Distant Galaxies

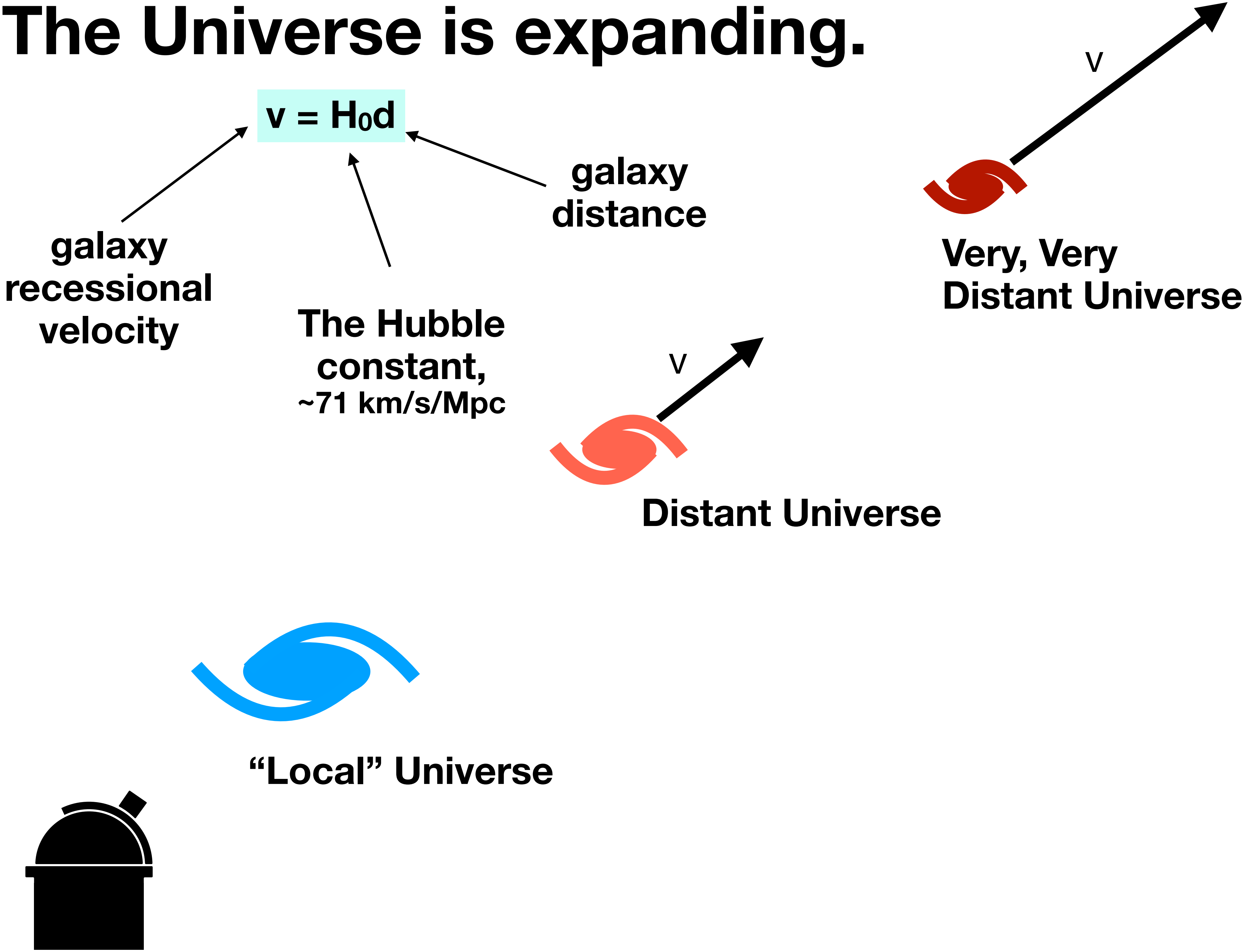
ASTR 400B, February 20, 2025

By The End of This Lecture You Should Have An Understanding of Why We Want To Find and Understand Far Away Galaxies And Why An Enormous Space Telescope With Infrared Capabilities Would Be Very Helpful To That End, And Also Exactly How We Find The Aforementioned Far Away Galaxies and A Little of What We’ve Learned About Them


Stephan's Quintet


Hubble Ultra-Deep Field

The Universe is expanding.



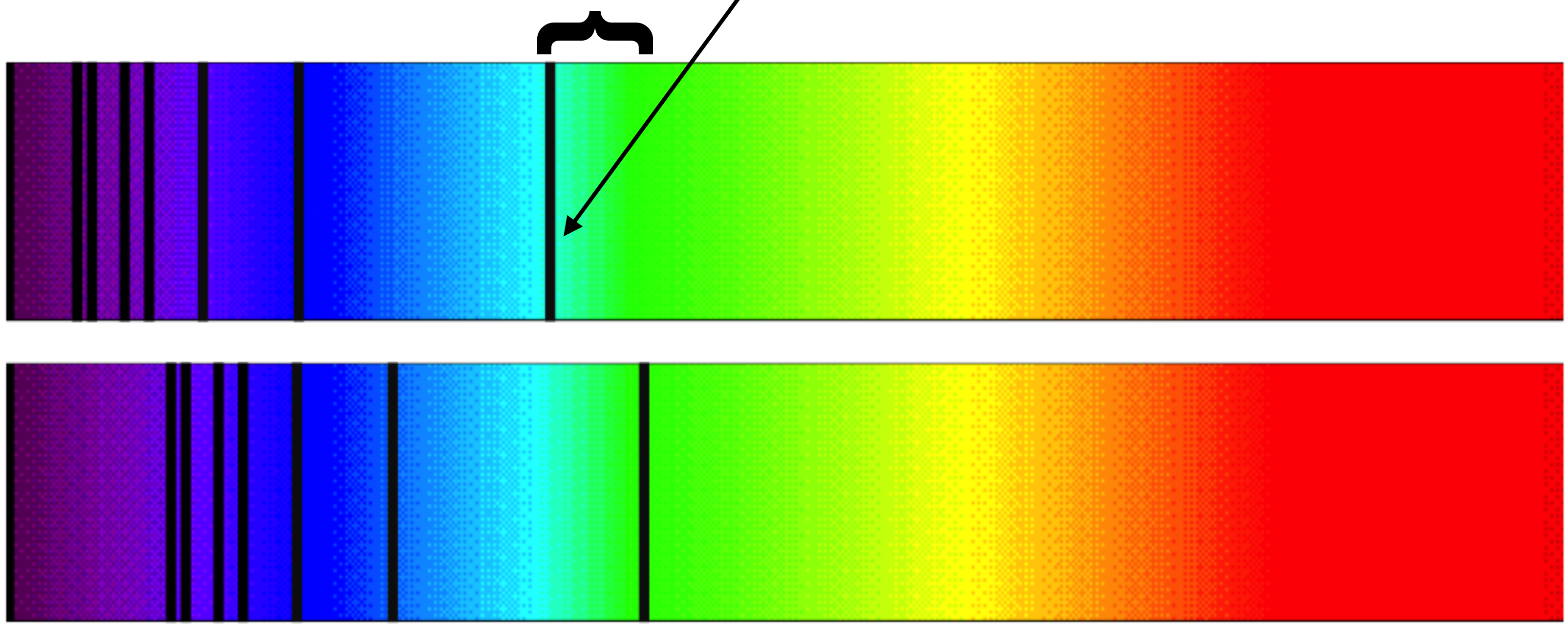
If you can find the velocity, you can calculate the distance! We can use the observed "redshift" of the galaxy to know the velocity.

$$v = H_0 d = cz$$

The speed of light

galaxy "redshift"

$$z = (\Delta\lambda \;/\; \lambda\text{rest})$$

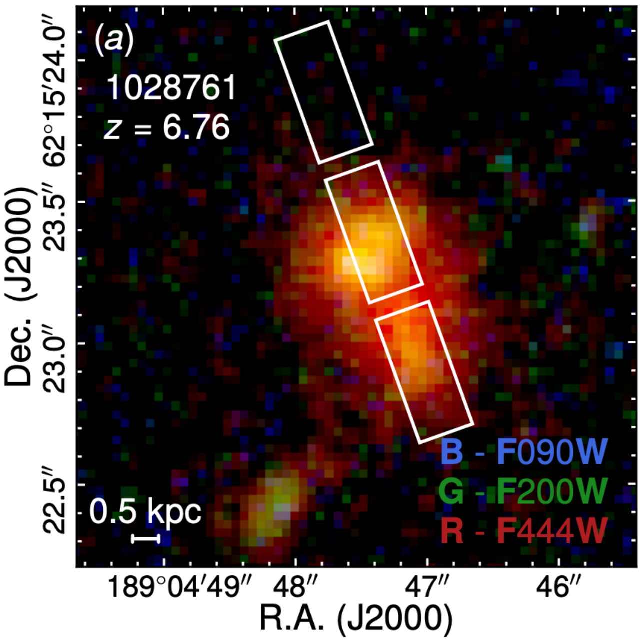


Rest Spectrum

Observed Spectrum

Galaxy spectra have features which can be used to calculate redshift

d'Eugenio et al (2024)

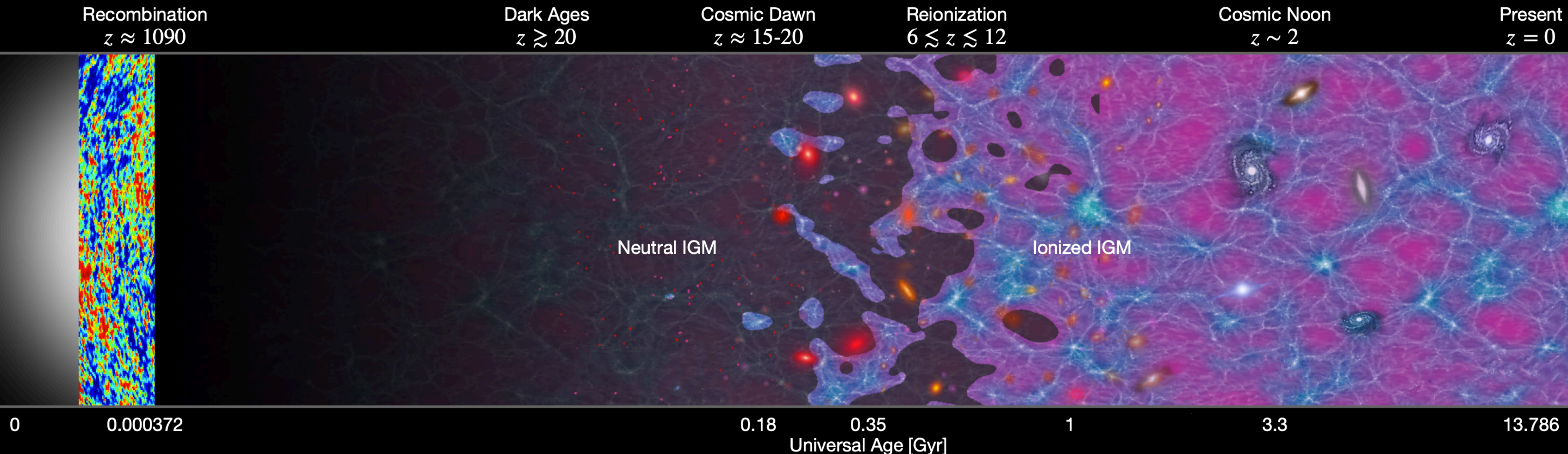


A galaxy spectrum is a combination of continuum emission from the large population of billions to hundreds of billions of stars, along with emission lines from ionized gas clouds.

There are also absorption features from both gas clouds as well as the atmospheres of stars.

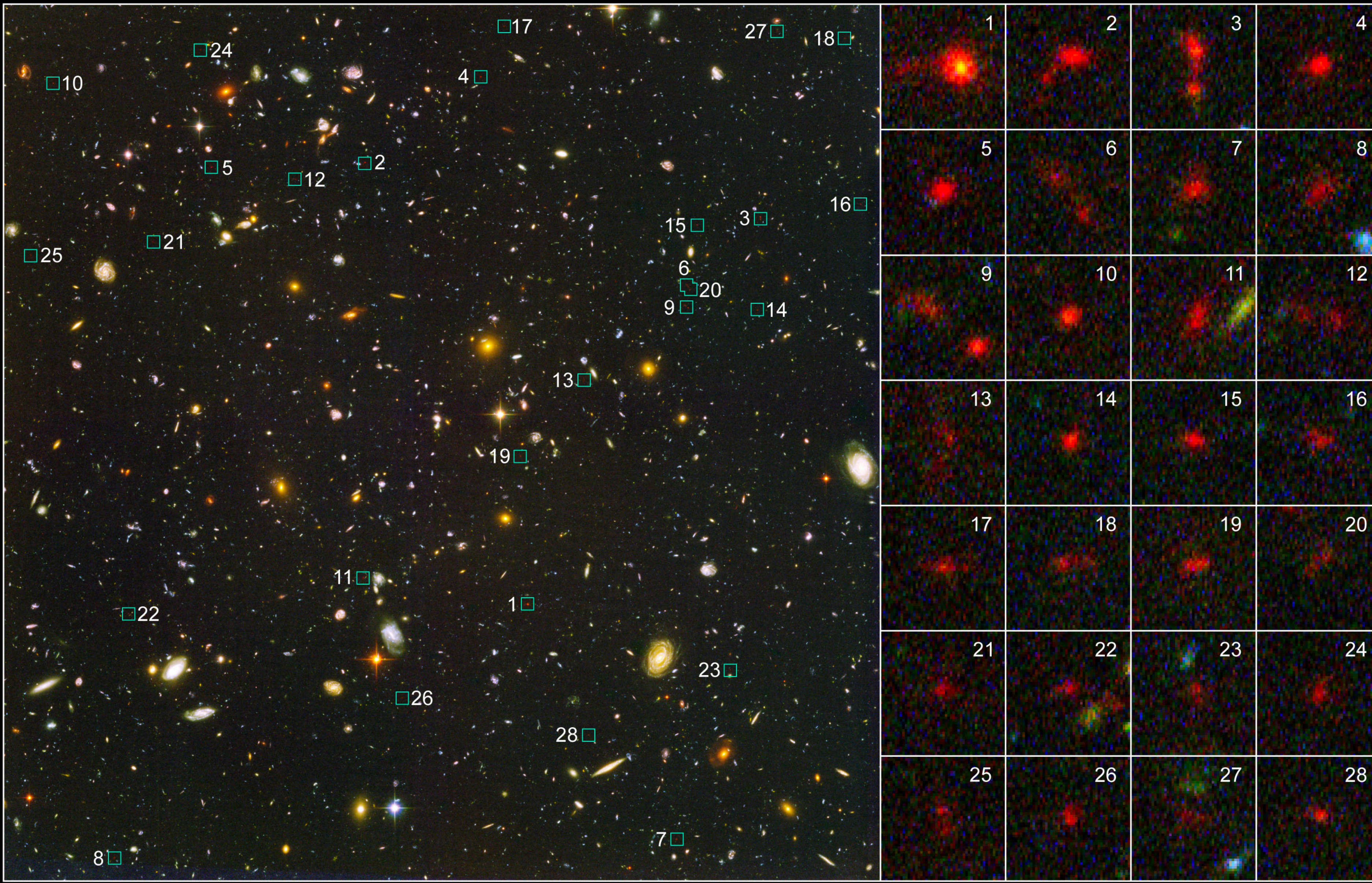
The History of the Universe

(well, according to extragalactic astronomers)



Robertson et al. 2010

The Big Bang → **Today**

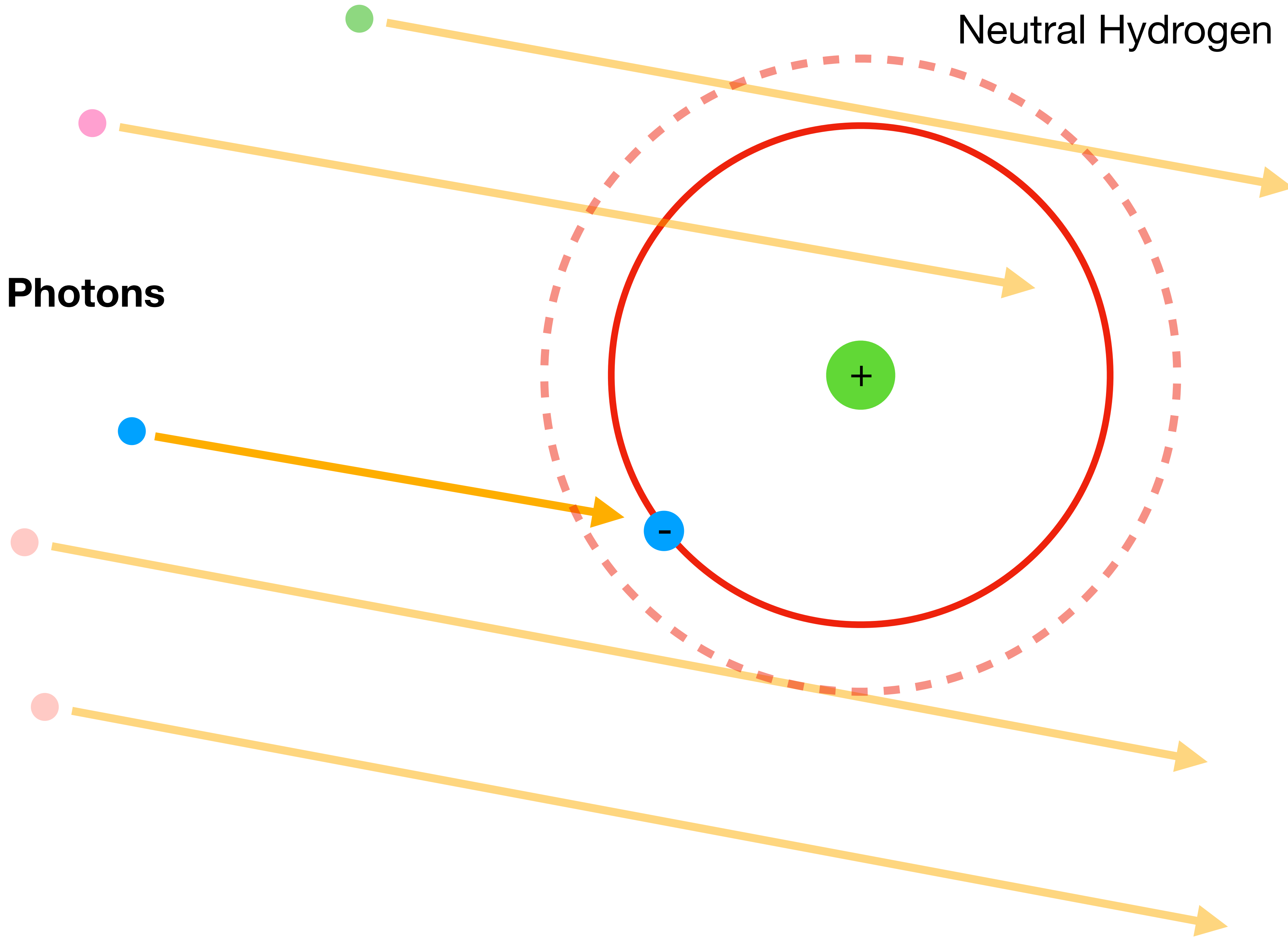


Distant Galaxies in the Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, R. Bouwens and G. Illingworth (University of California, Santa Cruz)

