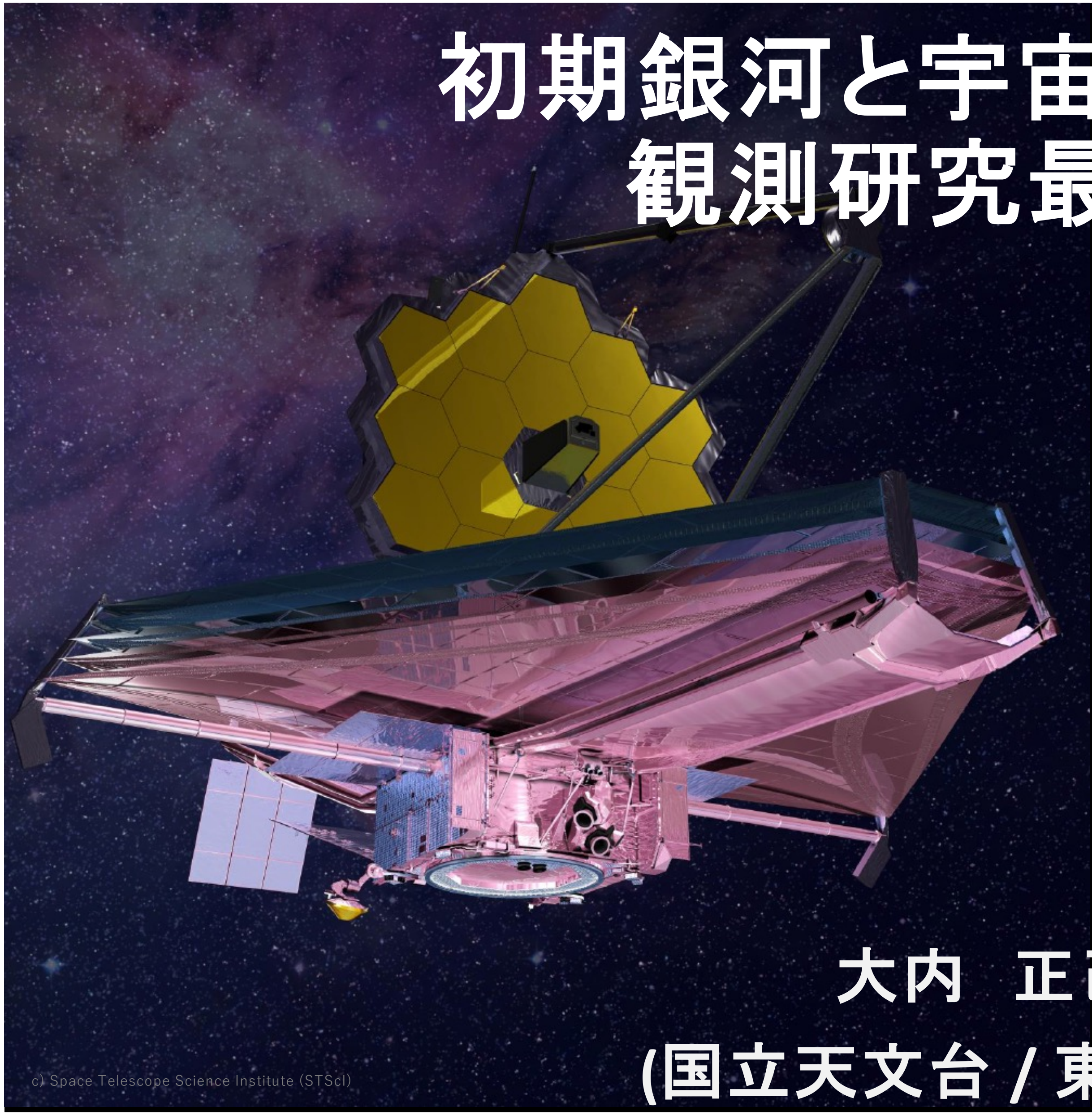
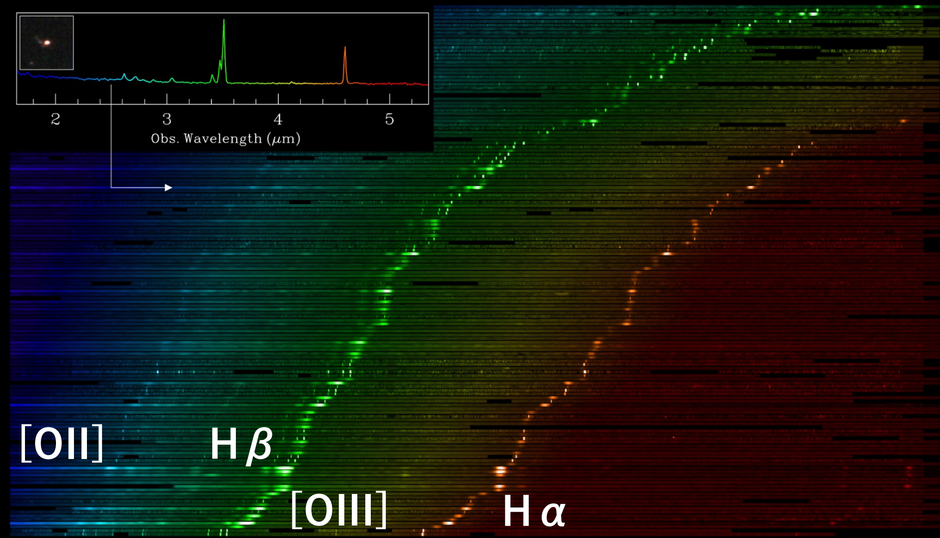
初期銀河と宇宙再電離の観測研究最前線





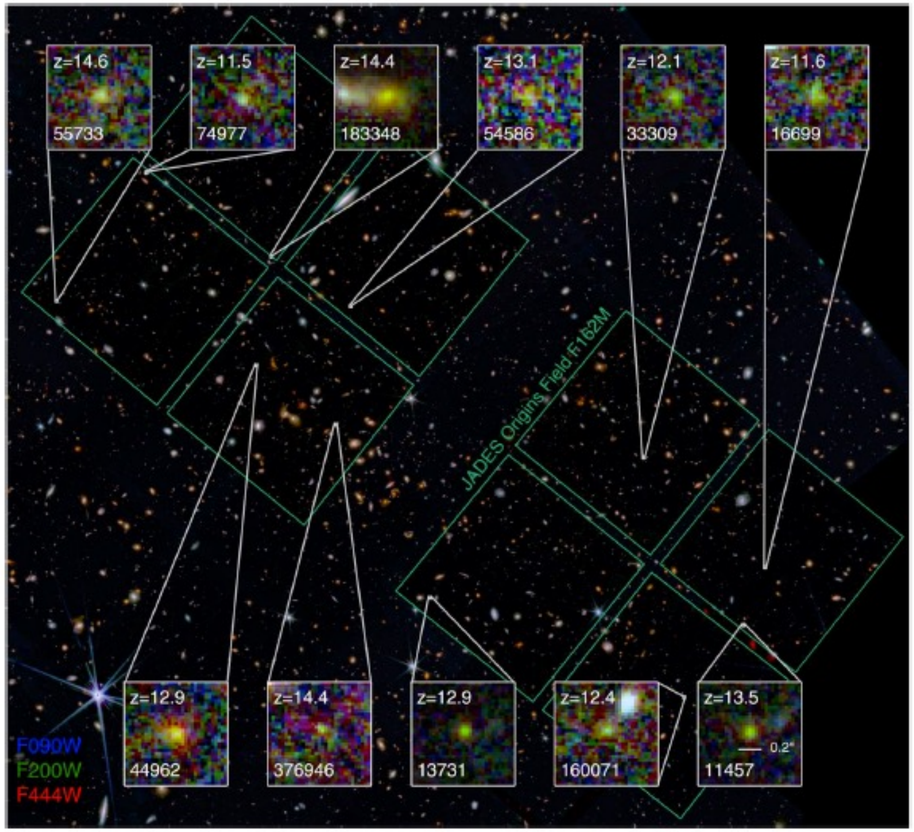
c) NASA, ESA, CSA, K. Nakajima et al.

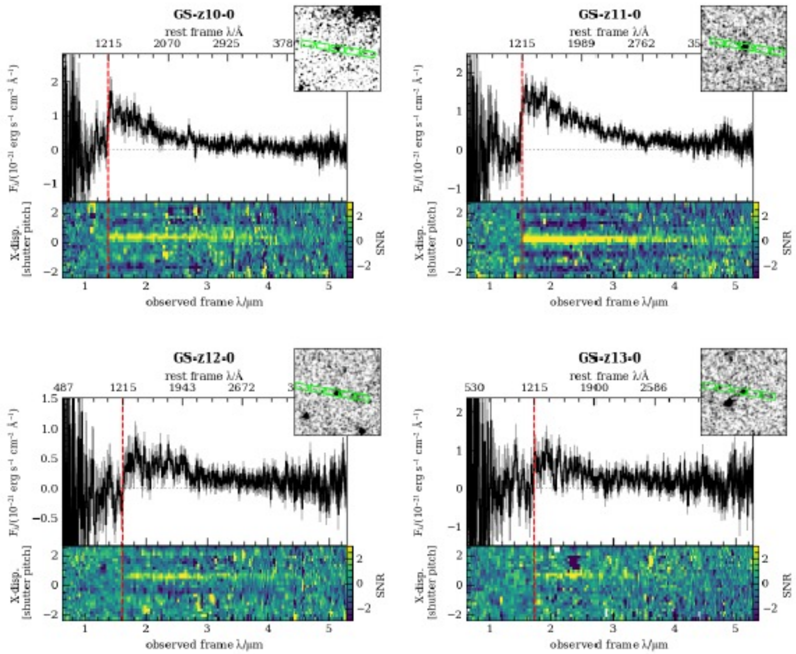
大内　正己

(国立天文台 / 東京大学)

Early Galaxies at z~13-14

Only ~300 Myr after BB





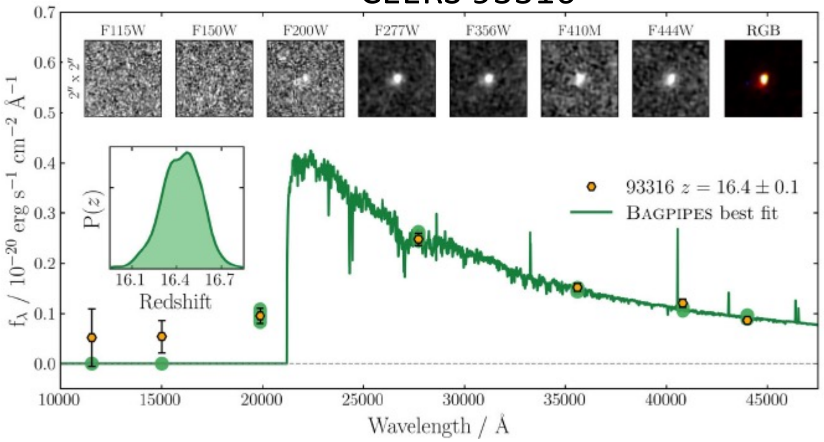
Curtis-Lake+23

Robertson+24

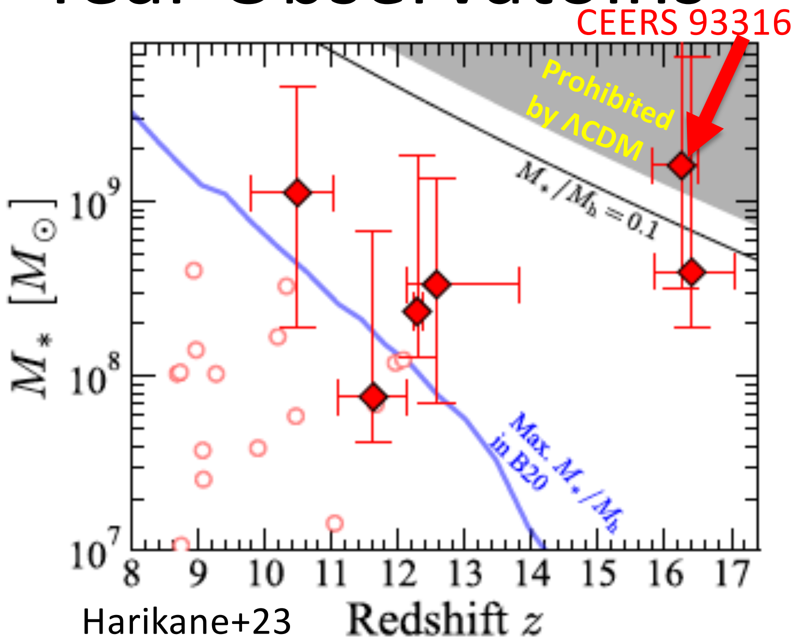
- Galaxy candidates up to z(phot)~15-17 (e.g. Donnan+23, Harikane+23)
- Galaxies confirmed up to z(spec)=13-14 (Curtis-Lake+23, Carniani+24a)

Too Many Massive Galaxies?
--Results from the 1st Year Observatoins--

CEERS 93316



Donnan+23

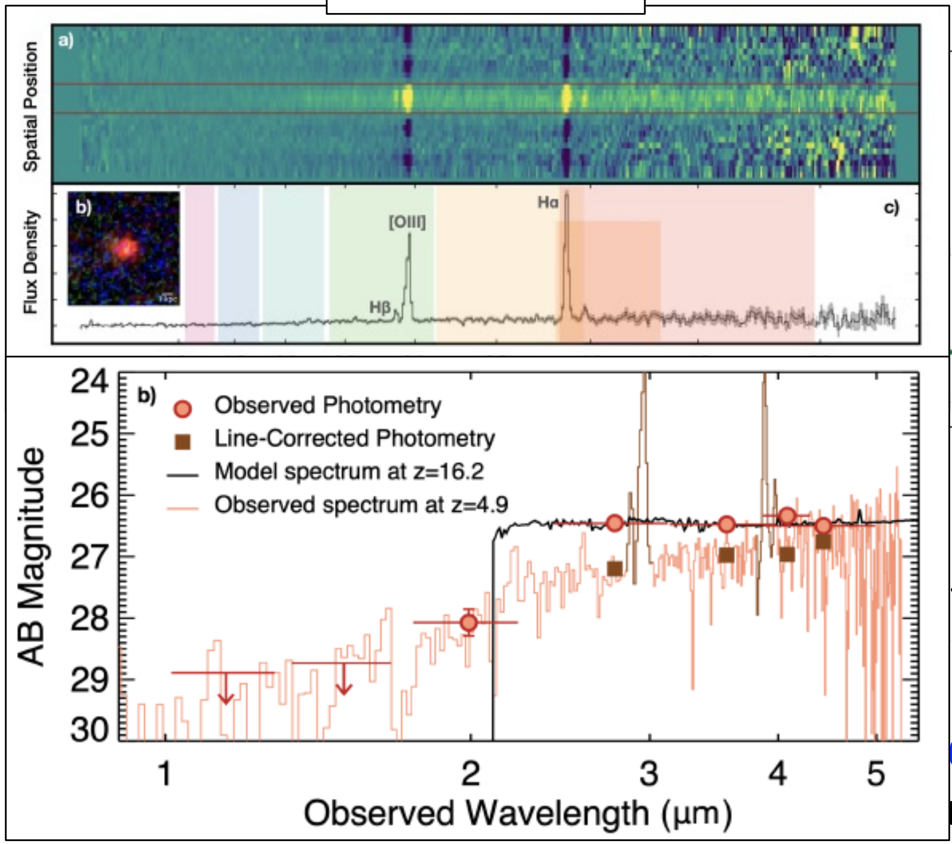


Harikane+23

- JWST early photometric results
  - Many bright (massive) galaxies at z(phot)>10 (Naidu+22, Atek+23, Finkelstein+23, Donnan+23, Harikane+23a)
  - Notable source: CEERS 93316 at z_{phot}=16.4 (Donnan et al. 2023)
- Too massive & early to form in DM halos → Problem in ΛCDM??
- Spectroscopic follow up observations
  - CEERS 93316→Strong emission line galaxy at z=4.9 mimicking the Lyα break
  - No immediate crisis of ΛCDM

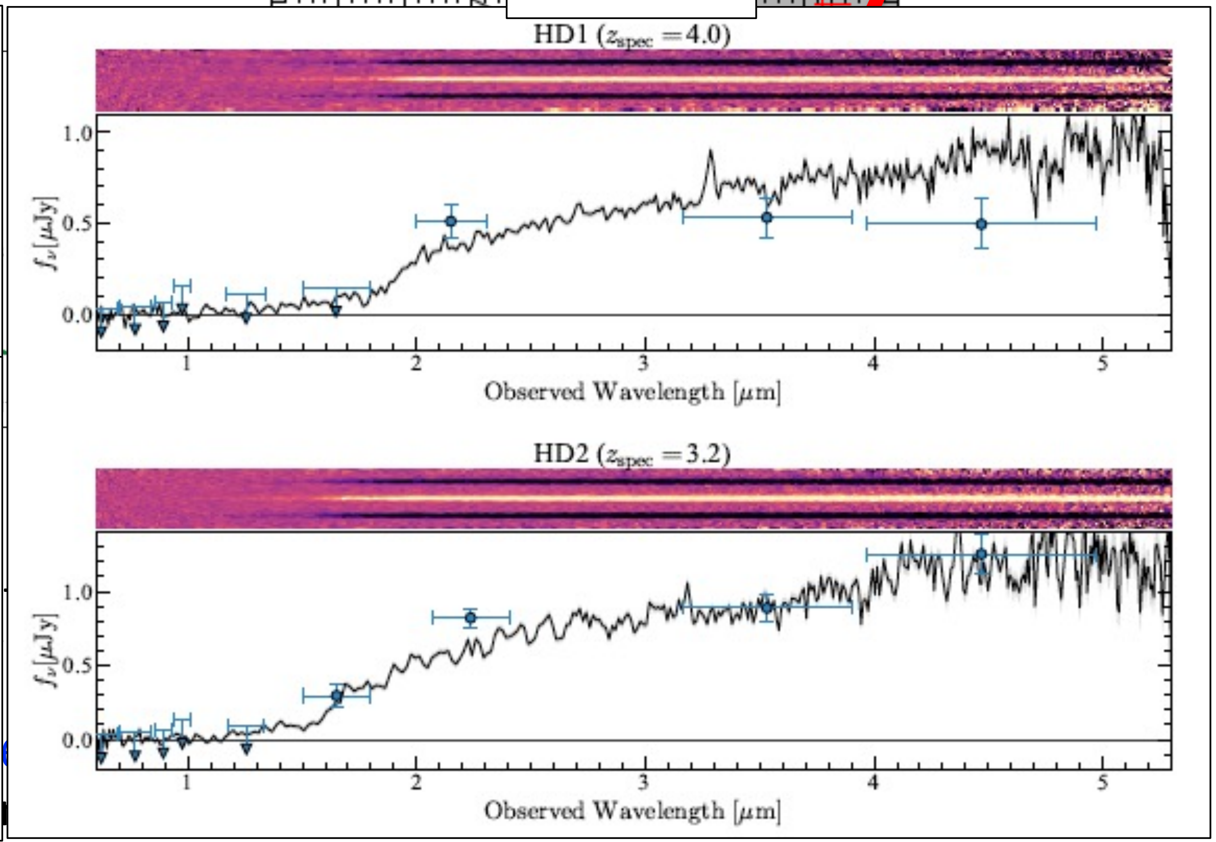
Too Many Massive Galaxies?
--Results from the 1st Year Observatoins--

