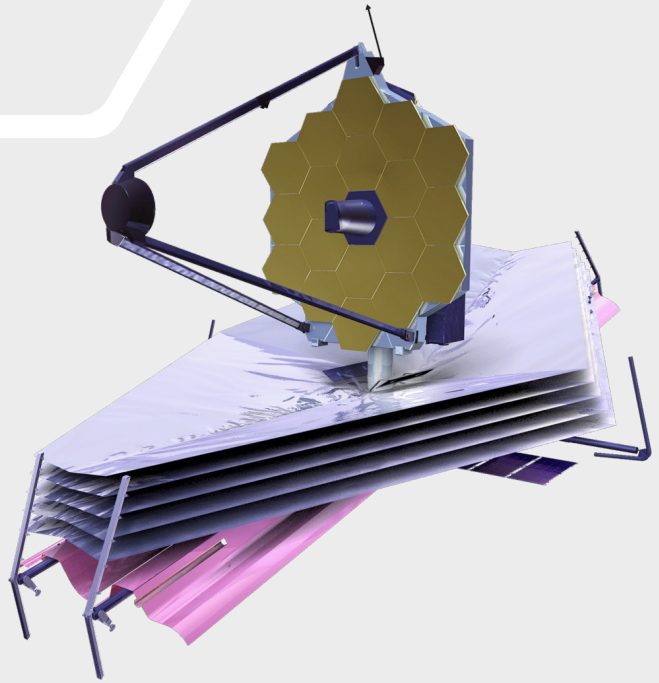
JWST results:
A revolutionary view of early galaxies



Paola Santini

INAF – Osservatorio Astronomico di Roma

INFN Colloquia, Firenze, 15 Apr 2024

DOUBLE ISSUE

DEC. 5 / DEC. 12, 2022

Photos of the Year

IMAGES THAT CHANGED HOW WE SEE THE WORLD... AND BEYOND

TIME

One of the James Webb Space Telescope's first pictures of the distant universe

time.com

Bhaumik Breakthrough of the Year Award launches p. 1145 | Policy reform for pathogen research oversight p. 1170 | Monopoles hopping on a fractal cluster pp. 1177 & 1218

Science

$15
16 DECEMBER 2022
science.org

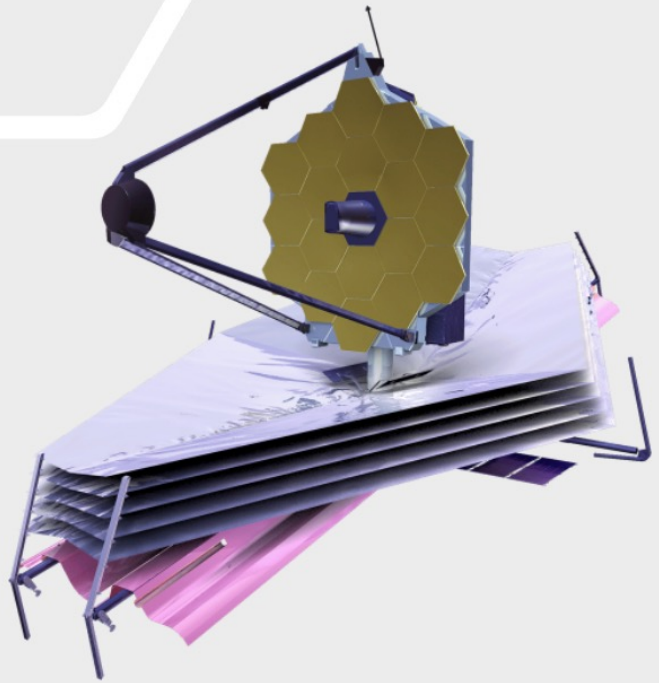
AAAS

2022

BREAKTHROUGH OF THE YEAR

Outline of the talk

- Why do we study the high-z Universe?
  State-of-the-art before JWST
- Overview of JWST:
  the ideal telescope for observing the earliest galaxies
- JWST major results
- Interpretations, challenges, open questions and future perspectives



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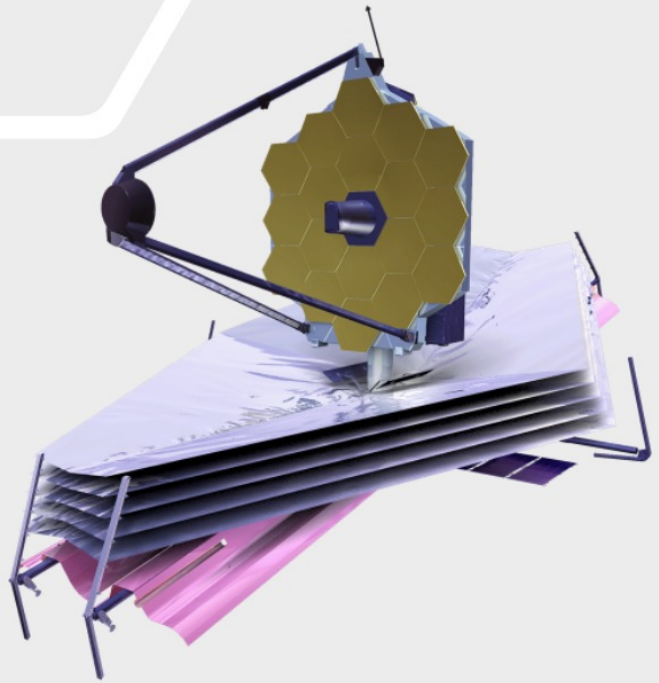
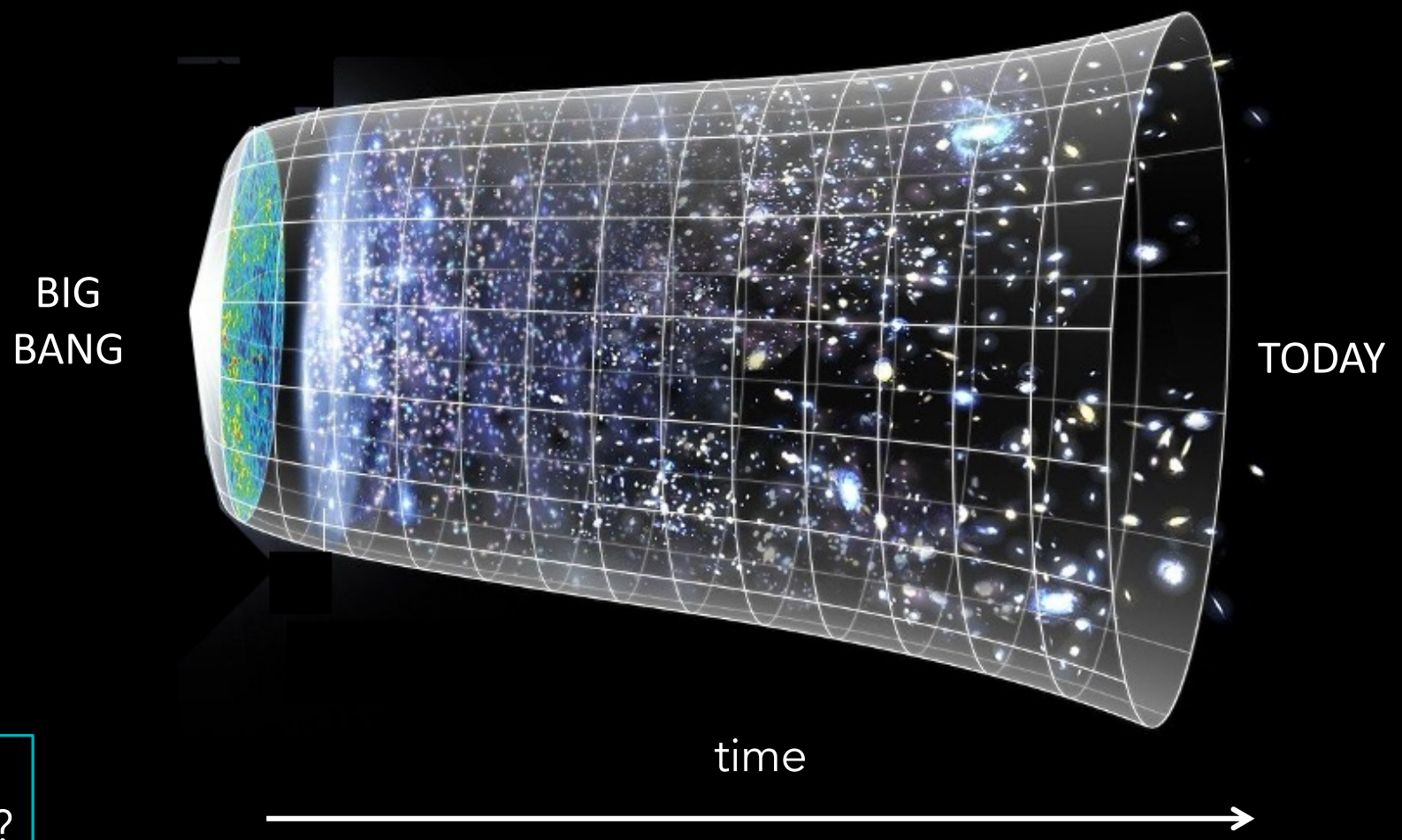


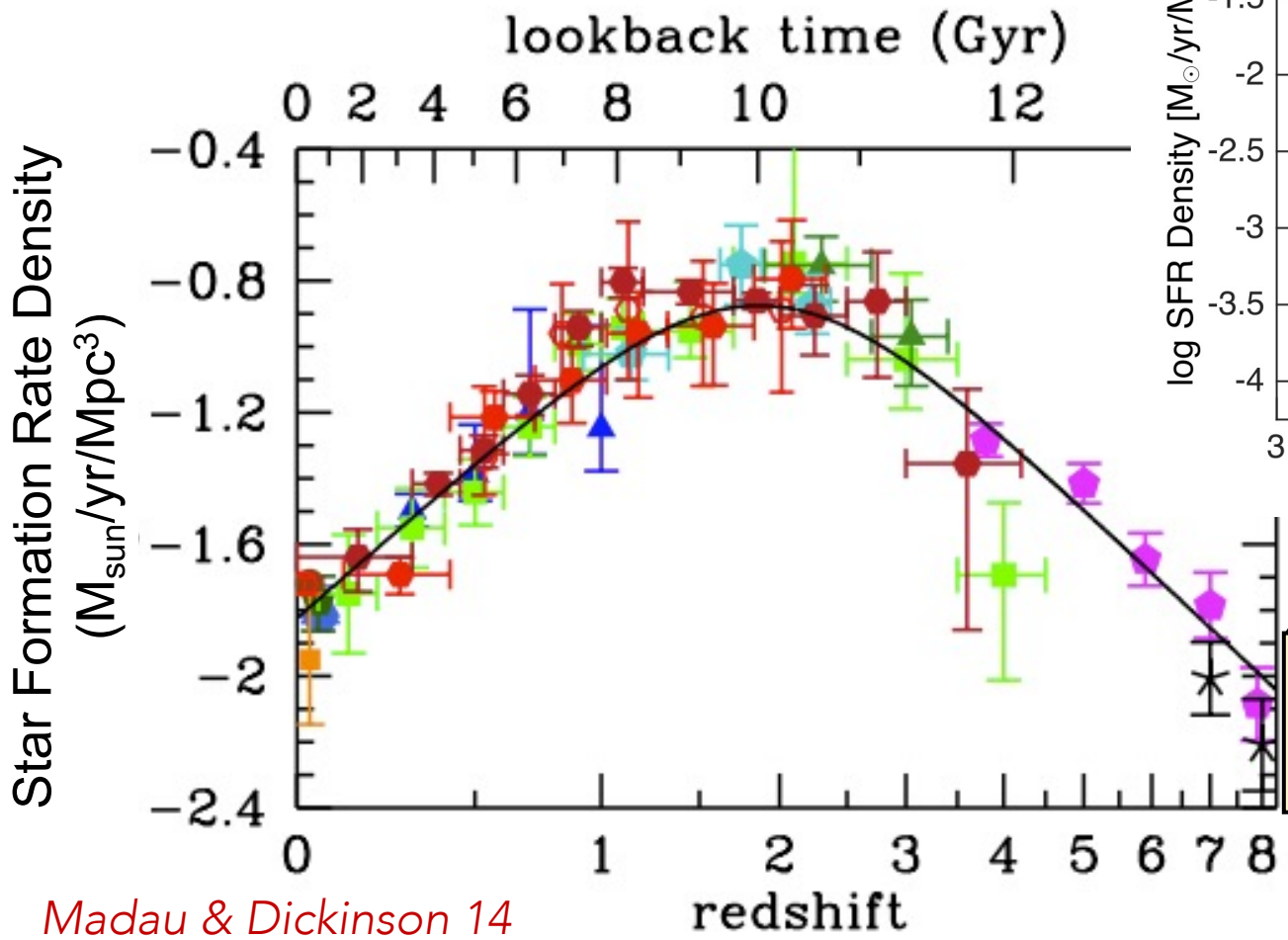
The primordial Universe was

- denser
- warmer
- no stars
- no “heavy” elements



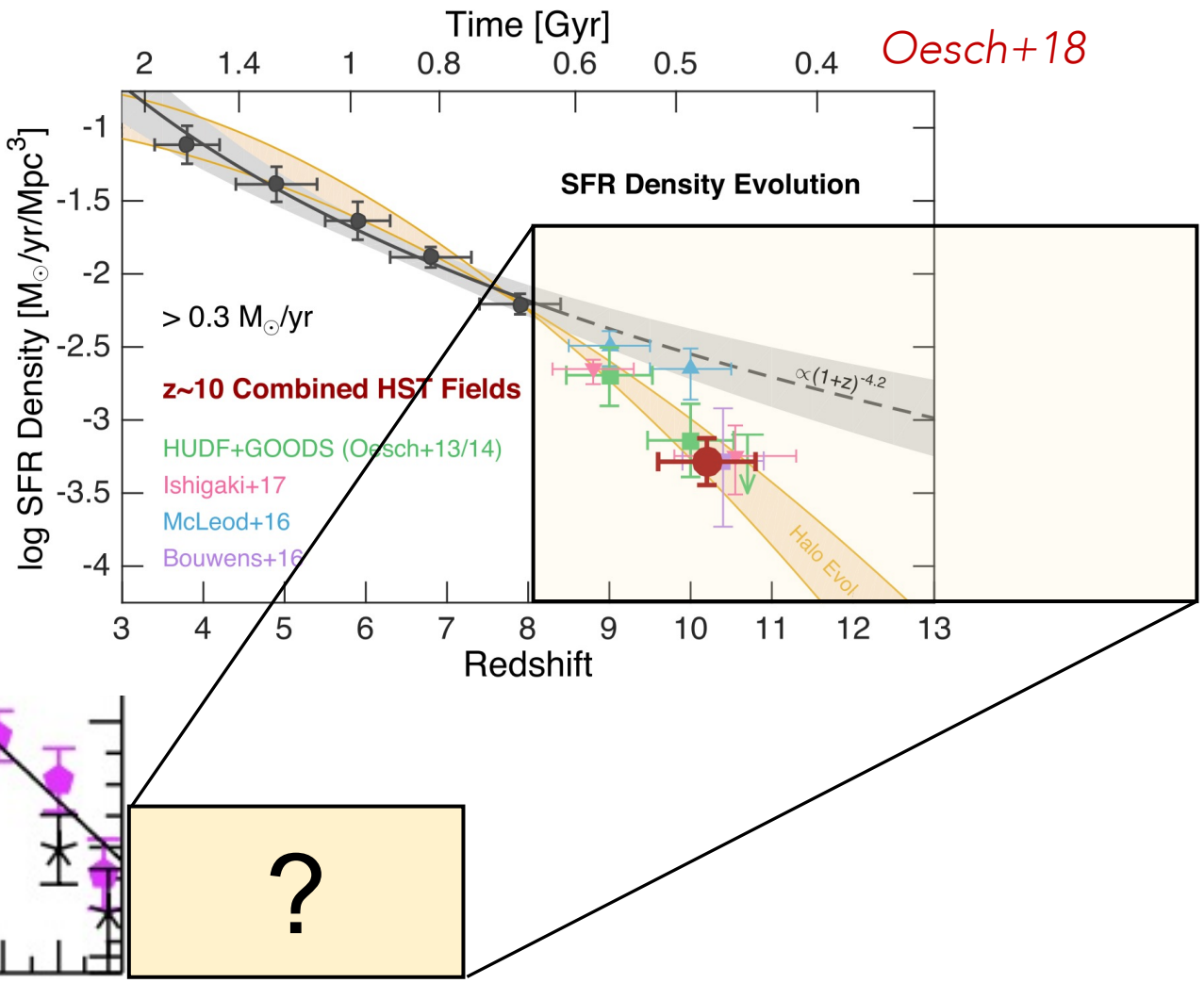
Open question
When did the first galaxies form?

The Star Formation History of the Universe



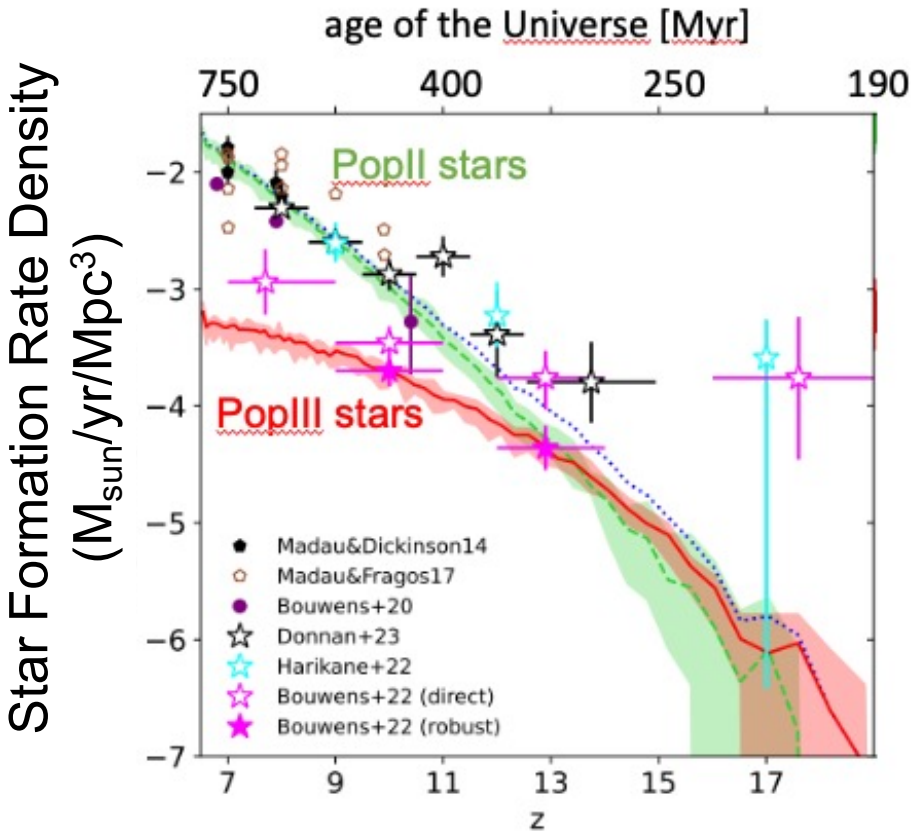
Madau & Dickinson 14

Oesch+18

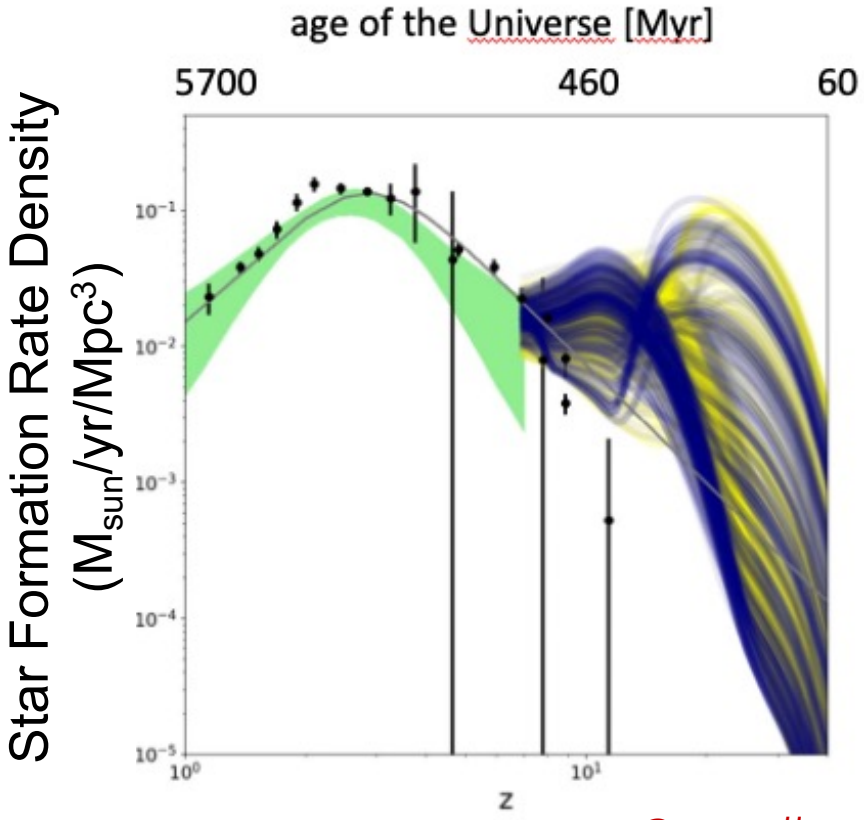


?

... UNKNOWN IN THE EARLIEST EPOCHS



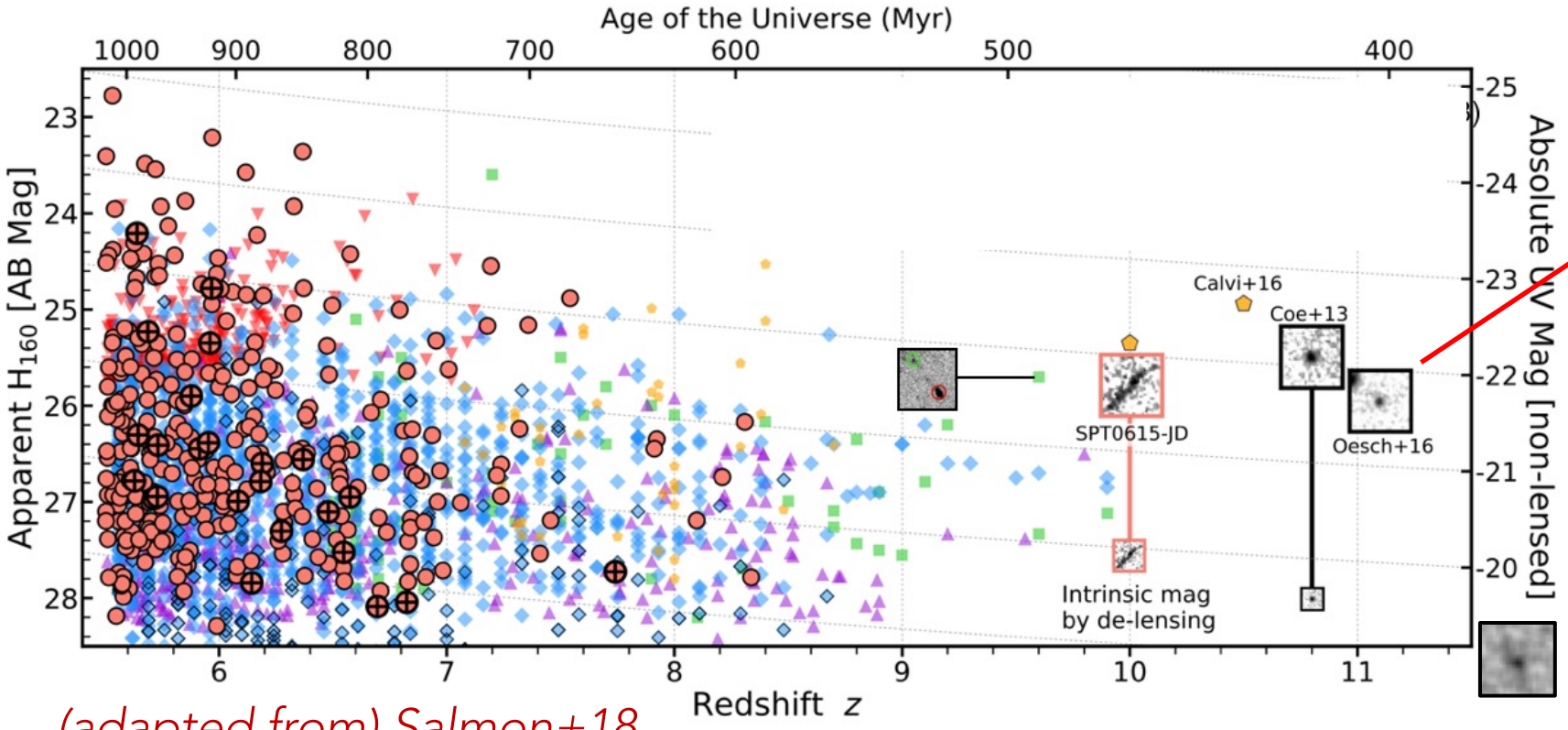
(adapted from) Venditti+23



Cappelluti+22

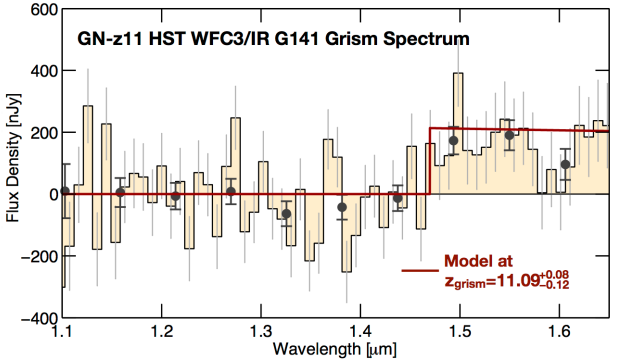
Fundamental for reionization, BH seeds, first stars, chemical evolution, etc

The Hubble legacy



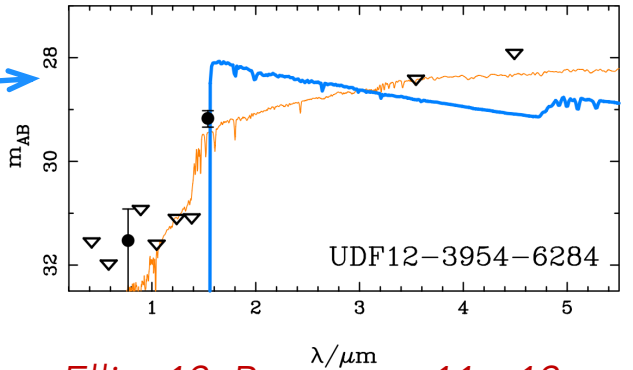
(adapted from) Salmon+18

Most distant spectroscopically confirmed galaxy



Oesch+16

Most distant photometrically selected galaxy

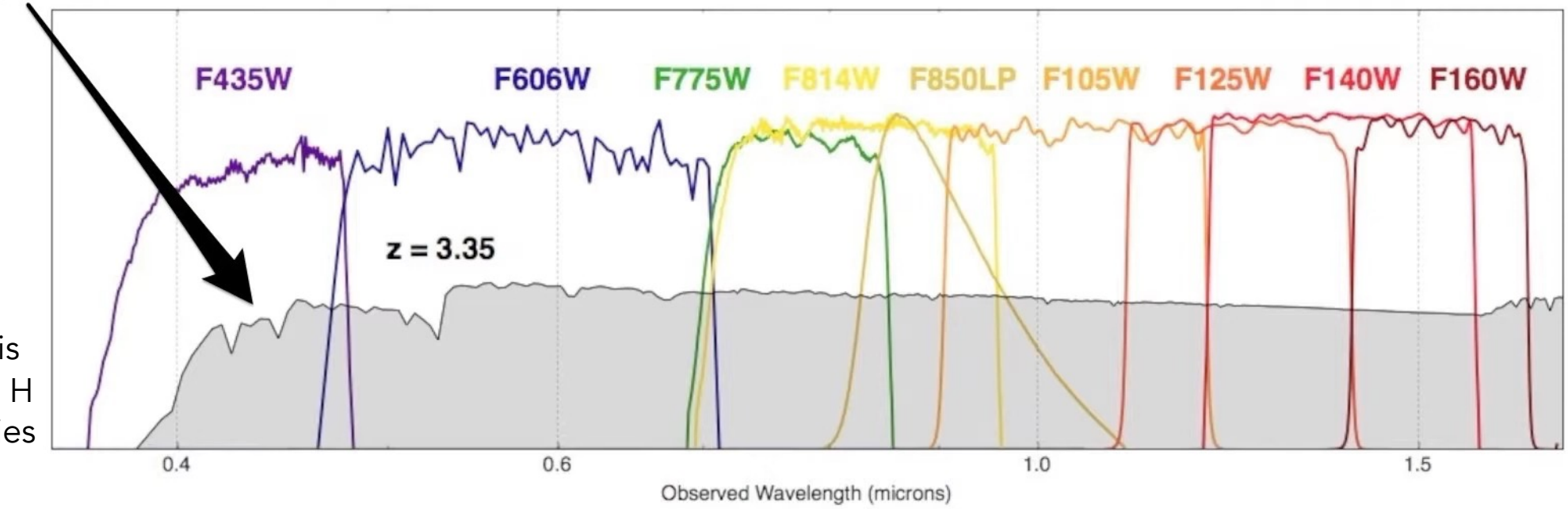


Ellis+13, Bouwens+11,+13

Why an IR telescope?

