Chasing the Reionizers of the Universe: Lyman Continuum Radiation with Hubble and the potential of Webb

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

& the HST ALCATRAZ, UVCANDELS & JWST PEARLS teams: incl. B. Smith, A. Blanche, S. Cohen, R. Jansen, T. McCabe, C. Redshaw, H. Teplitz, X. Wang, A. Alavi, A. Grazian, V. Mehta, M. Rafelski, S. Scarlata, J. Summers, R. O'Brien, S. Tompkins, T. Carleton, C. Conselice, J. Diego, S. Driver, H. Yan, J. Berkheimer, D. Coe, B. Frye, N. Grogin, W. Keel, A. Koekemoer, M. Marshall, N. Pirzkal, A. Robotham, R. Ryan Jr., C. Willmer, M. Dijkstra, A. Inoue, L. Jiang, J. MacKenty, R. O'Connell, J. Silk et al.

Plenary review at the North Carolina Astronomers Meeting

Saturday Sept. 23, 2023; Guilford Technical Community College; Jamestown, North Carolina

Outline

(1) The Power of Space- and Ground-based LyC Spectroscopy

(2) Lyman Continuum (LyC; $\lesssim$912 Å) constraints from HST WFC3/UVIS

(3) The Promise and Power of JWST for LyC constraints at High Redshift

(4) Summary and Conclusions:

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(2) Lyman Continuum (LyC; $\lesssim$912 Å) constraints from HST WFC3/UVIS

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(4) Summary and Conclusions:

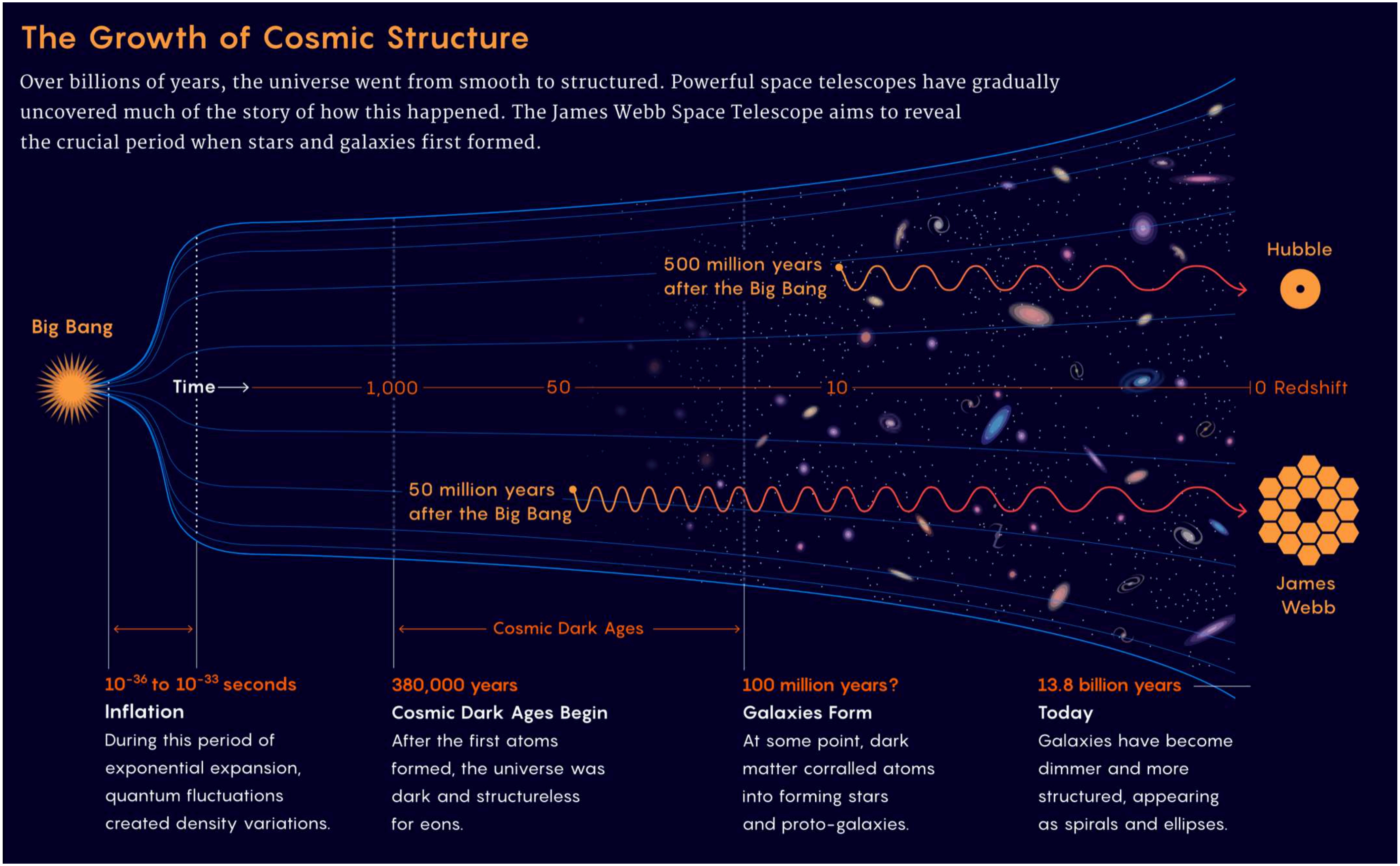
- (Faint) Galaxies: Smaller ISM holes, somewhat lower f_{esc}-fraction.

- (Weak) AGN: Bigger ISM holes, higher f_{esc} & dominate at z$\sim$2–3.

Sponsored by NASA/HST & JWST

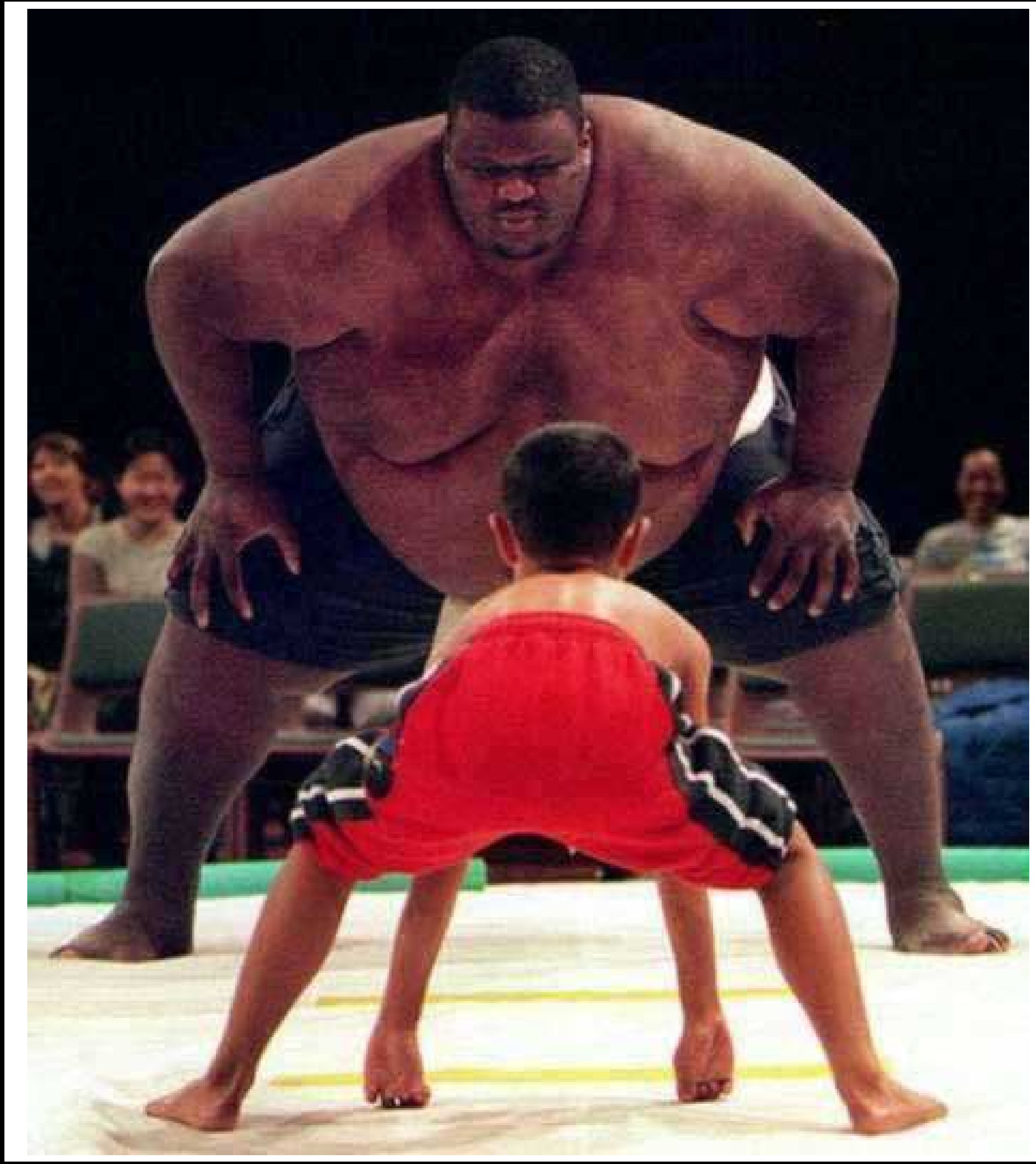
Arizona State University

Talk is on: http://www.asu.edu/clas/hst/www/jwst/jwsttalks/nc23_guilfordTCC_lyc_sciencetalk.pdf



Cosmic Reionization: What caused the Universe's last major phase transition?:

- UV-light, but from Active Galactic Nuclei (AGN) and/or (dwarf) galaxies?



At the end of reionization, it seems dwarfs had beaten the Giants, but ...

Hubble & Webb are telling us that Giants (AGN) outdid the dwarf (galaxies) ...

The Smoking Guns of Cosmic Reionization: Galaxies and (weak) AGN

Bronze "Falcon" gun in Heraklion's Historical Museum:

Venetian fortress Spinalonga in Elounda, Crete:

- LyC is very hard to measure directly, so I reserve the right to speculate!
- My theory will be simple: big Galactic fortresses with small holes!

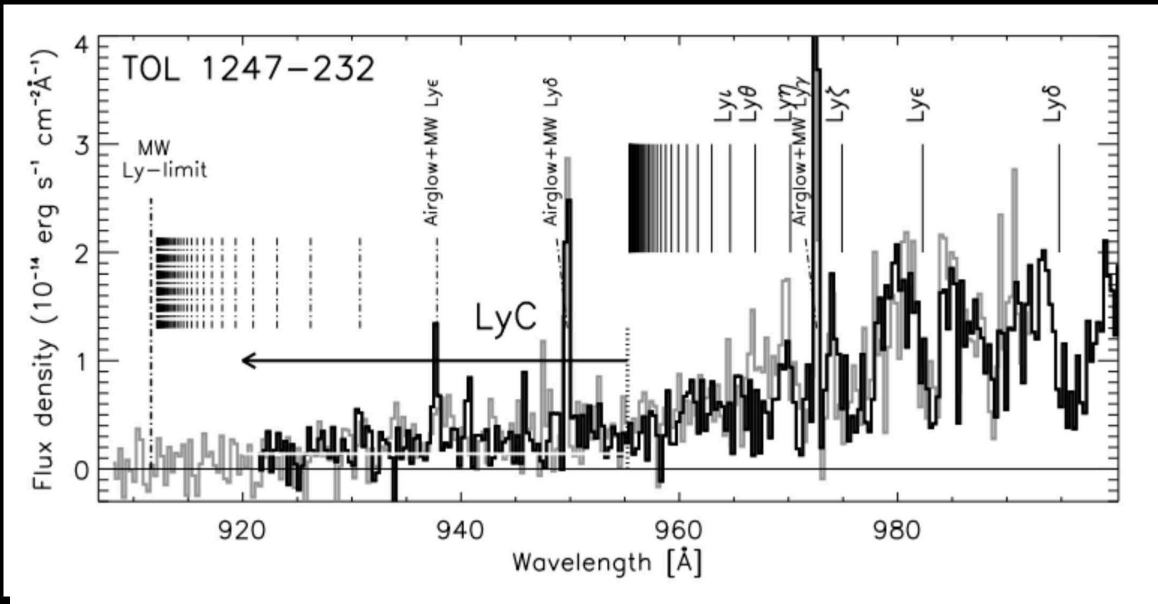
The Smoking Guns of Cosmic Reionization: Galaxies and (weak) AGN

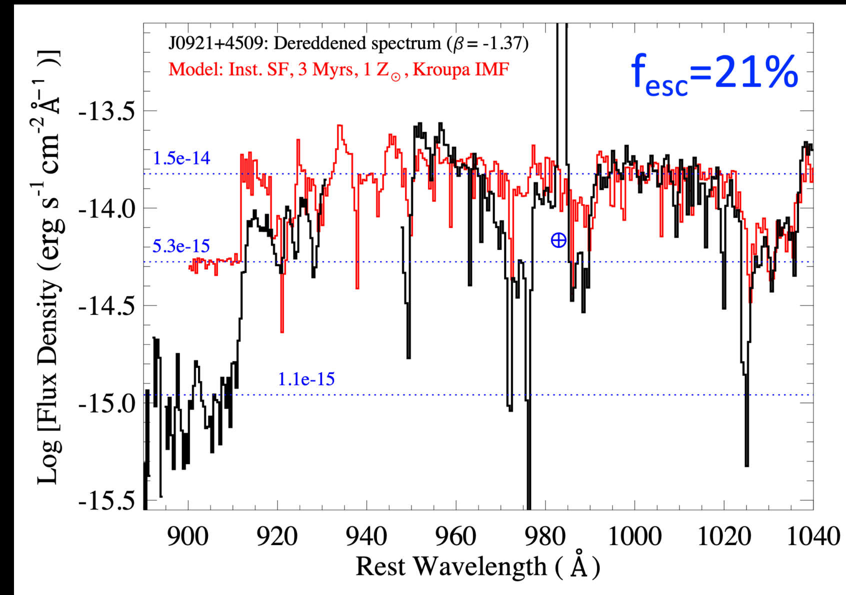
Bronze "Falcon" gun in Heraklion's Historical Museum: • Active Galactic Nuclei (AGN) contribute LyC through powerful outflows.

Venetian fortress Spinalonga in Elounda, Crete: • (Dwarf) Galaxies contribute LyC flux through small holes in their ISM.

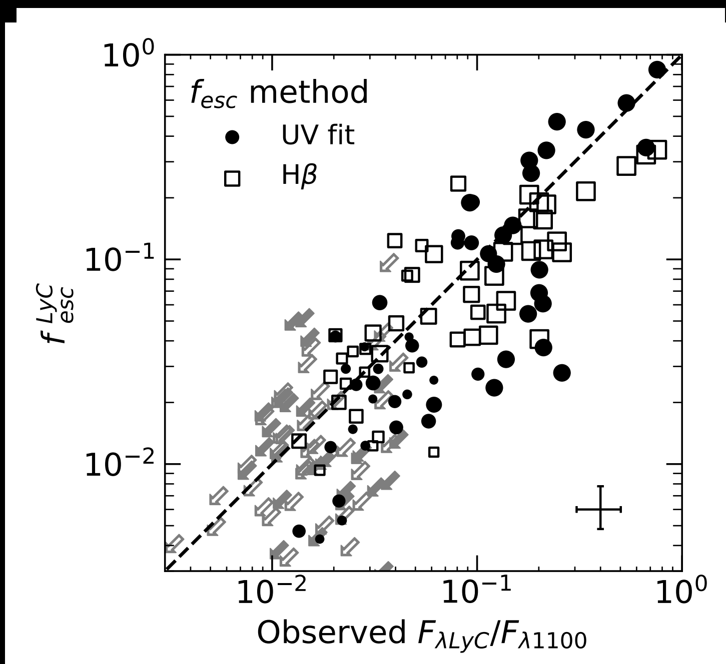
- Key question in reionization is: What is the LyC escape fraction f_{esc}?
- f_{esc} = fraction of emitted LyC light that escapes AGN or (dwarf) galaxy.

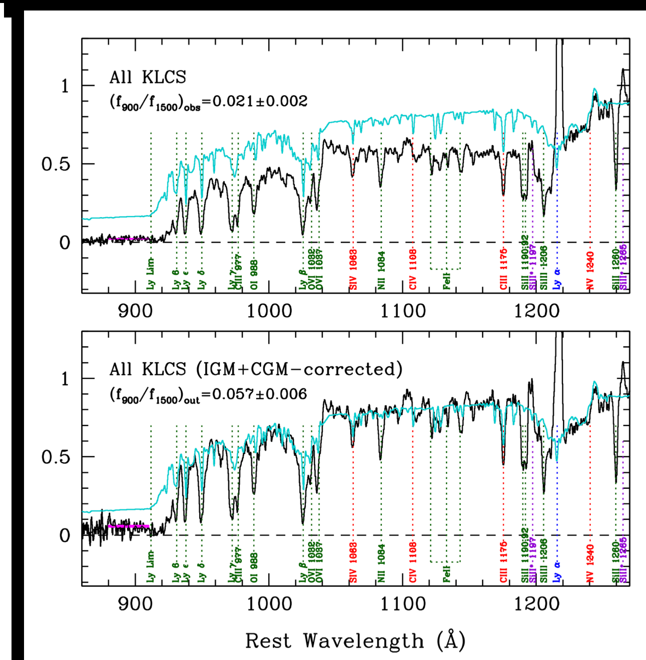
(1) The Power of Space- and Ground-based LyC Spectroscopy





Low-z LyC: FUSE f_{esc}≃1.4–2.4% z≳0.02 (Leitet+13; Left) — COS f_{esc}≃21% z=0.235 (Borthakur+14; Right)

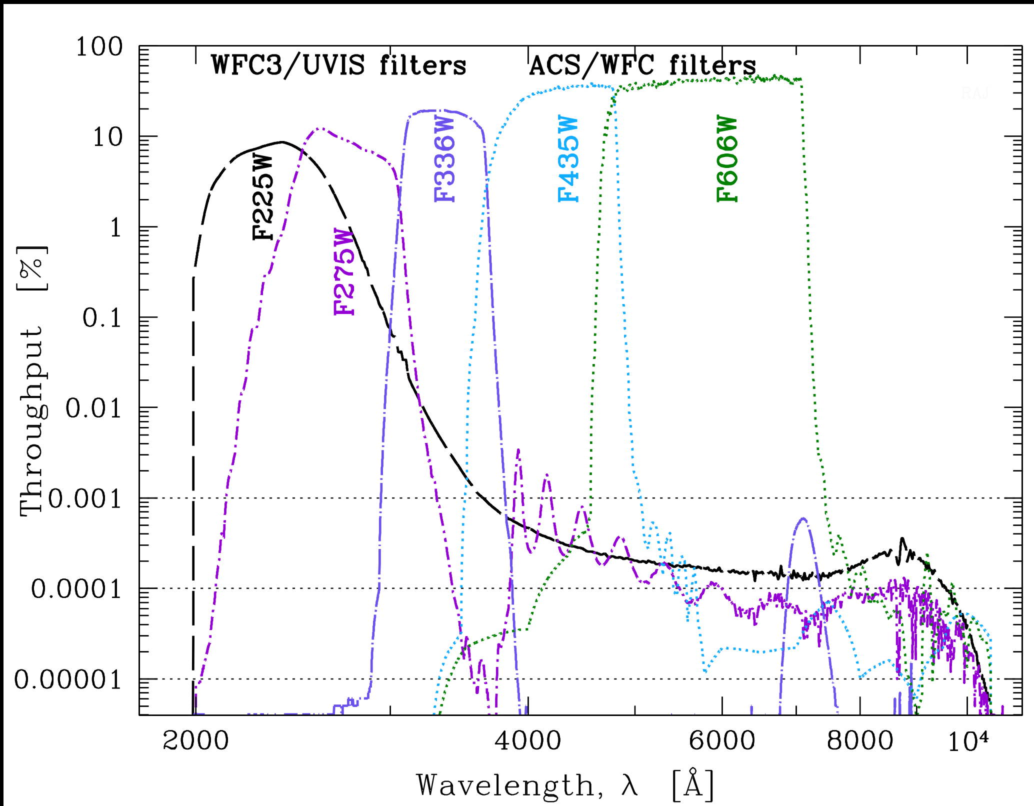


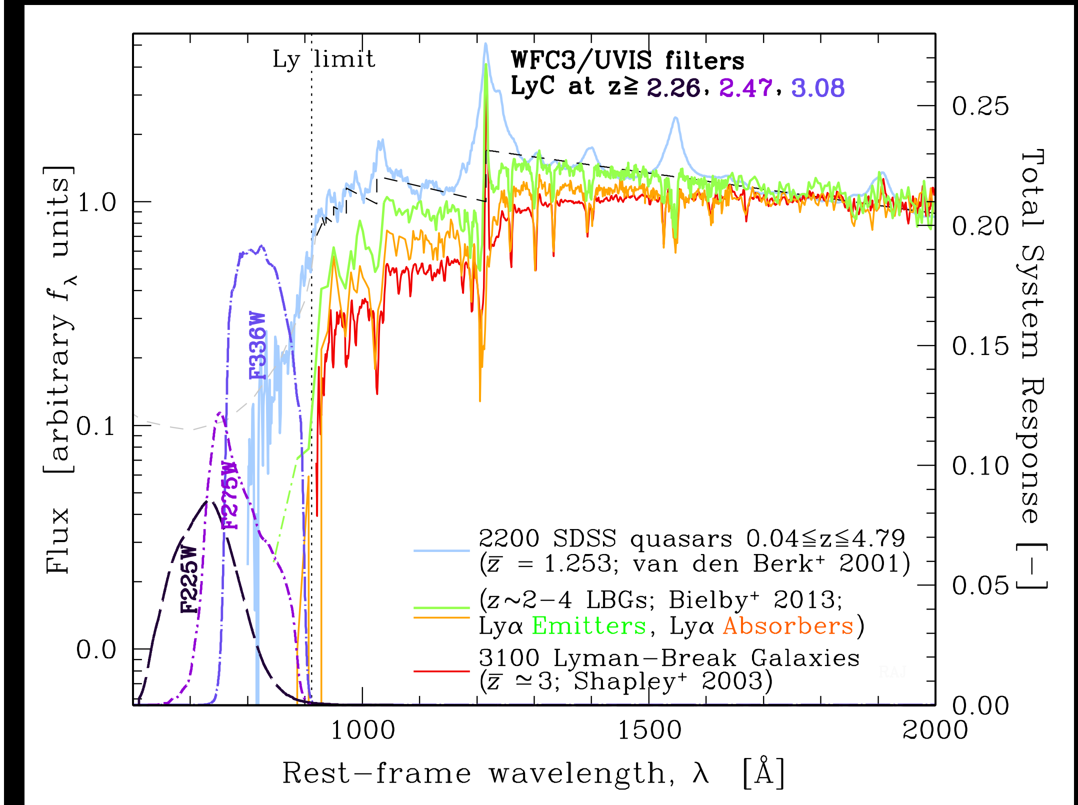


LyC samples: COS f_{esc}≃5–50% at z≃0.2–0.4 (Flury+22) — Keck f_{esc}≃6–9% at z≃3.05 (Steidel+18)

- Advantage: Spectral accuracy at λ≲912 Å; Disadvantage: Contamination uncertain and limited z-range.

