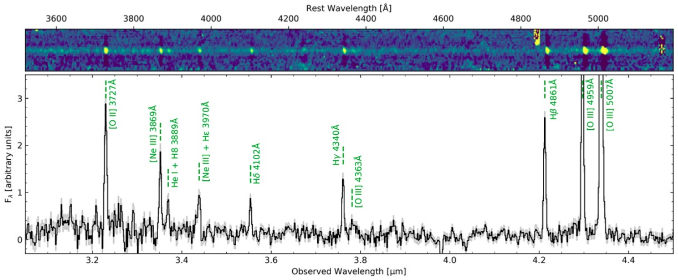


Green pea galaxy (Cardamone et al. 2009)

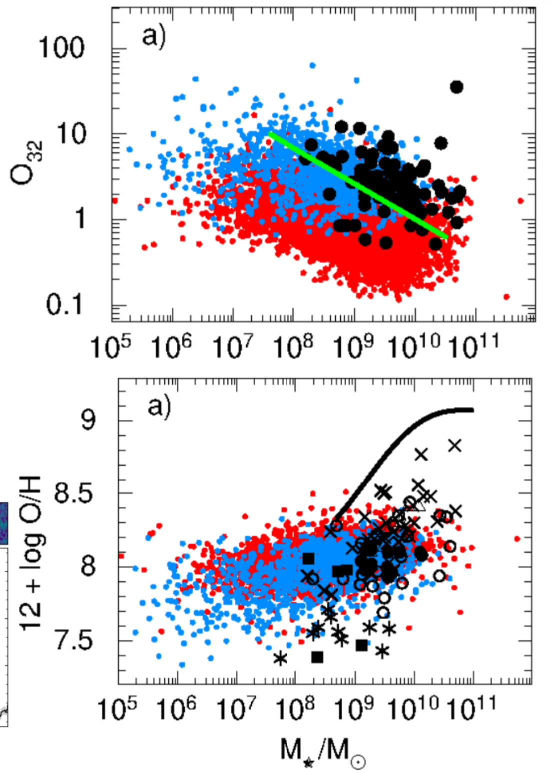


Zwicky et al. (1966)


Blueberries (Yang et al. 2017)



Schaerer et al. 2022



Izotov et al. (2021)

Motivation

- A complete census of EELGs in the local Universe is needed in order to fully understand the statistical properties of these galaxies, and identify those that could be analogs of the first galaxies for follow-up analysis
- To obtain that, we need:
  - A very wide survey
    - EELGs are very rare objects, very small volume available at low-z
  - A relatively deep survey
    - (i>17.8 mag, SDSS legacy spec. survey)
  - Better spectral resolution than broadband surveys

(Alternative) Motivation

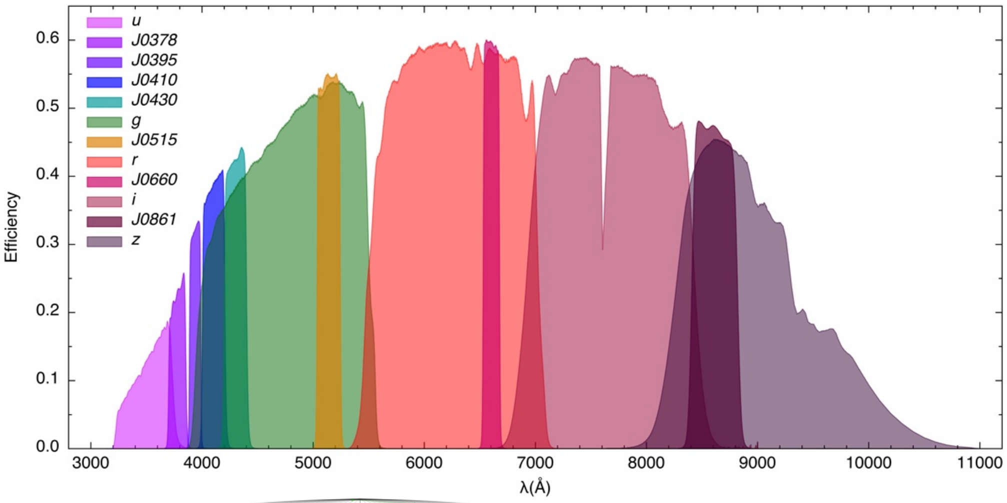
Can we get a relevant result to the very high redshift community in Marseille…

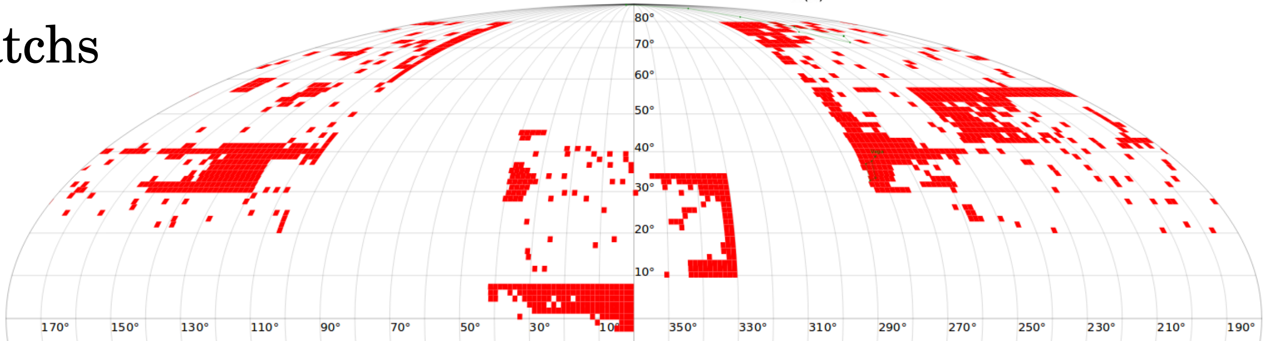
… with observational data from a facility with 0.2% of the budget of JWST?

(From an institute in Teruel, a Spanish city with 0.2% of the population in the Marseille area)

J-PLUS

- JAST80 at Observatorio de Javalambre (Teruel, Spain, 950 km from Marseille)
- Wide, multiband photometric survey
  - DR2: 2000 deg² (DR3 – 3000 deg²)
  - 12 filters (5 broad, 7 narrow-medium)
- Depth: 5σ 20.3 – 21.75 mag.
- Precursor of J-PAS
  - 56 filters 140A wide, 2.5m, 8000deg²
  - Started observations!
- Open access: www.j-plus.es
  - Images, catalogs, cross-matchs
- S-PLUS in the south



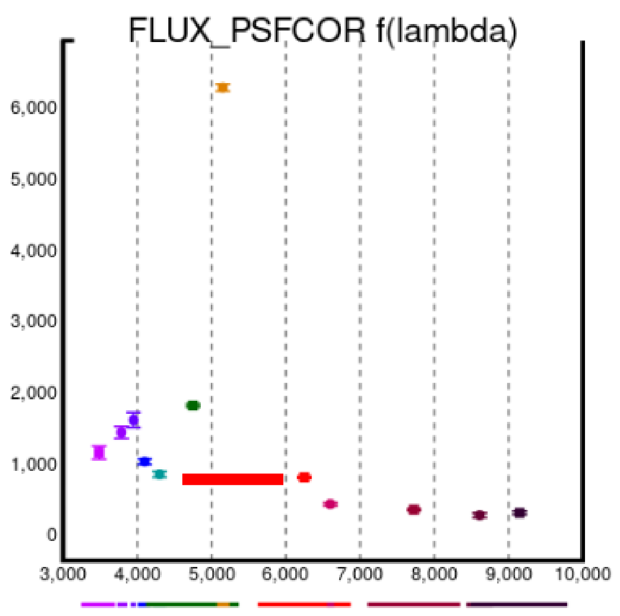


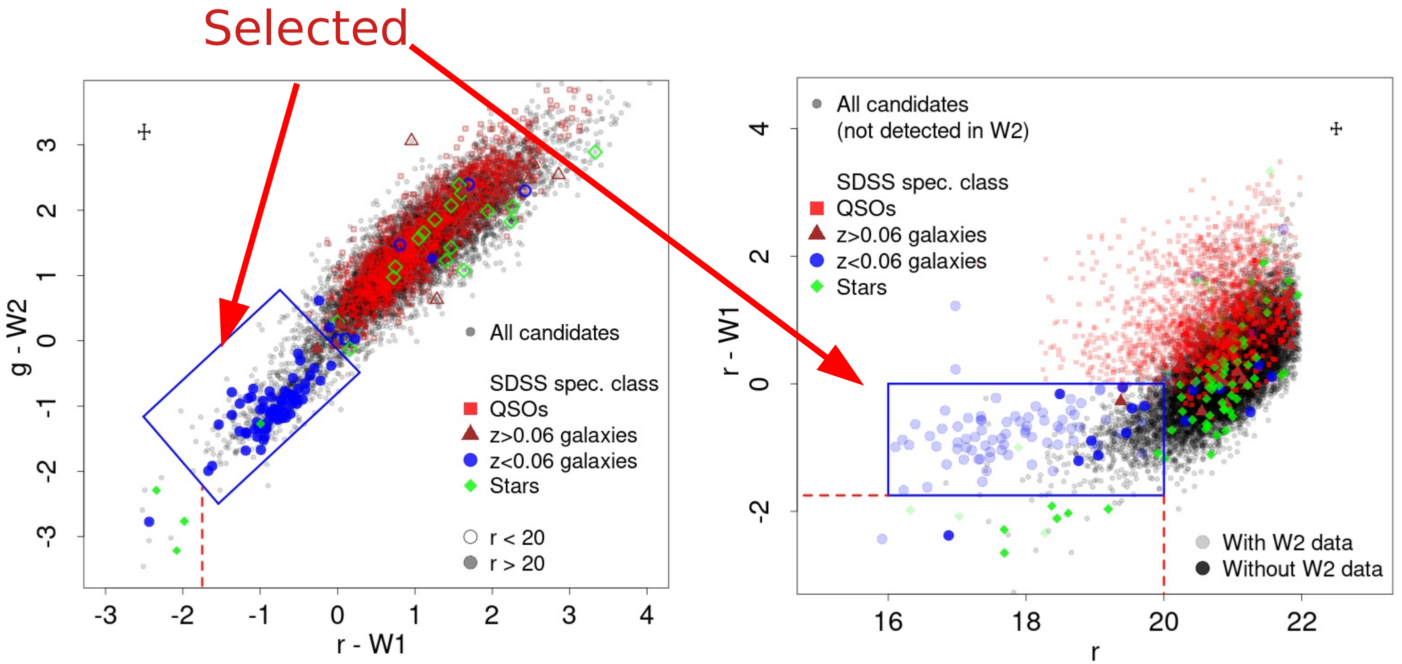
Cenarro et al. 2019

Sample selection - WISE

- Selecting galaxies that show excess of flux in the J0515 filter compared to rSDSS
  - J0515: $\lambda_{central}$ ~ 5140 Å. Width ~ 200 Å
    - [OIII] 5007+4959 at 0.015<z<0.055
  - $(F_\lambda[J0515]-F_\lambda[rSDSS])/F_\lambda[rSDSS] > 1$
    - 30336 objects

