Detecting and following-up extreme emission line galaxies in J-PLUS: connecting the local and early Universe

Alejandro Lumbreras Calle – CEFCA

alumbrerascalle@gmail.com - @alumbrerasc

CEFCA (Carlos López Sanjuan, J.A. Fernández-Ontiveros, R. Amorín, A. Hernán-Caballero, M. Akhlaghi)

IAA group (J.M. Vílchez, E. Pérez-Montero, C. Kehrig, J. Iglesias-Páramo, A. Arroyo Polonio)

Master Students (Jorge Porrón, [illegible]arlos Celma)





FONDO DE INVERSIONES DE TERUEL

GOBIERNO DE ARAGON

MINISTERIO DE CIENCIA E INNOVACIÓN

Plan de Recuperación, Transformación y Resiliencia

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Summary

- 1. Introduction and motivation
- 2. Detection of extreme emission line galaxies (EELGs) with J-PLUS
  - Detailed discussion of the [OIII] sample
  - Other selections
- 3. Spectroscopic analysis of J-PLUS EELGs
  - Longslit Spectroscopy
    - Comparison with other analogs and high-z objects
  - IFU/MOS
- 4. Other studies on J-PLUS EELGs
- 5. Summary

Introduction

- From the 1960s, many surveys have uncovered strongly star-forming galaxies in the nearby Universe
  - HII galaxies, BCDs, Green Peas, Luminous compact galaxies, Blueberry galaxies, emission line / Halpha dots, extreme emission line galaxies (EELGs)
  - Properties
    - Compact morphologies
    - Strong emission lines
    - Blue colors
    - Low metallicities
- Different observational approaches have been taken
  - Objective prism, multiband surveys (broad and mediumband filters), narrow band surveys, multiobject spectroscopy

Logroño-García et al. (2019)

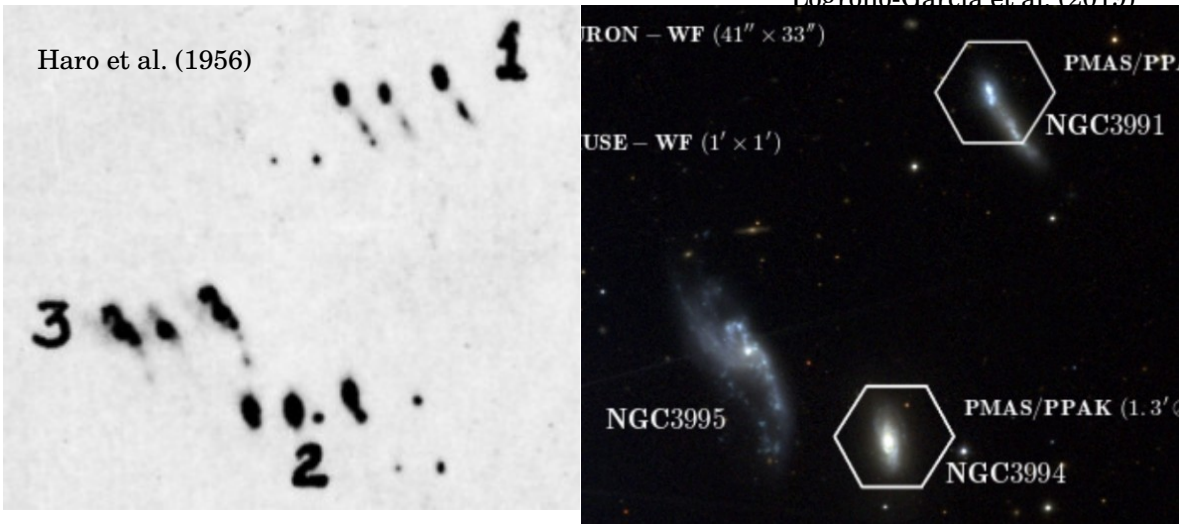
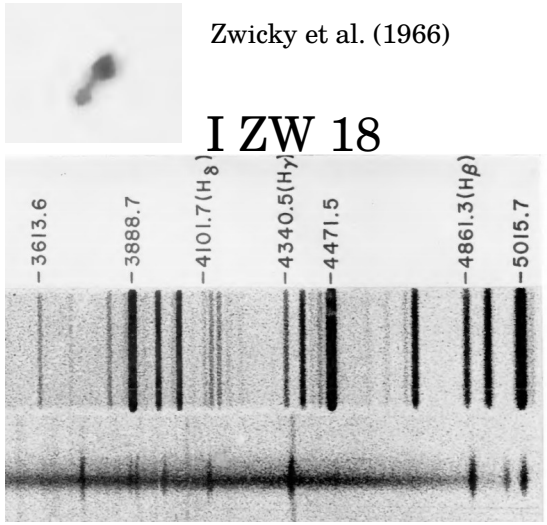


Figura 1. *En estas fotografías en tres colores las galaxias señaladas con los números 1, 2, 3, son NGC 3991, 3994 y 3995, respectivamente. Cada una aparece (de derecha a izquierda) en luz ultravioleta, amarilla y azul. A la derecha del grabado se indican con una flecha las tres imágenes de la galaxia Nº 4 de la Tabla I.*

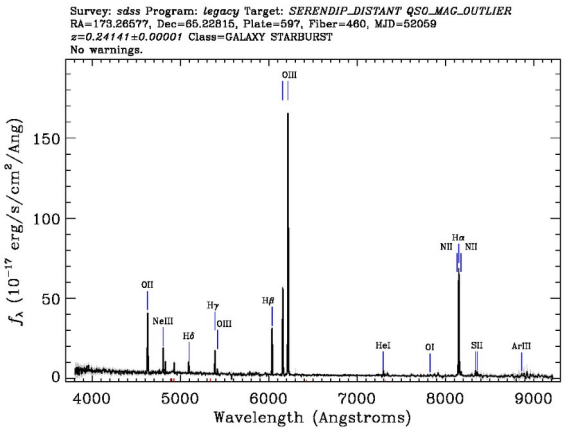
Zwicky et al. (1966)



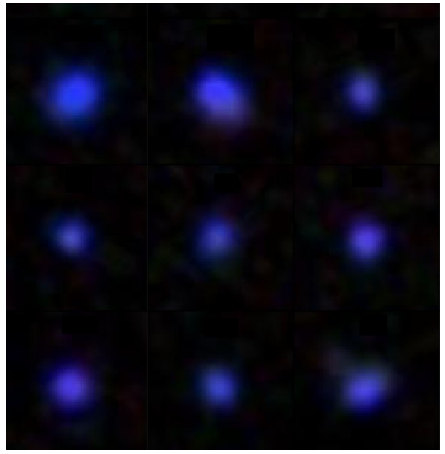


Introduction

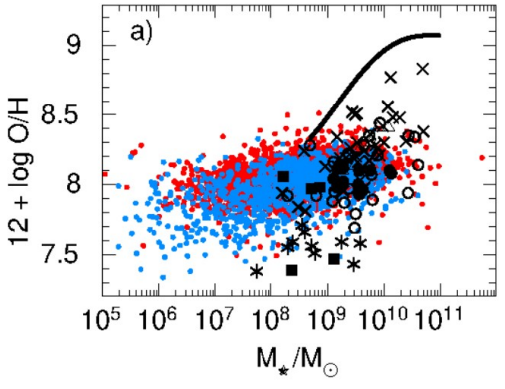
- In the past 15 years, the most extreme examples have been identified
  - Green Peas (Cardamone et al. 2009 and hundreds of follow-up studies)
  - Blueberry Galaxies (Yang et al. 2017)
  - High-z EELGs (Amorín et al. 2015, de Barros et al. 2018, Onodera et al. 2020, Tang et al. 2020)
- These samples share some general properties with typical galaxies at high redshift
  - Compact morphology, 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**

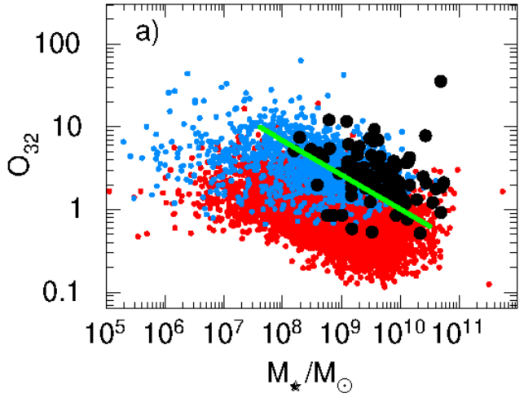


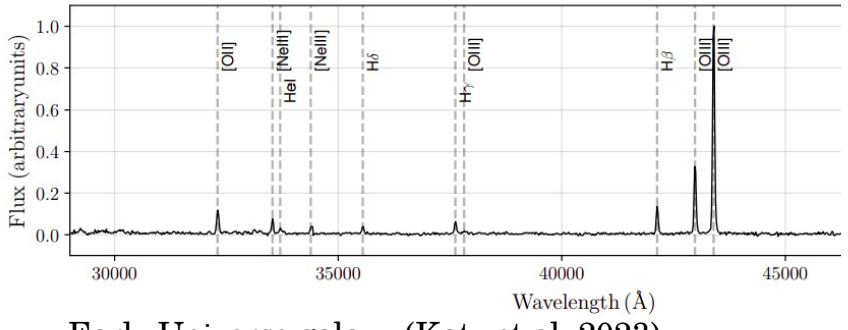
Green pea galaxy (Cardamone et al. 2009)



Blueberries (Yang et al. 2017)







Early Universe galaxy (Katz et al. 2023)

Goal and motivation

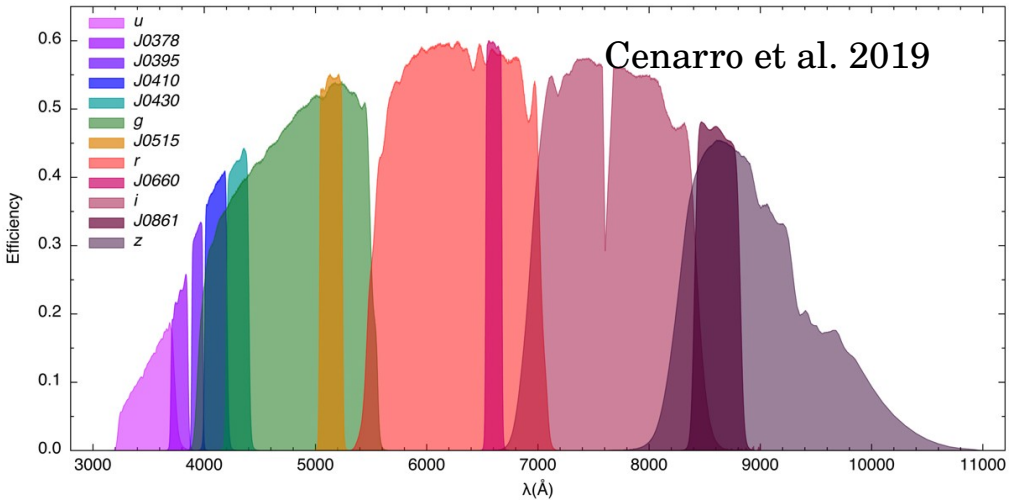
- Compile a complete sample of EELGs in the local Universe
  - To fully understand their statistical properties
  - To identify those that are the best analogs of the first galaxies in the Universe
- For that, we need:
  - A very wide survey (DR3: 3000 deg^2)
    - EELGs are very rare objects in the local Universe
  - A relatively deep survey (J-PLUS: 5σ 20.3 – 21.5 mag)
    - At i<17.8, SDSS spec. Survey is complete (and at i<19.5, DESI starts to be competitive)
  - Better spectral resolution than broadband surveys
    - J-PLUS has 7 narrowband/mediumband filters

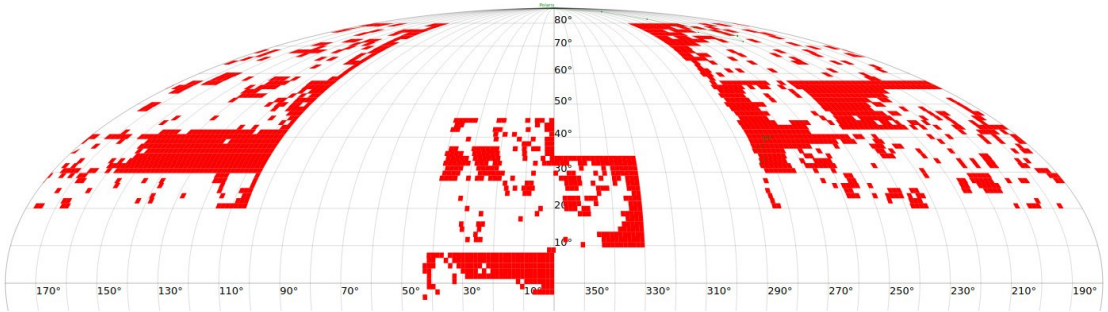
and that survey is...

J-PLUS

- JAST80 (80 cm) at Observatorio de Javalambre (OAJ, Teruel)
- 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
  - MiniJ-PAS (1deg², Bonoli et al. 2020)
    - EELGs: Iglesias-Páramo et al. (2022)
  - Started observations in 2023!
- Open access: www.j-plus.es
  - Images, catalogs, cross-matches
- S-PLUS in the south







2. Detection of extreme emission line galaxies (EELGs) with J-PLUS

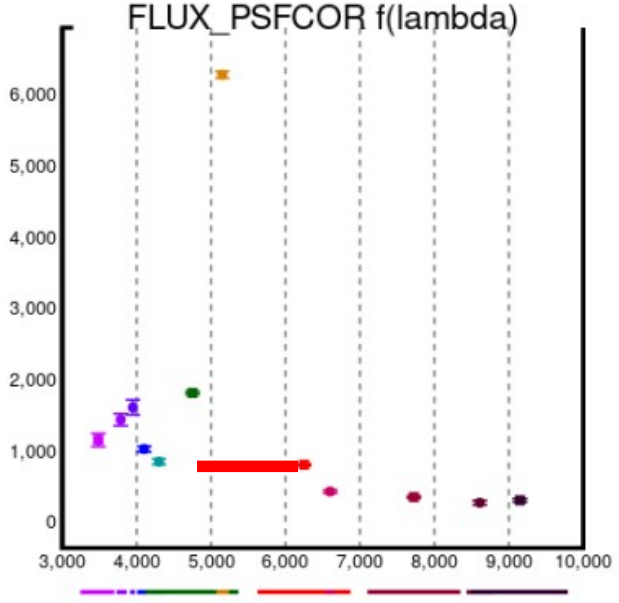
[OIII] EELGs sample selection

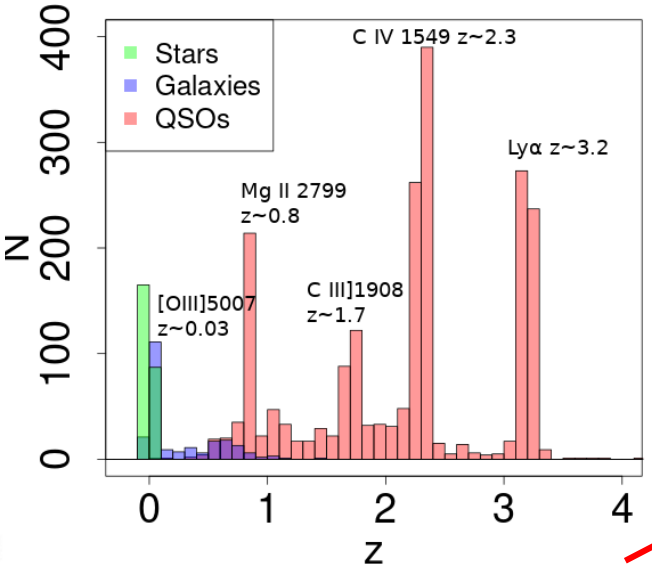
1. Selecting objects with excess of flux in the J0515 mediumband filter compared to a neighbouring broadband filter (rSDSS)

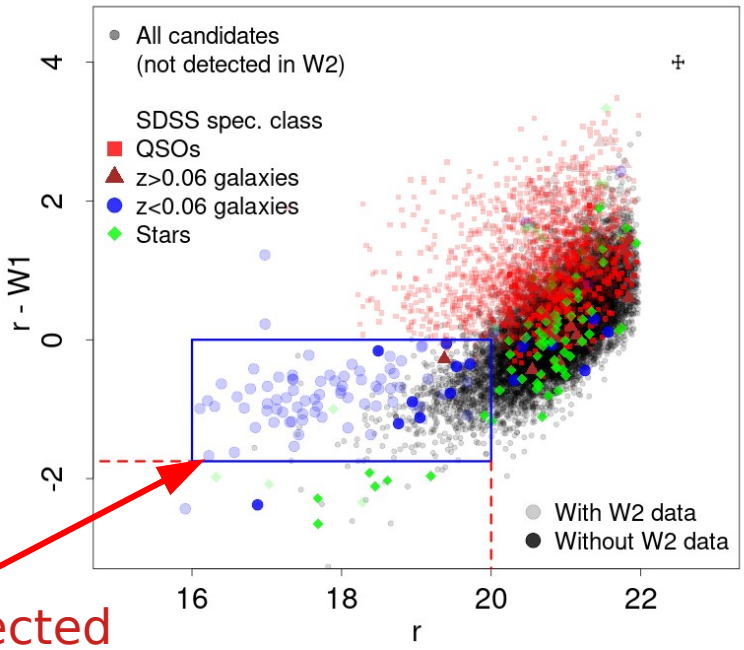
- Simply selecting excess of flux produces heavily contaminated samples
  - Mostly high-z QSOs with emission lines that fall in our filters

