Exploring the New High-z Frontier with JWST

严皞璟
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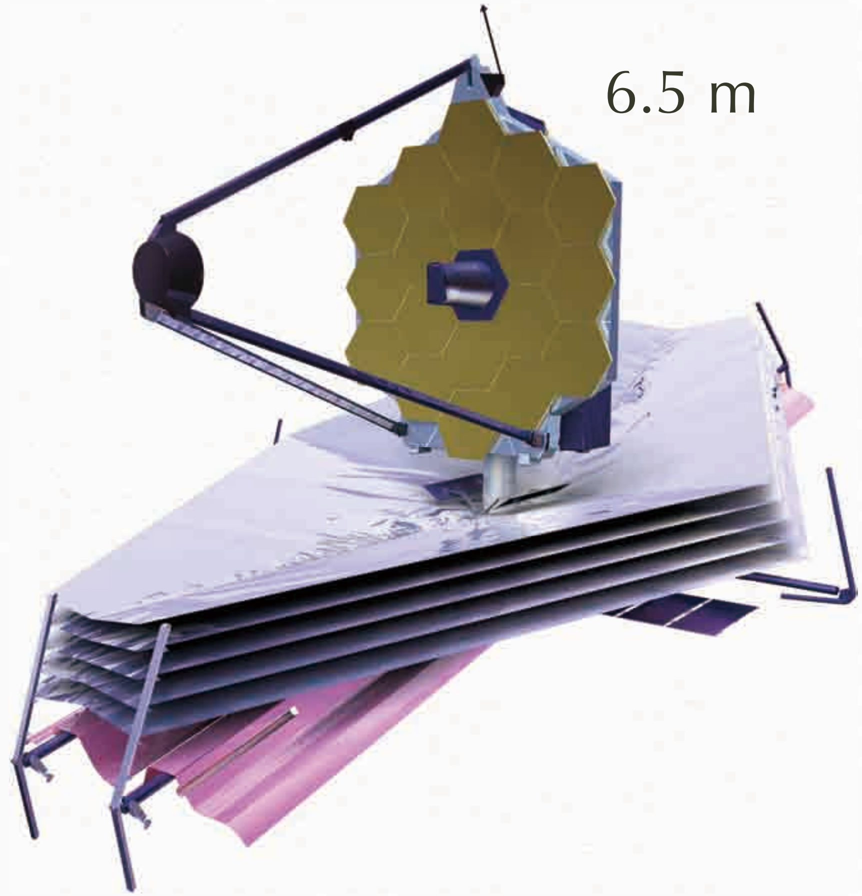
12/25/2023



- JWST was launched on December 25, 2021 in Kourou, French Guiana, by an Ariane 5 launch vehicle (of European Space Agency); arrived at S-E L2 on January 24, 2022 — lifetime 5-year minimum, 20-year expected

- **NASA**: $8.8B + $861M for 5-year; **ESA**: €700M; **CSA**: CA$200M => $10B+ !

JWST: more the successor to *Spitzer* than to *HST*

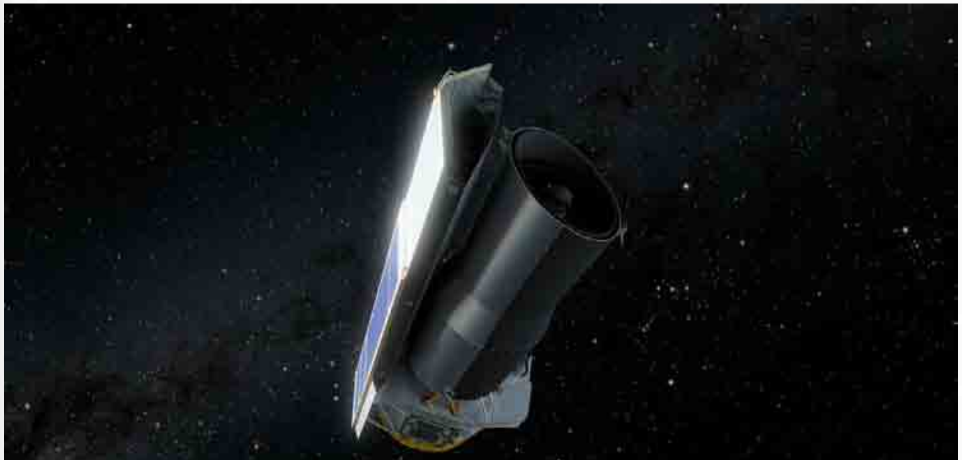
- JWST is often called as the successor to the *Hubble* Space Telescope (*HST;* 2.4-m)
- In terms of its discovery window, it is more the successor to the *Spitzer* Space Telescope (2003-2020; 0.85-m)
- *HST* works at 0.115-1.7 μm (UV to near-IR), while *Spitzer* worked at 3-160 μm (near-to-far-IR)
- JWST works at 0.6-28 μm (optical to mid-IR); the most powerful range is ~2-8 μm

HST (1990 -); 2.4-m

After the 5th service mission -

ACS: 0.22-0.95 μm
COS: 0.115-0.320 μm
STIS: 0.115-1.0 μm
WFC3: 0.2-1.7 μm

Cannot go beyond 2 μm because it is a warm telescope



Spitzer (2003 - 2020); 0.85 m

IRAC: 3-8.5 μm
IRS: 5.2-38 μm
MIPS: 22-170 μm

Only IRAC 3-5 μm kept working till Jan 30, 2020; everything else ceased operation in May 2009 after liquid helium exhausted

JWST Instruments

- Near-Infrared Camera (**NIRCam**) : imager working at 0.6-5 μm; mercury-cadmium-telluride (HgCdTe) detectors
- Near-Infrared Spectrograph (**NIRSpec**) : spectrograph working at 0.6-5 μm; HgCdTe detectors
- Mid-Infrared Instrument (**MIRI**) : imager (5.6-25.5 μm) + spectrograph (5-12 μm or 4.9-28.8 μm); arsenic-doped silicon (Si:As) detectors
- Fine Guidance Sensor/Near InfraRed Imager and Slitless Spectrograph (FGS/**NIRISS**) : guiding camera + imager/spectrograph (0.7-5.0 μm); HgCdTe detectors

It began in July 2023

- After ~6 months of commissioning, JWST began its official science operation in the 2nd week of July - but no data were released to any programs until after July 12

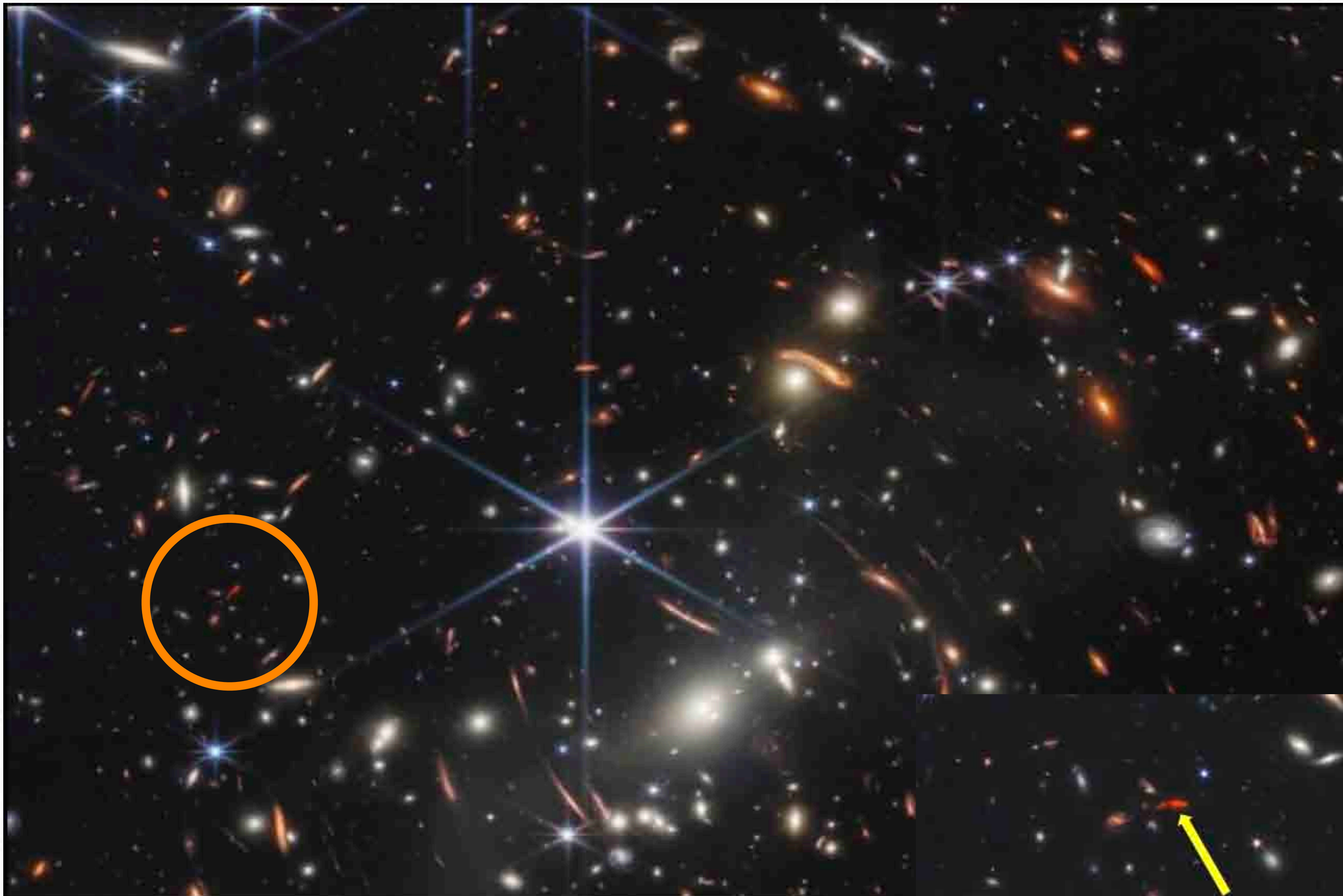
- NASA planned to release its “Early Release Observations” (ERO; done in June) on July 12 for PR

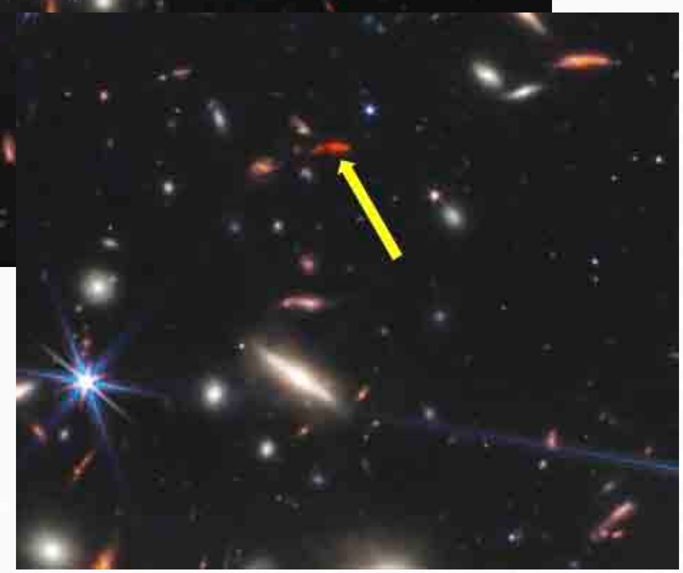
- The ERO targets were kept as a secret until July 8; among them there was a lensing cluster field SMACS 0723-73 (surprise!!!)

White House stole the thunder …

- President Biden & Vice President Harris received a briefing on July 11 (in the evening) on the first JWST image - it was SMACS 0723-73

- Within the hour, the full-resolution color image was distributed through internet

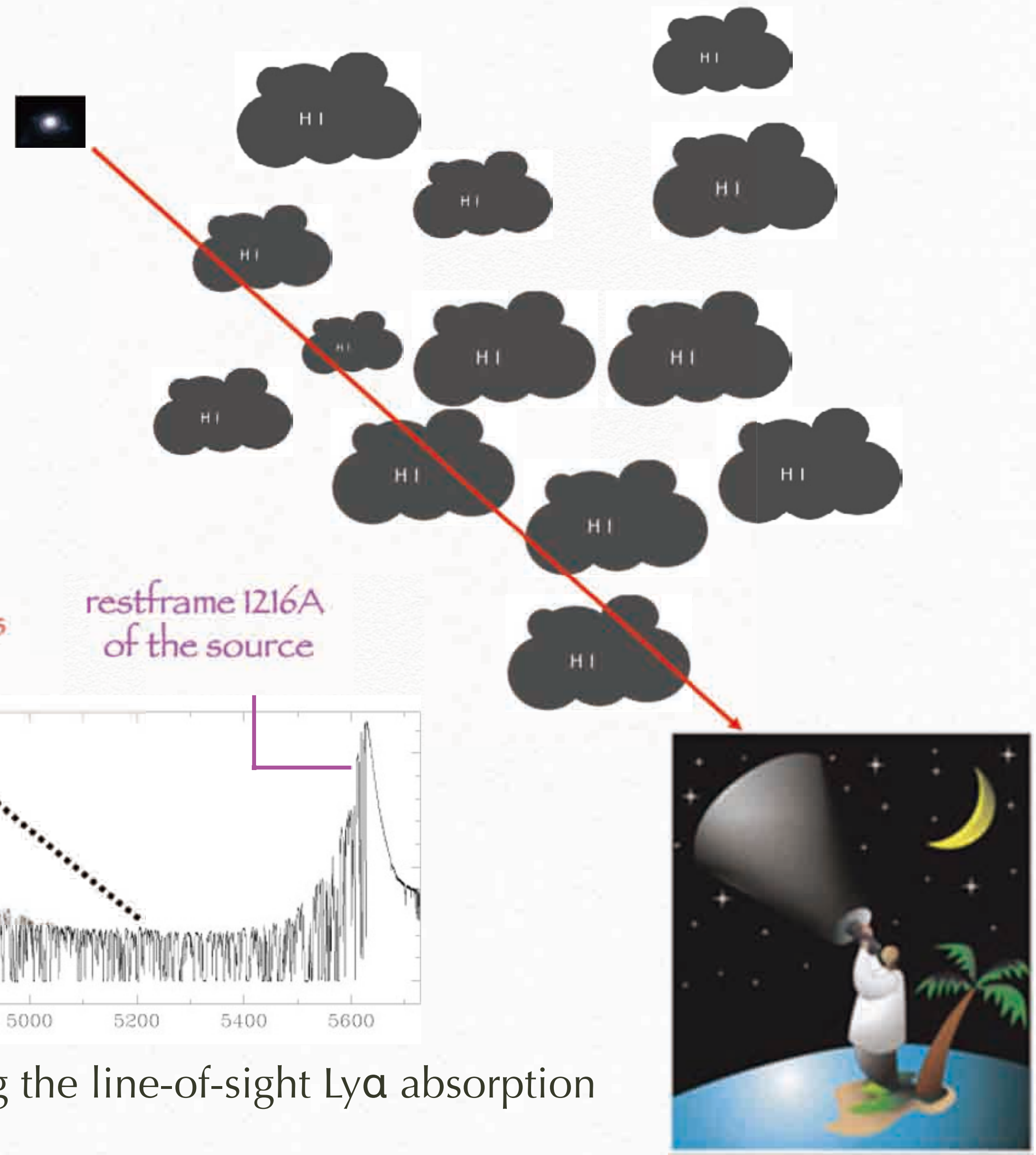


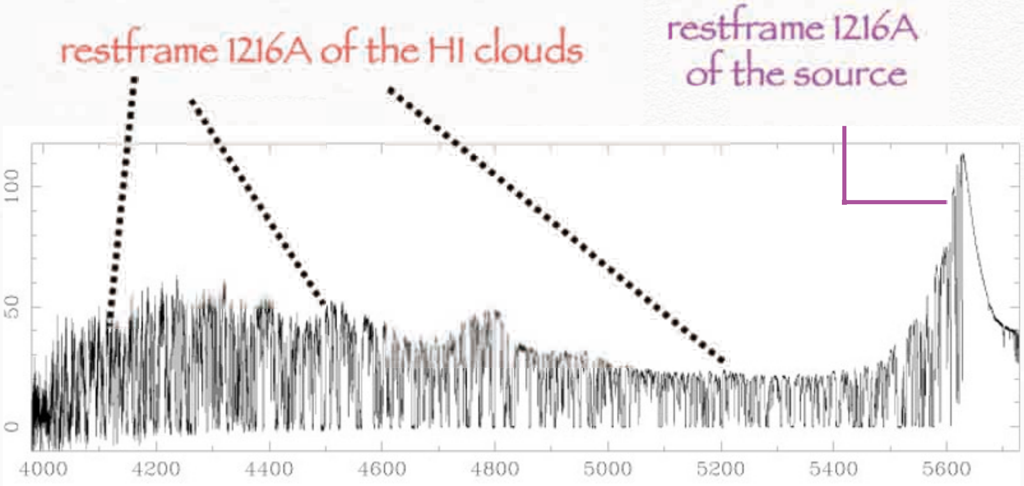


It's not visible in the HST WFC3 F160W (1.6 μm) image!

High-z signature: Lyman break

- Line-of-sight H I absorption (Lyman limit 912A + Lyα-forest 1216A) creates strong "Lyman-break" signature in spectra of objects at z>3 (Steidel & Hamilton 1992)





Spectrum of a z=3.6 quasar revealing the line-of-sight Lyα absorption

Searching for origins

- An ultimate goal of studying galaxy formation and evolution is to find and understand first luminous objects in the universe

  "First stars"

  "First galaxies"

  "First accreting black holes"

- With James Webb Space Telescope (JWST), we are getting closer than ever to this goal

HST ACS+NICMOS pushed to *z*~ 6-7

- Using NICMOS, we pushed to z~7 in the Hubble Ultra-deep Field (HUDF)

CANDIDATES OF $z \simeq 5.5$–7 GALAXIES IN *HST* UDF

TABLE 2
PHOTOMETRIC PROPERTIES OF THE THREE z_{850} DROPOUTS FOUND IN THE UDF NICMOS FIELD[a]

ID	R.A., Decl. (J2000)[b]	z_{850}(limit)[c]	J_{110}	H_{160}
1	3 32 38.74, −27 48 39.97	28.97	26.58 ± 0.05	24.68 ± 0.01
2	3 32 42.88, −27 48 09.52	28.52	27.01 ± 0.10	24.63 ± 0.02
3	3 32 42.56, −27 46 56.69	28.45	27.30 ± 0.06	26.11 ± 0.02

[a] The very red IR colors of these three z_{850} dropouts suggest that they are more likely lower redshift early-type galaxies. The only probable $z \simeq 7$ candidate left in our sample (not shown here) is the object pair 7a/7b in Table 1, which could be at the border of the $z \simeq 6$ bin and the $z \simeq 7$ bin.

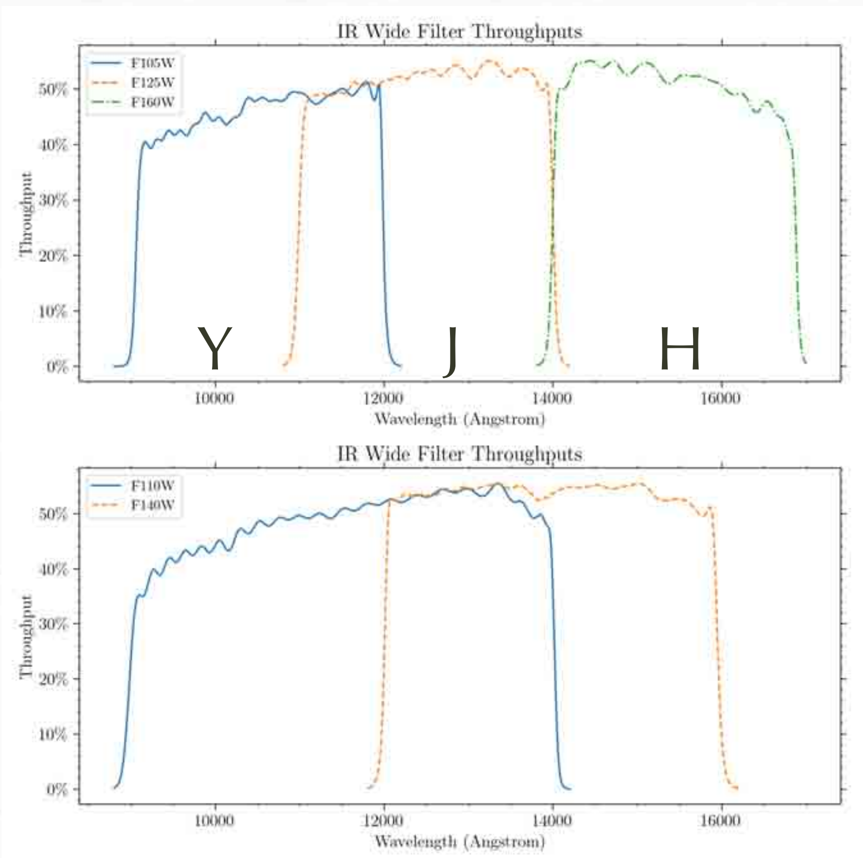
[b] Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[c] These magnitude limits are obtained by adding the flux within an aperture of 0ʺ.54 radius, which is not necessarily the size of the apertures that are used for J_{110} and H_{160} photometry.