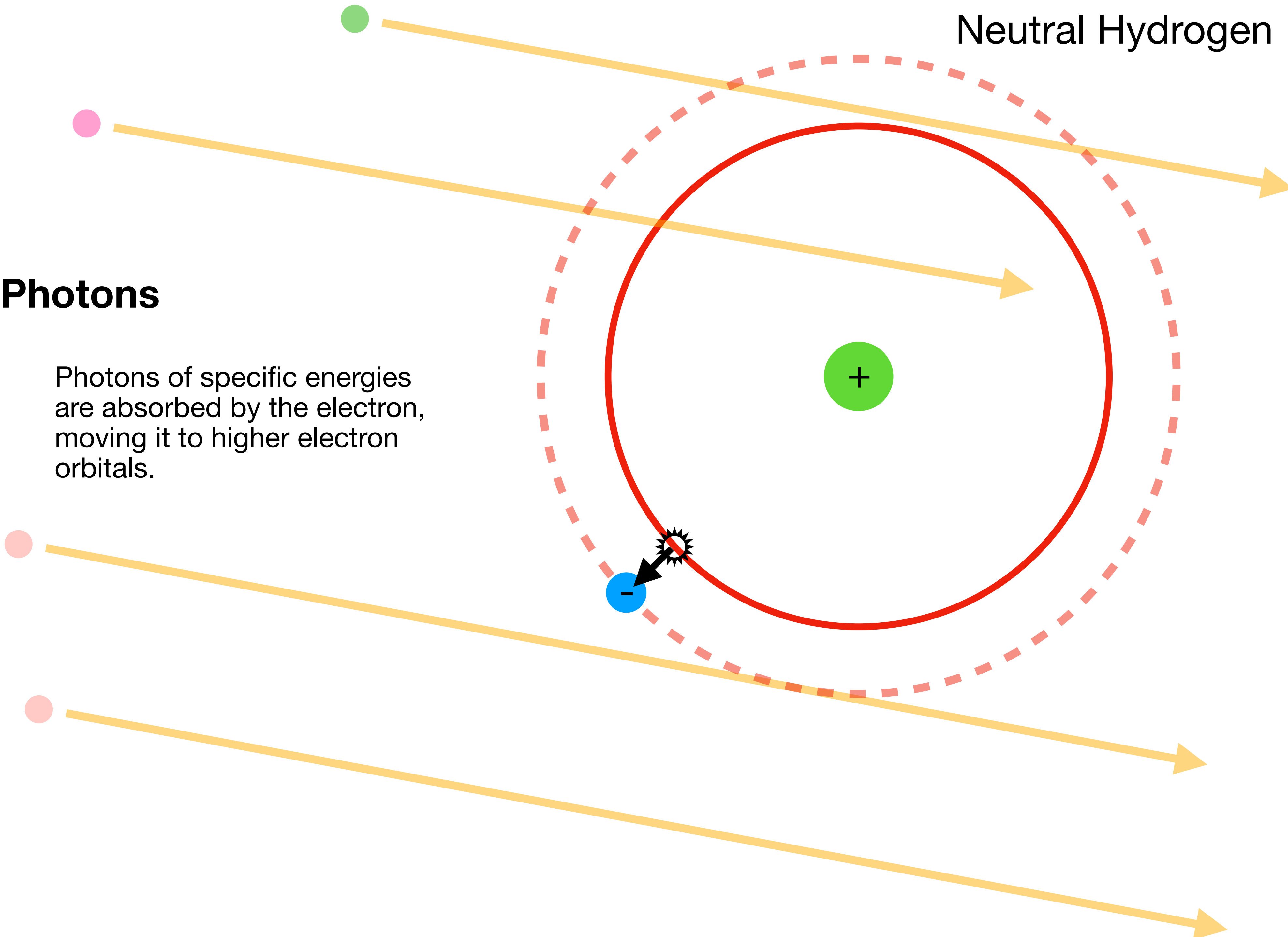
STScI-PRC06-12

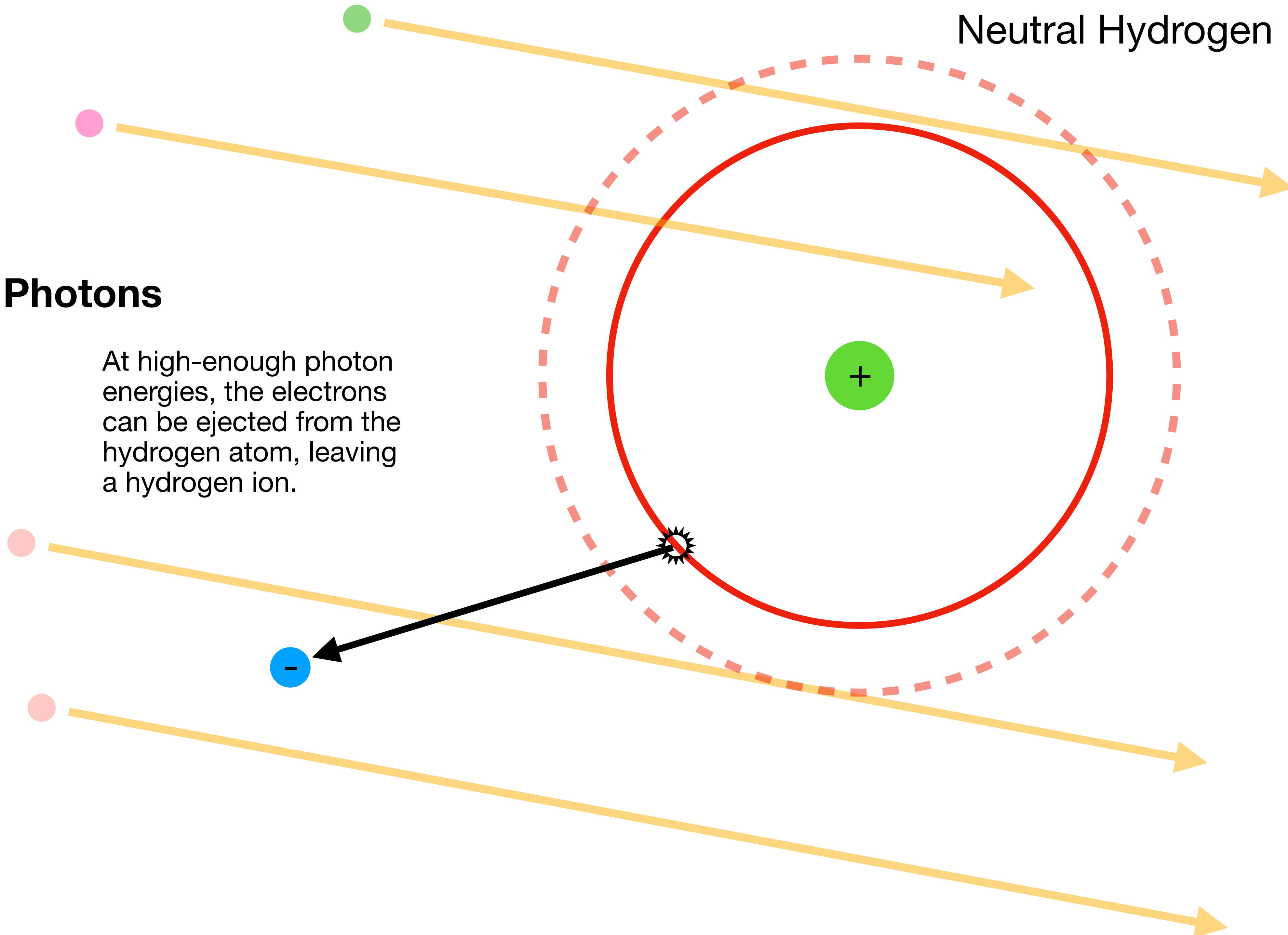


Neutral Hydrogen
Photons
+
-

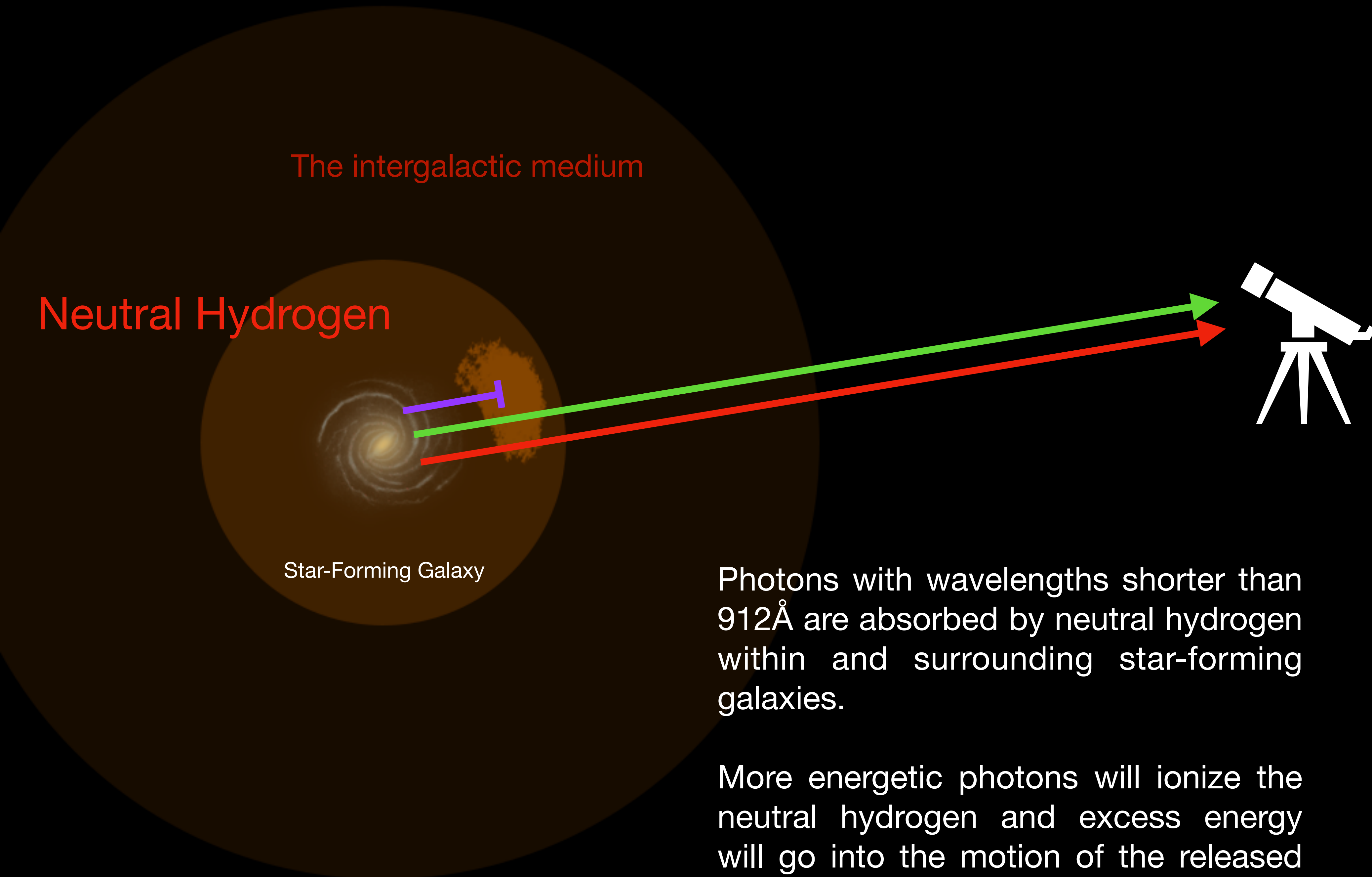
Photons

Photons of specific energies are absorbed by the electron, moving it to higher electron orbitals.




Neutral Hydrogen
Photons
At high-enough photon energies, the electrons can be ejected from the hydrogen atom, leaving a hydrogen ion.
+
-

The Lyman break arises due to neutral hydrogen surrounding galaxies.



Photons with wavelengths shorter than 912Å are absorbed by neutral hydrogen within and surrounding star-forming galaxies.

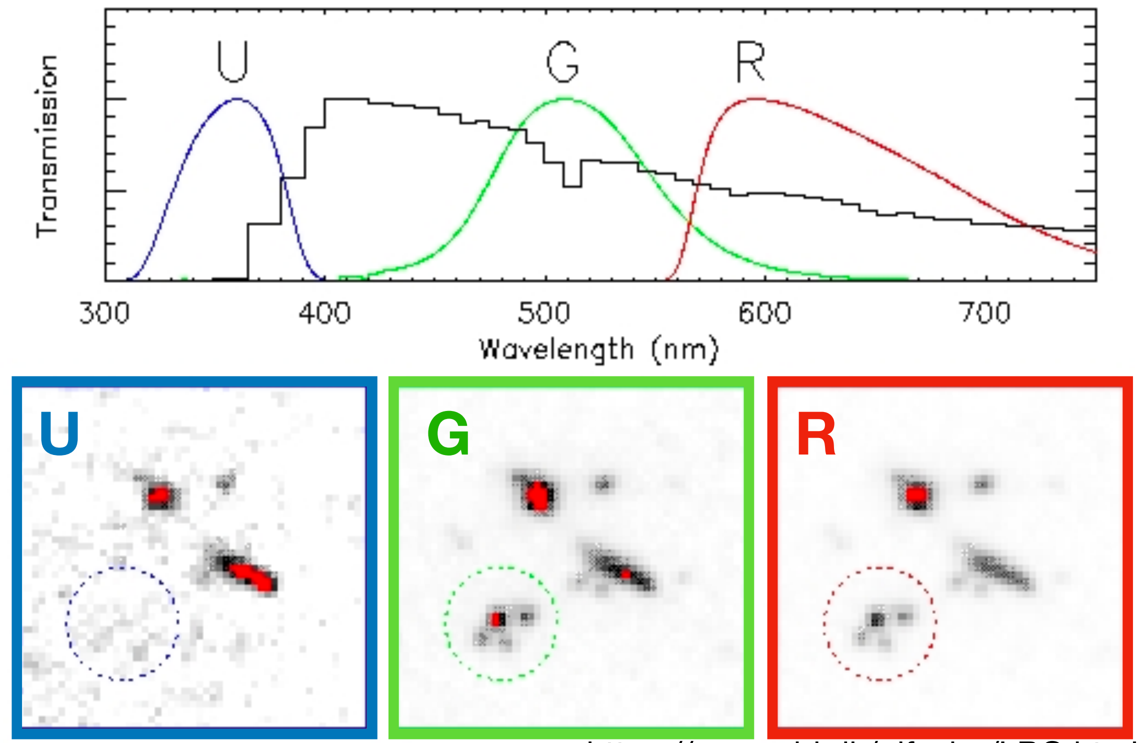
More energetic photons will ionize the neutral hydrogen and excess energy will go into the motion of the released electron.

“Lyman Break” Galaxies

Lyman break observed wavelength: 4000 Å

Lyman break rest wavelength: 1216 Å

z = (Δλ / λrest)
= (4000 Å - 1216 Å) / (1216 Å)
= **2.28**

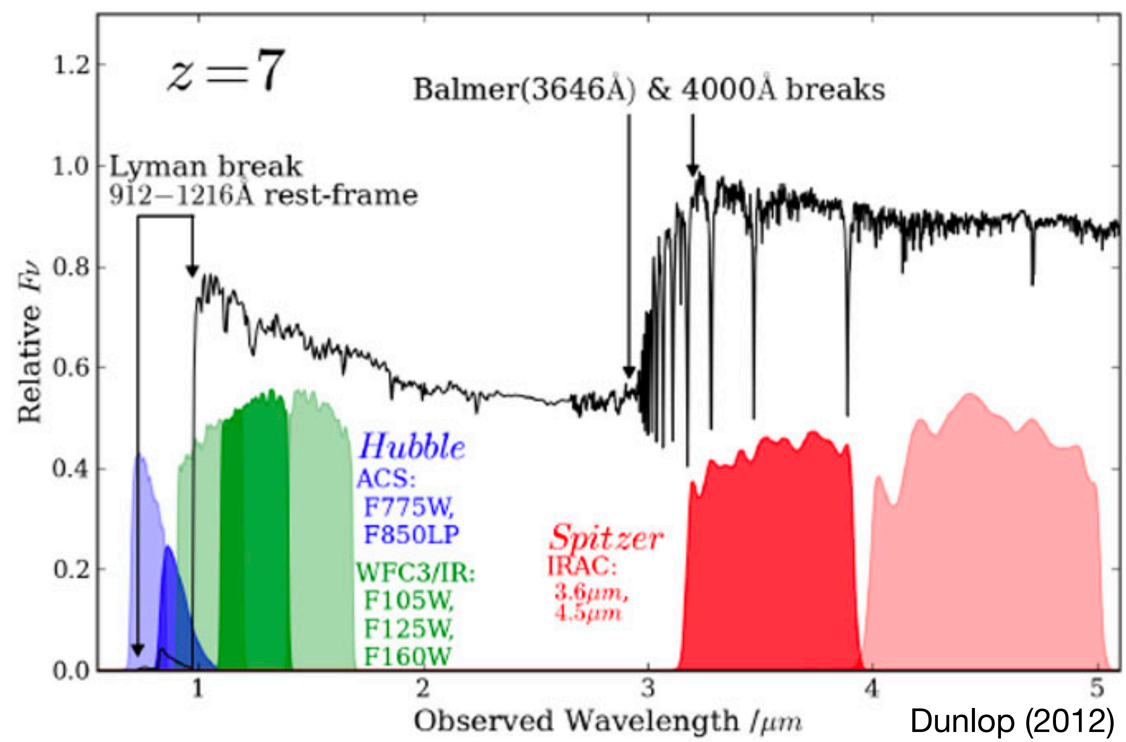


https://www.nbi.dk/~jfynbo/LBG.html

Lyman break observed wavelength: 10000 Å

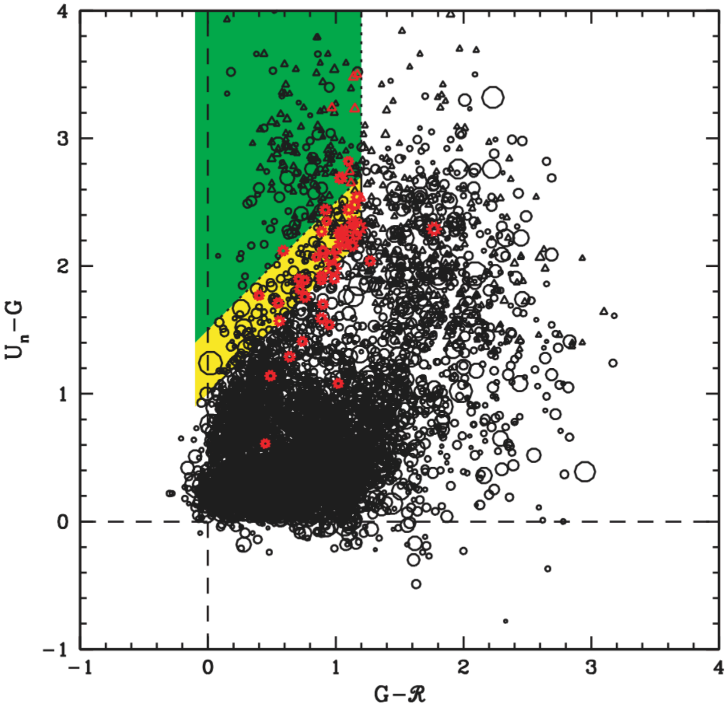
Lyman break rest wavelength: 1216 Å

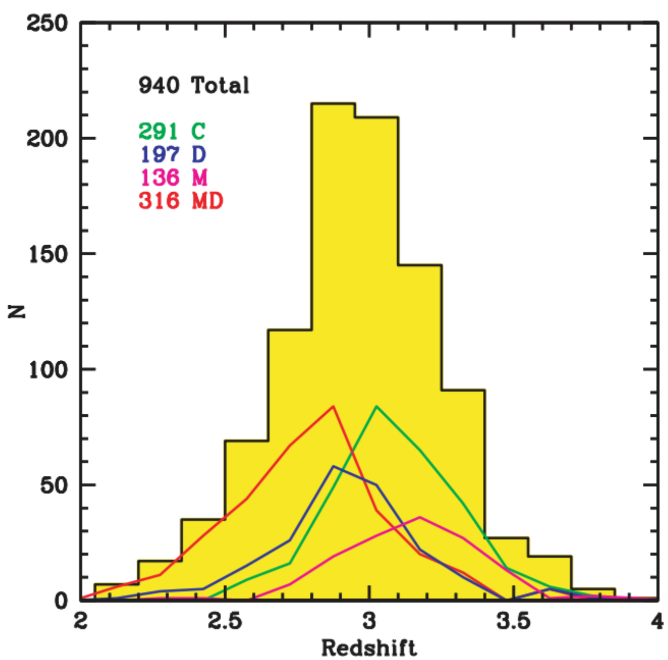
z = (Δλ / λrest)
= (10000 Å - 1216 Å) / (1216 Å)
= **7.22**



Dunlop (2012)

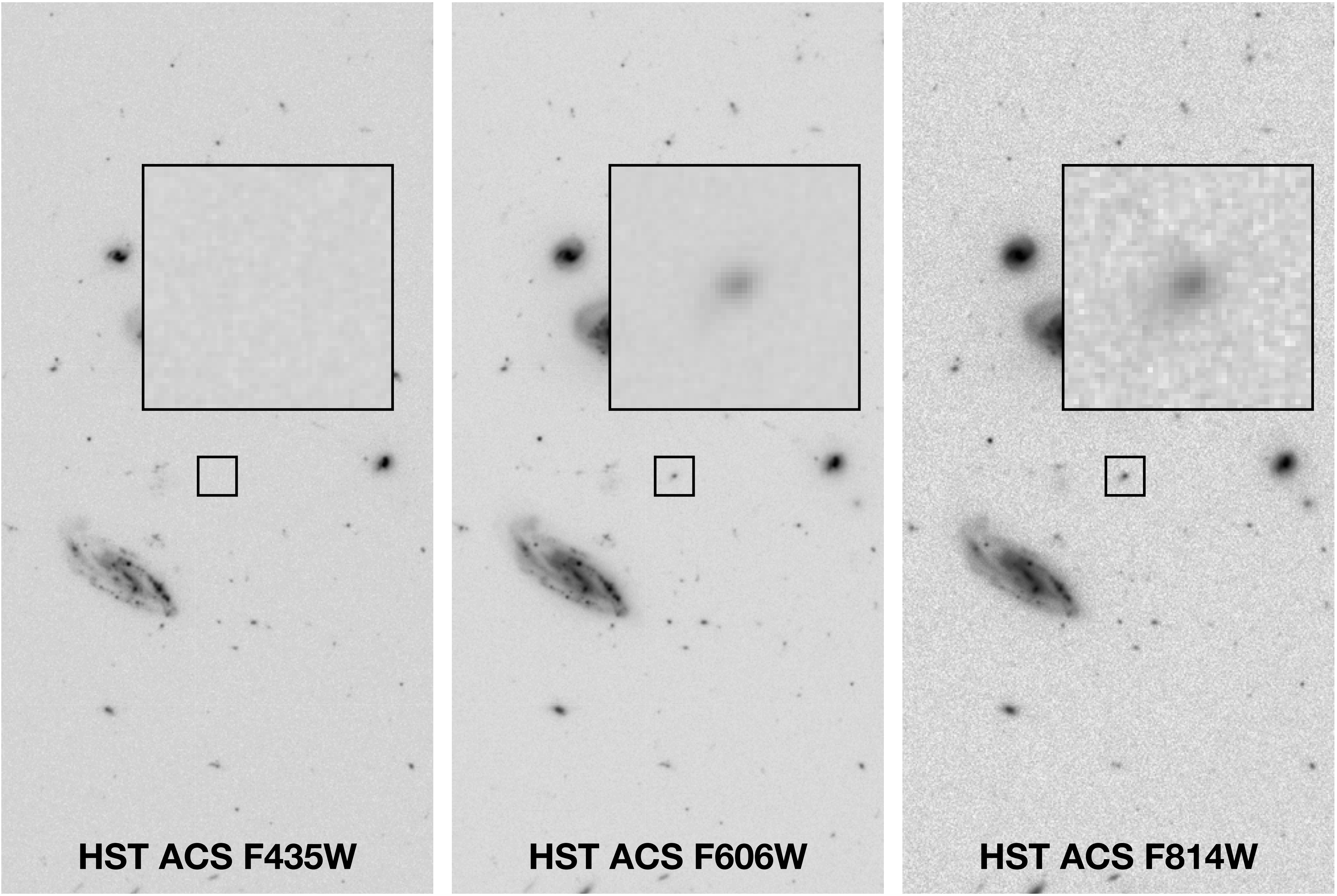
Lyman break galaxies were historically found by looking at “color-color” diagrams.





