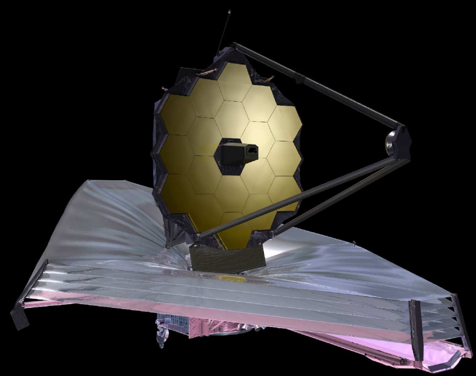
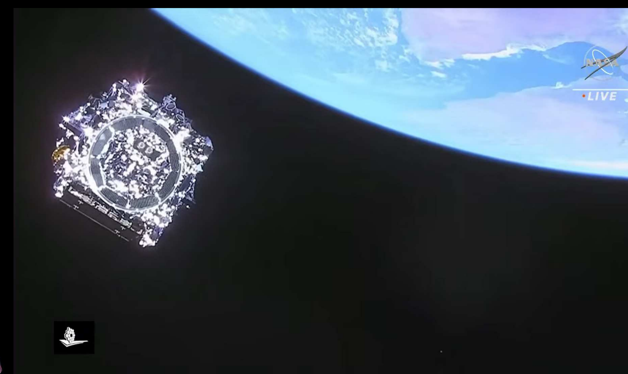
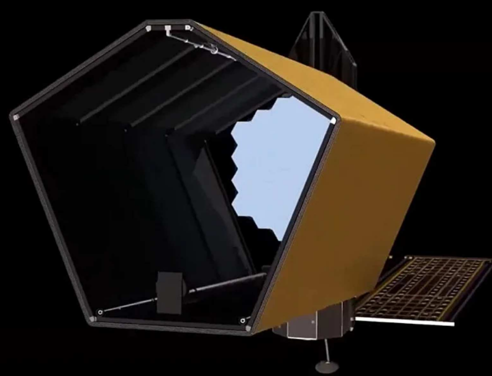
LyC studies from space in the next decades

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

+ HST SKYSURF, UVCANDELS and JWST PEARLS & SKYSURFIR teams: incl B. Smith, S. Cohen, R. Jansen + 130 scientists over 18 time-zones

Hubble	Webb (designed)	Webb (launched 2021)	Habitable Worlds
1973∼2034$^+$?	1996∼2031	1996∼2046$^+$?	2040∼2070$^+$?

Review at the "Escape of Lyman radiation from Galactic Labyrinths" Conference

Monday April 14, 2025; Sterrewacht Leiden, the Netherlands

PDF on: `http://www.asu.edu/clas/hst/www/leiden25_futureLyC_fromspace.pdf`

This talk is dedicated to our friend and PEARLS colleague Dr. Mario Nonino (07/2023).

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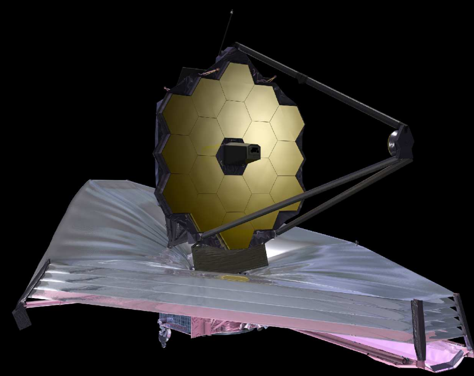
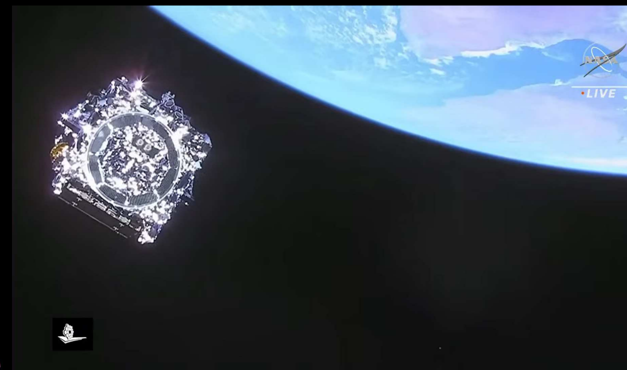
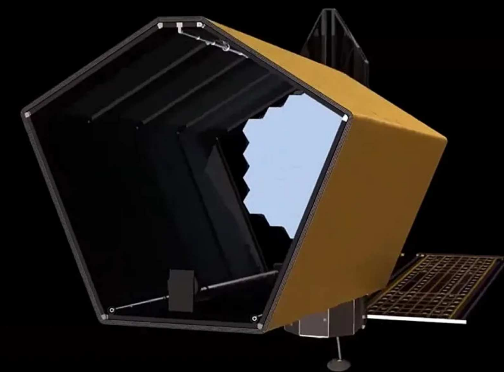
Hubble
1973∼2034^{+}?



Webb (designed)
1996∼2031



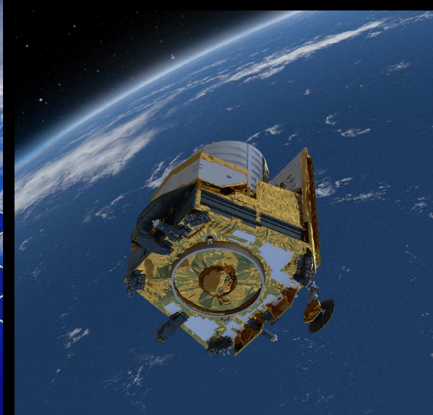
Webb (launched 2021)
1996∼2046^{+}?



Habitable Worlds
2040∼2070^{+}?

India Astrosat (2015)
2004∼2030^{+}?

China Xuntian (2027?)
2012∼2037^{+}?



Euclid (2023)
2009∼2035?

Roman (2027)
2011∼2037?

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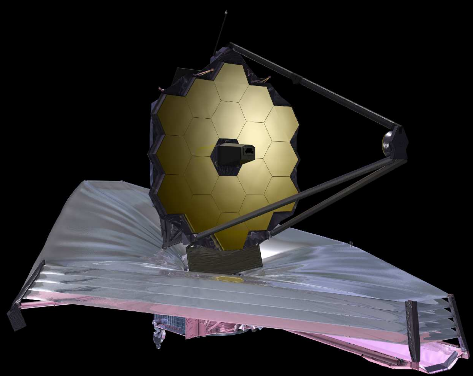
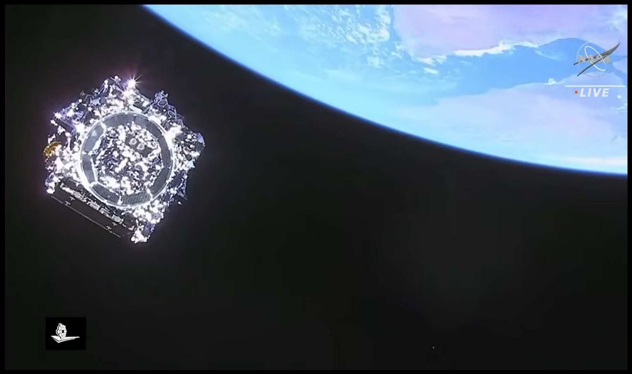
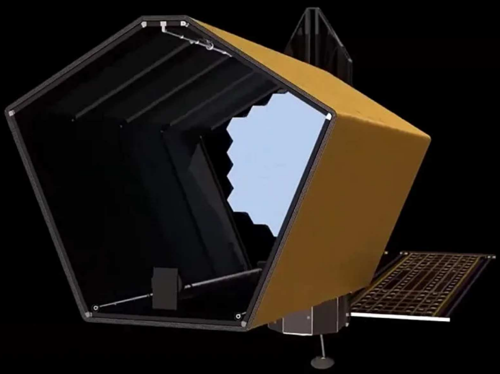
Hubble
$1973\sim2034^{+}$?



Webb (designed)
$1996\sim2031$



Webb (launched 2021)
$1996\sim2046^{+}$?



Habitable Worlds
$2040\sim2070^{+}$?

To those (understandably) concerned about events in the world today:

- HST survived 15 presidential, 30 congressional elections, 3 cancellations.
- JWST survived 8 presidential, 16 congressional elections, 2 cancellations.

LyC studies from space in the next decades

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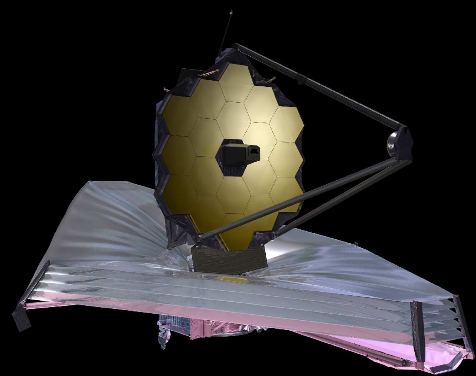
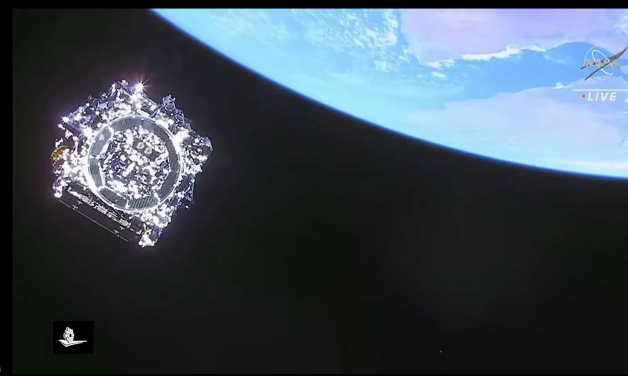
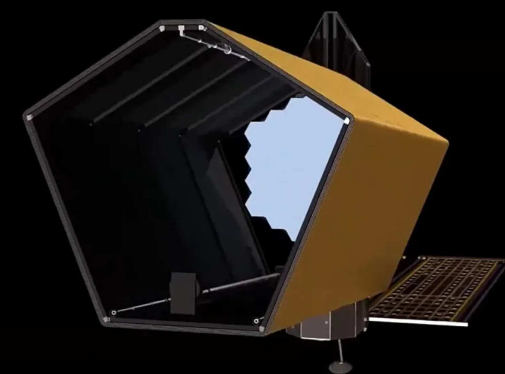




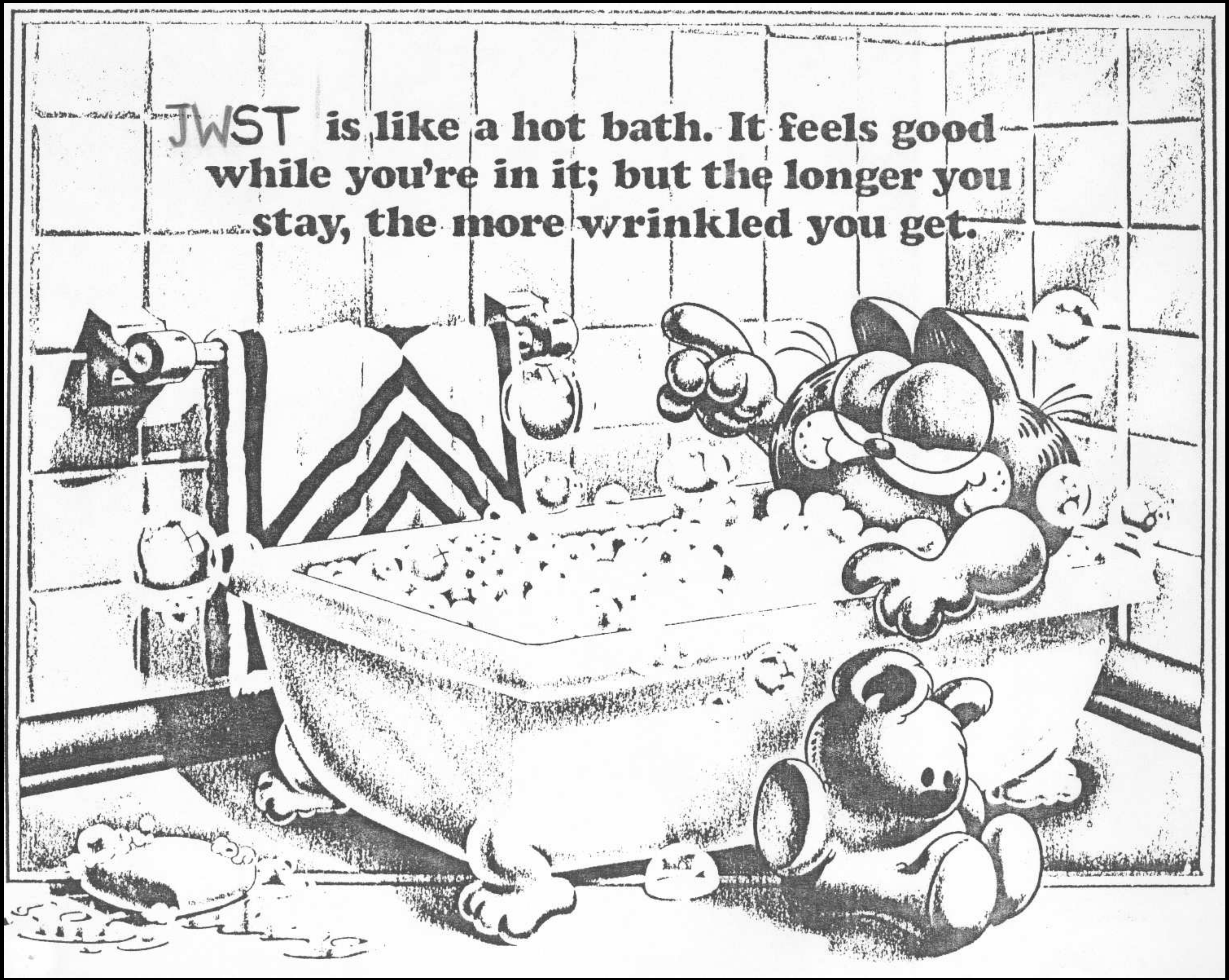


Hubble	Webb (designed)	Webb (launched 2021)	Habitable Worlds
1973$\sim$2034^{+}?	1996$\sim$2031	1996$\sim$2046^{+}?	2040$\sim$2070^{+}?

To those (understandably) concerned about events in the world today:

- HST survived 15 presidential, 30 congressional elections, 3 cancellations.
- JWST survived 8 presidential, 16 congressional elections, 2 cancellations.
- HST–HWO will span $\sim$25 US presidential & 50 congressional elections.

$\Longrightarrow$ Maintain the long-term vision to do LyC work 30 years from now!



WARNING: Both Hubble and James Webb are 50–60^{+} year projects:

$\Longrightarrow$ Maintain the long-term vision to do LyC work 30 years from now!

Outline

- (1) Uniquely complementary roles of Hubble and Webb:

  414–500 hr combined HST+JWST images ⇒ keep HST alive!

- (2) Viewing the Universe through the Eyes of Einstein"

- (3) Need space-based resolution for contamination-free LyC work

- (4) Habitable World Observatory requirements for LyC work

- (5) Summary and Conclusions

ASU Arizona State University

Sponsored by NASA/HST & JWST

PDF on: `http://www.asu.edu/clas/hst/www/leiden25_futureLyC_fromspace.pdf`

2025 Crete LyC Conference Summary: Smoking Guns of Cosmic Reionization

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

- LyC from (weak) AGN with outflows !

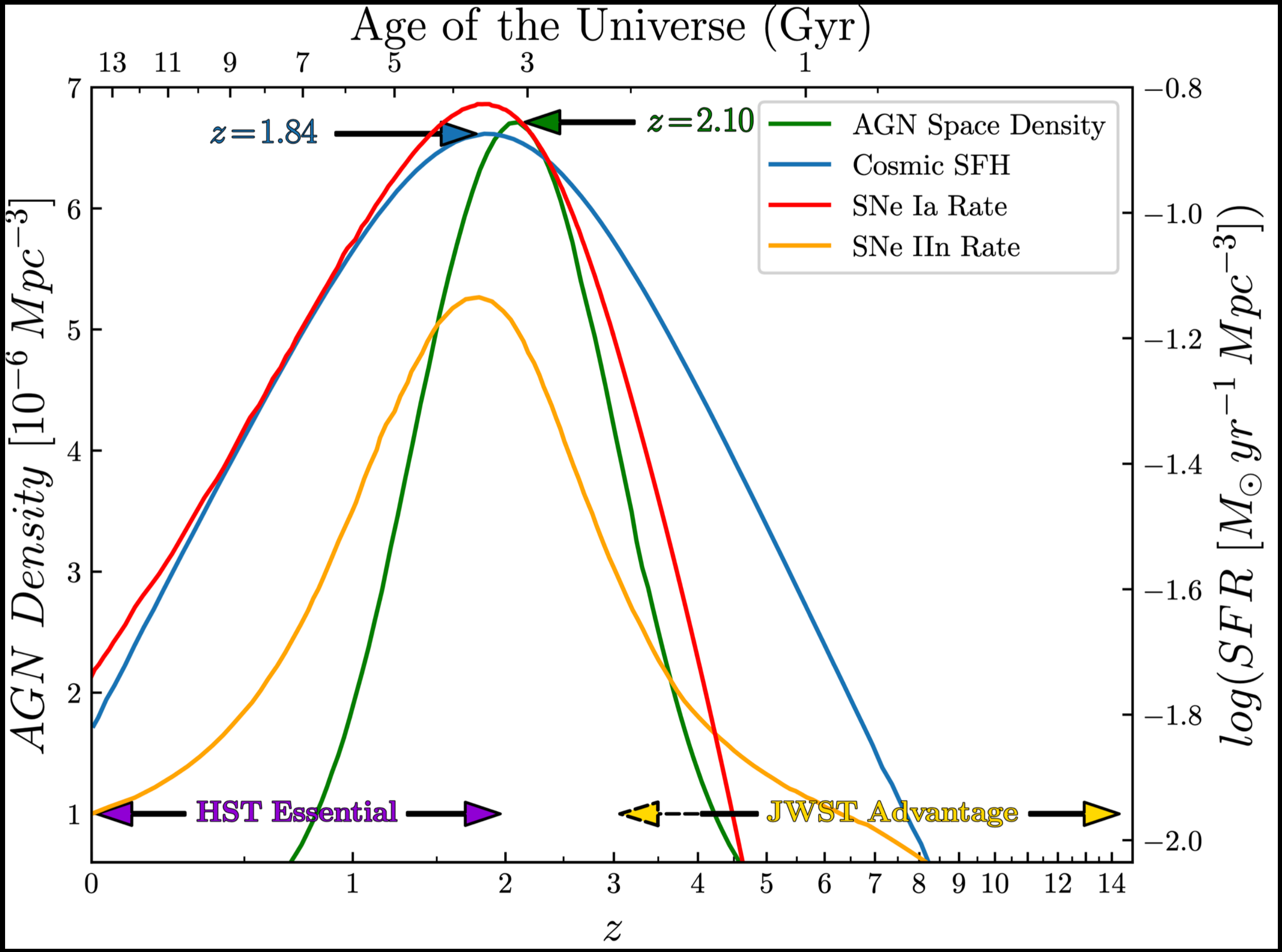
Venetian fortress Spinalonga in Elounda, Crete ...

- LyC from galaxies with (small holes) !

- Reionization by LyC escaping from Galactic fortresses with small holes!

Windhorst et al.

astro-ph/2410.01187



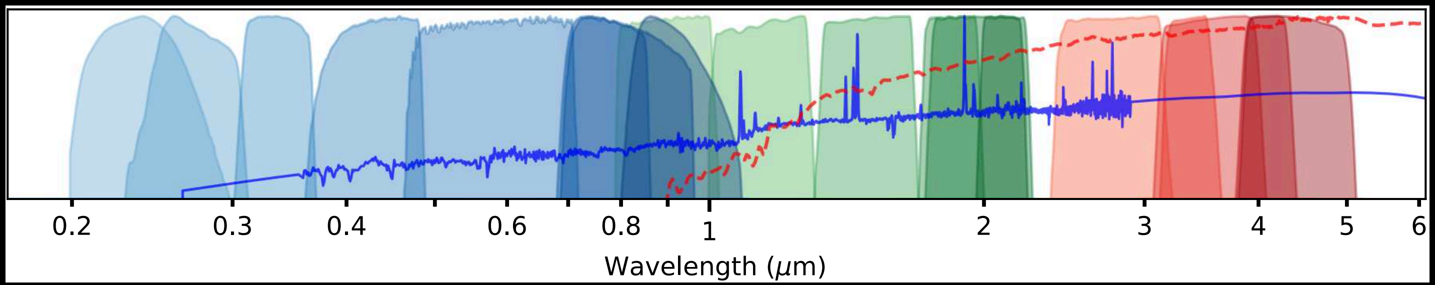
Age$\sim\frac{13.8}{(1+z)}+\ldots$ Gyr

Active galactic nuclei (AGN)

$\Longleftrightarrow$ BH accretion disks

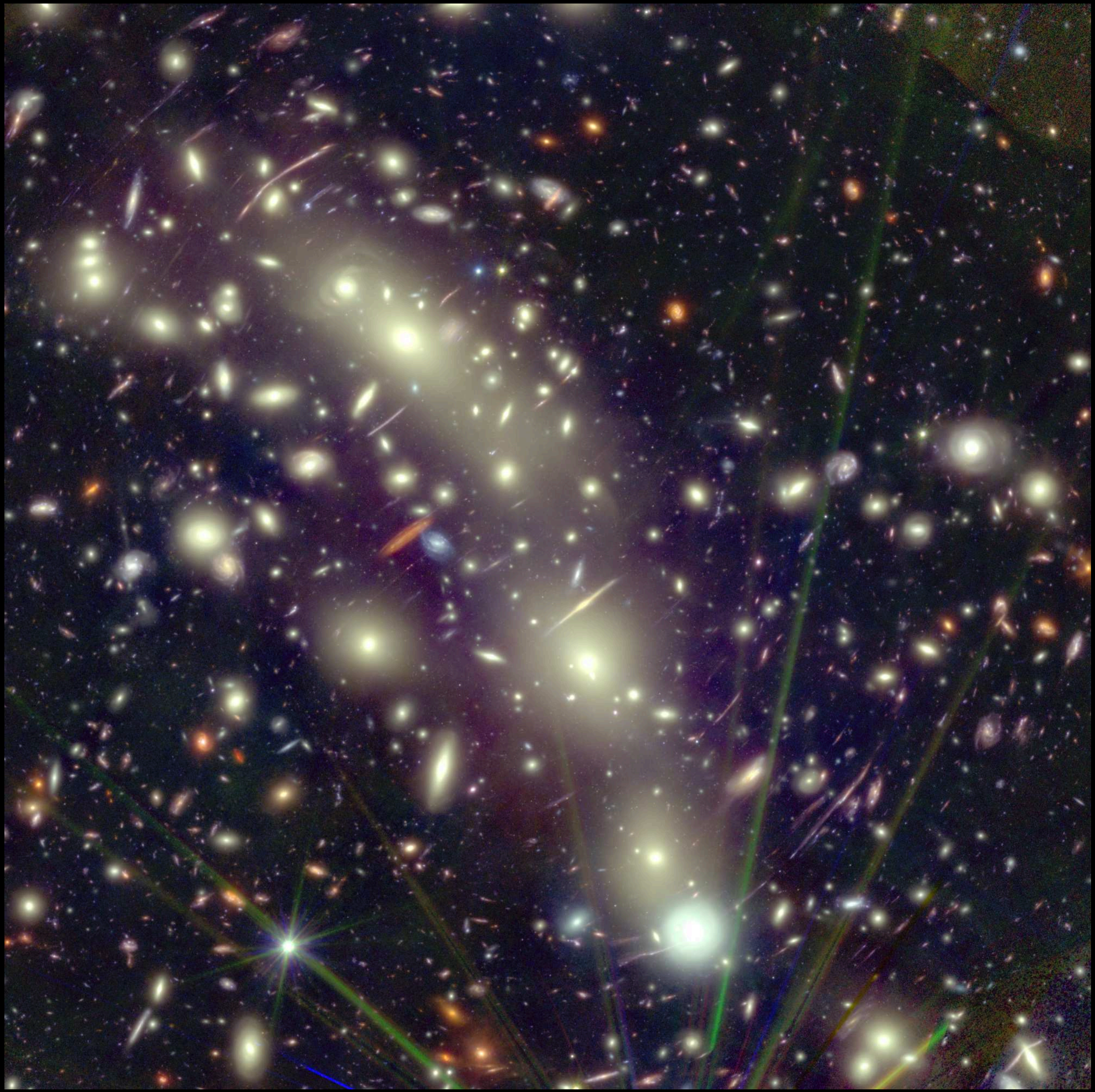
$\Longleftrightarrow$ Chandra X-ray sources

Star Formation, Supernova Rate, & Black Hole growth peak ~10 Gyr ago!



