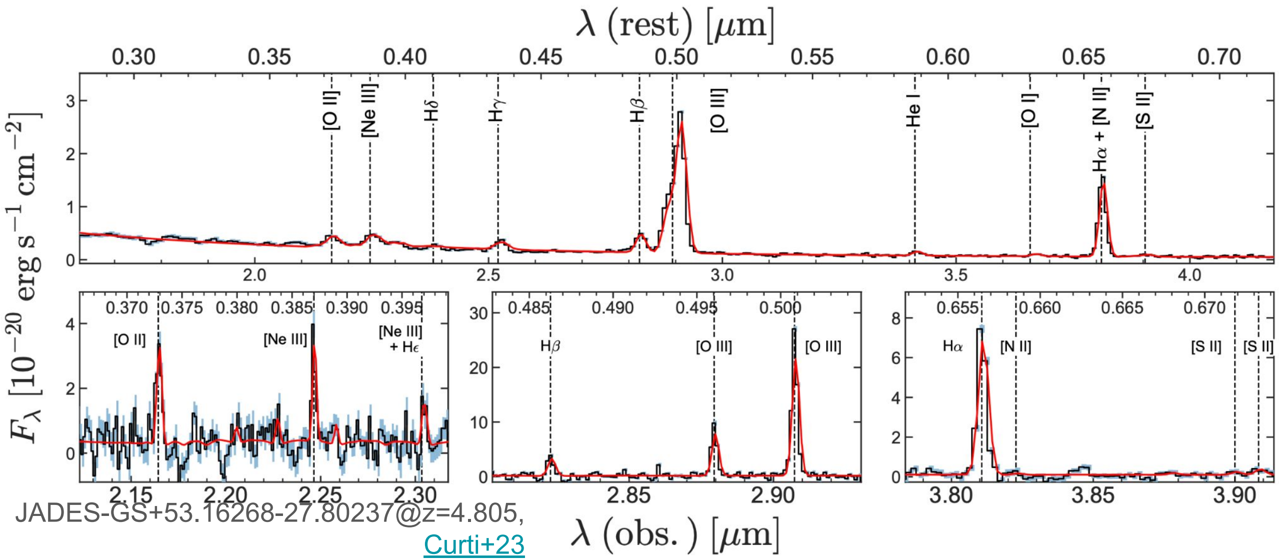
Galaxies in the Very Early Universe w/ JWST Spectroscopy

GGM, 15 Nov 2023

Bo Peng

Application of Spectroscopy

- Line wavelength: redshift
- Line / Line: temperature, metallicity, FMR
- Line / Continuum: EW



Prism(R=100)

Grating(R=1000)

JADES-GS+53.16268-27.80237@z=4.805, Curti+23

Click links for pages on:

https://highz.space

JWST Programs

JWST Data

JWST Meetings / Conferences

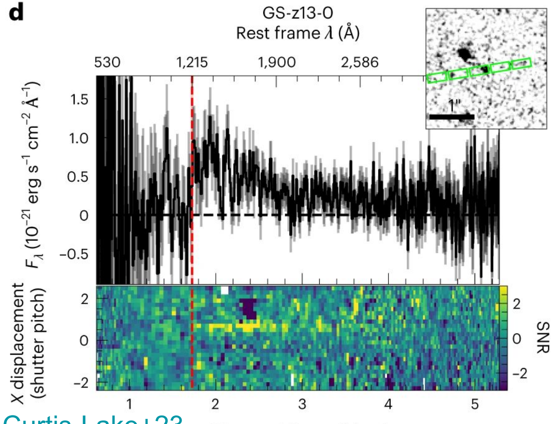
JWST papers on galaxies

High-z galaxies compiled from papers (beginning Aug 6 by Gabriel Brammer):
https://jwst-sources.herokuapp.com
Add yours here: https://github.com/dawn-cph/jwst-sources/

Redshift search/confirmation

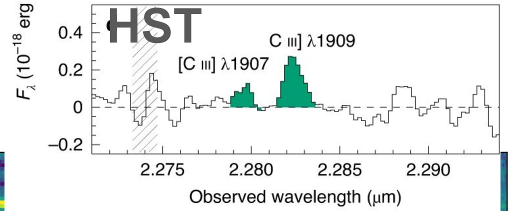
Confirm galaxy redshift spectroscopically

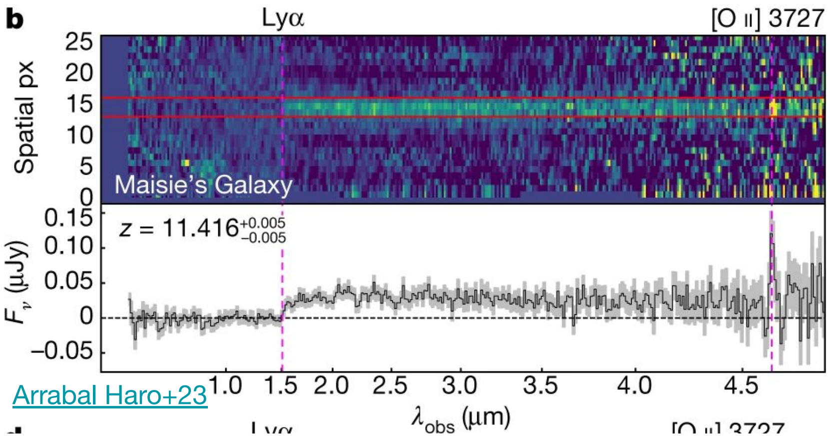
- Lyα break (record z=13.17±0.16, GS-z13-0, Robertson+23, Curtis-Lake+23)
- Spectral line (record z=11.416±0.005, Maisie's Galaxy, Arrabal Haro+23)
- More robust spec-z: GN-z11 JWST z=10.6034 ± 0.0013 (Bunker+23), refuting HST tentative spec-z 10.957±0.001 (Jiang+21)



