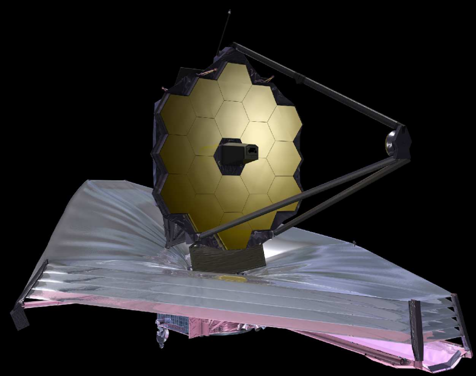
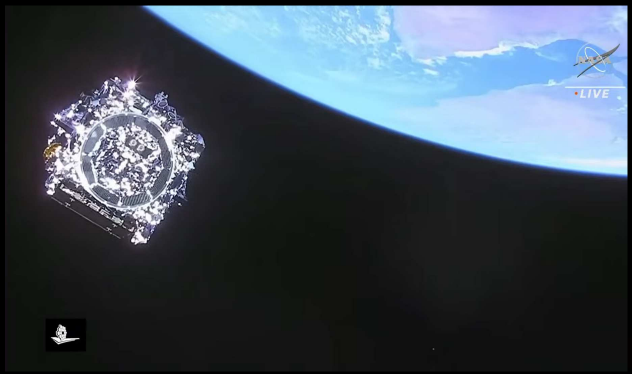
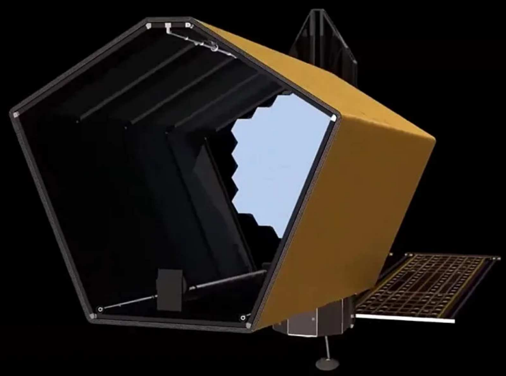
LyC studies from space in the next decades

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
$1973\sim2033^{+}$?	$1996\sim2031$	$1996\sim2046^{+}$?	$2040\sim2070^{+}$?

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`

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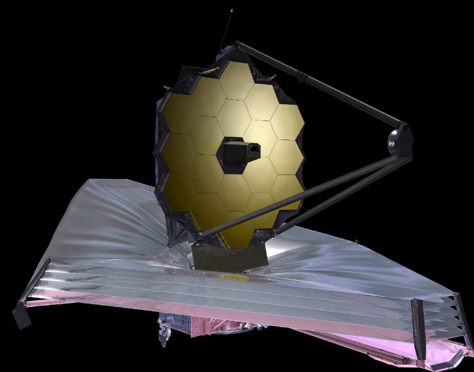
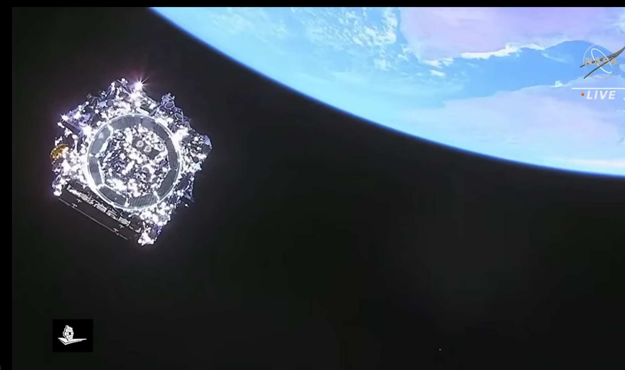
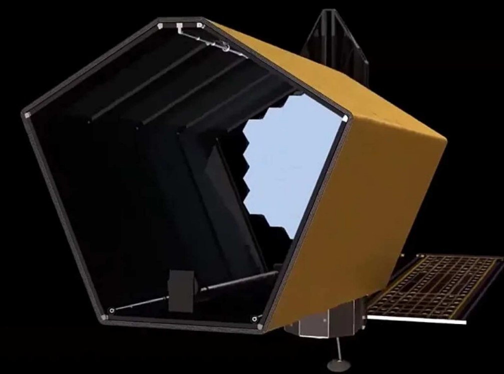
Hubble
1973∼2033^{+}?



Webb (designed)
1996∼2031



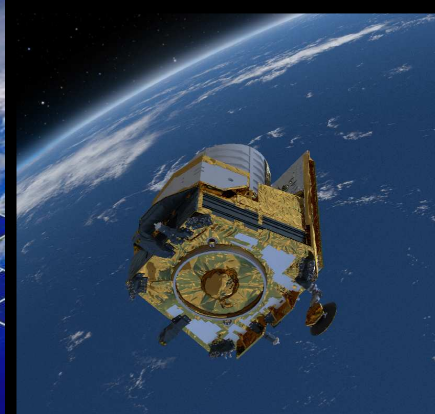
Webb (launched 2021)
1996∼2046^{+}?



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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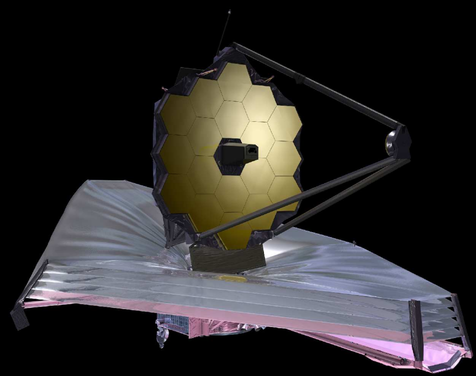

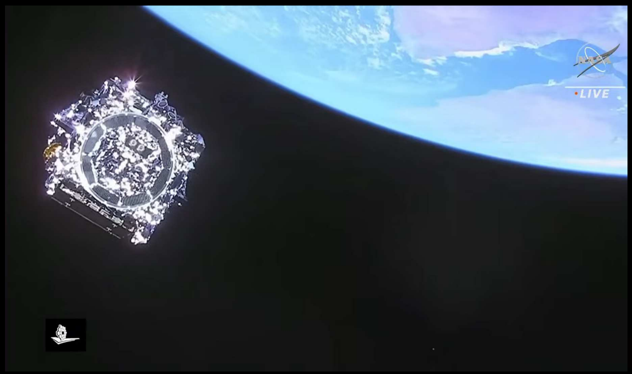

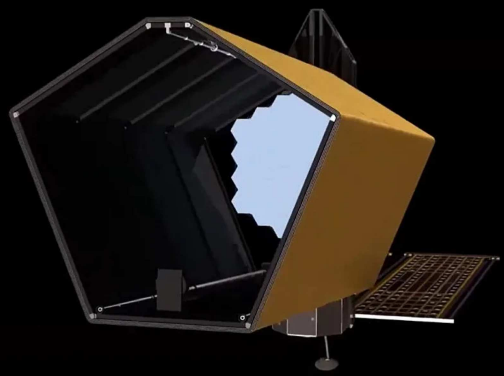

Hubble	Webb (designed)	Webb (launched 2021)	Habitable Worlds
1973∼2033^{+}?	1996∼2031	1996∼2046^{+}?	2040∼2070^{+}?

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

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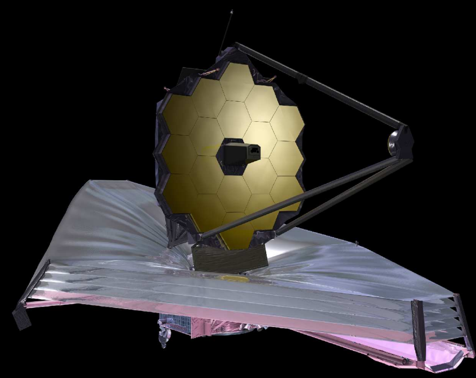
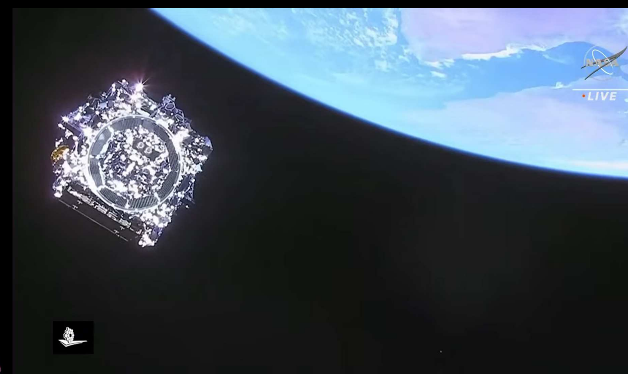
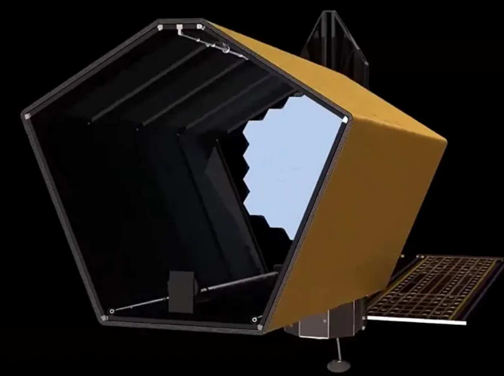
Hubble
1973∼2033$^+$?



Webb (designed)
1996∼2031



Webb (launched 2021)
1996∼2046$^+$?

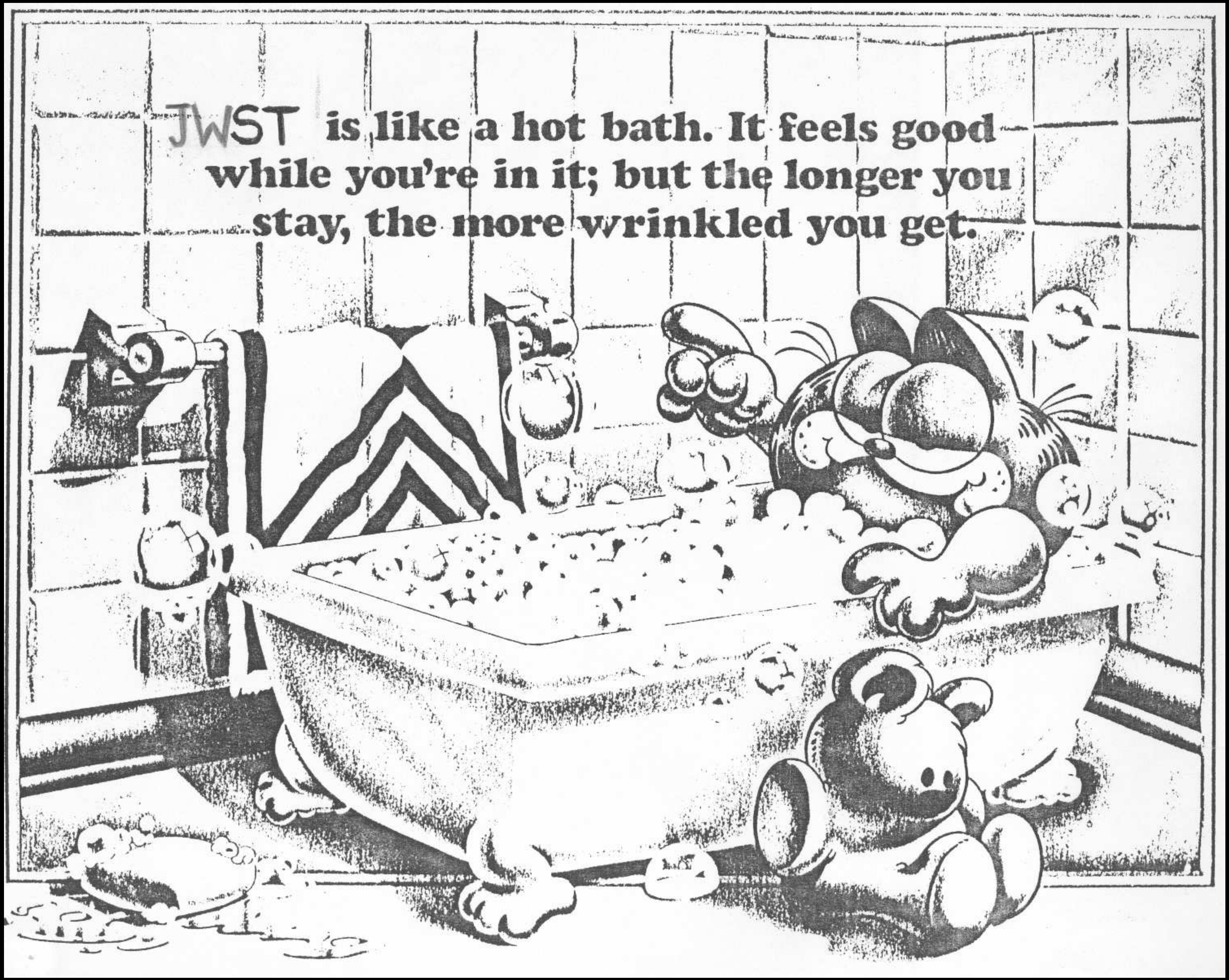


Habitable Worlds
2040∼2070$^+$?

