The tale of two telescopes: Hubble and Webb: Why Hubble is worth saving after 35 years

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+ HST SKYSURF and JWST PEARLS & SKYSURFIR teams: T. Carleton, S. Cohen, R. Jansen, J. Berkheimer, D. Carter, I. McIntyre, D. Kramer, T. McCabe, R. O'Brien, R. Ortiz, T. Acharya, H. Archer, P. Bahtia, C. Cain, L. Conrad, K. Croker, Z. Goisman, N. Foo, B. Frye, R. Honor, H. Ingram, P. Kamieneski, A. Koekemoer, M. Miller, P. Porto, C. Redshaw, B. Smith, J. Summers, S. Tompkins, H. Yan,
+ 100 more scientists over 18 time-zones

SESE Faculty Meeting Chalk Talk, ASU, Tempe, Arizona

Thursday Jan. 30, 2025.

SKYSURF-ers and HST+Webb researchers in ASU group (not all shown):

Outline

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

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

- (2) Webb's first images: the "Cosmic Circle of Life"

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

- (4) Summary and Conclusions

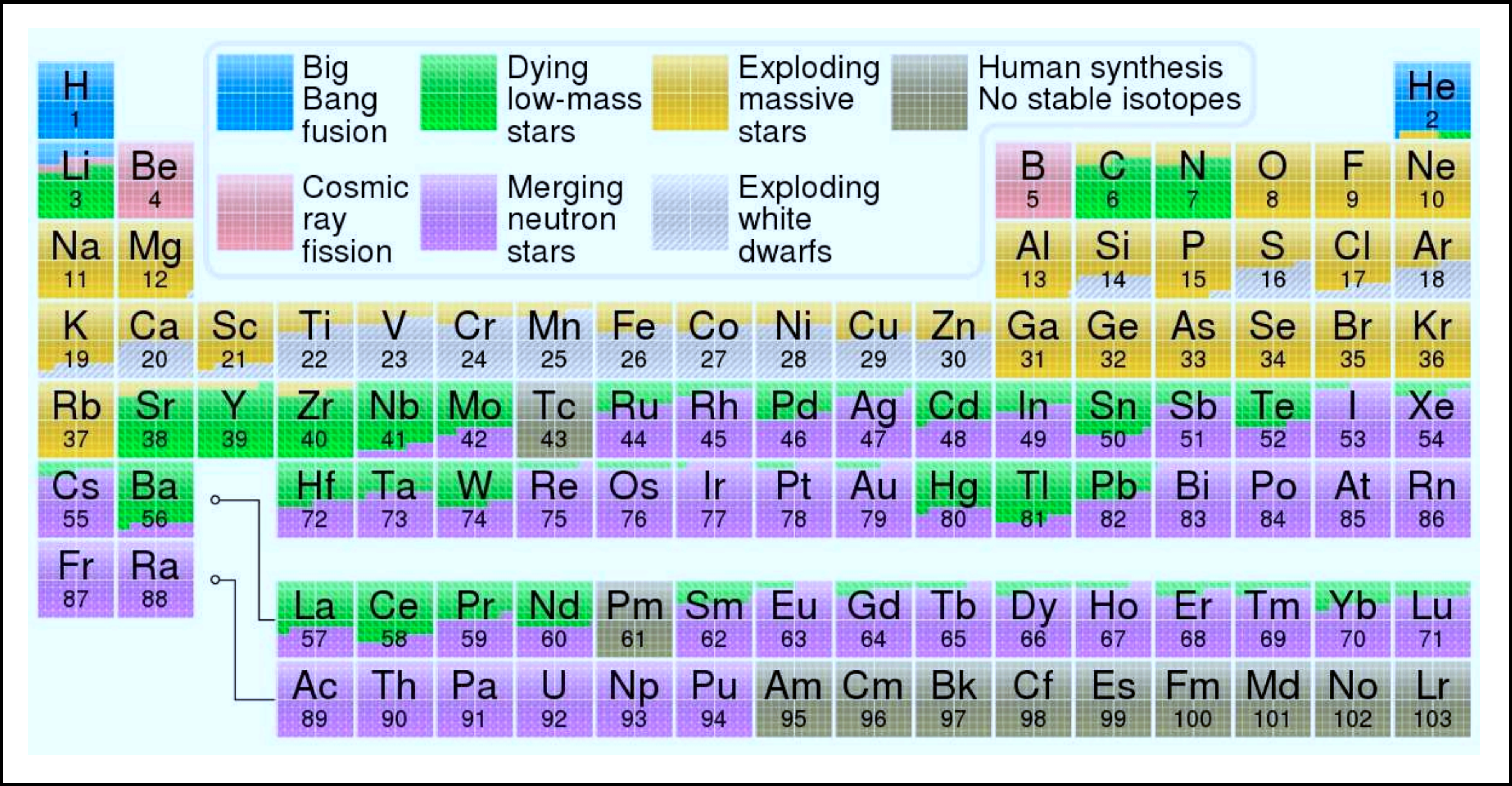
- (5) Spare charts

Sponsored by NASA/HST & JWST

Talk is on: http://www.asu.edu/clas/hst/www/sese_facmtg_jan25_hstjwst.pdf

Before we get to the cosmic circle of life, let's get this straight:

- This Periodic Table you learned in highschool is **NOT** the real one!:



(1) Hydrogen & Helium: the *only* chemical elements made in the Big Bang!

(2) All heavier elements made by (dying) stars: • Low mass stars ejecting their outer shells; • Supernova explosions; & • neutron star mergers.

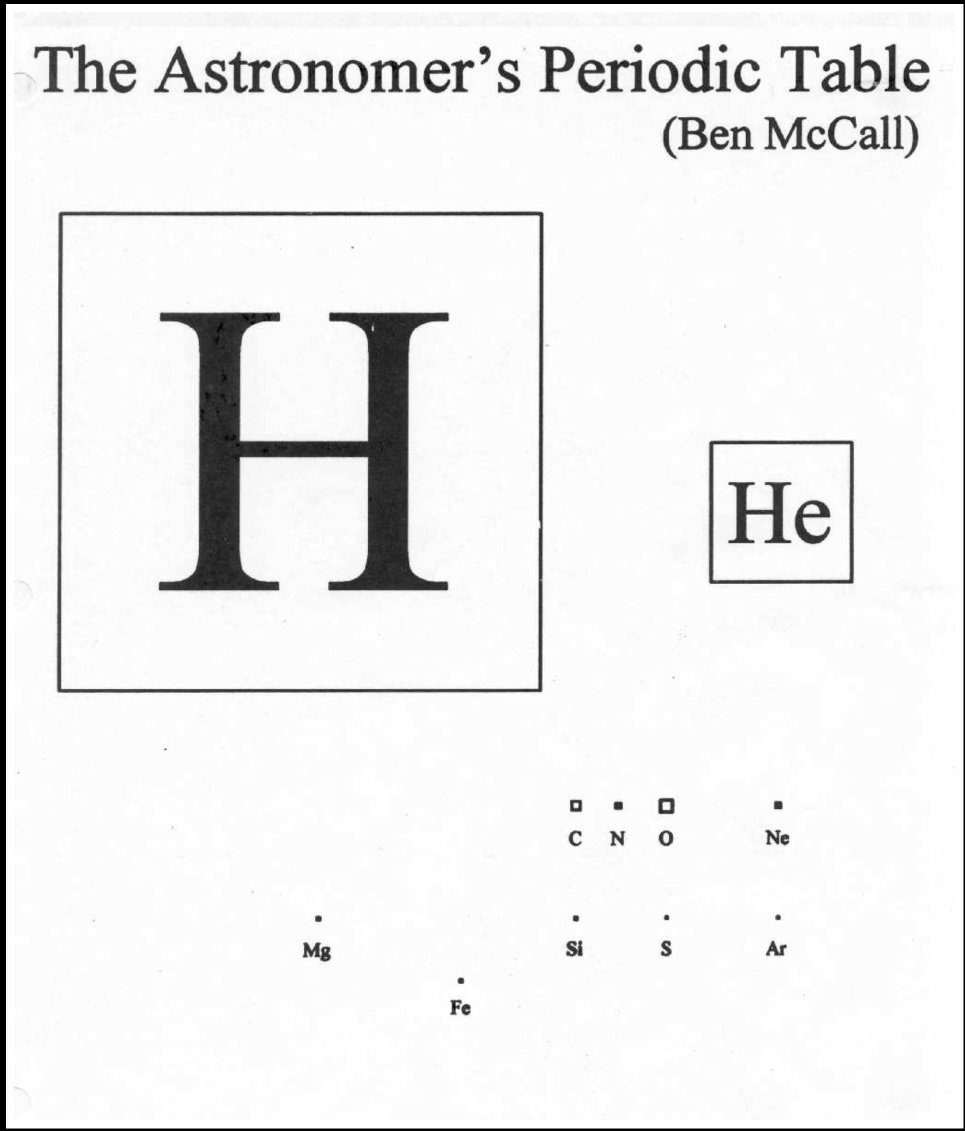
Here is the correct Astronomical Periodic Table:

(1) Hydrogen (76%) & Helium (24%) are the only chemical elements made in the Big Bang.

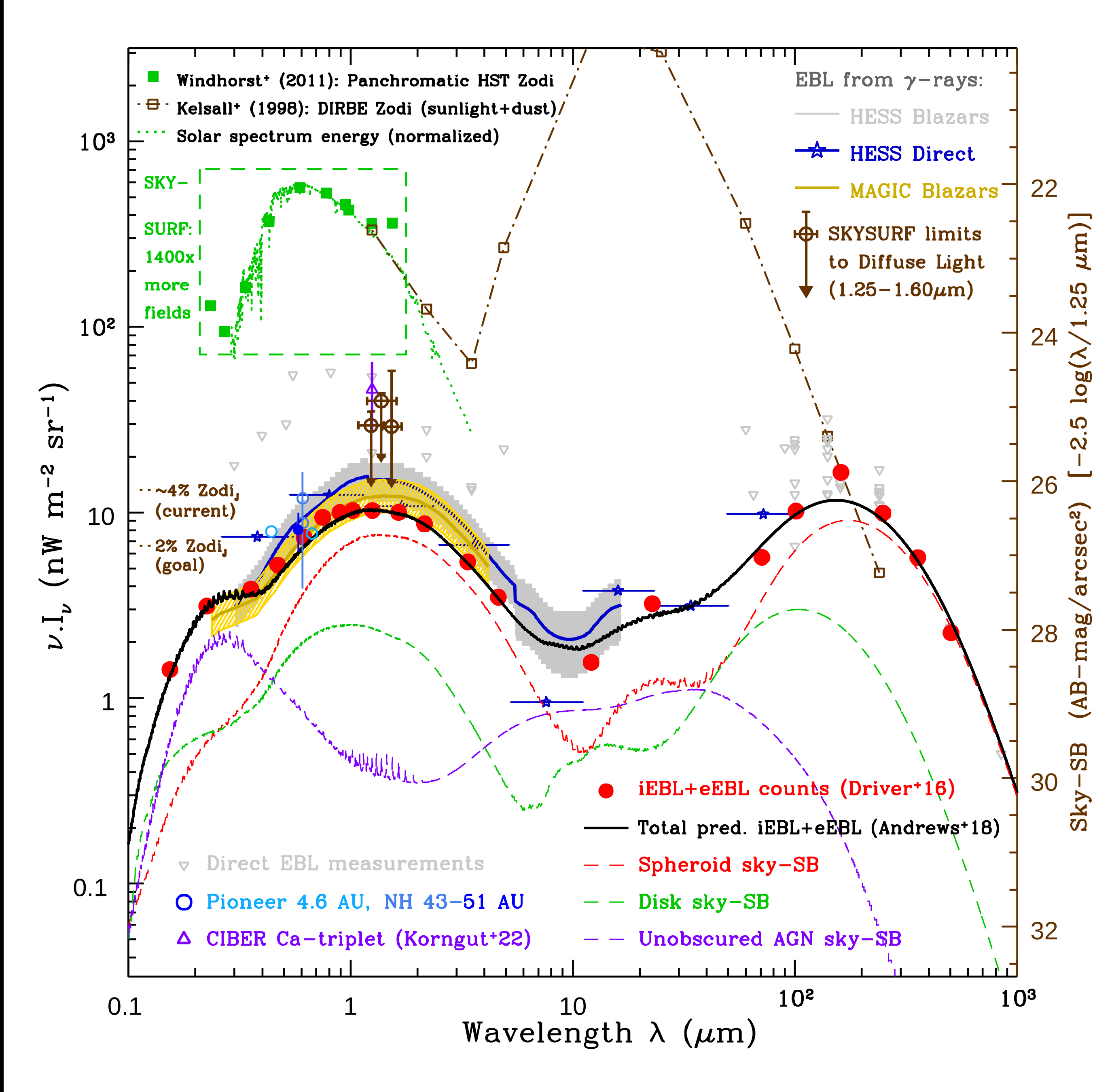
(2) Heavier chemical elements ($\lesssim$1%; "dust") made by (dying) stars:

- Late stages of stellar evolution, Supernova explosions & white dwarfs, and neutron star mergers distribute these throughout the universe.

$\Longrightarrow$ Planets and people are literally made from stardust!



- This is the real Periodic Table with cosmic abundance included.
- This has significant consequences for Hubble and Webb complementarity!



Fly's-eye energy vs. λ:

(Driver+ 2016; Windhorst+ 2018, 2022):

Sunlight scattered off the Zodiacal dust.

Thermal radiation from $\gtrsim$240 K Zodiacal dust.

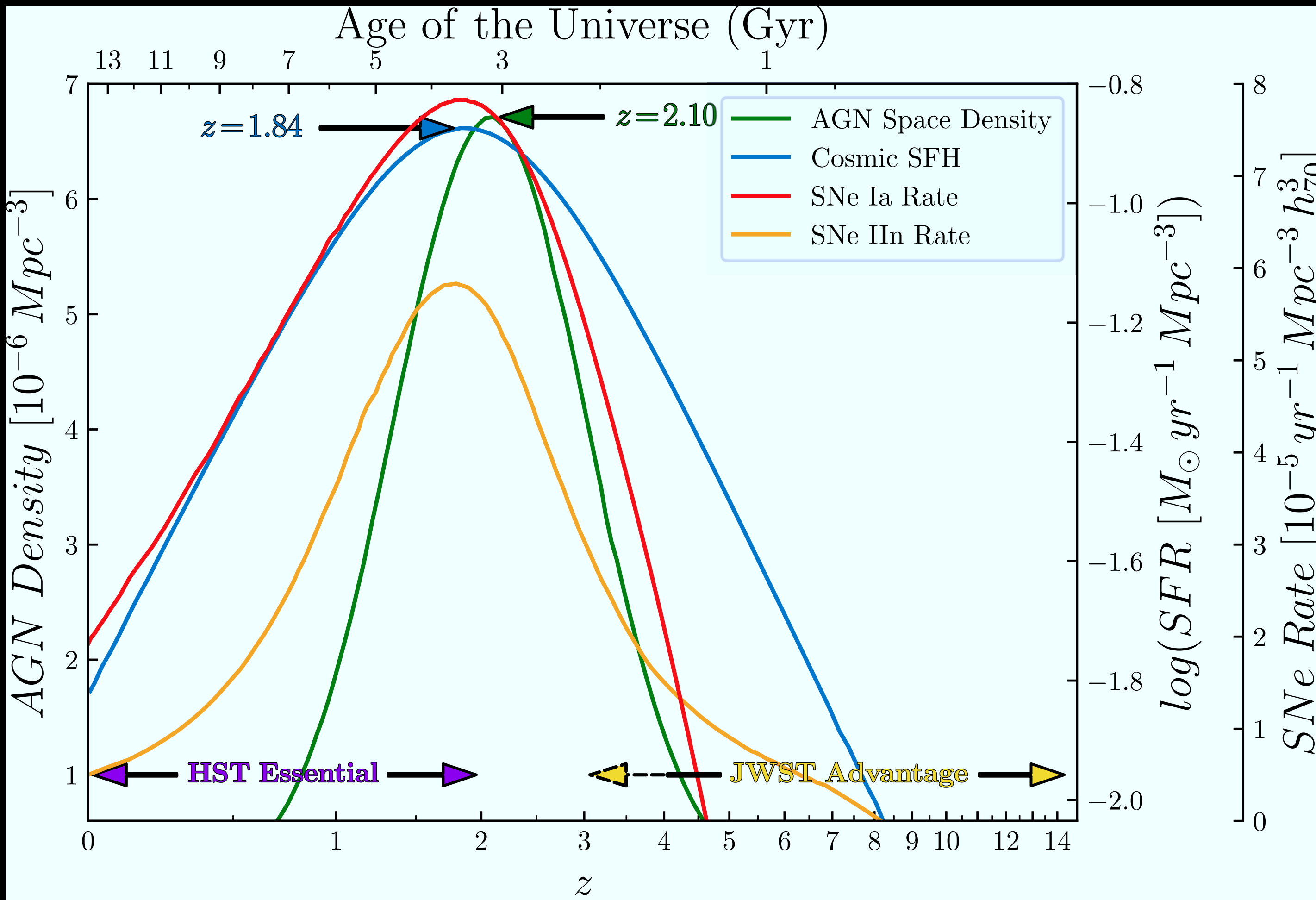
● integrated light from galaxy counts (+models).

New Horizon diffuse light (Lauer+ 2021, 2022; 43-51 AU).

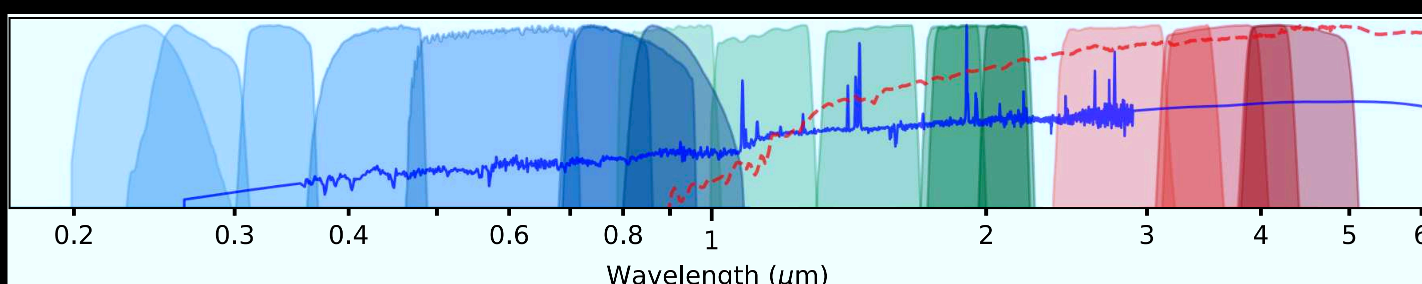
SKYSURF 1.25–1.6 μm diffuse light (Carleton+ 2022; O'Brien+ 2023; McIntyre+ 2024).

● Energy(cosmic SF+AGN) $\simeq$ 48%; Energy(dust) $\simeq$ 52% $\Rightarrow$ Dust wins !!

(Windhorst+ astro-ph/ 2410.01187)

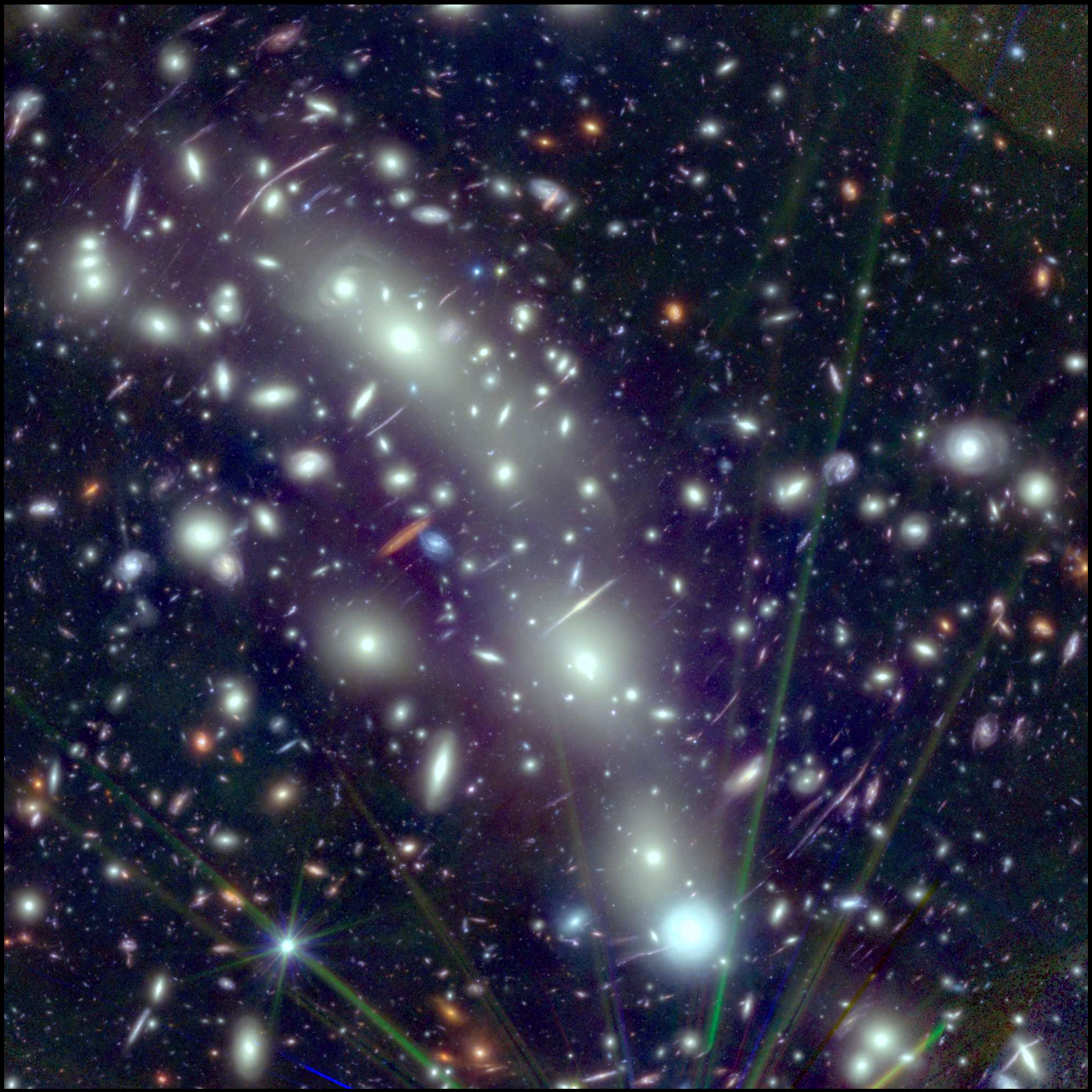


Star Formation, Supernova Rate, & Black Hole growth peak ∼10 Gyr ago!



⇒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).

