# New Insights on the First Stars and Galaxies from the *James Webb* Space Telescope

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SF2A – 2025 (Toulouse)

# Outline of my talk

- The remaining questions on the first billion years of the Universe

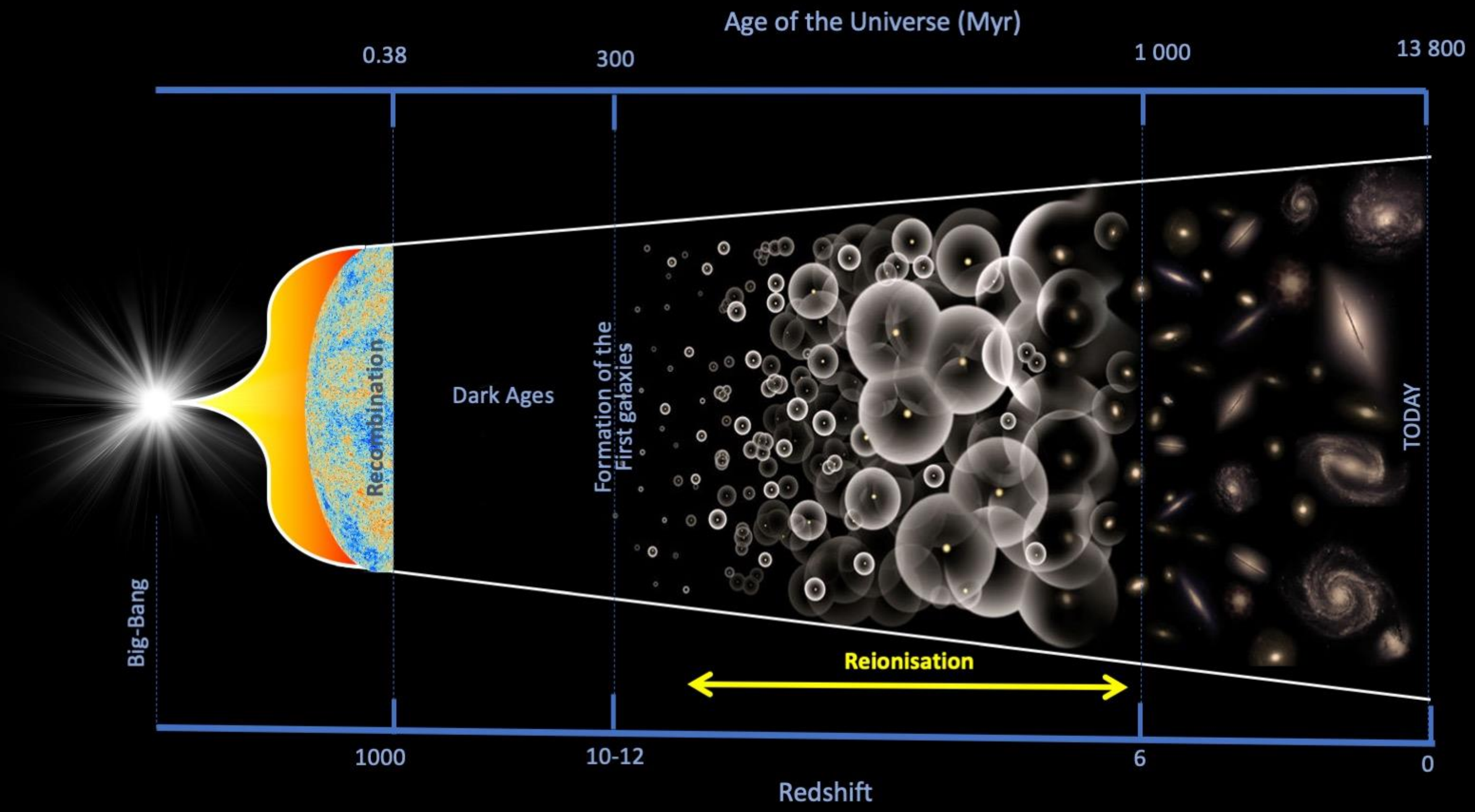
- The key results in less  than 3 years of JWST operations
  - The quest for Cosmic Dawn
  - Too early, too massive galaxies
  - AGNs are everywhere (!)
  - The first structure of the Universe
  - The first population of stars

Pictures from JWST – Credit : NASA / ESA/ CSA/ STScI

# The remaining questions on the first billion years of the Universe

Scientific Context

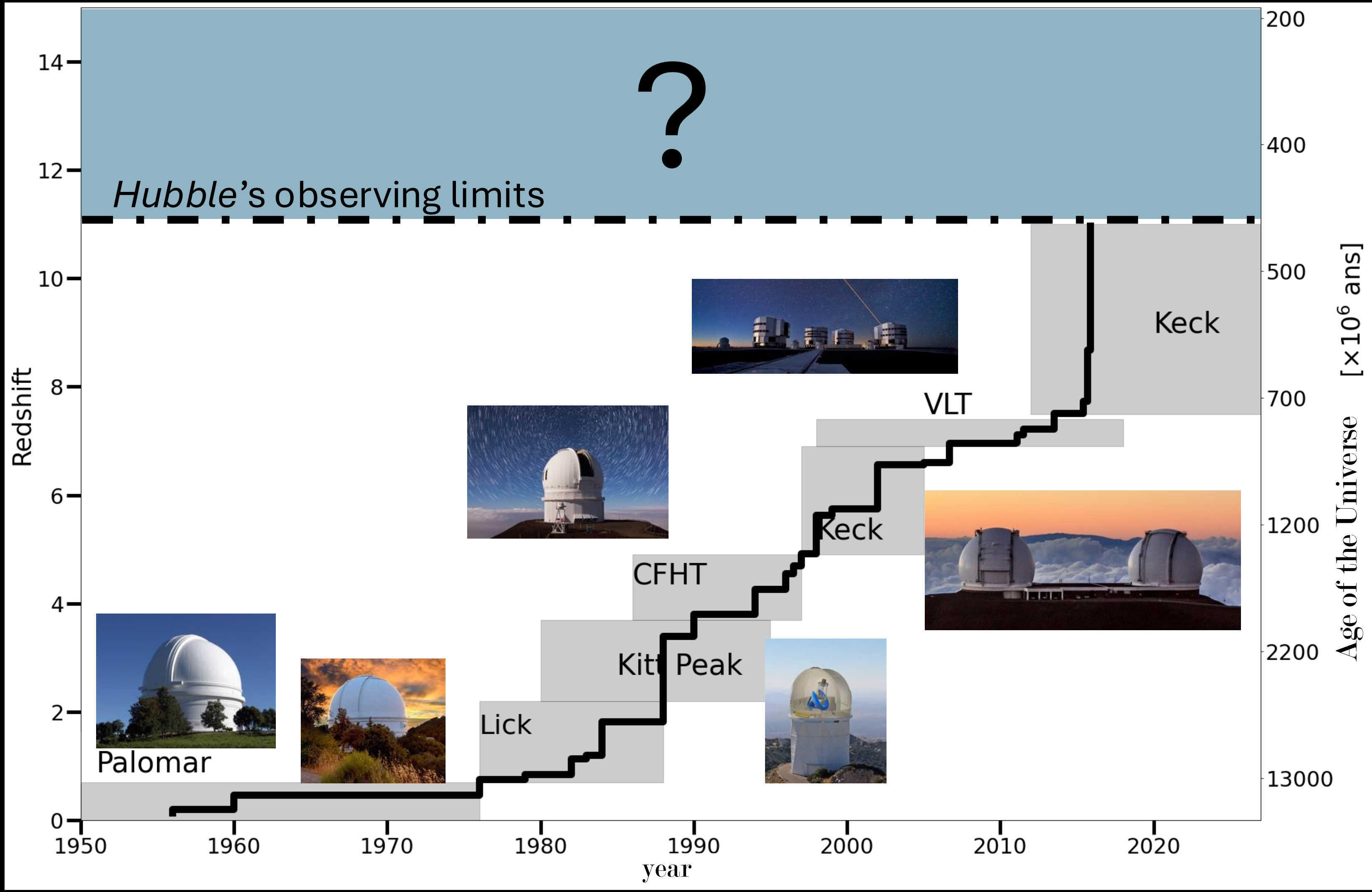
# The timeline of the Universe




**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 quest for Cosmic Dawn before JWST





Humason et al. 1956
Minkowski 1960
Spinrad et al. 1975
Spinrad & Smith 1976
Smith et al. 1979
Spinrad 1982
Spinrad & Djorgovsky 1984
Lilly 1988
Chambers et al. 1990
Lacy et al. 1994
Petitjean et al. 1996
Franz et al. 1997
Day et al. 1998
Hu et al. 1999, 2002
Pelló et al. 2004
Iye et al. 2006
Fontana et al. 2010
Vanzella et al. 2011
Ono et al. 2012
Shibuya et al. 2012
Finkelstein et al. 2013
Oesch et al 2014
Zitrin et al. 2015
Oesch et al. 2016

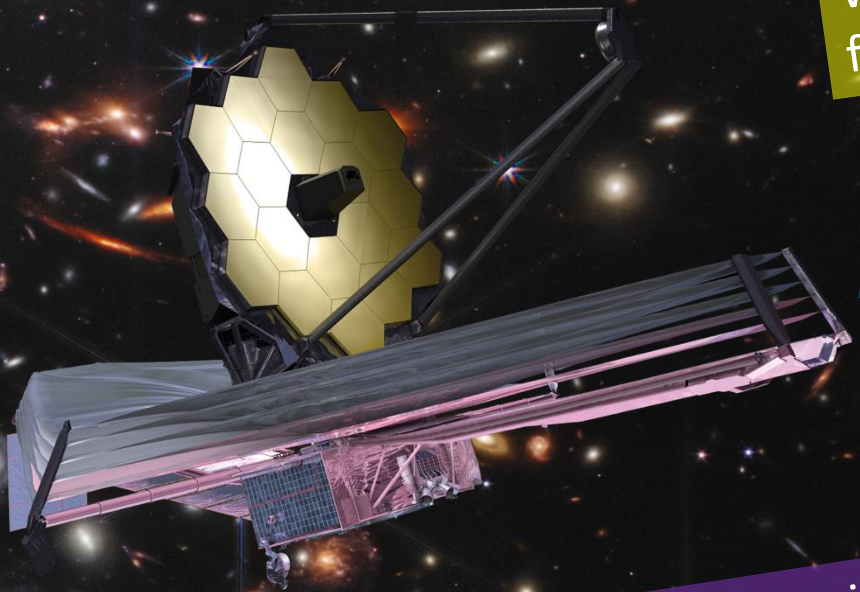
# The major questions that *Webb* will need to answer

What are the properties of protostars?

When did the first stars and galaxies form in the Universe ?

What are the properties of the first population of stars ?

What is the fraction of AGN in the early Universe ?

