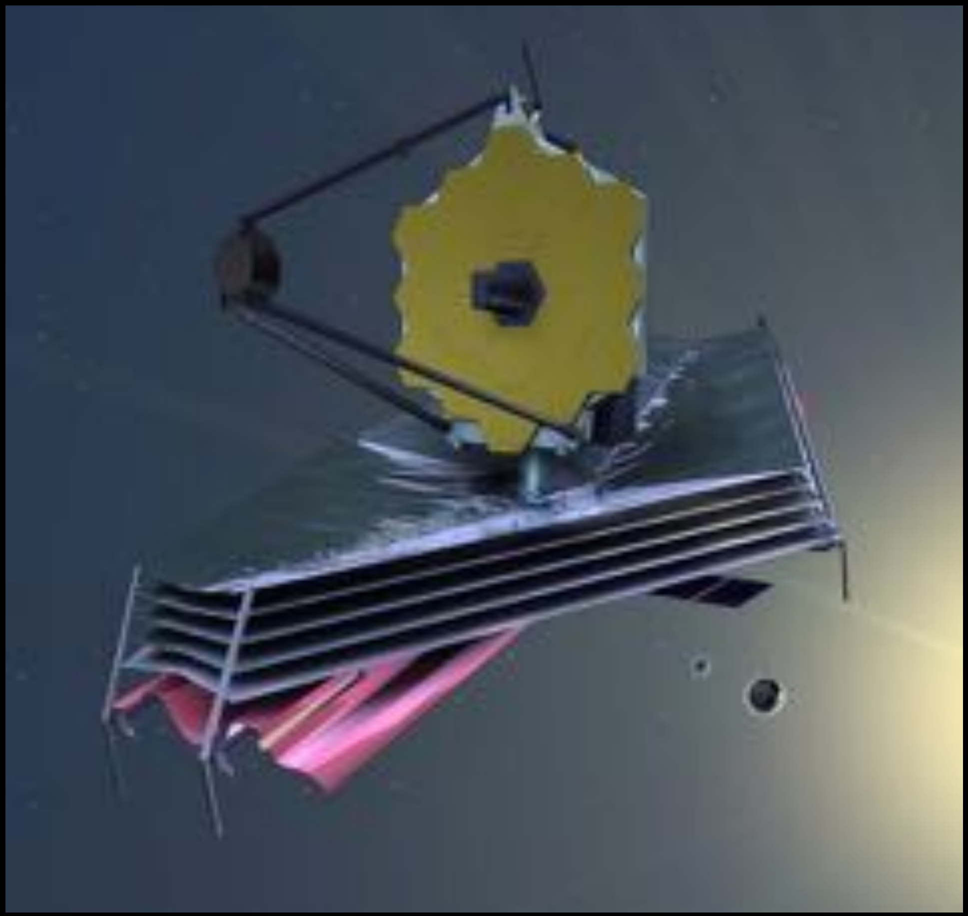
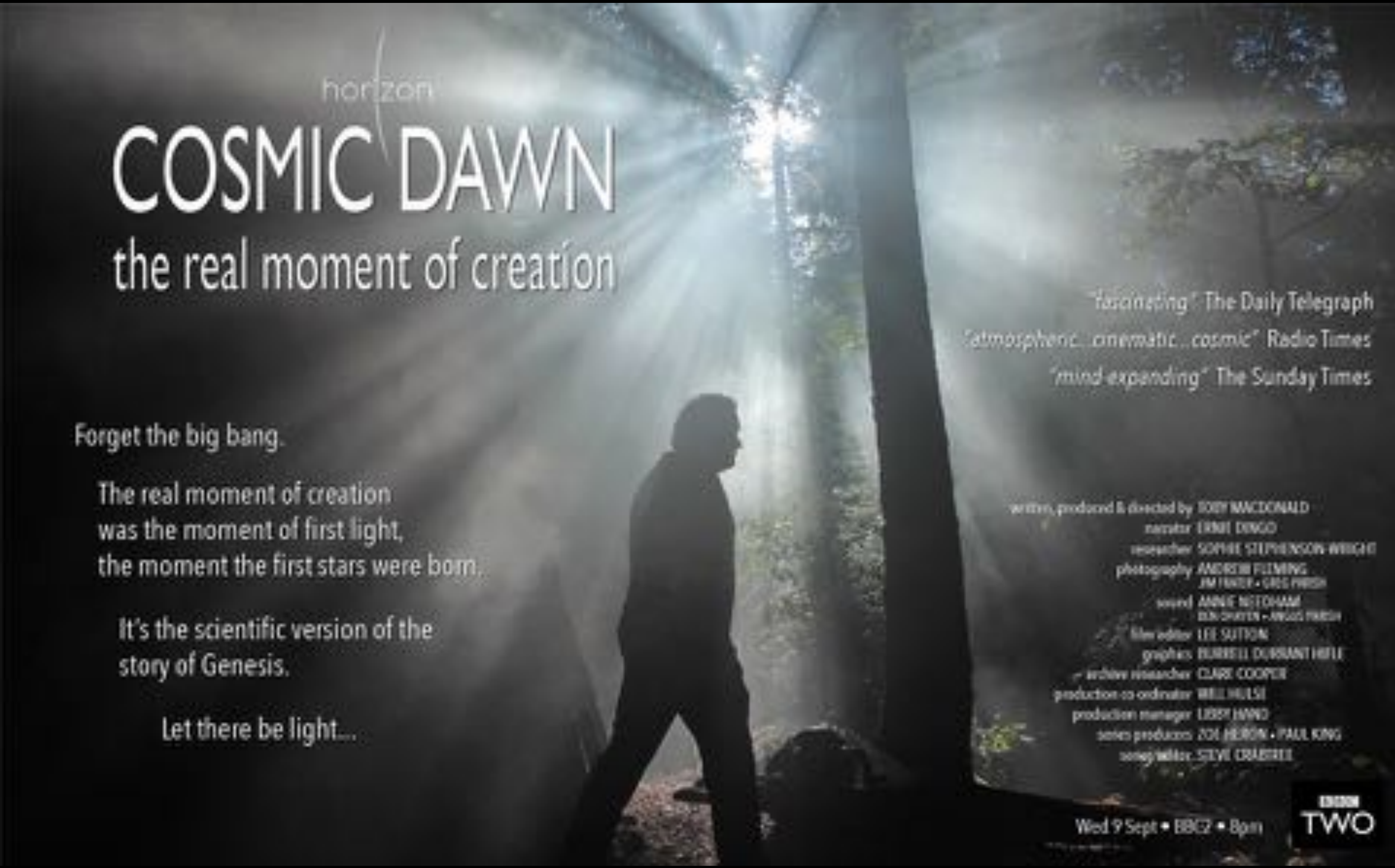
First Light – the dawn of stars & galaxies



Prof J Dunlop University of Edinburgh


horizon
COSMIC DAWN
the real moment of creation
"fascinating" The Daily Telegraph
"atmospheric...cinematic...cosmic" Radio Times
"mind-expanding" The Sunday Times
Forget the big bang.
The real moment of creation
was the moment of first light,
the moment the first stars were born.
It's the scientific version of the
story of Genesis.
Let there be light...
written, produced & directed by TOBY MACDONALD
narrator ERNIE DINGO
researcher SOPHIE STEPHENSON-WRIGHT
photography ANDREW FLEMING
sound ANNIE NEEDHAM
film editor LEE SUTTON
graphics BURRELL DURRANT HIFLE
archive researcher CLARE COOPER
production manager LIBBY HAND
series producers ZOE HERON • PAUL KING
series editor STEVE CRABTREE
Wed 9 Sept • BBC2 • 8pm
TWO

An origins story!

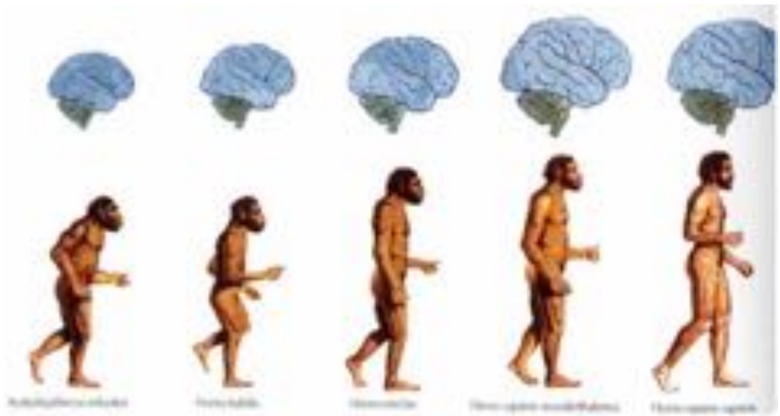
Where did the complexity of the modern Universe come from?

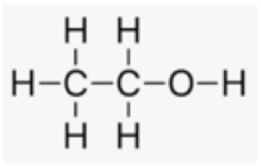
How and when were the elements required for life created?

Carbon

Oxygen

Iron

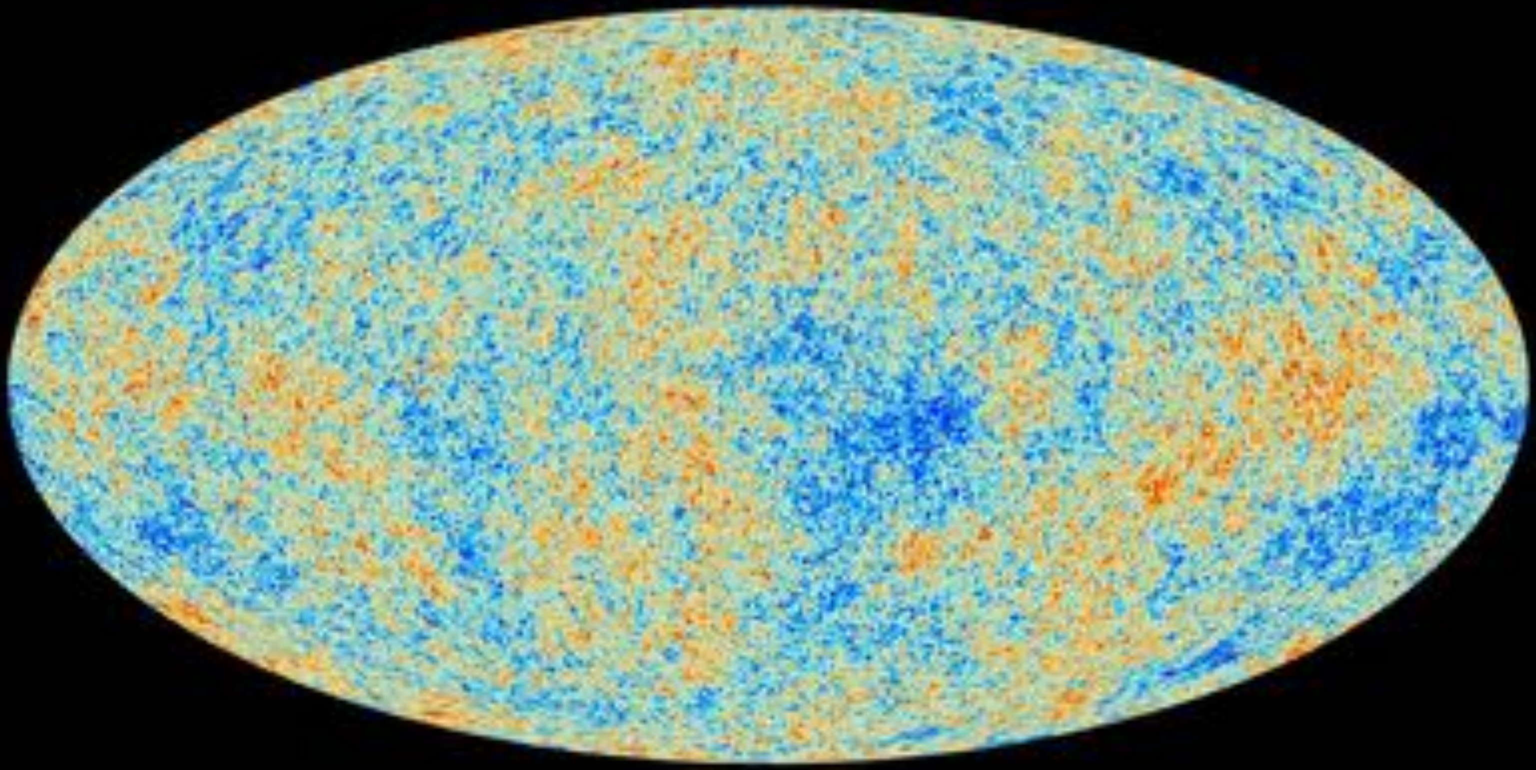




Ethanol

Not in the Big Bang ! – 15 minute stir-fry

The micro-wave background
Heat map of the early Universe (Planck)



13.7 billion years ago

Apart from Hydrogen and Helium
the Chemical Elements are all
formed in STARS
– slow cookers of the Universe !

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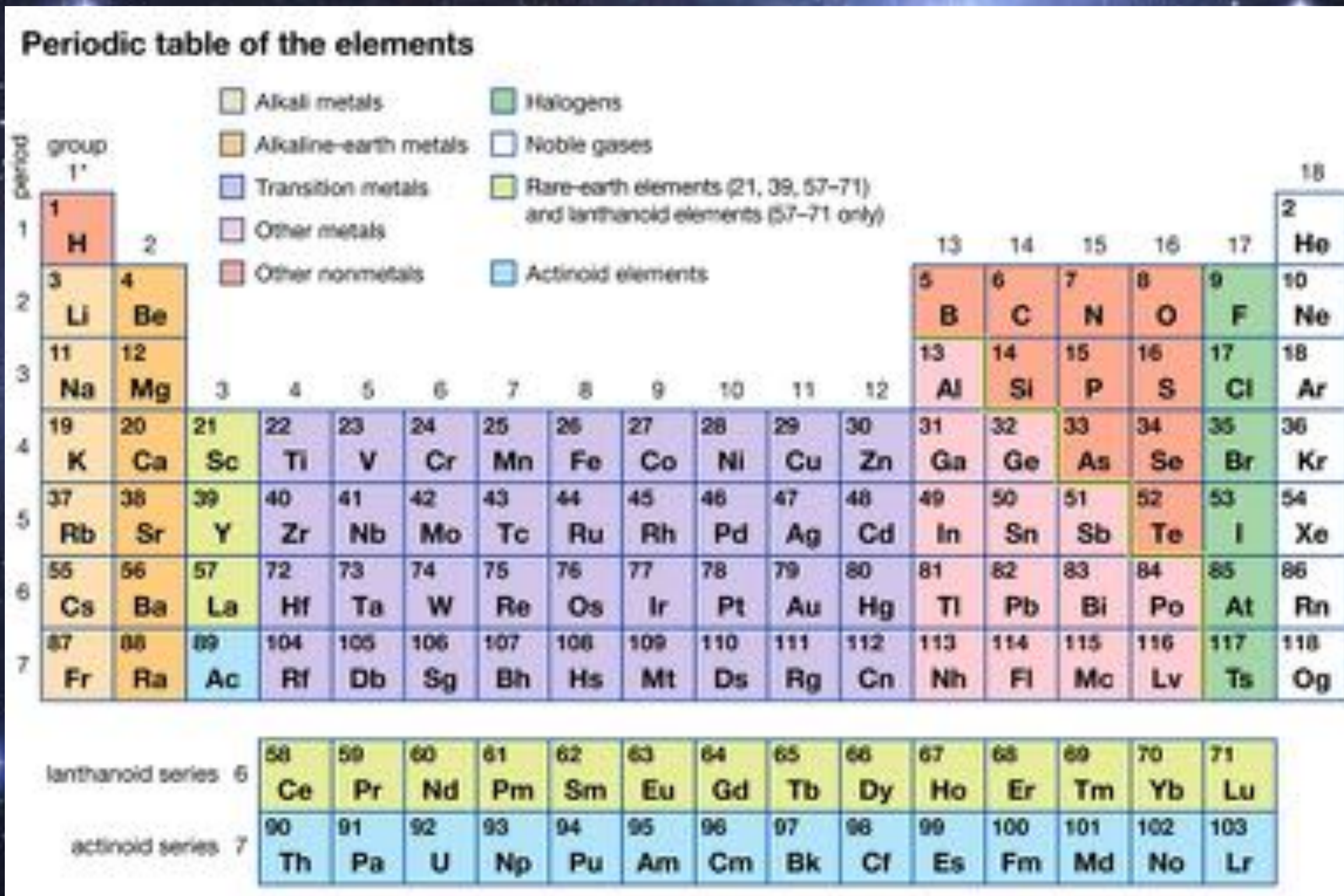
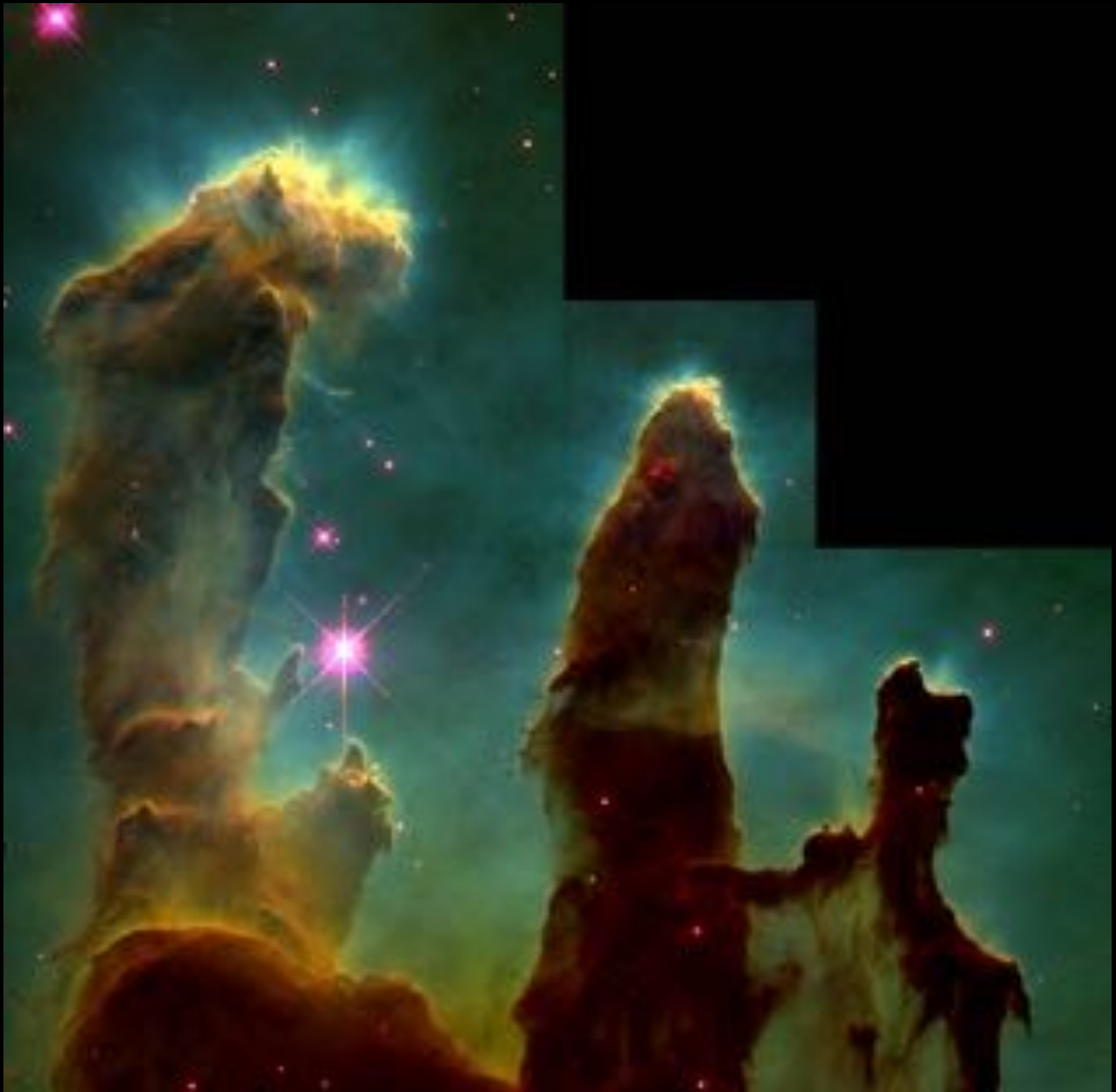
– slow cookers of the Universe !