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.

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



WARNING: Both Hubble and James Webb are 40–50^{+} 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) Need space-based resolution for contamination-free LyC work

- (3) Habitable World Observatory requirements for LyC work

- (4) Summary and Conclusions

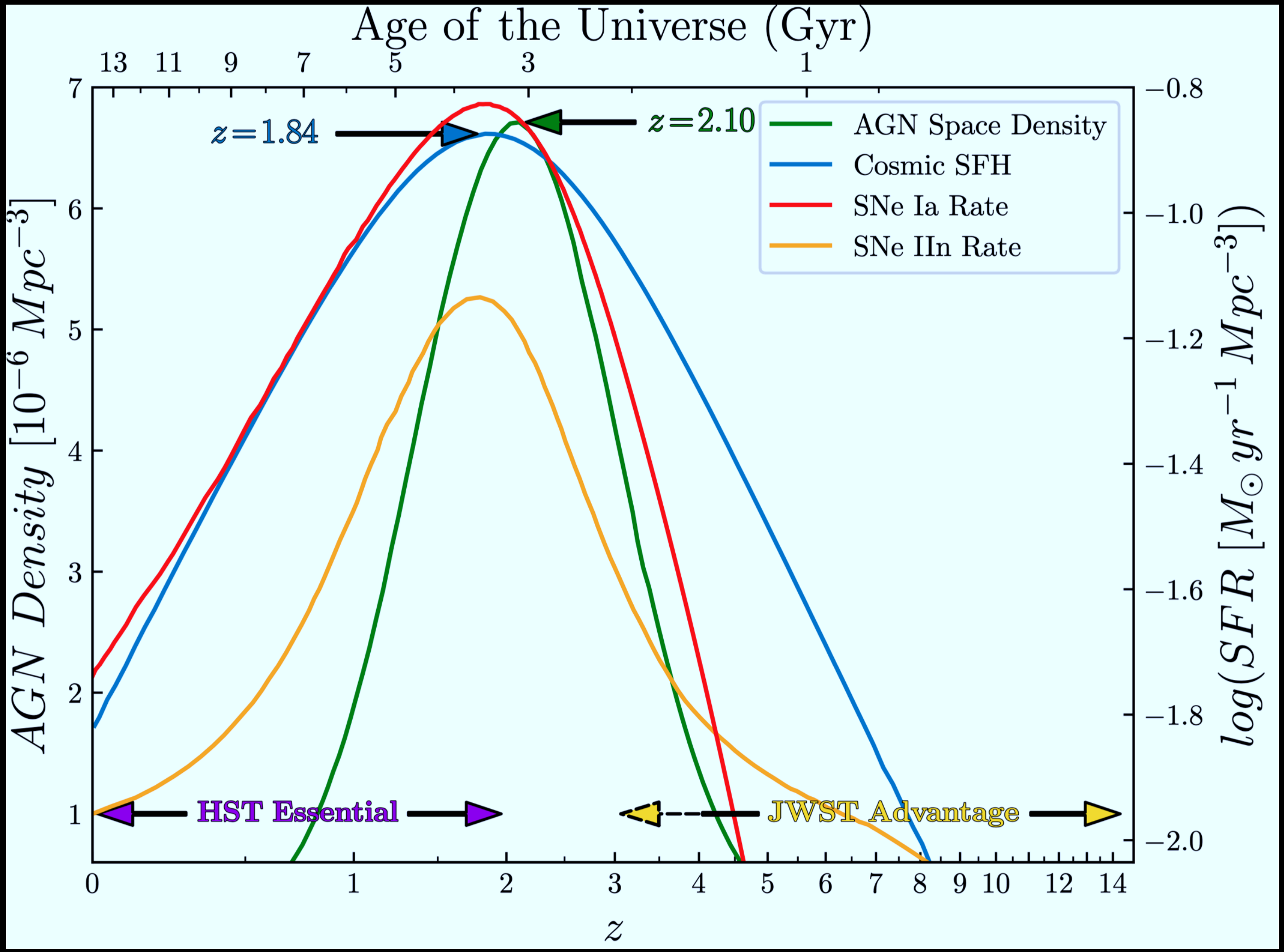
ARIZONA STATE UNIVERSITY

Sponsored by NASA/HST & JWST

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

Windhorst et al.

astro-ph/2410.01187



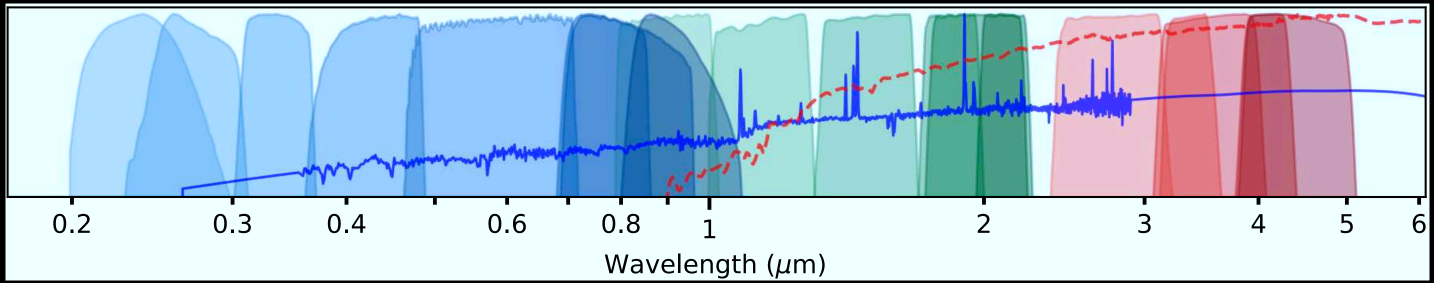
$\mathbf{Age} \sim \frac{13.8}{(1+z)} + \ldots$ **Gyr**

Active galactic nuclei (AGN)

$\Longleftrightarrow$ BH accretion disks

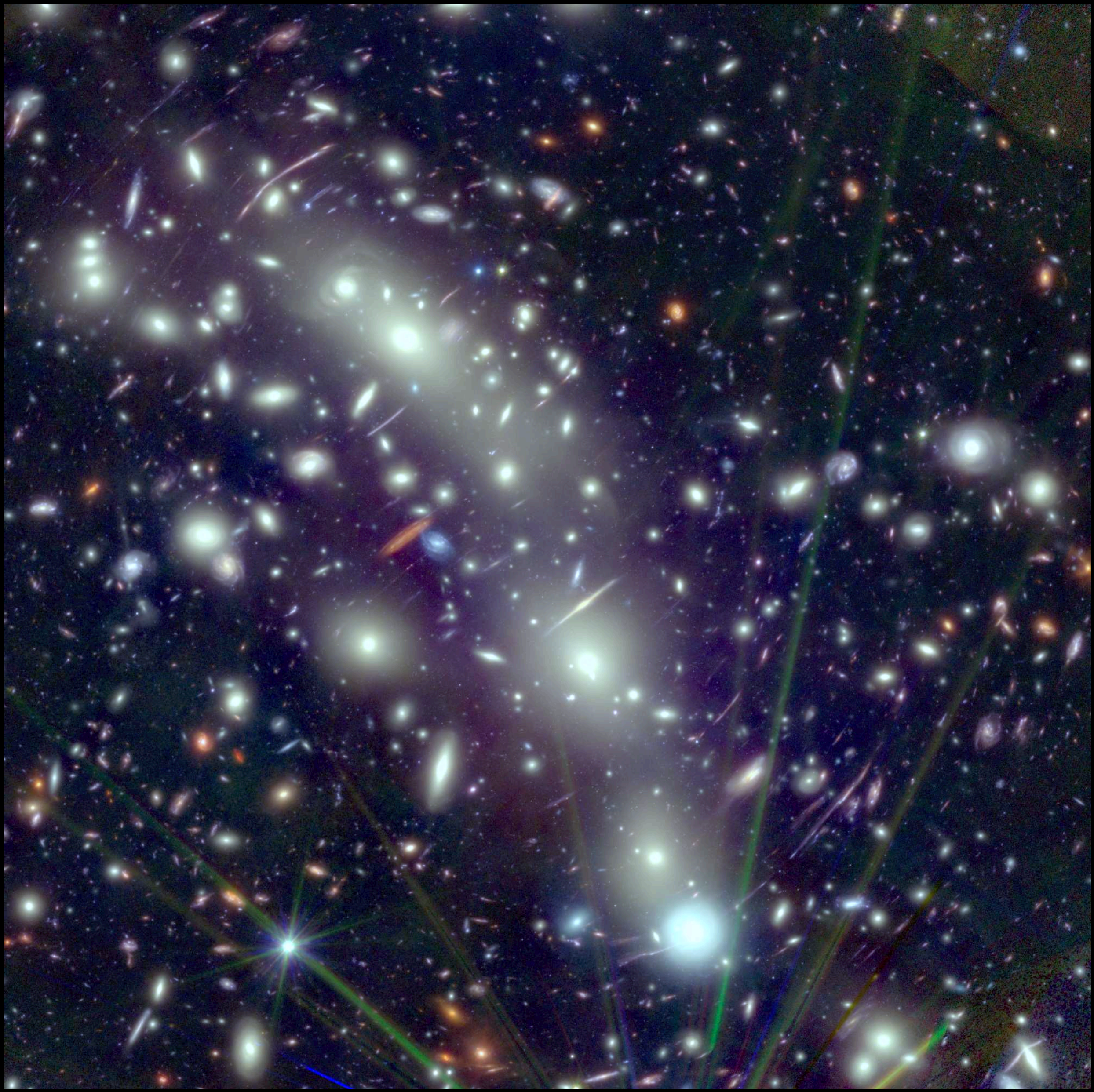
$\Longleftrightarrow$ Chandra X-ray sources

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



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

(1) Uniquely complementary roles of Hubble and Webb:

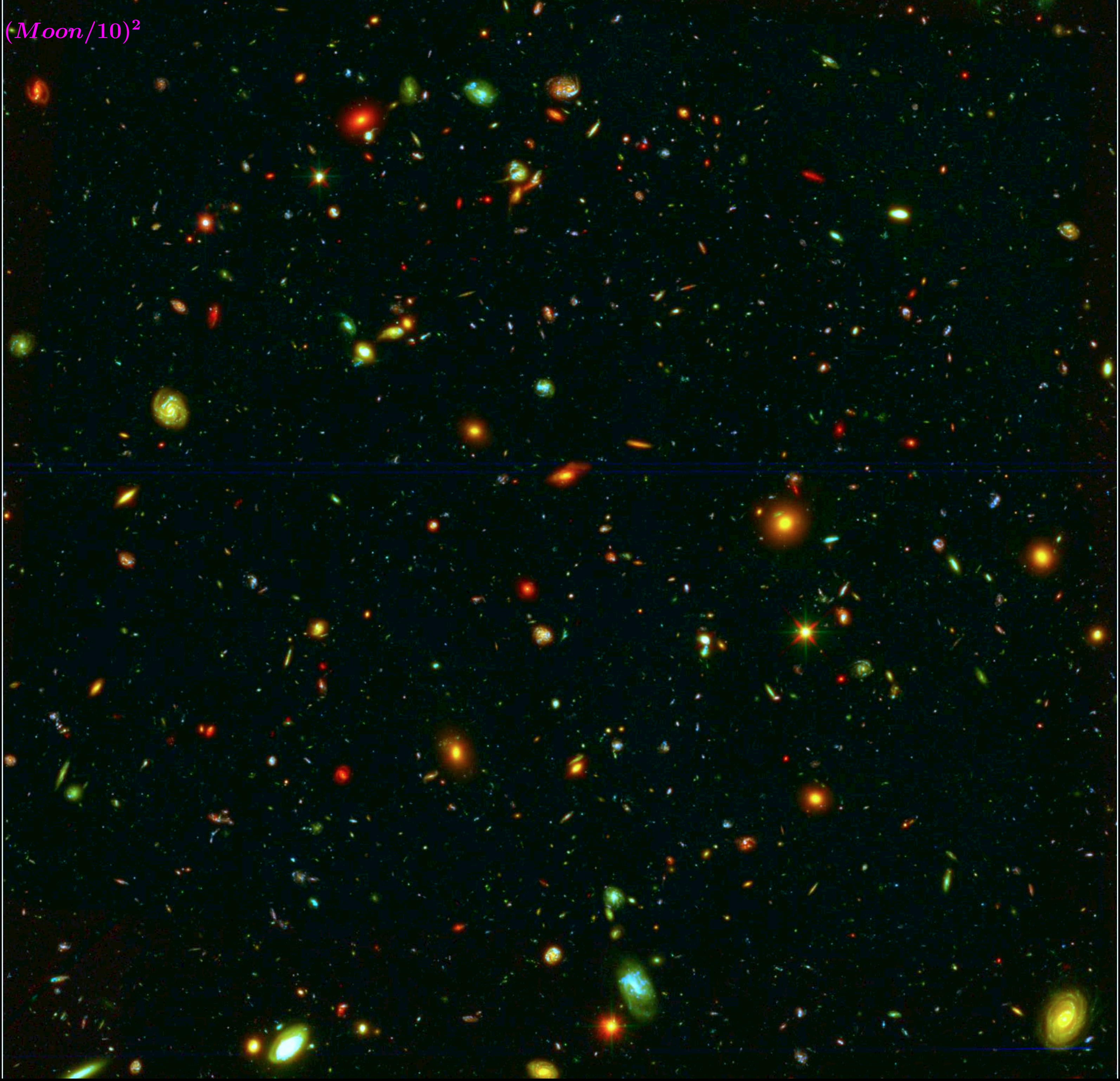


500 hrs HST+JWST: 45 filters (0.2–5.0μm), lensing cluster MACS0416:

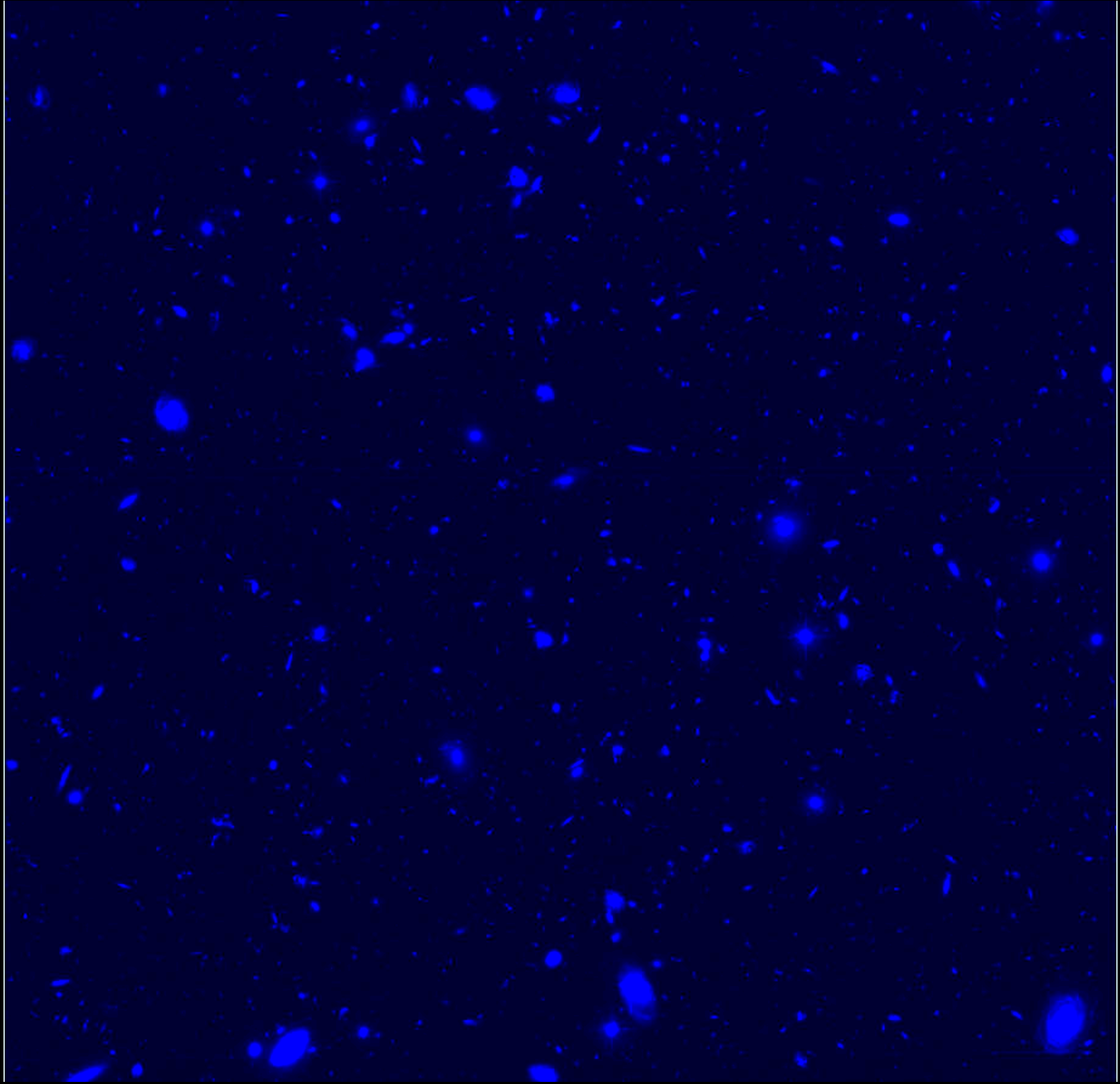
- HST darkest skies (10-$10^3\times$ darker) + JWST's dark skies (10^3–$10^5\times$ darker than ground based):