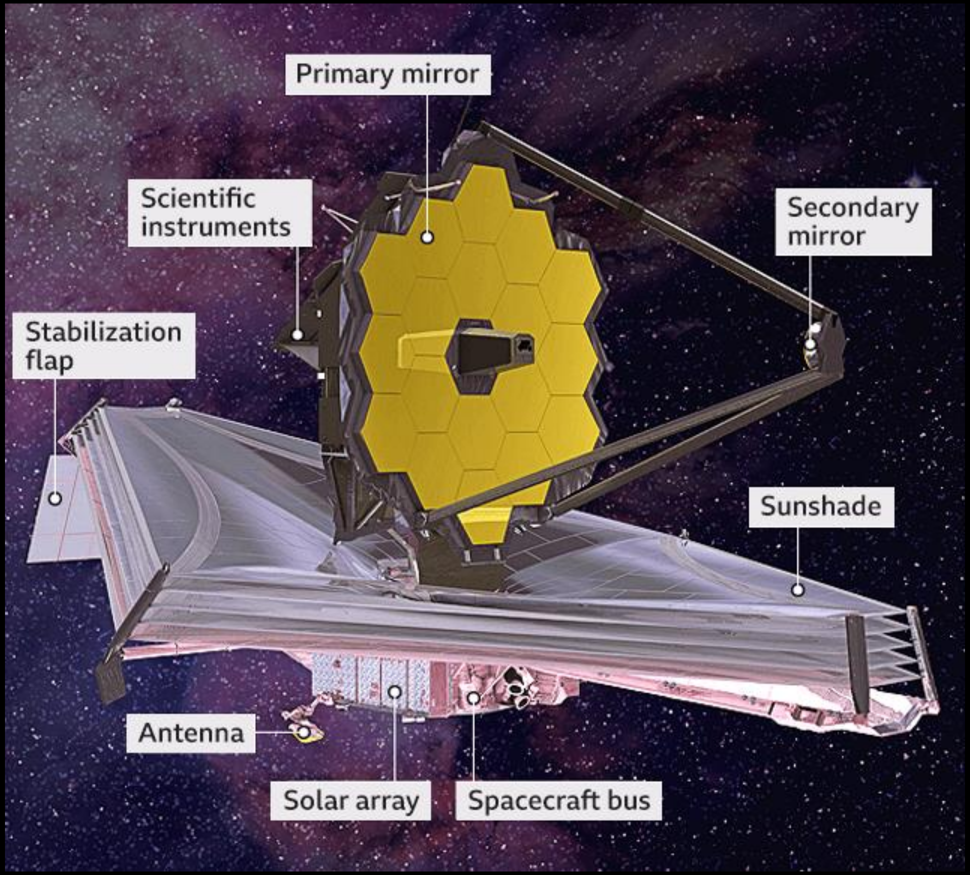


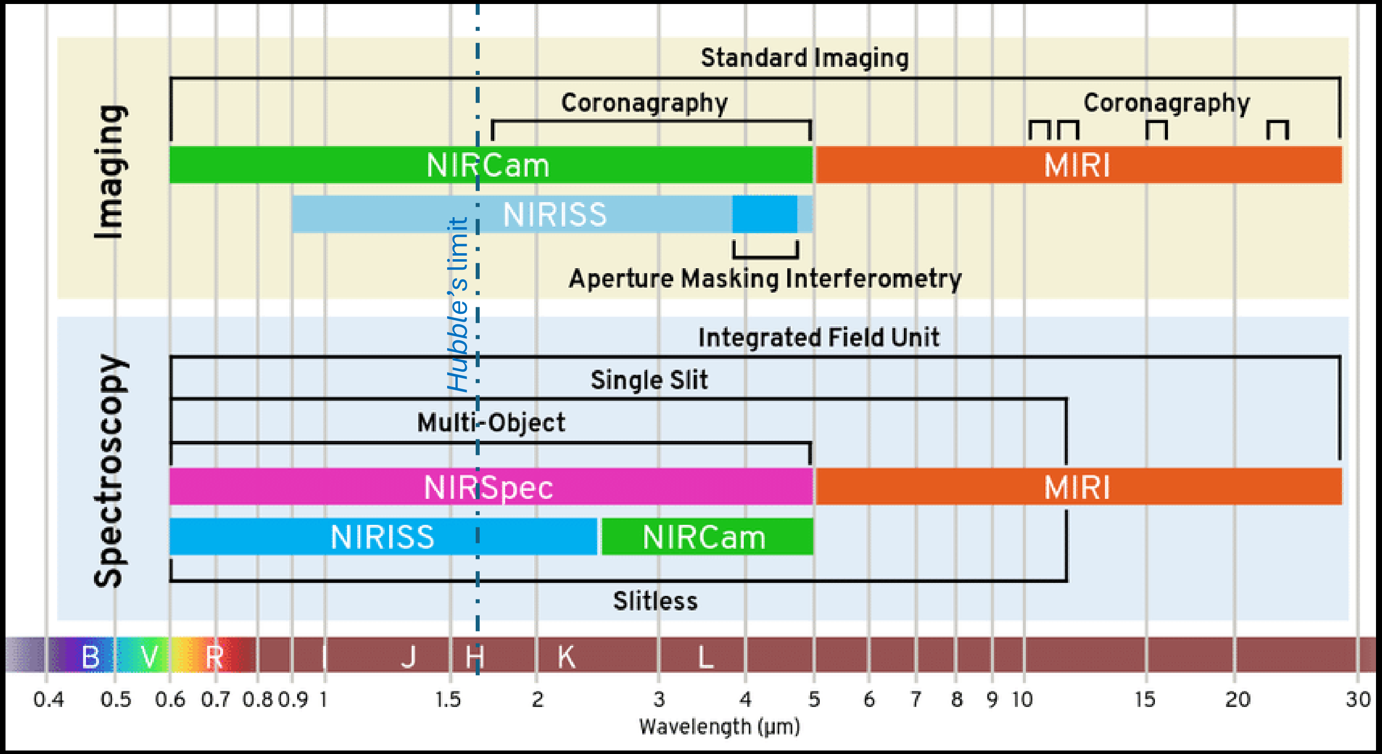
How did the first black holes form in the early Universe ?

How did the first galaxies form : isolated or in groups ?

How does the environment of primeval galaxies influence their evolution?

# The *James Webb* Space Telescope



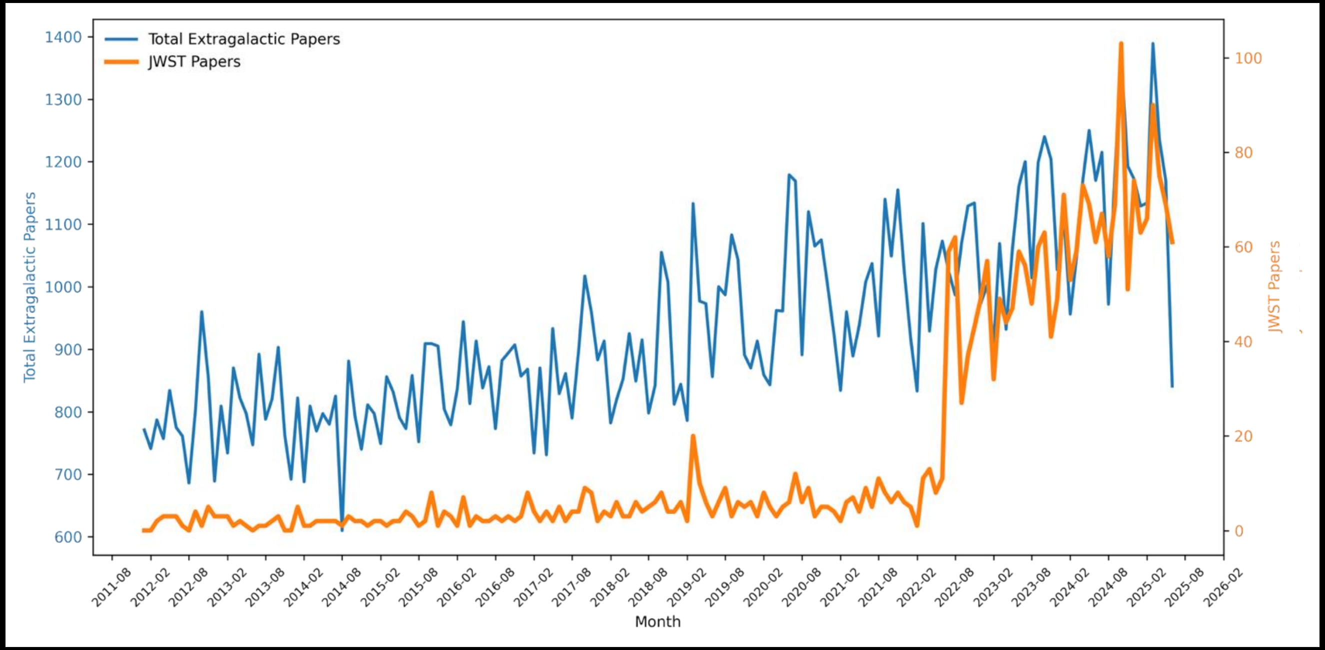




Credit : NASA / ESA/ CSA/ STScI

# The key results in less  than 3 years of JWST operations

*Disclaimer* : This is a biased view. Apologize if your favourite result is not presented

# The first month of JWST operations




Number of submitted papers on arXiv (extragalactic ) since 2012

**TIMELINE OF THE FIRST PUBLICATIONS**

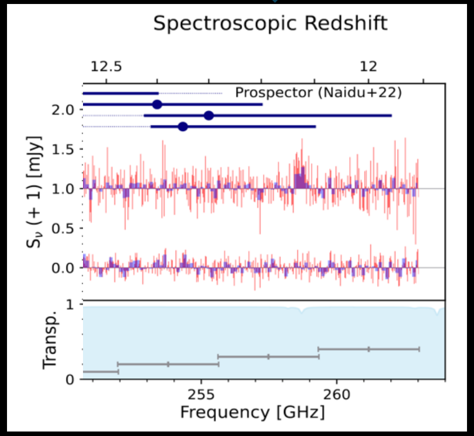
- **15 July** : Pascale et al. (2022) ; Mahler et al. (2022)
- **18 July** : Caminha et al. (2022)
- **19 July** : Carnall et al. (2022) ; Cheng et al. (2022)
- **20 July** : Castellano et al. (2022) ; Naidu et al. (2022) ; Ferreira et al. (2022)
- **21 July** : Schaerer et al. (2022)
- **22 July** : Suess et al. (2022)
- **25 July** : Adams et al. (2022) ; Leethochawalit et al. (2022)
- **26 July** : Atek et al. (2022) ; Roberts-Borsani et al. (2022) ; Trump et al. (2022) ; Curti et al. (2022) ; Sun et al. (2022) ; Donnan et al. (2022) ; Chen et al. (2022) ; Yan et al. (2022) ; Morishita et al. (2022) ; Santini et al. (2022), Merlin et al. (2022)

ERO SMACS0723
ERS GLASS
ERS CEERS
*Lensing*
Calibration data

# Some surprising results since July 2022

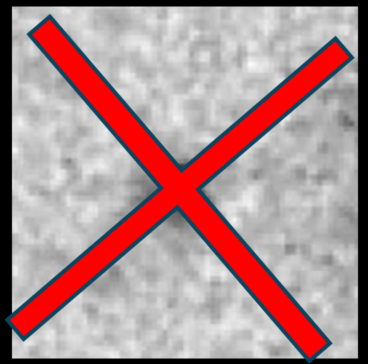
z=13

GLASS-z13 (Naidu et al. 2022)