Nowadays stars form in dense clouds of gas and dust

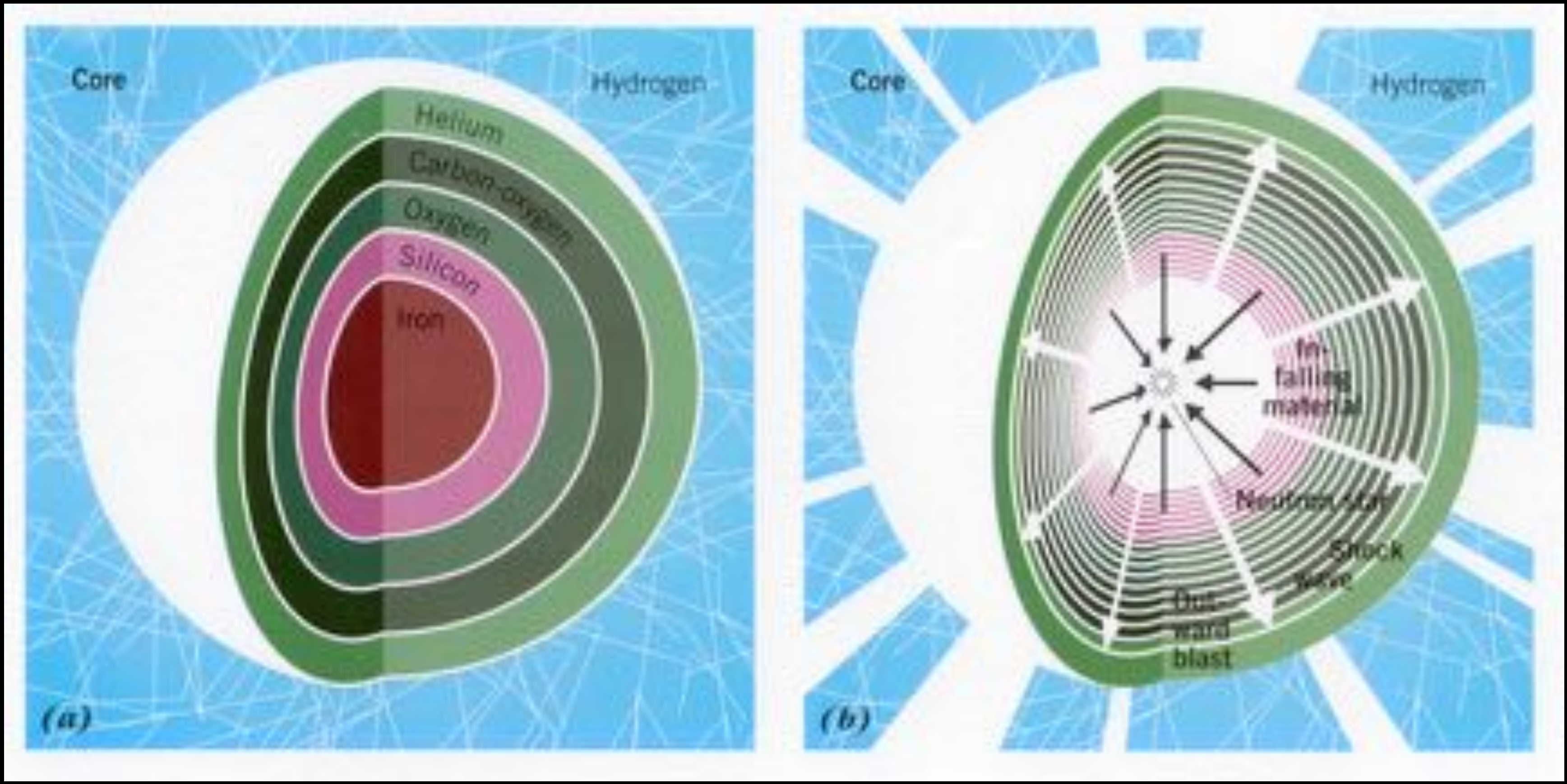


But there was no dust or heavier atoms/molecules to help cool the first gas clouds

One consequence is that we think first stars were giants

which lived fast, and died young, in “Supernovae”

Supernova 1987A



Core
Hydrogen
Helium
Carbon-oxygen
Oxygen
Silicon
Iron
(a)
Core
Hydrogen
Neutron star
Shock wave
Out-ward blast
(b)

Thus, the very first “Population III” stars

must have seeded the Universe with the first heavy elements

But they have not yet been seen

Searching for First Light.....

Our view of the Universe

- Telescopes are time machines!

Due to the finite speed of light…………

A step out in distance = a step back in time – “Lookback Time”

The Hubble Space Telescope

2.4-m diameter telescope launched in 1990

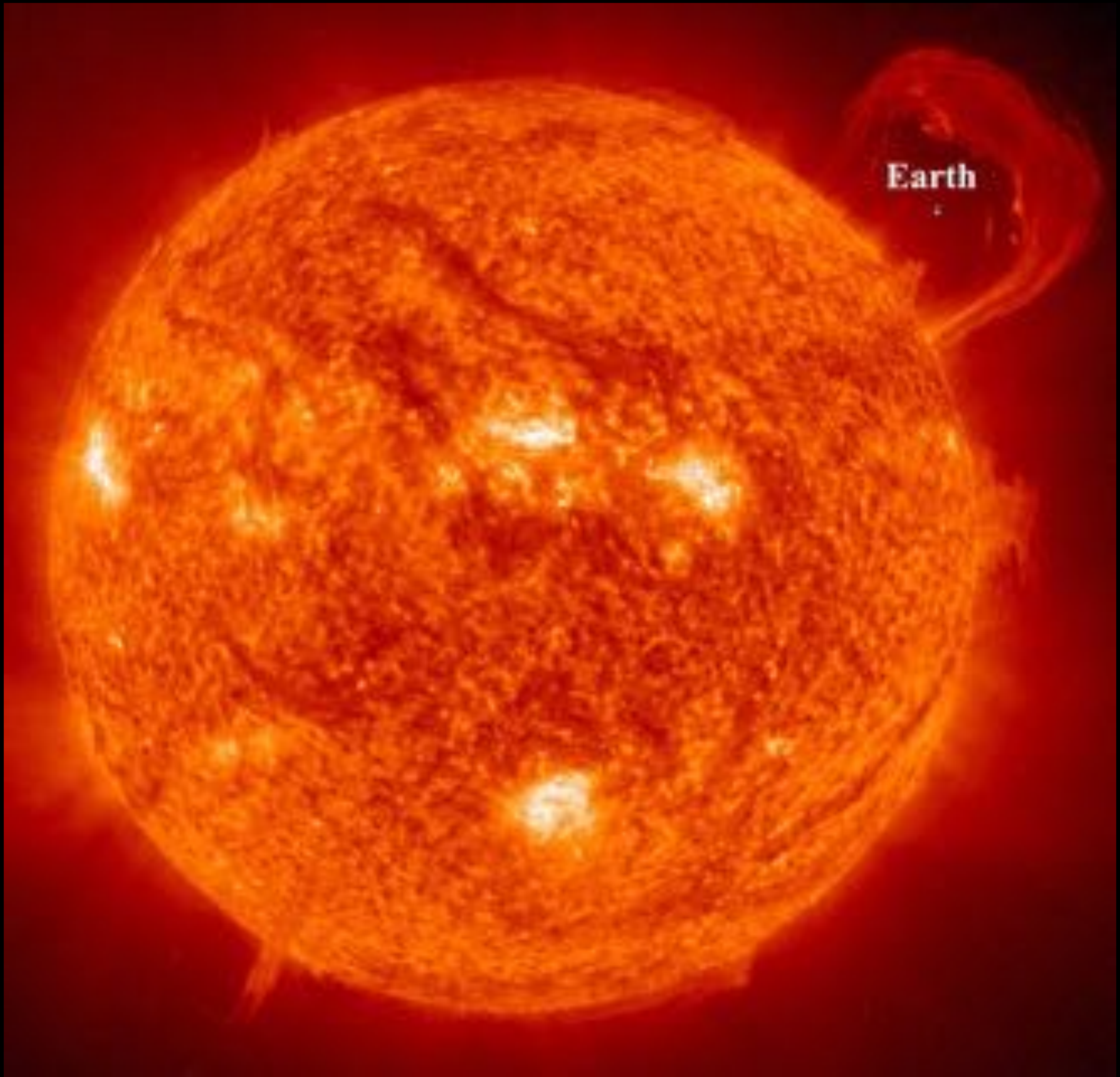
In orbit only 350 miles above earth – zips round the earth in 96 minutes

But reachable by the Shuttle – serviced/repaired/updated 5 times


Hubble Space Telescope
light travel time ~ 2 milliseconds

The Moon: ¼ million miles away – light takes 1.3 seconds to reach us

The Sun – 93 million miles away – light takes 8 minutes to reach us



Jupiter: 400 – 700 million miles – light takes 33 – 53 min to reach us

Pluto: 4000 million miles – light takes 5 hours to reach us

NASA’s New Horizons spacecraft took nearly 10 years to get to Pluto in July 2015

Andromeda/M31 – the nearest giant galaxy

Light takes 2.5 million years to come from M31

Galaxy cluster

~5 billion years ago

Hubble Ultra Deep Field

Deepest optical image of the sky, taken with Hubble in 2004

Looking back up to ~12.5 billion years

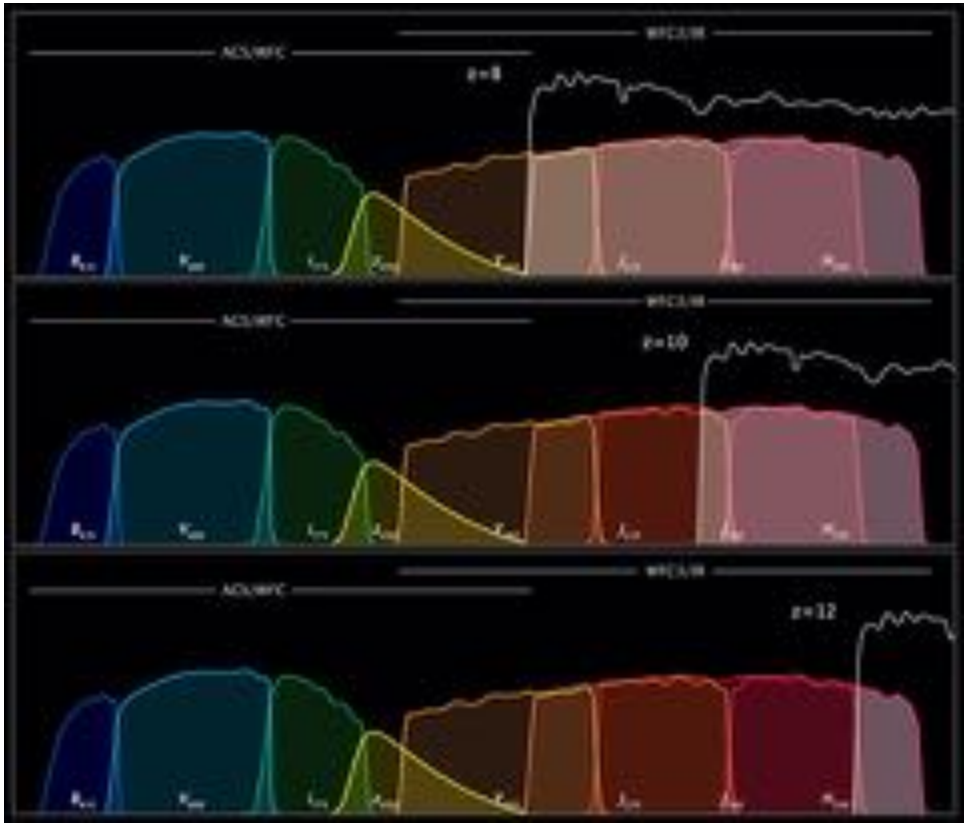
90% of age of the Universe

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

Discovering early (= high redshift) galaxies

Can't see further out/back in optical light due to redshift (z) and increasingly neutral Universe (Hydrogen atoms absorbing rest-frame UV light shortward of λ_{rest} = 121.6 nm).

