First Galaxies and their Local Analogues

Selected Chapters on Astrophysics
November 2025

Lecture 3: Little Red Dots and Galactic Gastronomy

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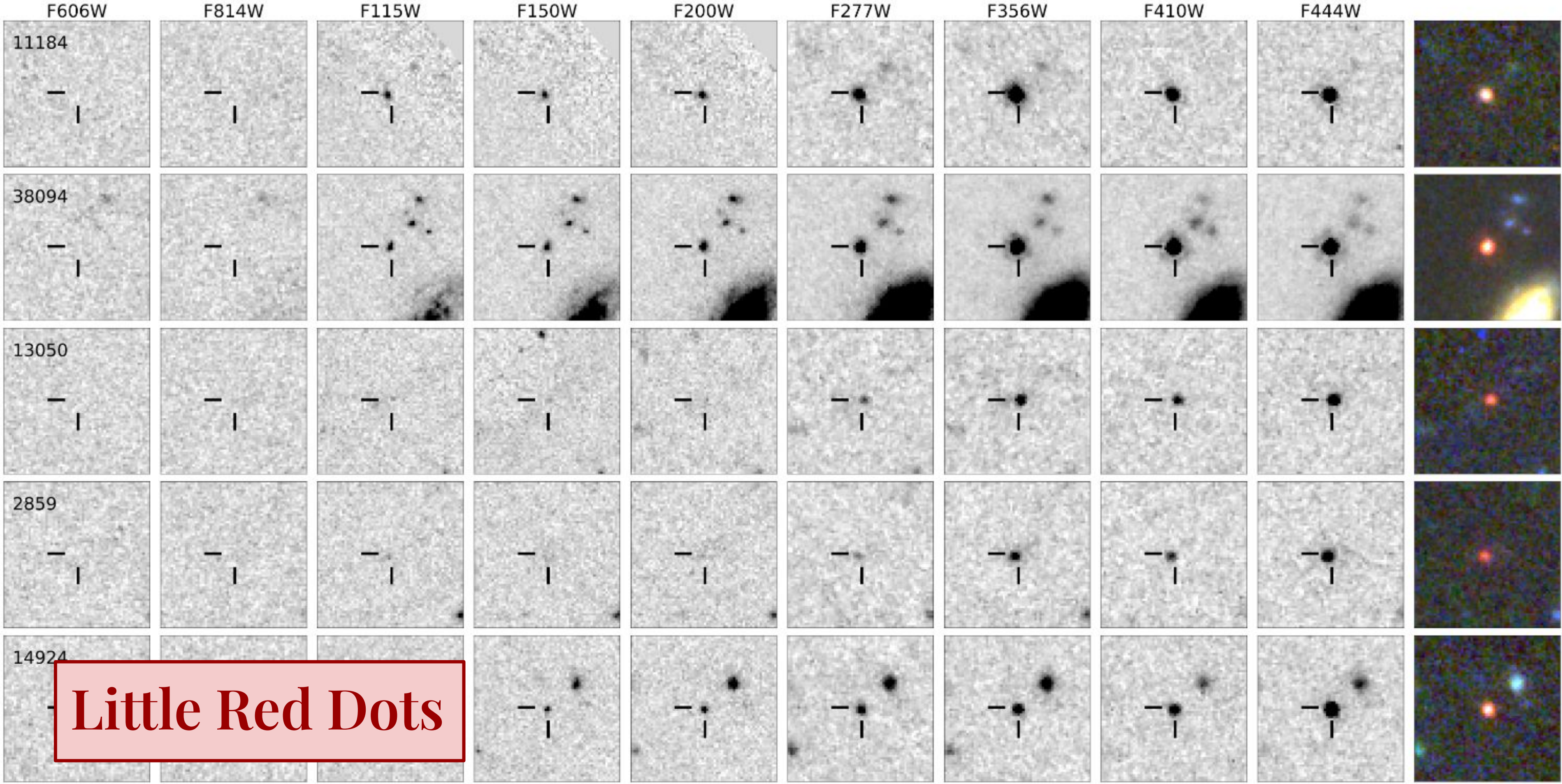
Little Red Dots



Little Red Dots

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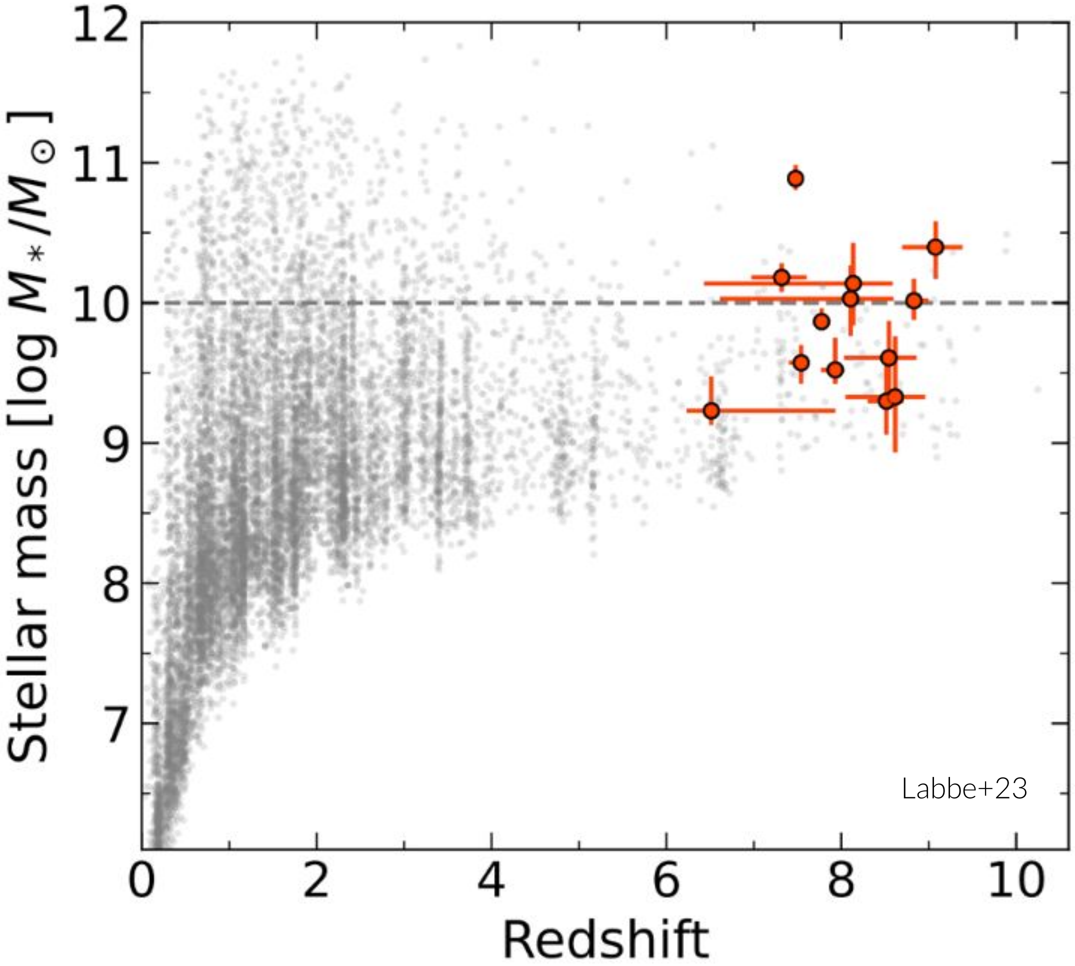
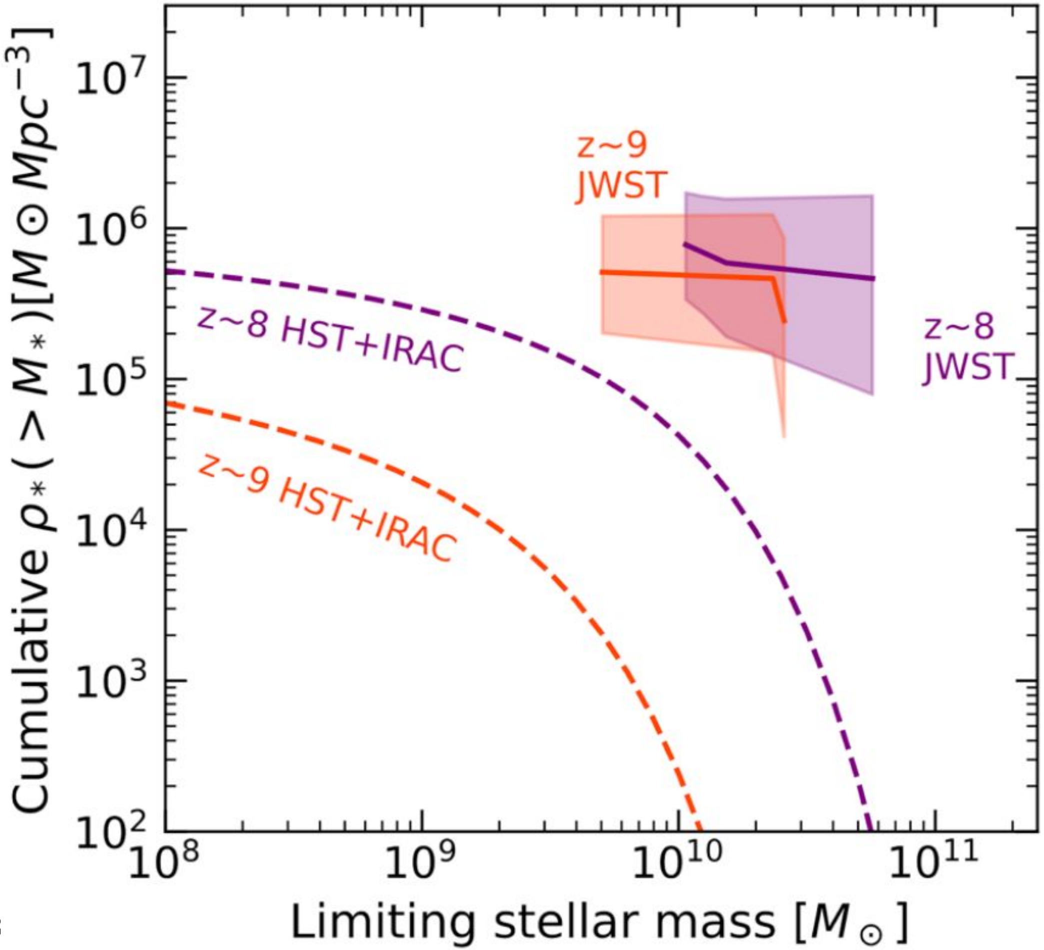


Little Red Dots



Labbe+23

Massive, evolved galaxies within 1 Gyr.

Stellar mass ~ 10^{11} M_{sun}

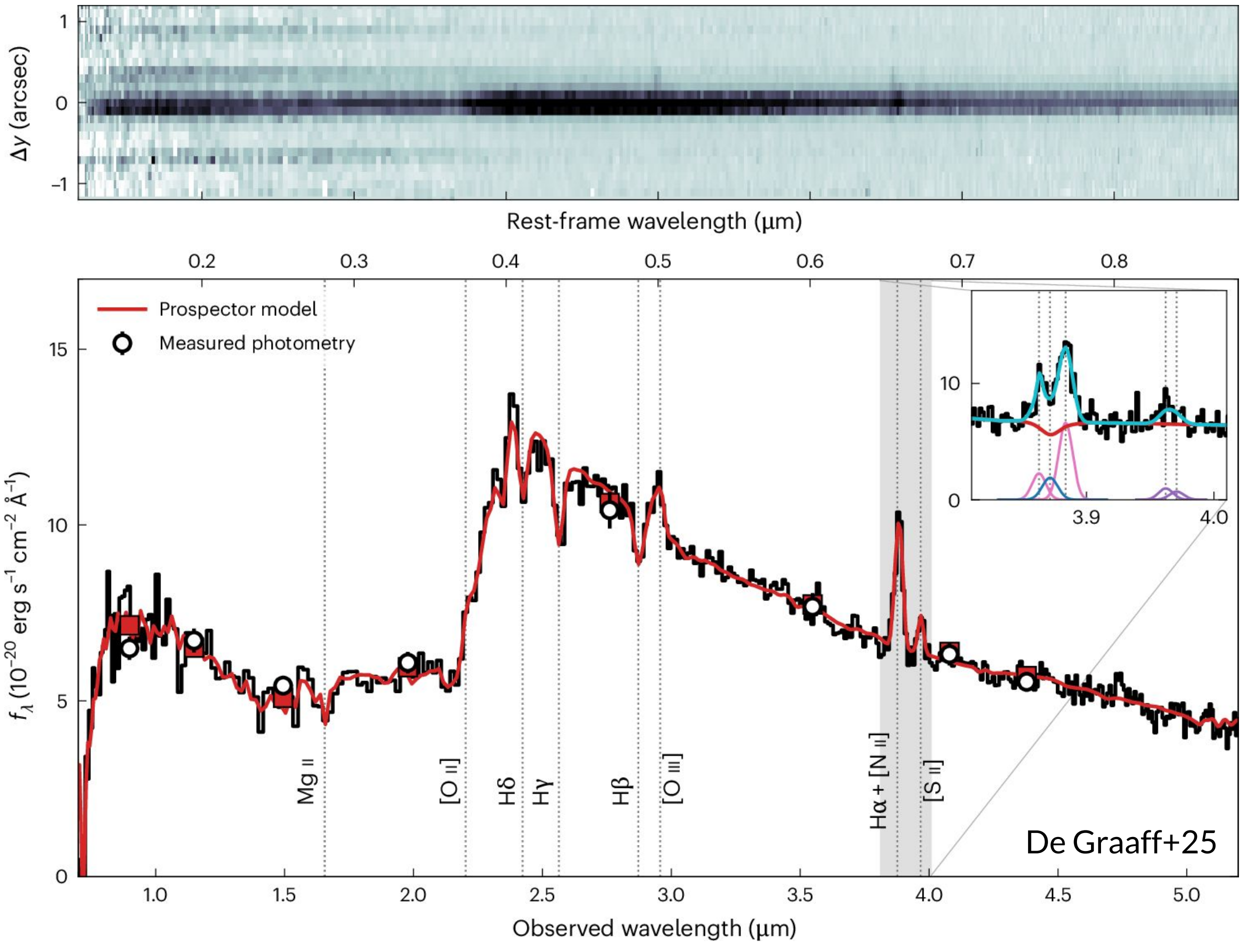
Balmer absorption features = lack of recent star formation

SFR ~ 4 M_{sun}/yr in last 100 Myr.

sSFR ~ 4 x 10^{-11} /yr

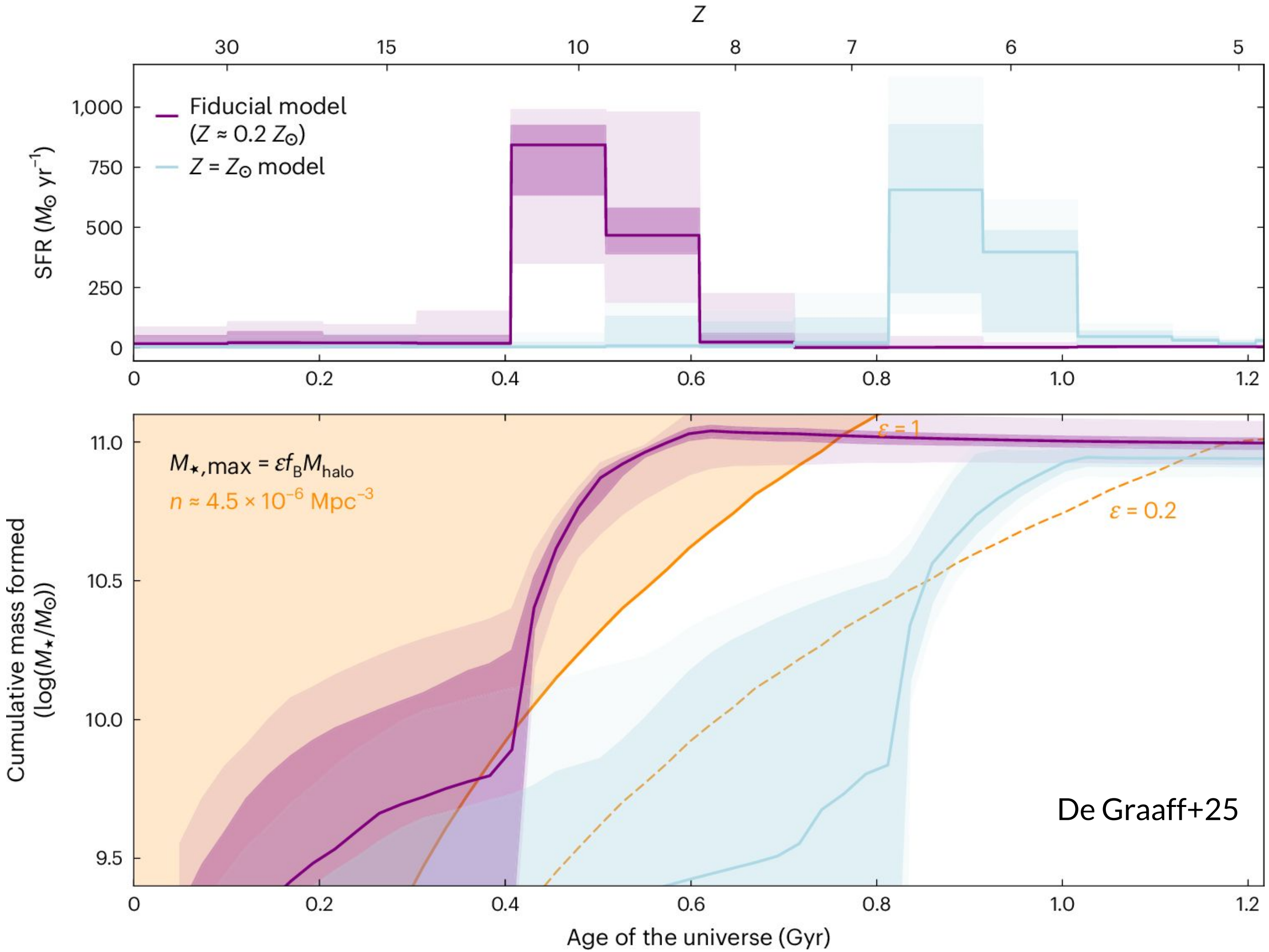
O III, N II, S II present. AGN activity?

Continuum is dominated by evolved stellar population



De Graaff+25

Extremely bursty Star Formation

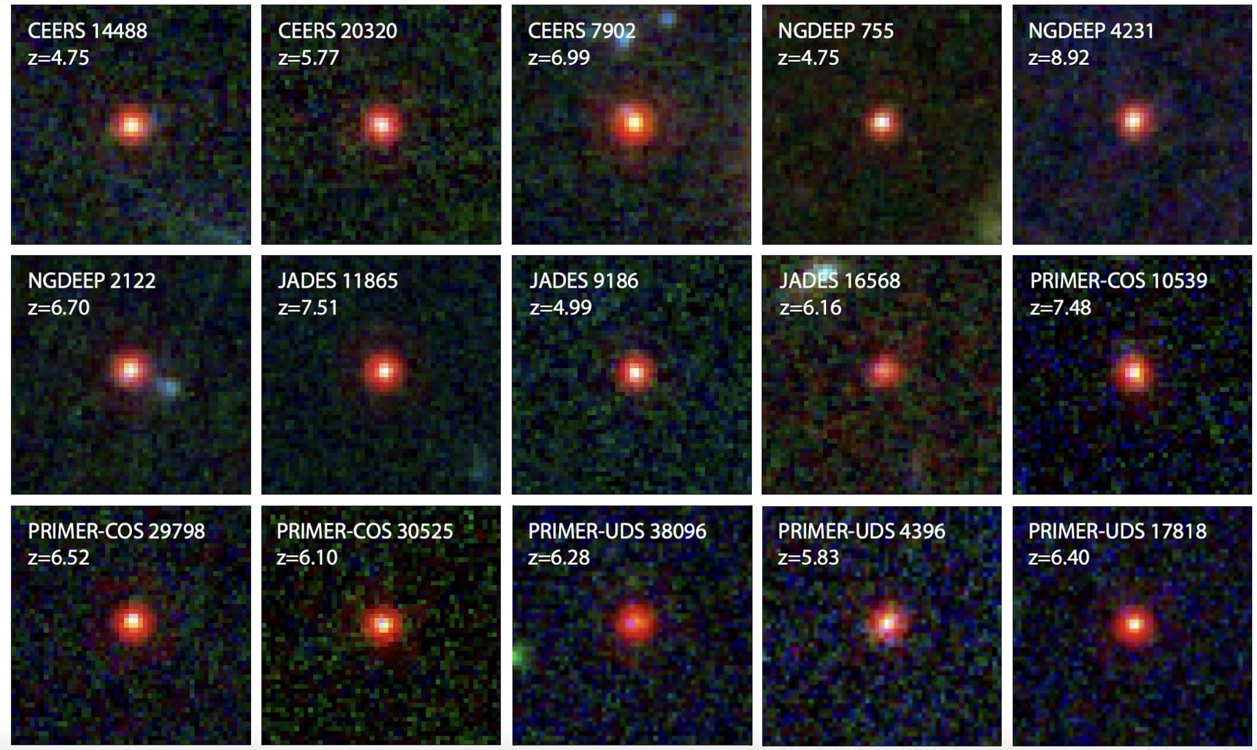


De Graaff+25

Little Red Dots

Common Parameters

- Point-like sources

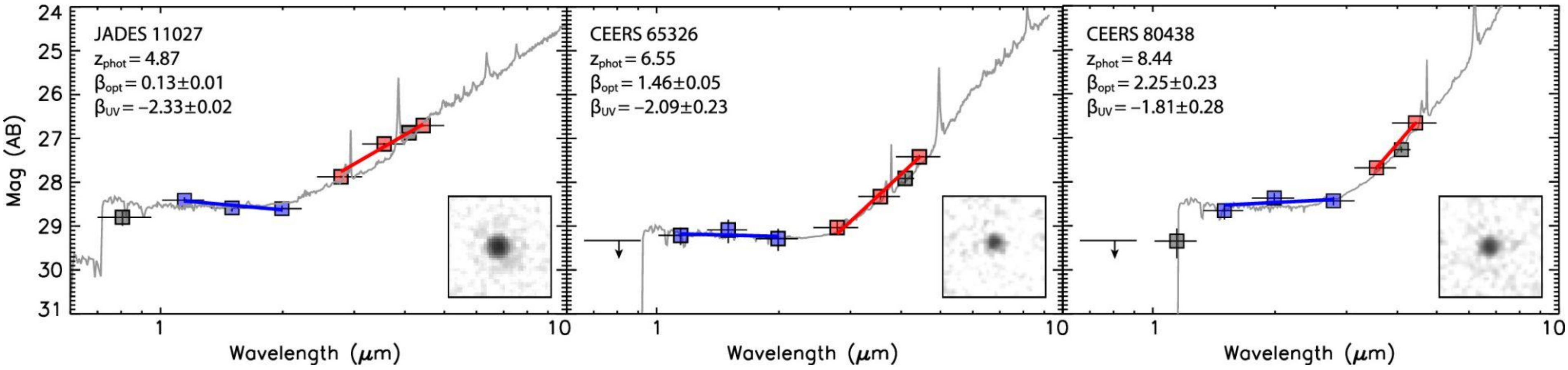


Kocevski+25

Little Red Dots

Common Parameters

- Peculiar UV and Optical slopes with inflection at 3600 (Balmer break).

