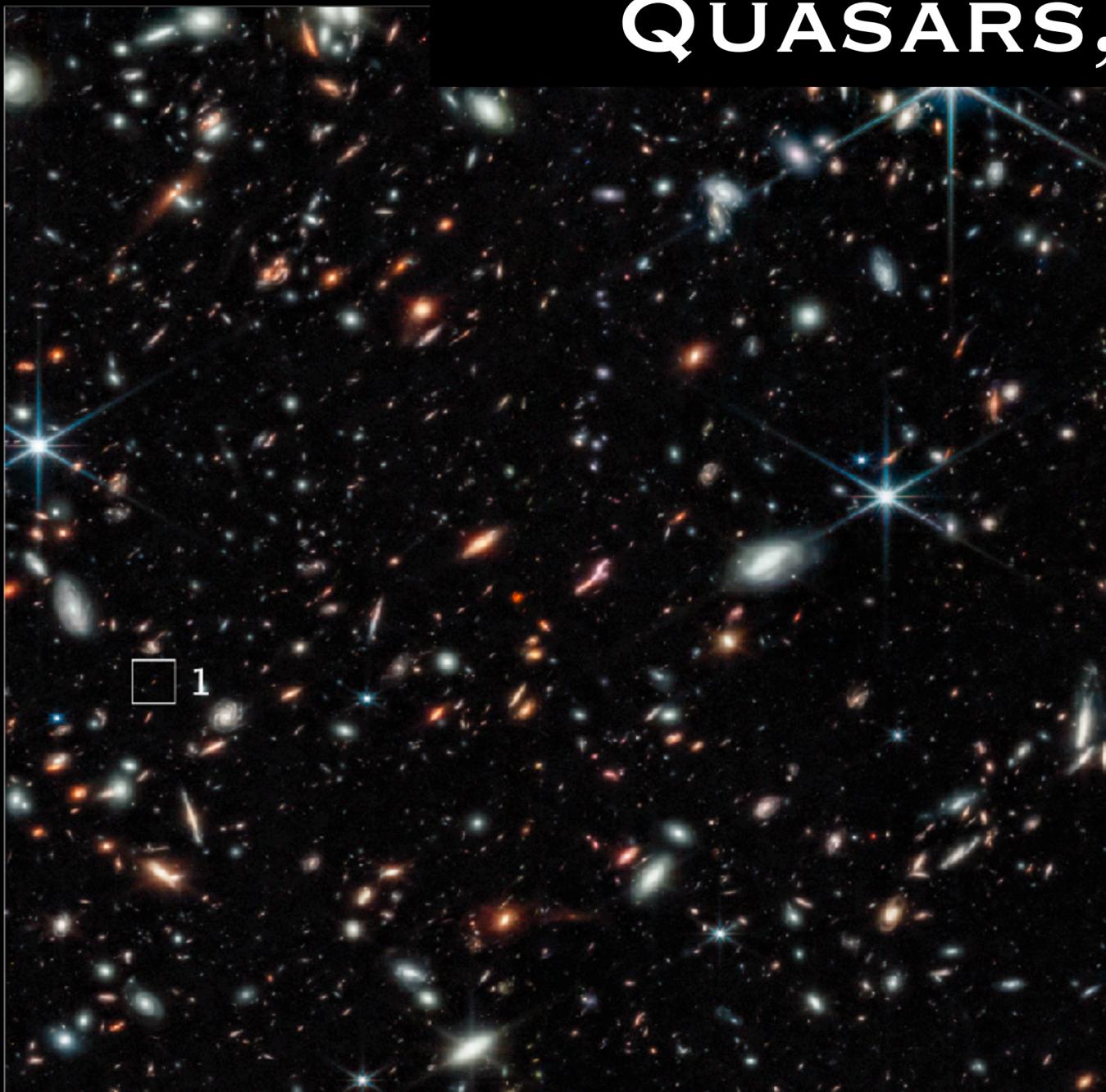
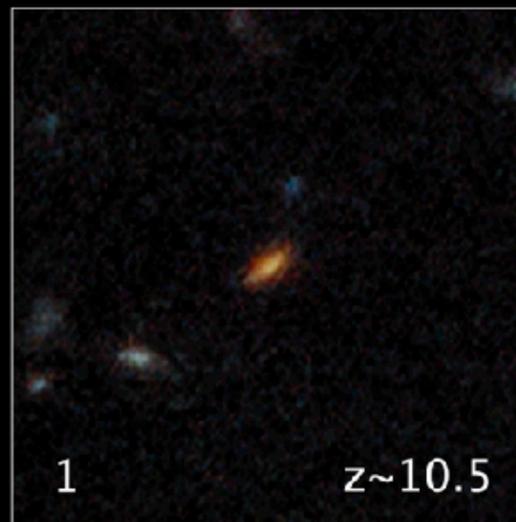


# THE EARLY UNIVERSE: FIRST STARS, QUASARS, REIONIZATION (#2)



JWST/NIRCam



ADRIANO FONTANA  
INAF

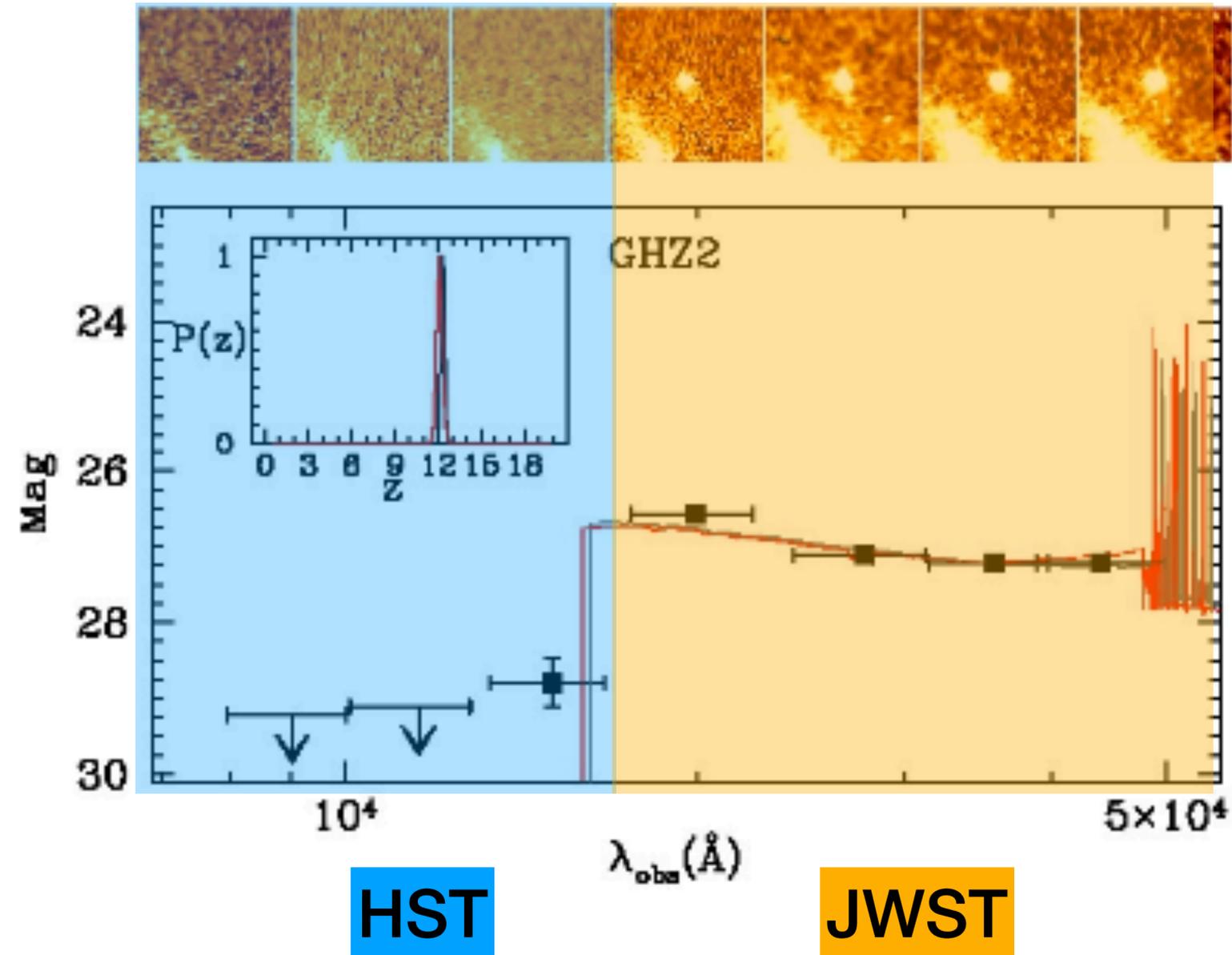


# JWST' UNIQUE FEATURES

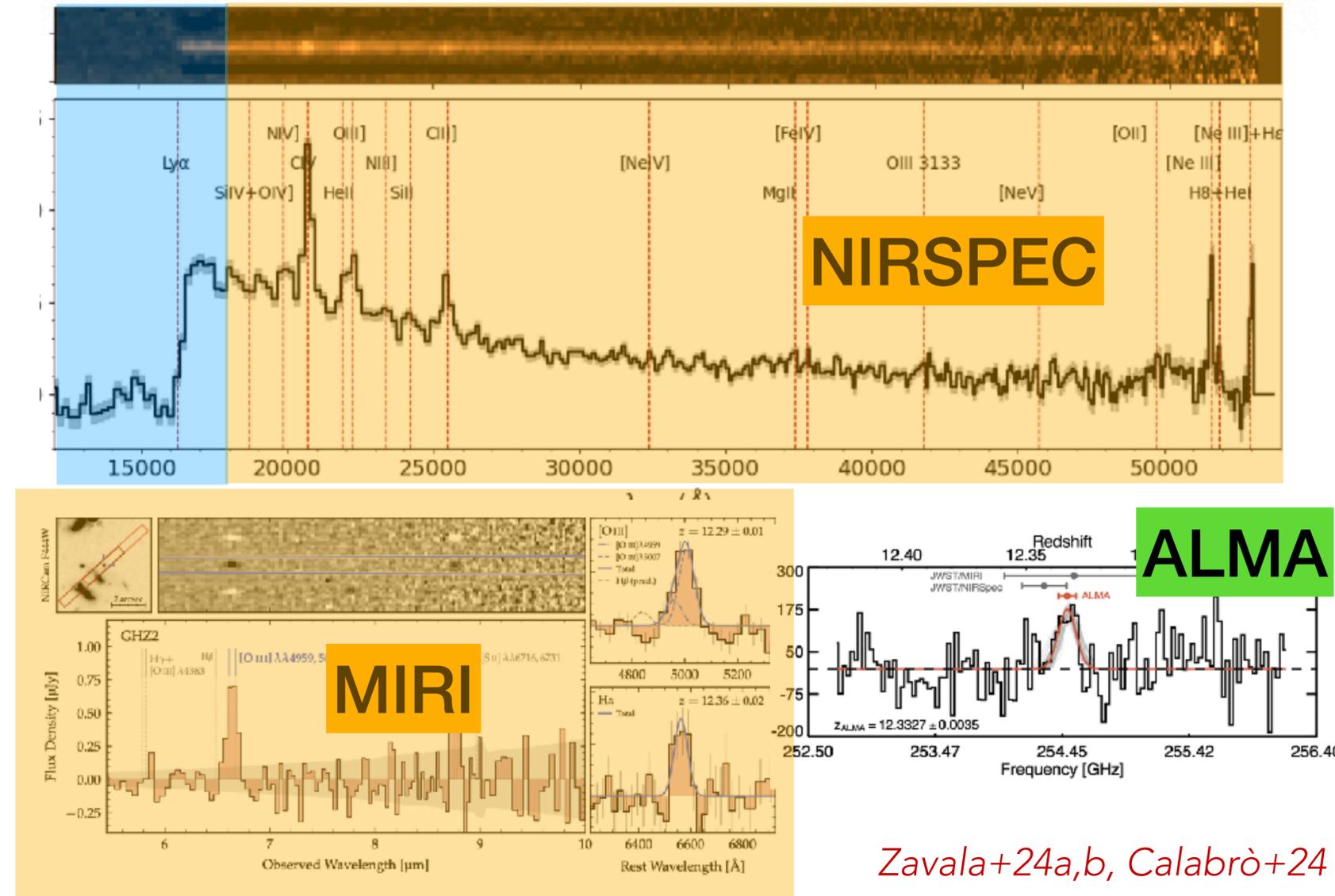
**GHZ2:** 'prototypical' example  
 - First galaxy detected at  $z > 11$

- Unexpectedly bright  
 - Spectrum full of bright UV lines

*Castellano, AF+24, 25*



*Castellano, AF+22*

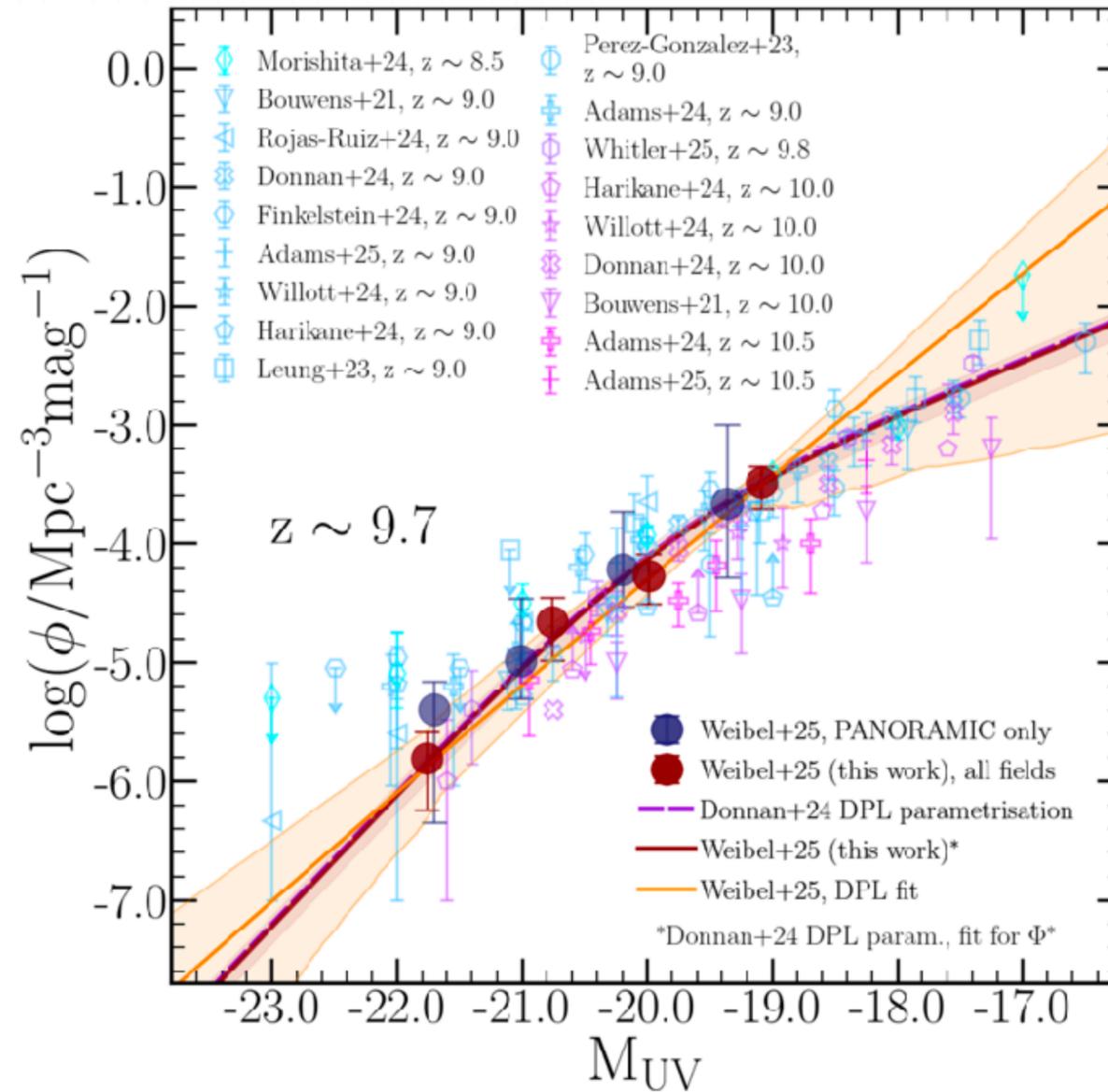


*Zavala+24a,b, Calabrò+24*

# THE JWST LUMINOSITY FUNCTION(S)

At  $z \sim 10$ , there is a considerable consistency among various determinations

