What the James Webb Space Telescope has Discovered by Seeing through the Eyes of Einstein

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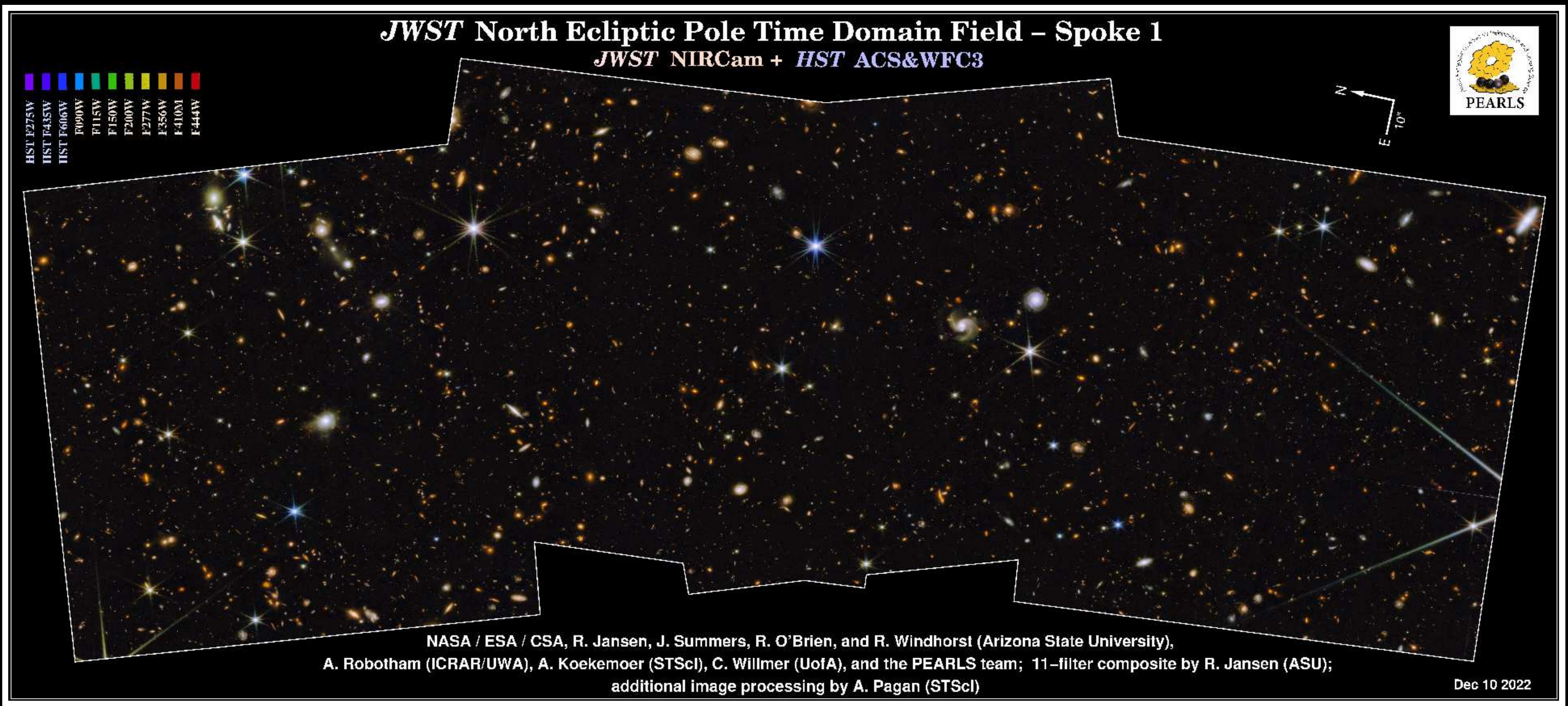


Review at the 33rd Texas Relativistic Astrophysics Symposium; Tempe, AZ

Friday December 12, 2025. All presented materials are ITAR-cleared. [FOV $\sim D_A/1000$].

Outline

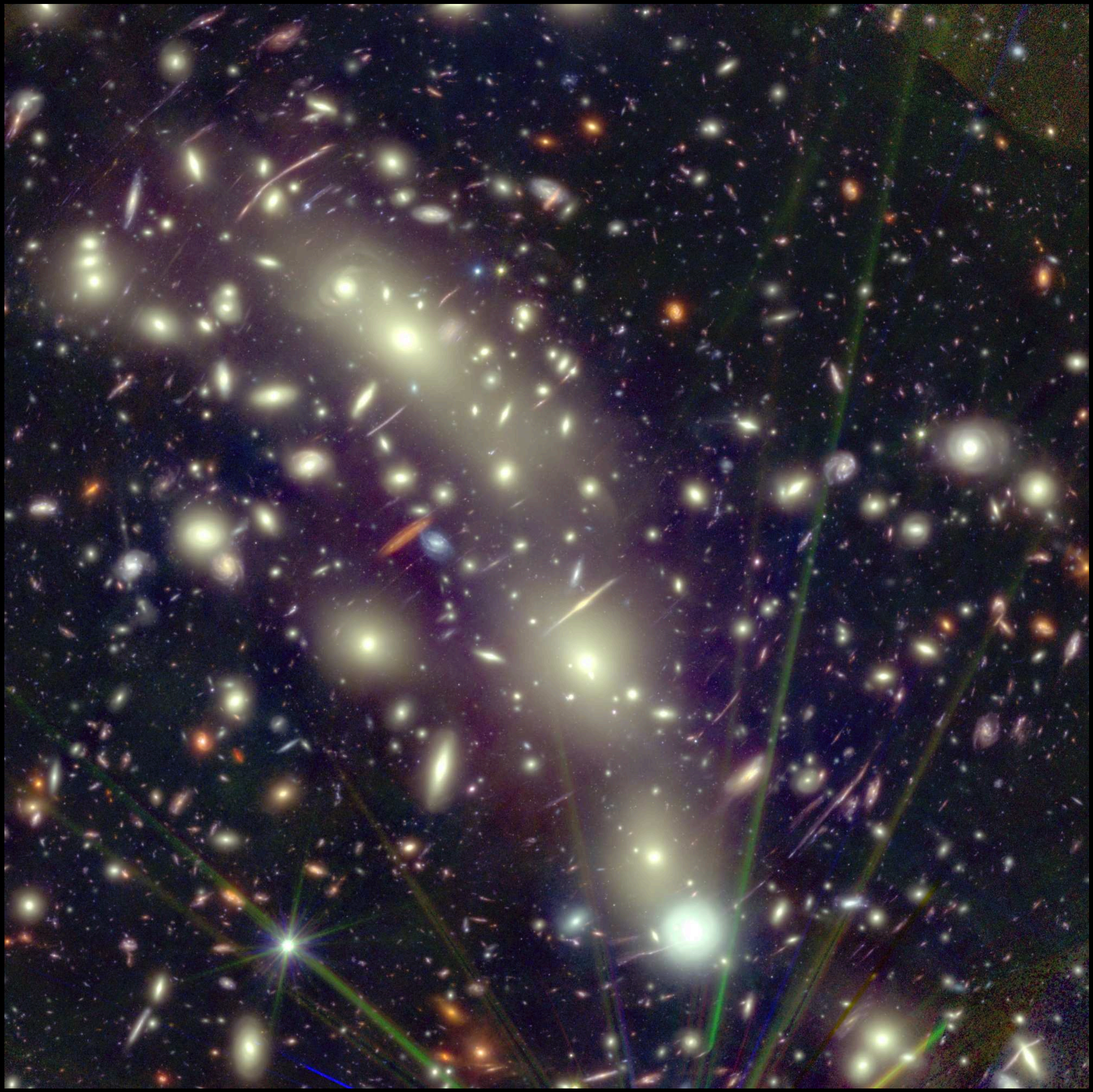
- (1) Uniquely complementary roles of Hubble and Webb
- (2) JWST: Viewing the Universe through the "Eyes of Einstein"
- (2a) JWST's view of Globular Clusters & ages over cosmic time
- (2b) JWST's lensed view of the first galaxies and first stars
- (2c) JWST constraints on Dark Matter: CDM vs. ΨDM
- (2d) Supermassive Black Hole Growth and its role in Galaxy Assembly
- (2e) Possible JWST constraints on nature of Dark Energy evolution
- (3) Summary and Conclusions

Sponsored by NASA/HST & JWST

Arizona State University

Talk is on: `http://lambda.la.asu.edu/raw/jwst/talks/texas25_jwst_v2.pdf`

(1) Uniquely complementary roles of Hubble and Webb:



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

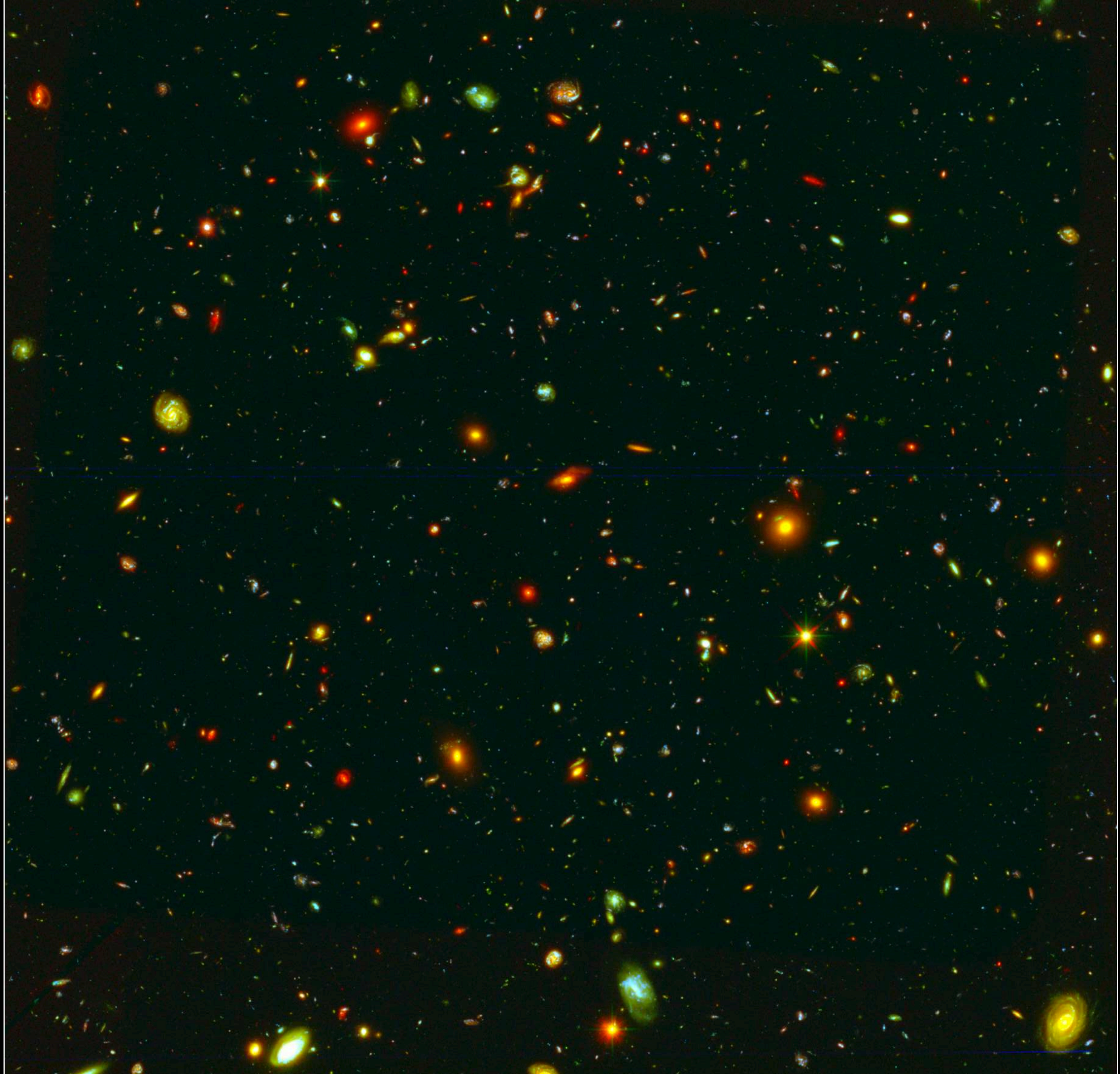
- HST darkest skies (10-$10^3\times$ darker) + JWST's dark skies (10^3–$10^5\times$ darker than ground based):

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

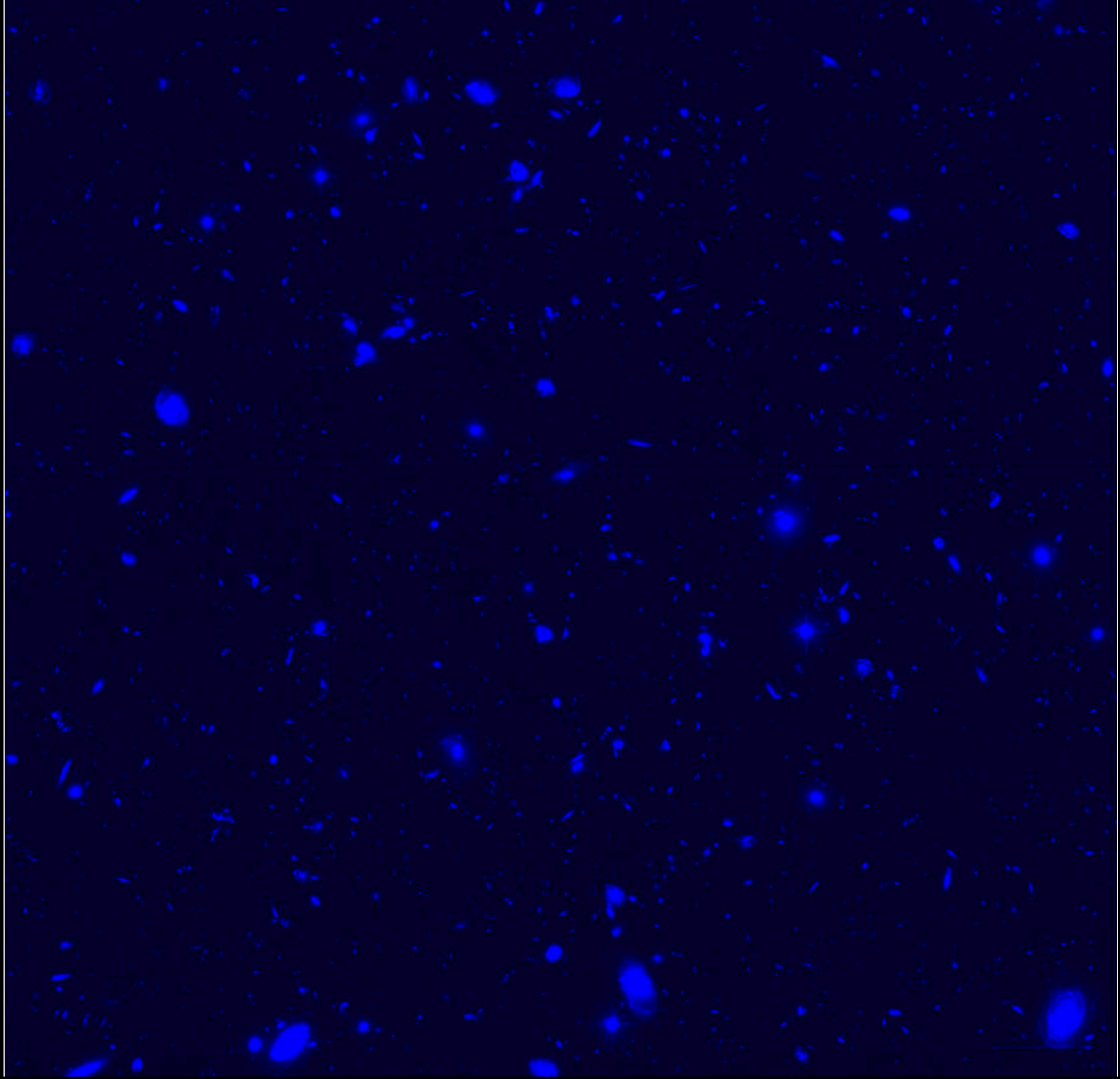
May 27, 2025: Deepest 120 hr JWST cluster image of Abell S1063 ($z=0.351$)!

Einstein's cosmic house of mirrors: many galaxies with supermassive black holes!

