

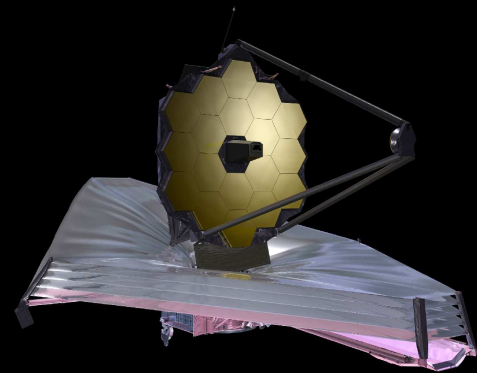
LyC studies from space in the next decades

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

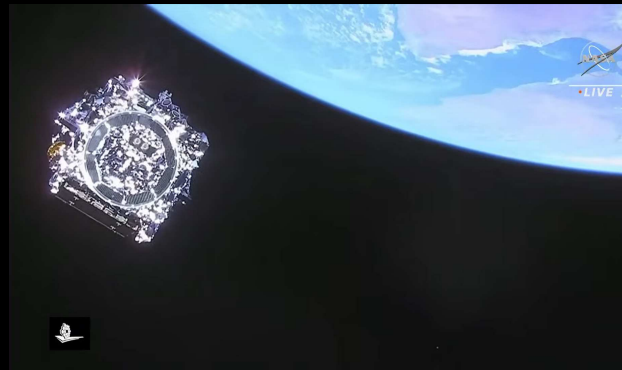
+ HST SKYSURF, UVCANDELS and JWST PEARLS & SKYSURFIR teams: incl B. Smith, S. Cohen, R. Jansen + 130 scientists over 18 time-zones



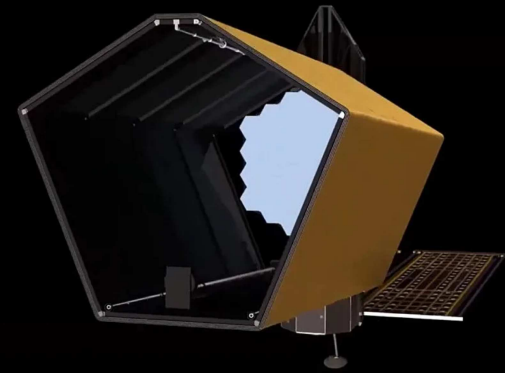
Hubble
1973~2034⁺?



Webb (designed)
1996~2031



Webb (launched 2021)
1996~2046⁺?



Habitable Worlds
2040~2070⁺?

Review at the “Escape of Lyman radiation from Galactic Labyrinths” Conference

Friday April 11, 2025; OAC, Kolymbari, Crete, Greece

PDF on: http://www.asu.edu/clas/hst/www/crete25_futureLyC_fromspace.pdf

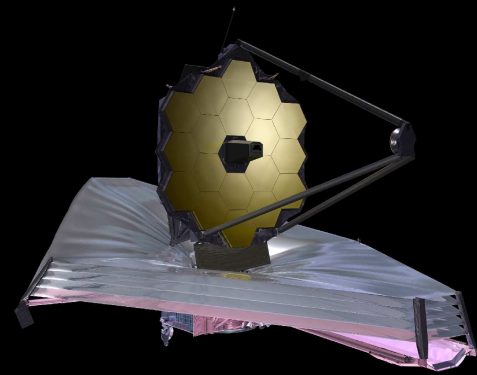
LyC studies from space in the next decades

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

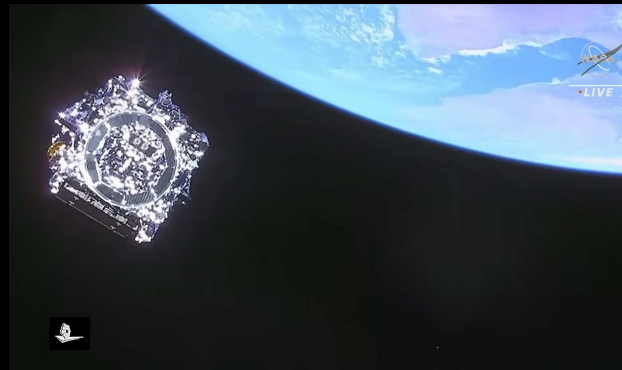
+ HST SKYSURF, UVCANDELS and JWST PEARLS & SKYSURFIR teams: incl B. Smith, S. Cohen, R. Jansen + 130 scientists over 18 time-zones



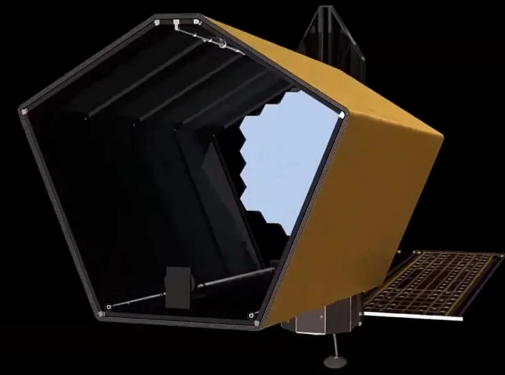
Hubble
1973~2034⁺?



Webb (designed)
1996~2031



Webb (launched 2021)
1996~2046⁺?



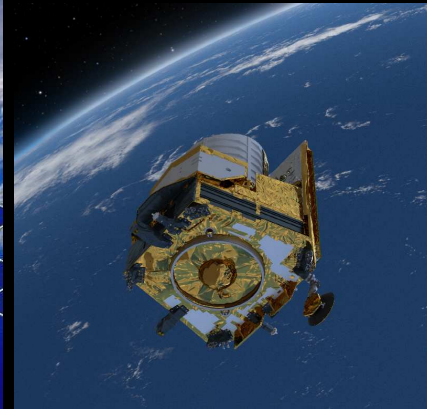
Habitable Worlds
2040~2070⁺?



India Astrosat (2015)
2004~2030⁺?



China Xuntian (2027?)
2012~2037⁺?



Euclid (2023)
2009~2035?



Roman (2027)
2011~2037?

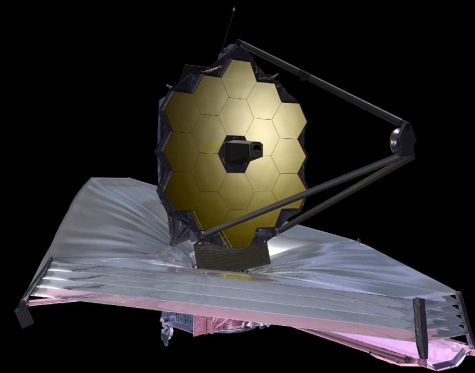
LyC studies from space in the next decades

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

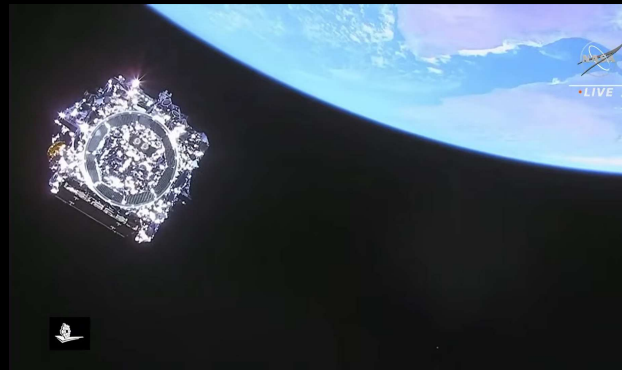
+ HST SKYSURF, UVCANDELS and JWST PEARLS & SKYSURFIR teams: incl B. Smith, S. Cohen, R. Jansen + 130 scientists over 18 time-zones



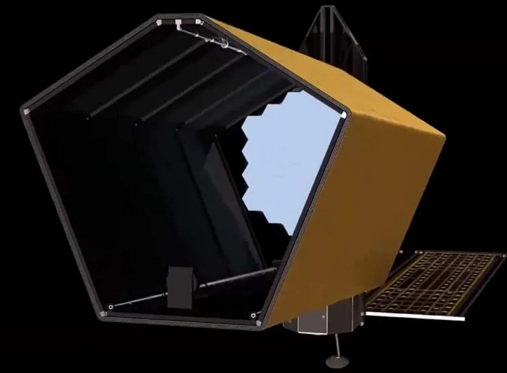
Hubble
1973~2034⁺?



Webb (designed)
1996~2031



Webb (launched 2021)
1996~2046⁺?



Habitable Worlds
2040~2070⁺?

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.

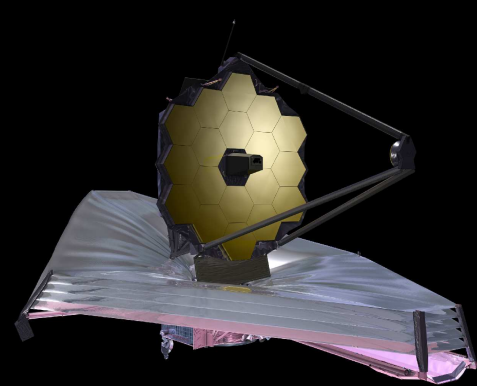
LyC studies from space in the next decades

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

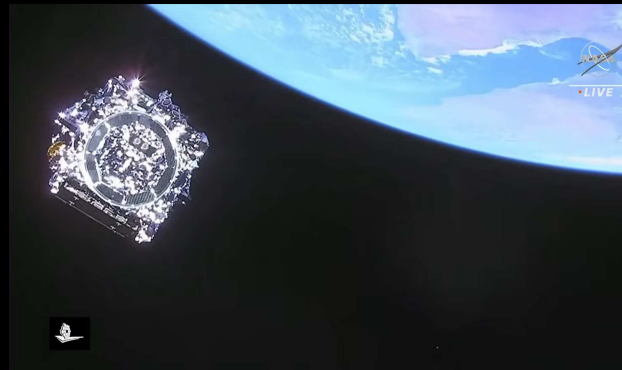
+ HST SKYSURF, UVCANDELS and JWST PEARLS & SKYSURFIR teams: incl B. Smith, S. Cohen, R. Jansen + 130 scientists over 18 time-zones



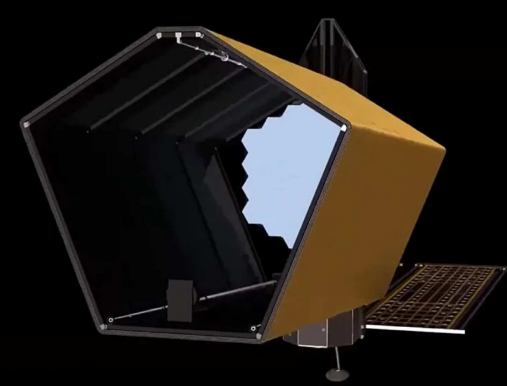
Hubble
1973~2034⁺?



Webb (designed)
1996~2031



Webb (launched 2021)
1996~2046⁺?



Habitable Worlds
2040~2070⁺?

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 ~25 US presidential & 50 congressional elections.
- ⇒ Maintain the long-term vision to do LyC work 30 years from now!

JWST is like a hot bath. It feels good while you're in it; but the longer you stay, the more wrinkled you get.



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

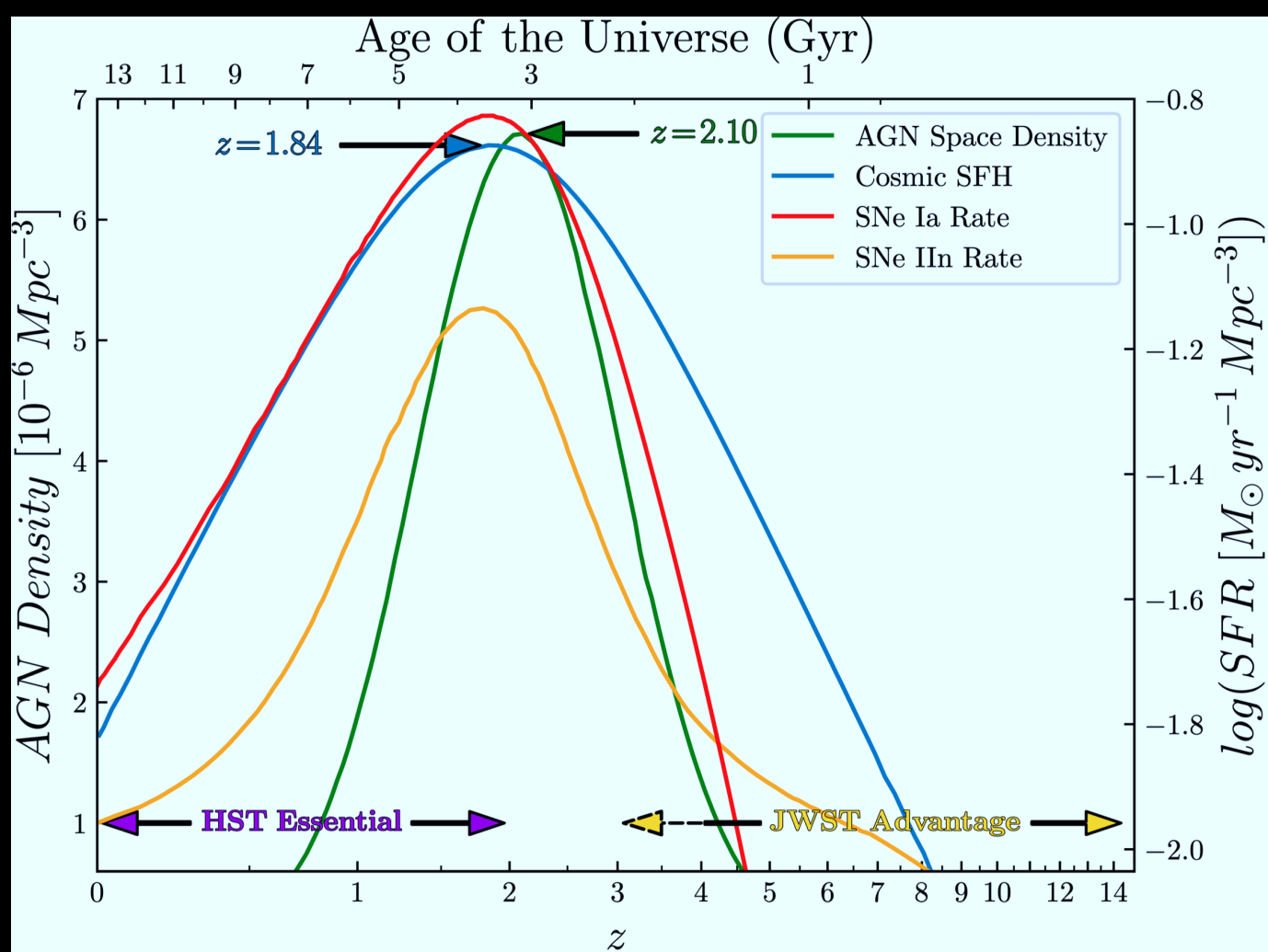
⇒ **Maintain the long-term vision to do LyC work 30 years from now!**