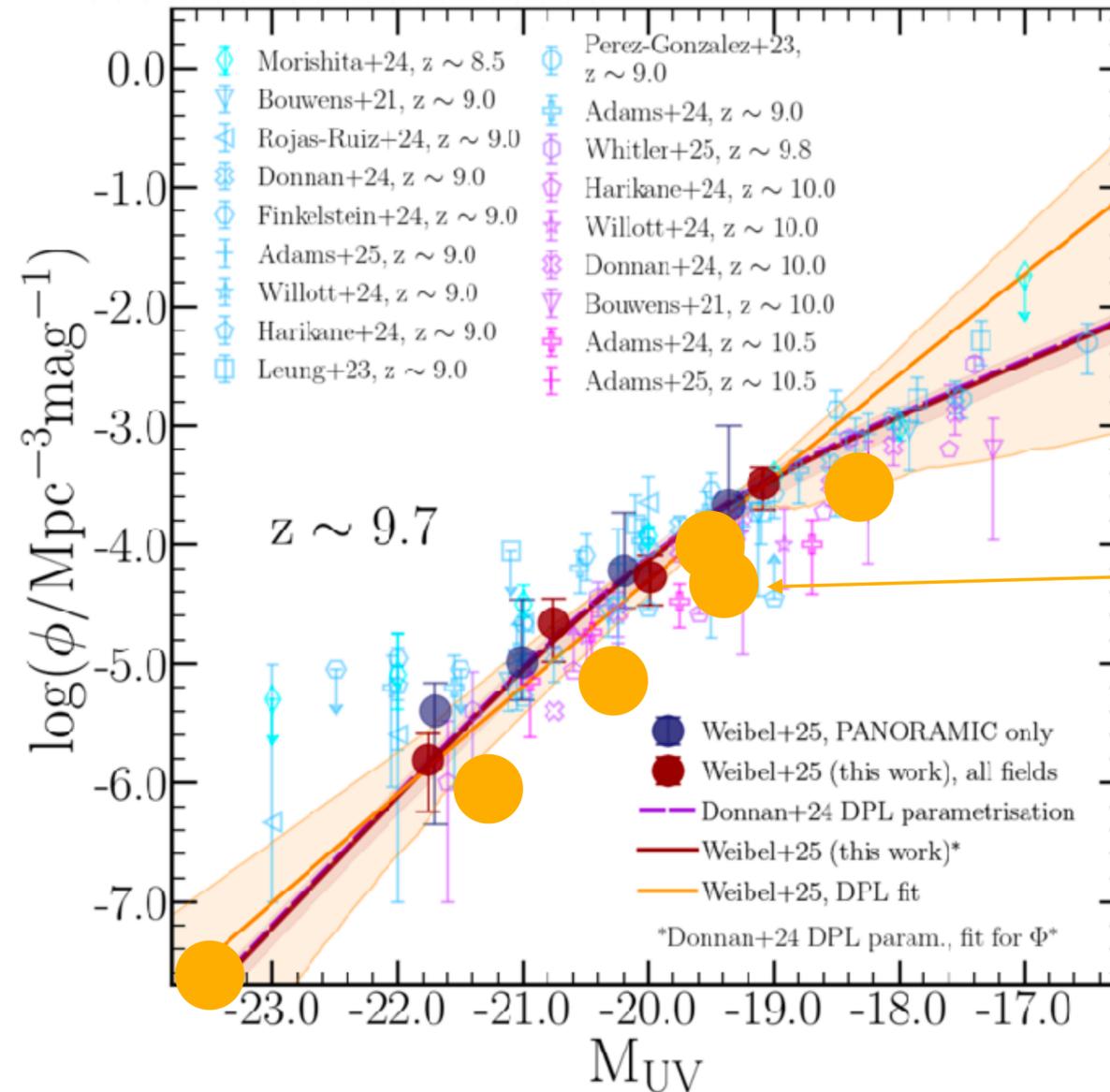
*Weibel+25*



# THE JWST LUMINOSITY FUNCTION(S)

At  $z \sim 10$ , there is a considerable consistency among various determinations  
Above most of the pre-JWST measurement

Weibel+25



McLoed+16,  
Oesch+18,  
Bowler+20

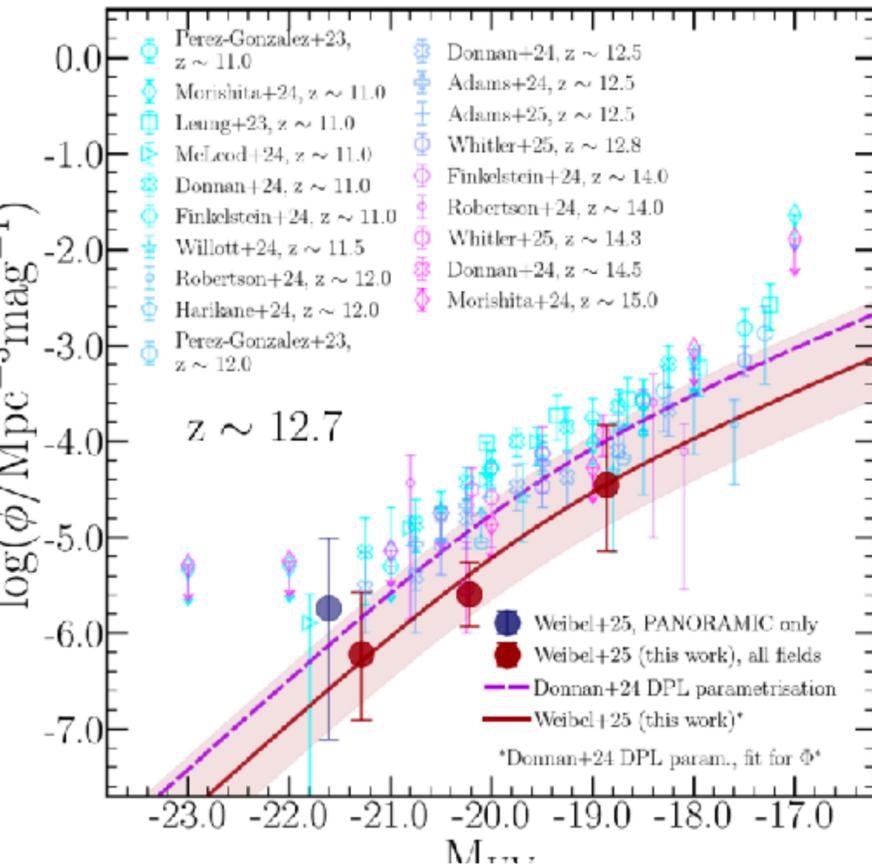
We had hit the limit of the  
HST capabilities..

Oesch+18, 9 objects in FF

# THE JWST LUMINOSITY FUNCTION(S)

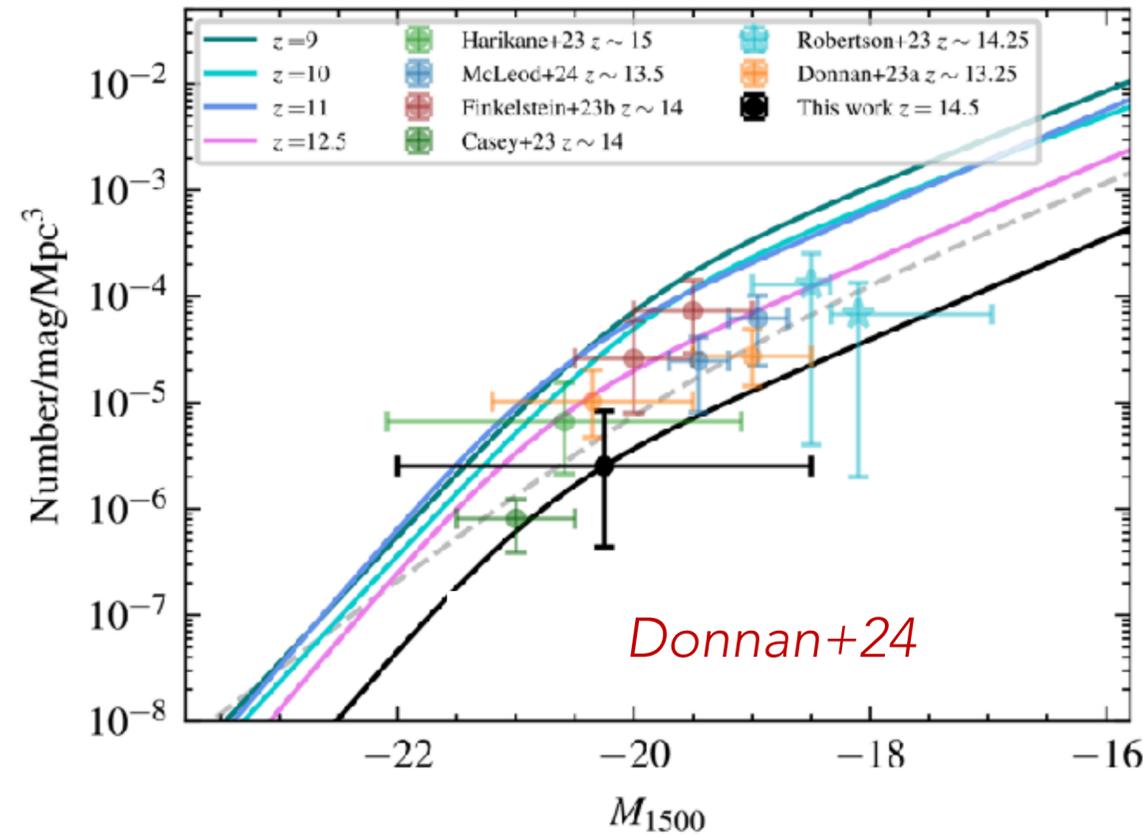
At  $z=12 - 14$ , there are still significant differences among different measurements

$z \sim 12.5$

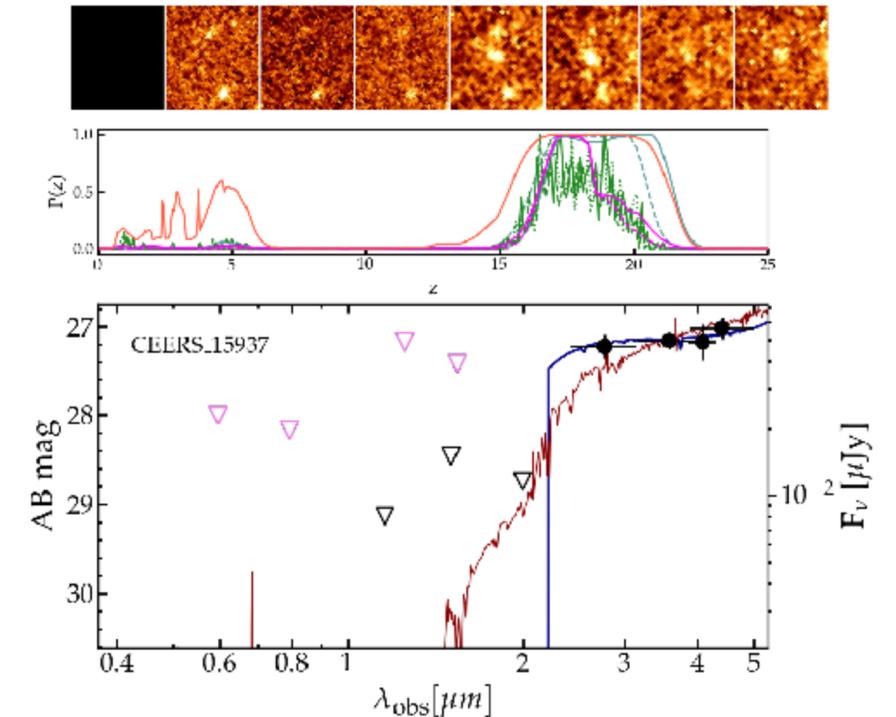


Weibel+25

$z \sim 14$



$z > 15$ ? Terra incognita



Castellano, AF +25

Gandolfi+25

Kokorev+25

Perez-Gonzalez+25,

Whitler+25

- ◆ Statistical error and systematics increase with  $z$
- ◆ Small-sample errors dominate at  $z > 13$
- ◆ Bright & faint sides poorly constrained, especially at  $z > 12$

