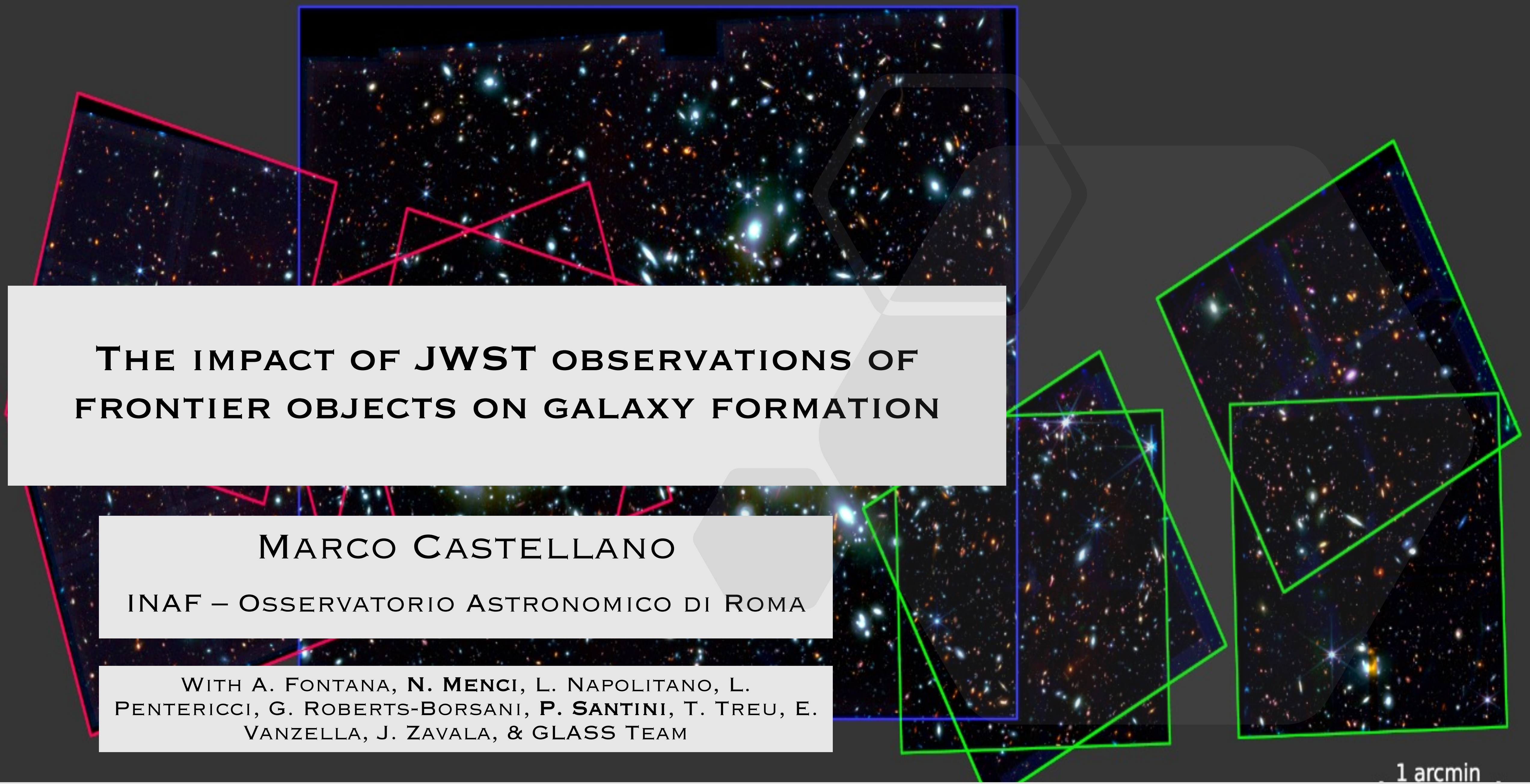


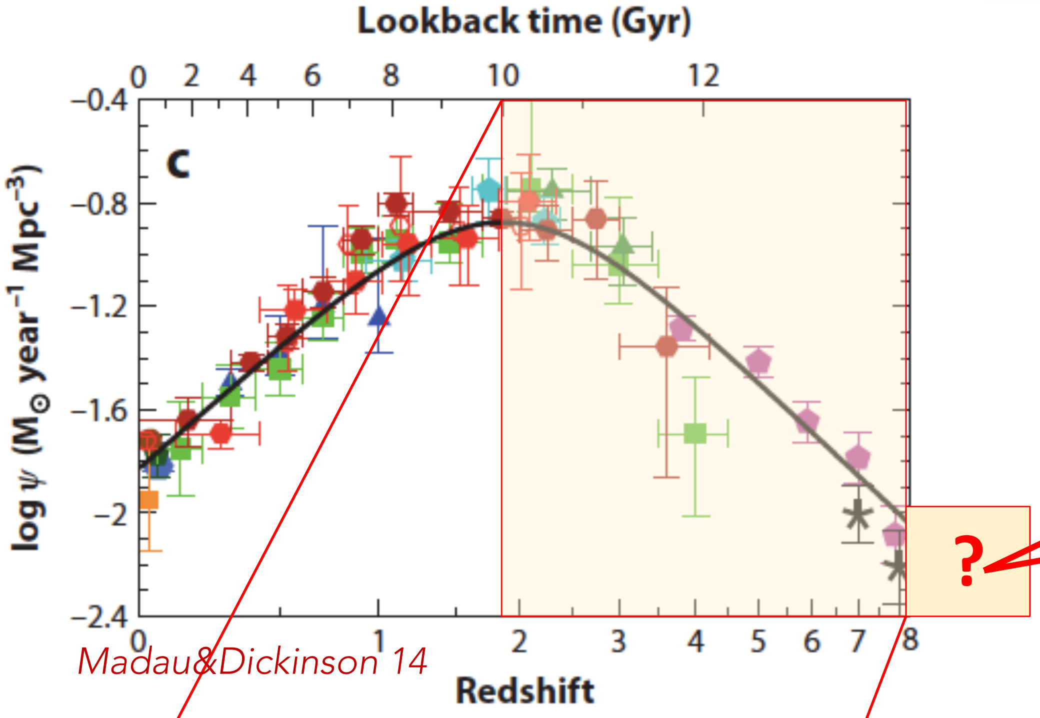
The impact of JWST observations of frontier objects on galaxy formation

Marco Castellano

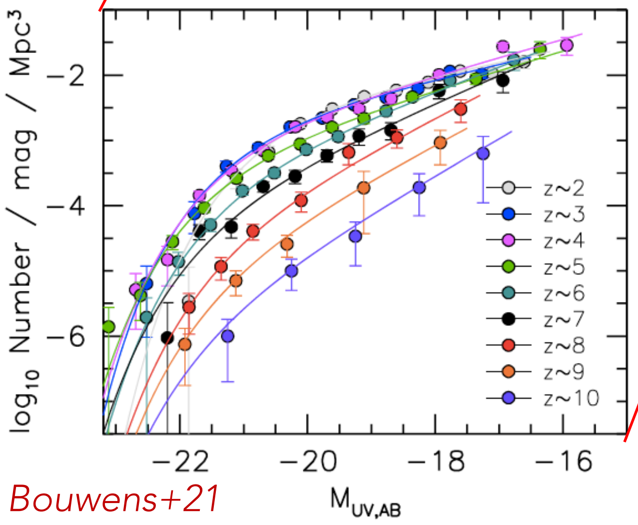
INAF – Osservatorio Astronomico di Roma

With A. Fontana, **N. Menci**, L. Napolitano, L. Pentericci, G. Roberts-Borsani, **P. Santini**, T. Treu, E. Vanzella, J. Zavala, & GLASS Team

The cosmic frontier: Re-ionization and cosmic dawn

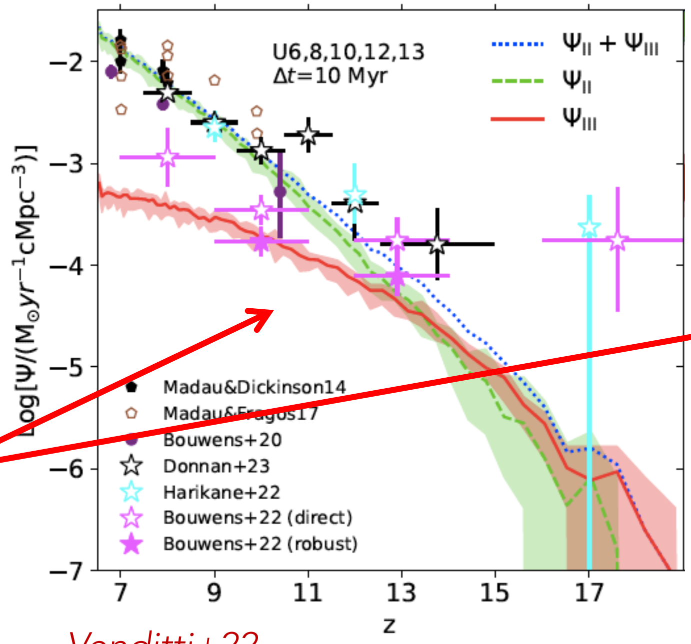


Madau&Dickinson 14



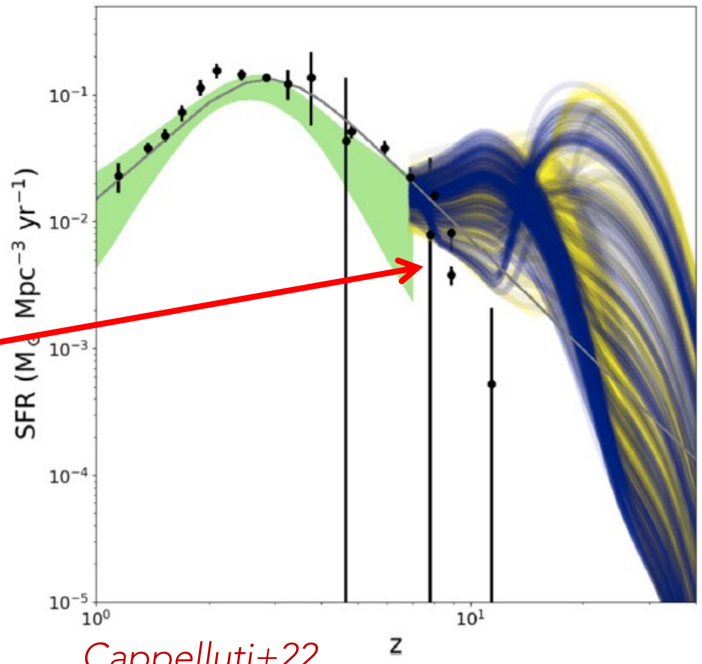
Bouwens+21

PopIII SFRD?



Venditti+22
Luca Graziani's talk

PBH-ΛCDM SFRD?



Cappelluti+22
Nico Cappelluti's talk

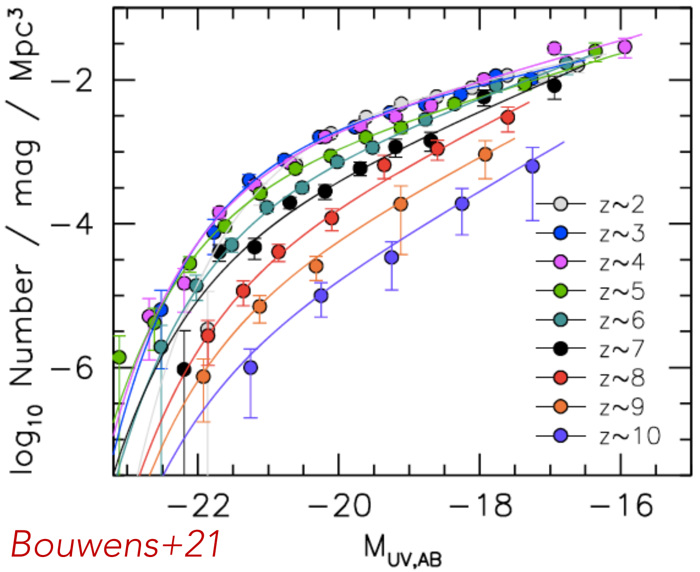
We (think we) know well the evolution of the SFRD after reionization

JWST has opened the exploration of the SFRD at z>10.

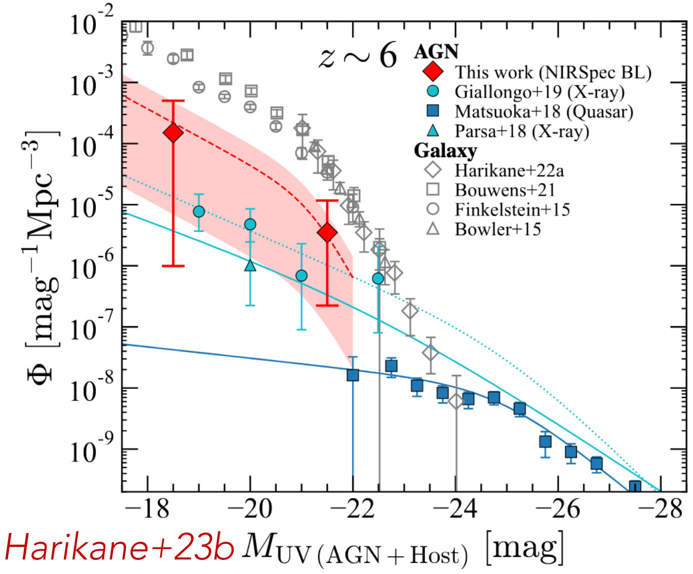
Fundamental for reionization, BH seeds, first stars, chemical evolution, etc