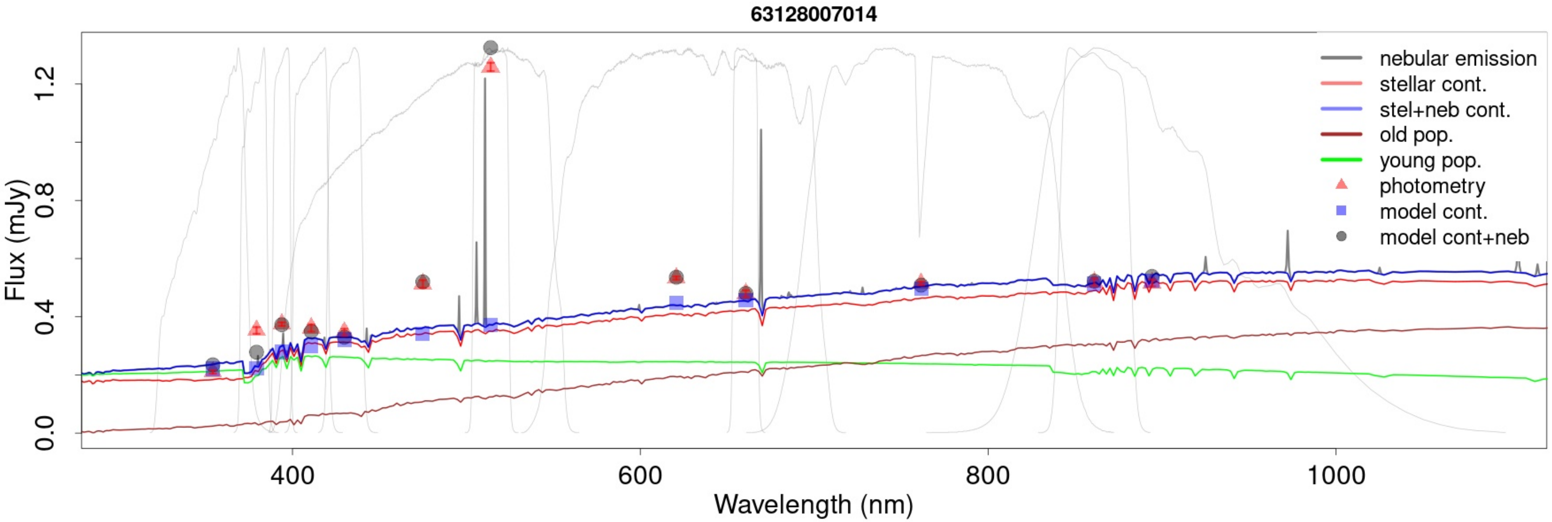
- The optical-IR colour allows us to separate QSOs and EELGs
- rSDSS<20 to ensure clear separation
- Separation QSO/Galaxy in the g-W2 vs. r-W1 and r-W1 vs. R diagrams
  - Spectroscopically confirmed objects:
    - >90% purity, >90% completeness
- **Sample of 1493 galaxies**





SED fitting

- SED fitting to extract physical information
  - CIGALE (Boquien et al. 2019)
- Parameters
  - Two stellar populations (BC03)
  - “Instant” bursts, old population parameters fixed



SED fitting

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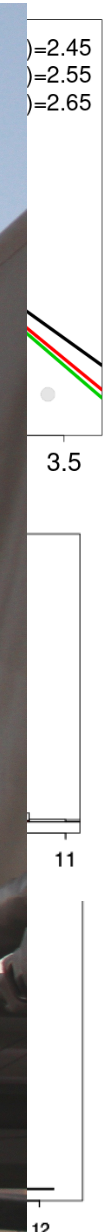
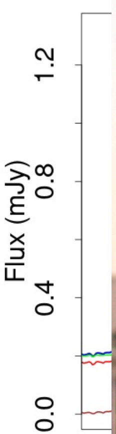


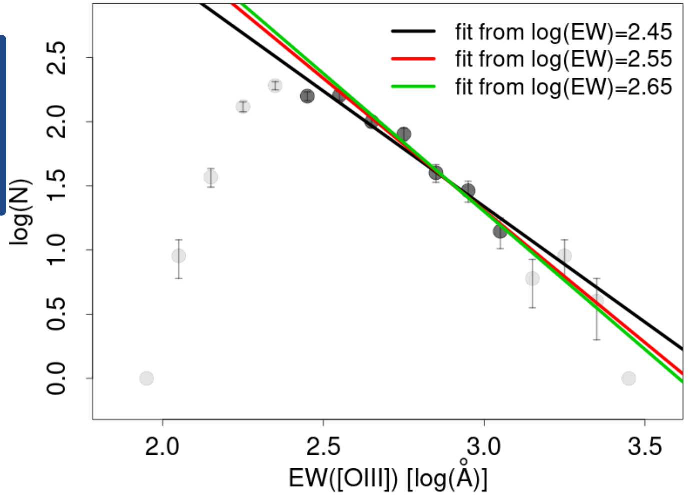


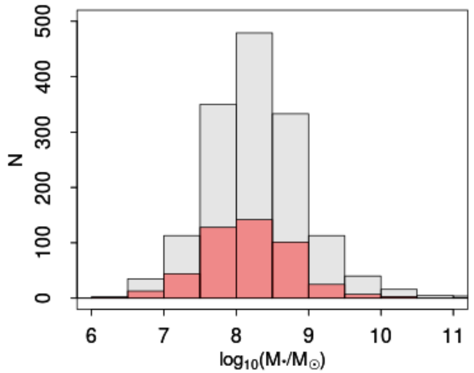
SED fitting

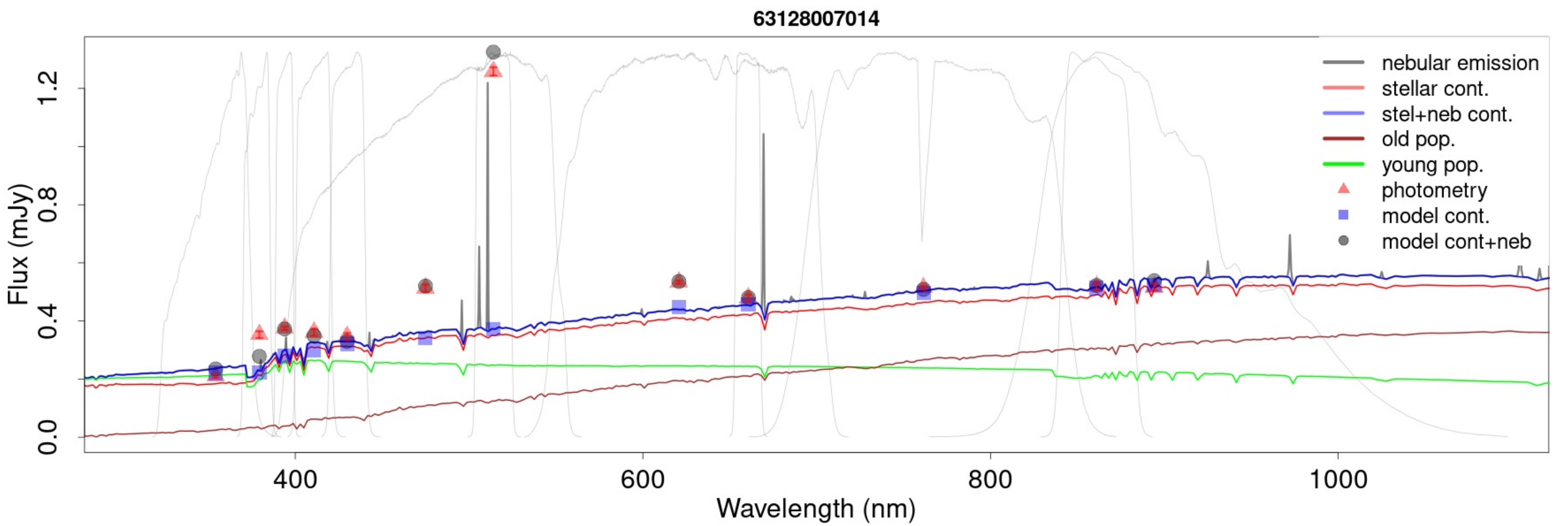
- SED fitting to extract physical information
  - CIGALE (Boquien et al. 2019)
- Parameters
  - Two stellar populations (BC03)
  - “Instant” bursts

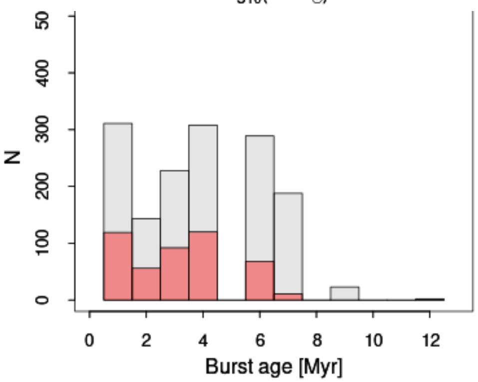
466 galaxies with EW([OIII])>300 Å

  - **410 of them previously unknown**
  - **EW threshold to ensure completeness**
- Very young burst (<=6 Myr)
- Low-mass galaxies
  - Median value ~ 10^8 $M_\odot$
- Low dust extinction
  - E(B-V) ~ 0.15

