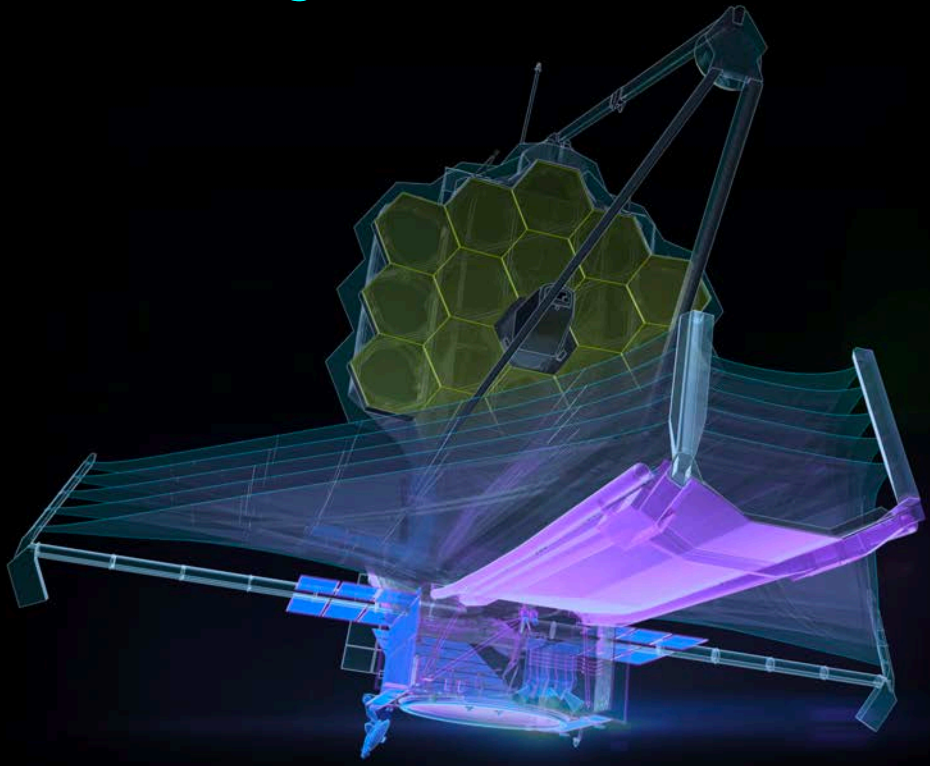
The Science Promise Now Being Realized After JWST's Decades of Challenges

Garth Illingworth
University of California Santa Cruz



what is going on in galaxies in the first ~500 Myr?

N3AS Lecture 2

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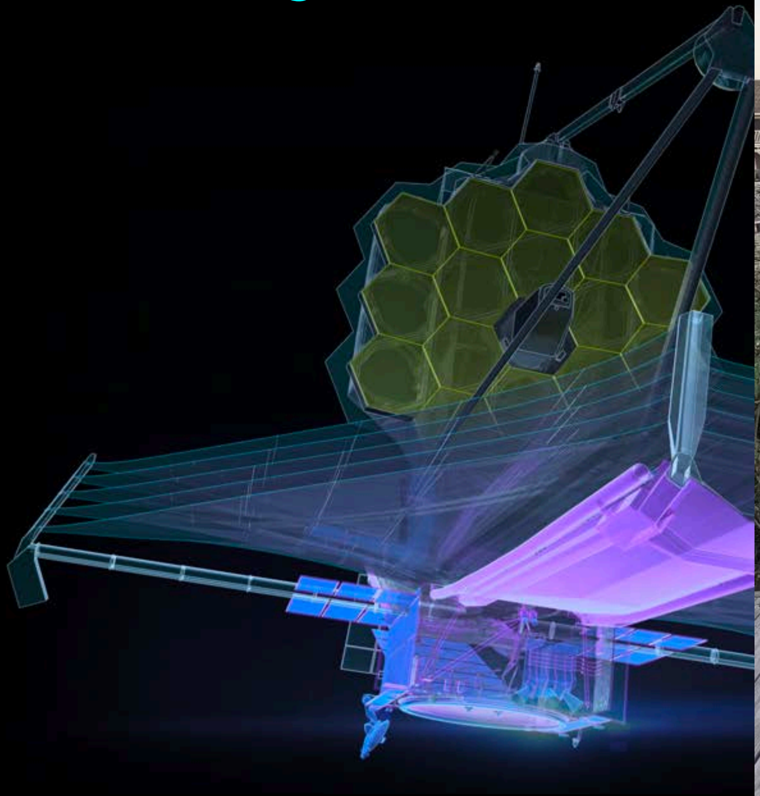

N3AS Lecture 2

JWST fame has spread far and wide…
posted Salem MA during Halloween 2022
sunshield deployment challenge though

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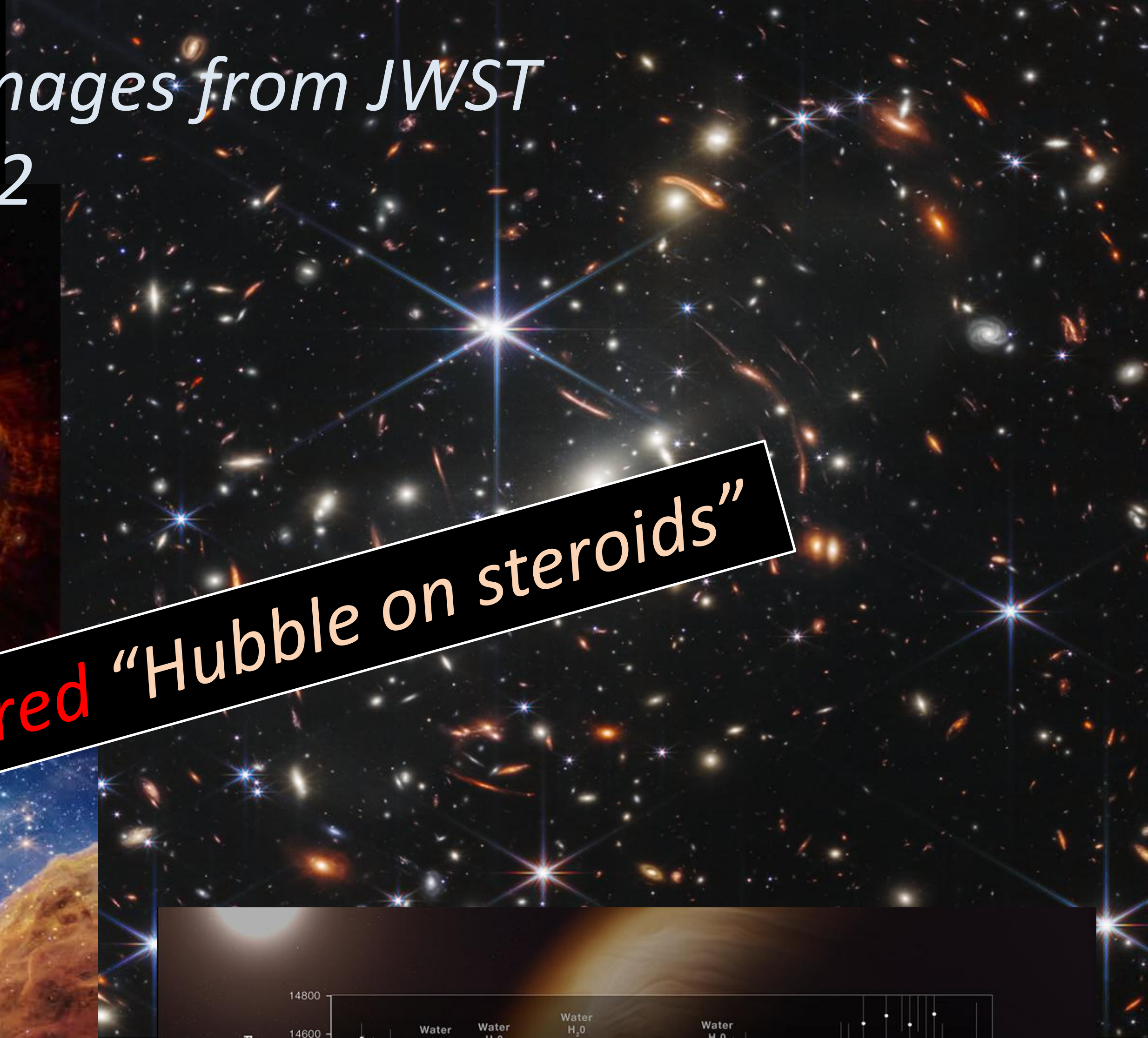
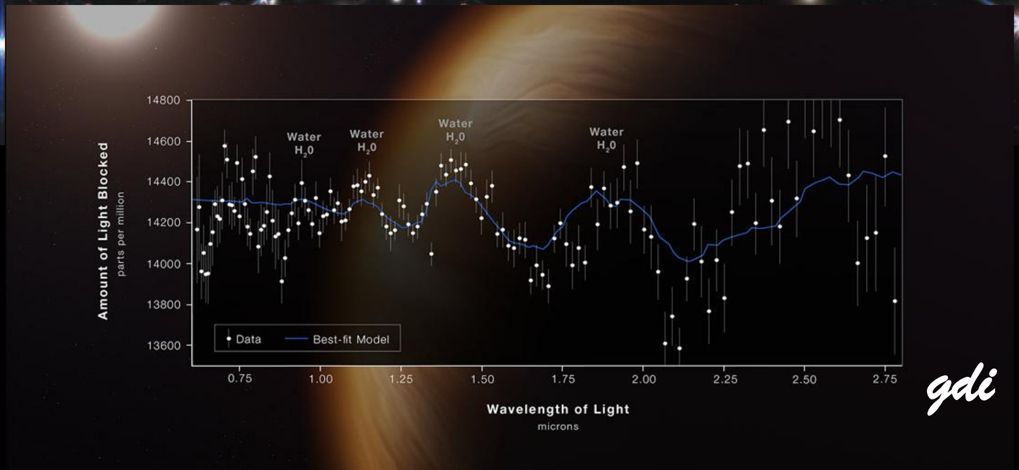
the first amazing science images from JWST

July 12 2022



JWST (“Webb”) is our infrared “Hubble on steroids”



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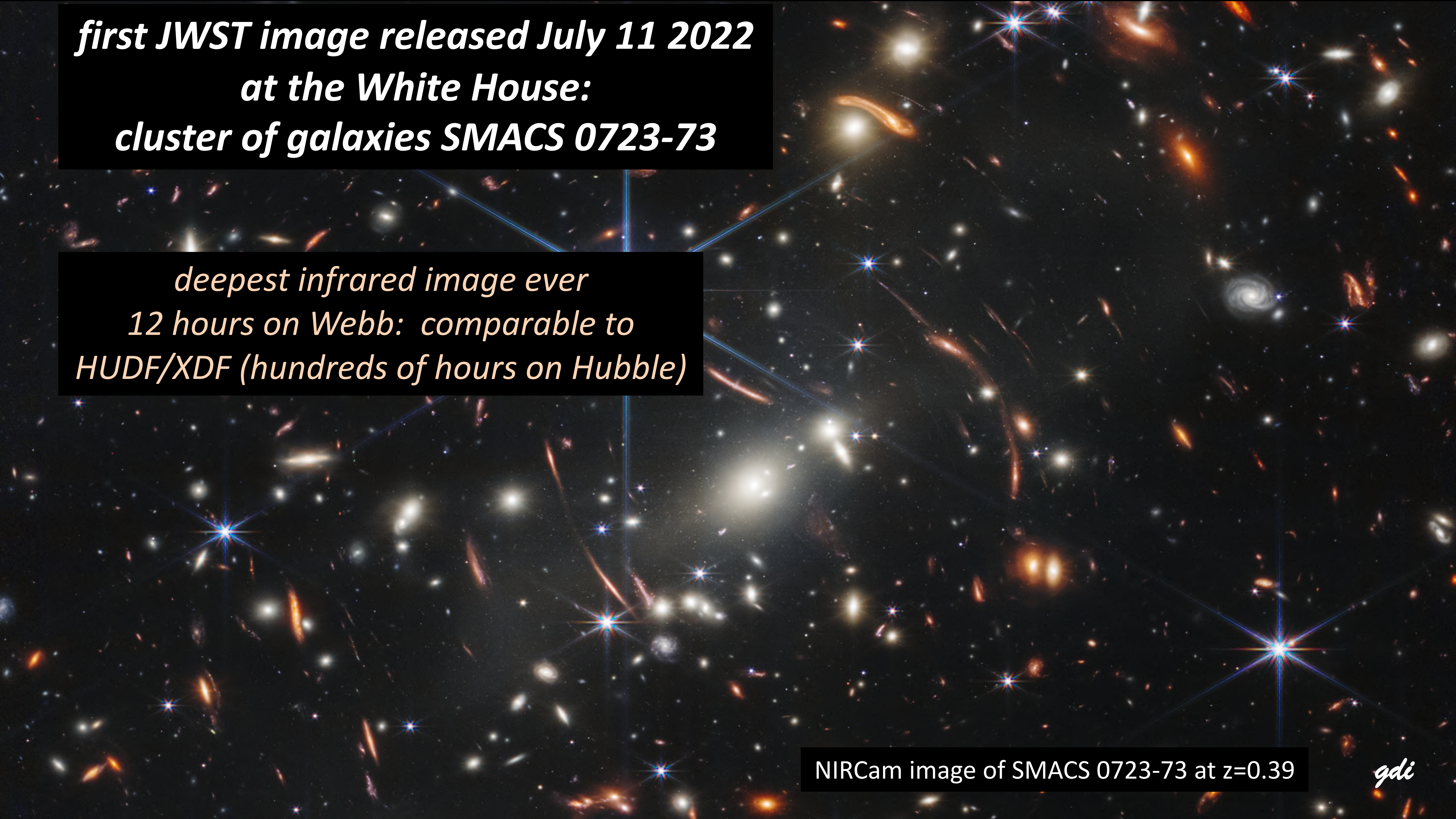
first JWST image released July 11 2022
at the White House:
cluster of galaxies SMACS 0723-73

deepest infrared image ever
12 hours on Webb: comparable to
HUDF/XDF (hundreds of hours on Hubble)



NIRCam image of SMACS 0723-73 at z=0.39

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goal of NGST was to see "first light"

find "first stars and galaxies"

explore the first 500 Myr (at redshift $z>10$)

JWST has taken key steps towards that "first light" goal

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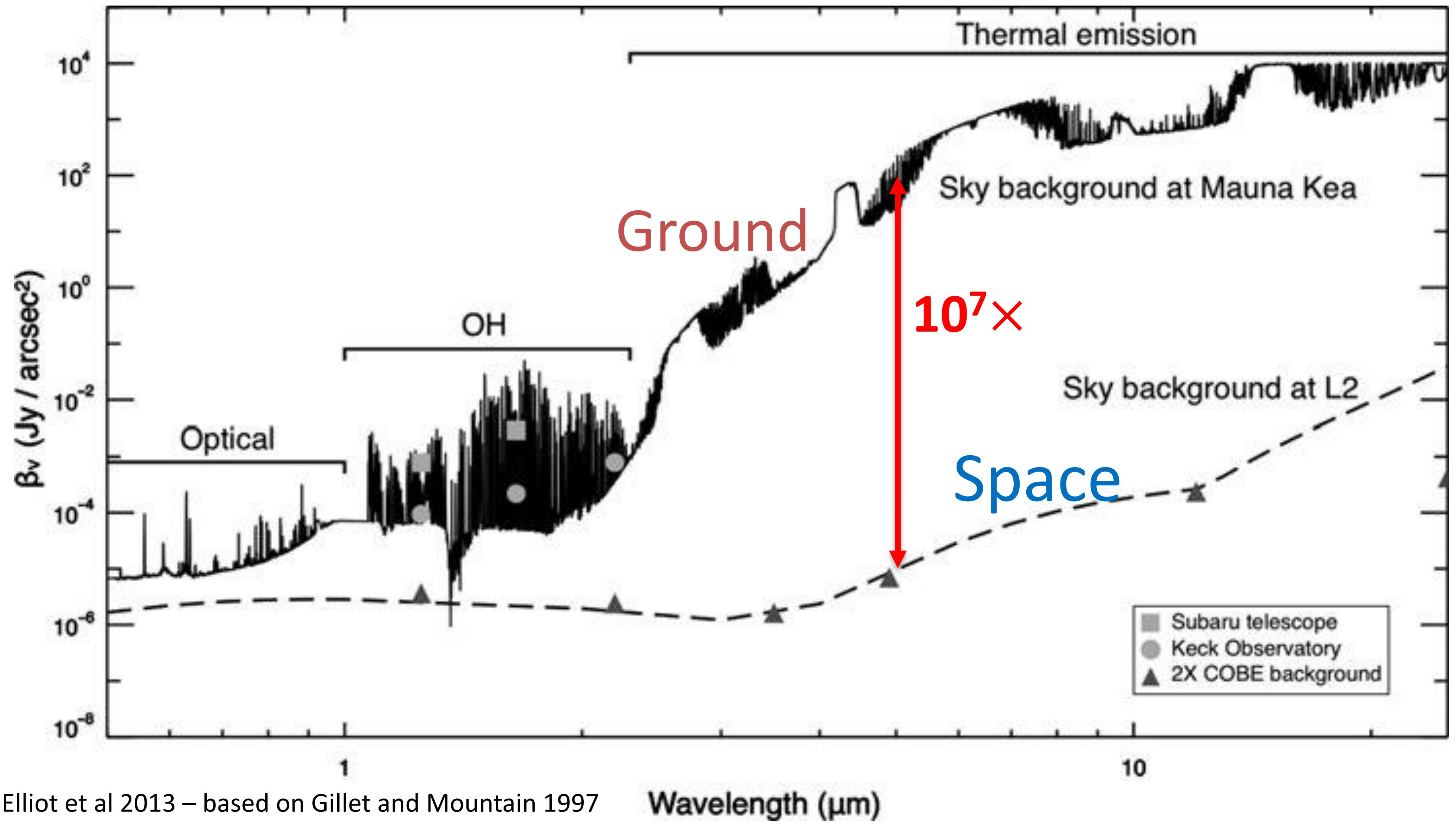
JWST is exploiting its incredible infrared sensitivity compared to the ground to reveal a wealth of galaxies, and diagnostics, in the first Gyr



Elliot et al 2013 – based on Gillet and Mountain 1997

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how we find and measure redshifts when we just have images

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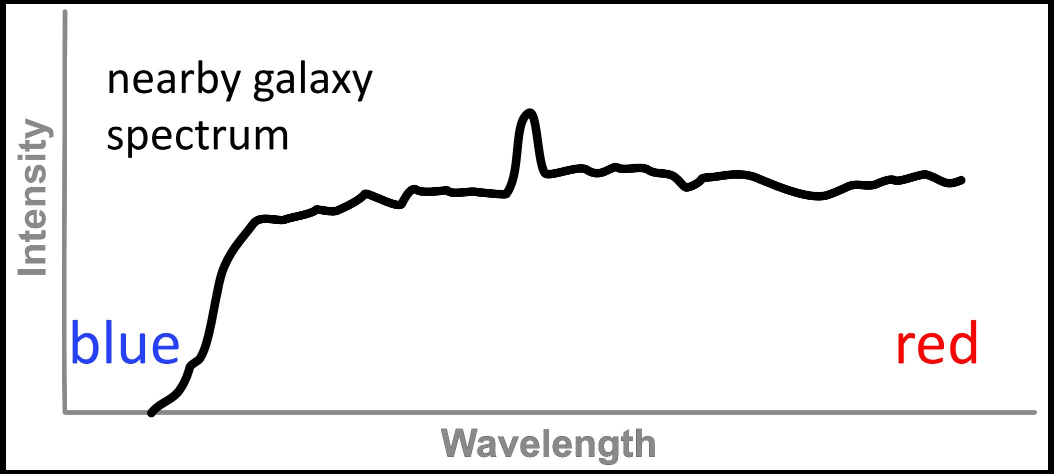


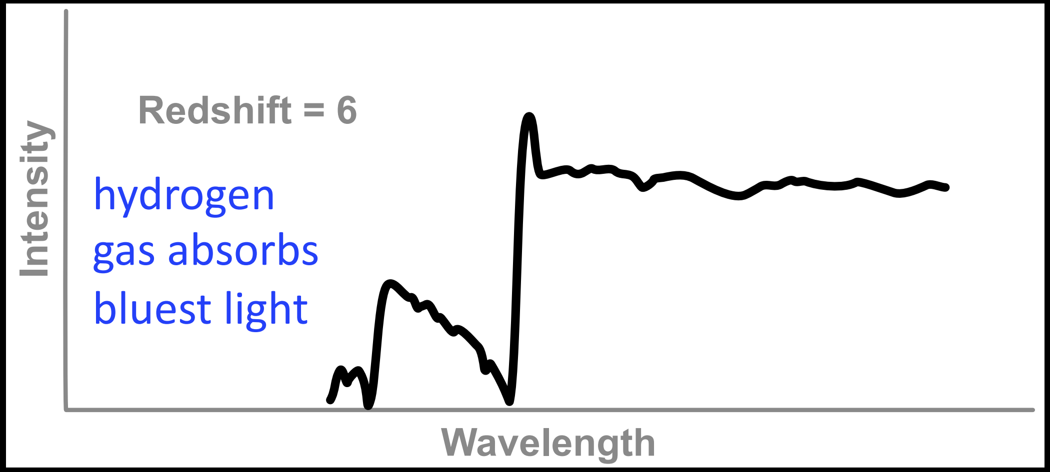
redshifts
("z")

hydrogen gas in the universe absorbs the bluest light (ultraviolet) light from galaxies

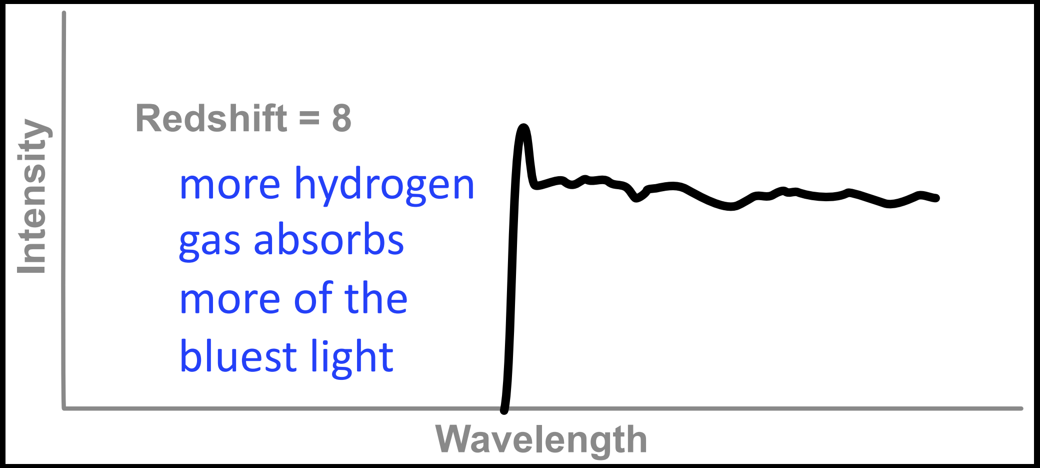
☞ find the break and it tells how fast the galaxy is moving

☞ change in wavelength gives redshift

z=6 spectrum shifted to red



z=8 spectrum shifted even more to red



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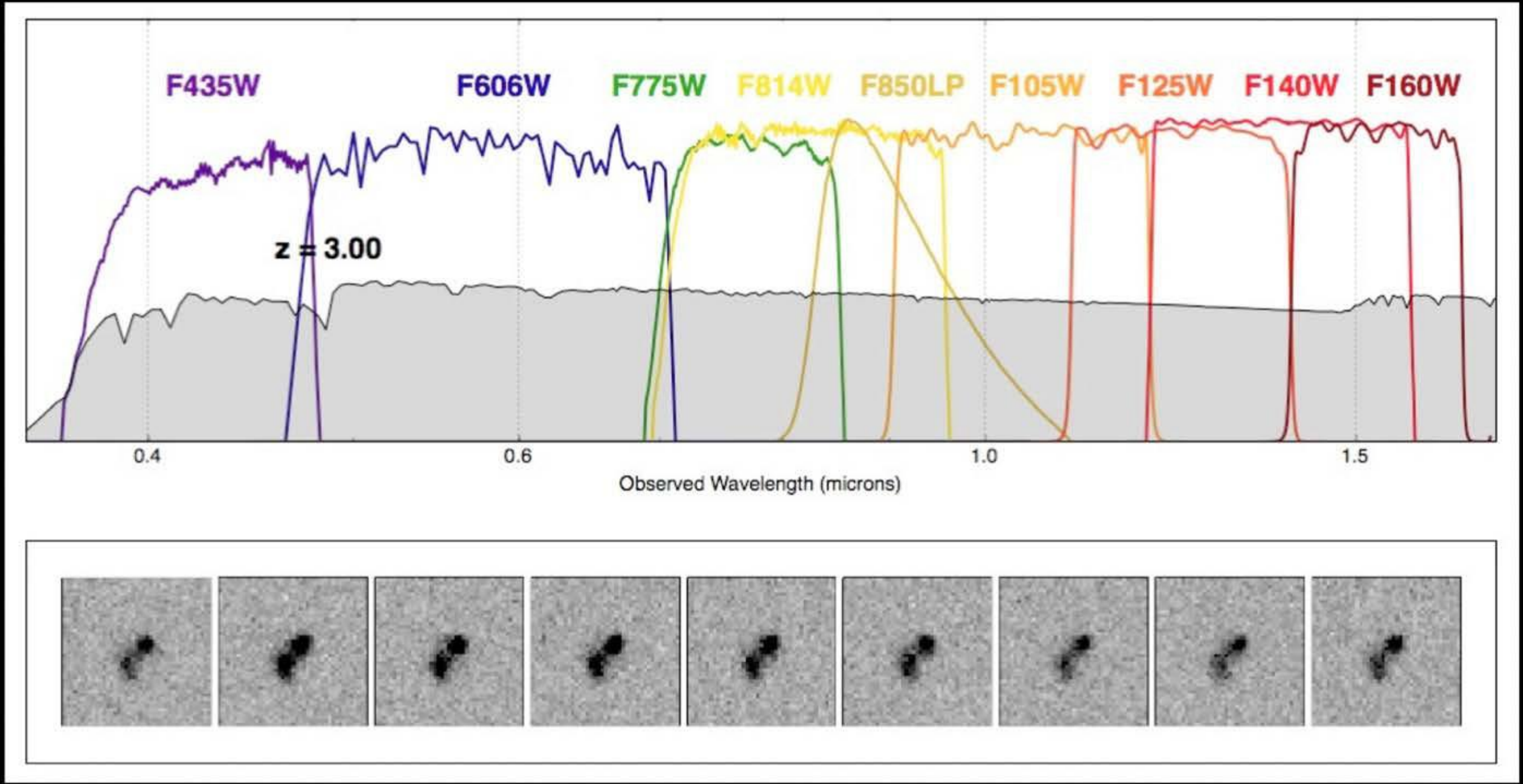
photometric redshifts (photo-z)
Hubble filter example – principle same for JWST but redder filters



found using photometric redshifts (photo-z) from wide-band filters
well-established technique and reliable (but never 100%) when properly used

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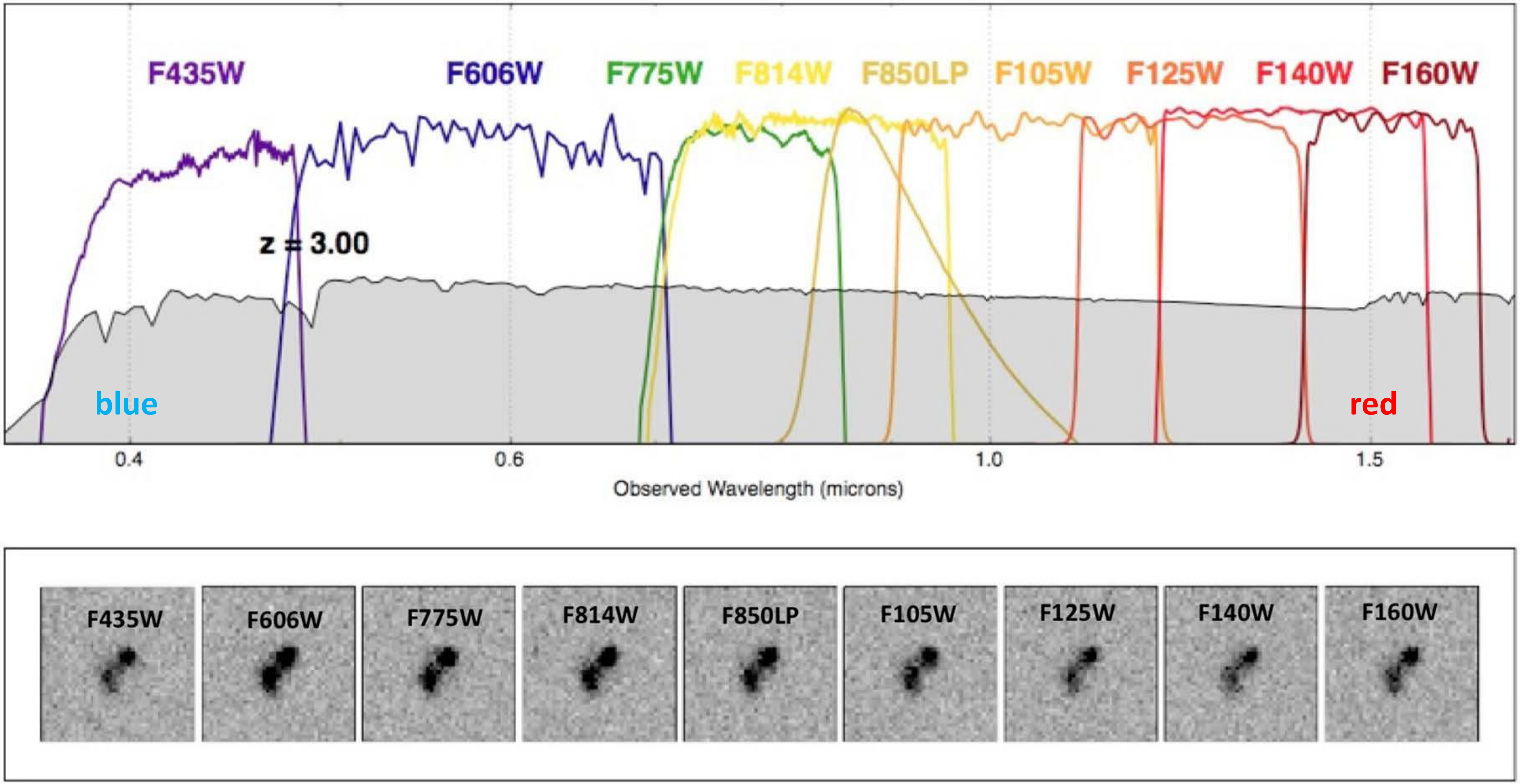
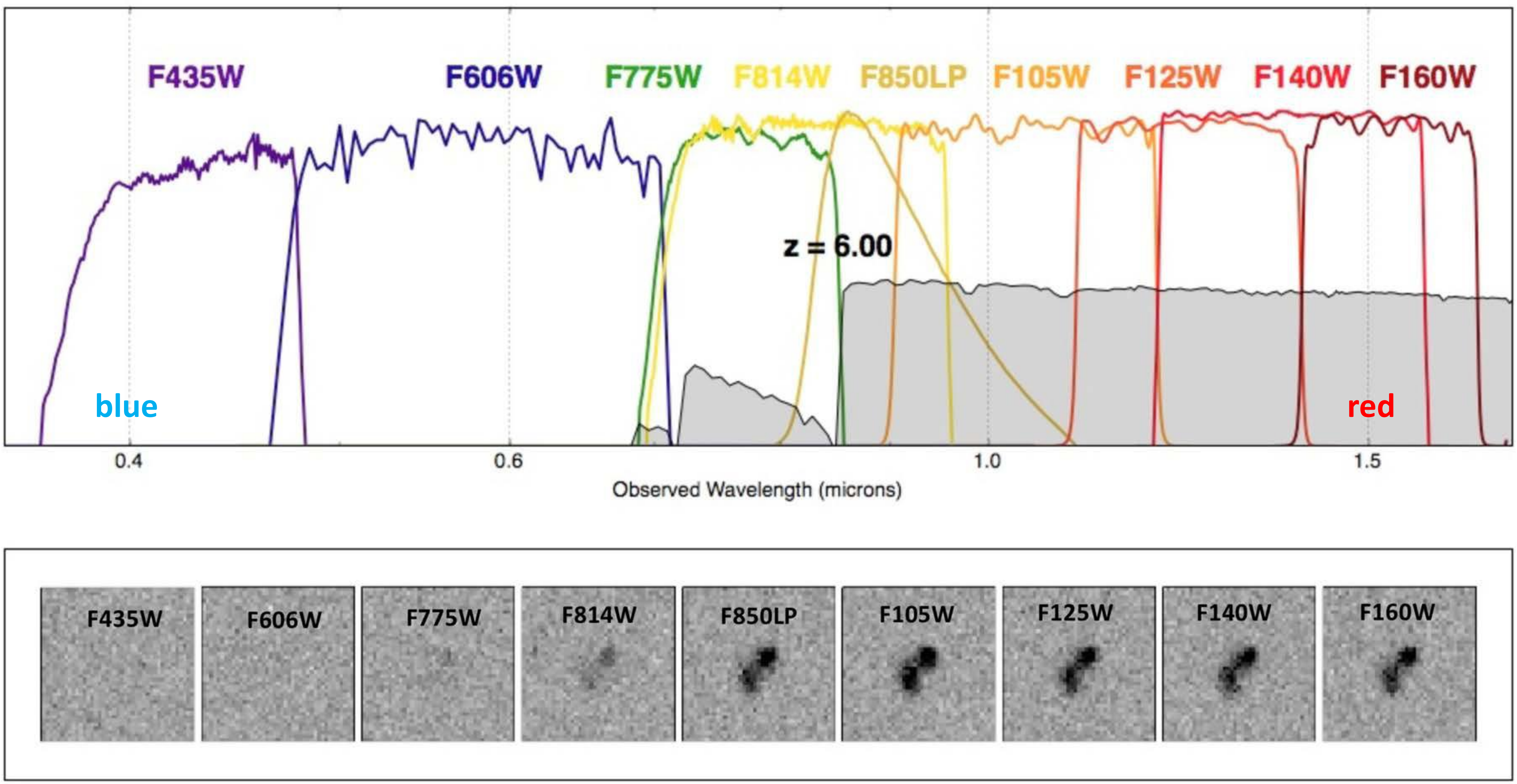


optical ACS

near-IR WFC3/IR

xdf.ucolick.org/



optical ACS

near-IR WFC3/IR

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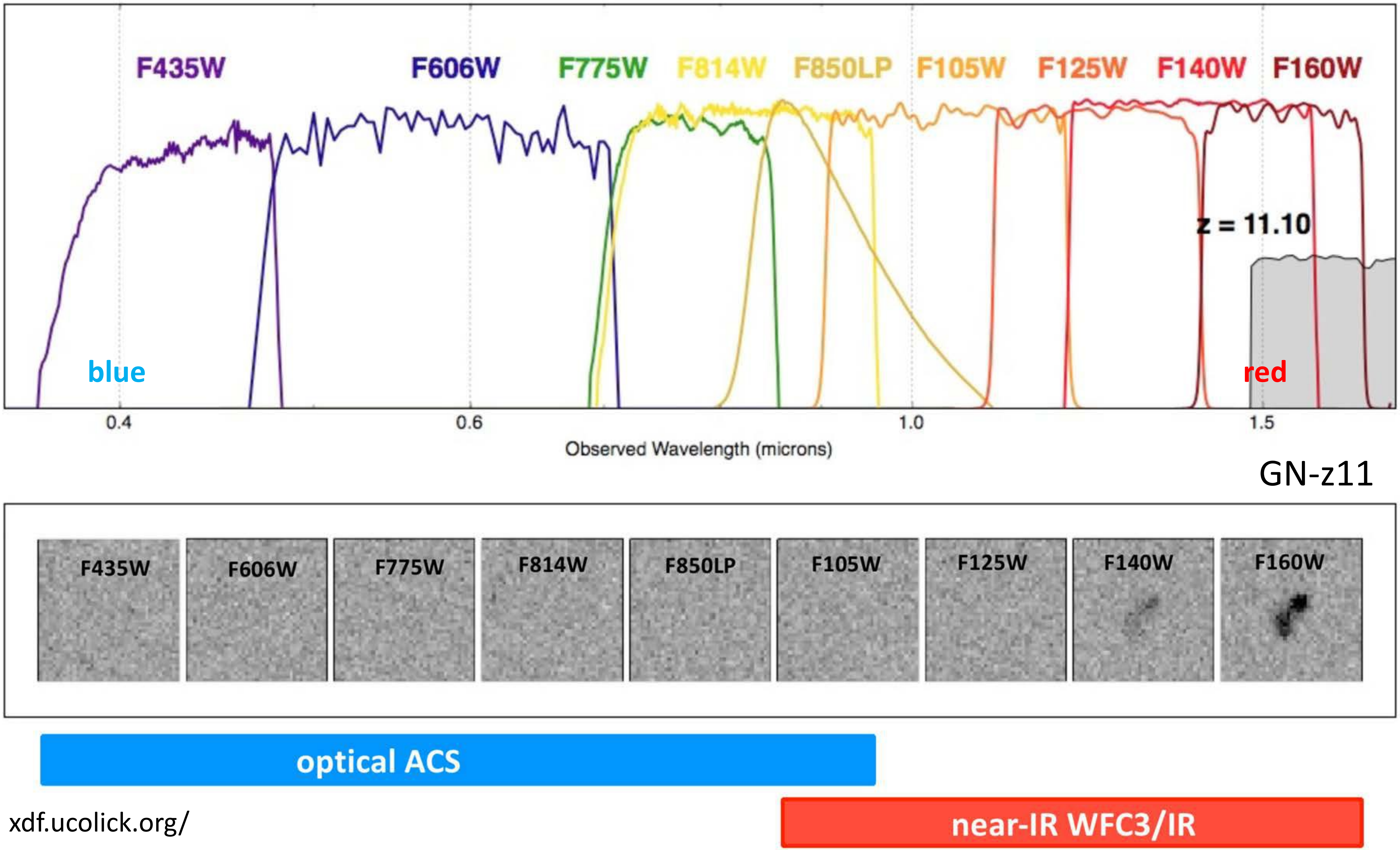
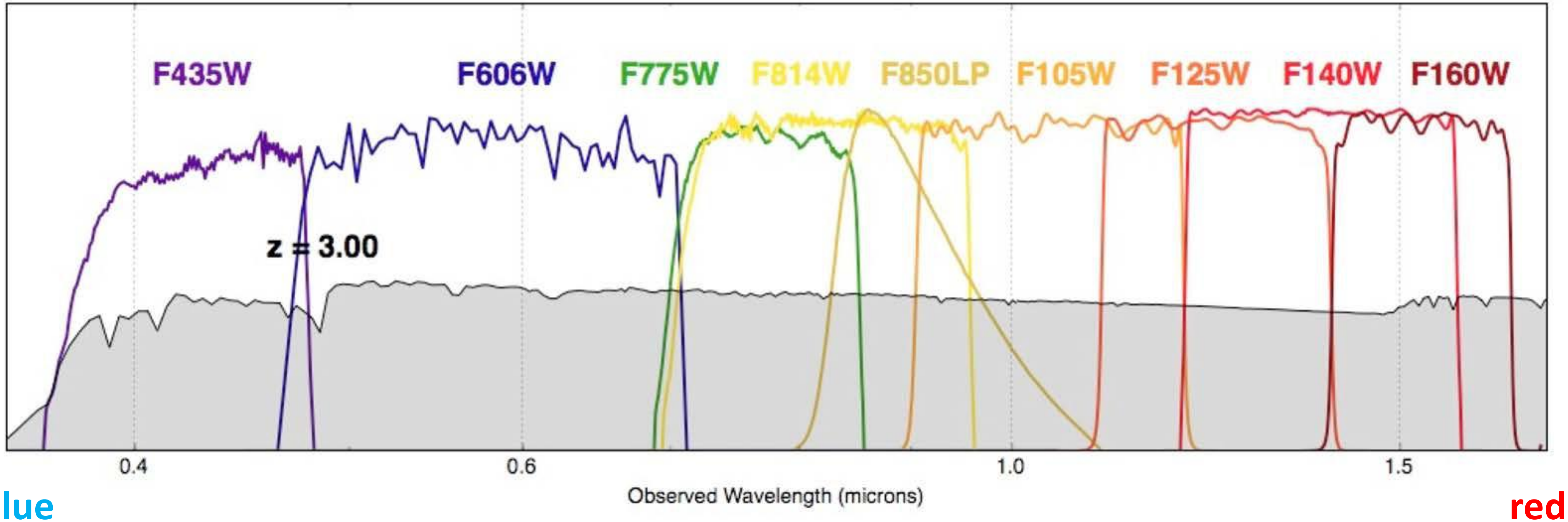