$\Rightarrow$HST best samples *unobscured* SFH & BH growth in last 10 Gyr ($z\lesssim2$), while JWST best samples *obscured* parts, especially in first 3 Gyr ($z\gtrsim3$).

(1) Uniquely complementary roles of Hubble and Webb:

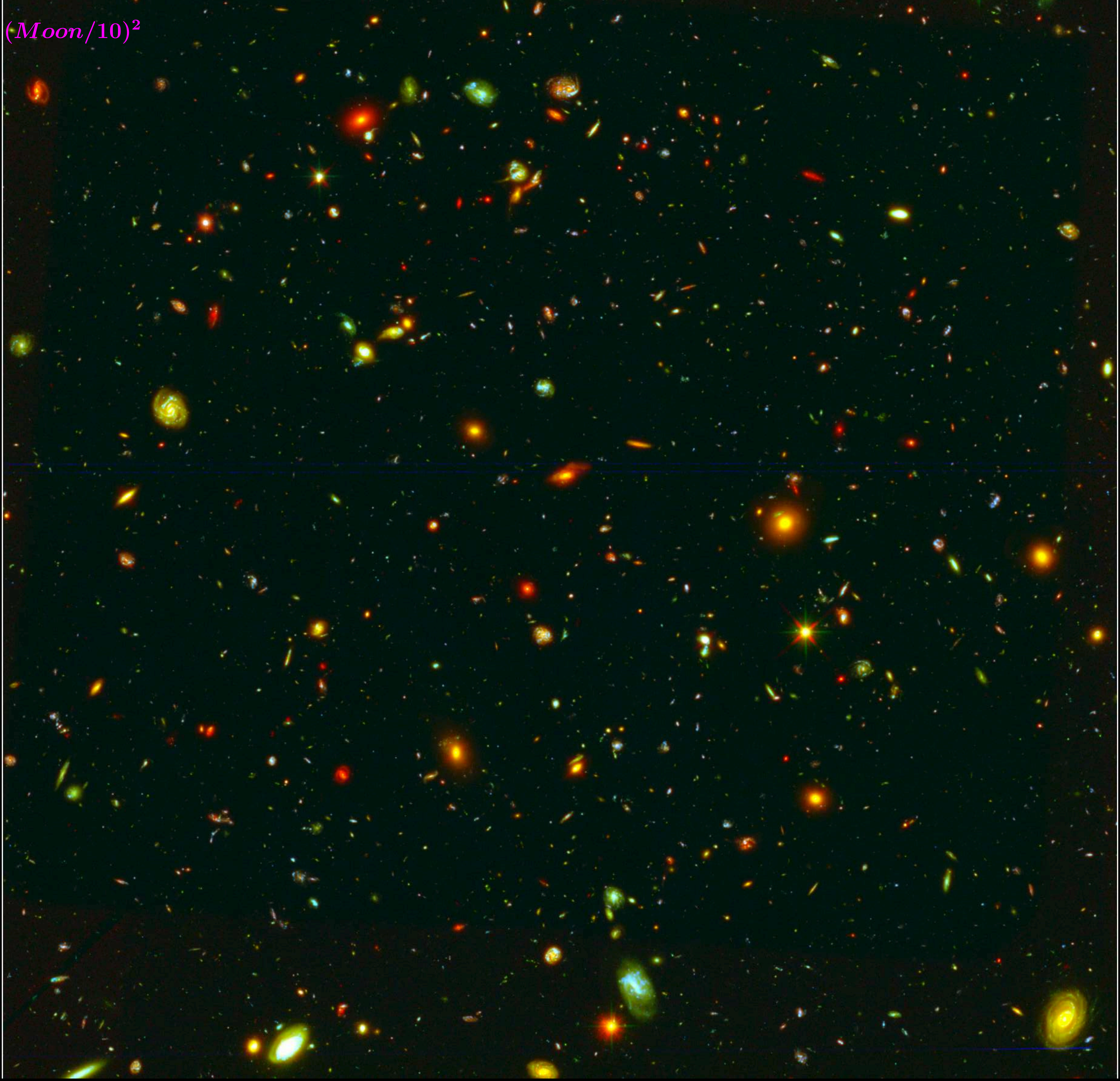


500 hrs HST+JWST: 45 filters (0.2–5.0μm), lensing cluster MACS0416:

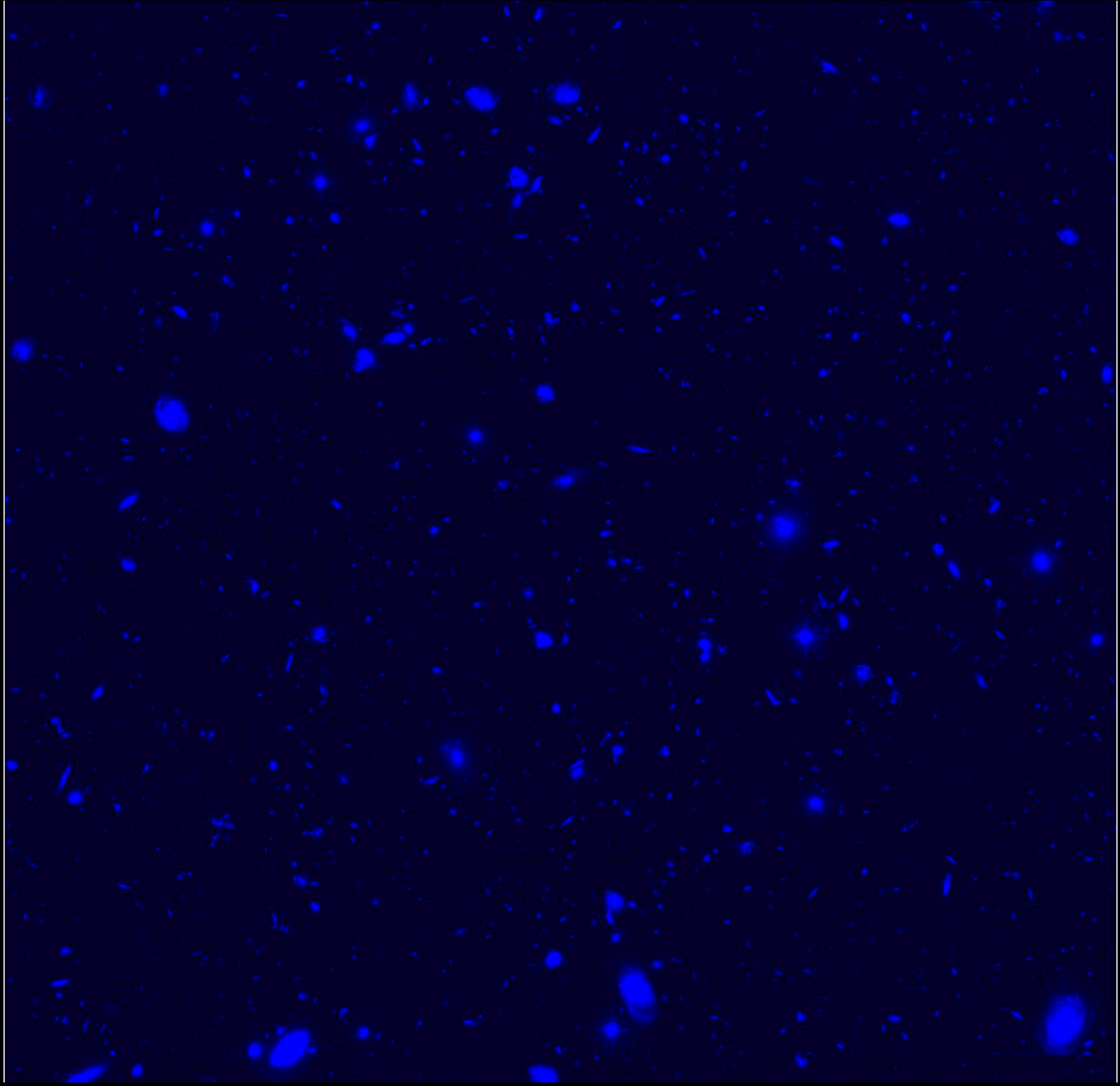
- HST darkest skies (10-$10^3\times$ darker) + JWST's dark skies (10^3–$10^5\times$ darker than ground based):

$\Longrightarrow$ HST & JWST reach 30–31 mag ($\simeq$1 nJy $\simeq$1 firefly from Moon).

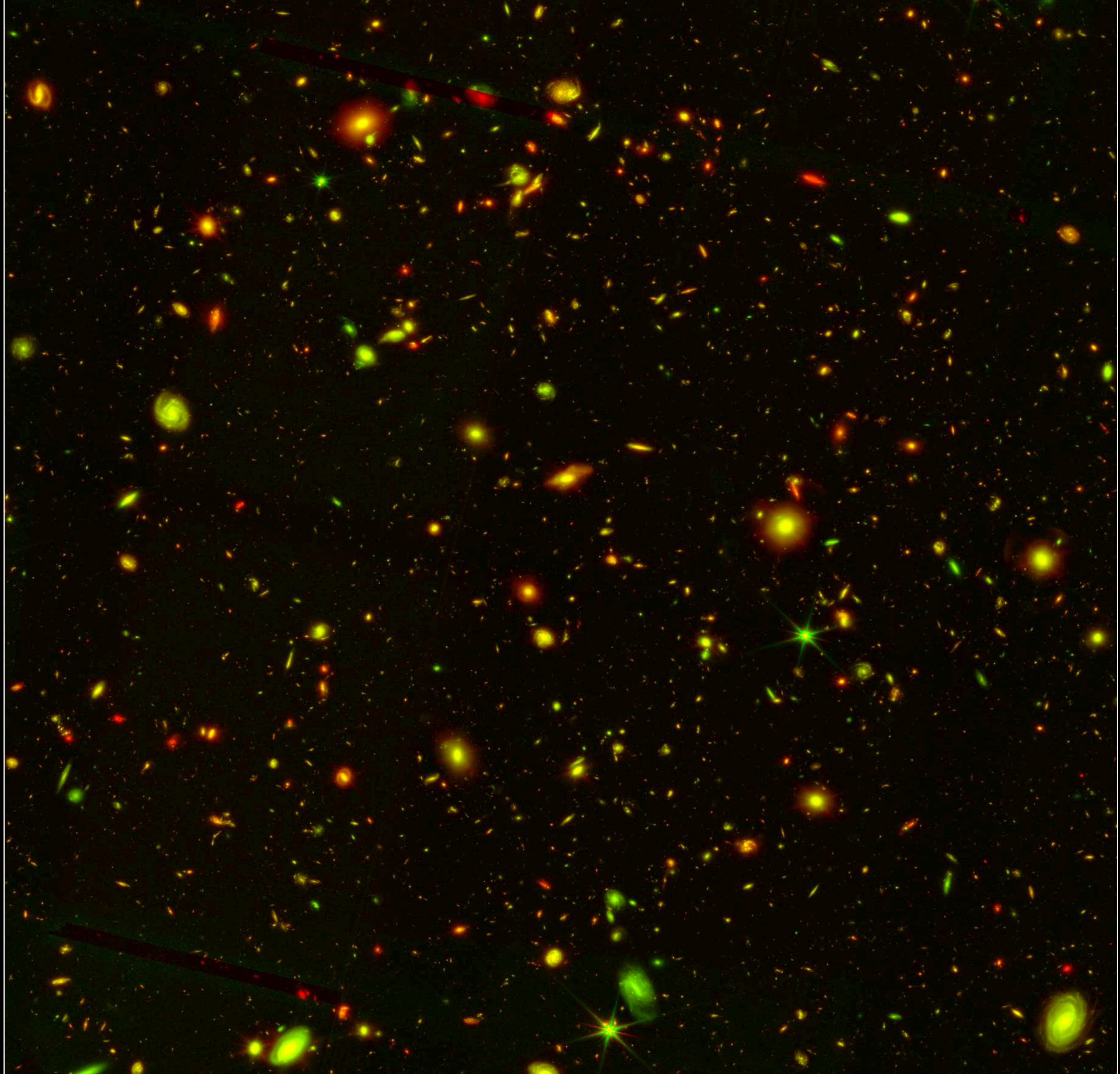
Field-of-View $\sim (Moon/10)^2$



556 hr HST Hubble UltraDeep Field: 12 filters at 0.2–1.6 μm (AB$\lesssim$31 mag; $\sim$1 nJy; full BGR).



361 hr HST Hubble UltraDeep Field: 8 HST-unique filters 0.2–0.9 μm (in false color blue).

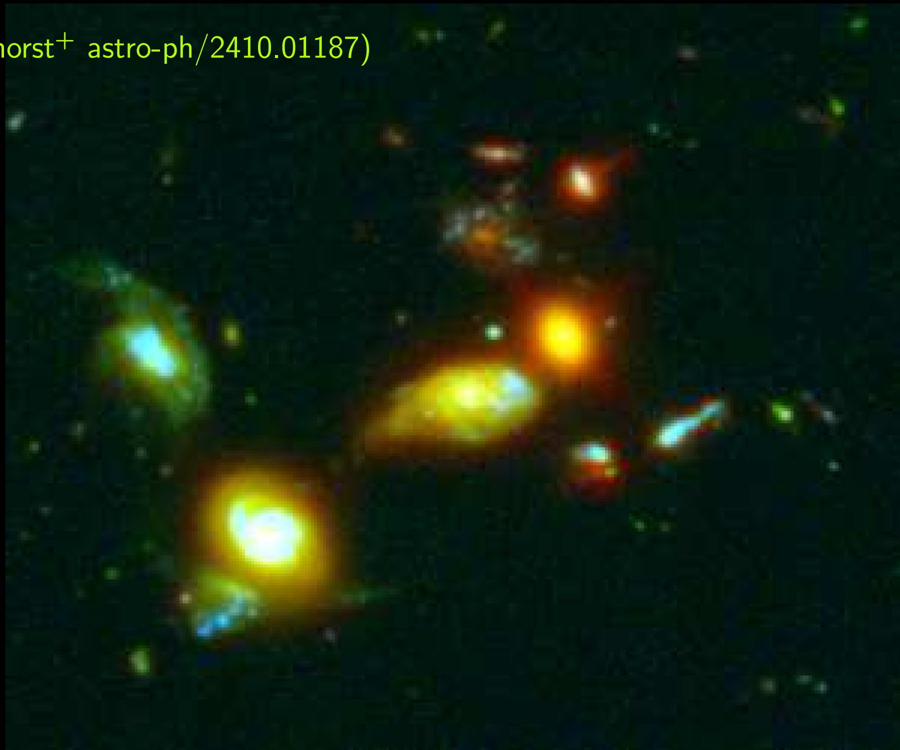


53 hr JWST/NIRCam Hubble UltraDeep Field: 12 filters at 0.9–5.0 μm (AB$\lesssim$31 mag; in green + red).

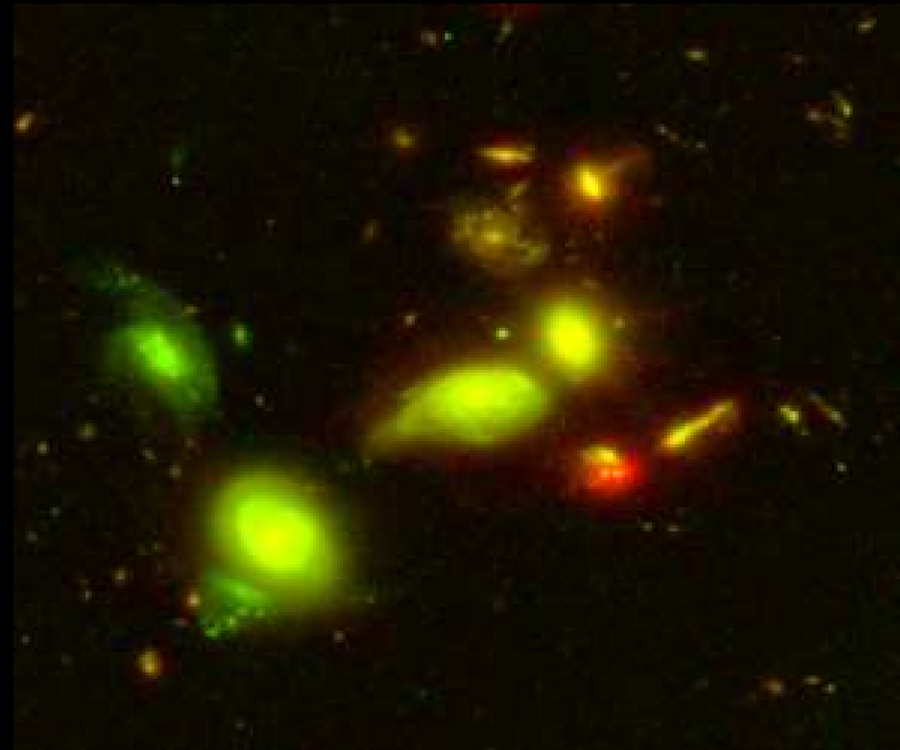
(Windhorst^{+} astro-ph/2410.01187)

414 hr HST+JWST Hubble UltraDeep Field: 20 filters at 0.2–5.0 μm (AB$\lesssim$31.5 mag; full BGR).