Outline

- (1) Uniquely complementary roles of Hubble and Webb:
414–500 hr combined HST+JWST images $\Rightarrow$ keep HST alive!
- (2) Need space-based resolution for contamination-free LyC work
- (3) Habitable World Observatory requirements for LyC work
- (4) Summary and Conclusions



Sponsored by NASA/HST & JWST

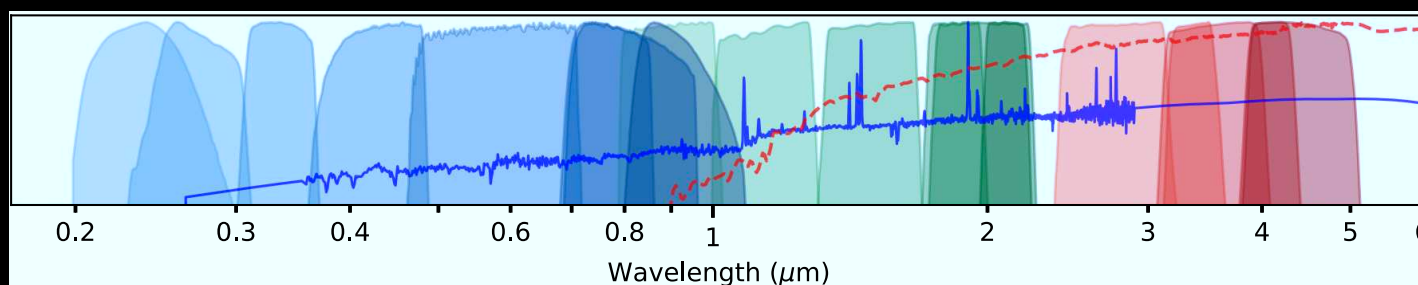


$$\text{Age} \sim \frac{13.8}{(1+z)} + \dots \text{ Gyr}$$

Active galactic nuclei (AGN)

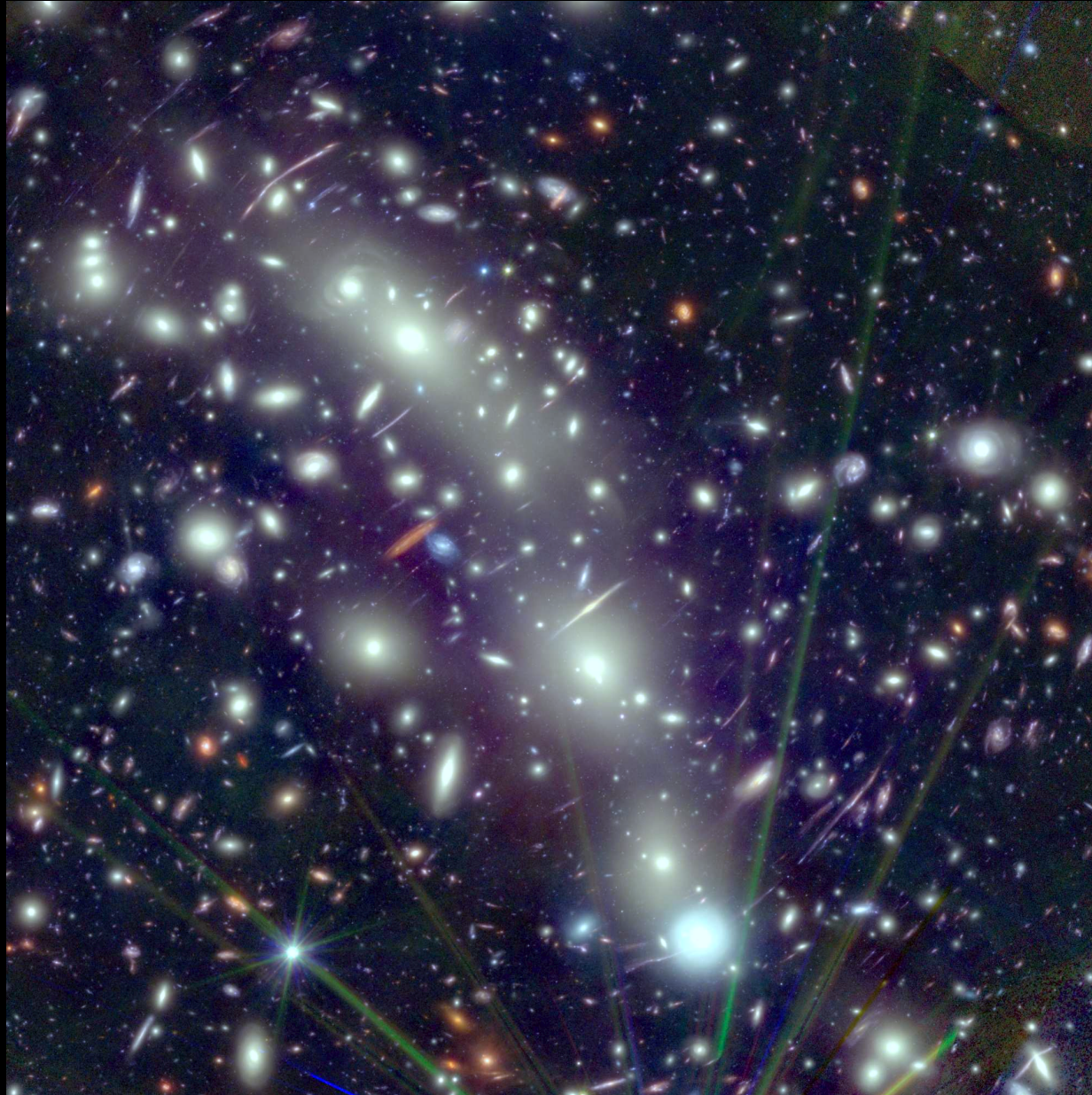
 $\longleftrightarrow$ BH accretion disks $\longleftrightarrow$ Chandra X-ray sources

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



$\Rightarrow$ HST best samples *unobscured* SFH & BH growth in last 10 Gyr ($z \lesssim 2$),
 while JWST best samples *obscured* parts, especially in first 3 Gyr ($z \gtrsim 3$).

(1) Uniquely complementary roles of Hubble and Webb:

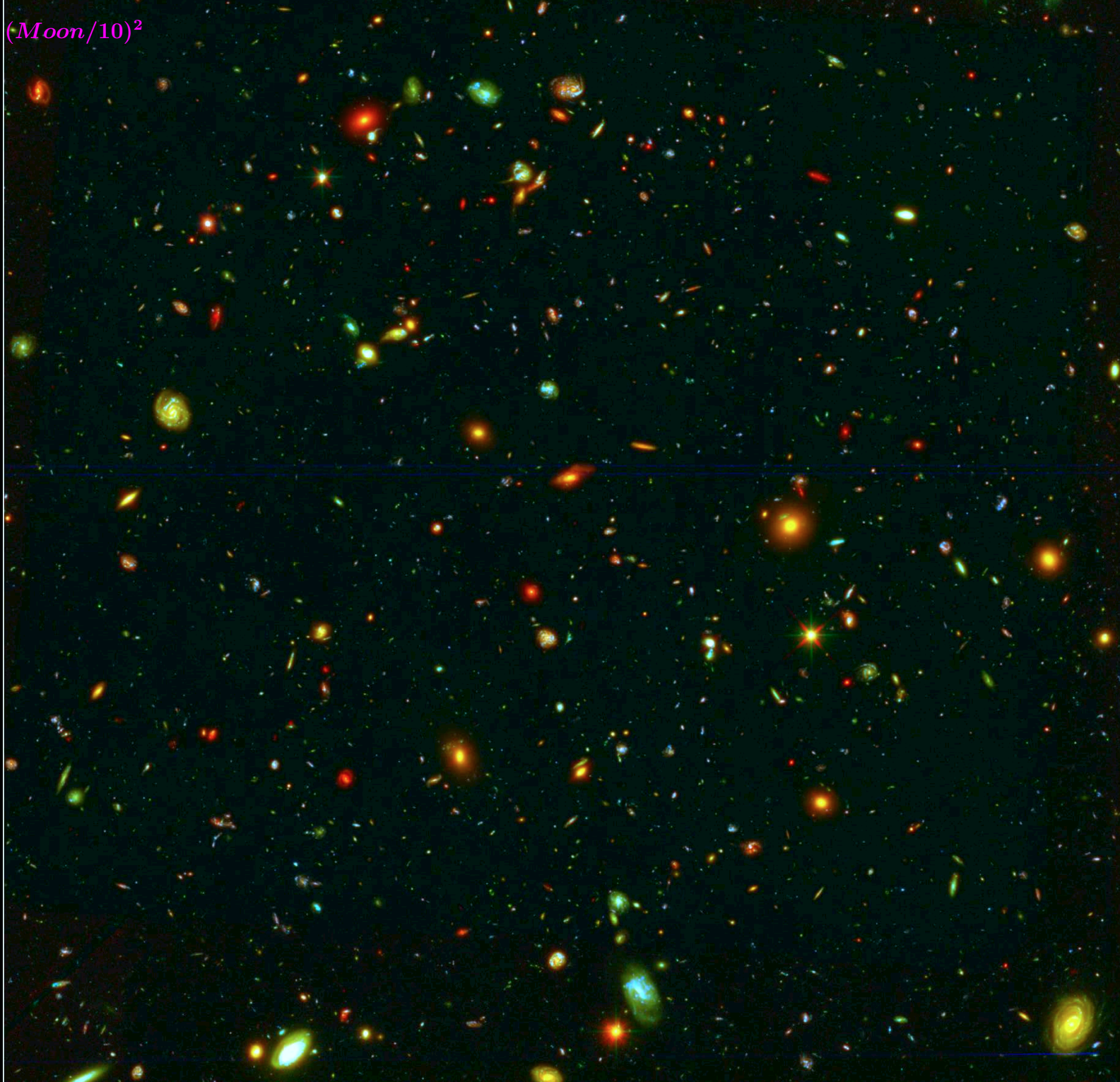


500 hrs HST+JWST: 45 filters ($0.2\text{--}5.0\mu\text{m}$), lensing cluster MACS0416:

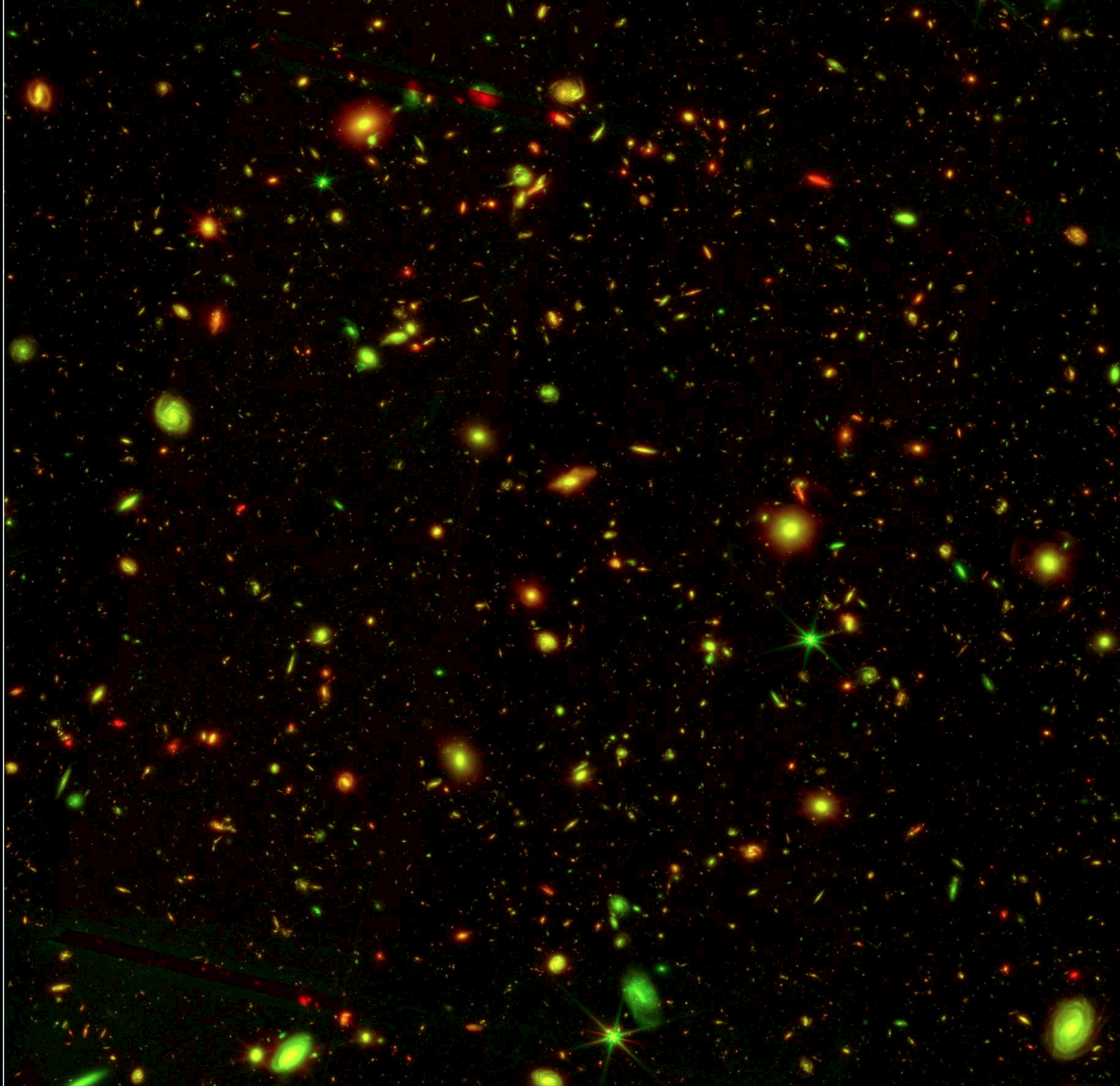
- HST darkest skies ($10\text{--}10^3\times$ darker) + JWST's dark skies ($10^3\text{--}10^5\times$ darker than ground based):

$\implies$ HST & JWST reach 30–31 mag ($\simeq 1\text{ nJy} \simeq 1$ firefly from Moon).