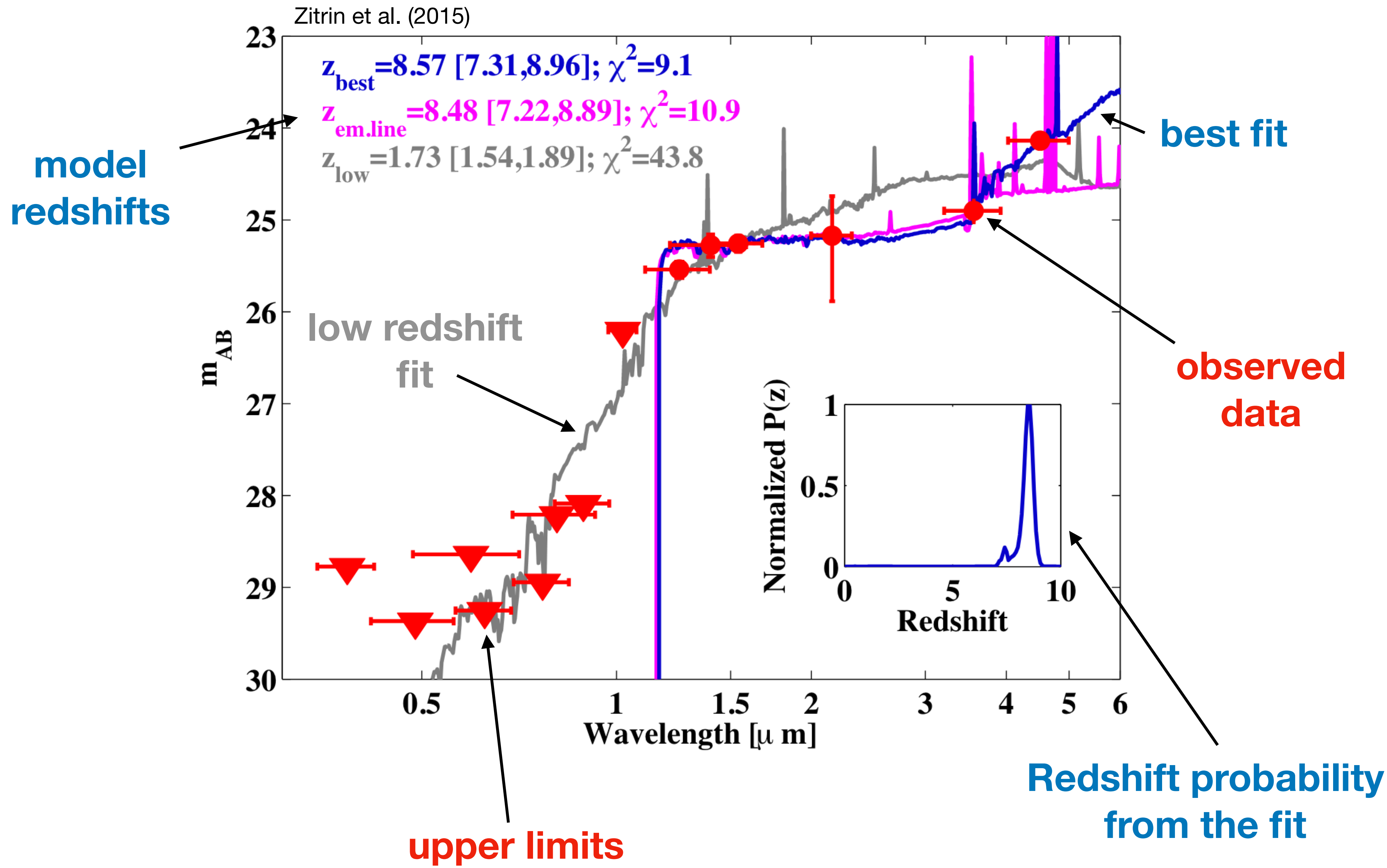
Steidel et al. (2003)

Hubble Ultra-Deep Field

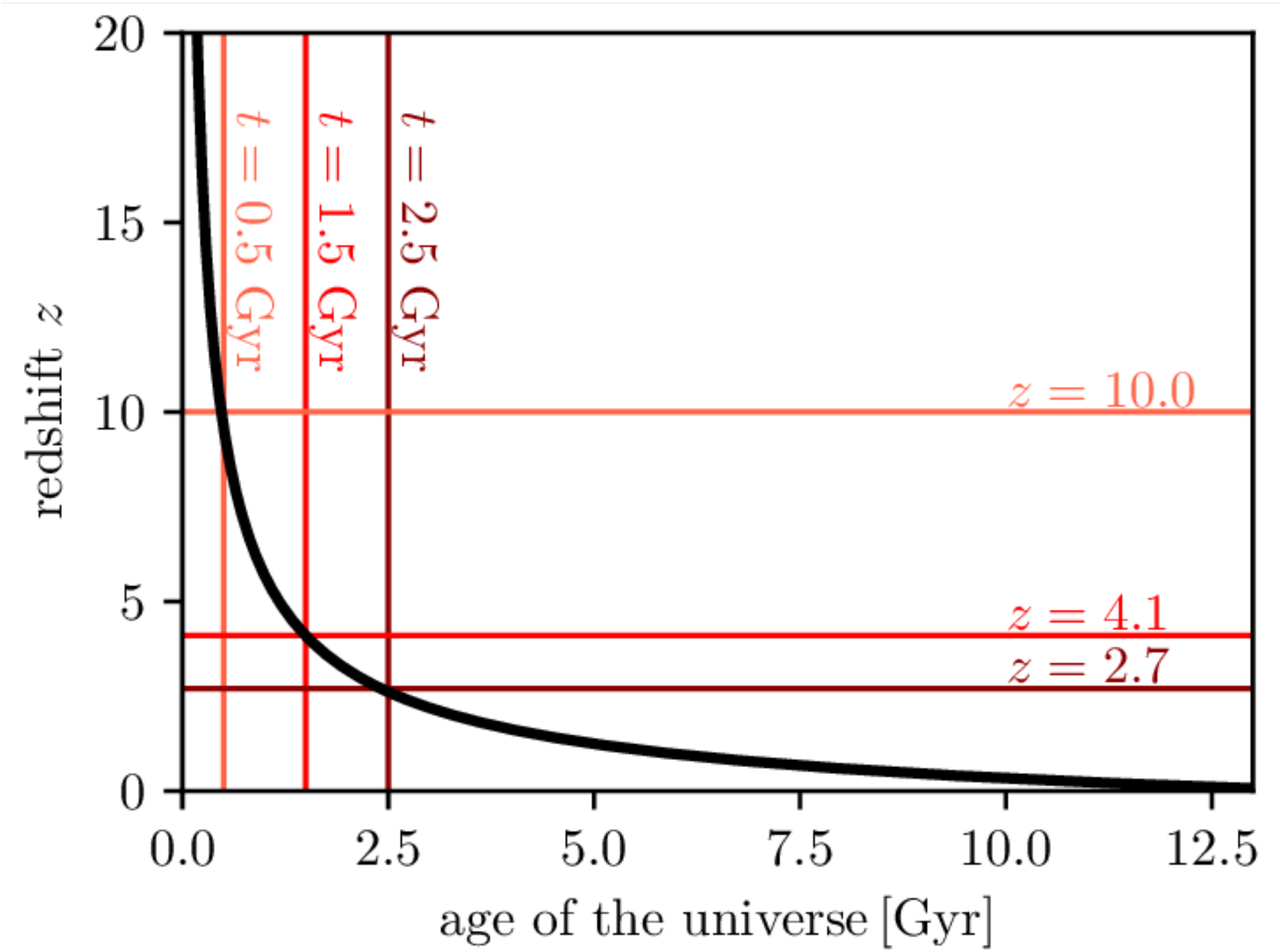


we now know this source is at z = 4.36!

Besides selecting based on color-color diagrams, there are ways to fit all of the observed data for a source simultaneously.



Redshift is not linear with the age of the Universe!



Big Bang
($z = \infty$)

Today
($z = 0$)

If you want to explore this yourself, one place to go is Ned Wright's Cosmology Calculator:

Enter values, hit a button

69.6	H_o
0.286	$Omega_M$
4.36	z
Open	Flat
0.714	$Omega_{vac}$
General	

Open sets $Omega_{vac} = 0$ giving an open Universe [if you entered $Omega_M < 1$]
Flat sets $Omega_{vac} = 1-Omega_M$ giving a flat Universe.
General uses the $Omega_{vac}$ that you entered.
Source for the default parameters.

For $H_o = 69.6$, $Omega_M = 0.286$, $Omega_{vac} = 0.714$, $z = 4.360$

- It is now 13.720 Gyr since the Big Bang.
- The age at redshift z was 1.404 Gyr.
- The light travel time was 12.316 Gyr.
- The comoving radial distance, which goes into Hubble's law, is 7562.7 Mpc or 24.666 Gly.
- The comoving volume within redshift z is 1811.824 Gpc^3.
- The angular size distance D_A is 1410.9 Mpc or 4.6019 Gly.
- This gives a scale of 6.840 kpc/".
- The luminosity distance D_L is 40536.0 Mpc or 132.212 Gly.

1 Gly = 1,000,000,000 light years or 9.461×10^{26} cm.
1 Gyr = 1,000,000,000 years.
1 Mpc = 1,000,000 parsecs = 3.08568×10^{24} cm, or 3,261,566 light years.

Tutorial: Part 1 | Part 2 | Part 3 | Part 4
FAQ | Age | Distances | Bibliography | Relativity

See the advanced and light travel time versions of the calculator.

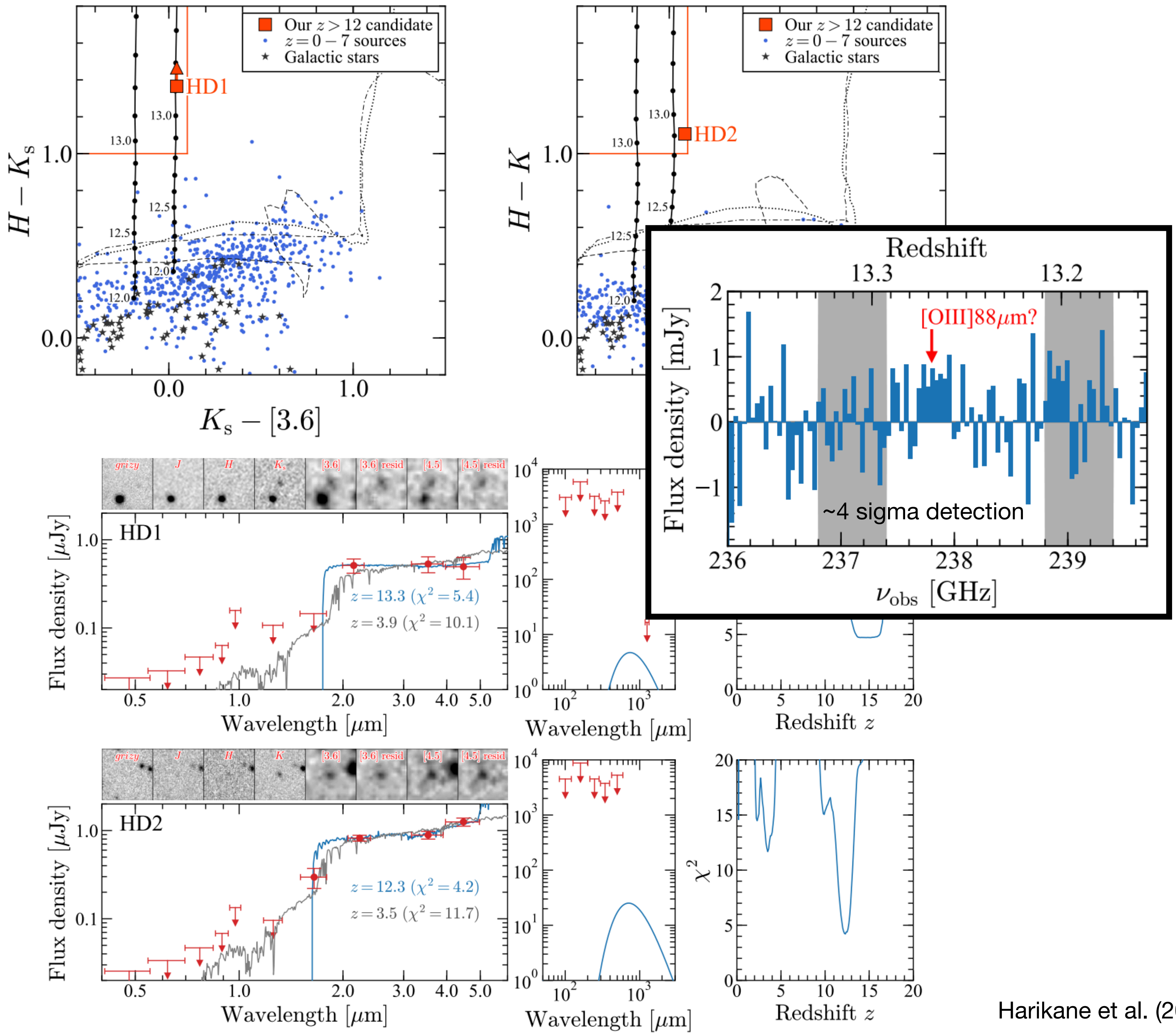
James Schombert has written a Python version of this calculator.

Ned Wright's home page

 If you use this calculator while preparing a paper, please cite Wright (2006, PASP, 118, 1711). Last modified on 07/23/2018 14:22:14

https://astro.ucla.edu/~wright/CosmoCalc.html

Some of the highest redshift pre-JWST objects were very hard to confirm spectroscopically.

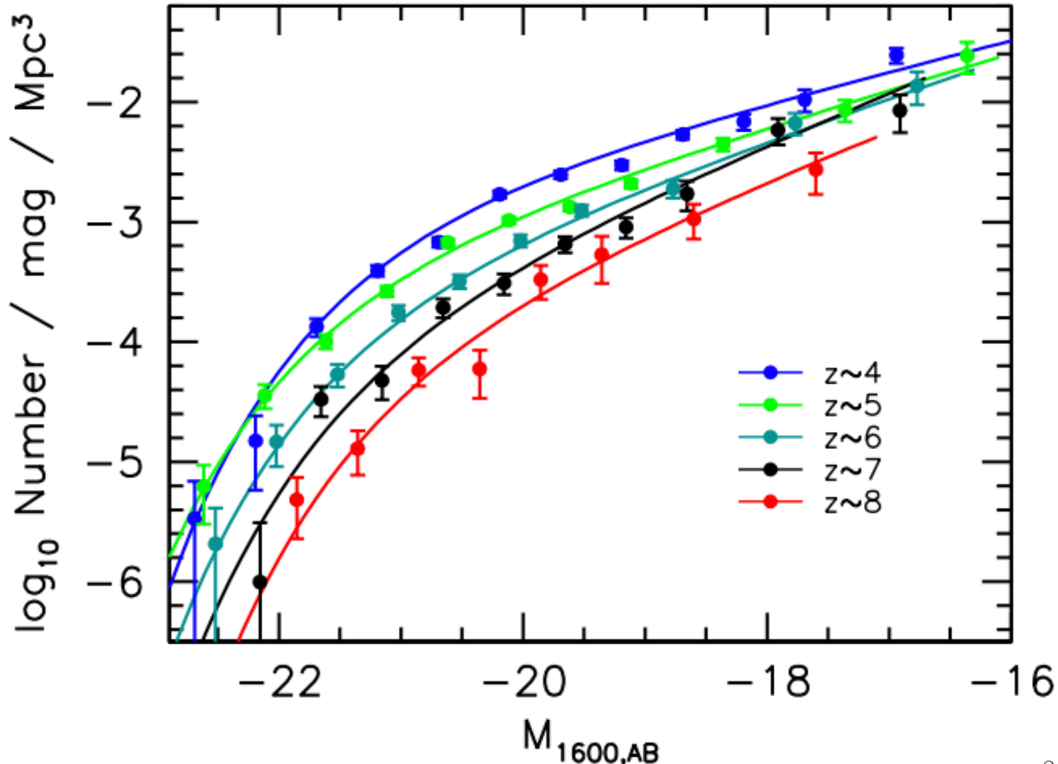


Harikane et al. (2022)

What can we do with a whole bunch of galaxy distances?

Selecting high-redshift galaxies allows us to understand the "luminosity function" of distant galaxies.

see also: Bowler et al. (2015), (2017) (2020); Oesch et al. (2018); Stefanon et al. (2019); Bouwens et al. (2021a); Harikane et al. (2021), among so many others.

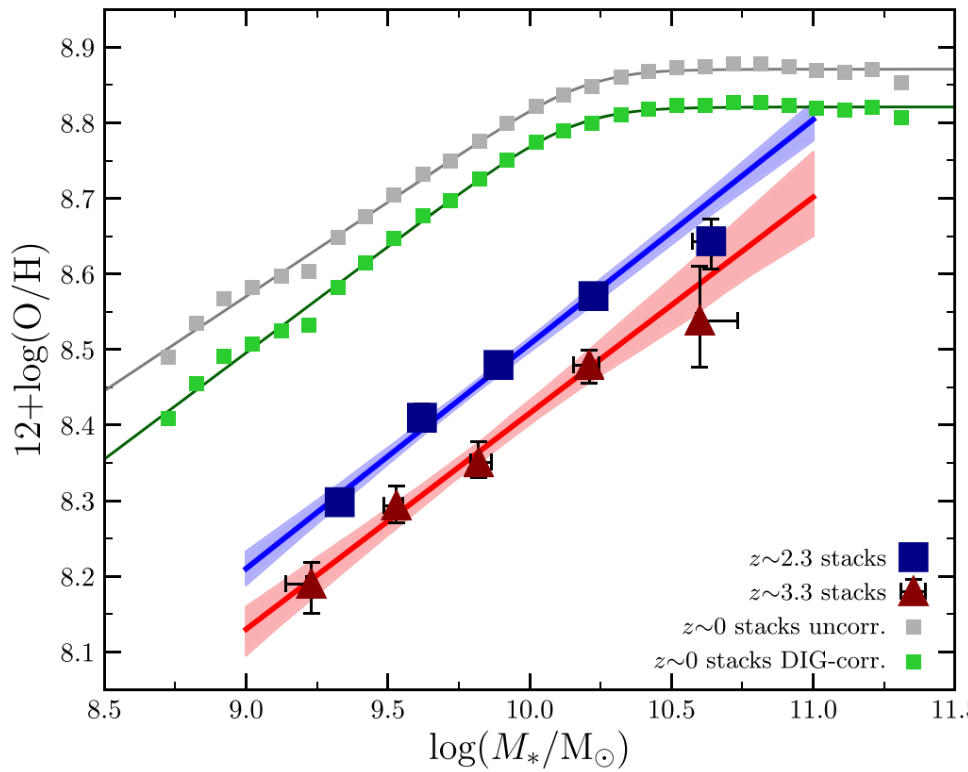


Bouwens et al. (2014)

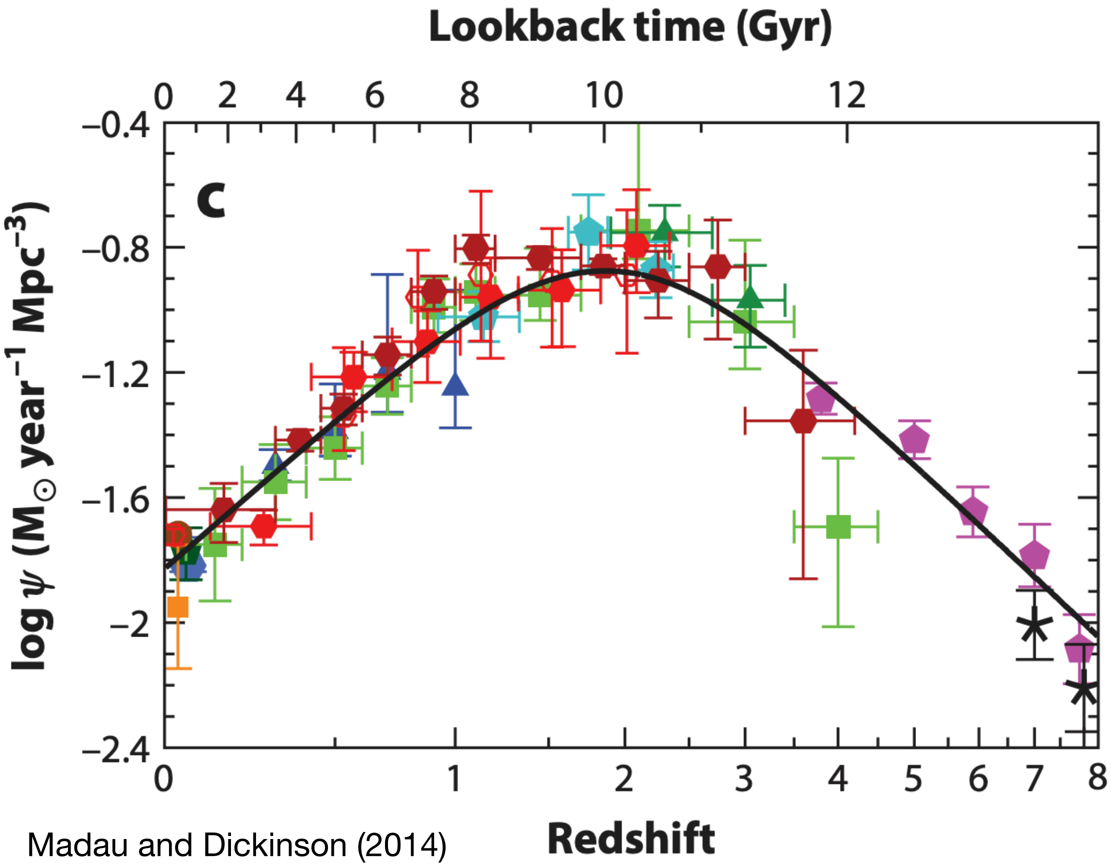
And, out to the redshift limits where we can observe metallicity-sensitive optical emission lines, the relationship between gas metallicity and galaxy stellar mass as a function of redshift.

see also: Savaglio et al. (2005); Erb et al. (2006a); Maiolino et al. (2008), Mannucci et al. (2009); Zahid et al. (2011), (2014a), (2014b); Wuyts et al. (2012), (2016); Belli et al. (2013); Henry et al. (2013); Kulas et al. (2013); Cullen et al. (2014); Maier et al. (2014); Steidel et al. (2014); Troncoso et al. (2014); Kacprzak et al. (2015), (2016); Ly et al. (2015), (2016); Sanders et al. (2015), (2018), (2020b); Hunt et al. (2016); Onodera et al. (2016); Suzuki et al. (2017)

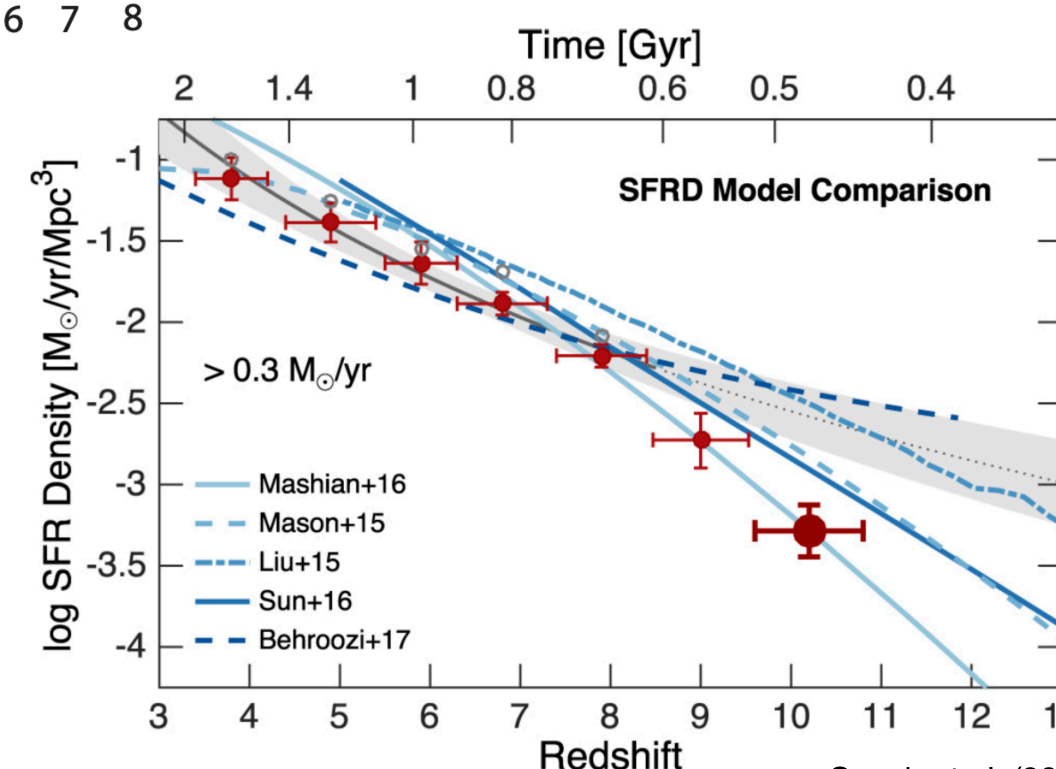
Sanders et al. (2021)



…as well as the evolution of the "SFR Density" over cosmic time.



