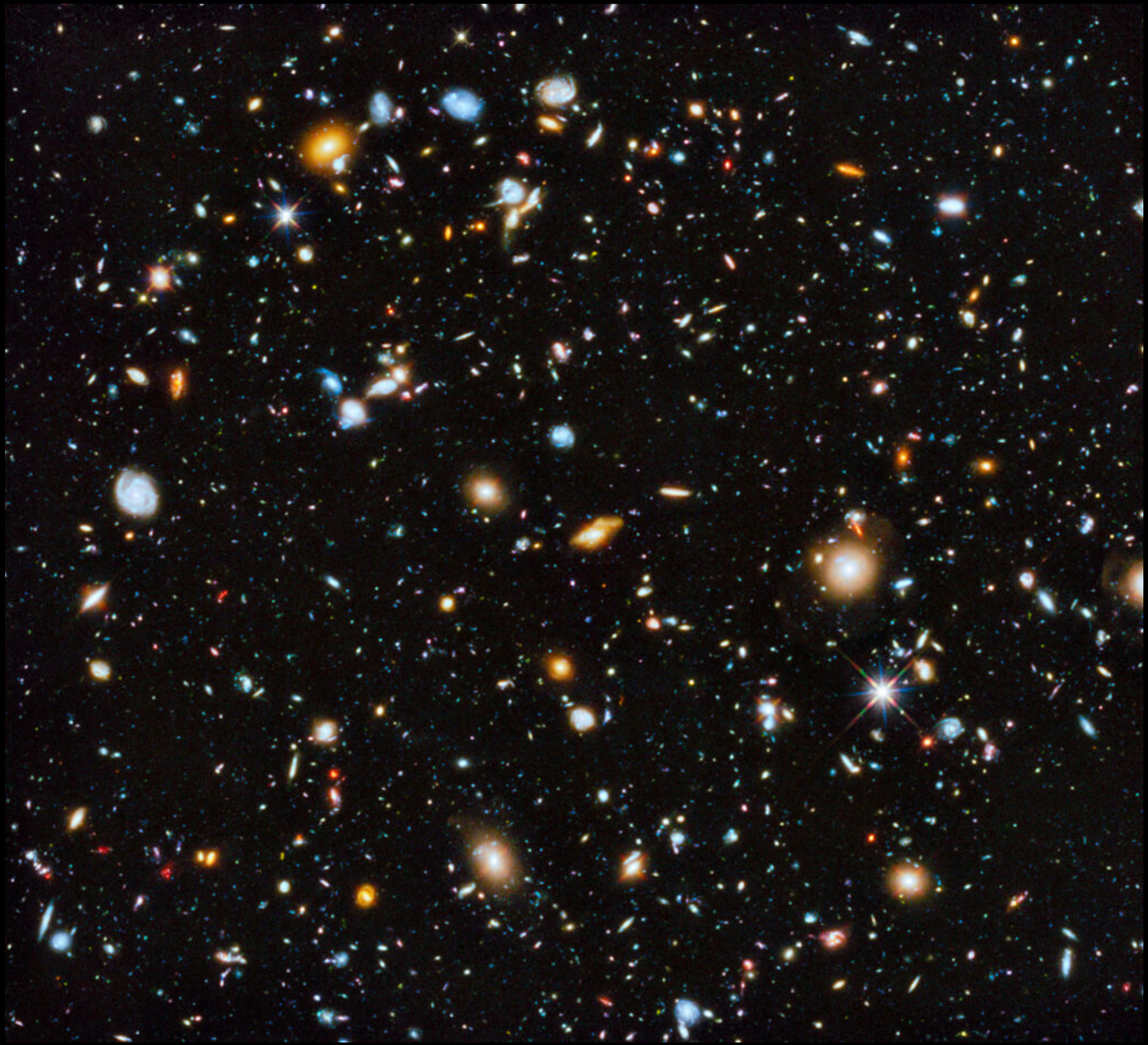
Illuminating Cosmic Dawn : Probing the first galaxies with AtLAST

Nicolas Laporte

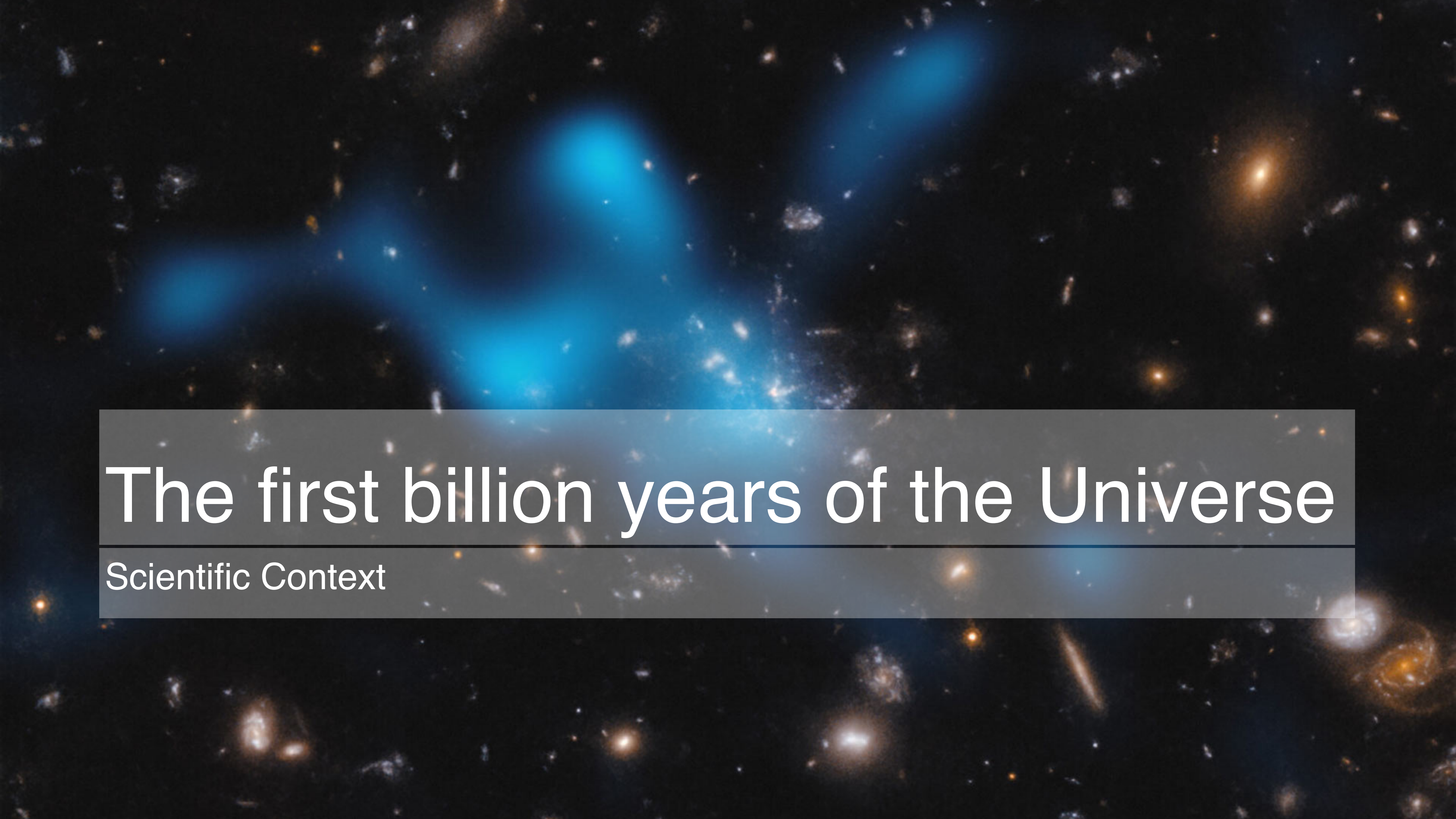
14th May 2025 – journées AtLAST

Outline

- The first billion years of the Universe
- New insights from JWST
    - Higher Star Formation Efficiency ?
    - A high abundance of protoclusters ?
    - Many AGNs within the first Gyr ?
- The key role of AtLAST



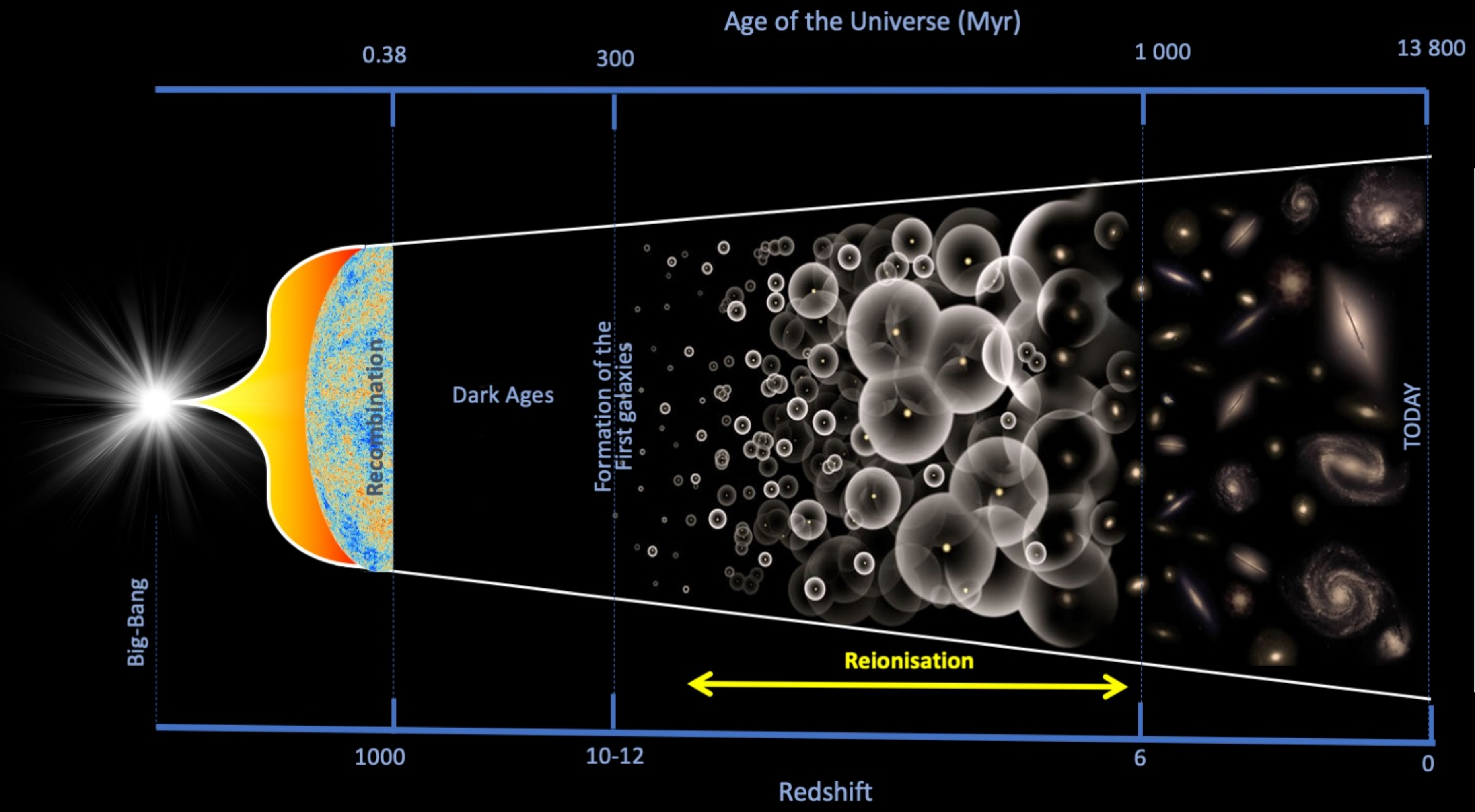
Hubble eXtreme Deep Field



The first billion years of the Universe

Scientific Context

A brief history of our Universe



REDSHIFT vs AGE OF THE UNIVERSE

- z=1100 : t=380,000 yrs
- z=15 : t=300 Myrs
- z=10 : t=500 Myrs
- z=7 : t=800 Myrs
- z=6 : t=1 Gyr
- z=2 : t=3.3 Gyr
- z=1 : t=6 Gyr
- z=0 : t=13.8 Gyr

The Epoch of Reionisation

- The **reionisation** is the process during which the neutral hydrogen formed at the recombination epoch is ionised

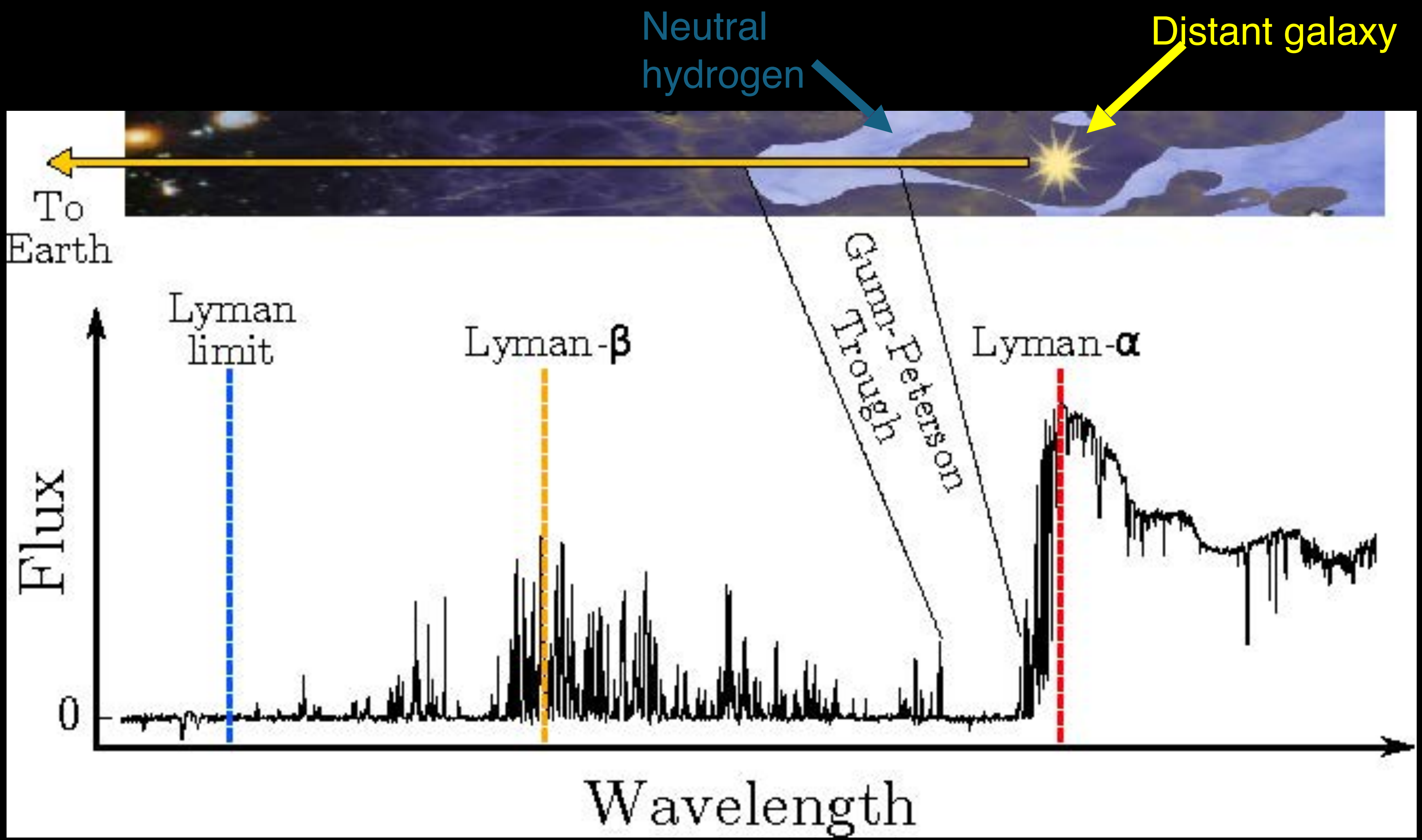
- The first stars are massive (up to 1000 $M_\odot$) with a short lifetime (a few million years) but they emit a large number of UV photons