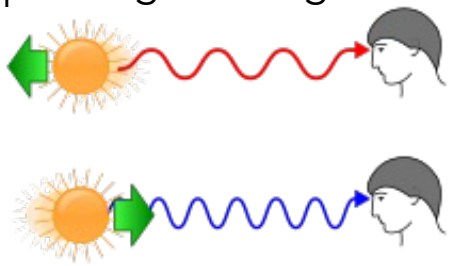
Simulation goes back in time from 1.8 Gyr to 360 Myr

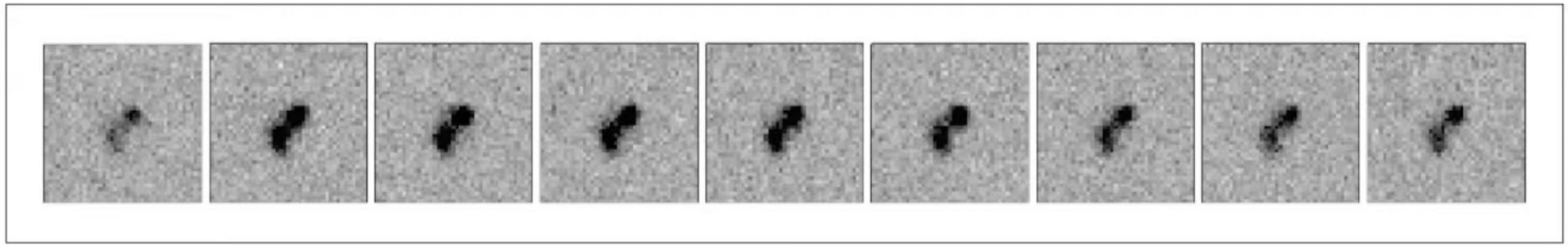
Detection of z>12 galaxies



Rest-frame UV light is absorbed by neutral H in and around galaxies

COSMOLOGICAL REDSHIFT: due to space expanding while light travels

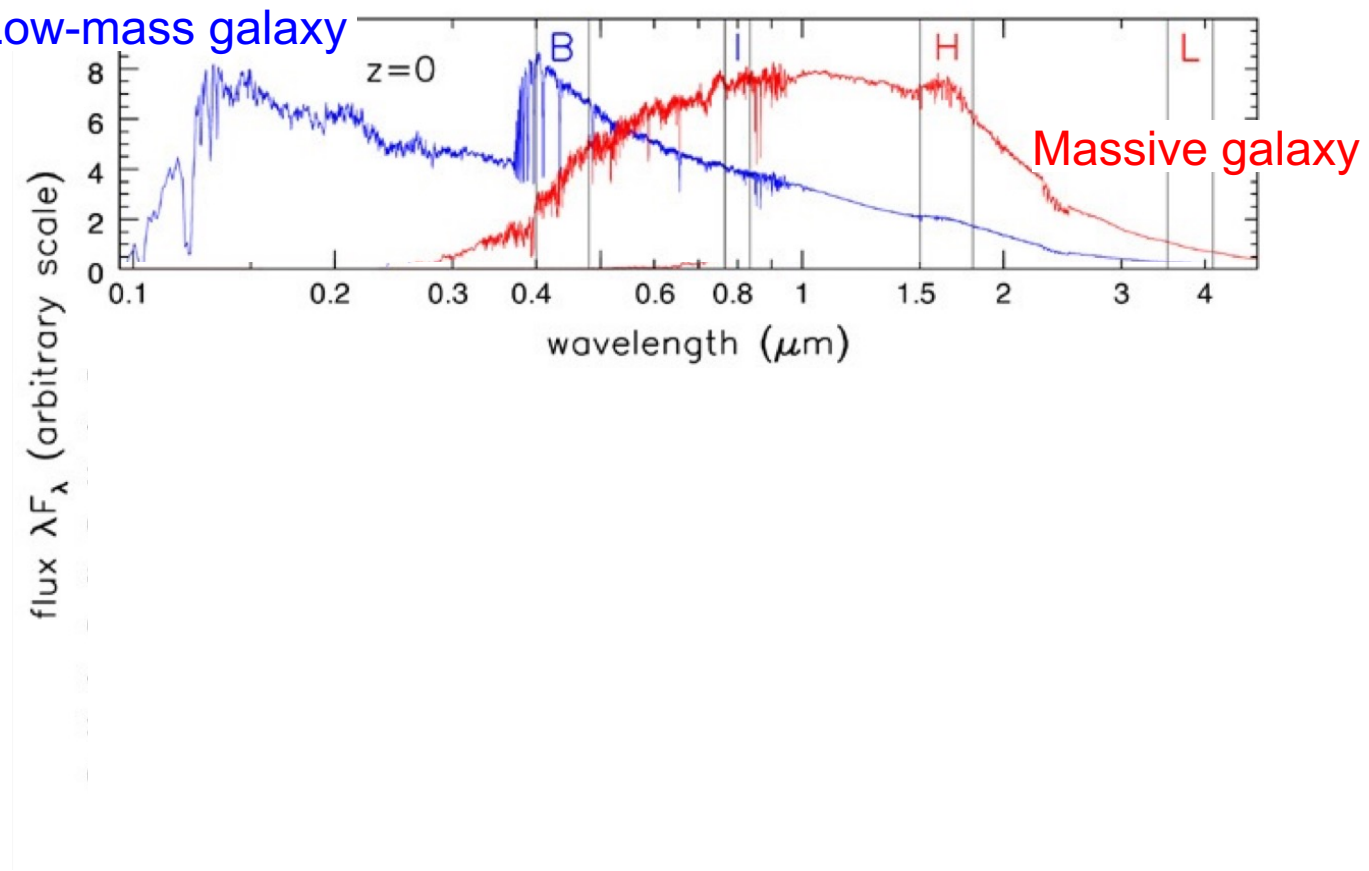




Credit: D. Magee, R. Bouwens, P. Oesch, & G. Illingworth

Why an IR telescope?

Estimate of physical properties (e.g. stellar mass) at high z



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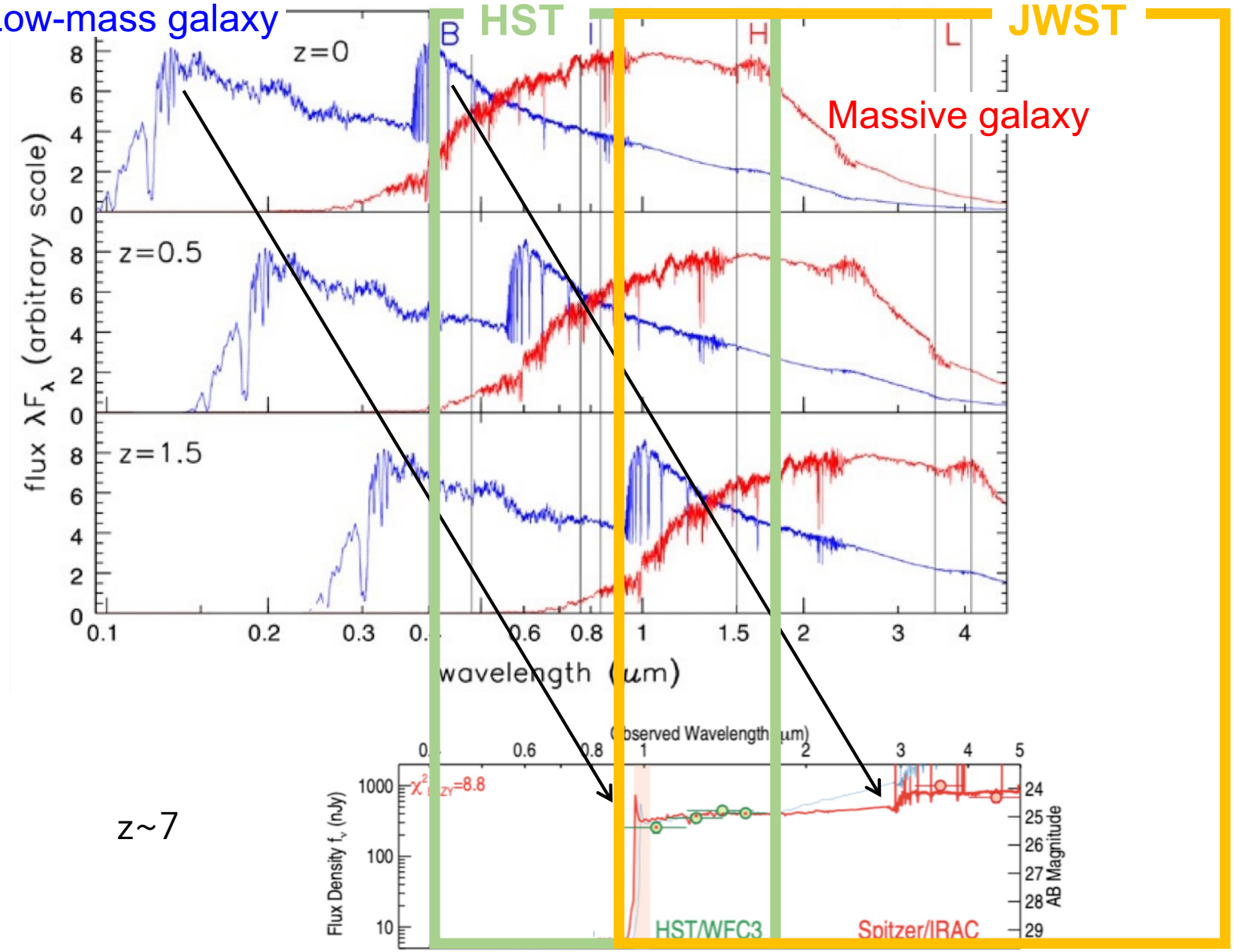

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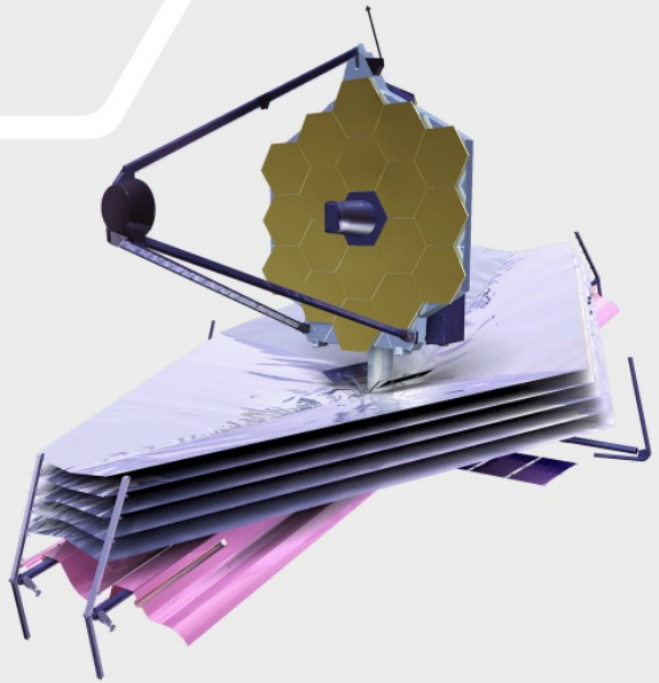
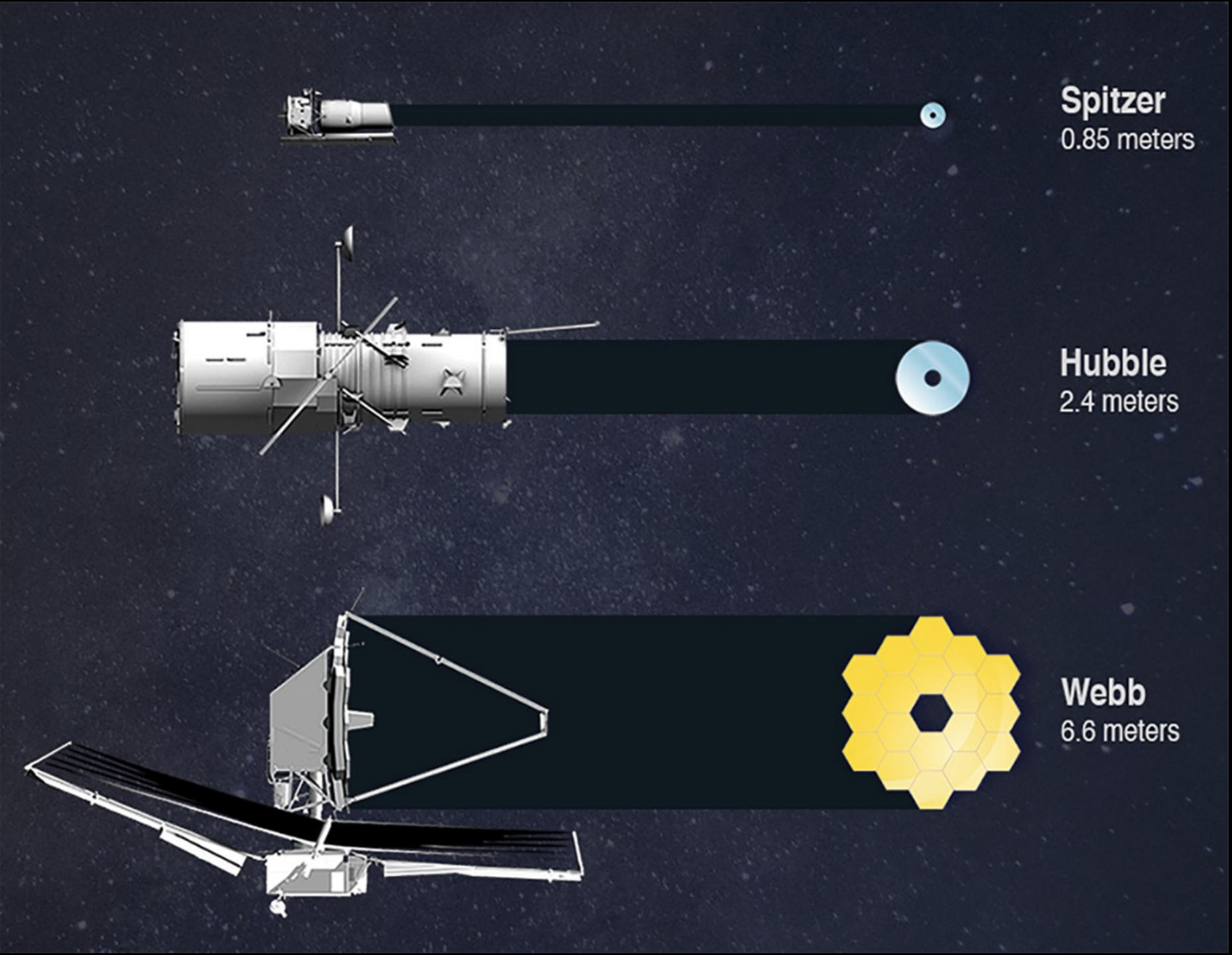
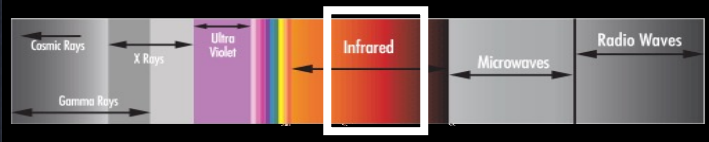
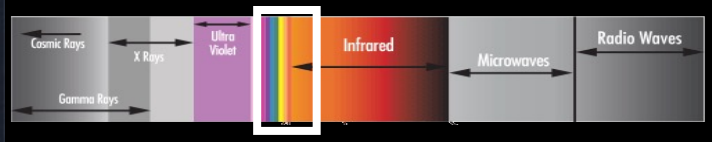
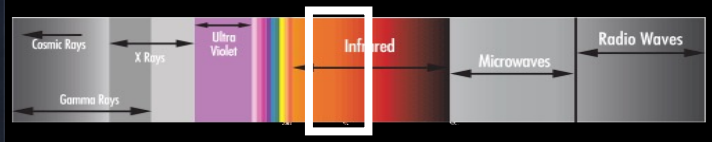


25 December 2021

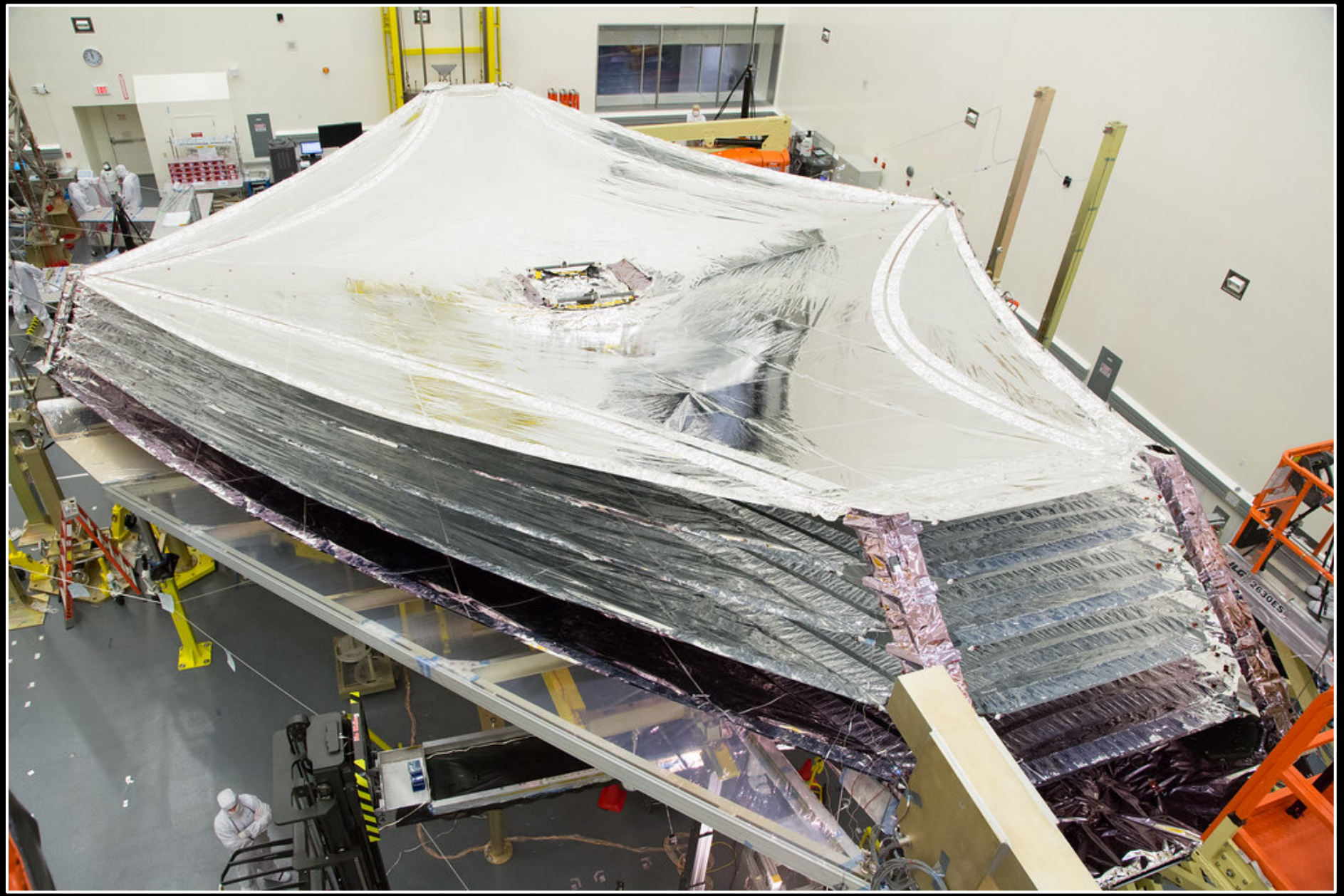


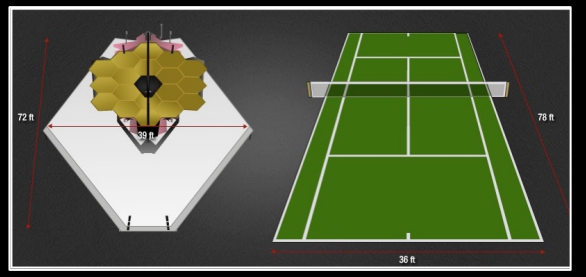


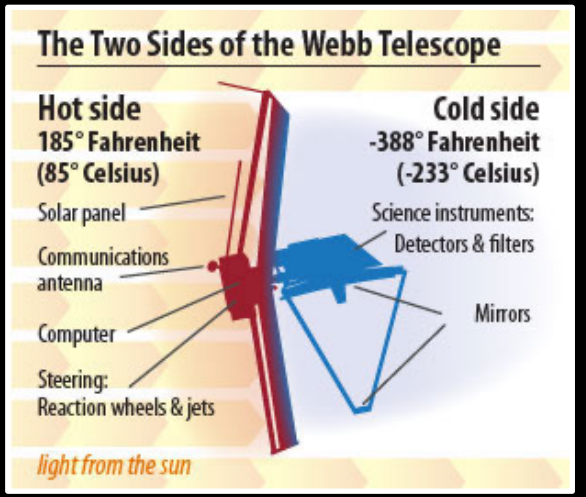


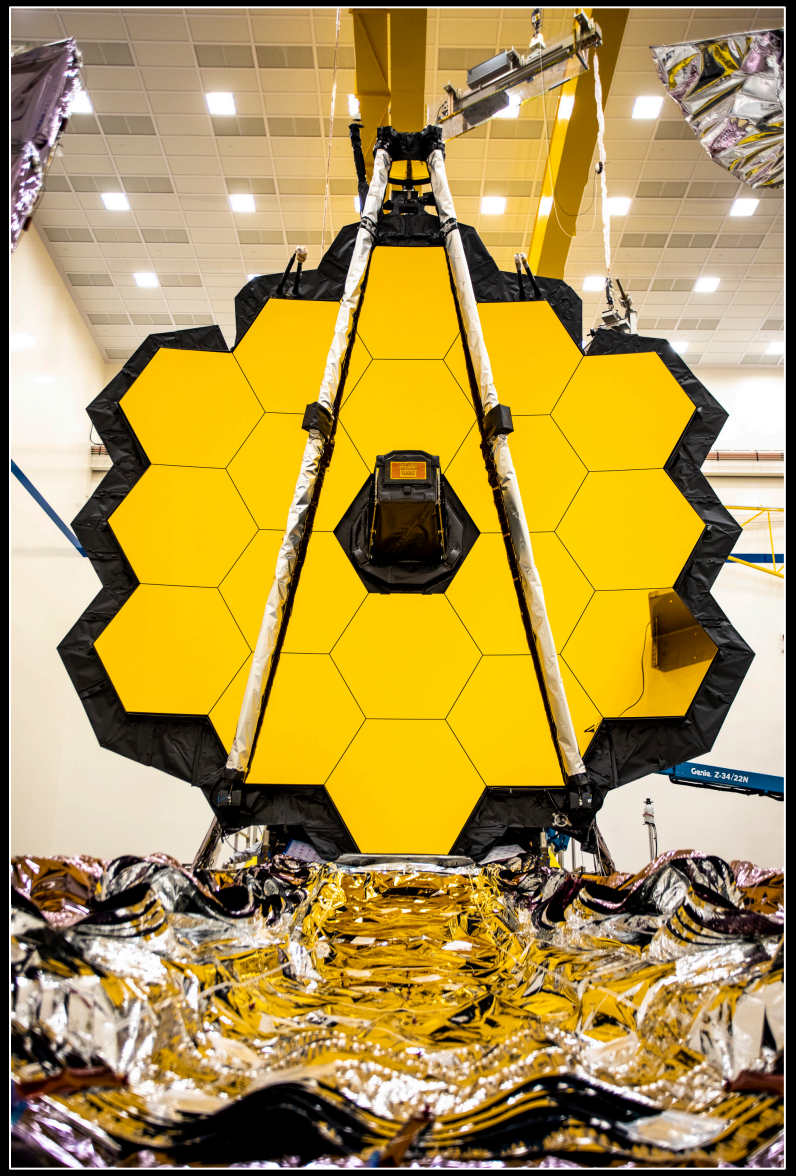


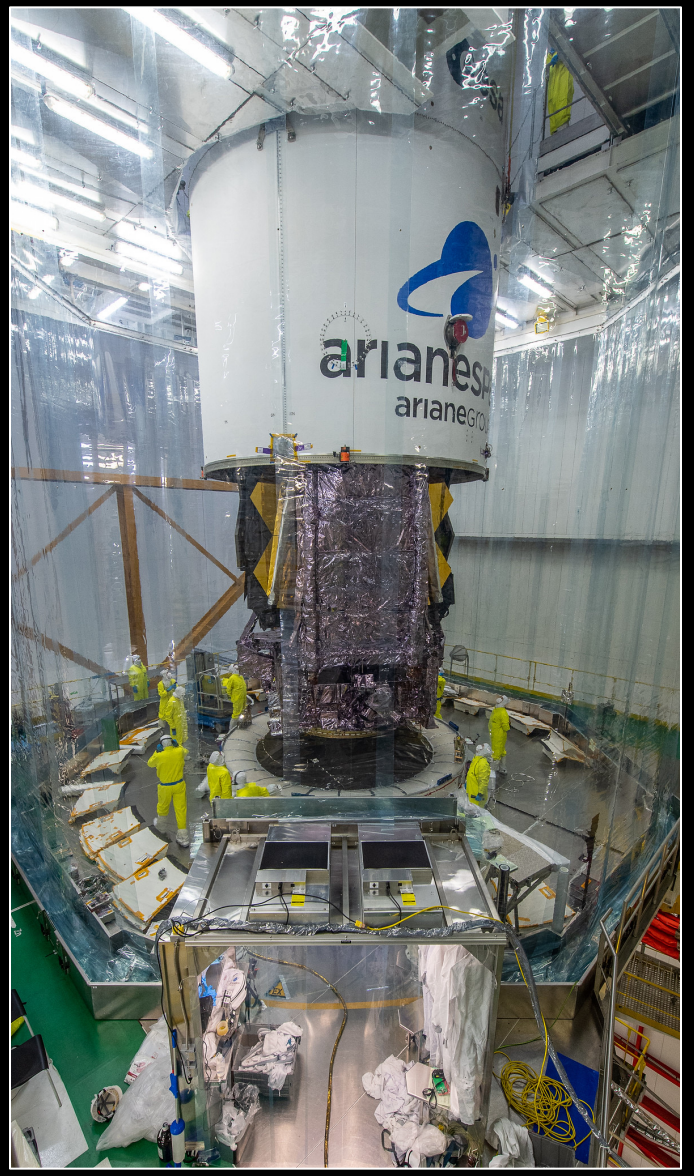
~6x and ~40x more collecting power than HST and Spitzer




72 ft
39 ft
78 ft
36 ft


The Two Sides of the Webb Telescope
Hot side
185° Fahrenheit
(85° Celsius)
Cold side
-388° Fahrenheit
(-233° Celsius)
Solar panel
Communications antenna
Computer
Steering:
Reaction wheels & jets
Science instruments:
Detectors & filters
Mirrors
light from the sun


Genie Z-34/22N


arianespace
arianegroup

Webb's Journey from Launch to L2

EARTH

Launch

Launch Vehicle Separates
Distance: ~ 10,000 km
~ 29 min

Solar Array Deploys
Distance: ~ 11,000 km
~ 33 min

Mid-Course Correction
Trajectory Burn
Distance: ~ 133,000 km
~ 14 hours

Sunshield Pallet Deploys
Distance: ~ 454,000 km
~ 3 days

Initial Sunshield Deploys
Distance: ~ 658,000 km
~ 6 days

Sunshield's Layers Separate
Distance: ~ 677,000 km
~ 8 days

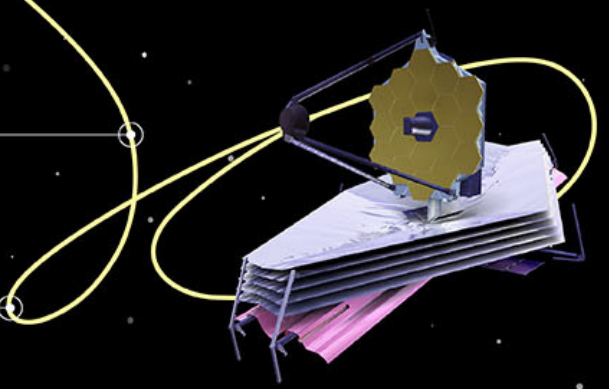
Secondary Mirror Unfolds
Distance: ~ 952,000 km
~ 10 days

Primary Mirror Wings Deploy
Distance: ~ 1,000,000 km
~ 13 days

344 single point failures!