2. Removing contaminants

- Clear separation QSO/Galaxy using WISE data (W1 – 3.4 μm)
- r-W1 vs. r diagrams
- Considering spectroscopically confirmed objects:
  - ~90% purity, ~90% completeness







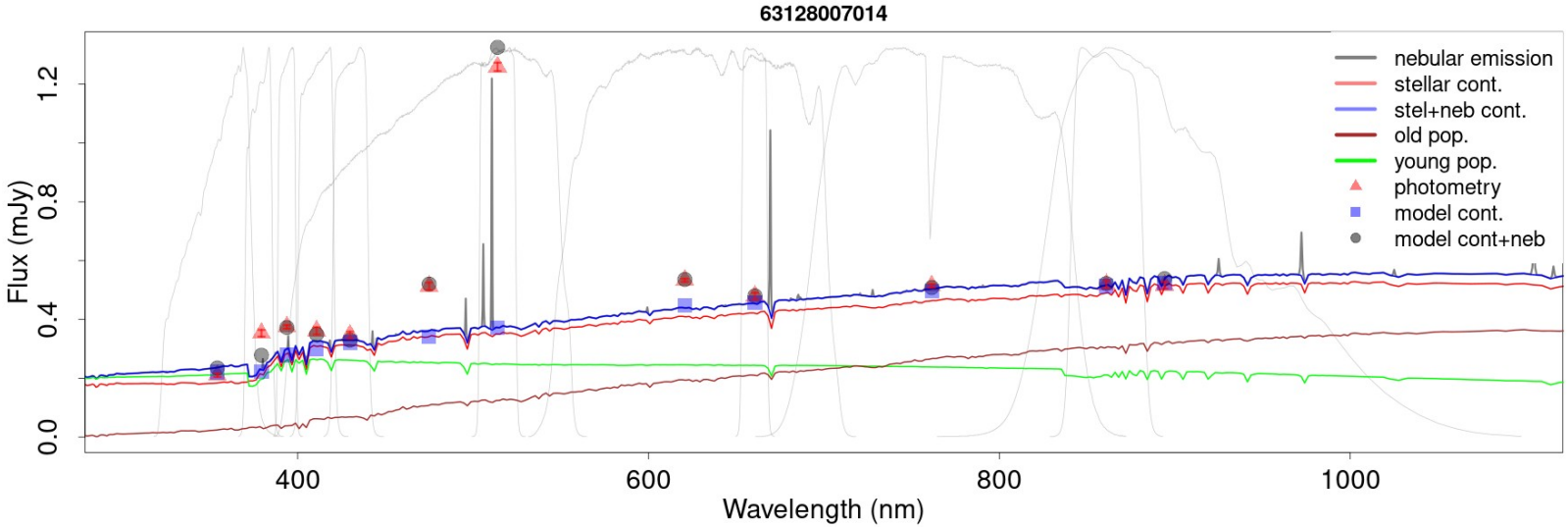
Selected

SED fitting and sample selection

- SED fitting to extract physical information
  - CIGALE (Boquien et al. 2019)
  - Two stellar populations (BC03) with instant bursts
  - Nebular emission (Inoue+2011)
- **Estimate continuum flux to calculate EW**
  - EW

[OIII] sample

- Very young burst (<=6 Myr)
- Low-mass galaxies
  - Median value $\log(M_*/M_\odot) \sim 8\ M_\odot$ (7.5-9)
- Low dust extinction E(B-V) ~ 0.15



- **466 galaxies with EW([OIII])>300 Å at 0.006<z<0.055**
  - **410 of them previously unknown**
    - **Largest sample since the release of SDSS spectra**
  - **~250 extra galaxies in J-PLUS DR3**

Lumbreras-Calle et al. 2022
arxiv:2112.06938

Number density of EELGs

- Number density of EELGs: ~ 1 per 4000 Mpc^3

Table 5. Number density of EELGs in this work, and comparison with several literature samples.

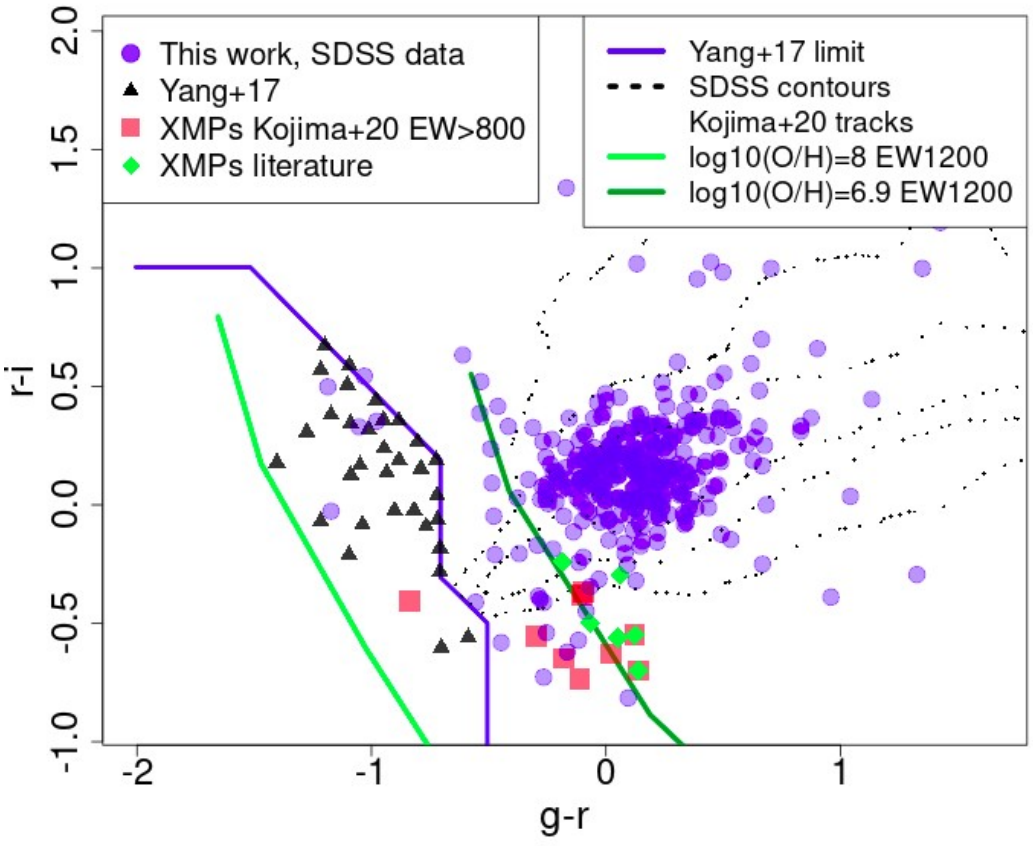
Sample	Selection method	N	Density [Mpc^{-3}]	Redshift range	EW limit [Å][a]	Mag. limit[b]	Mass limit $\log(M_\star/M_\odot)$
J-PLUS	Mediumband	394	$(2.45 \pm 0.27) \cdot 10^{-4}$	0.016 - 0.048	300	20.0	-
GAMA	Spectra	13	$(8.77 \pm 3.40) \cdot 10^{-5}$	0.016 - 0.048	300	19.0	-
J-PLUS comparison		113	$(6.96 \pm 0.96) \cdot 10^{-5}$				
SDSS	Spectra	90	$(1.37 \pm 0.23) \cdot 10^{-5}$	0.016 - 0.048	300	17.7	-
J-PLUS comparison		16	$(0.99 \pm 0.27) \cdot 10^{-5}$				
Yang et al. (2017)	Broadband	7	$(0.56 \pm 0.22) \cdot 10^{-6}$	0.016 - 0.048	1600	20.0	-
J-PLUS comparison		14 [c]	$(8.38 \pm 2.39) \cdot 10^{-6}$				
Cardamone et al. (2009)	Broadband	27	$(0.020 \pm 0.004) \cdot 10^{-6}$	0.18 - 0.32	400	-	9.52
J-PLUS comparison		2 [c]	$(1.240 \pm 0.890) \cdot 10^{-6}$	0.016 - 0.048			
Hα dots	Narrowband	6	$(1.60 \pm 1.50) \cdot 10^{-3}$	0.001 - 0.024	300	20.0	-
J-PLUS comparison		104 [c]	$(0.70 \pm 0.10) \cdot 10^{-3}$	0.016 - 0.024			

Comparable to magnitude-limited spectroscopic survey

20 – 50 times higher than broadband surveys

Comparable to narrowband surveys

[OIII] sample: Comparison with litterature

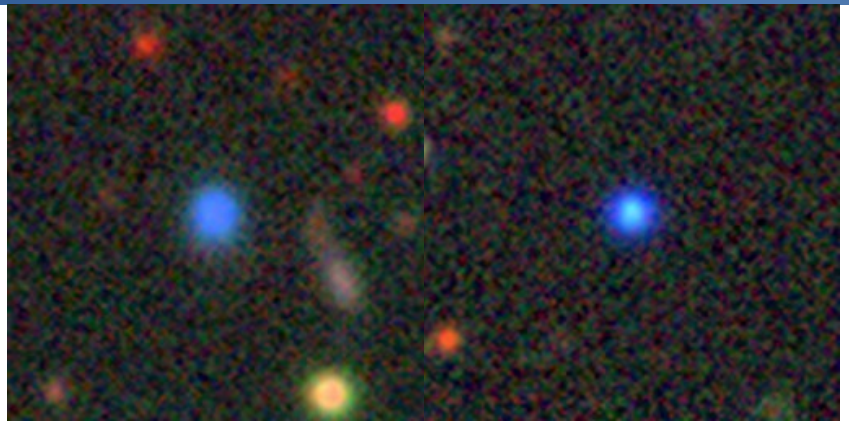


- More precise selection than broadband surveys

  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

[OIII] sample: morphologies



Compact

43 %



Semi-compact

38 %

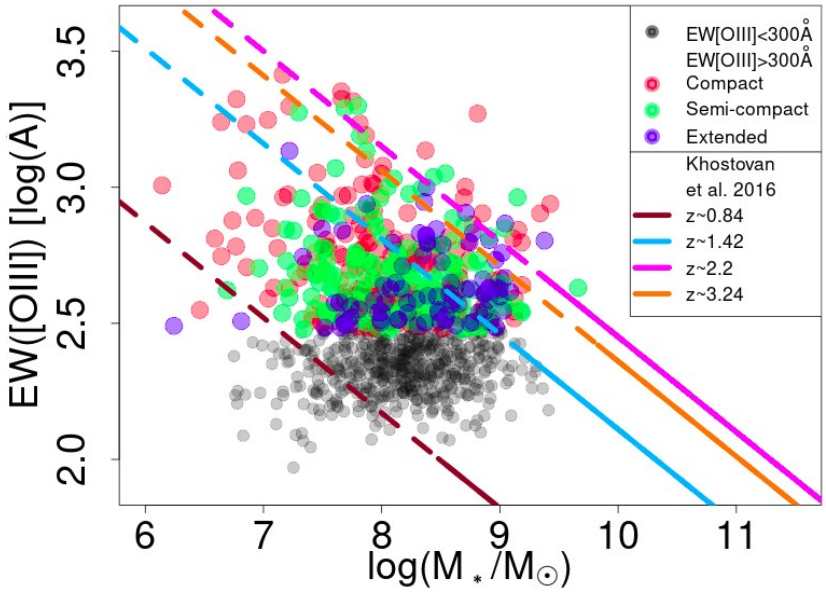
(tadpole, SF region + diffuse area, etc.)



Complex morphology

19%

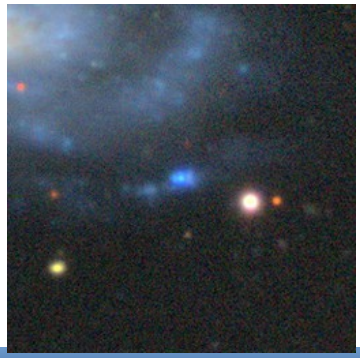
(multiple SF regions, mergers, etc.)



- Extended objects are slightly more massive ($10^{8.32}$ $M_\odot$ vs. $10^{8.04}$ $M_\odot$ in compact or $10^{8.15}$ $M_\odot$ in semi-compact galaxies)
- Extended show slightly lower EW (397 Å vs. 466 Å and 445 Å respectively)