The cosmic frontier: Re-ionization and cosmic dawn

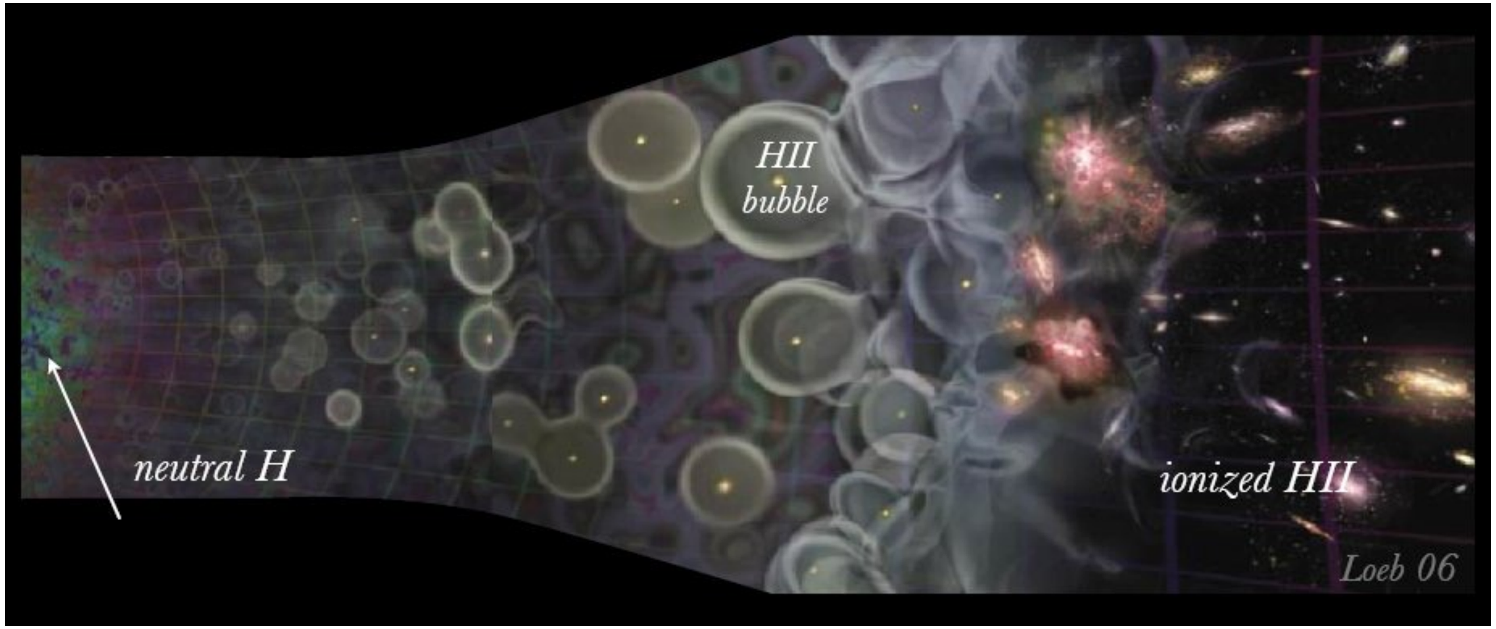
First ingredient: luminosity density



Bouwens+21



Harikane+23b



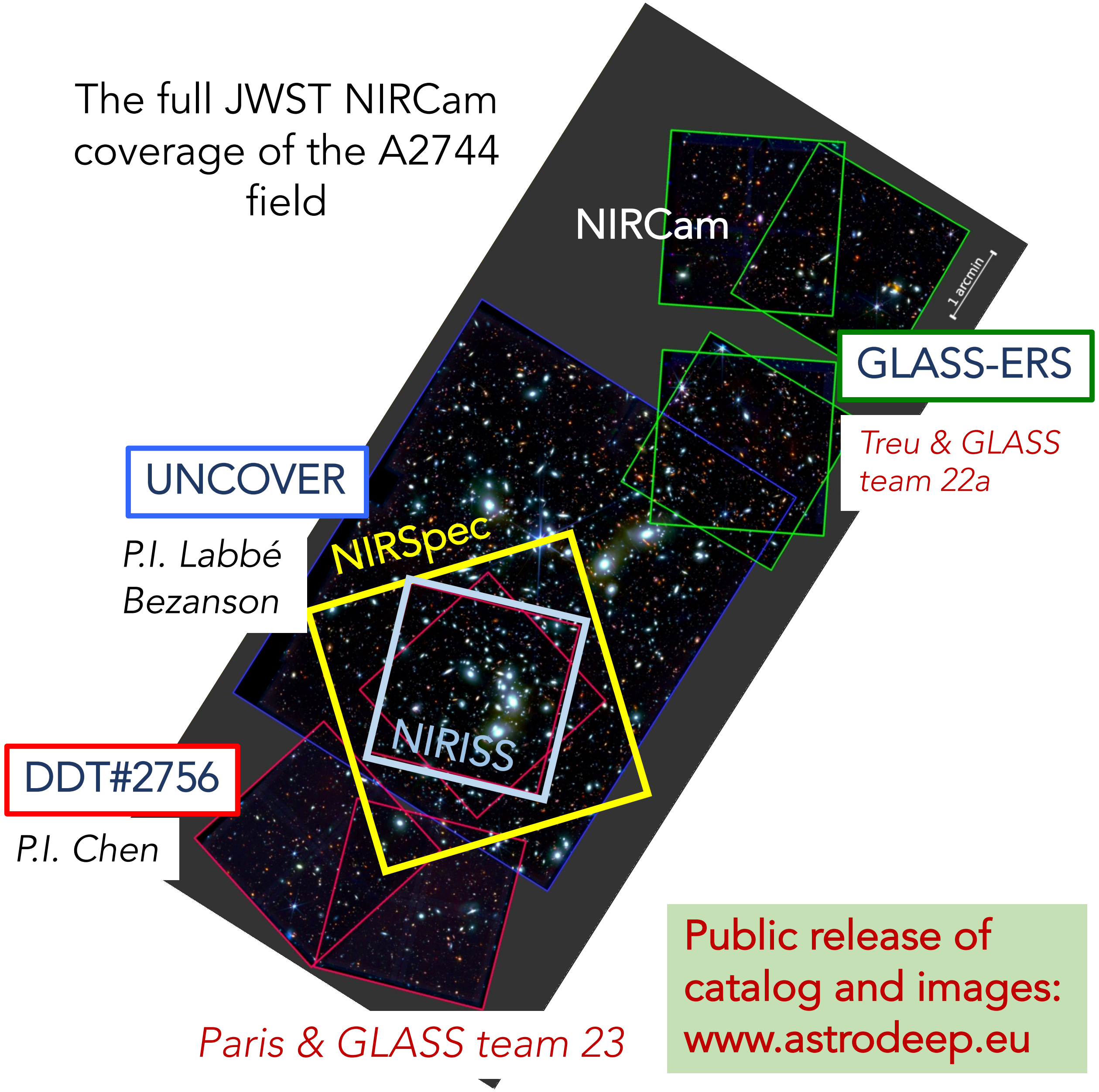
$$\dot{N} = \rho_{UV}\,\xi^*_{ion}\,f_{esc}$$

Which sources are driving reionization? Which are the timeline and topology of reionization?

First building block: measure the LF of the high redshift populations

JWST SURVEYS ON THE A2744 FIELD

The full JWST NIRCam coverage of the A2744 field



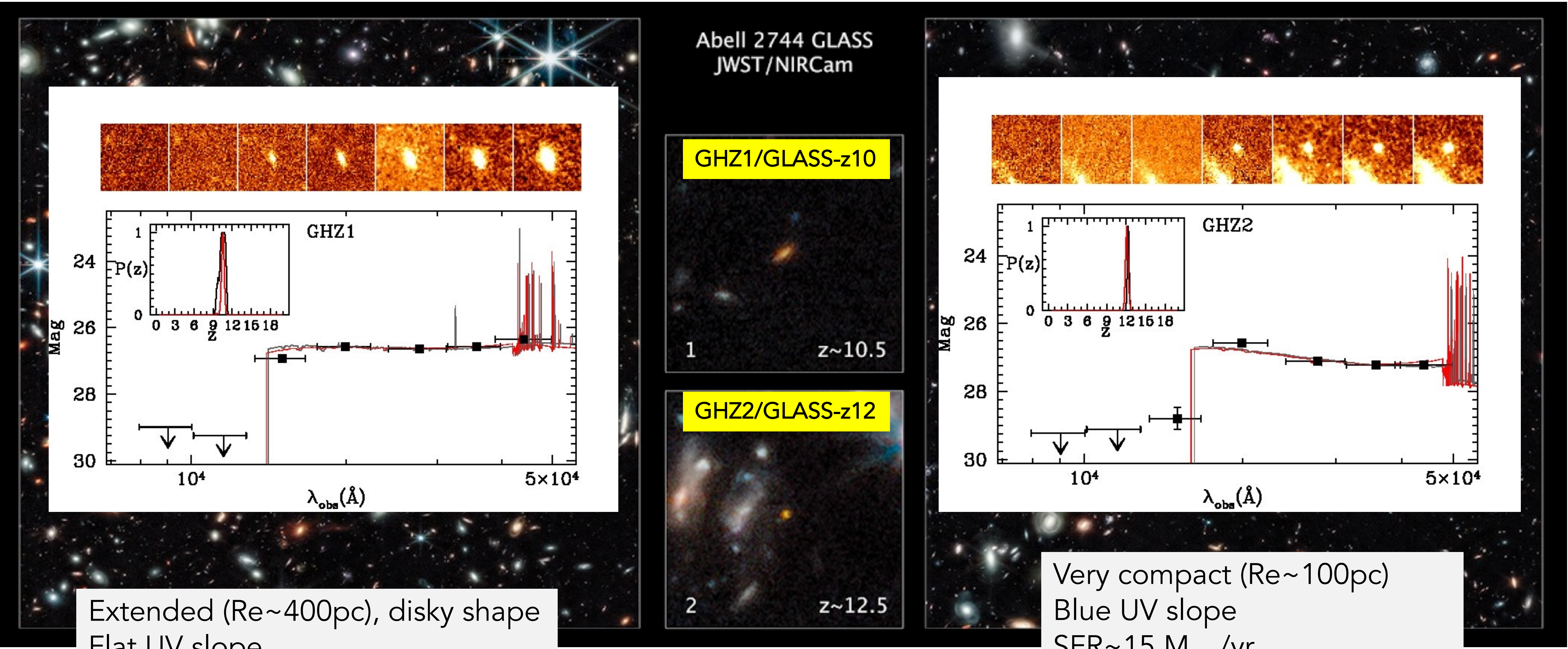
Public release of catalog and images: www.astrodeep.eu

The A2744 field has become one of the most revealing fields for high-redshift science

- Deep multi-band imaging from HST (Frontier Fields, BUFFALO) and JWST (UNCOVER, GLASS-ERS, DDT#2756).
- Extensive spectroscopic coverage with MUSE and JWST.
- Ancillary data: ALMA, Chandra.
- Accurate lensing models (Bergamini+23, Furtak+23).
- Several JWST programs in Cycle 2 and 3

Discovery and confirmation of very high-redshift galaxies (e.g., Roberts-Borsani+23, Boyett+23, Wang+23) and AGN (e.g., Labbe+23, Greene+23).

HIGH-REDSHIFT GALAXIES IN GLASS-JWST

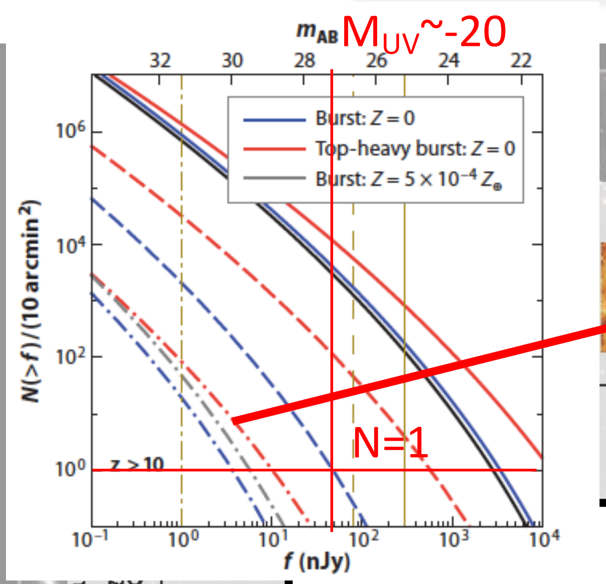


Extended (Re~400pc), disky shape
Flat UV slope
SFR~10 M_{sun}/yr

Very compact (Re~100pc)
Blue UV slope
SFR~15 M_{sun}/yr
High sSFR > 150 Gyr^{1}
High Σ_{SFR} ~ 100 Msun/yr/kpc^2

MC & GLASS team 22

High-redshift galaxies in GLASS-JWST



Predictions in Bromm & Yoshida ARA&A 2011

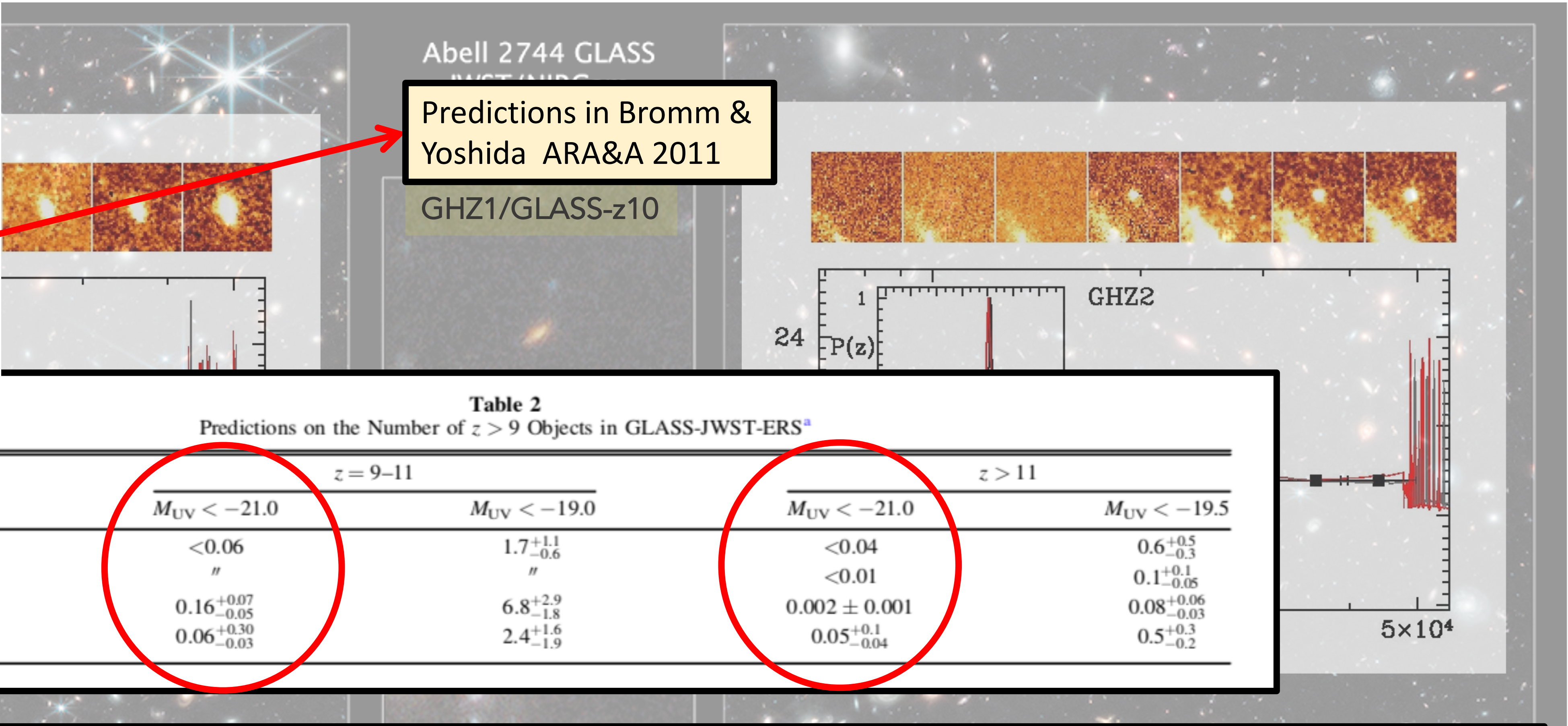


Table 2
Predictions on the Number of $z > 9$ Objects in GLASS-JWST-ERS[a]

UV LF	$z = 9$–11		$z > 11$	
	$M_{UV} < -21.0$	$M_{UV} < -19.0$	$M_{UV} < -21.0$	$M_{UV} < -19.5$
Oesch+18[b]	<0.06	$1.7^{+1.1}_{-0.6}$	<0.04	$0.6^{+0.5}_{-0.3}$
LF(z) Bouwens+21[c]	"	"	<0.01	$0.1^{+0.1}_{-0.05}$
Mason+15[d]	$0.16^{+0.07}_{-0.05}$	$6.8^{+2.9}_{-1.8}$	0.002 ± 0.001	$0.08^{+0.06}_{-0.03}$
Bowler+20[e]	$0.06^{+0.30}_{-0.03}$	$2.4^{+1.6}_{-1.9}$	$0.05^{+0.1}_{-0.04}$	$0.5^{+0.3}_{-0.2}$