2nd Mid-Course Correction
Trajectory Burn
Distance: ~ 1,400,000 km
~ 29 days

L2 Halo Orbit Begins
Distance: ~ 1,402,800 km
~ 29 days

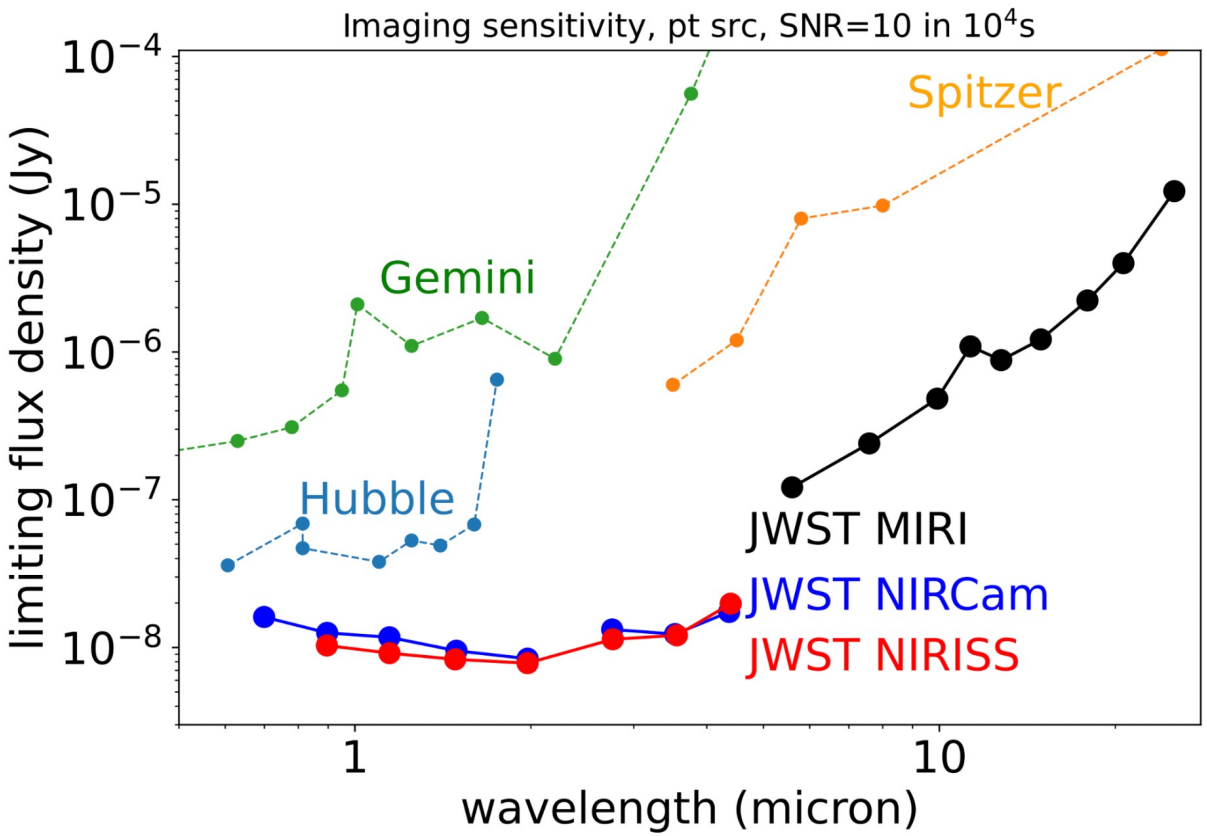


Webb on the Ariane 5 Rocket credit: ESA *Graphic credit: AURA* *Webb images: NASA Goddard Space Flight Center*

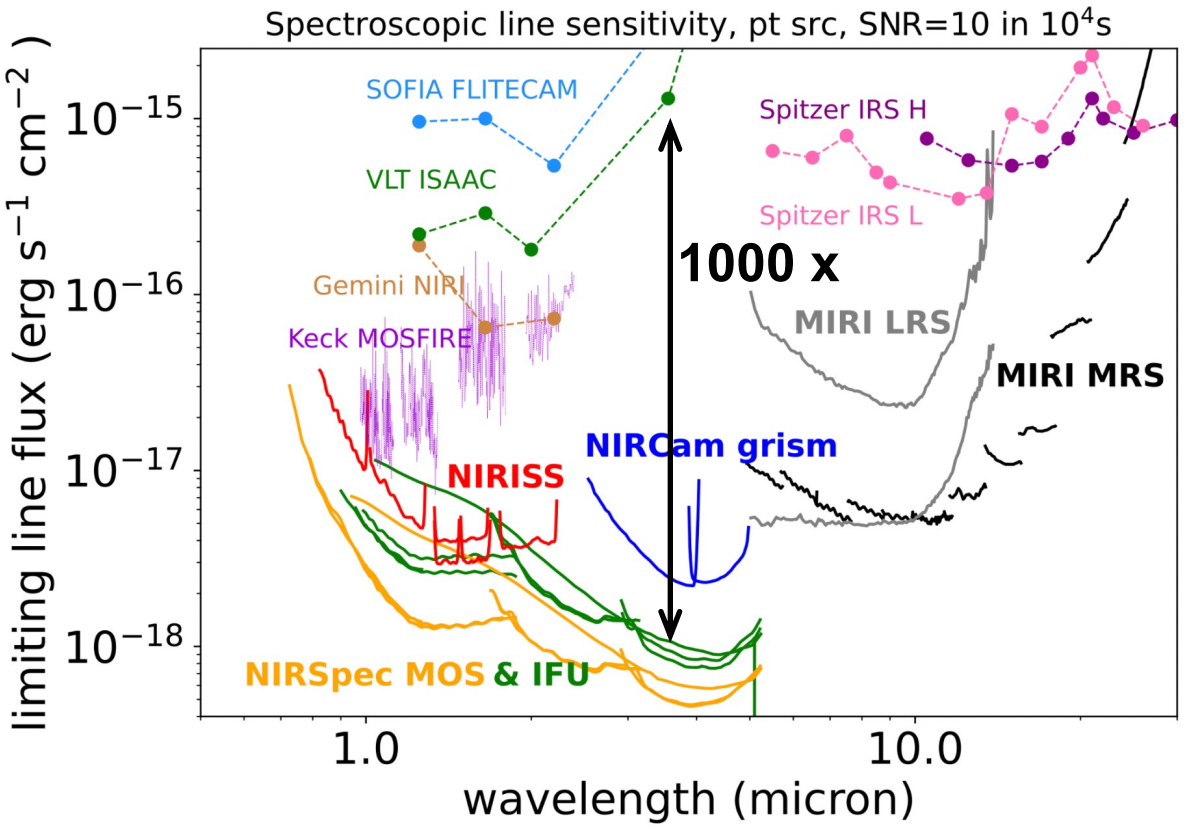
AURA

Huge leap in sensitivity

PHOTOMETRY



SPECTROSCOPY



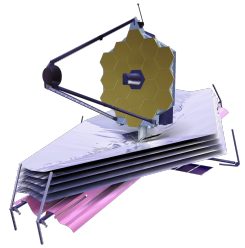
Rigby+23

Spitzer

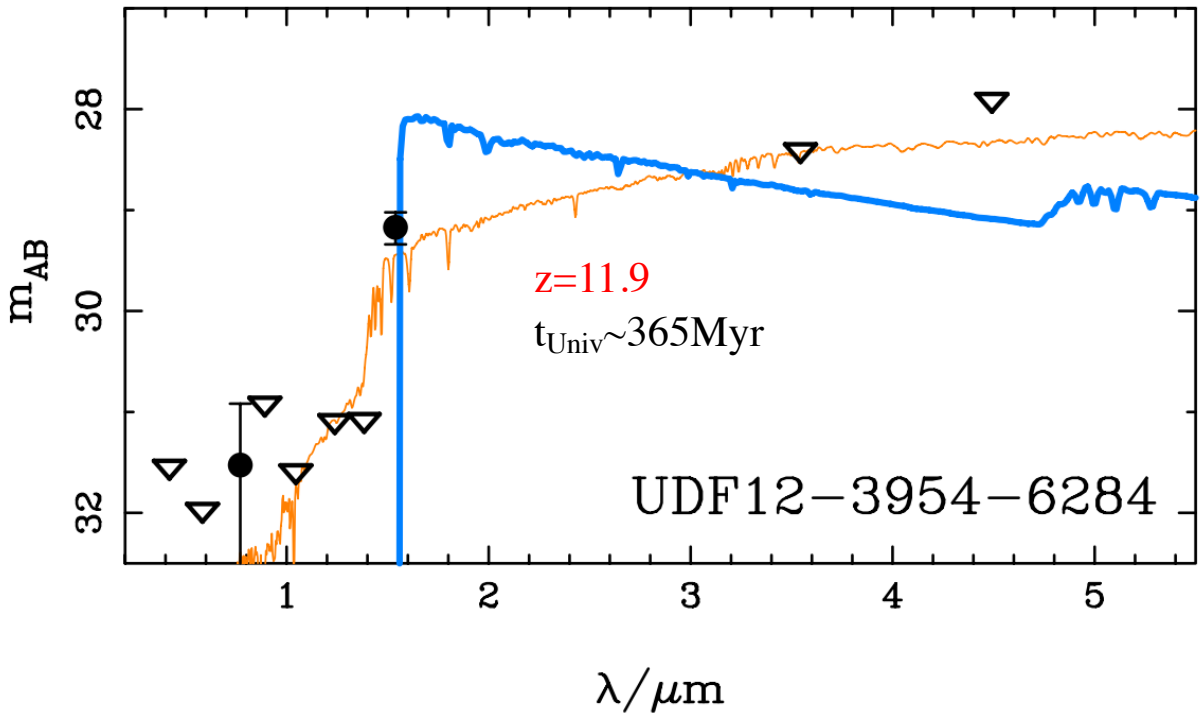
JWST

The ideal instrument for distant galaxies

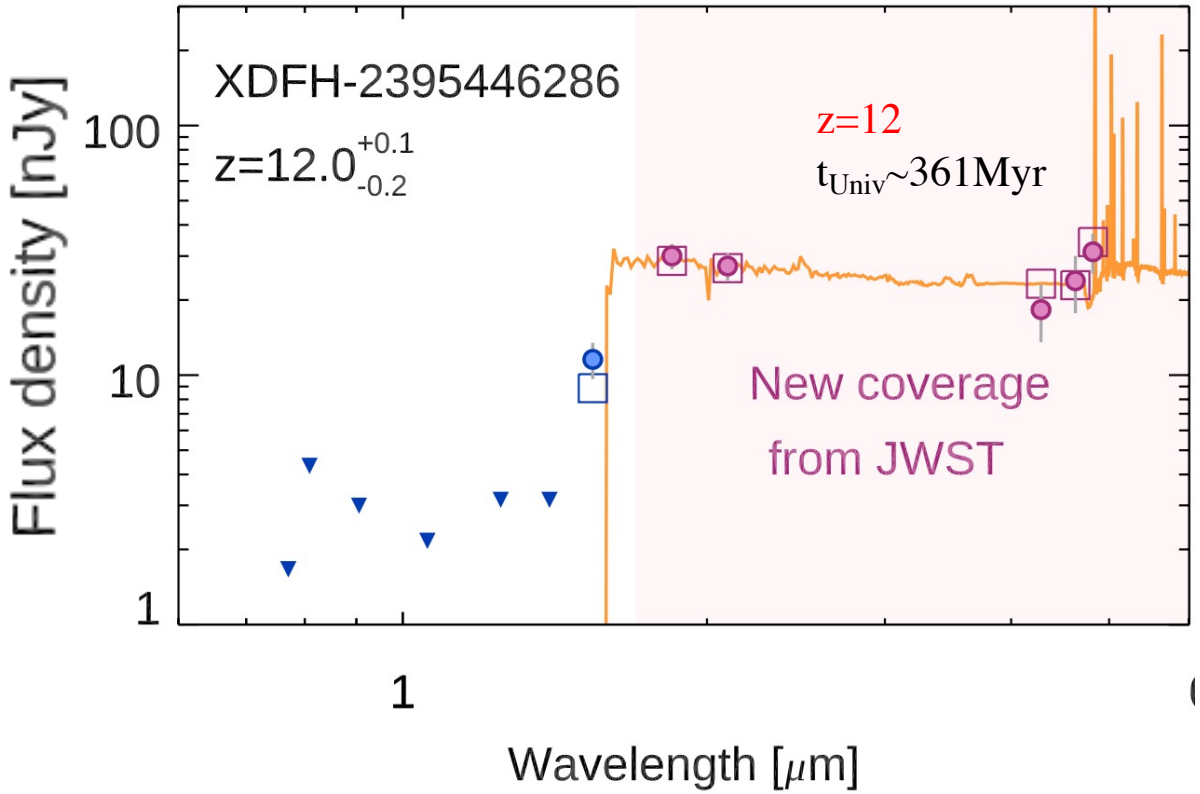
- detect distant galaxies (z>12)
- measure physical properties (z>7)



Ellis+13, Bouwens+11,+13



Bouwens+23a



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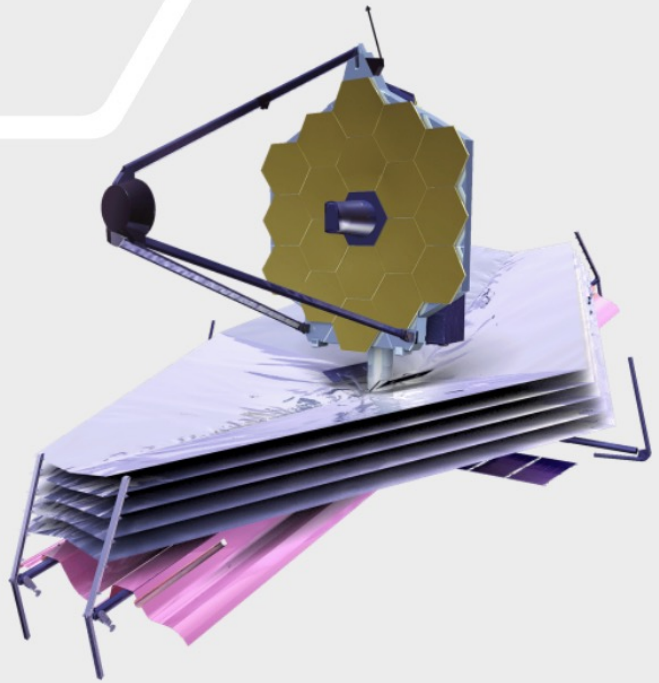
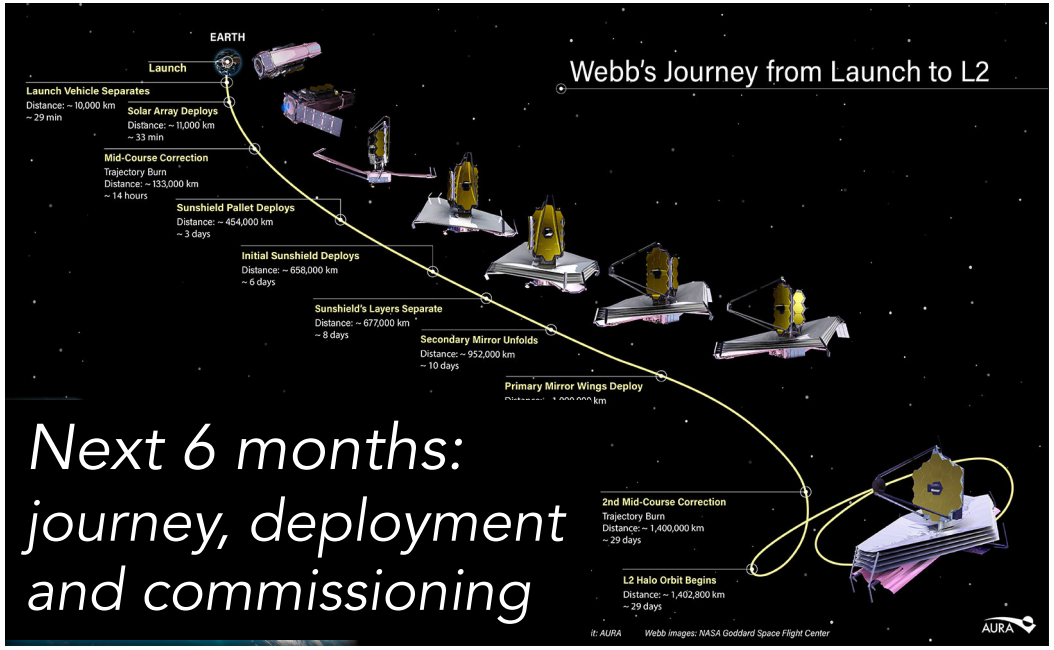
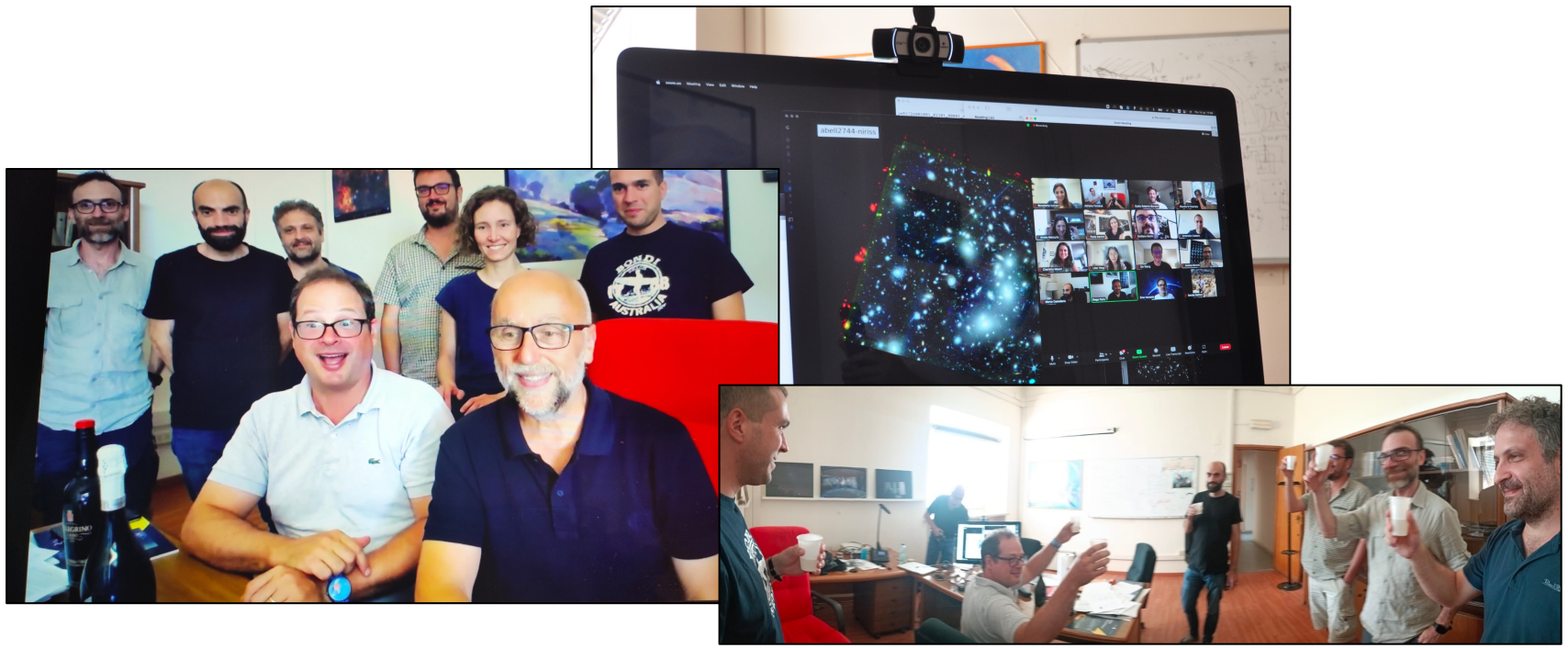
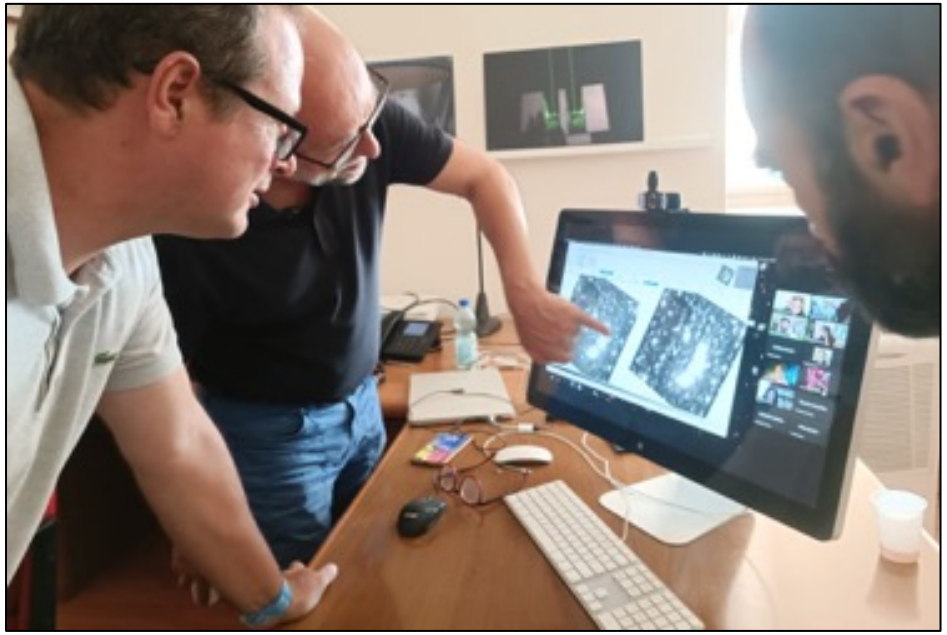
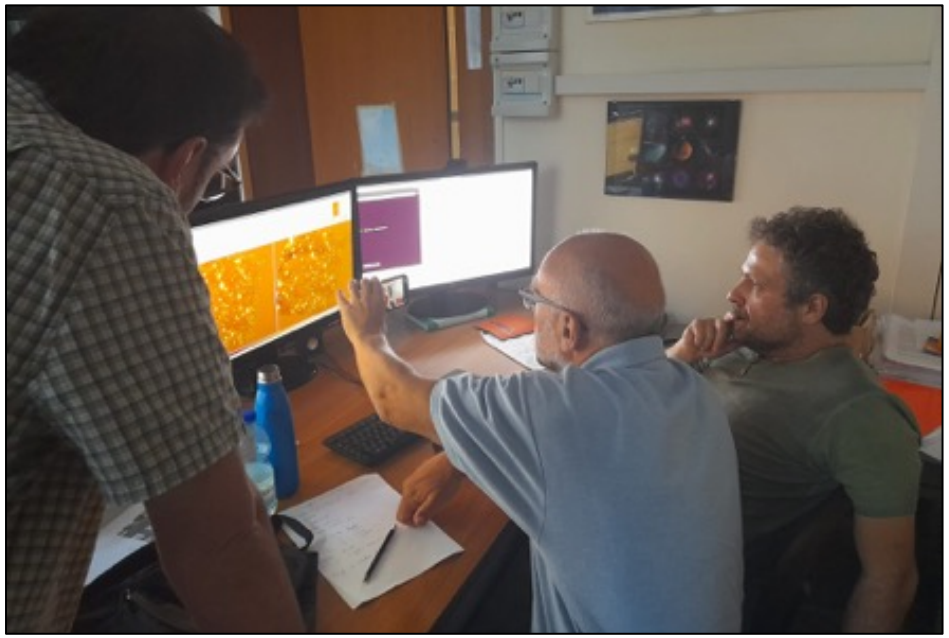




14 July 2022:
the first data were
made public





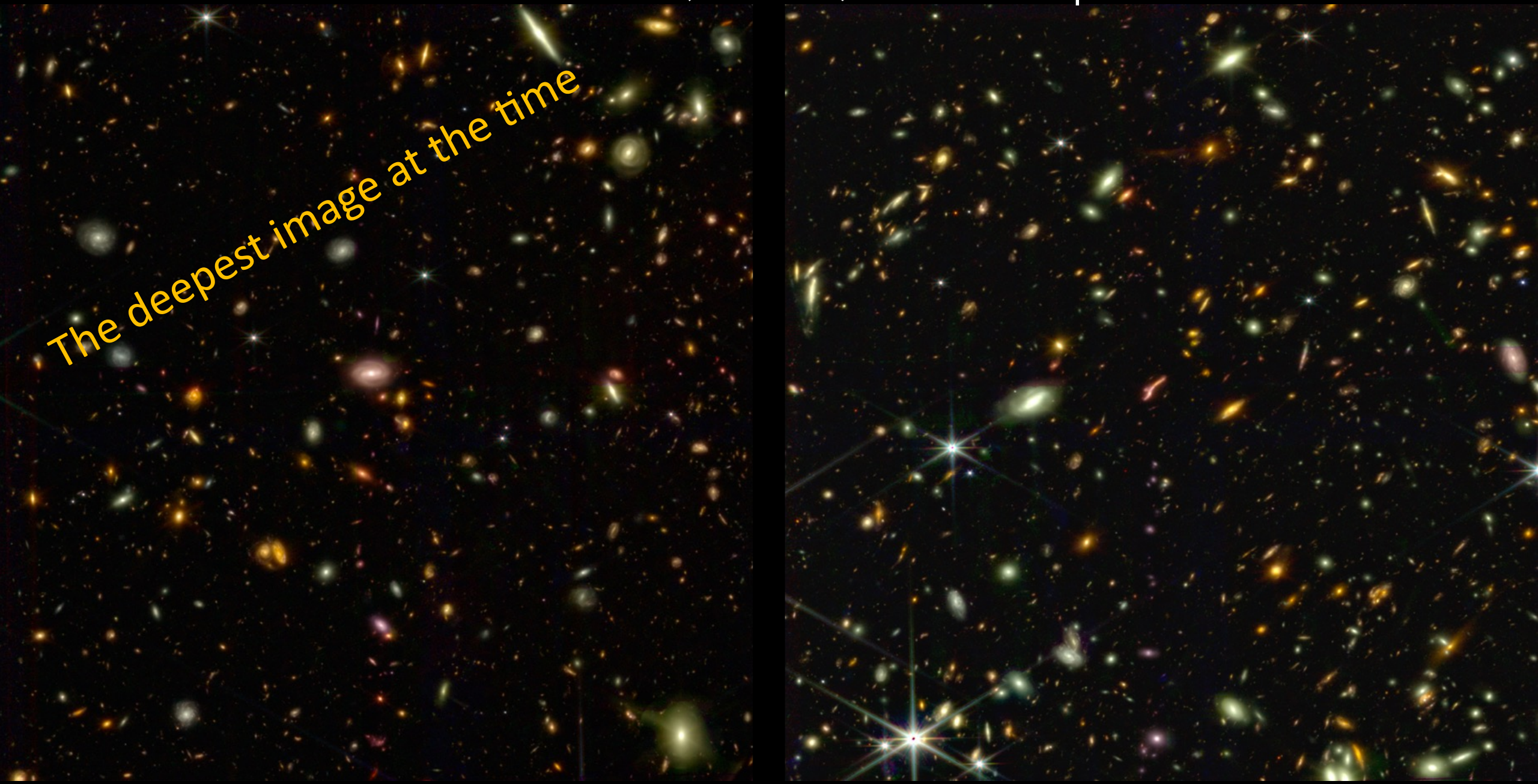


including data from the GLASS program (US/IT collaboration, PI Tommaso Treu)