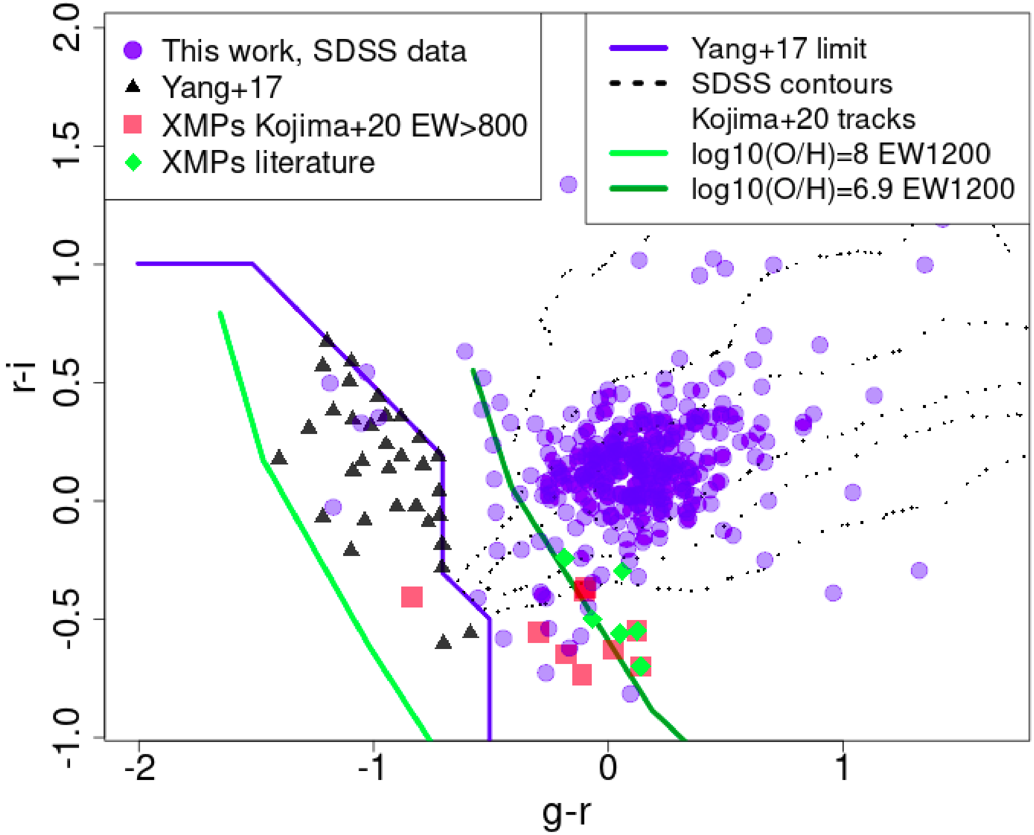








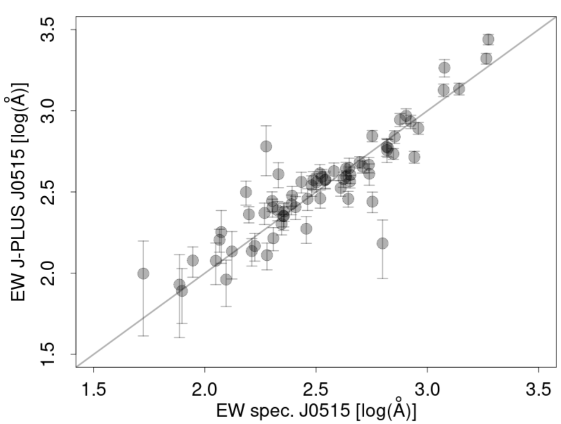
Comparison with previous work

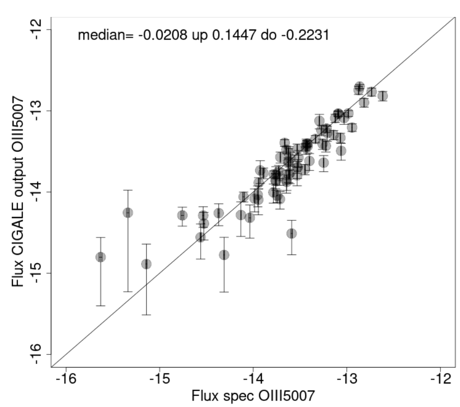


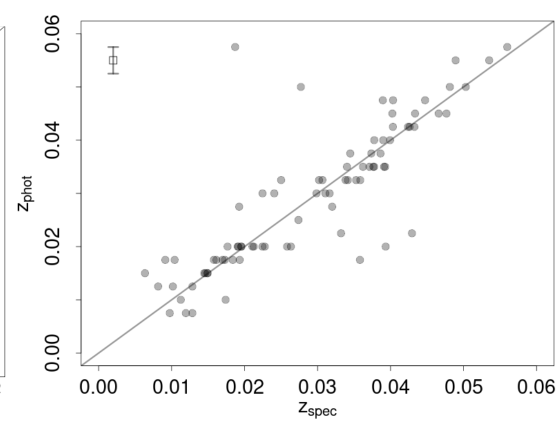
- More precise selection than broadband surveys

  20 – 50 times more density of objects than broadband selection (GPs, blueberries)

- Deeper than wide-field spectroscopic surveys
- Smaller selection bias
  - No direct bias against high Hα/[OIII]
  - No preselection
- As efficient in detection as magnitude limited spectroscopic or narrowband surveys





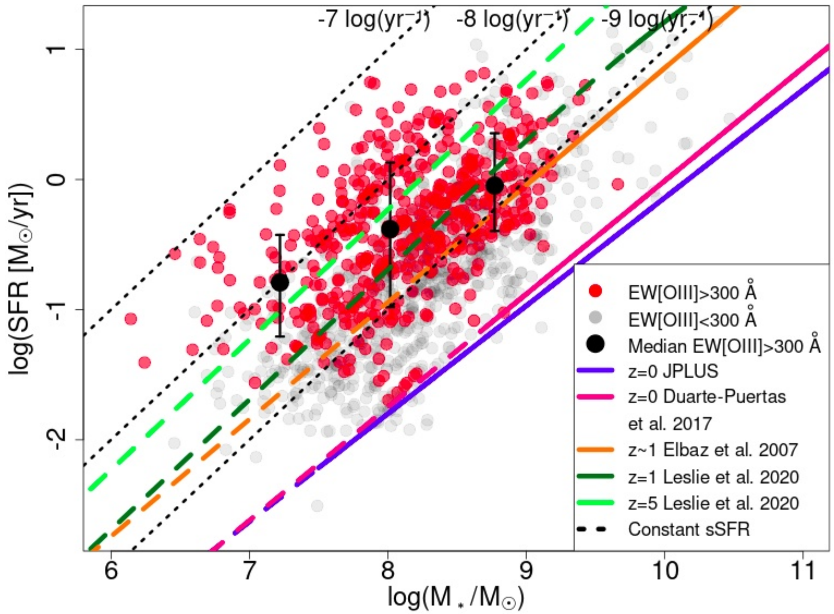


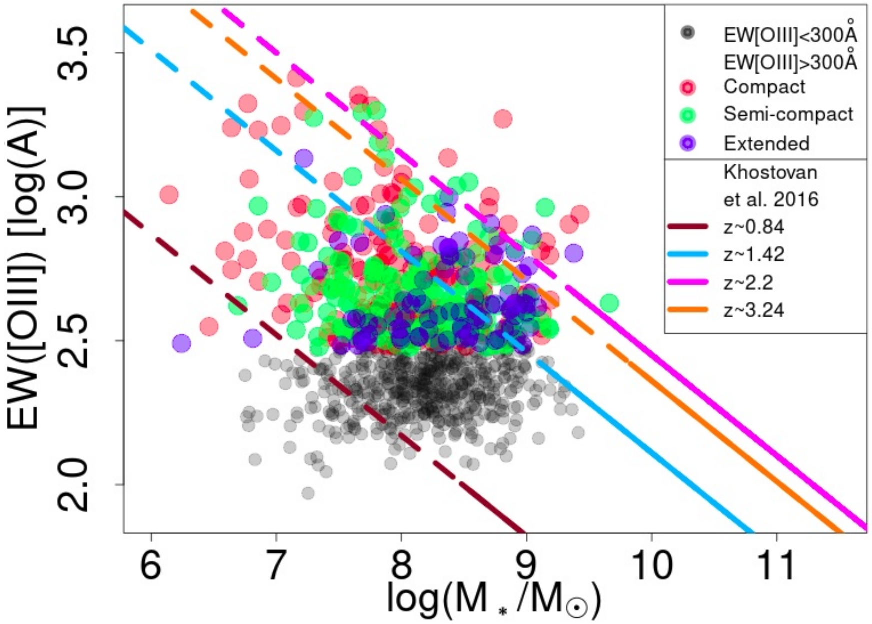
Great agreement in EW, line fluxes and redshift with spectra

<0.15 dex scatter

Results: SFR and EW vs Mass

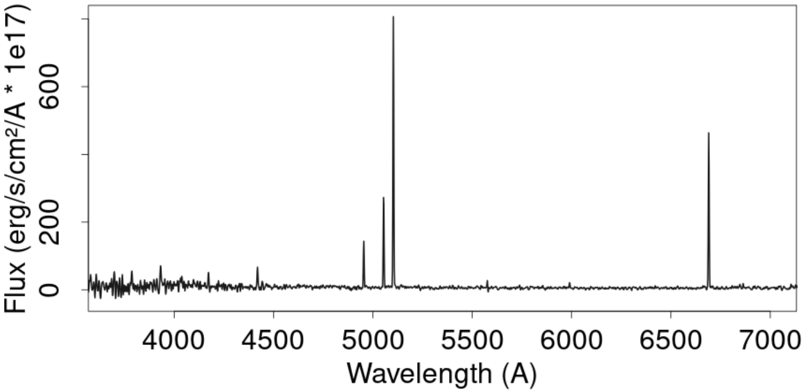
- SFR estimation using Hα (Kennicutt+98)
- Typical galaxy in our EW>300Å sample: 1.2 dex above local Main Sequence
  - Similar sSFR as typical galaxies at z~3-5
- The sample reaches very high EW([OIII])
  - Comparable to the expectations for typical low mass high-redshift galaxies





