First Galaxies and their Local Analogues

Selected Chapters on Astrophysics
November 2025

Lecture 2: JWST Discovery of Early Galaxies

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ALMA Regional Centre || Czech

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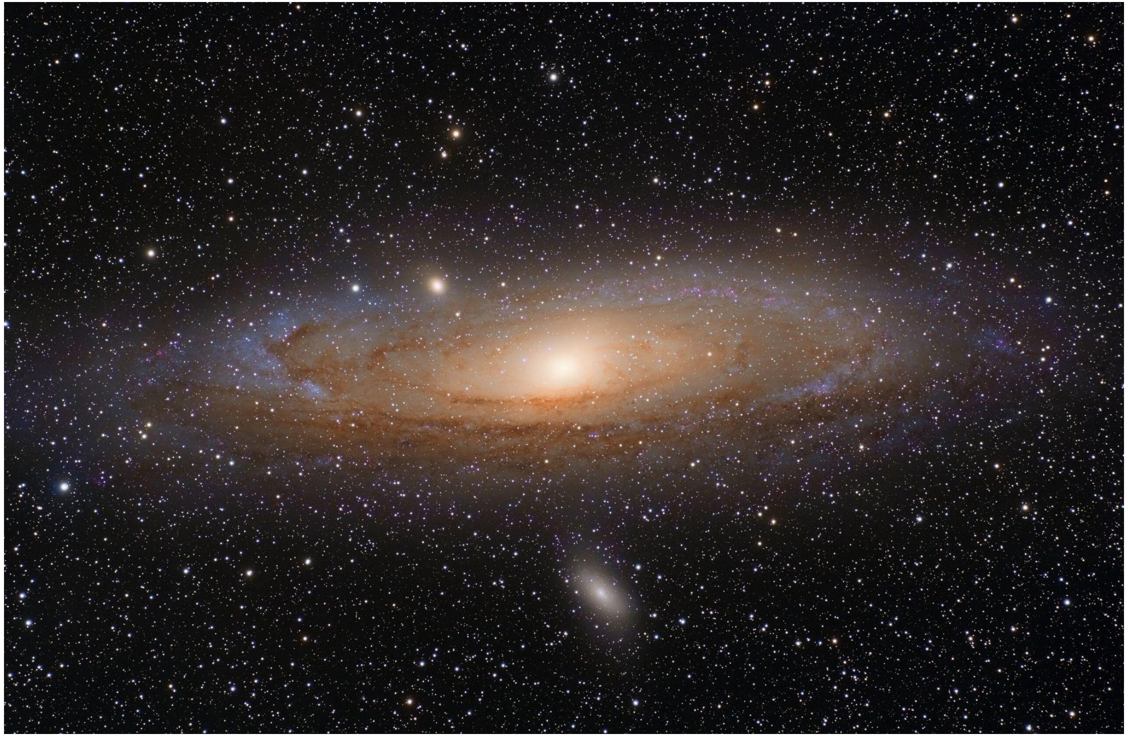
From Hubble to *Hubble*

Chasing the Redshift Frontier

From Hubble to *Hubble*

Discovery that Milky Way is not the whole Universe.

- Heber Curtis measured the distance to be 500,000 ly (1917).
- Edwin Hubble observations of Cepheid variables confirmed that Andromeda is not in the Milky Way.
- Subsequent discovery of numerous galaxies in the local Universe.



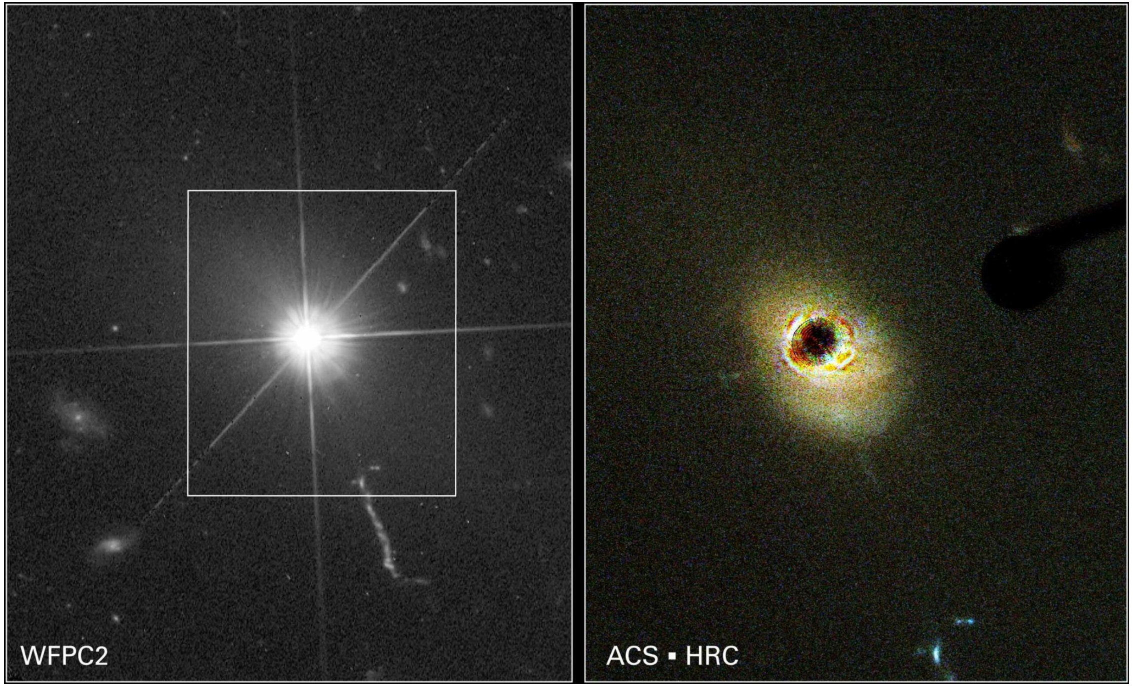
Brody Wesner https://commons.wikimedia.org/w/index.php?curid=175843981

From Hubble to *Hubble*

Era of quasars

Schmidt detection of quasars in 1960s:

- Several quasars discovered around z~0.5.
- Discovery of 3C9 at z=2.012 leapfrogged the z=1 and z=2 barrier and a look through the Cosmic Noon (also what was considered to be the smallest possible age of the Universe (10 Gyr).
- Further incremental discoveries in the 60s to sub-z~3.



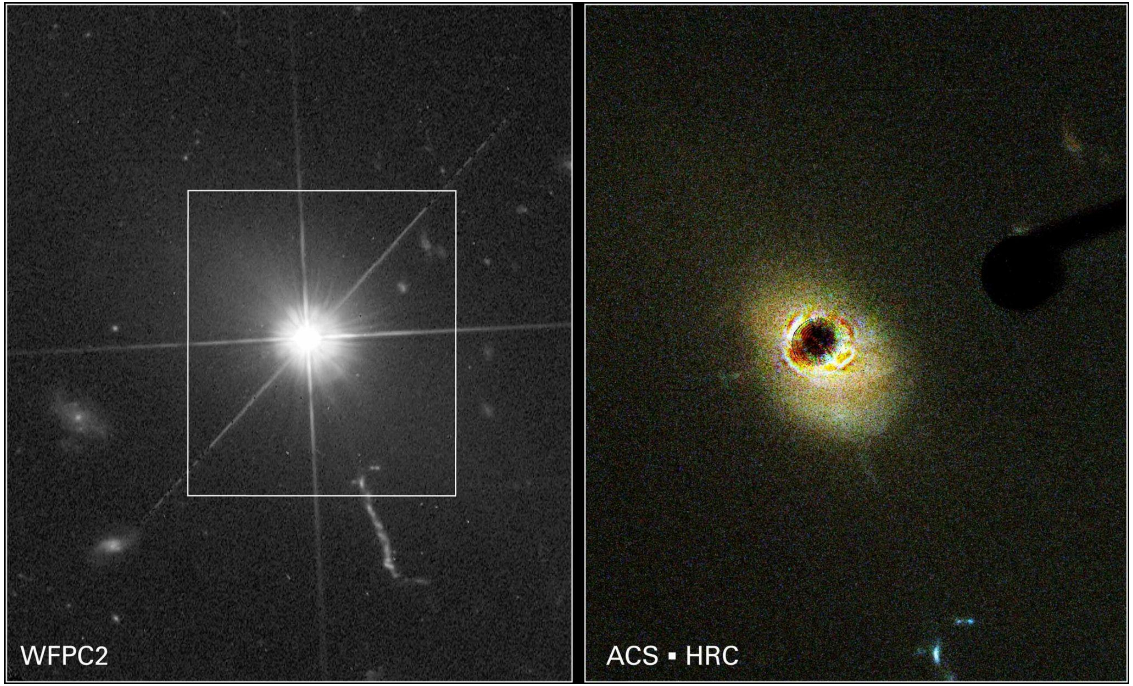
NASA and J. Bahcall (IAS)Credit for ACS image: NASA, A. Martel (JHU), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA http://hubblesite.org/newscenter/archive/releases/2003/03/image/b/

From Hubble to *Hubble*

Era of quasars

Pushing the boundaries in the 70s & 80s:

- Better telescopes and upgraded facilities led to discovery of quasars at z~3 and z~4.
- Most of the high-z sources detected until late 1990s were quasars.
- Hints of galaxy formation at z>5 from z~1.5 galaxies with the stellar age >3.5 Gyr.



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From Hubble to *Hubble*

The High-z revolution of the 90s and 00s

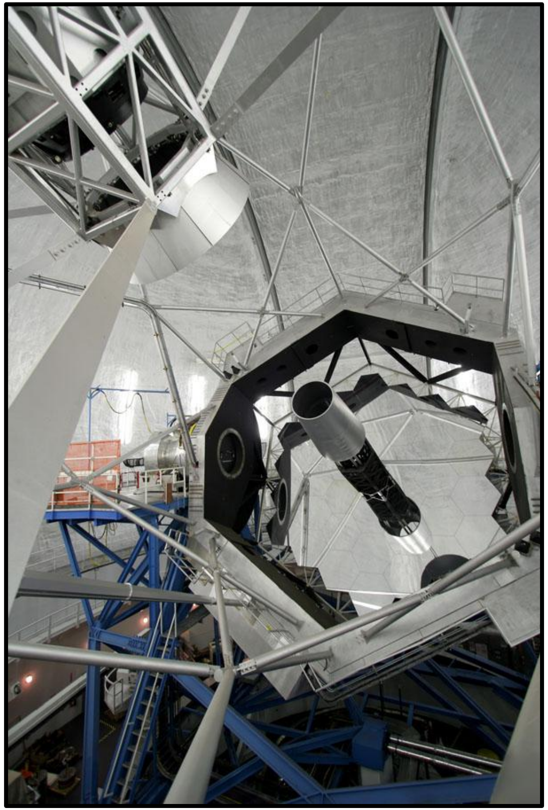
- Launch of *Hubble Space Telescope*
- 10-m class ground-based observatories (e.g. Keck, VLT).
- Large-scale surveys such as Sloan Digital Sky Survey
- Improved sensitivity with new tech: CCDs and multi-object spectroscopy, integral field unit spectroscopy (IFU), active and adaptive optics.

NASA, A. Martel (JHU), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

From Hubble to *Hubble*

The High-z revolution of the 90s and 00s

- 1998 - Discovery of multiple z>5 galaxies using Keck telescope and the dropout method for identifying high-z galaxies.
- *Hubble* Deep Field (HDF) and Subaru Deep Field images photometric identification of z>5 and z>6 galaxies.
- SDSS all-sky survey detected z>6 quasars.

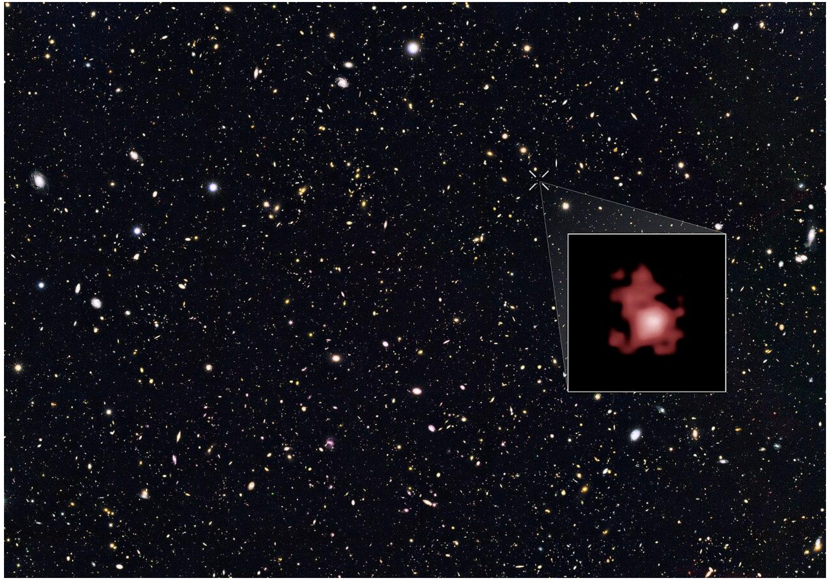


Keck telescope mirror By SiOwl https://commons.wikimedia.org/w/index.php?curid=7589650

From Hubble to *Hubble*

Pre-JWST records

- GRB detected at z~8.2 with *Swift* and VLT.
- Upgrades to *Hubble* (e.g. WFC3 instrument optimized for NIR) found galaxies beyond z~9.
- 2016: GN-z11, furthest galaxy known pre-JWST at z~11.09 (corrected to 10.9 by Keck and 10.6 by JWST)



GN-z11 observed in the GOODS field by Hubble, confirmed by multiple groundbases telescopes. By NASA, ESA, P. Oesch (Yale University), G. Brammer (STScI), P. van Dokkum (Yale University), and G. Illingworth (UC, Santa Cruz) -

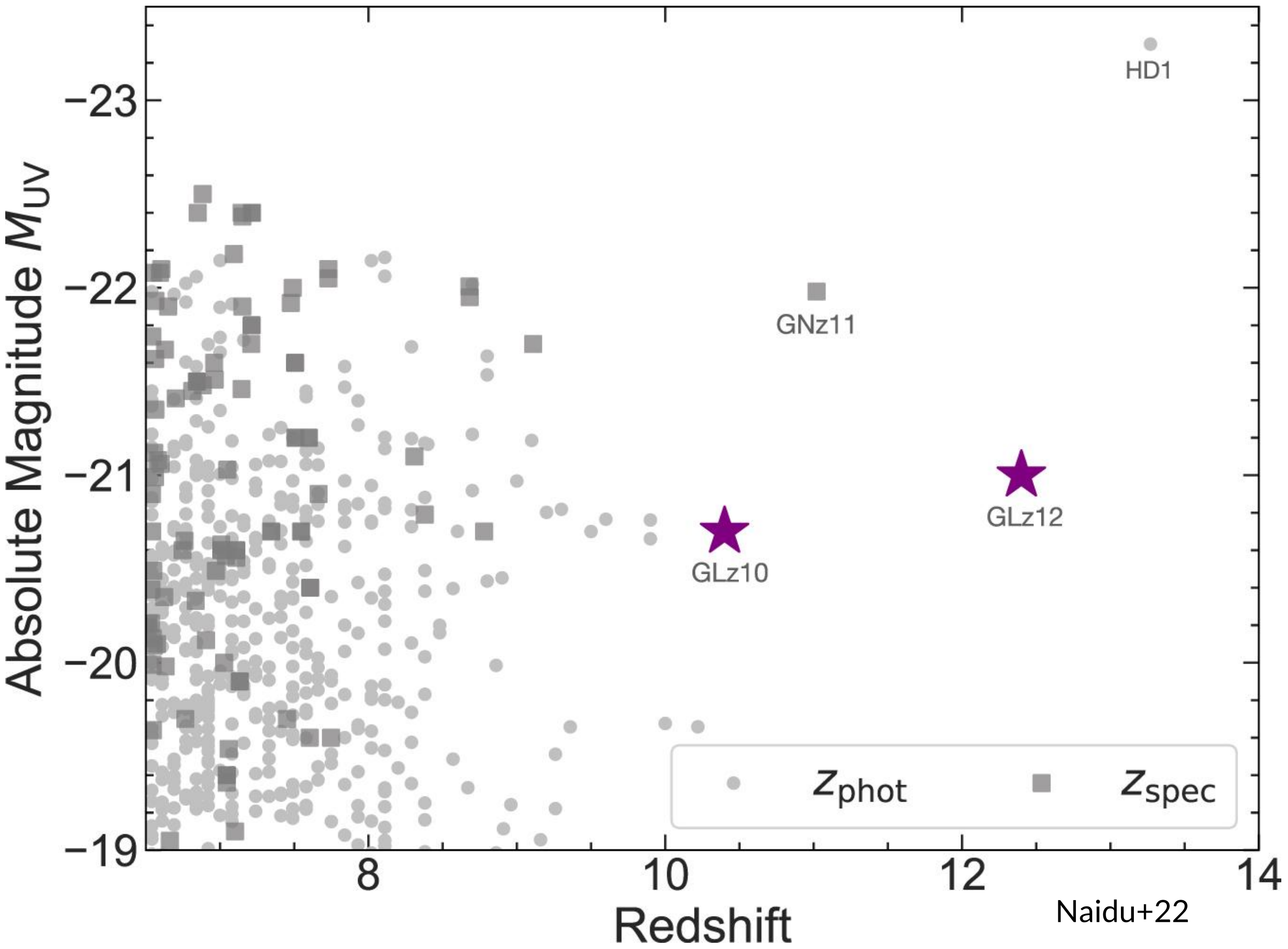
The JWST Era

The JWST Era

Galaxy cluster SMACS 0723: one of the first images from JWST.