Arrabal Haro+23



Harikane+24

ERS 93316



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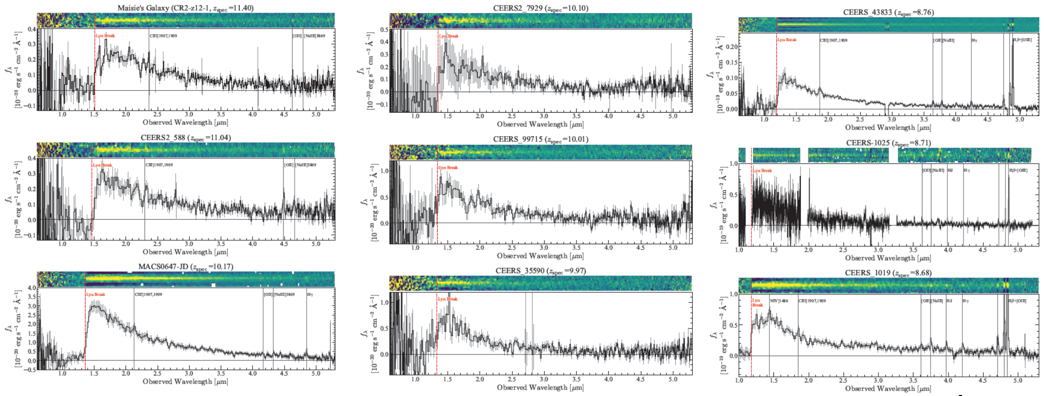
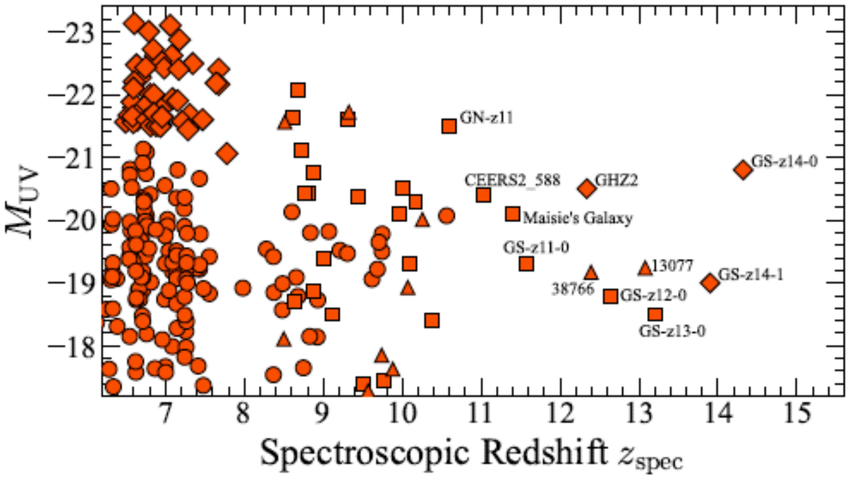
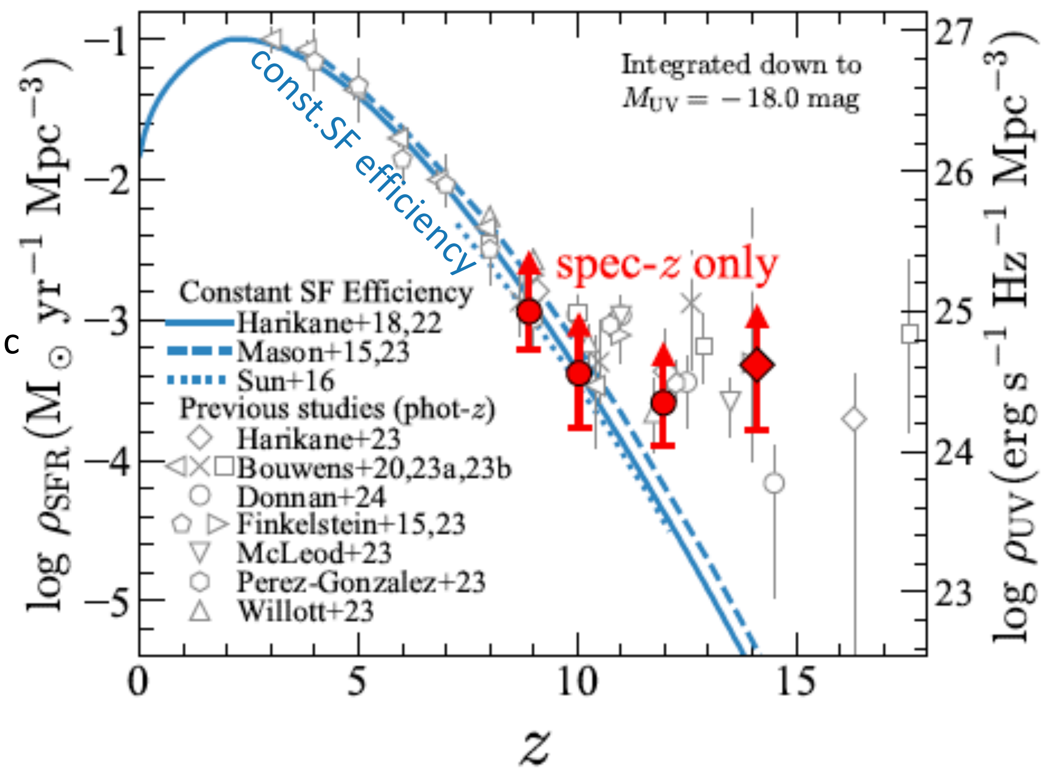
Very Efficient Star-Formation?



Harikane+23c



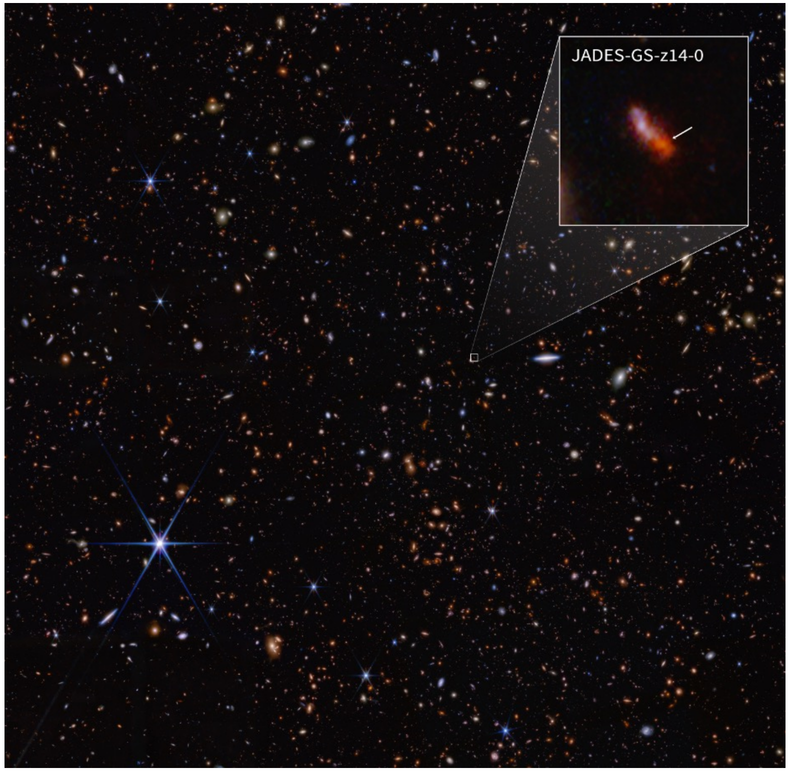
Harikane+24



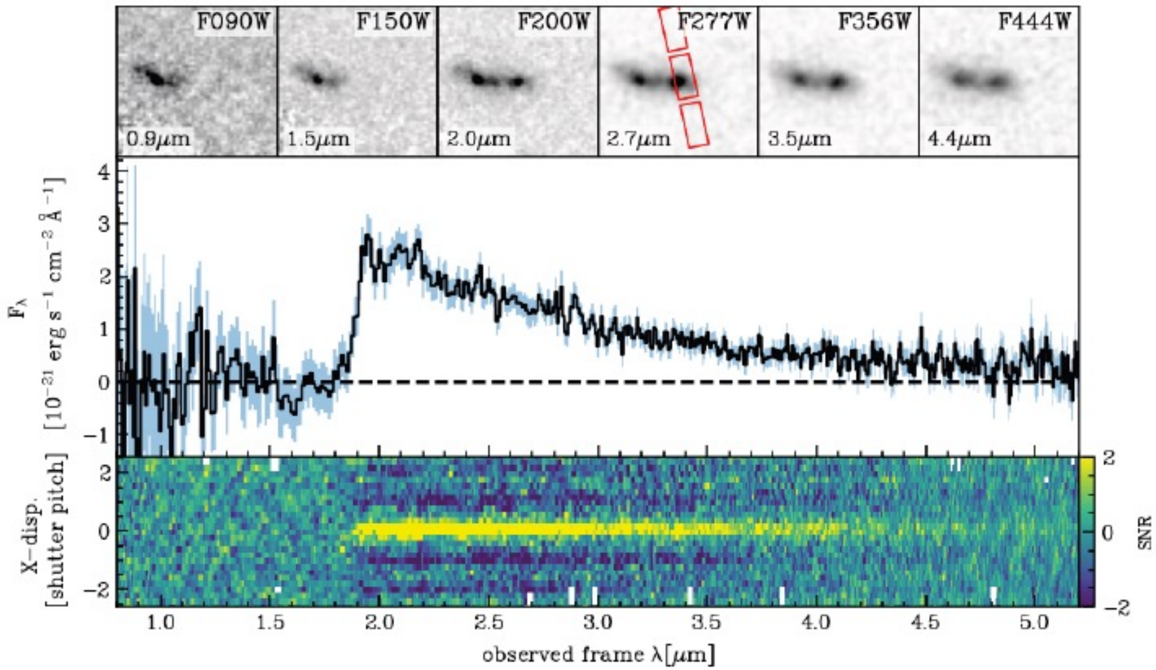
- ~20 galaxies at z(spec)=10-14 (JADES and various GO, ERS, ERO, DDT programs)
- Luminosity function securely constrained by spec. (mostly lower limits) → Abundant luminous galaxies
  - 1) Very efficient SF at z>10? Higher than the const.SF efficiency models f_{SF}=const (SFR=f_{SF} x f_b x dM_h/dt; f_{SF}~2% at z<10)

  Others? 2) Hidden AGN, 3)Top-heavy IMF/Pop-III (Ishida's talk), 4) Bursty SF, 5) Attenuation free, and 6) Flaw in cosmology

Spectroscopic Confirmation of a Very Bright Galaxiy GS-z14-0



NASA、ESA、CSA、STScI、Brant Robertson (UC Santa Cruz)、Ben Johnson (CfA)、Sandro Tacchella (Cambridge) & Phill Cargile (CfA)



Carniani+24a

- GS-z14-0 at z_{spec}= 14.2 (Carniani+24a, Helton+24, Schouws+24, Carniani+24b)
- Spec. confirmed (highest z, so far). Very bright (+extended r_e=260±20pc) galaxy
  - Significantly bright (not AGN-dominated) galaxy for the given redshift.

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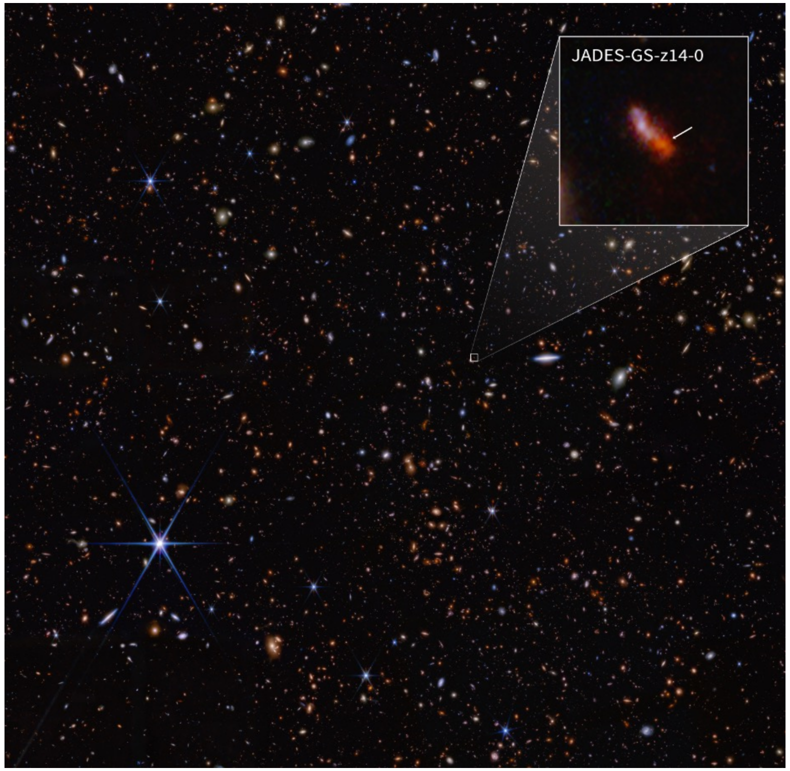

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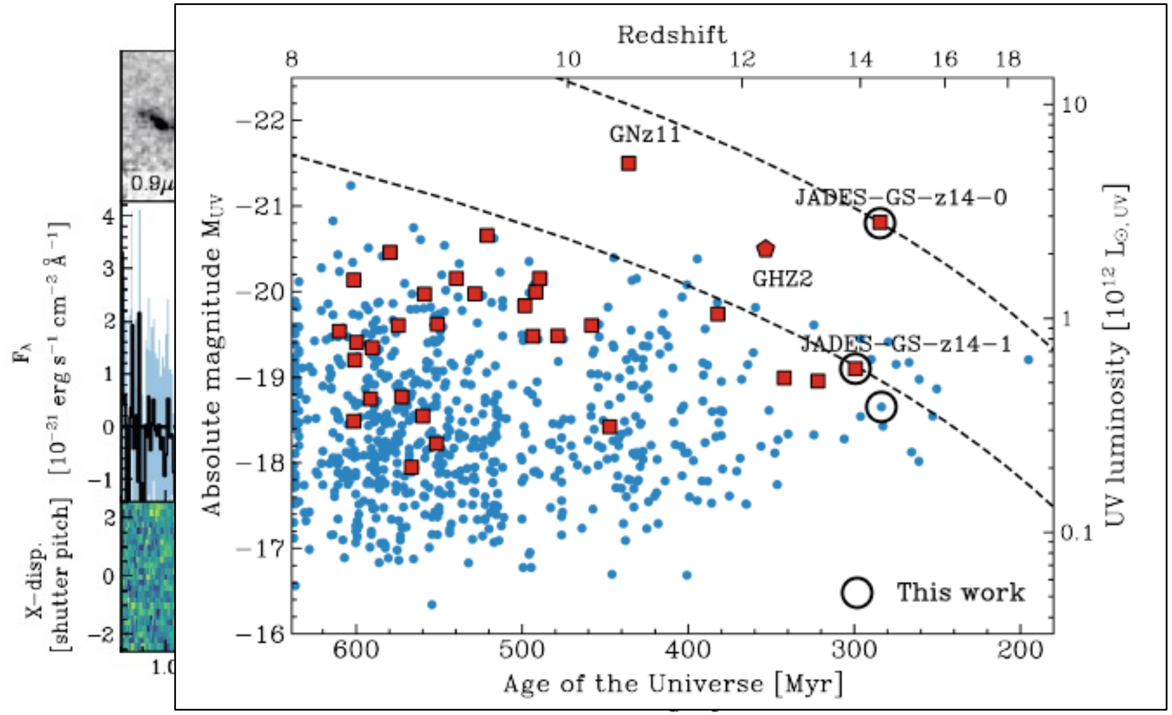