(2) HST WFC3/UVIS Constraints of LyC at z∼2.3–3.5.





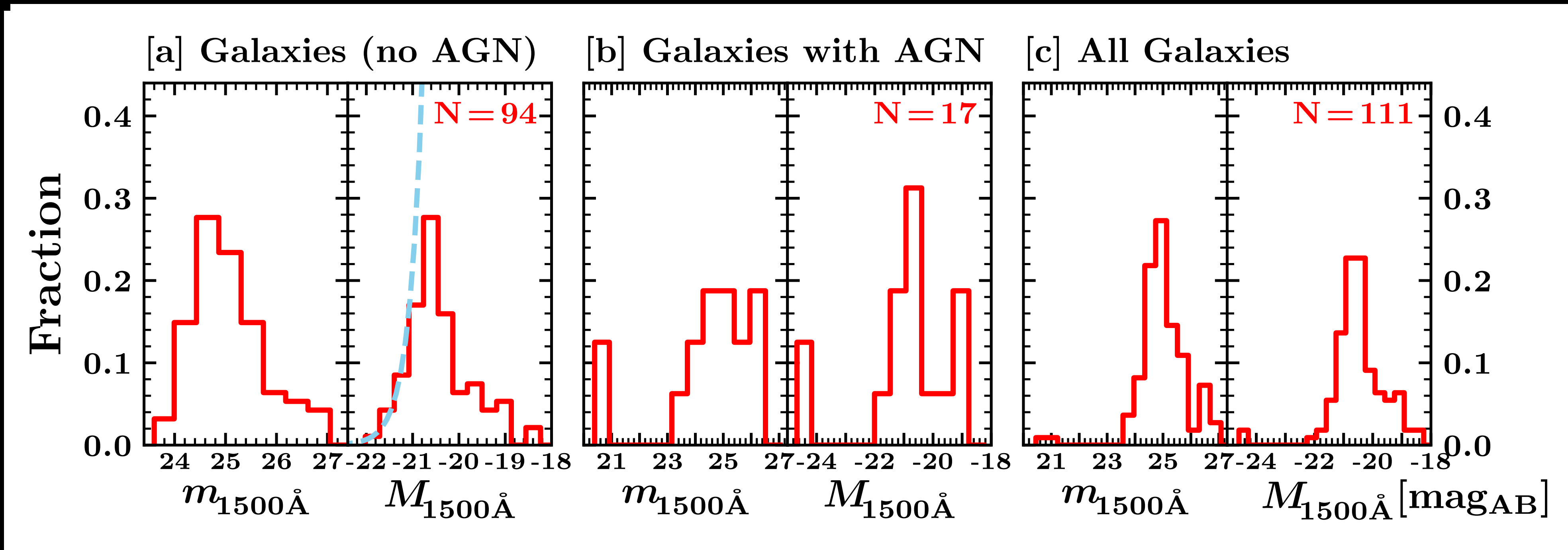
[Left] WFC3 designed to maximize throughput and minimize red-leak:

- Red-leaks $\lesssim 3\times10^{-5}$ of peak transmission, or $\lesssim$0.5% of LyC signals.

[Right] Composite rest-frame far-UV spectra of: SDSS QSOs at z≃1.3; LBGs at z≃2–4: Lyα emitters, & absorbers; & LBGs at z≃3.

- WFC3/UVIS F225W, F275W, F336W filters sample LyC (λ<912Å) at z≥2.26, z≥2.47, and z≥3.08 (best at low-end of each z-range).
- Lower z-bounds: *no* $\lambda>$ 912 Å below filter's red-edge (≡0.5% of peak).

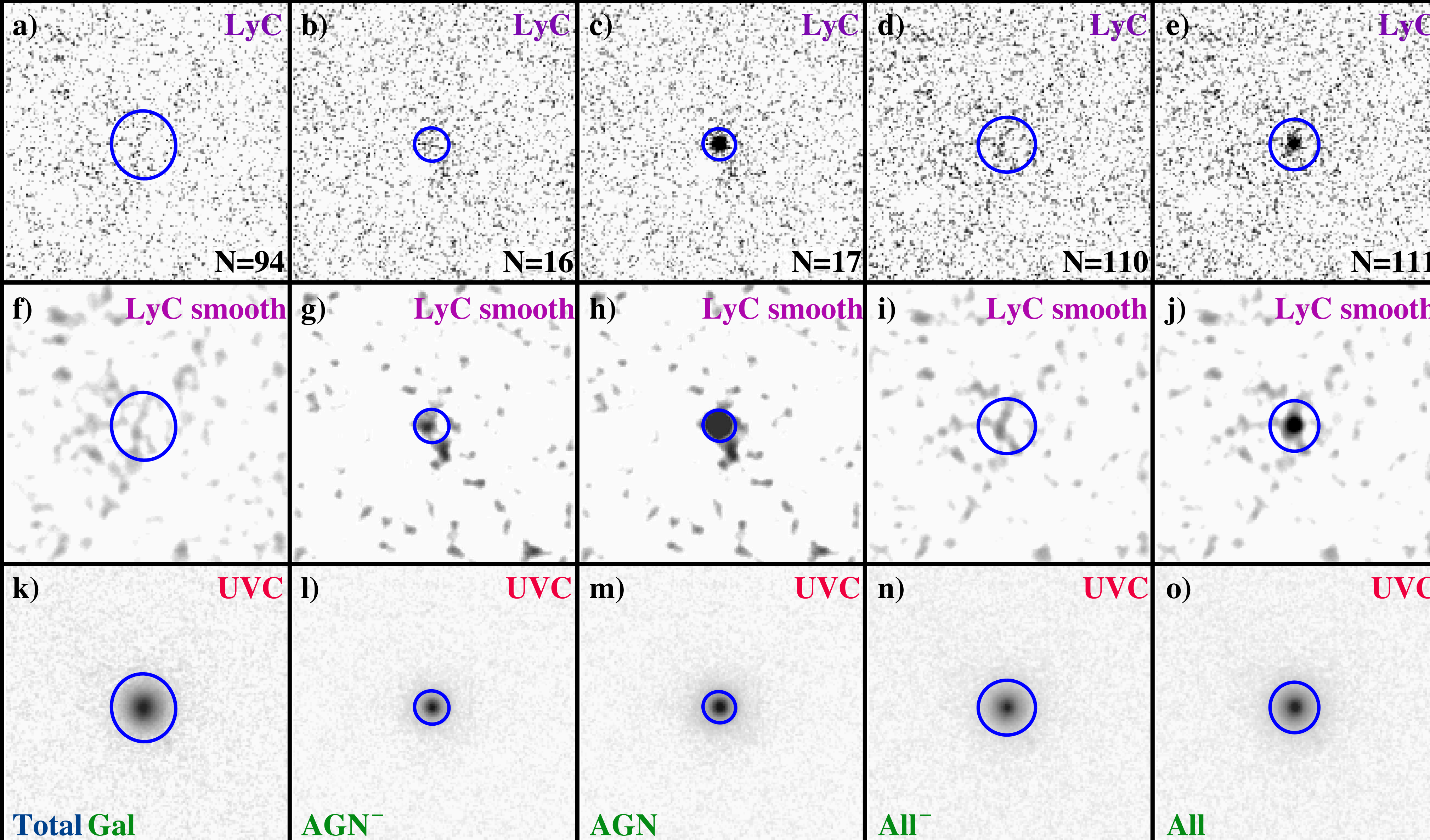
(2) Hubble WFC3 — Selection of Reliable Spectroscopic Samples



Apparent and absolute magnitude distributions (restframe 1550Å) of the "Gold" (>99% reliable z_{spec}) galaxy & weak AGN (em. line) samples.

(Smith et al. 2018, ApJ, 853, 191; Smith et al. 2020, ApJ, 897, 41):

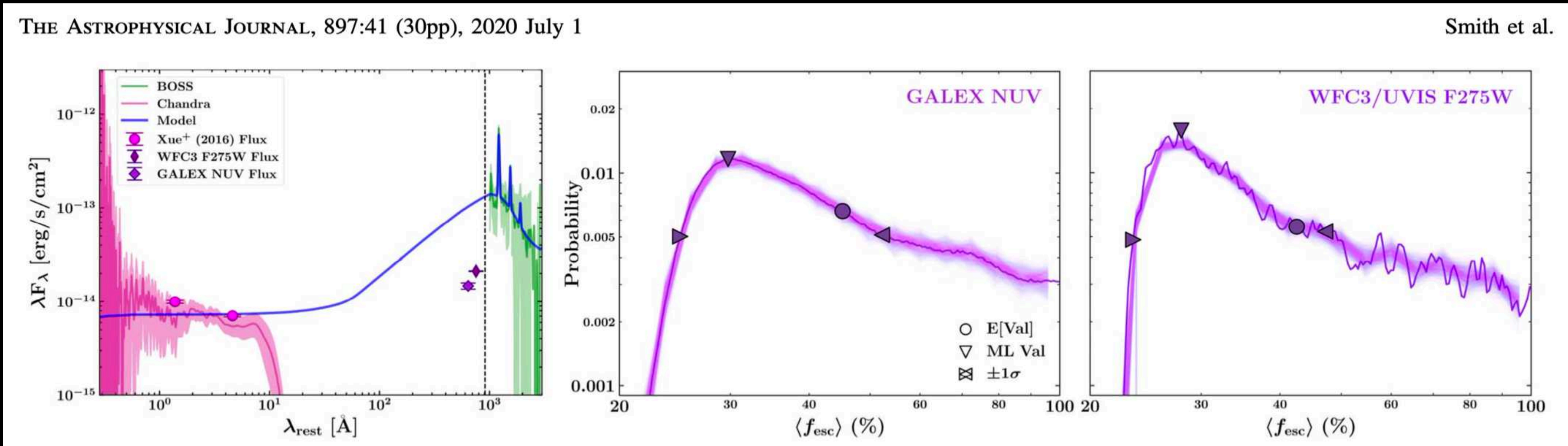
- Blue dotted: faint-end slope of gal counts & LF (Windhorst^{+} 2011, ApJ, 193, 27).
- Sample incompleteness for AB$\gtrsim$24.5-25, or M_{AB} (1650)$\gtrsim$–20.5 mag.
- LyC AB-fluxes & f_{esc}-values only valid for these selected luminosities.
- Galaxies with weak AGN have same N(M_{AB}) as galaxies without AGN.



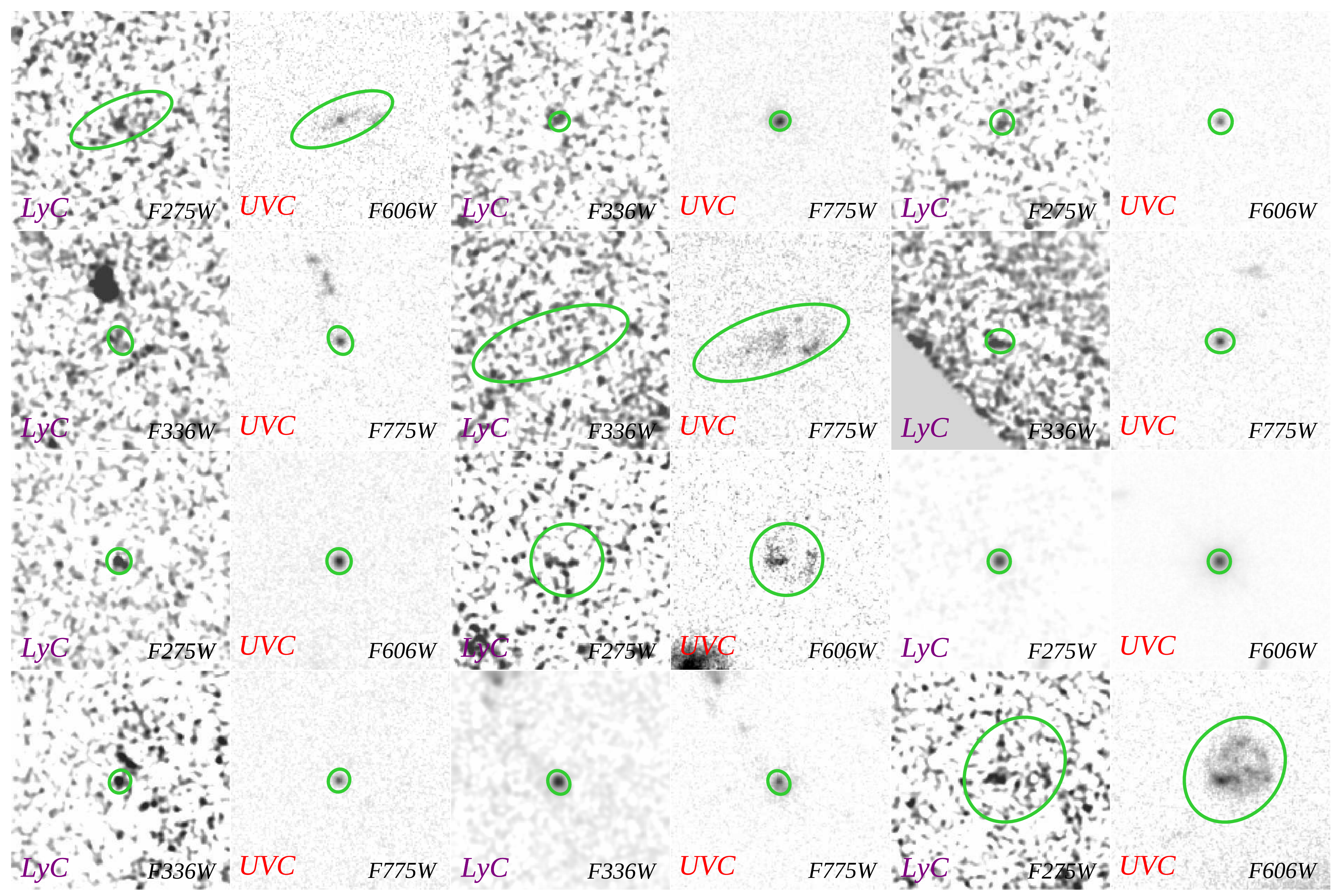
WFC3/ERS & HDUV AGN+Galaxy LyC stacking (Smith et al. 2018, ApJ, 853, 191; — 2020, ApJ, 897, 41).

- Rare (weak) AGN with robust spectroscopic redshifts at z$\simeq$2.3–3.5 dominate reionizing LyC flux in stacked WFC3/UVIS images (AB$\lesssim$29 mag).

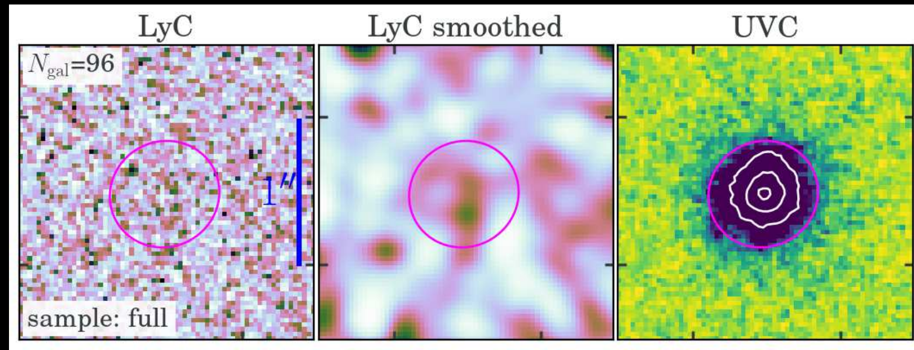
- Giants won: Need $\simeq$0$''$.04 WFC3 UV-PSF to remove all foreground interlopers at $>>$ 99% confidence!

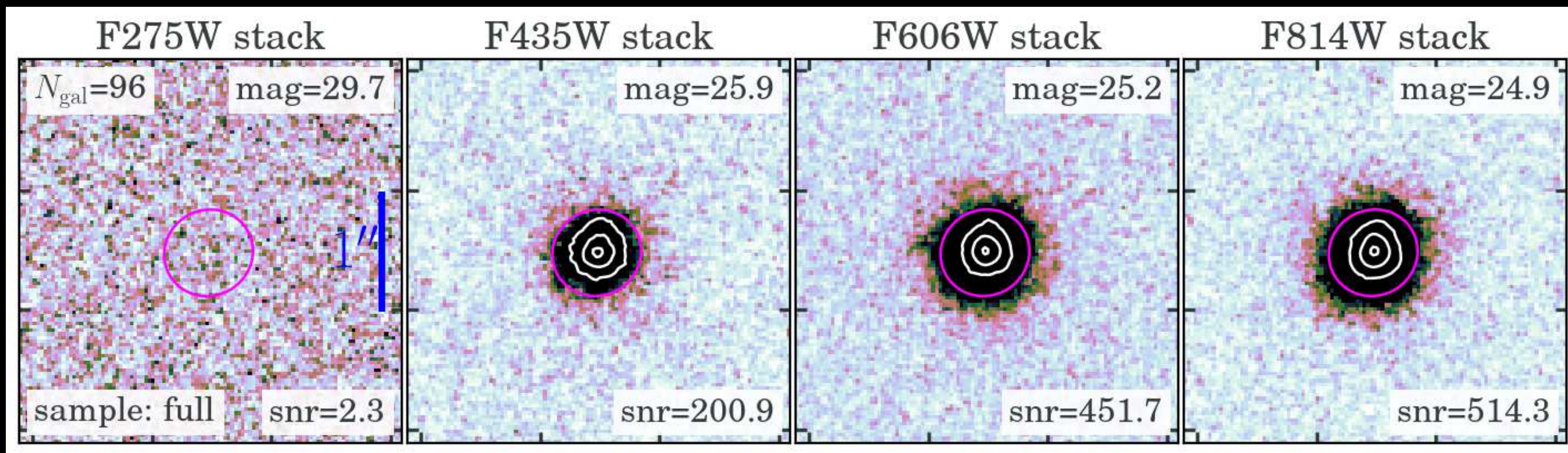


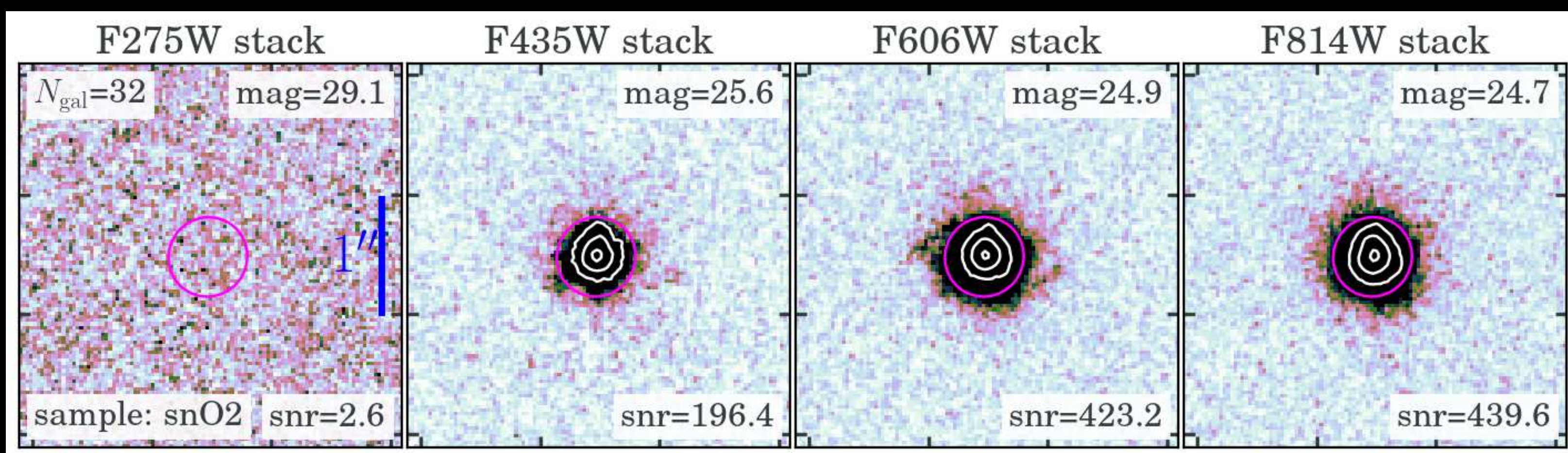
- CIGALE+XSpec SED fit to brightest LyC AGN at z=2.59 with Chandra X-ray spectrum (Smith, B. et al. 2020, ApJ, 897, 41):
- Accurate LyC escape fraction from HST & GALEX: $f_{esc}\simeq$28–30%.
- If these AGN representative, $f_{esc}\simeq$30% enough for Giants to win at z$\simeq$3!