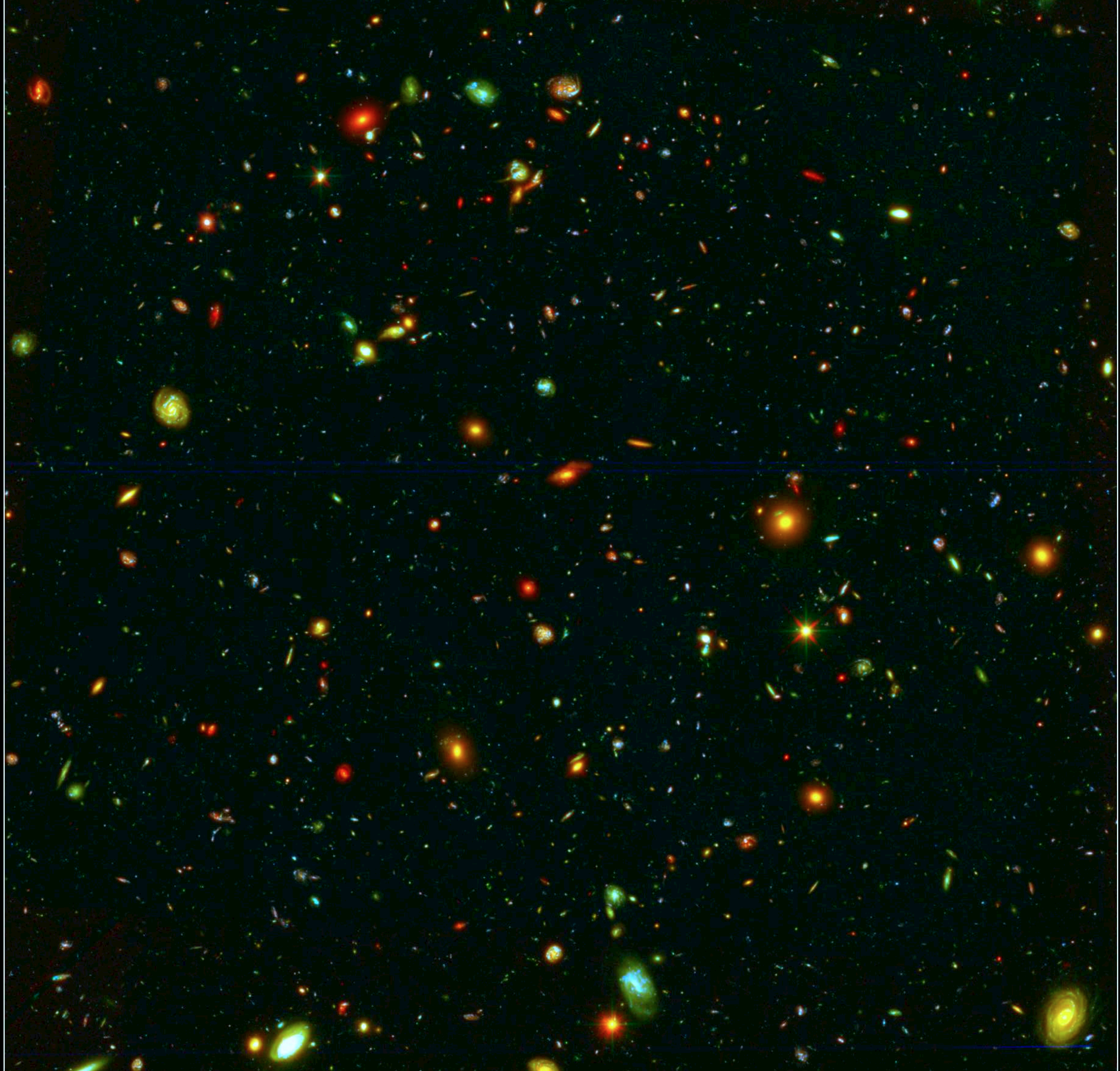
(1) Uniquely complementary roles of Hubble and Webb:



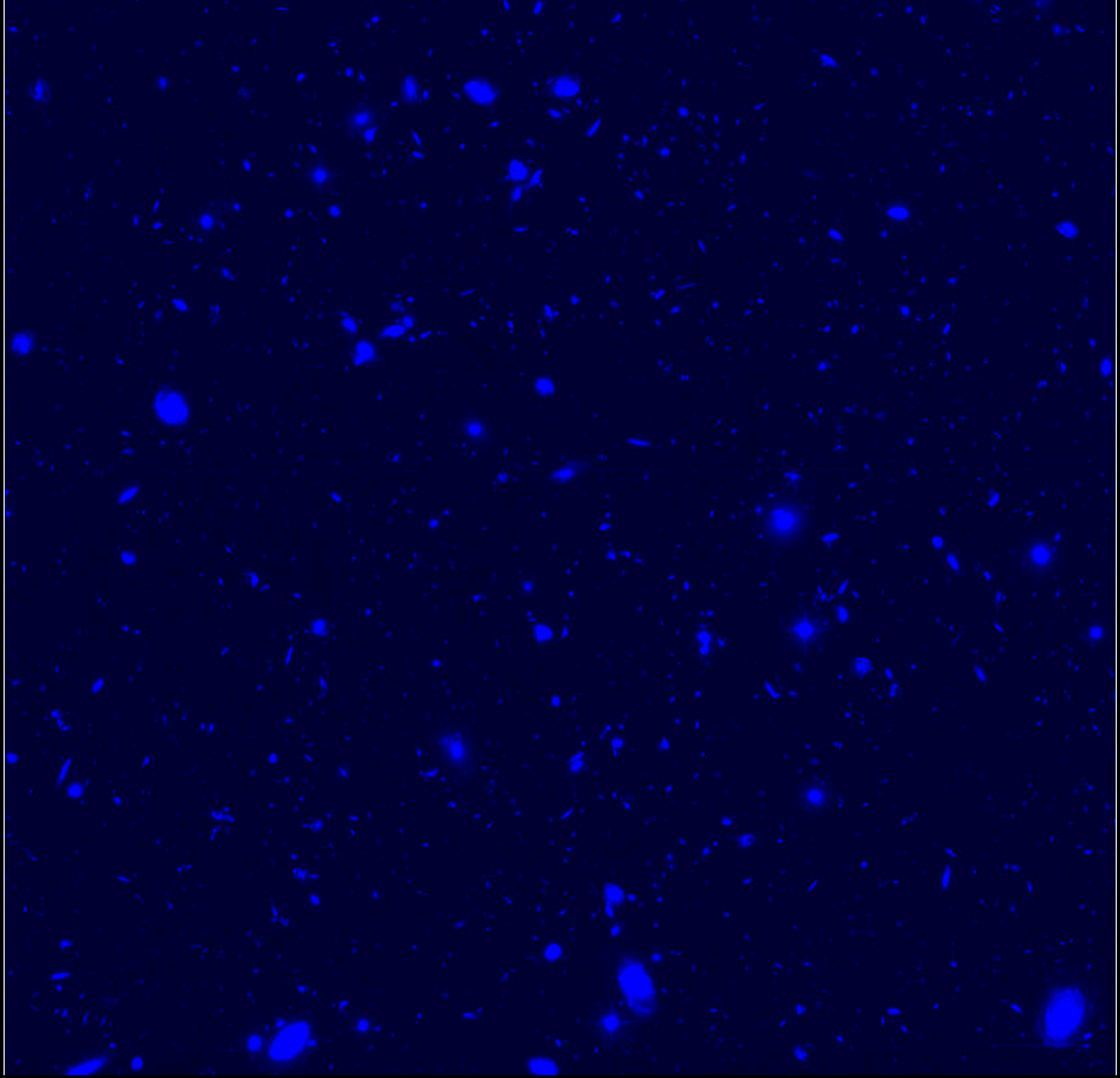
500 hrs HST+JWST: 45 filters (0.2–5.0μm), lensing cluster MACS0416:

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

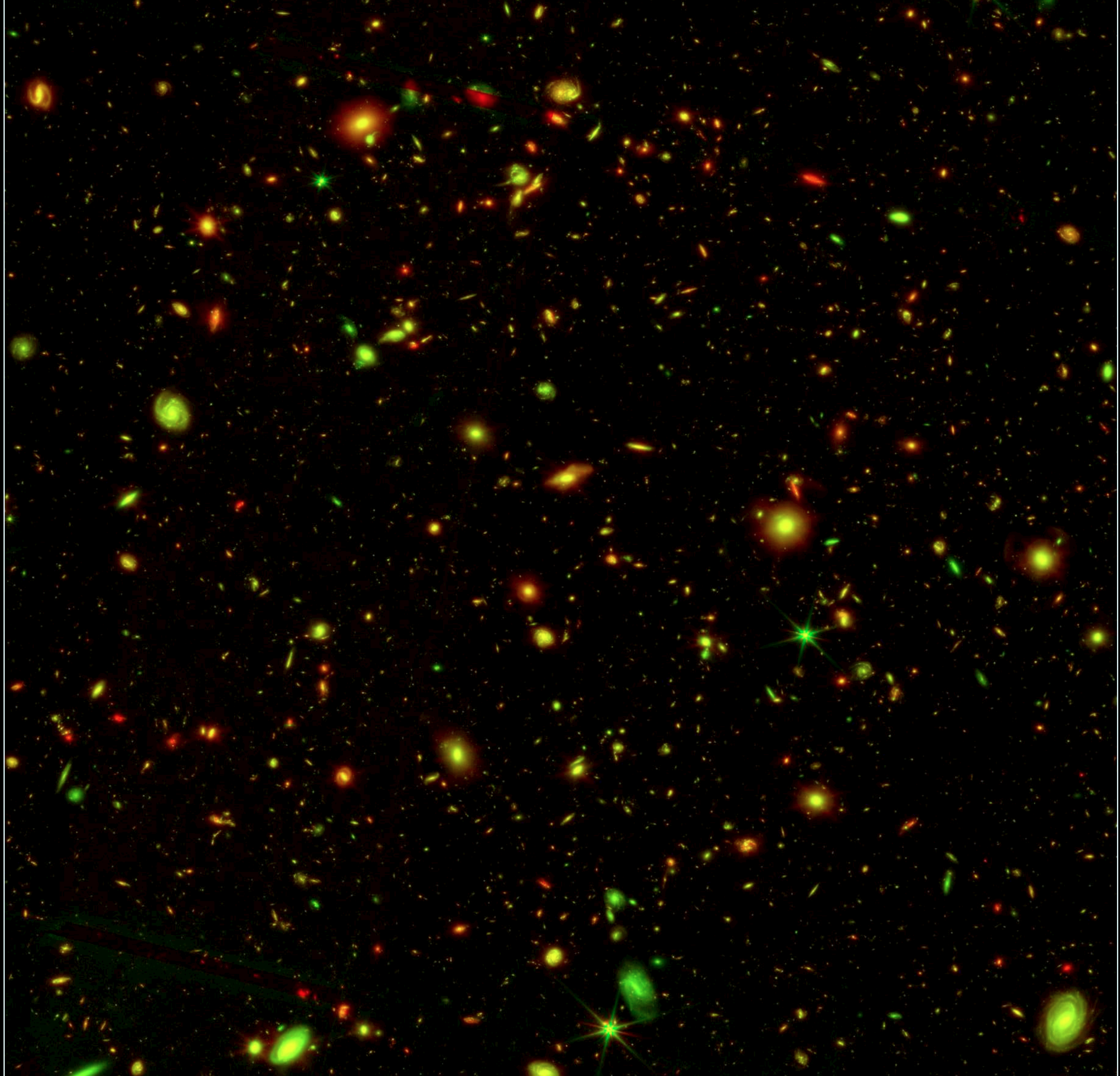
$\Longrightarrow$ HST & JWST reach 30–31 mag ($\sim$1 firefly from Moon).



556 hr HST Hubble UltraDeep Field: 12 filters at 0.2–1.6 μm (AB$\lesssim$31 mag; $F_\nu \gtrsim$2 nJy; full BGR).

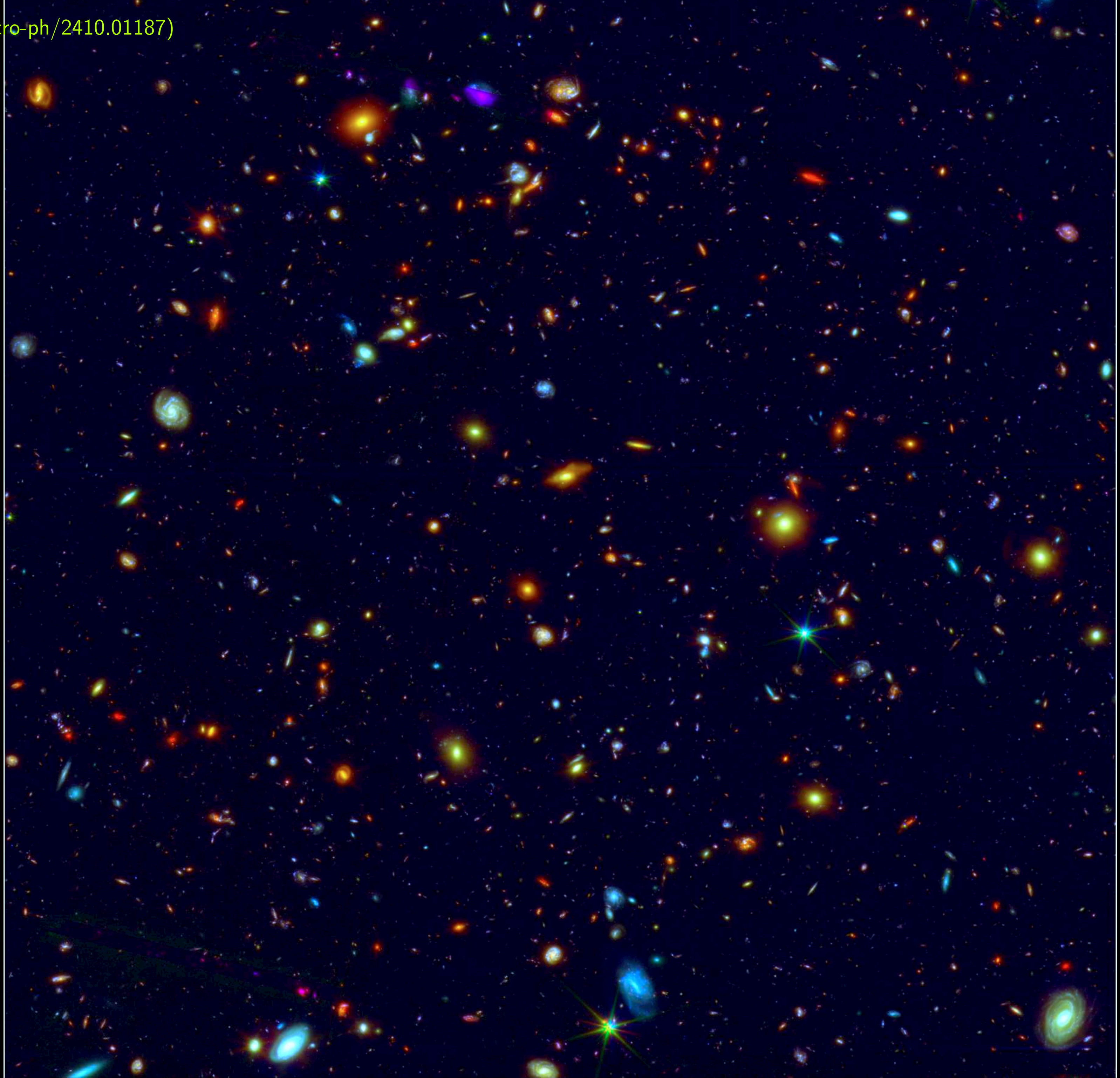


361 hr HST Hubble UltraDeep Field: 8 HST-unique filters 0.2–0.9 μm (in false color blue).



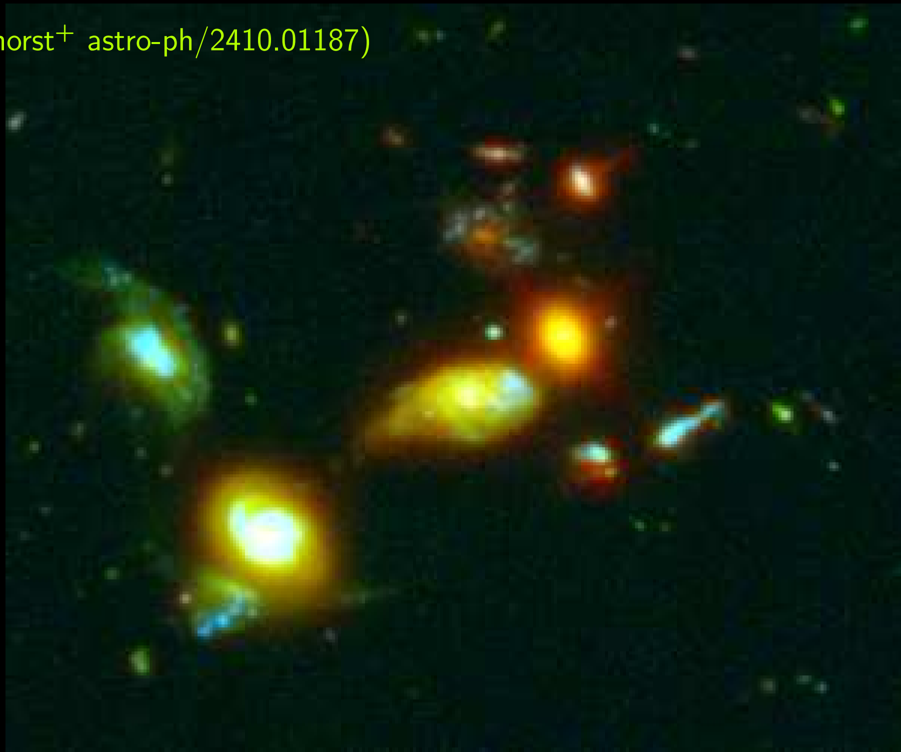
53 hr JWST/NIRCam Hubble UltraDeep Field: 12 filters at 0.9–5.0 μm (AB$\lesssim$31 mag; in green + red).

(Windhorst+ astro-ph/2410.01187)

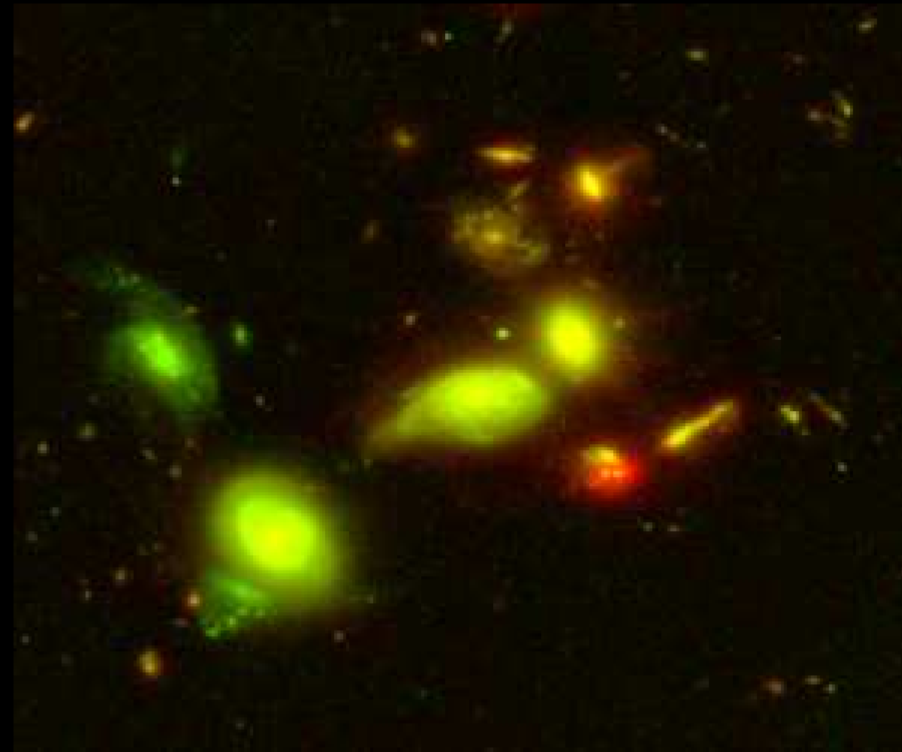


414 hr HST+JWST Hubble UltraDeep Field: 20 filters at 0.2–5.0 μm (AB$\lesssim$31.5 mag; full BGR).