Looking for objects which disappear, or "drop-out" at bluer wavelengths due to Lyman break
INFRARED imaging allows us discover higher redshift, hence earlier galaxies



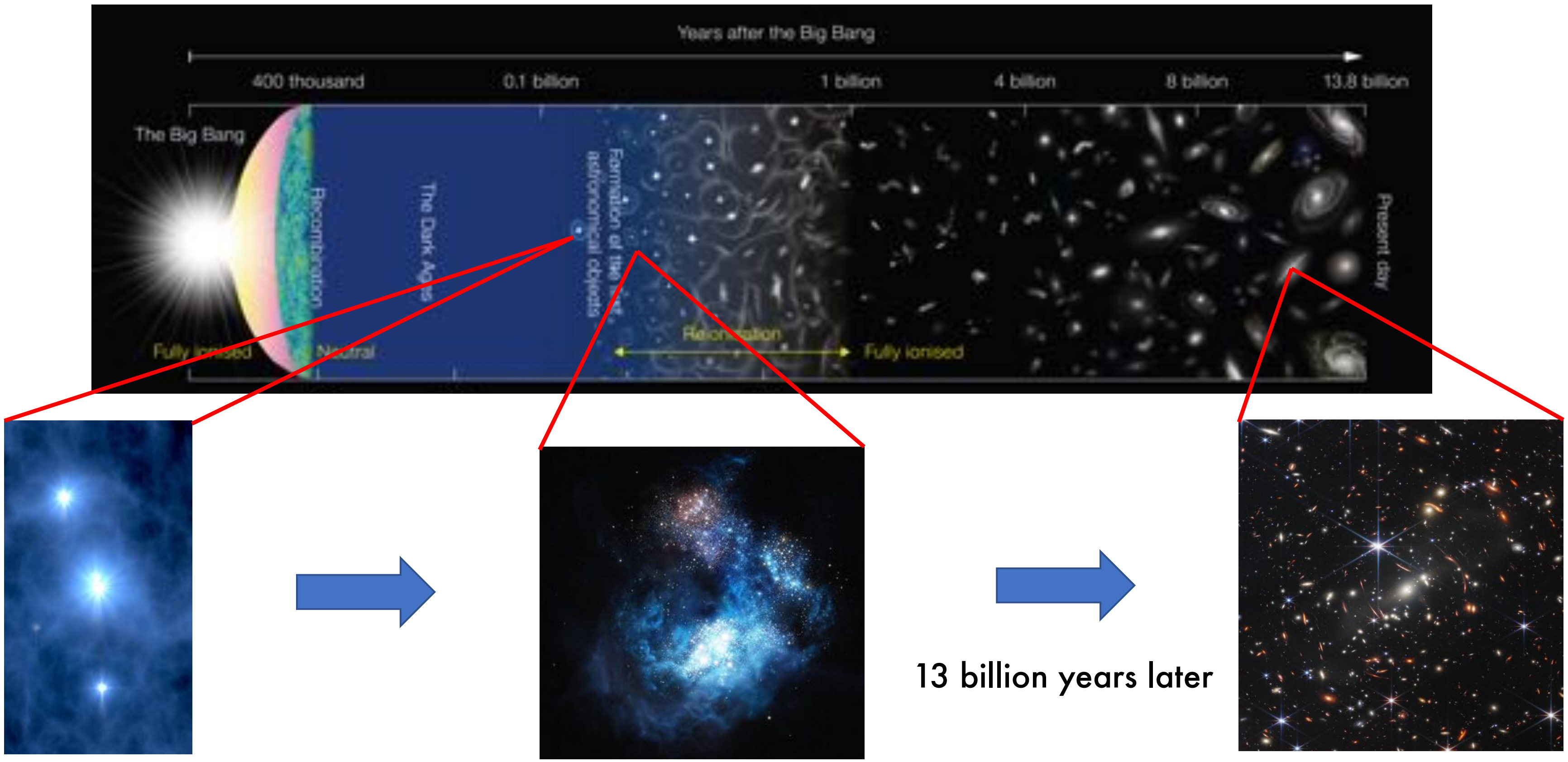
Redshift (z)
- a "stretch", not really a "shift"

$1+z = \lambda_{observed} / \lambda_{emitted}$

$$1+z = \frac{\text{size of Universe now}}{\text{size of Universe then}}$$

Hence redshift, z , is
a measure of lookback time

Cosmic history and galaxy evolution



First stars
z~30

First galaxies
z~20

"local" galaxies
z~0

Key Questions

When was Cosmic Dawn?

Was it a dramatic event in a narrow period of time or did the birth of stars and galaxies happen gradually?

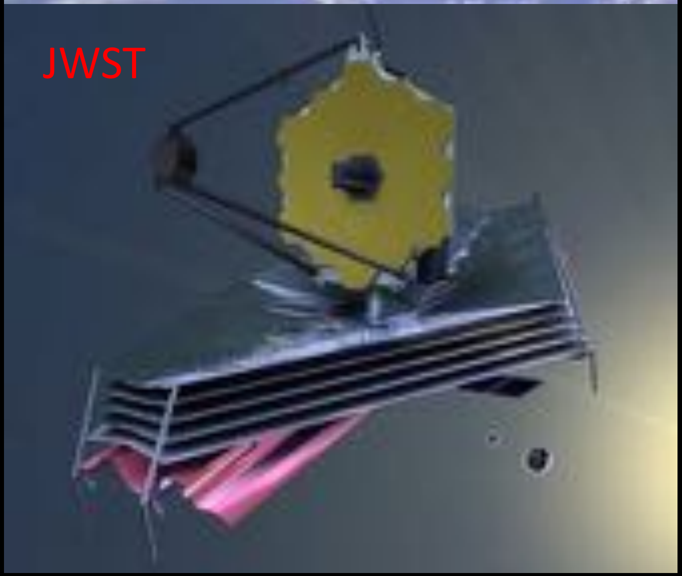
What did the first galaxies look like, and how did they form?

What drives/limits early star formation?
How early did heavy elements and cosmic dust form?
Can we find galaxies containing the very first - Population III – stars?

We need to find and study early galaxies to answer these questions

Key Facilities

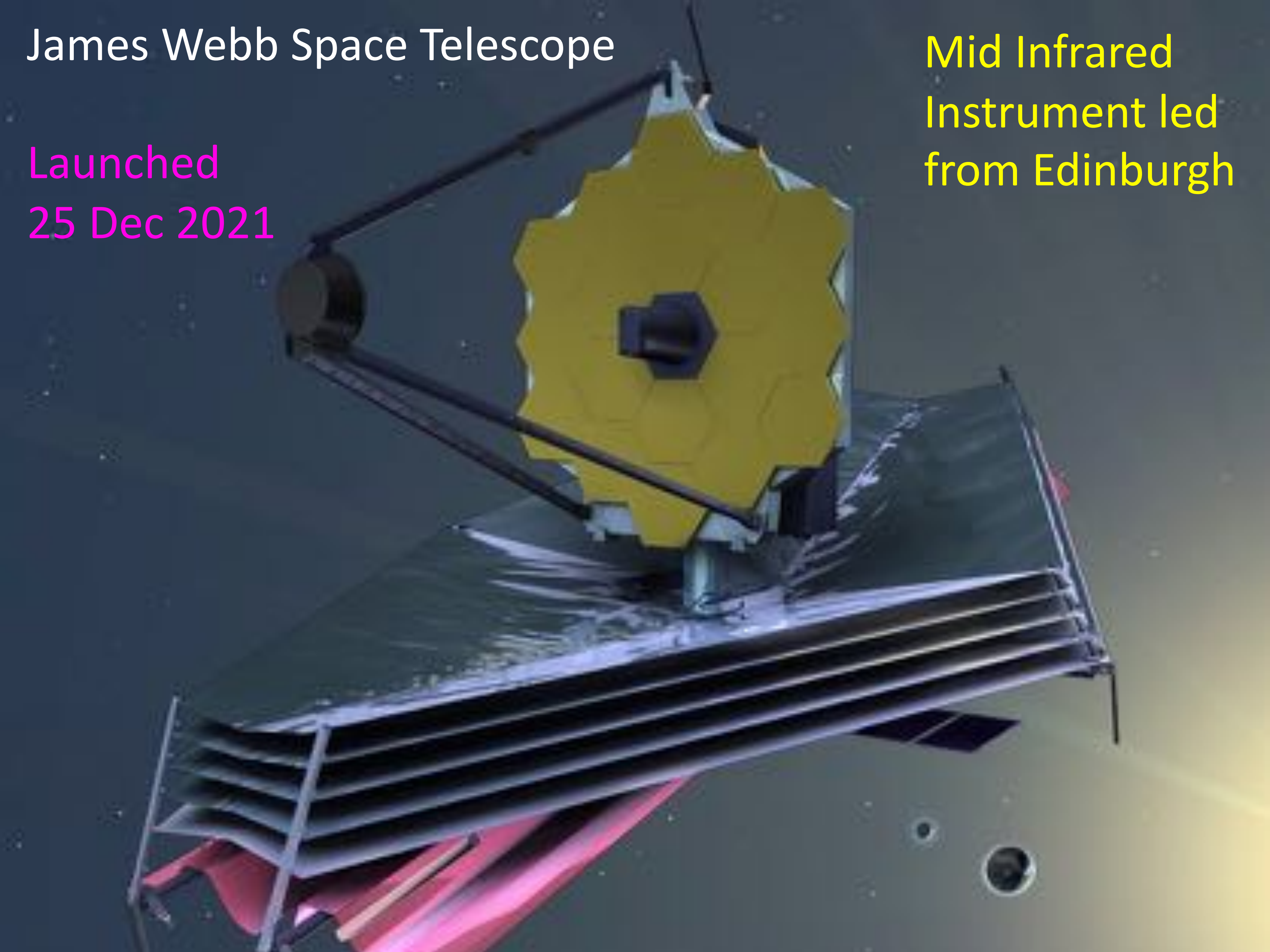
This work requires world-leading observatories on ground and in space



James Webb Space Telescope

Launched
25 Dec 2021

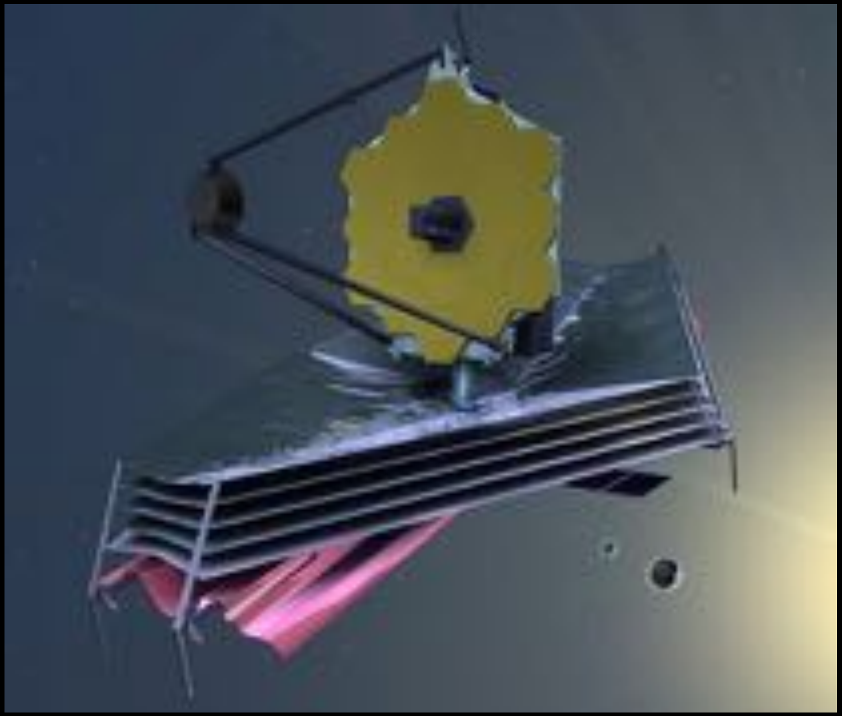
Mid Infrared
Instrument led
from Edinburgh



James Webb Space Telescope
Mirror diameter 6.5m

Hubble Space Telescope
Mirror diameter 2.4m

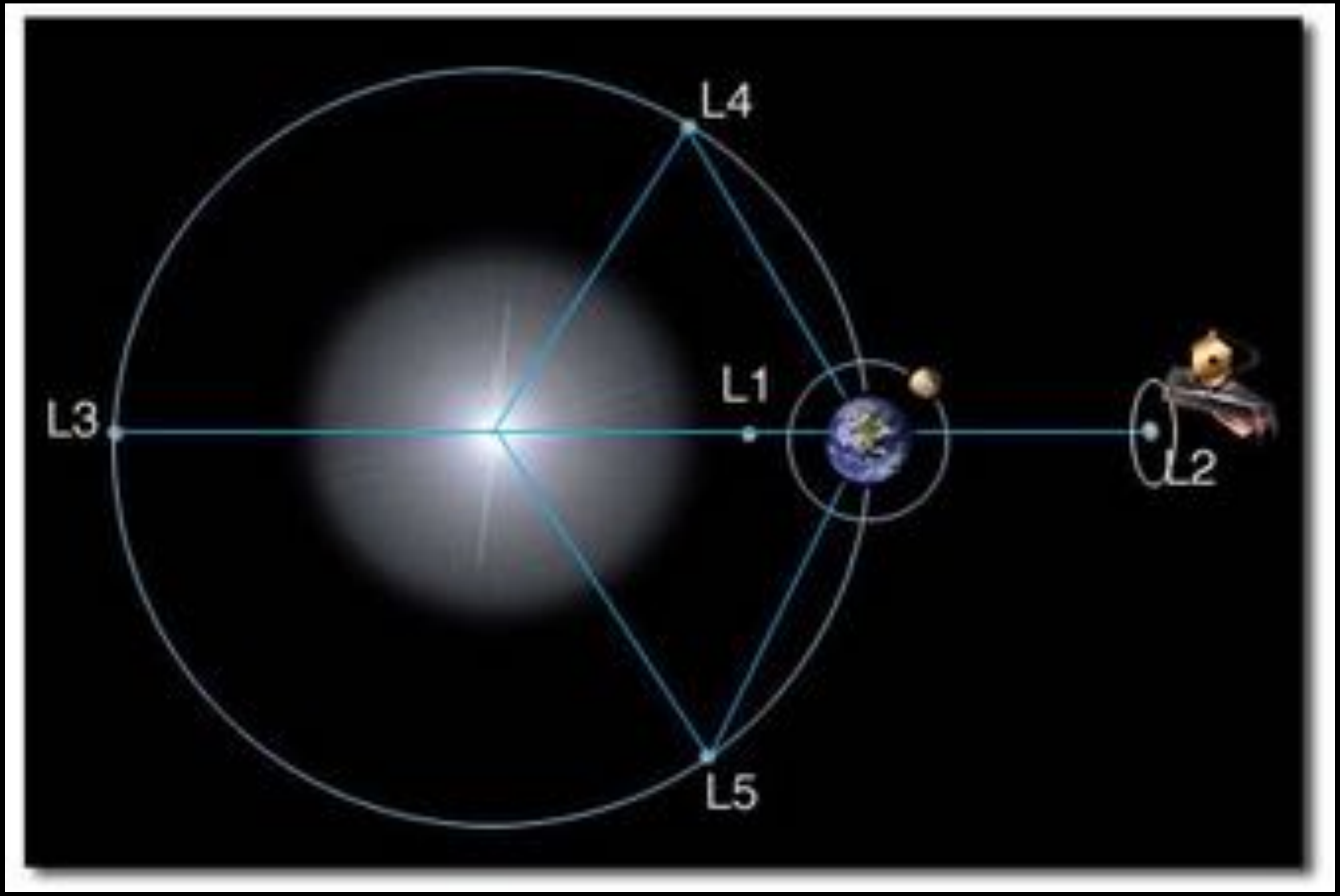
Spitzer
Mirror diameter 0.85m



Mirror collecting area at λ = 4 microns increased by factor > 50

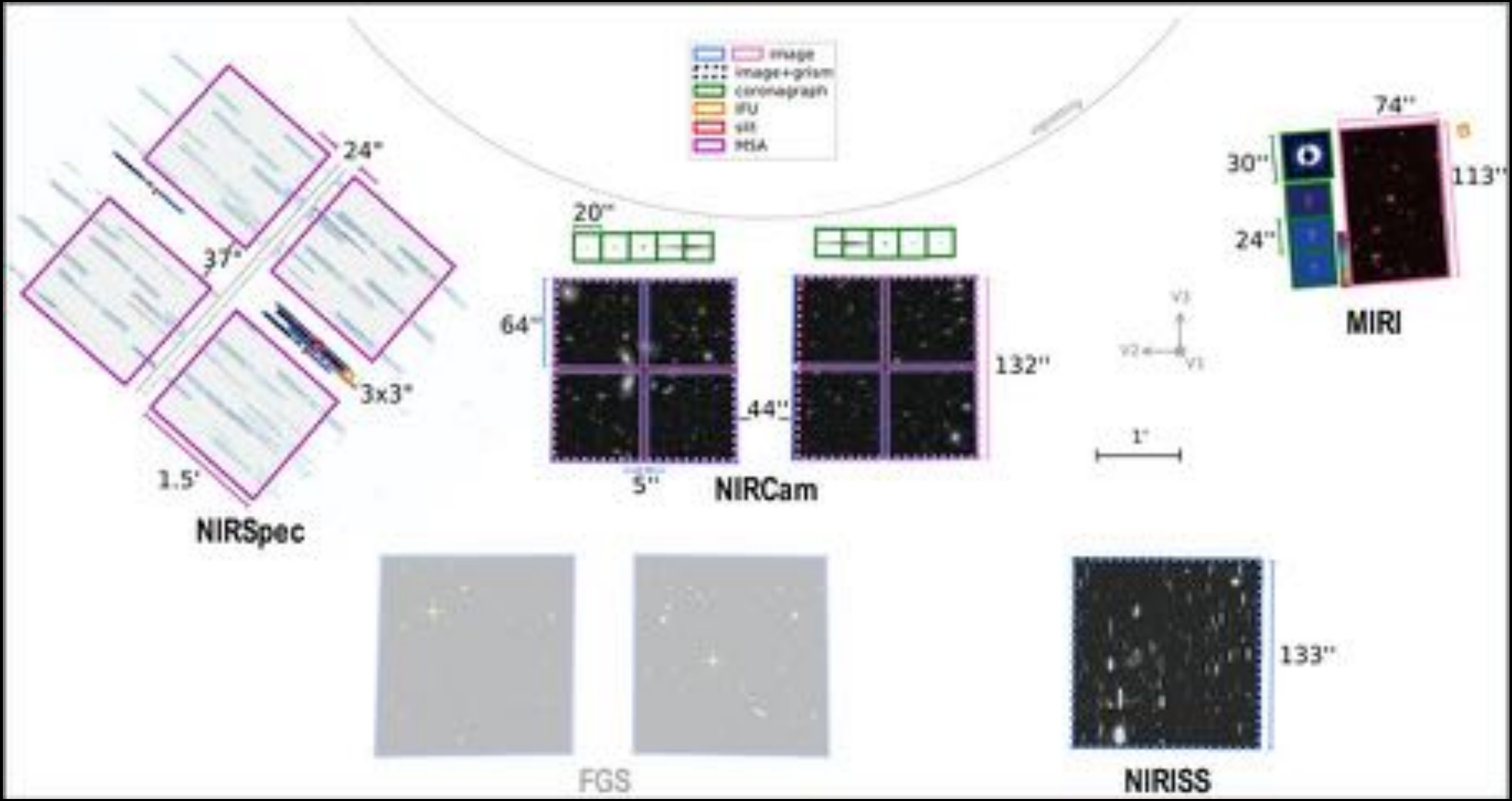
Hubble is next door, but JWST is now at Lagrangian Pt 2 (L2)
~ 1 million miles from Earth in opposite direction to Sun