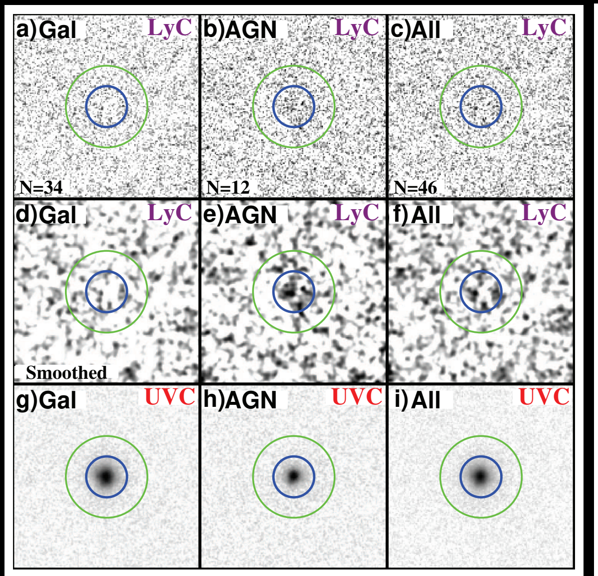
- UVCANDELS AGN LyC detections AB≃23.4–28.5 mag: f_{esc}≃30±25%.
- 12/58 detections (21%): <LyC opening angle>$\lesssim$40° (Smith, B. et al. 2023).

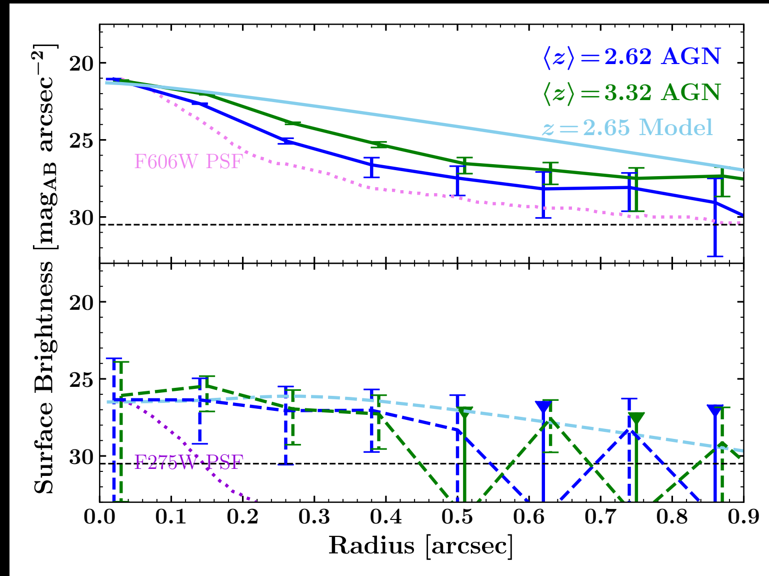


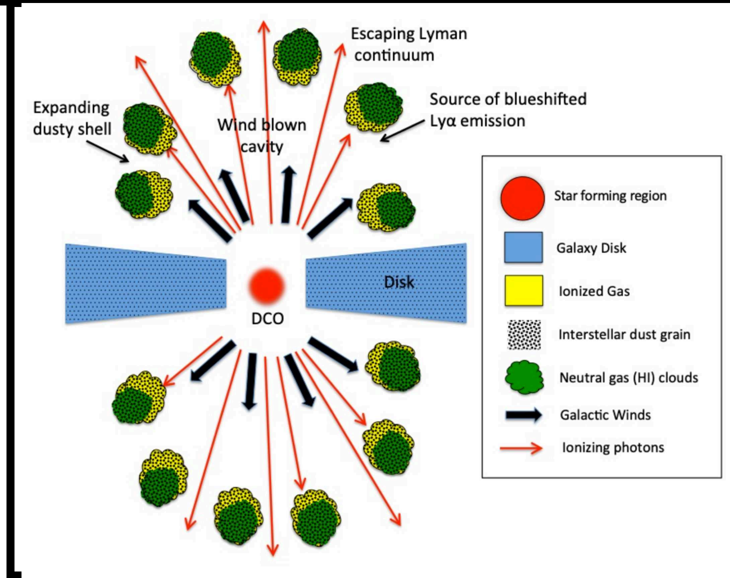




- UVCANDELS galaxy LyC detections AB$\simeq$25.5-26.6 mag, LyC stacks $\sim$29.1–29.7 mag; resulting f$_{esc}\simeq$6–10%. [1-cos($\boldsymbol{\theta_h}$)$\equiv$detected fraction]:
- 5/96 detections (5%): $<$LyC opening angle$>\lesssim$20° (Wang, Teplitz$^+$ 23, ApJ, subm.)







[*Left*]: WFC3 LyC stack of Gals, weak AGN and All, +non-ionizing UVC:

Clearly at z≃2.3-3.5, weak AGN dominate LyC flux!

[*Middle*]: Radial SB-profiles of stacked UVC [Top]; LyC stack [Bottom]:

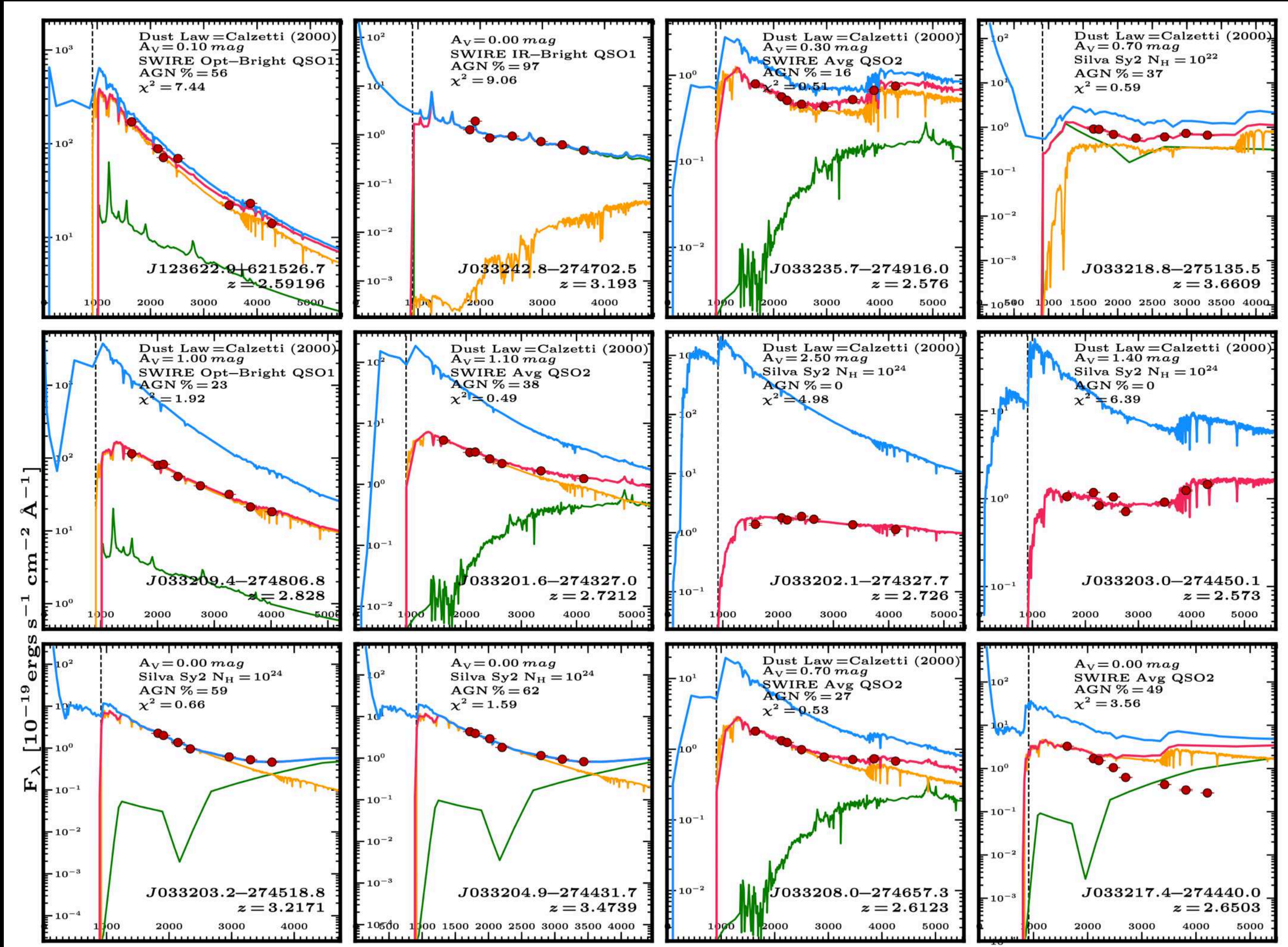
• LyC SB-profiles extended compared to PSFs, but very non-Sersic like!

Dashed: scattering model with ISM porosity+escaping LyC (Smith, B.+ 2018).

[*Right*]: Patchy ISM model of escaping LyC (& Lya) (Borthakur+14).

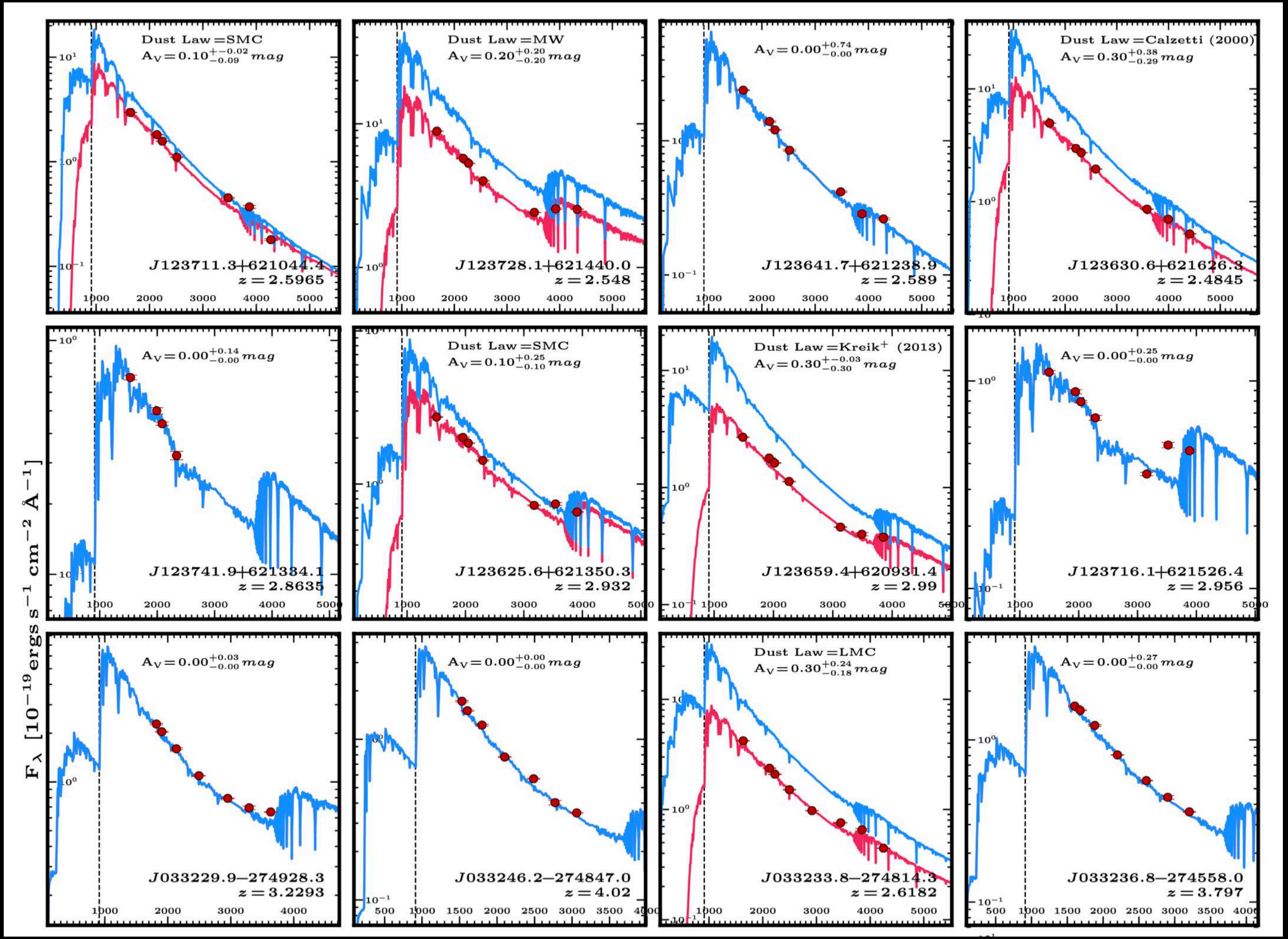
• WFC3 Galaxy and AGN <LyC opening angle>$\lesssim$20–40°, respectively.

• Weak AGN more/bigger holes than Gals; LyC not always from accretion disk



- AGN LyC stacking candidates with CIGALE+XSpec SED fits

(ALCATRAZ: Smith, B.+ 2020, ApJ, 897, 41; UVCANDELS: Smith, B., Wang, X., Teplitz, H.+ 2023).



- Galaxy LyC stacking candidates with CIGALE SED fits

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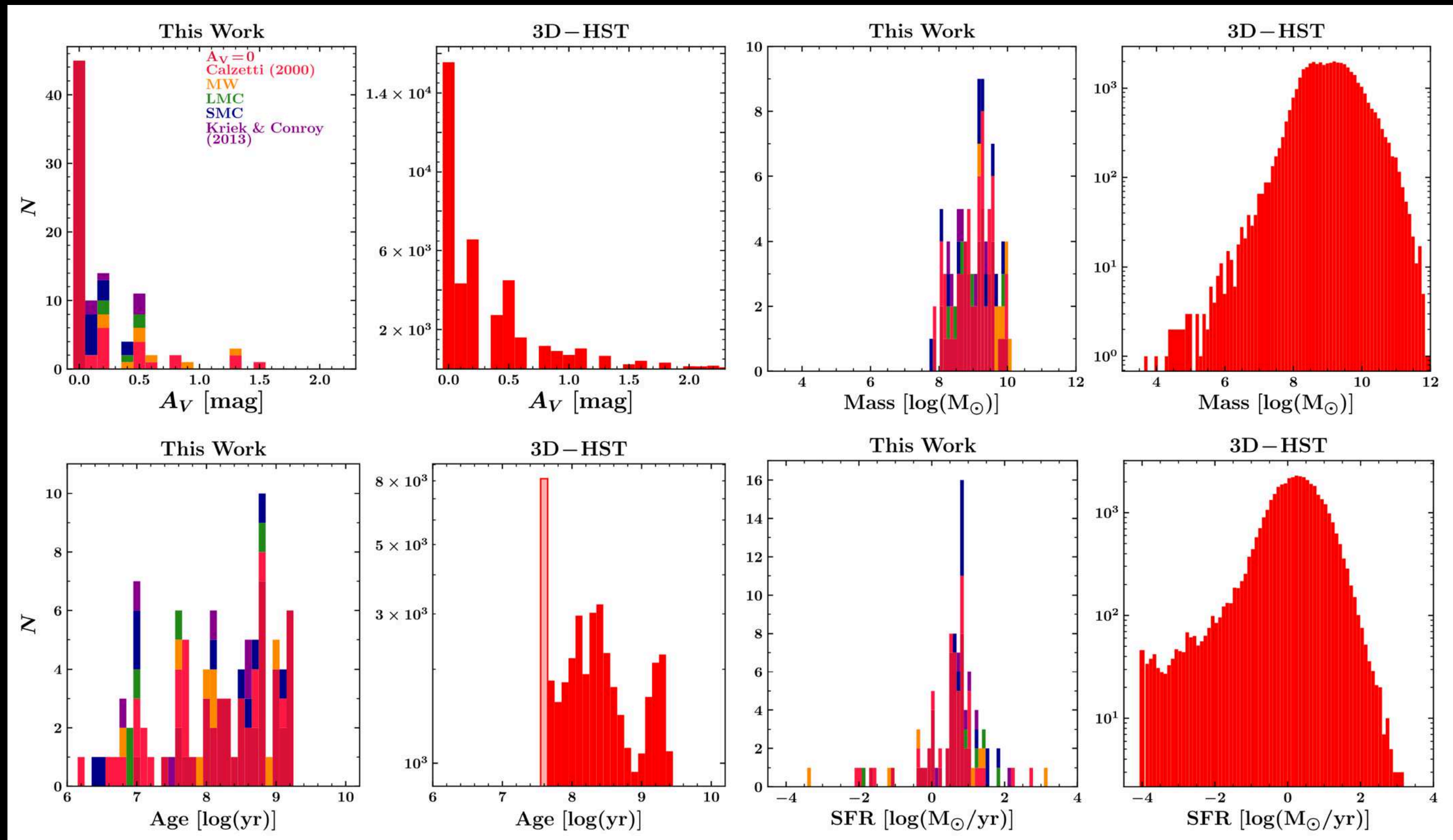
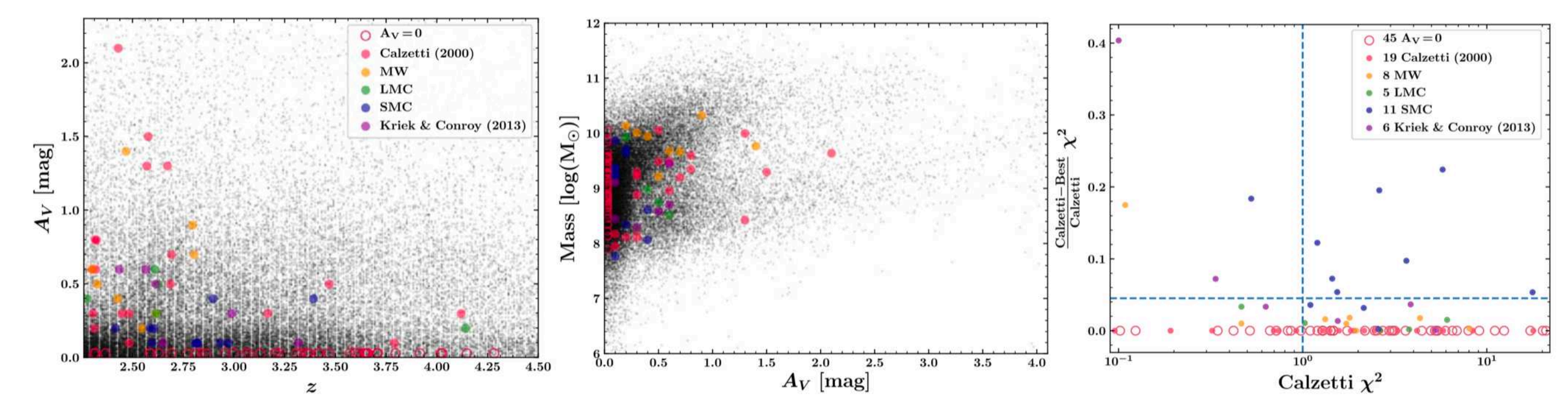


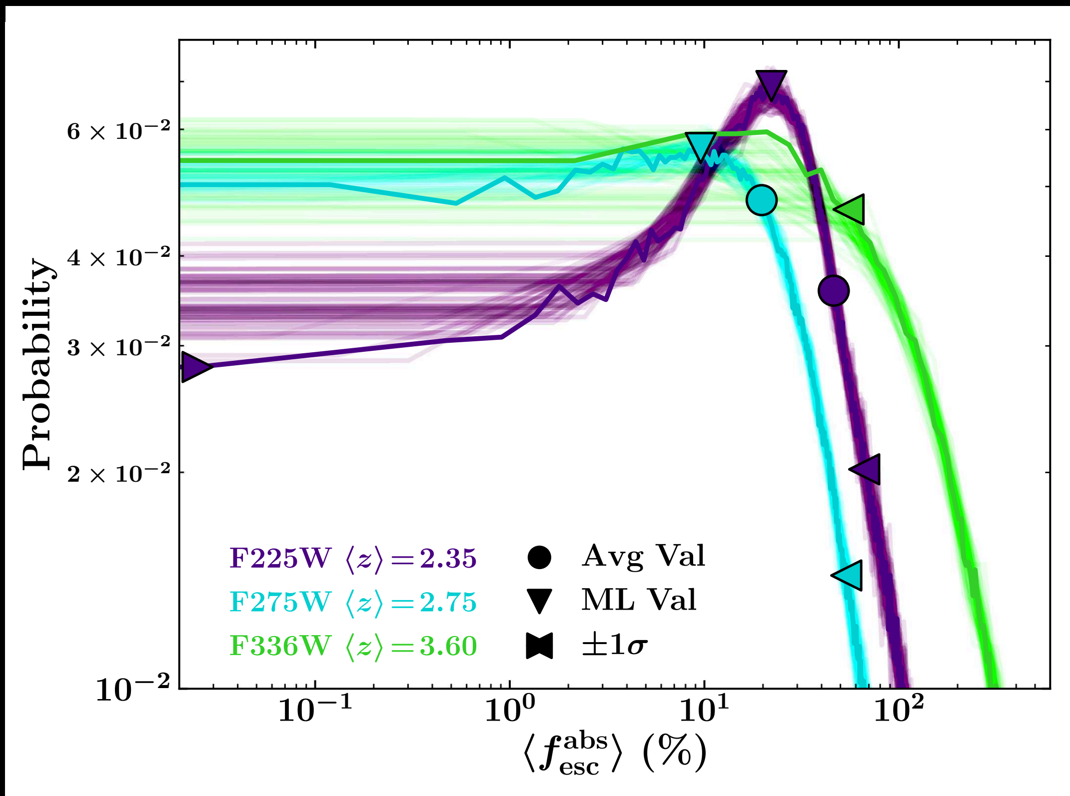
The Astrophysical Journal, 897:41 (30pp), 2020 July 1 Smith et al.