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

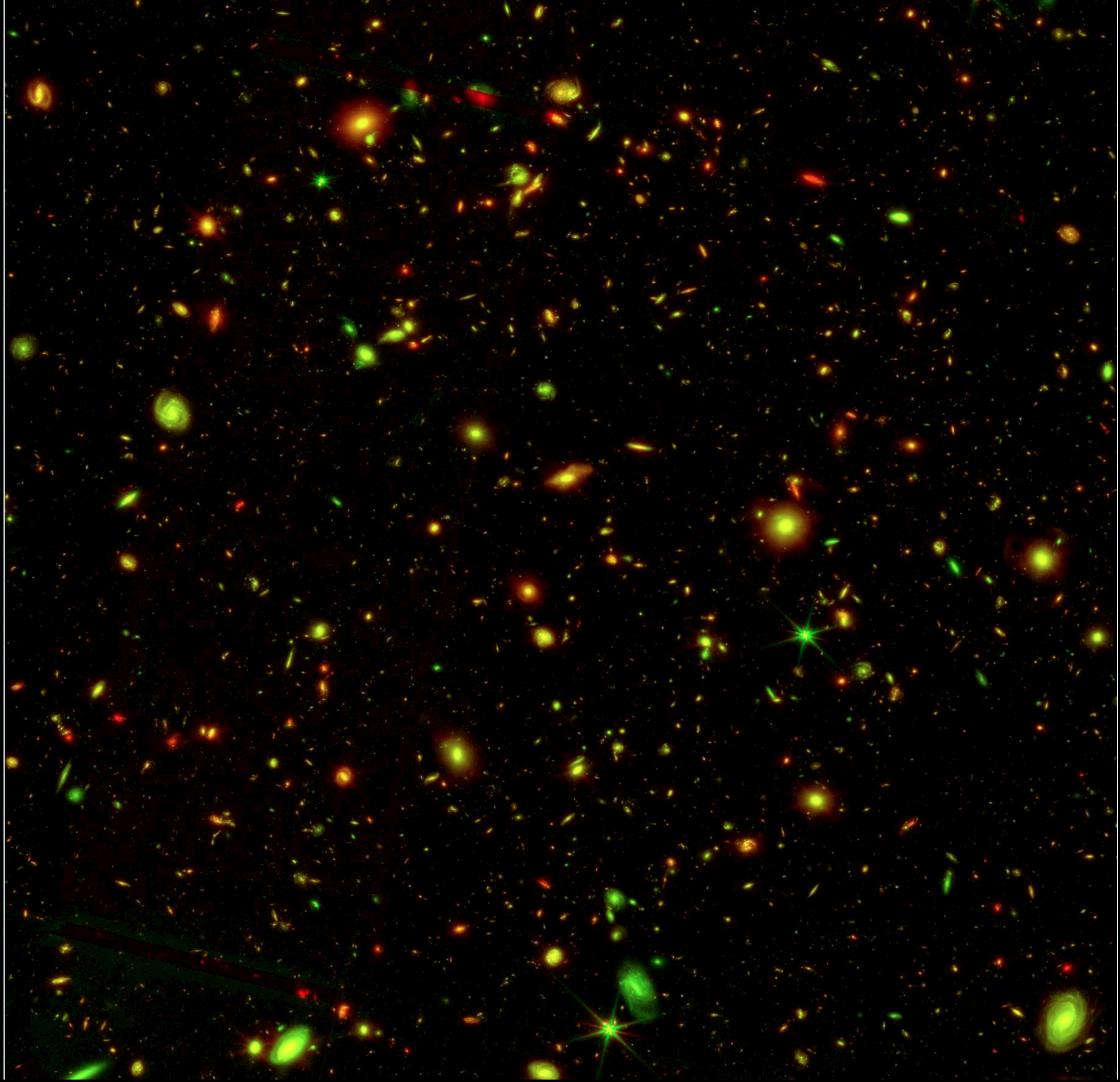
Field-of-View $\sim (Moon/10)^2$



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

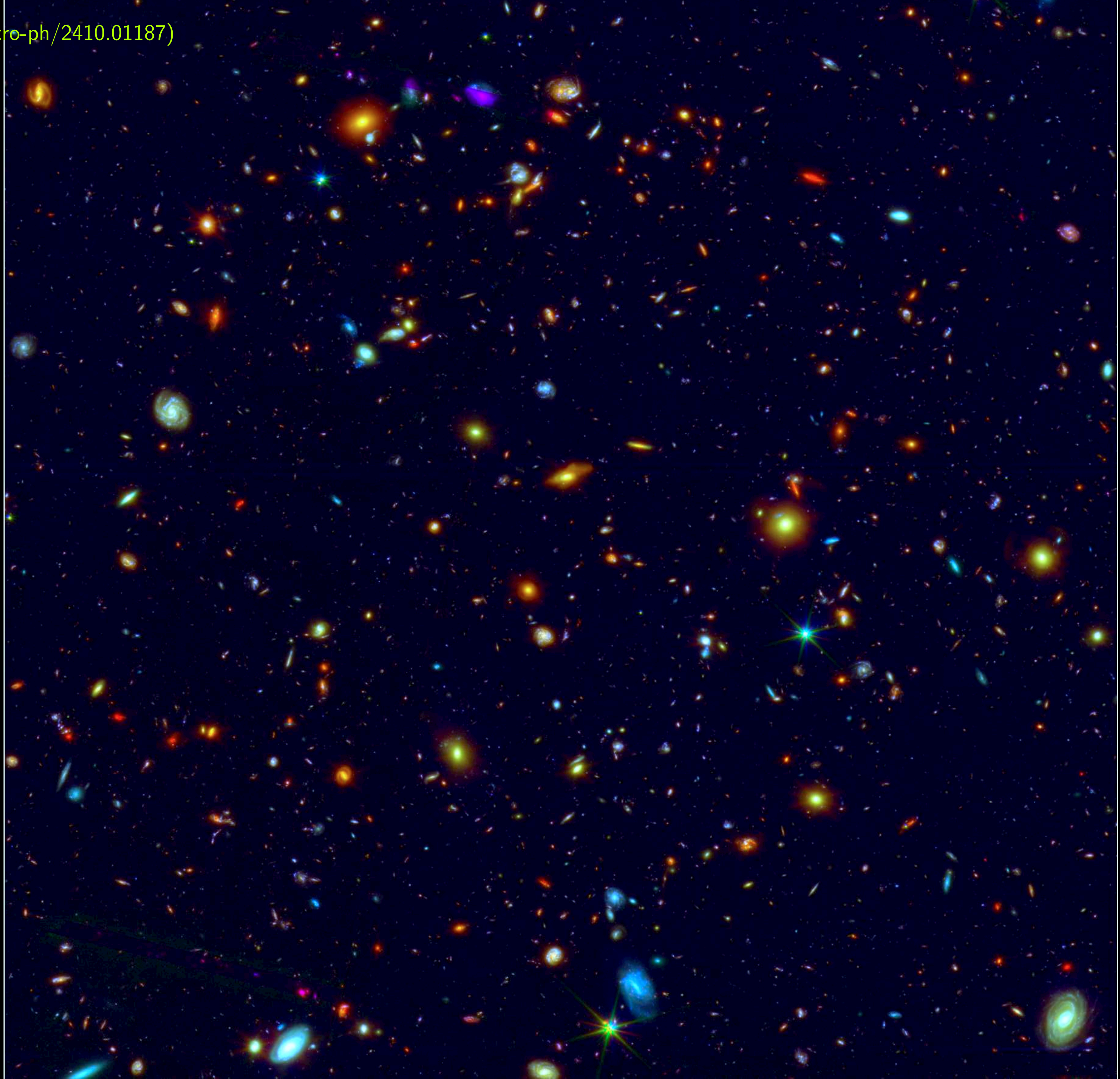


361 hr HST Hubble UltraDeep Field: 8 HST-unique filters 0.2–0.9 μm (in false color blue).



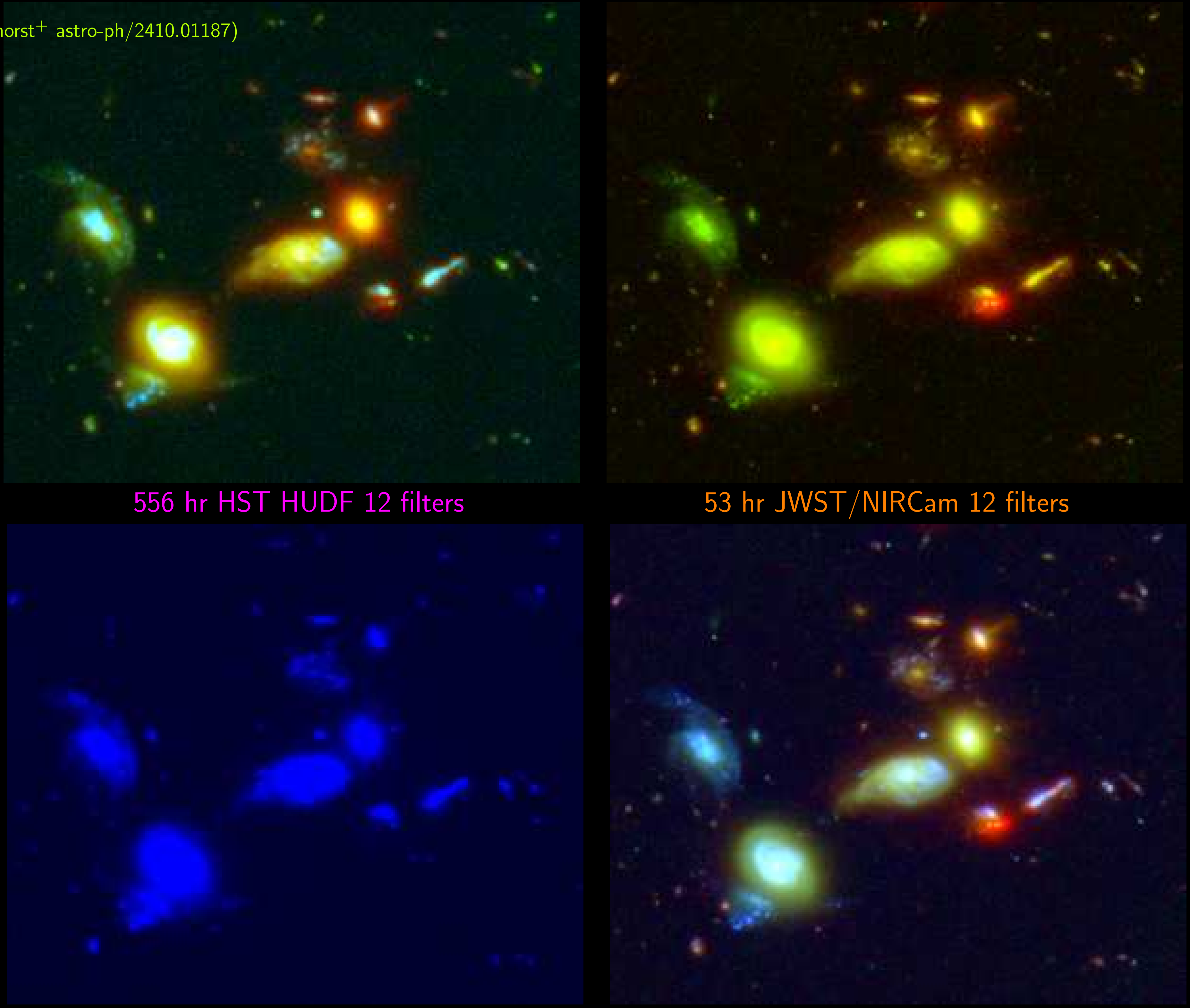
53 hr JWST/NIRCam Hubble UltraDeep Field: 12 filters at 0.9–5.0 μm (AB$\lesssim$31 mag; in green + red).

(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)