Images from the Legacy Survey viewer www.legacysurvey.com/viewer

Rejected: SF regions in large-scale spirals



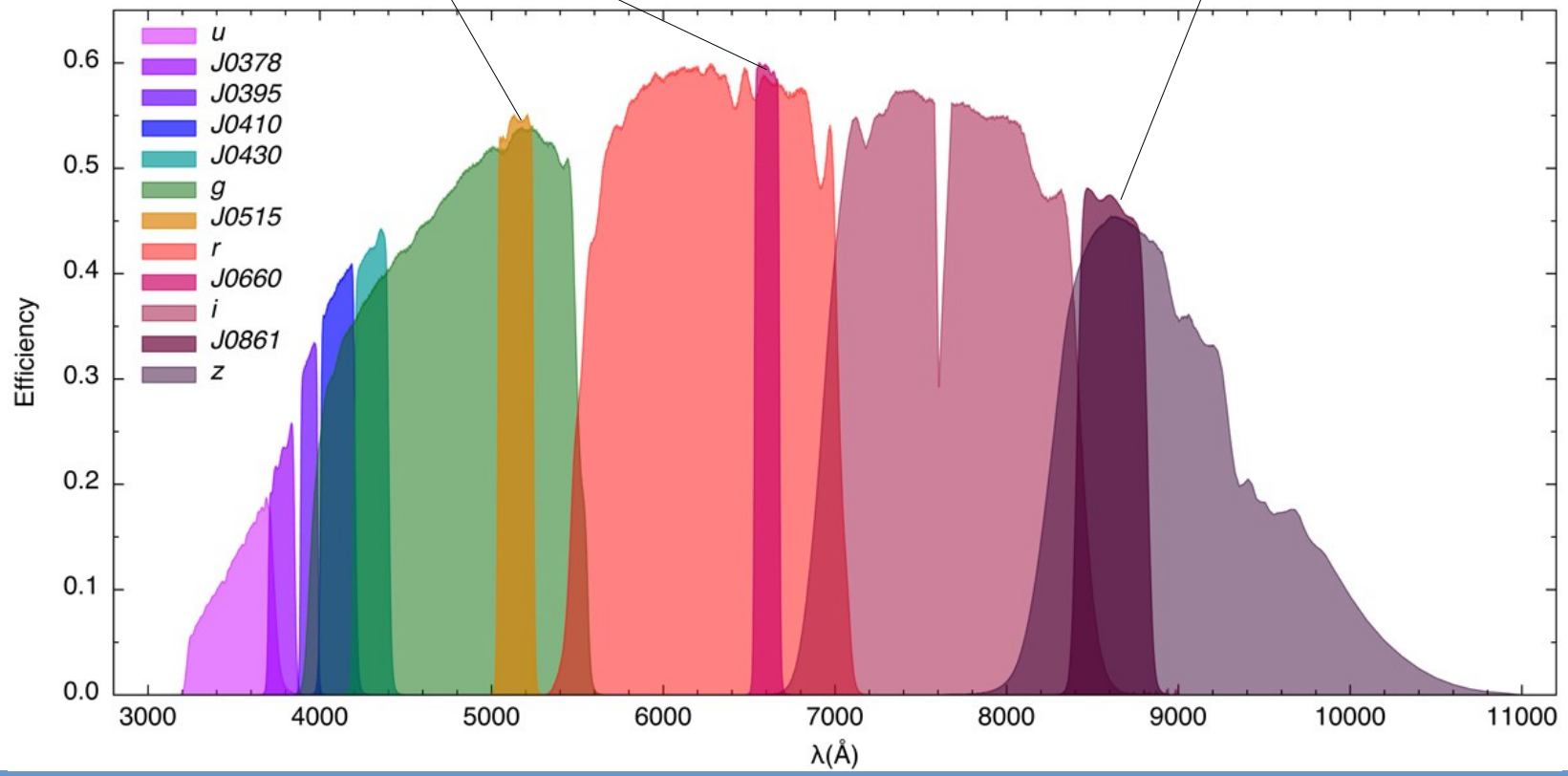
The narrowband J-PLUS EELG samples

3 filters - 3 redshift slices

[OIII]5007 emitters

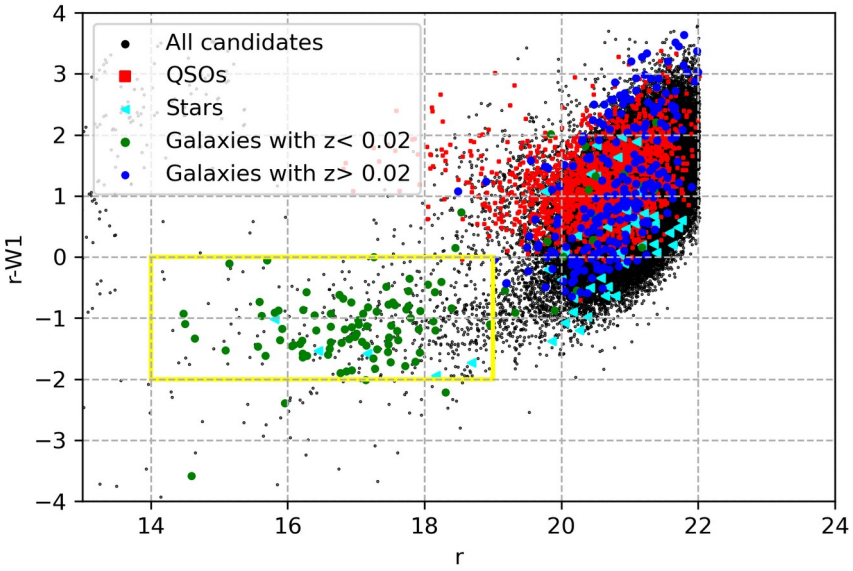
Hα emitter

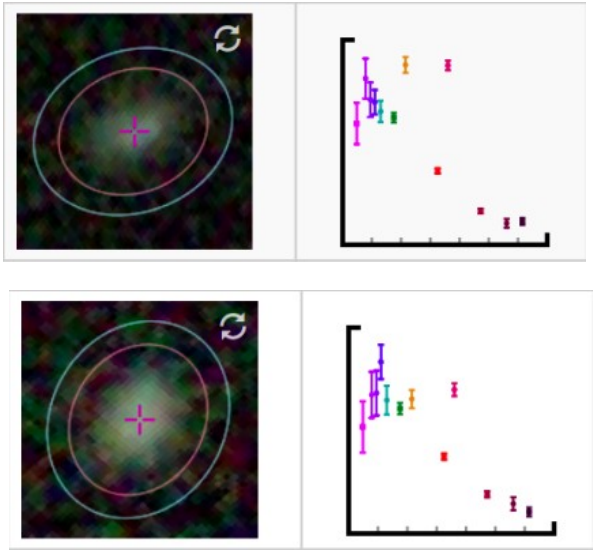


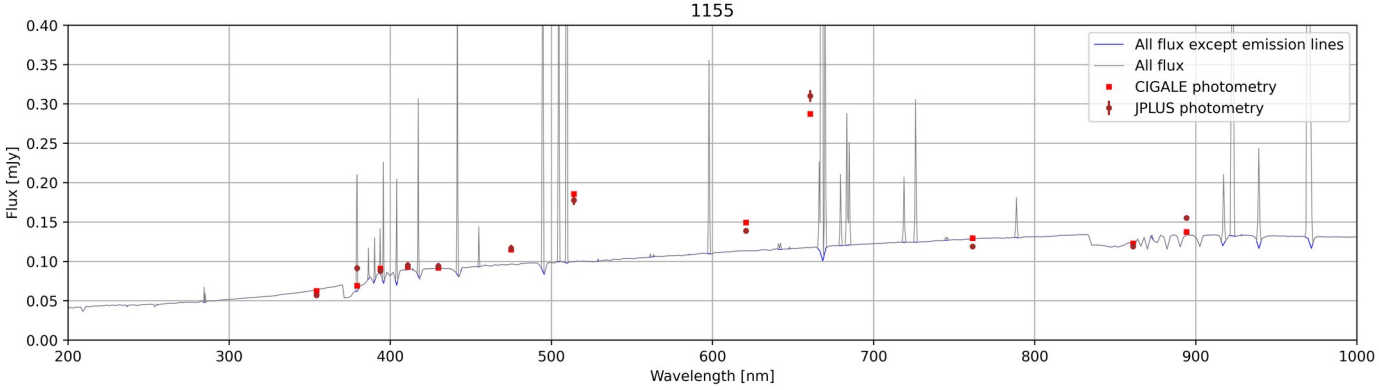


Hα z<0.02 selection (J0660)

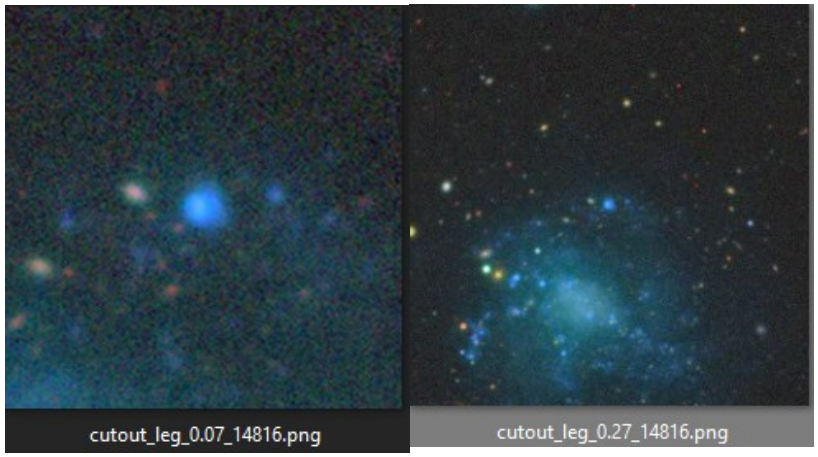
- Luis Soliveres' master thesis (VIU)
- 77 objects with EW(Hα)>200Å (DR3)
  - ~ 50 previously unclassified
- Much more numerous spurious detections
  - The J0660 covers rest-frame Hα
  - Local HII regions, or even planetary nebula
- Purity 93%, Completeness 73 %
- Lower median ages of the young population (5 Myr) and stellar masses (10^7.6 $M_\odot$)

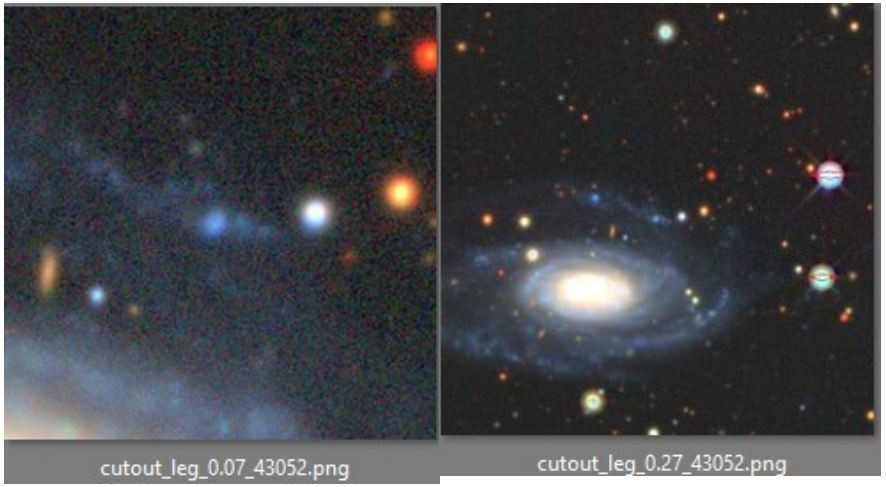


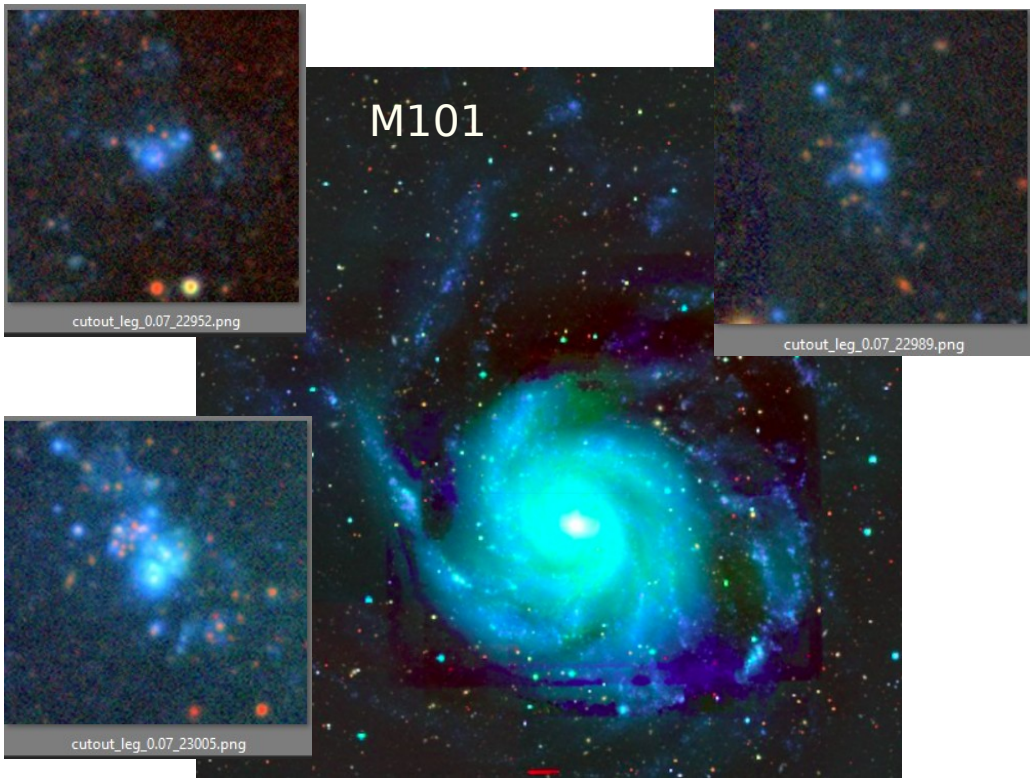


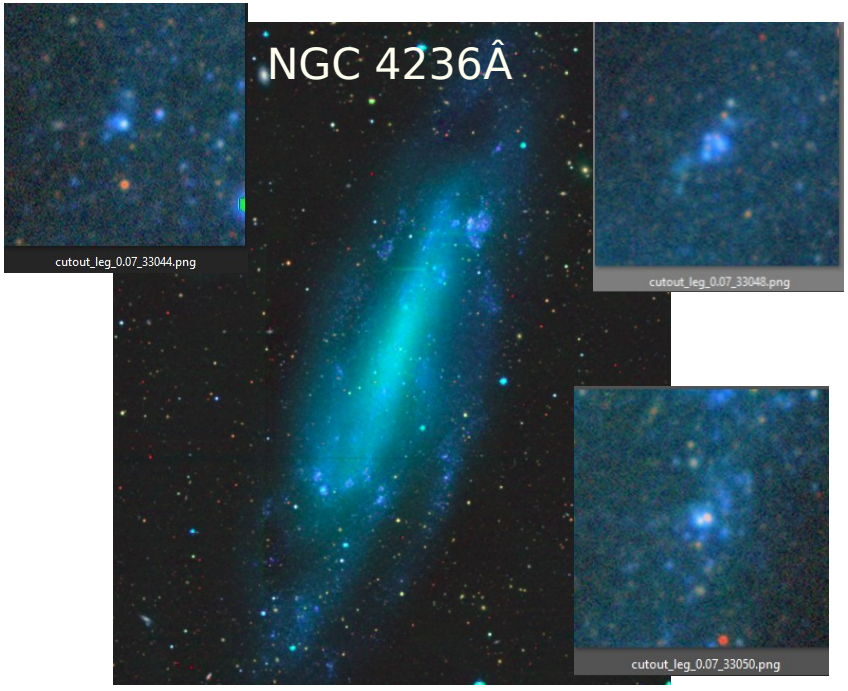


Regions of nearby galaxies



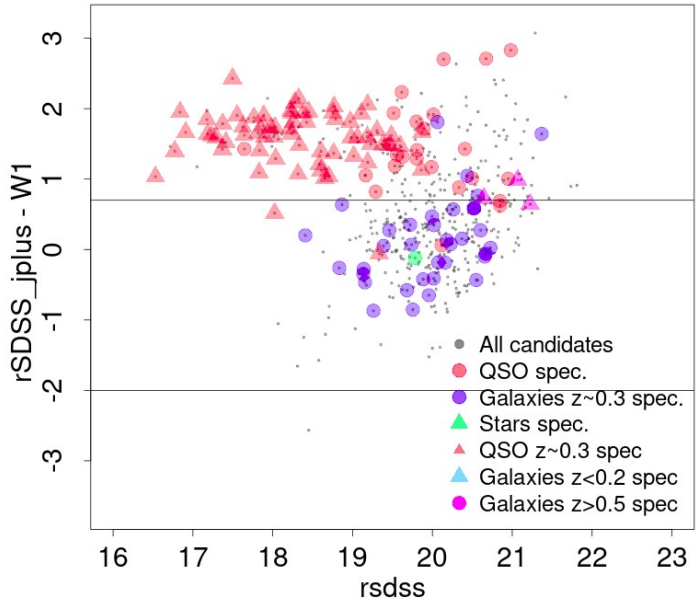


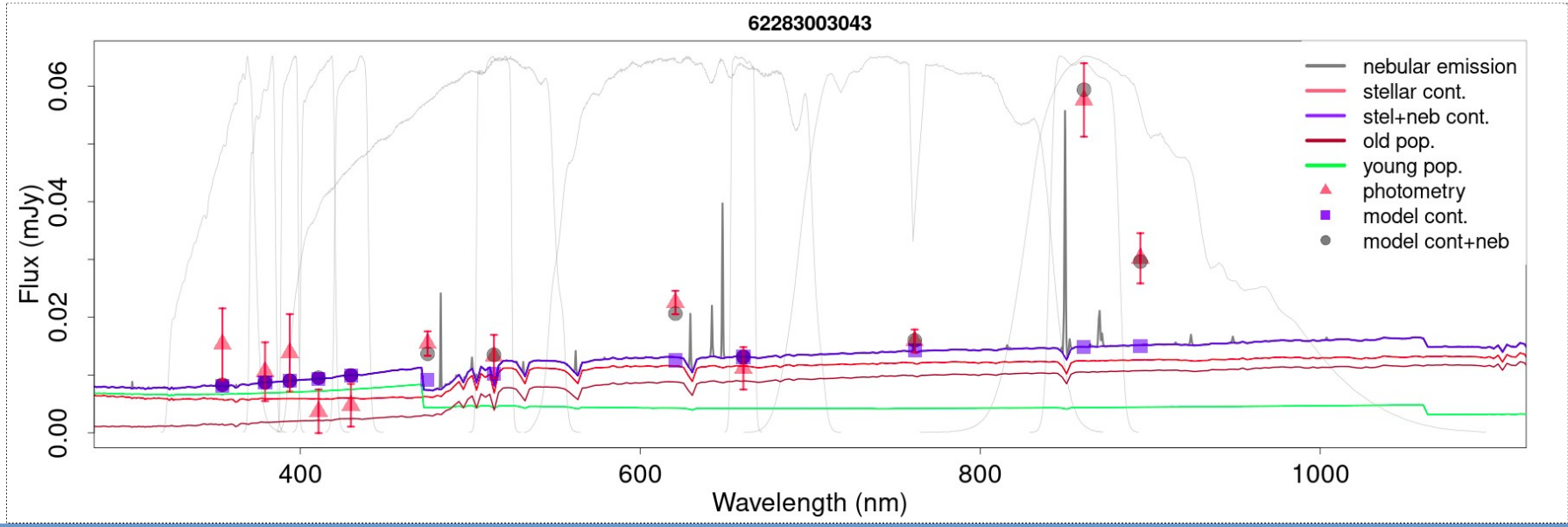


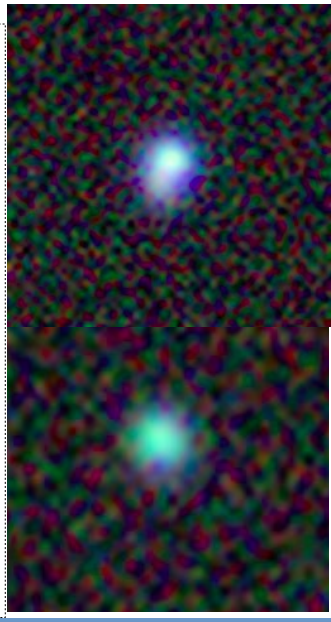


Hα z~0.3 selection (J0861)

- 497 objects with EW(Hα)>400Å (DR3)
  - 419 previously unclassified
- ~90% purity and ~ 80% completeness
- Higher stellar masses (~10^9 $M_\odot$)
- Includes the typical green peas (very large EW([OIII]) high [OIII]/[OII])
  - Also objets with high Hα/[OIII], missing in green peas
- More compact morphologies (observational effect) but not all!
  - 53% Compact, 41% Semi-compact, 6% Extended