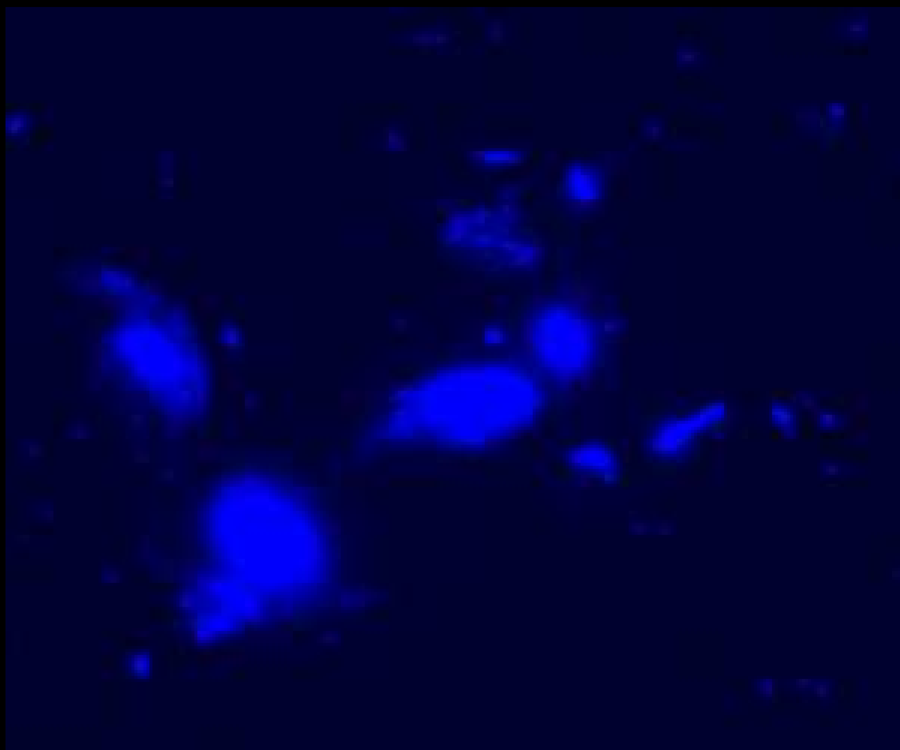
(Windhorst+ astro-ph/2410.01187)



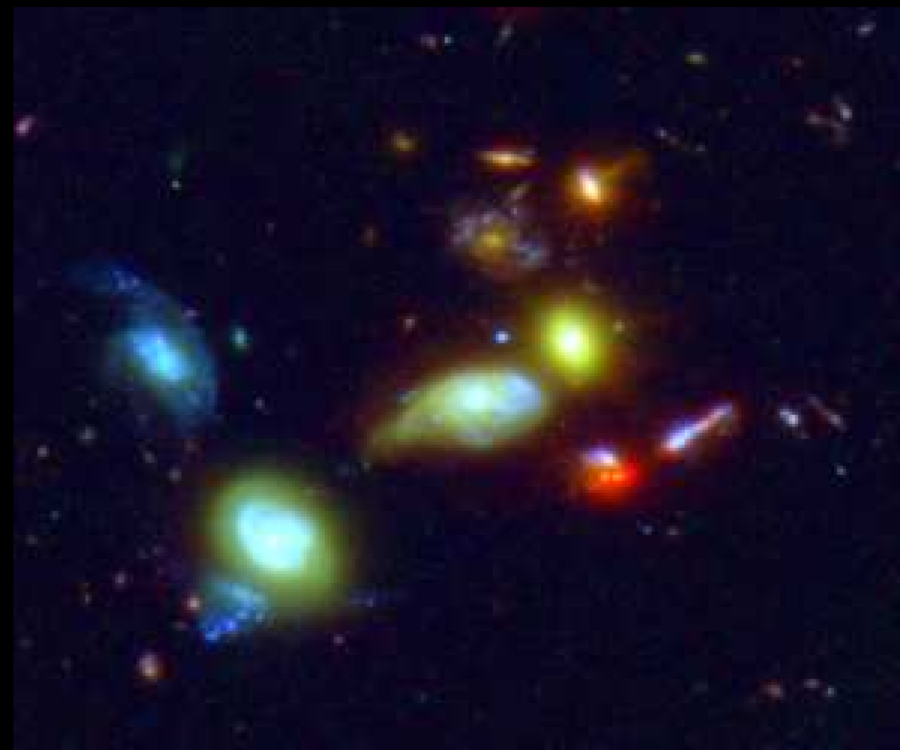
556 hr HST HUDF 12 filters



53 hr JWST/NIRCam 12 filters

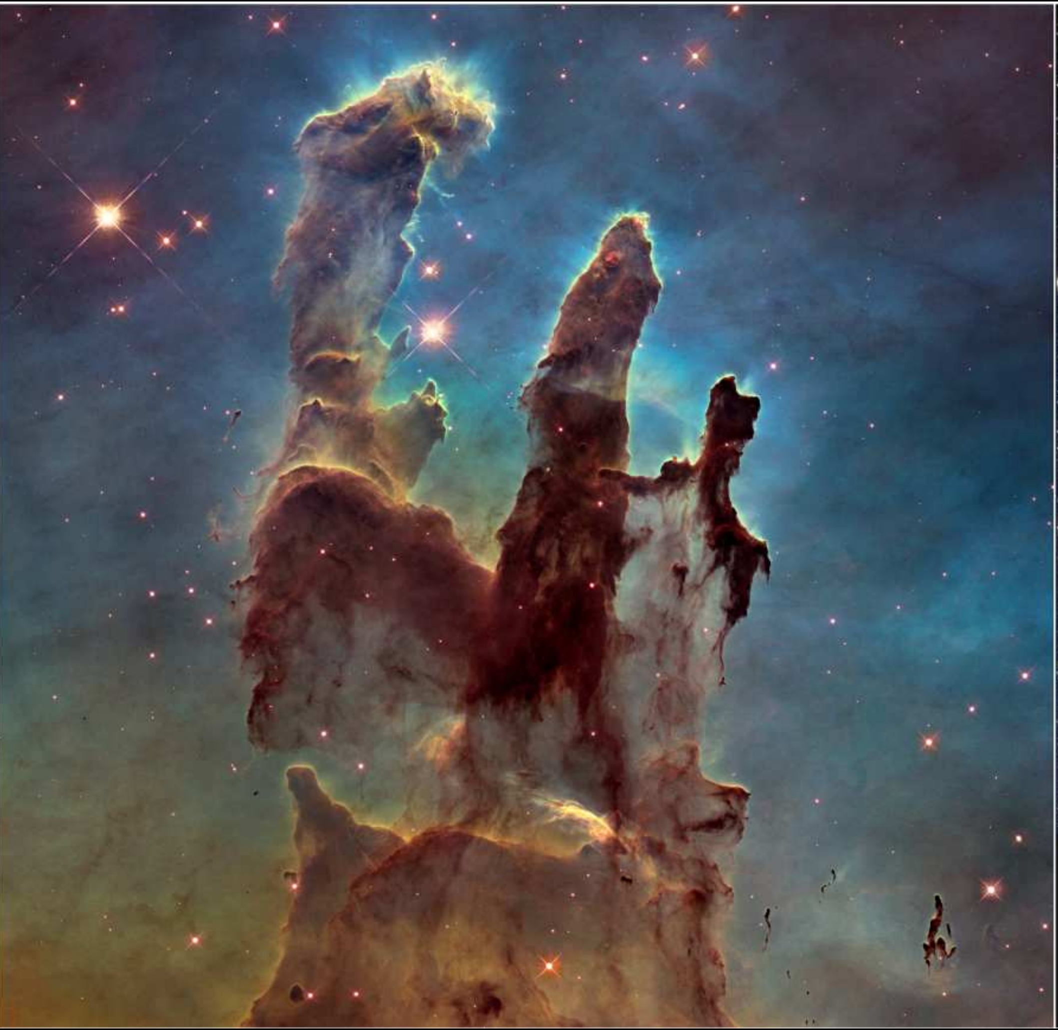


361 hr 8 HST-unique filters (false-blue)



414 hr HST+JWST 20 filters

• (2) Webb's first images: the "Cosmic Circle of Life"

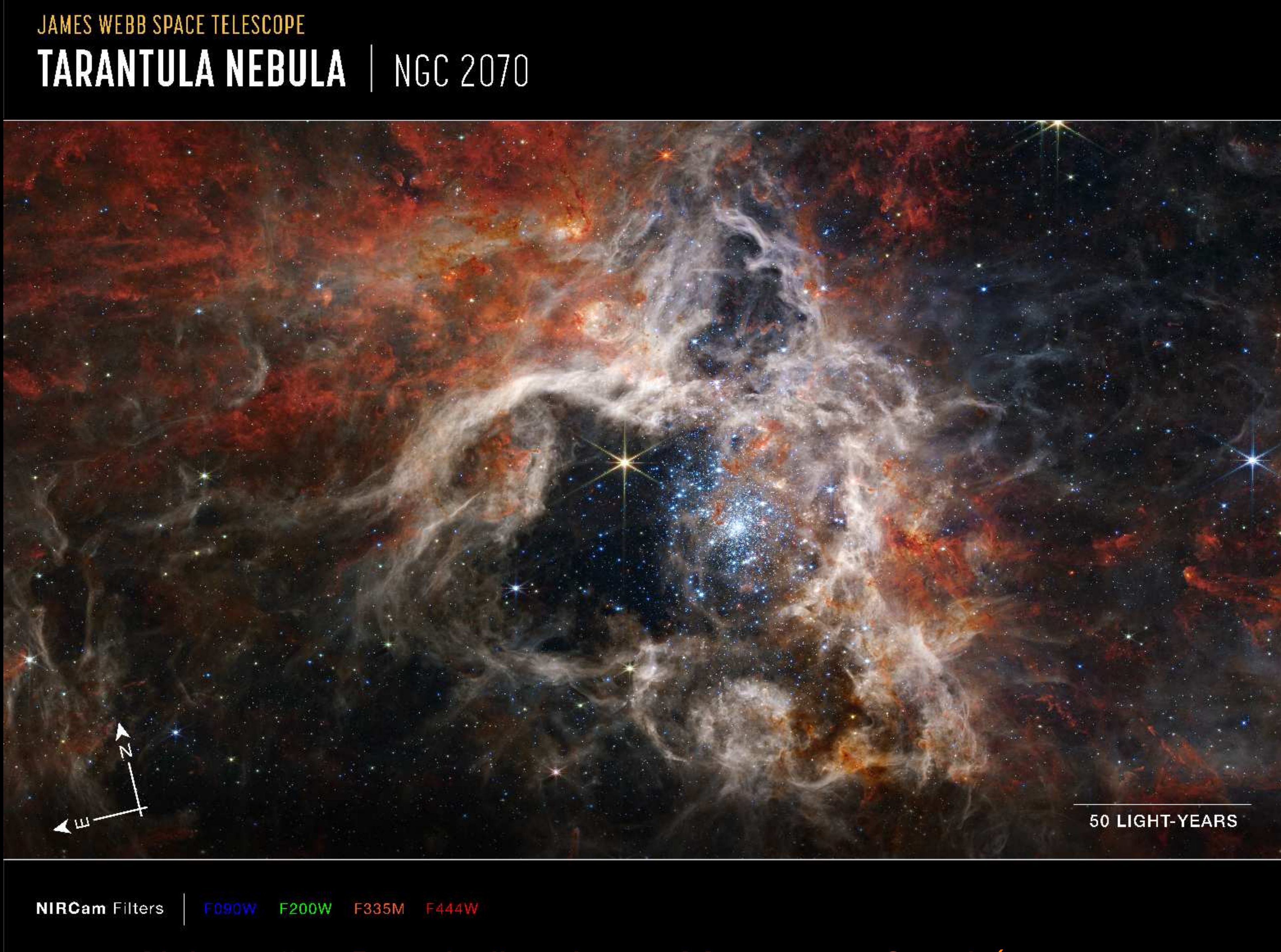


Hubble WFPC2 Eagle Nebula (1995) compared to JWST NIRCam (2022):

- The cradle of cosmic star-formation: NIRCam peers through the dust!

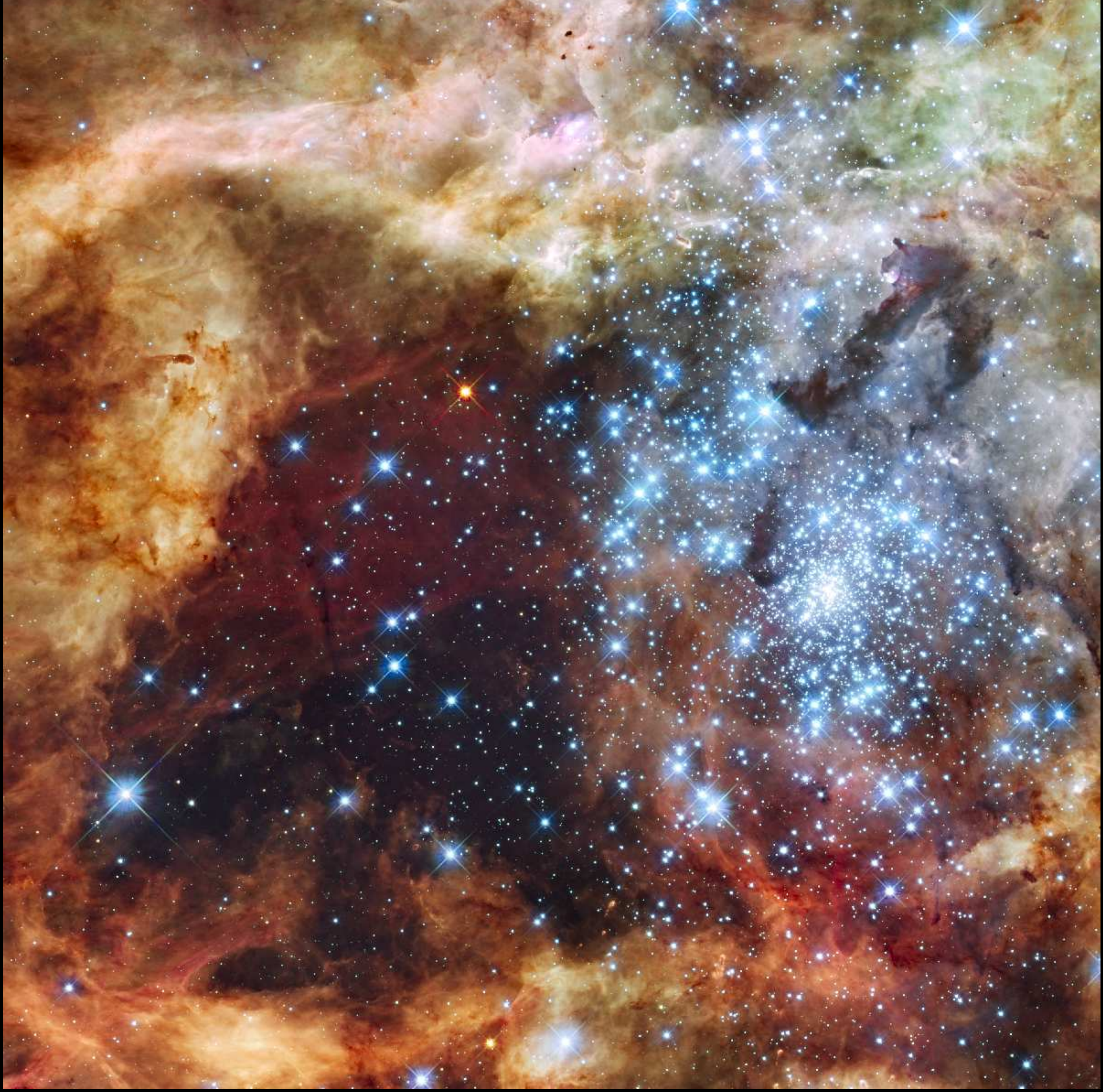
- The 1995 Hubble WFPC2 image (left) was made by Prof. Jeff Hester and Paul Scowen at ASU. It made it onto a US postage stamp!

Webb's MIRI shows the hauntingly beautiful cosmic dust pillars (8–15 μm)

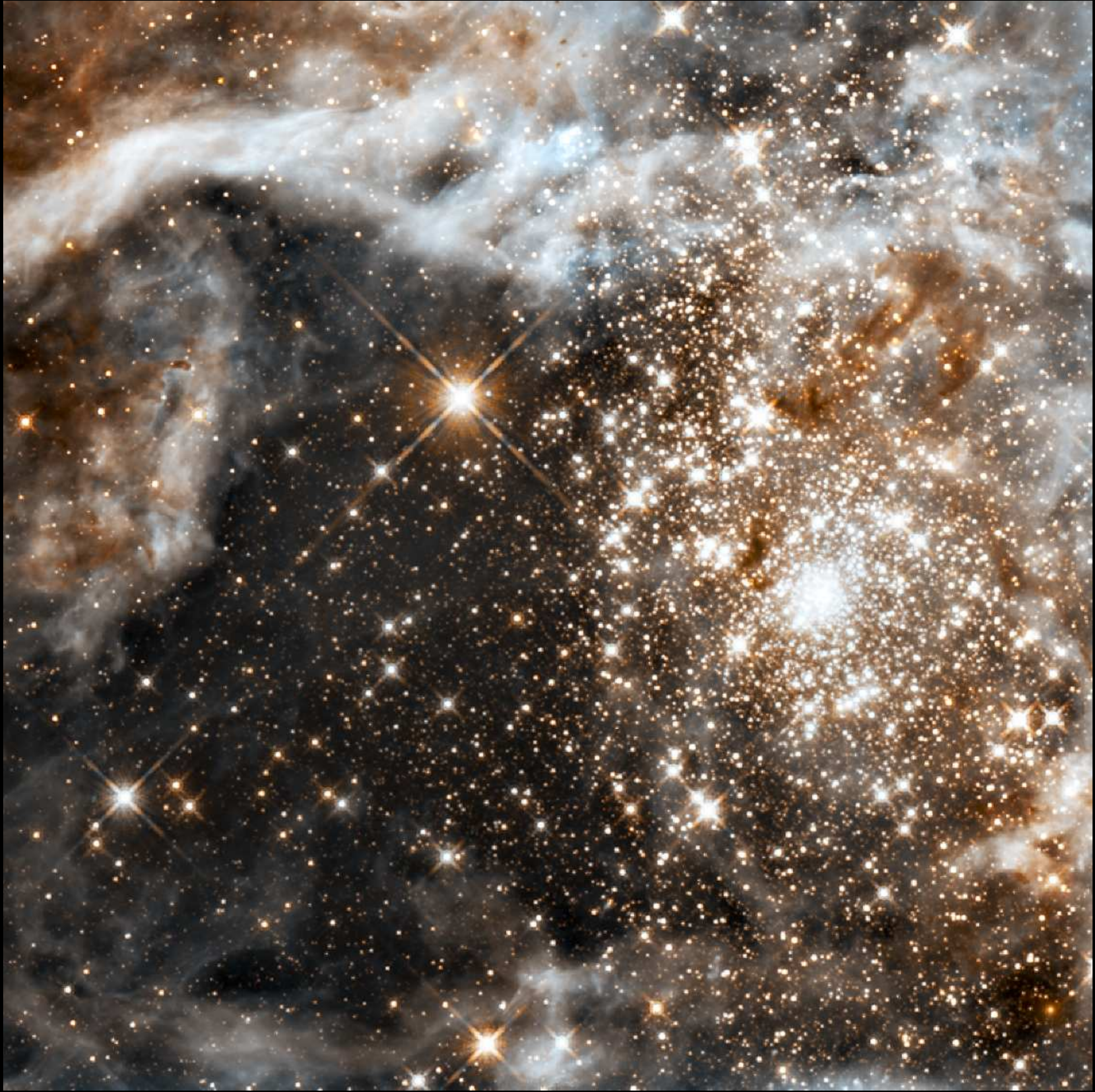


Tarantula Nebula "30 Doradus" in Large Magellanic Cloud (163,000 lyrs away)

Cradle of cosmic star-formation: massive stars trigger formation of sunlike stars



HST Wide Field Camera 3 UV–optical image of 30 Dor: hot massive stars.



HST WFC3 near-IR image of 30-Dor: massive and low-mass stars.

“Cosmic Cliffs” of star-formation in the Carina Nebula (NIR; 7600 light-years).

JWST tracing the “Cosmic Circle of Life” ...

Cosmic Cliffs of Star-formation in Carina Nebula (NIR+MIR):

Compared to optical/near-IR, mid-IR sees "Cradle of Cosmic Star-formation":

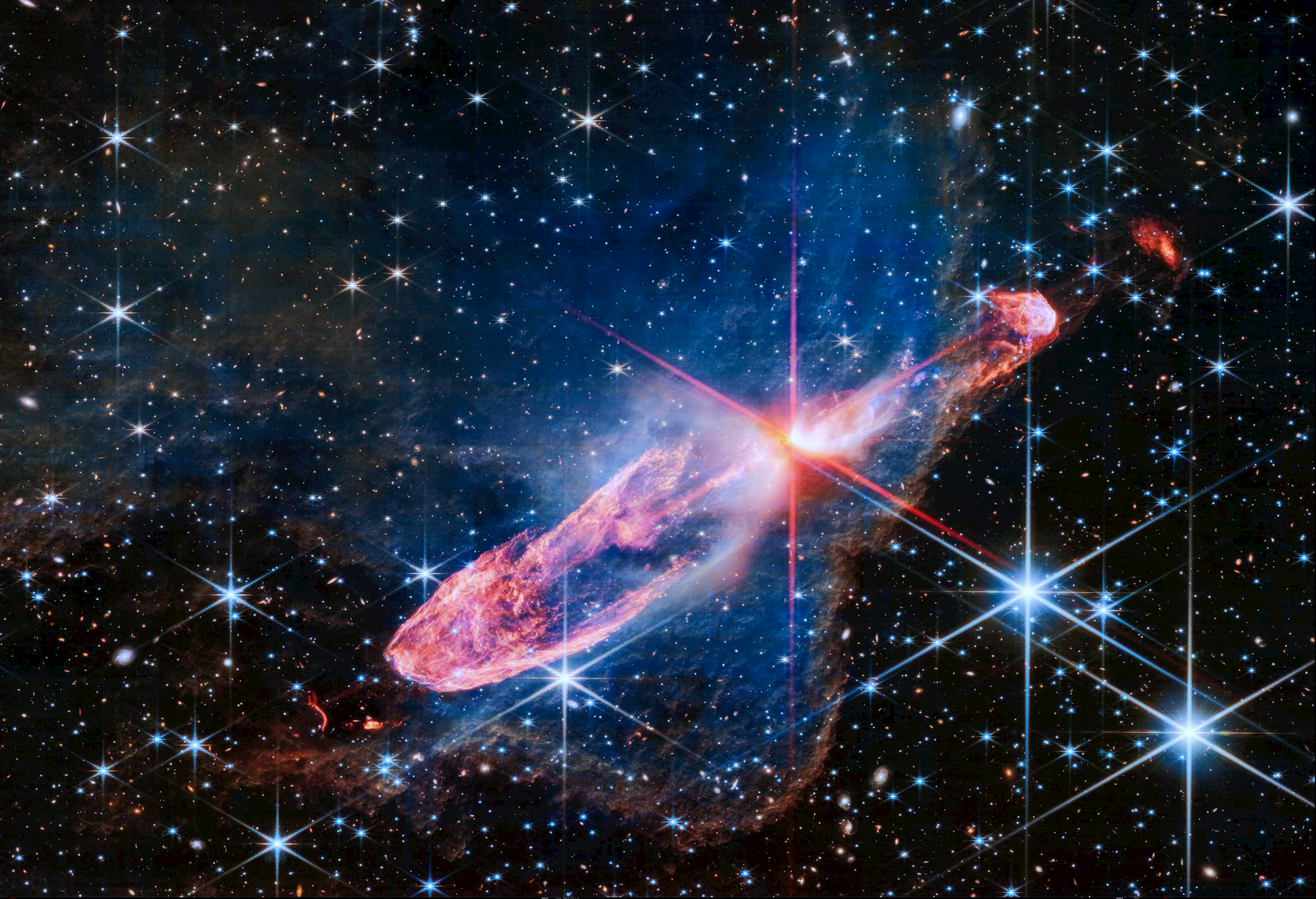
Deep inside the gas and dust, mid-IR reveals birth of young Sun-like stars.

Stellar birth: Protoplanetary "Hourglass Nebula" L1527 at 460 lyrs.

- A forming protostar with ∼30% of Sun's mass only 100,000 year old!
- Surrounding accreting gas, circumstellar disk, and outflow.
- Eventually, L1527 will start shining as a star, and have its own planets.