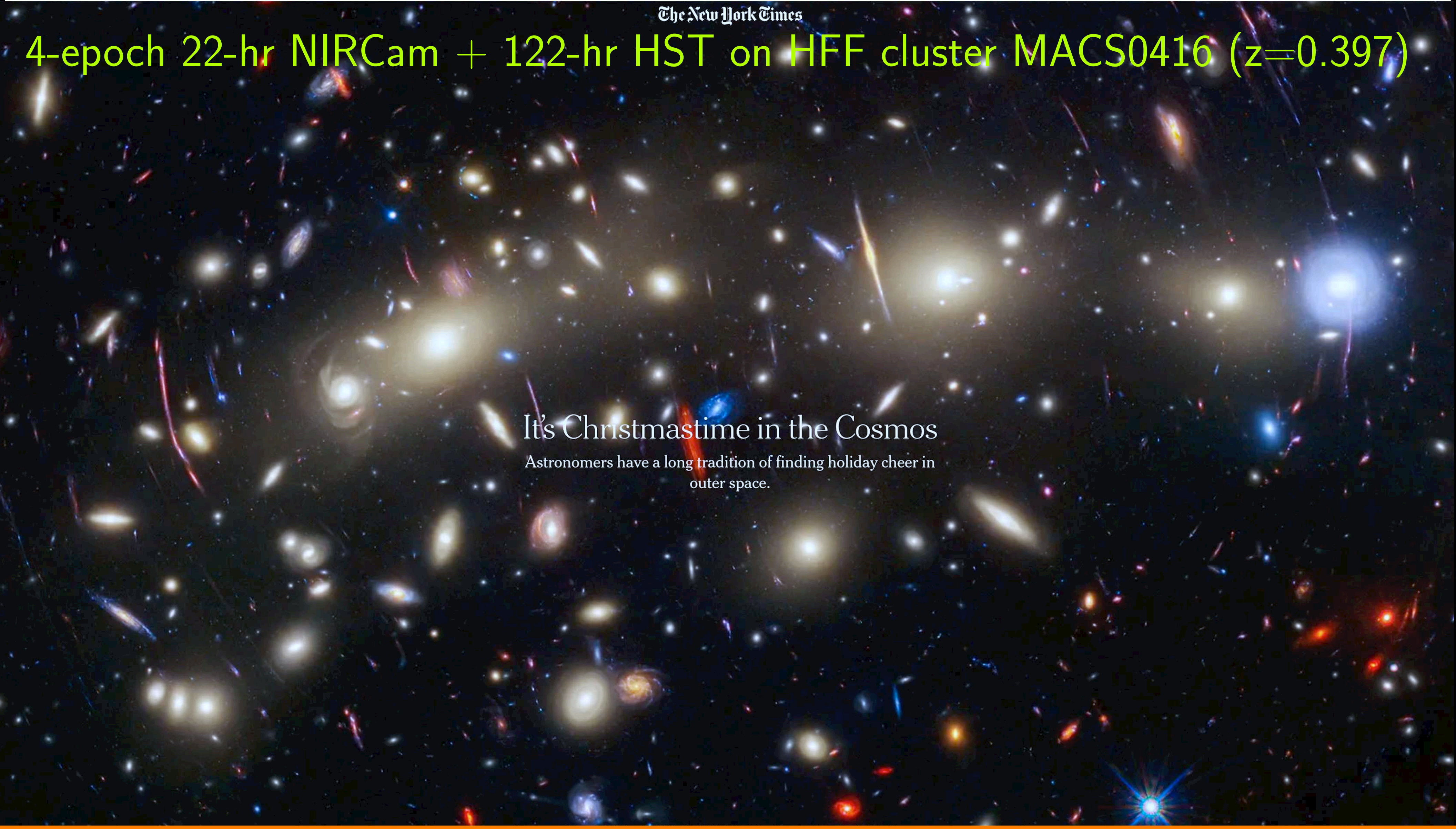
556 hr HST HUDF 12 filters

53 hr JWST/NIRCam 12 filters

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

414 hr HST+JWST 20 filters

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

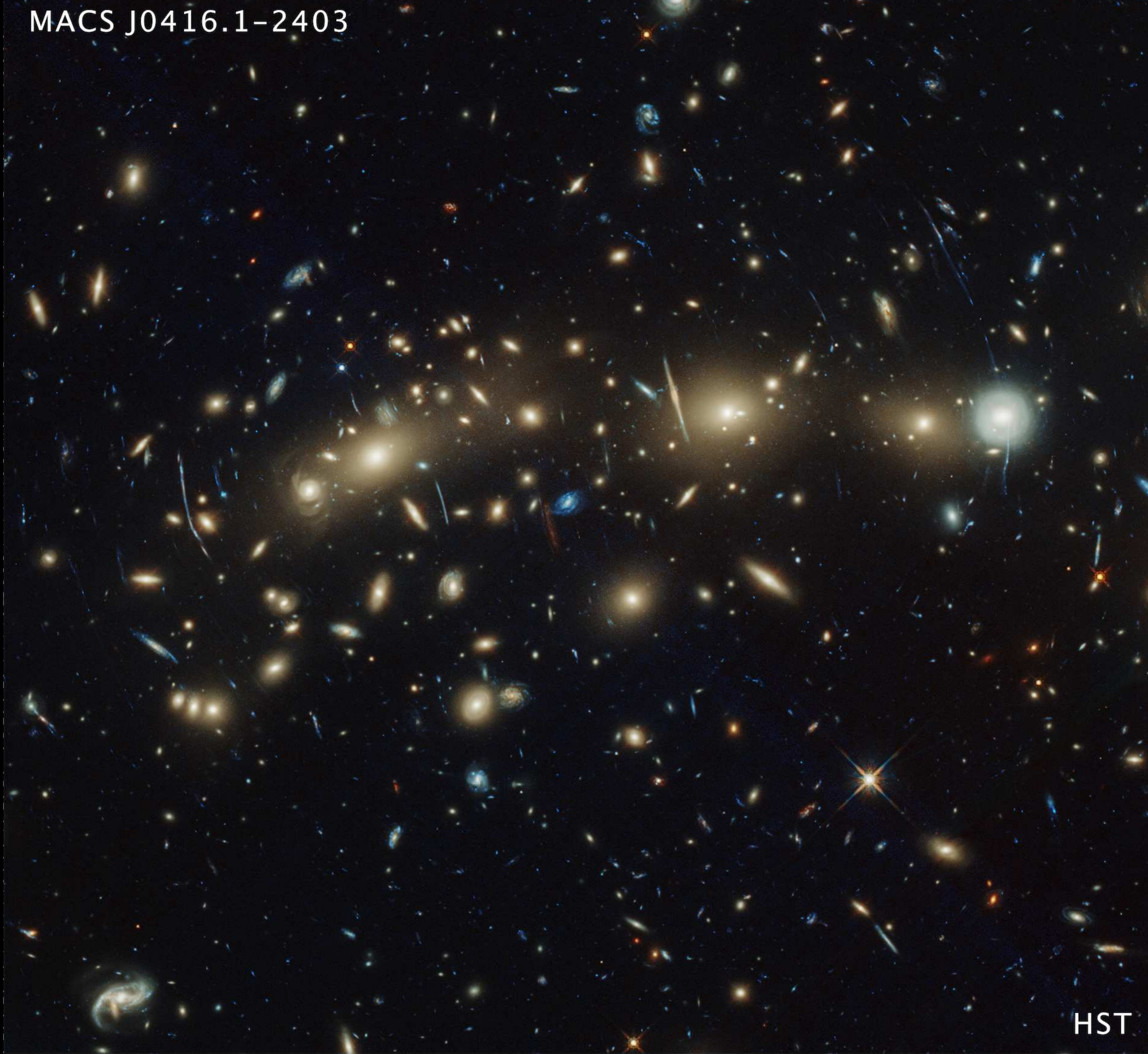


12 new caustic transits at $z \simeq 1$–2 from 4 epochs! (Yan, H.+, 2023, ApJS, 269, 42)

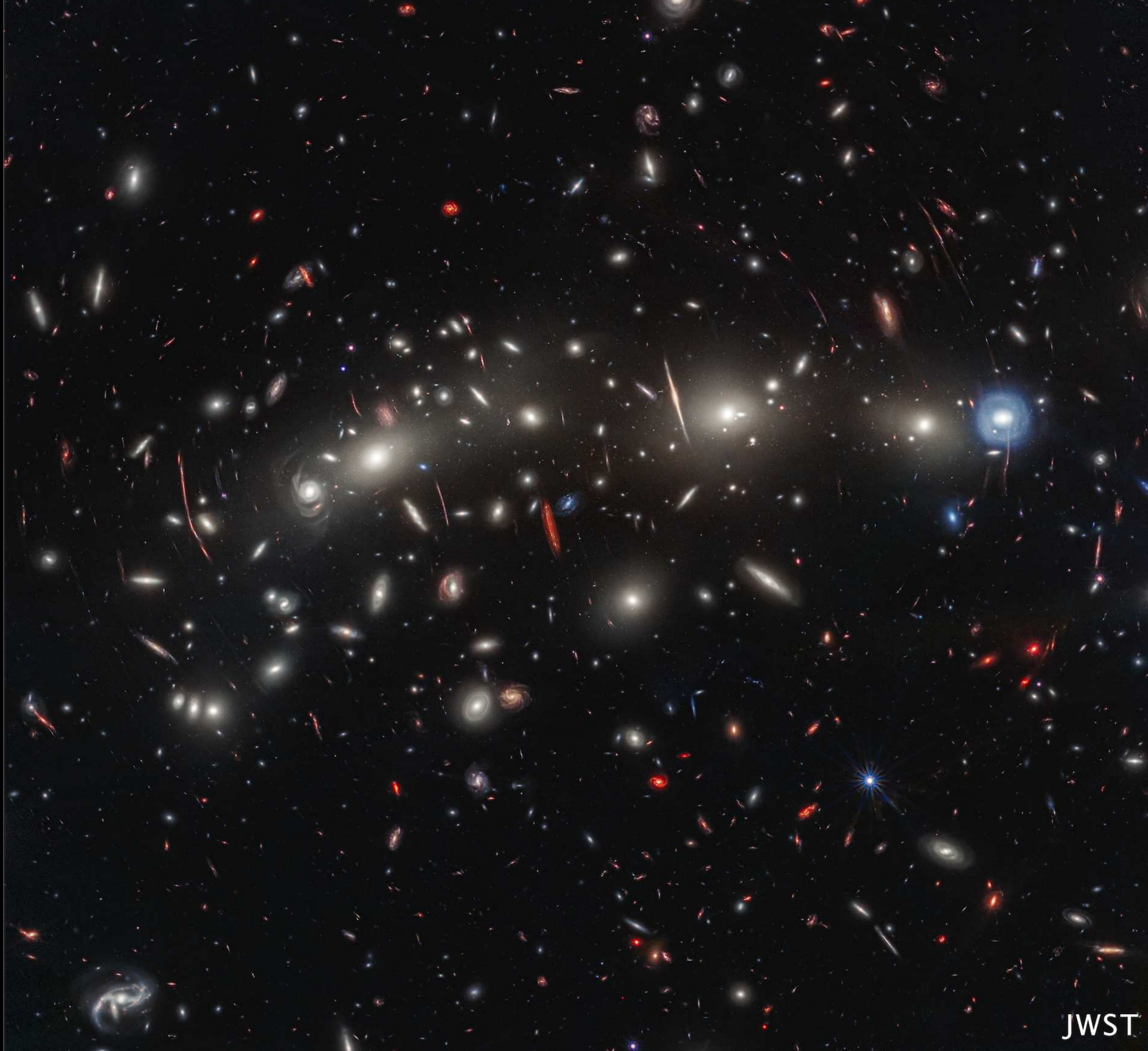
Extremely magnified binary star at z=2.091! (Diego, J.+, 2023, A&A 679, A31)

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?

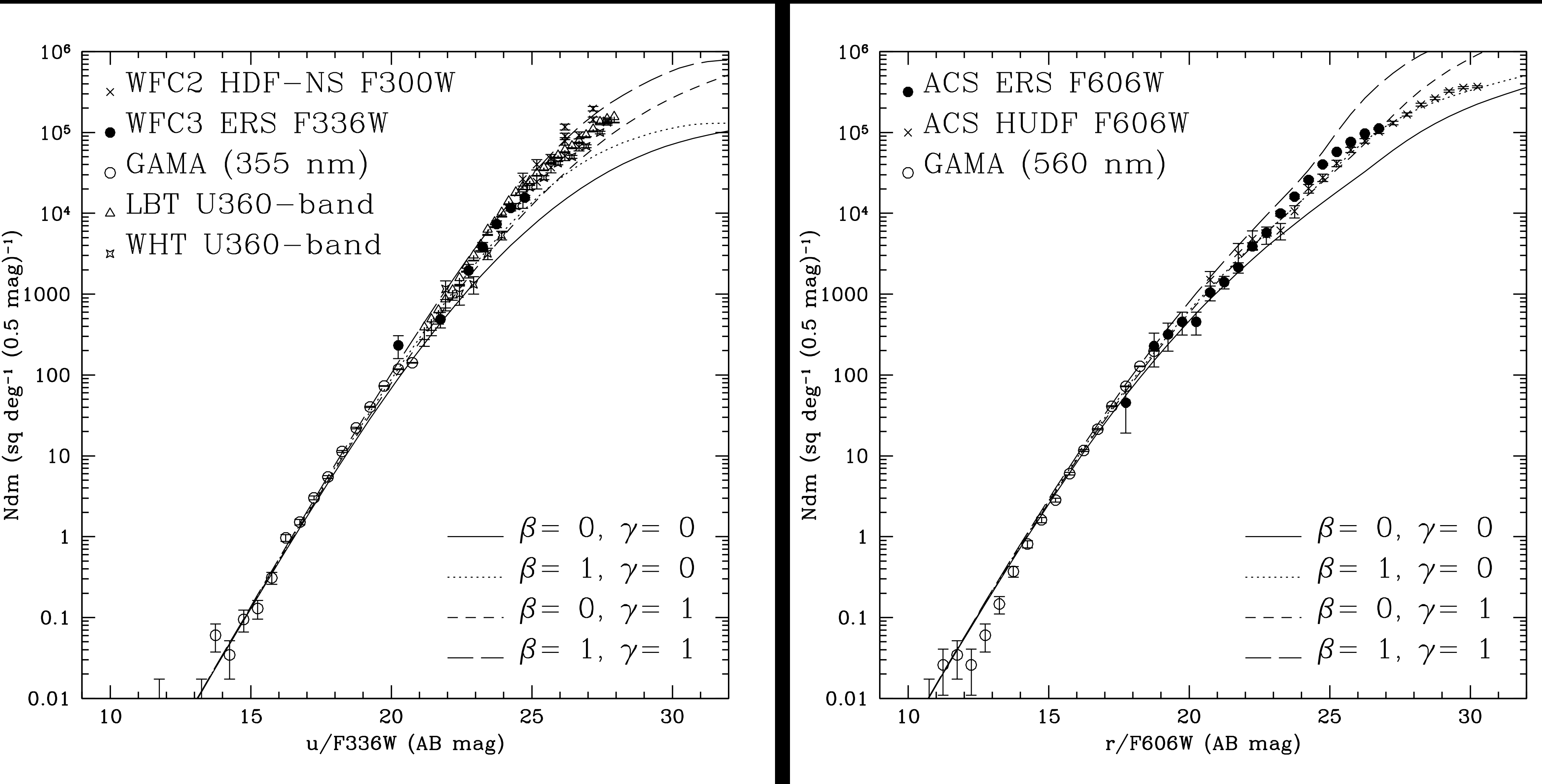


122 hr HST on Hubble Frontier Field cluster MACS0416 (z=0.397; 4.3 Blyr)