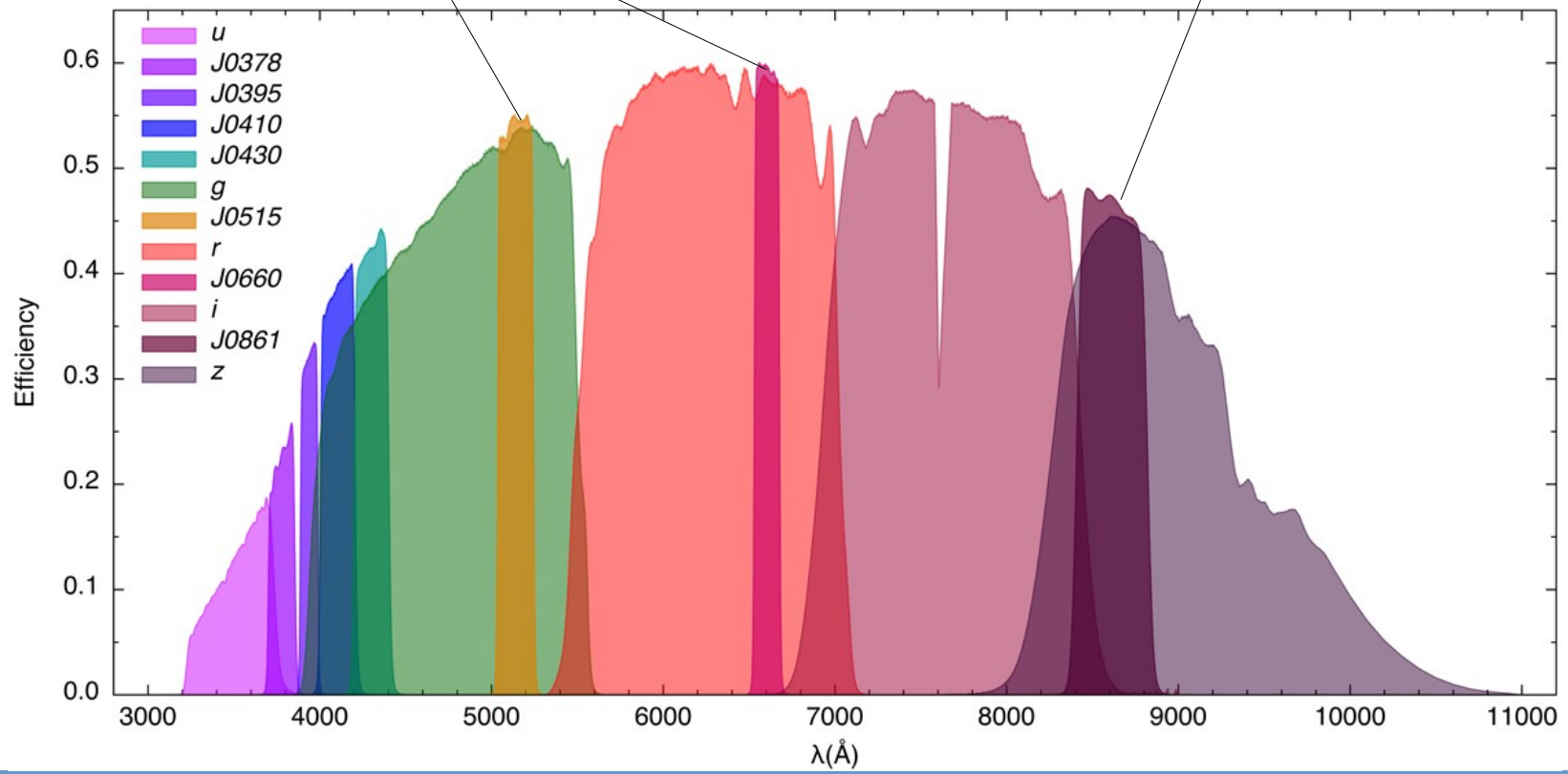
The previous EELG samples

3 filters - 3 redshift slices

[OIII]5007 emitters

Hα emitter





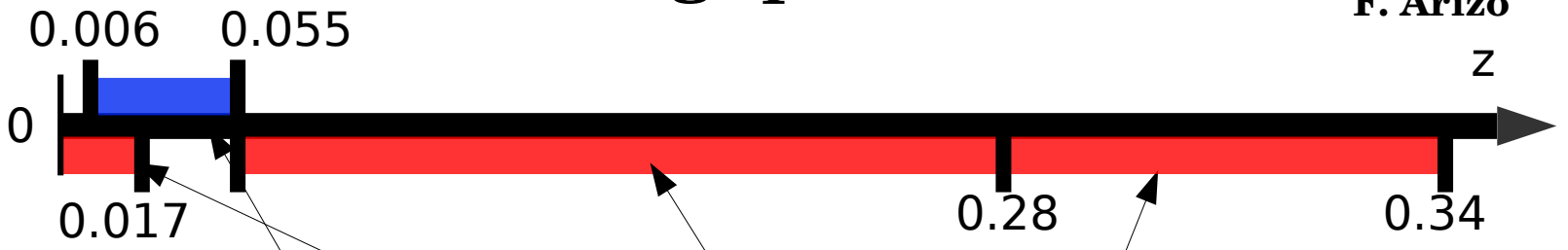
2023 New sample

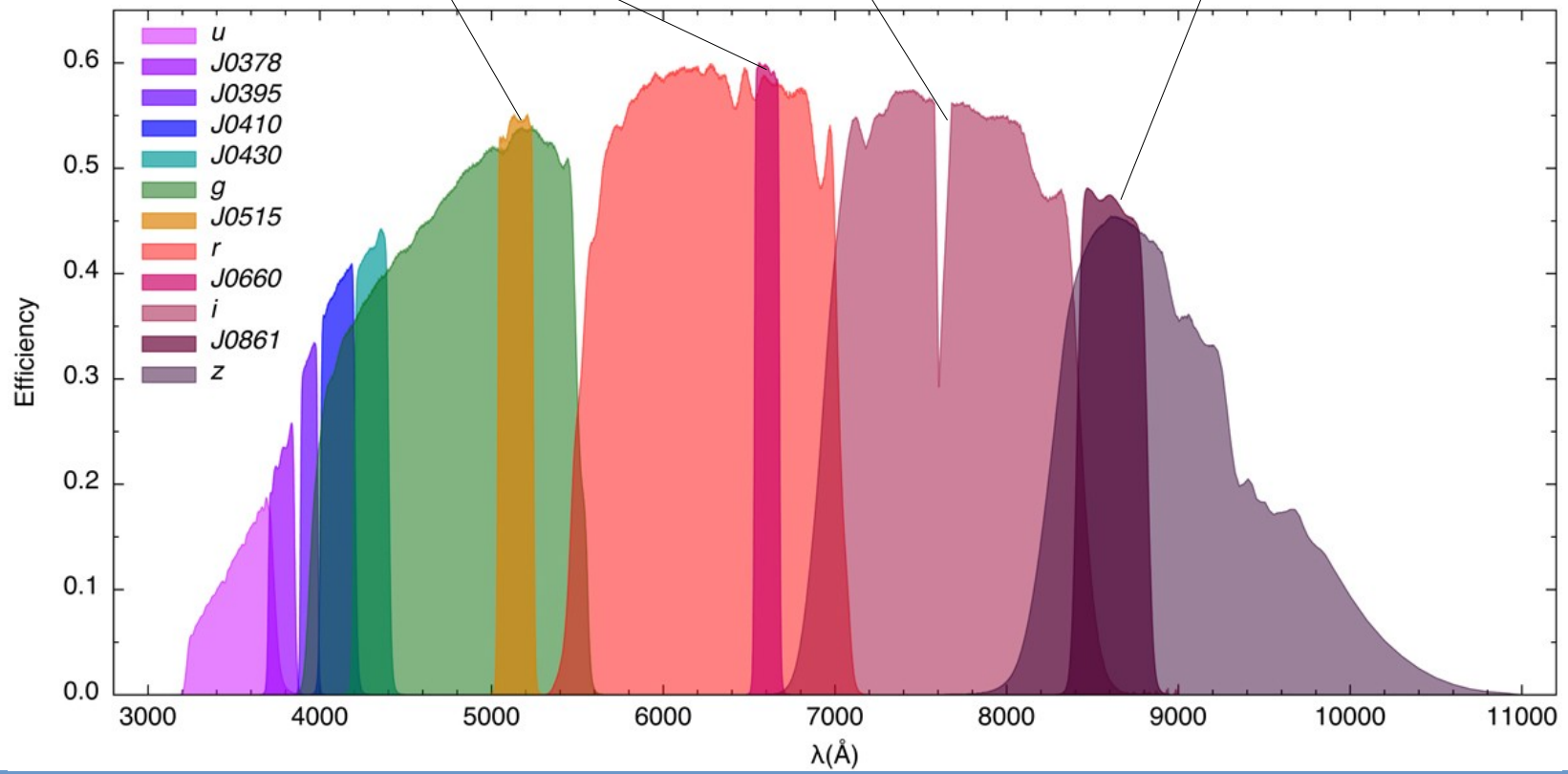
[OIII]5007 emitters

Hα emitter

Final redshift gap covered

With a tip from F. Arizo

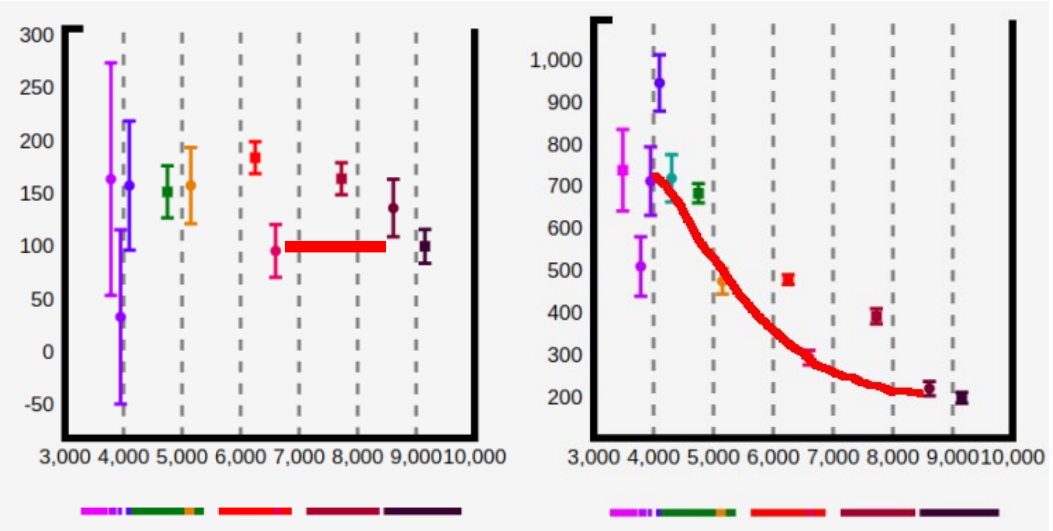




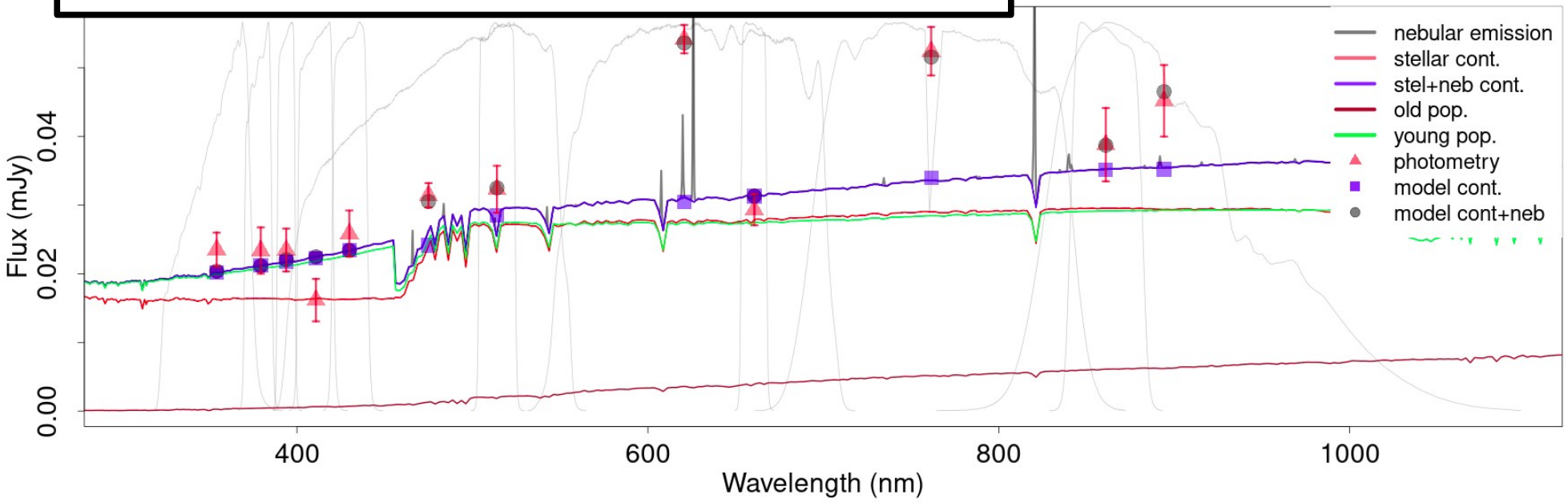
New sample selection – iSDSS

1. **Very strong emission lines significantly affect the flux <u>also in broadband filters</u>**
2. Broadband-only surveys are limited
   - All nearby filters may be contaminated by emission lines
3. <u>J-PLUS can measure accurately strong emission lines using broadband filter:</u>

   We can use a nearby narrowband filter to estimate the continuum

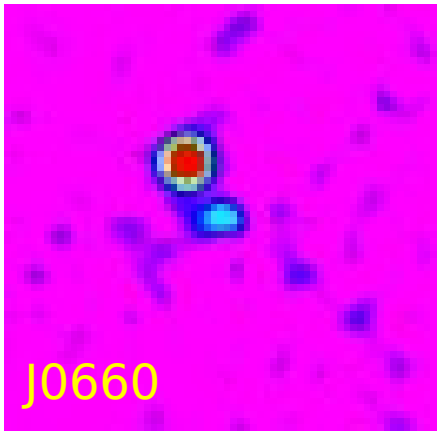


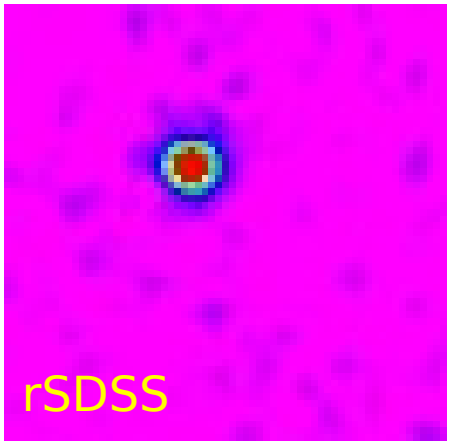
736 galaxies with EW(Ha)>600Å at 0.06<z<0.28

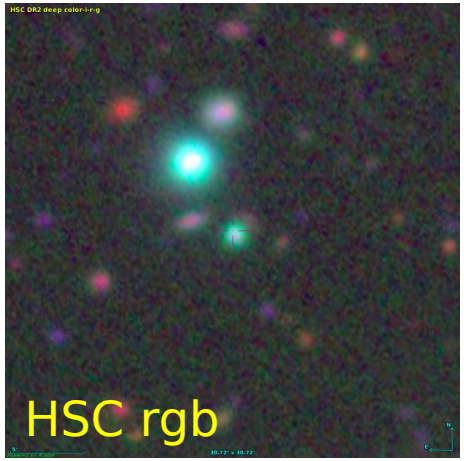


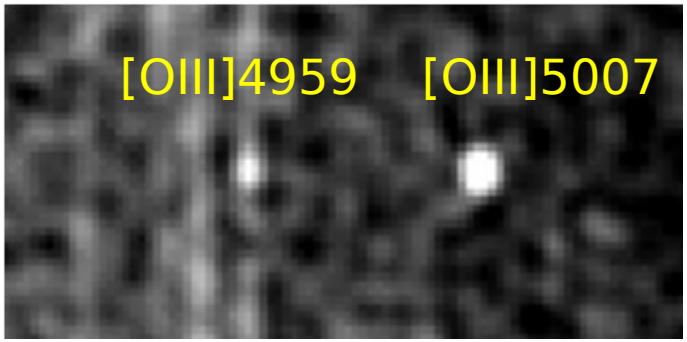
… and beyond: Single band detection!