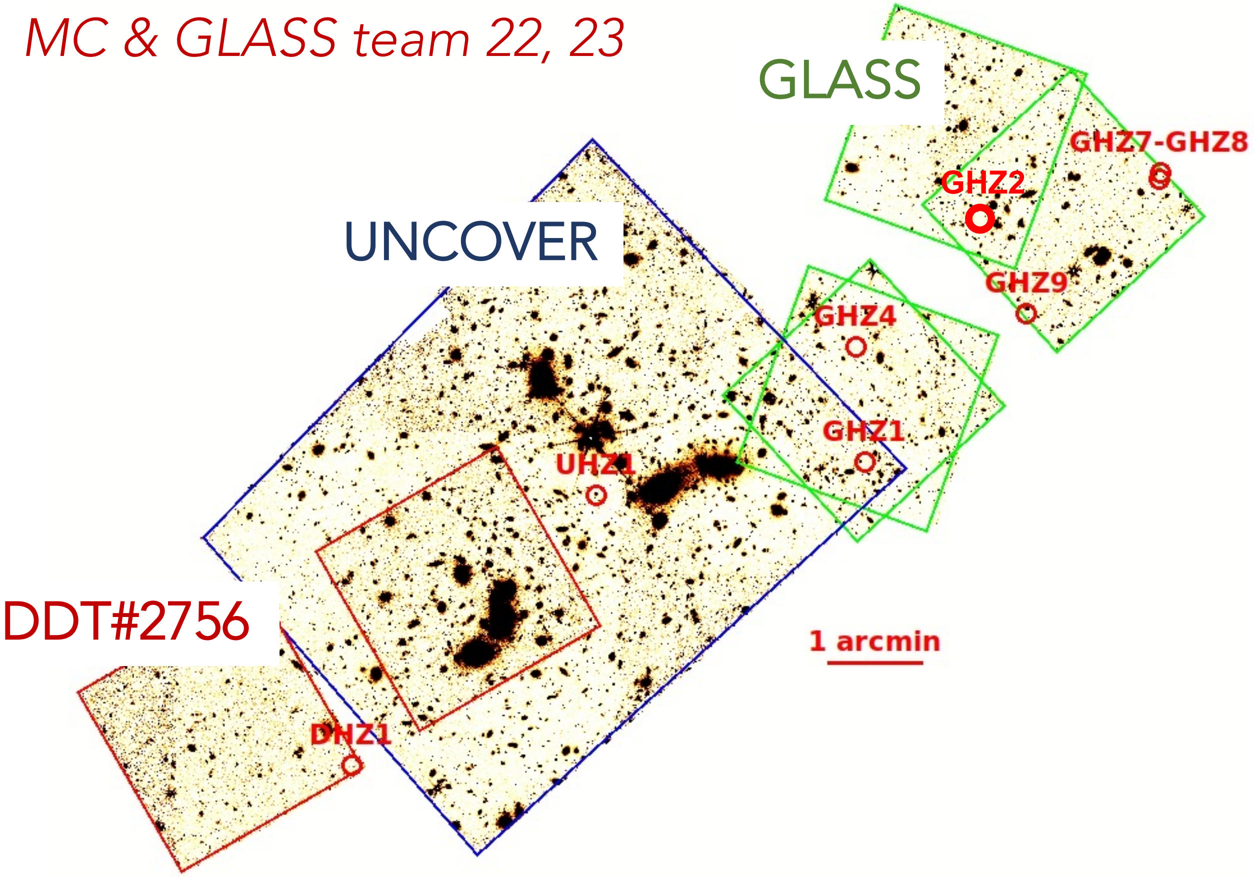
Low probability of finding these two objects in GLASS according to predicted evolution of the UV LF.

A high number-density compared to previous estimates and theoretical models.

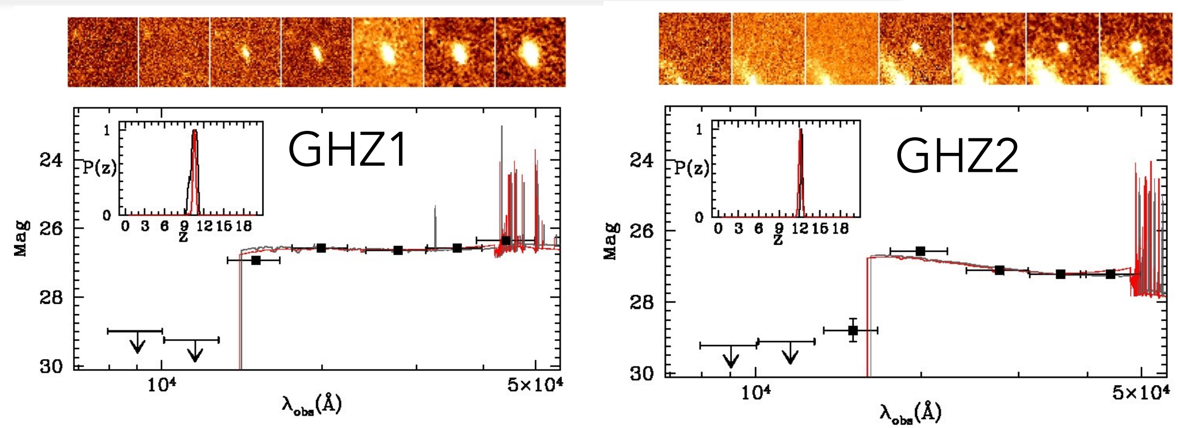
Consistent results from other surveys: CEERS (Finkelstein+22a,b), MDS (Perez-Gonzalez+23)

Even more High-redshift galaxies behind A2744

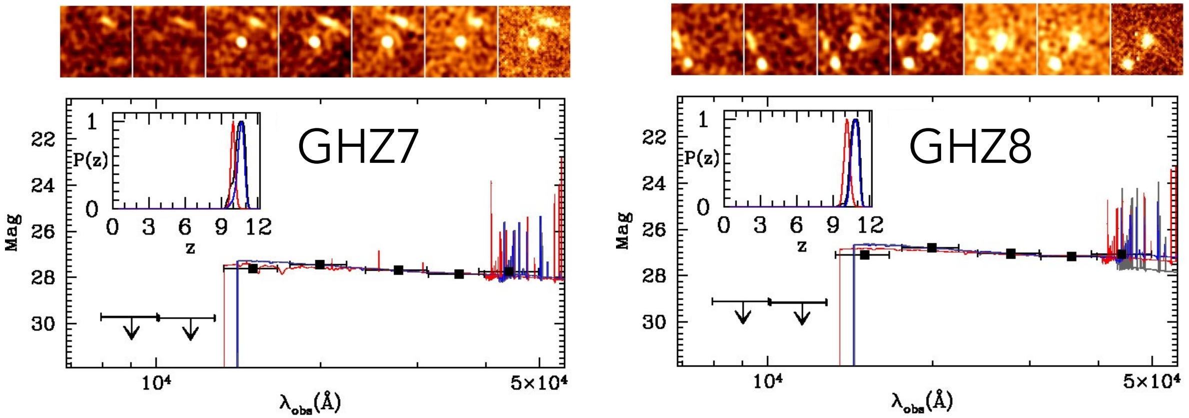
MC & GLASS team 22, 23



Robust candidates at z>9 analysed in several works, with a high density localized in the GLASS-ERS region. MC+22,+23, McLeod+23, Atek+23.



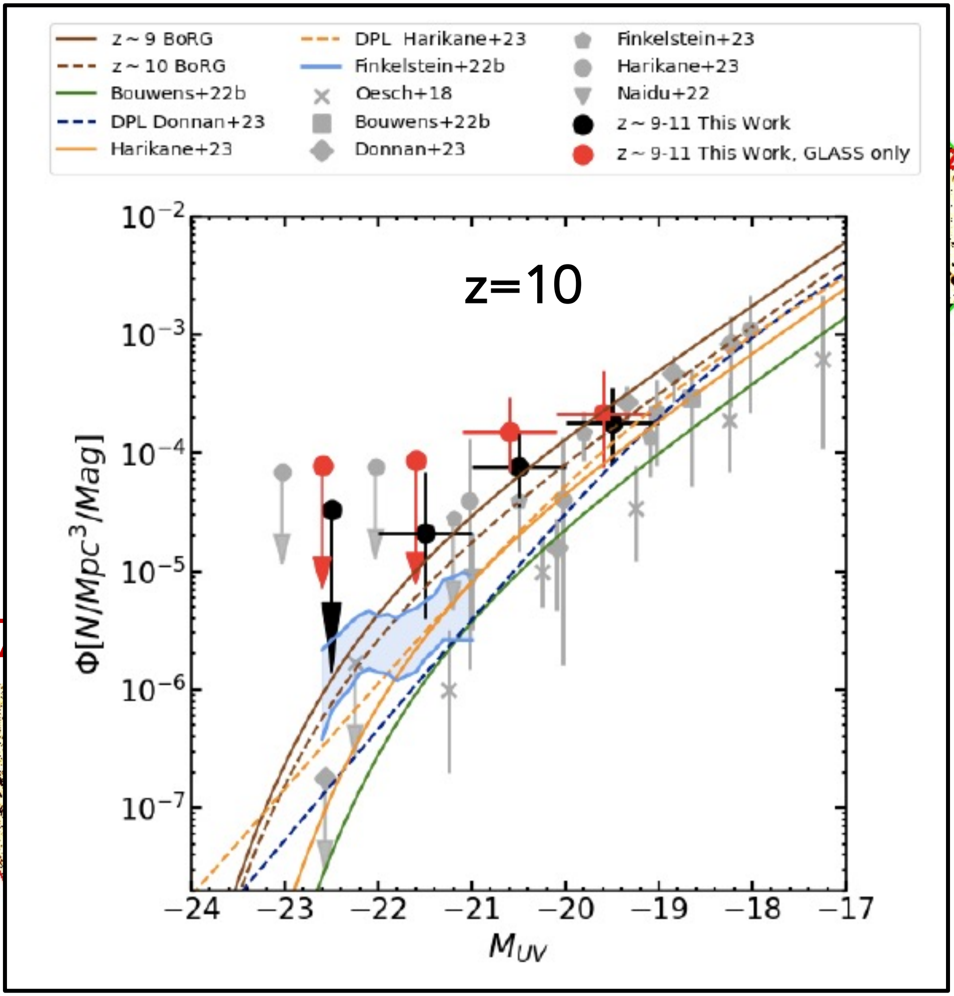
The first "unexpected" bright galaxies in JWST surveys: GHZ1 (z~10) and GHZ2 (z~12) (MC+22, Naidu+22)



A close pair of bright z~10 LBGs suggesting an overdensity in GLASS-ERS (MC+23).

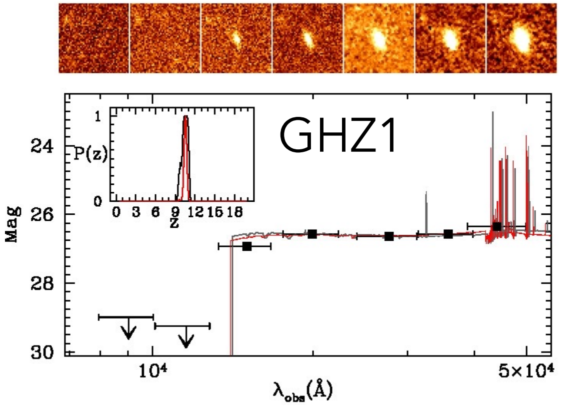
An excess of z~10 galaxies in the A2744 region

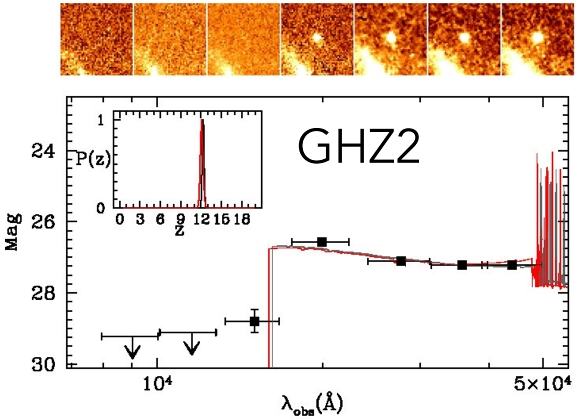
MC &



DDT#2

The UV LF at z~10 in the region even higher than other JWST estimates





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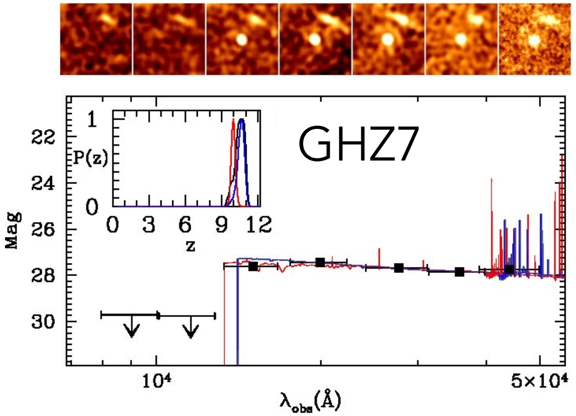
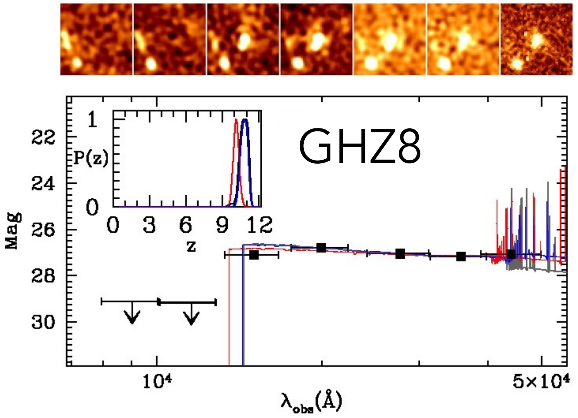
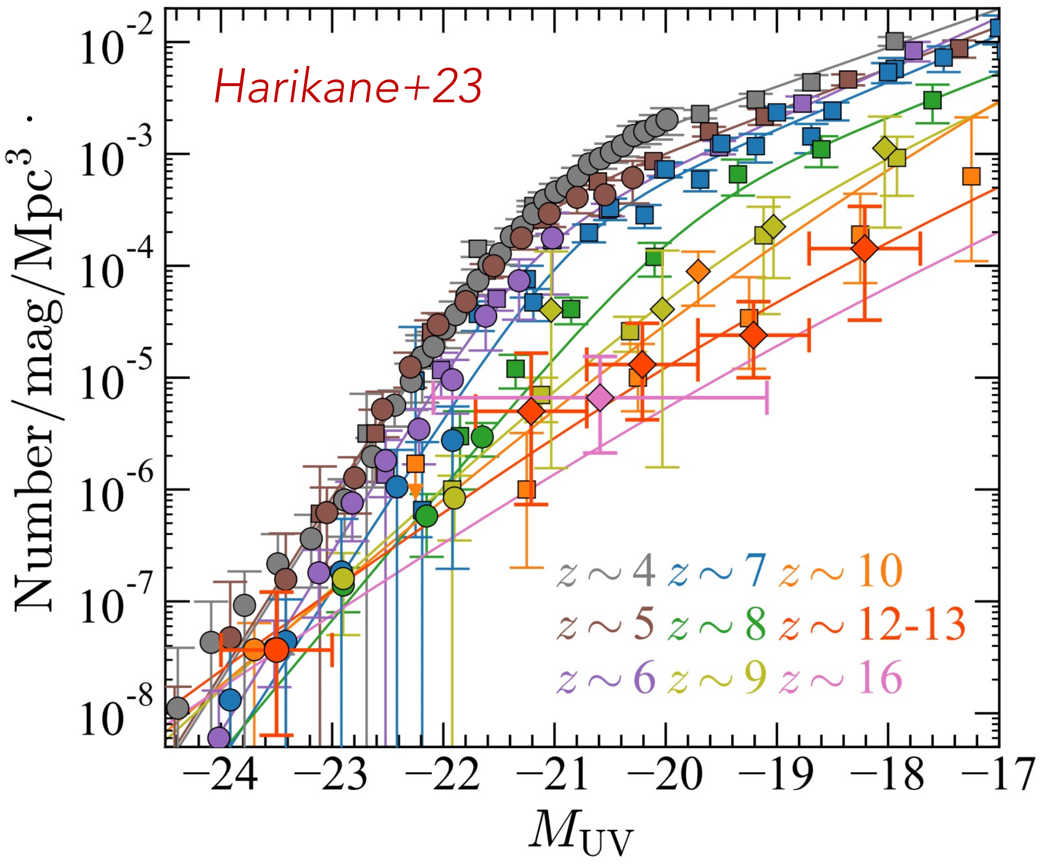
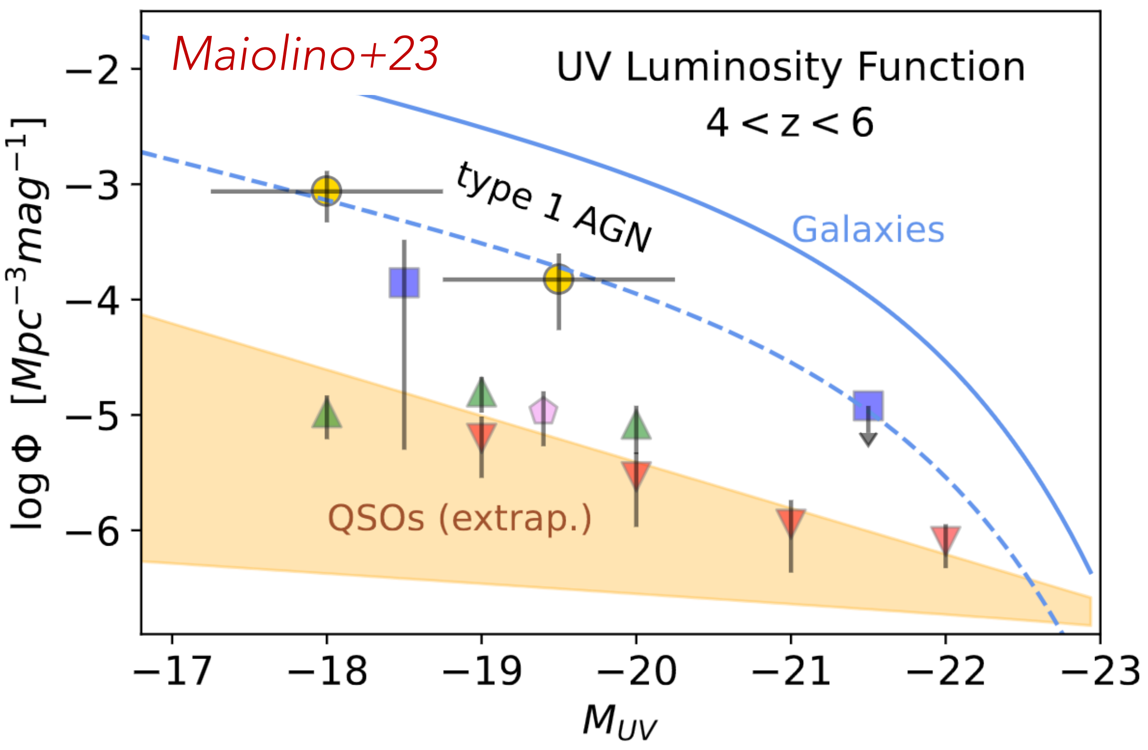