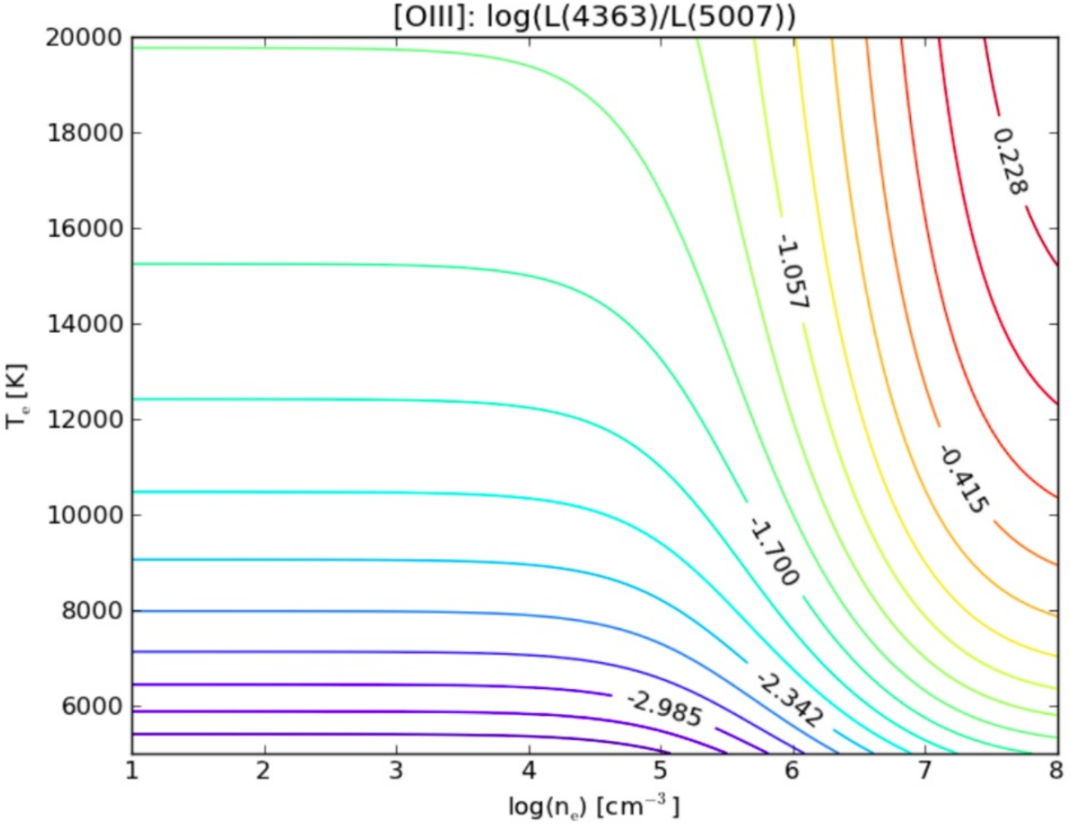
Follow-up spectra of the sample

- Longslit spectroscopy at the 2.5m INT at the Roque de los Muchcachos Observatory (La Palma)
  - IDS: 3500 Å - 7000 Å, R ~ 400
  - 30 galaxies observed
    - ALL are low redshift EELGs with strong emission lines
    - Typical mass below main sample ($10^{7.7}$ $M_{\odot}$ and higher EW (730 Å vs. 430 Å)
- Legacy SDSS spectra
  - 30 galaxies (already used in the sample validation)
  - Higher mass than the whole sample (10^9 $M_{\odot}$), no [OII] coverage in most
- Last minute news: DESI! 13th June data release: 10 additional galaxies

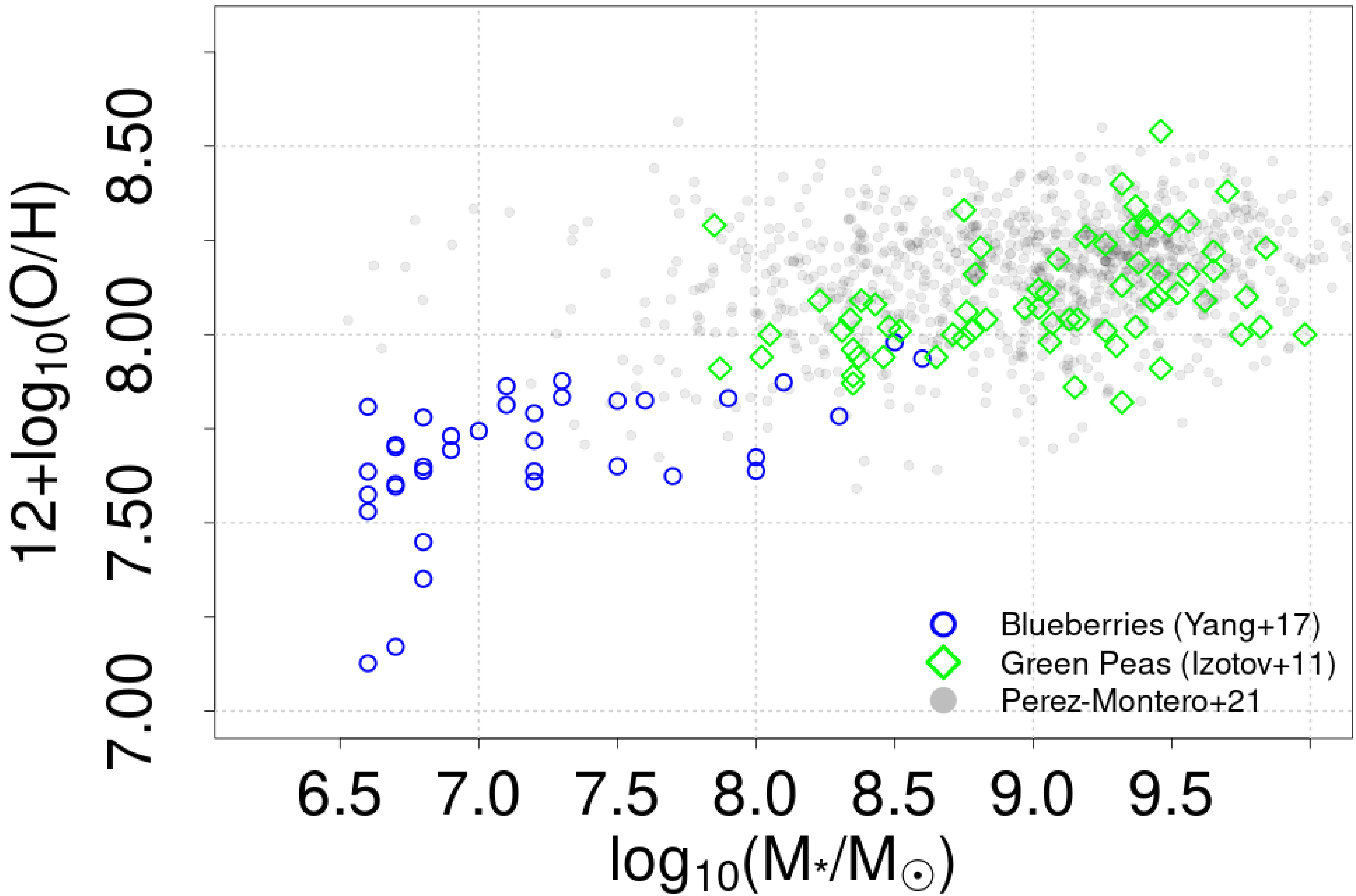


Spectroscopic data analysis

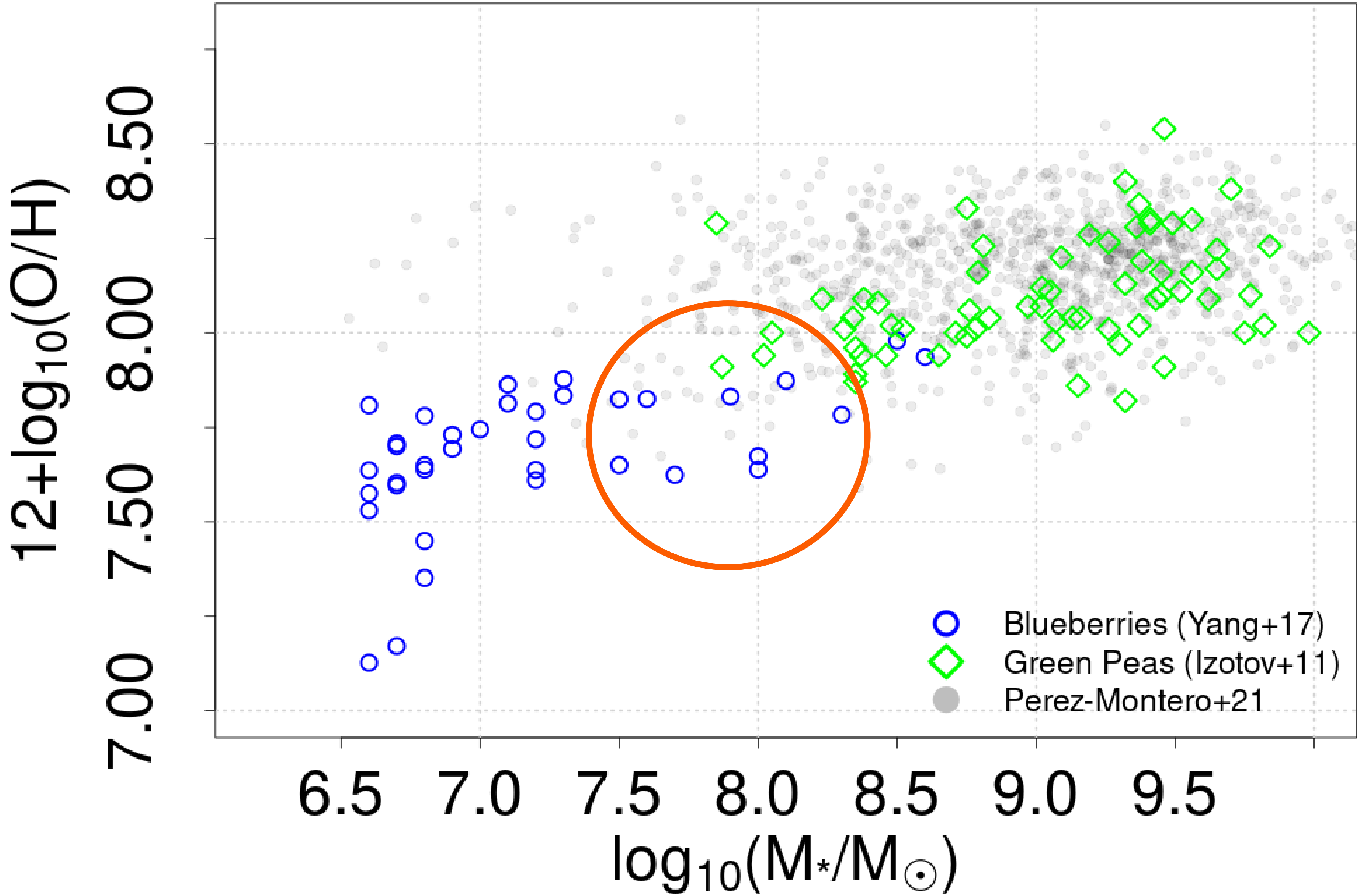
- Flux calibration with J-PLUS multiband photometry
- Dust extinction correction using the Balmer decrement method (typically low)
- Electronic density determined with [SII]6717/[SII]6731
  - Typically close to the low density limit (100 cm^{-3})
- <u>Abundance determination using the direct method</u>
  - Electron temperature with the [OIII]4363 emission line and Pyneb
  - 17/30 galaxies with [OIII]4363 detections in the INT sample