Curtis-Lake+23

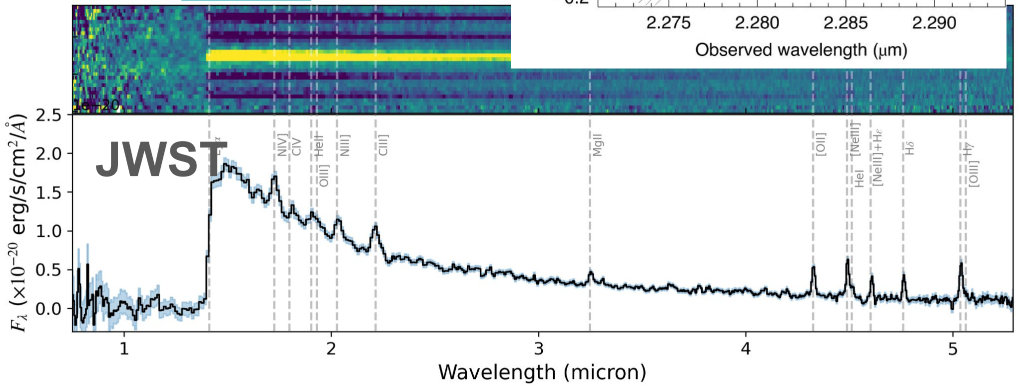
GN-z11, Jiang+21





Arrabal Haro+23

GN-z11, Bunker+21

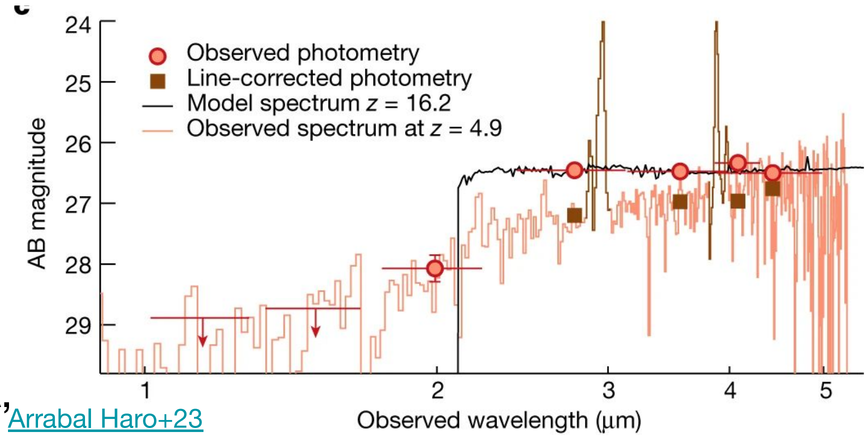


Redshift search/confirmation

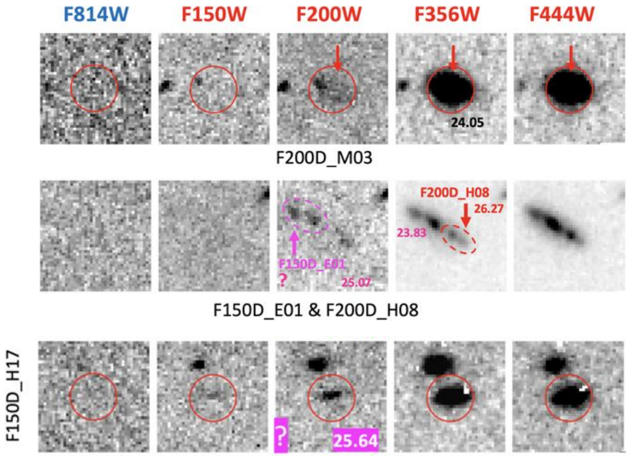
Confirmed galaxy redshift spectroscopically

Low-z interlopers

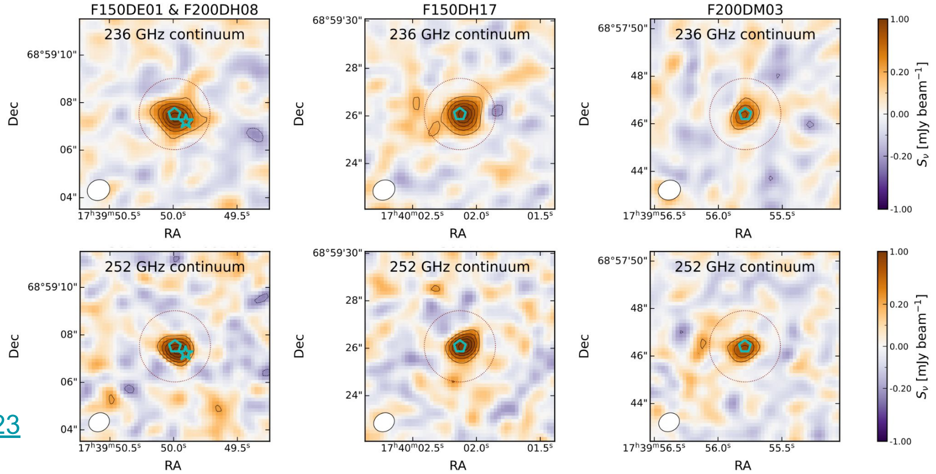
- High-EW line ([O III]&Hα) + red SED mimicking flat continuum (1/3 in Arrabal Haro+23)
- Sub-mm survey reveal Z < 5 dusty galaxies (2 bands ~mJy detection in Meyer+23 by NOEMA, 3/3 brightest in Yan+23 dropout sample)