## Conclusions#1

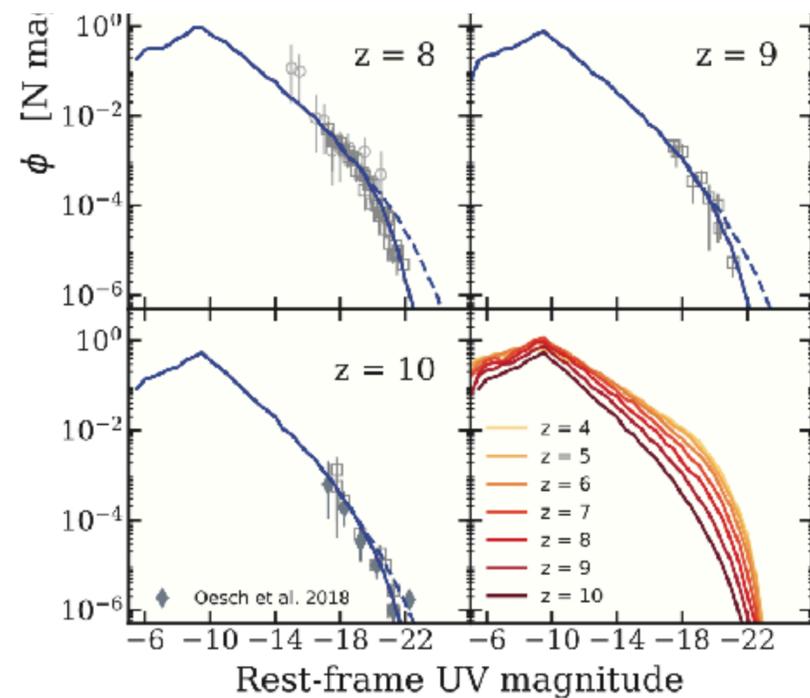
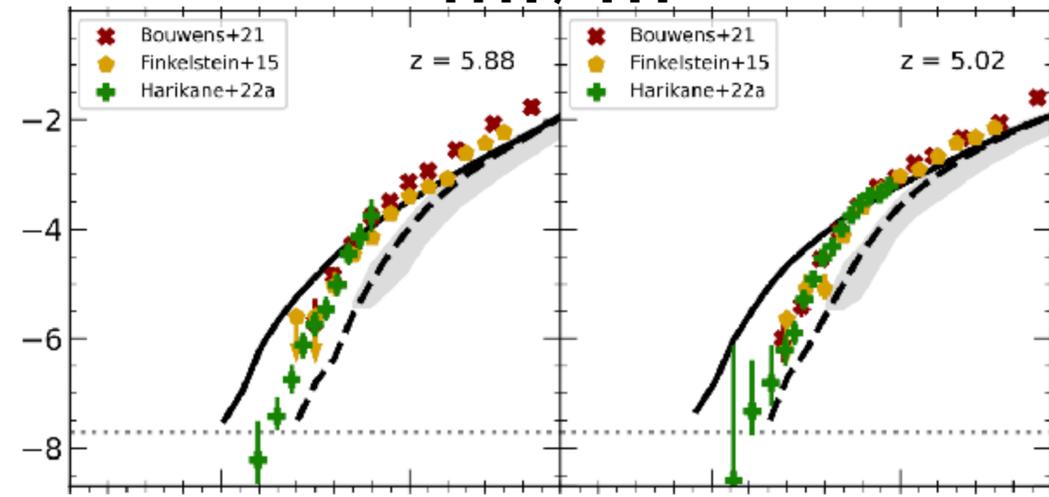
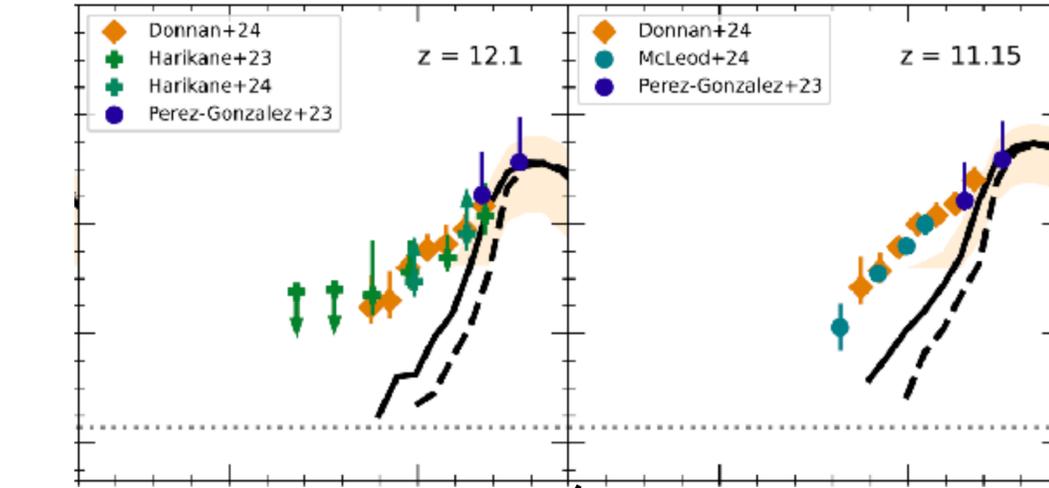
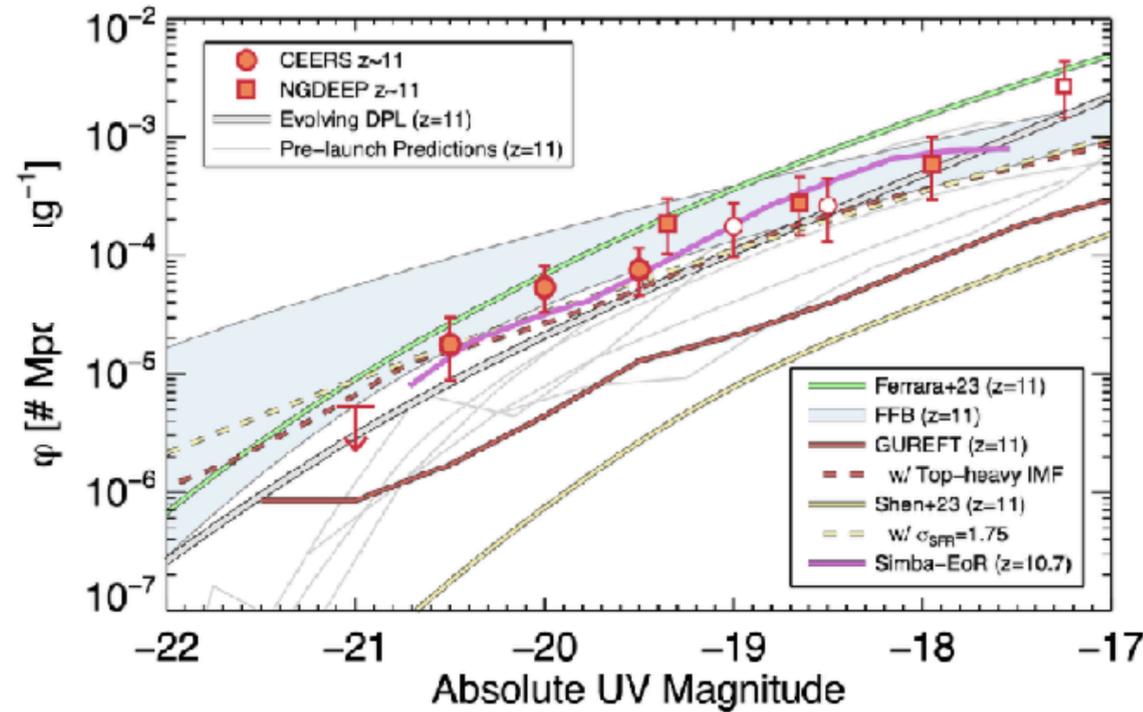
- ◆ We have not reached a solid statistical census at  $z > 10$ :  
we need larger/deeper surveys  
(community-wide efforts will come sooner or later).

# THE “EXCESS” OF $z > 10$ GALAXIES

Pre-JWST theoretical models were under-predicting UVLF at  $z > 10$ .

They assumed physical mechanism to remain “constant” at  $z > 10$

Finkelstein+24



Cantarella+ 2511.03787

Yung, Somerville+19

# EXCESS OF BRIGHT GALAXIES? ...EXCESS OF POSSIBLE INTERPRETATIONS...

---

- 📌 Stellar evolution: high L/M, low Z, binaries?, IMF? → *more luminous*
- 📌 Increased efficiency of star formation rate ( $\epsilon$ ) → *more massive*
- 📌 Bursty Star formation / Lack of feedback / Overcooling → *more luminous*
- 📌 AGN → *more luminous*
- 📌 Non standard cosmology → *more abundant/massive*

- Ferrara+22, Ziparo+23, Fiore+23, Mason+23, Shen+23, Harikane+23, Qin+23, Dekel+23, Dekel+24, Ferrara+24, Renzini 2023, Harikane+23, Haslbauer+22, Finkelstein+23, Yung+23, Padmanabhan & Loeb 23, Melia 23

# EXPLAINING THE LF EVOLUTION

As redshift increases, theoretical models need to include *progressive* changes to the physics of galaxy formation.

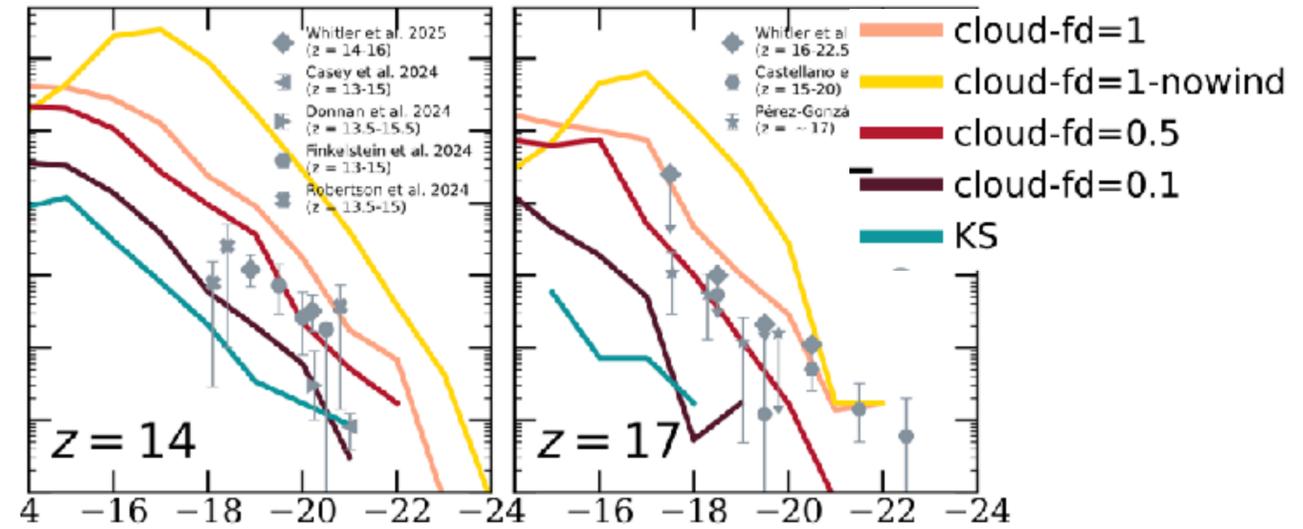
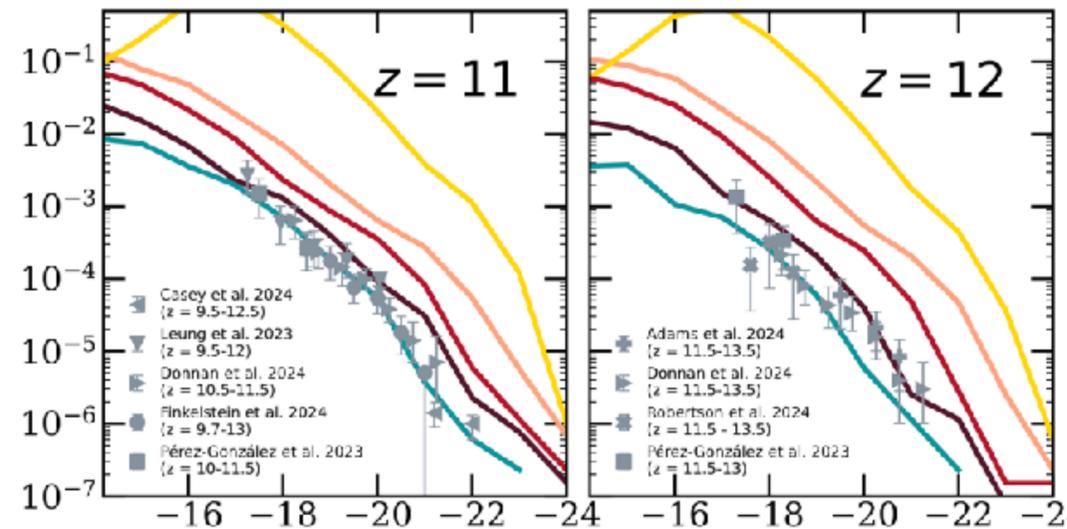
For instance...

Dekel+23 increases the efficiency  $\epsilon_{\text{FFB}}$

Ferrara+23,24,25 includes an **Attenuation-Free Model**

Cueto+24, Mauerhofer+25 evolving IMF

Somerville+25 increases density modulated SF + evolving dust content + burstiness



Somerville+25

*While this multi-faceted picture may seem **unsatisfying from an Occam's Razor perspective,***

