Focus on: The Earliest Star Formation

Alice Shapley UCLA

Image credit: NASA, ESA, CSA, and STScI

The Spectroscopic Revolution in Our Understanding of Star formation at High Redshift

Alice Shapley UCLA

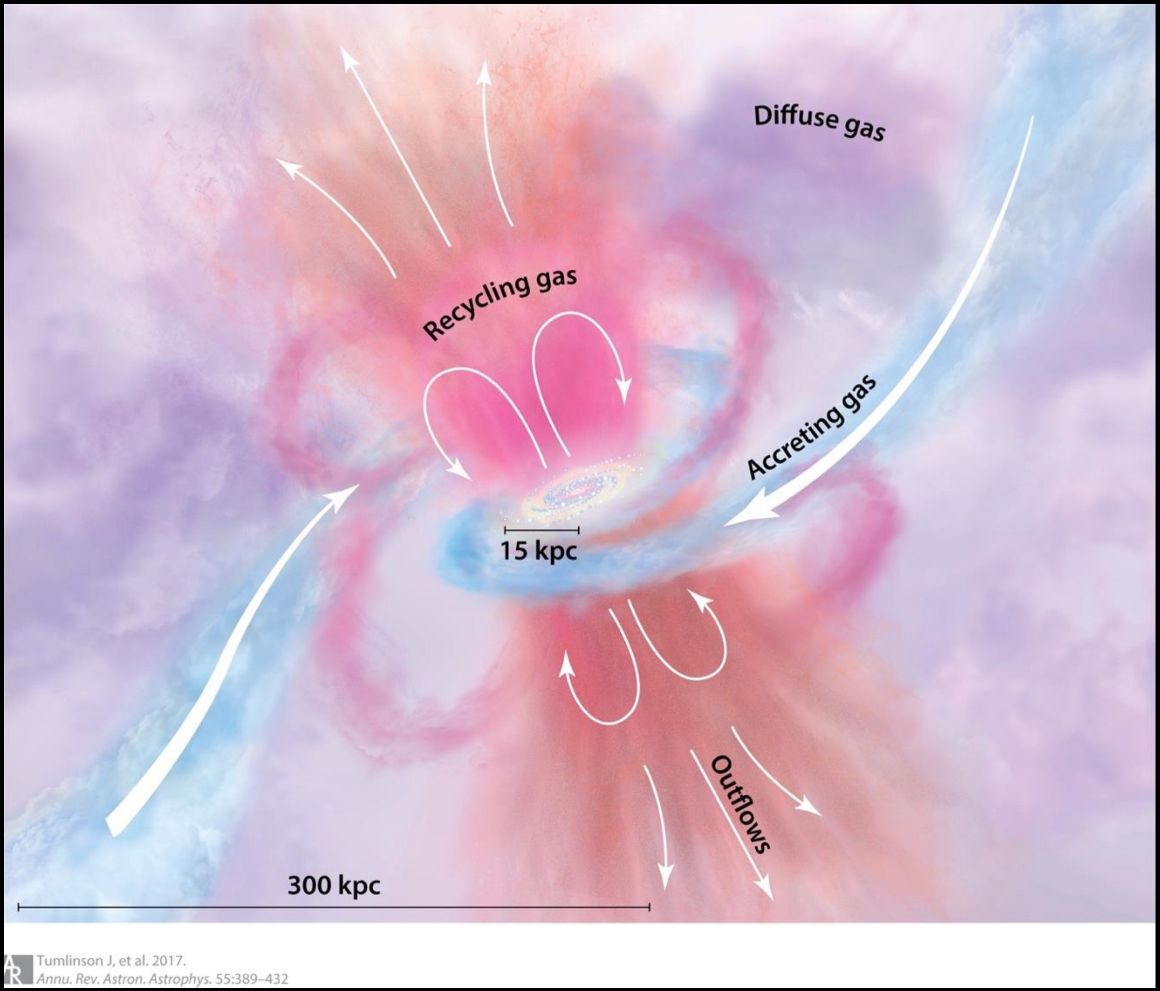
Image credit: NASA, ESA, CSA, and STScI

It’s the Spectra, Stupid!

Alice Shapley UCLA

Image credit: NASA, ESA, CSA, and STScI

Big Questions



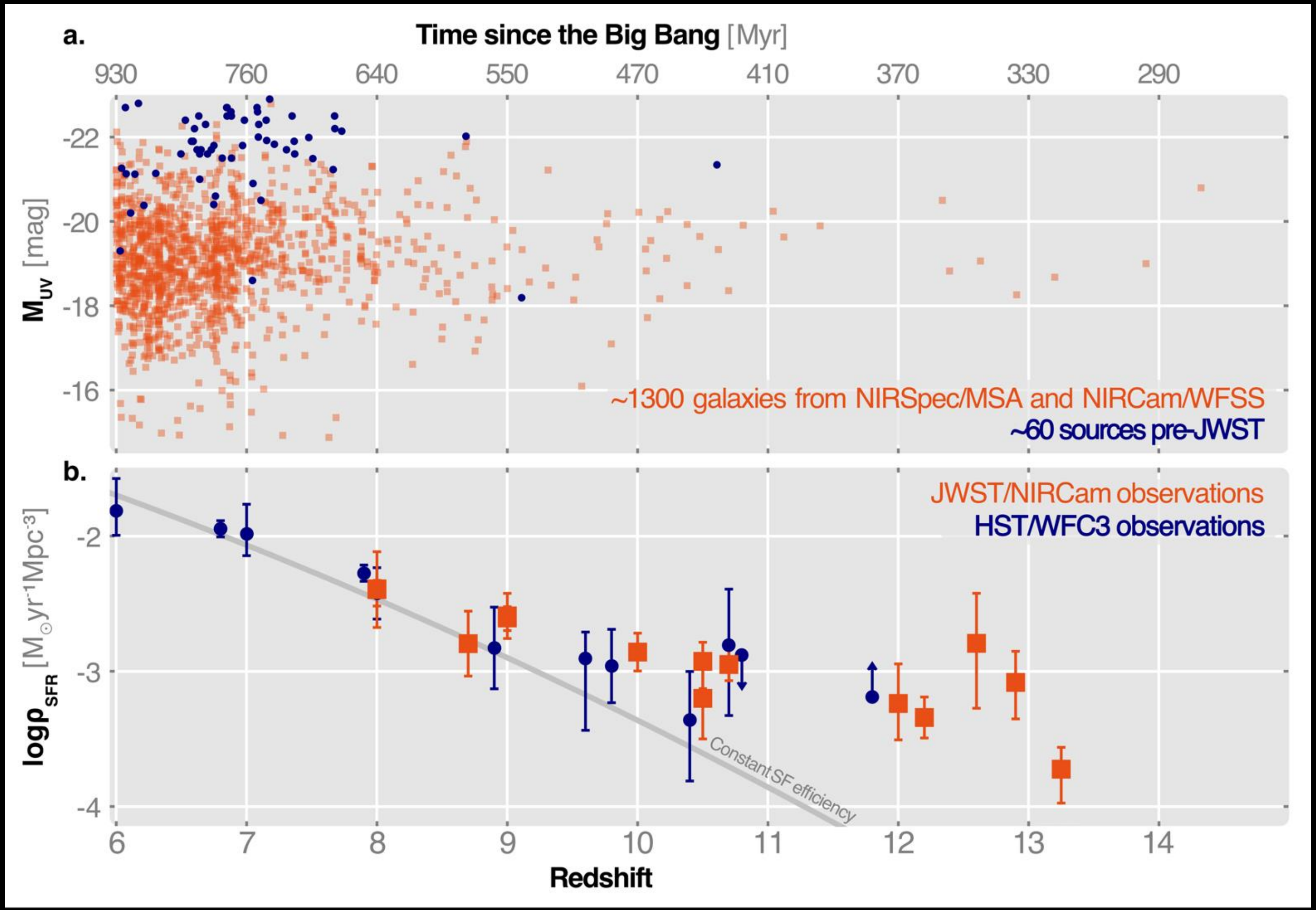
How do baryons cycle through galaxies?

How are galaxies assembled?

Tracing star formation in early galaxies addresses these key questions.

Bursty Star formation at High Redshift

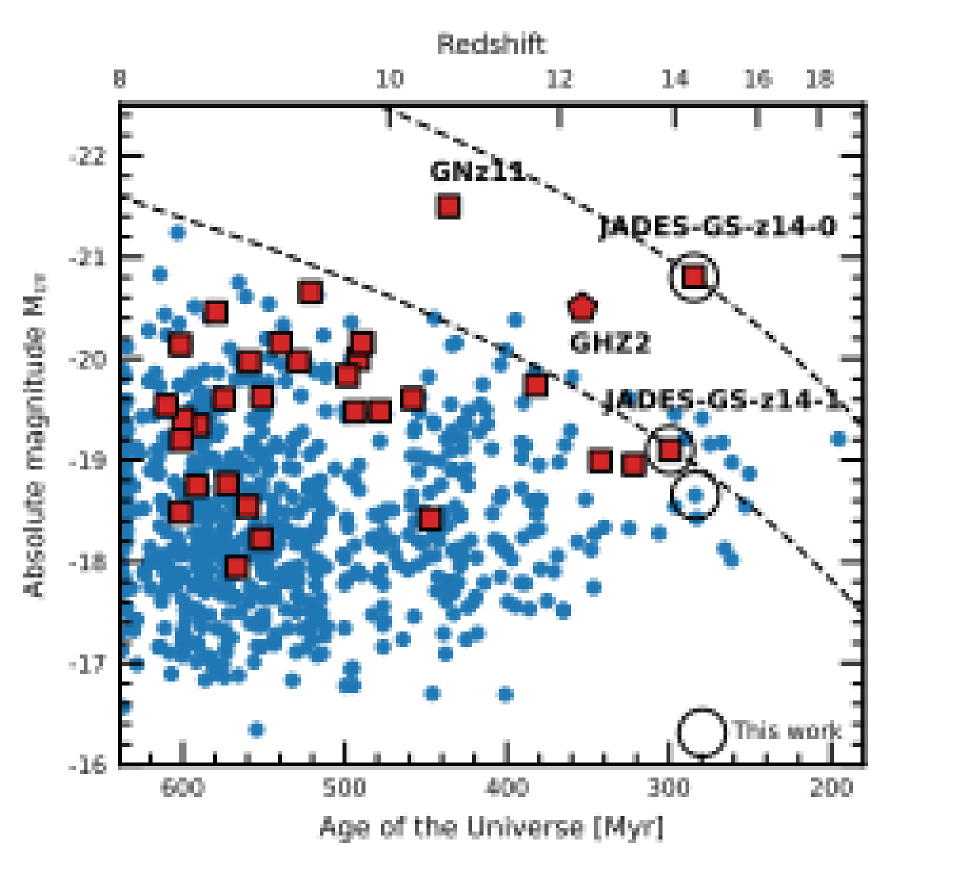
Adamo et al. 2024



Excess of UV luminous galaxies relative to pre-JWST predictions.

Bursty Star formation at High Redshift

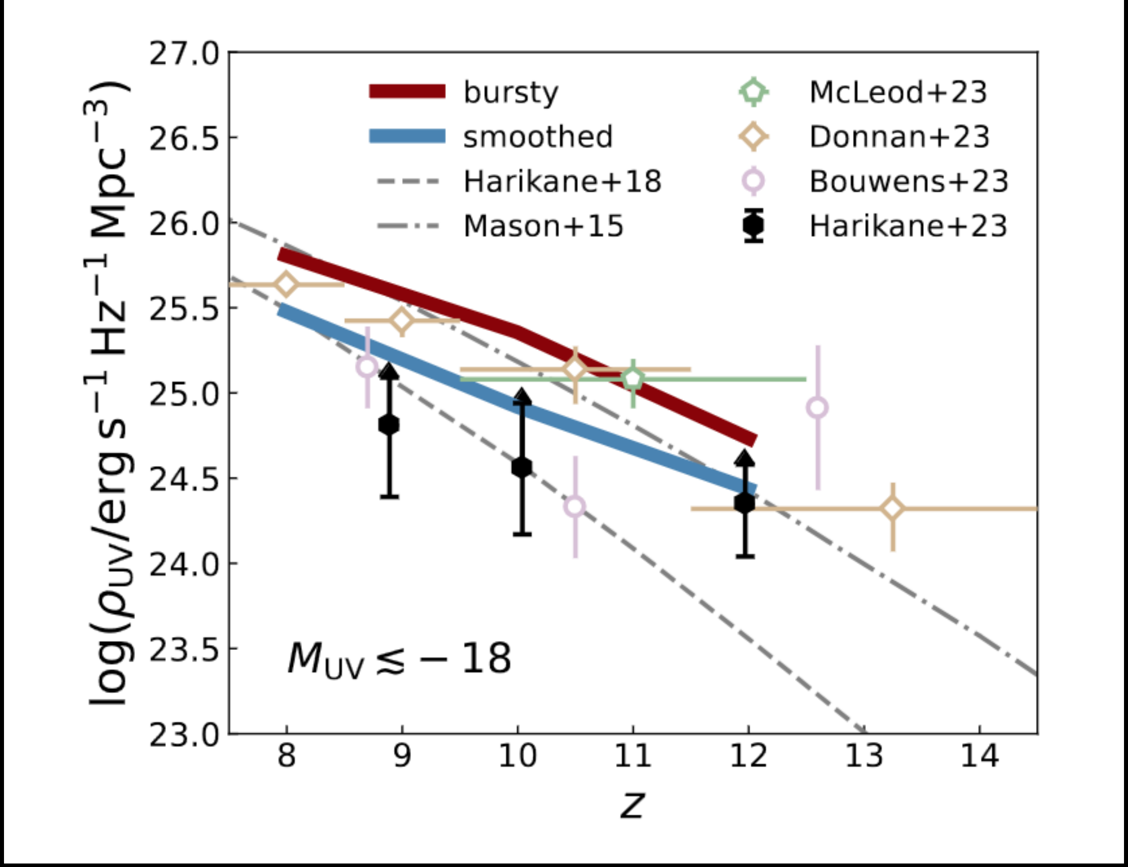
Carniani et al. 2024



Excess of UV luminous galaxies relative to pre-JWST predictions.

Bursty Star Formation in Simulations

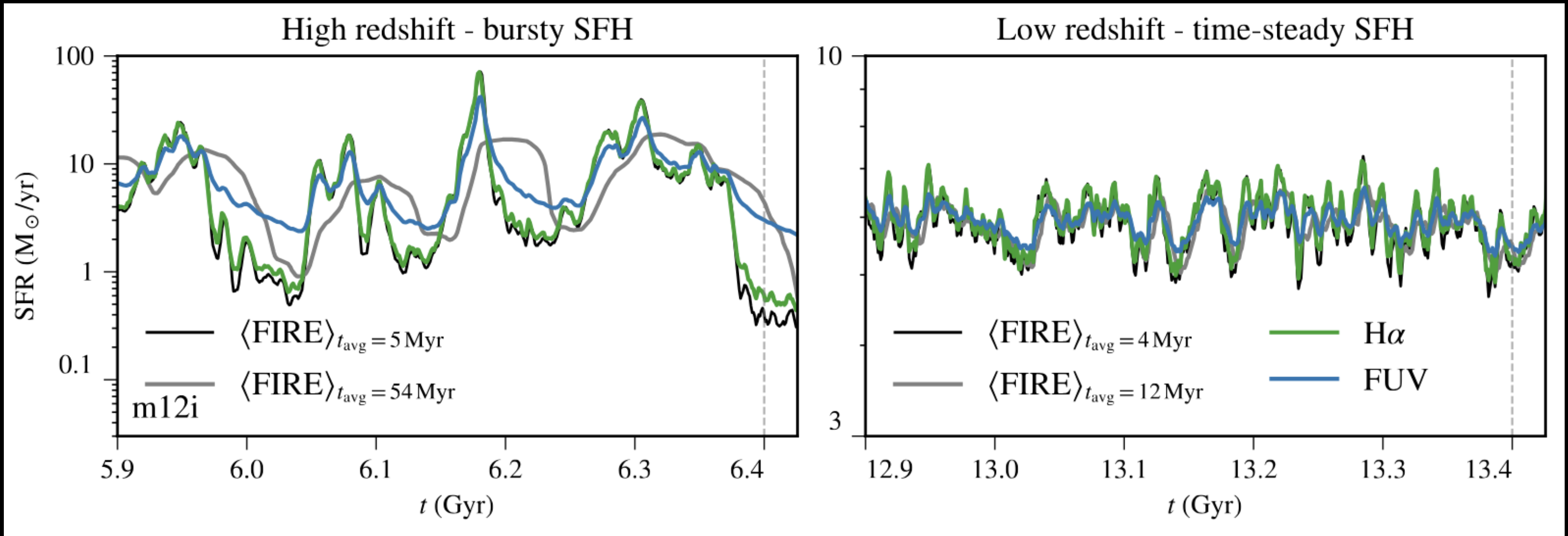
Sun et al. 2023



- **Models with bursty star-formation histories (red line) can reproduce the evolution of the UV luminosity density at z>10 (e.g., FIRE-2 simulations).**
- **Generally predictions are for more burstiness at higher redshift and lower mass.**

Bursty Star Formation in Simulations

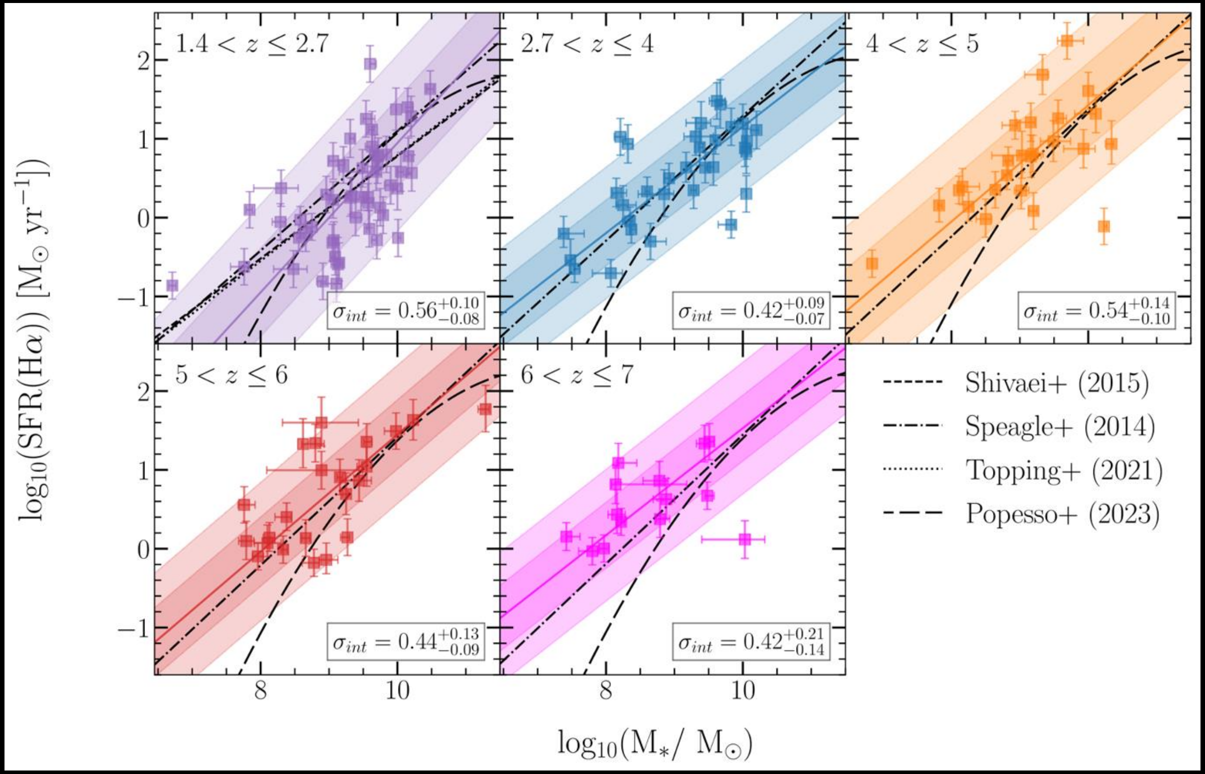
Flores Velazquez et al. 2021



- Hα closely traces the true SFR on ~5-10 Myr timescales.
- UV light traces the true SFR on ~50-100 Myr timescales.