Arrabal Haro+23



Yan+23



Meyer+23

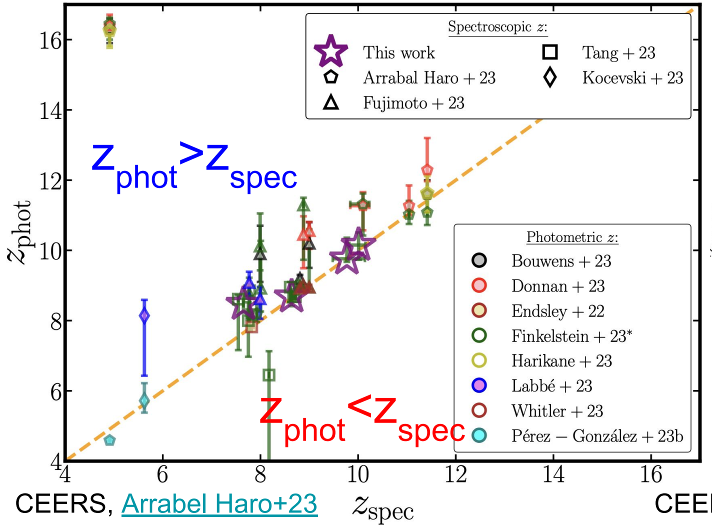
Redshift search/confirmation

Confirmed galaxy redshift spectroscopically

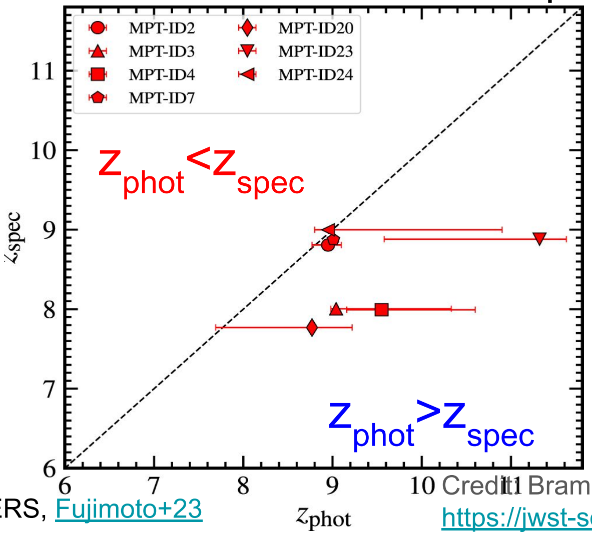
Low-z interlopers

Accurary of photo-z

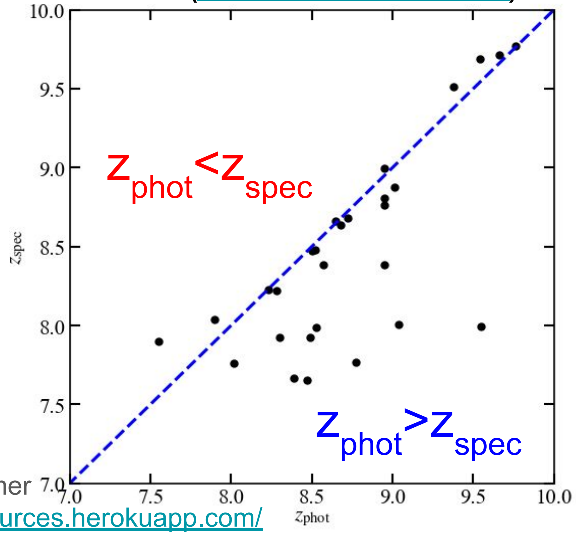
- Photo-z > spec-z @z > 6 (e.g. CEERS Fujimoto+23, SMACS0723 Carnall+23)
- SED template not representative, incomplete modelling of IGM (not damping wing), selection effect due to brighter@low-z or lack of line in NIRSpec@z>9.6? (Arrabel Haro+23)



CEERS, Arrabel Haro+23



CEERS, Fujimoto+23



Credit: Brammer
https://jwst-sources.herokuapp.com/

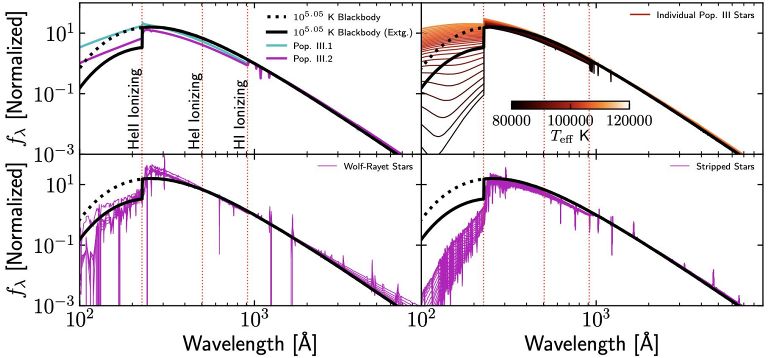
Redshift search/confirmation

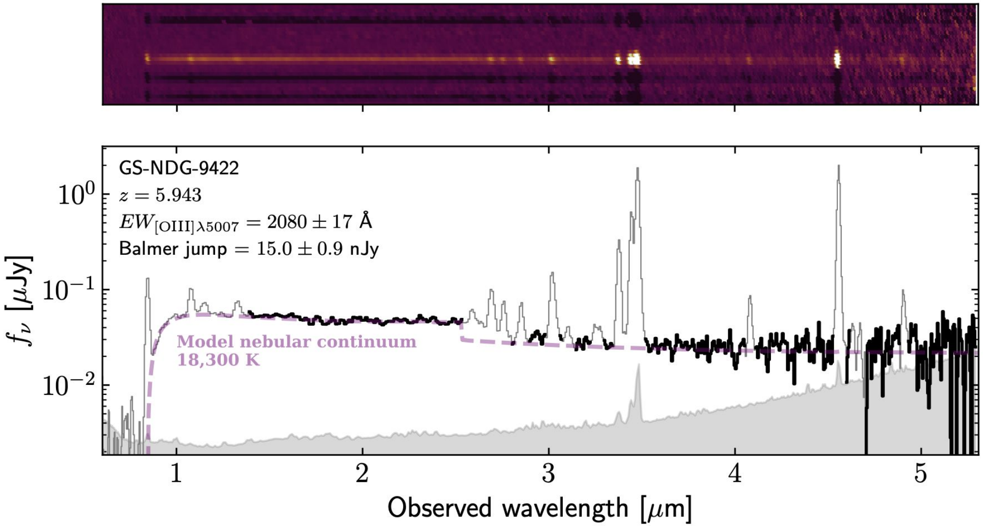
Confirmed galaxy redshift spectroscopically

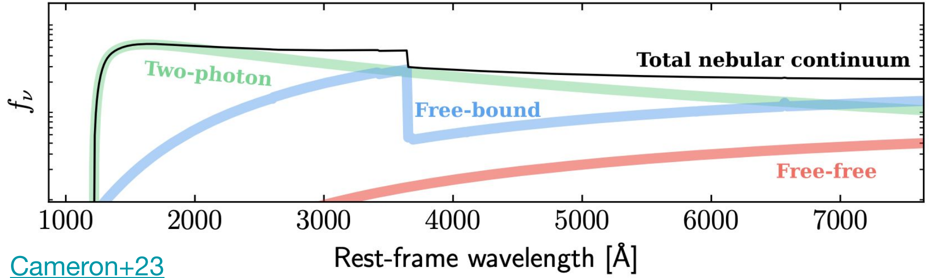
Low-z interlopers

Accurary of photo-z

- Alternative solution: two-photon (2s->1s) dominated continuum? (Cameron+23)
- Creating damped wing like Lyα + Lyα emission w/o need for fine-tuned geometry
- Extreme Q_0 + weak He II (disfavoring AGN or pop.III star) -> “consistent with ionization powered by low-metallicity massive stars, perhaps in the Wolf-Rayet phase”