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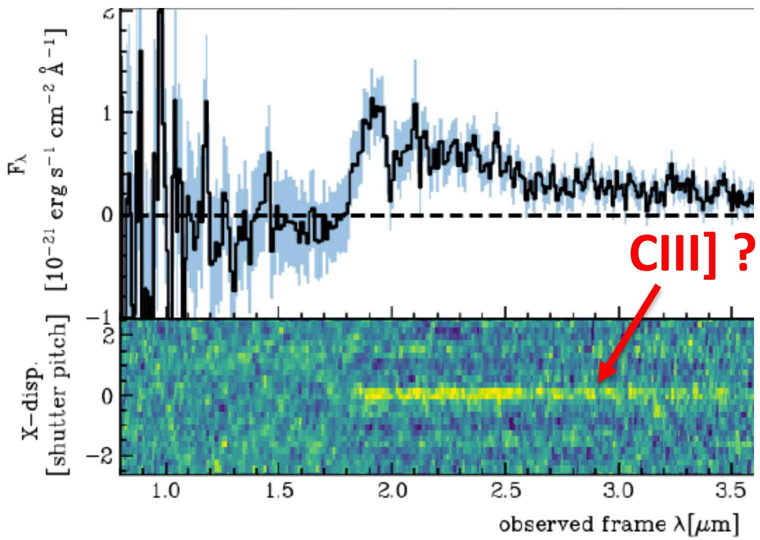
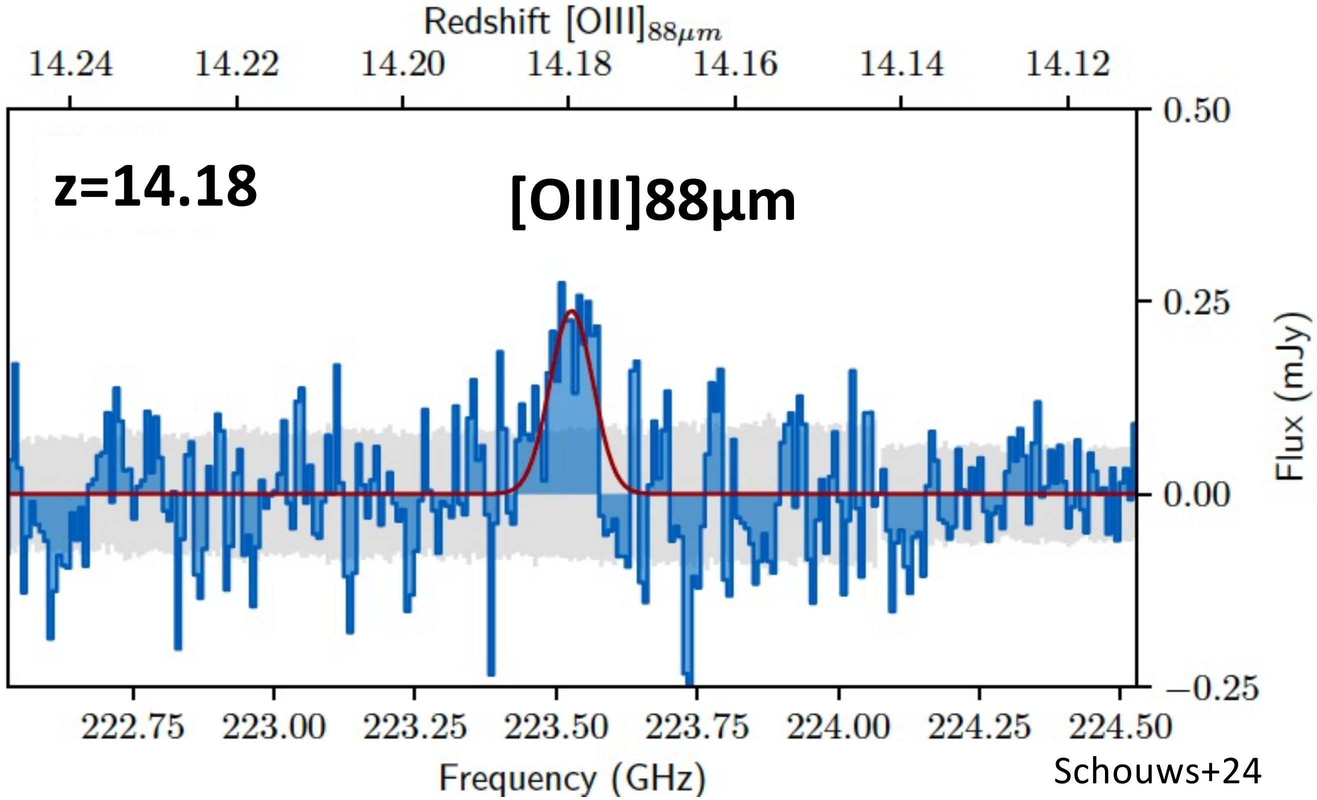
Signature of Chemical Enrichment





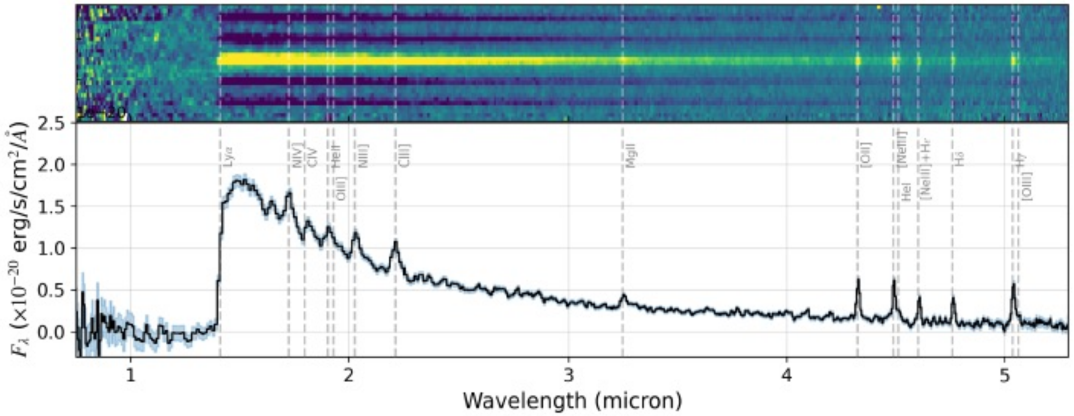
Schouws+24
(see+ Carniani+24)

GS-z14-0 at z=14.2

- JWST/NIRSpec: tentative (4σ) detection of CIII]1907,1909 ? (Carniani+24)
- ALMA follow up: [OIII]88um (7σ detection)
  – Suggesting Z≳0.1 $Z_\odot$ → Chemically enriched (Schouws+24, Carniani+24b).

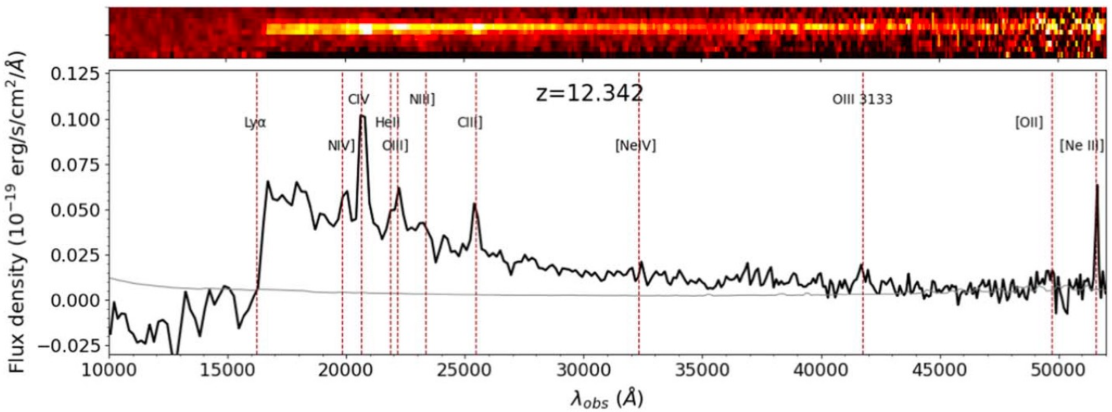
Metal Lines: Probes of Eary Chemical Enrichment

GN-z11
(z=10.60)



Bunker+23

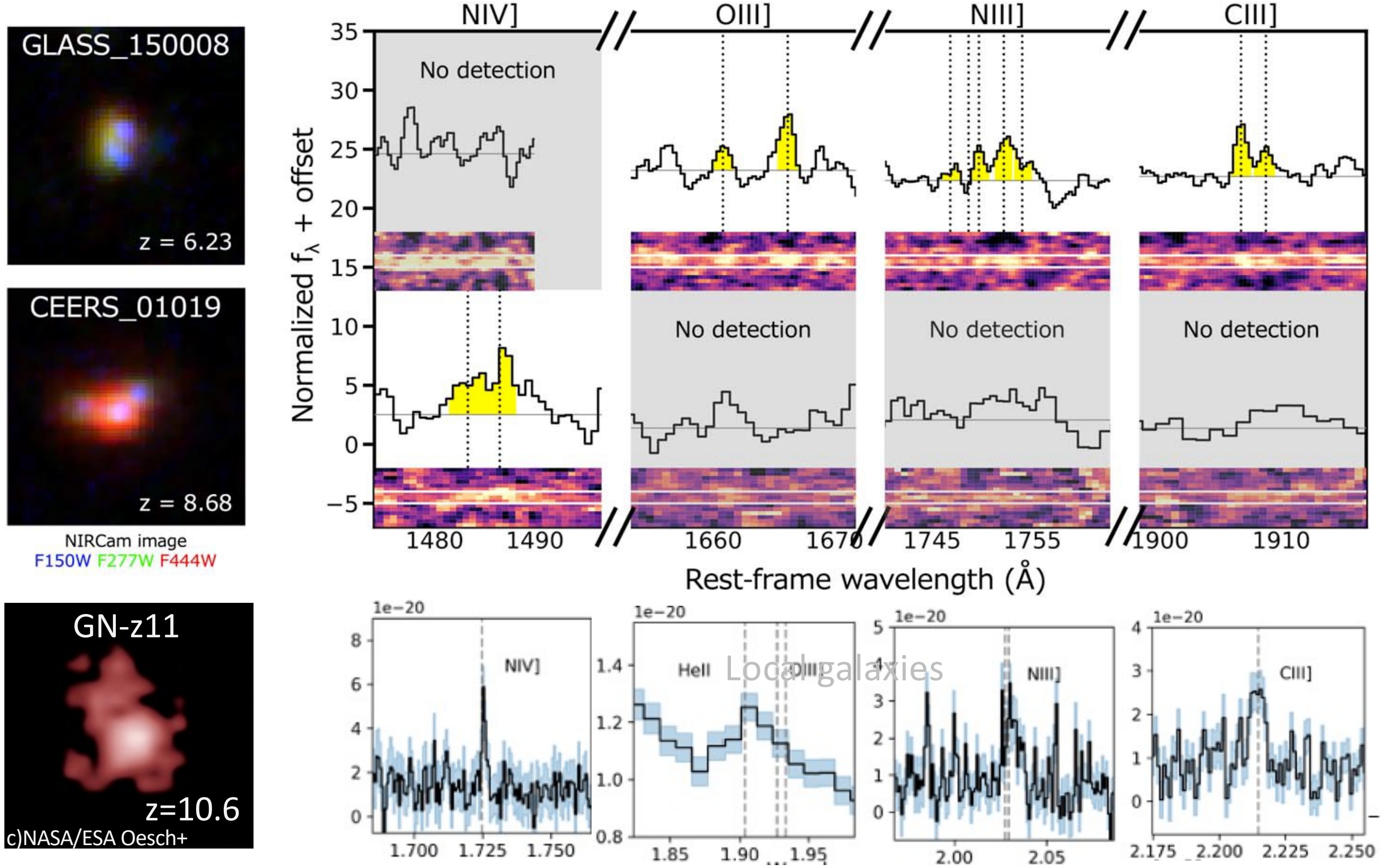
GHZ2
(z=12.34)



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...
  →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)
  – Unlike local galaxies w CCSNe. Chemical enrichment dominated by gas from hydrogen burning shell (outer envelope)?

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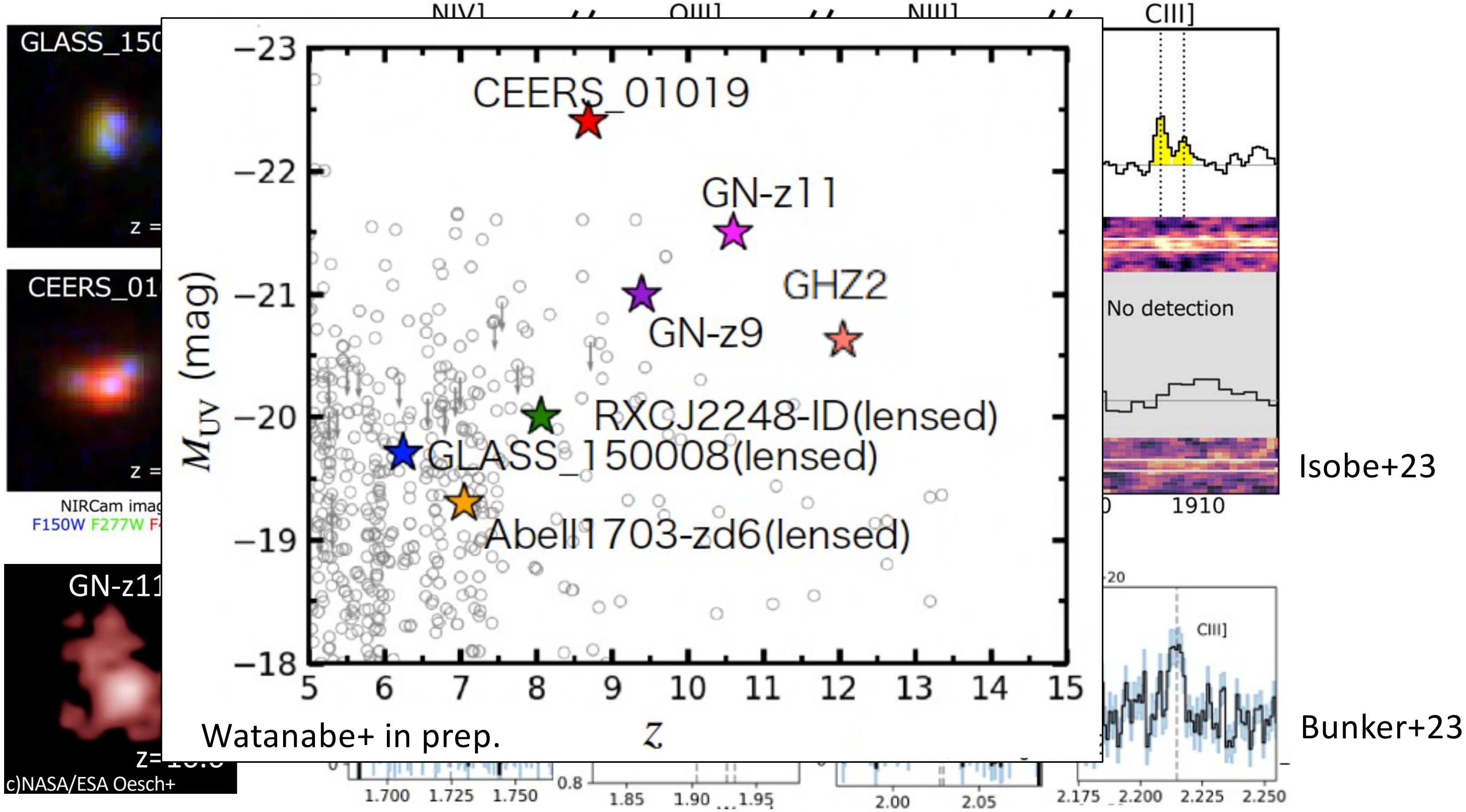

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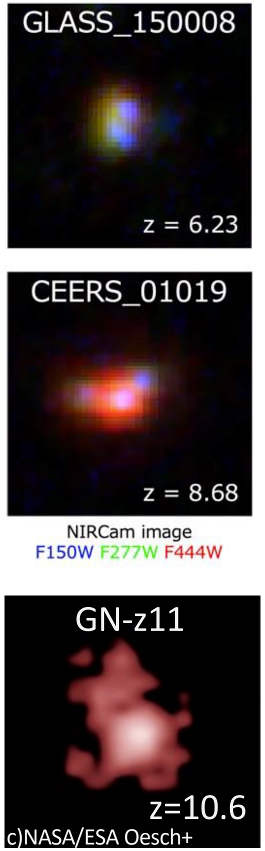

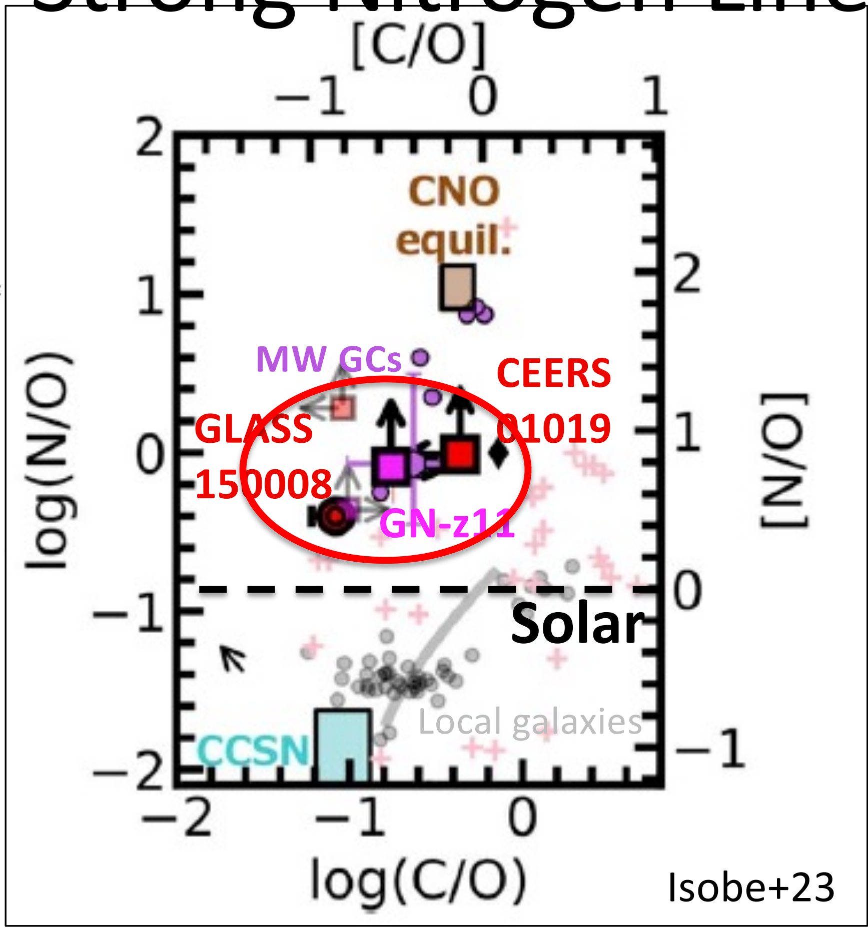

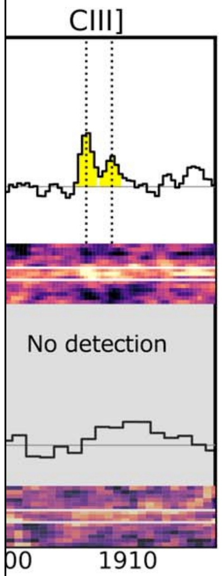

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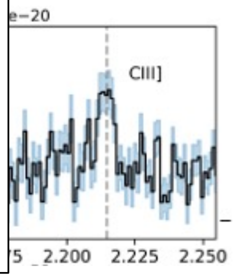