Several candidate galaxies at z=11-20 (photometric redshifts; Yan+23)

The JWST Era

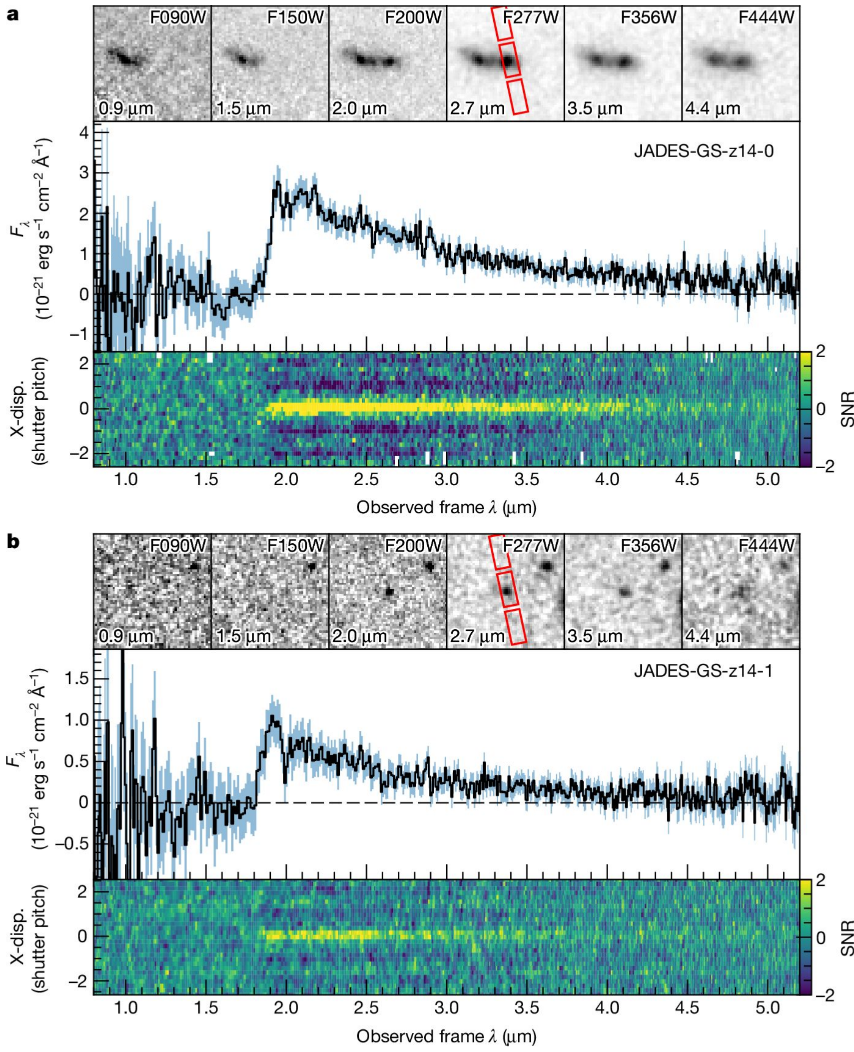


Naidu+22

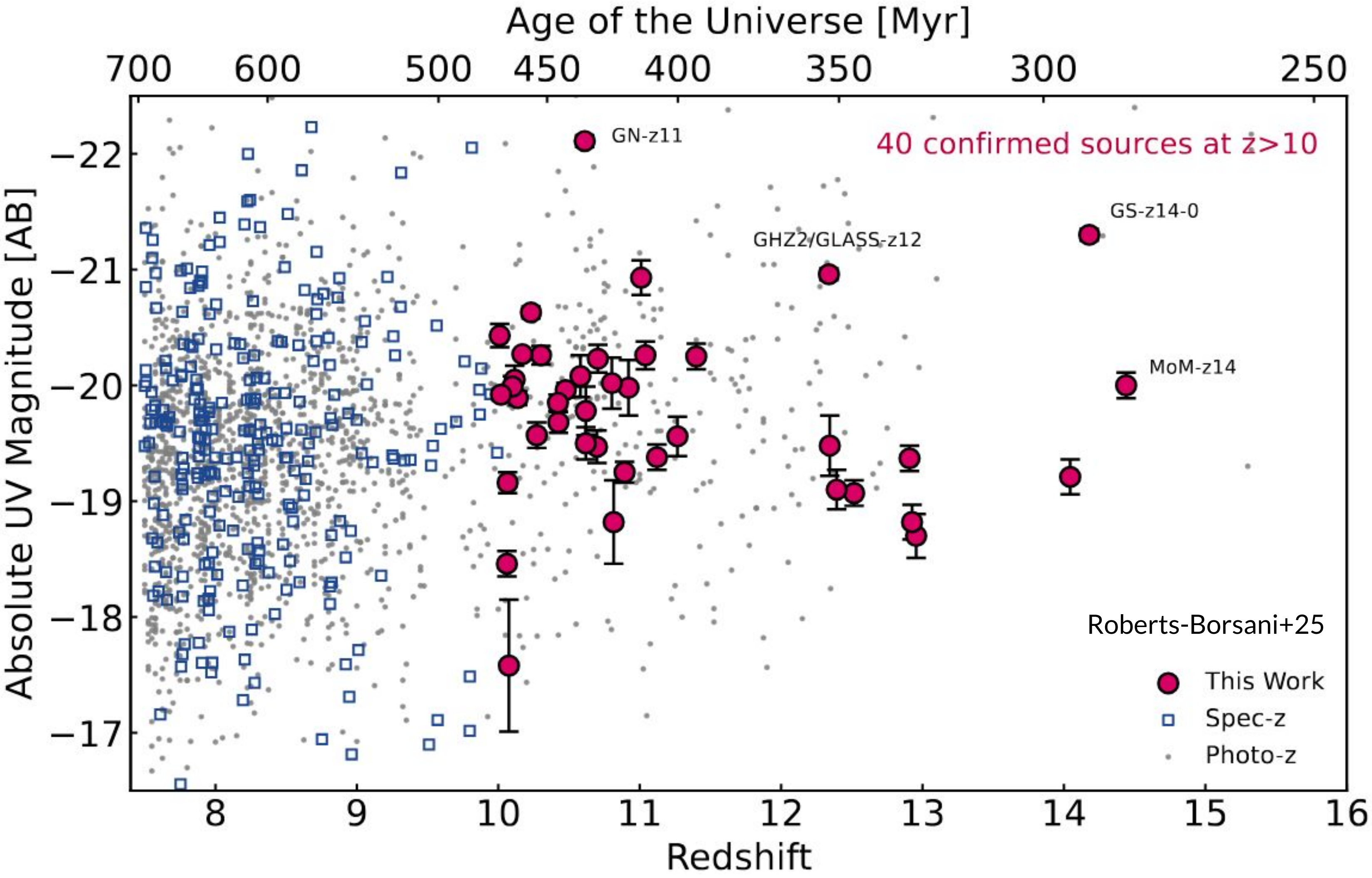
The JWST Era

Current record holder

- Carniani+2024 detected two galaxies at z=13.9 and 14.32, merely 290 Myr after the Big Bang.
- Naidu+2025 detected a galaxy at z=14.44 (not peer-reviewed yet).



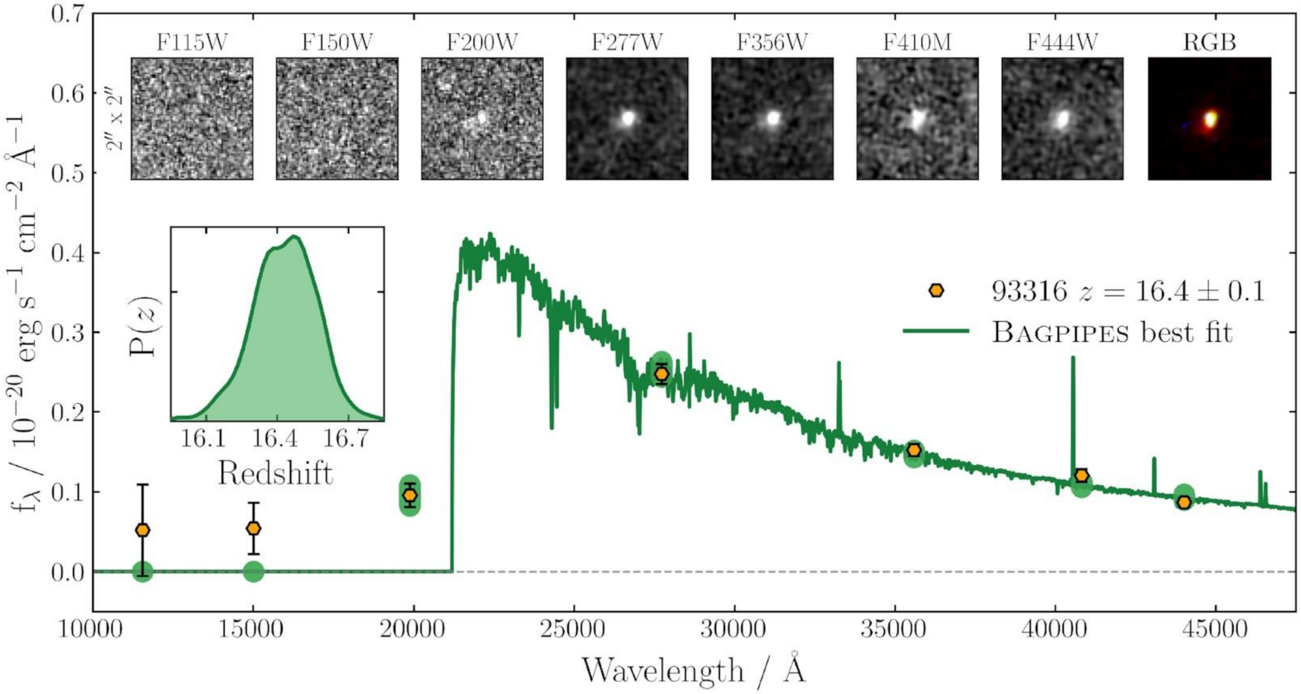
NIRSPEC spectra of two z~14 galaxies Carniani+24



Age of the Universe [Myr]
700
600
500
450
400
350
300
250
40 confirmed sources at z>10
GN-z11
GS-z14-0
GHZ2/GLASS-z12
MoM-z14
Roberts-Borsani+25
This Work
Spec-z
Photo-z
Absolute UV Magnitude [AB]
−22
−21
−20
−19
−18
−17
8
9
10
11
12
13
14
15
16
Redshift

The JWST Era

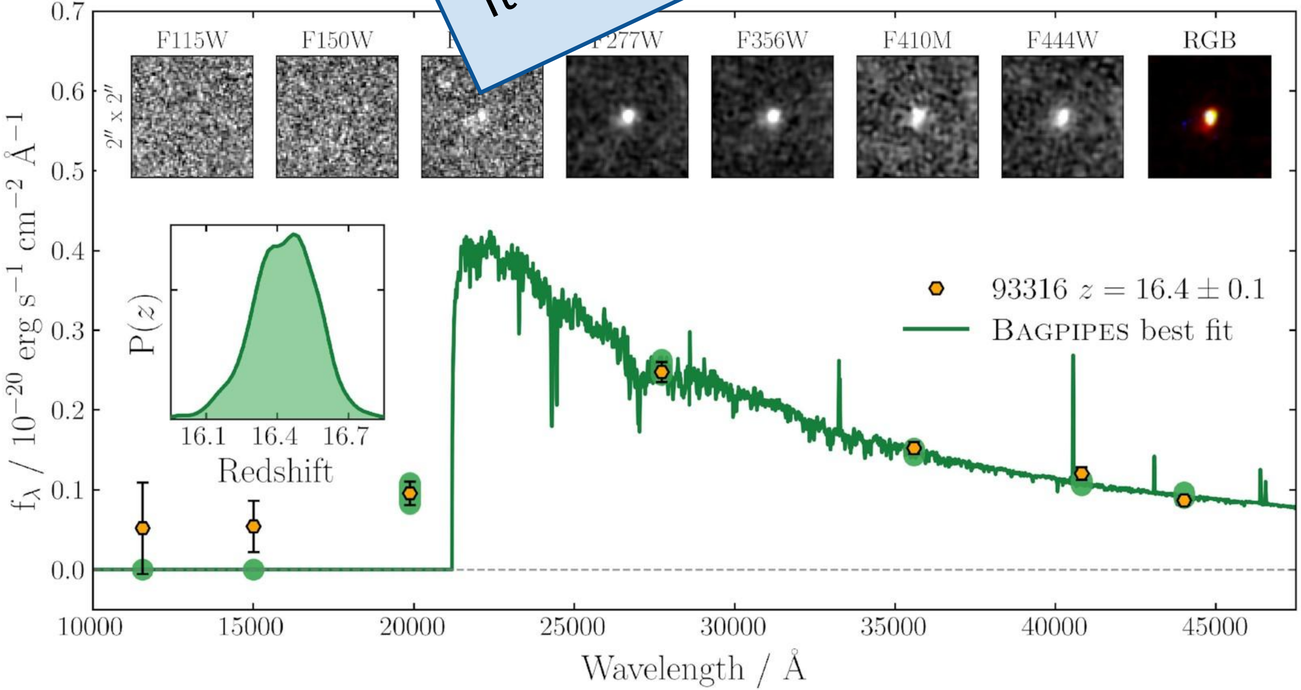
Amazing z=16.4 galaxy??



Donnan+23

The JWST Era

Unfortunately not!
It's a low-z interloper!!