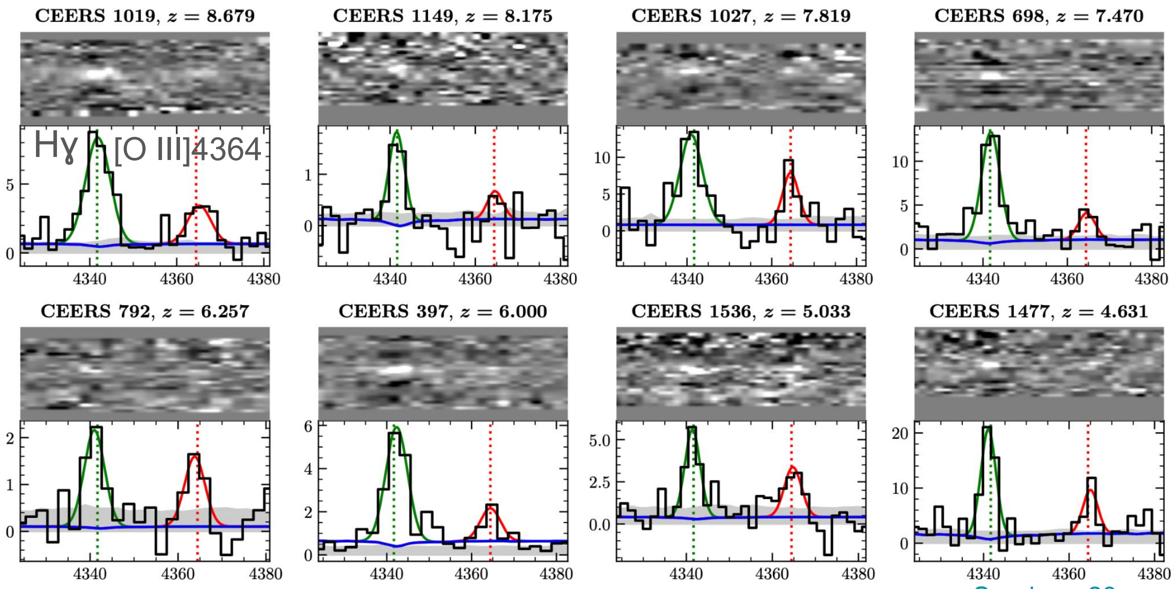


Cameron+23

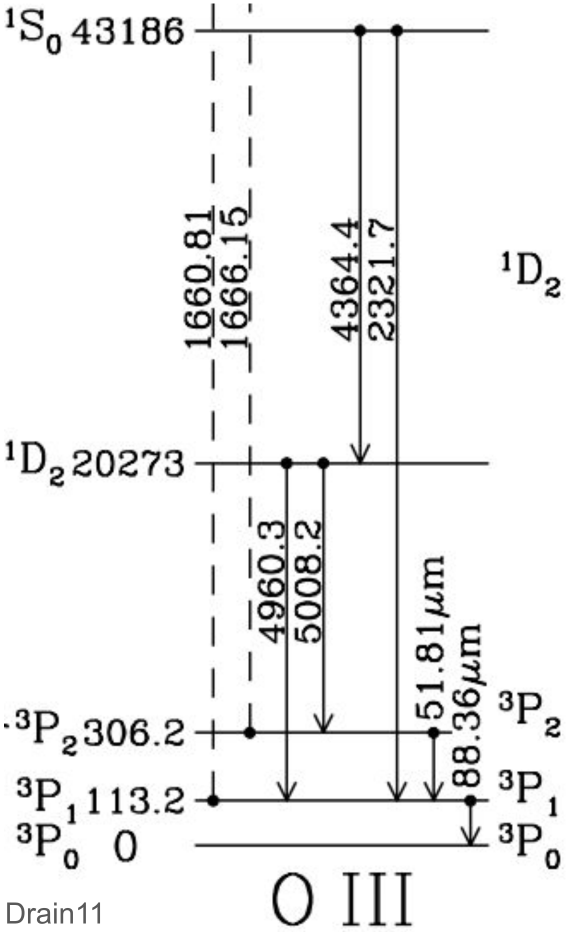
Temperature & Ionization

High electron temperature

- Common detection of [O III]4364Å auroral line (5.3eV, 6E5K), from hot gas
- [O III]4364/5007 probes temperature



Sanders+23



Drain11

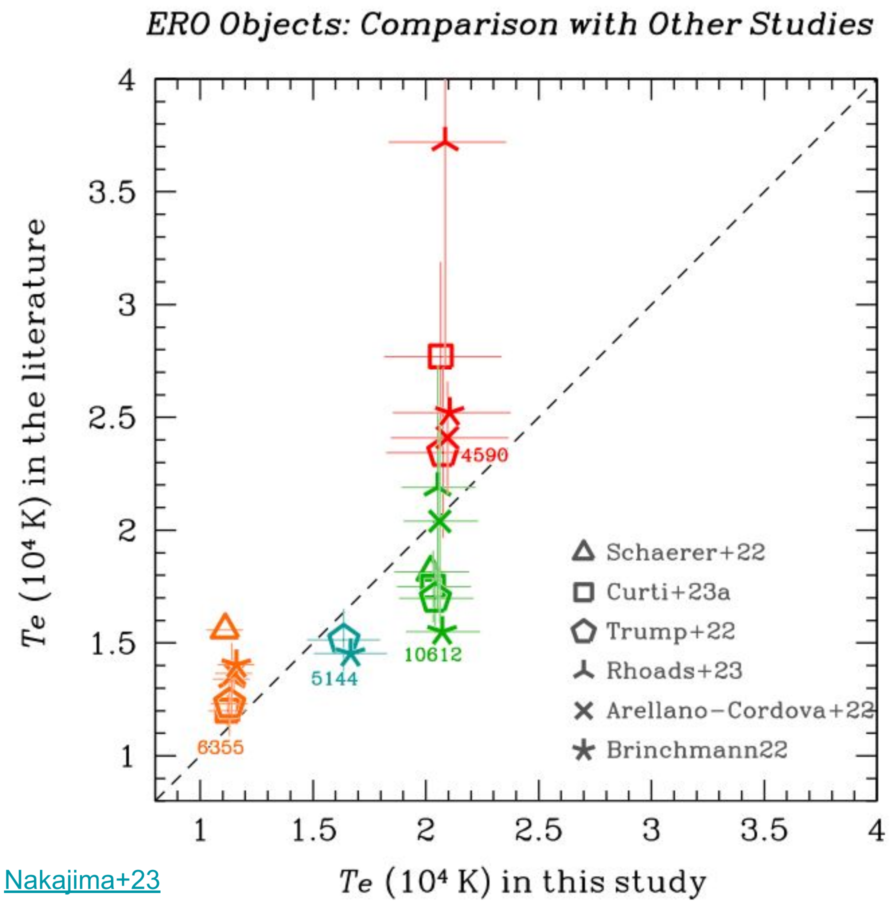
High electron temperature

Te high but not unphysically high

- Nakajima+23 that “carefully reduce and combine the spectra, as well as to extract the 1D” spectra revises down extremely high Te by previous work, all < 2.1E4 K
- Alleviating need for extraordinary radiation source like high-mass X-ray binary or high CR (e.g. Katz+23)

Possible AGN

- [Ne IV] line, blueshifted C IV trough in GN-z11 (Maiolino+23)