A close pair of bright z~10 LBGs suggesting an overdensity in GLASS-ERS (MC+23).

Consensus on the excess of bright galaxies (and AGN)





A high abundance of bright galaxies at z>9

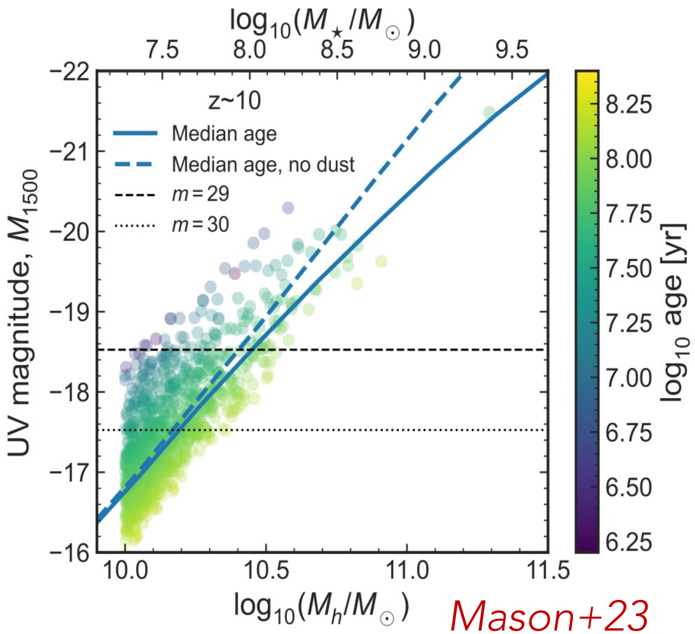
MC+22,+23, Finkelstein+23,+24; Donnan+23, McLeod+24, Harikane+23,+24; Perez-Gonzalez+23 and many others

A large number of AGN at high-redshift

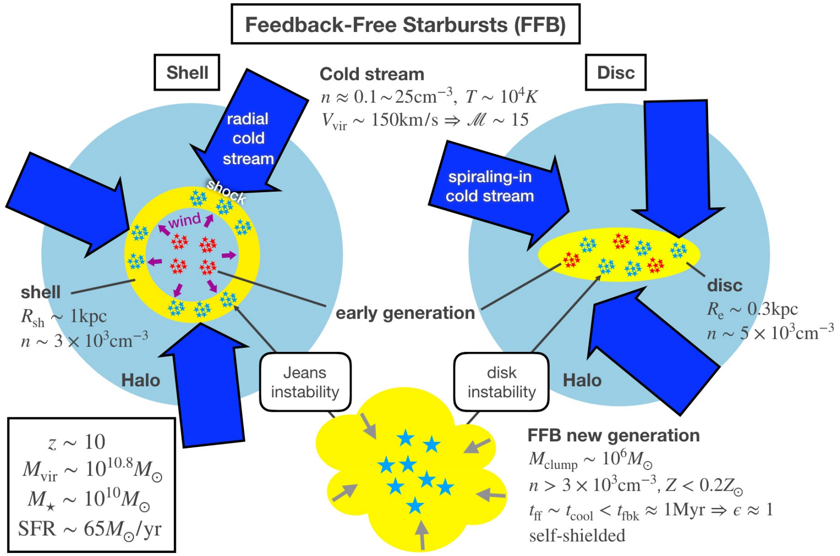
Barro+23, Matthee+23, Kocevski+23, Labbe+23, Furtak+23, Larson+23, Greene+23, Bogdan+23 and many others

Excess of bright galaxies? Excess of possible interpretations

- Decreasing dust attenuation, making galaxies brighter, almost compensates for the increasing shortage of their host halos (Ferrara+22). Dust could have been efficiently ejected during the very first phases of galaxy build-up (Ziparo+23, Fiore+23).
- SFR stochasticity: only the youngest (<10Myr) and most highly star-forming galaxies are detected so far, scattered up to 1.5 mag above the M_{UV}-M_h relation (Mason+23, Shen+23).
- Maximally efficient SF and ~10 Myr ages (max UV emission) (Mason+23).
- Star-formation efficiency at z~12-16 higher than at z<10 due to no suppression of the star formation at the pre-reionization epoch (Harikane+23, Qin+23).
- High star-formation efficiency and lack of feedback due to fast accretion (Dekel+23) and/or 'early overcooling' (Renzini 23).
- AGN or PopIII activity boosting UV emission, and/or presence of top-heavy IMFs (Kannan+22, Harikane+23, Haslbauer+22, Finkelstein+23, Yung+23, Trinca+24)
- Modified LCDM power spectrum with enhanced power at ~1Mpc scales (Padmanabhan & Loeb 23), alternative cosmologies (Melia 23), exotic objects (Ilie+23, Iocco&Visinelli 24).

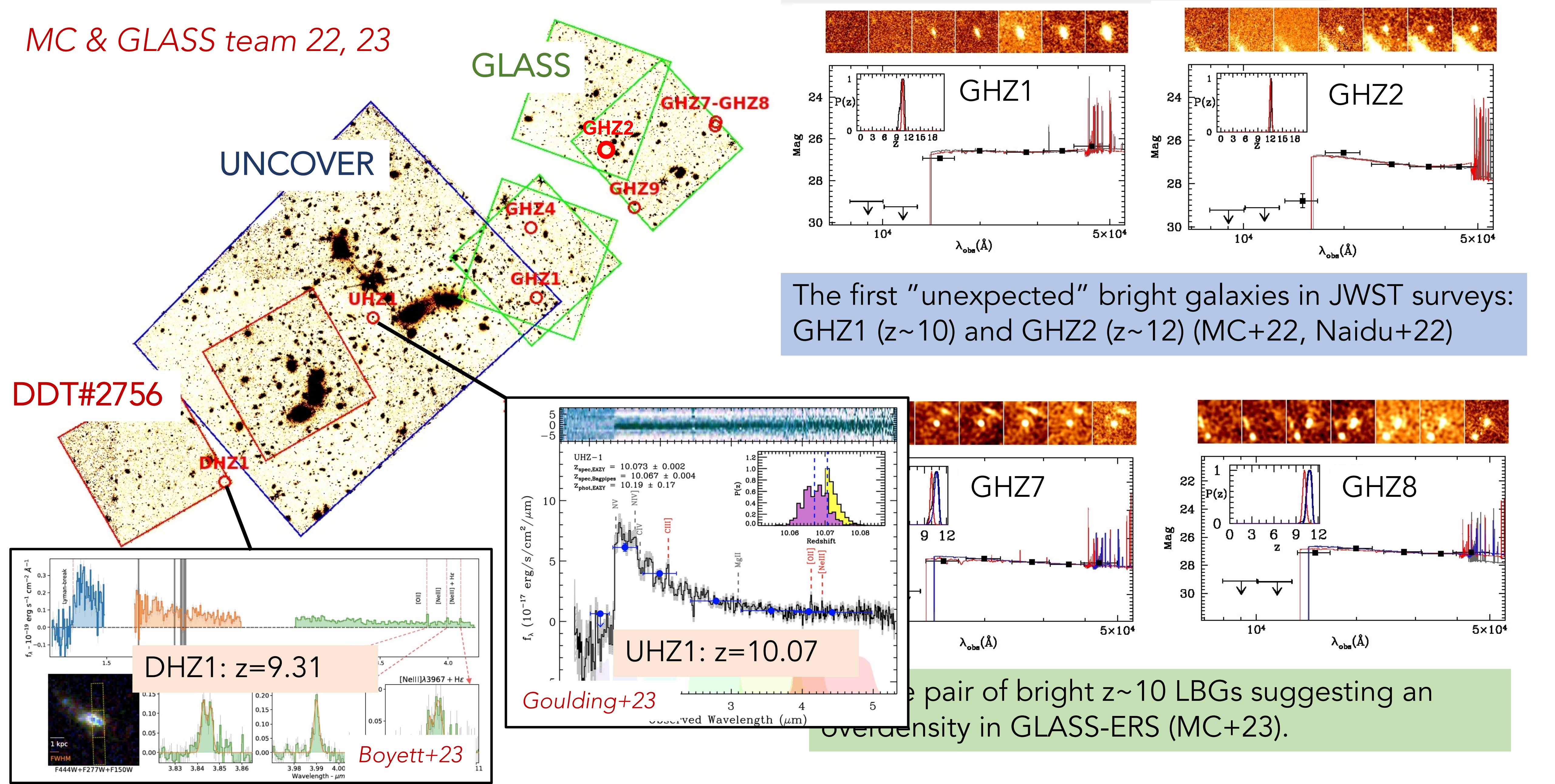


Mason+23



Dekel+23

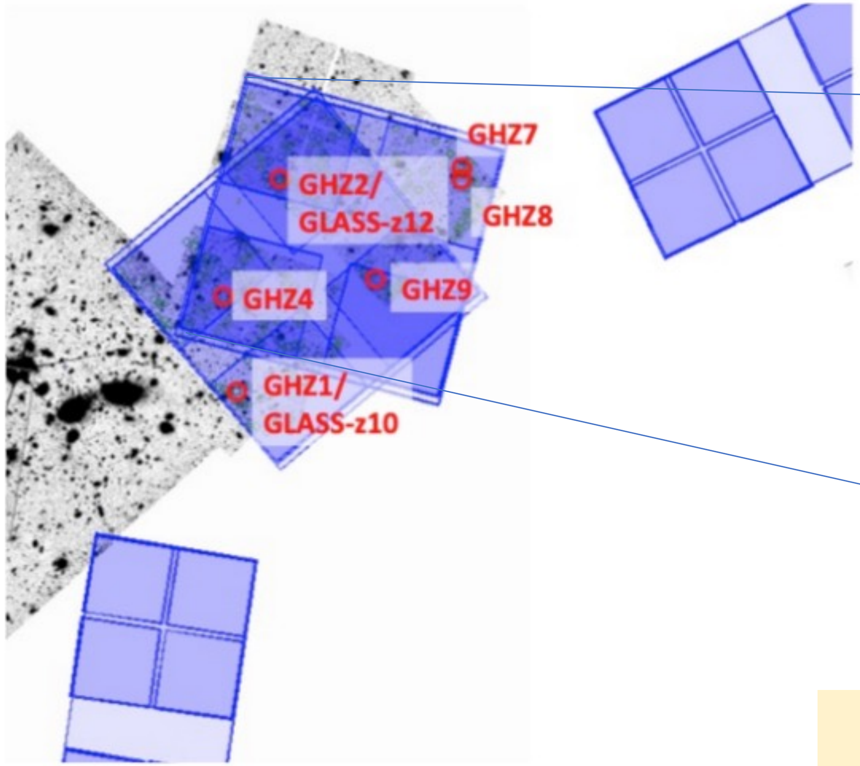
Spectroscopic follow-up of the A2744 region

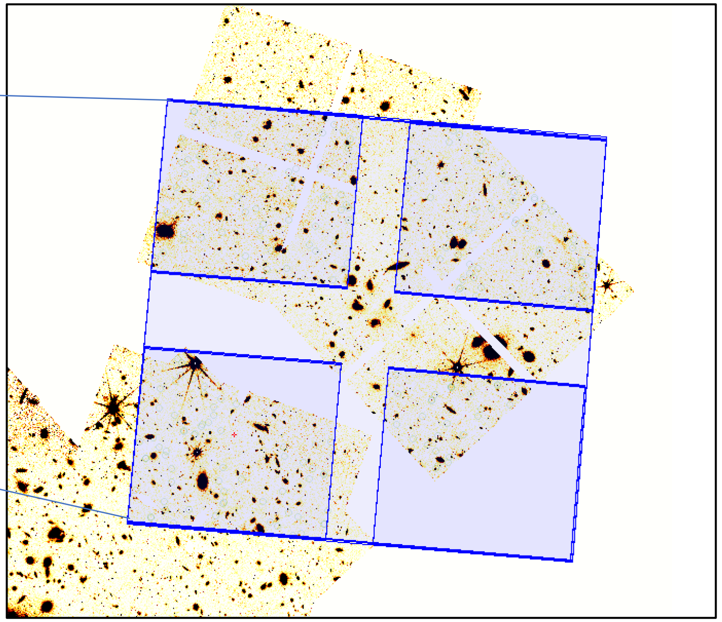


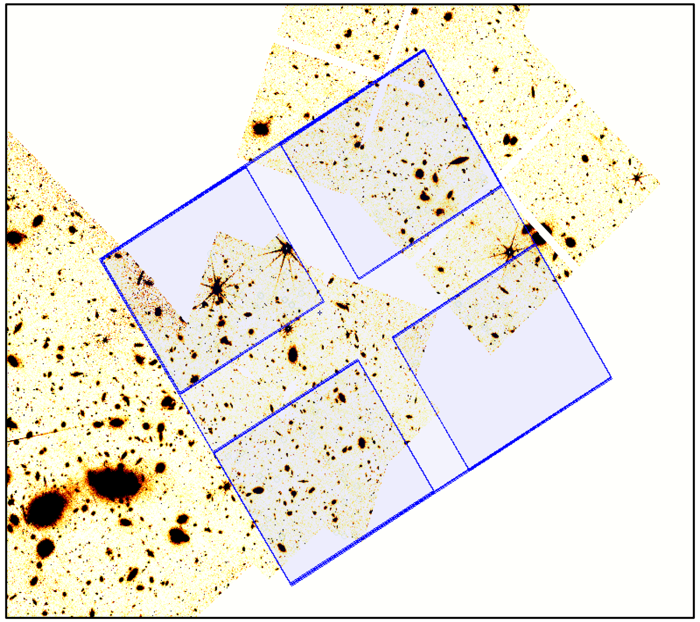
The first "unexpected" bright galaxies in JWST surveys: GHZ1 (z~10) and GHZ2 (z~12) (MC+22, Naidu+22)

…e pair of bright z~10 LBGs suggesting an …overdensity in GLASS-ERS (MC+23).