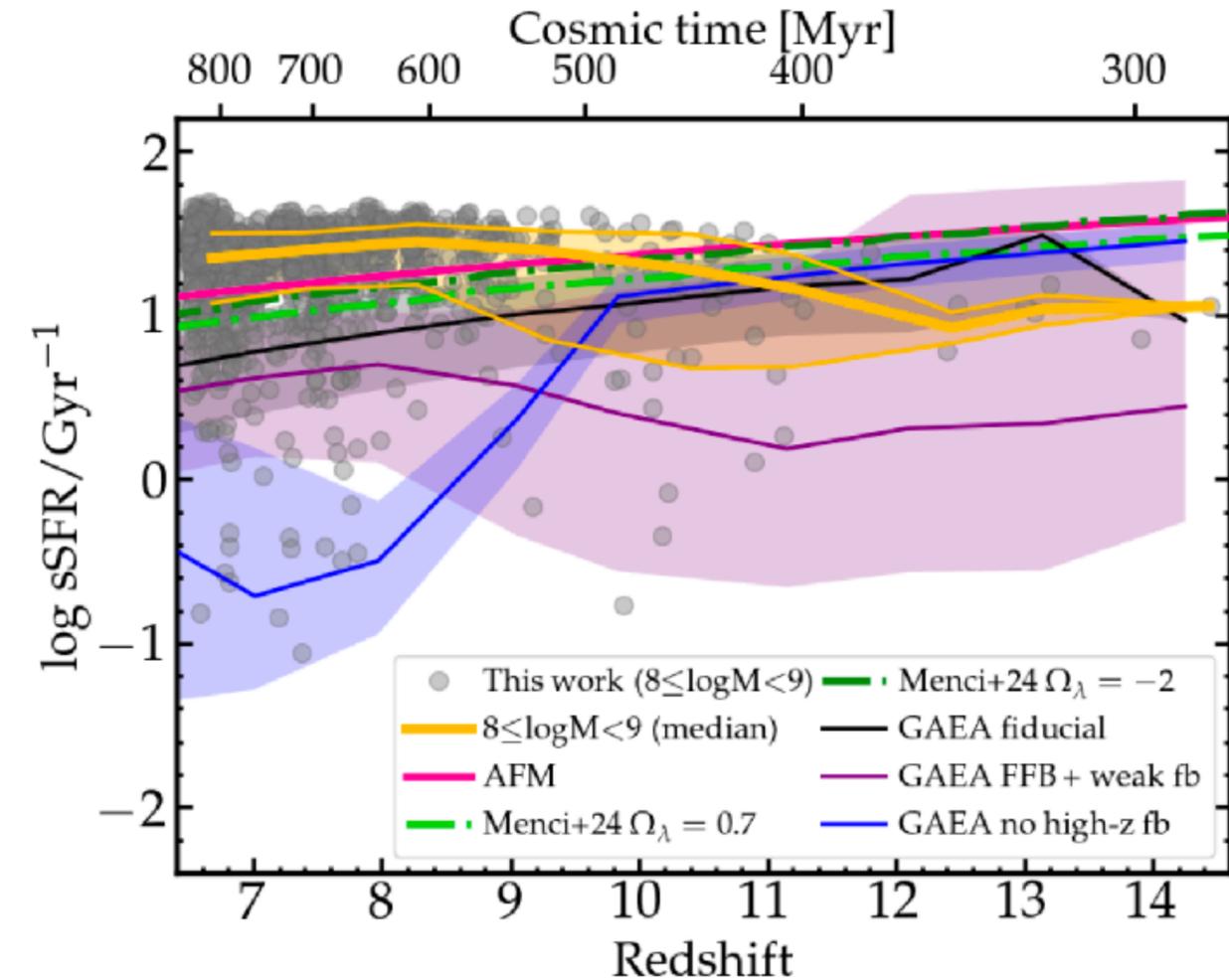
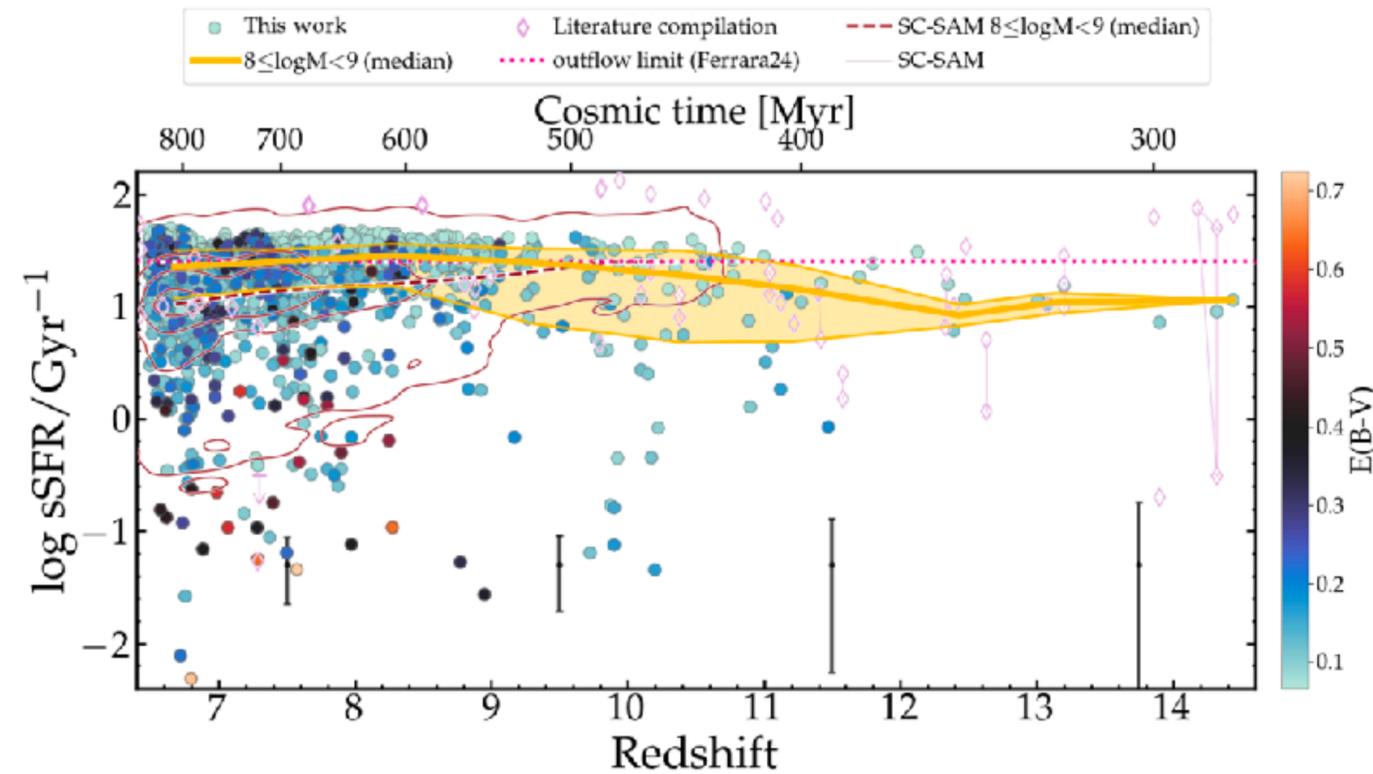
# WE NEED ADDITIONAL DISCRIMINATING TESTS..

## The evolution of the SSFR(z)

SED analysis on ASTRODEEP catalog (Merlin+24).

Non-parametric SFH including recent burst

Model comparison

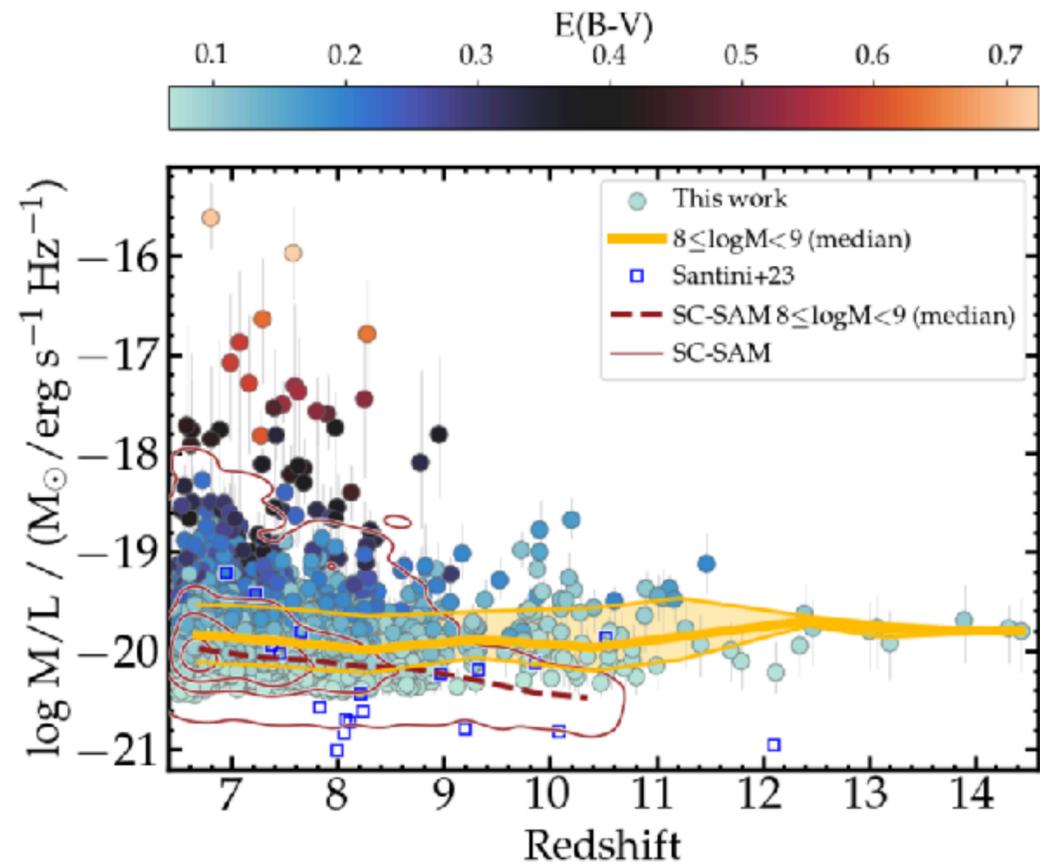


*Santini+2512.09139*

## Conclusions#2

- ◆ We need a combined effort combining observations and theory in a self-consistent manner to reveal physical processes ongoing in early galaxies

# DIVERSITY AMONG $z > 10$ GALAXIES



*Santini+2512.09139*

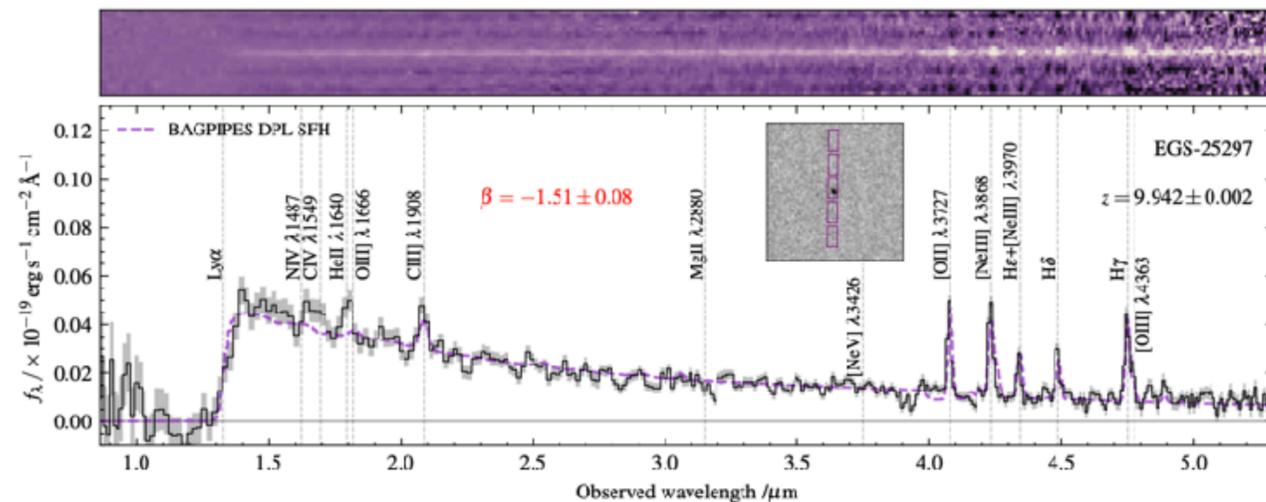
Different galaxy types:

- 75%: SF-ing, low dust  $E(B-V) \leq 0.2$
- Dusty star-forming galaxies
- low SFR (lulling)  $0 \leq E(B-V) \leq 0.7$

*Donnan+25*  
*Mitsuhashi+25*

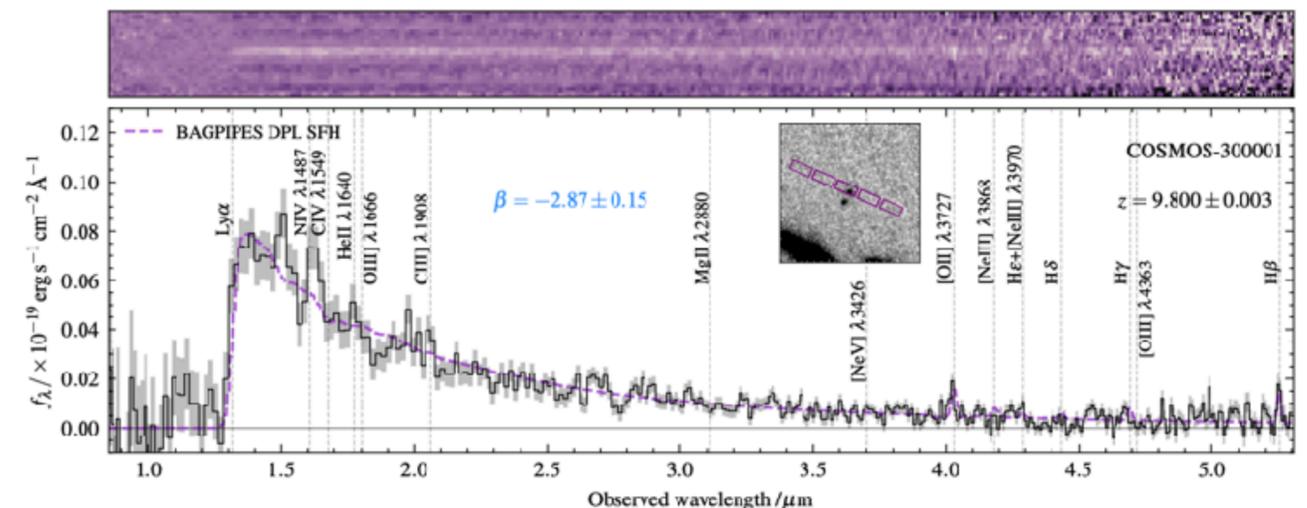
Three  $\beta$ -outlier at  $z \sim 10$

$\beta \sim -1.5$  High dust absorption



$\beta \sim -2.9$  No dust, high  $f_{\text{esc}}$ ?

Close to another similar object, merger-induced starburst?

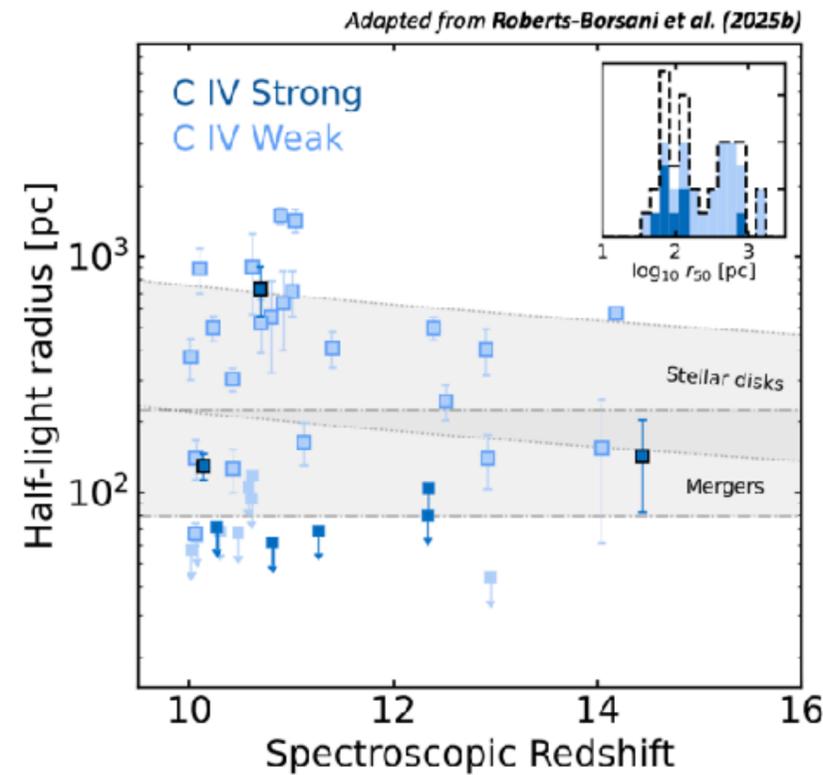


# DIVERSITY AMONG $z > 10$ GALAXIES

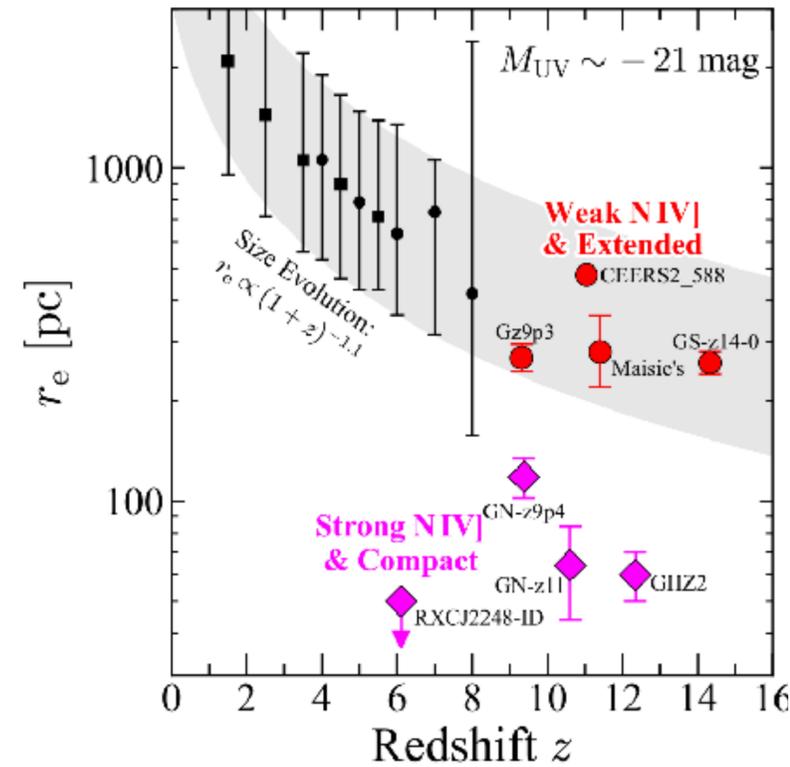
**Size and emission properties are correlated.**