Mass – metallicity relation



Mass – metallicity relation



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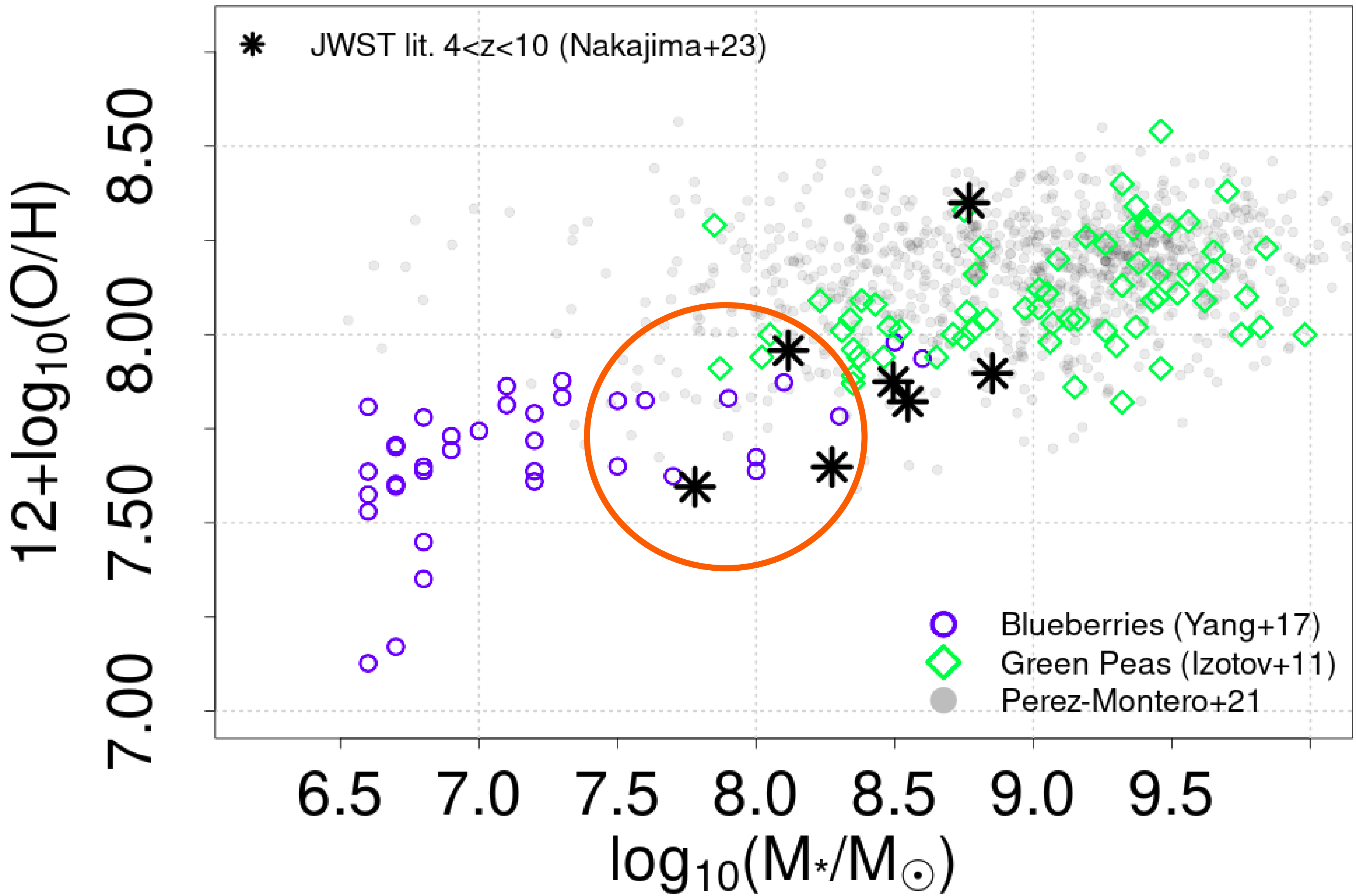

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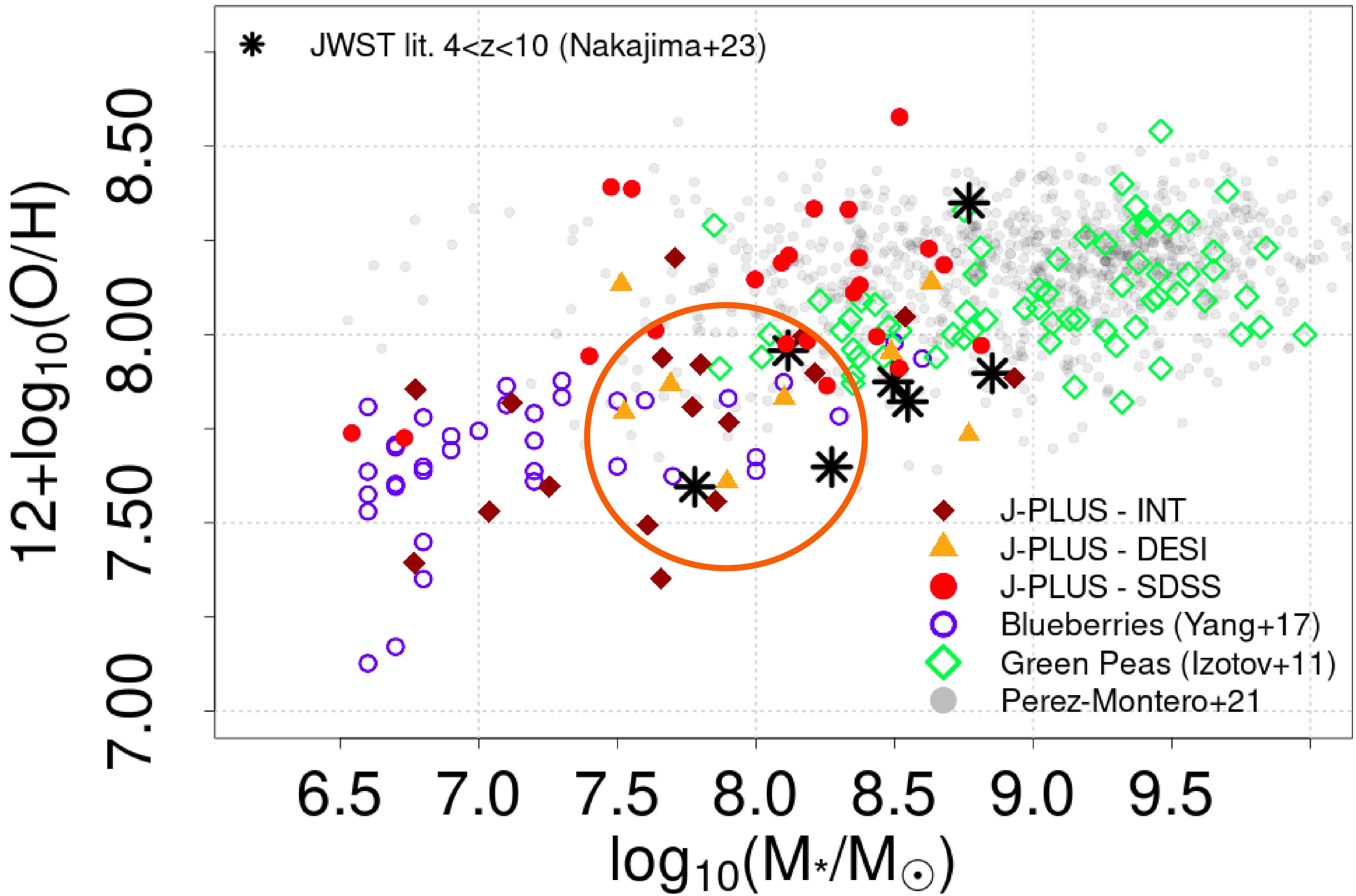