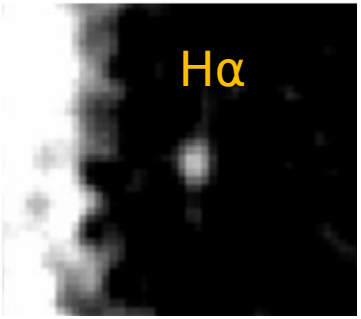
- Single-band selection
  - Objects detected in mediumband due to extreme emission line
  - NOT detected in broadband due to faint continuum
  - HOWEVER: There will be always flux in the broadband, even just due to the emission line, ~ 2 mag fainter
- Challenge: risk of misidentifications
- Preliminary test at the INT
  - J0660 detected (20.65 mag),
  - rSDSS undetected
  - Broadband-selected objects in deep HSC Subaru data (r=22.22 mag)
- Additional test with WEAVE











3. Detailed analysis of J-PLUS EELGs

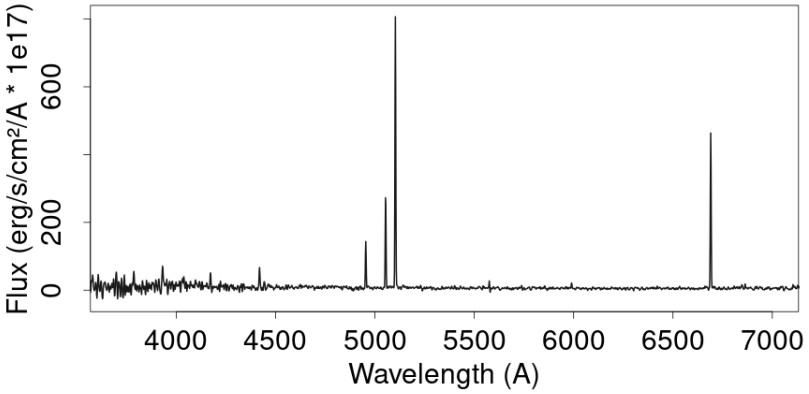
Follow-up spectra of the EELGs samples

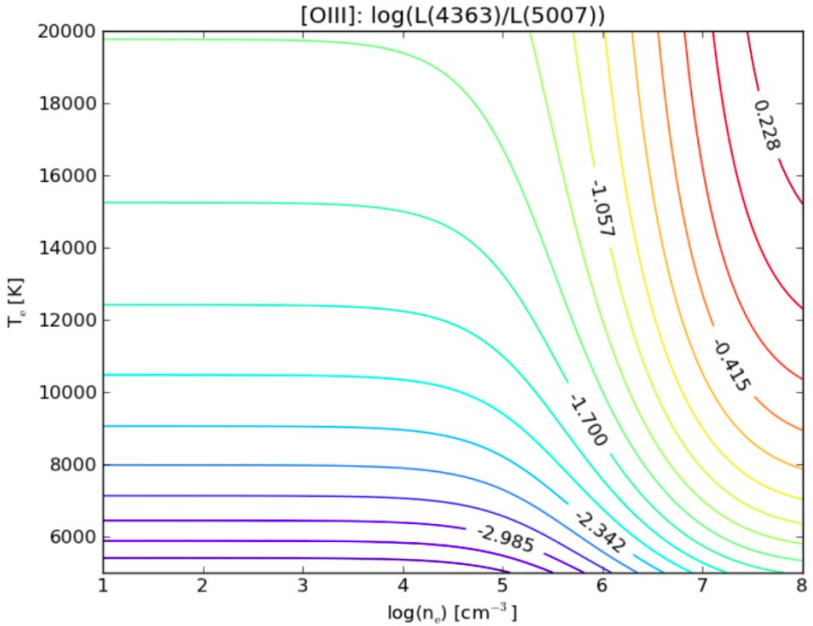
- Longslit spectroscopy at the 2.5m INT at the Roque de los Muchachos Observatory (La Palma)
  - IDS: 3500 Å - 7000 Å, R ~ 400
  - Pre-2023: ~50 galaxies observed
    - **ALL CONFIRMED** as low redshift EELGs with strong emission lines
  - 2023: In person observing run in July (~ 10 galaxies)
- Archival spectroscopic data (J0515)
  - 80 additional spectra
    - 50 from SDSS, 11 from DESI, 18 from LAMOST
- Filler proposal at GTC/OSIRIS proposal: accepted for 2024
  - Targeting fainter galaxies



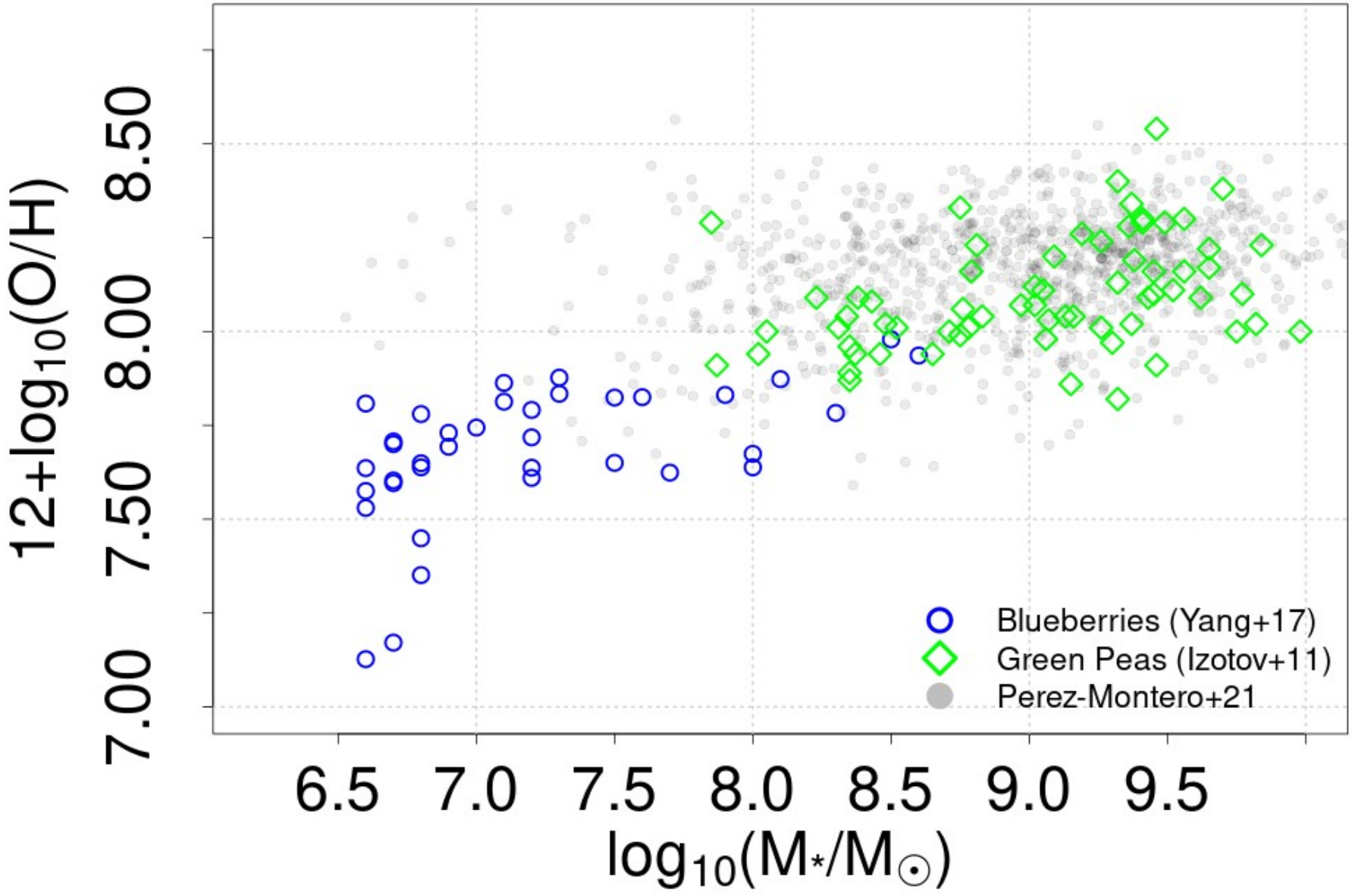
Follow-up spectra of the [OIII] sample

- Spectroscopic data analysis
  - Collaboration in Granada with Estallidos-IAA
  - Electronic density determined with [SII]6717/[SII]6731
    - Typically close to the low density limit (100 cm^{-3})
  - <u>Metallicity determination with the direct method</u>
    - Electron temperature with [OIII]4363 and Pyneb
      - Only available for a fraction of INT sources (~20)