Adriano Fontana, Diego Paris, Marco Castellano, Emiliano Merlin, Paola Santini

and the GLASS team

ERS GLASS-JWST (PI T. Treu) NIRCam 1st epoch



Credits: D. Paris

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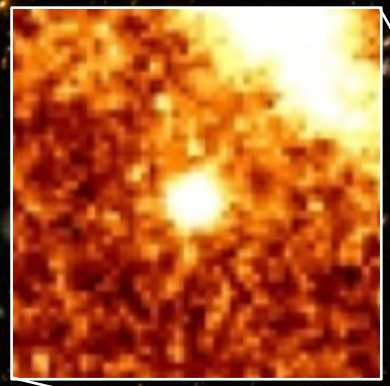


z=12.11
t_{Univ}~350Myr

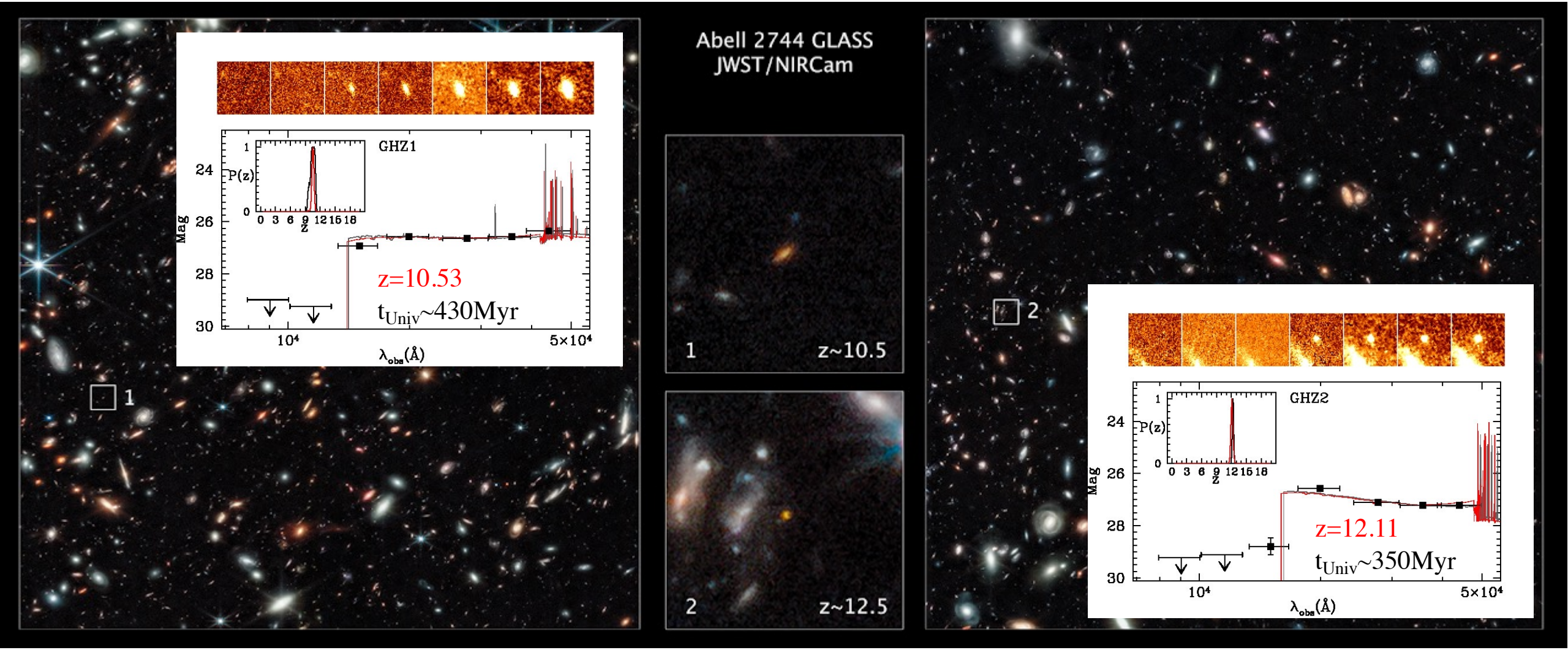
Castellano, Fontana, Treu, PS+22

(we were expecting
0.1 galaxies at z>9)

z=10.53
t_{Univ}~430Myr

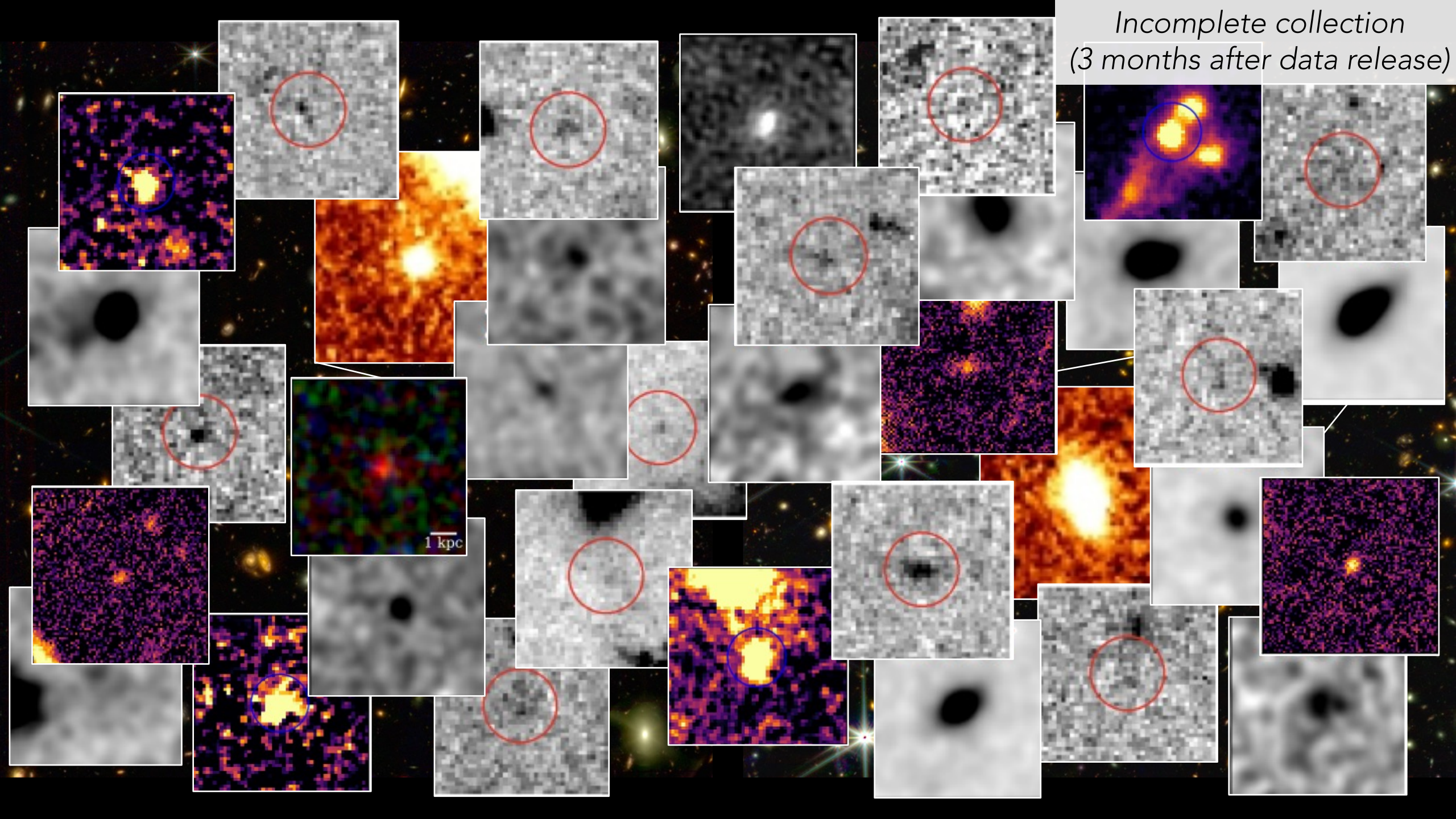
Credits: D. Paris

High-z galaxies in GLASS-JWST

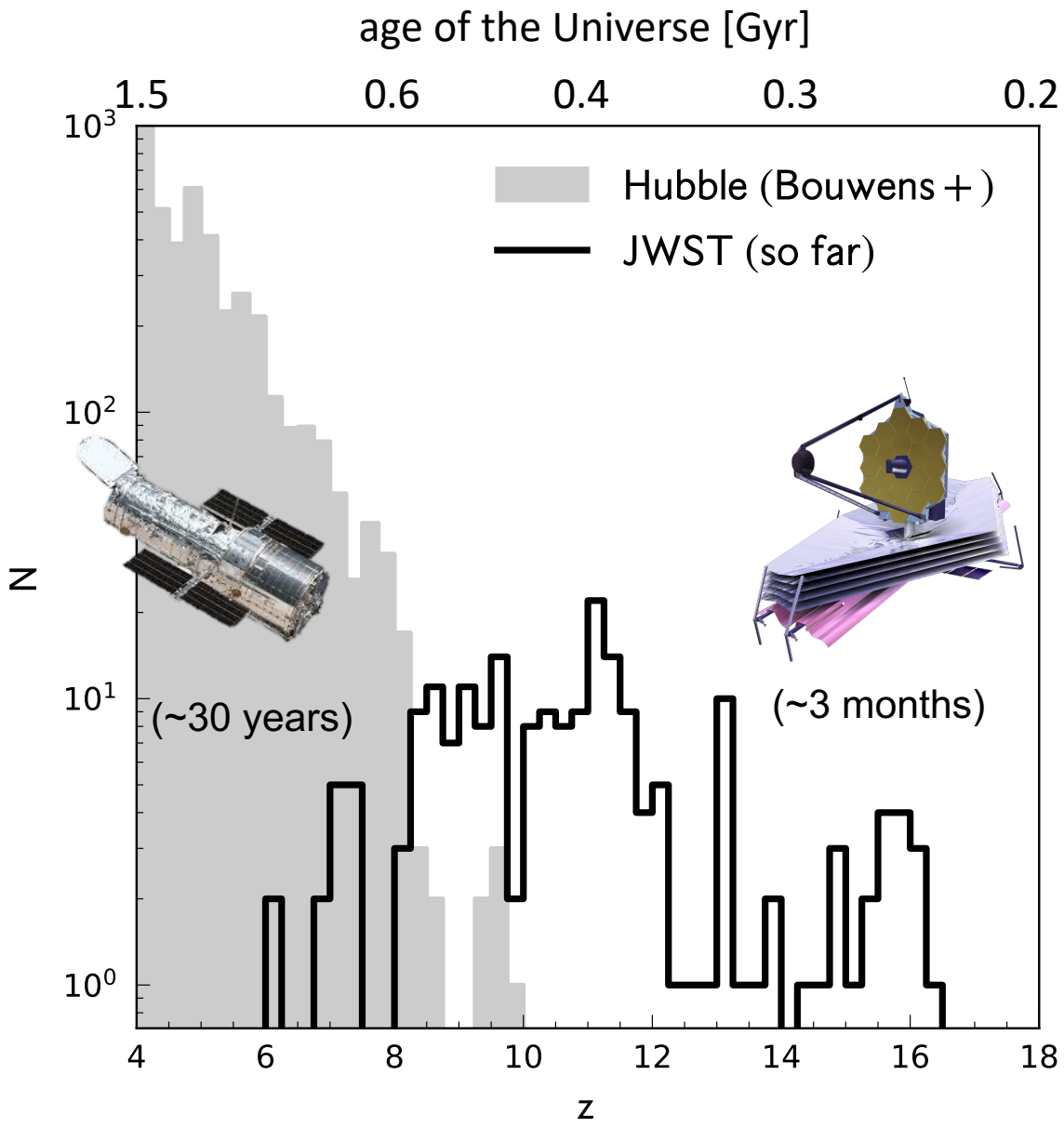


NASA Press Release, 17 Nov 2022

Castellano, Fontana, Treu, PS+22


Incomplete collection
(3 months after data release)
1 kpc

The high redshift frontier (after ~3 months)

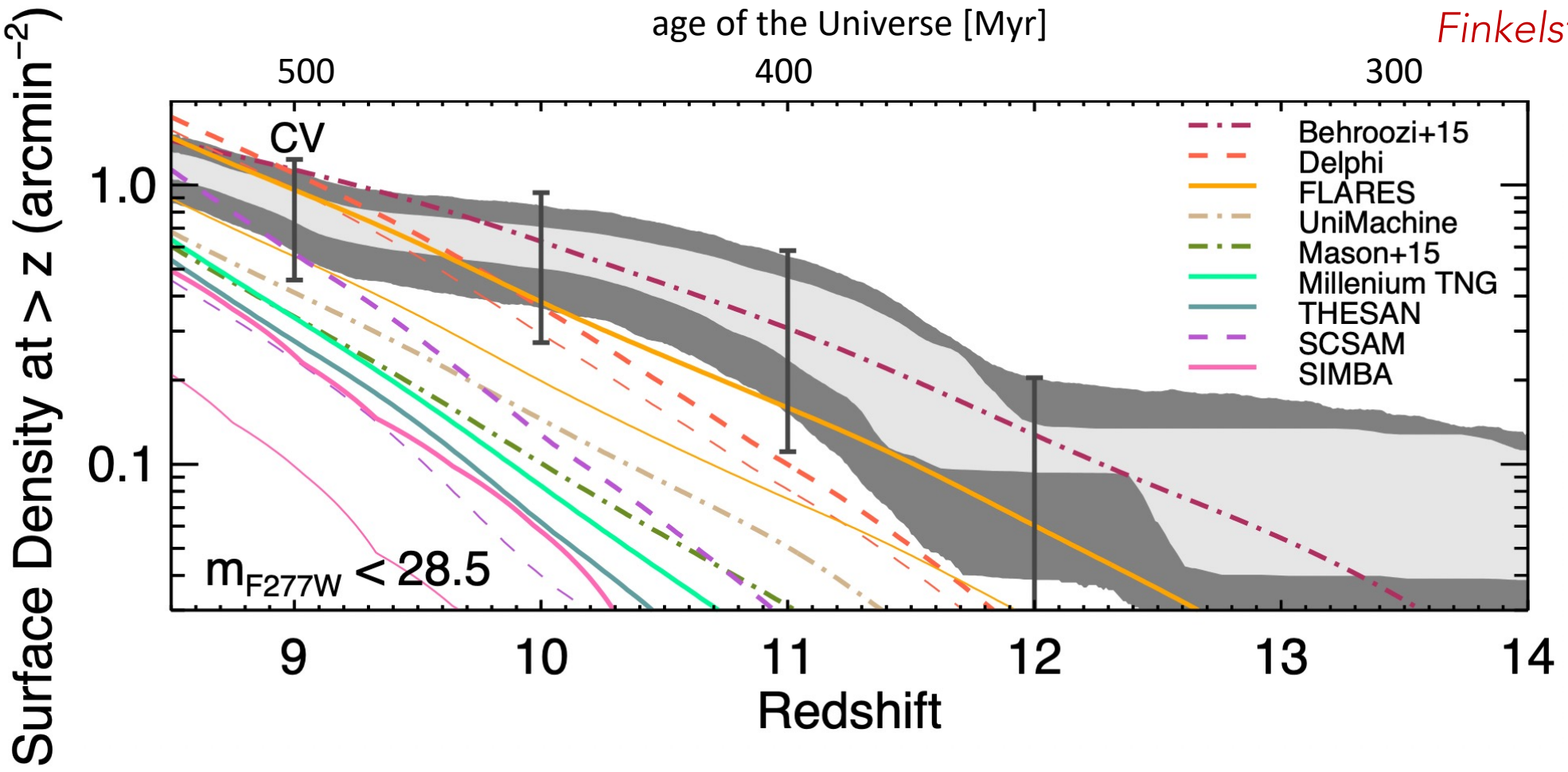


but severe discrepancies among different works (~10-20% overlap)!

Castellano, Fontana, Treu, PS+22
Naidu+22
Finkelstein,…PS+22
Harikane+23a
Castellano,..,PS+23
Atek+23
Donnan+23
Bouwens+23a
Bouwens+23b
Adams+23
Yan+23
Labbé+23
Rodighiero+23
Furtak+23
Bradley+23
…….

Courtesy: S. Wilkins

#1: TOO MANY EARLY/BRIGHT GALAXIES

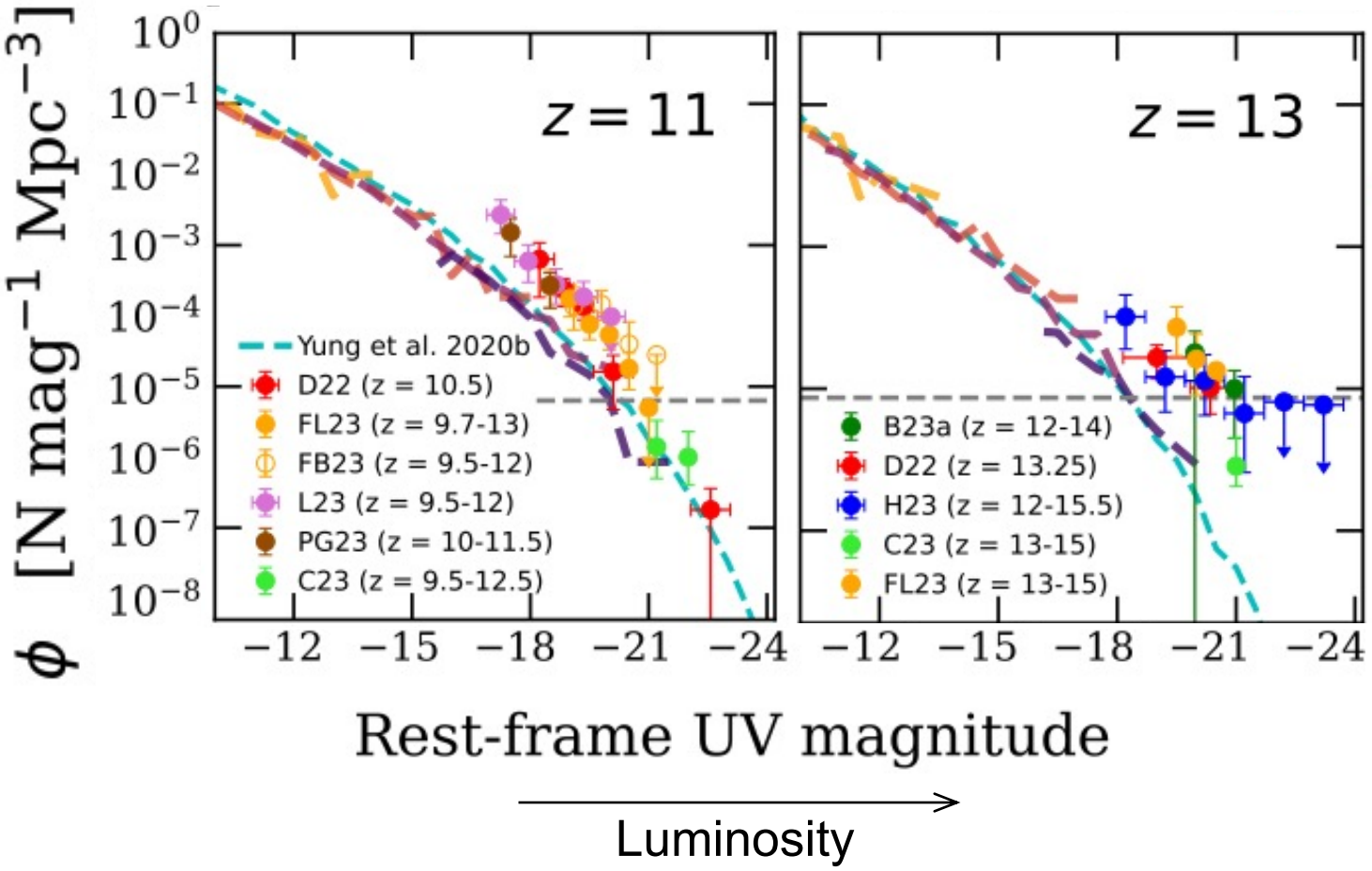


Finkelstein+23

see also Castellano+23, Mauerhofer+23, Harikane+23, Bouwens+23a,b, Adams+23, Donnan+23, McLeod+23, Chemerynska+23 subm., …

#1: TOO MANY EARLY/BRIGHT GALAXIES

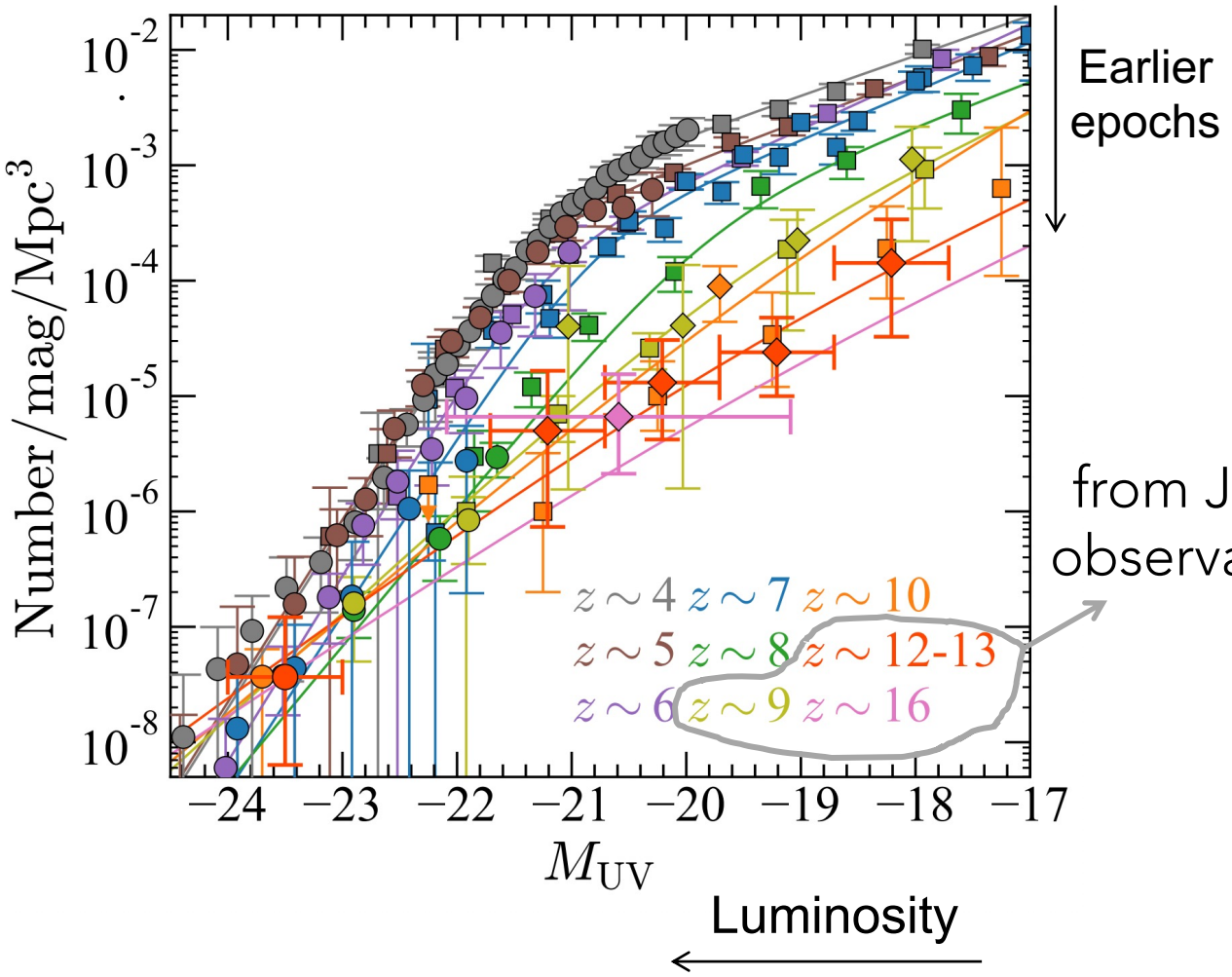
Yung+23



see also Castellano+23, Mauerhofer+23, Harikane+23a, Bouwens+23a,b, Adams+23, Donnan+23, McLeod+23, Chemerynska+23 subm., …

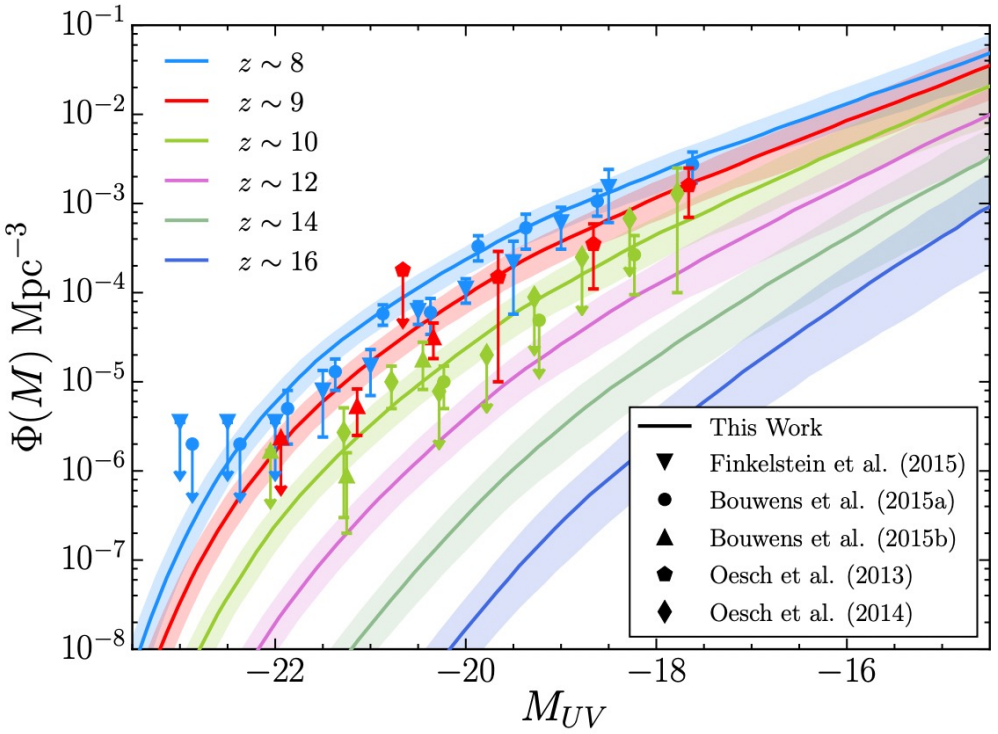
Very rapid galaxy formation ?

Weak evolution from z~16 to z~10



from JV
observat

These were the predictions…..



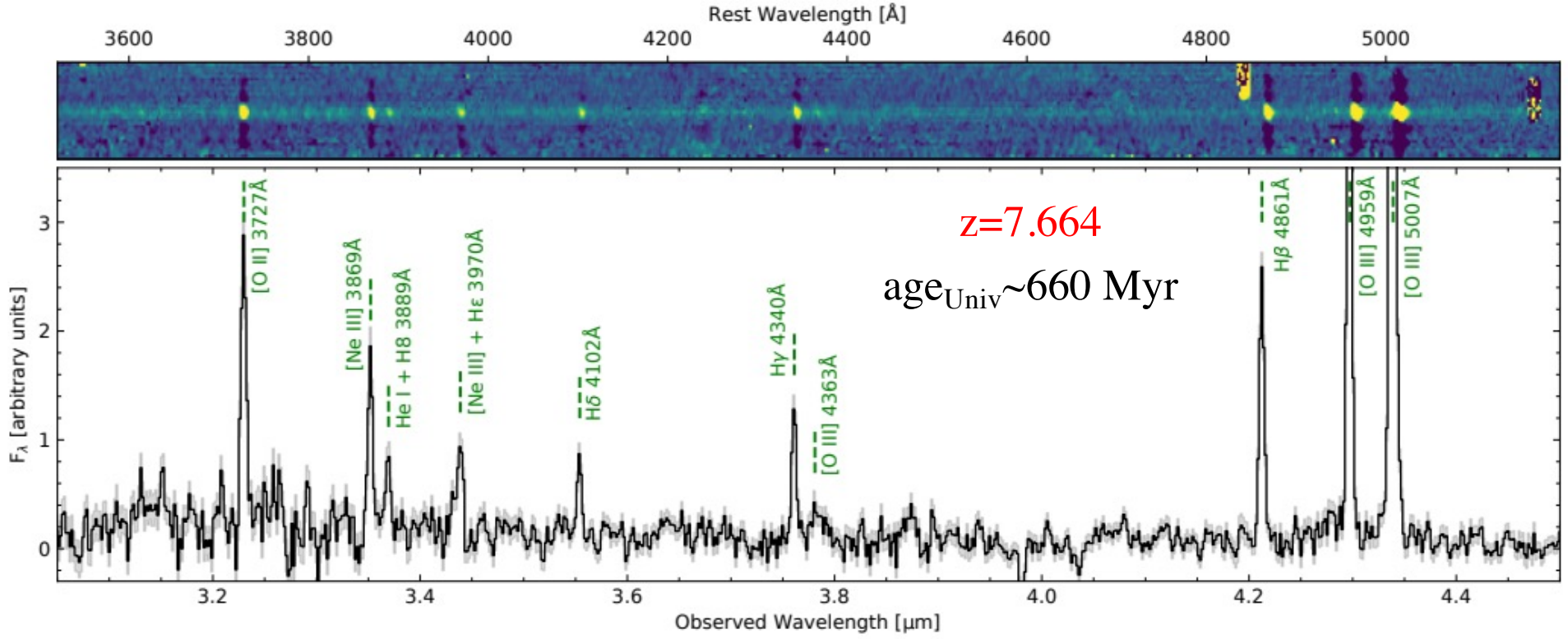
Harikane+23

Mason+15

Are all these candidates truly high-z?

