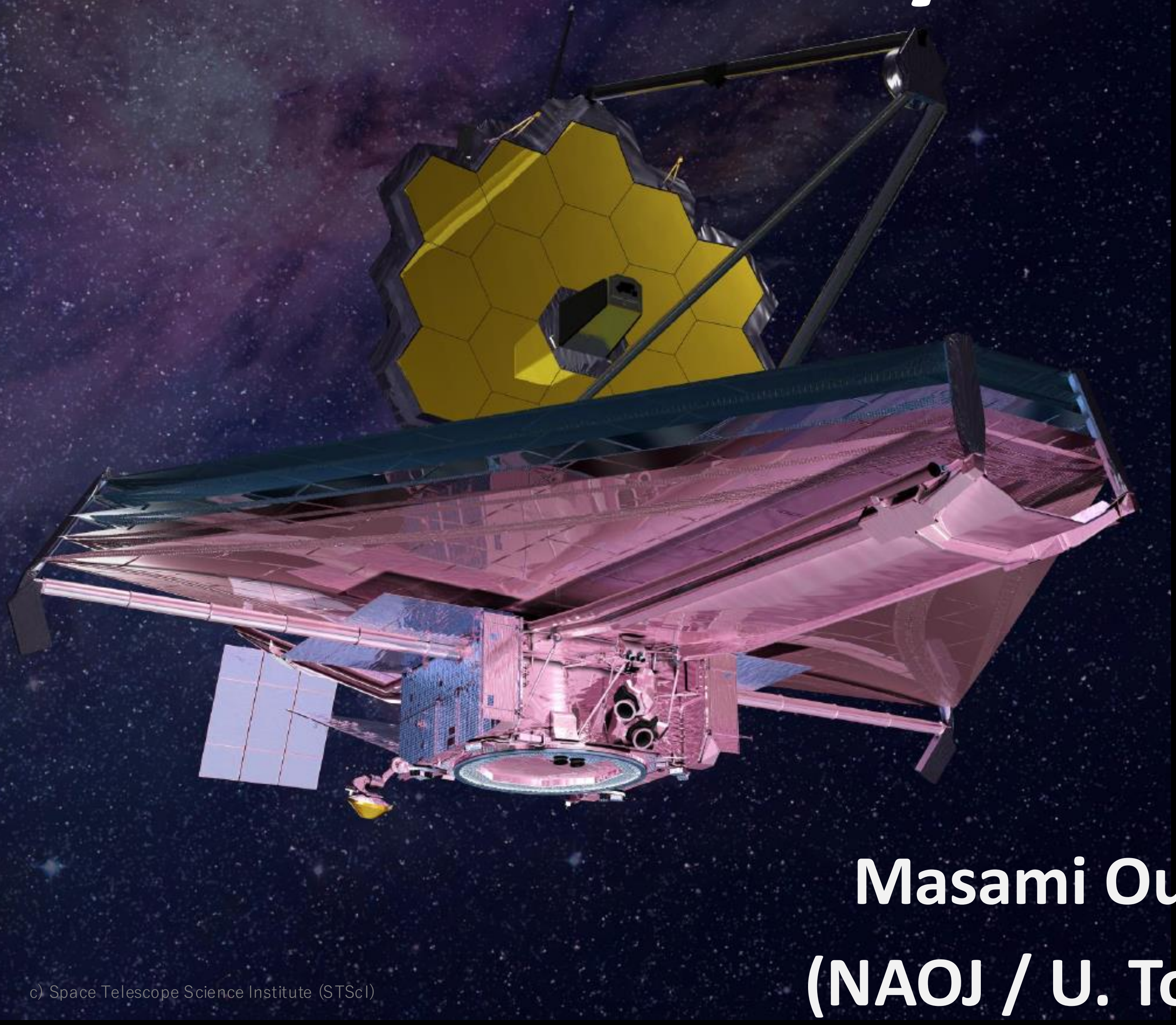
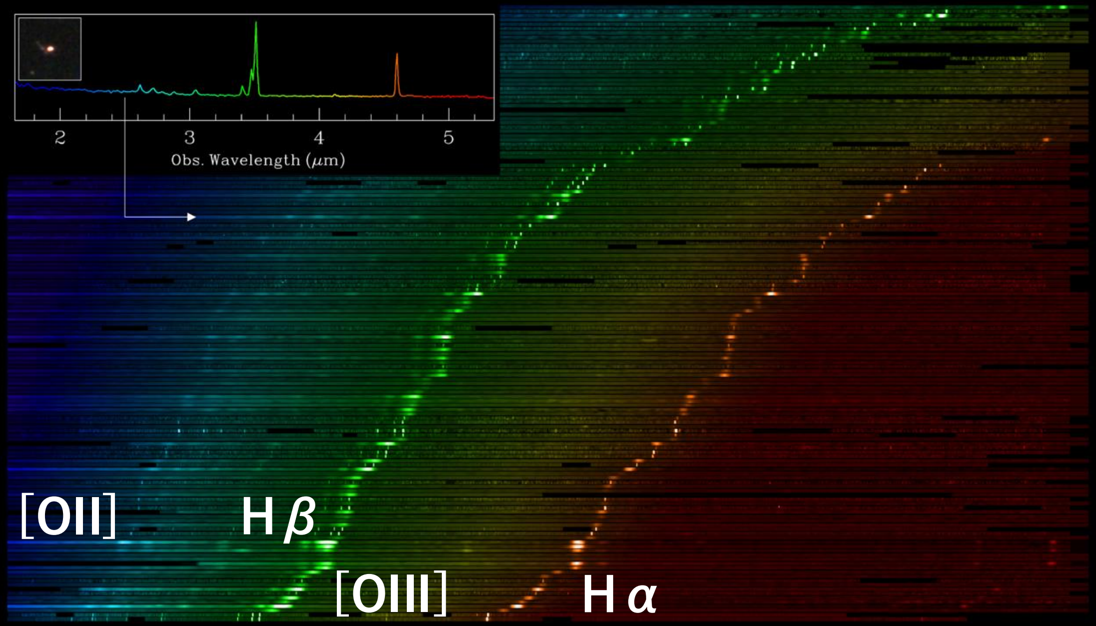
Focus on: Early Galaxy Formation





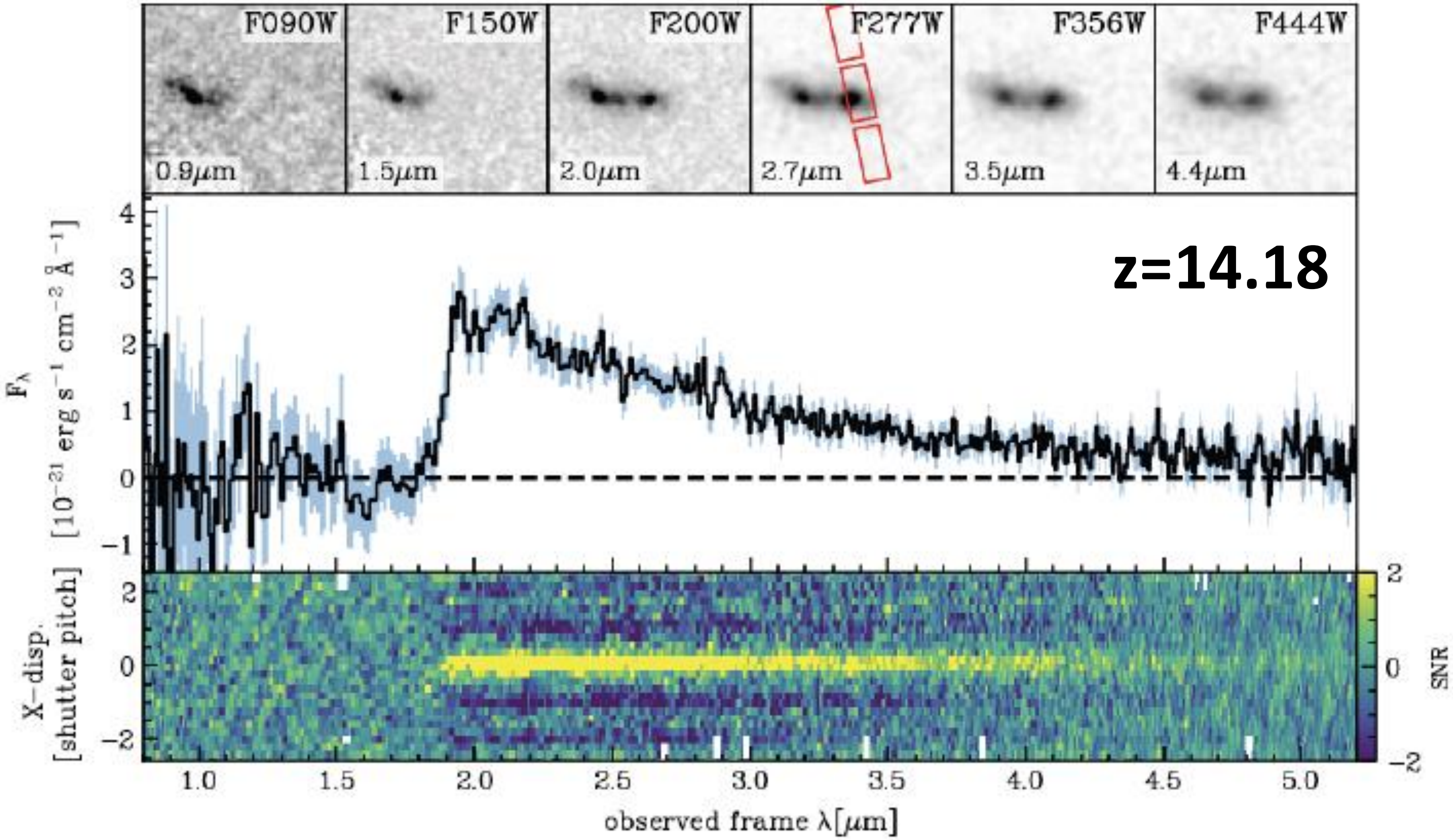
c) NASA, ESA, CSA, K. Nakajima et al.

Masami Ouchi

(NAOJ / U. Tokyo)

c) Space Telescope Science Institute (STScI)

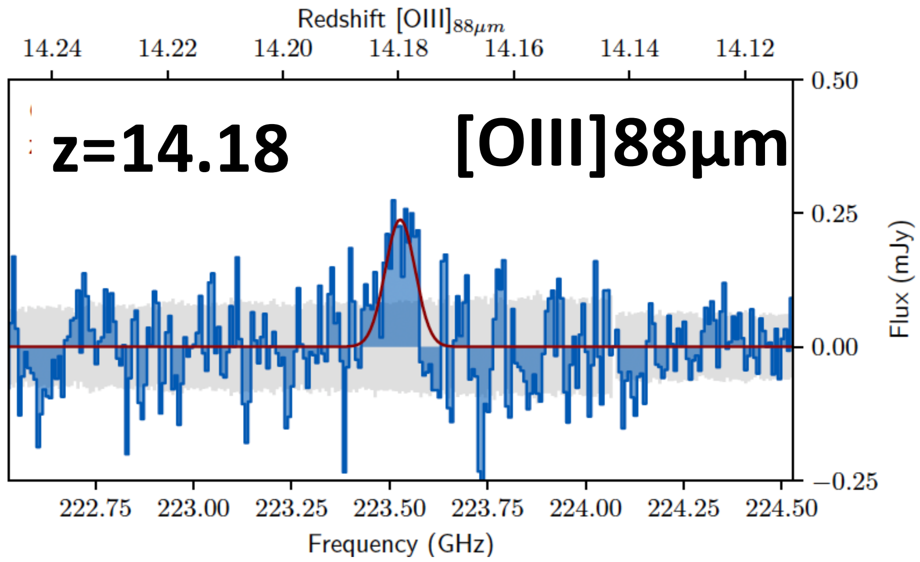
Early Galaxy Formation



Carniani+24a

- JWST observations have reached a galaxy at up to z=14.2 (Carniani+24a, Helton+24; see talks of Carniani and more)

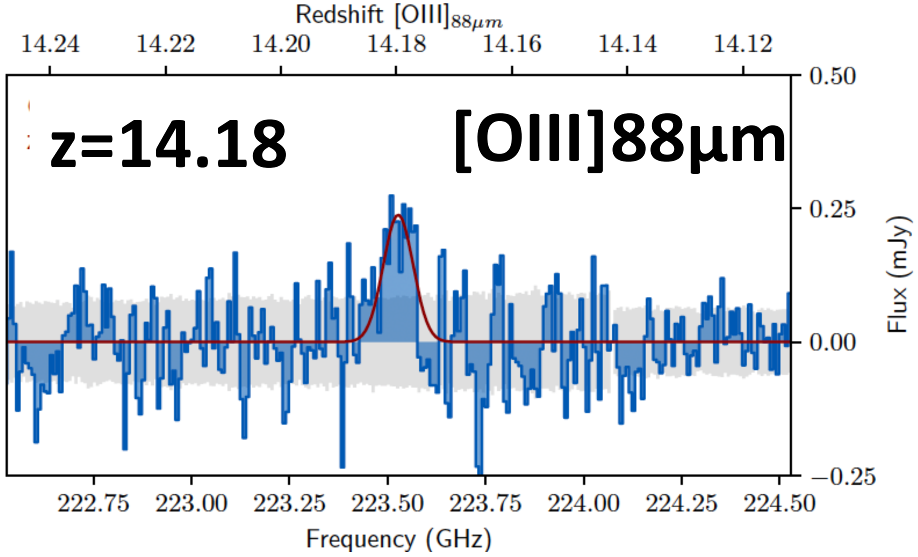
Early Galaxy Formation



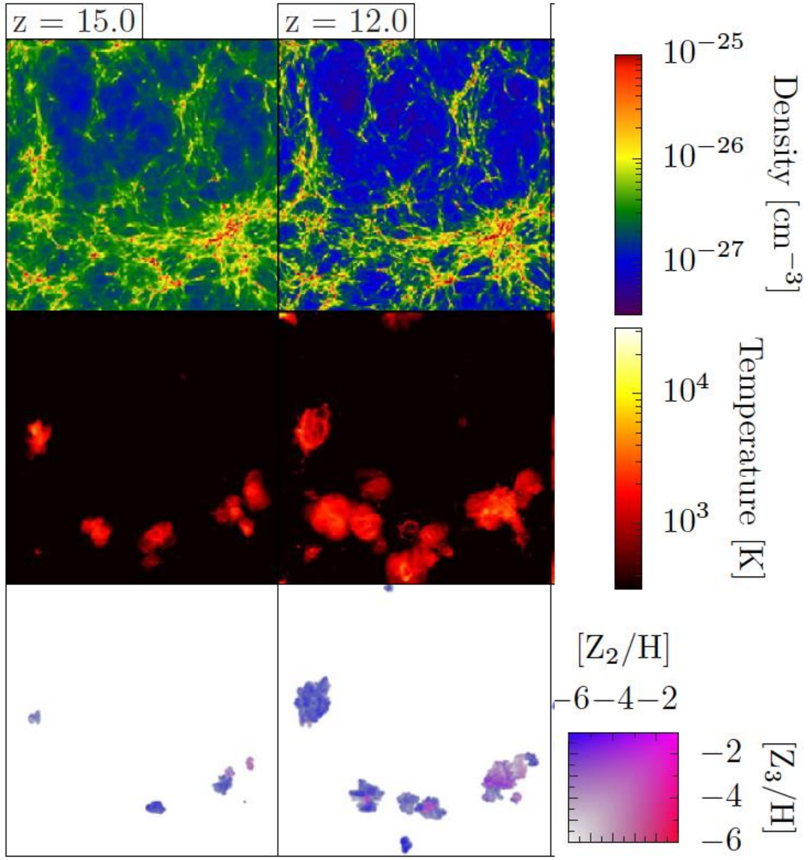
Schouws+24
(see+ Carniani+24)

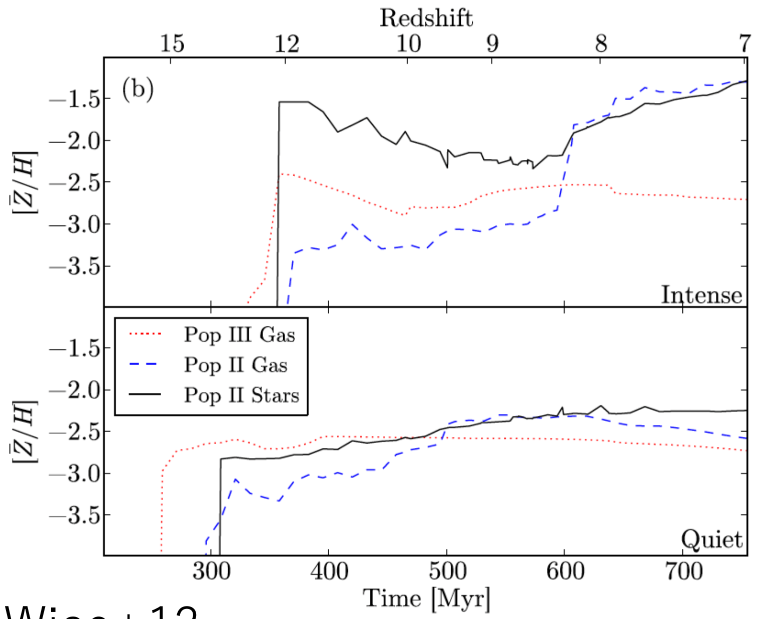
- JWST observations have reached a galaxy at up to z=14.2 (Carniani+24a, Helton+24; see talks of Carniani and more)
  - ALMA follow up: [OIII]88um emission → Suggesting $Z \gtrsim 0.1\ Z_{\odot}$: Already chemically enriched (Schouws+24, Carniani+24b).

Early Galaxy Formation



Schouws+24
(see+ Carniani+24)

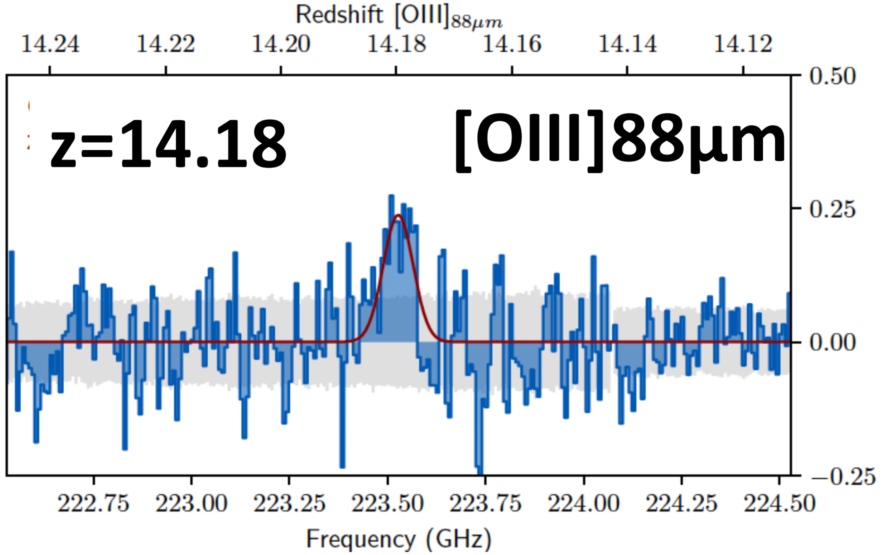




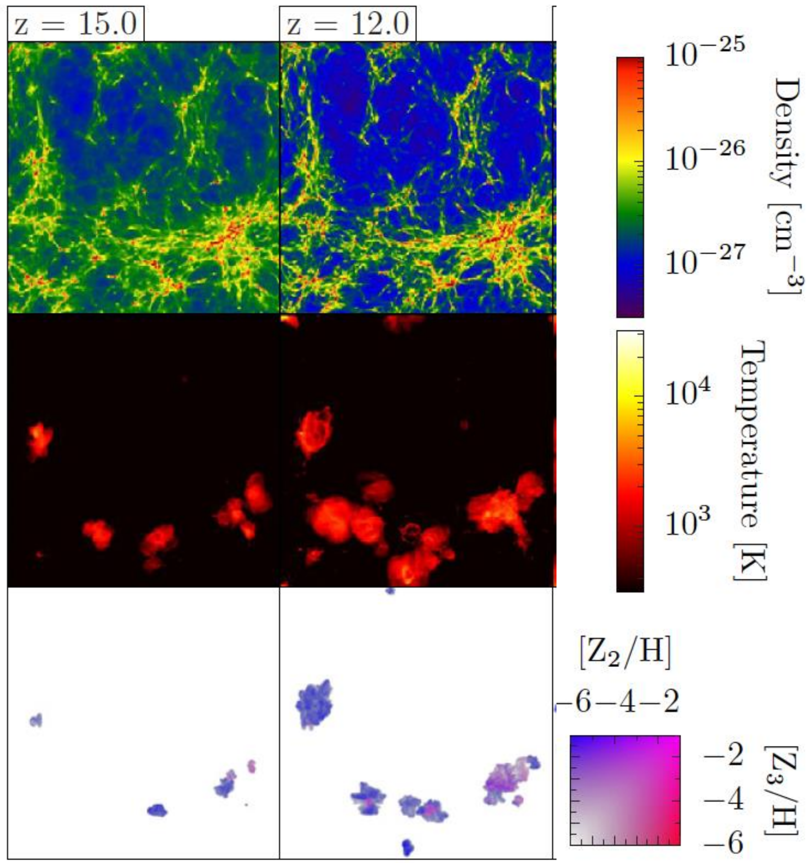
Wise+12

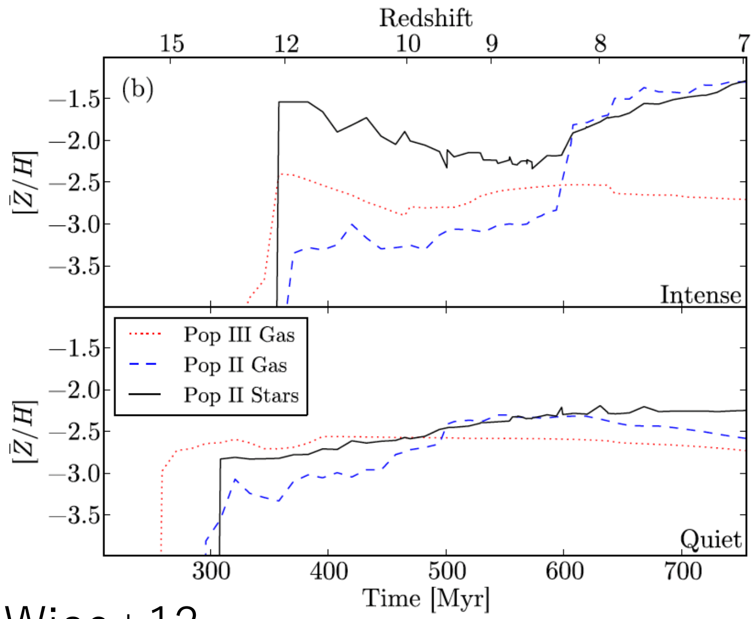
- JWST observations have reached a galaxy at up to z=14.2 (Carniani+24a, Helton+24; see talks of Carniani and more)
  - ALMA follow up: [OIII]88um emission → Suggesting $Z \gtrsim 0.1\ Z_\odot$: Already chemically enriched (Schouws+24, Carniani+24b).
  - PopIII star-formation producing abundant very massive stars in clusters: Followed by core-collapse supernovae (CCSNe) maybe including hypothetical pair-instability supernovae (PISNe) etc.

Early Galaxy Formation



Schouws+24
(see+ Carniani+24)



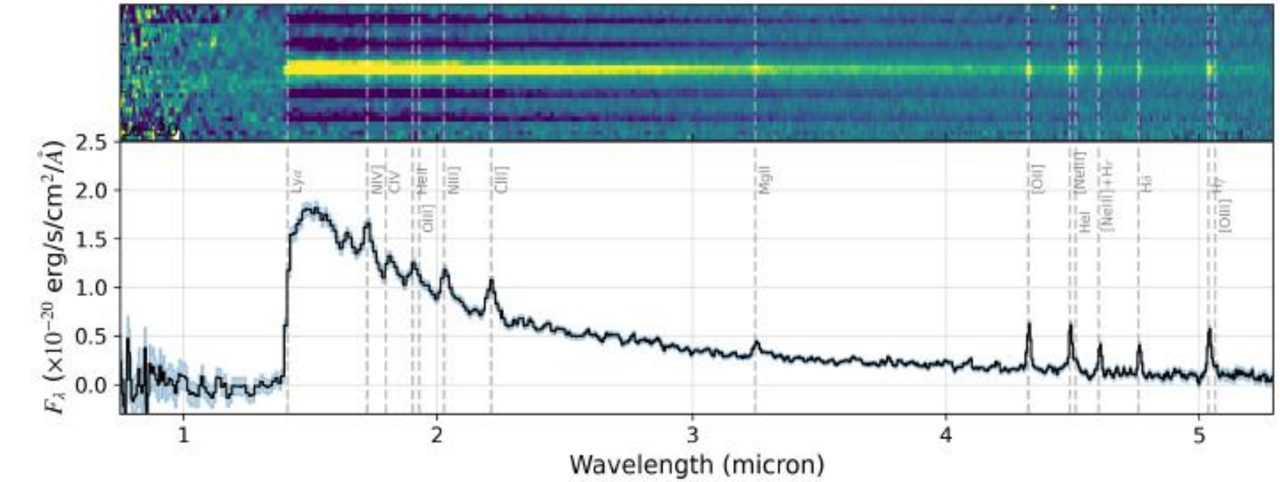


Wise+12

- JWST observations have reached a galaxy at up to z=14.2 (Carniani+24a, Helton+24; see talks of Carniani and more)
  - ALMA follow up: [OIII]88um emission → Suggesting $Z \gtrsim 0.1\ Z_\odot$: Already chemically enriched (Schouws+24, Carniani+24b).
  - PopIII star-formation producing abundant very massive stars in clusters: Followed by core-collapse supernovae (CCSNe) maybe including hypothetical pair-instability supernovae (PISNe) etc.
  - Is such an early star formation/chemical enrichment picture correct?