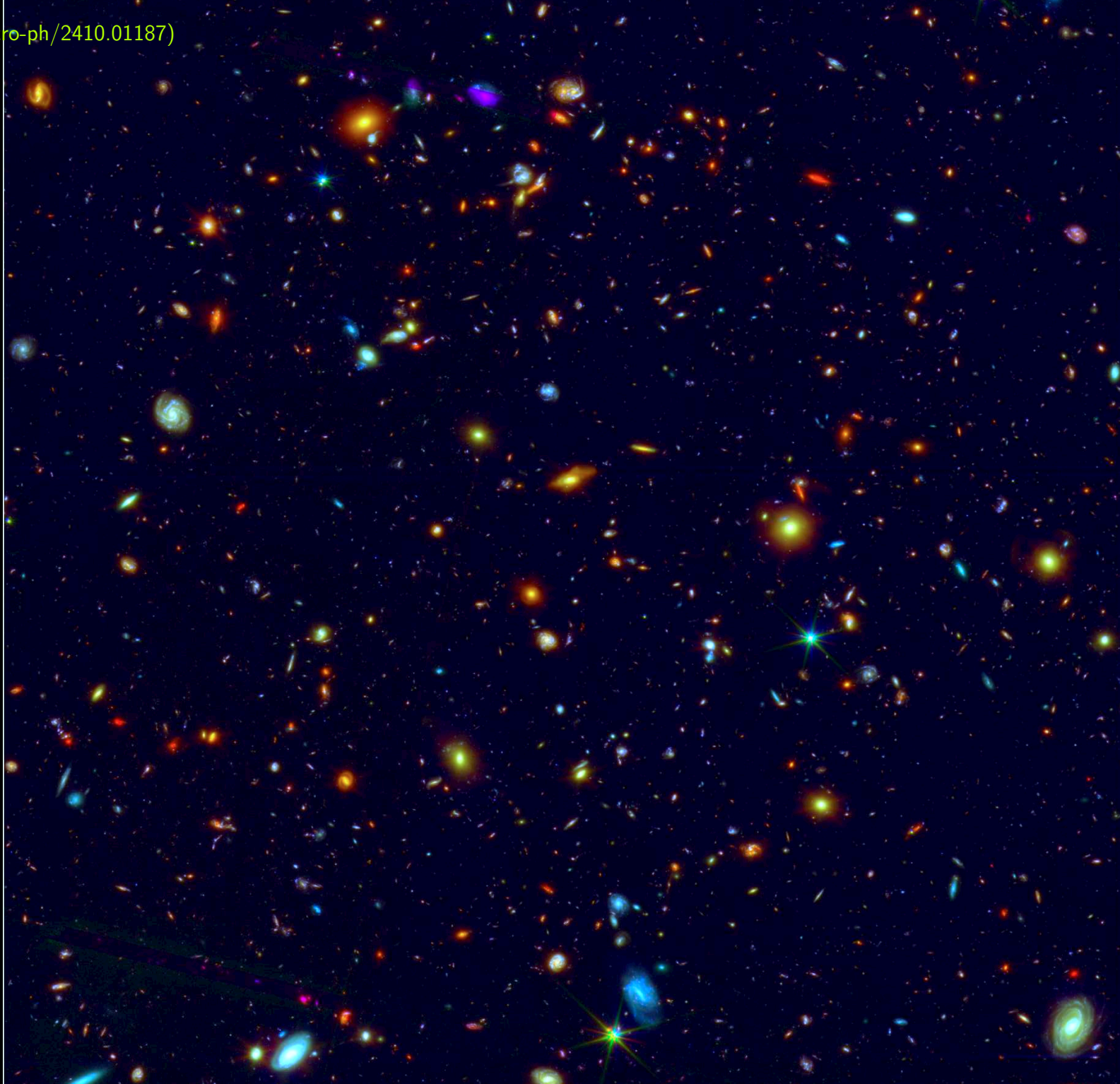
Field-of-View $\sim (Moon/10)^2$



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

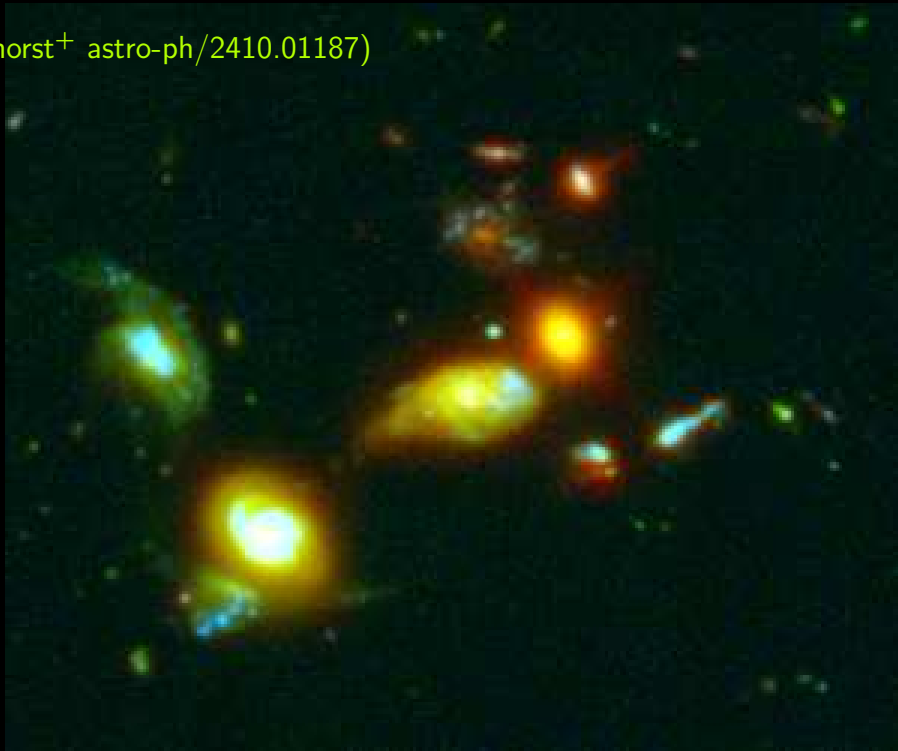


53 hr JWST/NIRCam Hubble UltraDeep Field: 12 filters at 0.9–5.0 μm ($\text{AB} \lesssim 31$ mag; in green + red).

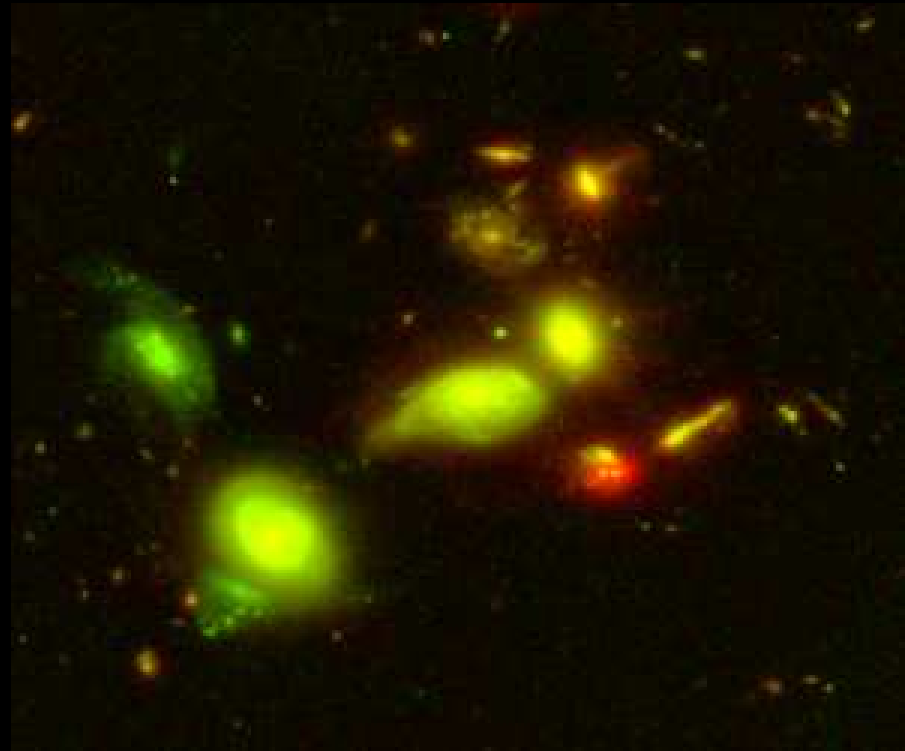


414 hr HST+JWST Hubble UltraDeep Field: 20 filters at 0.2–5.0 μm ($\text{AB} \lesssim 31.5$ mag; full BGR).

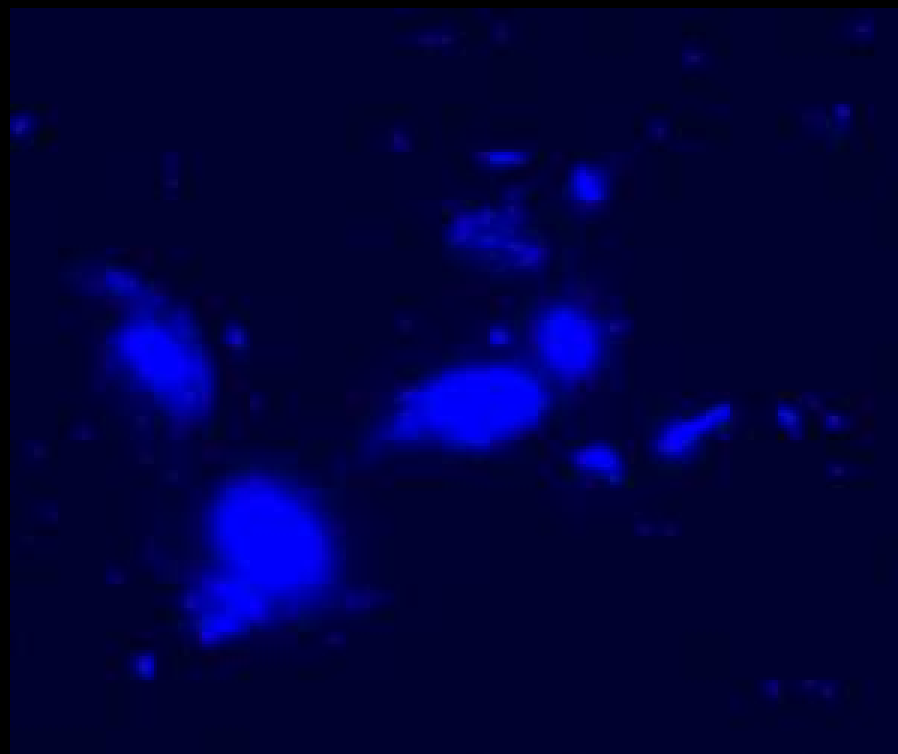
(Windhorst⁺ astro-ph/2410.01187)



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

4-epoch 22-hr NIRC2 + 122-hr HST on HFF cluster MACS0416 ($z=0.397$)

It's Christmastime in the Cosmos

Astronomers have a long tradition of finding holiday cheer in outer space.

