The Need for High-Fidelity, Deep Ultraviolet Space Imaging in the JWST Era

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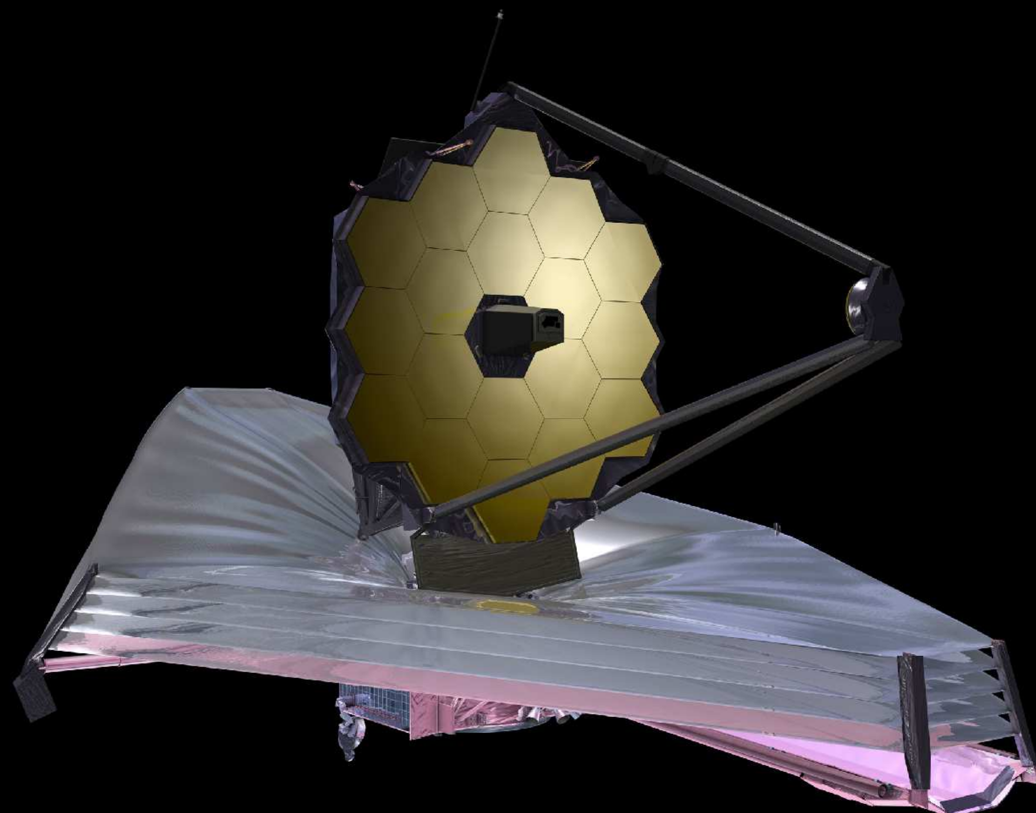


Talk at the Spring 2017 STScI Symposium on "Lifecycle of Metals Throughout the Universe"

Wednesday April 27, 2017; STScI, Baltimore, MD

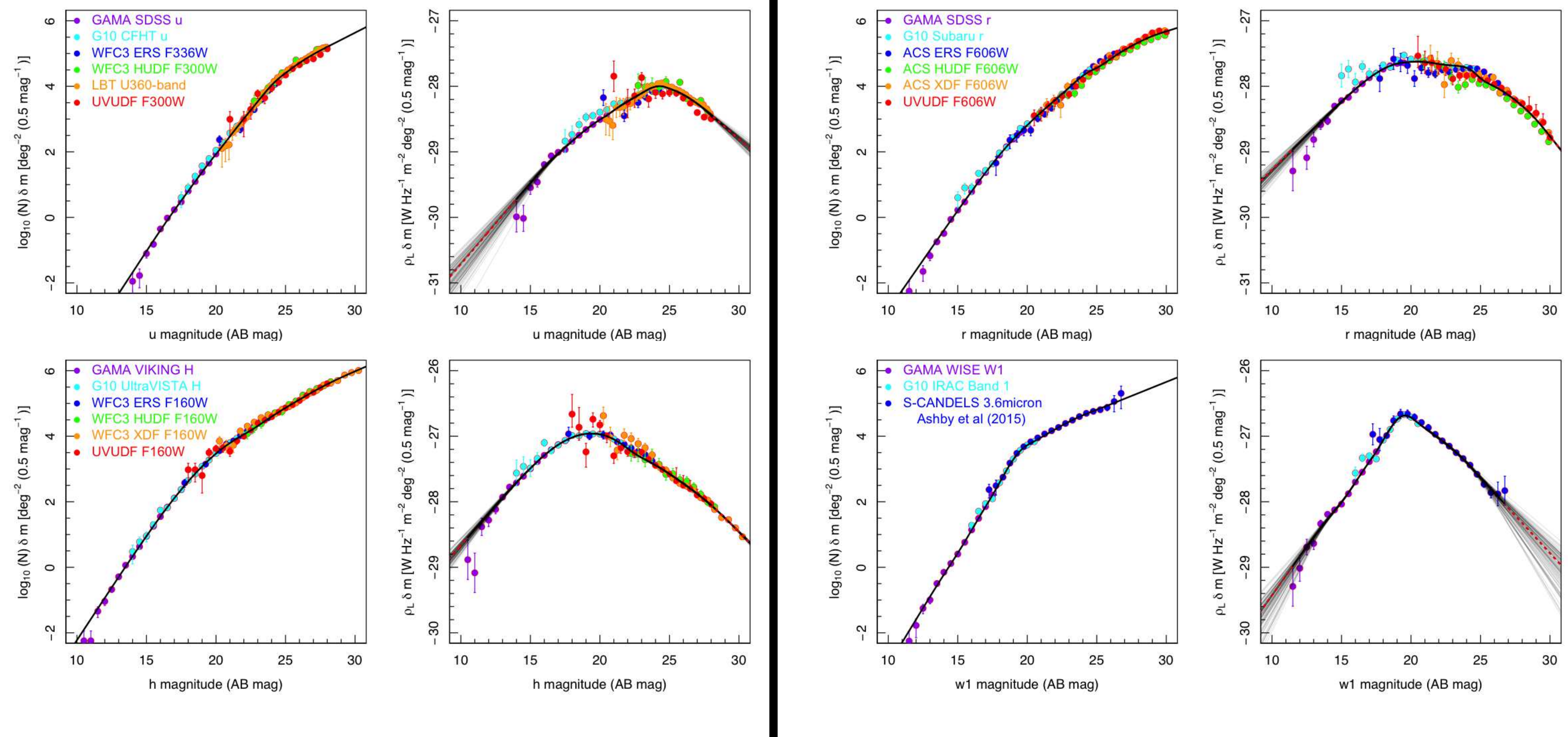
Outline

- (1) Extragalactic Background Light: Stars/Dust-energy $\simeq$ 50/50 %.
- (2) Power of Pristine HST WFC3 data for LyC Stacking.
- (3) Stacked Lyman-Continuum and UV-Continuum Light-Profiles.
- (4) LyC Escape vs. Redshift for Faint Galaxies & Weak AGN.
- (5) What will JWST & ATLAST do for LyC Escape studies?
- (6) Summary and Conclusions

Arizona State University

Sponsored by NASA/HST & JWST

Talk on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/stsci17_uvforjwst.pdf`

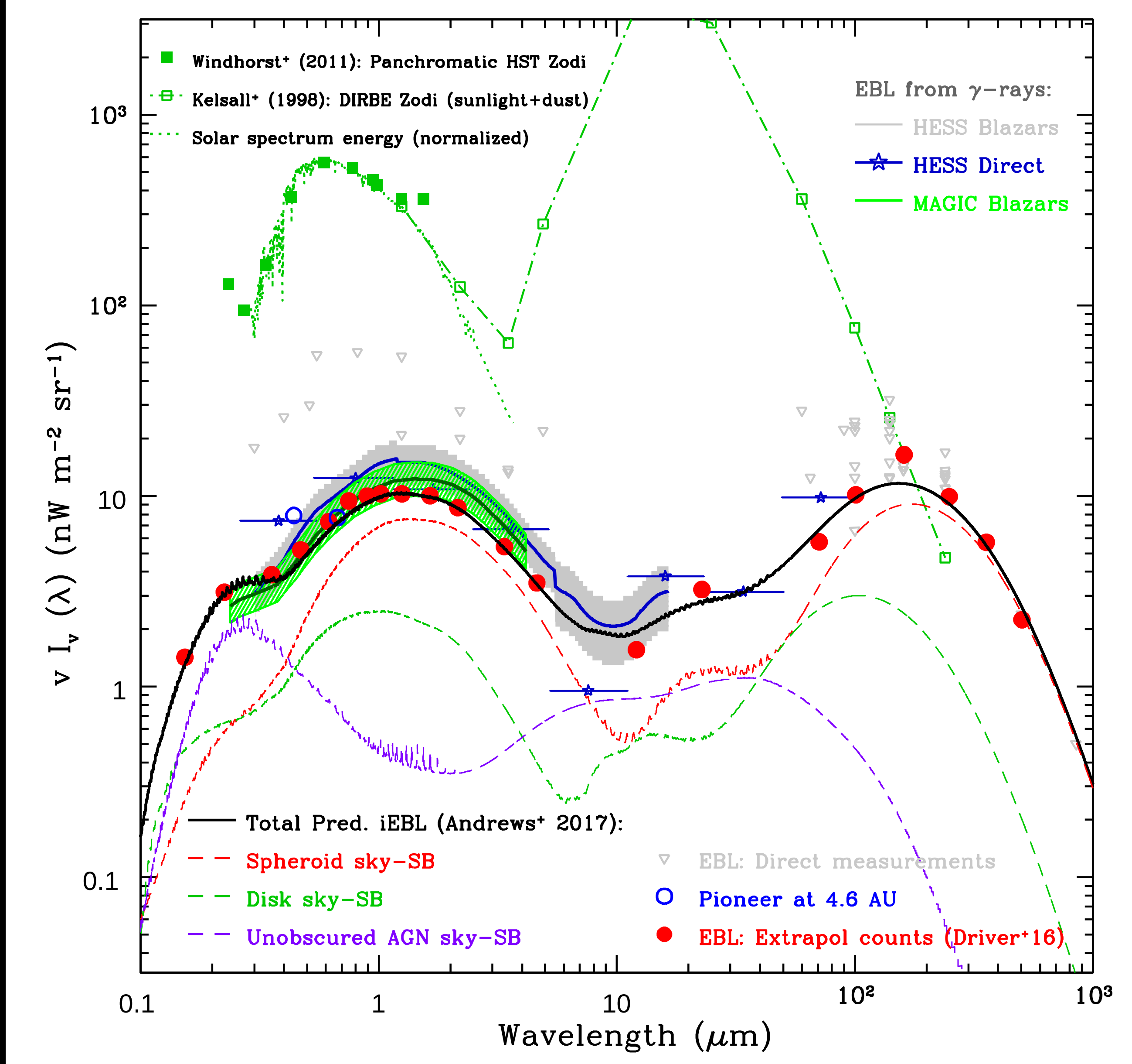


[Left panel in each pair]: Panchromatic 0.3–3.6 μm galaxy counts.

