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

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

N3AS Lecture 2
The Science Promise Now Being Realized After JWST’s Decades of Challenges

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

N3AS Lecture 2
the first amazing science images from JWST
July 12 2022

JWST (“Webb”) is our infrared “Hubble on steroids”
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
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
JWST is exploiting its incredible infrared sensitivity compared to the ground to reveal a wealth of galaxies, and diagnostics, in the first Gyr.
how we find and measure redshifts when we just have images
Redshifts ("z")

Hydrogen gas in the universe absorbs the bluest light (ultraviolet) light from galaxies. To find the break and determine how fast the galaxy is moving, we look at the change in wavelength, which gives the redshift.

- **z=6** spectrum: More hydrogen gas absorbs even more of the bluest light, shifting the spectrum more towards the red end.
- **z=8** spectrum: Even more hydrogen gas absorbs the light, causing the spectrum to shift even more towards the red end.
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
ACS+WFC3/IR: efficient redshifts to $z \sim 11$

*xdf.ucolick.org/*
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

adapted from Finkelstein 2016

← JWST covers this full range of wavelengths →
example of JWST NIRCam bands and redshifts
FRESCO (see later) in bold color

from Oesch et al 2023
spectral energy distributions – SED
challenge getting large samples

requires a lot of images in a lot of filters
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

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

BJ2021 – before JWST
eXtreme Deep Field (XDF) buildup movie

https://xdf.ucolick.org
size comparison:

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

Bly = billion light-years
the global stellar mass and cosmic star formation rate (SFR) density evolution

evolution of the global stellar mass density over 13 billion years

only a few measurements at $z > 6$

First Gyr

Madau & Dickinson 2014
cosmic star formation over all time

revealing the star formation rate density over 96% of time

stable characterization archaeology
diversity complexity evolution transition
dramatic growth extreme SF

figure credit Pascal Oesch
the first Gyr – the time when galaxies were born and began to grow

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

from the Millennium simulation

Springel+2005

rapid growth of galaxy-scale halos

z~10 to z~6

~500 Myr to ~1 Gyr

the reionization epoch

~30X
searching for the first galaxies

insights from Planck!
reionization epoch – Planck 2016/2018 results

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

reionization simulation: Alvarez et al. 2009
...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 $z \approx 10... (<1\% above z \approx 15)$

...an early onset of reionization is strongly disfavored by Planck data
Reionization constraints from Planck 2018

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

“...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”

Plank Collaboration Results I + 2018

Planck Collaboration VI+2018
For the first time we now know when galaxies started to really reionize the universe, this was around $z \sim 10$ or $\sim 500$ Myr.

"...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.
reionization history compared with observational astrophysical constraints

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

figure from Planck Collaboration XLVII + 2016

Bouwens+2015
Robertson+2015
Ishigaki+2015
reionization history compared with observational astrophysical constraints

"With the present value of $\tau$, 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 $M_{\text{UV}} < -17$ seems to be sufficient to comply with all the observational constraints without the need for high-redshift ($z = 10–15$) galaxies."

figure from Planck Collaboration XLVII + 2016
what constraints do we have on the first galaxies?

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


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 Labbé,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,9 and Andrea Weibel2

Castellano et al paper also submitted same day!


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

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

Naidu, Oesch et al 2022

NIRCam image of GLASS field
within weeks reports of large number of bright (massive?) early galaxies

some photo-z examples:
  \( z\sim17 \) (230 Myr): Donnan et al; Naidu et al
  \( z\sim20 \) (180 Myr): Yan et al
  \( z\sim16 \) (250 Myr): Atek et al;
  \( z\sim14 \) (300 Myr): Finkelstein et al

& massive “old” galaxies at \( z\sim8-10 \) (~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?
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 Ly\(\alpha\))
> poor templates (particularly with very strong emission lines)

Naidu et al 2022b paper on z\(^{\sim}17\) galaxy also found a z\(^{\sim}5\) photo-z solution, but low probability

first papers with redshifts indicated problems with photo-z (Zavala et al)
two of the z\(^{\sim}17\) objects actually at z\(^{\sim}5\)

NIRCam calibration issues also led to changes in photometric redshifts
**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).