Donnan+23

Low-z Interlopers pretending to be high-z galaxies

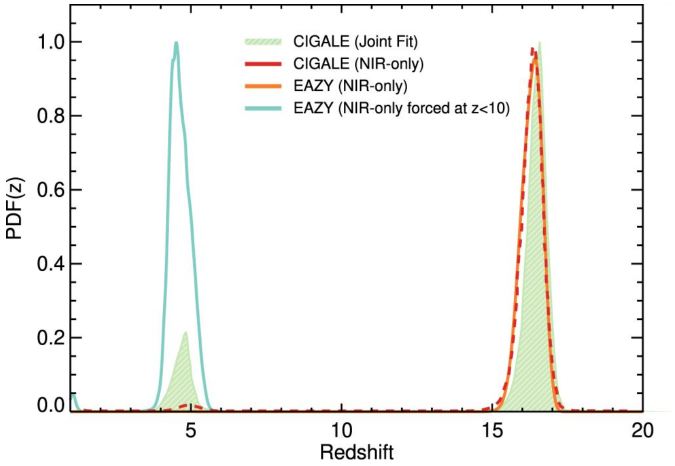
A galaxy at a much lower redshift, like z~5, can mimic Lyman alpha break signature:

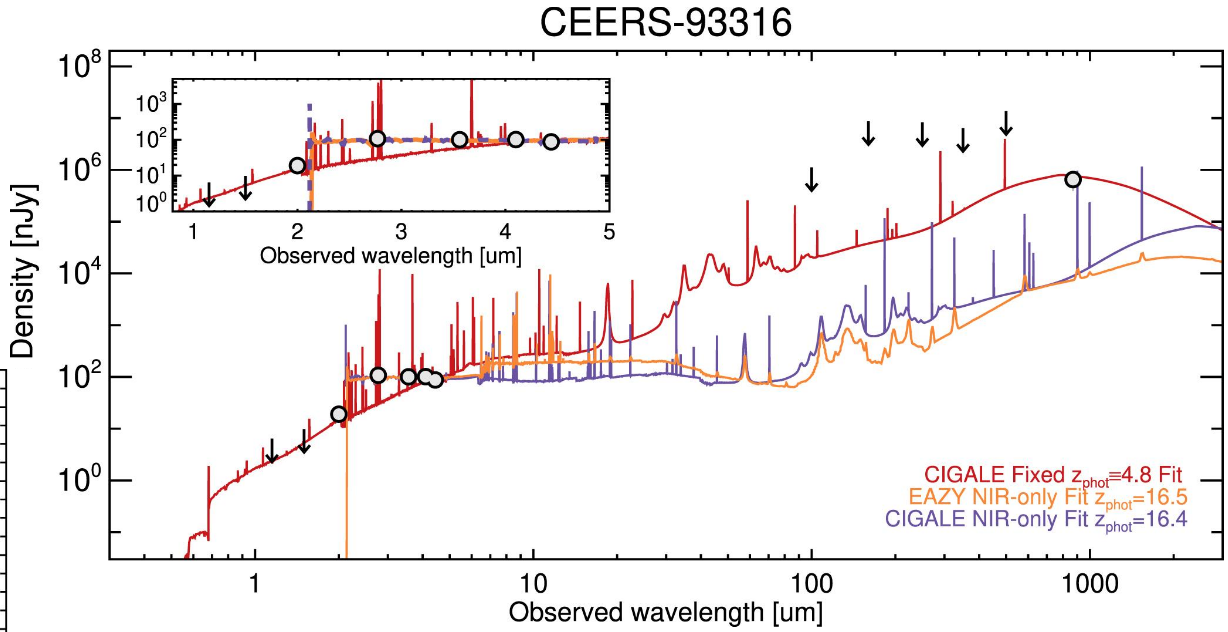
- **A strong Balmer Break or 4000A˚ Break:** caused by the buildup of older, redder stars, can be shifted into the same infrared filters as the z>10 Lyα break.

- **Dust Reddening:** Dust absorbs and scatters blue light more effectively than red light, making the galaxy appear much redder than it truly is. This can mimic the flux drop seen in a very high-redshift object.

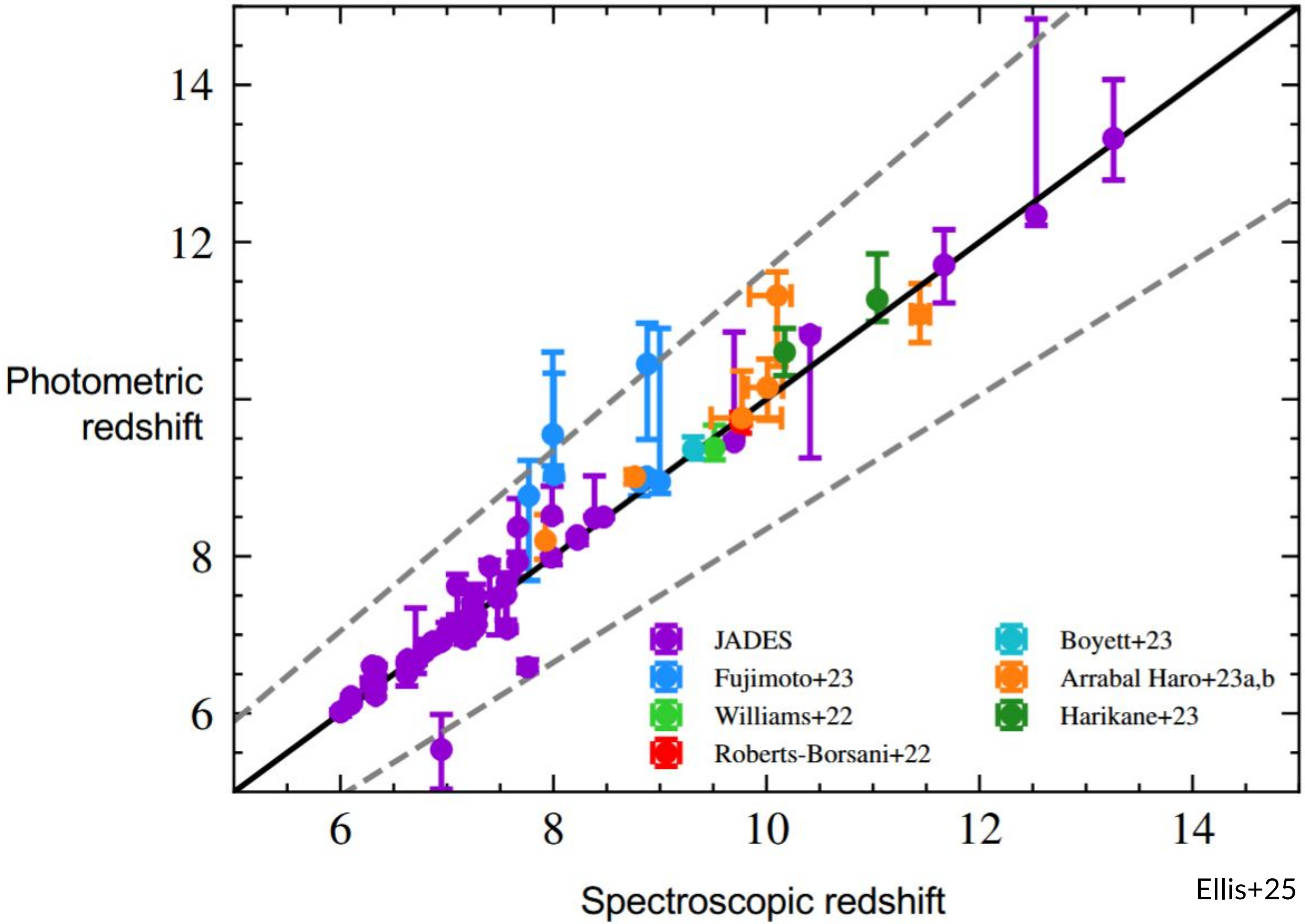
- **Strong Emission Lines (e.g., [OIII] and Hβ):** Extremely strong emission lines in the rest-frame optical (which are shifted to the near-infrared at z~5) can dominate the flux in one or two bands, leading to a misleadingly "steep" SED that favours an ultra-high-redshift solution when fitting with photometric templates.

Low-z Interlopers pretending to be high-z galaxies





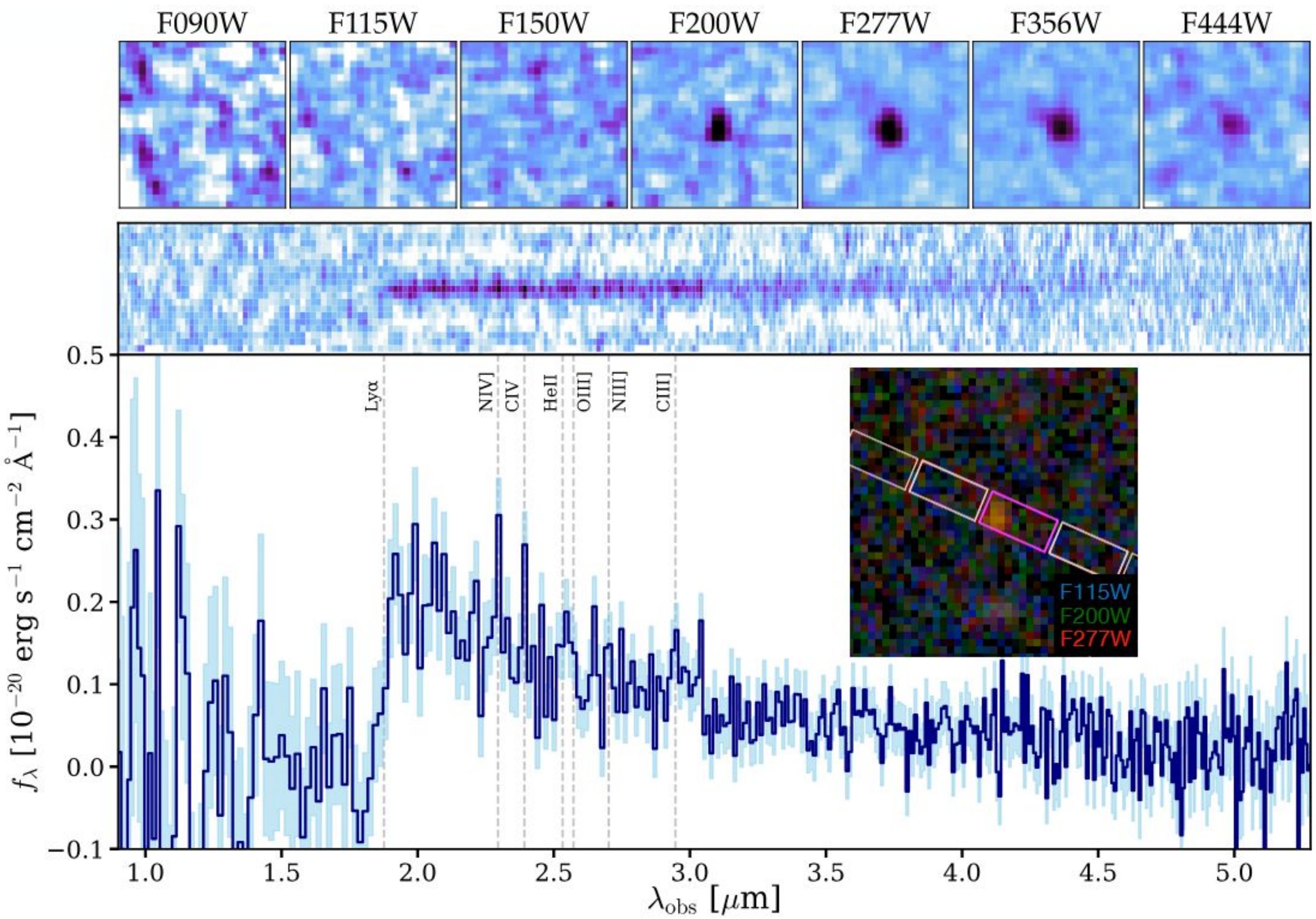
Zavala+23


Photometric redshift
Spectroscopic redshift
6
8
10
12
14
JADES
Fujimoto+23
Williams+22
Roberts-Borsani+22
Boyett+23
Arrabal Haro+23a,b
Harikane+23

Ellis+25

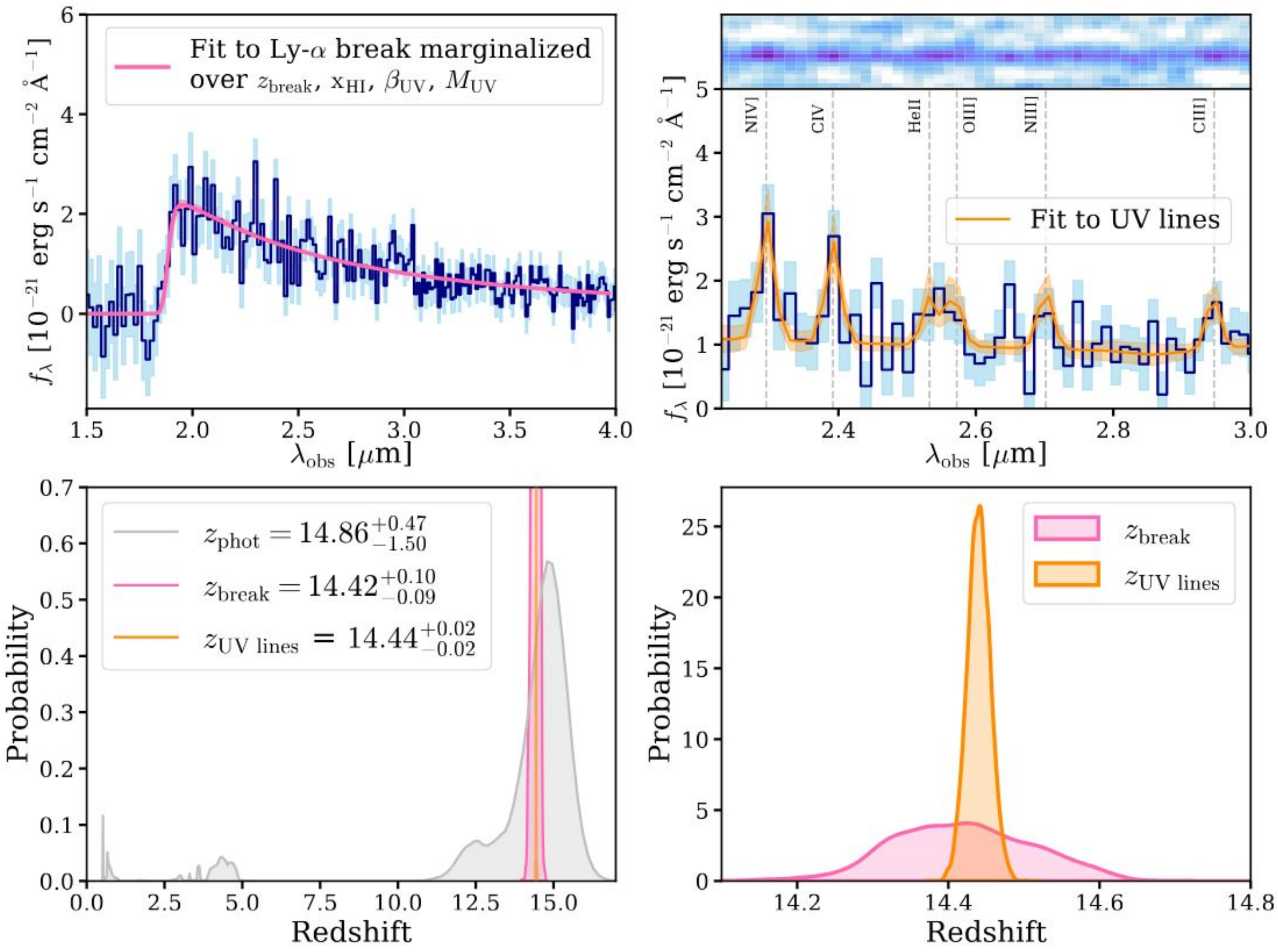
What do z>10 galaxies look like?