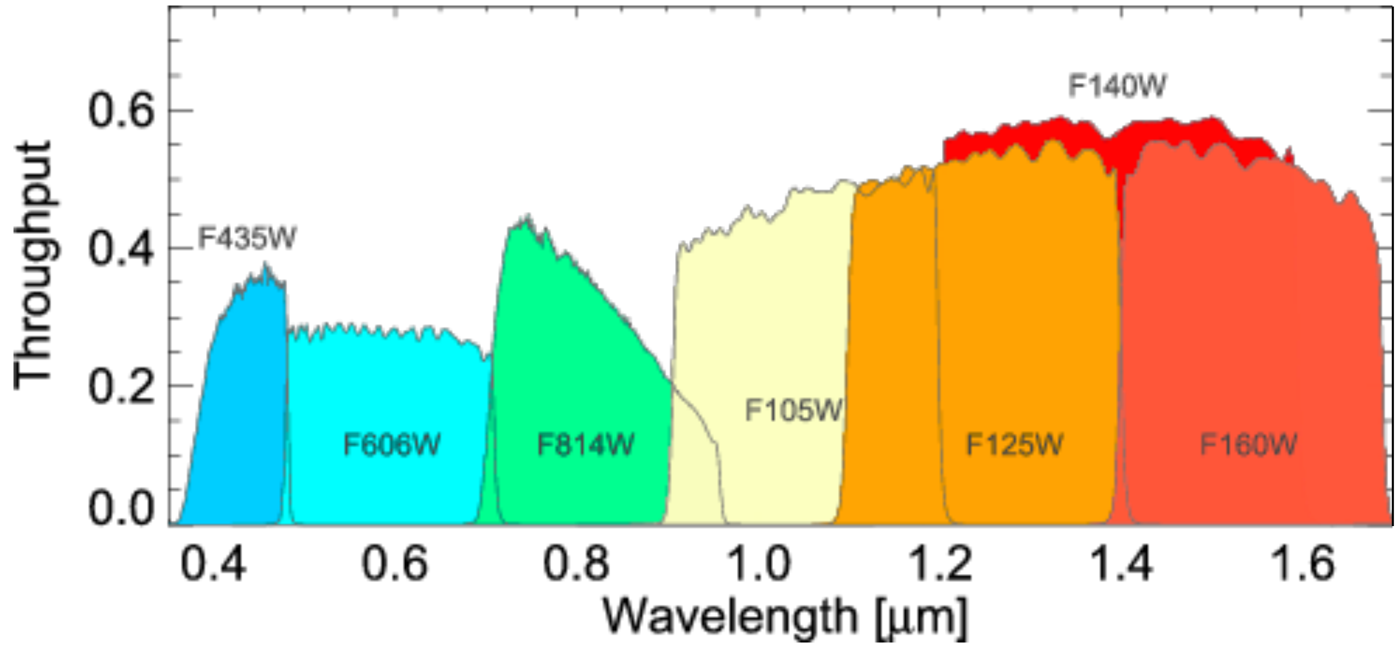
Madau and Dickinson (2014)



Oesch et al. (2018)

see also: Sanders et al. (2003); Takeuchi et al. (2003); Wyder et al. (2005); Schiminovich et al. (2005); Dahlen et al. (2007); Reddy & Steidel (2009); Robotham & Driver (2011); Magnelli et al. (2011) (2013); Cucciati et al. (2012); Bouwens et al. (2012a,b); Schenker et al. (2013); Gruppioni et al. (2013); Mason et al. (2015); Mashian et al. (2016); Sun & Furlanetto (2016); Liu et al. (2016)

…but observations of fundamental galaxy properties at higher redshifts is limited by our ability to see into the infrared.



HST ACS and WFC3 filters

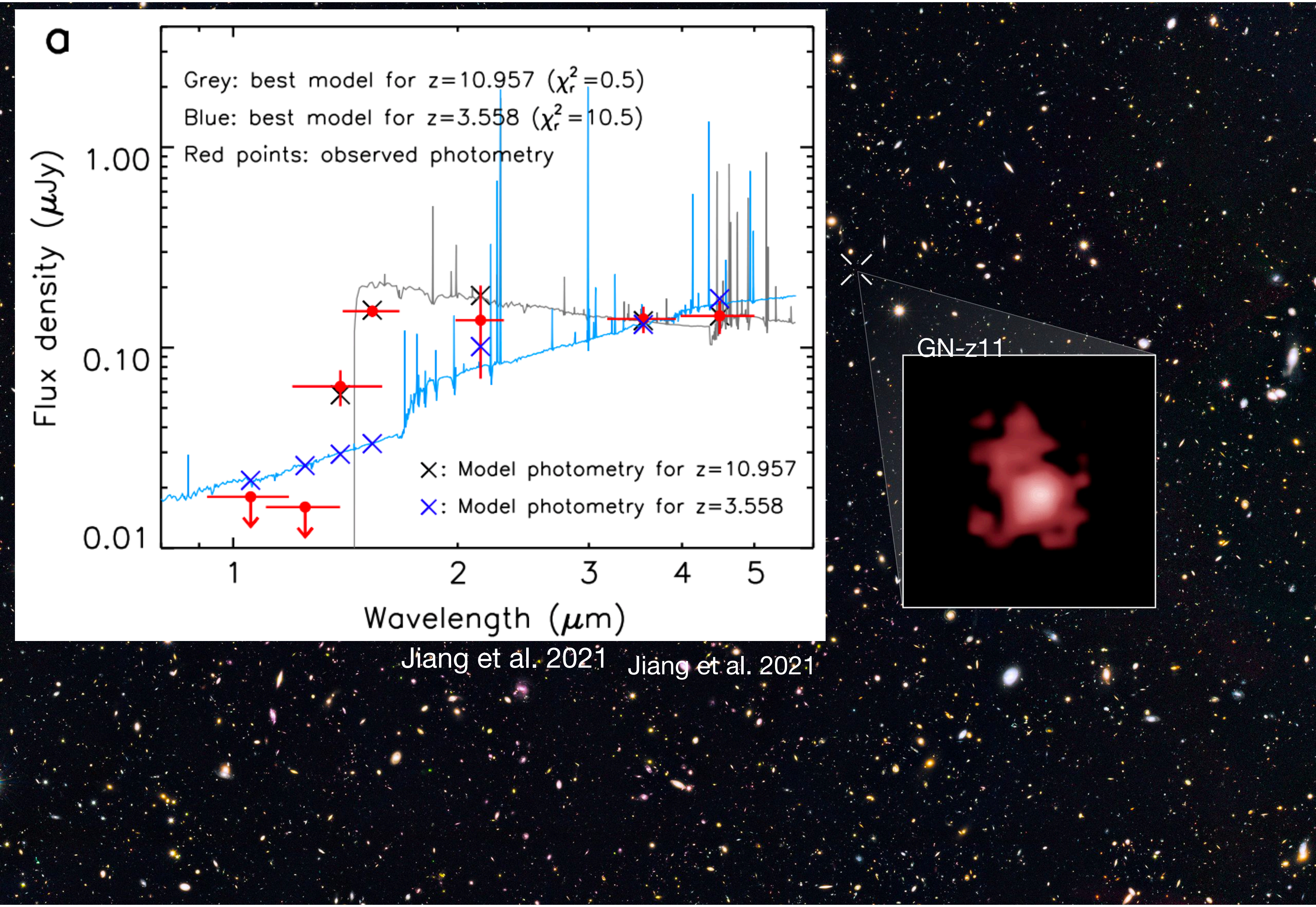
Lyman break observed wavelength: 1.4 microns

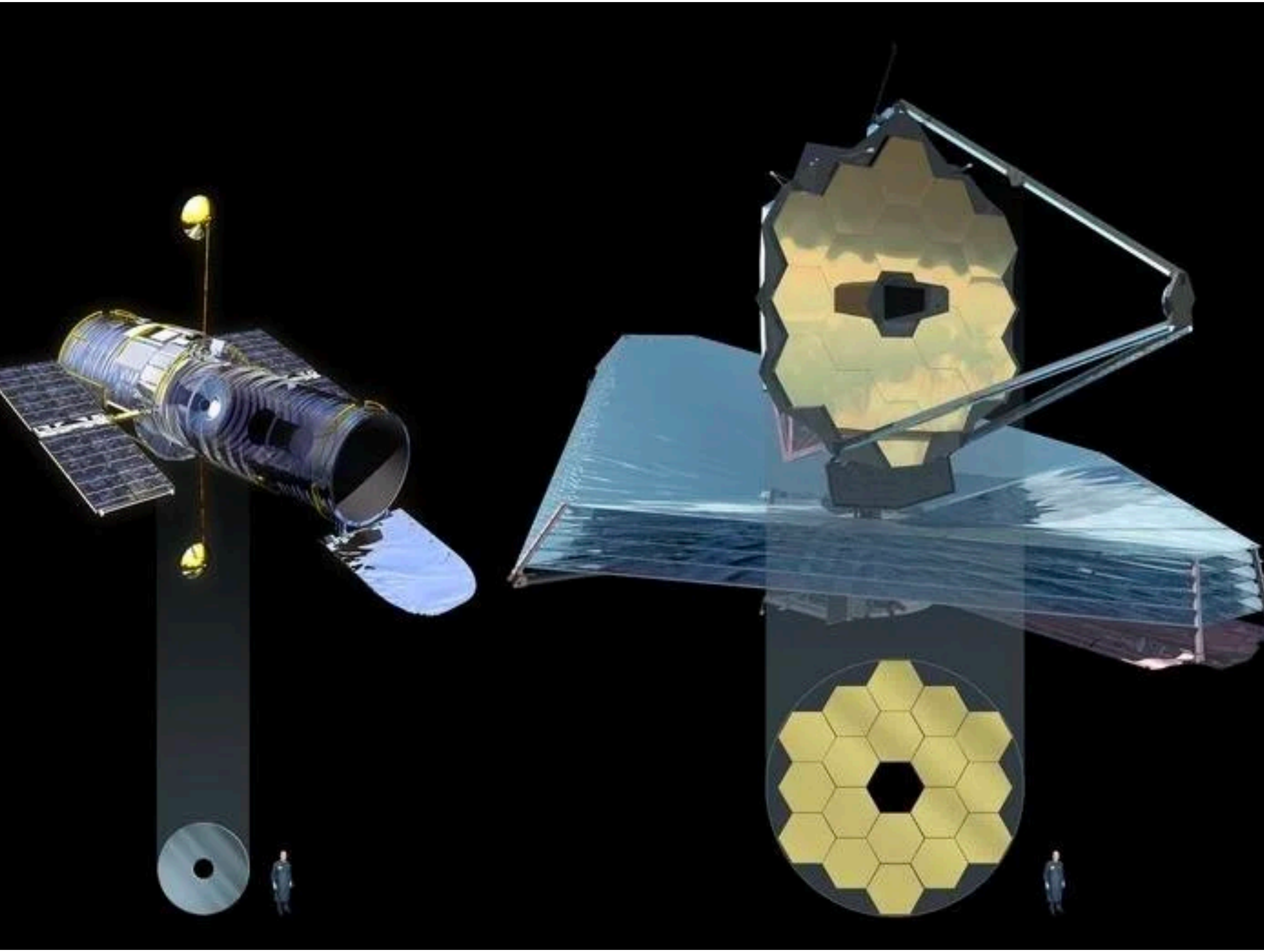
Lyman break rest wavelength: 1216 Å

z = (Δλ / λrest)
= (14000 Å - 1216 Å) / (1216 Å)
= **10.5**

…and we're limited to much lower redshifts for observing optical emission lines!

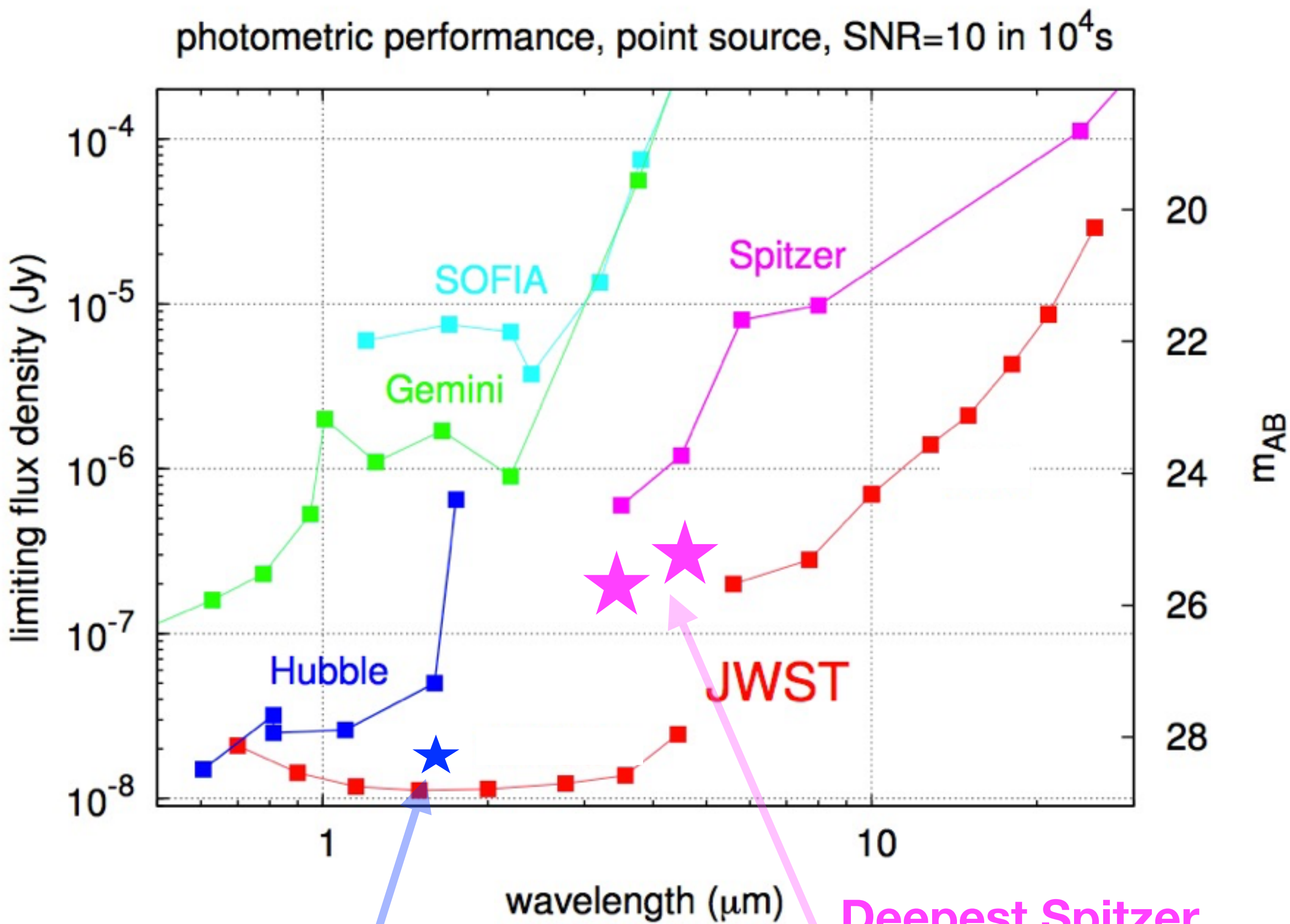
GN-z11 was one of the farthest “spectroscopically-confirmed” galaxies.





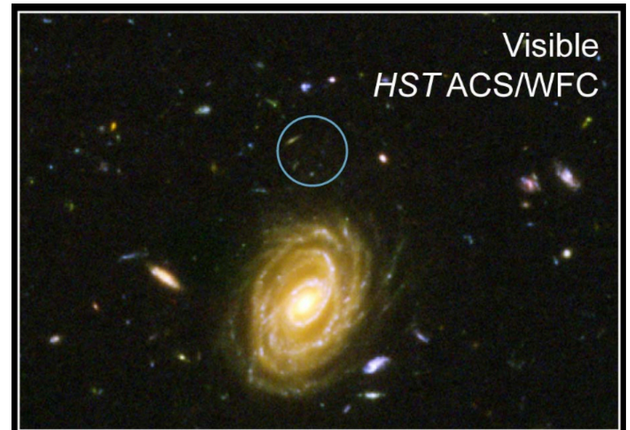
JWST is the largest astronomical mirror in space and carries the most sensitive infrared instruments.

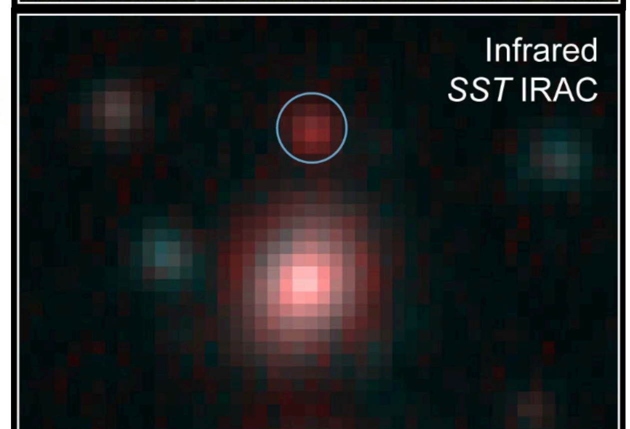
(2.7 hrs)

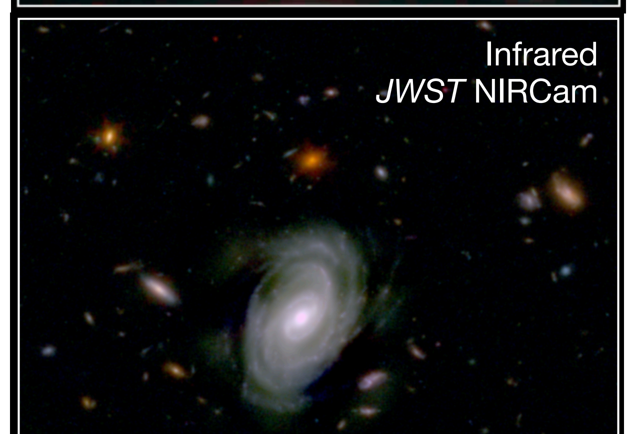


Deepest part of Hubble Ultra-Deep Field: Magnitude ~28.5 (66 hrs)

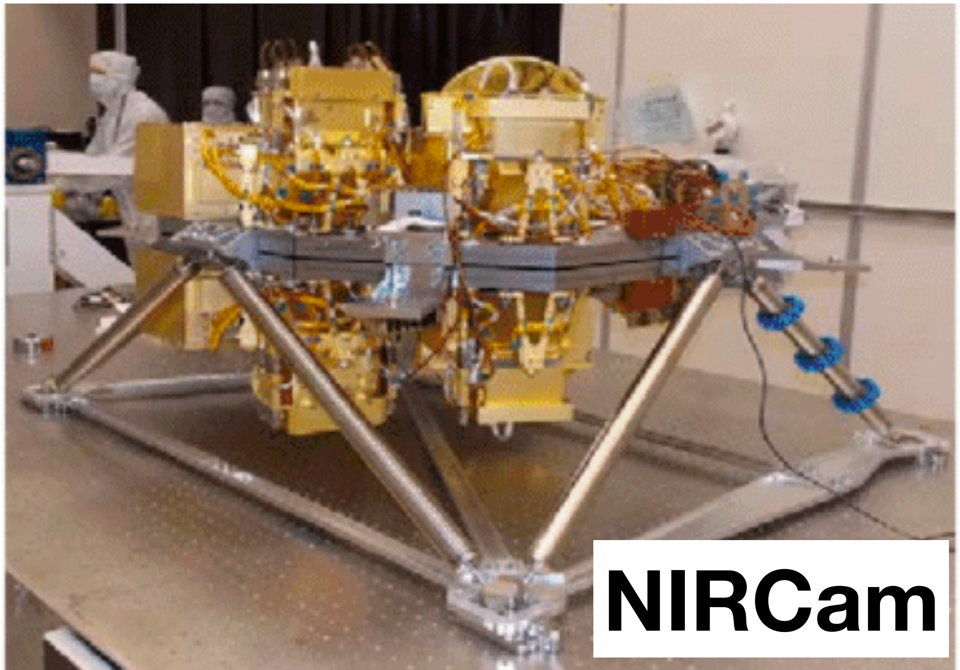
Deepest Spitzer image to date: Magnitude ~25.8 (200 hrs)