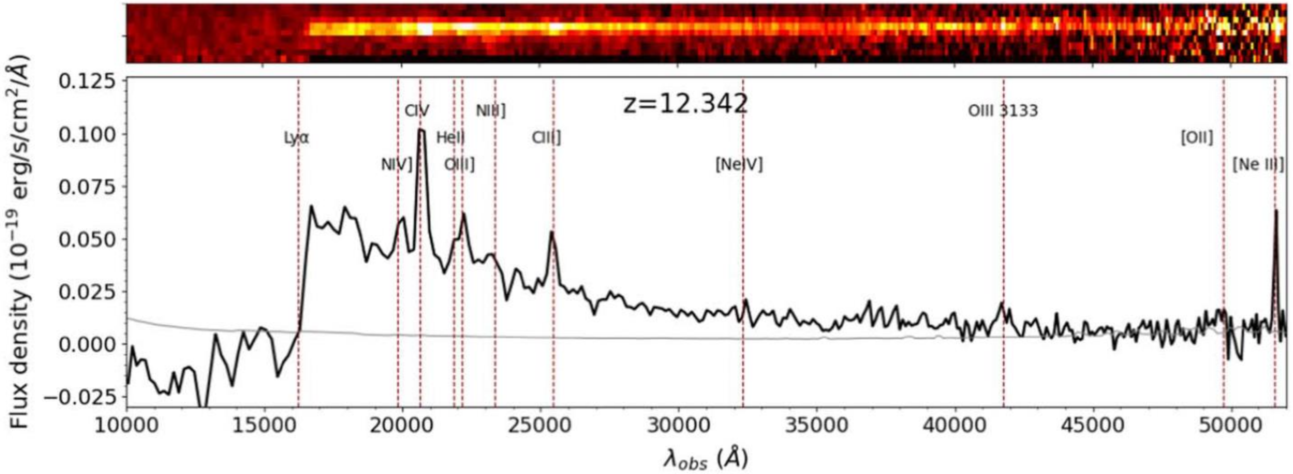
Early Star-Formation and Chemical Enrichment

GN-z11
(z=10.60)



Bunker+23

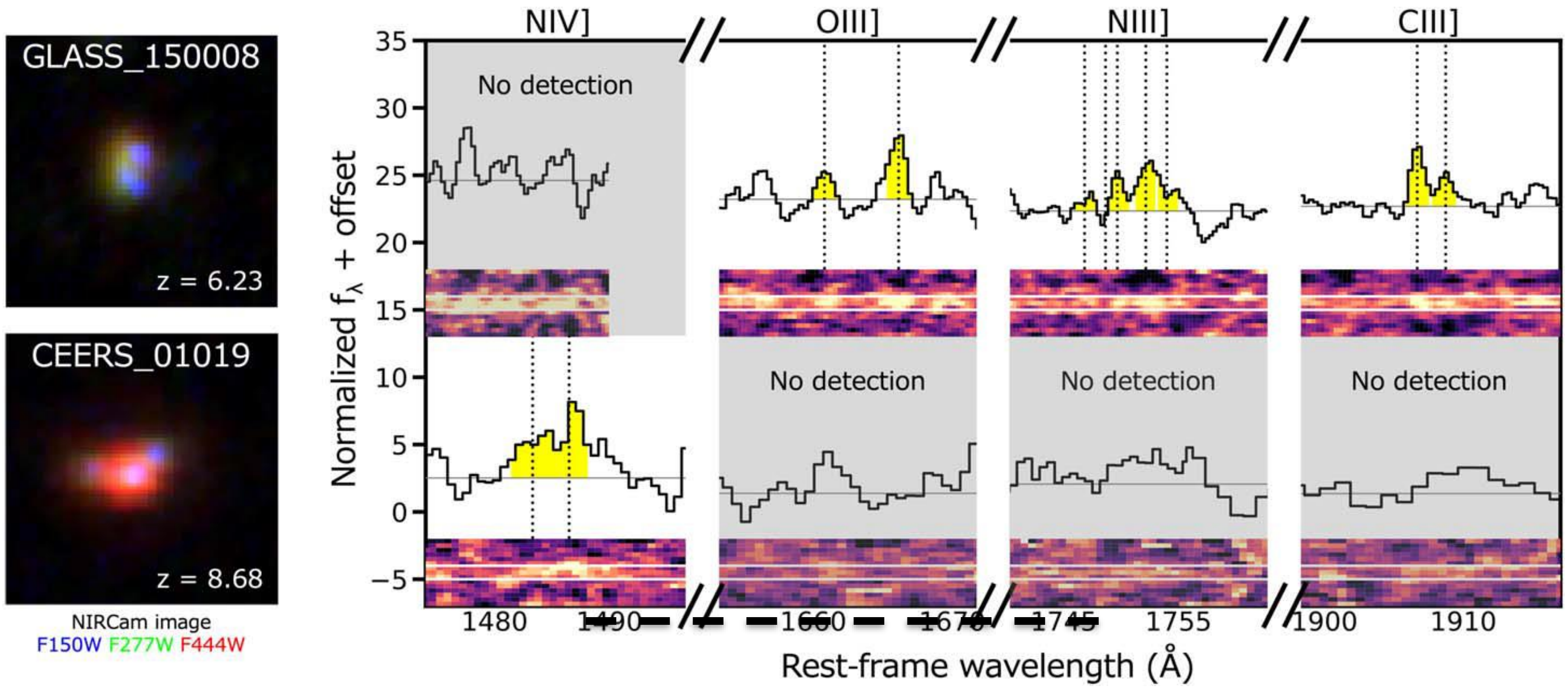
GHZ2
(z=12.34)



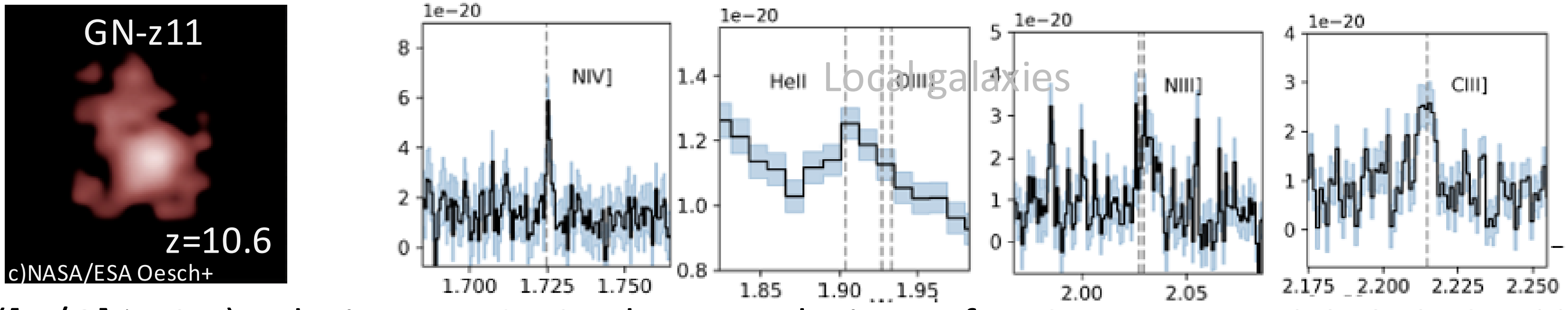
Castellano+24
+ MIRI [OIII] Hα (Zavala+24)

- JWST: Emission (absorption) features in the spectra at z~10
  → Early star-formation and chemical enrichment processes are encoded.

Strong Nitrogen Lines



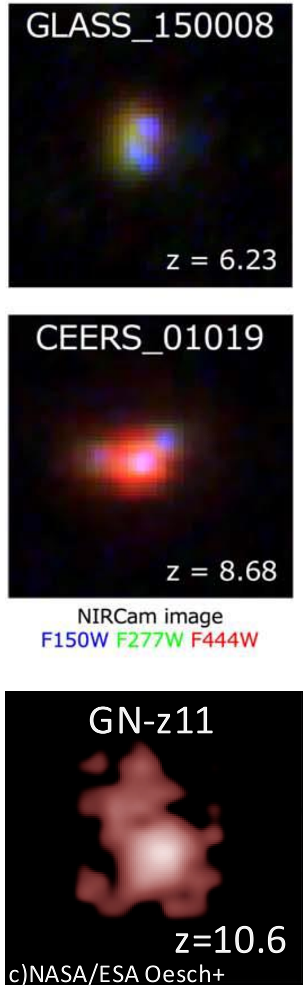
Isobe+23

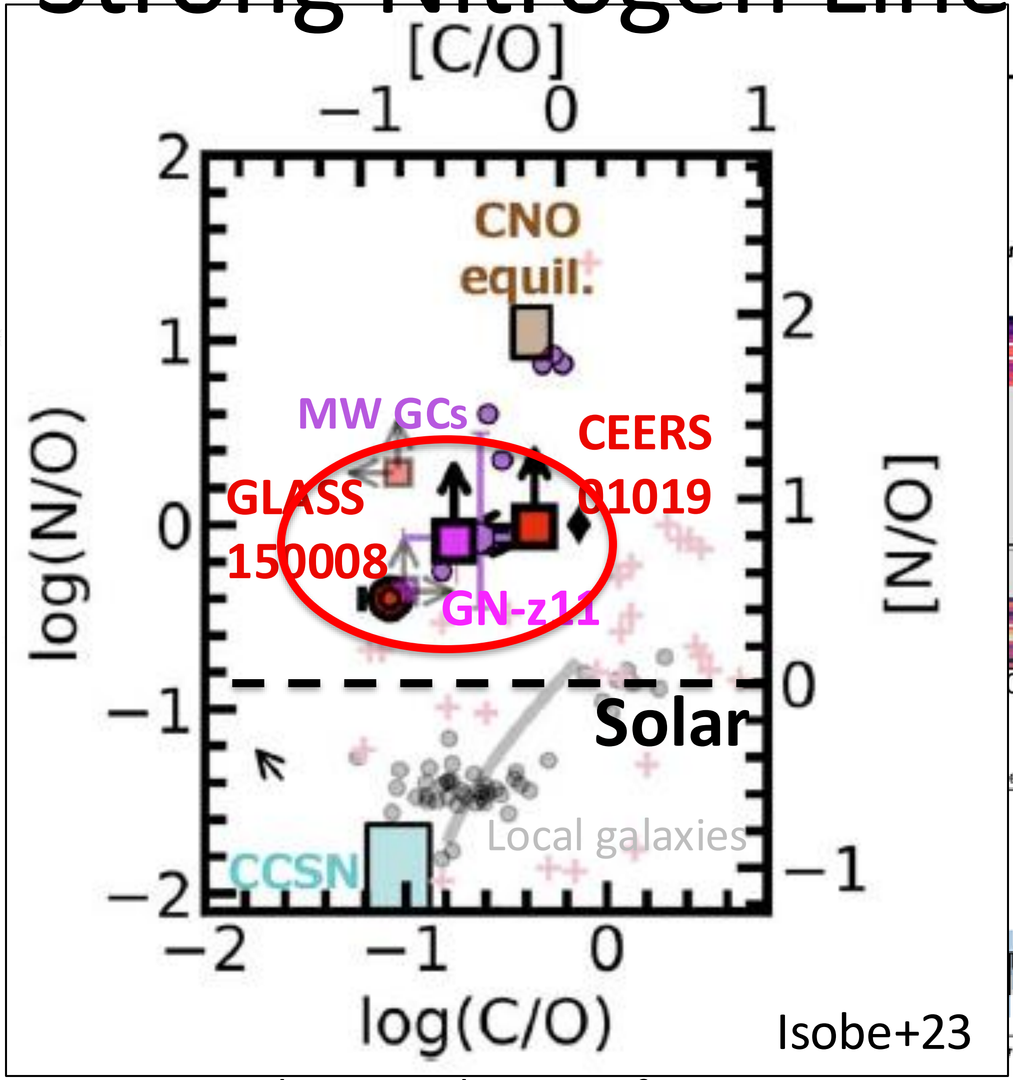


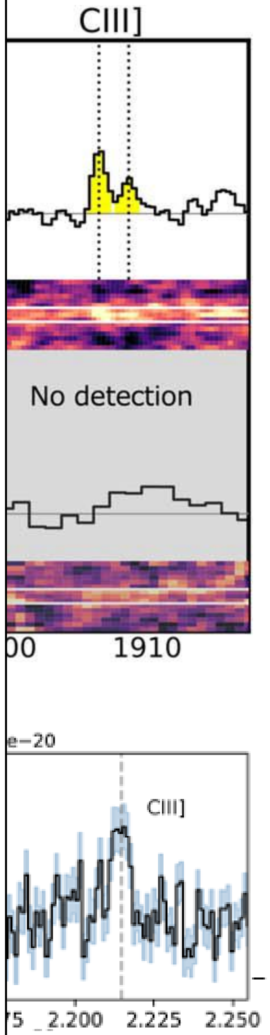
Bunker+23

- Nitrogen rich ([N/O] ≳ 0.5) galaxies at z~6-12. About 7 galaxies so far: GN-z11, CEERS 01019, GLASS 150008, GS-NDG-9422...

Strong Nitrogen Lines





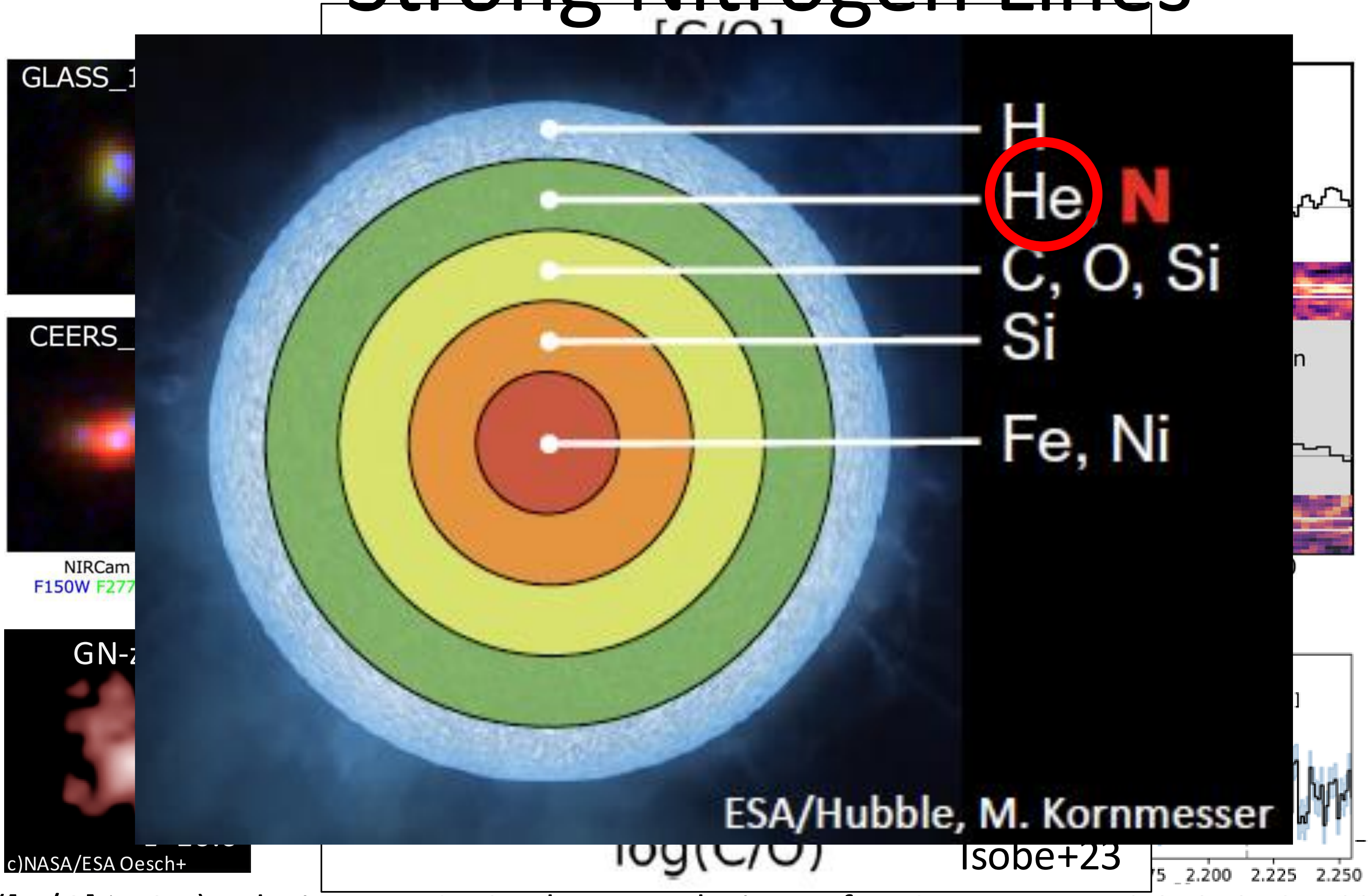


Isobe+23

Bunker+23

- Nitrogen rich ([N/O] ≳ 0.5) galaxies at z~6-12. About 7 galaxies so far: GN-z11, CEERS 01019, GLASS 150008, GS-NDG-9422...
  →Similar to globular cluster stars (+WR galaxy). Globular cluster formation? (Cameron+23, Isobe+23, Senchyna+24, Topping+24 and more)
- Characteristic chemical abundance ratios→ Something special in early star formation/chemical enrichment?
- CNO ratios: Abundance ratios skewed toward the CNO-cycle equiliburium in the CNO diagram (Isobe+23)

Strong Nitrogen Lines

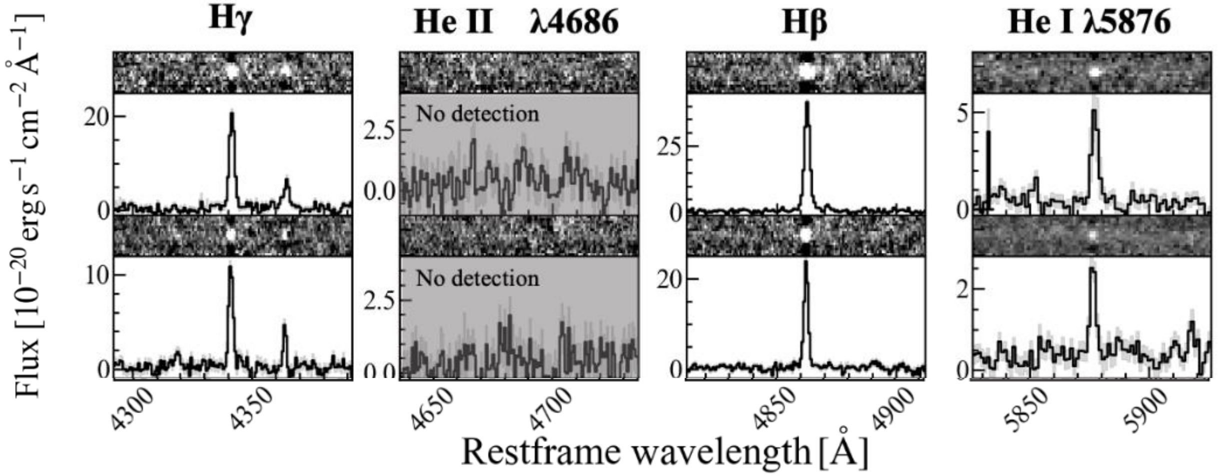


Isobe+23

Bunker+23

- Nitrogen rich ([N/O] ≳ 0.5) galaxies at z~6-12. About 7 galaxies so far: GN-z11, CEERS 01019, GLASS 150008, GS-NDG-9422...
  →Similar to globular cluster stars (+WR galaxy). Globular cluster formation? (Cameron+23, Isobe+23, Senchyna+24, Topping+24 and more)
- Characteristic chemical abundance ratios→ Something special in early star formation/chemical enrichment?
- CNO ratios: Abundance ratios skewed toward the CNO-cycle equilibrium in the CNO diagram (Isobe+23)
  - Unlike local galaxies w CCSNe. Chemical enrichment dominated by gas from hydrogen burning shell (outer envelope)?

Strong HeI λ5876 Lines

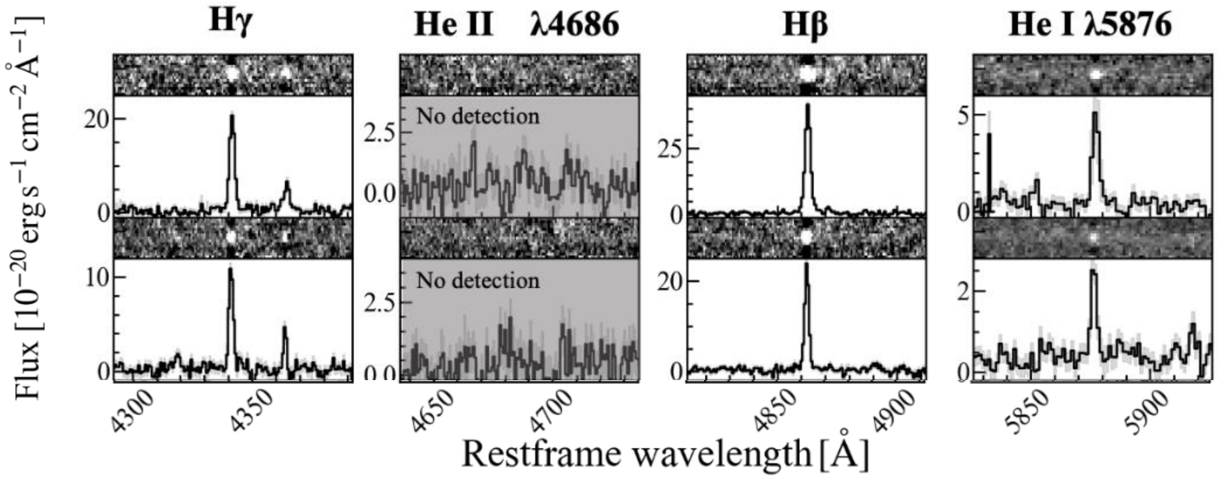


Hiroto Yanagisawa

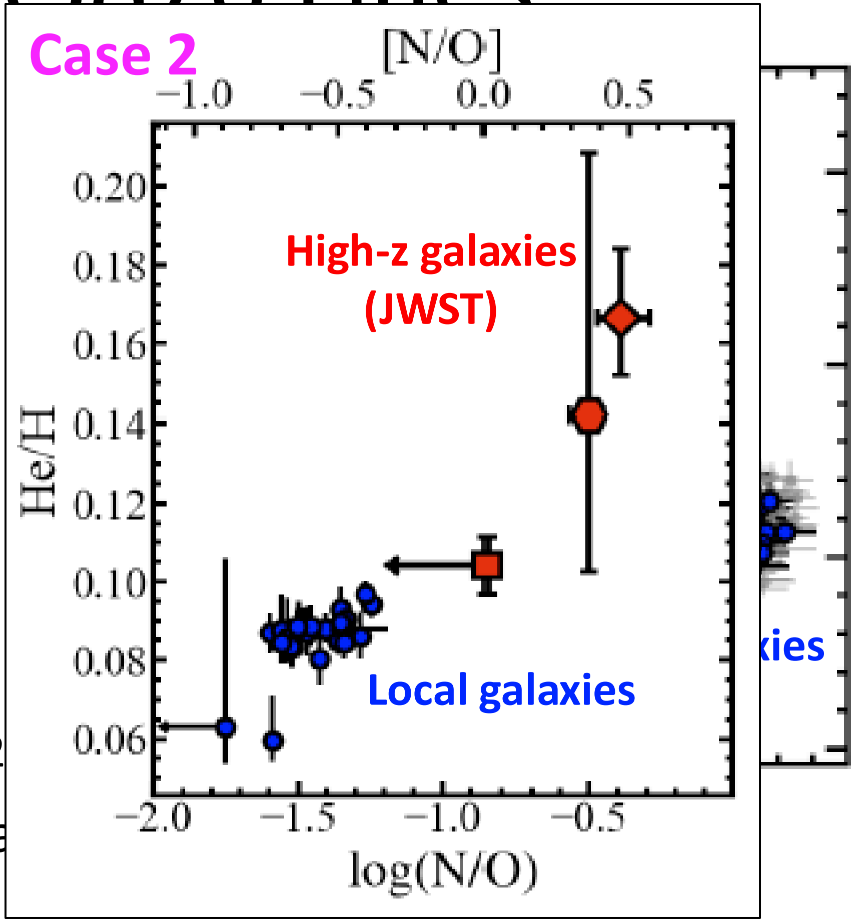
Yanagisawa et al. (2024)

- Strong HeI5876 lines for high N/O galaxies (See Shapley's talk)

Strong HeI λ5876 Lines



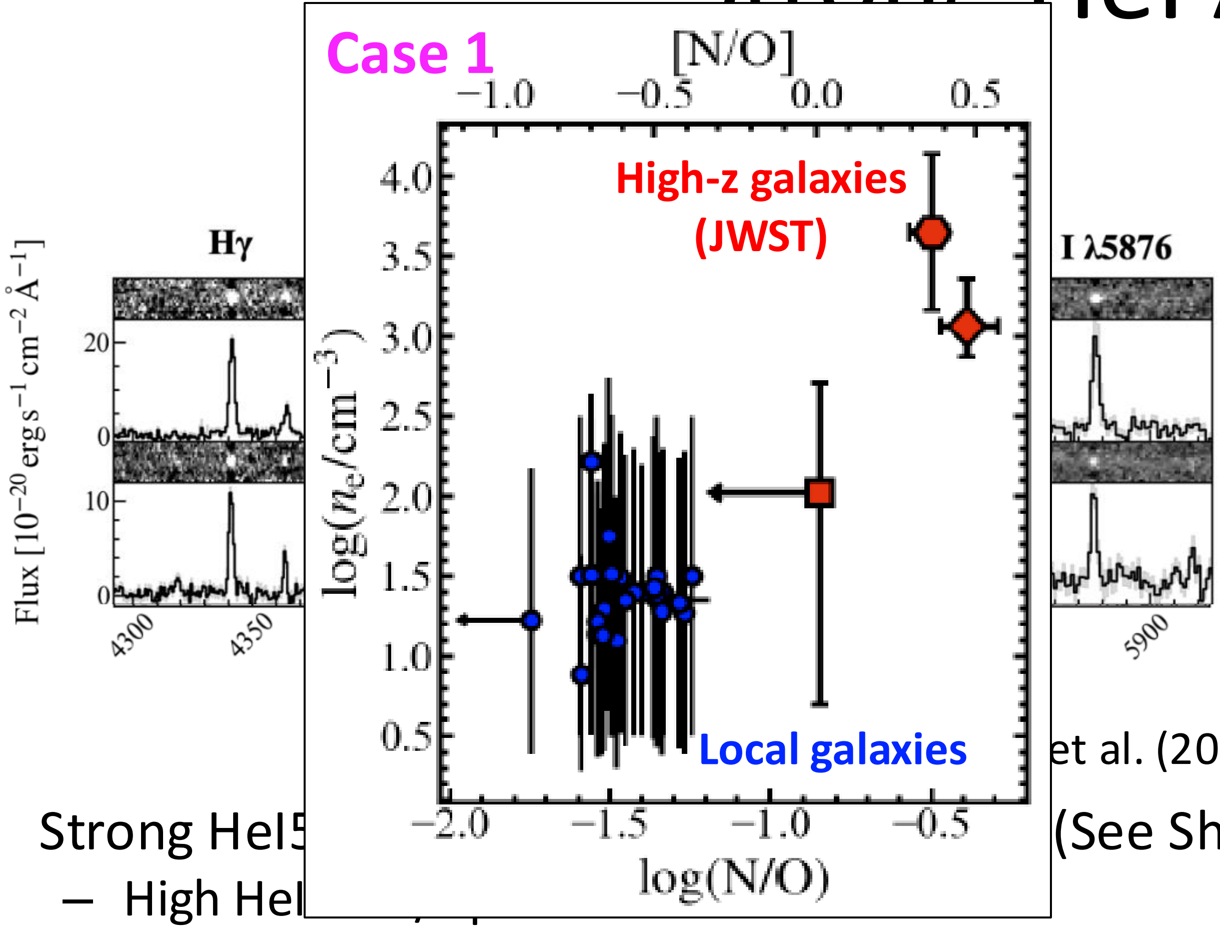
Yanagisawa et al. (202



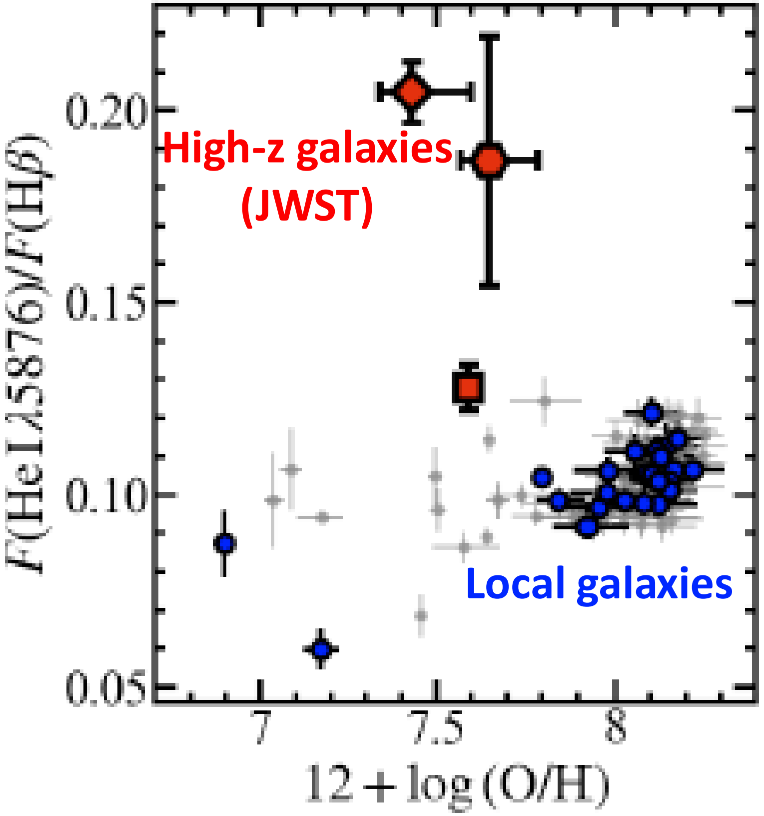
Hiroto Yanagisawa

- Strong HeI5876 lines for high N/O galaxies (See Sha
  - High HeI5876/Hβ ratios
- Why? Degeneracy between n_e and He/H (Needing HeI10830 line for resolving it)