MoM-z14



Naidu+25

MoM-z14



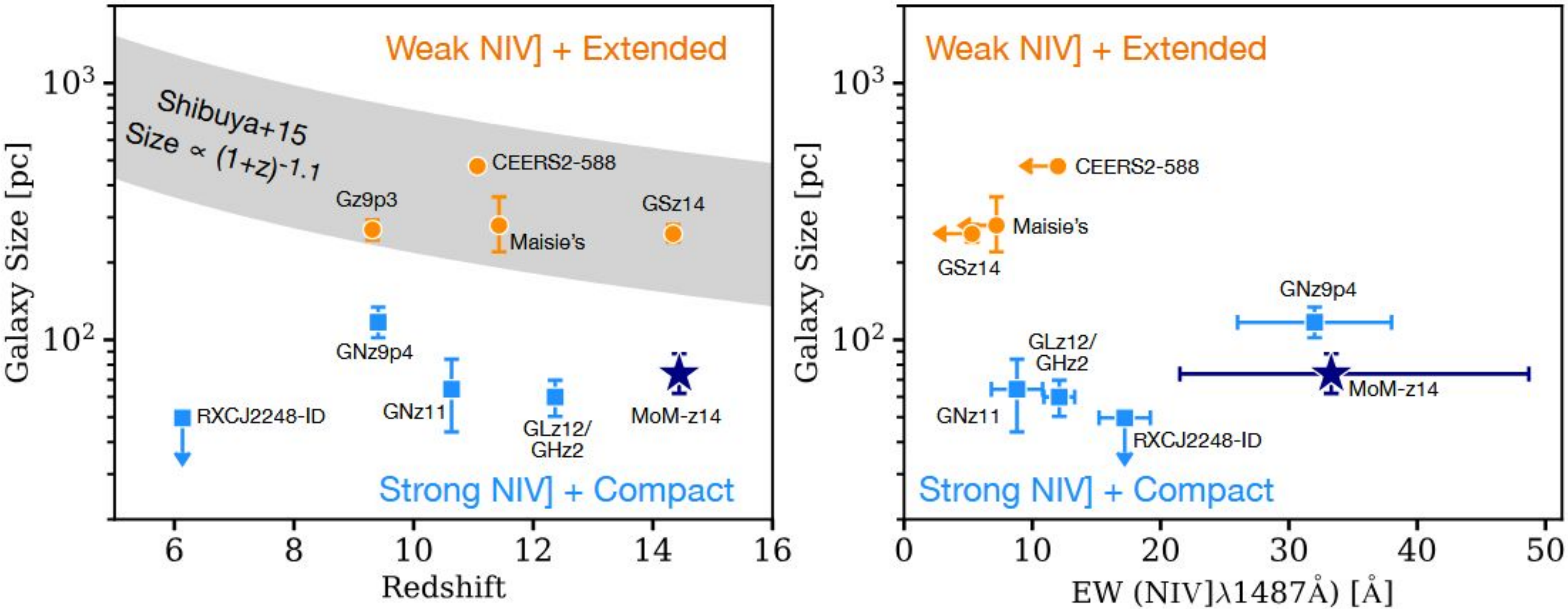
Naidu+25

MoM-z14

Empirical Properties	
R.A. [deg]	150.0933255
Dec. [deg]	2.2731627
Redshift (UV lines)	$14.44^{+0.02}_{-0.02}$
Redshift (Lyα break)	$14.42^{+0.10}_{-0.09}$
UV Luminosity ($M_{\rm UV}$)	$-20.23^{+0.06}_{-0.06}$
UV slope ($\beta_{\rm UV}$; $f_\lambda \propto \lambda^\beta$)	$-2.47^{+0.17}_{-0.17}$
Galaxy size (circularized $r_{\rm e}$) [pc]	74^{+15}_{-12}
Galaxy size (semi-major axis a) [pc]	147^{+19}_{-20}
Prospector SED modeling	
Stellar Mass ($\log(M_*/{\rm M}_\odot)$)	$8.1^{+0.3}_{-0.2}$
Star-Formation Rate (5 Myr)[${\rm M}_\odot$ yr^{-1}]	$13.0^{+3.7}_{-3.5}$
Star-Formation Rate (50 Myr) [${\rm M}_\odot$ yr^{-1}]	$2.2^{+1.5}_{-0.6}$
Dust Attenuation ($A_{5500\text{Å}}$)	$0.2^{+0.2}_{-0.1}$
Age (t_{50}/Myr)	$4.0^{+10.0}_{-1.4}$
Star-Formation Surface Density [$M_\odot$ yr^{-1} kpc^{-2}]	233^{+107}_{-107}
Stellar Surface Density ($\log(\Sigma_*/M_\odot$ kpc^{-2}))	$9.6^{+0.2}_{-0.7}$

Naidu+25

MoM-z14



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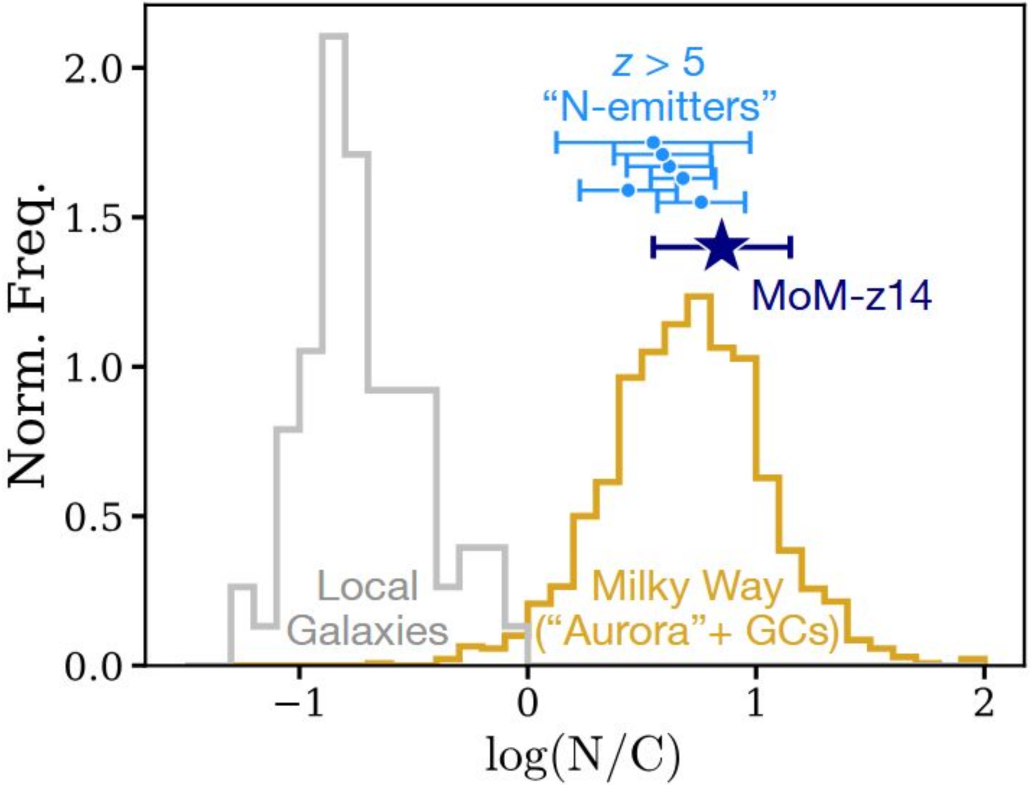
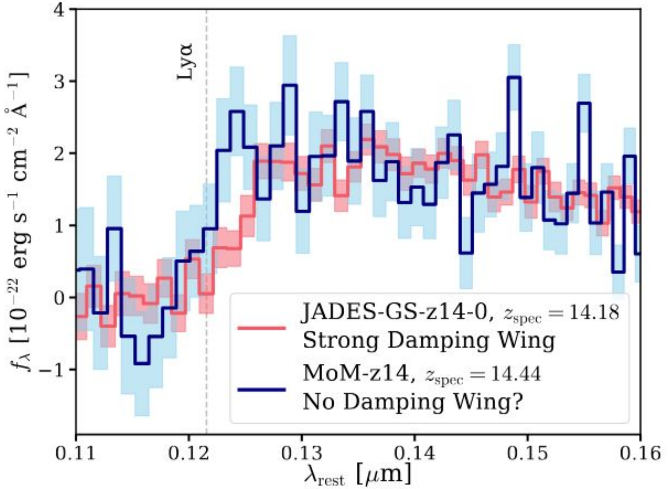
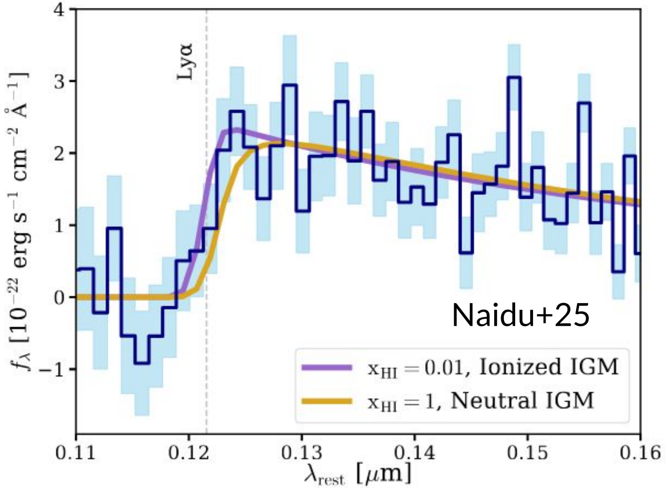
MoM-z14







Naidu+25

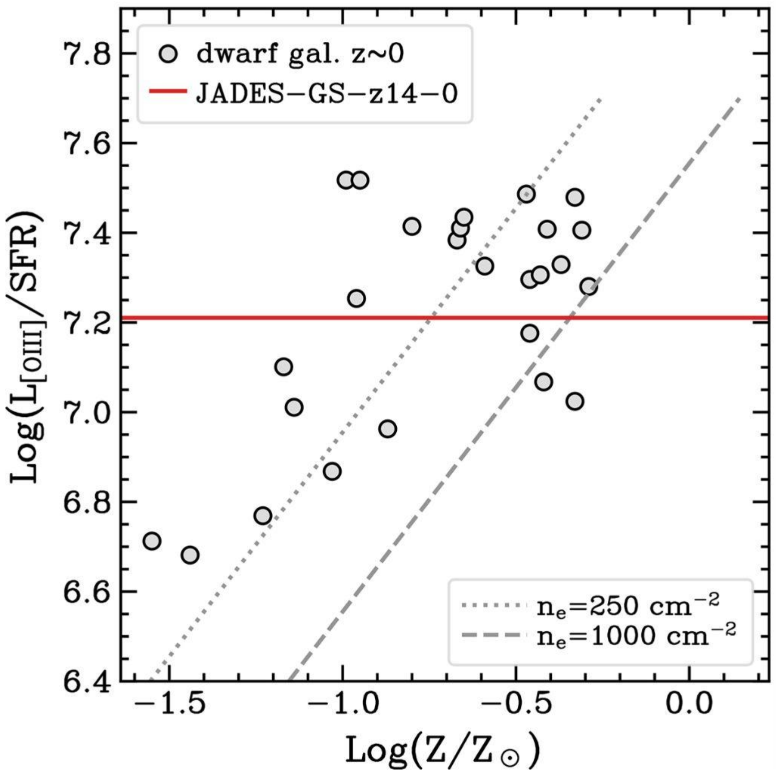
JADES-GS-z14-0

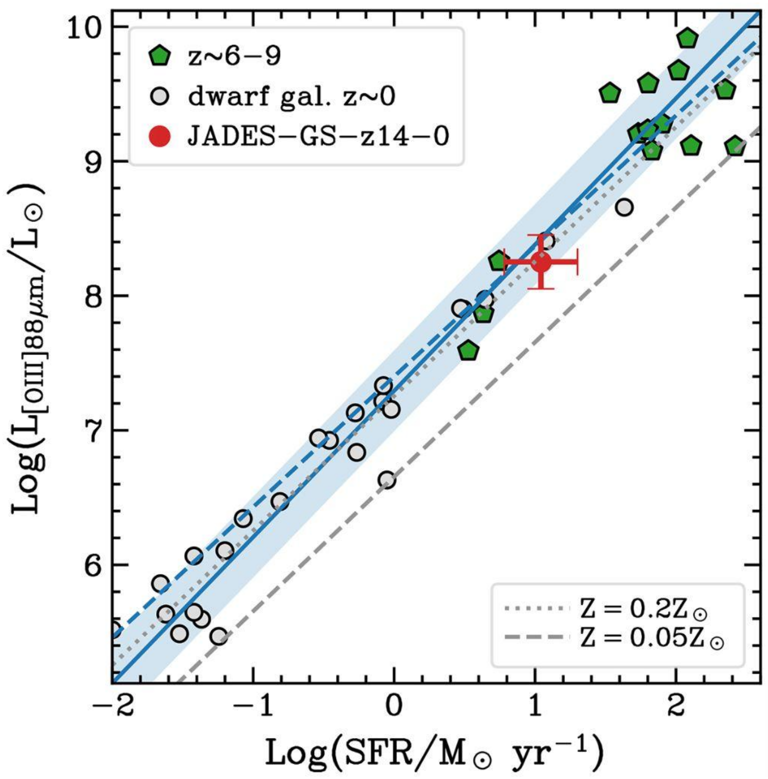
Carniani+25

	Parameter (1)	Free (2)	Description (3)	Prior (4)	Posterior (5)
Star-forming component	$z_{\rm obs}$	Y	Redshift	$\mathcal{N}(z_{\rm spec}, 0.001)$	$14.178^{+0.001}_{-0.001}$
	$\log M_\star[{\rm M_\odot}\,\mu^{-1}]$ (†)	Y	Total stellar mass formed	$\mathcal{U}(6, 10)$	$8.29^{+0.14}_{-0.09}$ $(^{+0.4}_{-0.1})$
	$\log Z[{\rm Z_\odot}]$	Y	Stellar and gas metallicity	$\mathcal{U}(-2, 0)$	$-0.78^{+0.03}_{-0.03}$ (± 0.03)
	$\log$ SFR ratios	Y	Ratio of the log SFR of non-parametric SFH	$\mathcal{T}(R(z)$ (‡)$, 1, 2)$	–
	$\sigma_\star$ [km s^{-1}]	Y	Stellar intrinsic velocity dispersion	$\mathcal{U}(0, 300)$	190^{+70}_{-70}
	n	Y	Power-law modifier of the dust curve (T22, Eq. (5))	$\mathcal{G}(0, 0.1; -1.0, 0.2)$	$0.06^{+0.05}_{-0.04}$
	τ_V	Y	Optical depth of the diffuse dust (T22, Eq. (5))	$\mathcal{U}(0, 2)$	$0.19^{+0.07}_{-0.05}$
	$\mu_{\rm d}$	Y	Ratio of optical depths of the birth clouds and τ_V	$\mathcal{G}(1, 0.1; 0, 2)$	$0.94^{+0.06}_{-0.07}$
	$\sigma_{\rm gas}$ [km s^{-1}]	Y	Intrinsic velocity dispersion of the star-forming gas	$\mathcal{U}(0, 1500)$	$1,310^{+90}_{-100}$
	$\log U$	Y	Ionization parameter of the star-forming gas	$\mathcal{U}(-4, -1)$	$-2.47^{+0.24}_{-0.18}$
	$f_{\rm esc}$	Y	Birth-cloud escape fraction of ionizing radiation	$\mathcal{U}(0, 1)$	$0.11^{+0.09}_{-0.07}$
	$\log N_{\rm H\,I}$	Y	Column density of neutral hydrogen	$\mathcal{U}(17, 25)$	$21.96^{+0.08}_{-0.09}$ (± 0.1)
Other	$j_{\rm spec}$	Y	Multiplicative noise inflation term for spectrum	$\mathcal{U}(0.5, 2)$	$1.5^{+0.3}_{-0.4}$
	$\log {\rm SFR}_{10}[{\rm M_\odot\,yr^{-1}}\,\mu^{-1}]$ (†)	N	SFR averaged over the last 10 Myr	–	$1.16^{+0.05}_{-0.07}$ (± 0.05)
	$\log {\rm SFR}_{100}[{\rm M_\odot\,yr^{-1}}\,\mu^{-1}]$ (†)	N	SFR averaged over the last 100 Myr	–	$0.29^{+0.14}_{-0.09}$ (± 0.1)
	$A_{\rm v}$[mag]	N	Optical dust attenuation	–	$0.19^{+0.07}_{-0.05}$ (± 0.05)
	$F_{\rm [O\,III]}[10^{-19}$ erg s^{-1} cm$^{-2}]$	N	FIR [O III]line flux	–	$2.77^{+0.79}_{-0.78}$ (± 0.05)
	Age [Myr]	N	Mass-weighted stellar age	–	40 ± 5

JADES-GS-z14-0

Carniani+25





Properties of z>10 galaxies

Stellar mass:

- Generally low mass, dwarf galaxies, between $7 < \log(M_*) < 9.5$ (although some estimates exceed $\log(M_*)\sim10$.