- Each star/galaxy produces ionised bubbles that eventually merge increasing the transparency of the Universe

Credit: the SPHINX collaboration

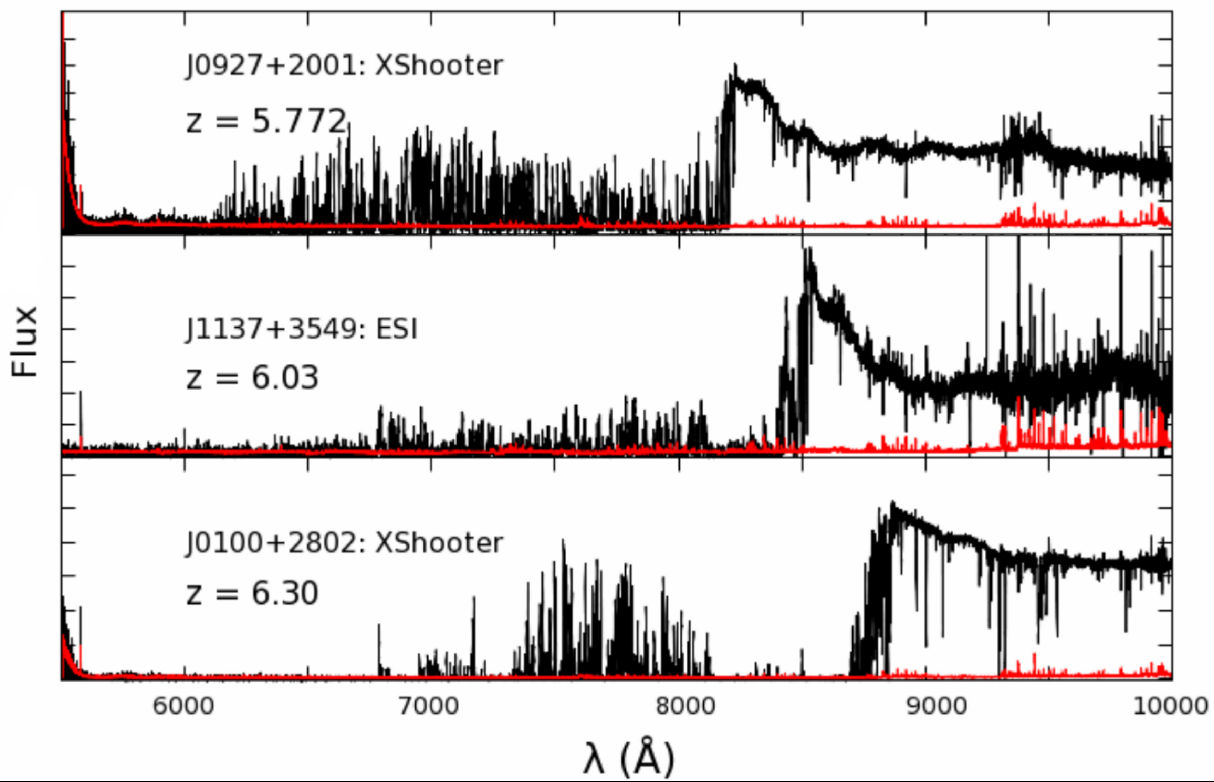
Rosdahl et al. (2022), Katz et al. (2022), Maji et al. (2022)

The Gunn Peterson Trough



- Distant galaxies emit UV photons, which ionise the surrounding neutral hydrogen.
- If neutral hydrogen lies along the line of sight (*i.e. the emission occurs during the EoR*) then an absorption feature appears in the galaxy's spectrum (the Gunn Peterson trought)

Observational probes of the EoR

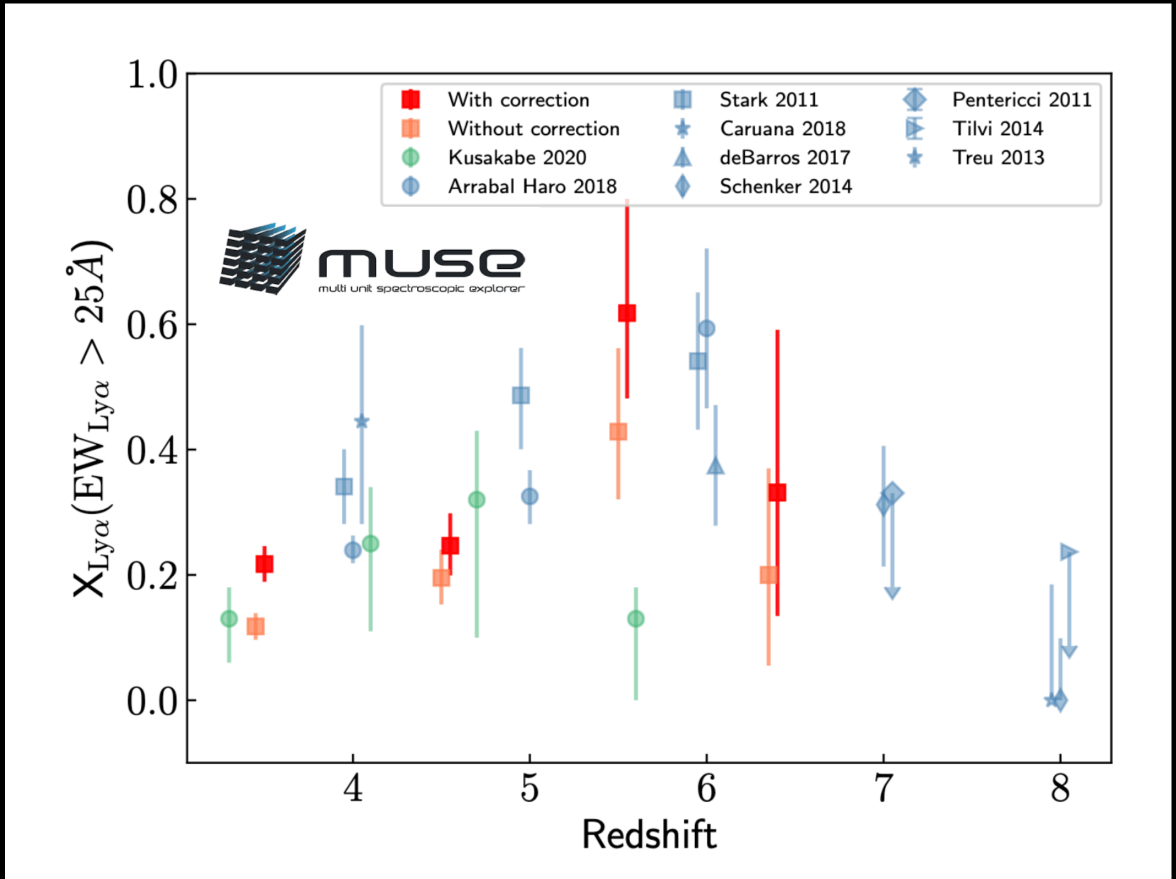


Bosman et al. (2018)

- Neutral Hydrogen clouds along the line of sight absorb radiation below the Lyman-alpha limit : this is **the Gunn Peterson effect.**
- To be detected, it requires very high signal-to-noise ratio.
- Therefore, this technique can only be applied to quasars spectra
- From distant quasars observations, the end of the reionisation epoch is estimated near $z \sim 6$

See also Fan et al. (2006), Bosman et al. (2022)

Observational probes of the EoR

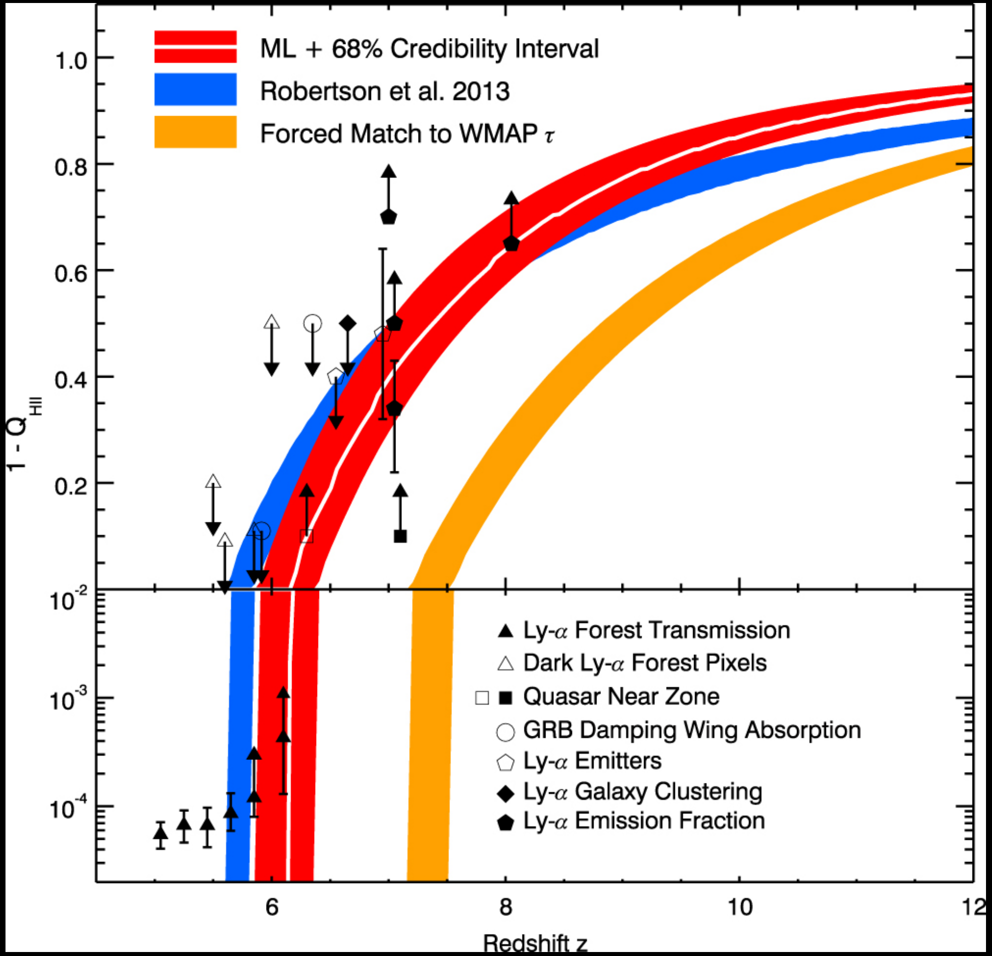


De la Vieuville et al. (2020)

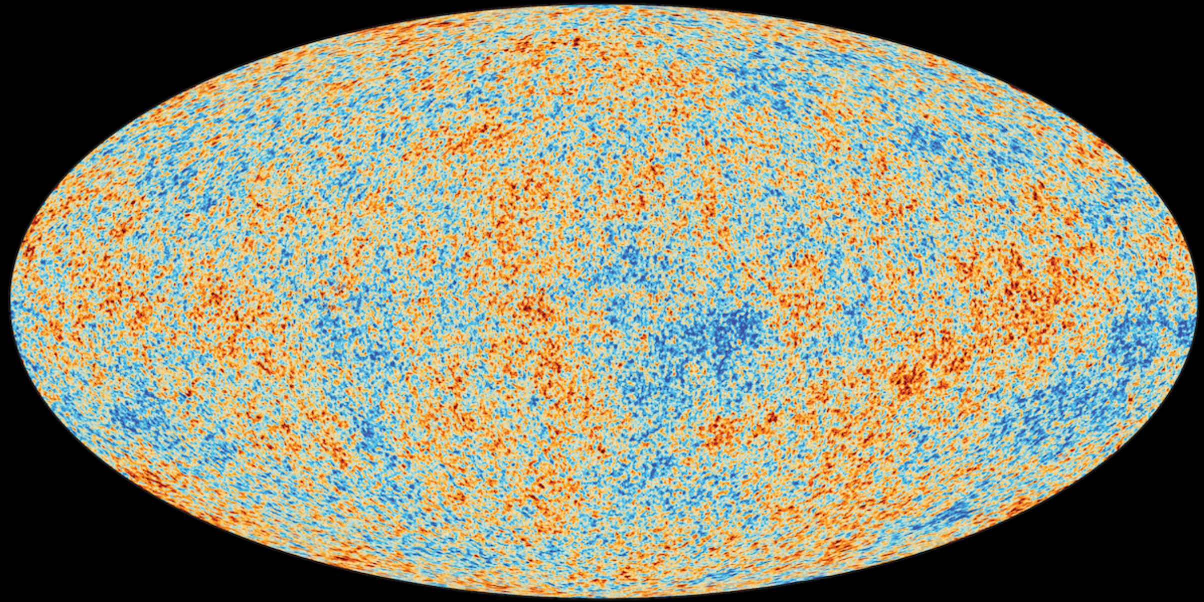
See also Stark et al. (2017), de Barros et al. (2019)

- The brightest UV rest-frame emission line expected in star-forming galaxies is Ly-α
- However, if Ly-α is emitted by a galaxy surrounded by neutral hydrogen, it will be absorbed
- Deep spectroscopic surveys show a strong decrease in the detectability of Ly-α at z>6