[Right panel in each pair]: Object counts normalized to α=0.4 slope.

- Integrated, extrapolated counts yield Extragalactic Background Light (EBL) with MC errors $\lesssim$10–20% (Driver$^+$ 2016, ApJ, 827, 108).

- At all 21 GAMA wavelengths (0.15–500 μm), counts attain converging slope (α <0.4) for AB$\gtrsim$18–25 mag $\Longrightarrow$ integrated, extrapolated EBL.



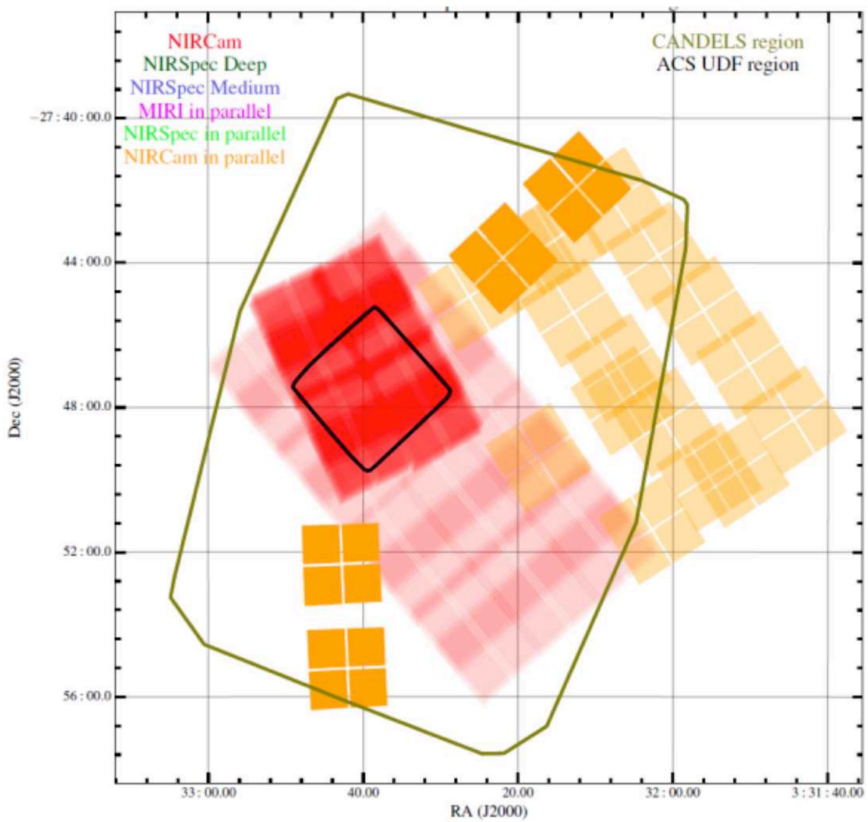
iEBL measurements of (Driver+ 16) compared to Andrews+ 17 models (MNRAS 464, 1569): Cosmic optical/far-IR background ≃ 48 / 52 %.

- iEBL consistent with Zodi-independent Blazar & Pioneer/NH constraints.
- Unobscured (weak) AGN contribute to sky-energy at $\lambda \lesssim 0.3\mu$m!

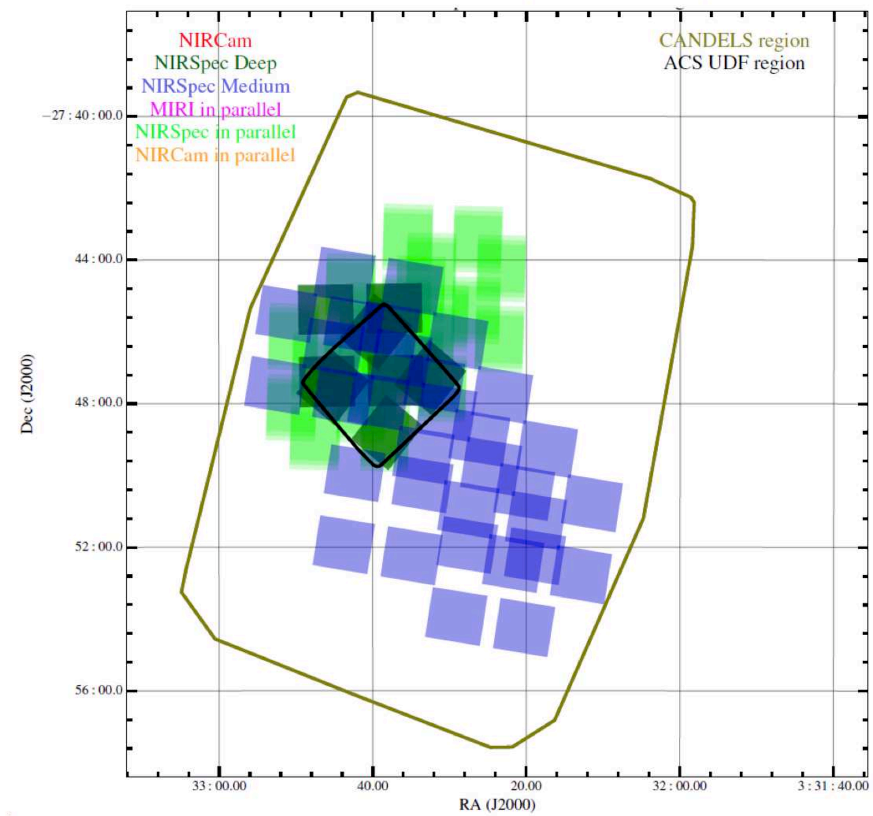
Science Preparations

- The NIRCam Team submitted a program to use all of its 900 hours of observing time in Cycle 1.
- The single largest chunk of time (425 hrs) will be used in a collaborative program with the NIRSpec GTO team (contributing 348 hrs) to study galaxy evolution. Both NIRSpec GTOs and NIRCam GTOs have worked very hard on this plan!

Proposed NIRCam UDF imaging.



Proposed NIRSpec UDF MOS spectroscopy



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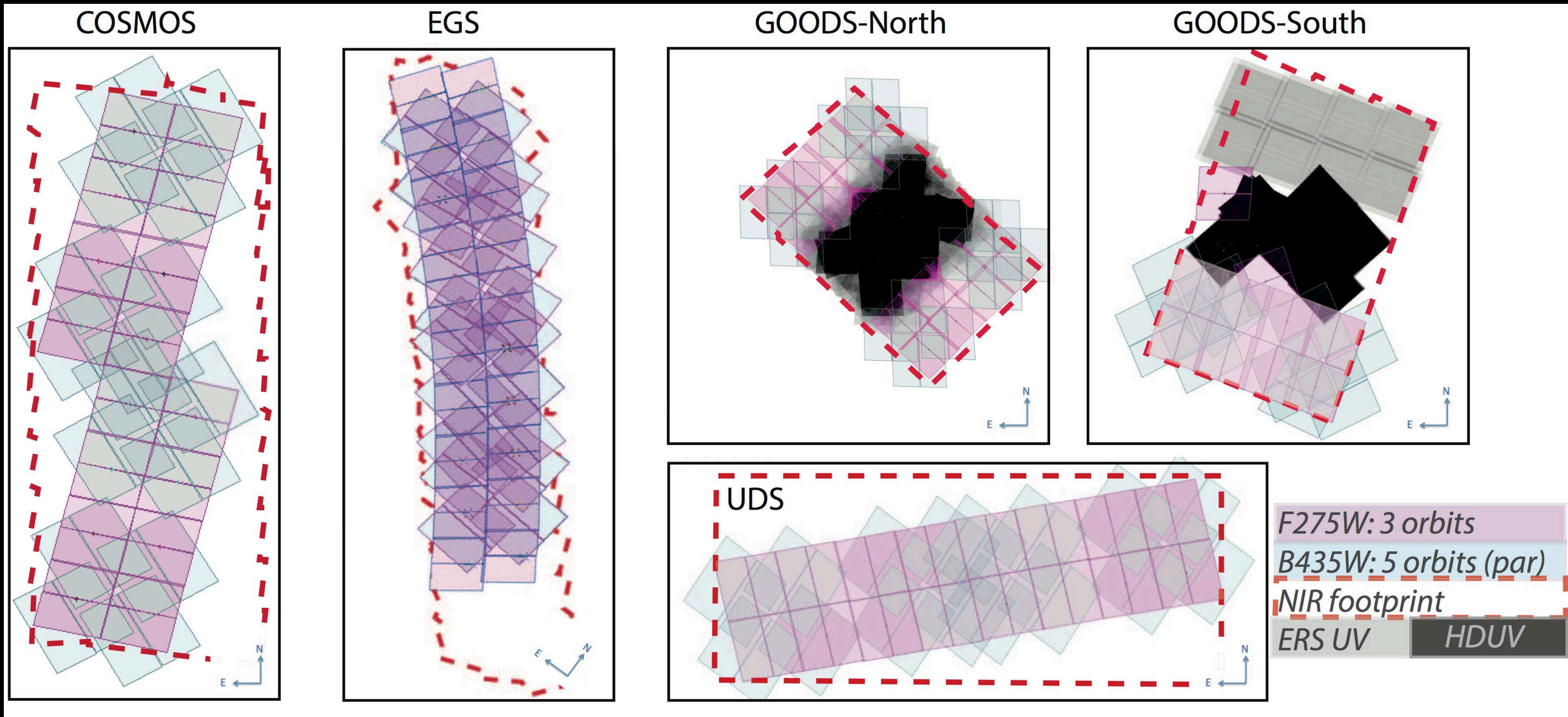
Many 100's of deep field hours will be spent in JWST Cycle 1 at $\lambda \gtrsim 0.9\mu$m.

Figure courtesy of Dr. Marcia Rieke, Christopher Willmer (UofA), & Chris Willott (Victoria).