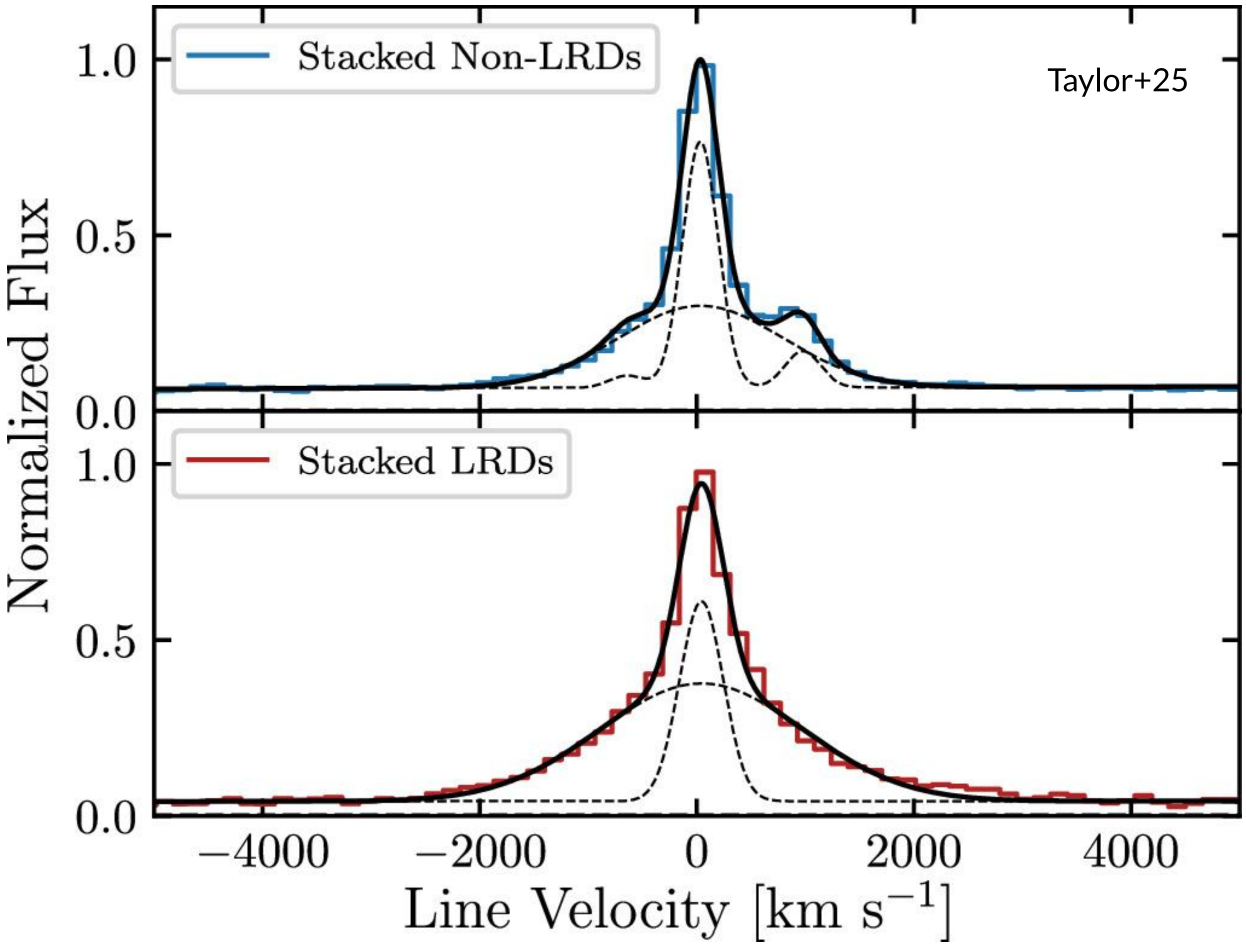


Kocevski+25

Little Red Dots

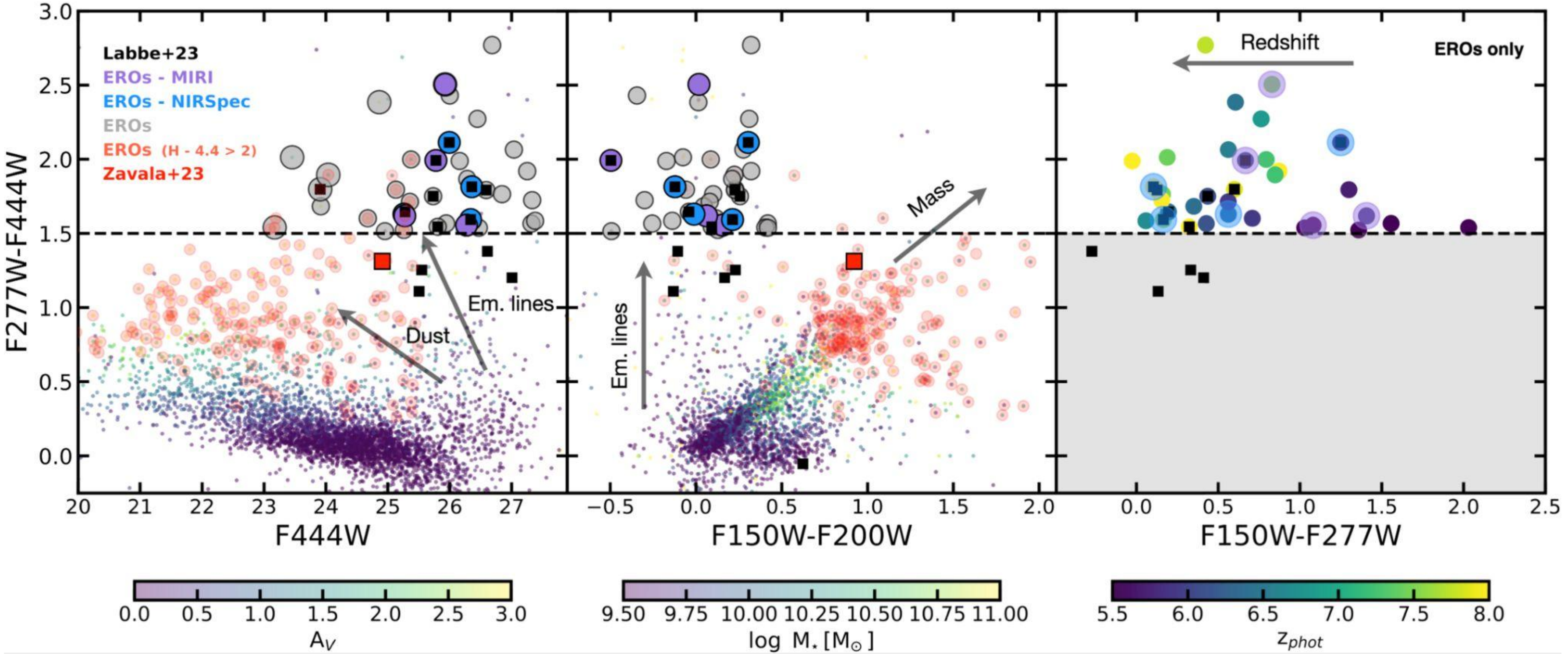
Common Parameters

- Broad emission lines.
- 1-3 dex weaker than QSOs at the same z.
- 15-30% of BLAGN population
- No variability