Strong HeI λ5876 Lines



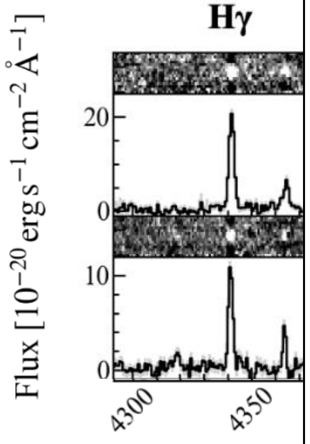
et al. (2024)

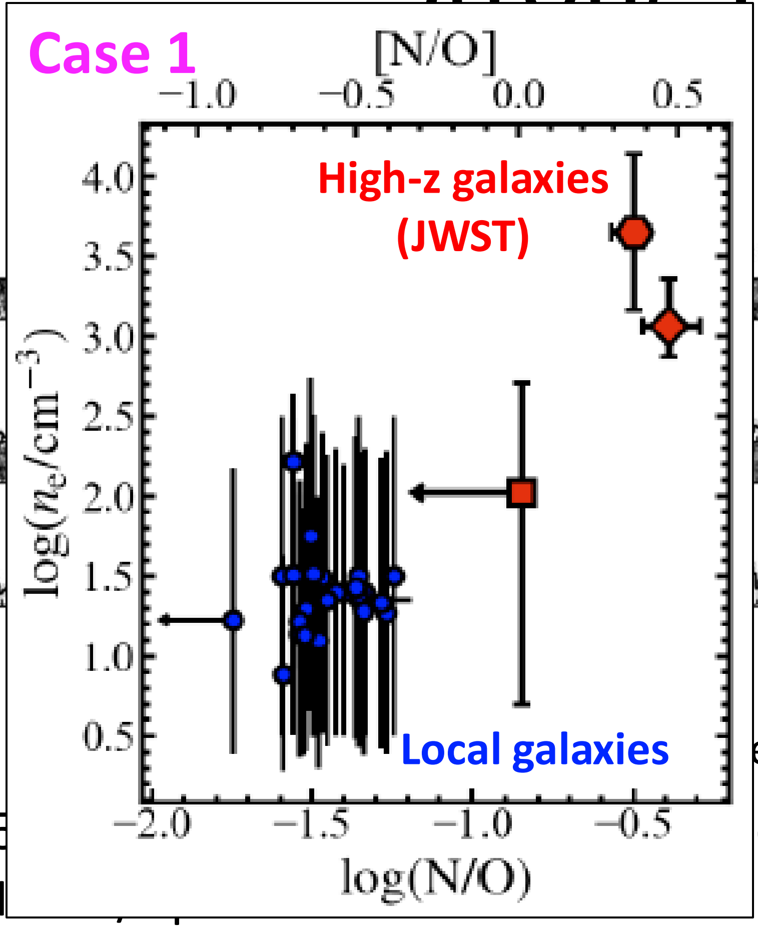


Hiroto Yanagisawa

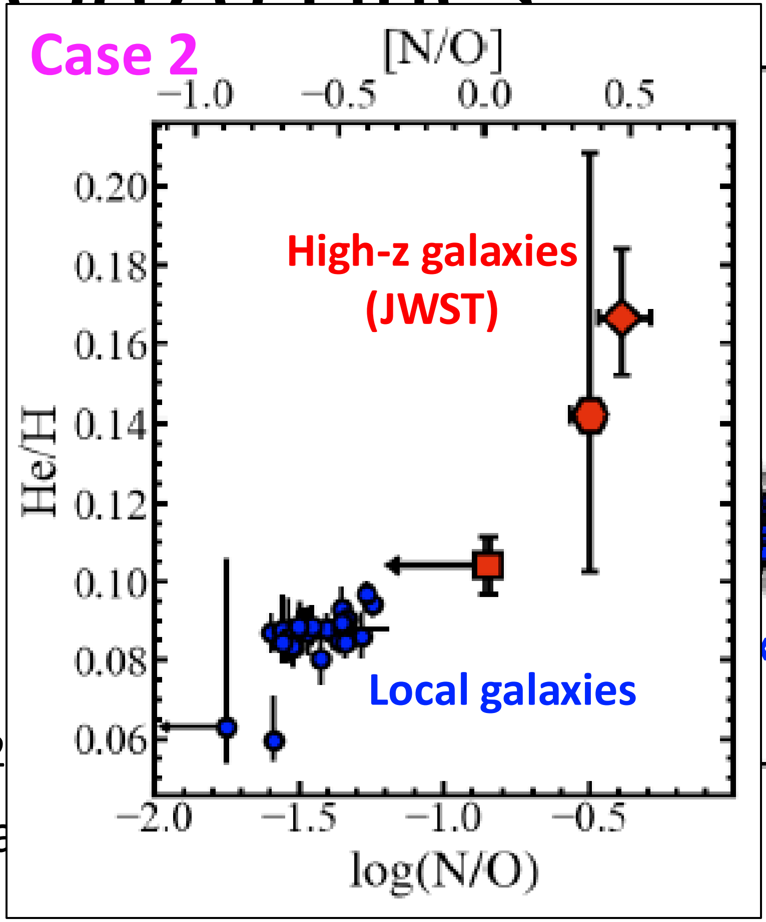
- Strong HeI5 (See Shapl
  - High HeI
- Why? Degeneracy between n_e and He/H (Needing HeI10830 line for resolving it)
  - Case 1: High HeI/Hβ ratios explained by n_e: Positive correlation between n_e and N/O
    - Strong He lines from dense clouds via collisional excitation. Suggestive of dense SF or AGN? (Topping+24)

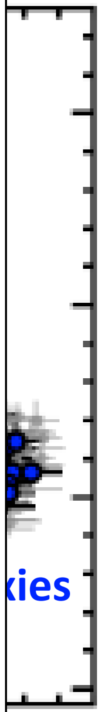
Strong HeI λ5876 Lines





et al. (202



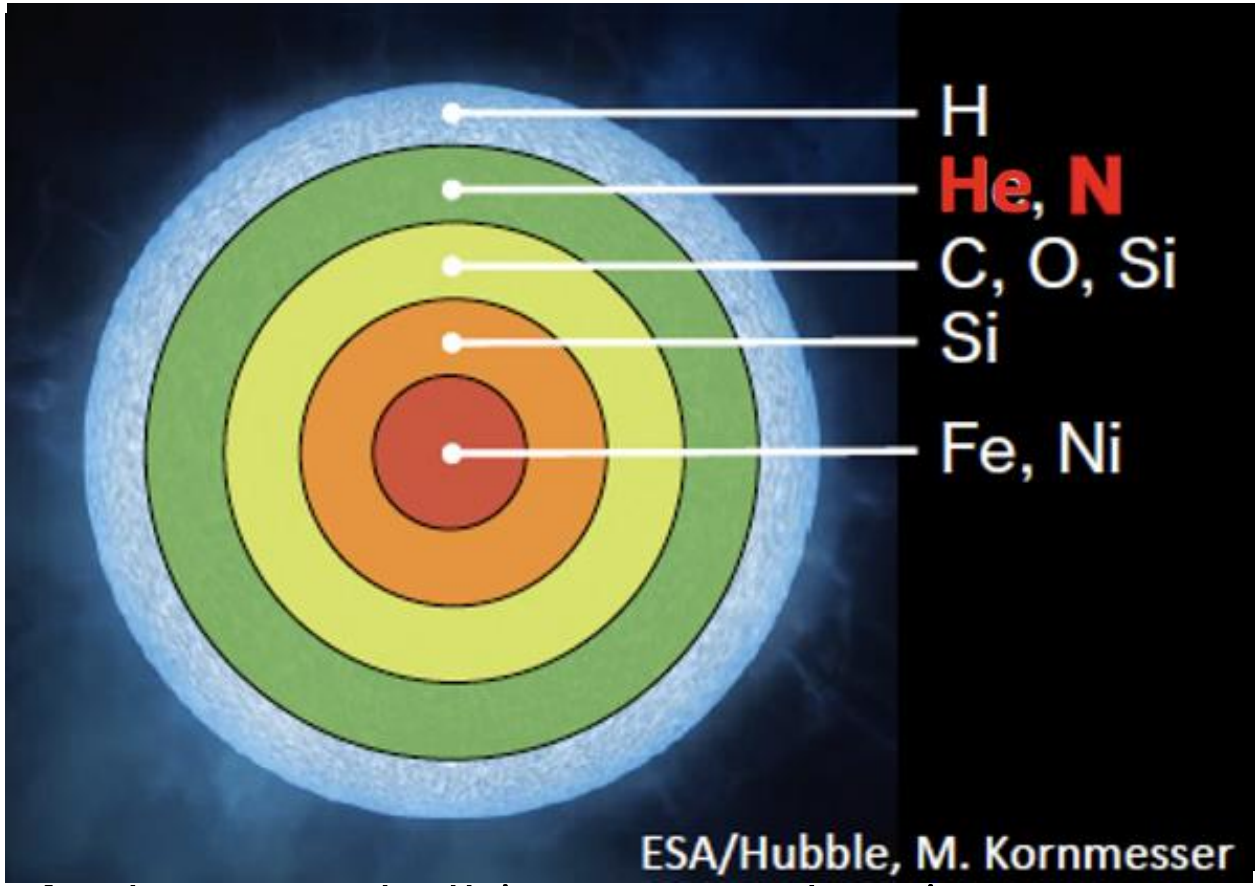


Hiroto Yanagisawa

- Strong HeI5 … (See Sha
  - High HeI …
- Why? Degeneracy between n_e and He/H (Needing HeI10830 line for resolving it)
  - Case 1: High HeI/Hβ ratios explained by n_e: Positive correlation between n_e and N/O
    - Strong He lines from dense clouds via collisional excitation. Suggestive of dense SF or AGN? (Topping+24)
  - Case 2: High HeI/Hβ ratios explained by N/O: Positive correlation between He/H and N/O
    - Consistent with the enrichment given by CNO-cycle equilibrium
    - Not a standard chemical enrichment of core-collapse supernova ejecta (showing rich N and He)

Origins of the Rich N (and He)

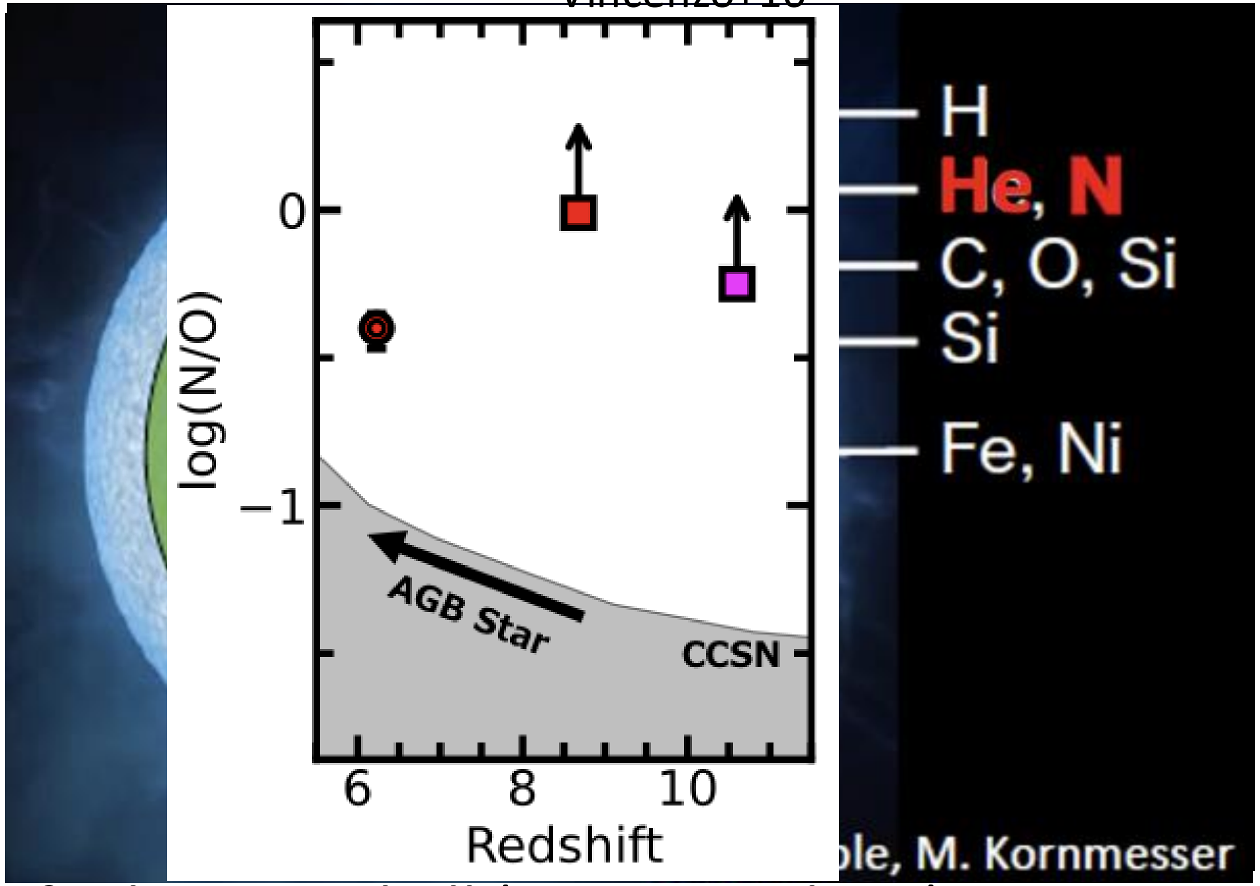
Origins of the Rich N (and He)



- ISM Enriched by gas of H burning shell (outer envelope)

Origins of the Rich N (and He)

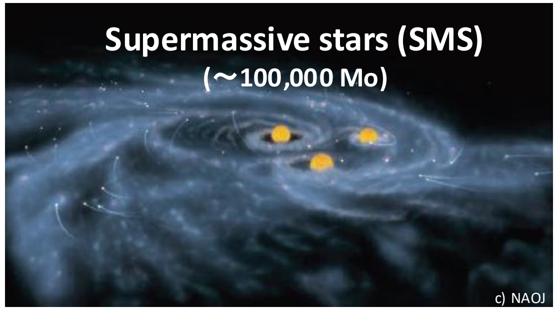
Vincenzo+16



- ISM Enriched by gas of H burning shell (outer envelope)

  Too early for enrichment by AGB stars for high-z galaxies

Origins of the Rich N (and He)

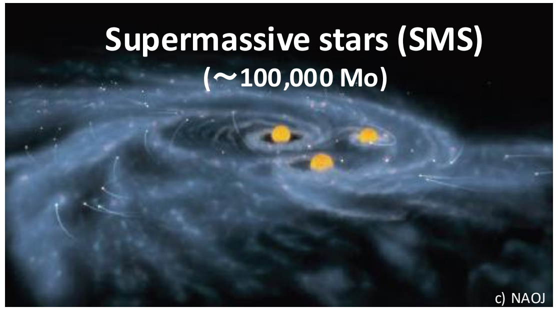


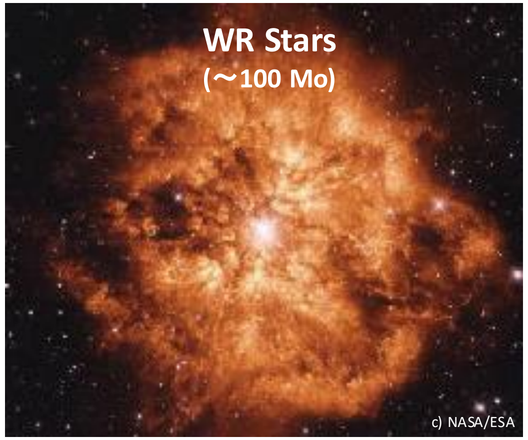
- ISM Enriched by gas of H burning shell (outer envelope)

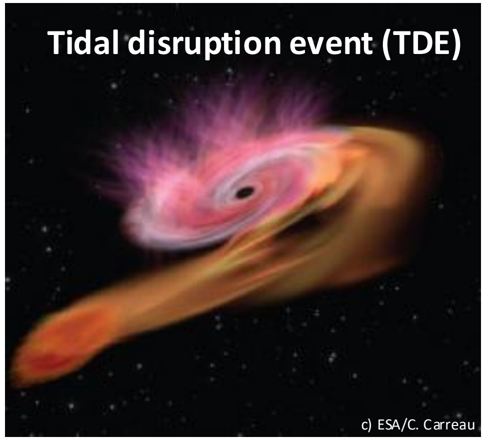
  Too early for enrichment by AGB stars for high-z galaxies

  – Super massive stars (SMS; Charbonnel+23)

Origins of the Rich N (and He)





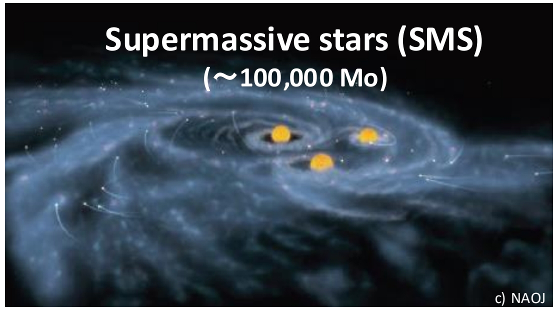


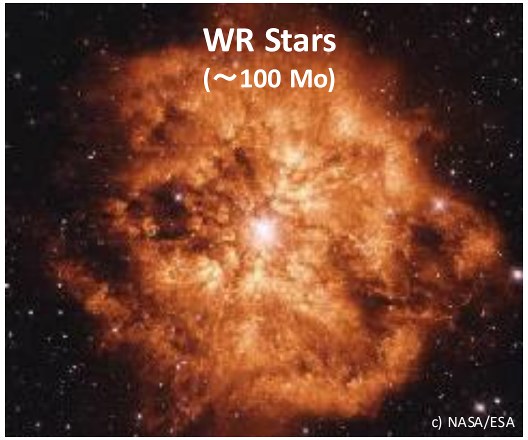
- ISM Enriched by gas of H burning shell (outer envelope)

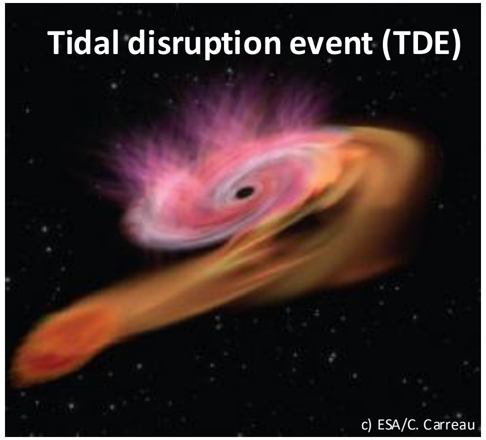
  Too early for enrichment by AGB stars for high-z galaxies

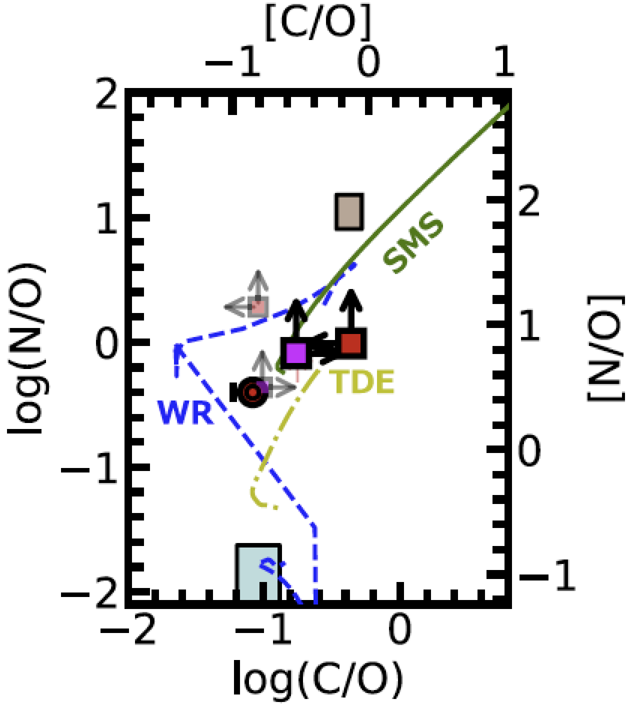
  – Super massive stars (SMS; Charbonnel+23)
  – Wolf-Rayet stars (WR; Cameron+23)
  – Tidal disruption event (TDE; Rees+88)

Origins of the Rich N (and He)



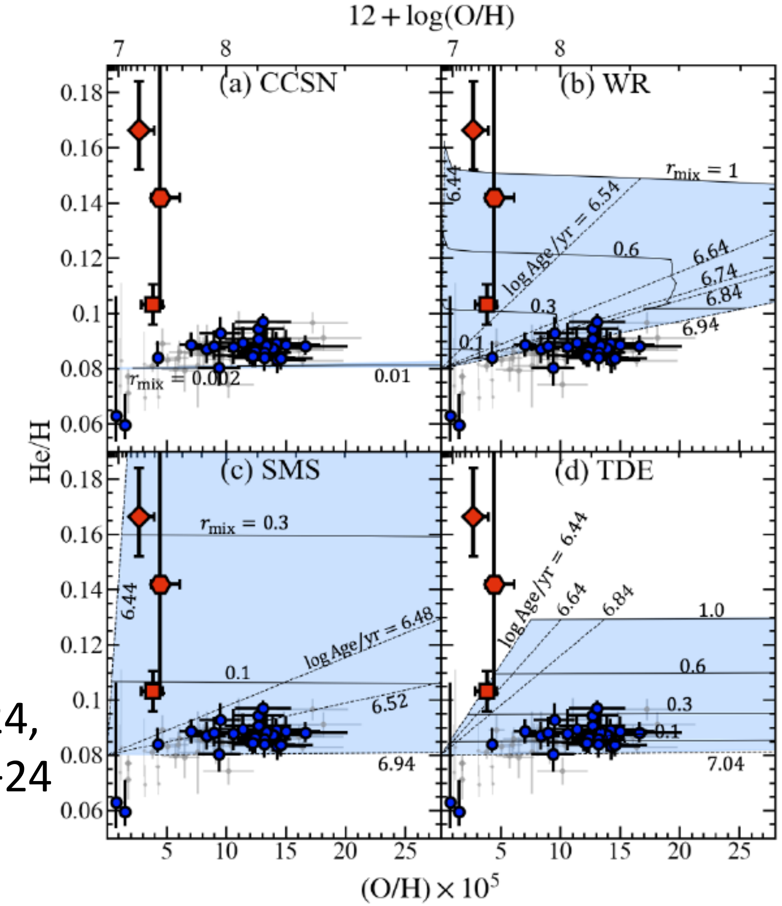






Watanabe+23, Isobe+23

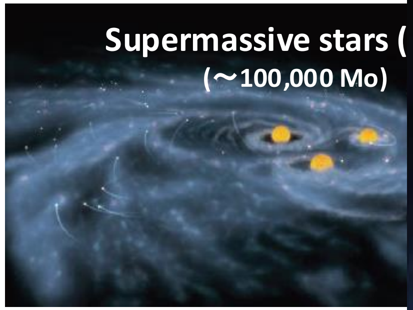
Kuria Watanabe

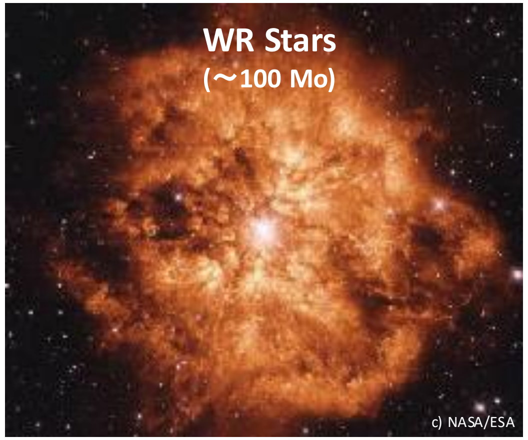


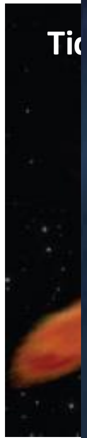
Watanabe+24,
Yanagisawa+24

- ISM Enriched by gas of H burning shell (outer envelope)
  Too early for enrichment by AGB stars for high-z galaxies
  - Super massive stars (SMS; Charbonnel+23)
  - Wolf-Rayet stars (WR; Cameron+23)
  - Tidal disruption event (TDE; Rees+88)
- Explaining N/O and He/H. Is SMS preferred for He/H??