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

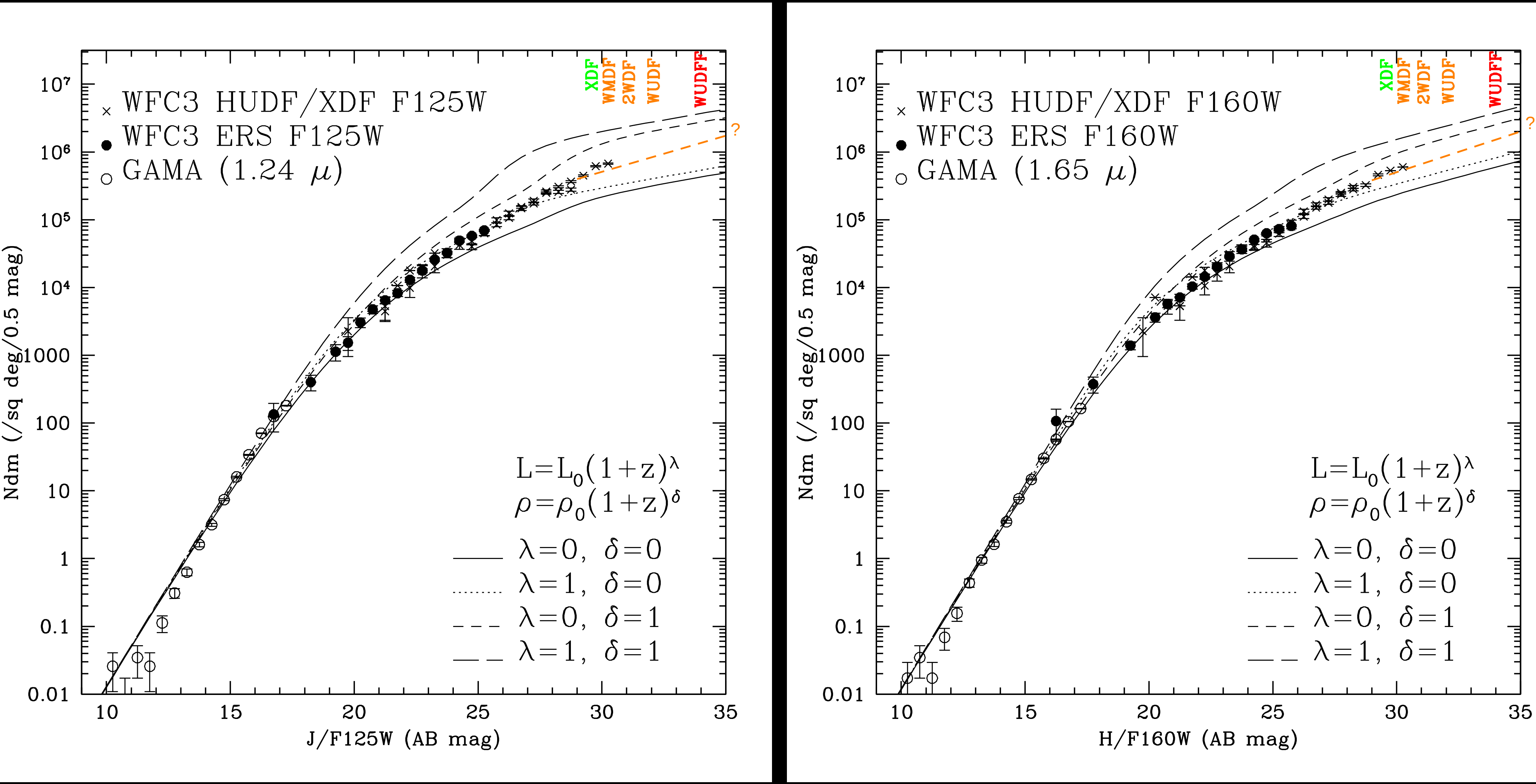
(2) Need space-based imaging for contamination-free LyC work



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

Faint-end blue count-slope≃0.30–0.40 dex/mag.

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



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

Faint-end near-IR count-slope≃0.12±0.02 dex/mag.

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

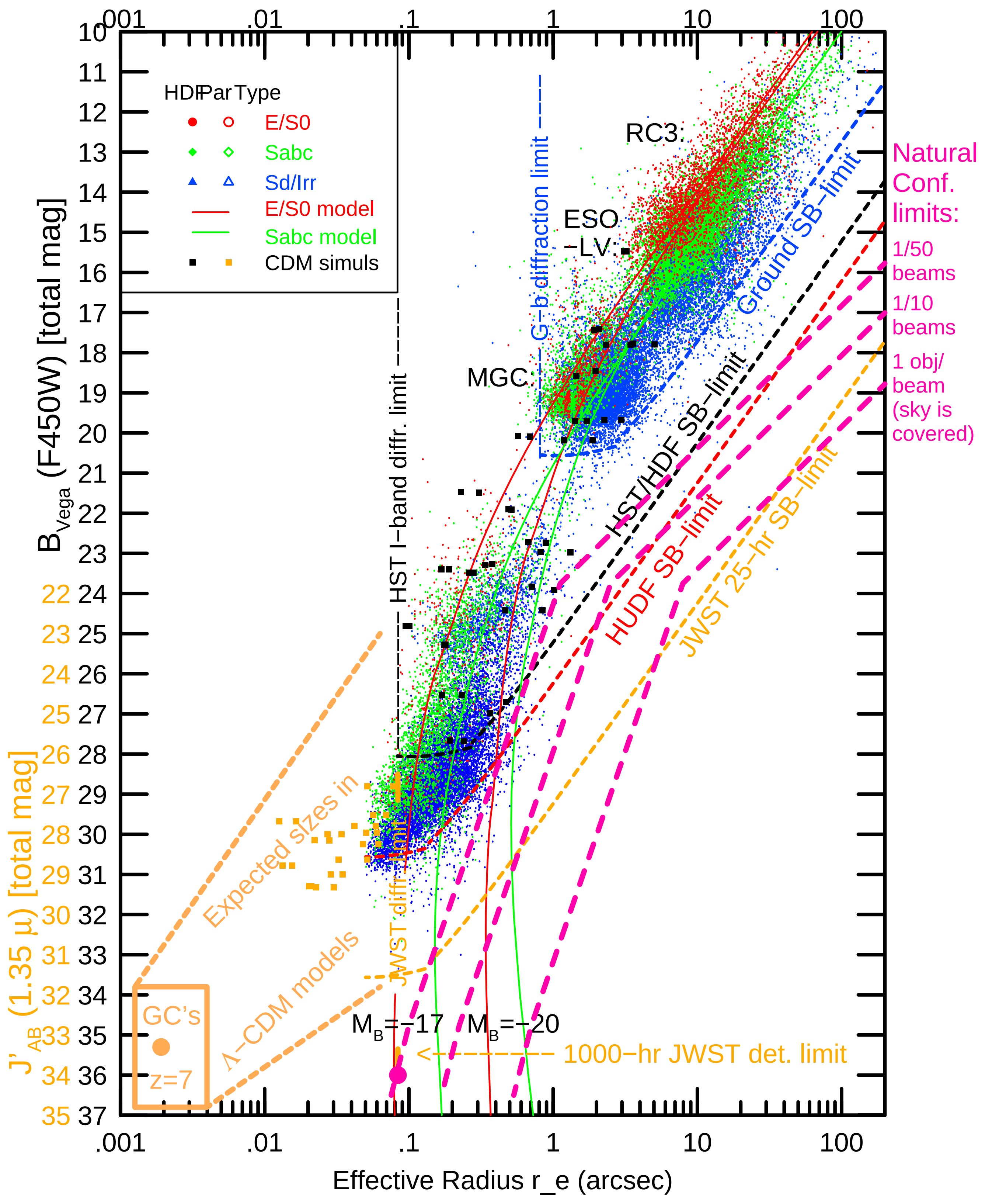
B, I, J AB-mag vs. half-light radii r_e from RC3 to HUDF limit are shown.

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.

SB$\lesssim$31 mag objects are likely globular or compact star clusters with FWHM$\gtrsim$0.″012



Combination of ground-based and space-based HST surveys show:

- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:

- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$-dimming), but also due to:

- (2a) hierarchical formation causing size evolution: $r_{hl}(z) \propto r_{hl}(0)\ (1+z)^{-1}$

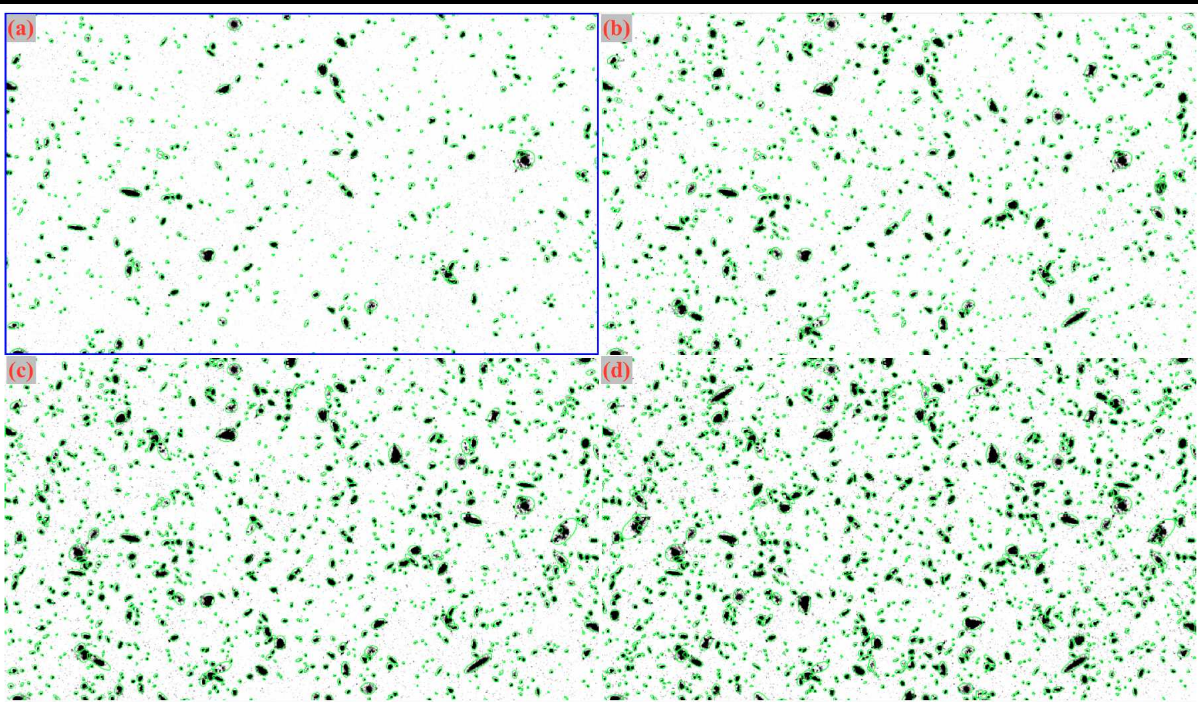
- (2b) increasing inability of object detection algorithms to deblend galaxies at faint mags ("natural" confusion $\neq$ "instrumental" confusion).

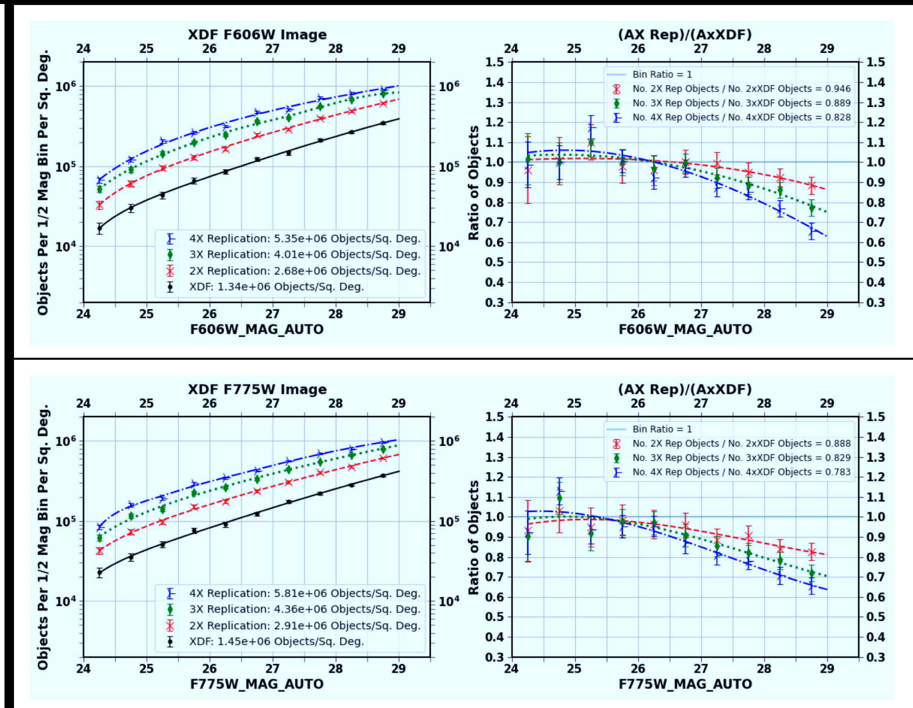
- (3) At AB$\lesssim$31 mag, will see 2×10^6–4×10^6 galaxies/deg^2. Most of these will have $r_{hl} << 0\farcs1$ FWHM (Kawata et al. 2006).