- There should be a measurable difference in the Hα-based SFRs vs. the UV-based SFRs if star formation is bursty.

Bursty SF Histories: Balmer Lines Back to Cosmic Dawn:



No mass dependence in the scatter.

(Clarke et al. 2024)

- **Public JADES+CEERS samples: 146 galaxies at z=1.4-7 with robust SFR(Hα), SFR(UV), M$_*$ → the "main sequence" tracing galaxy growth.**
- **SFR(Hα) suggests significantly more scatter → bursty SF histories.**
- **If SF histories are bursty, challenges in estimating M$_*$.**

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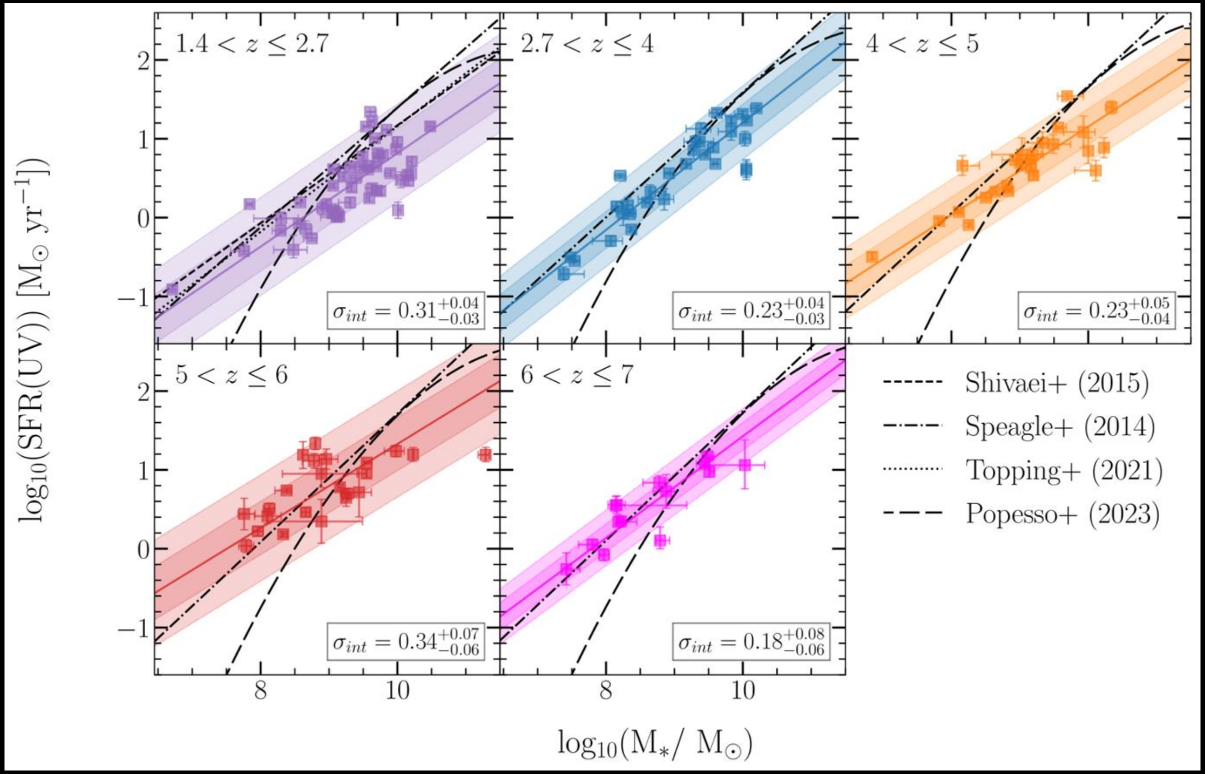

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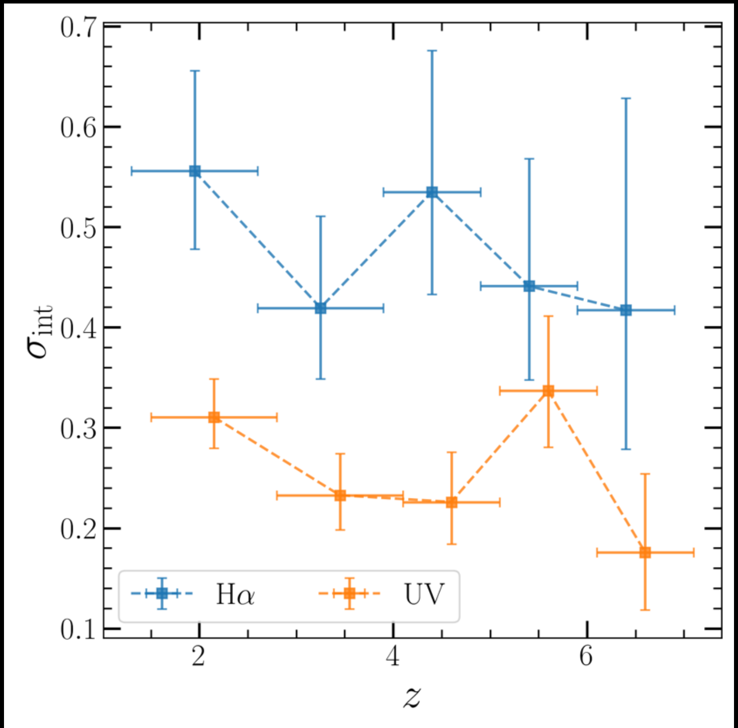
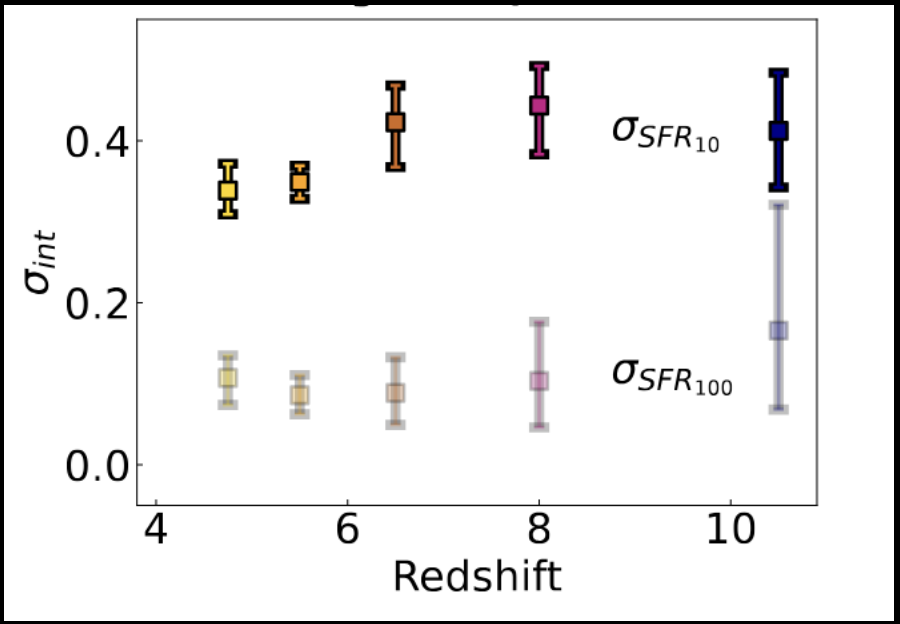


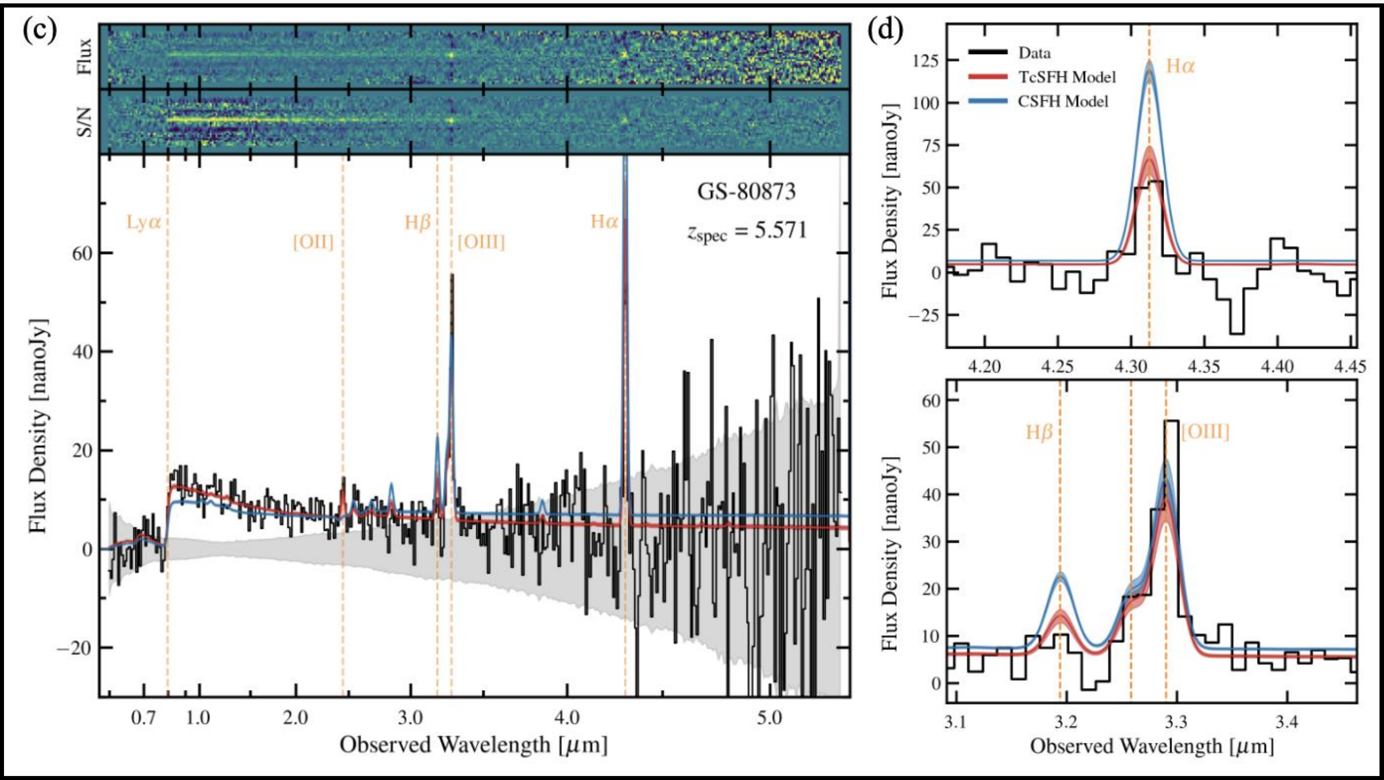
(Clarke et al. 2024)



(Cole et al. 2023)

- Intrinsic scatter higher for SFR(Hα) than SFR(UV).
- Same qualitative result for SFR_{10} vs SFR_{100} (Cole+2023).
- Bursty SF histories. What is redshift and M* dependence, though?

Bursty SF Histories: Balmer Lines Back to Cosmic Dawn:



(Endsley et al. 2024)

- Young galaxies at z~6 with low Hα/UV ratios (and low [OIII]) consistent with recent downturn in SFR --> burstiness.
- Such galaxies are more common at fainter M_{UV}.

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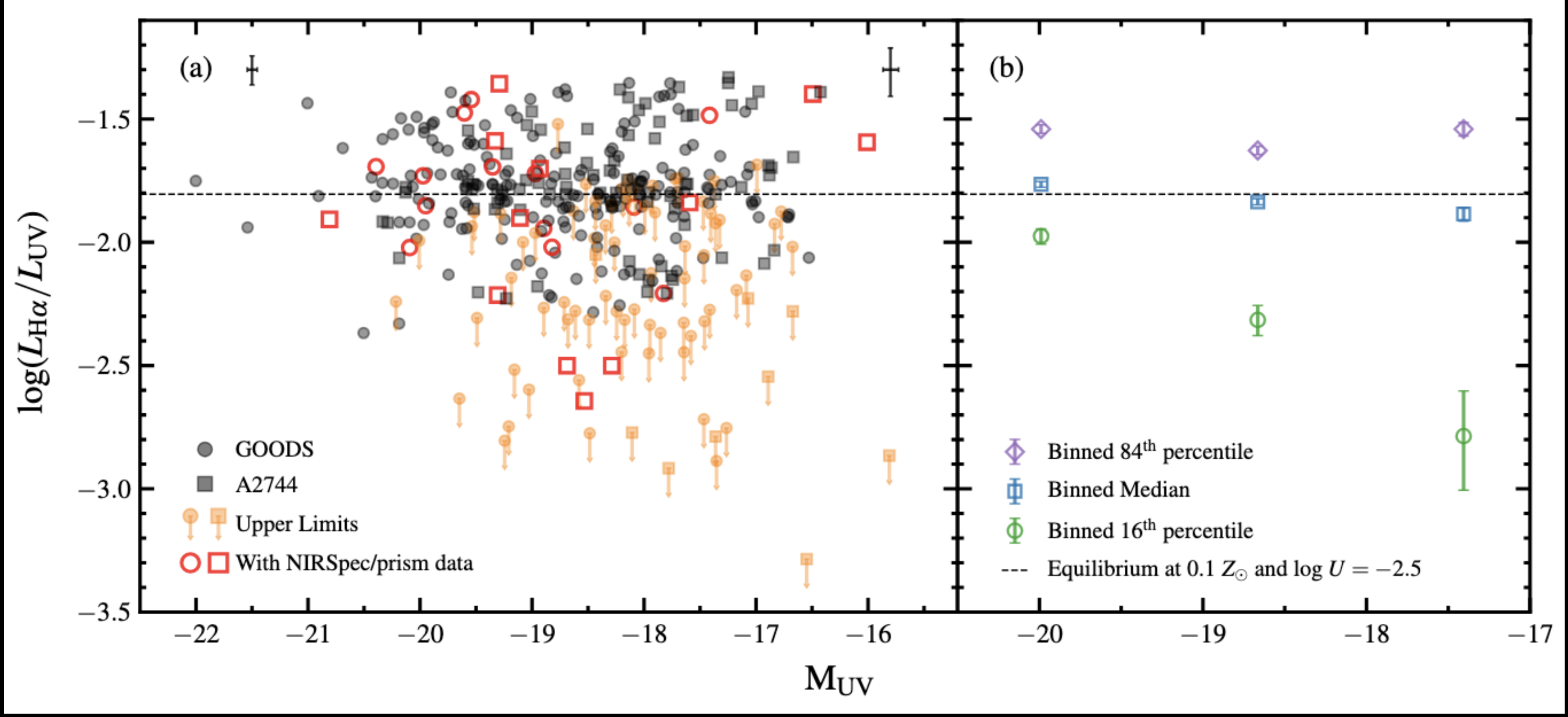

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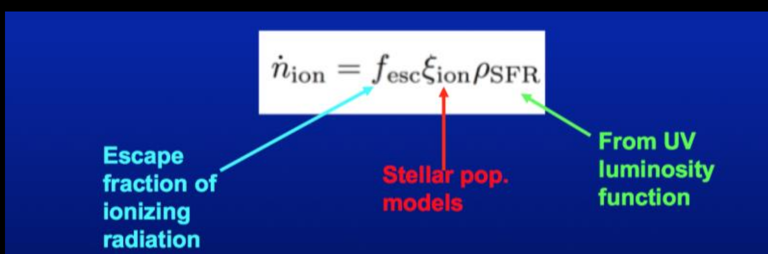
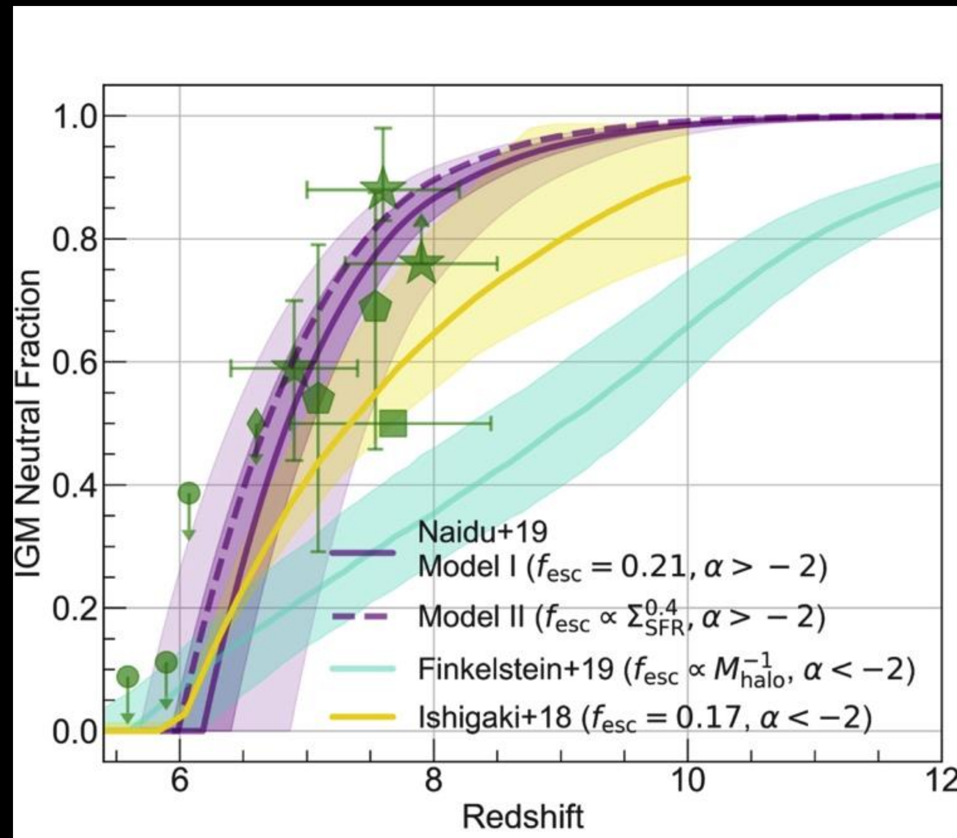
What is the timeline of reionization?