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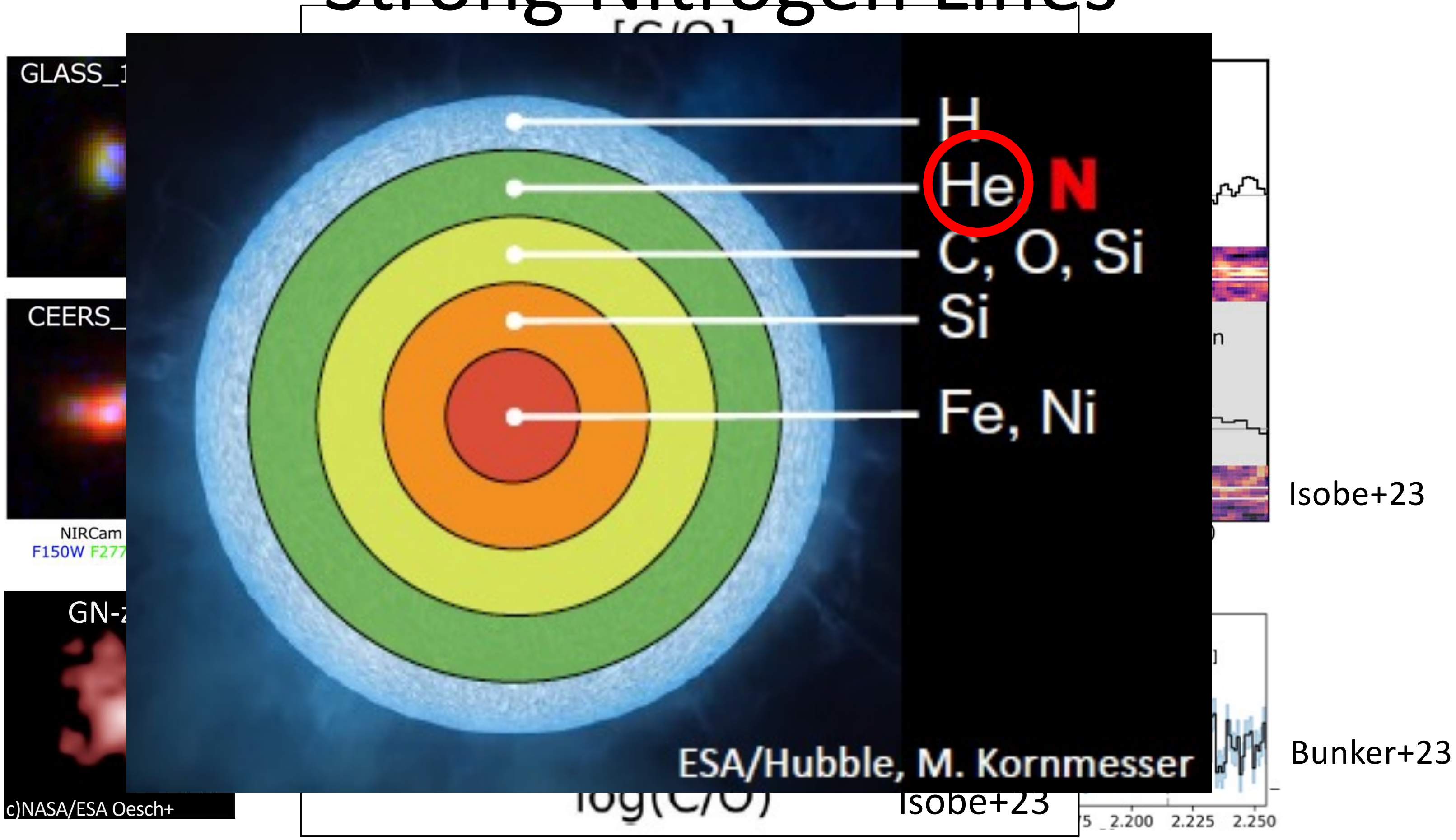

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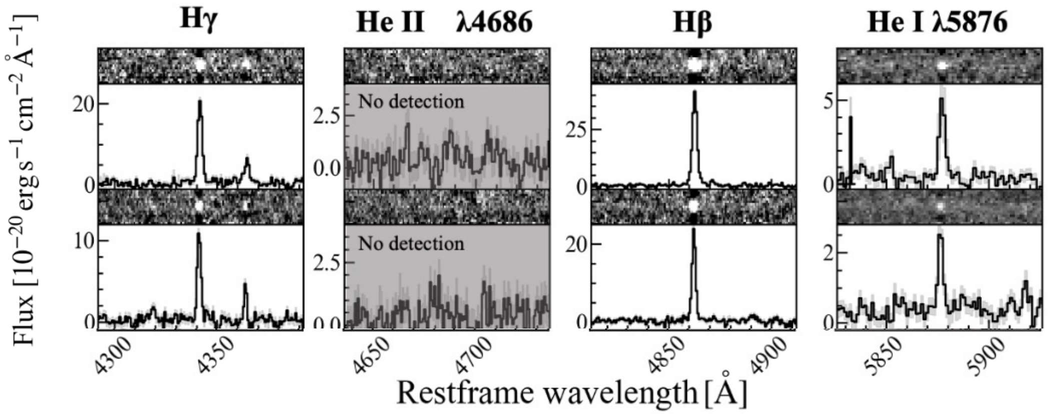
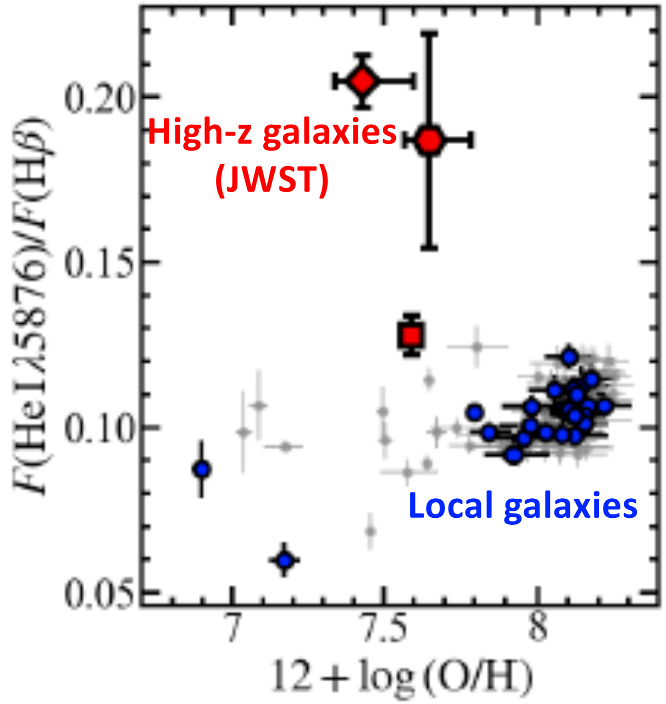
Strong HeI λ5876 Lines



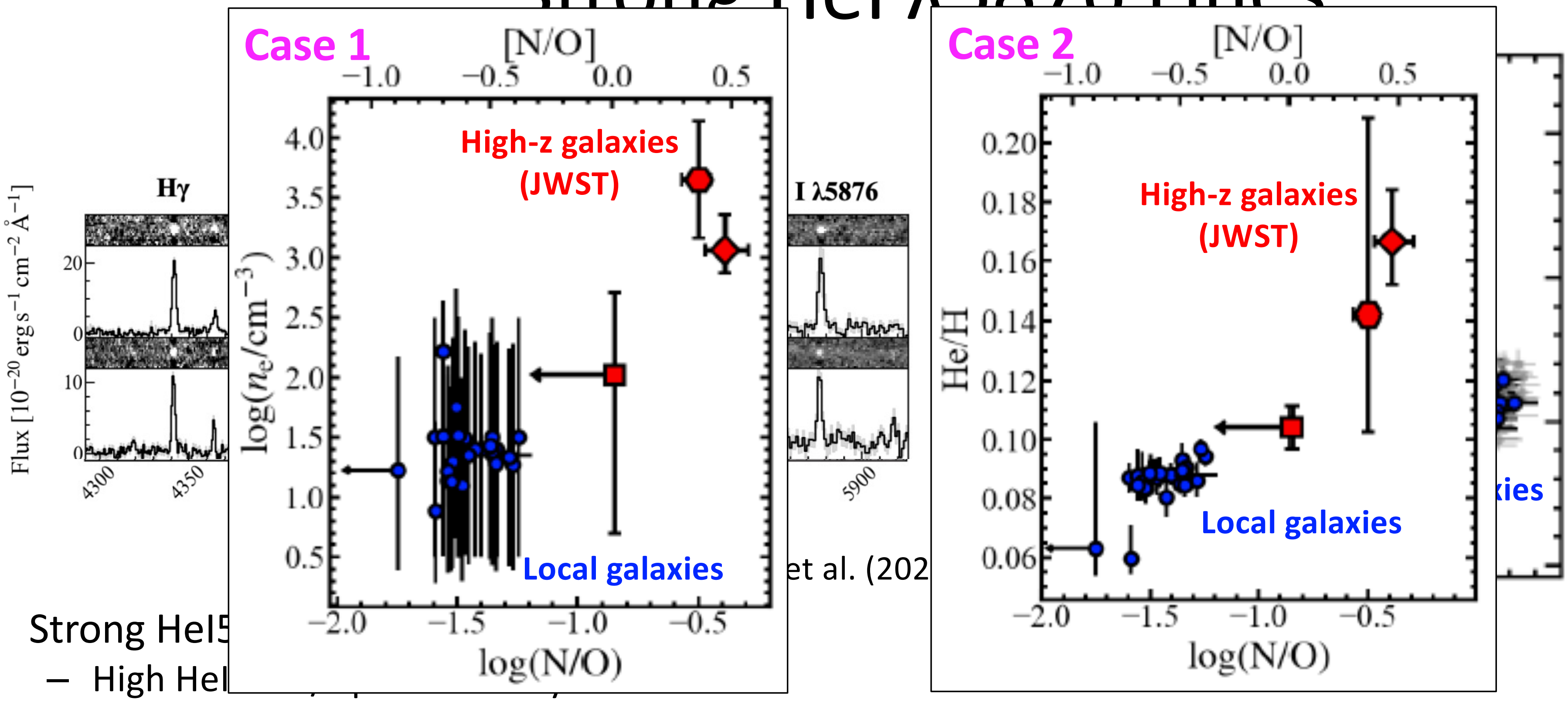
Yanagisawa et al. (2024)



Hiroto Yanagisawa

- Strong HeI5876 lines for high N/O galaxies
  - High HeI5876/Hβ ratios. 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)

Strong HeI λ5876 Lines




Hiroto Yanagisawa

- Strong HeI5
  - High HeI
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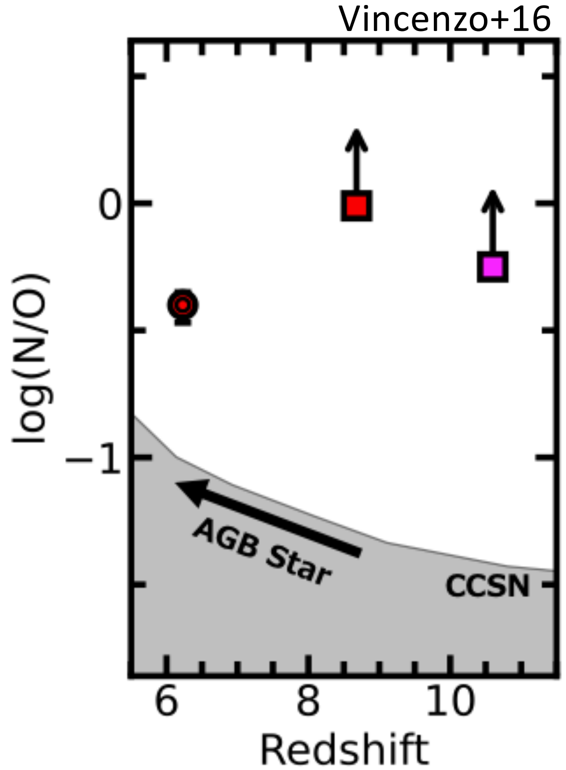
Origins of the Rich N (and He)



- 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)
- Explaining N/O and He/H. Is SMS preferred for He/H??

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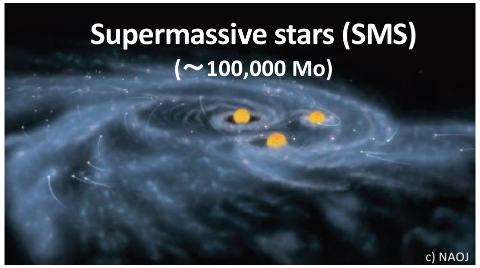
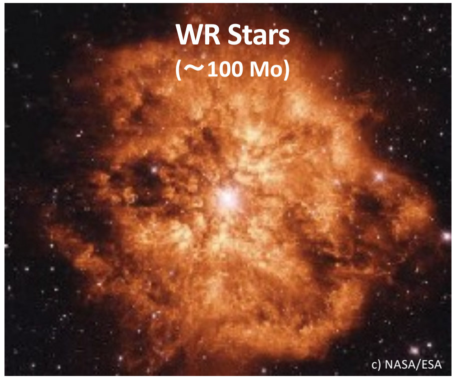
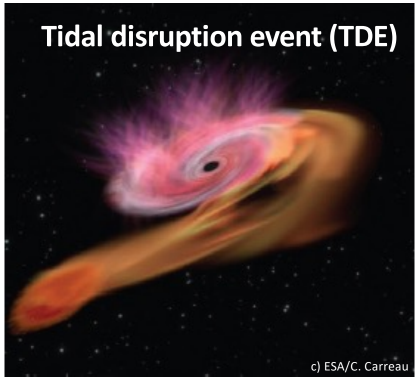
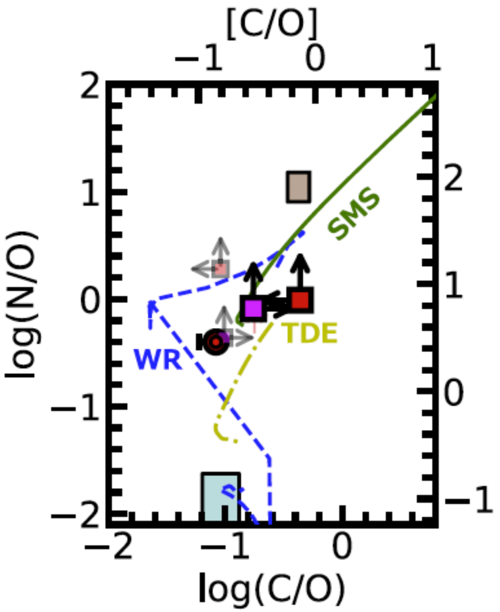
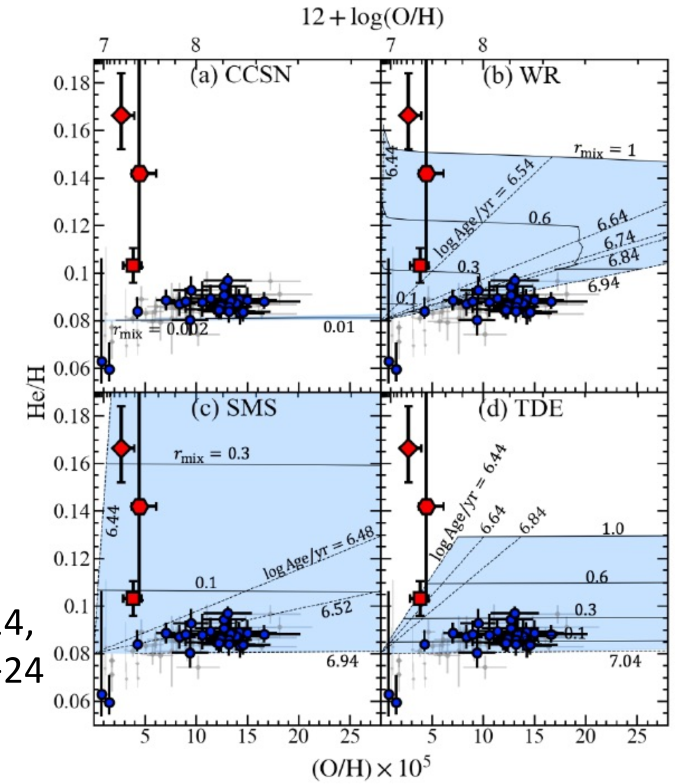








Watanabe+23, Isobe+23



Watanabe+24, Yanagisawa+24

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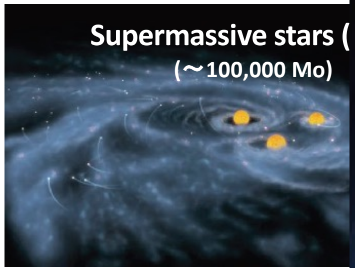
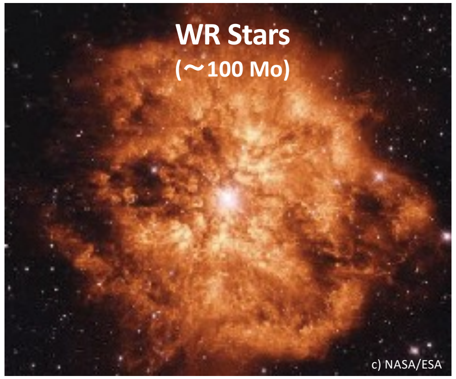
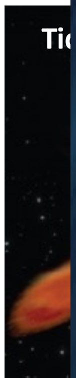
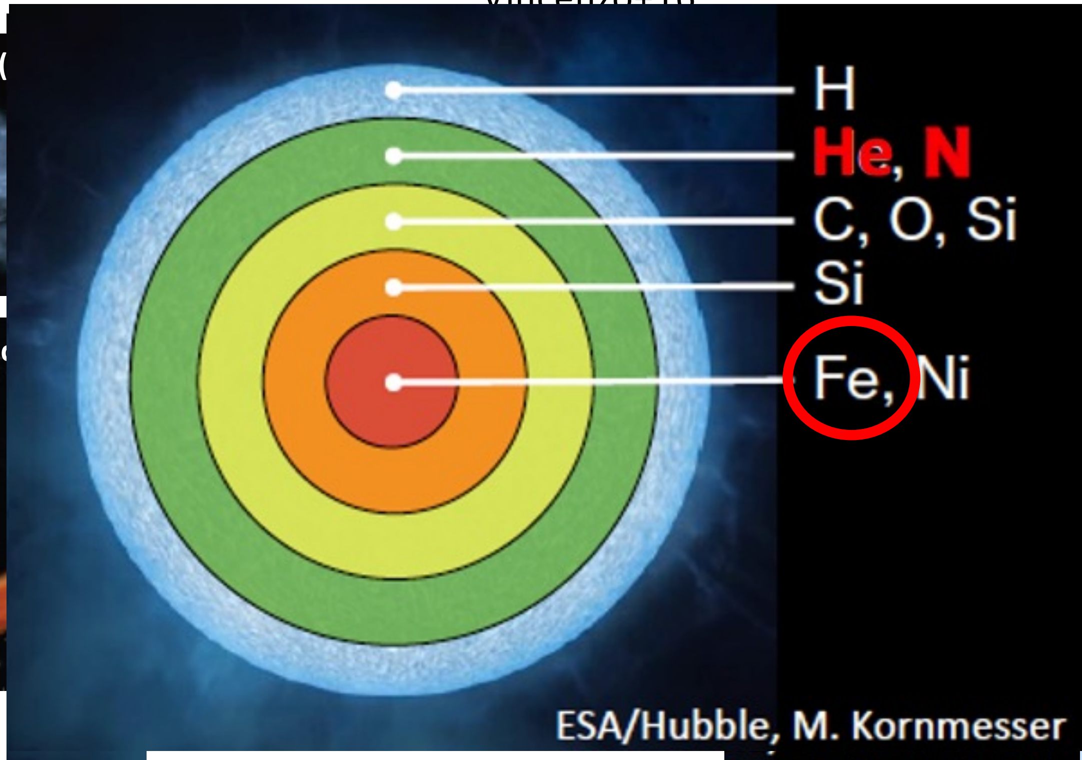
Vincenzo+16