Yan & Windhorst (2004; ApJ, 612, L93)

HST WFC3 pushed to *z*~10

- Using WFC3, the frontier was gradually pushed to *z* ~ 8 –10
- The most important observations were done in the HUDF (Sept. 2009) and the CANDELS (2010-2013) fields



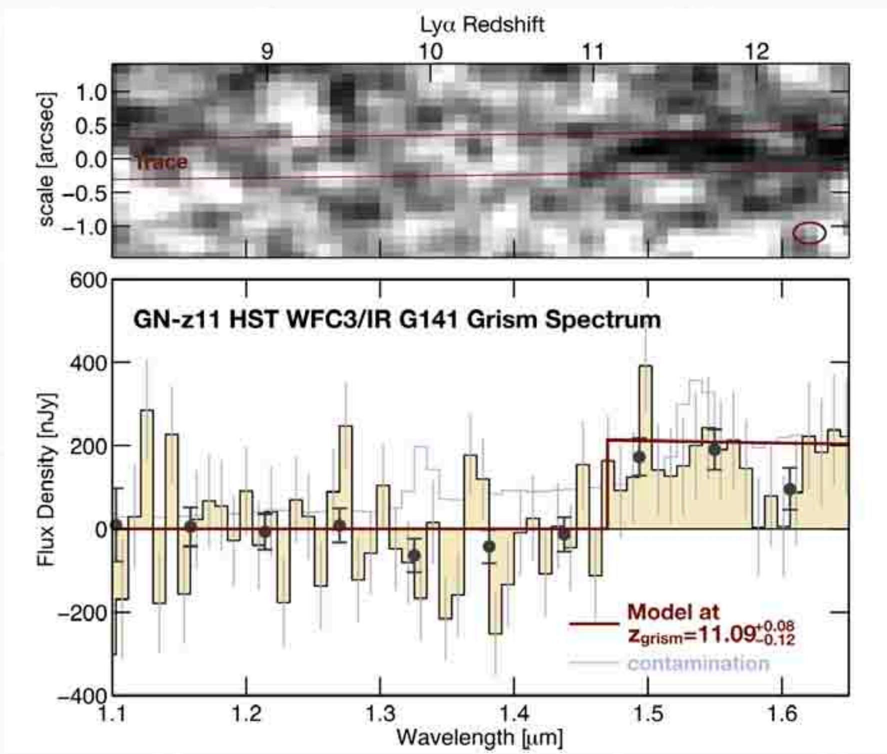
z=14000/1216-1 ~ 10.5

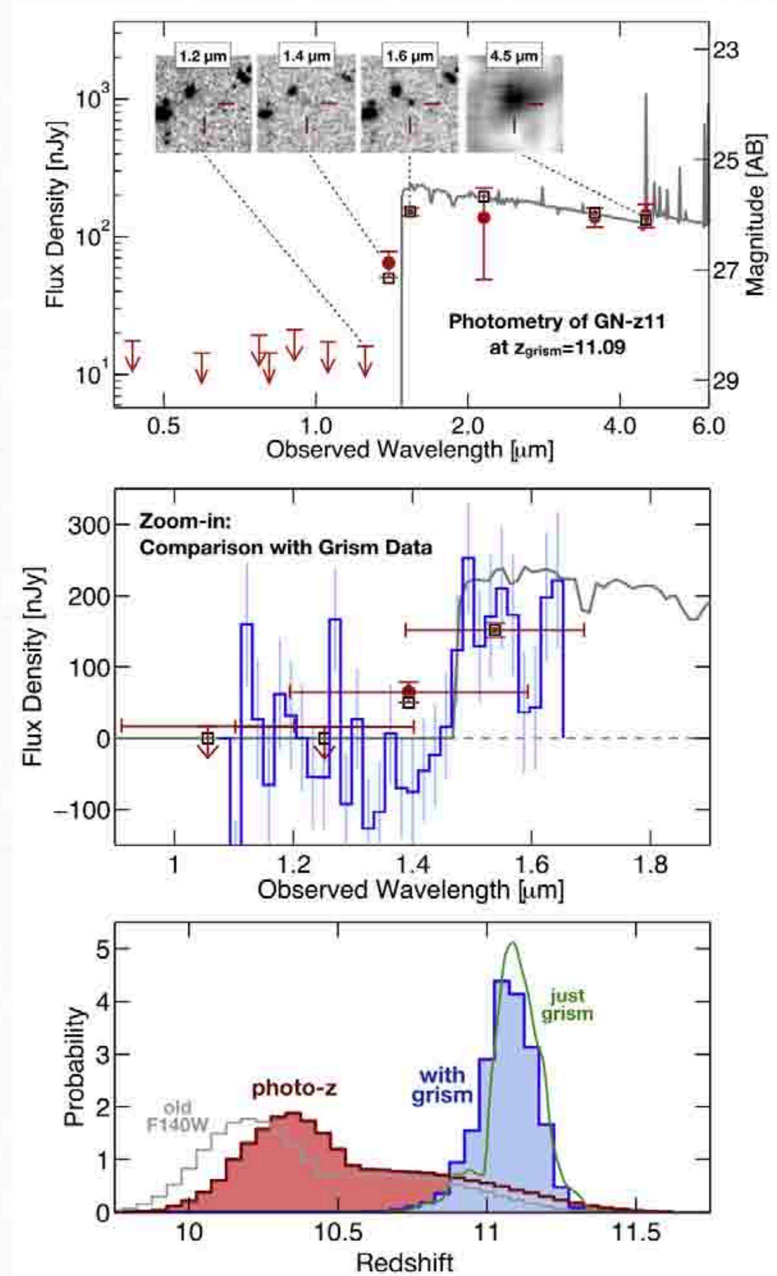
- This is well into the epoch of cosmic hydrogen reionization (ended at z~6.2)
- Controversies and problems began …

HST stopped at *z*~11

- Galaxy of the highest redshift detected by HST - Oesch et al. (2016; ApJ, 819, 129); candidate selected in CANDELS GOODS-North field

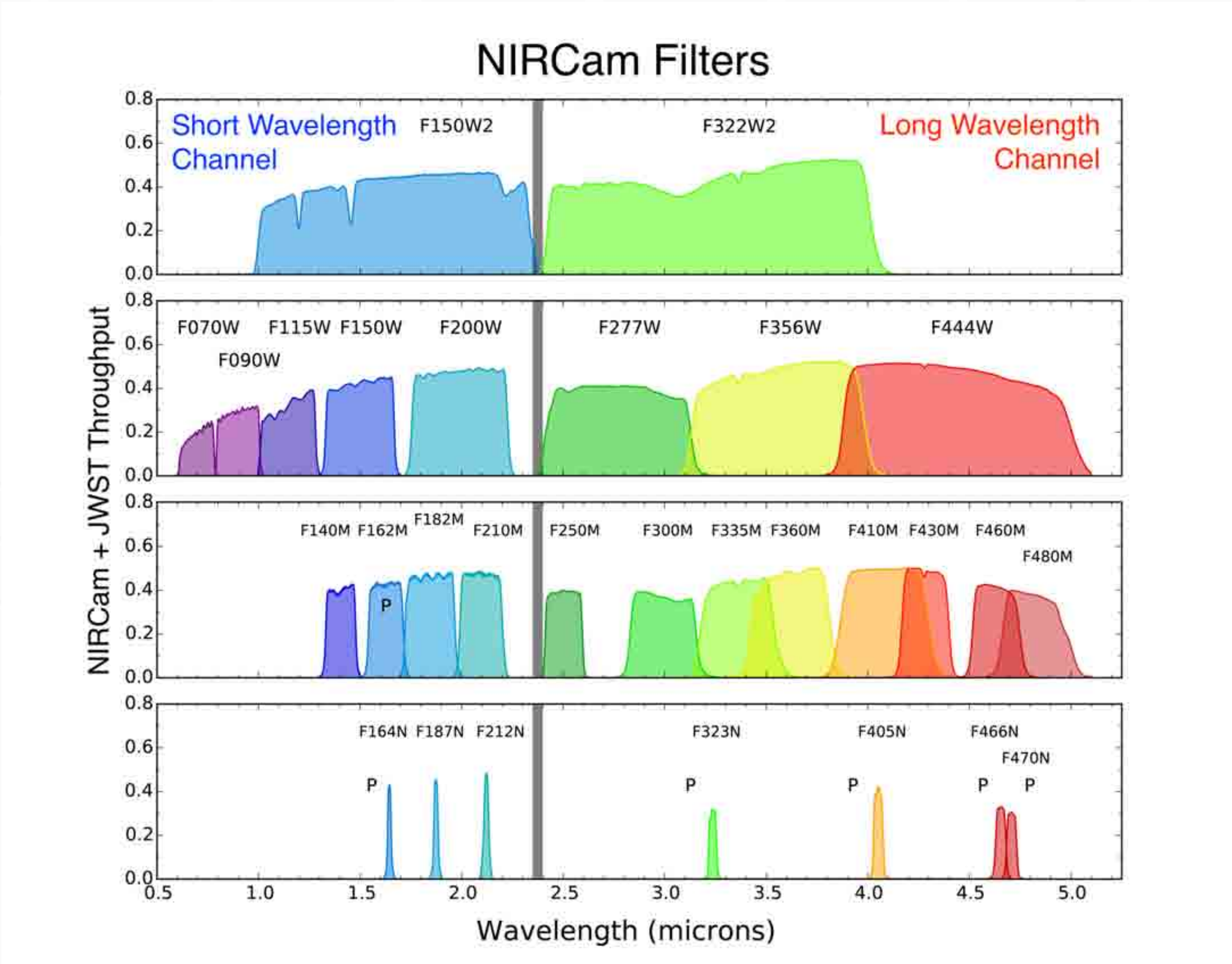
- "Confirmation" using HST WFC3 grism spectroscopy: z=11.09 (but see Jiang et al. 2021; z=10.957)





JWST pushing to z >11

- So it's all natural then to see JWST pushing beyond z~11 …



Pre-JWST picture of early galaxy formation

The Astrophysical Journal, 855:105 (12pp), 2018 March 10 https://doi.org/10.3847/1538-4357/aab03f

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The Dearth of $z \sim 10$ Galaxies in All *HST* Legacy Fields—The Rapid Evolution of the Galaxy Population in the First 500 Myr*

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- Prevailing idea of the community: very few galaxies at z > 11
- (The epoch of first galaxies should be at around z ~ 11)
- (In its first year, JWST probably wouldn't be able to find any galaxies beyond the HST record)

JWST changed the landscape

- JWST began its official science operation in the 2nd week of July, 2022 - but no data would be released to any programs until after July 12
- The floodgate was opened after the NASA news briefing to the White House on July 11
- The first set of JWST data immediately gave the community huge surprises
- Within two weeks, seven papers on searching for $z > 11$ galaxies appeared

- July 19: Castellano et al., two very bright candidates at z ~ 10.6 and 12.2
- July 19: Naidu et al., two very bright candidates at z ~ 10.4 and 12.4
- July 22: Adams et al., including one candidate at z ~ 11.5
- July 23: Yan et al., 87 candidates at z > 11, up to z ~ 28.3
- July 25: Atek et al., two candidates at z ~ 12
- July 25: Donna et al., six candidates at z > 12
- July 25: Finkelstein et al., one candidate at z ~ 11.8
- … more followed

THE ASTROPHYSICAL JOURNAL LETTERS, 942:L9 (20pp), 2023 January 1
https://doi.org/10.3847/2041-8213/aca80c

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First Batch of $z \approx 11$–20 Candidate Objects Revealed by the James Webb Space Telescope Early Release Observations on SMACS 0723-73

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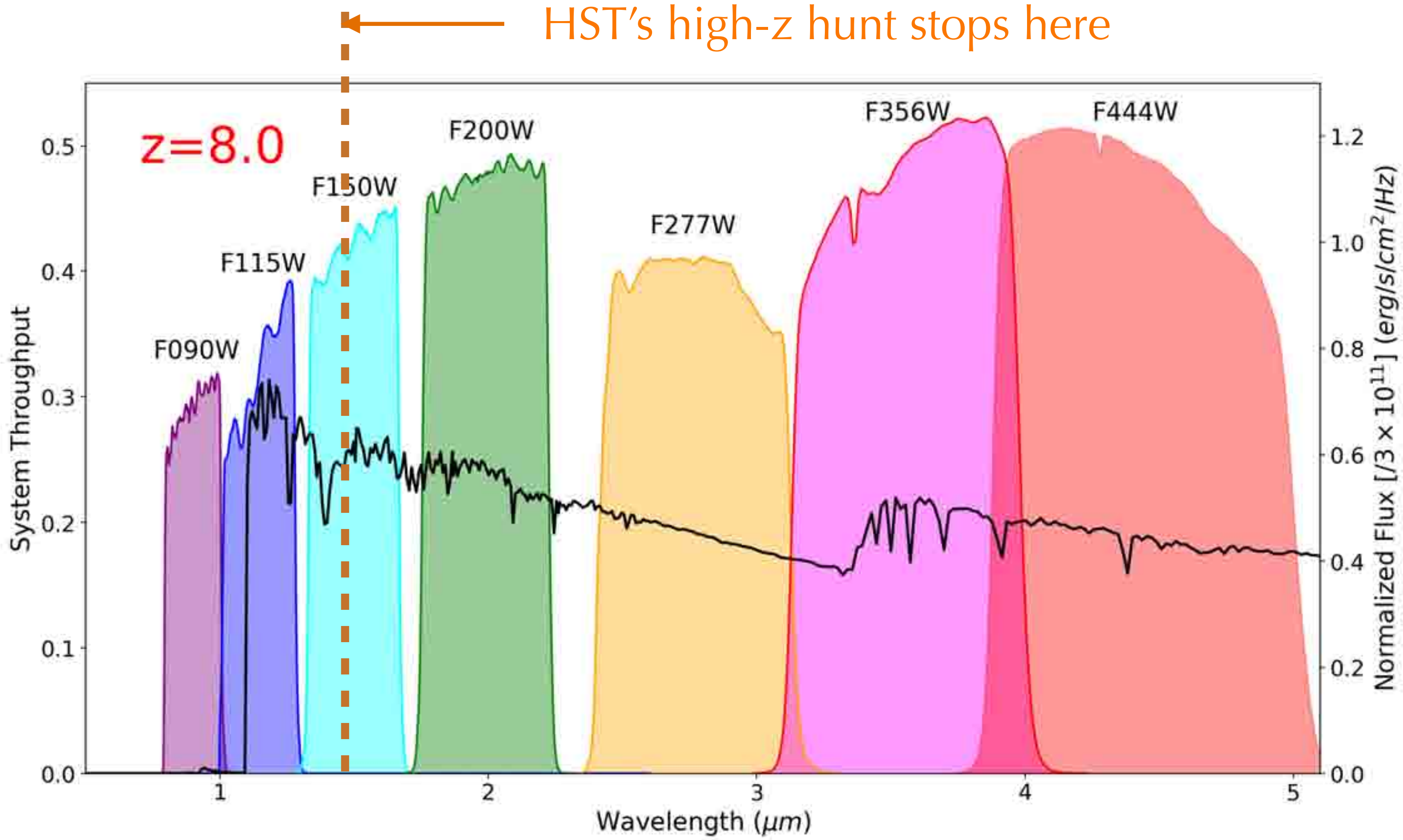
- For the first time, the possibility of a large population of galaxies at z > 11 was clearly shown
- This challenges the previous, widely-accepted picture of galaxy formation in the early universe

Dropout Selection of High-z Galaxies with NIRCam



- Dropout selection only depends on the line-of-sight H I absorption; it does not need to assume any specific type of galaxy SEDs
- Selecting F150W-, F200W-, and F277W-dropouts at $z \sim 12.7$ ($11.3 < z < 15.4$), 17.3 ($15.4 < z < 21.8$) and 24.7 ($21.8 < z < 28.3$)

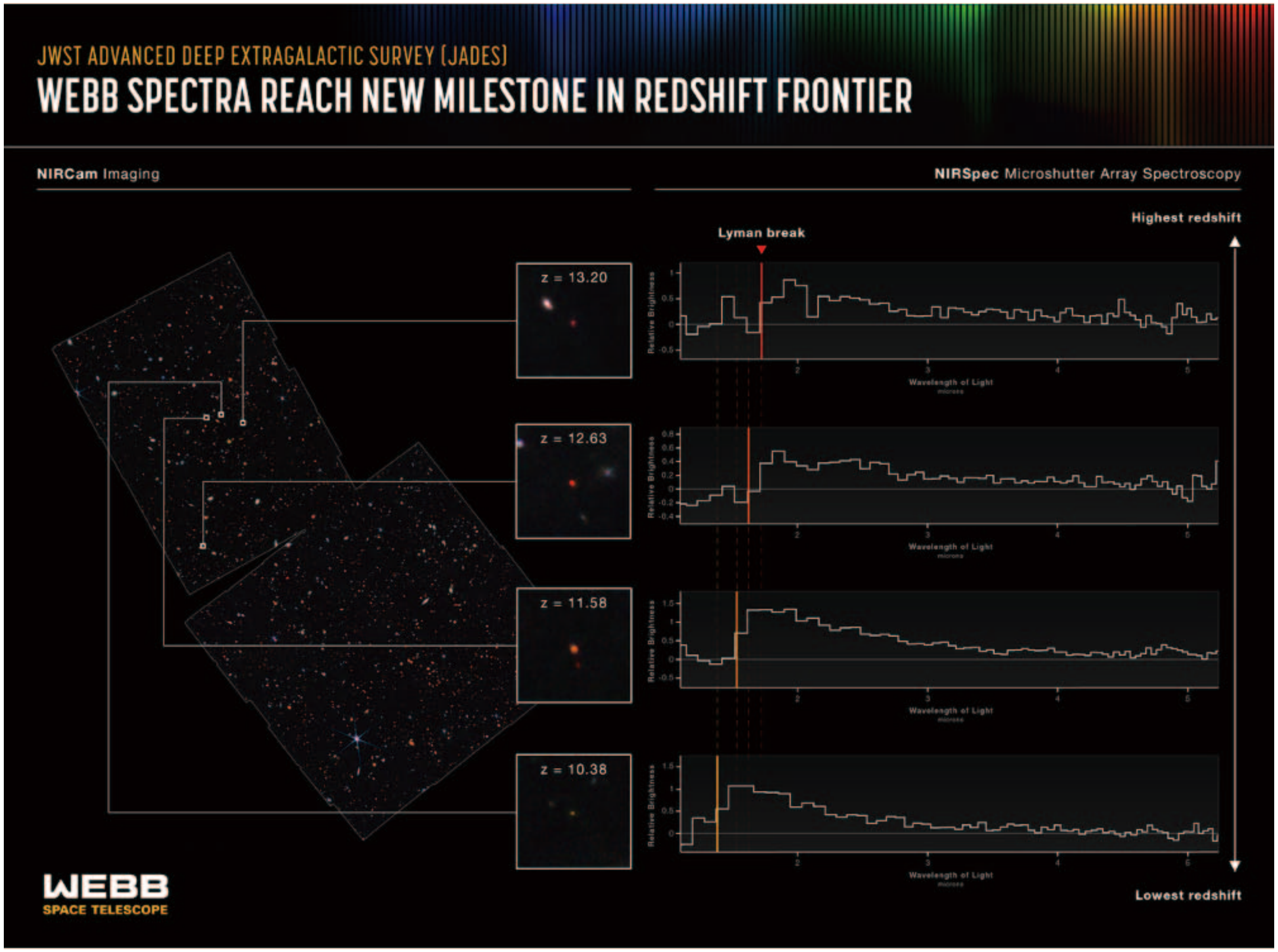
New Consensus after Year-1

- Candidate selections by various teams agree that there is a “too-bright and too-many” problem at $z > 11$ as compared to the previous studies

- Spectroscopic confirmation of some $z > 11$ galaxies suggests that the previous studies indeed underestimated the number density of galaxies at $z > 11$

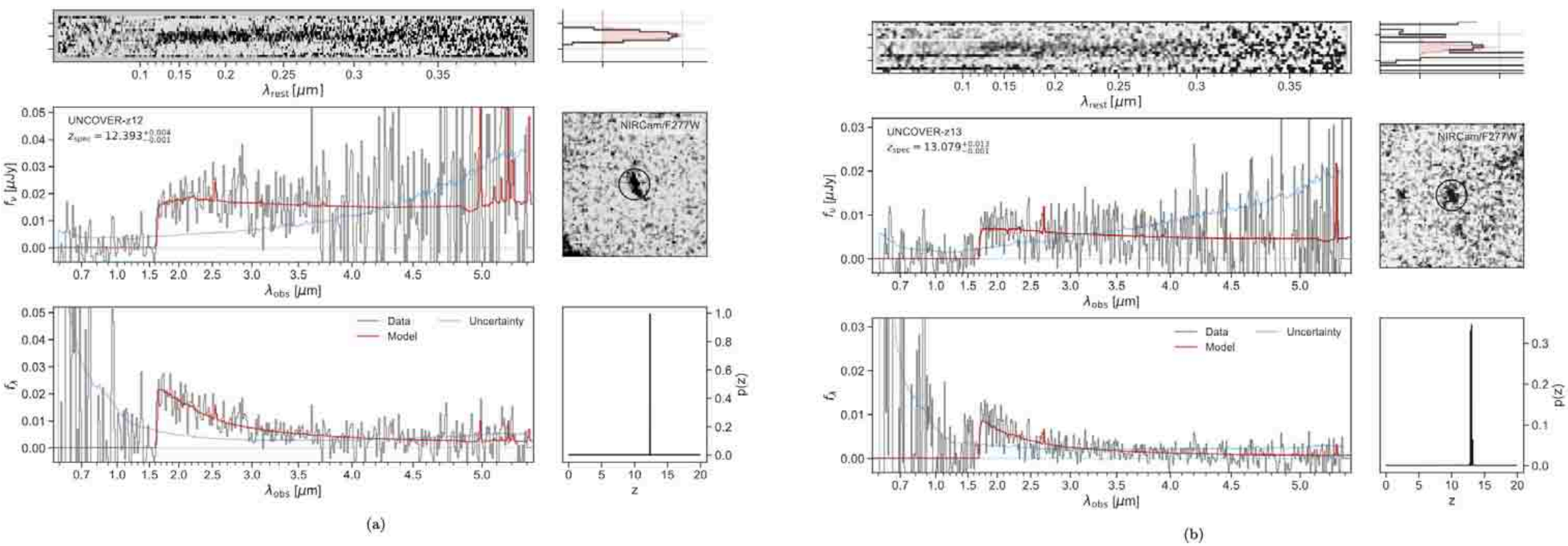
- A new picture must be built; many details need to be filled in