Observational probes of the EoR

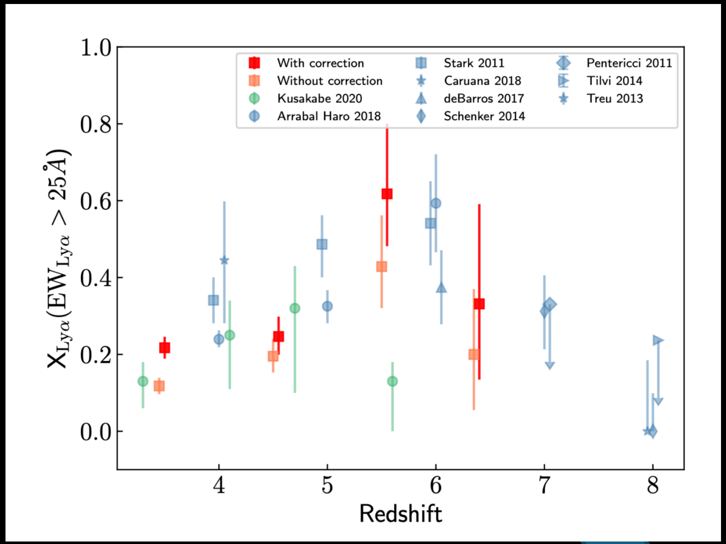


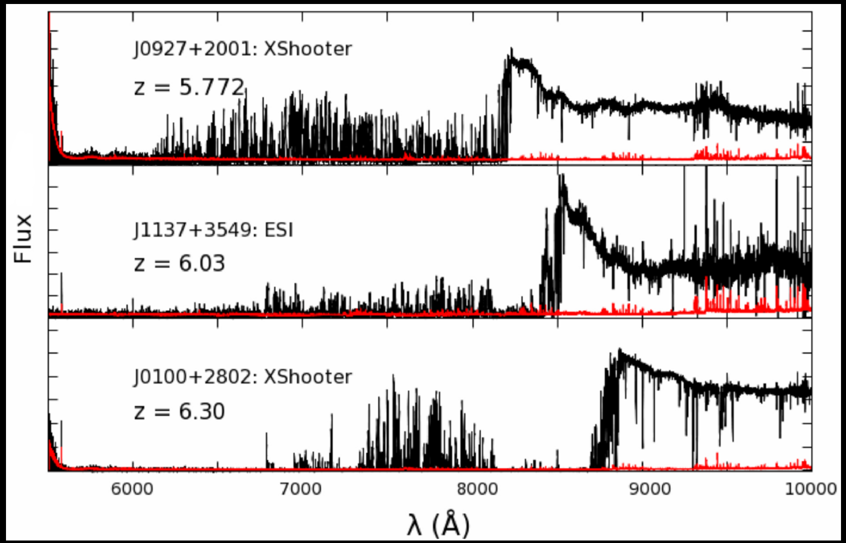
Robertson et al. (2015)

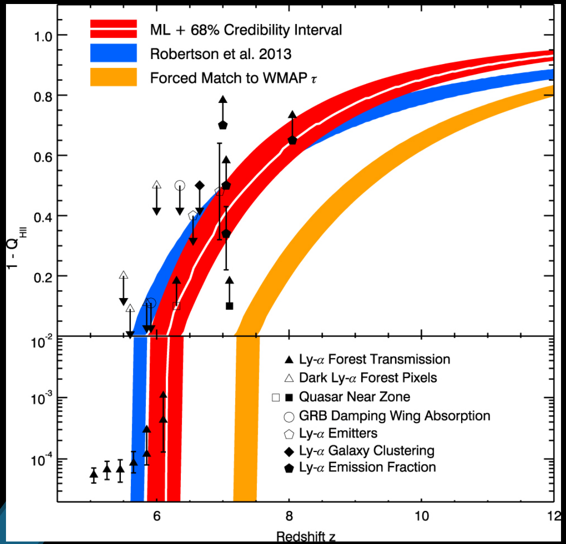


- The reionisation of the neutral hydrogen produces free electrons that interact with Cosmic Microwave Background (CMB) photons and induce polarization
- Measuring the Thomson optical depth from the CMB gives an estimate of the evolution of the neutral fraction over cosmic time
- *Planck* observations show that the neutral fraction of the hydrogen is negligible at z<6

Observational probes of the EoR

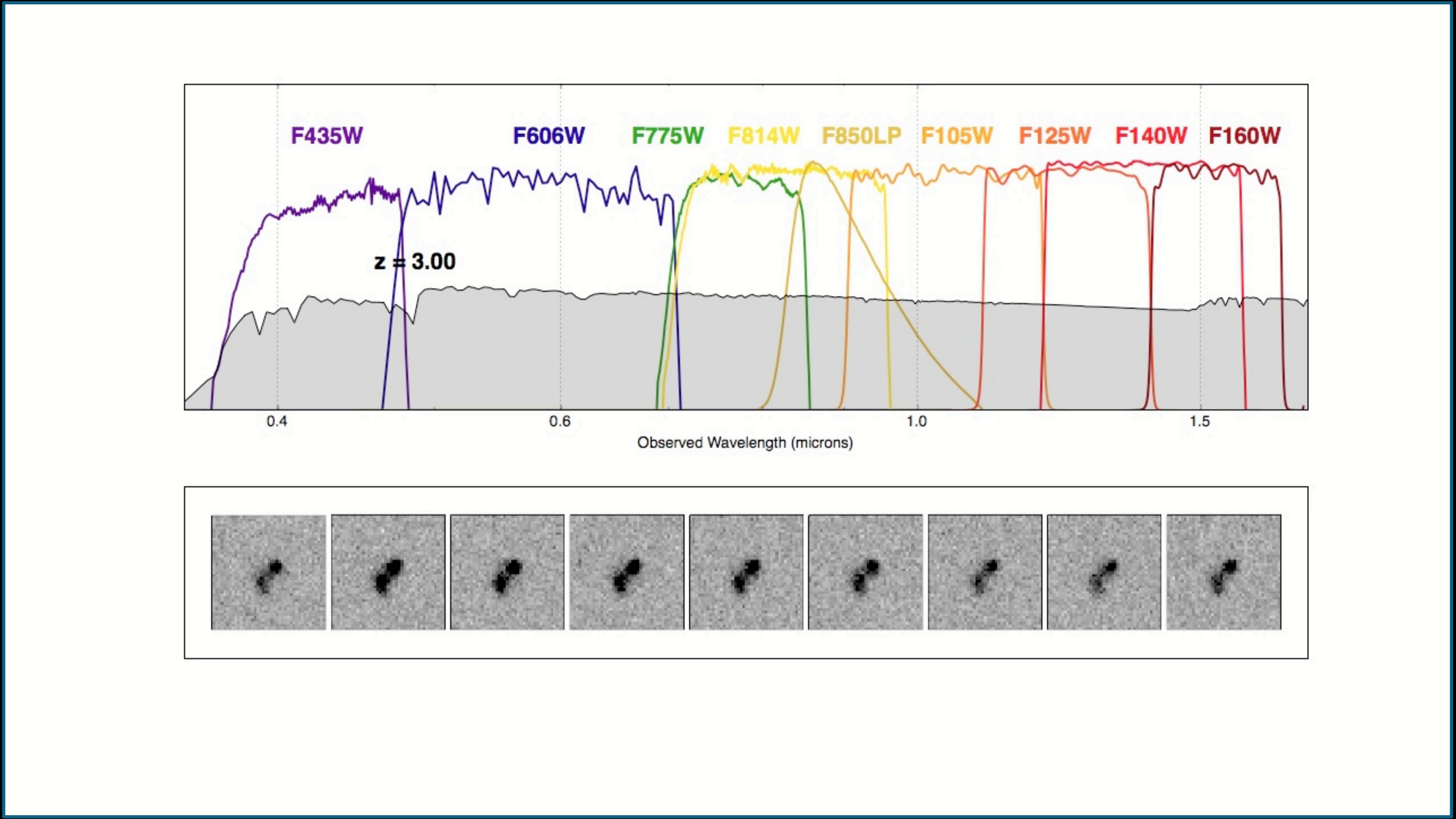




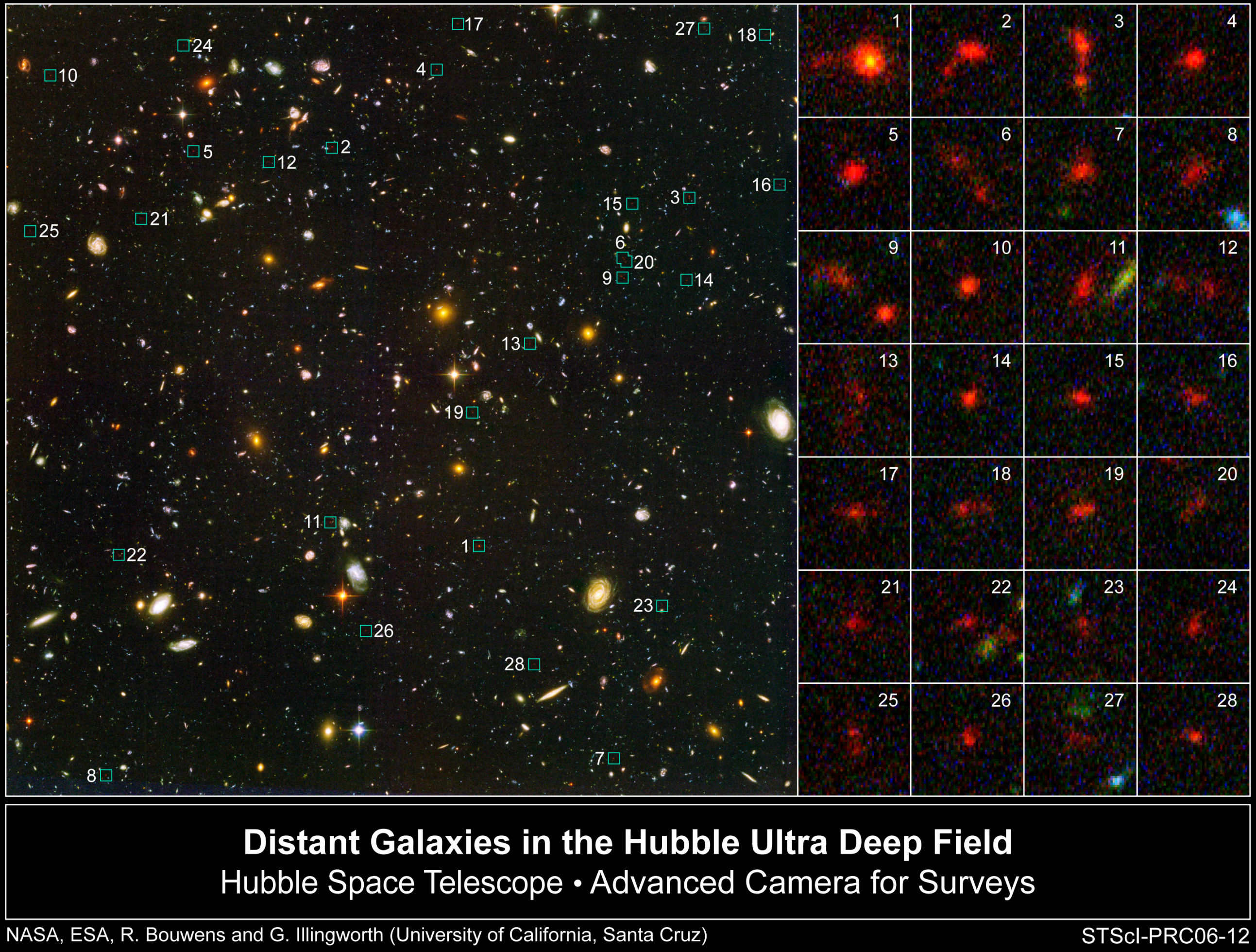


By z=6, the first population of galaxies has produced enough UV photons to ionise the neutral hydrogen formed at the recombination epoch.

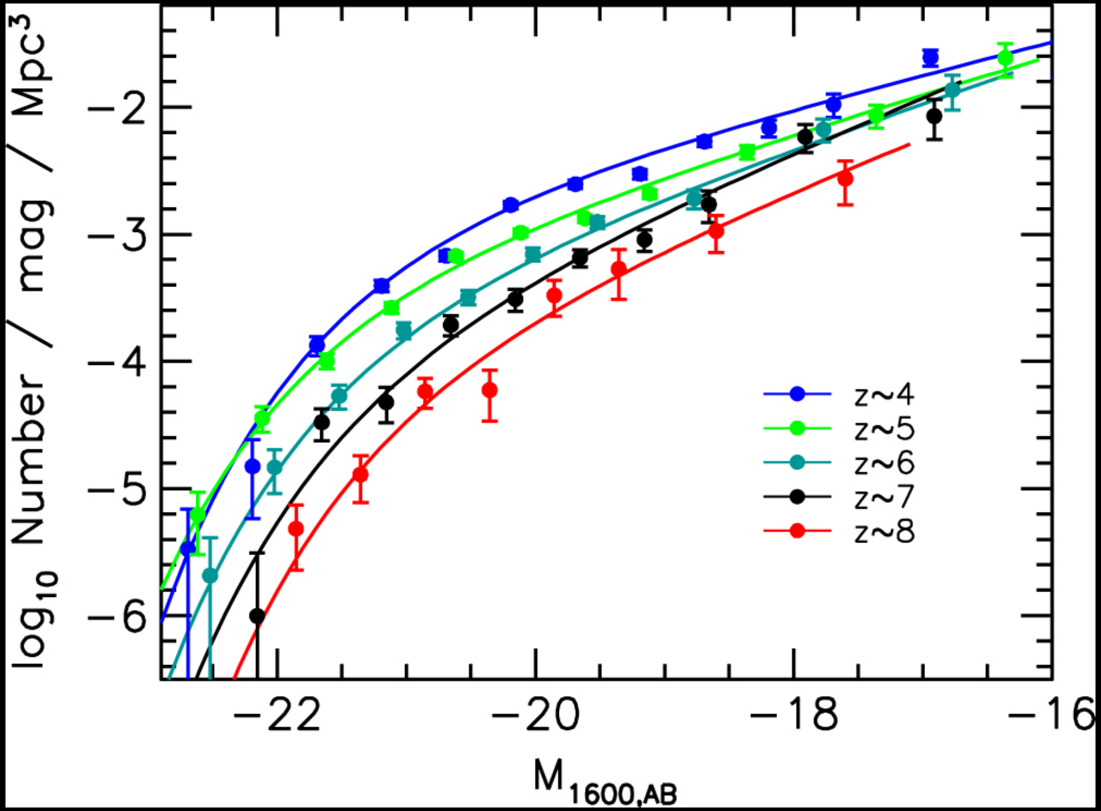
The Lyman Break technique *to identify the most distant galaxies*