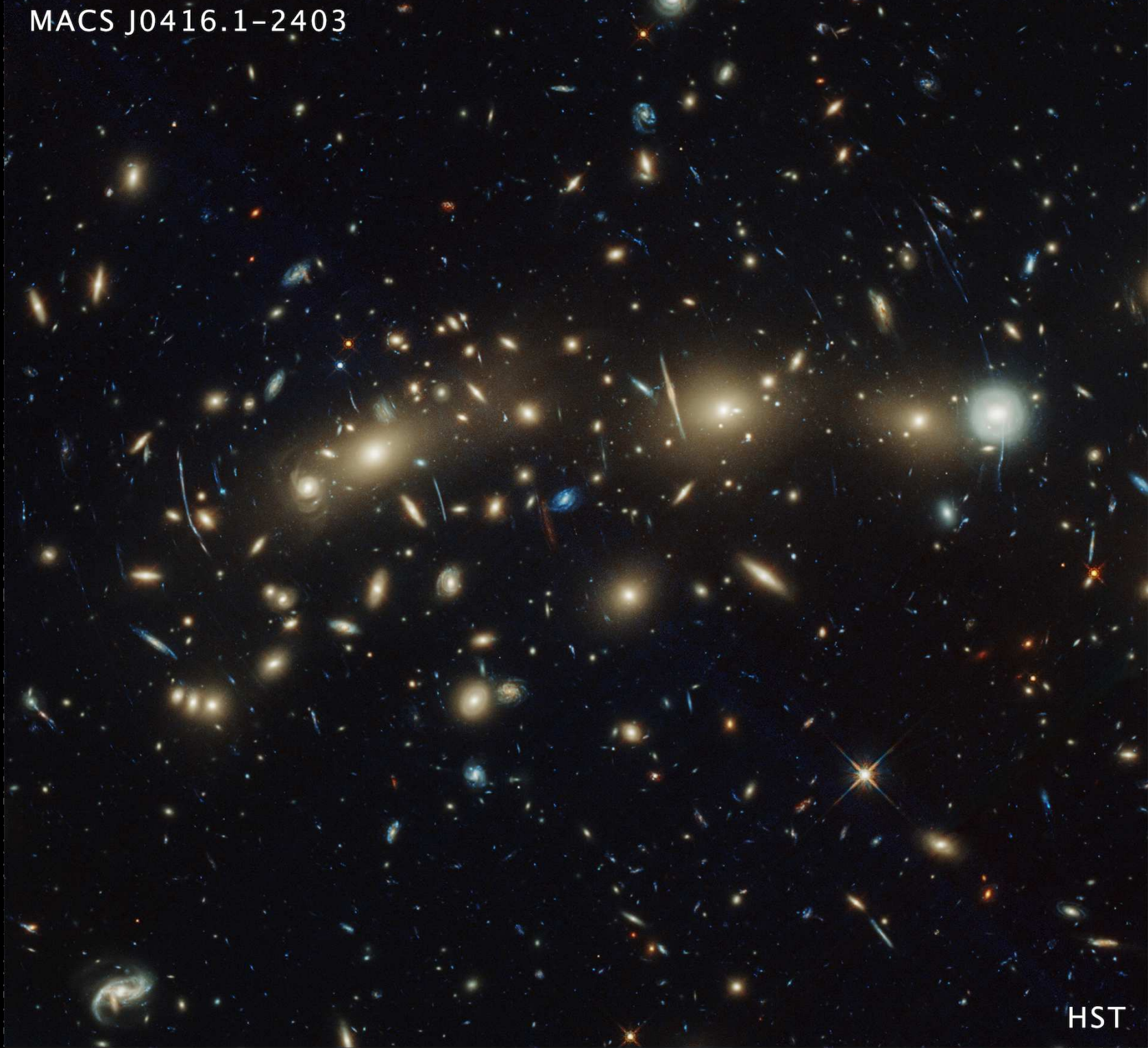
12 new caustic transits at $z \simeq 1-2$ from 4 epochs! (Yan, H.⁺, 2023, ApJS, 269, 42)

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

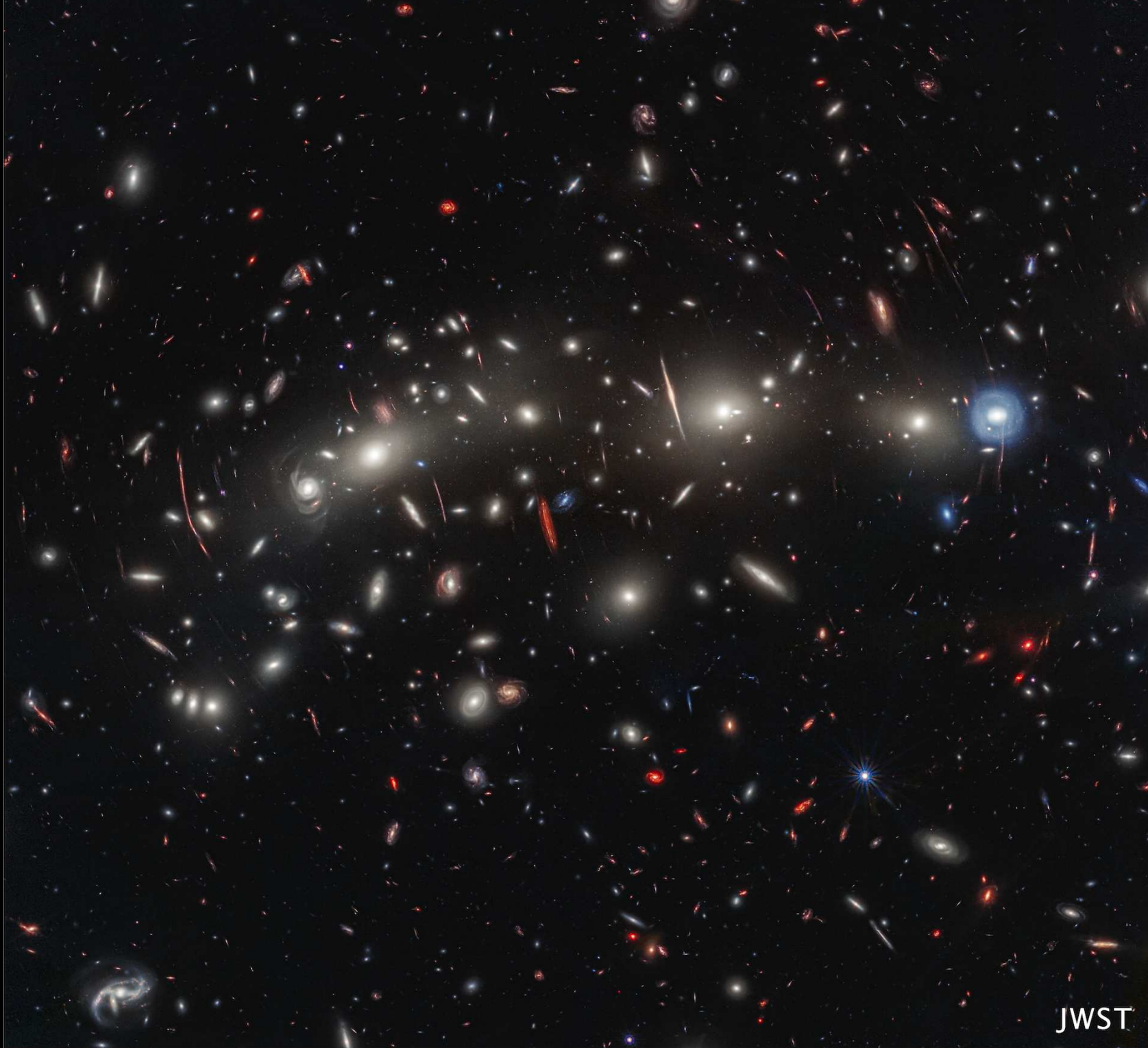
<https://www.cnn.com/2023/11/09/world/webb-hubble-colorful-galaxy-cluster-scn/index.html>

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

MACS J0416.1-2403

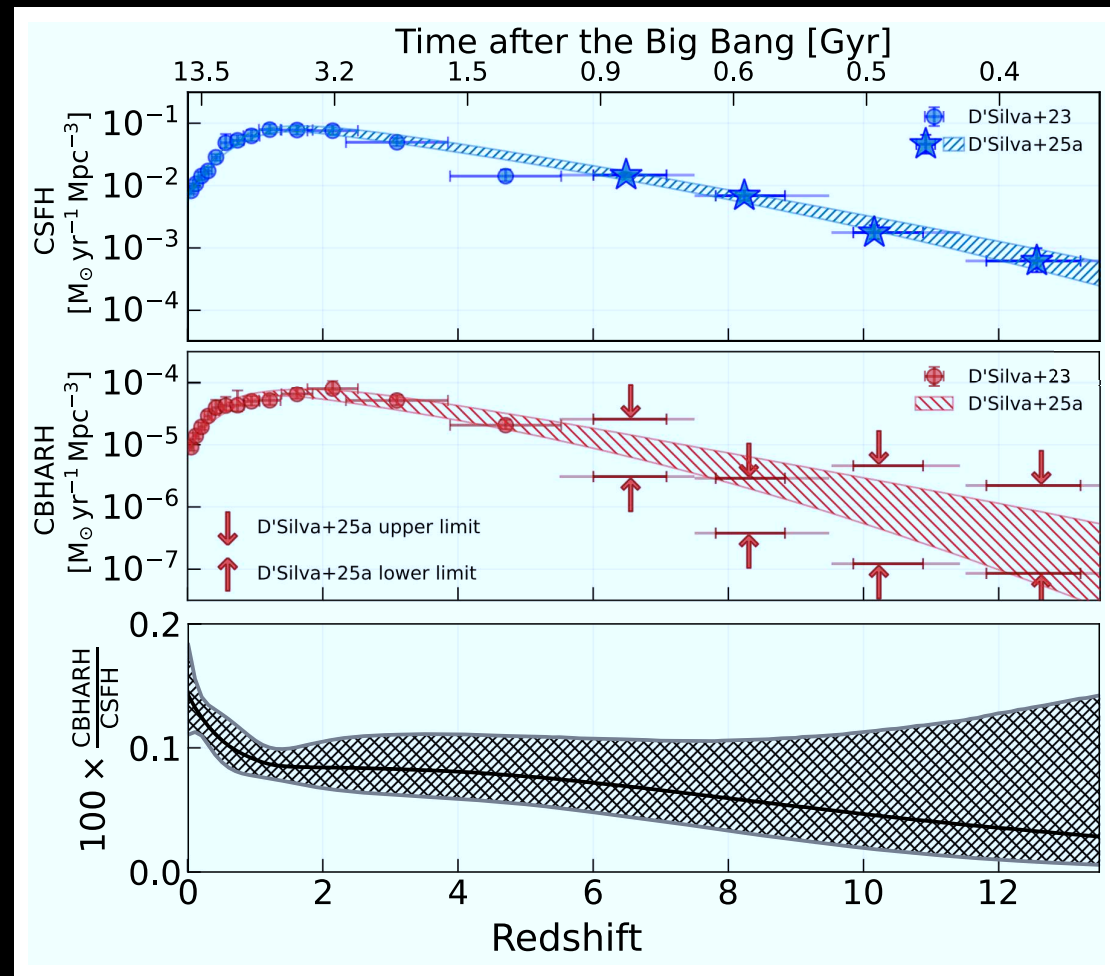
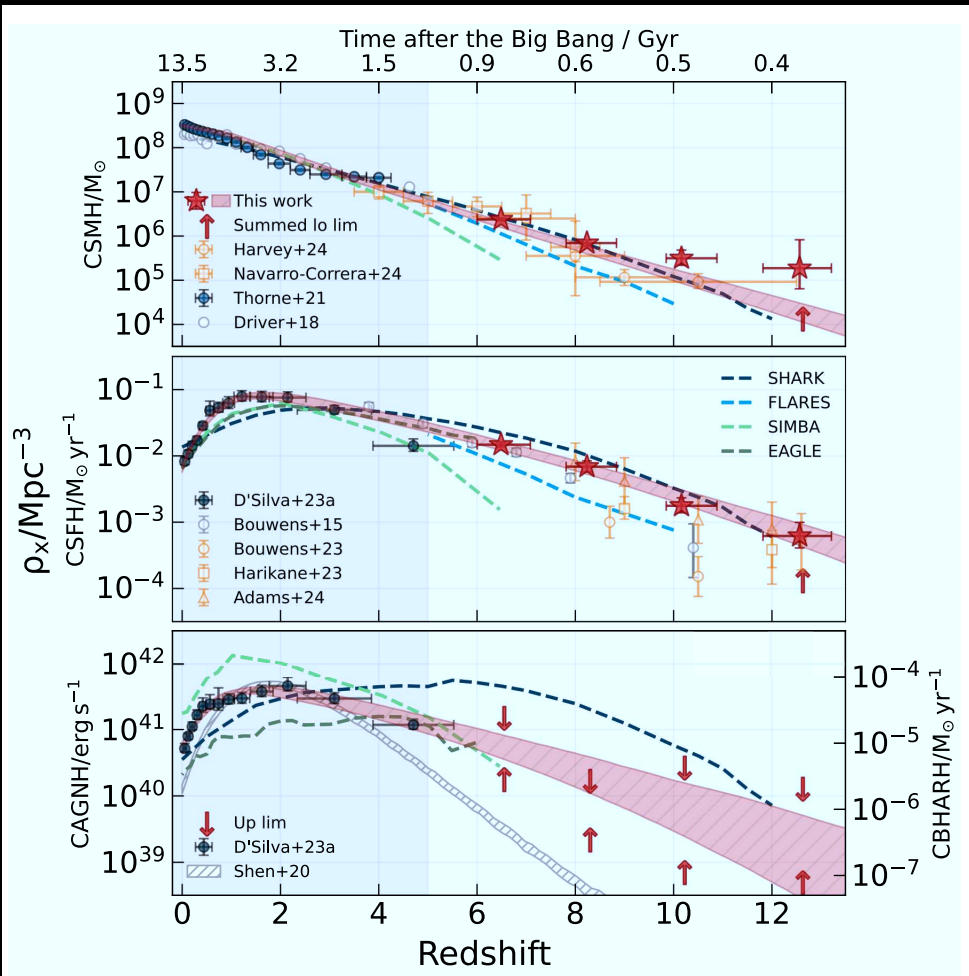


122 hr HST on Hubble Frontier Field cluster MACS0416 ($z=0.397$; 4.3 Blyr)