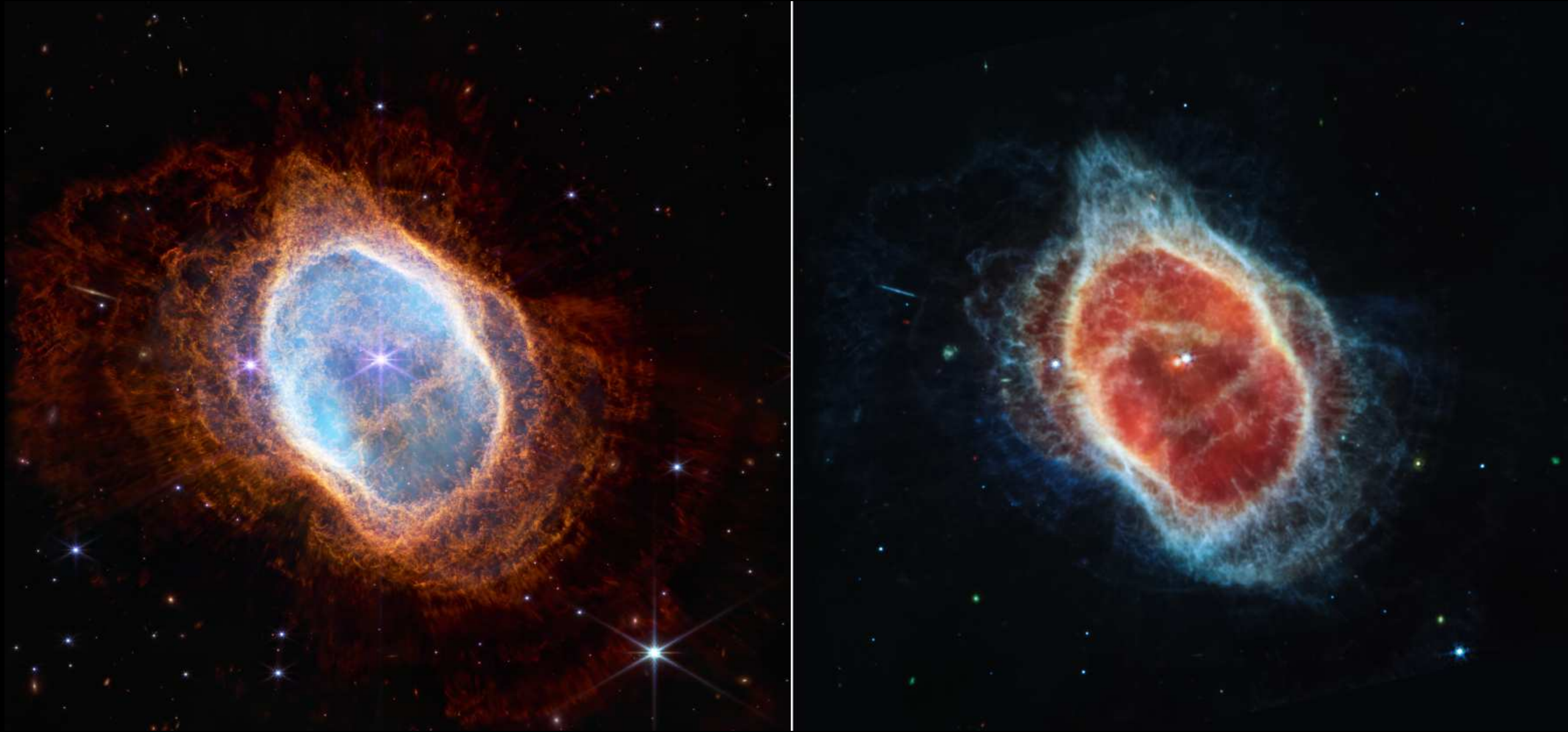
NIRCam+MIRI: ρ Ophiuchi dark cloud (closest stellar nursery at 456 lyrs):

- Cradle of star-formation contains Polycyclic Aromatic Hydrocarbons!



Newly forming stars Herbig-Haro 46/47 with jet-expelled material (1470 lyrs):

- Formation of Sun-like stars is messy: inflow and outflow of gas & dust!



Southern Ring Nebula (Near-IR+Mid-IR; 2500 light-years):

- You $*are*$ witnessing the “Cosmic Circle of Life” here ...
- This is a Sun-like star expelling its outer layers in retirement ...
- It has exhausted its hydrogen and helium as nuclear fuel ...

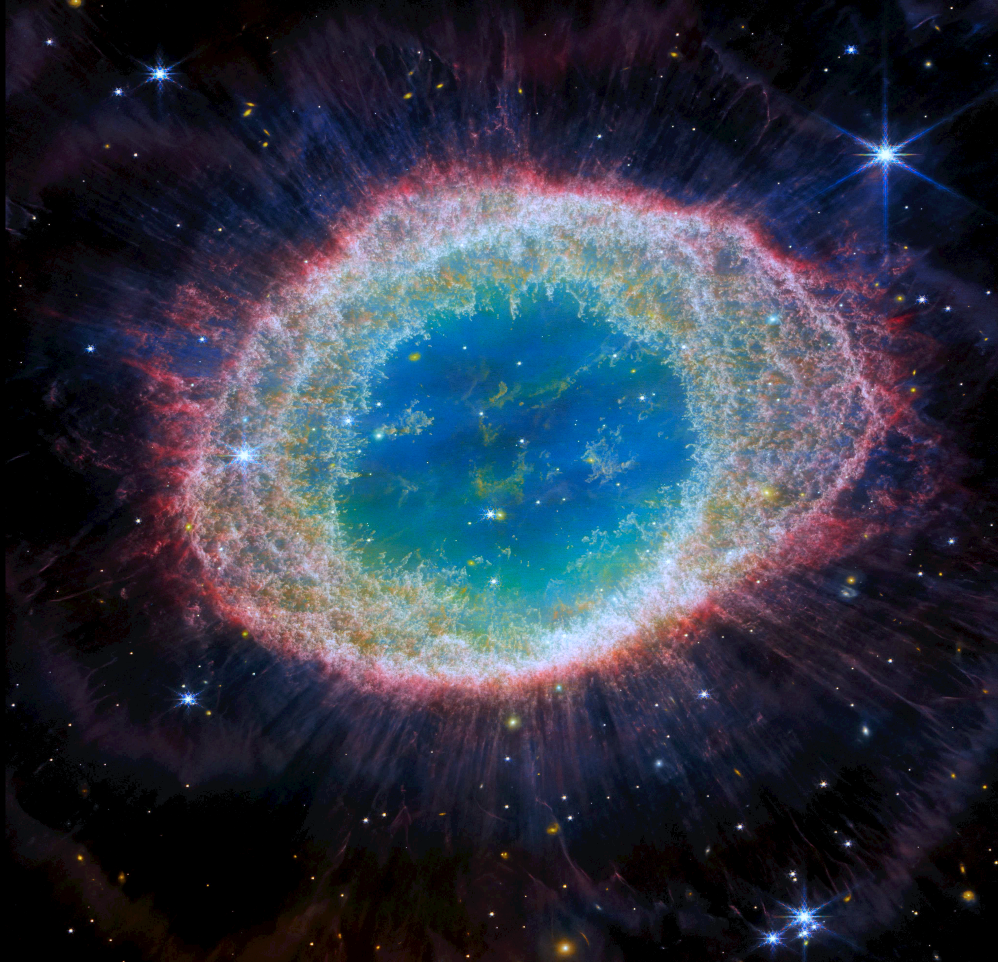
and expanded to $>>100\times$ its current size, engulfing the Earth.

This is how our Sun *will* come to an end in 5 Billion years (near-IR).

"... dust thou art, and unto dust shalt thou return".

From gas expelled by previous sun-like stars, new stars are born (mid-IR).

And thanks to the dust they expelled, new stars will form with planets ...

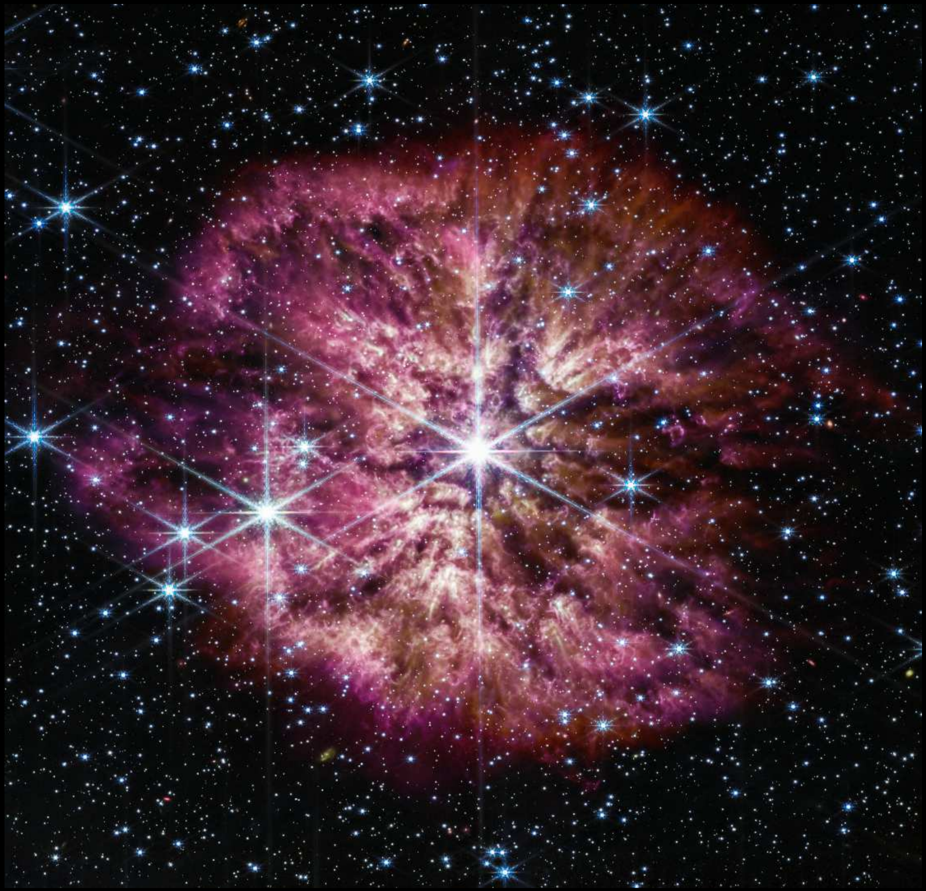
 

Webb images of THE Northern Ring Nebula in Lyra:

[Left] NIRCam & [Right] MIRI: mass loss in Asymptotic Giant Branch stage.

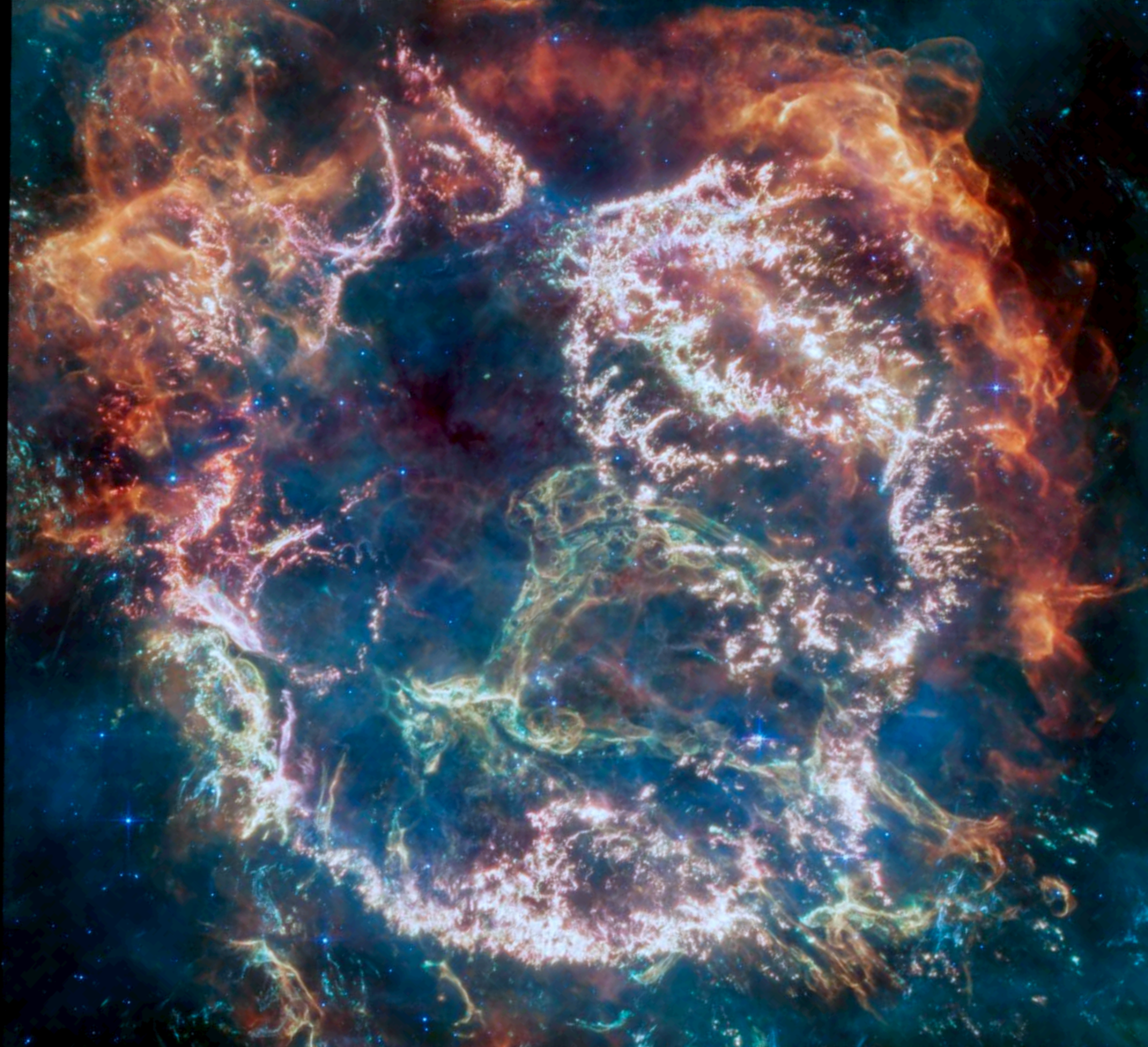
- This is how our Sun *will* come to an end in 5 Billion years ...

and leave an ultra hot dim white dwarf star behind in the center.

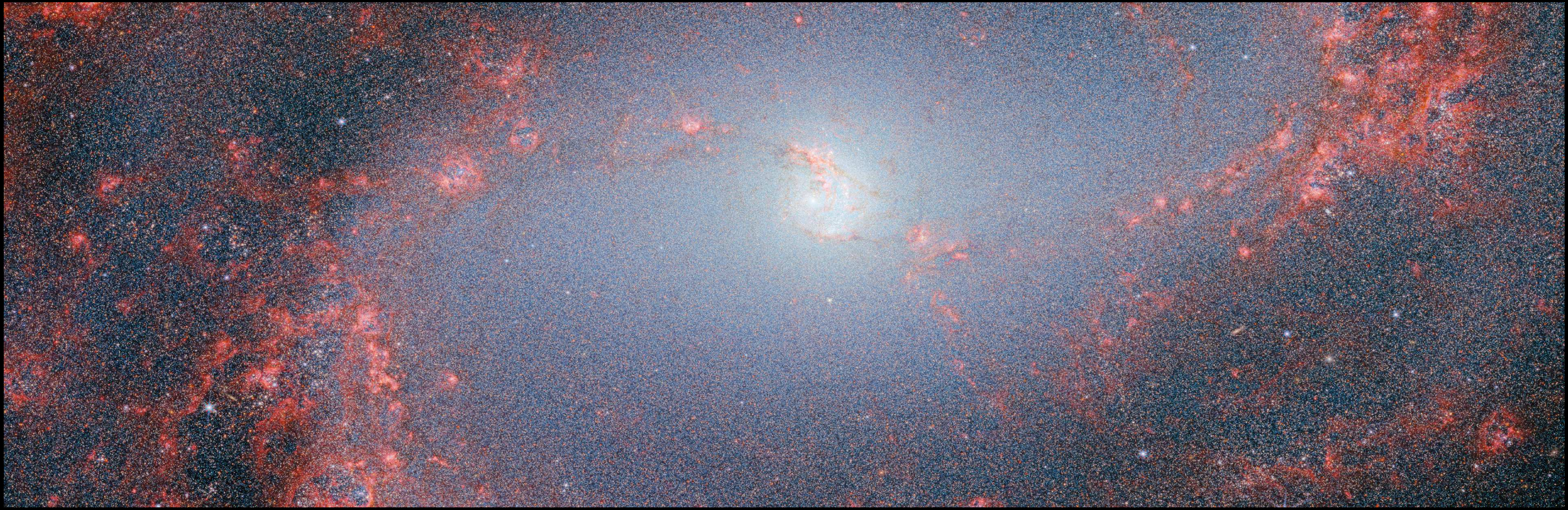


30 solar mass Wolf Rayet star WR124 shortly before it turns Supernova ...

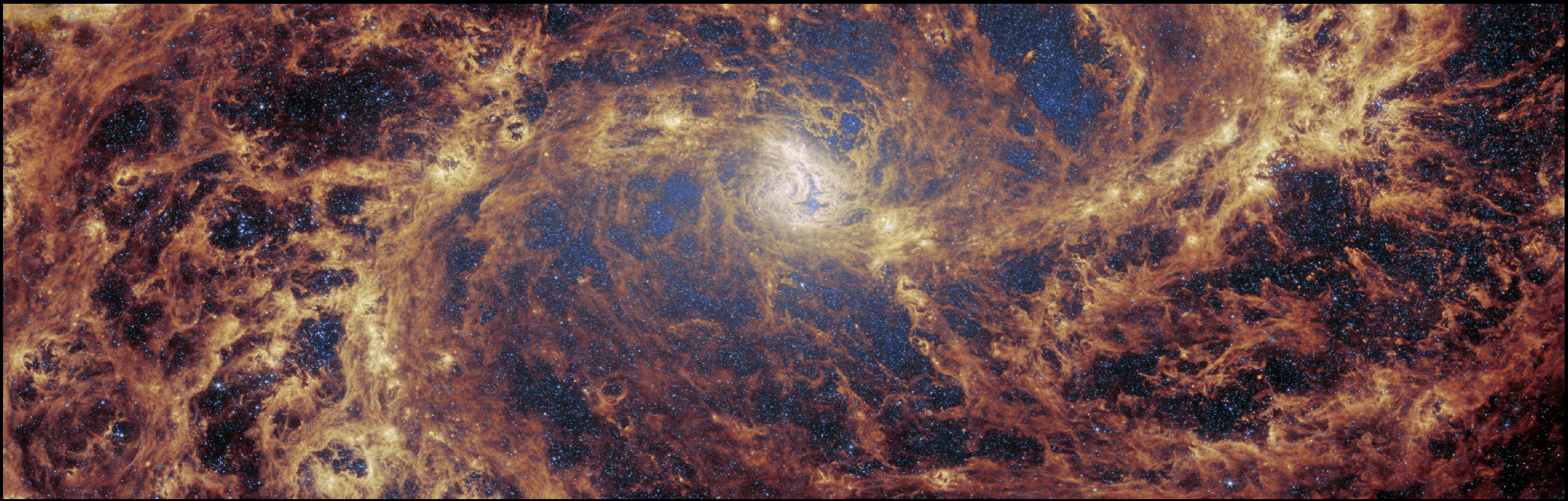
- [Left] NIRCam and [Right] MIRI — both showing recent mass loss.
- Prelude stage to Supernova also releases a lot of (dusty) mass!



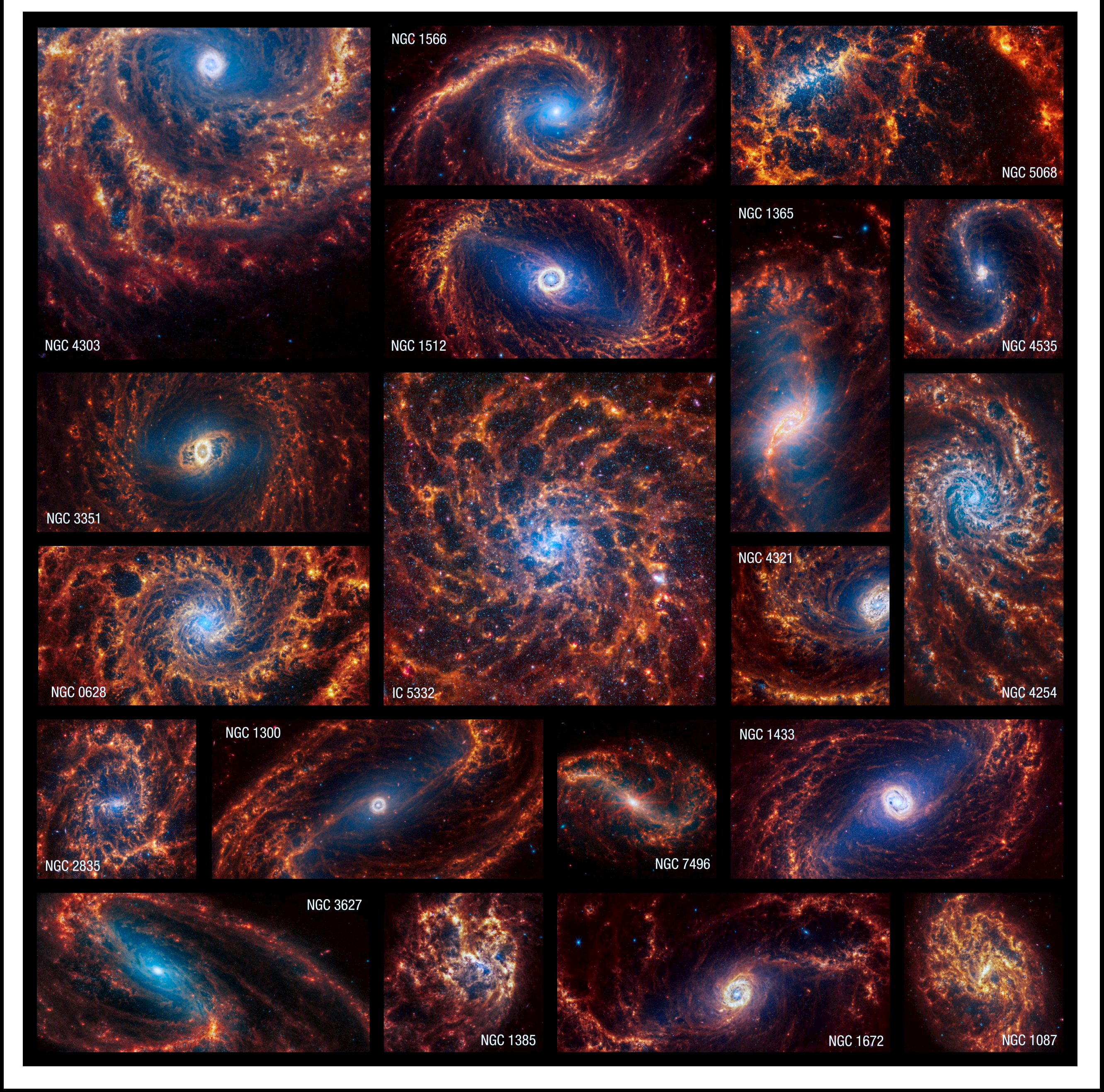
JWST MIRI: Supernova remnant Cassiopeia-A expelling gas, metals & dust!



M83 spiral galaxy NIRCam (near-IR): Through dust stars are made ...



M83 spiral galaxy MIRI (mid-IR): ... and dust is returned by stars!