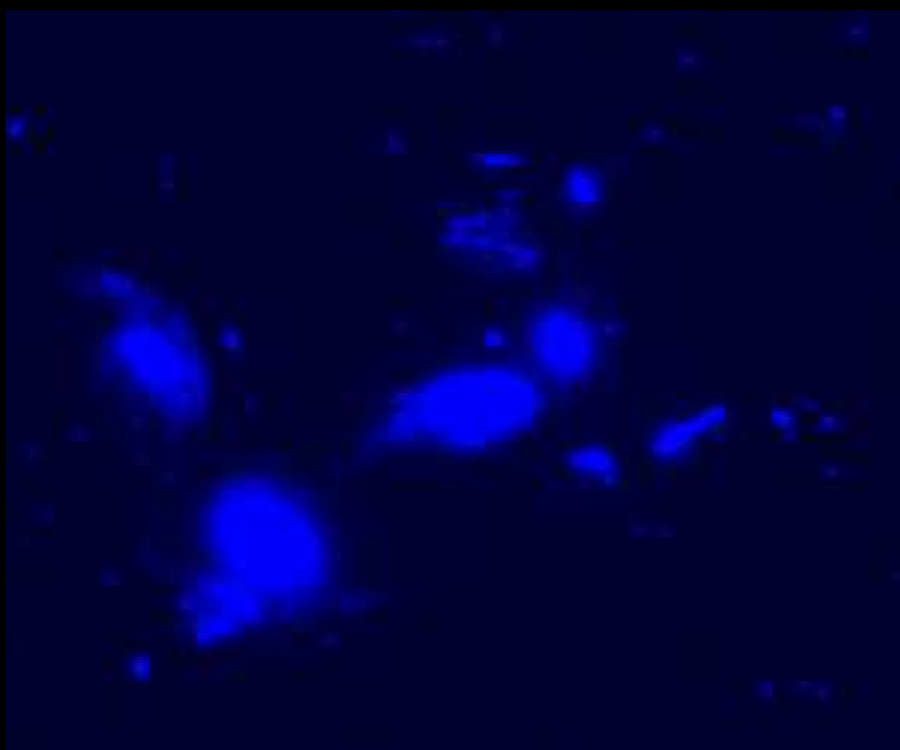
(Windhorst+ astro-ph/2410.01187)



556 hr HST HUDF 12 filters



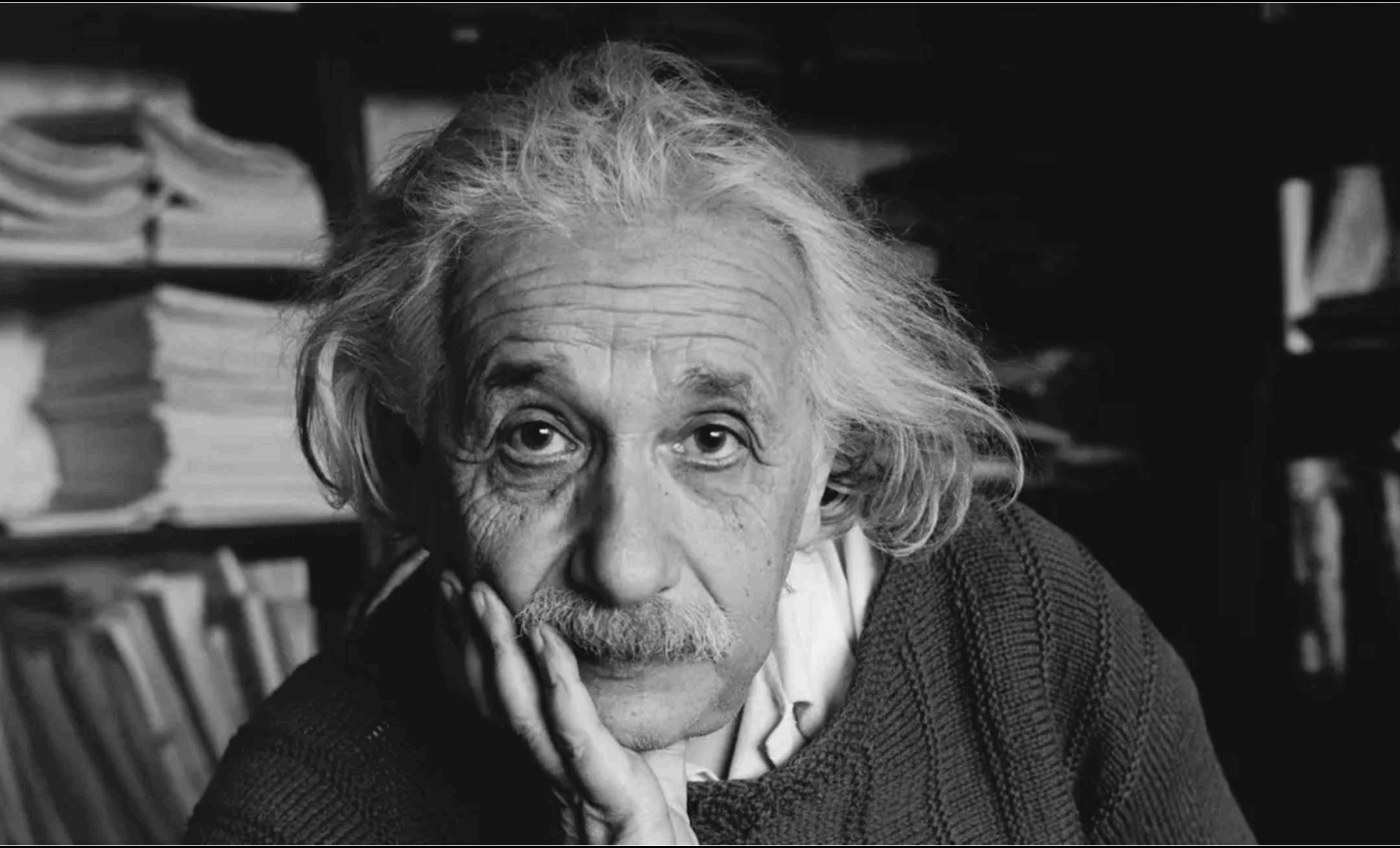
53 hr JWST/NIRCam 12 filters



361 hr 8 HST-unique filters (false-blue)

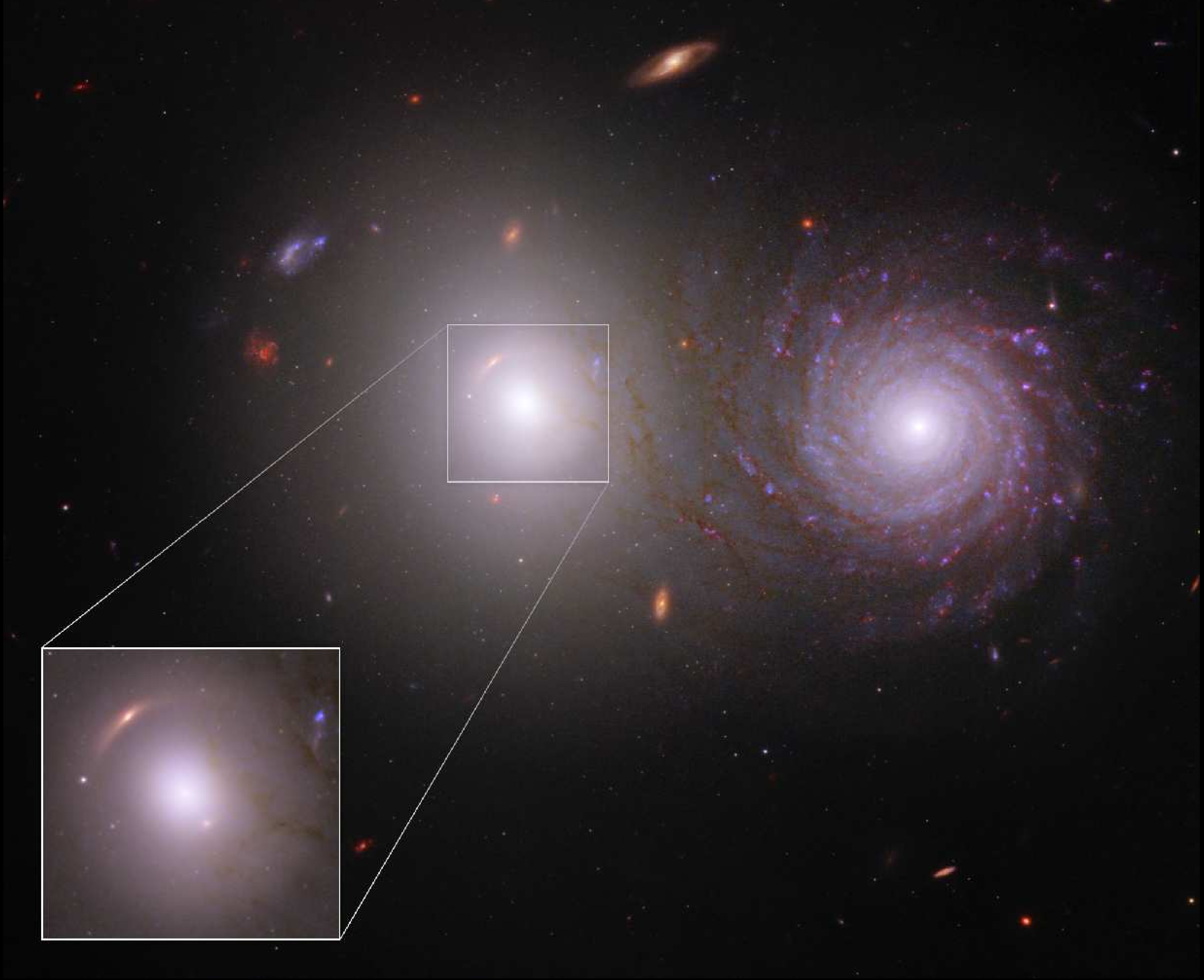
414 hr HST+JWST 20 filters

• (2) Viewing the Universe through the "Eyes of Einstein"



Webb is observing many things Einstein correctly predicted, yet doubted: Gravitational lensing, Black Holes, the Hubble Expansion, ...

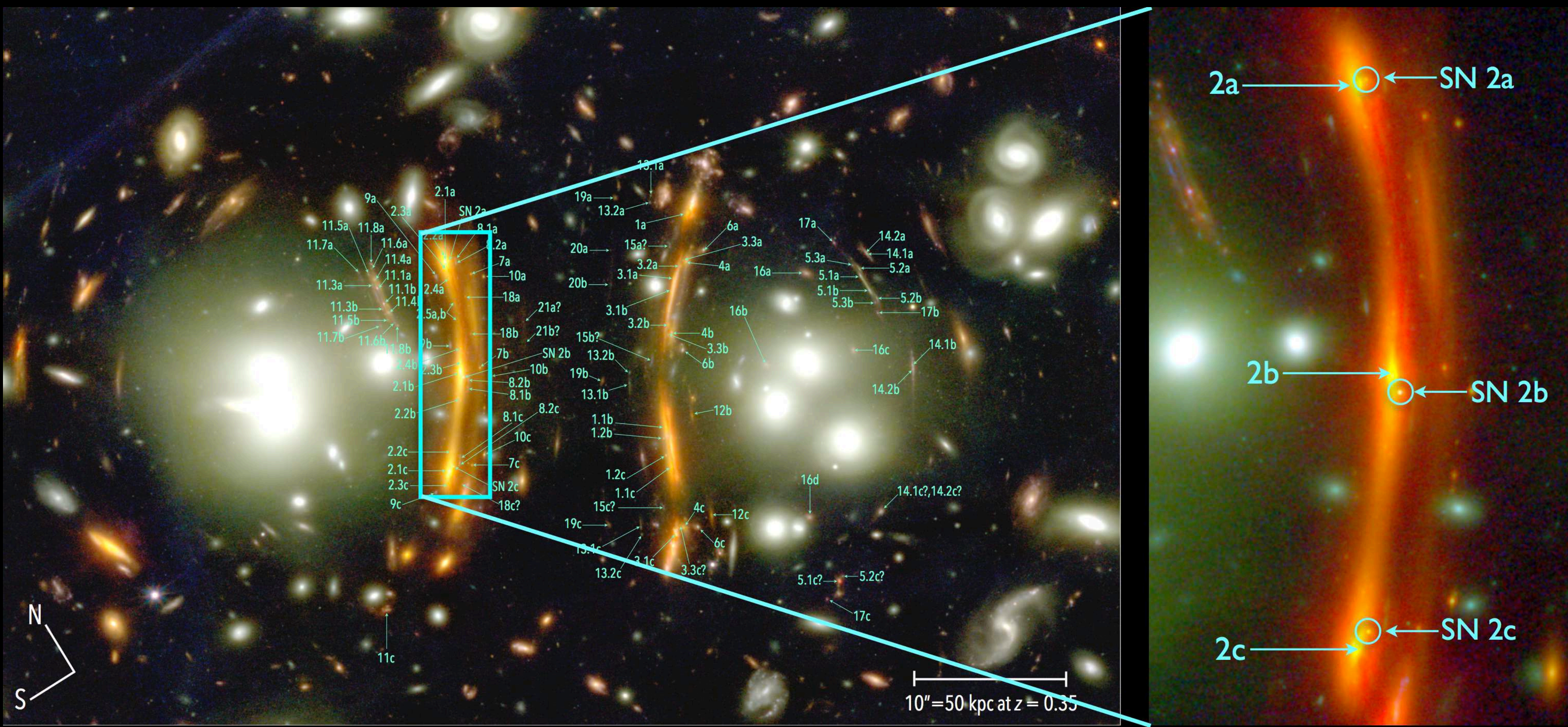
- Spiral overlapping Elliptical VV191: Tracing dust: small grains! (Keel$^+$ 23).
  - 150 Globular Clusters in z=0.0513 Elliptical (Berkheimer$^+$ 2024, ApJ, 964, L29).



... and the z=0.0513 Elliptical also lenses a background galaxy at z∼1 (Keel+ 2023, AJ, 165, 16)!

JWST image of most luminous far-IR Planck cluster G165 at z=0.35 found:
Lensed Supernova Ia at z=1.78 $\longrightarrow$ measured H_o=$75.4^{+8.1}_{-5.5}$, 10 Byrs ago!

https://bigthink.com/starts-with-a-bang/triple-lens-supernova-jwst/ (Frye+ 2023, Pascale+ 2025).



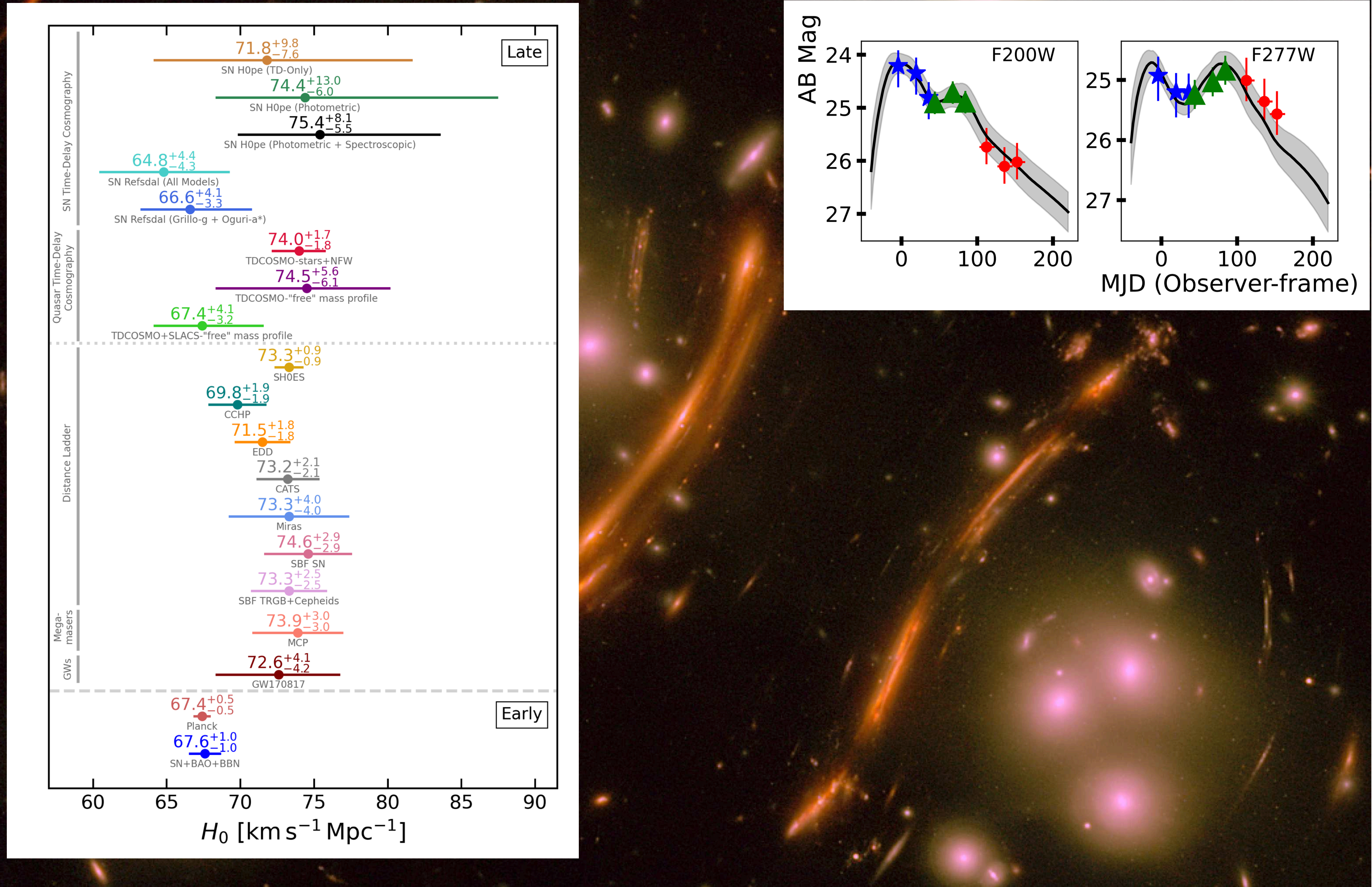
NIRCam in G165 shows: 3 bright point sources parity-flipped w.r.t. Arc-2:

- Clearly a lensed SN Type Ia at z=1.783, seen only 3.6 Byrs after BB!
- 3-epoch NIRCam: 9-point light curve! $\Longrightarrow$ measure $\boldsymbol{H_0}$ directly !

(Polletta$^+$ 2023, Frye$^+$ 2024, Chen$^+$ 2024, Kamieneski$^+$ 2024, Pierel$^+$ 2024, Pascale$^+$ 2025).

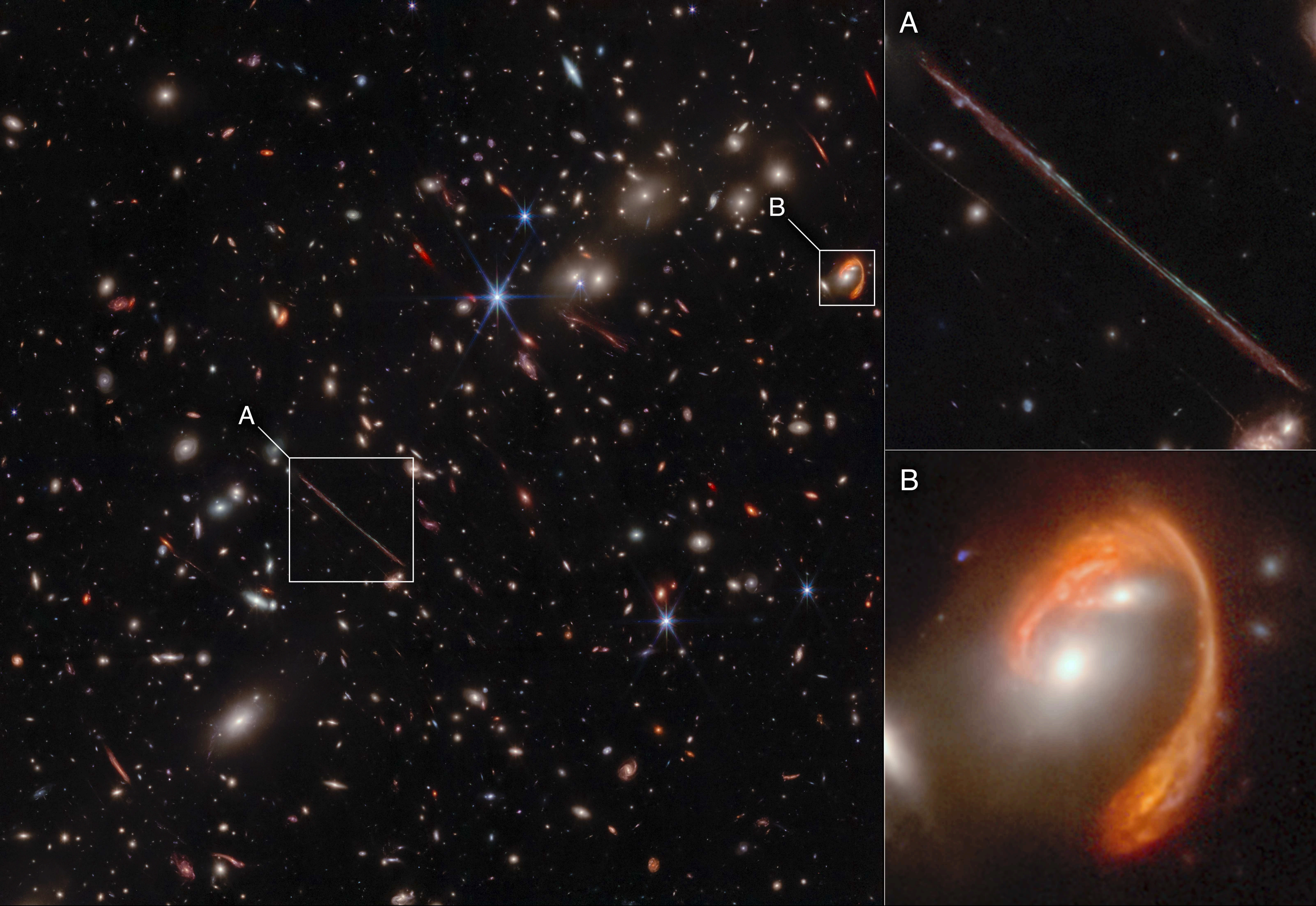
$\longrightarrow$ Regular monitoring of clusters with extreme SF to yield more lensed SNe!

- Total SFR$\simeq$200–350 $M_\odot$/yr predicts $\gtrsim$1 lensed SN/yr (Kamieneski$^+$ arXiv/2404.08058)



Pascale+ (2025, ApJ, 979, 13): Photo & spectro time delay: $H_o=75.4^{+8.1}_{-5.5}$ (at z=0.35).