The deepest survey *of the Hubble Space Telescope*

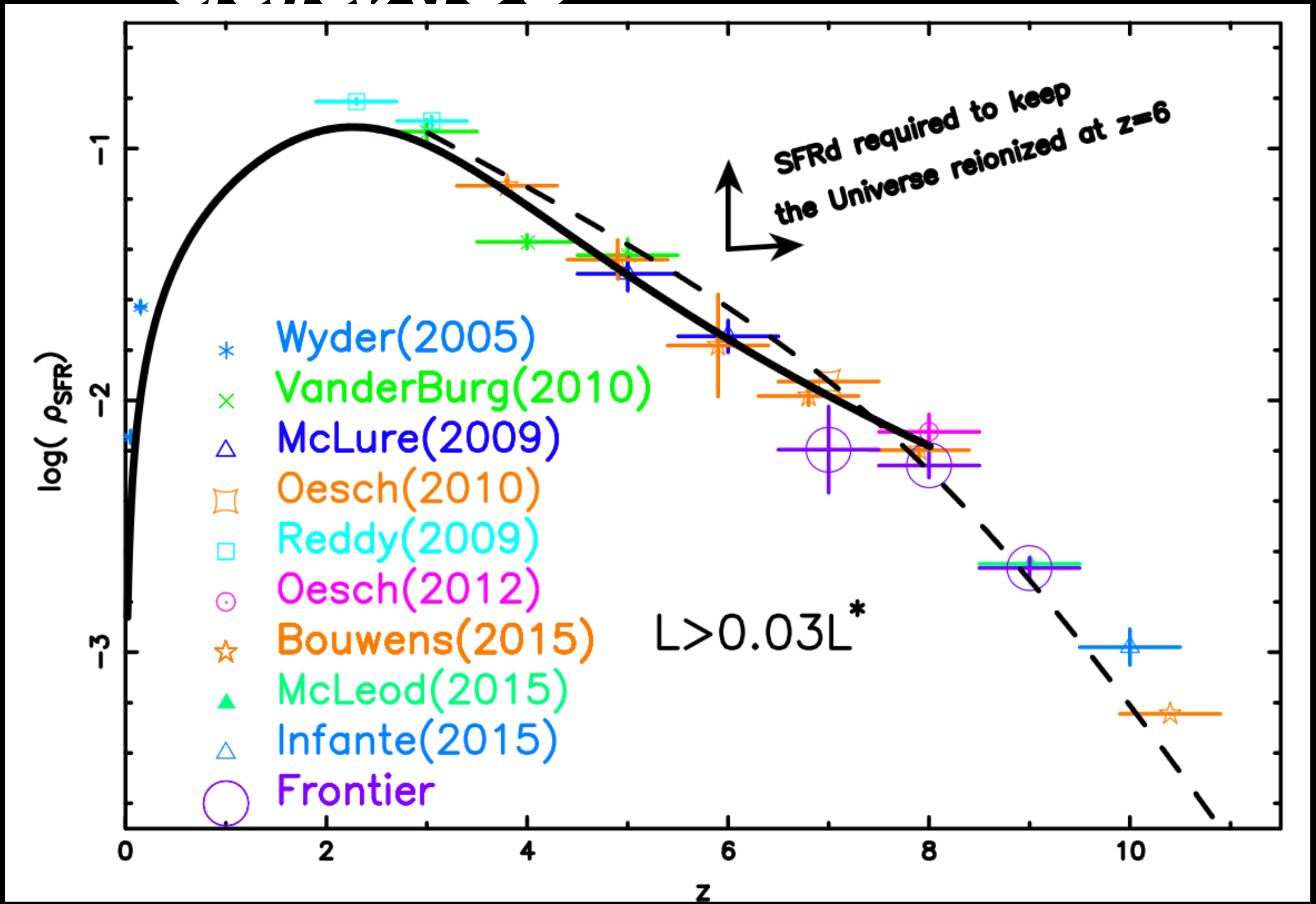


Bouwens et al. (2008)



Bouwens et al. (2015)

The UV photons production *by the most distant galaxies*



Laporte et al. (2016)

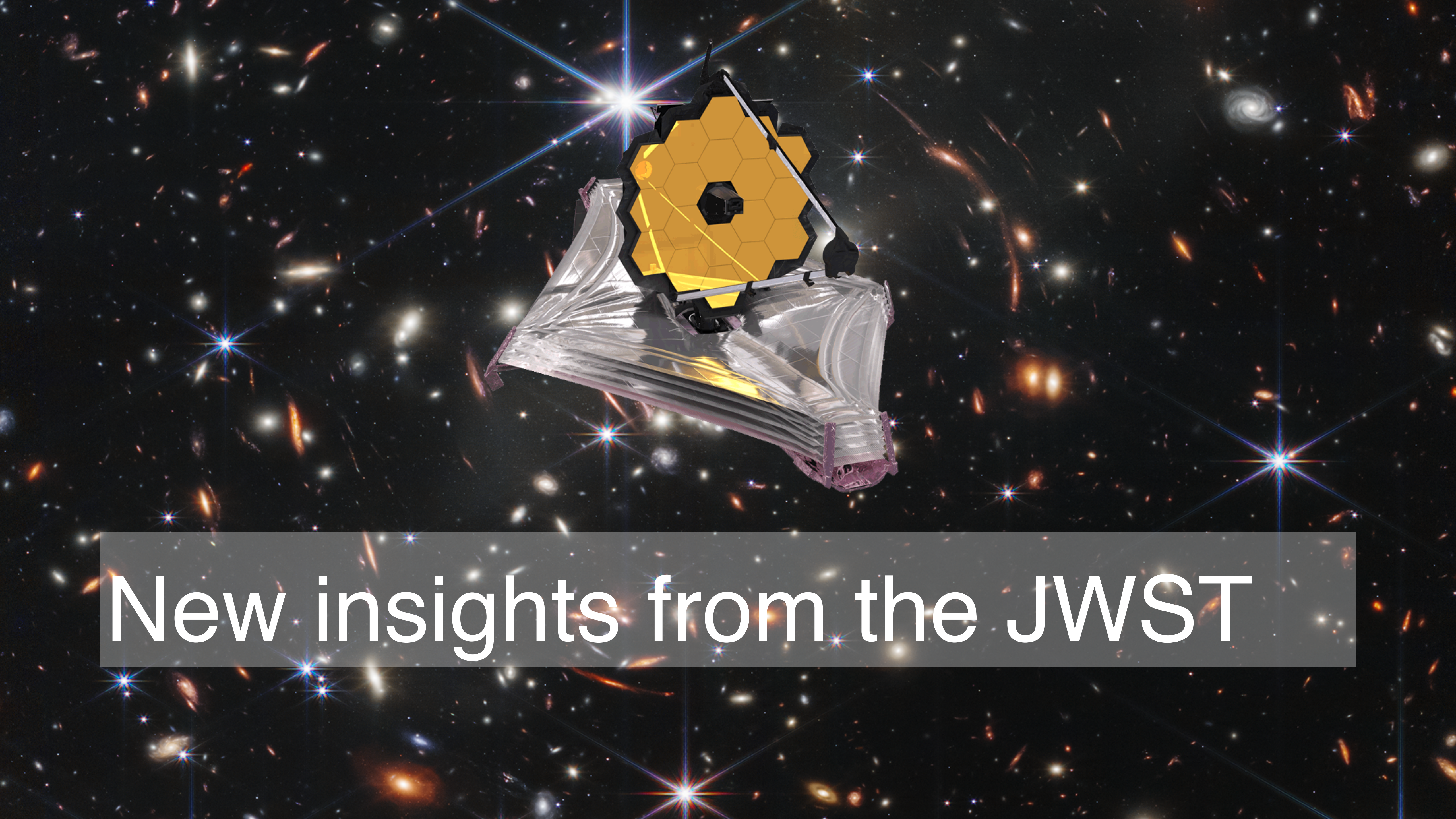
- Within the last decade, deep surveys (eg, CANDELS, Frontier Fields, WUDS, UltraVISTA) have discovered 1000s of galaxies at z>6 (Bouwens et al. 2015)
- Assuming that z>6 galaxies have similar properties as low-redshift galaxies, we cannot explain the end of the epoch of reionisation at z=6.

The Epoch of Reionisation : open questions

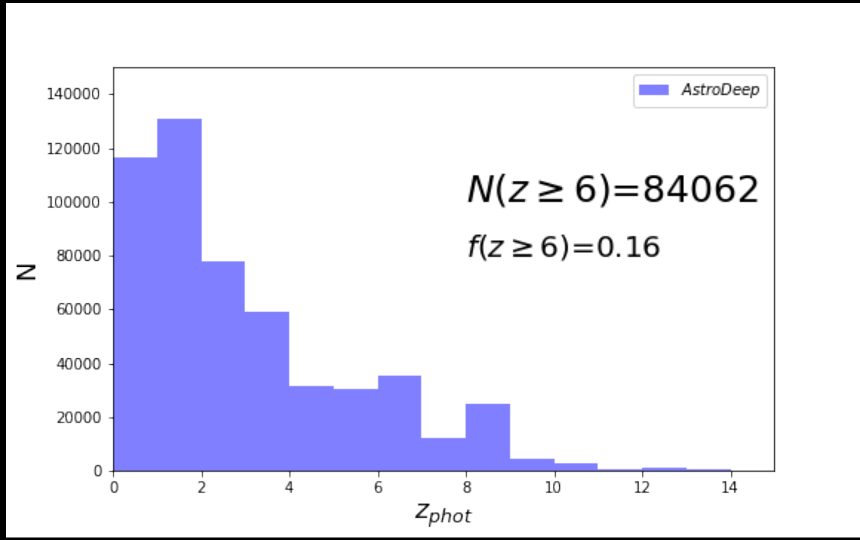
- When did the first galaxies form ?
- How did they form ?
- What are the physical properties of the first galaxies ?
- When did the first black holes form ?
- How did the first galaxies and black holes evolve over the first billion years ?

CANDELS/UDS – Grogin et al. (2011)

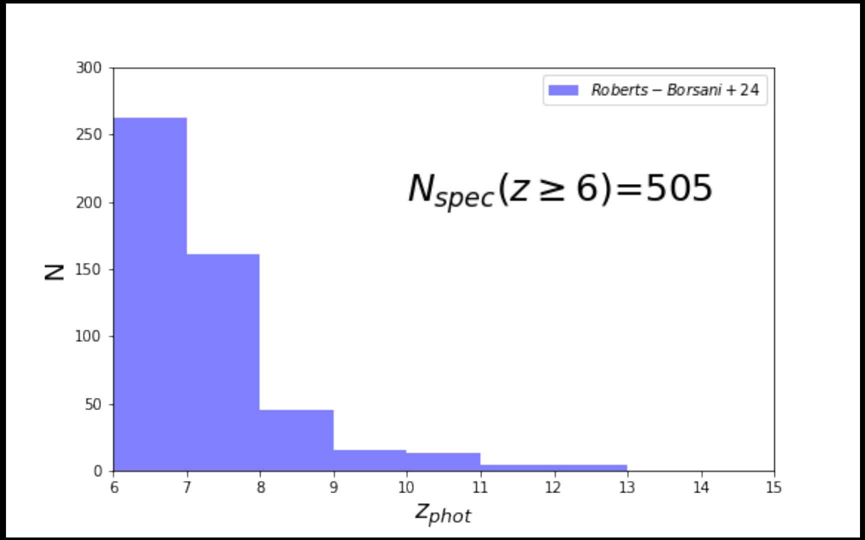
See also McCracken et al. (2012) Lotz et al. (2017), Pelló et al. (2018)


New insights from the JWST

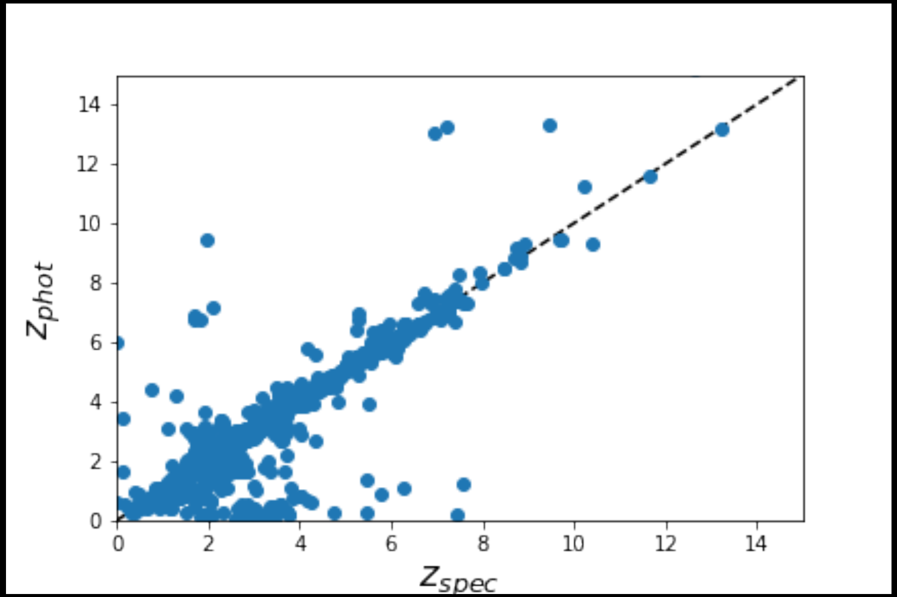
A large sample of galaxies at z>6



- The unprecedented depth of JWST data ($1.5\mu m \sim 30$AB at 5σ) leads to the detection of more than 80 000 z>6 galaxies.
- The multiplexing of NIRSpec/JWST $\sim$100 objects can be observed in one pointing with a sensitivity reaching 28AB at 5σ in 10 hrs.



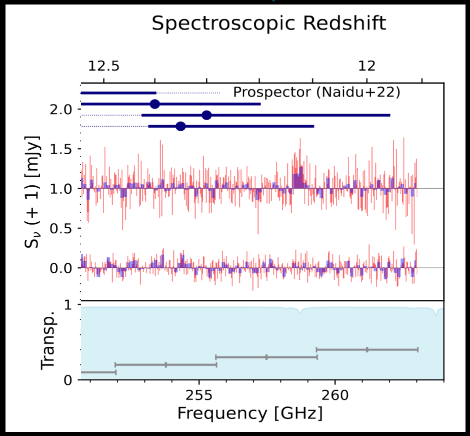
- Over 500 galaxies have been spectroscopically confirmed at z>6.
- This represents less than 1% of detected galaxies, and is biased towards the brightest ones



But this picture is not so perfect!