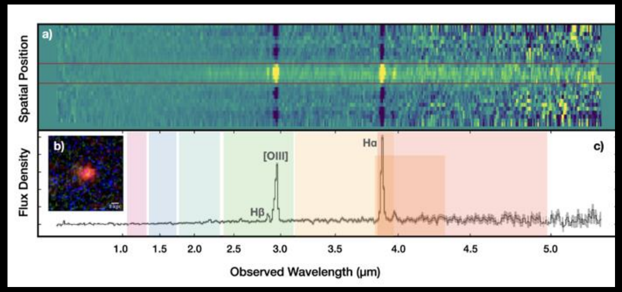



Bakx et al. (2022)

z=16.39±0.27

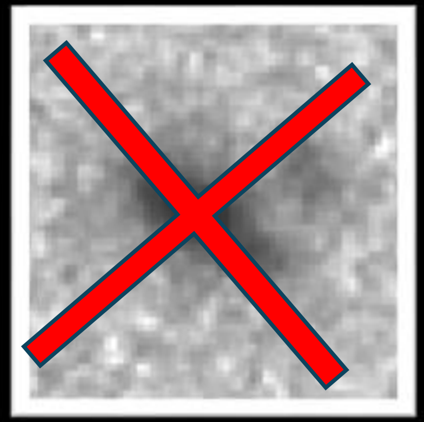


Donnan et al. (2022)

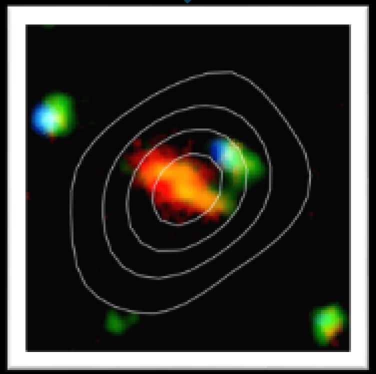



Arrabal-Haro et al. (2023)

z=17

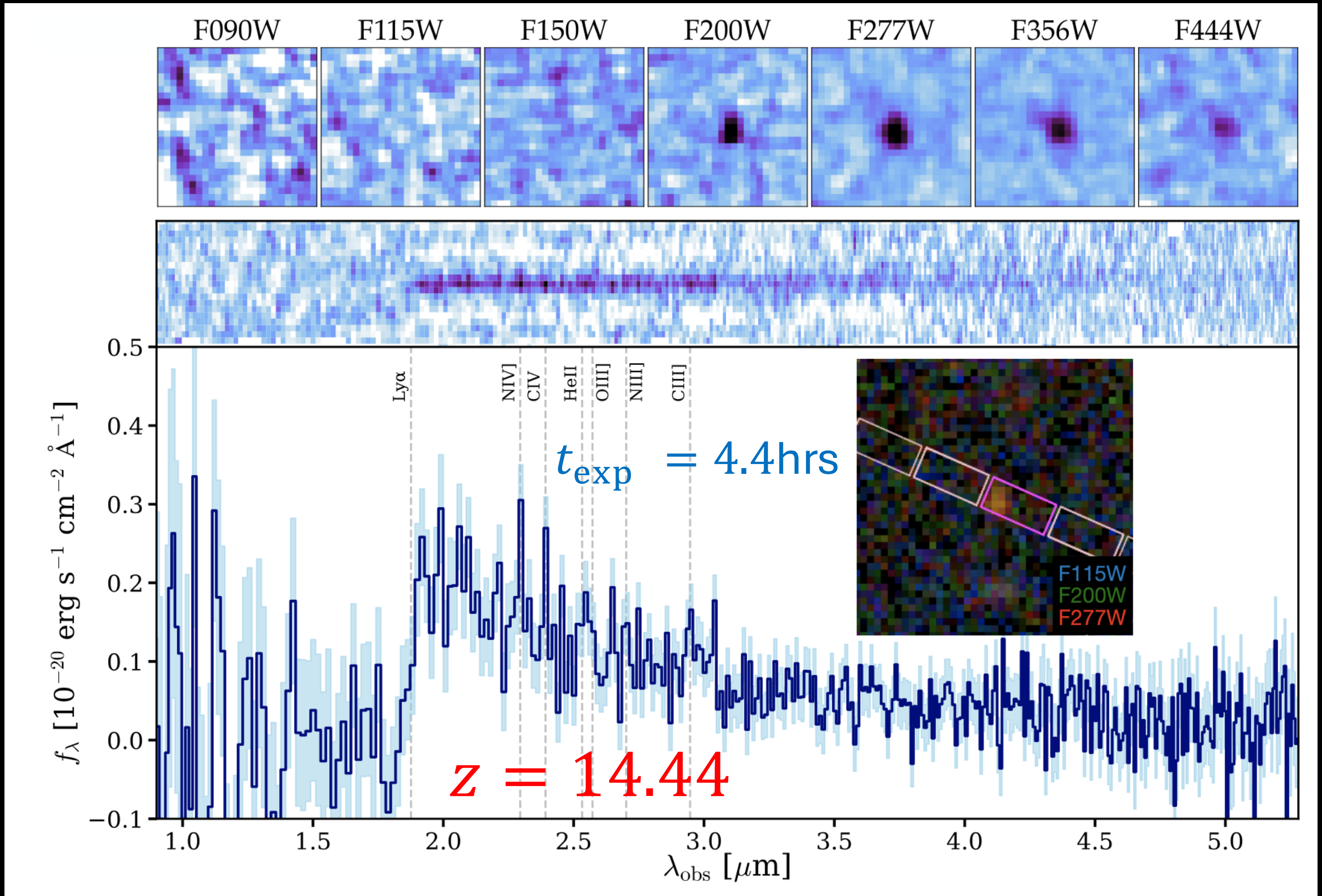


CEERS-DSFG-1 (Finkelstein et al. 2022)



Zavala et al. (2022)

# The current frontiers of the observable Universe

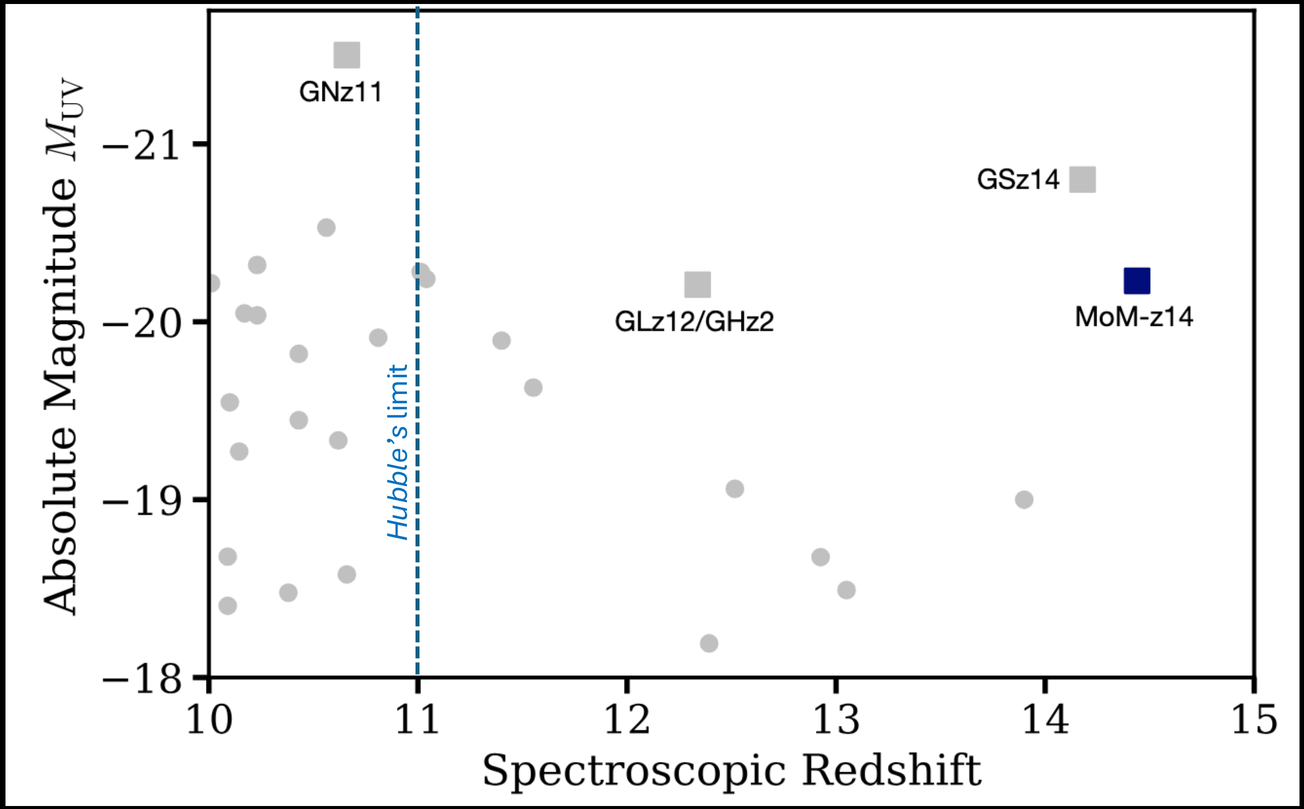



Naidu et al. (2025)

- Two spectroscopic observations modes :
  - Low resolution (R~100) for the stellar continuum
  - High resolution (R~2900) for emission/absorption lines

- To date, the most distant galaxy has been detected in GOODS-South at z~14.4 (300 million years after the Big-Bang)