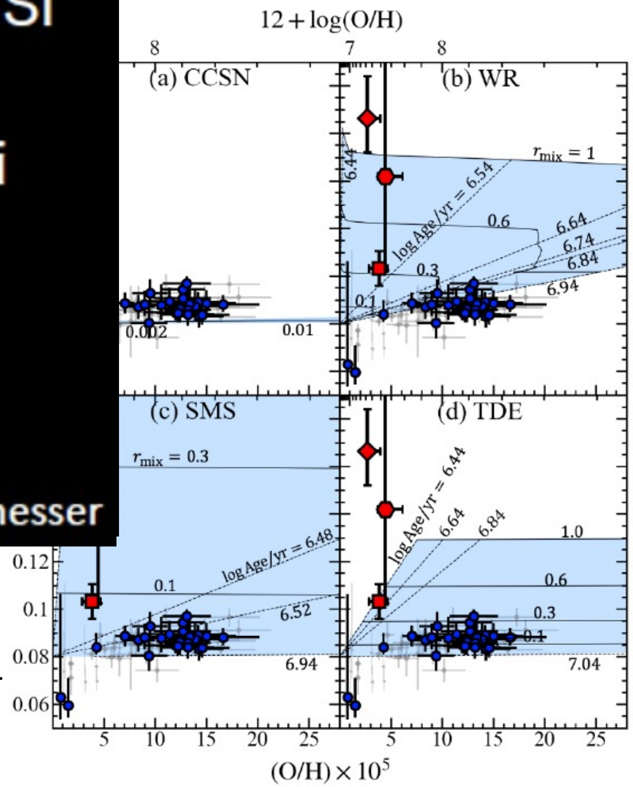








Kuria Watanabe



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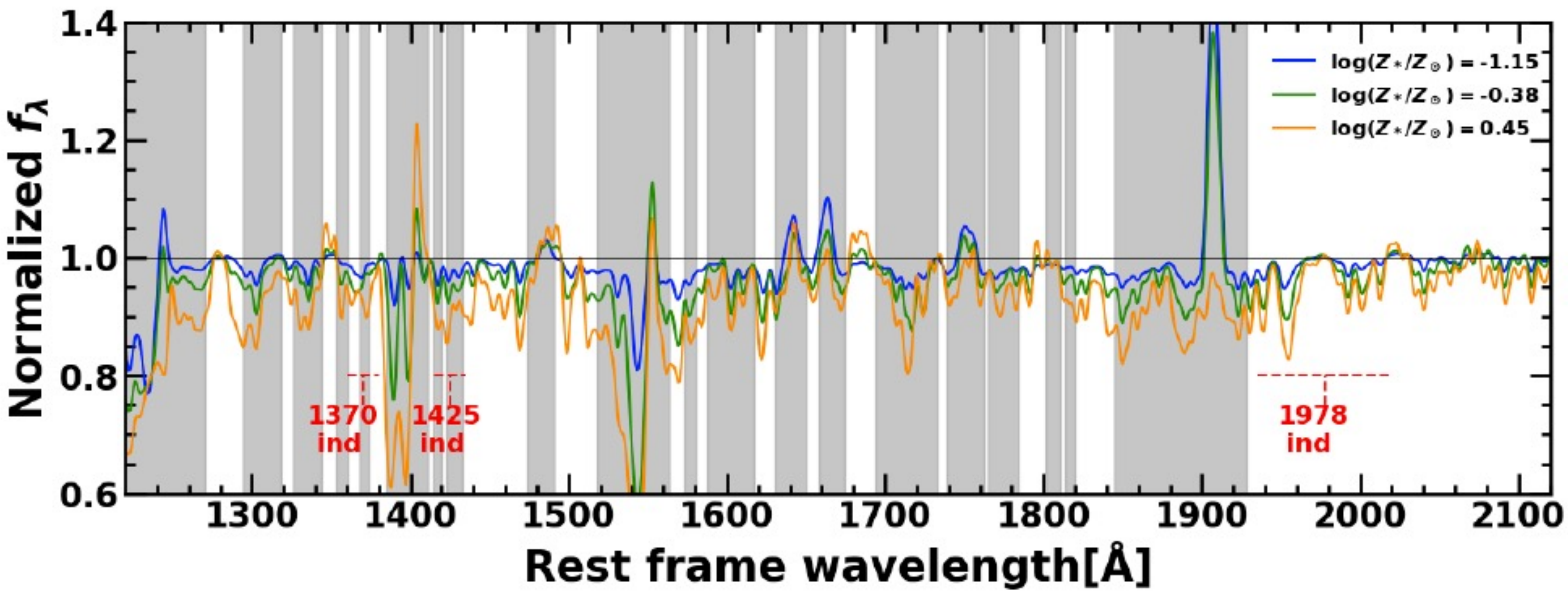
Fe Abundance (GN-z11)

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.

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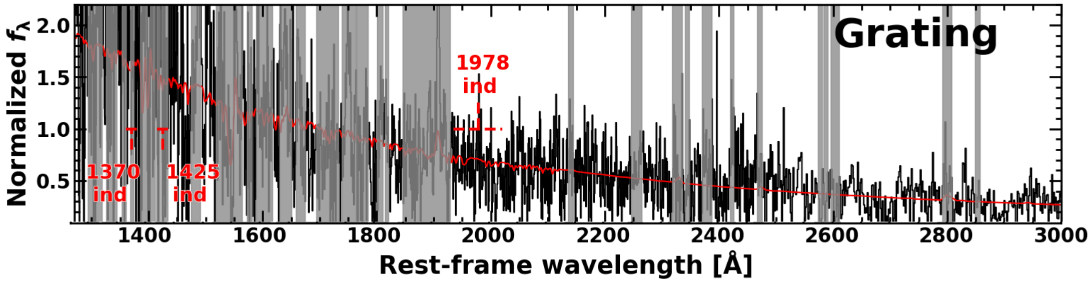

Minami Nakane

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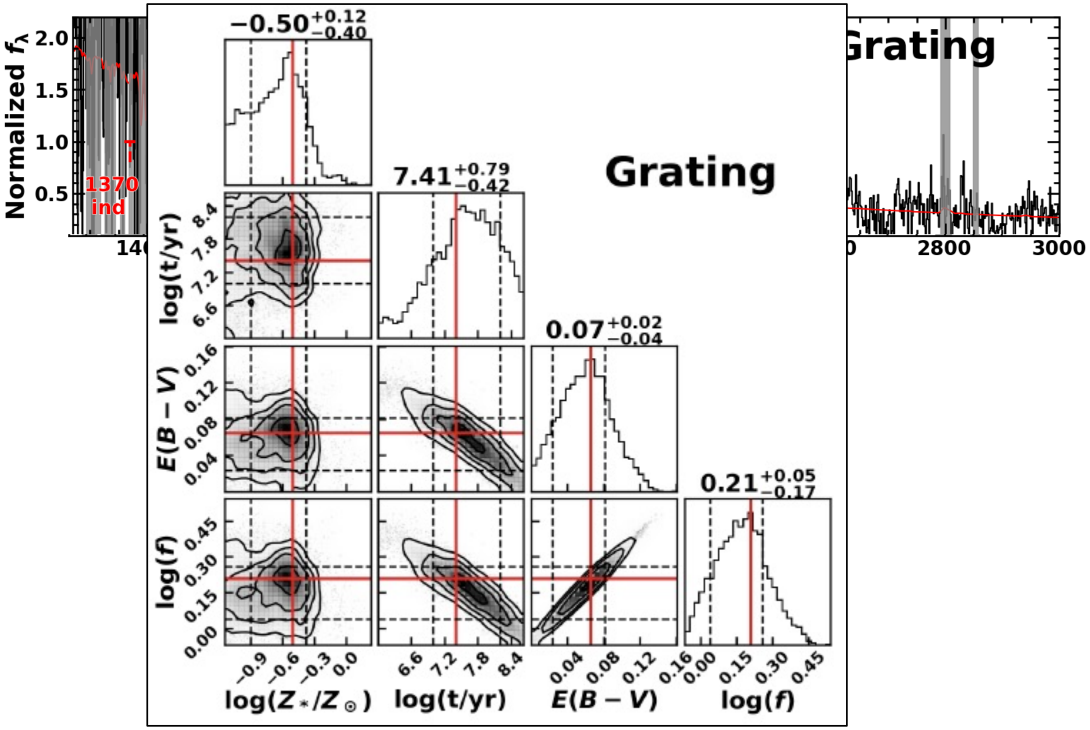

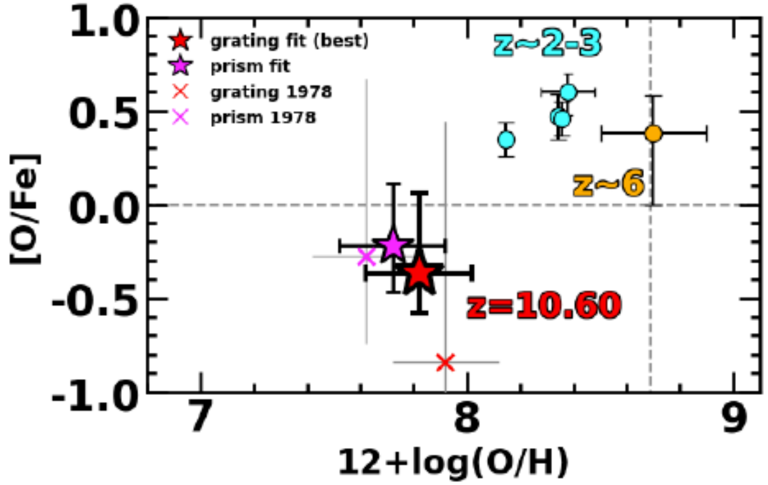

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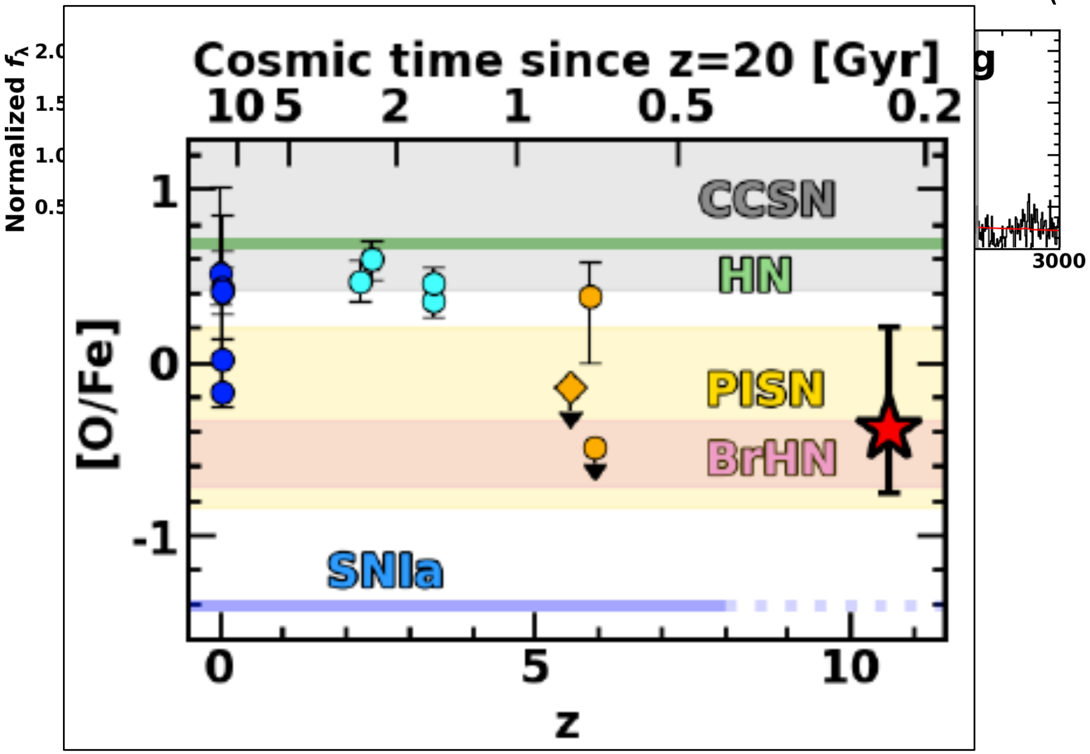
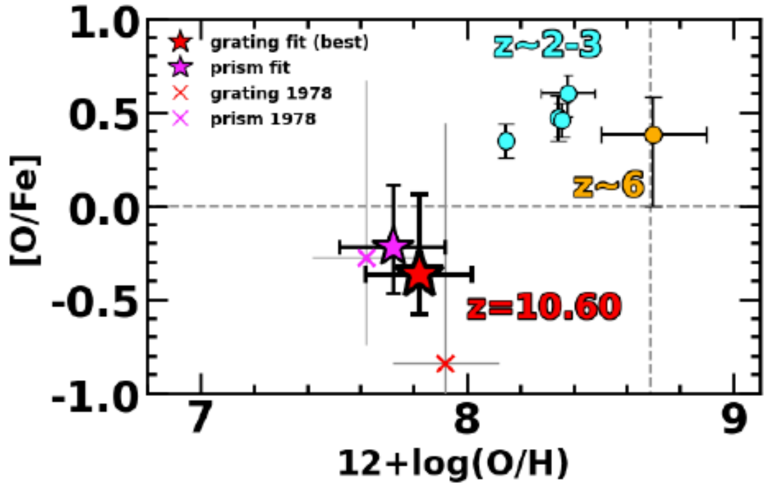
Fe Abundance (GN-z11)

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)
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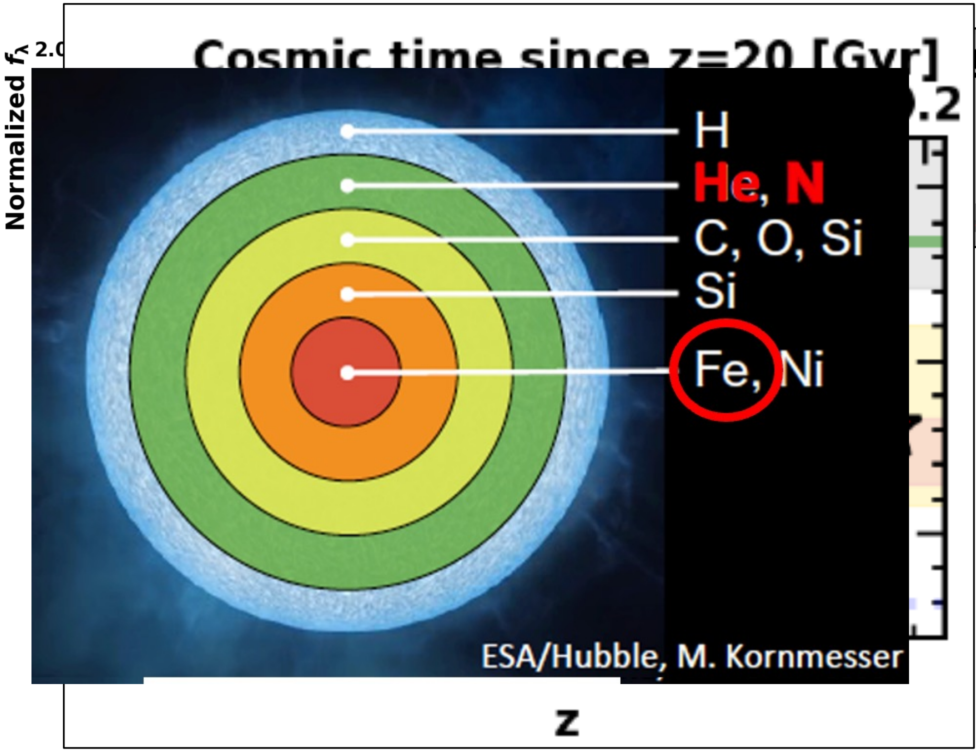