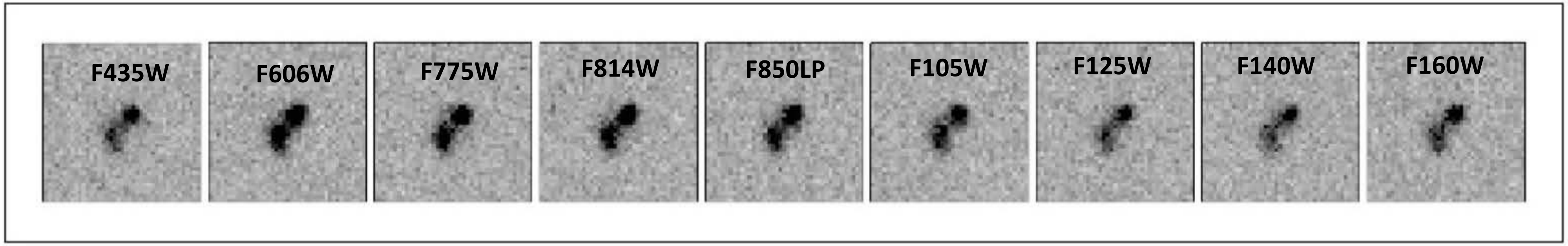
xdf.ucolick.org/

ACS+WFC3/IR: efficient redshifts to z~11



blue

red



optical ACS

near-IR WFC3/IR

xdf.ucolick.org/

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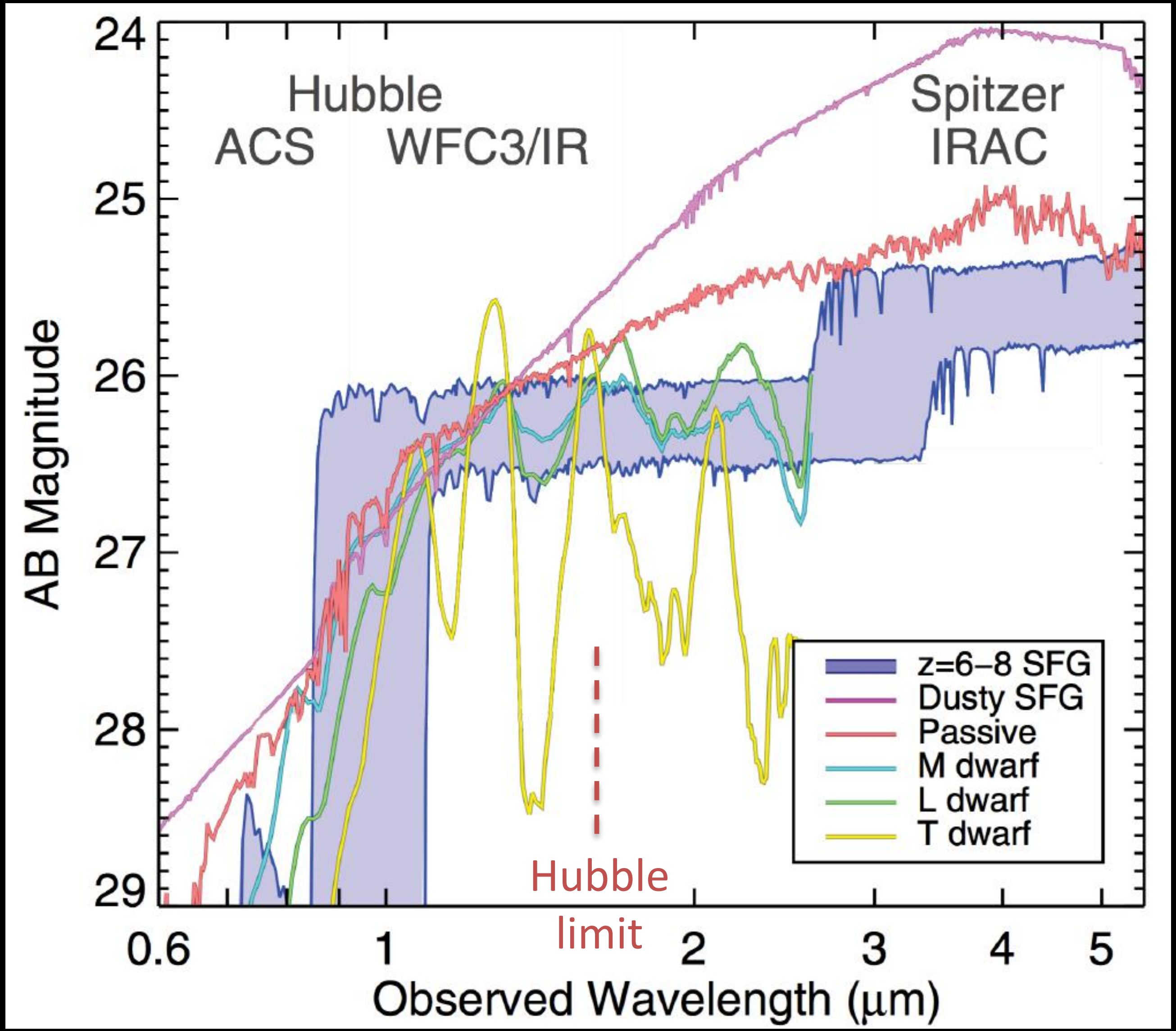
photometric redshifts

enable large, statistically-robust samples

Lyman break galaxies – LBGs (“dropouts”)

LBGs have a distinctly different shape for their spectral energy distribution (SED)

☞ reliable photometric redshift selection



← JWST covers this full range of wavelengths →

adapted from Finkelstein 2016

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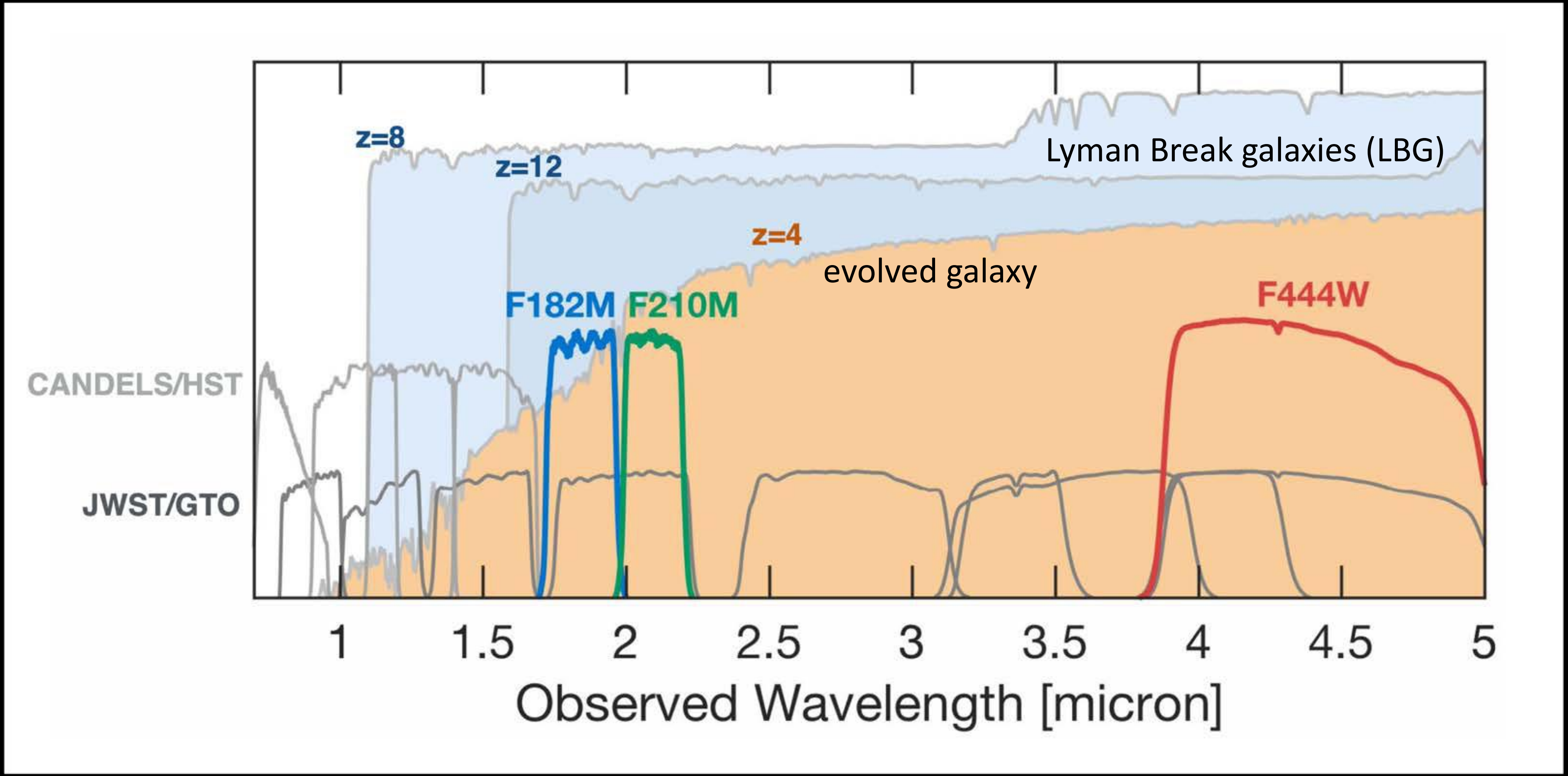
example of JWST NIRCam bands and redshifts FRESCO (see later) in bold color



spectral energy distributions – SED

from Oesch et al 2023

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challenge getting large samples

requires a lot of images in a lot of filters

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XDF (eXtreme Deep Field)

deepest ever Hubble image

nearly 2 million seconds of integration

nearly 3000 HST images

from 800 orbits of Hubble

for a 23 day total exposure

BJ2021 – before JWST ⟹

A decade of imaging on the Hubble Ultra Deep Field
The deepest image of the Universe

xdf.ucolick.org

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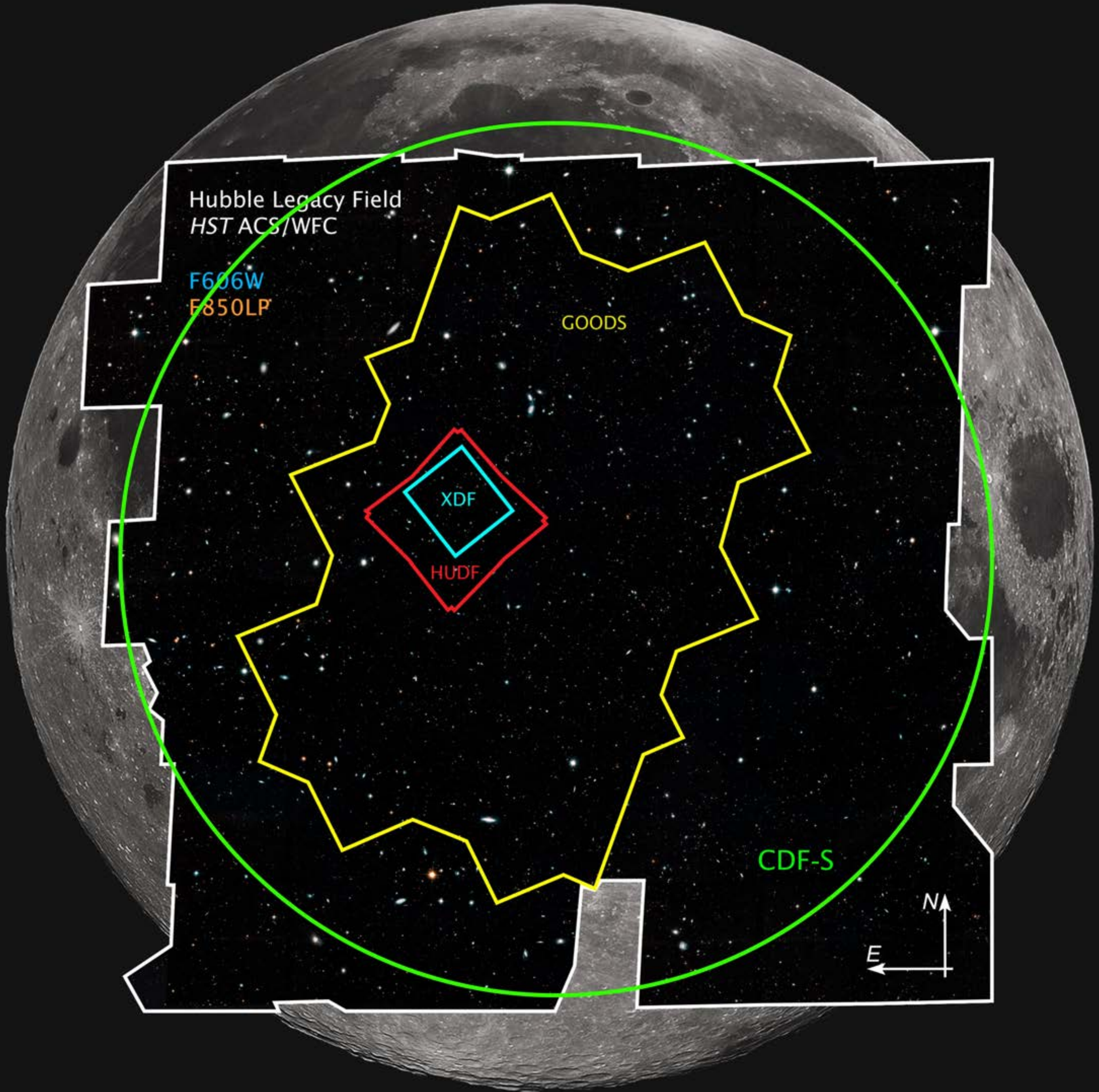
size comparison:

the Hubble Legacy Field with the Chandra Deep Field-South and a nearby astronomical object now known as Artemis



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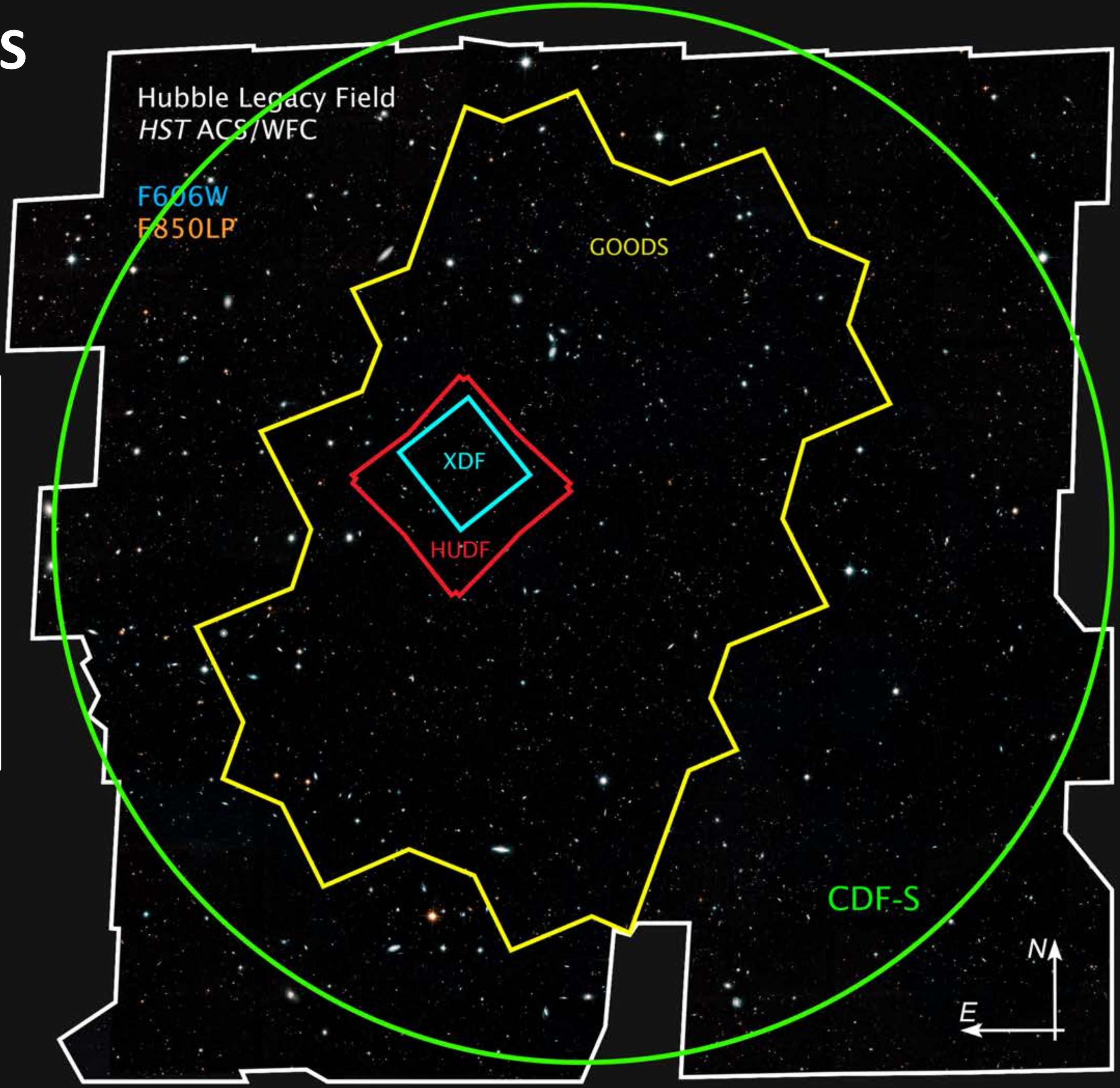
Hubble Legacy Field GOODS-S 2019

the three Great Observatories – Chandra, Hubble and Spitzer – have ***each*** contributed about 6-7 million seconds (about 75-80 days) of exposure on this field over the last 15-20 years



NASA, ESA, GDI, Magee + HLF Team 2019

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These deep/wide images (like the HLFs and the XDF) are a "history book"

the story of how galaxies formed and grew through nearly all of time

from "cosmic sunrise" a few hundred million years after the Big Bang through more than 13 billion years to recent times

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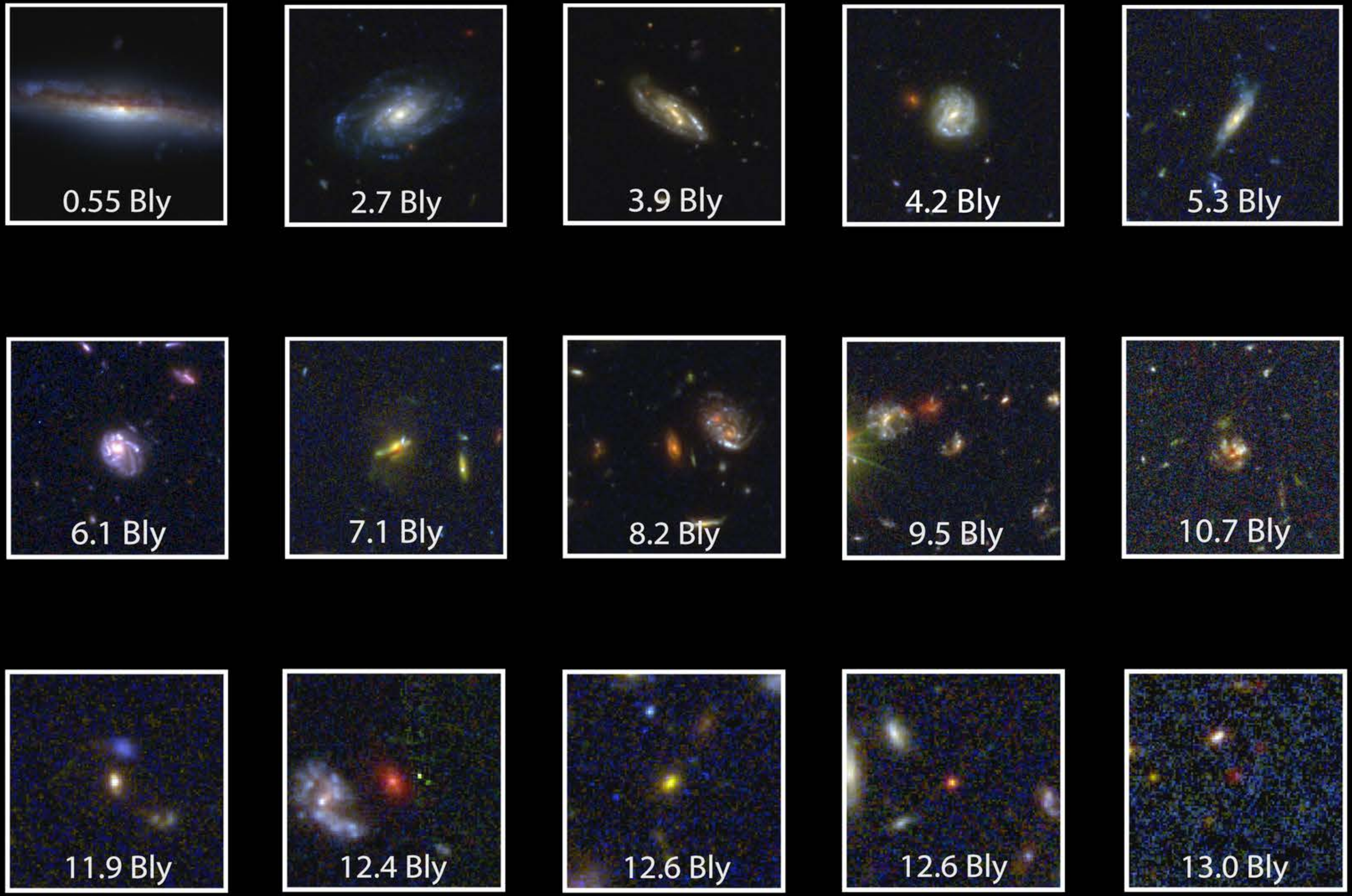
Hubble Legacy Field: Galaxies Across Time



Bly = billion light-years

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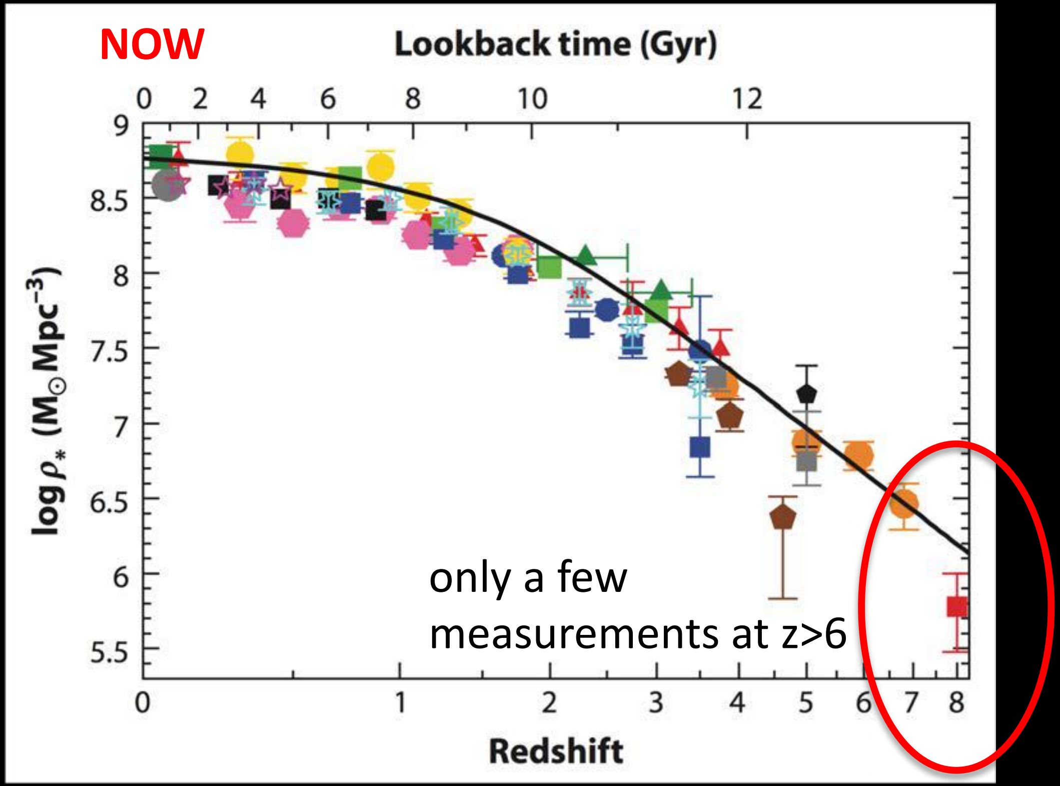
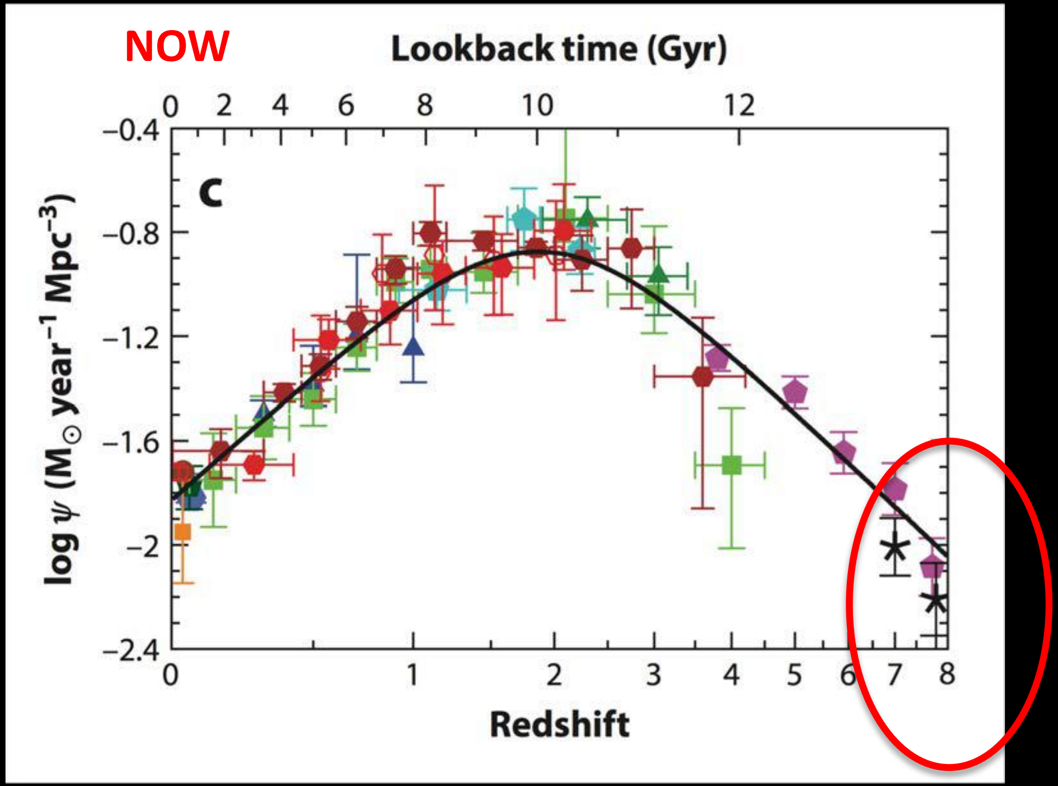
the global stellar mass and cosmic star formation rate (SFR) density evolution



First Gyr

evolution of the global stellar mass density over 13 billion years



First Gyr

evolution of the cosmic star formation rate density over 13 billion years

Madau & Dickinson 2014

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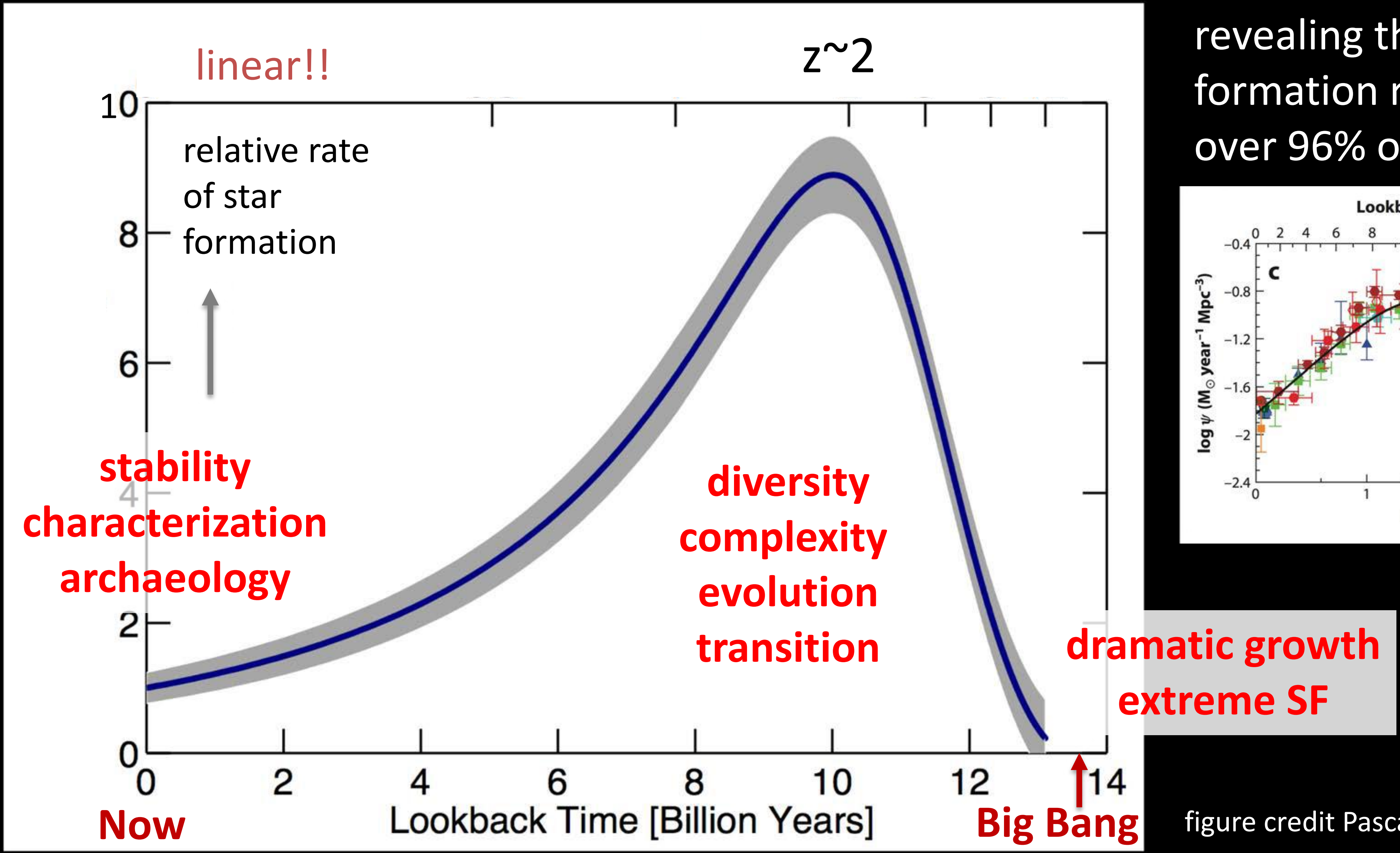
cosmic star formation over all time



revealing the star formation rate density over 96% of time

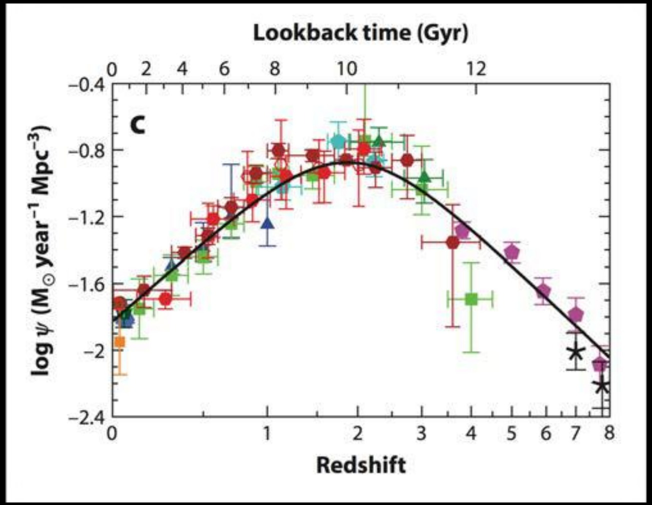


figure credit Pascal Oesch

the first Gyr – the time when galaxies were born and began to grow

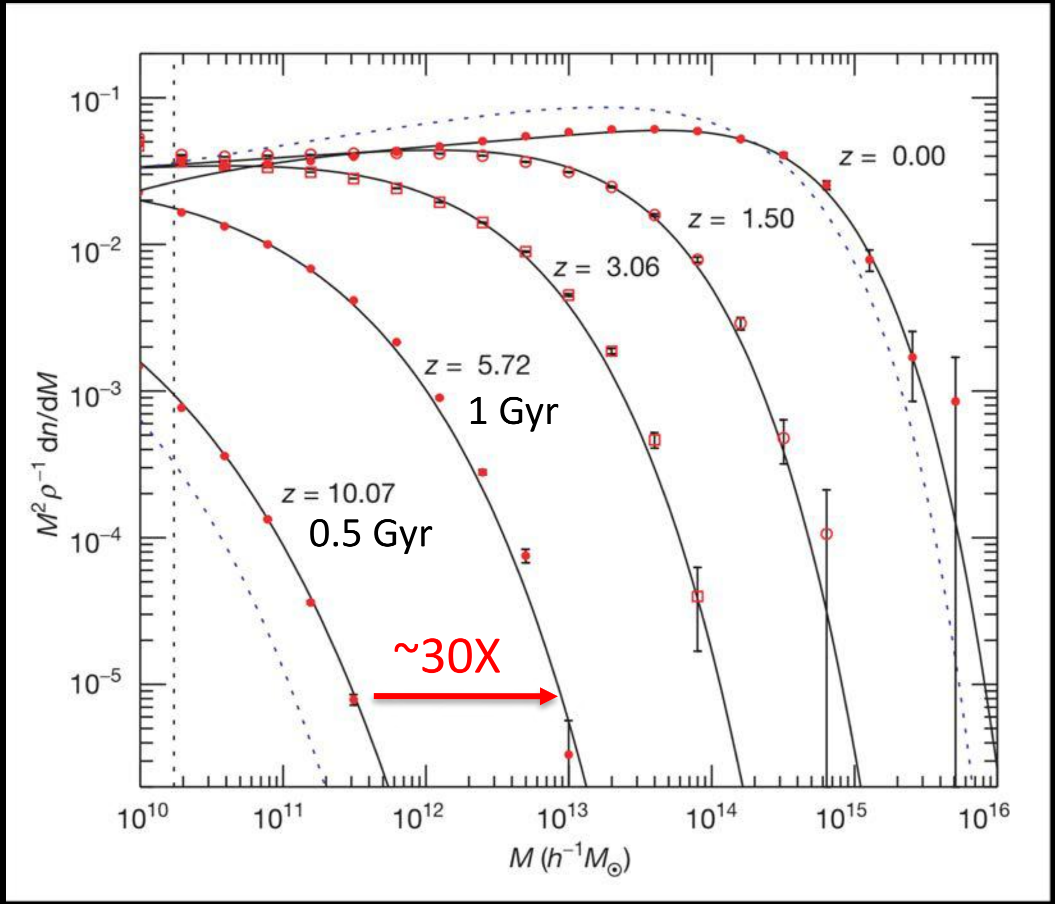
the first Gyr → when halos of L* galaxies first formed...
when significant metals first formed...
when the universe was reionized...