# The *current frontiers* of the observable Universe

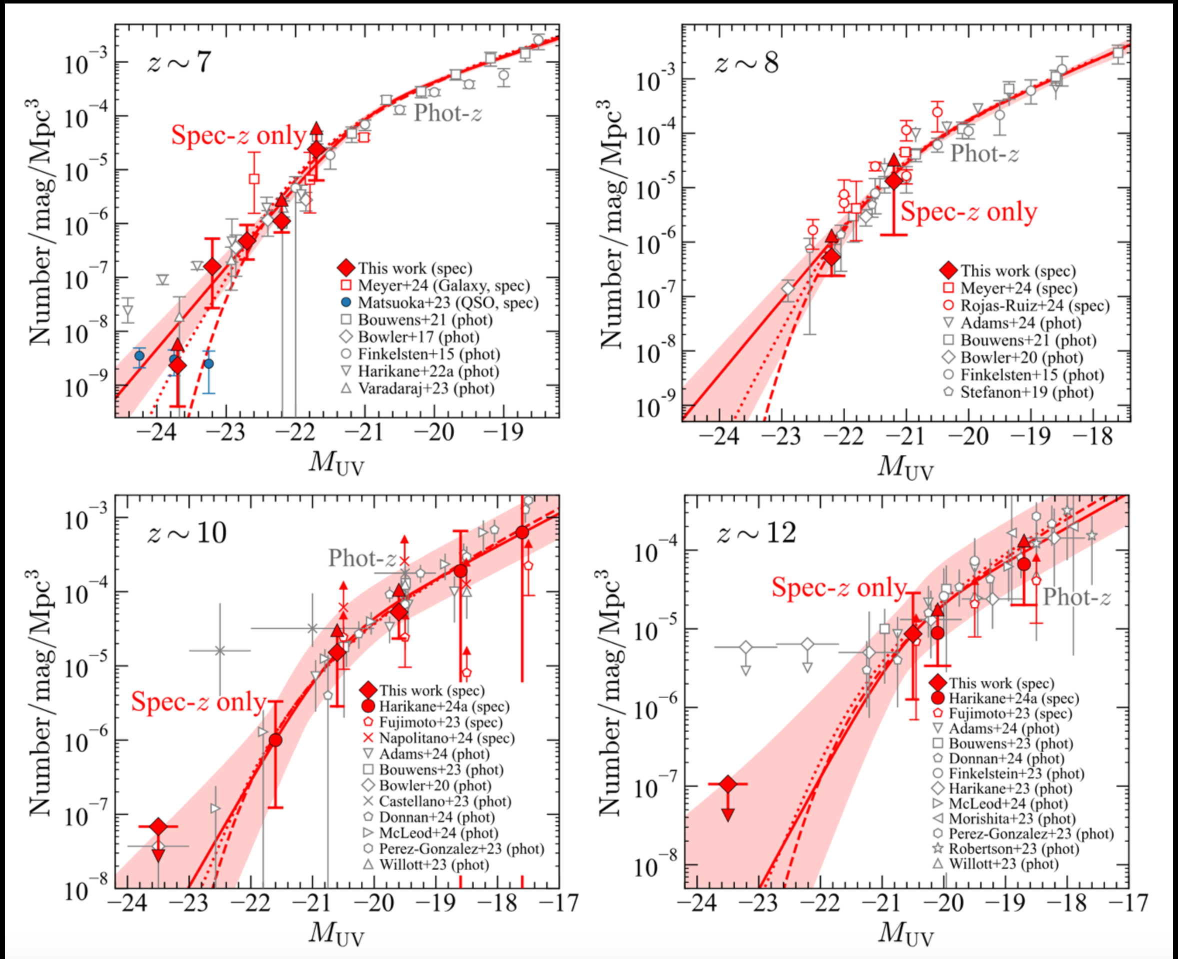



Naidu et al. (2025)

The properties of the most distant galaxy

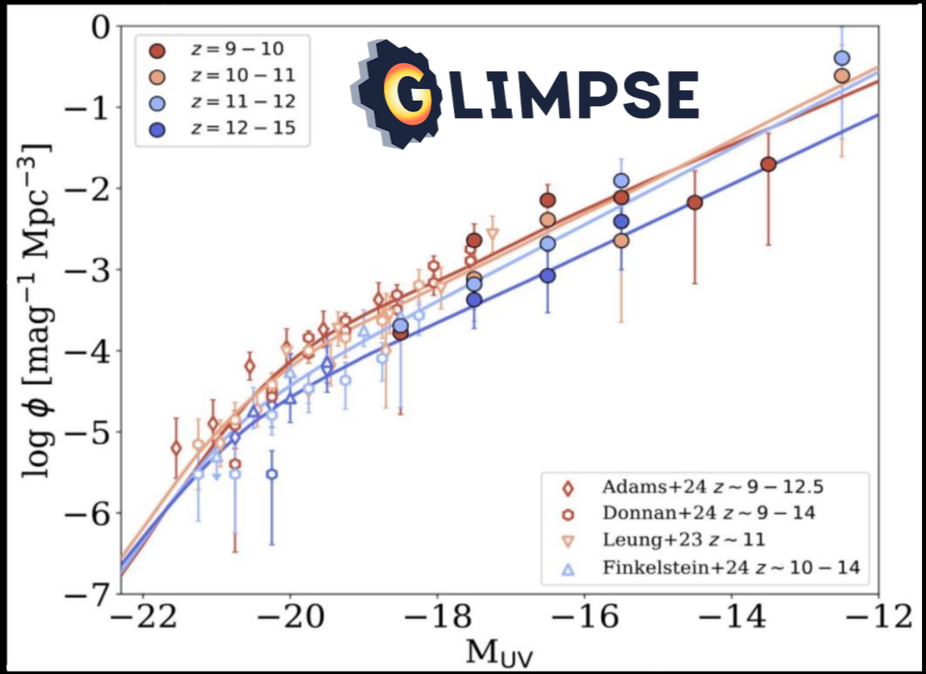
| Empirical Properties | |
|---|---|
| R.A. [deg] | 150.0933255 |
| Dec. [deg] | 2.2731627 |
| Redshift (UV lines) | $14.44^{+0.02}_{-0.02}$ |
| Redshift (Ly$\alpha$ break) | $14.42^{+0.10}_{-0.09}$ |
| UV Luminosity ($M_{\mathrm{UV}}$) | $-20.23^{+0.06}_{-0.06}$ |
| UV slope ($\beta_{\mathrm{UV}}$; $f_\lambda \propto \lambda^\beta$) | $-2.47^{+0.17}_{-0.17}$ |
| Galaxy size (circularized $r_{\mathrm{e}}$) [pc] | $74^{+15}_{-12}$ |
| Galaxy size (semi-major axis $a$) [pc] | $147^{+19}_{-20}$ |
| **Prospector** SED modeling | |
| Stellar Mass ($\log(M_*/\mathrm{M}_\odot)$) | $8.1^{+0.3}_{-0.2}$ |
| Star-Formation Rate (5 Myr )[$\mathrm{M}_\odot$ yr$^{-1}$] | $13.0^{+3.7}_{-3.5}$ |
| Star-Formation Rate (50 Myr) [$\mathrm{M}_\odot$ yr$^{-1}$] | $2.2^{+1.5}_{-0.6}$ |
| Dust Attenuation ($A_{5500\mathrm{\AA}}$) | $0.2^{+0.2}_{-0.1}$ |
| Age ($t_{50}$/Myr) | $4.0^{+10.0}_{-1.4}$ |
| Star-Formation Surface Density [$M_\odot$ yr$^{-1}$ kpc$^{-2}$] | $233^{+107}_{-107}$ |
| Stellar Surface Density ($\log(\Sigma_*/M_\odot$ kpc$^{-2}$)) | $9.6^{+0.2}_{-0.7}$ |

# The luminosity distribution of primeval galaxies



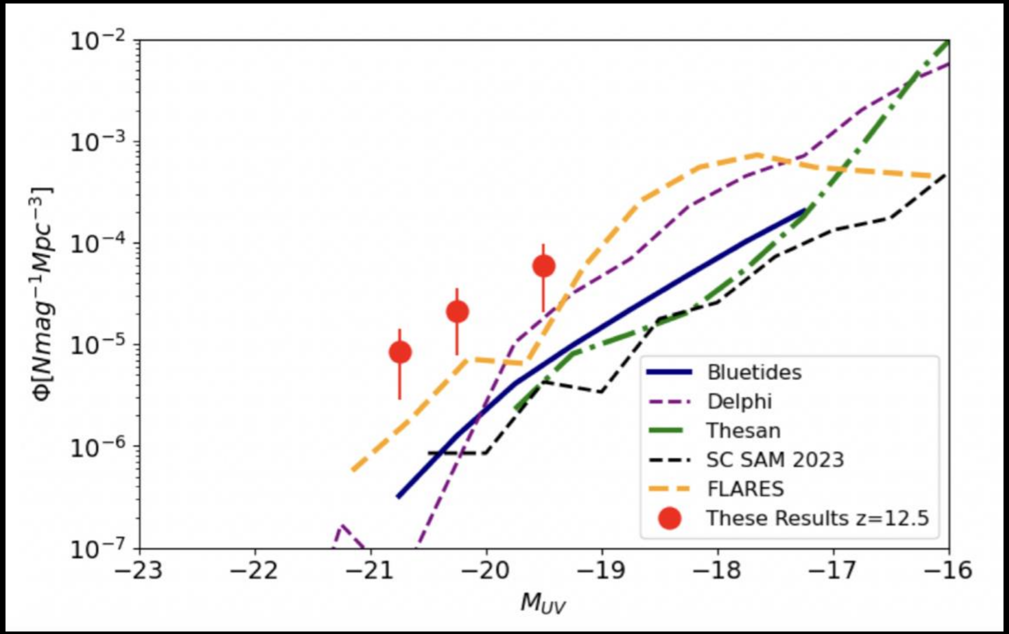

Harikane , ..., NL et al.(2025)

- The distribution in luminosity of the number densities of galaxies allows to constrain :
  - AGN activity
  - The minimum mass of the dark matter halo

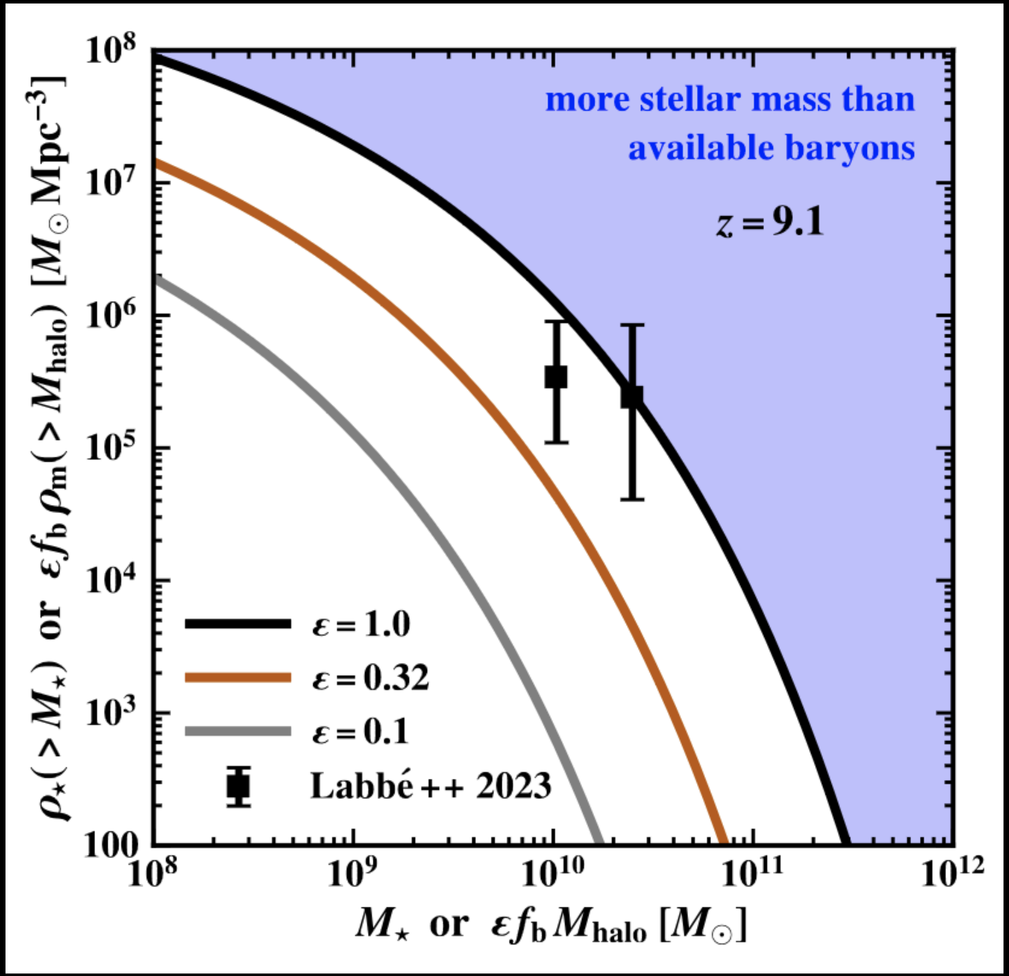



Chemerynska et al. (work in progress)