- much colder than Hubble (~50K)
- can see galaxies even if redshifted to $z > 20$



Instruments

JWST Focal Plane



Instruments
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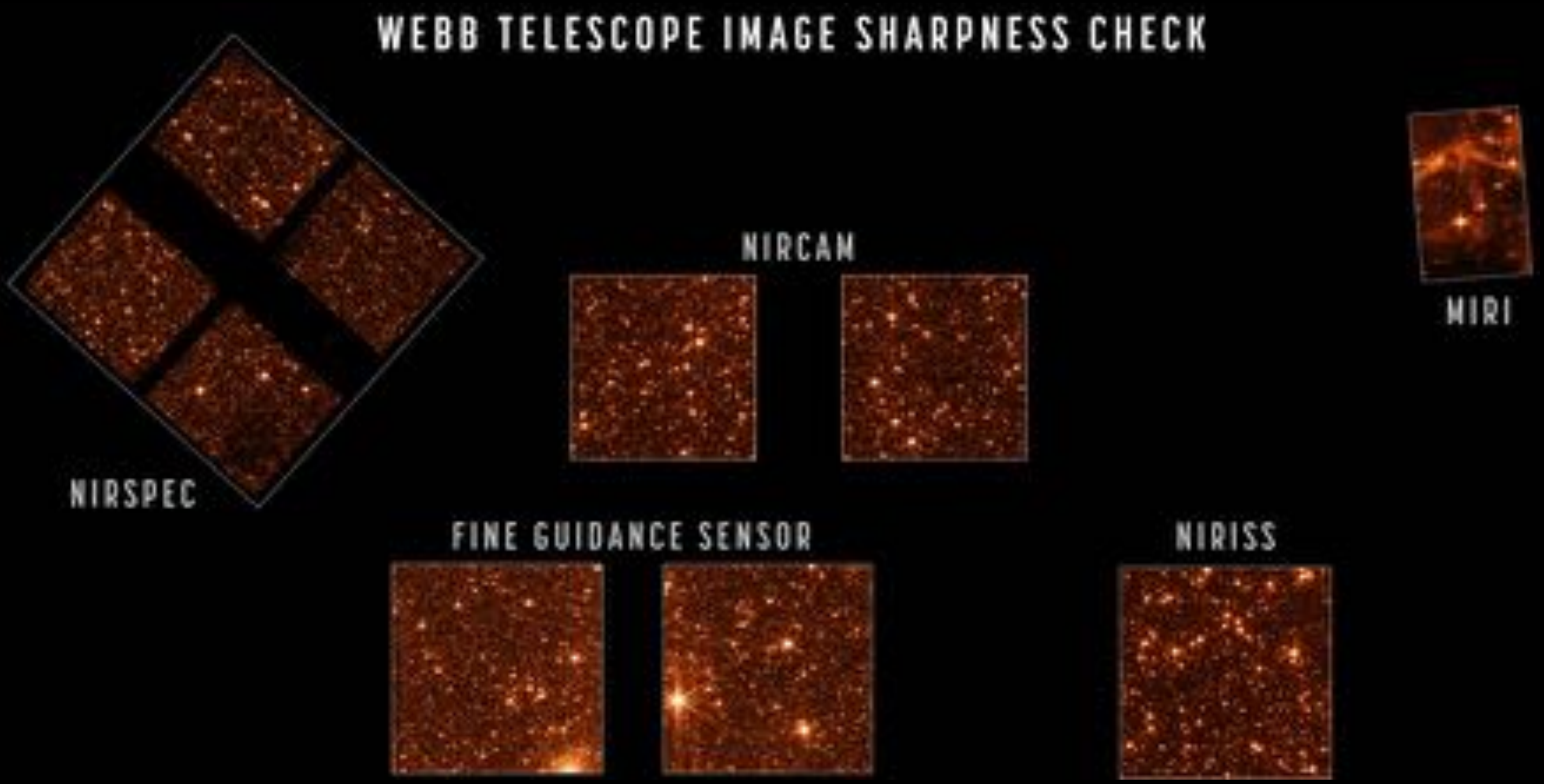
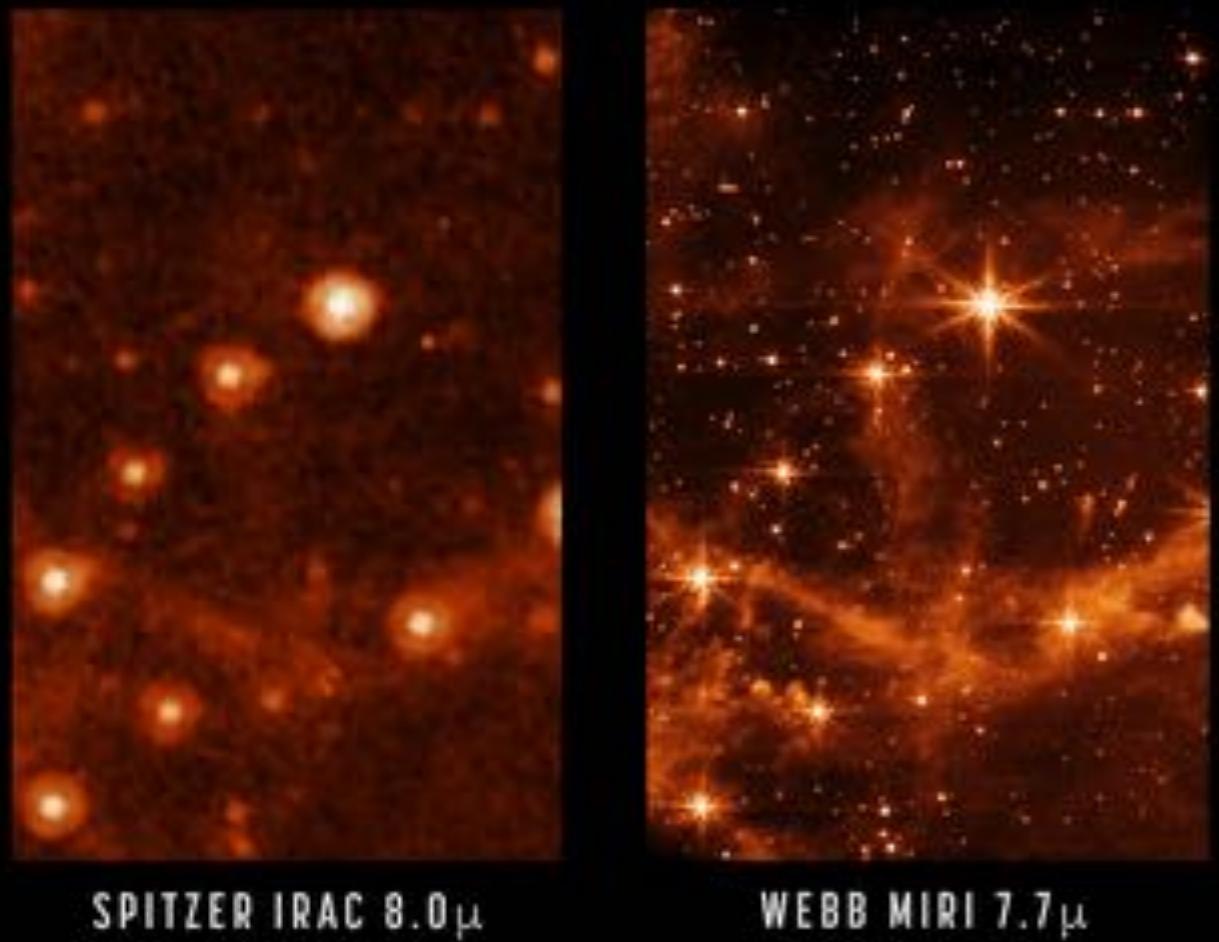


Spitzer to JWST – huge leap in infrared image quality

Spitzer to JWST – huge leap in infrared image quality

First real data from May 2022 !



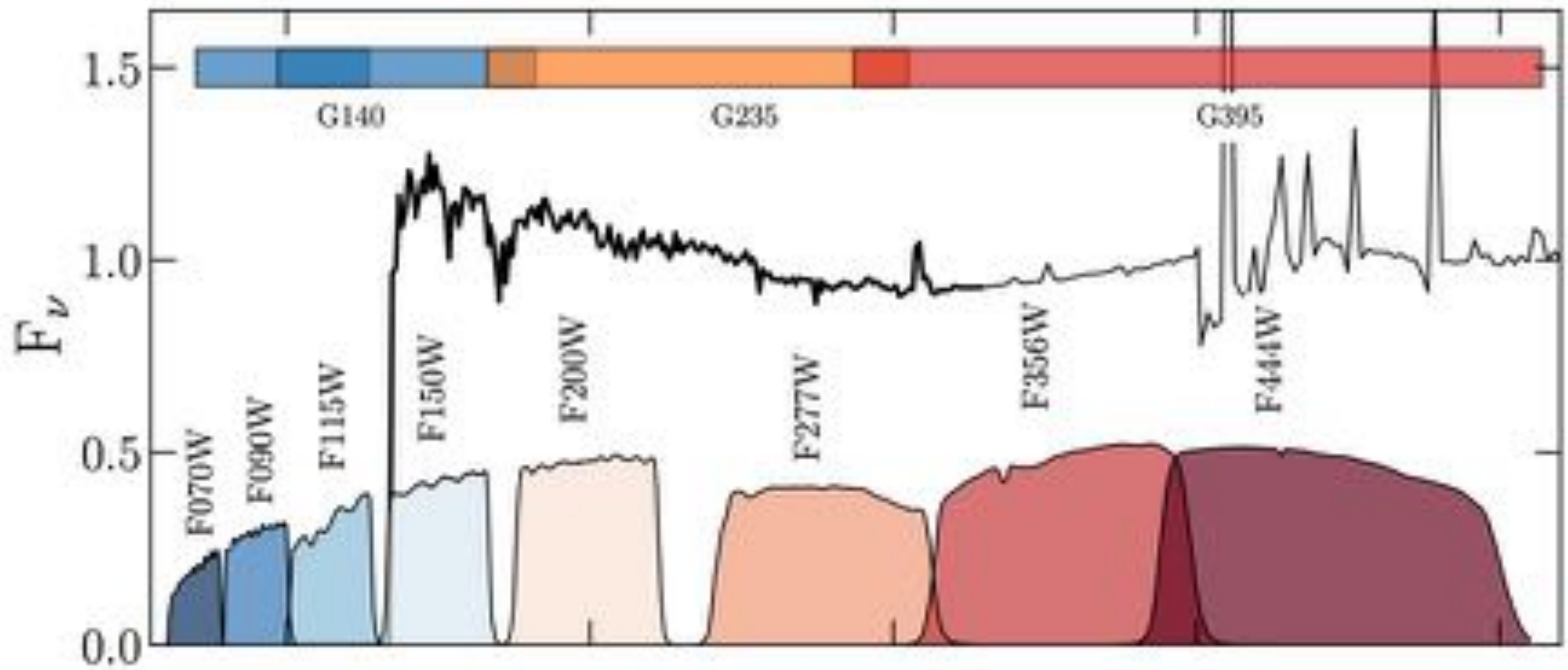
JWST is BETTER than expected/predicted !!

Recent Updates/Advances

- JWST works ! – better than expected/specified !
- JWST lifetime now > 10 years due to excellent European Space Agency launch
- First data (since July 2022) have revealed many more early galaxies than expected
- Galaxies already discovered out to z ~ 13, possibly z = 16
  - only 250 million years after the Big Bang……….running out of time

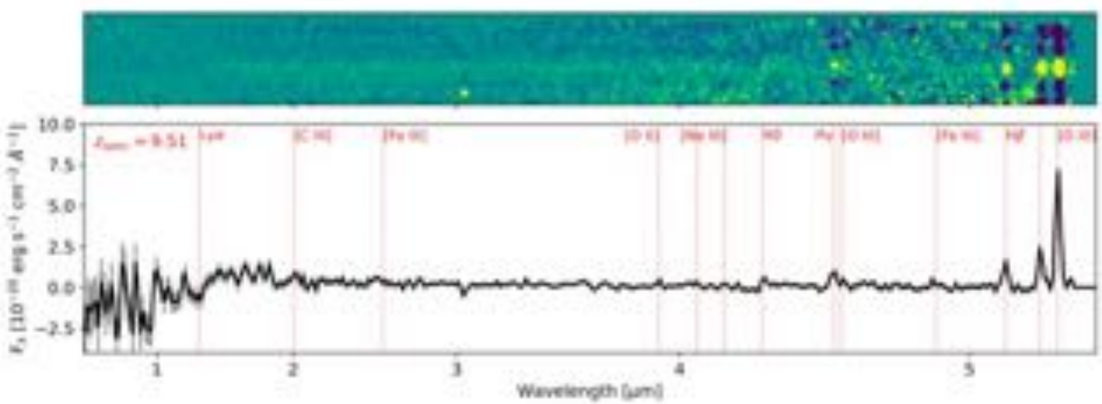


NIRCam-selected high-z galaxies being spectroscopically confirmed by NIRSpec



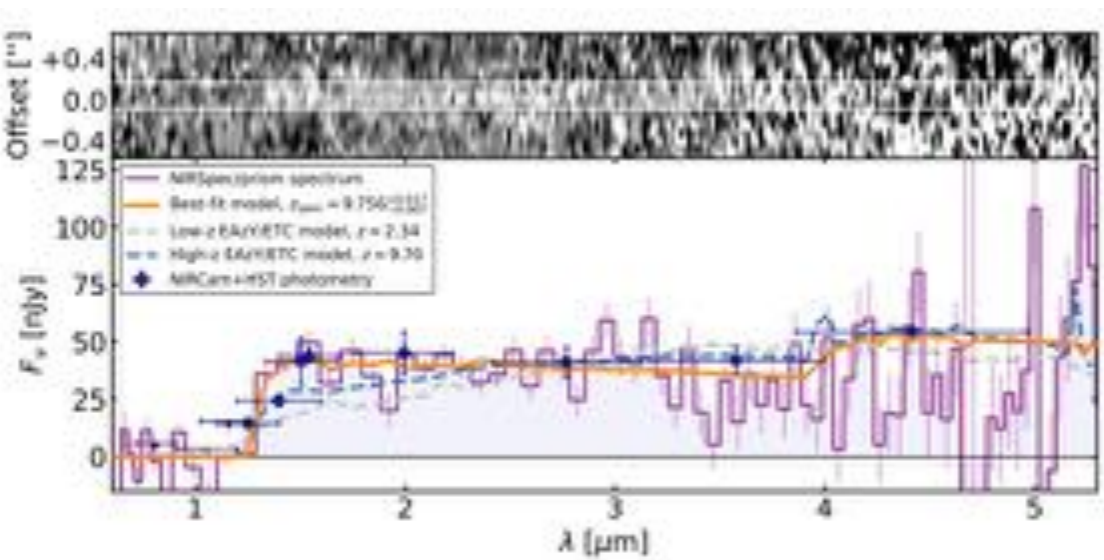
z = 10

NIRCam-selected high-z galaxies being spectroscopically confirmed by NIRSpec



z = 9.51

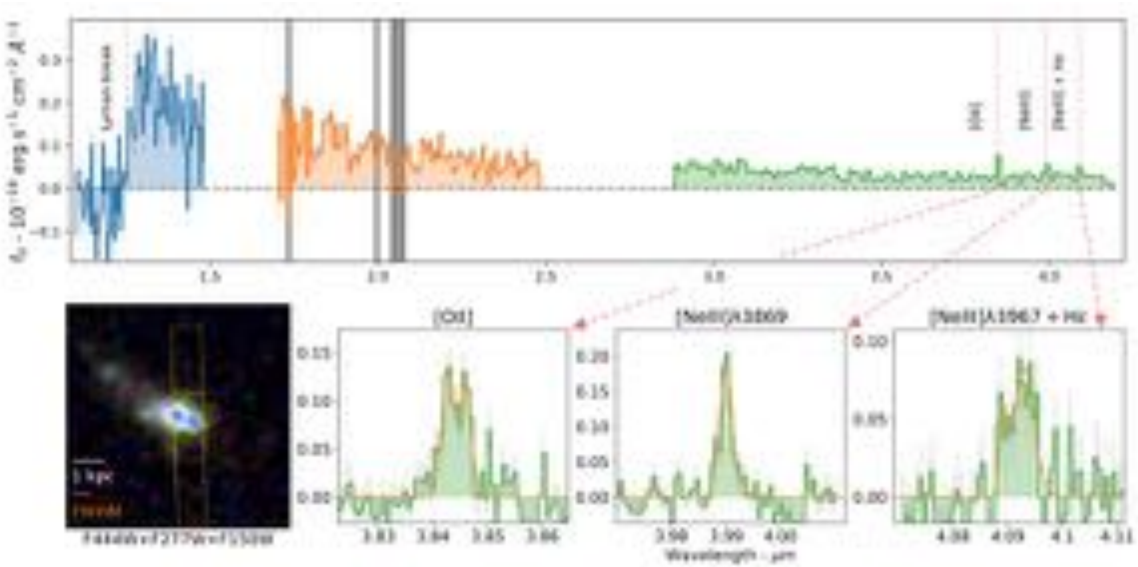
Williams, H. et al. (2022) arXiv:2210.15699