- Slow (democratic) vs. rapid (oligarchical) reionization.

- Ionizing photon production rate expressed as:



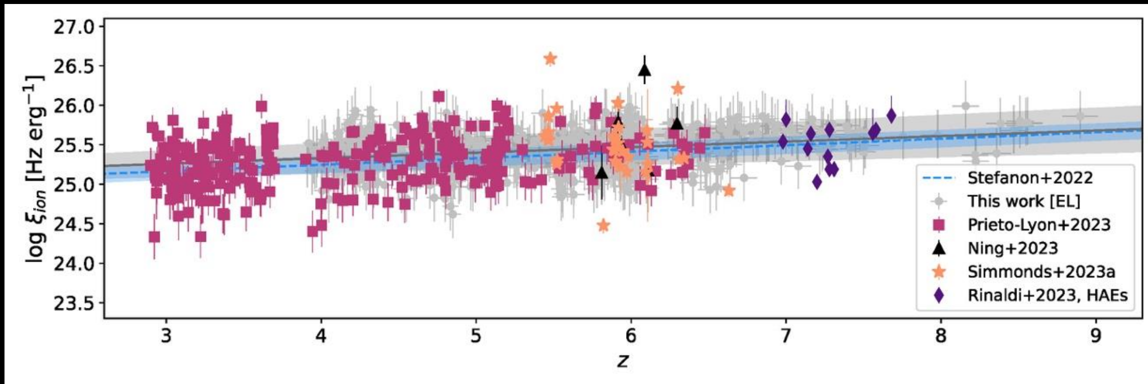
- The nature of reionization timeline determined by how ξ_{ion} and f_{esc}(LyC) depends on galaxy properties.



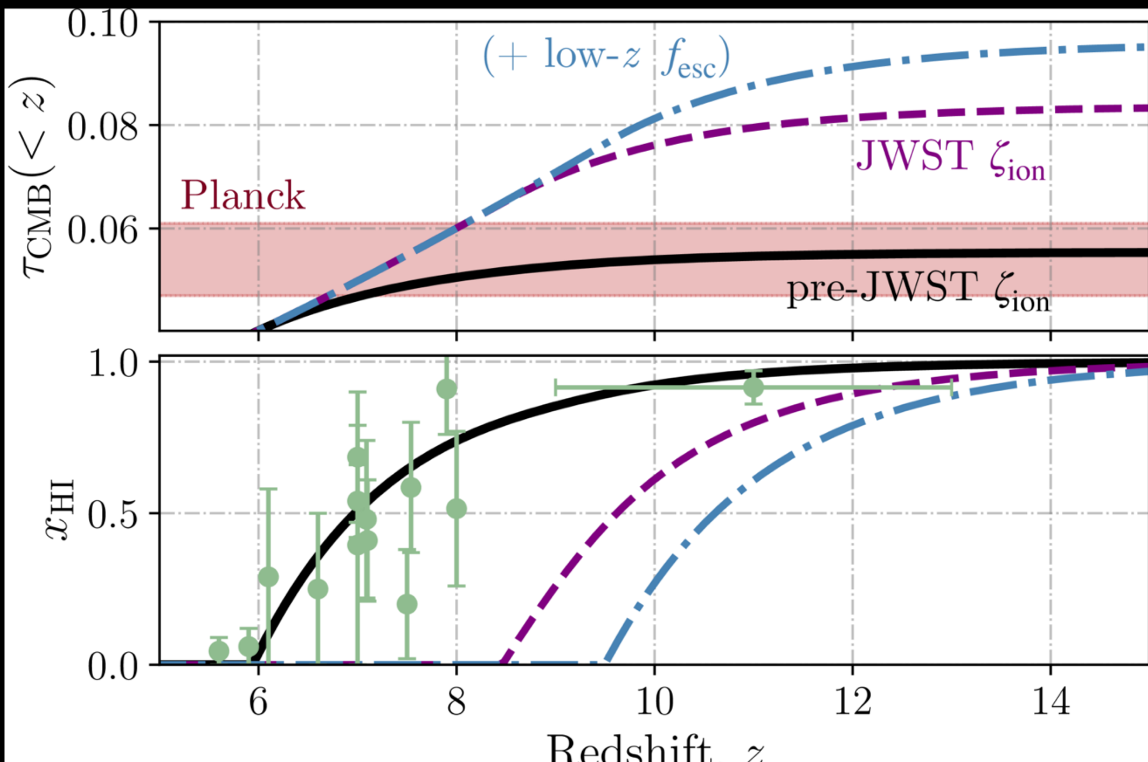
(Naidu et al. 2020)

An Ionizing Photon Budget Crisis?

(Simmonds et al. 2024a)



(Munoz et al. 2024)



- Based on initial, high estimates of ξ_{ion} from JWST, and other reasonable assumptions (LF, f_{esc} vs. galaxy properties)….reionization completes too early!
- ξ_{ion} from early JWST published work biased high. Need unbiased, spectroscopic (Hα/UV) measures.

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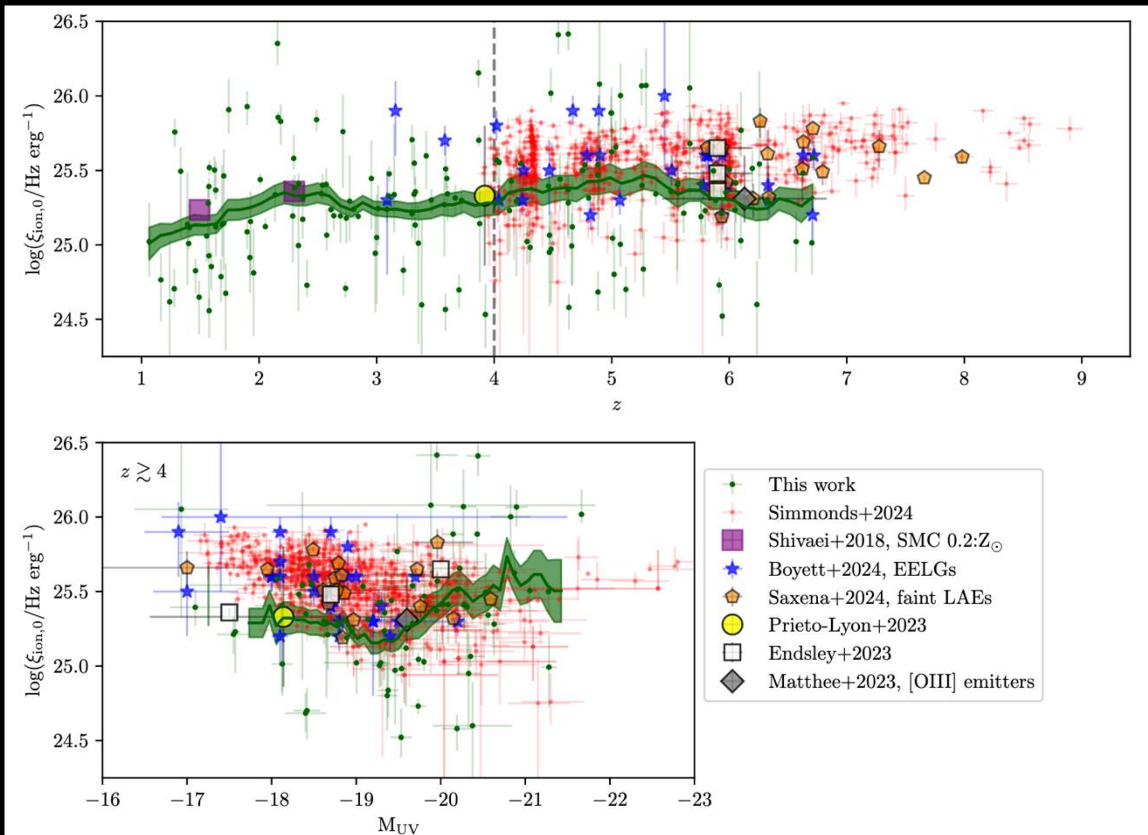

(Pahl et al. 2024; see also Simmonds+2024b)

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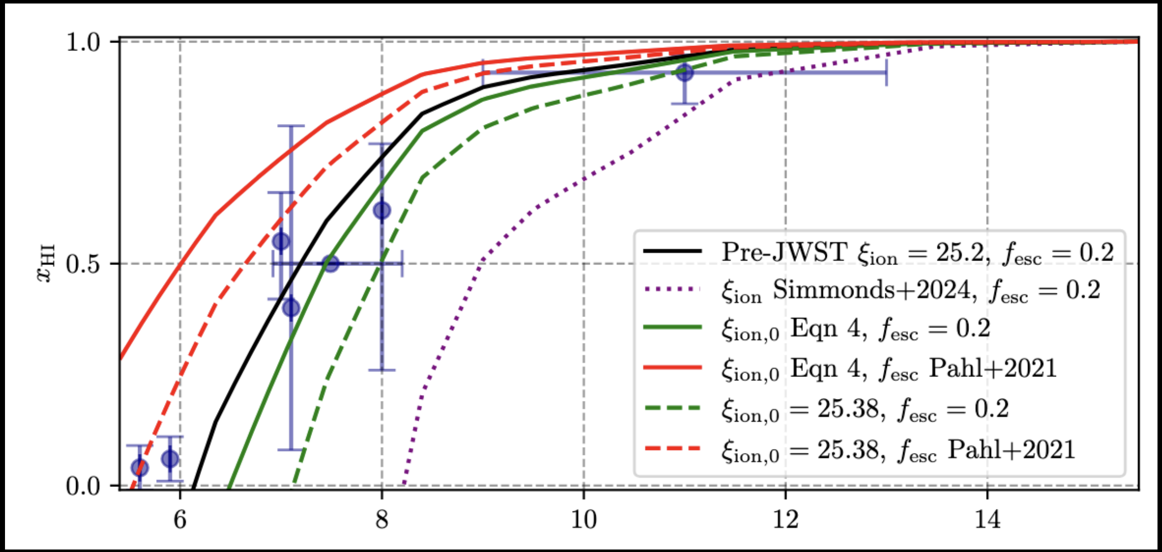

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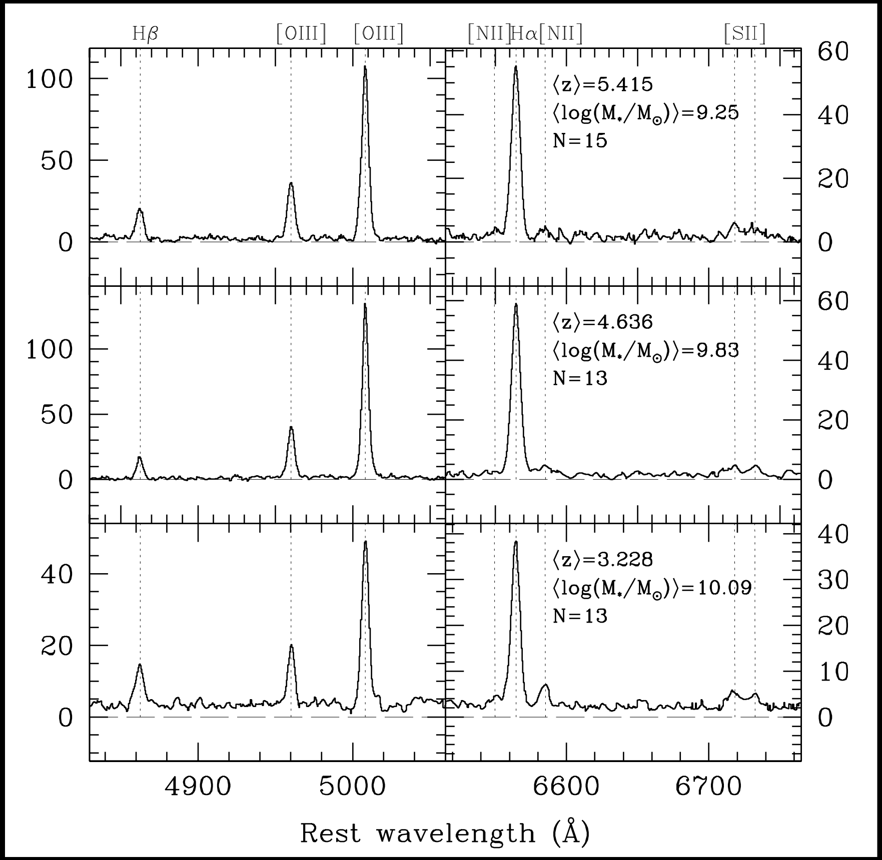
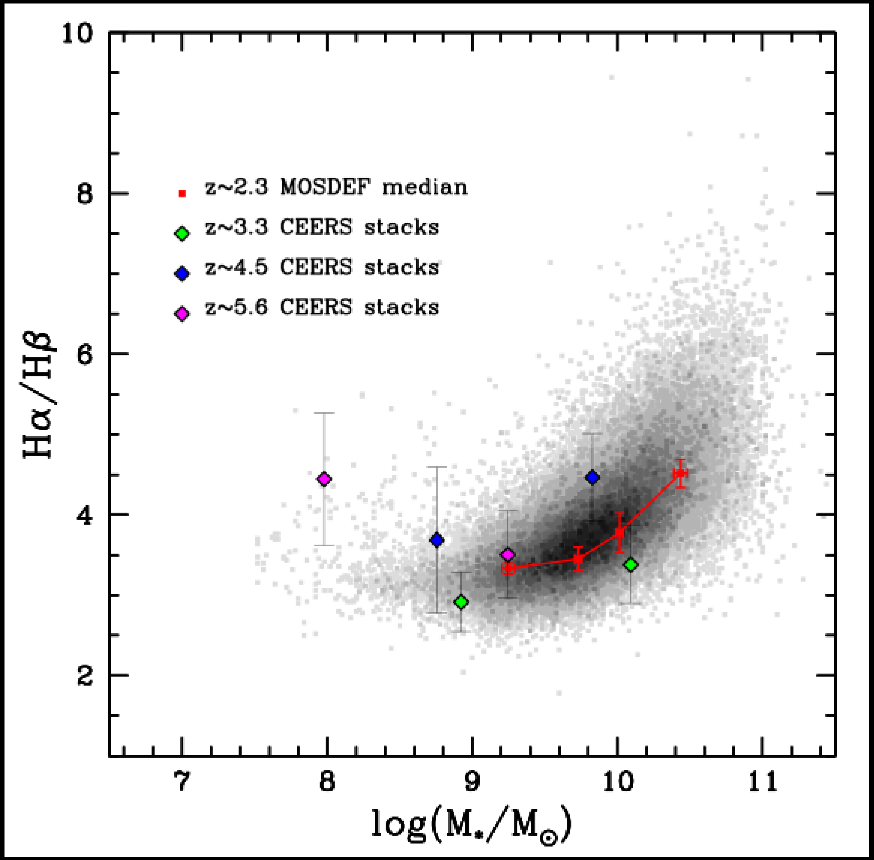
Dust and SFR

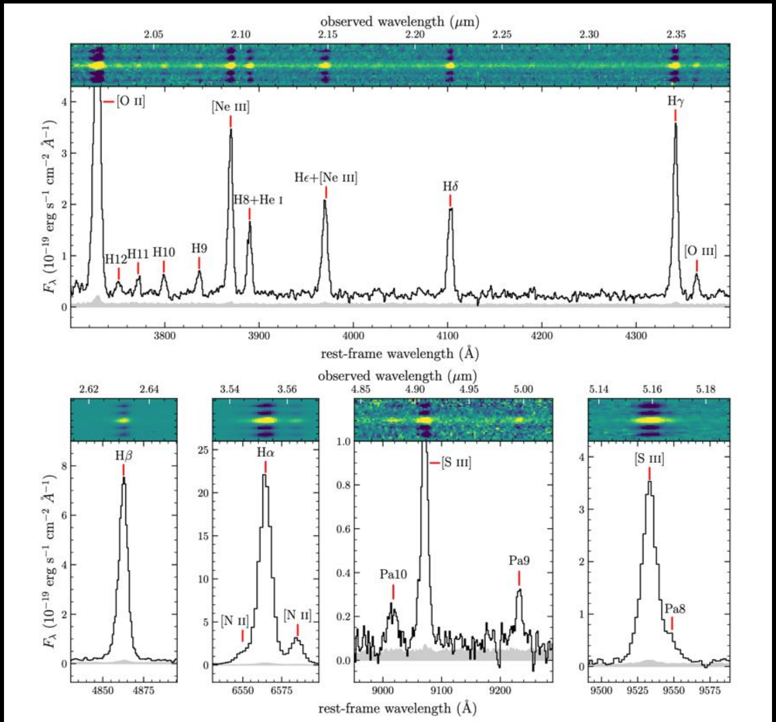
(Shapley et al. 2023a)

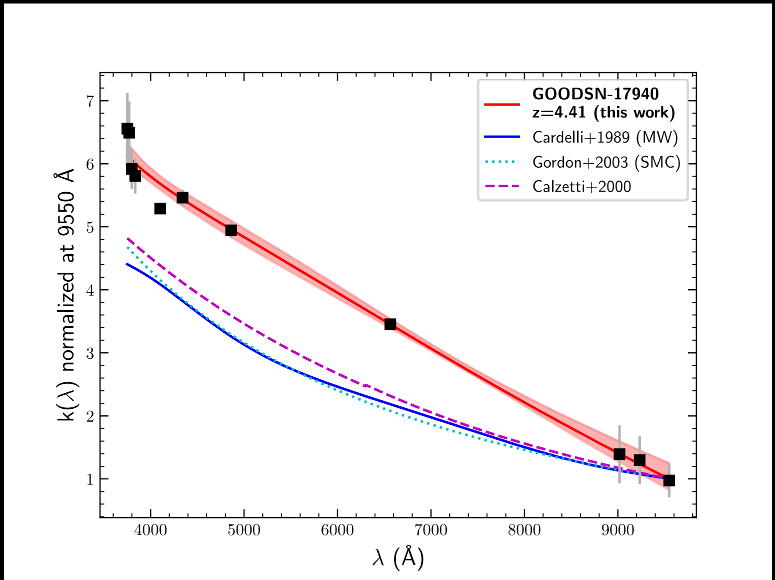




- SFR(Hα) requires dust correction.
- Initial estimates of nebular dust attenution based on Hα/Hβ.
- No clear evolution in Hα/Hβ at fixed M_* at z~3-6.5.
- Extending reach of attenuation vs. M_* relation.