# Too massive, too early ?



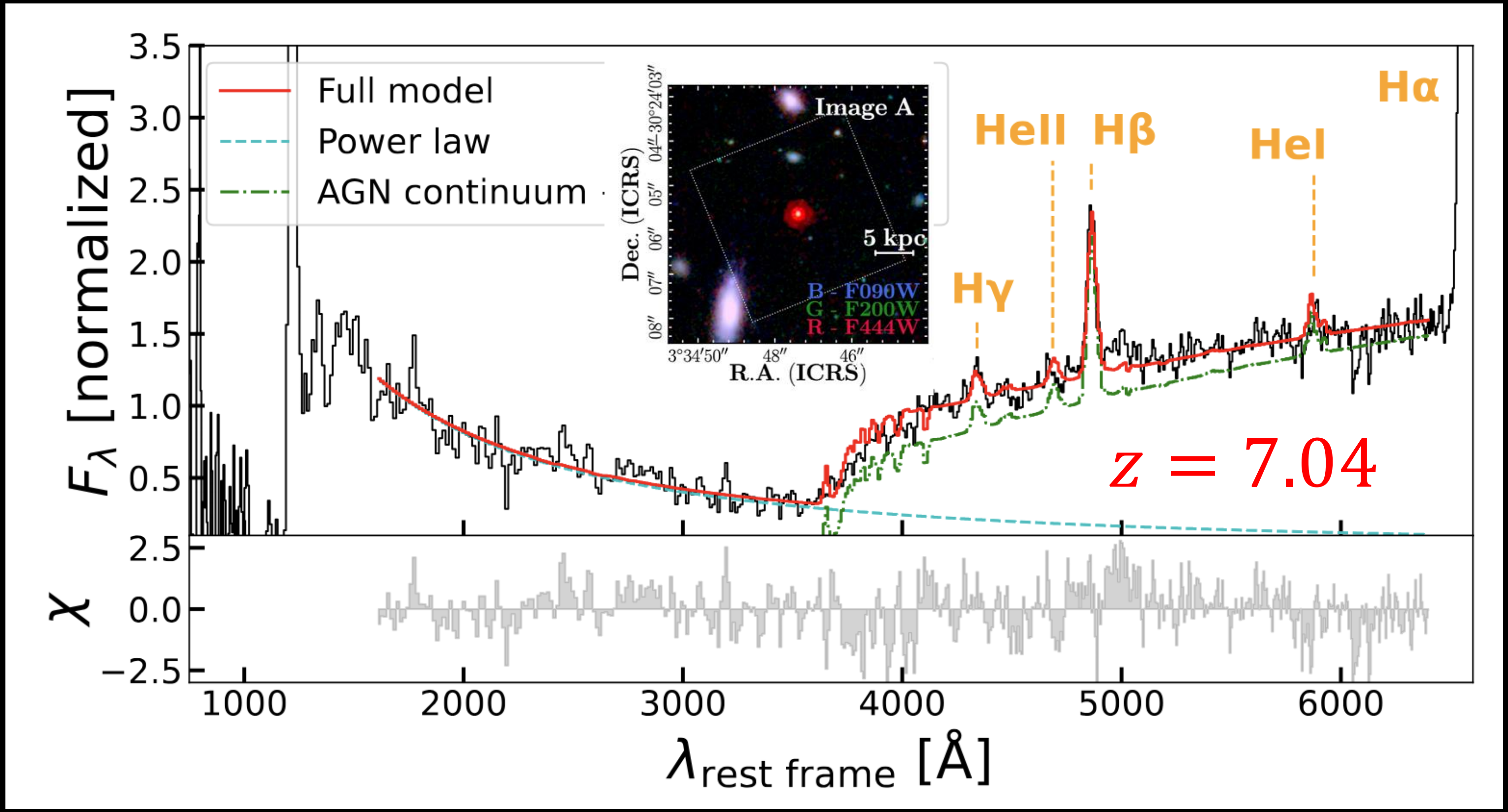

Adams et al. (2024)




Labbe et al. (2023)

- Comparison with simulations shows an overabundance of bright z>12 galaxies .
- Several hypothesis could explain this overabundance : higher star-formation efficiency, stochastic Star Formation History, contamination by interlopers

# A new class of objects : The Little Red Dots (LRD)



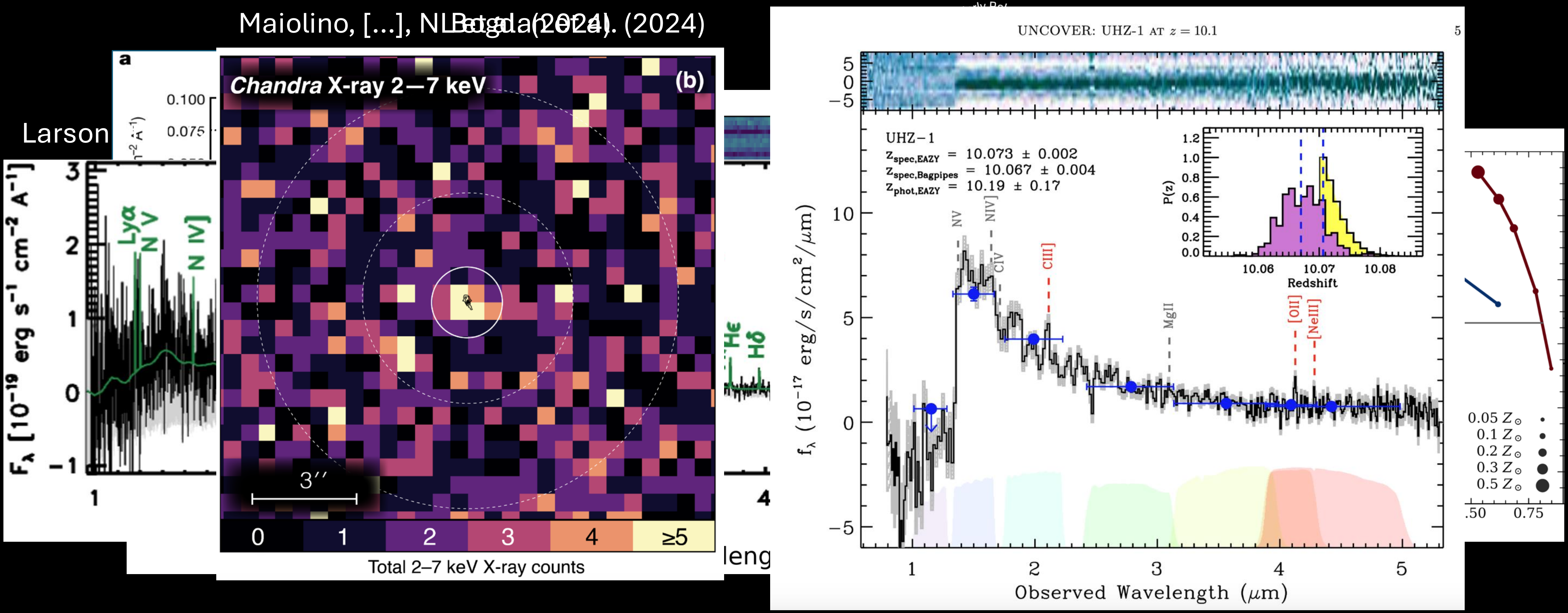

Li et al. (2025)

- At z>7, many compact galaxies are seen with an unusual Spectral Energy Distribution
- The 'V-shape' of their SEDs suggests that they are bursty , with an old stellar population
- Further spectroscopic observations have demonstrated that a fraction of these LRDs hosts AGNs

# Many AGNs in the epoch of reionisation ?

Maiolino, […], NLBogdan(2024)l. (2024)

Larson

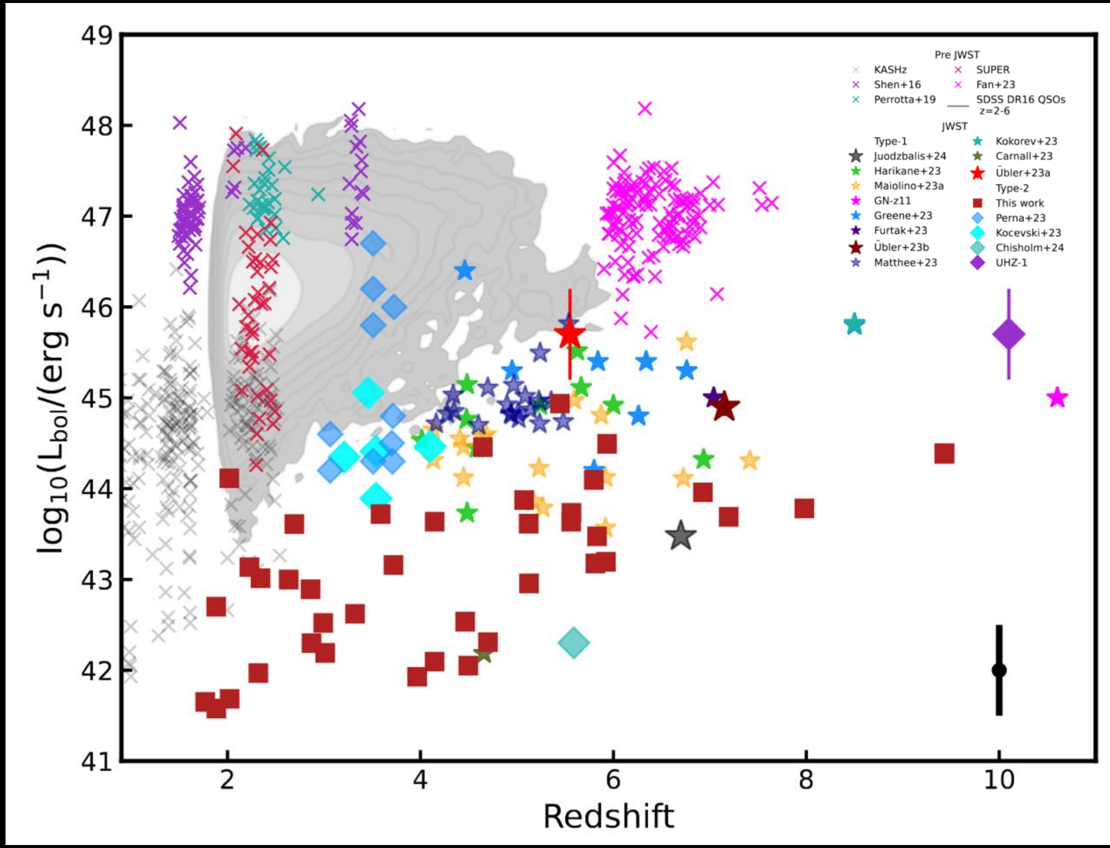



Goulding et al. (2024)

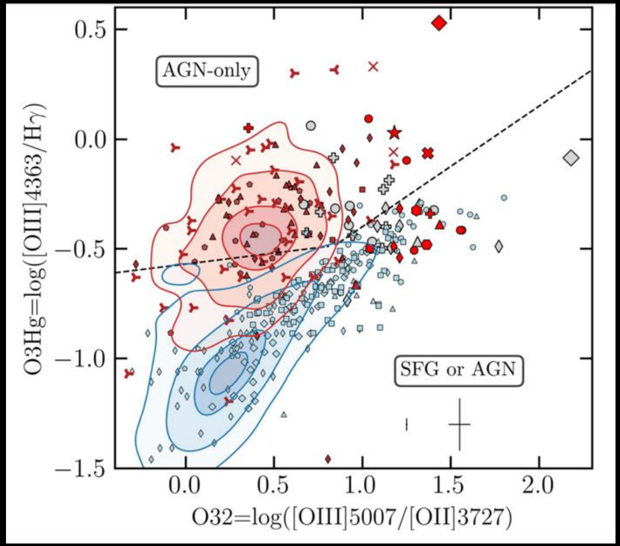
# Many AGNs in the epoch of reionisation ?