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

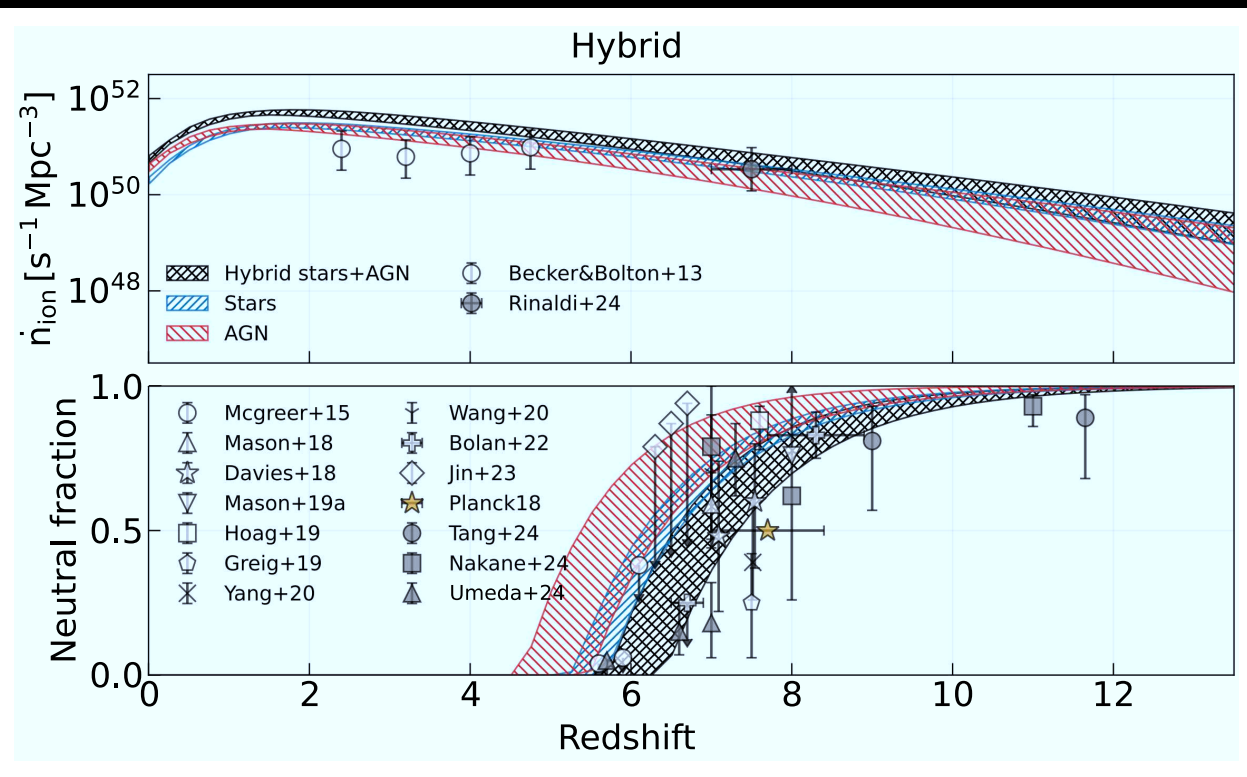
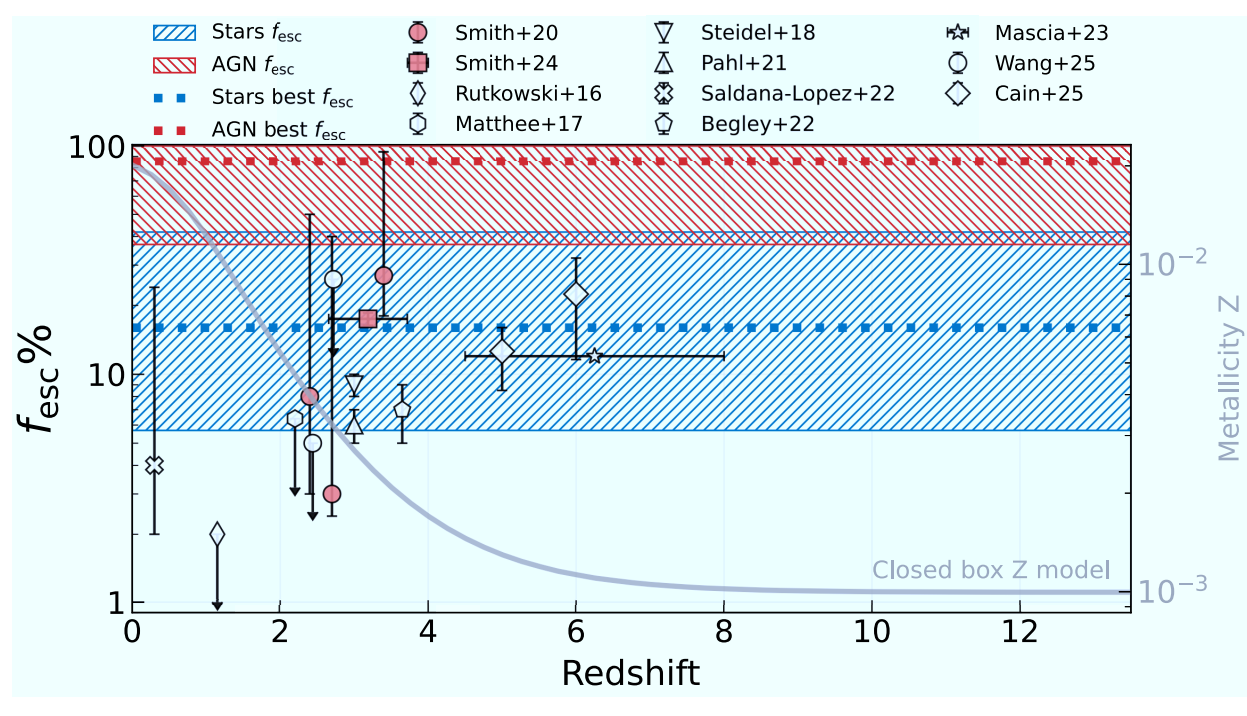
Summary of Cosmic SFH & AGN-FH from HST+JWST:



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

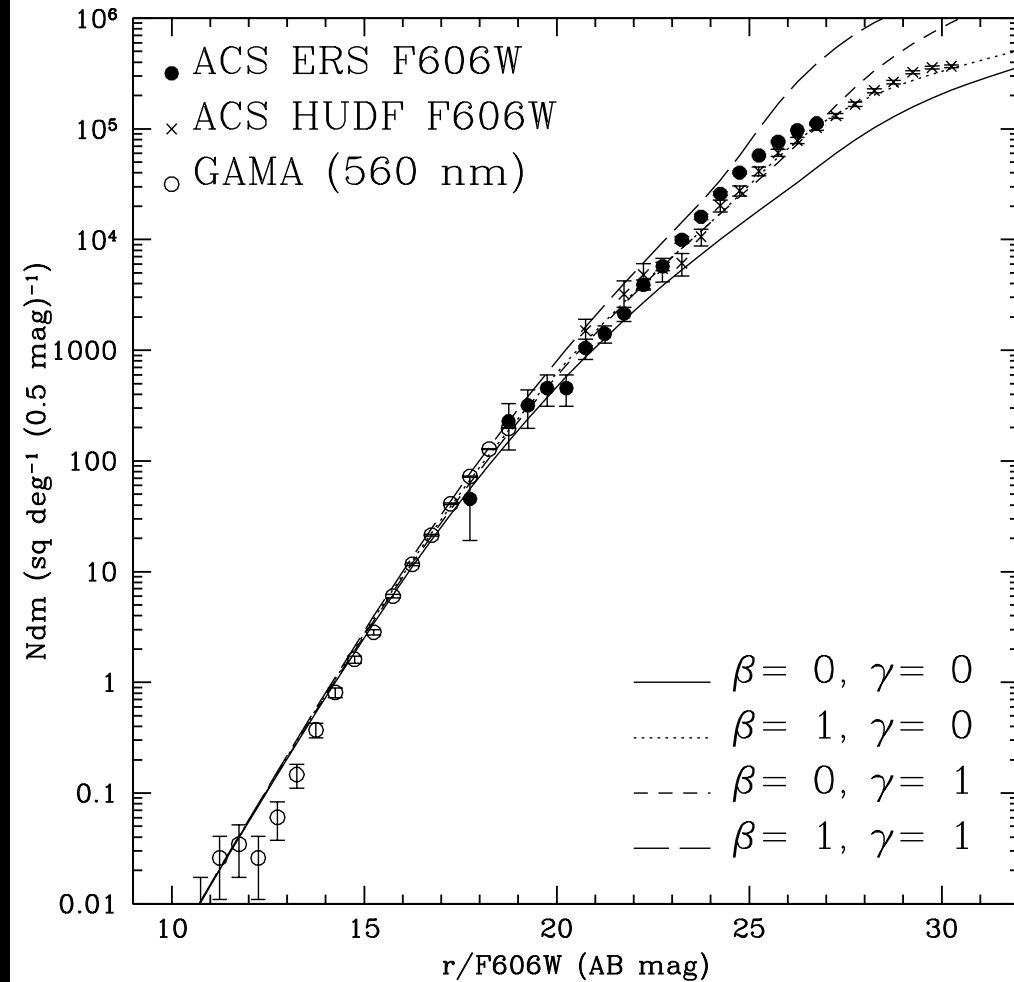
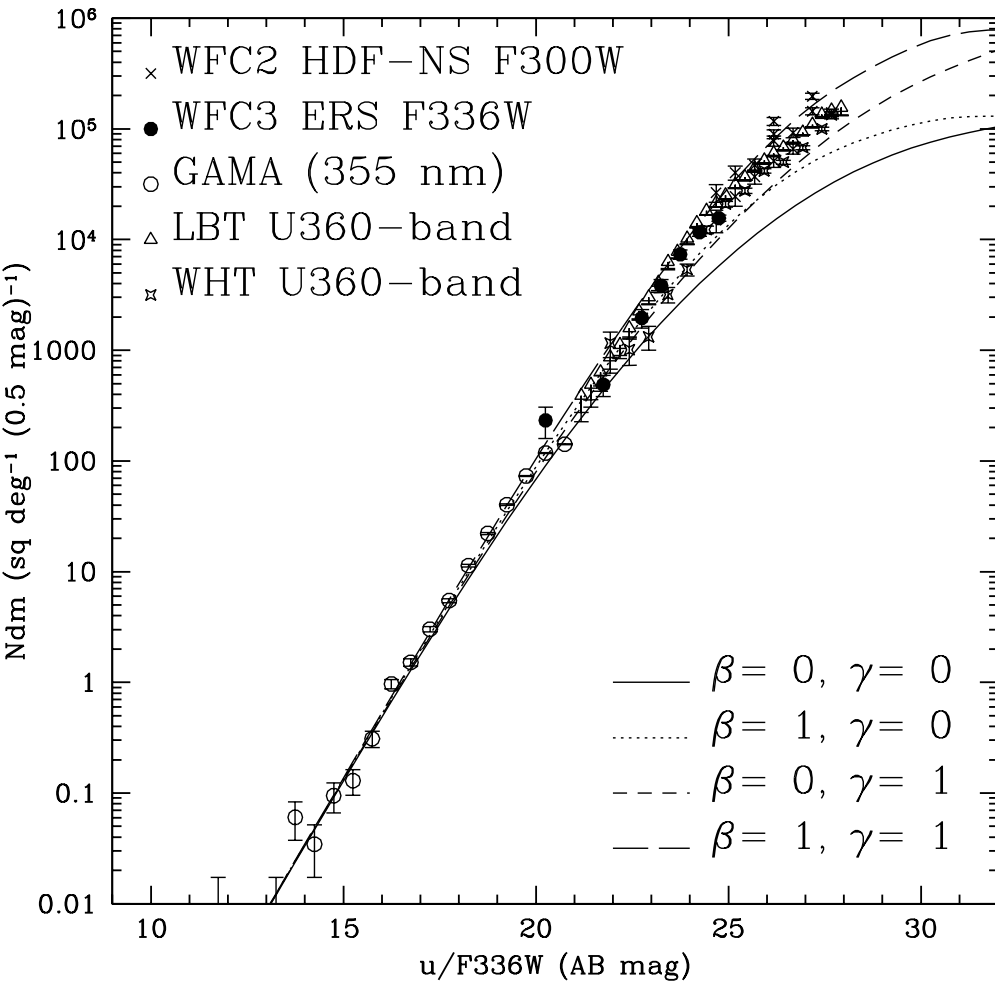
(J. D'Silva⁺ 2023, MNRAS, 524, 1448; — 2024, ApJL, 959, L18; — 2025, A&A, astro-ph/2503.03431).

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



● HST+JWST's cosmic SFH & AGN-FH consistent with $f_{\text{esc}}(z)$ & $X_{\text{HI}}(z)$.