NIRSpec follow-up of GLASS-ERS (GO-3073)







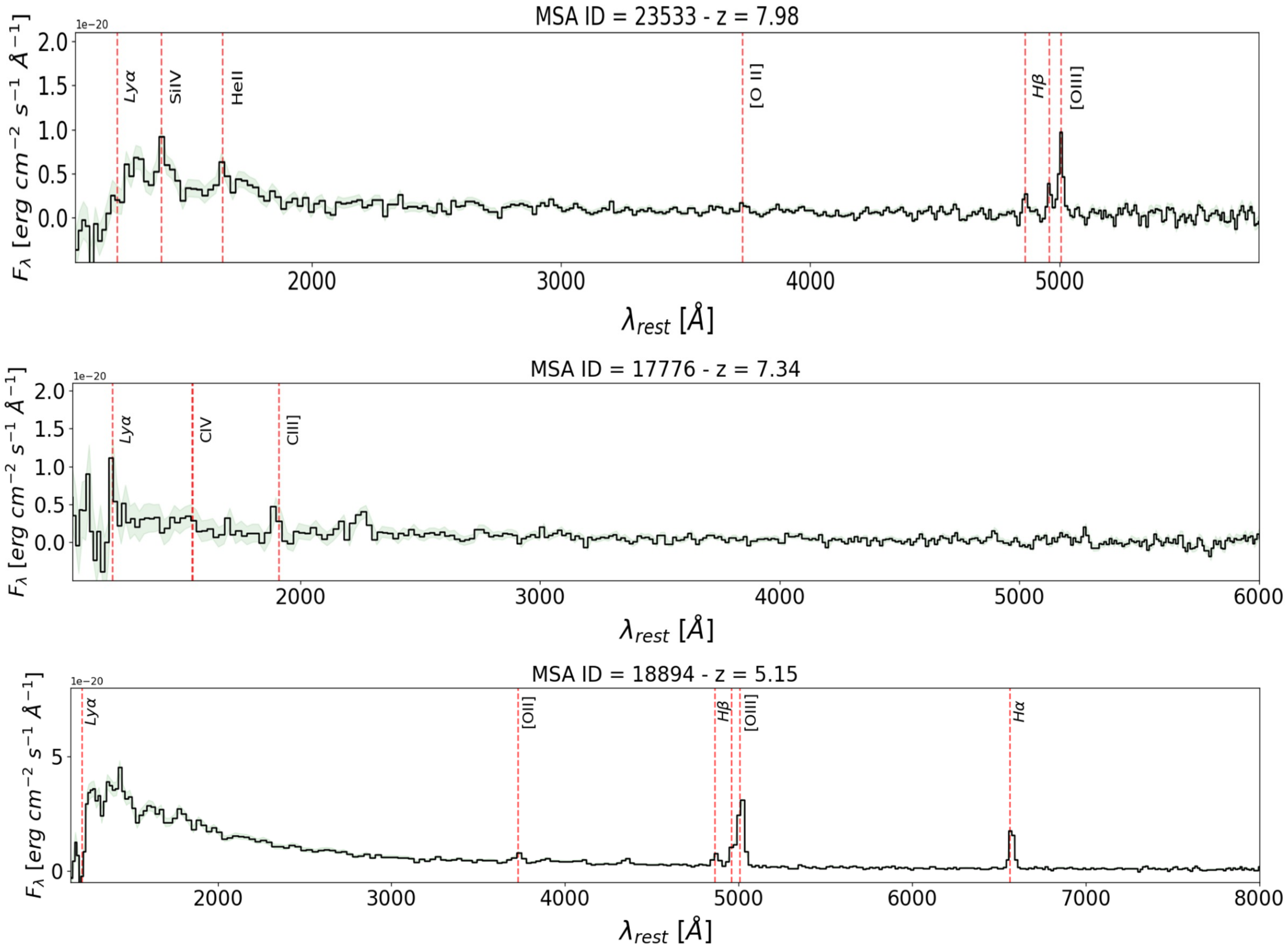
First pointing.
Observed on Oct. 25 2023
Primary targets: GHZ2, GHZ7, GHZ8, GHZ4, GHZ9

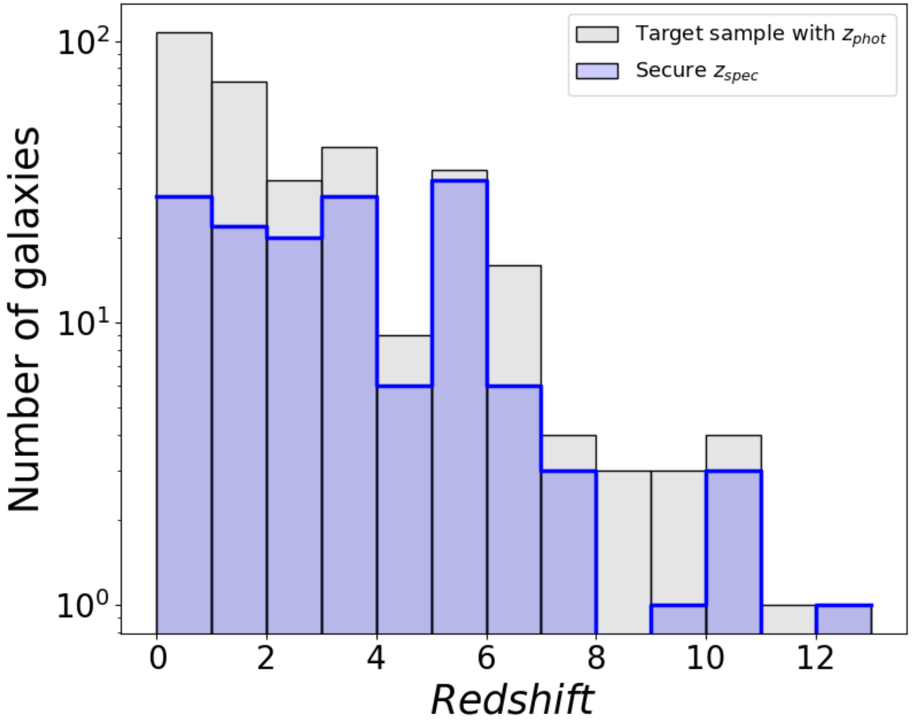
Second pointing.
Planned for June/July 2024
Primary targets: GHZ1, GHZ4, GHZ9

12 hours of NIRSpec PRISM on two pointings to confirm z~9-12 galaxies in the GLASS-ERS parallel

+ two flanking fields with NIRCam to extend the sample and map the potential overdensity

NIRSpec follow-up of GLASS-ERS (GO-3073)



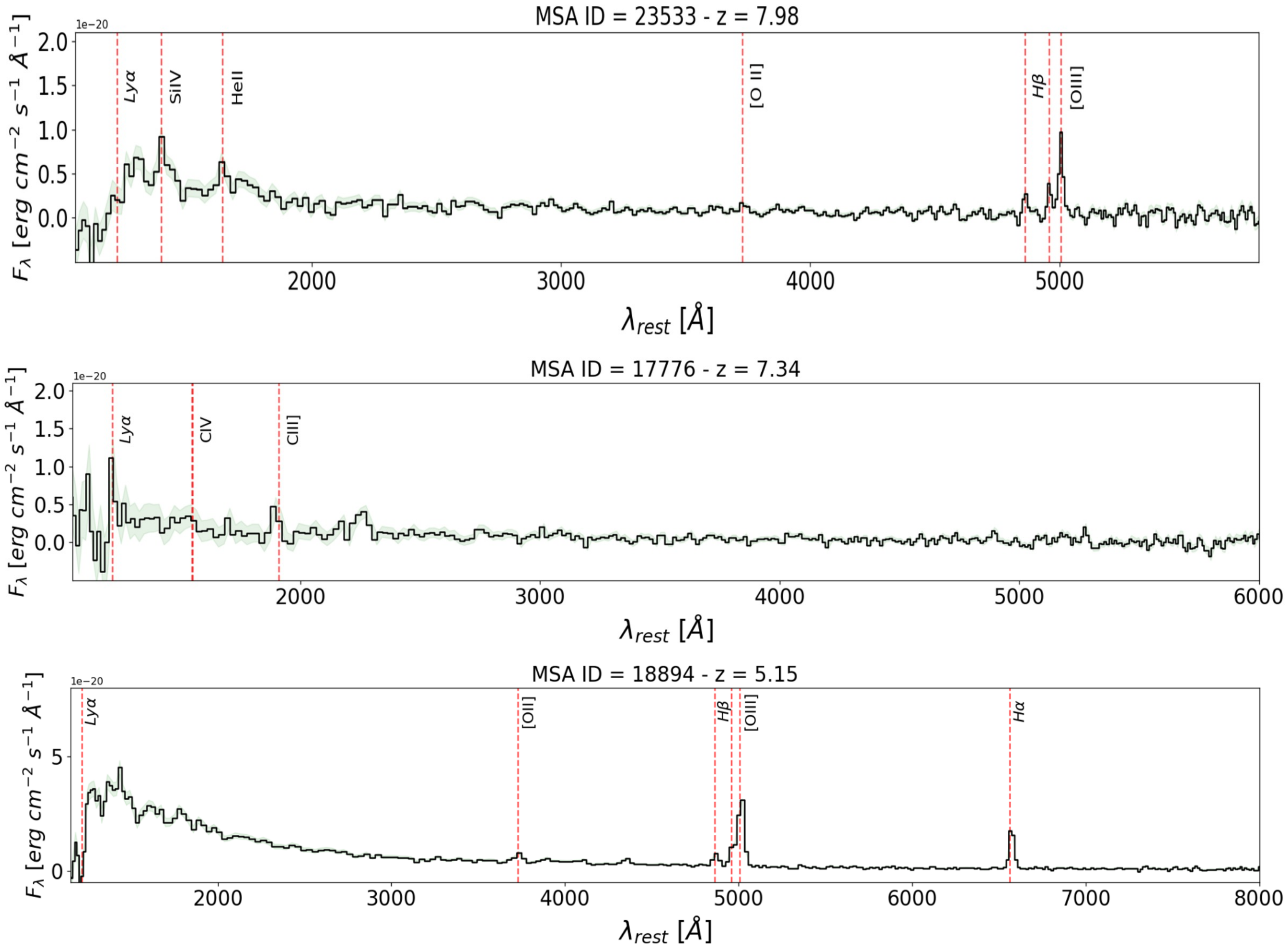


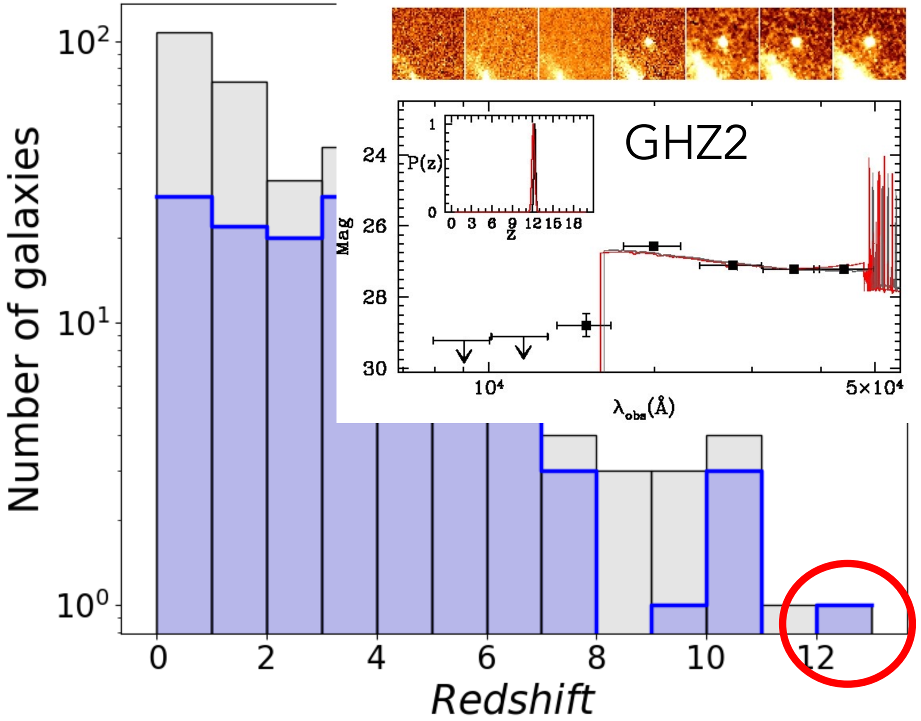
214 redshifts measured out of 334 targets

Several spec-z confirmations at z~10 (Napolitano et al., in prep.)

Data reduction by L. Napolitano

NIRSpec follow-up of GLASS-ERS (GO-3073)



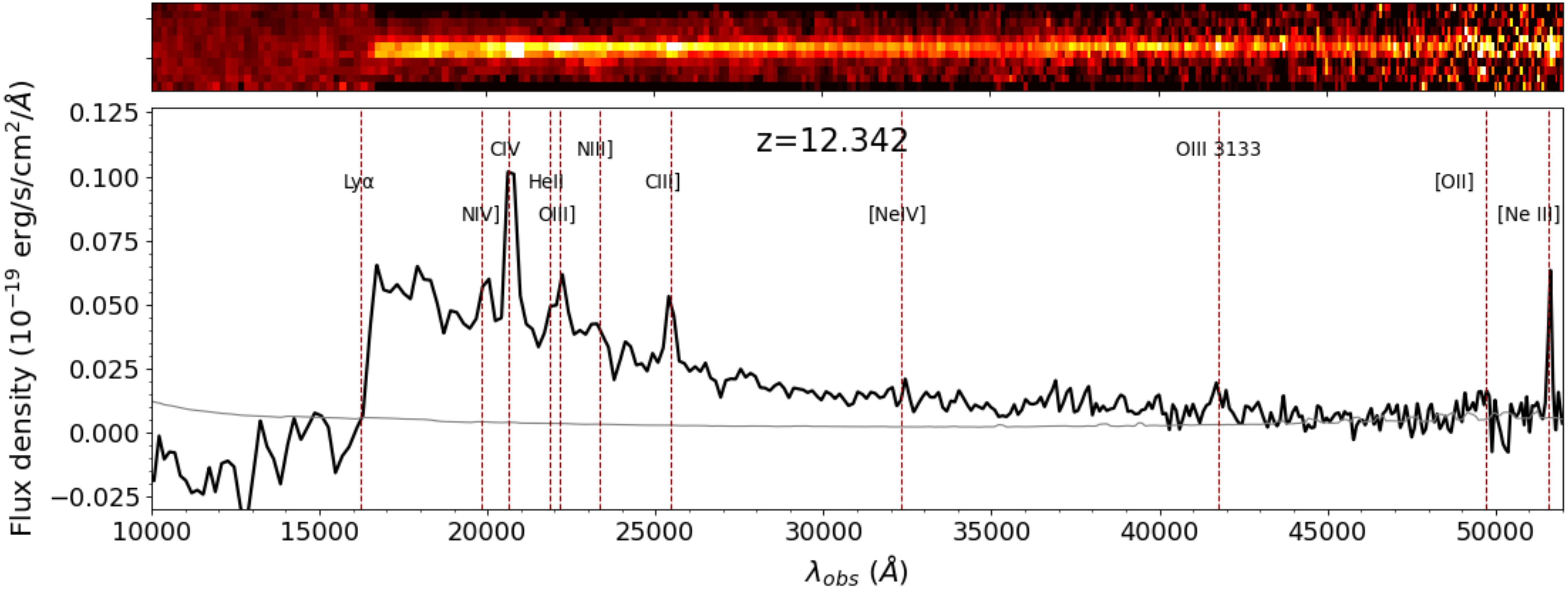


214 redshifts measured out of 334 targets

Several spec-z confirmations at z~10 (Napolitano et al., in prep.)