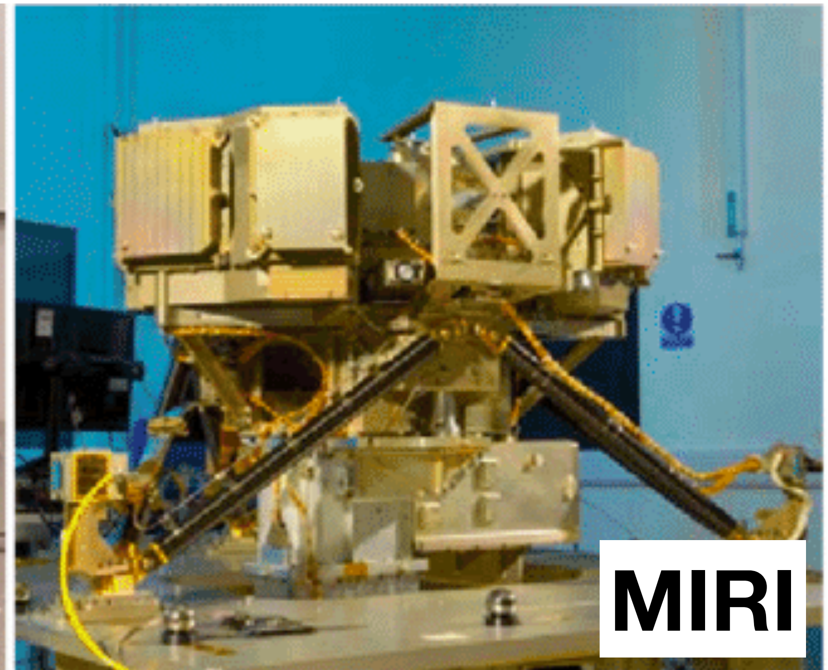






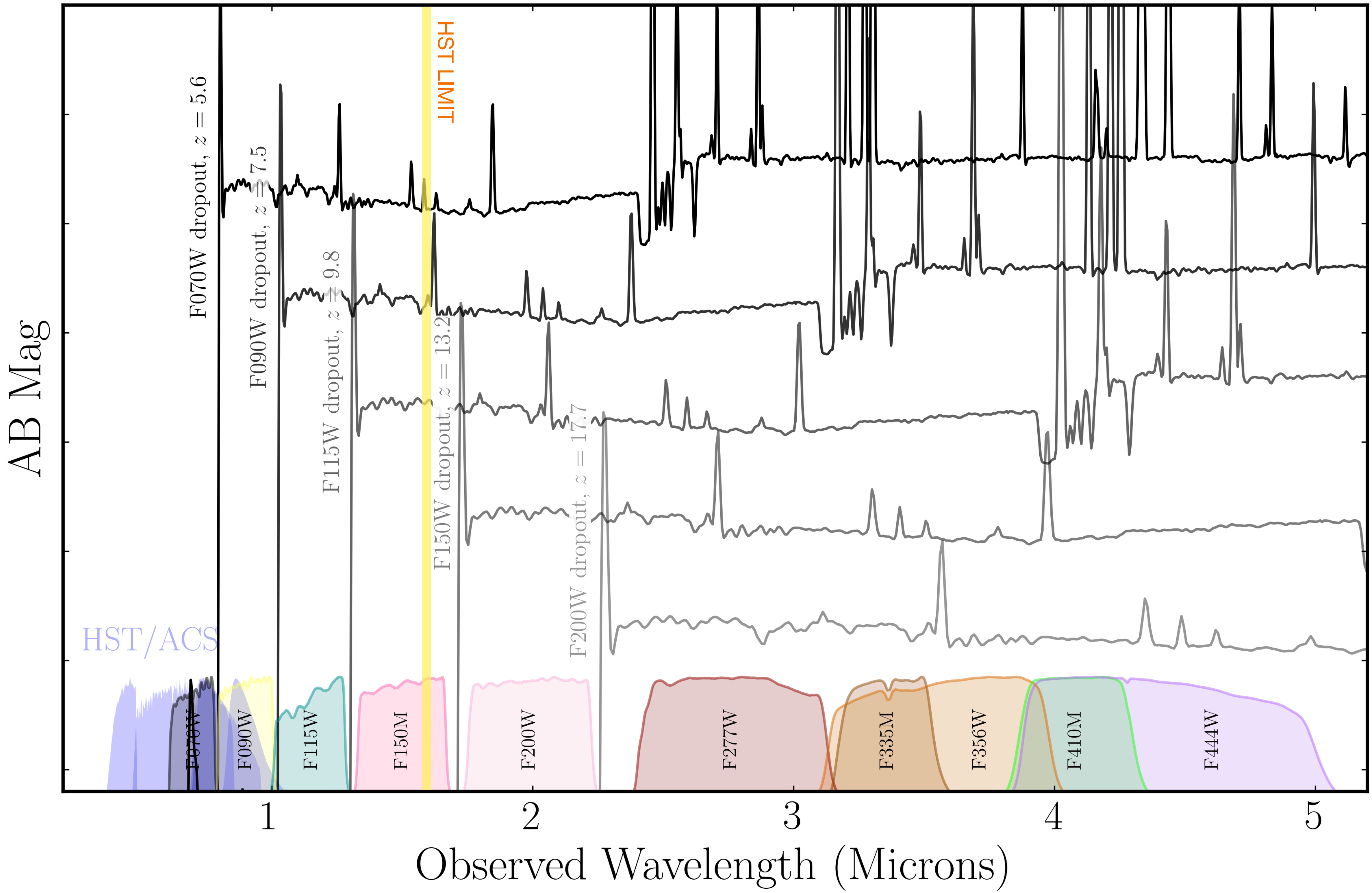
The Four Science Instruments on Board JWST





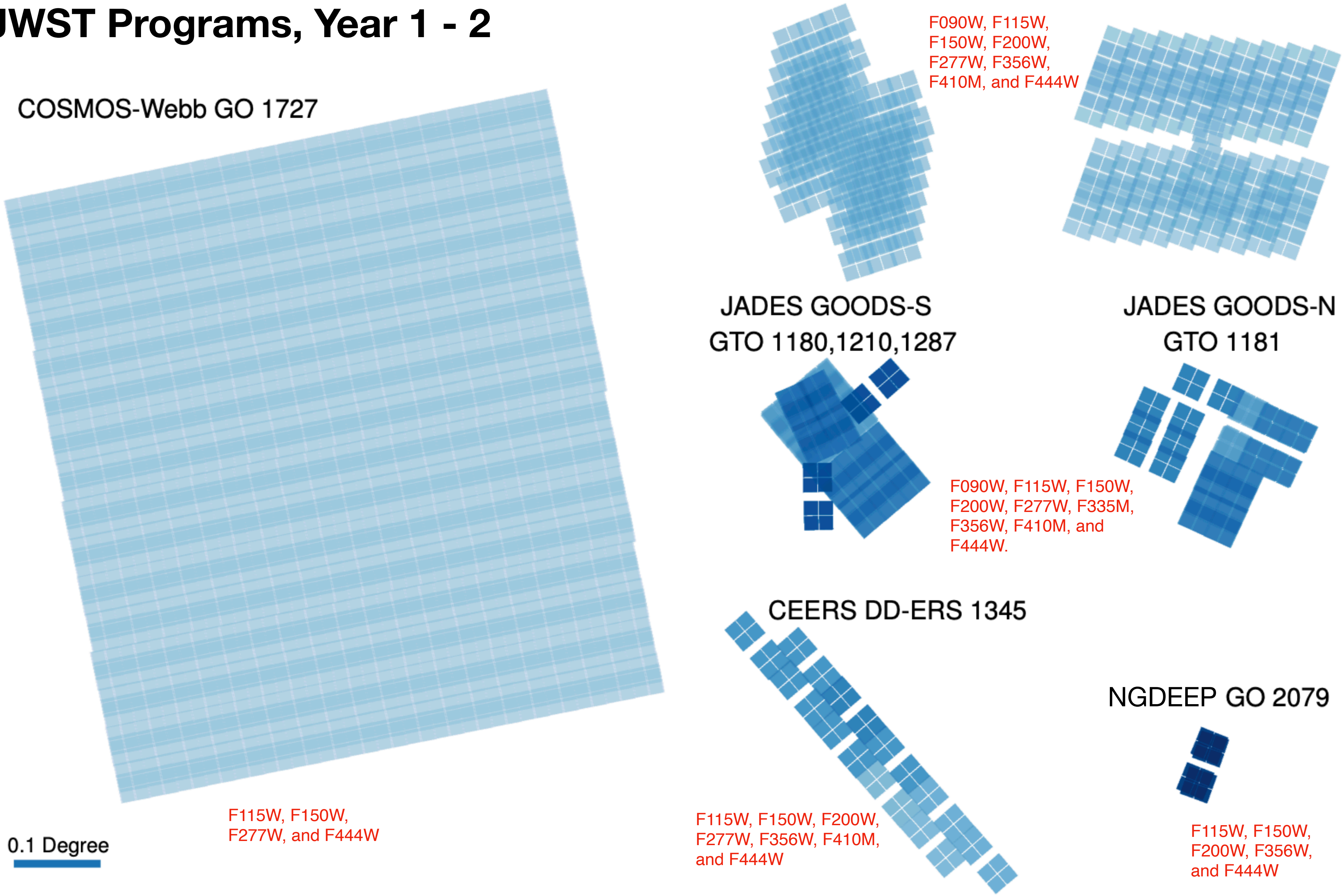

NIRCam

The SW filters on NIRCam allow us to search for very high-redshift Lyman dropouts.

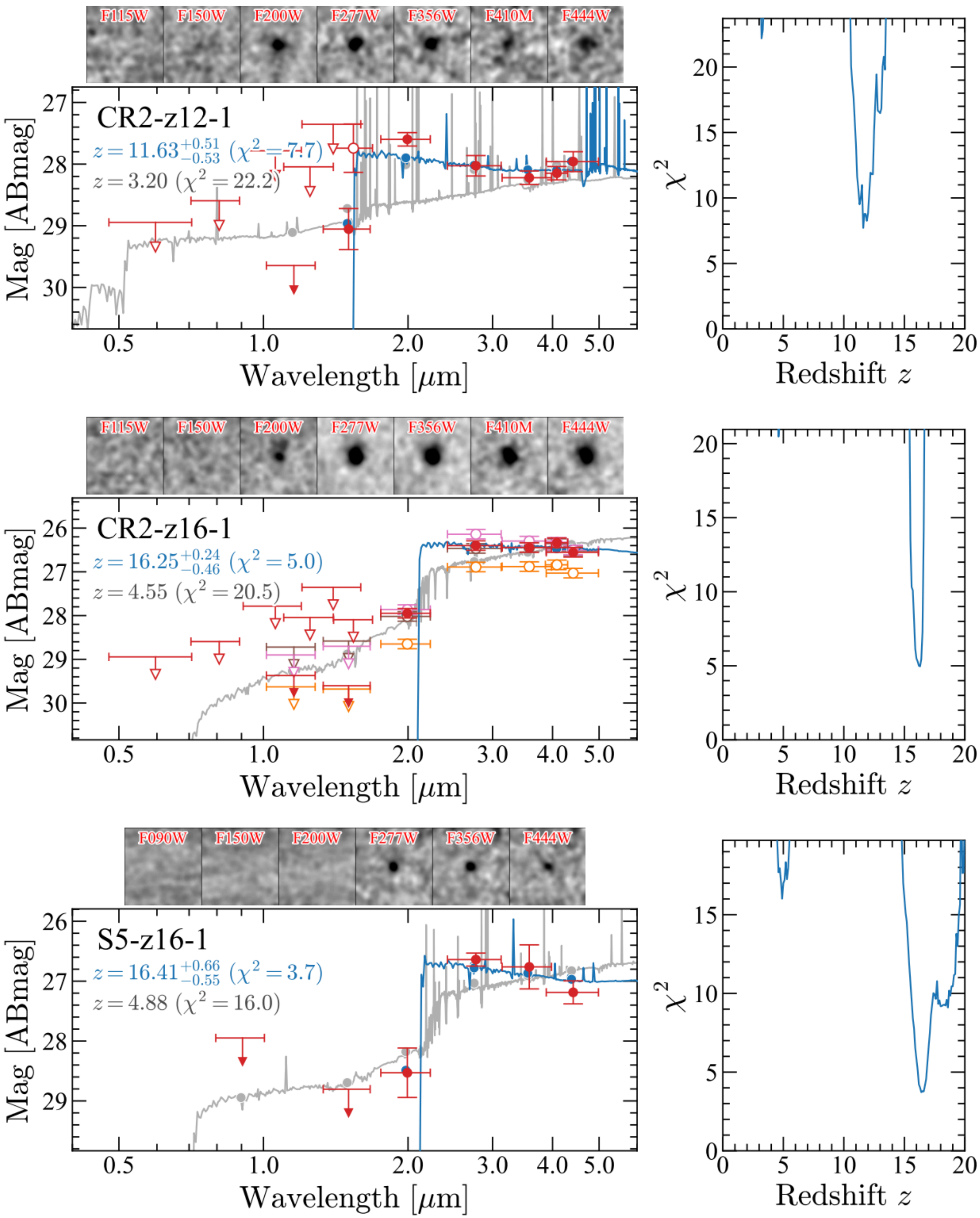


Hainline et al. (2020)

A Sample of the Large Extragalactic JWST Programs, Year 1 - 2



Robertson (2021)

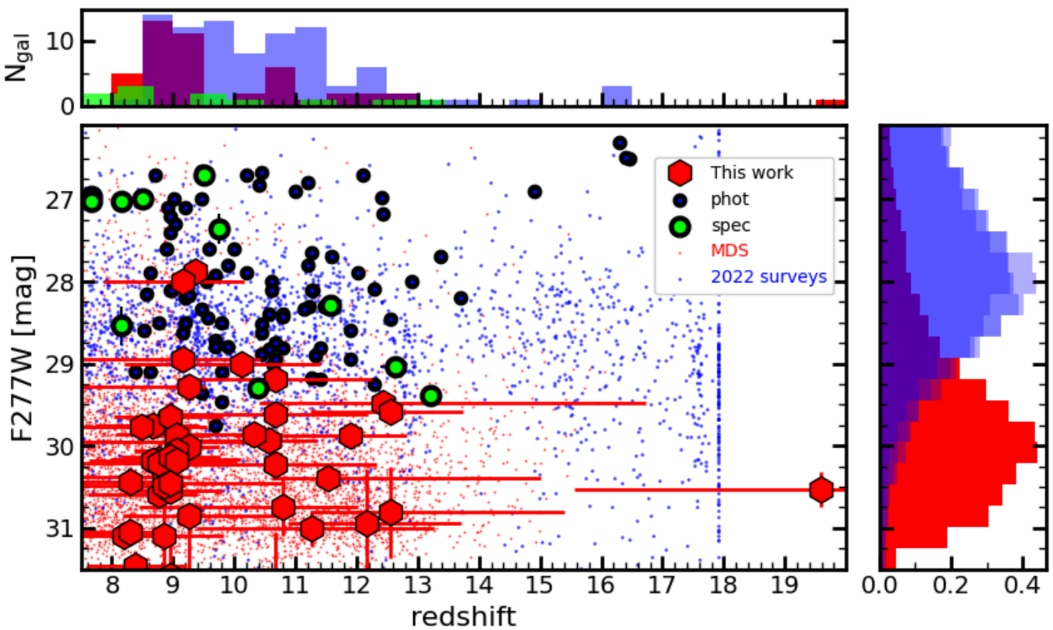


Early JWST/NIRCam results from deep extragalactic fields provided many promising high-redshift candidates at z > 11!

Harikane et al. (2022)

Early survey results have found candidate galaxies out to very high photometric redshifts across a broad magnitude range.

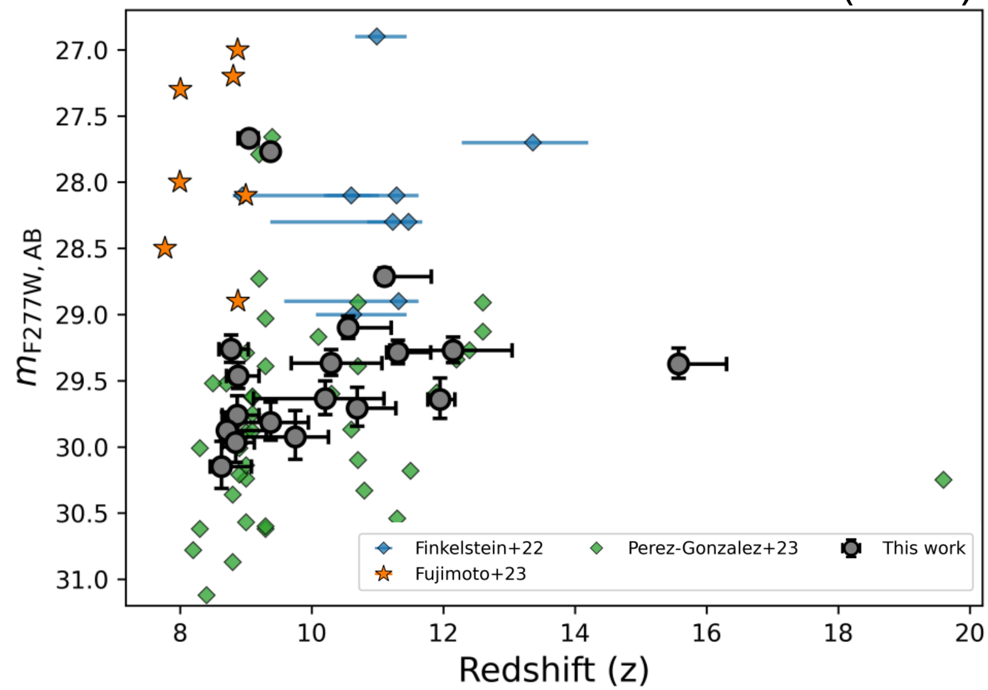
MIRI-DS



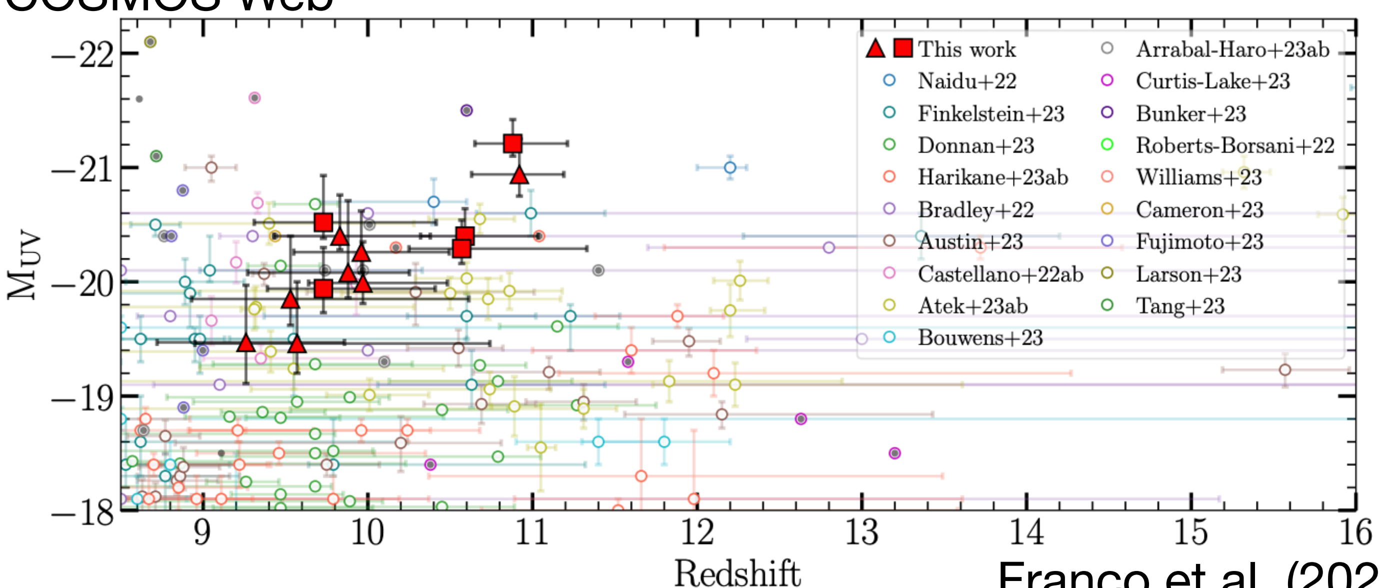
Perez-Gonzalez et al. (2023)

NG-DEEP

Austin et al. (2023)

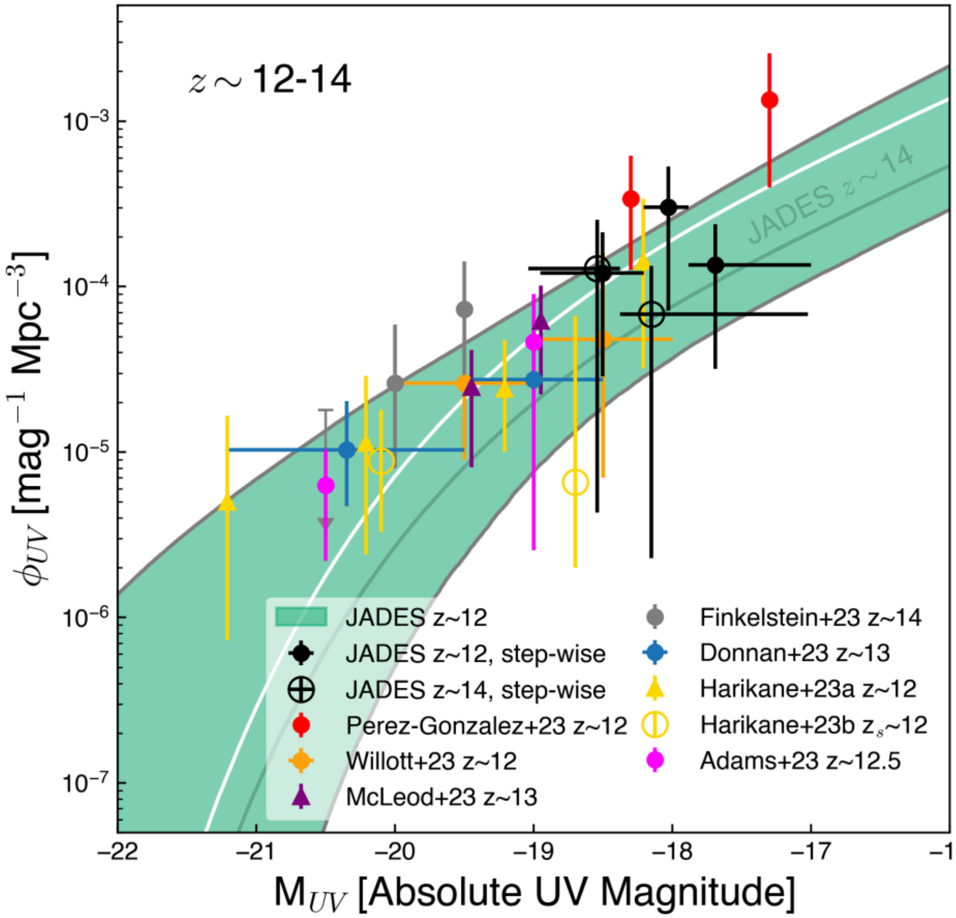


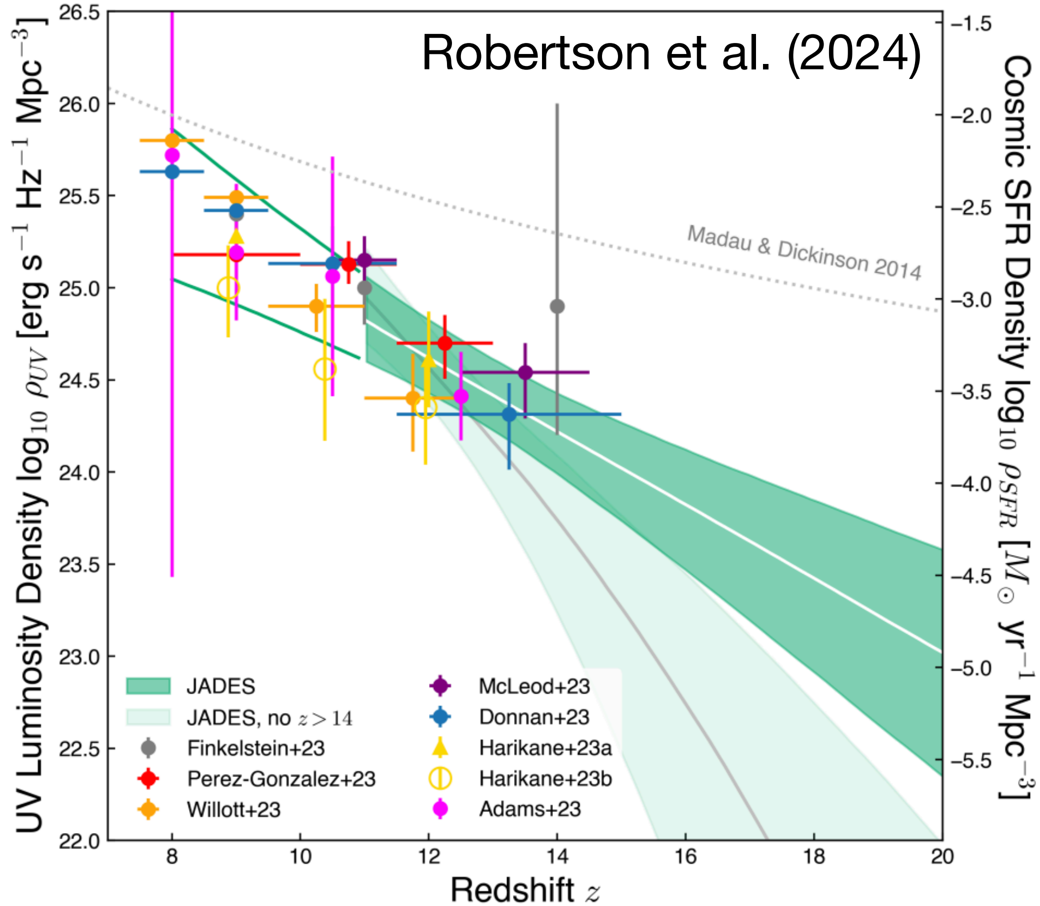
COSMOS Web



Franco et al. (2023)