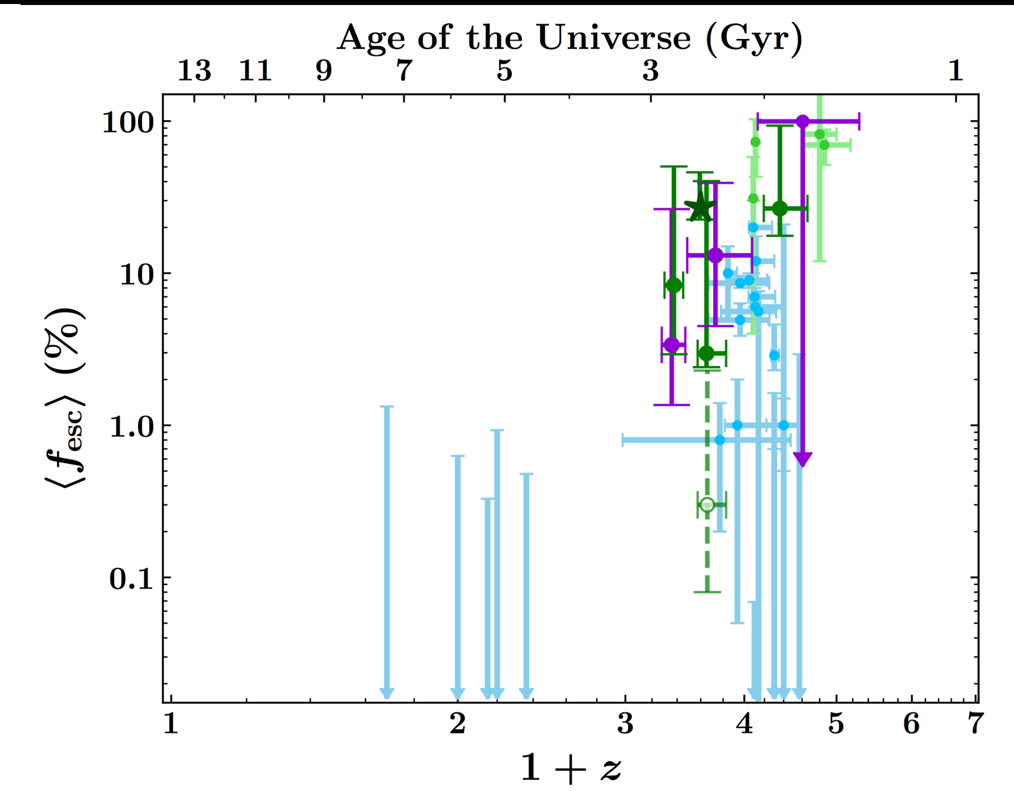


ERS & HDUV AGN+Galaxy CIGALE SED fits (Smith et al. 2020, ApJ, 897, 41):

- LyC SED parameters A_V, Mass, Age, SFR follow 3DHST sample: SMC extinction sometimes better fit.

(2) LyC Escape Fractions vs. z for Faint Galaxies & Weak AGN





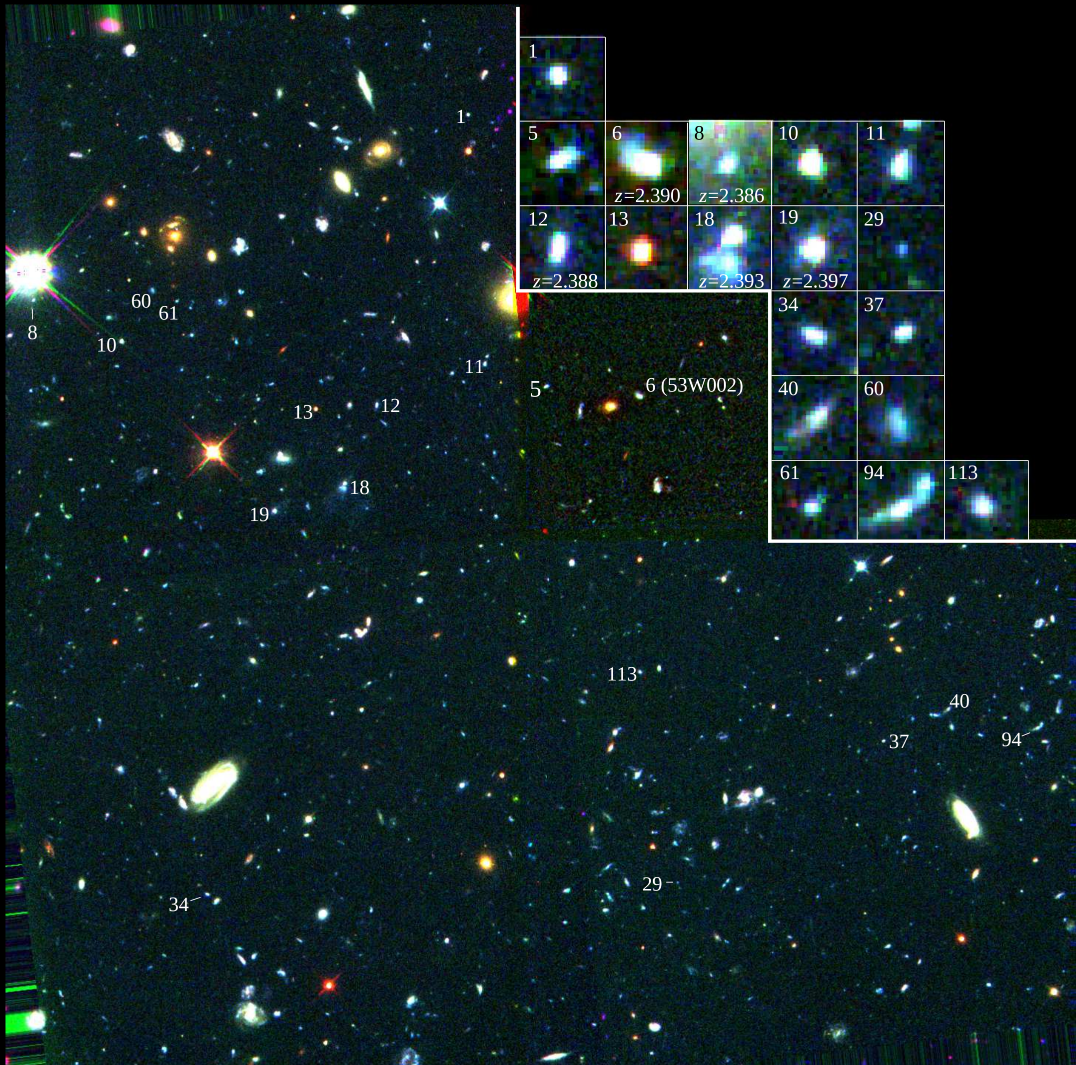
[Left] PDF of absolute f_{esc}-values (Inoue^{+} 2014), folding LyC fluxes + errors through 10^9 random LOS of IGM transmission (Smith+ 20, ApJ, 897, 41).

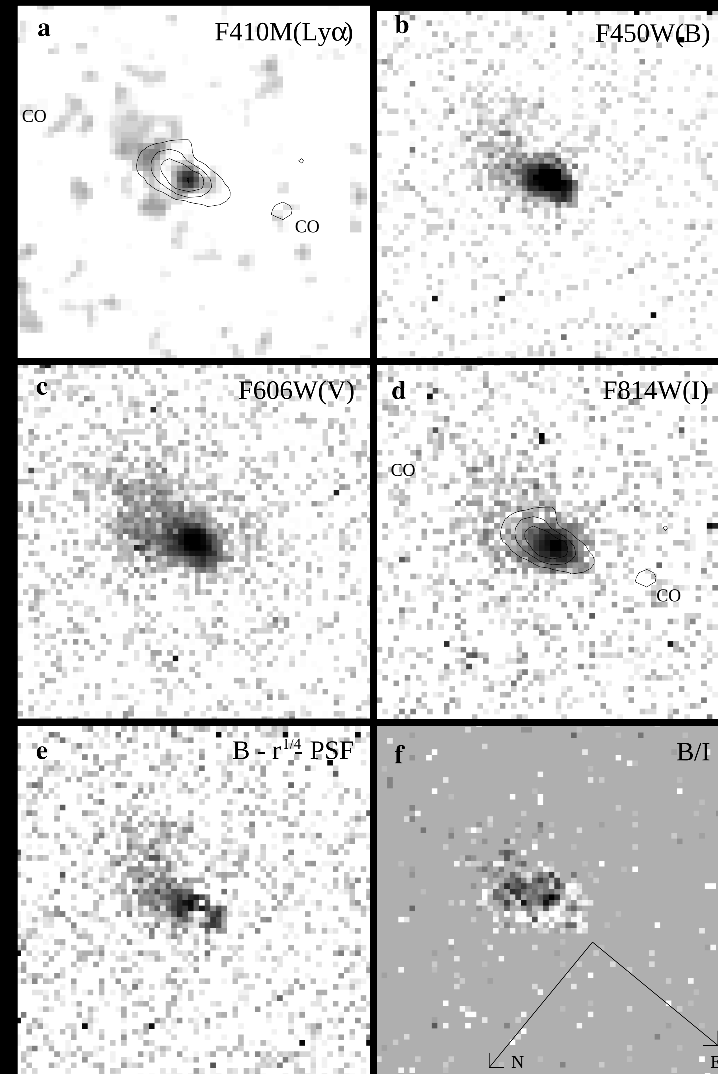
- Circles: average f_{esc}; triangles: modal f_{esc} with $\pm 1\sigma$ MC-range.

- [Right] Statistical samples: AGN & Galaxies f_{esc} high enough (5–30%) to maintain reionization at z$\simeq$2.3–3.5. Rare weak AGN dominate LyC.

- f_{esc} errors dominated by low S/N, IGM-transmission & sample variance.

Deep HST imaging of weak AGN outflow at z=2.390



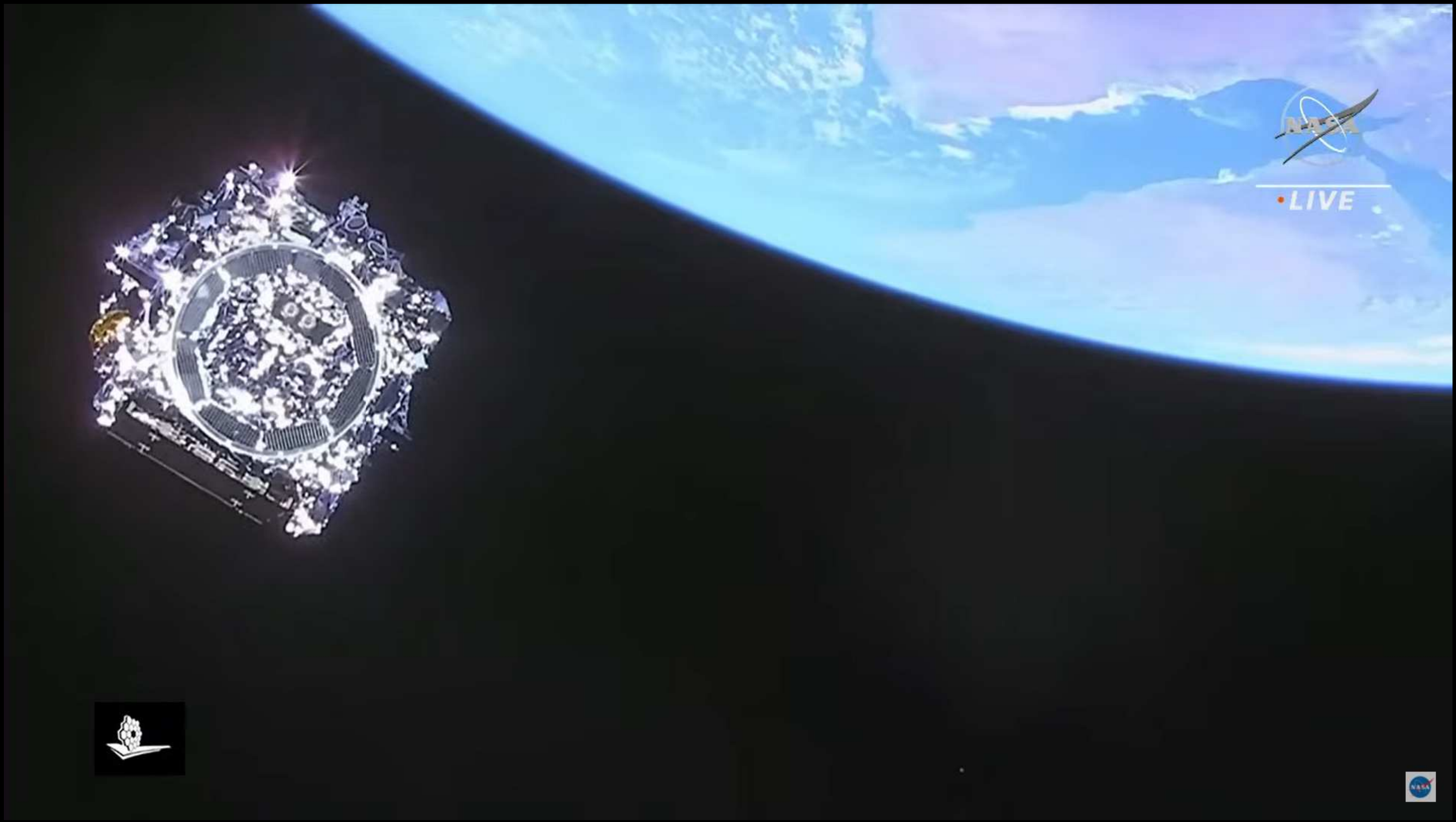


(Left): WFPC2 BVI + F410M (Lyα) on radio galaxy 53W002 + surrounding group of 17 z=2.39 Lyα candidates (Pascarelle+ 1996, Nature, 383, 45).

(Right): Radio galaxy 53W002 at z=2.390 (Windhorst et al. 1998, ApJL, 494, 27): stellar r$^{1/4}$-law + Lyα & blue continuum AGN-cloud.

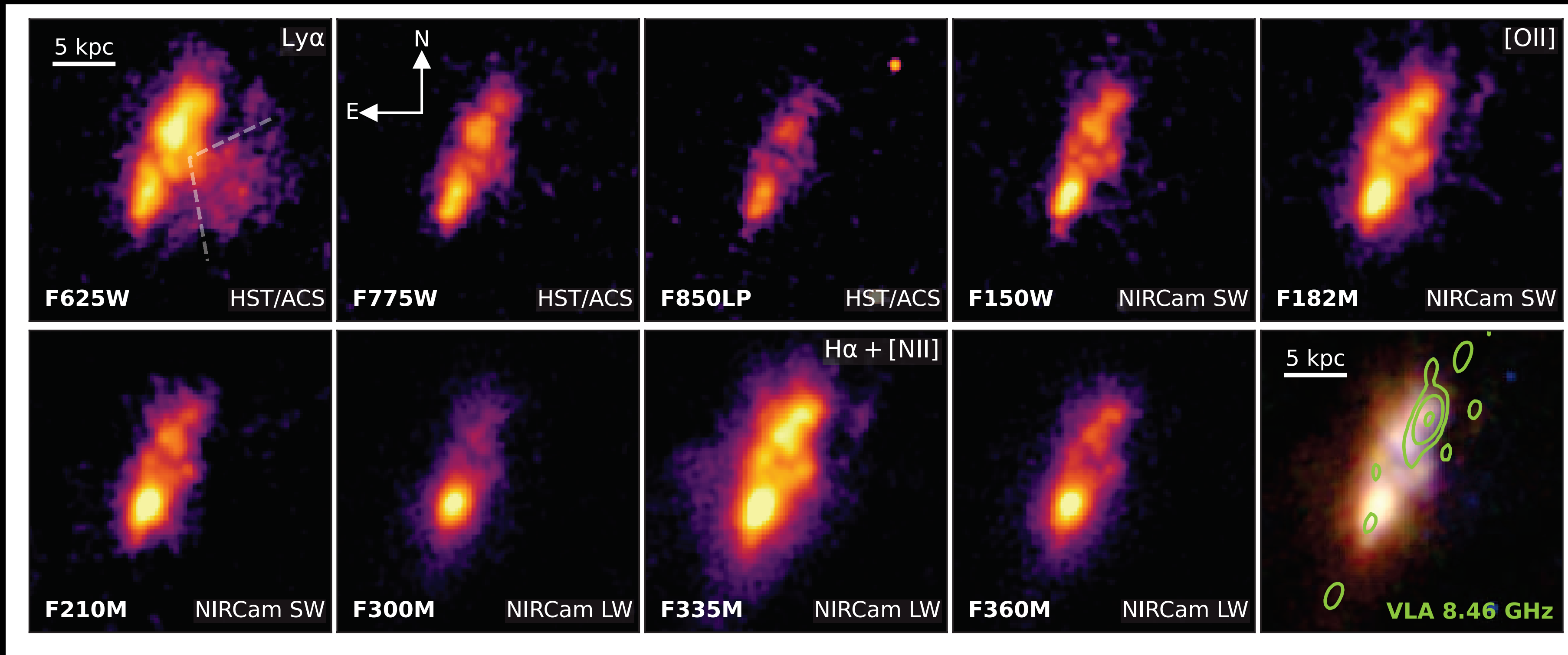
- Lyα may escape through outflow hole from radio jet ($\theta_h \simeq 20°$); LyC?