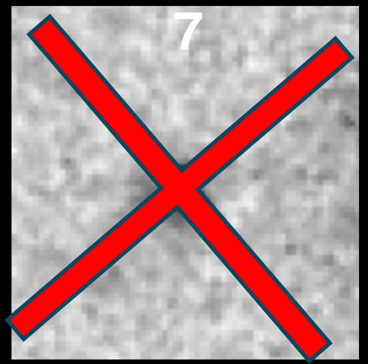
z=13

GLASS-z13 (Naidu et al. 2022)

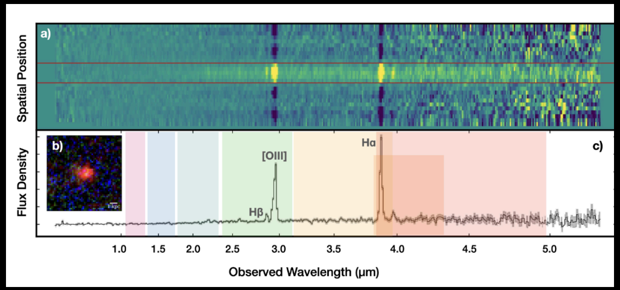


Bakx et al.

z=16.39±0.2

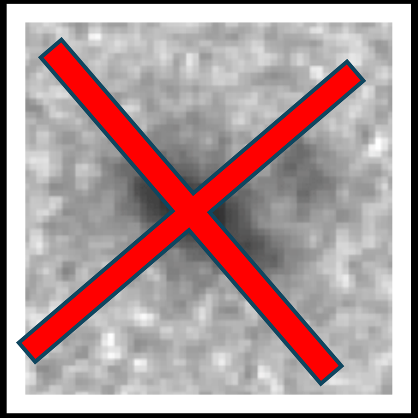


Donnan et al. (2022)

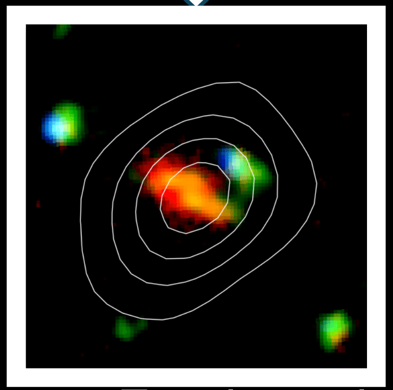


Arrabal-Haro et al. (2023)

z=17

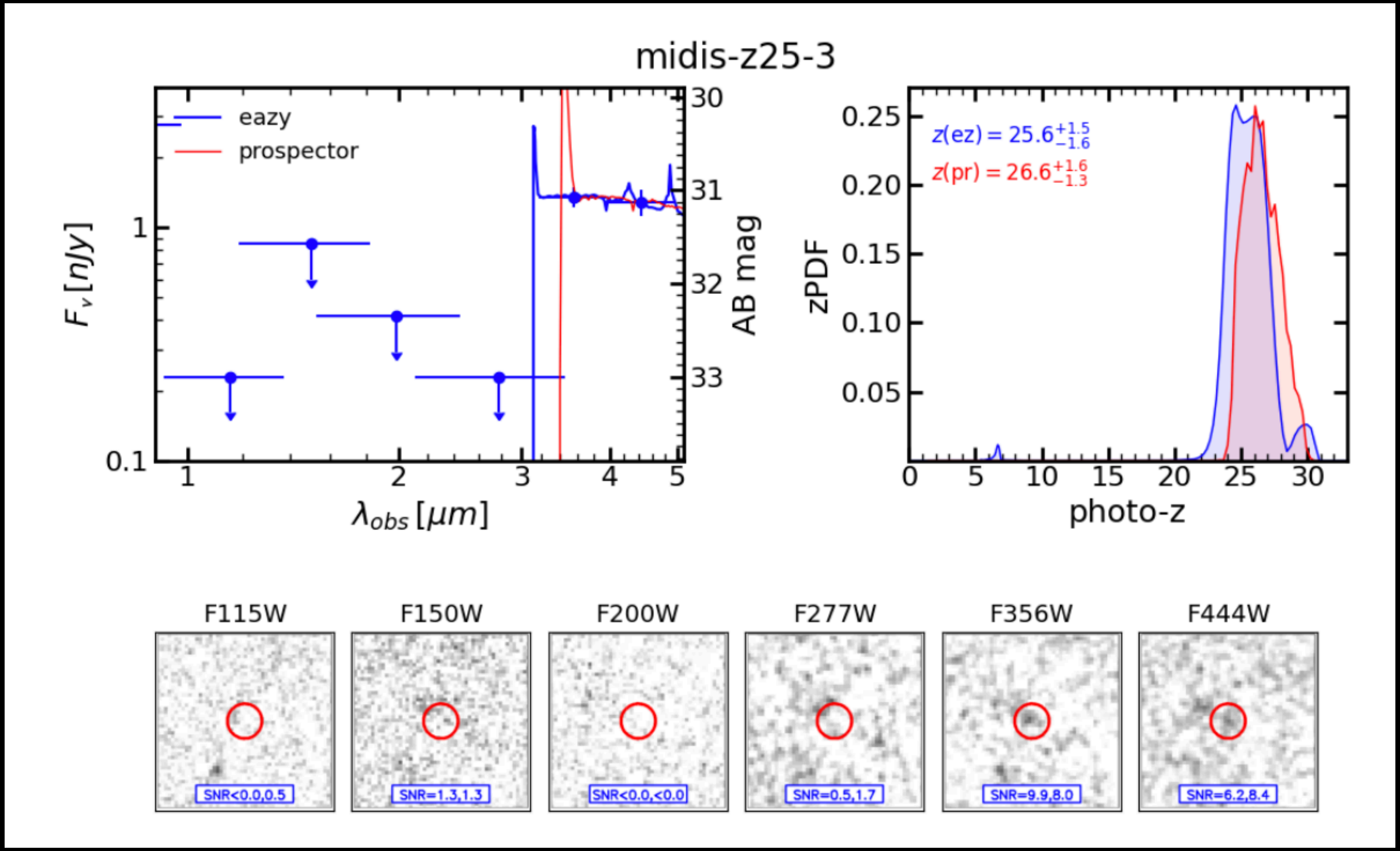


CEERS-DSFG-1 (Finkelstein et al. 2022)



Zavala et al. (2022)

But this picture is not so perfect!

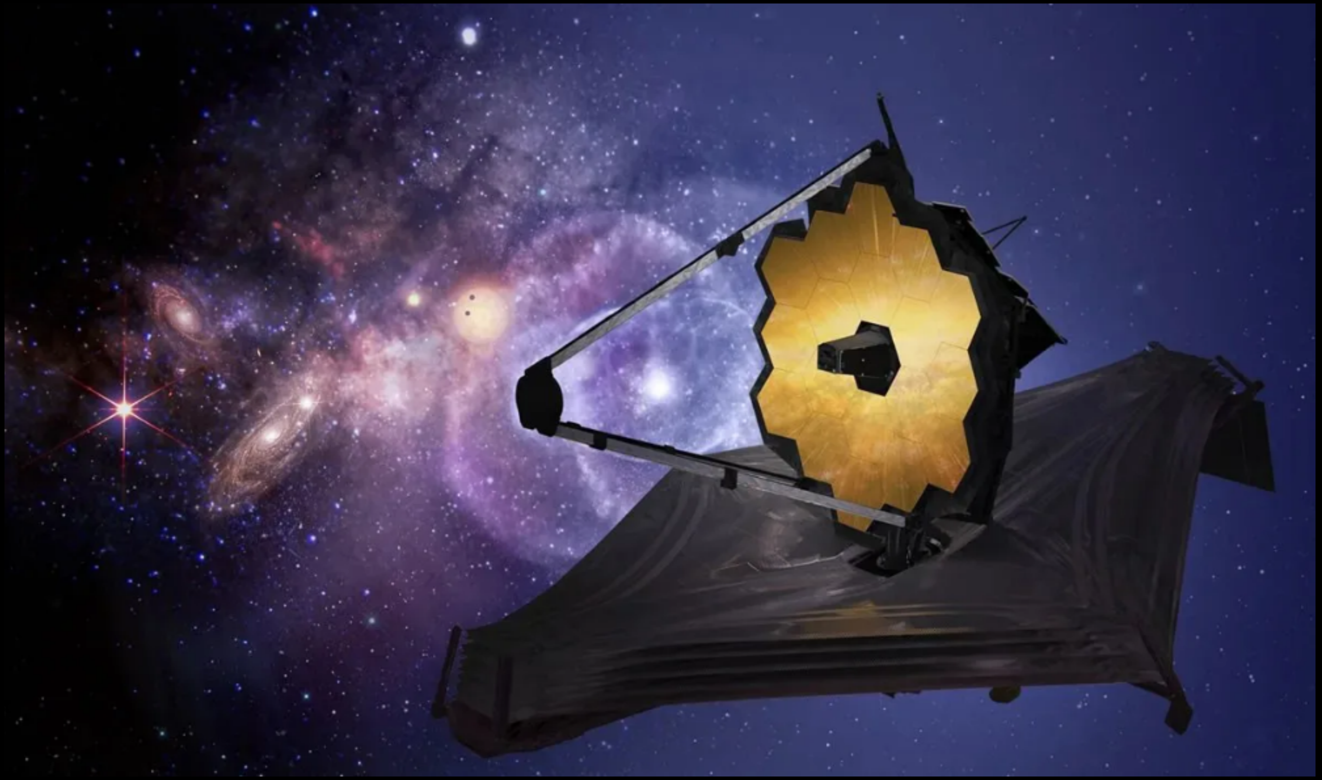


Perez-Gonzalez et al. (2025)

- Pushing the Lyman Break technique at the highest redshift detectable with the Webb leads to the detection of a few $z \sim 25$ candidates.
- Spectroscopic confirmation with JWST of these candidates will be challenging due to its wavelenght coverage.
- Could these galaxies be also dusty interlopers ?

But this picture is not so perfect!

- The <u>JWST is a fantastic telescope</u>, but it has some limitations :
  - Its field of view is very small : 3.6′ x 3.4′
  - Its wavelength coverage is large, but not sufficient to measure the Balmer decrement (and therefore the dust attenuation) at z>6

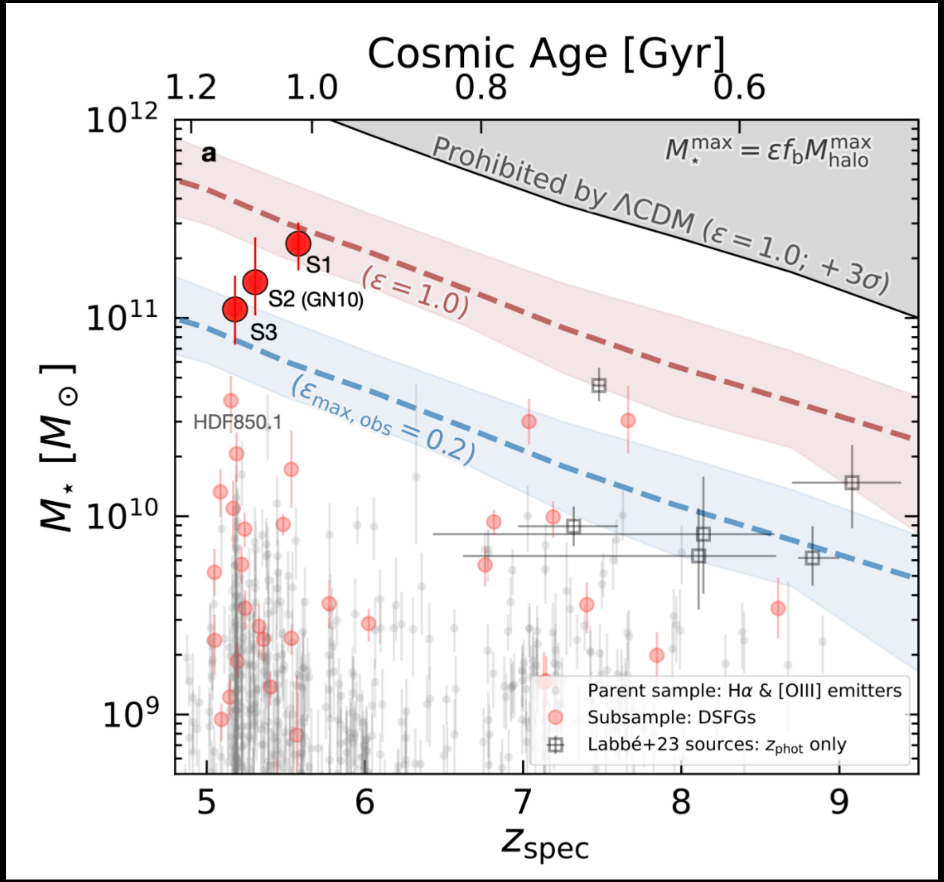


- The JWST cannot be considered as a *redshift machine*
- Its results (so far) are strongly affected by Cosmic Variance

An ideal instrument to push forward the study of distant galaxies after JWST would be one with a large field of view, with multiplexing capabilities and able to identify dusty interlopers

The new questions raised by the JWST

Is the **Star Formation Efficiency** of early galaxies higher than at low-redshift ?