Data reduction by L. Napolitano

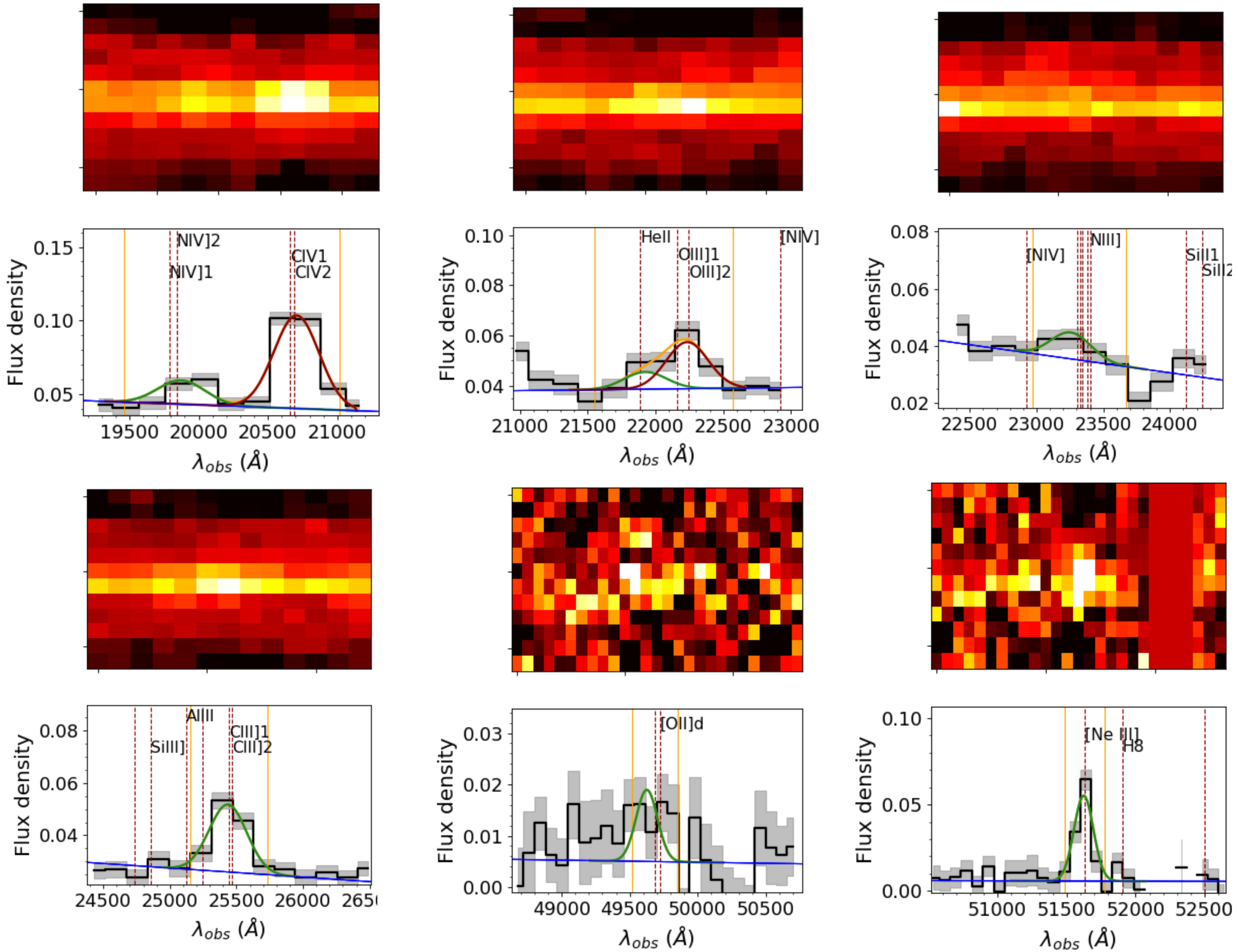
Spectroscopic confirmation of GHZ2/GLASS-z12



GHZ2/GLASS-z12 confirmed at z=12.34 by both NIRSpec and MIRI.
(z_{phot} =12.3 in MC+22, *zphot* code, the first JWST selections were not that bad after all…)

MC+ arXiv:2403.10238; Zavala, MC+ arXiv:2403.10491, Calabrò, MC+ arXiv:2403.12683

Detected emission lines in GHZ2/GLASS-z12



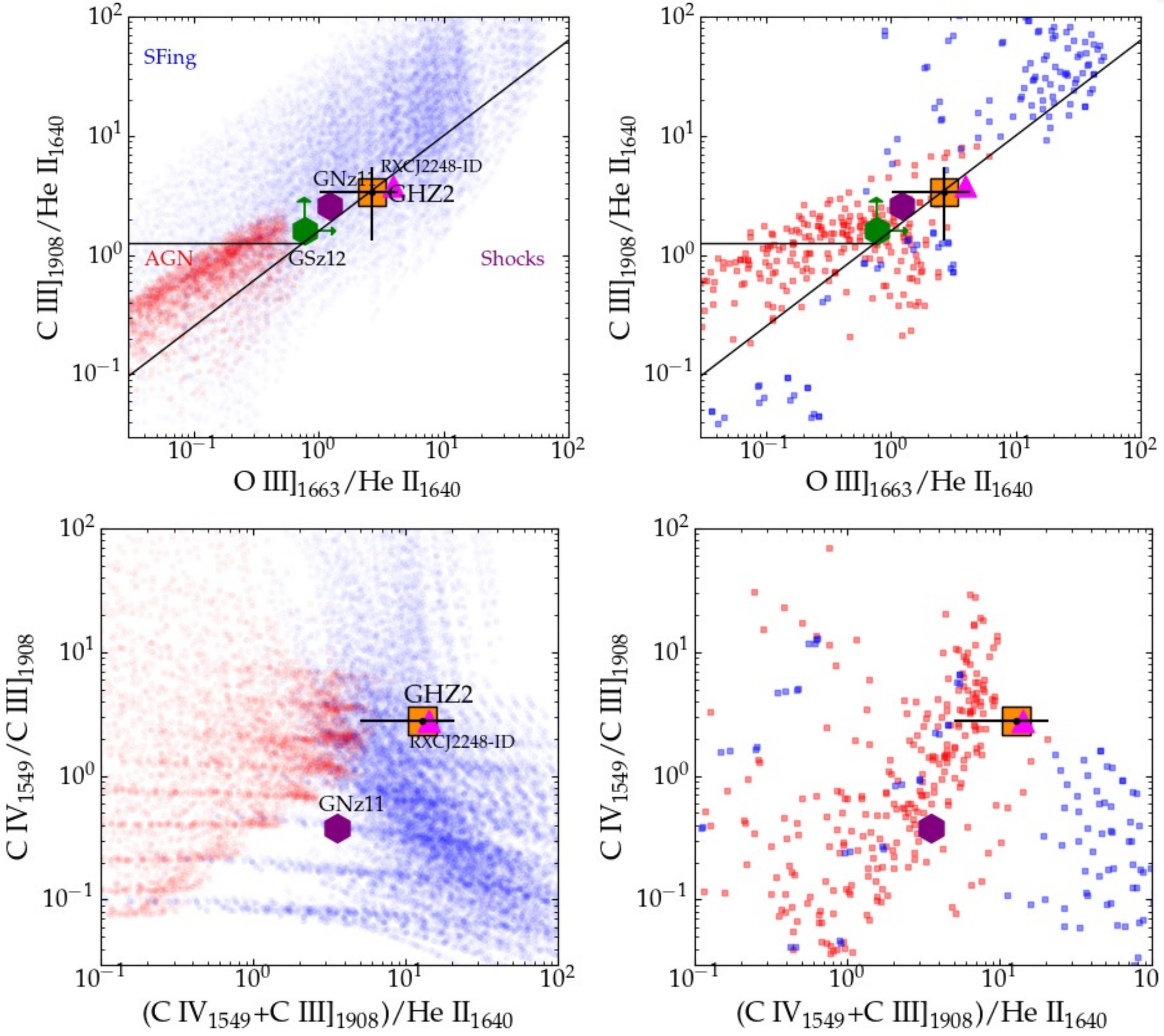
Several emission lines detected at high SNR:

NIV]λ1488, CIVλ1549, HeII λ1640, OIII] λ1663, CIII] λ1909, OII] λ3727, [NeIII] λ3868

High ionization conditions, EW(CIV)=46Å, Ne3O2=2.4.

Modeling with Gaussian fit and local continuum subtraction.

Star formation or AGN in GHZ2/GLASS-z12?



"Classic" BPT diagrams with UV lines.

Models from Feltre+16, Gutkin+16 (left) or Nakajima & Maiolino 2022 (right).

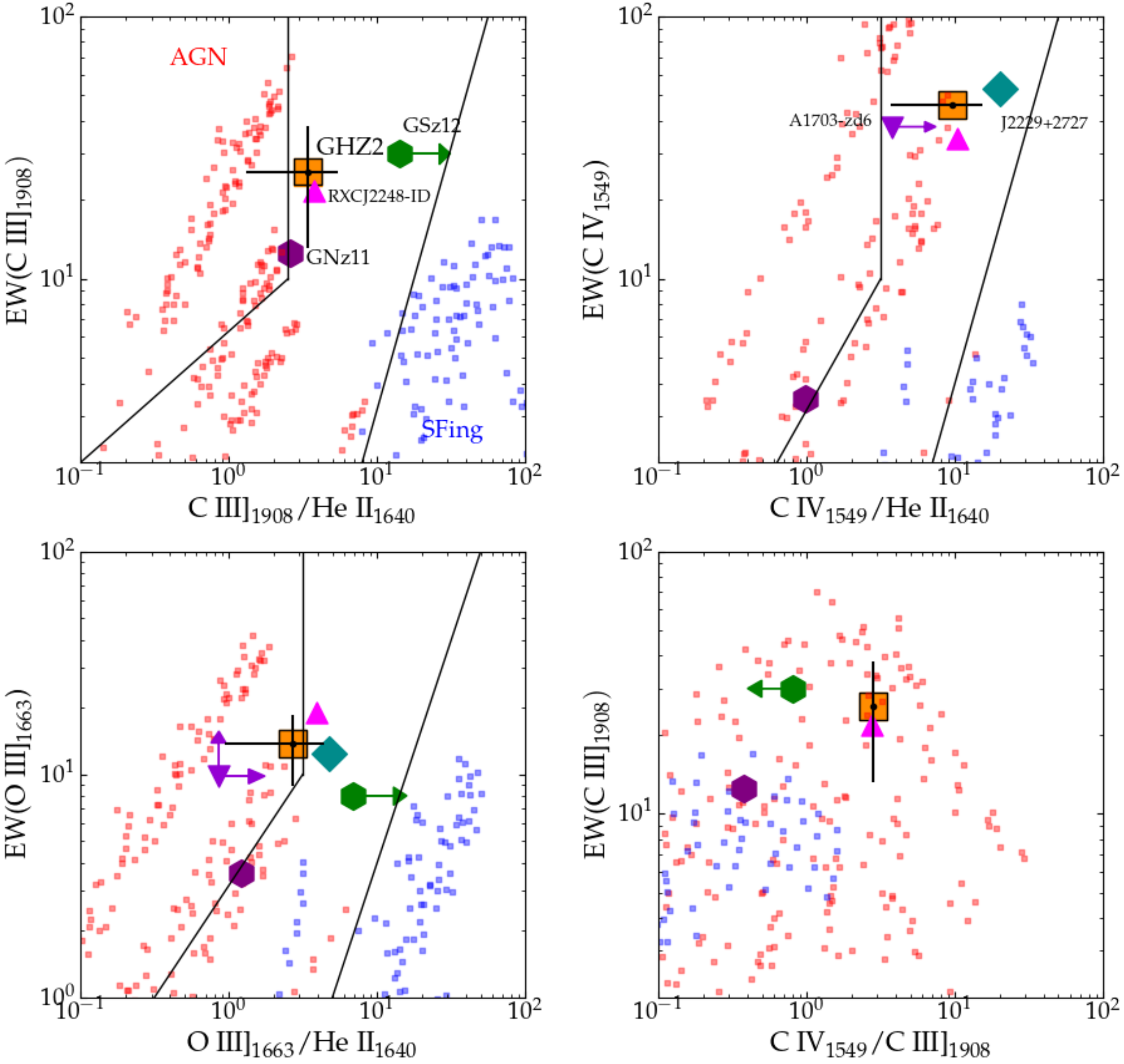
Selection criteria from Mingozzi+23

Line ratios compatible with both AGN and star-formation.

GNz11: Bunker+23, Maiolino+23
GSz12: D'Eugenio+23
RXCJ2248-ID: Topping+24

Blue: star-forming models
Red: AGN models

Star formation or AGN in GHZ2/GLASS-z12?



EW diagnostics.

Models from Nakajima & Maiolino 2022.