Excellent spectra at the high redshift frontier

Schaerer+22

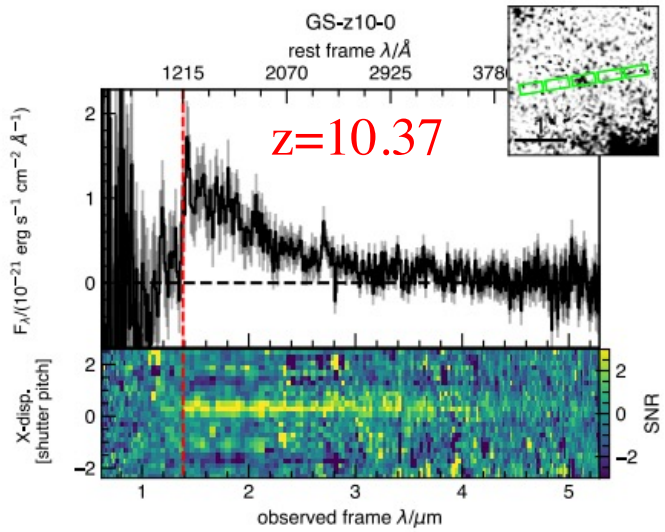


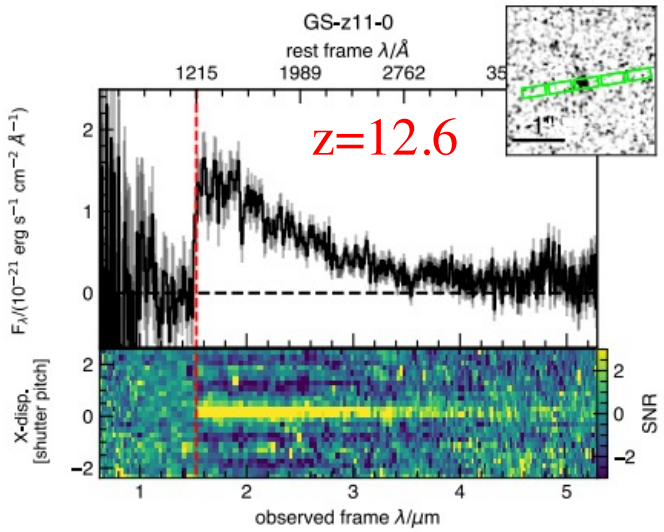
First observations of optical emission lines at high-z

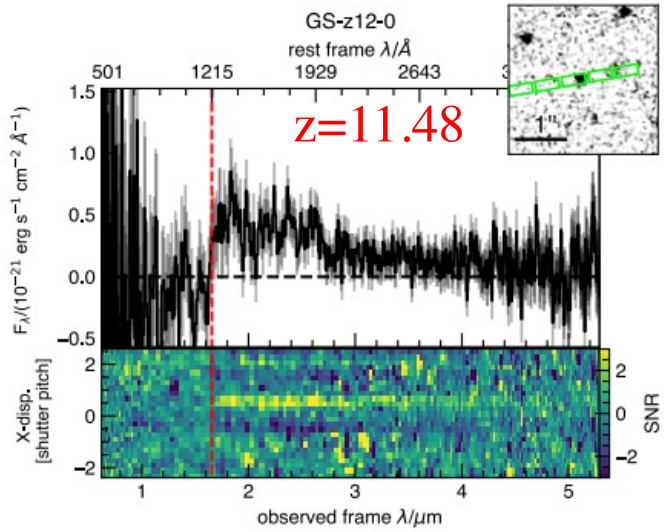
Excellent spectra at the high redshift frontier

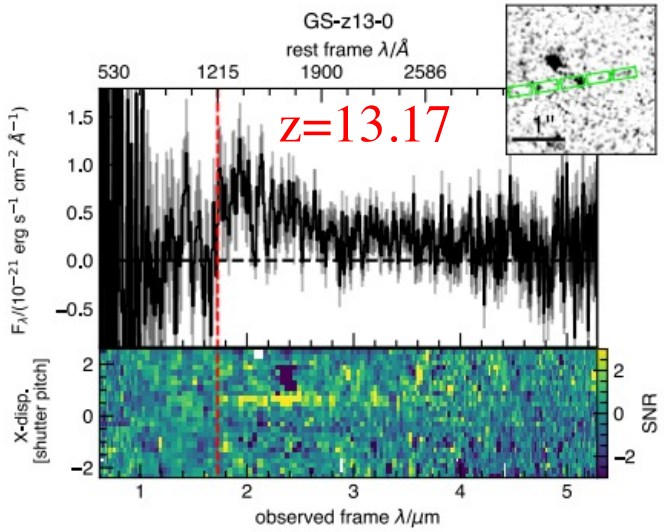
up to z~13!!

age_{Univ}~300-450 Myr





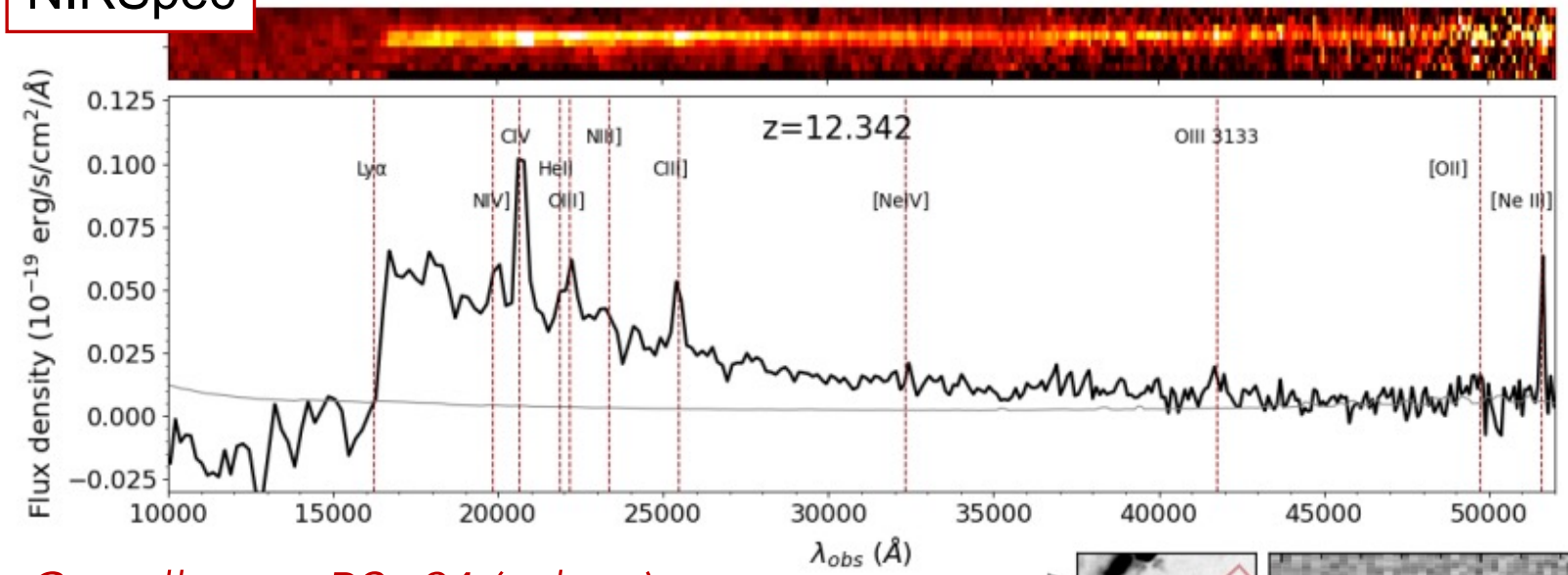




Curtis-Lake+23
see also Robertson+23

EXCELLENT #2: EARLY CHEMICAL ENRICHMENT FRONTIER

NIRSpec

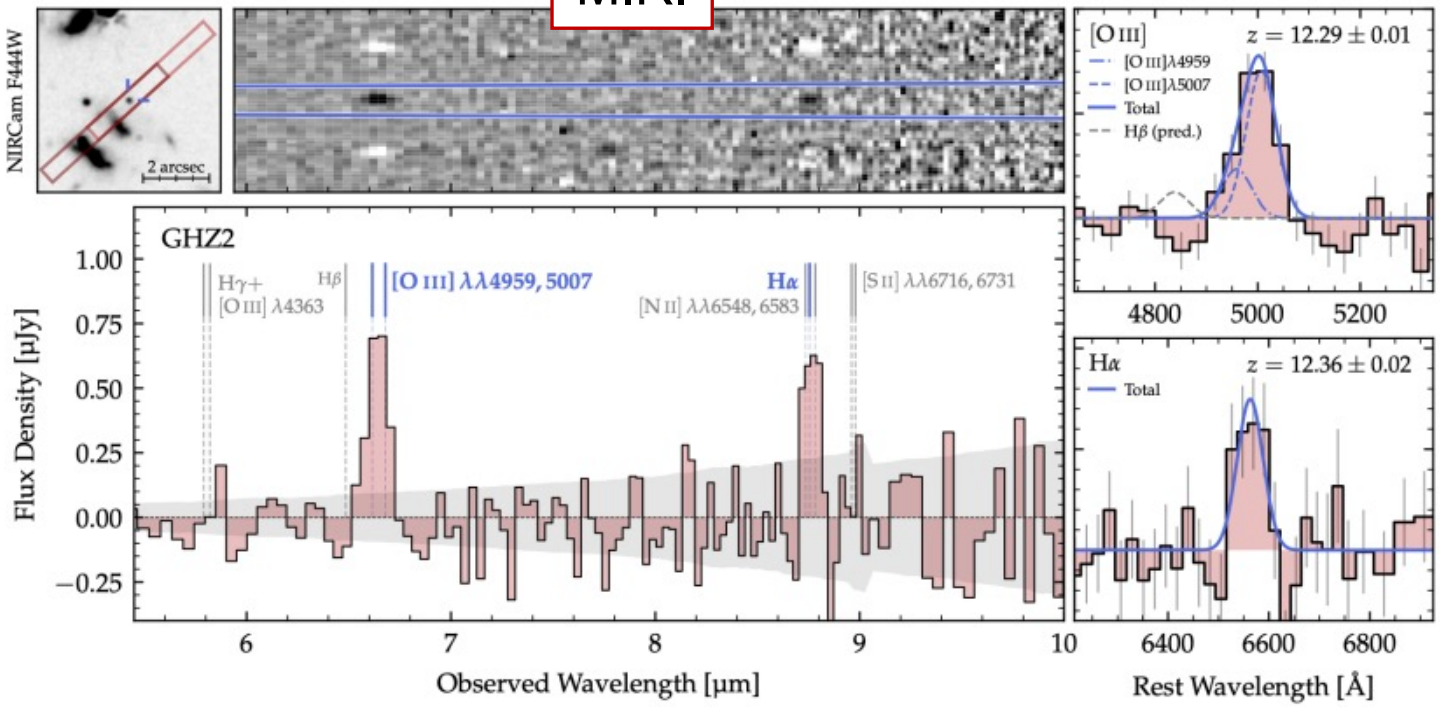


Castellano,..,PS+24 (subm.)

GHZ2
z=12.34
(347 Myr after the Big Bang)

MIRI

Zavala,..,PS+24 (subm.)

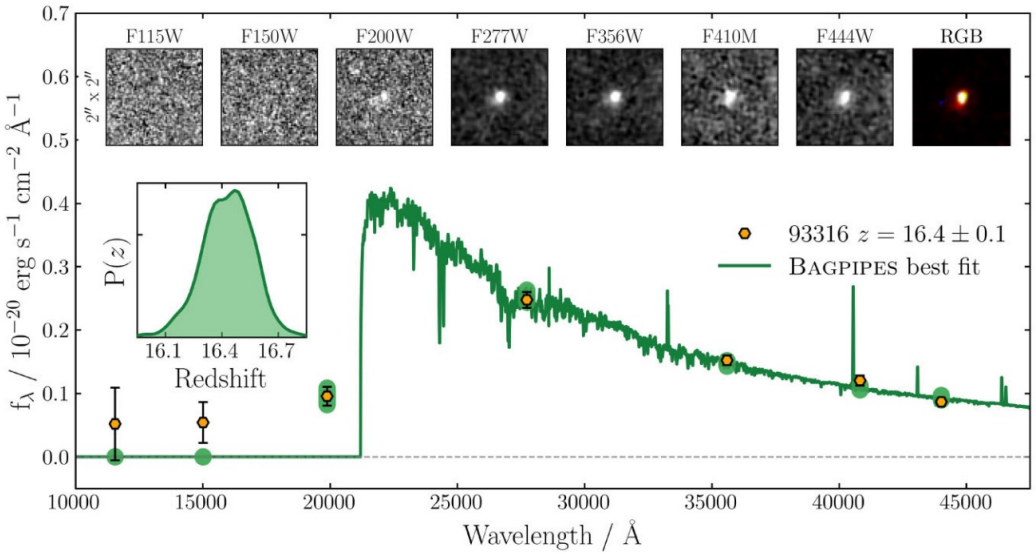


Heavy elements already in place!

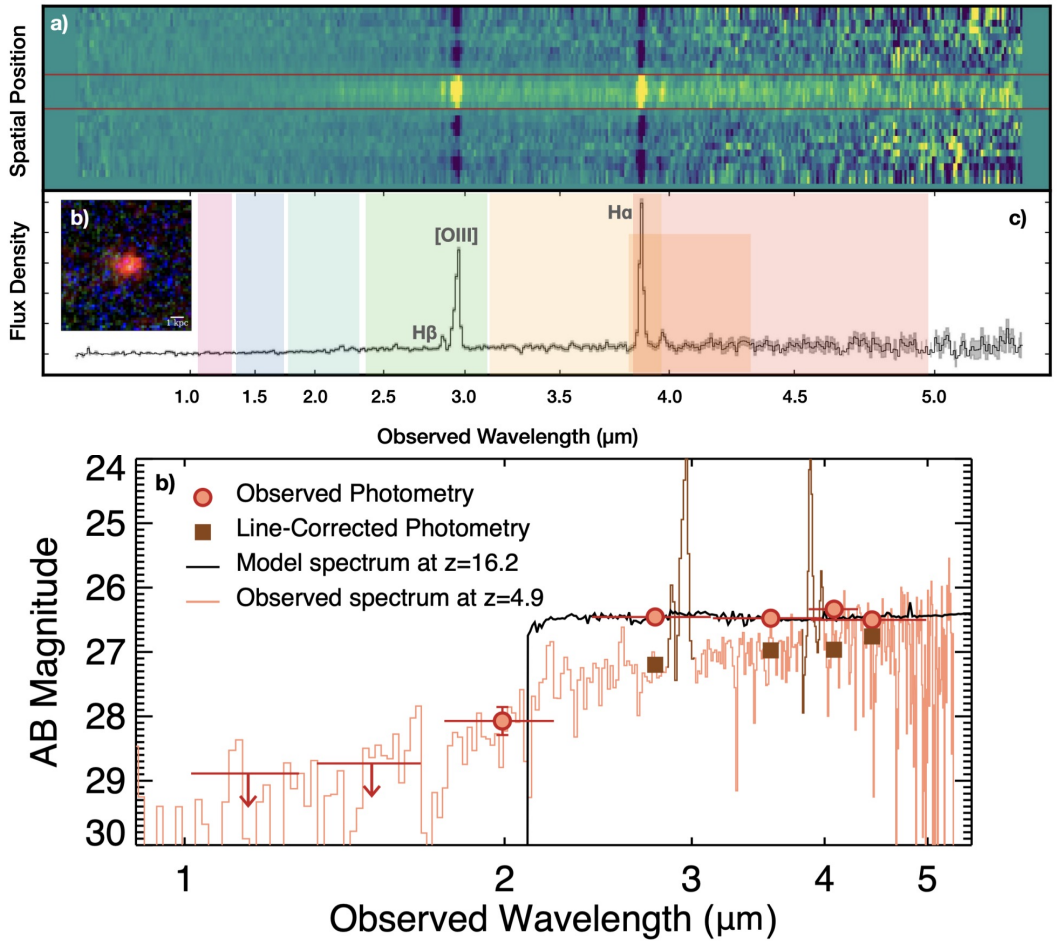
see also Schaerer+22, Sanders+23, Cameron+23, Curti+23, Tang+23, D'Eugenio+23, Nakajima+23, Calabrò+24 (subm.)…

Bad news...

The best z~16 candidate so far…



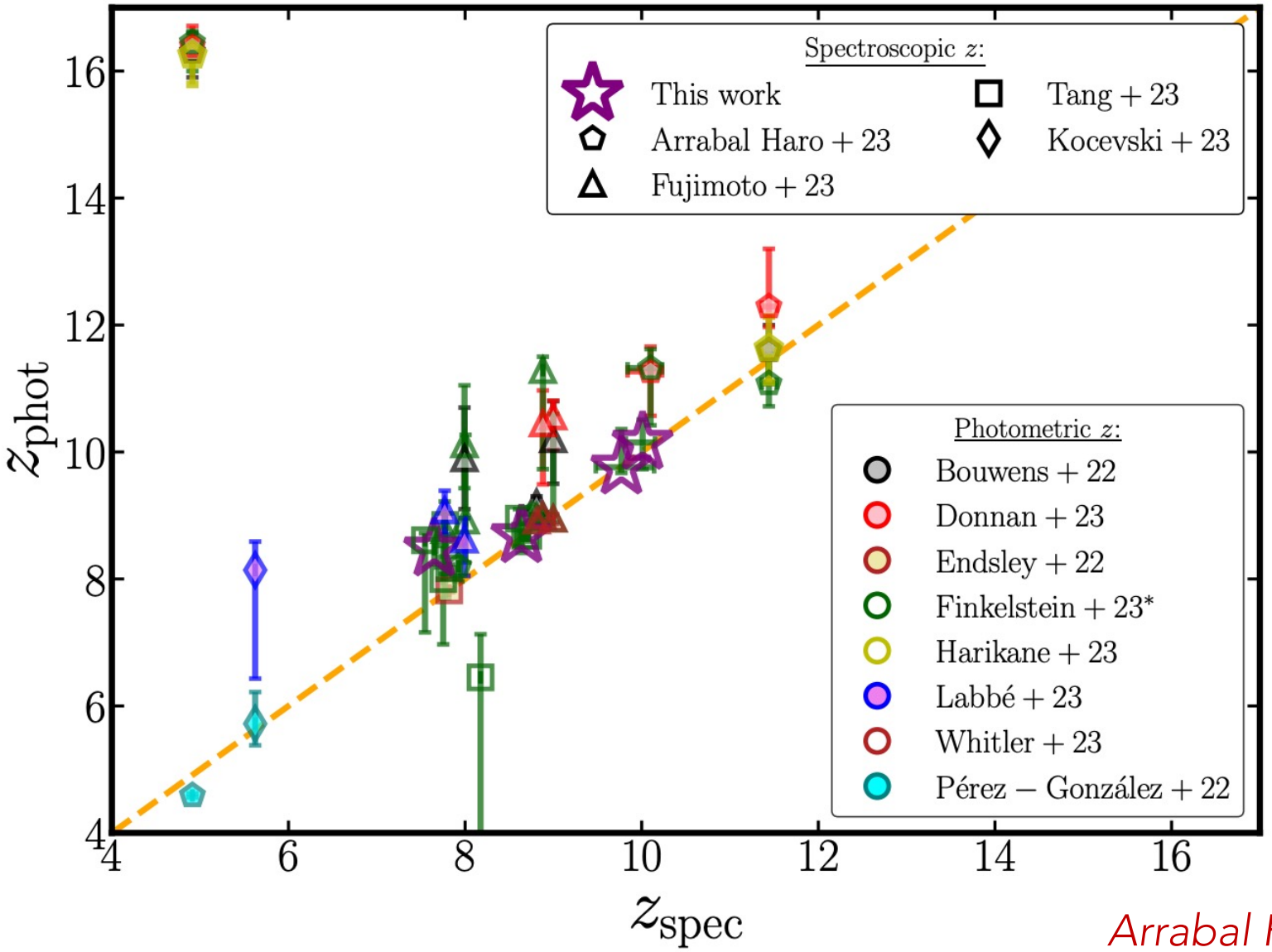
Donnan+23
see also Finkelstein+23, Bouwens+23b, Harikane+23, Naidu+23



…is actually at z~5

Arrabal Haro+23a

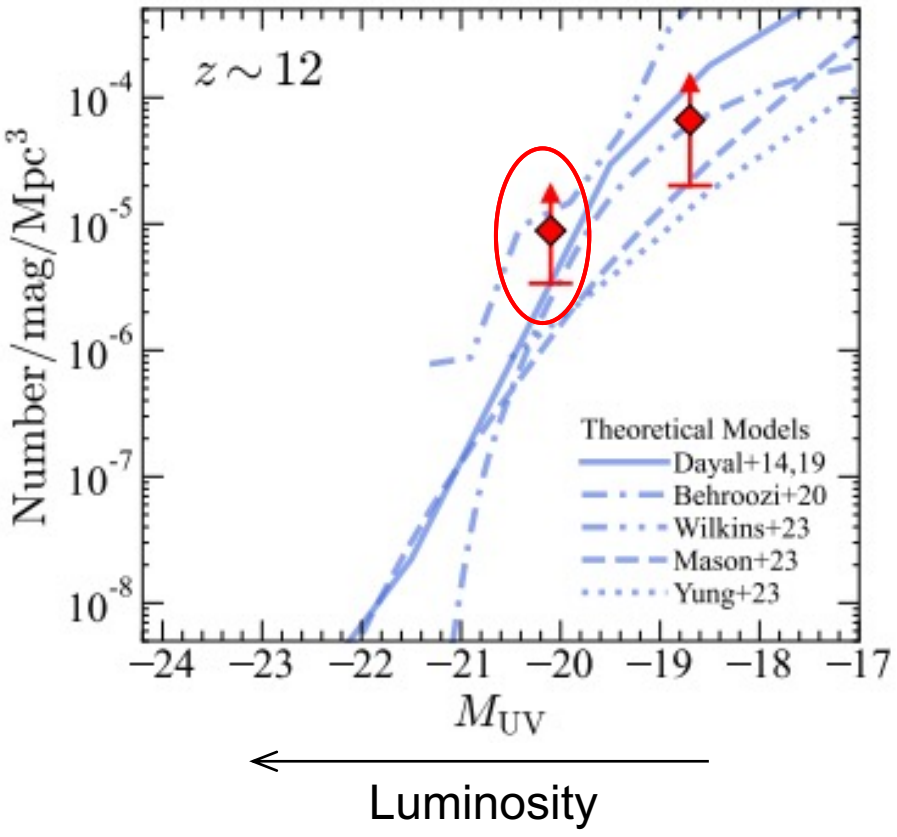
... AND GOOD NEWS!



Arrabal Haro, … PS+23b

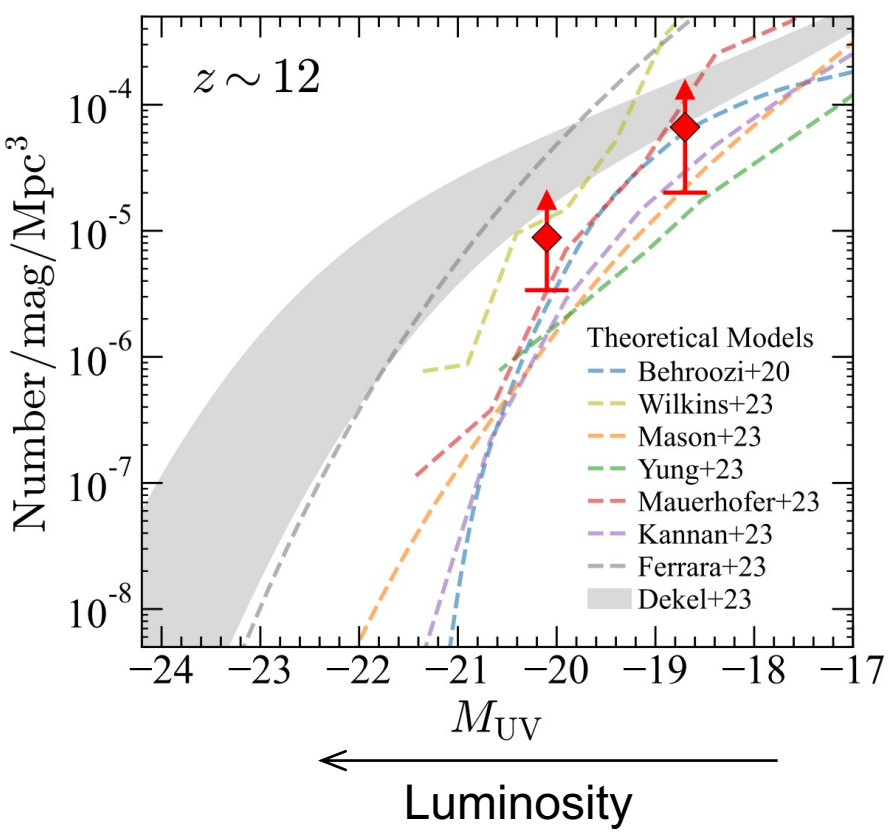
#1: TOO MANY EARLY/BRIGHT GALAXIES ?

Seems to be confirmed by spectroscopy



Harikane+ (subm.)

…but models have been revised in the past months

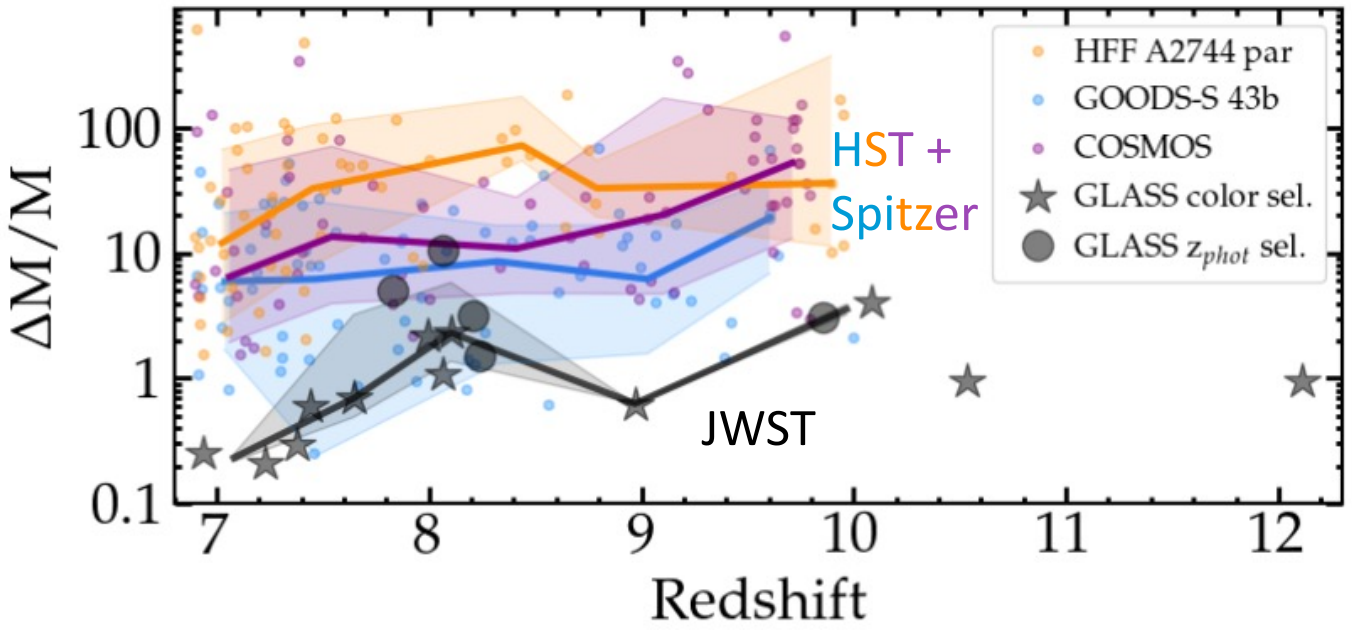


Harikane+24

JWST: IMPROVEMENT IN THE STELLAR MASS ESTIMATES

PS+23

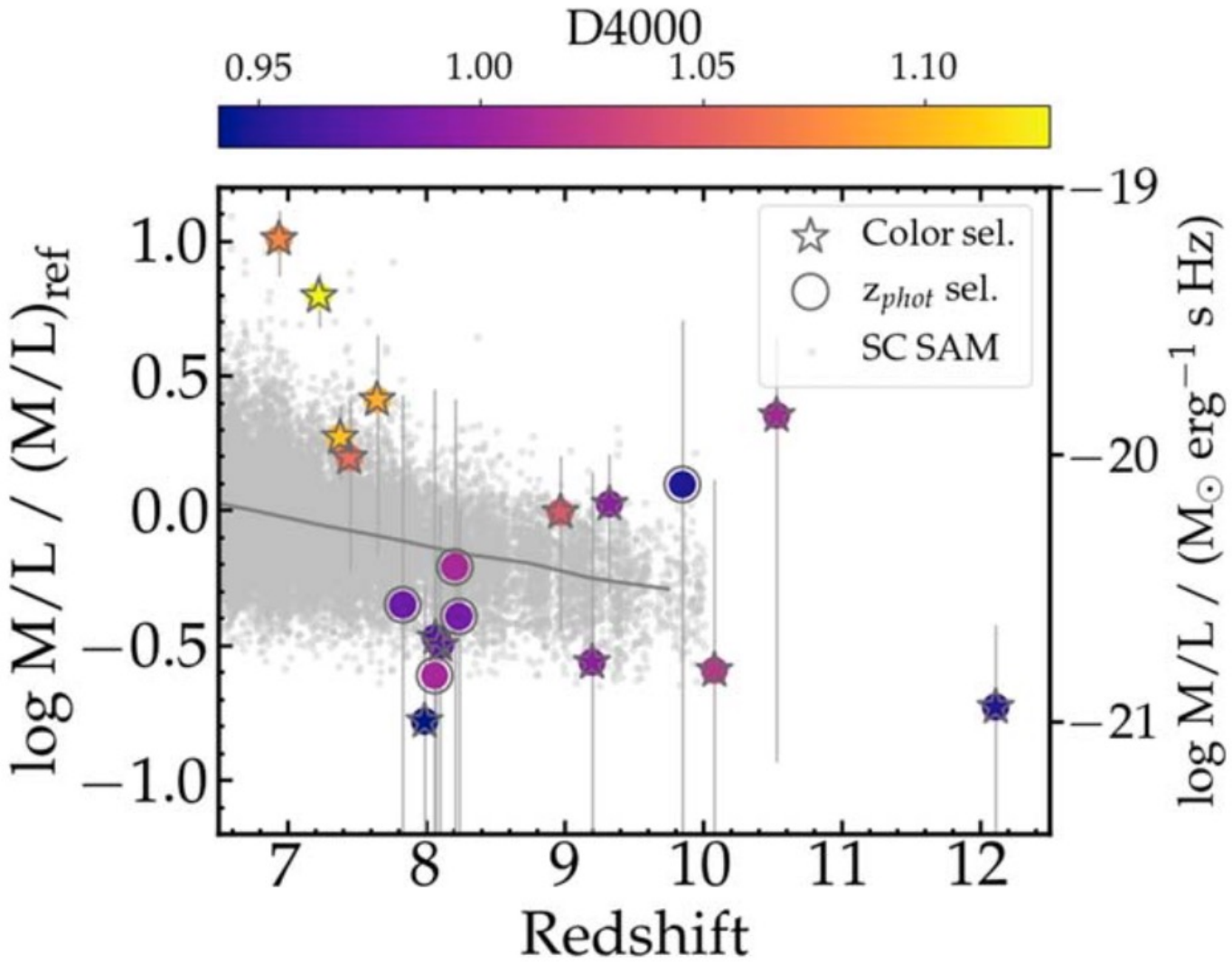
Stellar mass accuracies improved by ~10x (at least)



and better control of systematics

see also Papovich, … PS+23

#3: A VARIETY OF PHYSICAL CONDITIONS AT HIGH-Z



PS+23

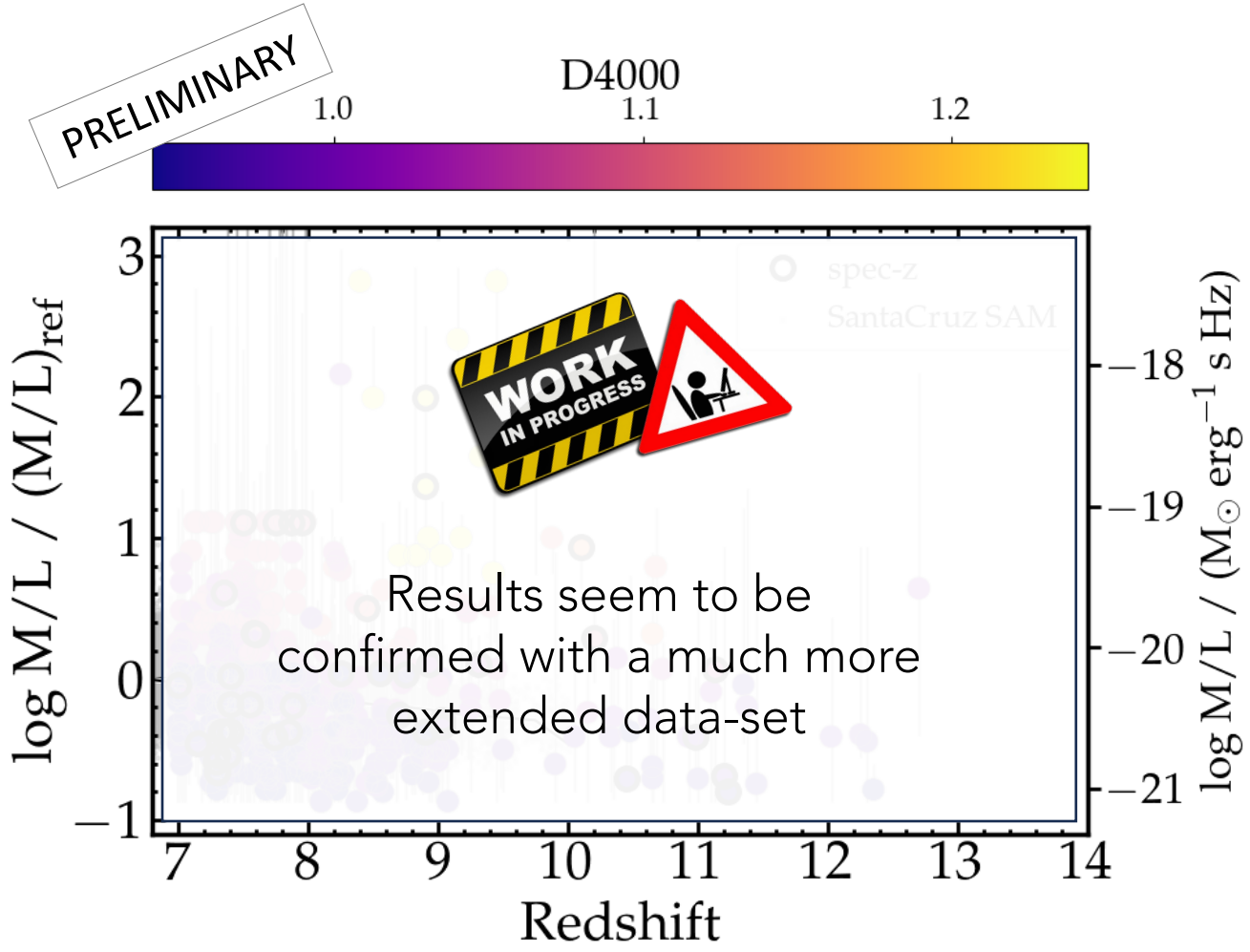
Wide range in Mass / Luminosity:

- heterogeneous high-z galaxy population (not reproduced by models)

Wide diversity also found in the ISM conditions
(Schaerer+22, Sanders+23, Cameron+23, Curti+23, Tang+23, D'Eugenio+23, Nakajima+23, …)

#3: A VARIETY OF PHYSICAL CONDITIONS AT HIGH-Z

PS+ (in prep.)

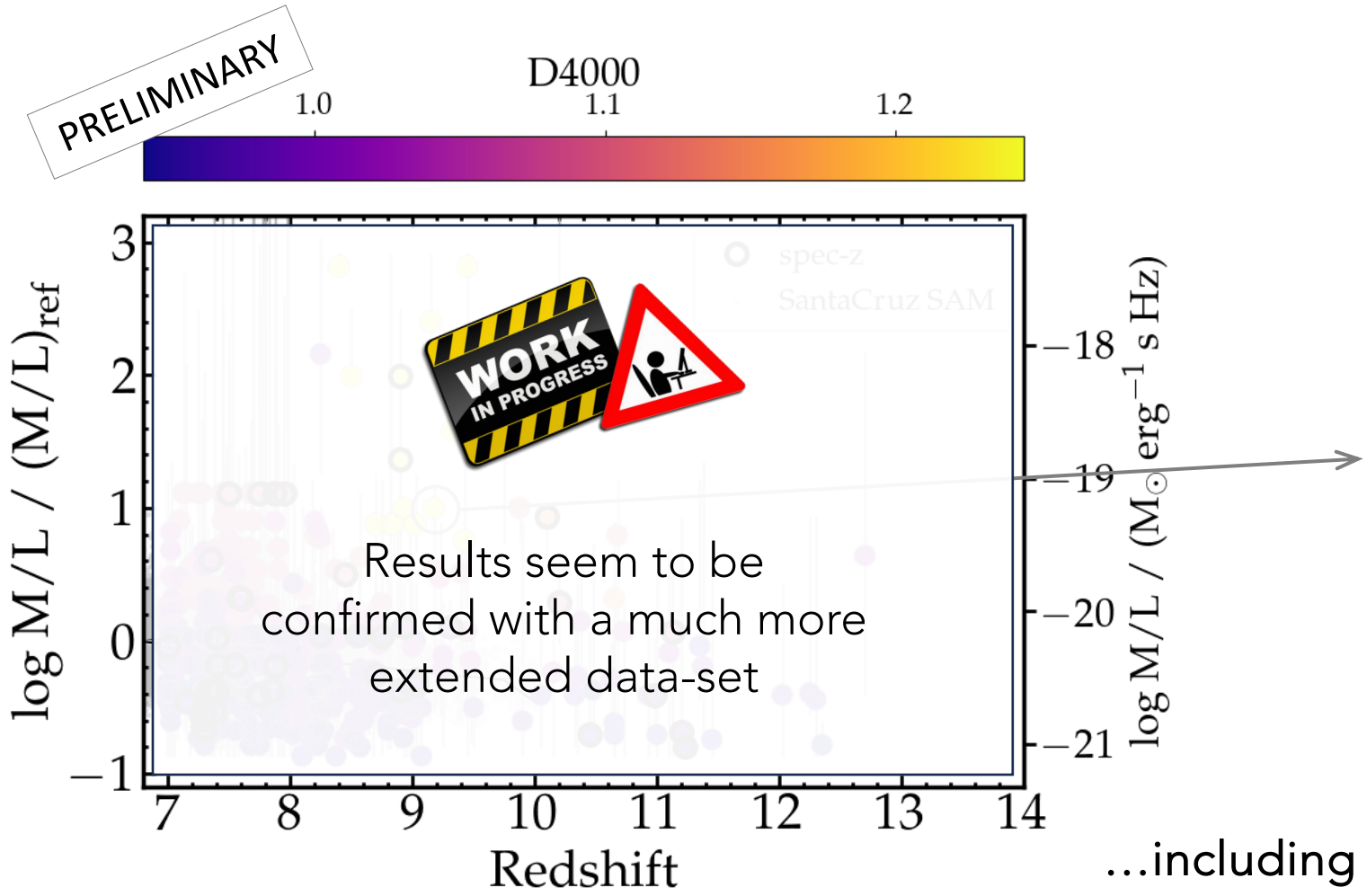


Wide range in Mass / Luminosity:

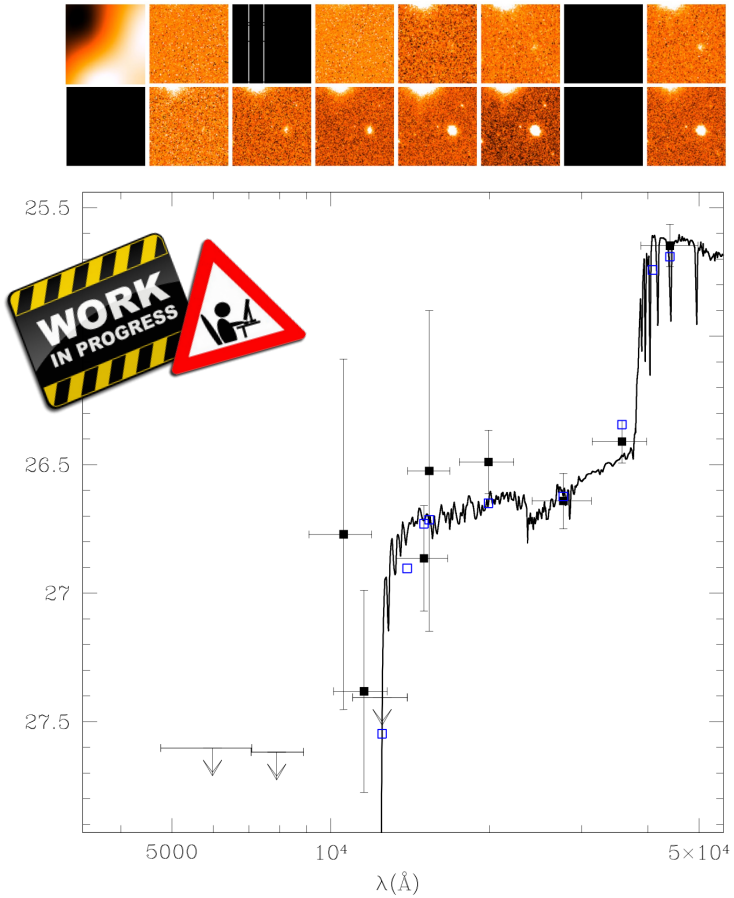
- heterogeneous high-z galaxy population (not reproduced by models)
- high M/L → evolved stellar populations (galaxy formation faster than thought?)

#3: A VARIETY OF PHYSICAL CONDITIONS AT HIGH-Z

PS+ (in prep.)



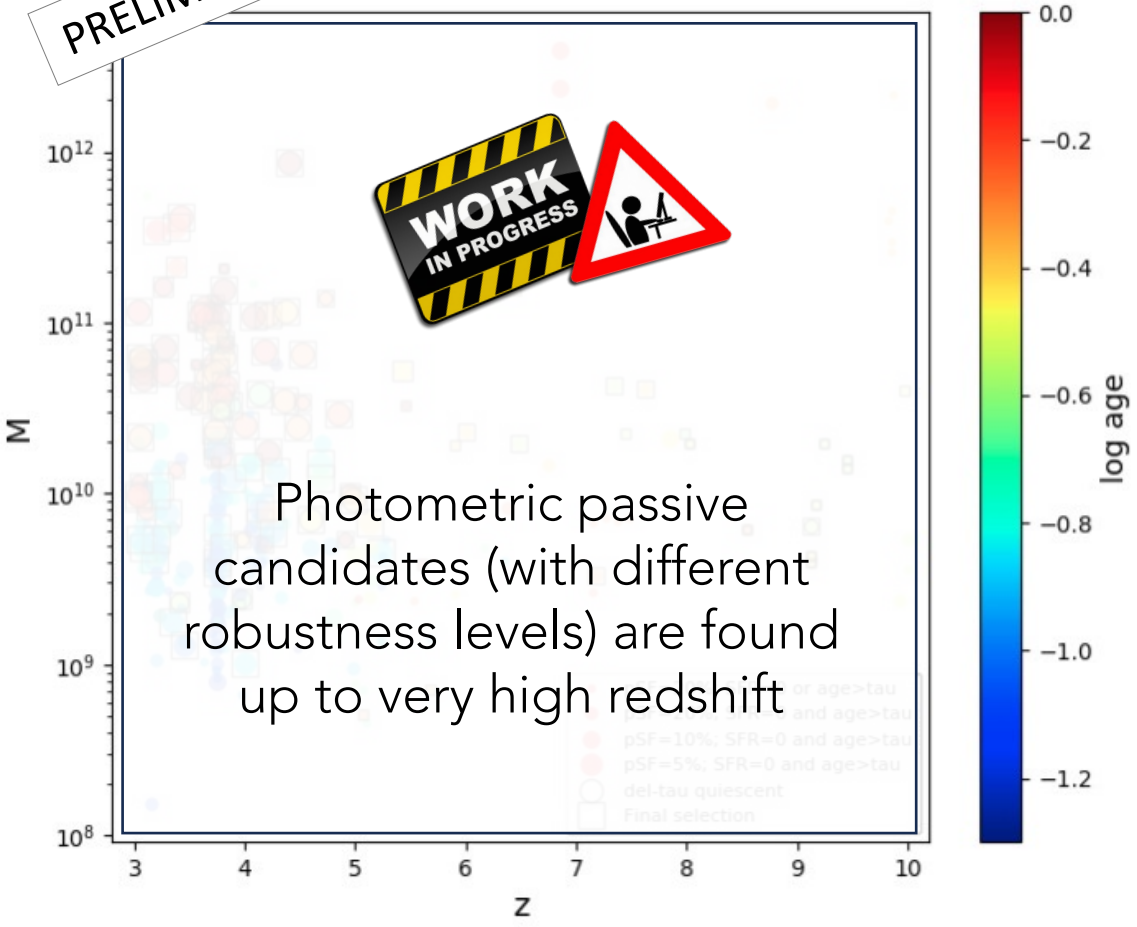
Merlin, PS+in prep.



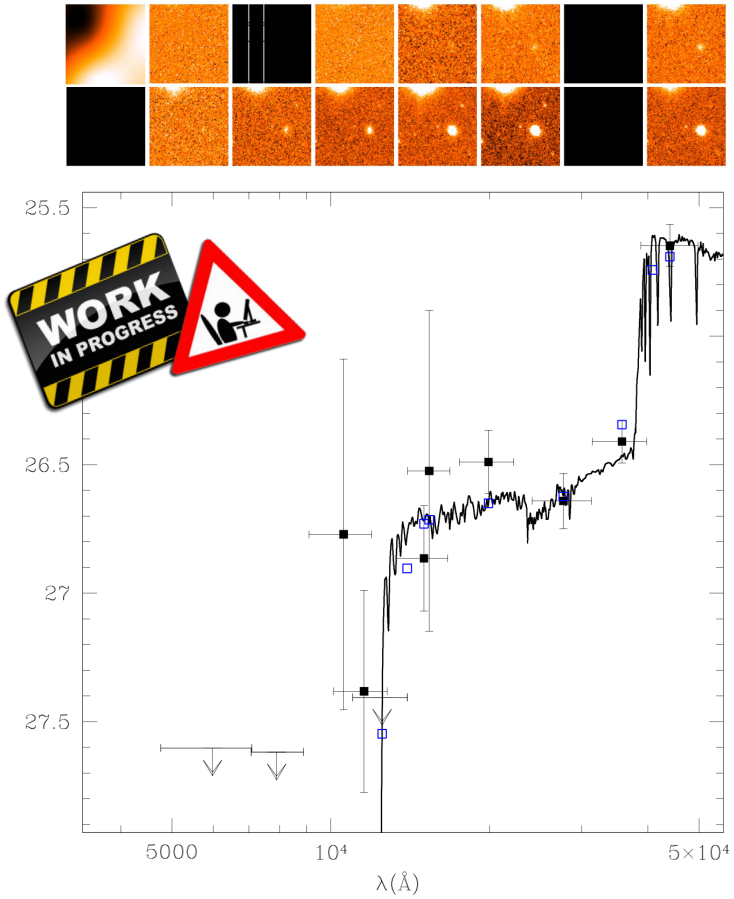
…including passive galaxies at very early epochs!

#4: PASSIVE GALAXIES IN THE FIRST GYR

PRELIMINARY

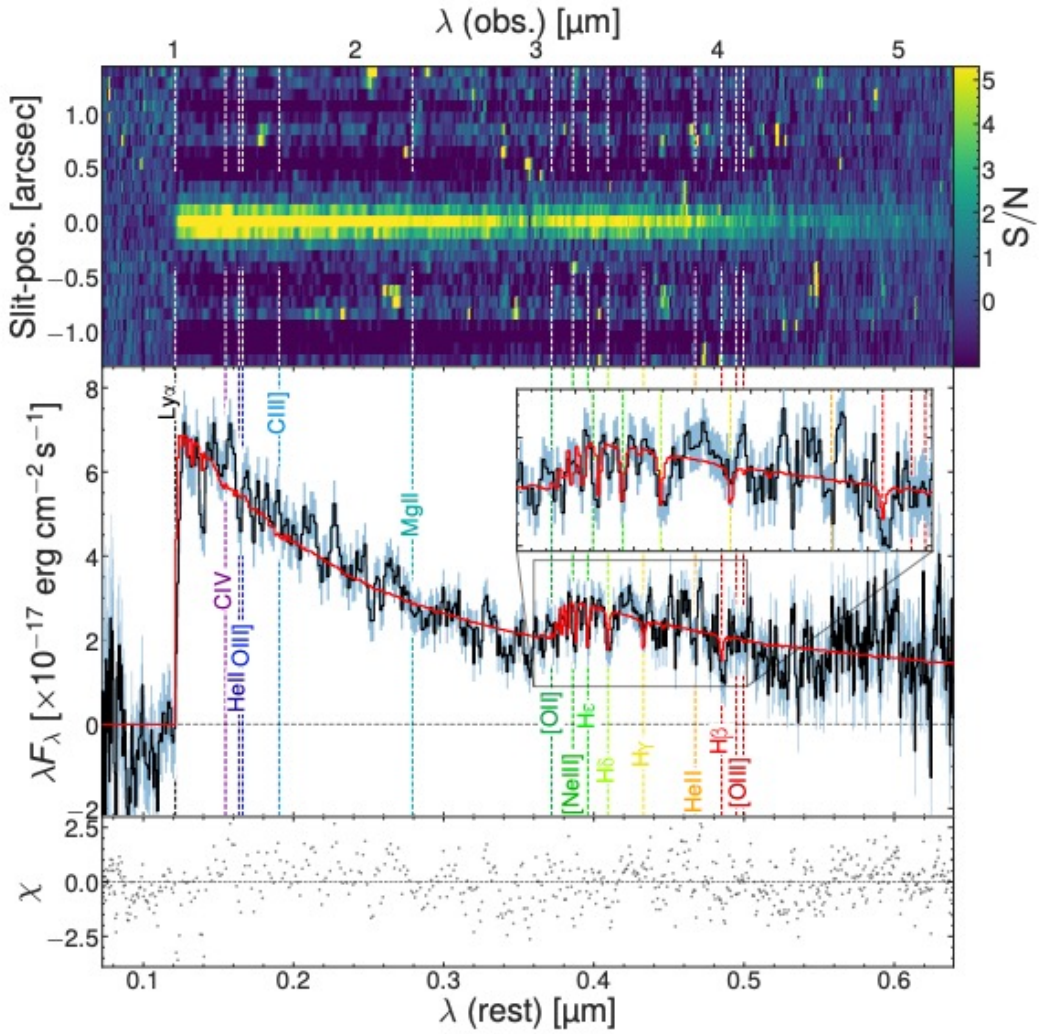


Merlin, PS+in prep.

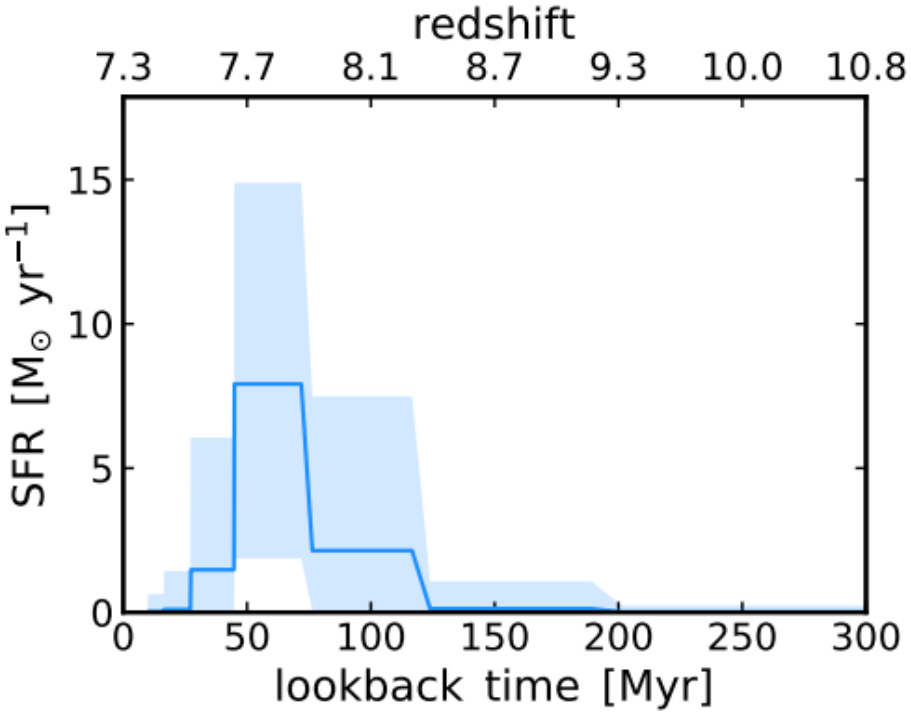


see also Valentino+23, Strait+23, Carnall+23a, Nanayakkara+24

#4: PASSIVE GALAXIES IN THE FIRST GYR



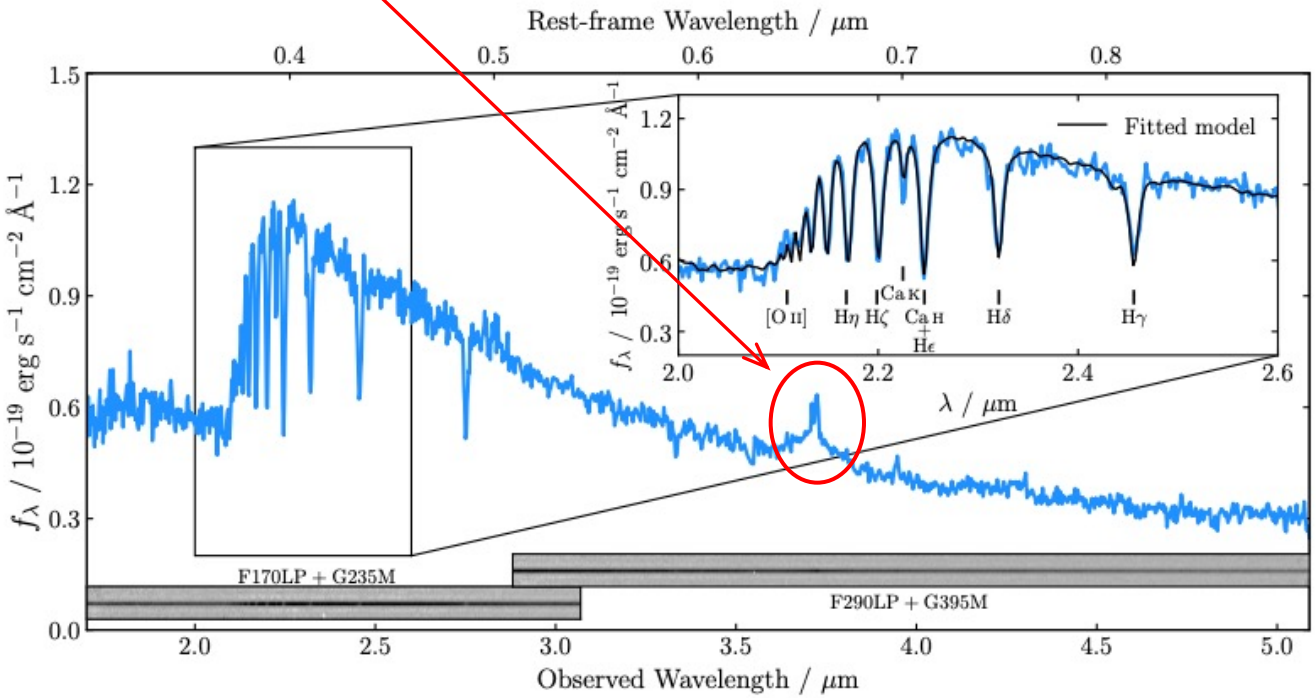
Recently quenched galaxy at z~7.3
(700 Myr after the Big Bang)

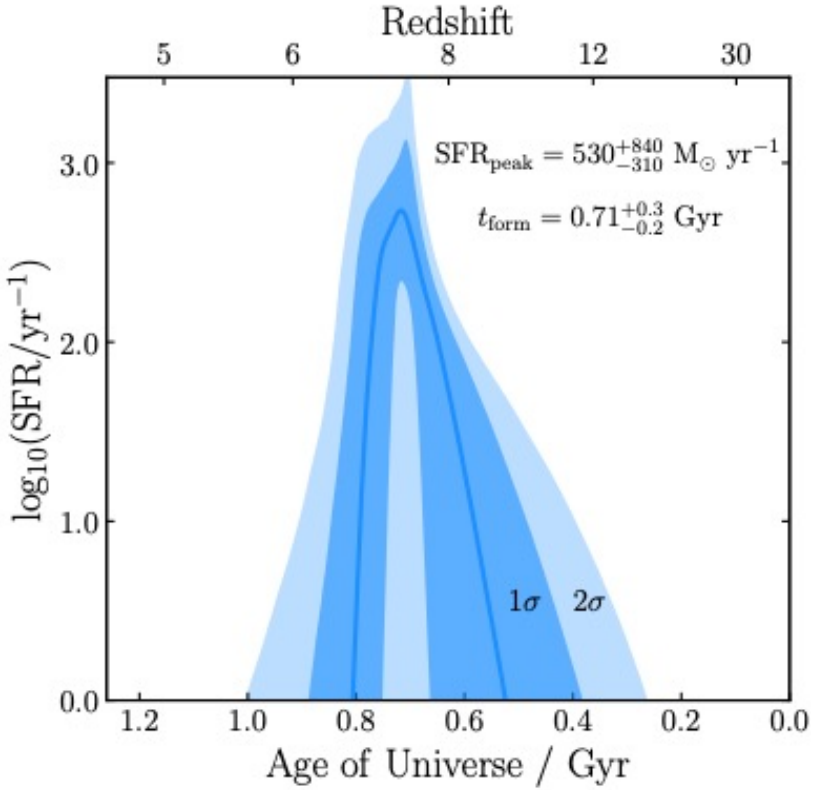


Looser+24

#4: PASSIVE GALAXIES IN THE FIRST GYR

Passive galaxy at z~4.7 (1.25 Gyr after the Big Bang), quenched ~600-800 Myr after the Big Bang by AGN feedback

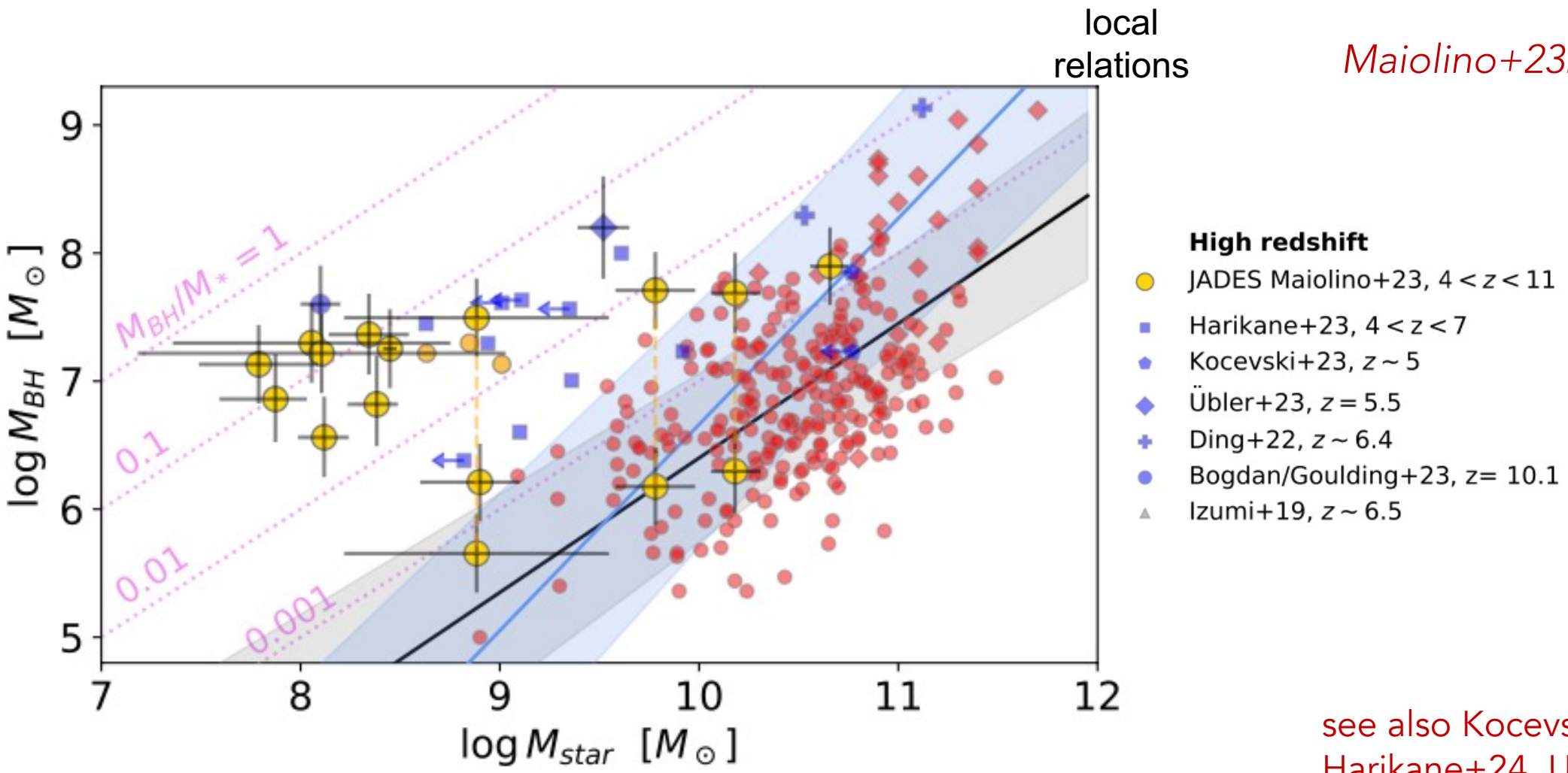




Carnall+23b

see also Strait+23, Kakimoto+24

#5: A LOT OF AGN, WITH RAPIDLY GROWING SMBH

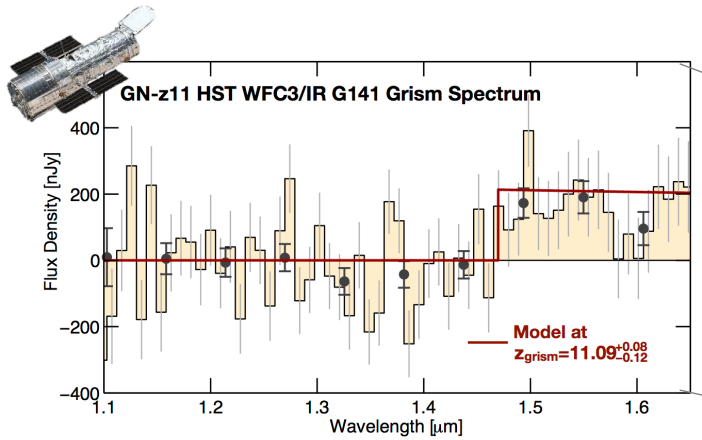


Maiolino+23b (subm.)