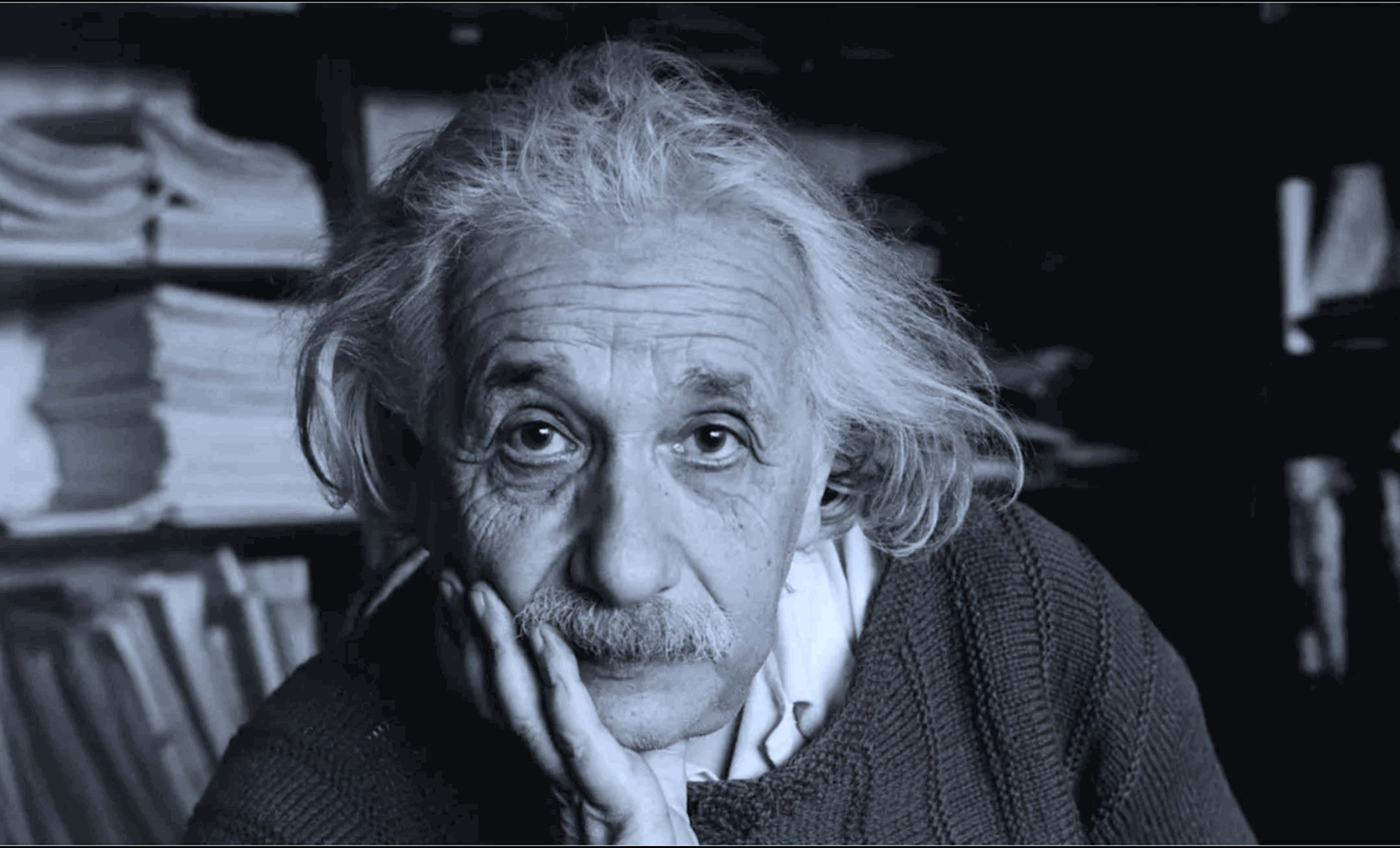


Webb NIRCam and MIRI images of nearby galaxies:

Star-formation and dust production ubiquitous throughout the universe:

"Cosmic Circle of Life" rules similarly throughout the universe!

- (3) 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, ...

Stephan's Quintet: 4 colliding galaxies (40 M-lyr; left spiral is foreground).

- These major "Cosmic Trainwrecks" are much more common in the past.
  - Sun-like stars formed in aftermath of minor "Cosmic Fender-benders".

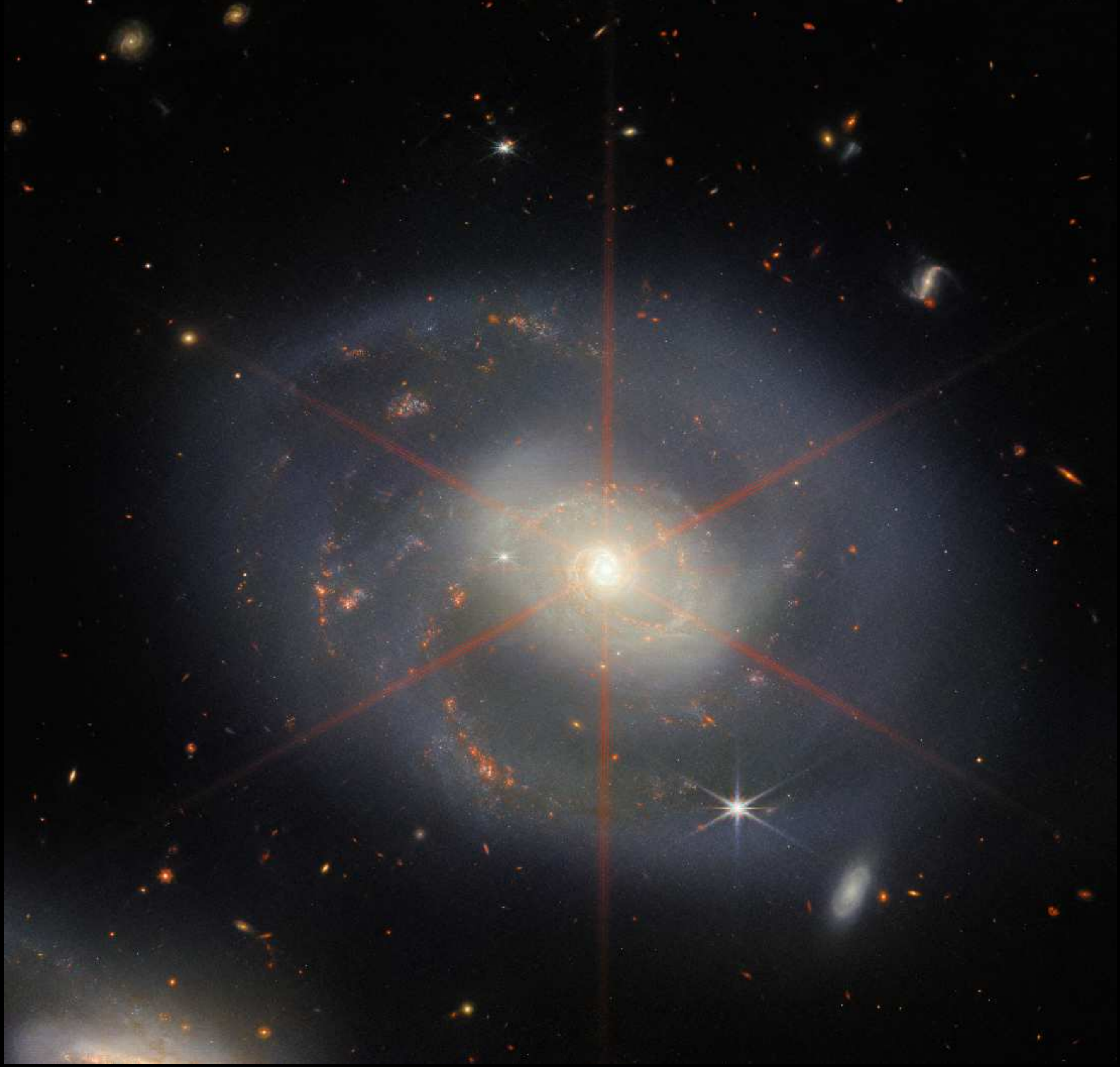
Stephan's Quintet: 4 colliding galaxies show "Beauty and a dusty Beast":

- Mid-IR shows molecular gas being pulled out during galaxy interaction.
- Gravity from collision in top galaxy feeds the Beast: central black hole!

NGC1433 a galaxy with dusty spiral arms at 48 million light-years

NGC7496 a galaxy with dusty spiral arms at 24 million light-years:

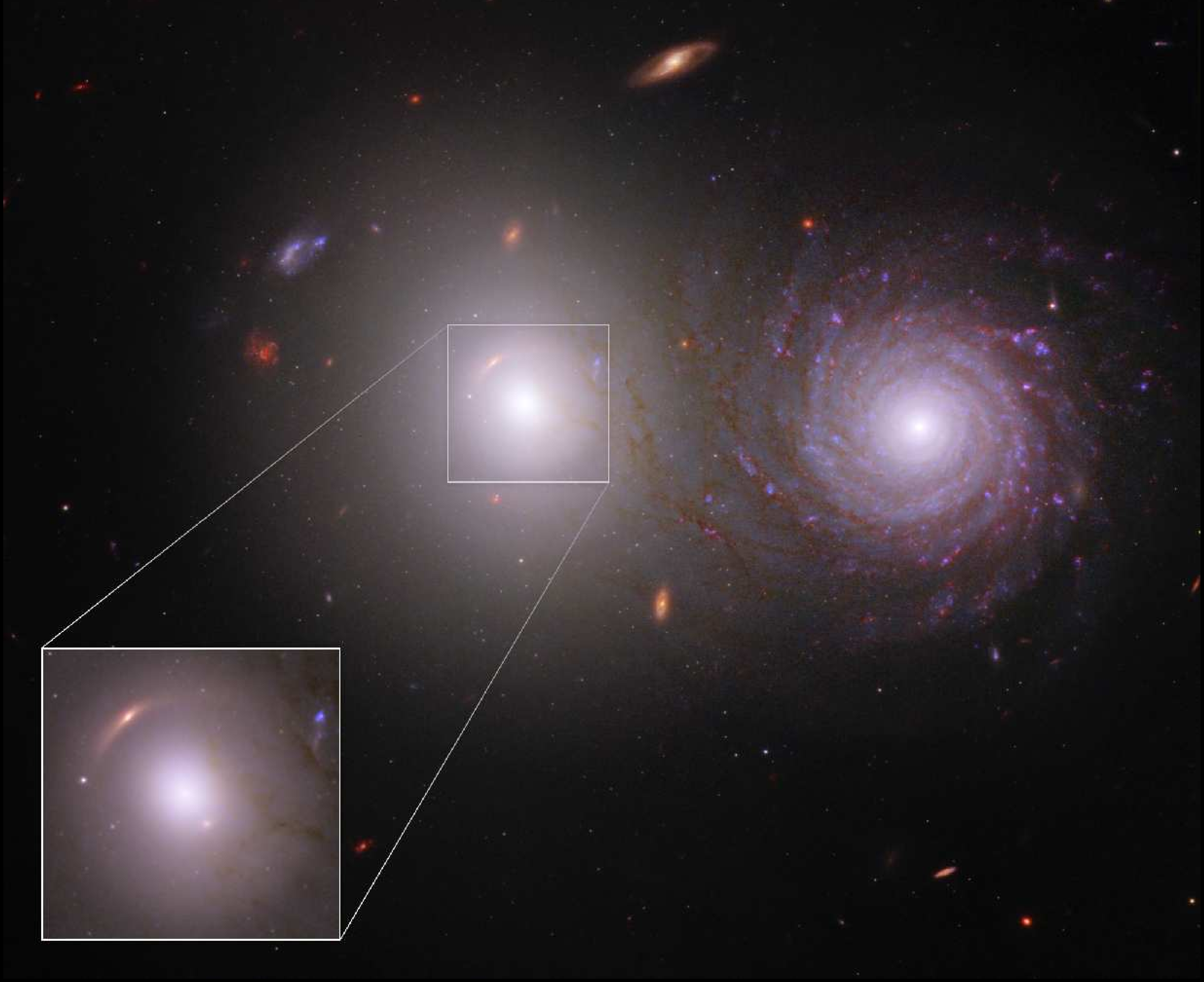
- Inner spiral arms feed the central monster (supermassive black hole!)



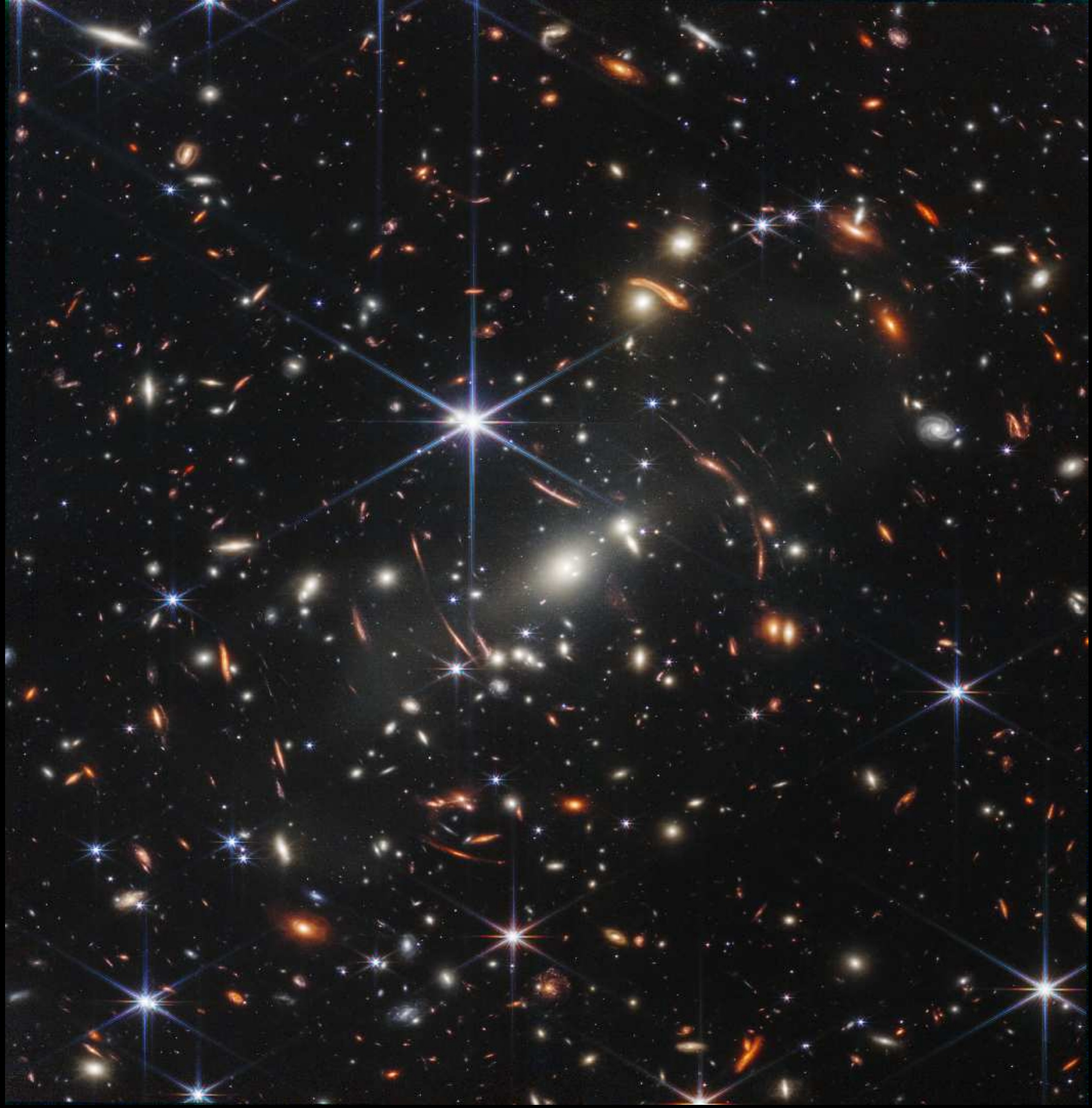
Don't feed the animals: NGC7469, a spiral galaxy at 220 million light-years:

- It has a supermassive black hole (SMBH) feasting on the in-falling gas!
- In area surrounding the SMBH, gas is expelled at very high speeds.

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

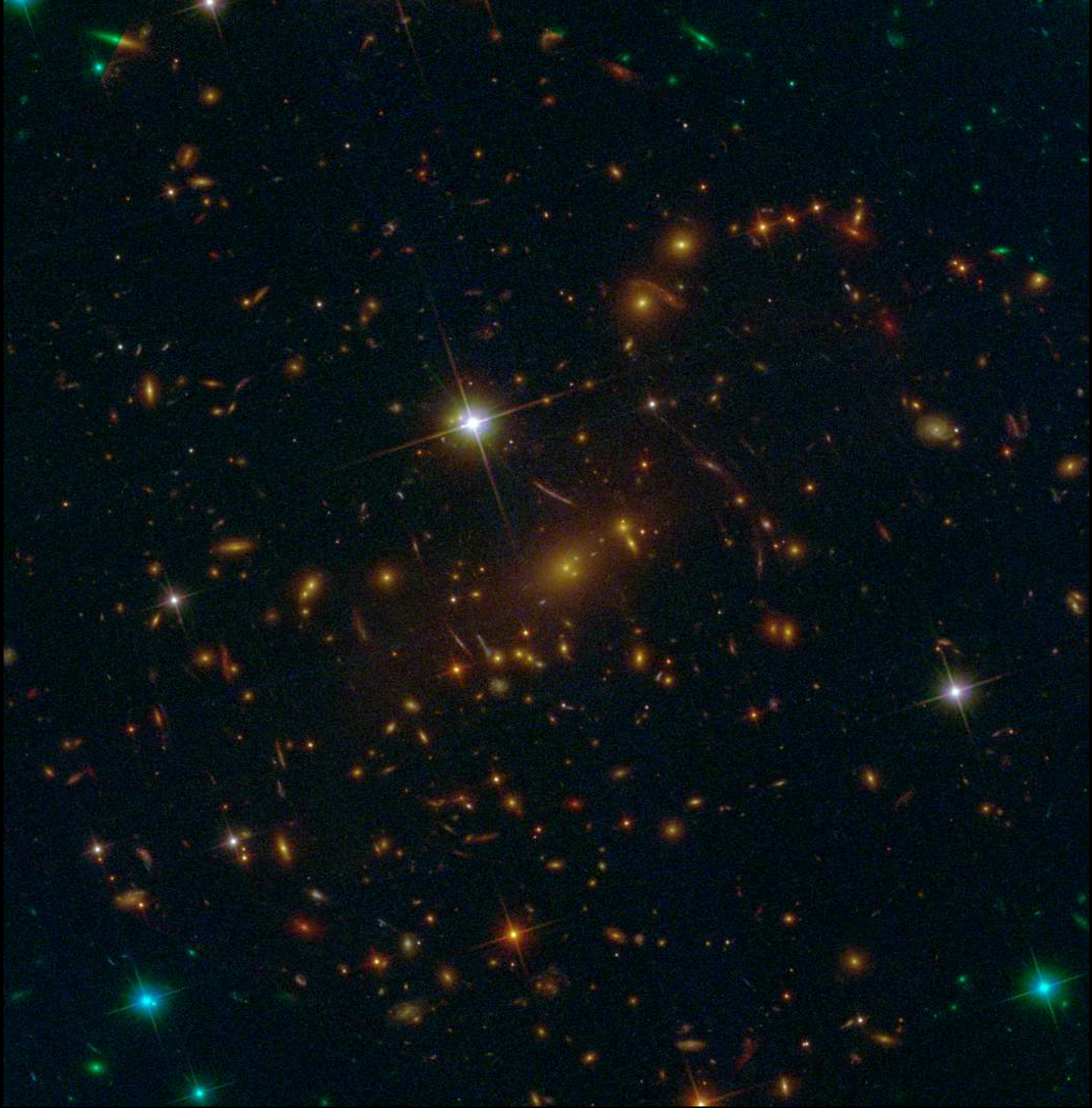


... and the z=0.0513 Elliptical also lenses a background galaxy at z∼1 (Keel^{+} 2023, AJ, 165, 16)!



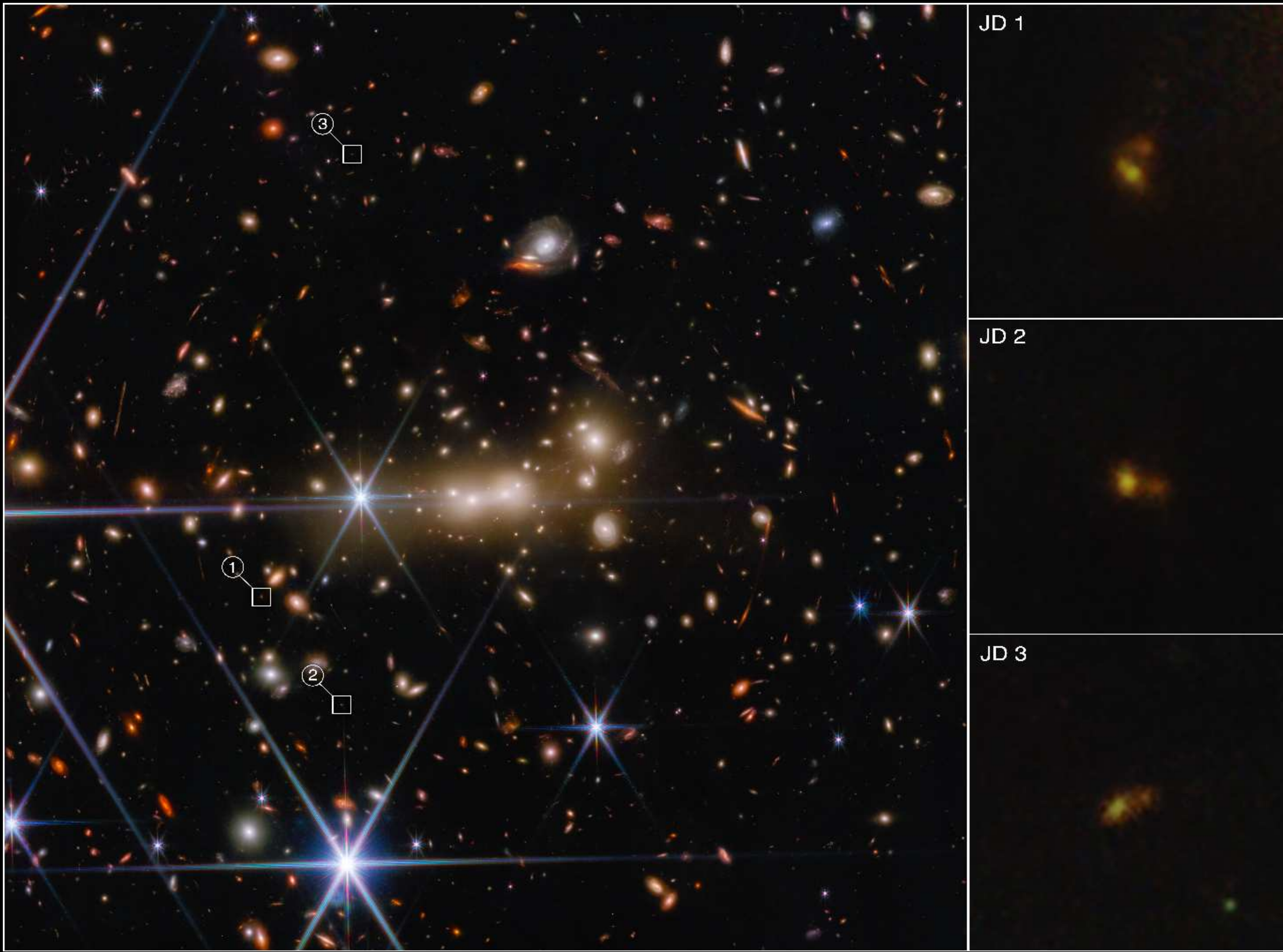
July 11, 2022: 12-hr Webb Deep Field on galaxy cluster SMACS 0723:

- Cluster galaxies already are ∼9 Byrs old, seen at 4.5 Blyr distance!