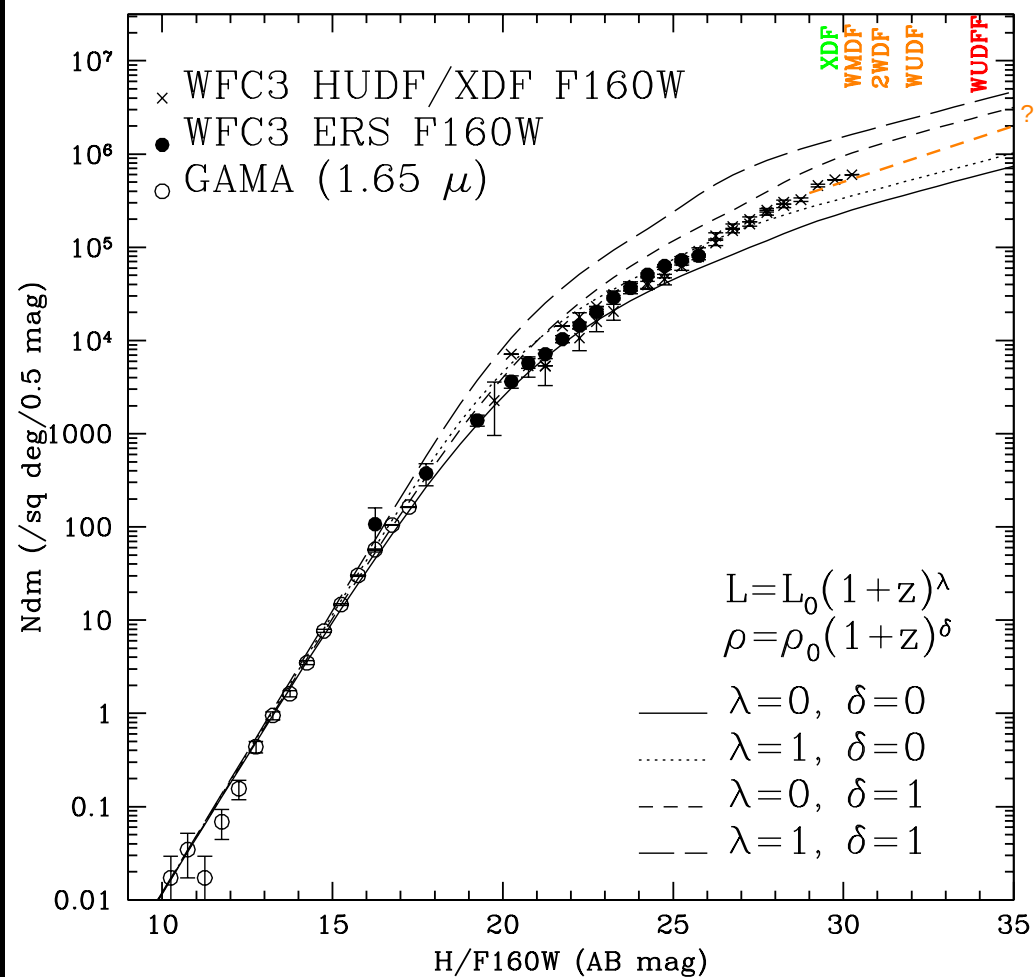
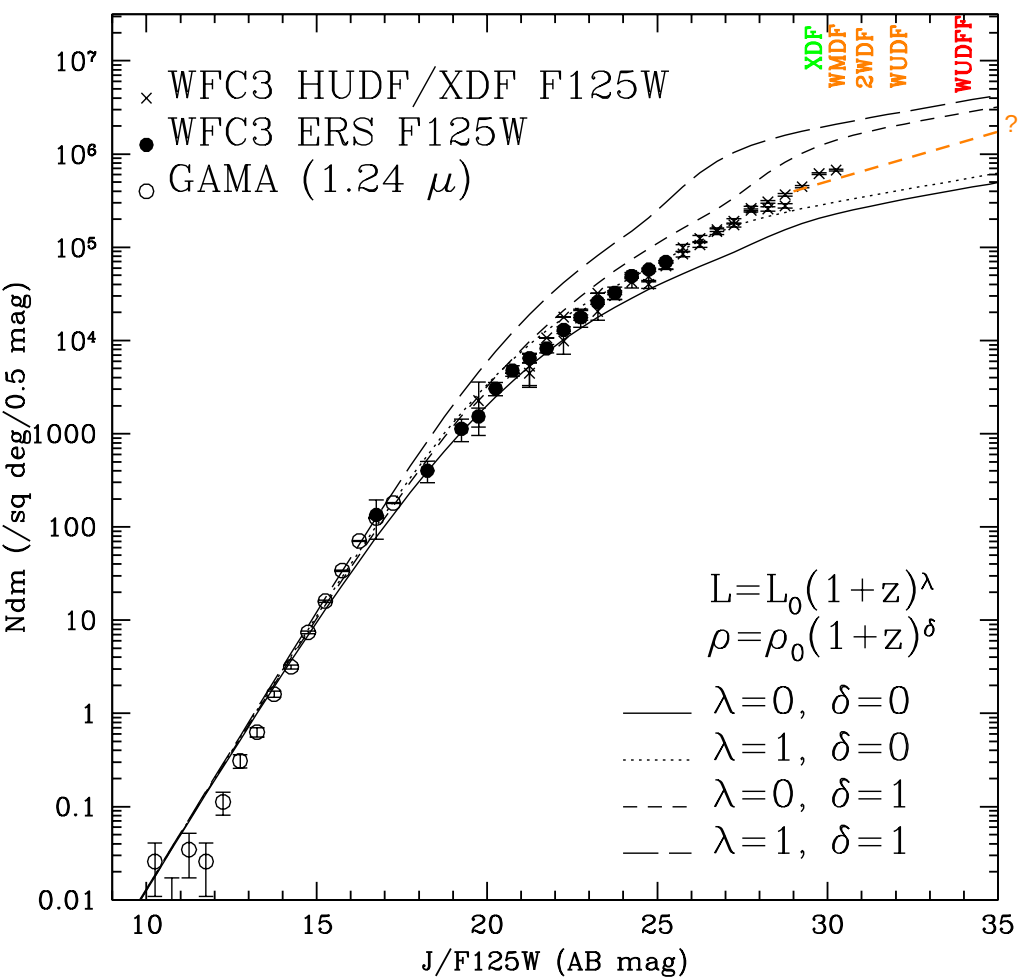
(2) Need space-based imaging for contamination-free LyC work !



U-band and V-band galaxy counts (Windhorst⁺2011).

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

Integrated surface density at $AB \lesssim 31$ mag: 3×10^6 deg $^{-2}$.

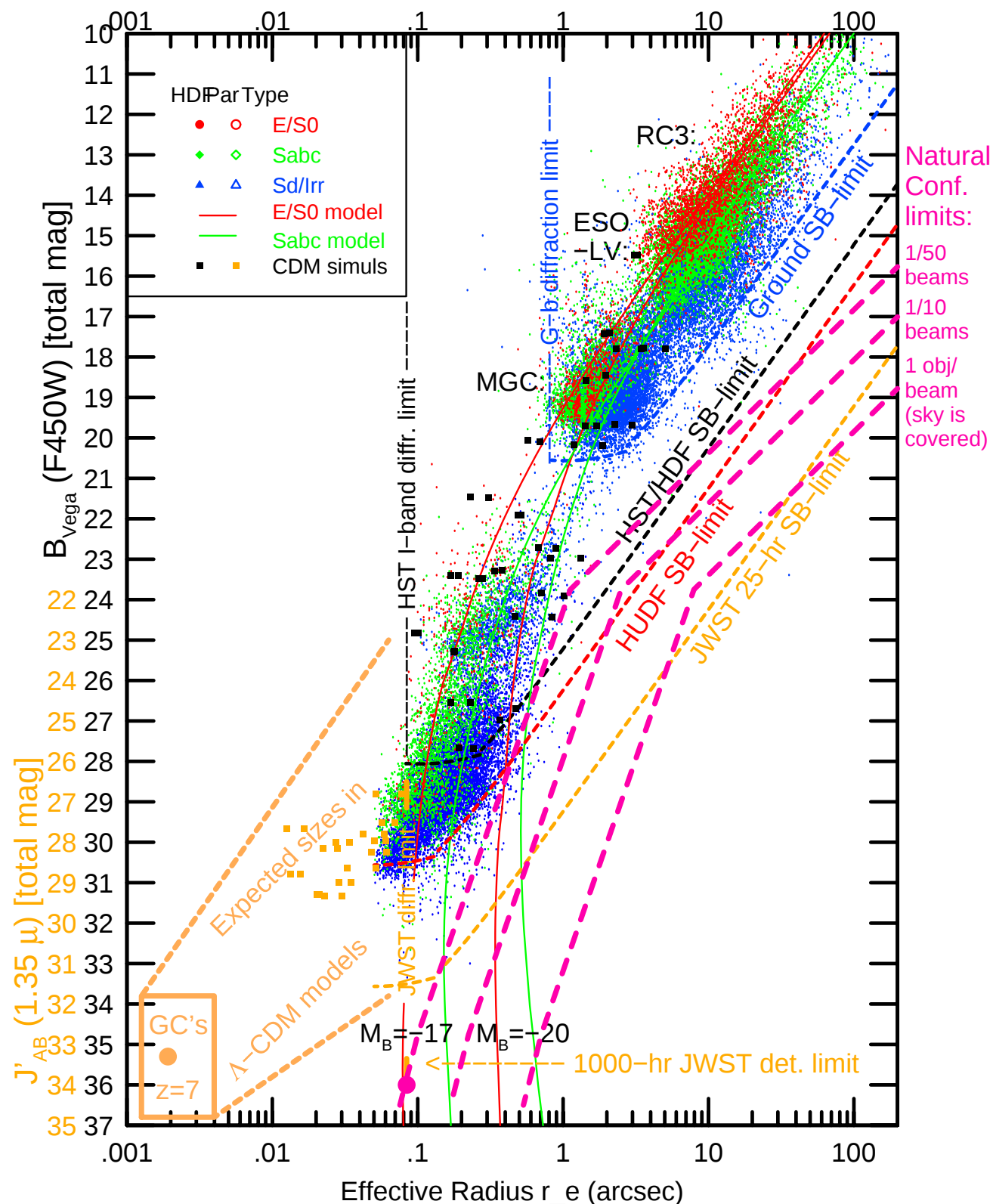


J-band and H-band galaxy counts (Windhorst⁺2011).

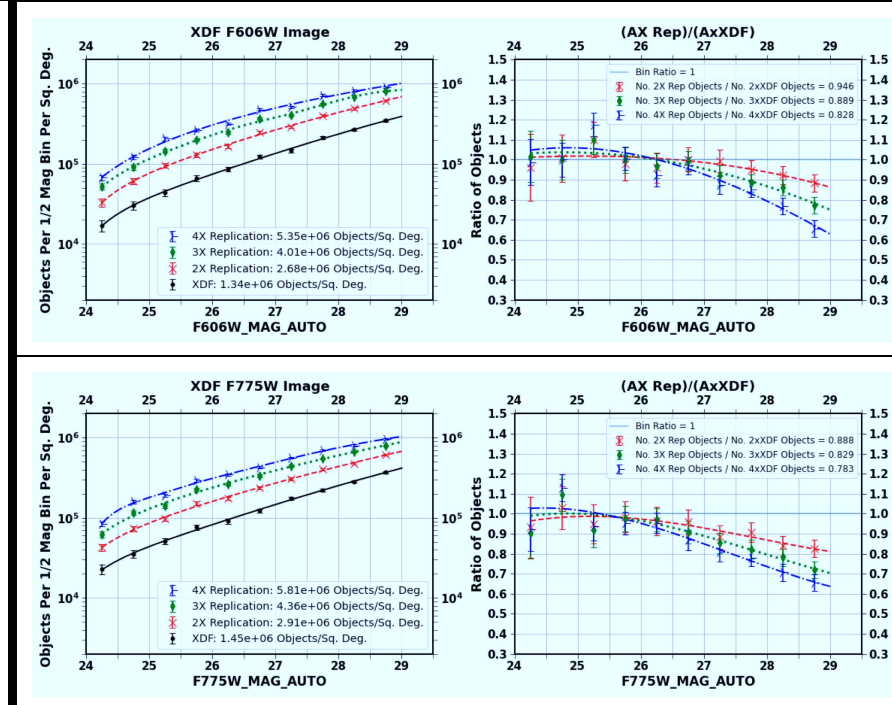
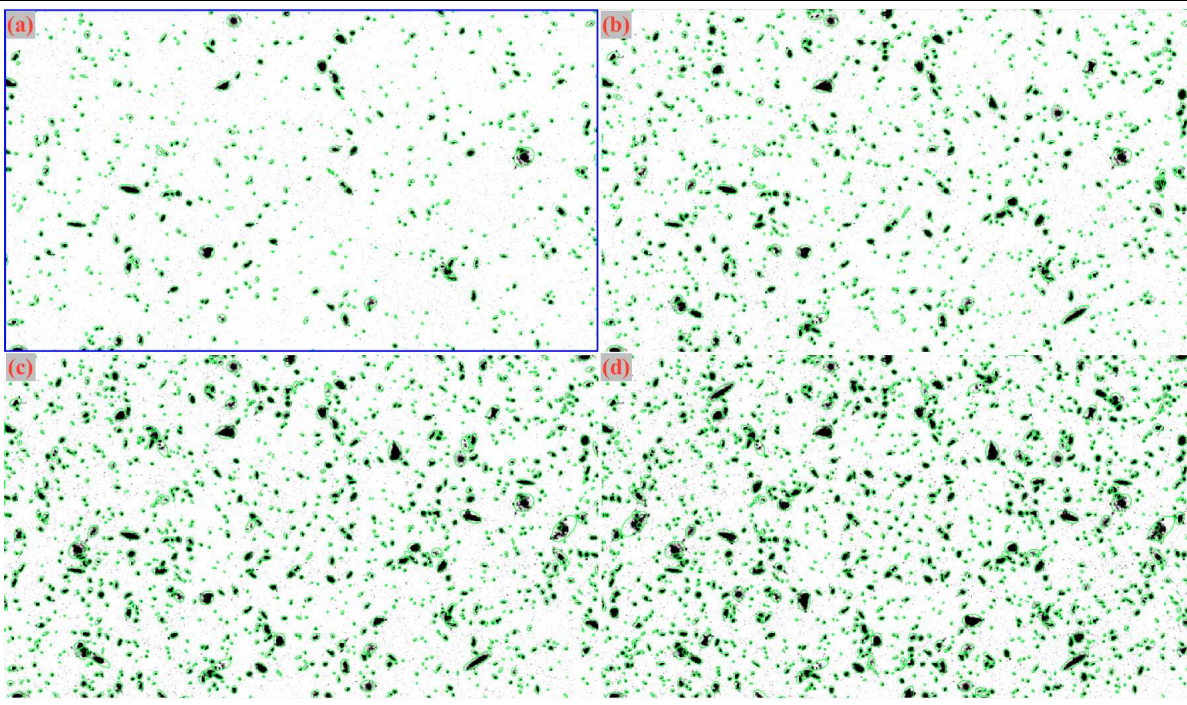
Faint-end near-IR count-slope $\simeq 0.12 \pm 0.02$ dex/mag.