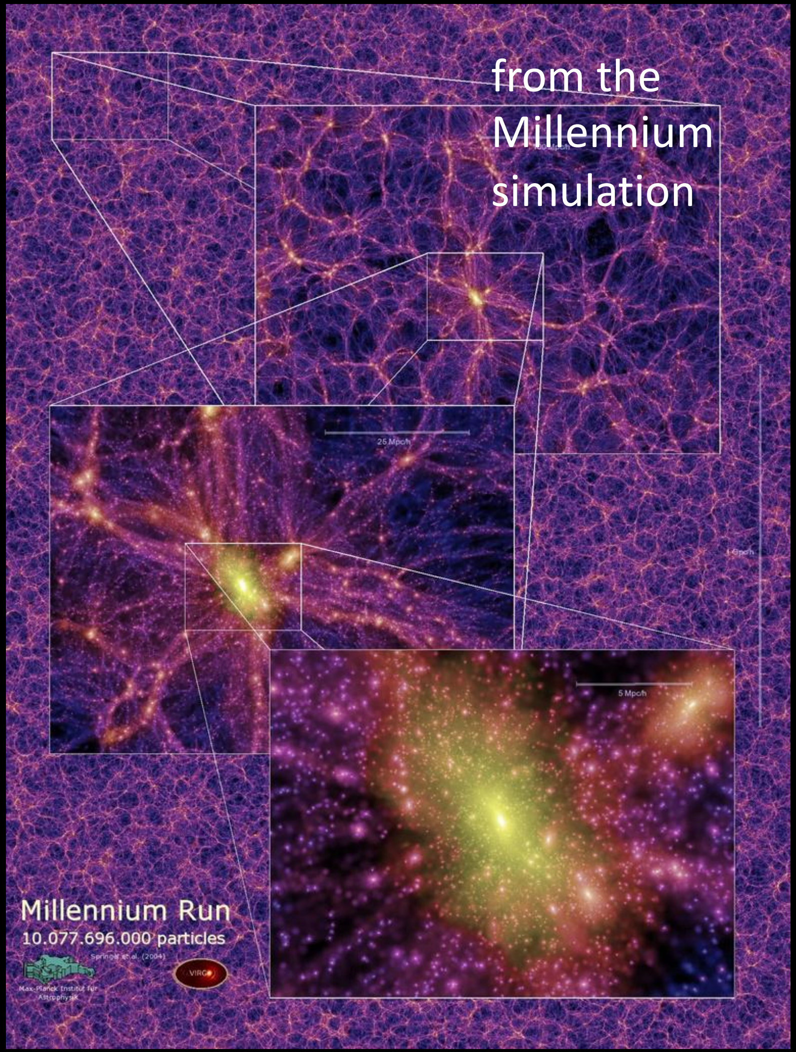
rapid growth of galaxy-scale halos

z~10 to z~6

~500 Myr to ~1 Gyr

the reionization epoch





Springel+2005

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searching for the first galaxies

insights from Planck!

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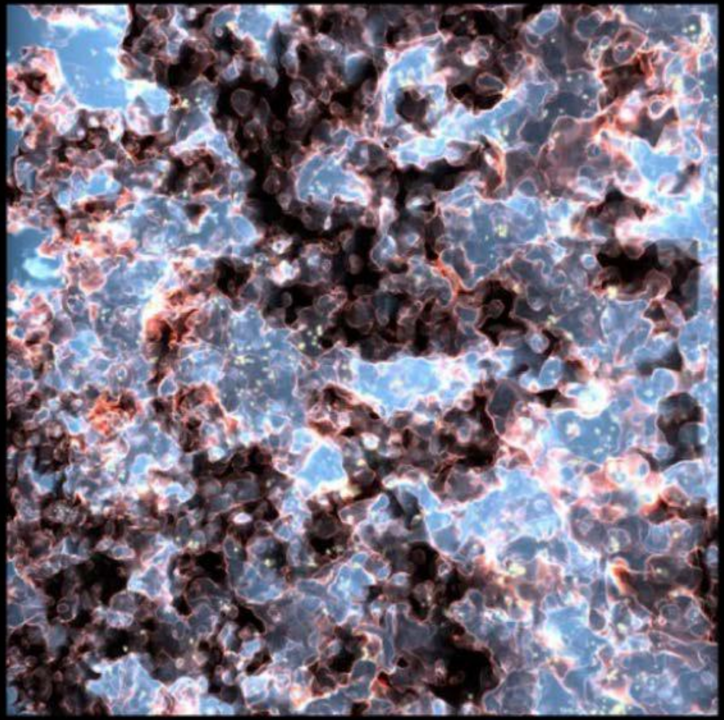
reionization epoch – Planck 2016/2018 results



reionization simulation: Alvarez et al. 2009

remarkable mission
that also set some
interesting and
valuable constraints
on reionization

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Planck 2016/2018

constraints on the reionization history

…Thomson optical depth: $\tau = 0.054 \pm 0.007$

…mid-point redshift at which reionization occurs is found to lie at $z = 7.7 \pm 0.7$

…upper limit to the width of the reionization period of $\Delta z < 2.8$.

…the Universe is ionized at much less than the 10% level at redshifts above $z \simeq 10$…
($<1\%$ above $z \simeq 15$)

…an early onset of reionization is strongly disfavored by *Planck* data

Planck Collaboration XLVII + 2016
Planck Results VI Cosmological Parameters + 2018
Planck Results I Overview and Legacy + 2018

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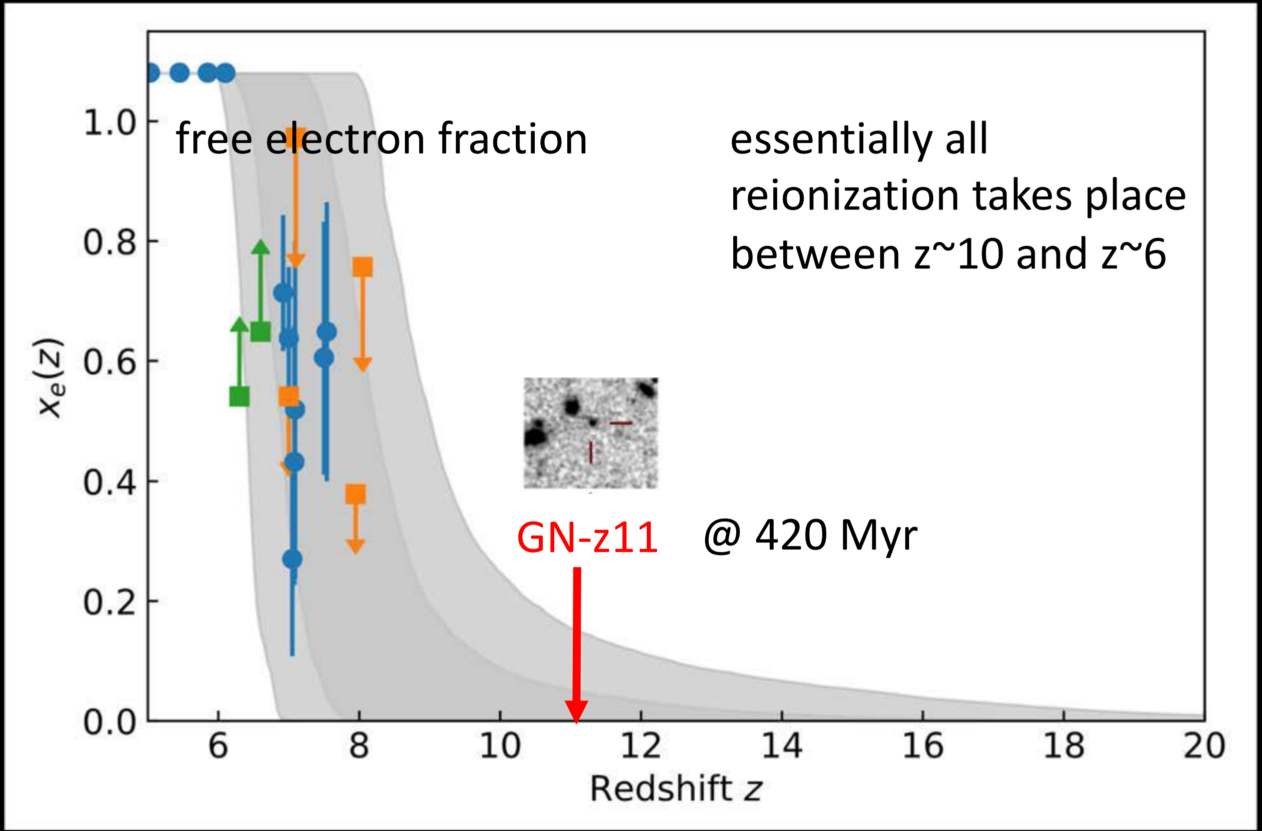
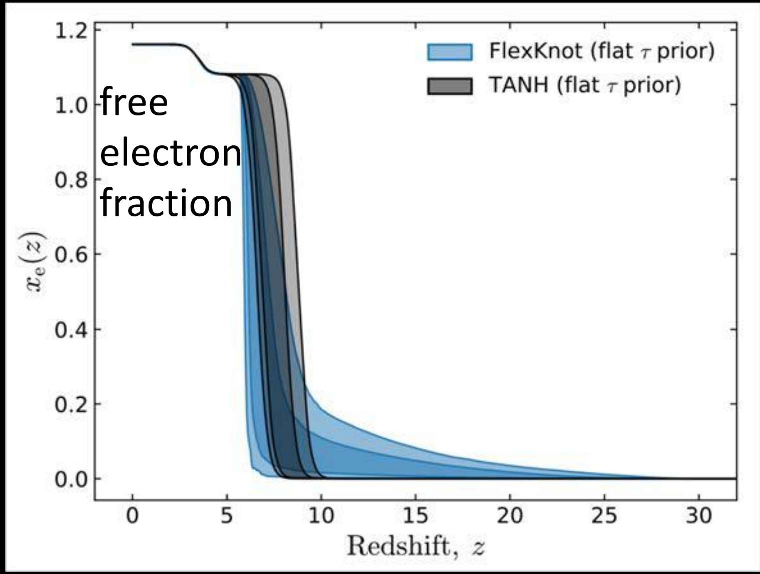
reionization constraints from Planck 2018



Plank Collaboration Results I + 2018



Planck Collaboration VI+2018

"….*Planck* data prefer a late and fast transition from a neutral to an ionized universe…."

"….non-standard early galaxies or significantly evolving escape and clumping factors are no longer required"

"….nor do the *Planck* results require ***any*** emission from high-redshift (z = 10–15) galaxies"

Hubble's GN-z11 (2016) is a pathfinder into the epoch of the earliest galaxies

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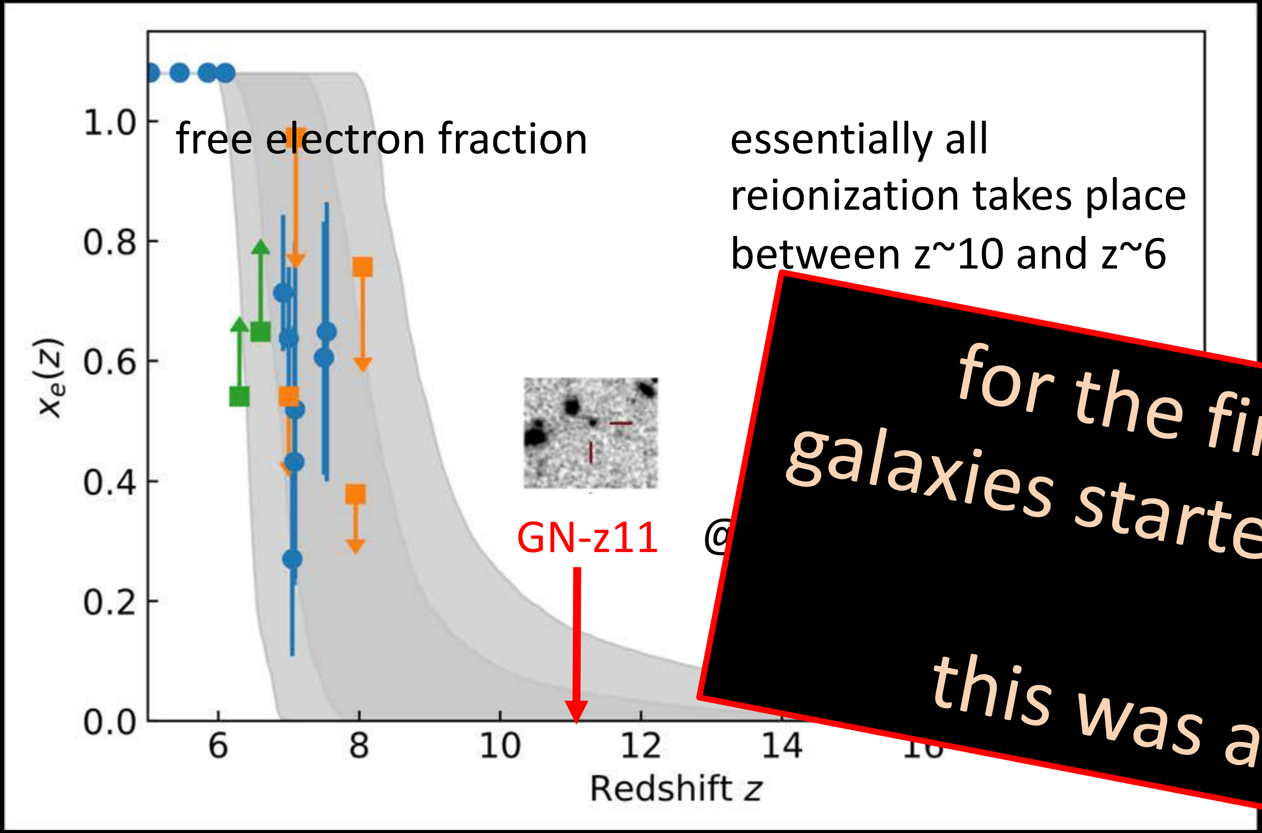
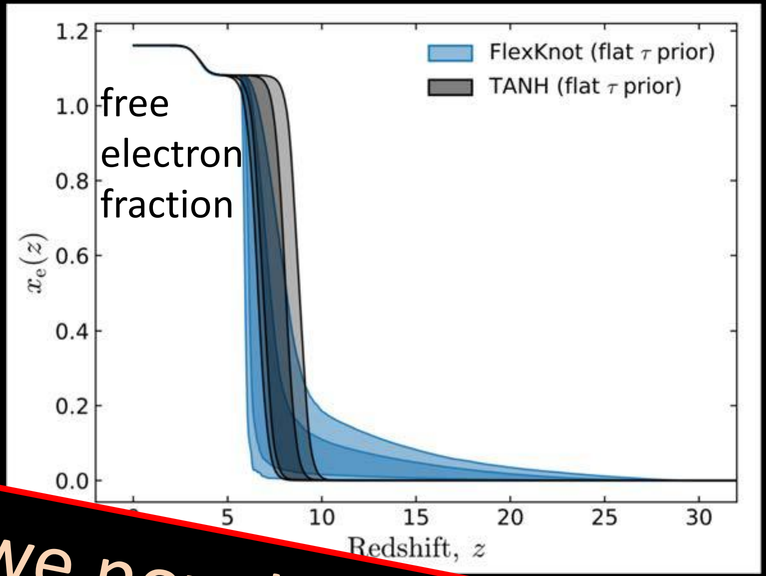
reionization constraints from Planck 2018



Plank Collaboration Results I + 2018



for the first time we now know when galaxies started to really reionize the universe

this was around z~10 or ~500 Myr

m a

"....non-standard early gala... volving escape and clumping factors are no longer ...red"

"....nor do the *Planck* results require ***any*** emission from high-redshift (z = 10–15) galaxies"

Hubble's GN-z11 (2016) is a pathfinder into the epoch of the earliest galaxies

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reionization history compared with observational astrophysical constraints

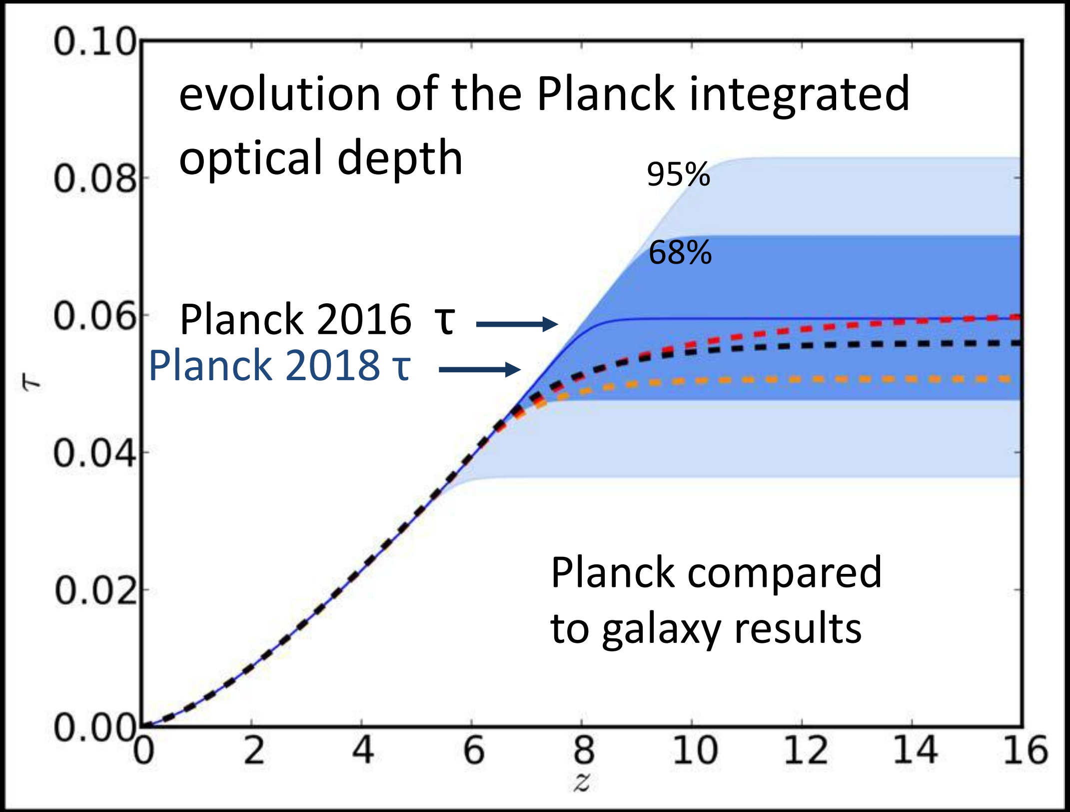

figure from Planck Collaboration XLVII + 2016

Bouwens+2015
Robertson+2015
Ishigaki+2015

striking consistency with Hubble results indicate that galaxies were responsible for reionization

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reionization history compared with observational astrophysical constraints

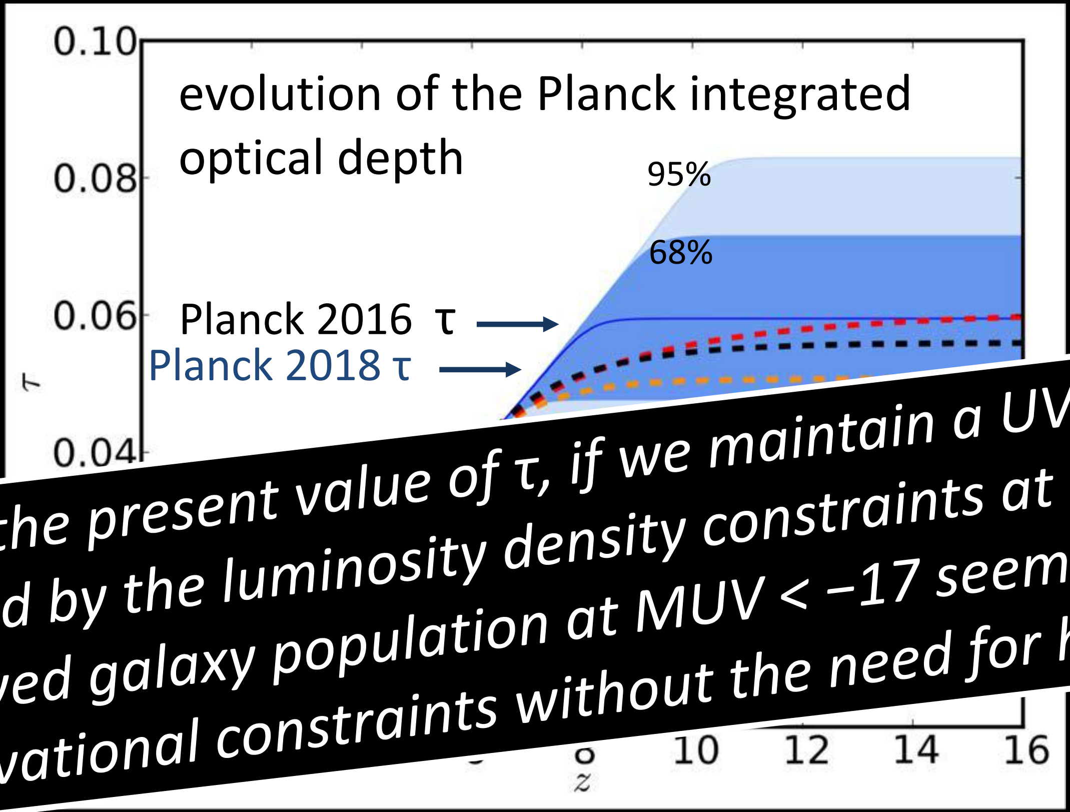

figure from Planck Collaboration XLVII + 2016

Bouwens+2015

Robertson+201

"With the present value of τ, if we maintain a UV-luminosity density at the maximum level allowed by the luminosity density constraints at redshifts z < 9, then the currently observed galaxy population at MUV < −17 seems to be sufficient to comply with all the observational constraints without the need for high-redshift (z = 10–15) galaxies."

Hubble results indicating that galaxies were responsible for reionization *what constraints do we have on the first galaxies?*

searching for the earliest galaxies

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within a week, on July 19 2022, the dramatic and extraordinary first images from JWST revealed the most distant galaxies ever seen

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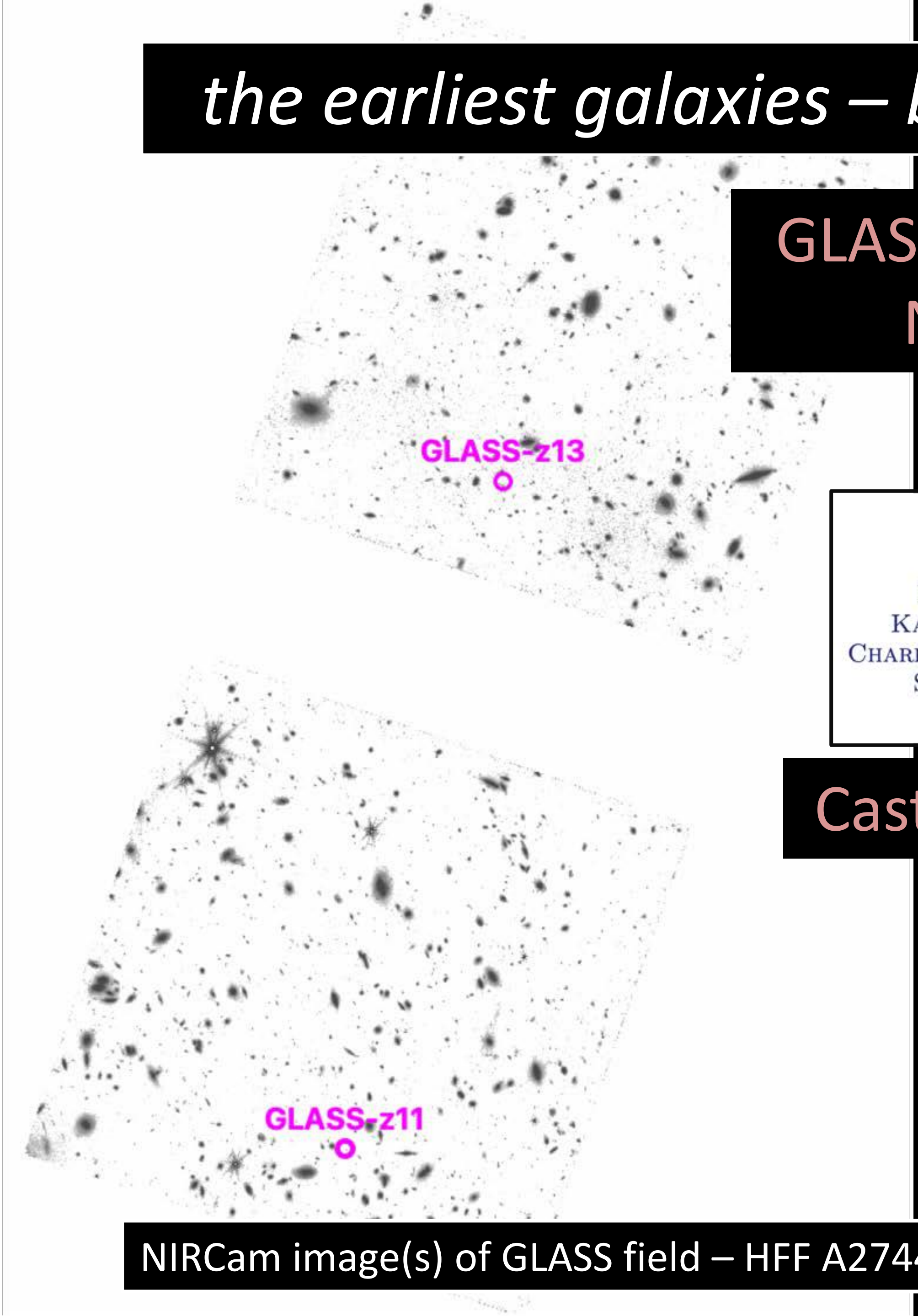
the earliest galaxies – beating Hubble's record in just 5 days!



GLASS Early Release Science data released July 14-15
Naidu, Oesch et al paper submitted July 19!

arXiv:2207.09434v1 [astro-ph.GA] 19 Jul 2022

Two Remarkably Luminous Galaxy Candidates at $z \approx 11 - 13$ Revealed by *JWST*

Rohan P. Naidu,[1] Pascal A. Oesch,[2,3] Pieter van Dokkum,[4] Erica J. Nelson,[5] Katherine A. Suess,[6,7] Katherine E. Whitaker,[8,9] Natalie Allen,[3] Rachel Bezanson,[10] Rychard Bouwens,[11] Gabriel Brammer,[3] Charlie Conroy,[1] Garth Illingworth,[12] Ivo Labbe,[13] Joel Leja,[14,15,16] Ecaterina Leonova,[17] Jorryt Matthee,[18] Sedona H. Price,[19] David J. Setton,[10] Victoria Strait,[3] Mauro Stefanon,[20,21] Sandro Tacchella,[22,23] Sune Toft,[3] John R. Weaver,[8] and Andrea Weibel[2]

Castellano et al paper also submitted same day!

arXiv:2207.09436 [astro-ph.GA]

Early results from GLASS-JWST. III: Galaxy candidates at z~9-15*

Marco Castellano,[1] Adriano Fontana,[1] Tommaso Treu,[2] Paola Santini,[1] Emiliano Merlin,[1] Nicha Leethochawalit,[3,4,5] Michele Trenti,[3,4] Uros Mestric,[6] Eros Vanzella,[6] Andrea Bonchi,[7] Davide Belfiori,[1] Mario Nonino,[8] Diego Paris,[1] Gianluca Polenta,[7] Guido Roberts-Borsani,[2] Kristan Boyett,[3,4] Antonello Calabrò,[1] K. Glazebrook,[9] Claudio Grillo,[10,11] Sara Mascia,[1] Charlotte Mason,[12,13] Amata Mercurio,[14] T. Morishita,[15] Themiya Nanayakkara,[9] Laura Pentericci,[1] Piero Rosati,[16,17] Benedetta Vulcani,[18] Xin Wang,[19] and L. Yang[20]

NIRCam image(s) of GLASS field – HFF A2744 parallel field

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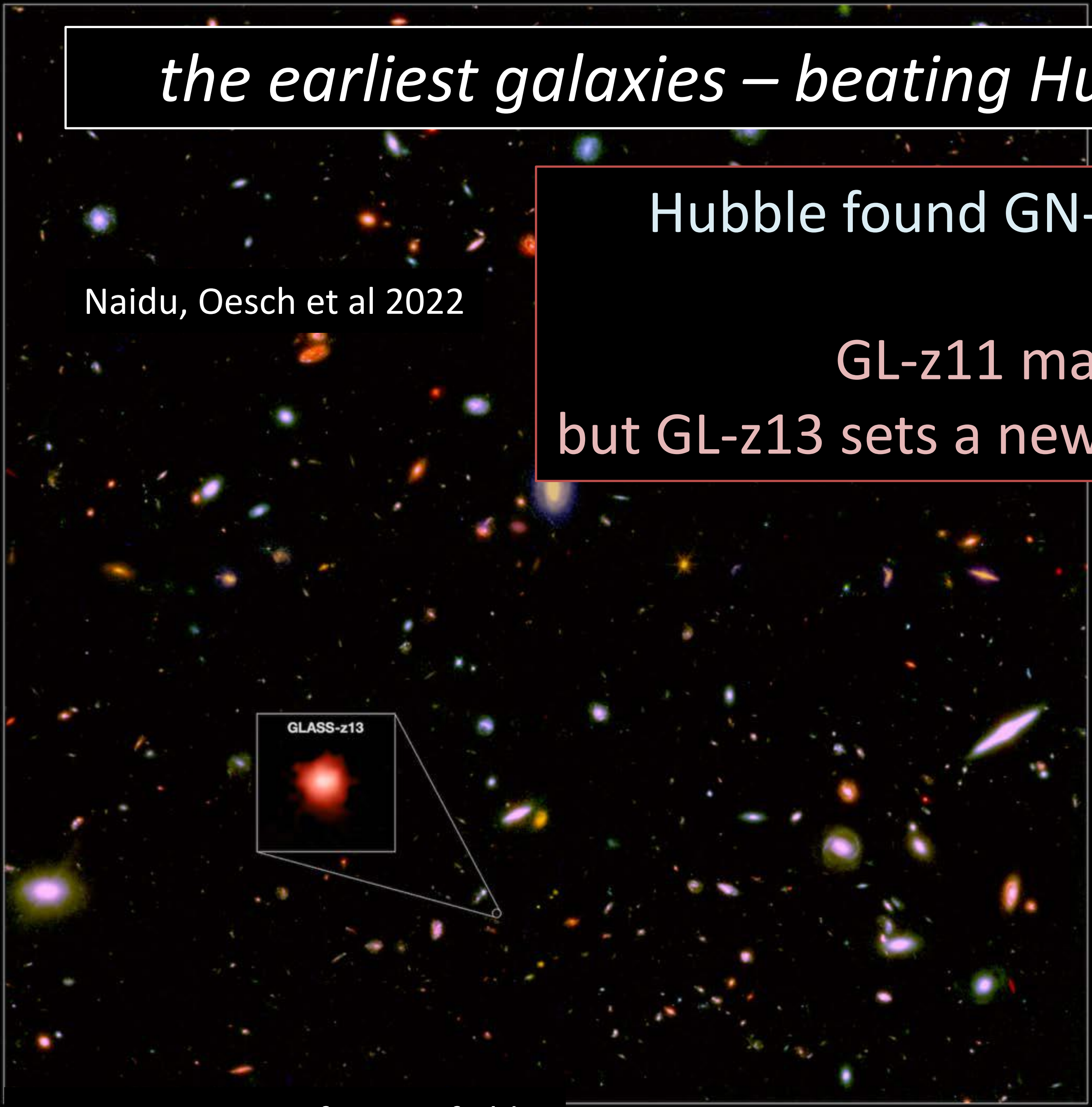
the earliest galaxies – beating Hubble's record in just 5 days!