z = 9.756

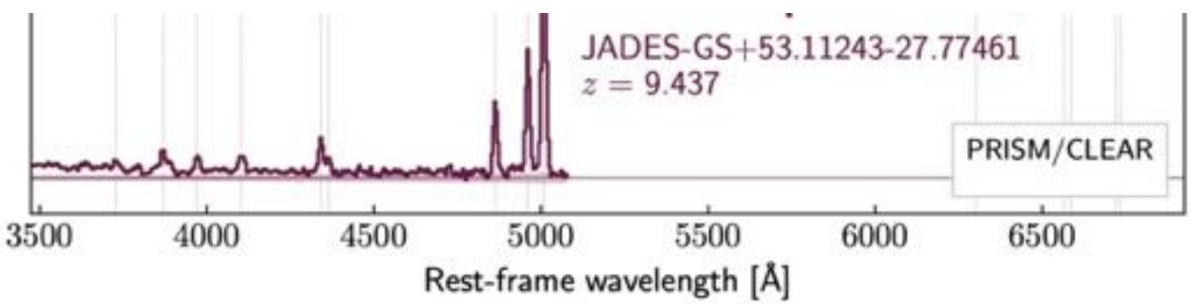
Roberts-Borsani et al. (2022) arXiv: 2210.15369

NIRCam-selected high-z galaxies being spectroscopically confirmed by NIRSpec



z = 9.313

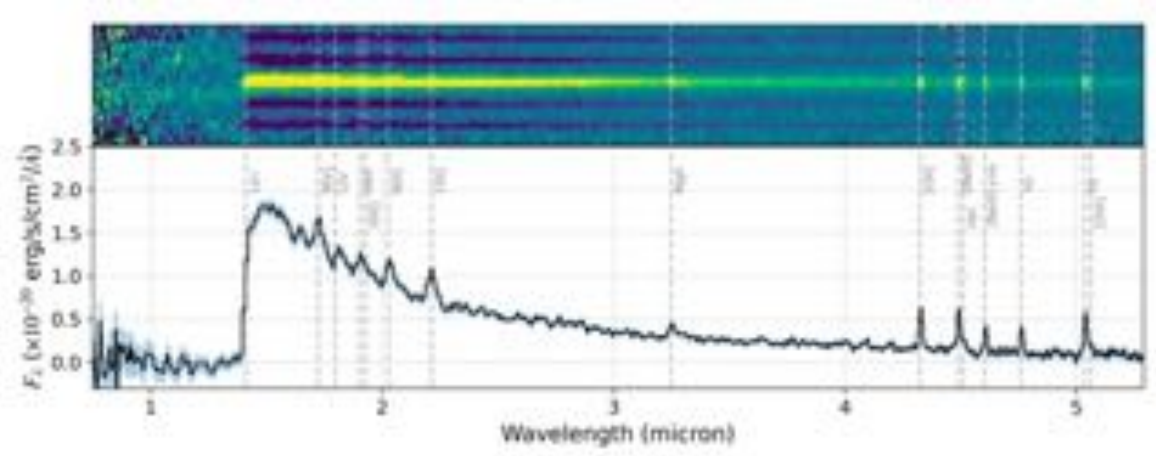
Boyett et al. (2023) arXiv:2303.00306



z = 9.437

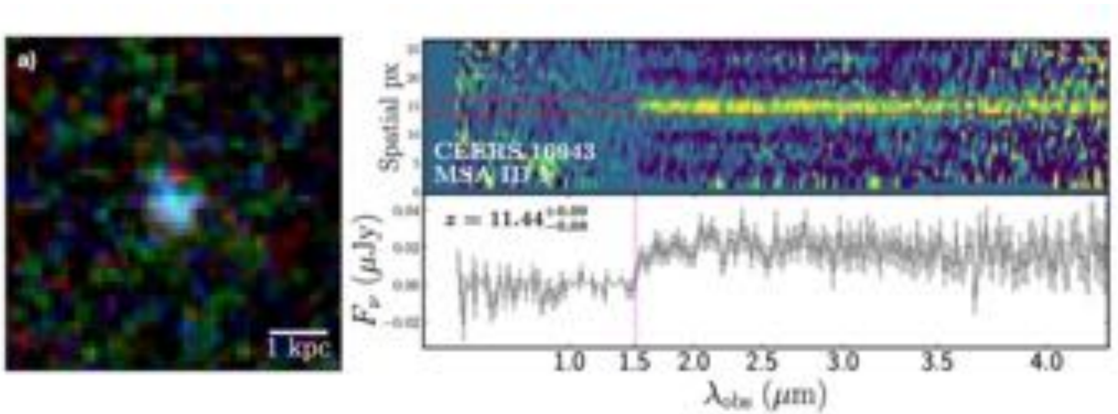
Cameron et al. (2023) arXiv: 2302.04298

NIRCam-selected high-z galaxies being spectroscopically confirmed by NIRSpec



z = 10.603 (GN-z11)

Bunker et al. (2023) arXiv:2302.07256



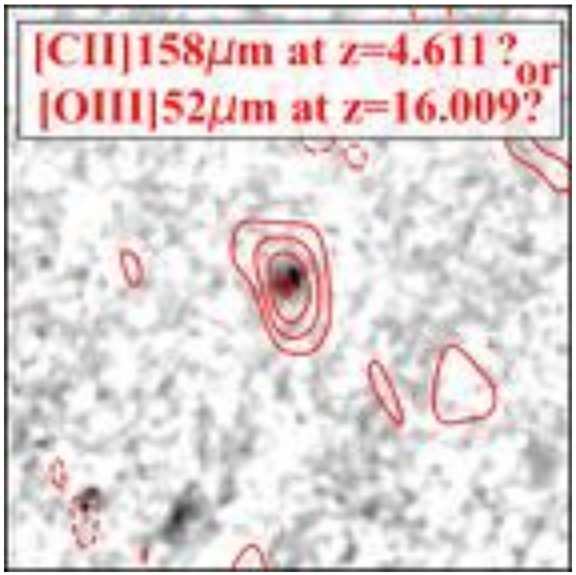
z = 11.44

Arrabal Haro et al. (2023) arXiv: 2303.15431

But note, no lines here at z > 10……strong rest-frame optical lines redshifted out, and no Ly α

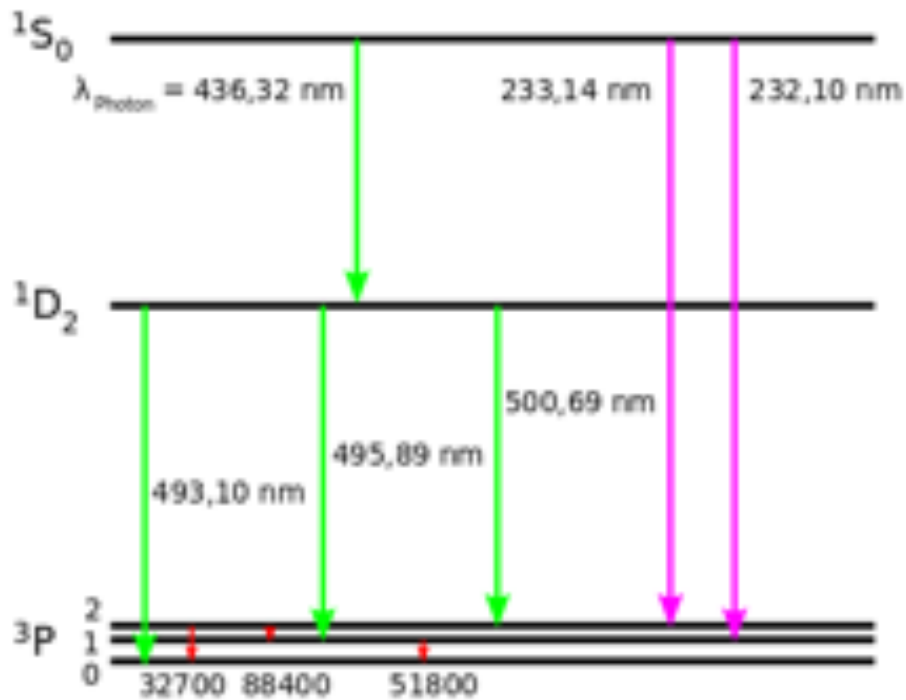
Can ALMA help? spectroscopic redshift at z = 16.1?

Fujimoto et al. (2022) arXiv:2211.03896

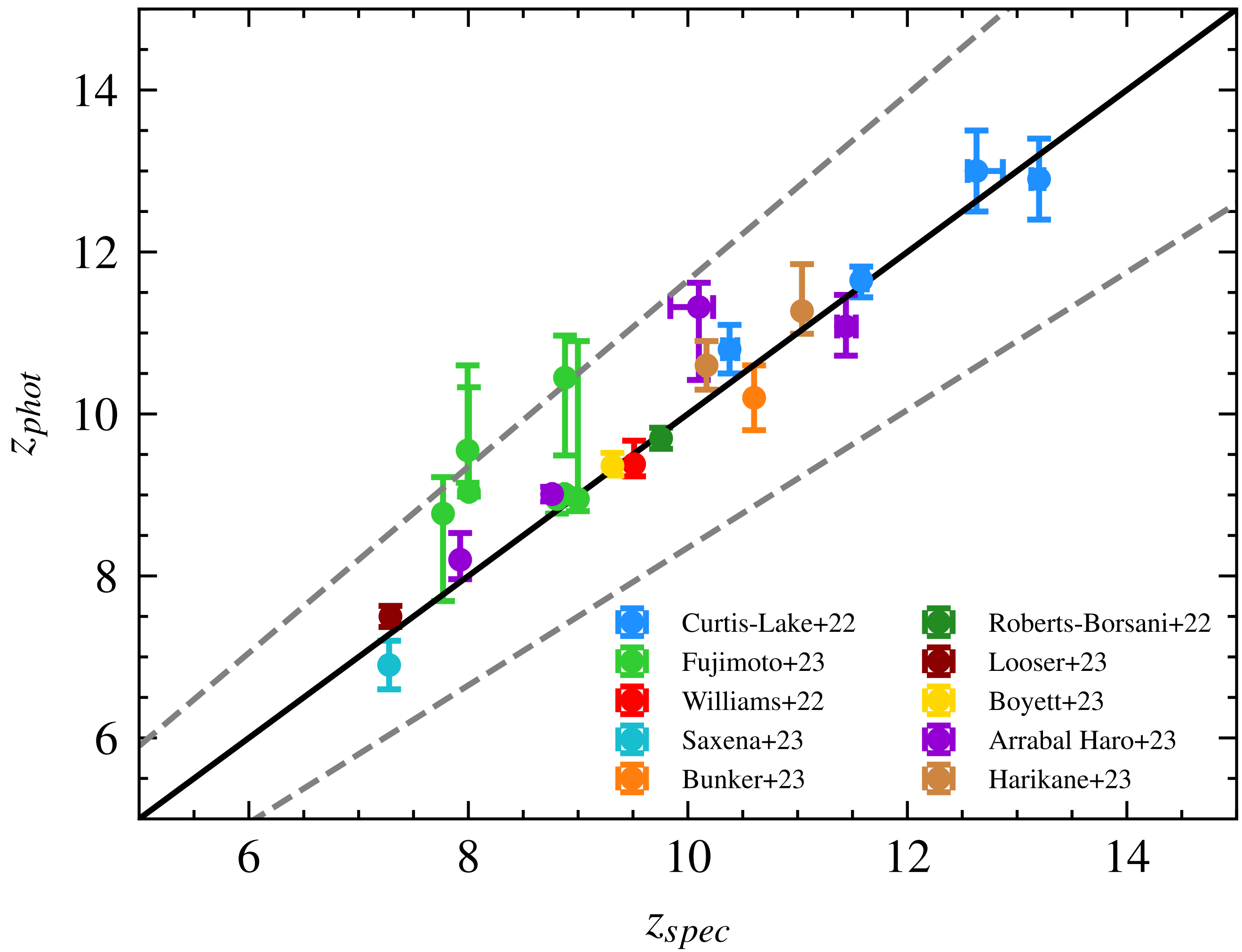


ALMA follow-up of z ~ 16 candidate from the Stephan's Quintet ERO NIRCam imaging

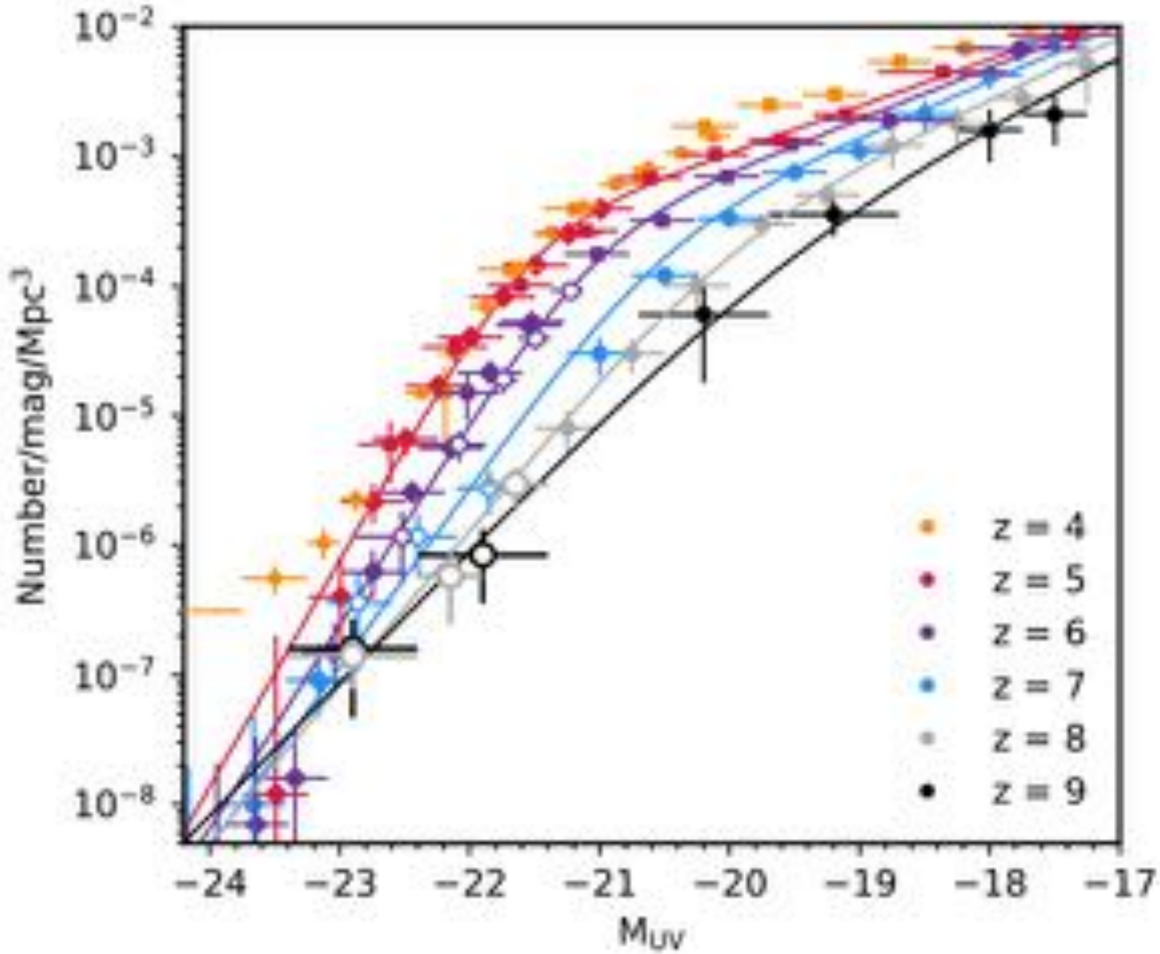
OIII = O^{2+}



Becoming clear that JWST NIRCam photo-zs are reliable



Galaxy demographics – the evolving Luminosity Function



Pre-JWST - decline in overall numbers of galaxies looking back to early times
- but also the Luminosity Function (LF) changing shape? Bowler et al. (2020)