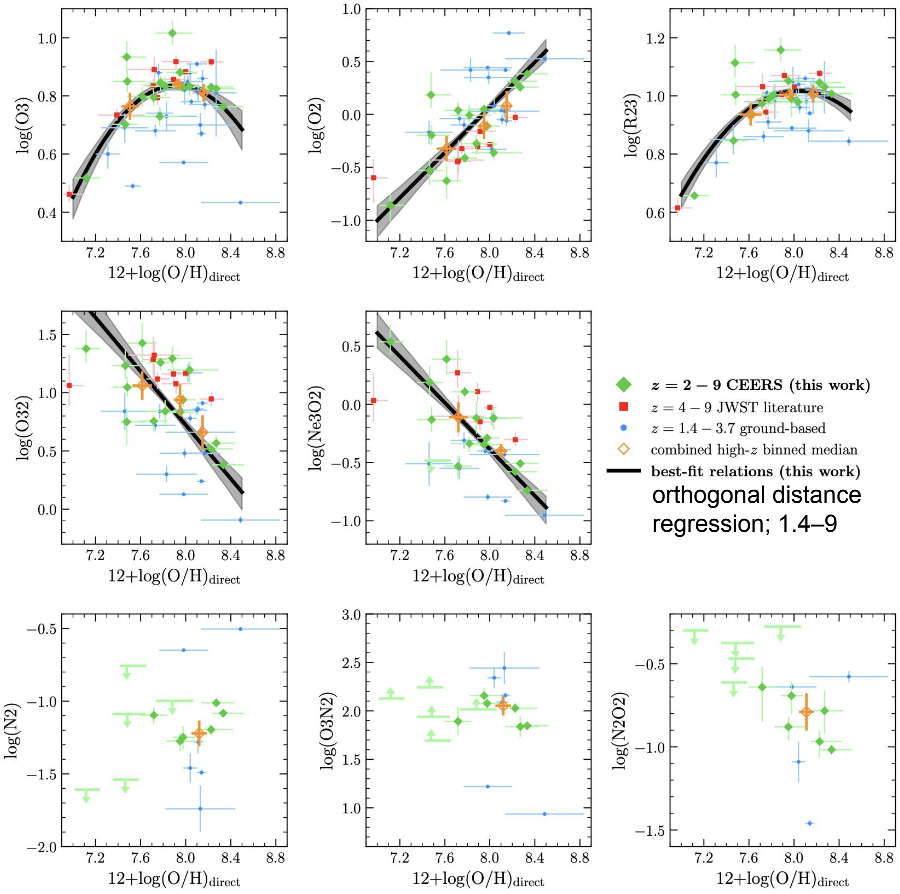


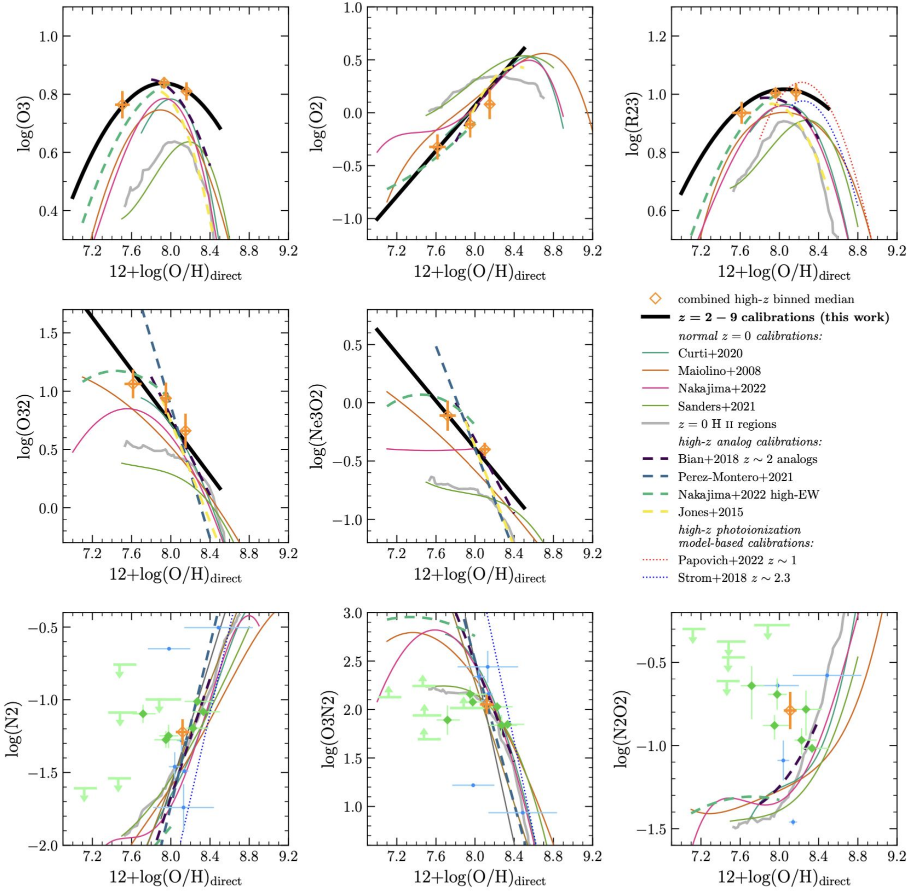
Nakajima+23

Metallicity

Robust metallicity calibration

- Te -> emissivity -> “direct” measurement of oxygen abundance
- Calibrating empirical relations (e.g. Sanders+23, Nakajima+23)
- Similar behavior as z>2
- Compared to z=0, oxygen based relation offset to higher ionization state, but similar to dwarf; nitrogen based relation doesn’t work well


z = 2 – 9 CEERS (this work)
z = 4 – 9 JWST literature
z = 1.4 – 3.7 ground-based
combined high-z binned median
best-fit relations (this work)
orthogonal distance regression; 1.4–9
log(O3)
log(O2)
log(R23)
log(O32)
log(Ne3O2)
log(N2)
log(O3N2)
log(N2O2)
12+log(O/H)direct


combined high-z binned median
z = 2 – 9 calibrations (this work)
normal z = 0 calibrations:
Curti+2020
Maiolino+2008
Nakajima+2022
Sanders+2021
z = 0 H II regions
high-z analog calibrations:
Bian+2018 z ∼ 2 analogs
Perez-Montero+2021
Nakajima+2022 high-EW
Jones+2015
high-z photoionization model-based calibrations:
Papovich+2022 z ∼ 1
Strom+2018 z ∼ 2.3
12+log(O/H)direct