Hubble found GN-z11 at 400 Myr after the Big Bang

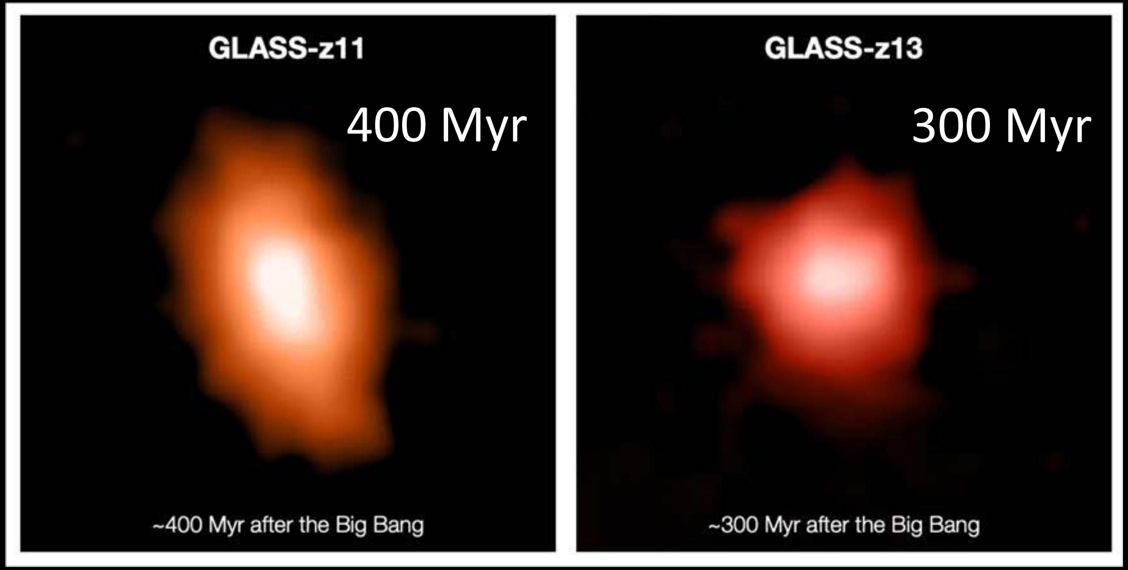
GL-z11 matches GN-z11 at ~400 Myr
but GL-z13 sets a new record at 300 Myr after the Big Bang

Naidu, Oesch et al 2022



NIRCam image of GLASS field

Credits: GLASS-z13 (Naidu et al. 2022, Castellano et al. 2022)
Raw data: T. Treu (UCLA) and GLASS-JWST. NASA/CSA/ESA/STScI
Color Images: P. Oesch & G. Brammer (University of Geneva & Cosmic Dawn Center, NBI, University of Copenhagen)



looking back through 97% of all time
to 13.4-13.5 billion years!

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within weeks reports of large number of bright (massive?) early galaxies

some photo-z examples:

z~17 (230 Myr): Donnan et al; Naidu et al

z~20 (180 Myr): Yan et al

z~16 (250Myr): Atek et al;

z~14 (300 Myr): Finkelstein et al

& massive "old" galaxies at z~8-10 (~550 Myr) that formed much earlier: Labbe et al

very confusing! too bright/too massive! too many! what was going on?

did "bright" really mean "massive"? issues with adequate baryon reservoirs? rate of buildup? cosmology was wrong?

calibration issues? wrong redshifts – photo-z problems?

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excitement about "early, bright, massive galaxies"

but caution indicated by concerns about photo-z from:

> inadequate depth of observational data
> possible wrong calibrations
> missing filters (particularly in the blue below the break at Lyα)
> poor templates (particularly with very strong emission lines)

Naidu et al 2022b paper on z~17 galaxy also found a z~5 photo-z solution, but low probability

first papers with redshifts indicated problems with photo-z (Zavala et al)
two of the z~17 objects actually at z~5

NIRCam calibration issues also led to changes in photometric redshifts

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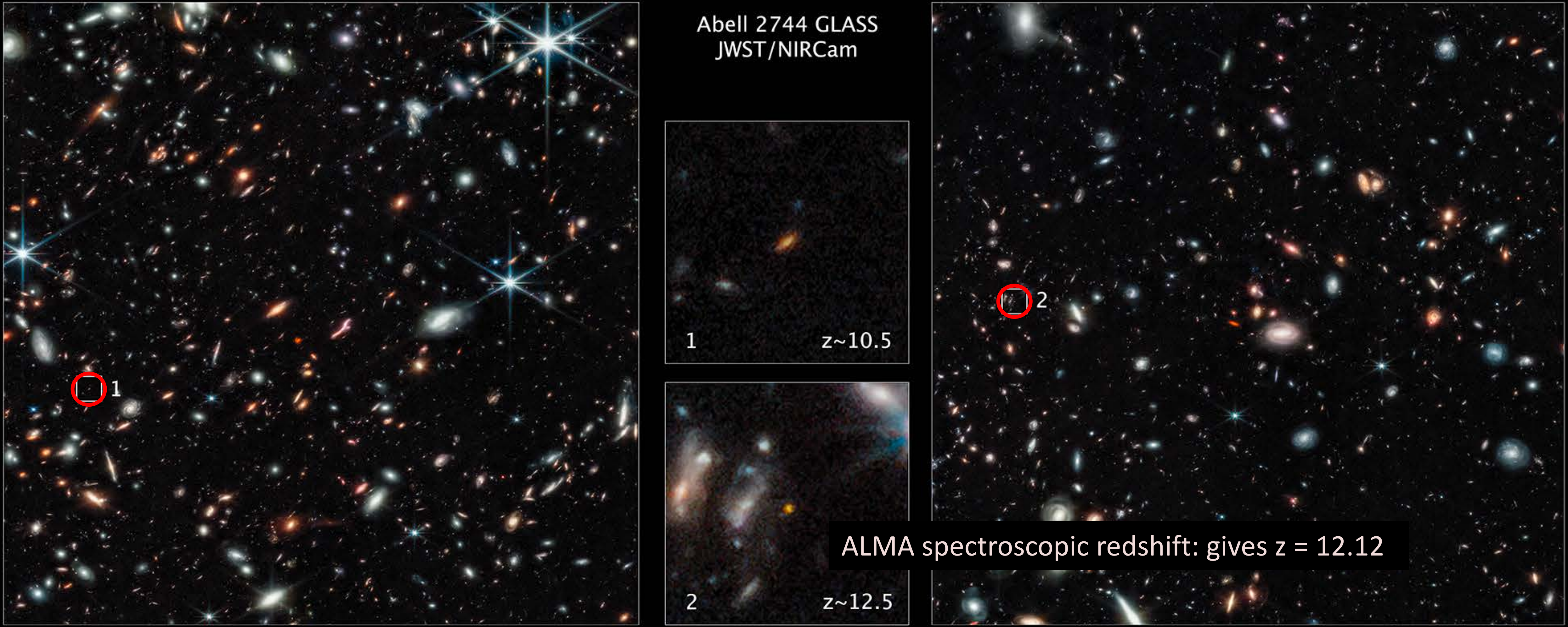
the earliest galaxies – beating Hubble's record in just 5 days!



two papers on first z>10 galaxies (July 19) had revised redshifts, but still at z>10, by publication in November (Naidu, Oesch et al & Castellano et al)

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Bouwens et al 2022b
analysis of the Photometric redshift results

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*Rychard Bouwen's analysis** in late 2022 of photo-z results*

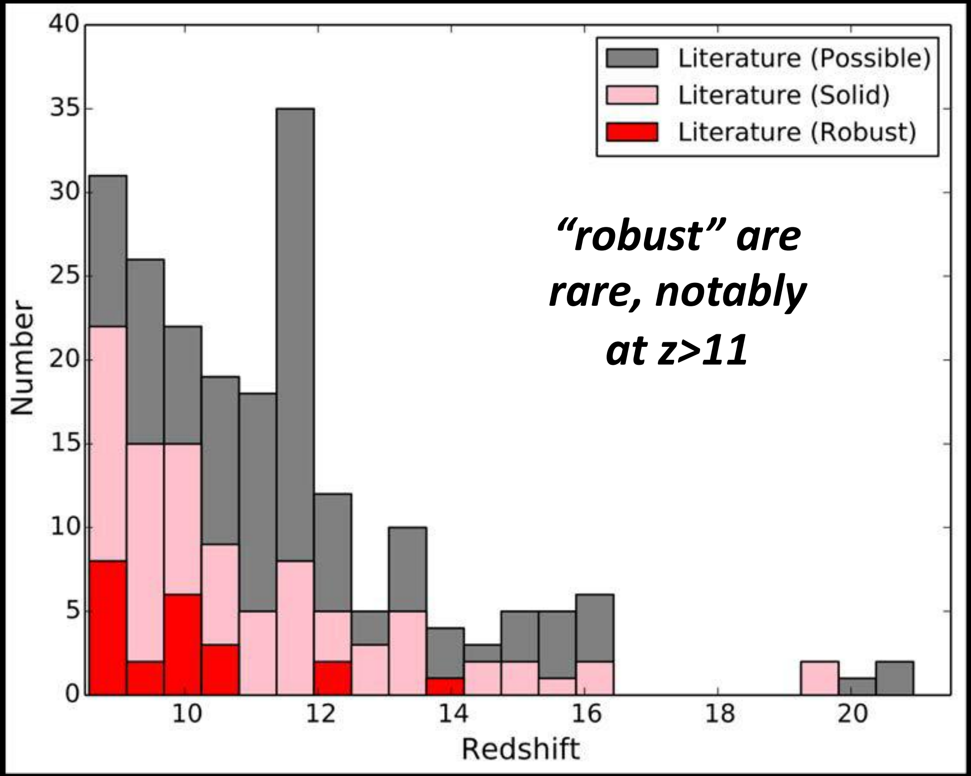
UV luminosity density results at $z > 8$ from the first *JWST*/NIRCam fields: limitations of early data sets and the need for spectroscopy

Rychard Bouwens,[1★] Garth Illingworth,[2] Pascal Oesch,[3,4] Mauro Stefanon,[5,6] Rohan Naidu,[7,8]
Ivana van Leeuwen[1] and Dan Magee[2]

clear problems with consistency of detections at z>8 in same fields between different groups

"The typical overlap between candidate lists in the earliest analyses were only ~10–20 per cent"

own selection + others => assigned photo-z samples into "robust", "solid", "possible"



**Harikane et al also did a very nice conservative analysis of the early results and found a substantial fraction to be unreliable detections

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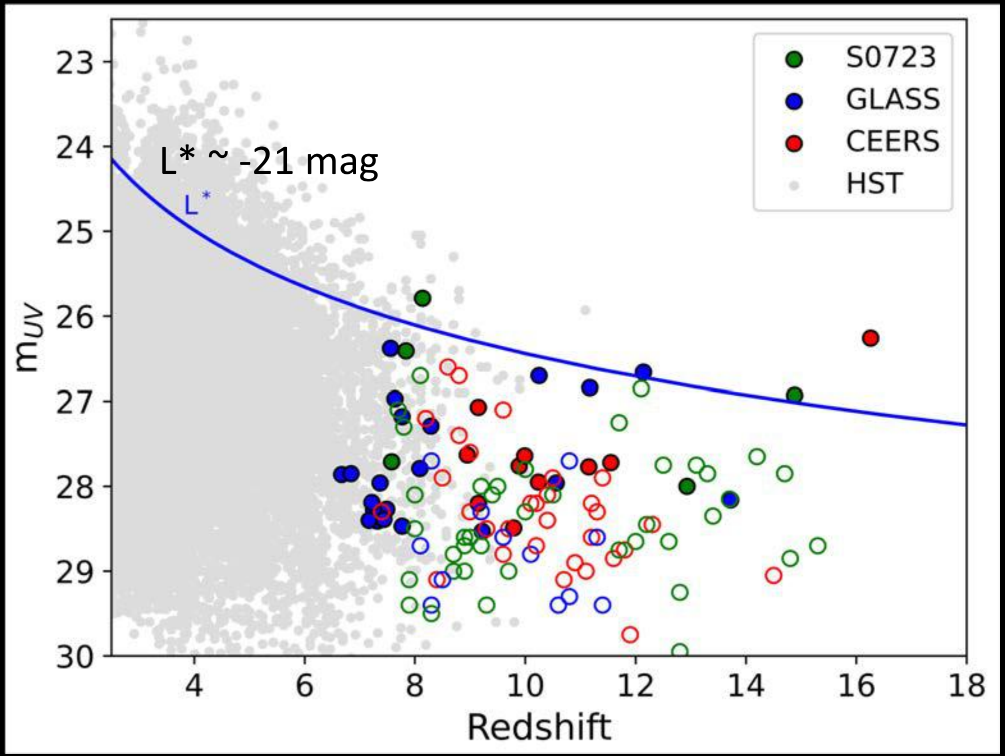
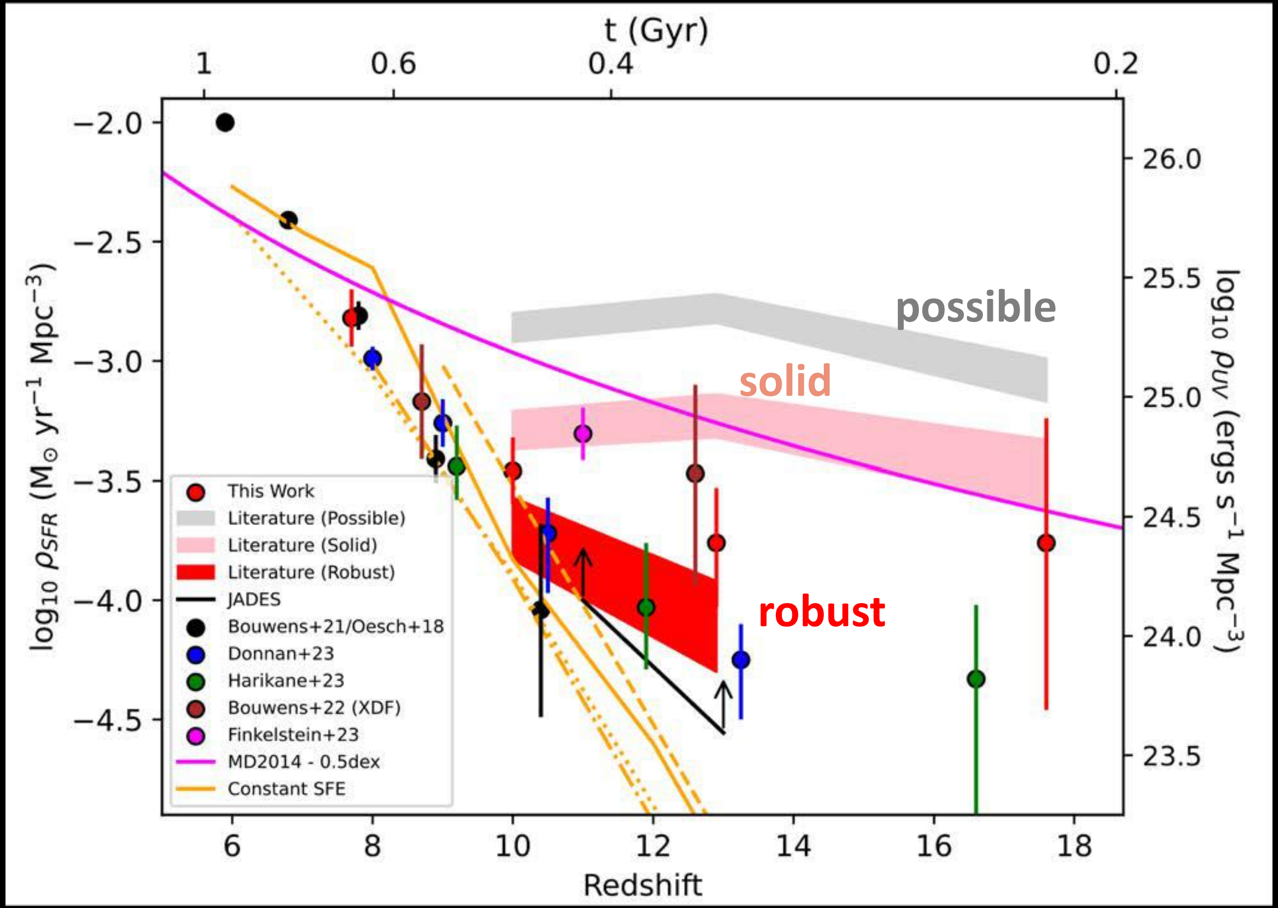
Bouwens et al analysis of photo-z samples



"robust" and "solid" candidates only
all fields (open) – 3 most-studied fields (filled)



UV luminosity density and star formation rate density (SFRD)
both "solid" and "possible" indicate high to extremely-high SFRD

at z>9 – candidates independently-detected:
"robust" – 90% had 2 or more
but only 26% for "solid"
and only 12% for "possible"

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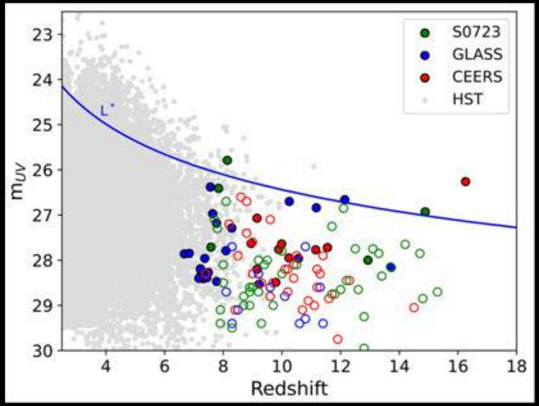
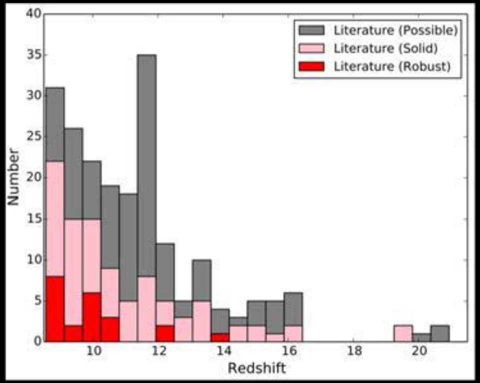
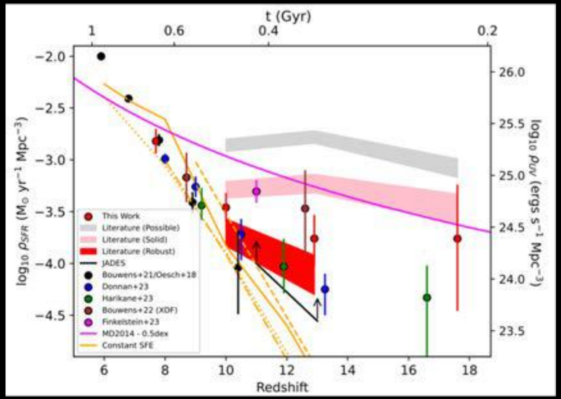
Bouwens et al analysis of photo-z samples







skeptical of the majority of the early photo-z measurements

lack of deep imaging overall, but particularly blueward of the break at Lyα
– crucial null detection needed to ensure that no lower redshift contamination or interlopers –

NIRCam calibration issues a secondary factor

photo-z templates with poor matches to emission line strengths – extremely strong lines

photometric redshifts (photo-z) are improving
some catastrophic failures but in many cases, with good deep data, and a conservative selection, the photo-z ≈ spec-z

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where do we go from here?   more spectra!

finding surprisingly poor agreement in source selections between different teams

Rychard Bouwens (2022) discusses the source(s) of the inconsistencies that he is finding

the lack of good high S/N blue data below the Lyα break is a challenge

(1) resolve NIRCam calibration issues (largely done but but some to go)
(2) higher S/N imaging (blue bands in particular)
(3) JWST spectra (emission lines?)
(4) ALMA data
(5) keep an open mind about the potential limitations of SED fitting at z>~10 and the standard assumptions

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Bouwens et al 2022a – Robertson et al 2022 – Curtis-Lake et al 2022

the HUDF/XDF z>10 galaxies

NIRCam photometric analyses and first spectra from NIRSpec

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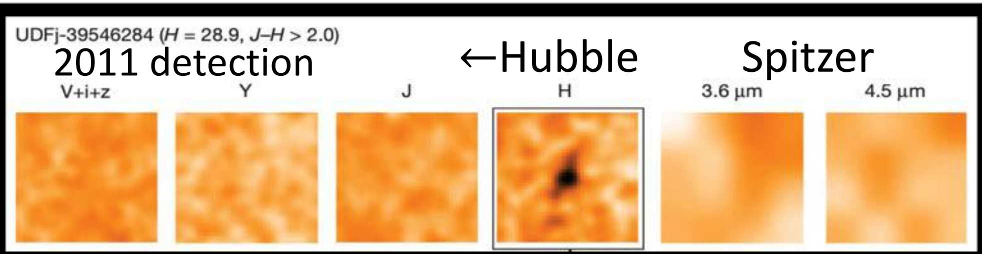
the HUDF/XDF has been a key region for studying the earliest galaxies for 20 years

LETTER Nature 2011

doi:10.1038/nature09717

A candidate redshift $z \approx 10$ galaxy and rapid changes in that population at an age of 500 Myr

R. J. Bouwens[1,2], G. D. Illingworth[1], I. Labbe[3], P. A. Oesch[4], M. Trenti[5], C. M. Carollo[4], P. G. van Dokkum[6], M. Franx[2], M. Stiavelli[7], V. González[1], D. Magee[1] & L. Bradley[7]



Ellis et al 2013 showed that $z \neq 10$ but $z \approx 12$

Brammer et al 2013 spectrum
tentative line detection – $z \approx 2$ or $z \approx 12$
inconclusive!

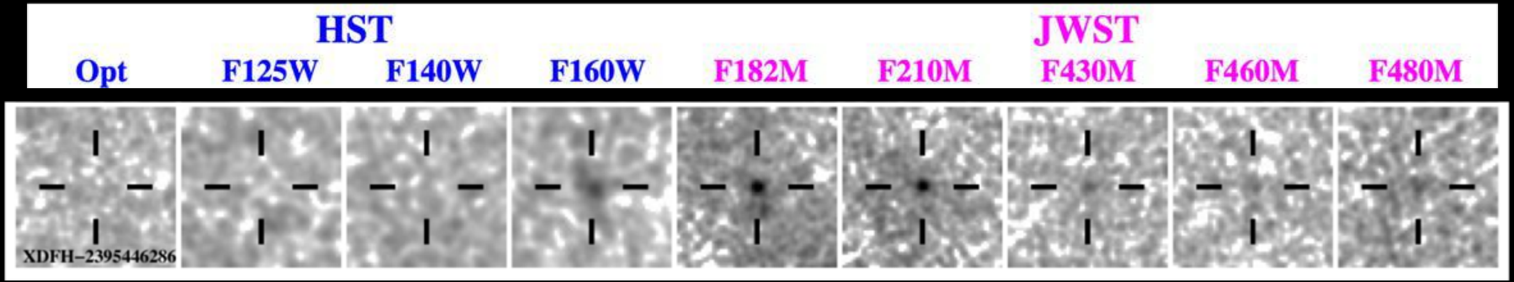
forgotten for 10 years until Bouwens et al 2022 found it again in JWST HUDF/XDF data with photo-z of 11.9-12.0

Evolution of the *UV* LF from $z \sim 15$ to $z \sim 8$ using new *JWST* NIRCam medium-band observations over the HUDF/XDF

Rychard J. Bouwens,[1★] Mauro Stefanon,[2,3] Gabriel Brammer,[4] Pascal A. Oesch[4,5] Thomas Herard-Demanche,[1] Garth D. Illingworth,[6] Jorryt Matthee[7] Rohan P. Naidu[8,9] Pieter G. van Dokkum[10] and Ivana F. van Leeuwen[1]

JWST provides a remarkable set of filters for z>10 galaxies

~1000 orbits of HST data (not equal in all filters)



just 30 hours of JWST data in total

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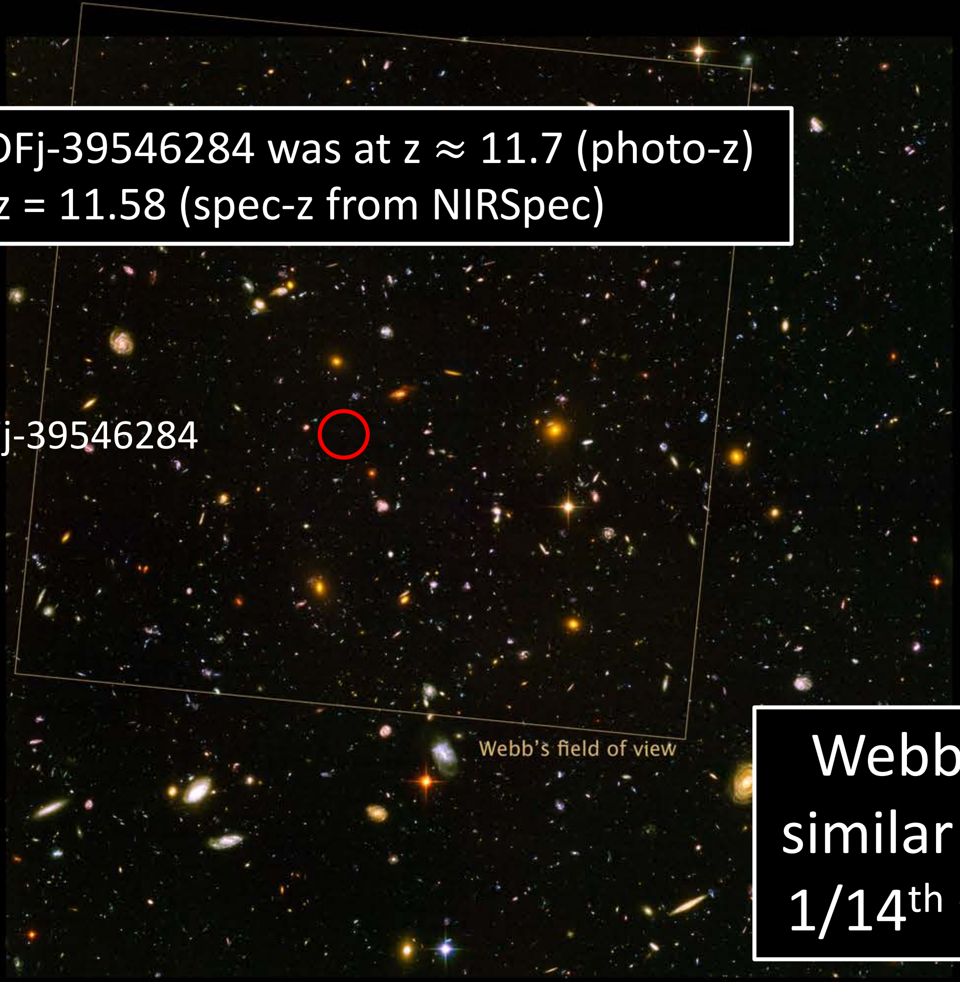
the HUDF/XDF has been a key region for studying the earliest galaxies for 20 years

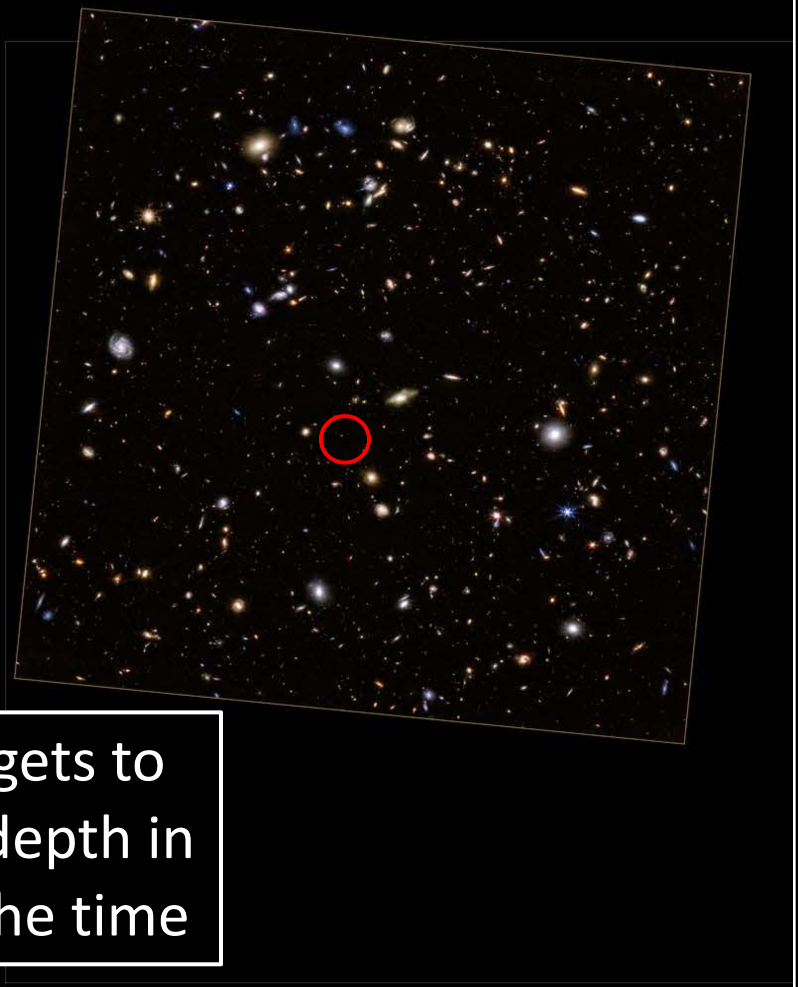
then JWST confirmed late last year that the suspected most-distant galaxy found by Hubble (in 2010) – found in the HUDF/XDF – is actually at z=11.6 (spectroscopic z)

JADES also revealed UDFj-39546284 was at $z \approx 11.7$ (photo-z) – and really at $z = 11.58$ (spec-z from NIRSpec)

JADES-GS-z11-0 = UDFj-39546284



Hubble UDF (exposure time: 11.3 days)



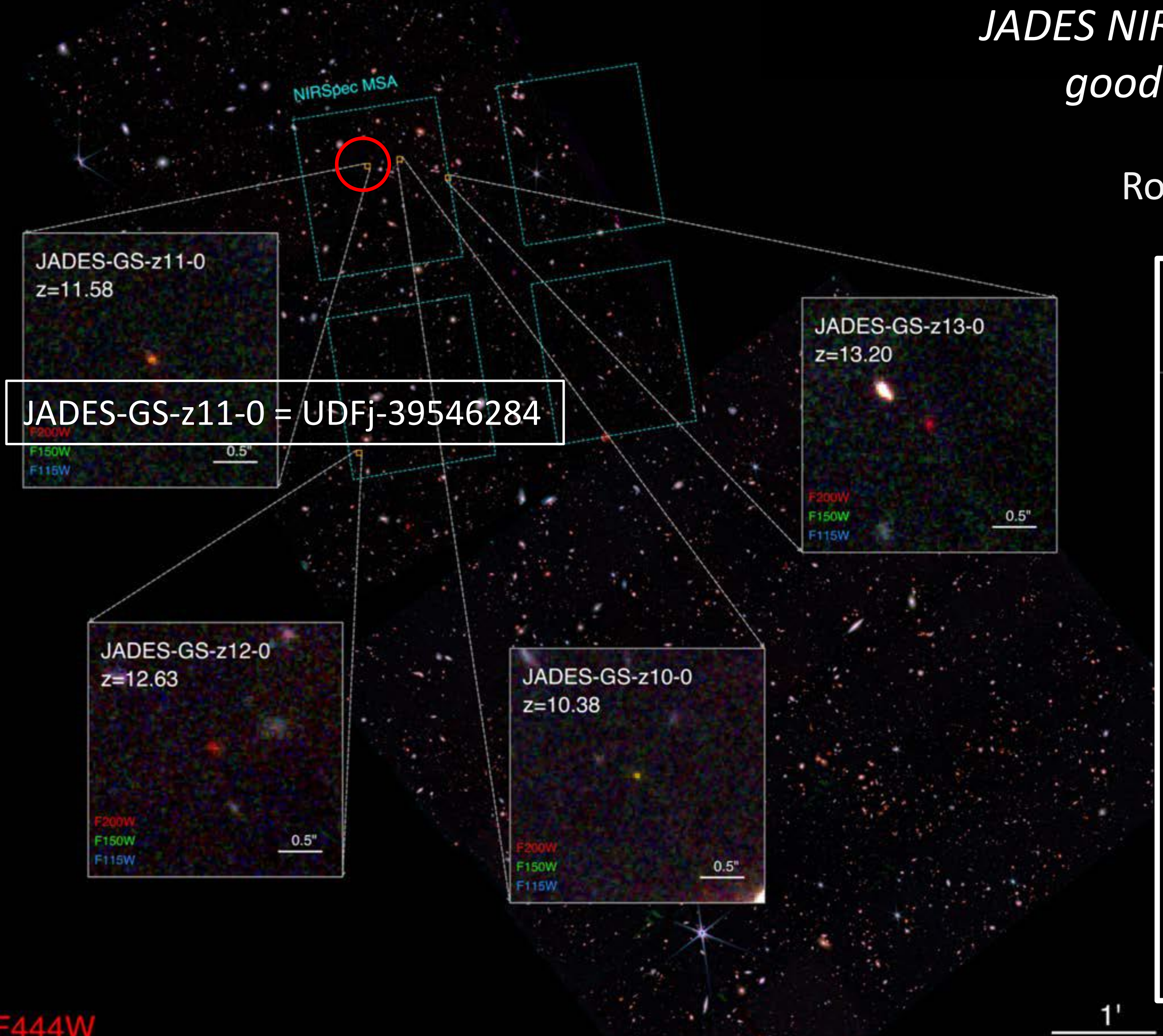
Webb (exposure time: 0.83 days)

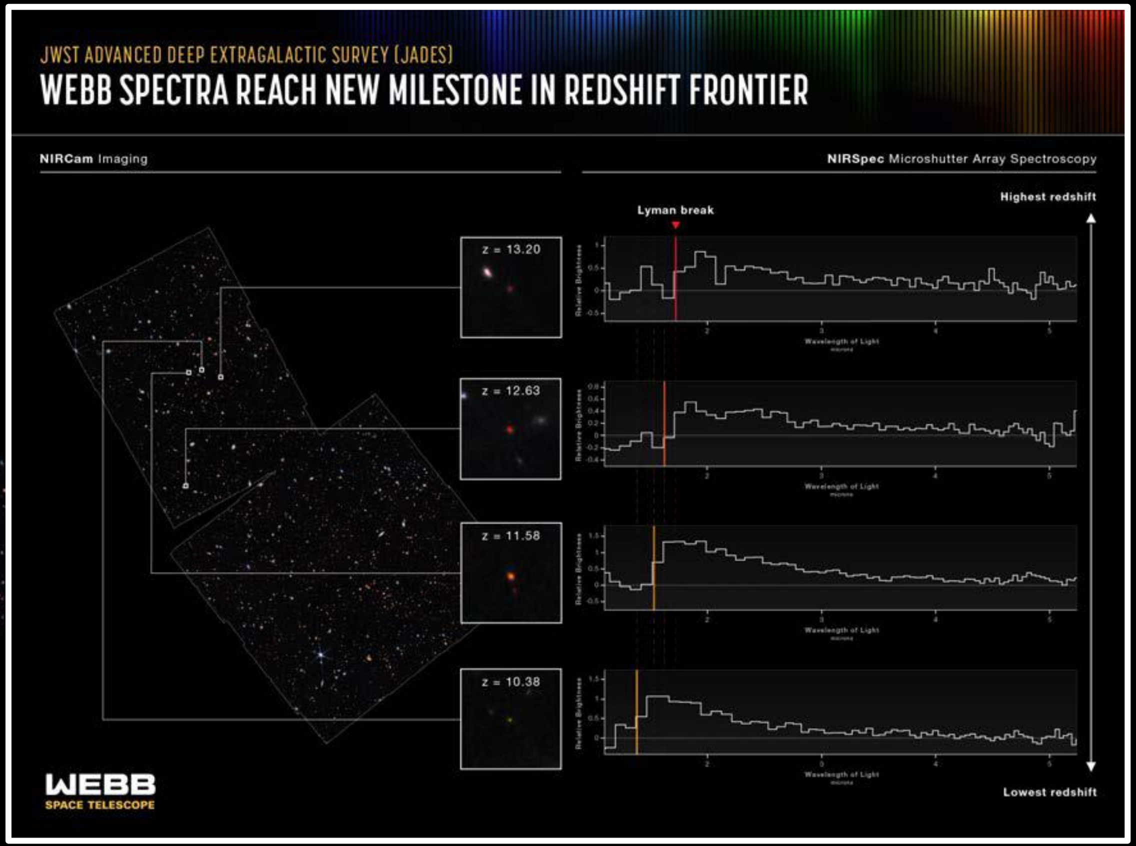
Webb gets to similar depth in $1/14^{th}$ the time

the first major spectroscopic measurements revealed how powerful JWST is

JADES NIRSpec & NIRCam study in GOODS-S
good photo-z and now also spectra

Robertson et al 2022 & Curtis-Lake et al 2022





F444W
F200W
F115W

JADES GOODS-S

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many of the photometric-redshift selected high-z galaxies are spectroscopically-confirmed to be at z>10, but far from all!

enough though that we can ask:

so what is going on with bright galaxies in the first 500 Myr?