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

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



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



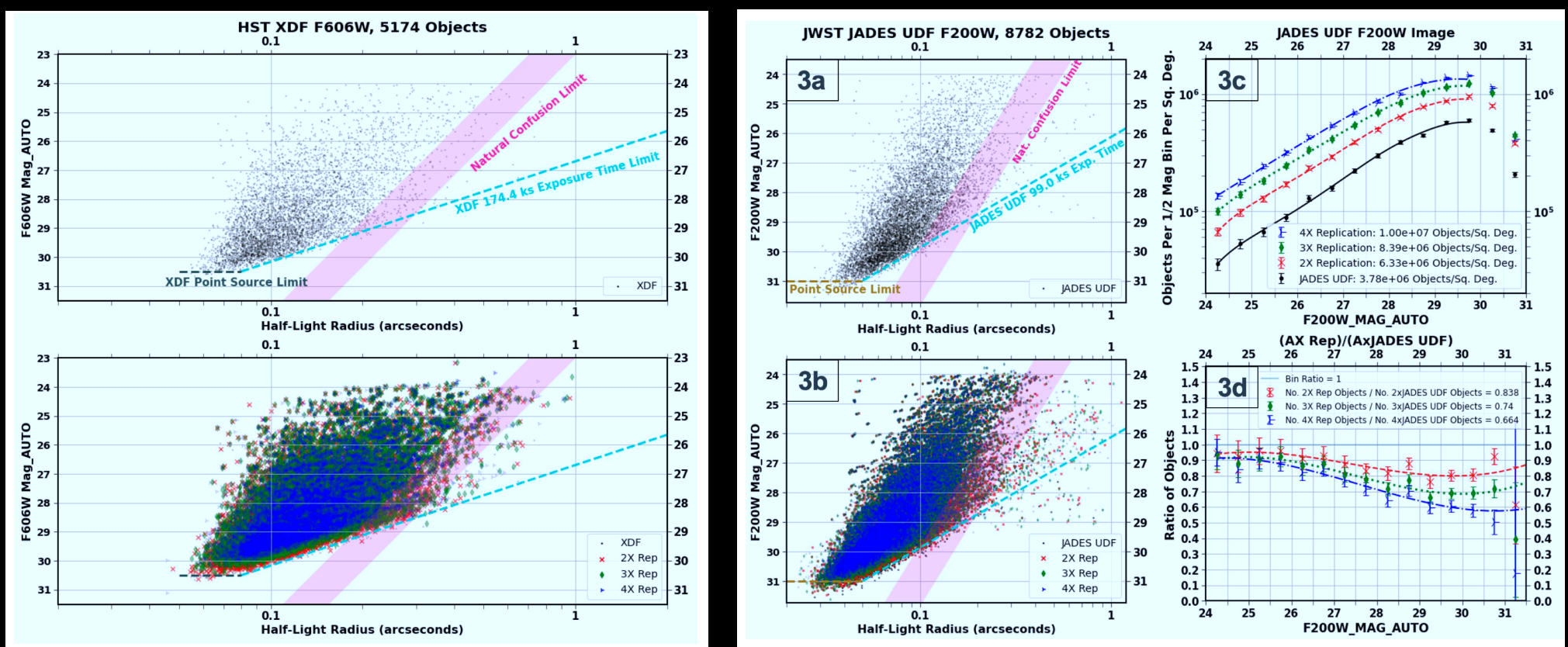
[Left]: Add HUDF image to itself $2\times$, $3\times$, $4\times$ after $n\times 90^\circ$ rotation:

[Right]: $4\times$ HUDF counts still $\gtrsim 65\%$ complete for $AB \gtrsim 28.5\text{--}29$ mag.

(Kramer⁺, 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.
- $3\text{--}4 \times 10^6$ galaxies/deg² at $AB \lesssim 31$ mag with $r_{hl} \lesssim 0''.1\text{--}0''.2$ FWHM.

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



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.

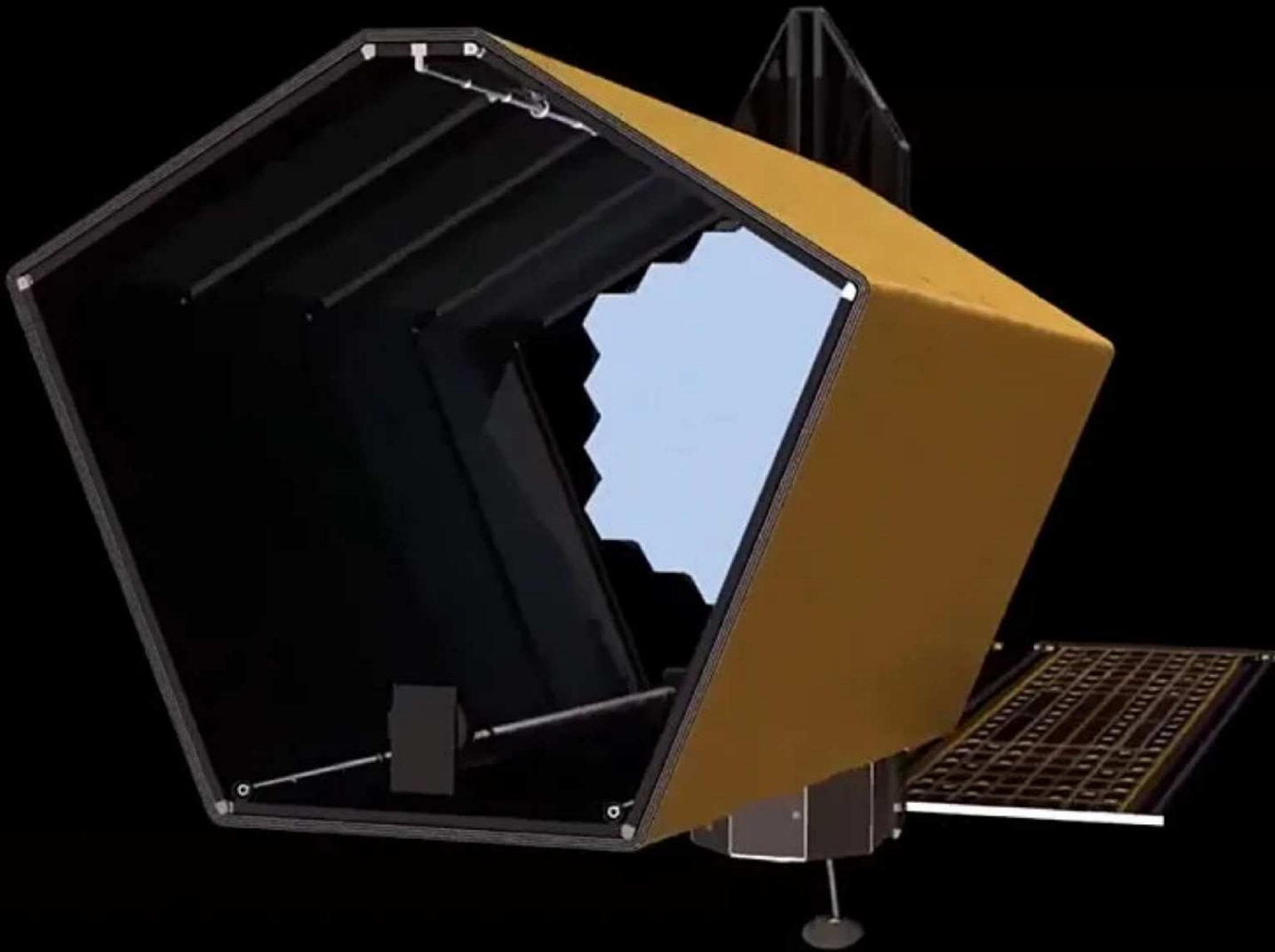
• $\lesssim 35\%$ of faintest galaxies lost due to statistical object overlap.

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

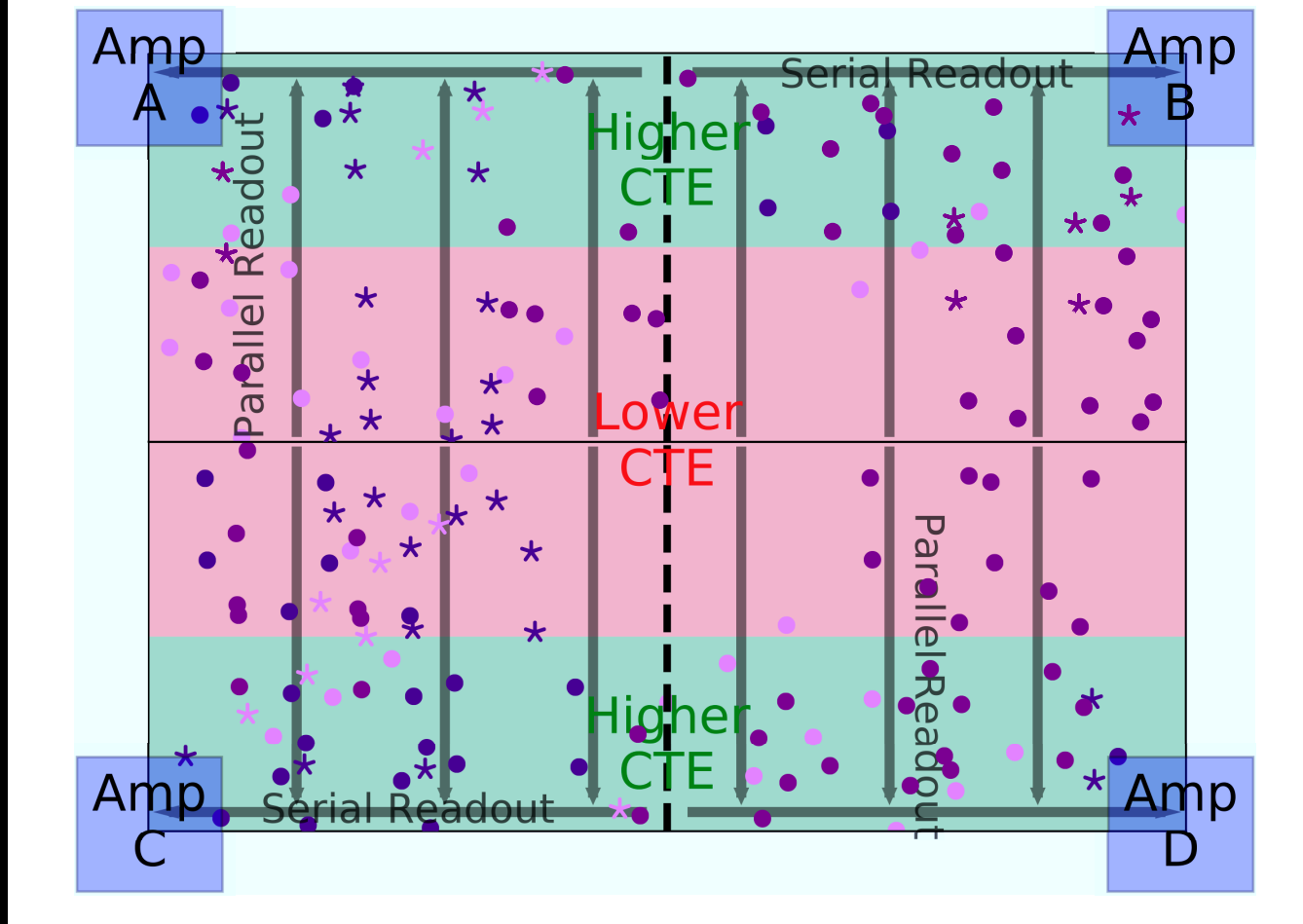
$\Rightarrow$ LyC work at UVC $\sim 24-27$ must avoid contaminants with AB $\lesssim 28-31$ mag!

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

(3) Habitable World Observatory requirements for LyC work



- Next generation $\gtrsim 6\text{--}8$ 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.



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.
- 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 & Supercollider. 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 $\Rightarrow$ Good $\Rightarrow$ Neutral $\Rightarrow$ Fair $\Rightarrow$ Poor.

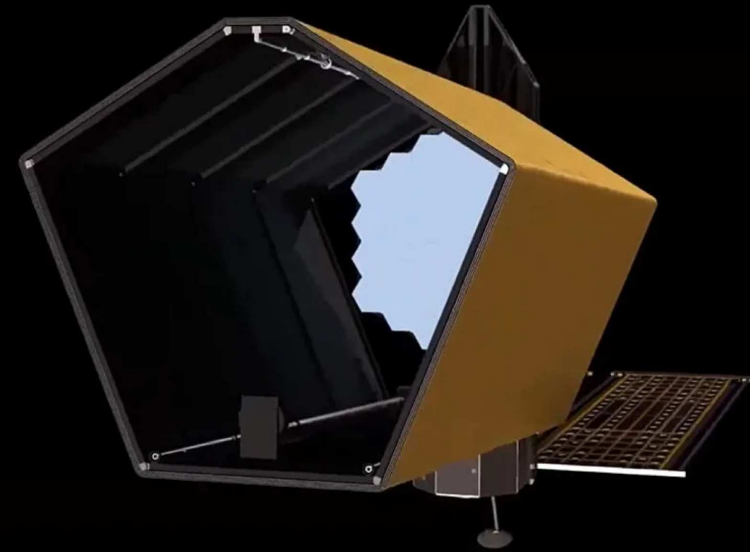
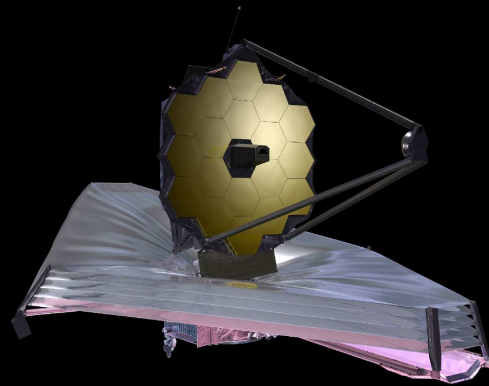
- (A) Scientific/Astro-Community Lessons
- (B) Technical Lessons
- (C) Management/Budget/Schedule Lessons
- (D) Political/Outreach Lessons

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

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

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



1973–2034⁺(!)