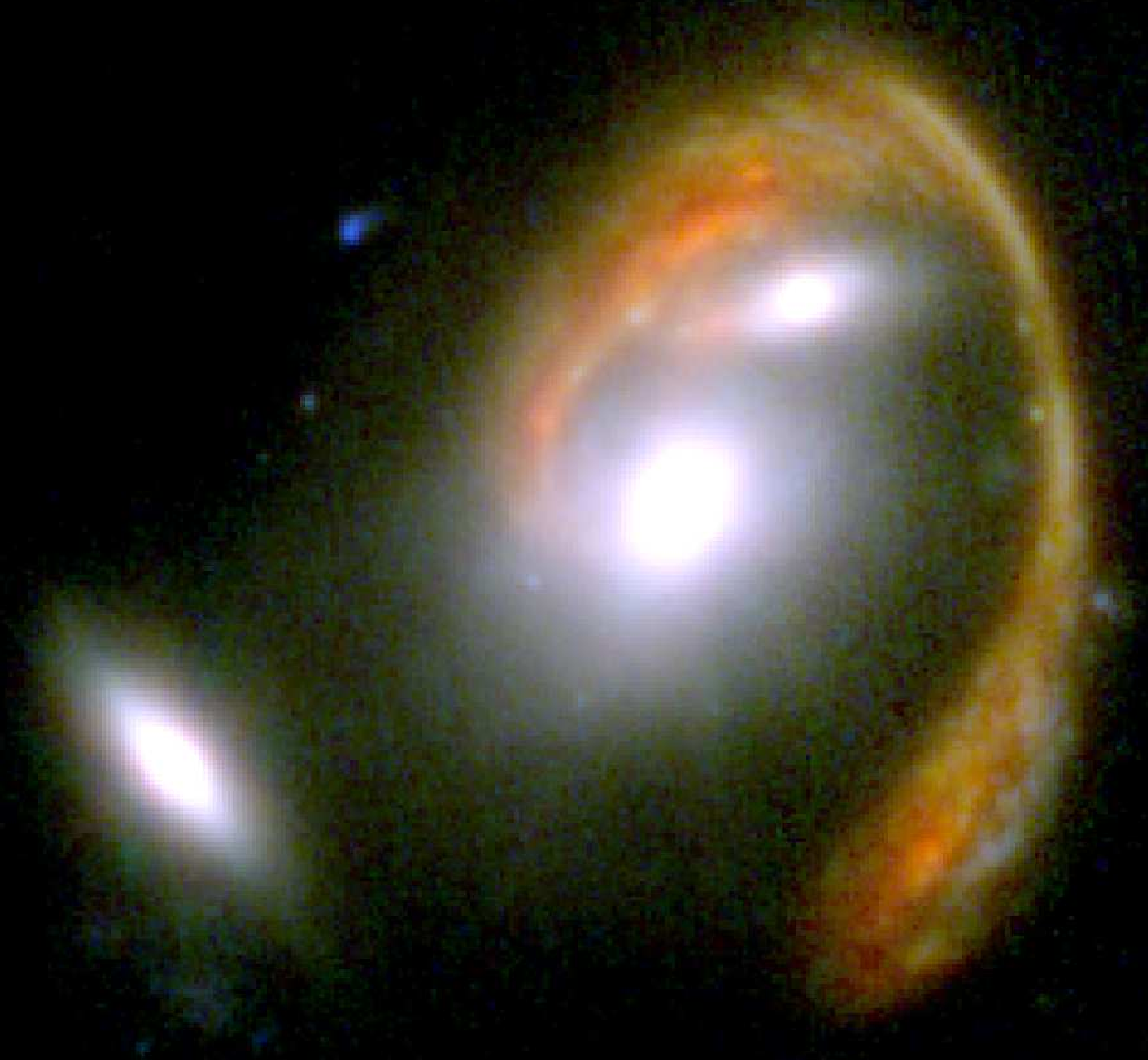
• Monitoring G165 predicts $\gtrsim$1 lensed SN-Ia/yr ! (Kamieneski+ 2024, ApJ, 973, 25)



Monster cluster El Gordo distorts distant galaxies into "pencils" (Diego$^+$22)

https://news.asu.edu/20230801-jwsts-gravitational-lens-reveals-distant-objects-behind-el-gordo-galaxy-cluster

(Kamieneski+ 2023, ApJ, 955, 91)

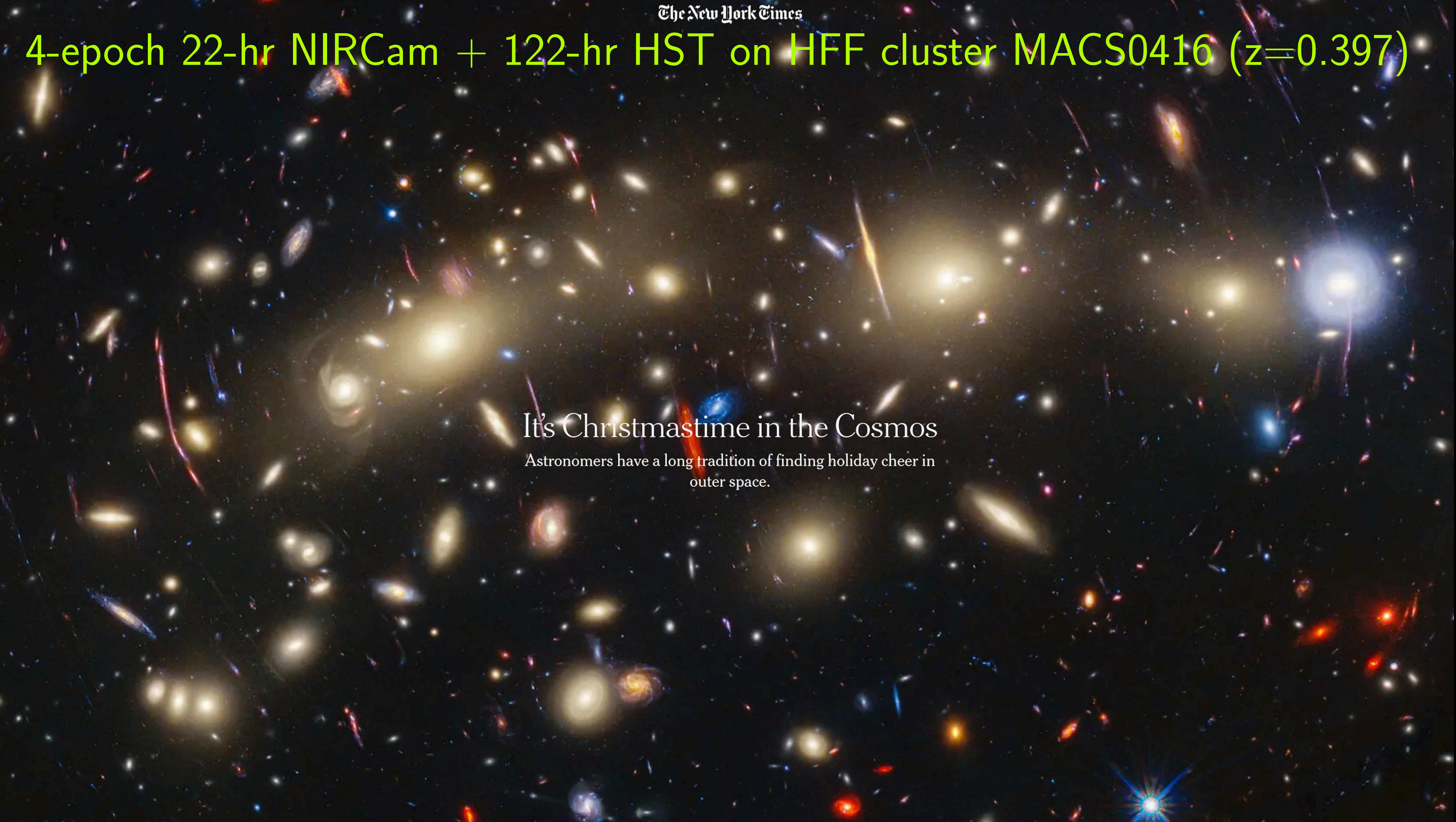


and El Gordo makes a super-lens “El Anzuelo” — Einstein’s fishhook!

https://webbtelescope.org/contents/news-releases/2023/news-2023-119

https://news.asu.edu/20230802-global-engagement-asu-webb-telescope-einstein-werner-salinger-holocaust

4-epoch 22-hr NIRCam + 122-hr HST on HFF cluster MACS0416 ($z=0.397$)

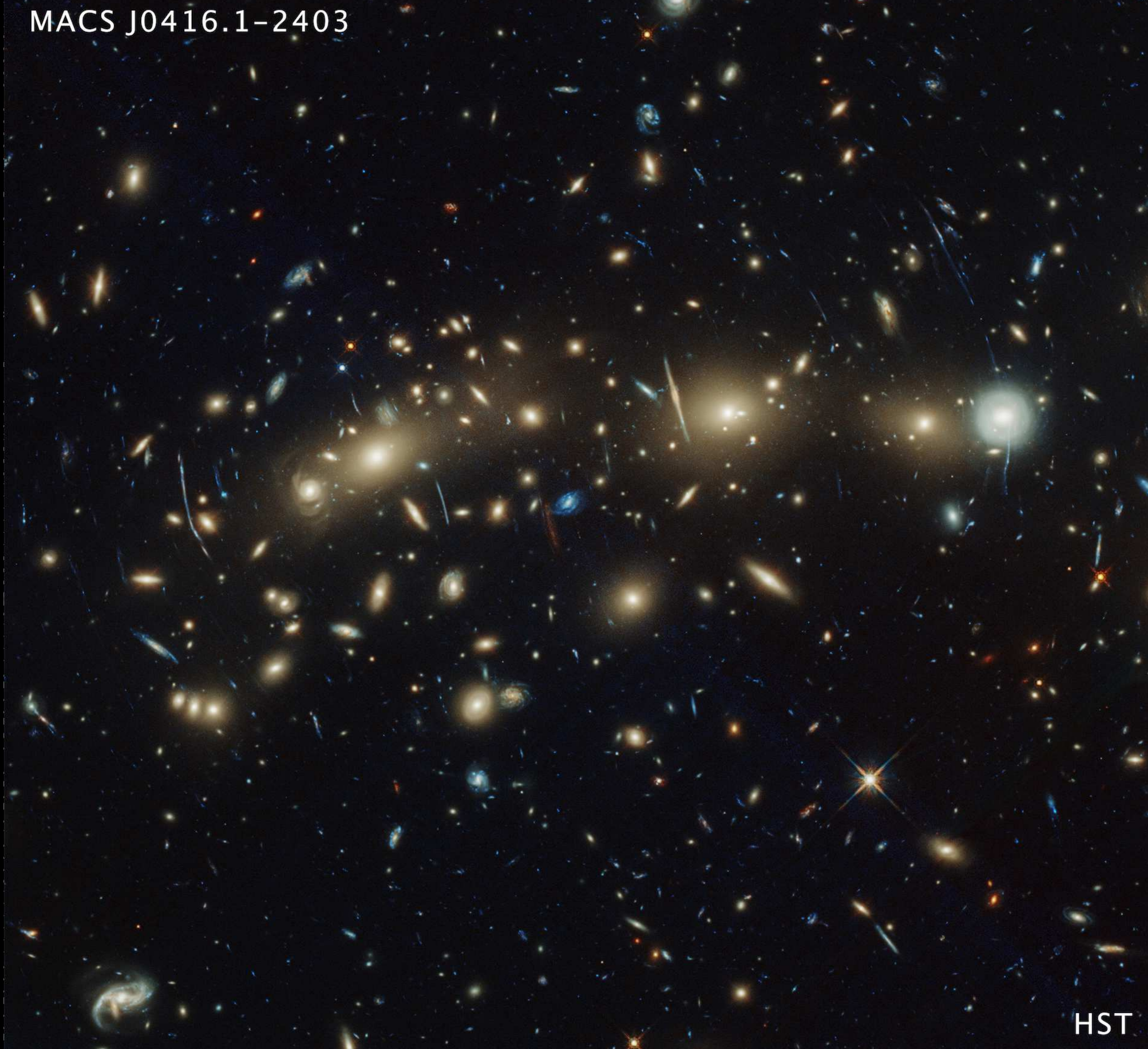


12 new caustic transits at $z \simeq 1$–2 from 4 epochs! (Yan, H.$^{+}$, 2023, ApJS, 269, 42)

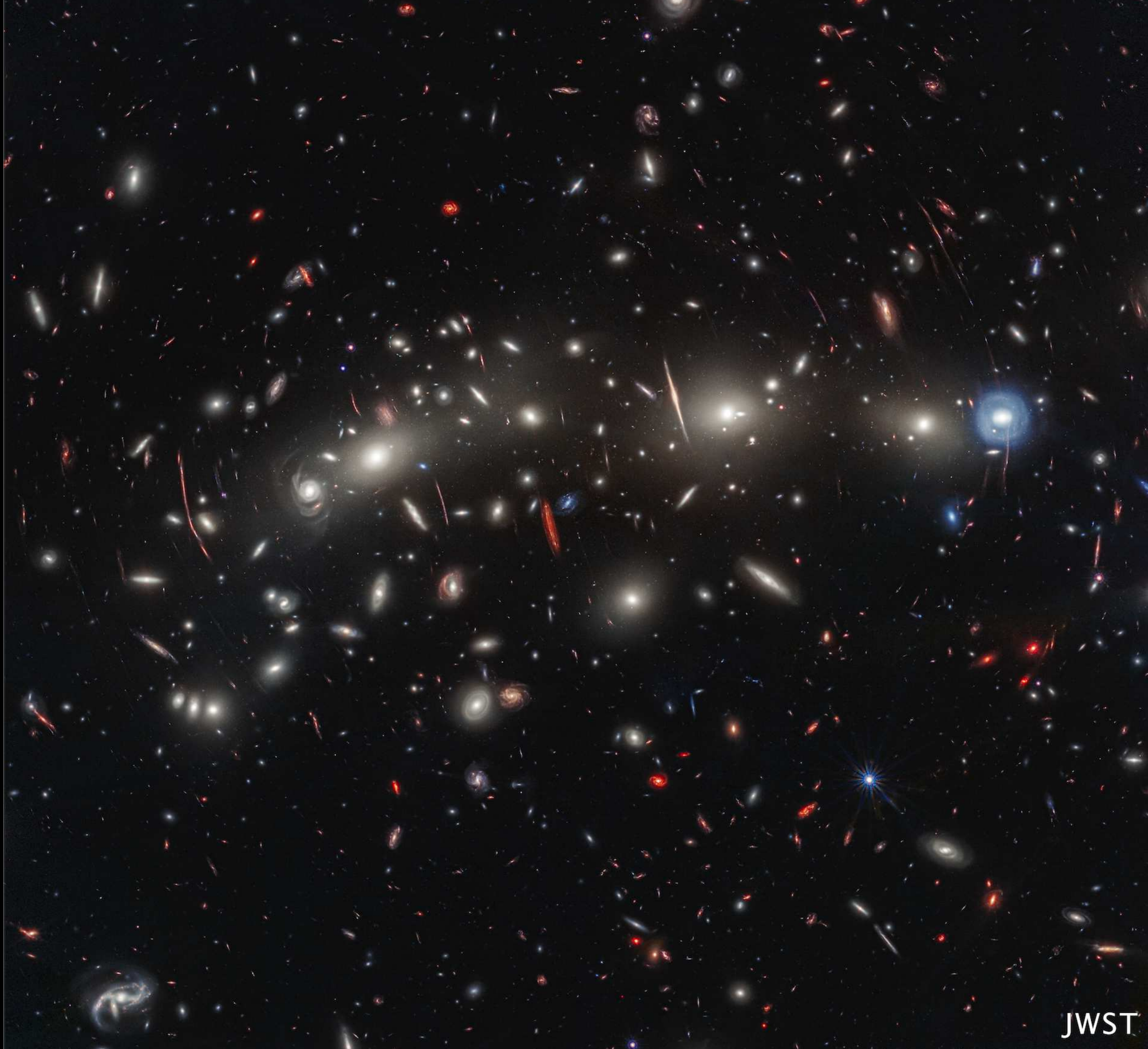
Extremely magnified binary star at $z=2.091$! (Diego, J.$^{+}$, 2023, A&A 679, A31)

https://www.cnn.com/2023/11/09/world/webb-hubble-colorful-galaxy-cluster-scn/index.html

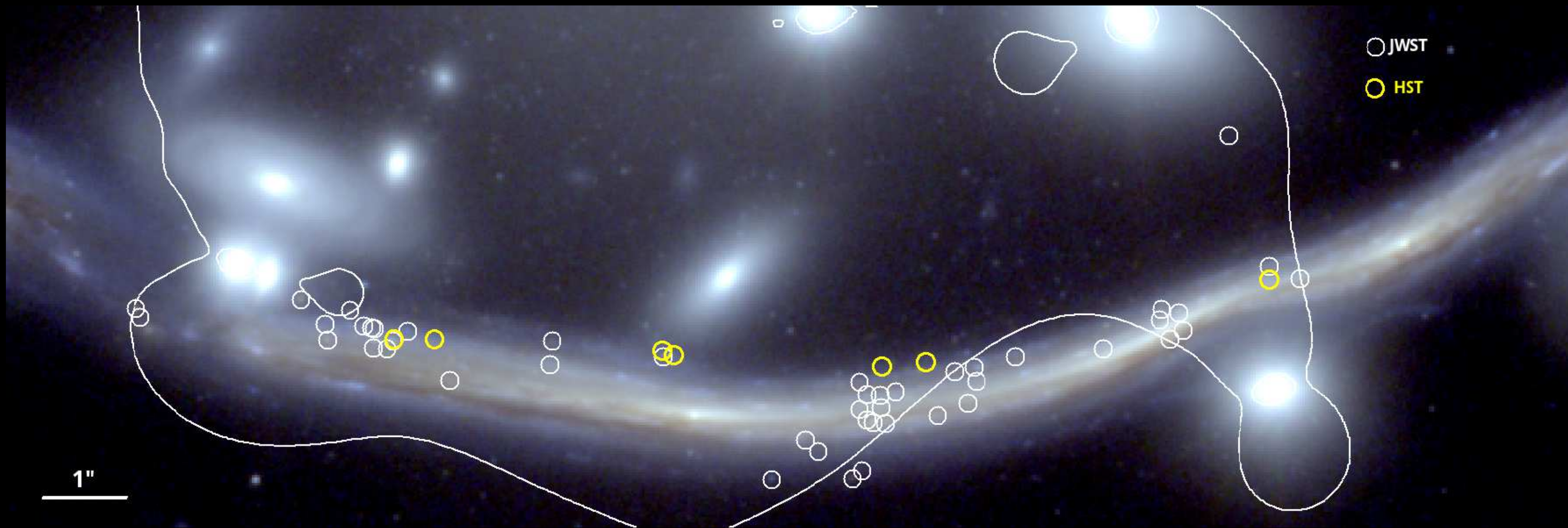
https://www.nytimes.com/2023/12/19/science/christmas-stars-galaxies-webb-nasa.html?

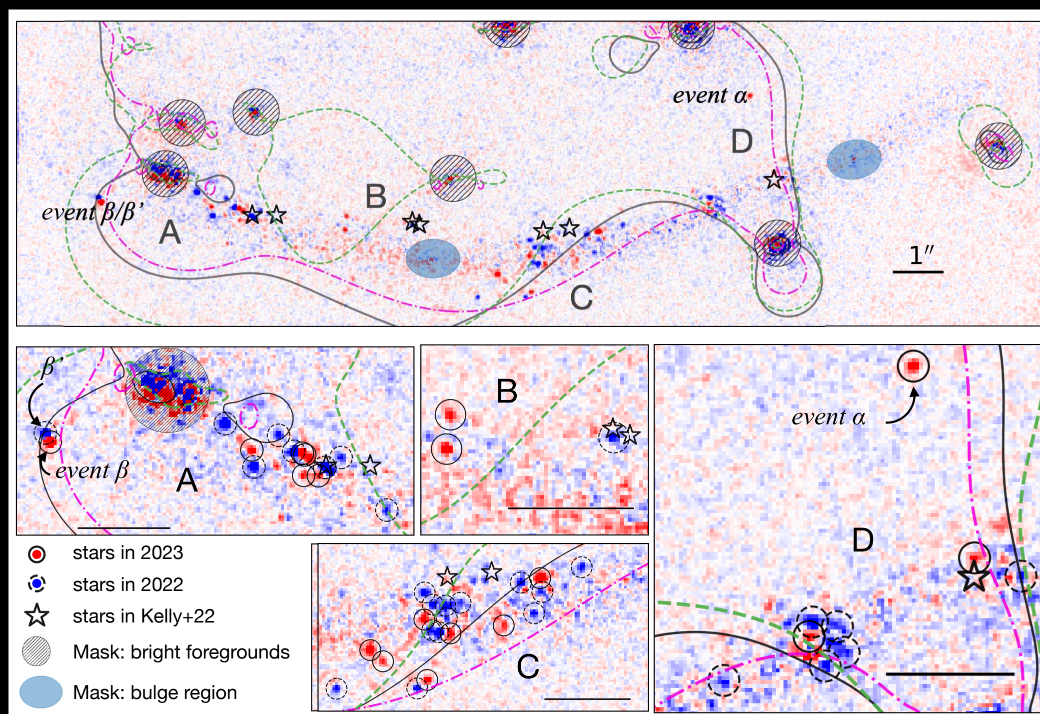


122 hr HST on Hubble Frontier Field cluster MACS0416 (z=0.397; 4.3 Blyr)



22 hrs JWST on Hubble Frontier Field cluster MACS0416 (z=0.397; 4.3 Blyr)