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an excellent approach to get insights is to use Hubble's z~11 galaxy GN-z11 as a pathfinder

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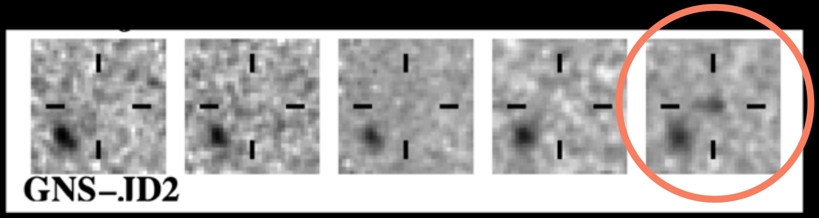
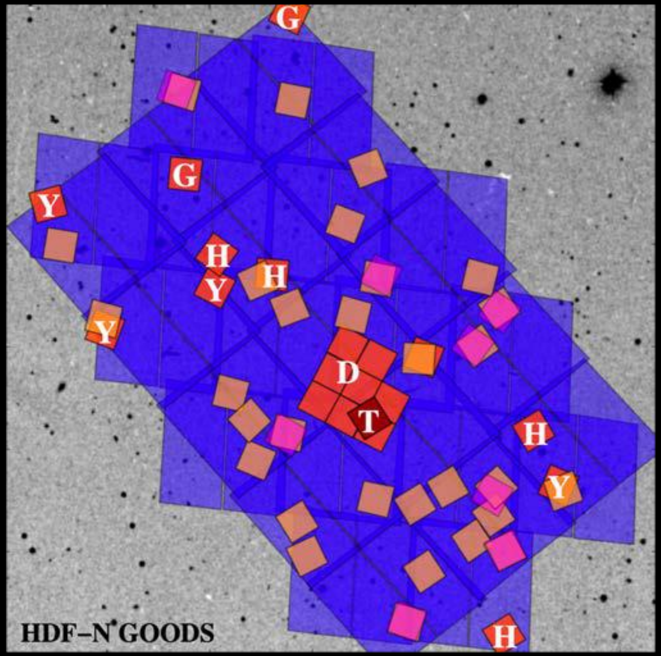
what constraints can we place on the earliest galaxies?

let us look at a really well-studied high-z galaxy GN-z11

observed on Hubble in GOODS-N with the first infrared camera: NICMOS
bright but seen in only one filter – 1.6 µm – H-band!



Bouwens et al 2010



suspected of being:
(i) a transient source (SNe)
(ii) spurious (since near edge of field)
(iii) maybe a z~9 galaxy

"However, we cannot rule out the possibility that it corresponds to a z ~ 9 galaxy (but we consider it very unlikely)."

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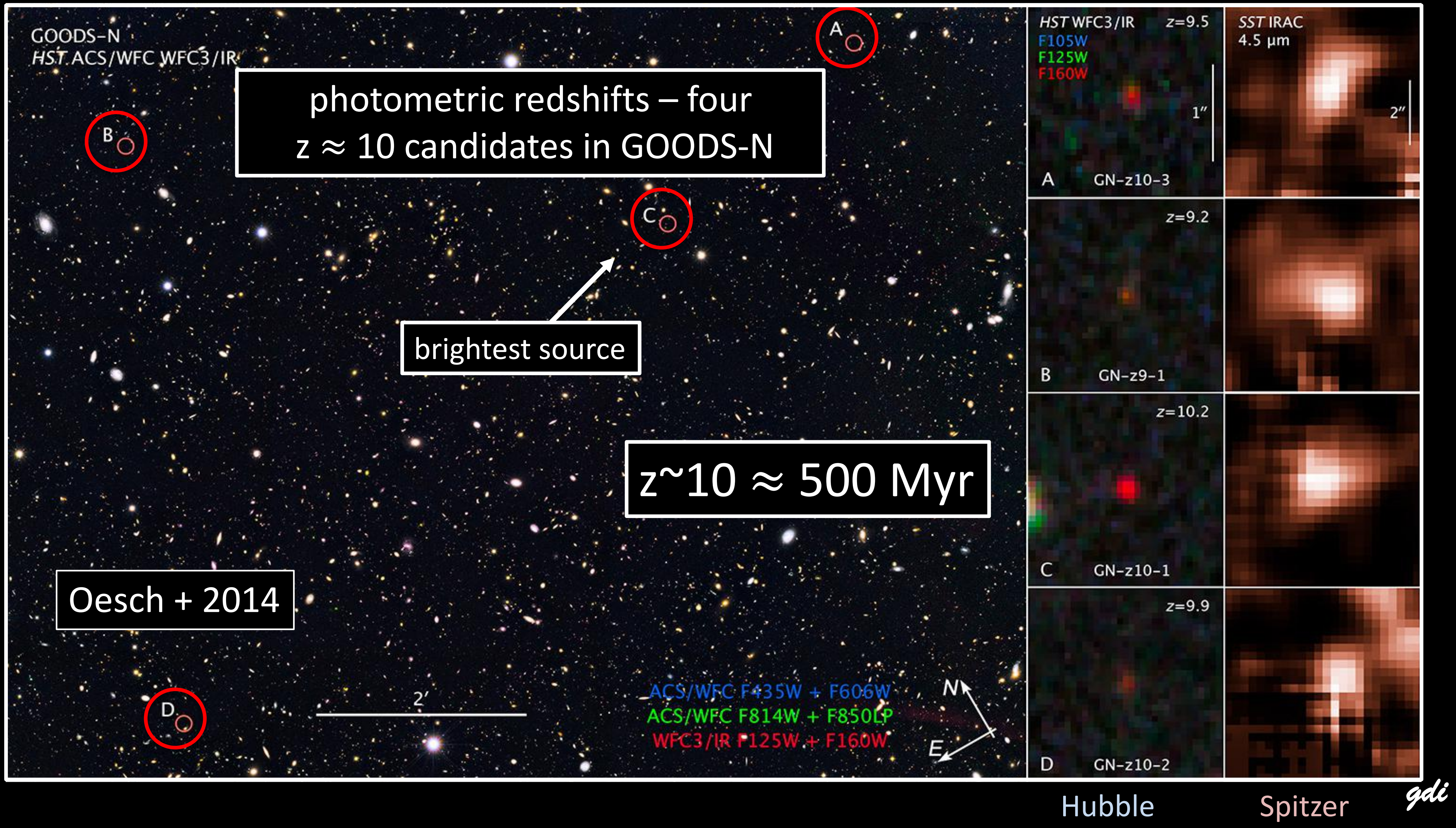
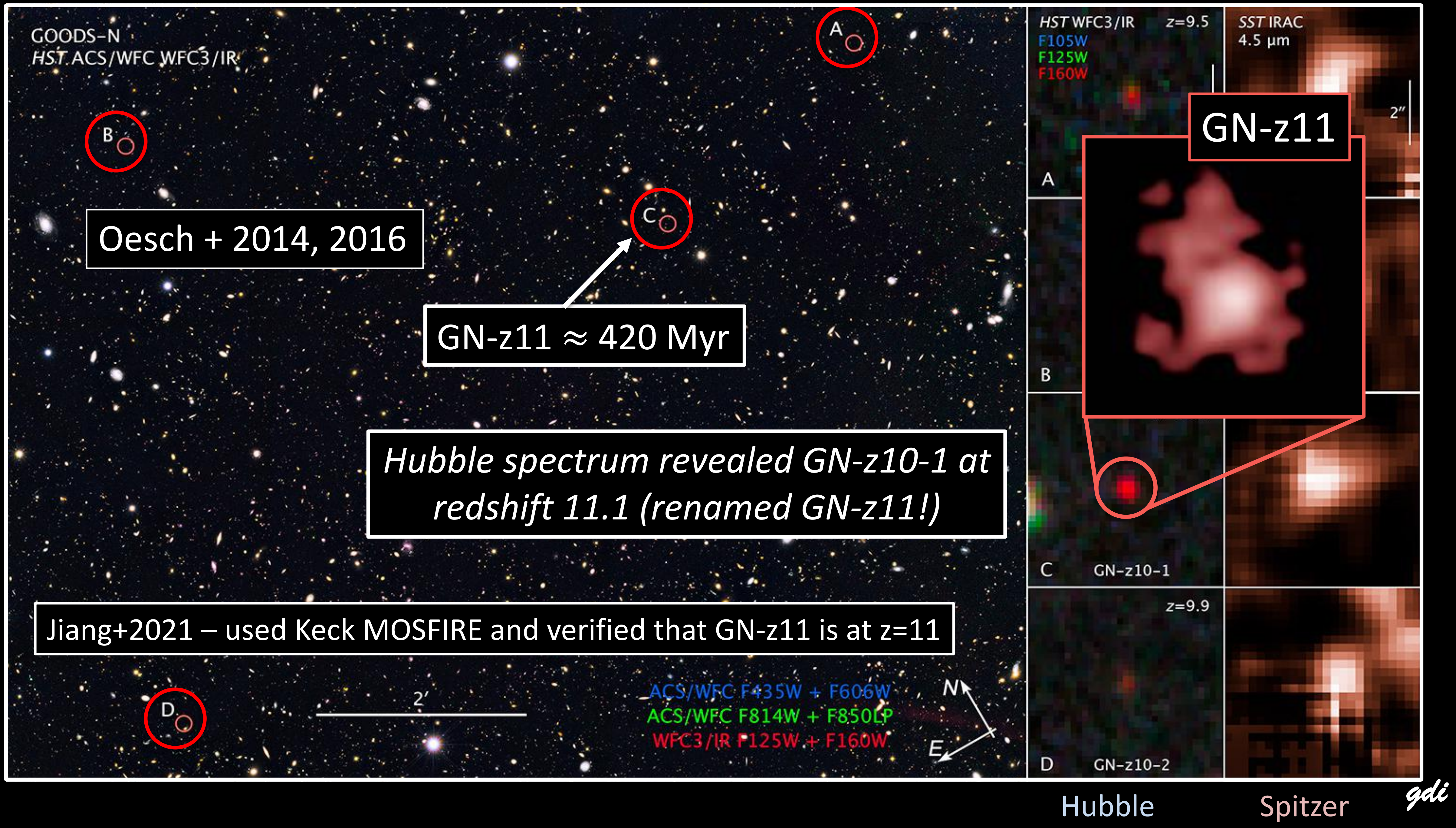


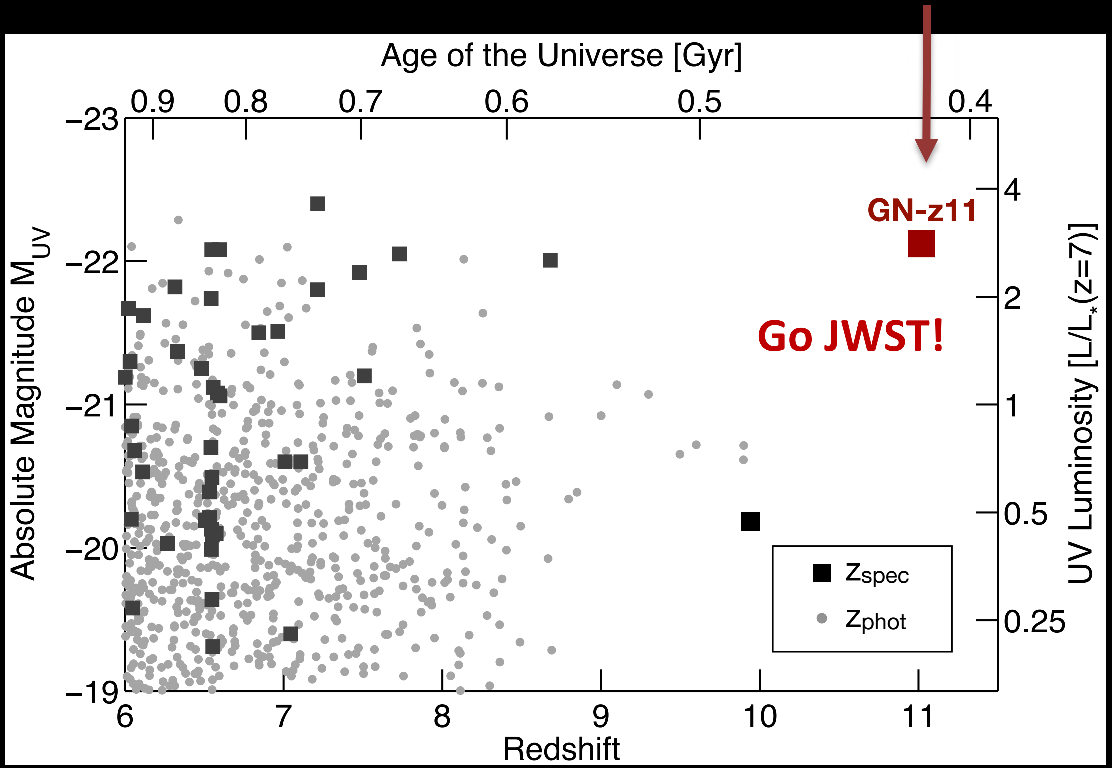
GOODS-N
HST ACS/WFC WFC3/IR
photometric redshifts – four
z ≈ 10 candidates in GOODS-N
A
B
C
D
brightest source
z~10 ≈ 500 Myr
Oesch + 2014
2′
ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W
N
E
HST WFC3/IR
F105W
F125W
F160W
z=9.5
1″
A GN-z10-3
SST IRAC
4.5 μm
2″
z=9.2
B GN-z9-1
z=10.2
C GN-z10-1
z=9.9
D GN-z10-2
Hubble
Spitzer
gdi

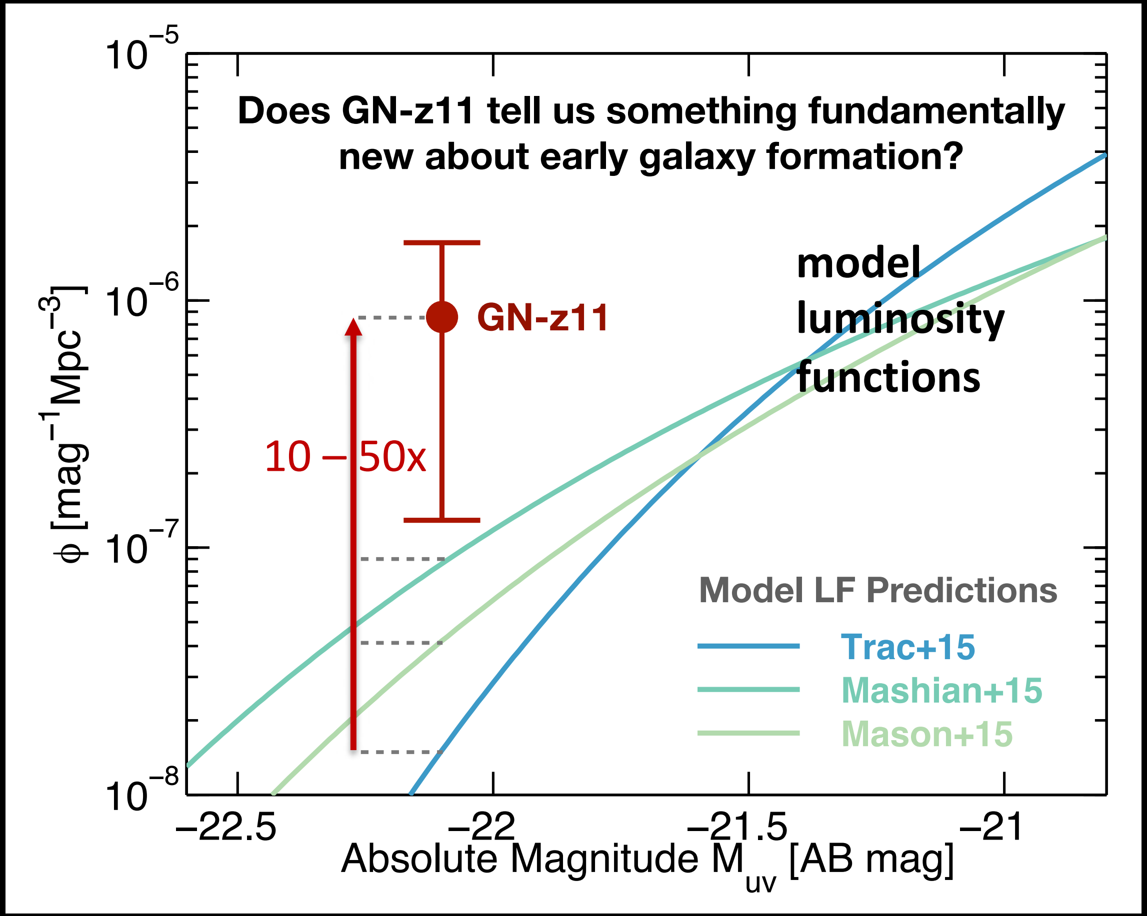


GOODS-N
HST ACS/WFC WFC3/IR
A
B
C
D
Oesch + 2014, 2016
GN-z11 ≈ 420 Myr
Hubble spectrum revealed GN-z10-1 at redshift 11.1 (renamed GN-z11!)
Jiang+2021 – used Keck MOSFIRE and verified that GN-z11 is at z=11
2′
ACS/WFC F435W + F606W
ACS/WFC F814W + F850LP
WFC3/IR F125W + F160W
N
E
HST WFC3/IR
z=9.5
F105W
F125W
F160W
SST IRAC
4.5 μm
2″
GN-z11
GN-z10-1
z=9.9
GN-z10-2
Hubble
Spitzer
gdi

the most distant galaxy found to date

surprising discovery of GN-z11:
HST+Spitzer are reaching into JWST territory





detection of GN-z11 in *existing data* is unexpected, given current models

Oesch+2016

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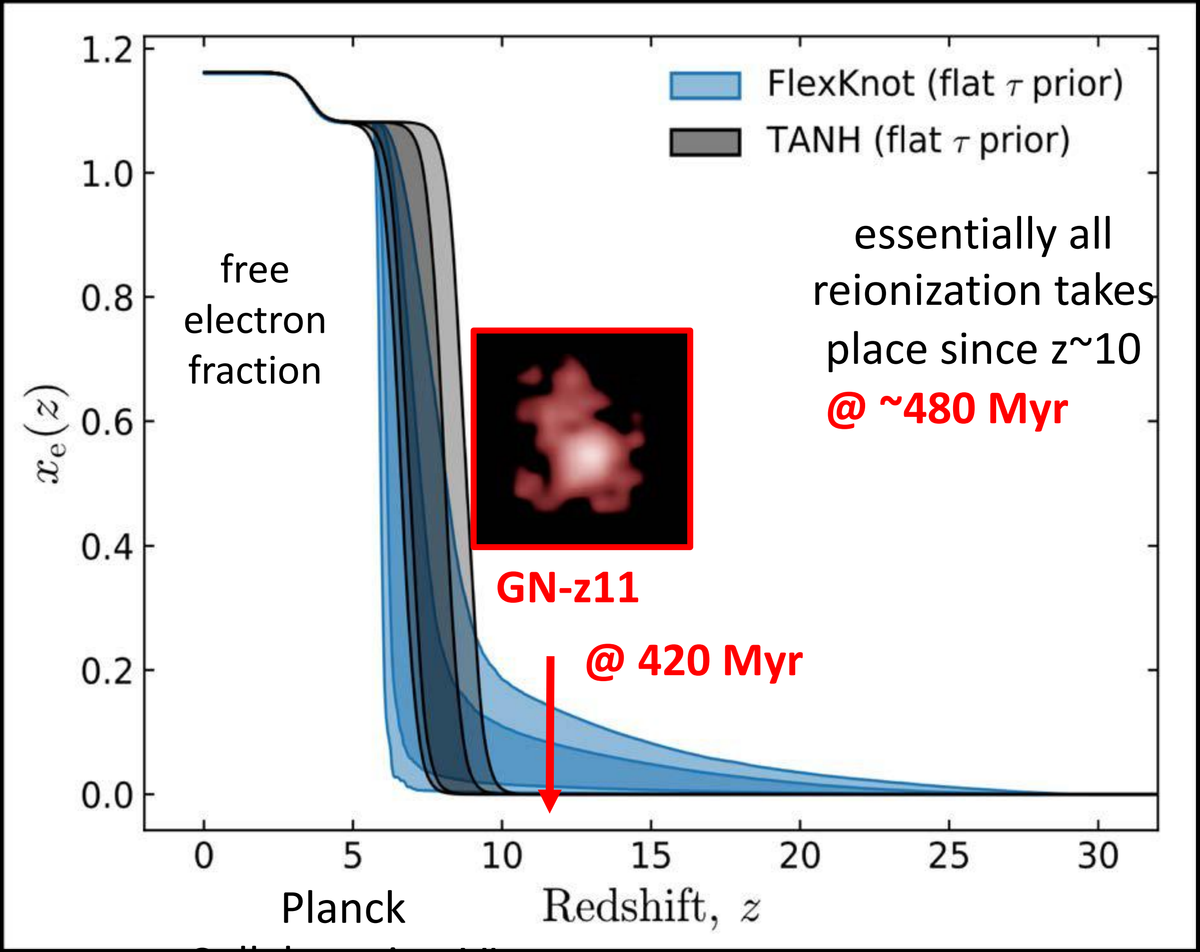
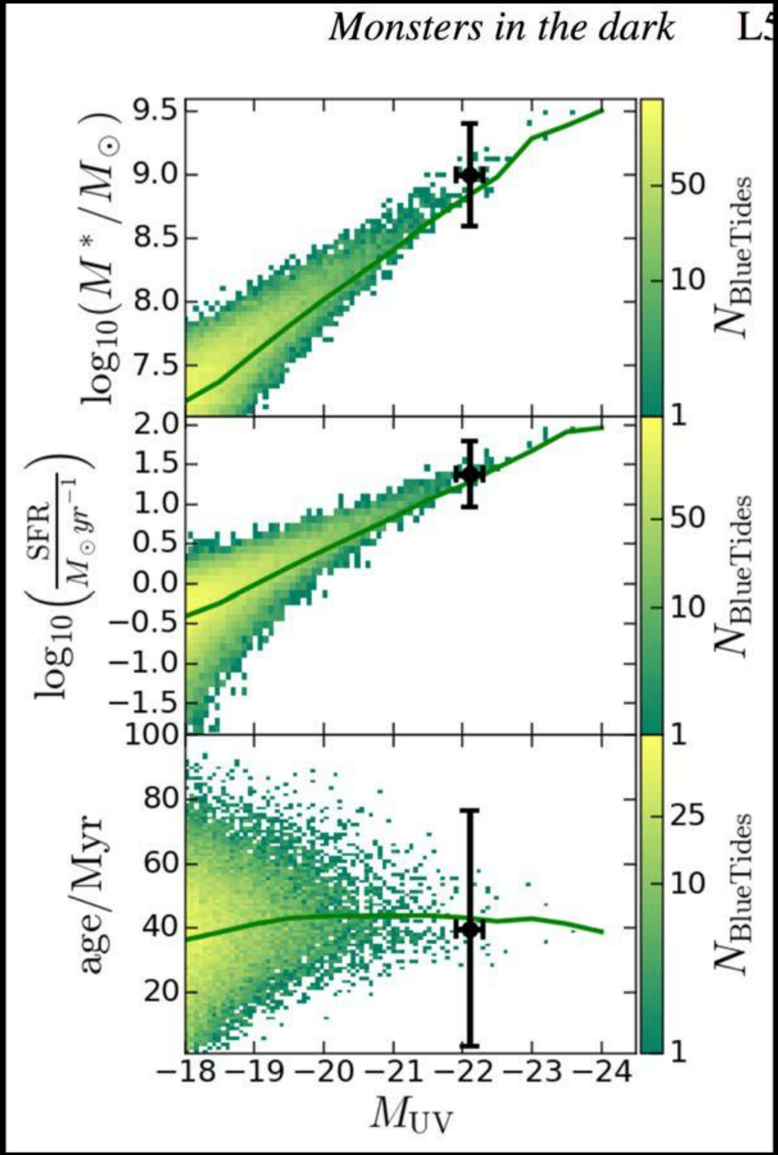
GN-z11 is a galaxy essentially in the pre-reionization epoch — an epoch we thought was inaccessible without JWST!



GN-z11 is a pathfinder for the earliest galaxies

Planck Collaboration Results I, VI 2018

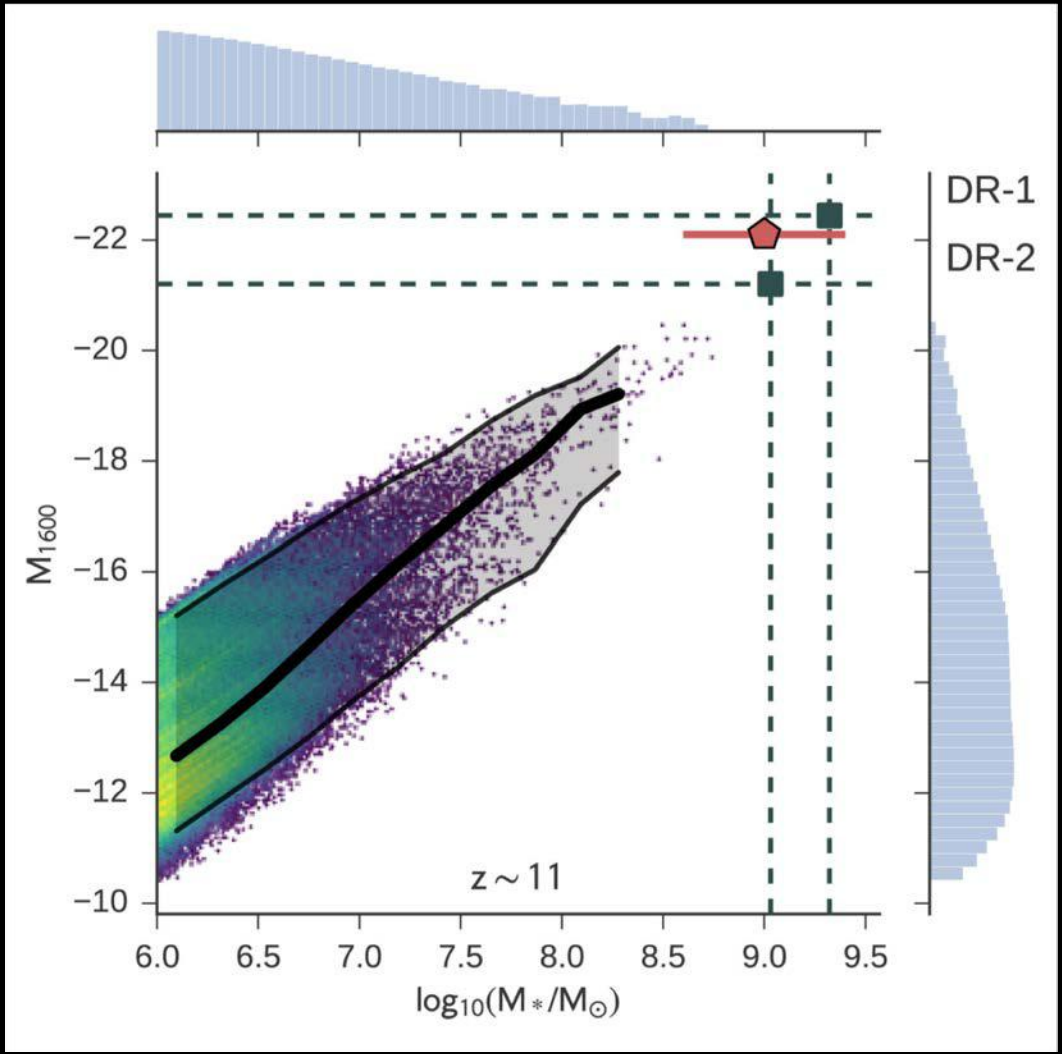


BlueTides

Waters+2016

GN-z11

simulations show that galaxies as massive as GNz-11 at z~11 are rare but not unexpected *per se*



Mutch+2016

DRAGONS

but it is unexpected to find GN-z11 in such small search volumes/areas (by factor 10-100)?

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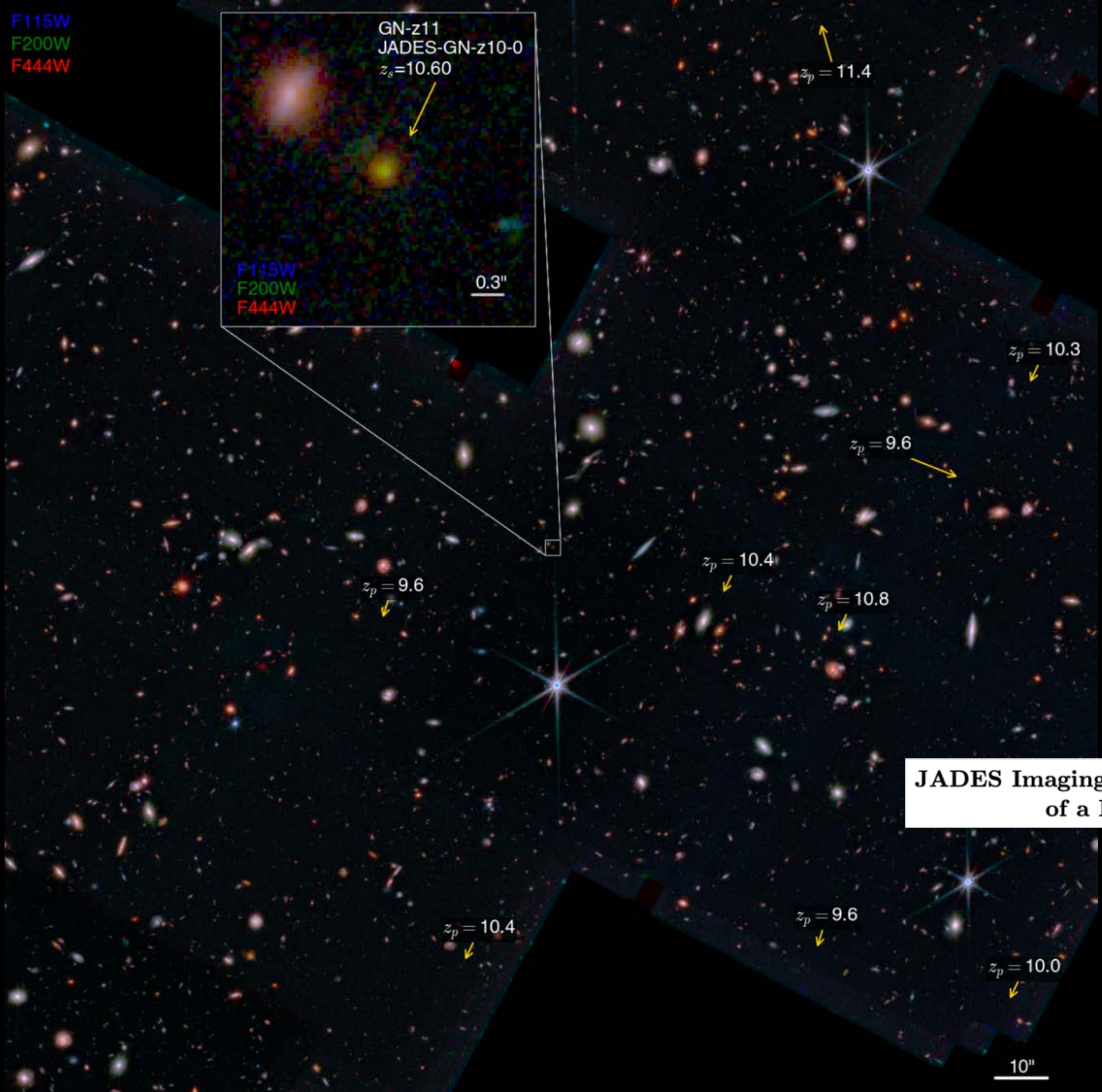

what is going on at z>10 (500 Myr) in bright galaxies?

lets look more closely at GN-z11

now through JWST's eyes…

JADES Imaging of GN-z11: Revealing the Morphology and Environment of a Luminous Galaxy 430 Myr After the Big Bang

Tacchella et al 2023

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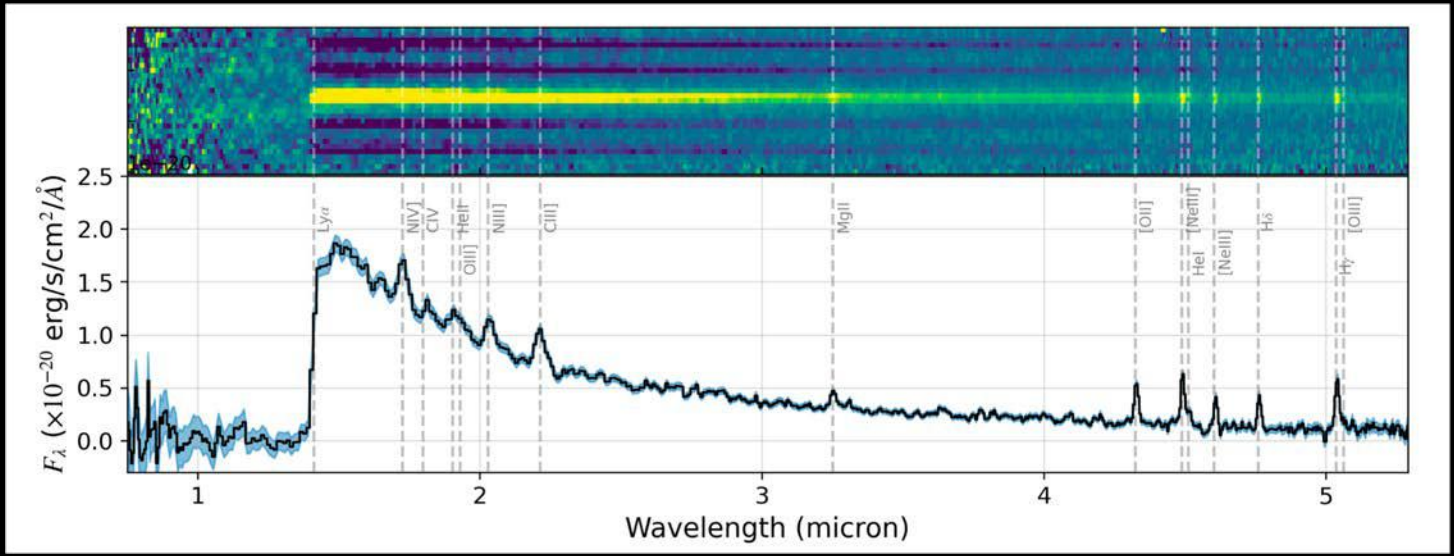
GN-z11 observed by JWST NIRSpec

JWST



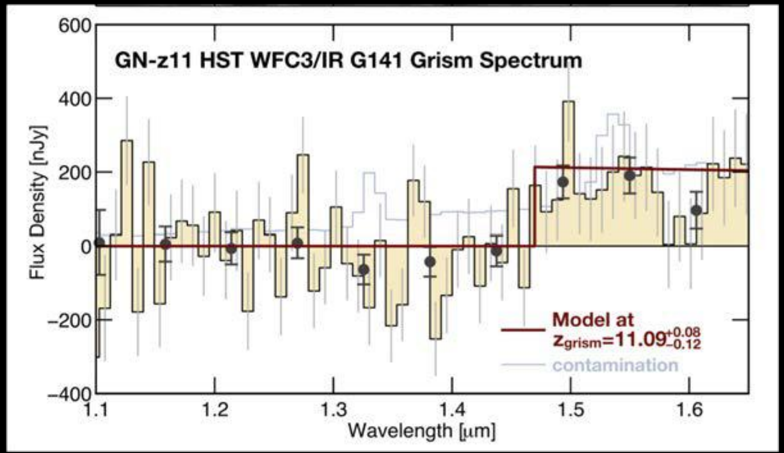
JWST NIRSpec
total time ~20 hrs
Bunker et al 2023

z = 10.603 (440Myr)

Hubble

numerous “metal” emission lines (N, C, O, Ne, Mg)– and redshifted Lyα

significantly enrichment at 440 Myr



Hubble WFC3/IR Grism
total time ~8 hrs
Oesch et al 2016

JADES NIRSpec Spectroscopy of GN-z11: Lyman-α emission and possible enhanced nitrogen abundance in a $z = 10.60$ luminous galaxy

Andrew J. Bunker[1,⋆], Aayush Saxena[1,2], Alex J. Cameron[1], Chris J. Willott[3], Emma Curtis-Lake[4], Peter Jakobsen[5,6], Stefano Carniani[7], Renske Smit[8], Roberto Maiolino[9,10,2], Joris Witstok[9,10], Mirko Curti[9,10,11], Francesco D’Eugenio[9,10], Gareth C. Jones[1], Pierre Ferruit[12], Santiago Arribas[13], Stephane Charlot[14], Jacopo Chevallard[1], Giovanna Giardino[15], Anna de Graaff[16], Tobias J. Looser[9,10], Nora Lützgendorf[17], Michael V. Maseda[18], Tim Rawle[17], Hans-Walter Rix[16], Bruno Rodríguez Del Pino[13], Stacey Alberts[19], Eiichi Egami[19], Daniel J. Eisenstein[20], Ryan Endsley[21], Kevin Hainline[19], Ryan Hausen[22], Benjamin D. Johnson[20], George Rieke[19], Marcia Rieke[19], Brant E. Robertson[23], Irene Shivaei[19], Daniel P. Stark[19], Fengwu Sun[19], Sandro Tacchella[9,10], Mengtao Tang[19], Christina C. Williams[24,19], Christopher N. A. Willmer[19], William M. Baker[9,10], Stefi Baum[25], Rachana Bhatawdekar[12,26], Rebecca Bowler[27], Kristan Boyett[28,29], Zuyi Chen[19], Chiara Circosta[12], Jakob M. Helton[19], Zhiyuan Ji[19], Jianwei Lyu[19], Erica Nelson[30], Eleonora Parlanti[7], Michele Perna[13], Lester Sandles[9,10], Jan Scholtz[9,10], Katherine A. Suess[23,31], Michael W. Topping[19], Hannah Übler[9,10], Imaan E. B. Wallace[1], and Lily Whitler[19]

A REMARKABLY LUMINOUS GALAXY AT Z = 11.1 MEASURED WITH *HUBBLE SPACE TELESCOPE* GRISM SPECTROSCOPY

P. A. Oesch[1,2], G. Brammer[3], P. G. van Dokkum[1,2], G. D. Illingworth[4], R. J. Bouwens[5], I. Labbé[5], M. Franx[5], I. Momcheva[2,3], M. L. N. Ashby[6], G. G. Fazio[6], V. Gonzalez[7,8], B. Holden[4], D. Magee[4], R. E. Skelton[9], R. Smit[10], L. R. Spitler[11,12], M. Trenti[13], and S. P. Willner[6]

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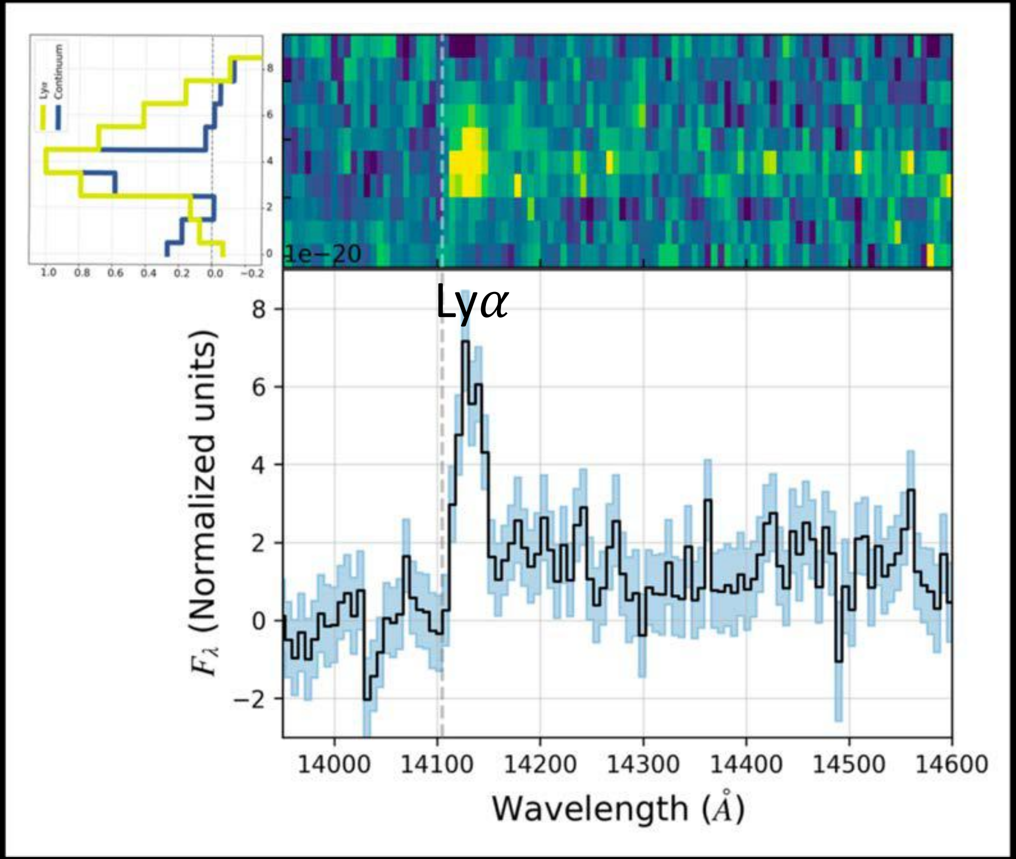
ionized bubble pre-reionization

Universe is predominantly neutral at z∼10 (per Planck)
z=10.6 is largely prior to the reionization epoch
(see earlier Planck discussion)

but we see Lyα!

redshifted Lyα suggests that GN-z11 is surrounded by an ionized bubble

Lyα we see comes from backscattering from outflows



Bunker et al 2023

Population III

are extremely luminous, high-mass, "zero-metal" Population III stars significant contributors to the highest redshift galaxies?