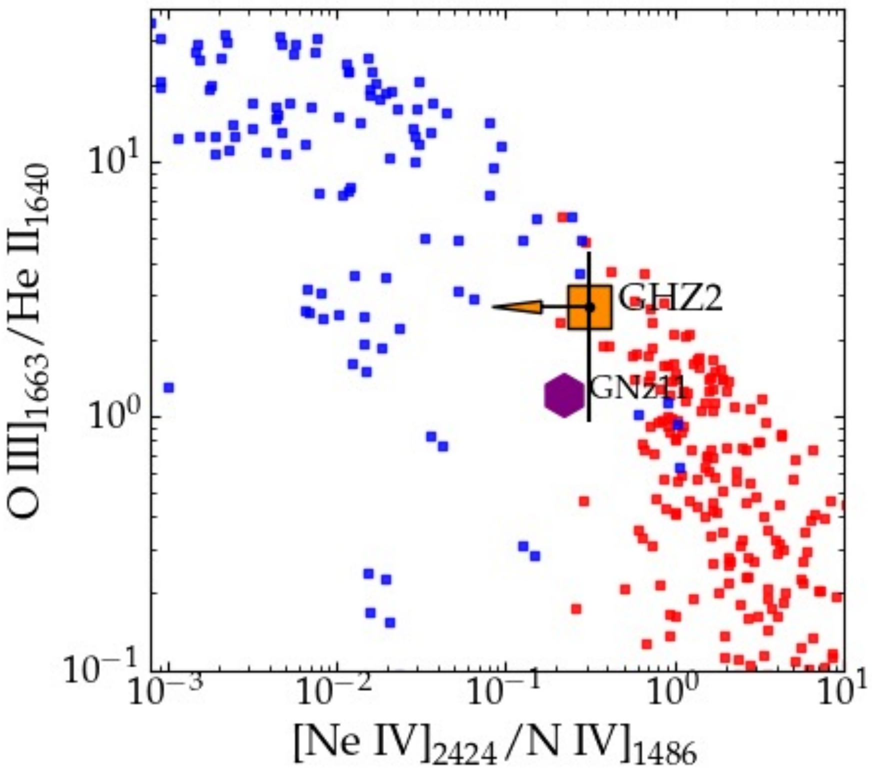
Selection criteria from Hirschmann+19

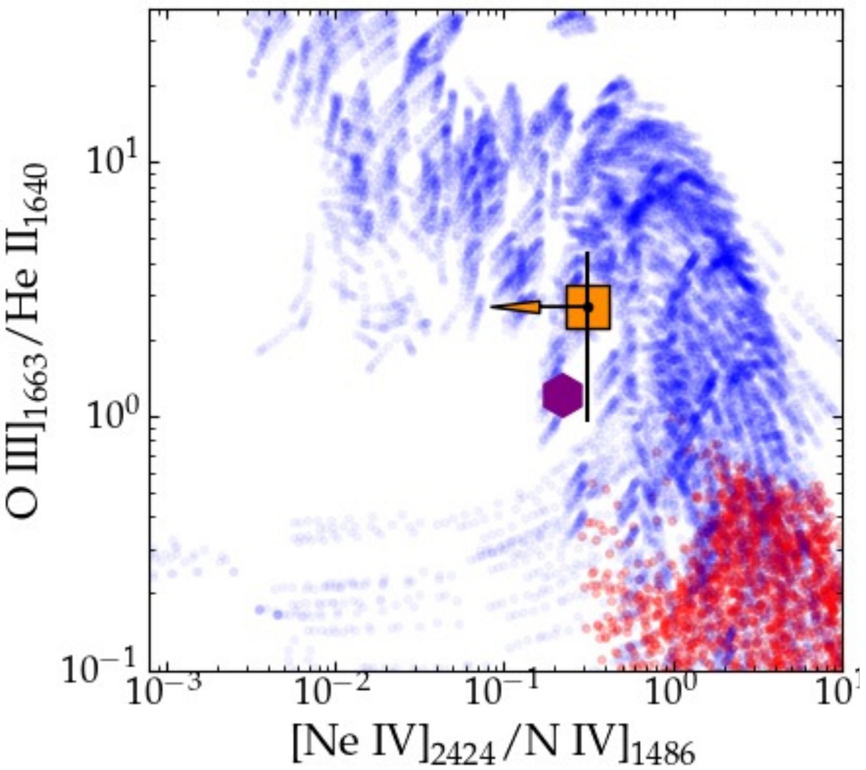
EW compatible with AGN and composites.

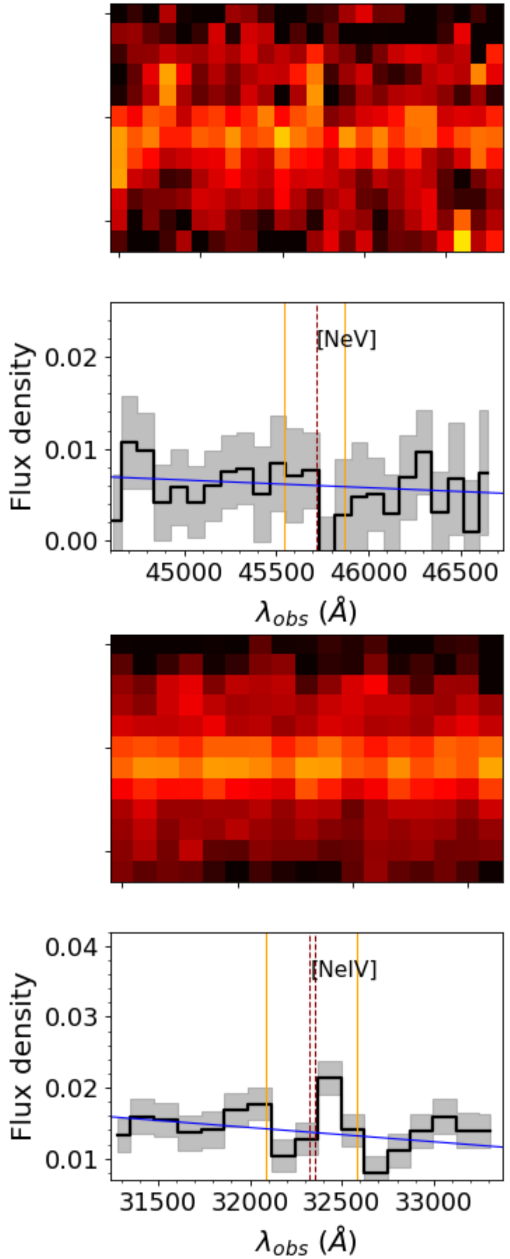
GNz11: Bunker+23, Maiolino+23
GSz12: D'Eugenio+23
RXCJ2248-ID: Topping+24
A1703-zd6: Stark+15
J2229+2727: Izotov+24

Blue: star-forming models
Red: AGN models

Star formation or AGN in GHZ2/GLASS-z12?





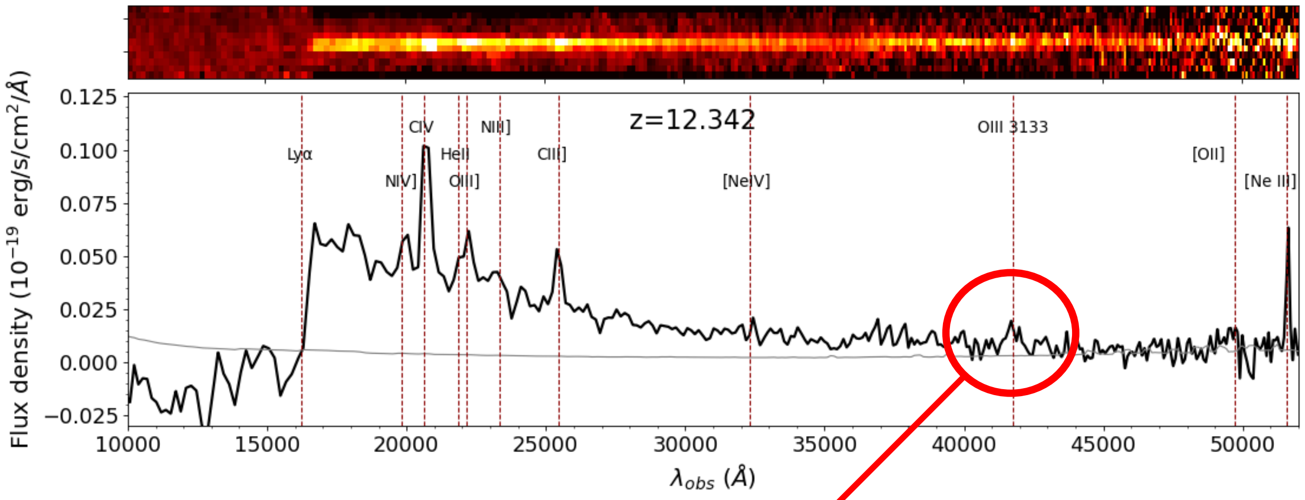


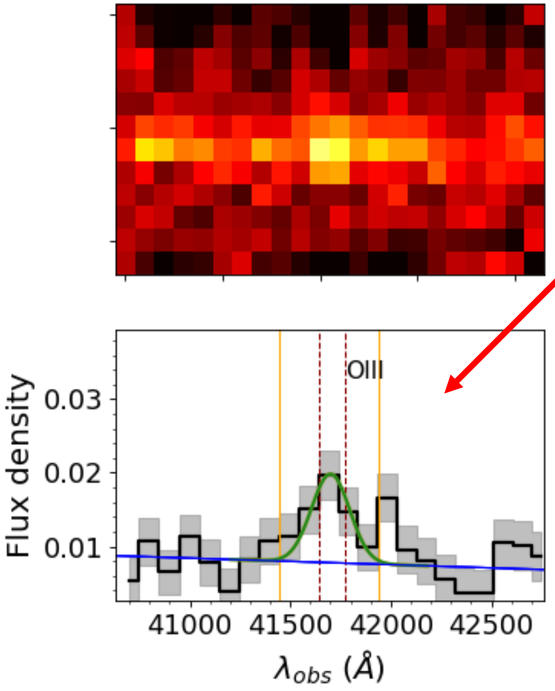
Very high-ionization lines diagnostics

Models from Nakajima & Maiolino 2022 (left), Feltre+16, Gutkin+16 (right).

<u>Non detection of high-ionization lines compatible with star-formation</u>.

First detection at high-z of OIIIλ3133 Bowen fluorescence line

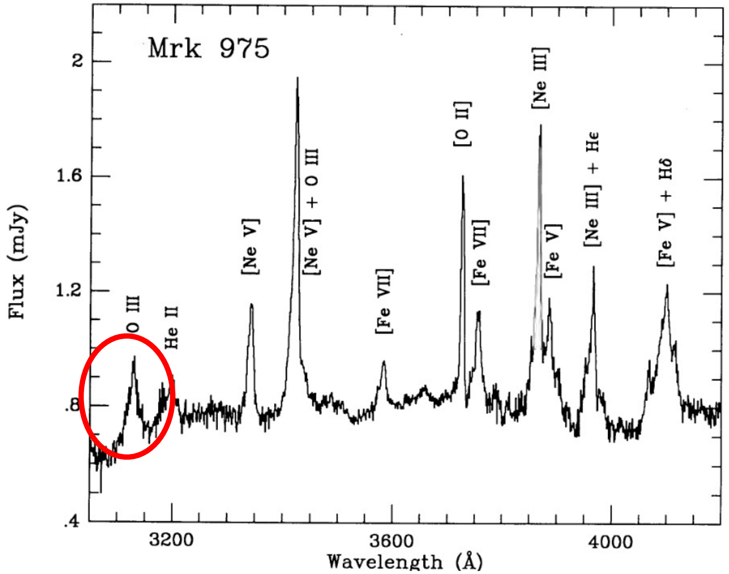




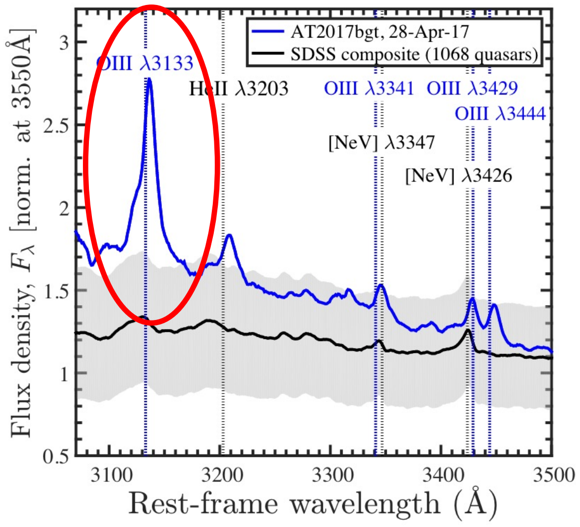
Evidence of OIII emitted through Bowen fluorescence (resonance with HeII Lyα 303.8Å).

Found in local Seyferts and SMBH, X-ray binaries, planetary nebulae.

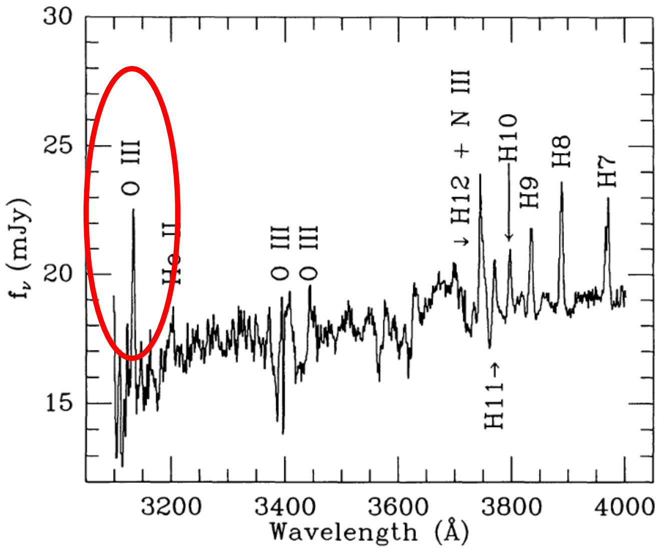
Local Seyferts, Shachter+90



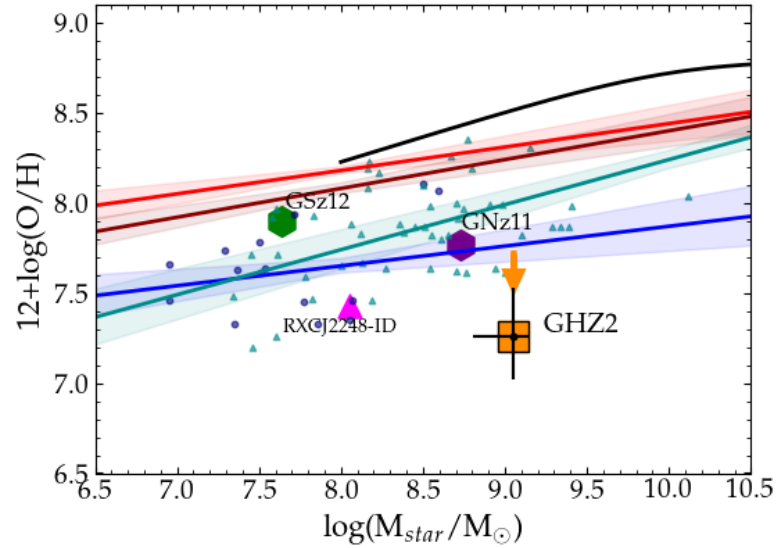
Flaring SMBHs, Trakhtenbrot+19

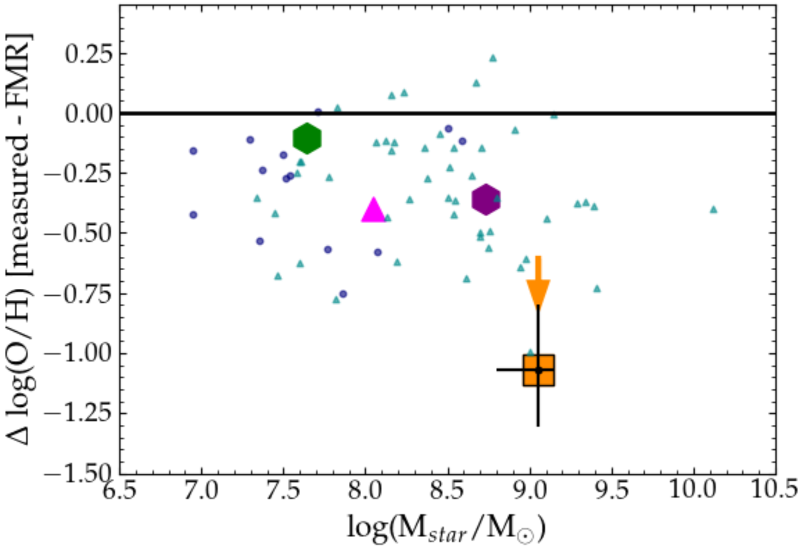


Sco X-1, Shachter+89



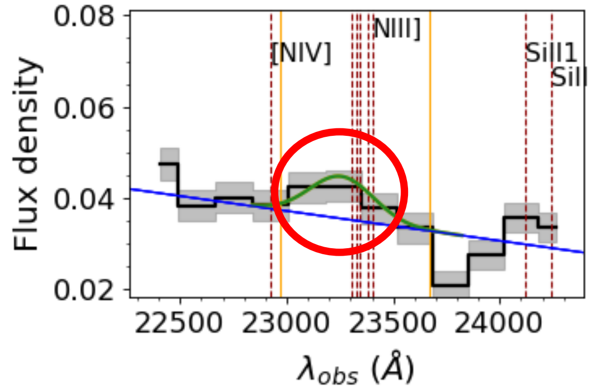
A LOW METALLICITY, HIGHLY IONIZING, N-ENHANCED GALAXY?