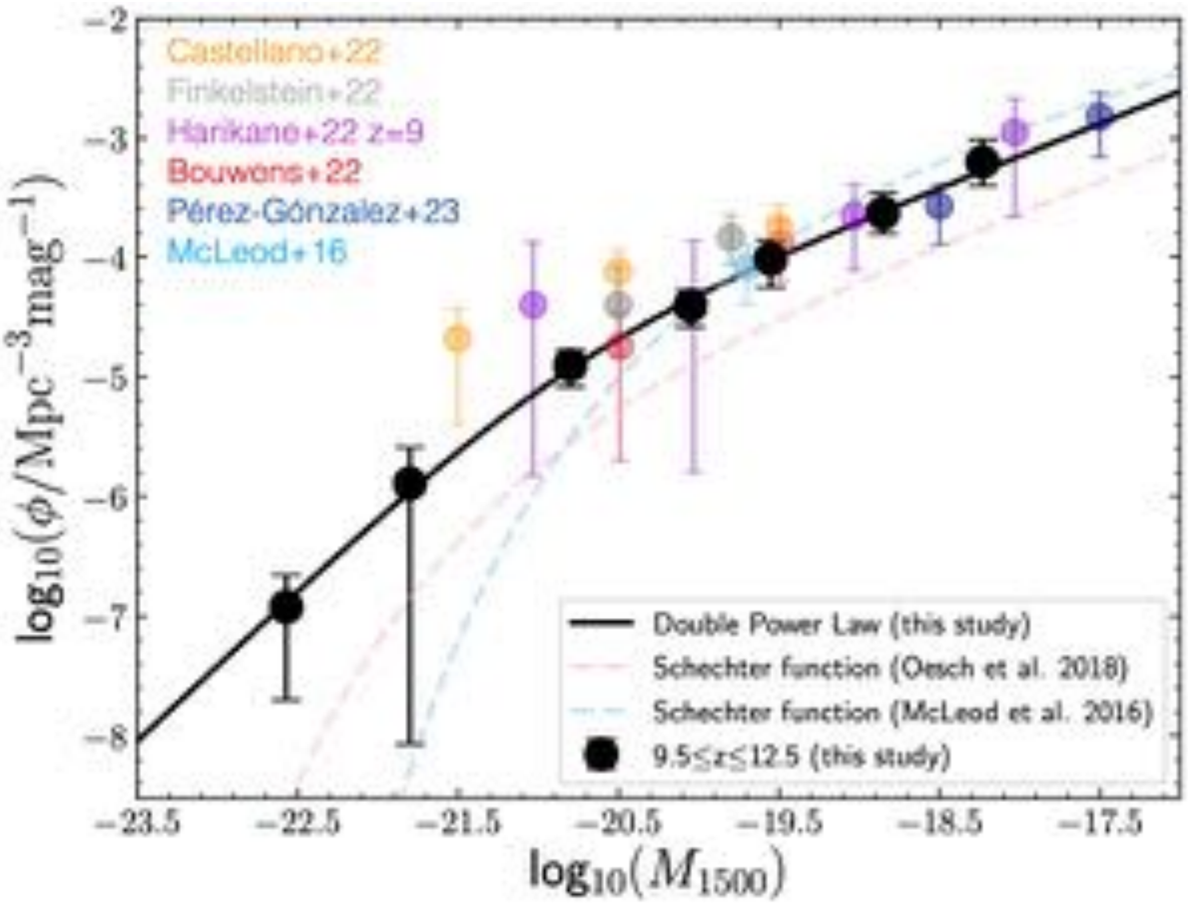
Latest results on extreme redshift luminosity function

Donnan et al. (2023a) + Donnan et al. (2023b) + McLeod et al. (2023) arXiv: 2304.14469

UltraVista DR5 +
JWST ERS/SMACS

HUDF HST +
JWST Medium Band

Compilation of 13 fields imaged with
JWST NIRCam: > 250 arcmin^2 in total



z = 11

400 Myr

Latest results on extreme redshift luminosity function

Donnan et al. (2023a) + Donnan et al. (2023b) + McLeod et al. (2023) arXiv: 2304.14469

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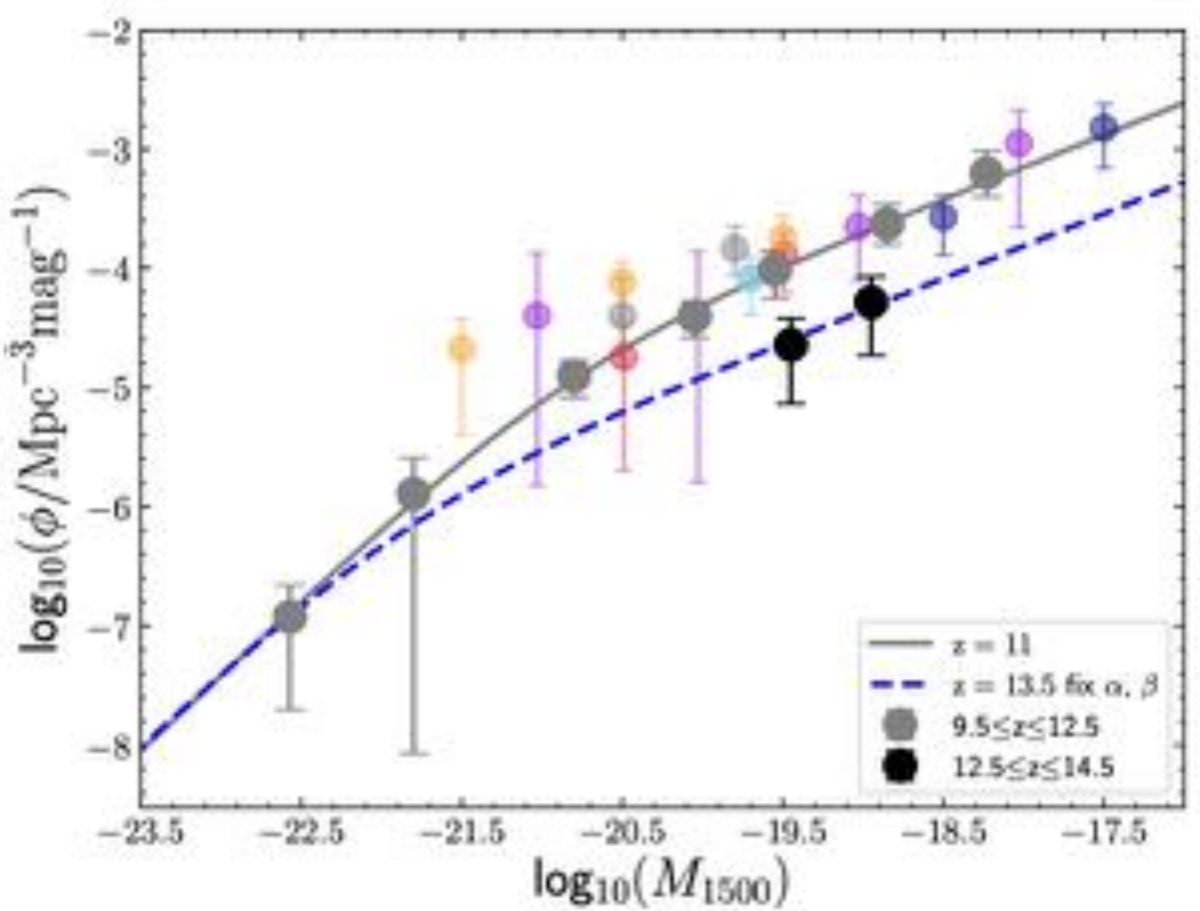
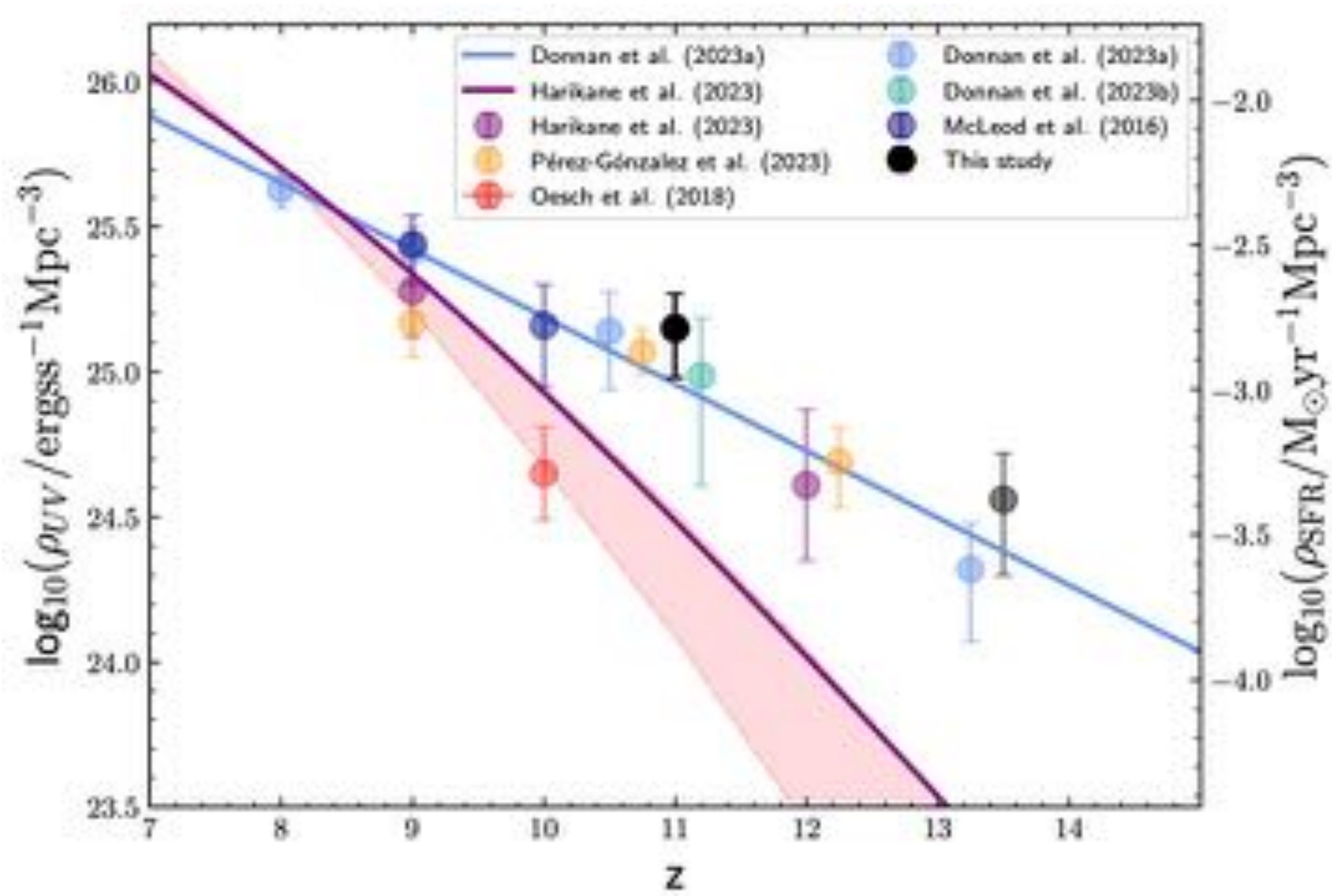


z = 13

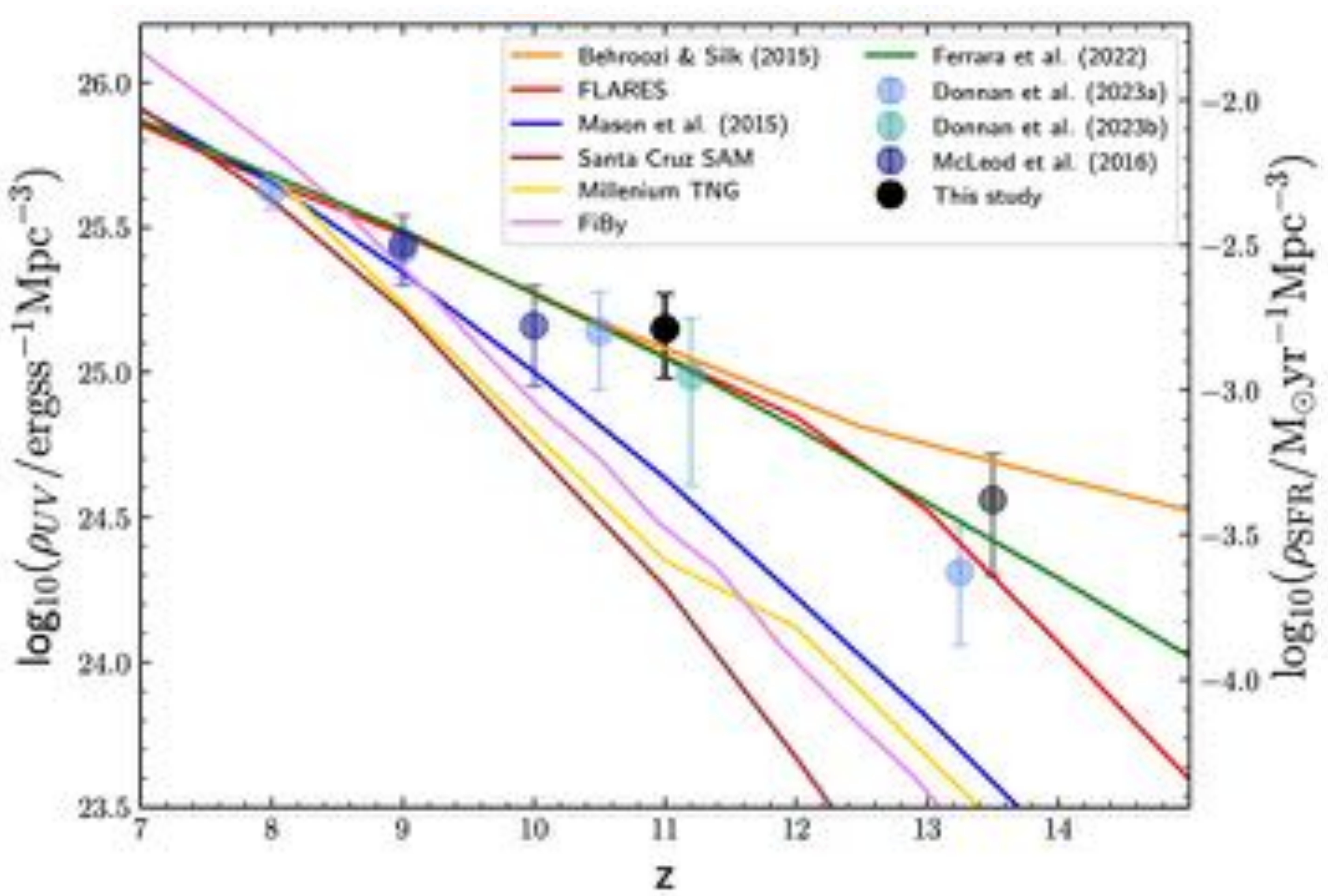
330 Myr

Implications for high-z star-formation rate density



McLeod et al. (2023)