Strong emitters are very compact:  $< 100$  pc

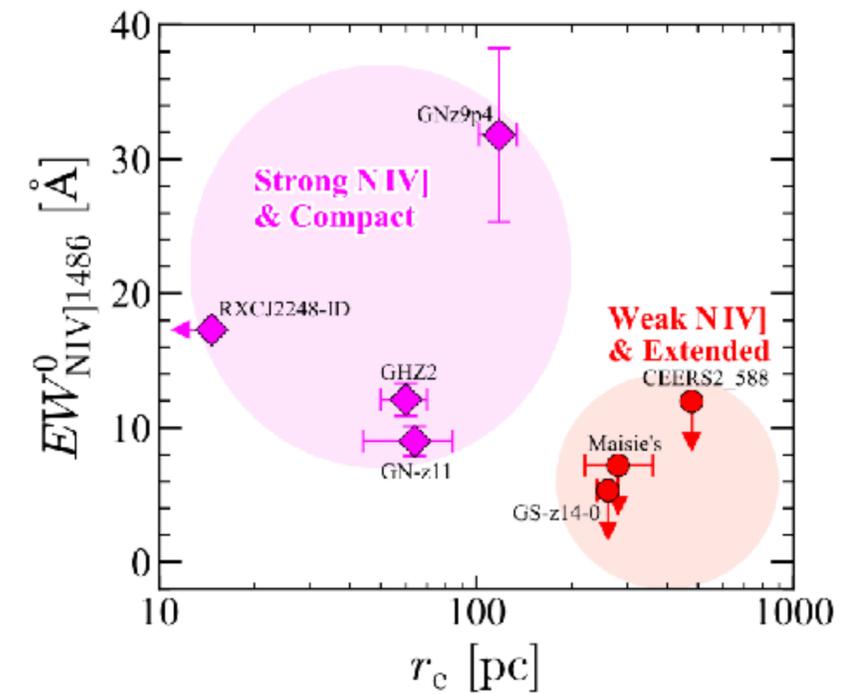
Weak emitters are on the evolutionary line of disks



*Roberts-Borsani, 2025*



*Harikane+, 25*



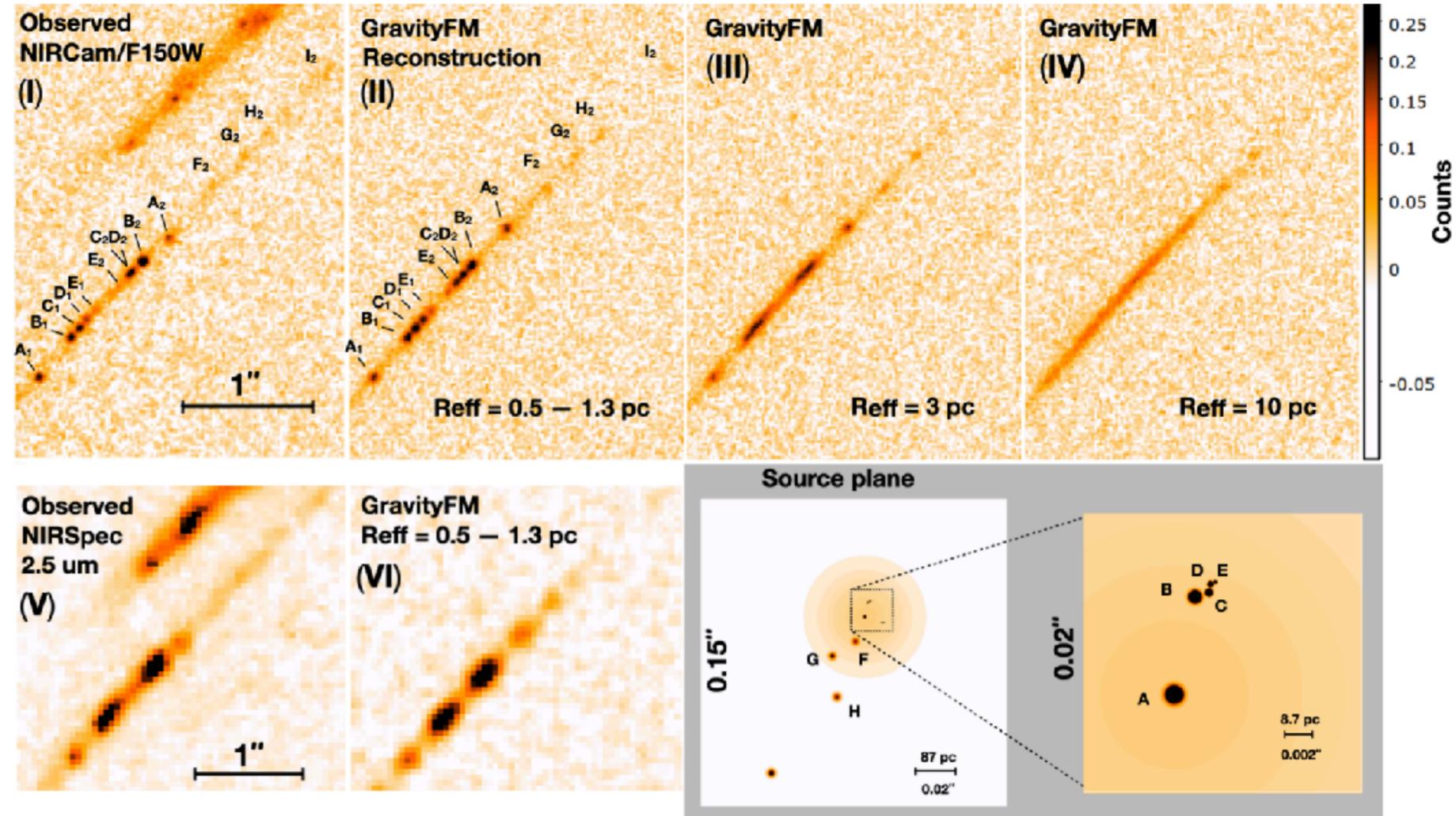
Simulations by Yajima+22,23 predict sizes oscillating between the two regimes..

*Also Naidu et al. (2025), Ono et al. (2025), D'Eugenio+24...*

# DIVERSITY **INSIDE** $z > 10$ GALAXIES

Strong lensing helps resolving star clusters

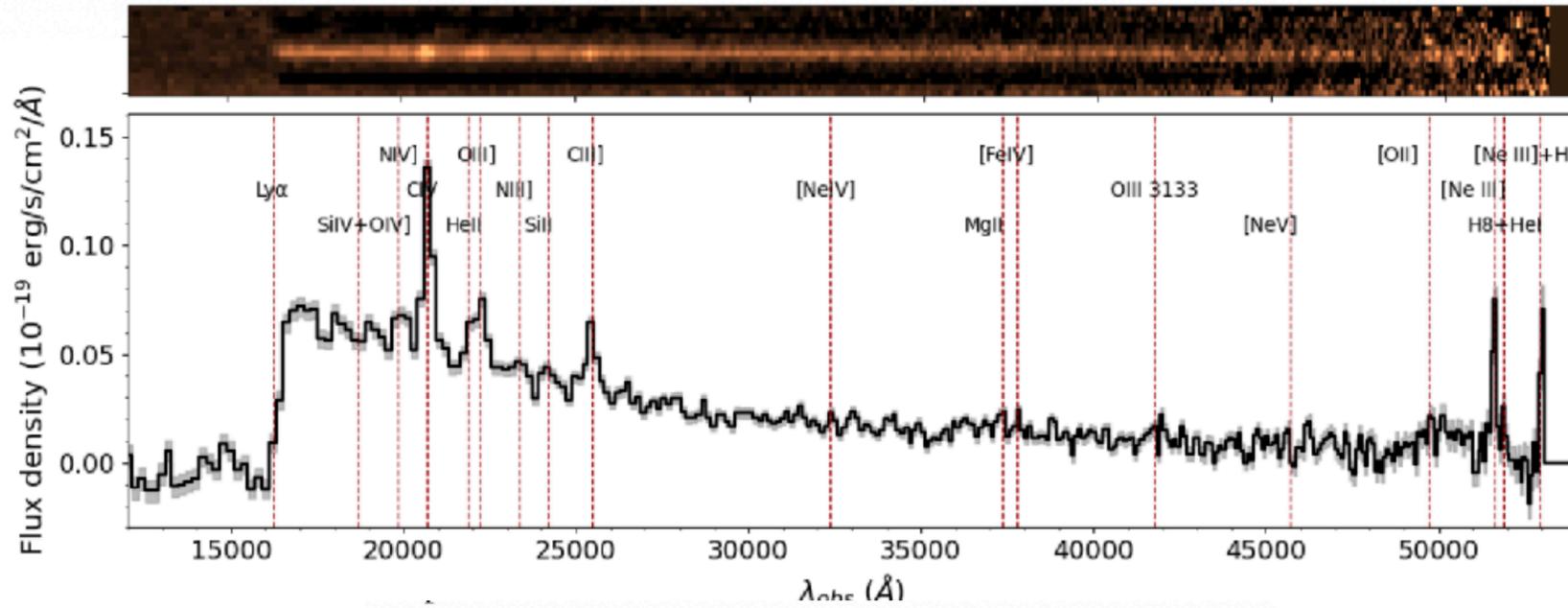
Cosmic Gems arc  $z=9.6$



*Messa, Vanzella+, 2025*

# DIVERSITY INSIDE $z > 10$ GALAXIES

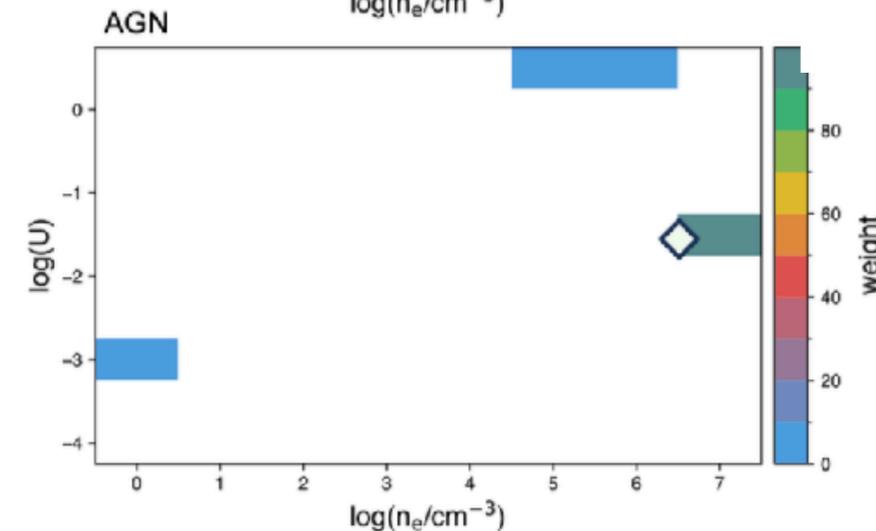
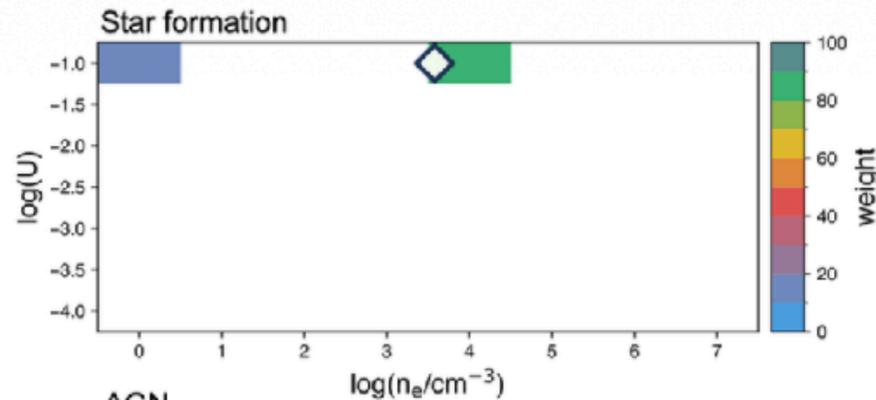
Castellano+, 2025



## GHZ2

Multi-zone and/or multi-component (AGN+gal) required.