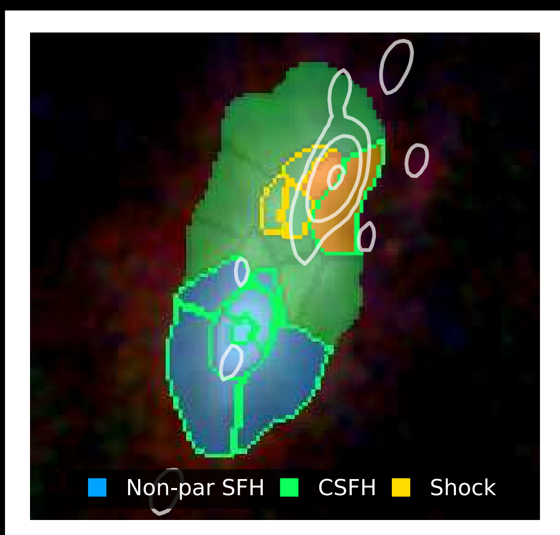
(3) The Promise and Power of JWST for LyC Constraints at High Redshift

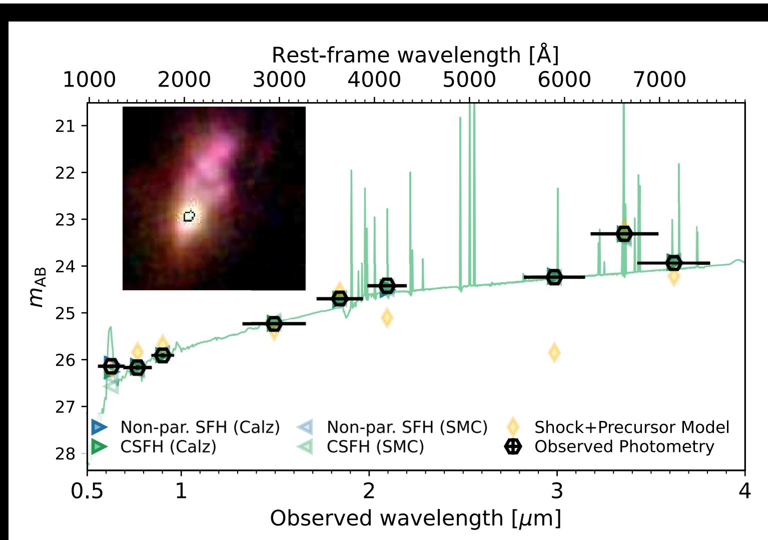


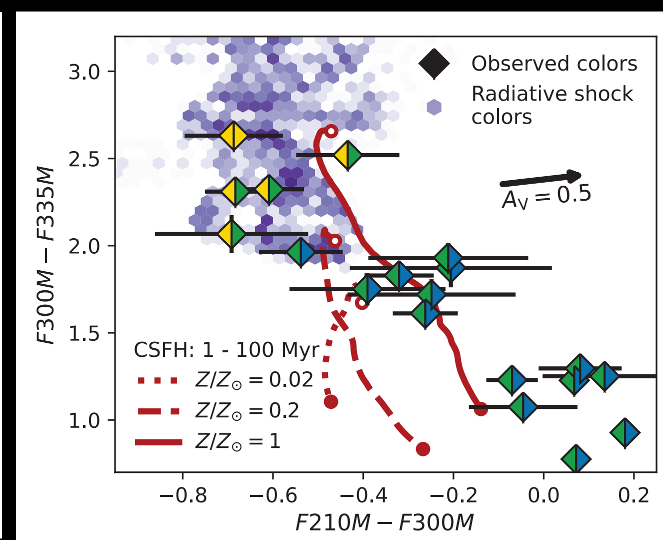
What LyC constraints can JWST provide at $z \gtrsim 4$ where the IGM is opaque?

- HST has had $\gtrsim$180,500 sunrises + sunsets since its April 1990 launch;
- JWST has had only 1 sunrise + 1 sunset since its Dec. 2021 launch!
- JWST: a $\gtrsim$10-year stable platform for very faint imaging & spectroscopy.





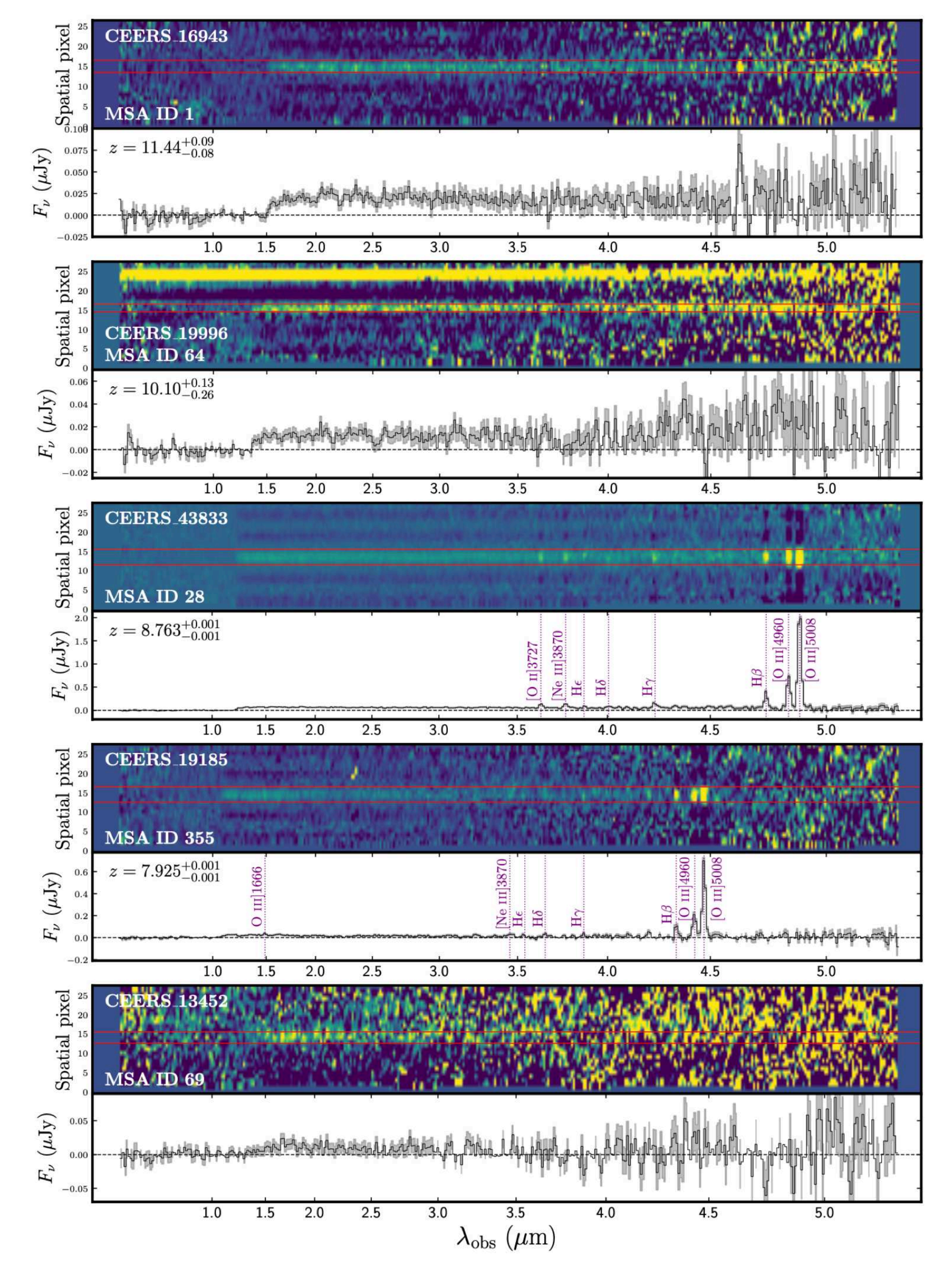


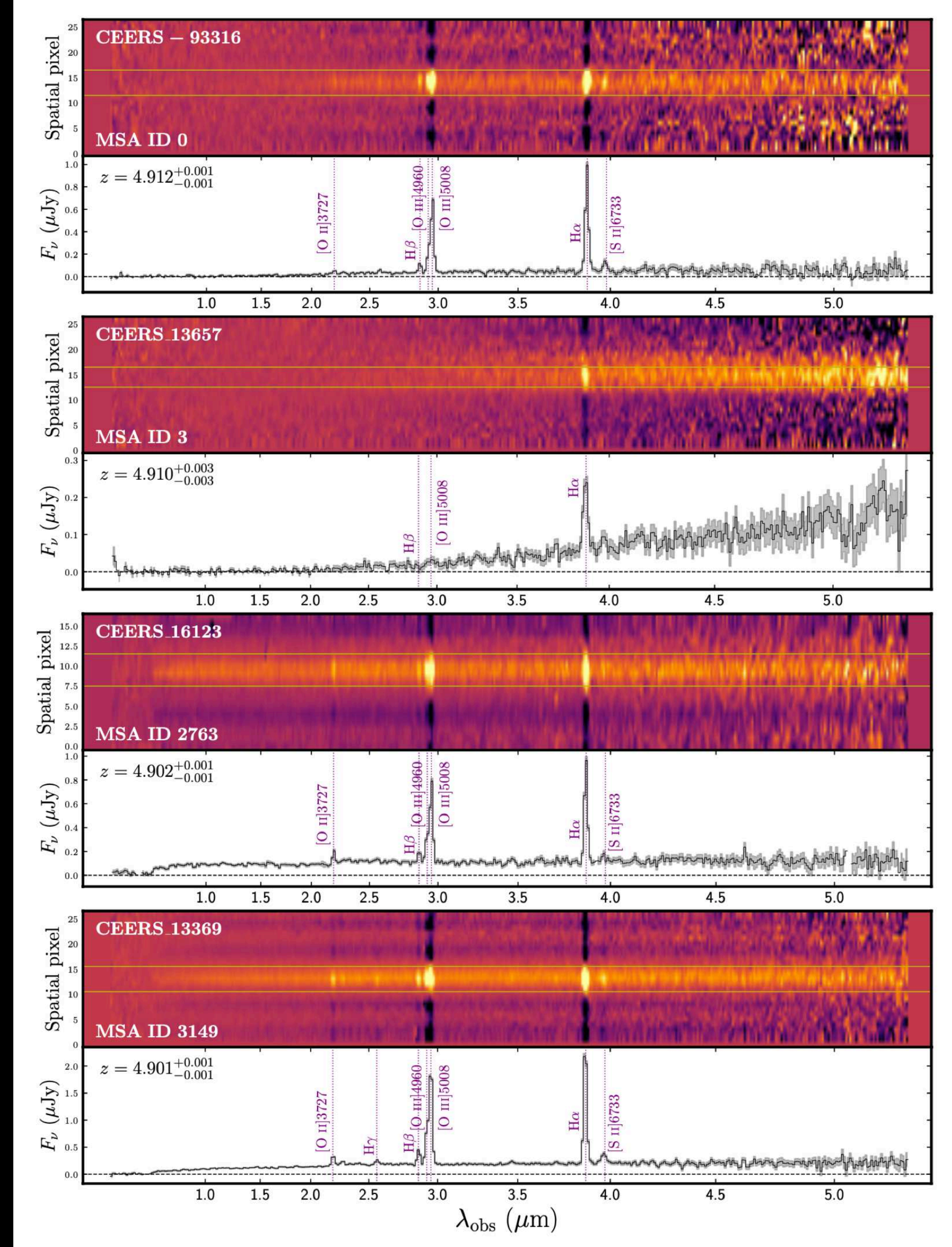


One of the most massive ($10^{10.9}$ $M_\odot$) high-z radio galaxies at z=4.11:

- TNJ1338: NIRCam medium-band SFR∼1600 $M_\odot$/yr; extreme jet-induced SFR≳500 $M_\odot$/yr, t_{SFR}≃4 Myr.

Opening angles: HST Lyα $\theta_h \lesssim 50°$; NIRCam+VLA jet $\theta_h \sim 10°$ (Duncan+ 2023, MNRAS, 522, 4548)

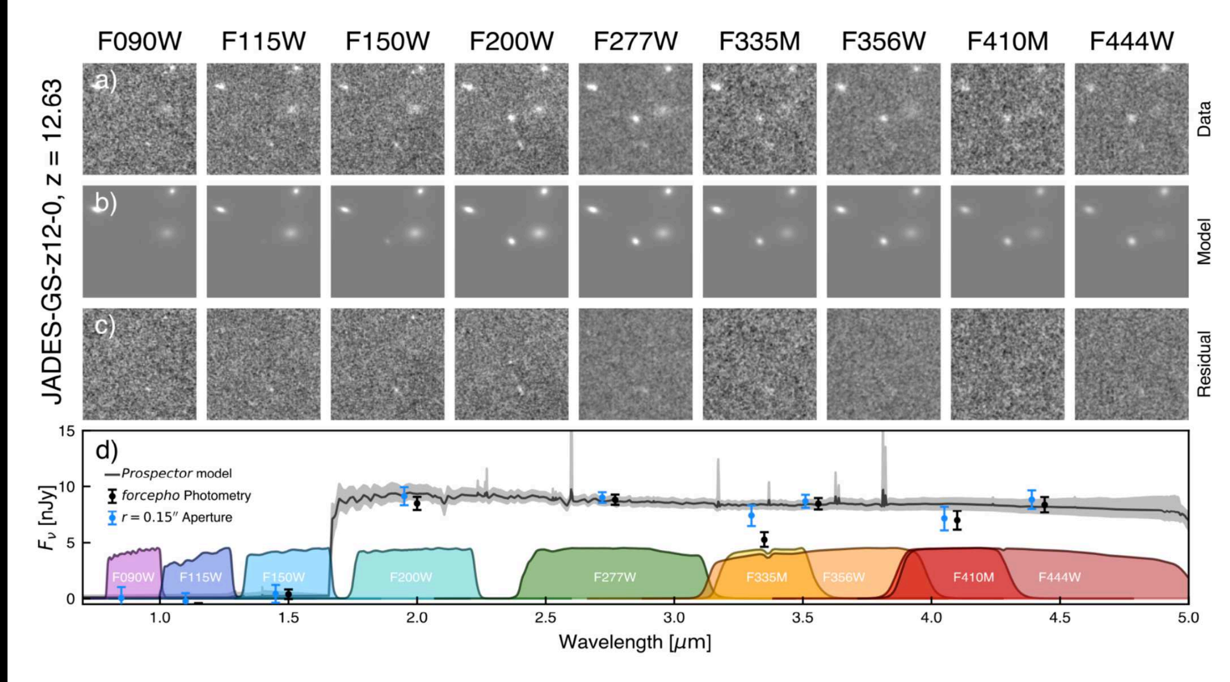


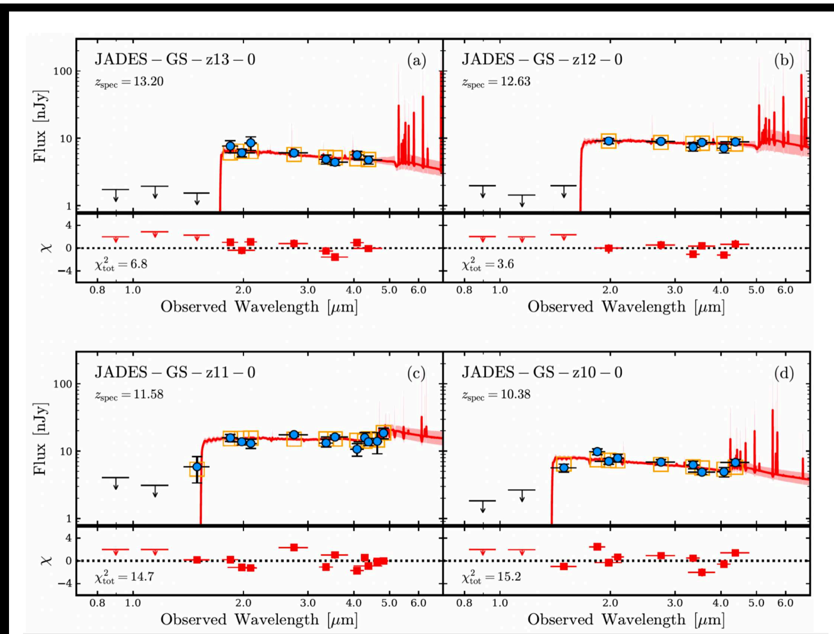


NIRSpec: CEERS-16943 now spectroscopically confirmed at z=11.44!

CEERS-93316 at z=4.912 (overdensity), not z∼16 (z_{phot} line-contaminated)!

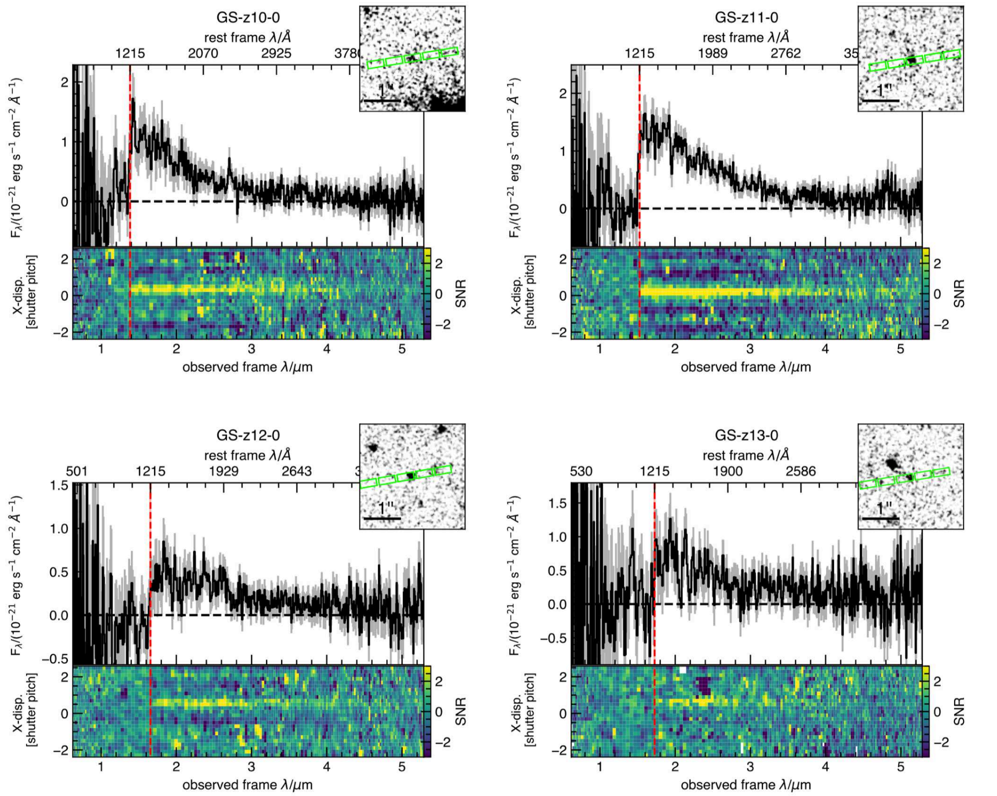
(Haro et al. astro-ph/2303.15431; see also Naidu et al. astro-ph/2208.02794)

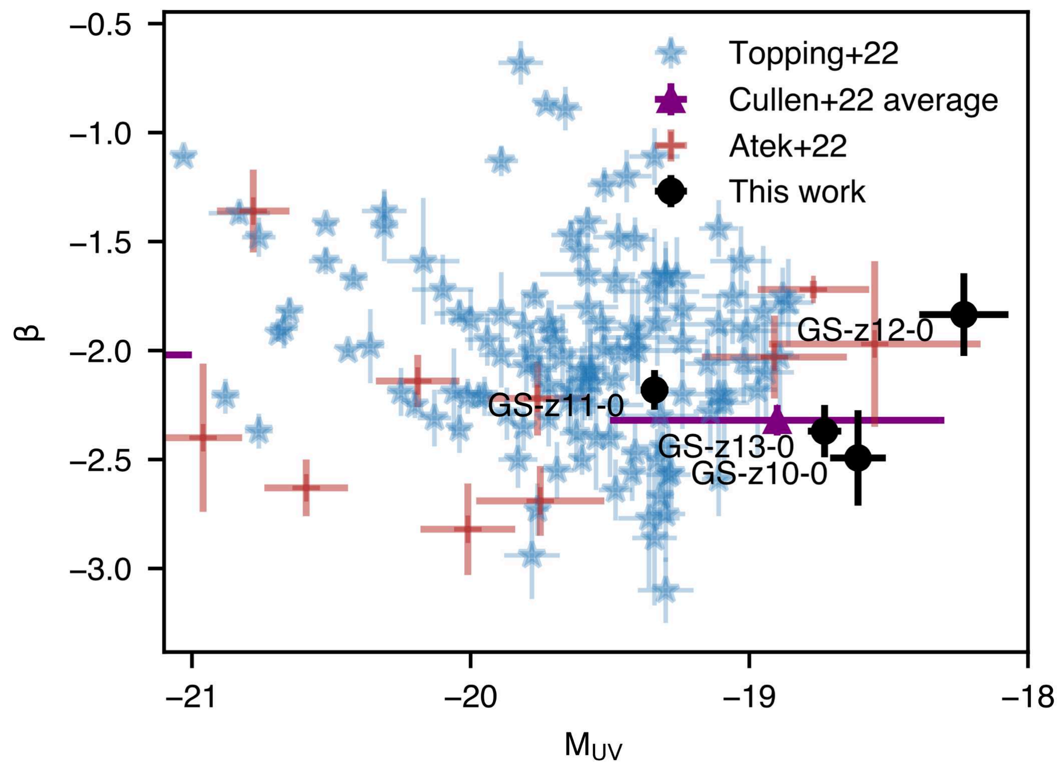




NIRSpec redshifts for four NIRCam $z_{phot}\simeq$10–13 candidates:

- $z_{phot}\simeq$10–13 candidates indeed at NIRSpec z_{spec}=10.38–13.20.
- SED-model yields $f_{esc}\simeq$20–70% (Robertson et al. 2023; astro-ph/2212.04480)



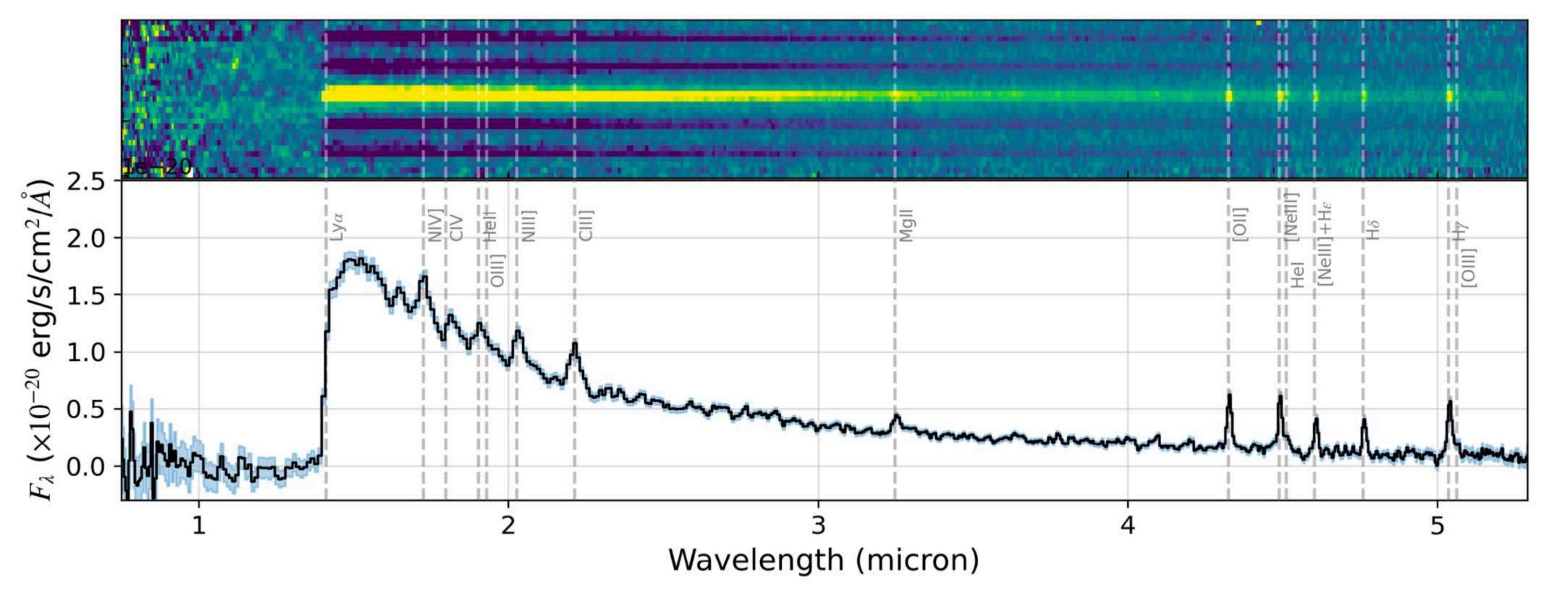


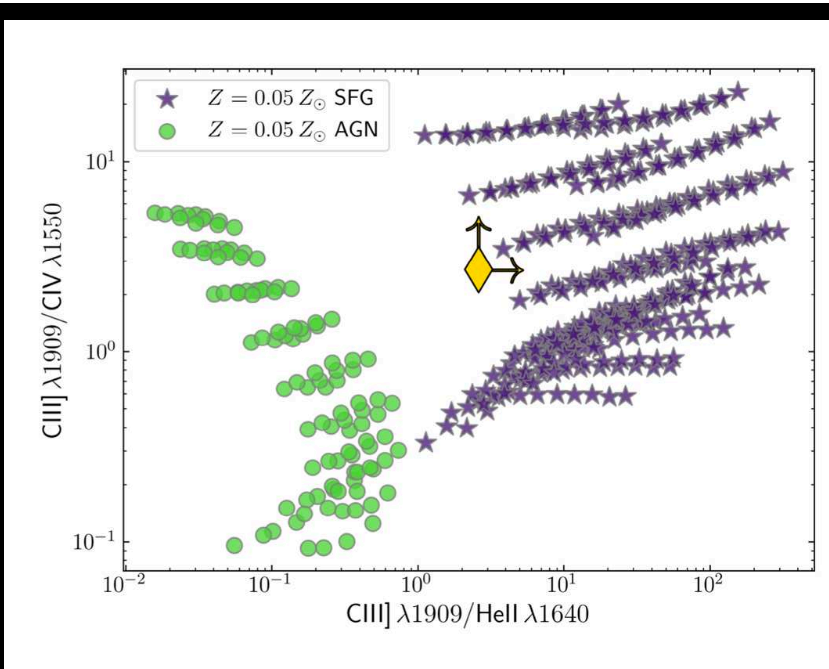
4 NIRCam-selected galaxies in GOODS-S with NIRSpec $10.3 \lesssim z_{spec} \lesssim 13.2$.

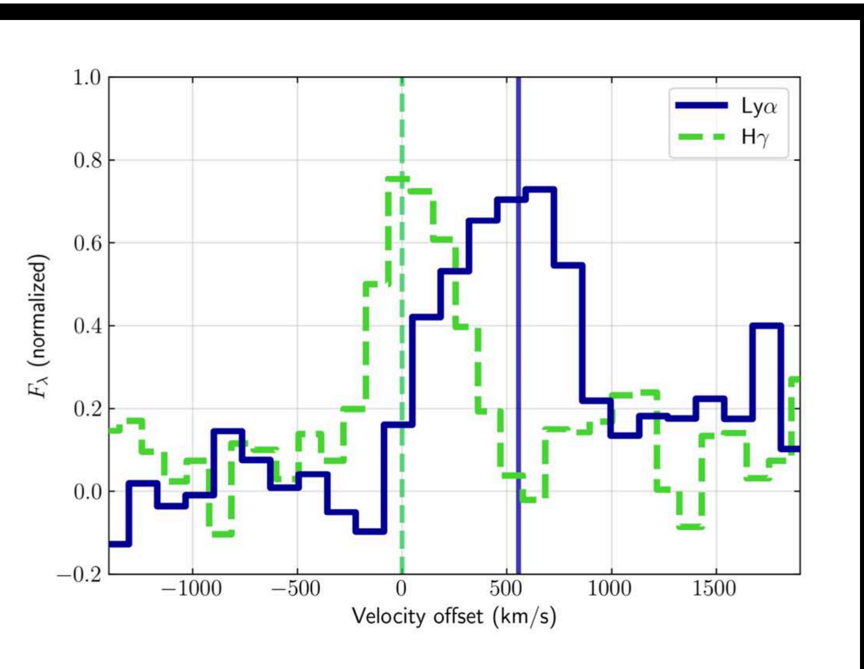
- Generally metal poor with masses $\sim 10^7$–10^8 $M_\odot$ and blue UV β-slopes.
- Significant Lyα -damping wings — good (future!) re-ionizers.

(Curtis-Lake, E. et al. 2023, astro-ph/2212.04568)

- These are not reionizers yet at $z \gtrsim 10$, but they will be by $z \simeq 7$–8!





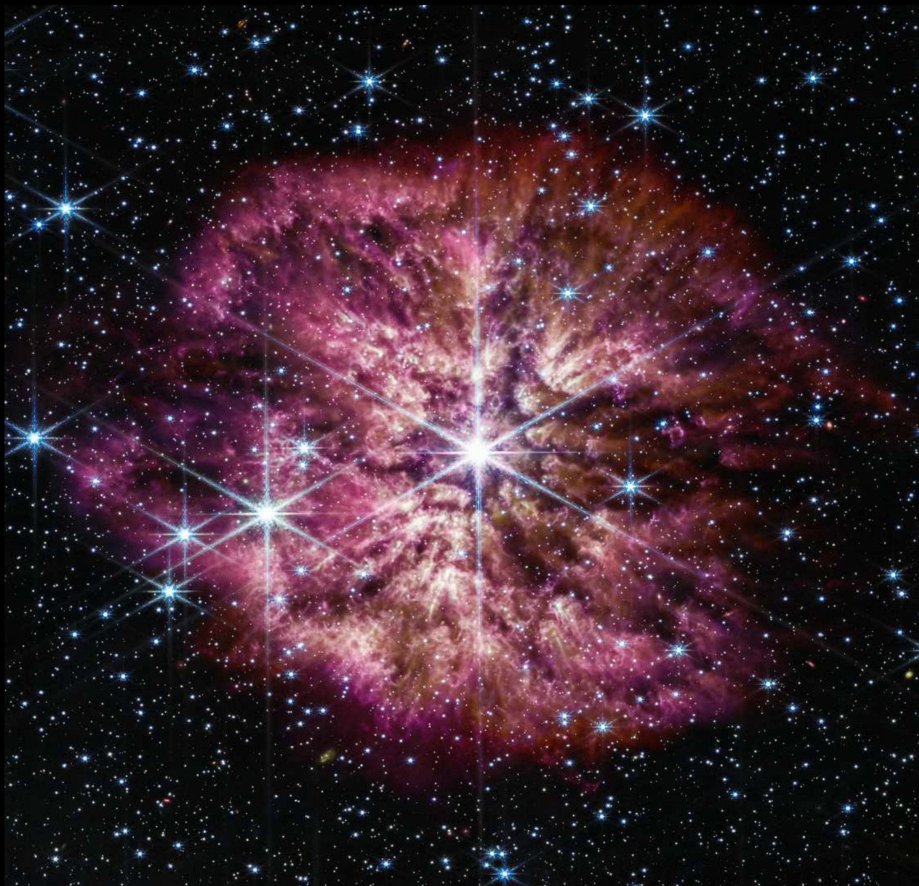


JWST NIRSpec spectrum of GN-z11; z_{spec}=10.603 instead of z_{phot}=11.09!

- UV β-slope≃–2.4; H, C, N, O, Mg em-lines/outflows: not AGN, but SFR≃20–40 $M_\odot$/yr.

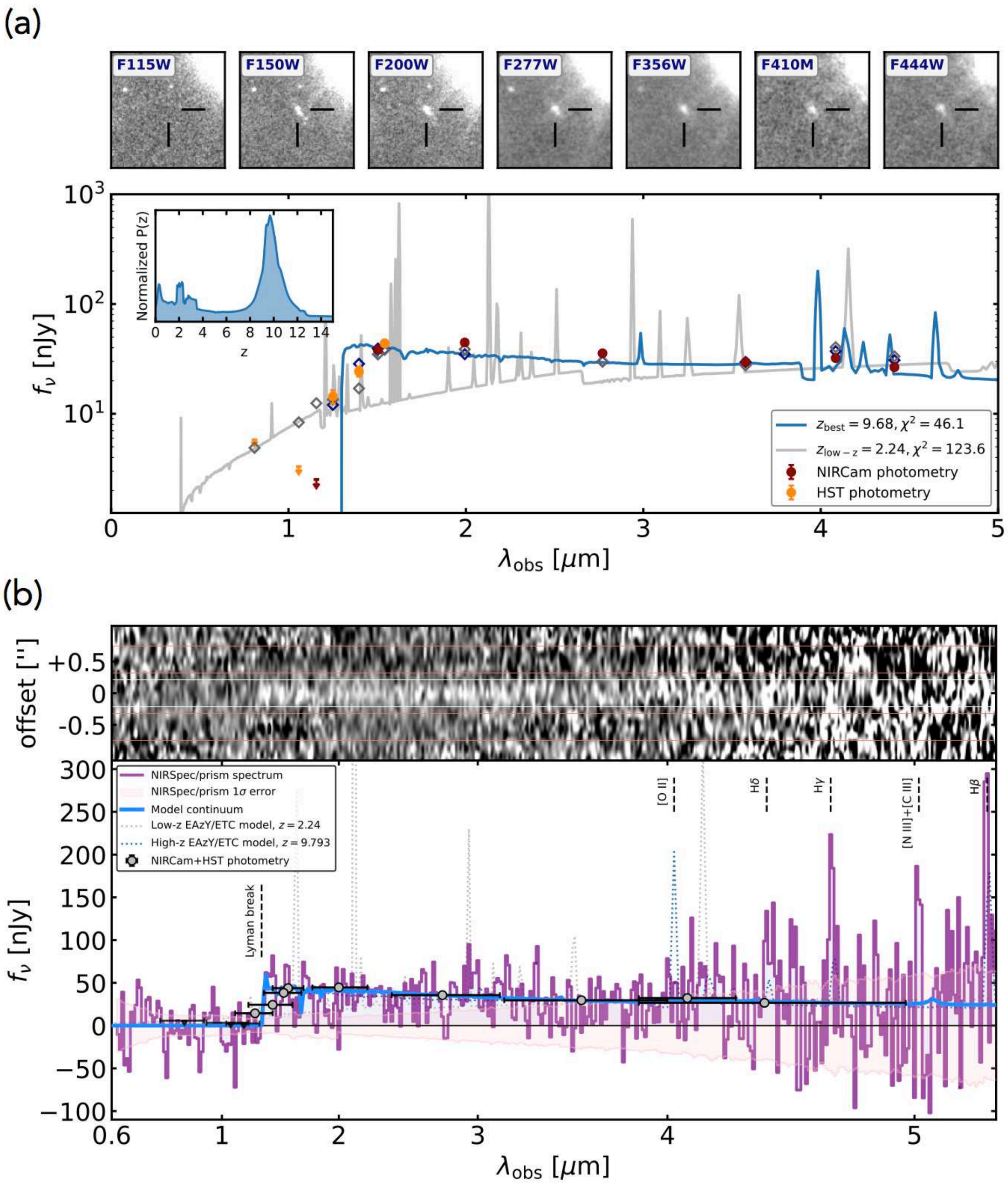
(Bunker et al. astro-ph/2302.097256v1). See my next musings on Nitrogen lines and Wolf Rayet stars.

Galaxy Outflows with HST and JWST: Let's talk Wolf-Rayet stars:



30 $M_\odot$ Wolf Rayet star WR124 shortly before it turns Supernova ...

- [Left] NIRCam and [Right] MIRI — both showing recent mass loss.
- Prelude stage to Supernova also releases $\sim$10 $M_\odot$ of (dusty) mass!
- "Cavities" at PA$\sim$75 & 255$\pm$15° suggests rapid stellar rotation!
- Future Supernova may poke $\theta_h\sim15^\circ$ holes in ISM $\longrightarrow$ use in f_{esc}-models!



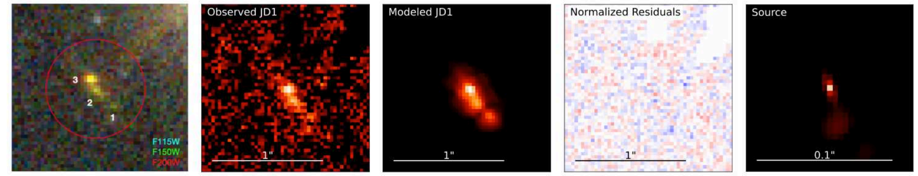
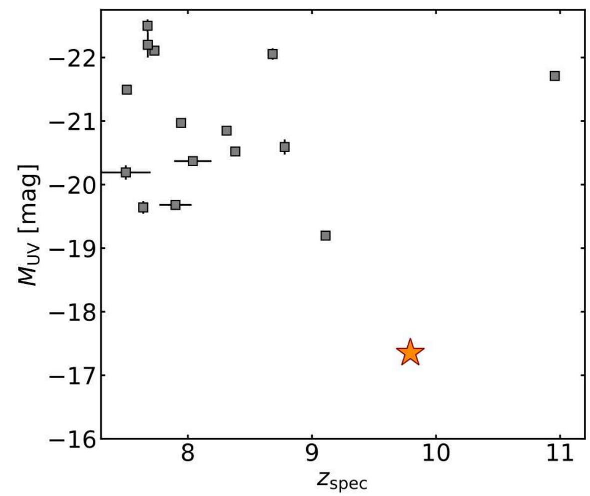


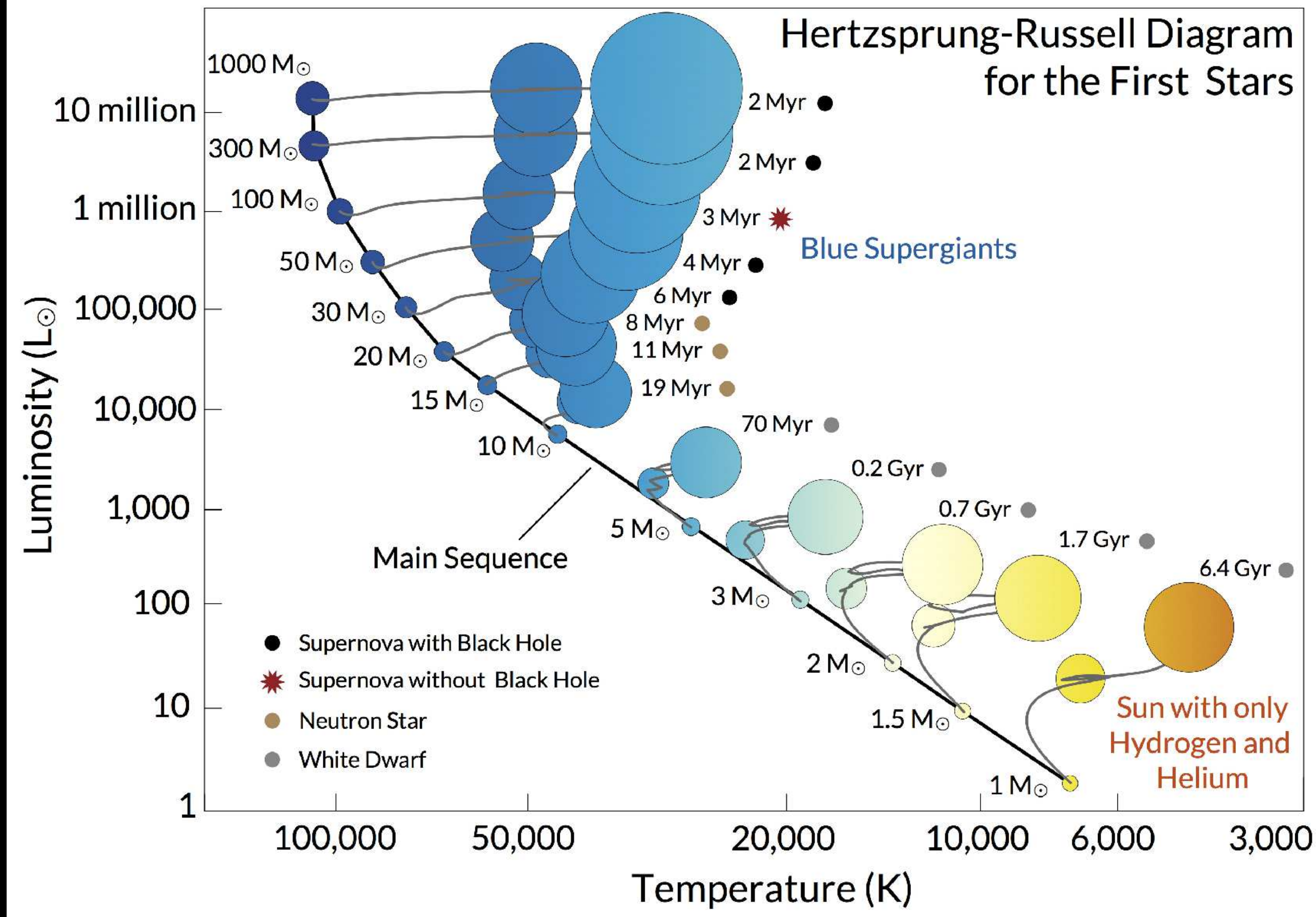
Figure 3. The morphology of JD1 from *JWST*-NIRCam imaging. From the left to right: an RGB (F115W, F150W, F200W) image of the galaxy system, the F150W image of the source, the `lenstruction` model of the source, the (1σ flux-normalized) residuals between the F150W data and the model, and the reconstructed source-plane galaxy. The sizes of the cutouts are labelled in each panel.



(Roberts-Borsani, G. et al. (2023, Nature, 618, p. 480; astro-ph/2210.15639)

Highly magnified dwarf galaxy behind A2744 is at NIRSpec z_{spec}=9.793!