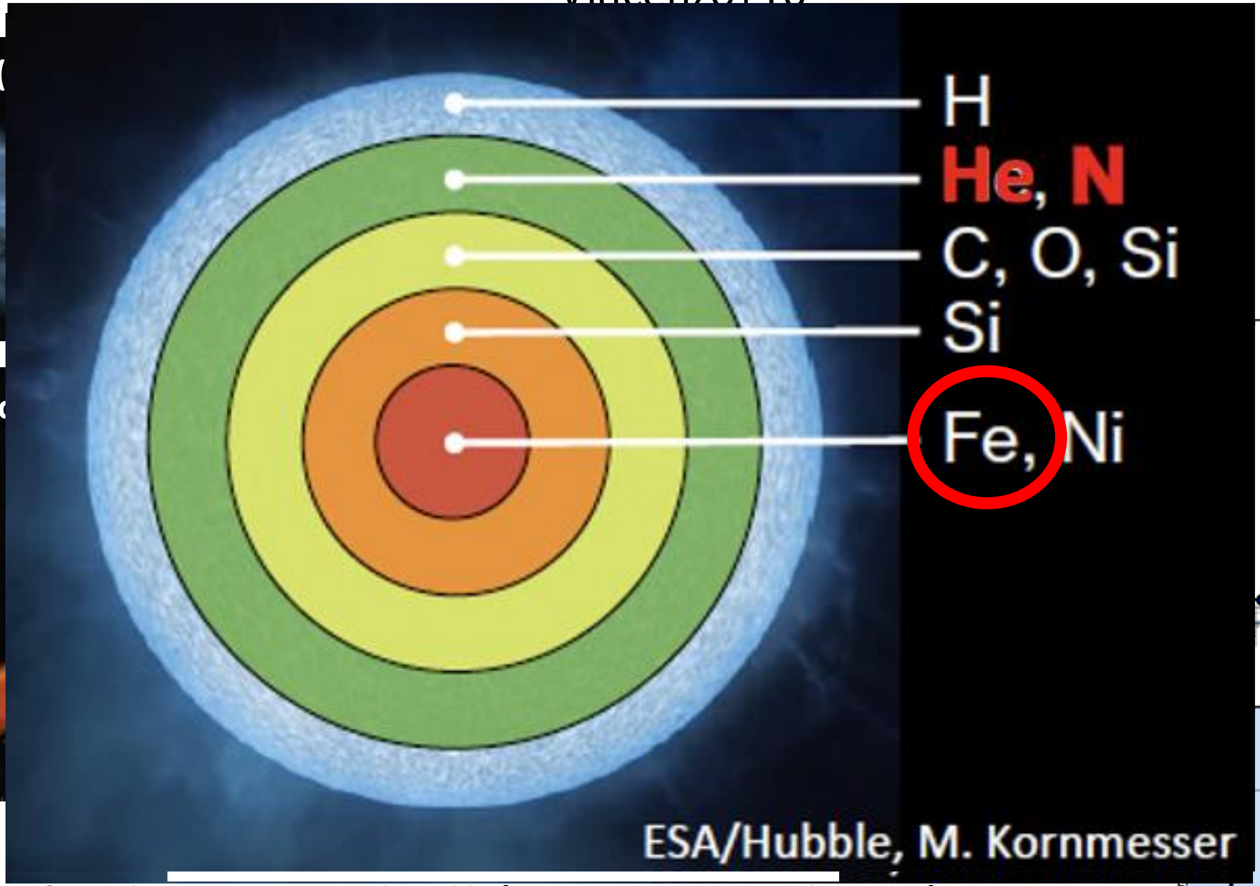
Origins of the Rich N (and He)



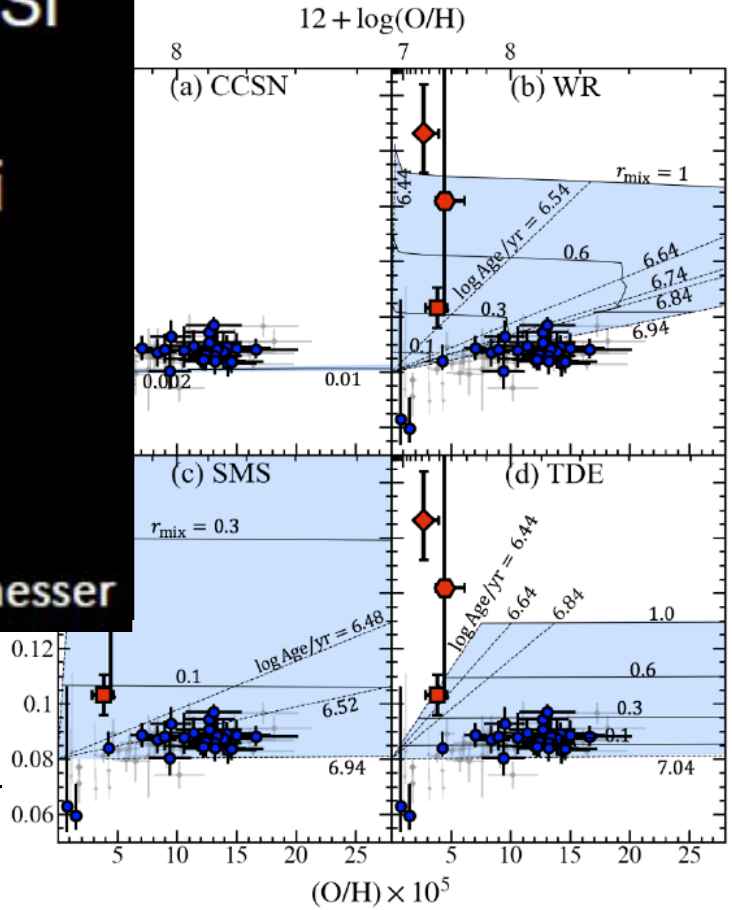




Vincenzo+16



Kuria Watanabe

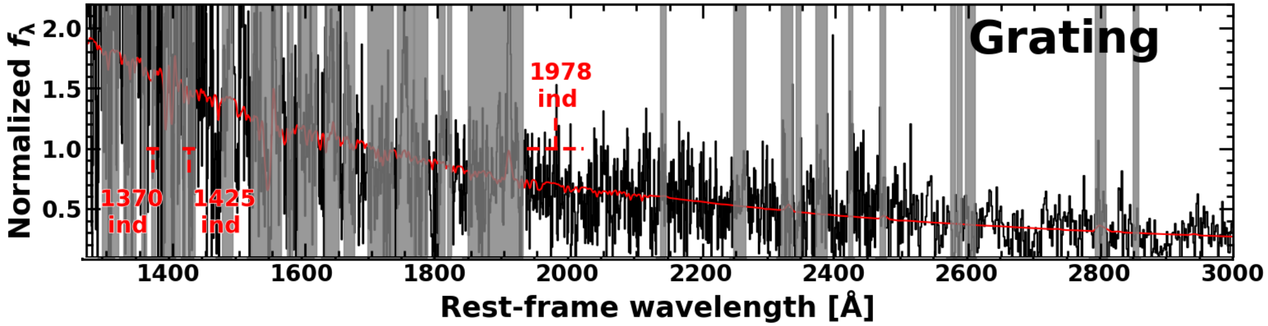


Watanabe+24,
Yanagisawa+24

- ISM Enriched by gas of H burning shell (outer envelope)
  Too early for enrichment by AGB stars for high-z galaxies
  - Super massive stars (SMS; Charbonnel+23)
  - Wolf-Rayet stars (WR; Cameron+23)
  - Tidal disruption event (TDE; Rees+88)
- Explaining N/O and He/H. Is SMS preferred for He/H??

Fe Abundance (GN-z11)

Nakane et al. (2024, ApJ in press)



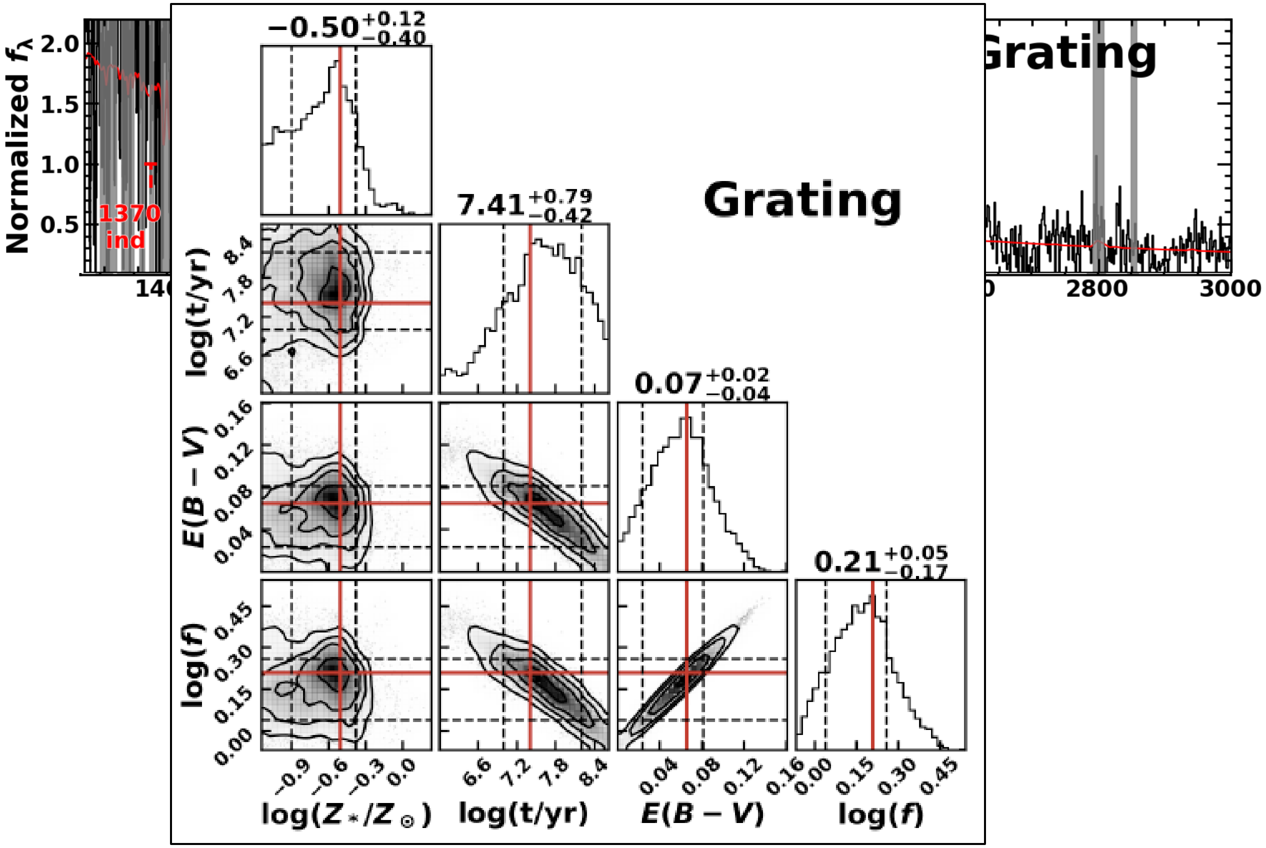
Minami Nakane

- Measuring Fe abundance w absorption lines in the UV continuum (Classical 1978 index / BPASS+CLOUDY model fitting)

Fe Abundance (GN-z11)

Nakane et al. (2024, ApJ in press)

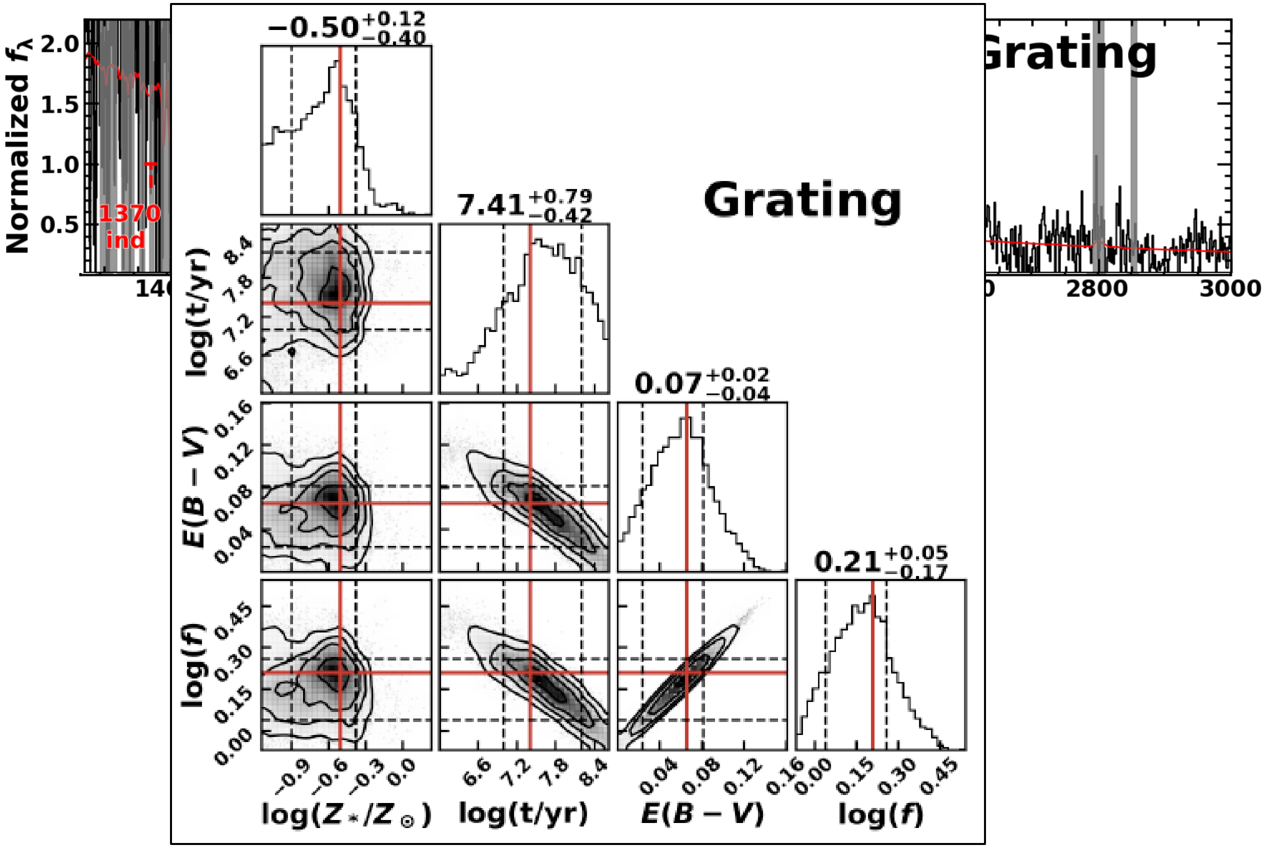
Minami Nakane

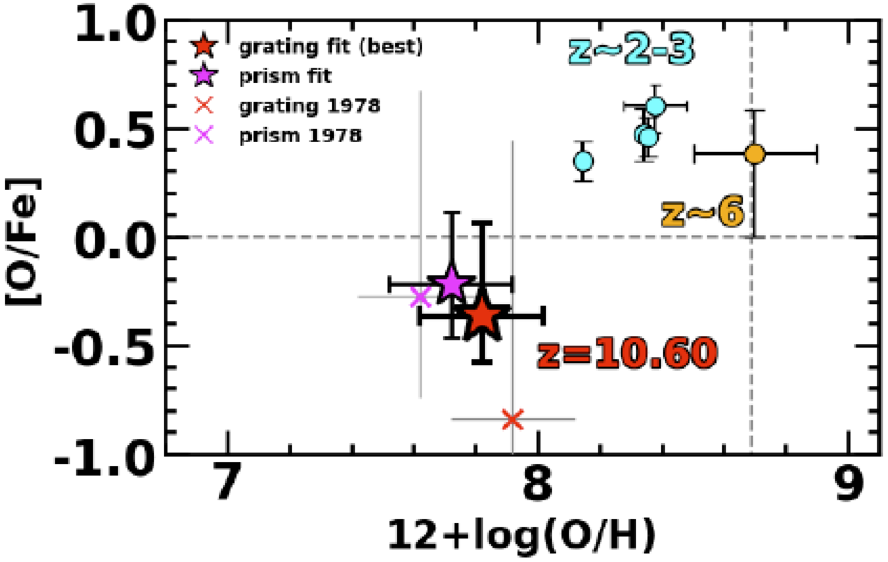


- Measuring Fe abundance w absorption lines in the UV continuum (Classical 1978 index / BPASS+CLOUDY model fitting)
  - [O/Fe] ~ -0.5 (Fe is about x3 more abundant than the Sun).Other techniques. AGN?→Similarly small [O/Fe] ≲-0.5 in case of AGN (Ji et al. 2024)

Fe Abundance (GN-z11)

Nakane et al. (2024, ApJ in press)



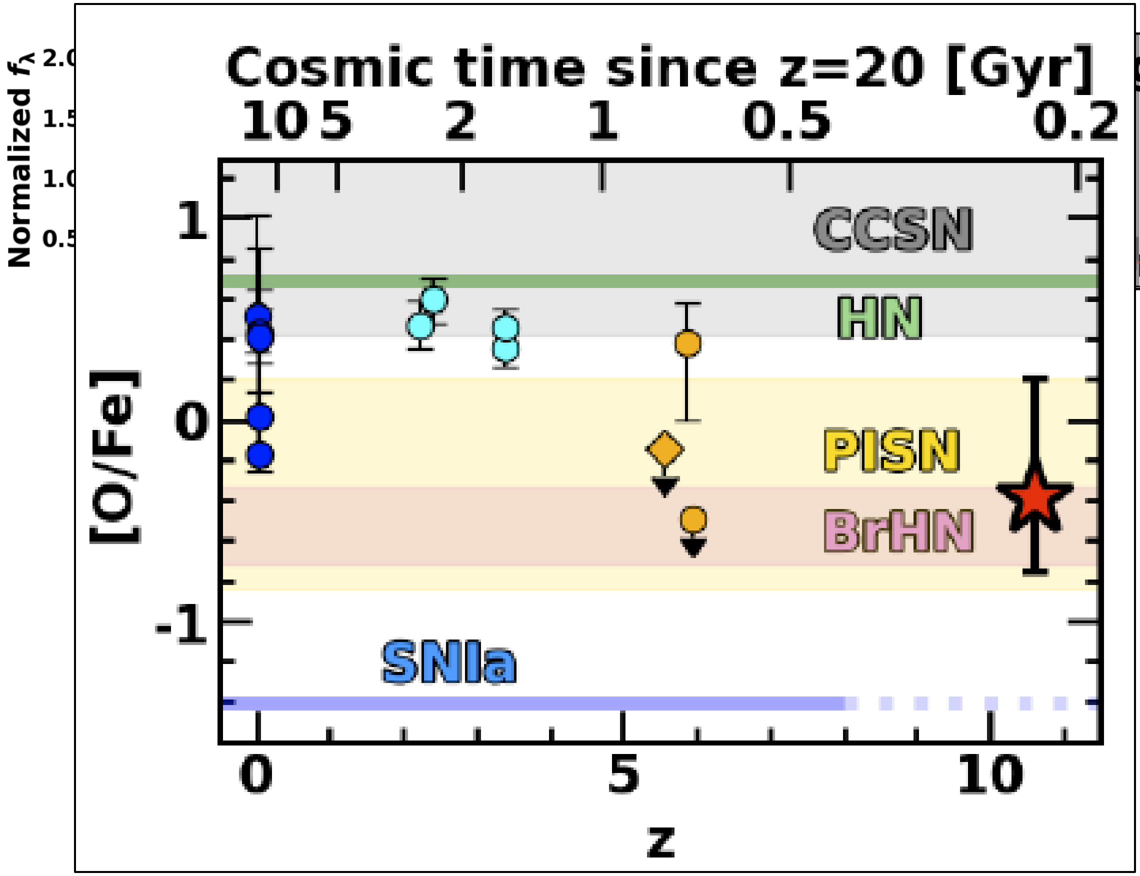


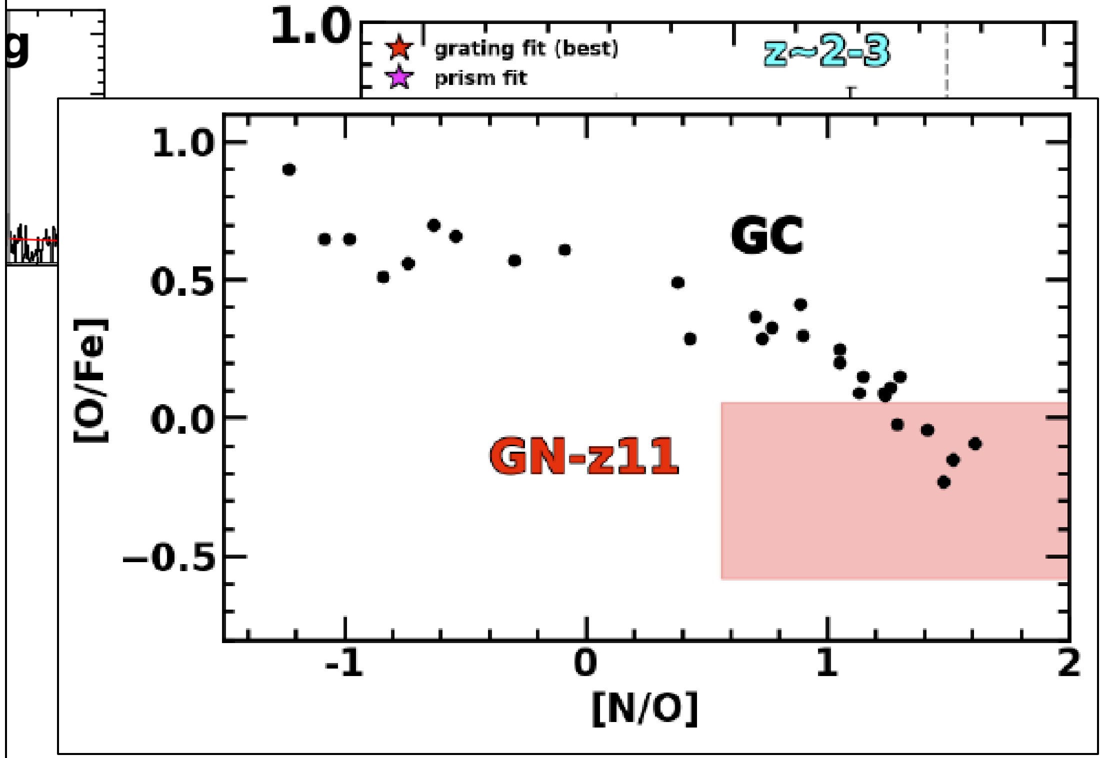
Minami Nakane

- Measuring Fe abundance w absorption lines in the UV continuum (Classical 1978 index / BPASS+CLOUDY model fitting)
  - [O/Fe] ~ -0.5 (Fe is about x3 more abundant than the Sun).Other techniques. AGN?→Similarly small [O/Fe] ≲-0.5 in case of AGN (Ji et al. 2024)
  - Fe rich at z=10 : Unlike z~2-3 and z~6 measurements obtained by the same technique

Fe Abundance (GN-z11)

Nakane et al. (2024, ApJ in press)



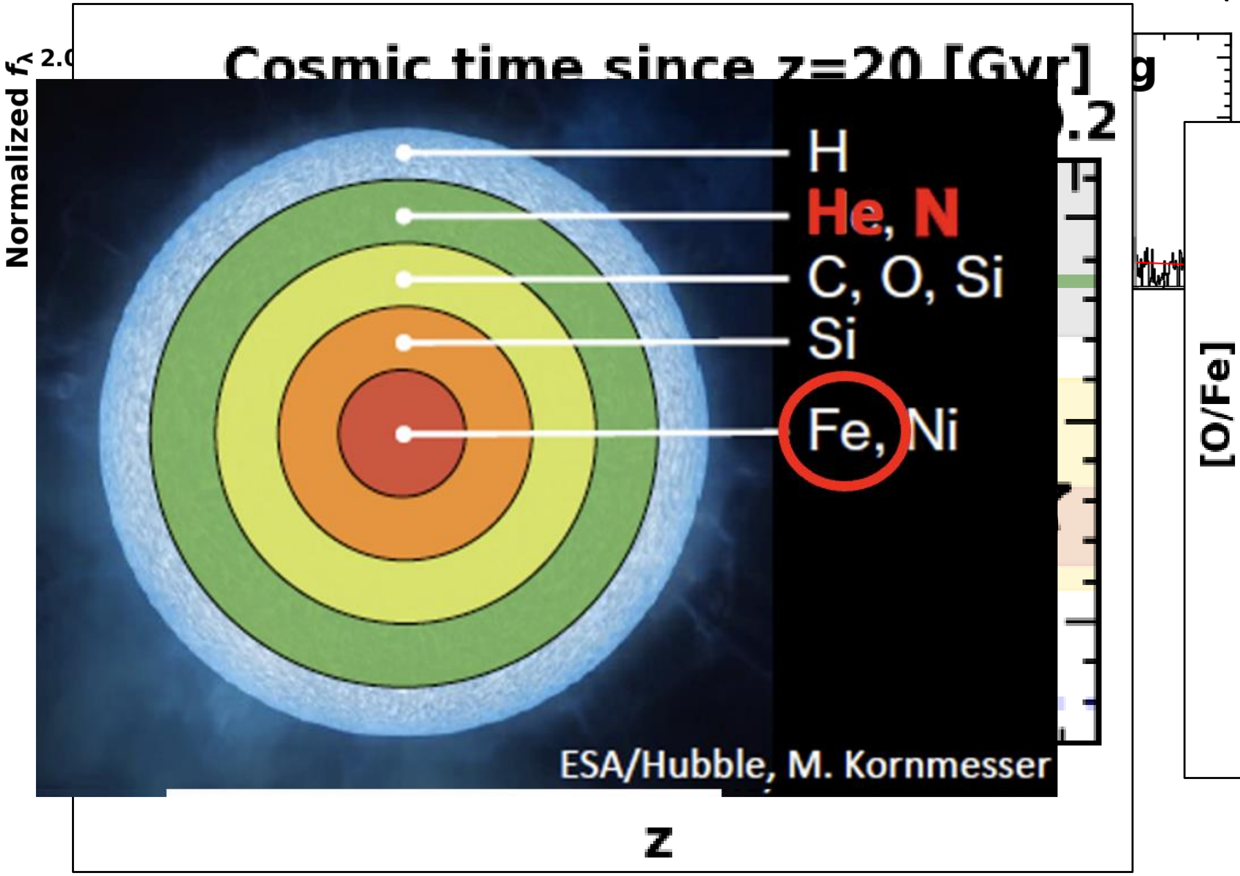


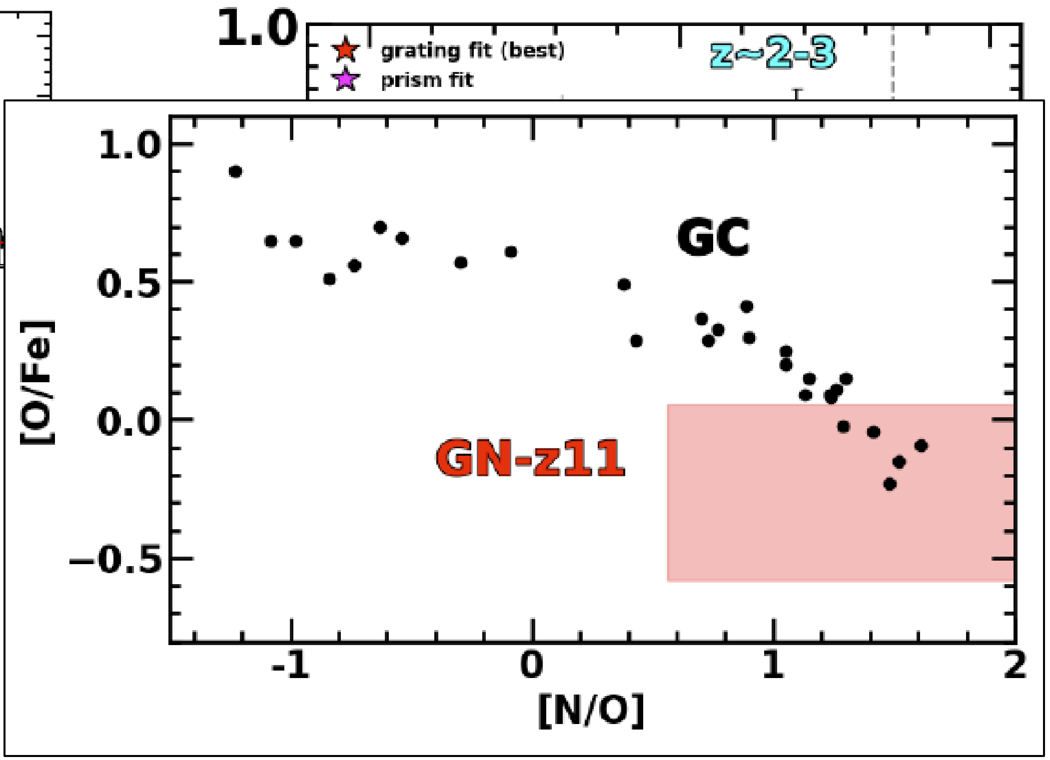
Minami Nakane

- Measuring Fe abundance w absorption lines in the UV continuum (Classical 1978 index / BPASS+CLOUDY model fitting)
  - [O/Fe] ~ -0.5 (Fe is about x3 more abundant than the Sun).Other techniques. AGN?→Similarly small [O/Fe] ≲-0.5 in case of AGN (Ji et al. 2024)
  - Fe rich at z=10 : Unlike z~2-3 and z~6 measurements obtained by the same technique
- SNIa for Fe enrichment? Cosmic time ~ 400 Myr / Star-formation only in ~200 Myr.
  - Very short delay time for SNIa formation (low mass star evolution -> white dwarf and gas accretion)
  - Characteristic SN explosions in metal poor early galaxies such as bright hypernovae or pair-instability supernovae (PISNe)?
- Globular cluster formation? -> Yes. Consistent in [O/Fe] as well as [N/O]. Why high [N/O] and low [O/Fe]? Open question.