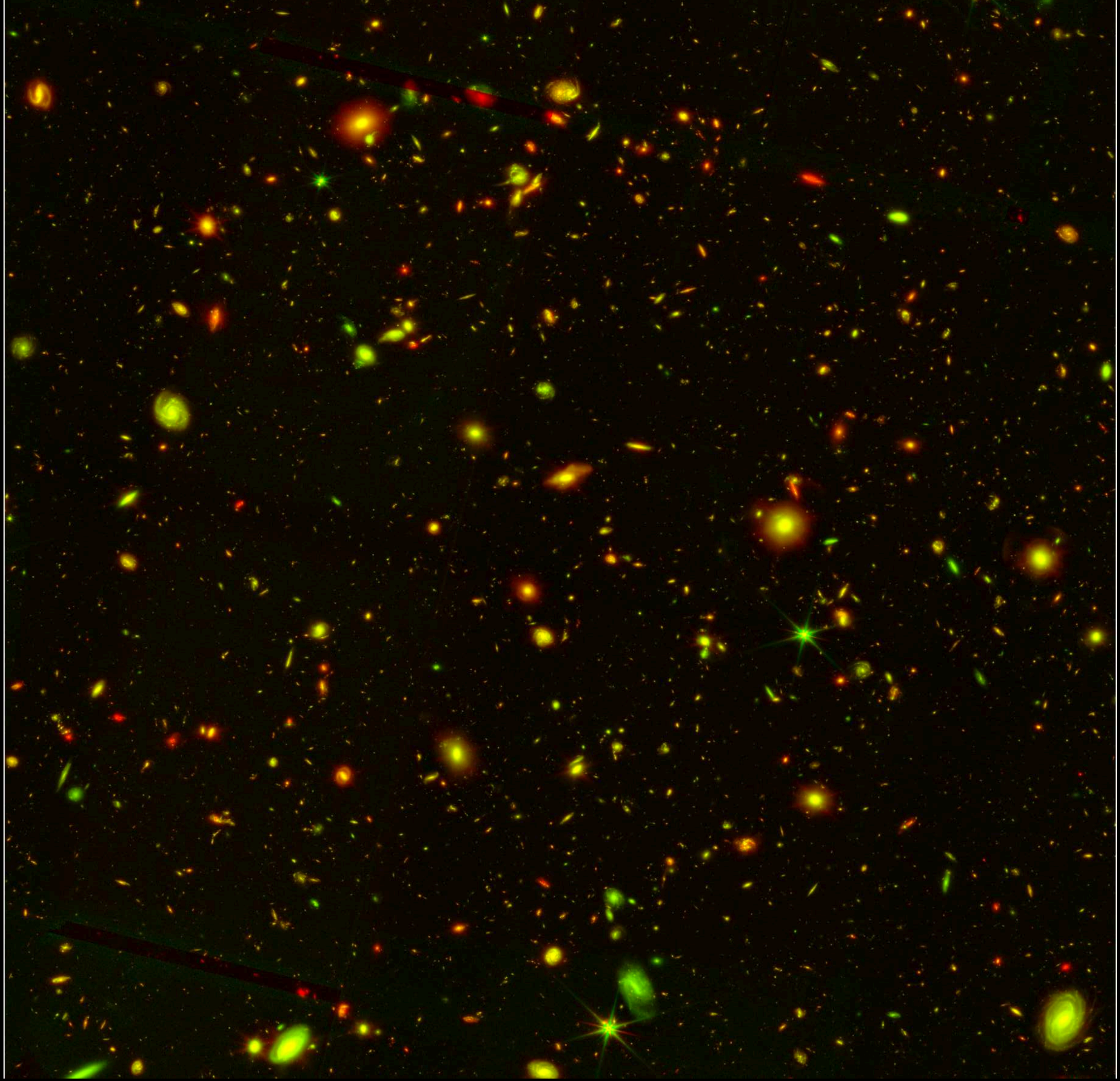
Atek$^+$ (2025): `https://www.esa.int/ESA_Multimedia/Images/2025/05/Webb_glimpses_the_distant_past`



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

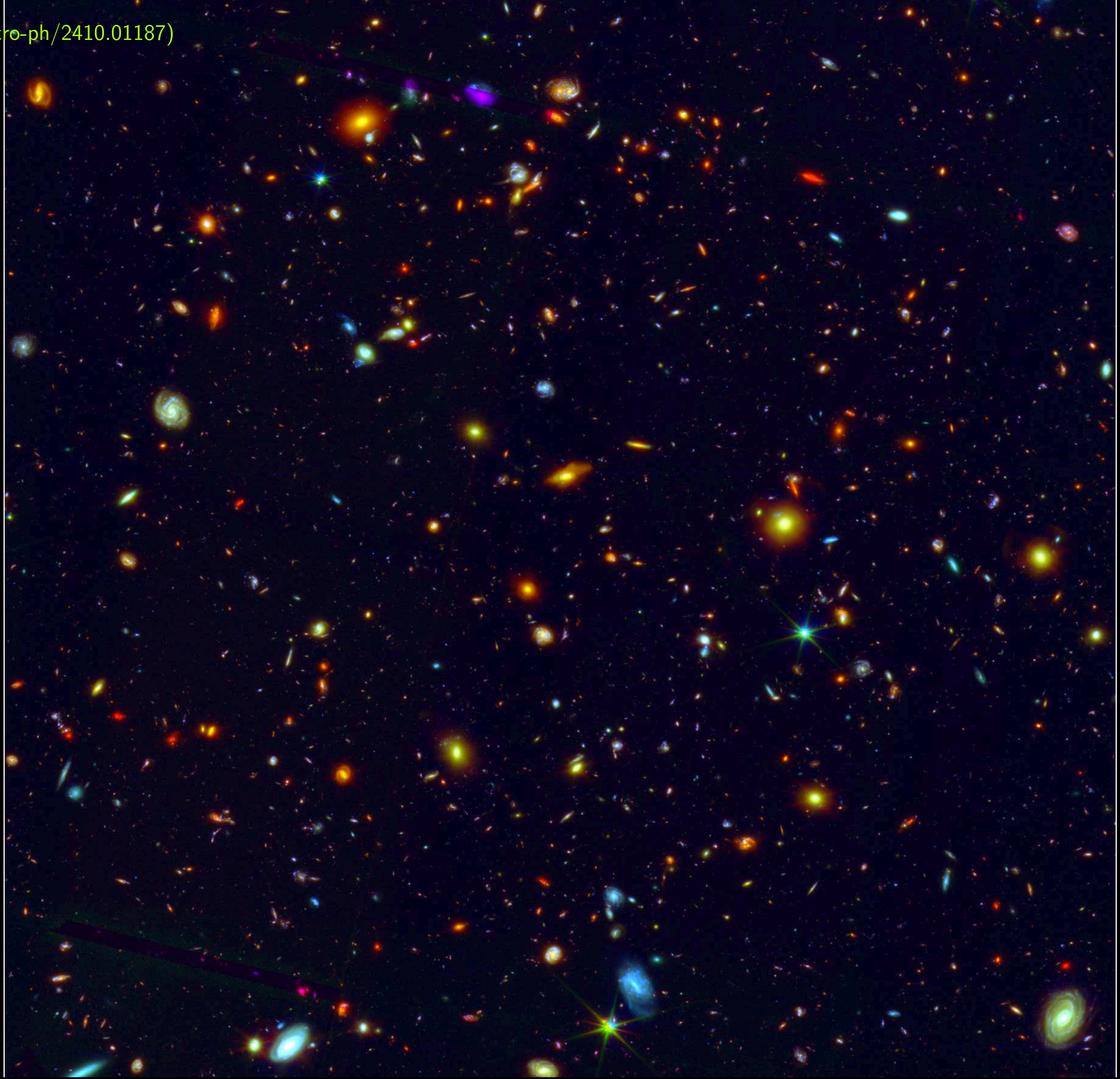


361 hr HST Hubble UltraDeep Field: 8 HST-unique filters 0.2–0.9 μm (in false color blue).



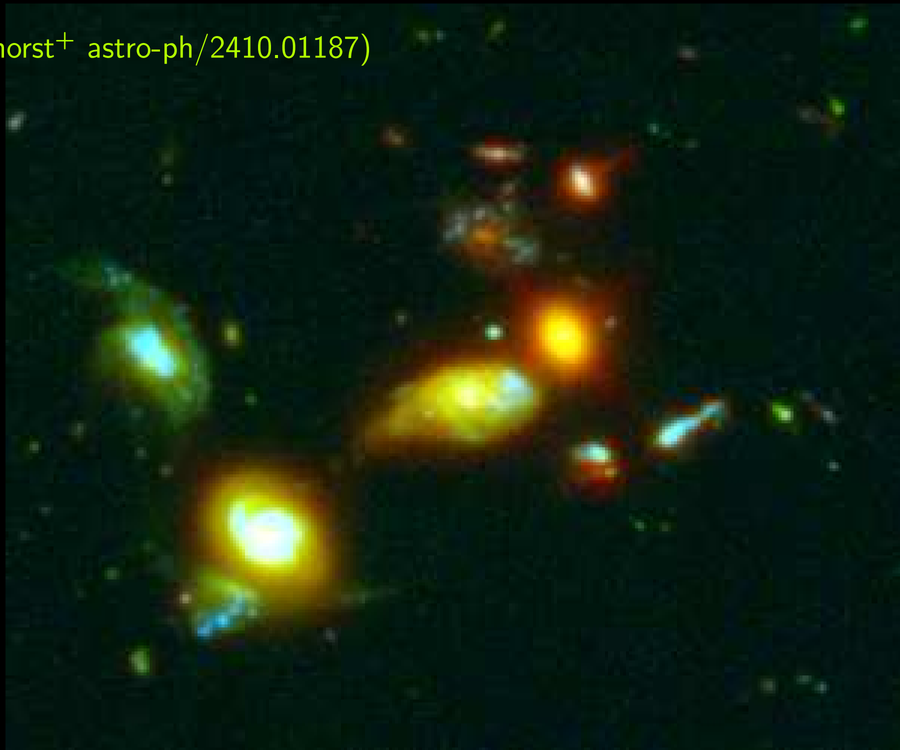
53 hr JWST/NIRCam Hubble UltraDeep Field: 12 filters at 0.9–5.0 μm (AB$\lesssim$31 mag; in green + red).