(See Harry Teplitz's talk).

Many 100's of deep field hours will be spent in JWST Cycle 1 at $\lambda \gtrsim 0.9 \mu$m.

- Likely, this will become 1000's of hours during JWST's lifetime!

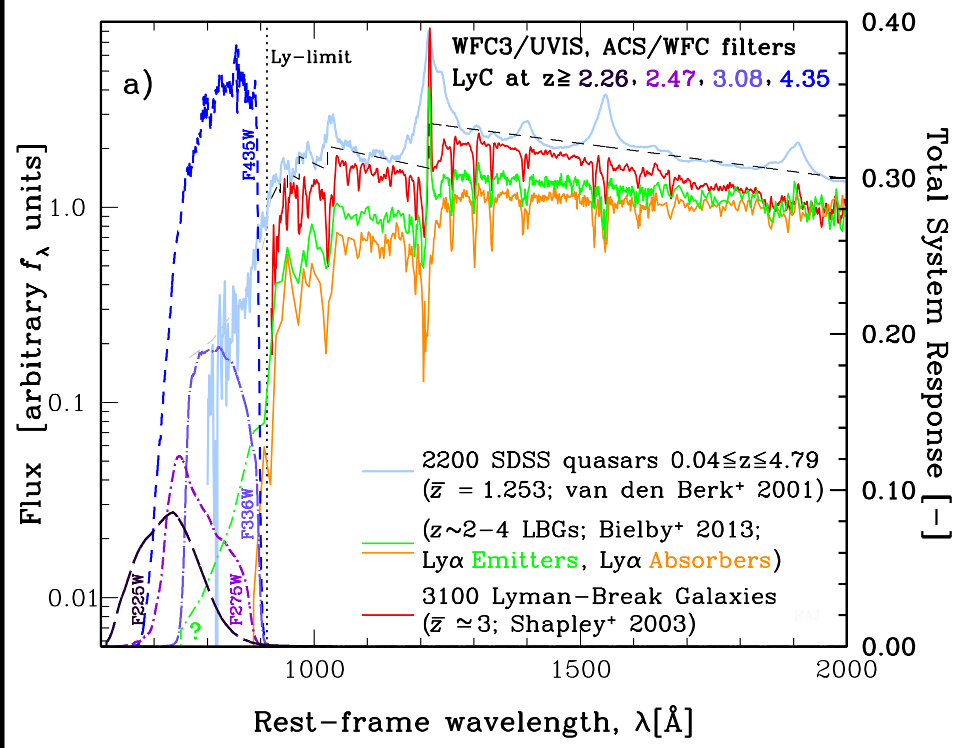
We will forever regret not having WFC3 UV-imaging of JWST survey fields!

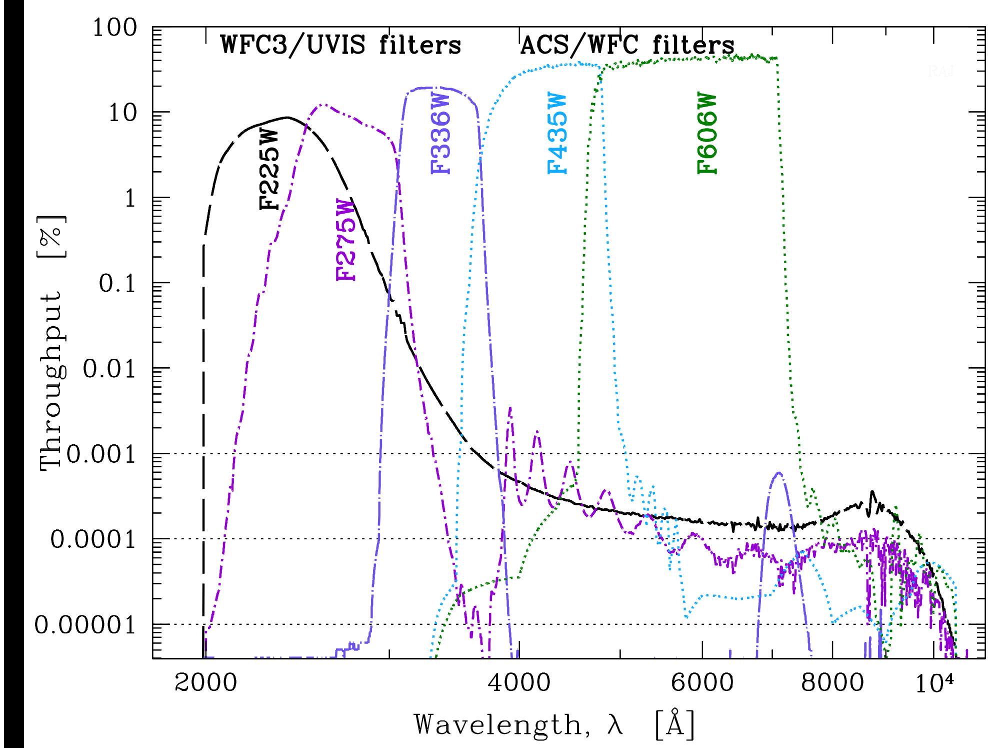
We must take the HST-unique UV images of the likely JWST survey fields!

Remember: Half the cosmic SF-energy can make it past the dust just fine!

(2) Power of Pristine HST WFC3 data for LyC Stacking: the ERS field.

10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).
(JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm + 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust).





[LEFT] Composite rest-frame far-UV spectra of:

SDSS QSOs at z≃1.3 (van den Berk et al. 2001);

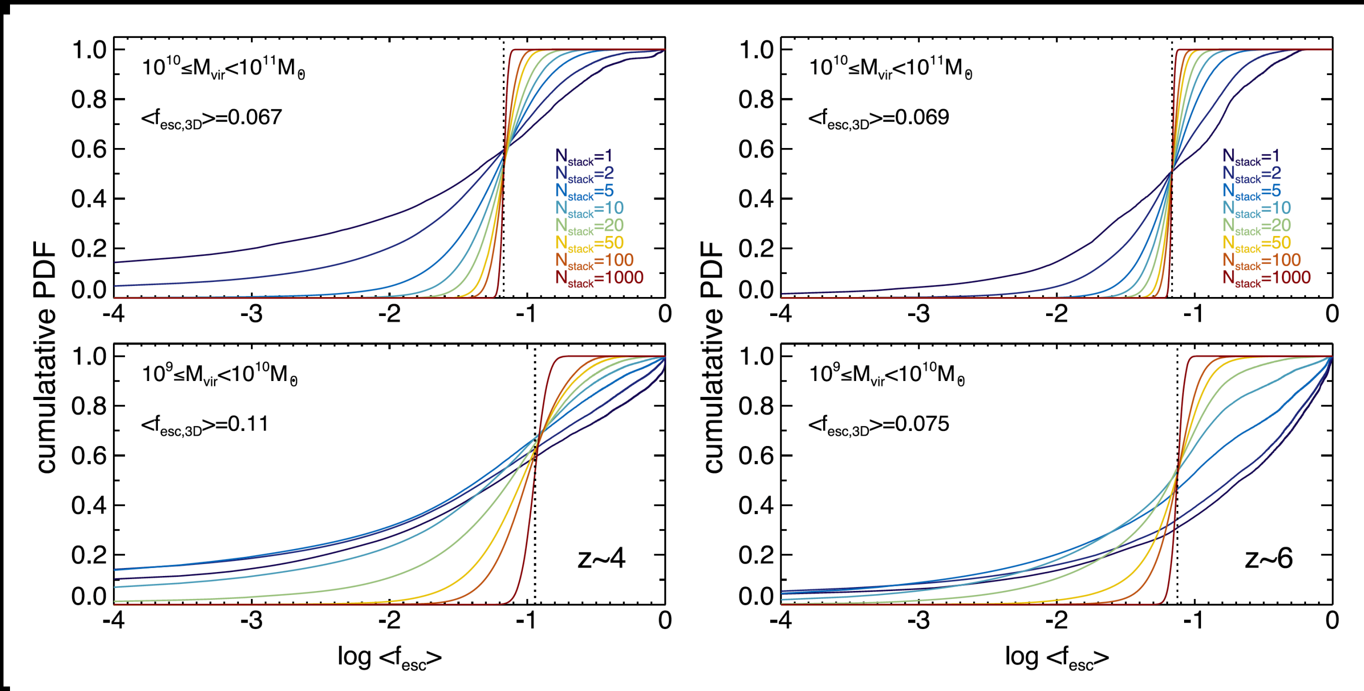
LBGs at z≃3 (Shapley et al. 2003);

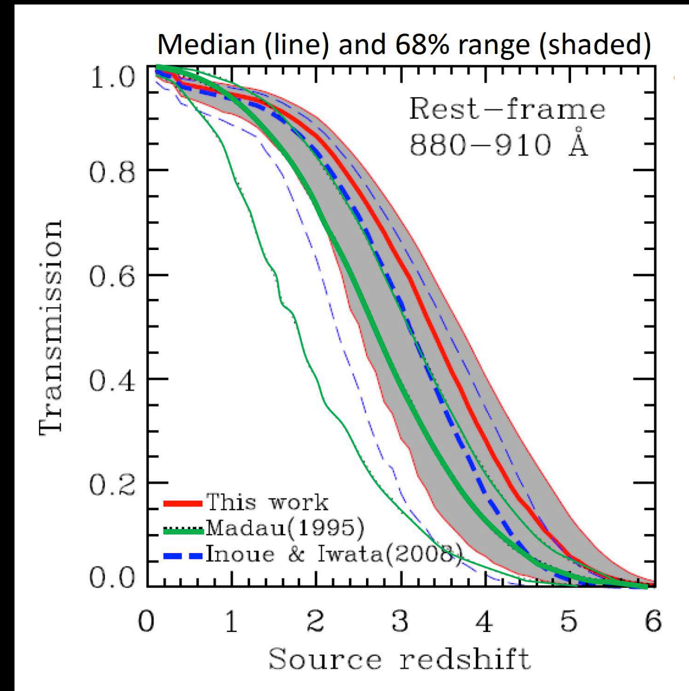
LBGs at z≃2–4 (Bielby et al. 2013, Lyα emitters, & absorbers).

- WFC3 F225W, F275W, F336W filters: LyC at z≥2.26, z≥2.47, z≥3.08.

[RIGHT] Total observed throughput curves, designed to maximize throughput and minimize red-leak, which is $\lesssim$0.6% of actual LyC signal.