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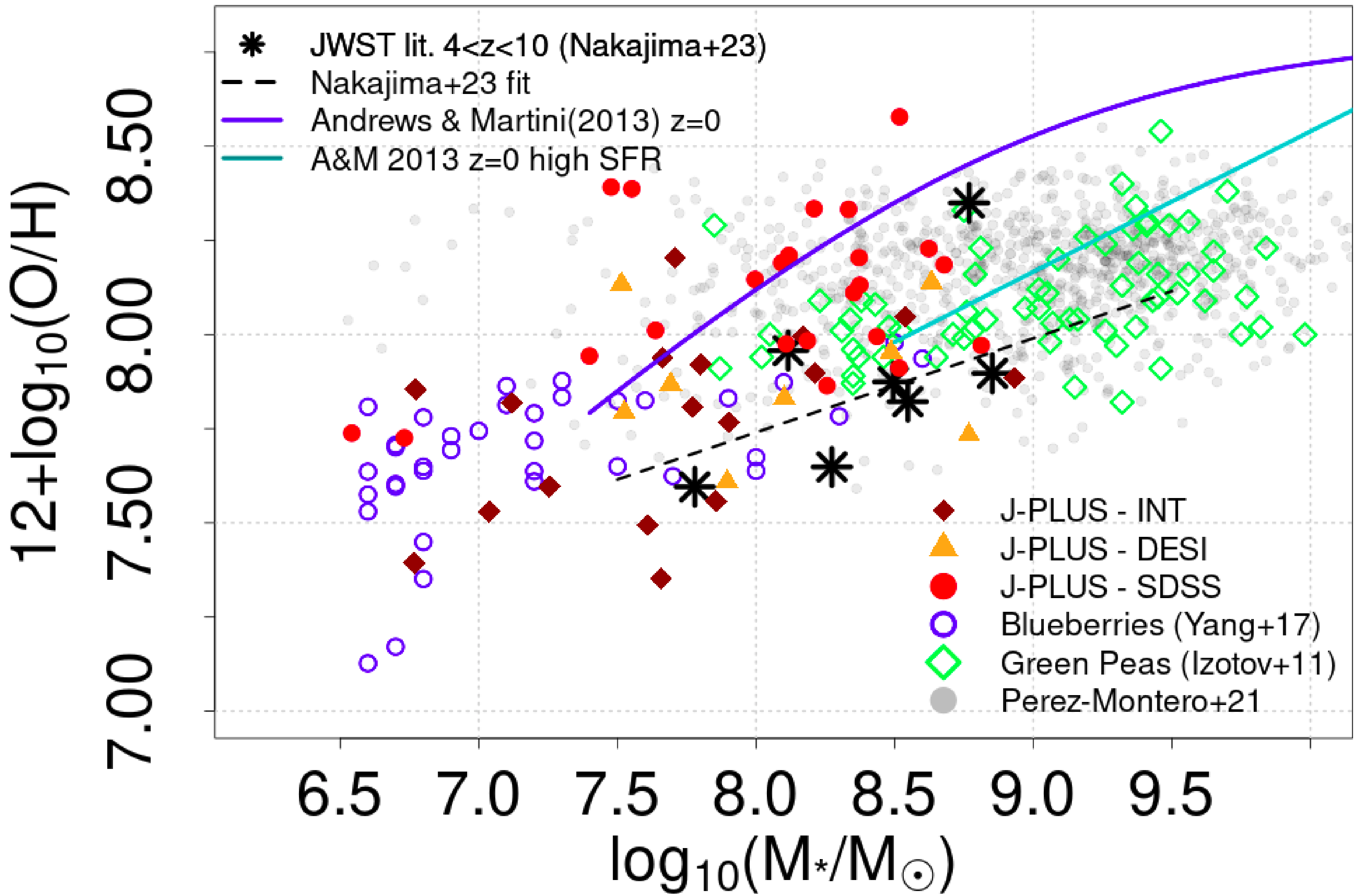
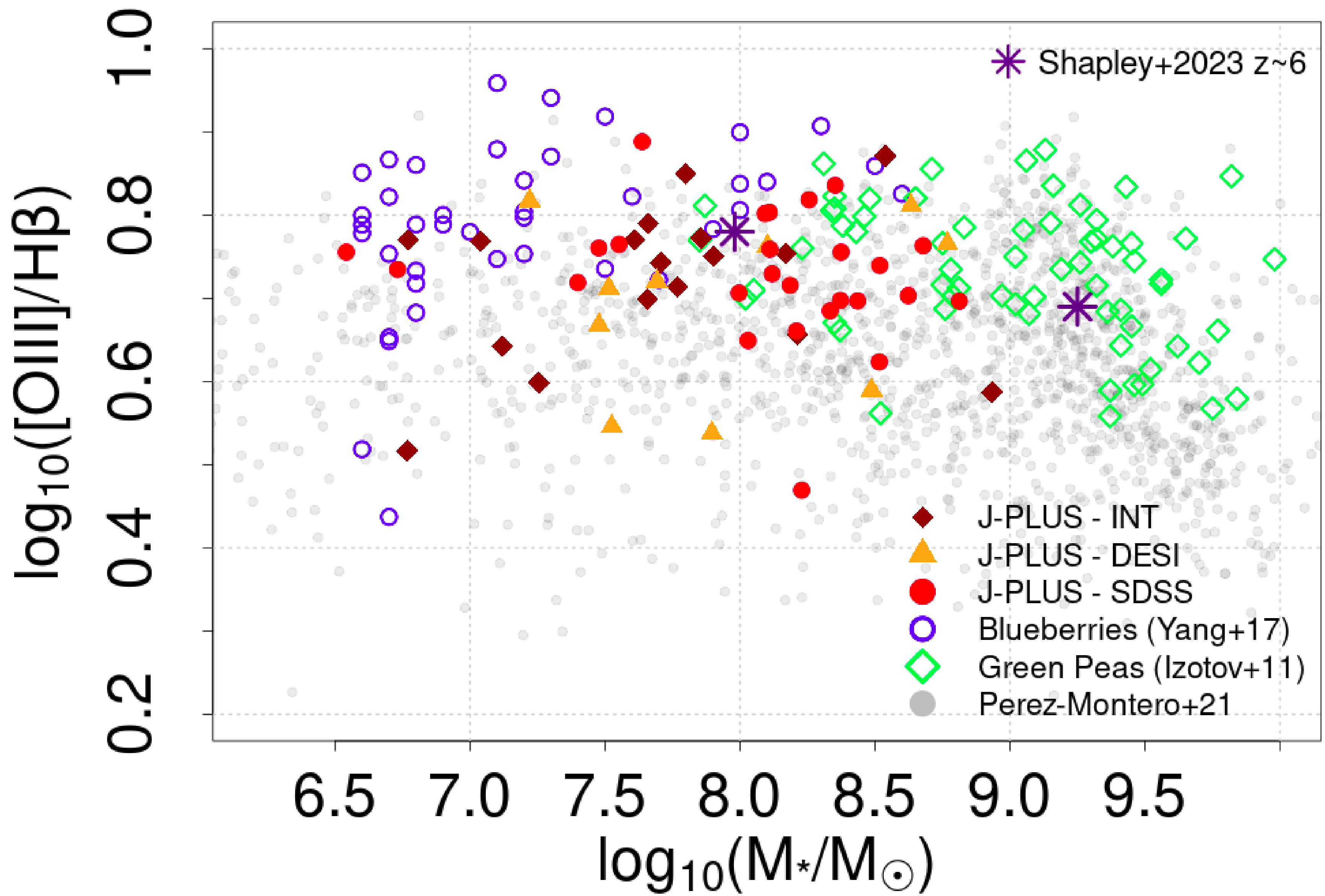
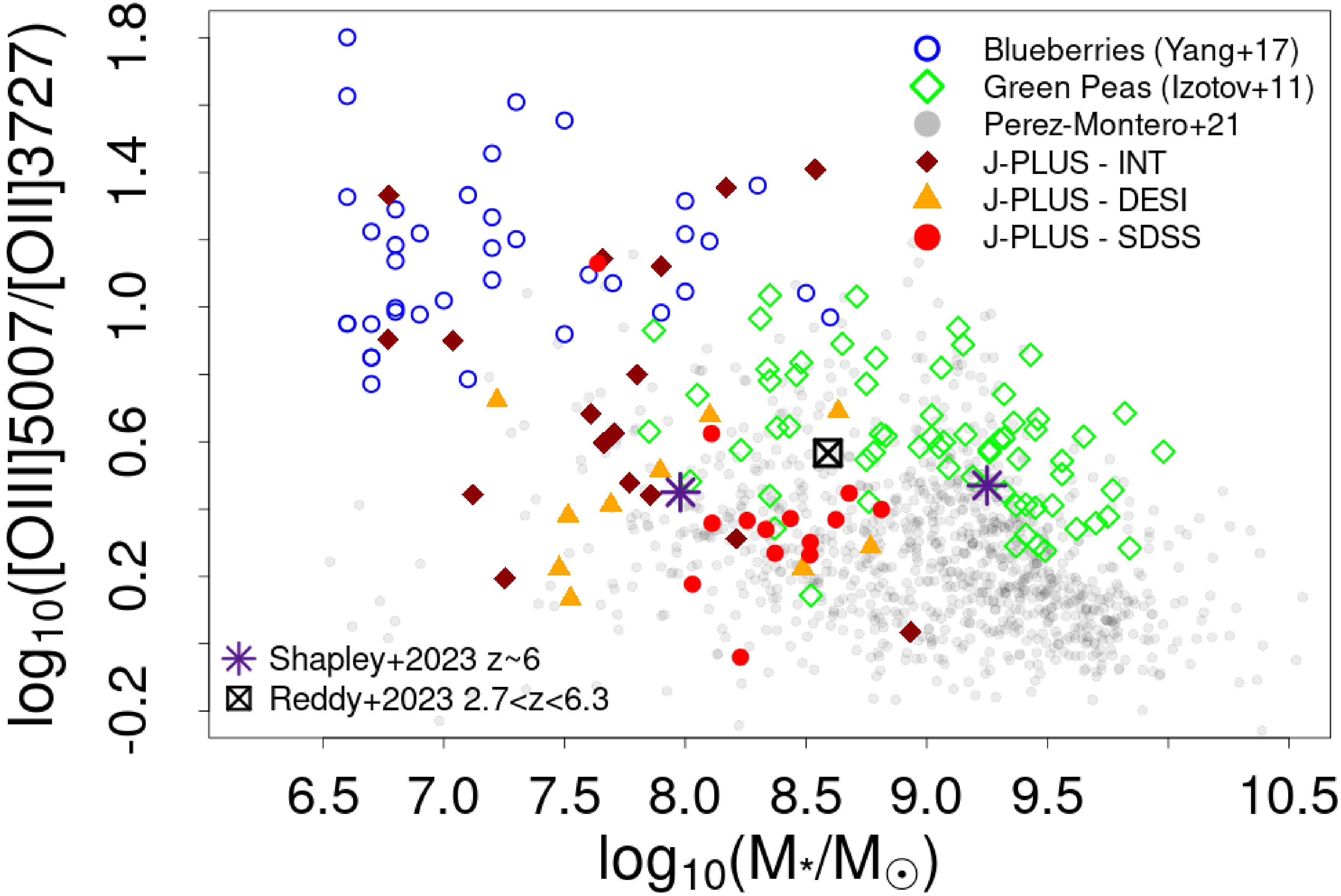