- After nearly 3 years of operations, JWST has detected many AGNs up to z~10.6 (Type 1 and 2)

- At z~6, AGN are found in 20-30% of the galaxies across different UV luminosity bins, increasing slightly with UV luminosity



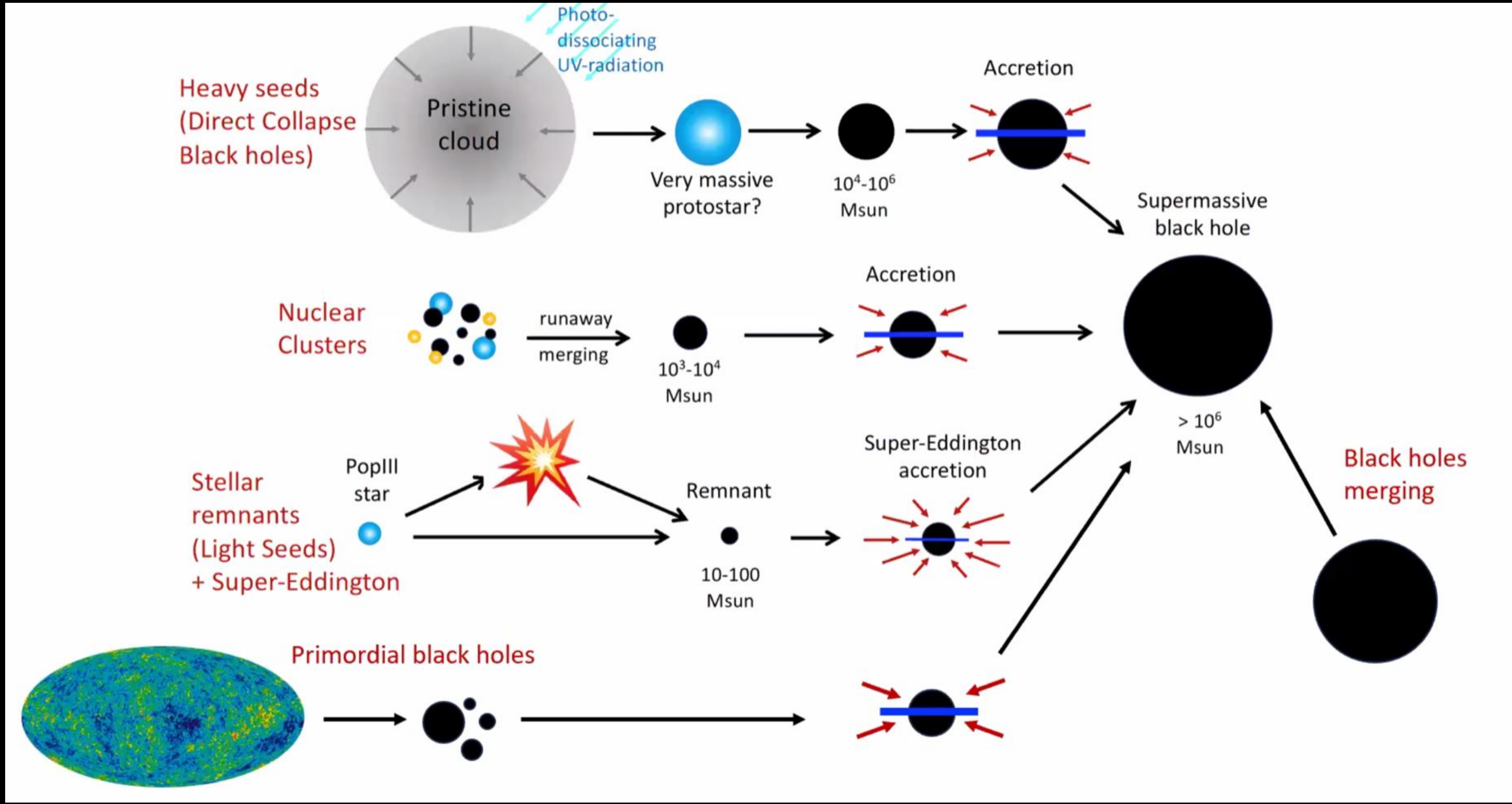

Scholtz et al. (2025)



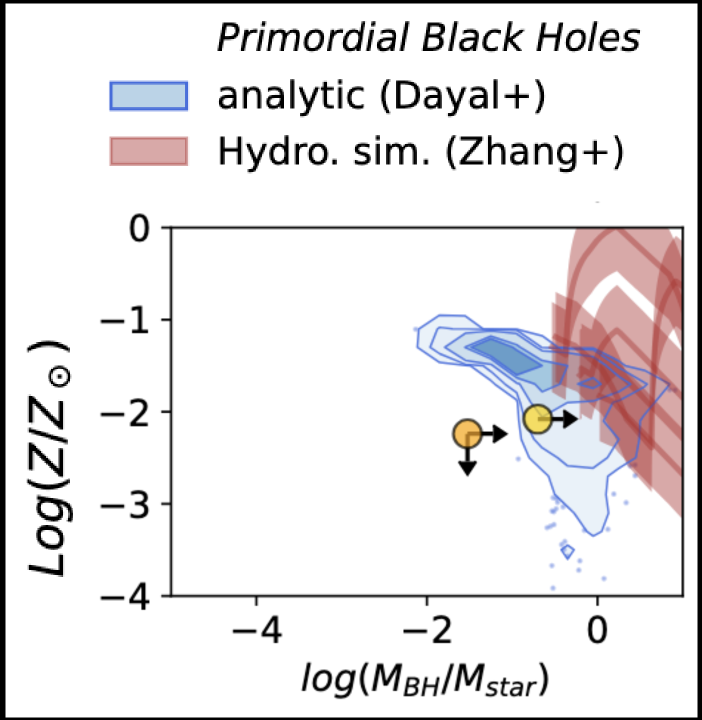

Mazzolari et al. (2024)

- New BPT diagrams have been proposed to facilitate the identification of AGN in the early Universe

# Many AGNs in the epoch of reionisation ?

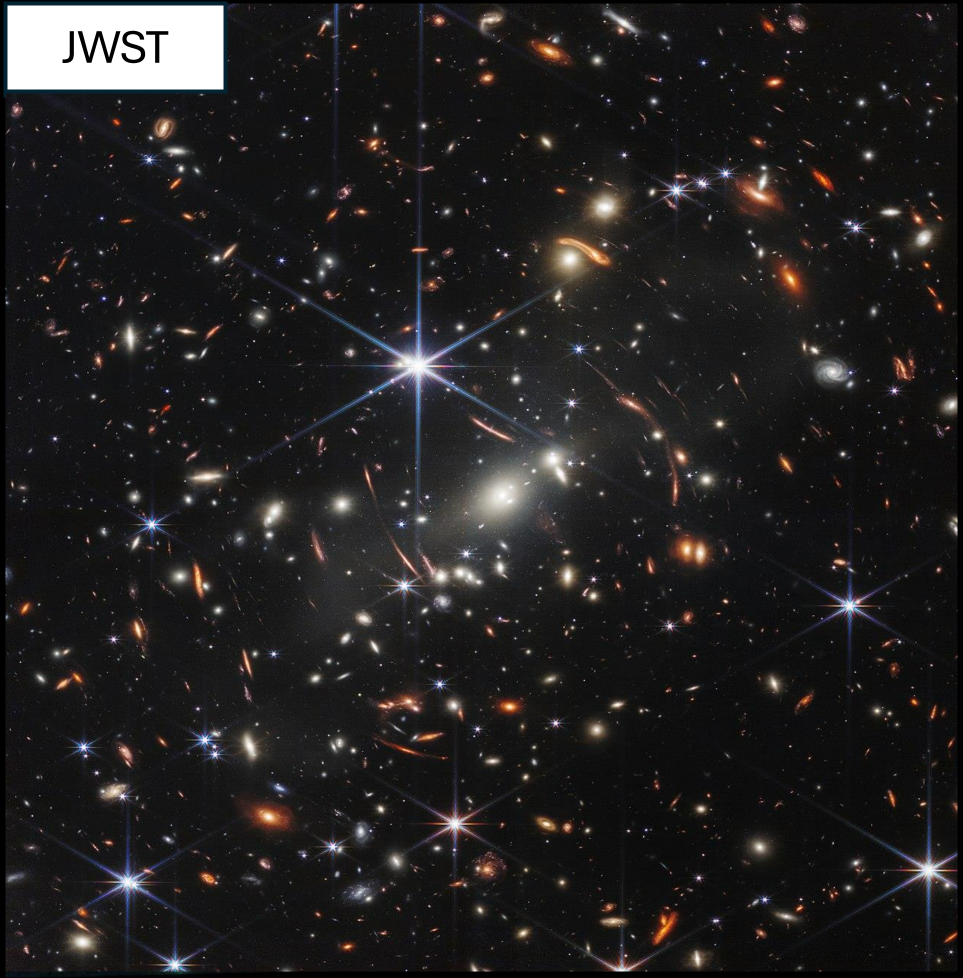



Courtesy of Roberto Maiolino

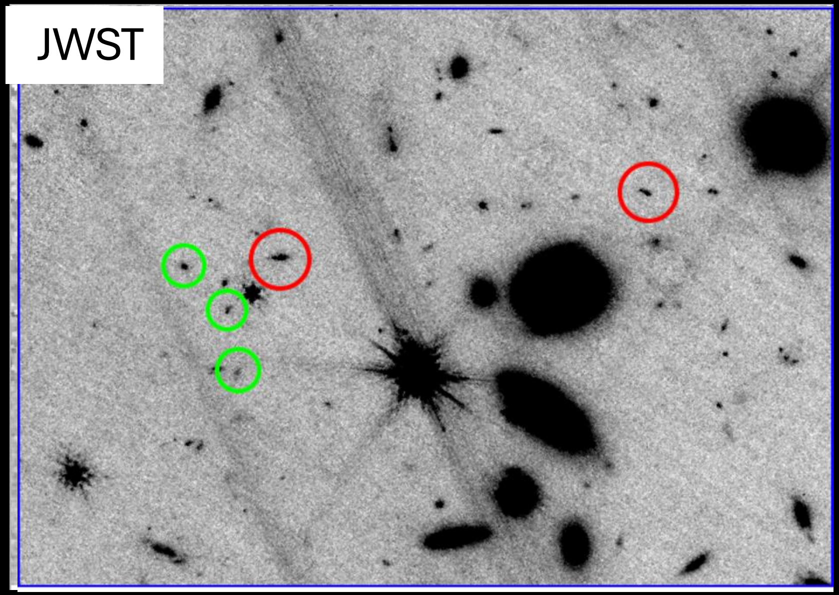



Maiolino,..NL et al. (2025)