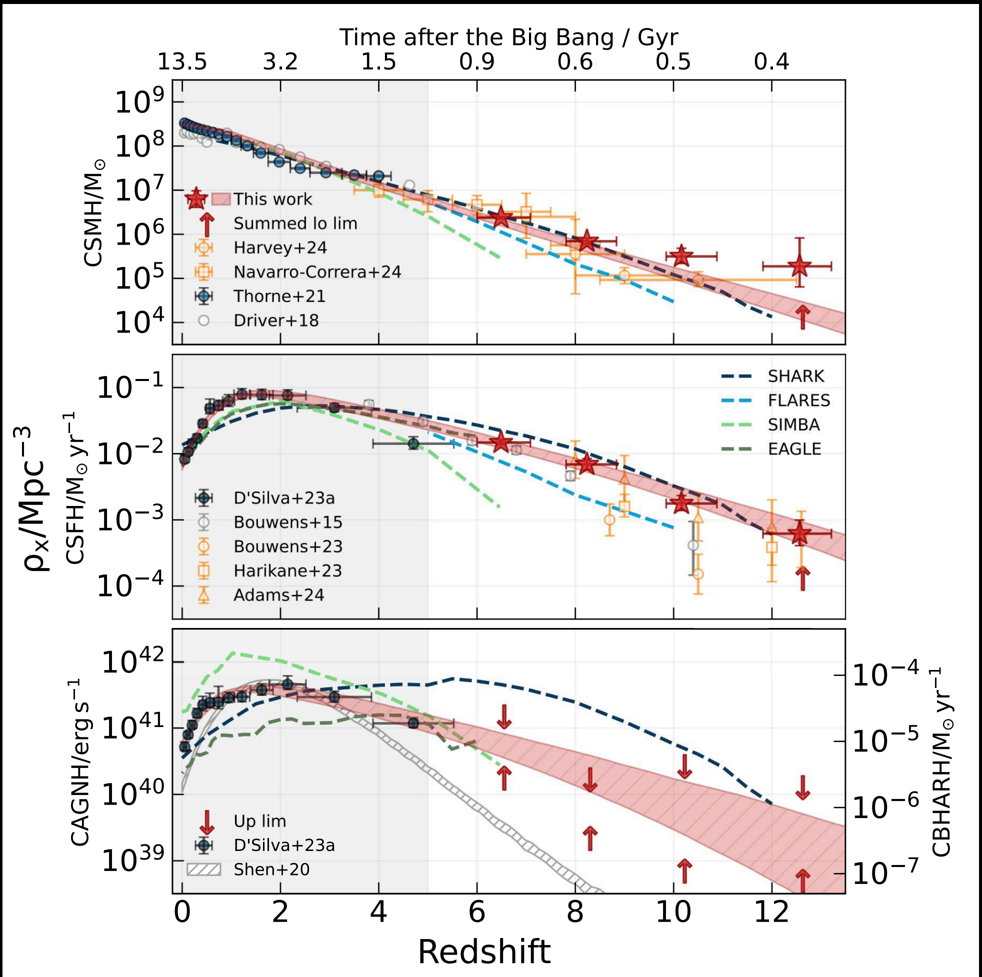


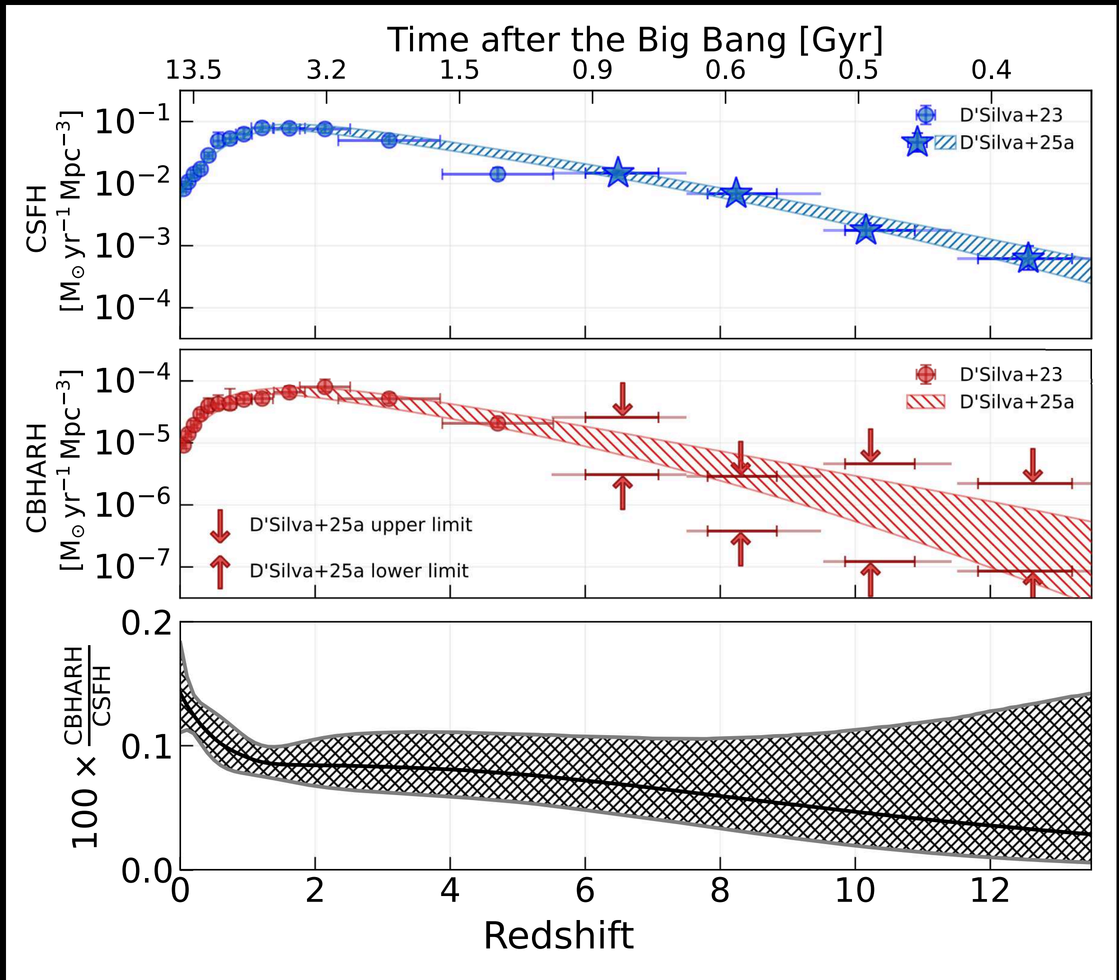
Abell 370 Dragon's arc: 44 individual caustic-transiting stars at z=0.73!

(Y. Fudamoto$^+$, *Nat. Astron. 9, 428*, astro-ph/2404.08045; J. Diego$^+$ 2024, A&A, 689, A167).

$\Longrightarrow$ JWST Time-Domain detects luminous stars at z$\gtrsim$0.7 directly!

Summary of Cosmic SFH & AGN-FH from HST+JWST:

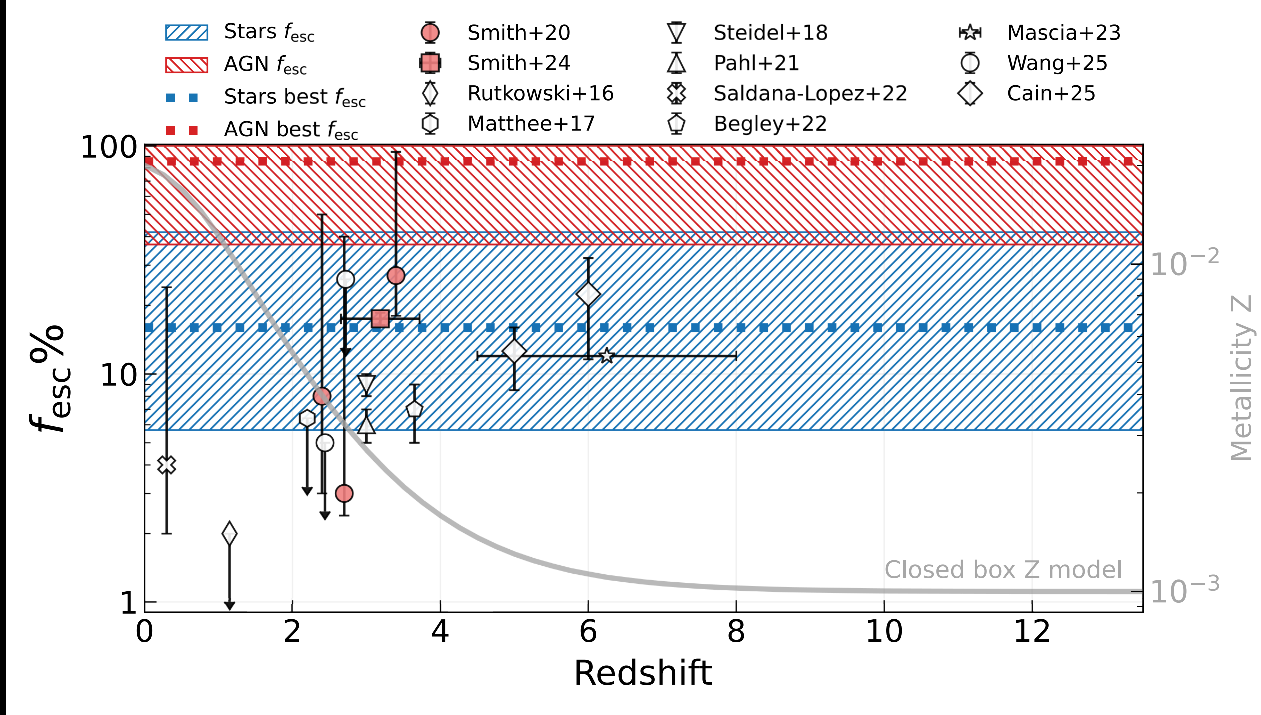




- Cosmic SFH & AGN-FH derived from multi-band HST+JWST data:
- Use ProSpect to decompose into galaxy & AGN SEDs.

(J. D'Silva+ 2023, MNRAS, 524, 1448; — 2024, ApJL, 959, L18; — 2025, A&A, astro-ph/2503.03431).

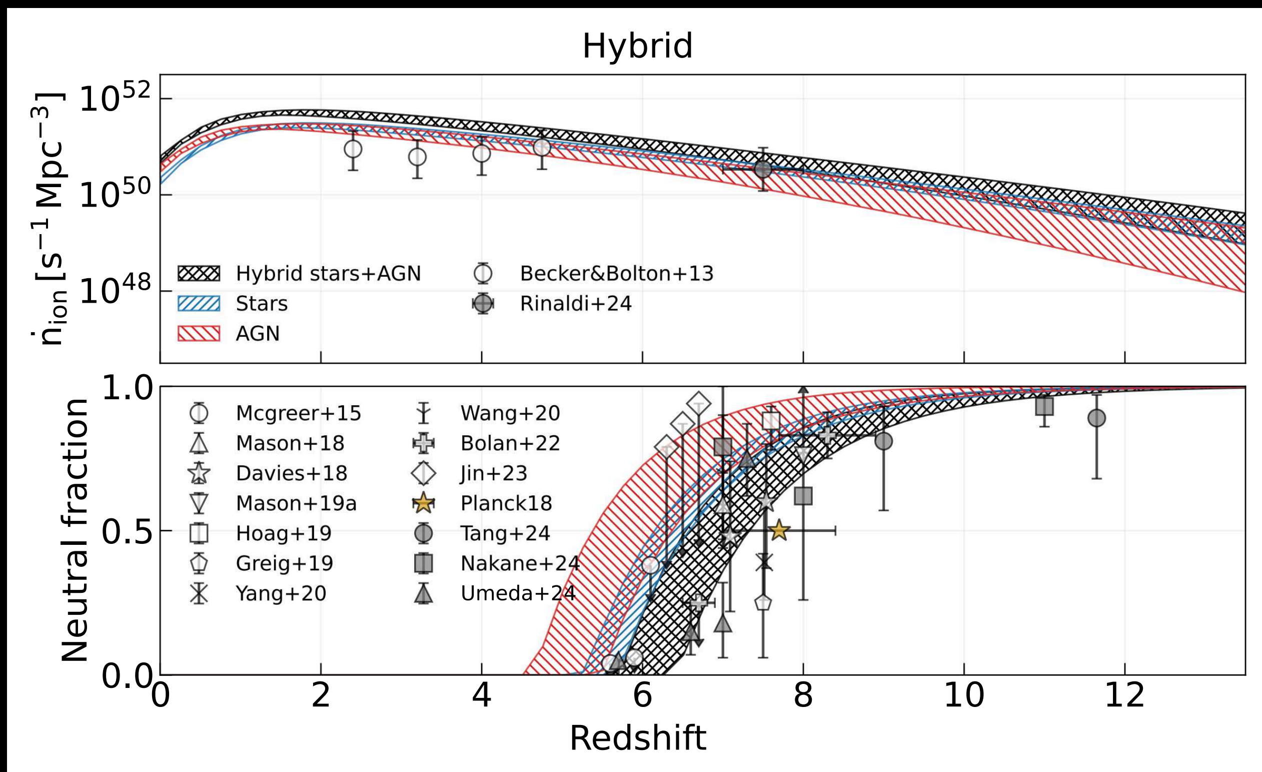
$\Longrightarrow$Within errors, AGN-FH/SFH $\simeq$ constant at $z \gtrsim 2$, but increases at $z \lesssim 1$.



J. D'Silva+ 2025a, A&A

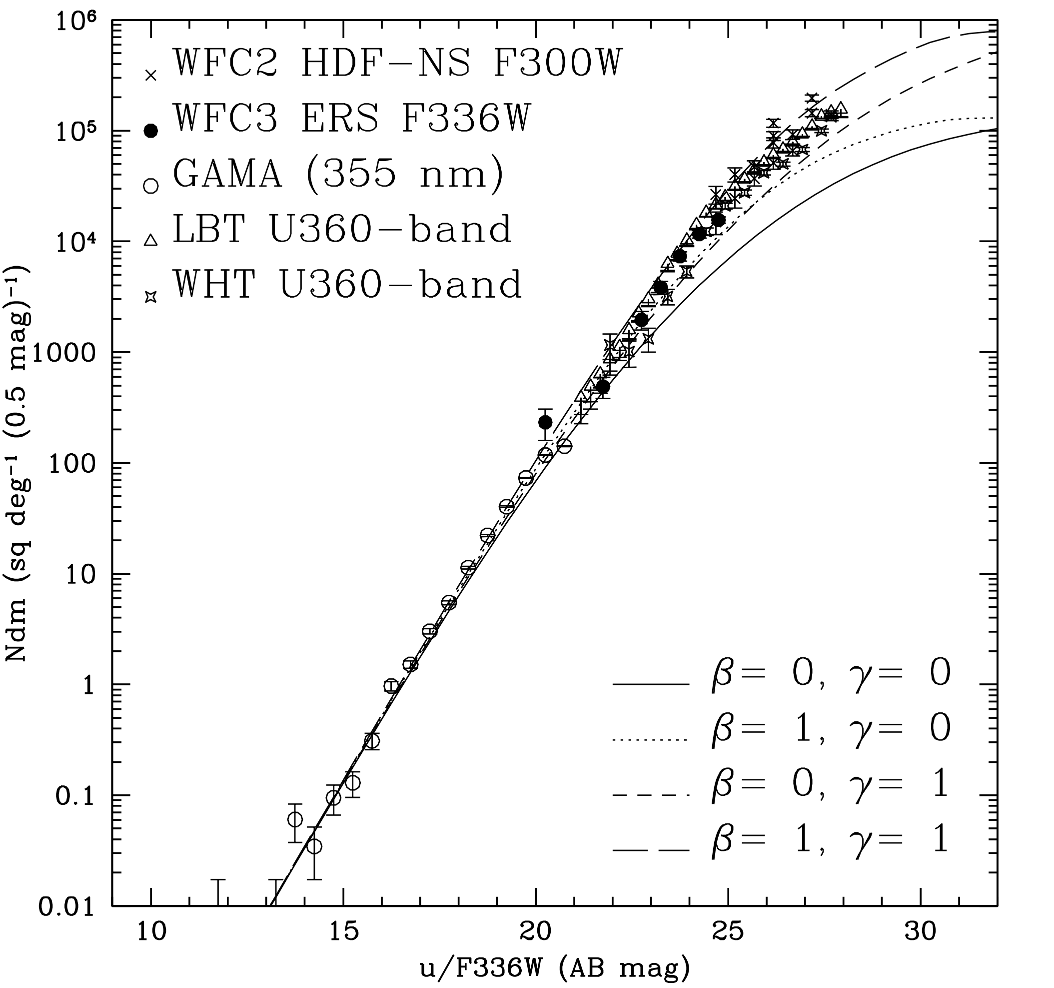
(astro-ph/2503.03431)

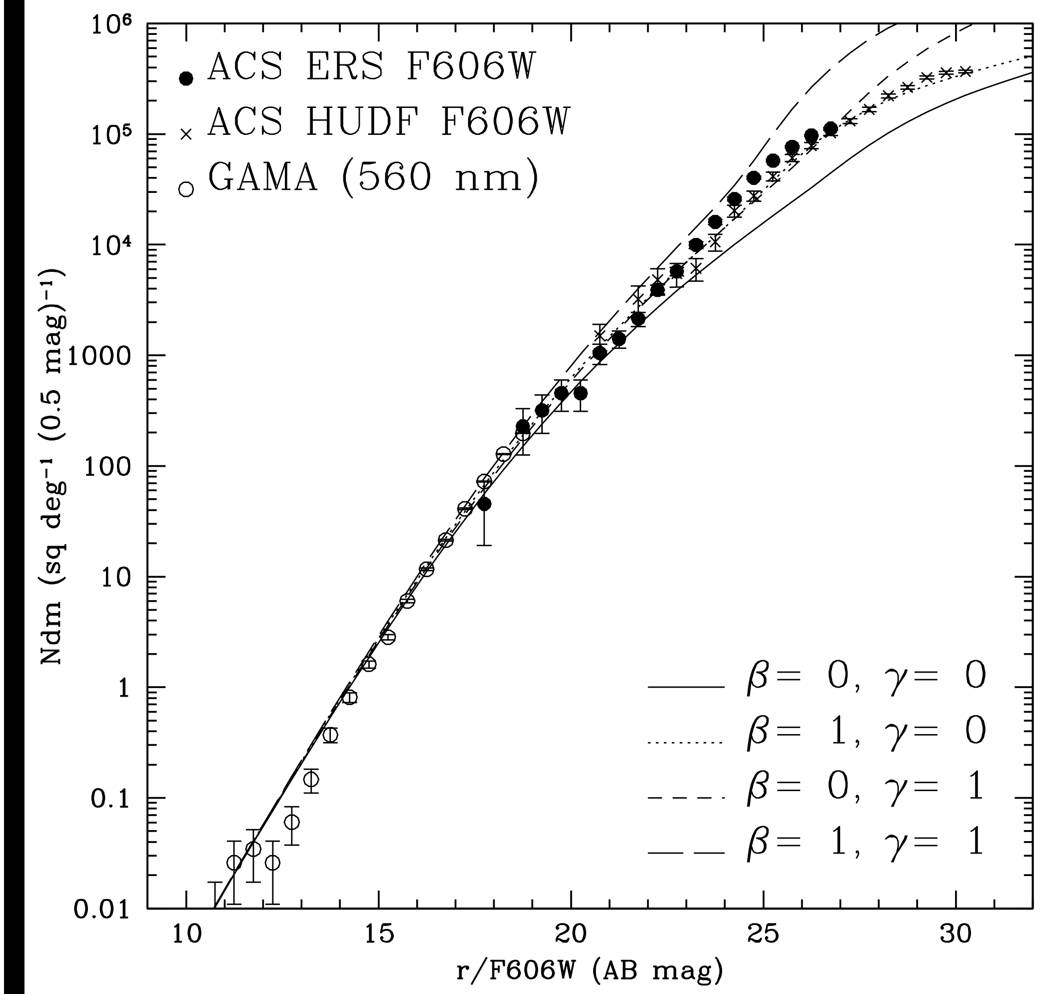
& — 2025b, in prep.



- HST+JWST's SFH & AGN-FH consistent with f_{esc}, n_{ion}, $X_{HI}(z)$.

(3) Need space-based imaging for contamination-free LyC work !



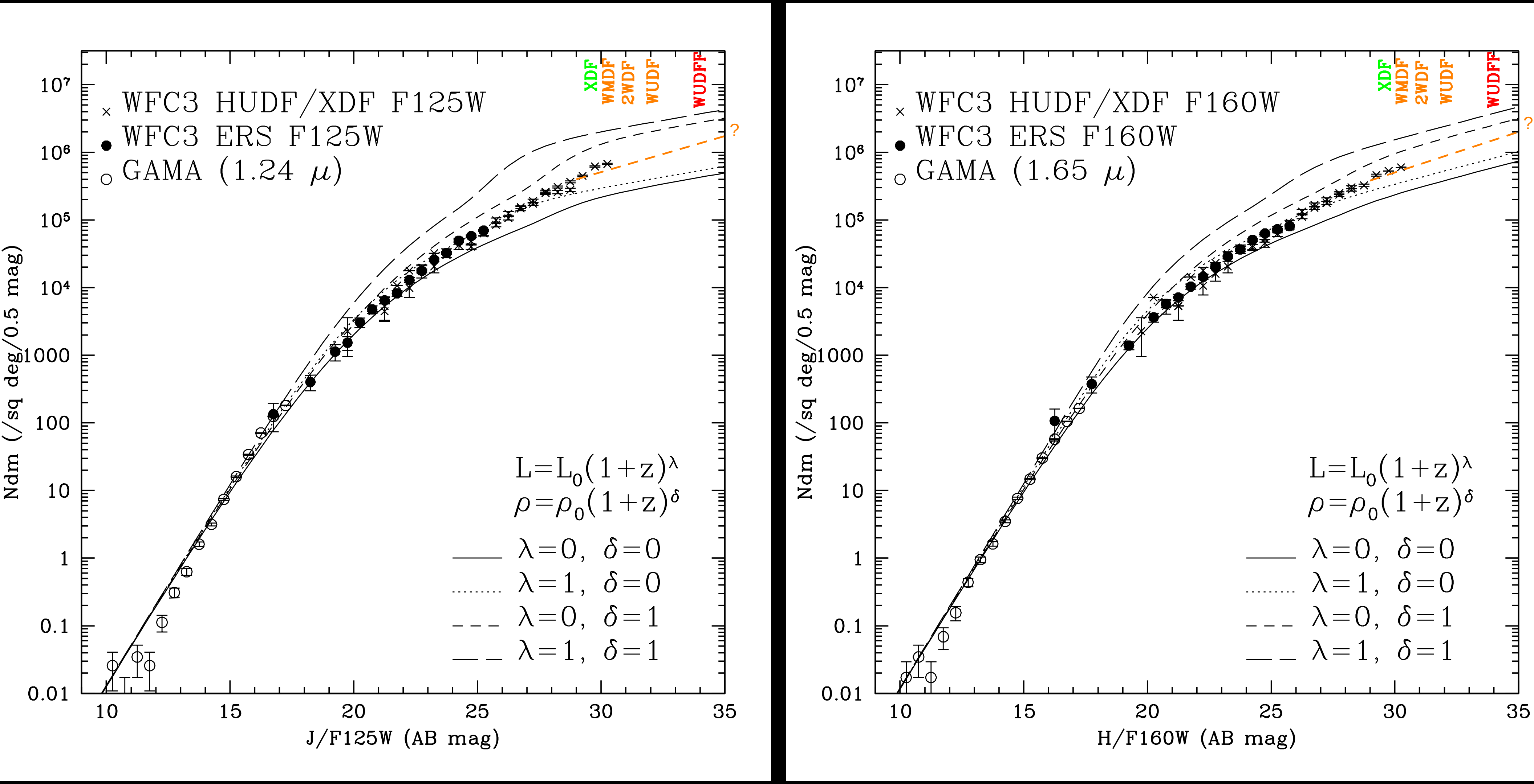


U-band and V-band galaxy counts (Windhorst^{+}2011, ApJS, 193, 27).

Faint-end blue count-slope$\simeq$0.30–0.40 dex/mag.

Integrated surface density at AB$\lesssim$31 mag: $3\times10^{6}\ \ deg^{-2}$.

(3) Need space-based imaging for contamination-free LyC work !



J-band and H-band galaxy counts (Windhorst$^+$2011, ApJS, 193, 27).

Faint-end near-IR count-slope$\simeq$0.12$\pm$0.02 dex/mag.

Integrated surface density at AB$\lesssim$31 mag: 4.2$\times 10^6$ deg^{-2} .