Xiao et al. (2024)

- Among the first submitted papers using JWST data, several claimed that massive primeval galaxies challenge the ΛCDM with extremely high star-formation efficiency

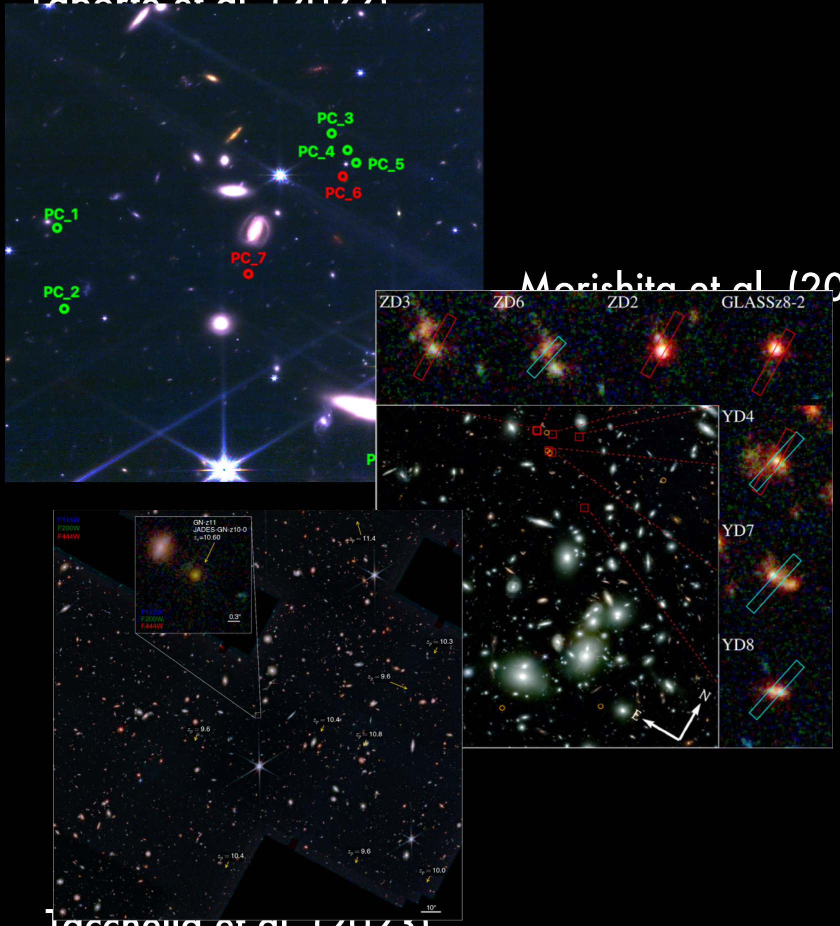
- At z>6, estimates of the SFE rely largely on assumptions.
- At z~5-6, however, estimates of the stellar mass are more robust and seem to indicate a SFE larger than the 20% observed at lower redshift

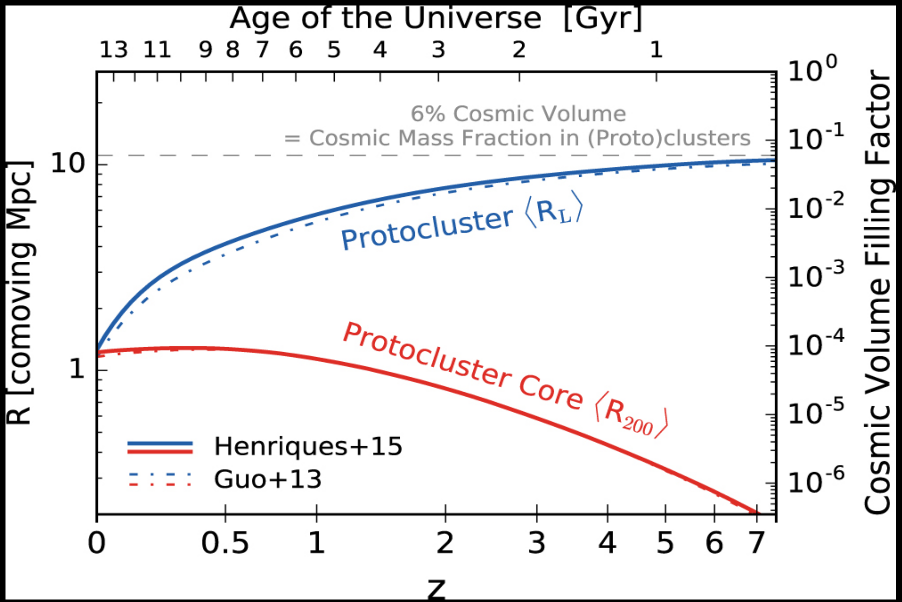
- To obtain robust measurements of the SFE, one needs to get a robust measurements of the SFR and of the gas reservoir in galaxies at z>6

The new questions raised by the JWST

How far back can we trace the first large-scale structures of the Universe?

- Within its first 3 years of observations, the JWST has identified several protoclusters at z>7
- But, given the limited field of view of JWST, these studies are limited to the protocluster core.

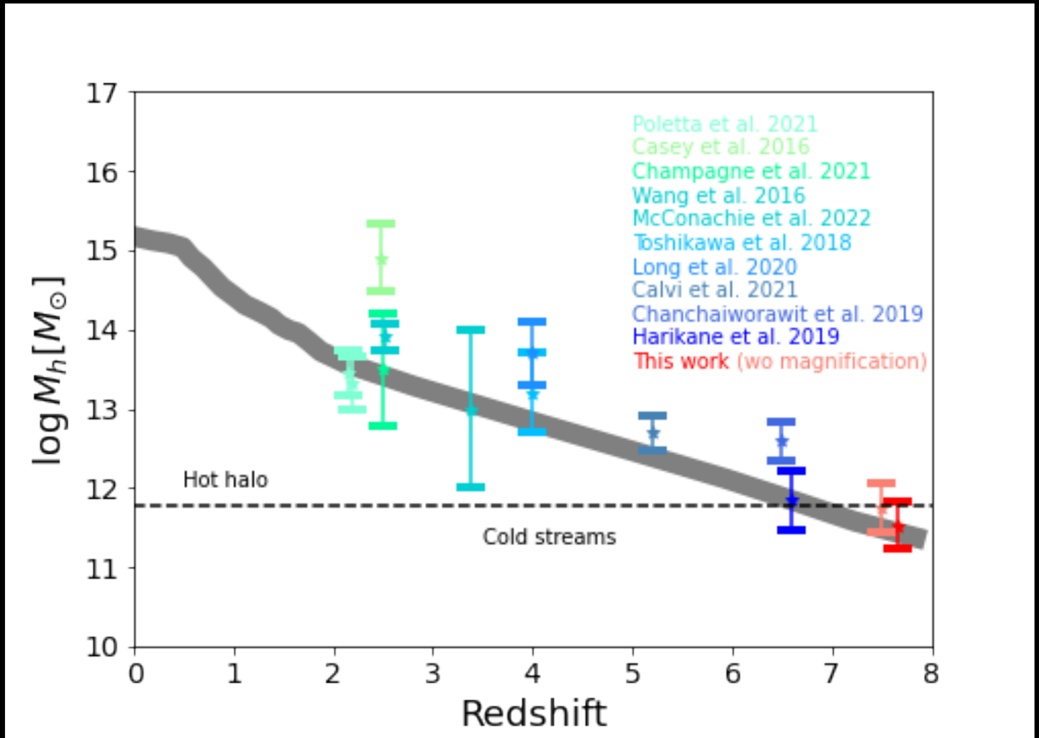




Chiang et al. (2017)

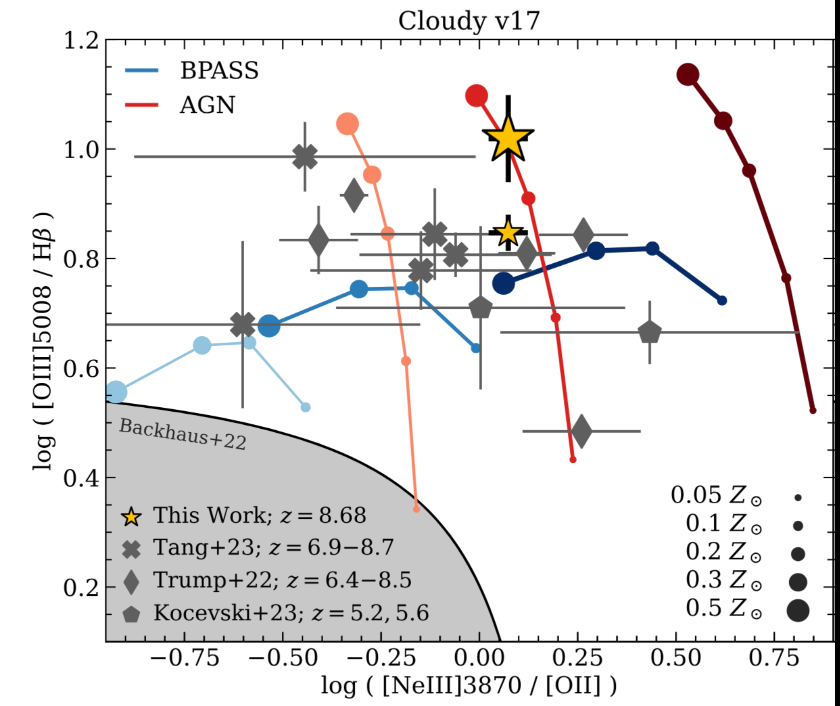
The new questions raised by the JWST

How far back can we trace the first large-scale structures of the Universe?



Laporte et al. (2022)

- The number of protoclusters known so far is not sufficient to study the evolution of the fark matter halo of these structures across cosmic time
- Interestingly, the brightest galaxies in all these structures host an AGN.

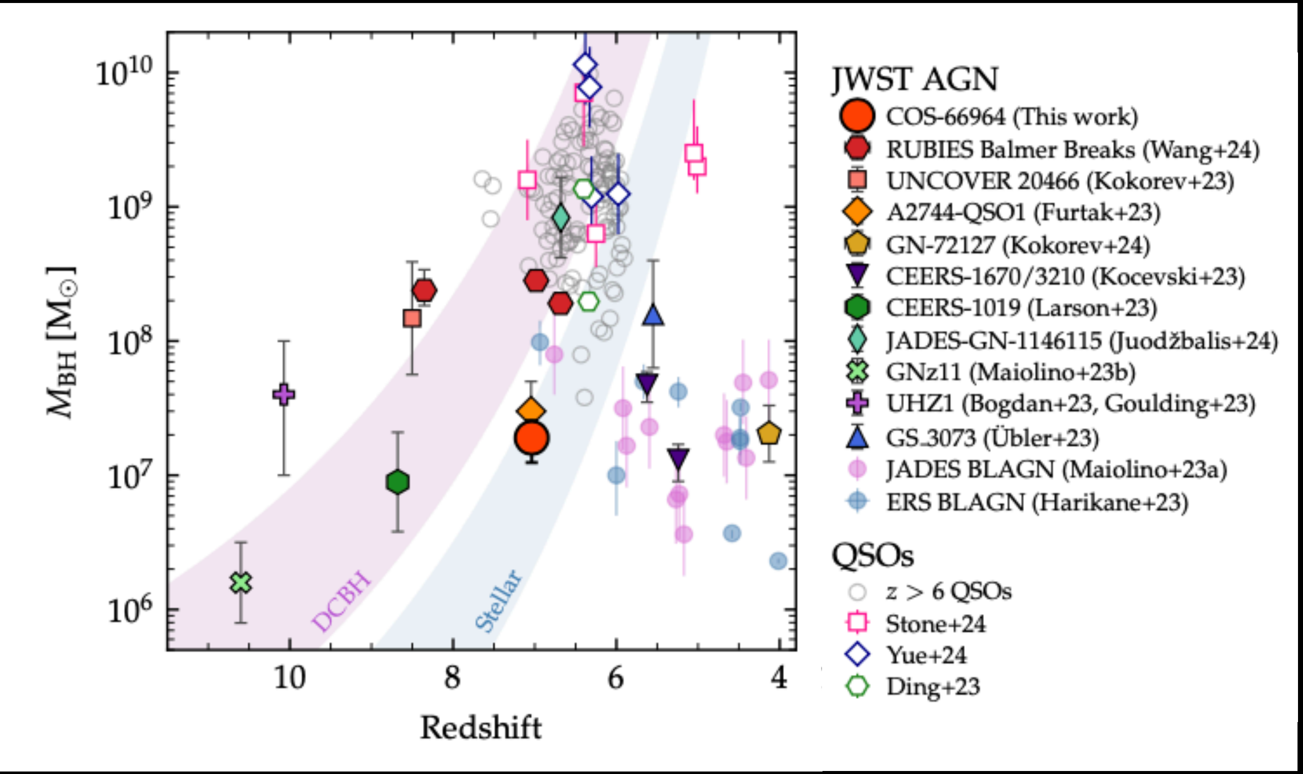


Larson et al. (2023)

- Our current view of protoclusters at high-redshift is biased and the spatial extent of theses structures is currently unknown. A much larger field of view is needed.

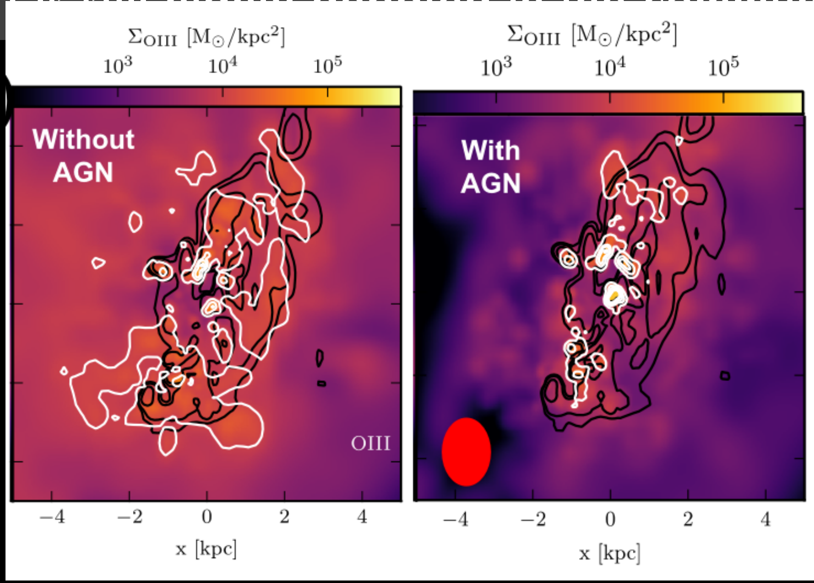
The new questions raised by the JWST

Are AGNs common in early protoclusters ?