- Filter red-leak wing ($\lambda \gtrsim$ 3648Å) is $\lesssim 3\times10^{-5}$ of peak transmission.





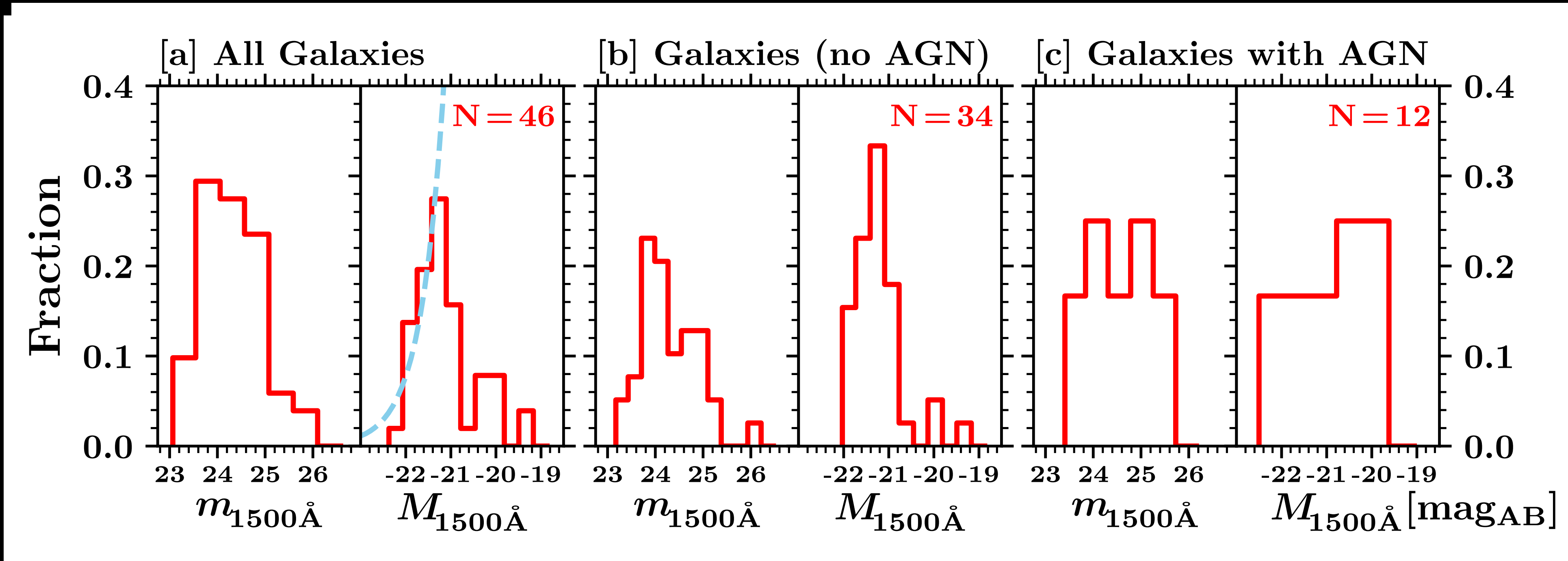
[LEFT] Cen & Kimm (2015): Simulated f_{esc} from stacking many objects: high-mass (top) & low-mass (bottom). ERS has N≃12–34 objects.

- Input f_{esc} values are reached when stacking many dozen objects.

[RIGHT] Inoue^{+} (2014): IGM transmission models for f_{esc}-calculations: Red is median and grey 68% range, based on MC simulations of $T_{IGM}(z)$.

- Uses updated absorber function+available data on Lyα forest, Damped Lyman Alpha (DLA) & Lyman Limit Systems (LLS) mean-free paths.

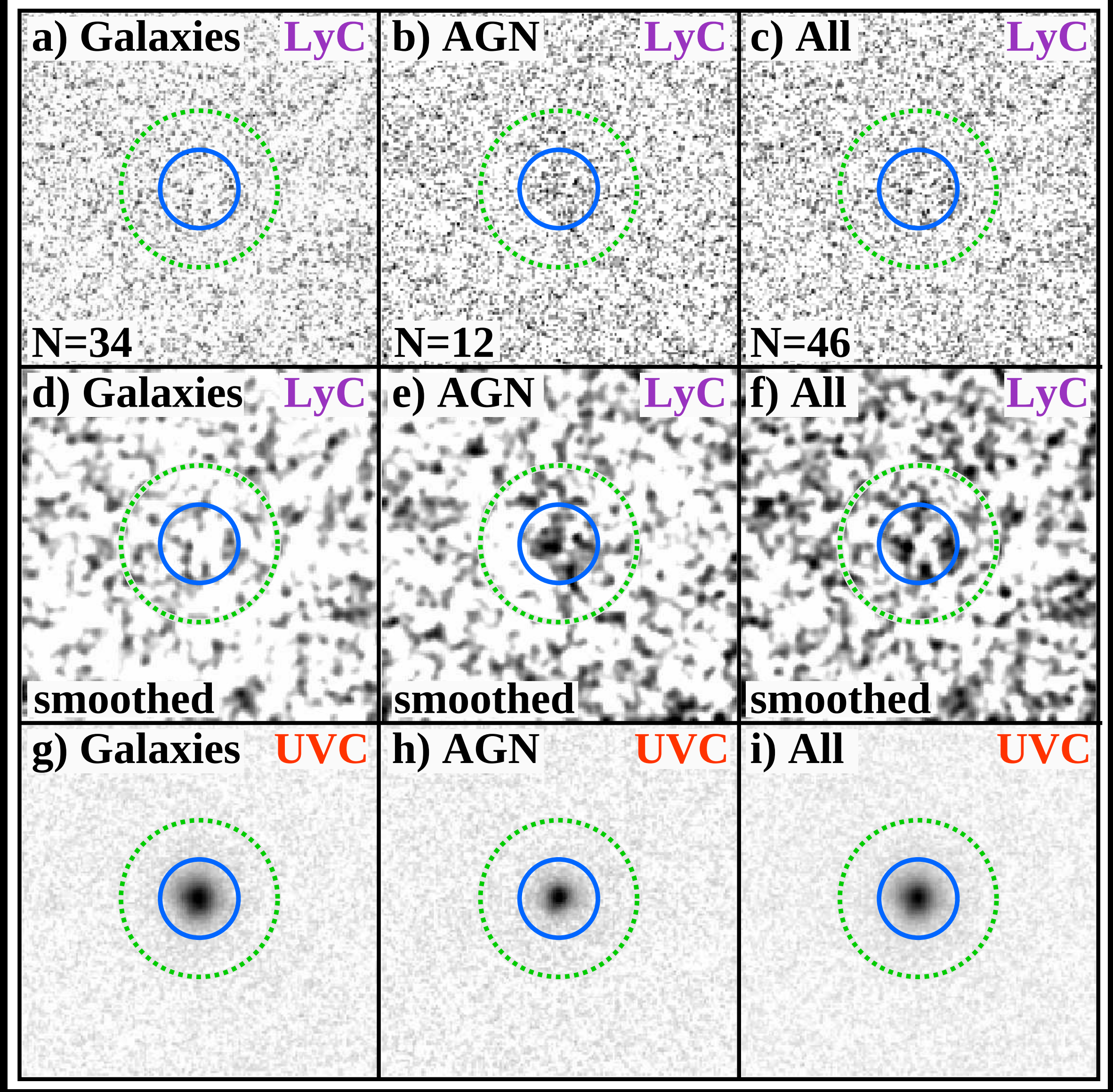
(2) Hubble WFC3 ERS field — Spectroscopic Sample Selection



Apparent and absolute magnitude distributions for most reliable redshift samples using all available VLT, Keck + HST grism spectra.

- Sample incompleteness starts at AB$\gtrsim$24 or M_{AB} (1550)$\gtrsim$–21 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.

(For details on ERS LyC sample, see: Smith et al. astro-ph/1602.01555)



Top/Middle: Weighted LyC stacks of galaxies and weak AGN at z=2.26–4.

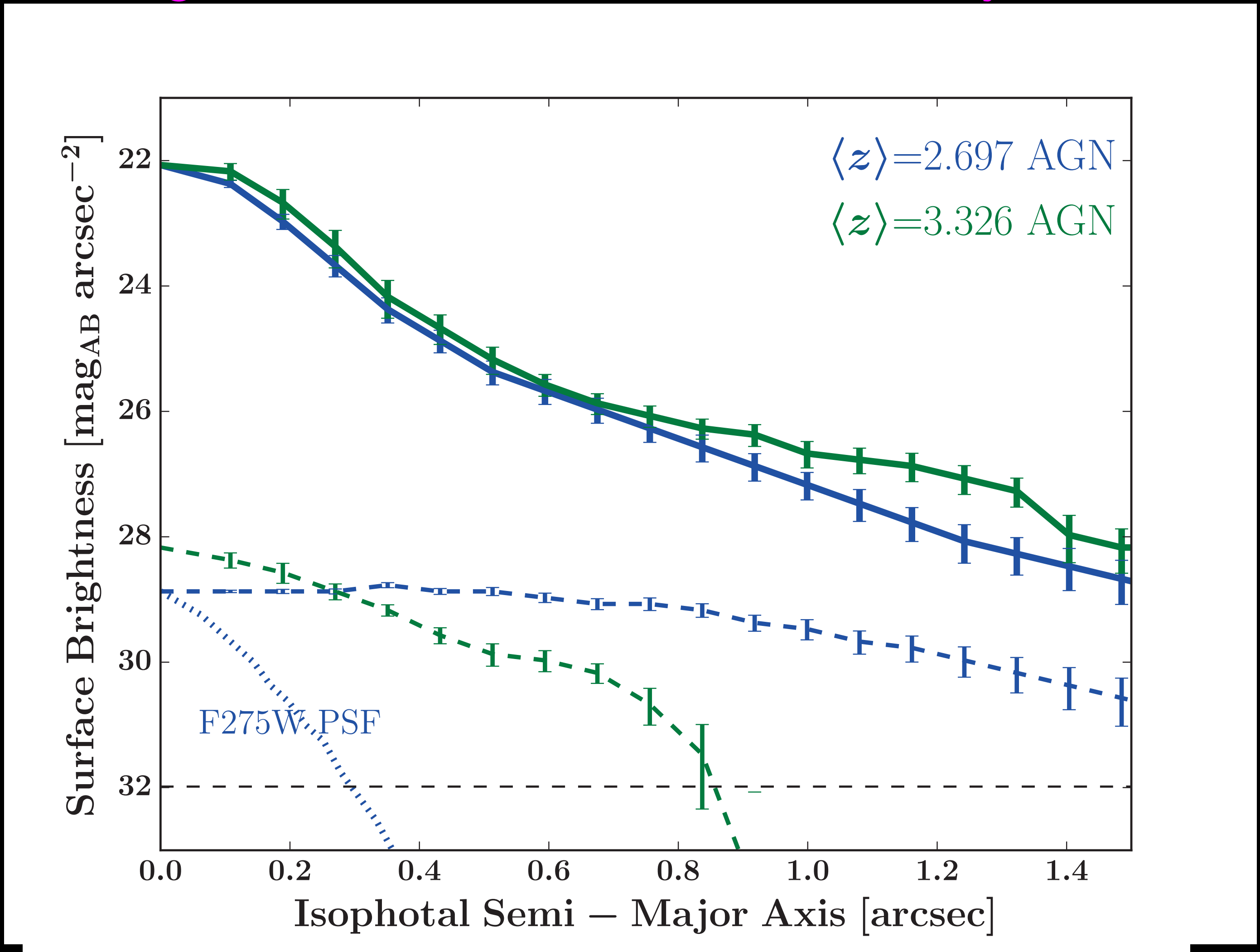
(WFC3: F225W z=2.26–2.47, F275W z=2.47–3.08, F336W z=3.08–4).