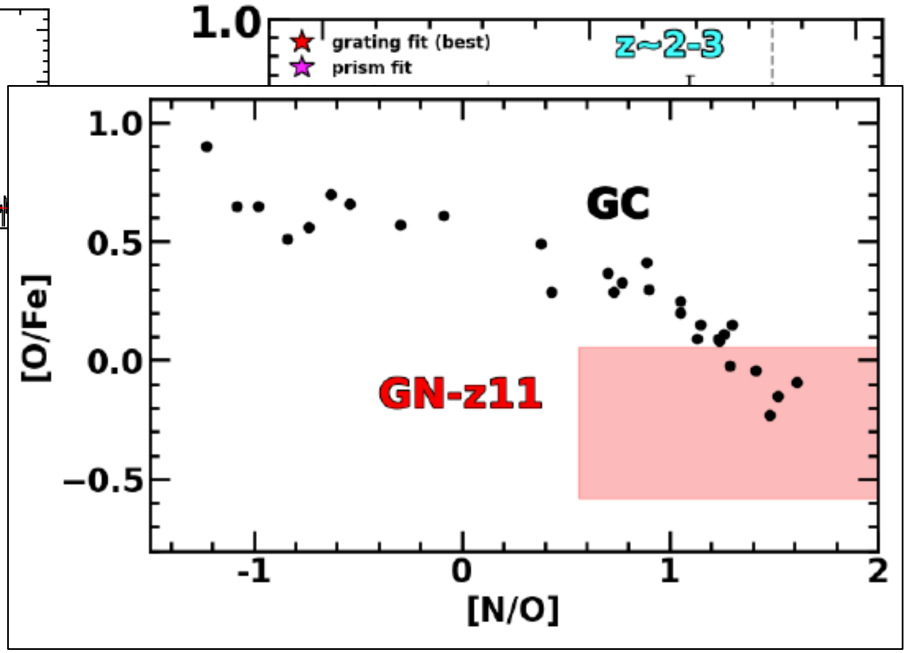

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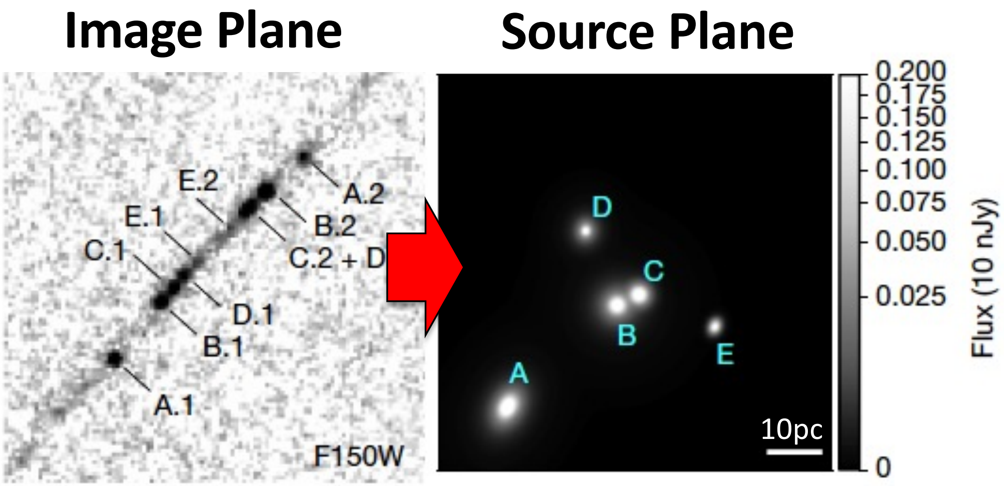
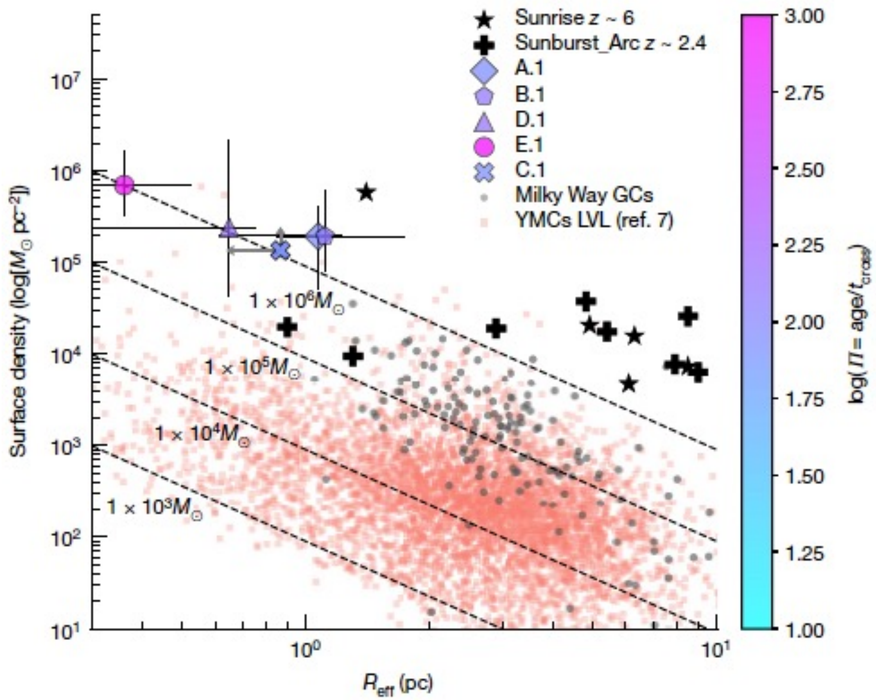
Globular Cluster Formation ?



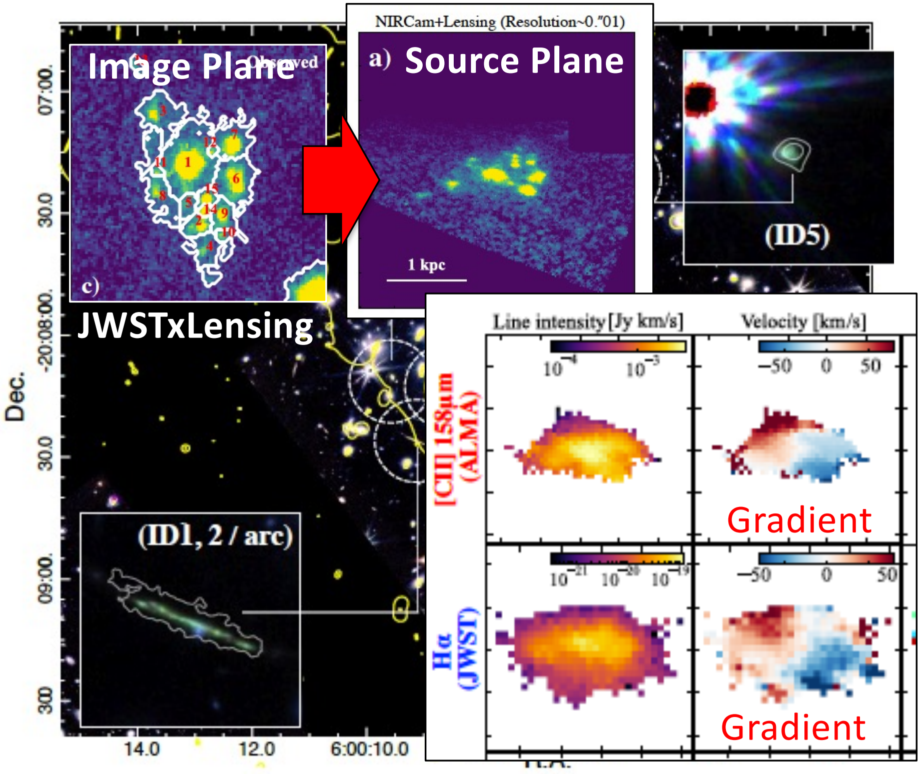
Adamo+24

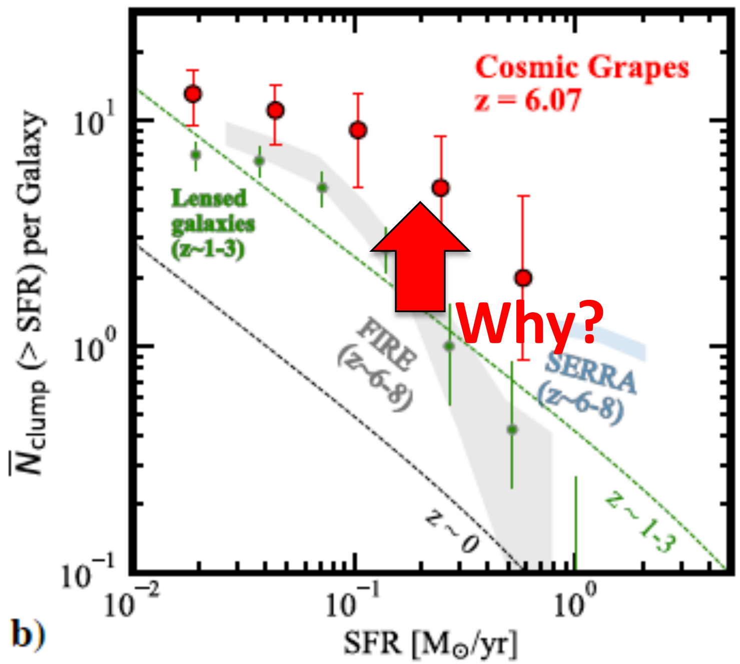


- Cosmic Gems: Lensed galaxy at z_{phot}~10 (μ~100-300)
  - 5 stellar clumps with M*~10^6Mo and r_e~1pc. Proto globular clusters? (Adamo+24)
  - Needing spectroscopy for testing chemical abundances, especially [N/O] enhancement

What are morphologies of larger scales (≳10 pc)?

Beyond Globular Clusters
Stellar Clumps and Disk



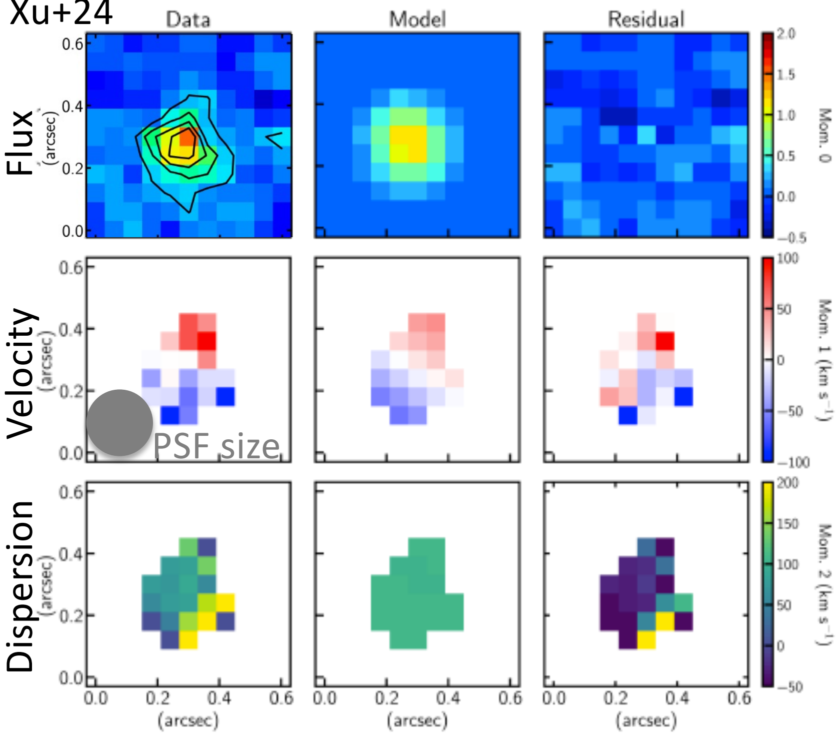


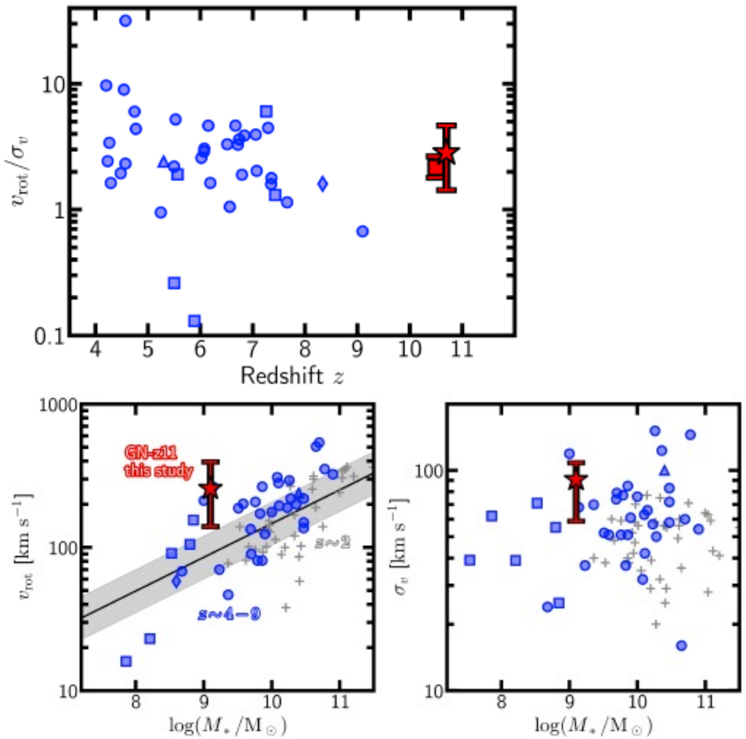
Fujimoto+24

- Cosmic Grapes: Lensed galaxy at z_{spec}=6.1 (μ~30; Fujimoto+24; see+ Mowla+24)
  - ≧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 an HeII clump (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. Needing deep/high-res data (+calib.) for a conclusion

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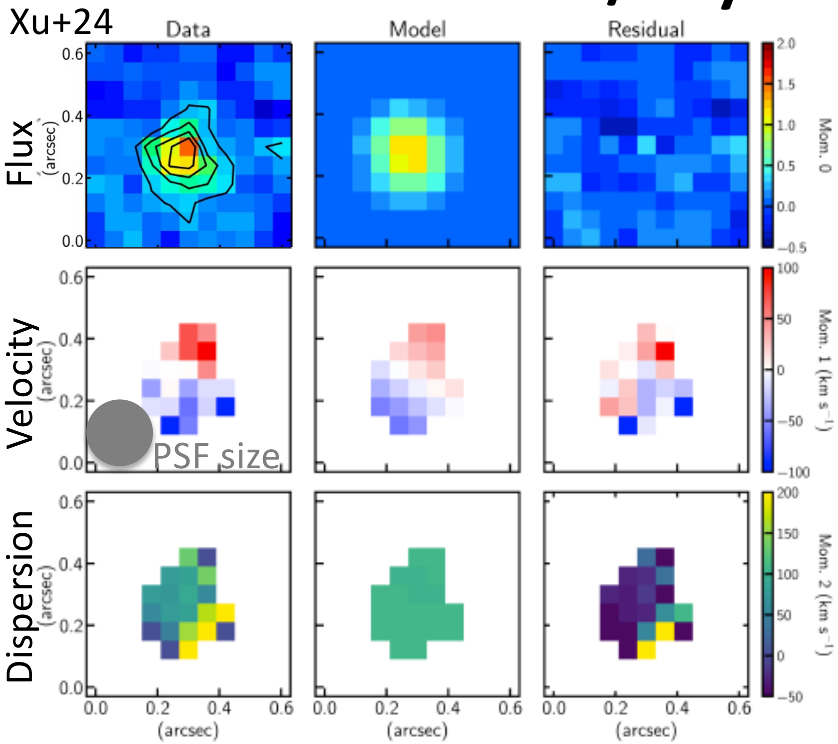

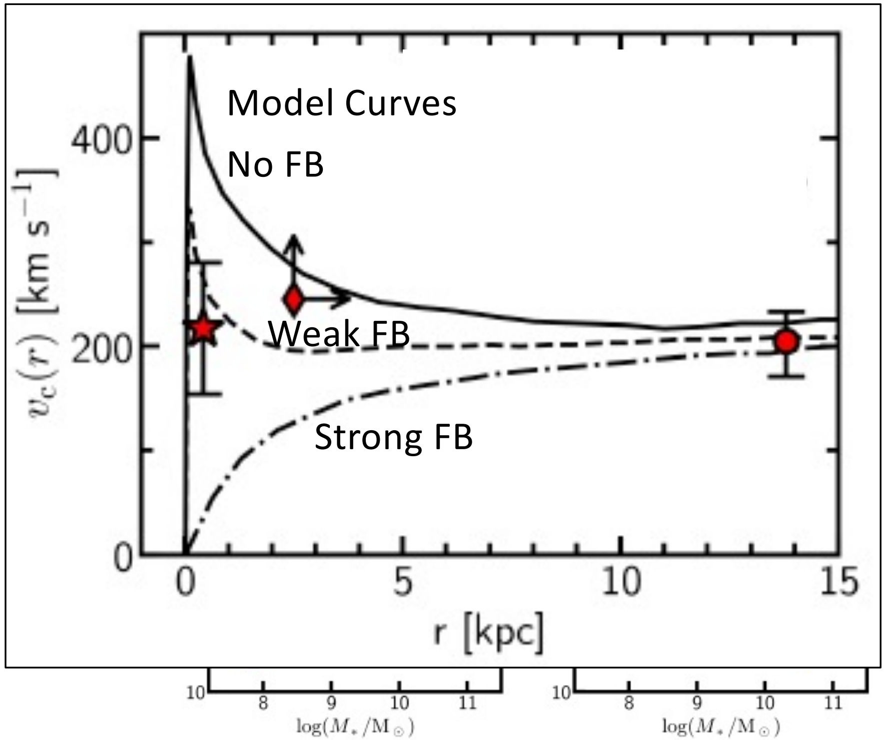

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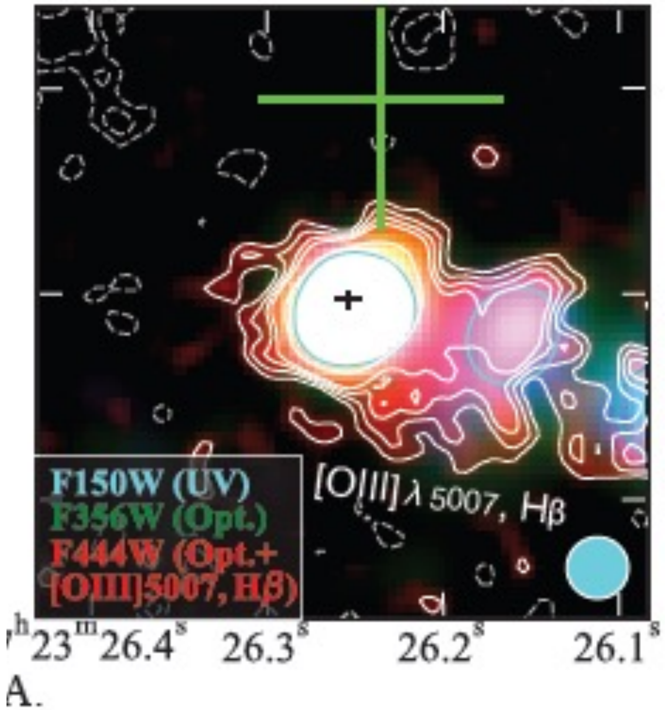
Weak Feedback? But Outflowing

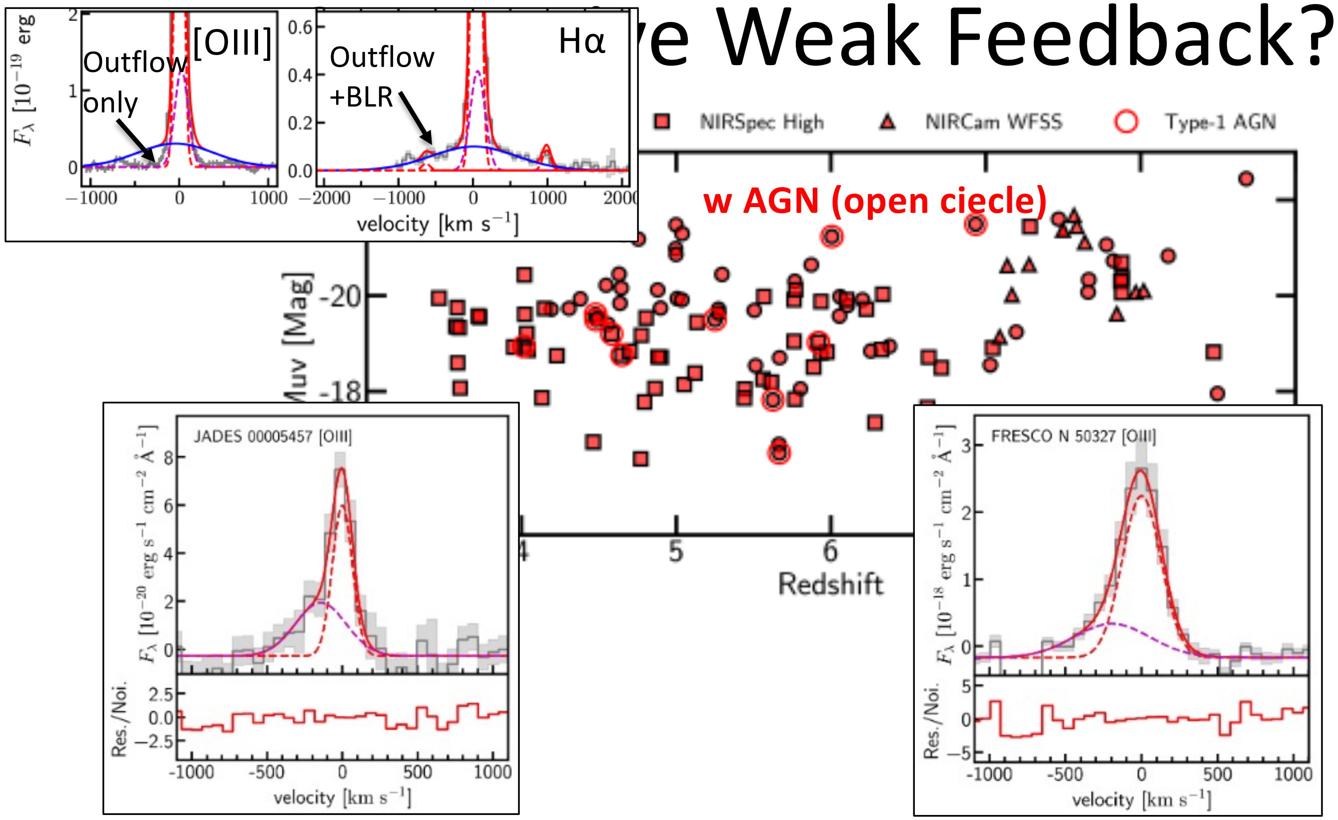
z=8.5 (ID4590)



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
e 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 $M^* \sim 10^9$Mo (see also Carniani+24)

  → Weak fountain outflows : Consistent w weak feedback?