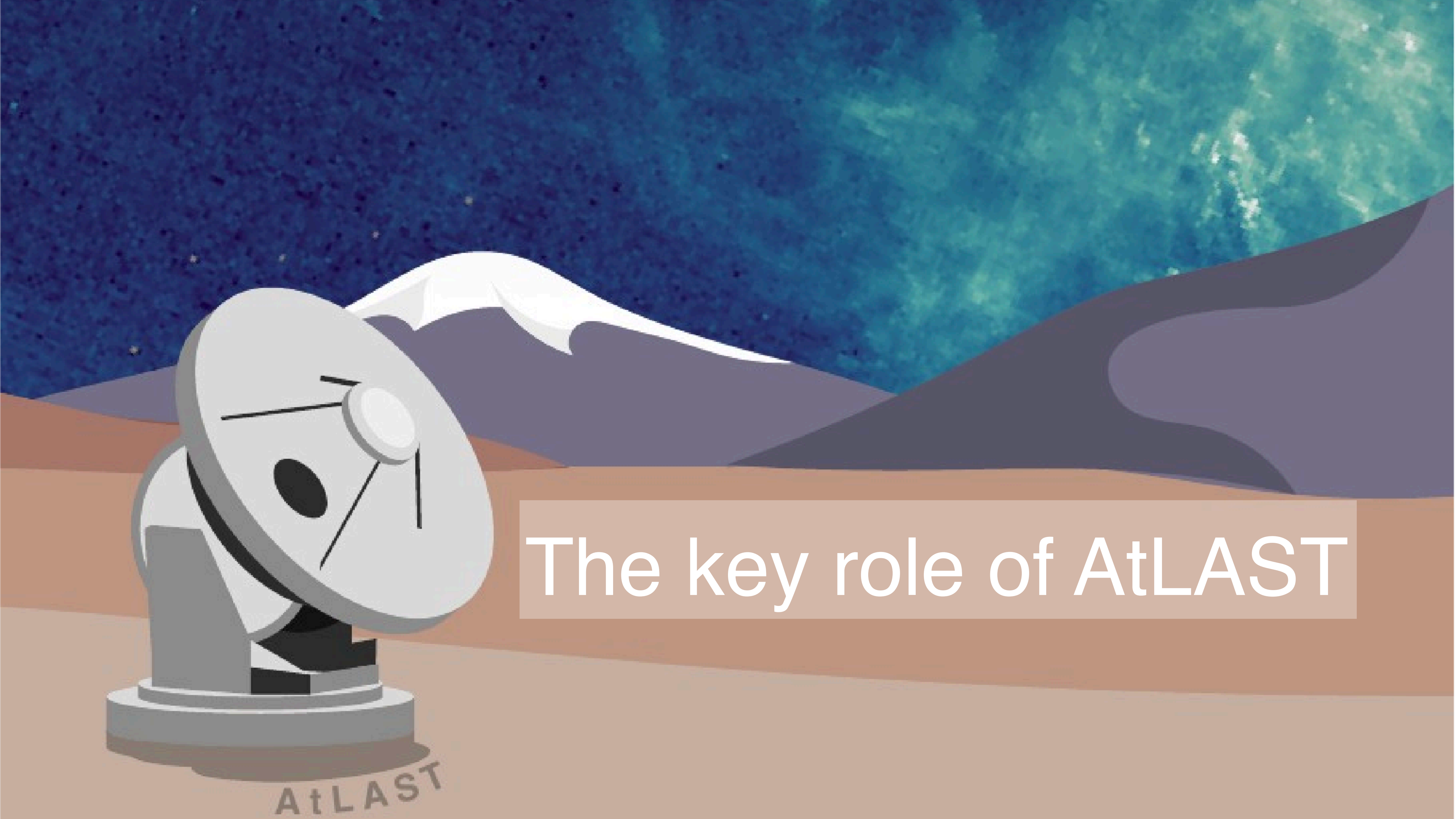
Atkins et al. (2025)

- The unexpected detections of AGN up to $z \sim 10.6$ raise the question about their formation so early in the history of the Universe.
- The method used to identify AGN activity at high-redshift is still highly debated in the community.

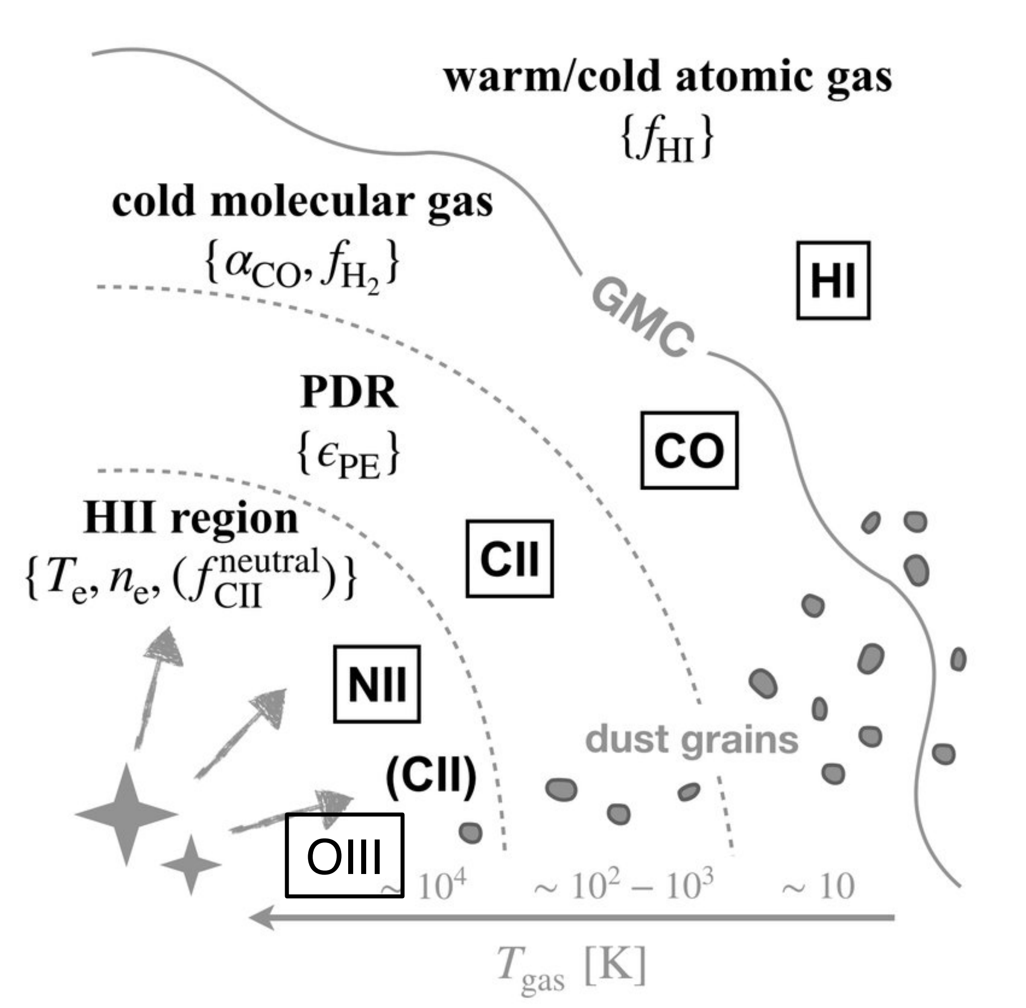


Katz et al. (in

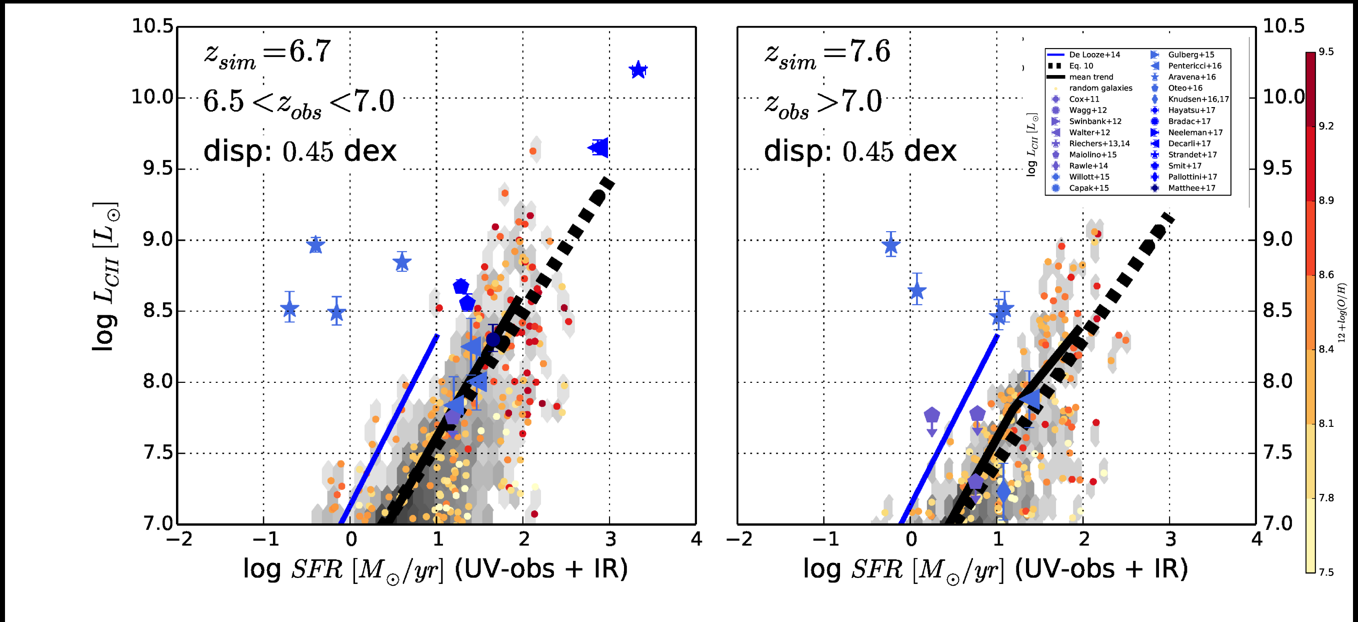
The key role of AtLAST



The key role of sub-mm observations : spectroscopic confirmation



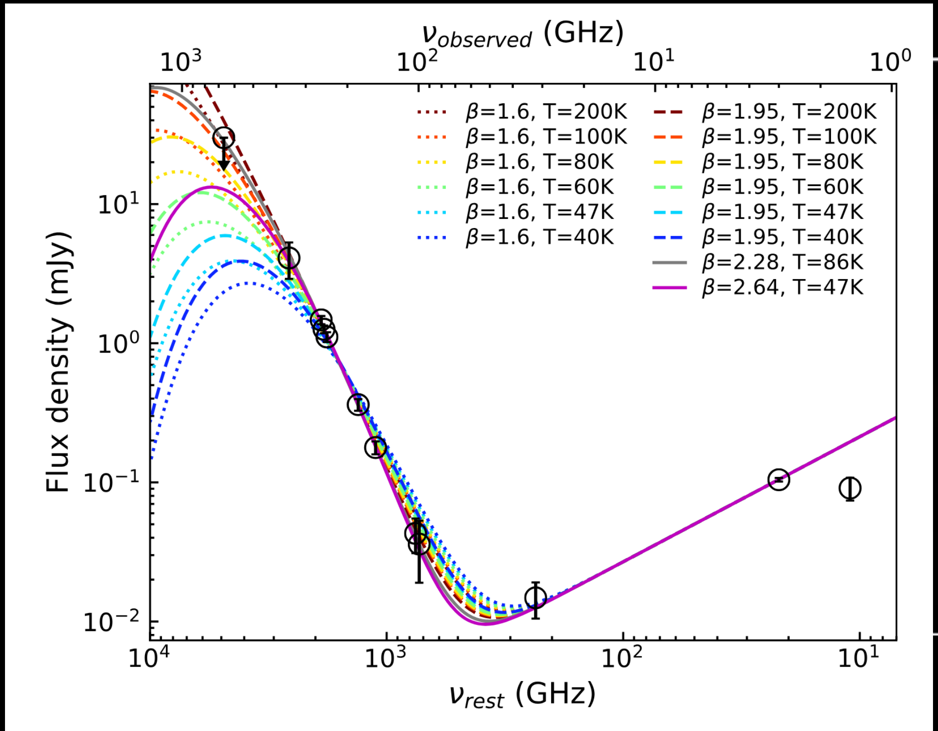
Sun et al. (2019)



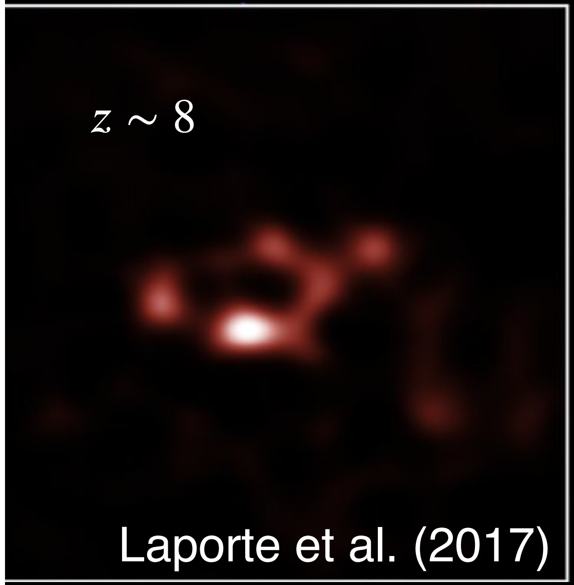
Lagache et al. (2018)

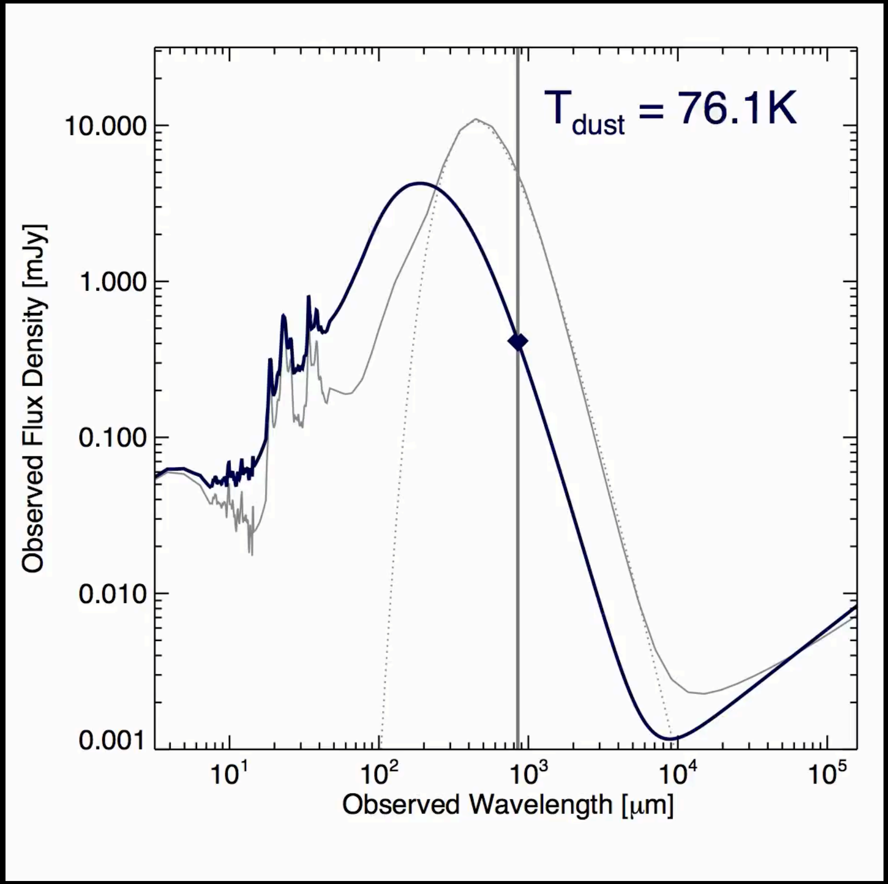
- The multi-phase ISM and the nature of primeval galaxies (star-forming) make the sub-mm domain an ideal wavelength range to detect emission lines
- Among FIR emission lines : [OIII]88μm and [CII]158 μm are key emission lines are the brightest at high-z

The key role of sub-mm observations : dust content of primeval galaxies



Wang et al. (2019)