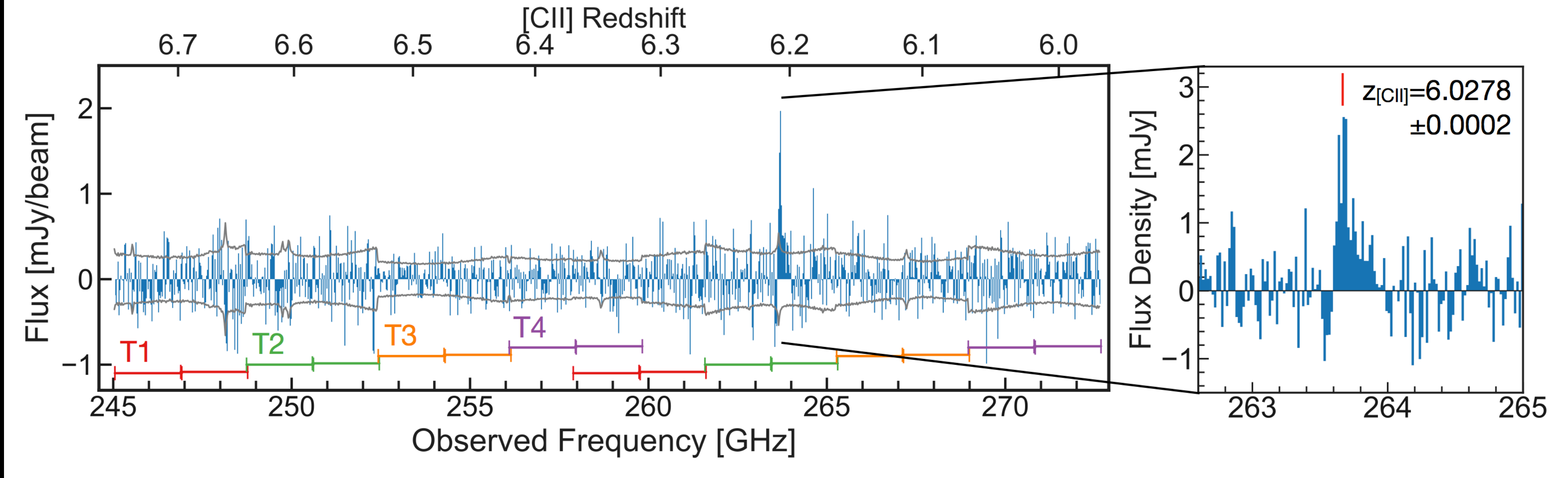
- $M_{UV} \simeq$–17.35 mag, r_e=150 pc, lowest known dwarf galaxy mass=$10^{7.19}$ $M_\odot$ at z≃10!
- Presence of $H\beta$, $H\gamma$, $H\delta$, N-III but *no* C, O suggests pristine object with WR stars of $\gtrsim$30 $M_\odot$.



Pop III star HR-diagram: MESA stellar evolution models for Z=0.0 $Z_\odot$.

(Windhorst, Timmes, Wyithe et al. 2018, ApJS, 234, 41).

- WR stars come from M$\gtrsim$20-30 $M_\odot$ stars, which live $\sim$6–8 Myrs.
- SN-driven outflows come from M$\gtrsim$8 $M_\odot$ stars, which live $\lesssim$30 Myrs.
- A 100 Myr starburst at z$\sim$10 will have SN-driven outflows for another $\sim$140 Myrs, *i.e.*, till z$\sim$8 maximizing ISM holes for LyC-escape by then.



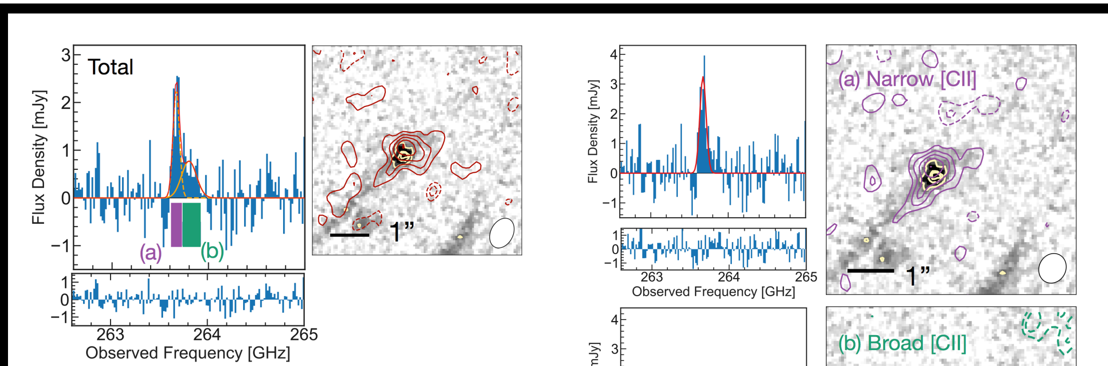
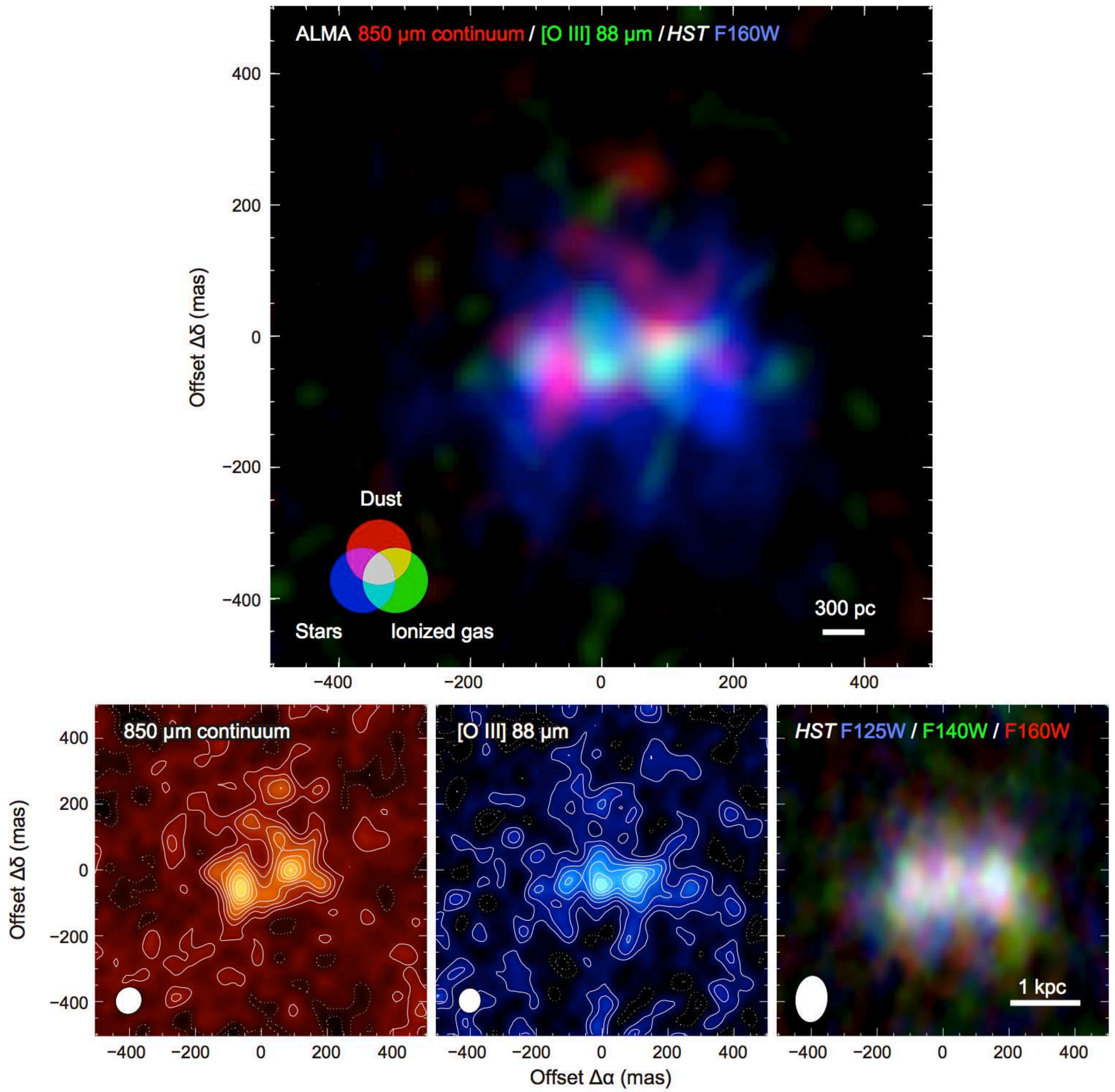


Figure 3. **Left panel:** The [C II] 158 μm emission line integrated over entire components. The red line shows the result of two-component 1-D Gaussian fitting to the spectra. Orange lines show individual Gaussians for narrow (dashed line) and broader (solid line) components. The residuals of the fits are indicated in the lower inset. The inset shows that there are no noticeable residuals by comparing to the rest of the frequency range. The frequency ranges indicated with the boxes (a) and (b) are used to make individual moment-0

Highly magnified galaxy behind MACS0308 at ALMA redshift z_{spec}=6.2078:

- Asymmetric ALMA [CII]-line suggests carbon outflow at v$\simeq$–230 km/s.
- Lack of detected 158μm dust continuum: SF in dust-free environment.

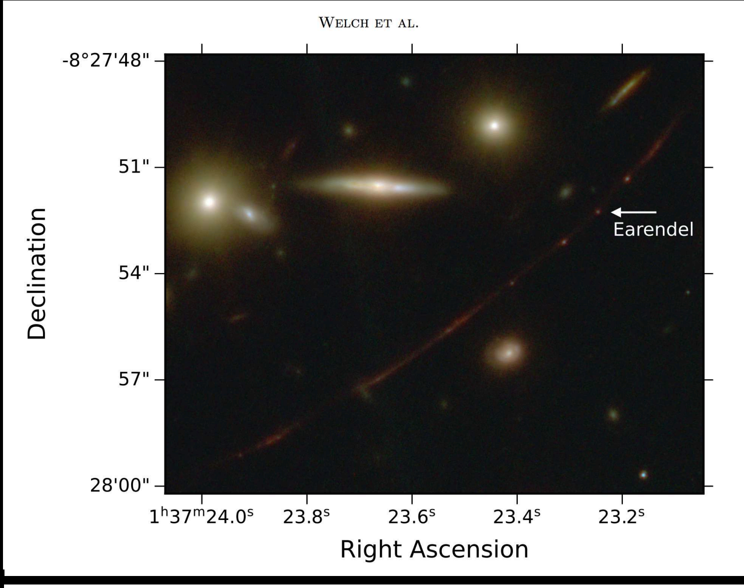
f_{esc} SED-modeling needed at z=6! (Fudamoto, Y. et al.; astro-ph/astro-ph/2303.07513)

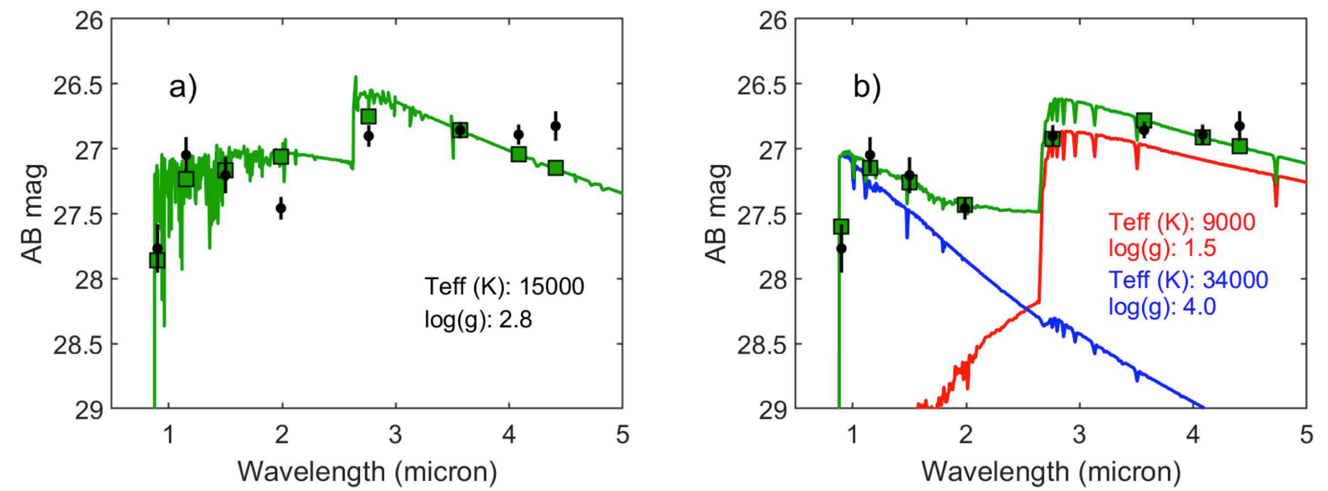


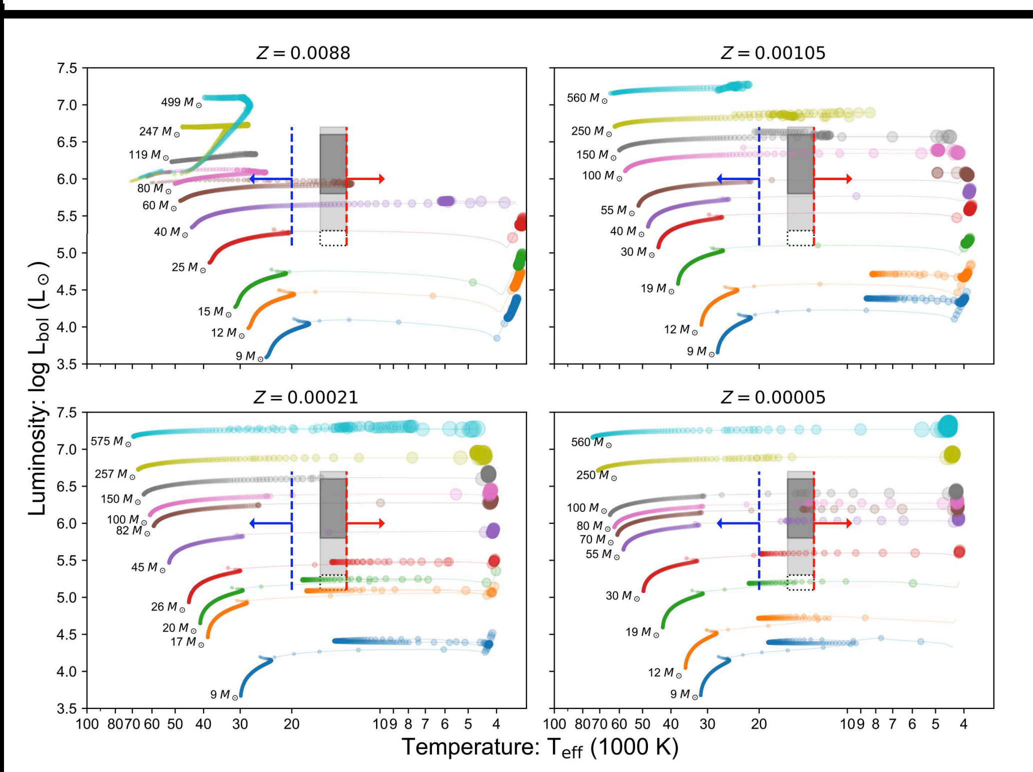
Highly magnified galaxy behind MACS0416 at ALMA redshift z_{spec}=8.312:

- Superbubbles produce galaxy-scale outflows + bulk-motion of ionized gas.

f_{esc} SED-modeling needed at z=8! (Tamura et al. 2023, astro-ph/2303.11539)







Welch, B., et al. 2022, ApJ, 940, L1 (astro-ph/ 2208.09007);

Welch, B., et al. 2023, ApJ, 943, 2 (astro-ph/ 2207.03532);

Vanzella, E., et al. 2023, ApJ, 945, 53 (astro-ph/ 2211.09839).

Highly magnified star (μ~9000) Earendel, behind cluster WHL0137, at z_{phot}=6.2±0.1:

- Best SED-fit: low $Z/Z_\odot$ double star, T_{eff} =9000+34,000 K, and L~$10^{5.3}$ + $10^{5.9} L_\odot$.
- JWST has the potential to study individual (binary) stars that contribute to reionization!

(4) Summary and Conclusions

(1) Space- and ground-based LyC spectroscopy has a unique role in LyC:

- Spectral accuracy at $\lambda \lesssim 912$ Å; Contamination more uncertain and more limited z-range.

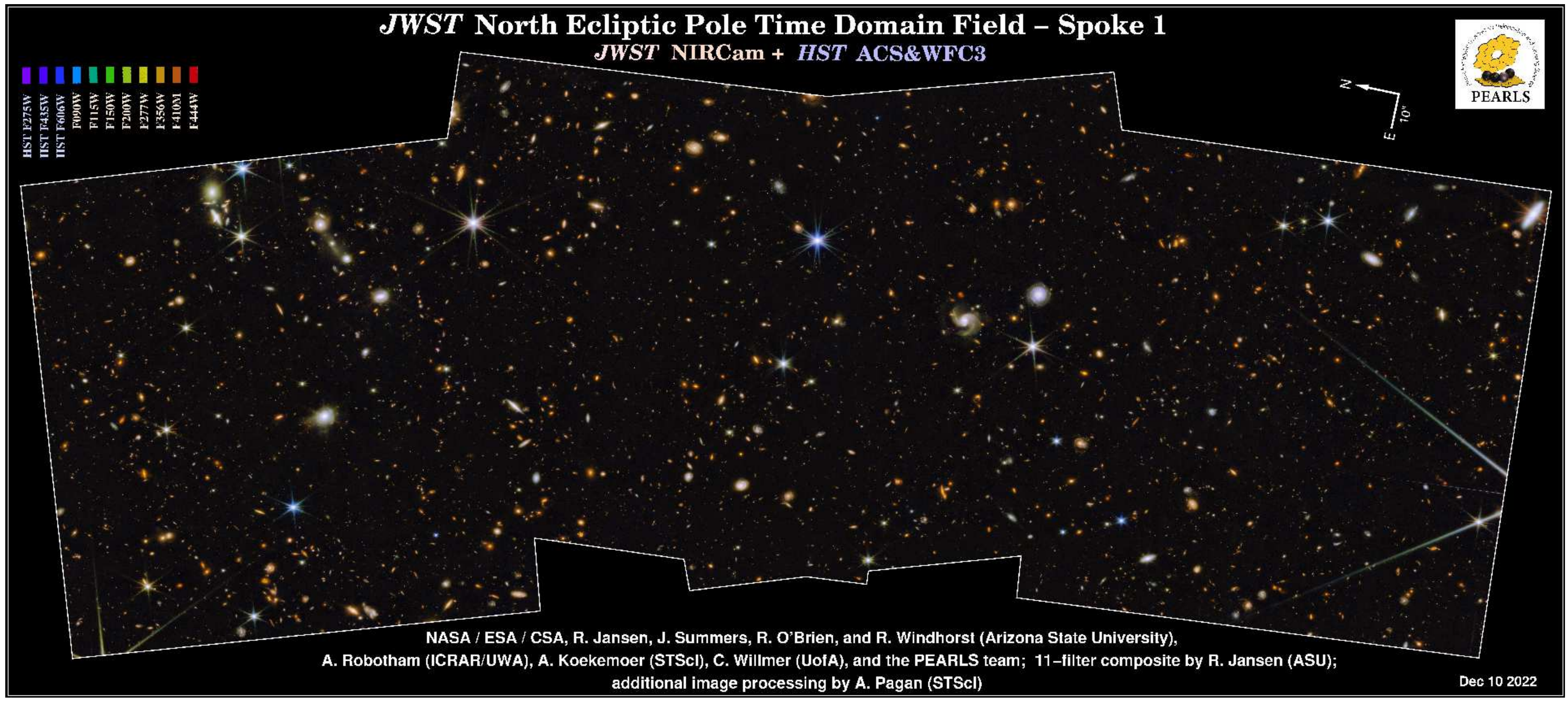
(2) WFC3 can measure LyC for galaxies + weak AGN at z$\simeq$2.3–3.5:

- WFC3 filters designed with low-enough redleak to enable this.
- Deepest 10-band HST images mask all foreground interlopers to AB$\lesssim$28.
- Weak AGN $\sim$3$\times$ brighter in LyC, but $\sim$2$\times$ less numerous than Gals.
- LyC SB-profiles much flatter than UVC, and very non-Sersic like.
- LyC escapes along few sight-lines offset from galaxy center: Outflows? Does ISM-porosity increase with galaxy radius?
- f_{esc} just large enough (AGN$\sim$30$\pm$25%; Gals: 5–10%) for reionization.

(3) JWST provides many smoking guns for reionization at z$\simeq$4–13:

- Many cases of (AGN, Gal) outflows, with <opening angles> $\theta_h \lesssim$20–40°.
- Expect many NIRSpec analyses of potential LyC emitters at z$\simeq$4–13.