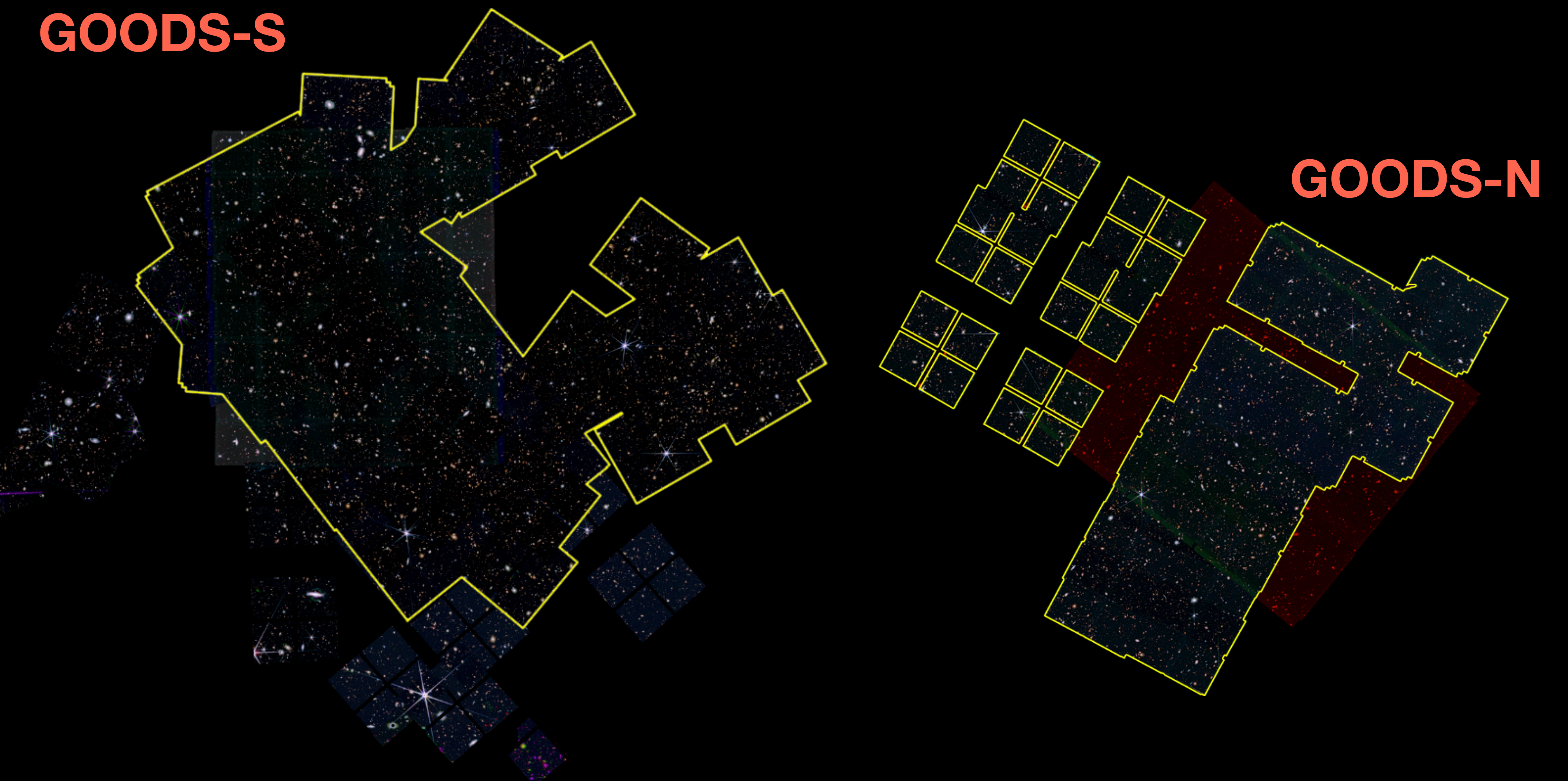
And tell a story of the universe’s somewhat less rapid buildup.



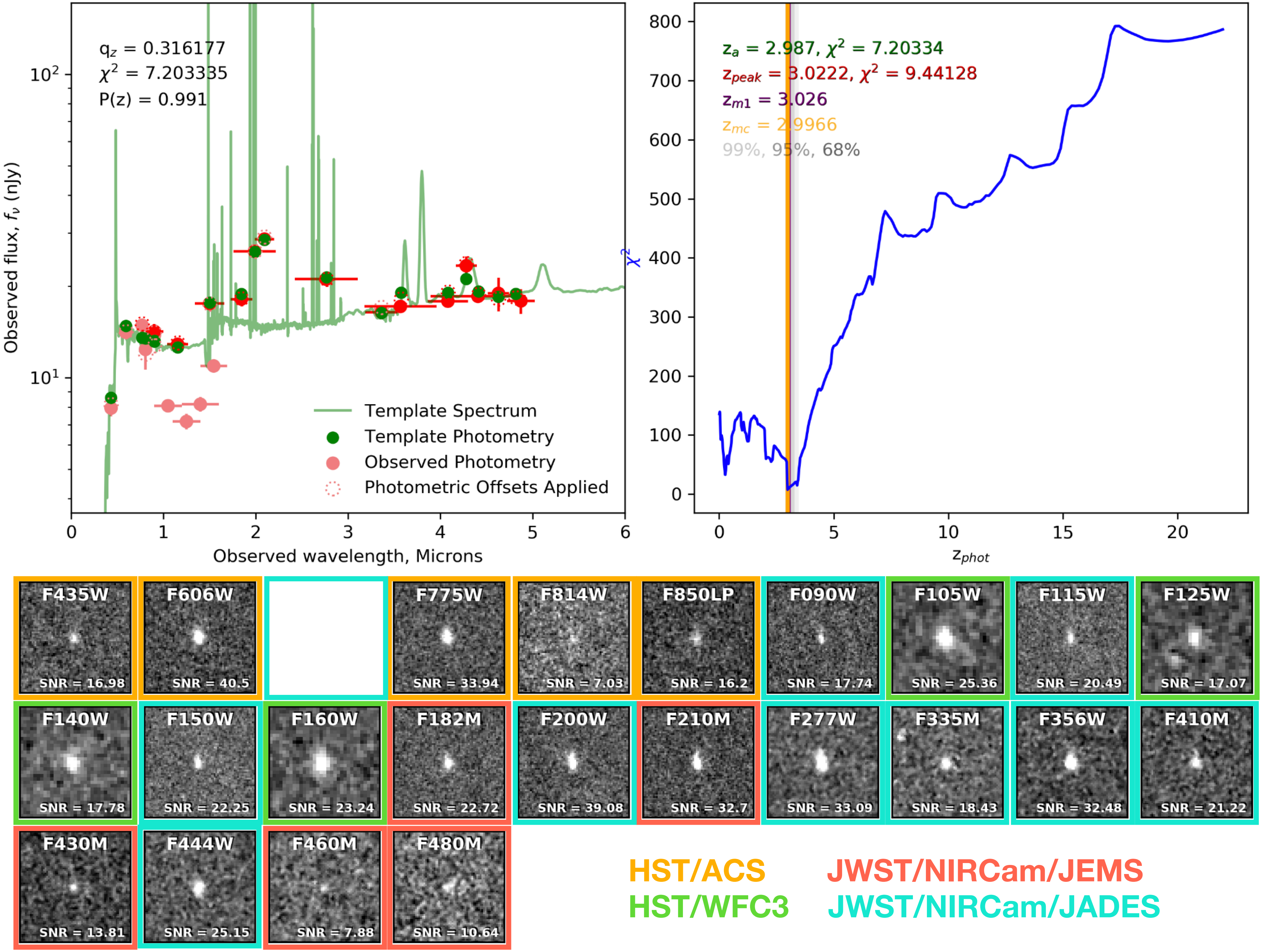


Instead of the first galaxies appearing at z = 10 - 12, as was suggested by HST, JWST hints that the evolution of galaxies was more gradual.

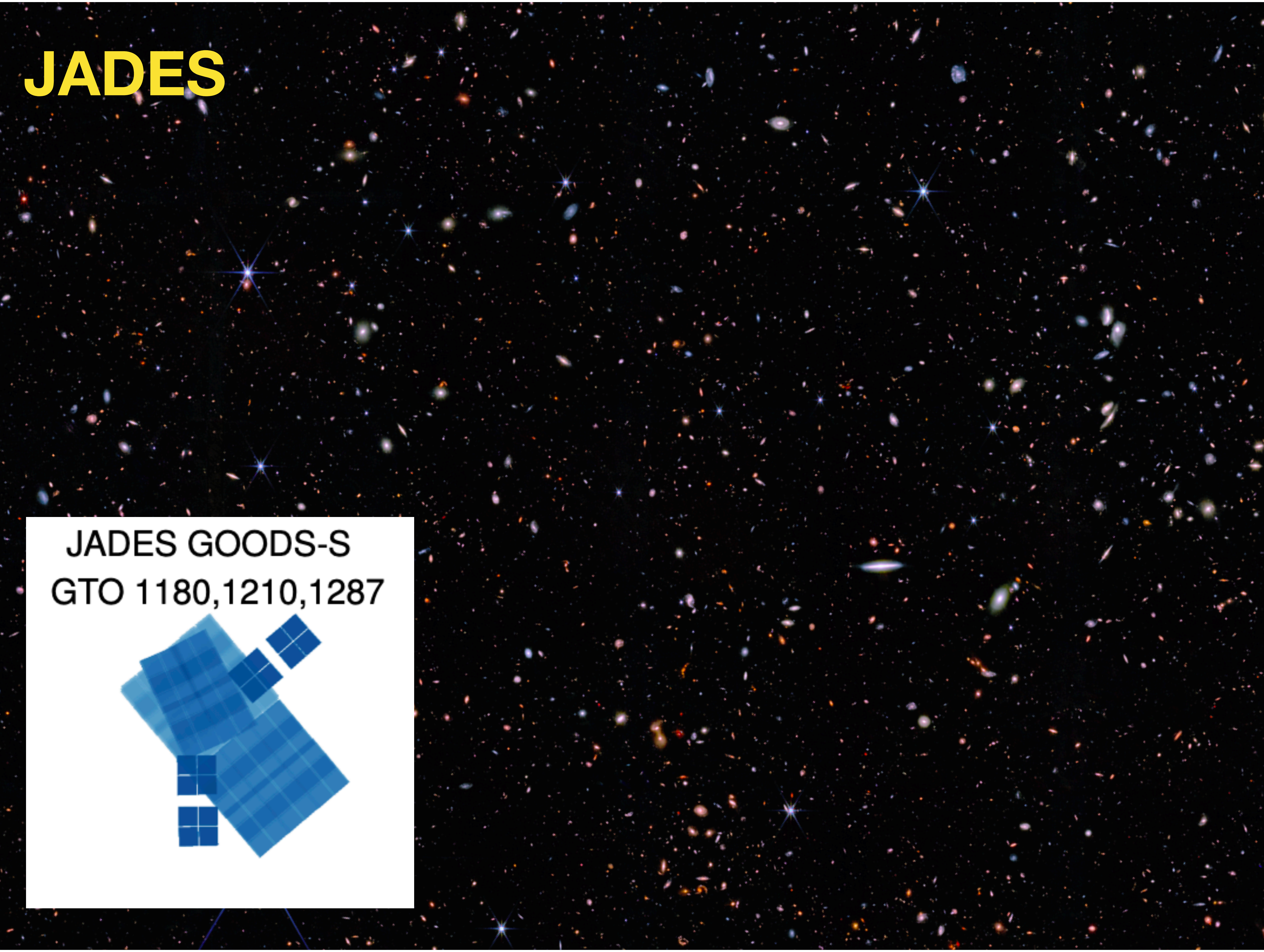
I am a member of the JADES Team.



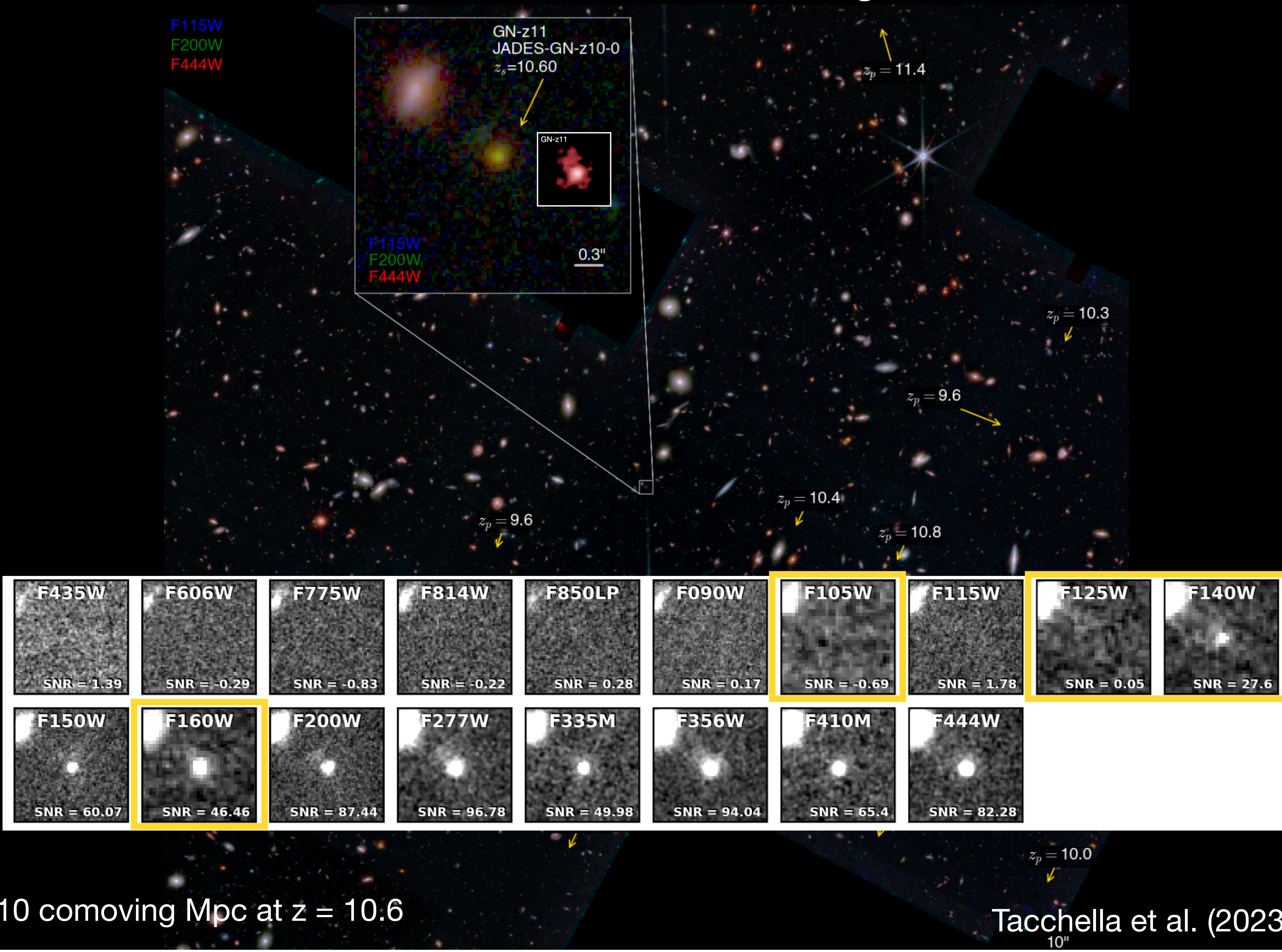
The JADES survey covers ~224 square arcminutes in two well-studied fields, and consists of imaging with a diverse filter set, along with NIRSpec and NIRCam grism spectroscopy, and MIRI photometry in a subfield.



$q_z = 0.316177$
$\chi^2 = 7.203335$
P(z) = 0.991
Template Spectrum
Template Photometry
Observed Photometry
Photometric Offsets Applied
Observed flux, f_ν (nJy)
Observed wavelength, Microns
$z_a = 2.987$, $\chi^2 = 7.20334$
$z_{peak} = 3.0222$, $\chi^2 = 9.44128$
$z_{m1} = 3.026$
$z_{mc} = 2.9966$
99%, 95%, 68%
χ^2
z_{phot}
F435W SNR = 16.98
F606W SNR = 40.5
F775W SNR = 33.94
F814W SNR = 7.03
F850LP SNR = 16.2
F090W SNR = 17.74
F105W SNR = 25.36
F115W SNR = 20.49
F125W SNR = 17.07
F140W SNR = 17.78
F150W SNR = 22.25
F160W SNR = 23.24
F182M SNR = 22.72
F200W SNR = 39.08
F210M SNR = 32.7
F277W SNR = 33.09
F335M SNR = 18.43
F356W SNR = 32.48
F410M SNR = 21.22
F430M SNR = 13.81
F444W SNR = 25.15
F460M SNR = 7.88
F480M SNR = 10.64
HST/ACS
HST/WFC3
JWST/NIRCam/JEMS
JWST/NIRCam/JADES


JADES
JADES GOODS-S
GTO 1180,1210,1287

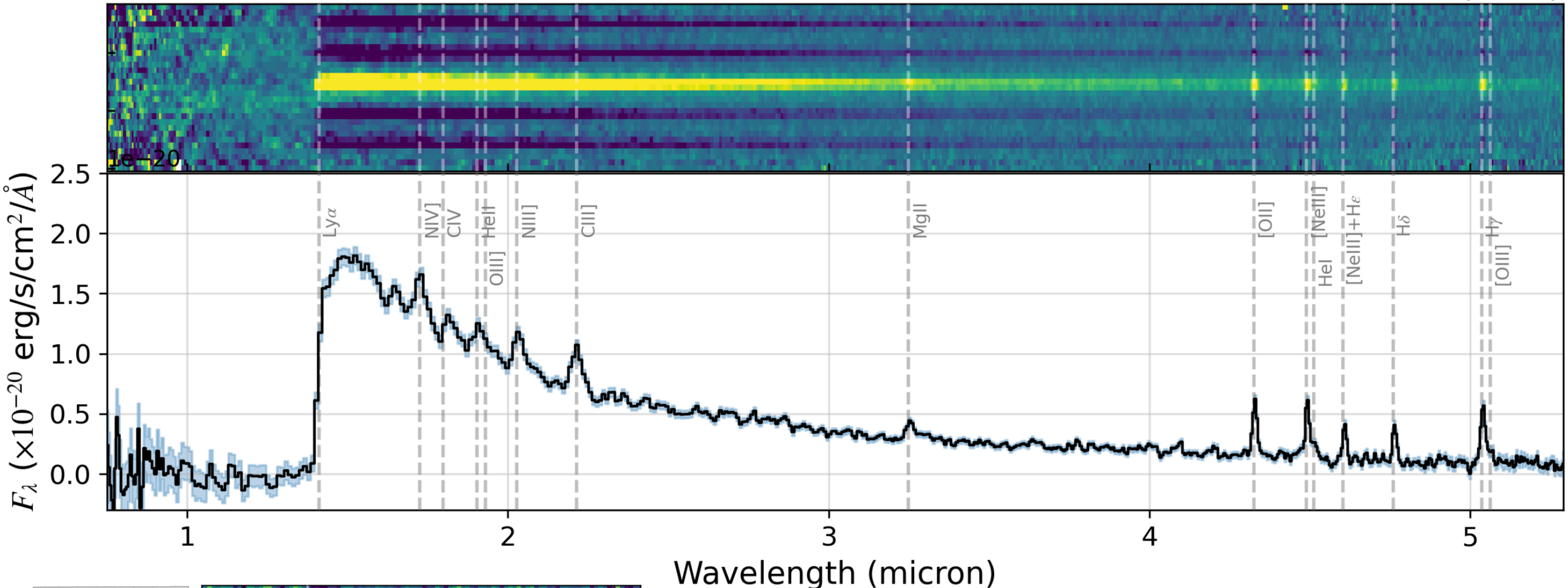
The HST discovered source GN-z11 was imaged with JADES