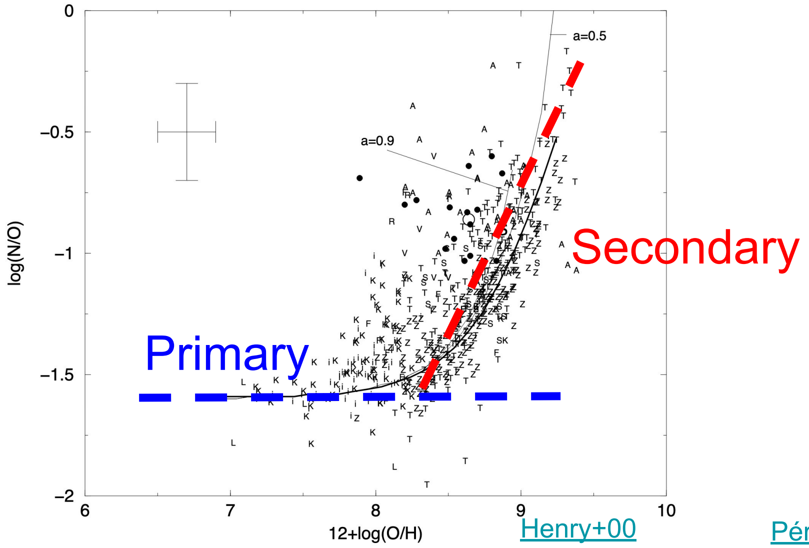
Sanders+23

Metallicity

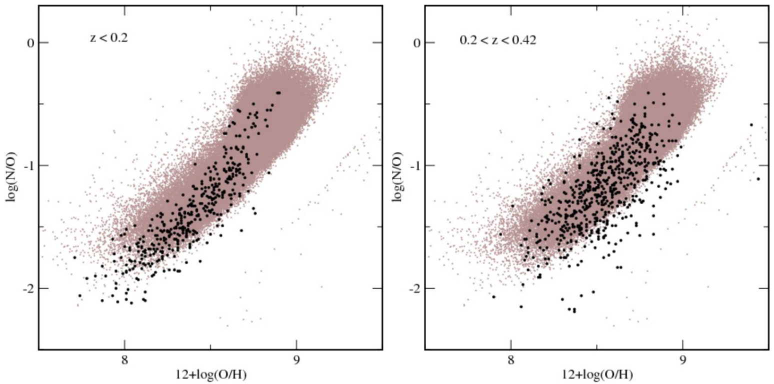
Robust metallicity calibration

Enhanced N/O?

- N III] λ1748/O III] λλ1660 -> N++/O++ (N++ 29.60 – 47.44 eV, O++ 35.12–54.94 eV) -> N/O
- O/H–N/O relation: O is primary production; N is primary (SN) + secondary (intermediate mass star, delayed) production
- Weak (if any) evolution in O/H–N/O up to z<0.42 (Pérez-Montero+13)



Henry+00



Pérez-Montero+13

Fig. 13. Relation between 12+log(O/H) and log(N/O) for the star-forming selected SDSS galaxies (in brown) and for zCOSMOS for $z < 0.2$ (black dots in *left hand panel*) and for $0.2 < z < 0.42$ (*right hand panel*).

Metallicity

Robust metallicity calibration

Enhanced N/O?

- GN-z11, N/O > 5 solar N/O (Bunker+23)
- Others (3/70) have high N/O @z>6, with extremely low C/N (Isobe+23)
- Enhanced N/O by ejecting CNO material, through WR star (Senchyna+23), supermassive stars (Charbonnel+23), TDE (Cameron+23), runaway stellar encounter in dense cluster (Cameron+23)?

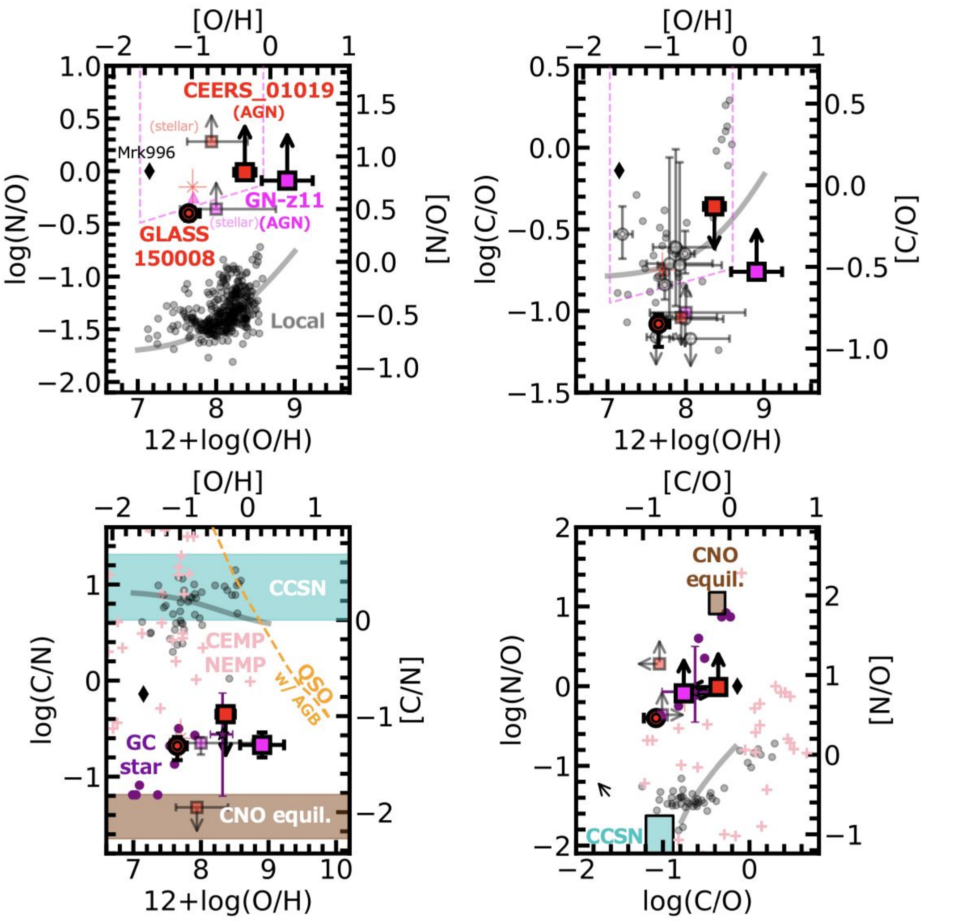


Figure 6. N/O (top left), C/O (top right), C/N (bottom left) as a function of 12 + log(O/H). N/O as a function of C/O (bottom right). The double red circle denotes the measurements of GLASS_150008 based on the stellar photoionization model. The measurements of CEERS_01019 (red square) and GN-z11 (magenta square) are based on the AGN photoionization models, while those based on the stellar photoionization models are shown by the semi-transparent red and magenta squares, respectively. The semi-transparent magenta dashed lines, magenta triangle, and red crosses are the abundance measurements of GN-z11 by Cameron et al. (2023), GN-z11 by Senchyna et al. (2023), and CEERS_01019 by Marques-Chaves et al. (2023), respectively, all of which are based on the stellar radiation. In the top right panel, C/O ratios of other galaxies in our sample are shown by the semi-transparent white circles. The double circles correspond to the measurements with T_e determinations. Mrk996, a Wolf-Rayet galaxy, is represented by the black diamonds (Senchyna et al. 2023; Berg et al. 2016). Local galaxies (Berg et al. 2016; Berg et al. 2019; Izotov et al. 2006) and Galactic H II regions (García-Rojas & Esteban 2007) are shown by the gray dots, while the gray curves are the empirical relation of the Galactic stars (Nicholls et al. 2017). The purple circles are dwarf stars in a globular cluster (GC) NGC6752 (Carretta et al. 2005), while those O/H values are taken from Senchyna et al. (2023). The purple stars show abundance ratio distributions of dwarf stars in a metal-rich GC 47 Tuc (Briley et al. 2004; D'Orazi et al. 2010). The pink pluses are carbon-enhanced metal-poor (CEMP) stars (Norris et al. 2013) and nitrogen-enhanced metal-poor (NEMP) stars (Beveridge & Sneden 1994). The cyan and brown shaded regions indicate yields of CCSN (Watanabe et al. 2023) and the equilibrium value of the CNO cycle (Maeder et al. 2015), respectively. The orange dashed line shows a chemical evolution model that reproduces emission-line ratios of quasars (Hamann & Ferland 1993), while nitrogen enrichment in the model is mainly caused by asymptotic giant branch (AGB) stars. The potential change of N/O and C/O by dust depletion (Ferland et al. 2013) is indicated by the length of the small black arrow at the bottom left corner of the bottom right panel.