# The environment of primeval galaxies

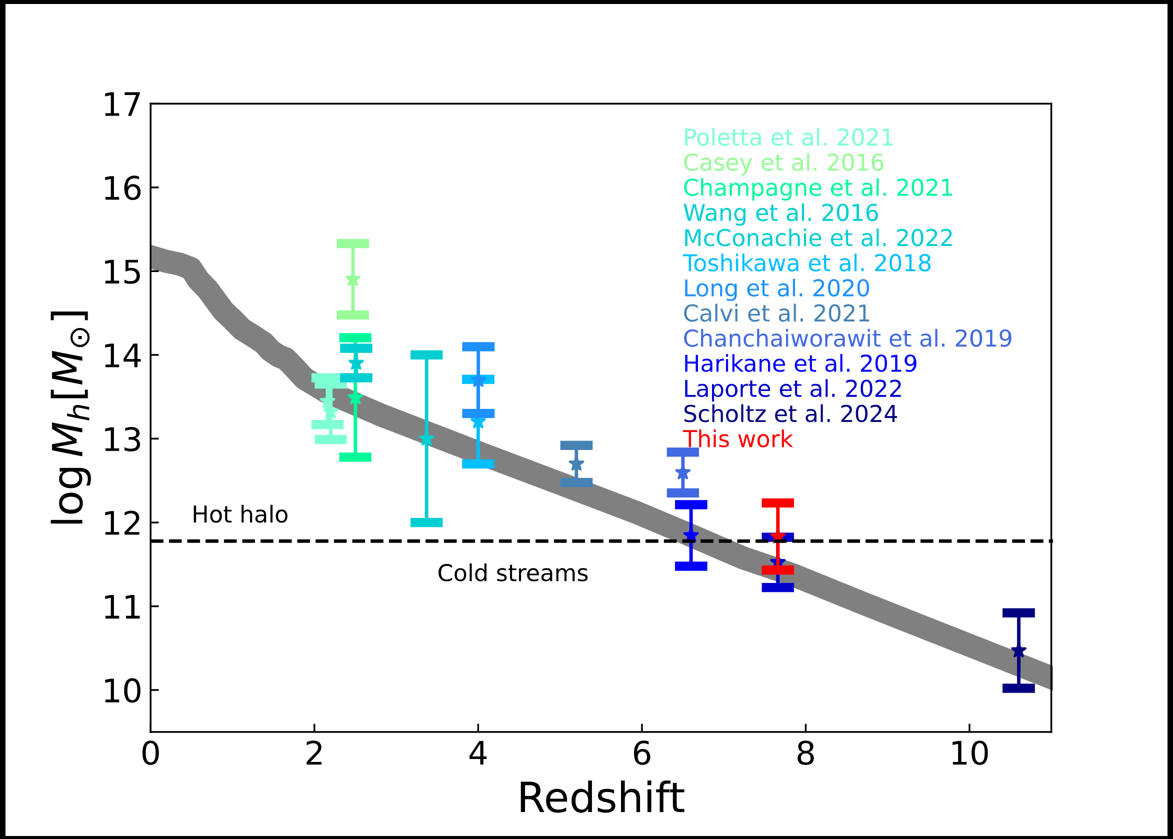



Laporte et al. (2022)

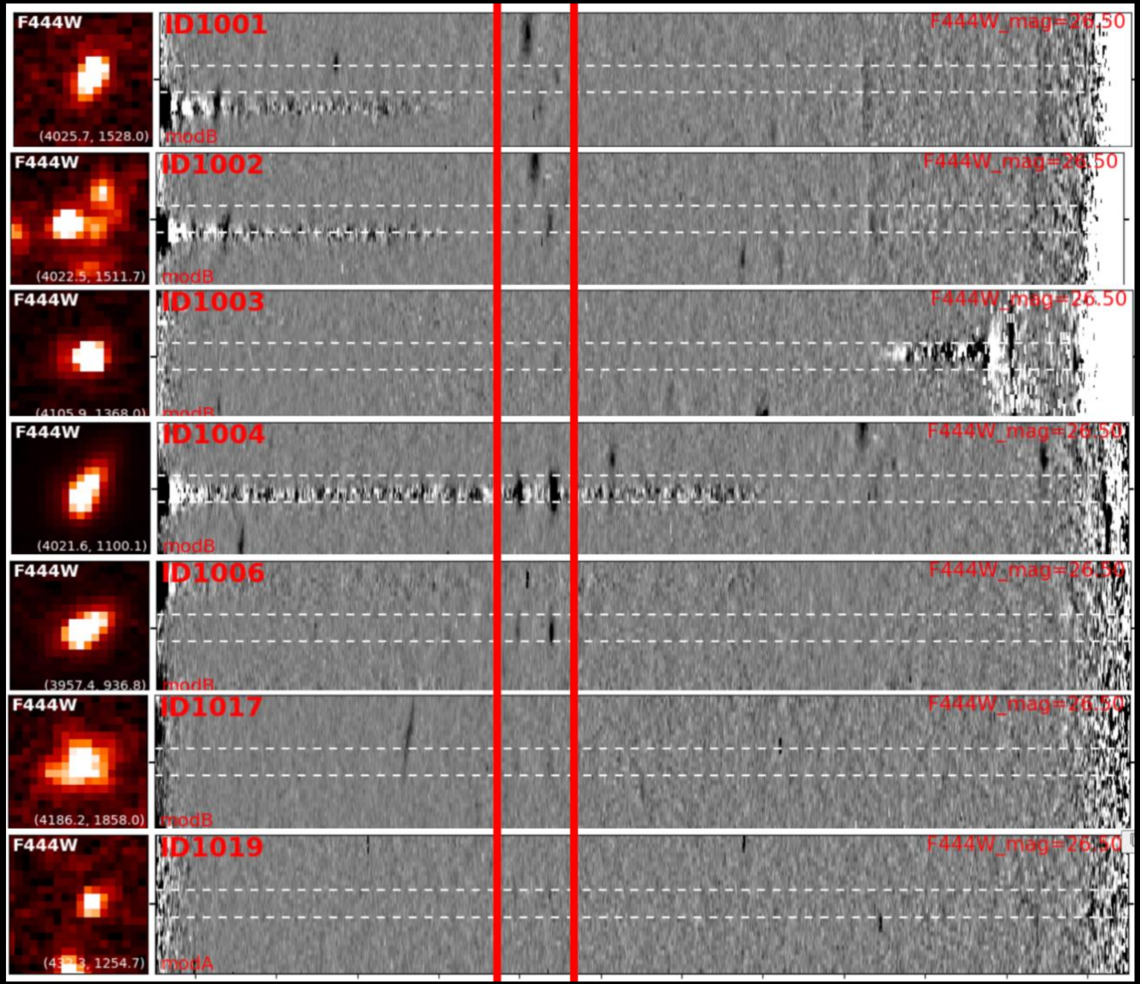



- *Webb* can detect galaxies well beyond *Hubble's limits*
- We can for the first time detect and study the first structure in the early Universe

# The environment of primeval galaxies



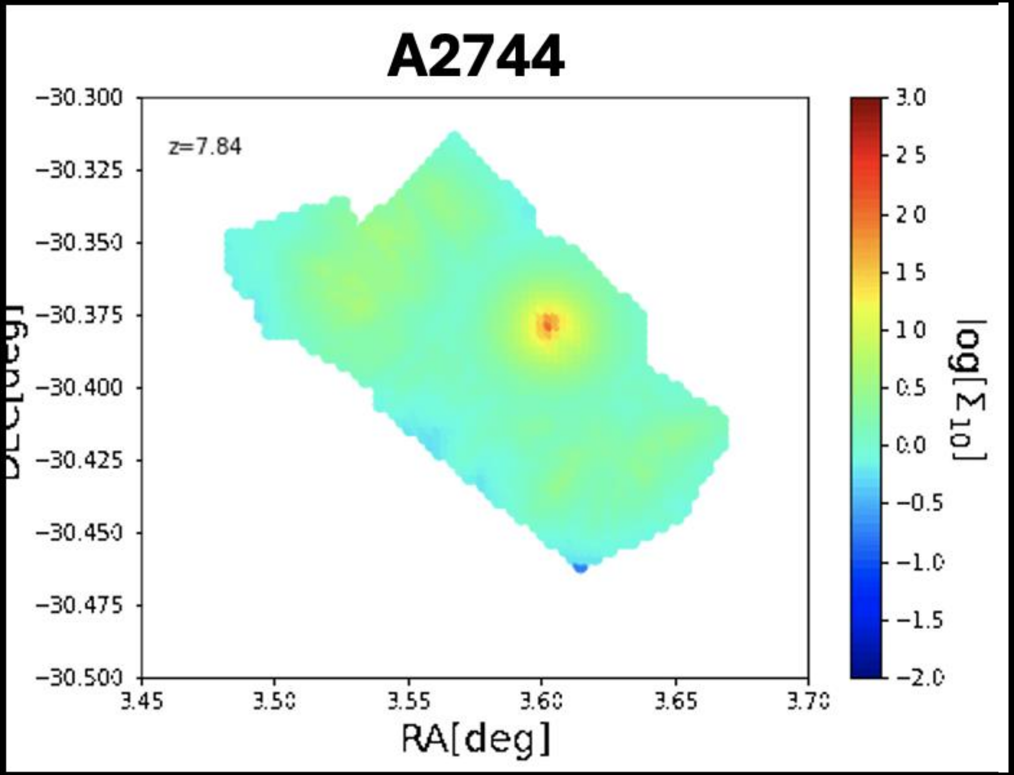

Witten, NL et al. (in prep)

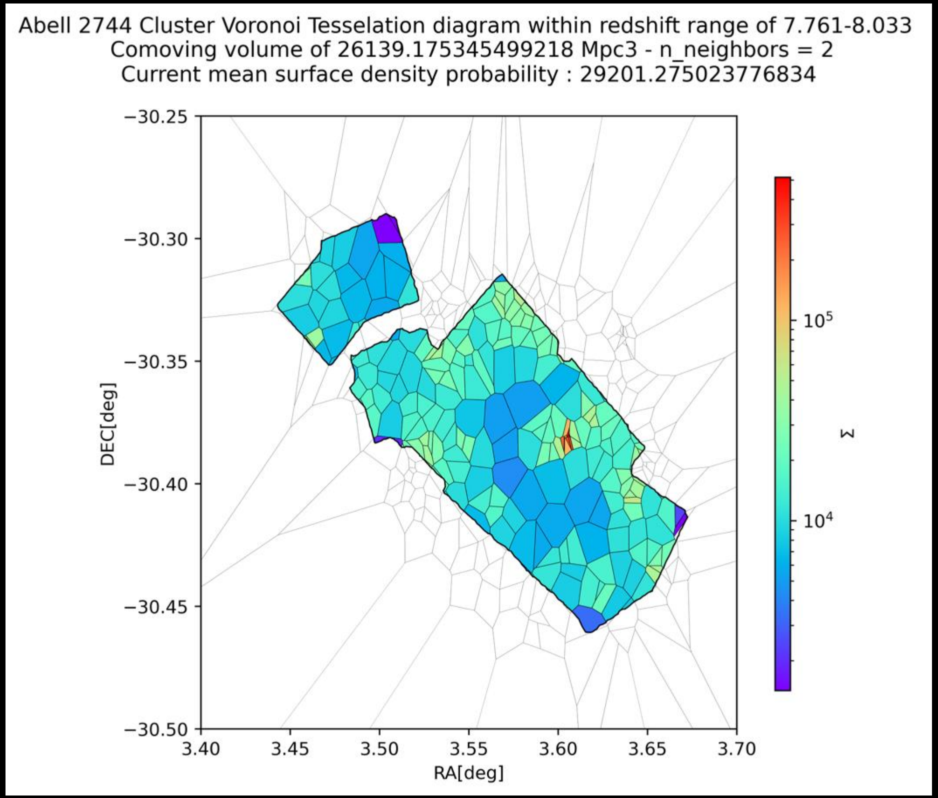



Witten, NL et al. (in prep)