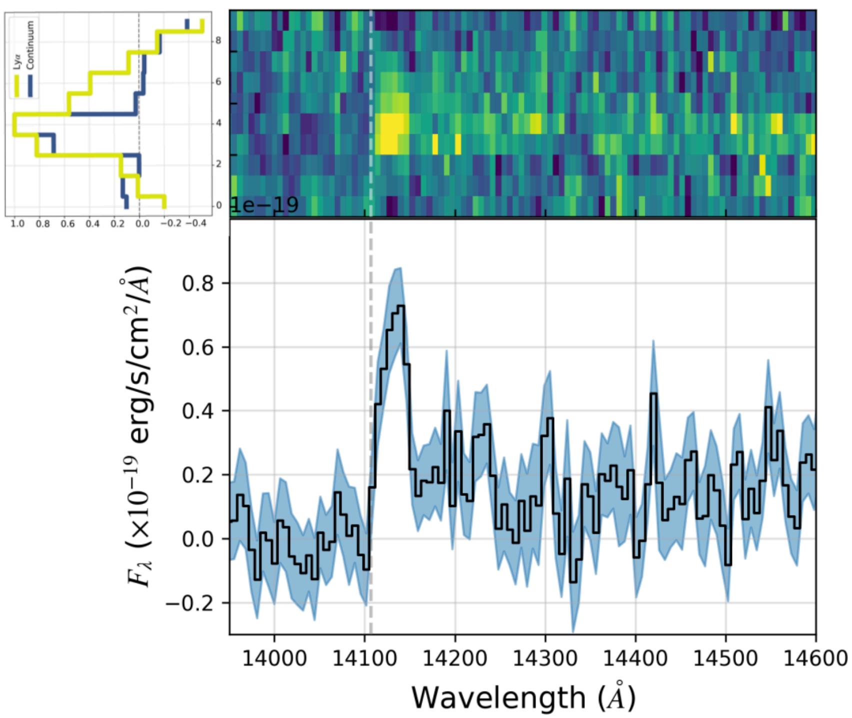


10 comoving Mpc at z = 10.6

Tacchella et al. (2023)

Bunker et al. (2023)

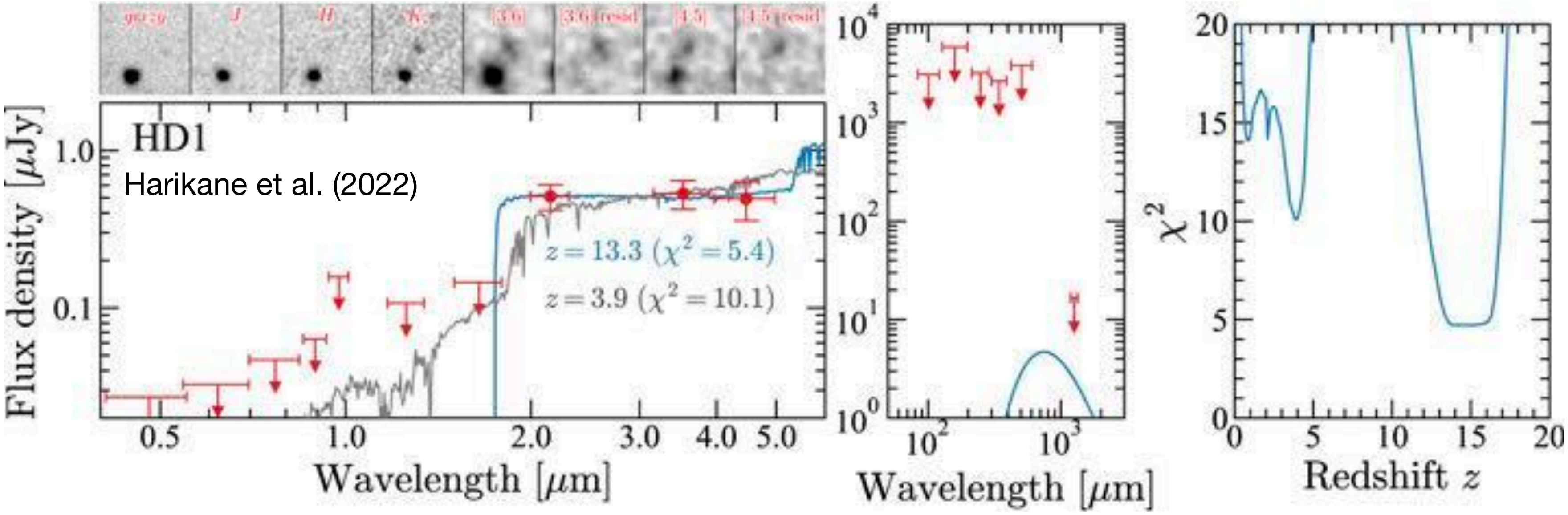


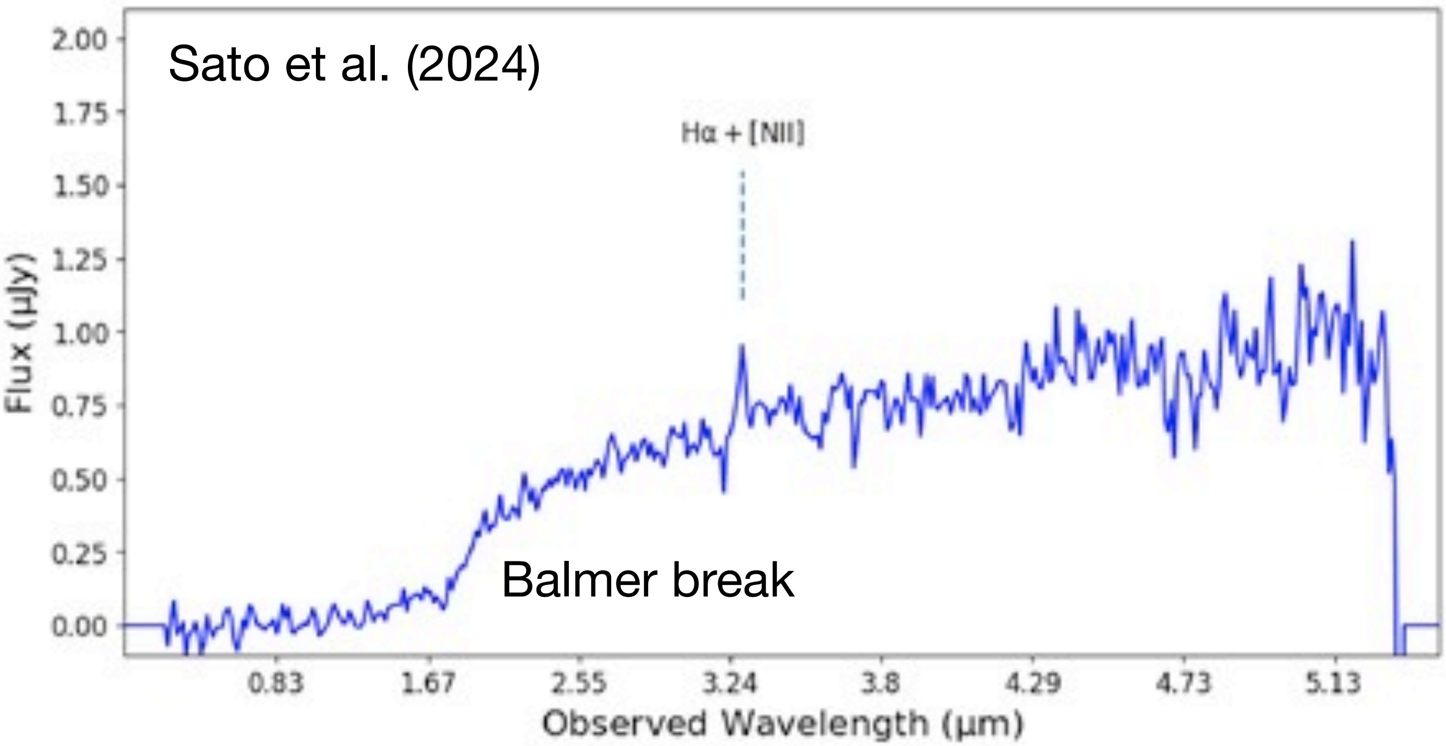


The UV-optical spectrum of GN-z11 has many strong emission lines, including a strong detection of Lyman-alpha only 400 million years after the Big Bang. The detection of [NeIV]λ2423 and CII*λ1335 lines point to the presence of an accreting supermassive black hole (Maiolino et al. 2023)

(see also: Senchyna et al. 2023, Nagele et al. 2023, Charbonnel et al. 2023, Cameron et al. 2023, Bekki et al. 2023, D'Antona et al. 2023, Bhatt et al. 2024, Kobayashi et al. 2024, etc etc for many papers discussing this spectrum)

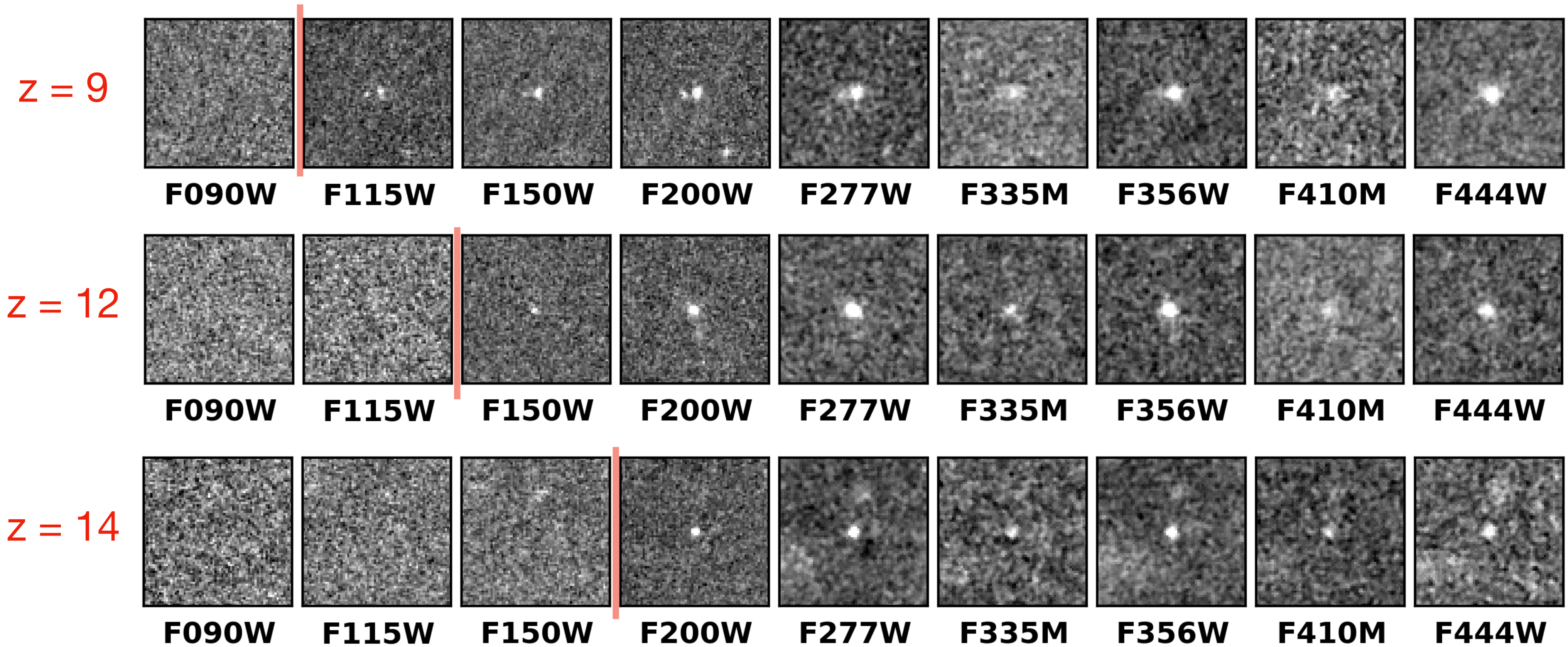
A side note: HD1 was observed with JWST/NIRSpec in late 2022/early 2023, and the spectrum indicates it is unfortunately a low-redshift interloper at *z* = 4.0.





This is the worry about a lot of these ultra distant "candidate" galaxies - they may not turn out to be truly that distant, muddying our understanding of galaxy evolution

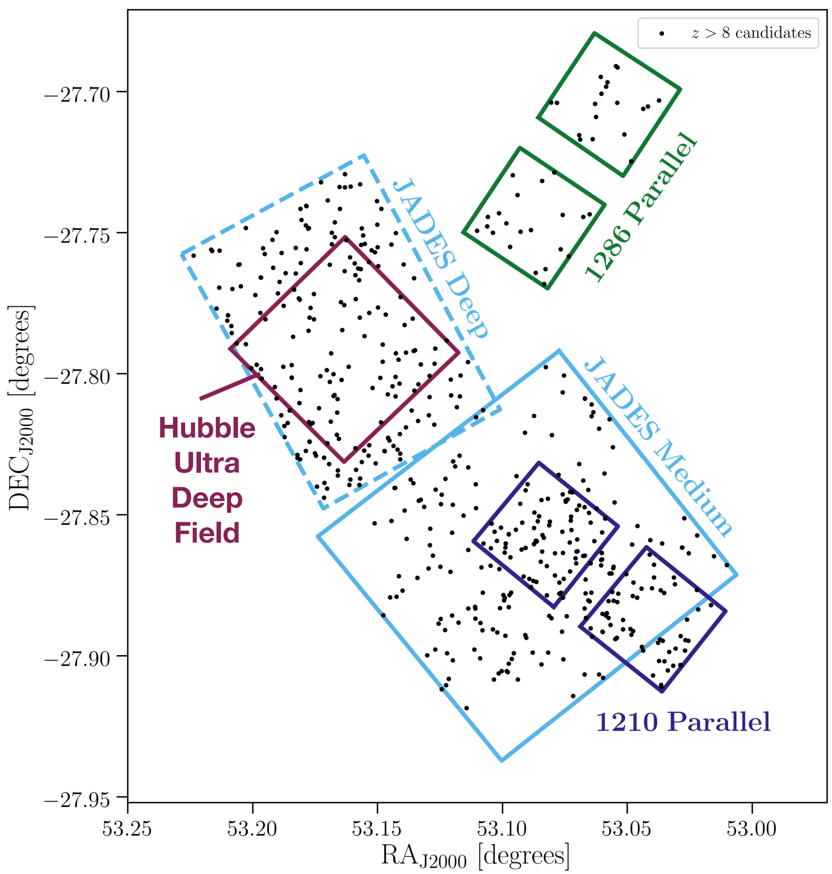
In JADES we use fifteen HST + NIRCam filters to for photometric redshift estimation with EAZY (Brammer et al. 2008), allowing us to characterize more than just the Lyman break.

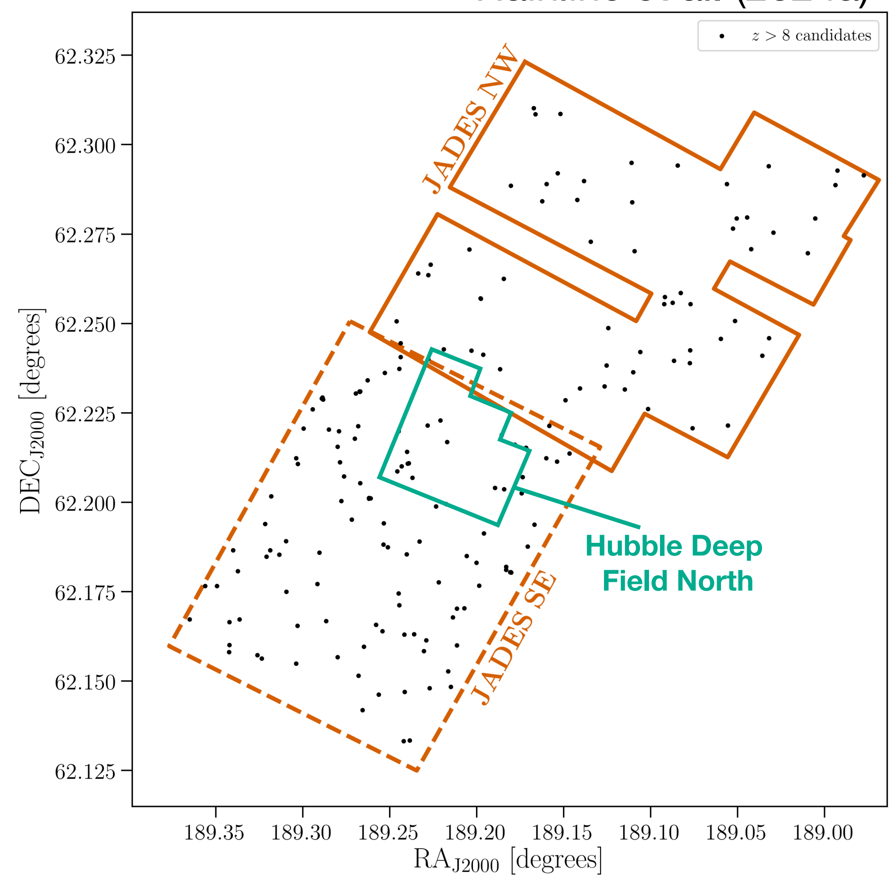


JWST NIRCam filters

We have found 717 galaxies and candidates at redshift $z > 8$ across the year one JADES footprint.

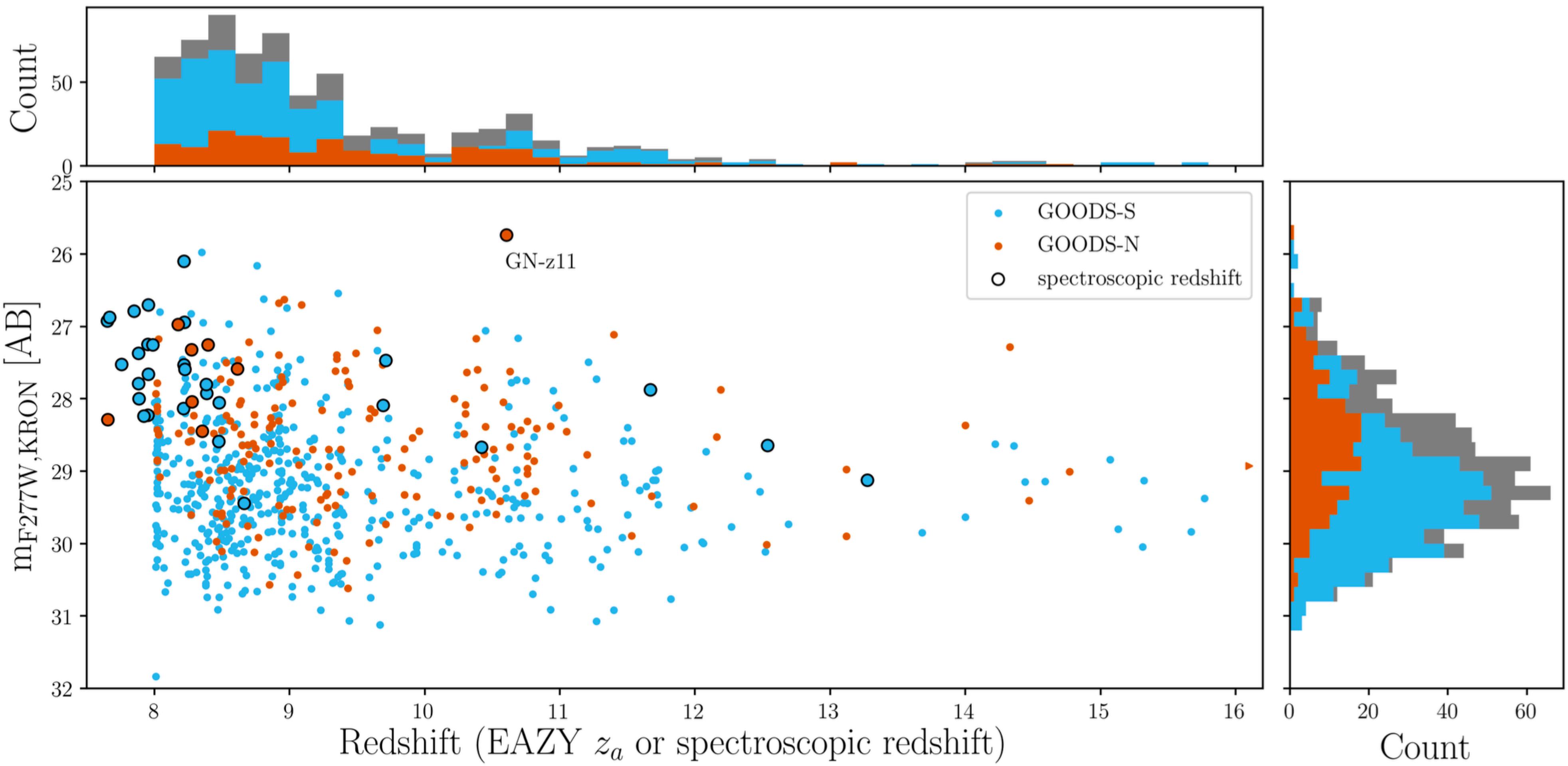
Hainline et al. (2024a)



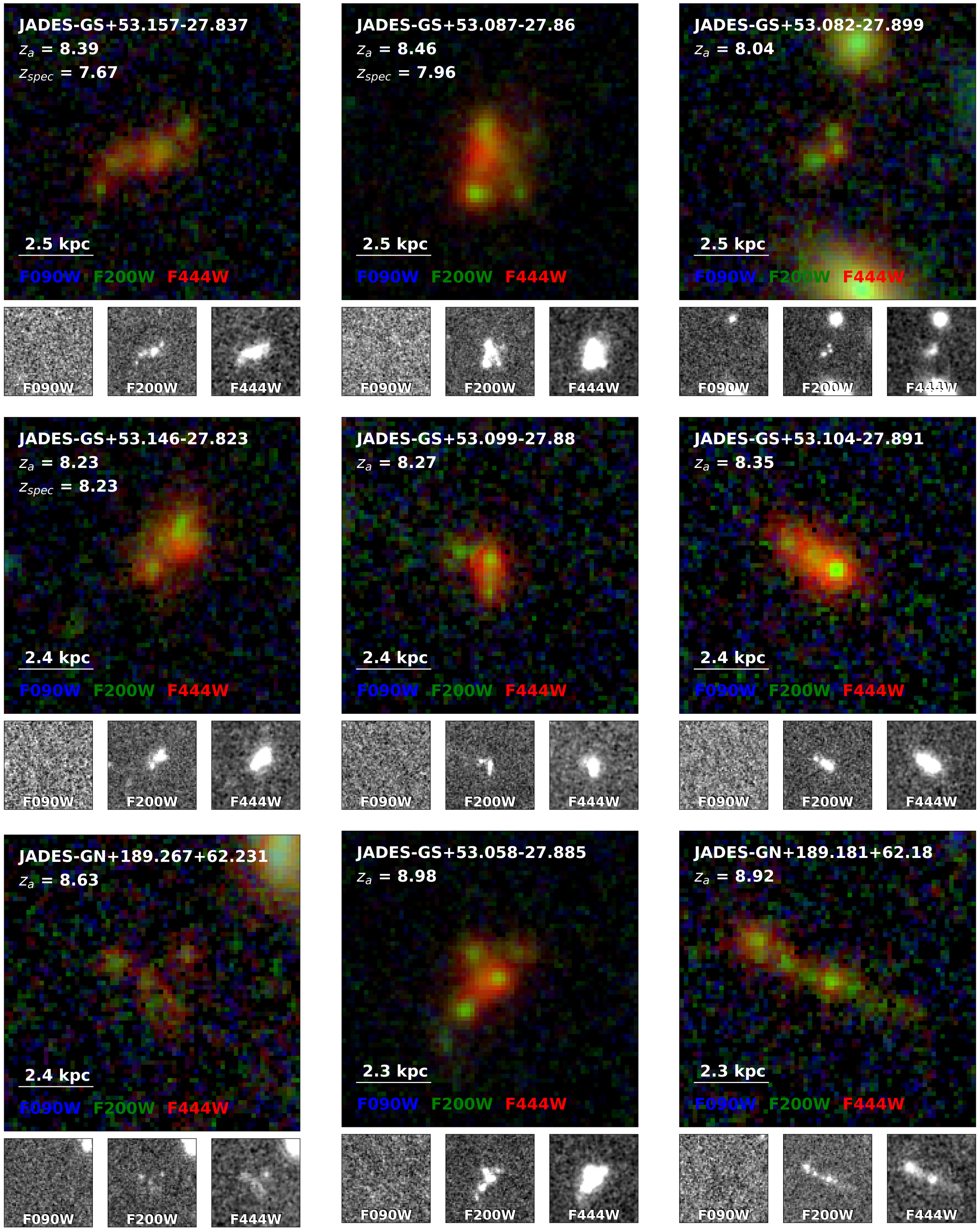


We have 7.8 sources per square arcminute in JADES Deep, and 13.9 sources per square arcminute in the ultra deep 1210 parallel.