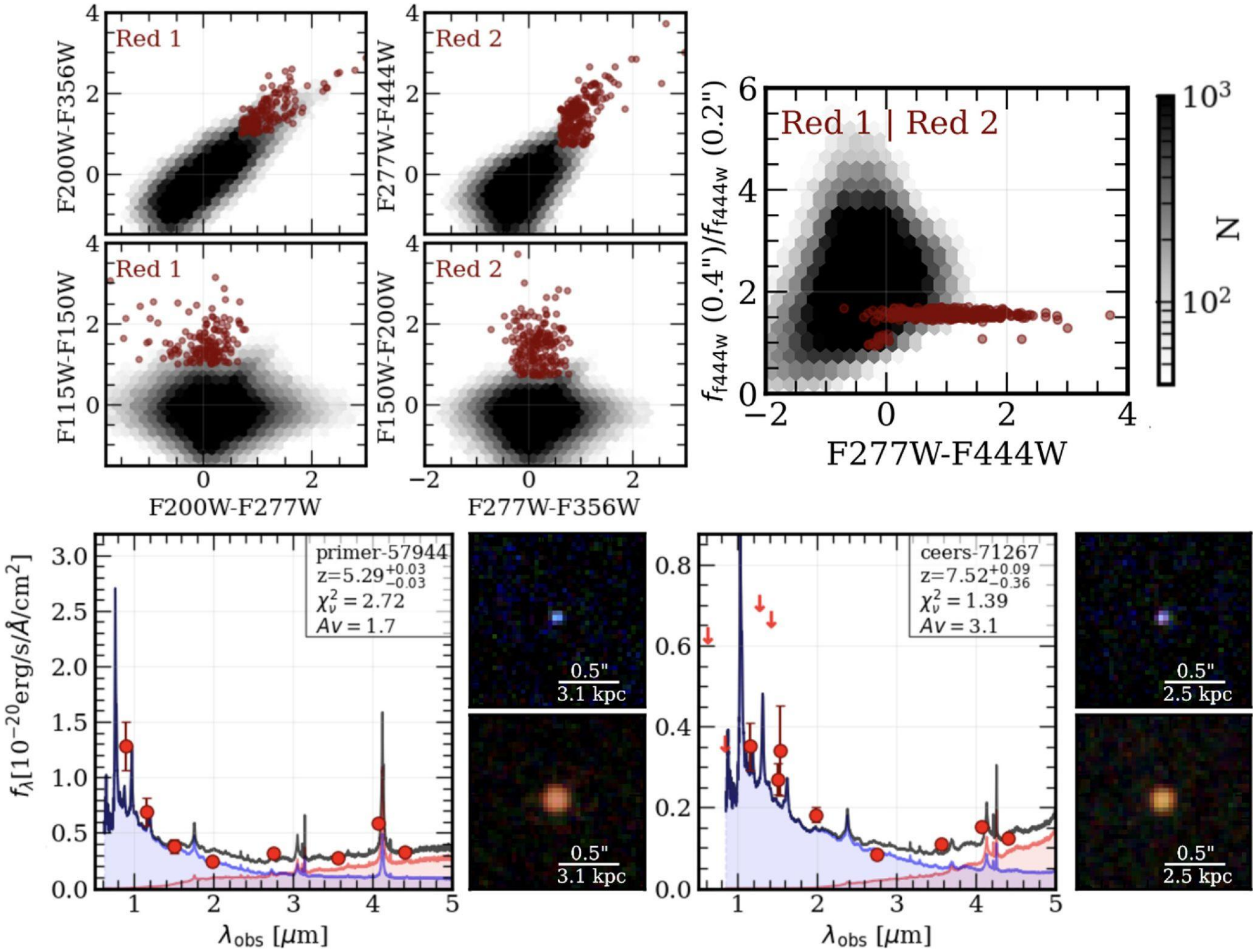


Selection criteria

Barro+23

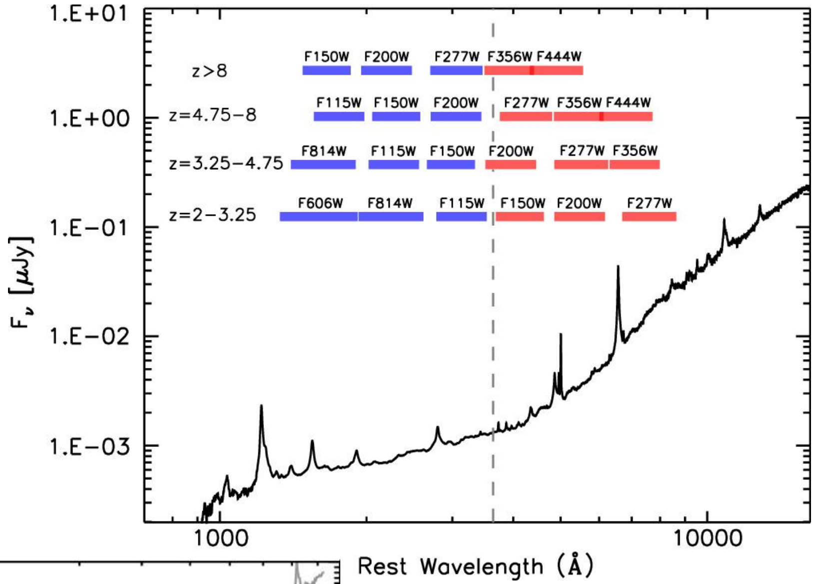


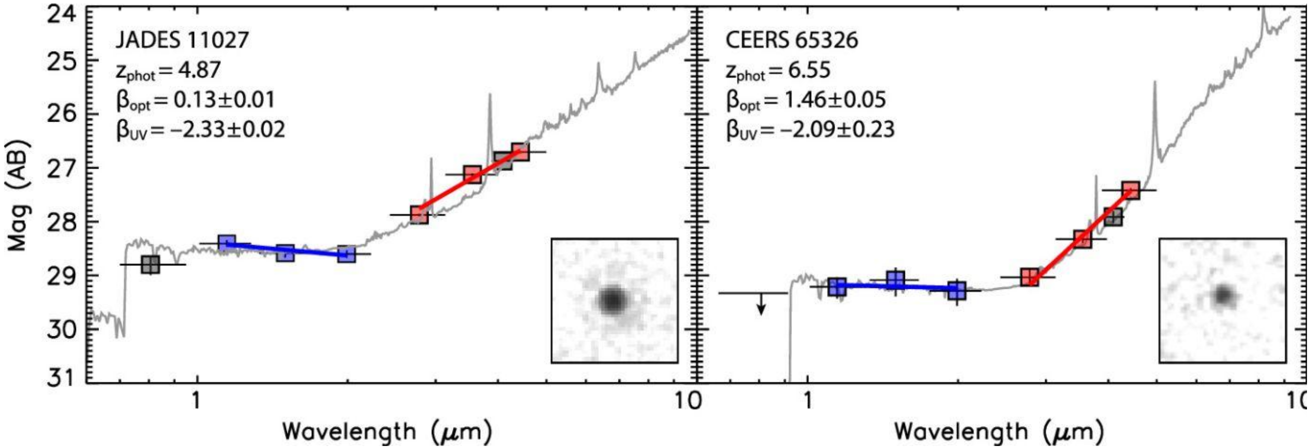
Selection criteria



Kokorev+24

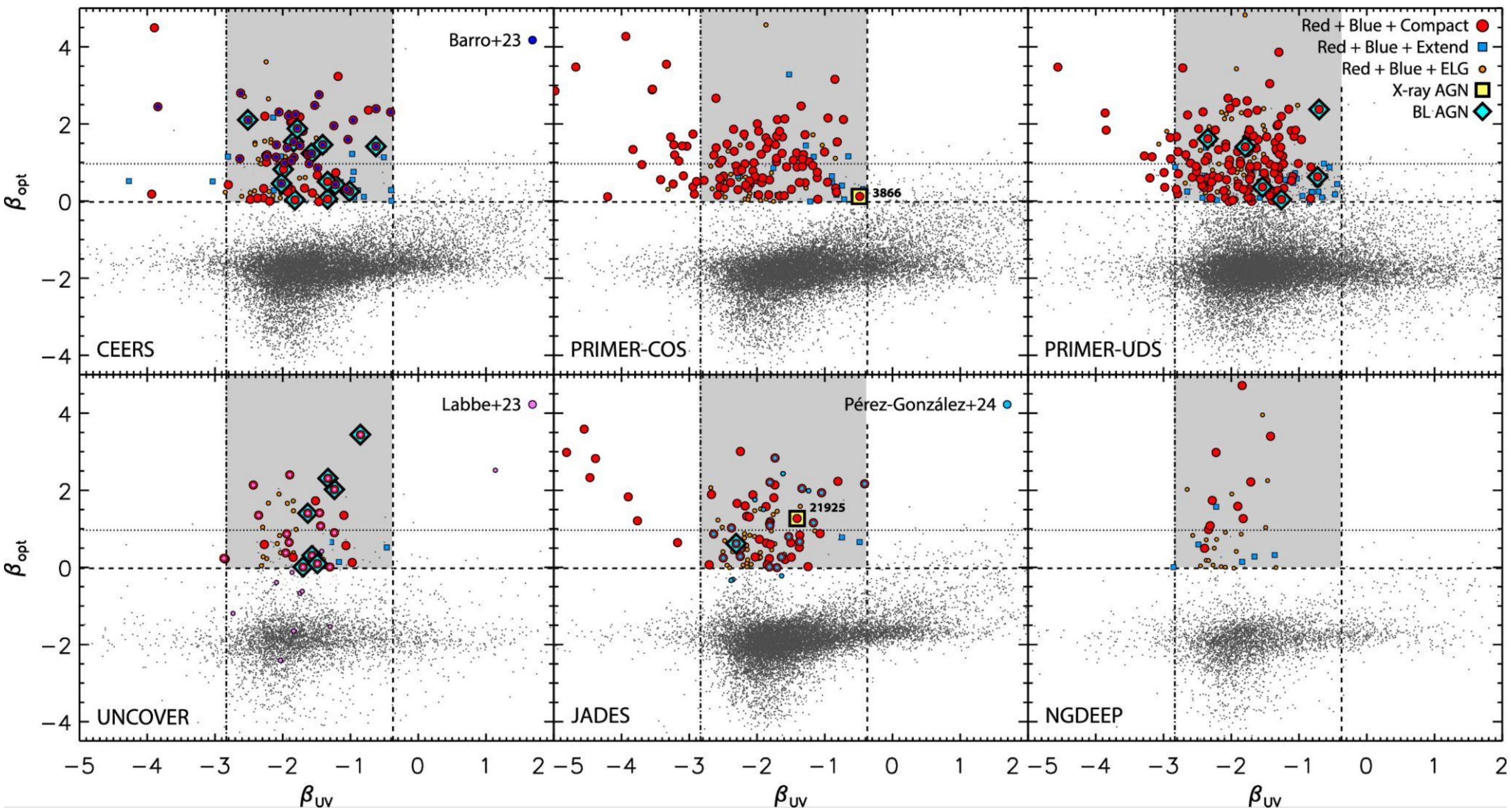
Selection criteria





Kocevski+25

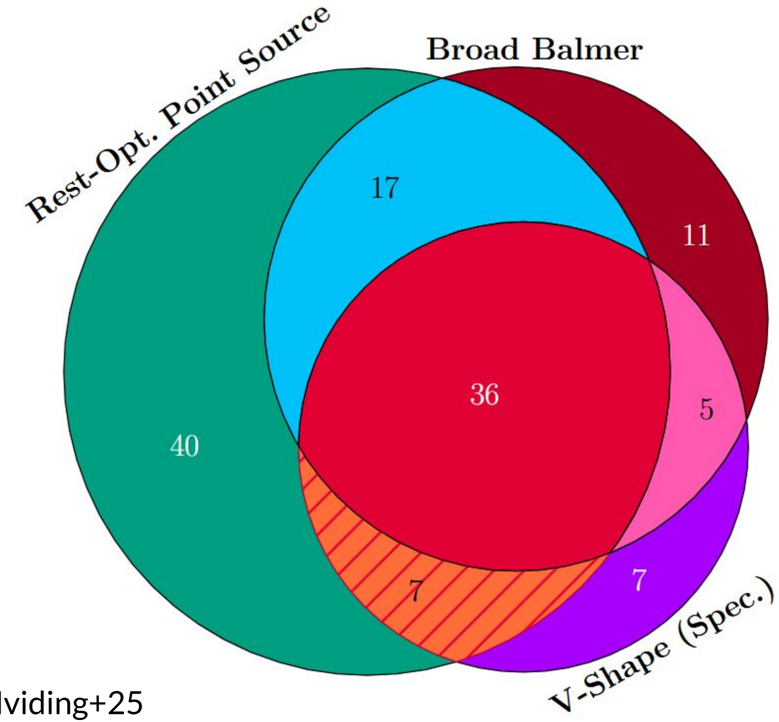
Selection criteria



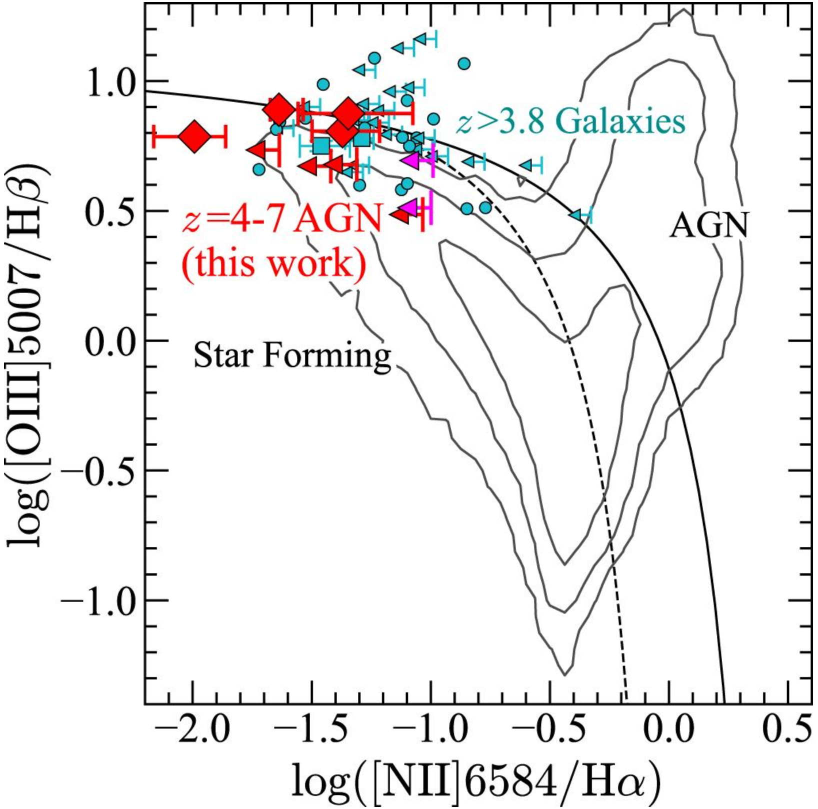
Kocevski+25

Selection criteria

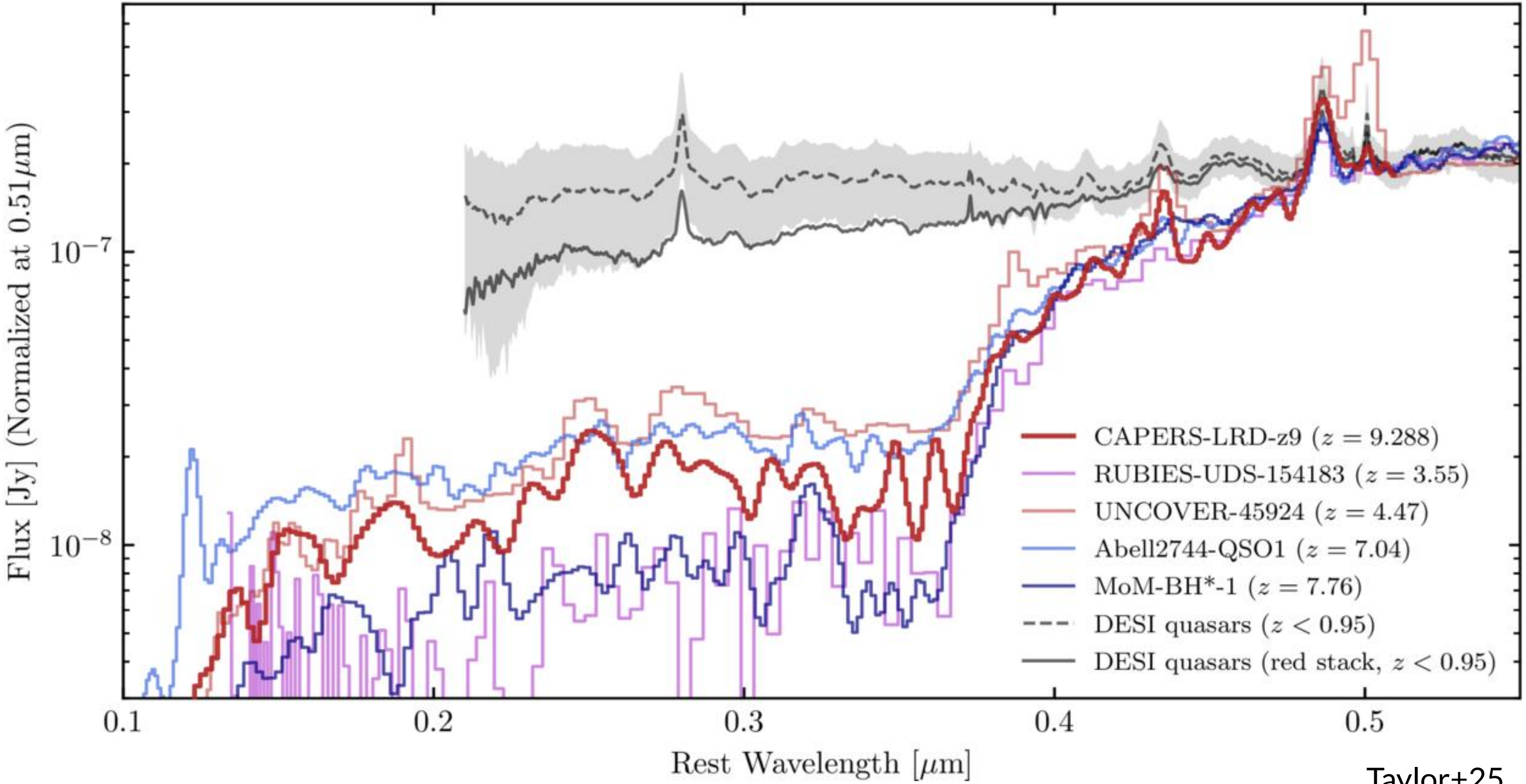
Harikane+23



Hviding+25



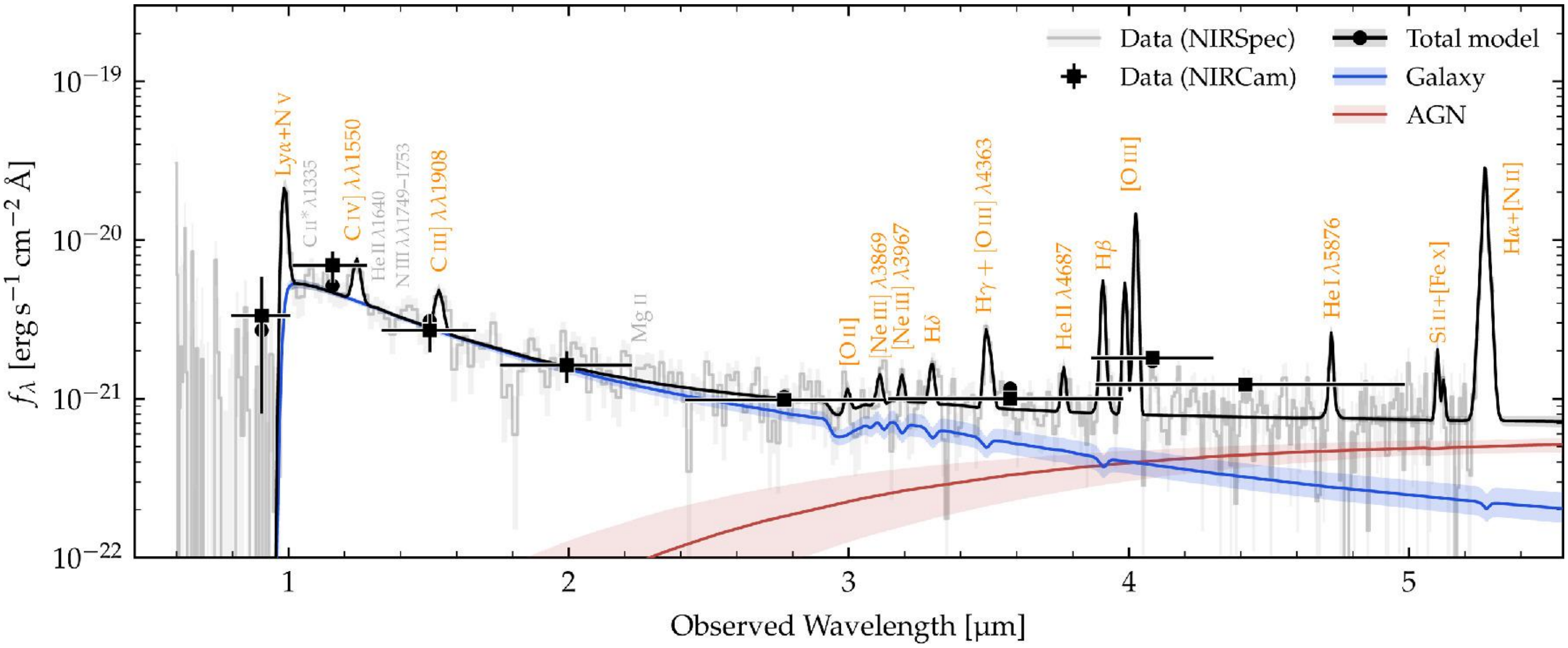
Complex Identity of LRDs



Taylor+25

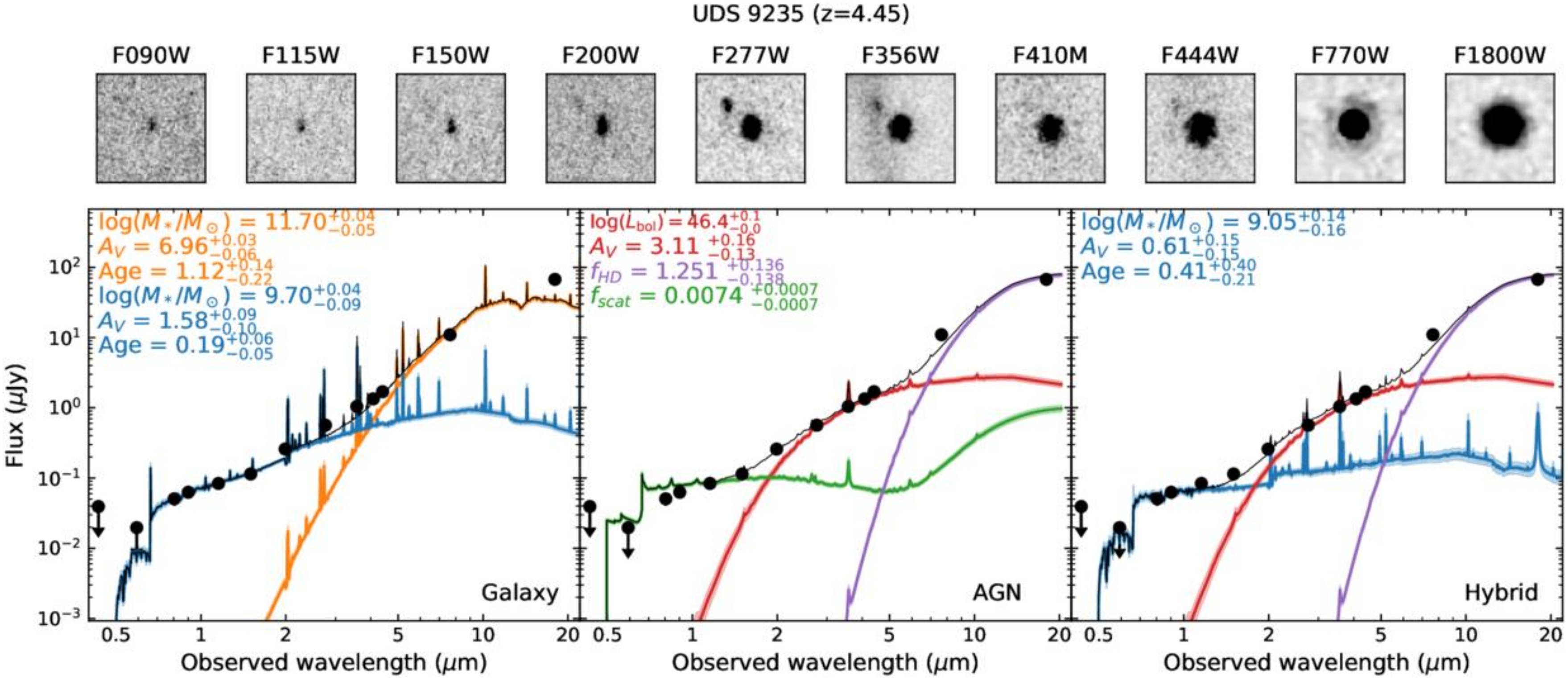
Complex Identity of LRDs

Akins+25



Complex Identity of LRDs

Leung+25



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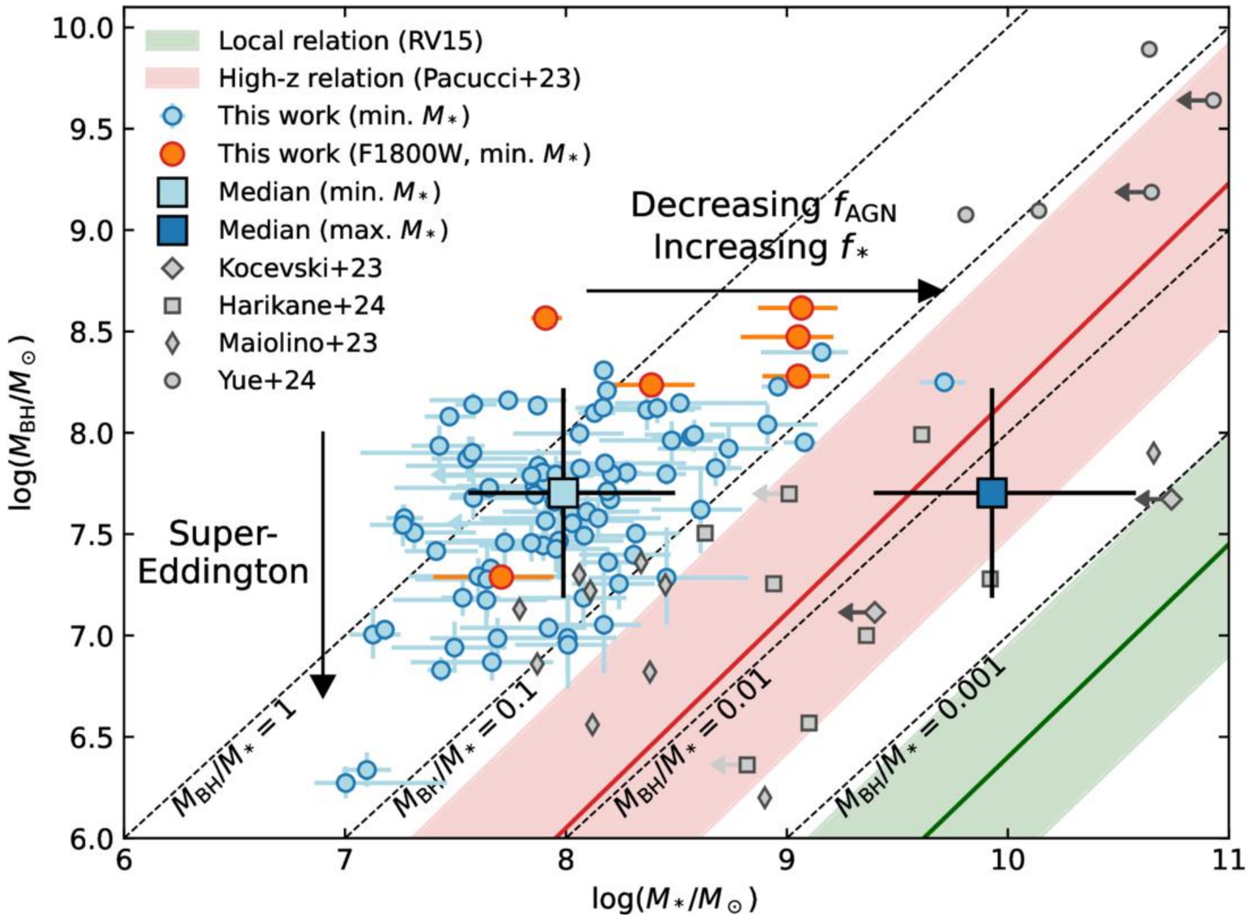
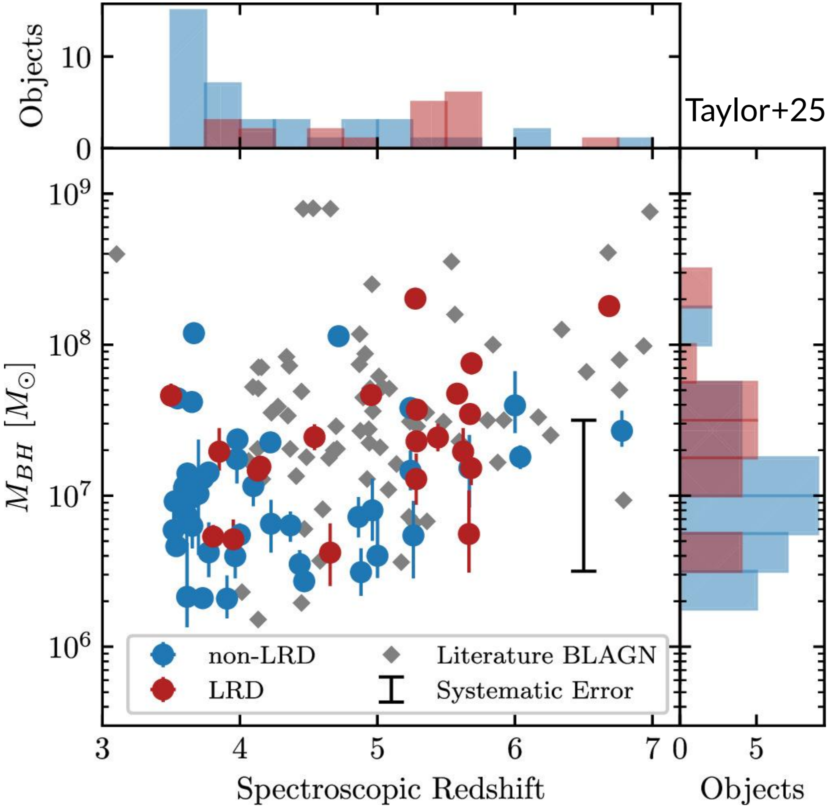


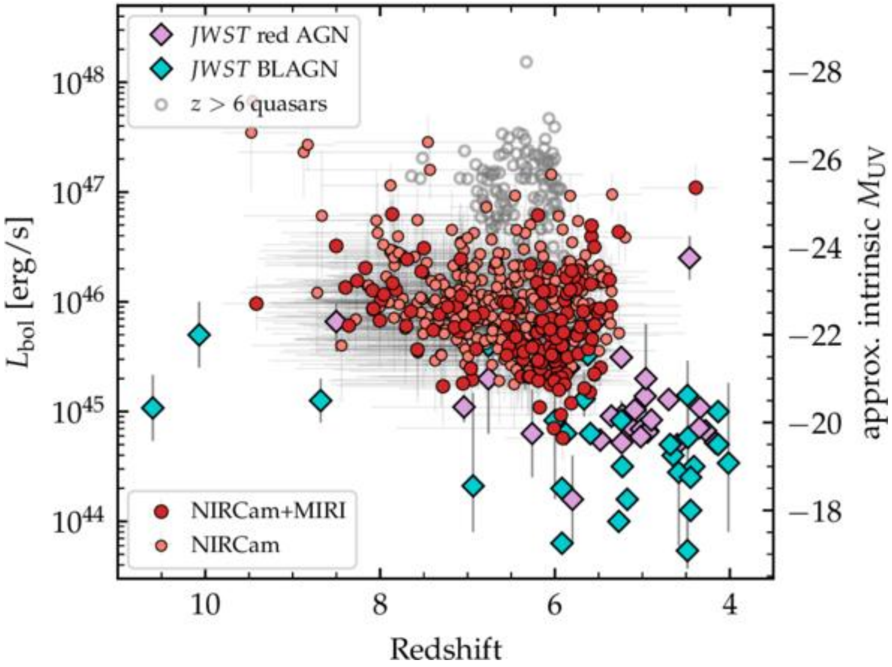
Leung+25

Complex Identity of LRDs



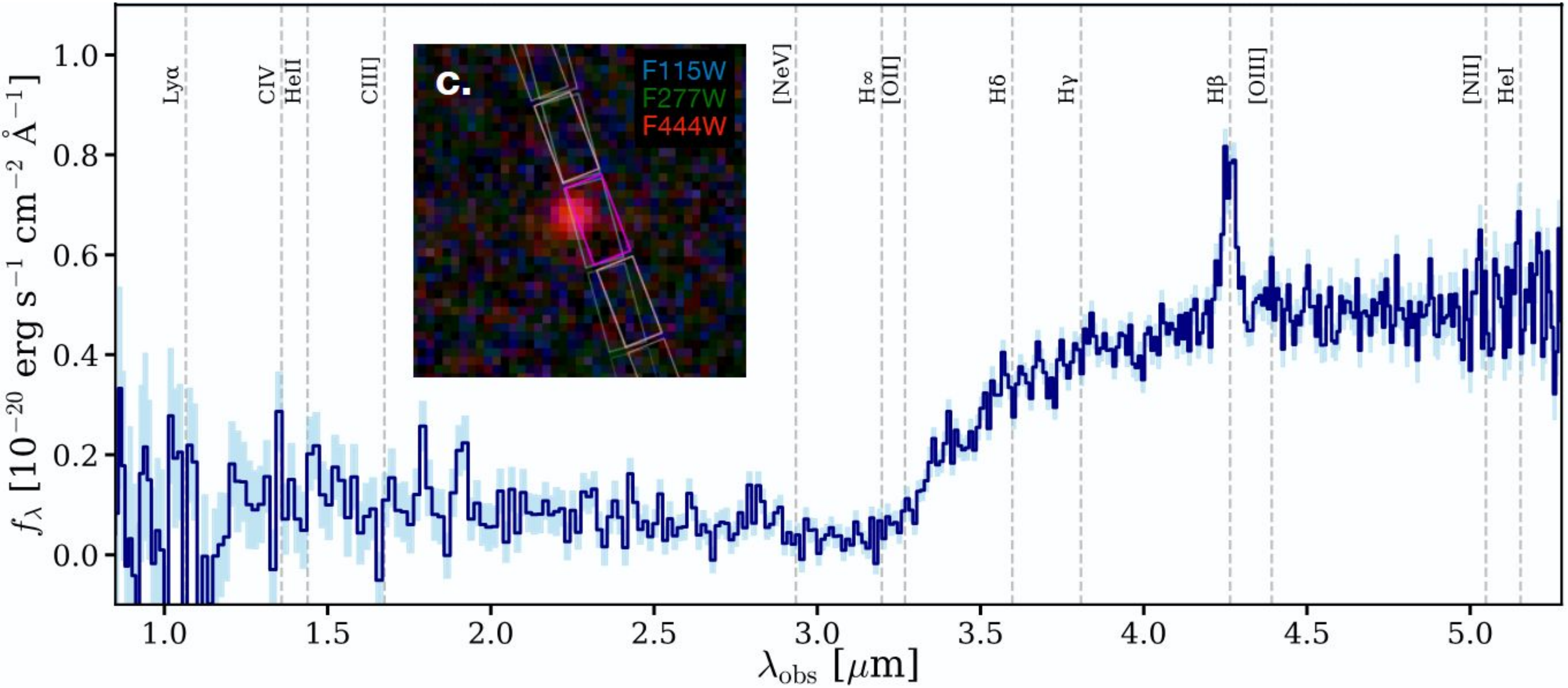
Taylor+25

Akins+25



Extreme LRDs

Naidu+25



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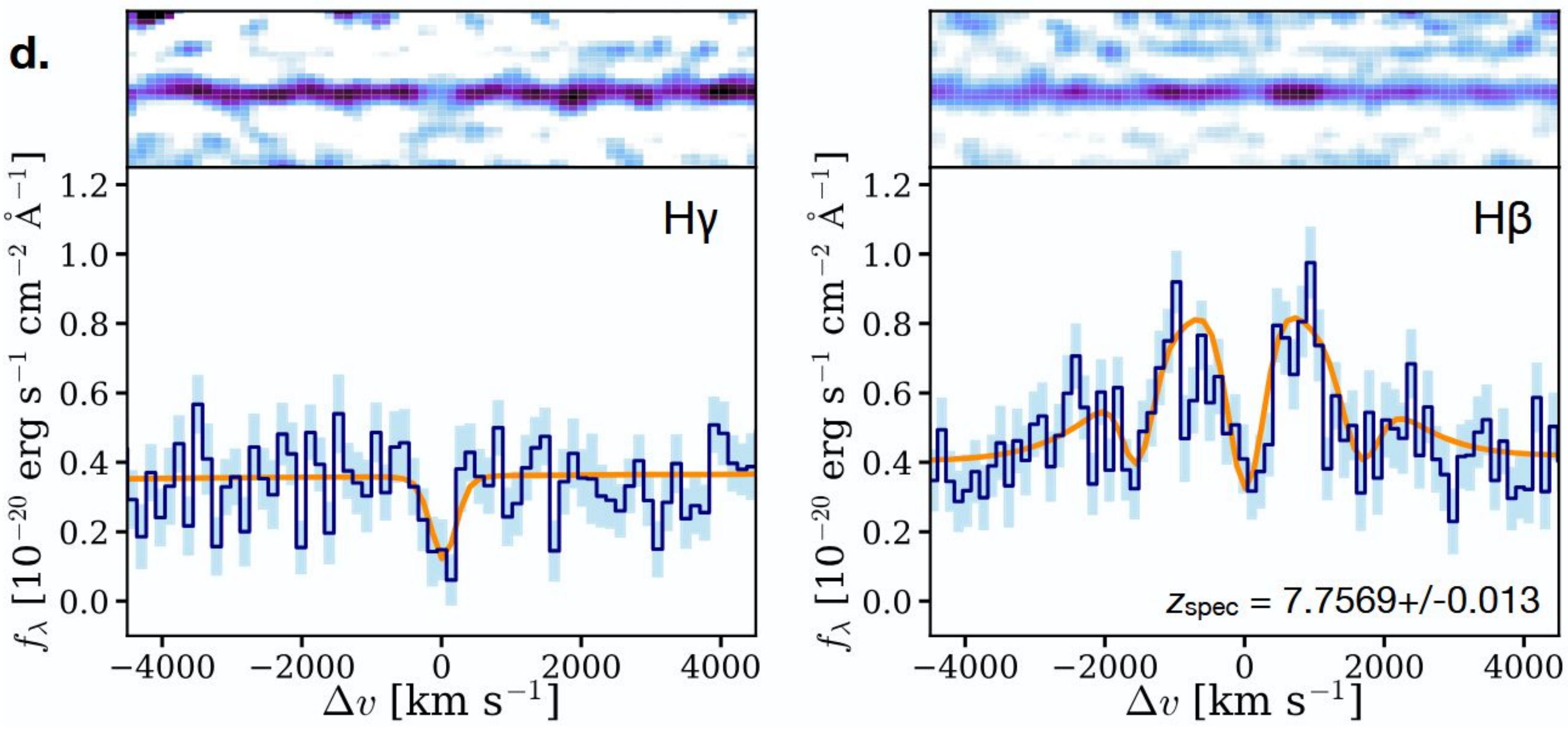