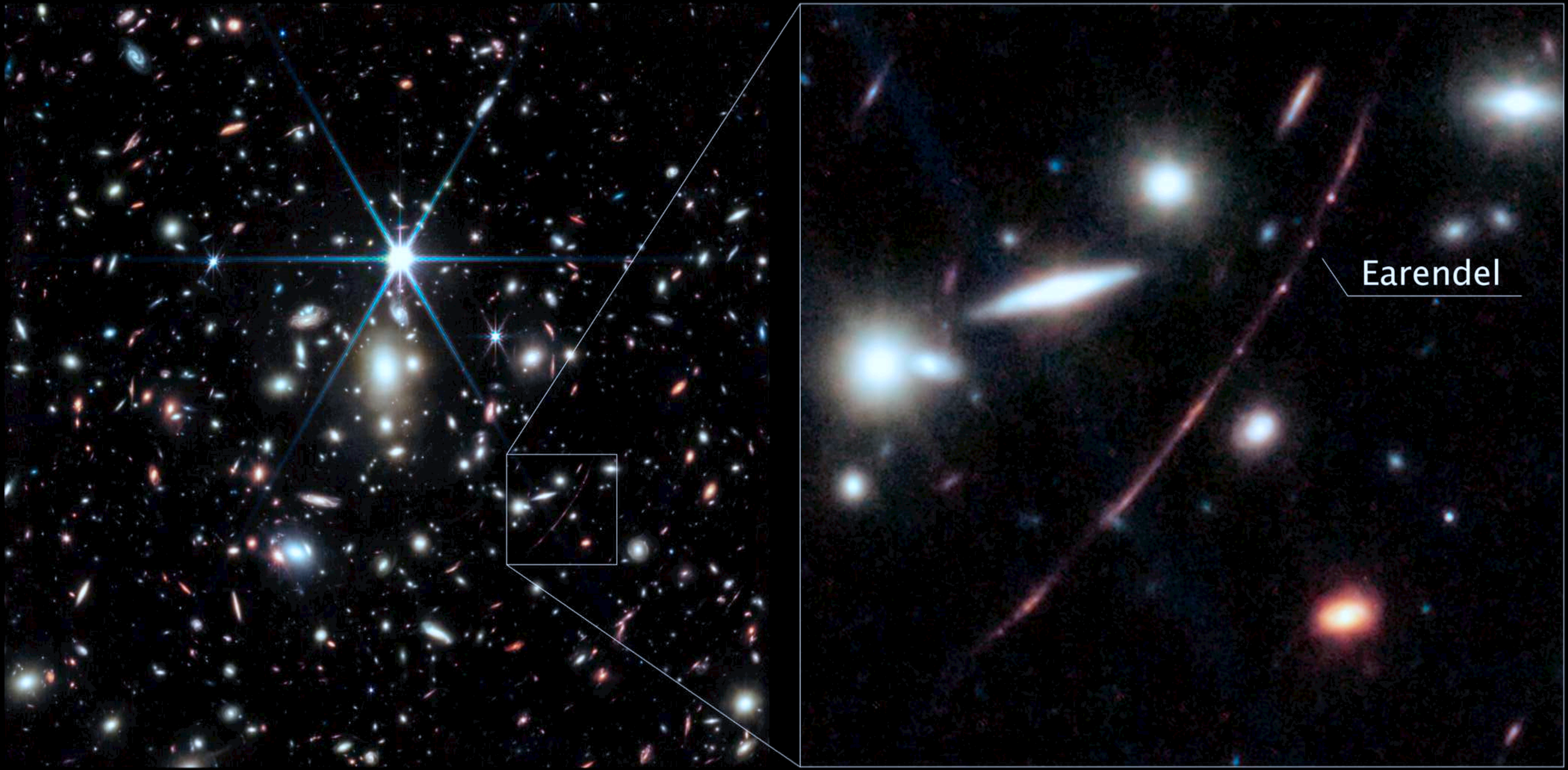


HST image of SMACS 0723: adds optical but not same depth as Webb!

- Cluster 3×older than the Earth today: we are cosmic late bloomers!



Cluster MACS0647 triply lensed a galaxy 0.4 Byrs after BB! (Hsiao, Coe^{+} 22)



NIRCam: Cluster WHL0137-08 with highly lensed arc at z=6.2 (0.9 Byr).

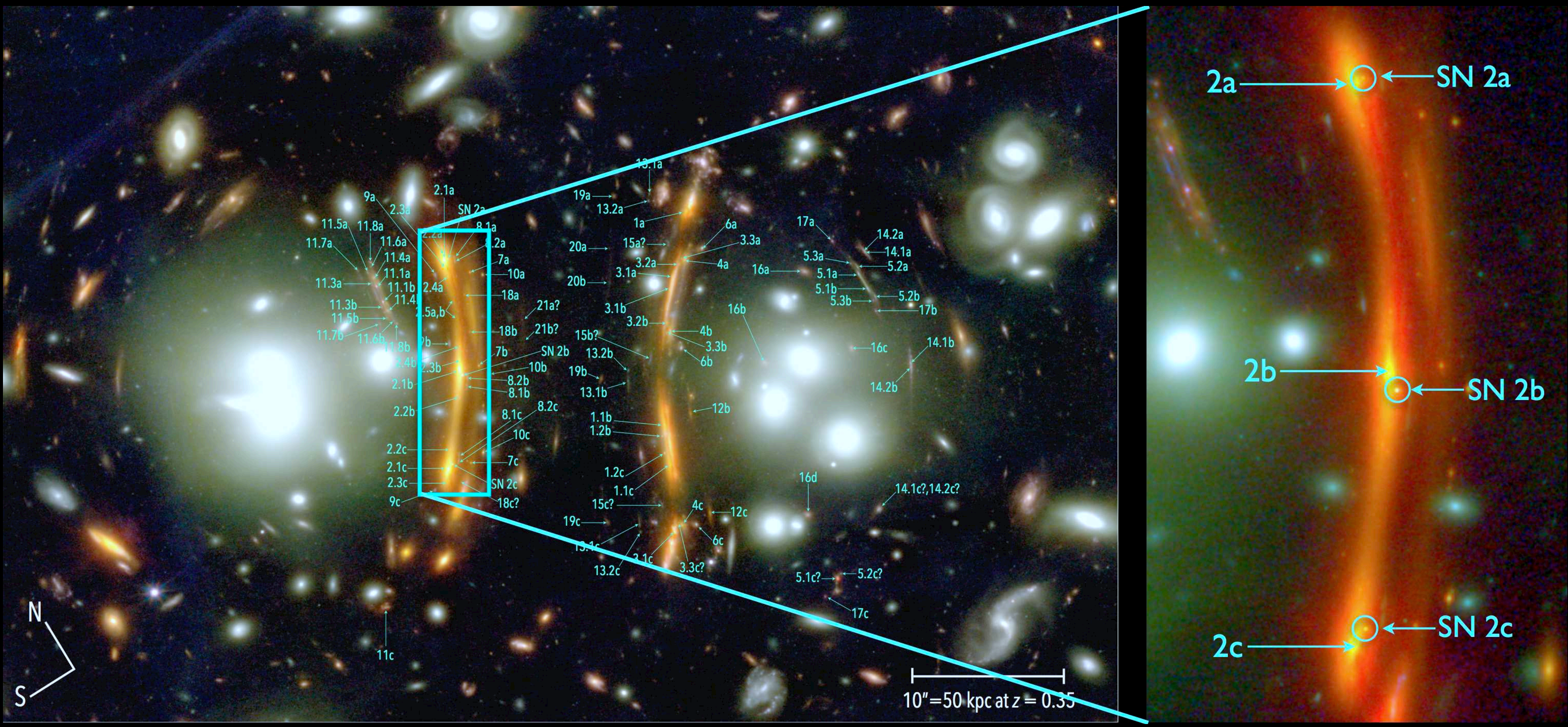
- Earendel: a highly magnified (double-)star seen in the first billion years after the Big Bang — the most distant star ever observed directly!

- Magnification $\mu \simeq 9000$ due to caustic crossing.

(Welch, B., Coe, D., incl. Timmes, F. X. & Windhorst R. et al. 2022, ApJ, 940, L1 and — 2022, *Nature*, 603, 815).

JWST image of most luminous far-IR Planck cluster G165 at z=0.35 found: Lensed Supernova Ia at z=1.78 → measure H_0 10 Byrs ago (Frye^{+}23)!

https://bigthink.com/starts-with-a-bang/triple-lens-supernova-jwst/



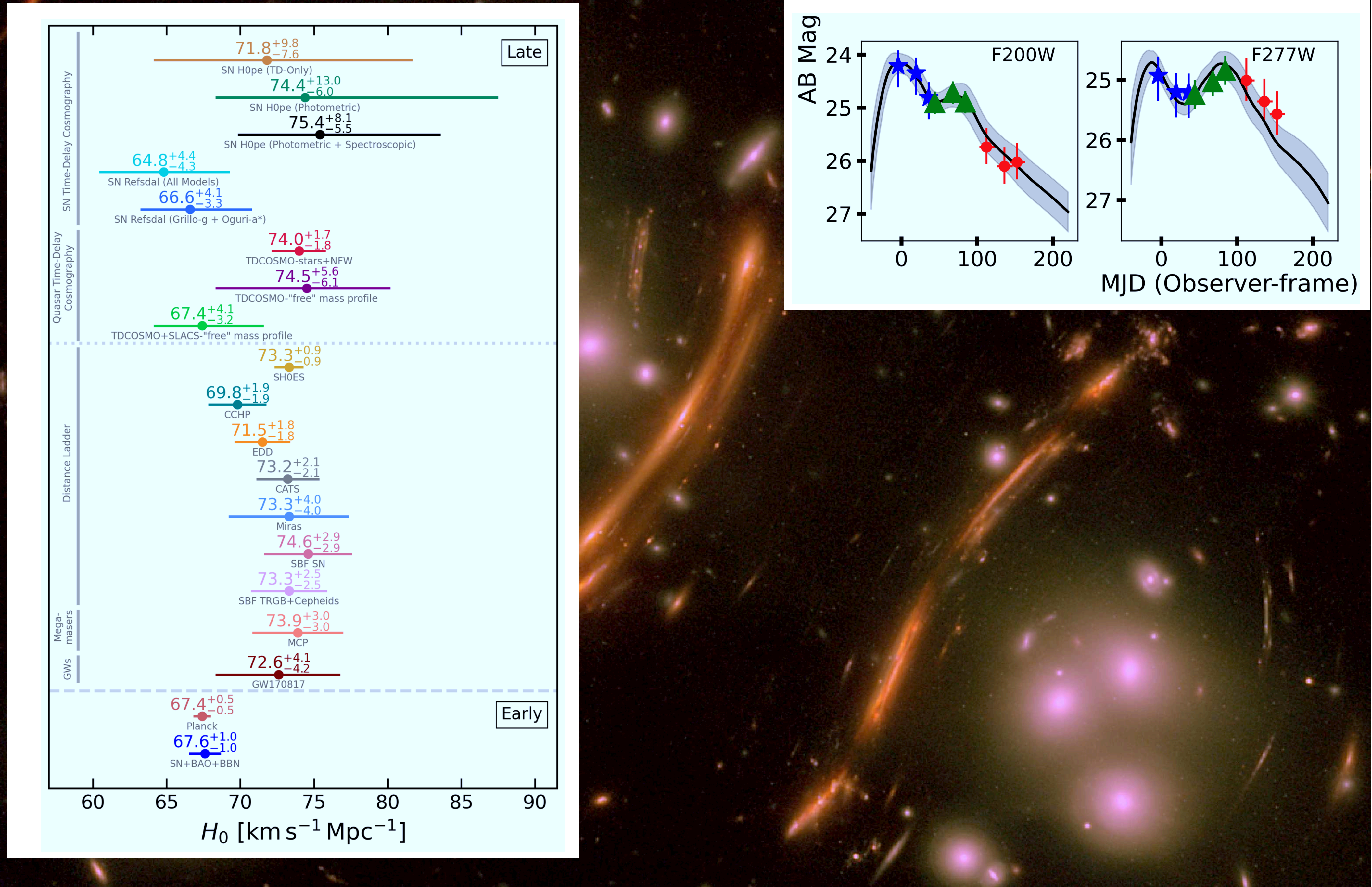
NIRCam in G165 shows: 3 bright point sources parity-flipped w.r.t. Arc-2:

- 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).

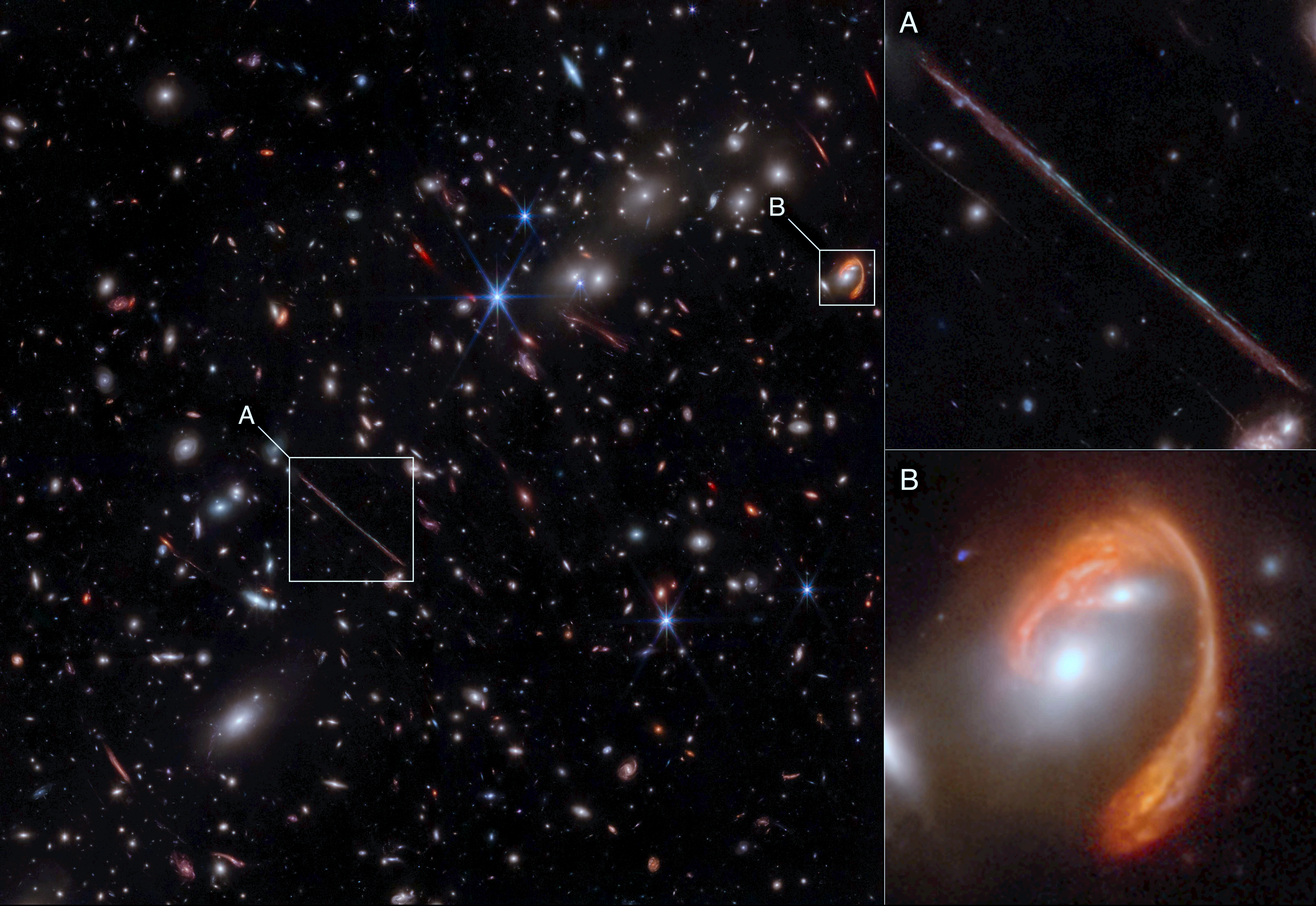
$\longrightarrow$ Regular monitoring of clusters with extreme SF to yield more lensed SNe!

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



Pascale+ (arXiv/2402.18902): Photo & spectro time delay: $H_o=75.4^{+8.1}_{-5.5}$ (at z=0.35).

• Monitoring G165 predicts ≳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

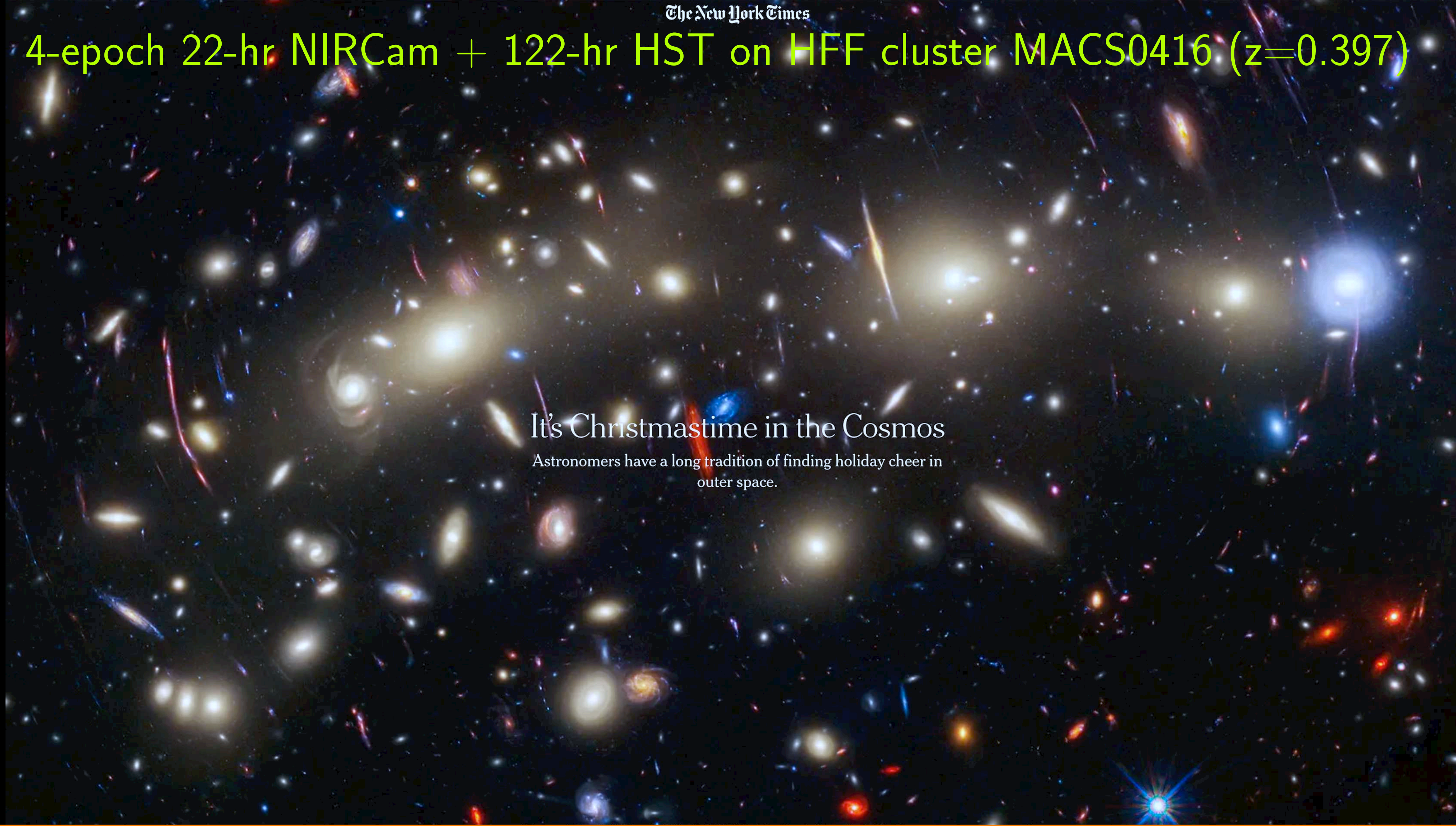
(Kamieneski+ 2023, ApJ, 955, 91)

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 ($z=0.397$)

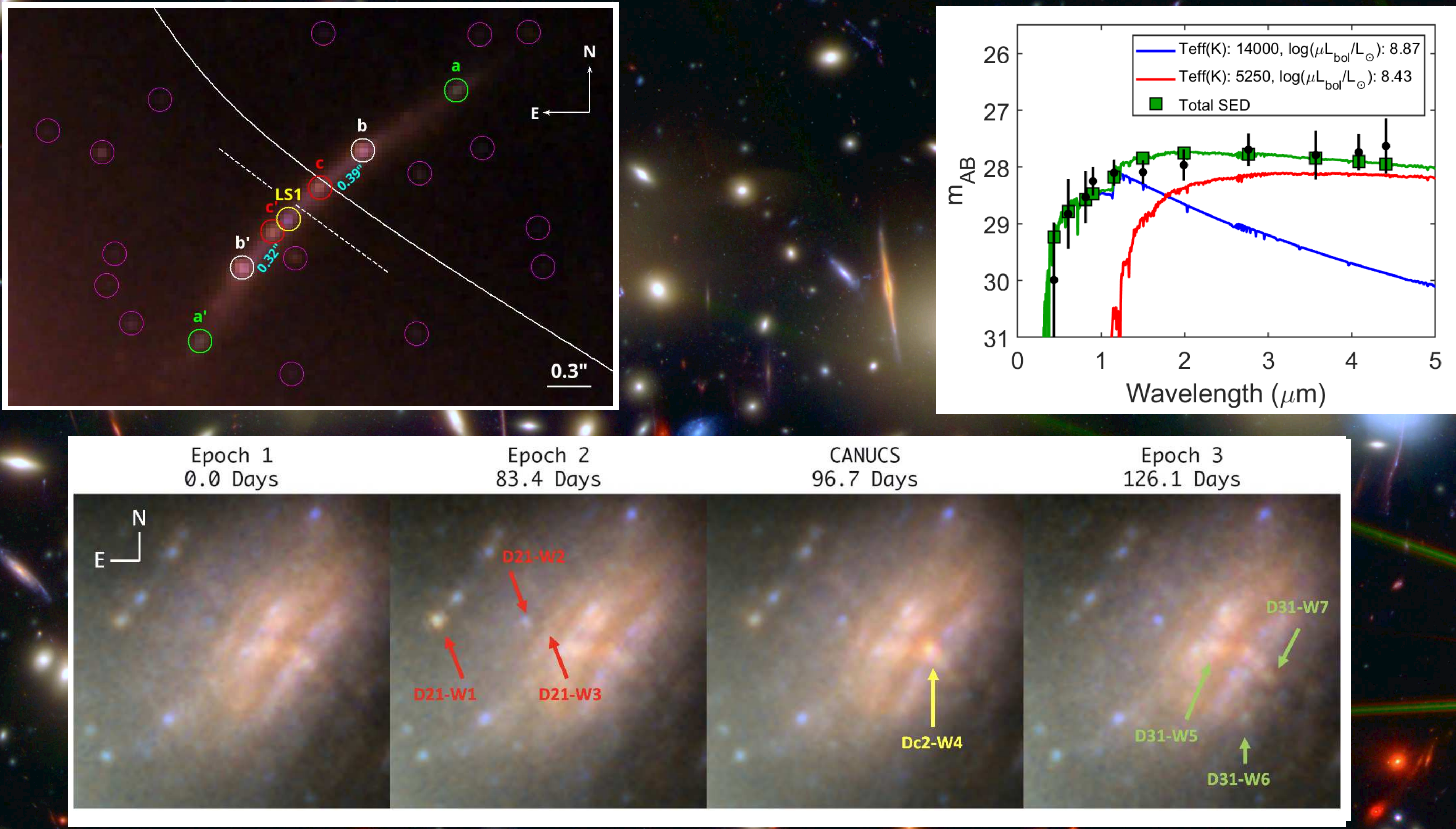


Yan, H.+ (2023, ApJS, 269, 42): 12 new caustic transits at $z\simeq1$–2 from 4 epochs!