(Windhorst$^+$ astro-ph/2410.01187)

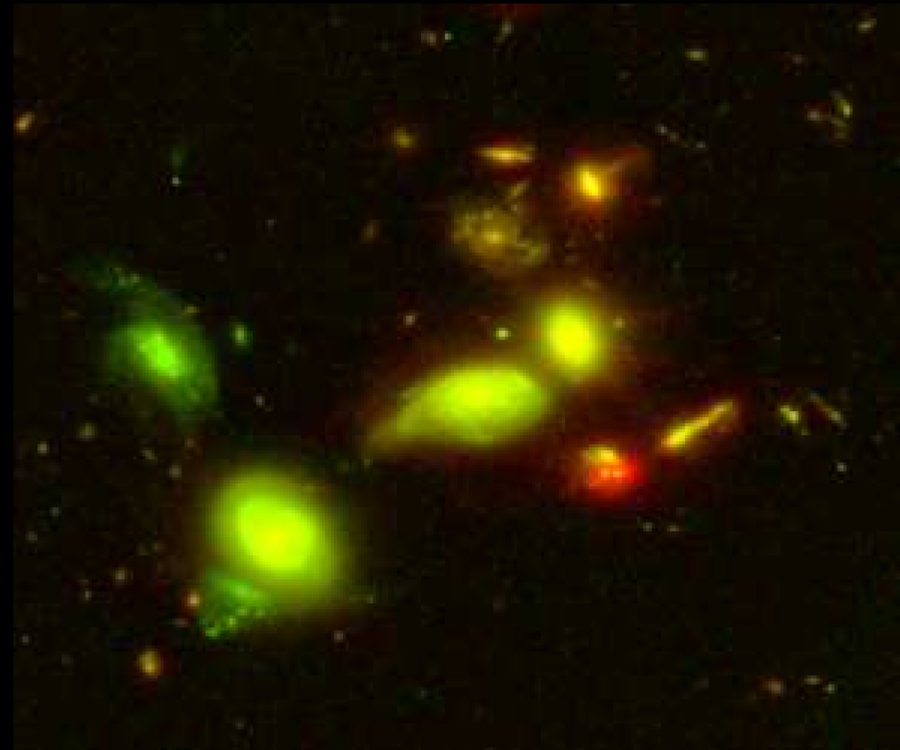


414 hr HST+JWST Hubble UltraDeep Field: 20 filters at 0.2–5.0 μm (AB$\lesssim$31.5 mag; full BGR).

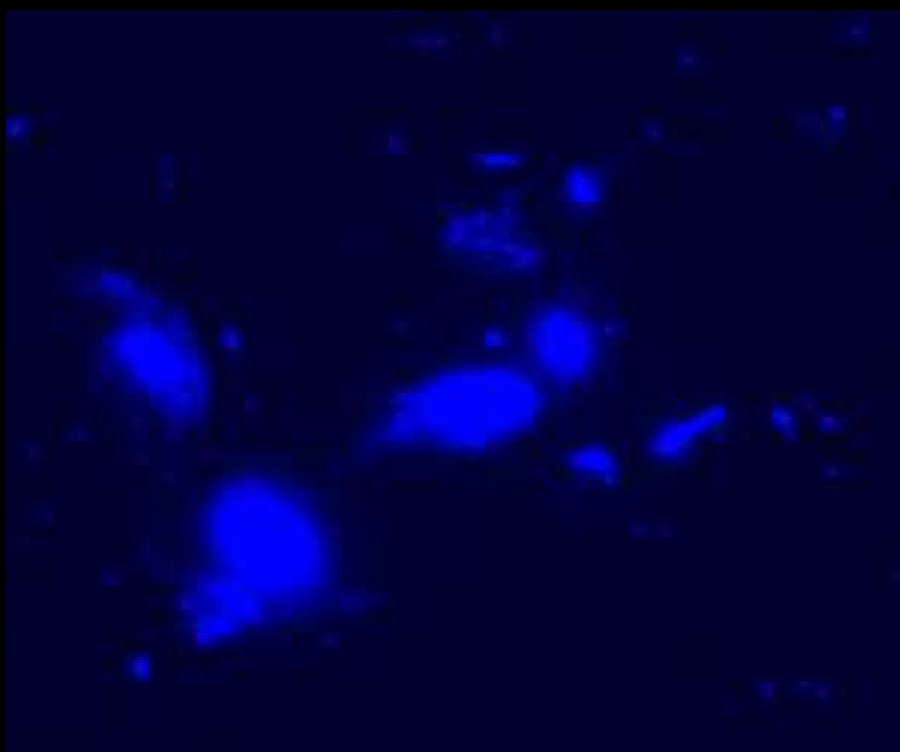
(Windhorst+ astro-ph/2410.01187)



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

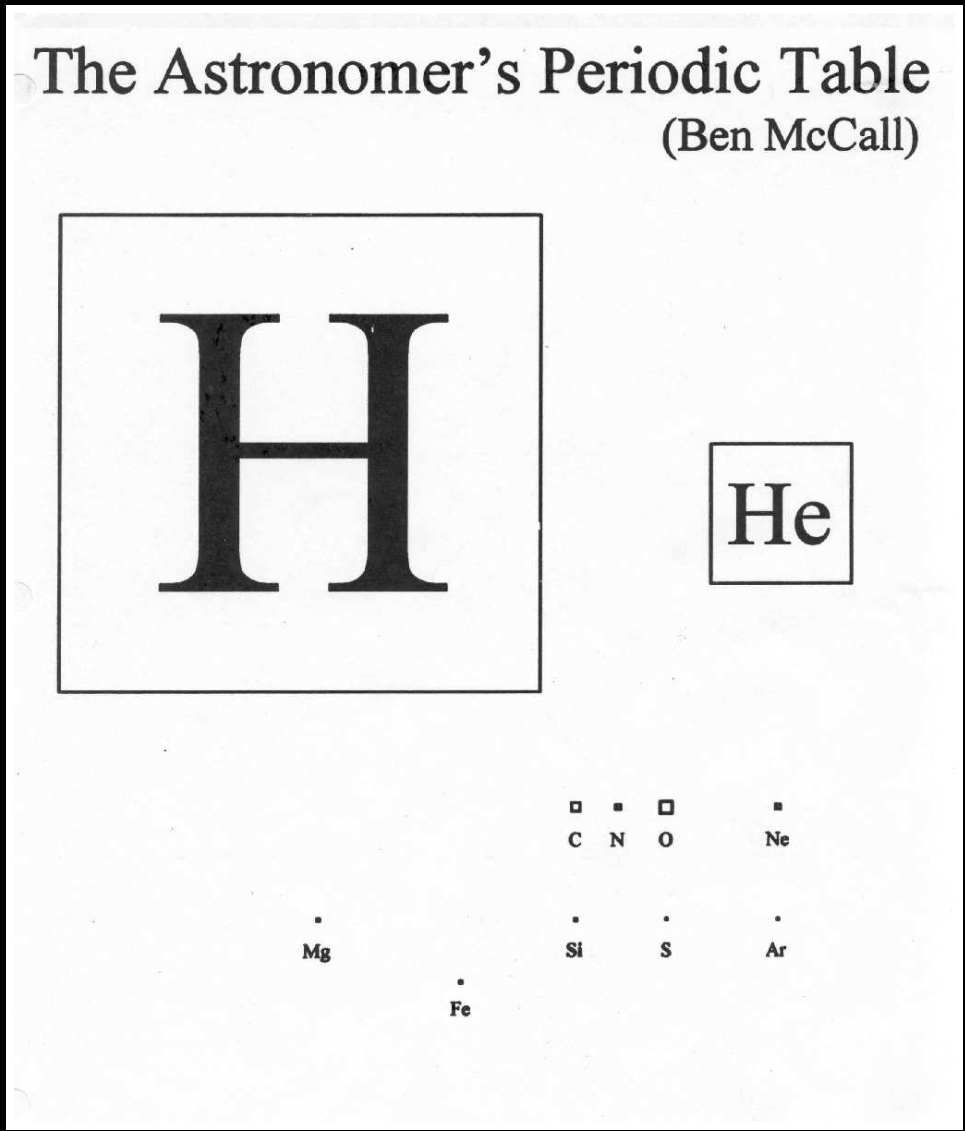
Implications from the actual Astronomer's Periodic Table:

(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 made from the 1% baryonic stardust!