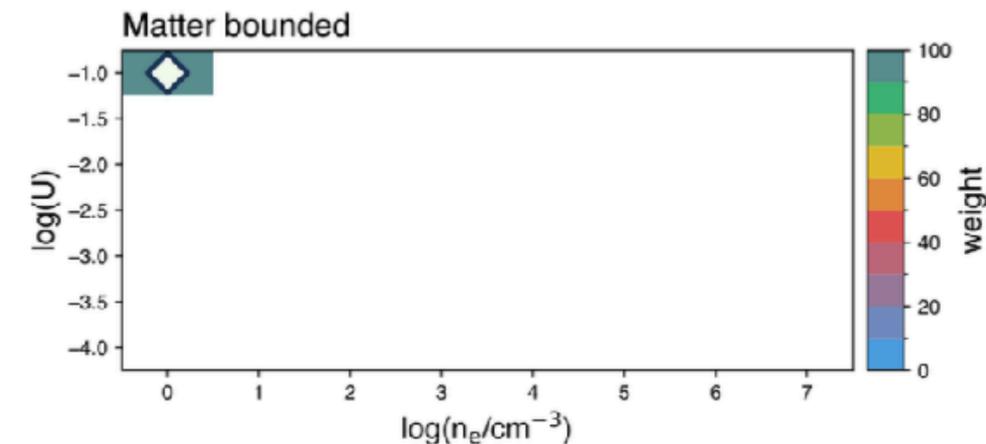
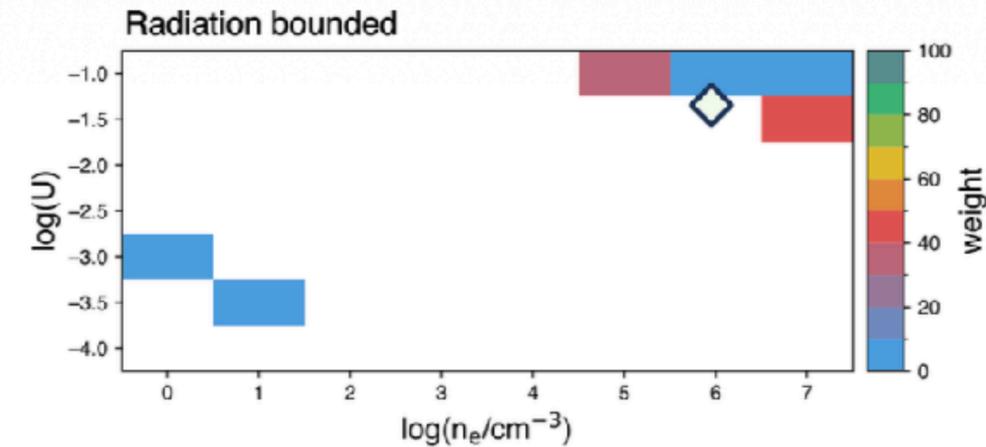
(see also ALMA/JWST combined analysis, e.g. Harikane+25)



## HOMERUN

Multi-zone fitting tool

Marconi+, 2024



## Conclusion#3

- ◆ **Are we seeing different “snapshots” of a common evolutionary path or are there intrinsically different tracks?**
- ◆ Can we explain the diversity within a single self-consistent theoretical model?

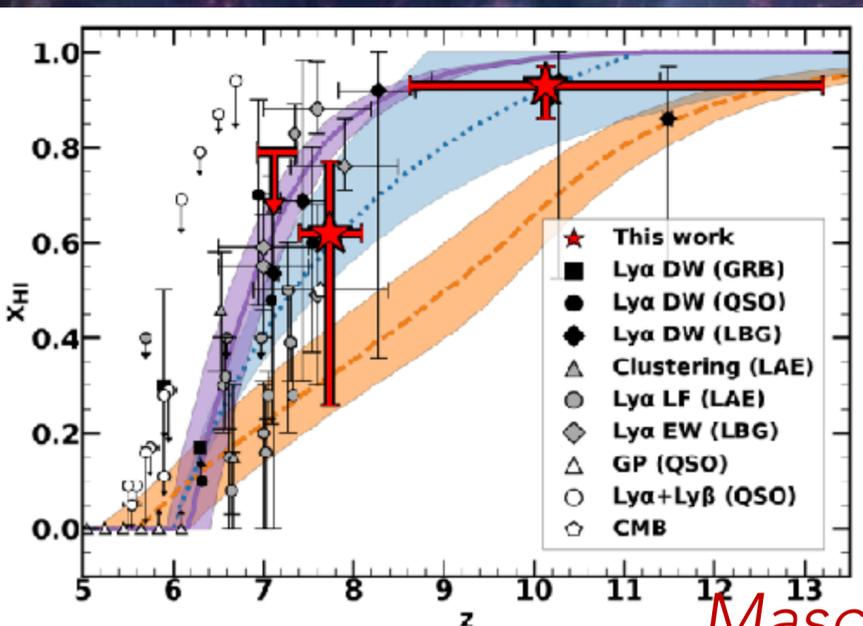
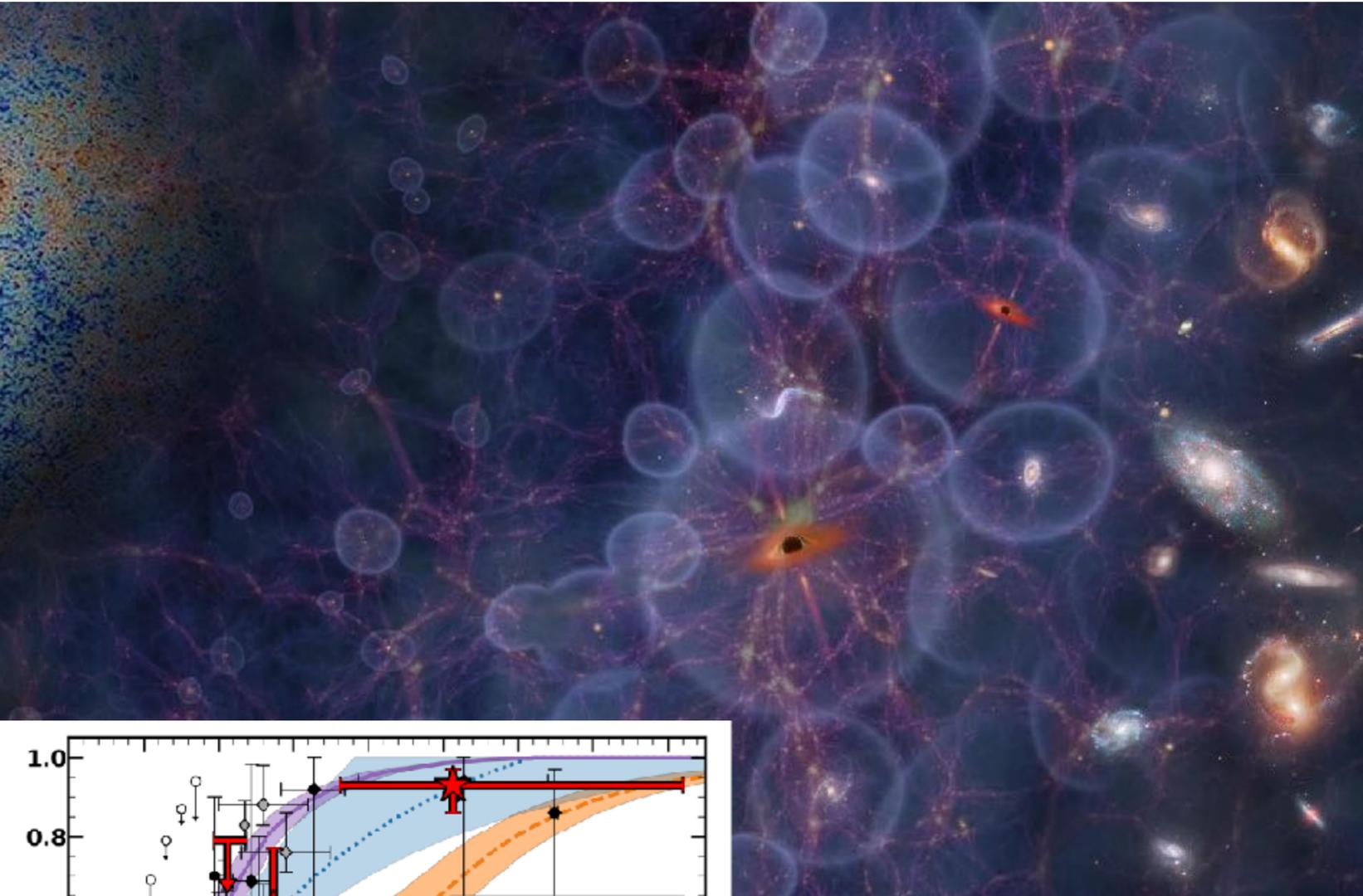
# WHAT ABOUT REIONIZATION?

The photon production rate:  
(N of galaxies) x (UV Emission) x (Escape Fraction)  
 $UVLD_{1500} \times \xi_{ion} \times f_{esc}$   
Must win over recombination in a clumpy (C) IGM

$UVLD \times \xi_{ion} \times f_{esc}$  and C are all difficult to measure, and often degenerate

JWST has found 1) *many* galaxies and a 2) *large ionising power* and 3) *escape fraction!*  
With AGNs on top!

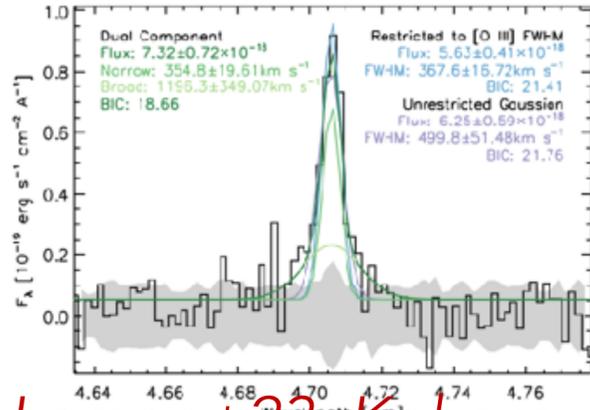
**Easy to explain reionisation... but still unclear which sources really dominated it.**



*Mascia+25, Liu+25, Llerena+25, Muñoz+ 24, Atek+24 etc*

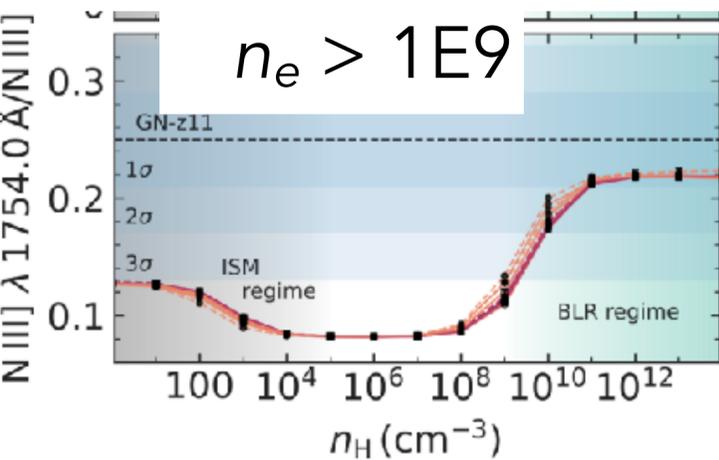
# JWST HAS IDENTIFIED A NUMBER OF FAINT AGN IN $z > 8$ GALAXIES

$z=8.67$



Larson+23, Kokorev+23

GN-z11  $z=10.6$

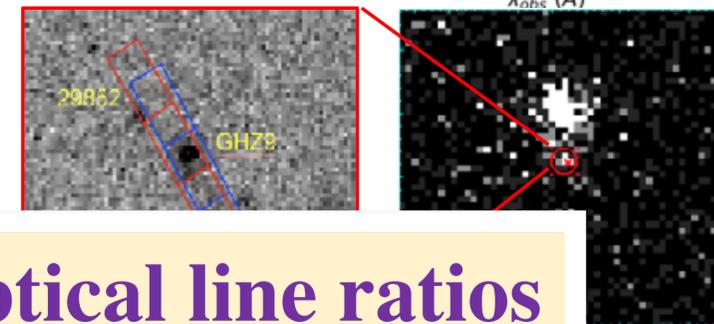
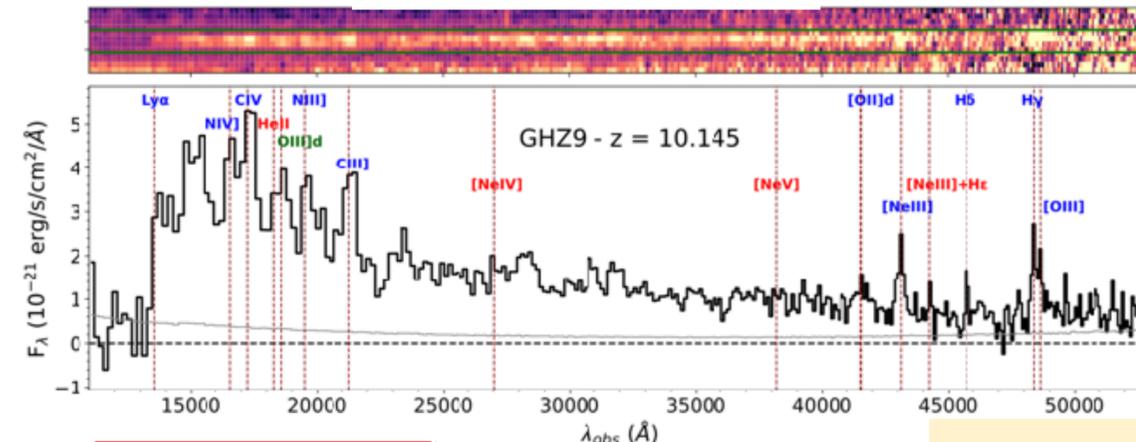


Bunker+23, Maiolino+23  
[Bouwens+10, Oesch+16, Xu+24  
(rotating disk!)]

The dual nature of GHZ9: coexisting AGN and star formation activity in a remote X-ray source at  $z=10.145$

LORENZO NAPOLITANO <sup>1,2</sup>, MARCO CASTELLANO <sup>1</sup>, LAURA PENTERICCI <sup>1</sup>, CRISTIAN VIGNALI <sup>3,4</sup>, ROBERTO GILLI <sup>4</sup>, ADRIANO FONTANA <sup>1</sup>

GHZ9  $z=10.125$



[NeIV] doublet  
ion. pot: 63.5eV

Rest-frame UV + optical line ratios  
compatible with *both* star-  
formation *and* AGN

Nitrogen-enhanced.