$M_{\rm UV}$	-20.49 ± 0.01
UV slope	-2.39 ± 0.07
$\log(M_{\rm star}/{\rm M}_\odot)$	$9.05^{+0.10}_{-0.25}$
SFR (${\rm M}_\odot$ yr^{-1})	$5.2^{+1.1}_{-0.6}$
sSFR (Gyr^{-1})	$4.7^{+5.1}_{-1.0}$
$\Sigma_{\rm SFR}$ (${\rm M}_\odot$ yr^{-1} kpc^{-2})	75 ± 4
Σ_M (${\rm M}_\odot$ pc^{-2})	$16.2^{+1.1}_{-5.4} \times 10^3$
A_V (mag)	$0.04^{+0.07}_{-0.03}$
12 + log(O/H)	$7.26^{+0.27}_{-0.24}$
log U	-1.78 ± 0.28

Star-forming scenario for GHZ2:
Compact star-forming region hosting star clusters with massive stars enriching ISM with Nitrogen (GC progenitor?).
Low metallicity, high ionization parameter, likely Ly-c emitter.
Significant deviation from the FMR



Metallicity and ionization :

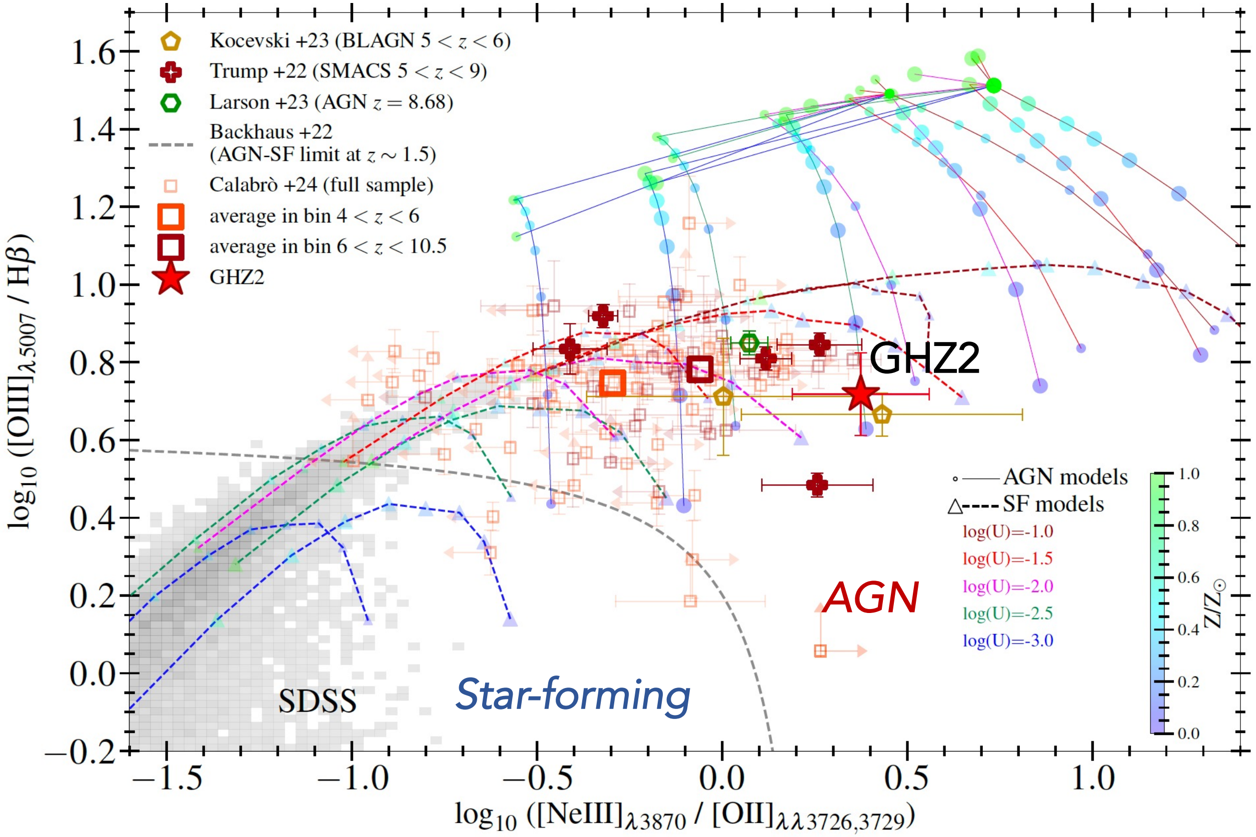
$Z < 0.1\ Z_{sun}$
log(U) > -2
N/O ~ 4-5 x solar *
C/O ~ 0.2-0.5 x solar

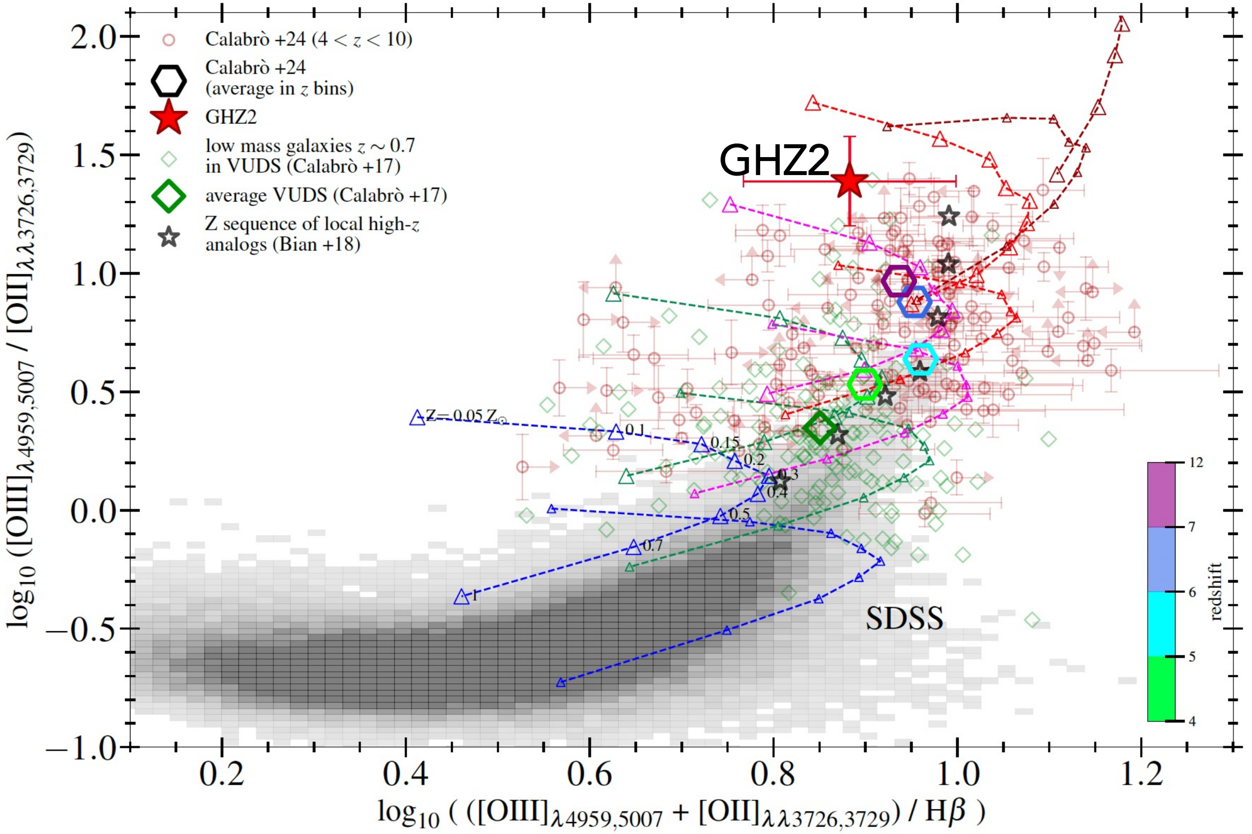
Global properties :

Very compact R_h<100 pc
log(M)>8.5 M_{sun}
SFR ~5-10 M_{sun}/yr

* NIII] meas. dependent on local continuum estimate, to be confirmed at higher resolution

Low metallicity, high ionization: joint NIRSpec - MIRI analysis





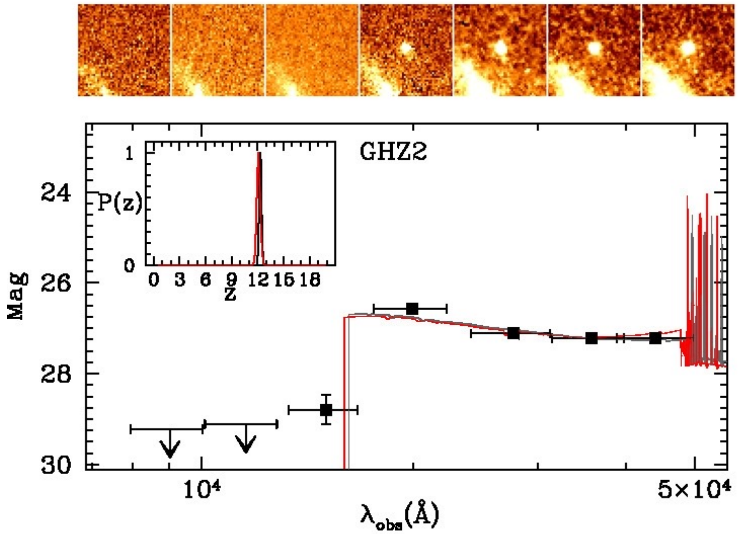
Index	Line ratio	Z^A	Z^B	Z^C	Z^D
		$Z_\odot$	$Z_\odot$	$Z_\odot$	$Z_\odot$
R2	-0.52 ± 0.20	-	-	$0.06^{0.11}_{0.03}$	$0.06^{0.09}_{0.04}$
R3[1]	0.72 ± 0.11	-	$0.12_{0.09}$	$0.08^{0.16}_{0.05}$	$0.05^{0.12}_{0.03}$
R23	0.88 ± 0.12	-	$0.11_{0.06}$	$0.08^{0.19}_{0.05}$	$0.05^{0.13}_{0.03}$
O32	1.39 ± 0.19	$0.11^{0.14}_{0.07}$	-	-	$0.07^{0.10}_{0.05}$
Ne3O2[2]	0.37 ± 0.18	$0.07^{0.10}_{0.06}$	-	-	$0.04^{0.05}_{0.02}$
Ne3O2Hd	0.59 ± 0.12	-	-	-	-
average		0.08 ± 0.02	0.11 ± 0.04	0.07 ± 0.03	0.054 ± 0.009

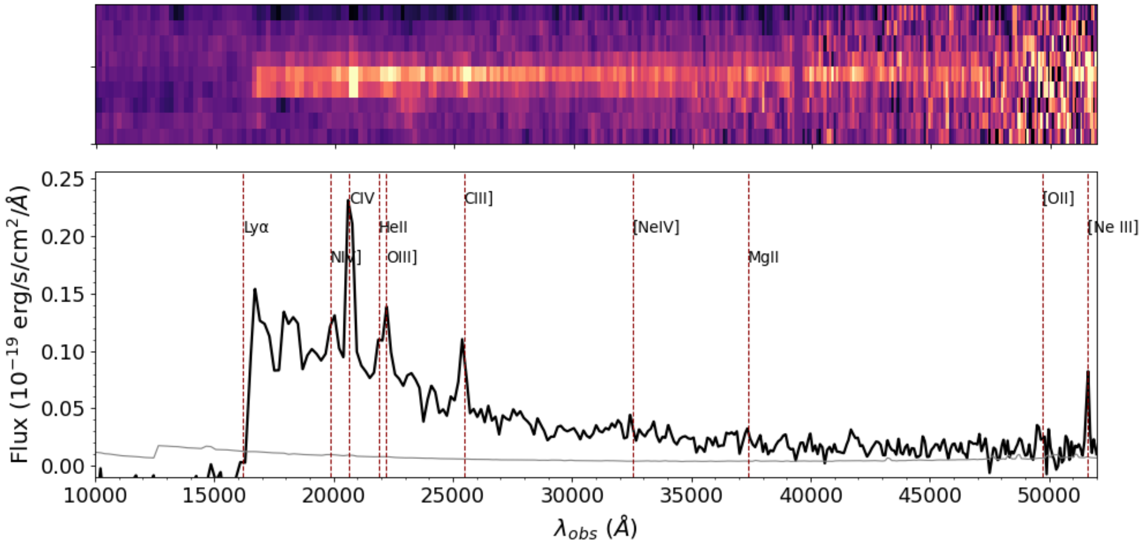
Combined analysis confirms:

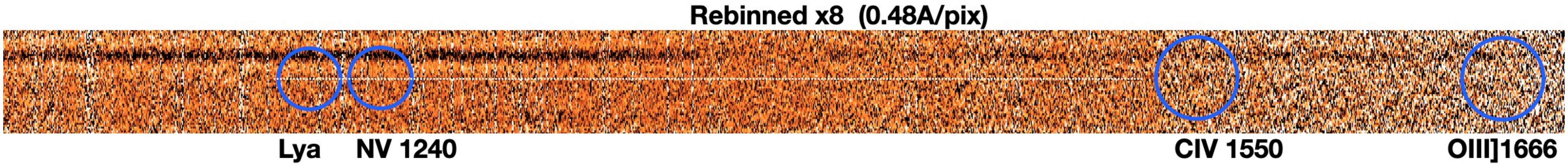
- Degeneracy AGN vs SFing diagnostics
- High ionization parameter log(U)>-2
- Metallicity ≤0.1 solar

Calabrò, MC+ arXiv:2403.12683

Only JWST can observe frontier objects



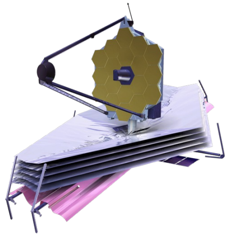




30 hours spectroscopic follow-up with X-Shooter (PI Vanzella) compared to NIRSPec PRISM.
SNR~4 detection of CIV (after some binning). Highest redshift reached from the ground.

Enables limits where NIRSpec is heavily affected by ISM and IGM: NVλ1240<1/4 CIVλ1550

Take-home messages



- JWST has opened a new frontier at cosmic dawn. The only instrument that can explore it for the foreseeable future.

- Discovery of a high abundance of galaxies and AGN at high-redshift. Why? Many hypothesis on the table.

- Spectroscopic follow-up of **frontier objects** is essential to answer these questions.

- The A2744 field has opened the way. First half of the NIRSpec follow-up program GO-3073 on the GLASS ERS region completed.

- Successful confirmation of galaxies at z~10-12 including the M_{UV}=-20.5 object GHZ2/GLASS-z12 at z=12.34.

- **Extremely ambiguous**: AGN or star-forming? **Extreme properties**: log(U)>-2, low-metallicity (≤ 0.1 Zsun), very low extinction, peculiar abundance patterns.

- Supersolar N/O in a compact, highly-ionizing object suggests a connection with GC formation.