Population III – the "first" stars – with "zero" metals

Pop III stars must have existed since gas at z>20-30 was just H, He (tiny amounts of Li)

but evidence for Pop III stars remains very weak

(1)

Detection of Pristine Gas Two Billion Years after the Big Bang

2011 z~3

Michele Fumagalli[1*], John M. O'Meara[2], and J. Xavier Prochaska[3]

$Z < 10^{-4} Z_\odot$

(2)

An extremely metal poor star complex in the reionization era: Approaching Population III stars with JWST ⋆

z=6.6

Vanzella et al 2023 found a very small ($\lesssim 10^4\ M_\odot$) clump of stars at z=6.6 (830 Myr) with extremely low metallicity $Z < 0.004 Z_\odot$

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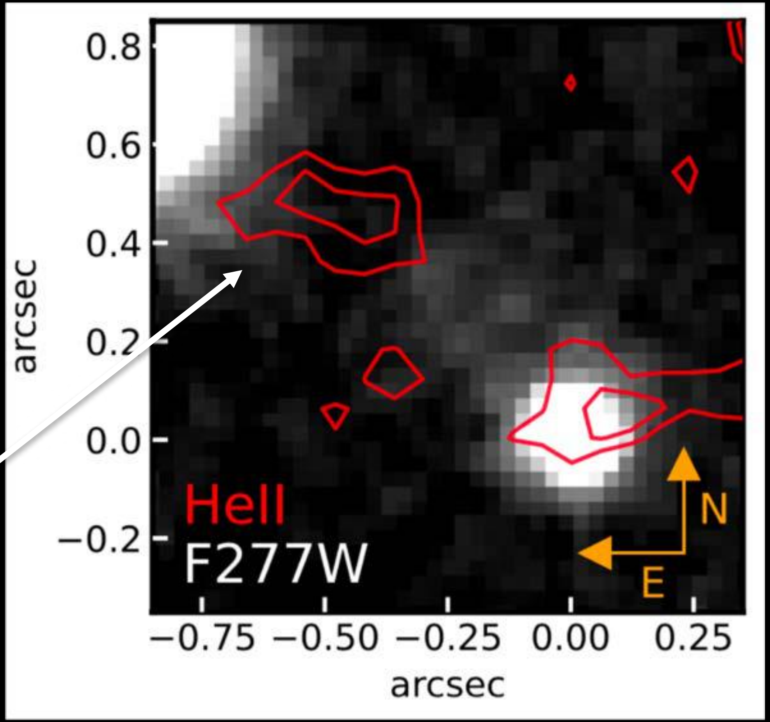
Pop III

are Pop III stars significant contributors?



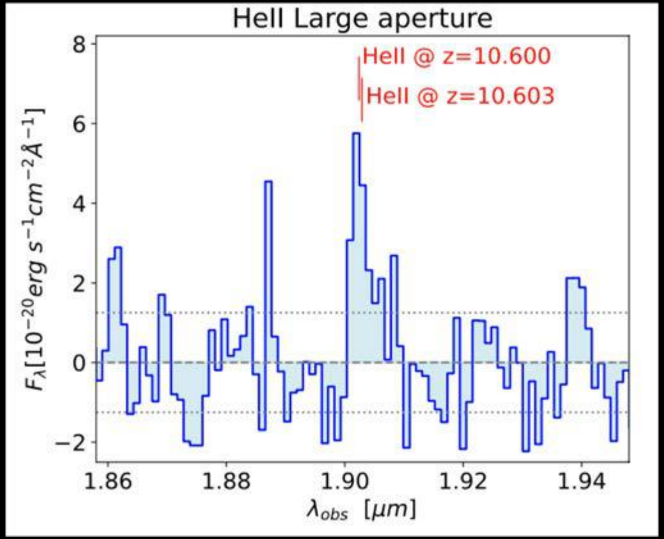
Pop III – indications now from GN-z11 and JWST NIRSpec

best evidence to date at early times
but still inconclusive!

(3)

JADES. Possible Population III signatures at z=10.6 in the halo of GN-z11

Maiolino et al 2023a detected weak HeII in GN-z11 halo possibly indicative of Pop III stars > 500 $M_\odot$



remains unclear how much Pop III contributes to the luminosity of early bright galaxies

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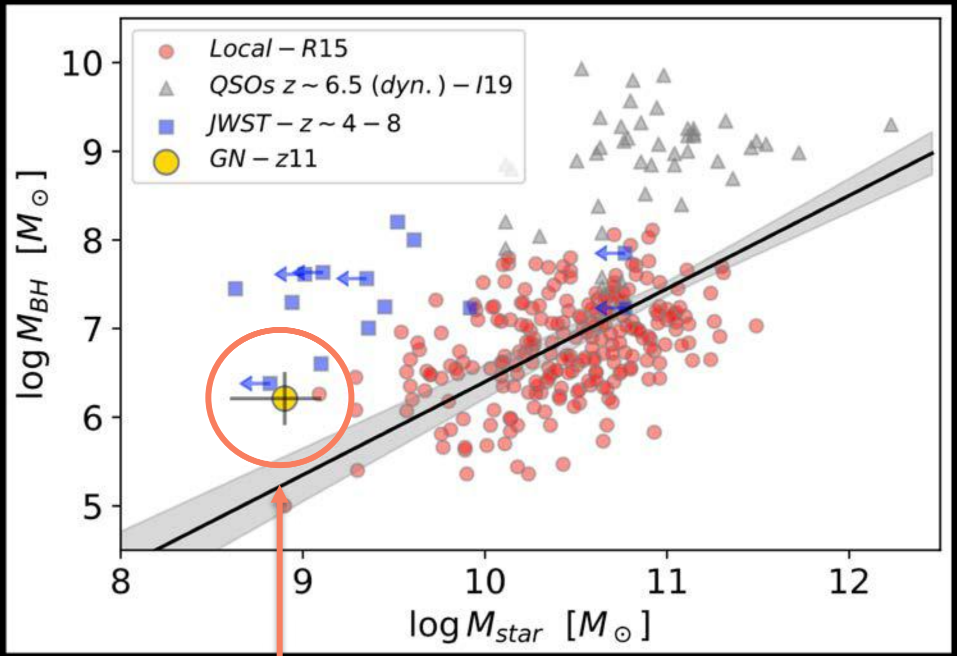
AGN – BH

do black holes/Active Galactic Nuclei (AGN) contribute significantly to making the highest redshift galaxies so bright?

must have early black holes, since AGNs are seen at $z \lesssim 8$

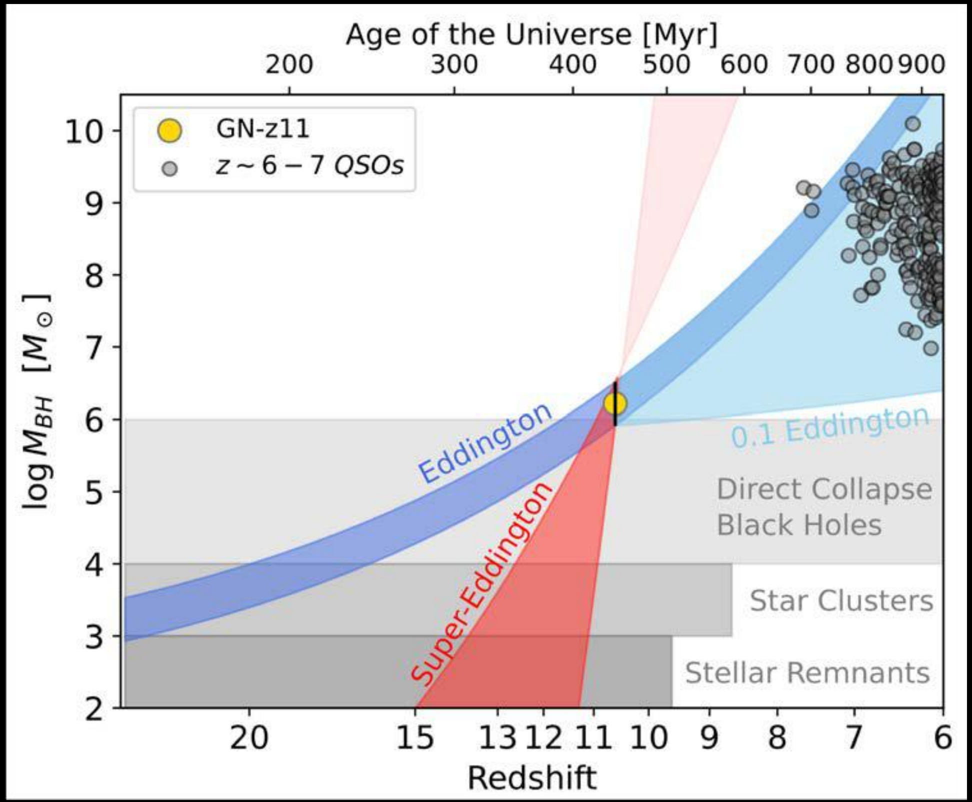
large black hole (BH) masses $\approx 10^7$ to 10^9 $M_\odot$



GN-z11 BH $\approx 10^{6.2}$ $M_\odot$

GN-z11 most likely has a massive black hole $\approx 10^{6.2}$ $M_\odot$

Maiolino et al 2023b



the AGN likely contributes significantly ($\approx$2/3rd) to the luminosity of GN-z11

the challenge of building massive BHs at such early times

(no x-ray detection)

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GN-z11 is giving us some clues as to what might be contributing to the unusual luminosity of the bright galaxies at z>10

AGN (black holes) and population III

but this is still very much "early days" with what is happening still TBD

is the stellar population more "top heavy" with massive stars?

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JWST is a “spectroscopic powerhouse”

spectroscopy is where JWST will leave its mark on astrophysics

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the FRESCO survey: an example of JWST's spectroscopic power

early galaxies have incredibly strong emission lines
– great for redshifts and diagnostics –
types of stars, gas properties, existence of dust, velocity structure, outflows, inflows,
if Active Galactic Nuclei (AGN $\Longrightarrow$ massive black holes),
potentially of population III – the first "metal-free" stars

great example of power of spectroscopy

"First Reionization Epoch Spectroscopically Complete Observations"

FRESCO (link here to paper describing the survey) exploits these strong lines and JWST's unique spectroscopic capability to obtain an emission line selected galaxy sample in the Epoch of Reionization (EoR)

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FRESCO survey design

NIRCam grism observations over 62 arcmin^2 in **CANDELS/Deep fields**

(2x4 mosaics over GOODS-North and South)

F444W grism R (2hr) + direct images (15min)

plus F182M + F210M images

Imaging sensitivity: ~28.2 AB mag (at 5σ) medium bands and F444W

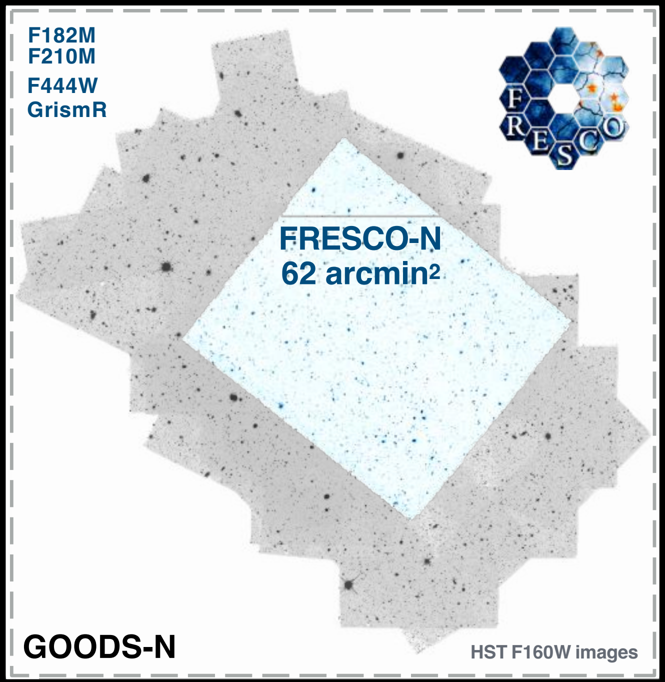
F444W: **grism spectra** 3.9-5.0 micron (R~1600)
line sensitivity: **2 x 10^{-18} erg/s/cm^2** (5sigma)

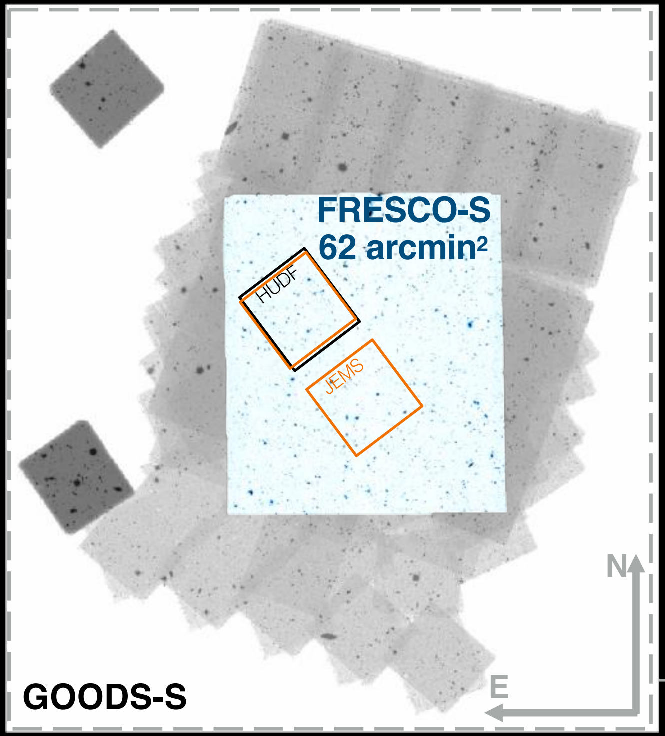
35.5hr science time, 53.8hr total

Data are **public immediately**

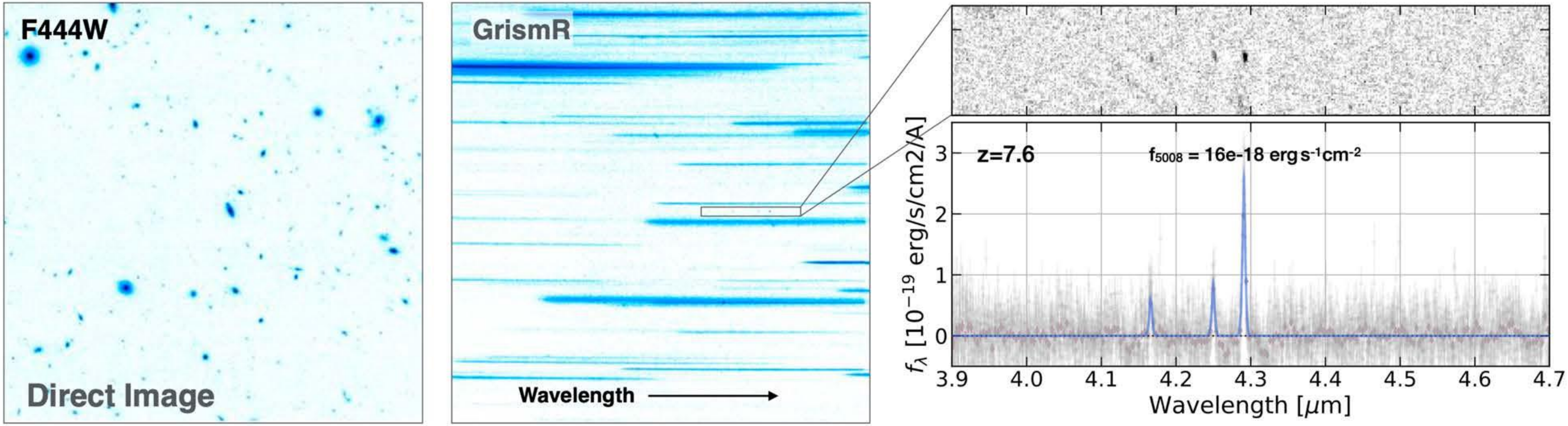
Observed between **November 11, 2022,** and **February 13, 2023**

see FRESCO survey paper: Oesch+23 arXiv2304.02026





NIRCam image and grism example



direct image left and grism spectra middle with an example redshift z = 7.6
2D and the extracted 1D spectra
from FRESCO GOODS-S

Oesch et al 2023

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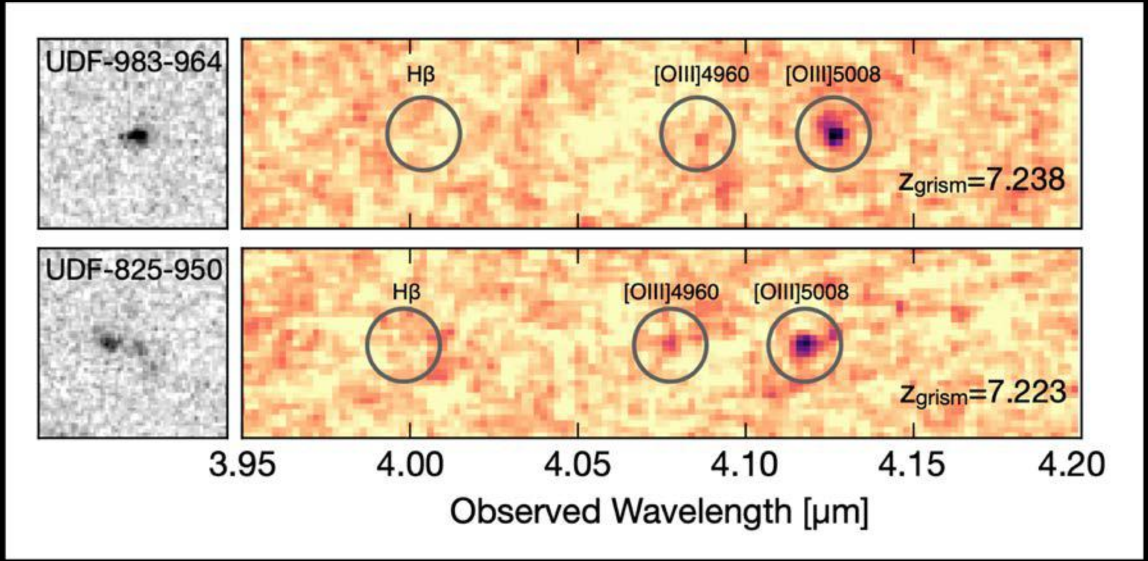
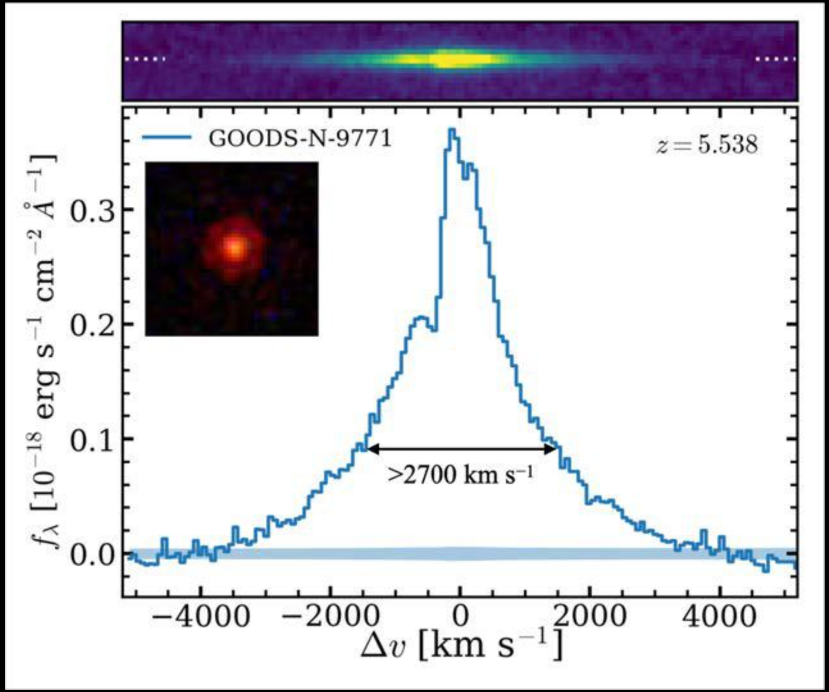
some examples of results from FRESCO that only JWST could do

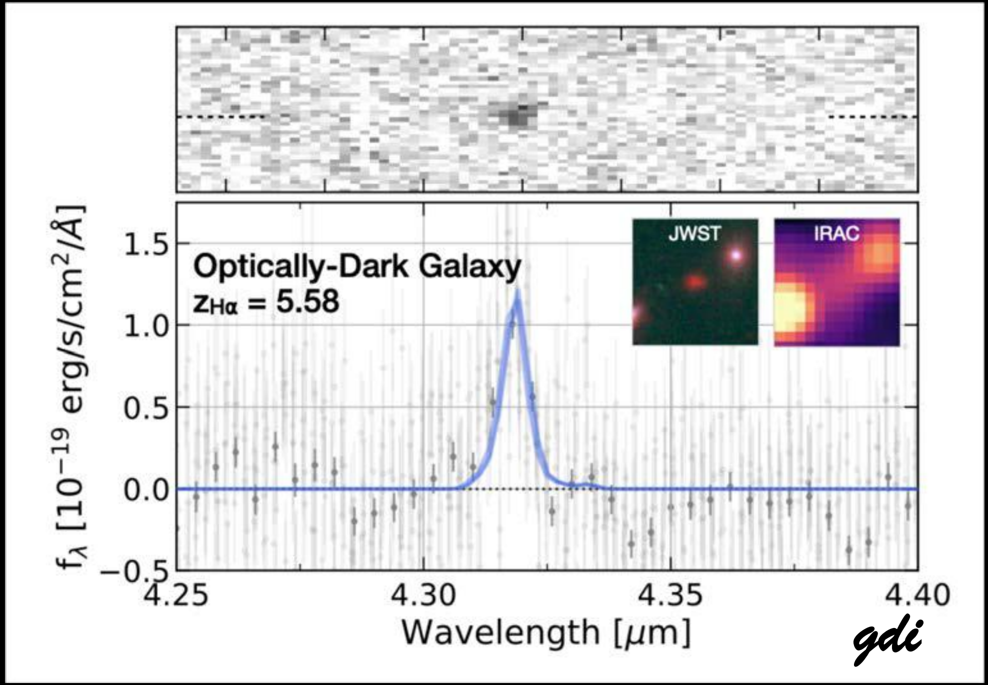
finally getting accurate redshifts for a pair of very faint galaxies in the reionization epoch at z=7.2

discovered using photo-z at z~7 back in 2004 by Bouwens et al from some of the first HST NICMOS IR data





an optically-dark galaxy that neither HST nor Spitzer could find – these massive galaxies are an important part of the high-redshift population (see below)



very broad spectral lines in a very compact object revealing a faint active galactic nucleus (AGN) – indicating a massive black hole FRESCO is finding many of these "little red dot AGNs"

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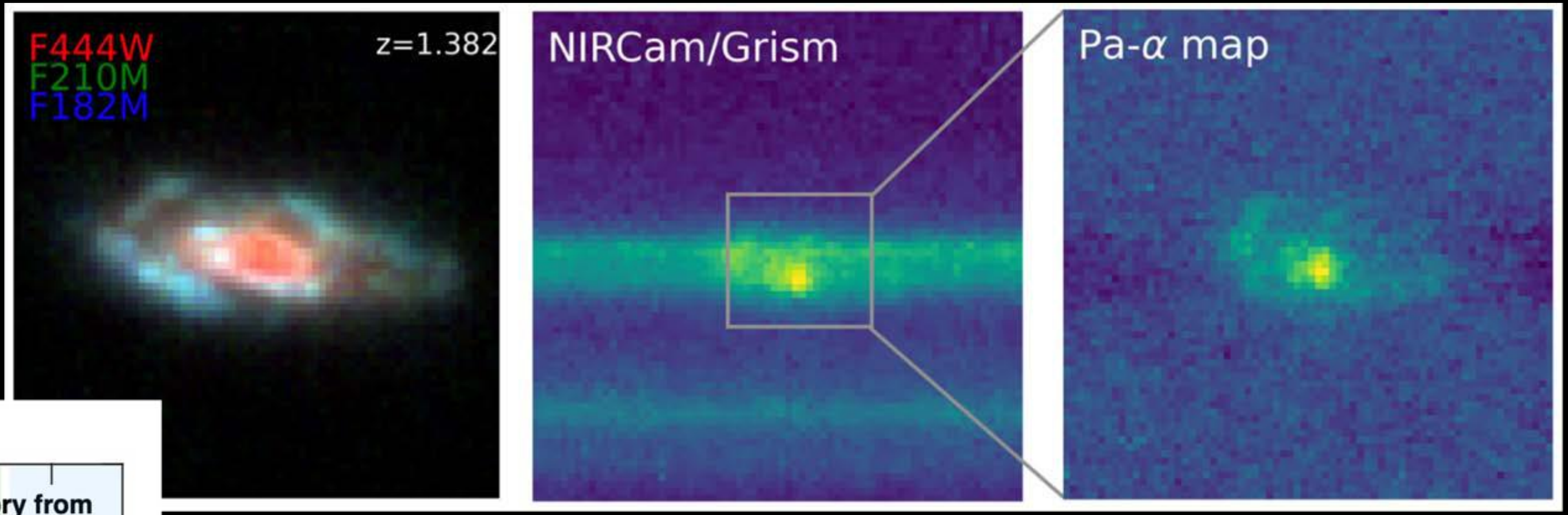
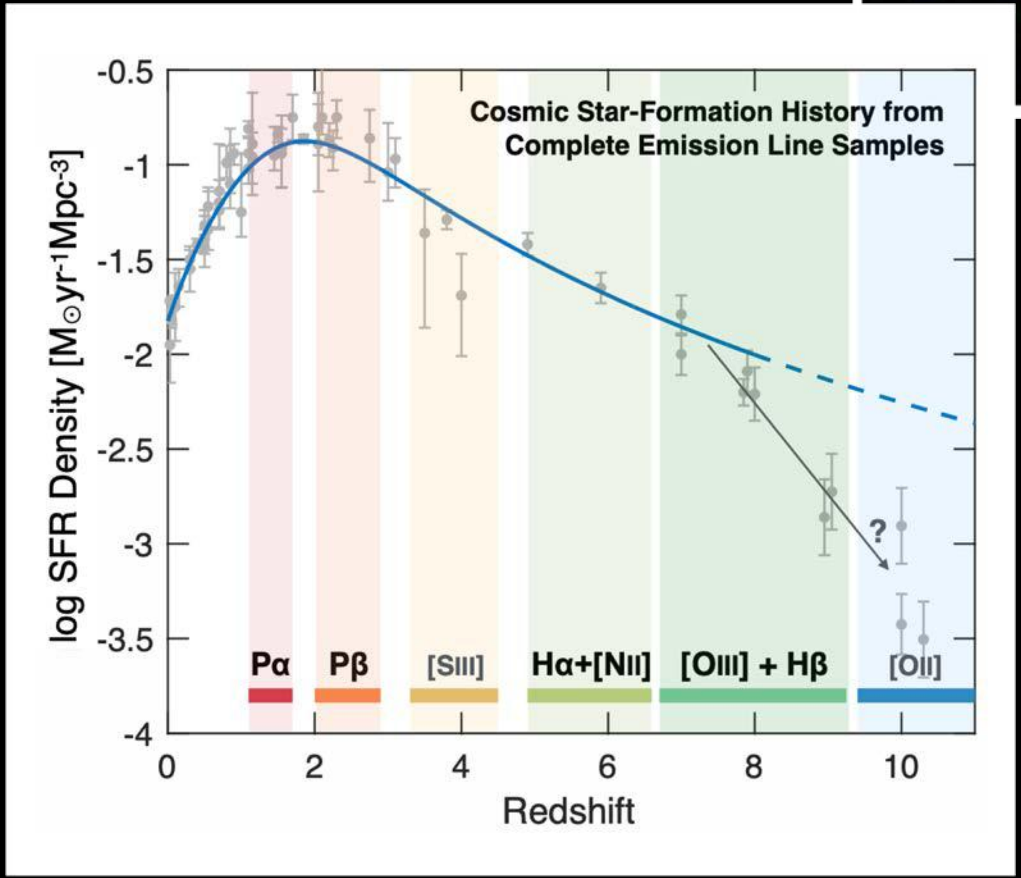
some examples of results from FRESCO that only JWST could do



spatial distribution of star formation from emission line maps from FRESCO can be mapped for galaxies over a wide-range of redshifts
left is FRESCO image map in the FRESCO-S field
middle is NIRCam/grism spectra for a dusty z = 1.38 galaxy
right is spatially resolved Paα map



mapping the cosmic star formation history from *complete* emission line redshift samples that cover the contentious z>9-10 region, through reionization to later times through the peak of the star formation at z~2-3, including dust-obscured samples that were not possible before

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stellar mass density in galaxies from JWST

the stellar mass density is the integral of past star formation

– at very early times the trend of SMD(z) and its extrapolation will provide an indication of the likely time of early galaxy buildup and constraints on "first galaxies" –