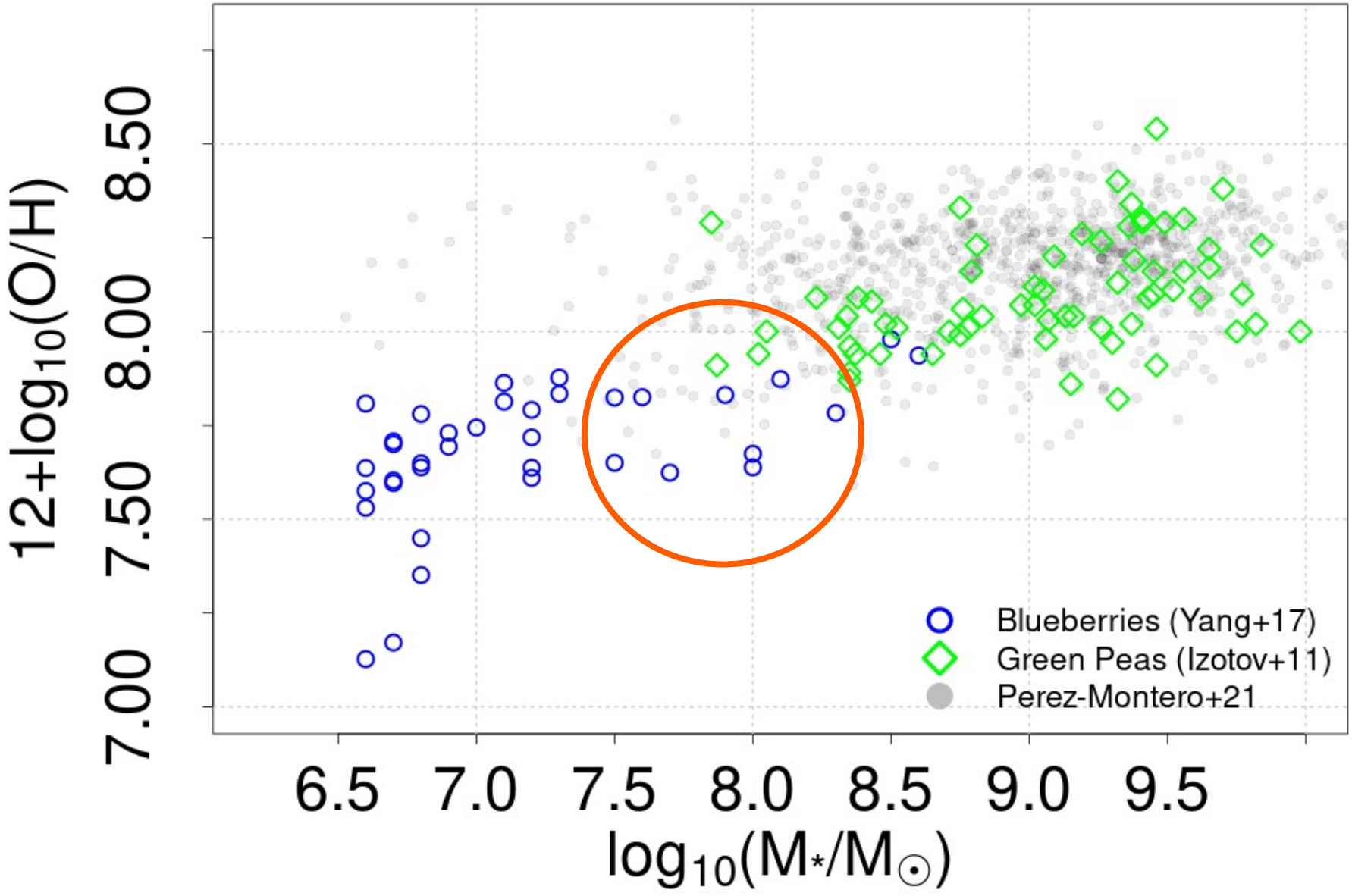




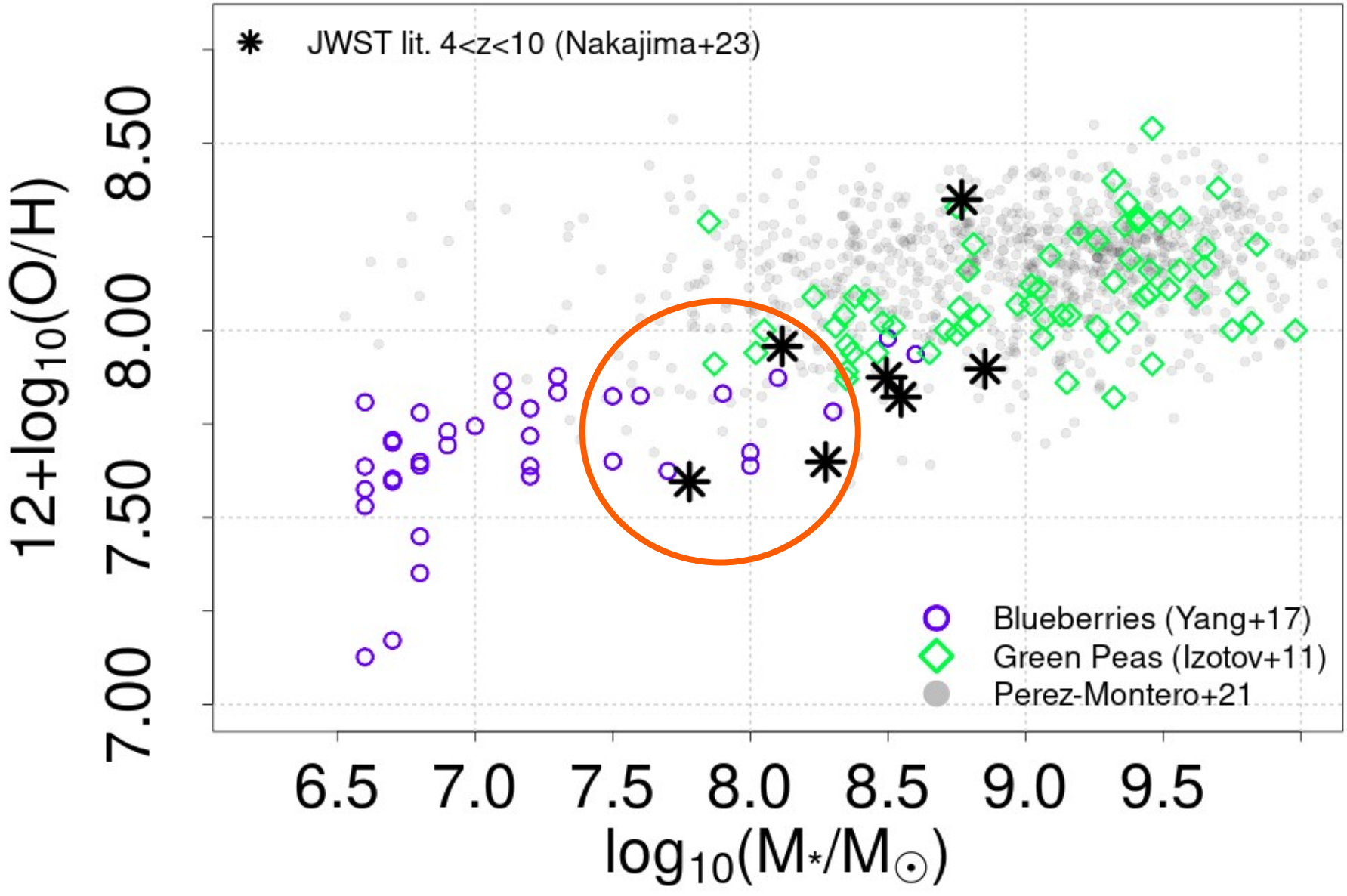
Mass – metallicity relation



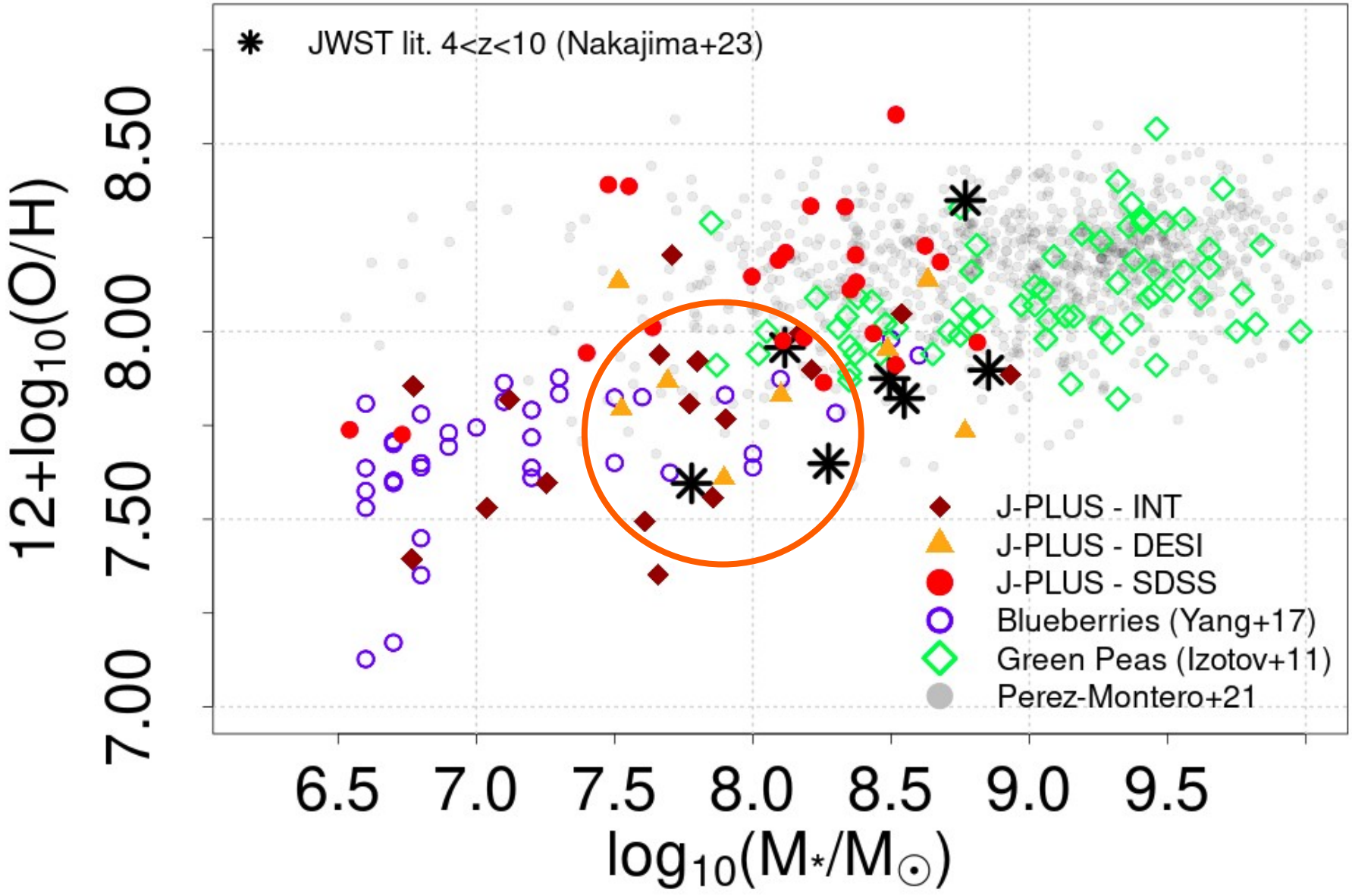
Mass – metallicity relation



Mass – metallicity relation



Mass – metallicity relation

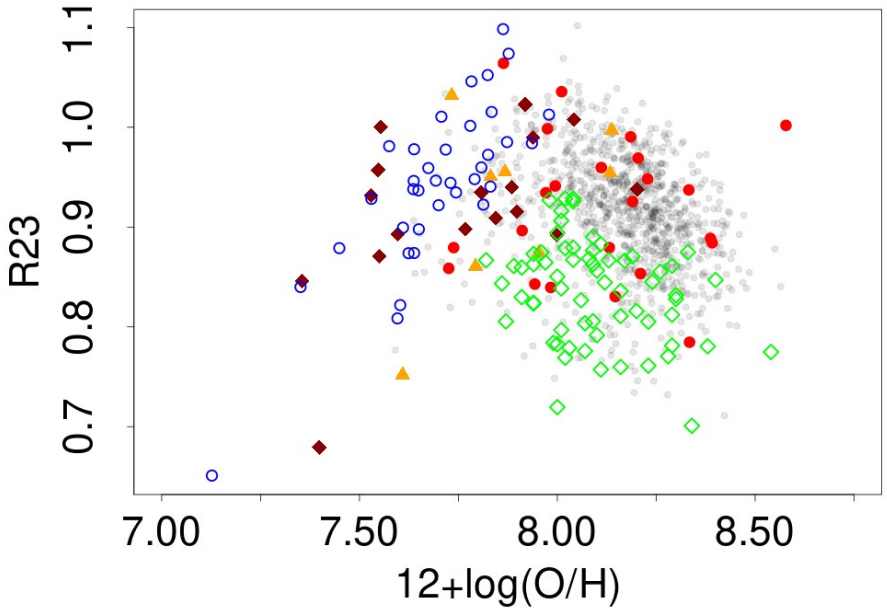


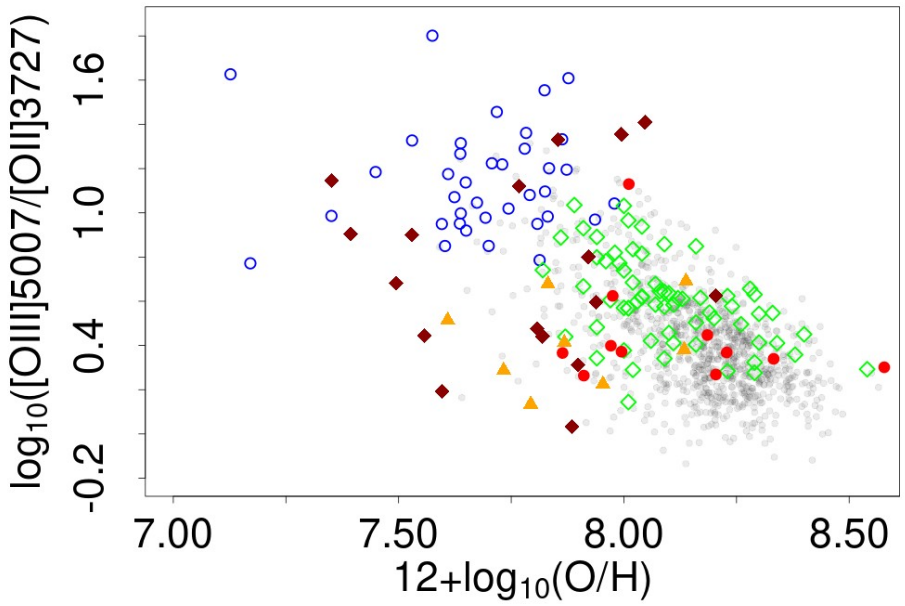
¿Empirical calibrations?

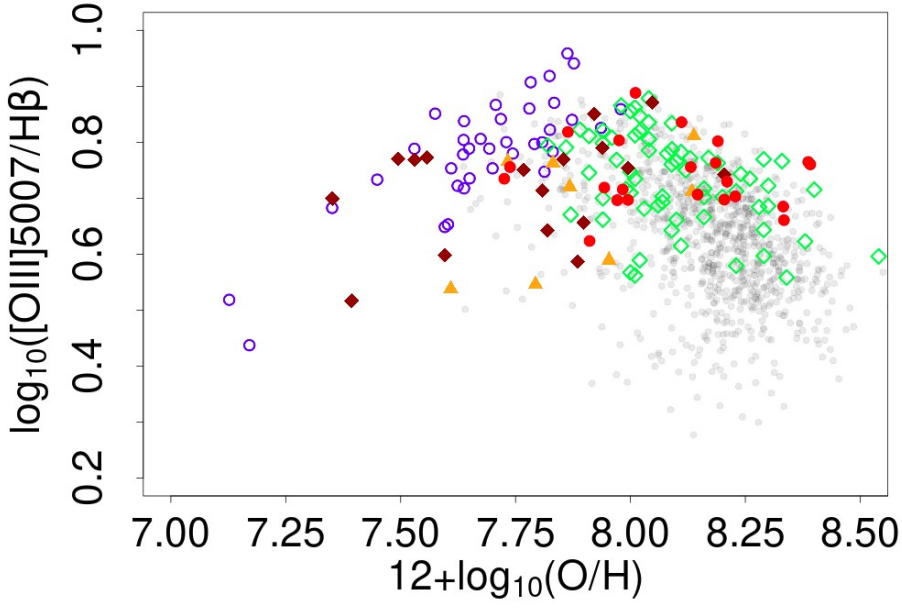
- Difficulty detecting the [OIII]4636 auroral line in large samples of very high redshift galaxies
  - Need for empirical metallicity calibrations
  - Key importance: use of low-z galaxy analogs

Very challenging so far

Laseter et al. (2023)

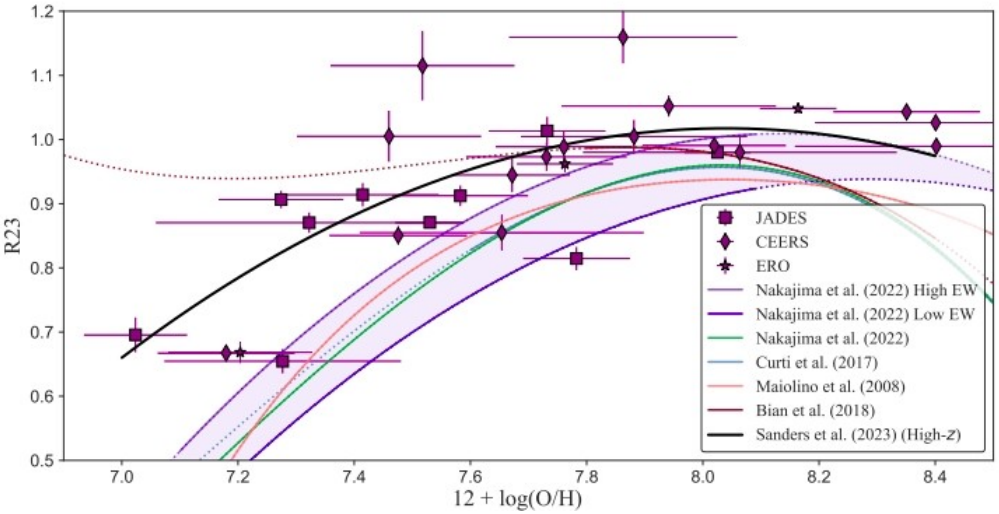


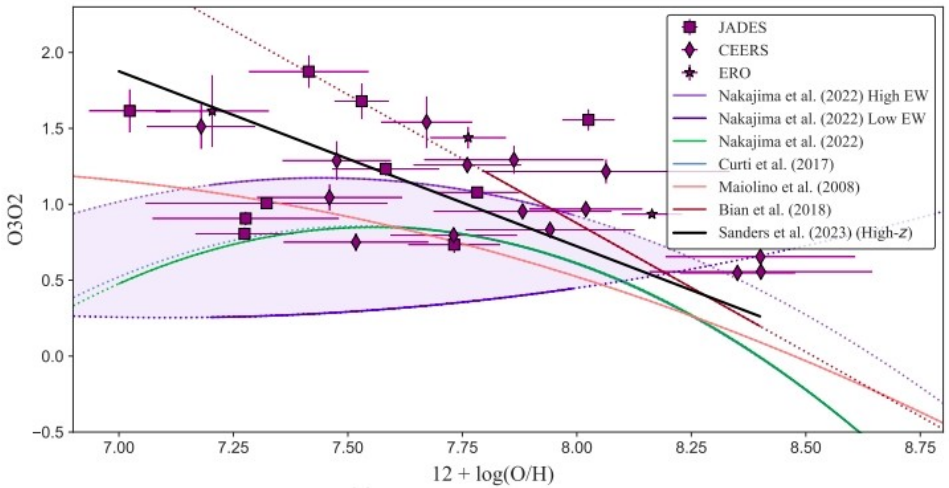


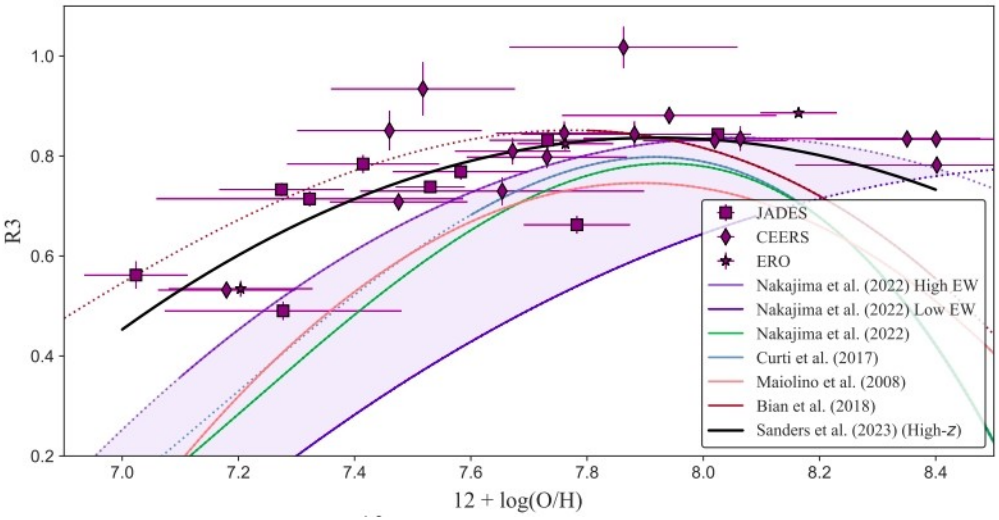


¿Empirical calibrations?

- 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)

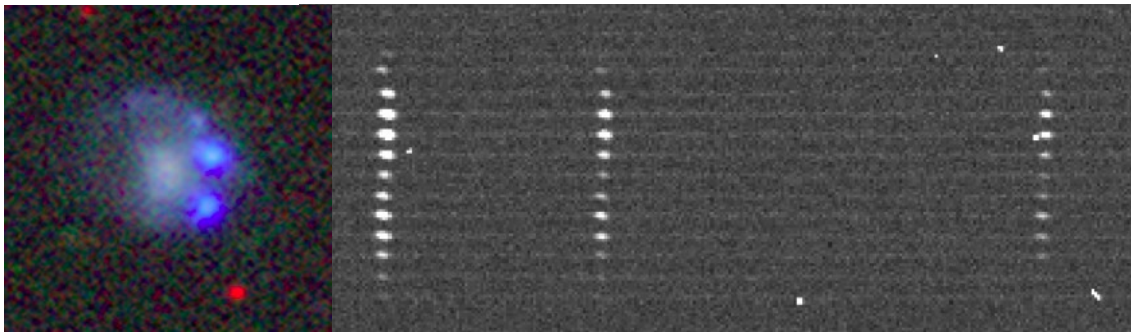






Other spectroscopic follow-up

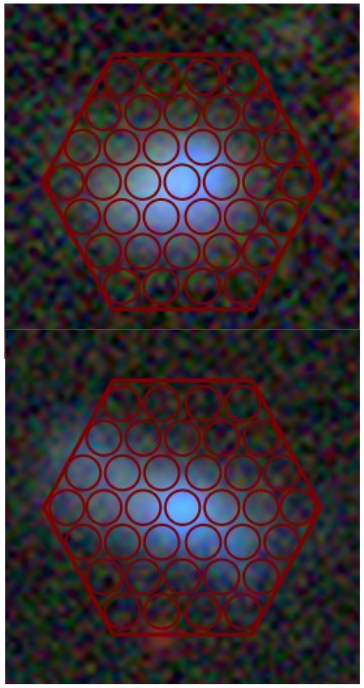
- PMAS
  - 3.5 at CAHA (Almería)
  - 3700 Å-7000 Å
    - R ~ 500 / ~1200
    - Only 2 galaxies (pilot project)

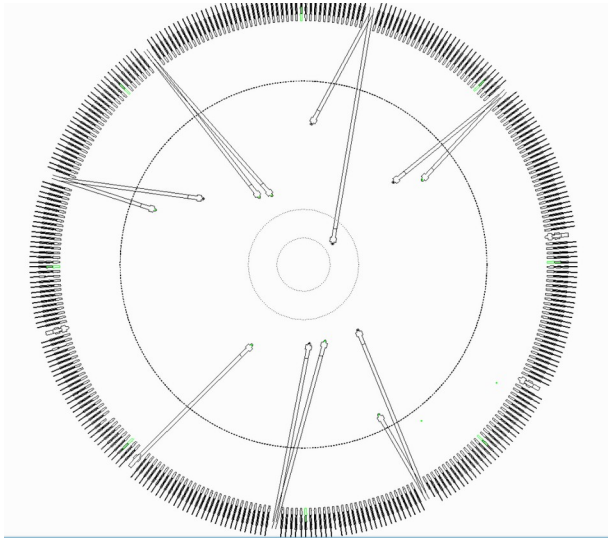


(near? future)

- WEAVE spectrograph @WHT
  - mini IFUs (P.I. Casiana M-T)
    - Science Verification proposal

      ~~2020~~ ~~Autumn 2022~~ ~~Spring 2023~~ ~~Autumn2023~~ Spring 2024?
    - Feedback processis in strongly star-forming galaxies
    - 2 fields of J-PLUS EELGs
      - 25 - 30 galaxies (within 2 deg² diameter)
    - High resolution
      - R~20 000
  - MOS
    - MiniJPAS (~1700 objects)
    - Follow-up of 9 EELGs from Iglesias-Páramo et al. 2022
    - Intense line emitters (85)
    - Single-band detection candidates (329)