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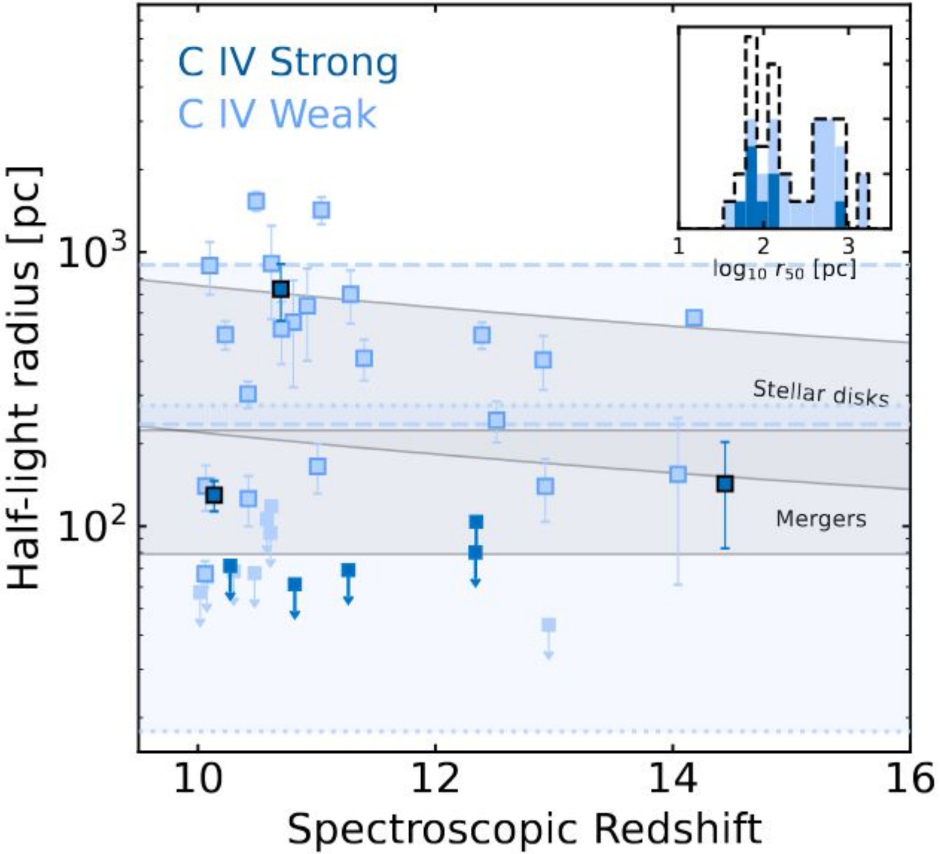
Galaxy Size:

- Two distinct populations: Some extended while others compact
- Half-light radius $<<1$ kpc, usually 100-500 pc.

Properties of z>10 galaxies

Roberts-Borsani+25



Physical Size of the galaxies

Properties of z>10 galaxies

Stellar mass:

- Generally low mass, dwarf galaxies, between $7 < \log(M_*) < 9.5$ (although some estimates exceed $\log(M_*) \sim 10$.

Galaxy Size:

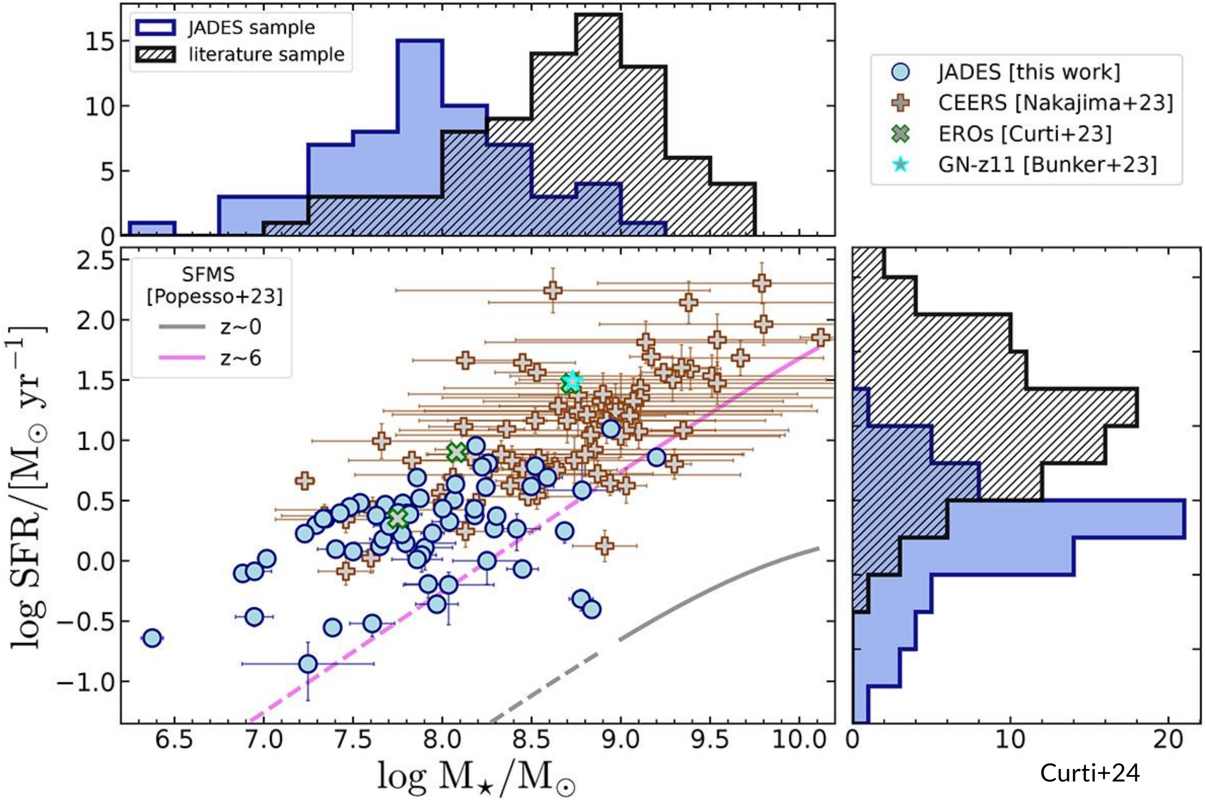
- Two distinct populations: Some extended while others compact
- Half-light radius <<1 kpc, usually 100-500 pc.

Star Formation Rate:

- Typically SFR ~ 1-10 M_{sun}/yr, with some objects reaching >50 M_{sun}/yr.
- Exceptionally high specific SFR (sSFR).

Properties of z>10 galaxies

SFR vs Stellar mass for z>6 galaxies



Curti+24

Properties of z>10 galaxies

Metallicities:

- Sub-solar metallicities: $Z/Z_{sun} < 0.1$, only found in low metallicity dwarf galaxies in the local Universe. Still higher than what's expected from the first or second generation of stars.

Properties of z>10 galaxies

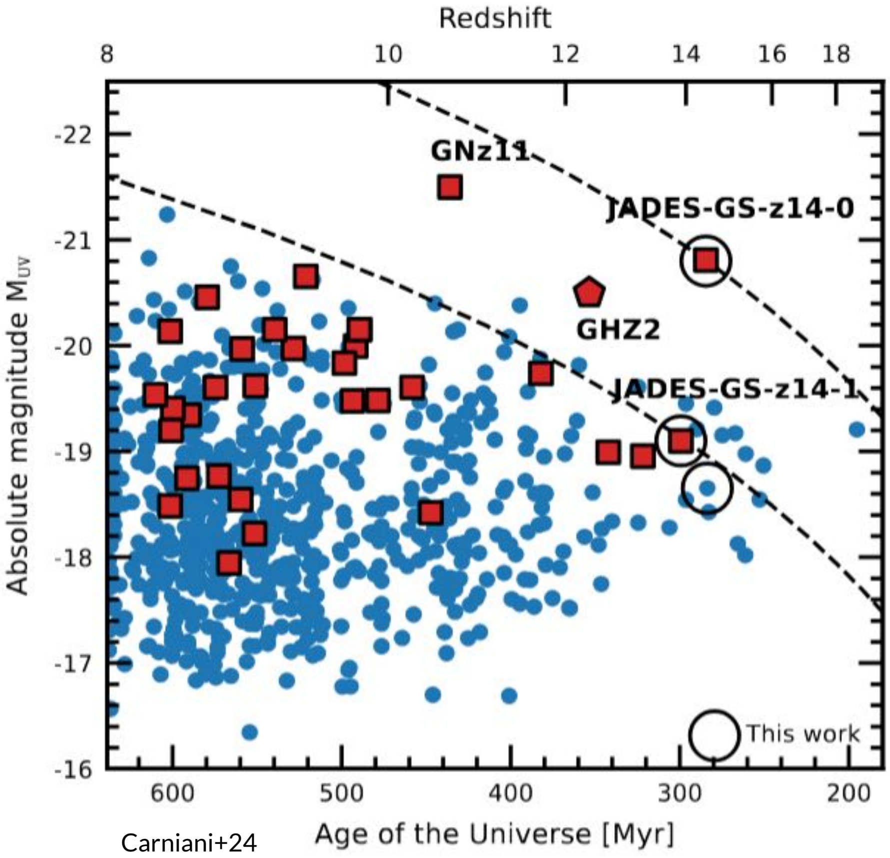
Roberts-Borsani+25

z_{spec}	M_{UV} [AB]	β	C III] EW [Å]	log U	Z [$Z_\odot$]	Age [Myr]	f_{burst} [< 3 Myr]
11.04±1.34	−19.56±0.57	−2.39±0.06	23±9	−0.08±0.08	0.09±0.03	16±5	0.69
10.61±1.18	−19.94±0.86	−2.15±0.02	11±2	−0.40±0.26	0.09±0.02	13±5	0.05
10.66±1.30	−20.03±1.00	−2.20±0.03	<2	−2.34±1.04	0.01±0.01	30±2	0.03
10.54±1.12	−20.02±0.77	−2.06±0.05	9±5	−2.22±1.15	0.02±0.01	56±4	0.01
10.49±1.04	−19.37±0.53	−2.19±0.08	28±22	−1.75±0.30	0.08±0.02	181±7	0.42
10.86±0.43	−20.00±0.37	−1.74±0.17	13±7	−1.38±0.17	0.16±0.04	222±18	0.29
10.49±1.34	−19.92±1.04	−2.18±0.02	7±3	−0.83±0.25	0.09±0.02	22±1	0.18
10.62±1.11	−19.78±0.54	−2.45±0.09	12±6	−2.62±0.40	0.05±0.02	11±5	0.05
10.46±1.15	−19.92±1.37	−2.21±0.21	6±5	−0.96±0.46	0.17±0.06	83±16	0.33
10.62±1.33	−19.44±0.47	−2.22±0.04	8±5	−2.67±0.66	0.01±0.01	31±5	0.12
10.86±1.07	−20.02±0.61	−2.06±0.06	10±4	−0.53±0.32	0.02±0.01	25±2	0.14

Big Results, Big Problems

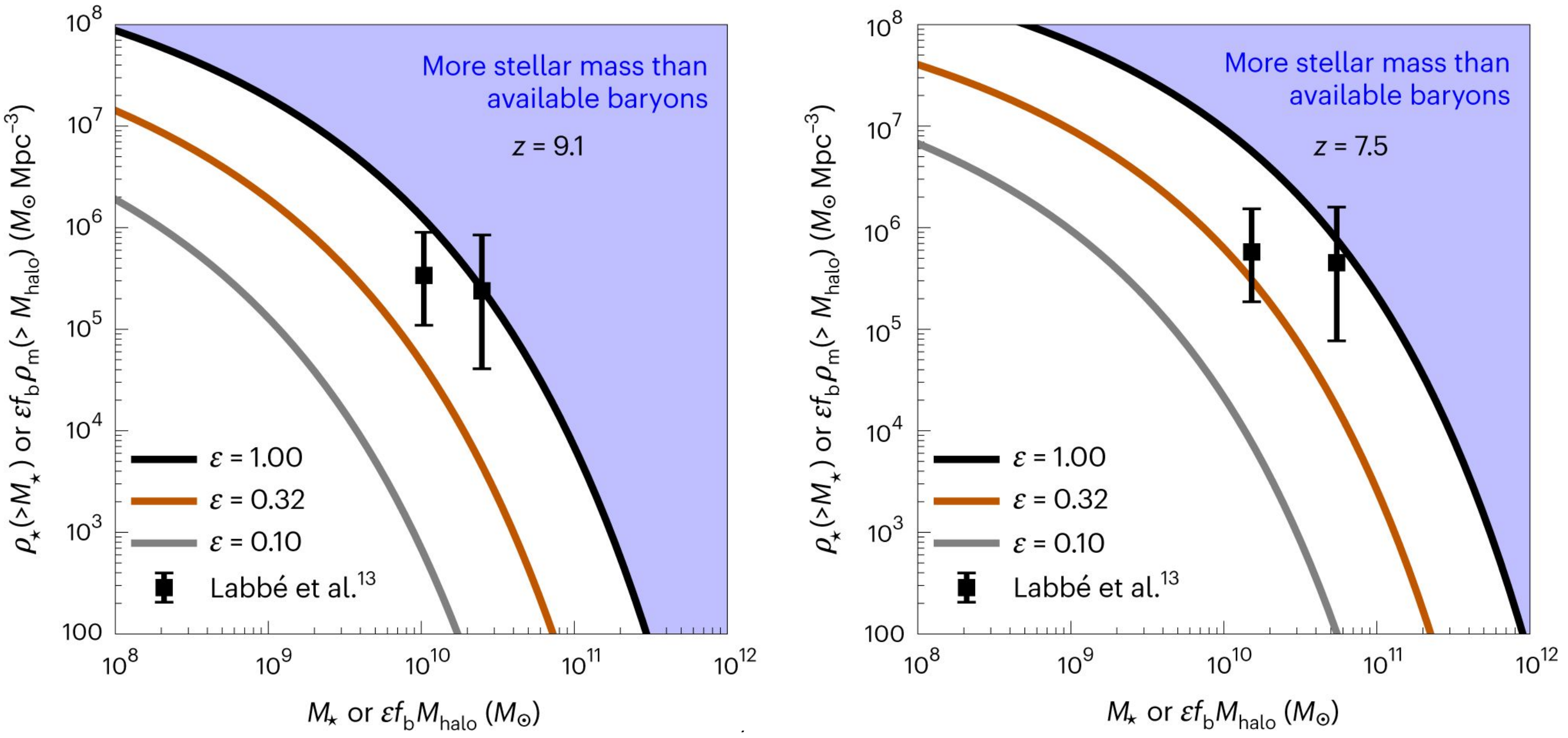
Big Results, Big Problems

Galaxies are too bright, too early.