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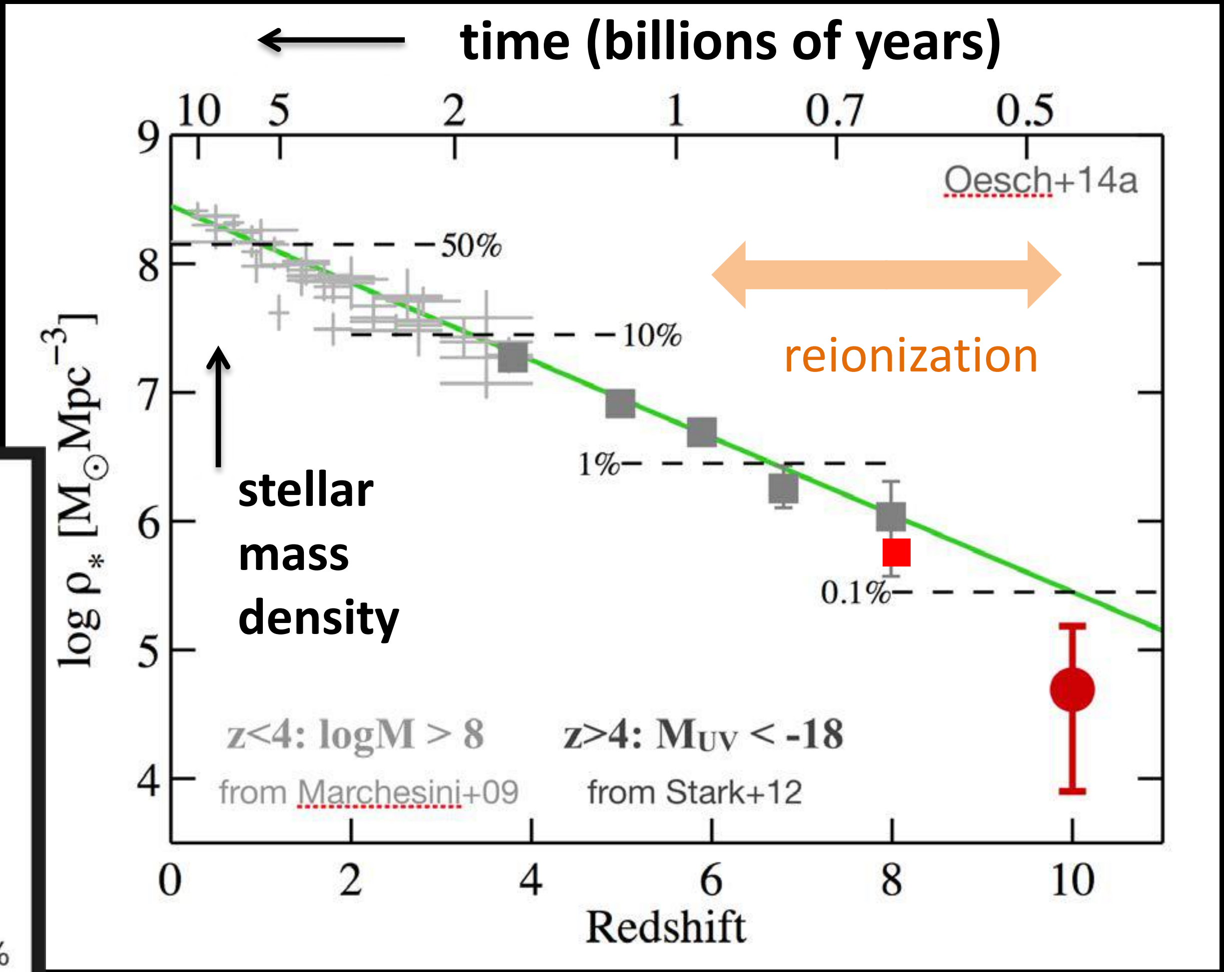
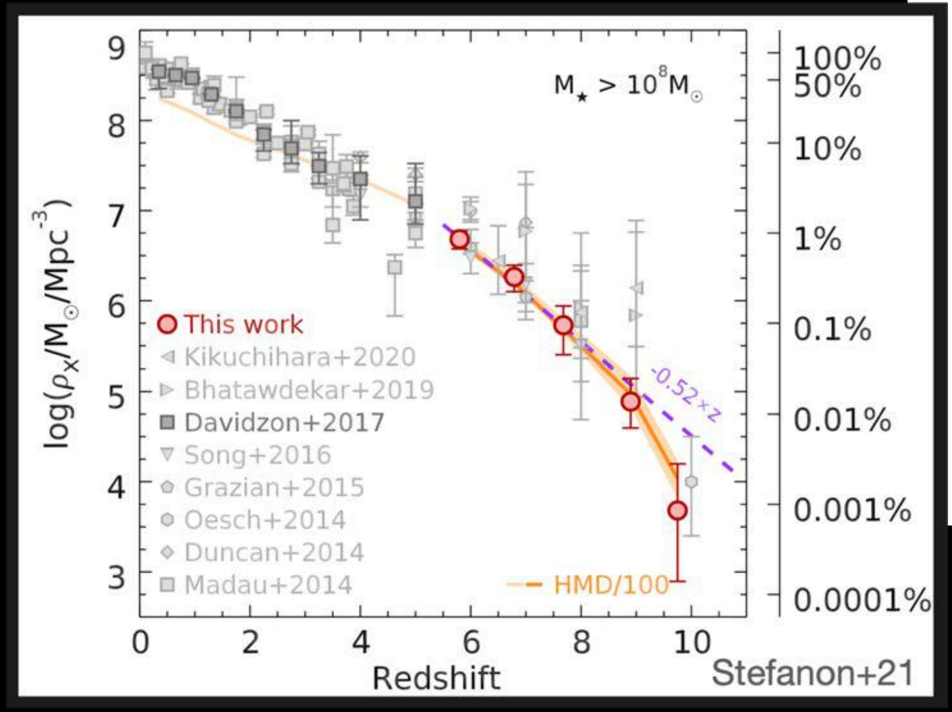
stellar mass density evolution



Oesch+2014



Stefanon+2021

only ~2% of stellar mass density built up by the end of reionization

only ~0.3% at the peak of reionization

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JWST is adding greatly to the stellar mass density discussion but somewhat confusingly…

"HST dark" galaxies not seen before

unclear trends in star formation rate density at $z>9$-10

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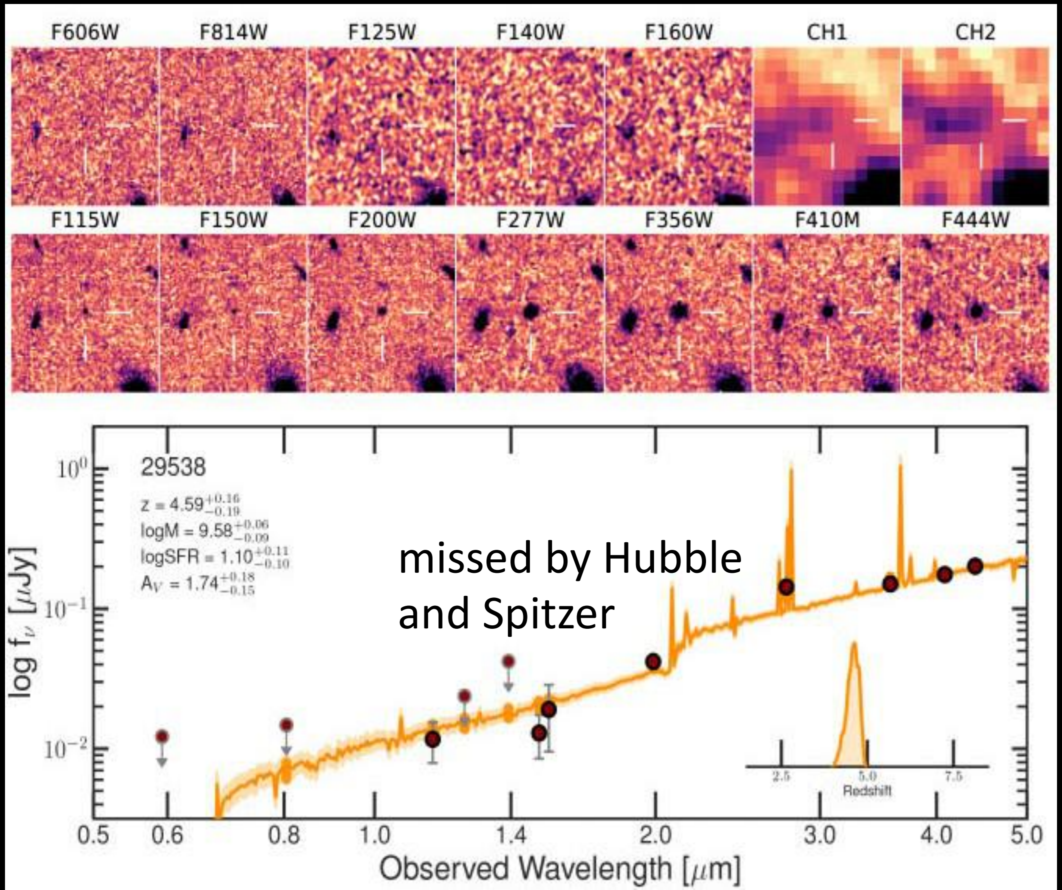
HST "Dark" Galaxies

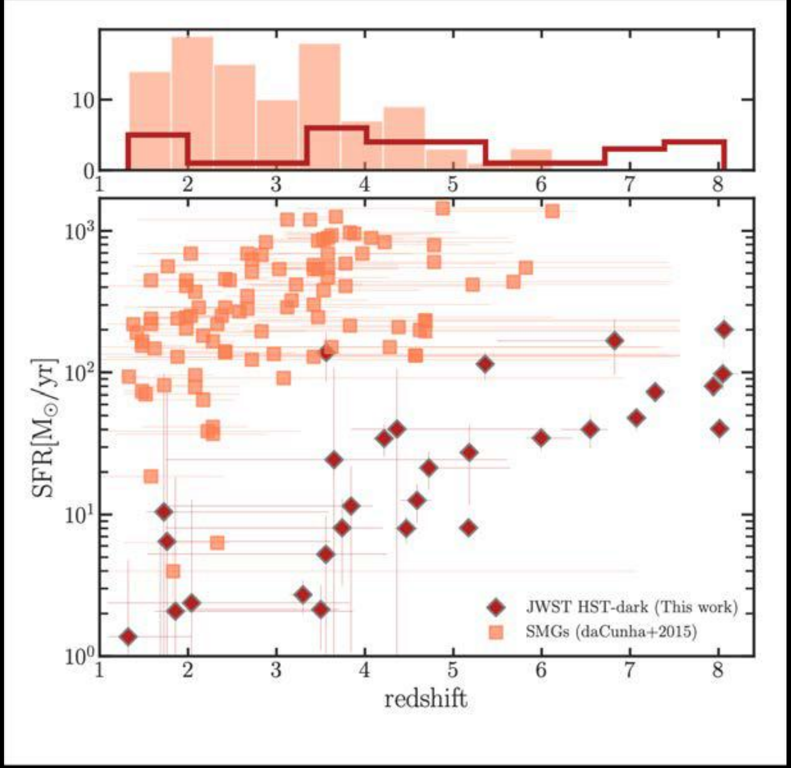


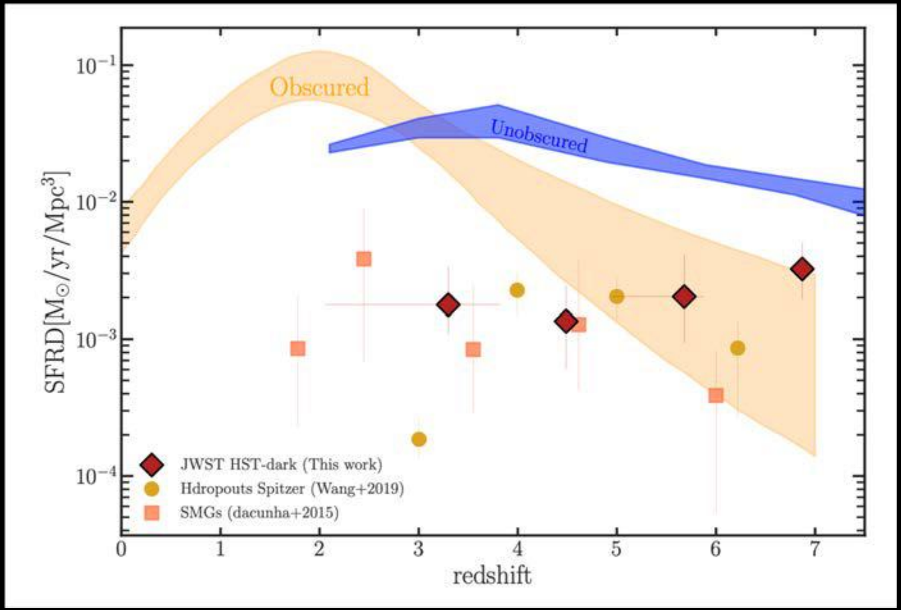
Hubble and Spitzer

JWST

missed by Hubble and Spitzer

star formation rate of dark galaxies compared to massive submm galaxies





star formation rate density of dark galaxies

JWST is revealing massive galaxies in the reionization epoch that have escaped detection with Hubble and Spitzer – their contribution to the stellar mass density is significant but not yet fully quantified

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the enigmatic situation with Hubble and Spitzer for high redshift galaxies to z~10 (480 Myr)

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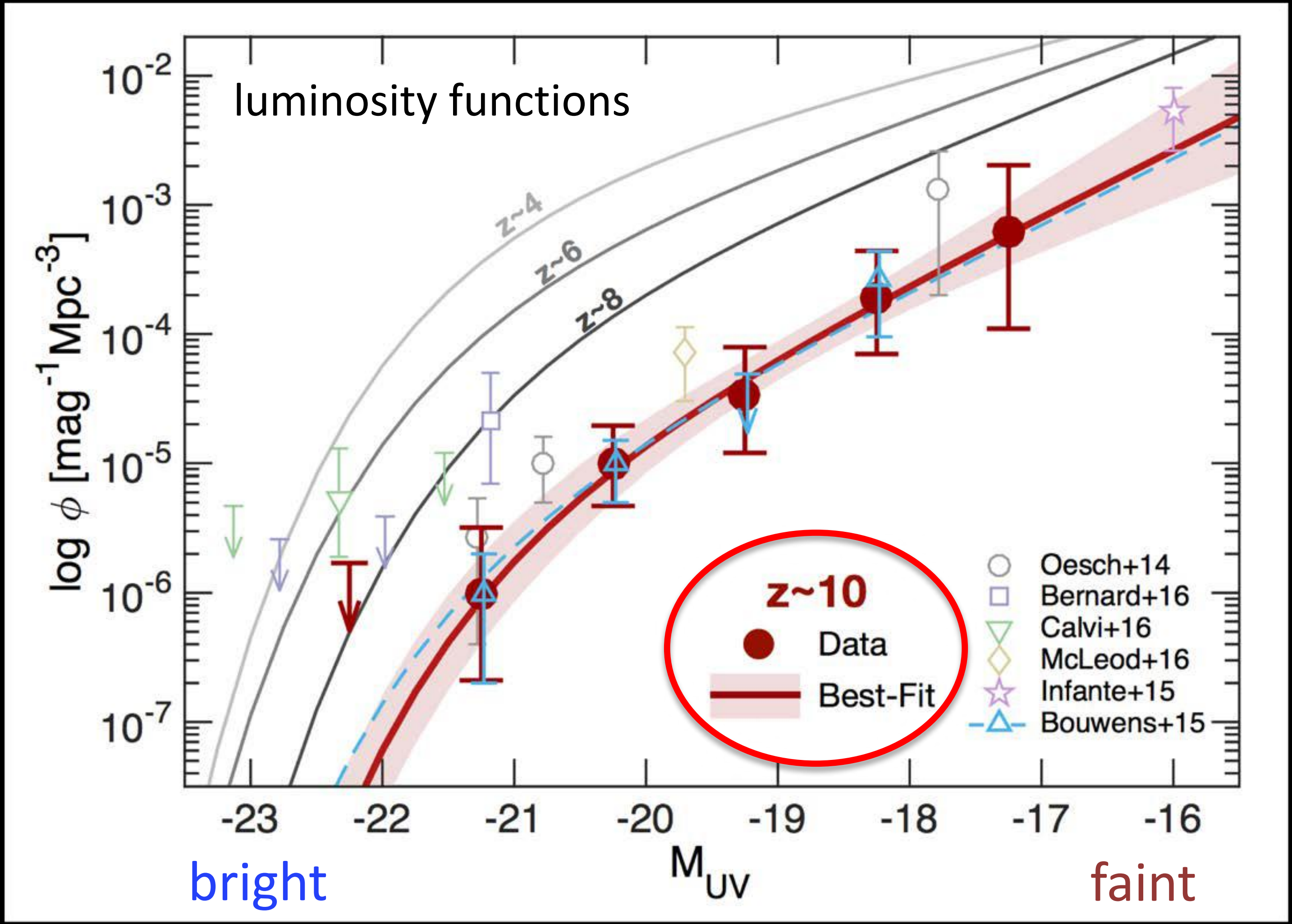
z~10 (500 Myr) galaxies are hard to find!



8 years of WFC3/IR imaging

searched every WFC3/IR dataset but we find only 9 galaxies at ~500 Myr

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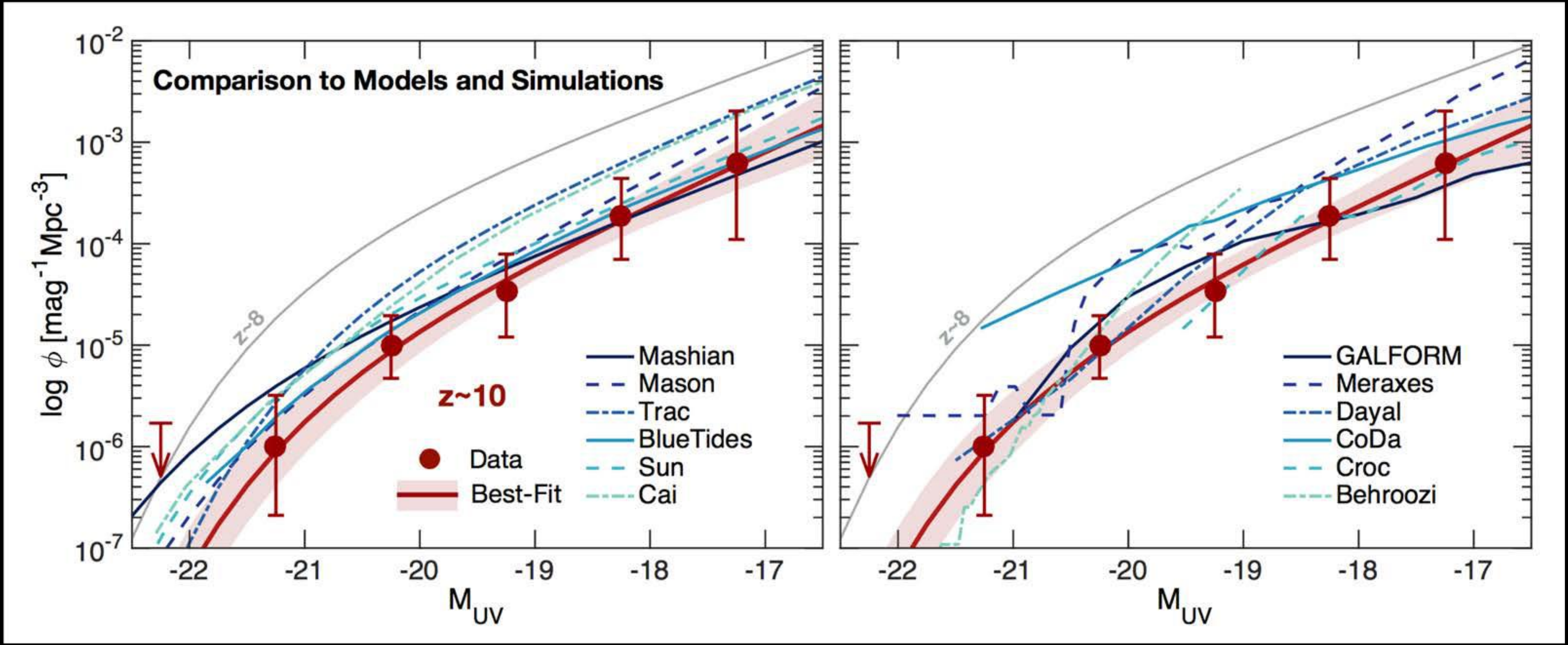
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

model comparisons – the luminosity function at z~10



considerable spread

shape matches (broadly) to models –

but models are consistently high

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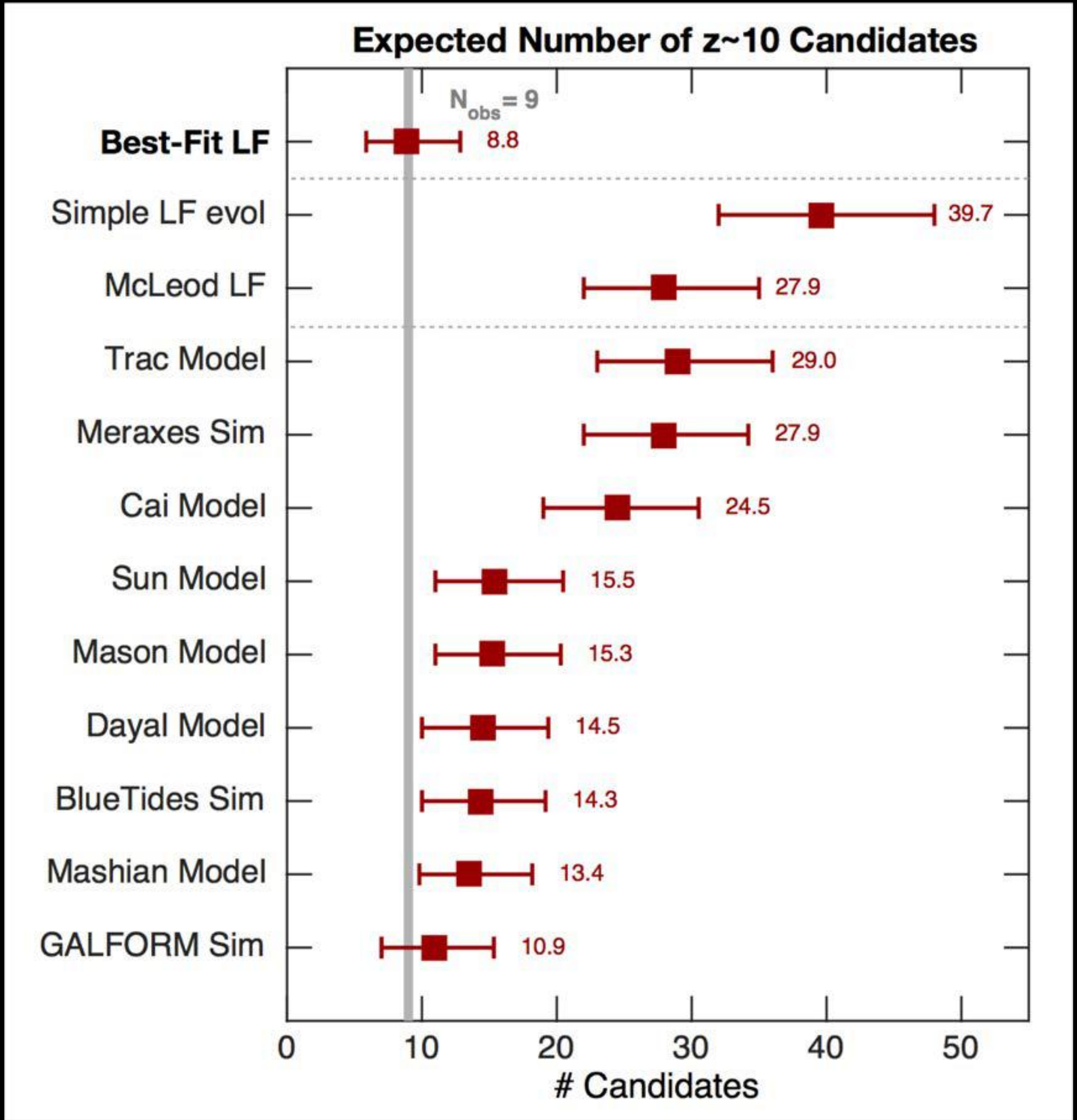
the case of the missing z~10 galaxies

number of z~10 galaxies from
"observed luminosity function"



the situation at z~10 is unexpected

the numbers of objects is smaller than predicted by models – the offsets are quite systematic

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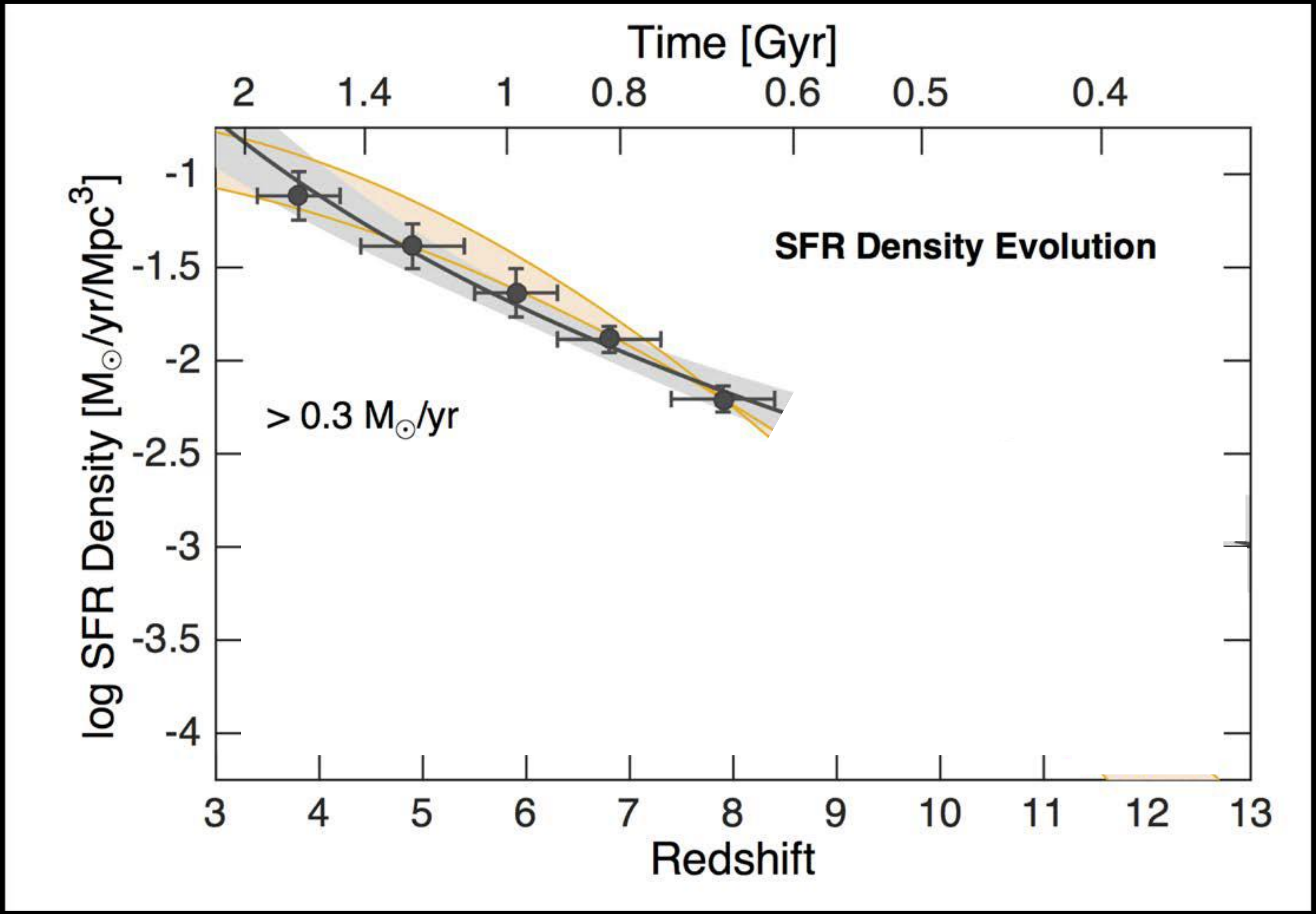
the star formation rate density to z~8 (650 Myr)



Oesch+2013,2014,2017

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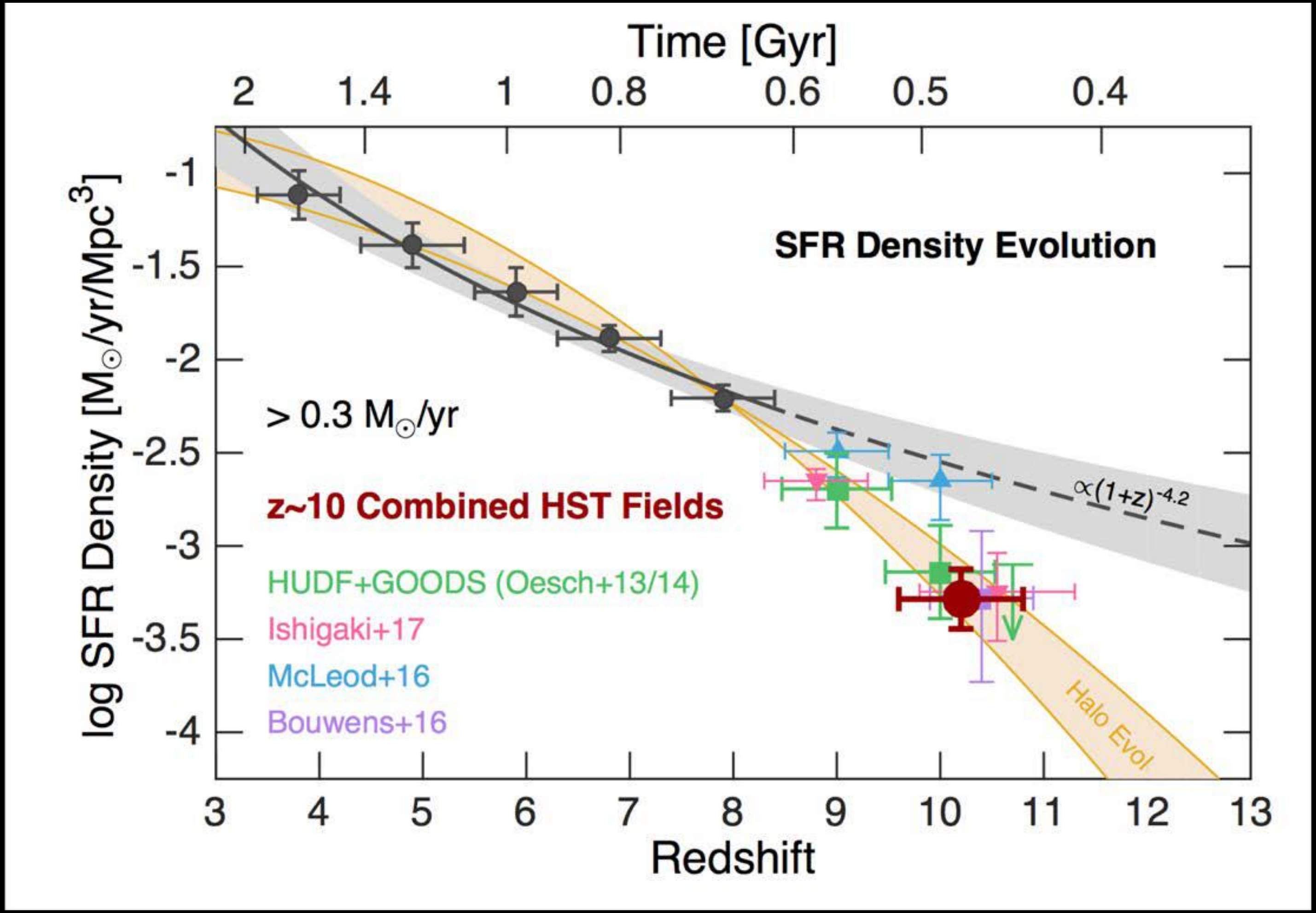
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

"accelerated evolution" – the star formation rate density at z~9-10

a trend to lower SFRD at z>8

"accelerated evolution"



Oesch+2013,2014,2017

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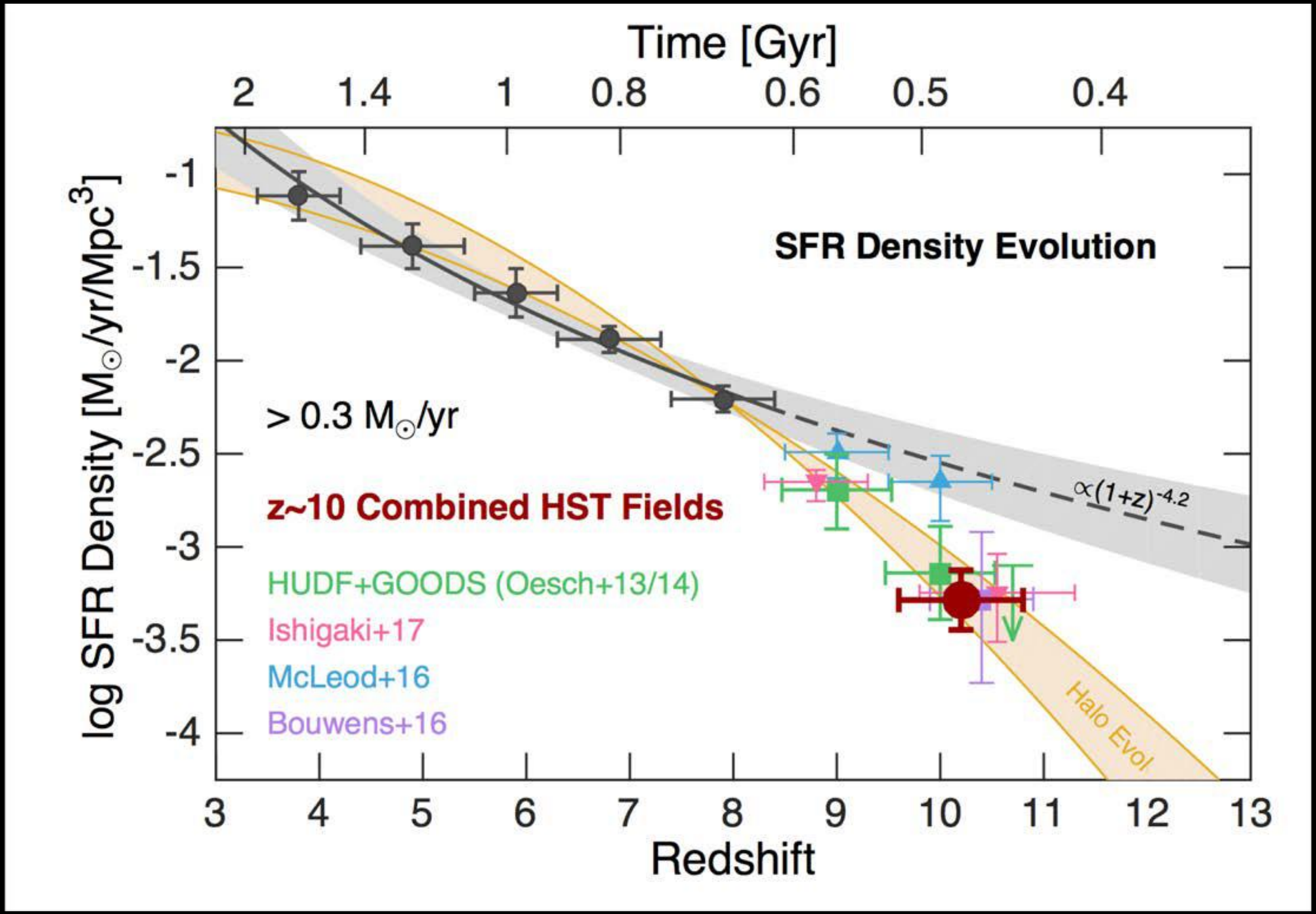
see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

"accelerated evolution" – the star formation rate density at z~9-10

clearly a trend to lower SFRD at z>8

"accelerated evolution" is actually consistent with the expected buildup* of dark matter halos over that time

*dark matter halo growth (>~10^{10} $M_{\odot}$) from HMFcalc – Murray+2013



Oesch+2013,2014,2017

gdi

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"accelerated evolution" – the star formation rate density at z~9-10

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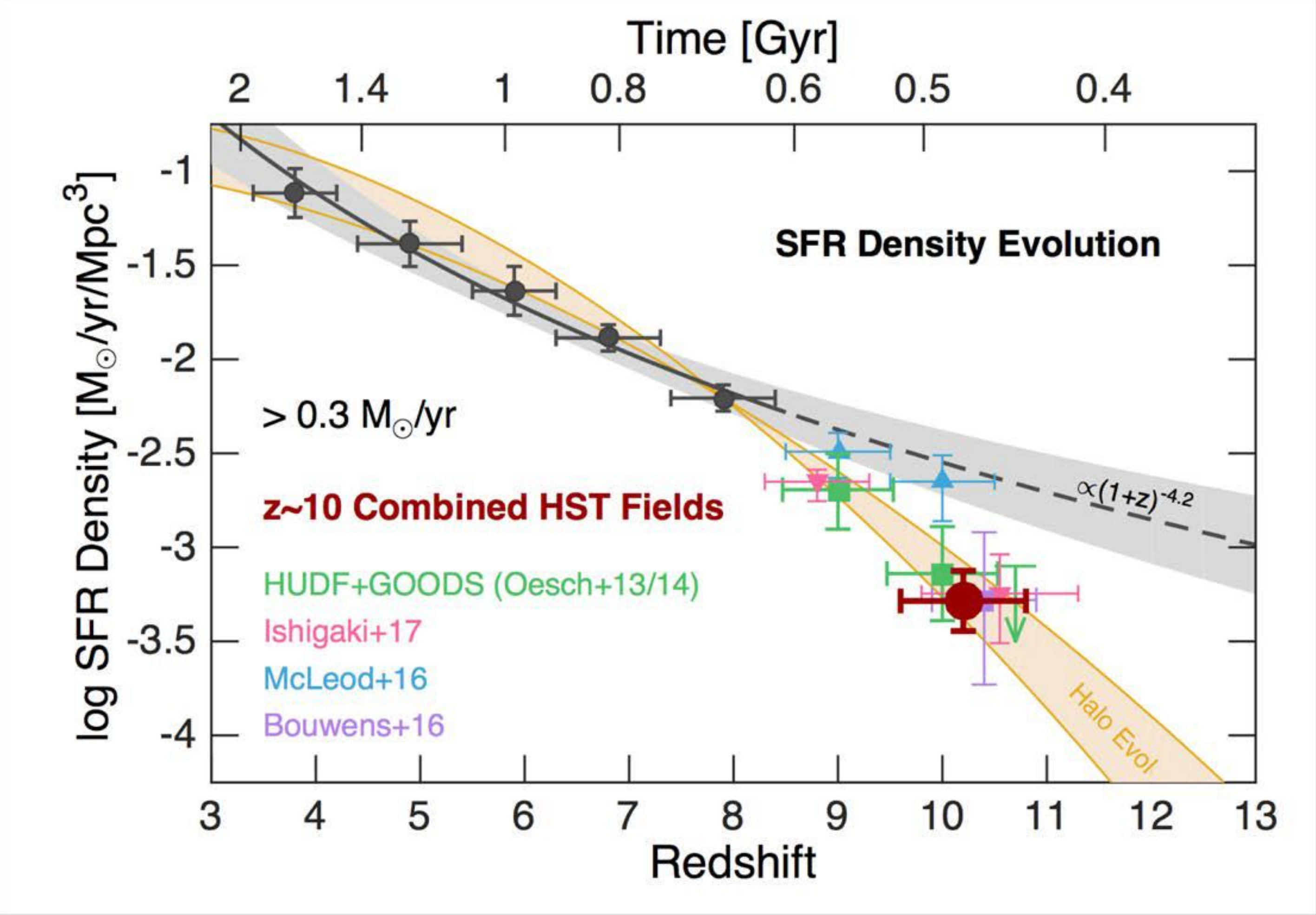
*dark matter halo growth (>~10^{10} $M_\odot$) from HMFcalc – Murray+2013

note: this result also indicates that there is no evolution in Star Formation Efficiency (SFE) with cosmic time