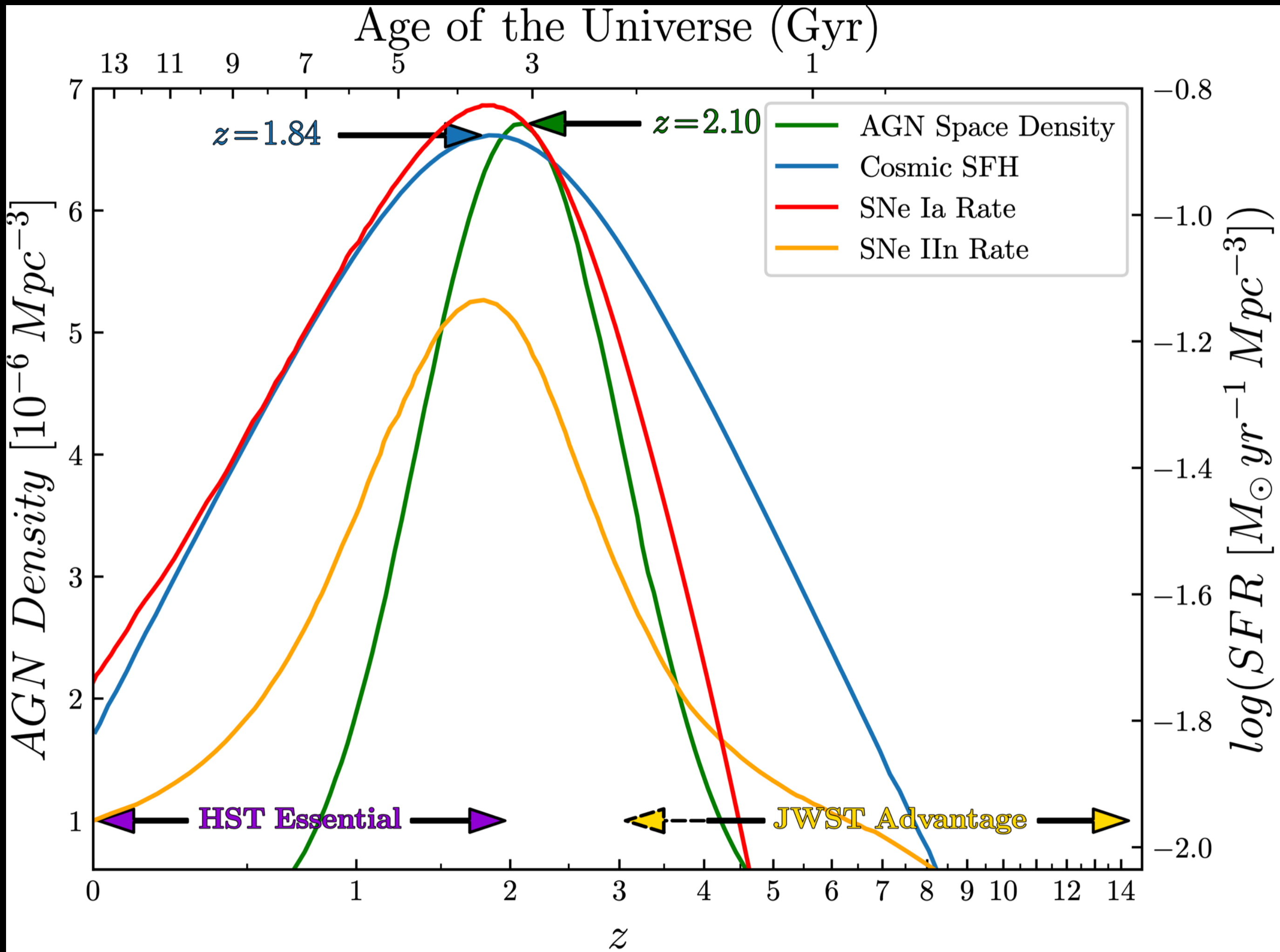


- The real Periodic Table with cosmic abundance included and has significant consequences for Hubble and Webb complementarity!

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

Windhorst et al.

astro-ph/2410.01187

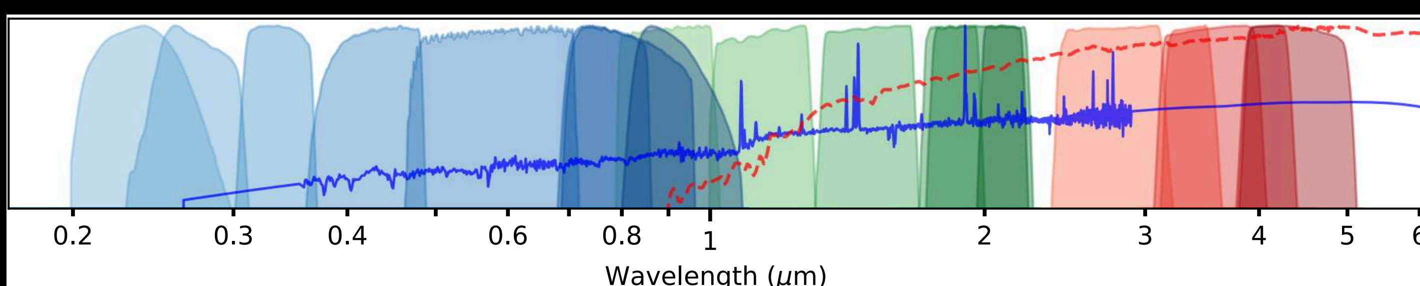


$$\mathbf{Age} \sim \frac{13.8}{(1+z)} + \ldots\ \mathbf{Gyr}$$

Active galactic nuclei (AGN)

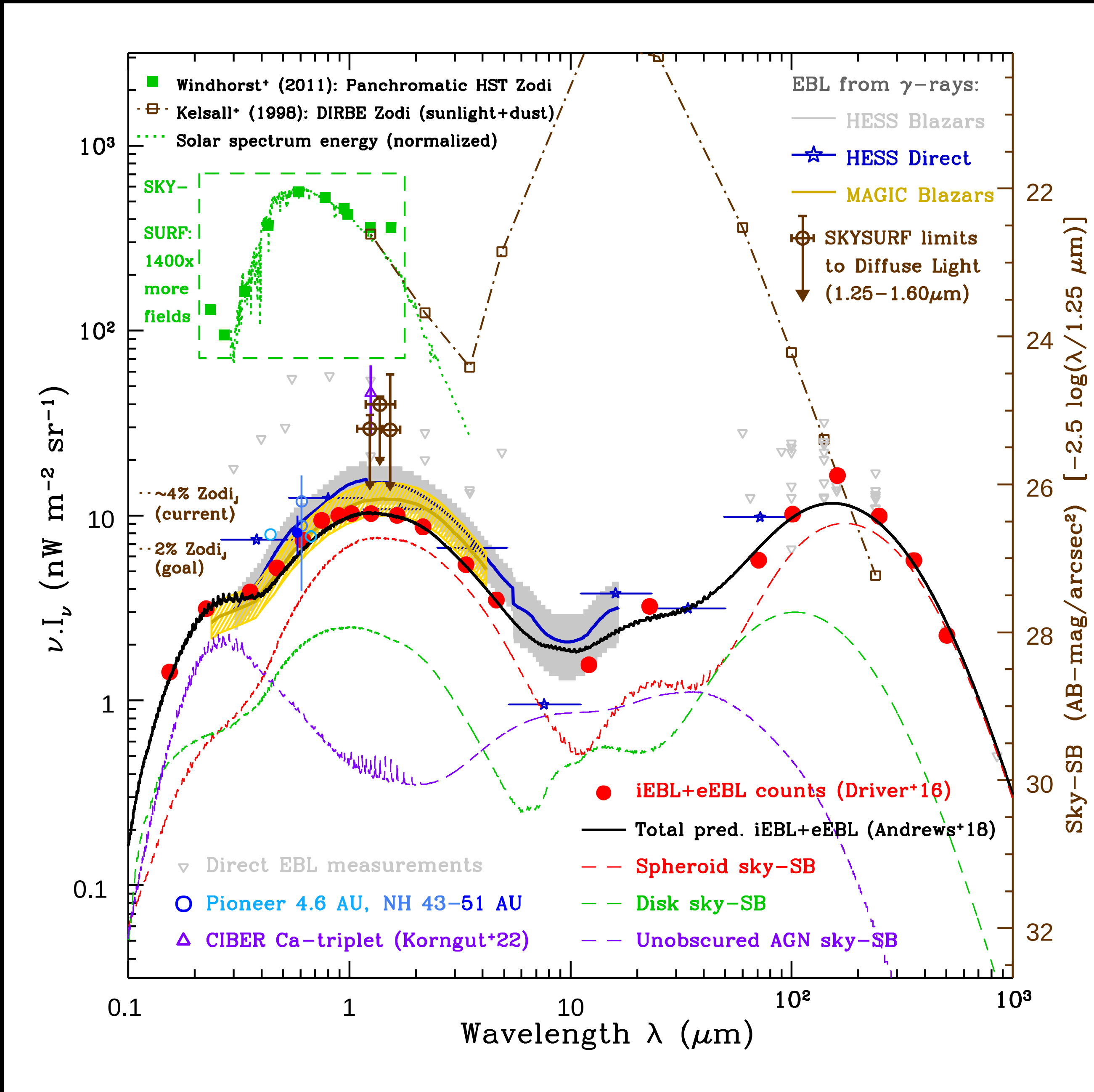
⟺ BH accretion disks

⟺ Chandra X-ray sources



⇒HST best samples *unobscured* SFH & BH growth in last 10 Gyr (z≲2), while JWST best samples *obscured* parts, especially in first 3 Gyr (z≳3).