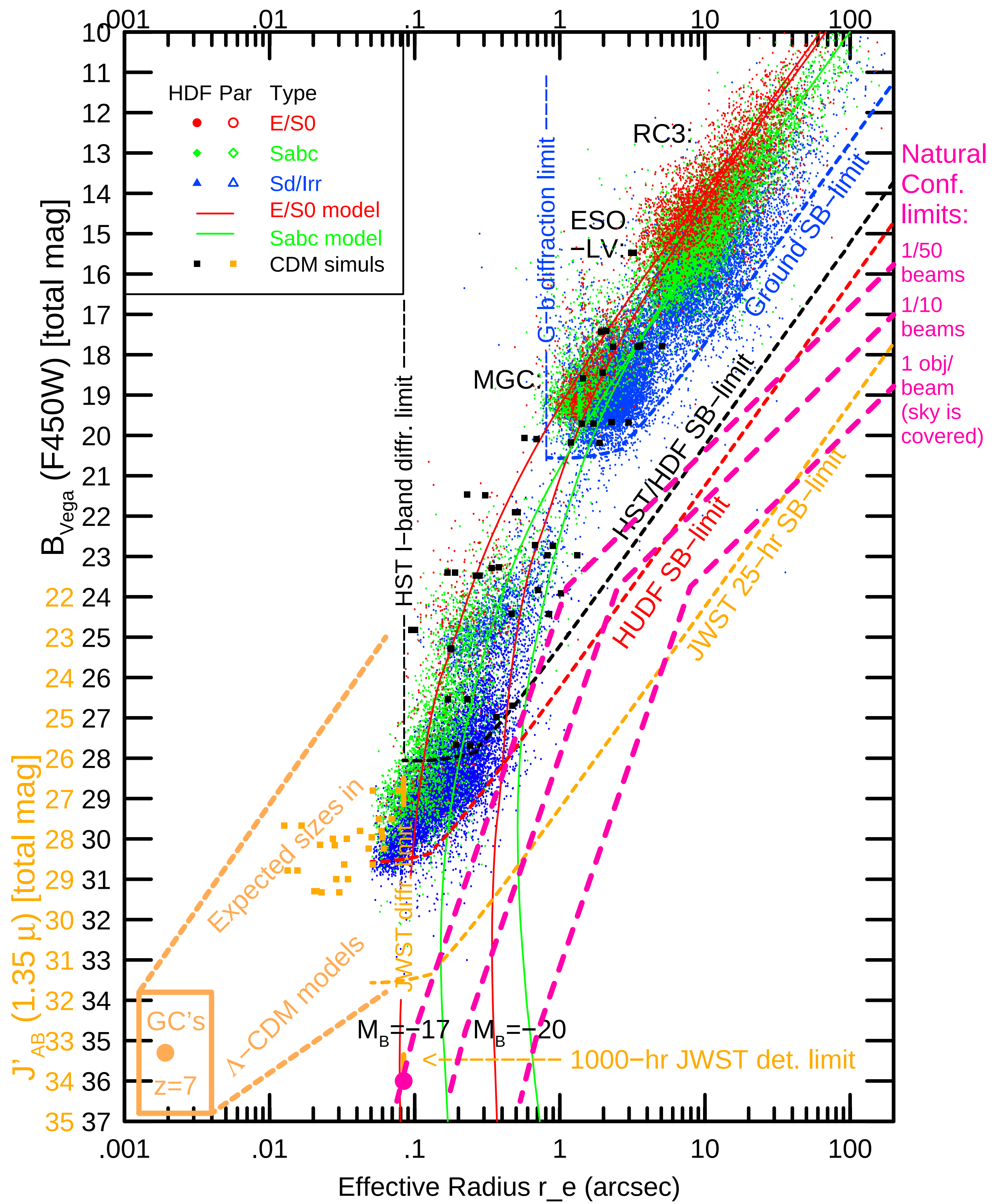
B, I, J AB-mag vs. half-light radii r_e from RC3 to HUDF.

All surveys limited by by SB (+5 mag dash)

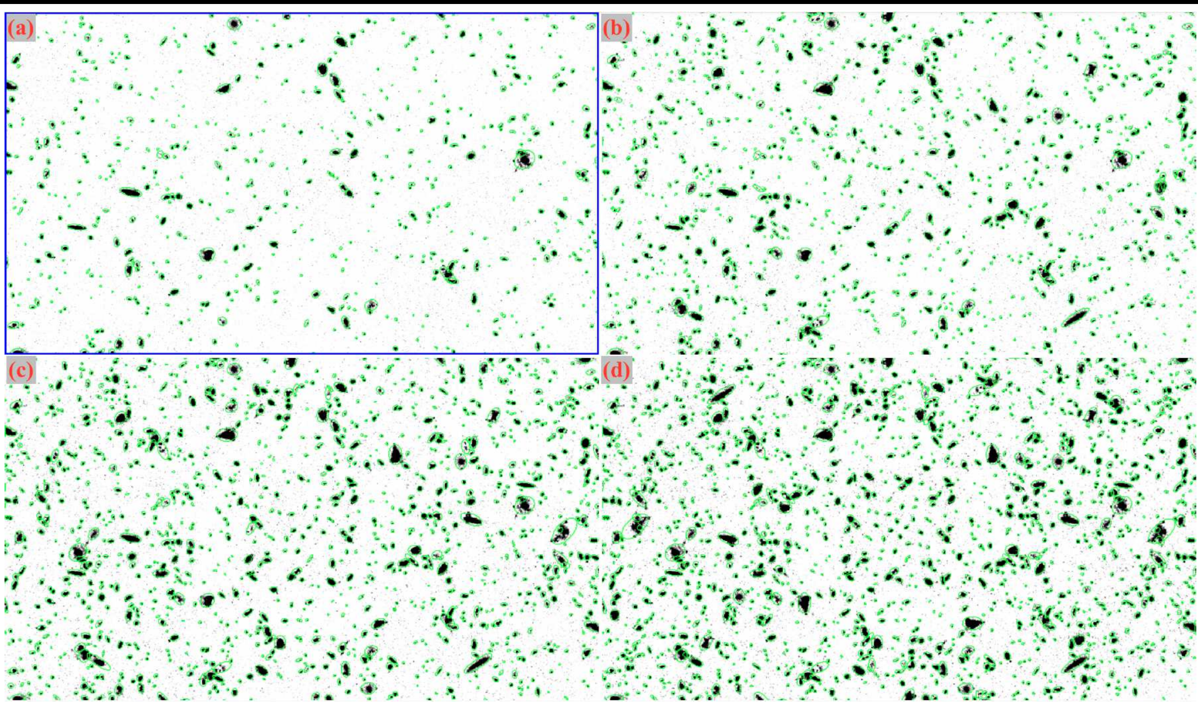
Deep surveys bounded also by object density:

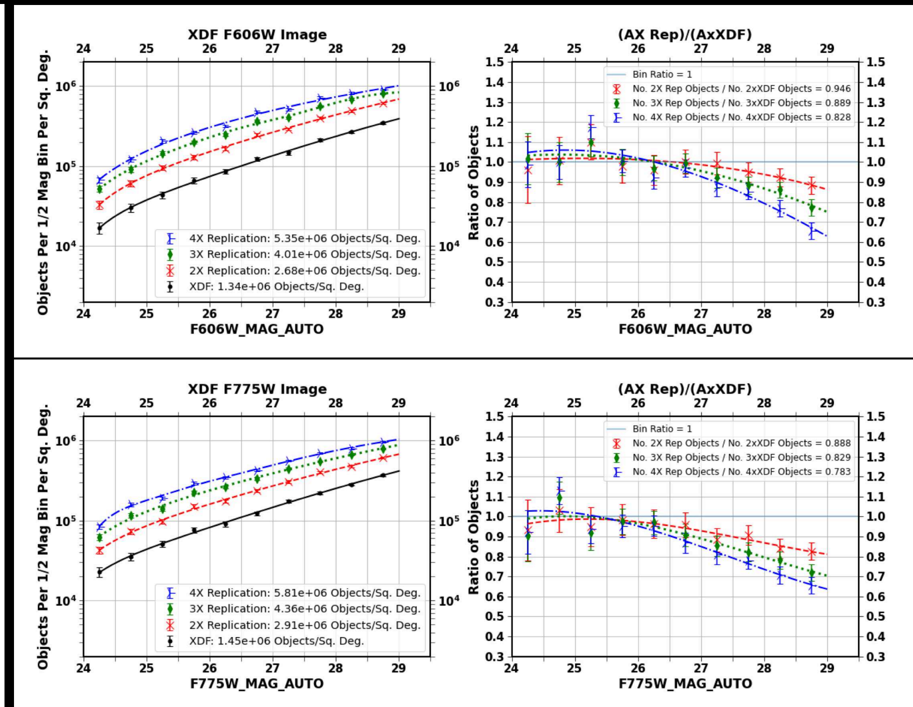
violet lines are gxy counts converted to to natural conf limits.

Since UVC/LyC$\lesssim$-3.7 mag, LyC imaging must avoid contaminants at all costs!



How much does deep-field object-overlap affect reliable LyC detections?





[Left]: Add HUDF image to itself 2×, 3×, 4× after n×90° rotation:

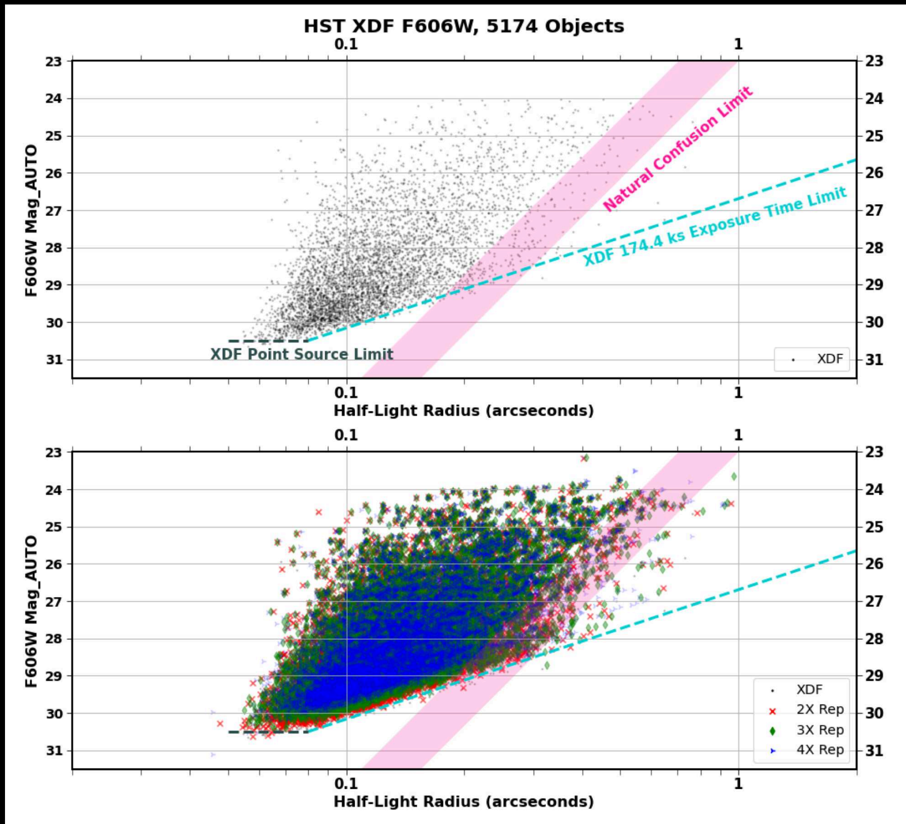
[Right]: 4×HUDF counts still $\gtrsim$65% complete for AB$\gtrsim$28.5–29 mag.

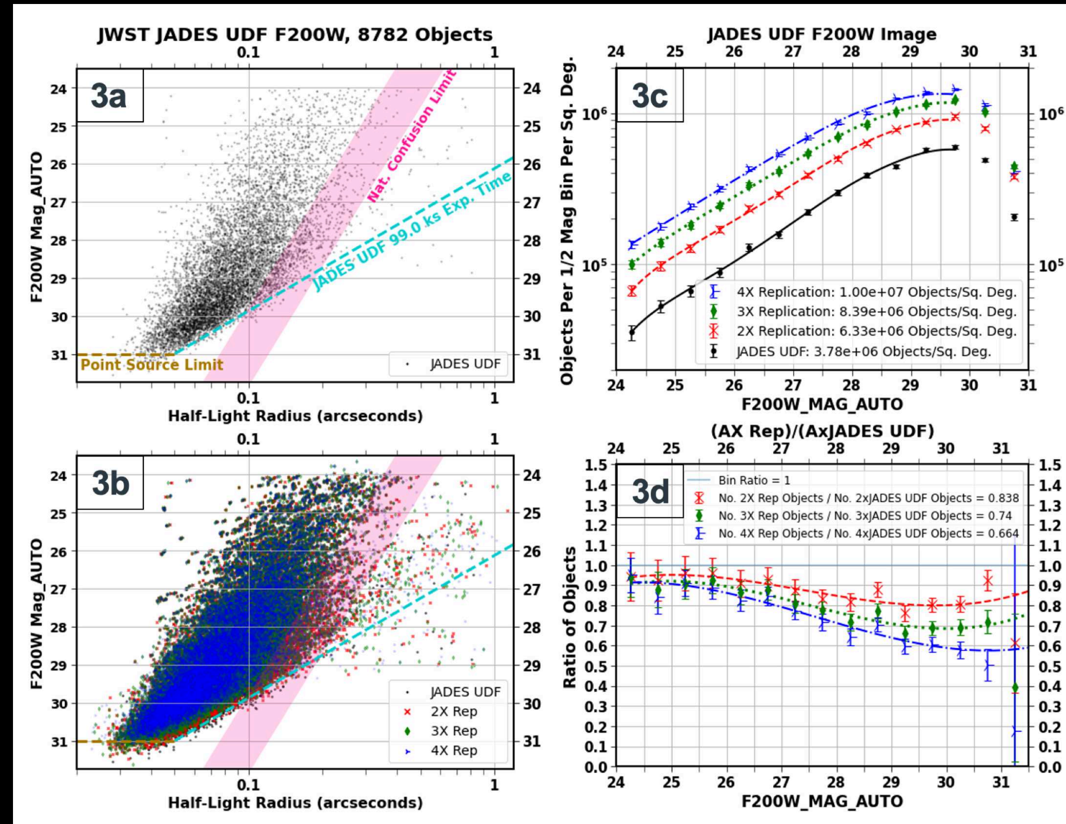
(Kramer, D.+, 2022, ApJL, 940, L15; astro-ph/2208.07218v2).

- Natural confusion ($\neq$ instrumental confusion): increasing inability of object detection algorithms to deblend extended galaxies at AB$\gtrsim$24 mag.

- 3–4$\times10^6$ galaxies/deg^2 at AB$\lesssim$31 mag with r_{hl} $\lesssim$0$''$.1–0$''$.2 FWHM.

(Windhorst+ 2008, Adv. in Space Res., 41, 1965 (astro-ph/0703171); — 2011, ApJS, 193, 27; — 2022, AJ, 164, 141; — 2023, AJ, 165, 13; see also Fernando Buitrago's talk).





Top: mag vs r_e for 174 ksec XDF (left) & 99 ksec JADES (middle) galaxies.

Bottom: Same for XDF & JADES rotated+replicated onto itself $2\times$, $3\times$, $4\times$.

Right: Counts and completeness functions for $2\times$, $3\times$, $4\times$ rotated images.

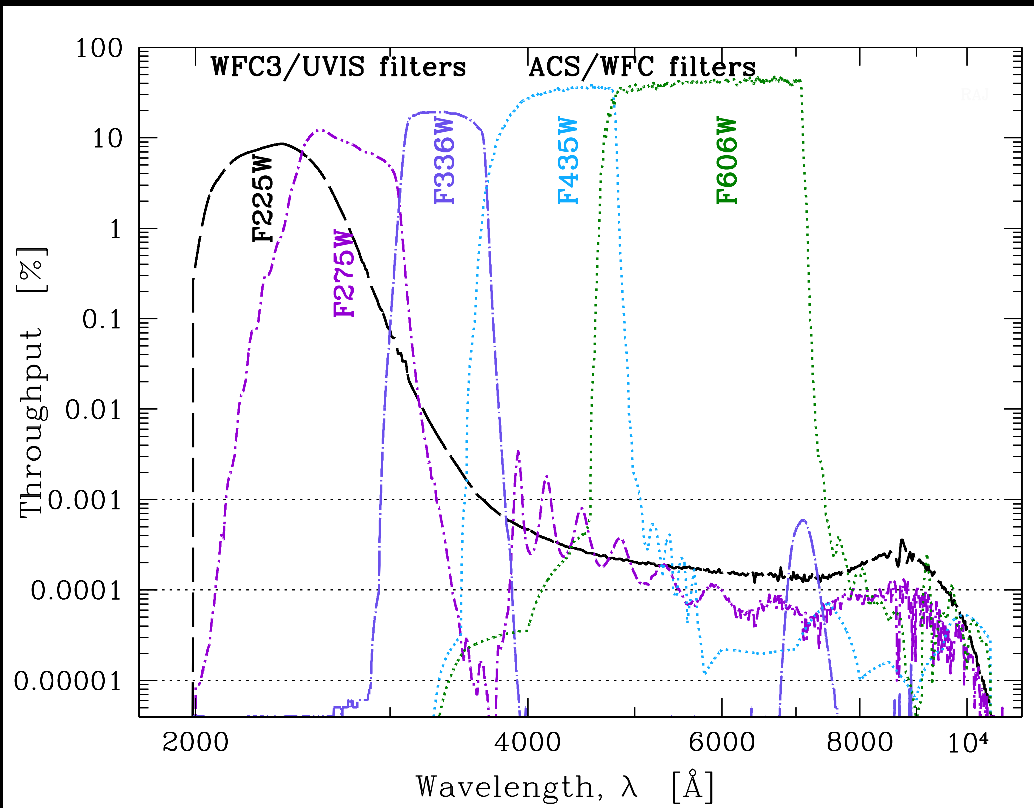
- $\lesssim$35% of faintest galaxies lost due to statistical object overlap.

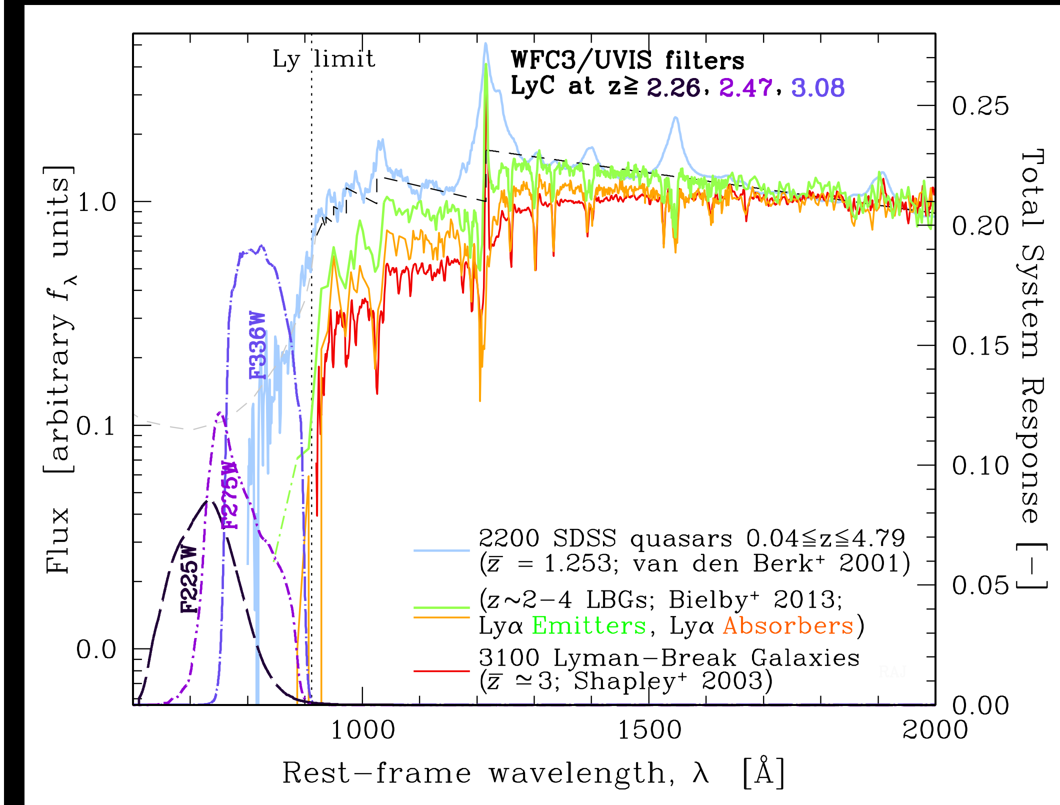
(Kramer, D.$^+$, 2022, ApJL, 940, L15; astro-ph/2208.07218v2).

$\Rightarrow$ LyC work at UVC$\sim$24-27 must avoid contaminants with AB$\lesssim$28–31 mag!

JWST: 1" LyC apert $\lesssim$30% contaminated by foreground UVC$\lesssim$31 mag!

• HST WFC3/UVIS Constraints of LyC at z∼2.2–3.5 (Smith[+] 2018).