Bottom: WFC3 + ACS UV-Continuum stacks (restframe ∼1550 Å).

- Masked *all* interlopers from 10-band χ^2 -stack to AB$\lesssim$28.5 mag.

AGN have LyC $\simeq$ 27.4-28.3 mag ($\gtrsim$2.7σ); Galaxies have LyC $\gtrsim$28.5 mag.

(3) Stacked Light-Profiles: UV-Continuum and Lyman-Continuum



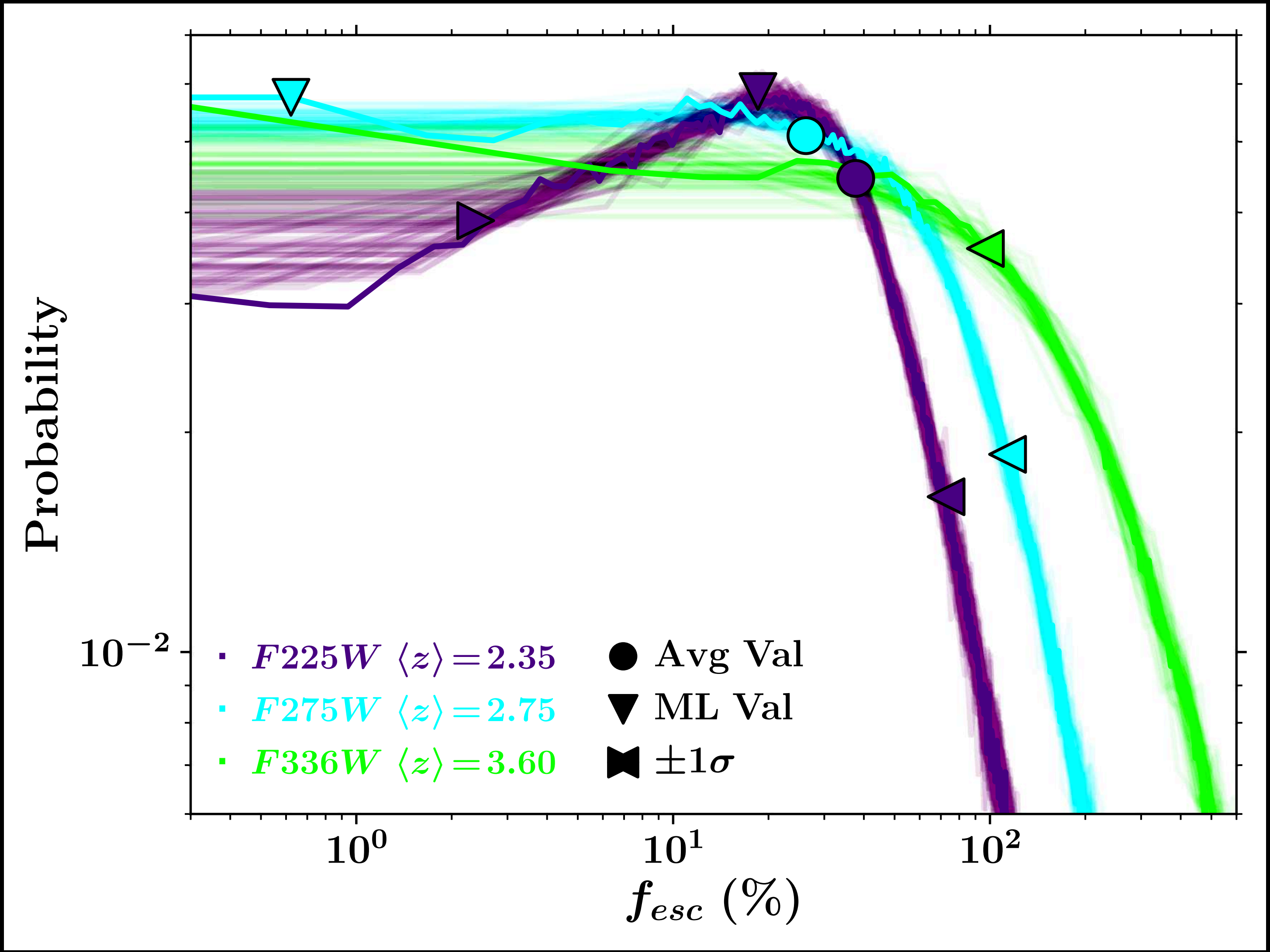
[*Top Curves*]: Radial SB-profiles of stacked non-ionizing UVC (*solid*).

[*Bottom Curves*]: Radial SB-profiles of stacked LyC signal (*dashed*):

The faint LyC emission has a very flat SB-distribution with radius:

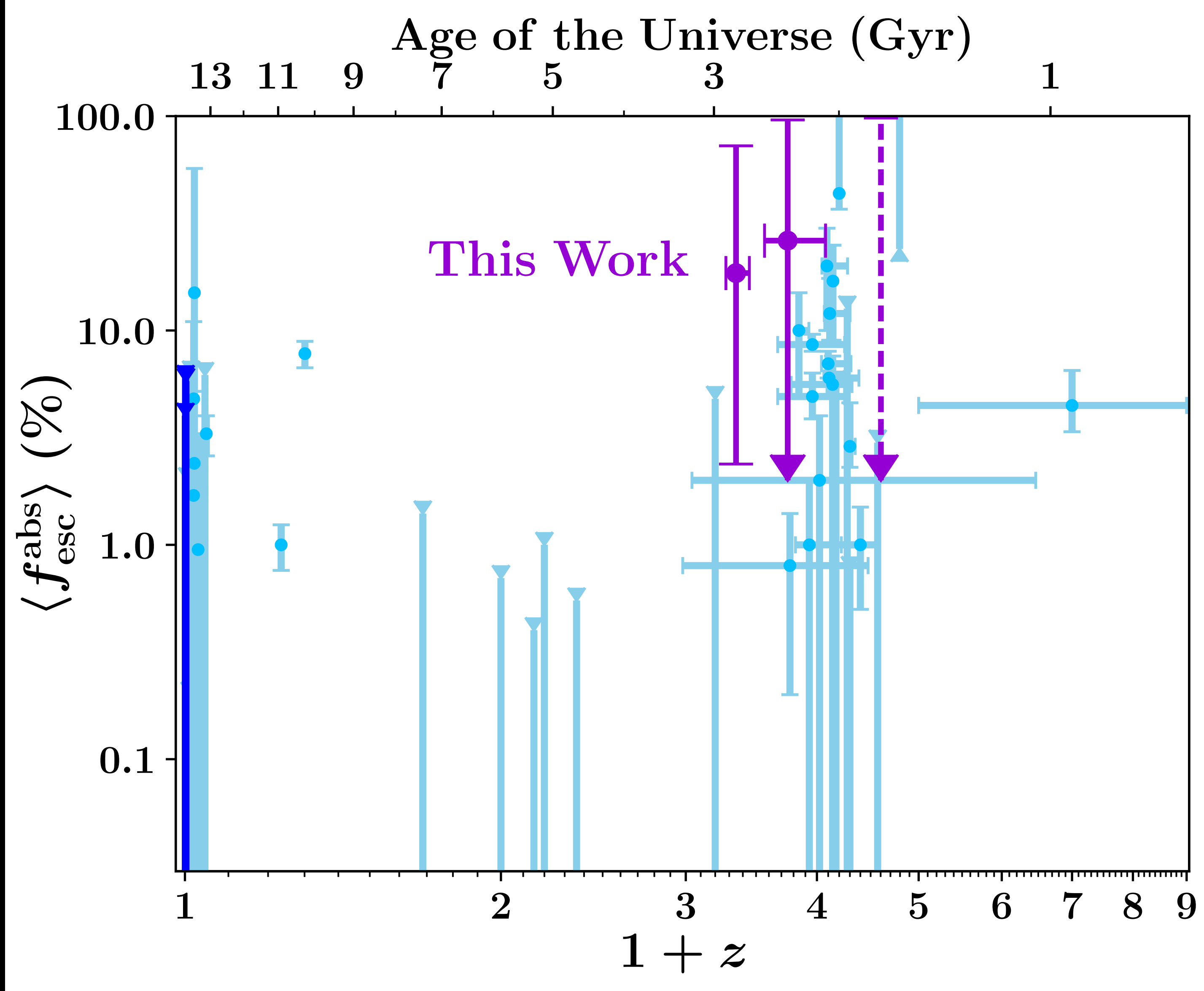
- Not centrally concentrated, with few clear sight-lines per galaxy.
- *On average* escapes along few random sight-lines through a porous ISM?

(4) LyC Escape vs. Redshift for faint Galaxies & Weak AGN



PDF of absolute f_{esc} -values (Inoue$^+$ 2014 Monte Carlo), folding LyC fluxes $\pm$ 1σ errors through 10^9 random LOS of IGM transmission.

- Downward triangles indicate the modal, and circles the average f_{esc} -values in each PDF.



f_{esc} -z: Published+ERS: (M_{AB} ≃–20 to –21; Dark: M_{AB} ≃–17 mag).

f_{esc} seems to increase at z≳2: Just high enough to maintain reionization?

- LyC for 12 weak AGN ∼3× higher than for 34 ERS galaxies ⟹ Weak AGN & galaxies may *both* contribute to reionization at 2.3≲z≲3.5.