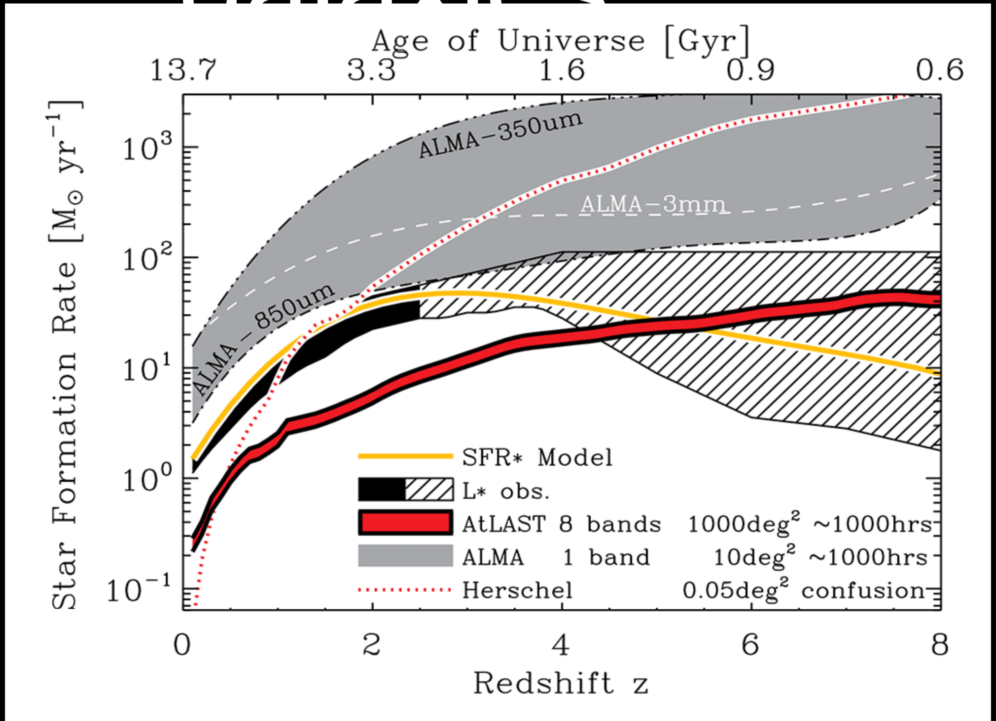




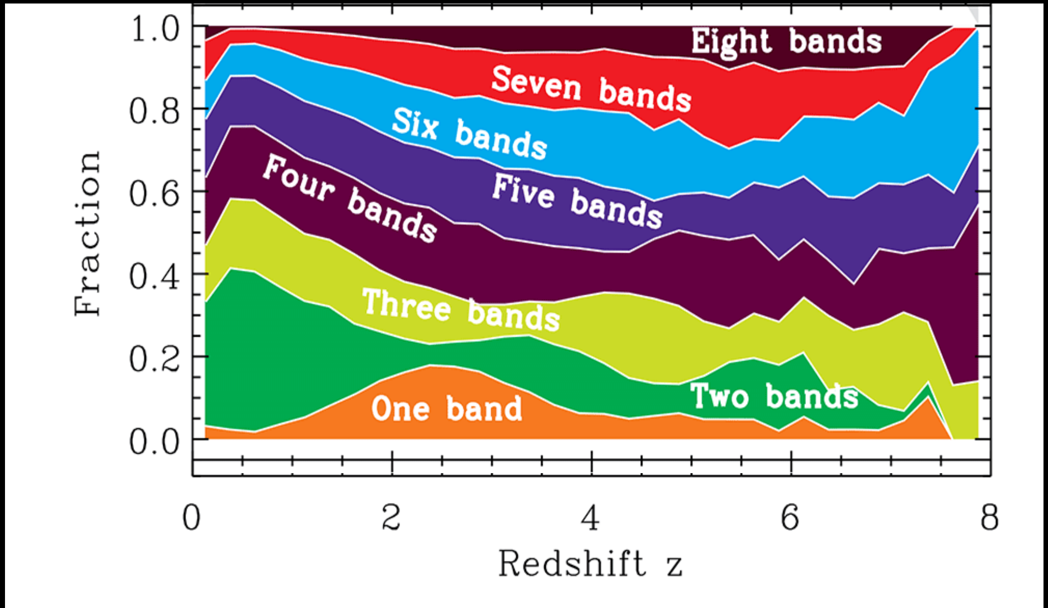
Courtesy of C. Casey

- Dust has been detected in several galaxies at $z \geq 6$
- For most of them, dust has been detected in only one ALMA band making the study of their dust content (mass, origins, etc..) non trivial.

A deep AtLAST survey to *uniquely* constrain the FIR SEDs of primeval galaxies



Van Kampen et al. (2024)



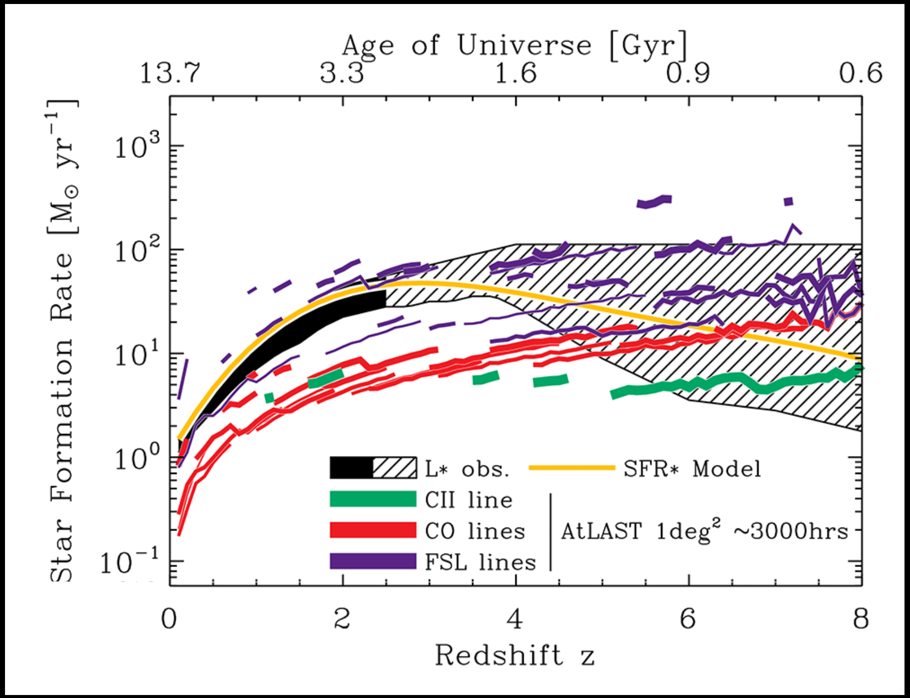
Van Kampen et al. (2024)

- With a 1000deg² -1000hrs AtLAST survey, $z \geq 6$ galaxies with SFR ranging from 20 to 40 $M_{\odot}/yr$ will be detected in 8 bands. In terms of H-band magnitude : 26-27 AB.

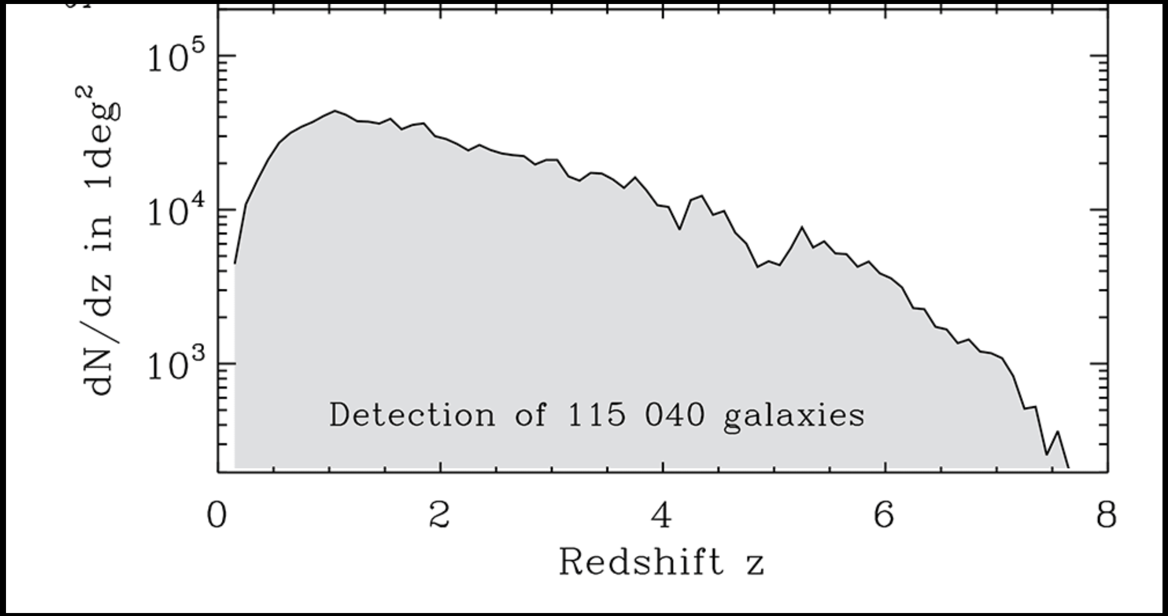
- Euclid/ESA will provide the perfect field to identify AtLAST candidates with its deep survey covering 50deg² with a 5σ sensitivity of 26.5 AB

- Assuming Bouwens et al. (2023) UV LF parameters, Euclid/ESA will detect $\sim$400 $z \geq 6$ galaxies.

AtLAST : an efficient redshift-machine for distant galaxies



Van Kampen et al. (2024)

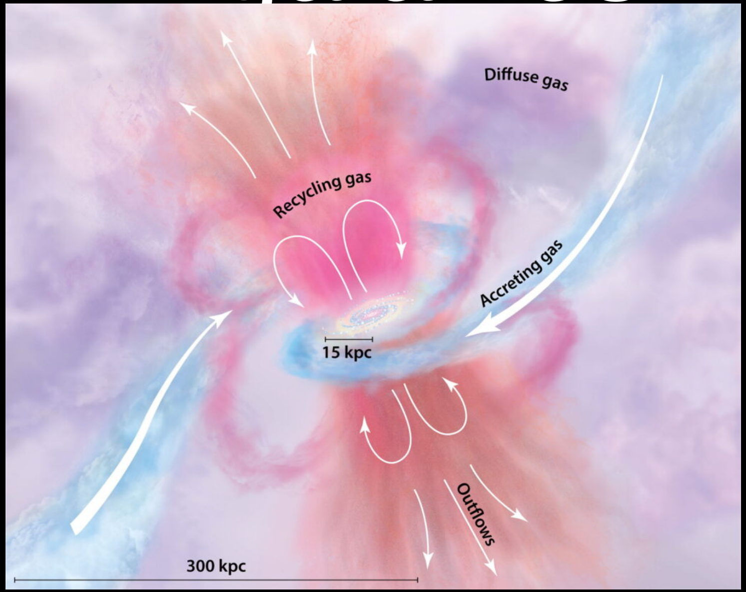


Van Kampen et al. (2024)

- AtLAST will be able to spectroscopically confirmed $z \geq 6$ galaxies with the detection of several emission lines : CII, CO and OIII

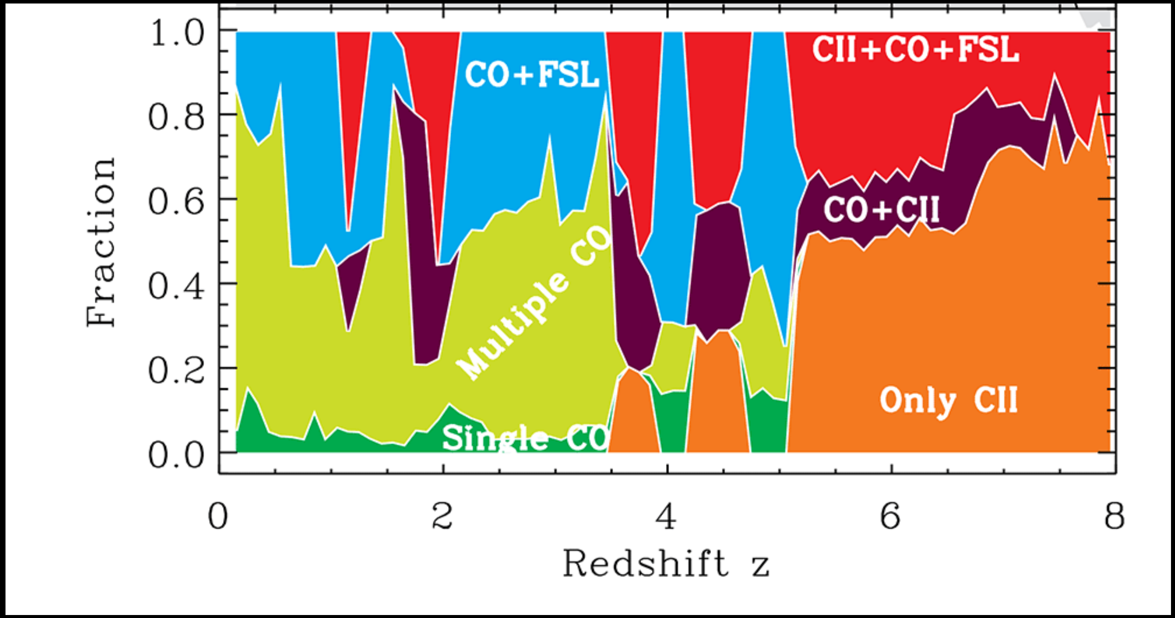
- The expected detection rate of AtLAST is $\sim$1000 $z \geq 6$ galaxies per square degree.
- Given its large field of view AtLAST will be ideal to confirm the large scale structure at high-redshift

A deep AtLAST survey to measure the star formation efficiency of primeval galaxies



Tumlinson et al. (2017)

- CO lines are the best tracer of molecular gas.
- At $z \geq 6$, ~50% of the galaxies detected in a 1000deg^2-1000hrs survey will have CO emission lines



Van Kampen et al. (2024)

- The Star Formation Efficiency (SFE) of very high-redshift galaxies is highly debated, but current estimates rely on indirect measurements
- The best way to estimate the SFE is by estimating the gas reservoir (M_{H_2}) as :

$$SFE = \frac{SFR}{M_{H_2}}$$

Illuminating Cosmic Dawn : Probing the first galaxies with AtLAST

Conclusion

AtLAST key properties
to study the distant Universe

- Much larger field-of view than ALMA
- A higher sensitivity
- A good spatial resolution

The key scientific questions
AtLAST will be able to address

- Is the SFE of primeval galaxies higher than what is observed at low-redshift ?
- How large are the first structures in the early Universe ?
- What are the properties of stardust at high redshift ?

Synergy with other instruments

- Euclid/ESA will provide within the next 10 years a robust sample of $z \geq 6$ candidates that will be ideal target for AtLAST
- MOSAIC/ELT will give the UV-rest frame counterpart of AtLAST detected sources

MOSAIC

esa

euclid