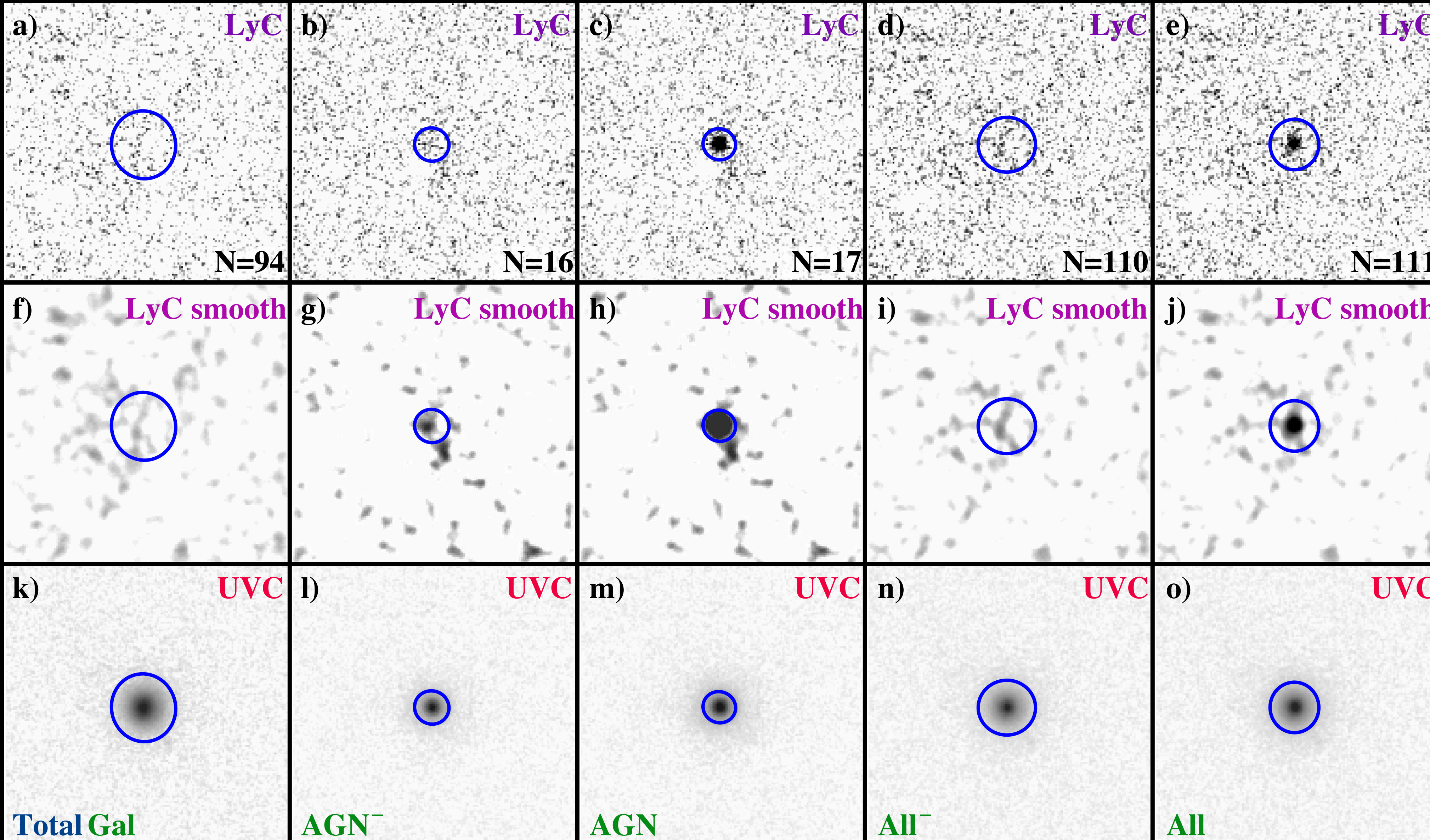
[Left] WFC3 designed to maximize throughput and minimize red-leak:

• Red-leaks $\lesssim 3\times10^{-5}$ of peak transmission, or $\lesssim$0.6% 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).

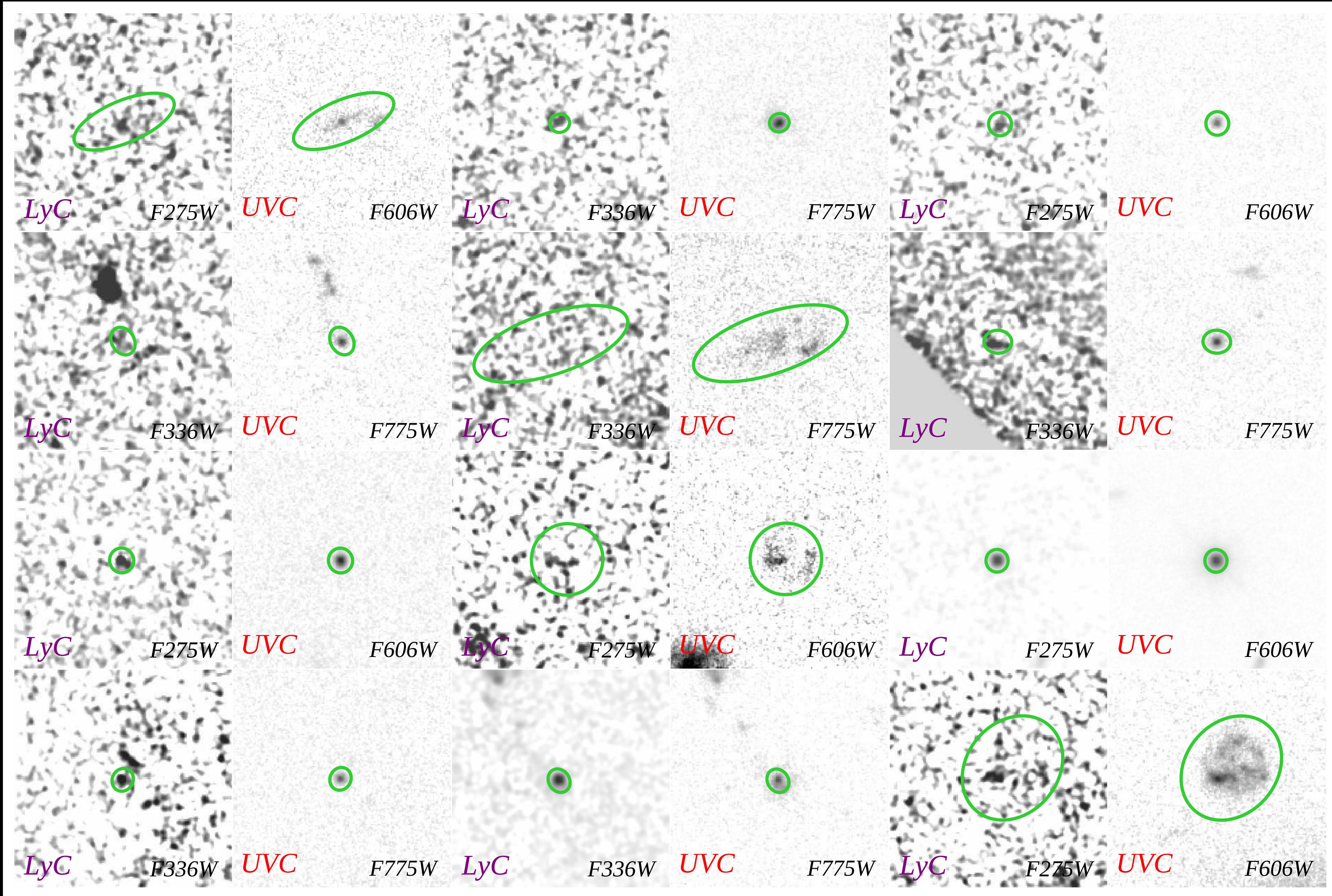
• Lower z-bounds: *no* λ> 912 Å below filter's red-edge (≡0.5% of peak).



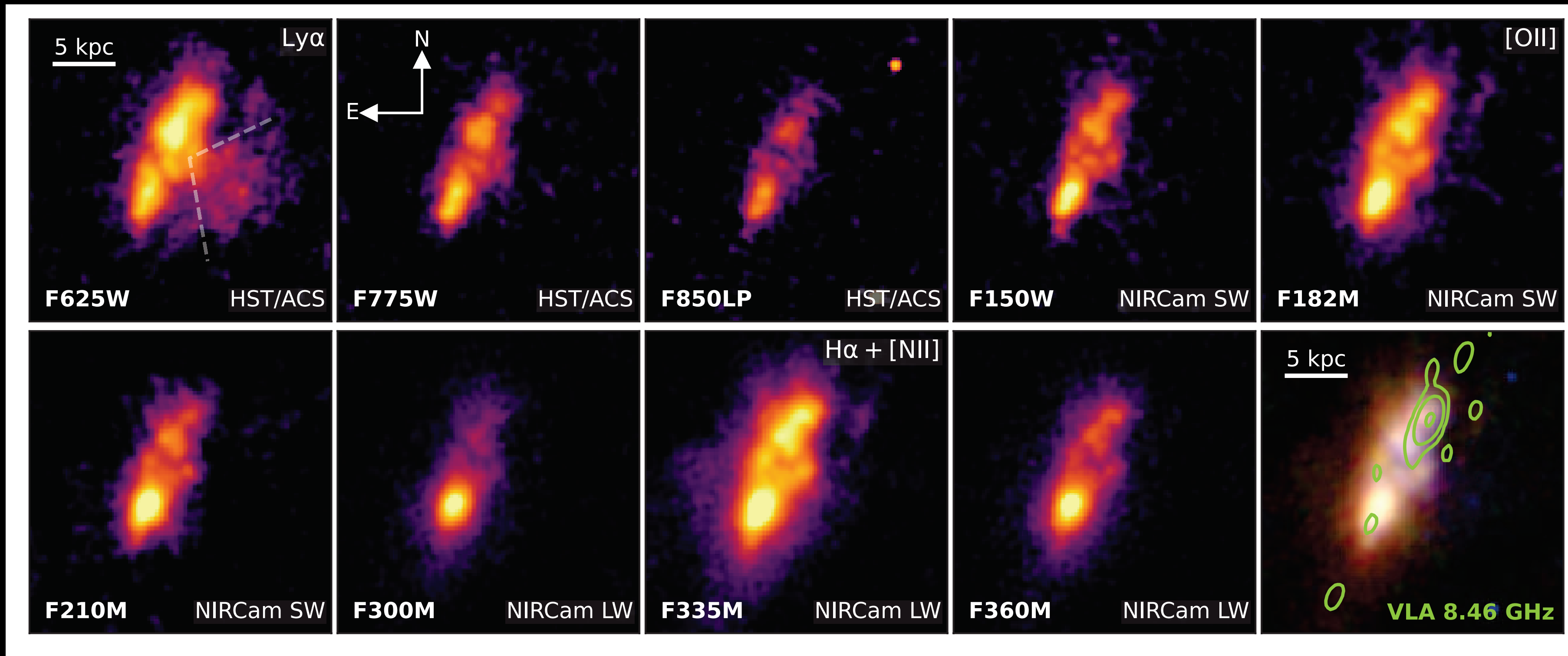
WFC3/ERS & HDUV AGN+Galaxy LyC stacking (Smith et al. 2018, ApJ, 853, 191; — 2020, ApJ, 897, 41).

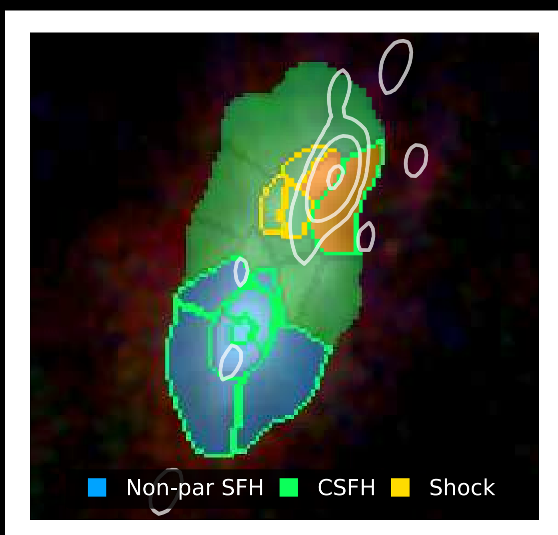
- Rare (weak) AGN with robust spectroscopic redshifts at z$\simeq$2.3–3.5 dominate reionizing LyC flux in stacked WFC3/UVIS images (AB$\lesssim$29 mag).

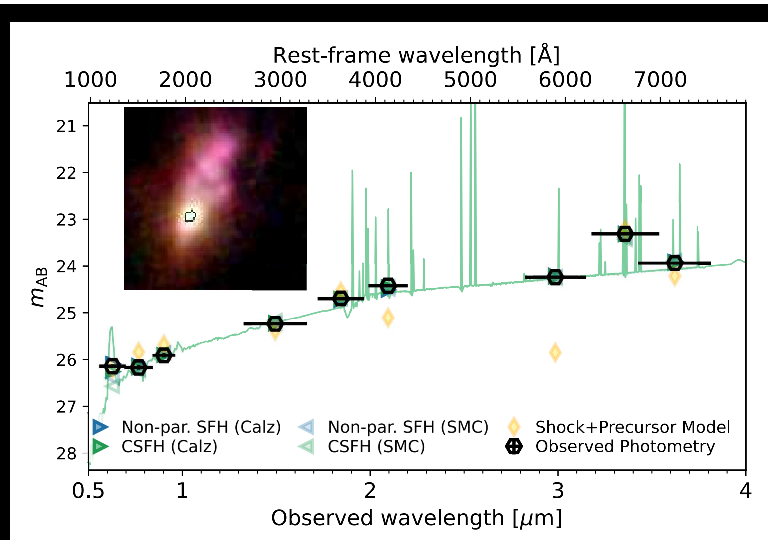
- Need $\simeq$0."04 WFC3 UV-PSF to remove all foreground interlopers at >> 99% confidence!

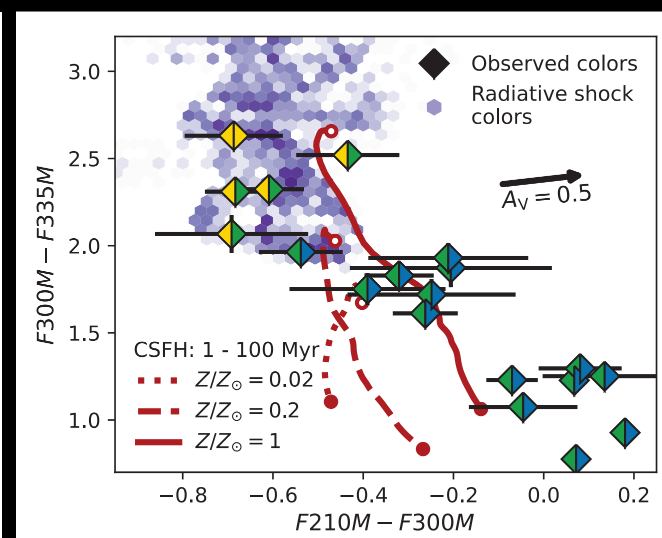


- UVCANDELS AGN LyC detections AB$\simeq$23.4–28.5 mag: $f_{esc} \simeq 30 \pm 25\%$.
- 12/58 detected (21%): $<$LyC opening $\theta$$>$$\lesssim$40° (Smith[+] 2024, ApJ, 964, 73).





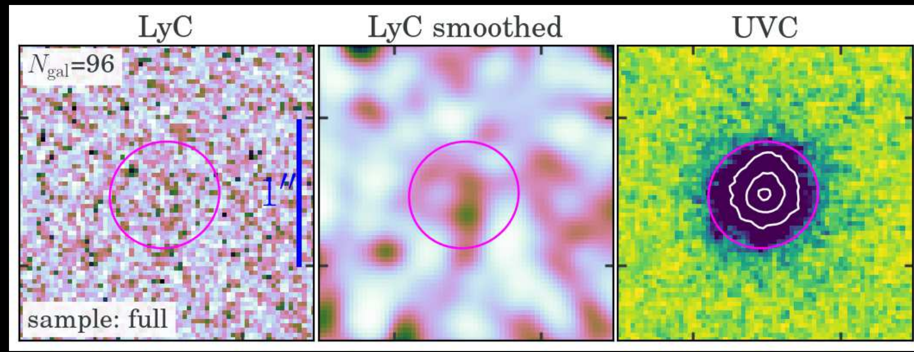


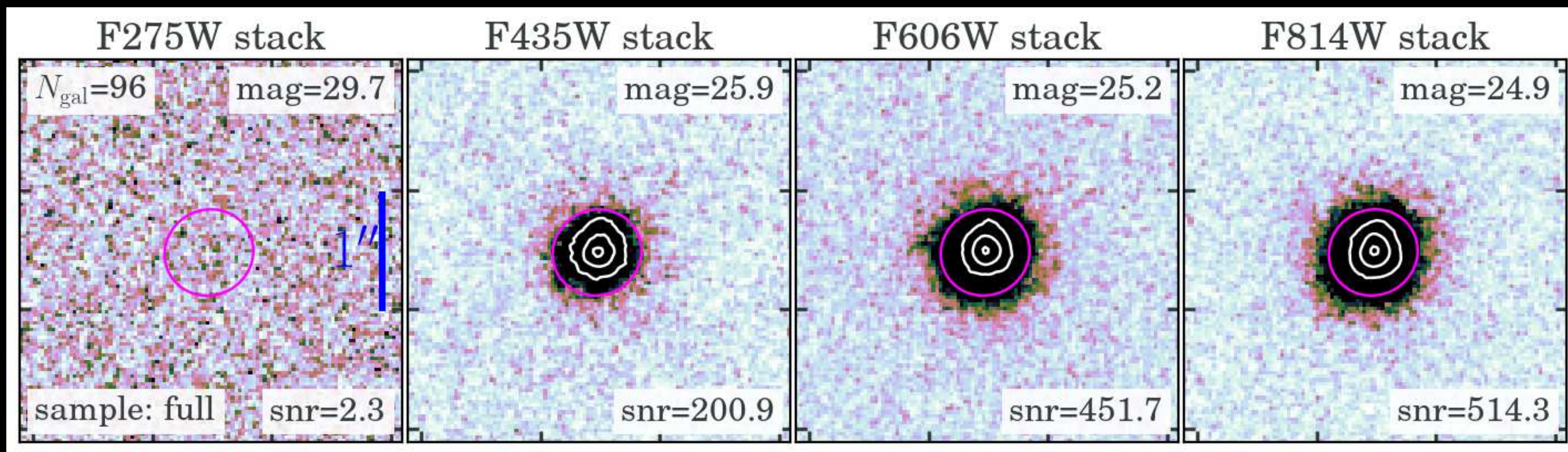


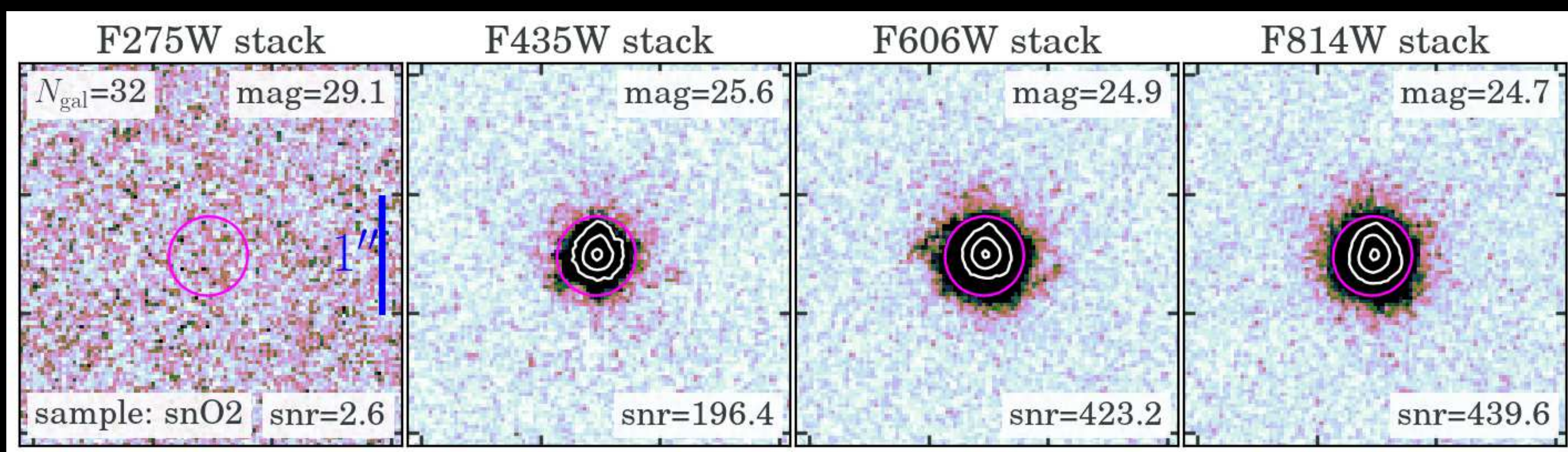
One of the most massive ($10^{10.9}$ $M_\odot$) high-z radio galaxies at z=4.11:

- TNJ1338: NIRCam medium-band SFR∼1800 $M_\odot$/yr; extreme jet-induced SFR$\gtrsim$500 $M_\odot$/yr, $t_{SFR}\simeq$4 Myr.