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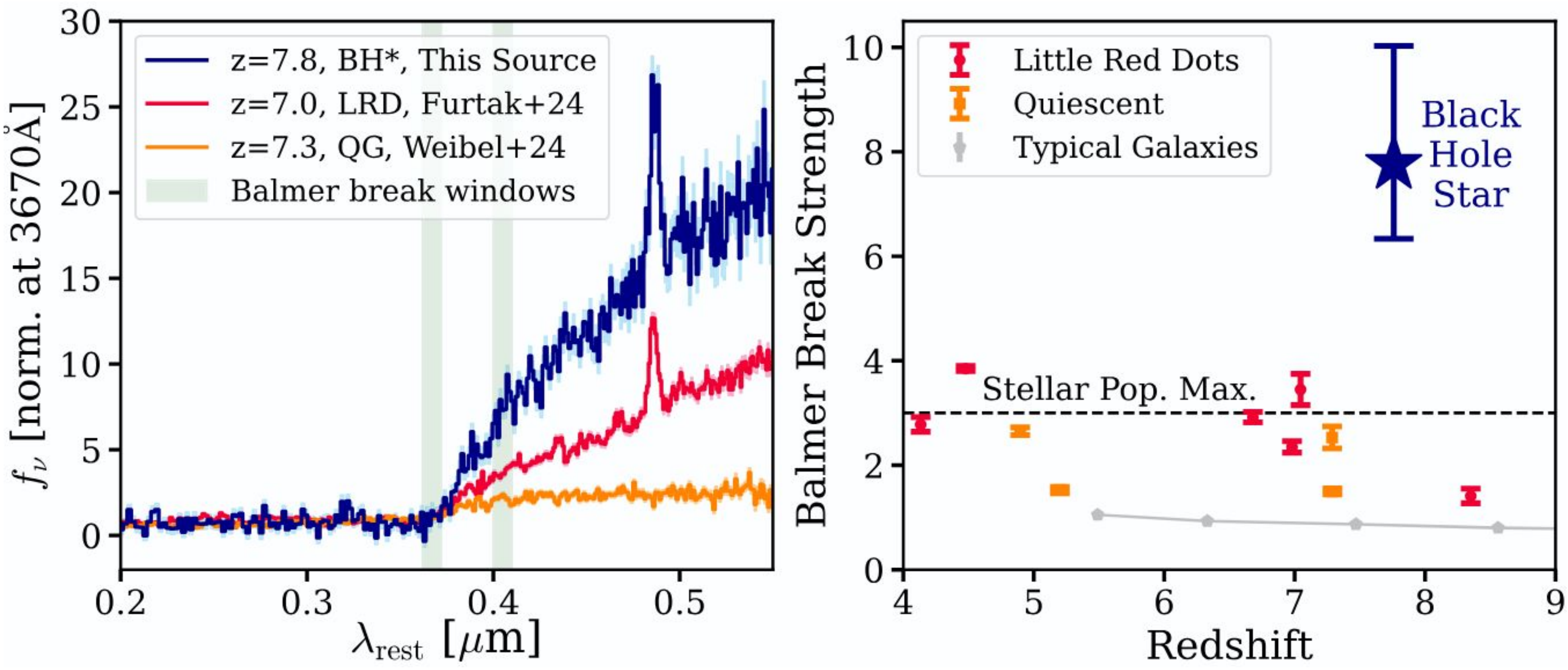
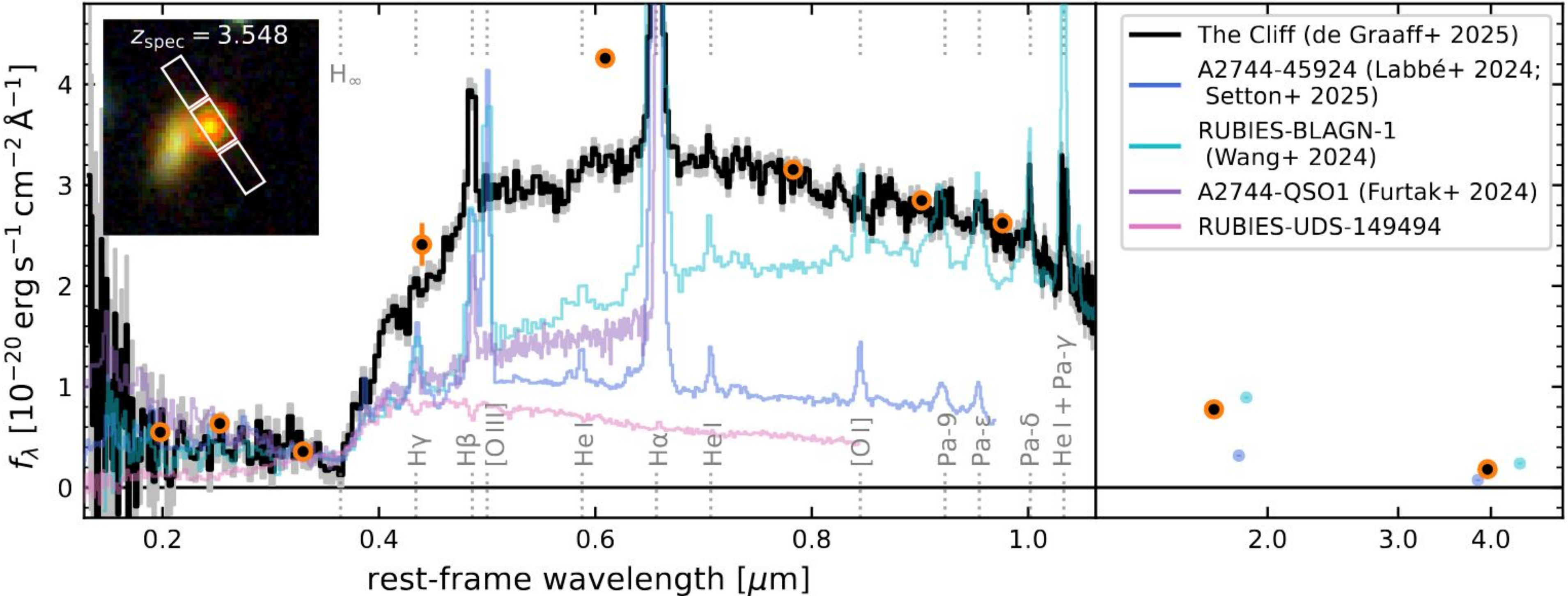
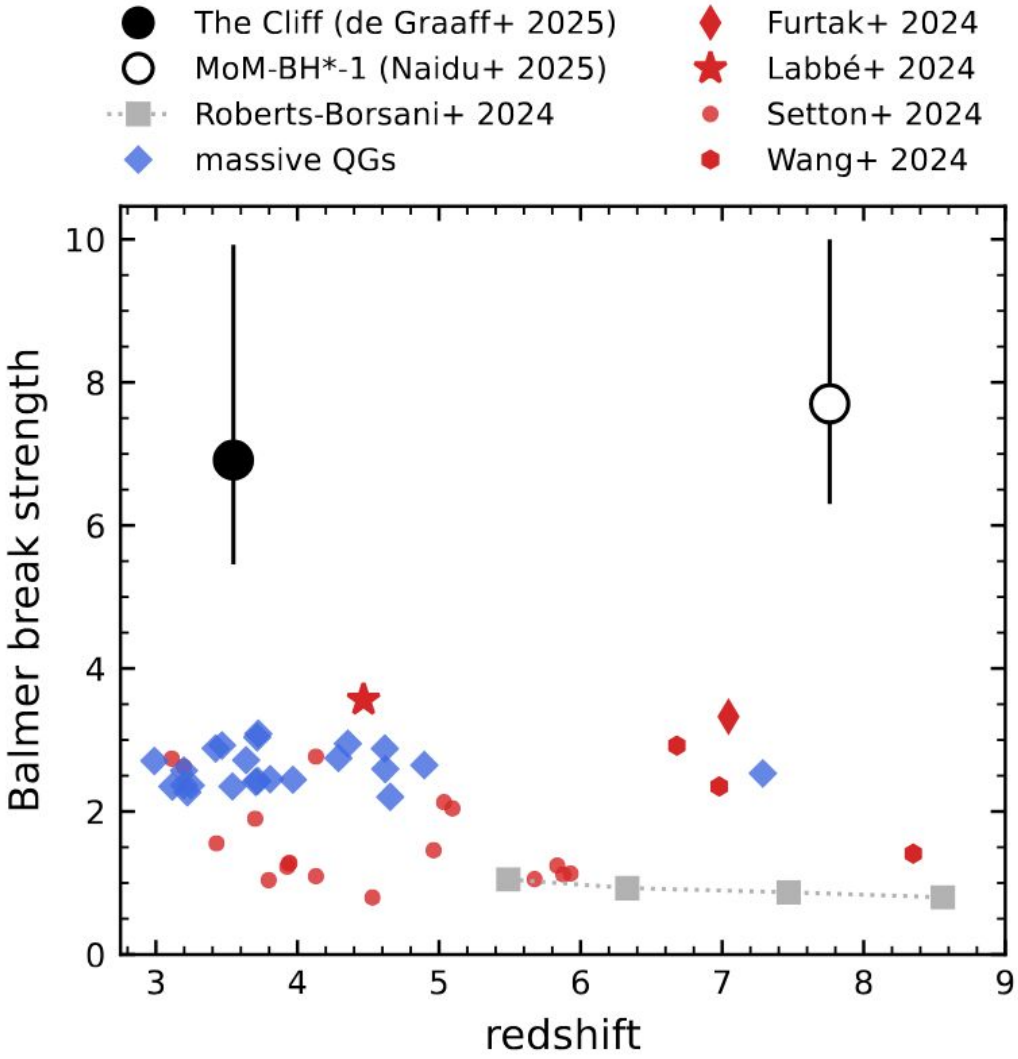