Fe Abundance (GN-z11)

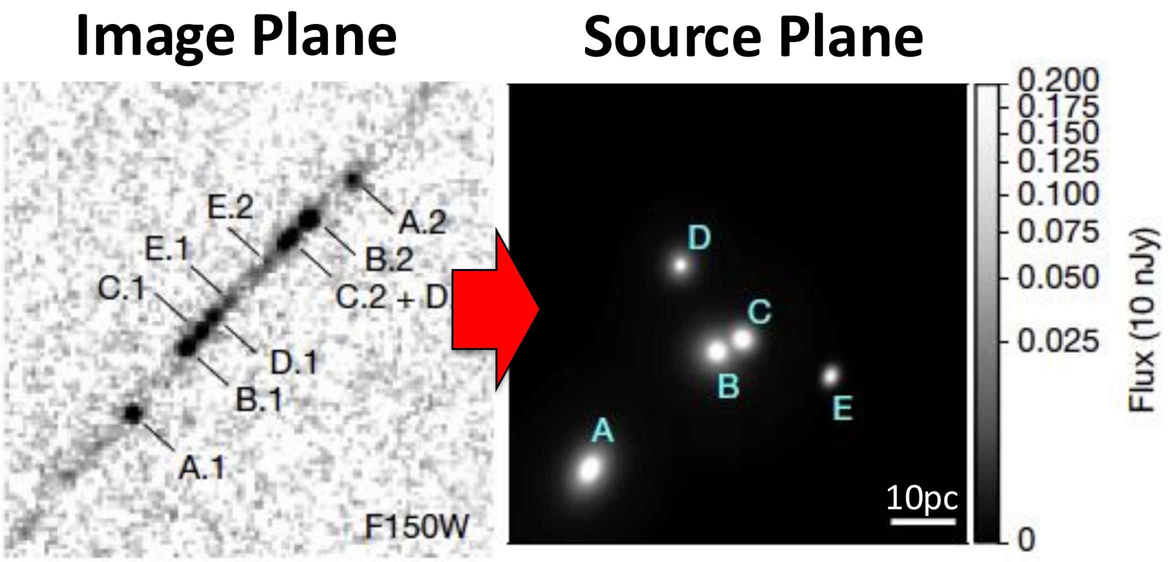
Nakane et al. (2024, ApJ in press)



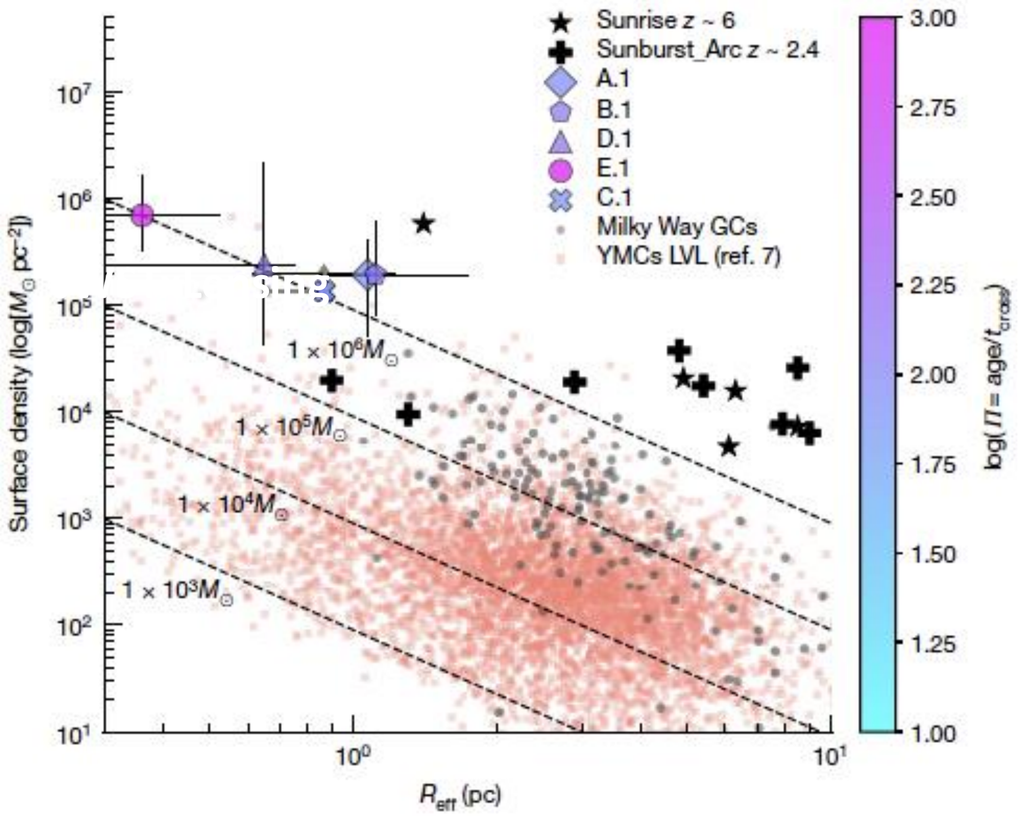


- Measuring Fe abundance w absorption lines in the UV continuum (Classical 1978 index / BPASS+CLOUDY model fitting)
  - [O/Fe] ~ -0.5 (Fe is about x3 more abundant than the Sun).Other techniques. AGN?→Similarly small [O/Fe] ≲-0.5 in case of AGN (Ji et al. 2024)
  - Fe rich at z=10 : Unlike z~2-3 and z~6 measurements obtained by the same technique
- SNIa for Fe enrichment? Cosmic time ~ 400 Myr / Star-formation only in ~200 Myr.
  - Very short delay time for SNIa formation (low mass star evolution -> white dwarf and gas accretion)
  - Characteristic SN explosions in metal poor early galaxies such as bright hypernovae or pair-instability supernovae (PISNe)?
- Globular cluster formation? -> Yes. Consistent in [O/Fe] as well as [N/O]. Why high [N/O] and low [O/Fe]? Open question.

Globular Cluster Formation ?



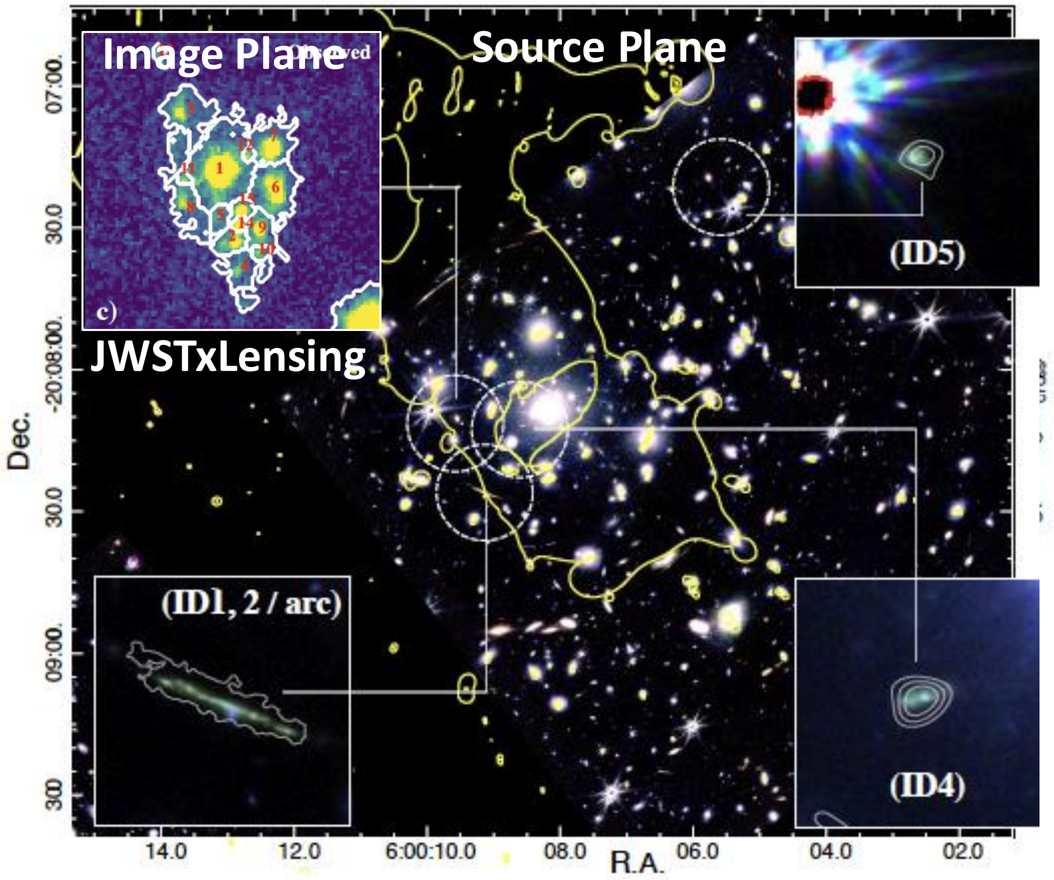
Adamo+24



- Cosmic Gems: Lensed galaxy at z_{phot}~10 (μ~100-300; Vanzella's talk)
  - 5 stellar clumps with M*~10^6Mo and r_e~1pc. Proto globular clusters? (Adamo+24)
  - Needing spectroscopy for testing chemical abundances, especially [N/O] enhancement

In larger scales (≳10 pc), many stellar clumps are found (e.g. Mowla+24, Fujimoto+24)

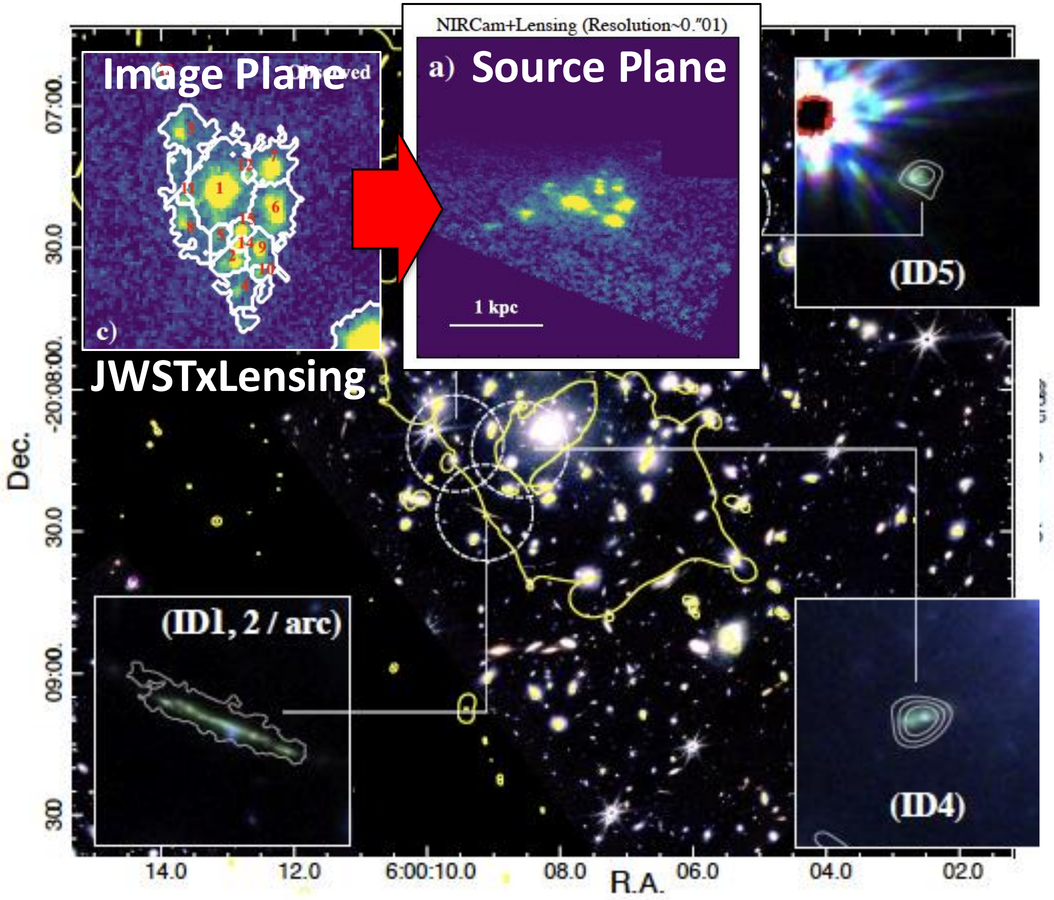
Beyond Globular Clusters
Stellar Clumps and Disk



Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto’s talk)

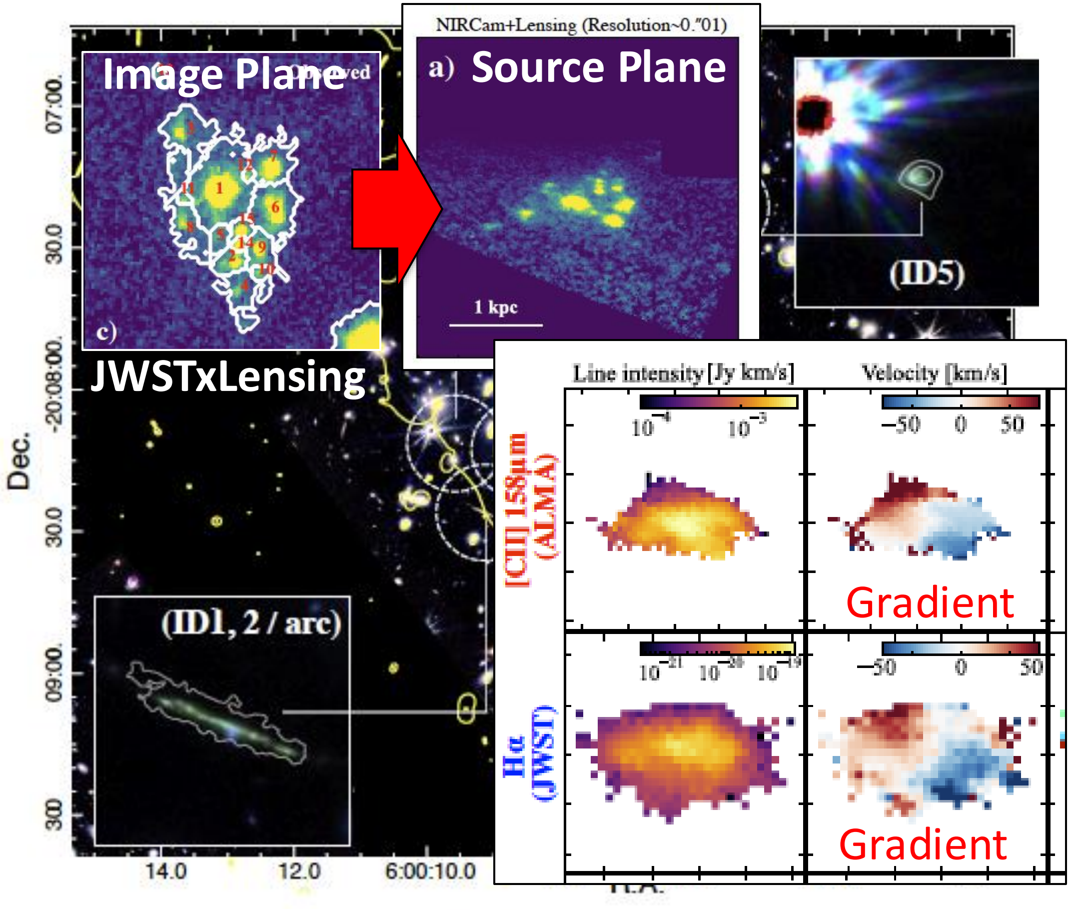
Beyond Globular Clusters
Stellar Clumps and Disk



Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto's talk)
  - ≧15 SF clumps →~70% continuum

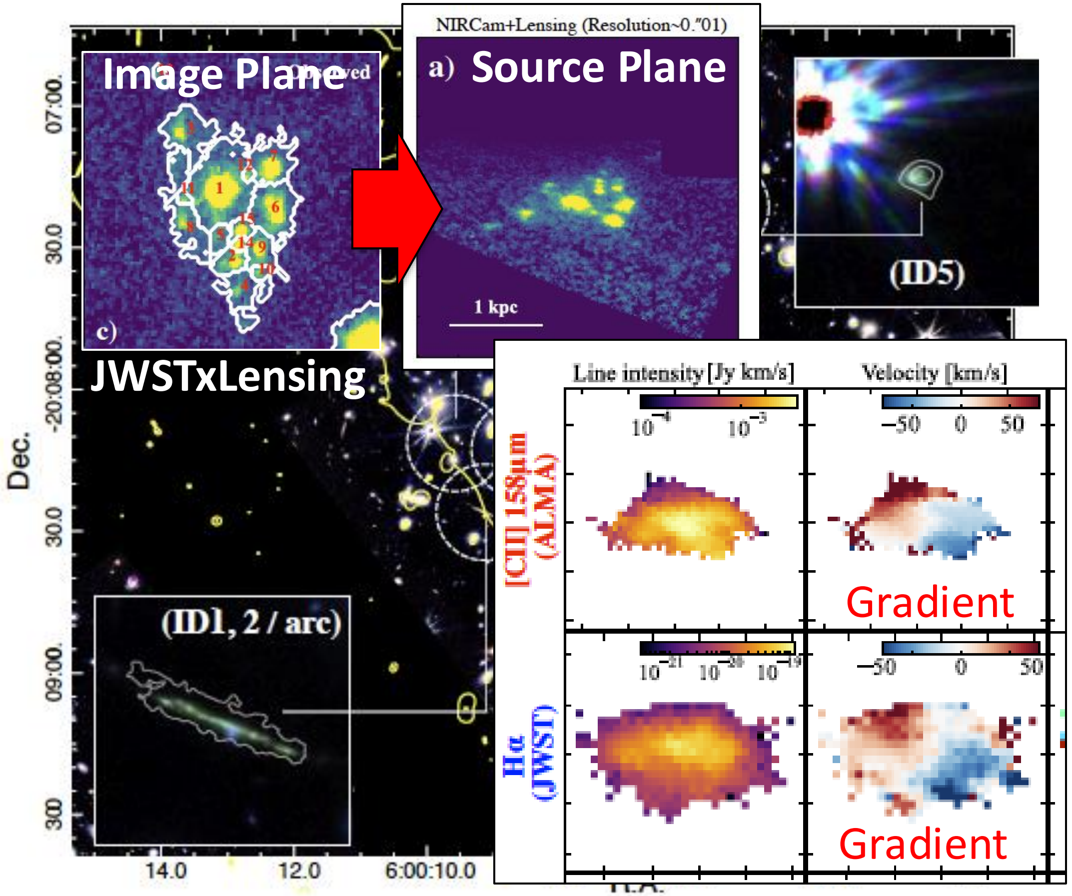
Beyond Globular Clusters
Stellar Clumps and Disk

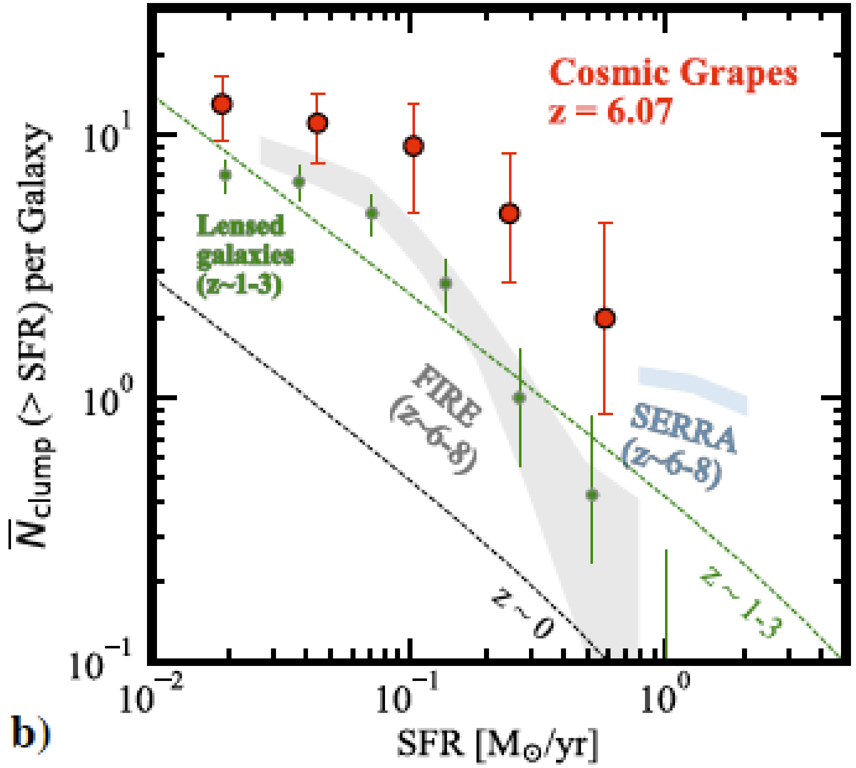


Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto's talk)
  - ≧15 SF clumps →~70% continuum
  - On a rotating disk (~70km/s) of cold [CII]158um (ALMA) & hot Hα gas (JWST)

Beyond Globular Clusters
Stellar Clumps and Disk

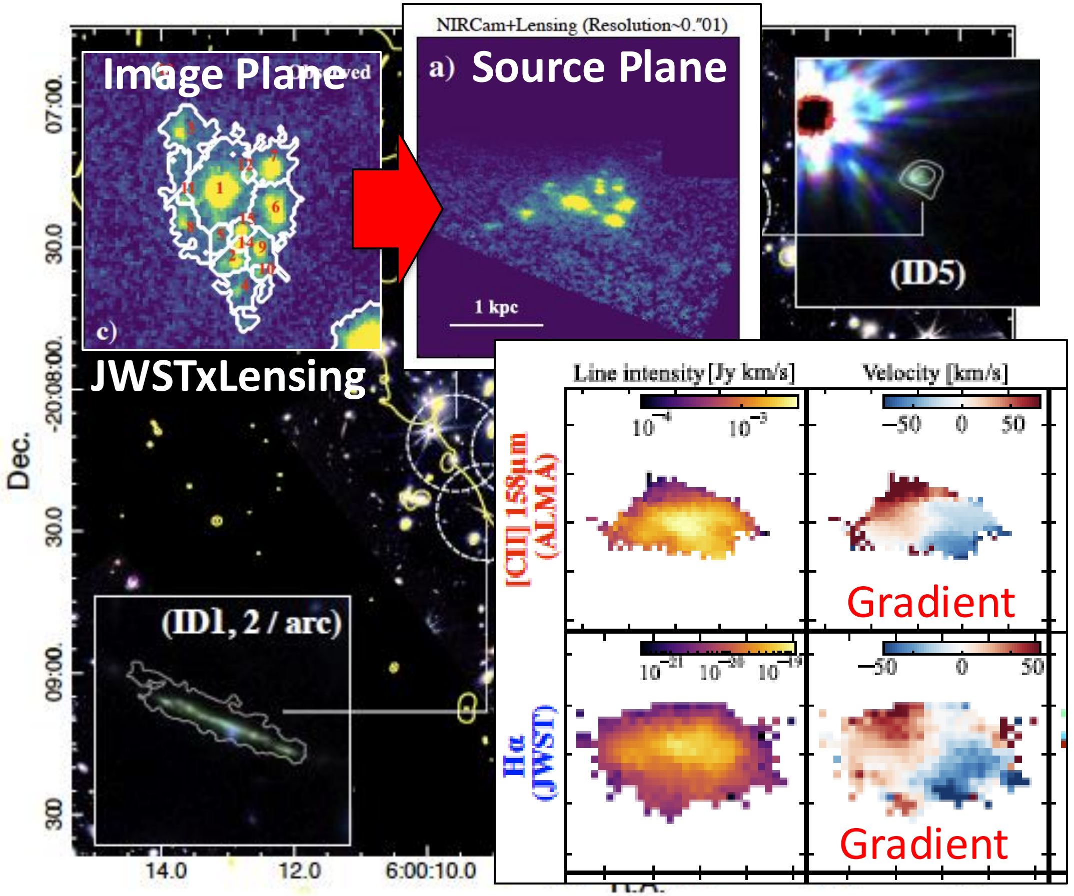


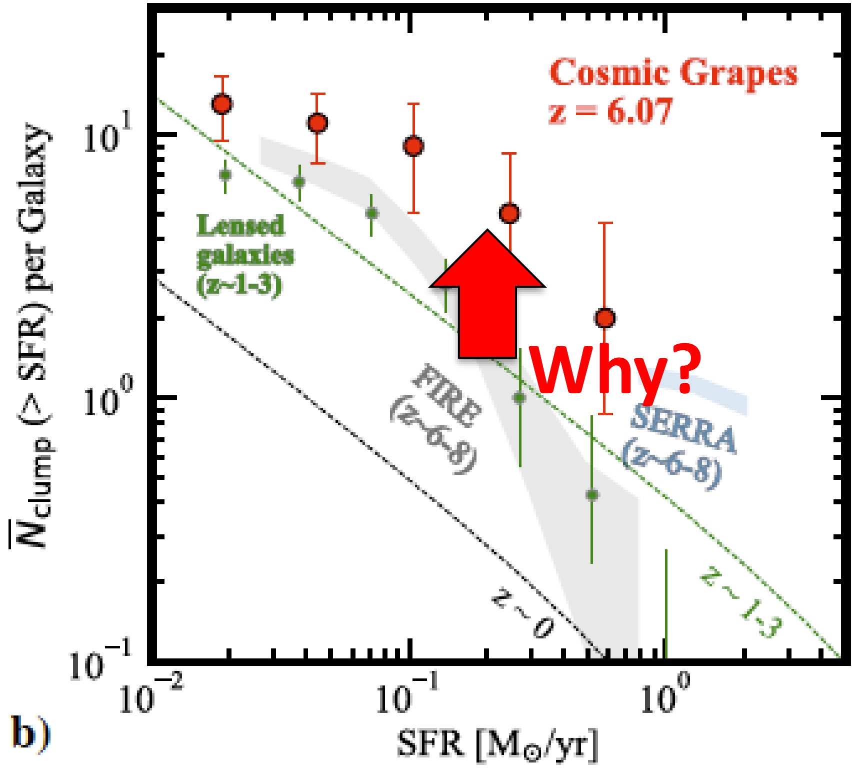


Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto's talk)
  - ≧15 SF clumps →~70% continuum
  - On a rotating disk (~70km/s) of cold [CII]158um (ALMA) & hot Hα gas (JWST)
  - Clumpy structures are not reproduced by numerical simulations. Why? (Suggestive Weak feedback??)

Beyond Globular Clusters
Stellar Clumps and Disk



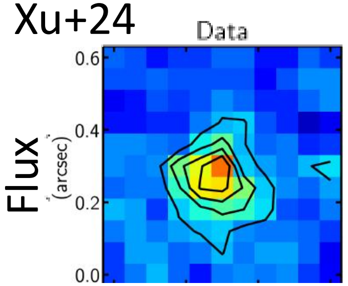


Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto's talk)
  - ≧15 SF clumps →~70% continuum
  - On a rotating disk (~70km/s) of cold [CII]158um (ALMA) & hot Hα gas (JWST)
  - Clumpy structures are not reproduced by numerical simulations. Why? (Suggestive Weak feedback??)