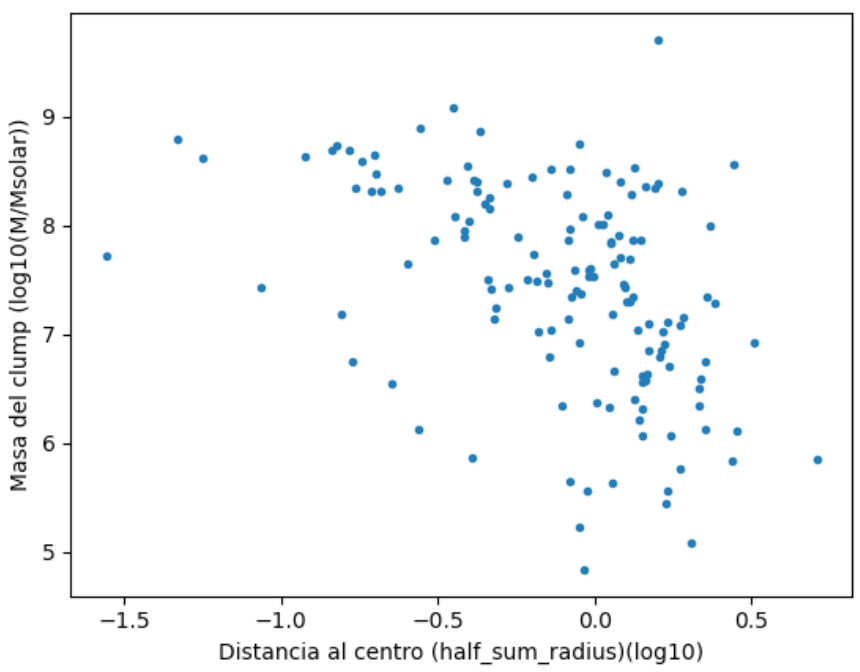


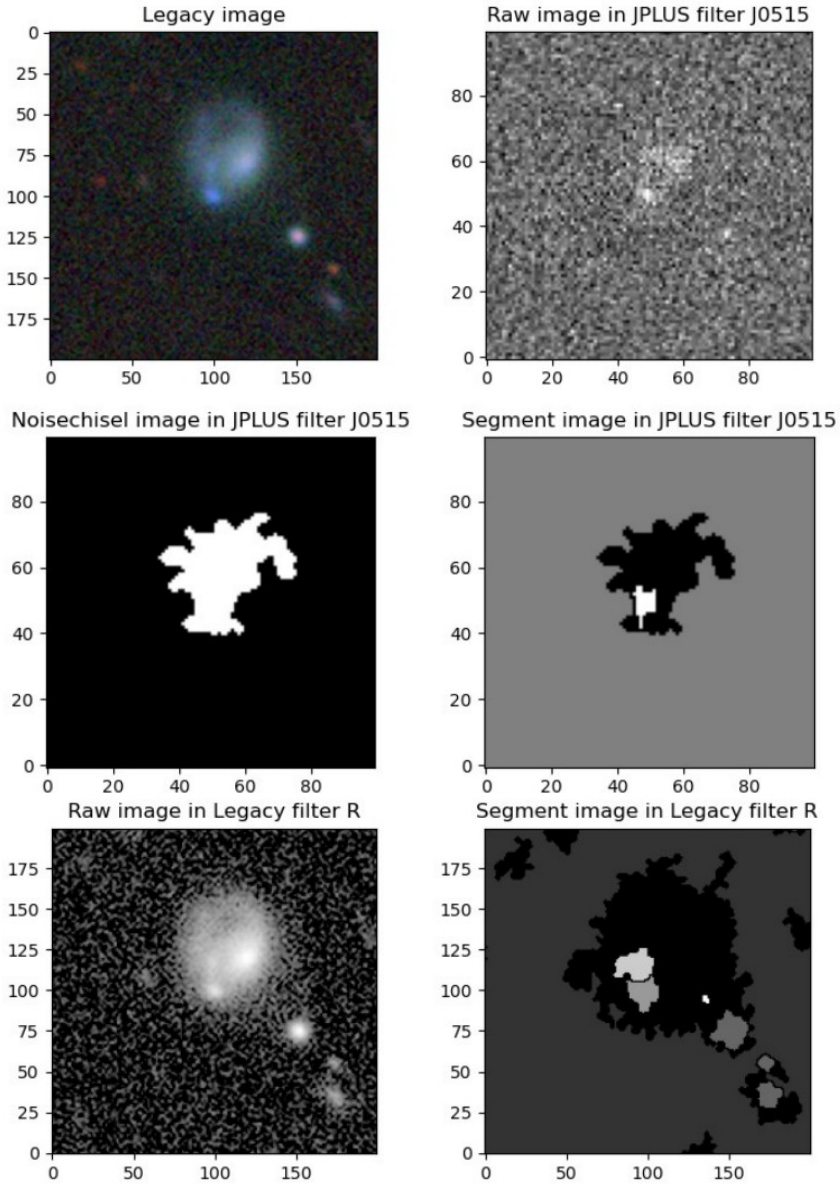


4. Additional studies on EELGs

Morphological analysis of EELGs

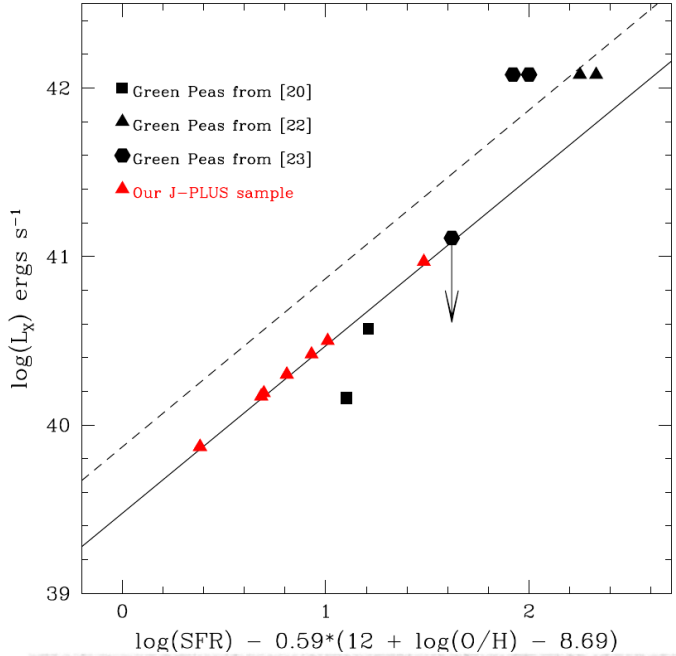
- **Jorge Porrón (Unizar) Master Thesis**
- Identify star-forming clumps in extended EELGs using GNUastro (Akhlaghi & Ichikawa (2015)
- <u>The narrowband filter in J-PLUS is just as good (even better) than deeper, higher resolution broadband data identifying clumps</u>
  - We select only SF clumps
- 90 EELGs, 140 clumps (14 galaxies with 0)
- The farther from the center of the galaxy, the smaller/less massive the clump (consistent with Hinojosa-Goñi et al. 2015 and others)

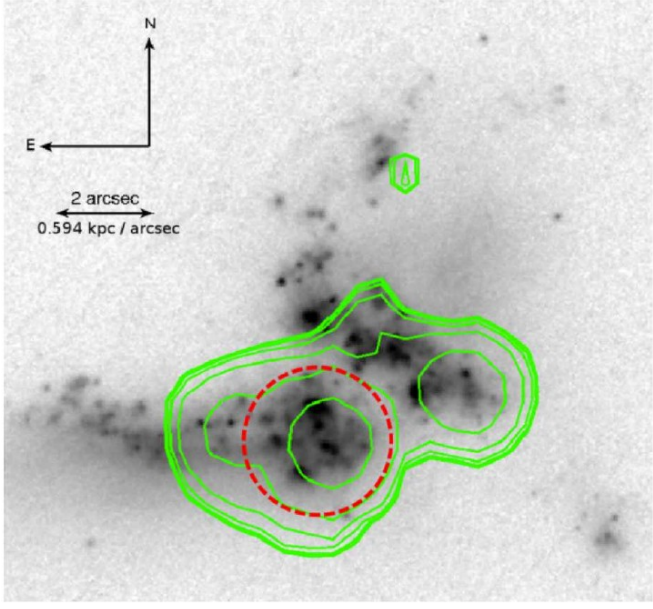




X-Ray (Chandra)

- **Do EELGs produce more X-ray binaries than expected?**
  - Predicted larger binary production in low-metallicity SF
  - X-ray detections in just a couple of EELGs
    - In some cases unresolved (AGN?)
- Accepted Chandra observations
  - PI J. Irwin (U. of Alabama)
  - Targeting 7 J-PLUS EELGs, 156 ksec
  - First observations in April 2024

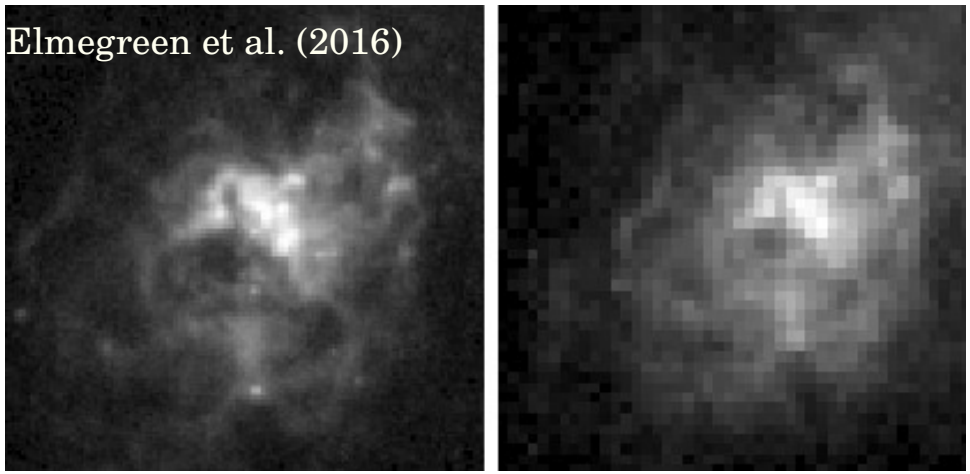


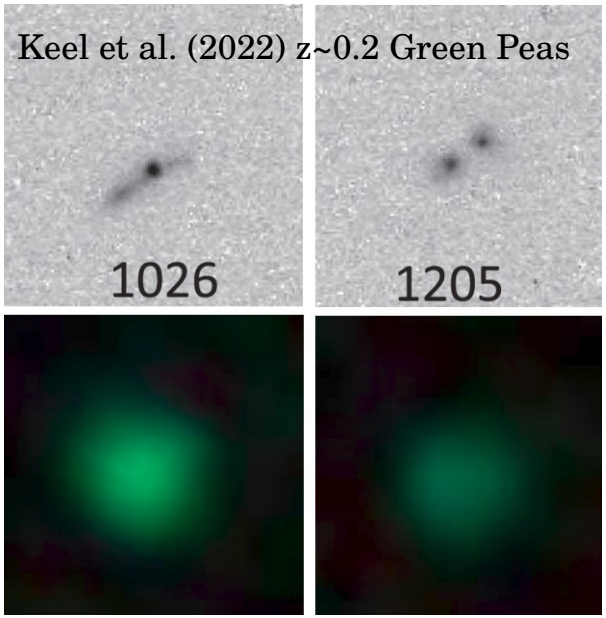


Chandra and HST observations

- Joint HST observations accepted for 2024/2025
  - High resolution imaging
    - Unveal the structure of the interstellar medium
  - 7 galaxies – 7 orbits
  - UV, near-IR and Hα filters

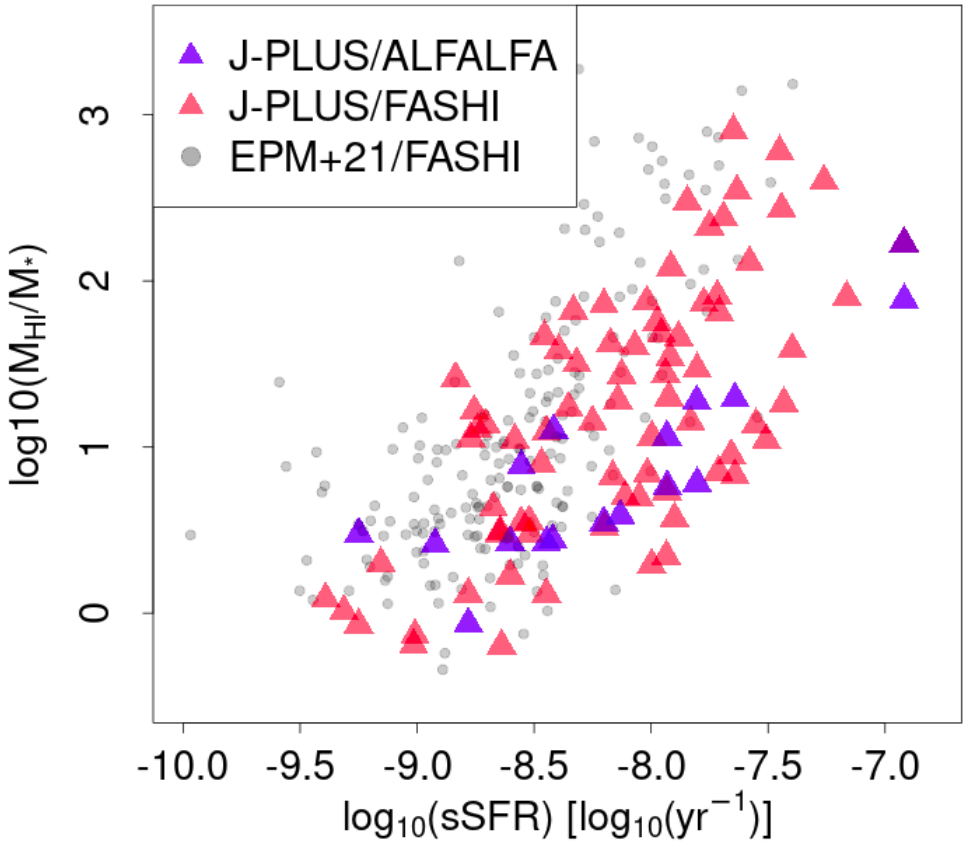






Radio emission: HI gas

- How are these starbursts being fueled? Why are they so extreme?
  - Key observable: HI gas, the "fuel" for star-formation
- 90 J-PLUS EELGs (z<0.06) with HI detections
  - 17 in ALFALFA
  - 73 additional in FASHI (Zhang et al. 2023) with the FAST 500 m radiotelescope
- Preliminary cross-match (60")
- Preliminary result
  - Steep and clear correlation between gas-to-stellar mass ratio and sSFR
    - The more gas you have available, the more extreme you burst is?

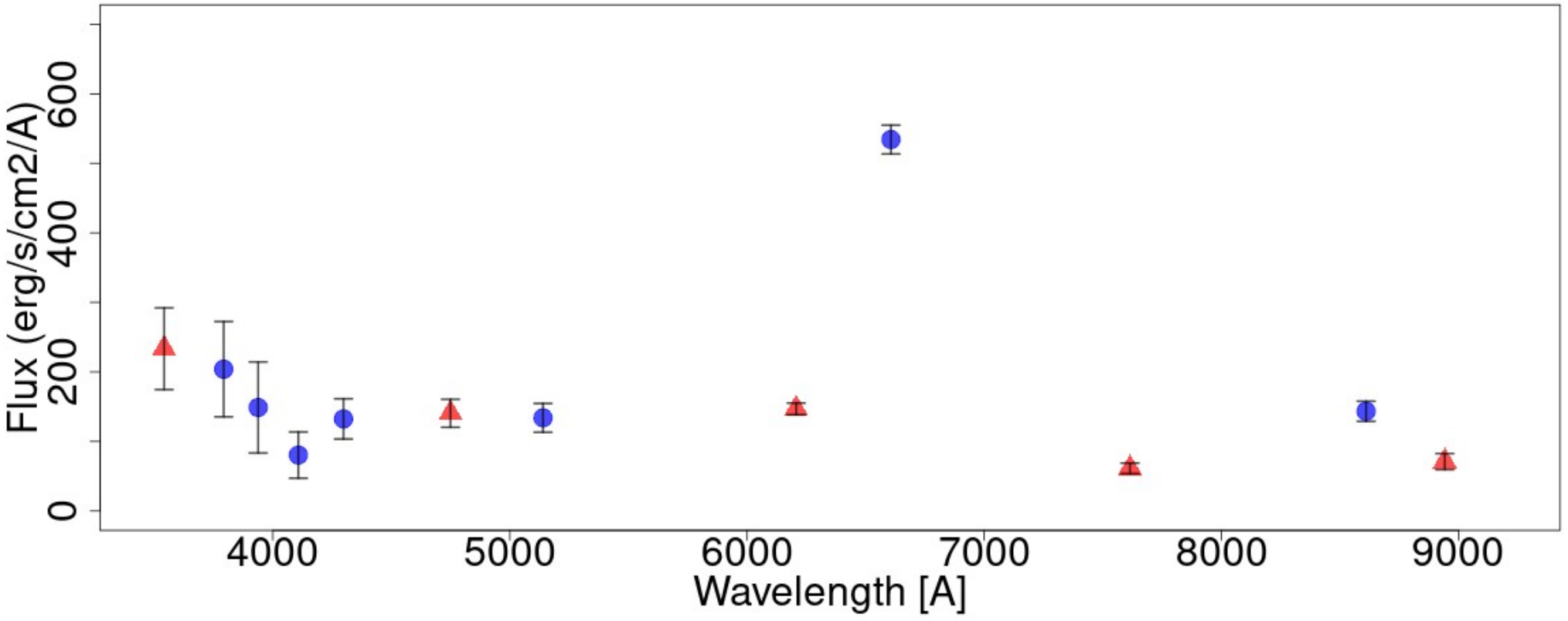


J-PAS

- Observations for the full survey started in spring 2023
- Within the collaboration, we already have a interim data release
  - 6.7 deg² released with data on all filters
  - ~30 deg² have been observed with all filters
  - In the coming months we will have internal data releases with wider area