# The environment of primeval galaxies

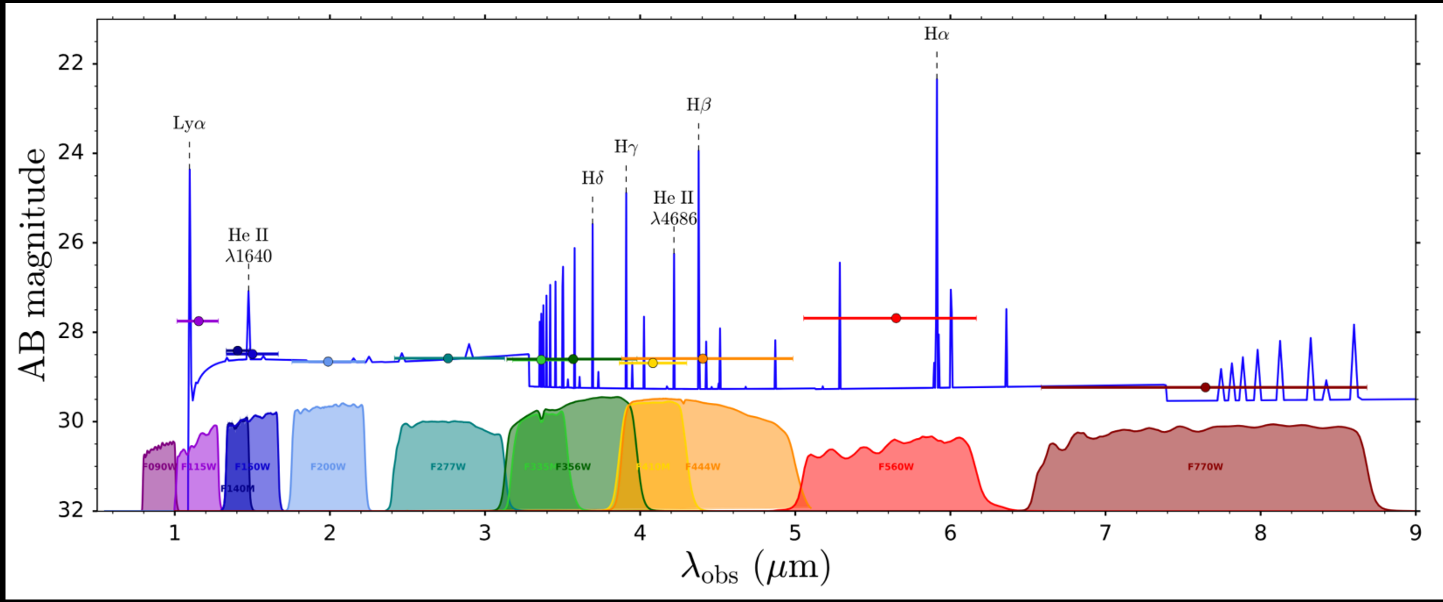
Thanks to the huge sensitivity of JWST compared to HST, one can now study the spatial distribution of galaxies over a large range of luminosities across Cosmic Time to detect the first structure in the early Universe




Laporte et al. (in prep)

# The *grail* of modern astronomy : the first stars

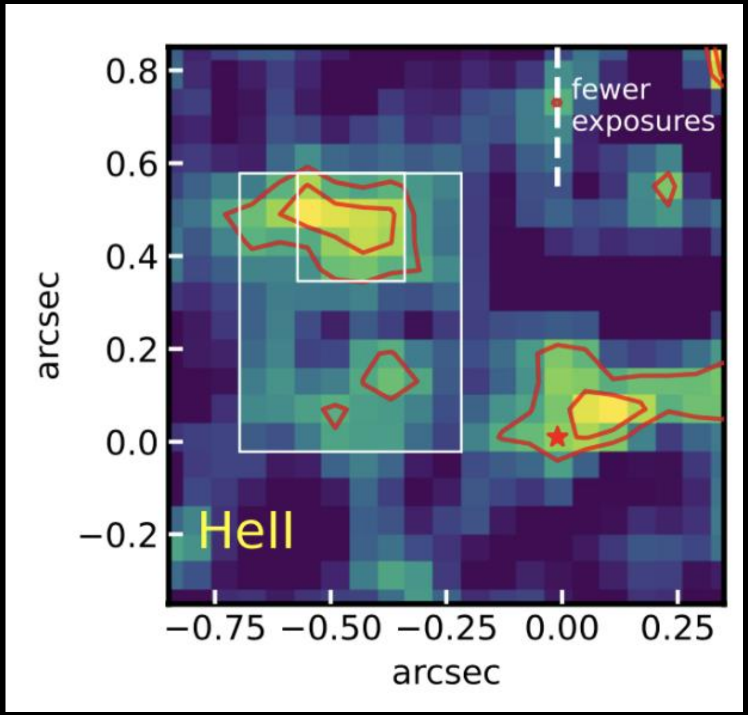



Trussler et al. (2023)

This technique will lead to the selection of photometrically candidates. Spectroscopic confirmation will be needed to confirm the nature of these sources

- The first generation of stars (popIII stars) are expected to :
  - be massive (>$10^3$ $M_\odot$ )
  - have a short lifetime (<10Myr)
  - have an extremely low metallicity
- One way to identify them is by looking for galaxies with strong H$\alpha$ and no [OIII] 5007
  - be massive (>$10^3$ $M_\odot$ )
  - have a short lifetime (<10Myr)
  - have an extremely low metallicity

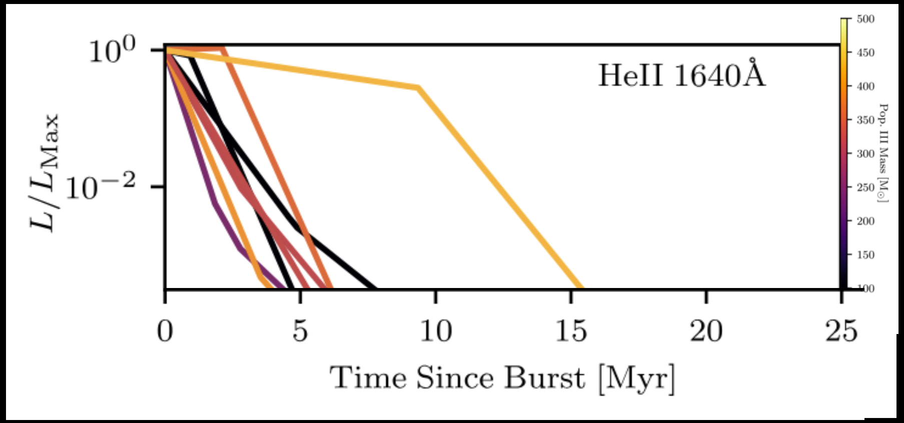
# The *grail* of modern astronomy : the first stars




Maiolino, ..., NL et al. (2024)

- The spectroscopic confirmation of these popIII candidates will be done with the detection of the HeII,$\lambda$1640 emission lines

- But this is challenging, because of the 'lifetime' of this emission line in popIII stars




Katz et al. (2023)

To reach this new frontier, one need large spectroscopic follow-up campaign

An exciting time in extragalactic astronomy with JWST

…but JWST will not address all questions in primeval galaxies

Conclusion

# The Extremely Large Telescope is around the corner !

Credit: ESO

- The Extremely Large Telescope (ELT) is under construction in Chile
- The telescope is done at $\sim 85\%$
- Its first technical light is expected in 2028, with the commissionning of the first light instruments in $\sim 2029$, and the first generation in $\sim 2030$

# The implication of the french community

$\lambda = 3 - 13\mu m$

$\lambda = 0.47 - 2.45\,\mu m$

up to 3,000

$\lambda = 0$

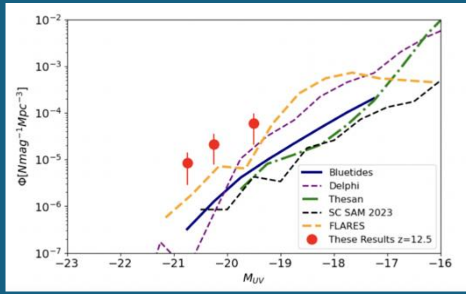
R=5,00

WE NEED YOU

ELT Session on Friday
S21 – Salle C102

# Are we at the dawn of a cosmological revolution ?

## Too many high-redshift galaxies ?

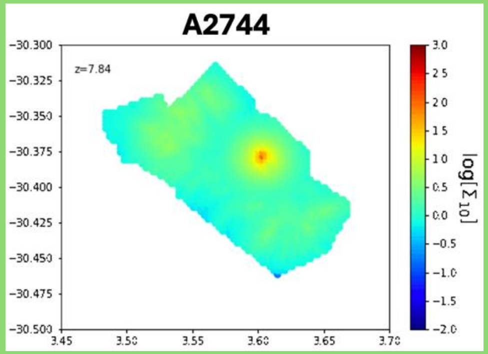



An overabundance of bright galaxies in the early Universe is observed, in contradiction with simulations

Several hypotheses are considered to explain this *excess :*

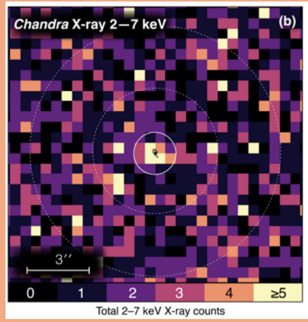
- Higher star formation efficiency
- Stochastic Star Formation History
- Higher rate of contamination by mid-z interlopers

## The first structure of the Universe




Thanks to the unprecedented sensitivity of JWST images, one can build for the first time densty maps within the first billion years and reveal the first structures !

## AGNs are everywhere !




Within its first months of operation the *Webb* has identified a large number of AGN up to z>10

The origin of these SMBH is still highly debated, but could be the signature of the primordial black holes formed during the inflation phase

## The first population of stars : the next frontier !

Although the quest for the popIII stars has only started, the Webb has already identified several robust candidates.

**The ELT is just around the corner and France is one of the leading countries: it is <u>now</u> that we should start thinking about the ELT Science !**

# The implication of the French community

The French community is involved in the largest and deepest extragalactic survey (1551 hrs)

Since Cycle 1, 28 proposals have French PI totalising more than 1000 hrs.