(5) What will JWST & ATLAST do for LyC Escape studies?

JWST FGS+NIRCam: R≃150, 0.8–5.0μm grism spectra to AB≲28:

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

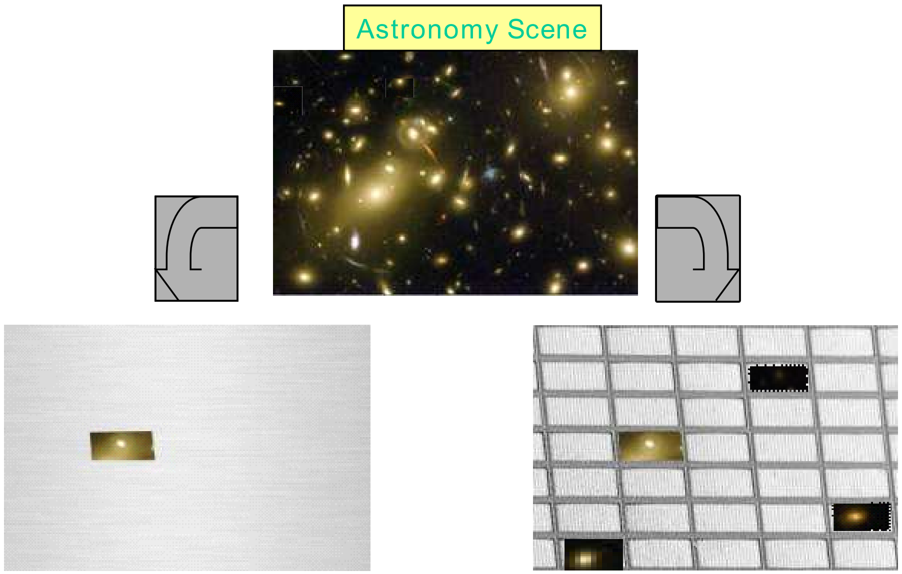
NIRSpec: JWST's short-wavelength (λ≃1–5.0μm) spectrograph:

- 100's of simultaneous faint-object spectra of LyC candidates to AB≲27.

Concentrate on galaxies *and* weak AGN at z≳2.3 with WFC3 UV-images.

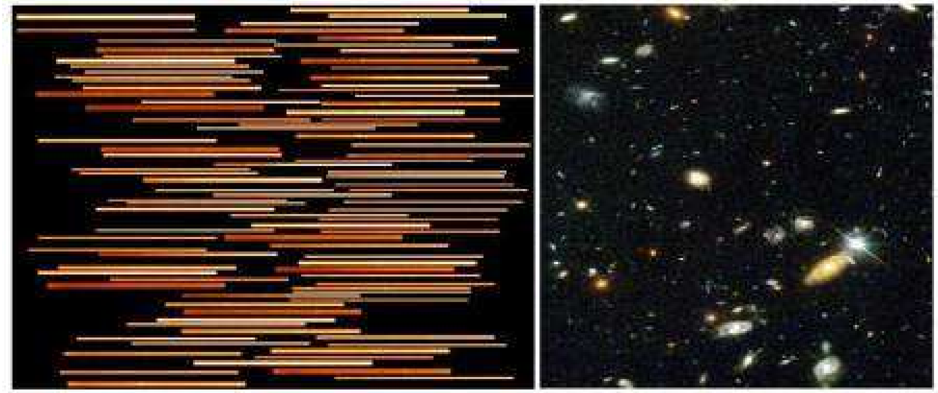
- 12 m ATLAST (or 2.5 m ANUBIS) will 100-fold LyC imaging samples.

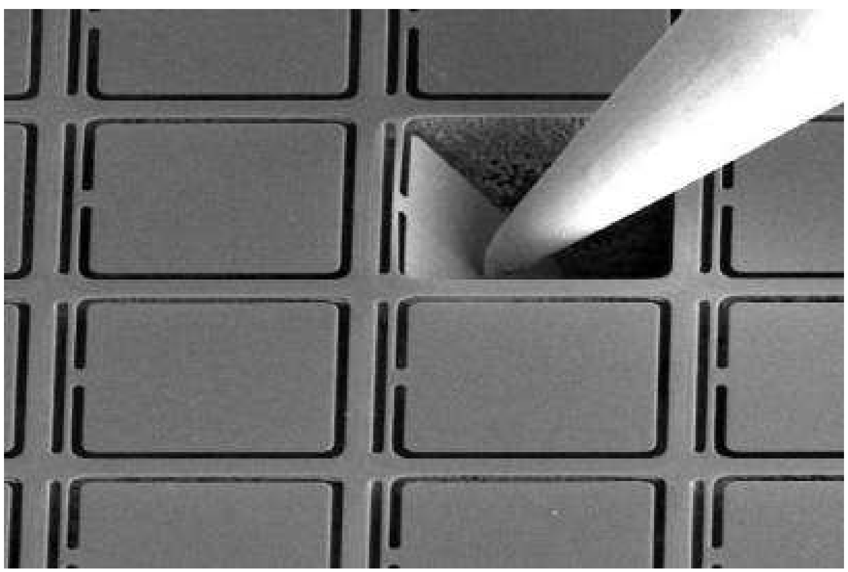
Micro Shutters



Metal Mask/Fixed Slit

Shutter Mask





(6) Summary and Conclusions

(1) 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.
- Careful spectroscopic redshift selection critical for reliable samples.
- Deepest 10-band HST images mask all foreground interlopers to AB$\lesssim$27.5.
- Samples of many dozens needed to detect stacked LyC signal.

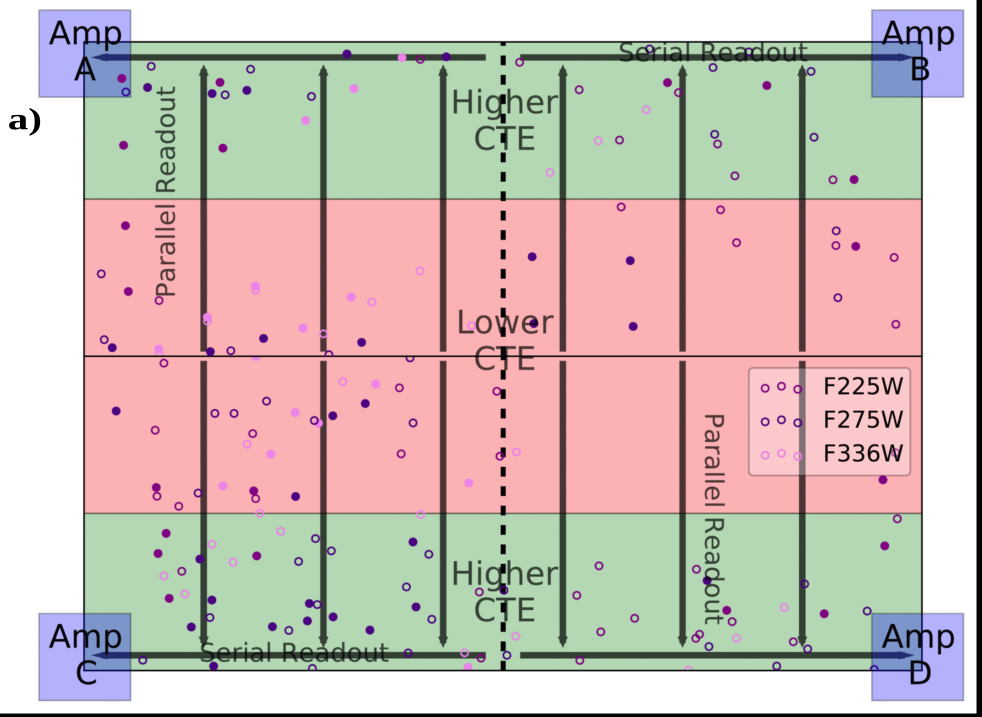
(2) Marginal LyC signal in stacks of N=12–34 objects at z=2.3–3.5.

- Weak AGN 3$\times$brighter in LyC, but 3$\times$ less numerous than galaxies.
- Stacked AGN LyC SB-profiles flatter than the UV-continuum profile.
- LyC escapes along few sight-lines offset from galaxy center: Outflows? Or ISM-porosity increases with galaxy radius?

(3) f_{esc} (z) may be just large enough ($\gtrsim$10%) at z$\gtrsim$2.3 for reionization?

- LyC of weak AGN as important as faint galaxies at 2.3$\lesssim$z$\lesssim$3.5.
- Need JWST NIRISS + NIRSpec spectra for LyC objects to AB$\lesssim$28 mag.
- Need 2–12m UV telescopes (ANUBIS, ATLAST) to sample many 100's.

SPARE CHARTS



Detector location of "high-CTE" and "low-CTE" sub-samples: WFC3/UVIS F225W, F275W, F336W.

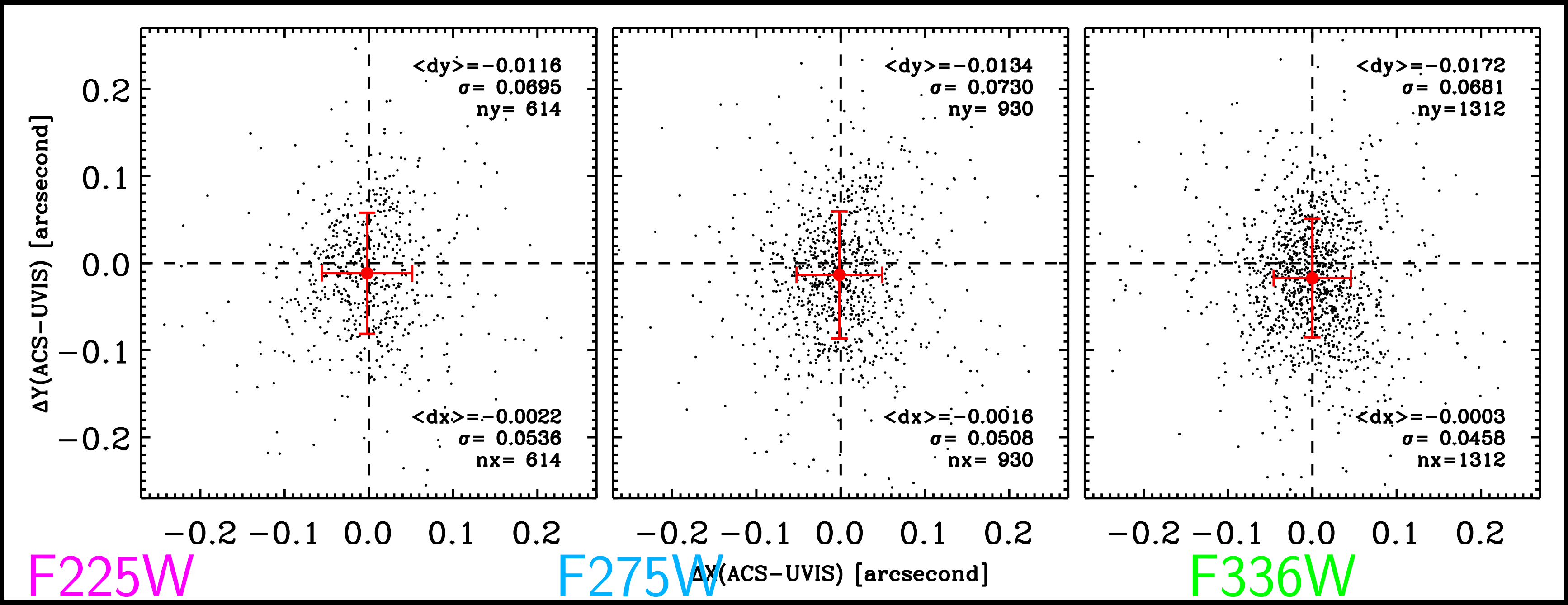
Green regions are closest to parallel read-out amplifier. Red regions are furthest from amplifiers, and may suffer more from CTE-degradation.