Dust Attenuation curve for Individual Galaxies: z=4.4 Example





GOODSN-17940 (z=4.41) Spectrum has 70+ em/abs features detected.

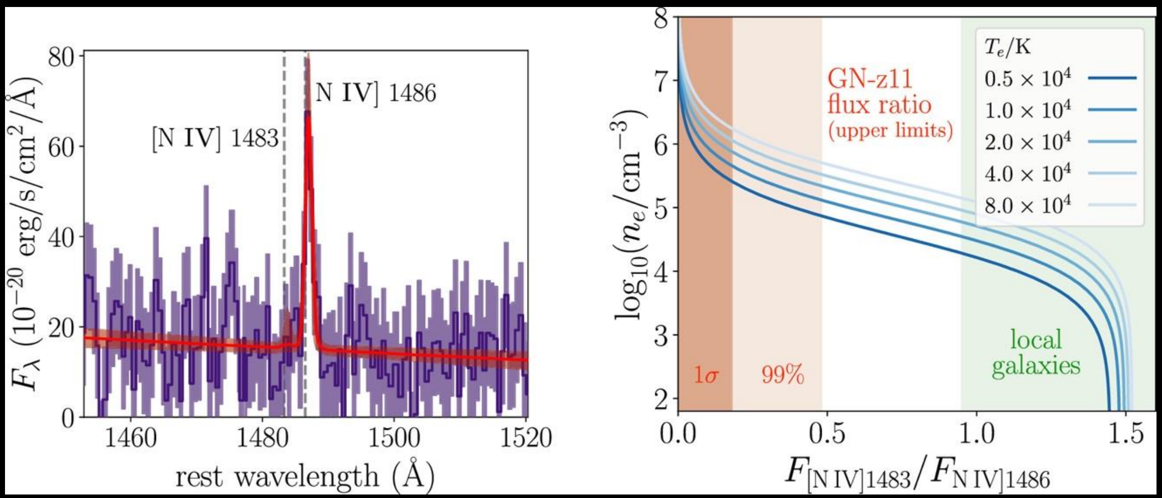
Based on 11 H recombination lines, nebular attenuation curve is not MW!

Similar analysis possible for 25 galaxies in the AURORA survey (see Naveen Reddy's talk).

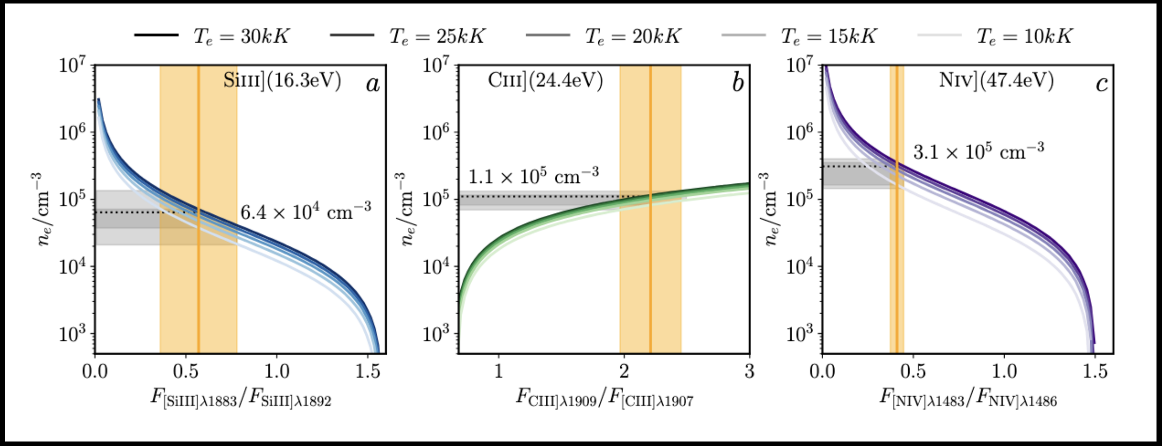
Sanders et al. 2024

Why is the density so high?

GN-z11 (z=10.6)



RXCJ2248-ID (z=6.1)



- **Exceptionally high electron densities inferred in, e.g., GN-z11 and RXCJJ2248-ID (based on UV transitions).**
- **Steady evolution in average inferred electron density vs. redshift.**
- **Meanwhile, no strong dependence of density on galaxy properties at fixed z.**

(Senchyna et al. 2023;Topping et al. 2024a)

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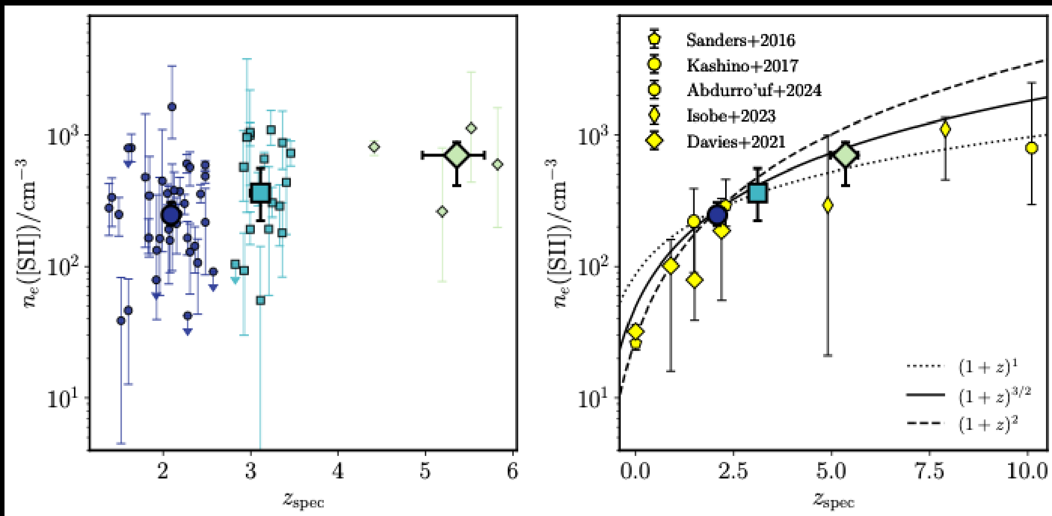

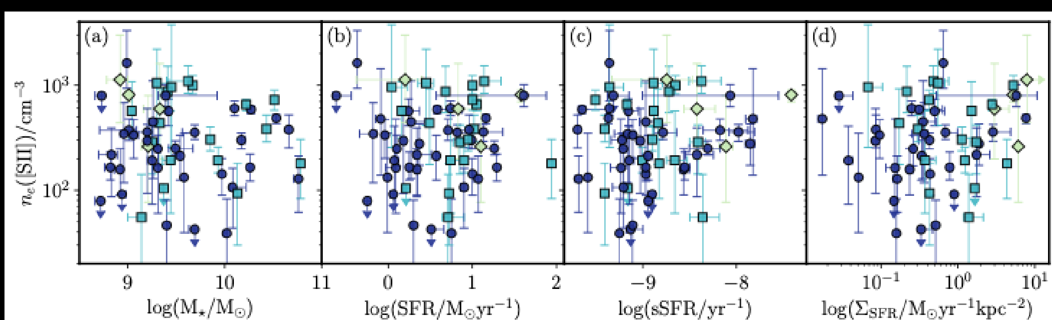

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Topping et al. 2024, in prep

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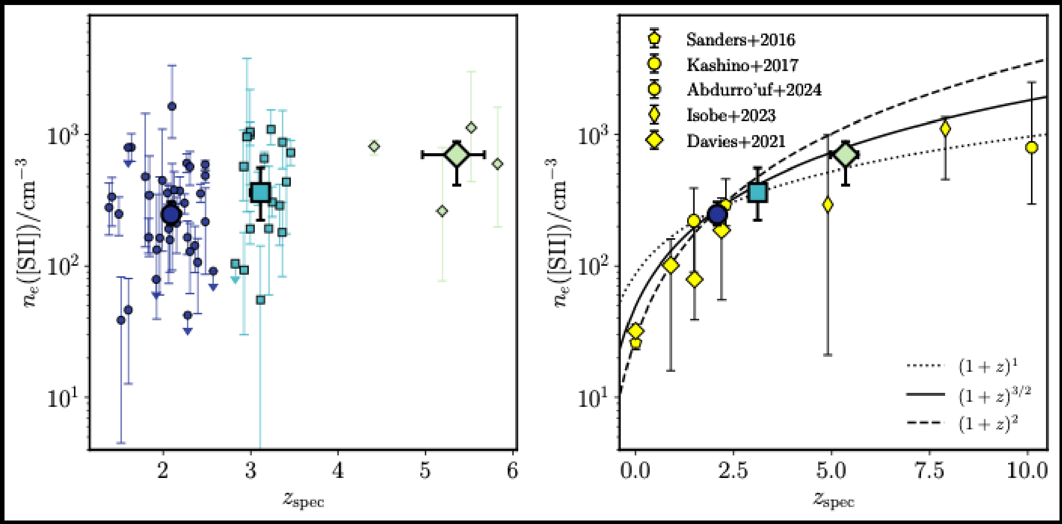

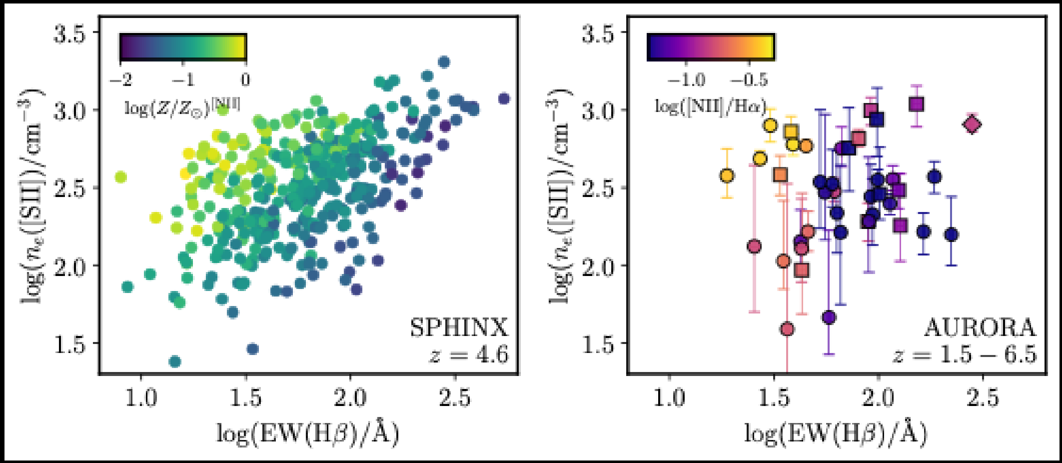

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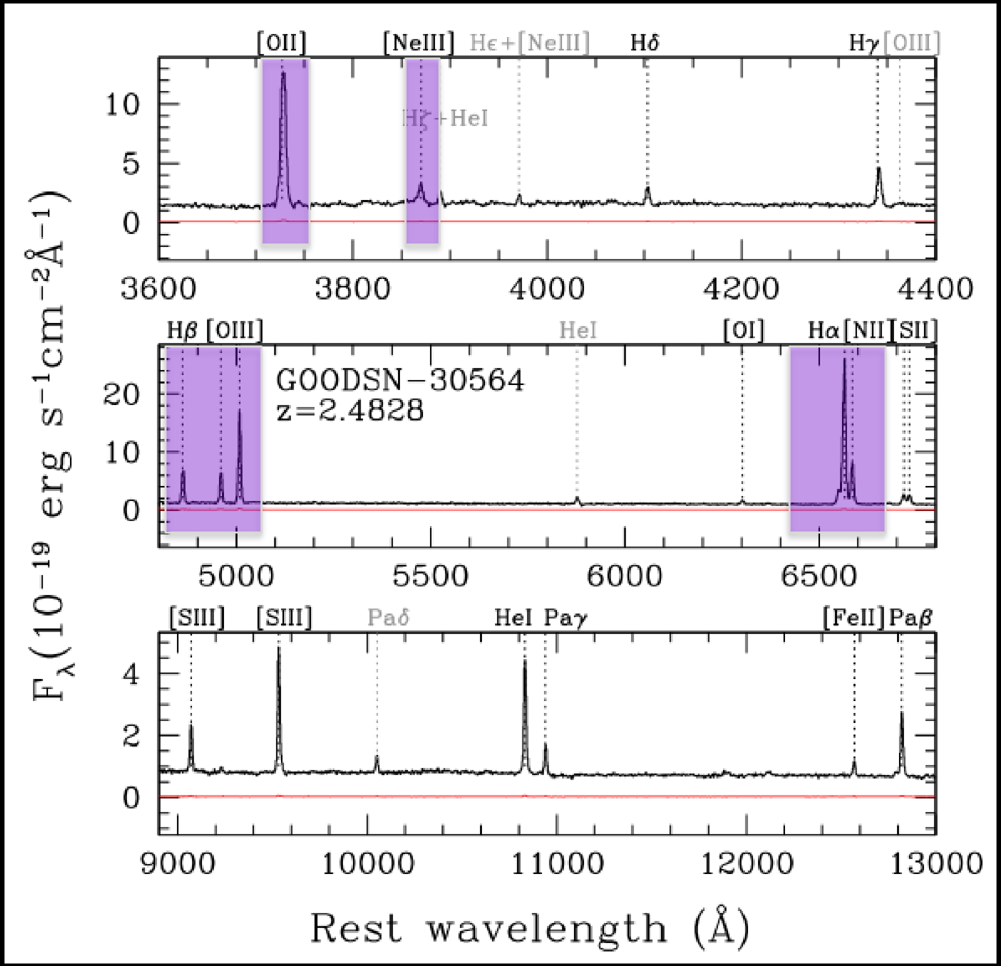
Topping et al. 2024, in prep

Rest-Optical Spectrum → 12+log(O/H)

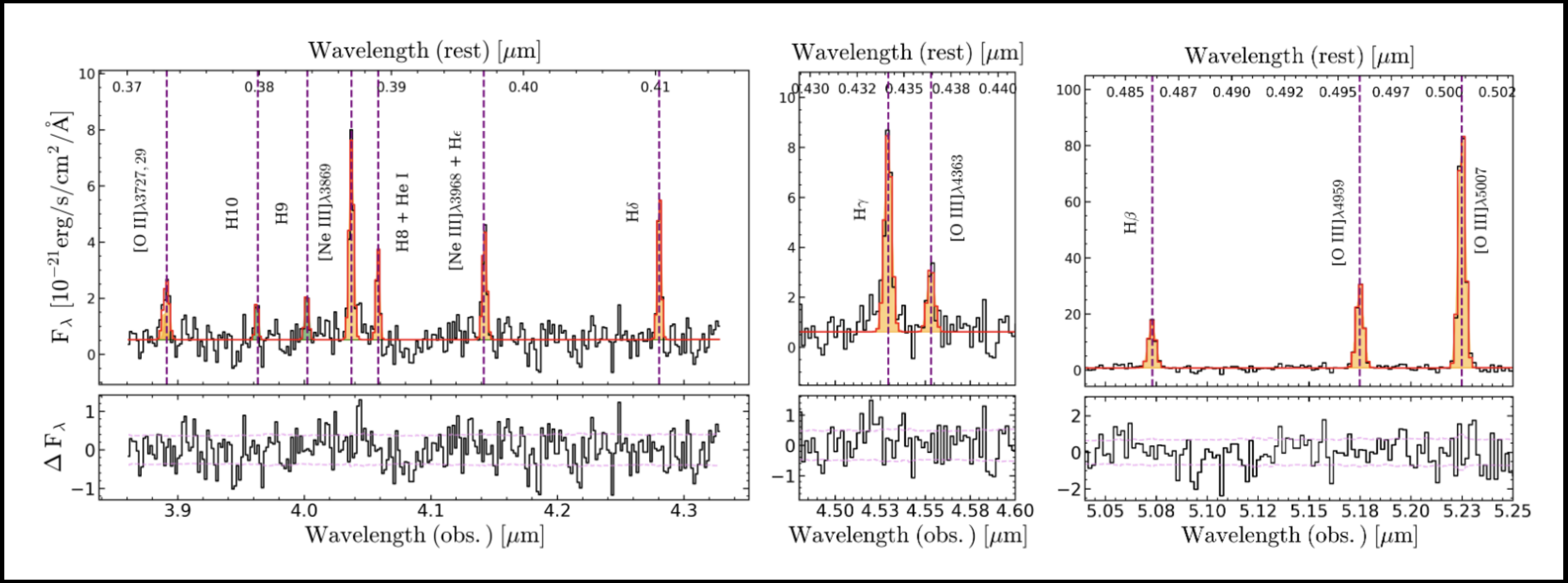
(Shapley et al. 2024a)



- Infer 12+log(O/H) (gas-phase oxygen abundance) from nebular emission lines.
- For high redshift (pre-JWST), the standard was to use calibrations of strongest rest-optical emission lines from H, O, Ne, N (purple).
- We can do better.