Structure/Dynamics of a Galaxy at z>10

Xu+24

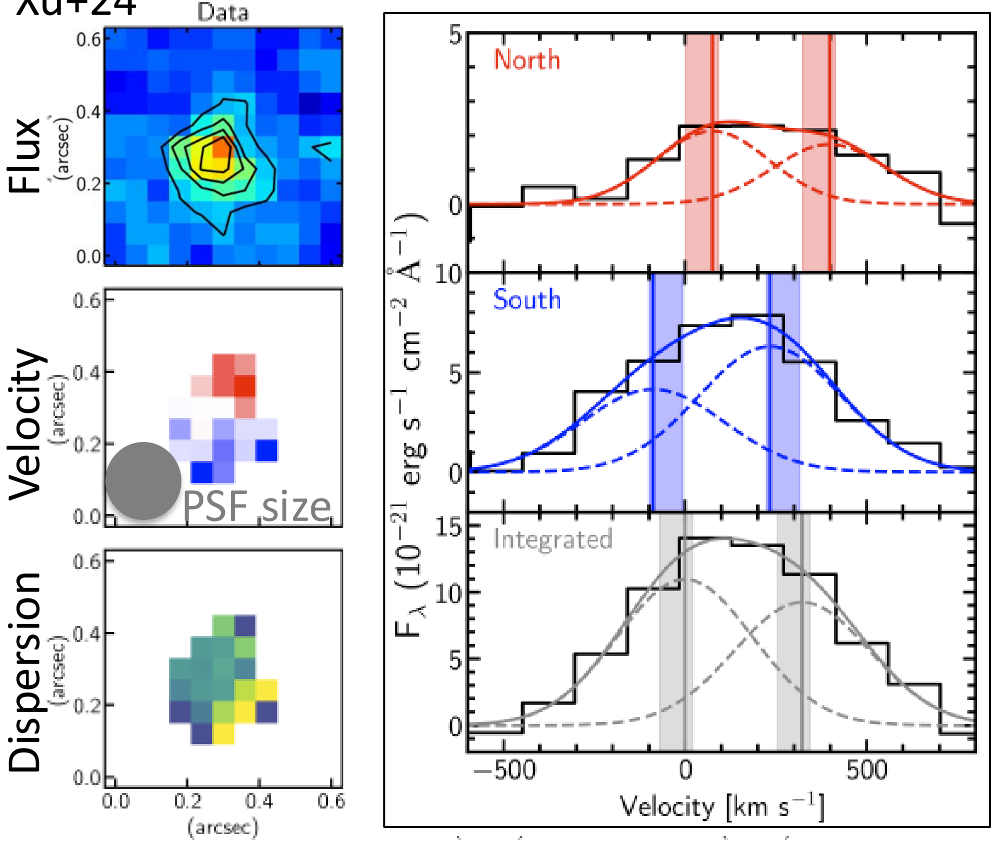


Yi Xu

- Revisiting the deep NIRSpec IFU data (useful 15 hrs) of GN-z11 (z=10.6) taken for targeting HeII clumps (Maiolino+23)
  - [OIII]5007 and Hα beyond NIRSpec λ coverage → CIII] emission in UV.
  - Compact, but spatially extended morphology → No signatures of mergers (single source) or outflows (no broadlines)

Structure/Dynamics of a Galaxy at z>10

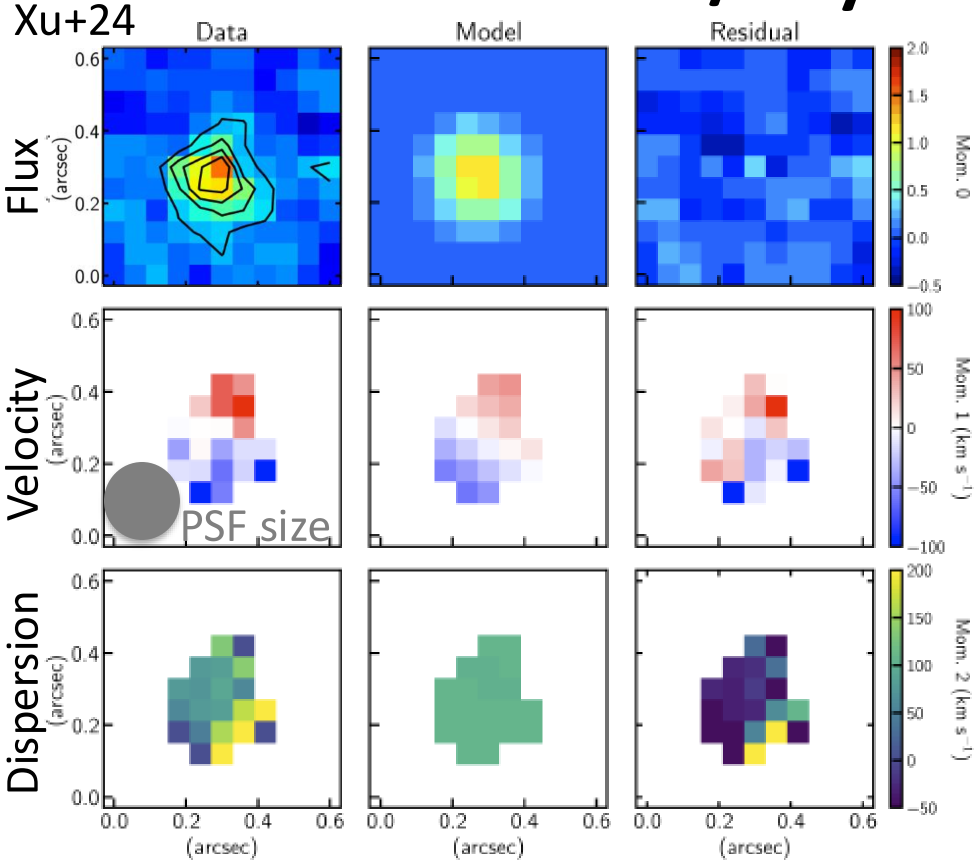
Xu+24



Yi Xu

- Revisiting the deep NIRSpec IFU data (useful 15 hrs) of GN-z11 (z=10.6) taken for targeting HeII clumps (Maiolino+23)
  - [OIII]5007 and Hα beyond NIRSpec λ coverage → CIII] emission in UV.
  - Compact, but spatially extended morphology → No signatures of mergers (single source) or outflows (no broadlines)
  - Velocity gradient: Spatially varying density for doublet ratio CIII]λλ1907,1909 → No (over the entire allowed ratios in n_e)

Structure/Dynamics of a Galaxy at z>10

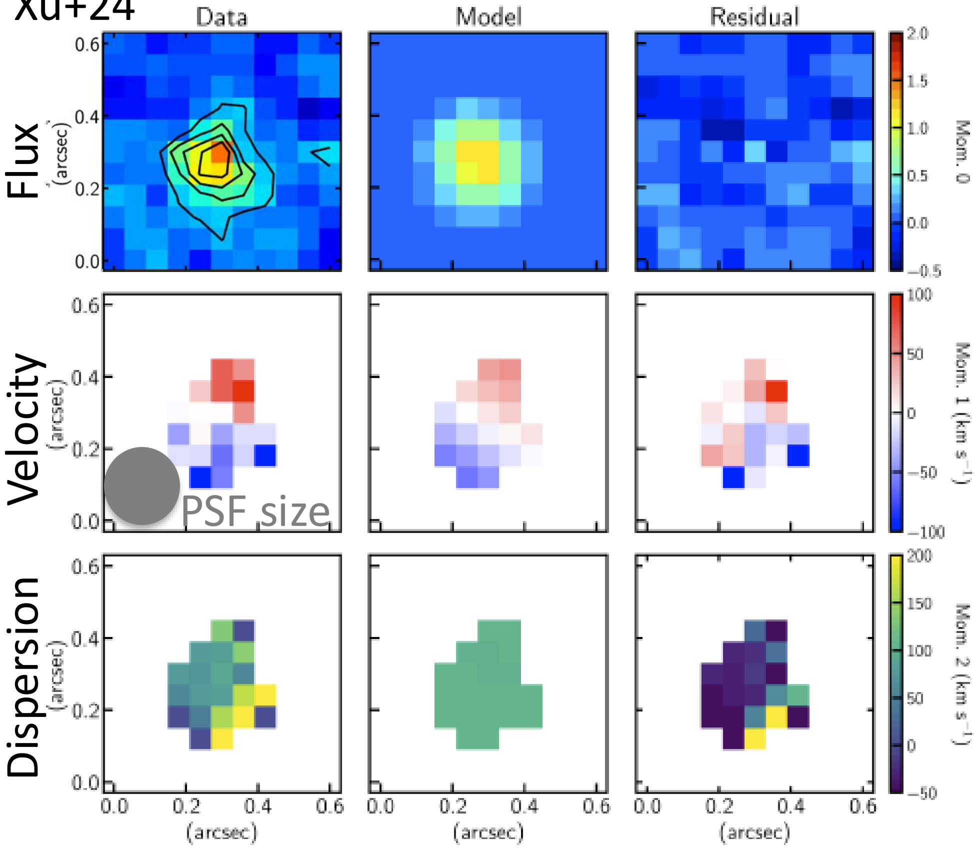


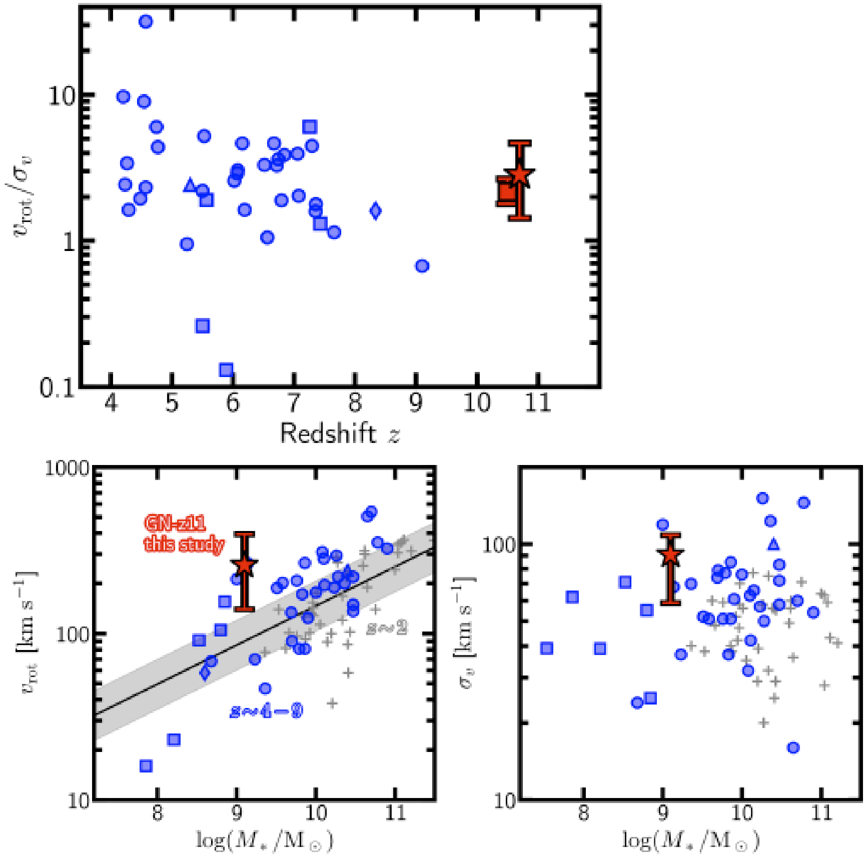
Yi Xu

- Revisiting the deep NIRSpec IFU data (useful 15 hrs) of GN-z11 (z=10.6) taken for targeting HeII clumps (Maiolino+23)
  - [OIII]5007 and Hα beyond NIRSpec λ coverage → CIII] emission in UV.
  - Compact, but spatially extended morphology → No signatures of mergers (single source) or outflows (no broadlines)
  - Velocity gradient: Spatially varying density for doublet ratio CIII]λλ1907,1909 → No (over the entire allowed ratios in n_e)
- For a case of a disk, forward modeling → V_{rot}=257 (+138/-117) km/s, σ_v=91 (+18/-32) km/s, V_{rot}/σ_v=2.8 (+1.8/-1.4)

Structure/Dynamics of a Galaxy at z>10

Xu+24



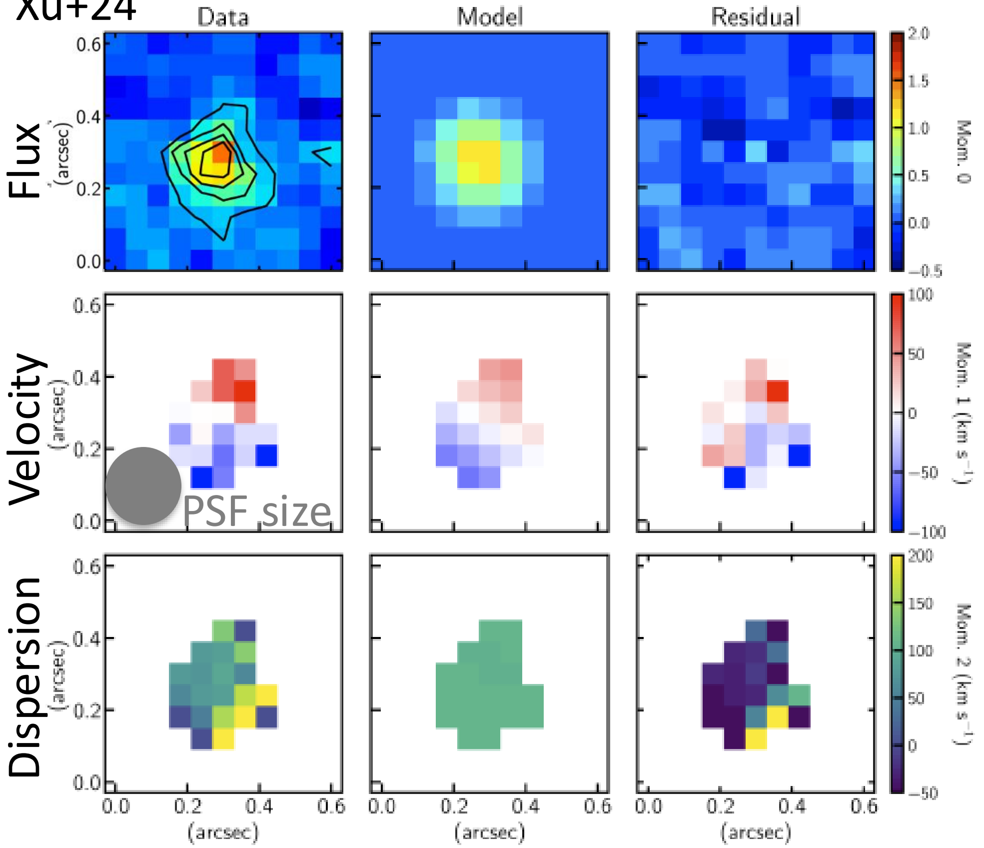


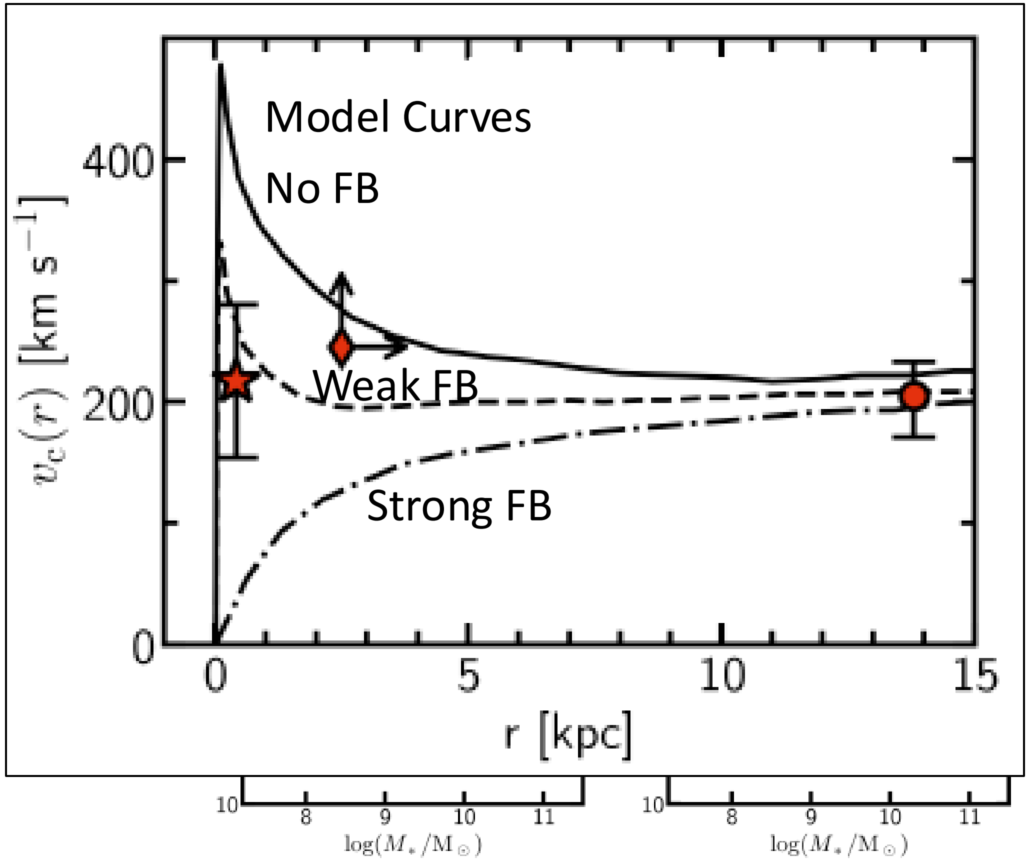
Yi Xu

- Revisiting the deep NIRSpec IFU data (useful 15 hrs) of GN-z11 (z=10.6) taken for targeting HeII clumps (Maiolino+23)
  - [OIII]5007 and Hα beyond NIRSpec λ coverage → CIII] emission in UV.
  - Compact, but spatially extended morphology → No signatures of mergers (single source) or outflows (no broadlines)
  - Velocity gradient: Spatially varying density for doublet ratio CIII]λλ1907,1909 → No (over the entire allowed ratios in n_e)
- For a case of a disk, forward modeling → V_{rot}=257 (+138/-117) km/s, σ_v=91 (+18/-32) km/s, V_{rot}/σ_v=2.8 (+1.8/-1.4)

Structure/Dynamics of a Galaxy at z>10

Xu+24



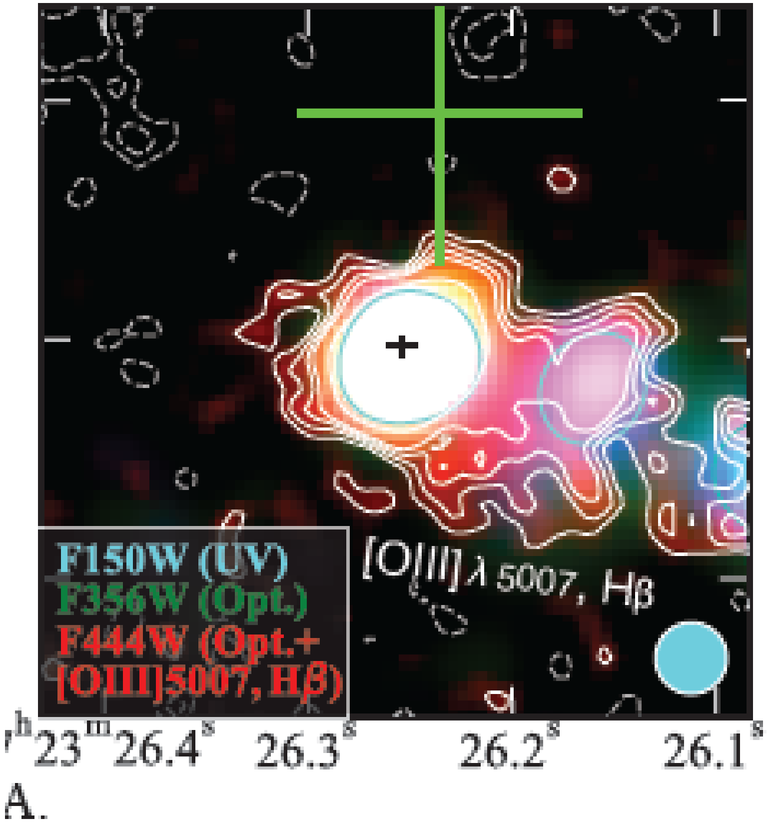


Yi Xu

- Revisiting the deep NIRSpec IFU data (useful 15 hrs) of GN-z11 (z=10.6) taken for targeting HeII clumps (Maiolino+23)
  - [OIII]5007 and Hα beyond NIRSpec λ coverage → CIII] emission in UV.
  - Compact, but spatially extended morphology → No signatures of mergers (single source) or outflows (no broadlines)
  - Velocity gradient: Spatially varying density for doublet ratio CIII]λλ1907,1909 → No (over the entire allowed ratios in n_e)
- For a case of a disk, forward modeling → V_{rot}=257 (+138/-117) km/s, σ_v=91 (+18/-32) km/s, V_{rot}/σ_v=2.8 (+1.8/-1.4)
- Halo circular velocity of the halo via Behroozi+19: $v_c(r_{200})$=217±63 km/s: Circular velocity comparable w the one at the center?
- If it is true -> Suggesting weak feedback allowing the compact disk at the center? (e.g. Kimm+15, Hopkins+23)
  →consistent w abundant bright star-forming galaxies at z>10 (see Oesch's talk). Needing deep/high-res data for a conclusion

Feedback and Outflow

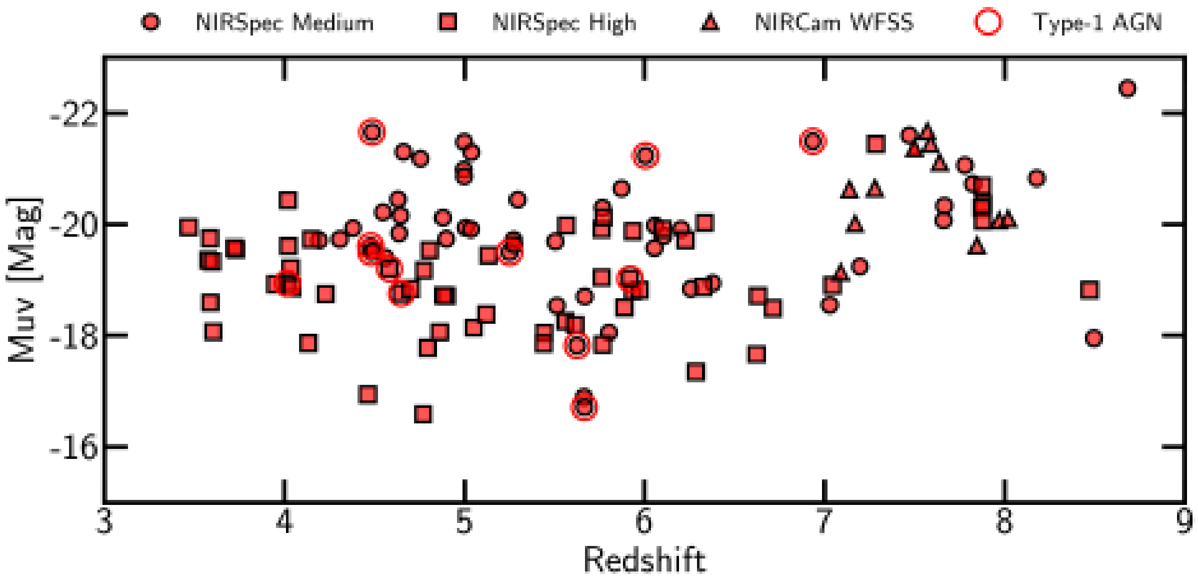
z=8.5 (ID4590)



Fujimoto+23

- Spatially extended ionized gas emission (e.g. Fujimoto+23, Zhang+23)
  - Extended more than stellar components for galaxies at z~4-9
  - Signature of outflows?

Outflows
Suggestive Weak Feedback?



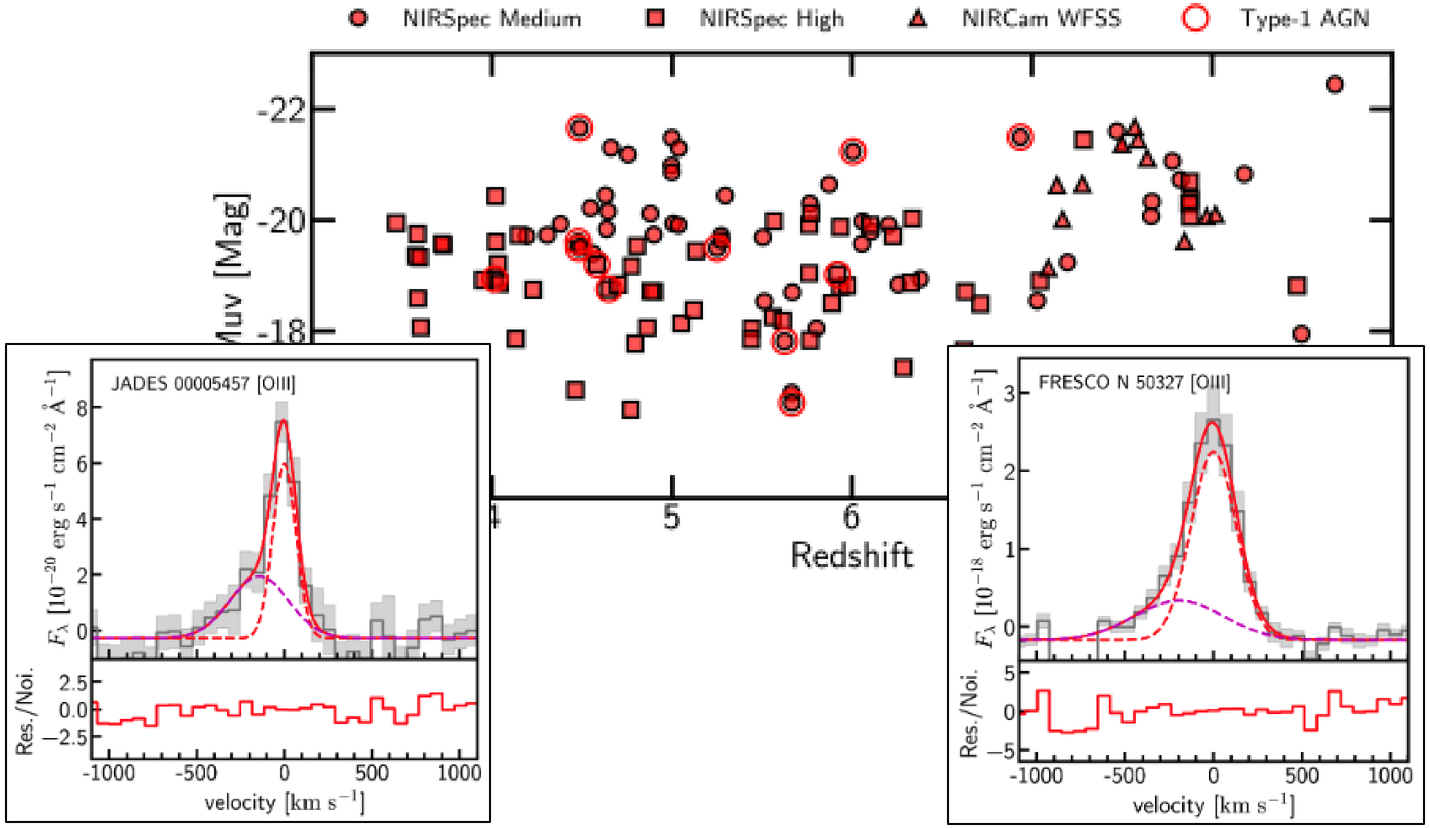
Xu et al. 2023

Yi Xu

- 130 galaxies (incl. 12 AGN) at z=3-9: ERS, JADES (Bunker+) & FRESCO (Oesch+) data (see+Carniani+23, Zhang+23)

Outflows
Suggestive Weak Feedback?