- Filled circles show marginal LyC signal in individual objects:
- These are fairly uniformly distributed across individual CCDs.

Average stacked LyC diff: Δ(Lower-CTE–High-CTE) $\lesssim$0.35 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.

(2) WFC3 & ACS Lyman Continuum Stacking, Systematics, & Fluxes



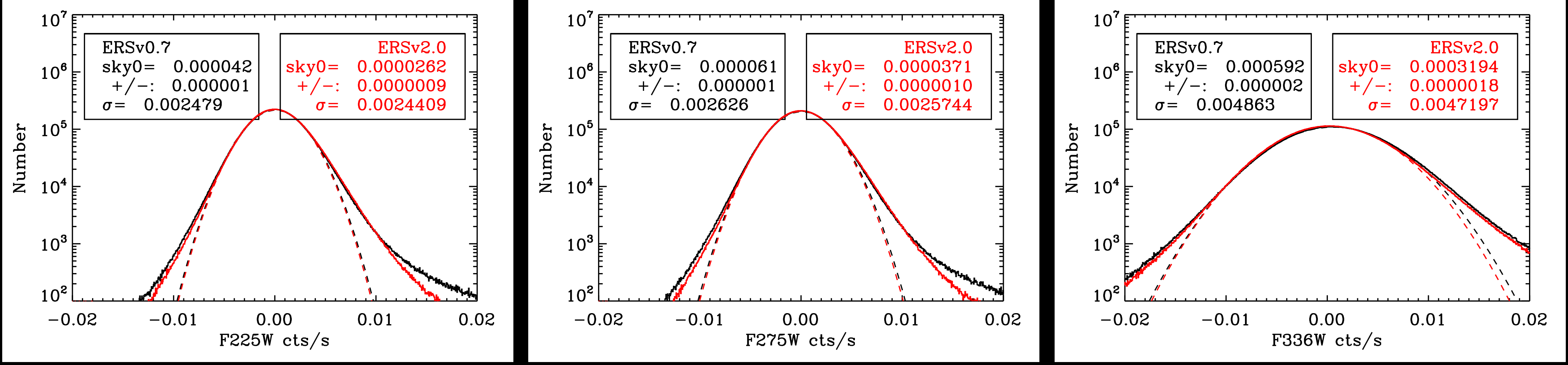
The first & hardest part was to get the WFC3 astrometry right:

- Pre-flight 2009 ERS geo-distortion had $\lesssim$0.″45 offsets at image borders compared to GOODS v2.0 (Windhorst et al. 2011 ApJS, 193, 27).

- In-flight 2013 geo-distortion correction yielded excellent registration of all WFC3/UVIS tiles to the ACS F435W mosaics (Kozhurina et al. 2014).

- Compared to GOODS, all offsets are now $\lesssim$0.″02 ±0.06 (rms) in all LyC filters (Smith et al. 2017) — this no longer blurs any LyC signal!

- Any LyC signal can now be measured and stacked, including removal of all foreground interlopers (AB$\lesssim$27.5), and measurement of LyC light-profiles.

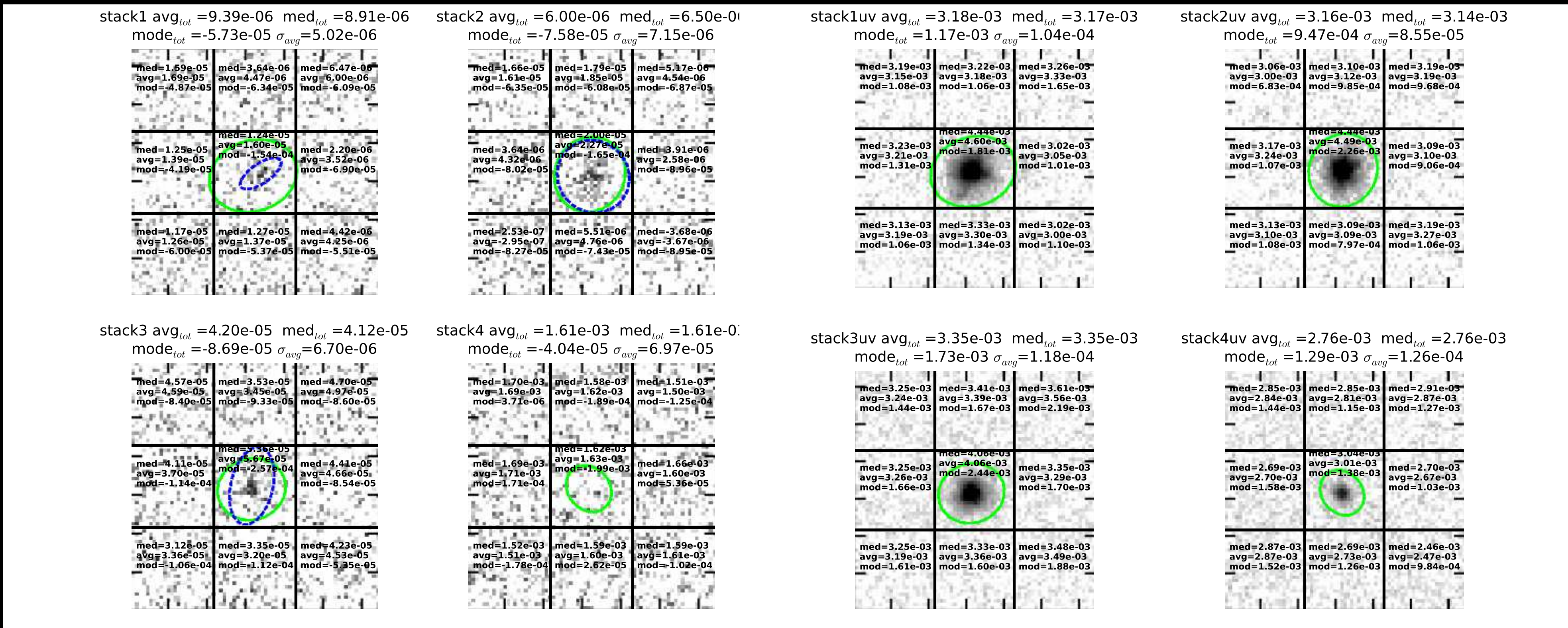


Residual sky-background levels in the drizzled WFC3/UVIS ERS mosaics:

- Black lines: Best fit to the 2009 ERS v0.7 mosaics of Windhorst et al. (2011), which used pre-flight thermal vacuum flat-fields.
- Red lines: Current mosaics (ERS v2.0; Smith et al. 2017), using best available on-orbit calibrations.

- Global *residual sky-background levels (in ADU/sec)* remaining after drizzling the ERS mosaics are ∼30.29, 29.99, and 28.15 mag arcsec^{-2} .
- Removed in 3 stages: globally during drizzling (zodi≃25.5 mag/"^{2}), locally before stacking, and again locally after stacking (to do photometry). This is absolutely critical for optimal LyC stacking.
- Final 71×71 pix (6."39×6."39) LyC stacks allow *residual* local sky-subtraction to ≲32.3 mag arcsec^{-2} .