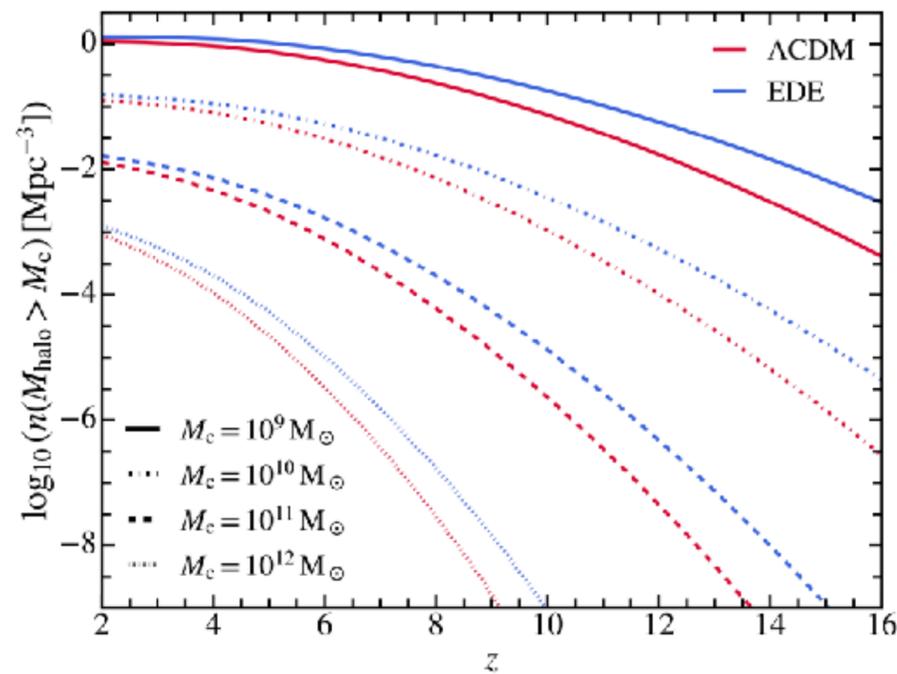
Associated to X-ray  
emission implying a

$$M_{\text{BH}} \sim 10^8 M_{\text{sun}}$$

# $\Lambda$ -CDM COSMOLOGY IS CHALLENGED

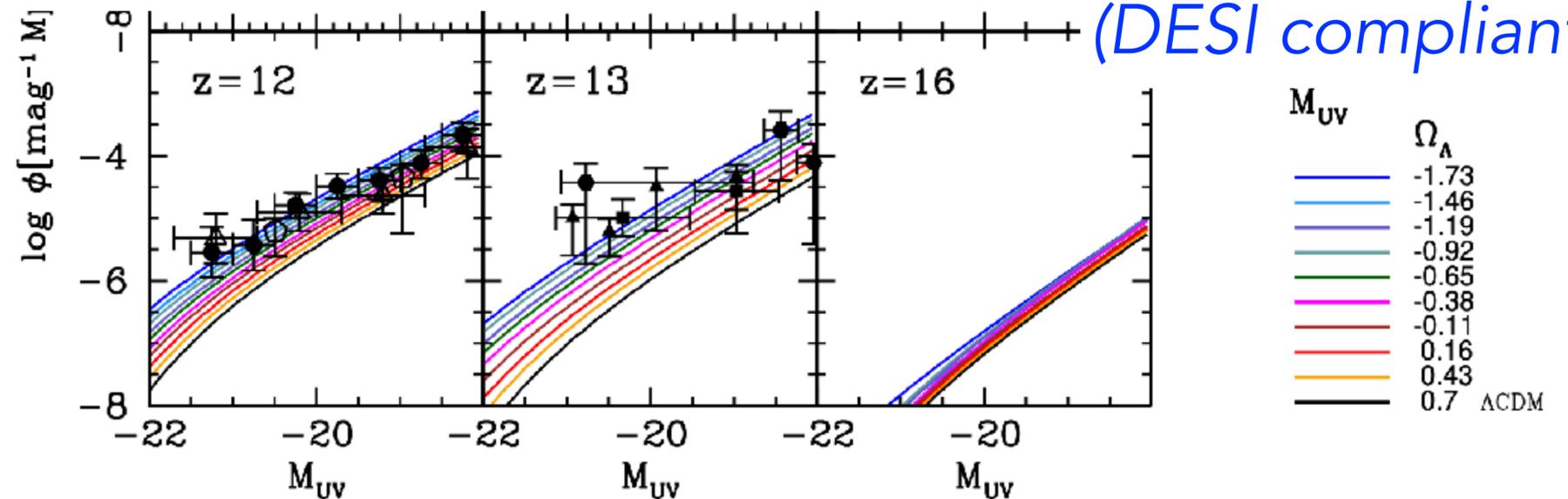
What would be the impact of non  $\Lambda$ -CDM cosmologies?  
They change the DM Halo distribution and help forming  $z \sim 12$  galaxies without invoking extreme baryonic process

**Early Dark Energy**  
Fast expansion  
before recombination



Shen+24

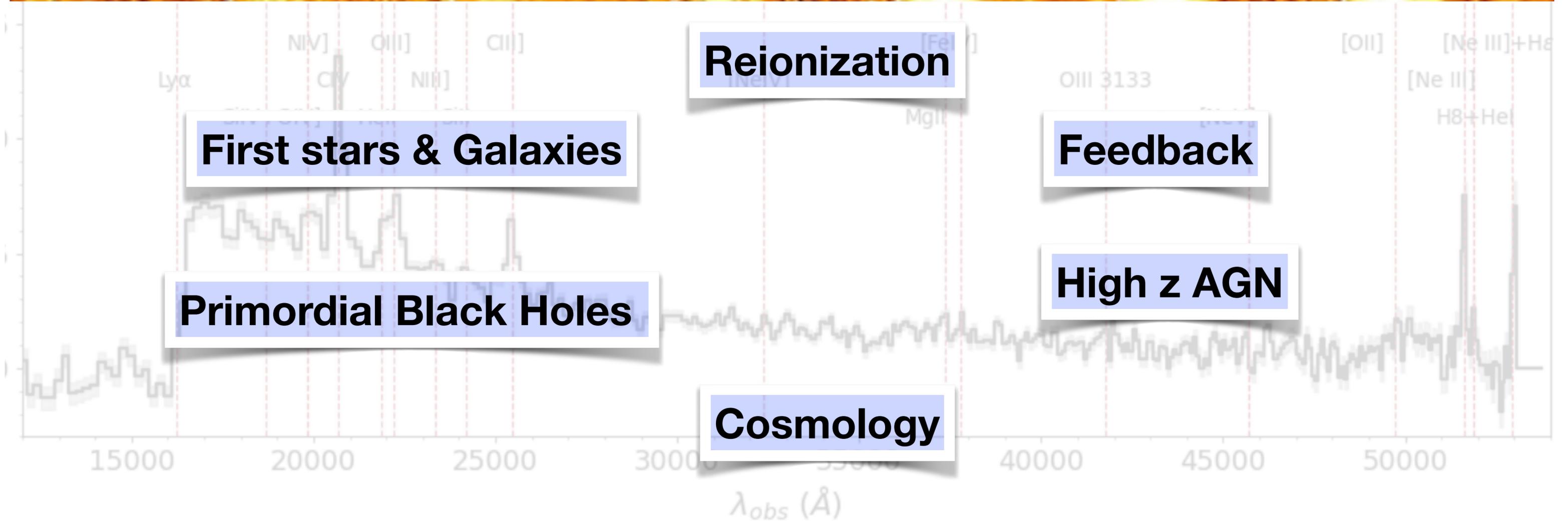
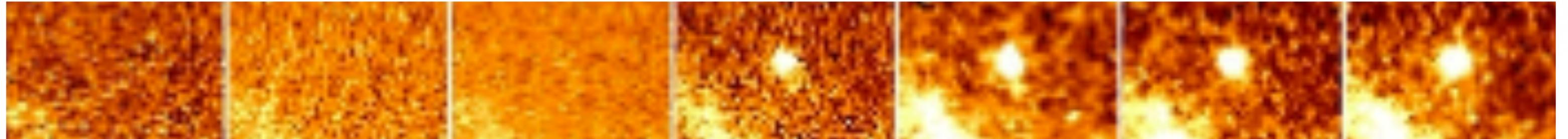
**"Phantom" models:**  
Negative  $\Omega_\Lambda$  +  
quintessence  
(DESI compliant)



Menci+24

# Looking forward...

We need a **synergic, multi-disciplinary** approach



## Looking forward...

- ◆ JWST will keep leading the revolution for a decade:
  - ◆ No similar facility even at the horizon
  - ◆ The pressure is extremely high (15:1)
  - ◆ Community-wide efforts will come sooner or later.

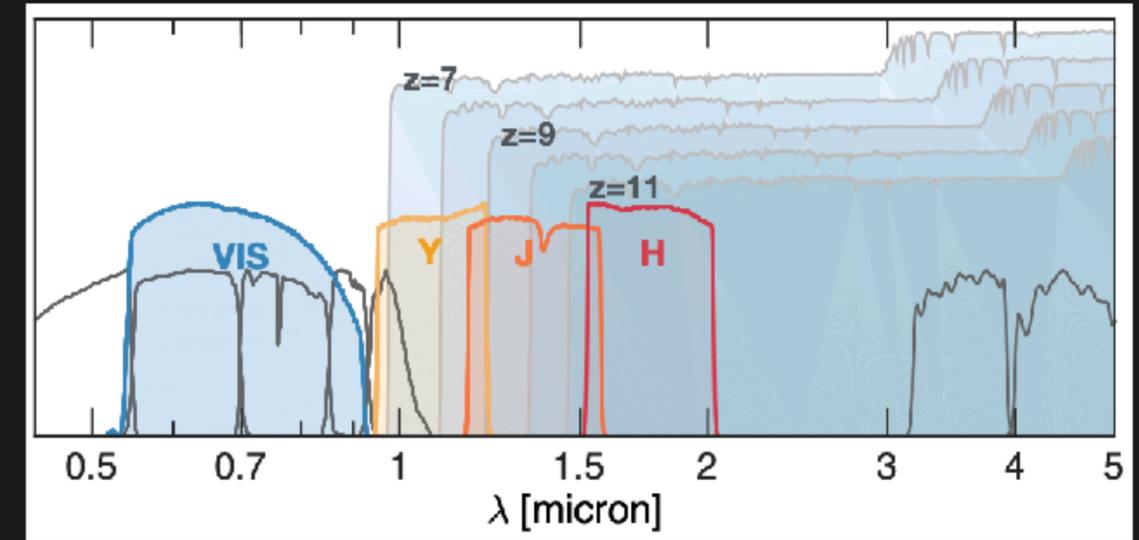
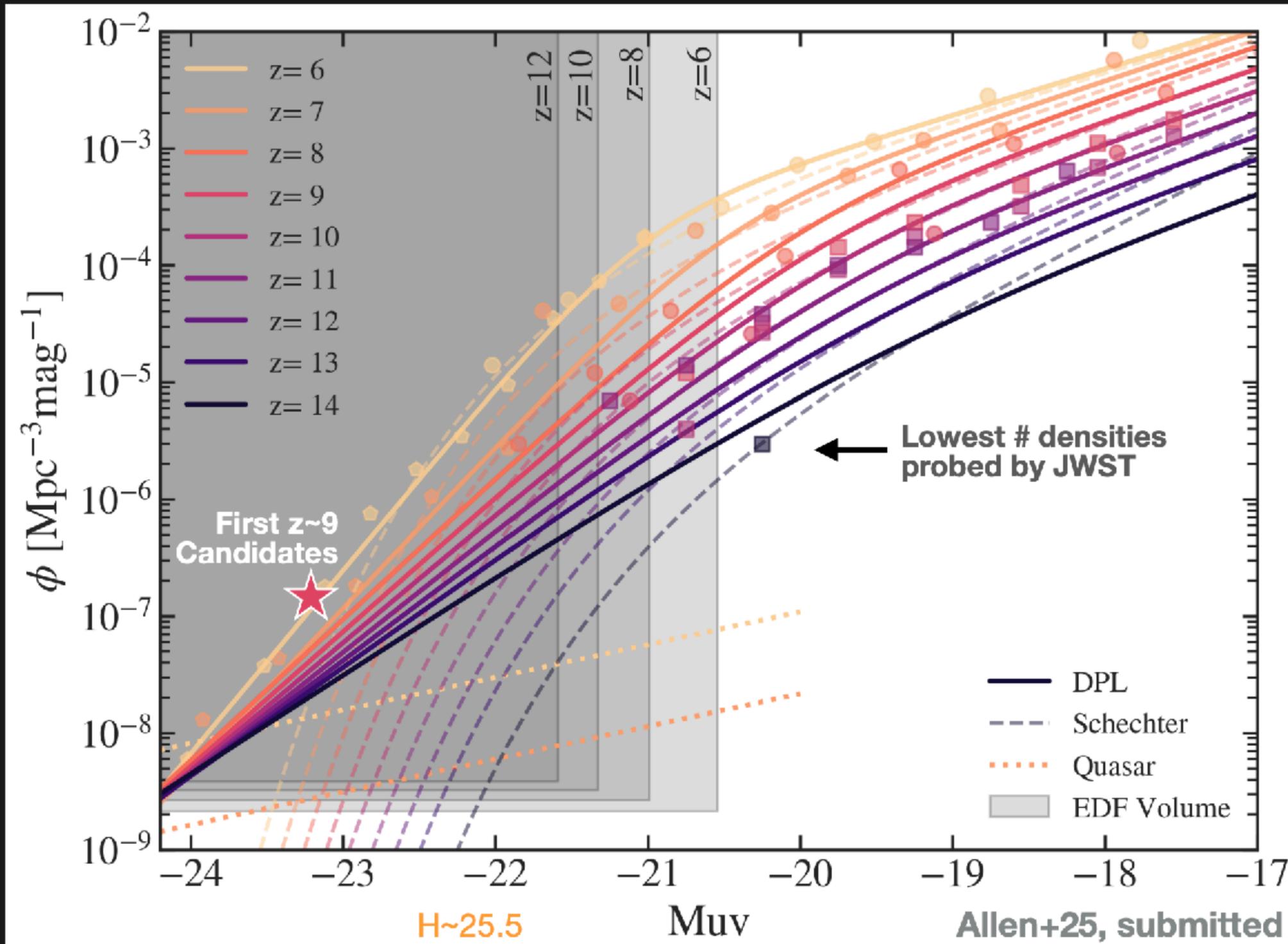
## Looking forward...

- ◆ JWST will keep leading the revolution for a decade:
  - ◆ No similar facility even at the horizon
  - ◆ The pressure is extremely high (15:1)
  - ◆ Community-wide efforts will come sooner or later.
- ◆ ALMA will complement JWST (looking ahead to ALMA40...)

## Looking forward...

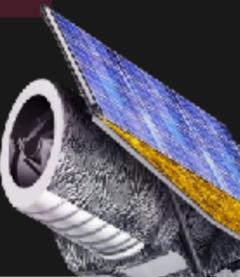
- ◆ JWST will keep leading the revolution for a decade:
  - ◆ No similar facility even at the horizon
  - ◆ The pressure is extremely high (15:1)
  - ◆ Community-wide efforts will come sooner or later.
- ◆ ALMA will complement JWST (looking ahead to ALMA40...)
- ◆ Euclid will explore the bright side of the galaxy population

# Large Numbers of Galaxies Expected with Euclid



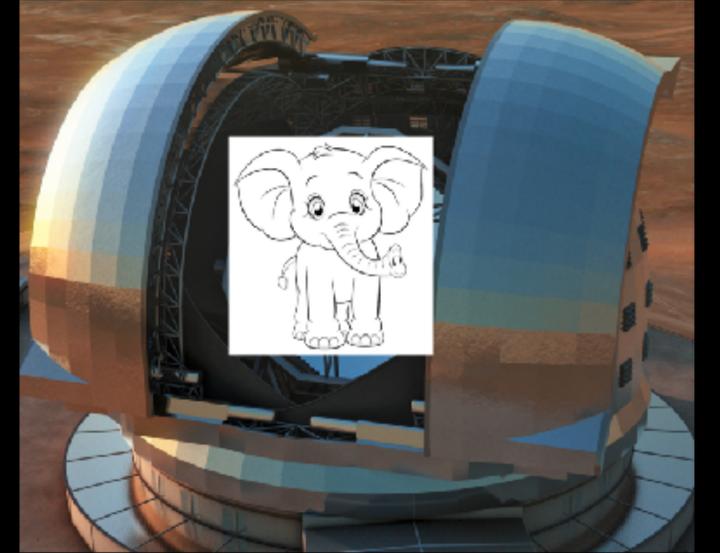
## Approximate Numbers in Euclid/Deep 53 deg<sup>2</sup>

	DPL	SCH
z=8-10	6000	8500
z=10-12	1000	700
z=12-13	130	10

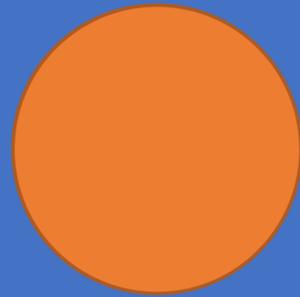


## Looking forward...

- ◆ JWST will keep leading the revolution for a decade:
  - ◆ No similar facility even at the horizon
  - ◆ The pressure is extremely high (15:1)
  - ◆ Community-wide efforts will come sooner or later.
- ◆ ALMA will complement JWST (looking ahead to ALMA40...)
- ◆ Euclid will explore the bright side of the galaxy population
- ◆ MOONS@VLT will add useful data (lya clustering at  $z \sim 7$ )
- ◆ SKA(1) will provide new hints on reionisation timescale and nature of sources (21-cm power spectrum)
- ◆ In the long term, GW experiments will provide new data on BH merging
- ◆ The BIG elephant in the room...