Abell 2744 GLASS JWST/NIRCam

ALMA spectroscopic redshift: gives $z = 12.12$
Bouwens et al 2022b
analysis of the Photometric redshift results
Rychard Bouwen’s analysis** in late 2022 of photo-z results

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

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,1,2 Garth Illingworth,2,3 Pascal Oesch,3,4 Mauro Stefanon,5,6 Rohan Naidu6,7,8 Ivana van Leeuwen1 and Dan Magee2

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 $\sim 10–20$ per cent”

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

“robust” are rare, notably at $z>11$
Bouwens et al analysis of photo-z samples

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

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

UV luminosity density and star formation rate density (SFRD)
both "solid" and "possible" indicate high to extremely-high SFRD
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
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 Ly$\alpha$ 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$>\sim10$
and the standard assumptions
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
the HUDF/XDF has been a key region for studying the earliest galaxies for 20 years

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

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
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

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

Hubble UDF (exposure time: 11.3 days)  Webb (exposure time: 0.83 days)
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
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?
an excellent approach to get insights is to use Hubble’s z~11 galaxy GN-z11 as a pathfinder
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!

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).”
photometric redshifts – four $z \approx 10$ candidates in GOODS-N

$z \approx 10 \approx 500$ Myr

Oesch + 2014
Jiang+2021 – used Keck MOSFIRE and verified that GN-z11 is at $z=11$

Hubble spectrum revealed GN-z10-1 at redshift 11.1 (renamed GN-z11!)

Oesch + 2014, 2016

GN-z11 ≈ 420 Myr
the most distant galaxy found to date

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

Go JWST!

Oesch+2016

Model LF Predictions

Trac+15
Mashian+15
Mason+15

Does GN-z11 tell us something fundamentally new about early galaxy formation?

model luminosity functions

φ [mag$^{-1}$Mpc$^{-3}$]

10$^{-5}$ 10$^{-6}$

10$^{-7}$ 10$^{-8}$

10$^{-9}$ 10$^{-10}$

10$^{-11}$ 10$^{-12}$

10$^{-13}$ 10$^{-14}$

10$^{-15}$ 10$^{-16}$

10$^{-17}$ 10$^{-18}$

10$^{-19}$ 10$^{-20}$

10$^{-21}$ 10$^{-22}$

Absolute Magnitude $M_{uv}$ [AB mag]

-22.5 -22 -21.5 -21

-20 -19

-21 -22

-23

Redshift

0.4

0.5

0.6

0.7

0.8

0.9

Age of the Universe [Gyr]

0.5

0.25

0.5

1

2

4

UV Luminosity [$L/L_*(z=7)$]

0.06 (Bouwens et al. 2015b) ± 0.03

1.2 (Finkelstein et al. 2015) ± 0.08

0.002 (Finkelstein et al. 2015) ± 0.003

SUMMARY

The above estimates illustrate that our discovery of GN-z11 is unexpected, given current models.

The redshift and UV luminosities of known high-redshift galaxies are listed in Table 3.

The interpretation that we indeed detect the continuum flux from GN-z11 is supported by the morphology of the spectrum, the fact that the counts fall off more steeply than expected based on (1) the currently best estimates of the number of expected bright galaxies, and (2) based on theoretical models and simulations.

The grism spectrum is completely consistent with a very young, high-redshift galaxy at $z=11$, with aUV slope of $402$ Myr.

The most distant galaxy found to date

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

Essentially all reionization takes place since $z \approx 10 @ \approx 480$ Myr

GN-z11 is a pathfinder for the earliest galaxies.

Planck Collaboration Results I, VI 2018
but it is unexpected to find GN-z11 in such small search volumes/areas (by factor 10-100)?

BlueTides Waters+2016

simulations show that galaxies as massive as GNz-11 at z~11 are rare but not unexpected *per se*
what is going on at $z>10$ (500 Myr) in bright galaxies?