Launch: 1990

Σ_{FC} : $\gtrsim 20$ B\$

1996–2046⁺

2021

$\gtrsim 10$ B\$

2012–2037?

$\gtrsim 2027$

~ 3 B\$

2025–2070⁺?

$\gtrsim 2040?$

15–20 B\$?

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

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.

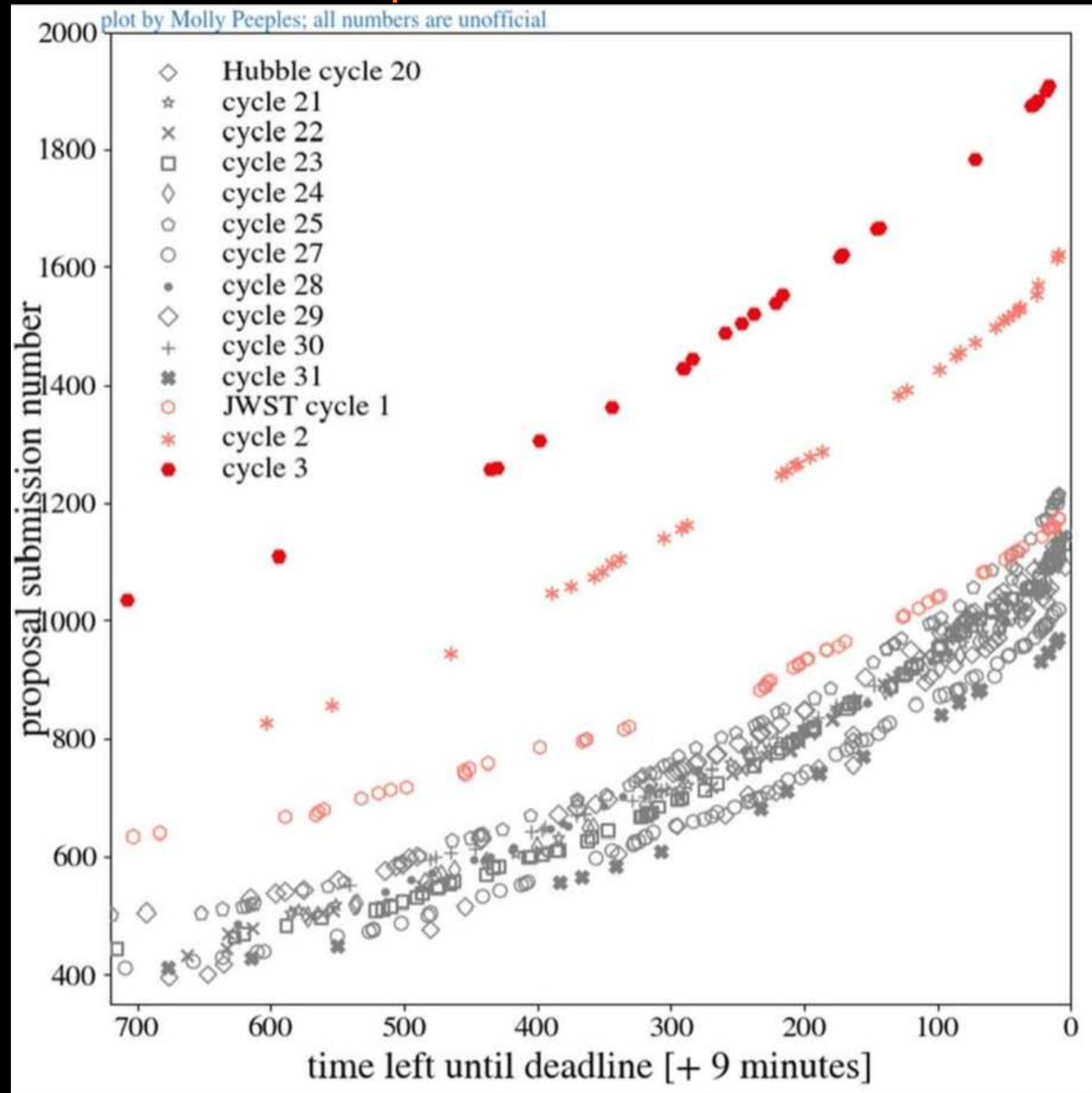


- Infighting killed the 1988 Superconducting Supercollider in Texas (left).
- Canceled project funds never returns: CERN didn't make that mistake (right).
 - ⇒ Avoid infighting with other (exoplanet) HWO stake-holders.
- Design HWO for exoplanets, reionization, and everything in between.

(4) 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) Need space-based resolution for contamination-free LyC at $z \simeq 2.3\text{--}3.5$
 - Design HWO filters with low-enough redleak to enable this.
 - Deepest multi-band images to mask foreground $AB \lesssim 30$ interlopers.
- (3) 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.
 - Wide-field UV IFU, & UV MSA Spectrograph — needs development.
- (4) Coherent team: design HWO for science from exoplanets to reionization.

Spare charts



- 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](#)).

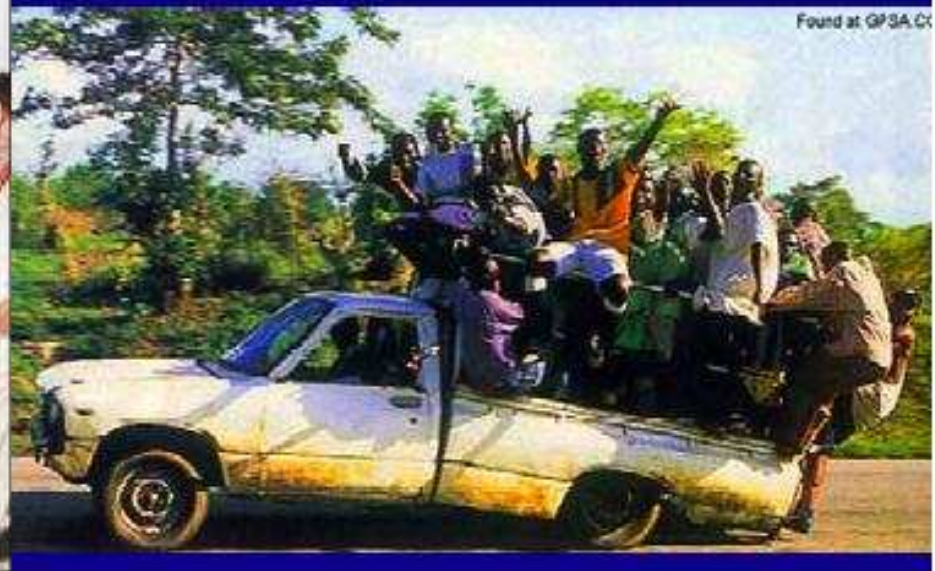
What the Scientists See:



What the Project Manager Sees:



The Happy Balance



Found at GPSA.CX

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

PEARLS papers, press releases and other URLs

Talk: http://www.asu.edu/clas/hst/www/jwst/crete25_futureLyC_fromspace.pdf Data: <https://sites.google.com/view/jwstpearls>
<https://hubblesite.org/contents/news-releases/2022/news-2022-050>
<https://blogs.nasa.gov/webb/2022/10/05/webb-hubble-team-up-to-trace-interstellar-dust-within-a-galactic-pair/>
<https://blogs.nasa.gov/webb/2022/12/14/webb-glimpses-field-of-extragalactic-pearls-studded-with-galactic-diamonds/>
<https://esawebb.org/images/pearls1/zoomable/>
<https://webbtelescope.org/contents/news-releases/2023/news-2023-119>
<https://news.asu.edu/20230801-jwsts-gravitational-lens-reveals-distant-objects-behind-el-gordo-galaxy-cluster>
<https://hubblesite.org/contents/news-releases/2023/news-2023-146>
<https://www.nytimes.com/2023/12/19/science/christmas-stars-galaxies-webb-nasa.html?>
<https://bigthink.com/starts-with-a-bang/triple-lens-supernova-jwst/>

- Adams, N. J., Conselice, C. J., Austin, D., et al. 2024, ApJ, 965, 169 (astro-ph/2304.13721v1)
- Austin, Duncan, Conselice, C. J., Adams, et al. 2024, ApJ, submitted (astro-ph/2404.10751)
- Berkheimer, J. M., Carleton, T., Windhorst, R. A., et al. 2024, ApJ, 964, L29 (astro-ph/2310.16923v2)
- Carleton, T., Windhorst, R. A., O'Brien, R., et al. 2022, AJ, 164, 170 (astro-ph/2205.06347)
- Carleton, T., Cohen, S. H., Frye, B., et al. 2023, ApJ, 953, 83 (astro-ph/2303.04726)
- Carleton, T., Ellsworth-Bowers, T., Windhorst, R. A., et al. 2024, ApJL, 961, L37 (astro-ph/2309.16028)
- Chen, W., Kelly, P. L., Frye, B. L., et al. 2024, ApJ, 970, 102 (astro-ph/2403.19029)
- Diego, J. M., Meena, A. K., Adams, N. J., et al. 2023, A&A, 672, A3 (astro-ph/2210.06514)
- Diego, J. M., Sun, B., Yan, H., et al. 2023, A&A, 679, A31 (astro-ph/2307.10363)
- Diego, J. M., Adams, N. J., Willner, S., et al. 2024, A&A, 690, 114 (astro-ph/2312.11603)
- Diego, J. M., Li, S. K., Amruth, A., et al. 2024, A&A, 690, A359 (astro-ph/2404.08033)
- D'Silva, J. C. J., Driver, S. P., Lagos, C. D. P., et al. 2024, ApJL, 959, L18 (astro-ph/2310.03081v1)
- Duncan, K. J., Windhorst, R. A., et al. 2023, MNRAS, 522, 4548–4564 (astro-ph/2212.09769)
- Frye, B. L., Pascale, M., Foo, N., et al. 2023, ApJ, 952, 81 (astro-ph/2303.03556)
- Frye, B. L., Pascale, M., Pierel, J., Chen, W., Foo, N., et al. 2024, ApJ, 961, 171 (astro-ph/2309.07326v1)

Fudamoto, Y., Sun, F., Diego, J. M., et al. 2025, [Nature Astron.](#), **9**, 428 (astro-ph/2404.08045)

Juodzbališ, I., Conselice, C. J., Singh, M., et al. 2023, MNRAS, 525, 1353 (astro-ph/2307.07535)

Kamieneski, P. S., Frye, B. L., Pascale, M., et al. 2023, ApJ, 955, 91 (astro-ph/2303.05054)

Kamieneski, P. S., Frye, B. L., Windhorst, R. A., et al. 2024, ApJ, 973, 25 (astro-ph/2404.08058)

Keel, W. C., Windhorst, R. A., Jansen, R. A., et al. 2023, AJ, 165, 166 (astro-ph/2208.14475)

Nabizadeh, A., Zackrisson, E., Pacucci, F., et al. 2024, A&A, 683-58 (astro-ph/2308.07260)

O'Brien, R., Carleton, T., Windhorst, R. et al. 2023, AJ, 165, 237 (astro-ph/2210.08010)

O'Brien, R., Jansen, R. A., Grogin, N. A., et al. ApJS, 272, 19 (astro-ph/2401.04944)

Ortiz, III, R., Windhorst, R. A., Cohen, S. H., et al. 2024, ApJ, 974, 258 (astro-ph/2404.10709)

Pascale, M., Frye, B., Pierel, J., et al. 2025, ApJ, 979, 13 (astro-ph/2403.18902)

Pierel, J. D. R., Frye, B. L., Pascale, M., et al. 2024, ApJ, 967, 50 (astro-ph/2404.02139)

Polletta, M. del Carmen, Nonino, M., Frye, B., et al. 2023, A&AL, 675, L4 (astro-ph/2306.12385)

Robertson, C., Holwerda, B. W., Young, J., et al. 2024, AJ, 167, 263 (astro-ph/2403.15619)

Smail, I., Dudzeviciute, U., Gurwell, M., et al. 2023, ApJ, 958, 36 (astro-ph/2306.16039)

Summers, J., Windhorst, R. A., Cohen, S. H., et al. 2023, ApJ, 958, 108 (astro-ph/2306.13037)

Trussler, J. A. A., Conselice, C. J., Adams, N., et al. 2024, MNRAS, 527, 11627–11650 (astro-ph/2308.09665)

Willner, S. P., Gim, H. B., Polletta, M. et al. 2023, ApJ, 958, 176 (astro-ph/2309.13008)

Windhorst, R., Timmes, F. X., Wyithe, J. S. B., et al. 2018, ApJS, 234, 41 (astro-ph/1801.03584)

Windhorst, R. A., Carleton, T., O'Brien, R., et al. 2022, AJ, 164, 141 (astro-ph/2205.06214)

Windhorst, R. A., Cohen, S. H., Jansen, R. A., et al. 2023, AJ, 165, 13 (astro-ph/2209.04119)

Windhorst, R. A., Summers, J., Carleton, T., et al. 2025, J. BAAS, 57, 1, in press ([astro-ph/2410.01187](#))

Yan, H., Cohen, S. H., Windhorst, R. A., et al. 2023, ApJL, 942, L8 (astro-ph/2209.04092)

Yan, H., Ma, Z., Sun, B., et al. 2023, ApJ, 2023, ApJS, 269, 43 (astro-ph/2307.07579)