Yi Xu

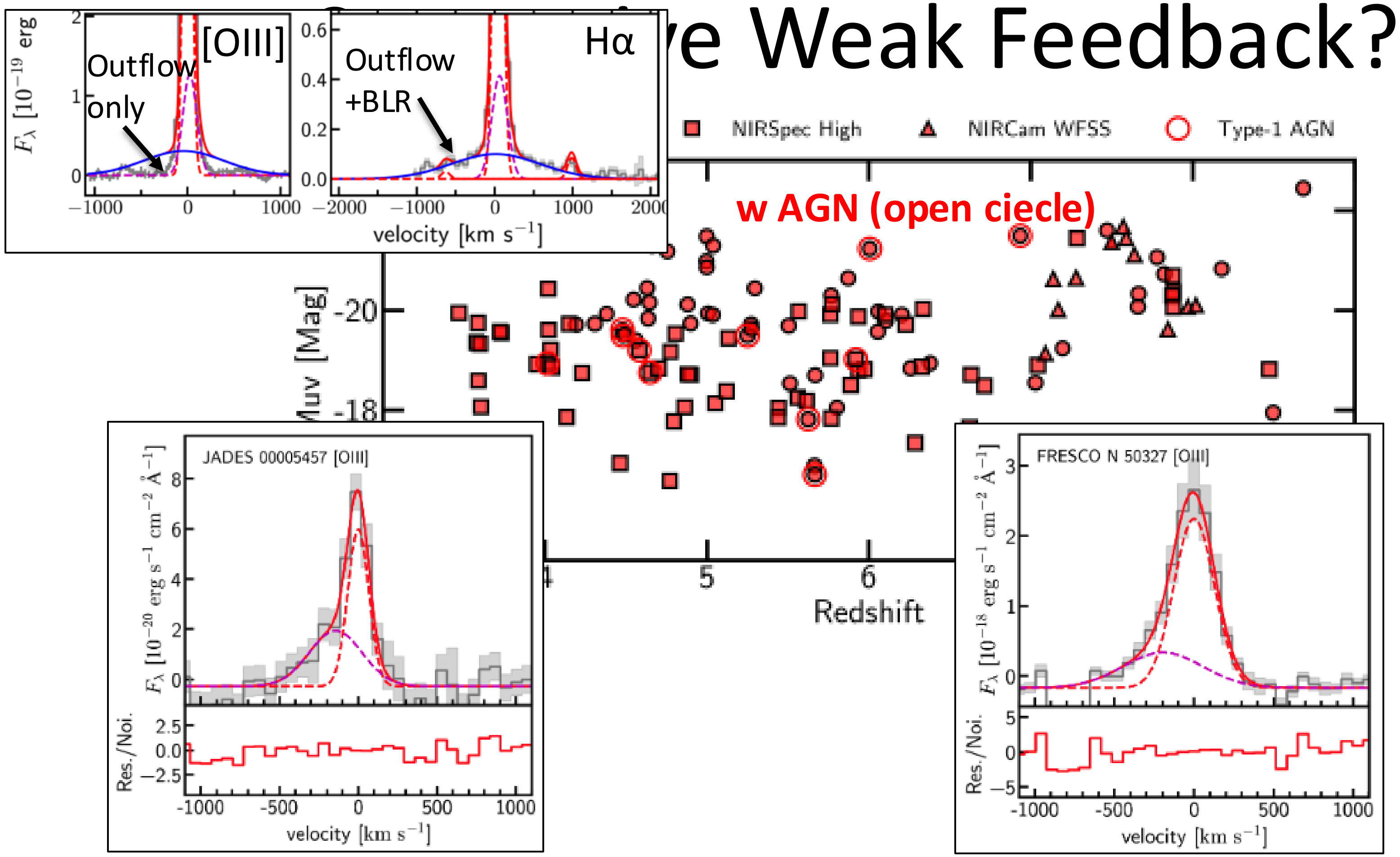


Xu et al. 2023

- 130 galaxies (incl. 12 AGN) at z=3-9: ERS, JADES (Bunker+) & FRESCO (Oesch+) data (see+Carniani+23, Zhang+23)
  - 30/130 with spec. outflow signatures

Outflows

ve Weak Feedback?



Yi Xu

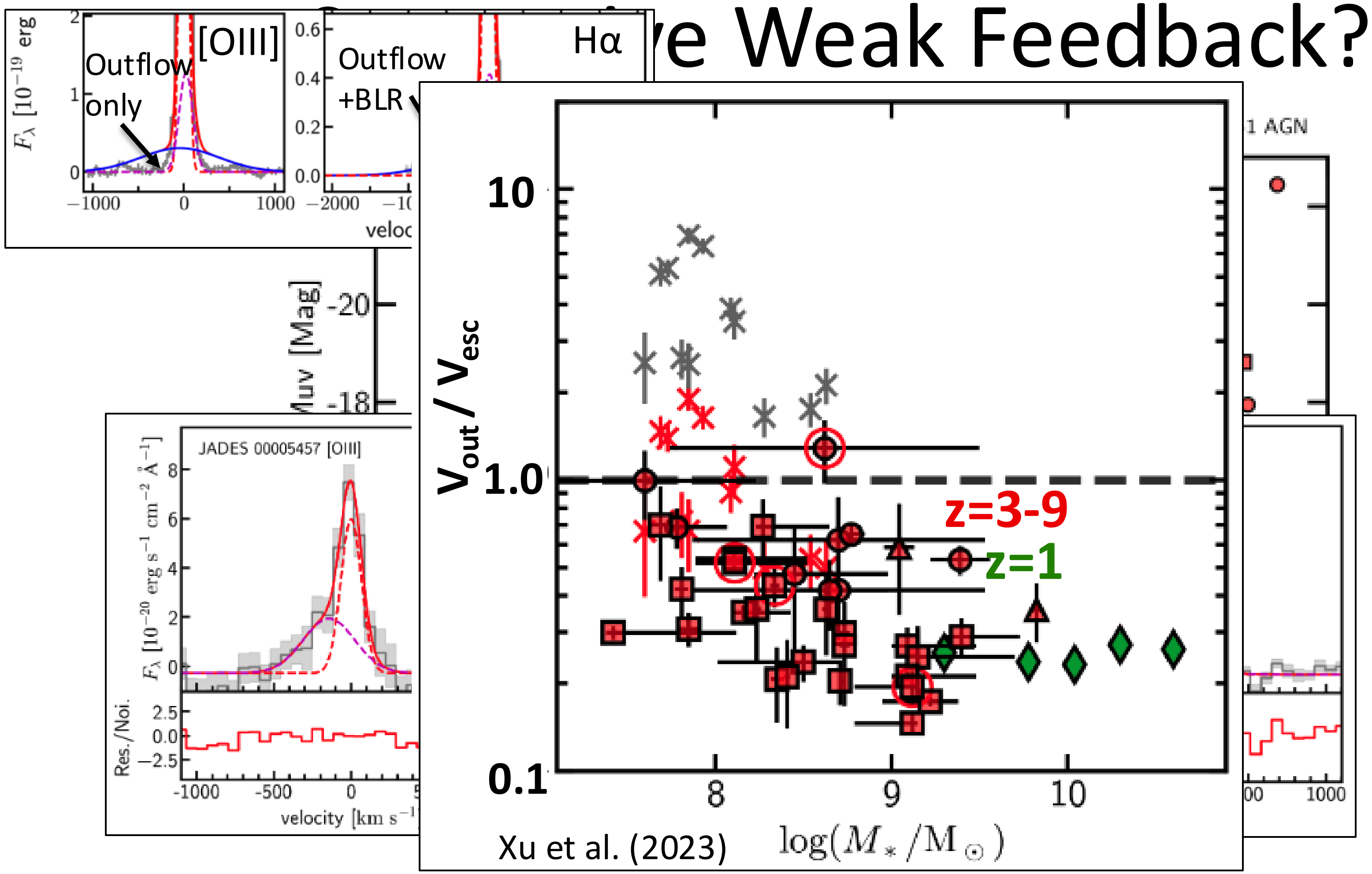
Xu et al. 2023

- 130 galaxies (incl. 12 AGN) at z=3-9: ERS, JADES (Bunker+) & FRESCO (Oesch+) data (see+Carniani+23, Zhang+23)
  - 30/130 with spec. outflow signatures
  - 4/30 outflow objects have AGN signature (Type 1)

Outflows

ve Weak Feedback?

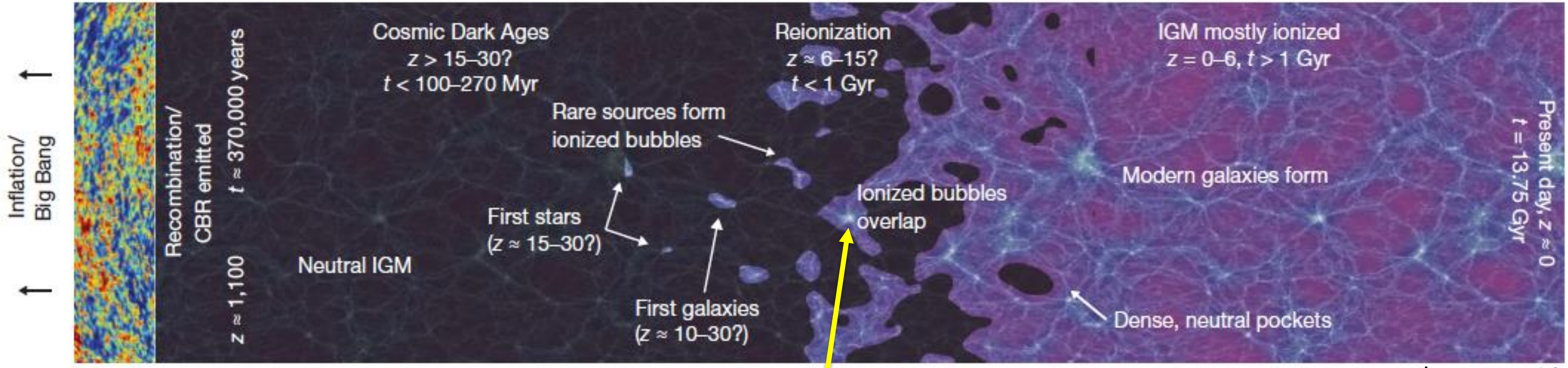
Yi Xu



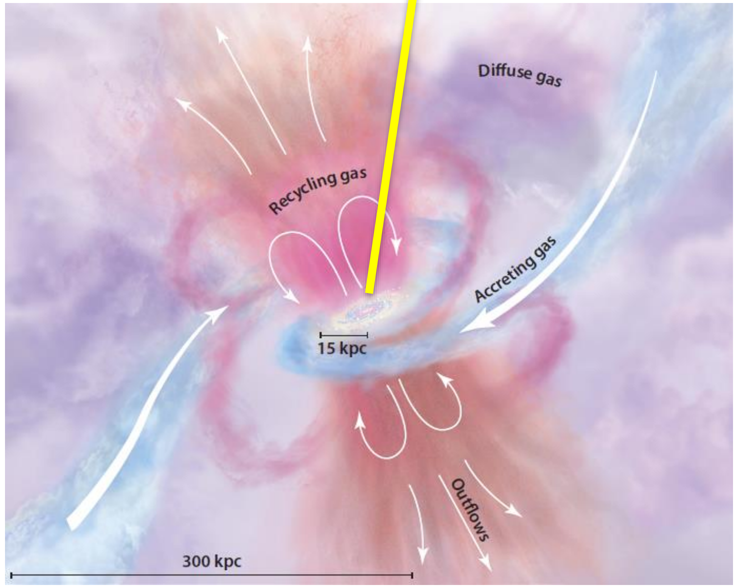
Xu et al. 2023

- 130 galaxies (incl. 12 AGN) at z=3-9: ERS, JADES (Bunker+) & FRESCO (Oesch+) data (see+Carniani+23, Zhang+23)
  - 30/130 with spec. outflow signatures
  - 4/30 outflow objects have AGN signature (Type 1)
- V_{out} ~100-200 km/s depending on SFR: $V_{out} \lesssim V_{esc}$ for the majority at M*~10^9Mo (see also Carniani+24)
  → Weak fountain outflows : Consistent w weak feedback?

Galaxy-IGM Interaction: Radiation (beyond Gas)
Cosmic Reionization

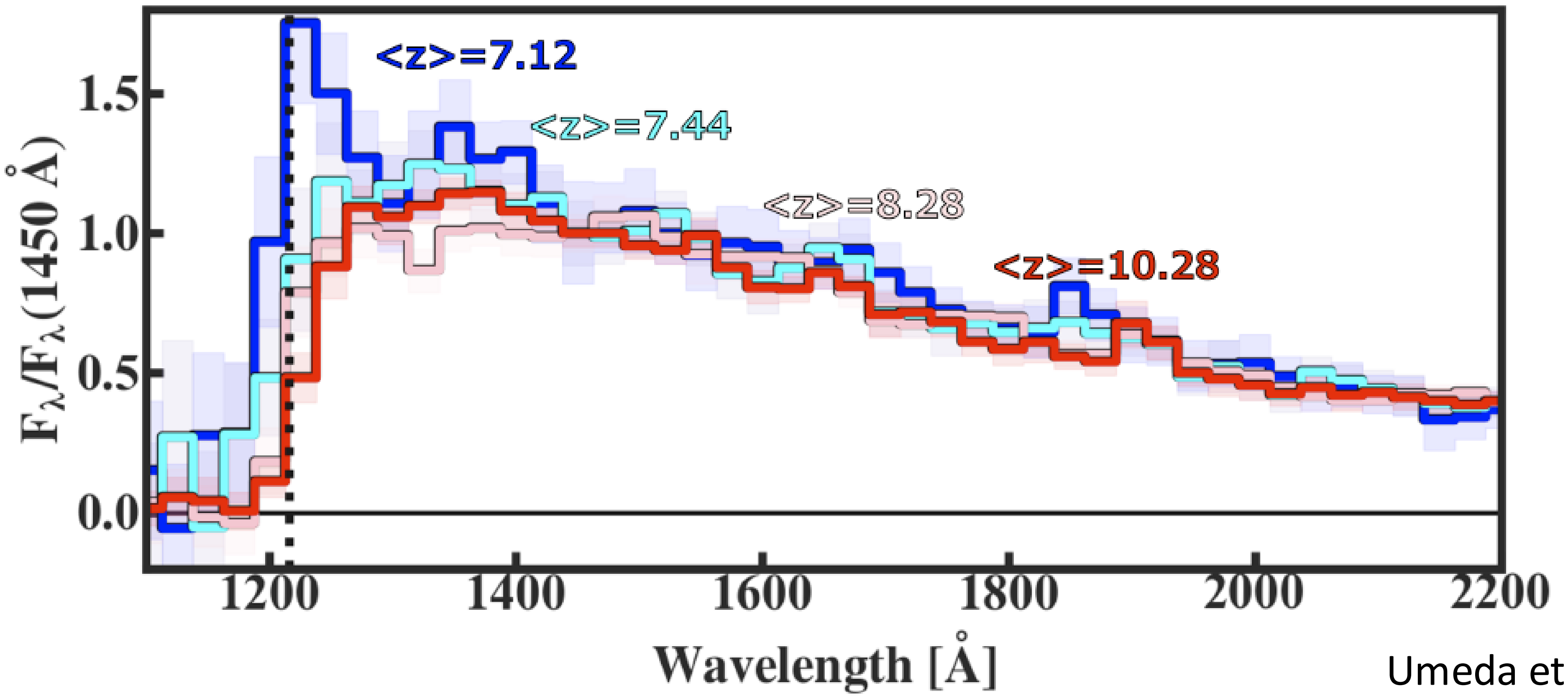


Robertson+10



Tumlinson+17

Evolution of Galaxy Spectra around Lyα



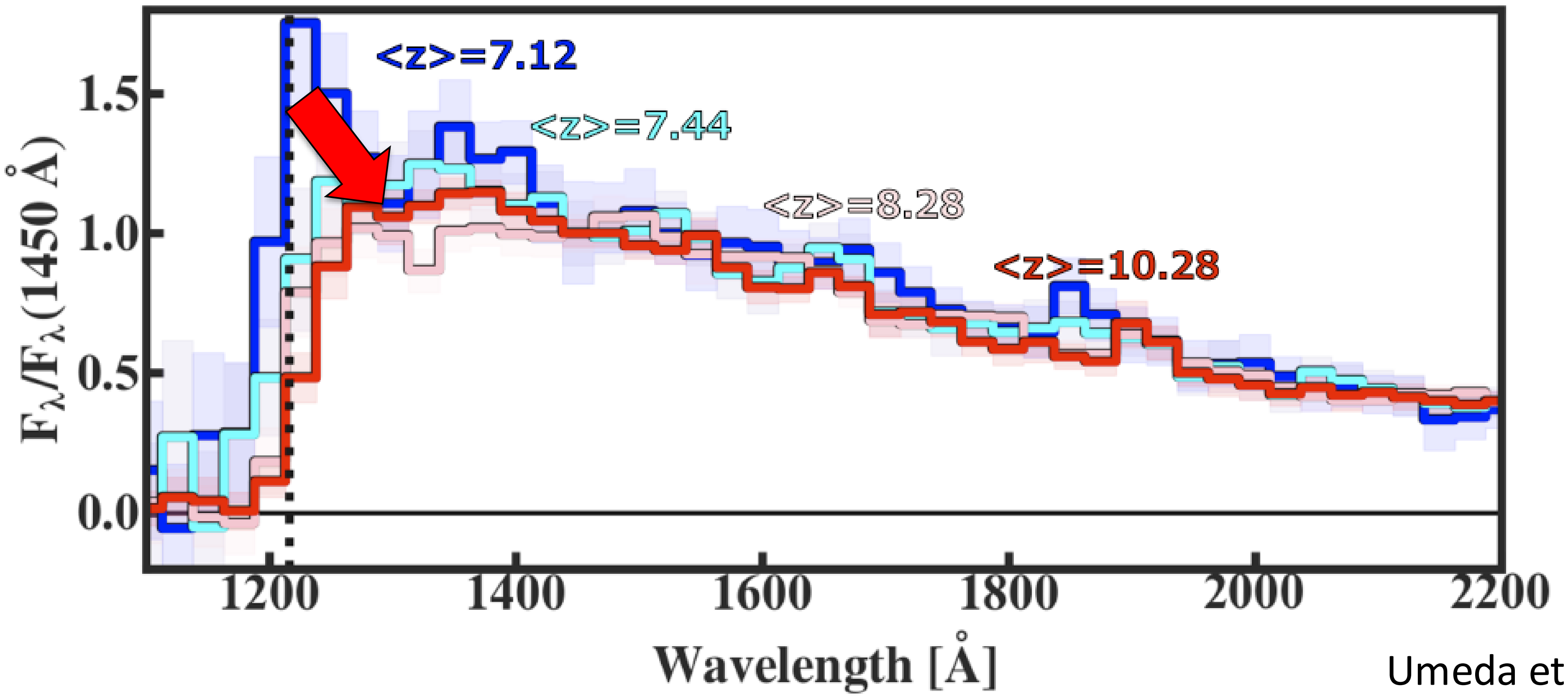
Hiroya Umeda

Umeda et al. (2024)

- Average spectra of galaxies at z=7-12 (JWST CEERS Finkelstein+23, JADES Bunker+23, GO, and DDT)

Evolution of Galaxy Spectra around Lyα

Hiroya Umeda



Umeda et al. (2024)

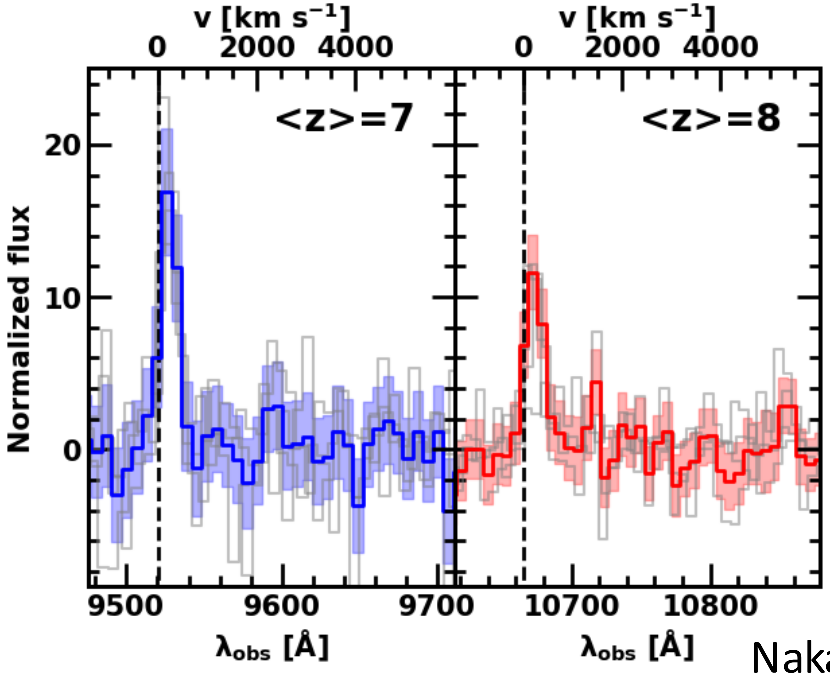
- Average spectra of galaxies at z=7-12 (JWST CEERS Finkelstein+23, JADES Bunker+23, GO, and DDT)
- Clear evolution around Lyα towards high-z
  - Weaker Lyα
  - Weaker UV continuum at ~1216A

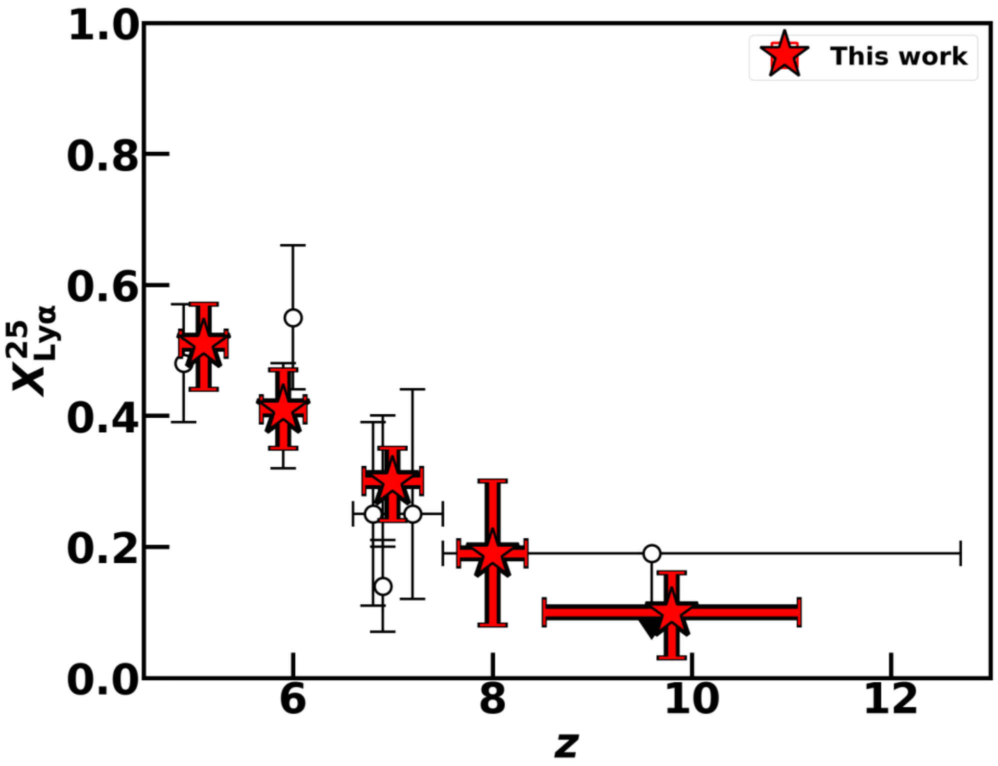
  →More Lyα damping wing (DW) absorption given by increasing neutral hydrogen at higher redshift
- Lyα emission/UVcont.abs.(e.g.Curtis-Lake+23,Hsiao+23,Umeda+24,Heintz+23/+24,Nakane+24,Tang+24)

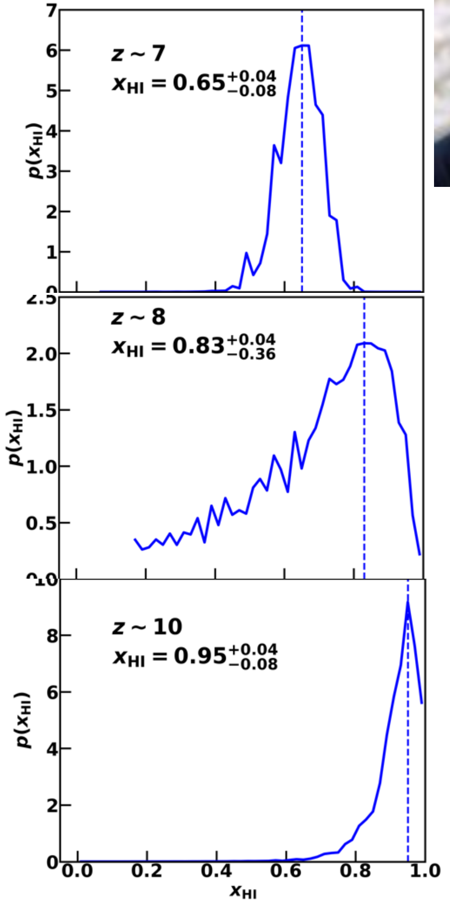
Evaluating Lyα Emission Evolution

Minami Nakane

Yuta Kageura







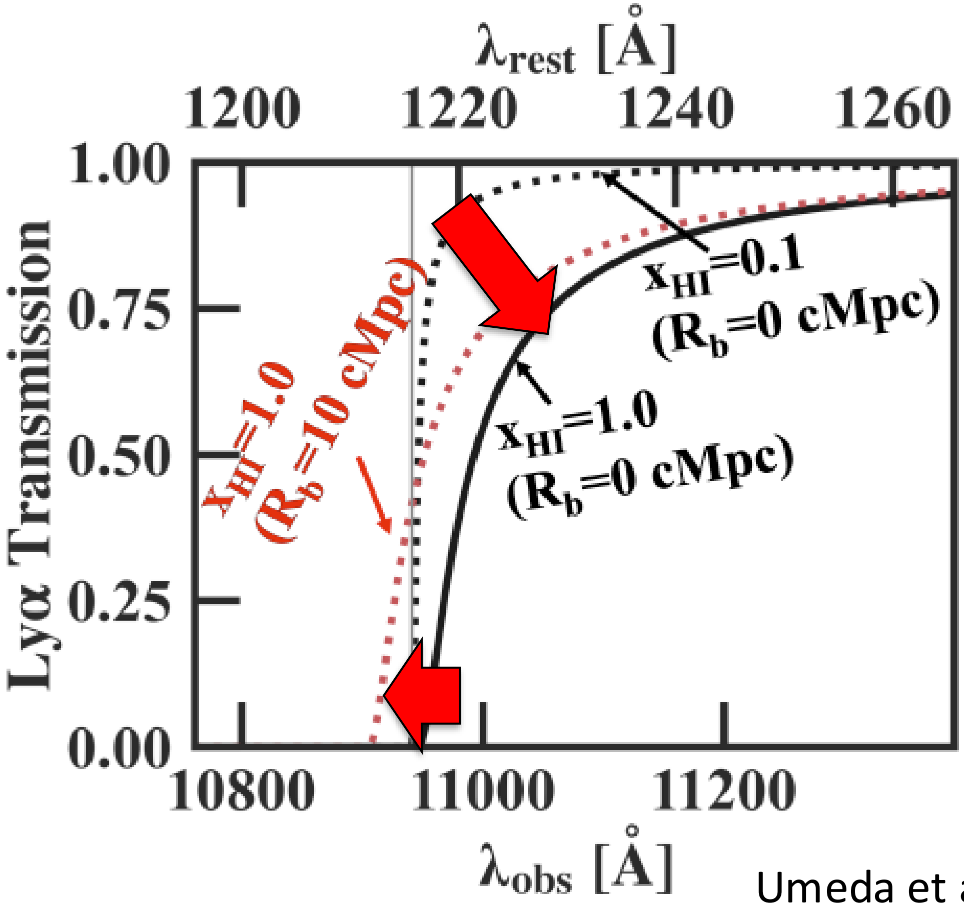
Nakane et al. (2024), Kageura+ in prep.