Beyond O/H: abundance pattern

JADES-GS-z9-0 z=9.43

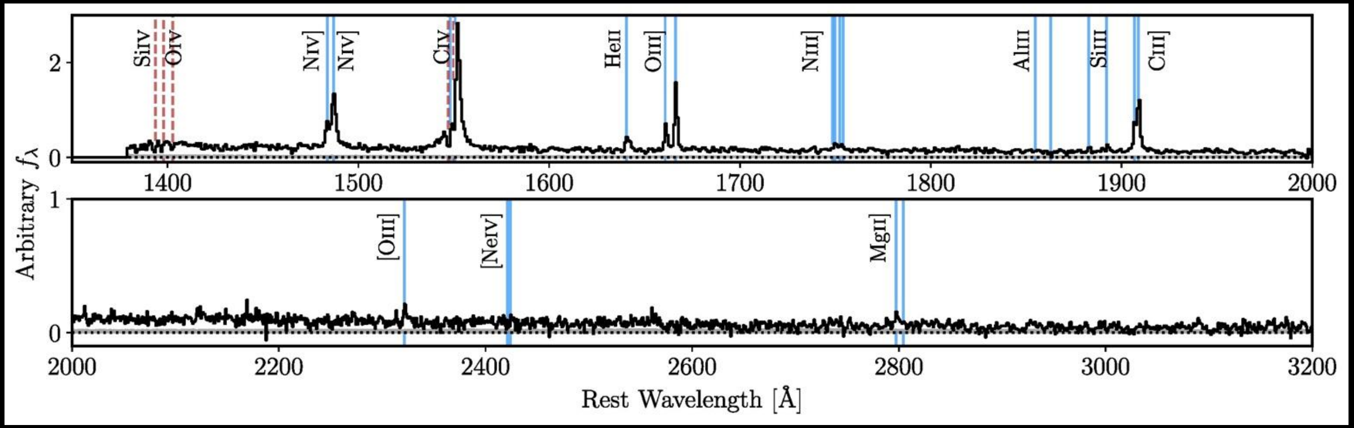


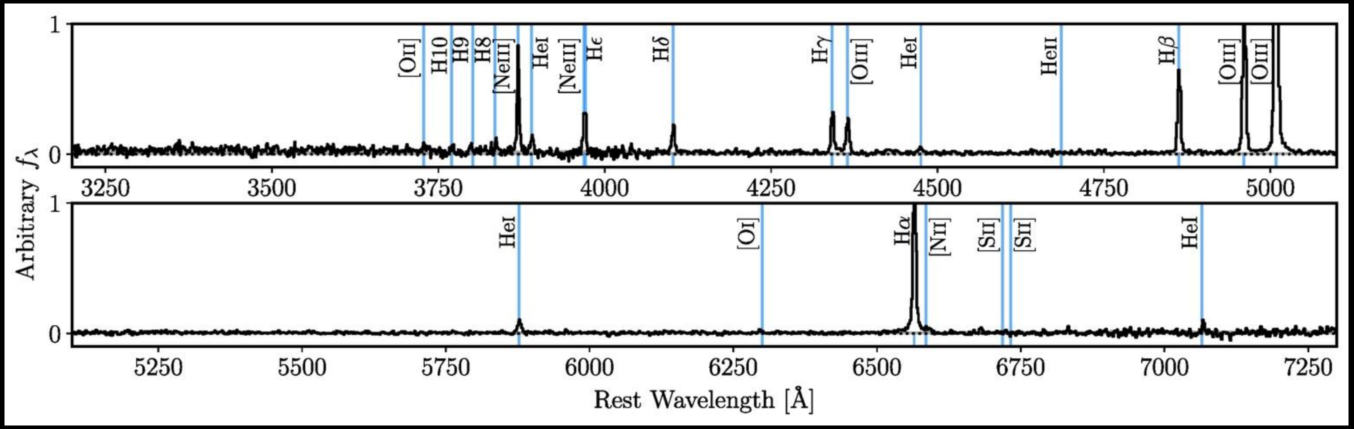
- Ultradeep NIRSpec spectroscopy spanning rest-UV through 5000AA (including [OIII]4363), yielding C/O, N/O, Ne/O. Other work has highlighted Ar/O.
- Use for independent constraints on IMF, star-formation history.

Curti et al. 2024

Beyond O/H: abundance pattern

RXCJ2248-ID (z=6.13)

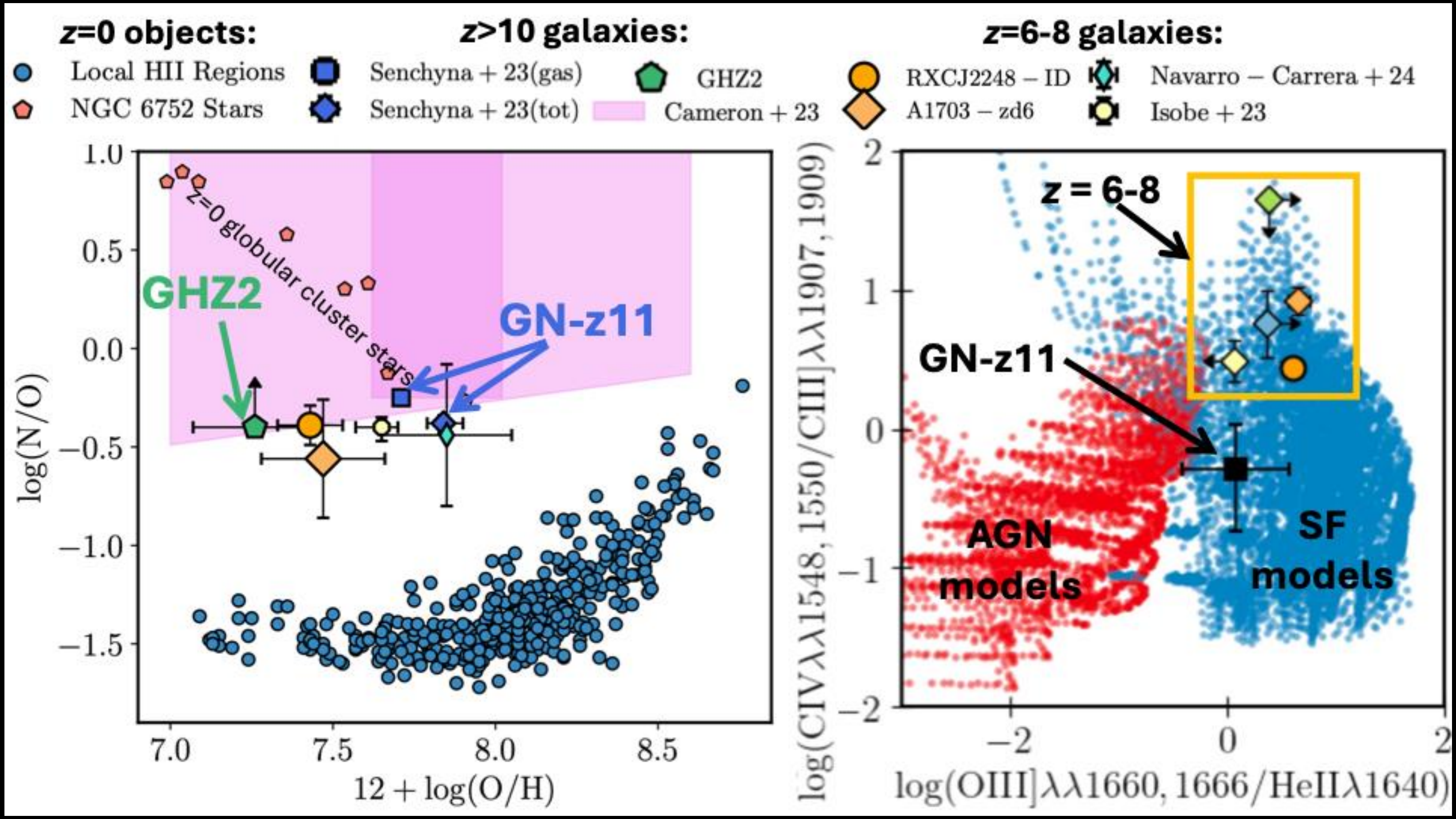




- **Ultradeep NIRSpec spectroscopy spanning rest-UV through 7250AA (including [OIII]4363), yielding C/O, N/O. Other work has highlighted Ar/O.**
- **Use for independent constraints on IMF, star-formation history.**

Topping et al. 2024a

Beyond O/H: abundance pattern

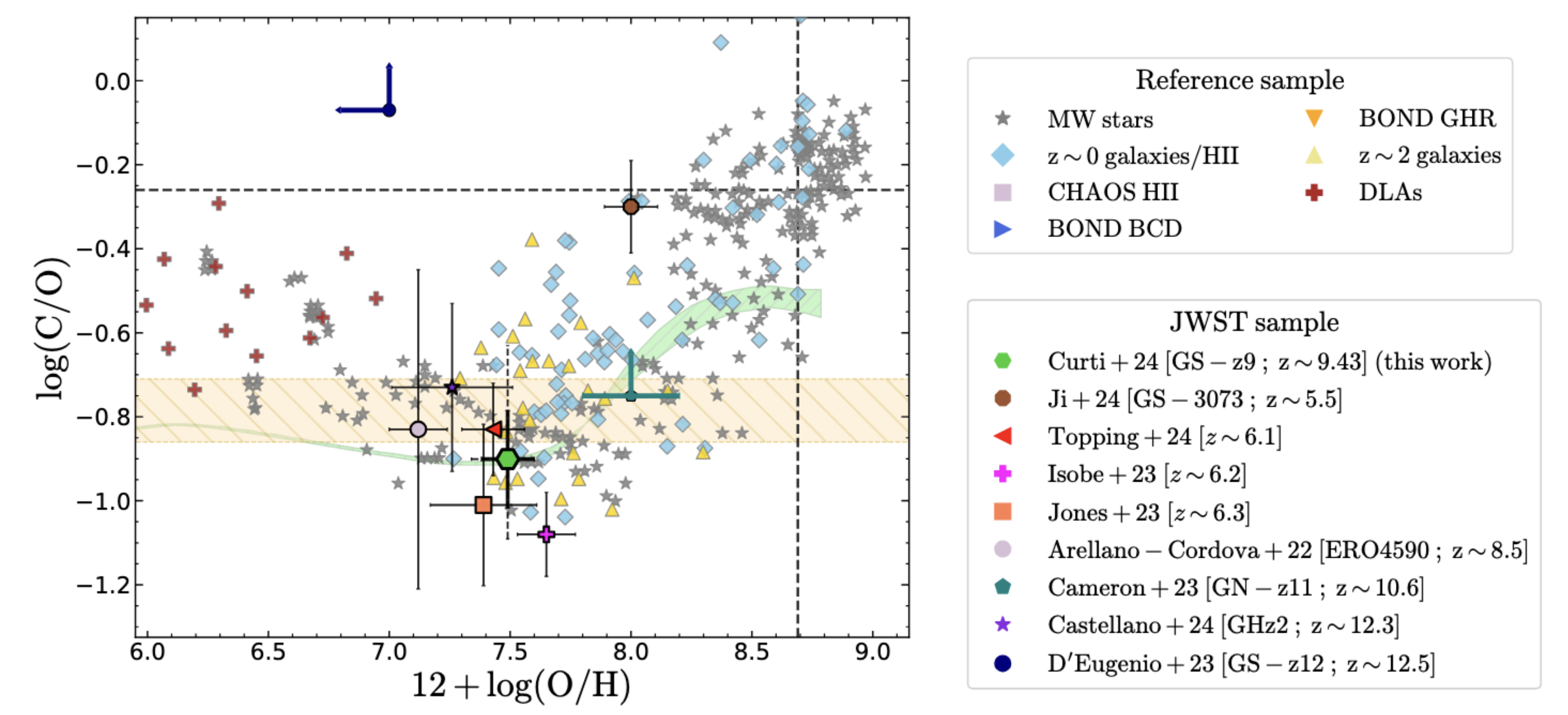


(Topping et al. 2024b)

- Rest-UV nitrogen emission in luminous z>6 galaxies implies both high density ($n_e \geq 10^6$ cm^{-3}) and N/O like globular clusters.
- Maybe these systems feature dense N-rich ejecta from early stellar populations embedded in globular cluster precursors (Pascale et al. 2023).

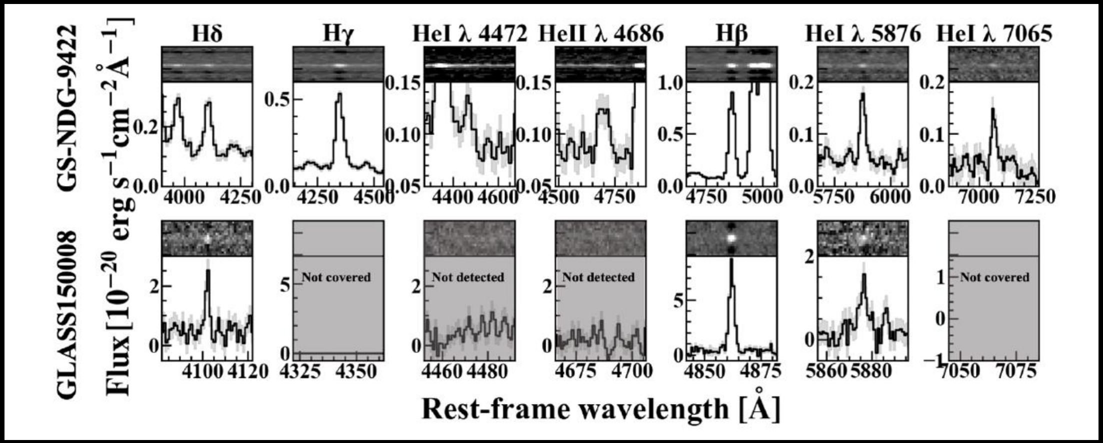
Beyond O/H: abundance pattern

(Curti et al. 2024)

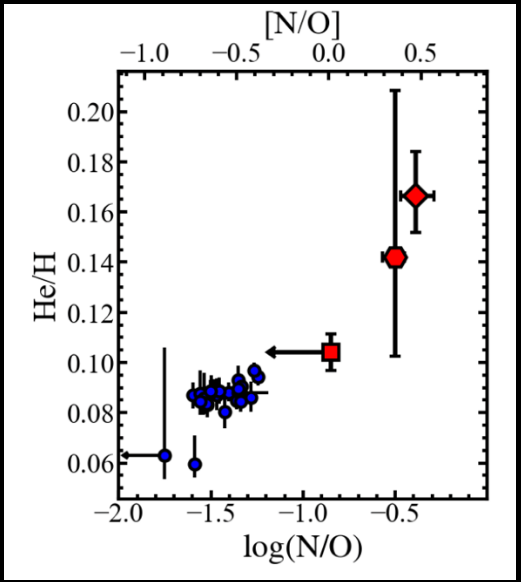


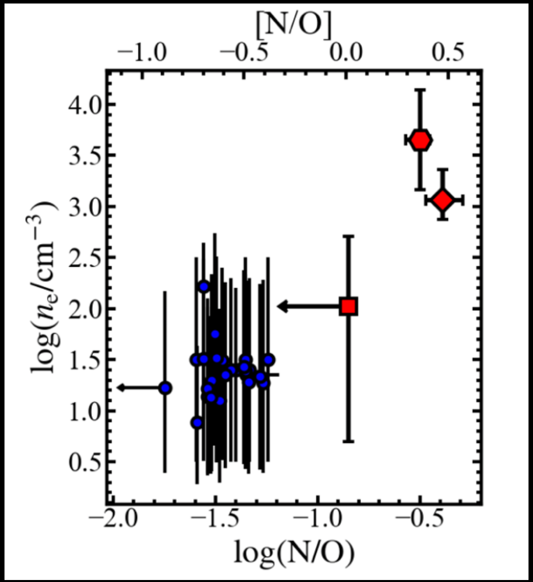
- At the same time, sub-solar C/O.
- Maybe these systems feature dense N-rich ejecta from early stellar populations embedded in globular cluster precursors (Pascale et al. 2023).

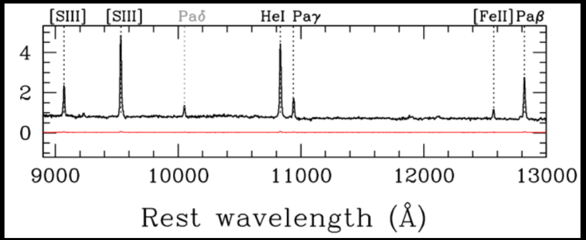
Beyond O/H: helium abundance



- Use He/Hβ to infer He/H at z~6 (3 galaxies).
- Enhanced, and correlated with N/O suggesting non-standard origin for He and N.
- Degeneracy wrt to electron density. Either He/H is higher than in local systems, or else density is.
- Detection of near-IR HeI line (1.08 μm) will break degeneracy. Easily detected in z~2-3 galaxies.