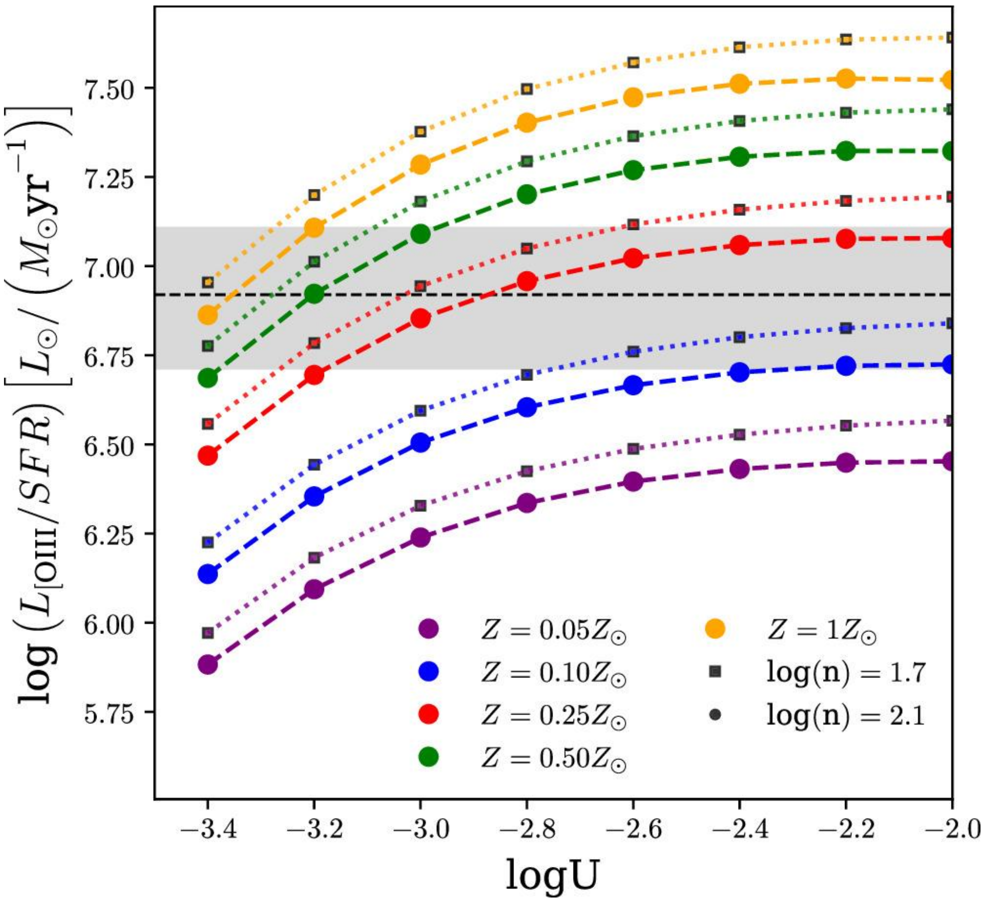
Carniani+24

Big Results, Big Problems



Schouws+25

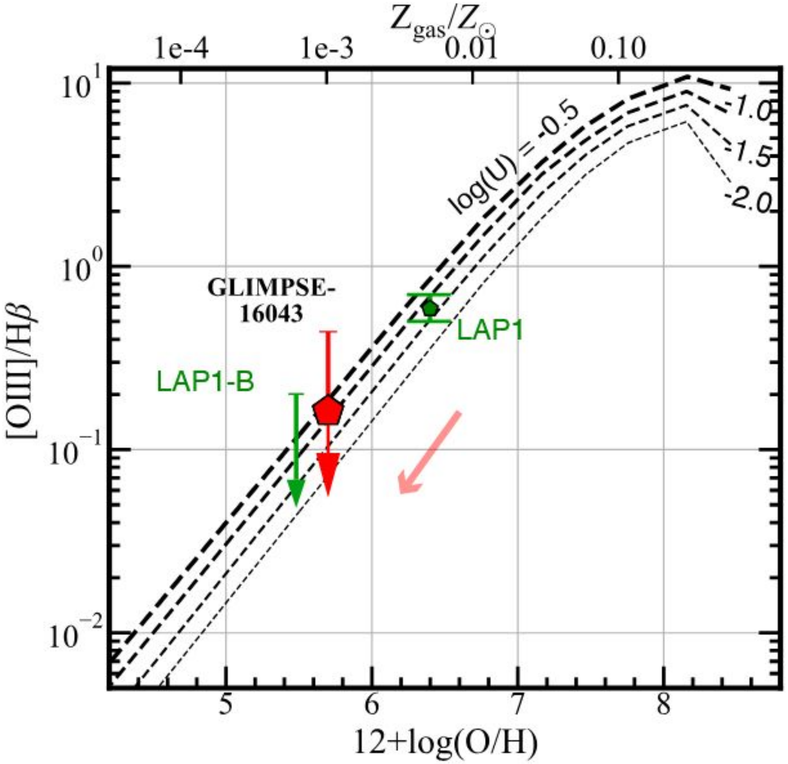
Big Results, Big Problems

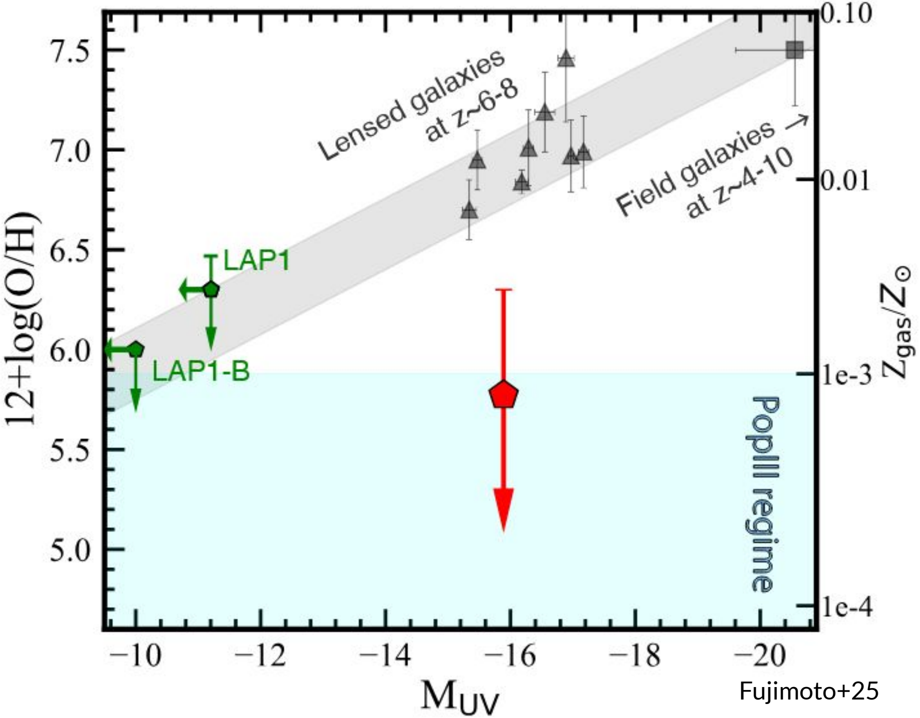


High metallicity way too early in the Universe.

Big Results, Big Problems

Extreme low-metallicity sources <1 Gyr after the Big Bang.

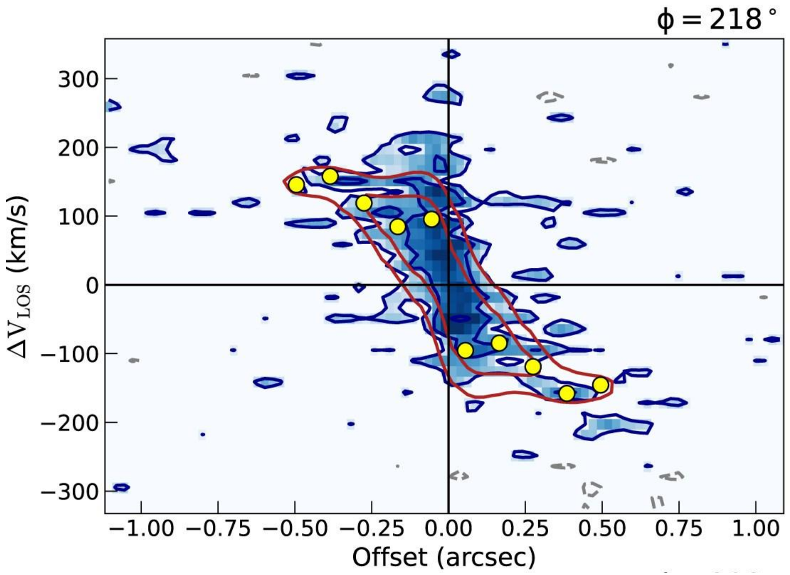


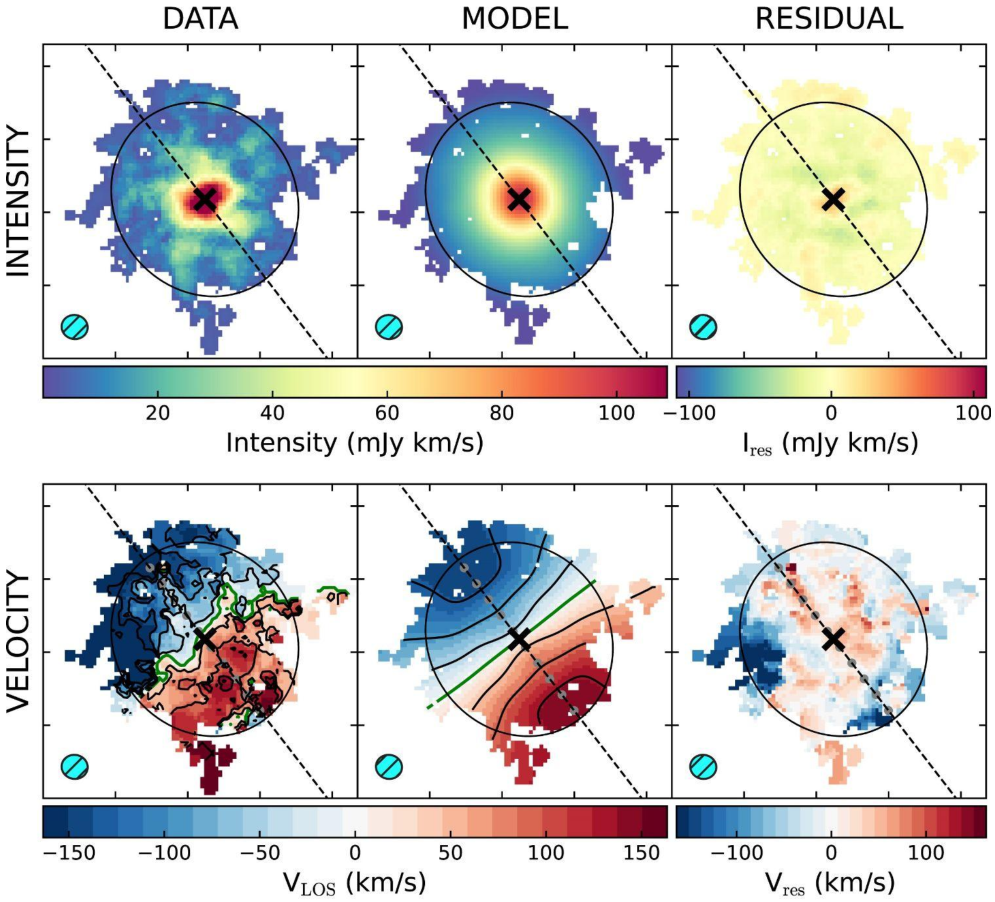


Fujimoto+25

Big Results, Big Problems

Disk galaxies already by z~7 (or even earlier)





Rowland+24

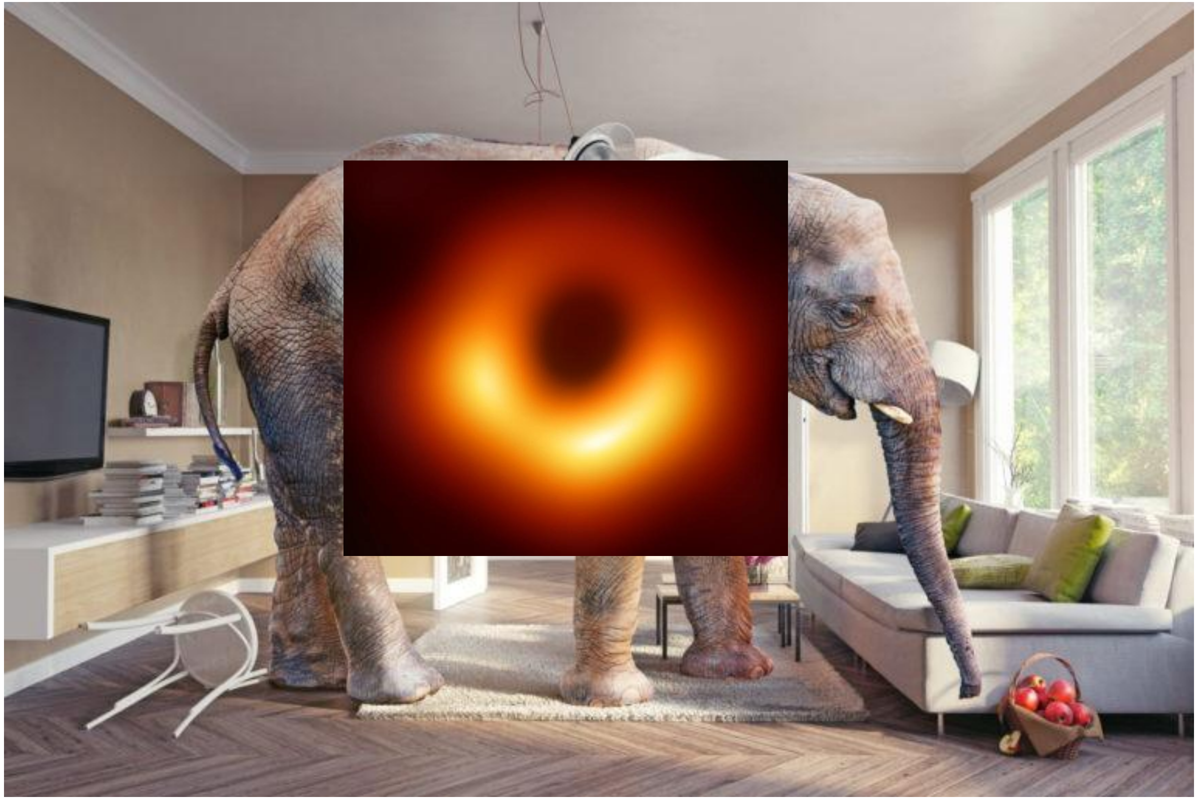
Big Results, Big Problems

The Big Elephant in the Room

Big Results, Big Problems

The Big Elephant in the Room

Supermassive Black Holes

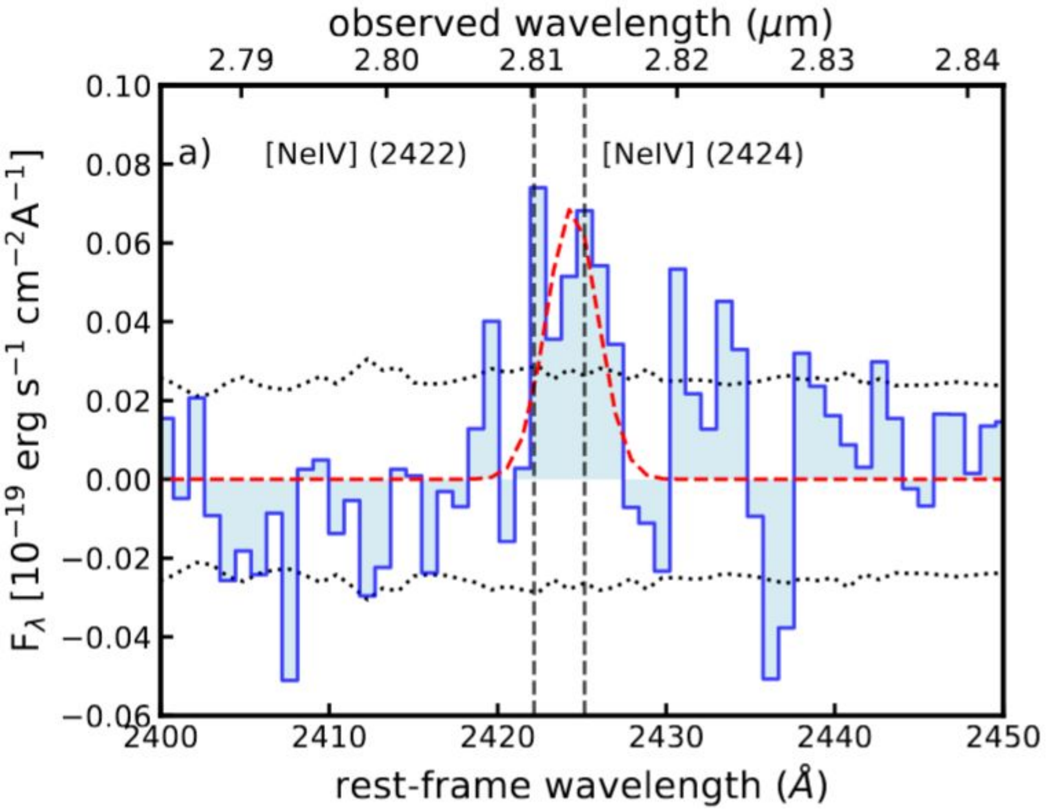


GN-z11

Clear detection of Ne IV doublet, which is a strong indicator of AGN activity.