Extreme LRDs

De Graaff+25



Extreme LRDs



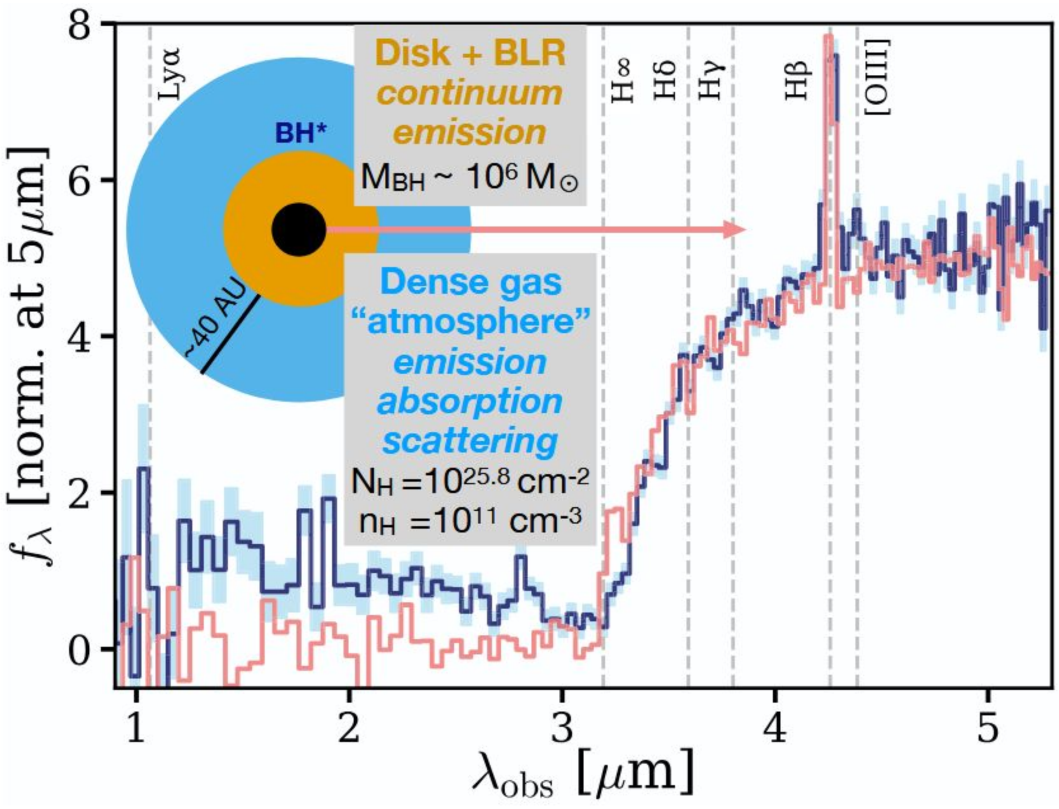
De Graaff+25

Extreme LRDs

Naidu+25

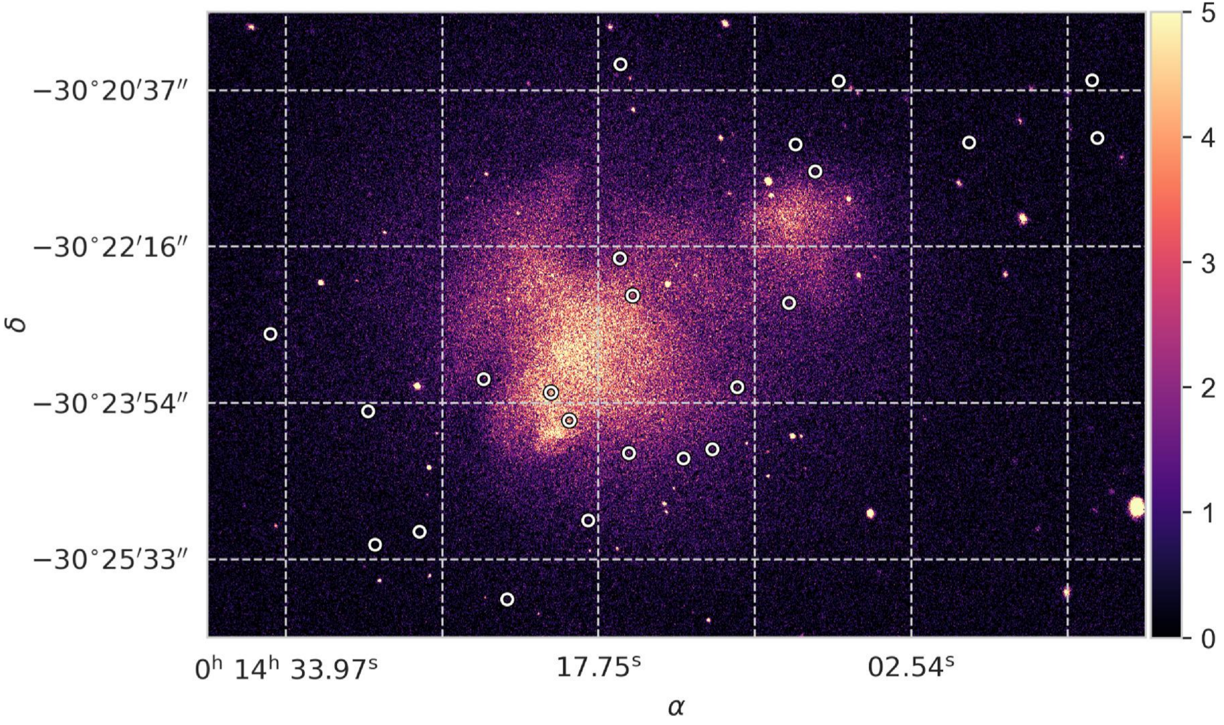
The Black Hole Star model

A black hole surrounded by a cacoon of dust-free gas

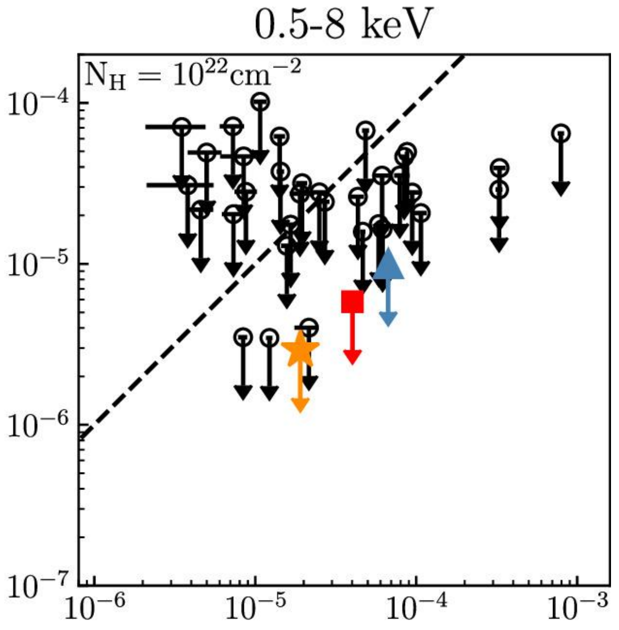


LRDs in other bands

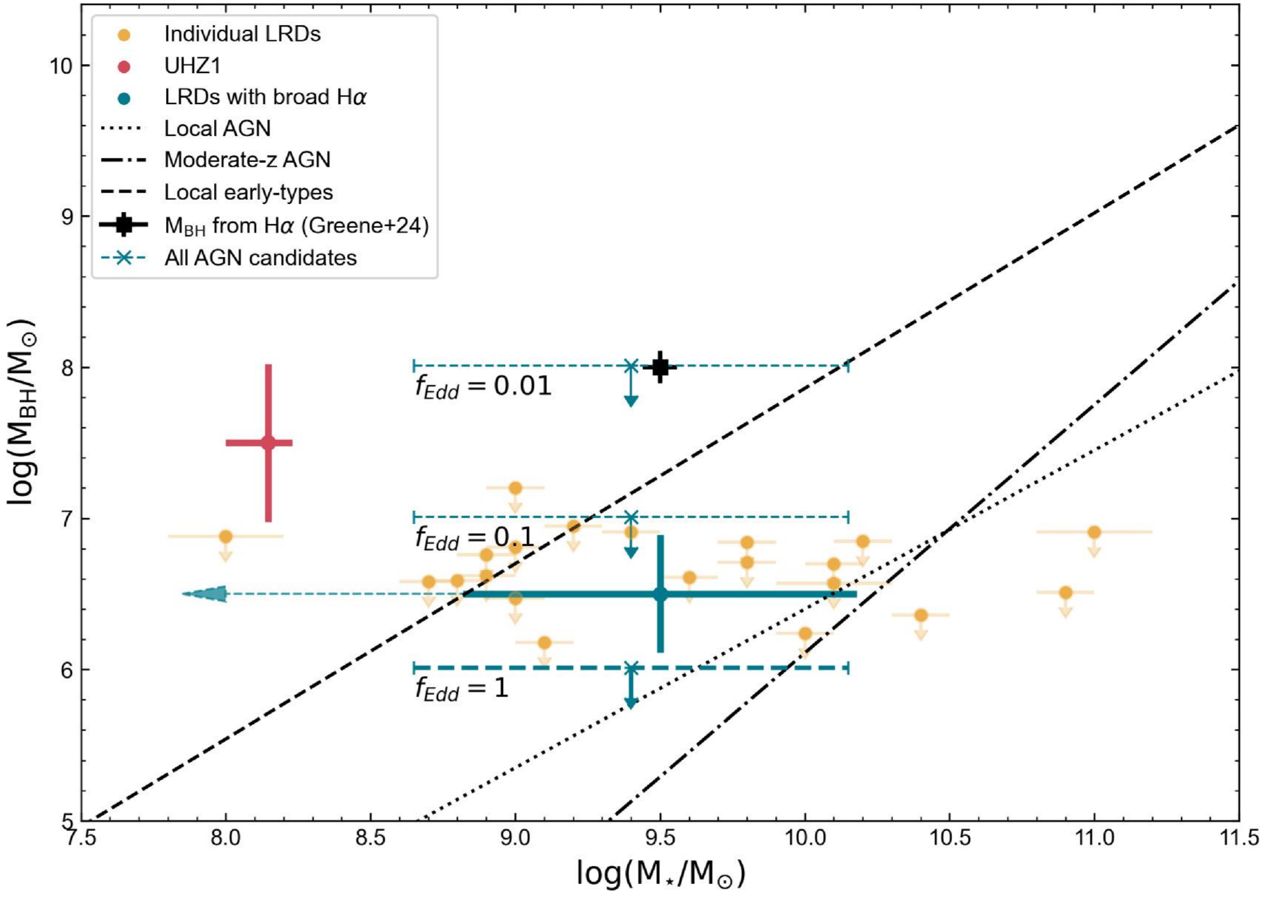
X-ray Observations of LRDs



Ananna+24



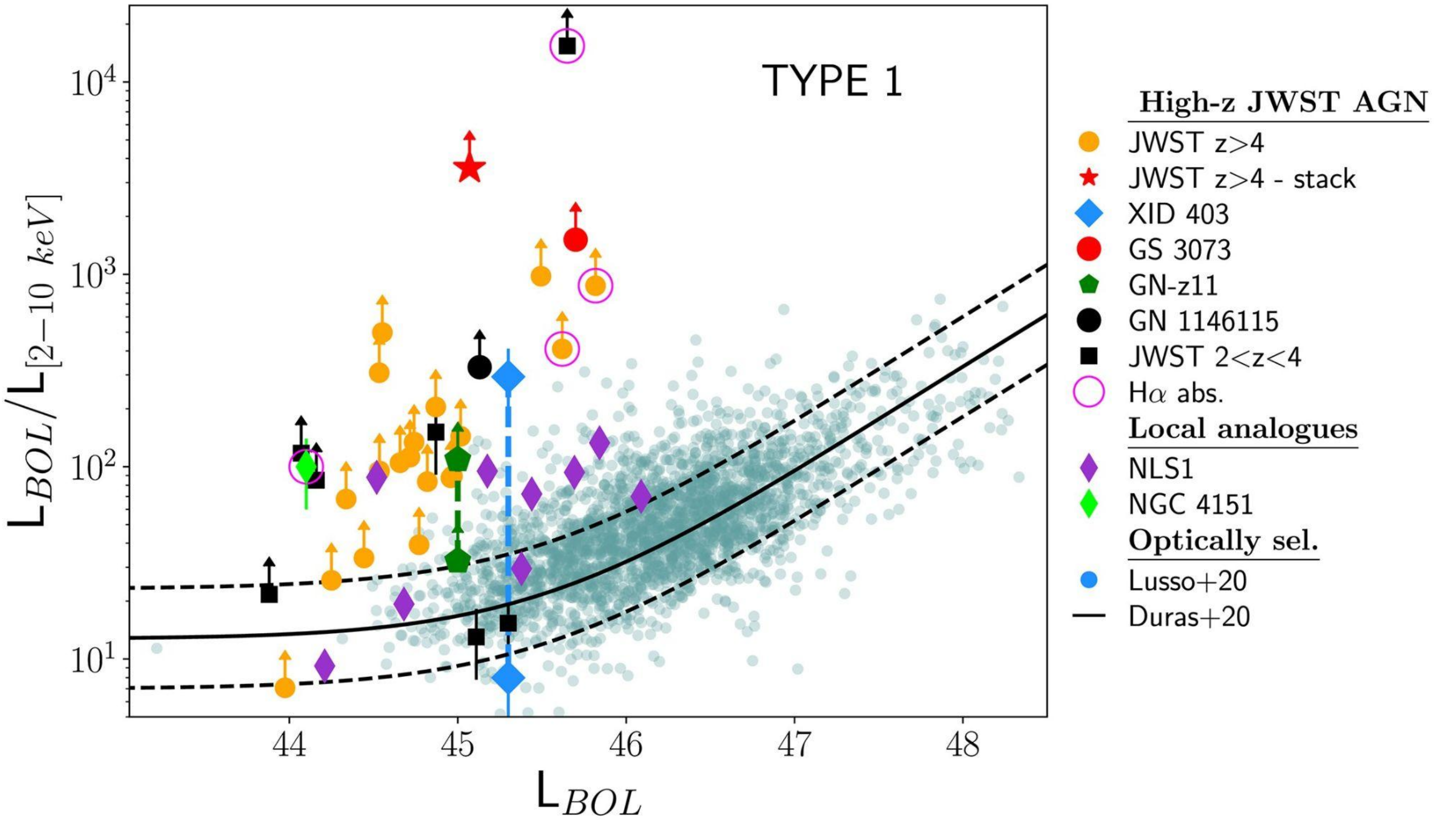
Yue+24



Individual LRDs
UHZ1
LRDs with broad Hα
Local AGN
Moderate-z AGN
Local early-types
M_BH from Hα (Greene+24)
All AGN candidates
f_Edd = 0.01
f_Edd = 0.1
f_Edd = 1
log(M_BH/M_⊙)
log(M_⋆/M_⊙)
10
9
8
7
6
5
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5

Ananna+24

X-ray Observations of LRDs



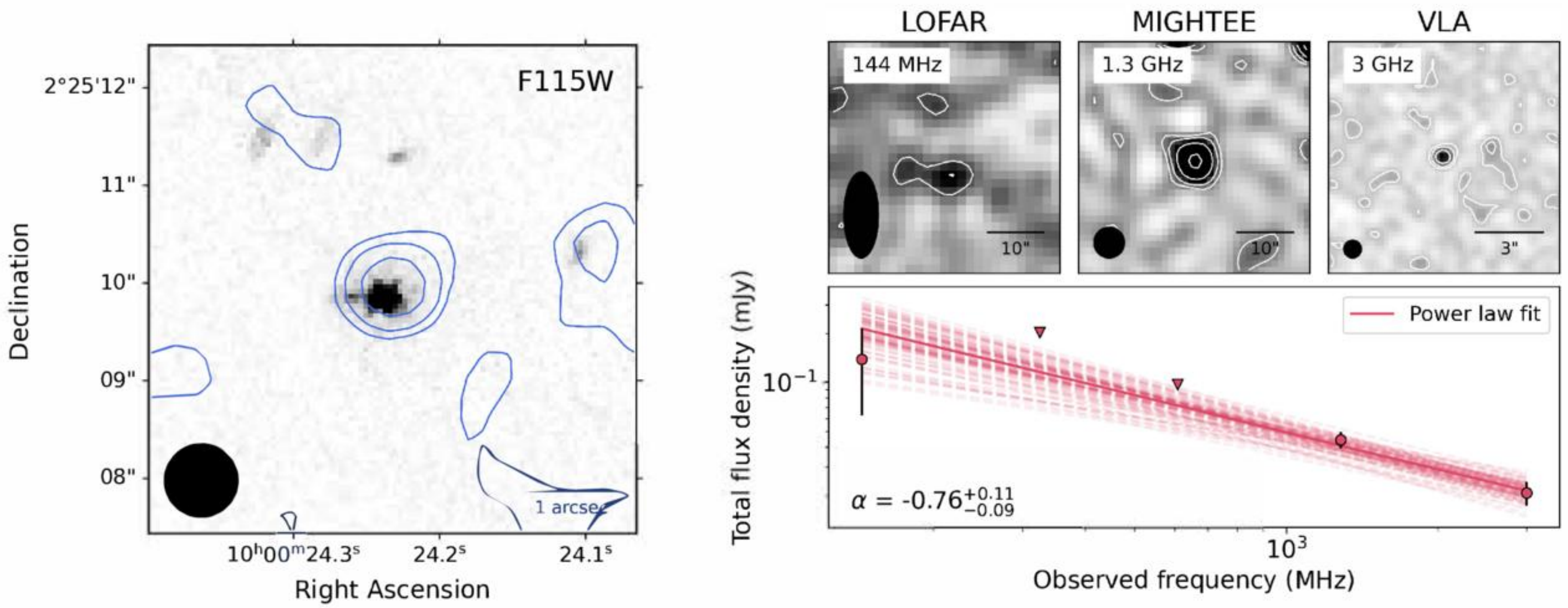
Maiolino+25

X-ray observation of LRDs

- Are LRDs X-ray underluminous?
- Or are we overestimating BH mass, bolometric luminosity etc.?
- Do they even have an AGN?

Radio Observations of LRDs

Gloudemans+25



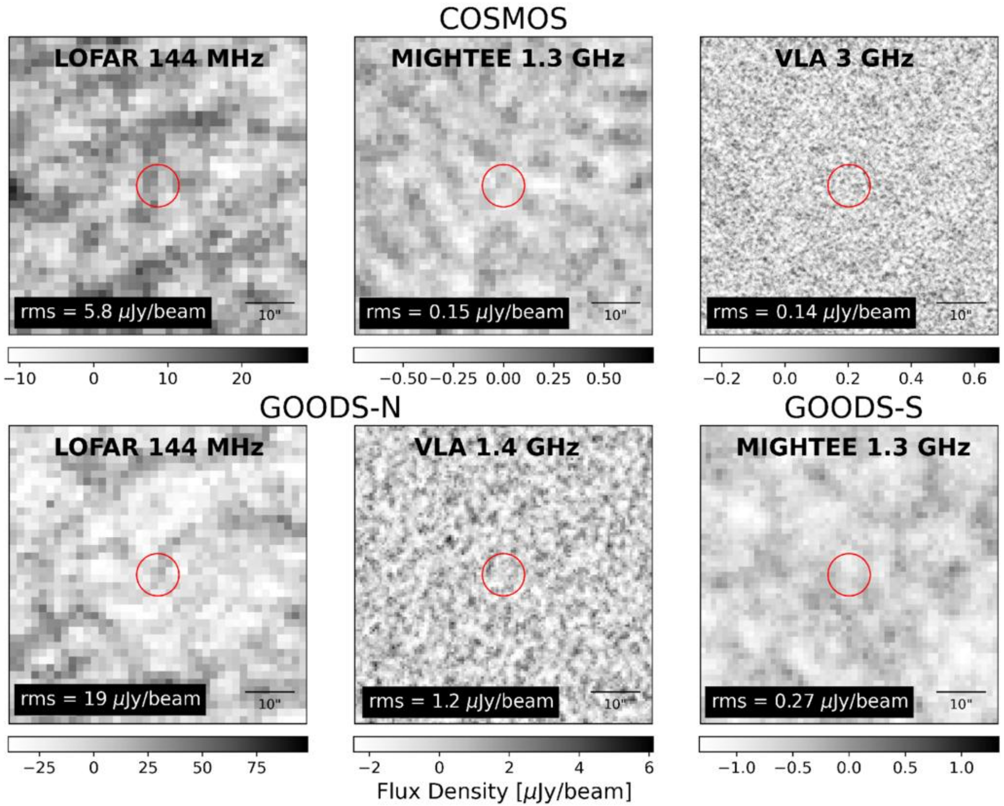
One source detected, previously known X-ray AGN

Radio Observations of LRDs

Stacked radio images of different AGN candidates in multiple fields

All stacks result in non-detection.

Gloudemans+25



Conclusions

- Little Red Dots are a peculiar class of sources with complex, confusing properties.
- What they are made of depends on your preferred fitting models, but there are no easy answers.
- They are either extremely massive galaxies that break early galaxy formation models, or host AGNs which are overmassive, with unusual SEDs and possibly break galaxy formation models.
- Although brightly detected in JWST, they are undetected in X-rays and radio. Is that because they don't emit at those bands, or are we overestimating the SMBH properties? Or has JWST outpaced the other observatories in terms of sensitivity and detectability?

The need for local counterparts

The need for local counterparts

- Getting a large sample with JWST is expensive.
- Multiwavelength data is not possible for most sources
- Radio and X-rays not able to access such high redshifts.
- High angular resolution is not accessible for high-z sources.

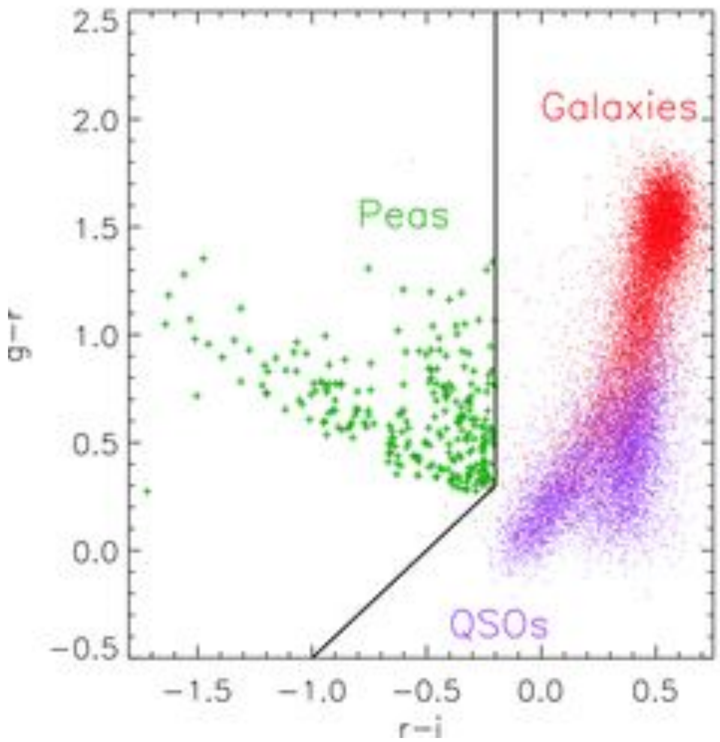
Green Peas

Cardamone et al., 2009

Green Peas

- Low stellar mass ($M_\star \simeq 10^9\ M_\odot$)
- Compact ($\simeq$ 1 kpc)
- Highly star-forming (SFR > 10 $M_\odot\ yr^{-1}$)
- Sub-solar metallicities (log(O/H)+12 $\simeq$ 8.2)
- Relatively nearby (z $\simeq$ 0.3, DA $\simeq$3 Gyr)
- Distinctive green colour due to enhanced [OIII] λ5007 emission driven from star formation.

See e.g. Cardamone et al., (2009), Izotov et al. (2011)

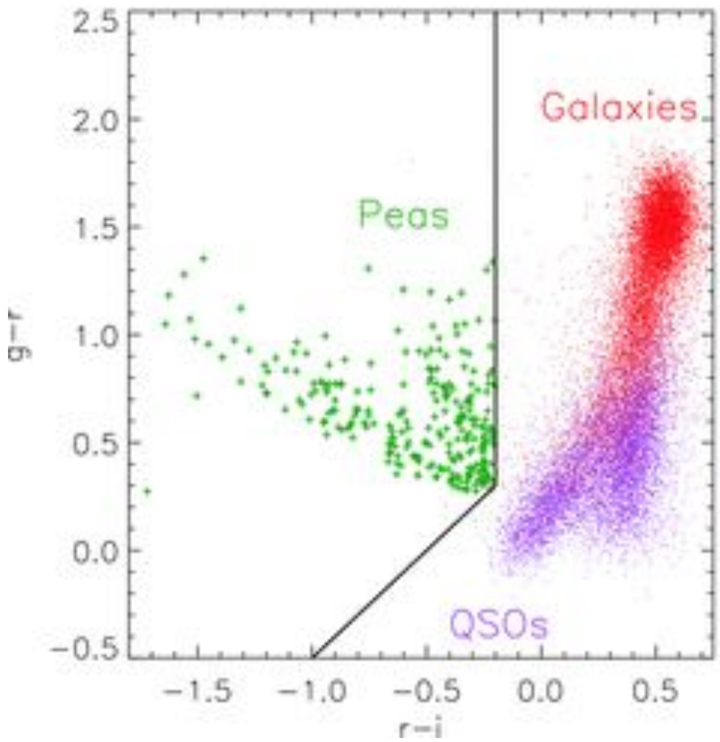


Cardamone et al., 2009

Green Peas

Lyman continuum escape

- Strong UV Lyα lines, comparable to high-z starburst galaxies known as Lyman-Alpha Emitters.
- Substantial escape fraction (tens of percent) of ionizing Lyman continuum (LyC).
- The only low-redshift population where significant amounts of LyC escape have been observed.



Cardamone et al., 2009

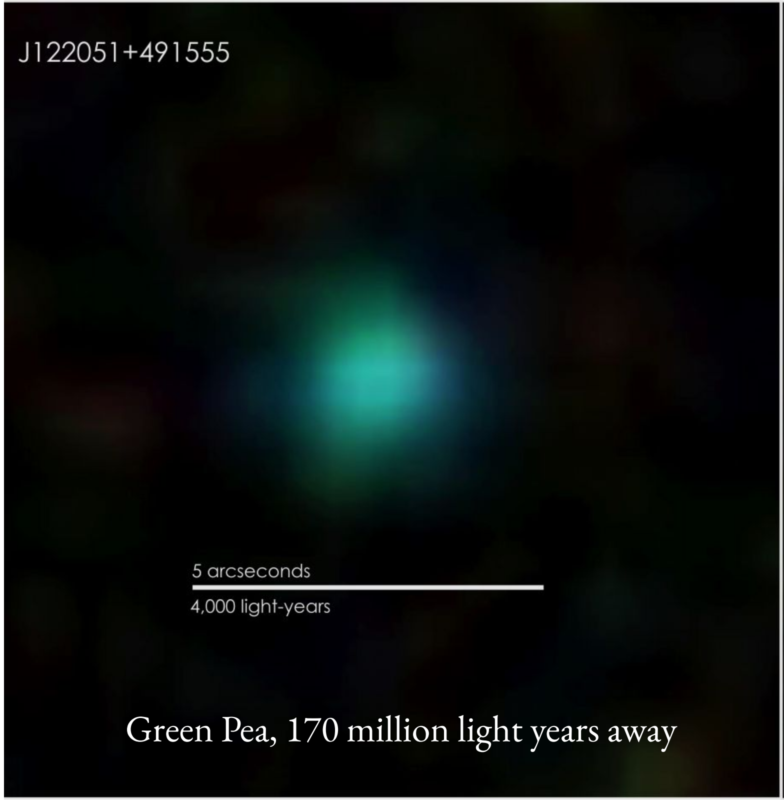
See e.g. Henry et al. (2015), Izotov et al. (2016)

Blueberries

- star-forming galaxies similar to GPs but closer & smaller.
- Lower stellar mass ($M_\star < 10^8\ M_\odot$)
- Compact (< 1 kpc)
- Highly star-forming (SFR ≃1–10 $M_\odot\ yr^{-1}$)
- Lower SFR but higher sSFR = SFR/$M_\star$
- Sub-solar metallicities (log(O/H)+12 < 8.2)
- Nearby (z < 0.1, DA ≃1.25 Gyr)
- Distinctive blue colour due to high SFR

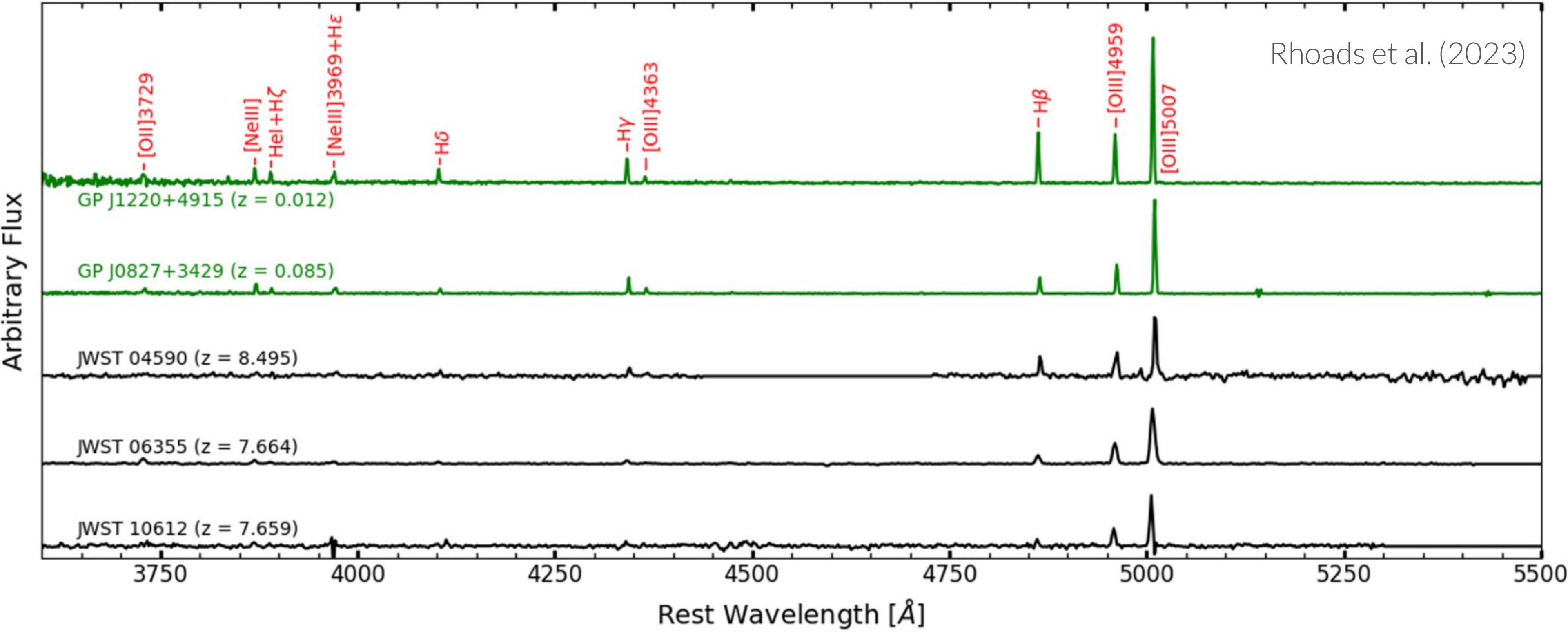
See e.g. Yang et al. (2017), Jaskot et al. (2019), McKinney et al. (2019)