Current confirmed redshift record



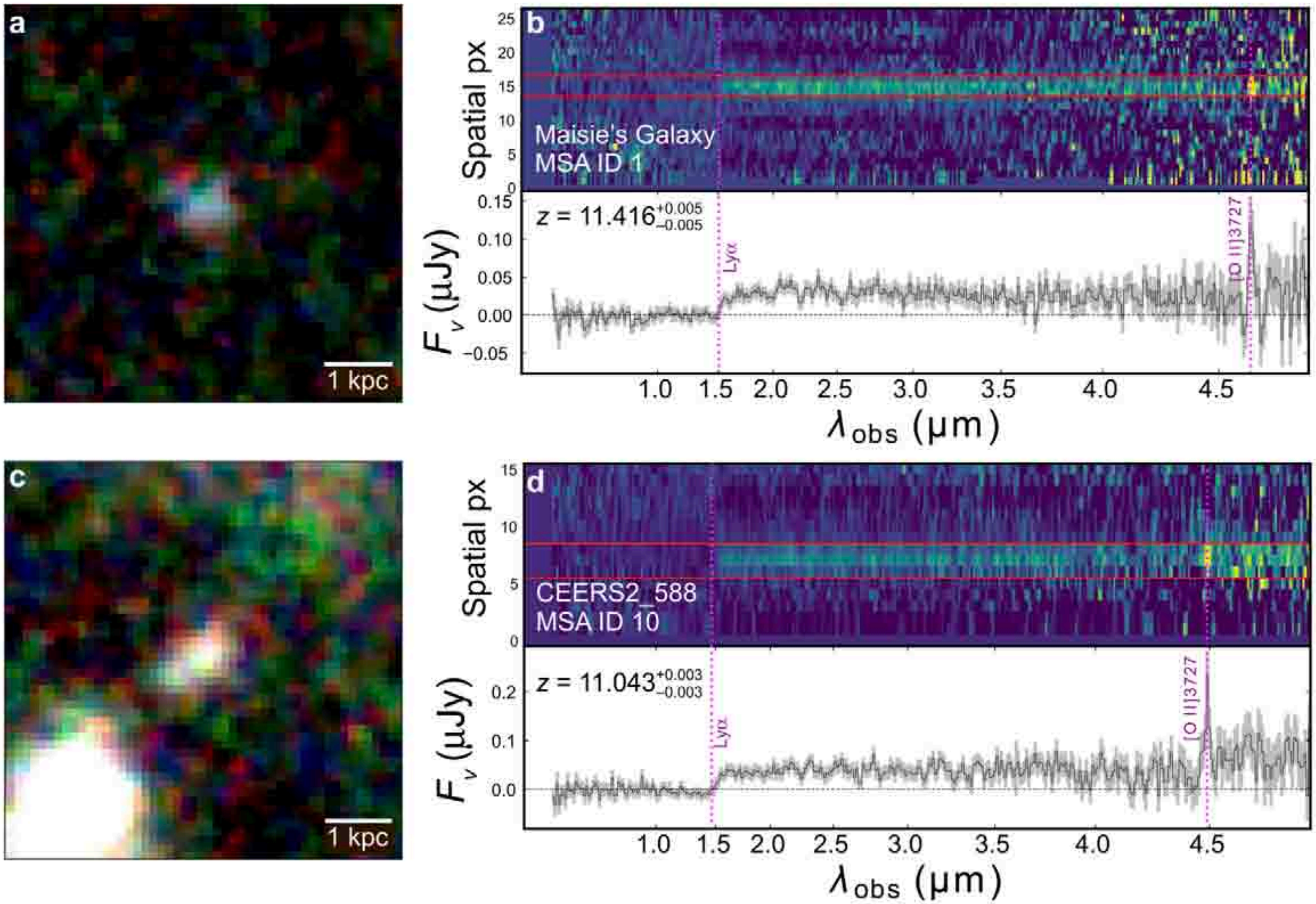
- The JADES collaboration set a new record of z=13.2 (Robertson et al. 2023; Curtis-Lake et al. 2023)

More spectroscopic confirmations



- The UNCOVER collaboration identified a z=12.39 galaxy and a tentative z=13.08 one (Wang et al. 2023)

More spectroscopic confirmations



- The CEERS collaboration identified one at z=11.42 and another at z=11.04 (Arrabal Haro et al. 2023)

A systematic search at z > 11.3

Cornell University

We gratefully acknowledge support from the Simons Foundation, member institutions, and all contributors. Donate

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Astrophysics > Astrophysics of Galaxies

[Submitted on 25 Nov 2023]

Candidate Galaxies at z ~ 11.3--21.8 and beyond: results from JWST's public data taken in its first year

Haojing Yan, Bangzheng Sun, Zhiyuan Ma, Chenxiaoji Ling

We present a systematic search of candidate galaxies at z > 11.3 using the public Near Infrared Camera data taken by the James Webb Space Telescope (JWST) in its Cycle 1, which include six blank fields totalling 386 sq.arcmin and two lensing cluster fields totalling 48 sq.arcmin. The candidates are selected as F150W, F200W and F277W dropouts, which correspond to z ~ 12.7 (11.3 < z < 15.4), 17.3 (15.4 < z < 21.8) and 24.7 (21.8 < z < 28.3), respectively. Our sample consists of 123 F150W dropouts, 52 F200W dropouts and 32 F277W dropouts, which is the largest candidate galaxy sample probing the highest redshift range to date. The F150W and F200W dropouts have sufficient photometric information that allows contaminant rejection, which we do by fitting to their spectrum energy distributions. Based on the purified samples of F150W and F200W dropouts, we derive galaxy luminosity functions at z ~ 12.7 and 17.3, respectively. We find that both are better described by power law than Schechter function and that there is only a marginal evolution (a factor of < 2) between the two epochs. The emergence of galaxy population at z ~ 17.3 or earlier is consistent with the suggestion of an early cosmic hydrogen reionization and is not necessarily a crisis of the LCDM paradigm. To establish a new picture of galaxy formation in the early universe, we will need both JWST spectroscopic confirmation of bright candidates such as those in our sample and deeper surveys to further constrain the faint-end of the luminosity function at M > -18 mag.

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- We carried out a systematic search for candidate galaxies at z > 11.3 using the year-1 public JWST data totaling 434 arcmin^2

Using Public NIRCam Data in Cycle-1

- Cycle-1 NIRCam broad-band data in the public domain:
    - PRIMER (UDS1 + COSMOS; Dunlop et al. 2022)
    - CEERS (in EGS; Finkelstein et al. 2022)
    - NGDEEP (parallel field P1 to the HUDF)
    - JADES (DR1 in GOODS-S; Rieke et al. 2023)
    - UNCOVER + DD2756 (in and around Abell 2744; Bezanson et al. 2022; Chen et al. 2023)
    - GLASS (parallel field to Abell 2744; Treu et al. 2022)
    - ERO SMACS 0723 (Pontoppidan et al. 2022)
- We used our own reductions for all, except JADES in GOODS-S