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

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?

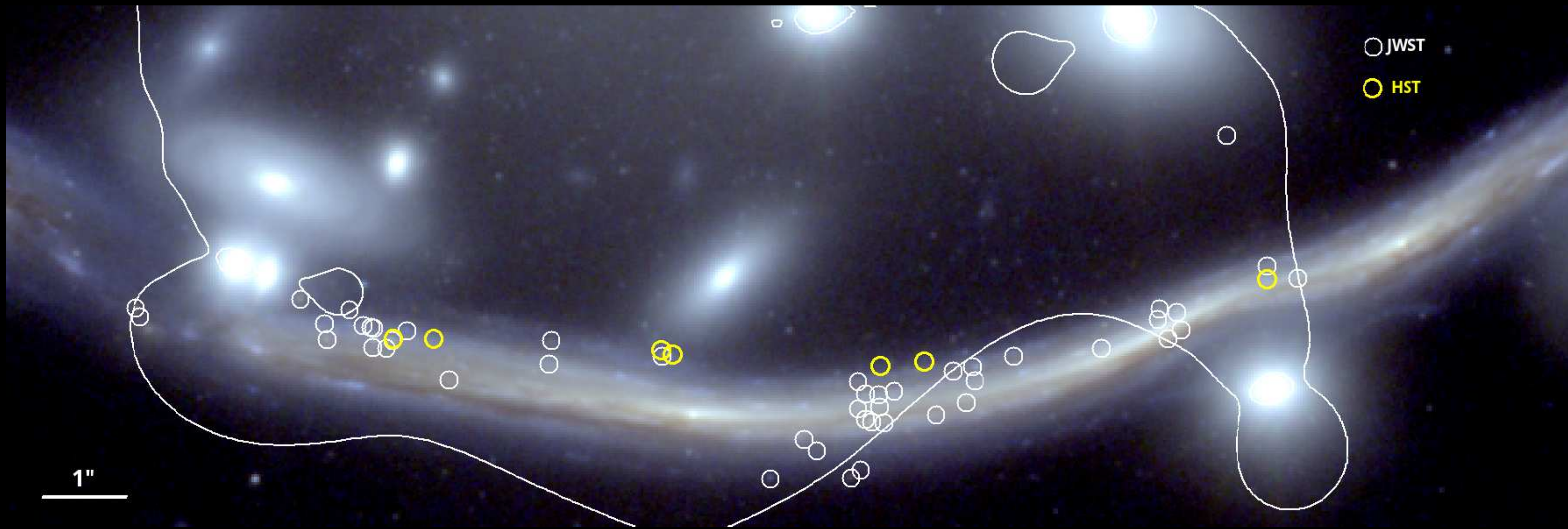


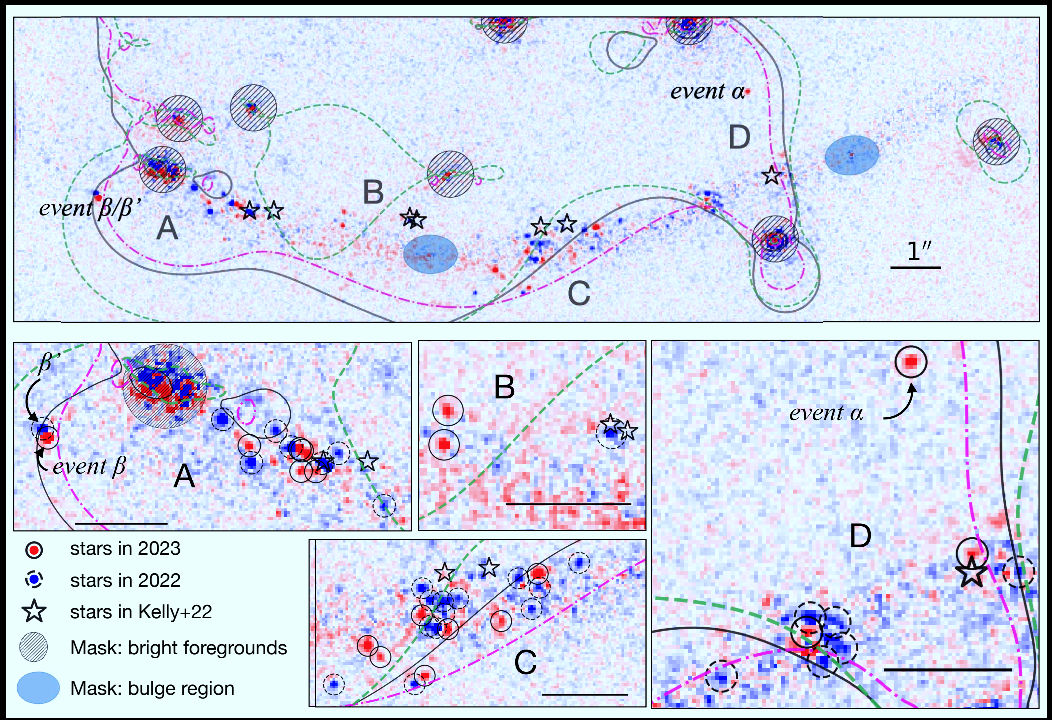
Yan, H.$^{+}$ (2023, ApJS, 269, 42): 12 new caustic transits at z≃1–2 from 4 epochs.

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

$\Longrightarrow$ Regular monitoring of several clusters can see stars at z$\gtrsim$1 directly!

- With magn≃1000-4000, many have spectra of binary stars at z≃1–2!





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

(Y. Fudamoto^{+}, *Nat. Astron.*, 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 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) Webb's first images trace the "Cosmic Circle of Life":

- Formation and evolution of stars and dust over cosmic time.
- This dust helped form exoplanets and building blocks for life.

(3) Webb is observing the epochs of First Light, Galaxy Assembly & Super Massive Black Hole-growth in detail (much through grav. lensing):

- Formation of the first stars, star-clusters, SMBH's after 0.2 Byr.
- How galaxies form and produce their dust over 13.5 Billion years.

(4) HST maps (unobscured) SF in the last 10 Gyr, complementing Webb's advantage in the first 3-Gyr:

- Hubble must be kept operational to maximize Webb's science return!

SPARE CHARTS

PEARLS papers, press releases and other URLs

Talk: http://www.asu.edu/clas/hst/www/jwst/sese_facmtg_jan25_hstjwst.pdf   Data: https://sites.google.com/view/jwstpearls

https://hubblesite.org/contents/news-releases/2022/news-2022-050

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https://esawebb.org/images/pearls1/zoomable/

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

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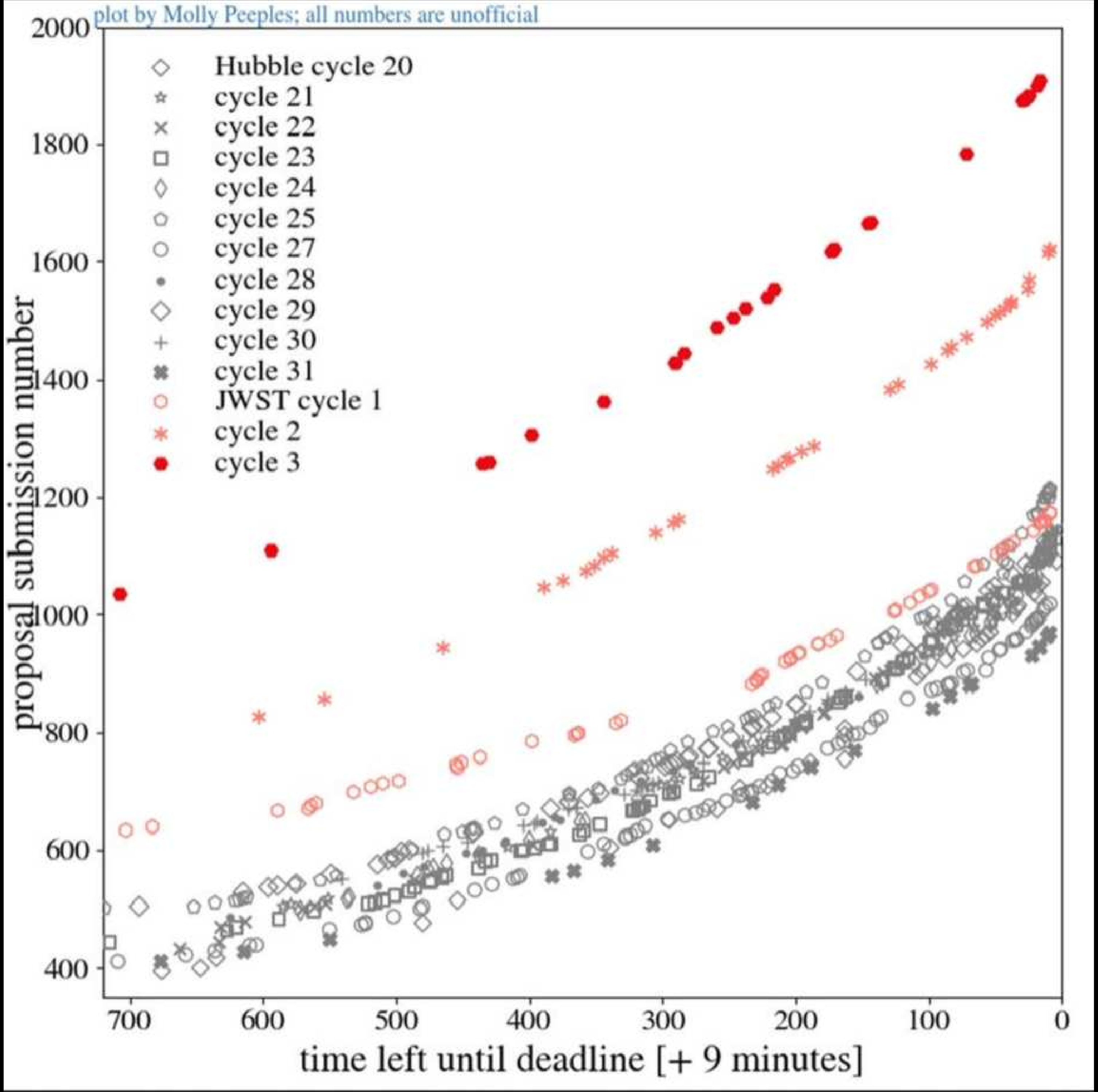
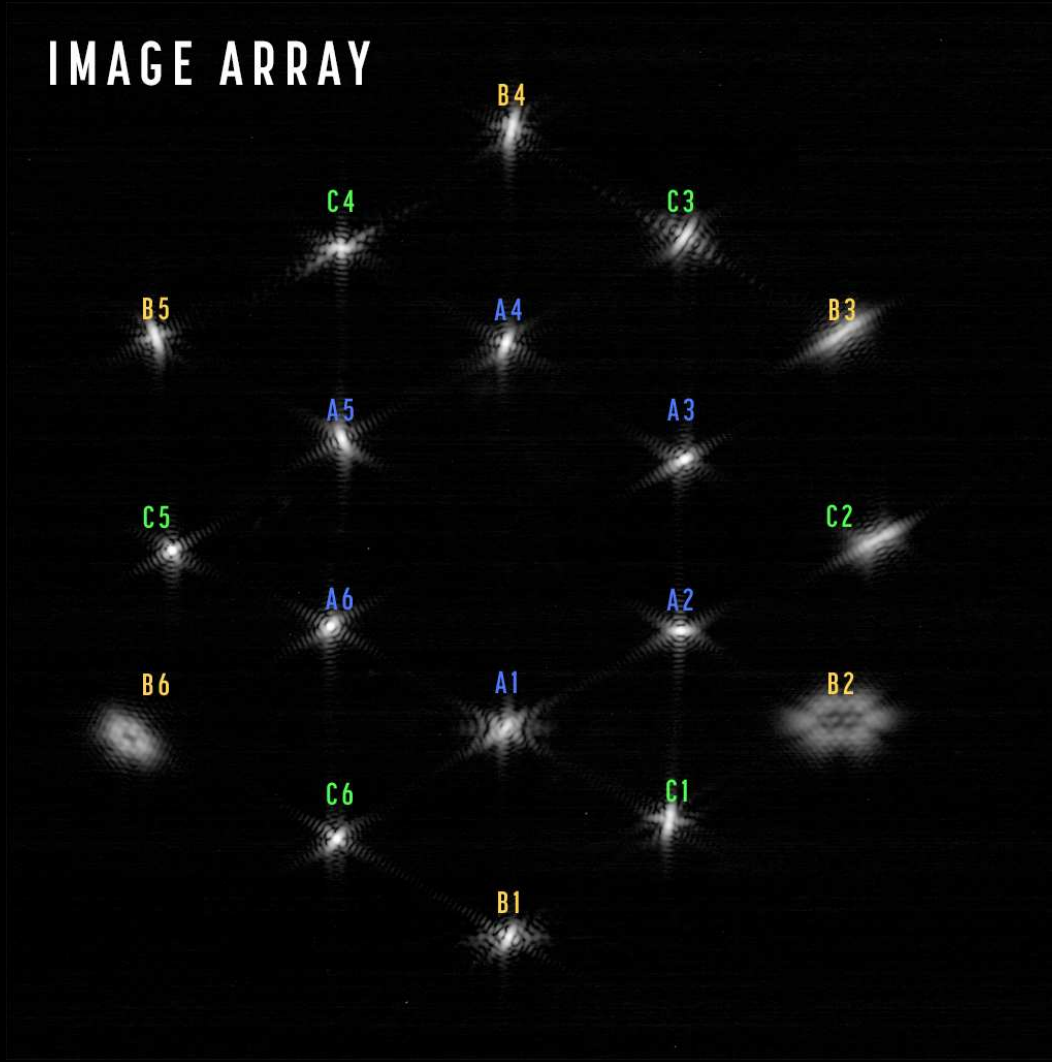


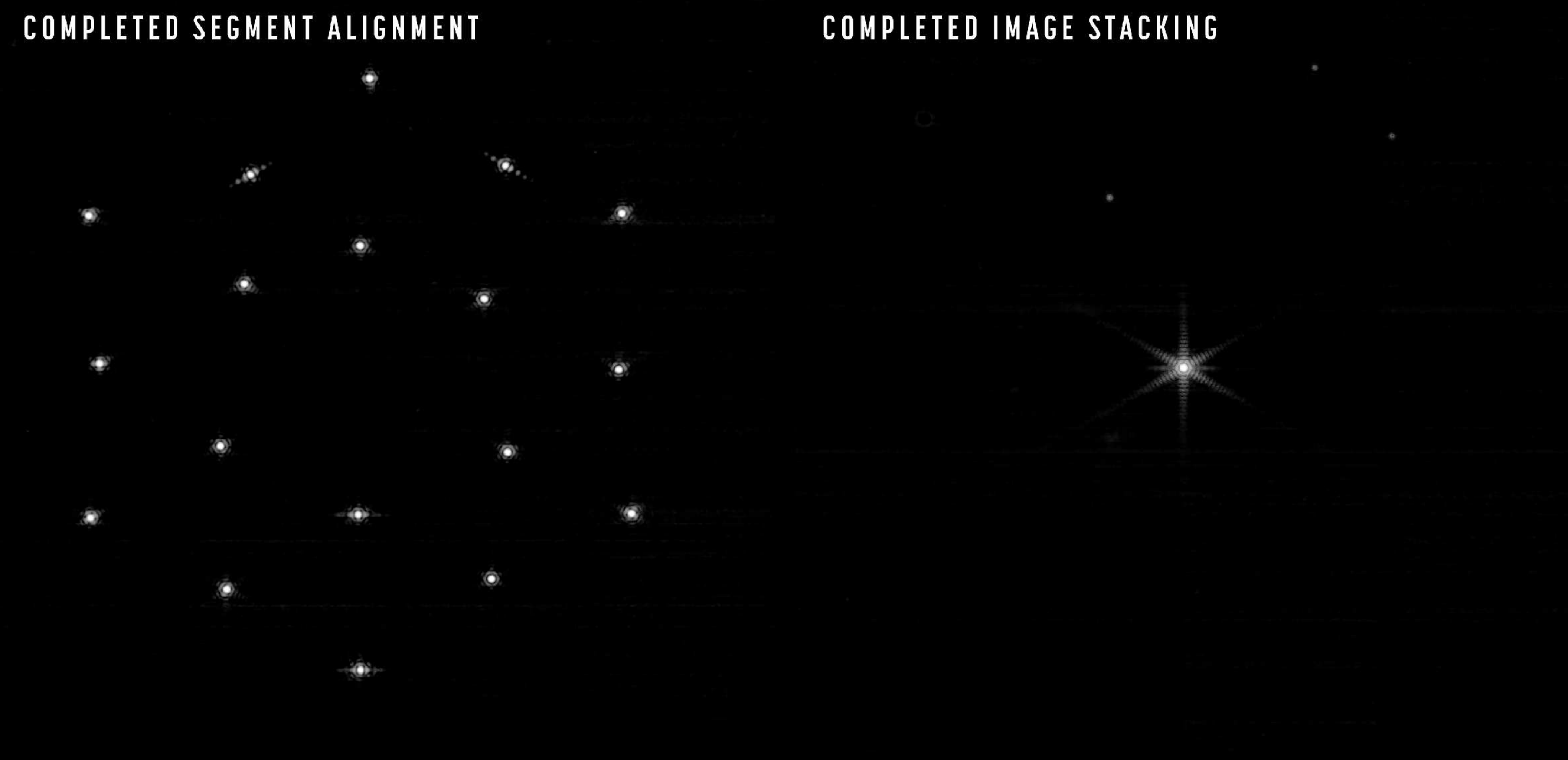
Oct 2023: Webb is now THE highest-in-demand NASA Flagship mission ever!

Webb is finally launched from Kourou on December 25, 2021!

Dec. 25, 2021: Webb seen shortly after launch over Africa using the Ariane V on-board camera.



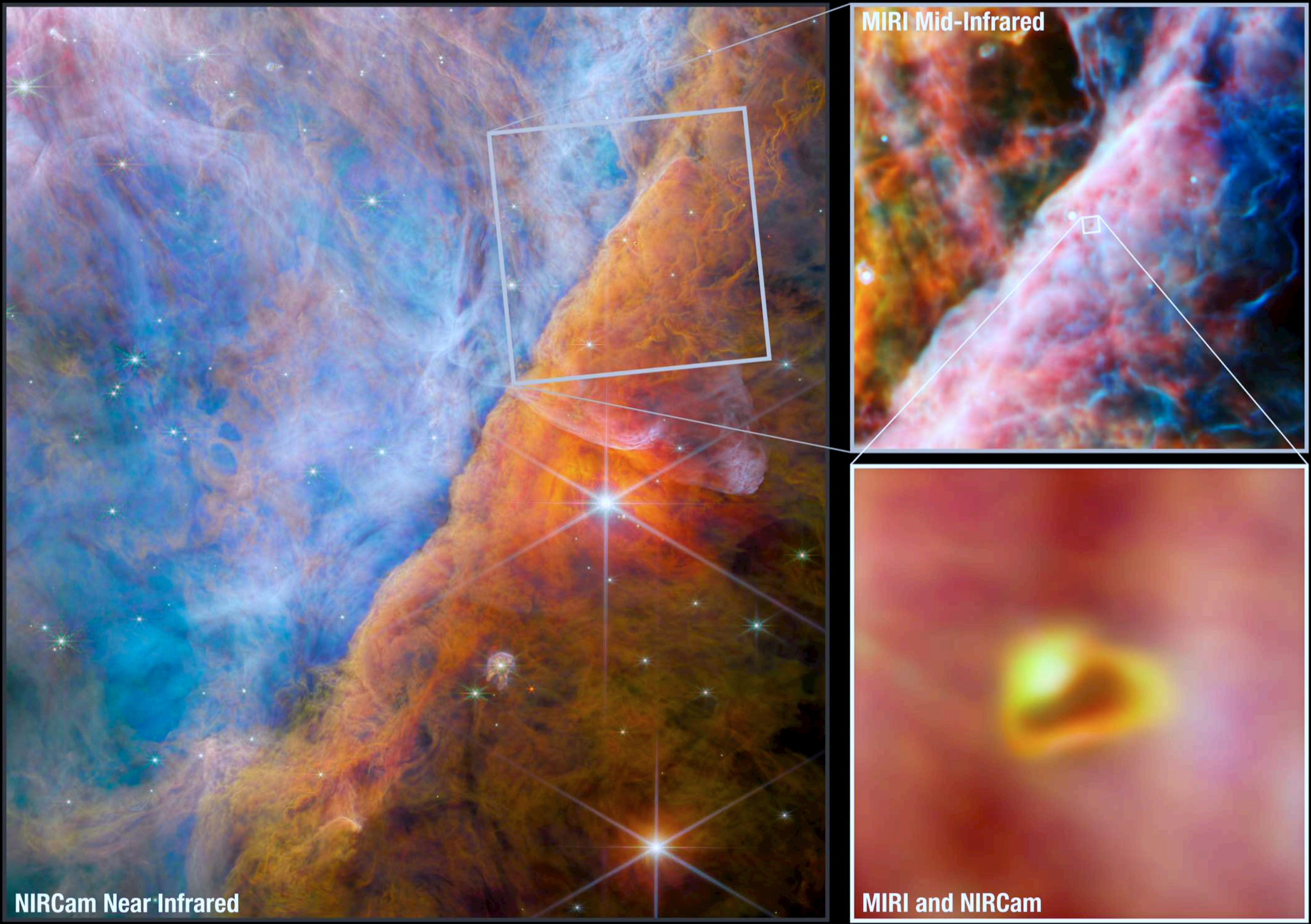
Feb. 2022: Webb's first selfie (left) and First Light raw image (right).