Isobe+23

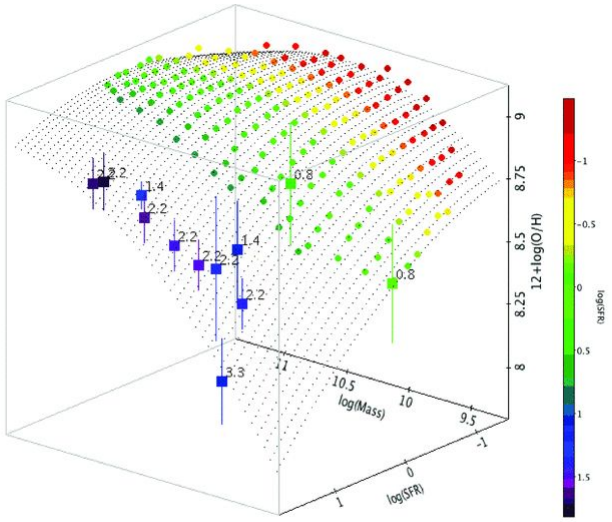
Metallicity & FMR

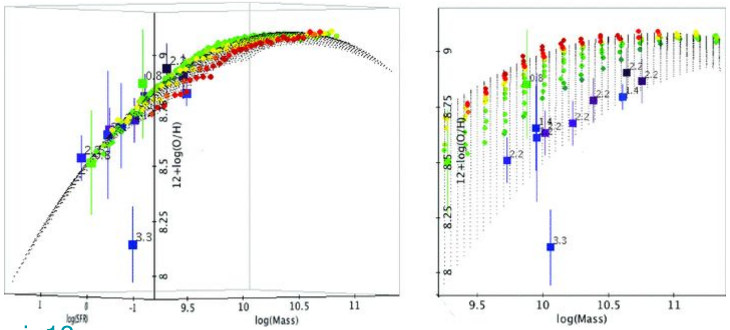
Robust metallicity calibration

Enhanced N/O?

Fundamental metallicity relation

- O/H ~ M* - SFR^0.5 (Mannucci+10, Curti+20)
- MZR: result of FMR and SF MS evolution
- An equilibrium state between accretion (fueling SF), outflow (ejecting metal), and enrichment history (Dayal+13)
- No evidence of evolution up to z~3.5 (e.g. Sanders+20)





Mannucci+10

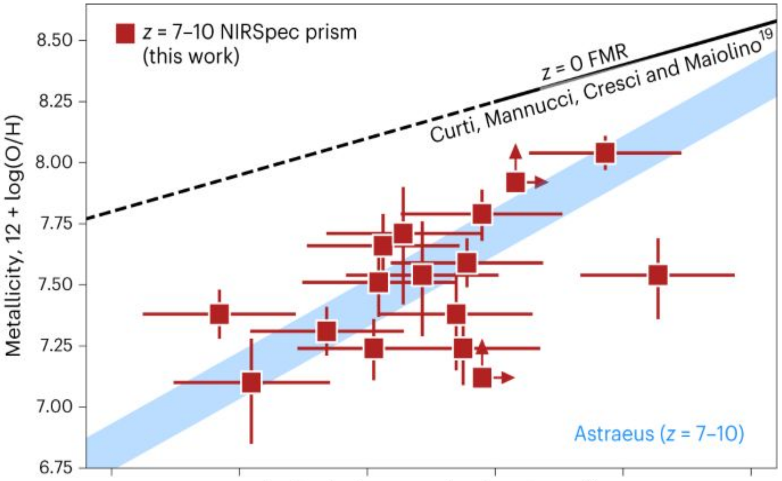
Metallicity & FMR

Robust metallicity calibration

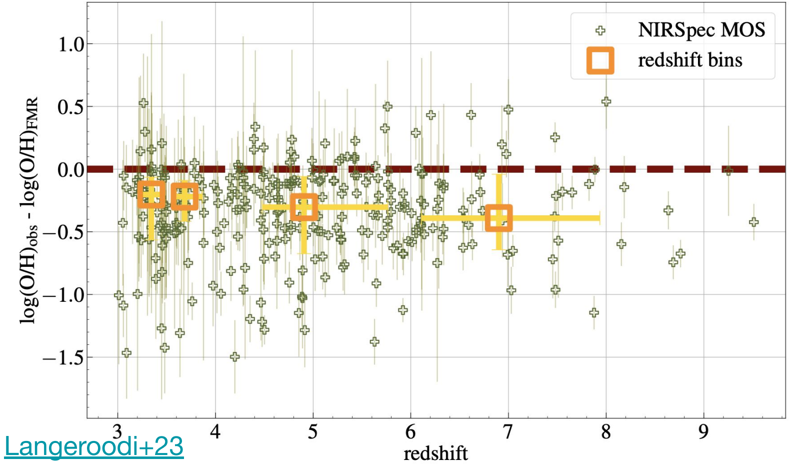
Enhanced N/O?

Fundamental metallicity relation

- See clear offset @z>7, and mild evolution from z=3 (Heintz+23 w/ O3, Nakajima+23 and Curti+23 proper calibration, Langeroodi+23 bigger sample)
- Suggesting strong accretion not in equilibrium