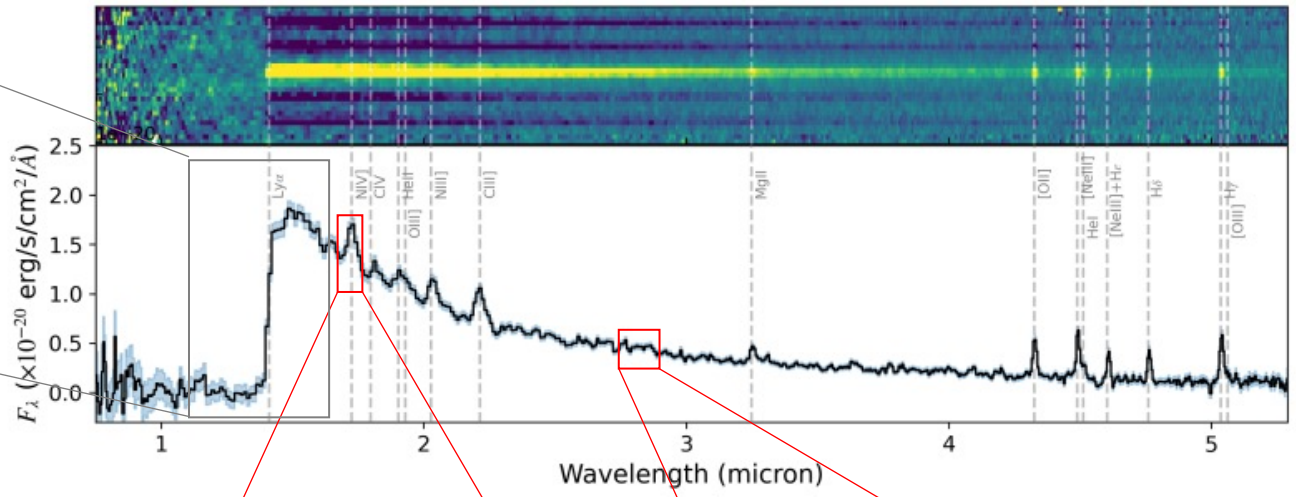
- First discovery of low-luminosity AGN at high-z
- Black holes grow faster than their host galaxies at high-z

see also Kocevski+23, Harikane+24, Ubler+23, Pacucci+23, Matthee+24, Scholtz+23 subm., Labbé+23b subm., …

#5: A LOT OF AGN, WITH RAPIDLY GROWING SMBH

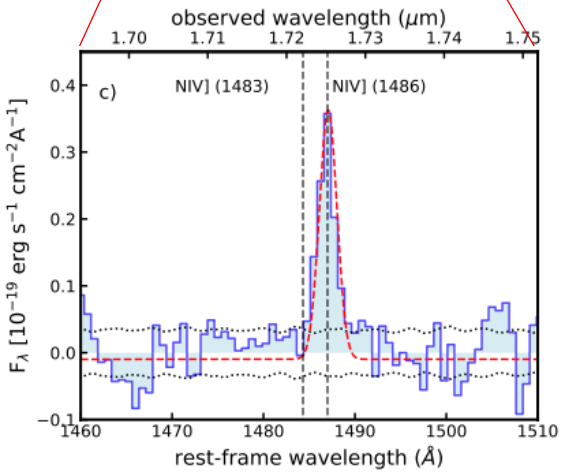


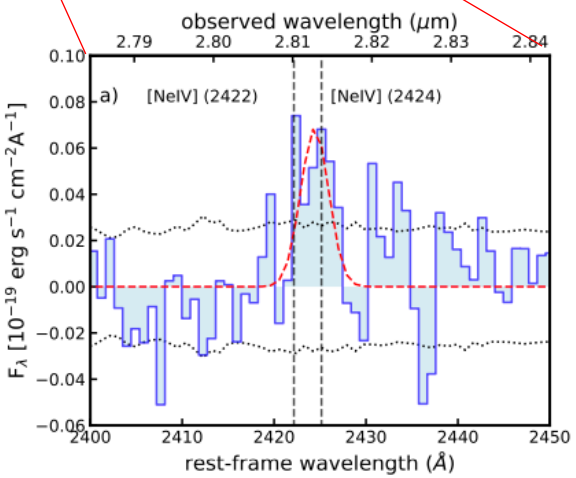
Oesch+16



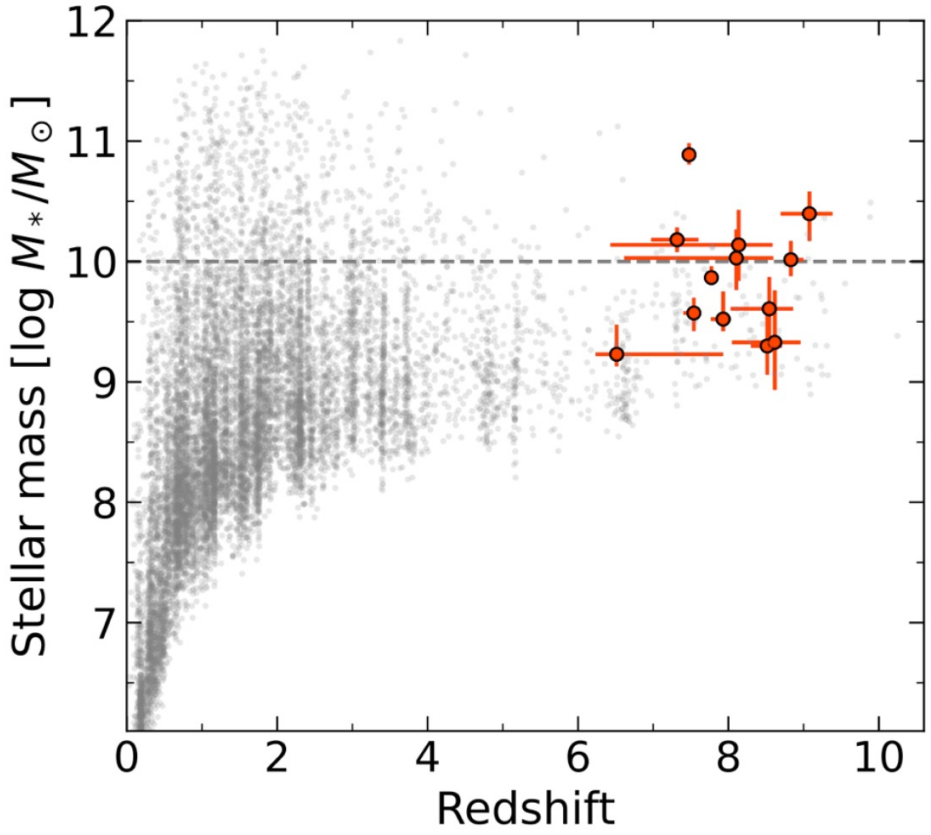
Bunker+23
Maiolino+24

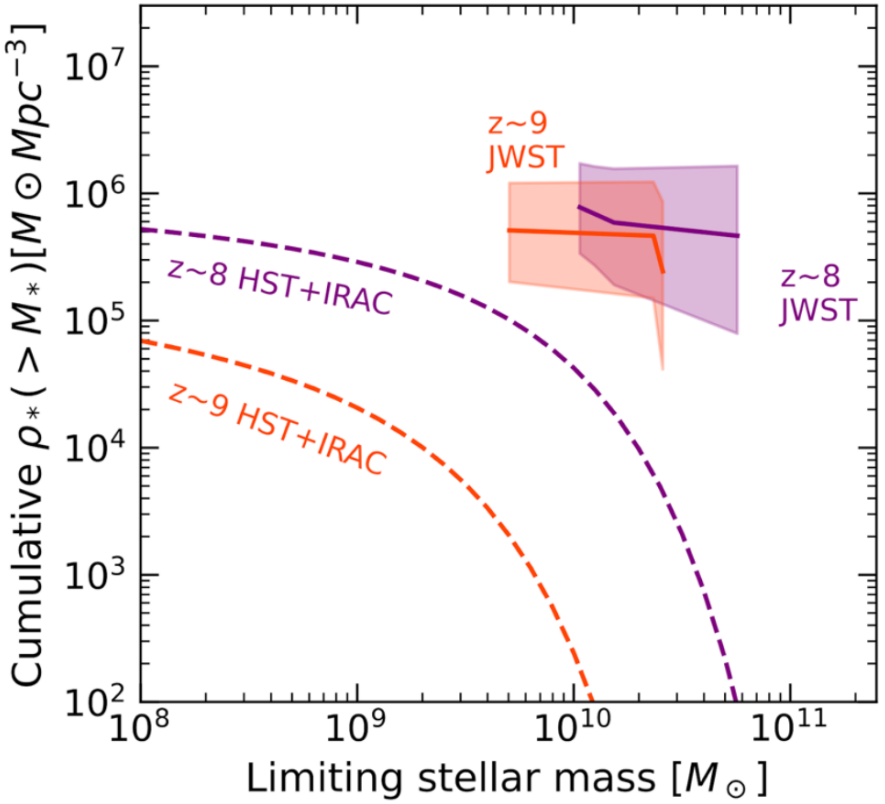
GN-11
z=10.6
(430 Myr after the Big Bang)
M_{BH}~$10^{6.2}$ Msun





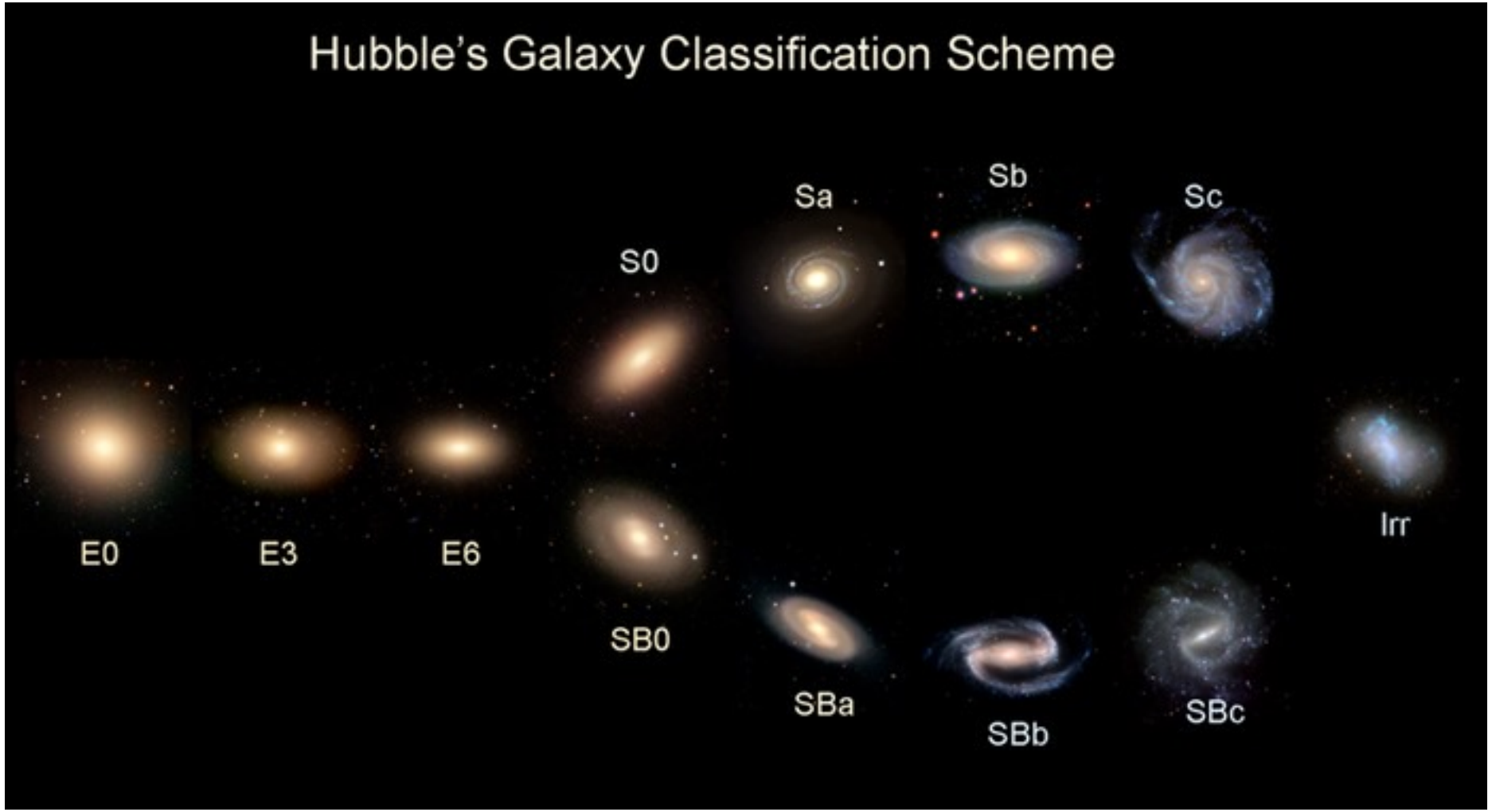
#6: very massive galaxies in the first Gyr



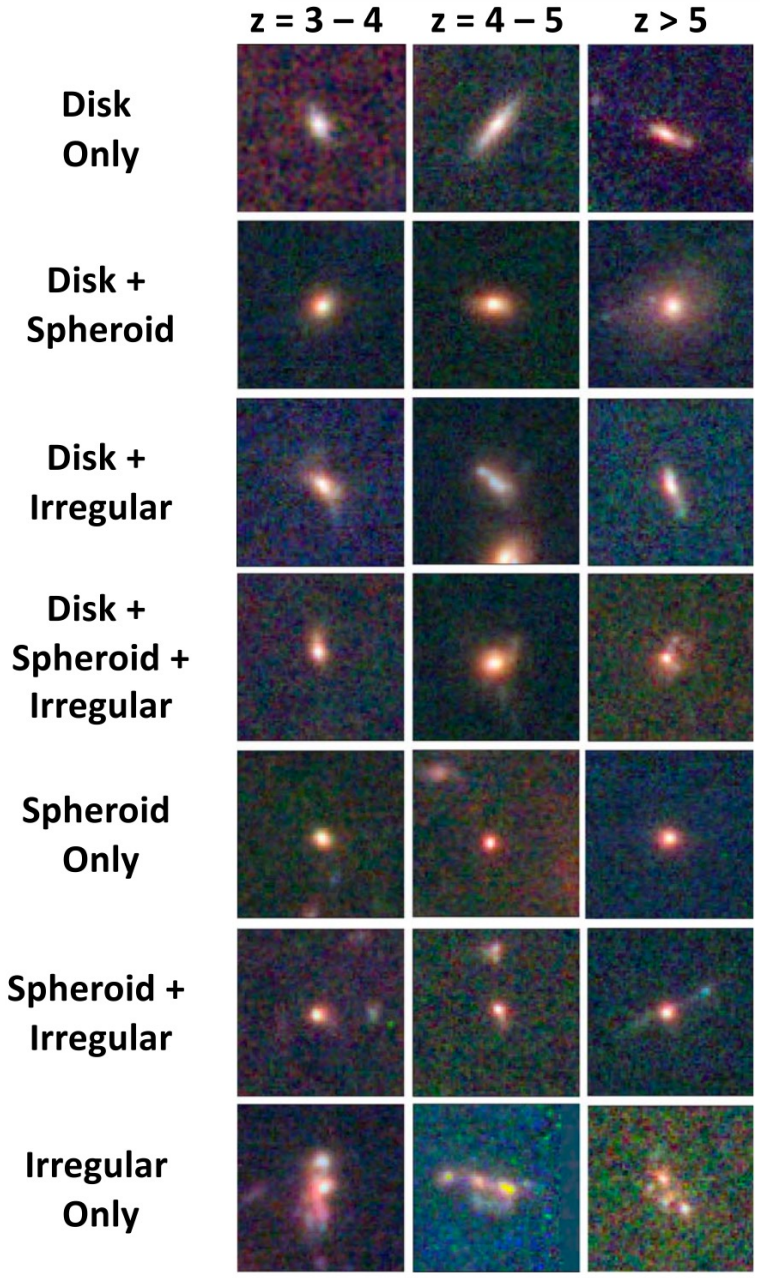


Labbé+23a

Galaxy morphology & structure



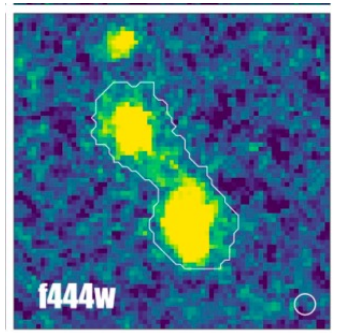
Galaxy morphology & structure at high-z



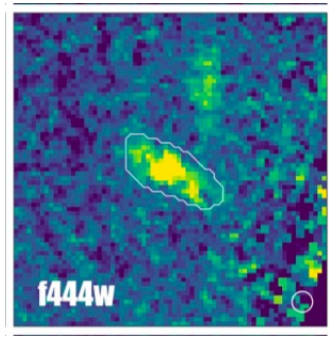
Kartaltepe+23

Wide diversity of morphologies

z~7 (t_{Univ}~750Myr)

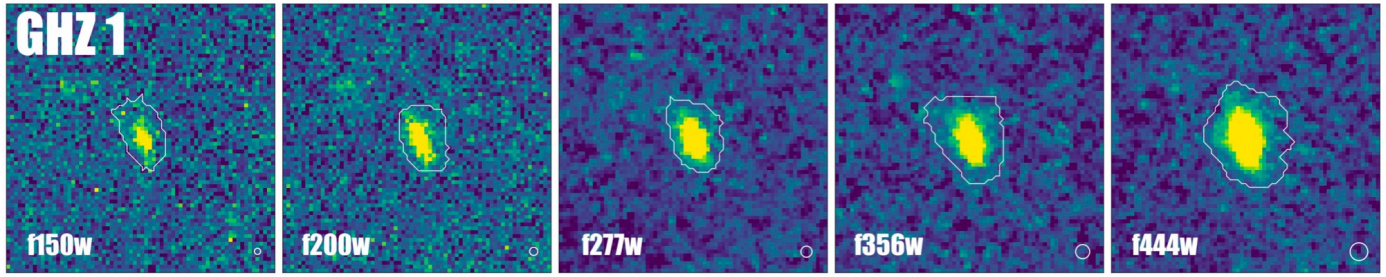


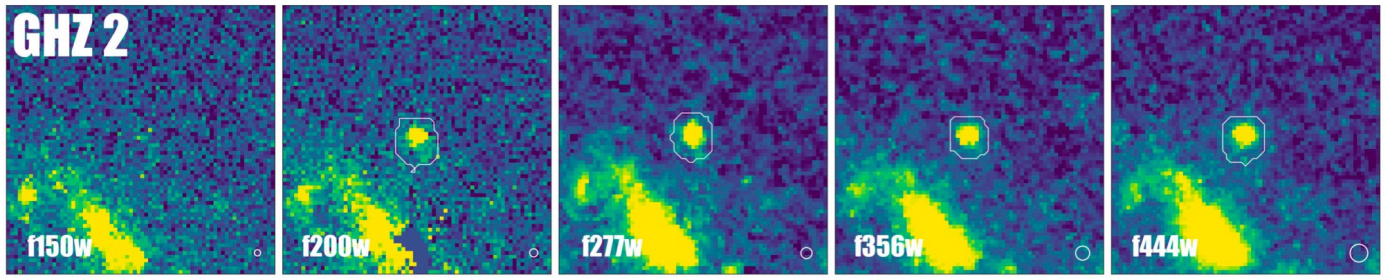
z~8 (t_{Univ}~630Myr)



Treu, …PS+23

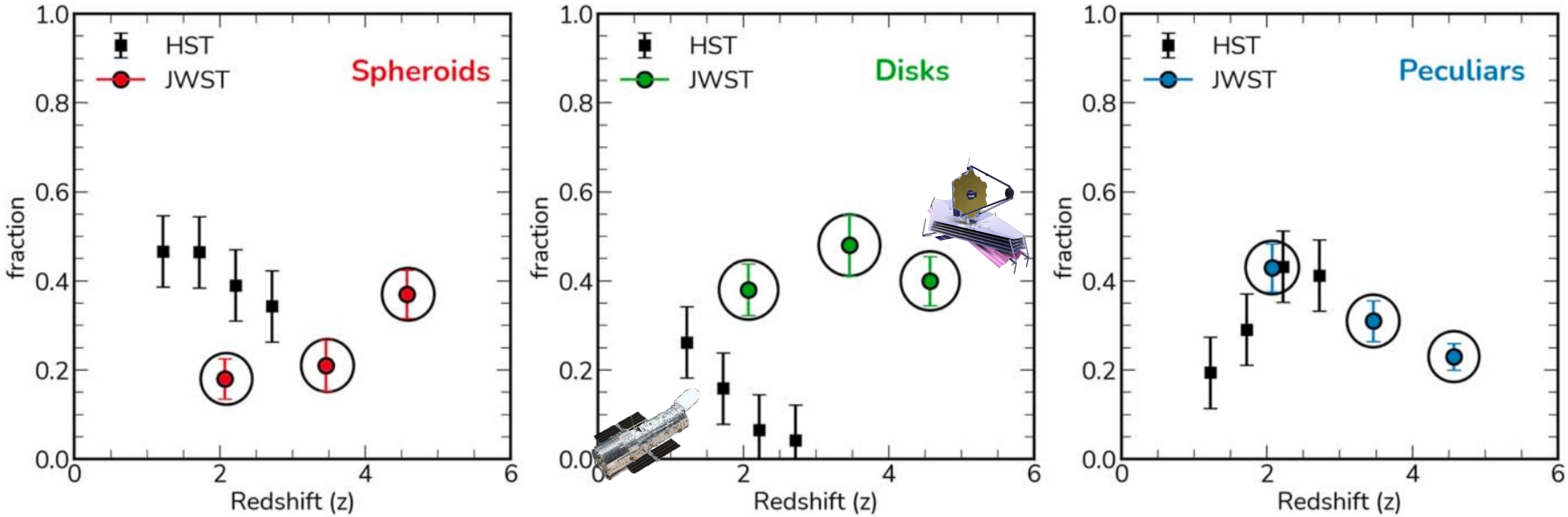
z=10.53 (t_{Univ}~430Myr)





z=12.11 (t_{Univ}~350Myr)

#7: A LOT OF DISKS



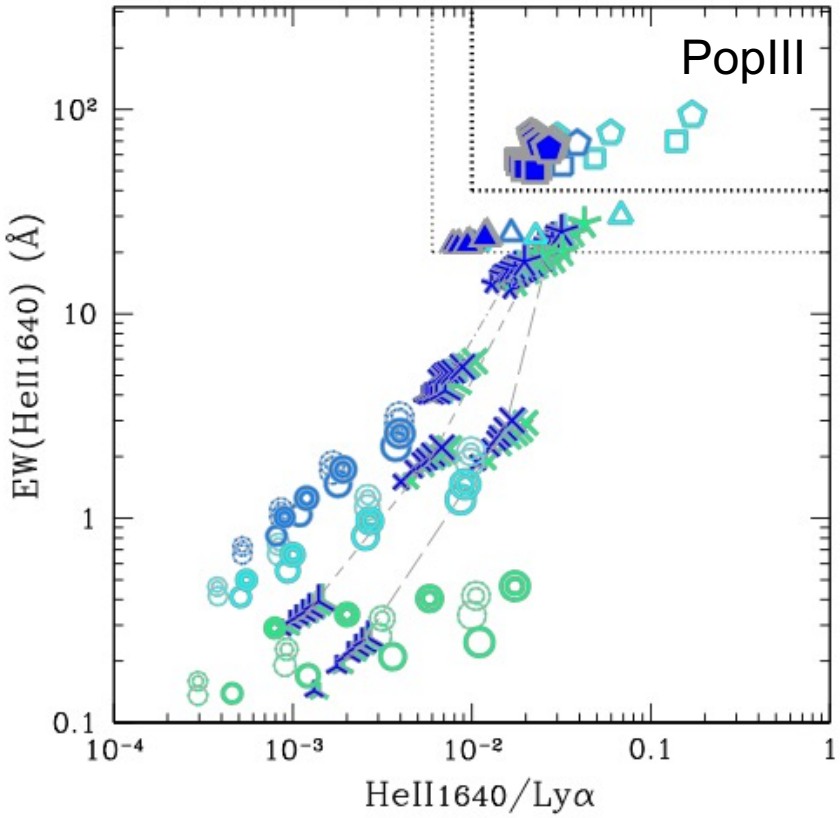
Disks dominate up z~5 (t_{Univ}~1.15 Gyr)

Ferreira+23
see also Kartaltepe+23,
Jacobs,…,PS+23

The first stars (Pop III)

Formed from pristine gas → less opacity, less cooling, less fragmentation →
much bigger 100-1000 M_{sun}

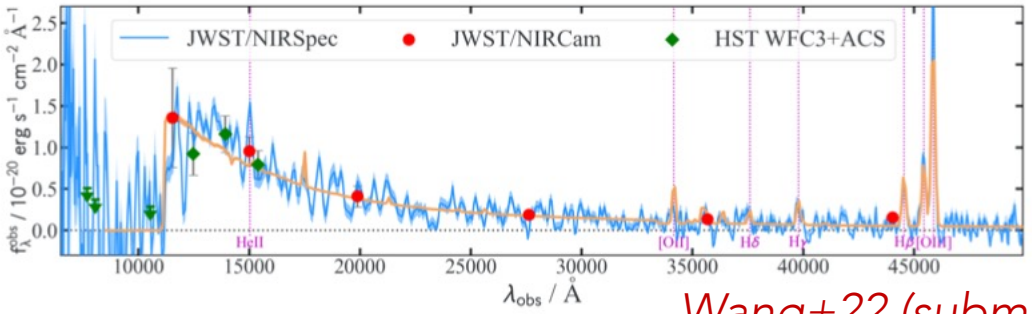
Signature: hard radiation field (→ HeII line) + negligible metallicity



Nakajima & Maiolino 22

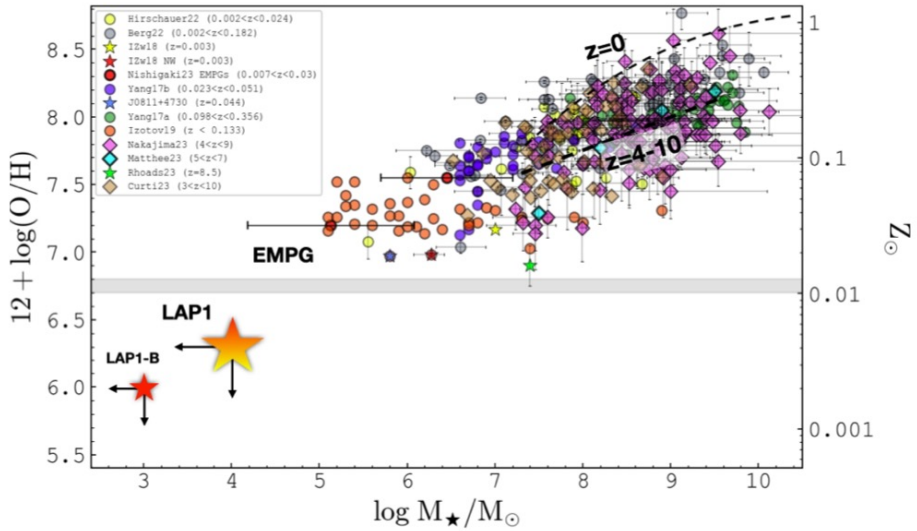
Evidence of first stars (PopIII)?