- (4) At ORCAS FWHM$\sim$$0\farcs012$ (5 m.a.s. pixels), expect some fraction (10%?) to be point sources — globular clusters or compact star clusters? Exact number will require higher-resolution hierarchical simulations.

- For details, see Windhorst, R. A., et al. 2008, Advances in Space Research, Vol. 41, 1965, (astro-ph/0703171) or Windhorst et al. 2011, ApJS, 193, 27 (astro-ph/1005.2776).

Can undetected (low-SB) galaxies cause 0.3 dex of Diffuse Light?





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

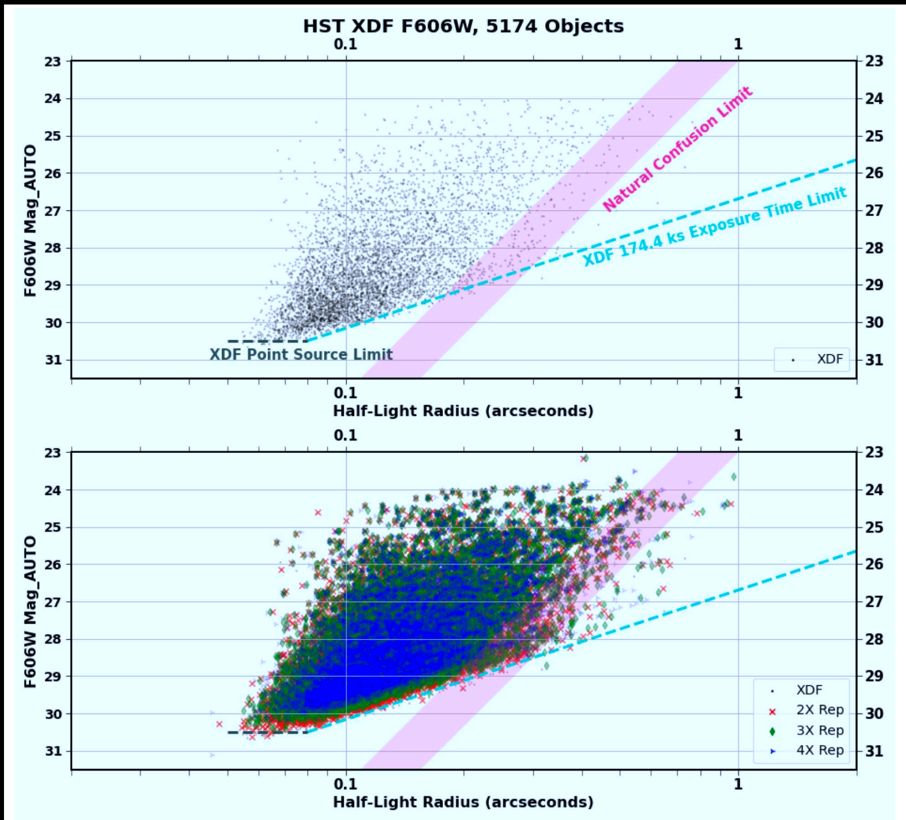
[Right]: 4×HUDF counts still ≳65% complete for AB≳28.5–29 mag.

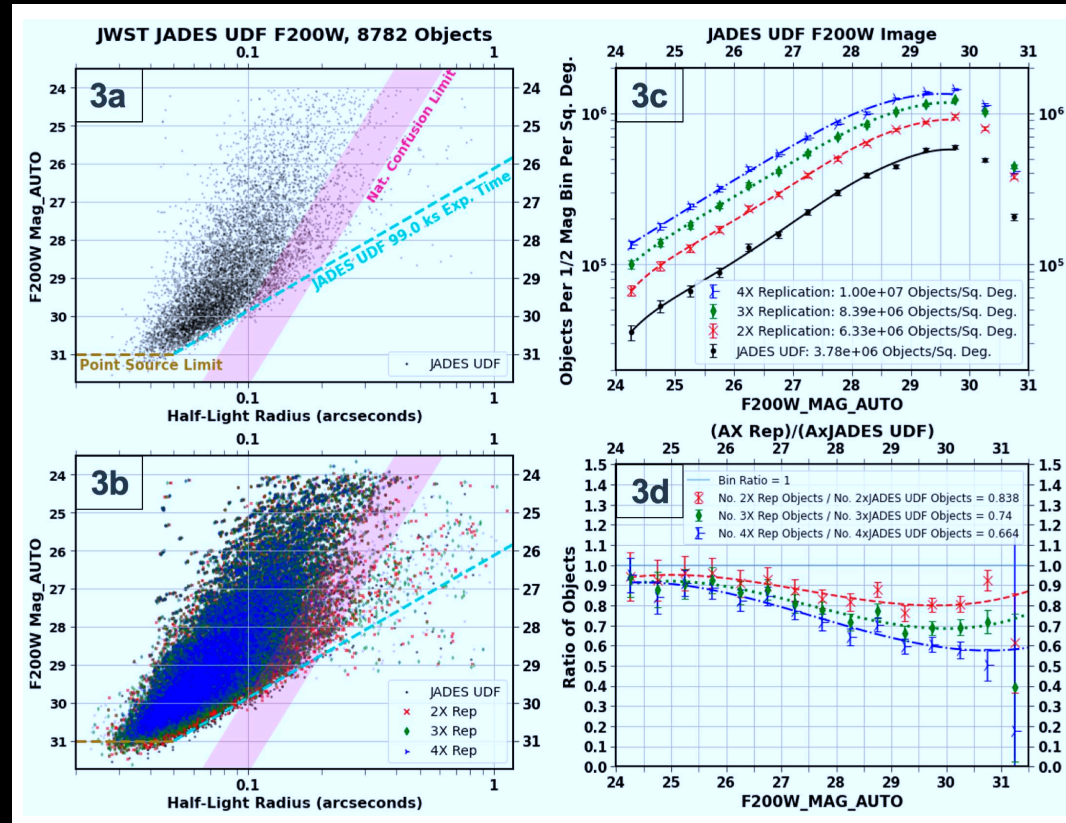
- Crowding not enough to explain factor ∼2 diffuse flux at AB≳24 mag.

⟹ Cannot explain diffuse light through missing ordinary galaxies!

- Missing diffuse light caused by other sources? (dim Zodi component!)

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





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

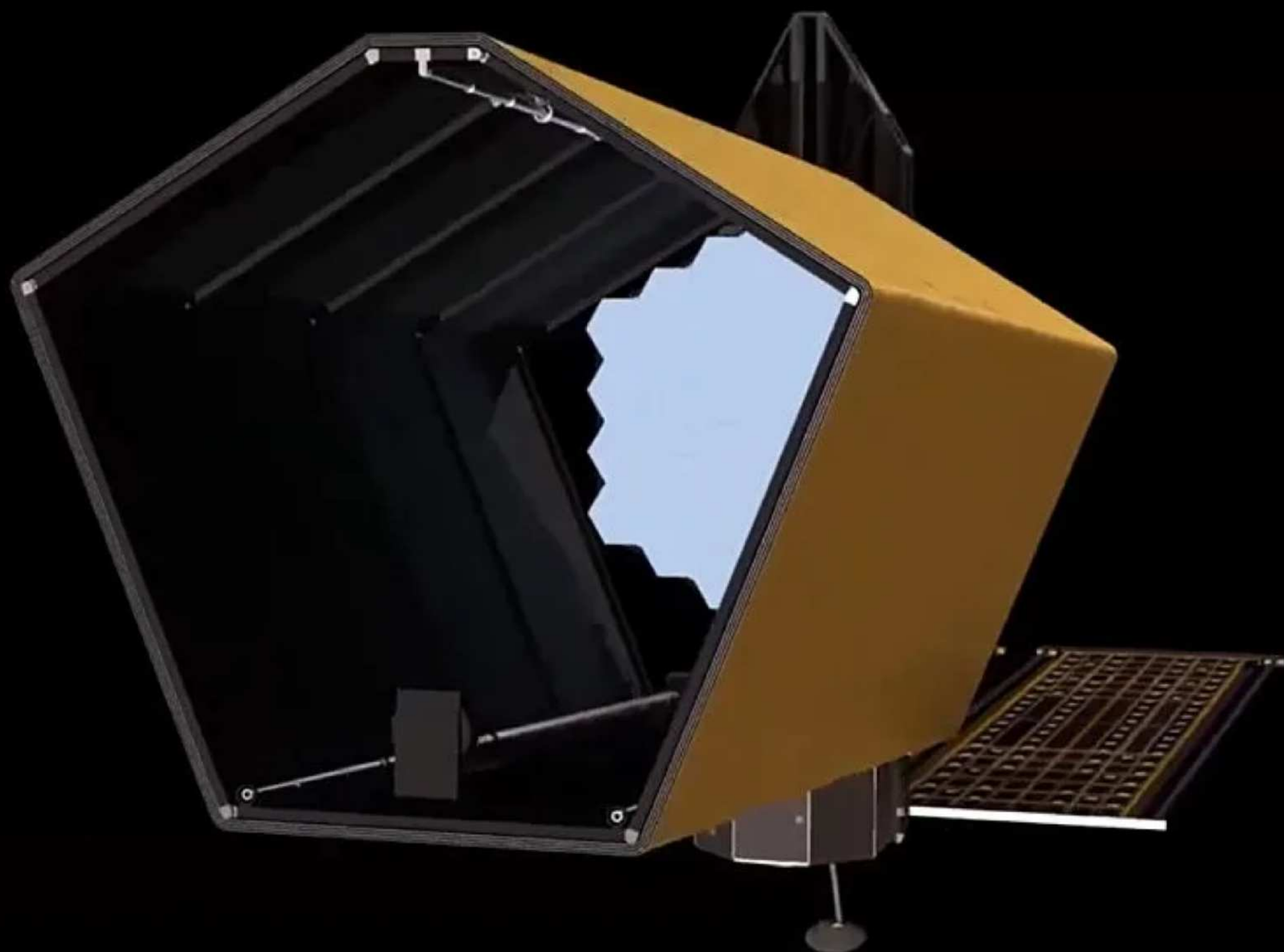
Bottom: Same for XDF & JADES rotated+replicated onto itself 2×, 3×, 4×.

Right: Counts and completeness functions for 2×, 3×, 4× rotated images.