Webb's first segment alignment (left) and first image stack (right).

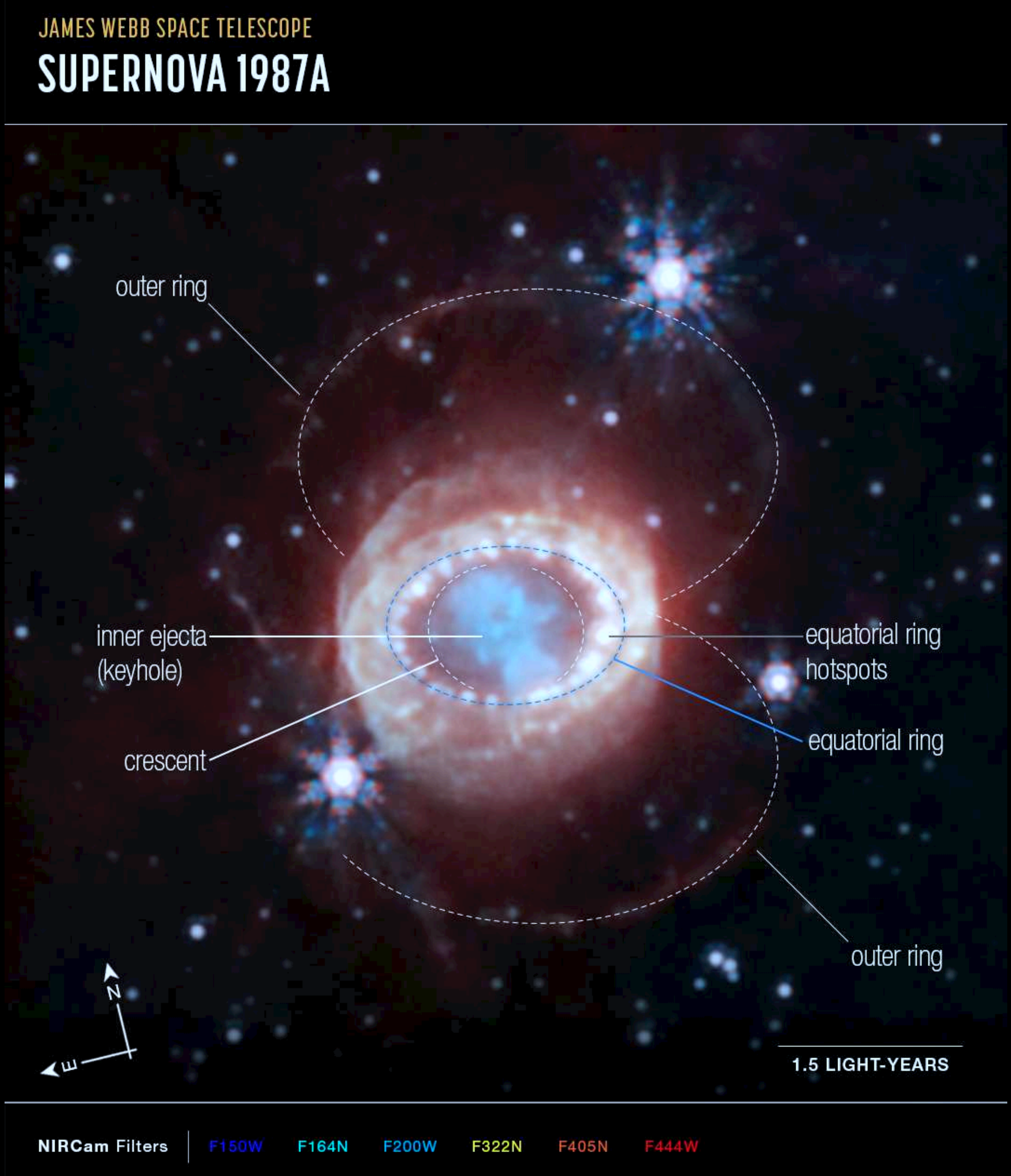
March 16, 2022: Webb's first fully focused image publicly released !!
Note the plethora of faint galaxies — Webb's looking back in time!

https://www.nasa.gov/press-release/nasa-s-webb-reaches-alignment-milestone-optics-working-successfully



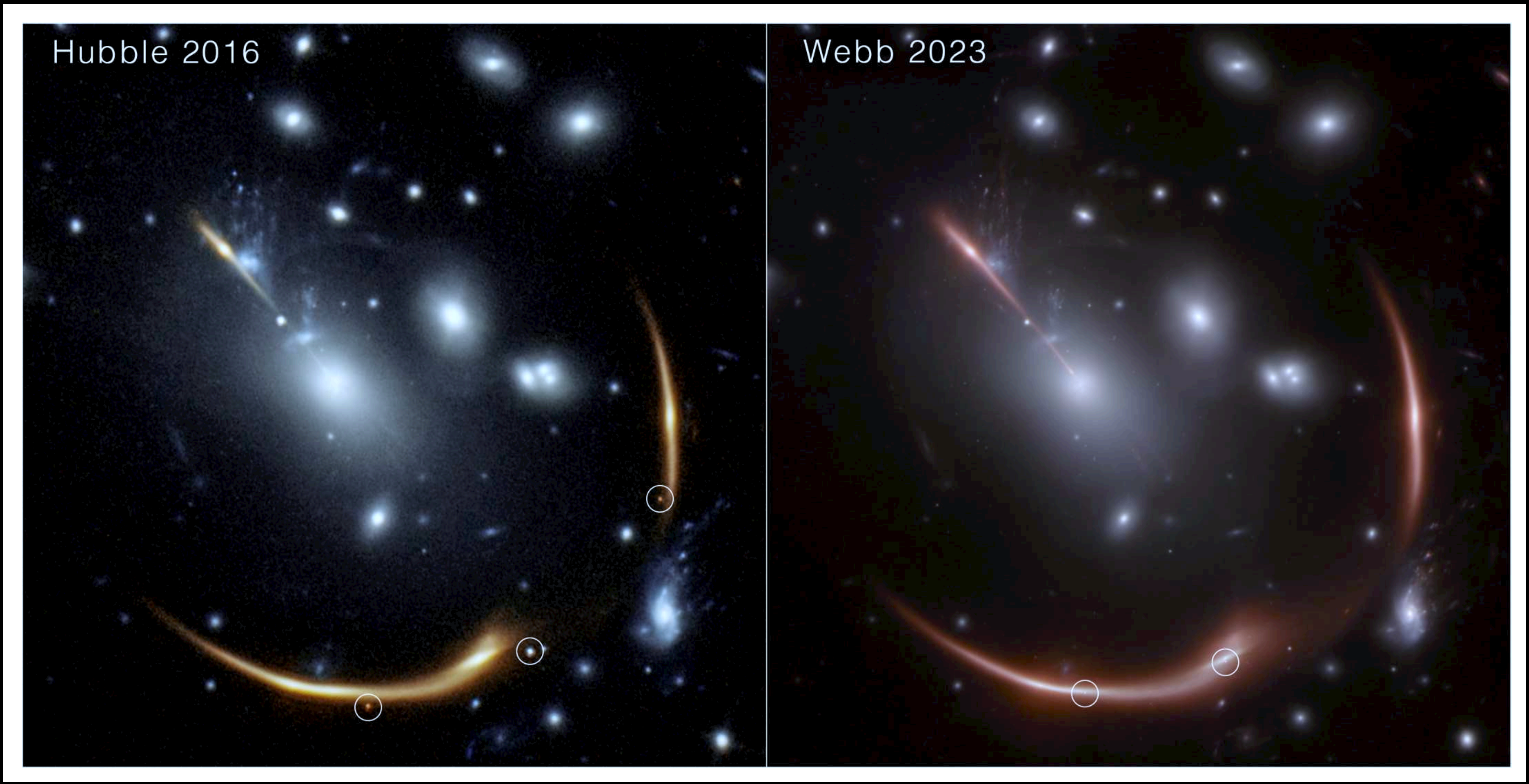
JWST NIRCam+MIRI: Cosmic Cliff-like in Orion's Trapezium (1344 lyrs):

- New stars are forming containing the carbon chain "Methyl Cation"



NIRCam: Remnants of Supernova 1987A seen in Large Magellanic Cloud

- Shells outflowing over the decades caused hour-glass shaped bubbles



Hubble saw a lensed Supernova Ia behind this galaxy cluster in 2016:

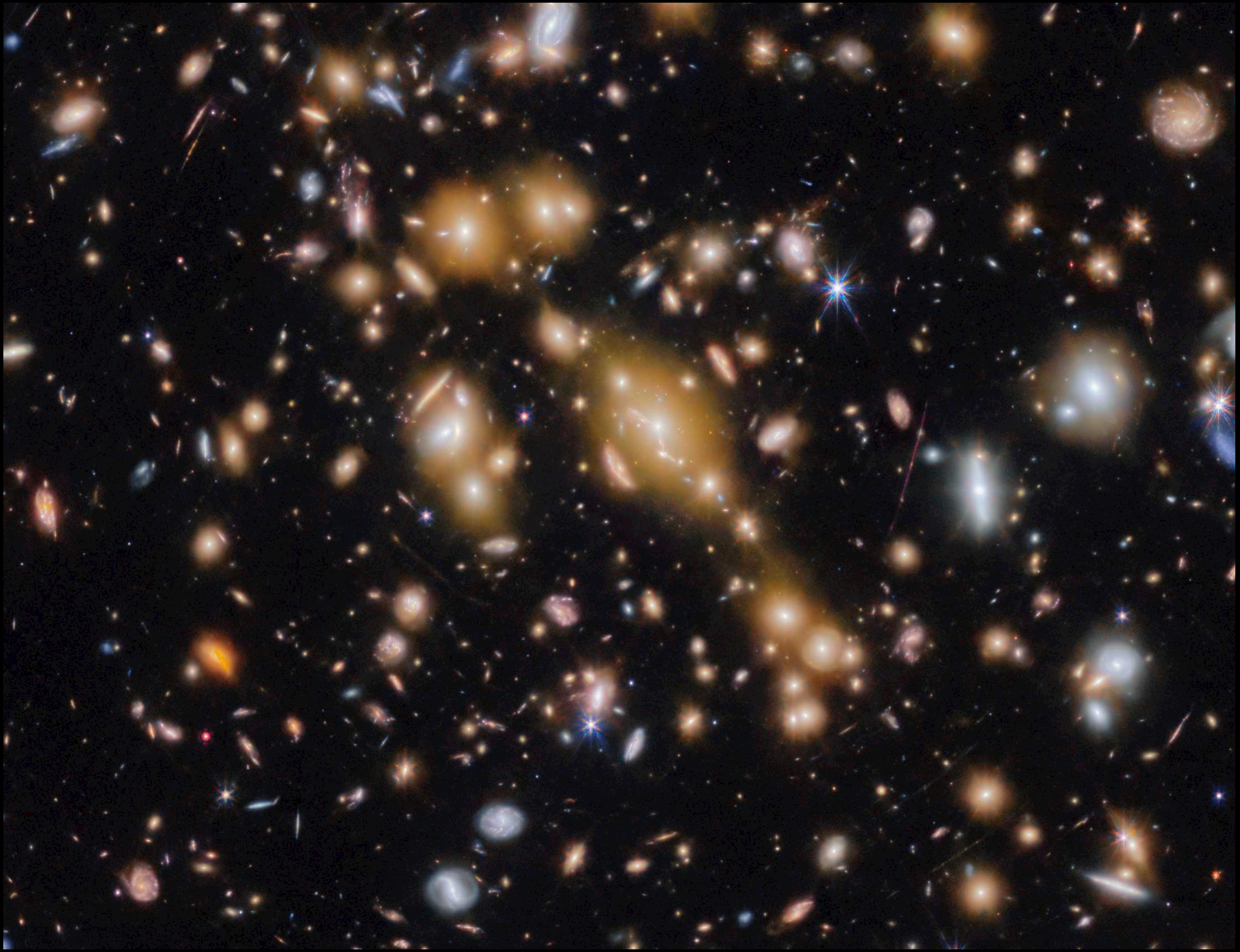
Webb saw more distant lensed Supernova at z=1.9 (age 3.5 Byrs) in 2023!

$\Longrightarrow$ “SN Encore”: Lensing is the gift that keeps on giving!

122 hr HST + 22 hr JWST on Frontier Field cluster MACS0416 (4.3 Blyr)

- The power of Two Telescopes: Webb collects 6× more light than Hubble!

NASA press release for Nov. 9, 2023: `https://webbtelescope.org/contents/news-releases/2023/news-2023-146`



z=0.97 cluster SPT0615: lenses young globular clusters at z=10.2 !

Adamo+ (2024, Nature 632, 513): ∼50 Myr old, formed at z∼11! https://esawebb.org/news/weic2418/

- $z \gtrsim 1$ universe is littered with galaxy mergers and supermassive black holes!

We live in a *boring* galaxy away from major mergers & SMBHs!

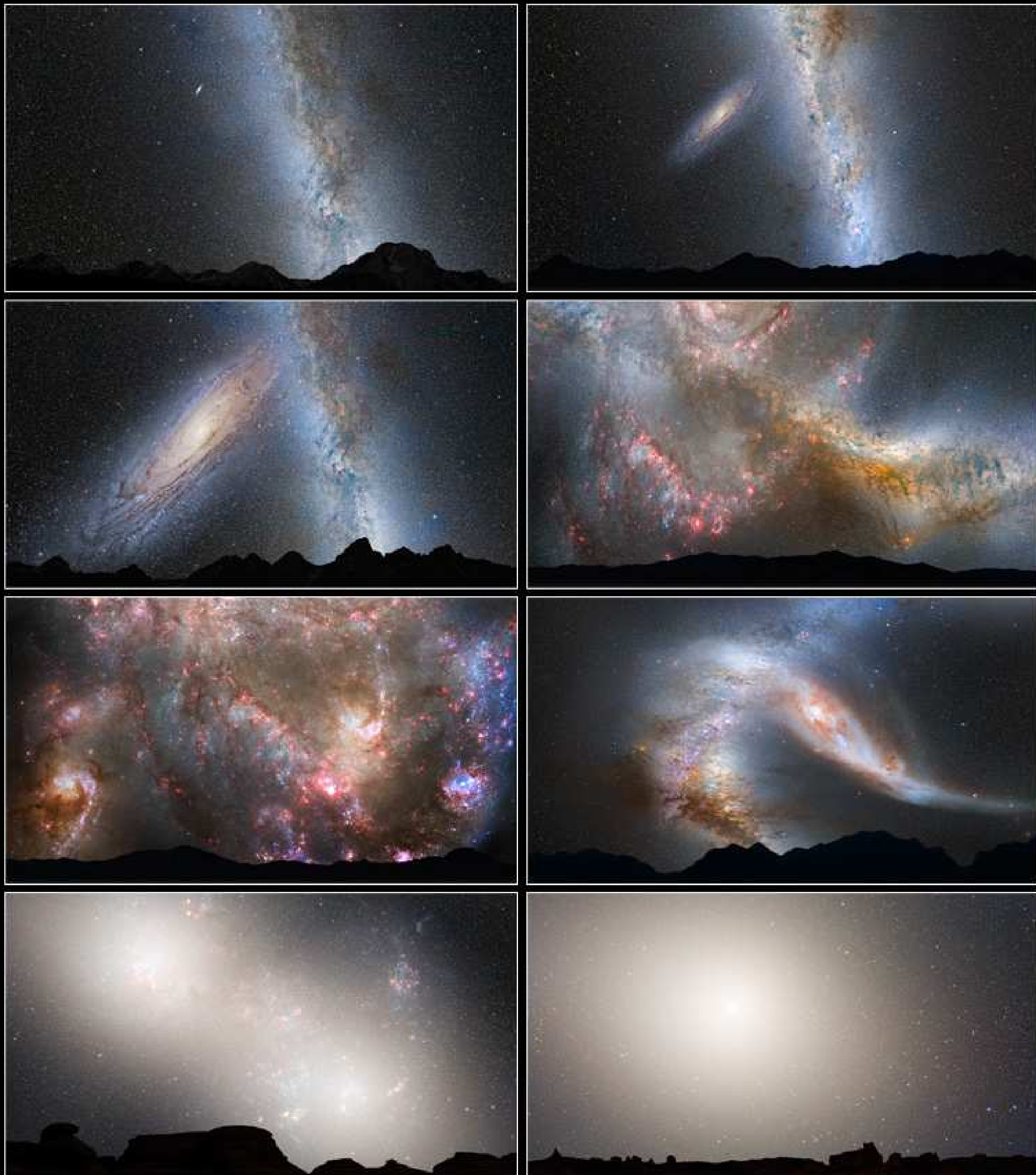


Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger ▪ STScI-PRC12-20b

Will this ever happen to our own Galaxy?

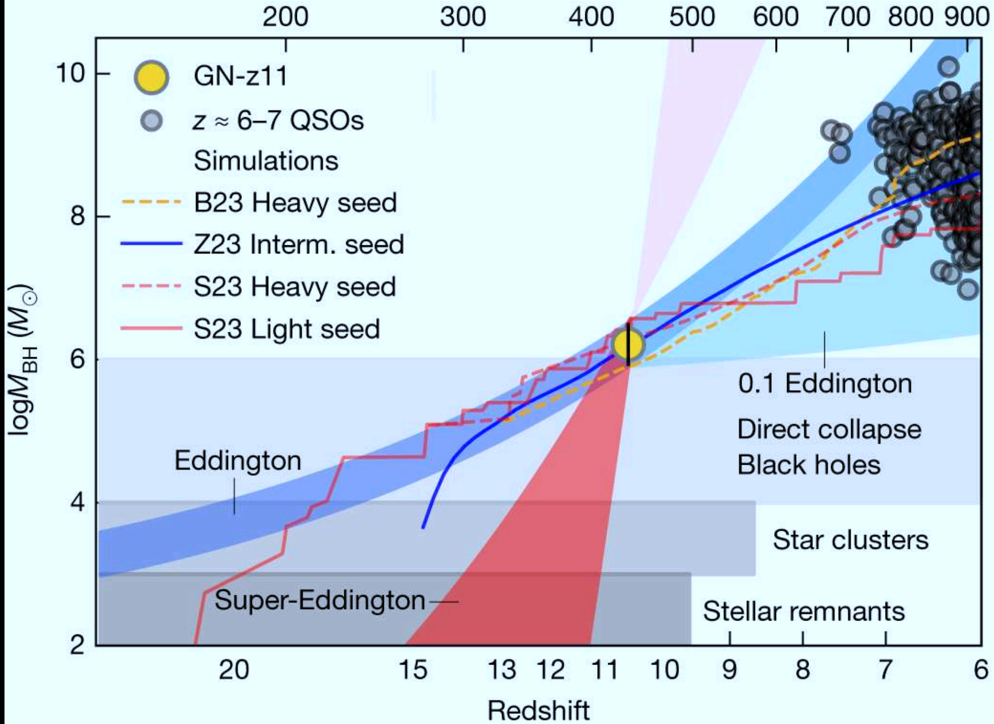
YES! Hubble showed no lateral motion of Andromeda:

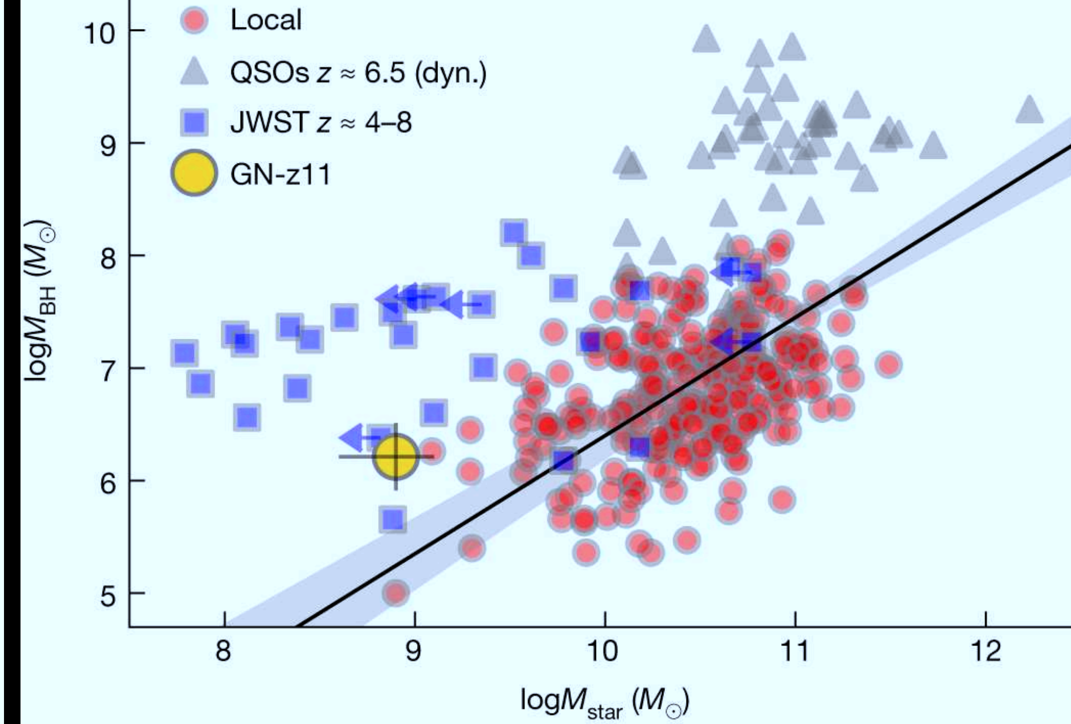
Approaches at –110 km/s.

Hence, Andromeda will merge with Milky Way!

The two blackholes (10^6–10^7 suns) will also merge!

Not to worry: only 4–5 Byr from today!





[Left] (Super Massive) Black Hole growth may start before z≃20 (175 Myr).

[Right] This results in overweight SMBHs compared to their host galaxies at z≃4–8 (or in the first 0.6–1.5 Byr)!

($e.g.$, Maiolino et al. 2024, Nature, 627, 59)

Who came first: chicken (Galaxy) or egg (SMBH)?: Most certainly the egg!