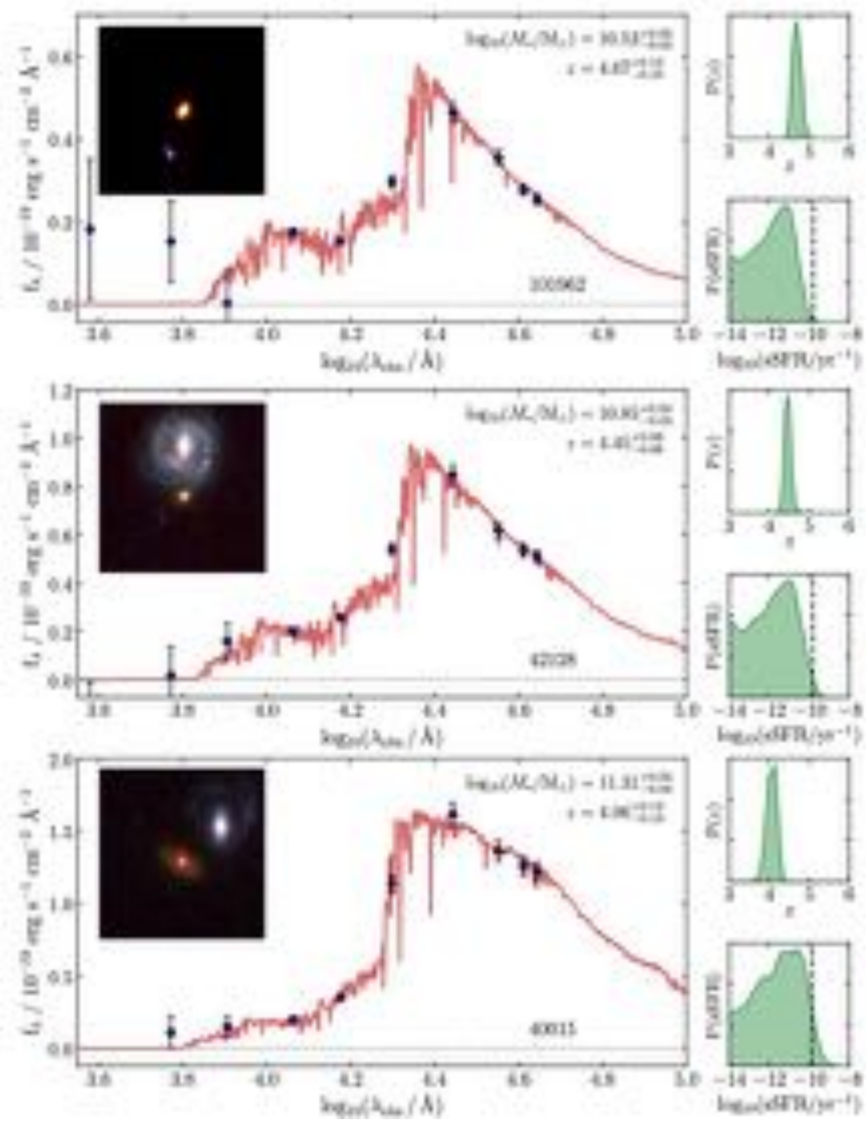
Comparison with theoretical predictions….

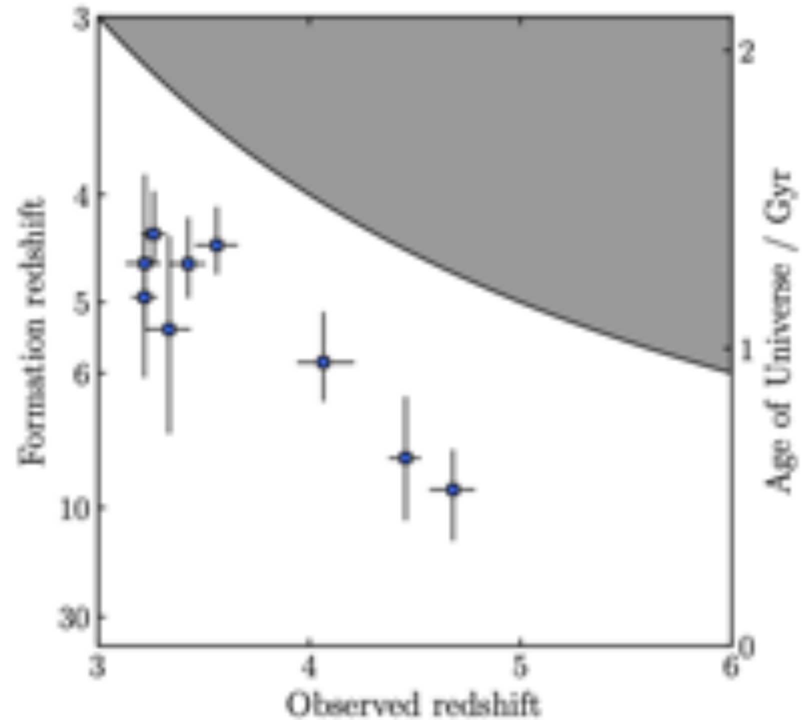


McLeod et al. (2023)

Highest redshift quiescent galaxies

– signposts of even earlier star-formation activity





Challenge for galaxy formation models

....but not (yet) to ΛCDM Cosmology

Carnall et al. (2022b)

New headline result published in Nature this week

Massive quiescent galaxy at z = 4.7 – NIRSpec spectroscopy. Carnall et al. (2023)

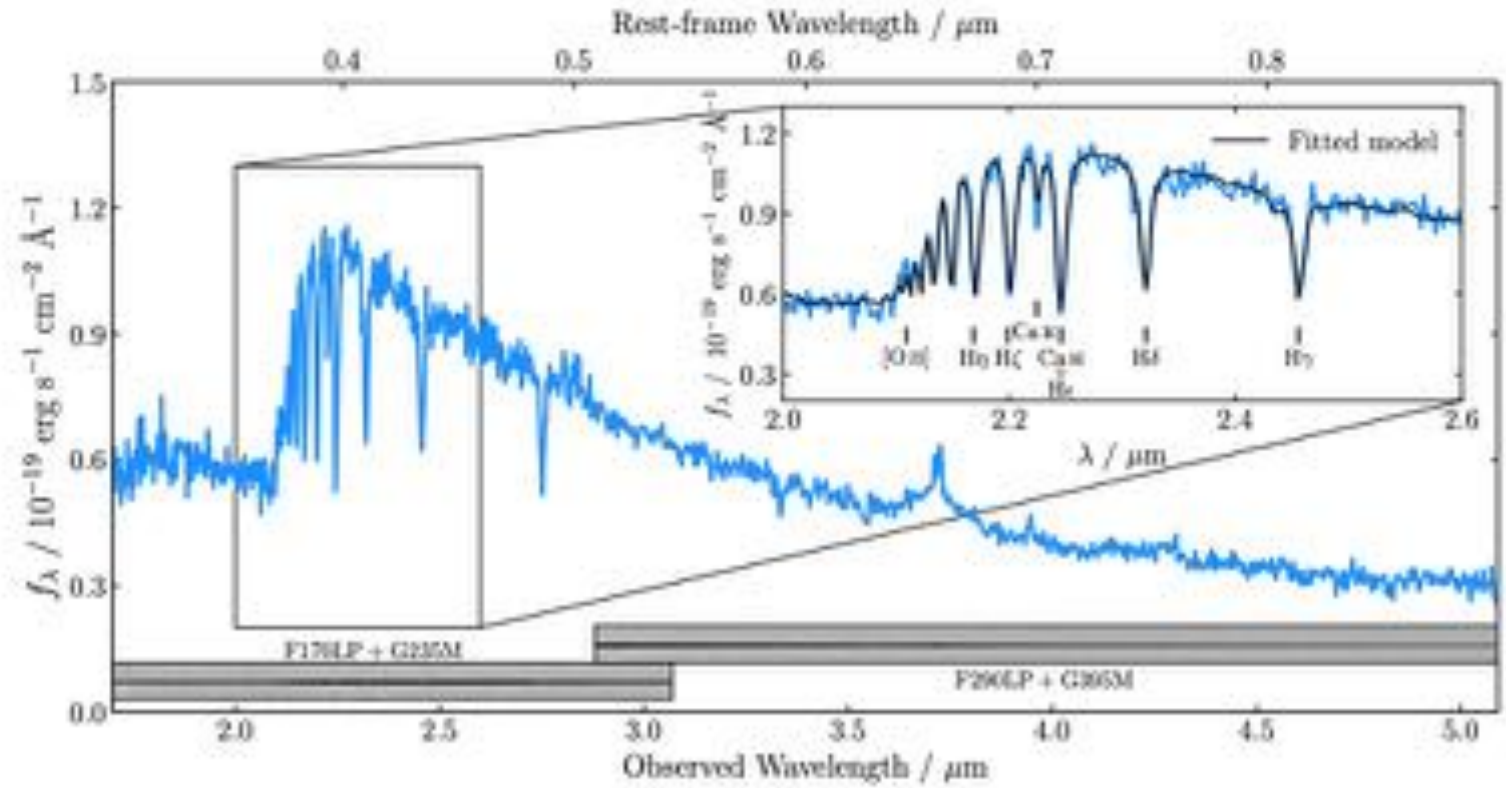
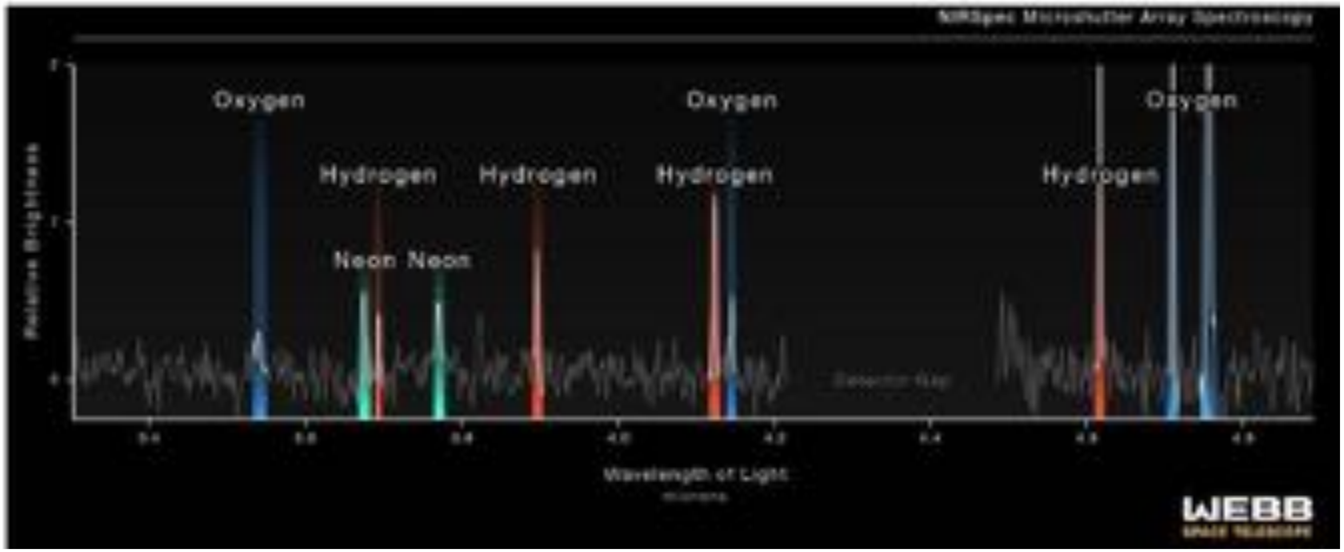


Fig. 1 JWST NIRSpec observations of GS-9209. Data were taken using the G235M and G395M gratings ($R = 1000$), providing wavelength coverage from $\lambda = 1.7 - 5.1\mu m$. The galaxy is at $z = 4.658$, and exhibits extremely deep Balmer absorption lines, similar to lower redshift post-starburst galaxies, clearly indicating this galaxy experienced a significant, rapid drop in star-formation rate (SFR) within the past few hundred million years. The spectral region from $\lambda = 2.6 - 4.0\mu m$, containing $H\beta$ and $H\alpha$, is shown at a larger scale in Fig. 2.

Physical properties of early galaxies

JWST NIRSpec spectroscopy: early results show Oxygen at z > 8



$z = 8.49730$

$M_* = 2.5 \times 10^7\ M_{sun}$

Carnall et al. (2023)

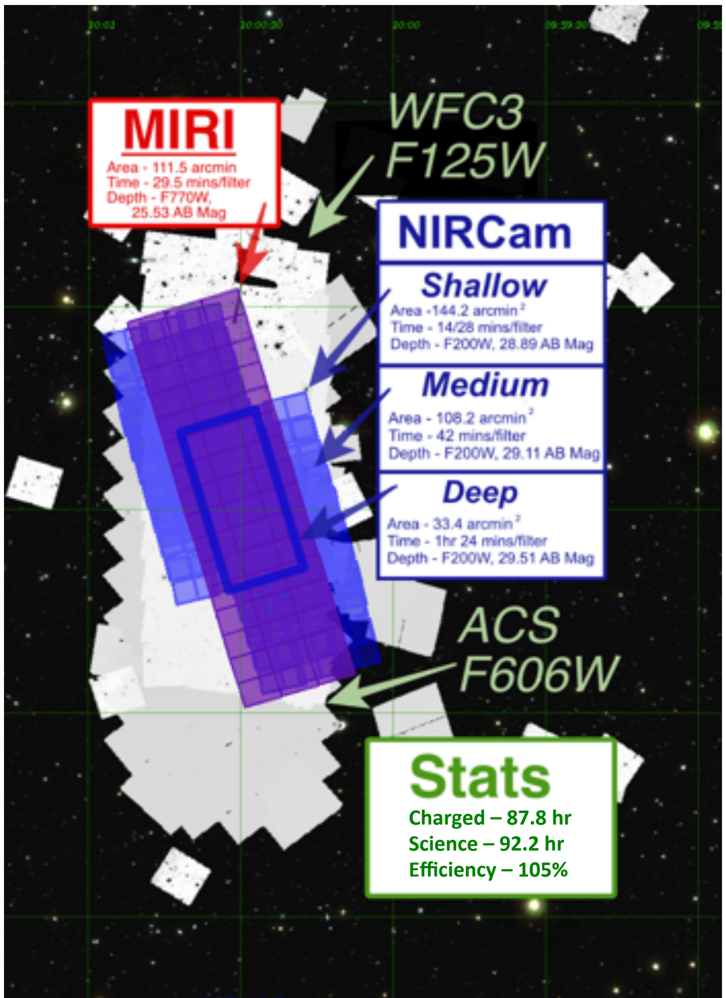
Data shows presence of Oxygen and Neon – already chemically enriched to > 2% solar.

JWST NIRSpec (and ALMA) follow-up in JWST Cycles 2 and 3 will be key to understanding the galaxies revealed by the early JWST NIRCam surveys

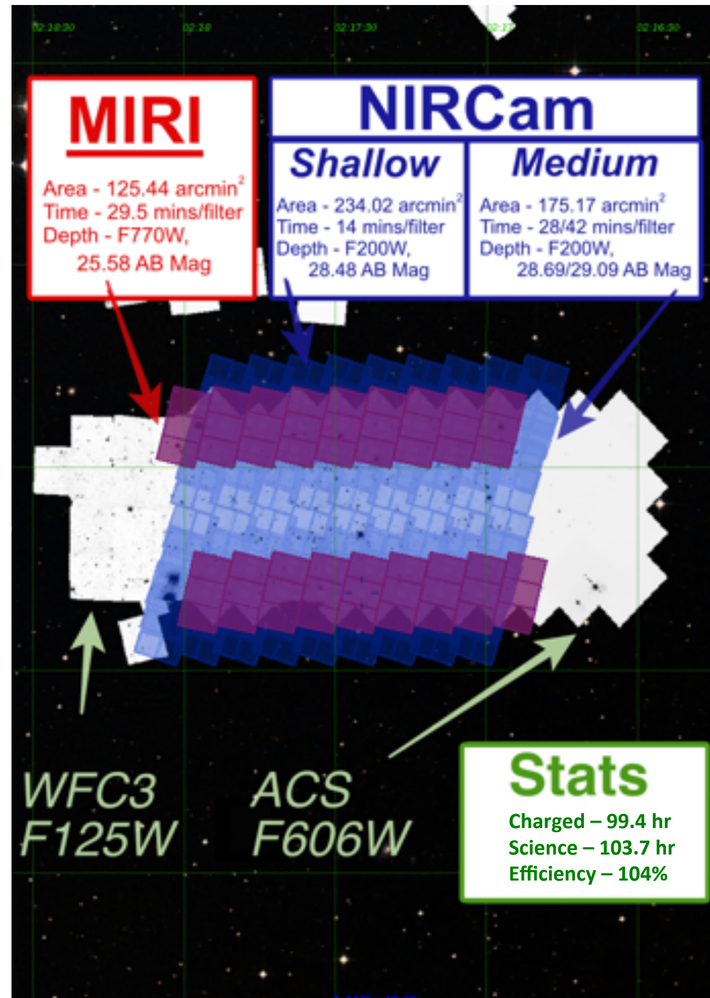
The search for the first stars and galaxies goes on....