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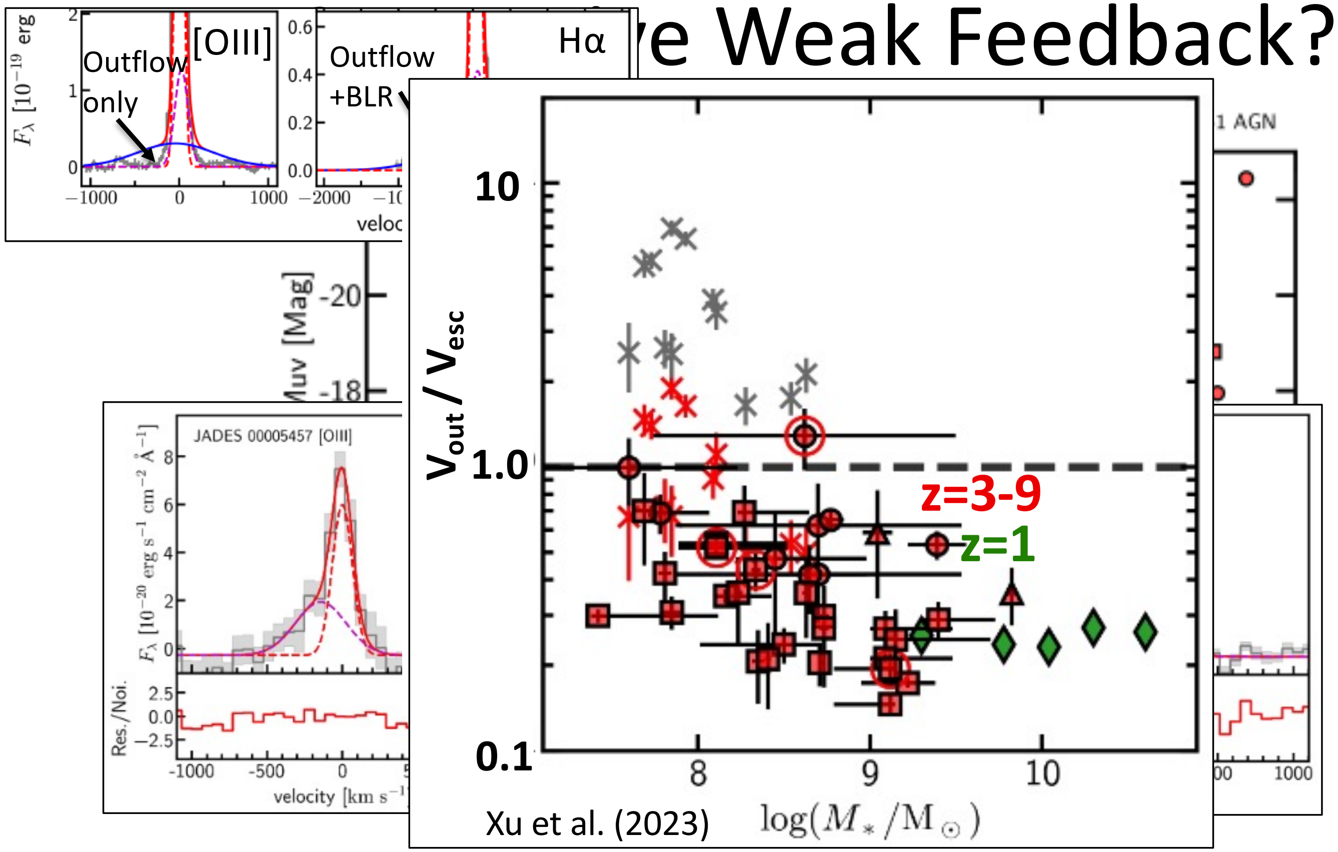

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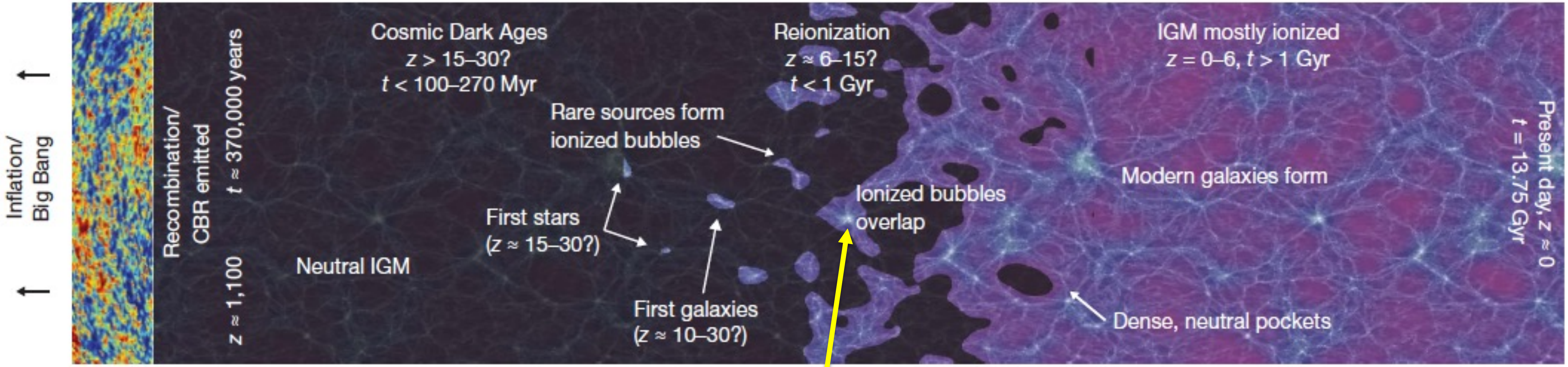
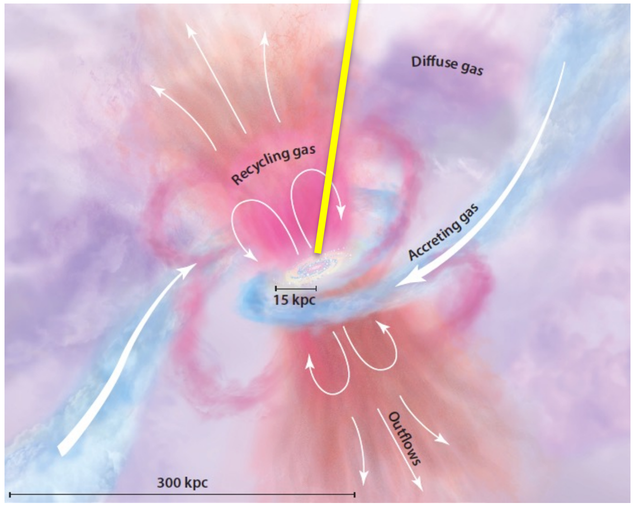
Galaxy-IGM Interaction: Radiation (beyond Gas)
Cosmic Reionization



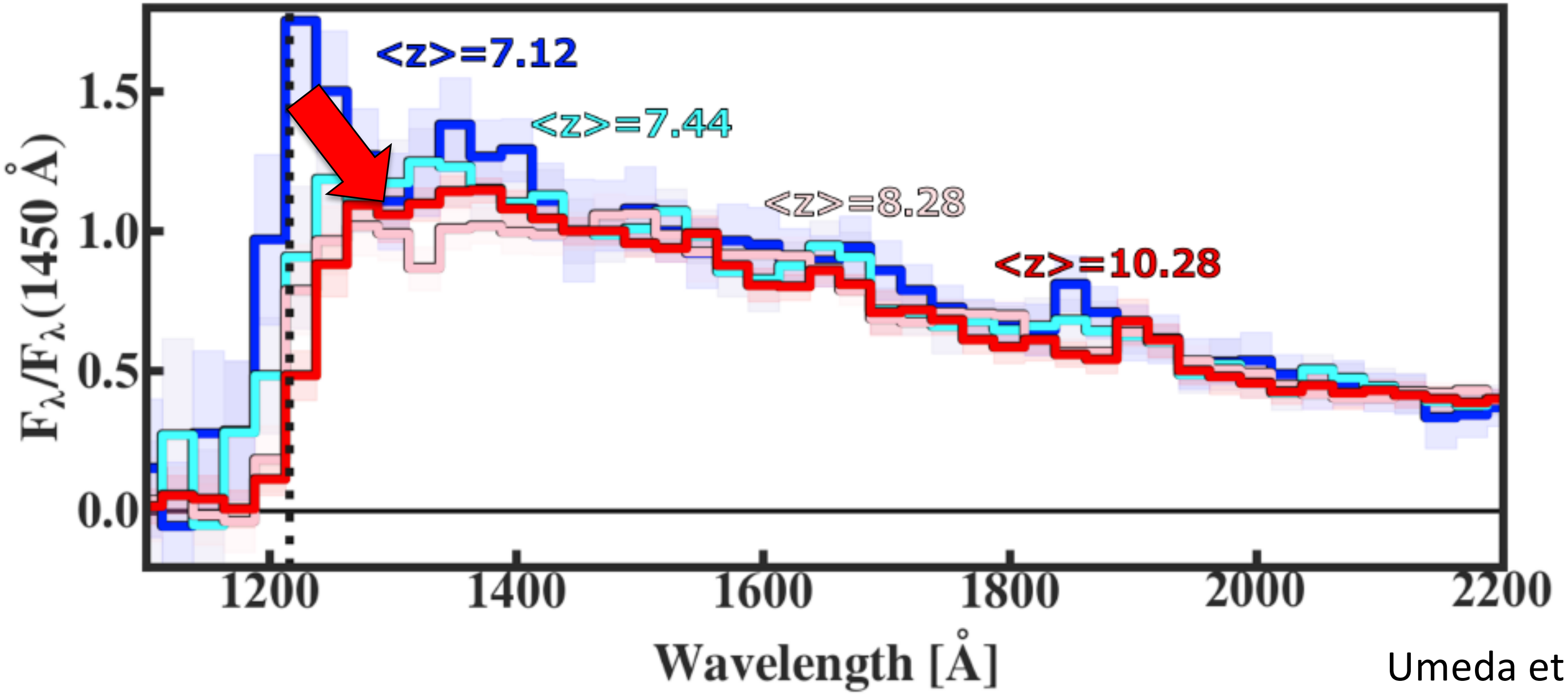
Robertson+10



Tumlinson+17

Evolution of Galaxy Spectra around Lyα

Hiroya Umeda



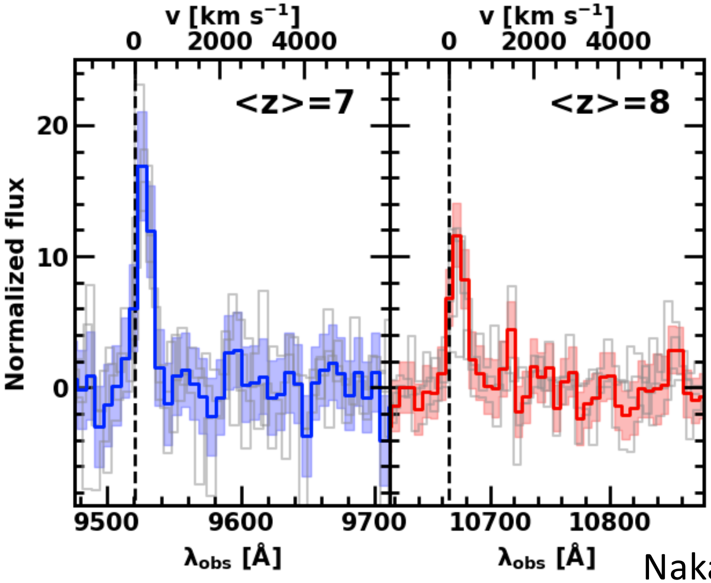
Umeda et al. (2024)

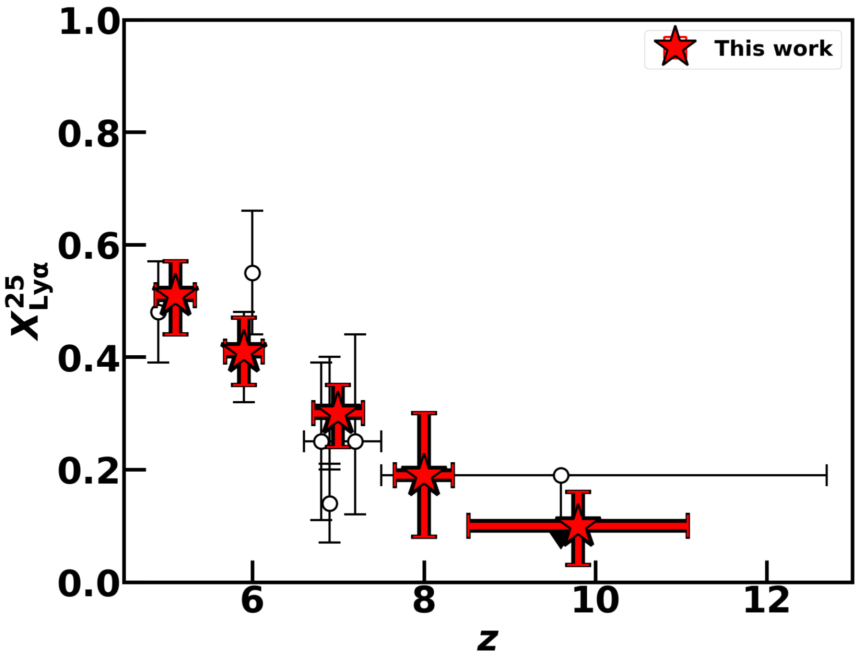
- Average spectra of galaxies at z=7-12 (JWST CEERS Finkelstein+23, JADES Bunker+23, GO, and DDT)
- Clear evolution around Lyα towards high-z
  - Weaker Lyα
  - Weaker UV continuum at ~1216A

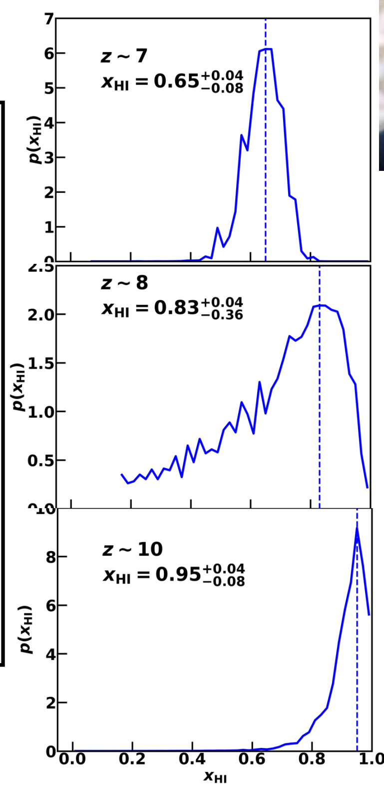
  →More Lyα damping wing (DW) absorption given by increasing neutral hydrogen at higher redshift
- Lyα emission/UV cont. abs.(e.g.Curtis-Lake+23,Hsiao+23,Umeda+24, Heintz+23/+24,Nakane+24,Tang+2