SPARE CHARTS

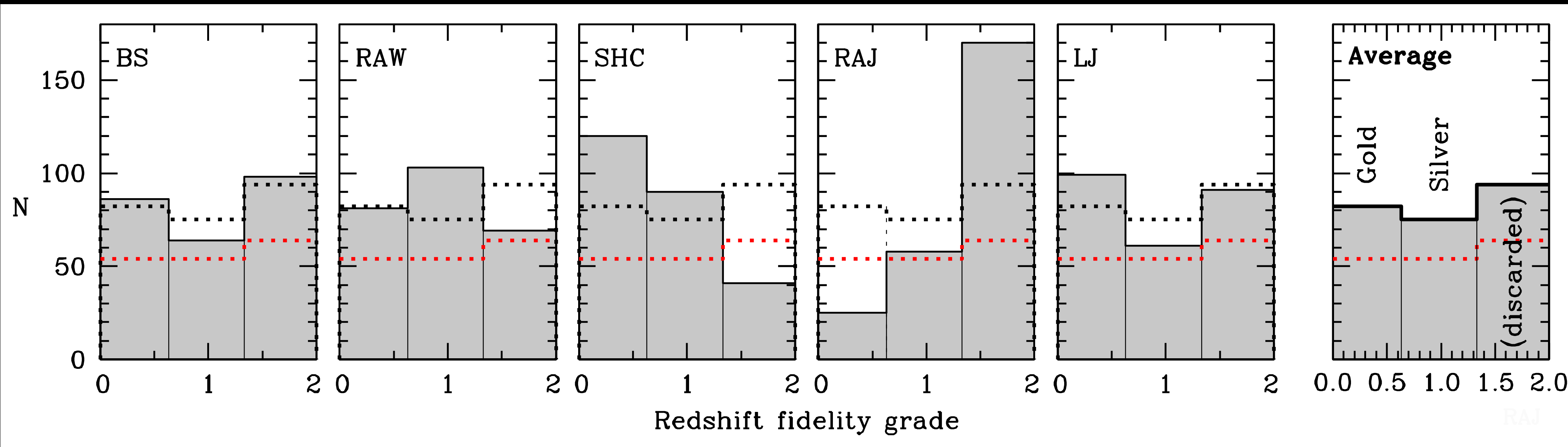


North Ecliptic Pole (NEP) Time Domain Field (TDF) from PEARLS project:

(PEARLS = Prime Extragalactic Areas for Reionization and Lensing Science; Windhorst et al. 2023, Astron. J., 165, 13; astro-ph/2209.04119)

- The NEP TDF is unique: Webb can observe it 365 days per year!
- Some remarkable results in PEARLS and other recent JWST projects:
- Seyferts and spirals with weak AGN seen abundantly in the images.
- (Old SED) tidal tails everywhere. Abundance of red (dusty) spirals.

(2b) Hubble WFC3 ERS — Spectroscopic Sample Selection



Comparison of redshift reliability (spectrum quality) assessments, from best (0.0) to poorest (2.0), by five co-authors [BS, RAW, SHC, RAJ, and LJ]:

- Measuring LyC escape fractions of $f_{esc} \simeq 6.0\%$ at $\gtrsim 3\sigma$ requires very low interloper fraction (Siana$^+$ 2015; Vanzella$^+$ 2015).
- Mask-out all interlopers from 10-band ERS mosaics to AB$\lesssim$28 mag.
- Use all VLT, Keck, & HST grism spectra to get most reliable samples:
- "Gold" sample: highest fidelity (grades=0–0.63): z_{sp}'s very likely correct.

What critical aspects does JWST add to HST's LyC Escape studies?

JWST FGS+NIRCam: R$\simeq$150, 0.8–5.0μm grism spectra to AB$\lesssim$28–29:

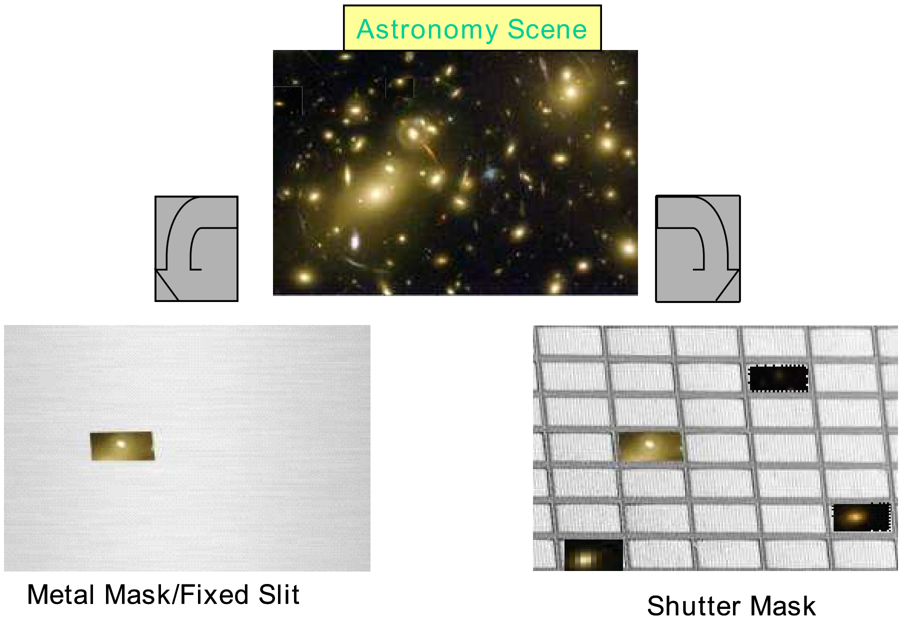
- Larger, fainter SED+z$_{spec}$-samples of LyC candidates in HST UV fields.

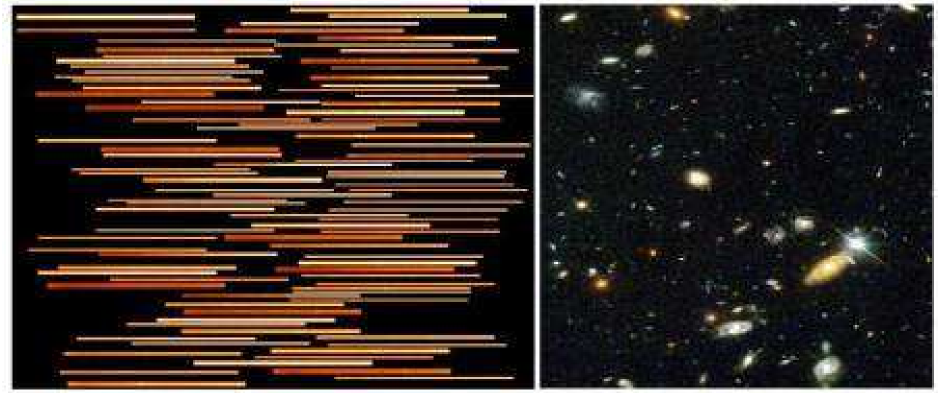
NIRSpec: JWST's short-wavelength ($\lambda\simeq$1–5.0μm) spectrograph:

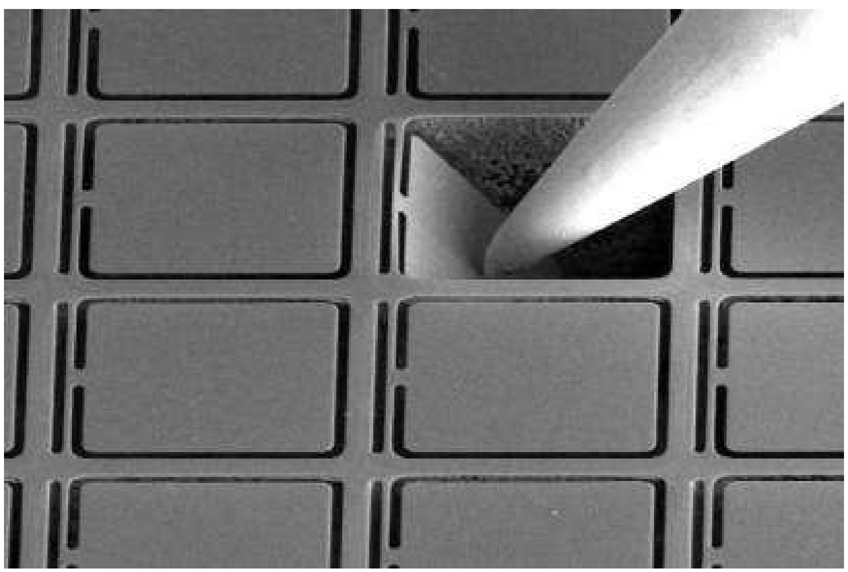
- 100's of simultaneous faint-object spectra of LyC candidates to AB$\lesssim$28.

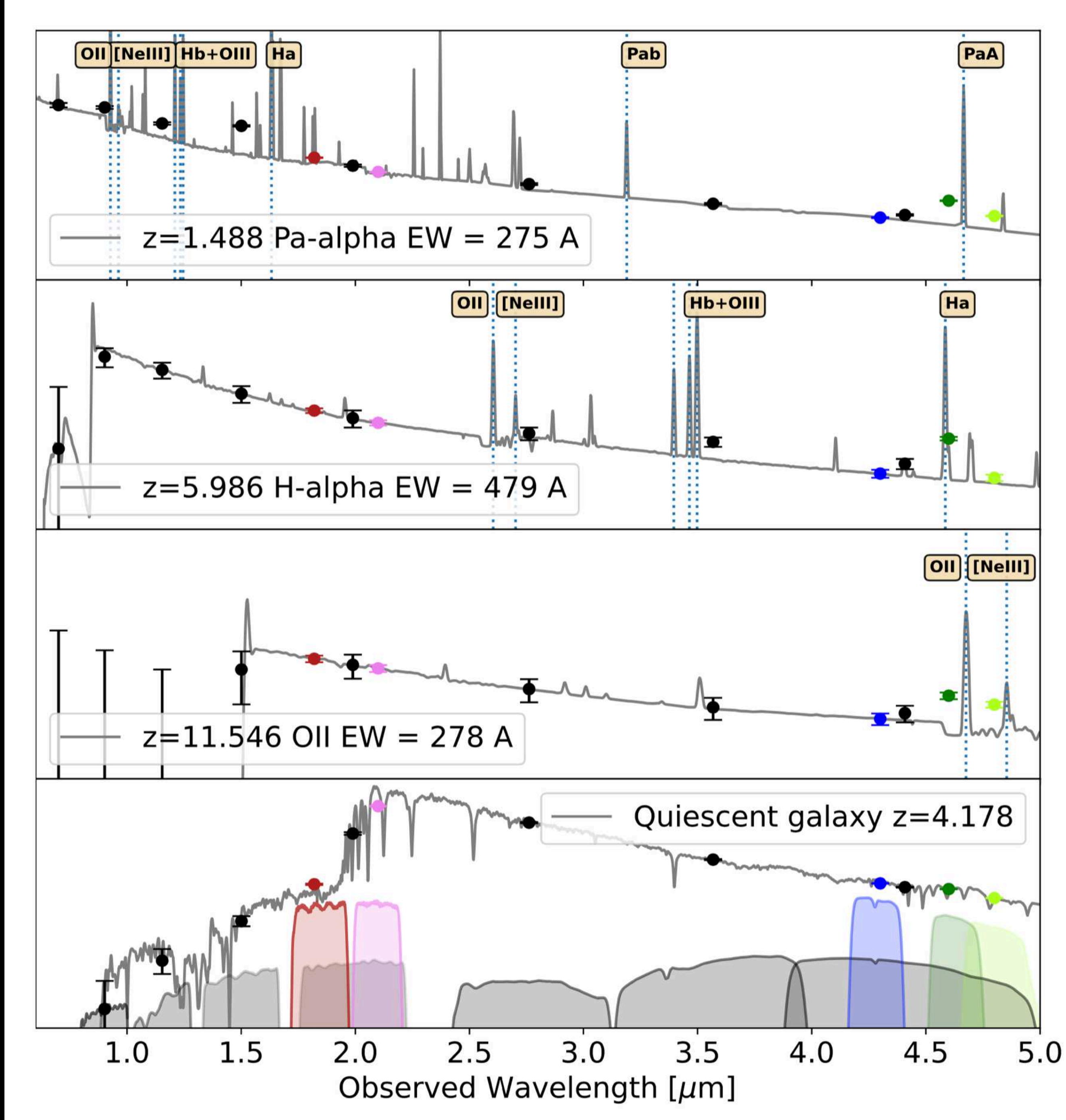
Concentrate on the most dusty (far-IR selected) $A_V\gtrsim$1 objects at z$\gtrsim$2.3!

Micro Shutters

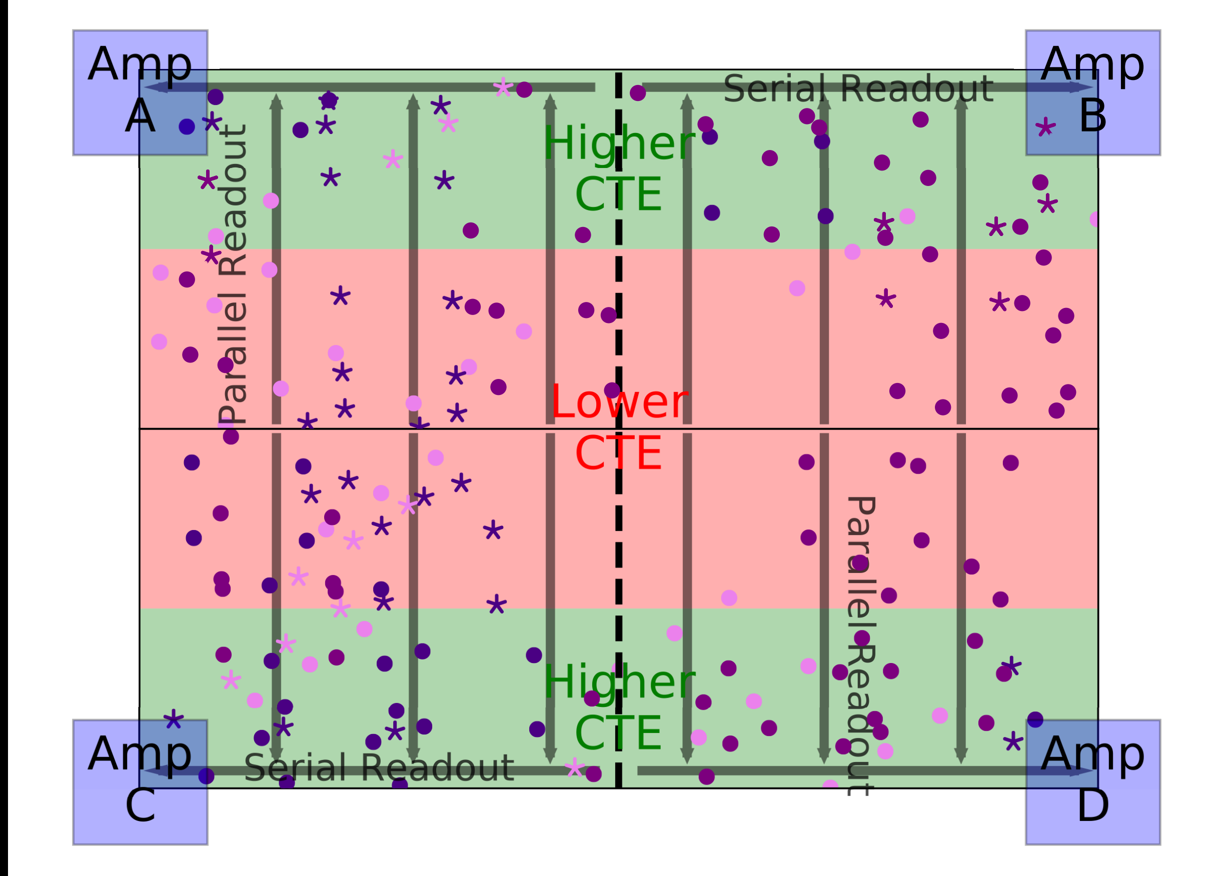








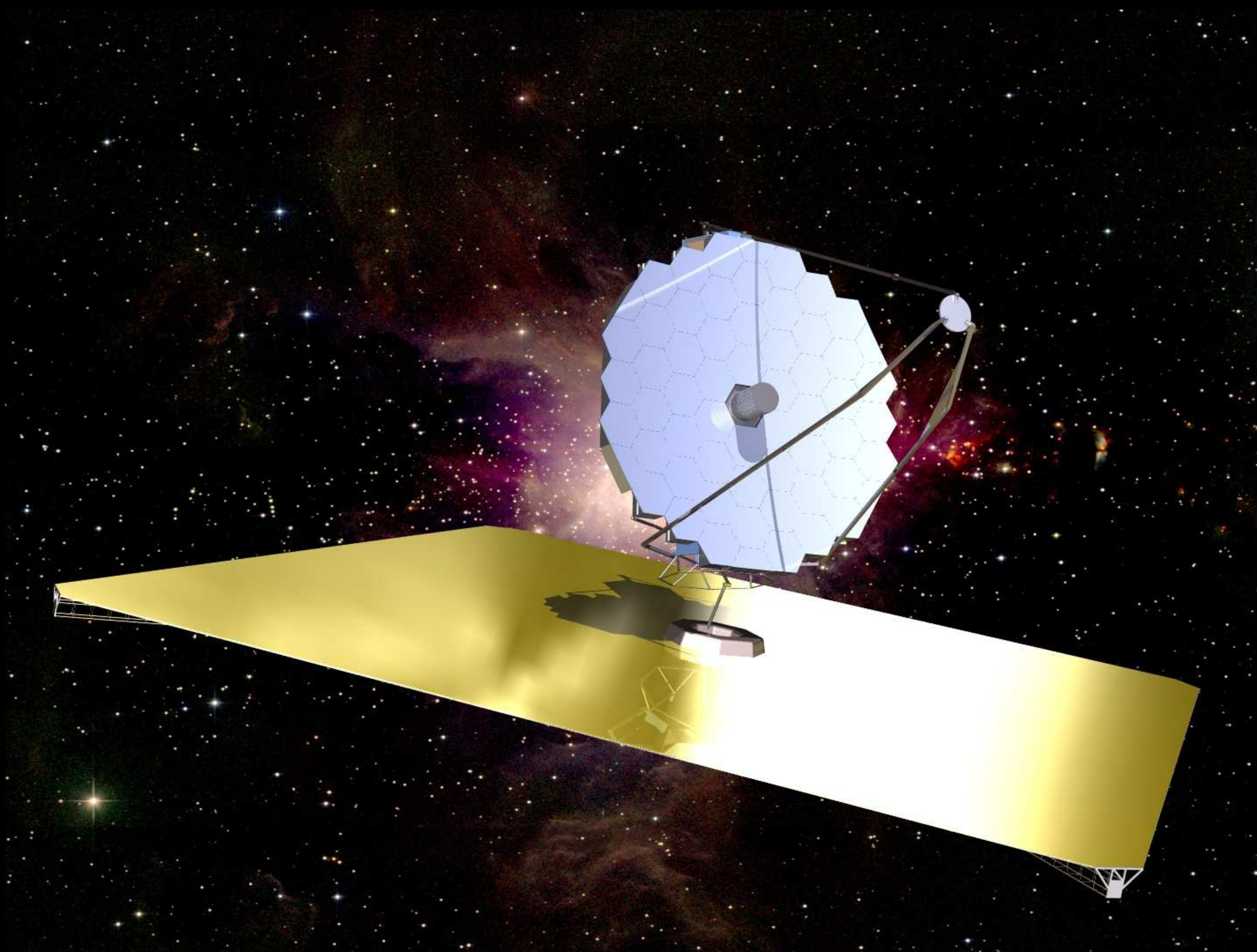
JWST Medium-band Survey of HUDF: strong line-emitting candidates at $1.5 \lesssim z \lesssim 11$ (Williams et al. 2023; astro-ph/2301.09780).



Main CCD LyC limitation: Charge-Transfer Efficiency (CTE) degradation. "Higher-CTE" & "Lower-CTE" sub-samples for WFC3/UV filters:

- Green regions are closest to parallel read-out amplifier. Red regions are furthest from amplifiers, and may suffer more from CTE-degradation.
- Filled circles: objects w/ marginal LyC signal fairly uniformly distributed. Average LyC diff: Δ(Lower-CTE–Higher-CTE)$\lesssim$0.3 mag.

$\Longrightarrow$ Less than four months after WFC3's launch, CTE-induced systematics are not yet larger than the random errors in the LyC signal.



• Next generation $\gtrsim$6-meter UV-optical space telescope (HWO) essential for AB$\lesssim$30 detections and AB$\sim$32 mag for LyC stacks (N$\gtrsim10^4$).

• Need: L2 servicing, periodic CCD replacement, or wide-field UV IFU.

• References and other sources of material

Talk: http://www.asu.edu/clas/hst/www/jwst/nc23_guilfordTCC_lyc_sciencetalk.pdf Data available on:

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