Fly's-eye energy in Universe vs. λ: (Driver+ 2016; Windhorst+ 2018, 2022, 2023):



Sunlight scattered off the Zodiacal dust +

thermal radiation from $\gtrsim$240 K Zodiacal dust:

$\gtrsim$95% of HST photons come from $\lesssim$3 AU!

$\gtrsim$98% of JWST photons come from $\lesssim$3 AU!

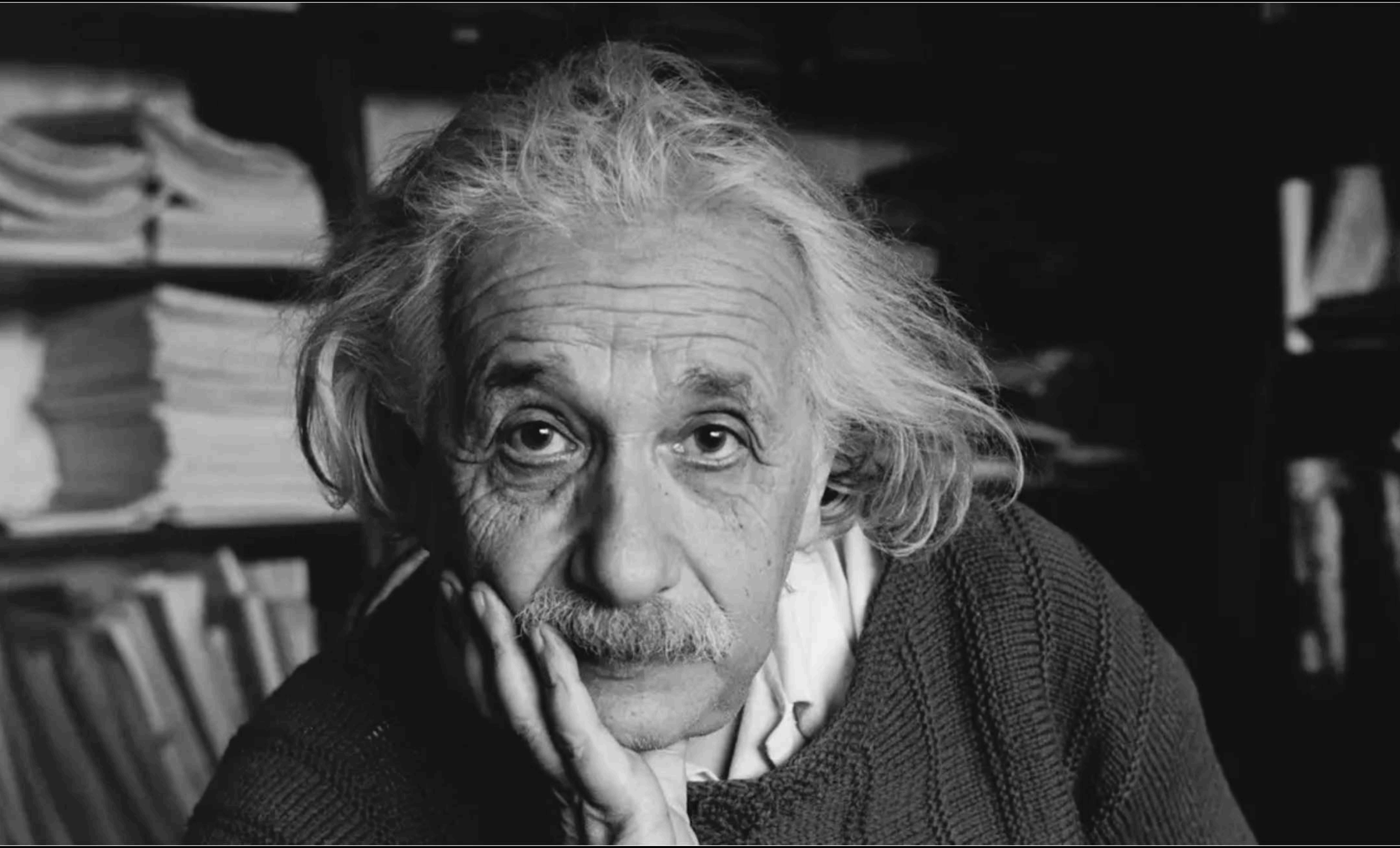
• integrated light from galaxy counts (+models).

SKYSURF 1.25–1.6 μm diffuse light (Carleton+ 2022; O'Brien+ 2023, 2025; McIntyre+ 2024).

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

• $\Rightarrow$ 1% of the baryons ("dust") produce ~52% of Energy (except CMB)!

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

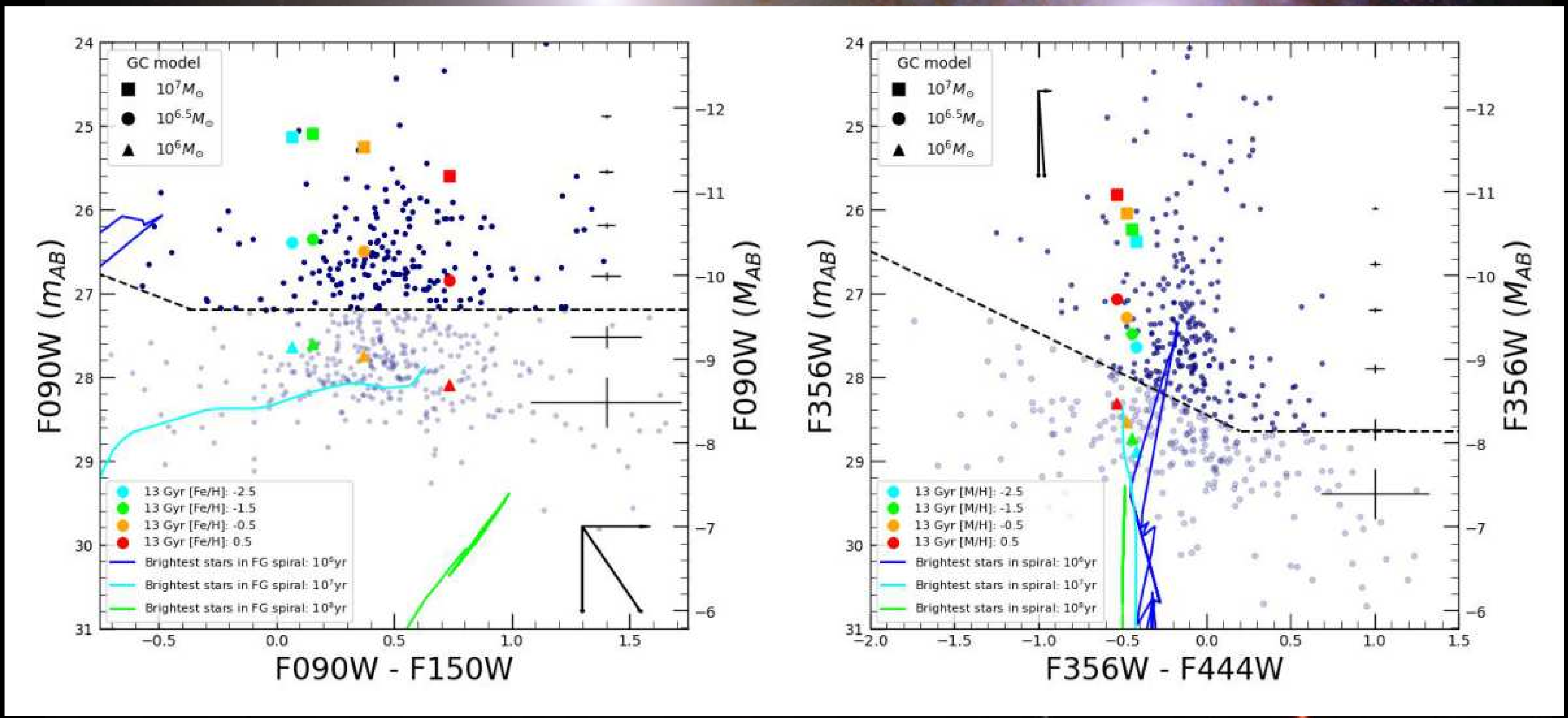


Webb is observing many things Einstein correctly predicted, yet doubted:

Gravitational lensing, Black Holes, the Hubble Expansion, Λ ...