Heintz+23

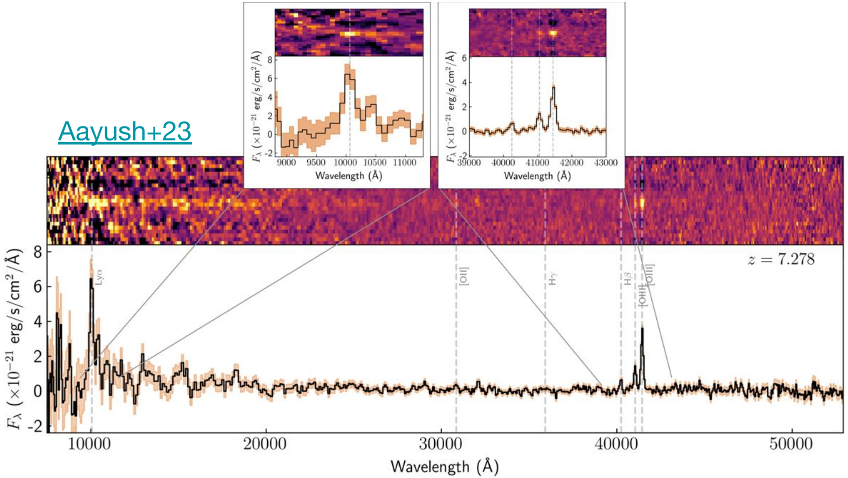


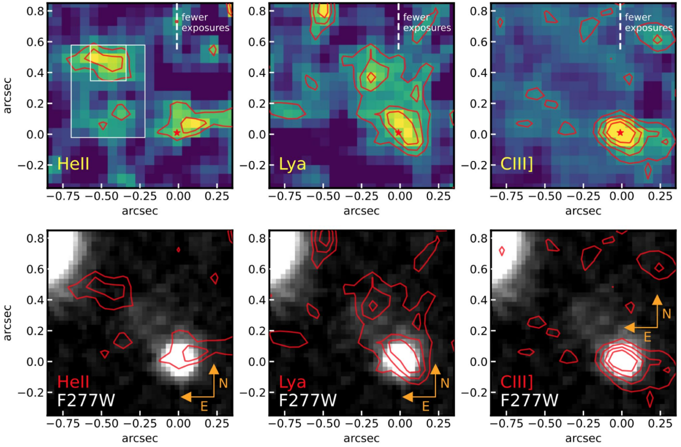
Langeroodi+23

EW

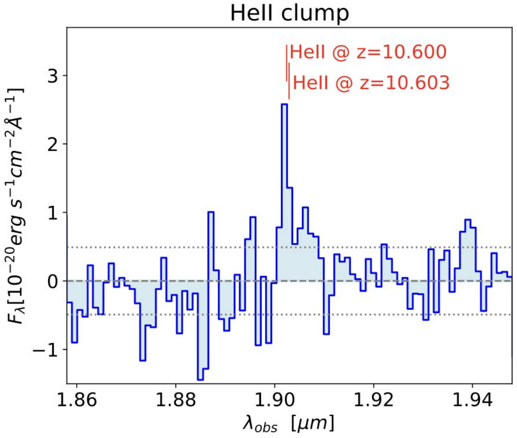
- High-EW Lyα (388 Å), small Lyα offset (113 km/s) in a z=7.28 galaxy, little H I in galaxy, located in an ionized bubble (Aayush+23)
- GN-z11, large He II EW offset from center, pop III star? (Maiolino+23)

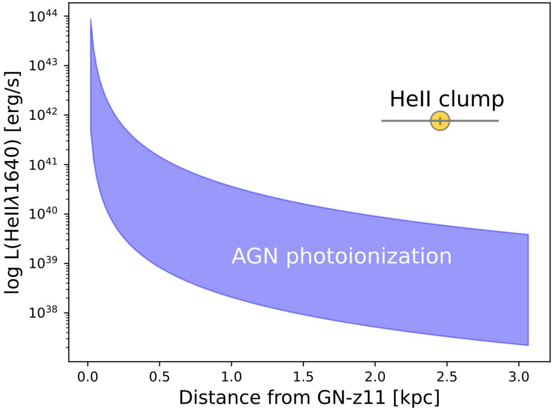
Aayush+23





Maiolino+23





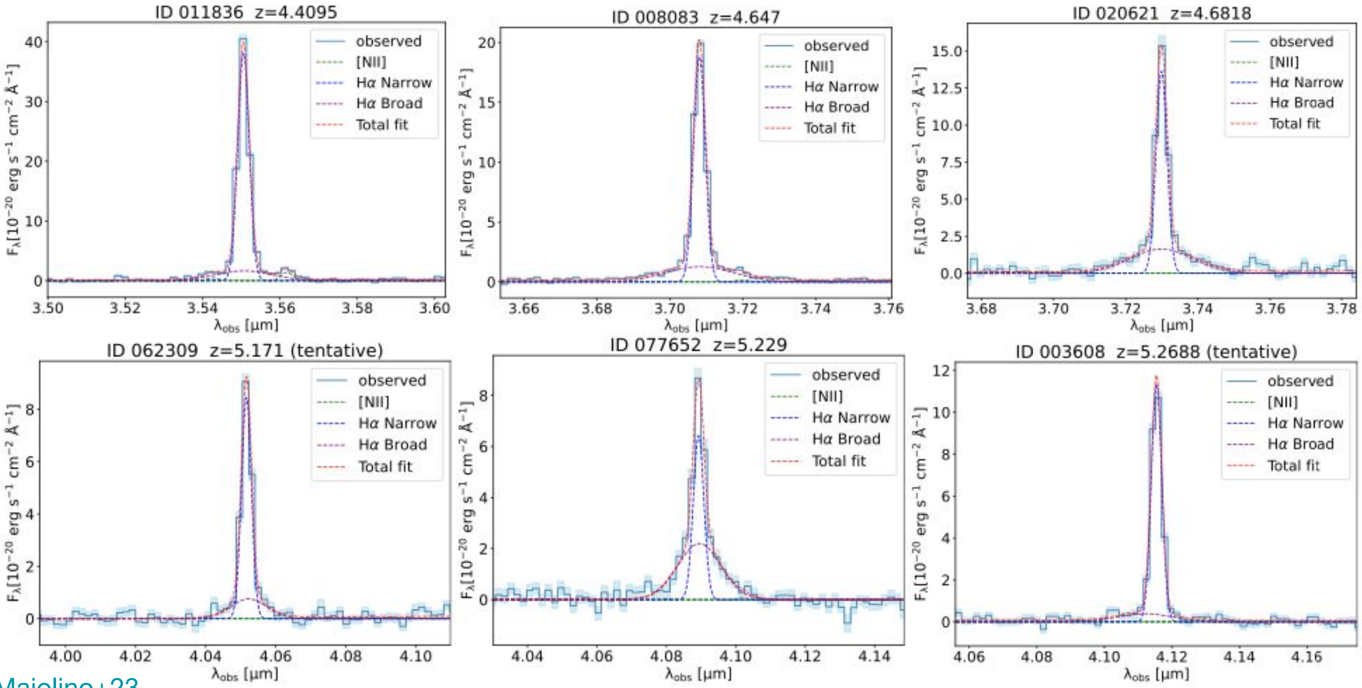
What we (might) have learnt about galaxies in the early universe w/ JWST spectroscopy

- Spec-z is important, be cautious w/ photo-z
- Galaxies in early universe have high ionization state, low-metallicity and hot gas
- Some w/ potentially enhanced N/O, strong WR presence?
- A potential evolution in FMR, suggesting strong accretion

https://highz.space

Line Profile

Looking for black hole: 12 broad Hα sources @z=4.4~6.8, lying at the low-mass locus in BPT diagram (Maiolino+23)



Maiolino+23