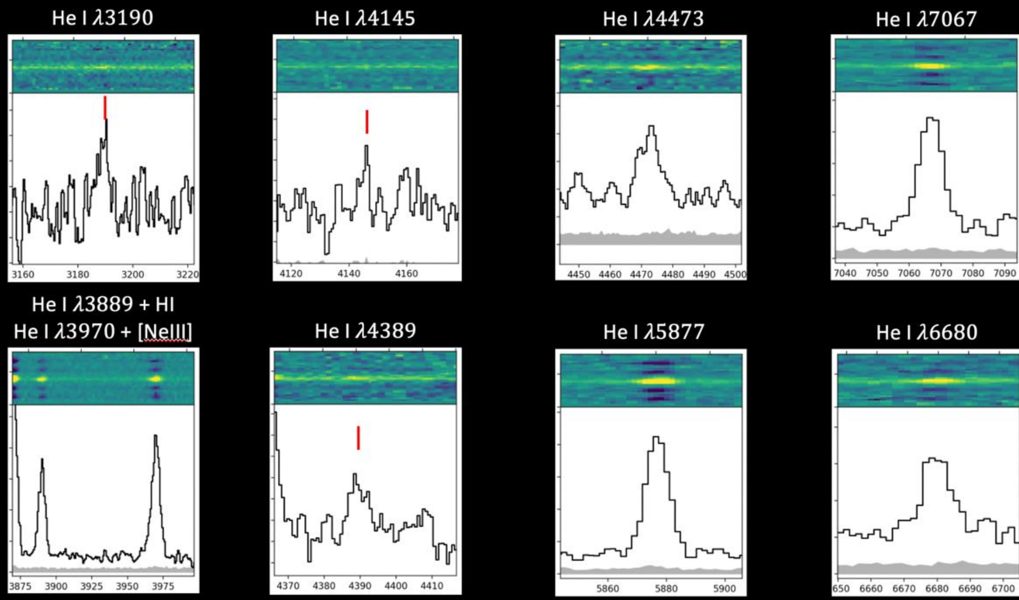






Yanagisawa et al. 2024

Beyond O/H: helium abundance



8 He I lines detected at z=4.41 galaxy from AURORA!

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- Enhanced, and correlated with N/O suggesting non-standard origin for He and N.
- Degeneracy wrt to electron density. Either He/H is higher than in local systems, or else density is.
- Detection of near-IR HeI line (1.08 μm) will break degeneracy. Easily detected in z~2-3 galaxies.
- Abundance of He, N, C, Ar, in addition to O sheds light on early star formation through chemical enrichment!

Sanders et al. 2024, in prep

Looking Ahead: The Spectroscopic Promise of JWST

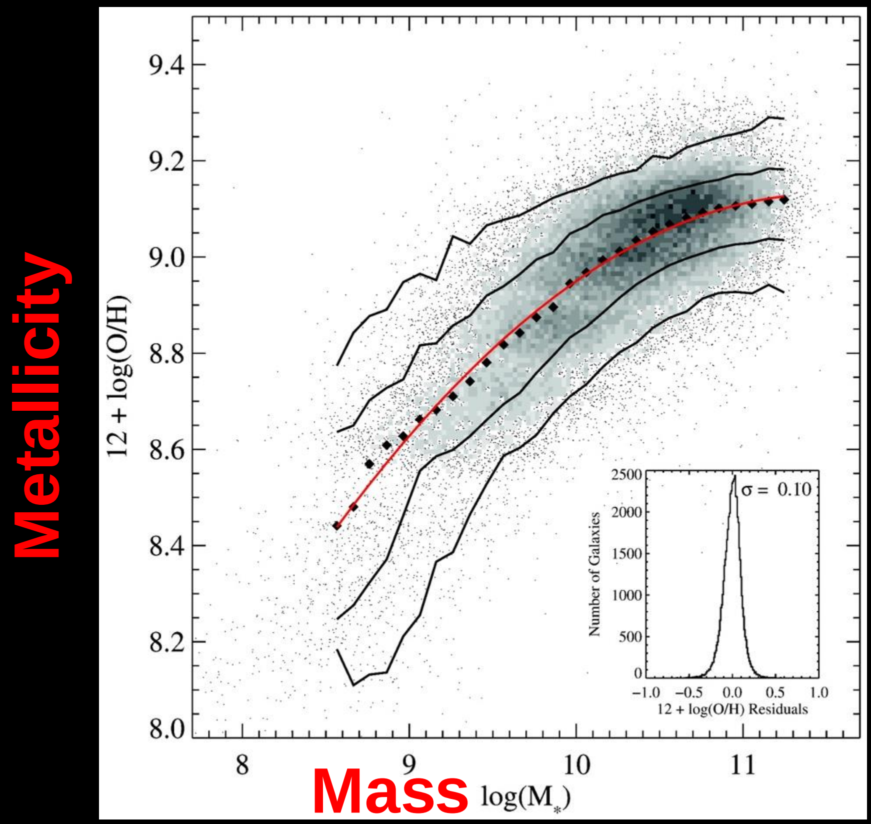
- **JWST spectroscopy is bringing many “holy grails” of galaxy formation within view (e.g., robust instantaneous SFRs measured all the way back to Cosmic Dawn).**

- **Truly remarkable star-formation conditions revealed in the first billion of cosmic time (GN-z11, GHZ2, RXCJ2248-ID), but many puzzles remain.**

- **For robust statistics and comparisons with models, we need representative samples and sufficient numbers with deep spectra (e.g., Cycle 3 CAPERS program is a start, but low resolution). NIRSpec is up to the task, so we should dream big!**

- **We can now perform true astrophysical (spectroscopic) measurements where it was previously IMPOSSIBLE.**

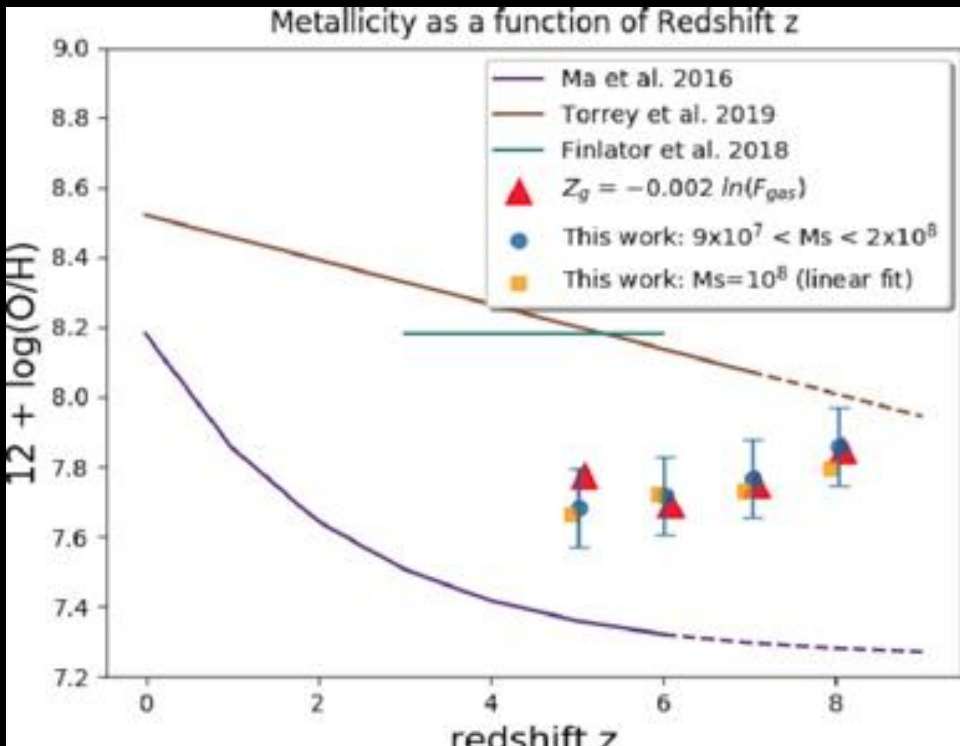
Mass Metallicity Relation (MZR)



- Variation in metal content of galaxies with galaxy mass indicates how gas cycles through galaxies (inflows, outflows, star formation) – e.g., how does outflow mass-loading factor vary with galaxy mass and redshift?

(Tremonti et al. 2004)

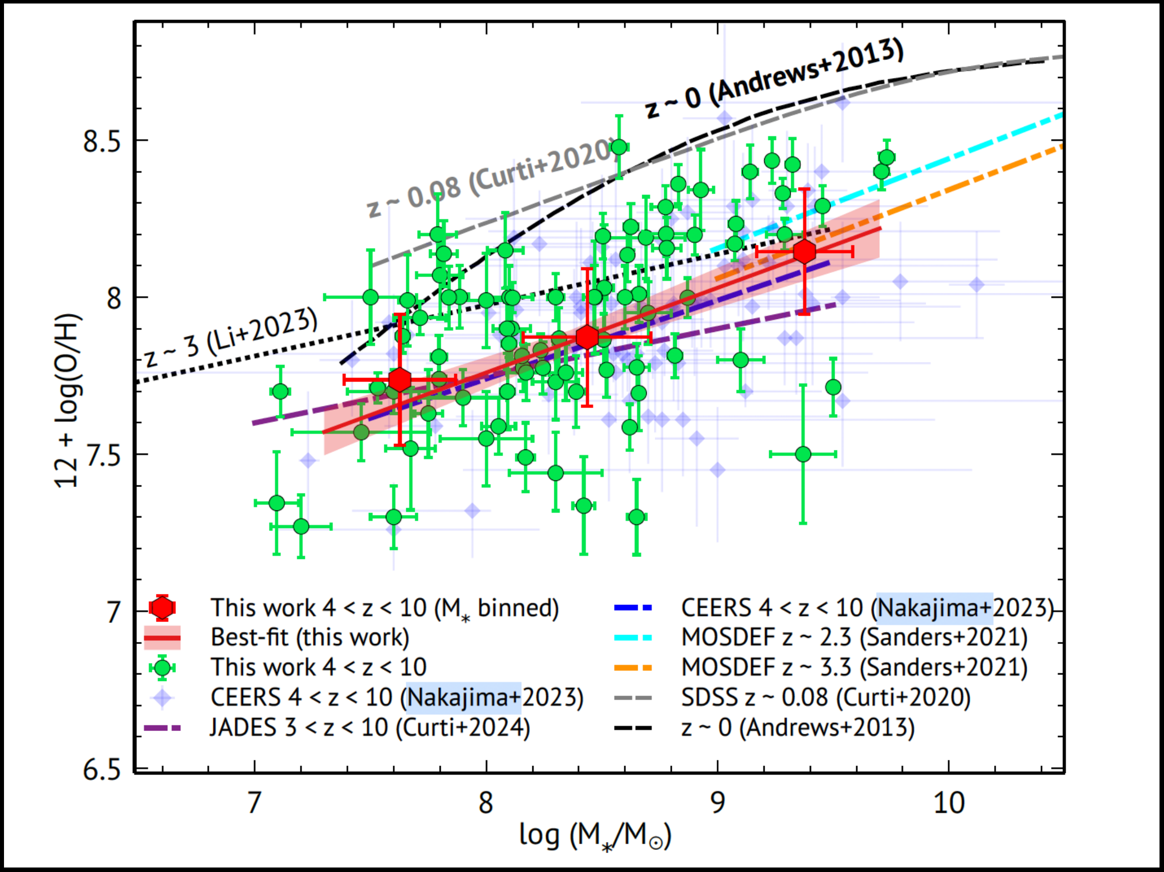
MZR Evolution at z>3



(Langan et al. 2020)

- **Drastically different predictions for mass-metallicity relation (MZR) evolution at z>3 in different hydrodynamical simulations.**
- **NIRSpec observations will be able to distinguish among them.**
- **Require robust metallicity calibrations. Larger samples.**

MZR Evolution at z>3

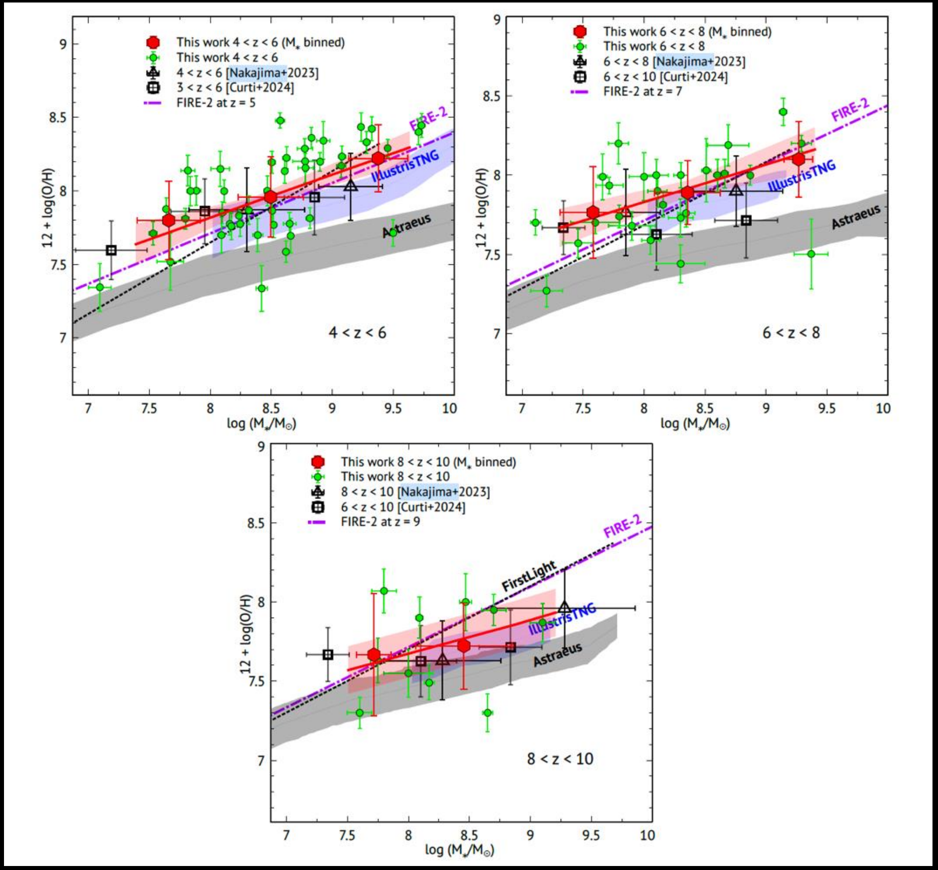


(Sarkar et al. 2024)

- Weak MZR evolution consistent with some simulations, not others.
- Require feedback that doesn't remove too many metals and/or accretion that doesn't cause too much dilution.

MZR Evolution at z>3

(Sarkar et al. 2024)



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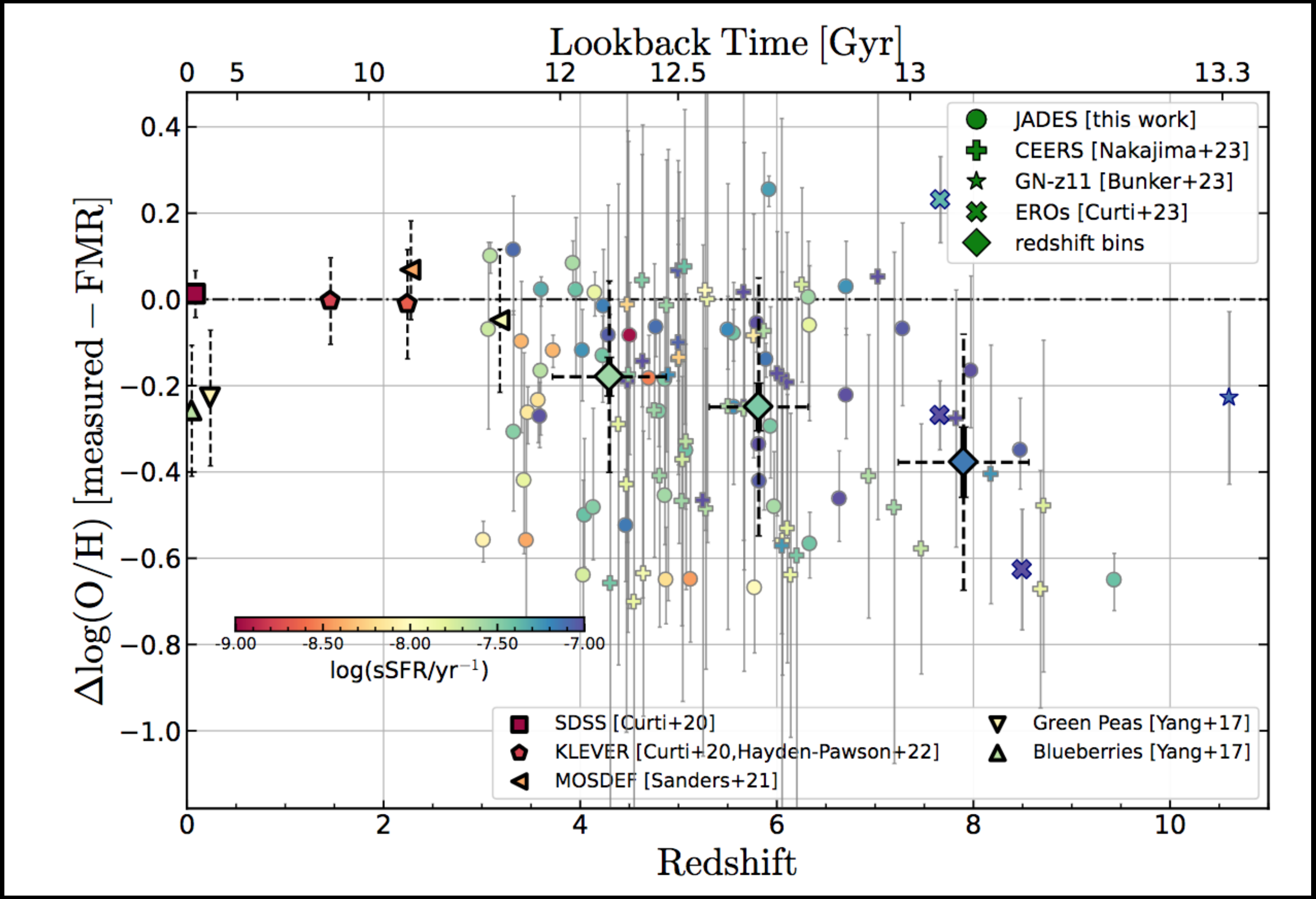
FMR Evolution at z>3



(Curti et al. 2023b)

FMR=Fundamental Metallicity Relation (M*, Z, SFR)

What Now?