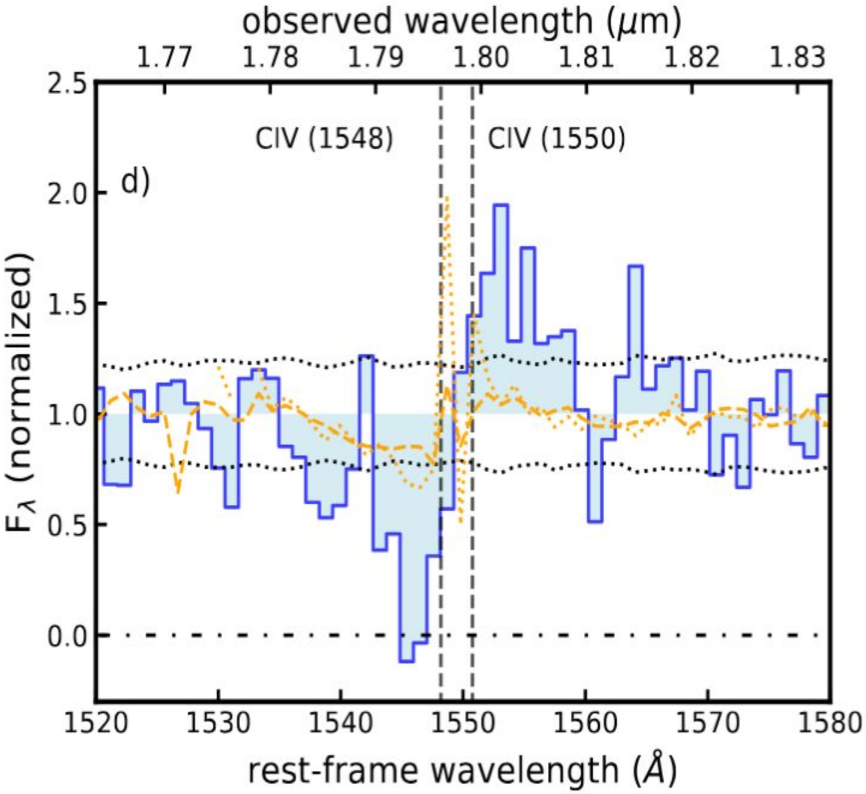
CII*λ1335 also detected, which is usually seen in AGN and not in SF galaxies.

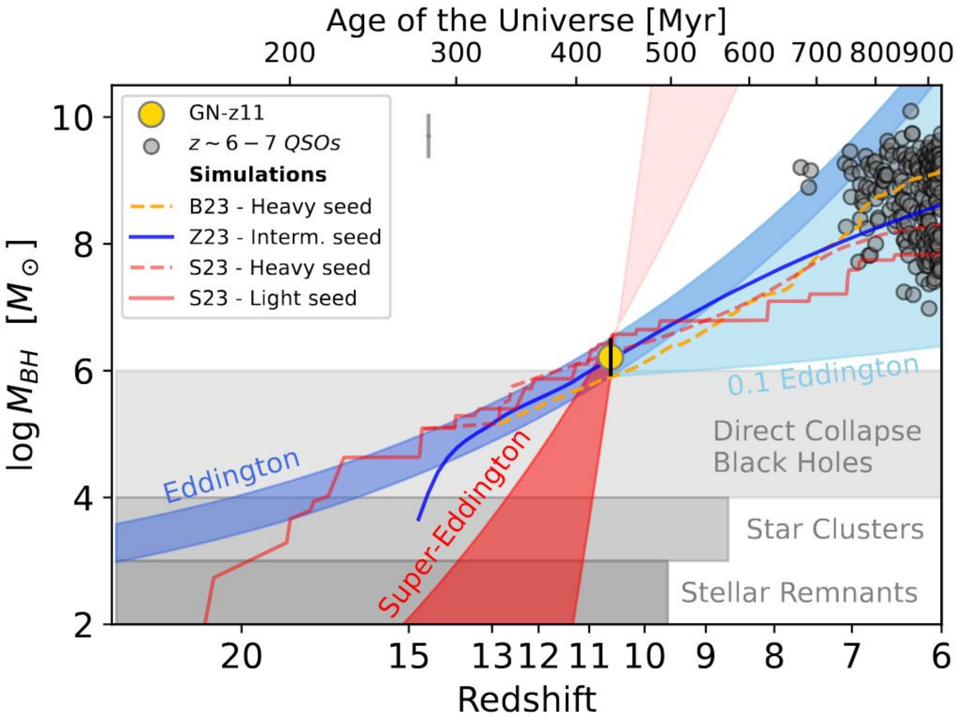
Multiple detected lines require ISM densities of >10^9 cm^{-3}, which are not found in HII regions but are common in BLRs.



Maiolino+23

GN-z11





Maiolino+23

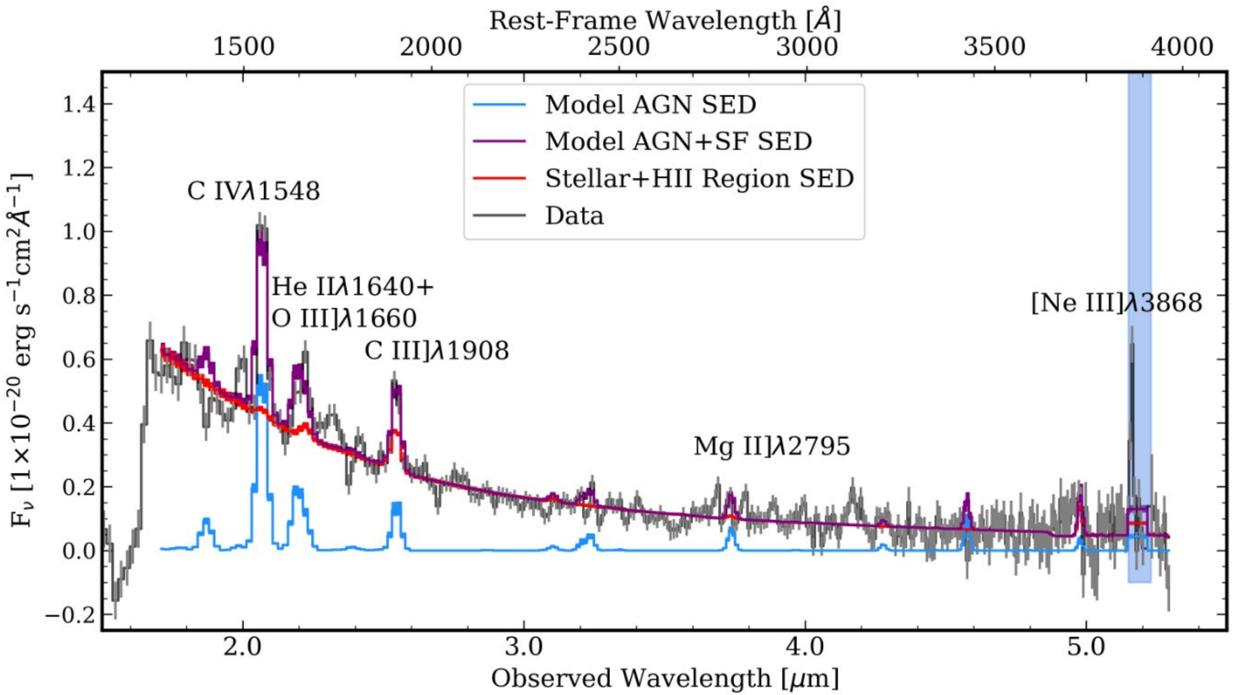
GHZ2

SED modelling approach:

High ionization lines require a SF+AGN contribution.

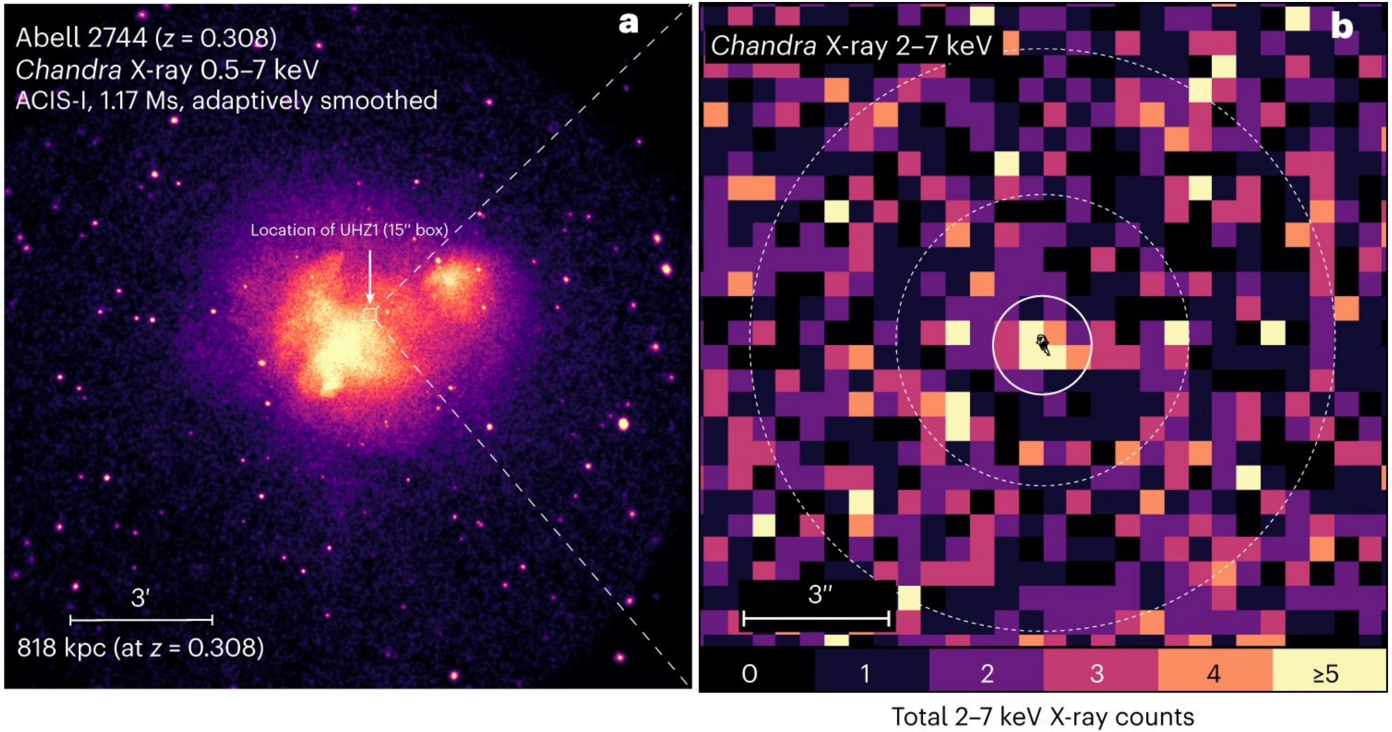
AGN contribution between 25 and 54%.