Over 93% of the sources presented are new to this sample, and they extend down to 31 - 32 mags AB, at 2.7 microns.



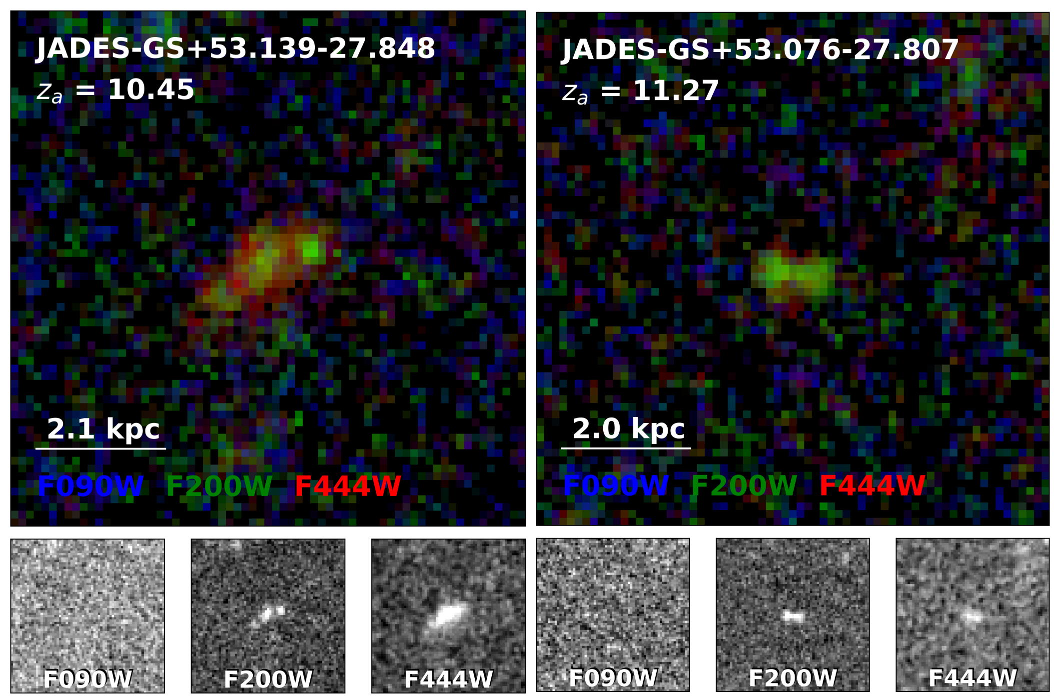
Hainline et al. (2024a)



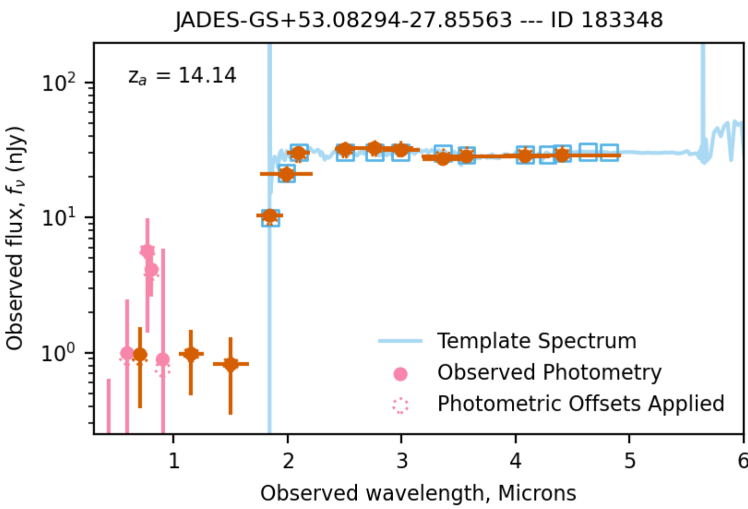
Hainline et al. (accepted)

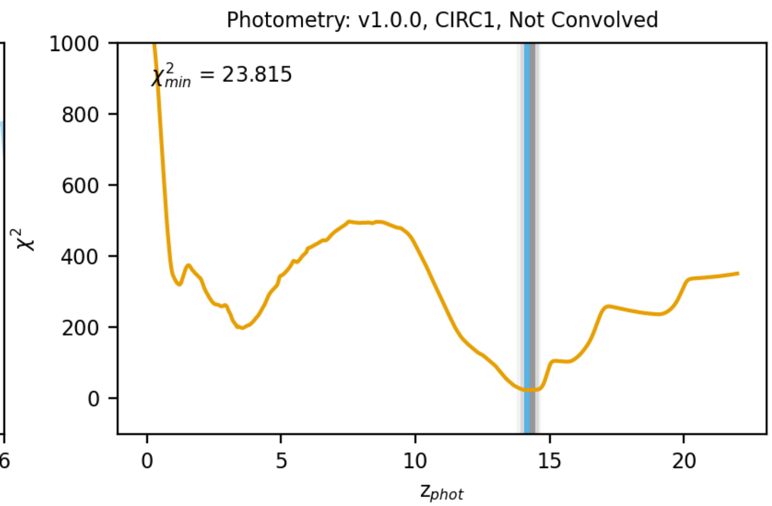
Many of our galaxies and candidates have complex shapes with multiple clusters of star formation, showing us the early growth of galaxies.

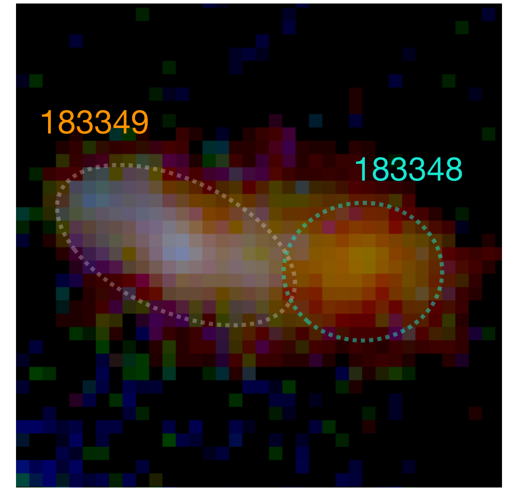
These two candidates are from only 400 - 450 Million years after the Big Bang

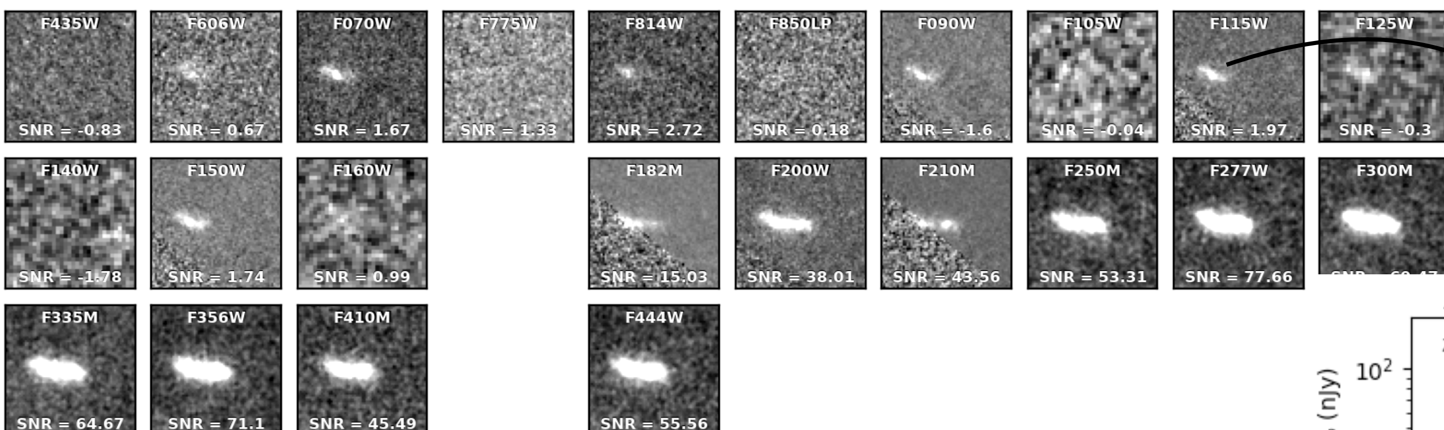


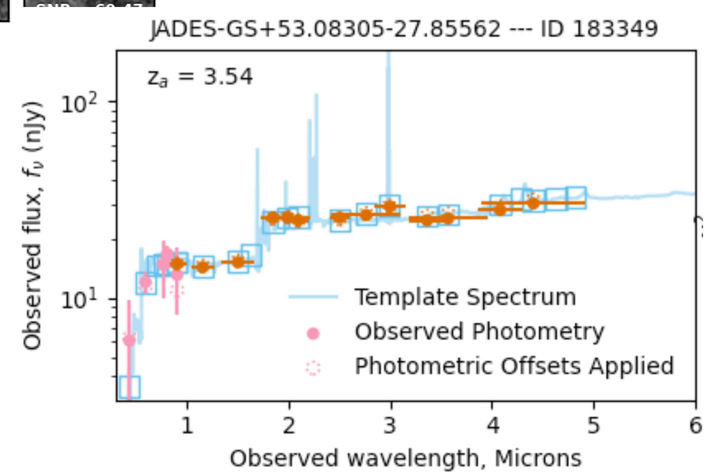
One source, ID 183348, was very confusing given it’s proximity to another, closer galaxy.





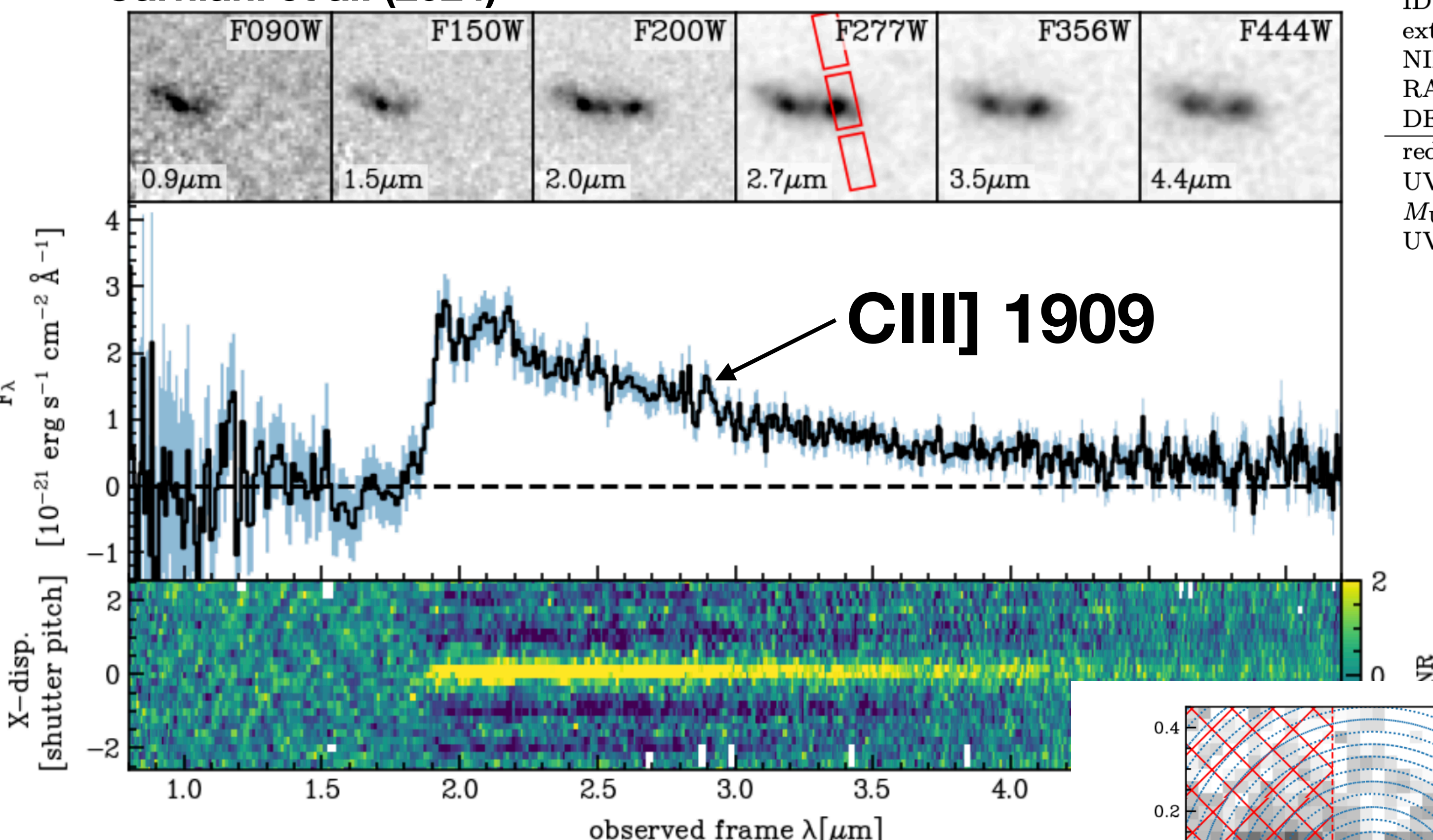




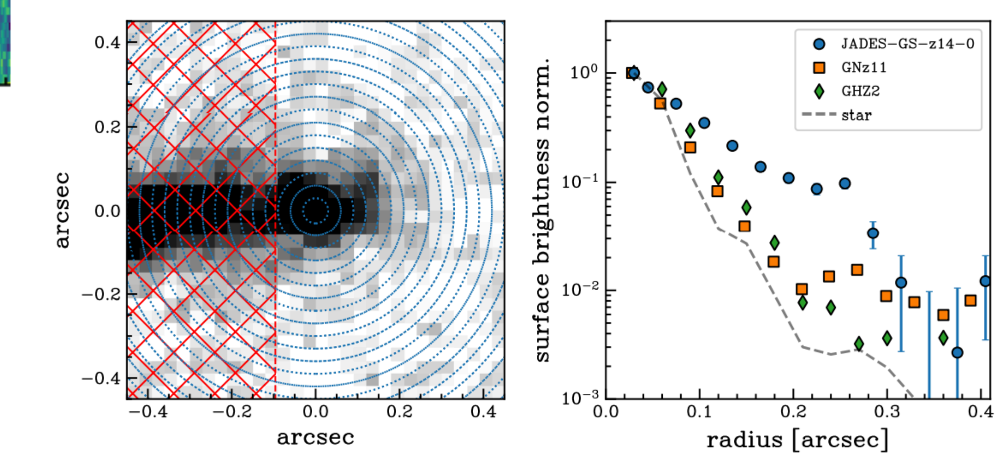


JADES-GS-z14-0 (*z* = 14.18, MUV = -20.8) was confirmed to be the most distant galaxy humans have (currently!) ever observed.

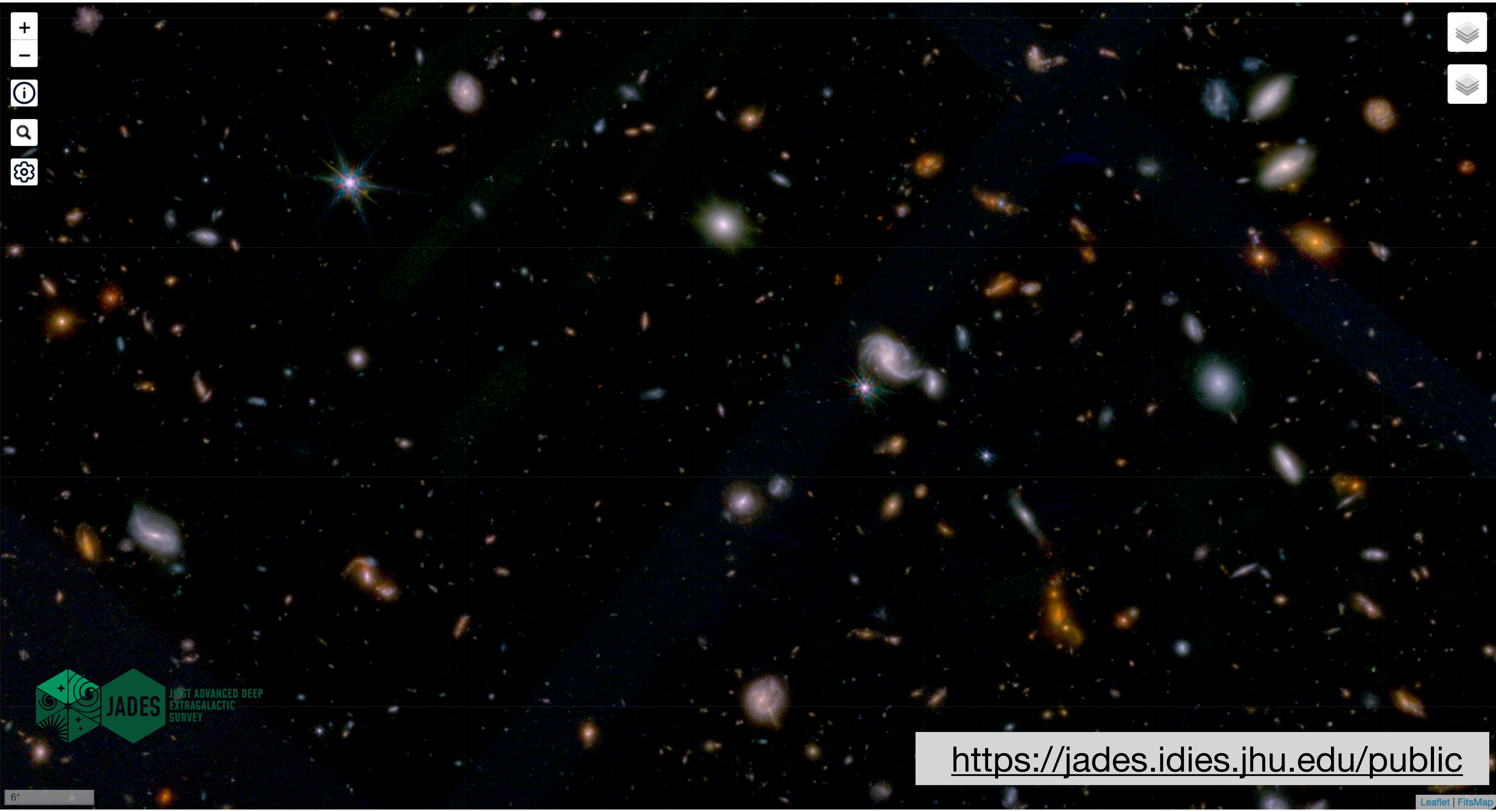
Carniani et al. (2024)



ID	JADES-GS-z14-0
extended ID	JADES-GS-53.08294-27.85563
NIRCam ID	183348
RA[ICRS]	3:32:19.9049
DEC[ICRS]	-27:51:20.265
redshift	$14.32^{+0.08}_{-0.20}$
UV slope β	-2.20 ± 0.07
$M_{\rm UV}$	-20.81 ± 0.16
UV radius ($r_{\rm UV}$) [pc]	260 ± 20



Our JADES Deep data is public, with photometric and spectroscopic reductions available on the STScI MAST.



In addition, we have a full interactive JADES Deep fitsmap viewer available for exploring the data.

Conclusions

JWST has opened a new and exciting era of extragalactic astronomy!

- Fundamental questions about the evolution of the universe from the end of the dark ages to today require **observations of galaxies at increasingly high redshifts.**
- One of the primary quantities required to explore these questions is redshift. **Between spectroscopic surveys and photometric redshift techniques, measuring galaxy distances is made easier with large telescopes that probe longer wavelengths.**
- JWST, with its 6.5 meter mirror and suite of infrared imaging and spectroscopic instruments, **is ideal for discovering and characterizing galaxies at the redshift frontier ($z > 10$).**
- The first two years of JWST surveys include large, shallow area surveys as well as very deep, but small surveys. **JADES, the JWST NIRCam/NIRSpec GTO program, recently completed, is the most comprehensive extragalactic survey in the first few years of JWST.**
- **With JADES, have found many thousands of galaxies above $z > 6$, including the first confirmed galaxies at $z > 11$, providing key answers to questions about galaxy evolution and reionization.**