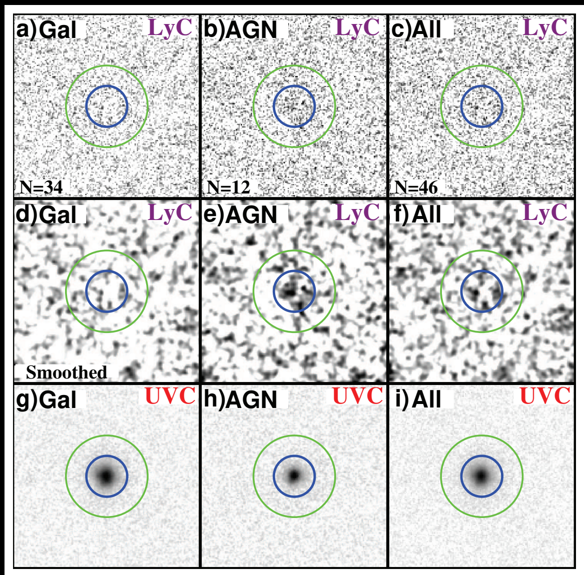
Opening angles: HST Lyα $\theta_h\lesssim$50°; NIRCam+VLA jet $\theta_h\sim$10° (Duncan$^+$ 2023, MNRAS, 522, 4548)

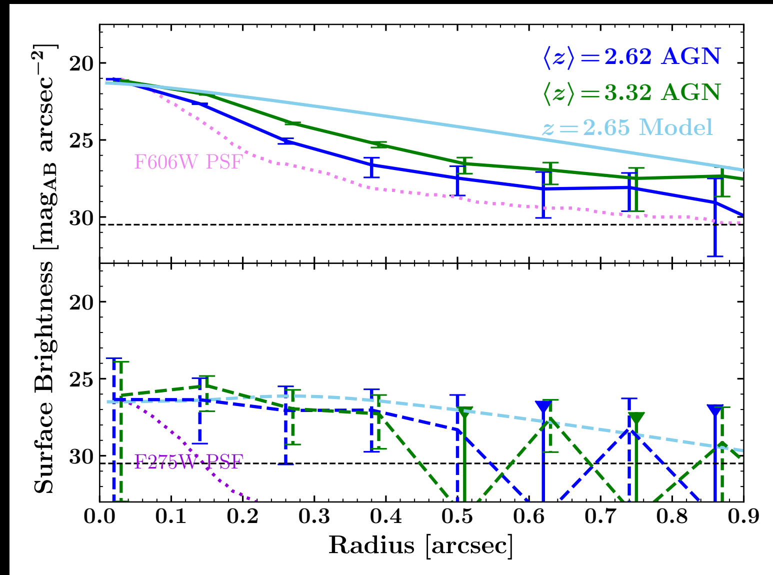


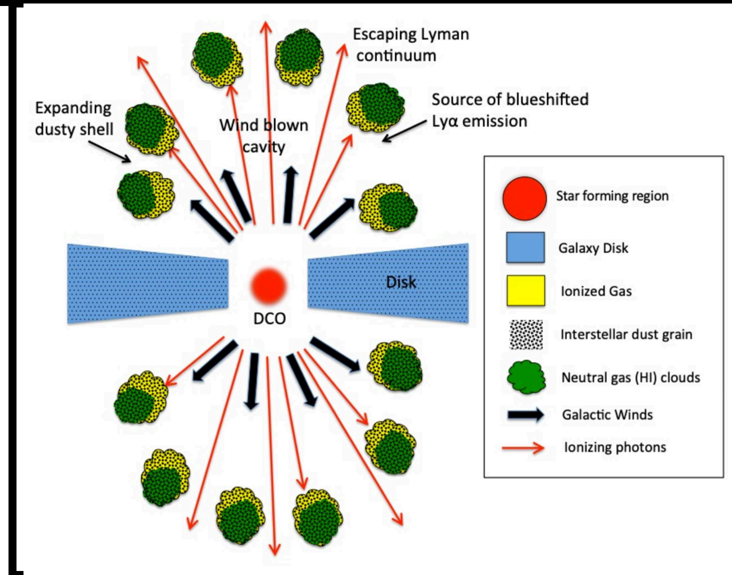




- UVCANDELS galaxy LyC detections AB$\simeq$25.5-26.6 mag, LyC stacks $\sim$29.1–29.7 mag; resulting $f_{esc}$$\sim$6–10%. [1-cos($\theta_h$)$\equiv$detected fraction]:
- 5/96 detected (5%): $\langle$LyC opening$\,\theta\rangle \lesssim 20^\circ$ (Wang+ 2025, ApJ, 980, 74)







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

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

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

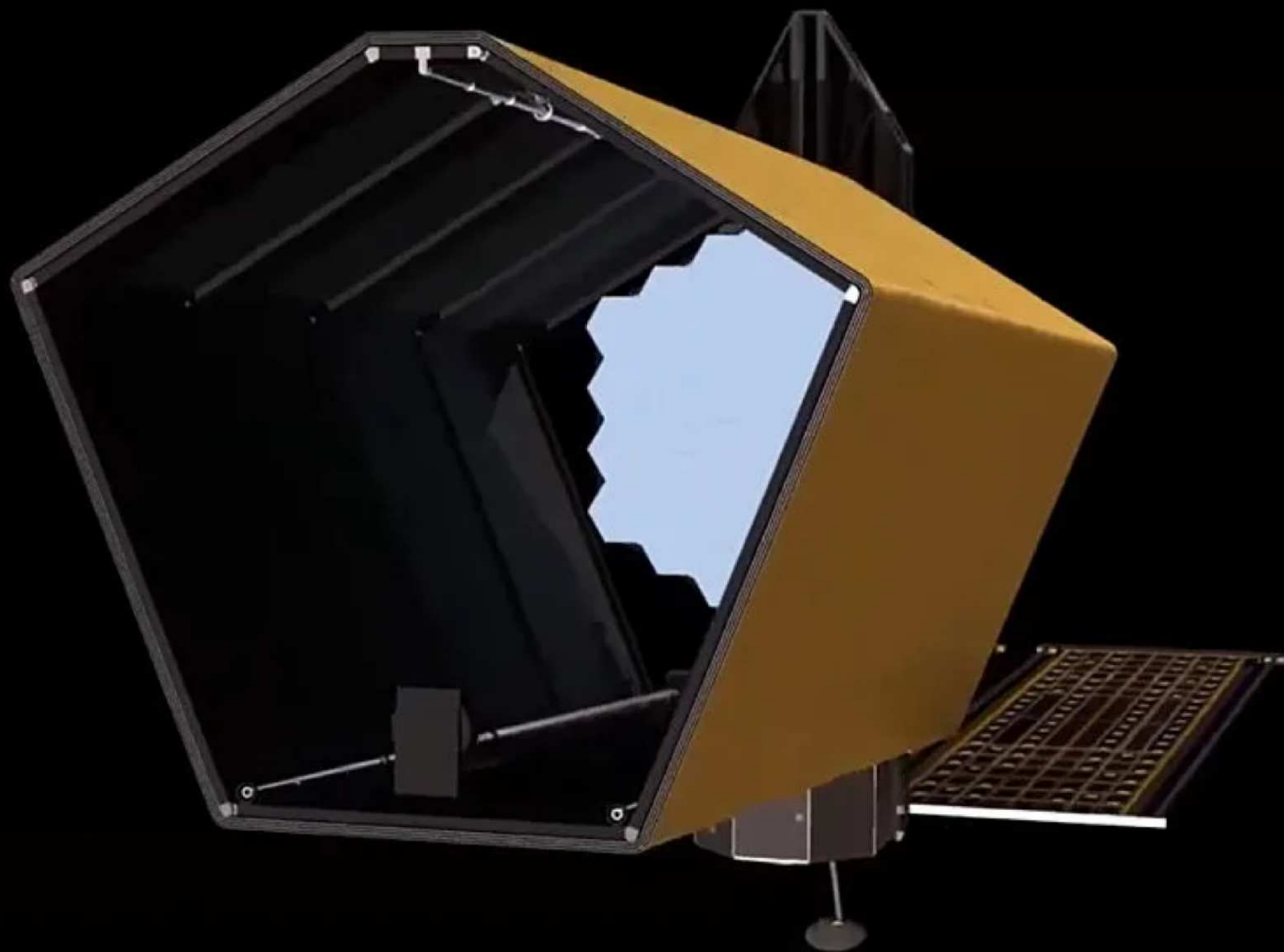
Dashed: scattering model with ISM porosity+escaping LyC (Smith, B.+ 2018).

[*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

(Smith, B.+ 2018, ApJ, 853, 191; — 2020, ApJ, 897, 41; — 2024, ApJ, 964, 73; Wang+ 2025, ApJ, 980, 74).

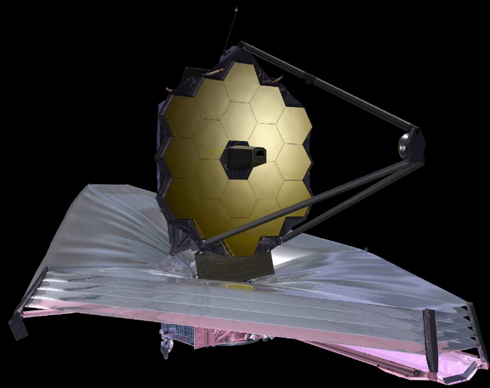
(4) Habitable World Observatory requirements for LyC work

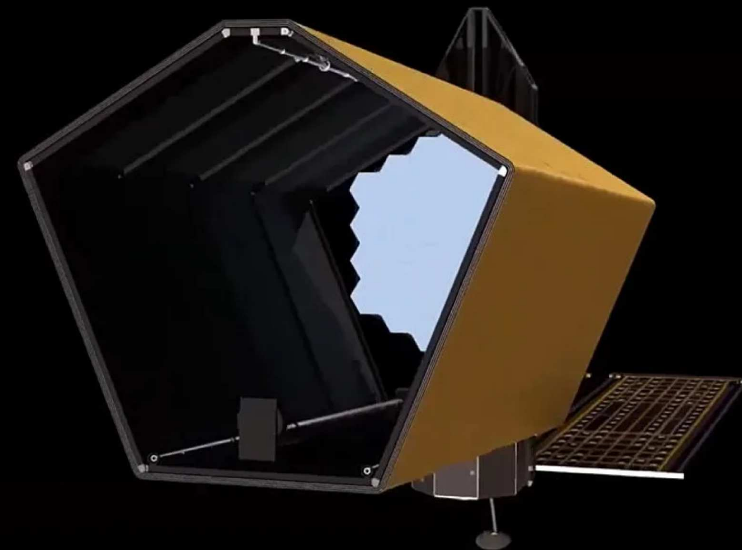


- Next generation $\gtrsim$6–8 meter UV-optical space telescope (HWO) essential for AB$\lesssim$30 detections and AB$\sim$32 mag for LyC stacks (N$\gtrsim 10^4$).
- Need: L2 servicing, periodic CCD replacement, & wide-field UV IFU/MSA.

Past, Present and Future: Can and will the dream continue?

True relative size: Hubble, James Webb, Roman, & HWO

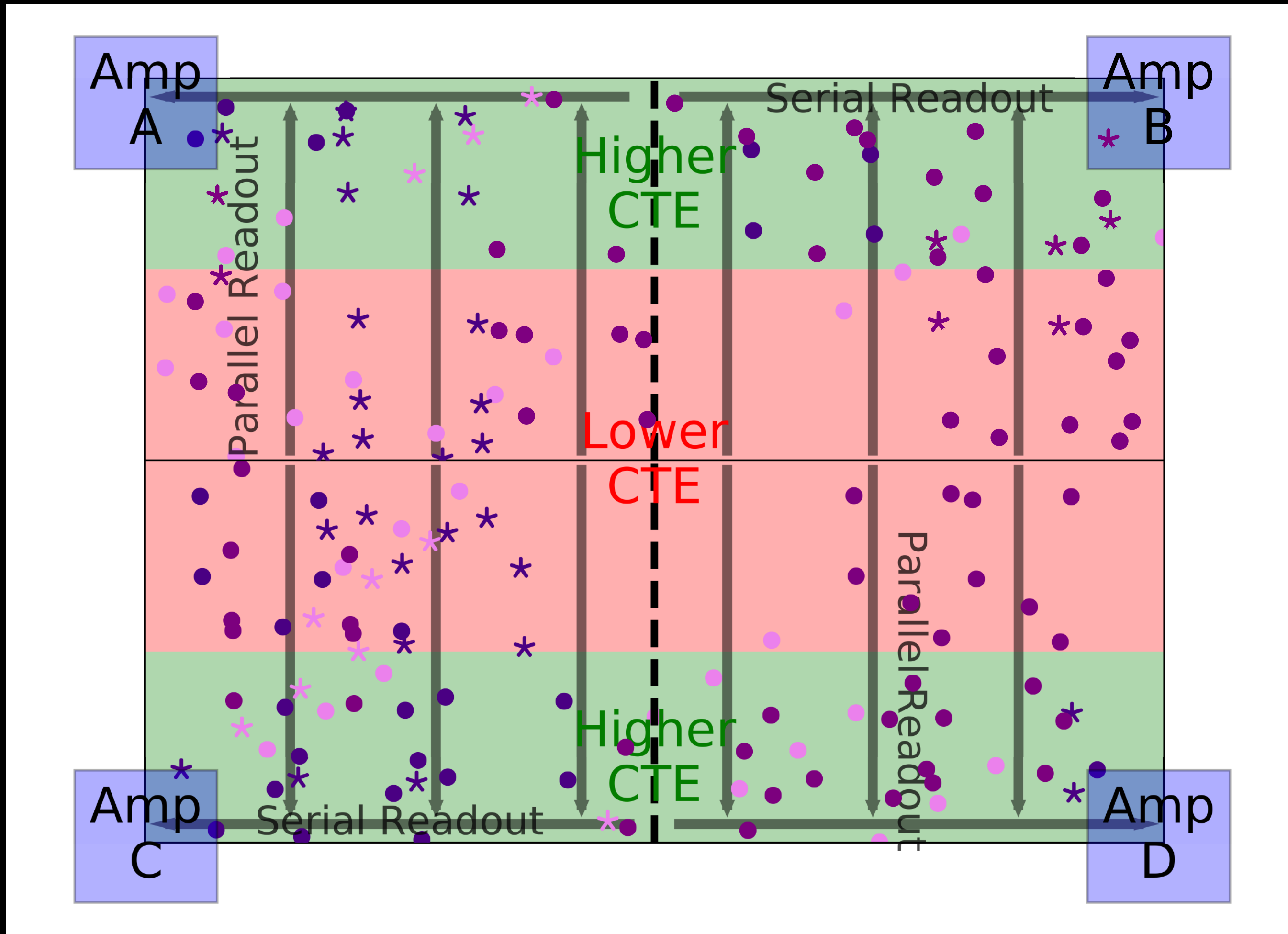



1973–2034$^+$(!)	1996–2046$^+$	2012–2037?	2025–2070$^+$?
Launch: 1990	2021	$\gtrsim$2027	$\gtrsim$2040?
Σ_{FC}: $\gtrsim$20 B$	$\gtrsim$10 B$	$\sim$3 B$	15–20 B$?

- My goal today: Inspire the younger folks in the audience to successfully build the Habitable Worlds Observatory (HWO).

Many speakers this conference already talked about future prospects, amongst others: Pratika Dayal, Andrea Grazian, Sara Mascia, Ivan Nikolić, Allison Strom, Ana Sofia Uzsoy, Alessandra Venditti, and others.



B. Smith+ (2018 & ApJ, 853, 191)

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 suffer more from CTE-degradation.

- CTE-degradation may be mitigated by s/w corrections (Anderson 2016, 2021).

- CTE-loss linear with time/CR-flux: need CCD replacement every 10 yrs!

Summary of lessons learned from JWST:

What is required to make Mega-Science projects succeed?

• JWST Lessons: Mega-project lessons also apply to HST & HWO. Key is that scale of efforts goes beyond what people are used to.

• Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates.

Consumers Report: Very Good ⇒ Good ⇒ Neutral ⇒ Fair ⇒ Poor.

- (A) Scientific/Astro-Community Lessons
- (B) Technical Lessons
- (C) Management/Budget/Schedule Lessons
- (D) Political/Outreach Lessons

I thank Drs. S. Cohen, G. Illingworth, R. Jansen, J. Mather, E. Smith, R. Smith & H. Thronson for comments.

Full 1-hr talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/fall2020_jwstlessons.pdf`

- Infighting killed the 1988 Superconducting Supercollider in Texas (left).
- Canceled project funds never returns: CERN didn't make that mistake (right).

$\Longrightarrow$ Avoid infighting with other (exoplanet) HWO stake-holders.

- Design HWO for exoplanets, reionization, and everything in between.

Summary: Main Lessons from the JWST Project:

(1) Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates:

(A) JWST Scientific/Astro-Community Lessons:

- 1) Project is a must-do scientifically and cannot be done any other way.
- 2) Keep advocating Mega-project to community until launch/first light.
- 3) Don't ignore importance of communication with patrons: Scientists, international partners, contractors, tax-payers, Congress, White House.
- 4) Don't have community infighting ("My mission is better than yours" — One key reason for Supercollider (SSC) demise).

(B) JWST Technical Lessons:

- 1) Use advanced technologies being developed elsewhere, if possible.
- 2) Know when not to select the most risky technologies.
- 3) Do your hardest technology development upfront. Have all critical components at TRL-6 before Mission Preliminary Design Review (PDR).

(C) JWST Management/Budget/Schedule Lessons:

• 1) Make conservative full end-to-end budget before Mission CDR.

• 2) Make sure budgets are externally reviewed, and at $\gtrsim$80% joint cost+ schedule confidence level. (Could not do $\lesssim$2010; Did so early 2011).

• 3) Plan & effectively use 25–30% ($+schedule!) contingency each FY.

(D) JWST Political/Outreach Lessons:

• 1) Assemble, maintain and fully use a broad Coalition of supporters and advocates who will fight for the project (SSC did so too late).

• 2) Have strong multi-partisan & multi-national support for project.

• 3) Strong technology benefits/lessons *TO* other parts of government.

• Today, JWST *is* the telescope that the community asked for almost 30 years ago, and has become an amazing reality. JWST has become the most-in-demand NASA Astrophysics mission ever (see spare charts).

OVERALL CONCLUSION: JWST was built and launched right, but we had to learn our lessons over 25 years.

(5) Summary and Conclusions

(1) HST and JWST uniquely complement each other to trace cosmic star-formation and (supermassive) black-hole formation over 13.5 Gyr.

(2) (Faint) galaxies and (weak) AGN contribute similar LyC vs. redshift.

Dusty objects w outflows especially good at LyC escapei(θ, nr of holes)!

(3) Need space-based resolution for contamination-free LyC at z$\simeq$2.3–3.5

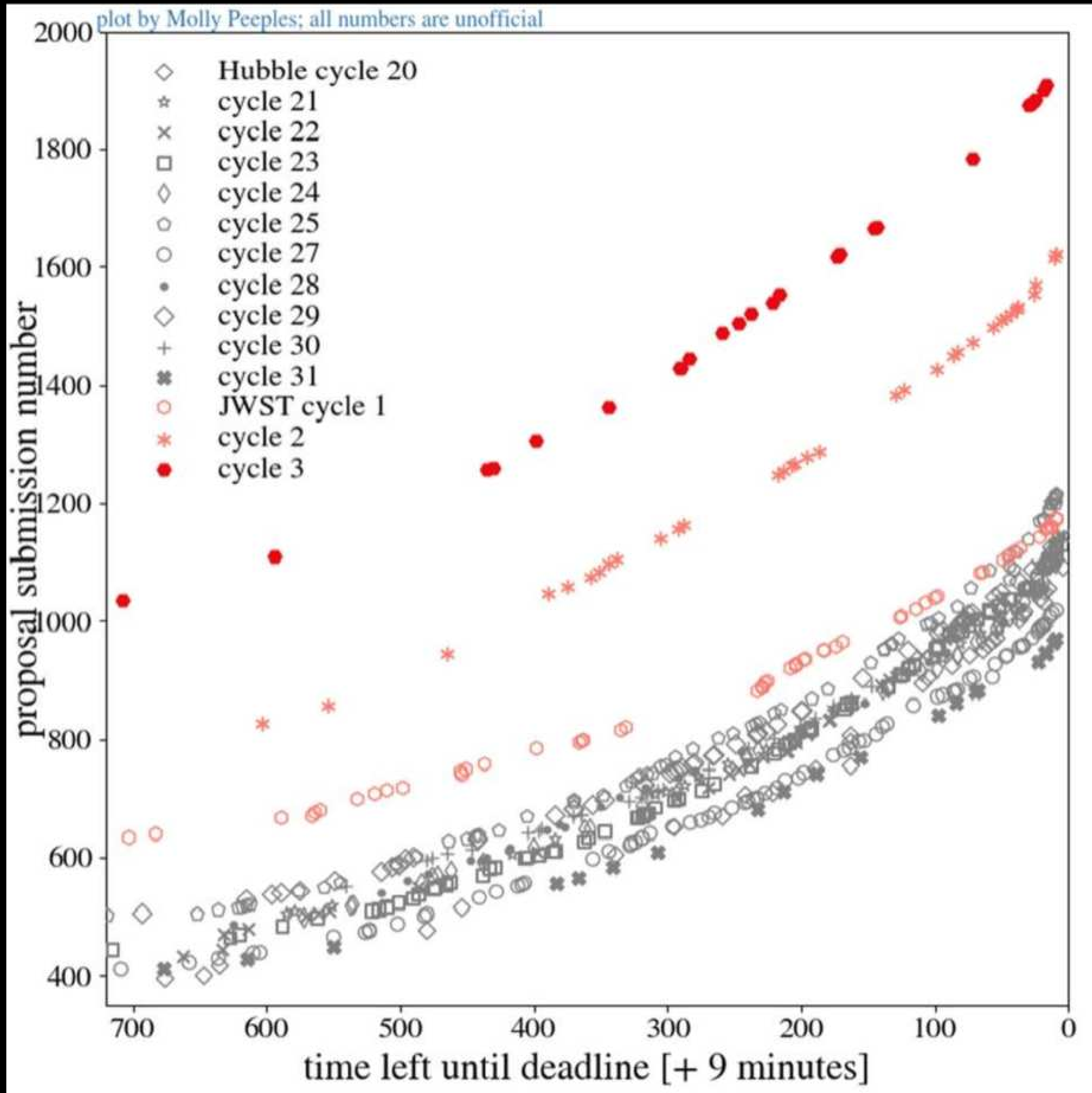
- Design HWO filters with low-enough redleak to enable this.
- Deepest multi-band images to mask foreground AB$\lesssim$31 mag interlopers.

(4) Habitable World Observatory requirements for LyC work:

- L2 servicing every 5–10 years or so — is feasible to L2.
- Wide-field UV sensitized CCDs with periodic replacement in L2.
- Wide-field UV IFU, & UV MSA Spectrograph — needs development.

(5) Coherent team: design HWO for science from exoplanets to reionization.

Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).



• Webb is now THE highest-in-demand NASA Flagship mission ever,

but Hubble remains in at least as high a demand as it was 30 years ago!

(1) SCIENCE IMPACT BY THE HST & JWST COMMUNITY (Feb. 2025):

- HST: $\gtrsim$500–1000 refereed papers/year by the community since 1990.
- 45,900 HST papers on ADS, 948,800 citations since 1990, h_{HST}=322!
- JWST: over 2300 refereed papers (57k cites), since July 2022 alone!
- In year 1-3: JWST already outdoing HST's yearly production.

(2) NEWS RELEASES BY THE HST & JWST COMMUNITY (Feb 2025):

- NASA's Hubble Space Telescope (HST) had 1,100 science press releases since 1990, each with $\gtrsim$400 million readers (or impressions) worldwide.
- $\sim 480 \times 10^9$ reads (or impressions) of Hubble press releases in total $\Rightarrow$
- *On average* each human on Earth would have read $\gtrsim$60 Hubble stories during their lifetimes.
- HST is the most publicized space astrophysics mission in NASA history.
- JWST: $\gtrsim$170 press releases since 2022, each 0.5–1 billion readers.
- JWST is now the most-in-demand space mission in NASA history.
- ASU Cosmology: 10 billion readers from $\gtrsim$10 releases since 2022 (URL).

Related papers, press releases and other URLs

Talk: http://www.asu.edu/clas/hst/www/jwst/leiden25_futureLyC_fromspace.pdf Data: https://sites.google.com/view/jwstpearls

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