Comparison between GPs and early galaxies

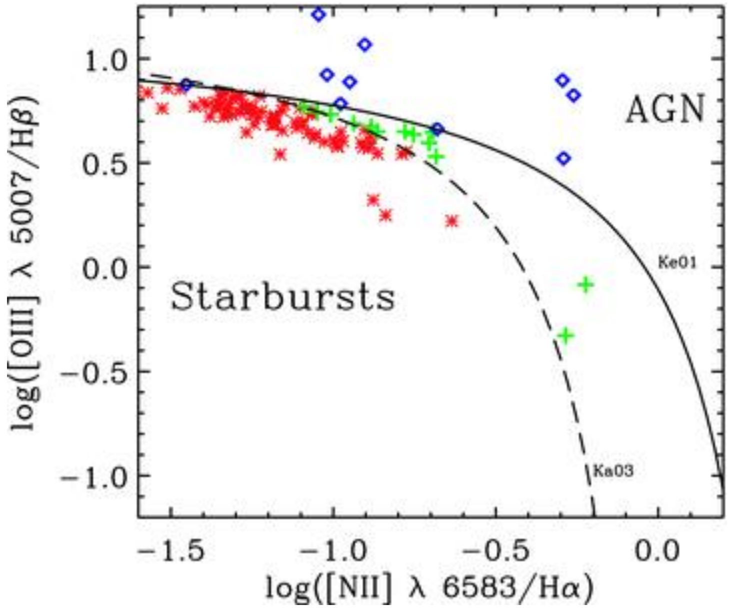


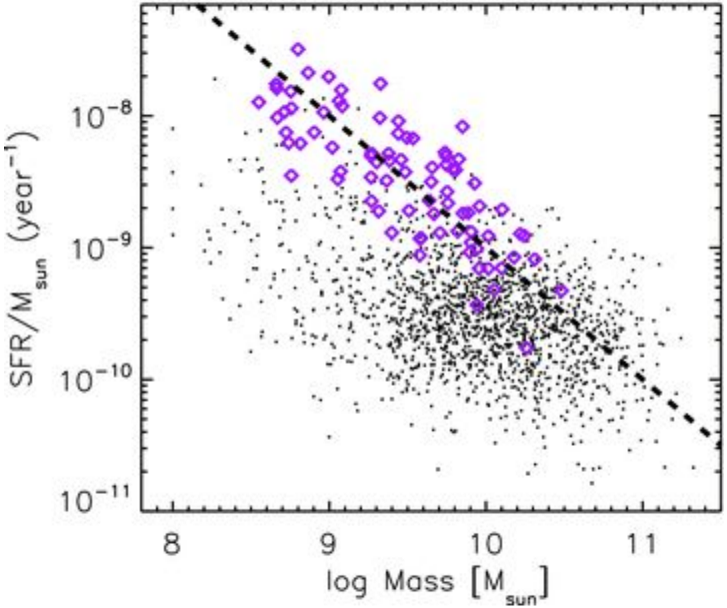
Hall et al. 2023

Comparison between GPs and early galaxies



Optical classification





Cardamone et al., 2009

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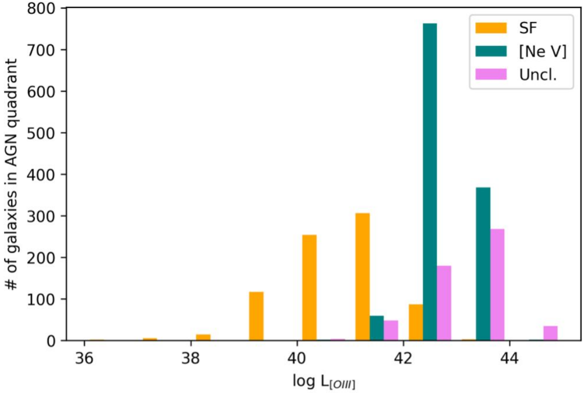
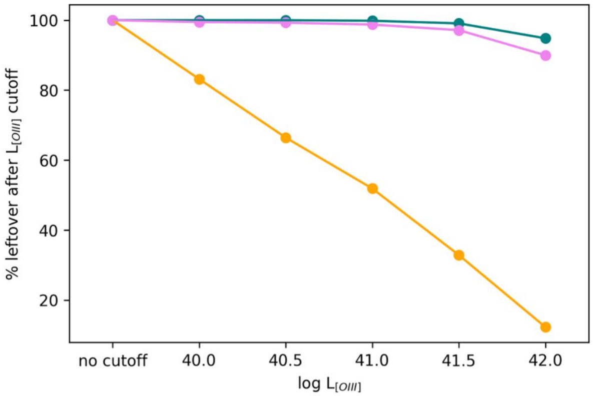
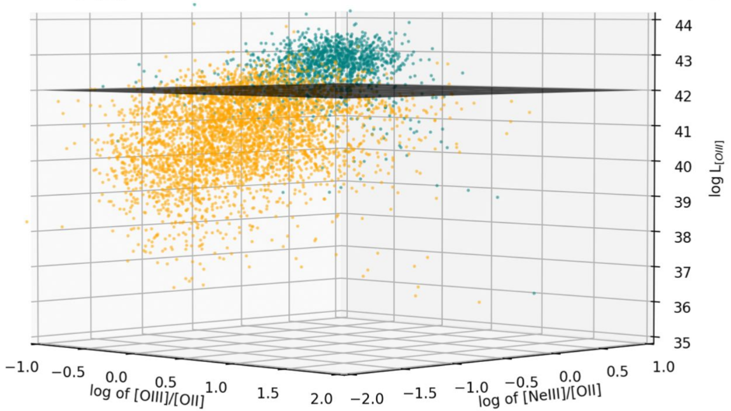






3D classification diagram

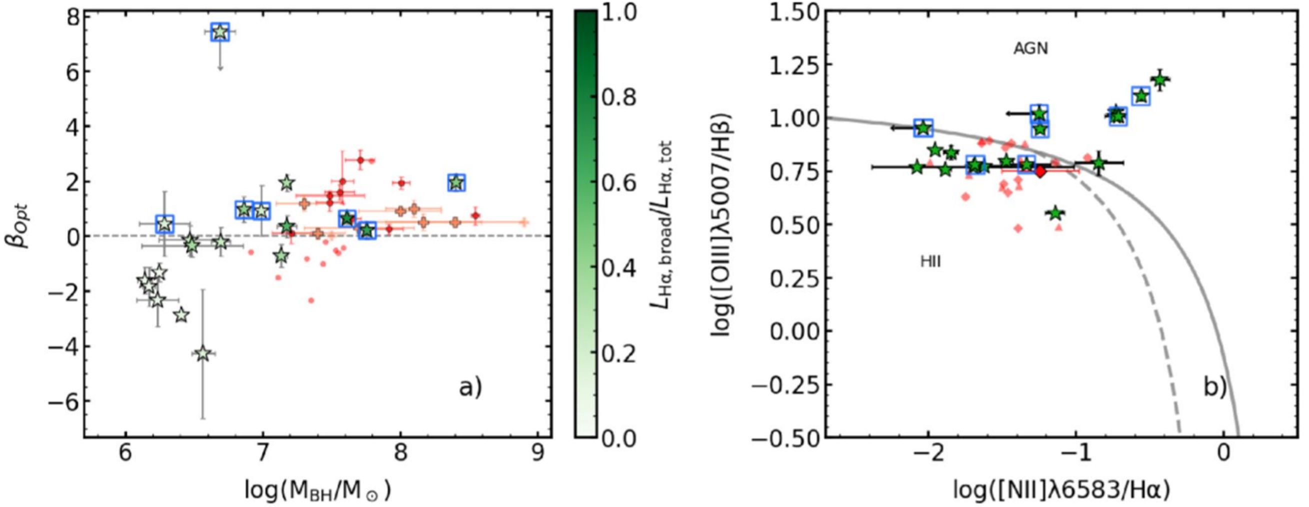
- [O III]/[O II]
- [Ne III]/[O II]
- $L_{O\ III}$ cutoff

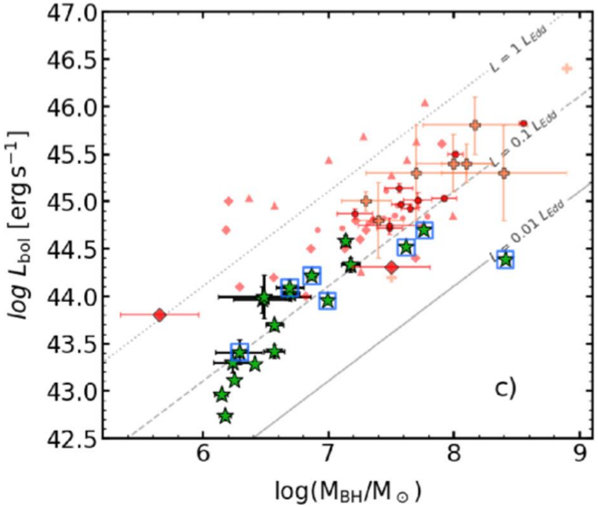
Green Pea like galaxies (GPs, grey peas, purple grapes) classified as AGN.

No AGN signatures like NeV or HeII.

Spectra similar to W-R galaxies, but no local W-R galaxies have such high $L_{O\ III}$

Feuillet et al. (2024)



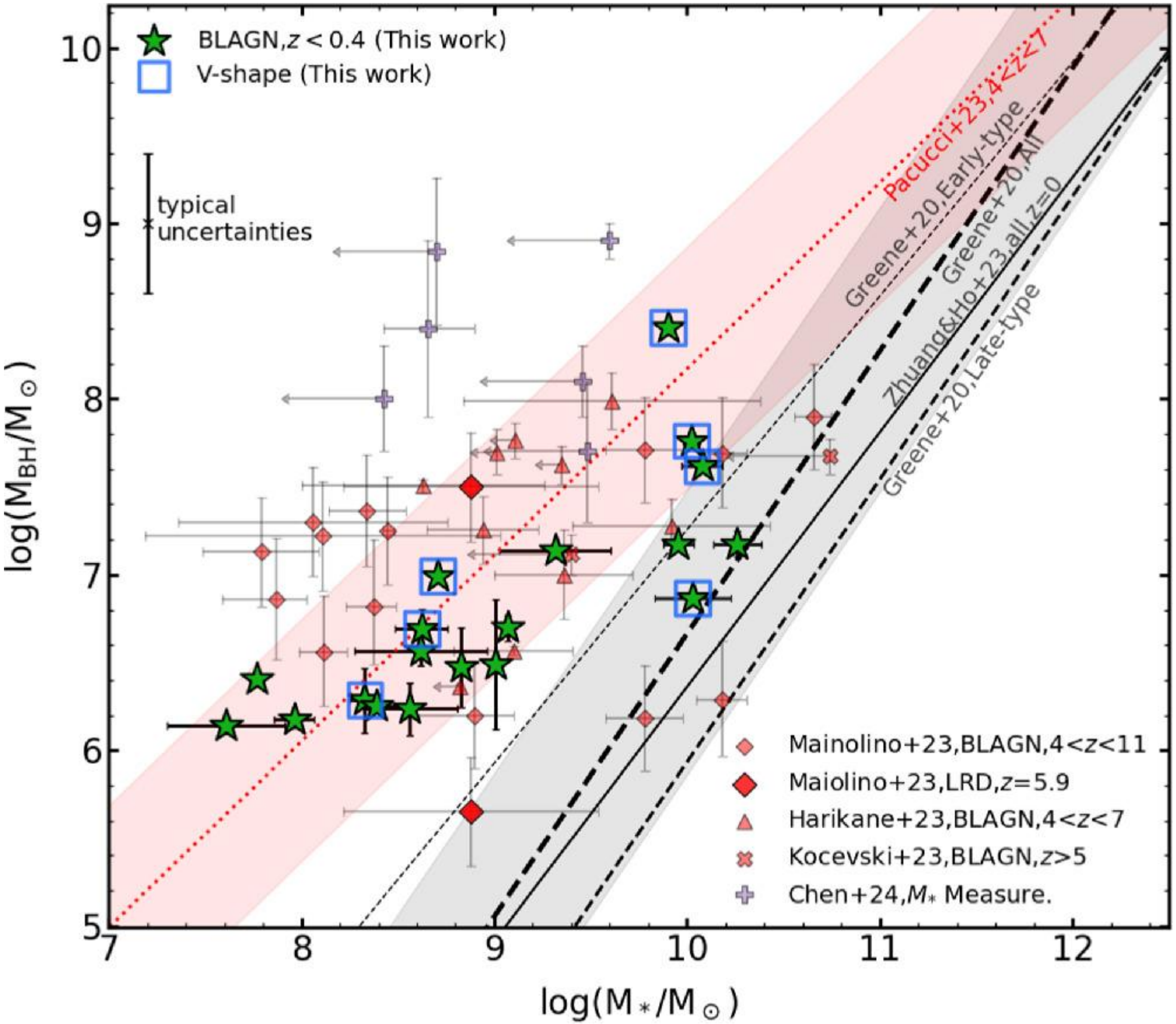


Broad line GPs

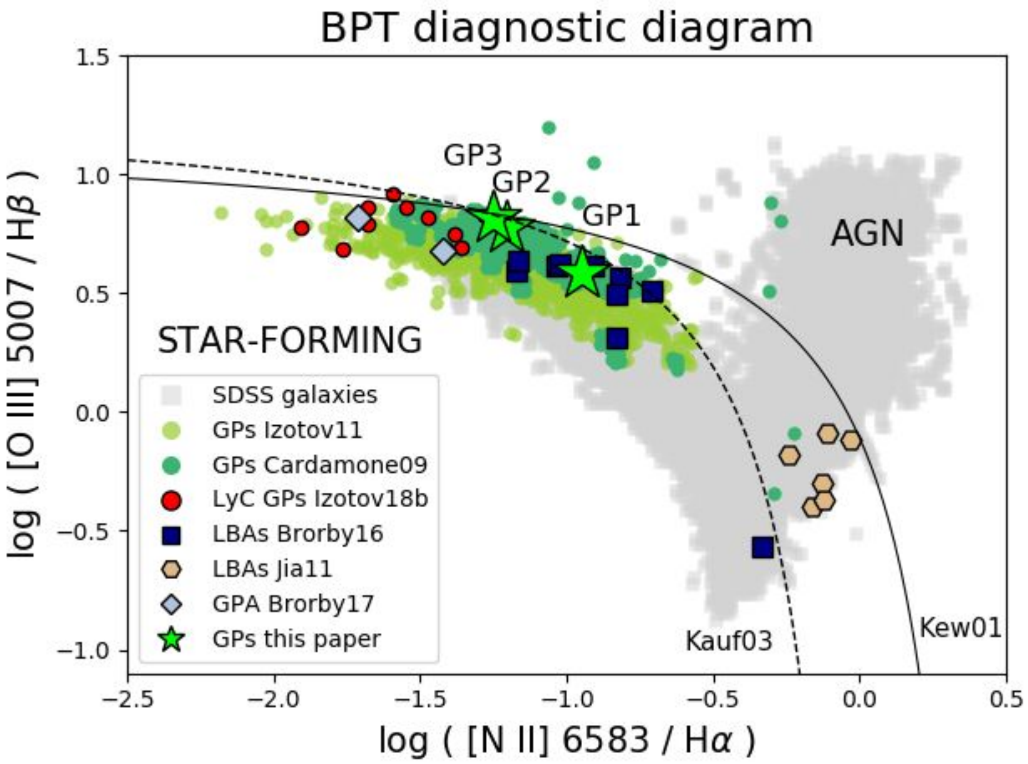
Lin+25

Broad line GPs

Lin+25



Optical classification



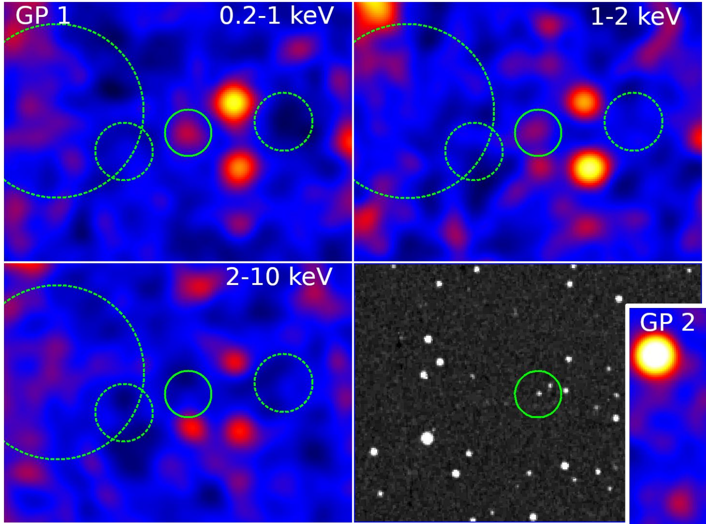
Svoboda et al. 2019

3 GPs selected for X-ray observations

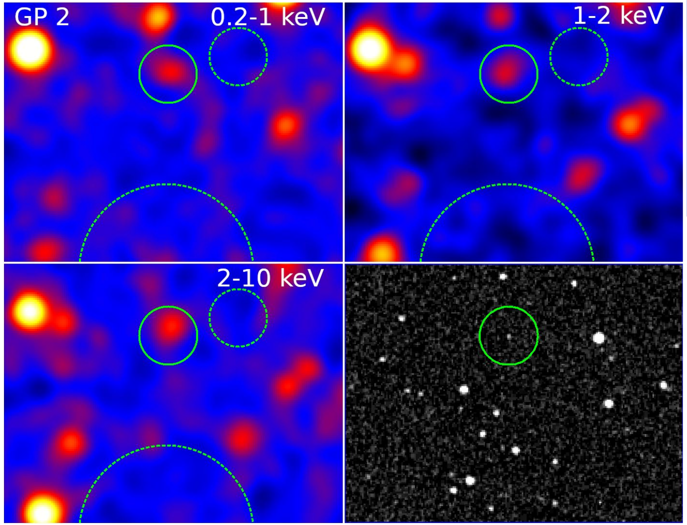
- ➔ SFR ≅ 20 – 60 M_{sun}/yr
- ➔ metallicity: log[O/H] + 12 ≈ 8.1
- ➔ Redshift: z ≈ 0.2 – 0.3
- ➔ Classified as star-forming.

X-ray observations

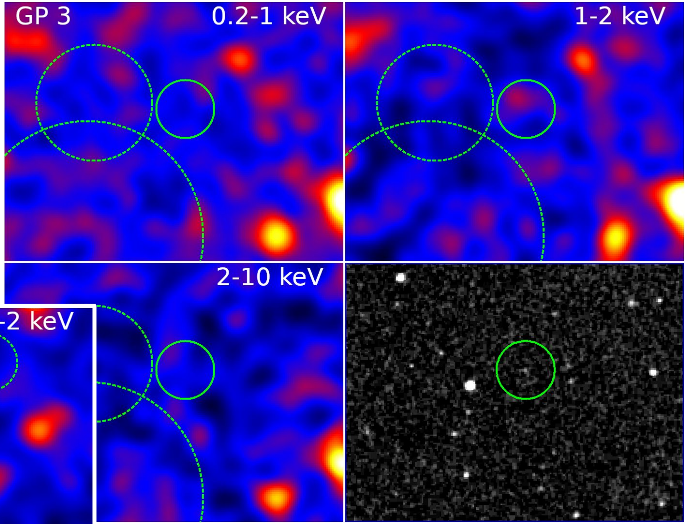
Svoboda et al. 2019



GP 1:
clear detection in soft X-rays (<2 keV)

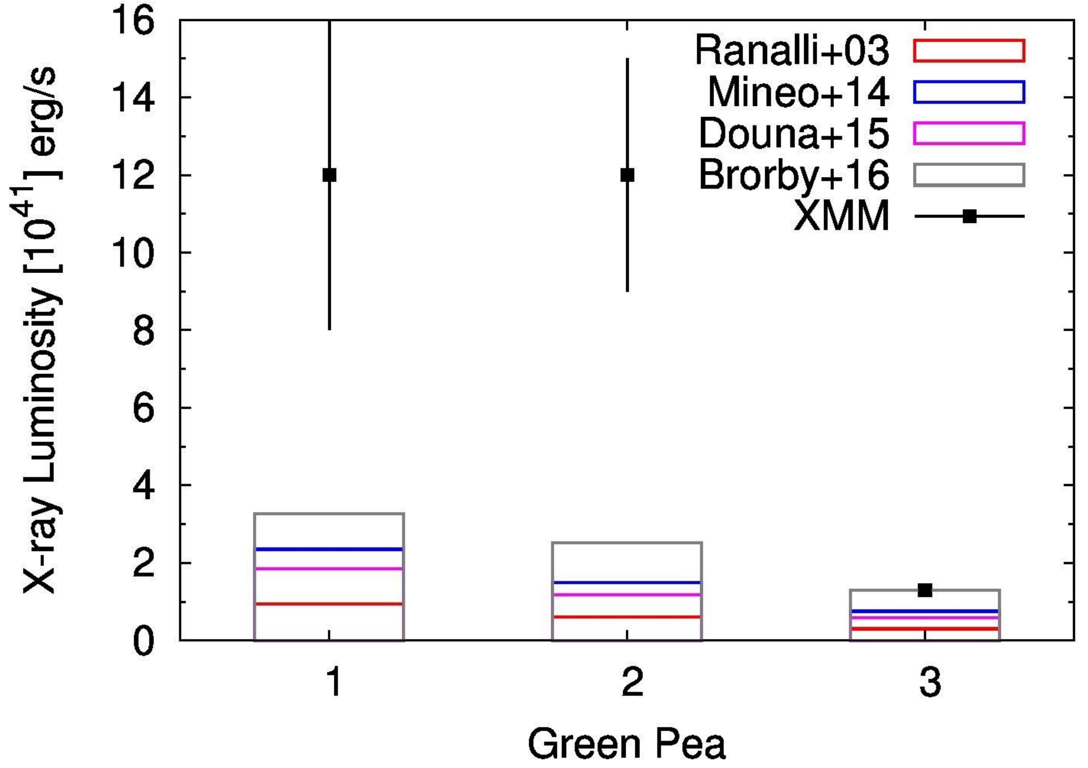


GP 2:
detection in full X-ray band (0.5 – 10 keV)



GP 3:
No clear detection.