• (Larger and more representative spectroscopic samples. Test feedback models. Of course.)

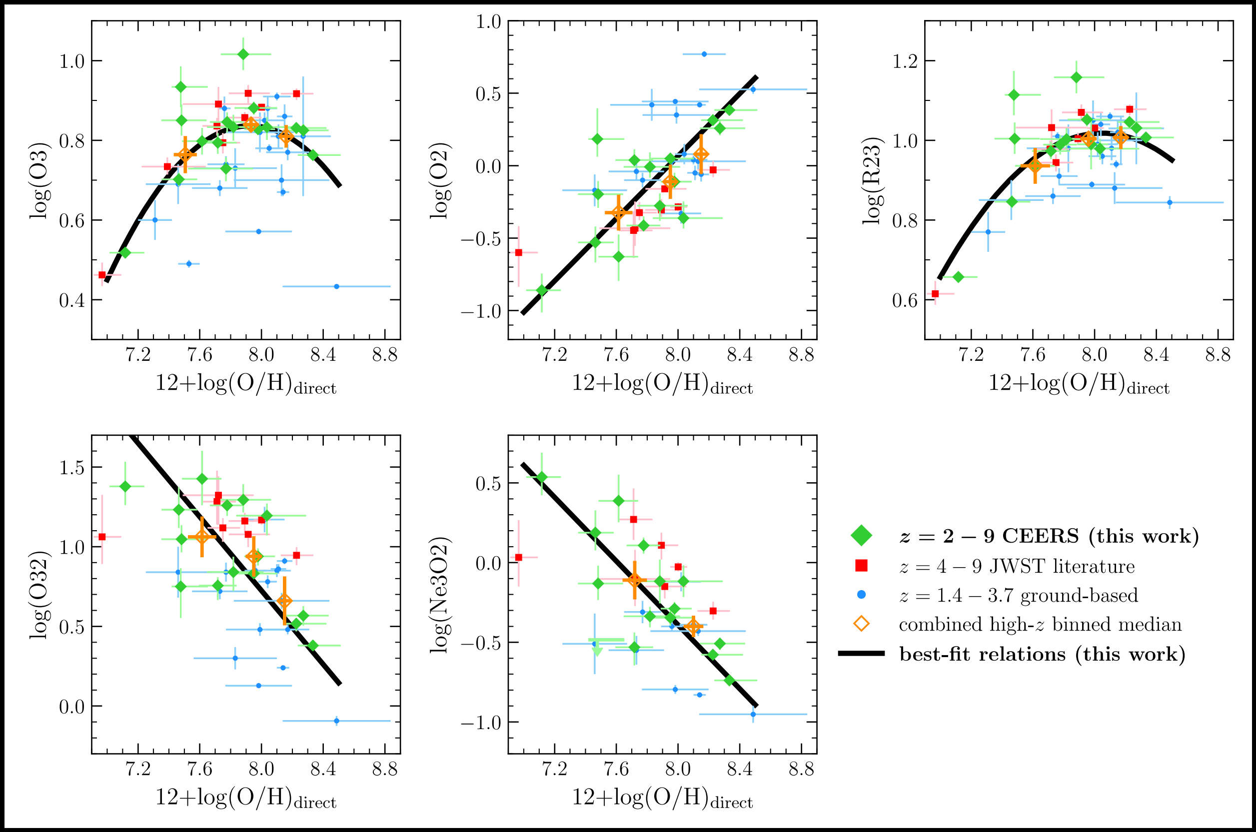
BUT, really…..

• Some perspective: JWST/NIRSpec enables studies at $z>4$ into Cosmic Dawn that were not possible previously *even for Cosmic Noon!*

• Robust metallicities based on high-redshift (not local) calibrations.
• Chemical abundance patterns.
• Densities.
• Dust attenuation curves.
• The truly unexpected….

Direct Metallicity Calibrations at High Redshift

Strong-line Ratio



Direct Metallicity

- Direct-metallicity calibrations so far from CEERS (Sanders+2024) and JADES (Laseter+2024).
- Larger dynamic range needed (up to solar). Higher S/N ideal.

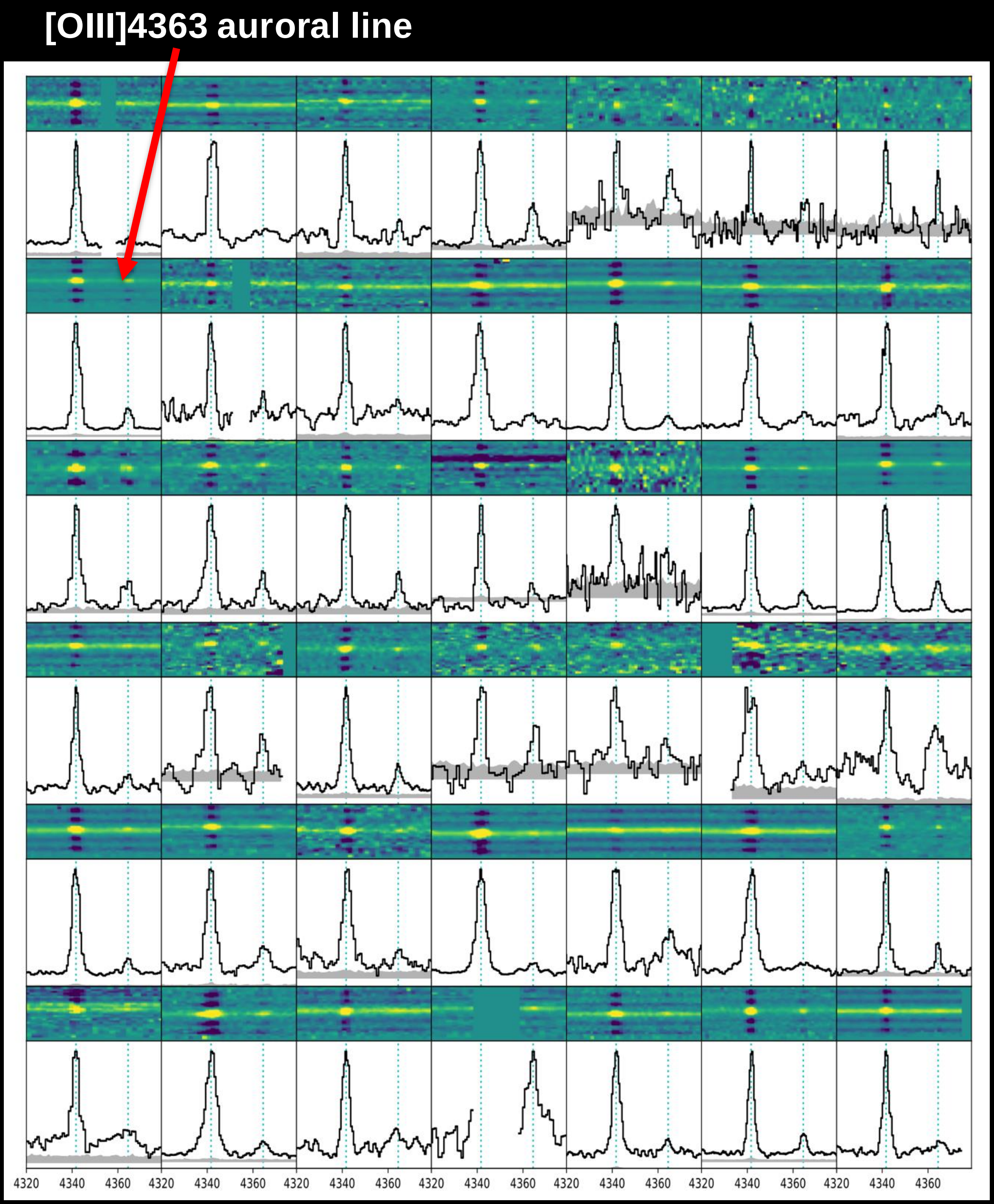
Sanders et al. 2024a

More Direct Metallicities

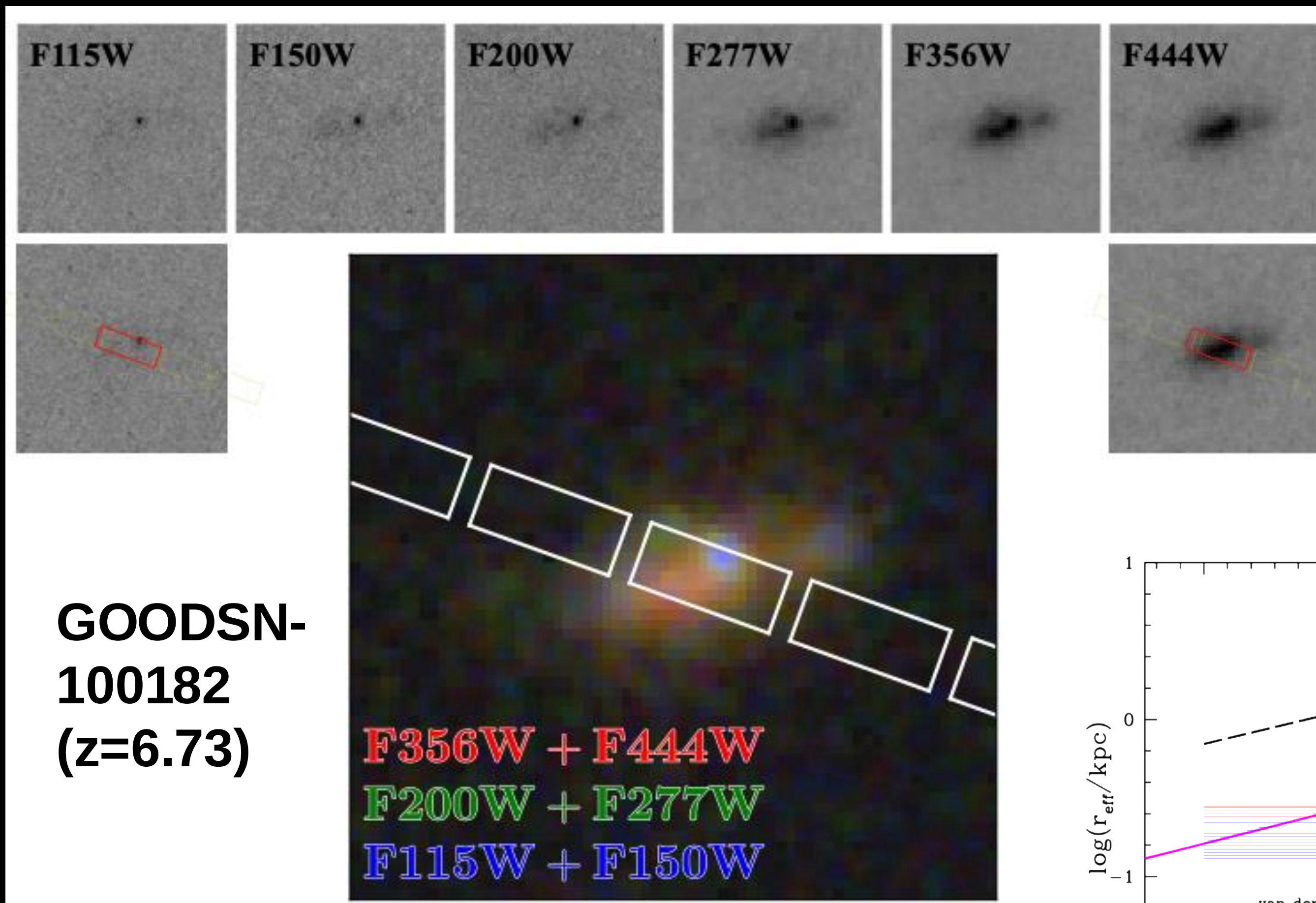
AURORA Cycle 1 Program (Co-PIs Shapley+Sanders)

51 galaxies with at least 1 auroral line detection →

- **51 new direct metallicities, including 8 at z>5.**
- **Robust metallicity calibrations at high redshift for large spectroscopic samples of strong emission lines.**
- **See also MARTA and CECILIA Cycle 1 Programs.**

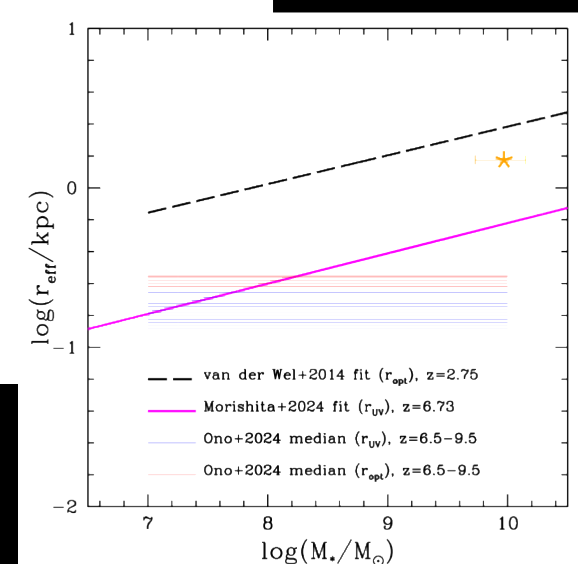


The Truly Unexpected



GOODSN-100182 (z=6.73)

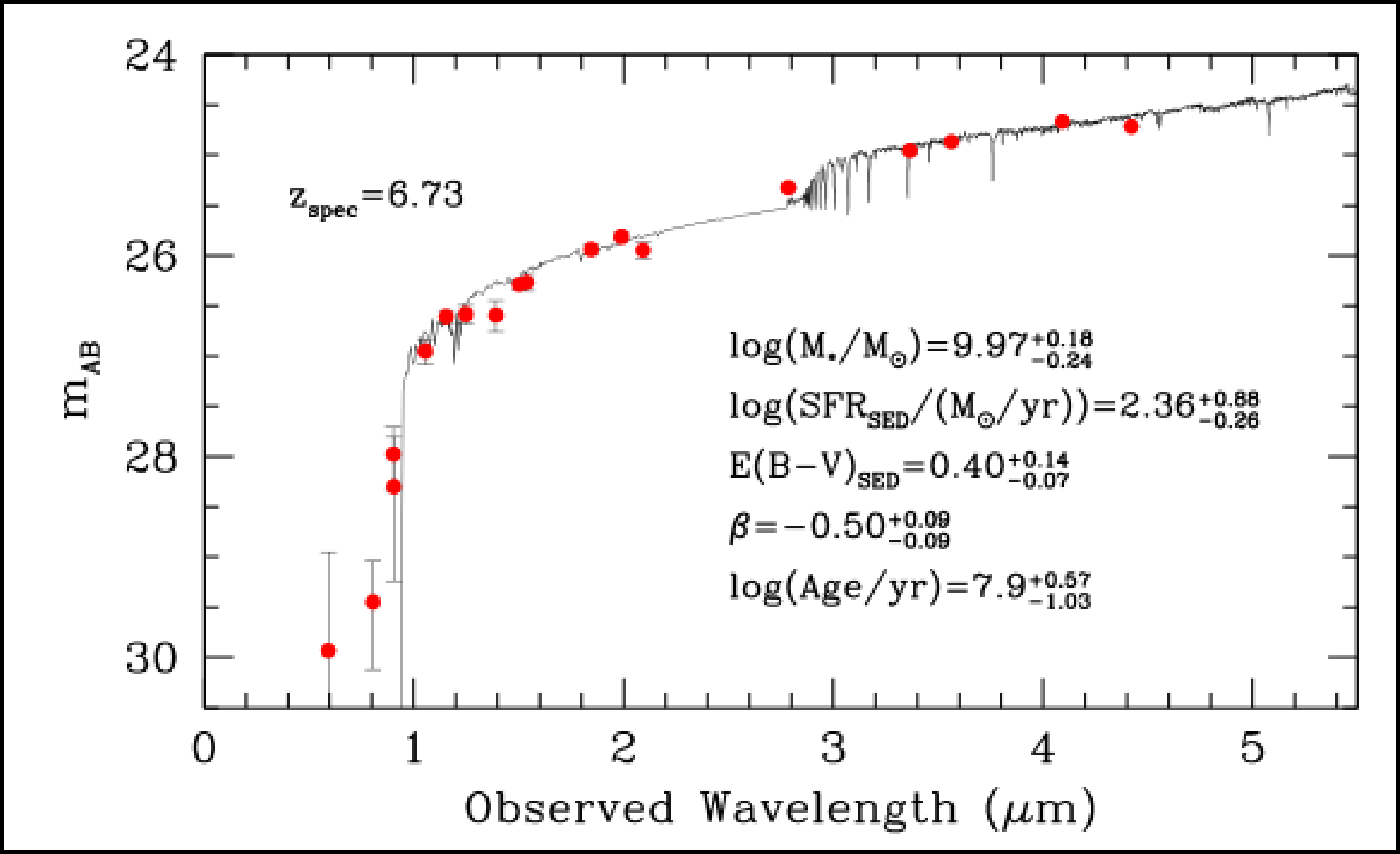
(See also Nelson+2023, z=5.3)



Large (r_e~1.5 kpc)