- ~400 galaxies at z=7-13 w med-resolution data:JADES (D'Eugenio+24), CEERS(Finkelstein+23), GO etc.
  - Fraction of Lya emitting galaxies: Smaller towards higher redshift (See also Tang+24)
- Comparisons with previous simulations (Dijkstra+11, Mason+18) and our 21cmFAST modeling (Kageura+)
  - Performing a Bayesian inference for EW(Lya) distribution

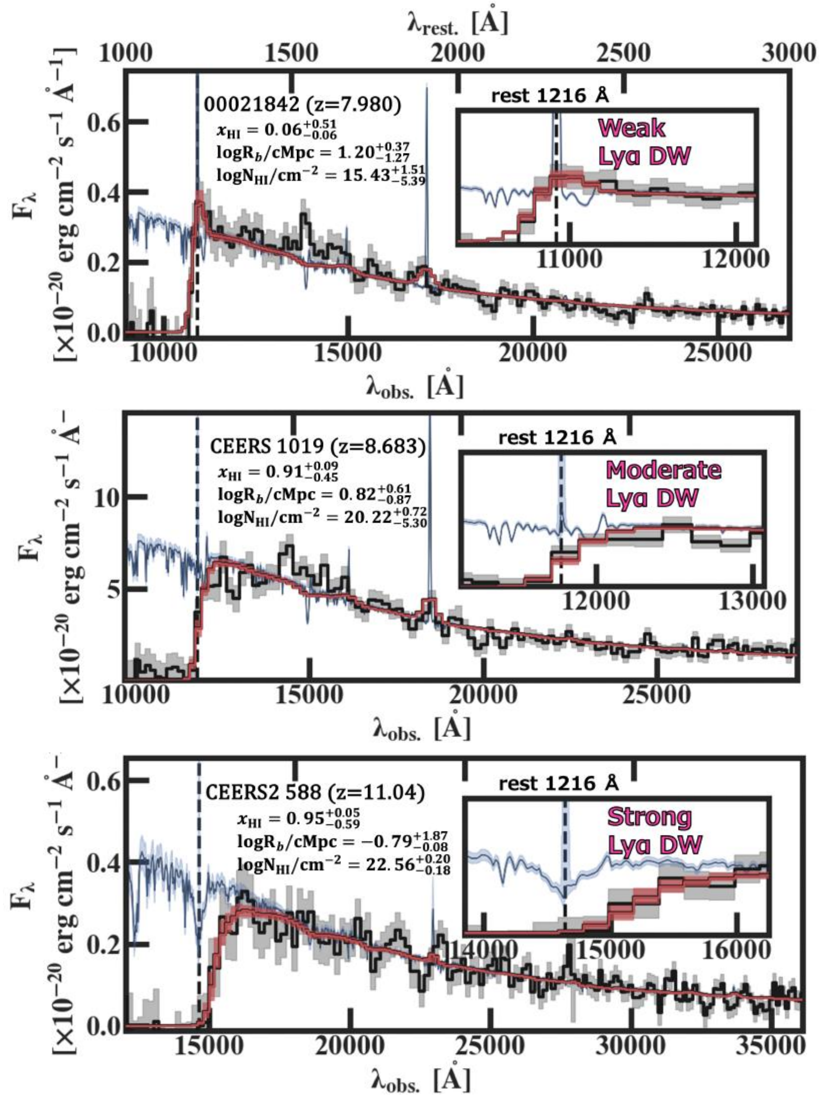
    → x_{HI} =0.65 (+0.04/−0.08), 0.83 (+0.04/−0.36), and 0.95 (+0.04/-0.08) at z ~ 7, 8, and 9-13, respectively. Late reionization.

UV Continua of Bright Galaxies

Hiroya Umeda

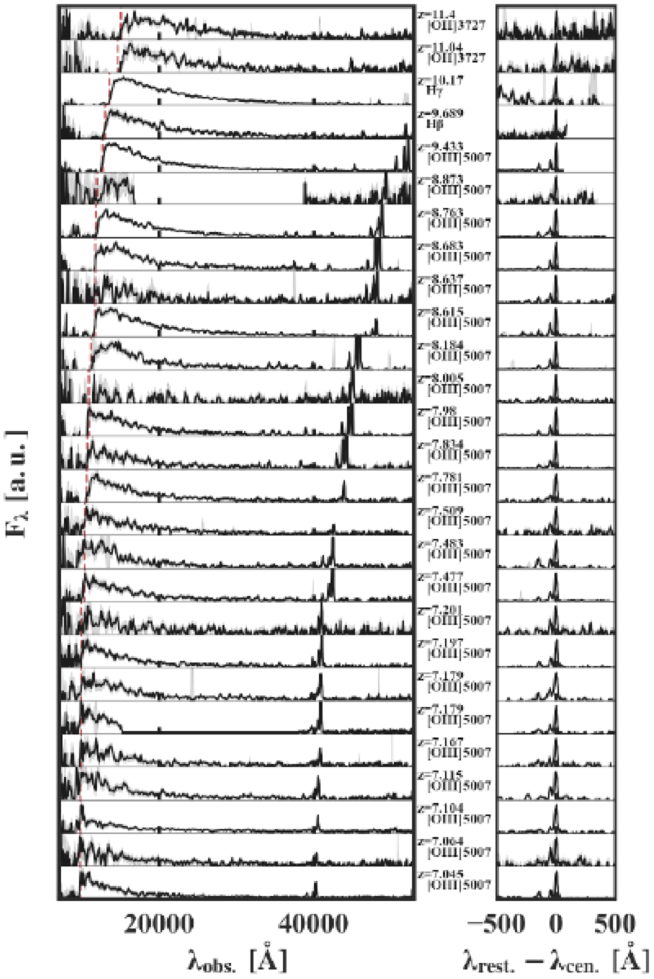


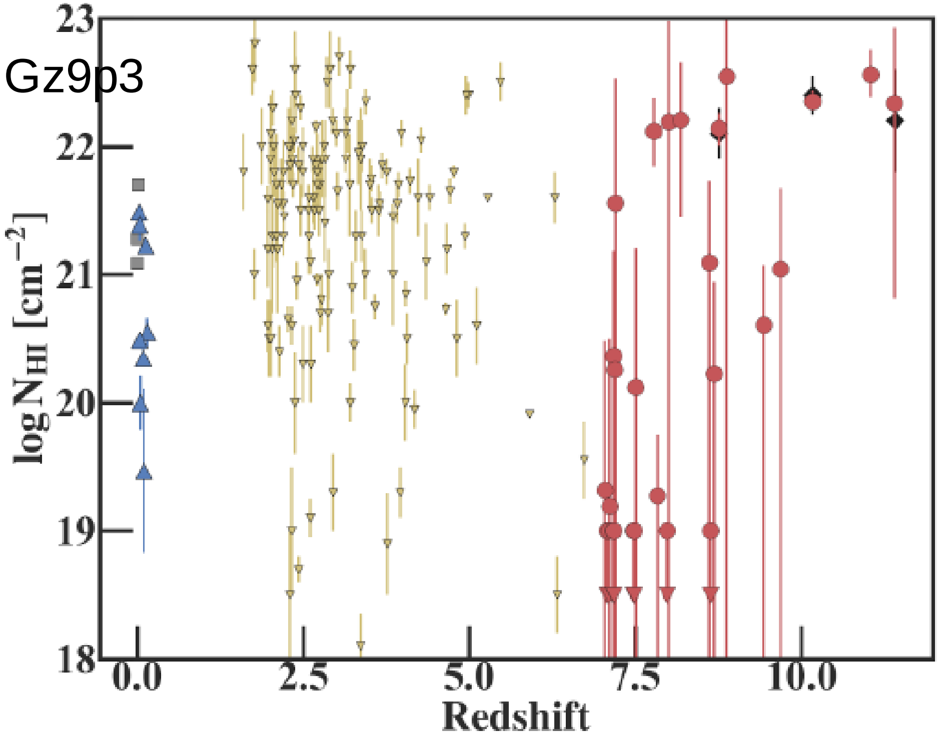
Umeda et al. (2024)

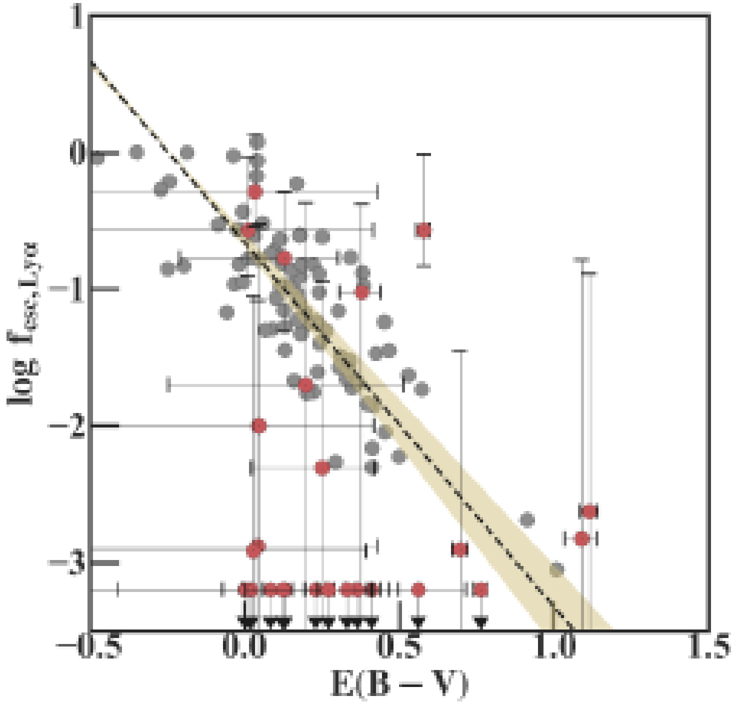


- Galaxy UV continuum
  - Lyα DW (x_{HI})→ Sharp absorption at >1216A
  - Ionized bubble radius (R_b) → Flatter absorption
  - Stellar cont., CGM abs., and Lya emission modeled with Prospector (Johnson+21) + BPASS via MCMC method

Decoding the UV Spectral Shapes



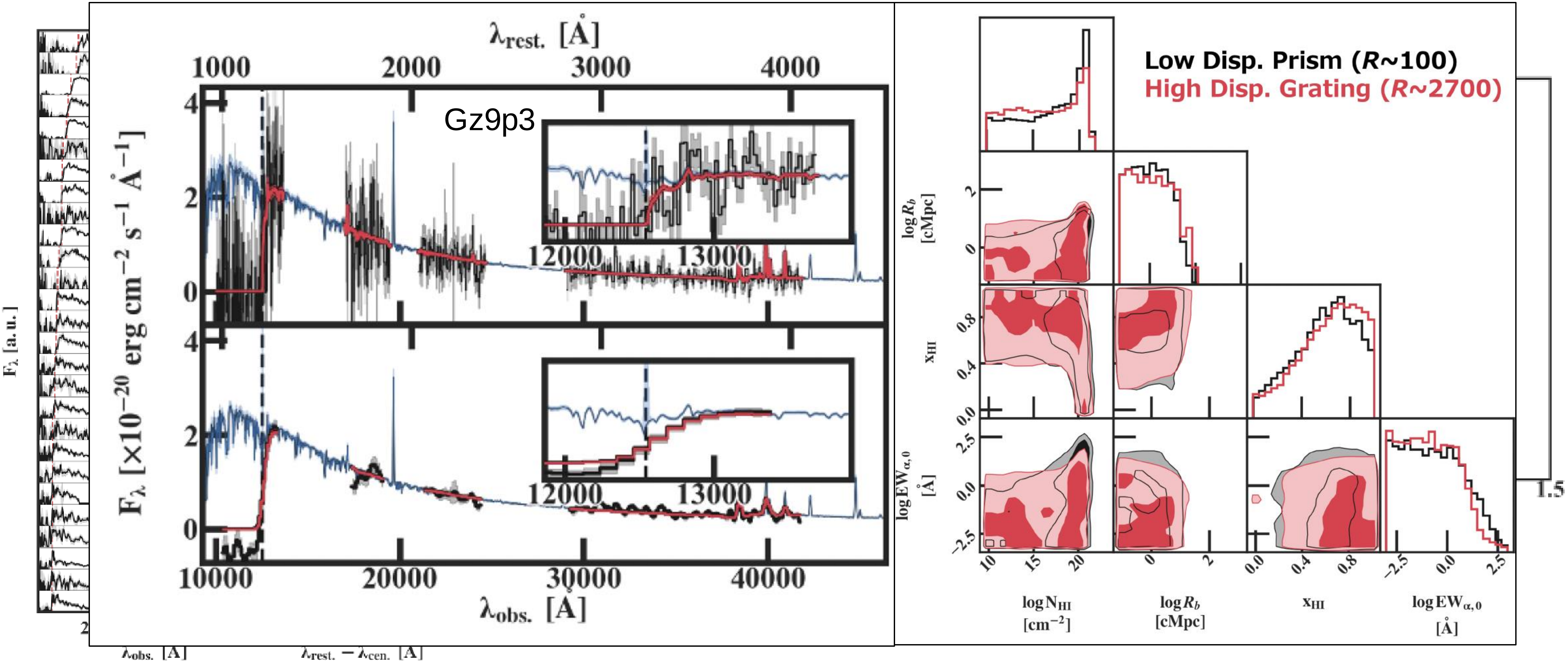




Umeda et al. (2024)

- Applying to bright galaxy spectra at z(spec)=7-12 from the early JWST observaions of ERS, DDT, and GO
- N_{HI} of the CGM comparable w the previous estimates over z~2-10 (e.g. Heintz+23/24)
- Lyα escape fraction $f_{esc,Ly\alpha}$ consistent with low-z galaxies on the $f_{esc,Ly\alpha}$ vs. E(B-V) plane

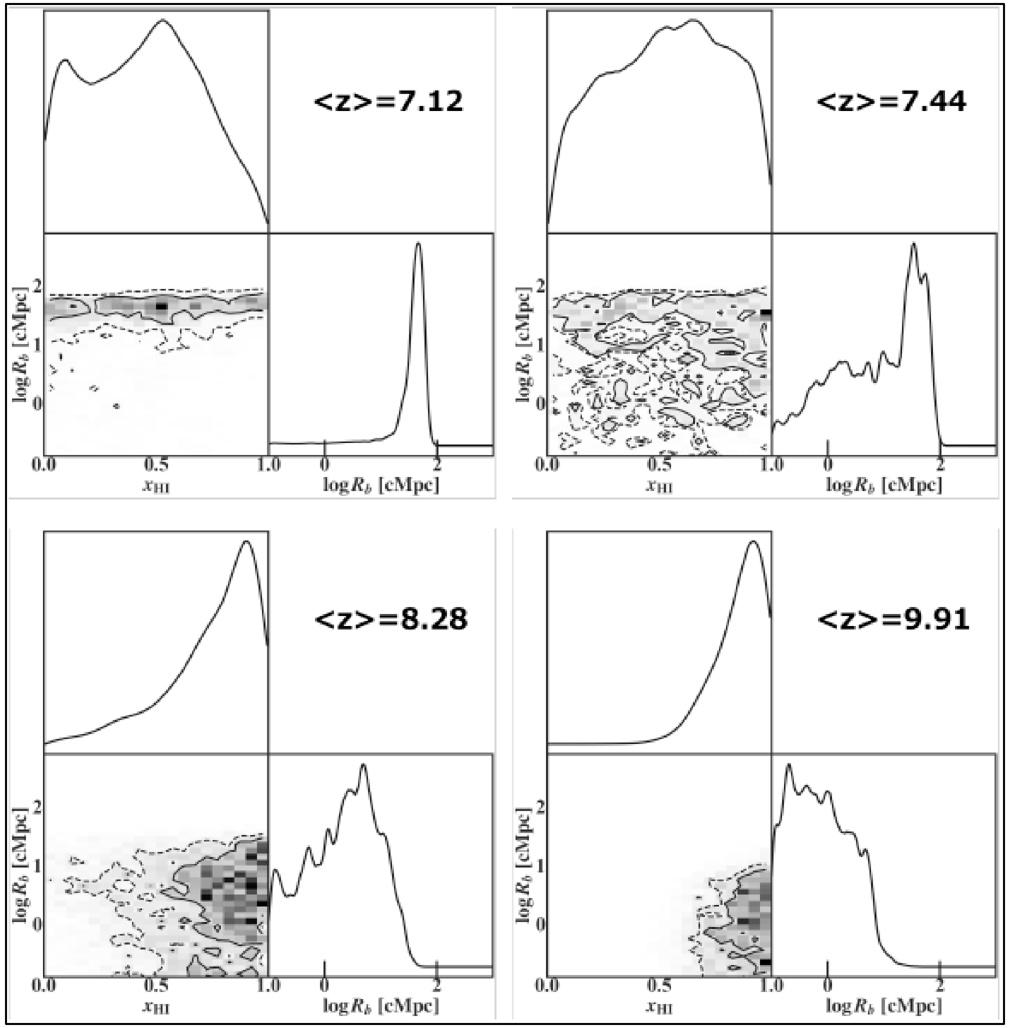
Decoding the UV Spectral Shapes



- Applying to bright galaxy spectra at z(spec)=7-12 from the early JWST observaions of ERS, DDT, and GO
- N_{HI} of the CGM comparable w the previous estimates over z~2-10 (e.g. Heintz+23/24)
- Lyα escape fraction $f_{esc,Ly\alpha}$ consistent with low-z galaxies on the $f_{esc,Ly\alpha}$ vs. E(B-V) plane
- Spectral resolution effects? → Confirming consistent results between high and low resolutions within the errors

x_{HI} and Ionized Bubble Radius

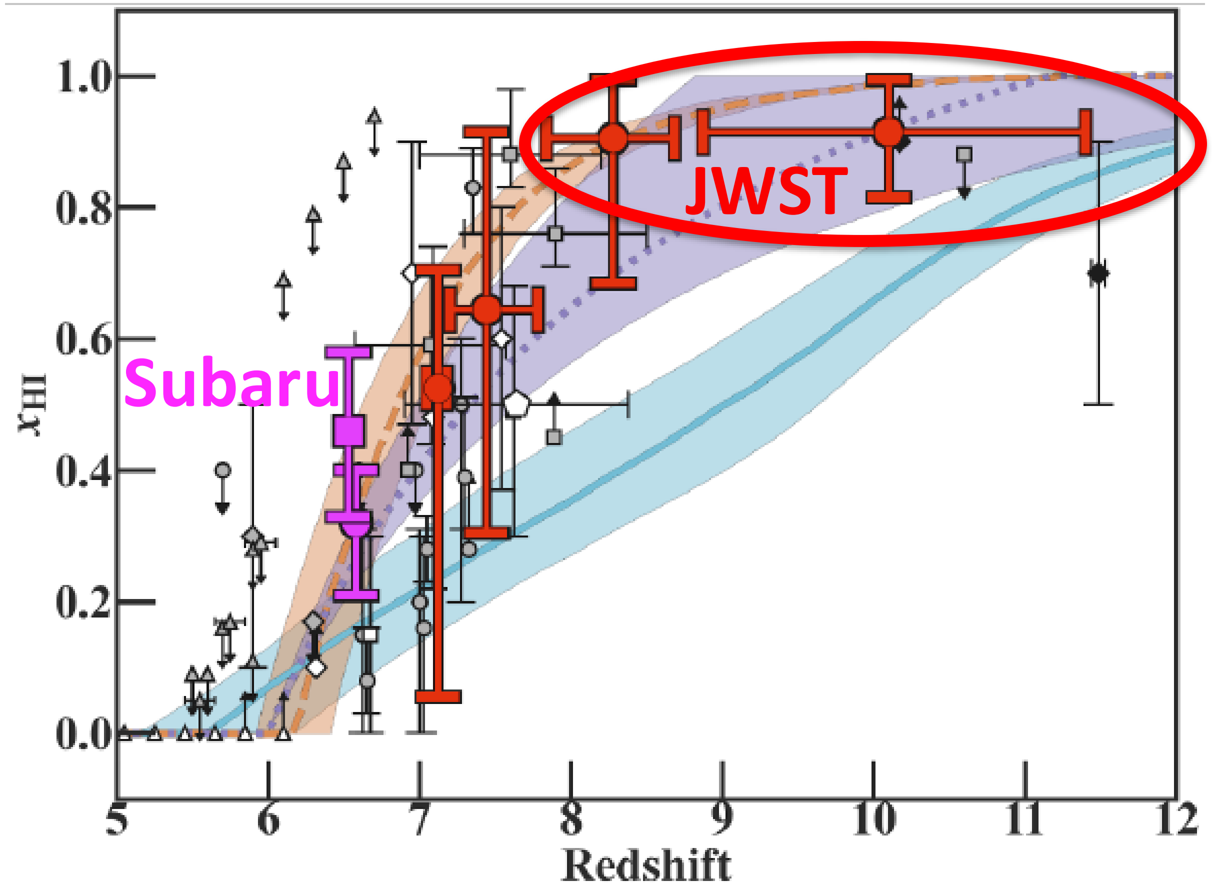
Umeda et al. (2024)

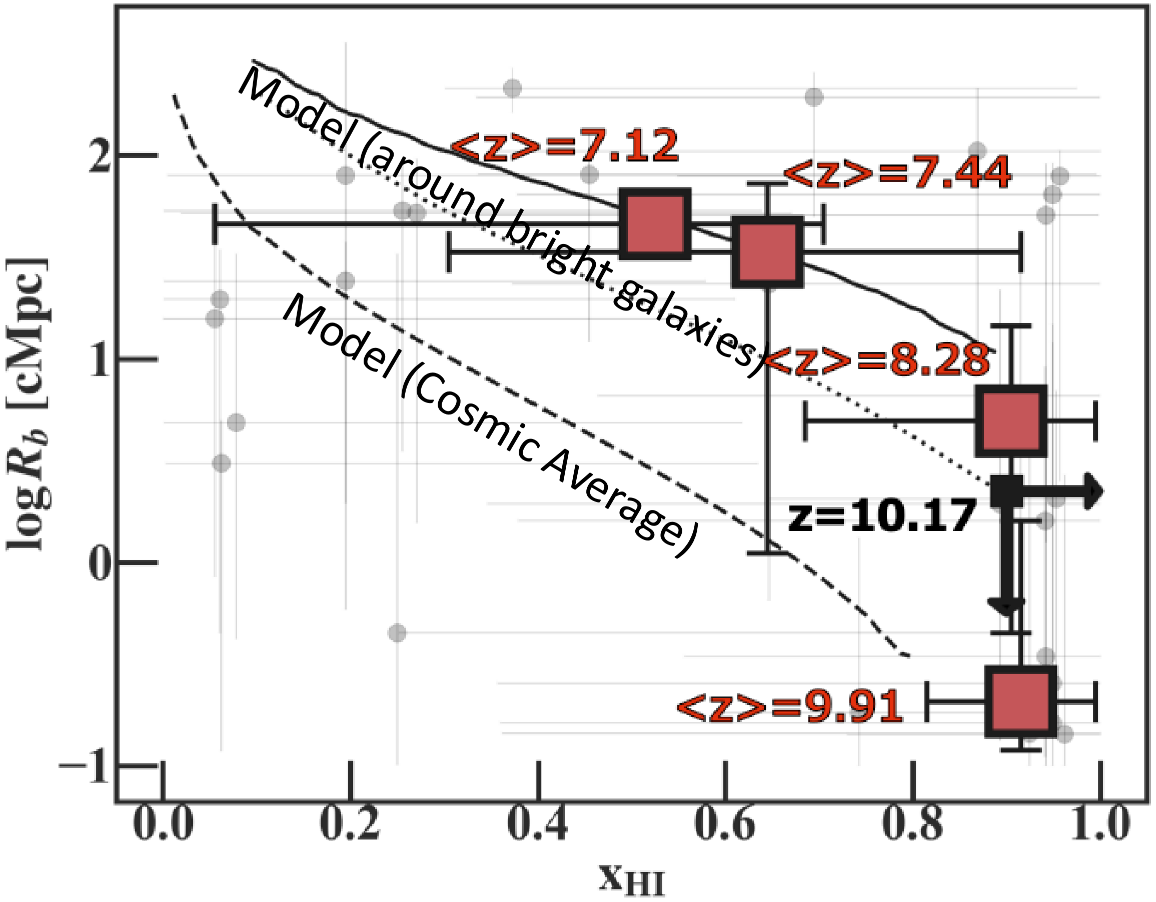


- Larger x_{HI} and smaller R_b towards high-z

x_{HI} and Ionized Bubble Radius

Umeda et al. (2024)





- Larger x_{HI} and smaller R_b towards high-z
- Neutral hydrogen frac. x_{HI} : Again, suggesting the late reionization whose major x_{HI} evolution takes place at z$\lesssim$8
- Large ionized bubble sizes beyond the cosmic average (Furlanetto+05). Problem?
  - Due to the large ionized bubbles around the bright galaxies (brightest galaxies at these redshifts; Lu+23)
  - Should be resolved w Bubble size distribution by more realistic modeling (Kageura in prep.)

Summary

Early galaxy formation probed by high-resolution/sensitivity JWST observations
---beyond the luminosity and abundance---

- Early star formation and enrichment
  - Rich N (+possibly He) in bright galaxies. Site of globular cluster formation?: Needing enrichment by CNO-cycle equil. gas (from H burning shell) SMS, WR, and/or TDE?
  - Rich Fe in a bright galaxy at z~10: Short delay time of SNIa or evidence of PISN in metal poor SB?

- Morphology and dynamics
  - Stellar clumps with $M^* \sim 10^6$Mo and $r_e \sim 1$pc. Proto globular clusters?
  - Rotating disk w many (>15) compact SF clumps at z~6, indicative of disk instability w weak feedback?
  - Velocity gradient of GN-z11. Fast rotating disk at z=10.6? If real, suggestive of weak feedback?
  - Outflow $V_{out} < V_{esc}$ for the majority at $M^* \sim 10^9$Mo: Weak fountain outflows. → weak feedback?

- Cosmic reionization (driven by early galaxy formation)
  - Clear evolution of Lyα damping wing absorptions (larger x_{HI} towards z~10)
  - Lya emission and UV-cont. evolution of galaxies: $x_{HI} \sim 0.9$ at $z \gtrsim 8$. Major x_{HI} evolution at $z \lesssim 8$ (Late reionization)
  - Suggestion of ionized bubbles larger than expectation?