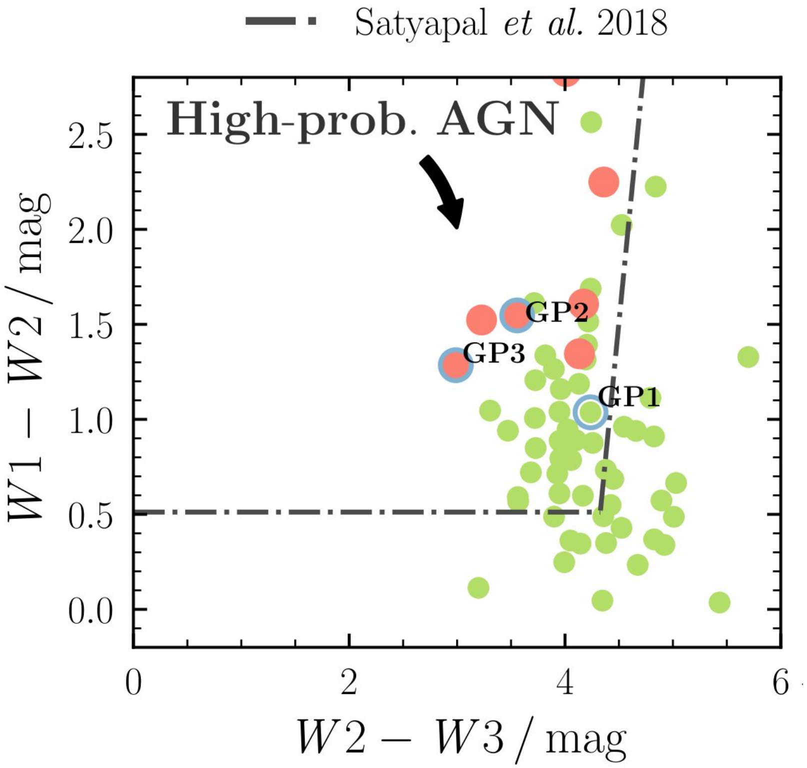
X-ray observations

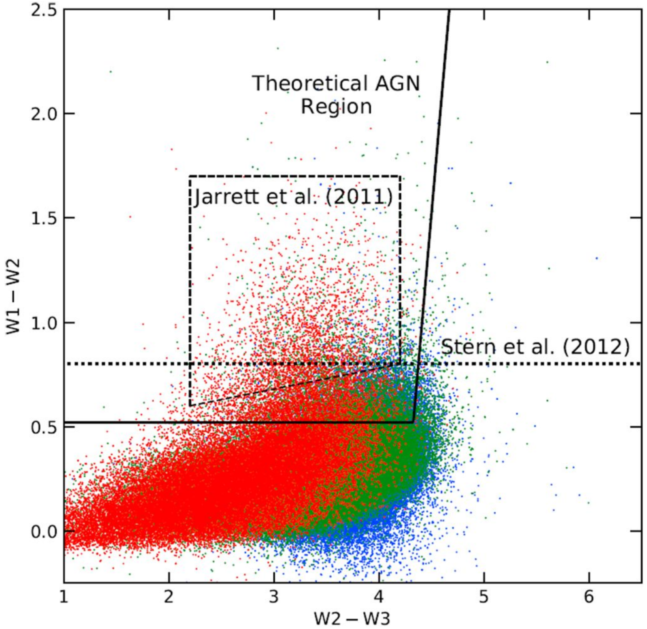


- GP 1 and GP 2 are largely above different L_X – SFR – (metallicity) empirical relations.
- X-ray luminosity >10^{42} erg/s.
- GP 3 only upper limit consistent with predictions

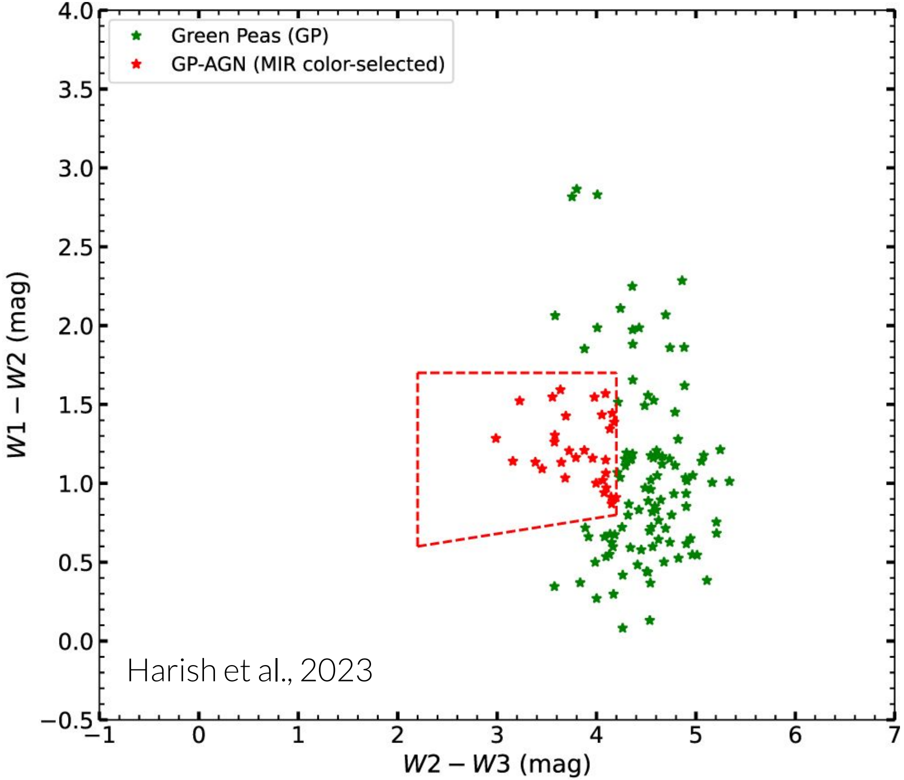
Svoboda et al. 2019

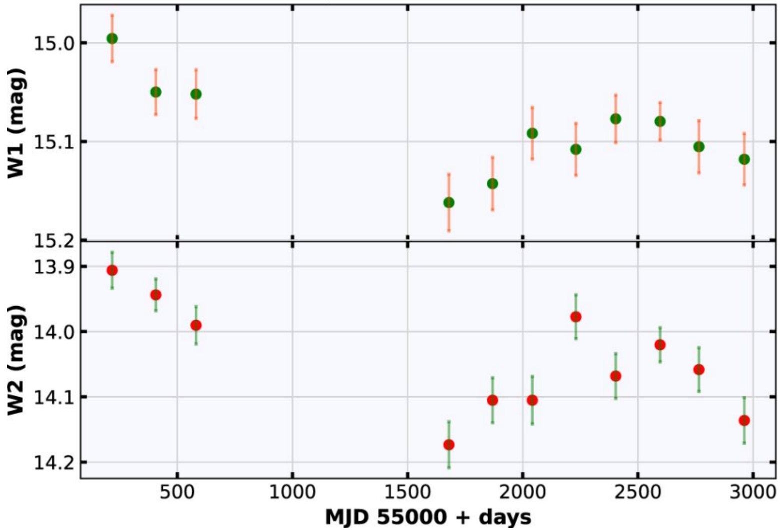
Mid-IR classification

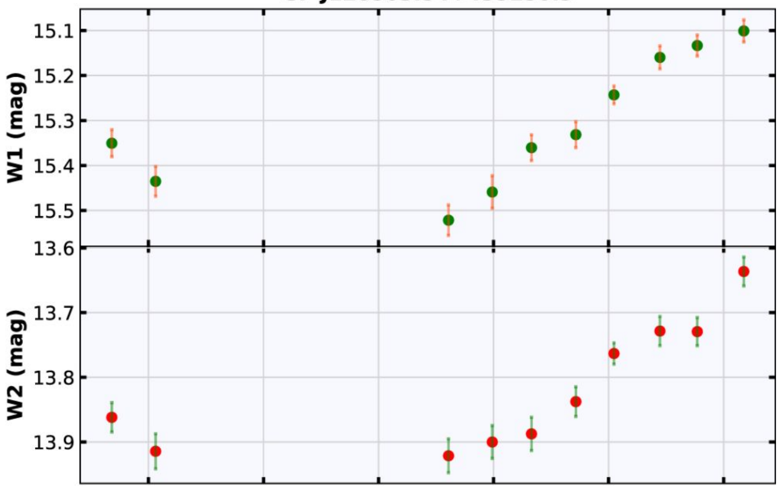




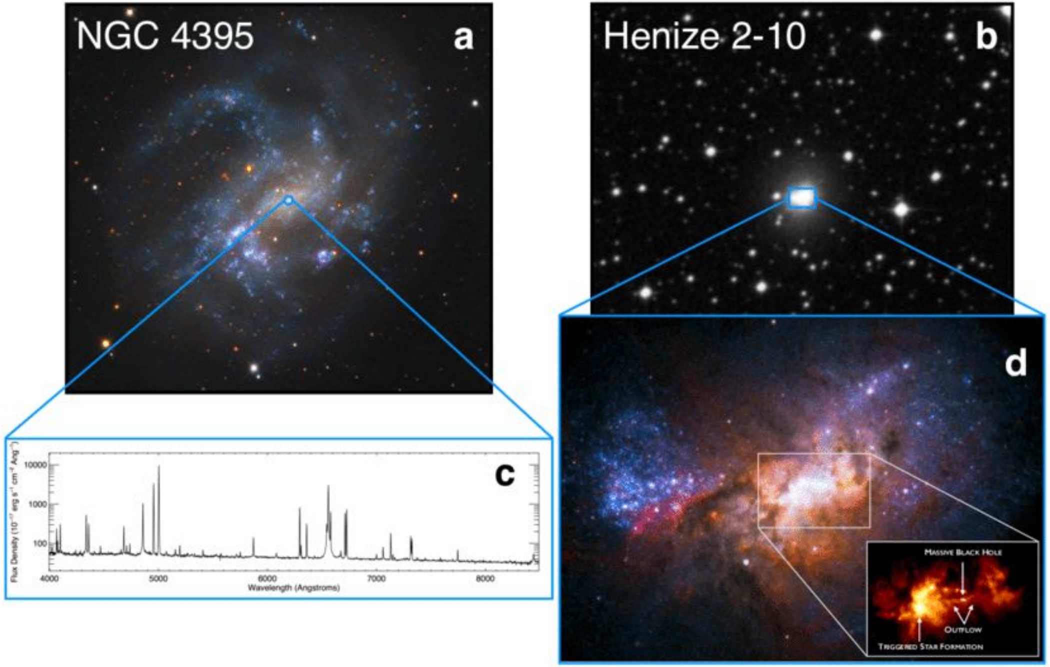
Mid-IR classification







Evidence of AGN in dwarf galaxies



Schutte & Reines et al., 2021

Evidence for AGN in dwarf galaxies

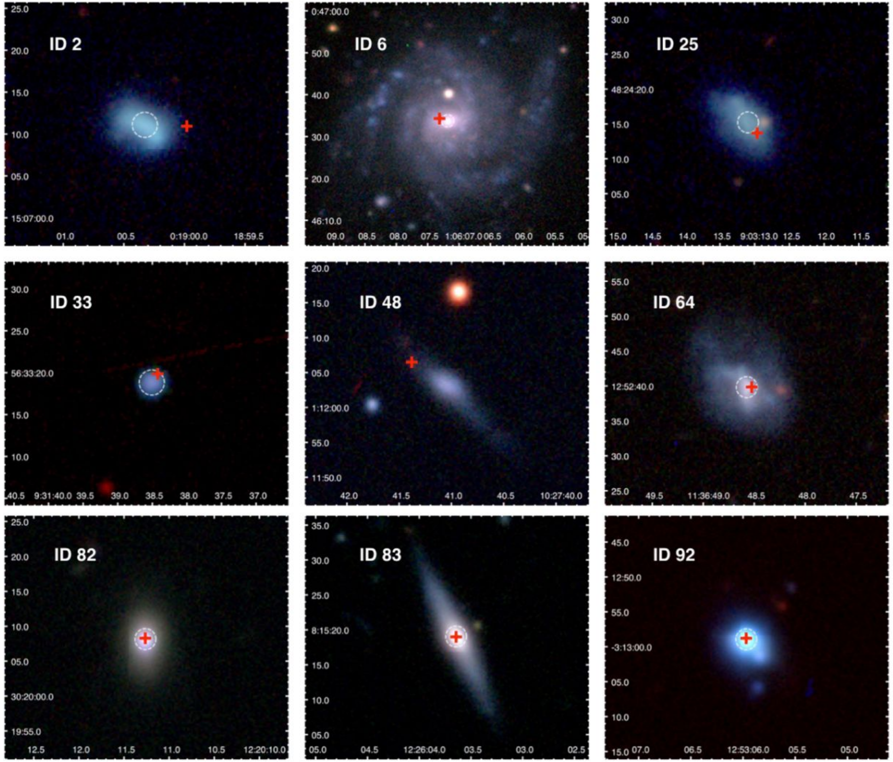
- NGC 4395 (Filippenko & Sargent, 1989)

More examples and systematic studies

- Greene & Ho (2004, 07, 20)
- Mezcua et al. (2016, 18, 20, 22), Ferre-Mateu et al. (2019)
- Reines et al. (2012, 19, 22)
- Baldassare et al. (2017)
- Pardo et al. (2016)
- Birchall et al. (2020)

AGN candidates based on detected high X-ray flux, disagreement with BPT classification in 85% sources

AGN candidates in dwarf galaxies



AGN candidates via radio detections

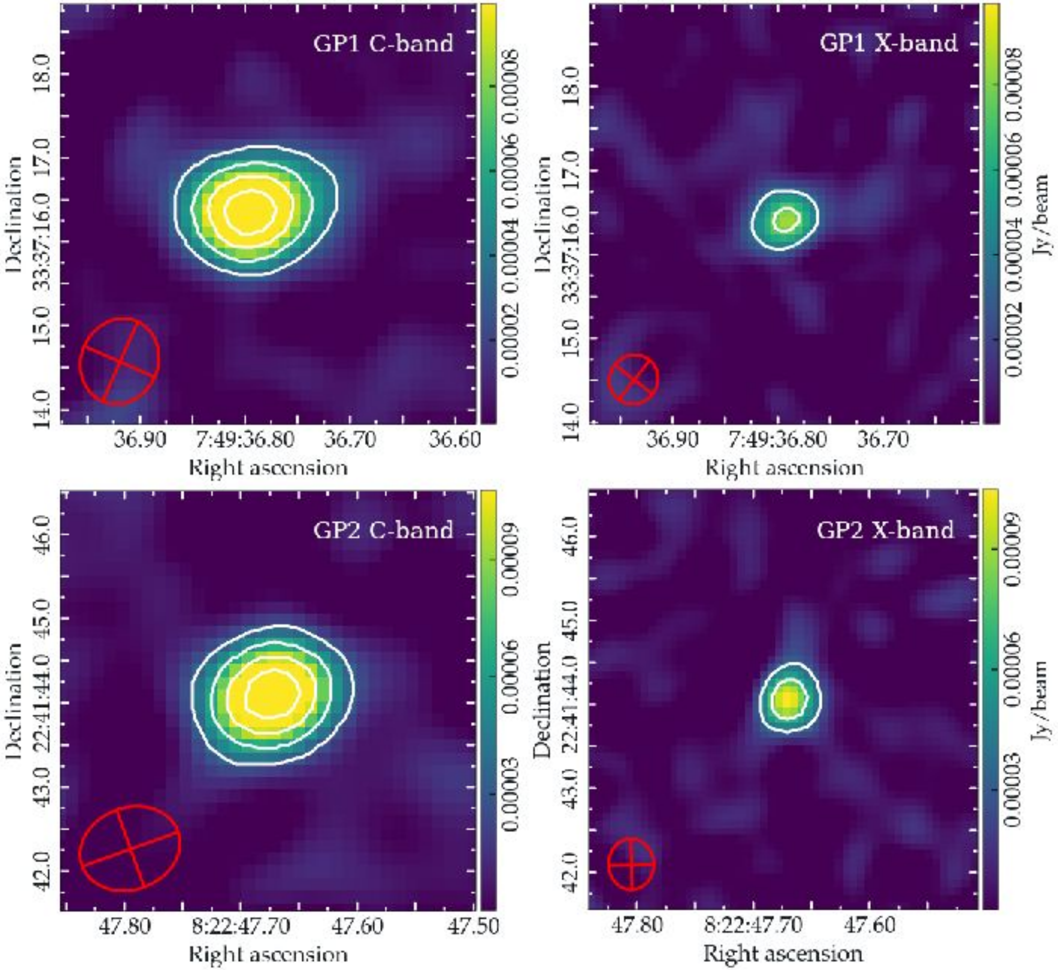
- Local dwarf galaxies observed with VLA at high resolution.
- 13 dwarf galaxies show signs of (offset) AGN candidates, some show signs of mergers.

Reines et al., 2020

Radio observations

JVLA observations of the three GPs; GP3 was not detected.

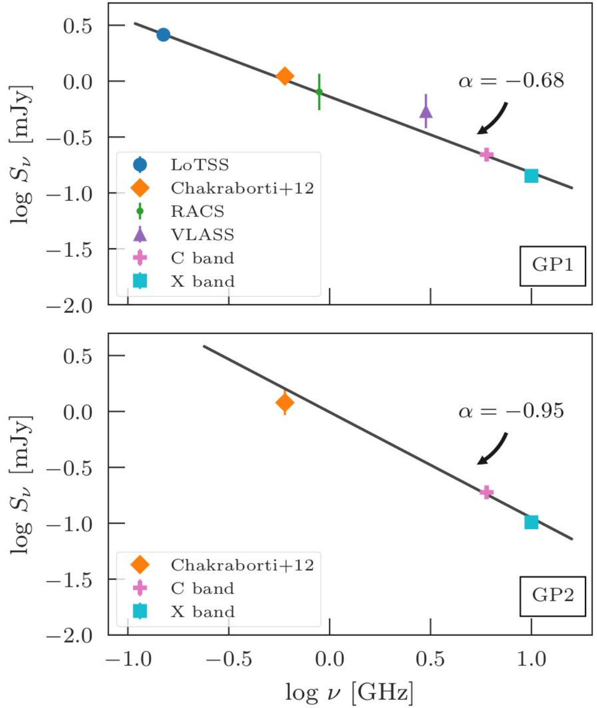
Source	Time on source [min]	Effective Frequency [GHz]	Total flux [μJy]	Beam size [$'' \times ''$]
GP1	14.2	6.0	220±6	1.0×0.9
	14.5	10.0	142±10	0.6×0.6
GP2	13.4	6.0	189±11	1.2×0.9
	13.9	10.0	102±9	0.6×0.5

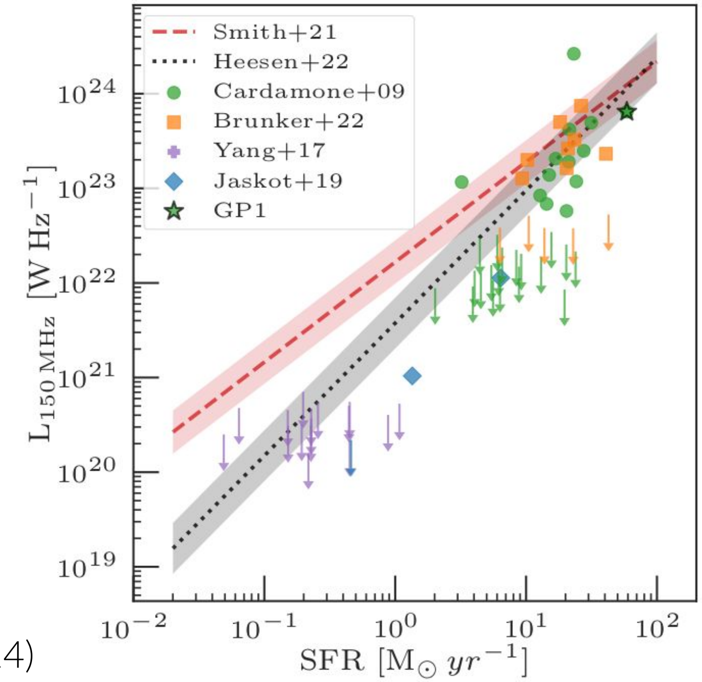


Borkar et al. (2024)

Radio properties of GPs

The luminosities of most detected sources are either consistent or underluminous with respect to SFR. All the undetected sources are significantly underluminous.