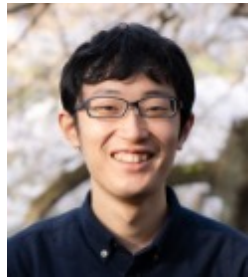
Evaluating Lyα Emission Evolution

Minami Nakane









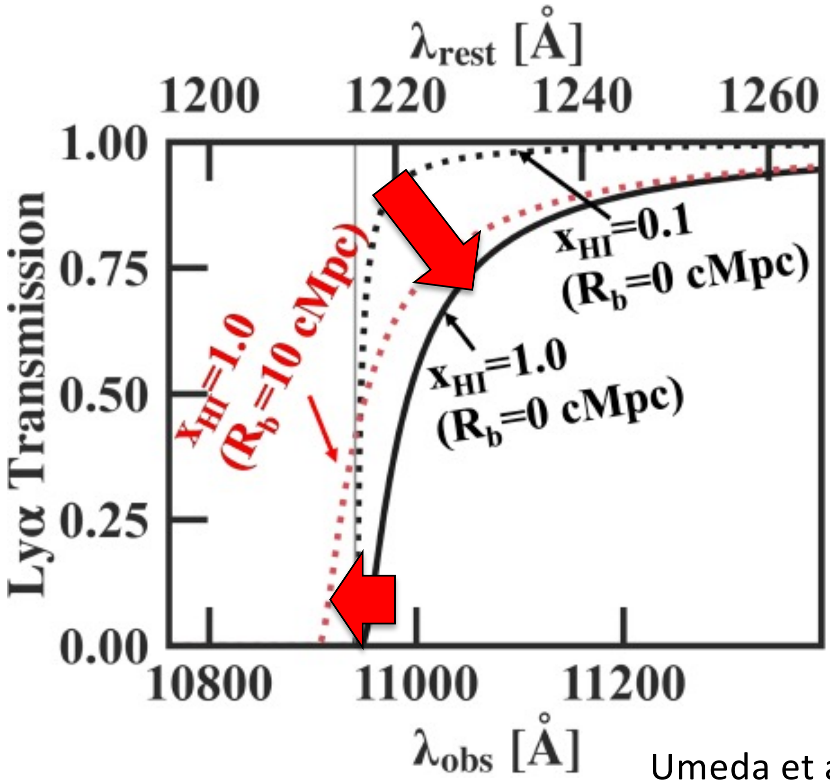
Yuta Kageura

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



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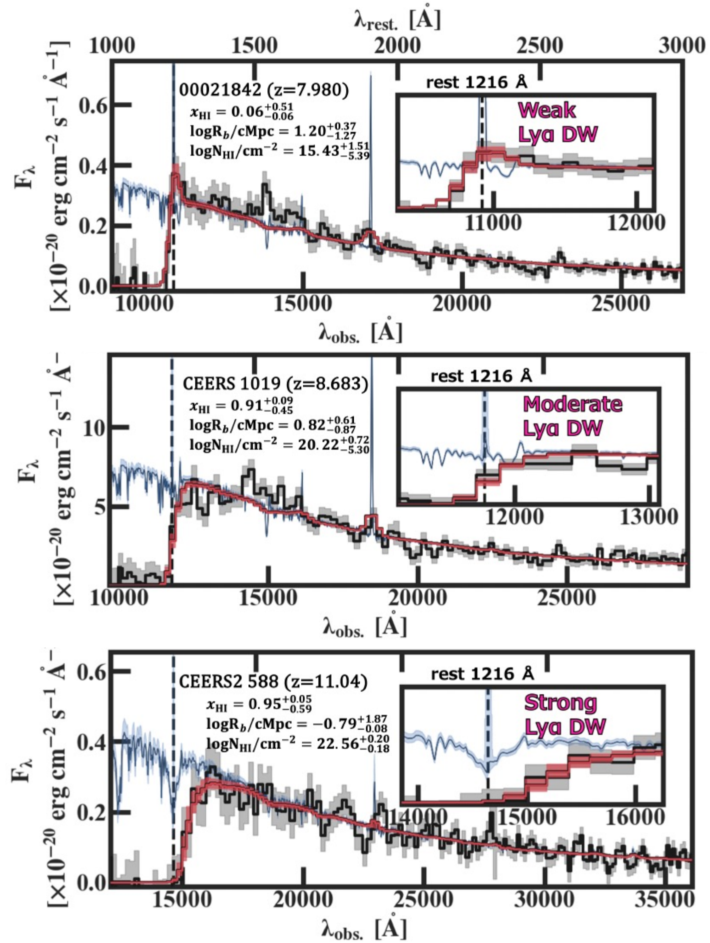
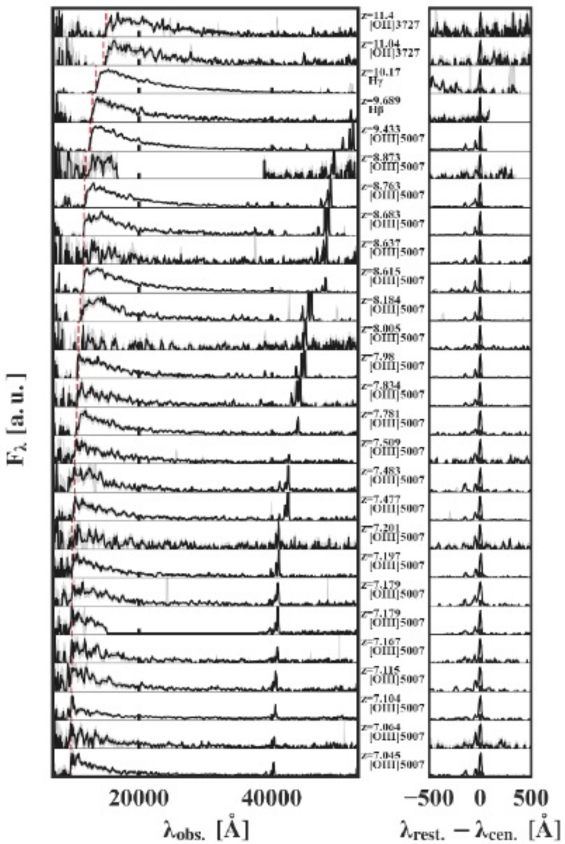
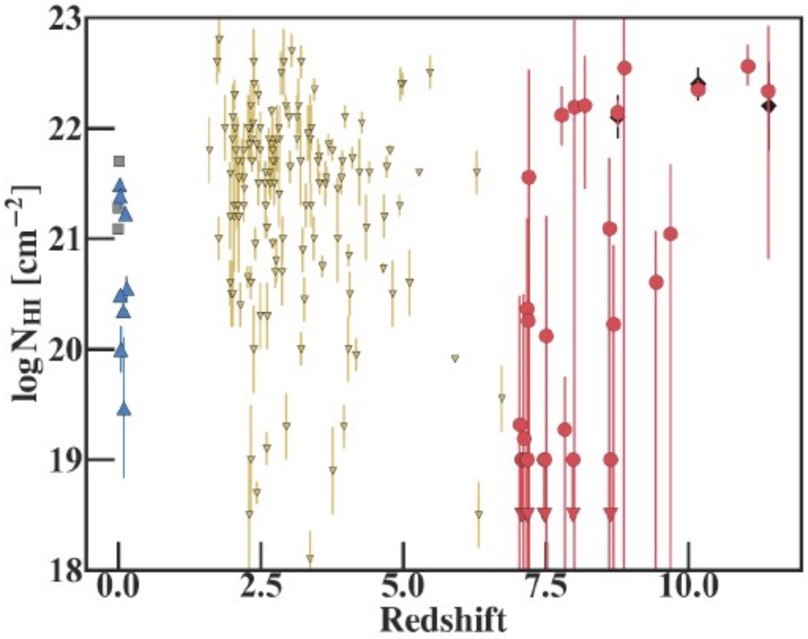


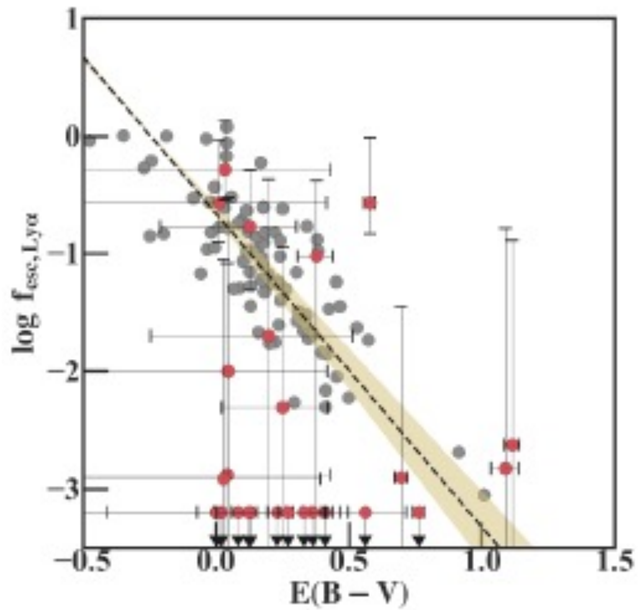
Hiroya Umeda

- 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
- Spectral resolution effects? → Confirming consistent results between high and low resolutions within the errors

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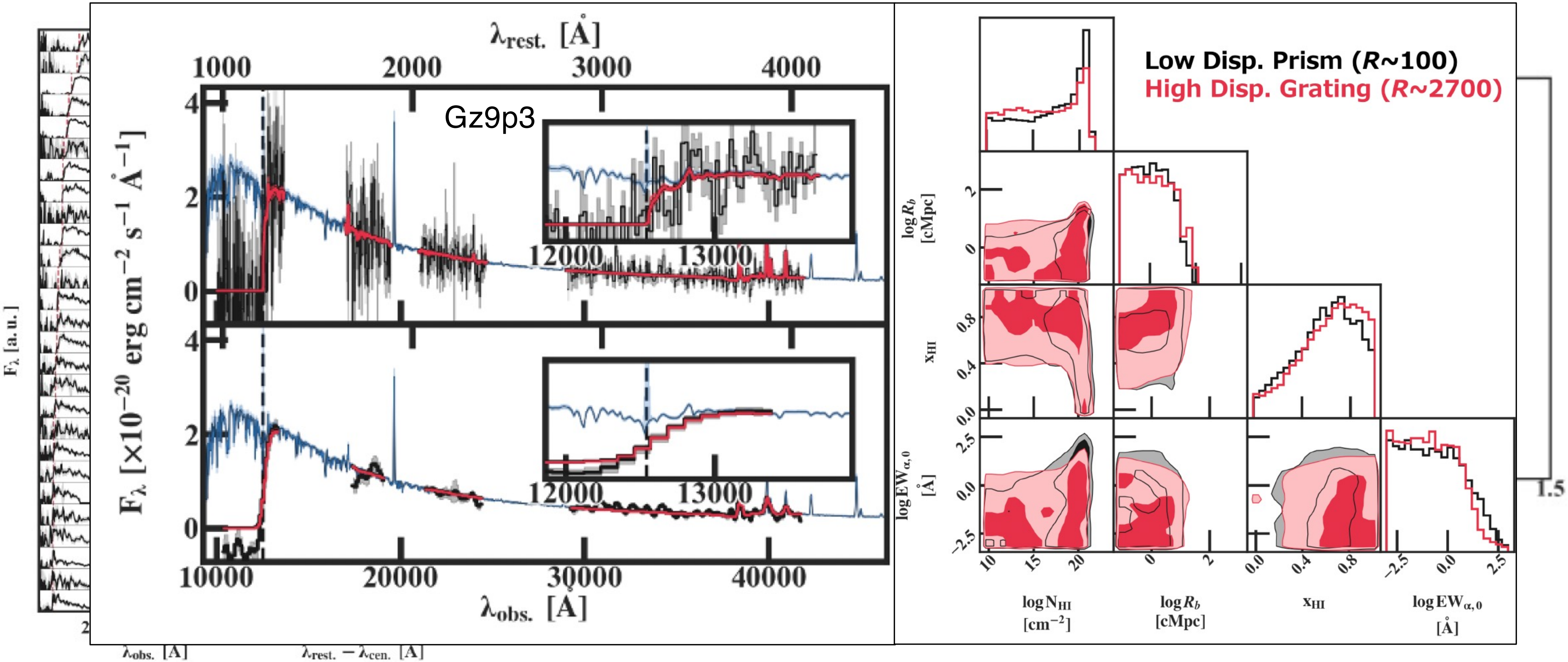

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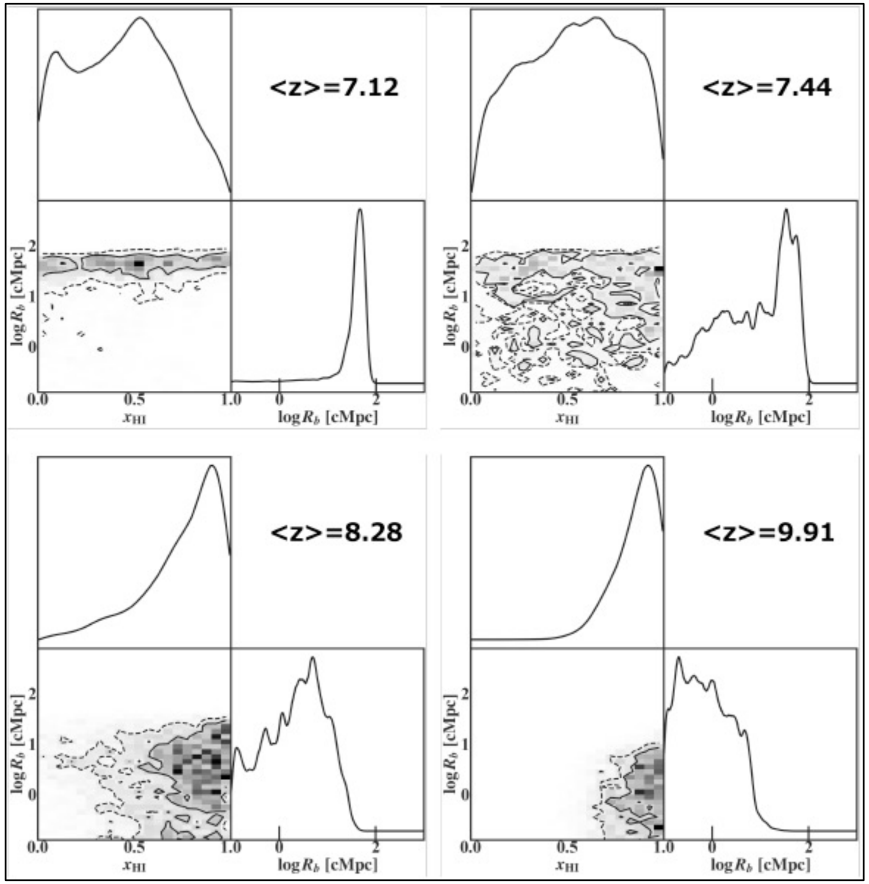
x_{HI} and Ionized Bubble Radius

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.)

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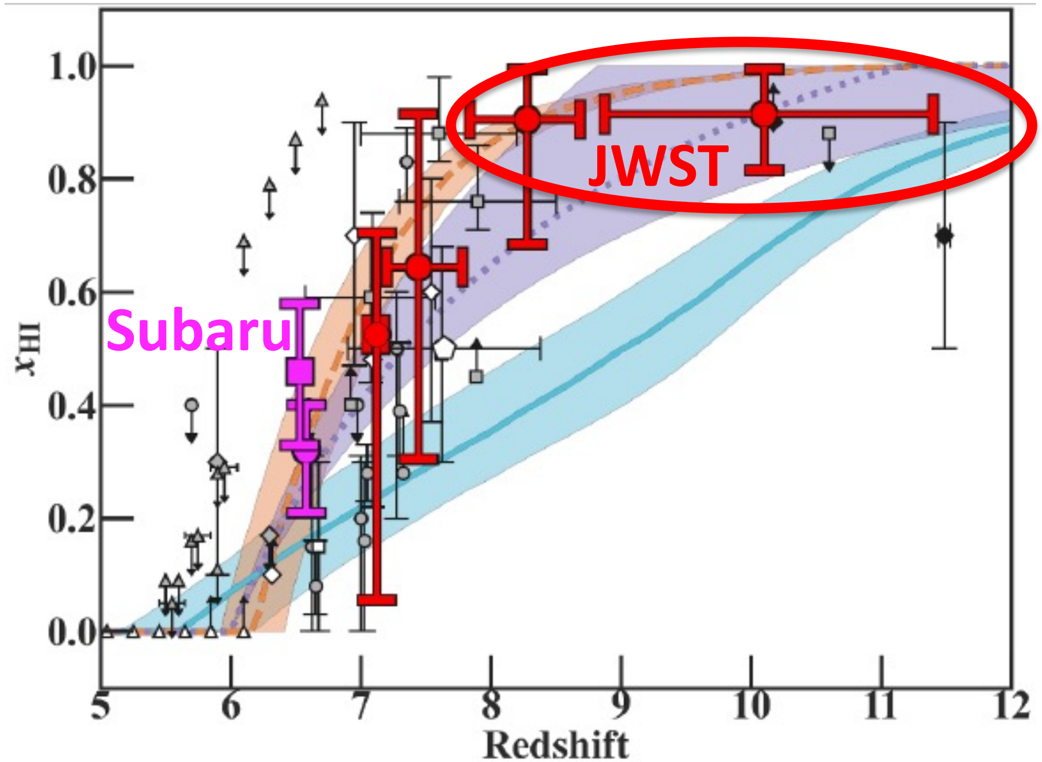

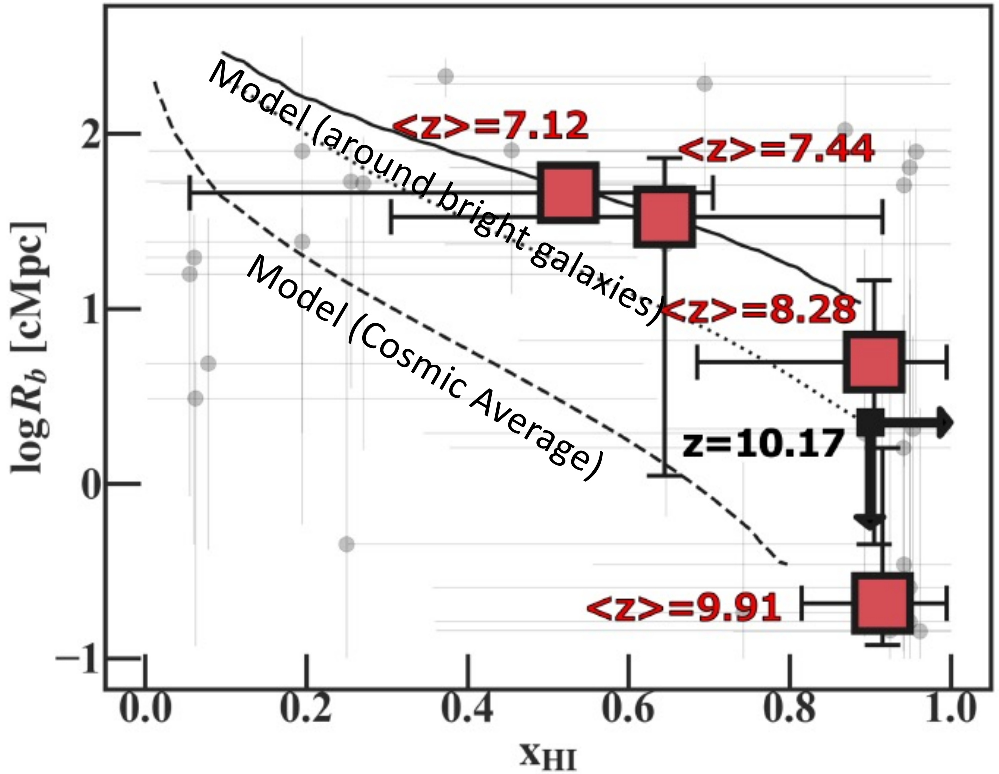

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Summary

Early galaxy formation probed by high-resolution/sensitivity JWST observations

- Early star/galaxy formation
  - Massive galaxies w spec redshifts: So far no clear violation of ΛCDM, but abundant overluminous galaxies
  - Many suggestions: Efficient SF, hidden AGN, top-heavy IMF (w Pop-III), bursty SF, Attenuation free, or flaw in cosmology
  - GS-z14-0: Spatially-extended bright galaxy at $z=14.2$

- Chemical 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? (GC problem: N/O-O/Fe)

- Morphology and dynamics
  - Stellar clumps with $M^*\sim10^6$Mo and $r_e\sim1$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 $M^*\sim10^9$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: $x_{HI}\sim0.9$ at $z\gtrsim8$. Major x_{HI} evolution at $z\lesssim8$ (Late reionization)
  - Suggestion of ionized bubbles larger than expectation?