PRIMER UDS1

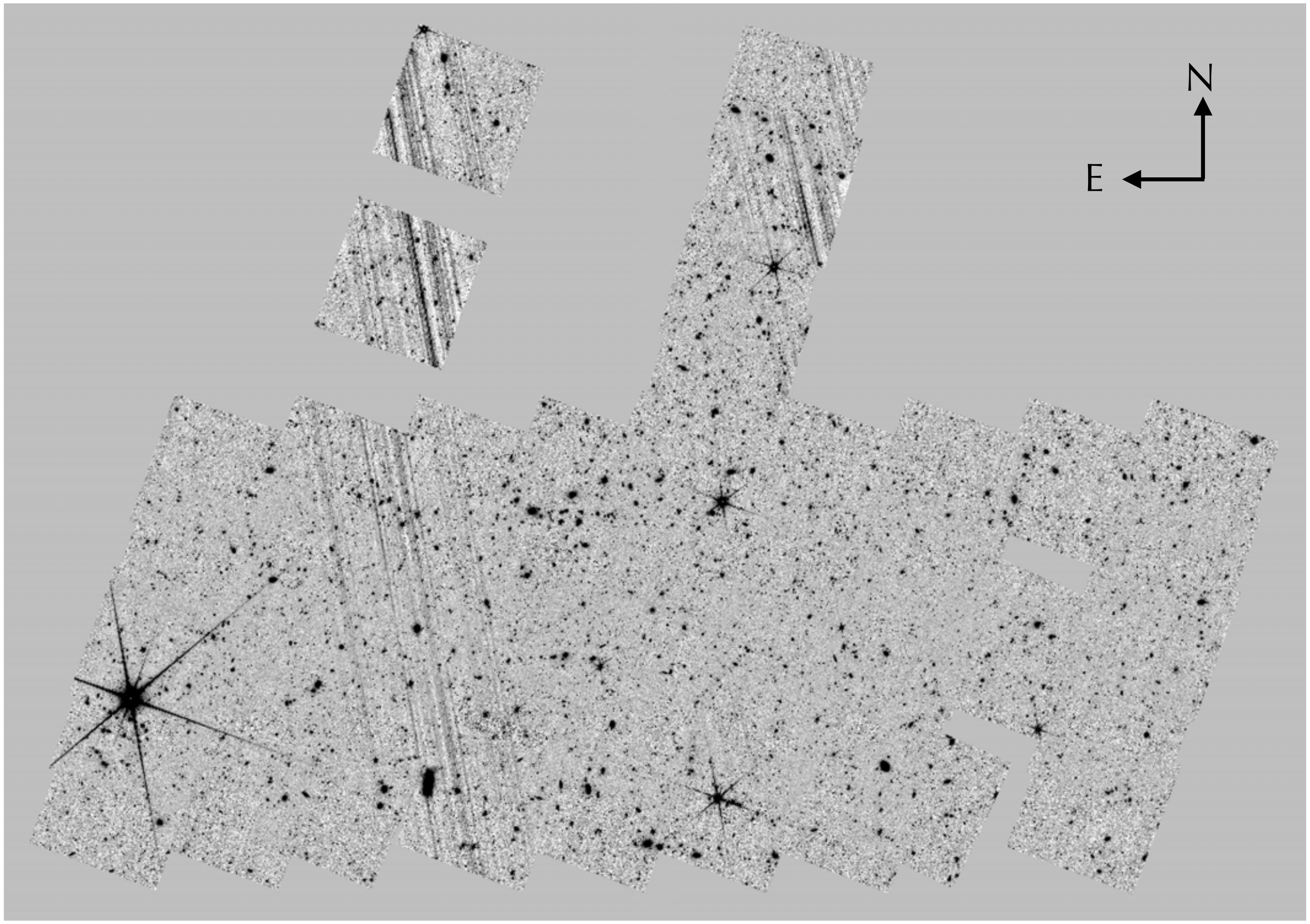
Effective area

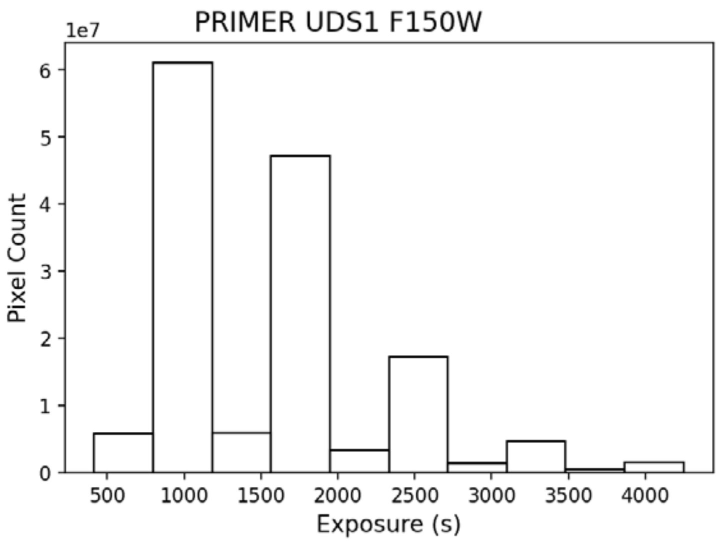
114.45 arcmin^2

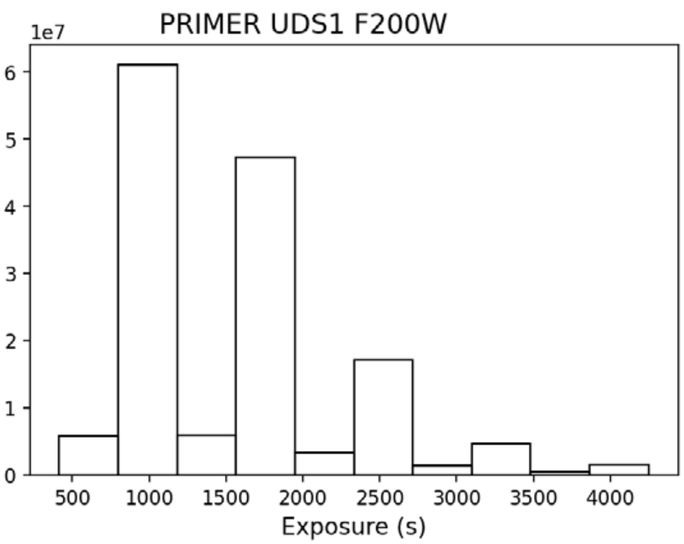
F090W, F115W, F150W, F200W

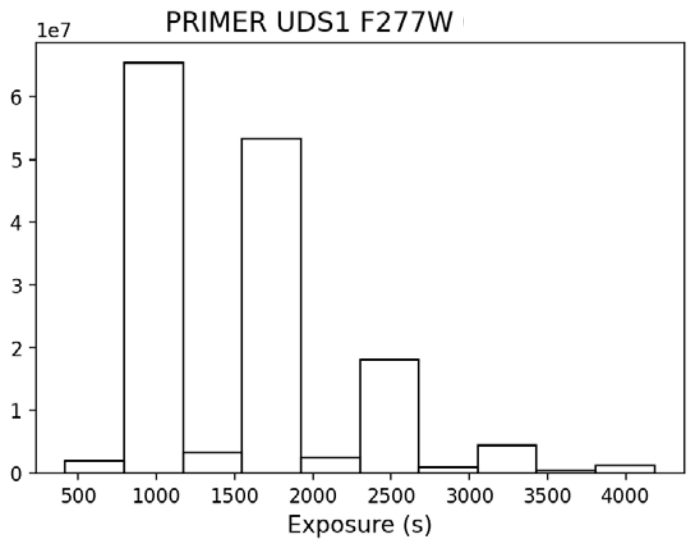
F277W, F356W, F410M, F444W

~1-2 ks







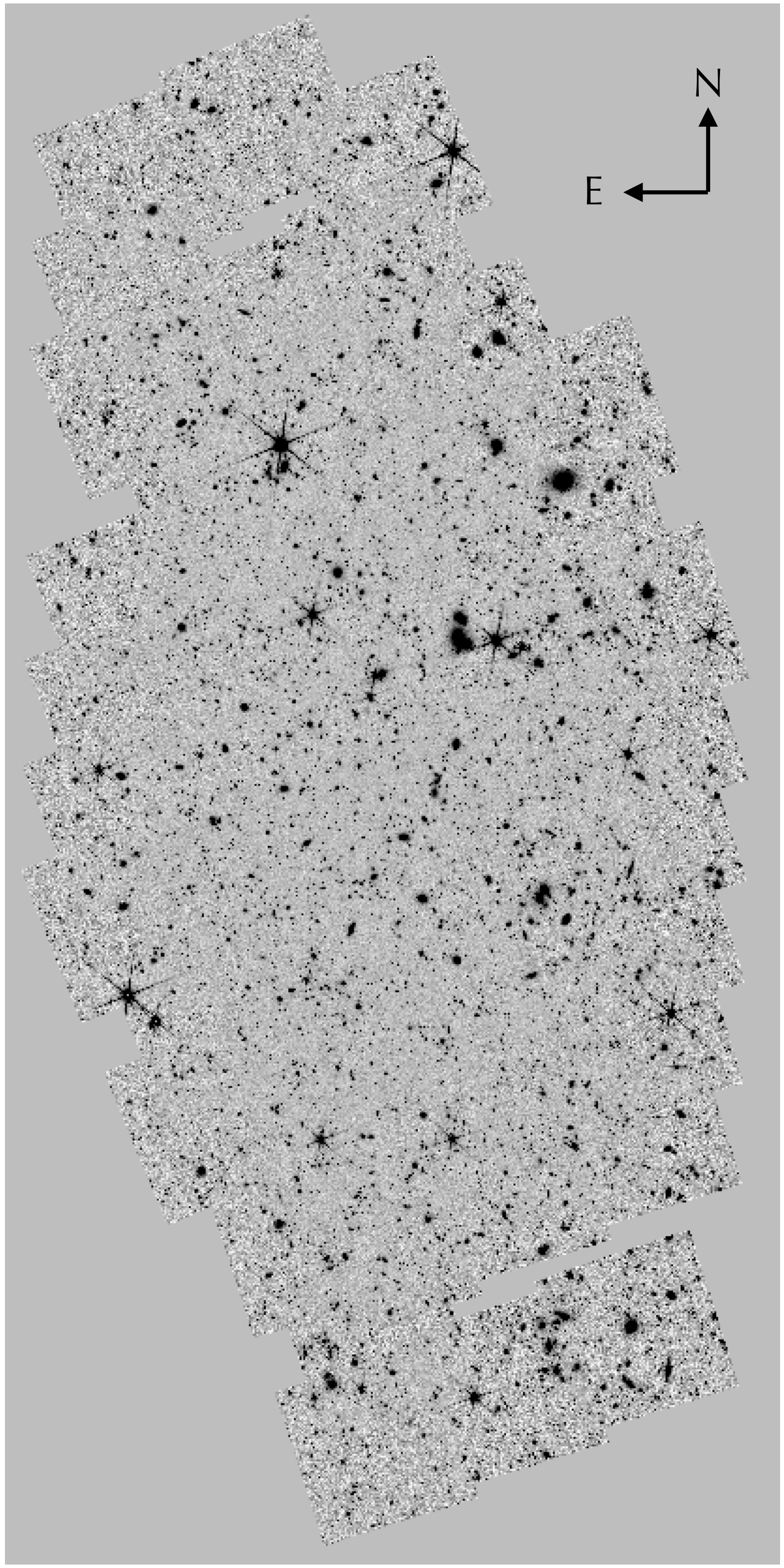


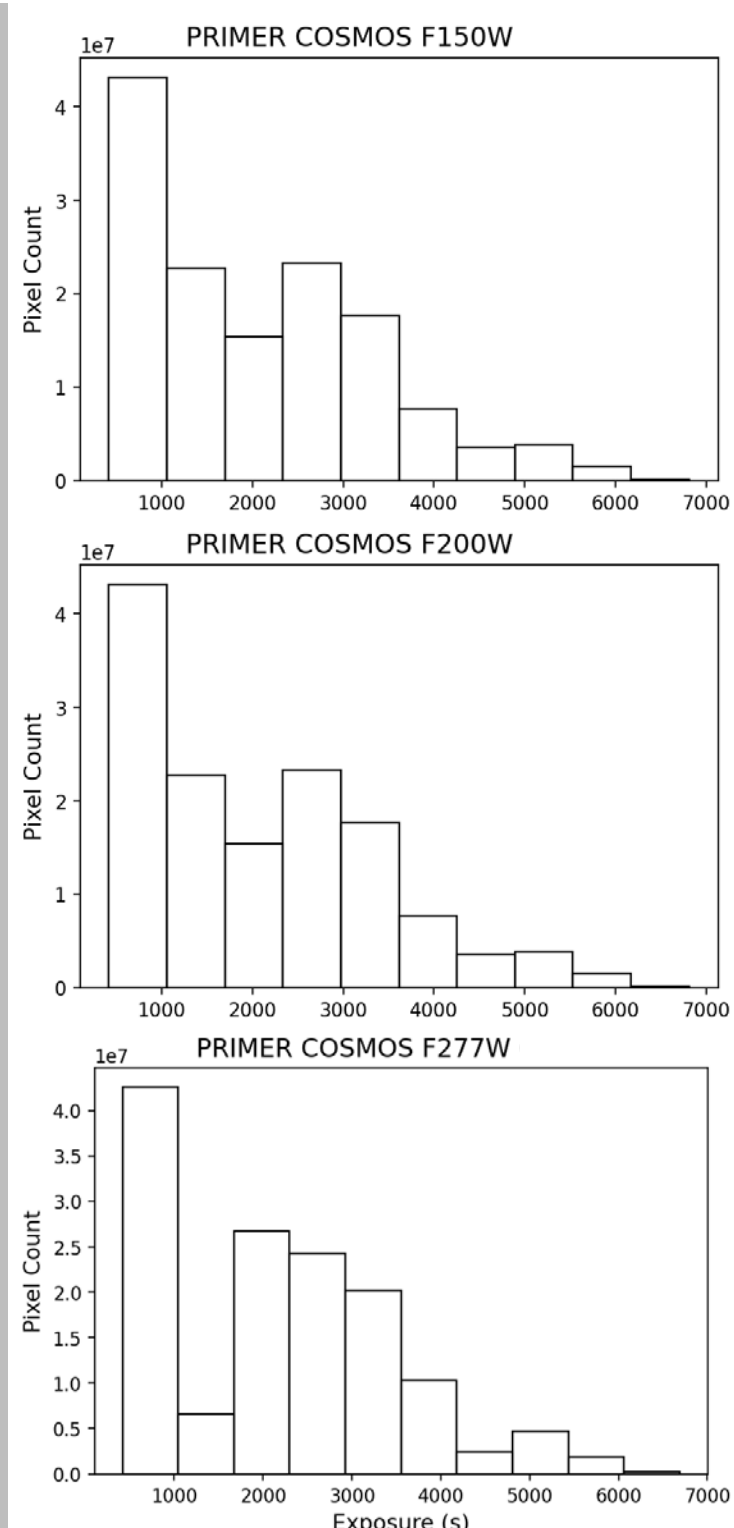
PRIMER COSMOS

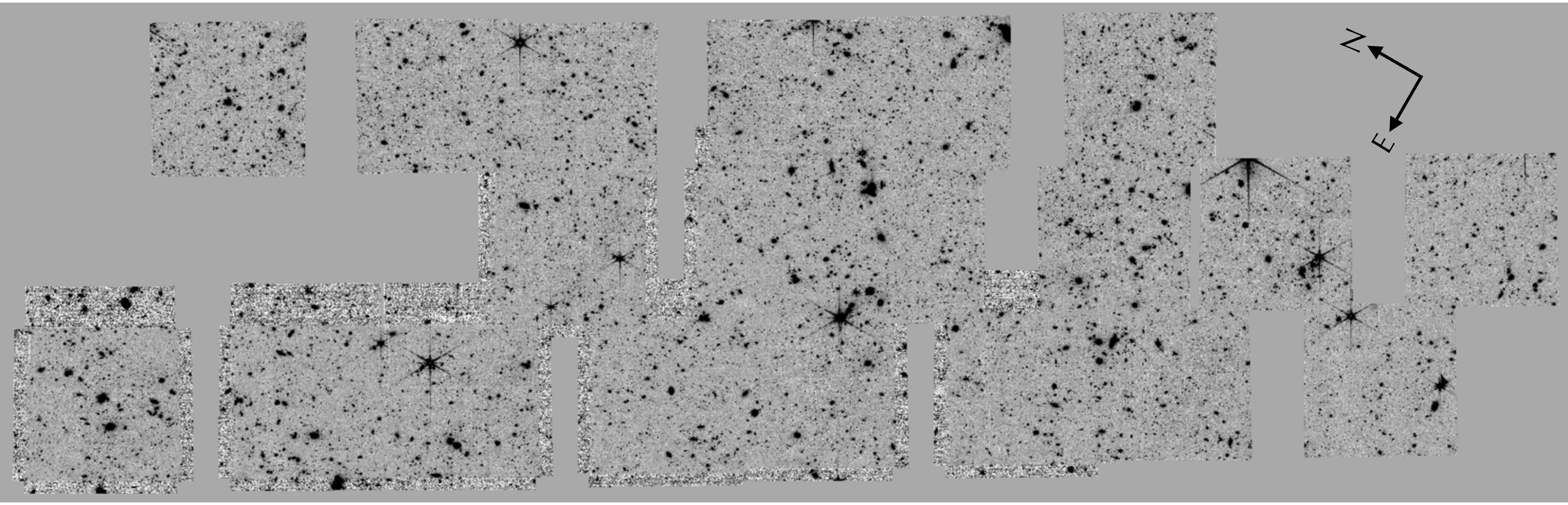
Effective area:
137.13 arcmin^2

F090W, F115W,
F150W, F200W
F277W, F356W,
F410M, F444W

~2.5 ks





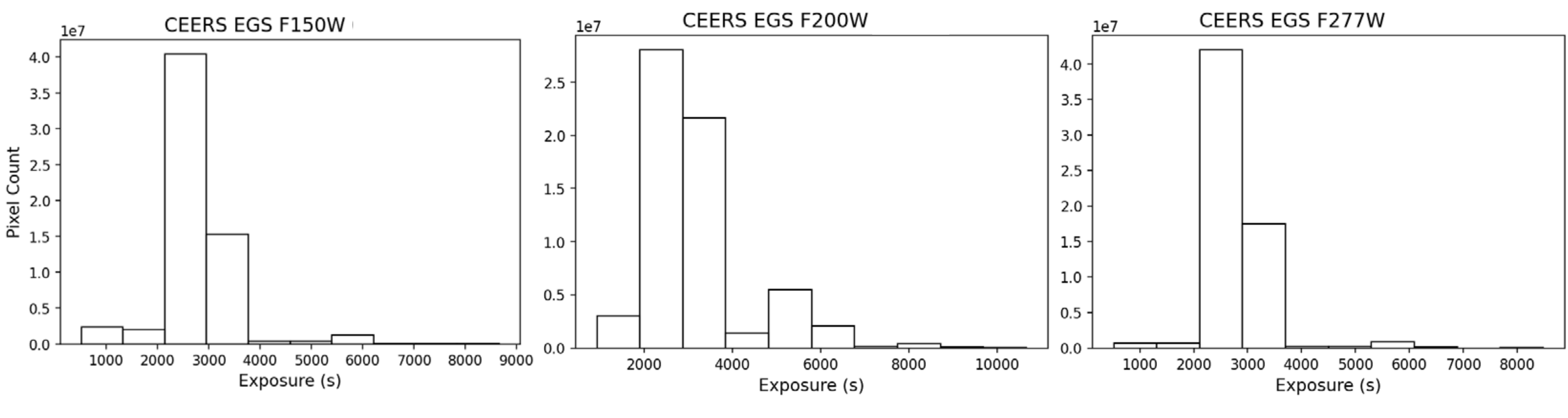


CEERS

Effective area 86.45 arcmin^2

F115W, F150W, F200W, F277W, F356W, F410M, F444W

~2.5 ks

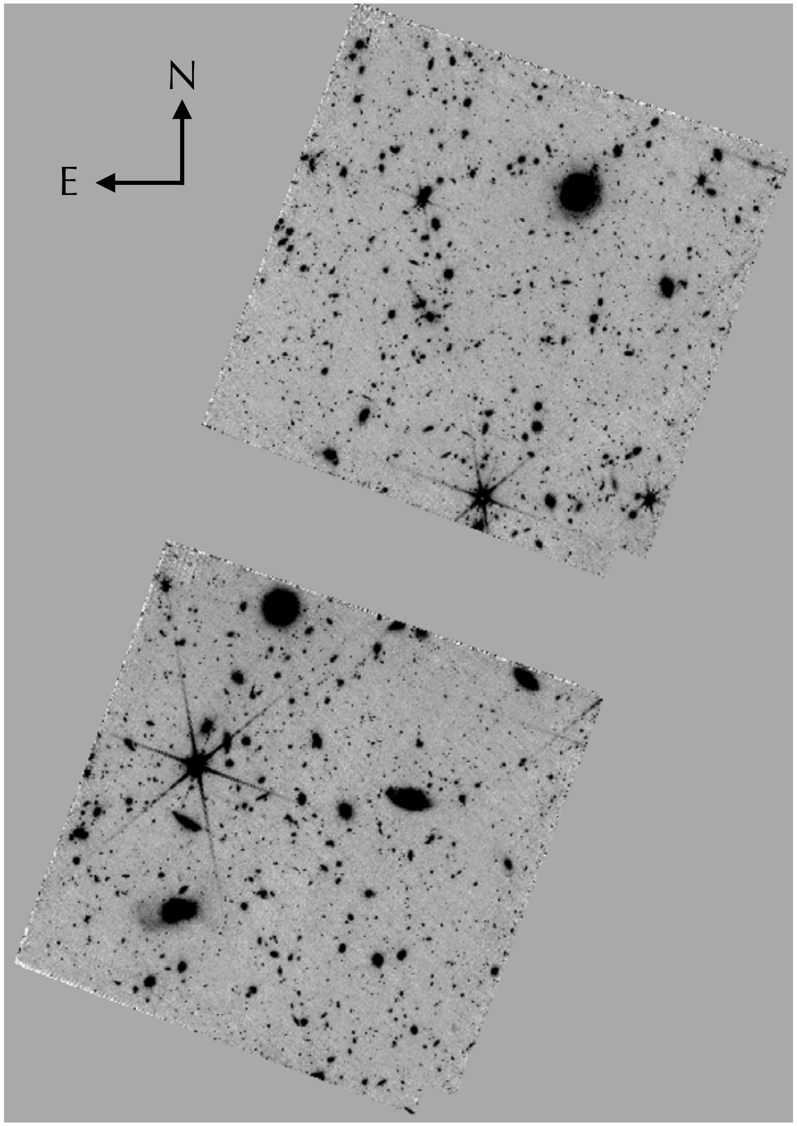


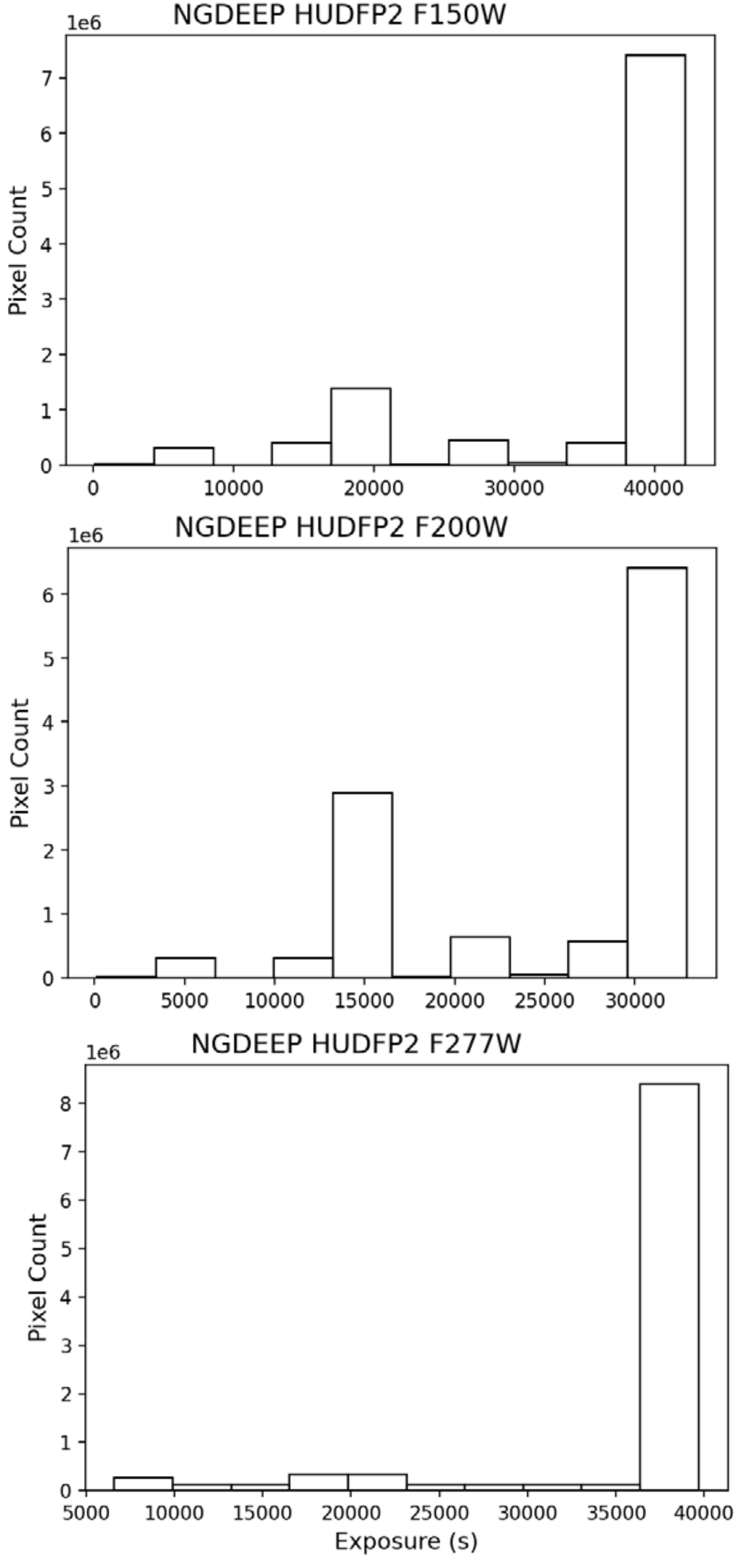
NGDEEP

Effective area:
9.14 arcmin^2

F115W, F150W, F200W
F277W, F356W, F444W

~30-40 ks



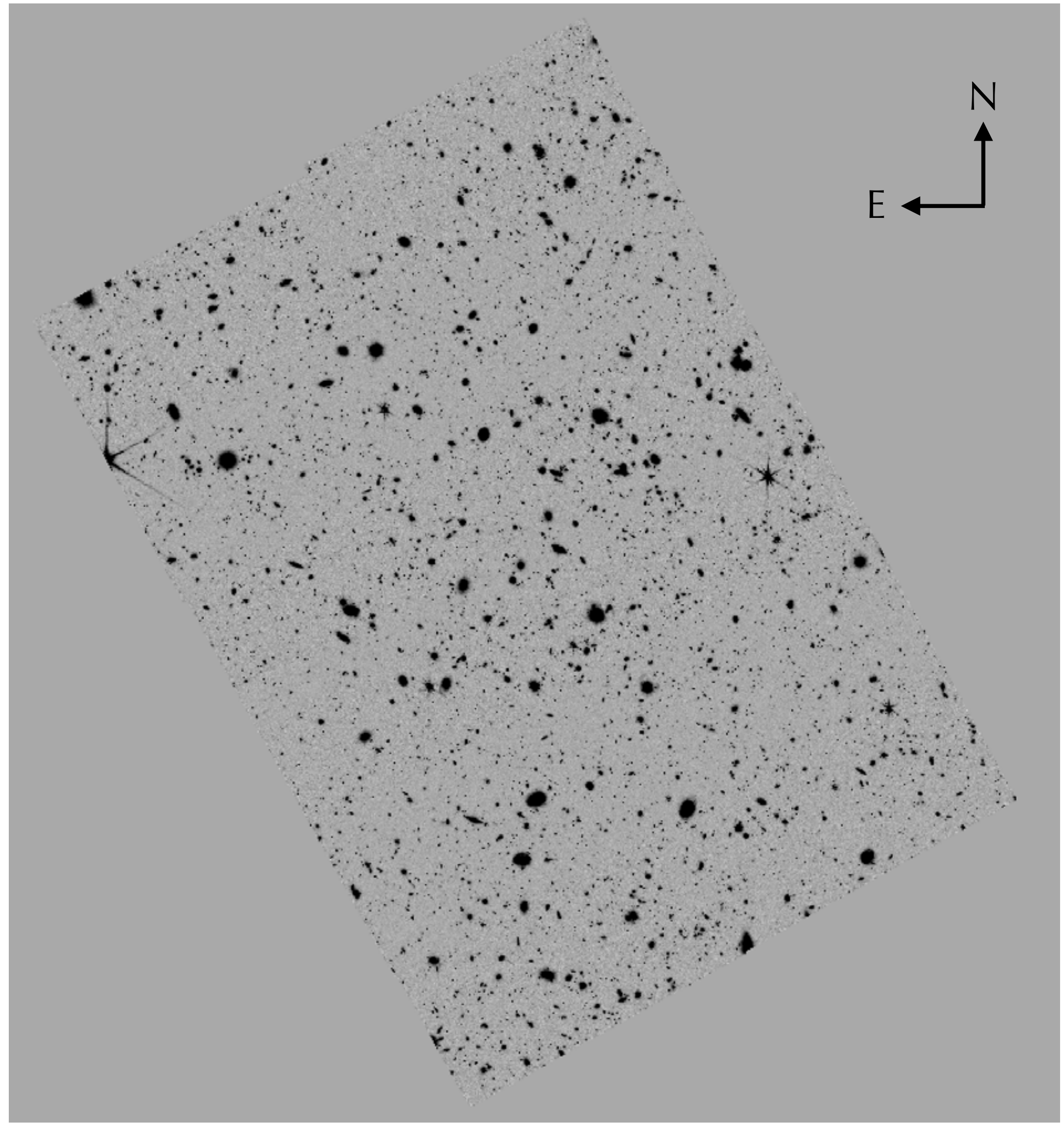


JADES DR1