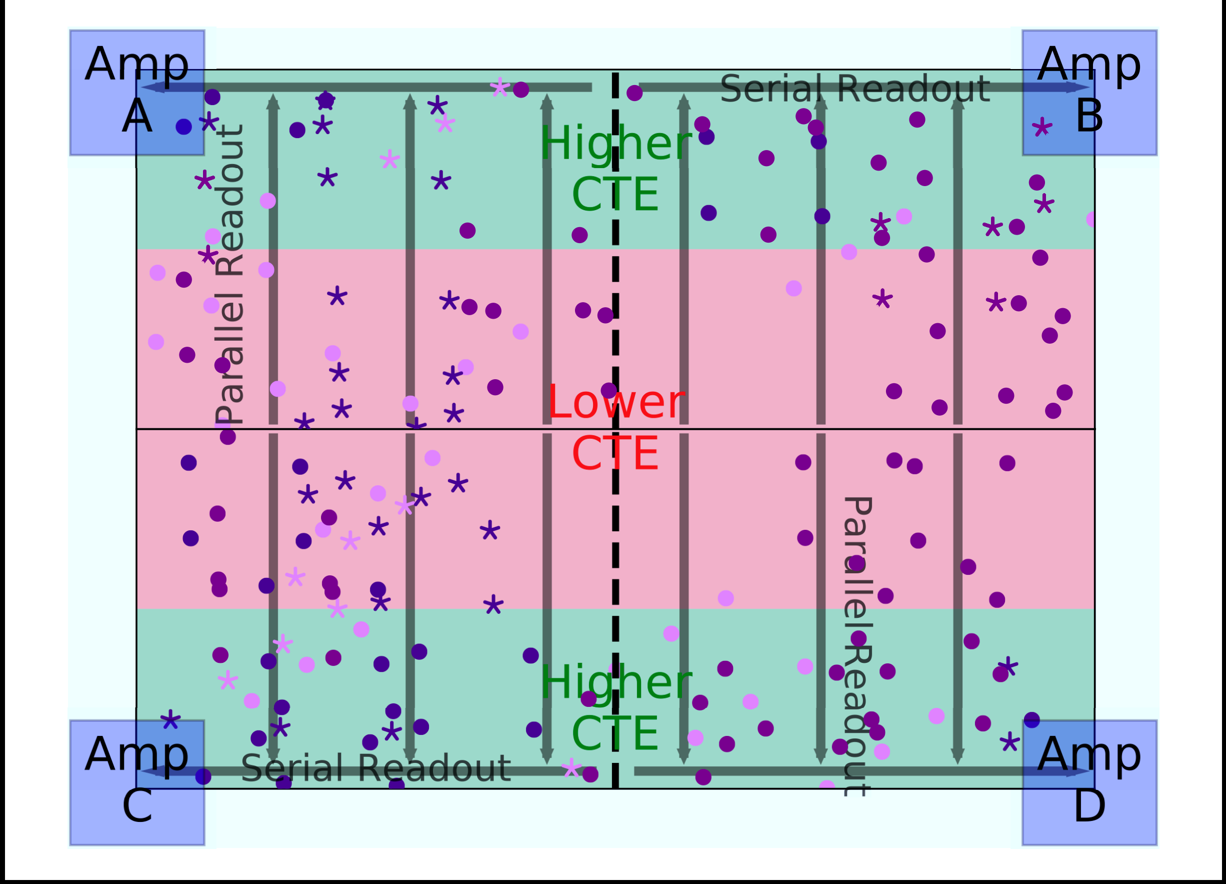
- $\lesssim$35% of faintest galaxies lost due to statistical object overlap.
- Factor of $\sim$2 in Diffuse Light not explained by missing faint galaxy pops.
- Faint gals are $\lesssim$10% of IGL $\Rightarrow$ need factor $\gtrsim$10 in missing objects!

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

(3) Habitable World Observatory requirements for LyC work



- Next generation $\gtrsim$6-meter UV-optical space telescope (HWO) essential for AB$\lesssim$30 detections and AB$\sim$32 mag for LyC stacks (N$\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 can in part be mitigated by s/w corrections (Anderson 2016, 2021).

- CTE loss linear with time/CR-flux, requires L2 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 ⇒ Good ⇒ Neutral ⇒ Fair ⇒ Poor.

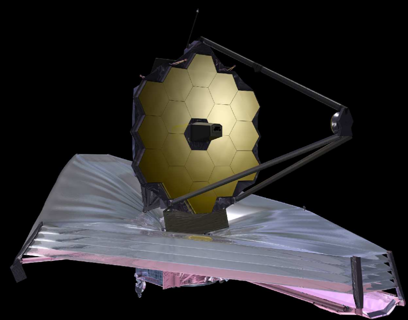
- (A) Scientific/Astro-Community Lessons
- (B) Technical Lessons
- (C) Management/Budget/Schedule Lessons
- (D) Political/Outreach Lessons

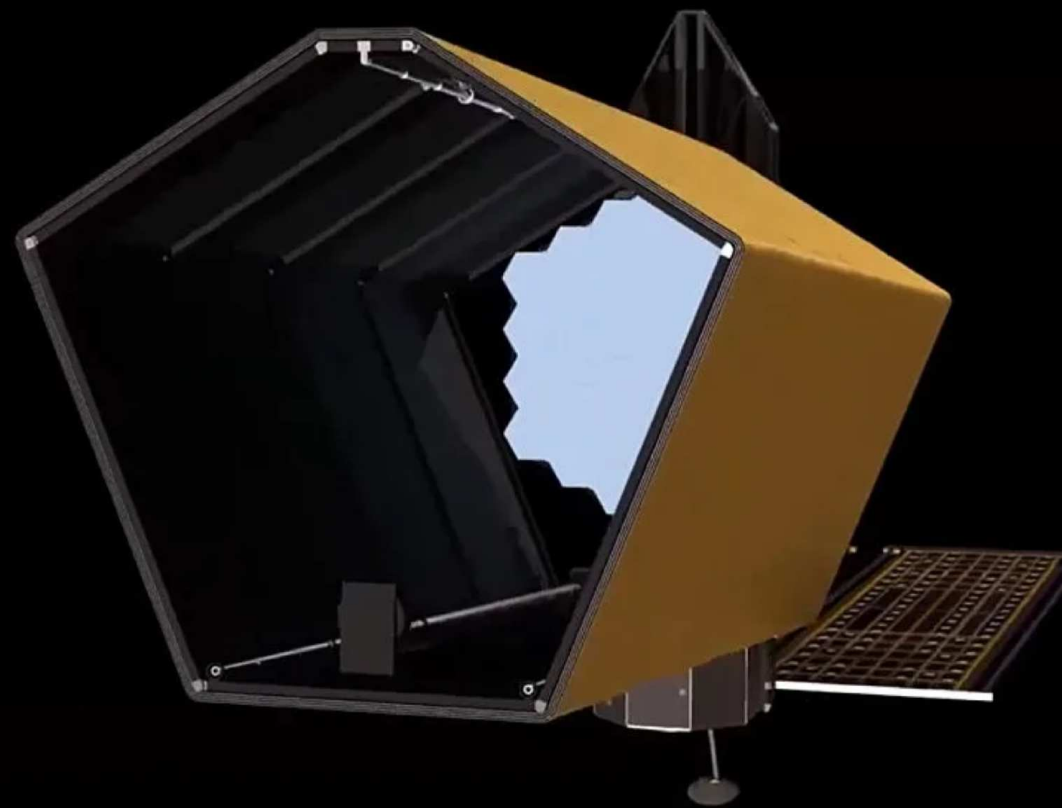
I thank Dr. Seth Cohen, Garth Illingworth, Rolf Jansen, John Mather, Eric Smith and Harley Thronson for useful comments.

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

	Hubble	James Webb	Roman	HWO
	1965–2033^{+}(!)	1996–2046^{+}	2012–2037?	2025–2070^{+}?
Launch:	1990	2021	≳2027	≳2040?
Σ_FC:	≳20 B$	≳10 B$	∼3 B$	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.

• JWST *is* the telescope that the community asked for 17 years ago, and it is coming into being as we speak. The community should get ready to submit JWST proposals in less than 3.5 years from today!

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

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

$\Longrightarrow$ 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 $z \simeq 2.3$–3.5

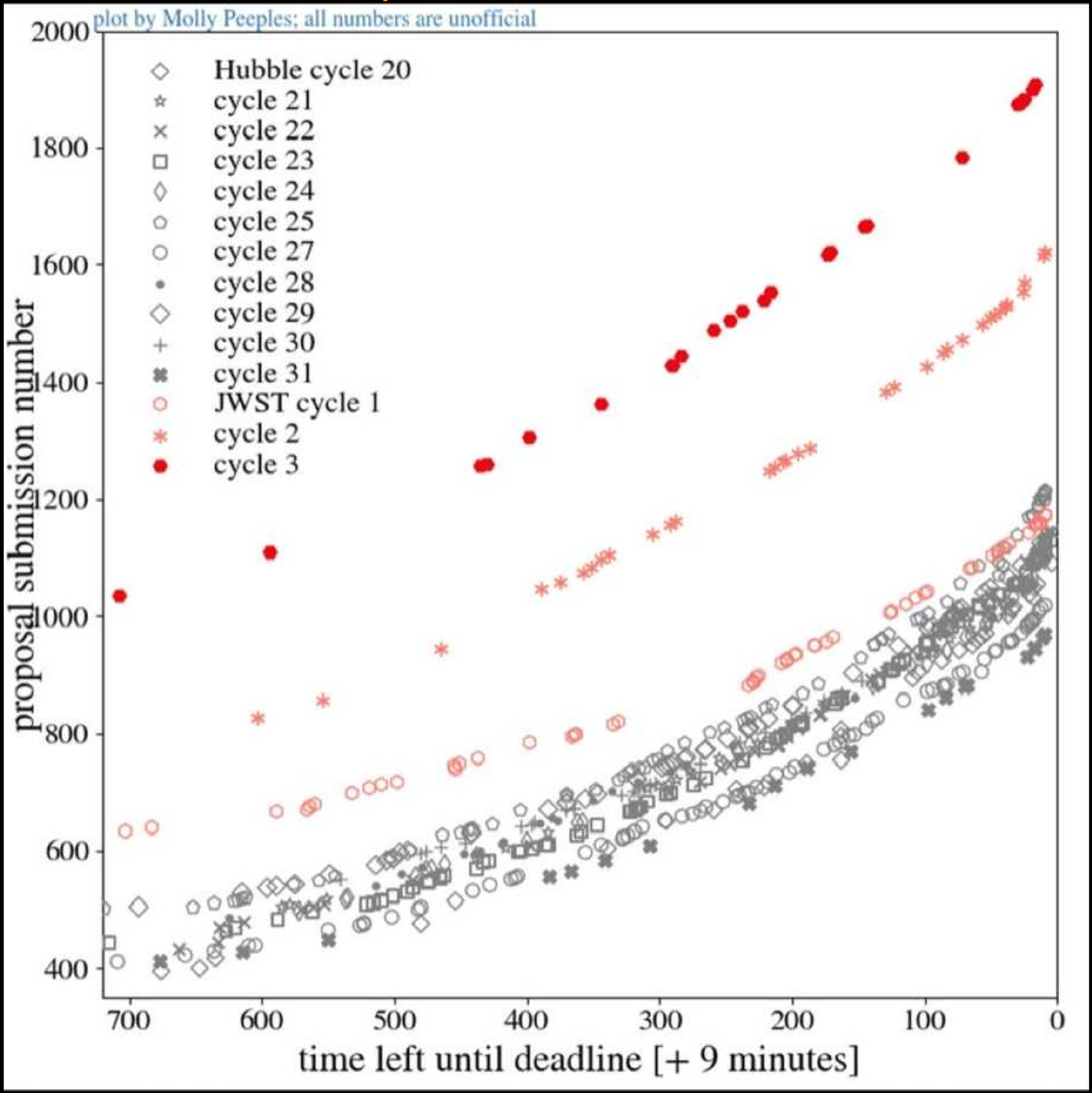
- Design HWO filters with low-enough redleak to enable this.
- Deepest multi-band images to mask foreground $AB \lesssim 30$ interlopers.

(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.
- $\sim 480\times10^9$ 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).

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, Nat. Astron., in press (astro-ph/2404.08045)
Juodzbalis, 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. 2024, 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)