Let's 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
numerous "metal" emission lines (N, C, O, Ne, Mg)– and redshifted Lyα significantly enrichment at 440 Myr

GN-z11 observed by JWST NIRSpec

JWST NIRSpec

total time ~20 hrs
Bunker et al 2023

z = 10.603 (440Myr)

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. Bunker1,4, Aayush Saxena1,2, Alex J. Cameron1, Chris J. Willott3, Emma Curtis-Lake1, Peter Jakobsen1,6, Stefano Campana1, Renkui Sun2, Roberto Maiolino1,8,10,12, Boris Witsch1,10, Mirko Curto1,10,11, Francesco D'Incalci2,5,11,12, Gareth C. Jones1, Pierre Ferruit5, Santiago Arias5, Stephanie Chargel1, Jacopo Chevallard1, Giovanna Giardino1, Anna de Graaff1, Tobias J. Looij1,10, Nora Lützgendorf1, Michael V. Masuda1, Tim Rawle1, Hans-Walter Rix1, Bruno Rodriguez Del Pino1, Stacey Albers5, Eiichi Egami9, Daniel J. Eisenstein2, Ryan Eydslev1, Kevin Hinton1, Ryan Hasen1, Benjamin D. Johnson1, George Rieke1, Marcia Rieke1, Brian E. Robertson3, Irene Shivani1, Daniel F. Stark1, Fengwei Sun1, Sandro Tacchella1,10, Mengtao Tang1, Christina C. Williams1,2, Christopher N. A. Willmer1, William M. Baker2,3,6,8,46, Ralf Baume1, Ruchana Bhatwadekar1,2,26, Rebecca Bowker1, Kristian Bovy2,9,38, Zeyi Chen1,8, Chuan Cui26, Jakob M. Helou1, Zhiyuan J1, Joaowei Lyu1,8, Erica Nelson9, Eleonora Parlant1, Michele Perna1, Lester Sanders1,8,10, Jan Scholtz1,10, Katherine A. Sues1,8,10, Michael W. Topping3, Hannah Olof2,10, Imaan E. B. Wallace1, and Lily Whiter1
Universe is predominantly neutral at $z \approx 10$ (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 z~3

Michele Fumagalli, John M. O’Meara, and J. Xavier Prochaska

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 (≤10^4 M_{\odot}) clump of stars at z=6.6 (830 Myr) with extremely low metallicity Z < 0.004Z_{\odot}
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!

Maiolino et al 2023a detected weak HeII in GN-z11 halo possibly indicative of Pop III stars > 500 M☉

remains unclear how much Pop III contributes to the luminosity of early bright galaxies
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 $10^{9} \, M_{\odot}$

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

the challenge of building massive BHs at such early times (no x-ray detection)

Maiolino et al 2023b

GN-z11 most likely has a massive black hole $\approx 10^{6.2} \, M_{\odot}$
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?
JWST is a “spectroscopic powerhouse”
spectroscopy is where JWST will leave its mark on astrophysics
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 \⇒\ 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)
FRESCO survey design

NIRCam grism observations over 62 arcmin² in CANDELS/Deep fields
(2x4 mosaics over GOODS-North and South)

F444W grism R (2hr) + direct images (15min)
plus F182M + F210M images

**Imaging** sensitivity: \( \sim 28.2 \) AB mag (at 5\( \sigma \)) medium bands and F444W

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

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](https://arxiv.org/abs/2304.02026)
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
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 $z \sim 7$ 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”
some examples of results from FRESCO that only JWST could do

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
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” –
stellar mass density evolution

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

only ~0.3% at the peak of reionization
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
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.
the enigmatic situation with Hubble and Spitzer for high redshift galaxies to $z \sim 10$ (480 Myr)
z\sim10 (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 \sim 500 Myr

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

Oesch+2017
model comparisons – the luminosity function at z~10

considerable spread
shape matches (broadly) to models –
but models are consistently high

Oesch+2017
The case of the missing z~10 galaxies

The situation at z~10 is unexpected. The numbers of objects is smaller than predicted by models – the offsets are quite systematic.

Oesch+2017
the star formation rate density to $z \sim 8$ (650 Myr)
"accelerated evolution" – the star formation rate density at $z \sim 9-10$

a trend to lower SFRD at $z>8$

"accelerated evolution"

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 $z\sim 9-10$

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

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
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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

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

Oesch+2013,2014,2017
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...

Oesch+2017

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

Dramatic 10X drop from initial expectations by $z \approx 11$.

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

“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
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.

Oesch+2017

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

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

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Bouwens et al 2022
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robust possible

outcome is still TBD!!
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
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)
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)....
JWST has only just got started in revealing the nature of galaxies in the first 500 Myr at z>10!

Garth Illingworth
University of California
Santa Cruz

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