Effective area:
25.5 arcmin^2

F090W, F115W, F150W, F200W
F277W, F355M, F356W, F410M, F444W

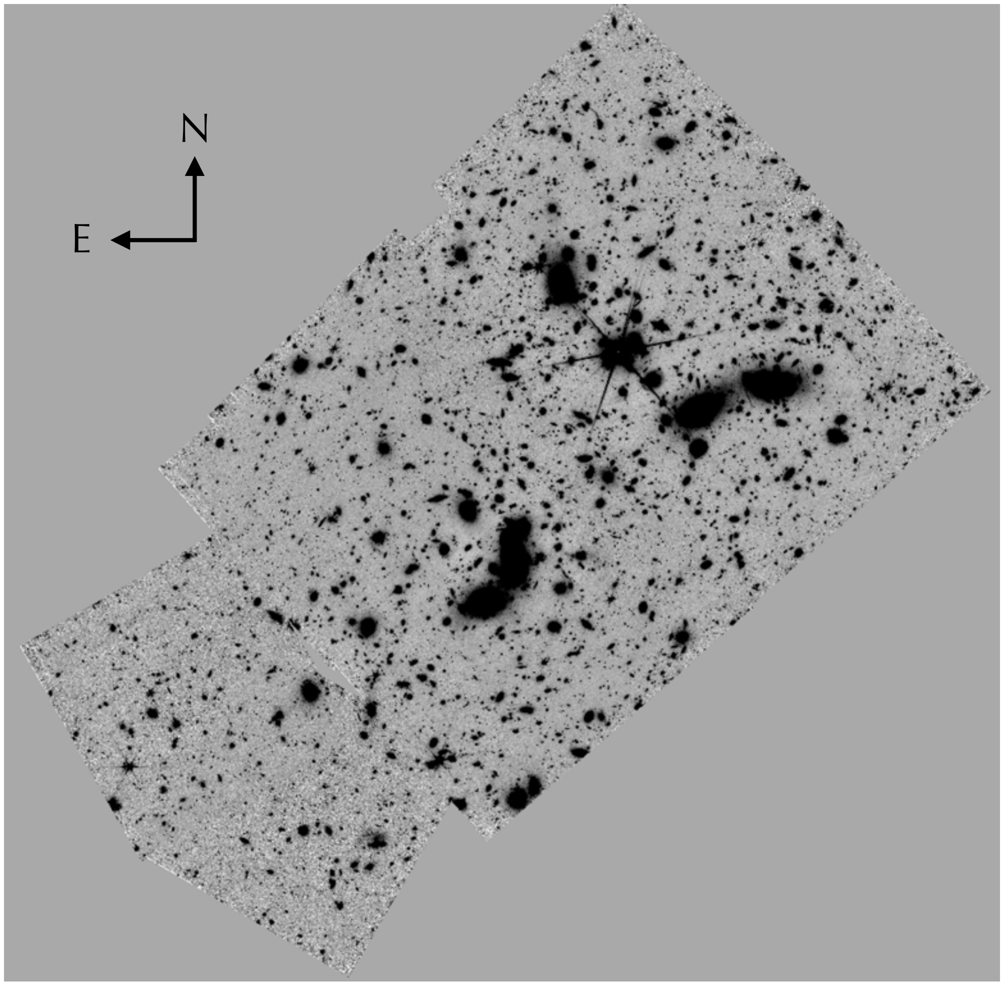
Exposure times 14 - 60 ks per band



UNCOVER + DD2756

Effective area

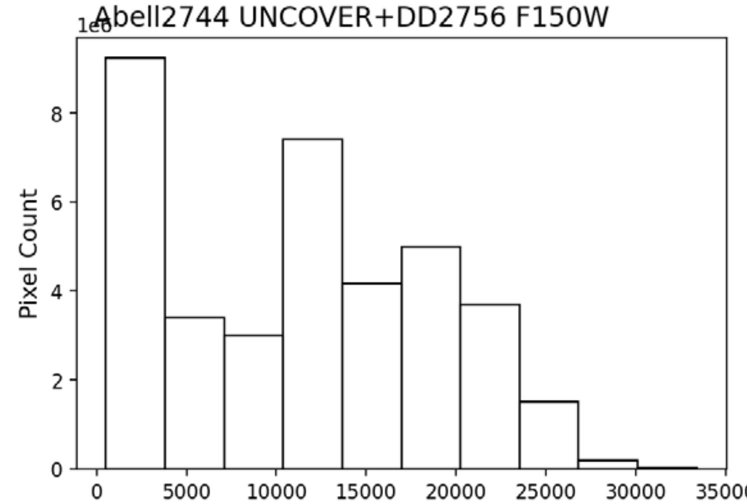
37.04 arcmin²

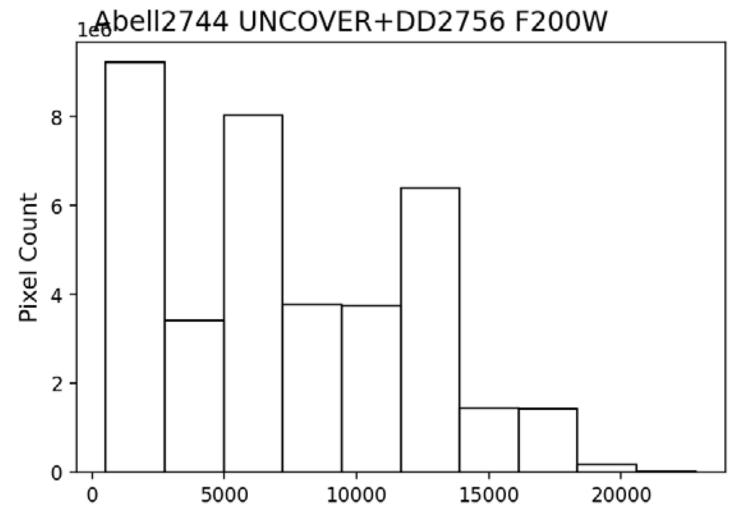


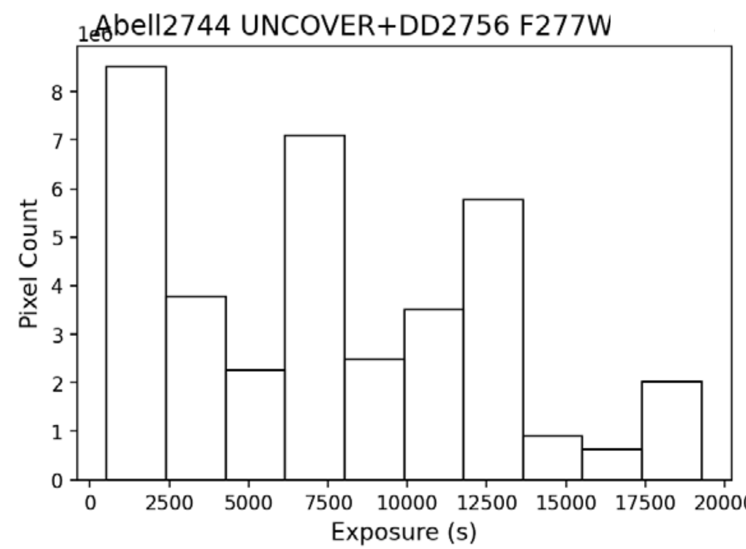
F115W, F150W, F200W

F277W, F356W, F410M, F444W

~15 ks



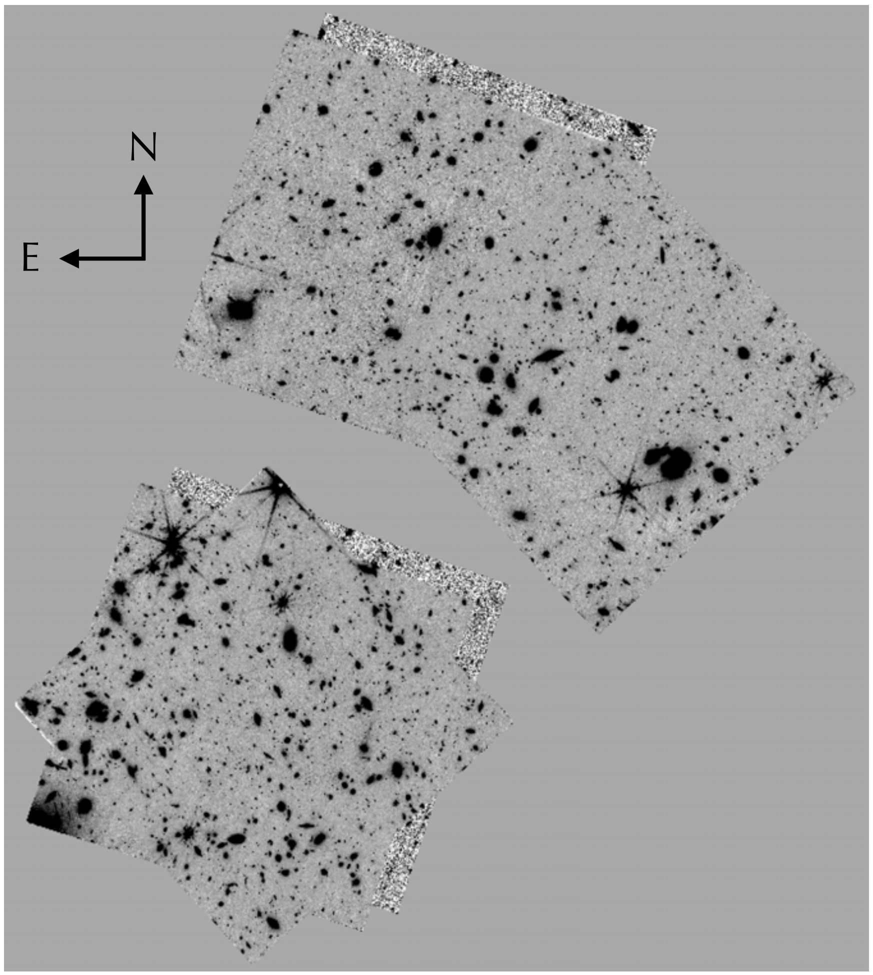




GLASS

Effective area

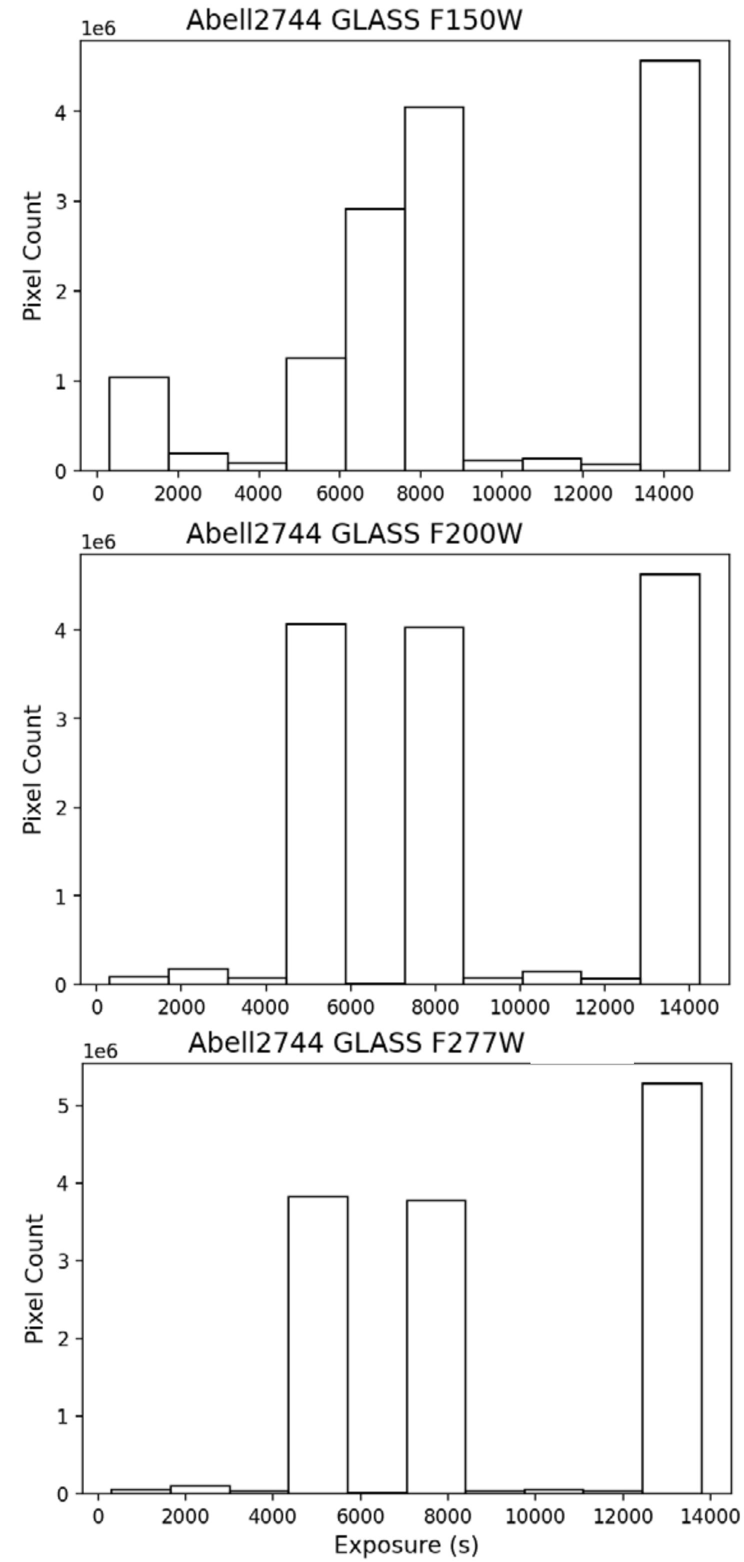
12.31 $arcmin^2$



F090W, F115W, F150W, F200W

F277W, F356W, F444W

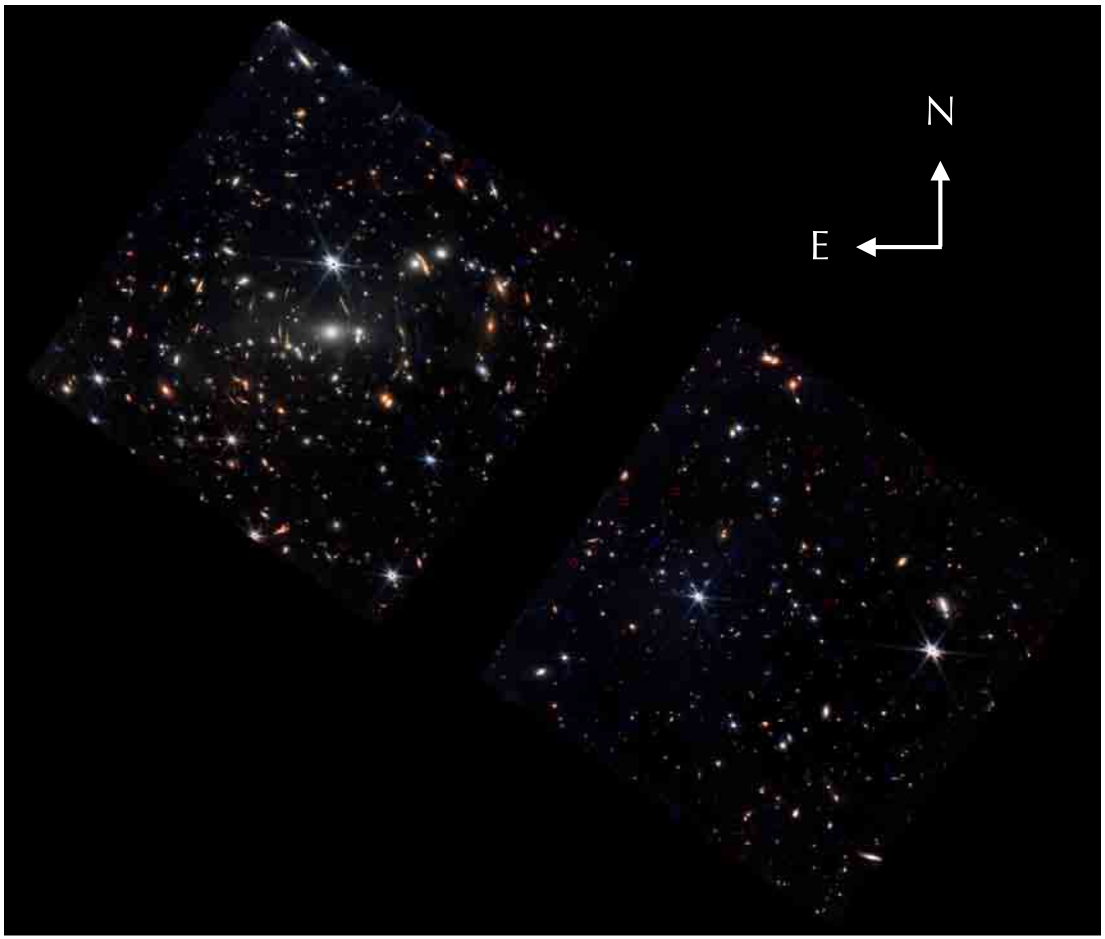
~8 ks



ERO SMACS0723

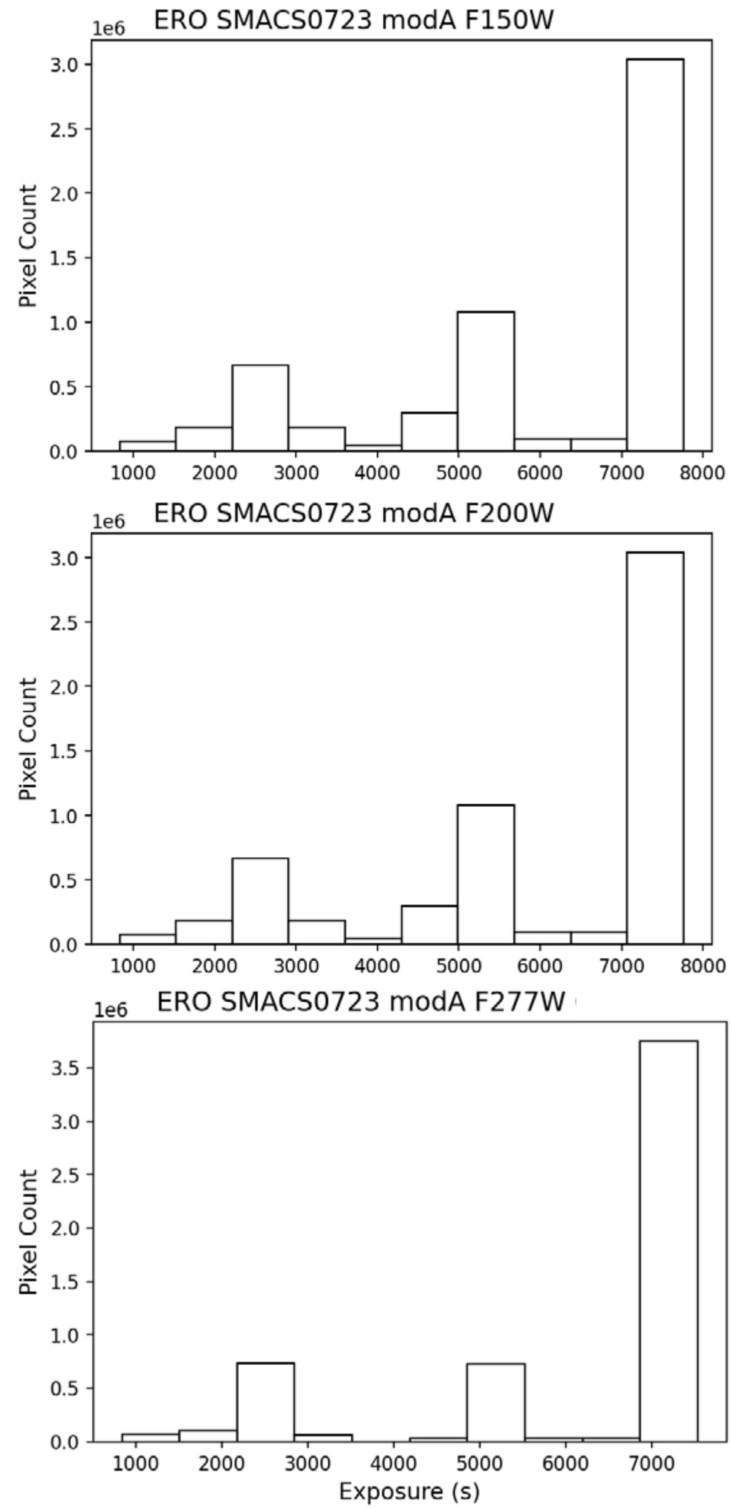
Effective area

11.08 $arcmin^2$



F090W, F150W, F200W
F277W, F356W, F444W

~7 ks



PRIMER

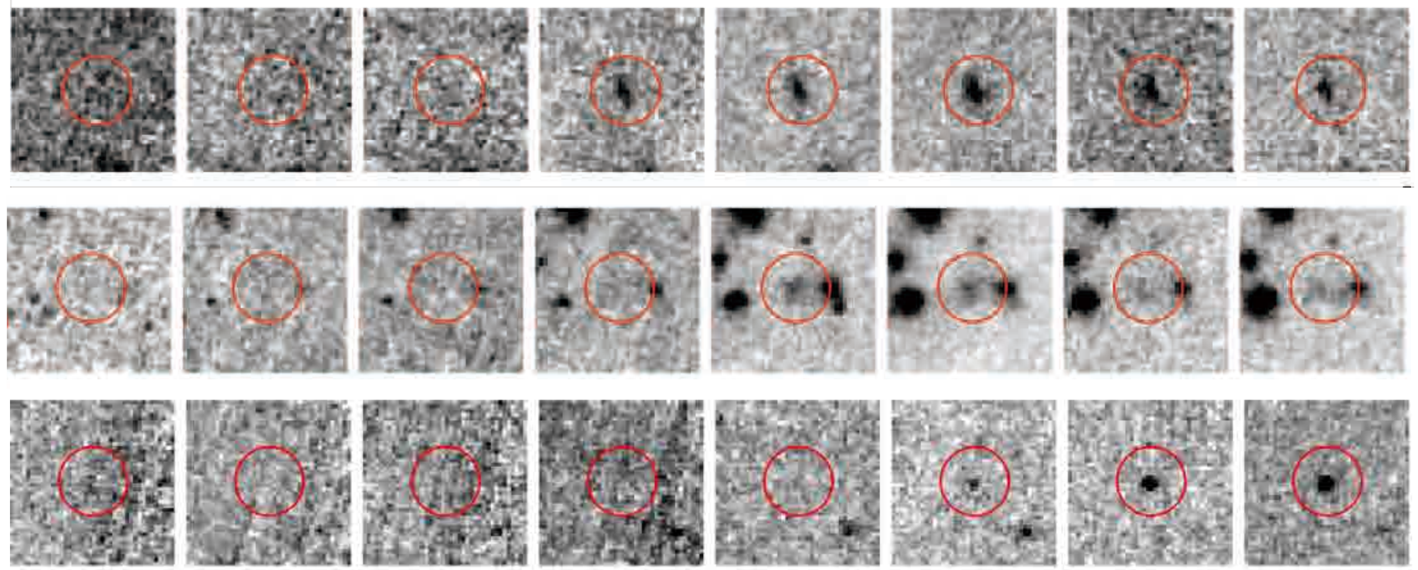
Dropout examples

F090W F115W F150W F200W F277W F356W F410M F444W