[OIII]/Hβ



Shapley+2023 z~6
J-PLUS - INT
J-PLUS - DESI
J-PLUS - SDSS
Blueberries (Yang+17)
Green Peas (Izotov+11)
Perez-Montero+21
log10([OIII]/Hβ)
1.0
0.8
0.6
0.4
0.2
6.5
7.0
7.5
8.0
8.5
9.0
9.5
log10(M*/M⊙)

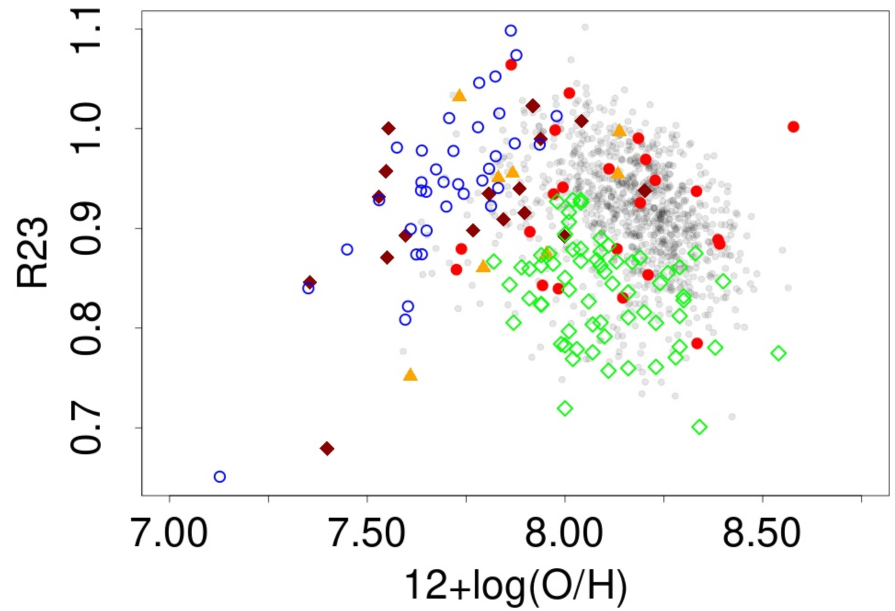
[OIII]/[OII]

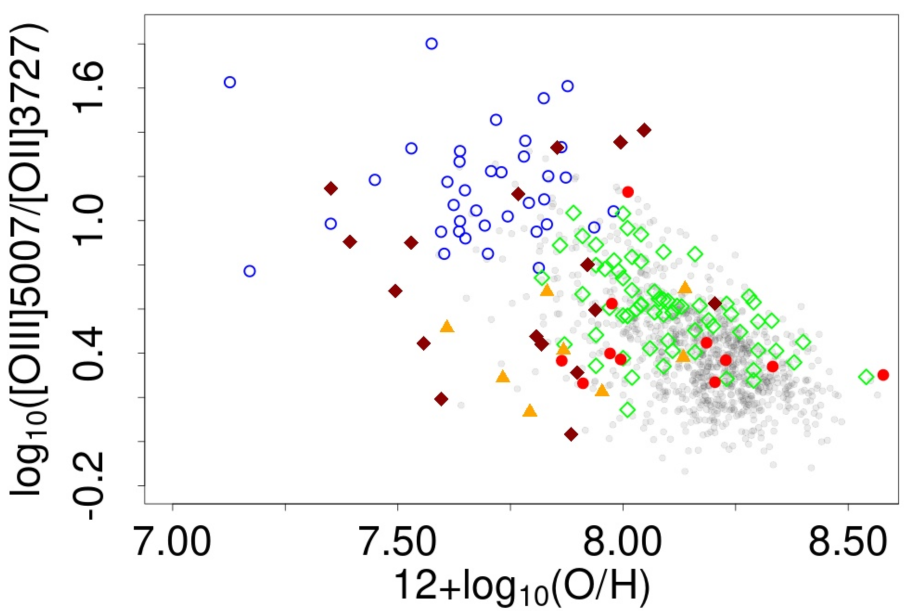


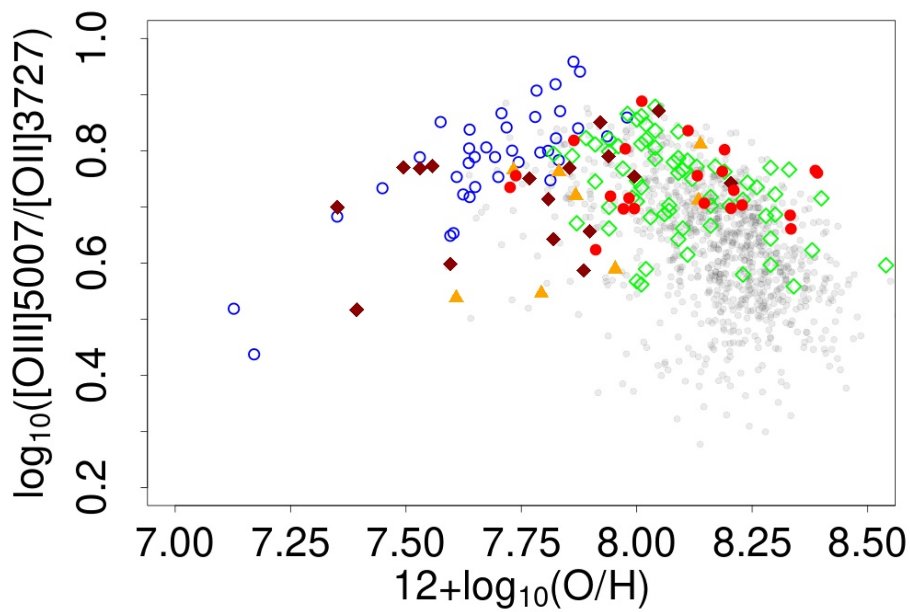
Blueberries (Yang+17)
Green Peas (Izotov+11)
Perez-Montero+21
J-PLUS - INT
J-PLUS - DESI
J-PLUS - SDSS
Shapley+2023 z~6
Reddy+2023 2.7<z<6.3
-0.2
0.2
0.6
1.0
1.4
1.8
log10([OIII]5007/[OII]3727)
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.5
log10(M*/M⊙)

¿Empirical calibrations?

- Difficulty detecting the [OIII]4636 auroral line in large samples of very high redshift galaxies
  - Need for empirical metallicity calibrations
  - Key importance: use of low-z galaxy analogs

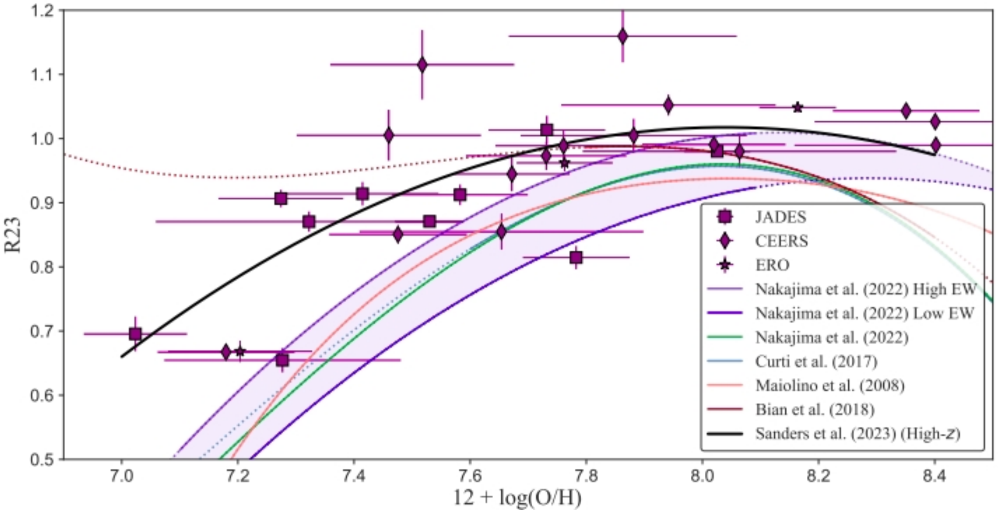


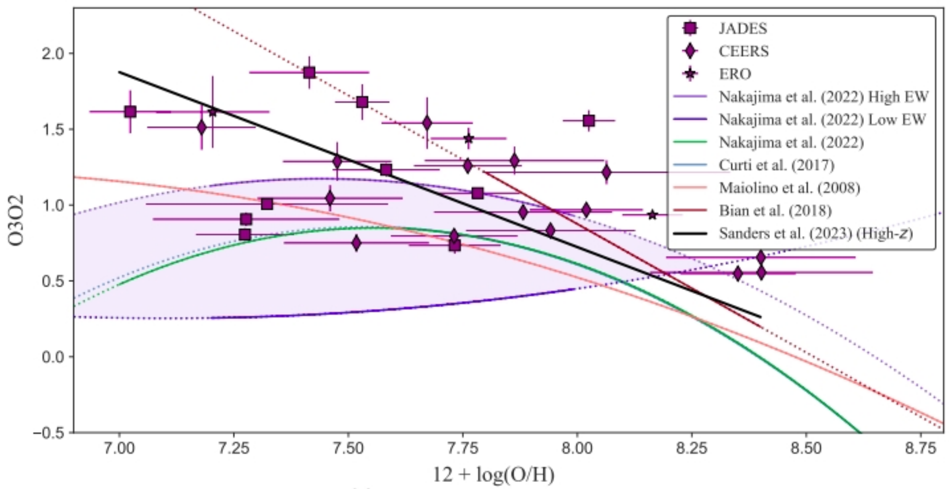


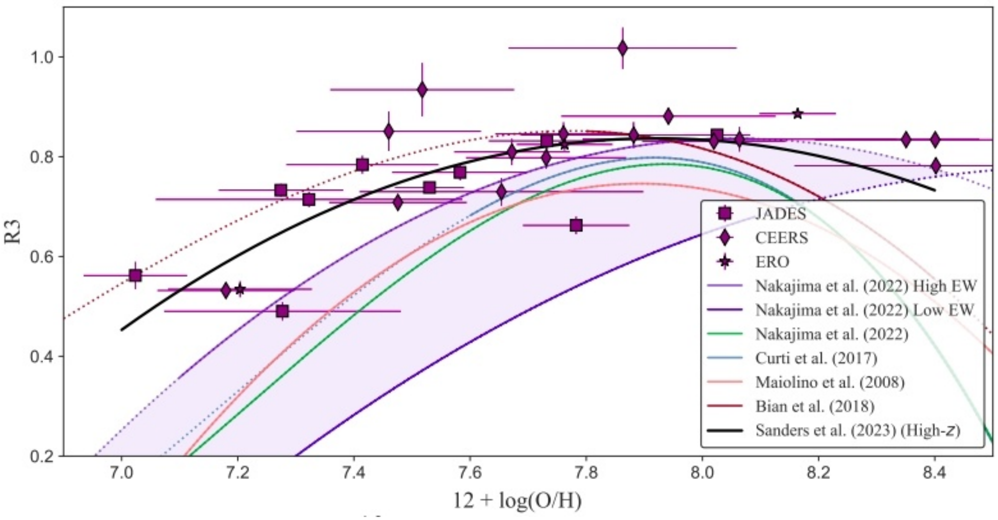


¿Empirical calibrations?