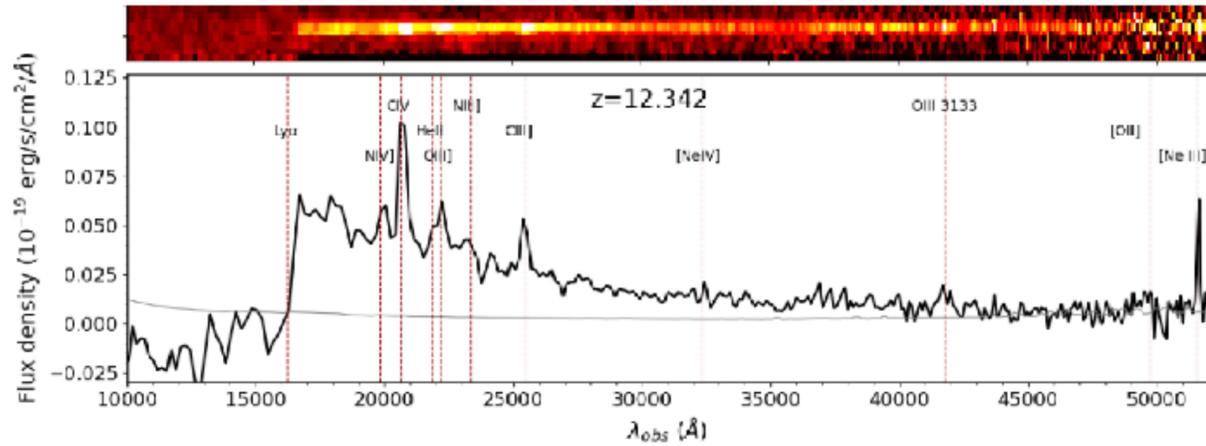
**James Webb**



**Extremely  
Large  
Telescope**

# GHZ12 @ ELT

How many galaxies host a BH? What is the BH mass?

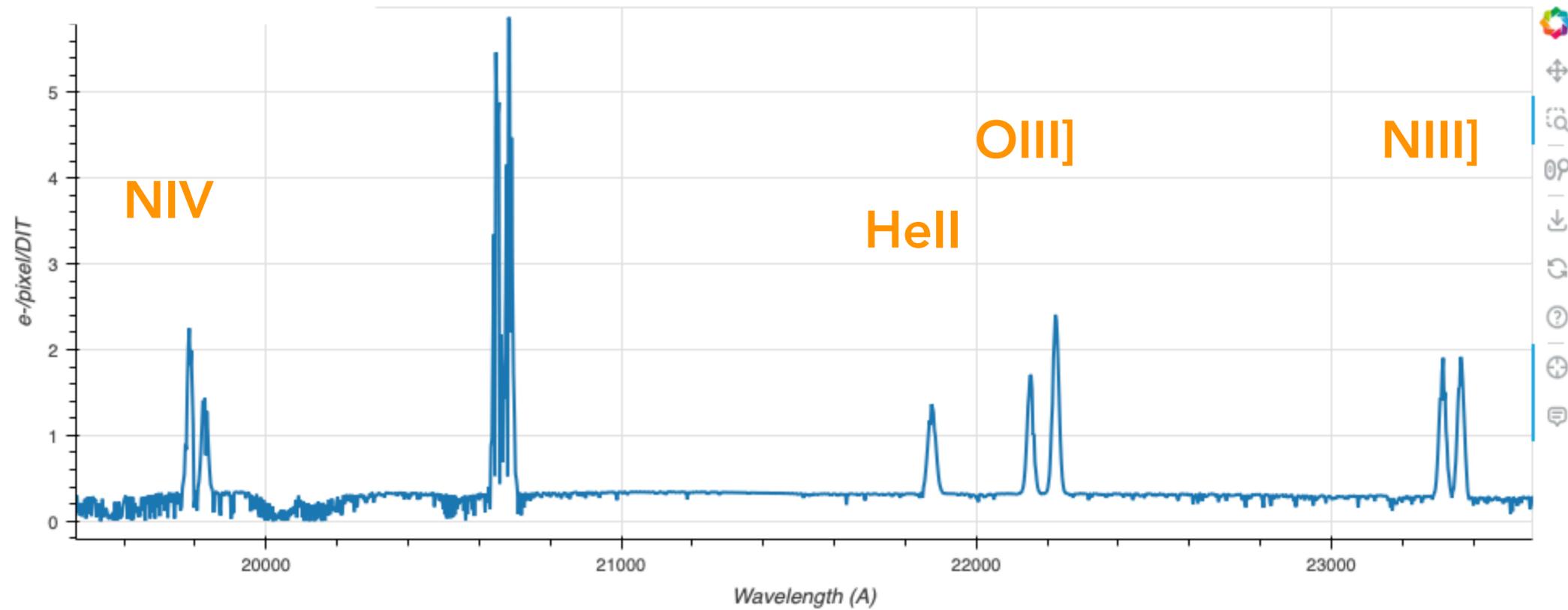


CIV

Wavelength (Å)

NIRSPEC

Castellano+2024.10



SHARP/ELT simulator

# THE QUESTIONS ON THE GROUND

---

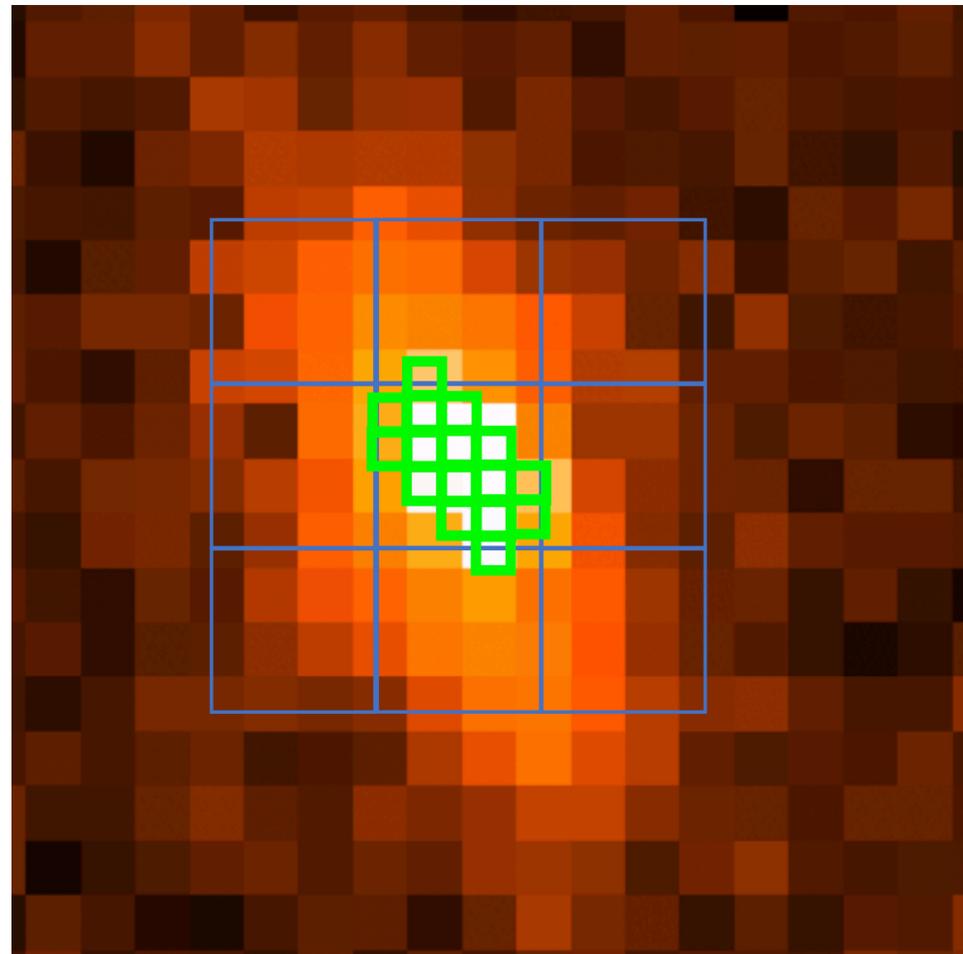
Internal Dynamics will be hardly measured with JWST → no 3D shape, Mass.

GHZ1  $z \sim 10$

GHZ2  $z \sim 12$

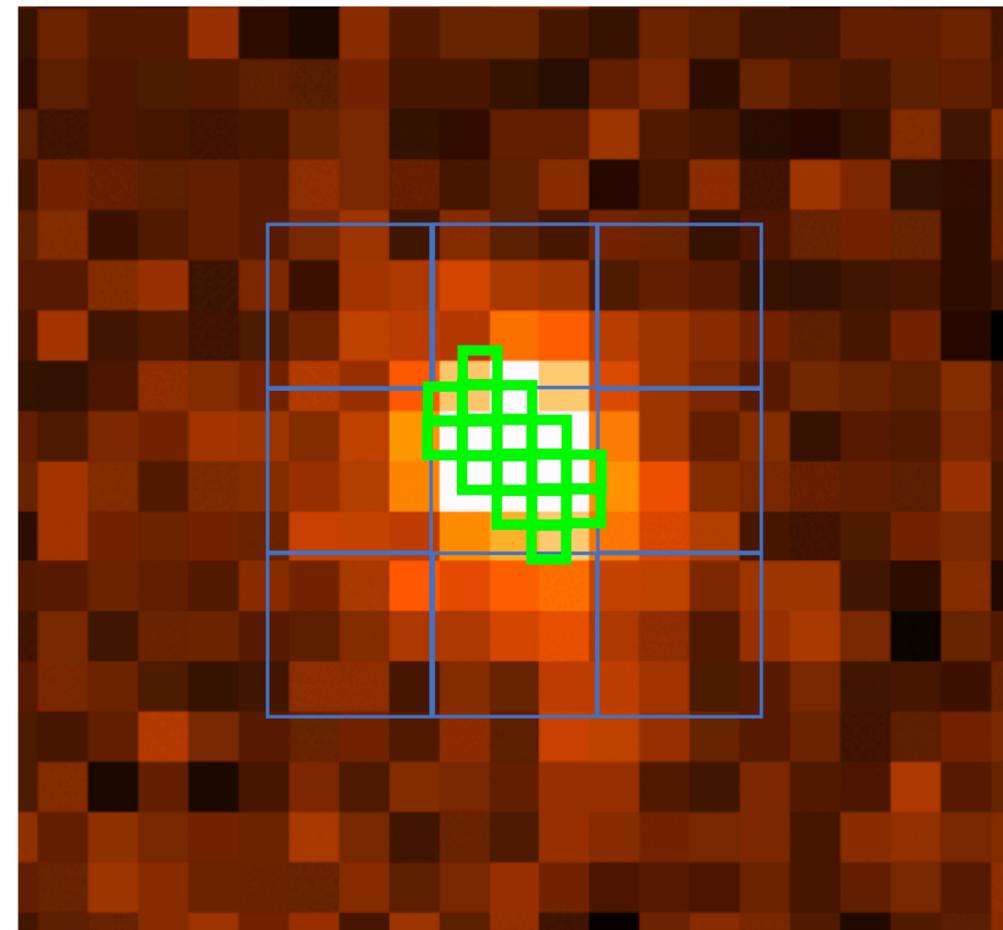
Two of the brightest galaxies ever detected  $z > 10$

  
JWST  
IFU



*Is it a rotating disk at  $z=10$ ???*

  
ELT  
HARMONI



*Composite AGN???*

## Looking forward...

- ◆ JWST will keep leading the revolution for a decade:
  - ◆ No similar facility even at the horizon
  - ◆ The pressure is extremely high (15:1)
  - ◆ Community-wide efforts will come sooner or later.
- ◆ ALMA will complement JWST (ALMA40 would be terrific!)
- ◆ Euclid will explore the bright side of the galaxy population
- ◆ MOONS@VLT will add useful data (Ly $\alpha$  clustering at  $z \sim 7$ )
- ◆ SKA(1) will provide new hints on reionisation timescale and nature of sources (21-cm power spectrum)
- ◆ In the long term, GW experiments will provide new data on BH merging
- ◆ The BIG elephant in the room...**ELT IS COMING** and will represent a ground-breaking opportunity

# Summary of (my personal) Open Issues

## Observations

- ◆ Measure the evolution of the UVLF with high statistical accuracy, as  $d\phi/dz$  is small.
- ◆ We need wider/deeper surveys to beat statistical and cosmic variance.
- ◆ Increase completeness by expanding the spec. validation to lower-quality candidates at all  $z$ .
- ◆ Cross-validate the “technicalities” in the LF computation.
- ◆ We need MIRI observations at  $z > 10$  to secure stellar masses and optical lines!!!!
- ◆ Extend our observations to low mass/luminosity galaxies as they correspond to the first stages of evolution.
- ◆ We need a combined effort to consolidate the accuracy and robustness of rest-frame measurements.
- ◆ Improve “reliability” in the measurements of rest frame properties.
- ◆ Confirm/dispute existing  $z > 15$  candidates
- ◆ Characterise interlopers
- ◆ Design an “end of the world” survey to explore  $z > 15$ .
- ◆ Prepare for ELT science: higher spatial and spectral resolution and later S/N (at  $\lambda < 2.4\mu\text{m}$ ).

## Interpretation

- ◆ The multi-faceted nature of high  $z$  galaxies adds complexity to the problem.
- ◆ How can we build theoretical models that cover a wide range of spatial scales and physical conditions?
- ◆ Elephant in the room (or under the carpet): dust!
- ◆ We need a combined effort to consolidate the accuracy and robustness of rest-frame measurements.
- ◆ Can we start to discard some theoretical option?
- ◆ We should expand the forward modelling approach to reduce obs/theo mismatches.
- ◆ Refine models in order to reduce the spread in the predictions at  $z > 15$