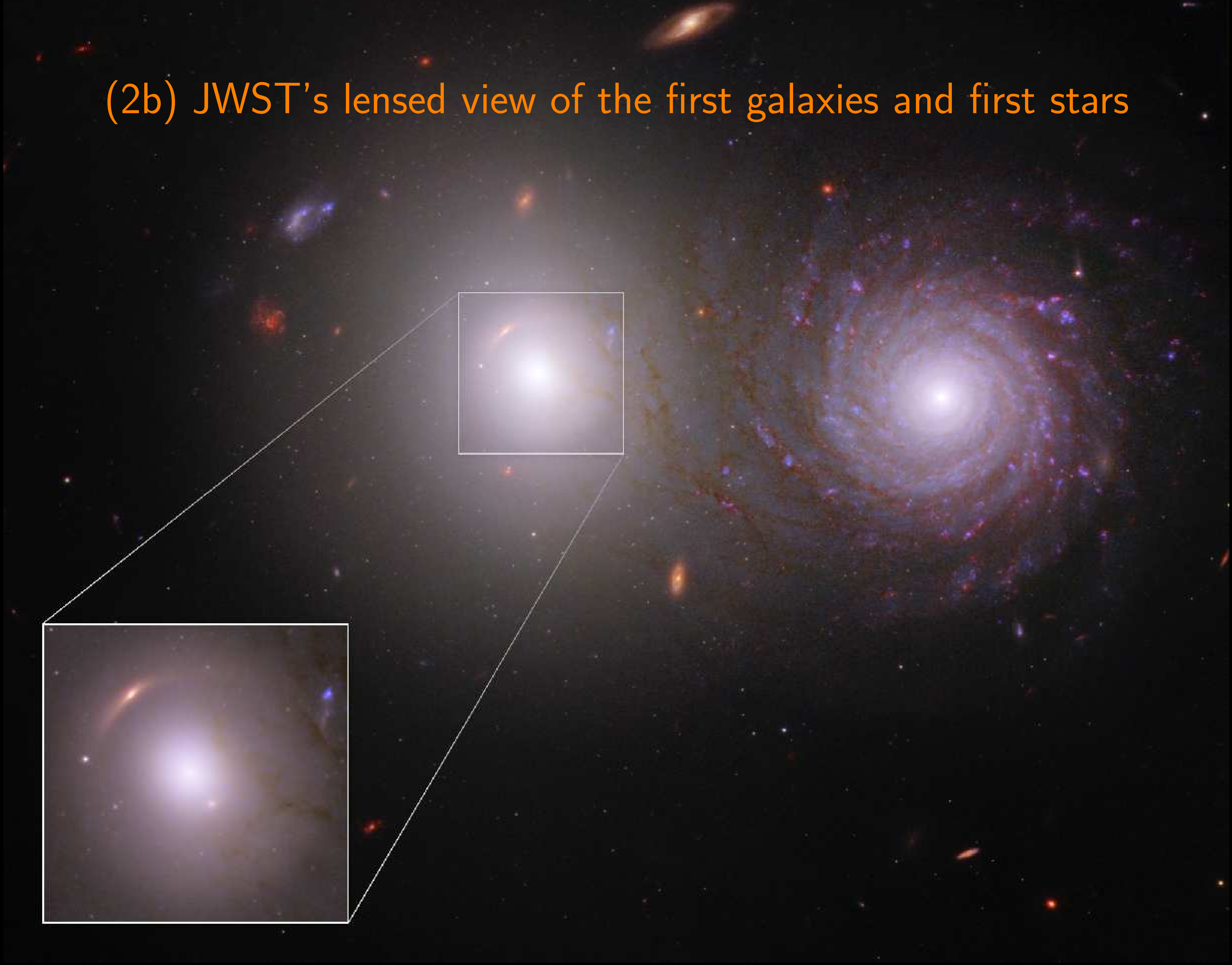
(2a) JWST's view of Globular Clusters & ages over cosmic time

- Spiral overlaps elliptical VV191: Tracing small dust grains! ($R_V \sim 1.7$; Keel$^+$ 23).
  - 150 Globular Clusters in $z=0.0513$ Elliptical (Berkheimer$^+$ 2024, ApJ, 964, L29).



- Spiral overlaps elliptical VV191: Tracing small dust grains! ($R_V \sim 1.7$; Keel+ 23).
- Webb measures GC masses/ages at large distances! (Berkheimer+ 2024, ApJ, 964, L29).

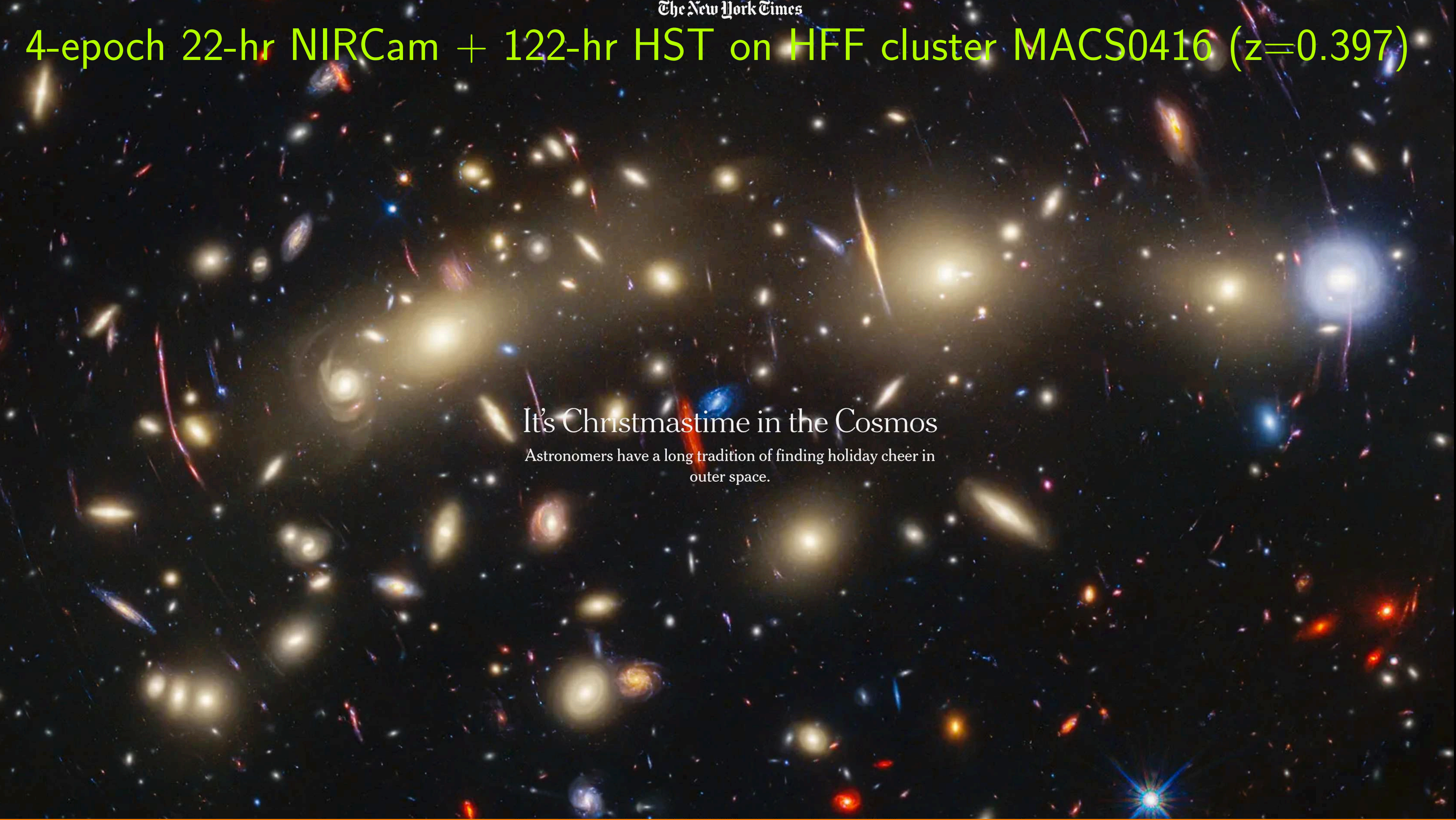
(2b) JWST's lensed view of the first galaxies and first stars



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

- Galaxy-Galaxy lensing is not uncommon with JWST (Adams+ 2025, MNRAS 543, 353; Ferrami+ 2025)