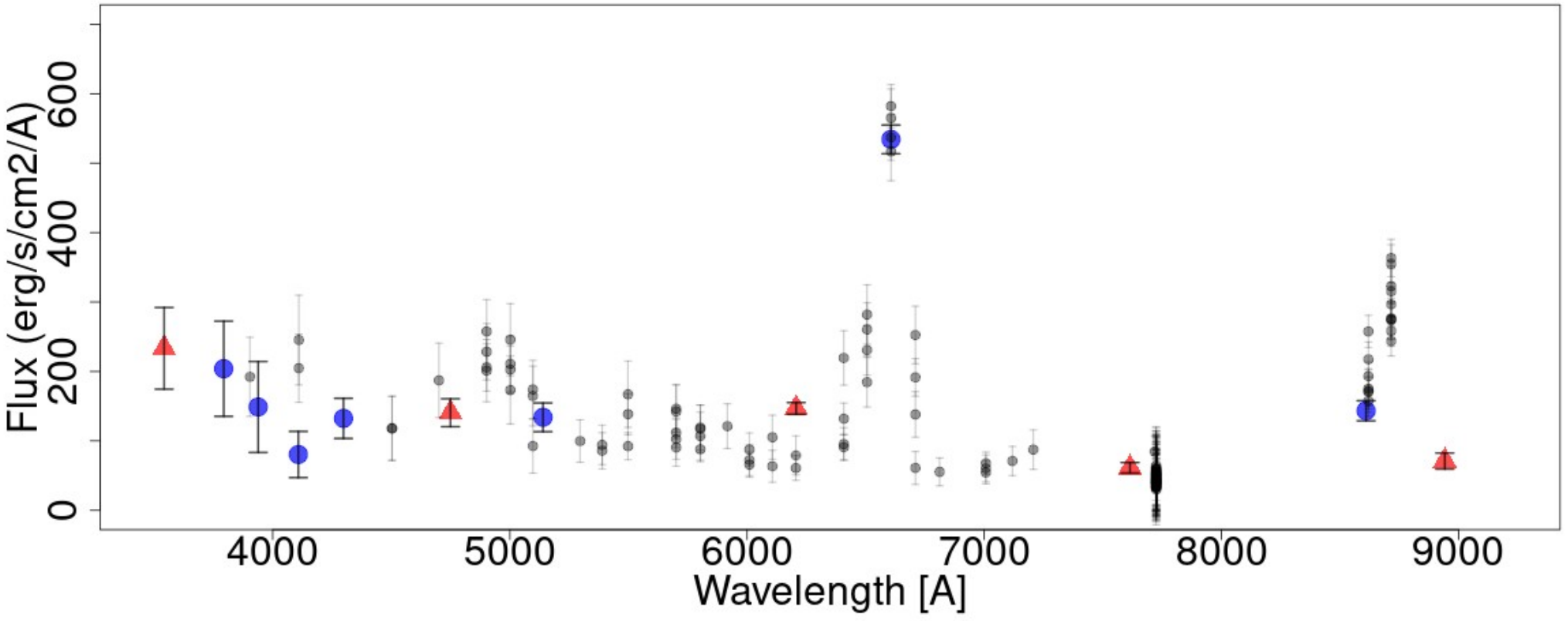
J-PAS – Initial EELG results

- z~0.3 extreme Hα emitter in J-PLUS (J0861)



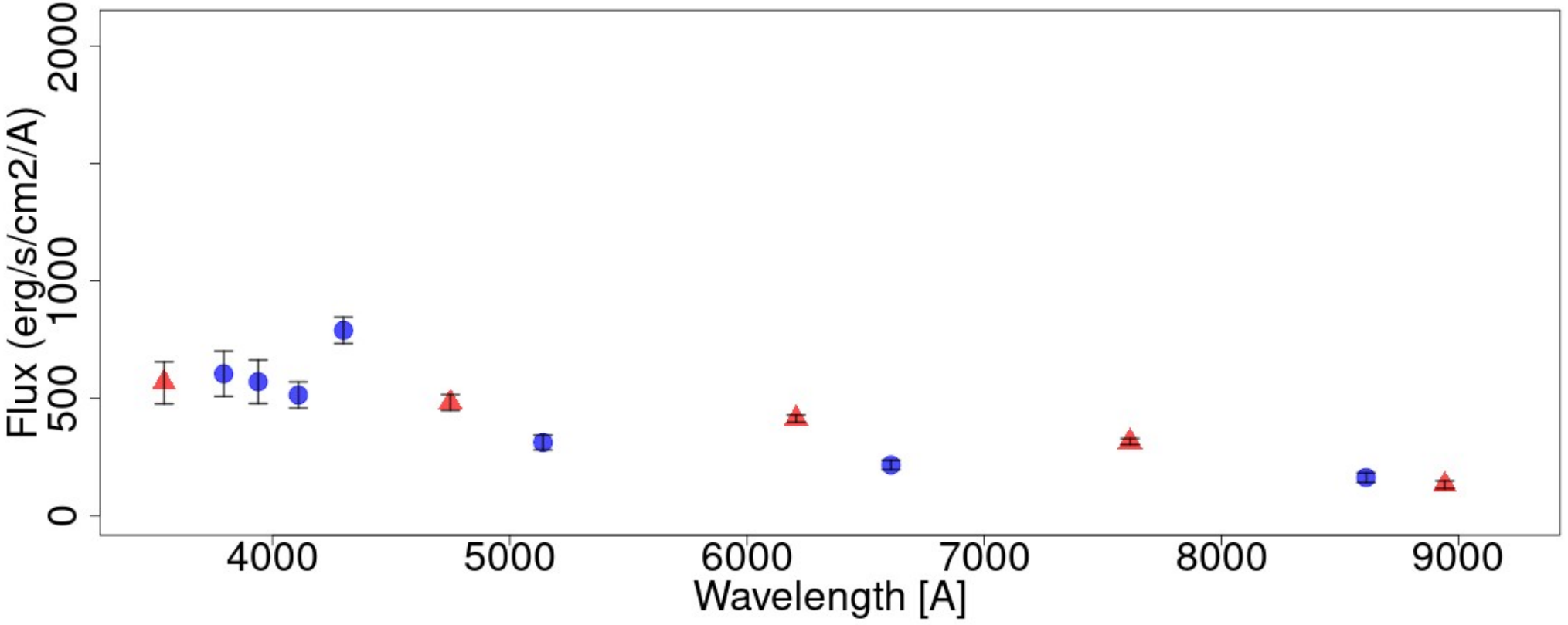
J-PAS – Initial EELG results

- z~0.3 extreme Hα emitter in J-PLUS (J0861)



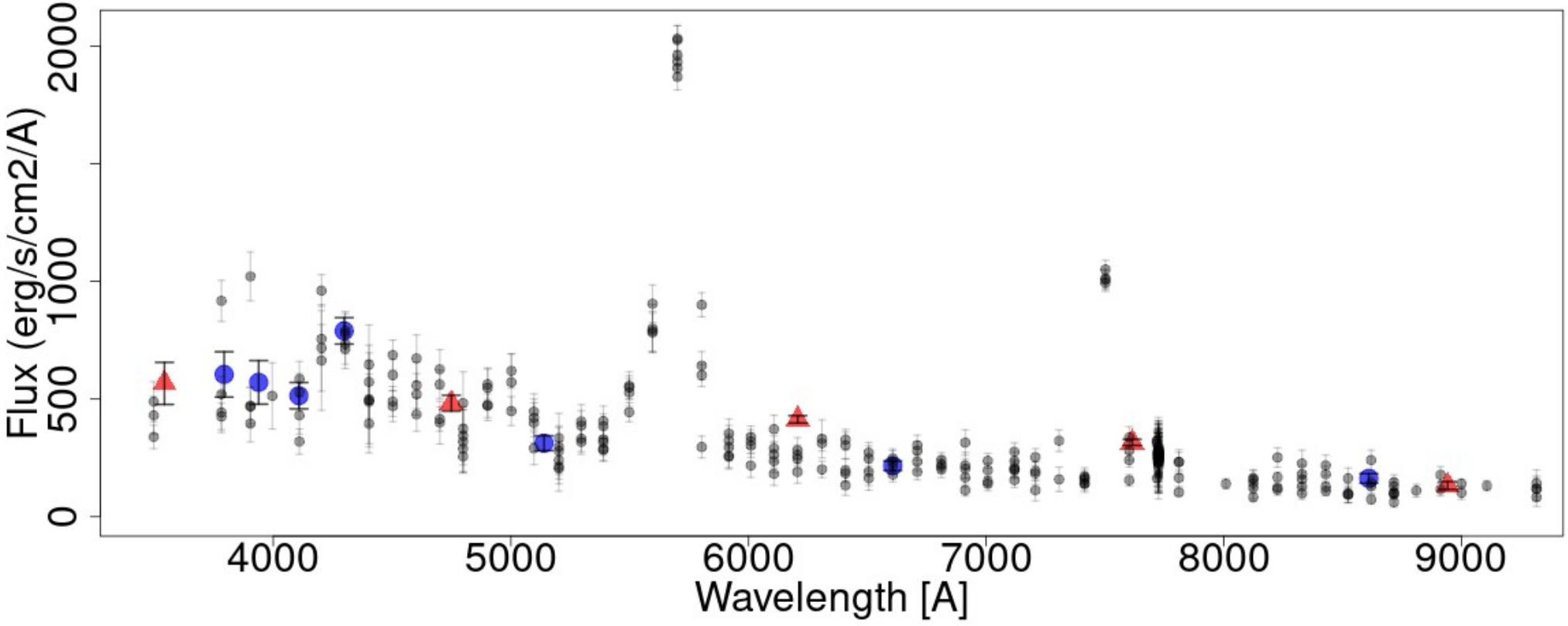
J-PAS – Initial EELG results

- z~0.14 extreme Hα emitter in J-PLUS (iSDSS)



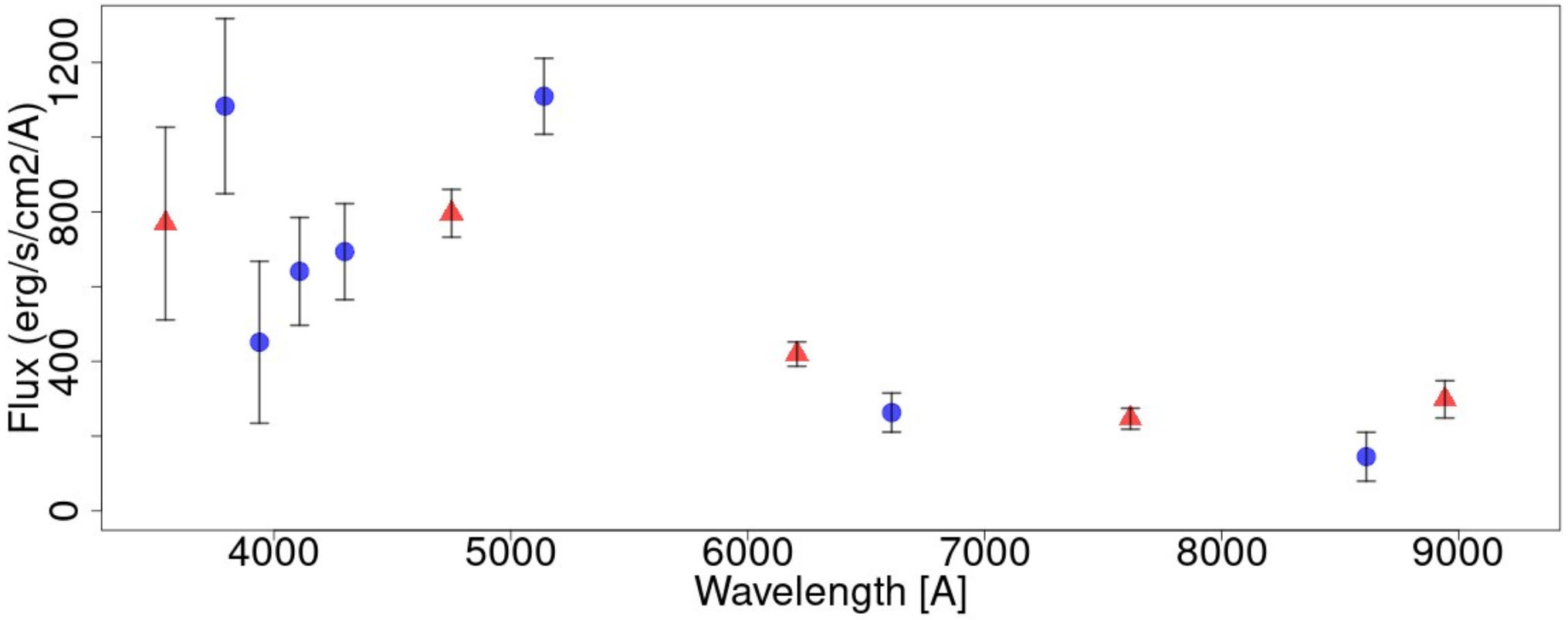
J-PAS – Initial EELG results

- z~0.14 extreme Hα emitter in J-PLUS (iSDSS)



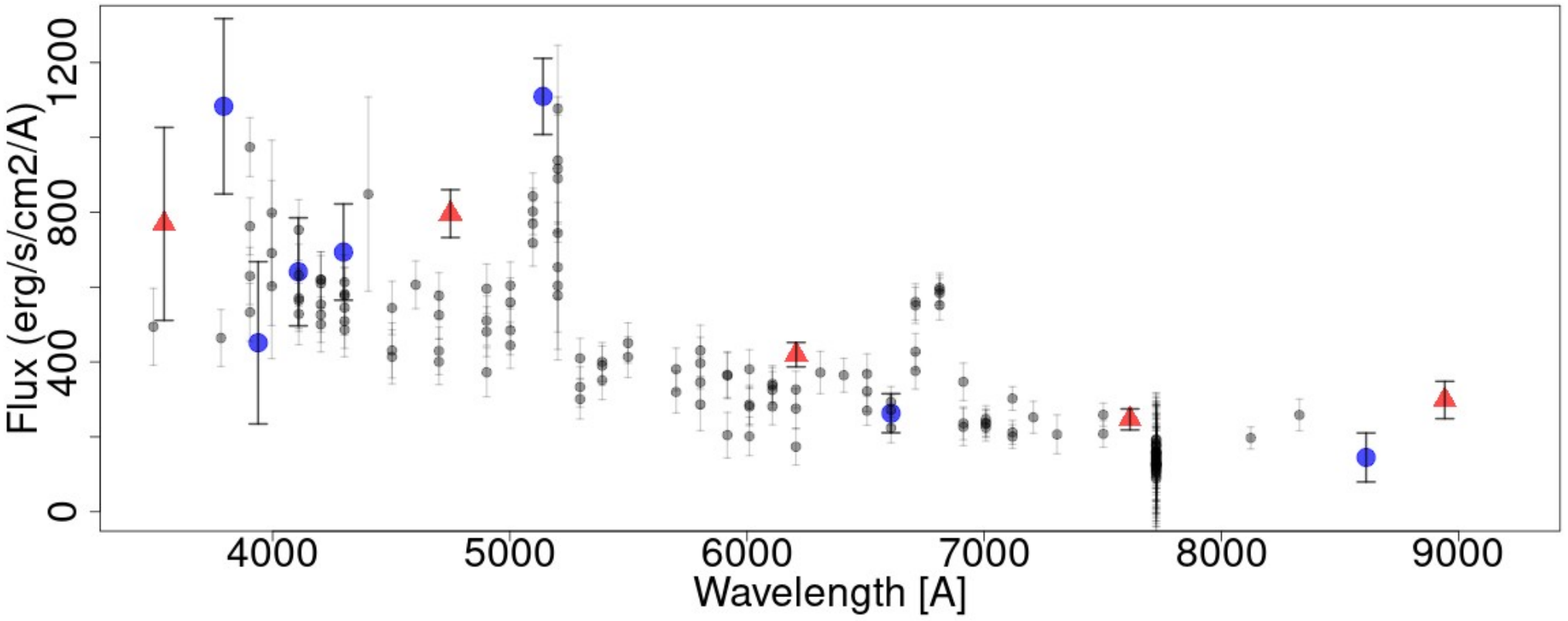
J-PAS – Initial EELG results

z~0.036 extreme [OIII] emitter in J-PLUS



J-PAS – Initial EELG results

z~0.036 extreme [OIII] emitter in J-PLUS



Summary and Conclusions

- Compiled four large, complete samples of extreme emission line galaxies at z<0.35 using J-PLUS of more than 1000 sources
  - [OIII] emitters (J0515), Hα emitters (J0660, J0861, iSDSS filters)
    - EW>300/200/400/600 Å
  - Most previously unclassified as EELGs
  - Very efficient, unbiased selection of EELGs
  - High purity (>90%), high completeness (>90%)
- SED fitting reveals very young, low mass galaxies with little dust extinction
- Follow-up spectroscopy
  - INT: 40 [OIII] +20 Ha emitters observed, all confirmed
    - Low density, low metallicities
    - Stellar masses and metallicities in a “gap” between Blueberry galaxies and Green Peas
    - Comparable with JWST z>4 galaxies
- Future:
  - Publish spectrocopy paper + Hα selections
  - More data! GTC spectra, WEAVE IFU+MOS, HST, Chandra, HI... and J-PAS!

A&A Lumbreras-Calle et al. 2022 arxiv:2112.06938

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