(2) WFC3 & ACS Lyman Continuum Stacking, Systematics, & Fluxes

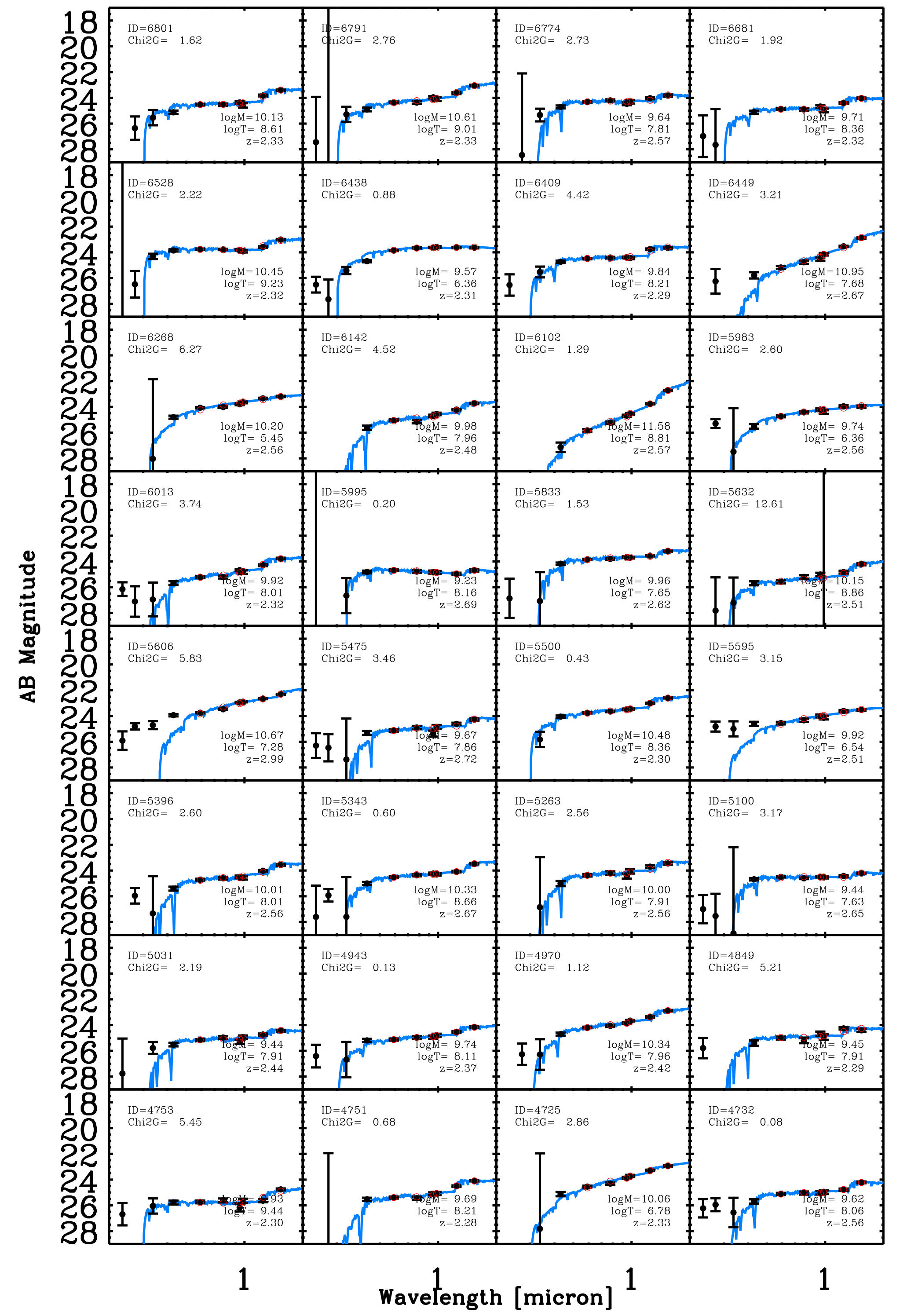


"Tic-tac-toe" sky-background analysis of 71×71 pixel (6.″39×6.″39) stacks: LyC [*left 4 panels*] and UVC [*right 4 panels*].

- Sky-background subtracted in 3 stages: *more globally* upon drizzling, *locally* before stacking, and *locally* before final photometry.

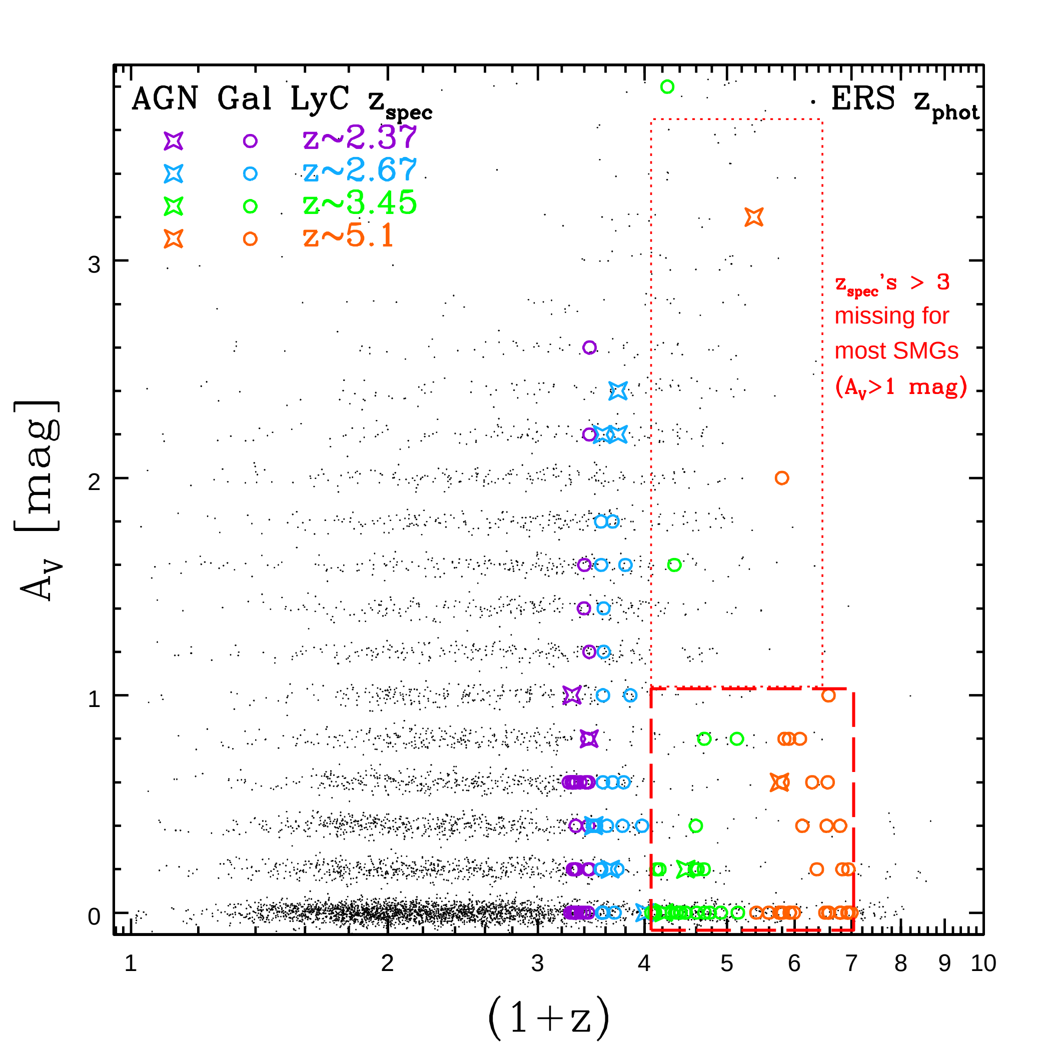
- Residual UV sky-gradients fainter than ∼32.3 mag arcsec^{-2} across photometric apertures.

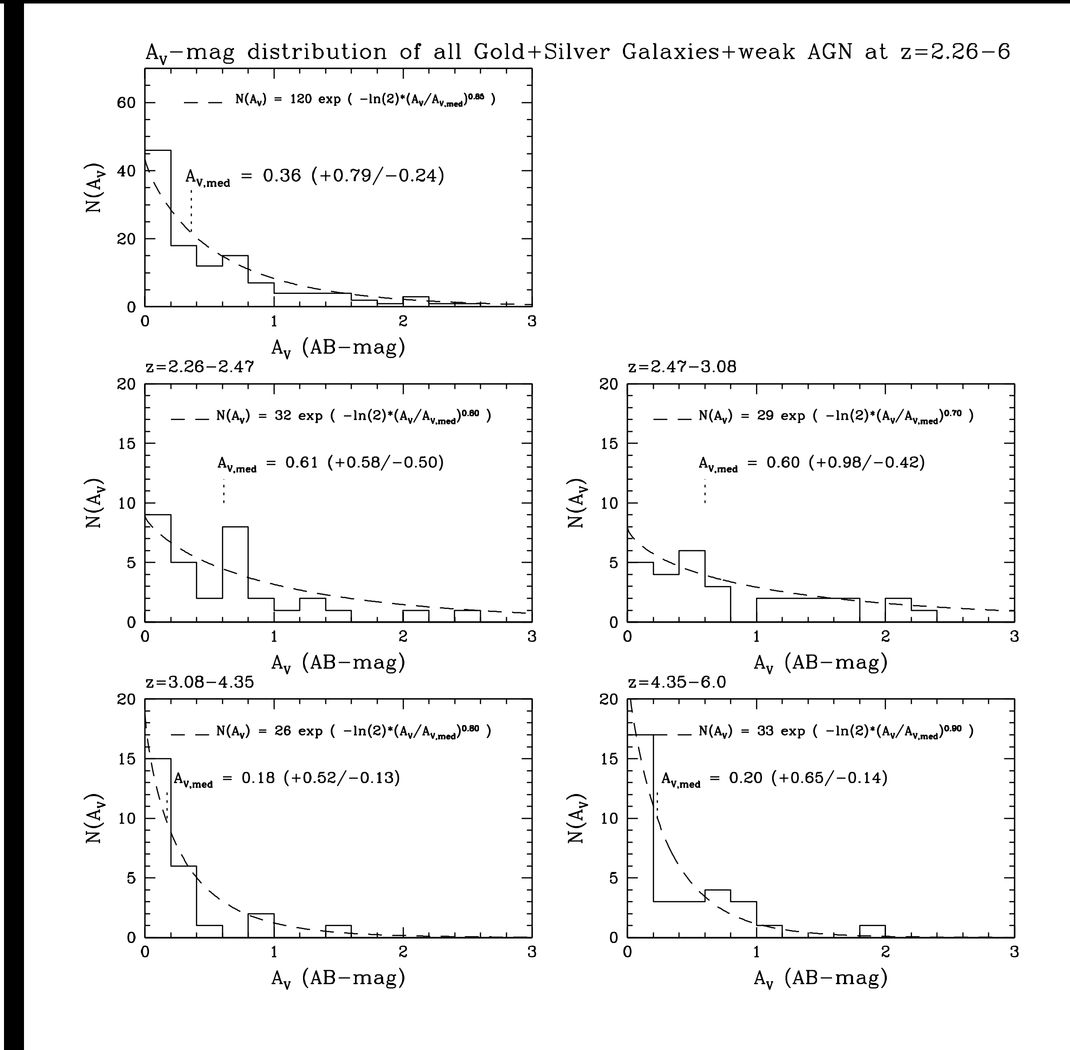
- This is fainter than the LyC SB-signal where this can be measured, and may impose a (fundamental?) limit to how many images can be stacked.



Example of SED fits used for f_{esc} (MC) etc, using $\lambda \gtrsim 1216$ Å and $z \equiv z_{spec}$.

(4) Spectral Energy Distribution (SED)-fitting & Dust (A_V)-distribution





[LEFT]: Best-fit A_V from 10-band SEDs for all ERS galaxies (black dots).

Circles: galaxies; Asterisks: AGN at: z=2.37, z=2.68, z=3.45.

[RIGHT]: Adopted distributions N(A_V) for total LyC samples:

Median A_V increases from $\sim 0.2^m$ at z=3–4 to $\sim 0.6^m$ at z=2.3–2.7.

Gxy+Agn selected at z_{sp}=3.45–4 miss ~50% of dusty ($A_V \gtrsim 1$) objects.