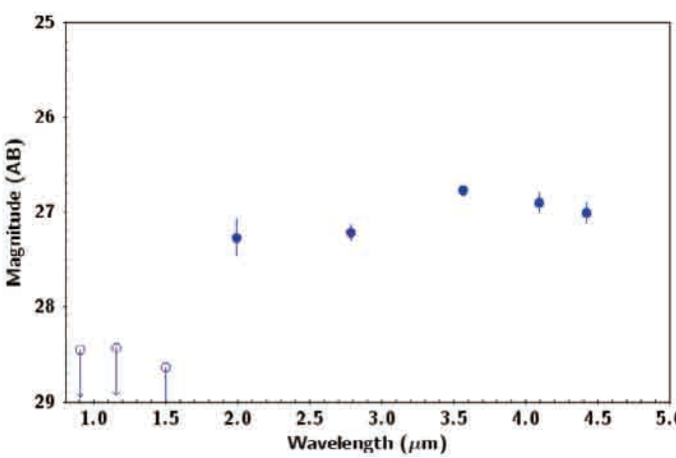
UDS1_F150D_036

UDS1_F200D_058

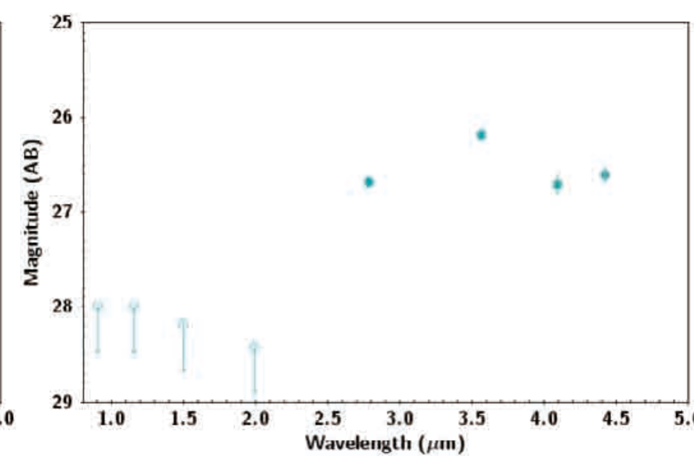
UDS1_F277D_069



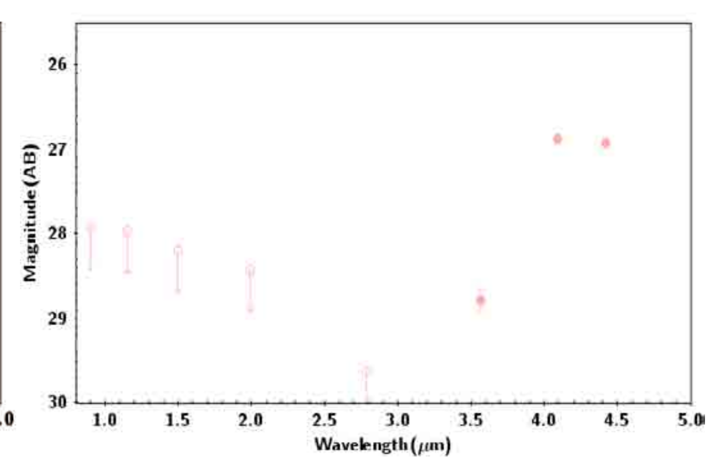
UDS1_F150D_036



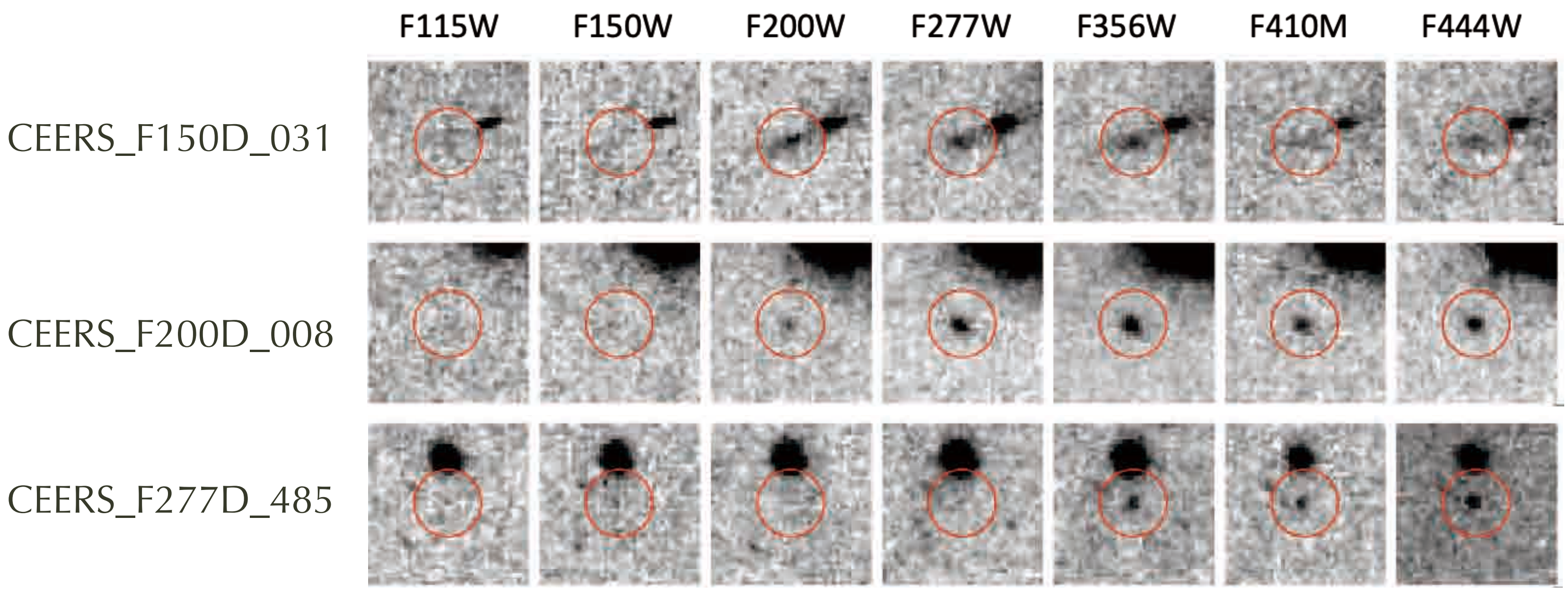
UDS1_F200D_058



UDS1_F277D_069



CEERS
Dropout examples



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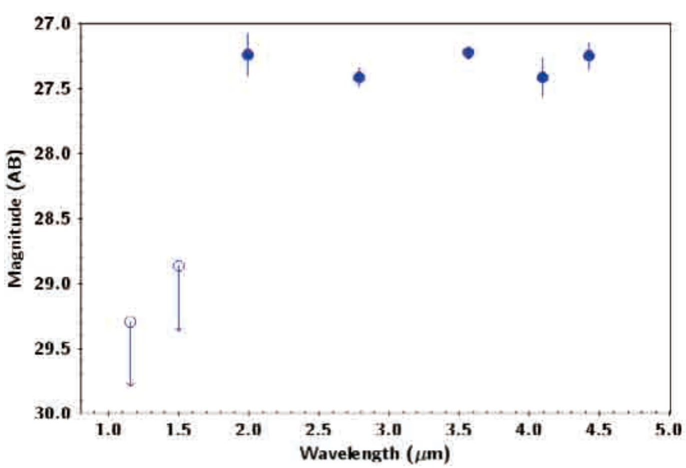
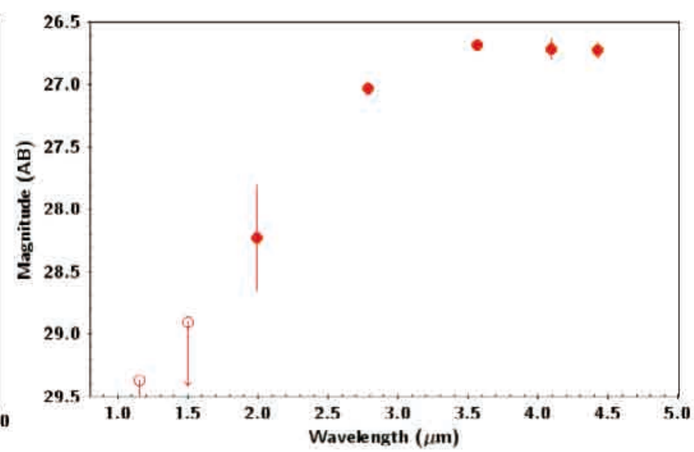
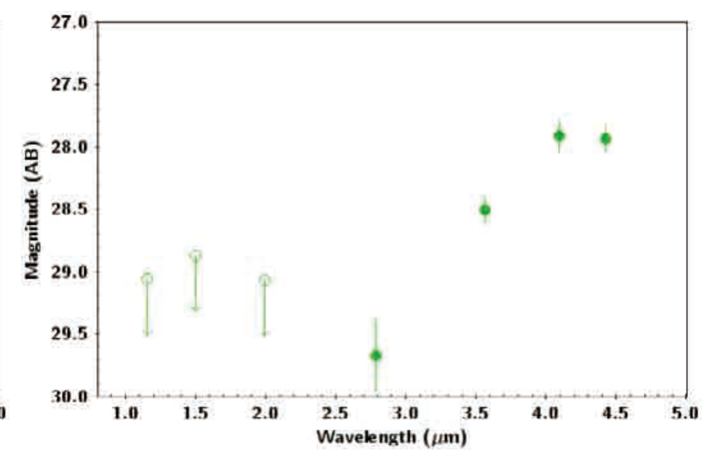


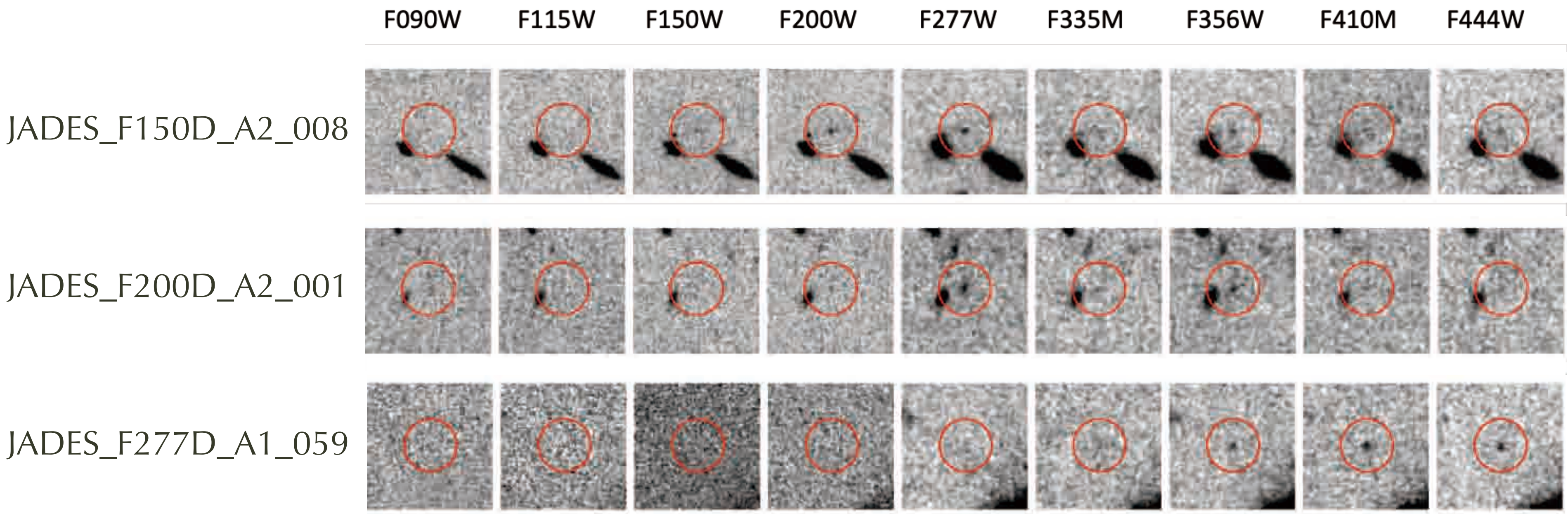
CEERS_F200D_008



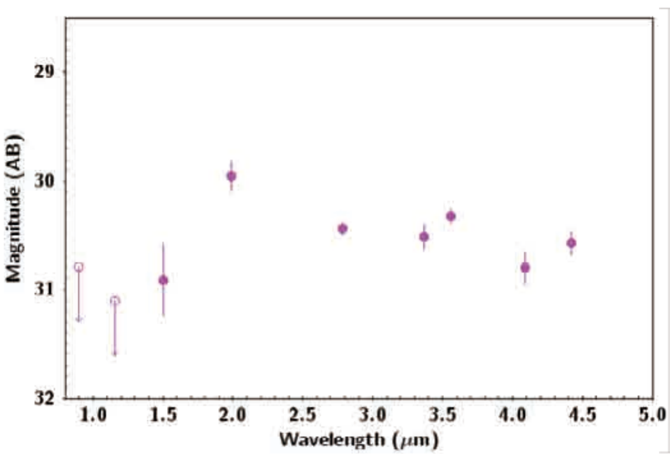
CEERS_F277D_485



JADES DR1
Dropout examples



JADES_F150D_A2_008



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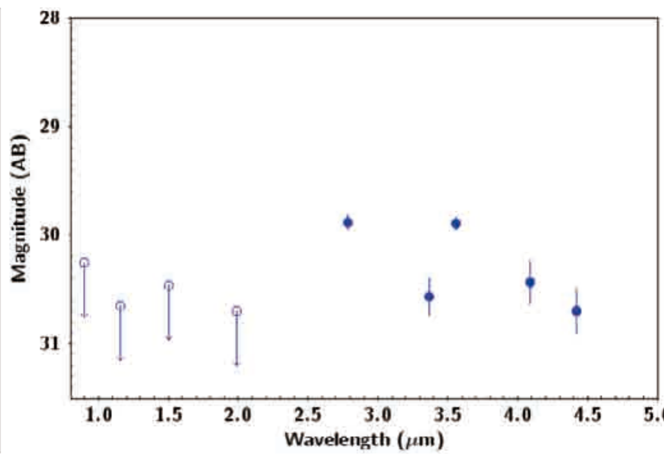

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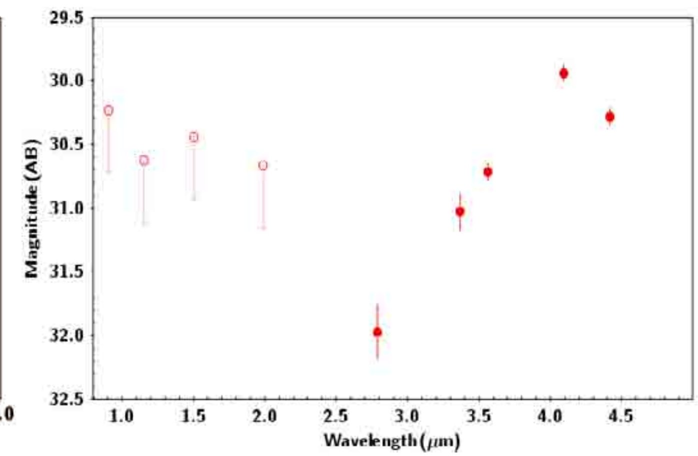
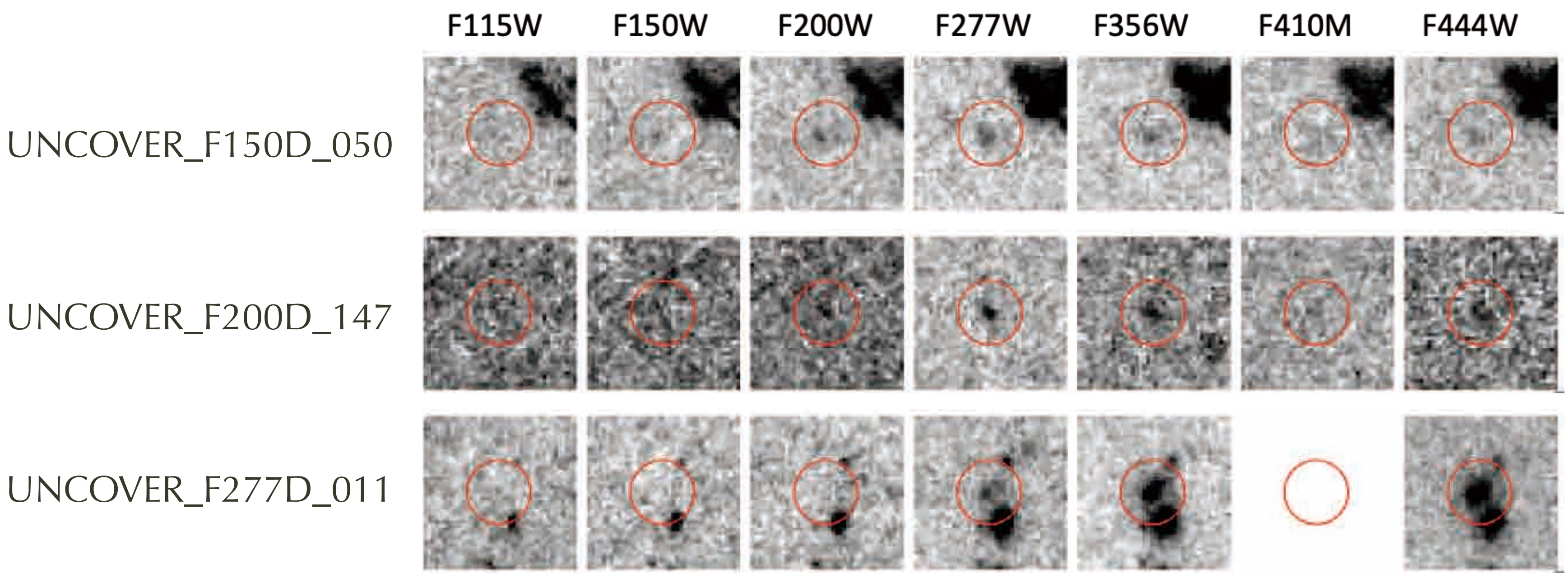
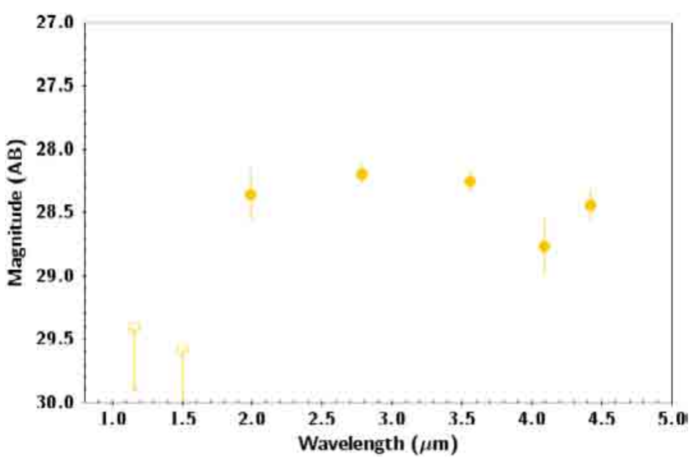