- Difficulty detecting the [OIII]4636 auroral line in large samples of very high redshift galaxies
  - Need for empirical metallicity calibrations
  - Key importance: use of low-z galaxy analogs
- Very challenging so far
  - Laseter et al. (2023)

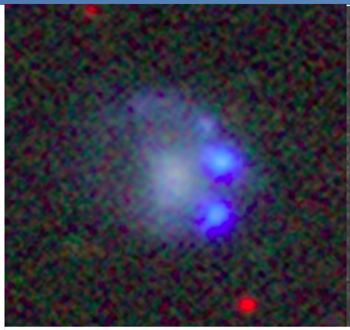


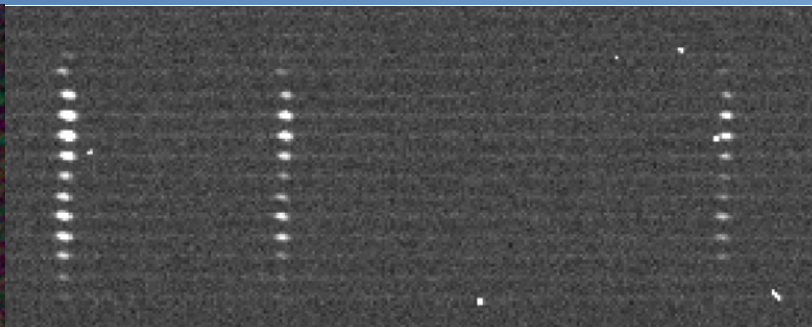




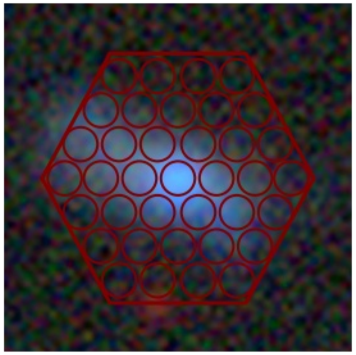
Other follow-up studies

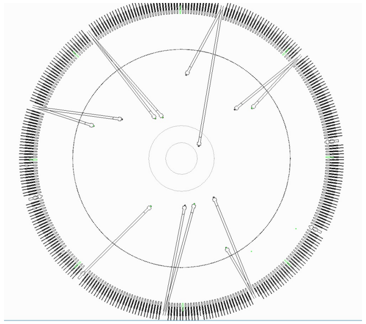
- Spatially resolved spectrocopy (IFU)
  - Pilot program at 3.5m in CAHA (Almería)
  - WEAVE at the 4.2m WHT (La Palma)
    - Science verification
    - 20 mini IFUs per 2deg² field
    - High resolution (R~20 000)

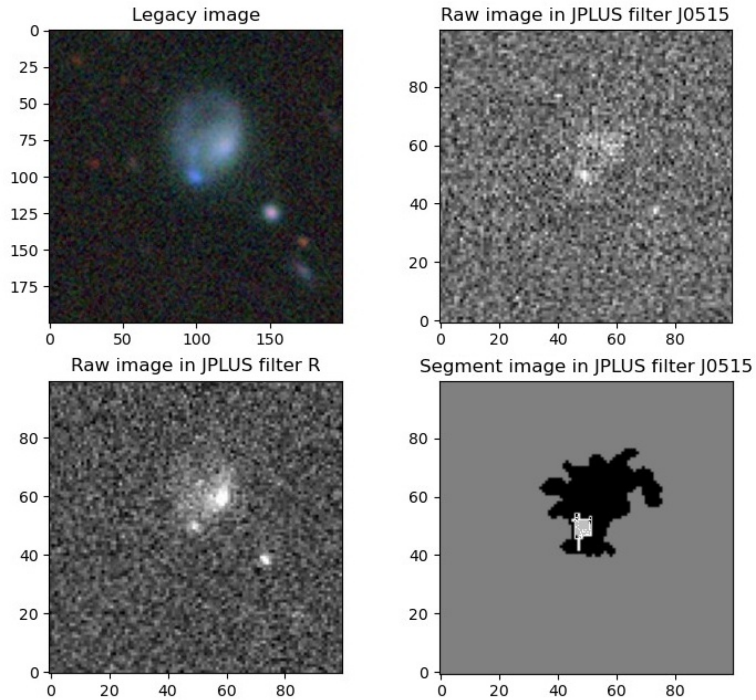




- Resolved photometric analysis of clump properties (Jorge Porrón master thesis)
  - 90 extended EELGs studied, 140 clumps found in [OIII] images
  - Clump masses ~ 10^8 (1/10 of the galaxy)
  - Larger and more star forming clumps towards de center, as found with HST at higher redshift
- X-ray follow-up (XMM-Newton)
  - Test the dependence of X-ray flux with SFR-Metallicity for extreme objects

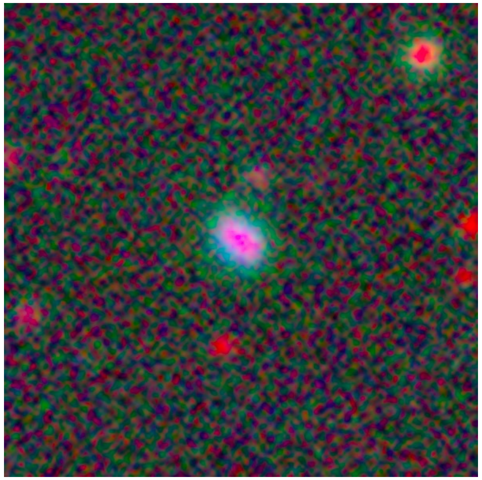


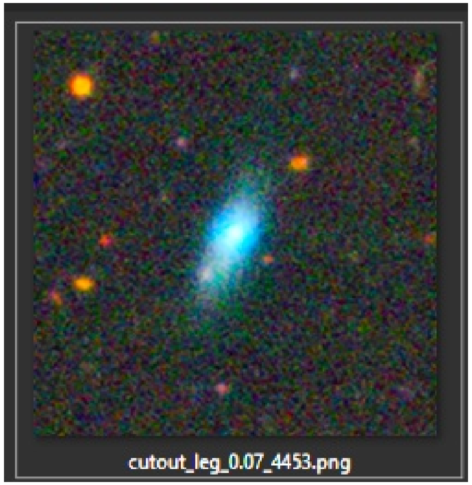




Associated studies

- J-PLUS DR3 (1000 additional deg^2: ~200 extra EELGs)
- Hα selected "green pea" galaxies in J-PLUS
  - $0.28<z<0.34$, $M_* \sim 10^9\ M_\odot$
  - ~370 objects with EW(Ha)>400Å. 15/15 confirmed in follow-up spectroscopy
  - Less biased towards high [OIII]/Hα ratio than GPs
- Low mass, local extreme Hα emitters (master thesis of Luis Soliveres)
  - 88 objects with EW(Hα)>200Å, 53 previously unclassified. 3/3 confirmed in spectroscopy
  - $z<0.017$, $M_* \sim 10^{7.8}\ M_\odot$
- Additional spectroscopic follow-up (in 5 days!)
- J-PAS (60 filters, mag. 23): first internal data release coming soon (observations ongoing)





Summary and ongoing work

- **With the J-PLUS mediumband survey, we compile the largest sample of extreme emission line galaxies in the local Universe since SDSS spectra.**
  - 466 galaxies (410 new) EW([OIII]>300Å at z<0.06)
  - Very efficient, unbiased selection of EELGs
  - High purity (>95%), high completeness (>90%)
- SED fitting reveals very young, low mass galaxies with little dust extinction
- SFR and EW comparable to high-redshift (z ~ 3-5) systems
- Spectroscopic analysis
  - Stellar masses and metallicities in a "gap" between Blueberry galaxies and Green Peas
  - Similar masses and metallicities as JWST galaxies at 4<z<10
  - Reaching a wide variety of excitation states ([OIII]/[OII] and [OIII]/Hα ratios)
    - Some galaxies with apparent lower values, as z~5 galaxies with JWST
- Ongoing work
  - Other z J-PLUS selections: z ~ 0.3 Hα selected "Green Peas" and local Hα emitters
  - Additional spectroscopy, IFU follow-up
  - 2-D analysis of resolved targets

Take-home messages

- **Very low redshift analogs can play a key role in the understanding of reionization era galaxies**
  - Improving strong-line metallicity callibrators
  - Performing studies impossible on faint, distant galaxies
    - Resolved analysis
    - Multiwavelength studies (Radio, X-Ray, etc.)
- **Current samples of low-z EELGs are small and biased towards specific kind of objects due to their selection, not fully matching high-z populations**
  - Need for more precise, intermediate mass, unbiased selections
- **J-PLUS / J-PAS: Very wide multifilter surveys are the most efficient tool to find and characterize the missing high-z analogs**

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Lumbreras-Calle et al. (2022)
arXiv:2112.06938

Additional slides