Oesch+2013,2014,2017

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see also: Zheng+2012; Coe+2013; Bouwens+2013,15,16; Ellis+2013; McLure+2013; Ishigaki+2014,17; Infante+2015; Bernard+2016; Calvi+2016; McLeod+2016

model comparisons – the star formation rate density at z>6

note that there is a large range of shapes/slopes from the models!

we need new/better observations to guide the models…

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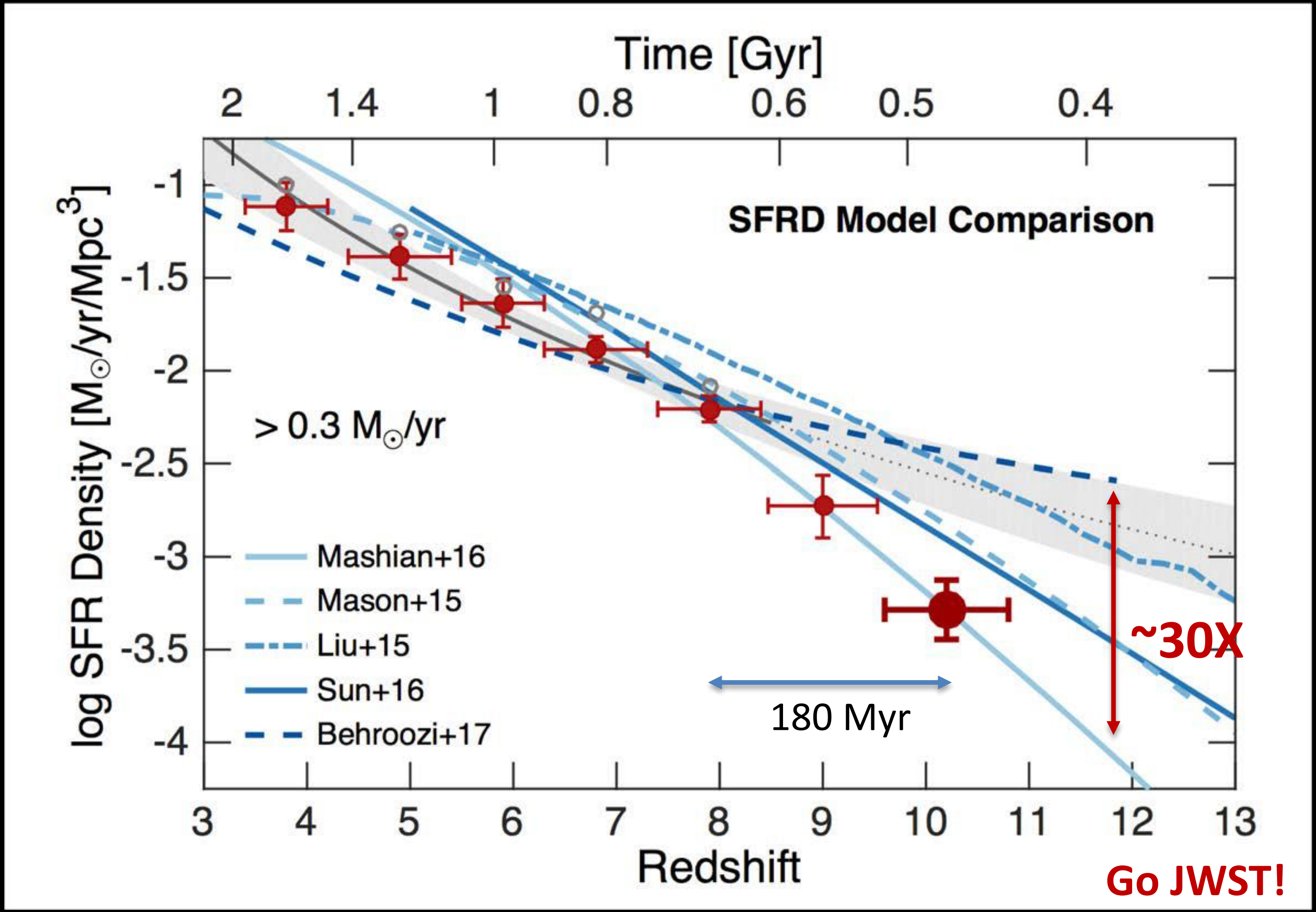

see also: Zheng+12, Coe+13, Bouwens+13/16/18, Ellis+13, McLure+13, Ishigaki+14, McLeod+16, Bowler+20

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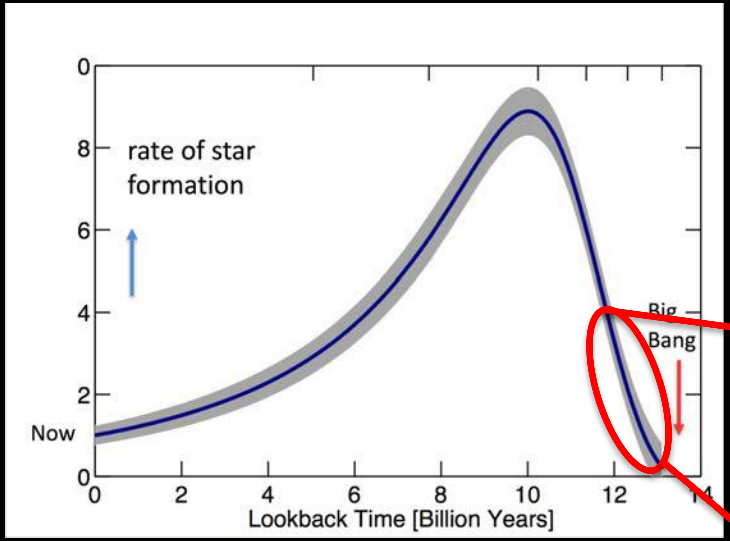
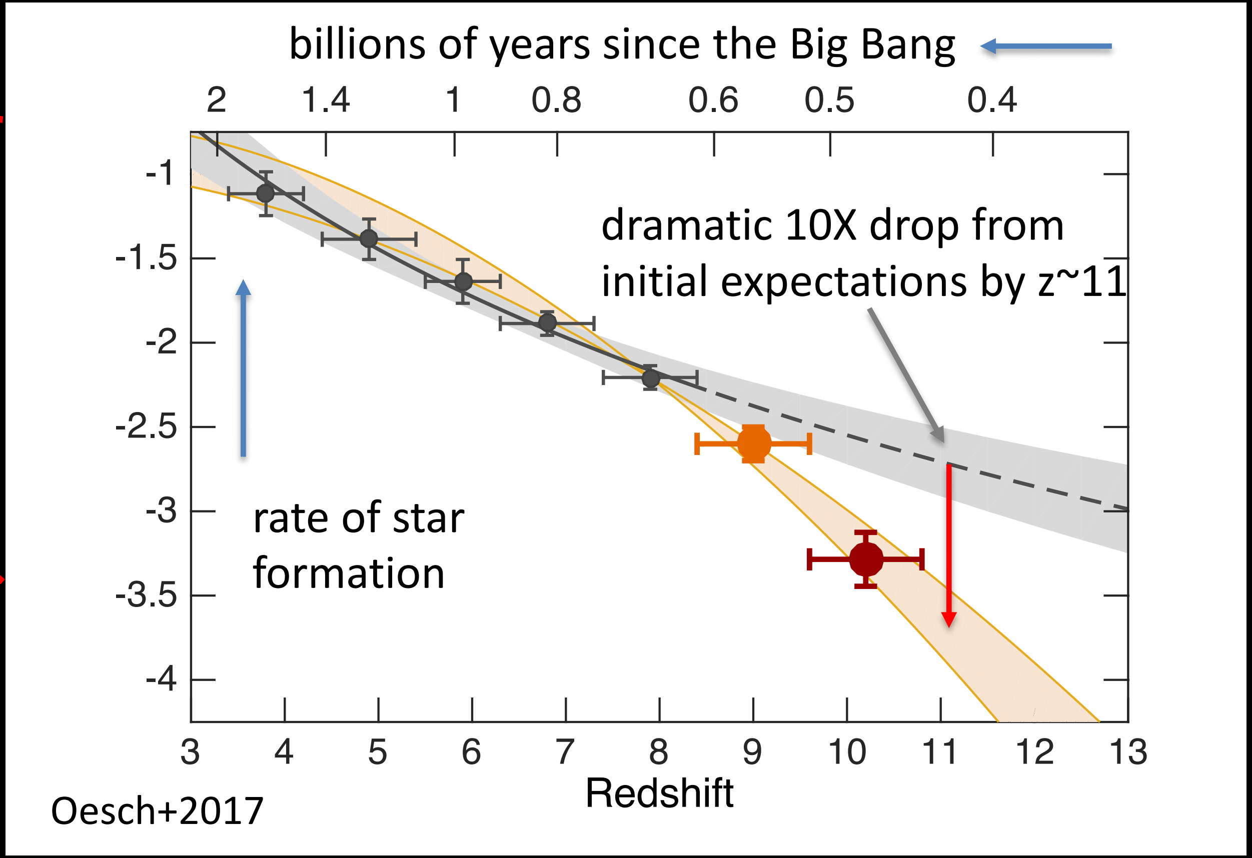
way fewer galaxies than expected at redshift 10!



there are far fewer galaxies than we (naively) expected at early times



galaxies appear to be evolving rapidly earlier than 650 million years

see also: Zheng+12, Coe+13, Bouwens+13/16/18, Ellis+13, McLure+13, Ishigaki+14, McLeod+16, Bowler+20

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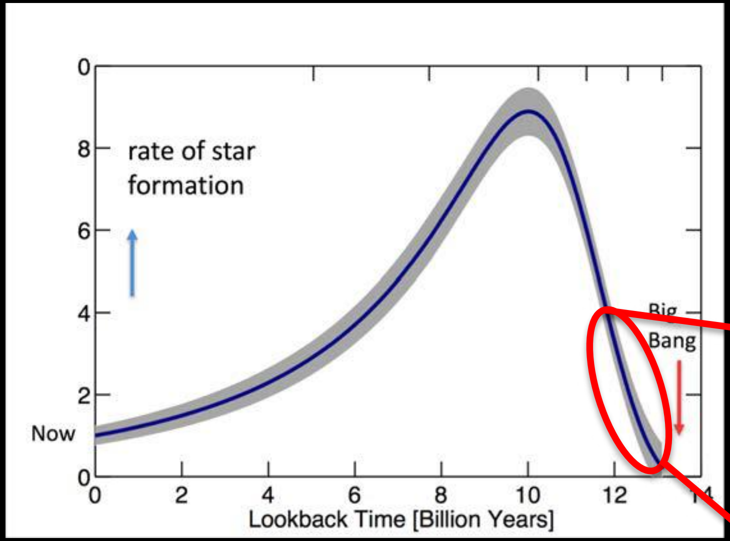

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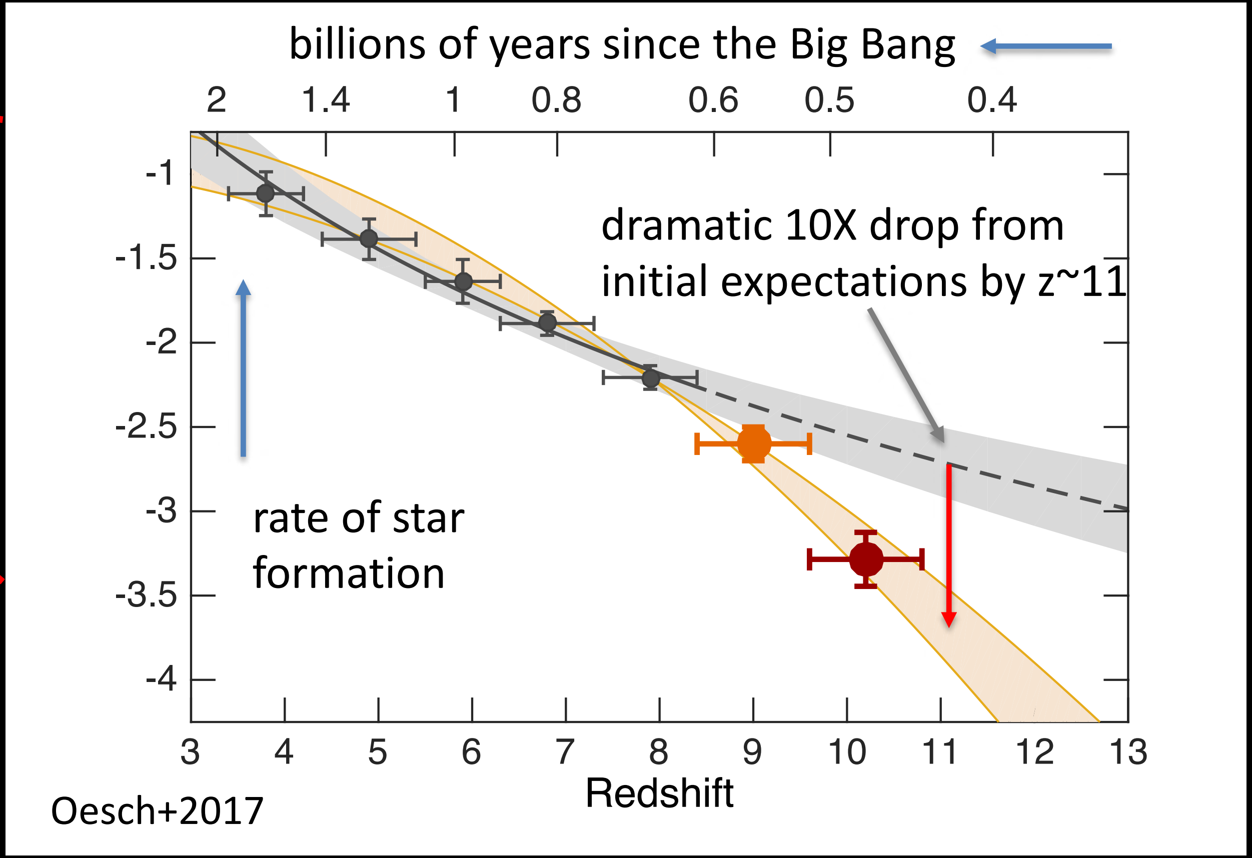

galaxies appear to be evolving rapidly earlier than 650 million years

“accelerated evolution” has been controversial
but nonetheless is consistent with stellar mass growing as the dark matter halos

see also: Zheng+12, Coe+13, Bouwens+13/16/18, Ellis+13, McLure+13, Ishigaki+14, McLeod+16, Bowler+20

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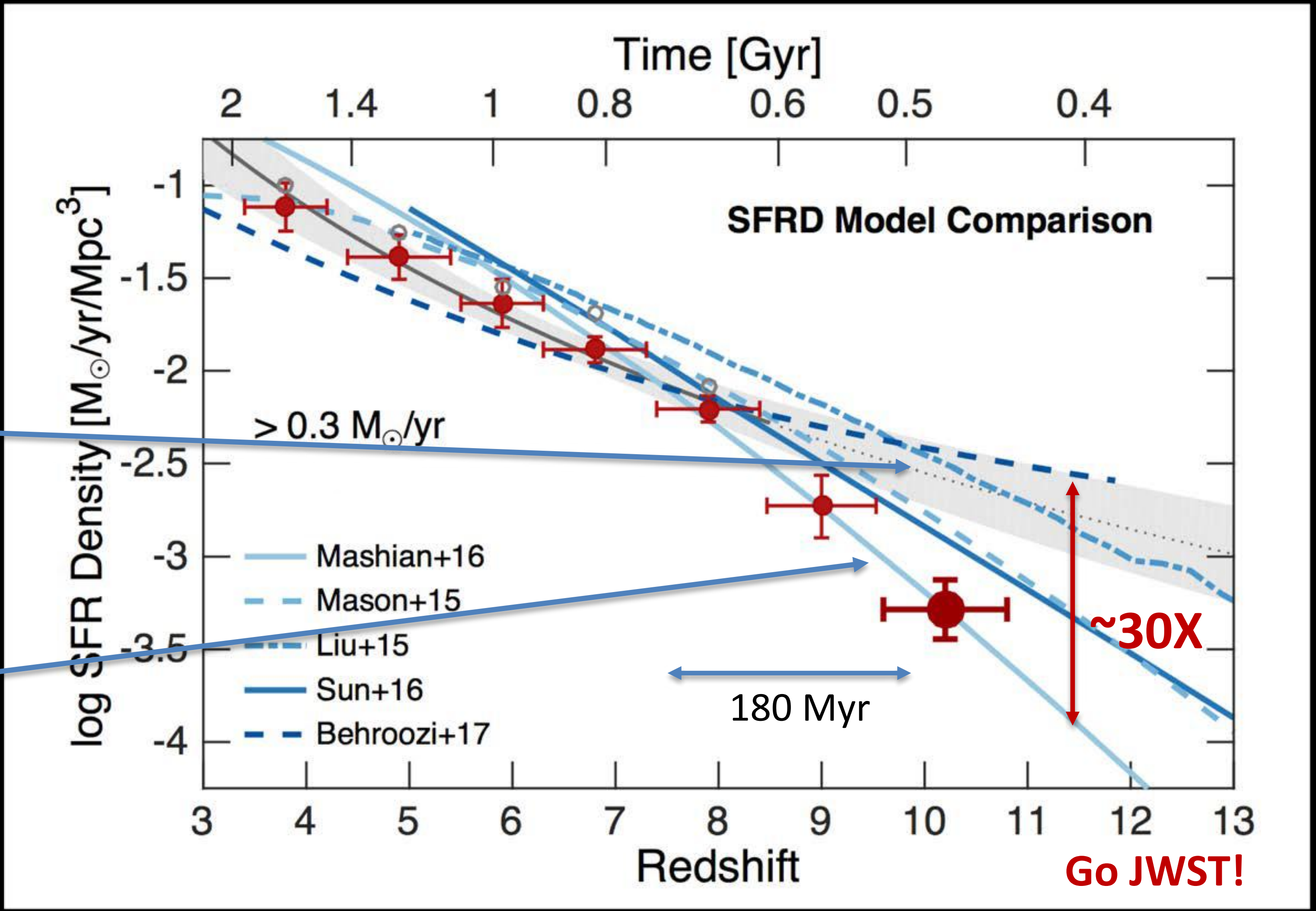
model comparisons – the star formation rate density at z>6

the models imply very different star formation histories at z>9-10 in the first 500 Myr

if galaxies lie along this dashed or dotted curve it means that the stellar mass is growing more rapidly until z~9-10 than the growth of the dark matter halos
i.e. increasing star formation efficiency

if galaxies lie along this solid curve it means that the stellar mass grows along with the growth of the dark matter halos consistently over time
i.e. constant star formation efficiency



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model comparisons – the star formation rate density at z>6

the models imply very different star formation histories at z>9-10 in the first 500 ...

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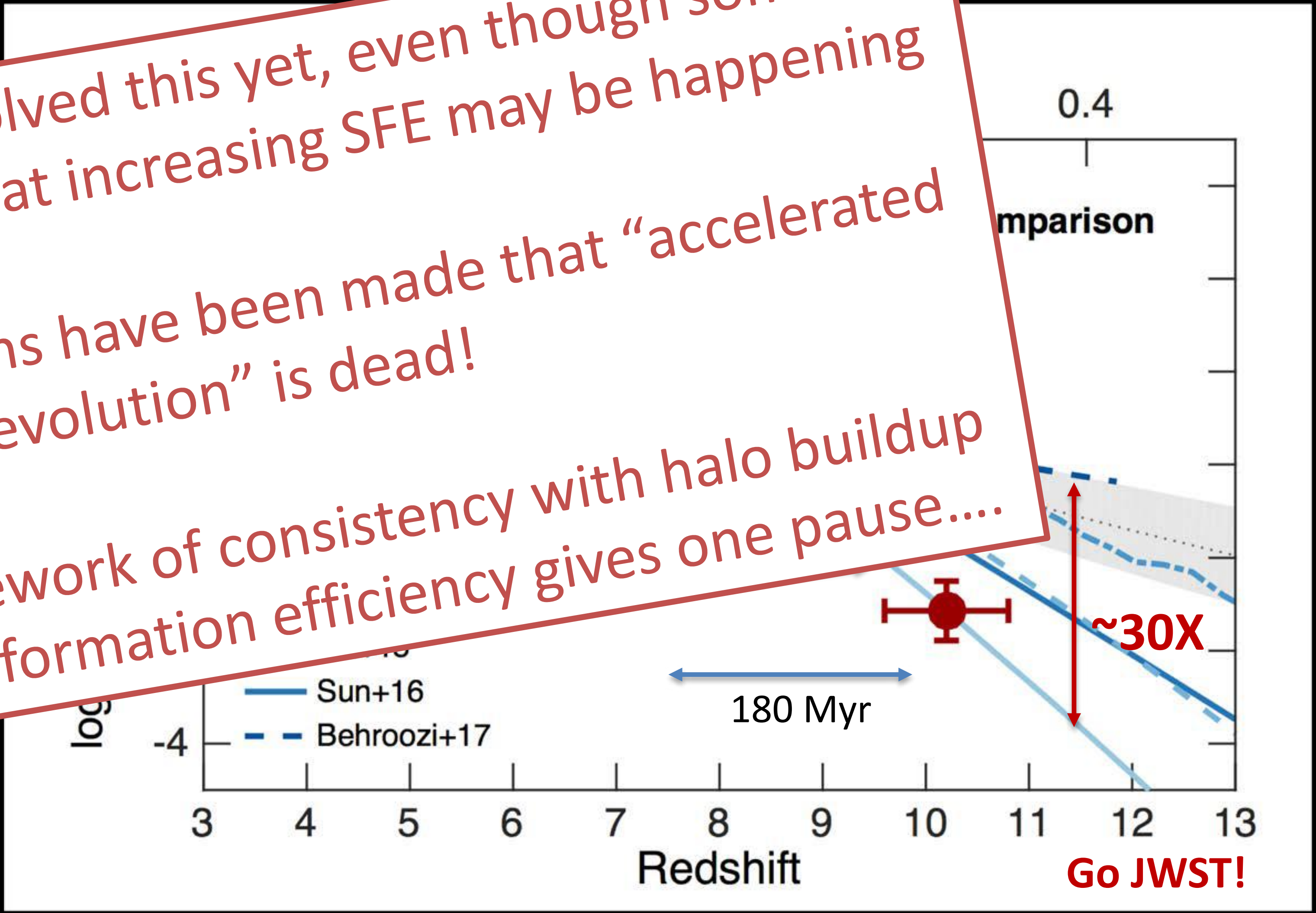

JWST has not resolved this yet, even though some evidence suggests that increasing SFE may be happening

some stronger claims have been made that "accelerated evolution" is dead!

the physical framework of consistency with halo buildup and constant star formation efficiency gives one pause....

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model comparisons – the star formation rate density at z>6

the models imply very different star formation histories at z>9-10 in the first 500

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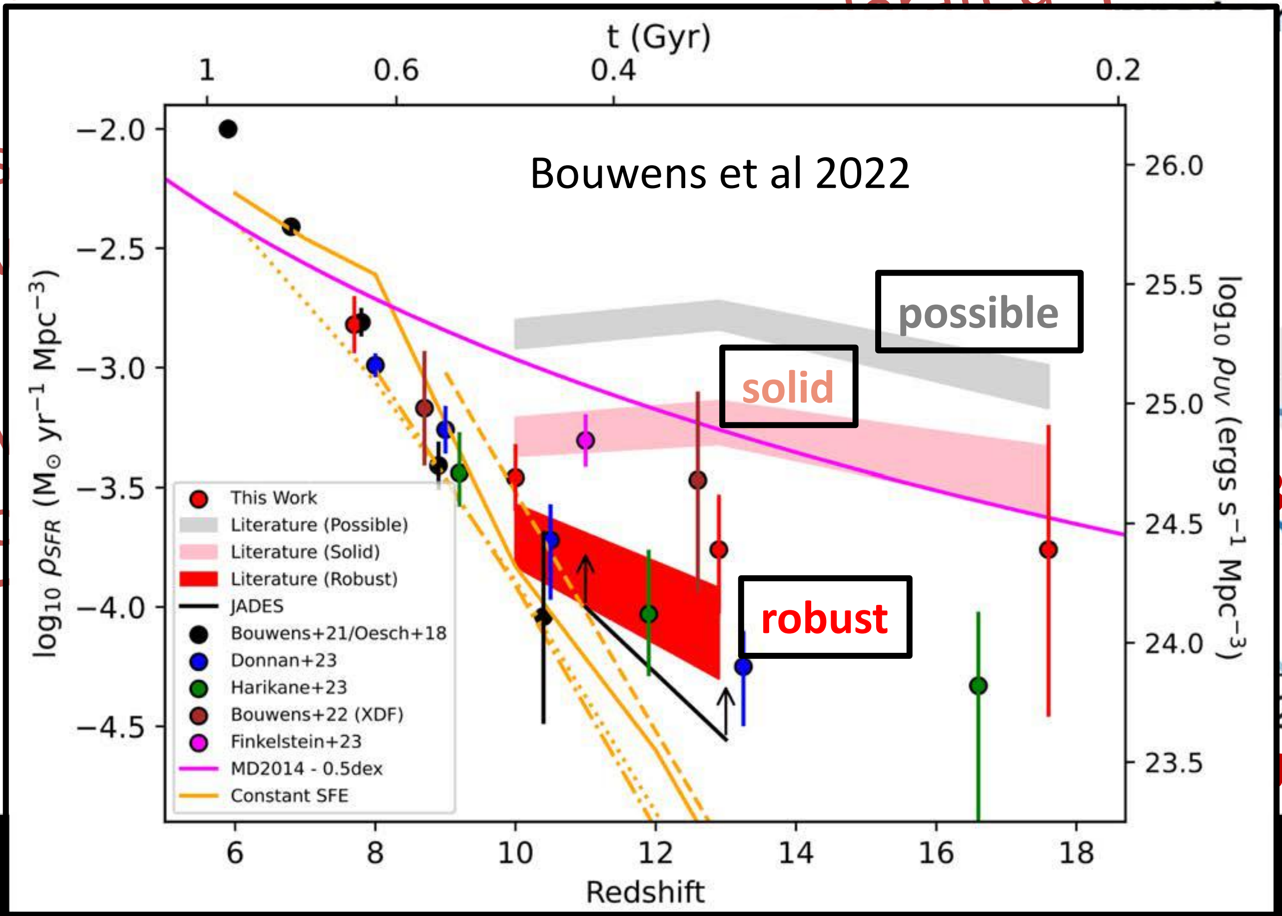

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JWST!

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model comparisons – the star formation rate density at z>6

the models imply very different star formation histories at z>9-10 in the first 500

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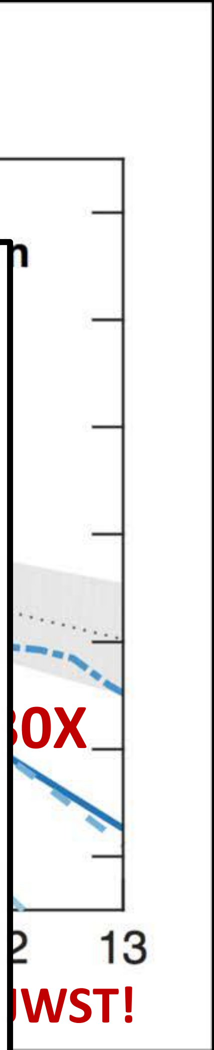

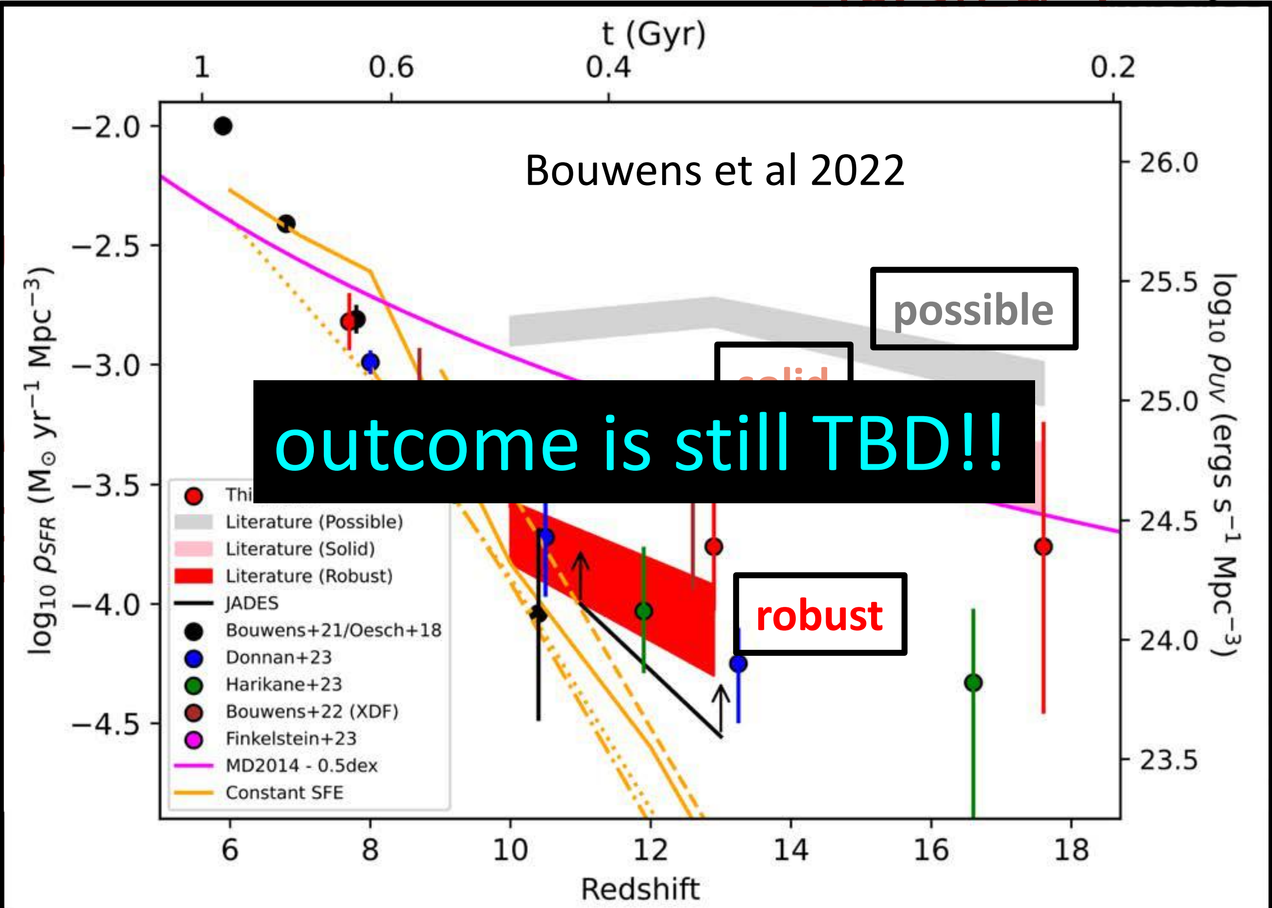

outcome is still TBD!!

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much learned about the earliest galaxies but a real puzzle has surfaced…..

something unexpected is going on with galaxies in the first 400-500 million years

initially a number of bright galaxies just 200-250 million years from the Big Bang were reported
these initial “discoveries” are now likely to be mostly wrong – we did not properly interpret what we were seeing

but what has continued to be striking is that we are finding far more bright galaxies
just 300-500 million years after the Big Bang – we do not understand what is going on

speculation is running rife, much of which I suspect is wrong, but this is one of the
fascinating results from Webb in 2022/23 and one that still is puzzling astronomers

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Bottom line re bright early galaxies:

the very bright early galaxies seen in the first 500 Myr at z>10 **are** an enigma

but bright ≠ massive (necessarily!)

[1] many of the galaxies claimed to be at z>10 will be found to be at z<10 – too many poor-quality photometric redshifts

[2] black holes will likely be larger and more prevalent and AGNs could contribute a large fraction of the light

[3] the stars (stellar populations) could be very different with much more light from a given mass (extremely luminous stars: Pop III – and other types of massive stars)

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I suspect a top-heavy IMF at early times and a lower total stellar mass will prove to be common; and that AGNs will be more common than expected
– for the subset of z>10 galaxies that are really at z>10 –

my prediction is that the issues/questions around the very bright galaxies in the first 500 Myr will be resolved without needing to impact our current standard cosmology

remember Occam's Razor – first evaluate the simplest, least disruptive hypothesis, and then the next least disruptive to our established knowledge and understanding, and so on….

ΛCDM (Lambda CDM) cosmology is safe (for the moment)…

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JWST has only just got started in revealing the nature of galaxies in the first 500 Myr at z>10!


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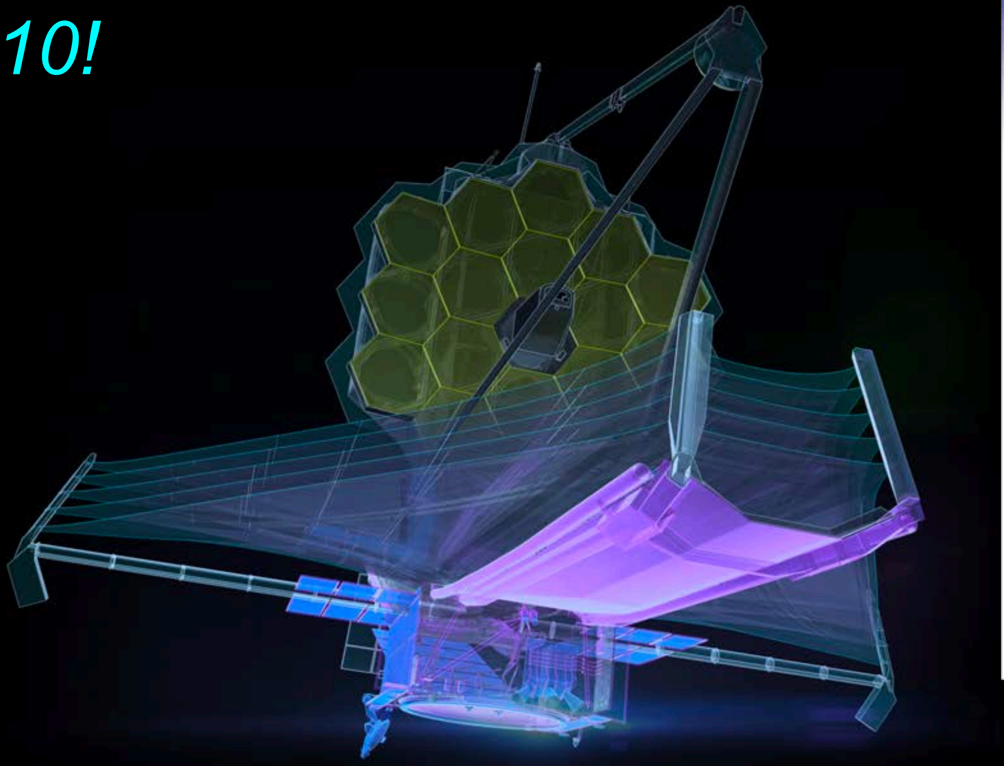

the question remains ⇒
*what really **is** going on in galaxies in the first ~500 Myr?*

N3AS Lecture 2

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