UNCOVER+DD2756

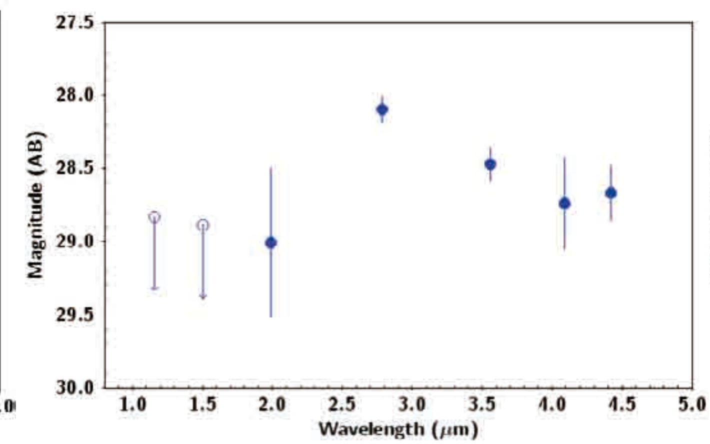
Dropout examples



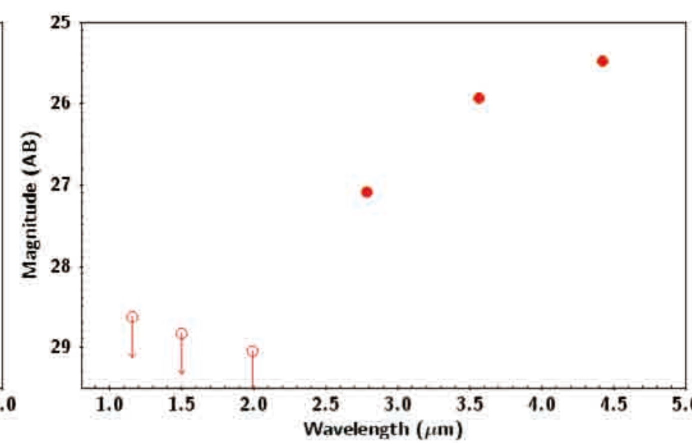
UNCOVER_F150D_050



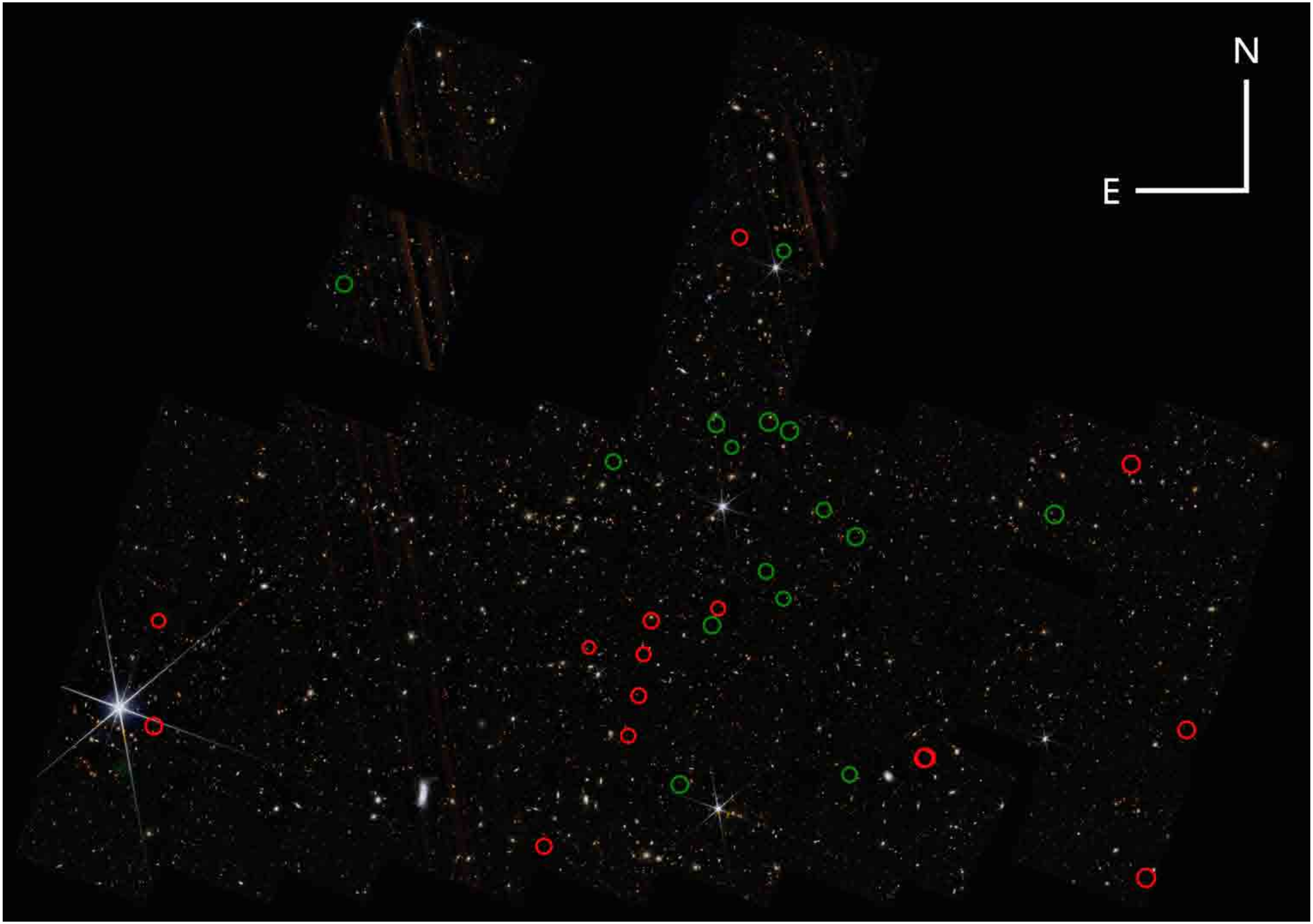
UNCOVER_F200D_147



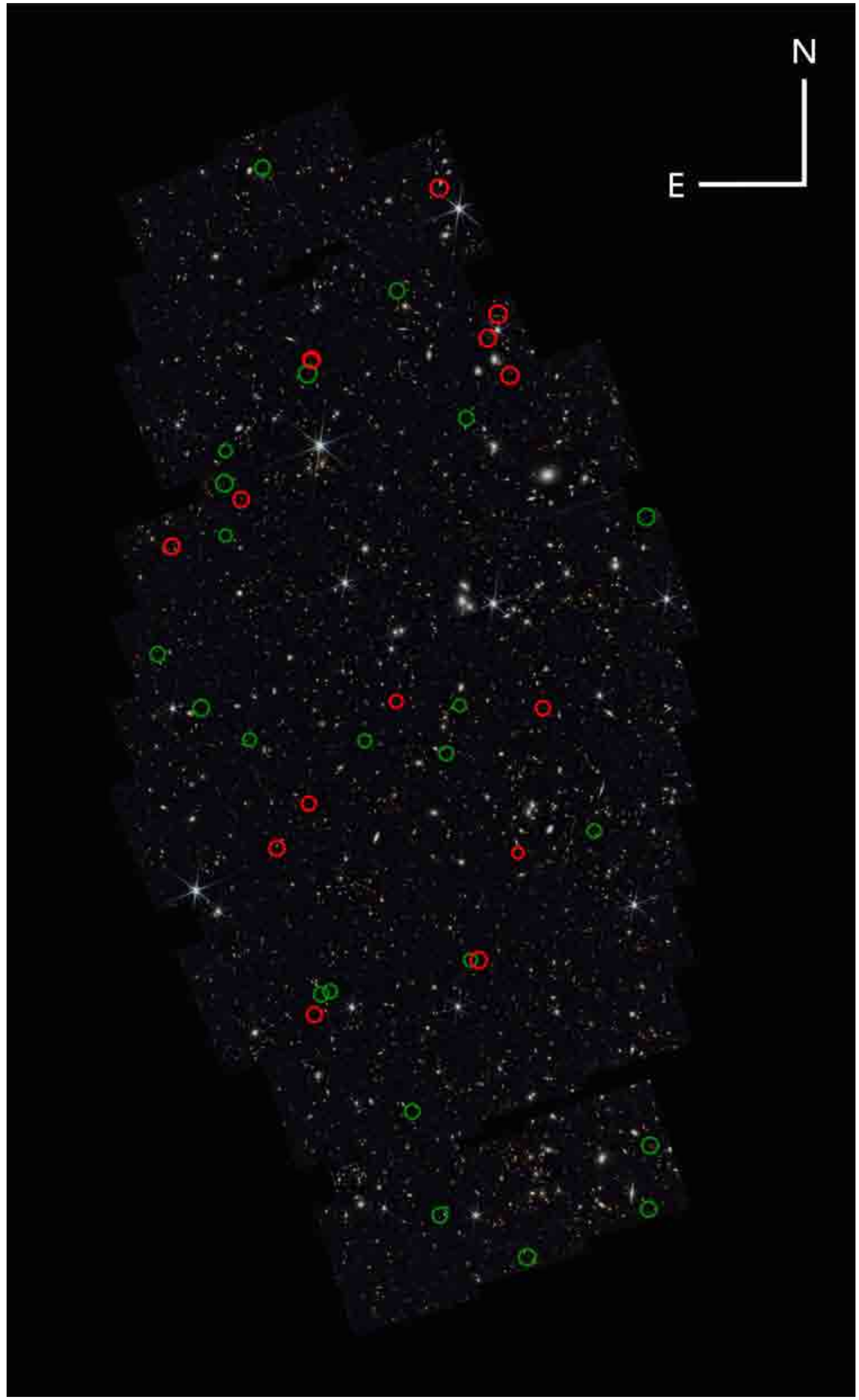
UNCOVER_F277D_011



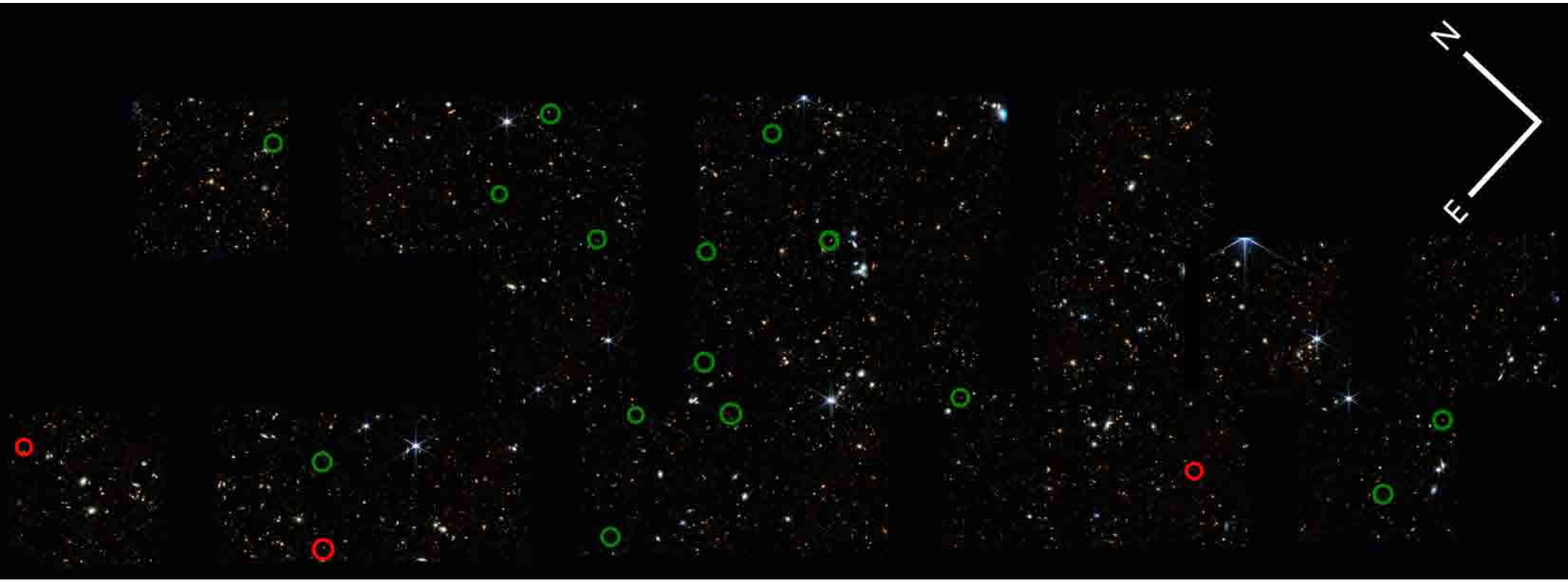
PRIMER UDS1



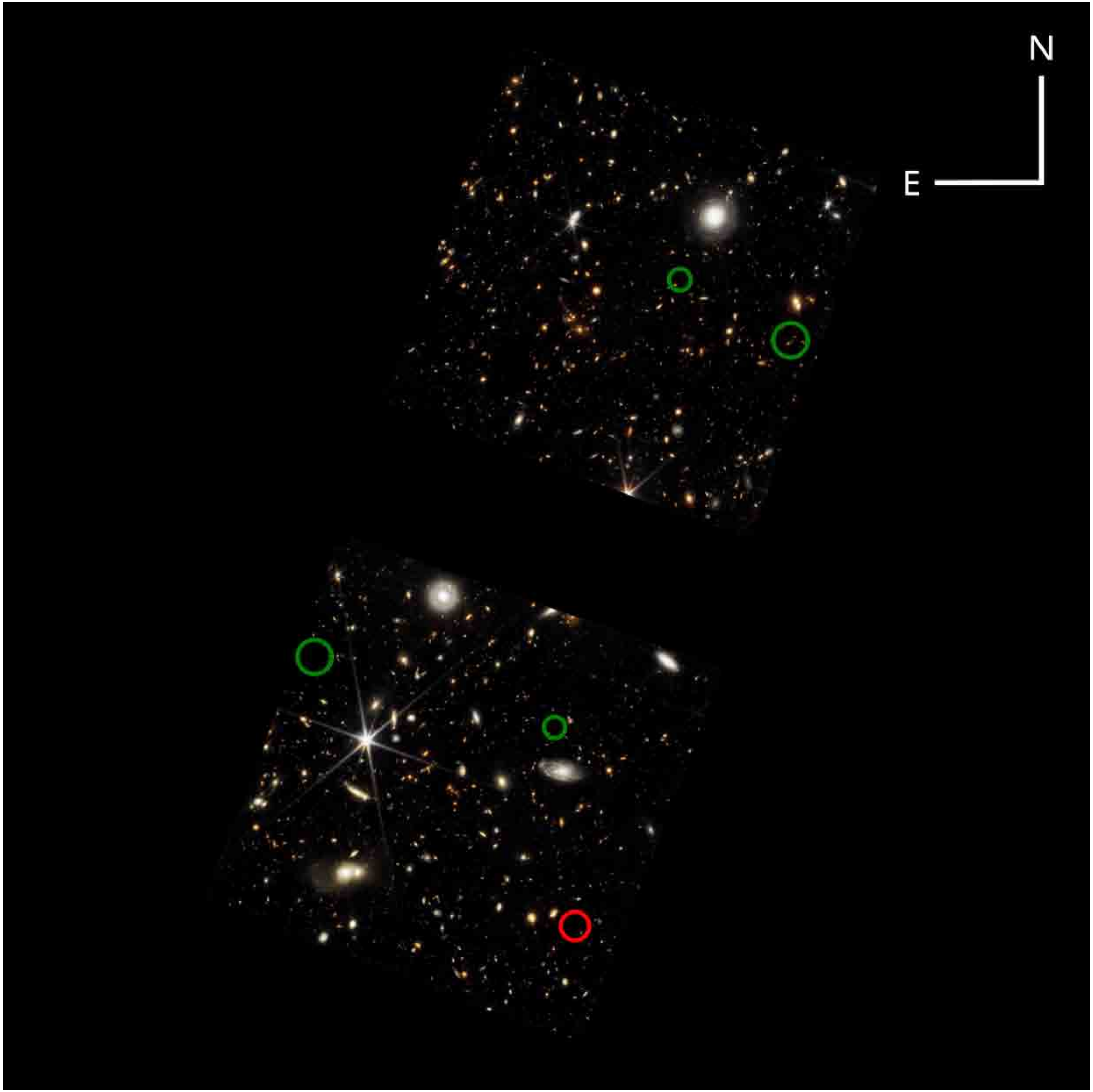
PRIMER COSMOS



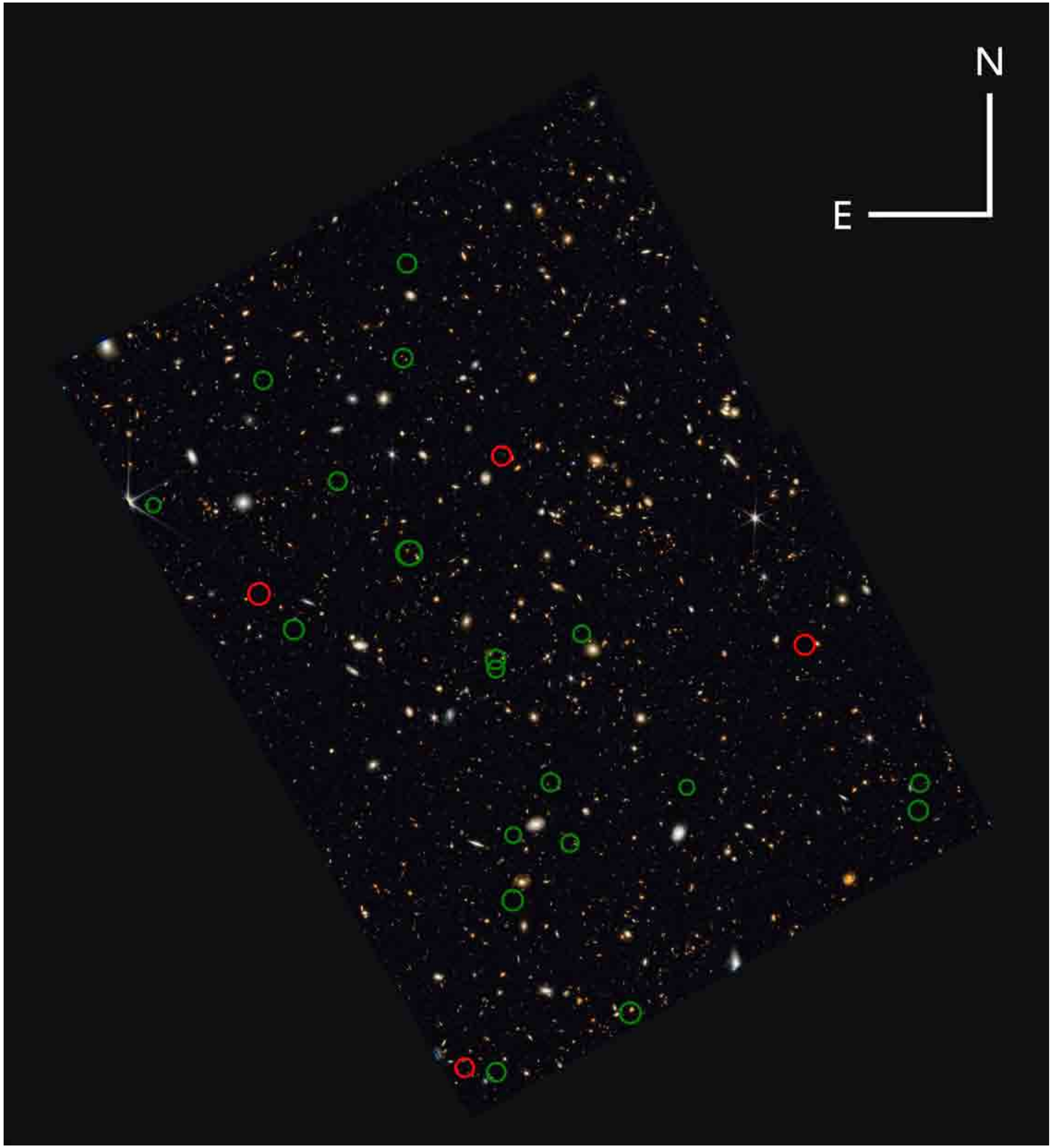
CEERS



NGDEEP



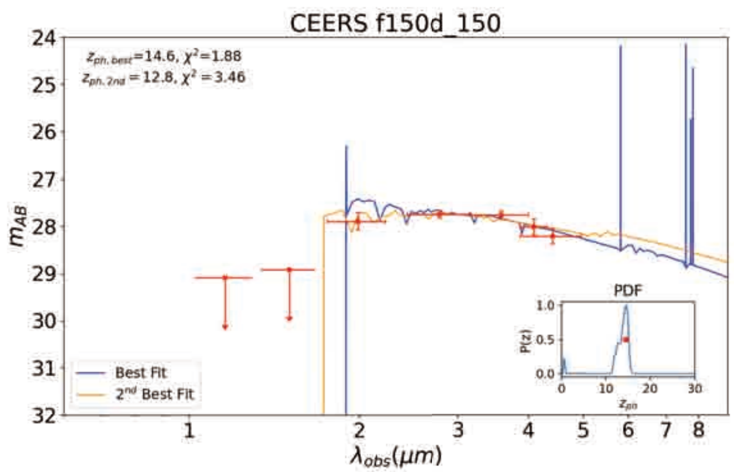
JADES GOODS-S

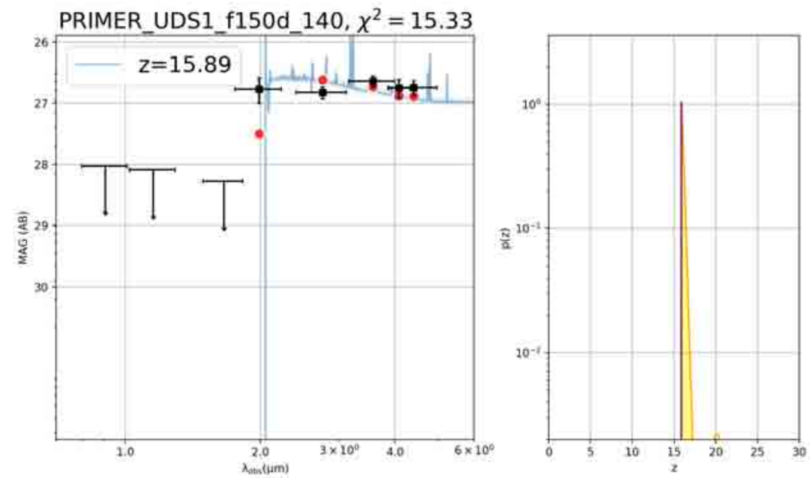


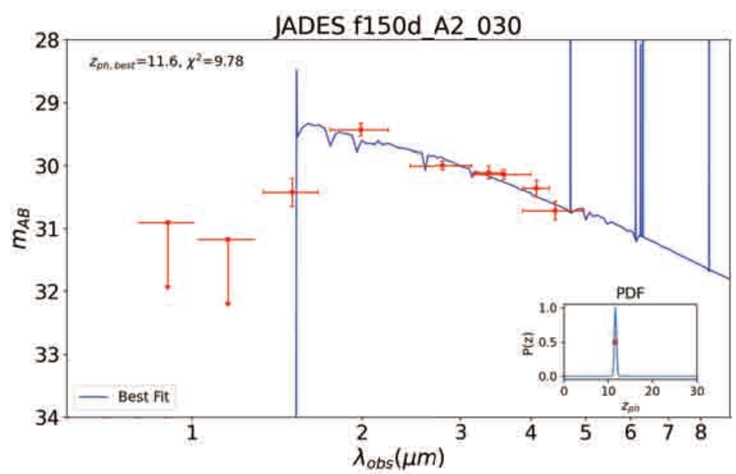
Contaminations ?

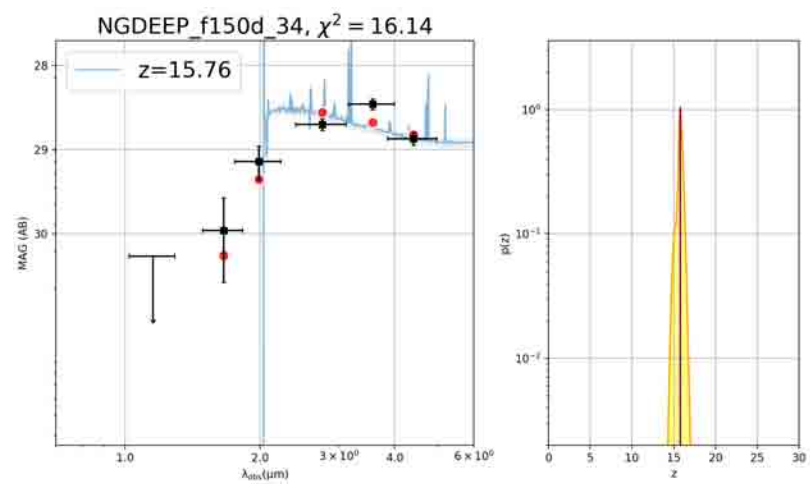
- SED-fitting to assess the contamination rates
  - Two different softwares/templates: Le Phare (w/ emission lines) and EAZY (using set 3 + 4)