The future – JWST just beginning

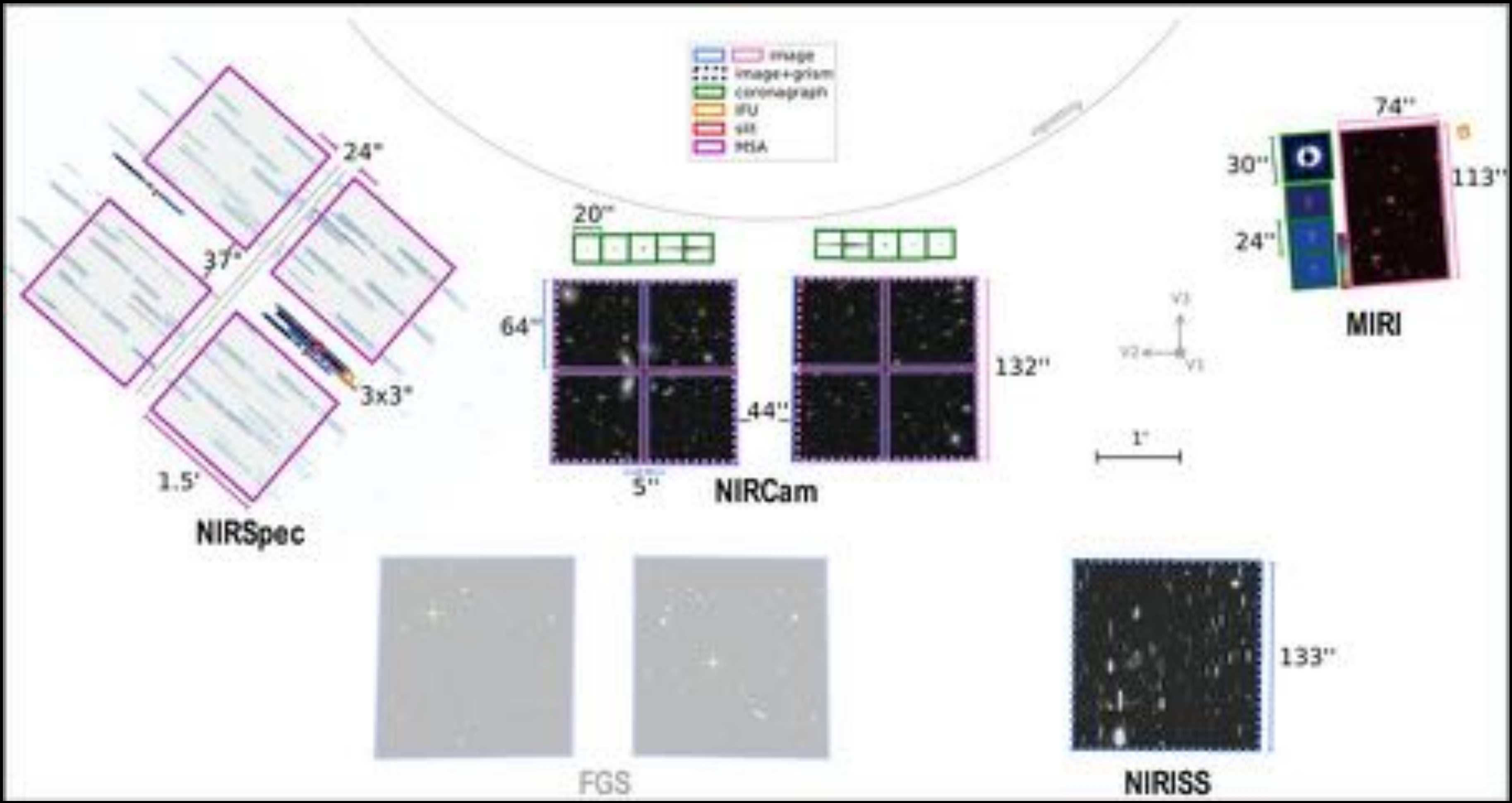
COSMOS



UDS

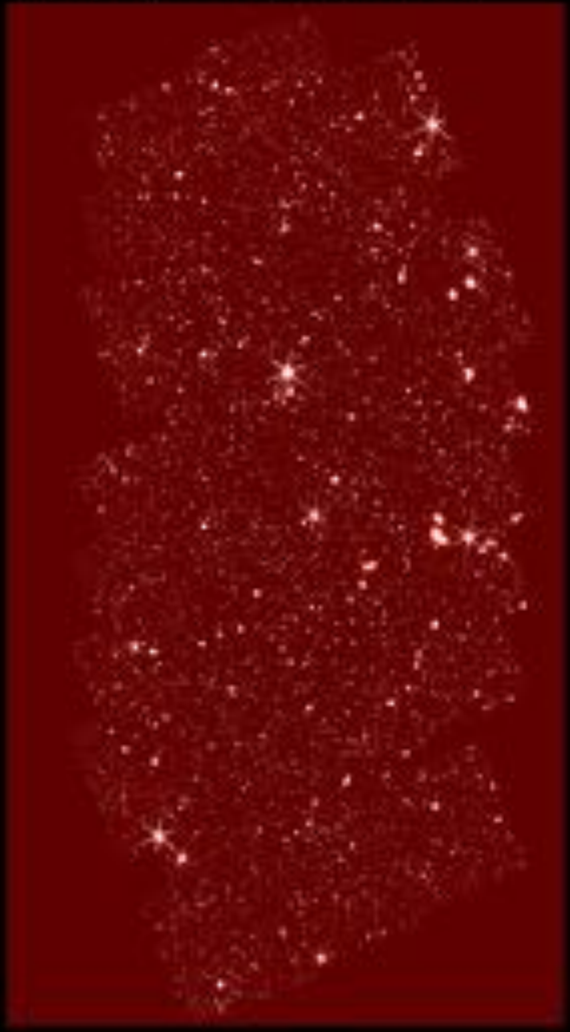


Instruments
JWST Focal Plane

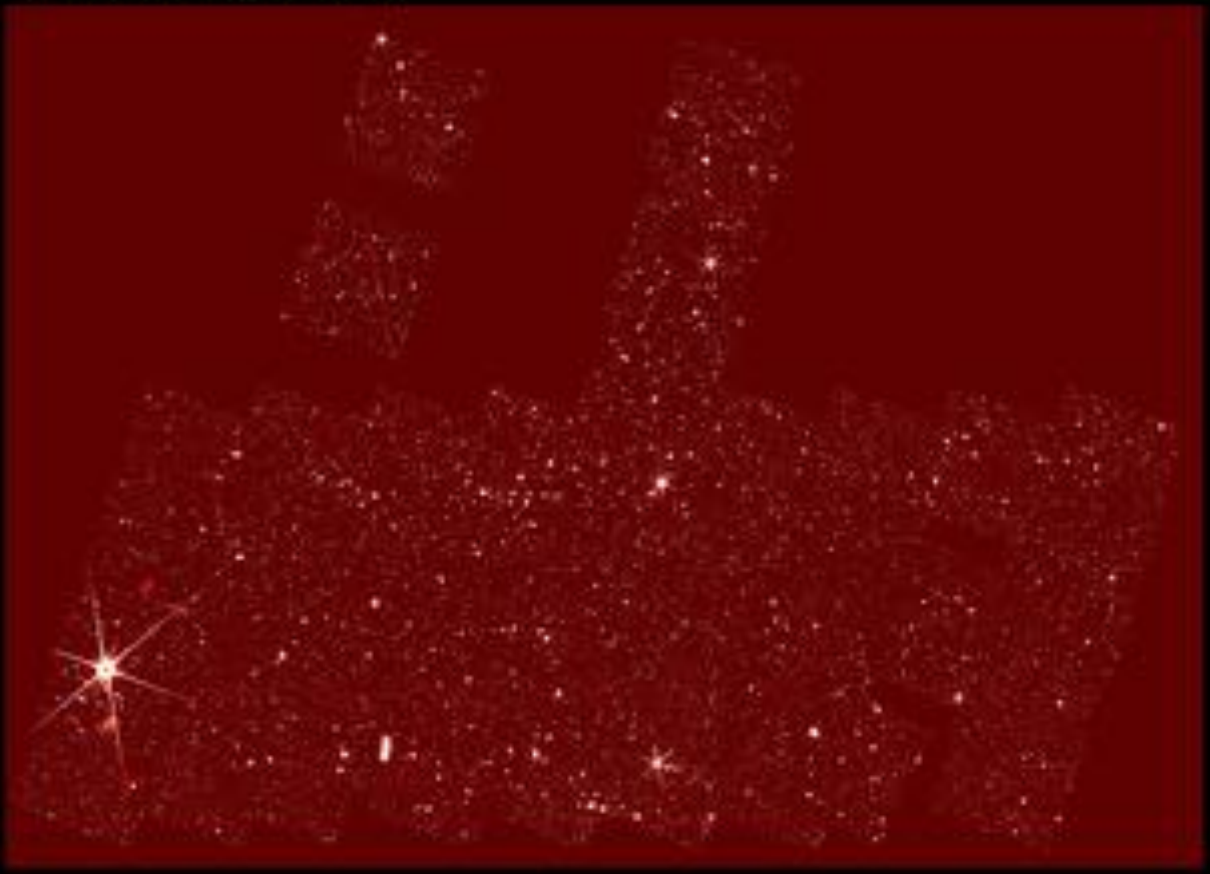


PRIMER (PI: J. Dunlop)

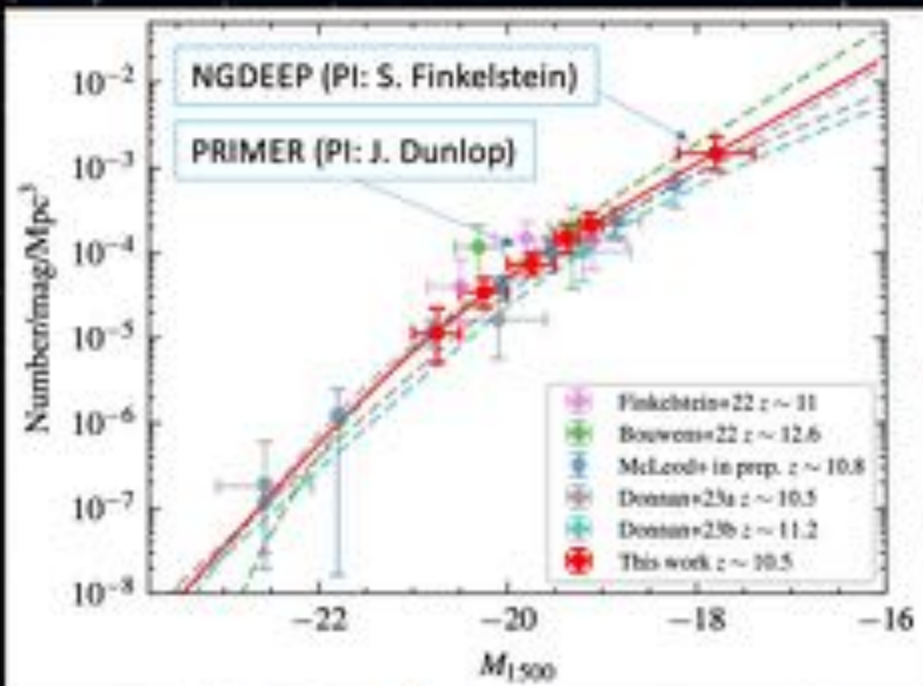
COSMOS ~86 sq. arcmin



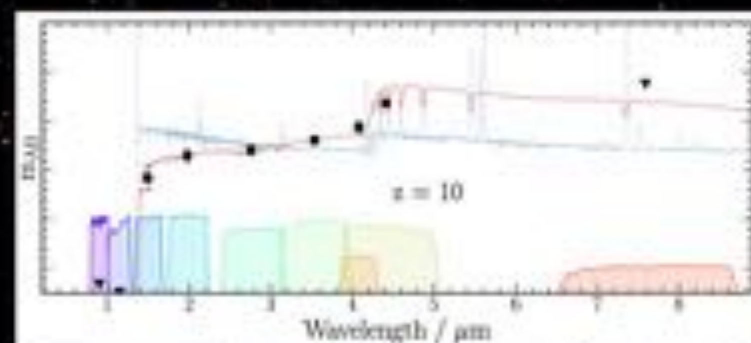
UDS ~146 sq. arcmin

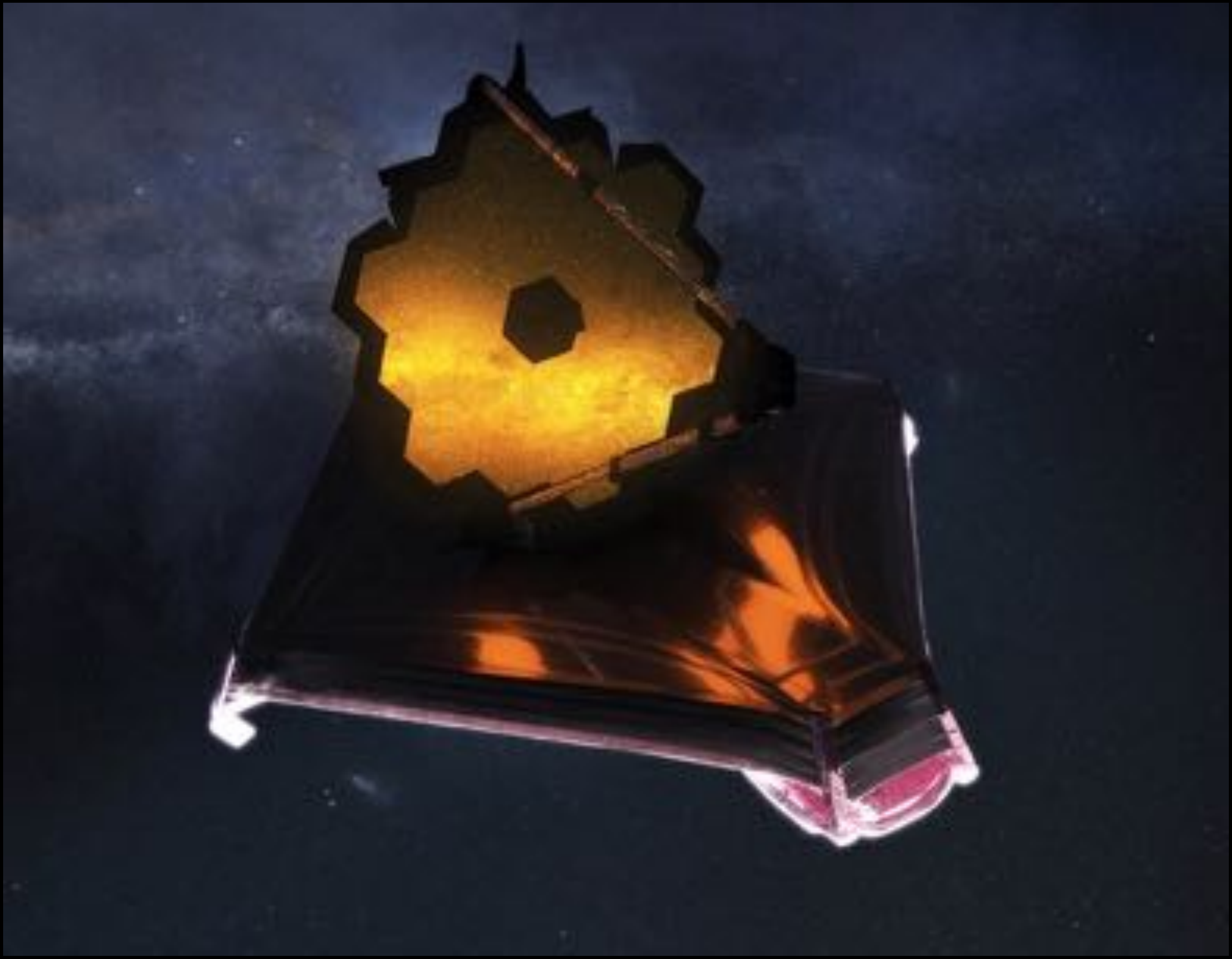


PRIMER Preliminary UV LF at $z \sim 10.5$



- Improved dynamic range in M_{UV}
- Constrain shape of LF at z>10
- Large sample size of targets for JWST/NIRSpec, ALMA and Keck/MOSFIRE observations





https://www.youtube.com/watch?v=RzGLKQ7_KZQ