Radio SEDs of the two GPs show a characteristic synchrotron spectrum

Borkar et al. (2024)

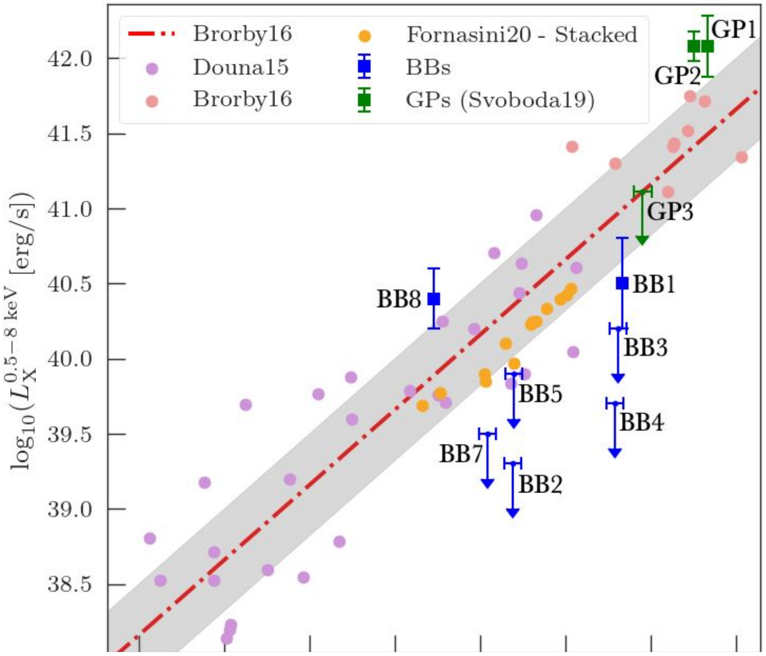
Radio properties of GPs

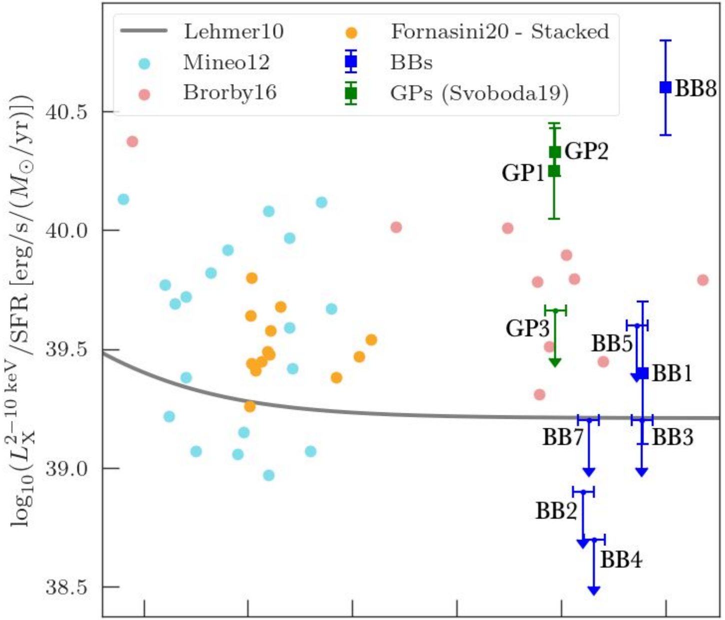
GPs classified as Narrow-line Seyfert 1s are all strong radio sources

				LoTSS	TGSS	NVSS	FIRST	VLASS	
C09 N2	14:19:18.900	+51:02:40.142	0.3236	6.8	—	—	1.45	1.4	NLS1
C09 N3	16:22:09.407	+35:21:07.269	0.2660	13.2	—	—	2.0	1.8	NLS1
C09 N4	07:49:32.947	+28:34:06.750	0.3369	342	390	27	28	10.2	NLS1
C09 N5	11:29:07.104	+57:56:05.206	0.3123	11.4	—	—	1.92	1.8	NLS1
C09 N6	11:26:15.265	+38:58:17.389	0.3365	2.2	—	—	1.2	—	NLS1
C09 N7	08:18:00.198	+19:18:10.181	0.3245	—*	—	—	1.4	0.93	NLS1

Borkar et al. (2024)

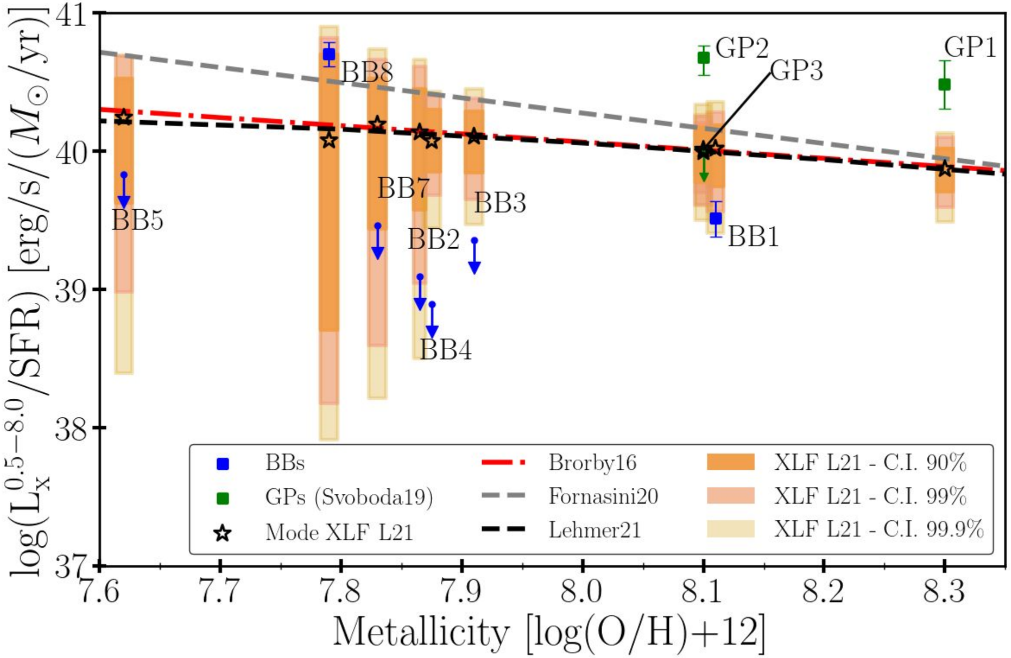
X-ray observations of Green Pea/Blueberry galaxies





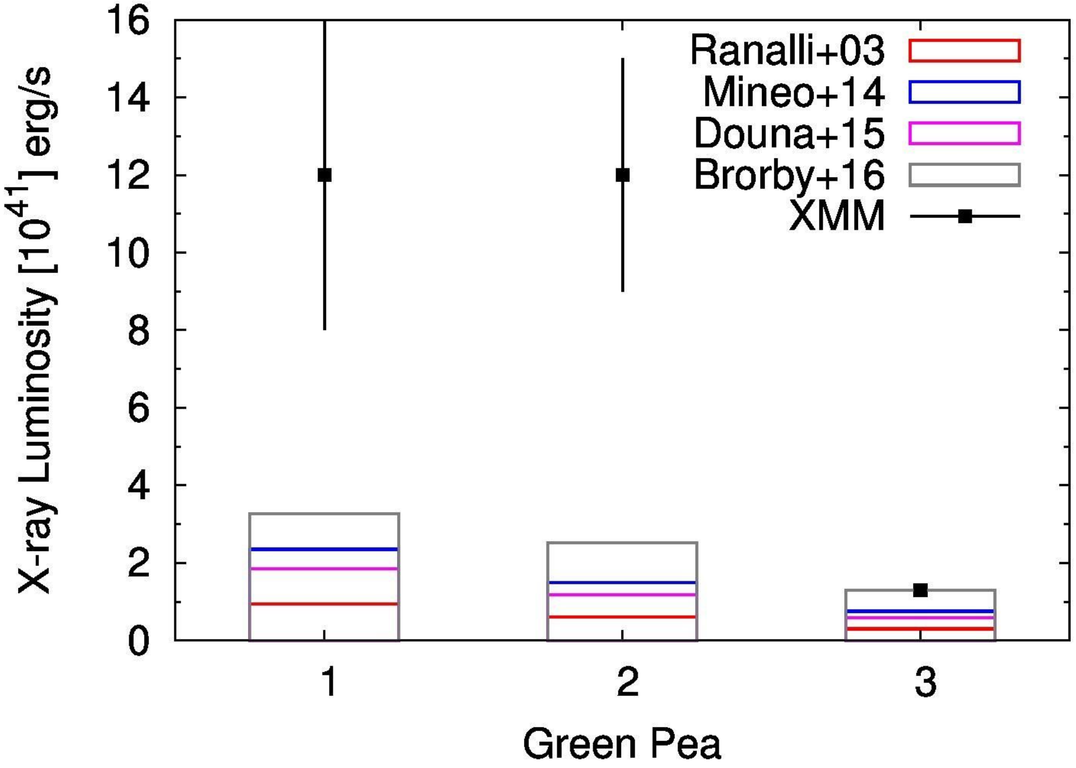
Adamcová et al., 2024

X-ray observations of Green Pea/Blueberry galaxies



Adamcová et al., 2024

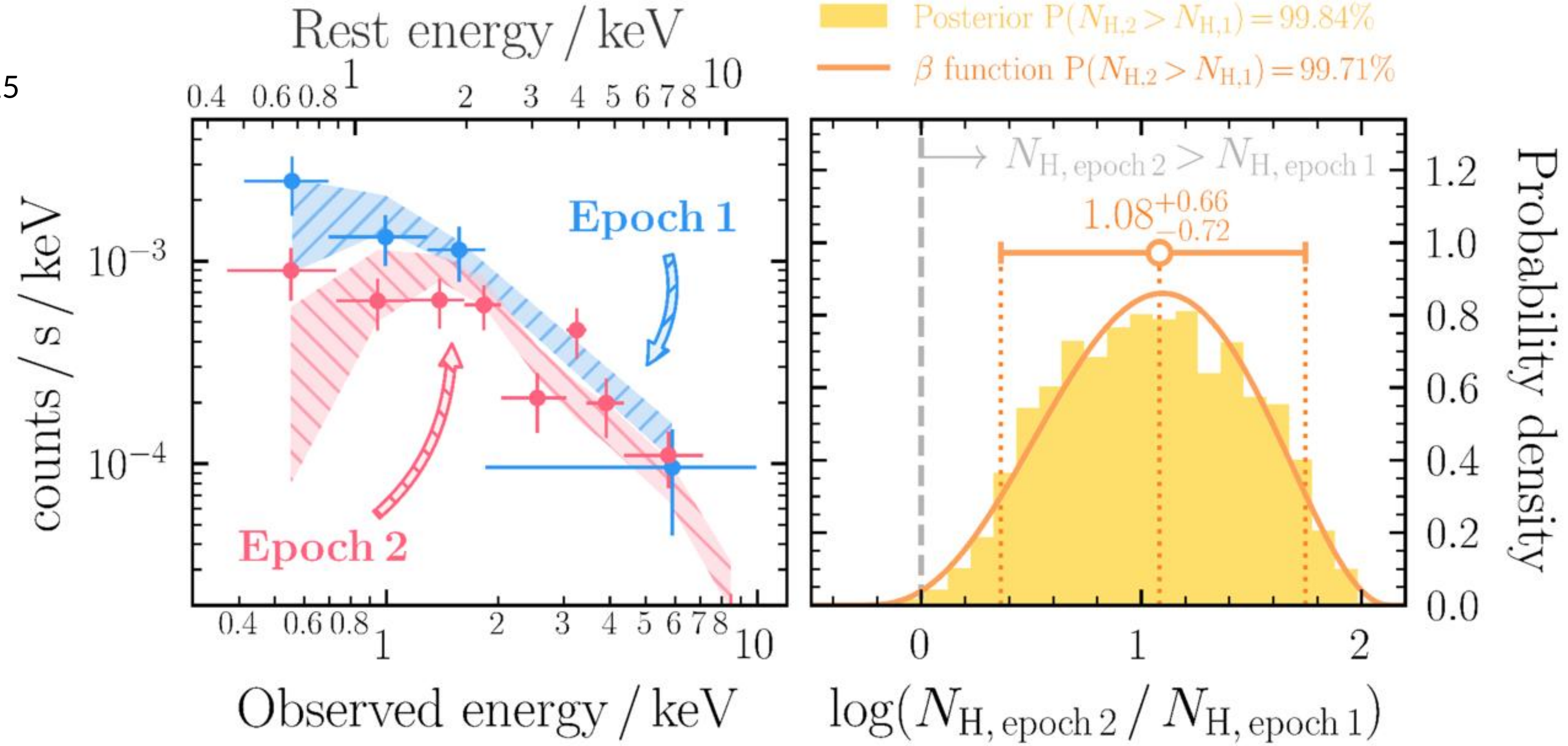
AGN hiding in a Green Pea galaxy?



- GP2 from Svoboda et al., (2019), observed with XMM-Newton for a total of 110 ks.

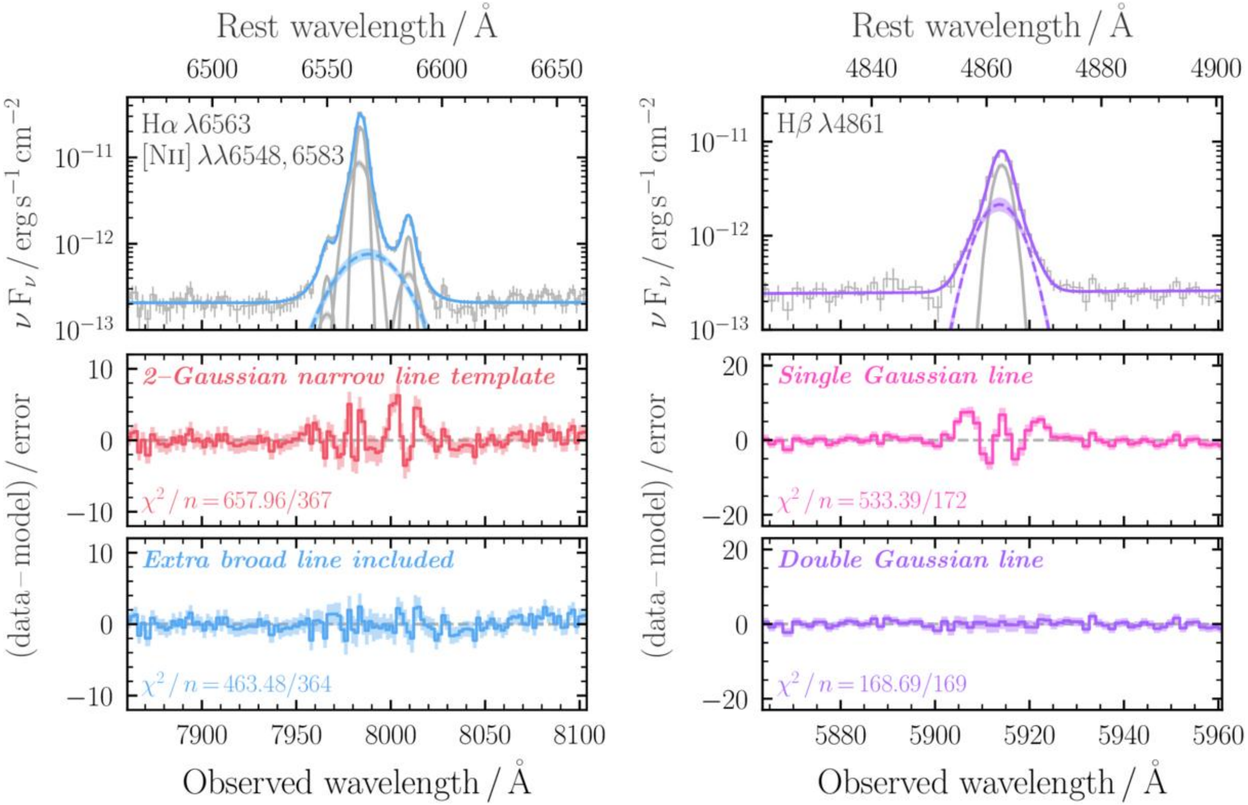
AGN hiding in a Green Pea galaxy?

Boorman+25



AGN hiding in a Green Pea galaxy?

Boorman+25



AGN hiding in a Green Pea galaxy?

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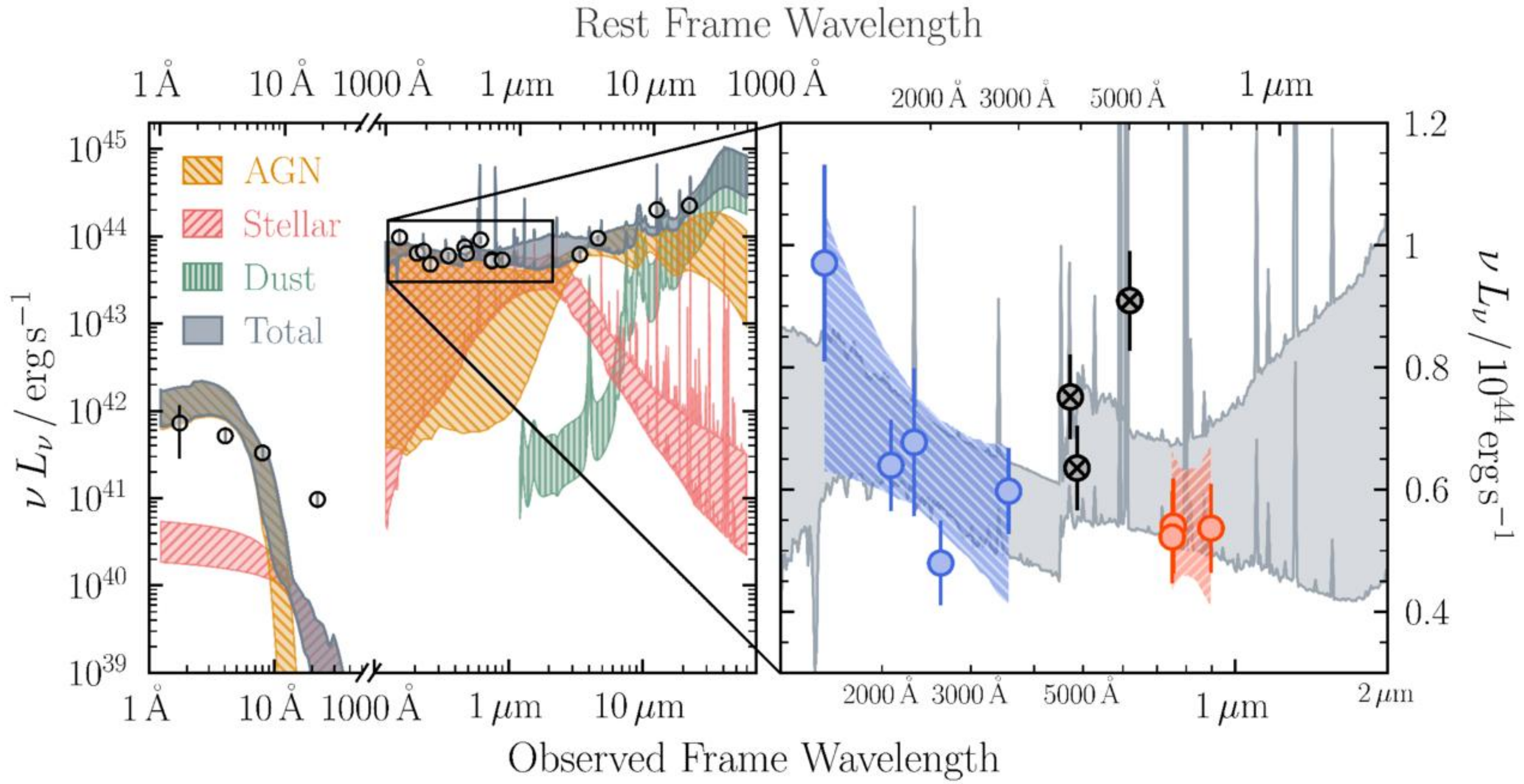

AGN hiding in a Green Pea galaxy?

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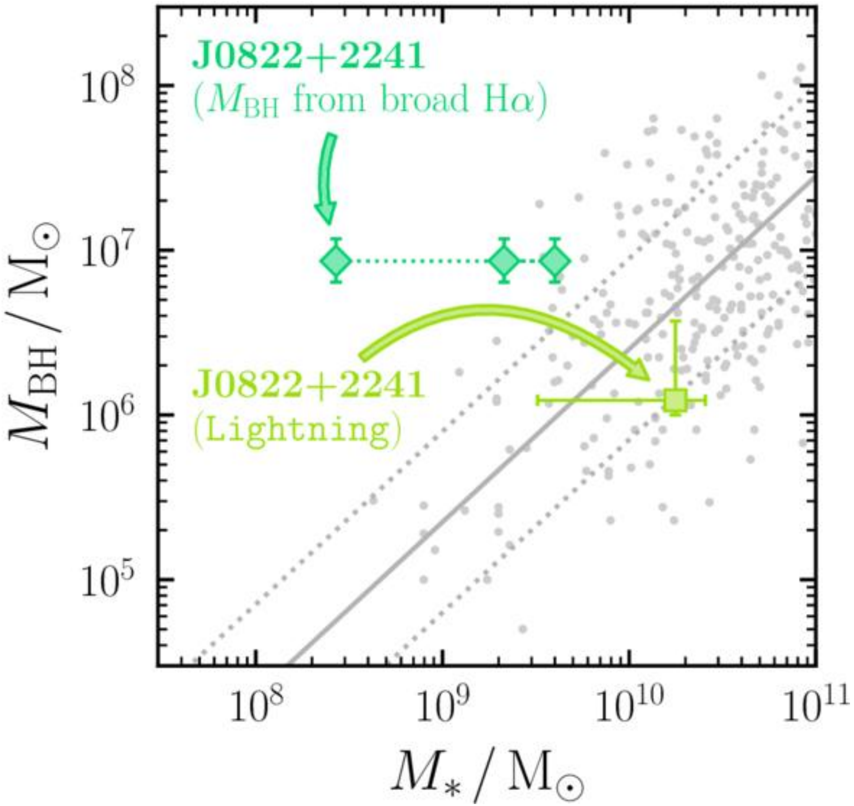

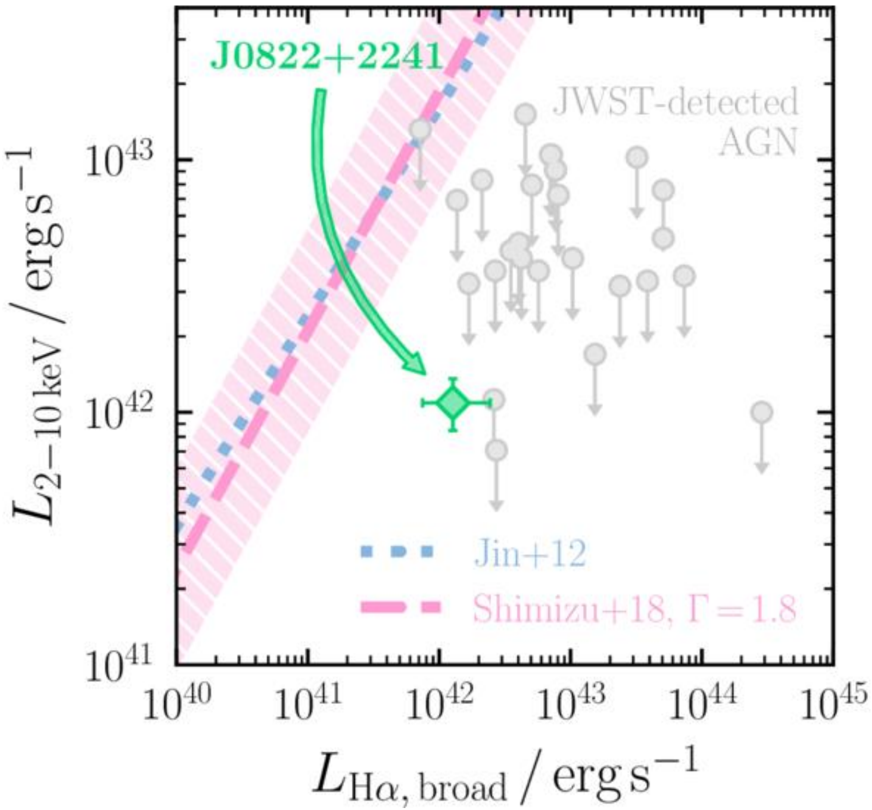

Conclusions

- Green Peas and Blueberries are local analogues of the first galaxies in the Early Universe.
- Classifying highly star-forming, low-mass, low-metallicity galaxies is complicated, and different classifying mechanisms give contradictory results.
- Majority of the GPs and BBs are significantly underluminous compared to the L-SFR relations.
- The L-SFR relations, established for "normal" galaxies, need updating for the dwarf galaxies at low-mass, low-SFR (but high sSFR) end.
- Detection of strong X-ray or radio emission in such galaxies can indicate presence of massive black hole activity.

Assignment

- Extract the sample of Green Pea galaxies from Cardamone et al., 2009 (both star forming and NLS1s) and classify them using the BPT diagram, and WISE colour-colour plot.
- In brief, describe the common AGN/star forming galaxy classification methods used here (BPT diagram and WISE colour-coluor plot) and their limitations when dealing with low-metallicity dwarf galaxies (or the high-z counterparts).