Log BH mass ~ 6.9-7.9



Chavez Ortiz+25

UHZ1

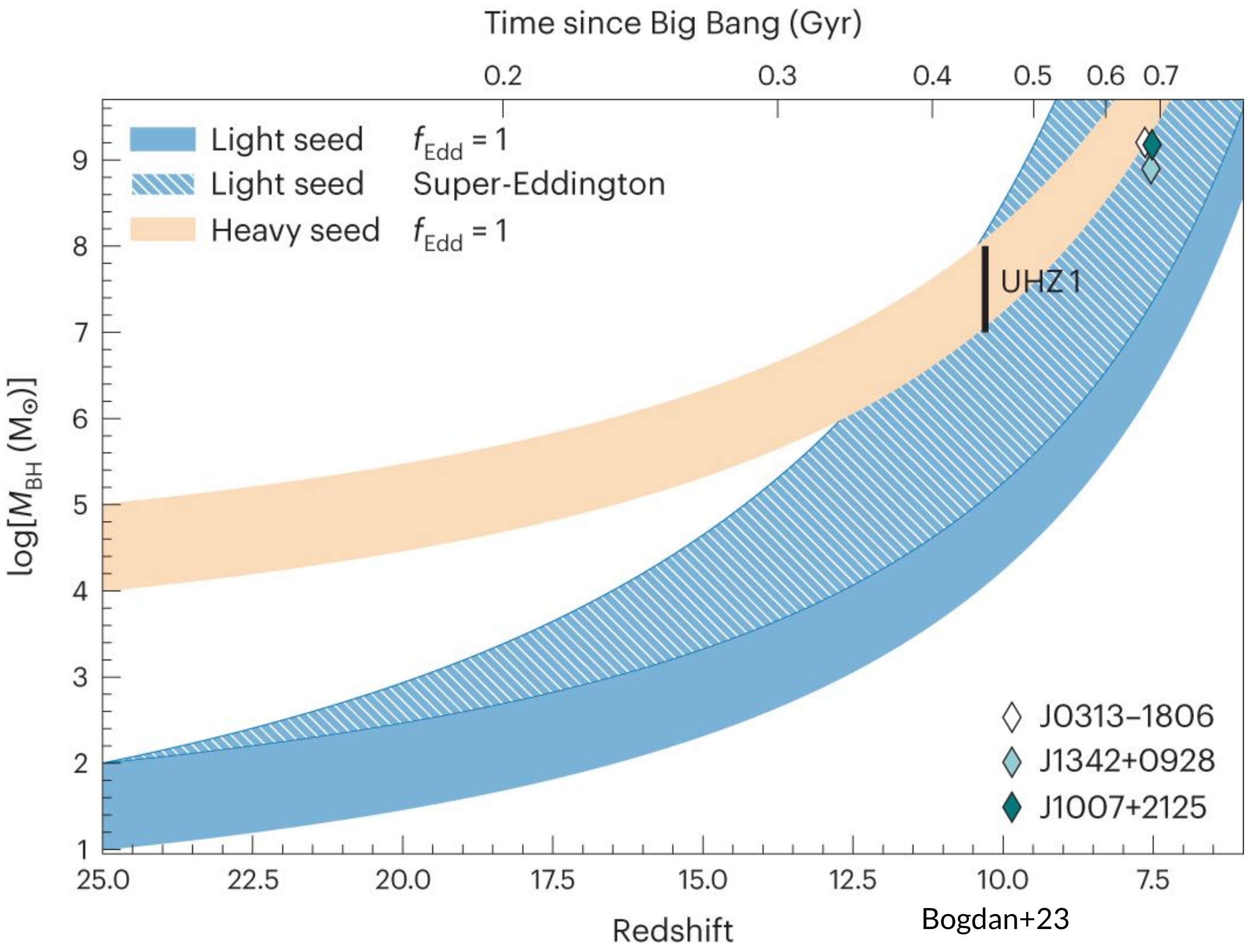


Bogdan+23

UHZ1

Crude estimate of BH mass from X-ray luminosity

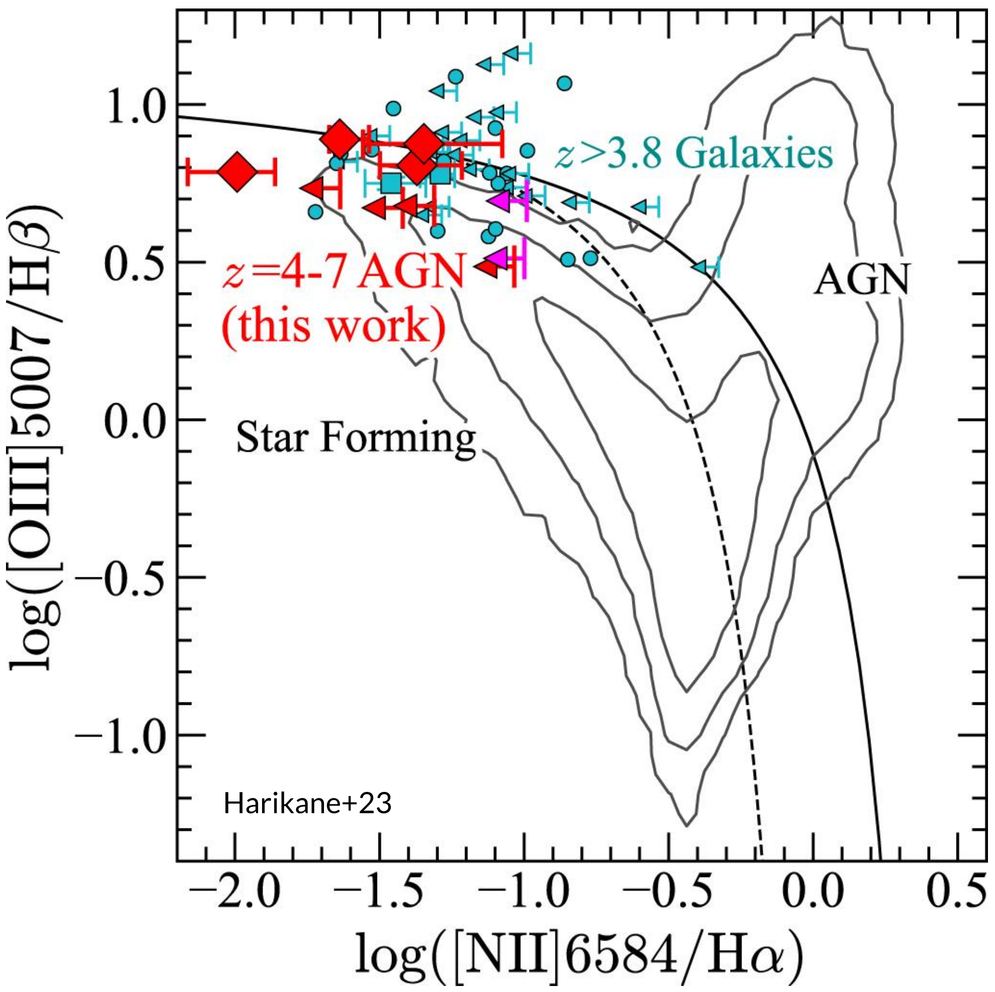
log(M) ~$10^{7\text{-}8}$ M_{sun}



Bogdan+23

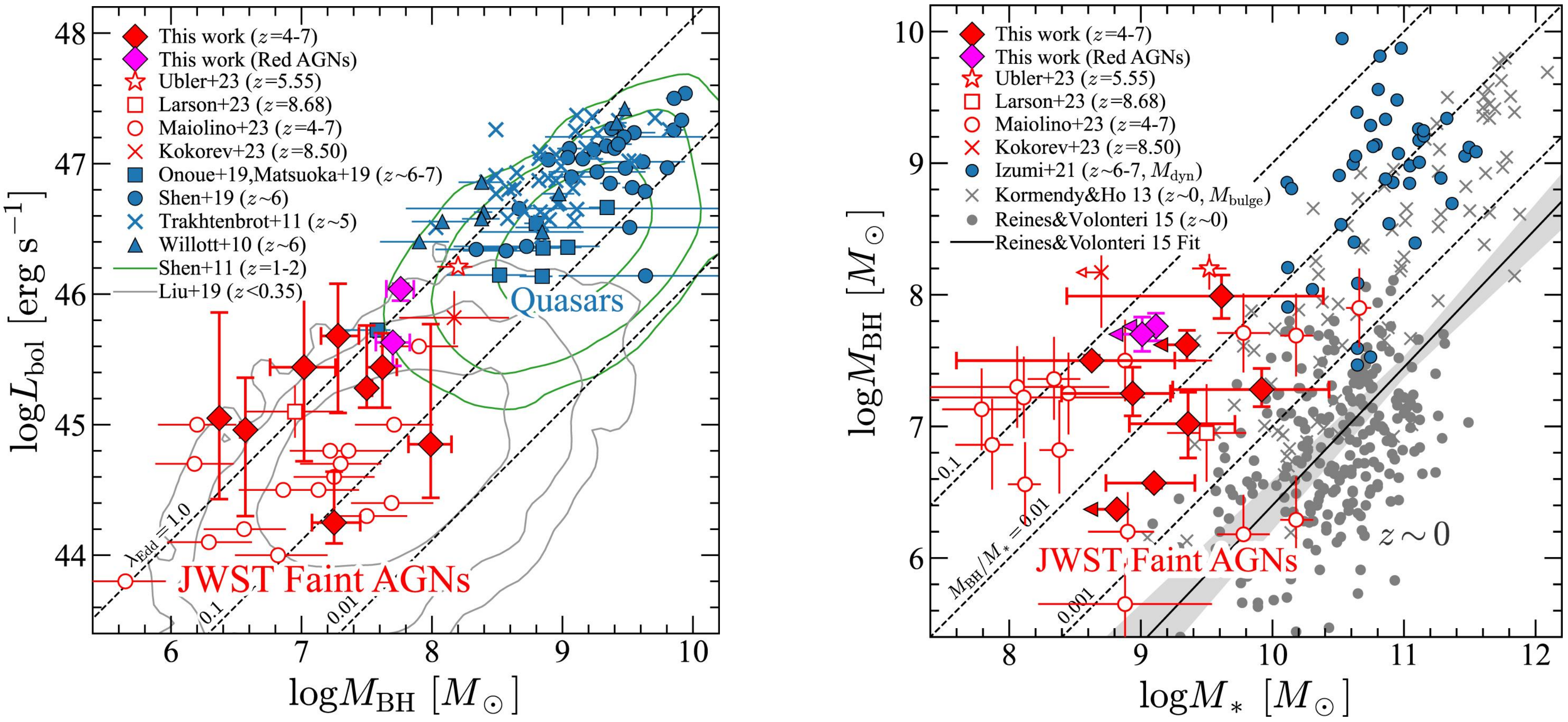
High-z Population

The BPT Diagram, standard method for classifying z<2 galaxies, does not conclusively classify high-z broad line AGN sources as AGNs.



High-z Population

Harikane+23

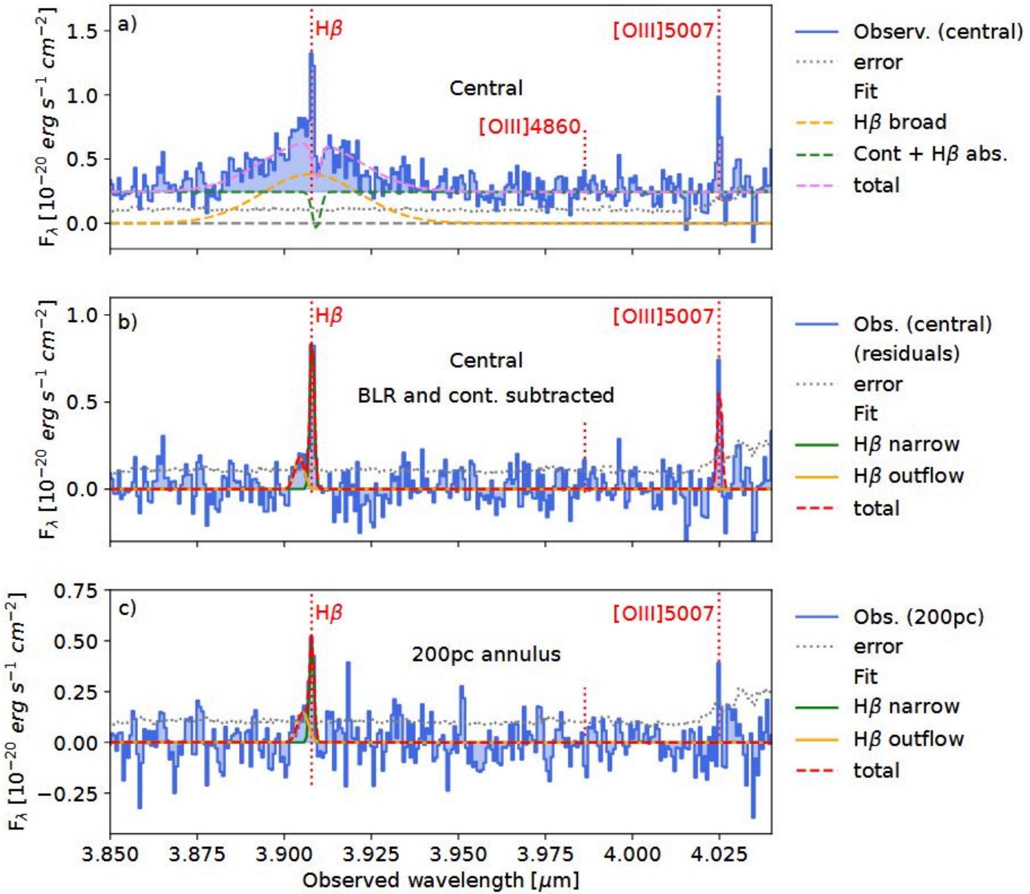


A “Naked” black hole?

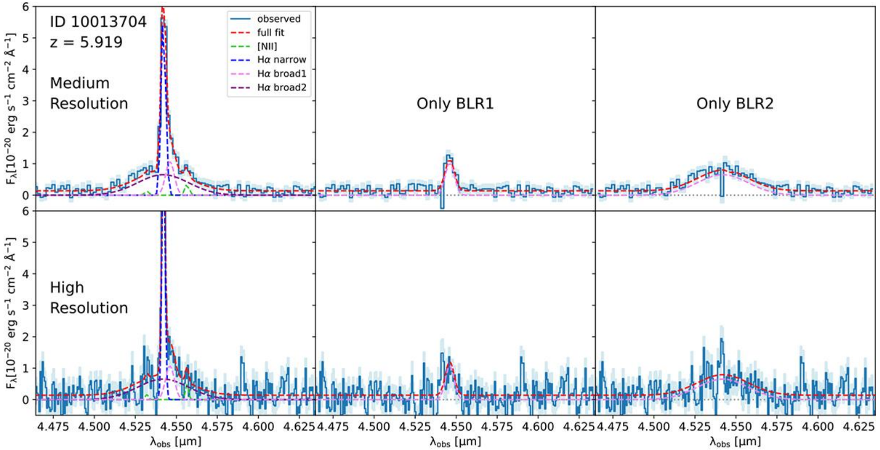
Abell2744-QSO1

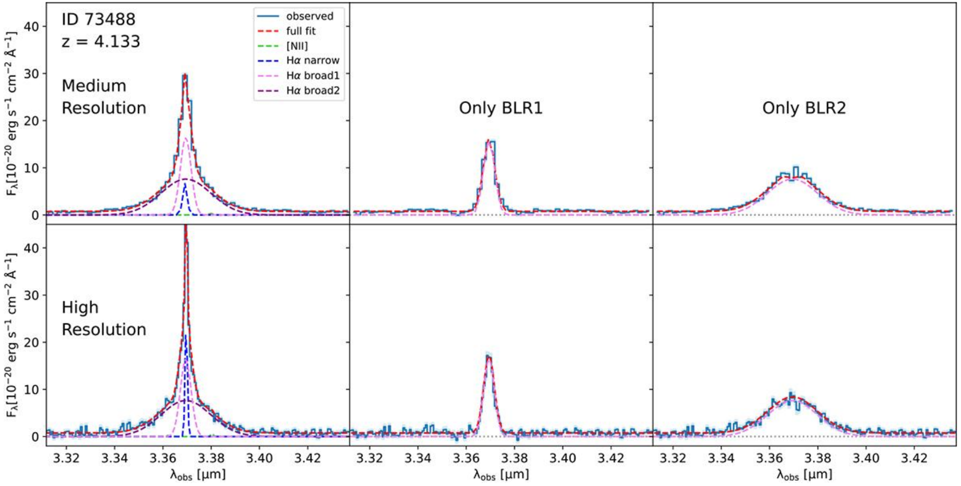
- A 10^7 M_{sun} SMBH at z~7.
- Very low-metallicity galaxy ($Z/Z_{sun} < 10^{-3}$).
- Host galaxy mass <$2x10^7$ M_{sun} (effectively $M_{BH}/M_* > 2$).
- Possibly originating from primordial BHs?

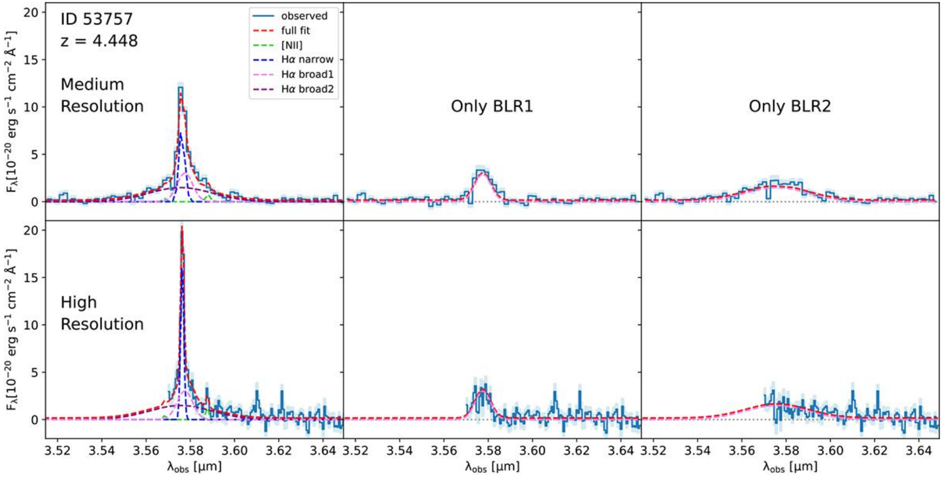
Maiolino+25



Dual AGN?







Maiolino+24

Summary

- We now have 40+ galaxies detected at $z>10$.
- They are low-mass, low-metallicity, highly star-forming galaxies. They are compact (<1kpc) , but show different morphologies (extended vs point-like).
- They are too bright, too massive, too high metallicity too early in the Universe. They seem to be forming settled disks within the first Gyr (possibly very early).
- Finding SMBH is hard, but many candidates identified. They are overmassive, accreting at a high rate, and must be present very early during galaxy formation.