Shapley et al. 2024b, in prep

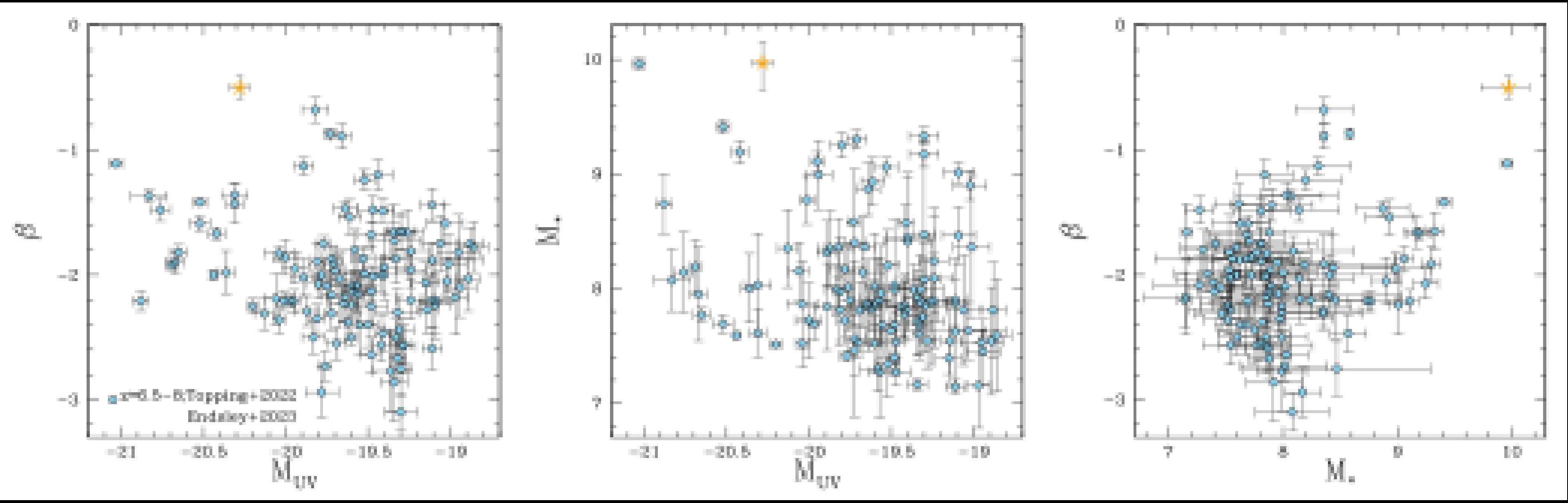
The Truly Unexpected



Massive (M_*~10^{10} M_{sun})

Shapley et al. 2024b, in prep

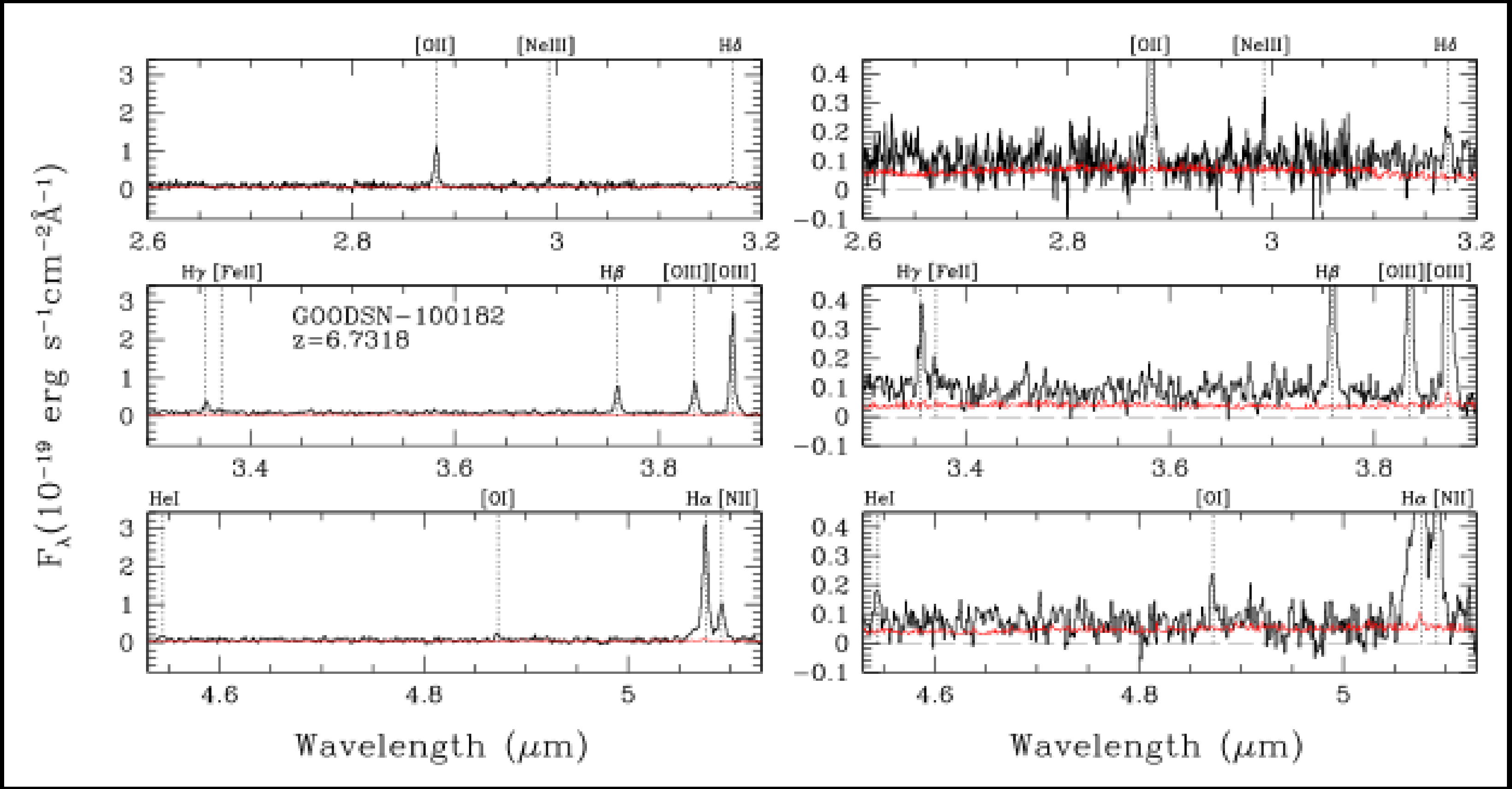
The Truly Unexpected



Dusty (β=0.5)

Shapley et al. 2024b, in prep

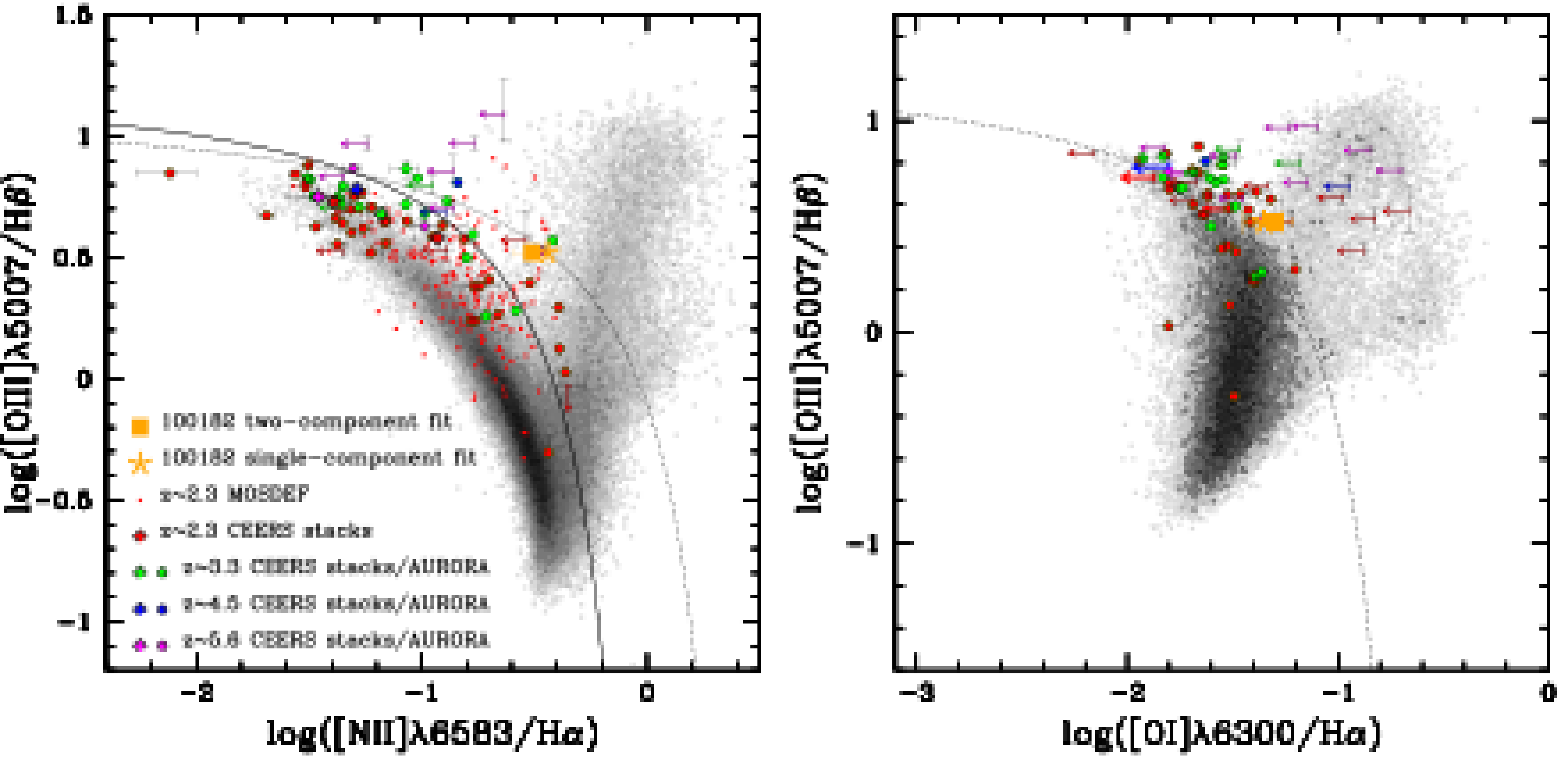
The Truly Unexpected



And the spectrum……

Shapley et al. 2024b, in prep

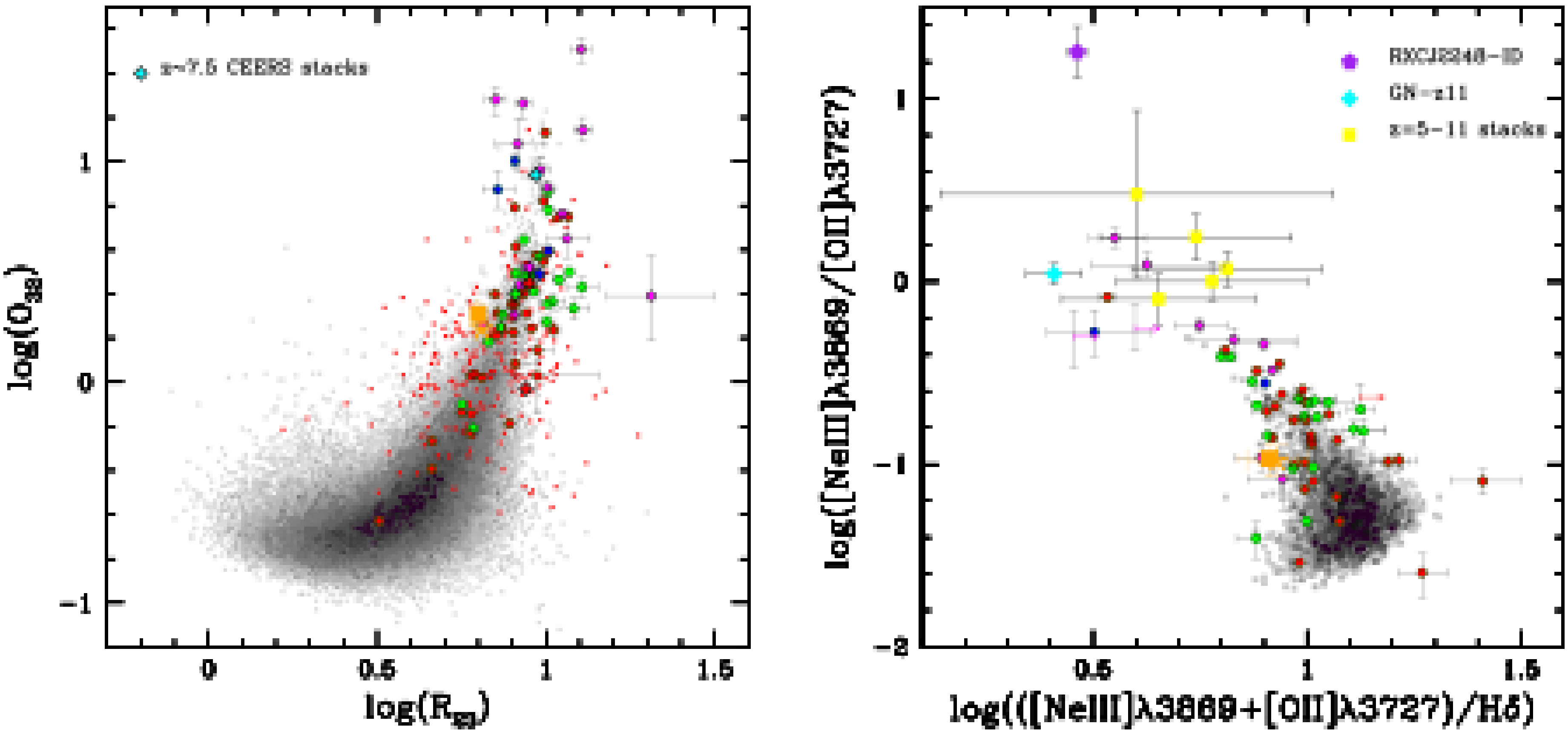
The Truly Unexpected



Large, massive, dusty, metal-rich, galaxy, with excitation properties like z~2-3 star-forming galaxies. But at z~7. How did it form???

Shapley et al. 2024a; 2024b, in prep

The Truly Unexpected



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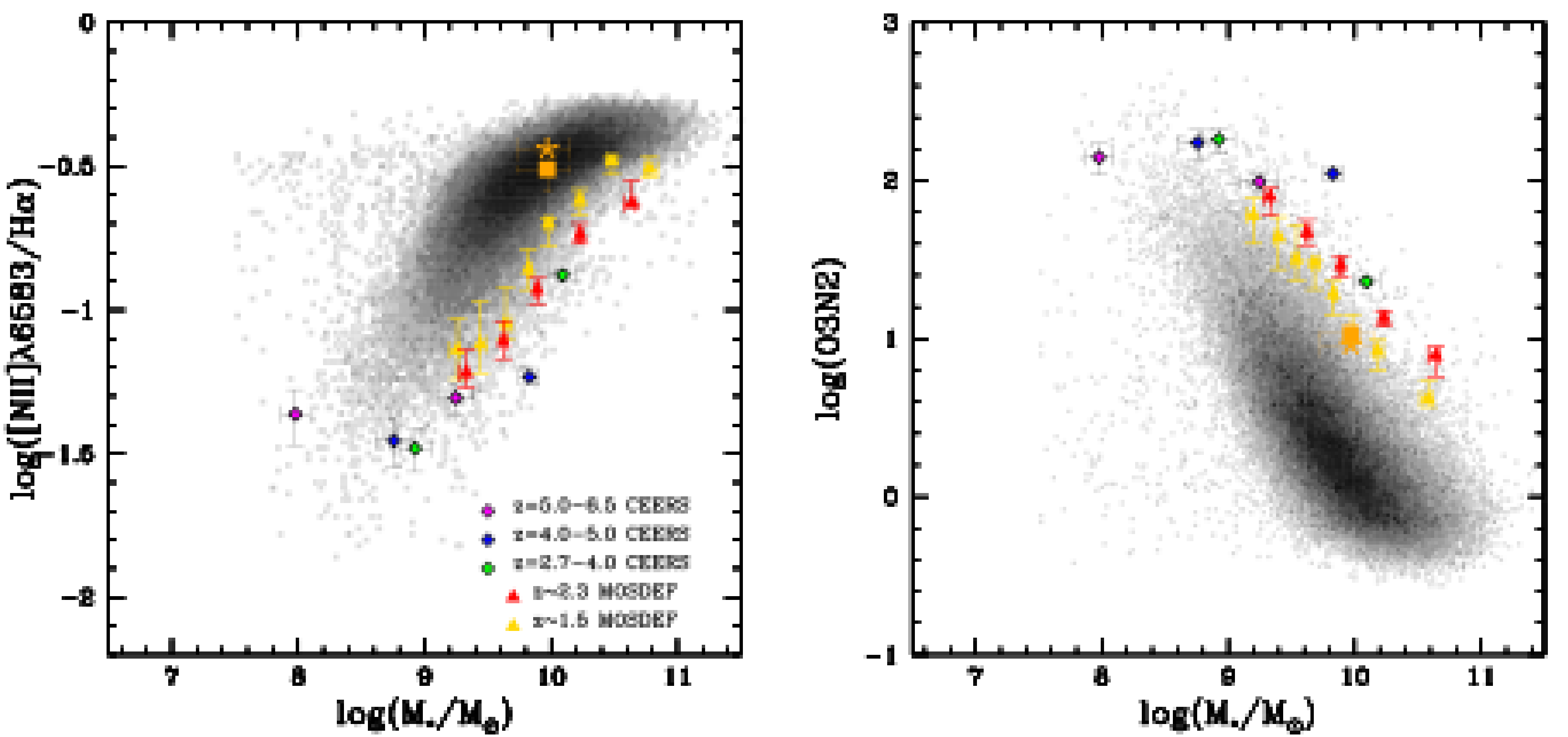

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