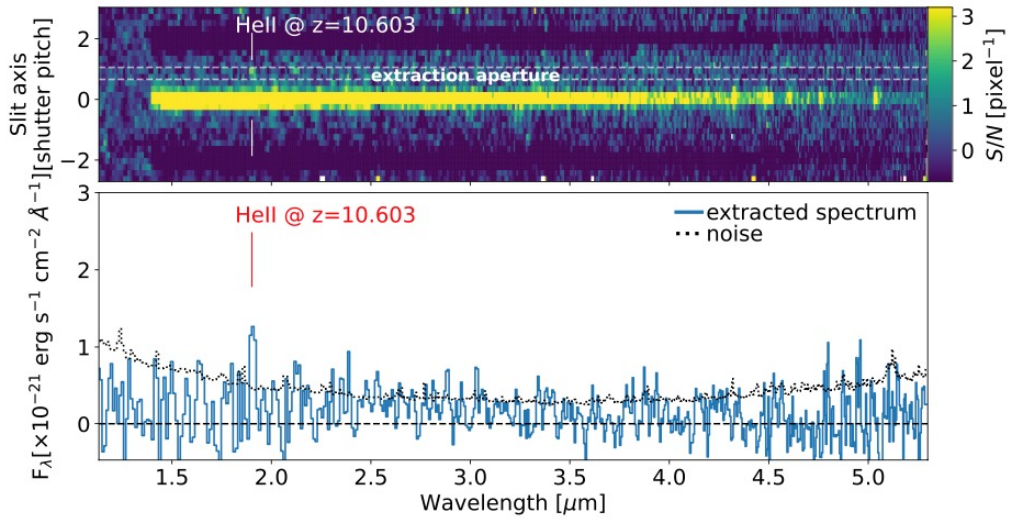
Tantalizing detection of mixed PopIII+PopII emitter at z~8



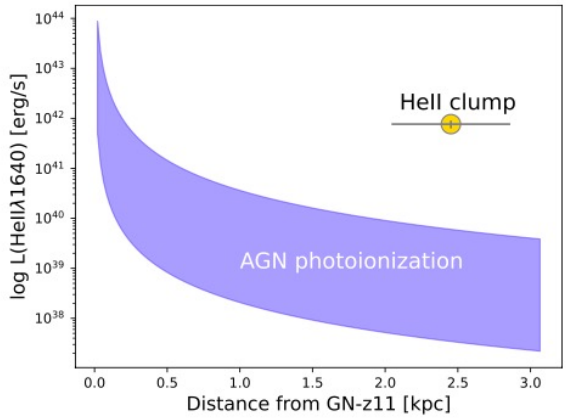
Wang+22 (subm.)

Vanzella+23



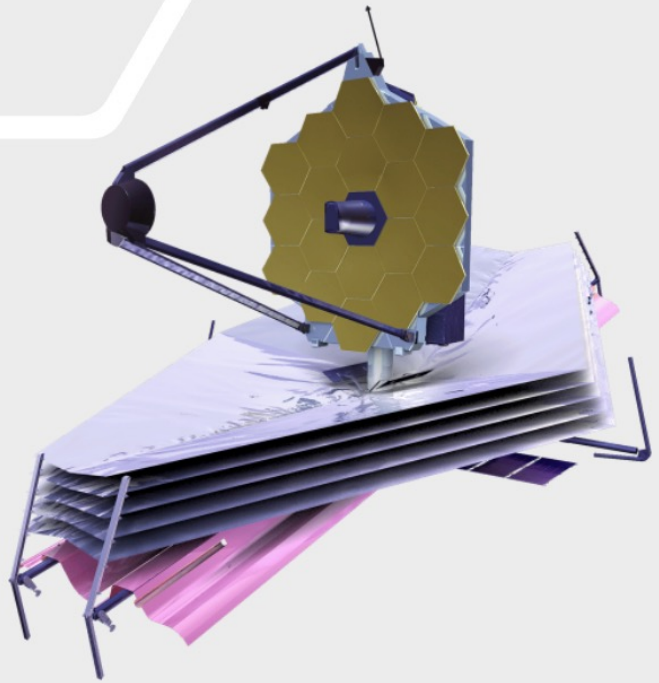


Maiolino+23 (subm.)



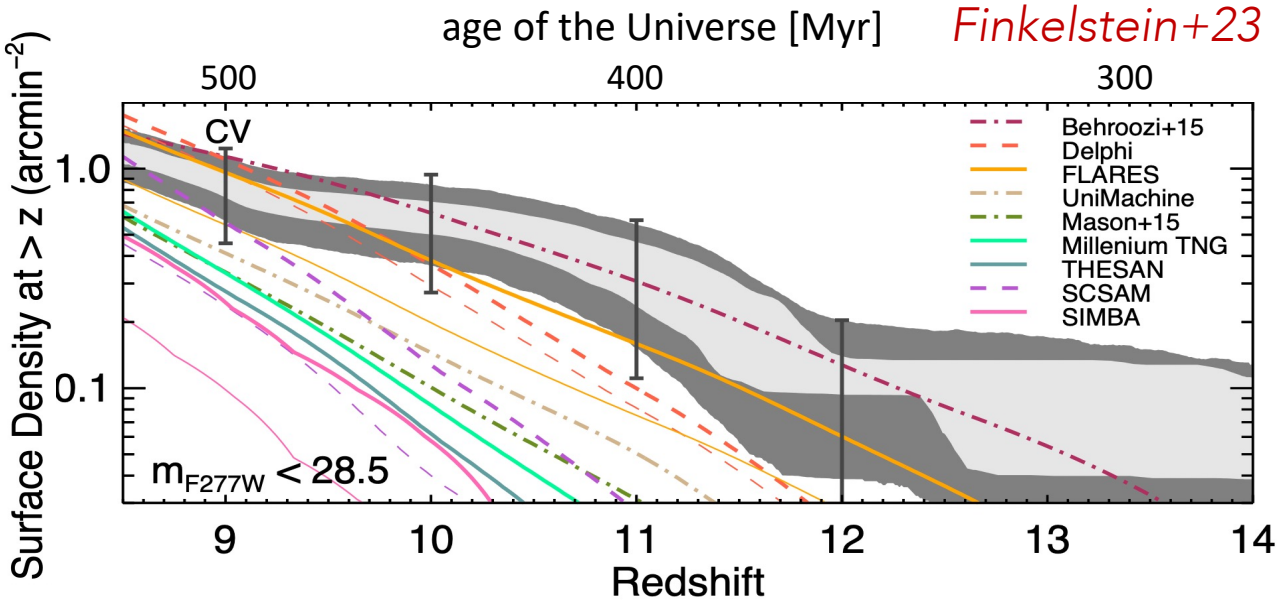
Outline of the talk

- Why do we study the high-z Universe?
  State-of-the-art before JWST
- Overview of JWST:
  the ideal telescope for observing the earliest galaxies
- JWST major results
- Interpretations, challenges, open questions and future perspectives



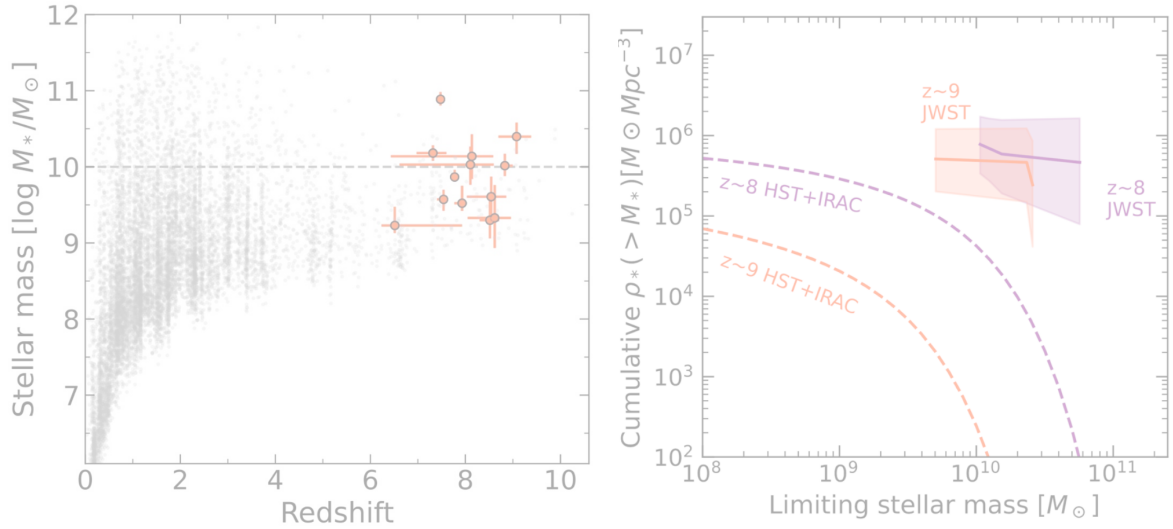
Two key tensions

Excess of early bright galaxies



Finkelstein+23

Stellar masses are too large



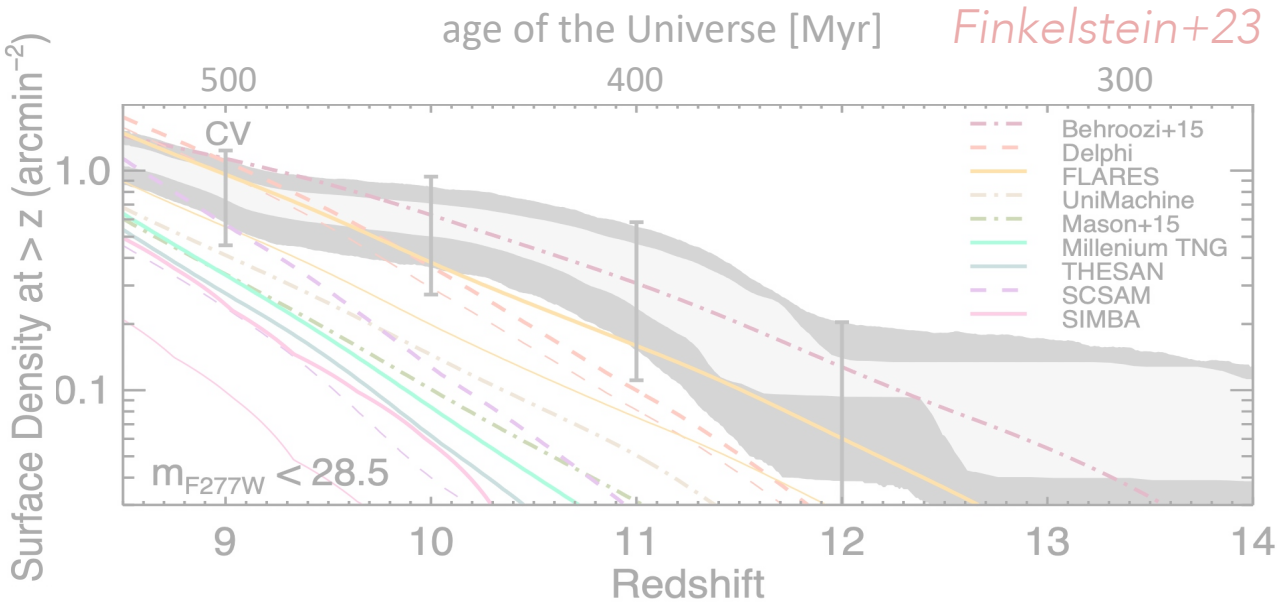
Labbé+23a

Excess of early bright galaxies

- Higher SF efficiency (Inayoshi+22, Harikane+23, Qin+23, Dekel+23, Mason+23, Renzini+23, Finkelstein+23, Yung+23, …)
- Negligible dust (Ferrara+23a,b, Ziparo+23, Fiore+23, Cullen+23, Topping+23, …)
- Top-heavy IMF, possibly PopIII stars–related (Haslbauer+22, Harikane+23a, Yajima+23, Finkelstein+23, Yung+23, Cameron+23b, Trinca+24, …)
- AGN contribution to UV radiation (e.g., Kocevski+23, Maiolino+23subm., Labbé+23, D'Silva+23., …)
- Stochasticity (Mason+23, Mirocha&Furlanetto+23, Shen+23, Strait+23, Looser+23subm., Looser+24 …) in SF histories, dust attenuation variations, halo assembly; but see Pallottini&Ferrara23
- Modified cosmological model (Padmanabhan&Loeb23, Melia23,…)
- …. or more likely a combination of these

Two key tensions

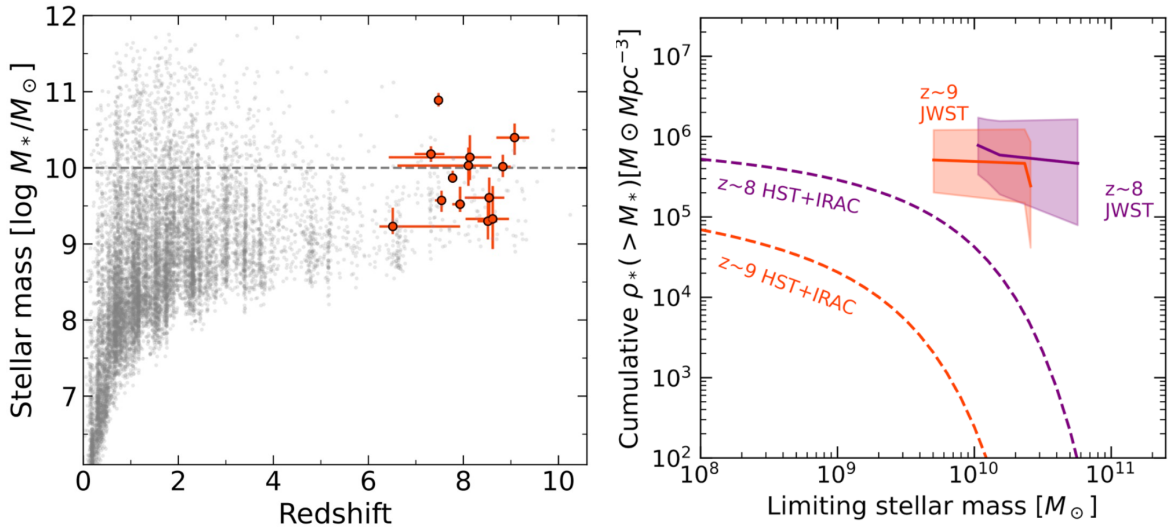
Excess of early bright galaxies



Finkelstein+23

Stellar masses are too large

Labbé+23a



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COSMOLOGY

JWST's First Glimpses of Early Galaxies Could Break Cosmology

The James Webb Space Telescope's first images of the distant universe shocked astronomers. Is the discovery of unimaginably distant galaxies a mirage or a revolution?

By Jo

The Guardian

James Webb telescope detects evidence of ancient 'universe breaker' galaxies

Huge systems appear to be far larger than was presumed possible so early after big bang, say scientists

SCI NEWS

Webb Discovers Impossibly Massive Galaxies in Early Universe

The Brussels Times

'Real shocker': Six massive galaxies could upend 'settled science'

Thursday, 23 February 2023

The James Webb Space Telescope discovers enormous distant galaxies that should not exist

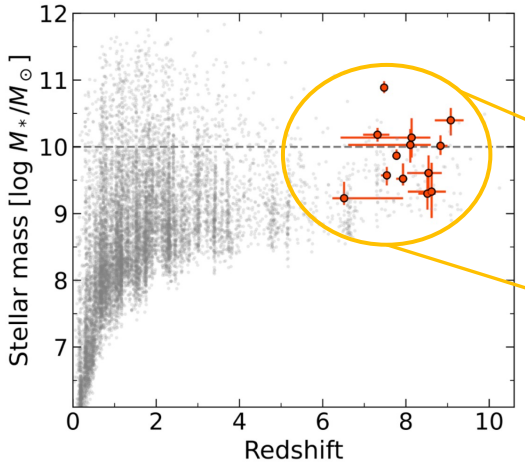
SPACE.com

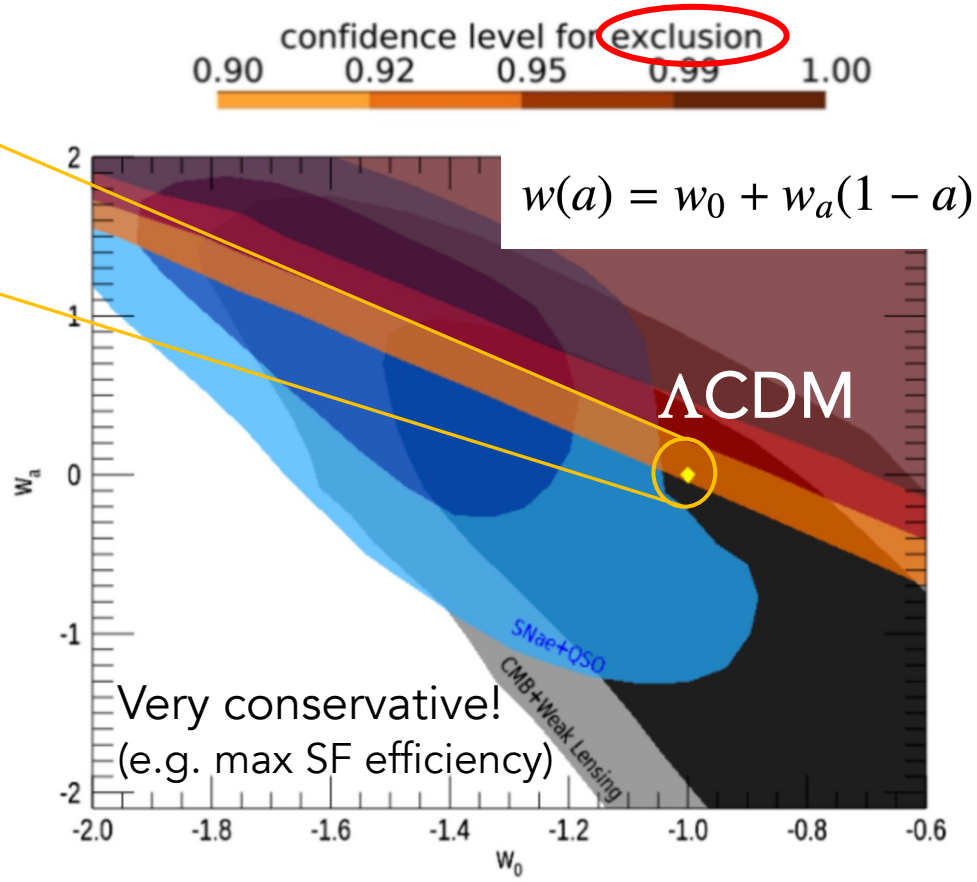
By Tereza Pultarova published February 22, 2023

Giant, mature galaxies seem to have filled the universe shortly after the Big Bang, and astronomers are puzzled.

Need "new physics"?

Labbé+23





Adapted from Menci, Castellano, PS+22

see also Boylan-Kolchin23, Lovell+23 for similar analyses

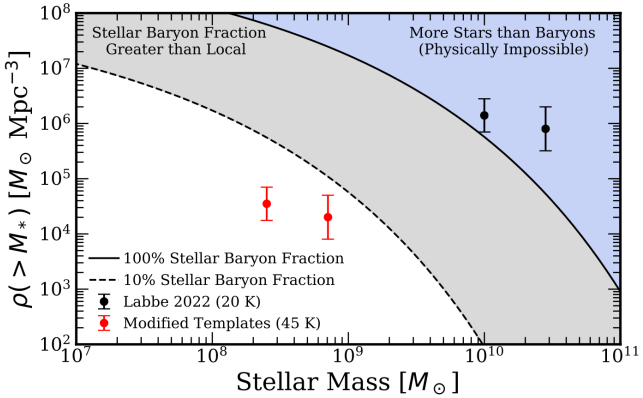
see also Lin+23, Gong+23, Parashari&Laha23

Inconsistency (1.5σ) with ΛCDM: measured galaxy masses are too large compared to the total mass budget of baryons within sufficiently massive DM halos

Observational caveats !

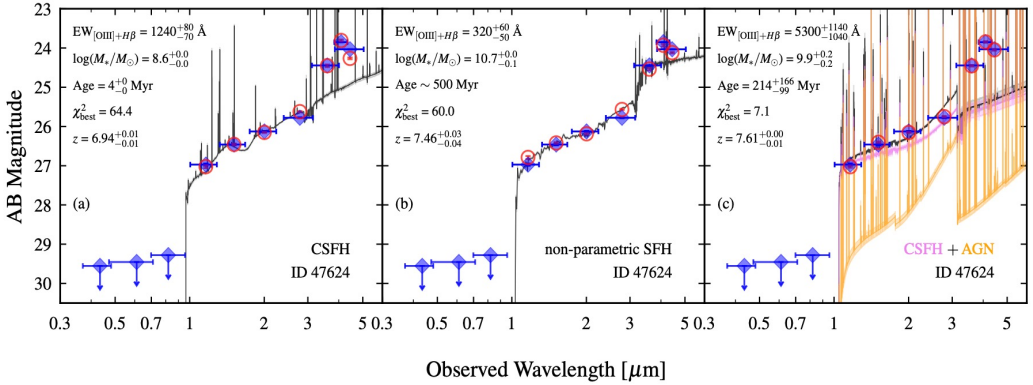
- Templates are calibrated in the local Universe (e.g. IMF)

Steinhardt+22
(see also Haslbauer+22)



- Impact of strong nebular emission (extremely young stellar populations, PopIII stars, AGN)

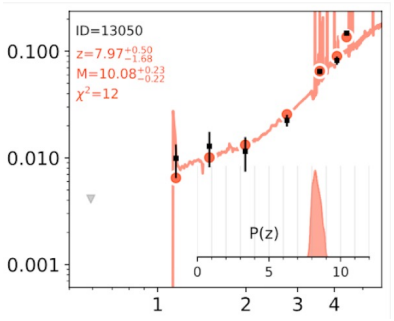
Endsley+23
see also Arrabal Haro+23a



- Unidentified AGN contribution

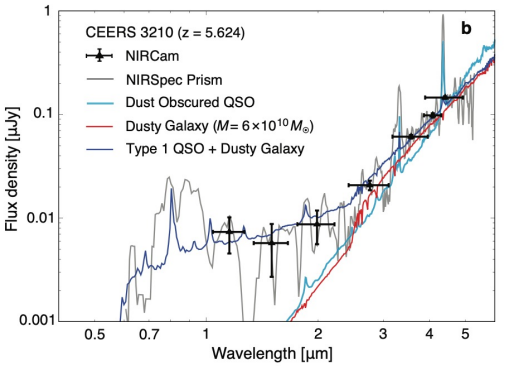
see also Labbé+23b (subm.)

Labbé+23a



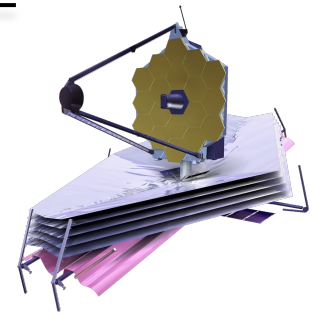
SPECTROSCOPY

Kocevski+23

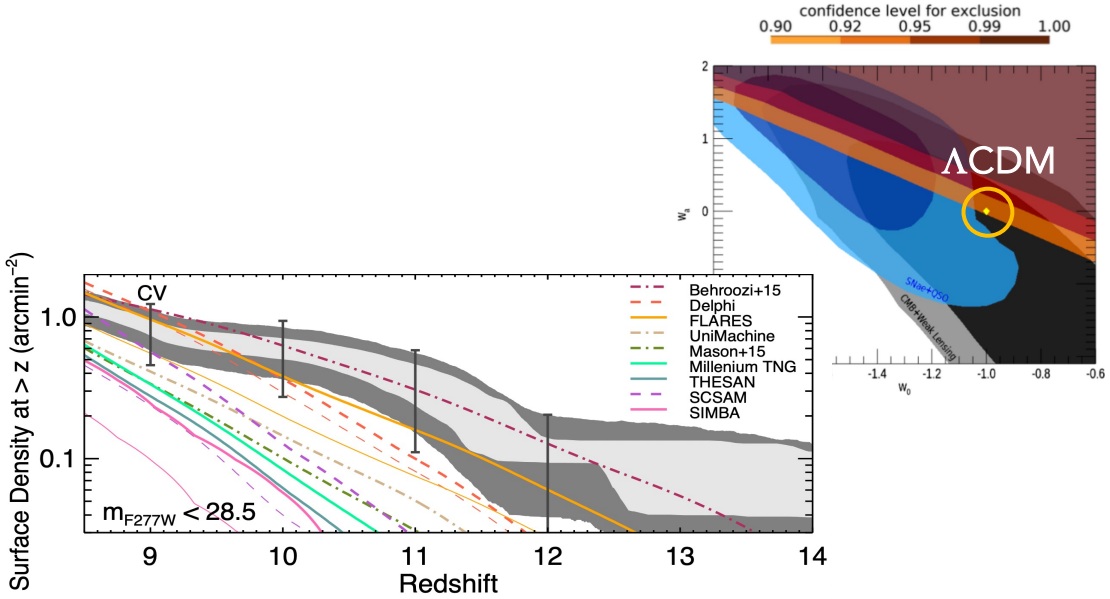


SPECTROSCOPY

Take-home messages



- JWST operates better than expected
- Only tentative evidence for the first stars (and galaxies) so far, but a lot of **unexpected** results



- Potentially impacting our understanding of galaxy formation
- → keep collecting spectroscopy

In the first Gyr:

too many early/bright galaxies,

rapidly chemically enriched,

coming in a variety of physical conditions,

including passive galaxies already in place,

a lot of AGN, with rapidly growing SMBH,

galaxies that have already assembled a lot of mass,

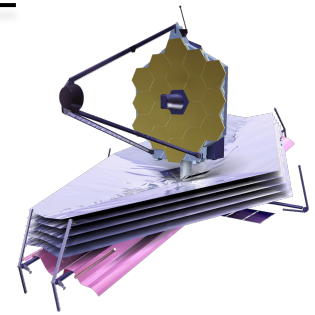
and a lot of disks

→ VERY RAPID GALAXY FORMATION AT HIGH Z?

“The history of astronomy is a history of receding horizons.”

Edwin Hubble
The Realm of the Nebulae, 1936

Take-home messages



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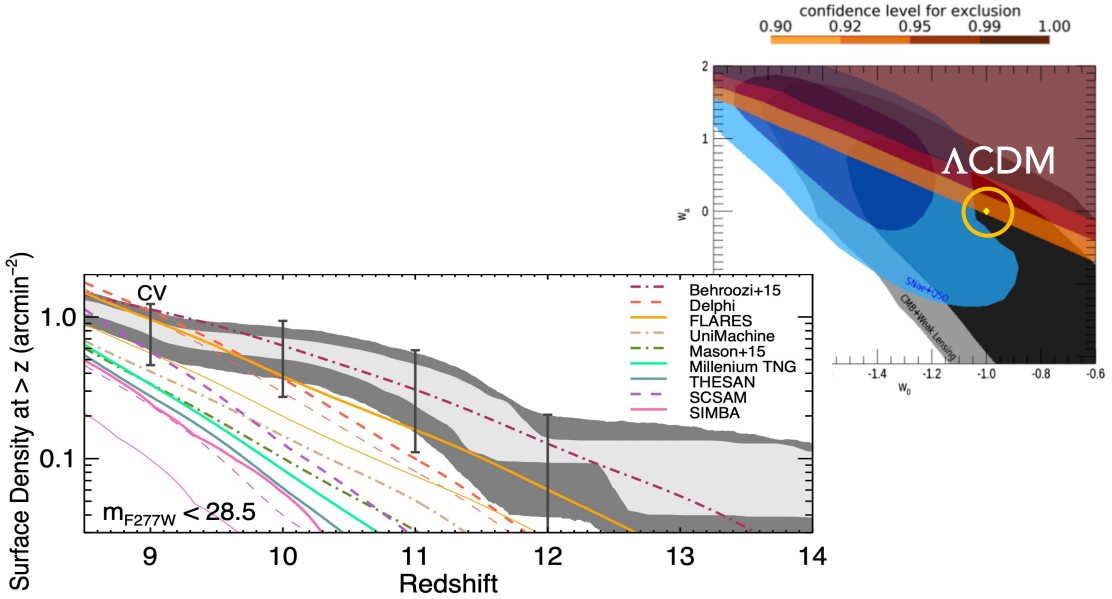

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Thank you for your attention