Examples of good candidates









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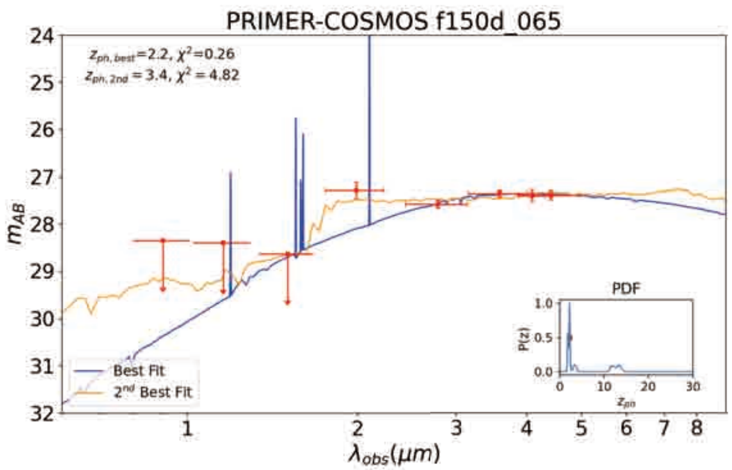
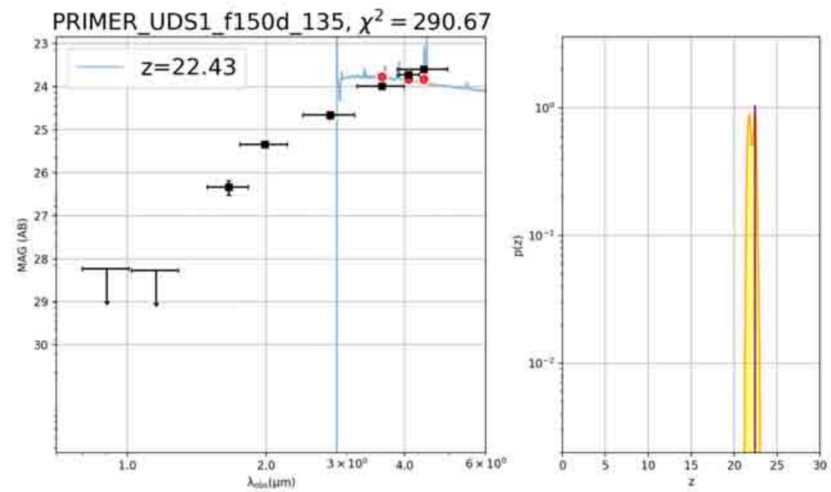
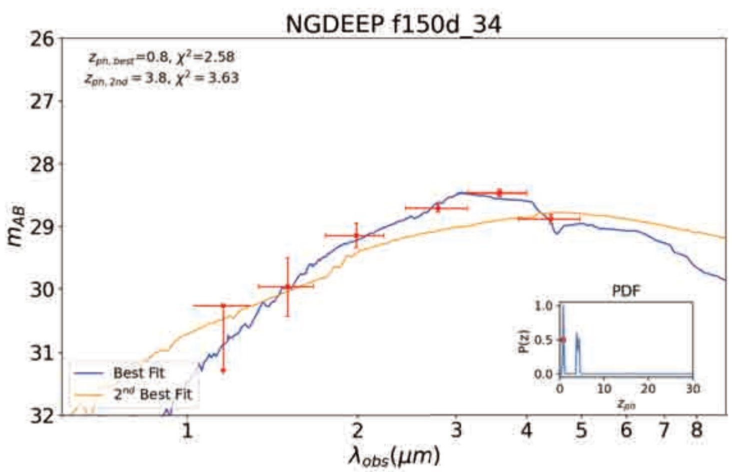
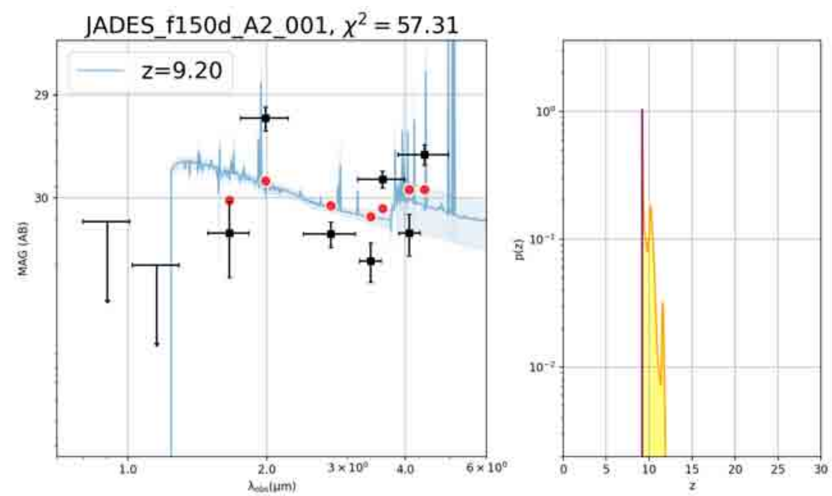
Examples of **bad** candidates





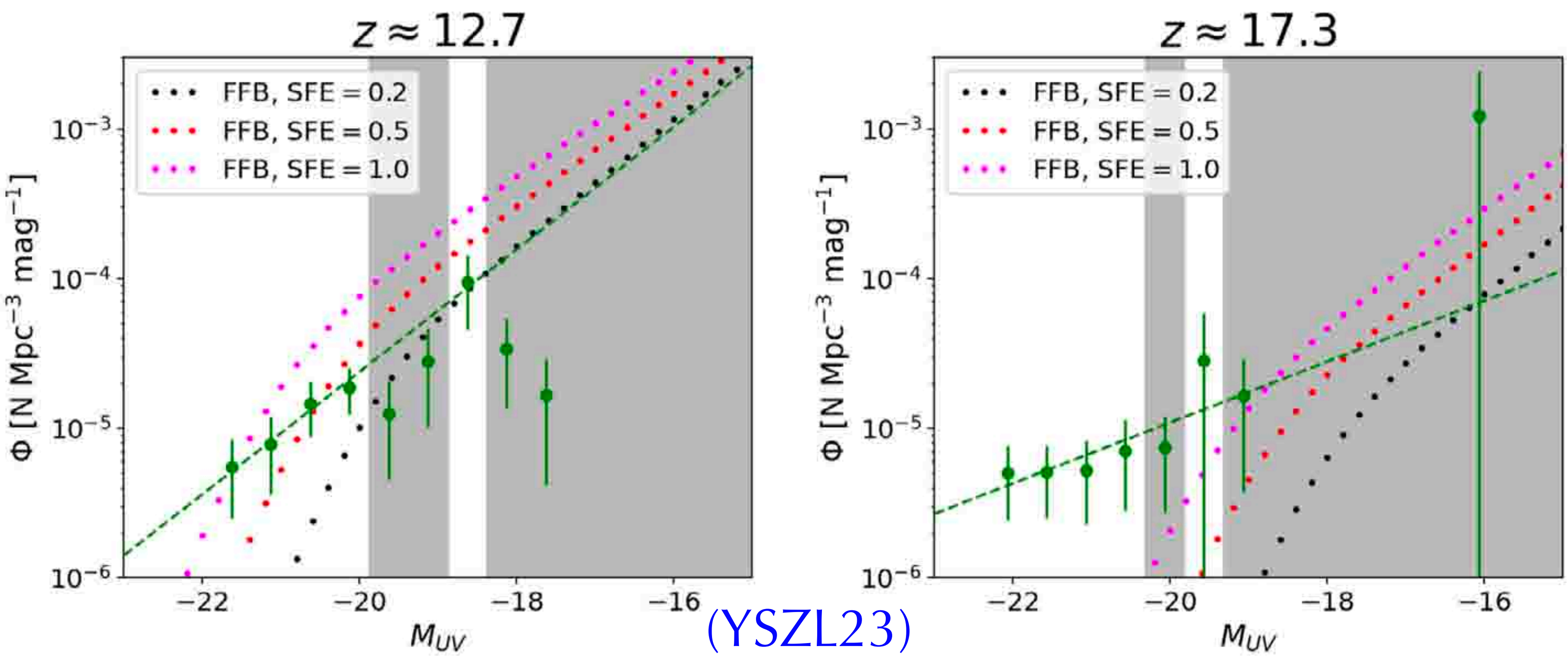




Deriving Luminosity Functions

- Using the two sets of purified F150W and F200W dropouts
- No attempt to purify the F277W dropouts due to the limited passbands with positive detections
- Lensing magnification corrected in UNCOVER (model as in Furtak et al. 2023) and SMACS 0723 (model as in Pascale et al. 2022)
- Incompleteness corrected through simulations

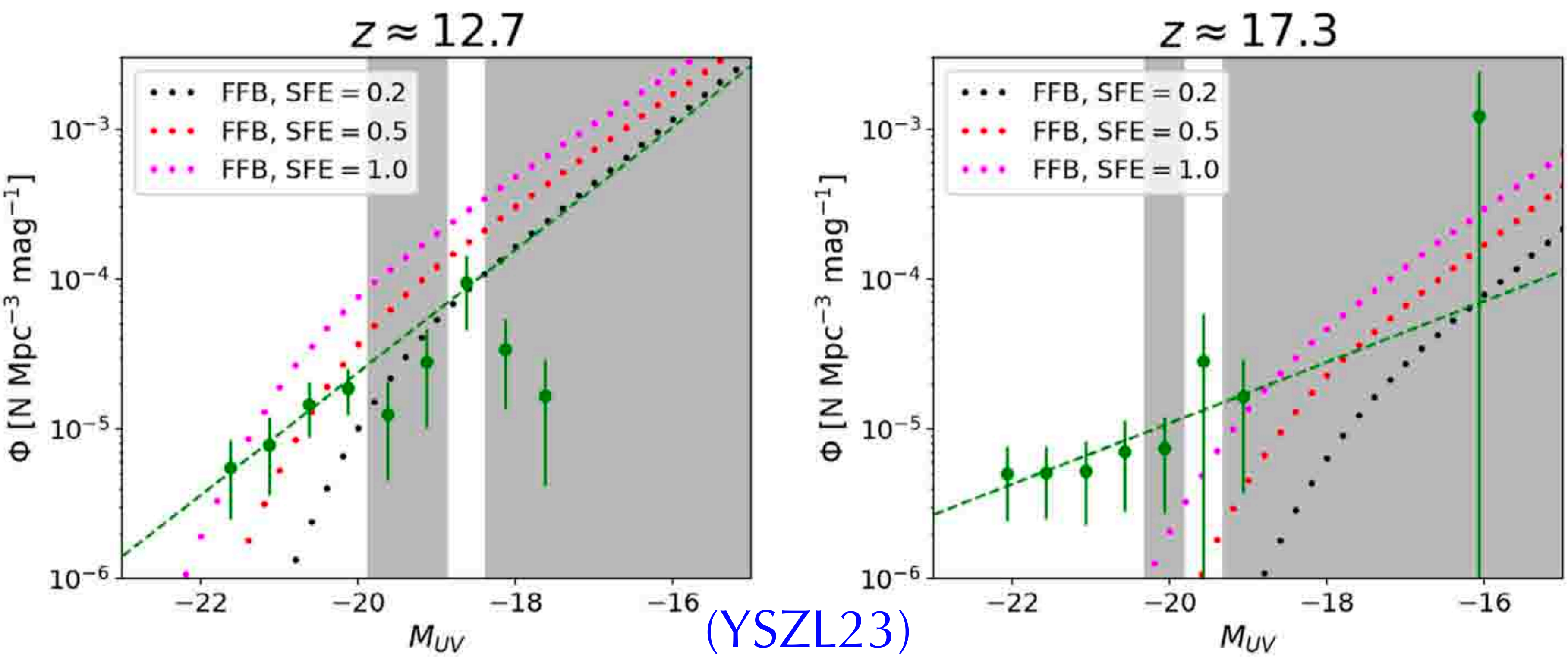
Tentative luminosity functions (LFs)



(YSZL23)

- Total sample consists of 123, 52 and 32 F150W, F200W and F277W dropouts
- LFs based on "purified" F150W and F200W dropouts: (1) better fitted by power-law rather than Schechter function; (2) moderate evolution of < 2x
- Models within the ΛCDM paradigm could explain such objects so early in time

Tentative luminosity functions (LFs)



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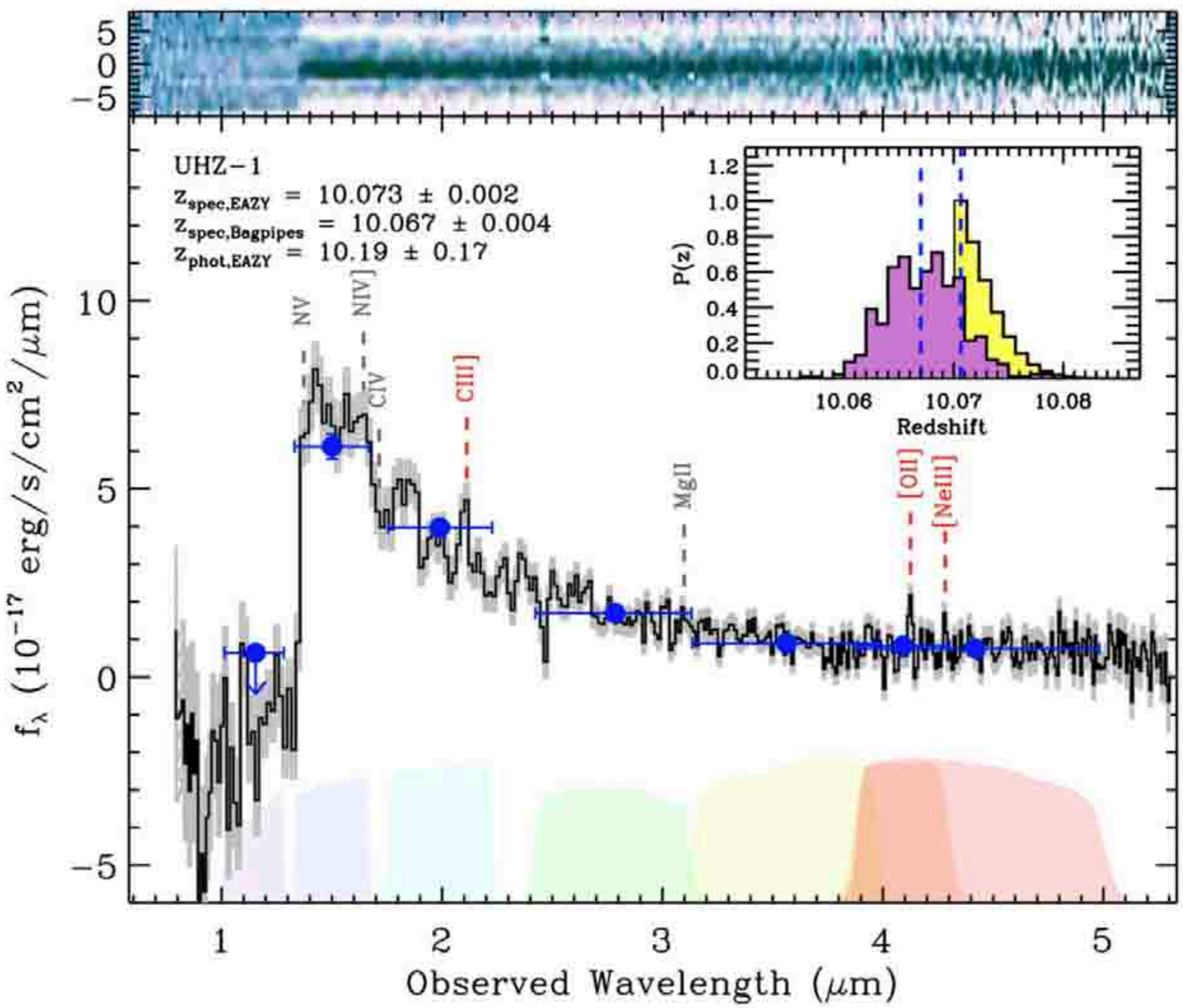
Early emergence of AGN

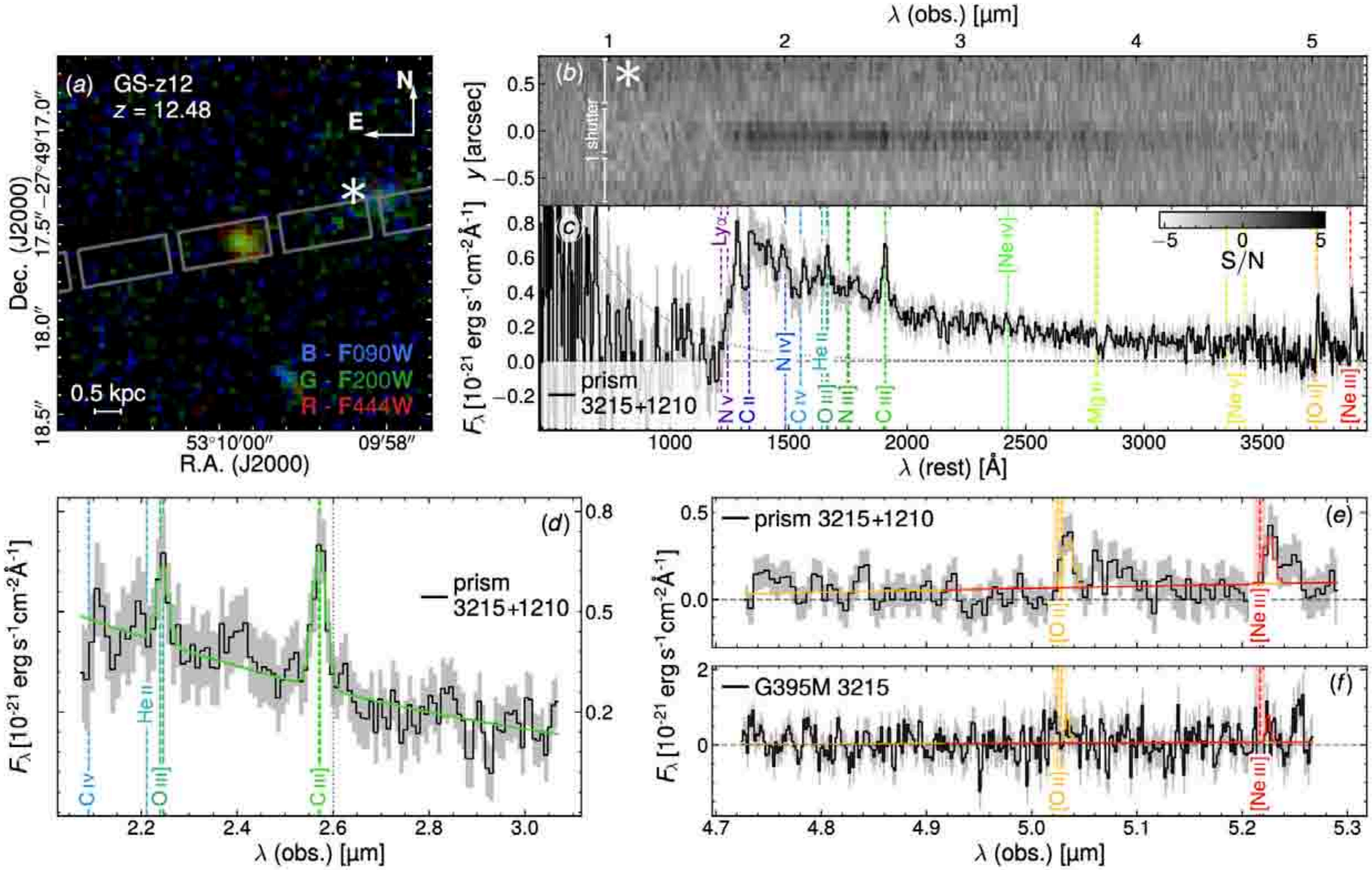


Strong emission in 2-7 keV Rest-frame 20-80 keV; can only be produced by accreting BH

L_X (2-10 keV) > 2×10^{44} erg/s
$M_{BH} \sim 10^{7-8}\ M_{sun}$

- Supporting evidence for an early onset of galaxy population: the UNCOVER collaboration identified an X-ray AGN at z=10.07 (Goulding et al. 2023)

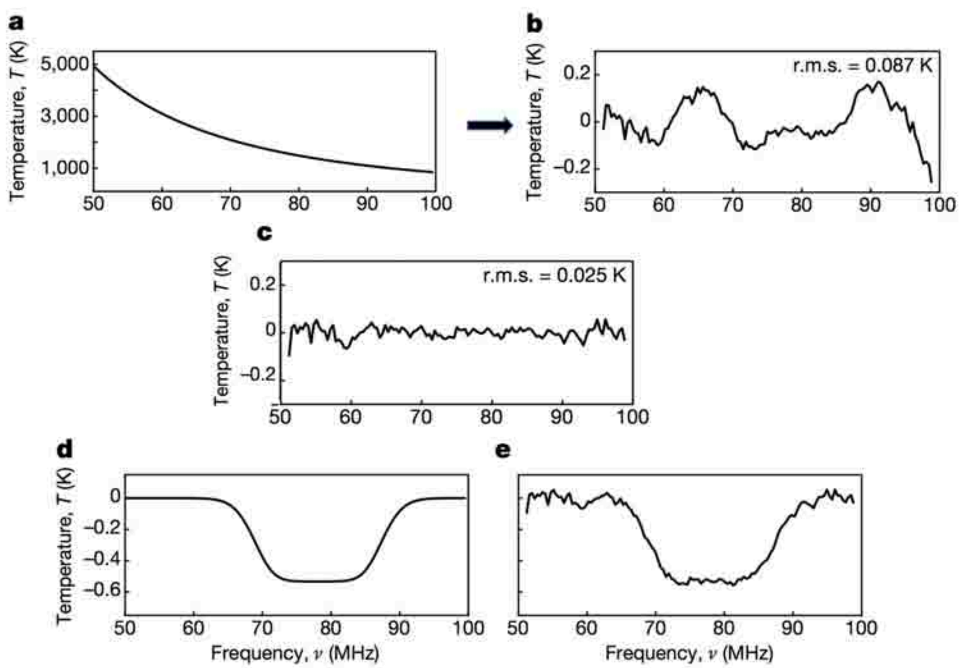
A z ~ 12 galaxy already polluted by metals



- Supporting evidence for an early onset of galaxy population: the JADES collaboration detected multiple metal lines in a galaxy at z=12.48 (D'Eugenio et al. 2023)

Epoch of Reionzation (EoR)

- *Experiment to Detect the Global EoR Signature* ("EDGES"; Bowman et al. 2018) suggests $z_{re} \sim 17.2$ (13.6 - 23.1) based on the tentative detection of 78 MHz absorption line



Bowman et al. (2018)

- F150W (z~12.7) and F200W (z~17.3) dropouts — if they are indeed at the suggested high-z — are consistent with the latter

- F277W-dropouts … z~25?

Summary

- In contradiction to most studies before July 2022, JWST shows that a large number of galaxies could already be in place at $z > 11$
  - Spectroscopic confirmation up to $z=13.2$
  - Candidates up to at least $z \sim 21.8$
- AGN at $z > 10$ and metal abundance in galaxy at $z>12$ all support a very early emergence of galaxy population
- The epoch of first galaxies is likely at $z \sim 17.3$ (consistent with z_{re} inferred from the global H I 21cm measurement)
- Galaxy LF at $z \sim 12.7$ and $z \sim 17.3$ better fitted by power-law than Schechter function
- A lot of details are still needed to rebuild a new picture of early galaxy formation