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

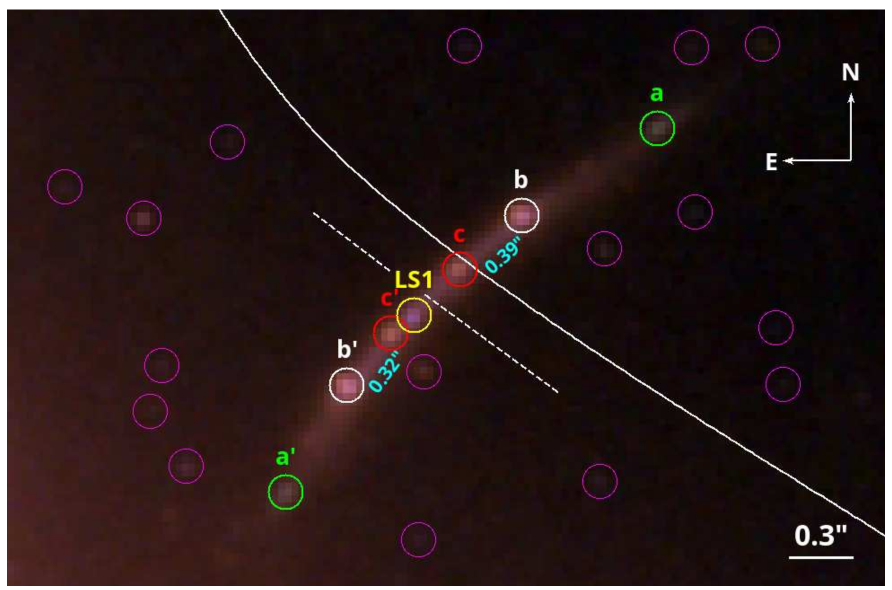


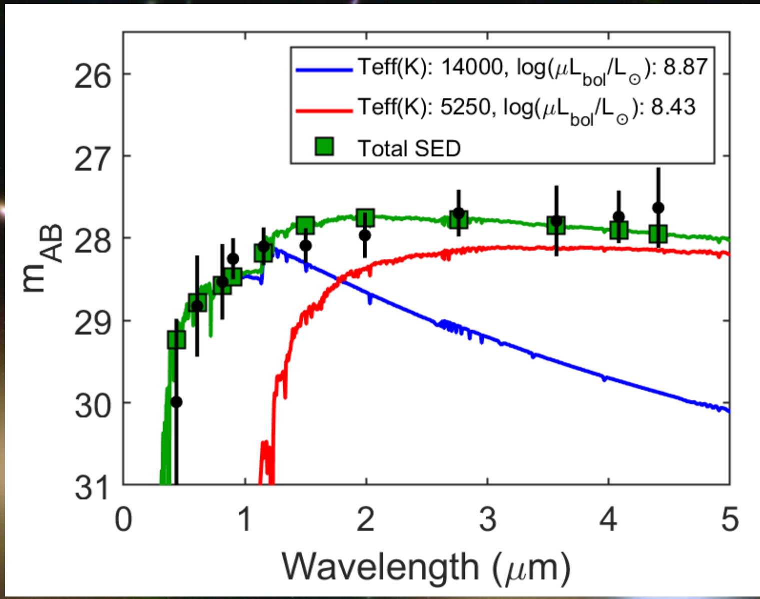
12 new caustic transits at $z \simeq 1$–2 from 4 epochs! (Yan, H.[+], 2023, ApJS, 269, 42)

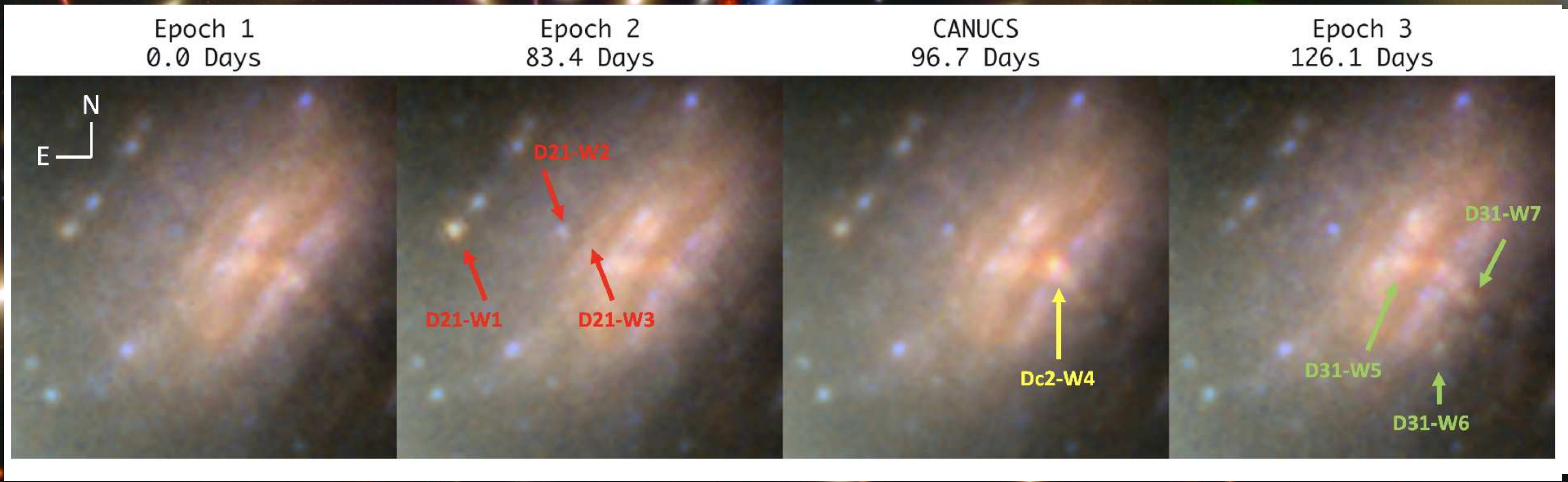
Extremely magnified binary star at $z=2.091$! (Diego, J.[+], 2023, A&A 679, A31)

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?





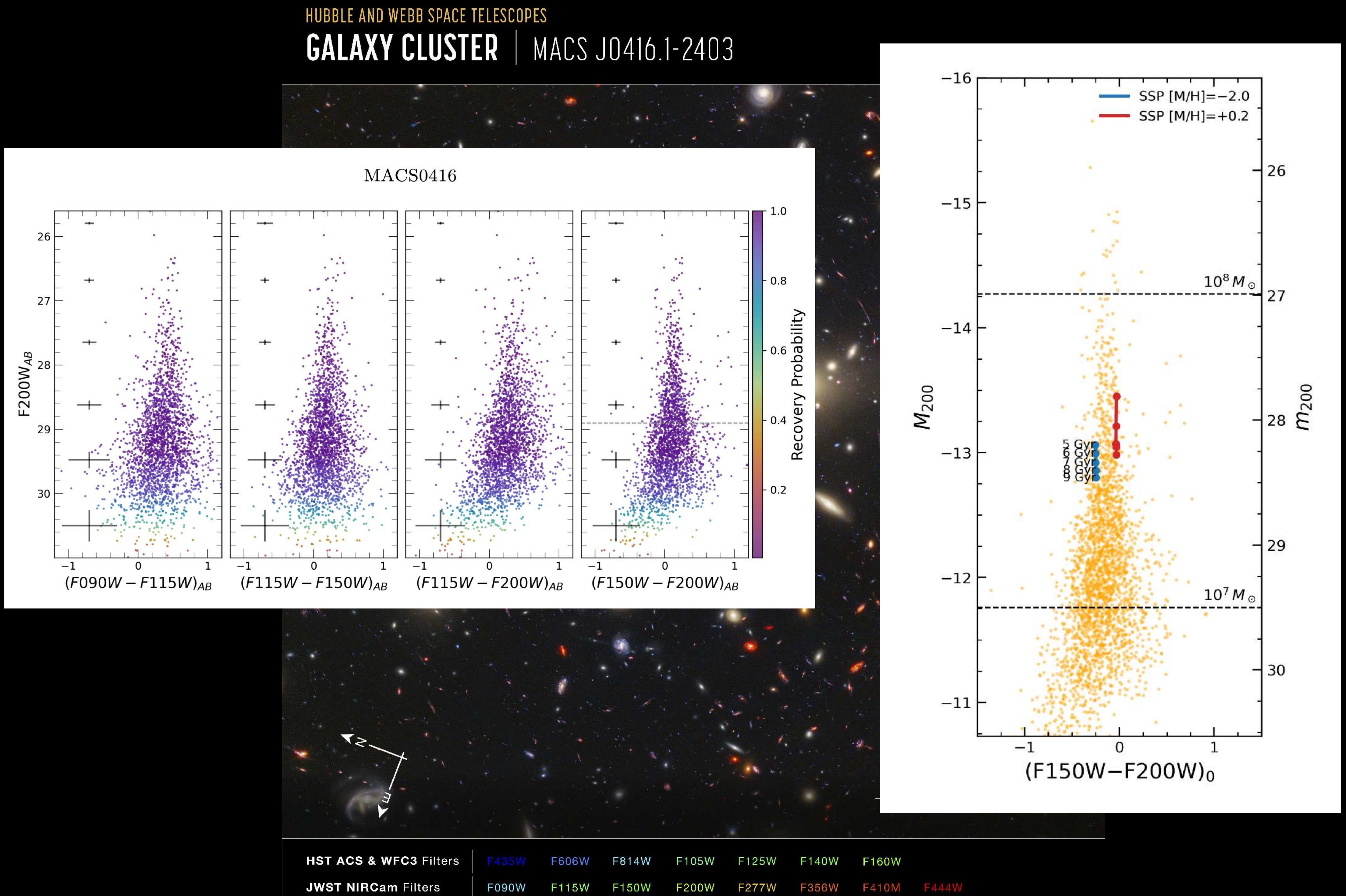


Yan, H.$^+$ (2023, ApJS, 269, 42): 12 new caustic transits at z≃1–2 from 4 epochs!

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

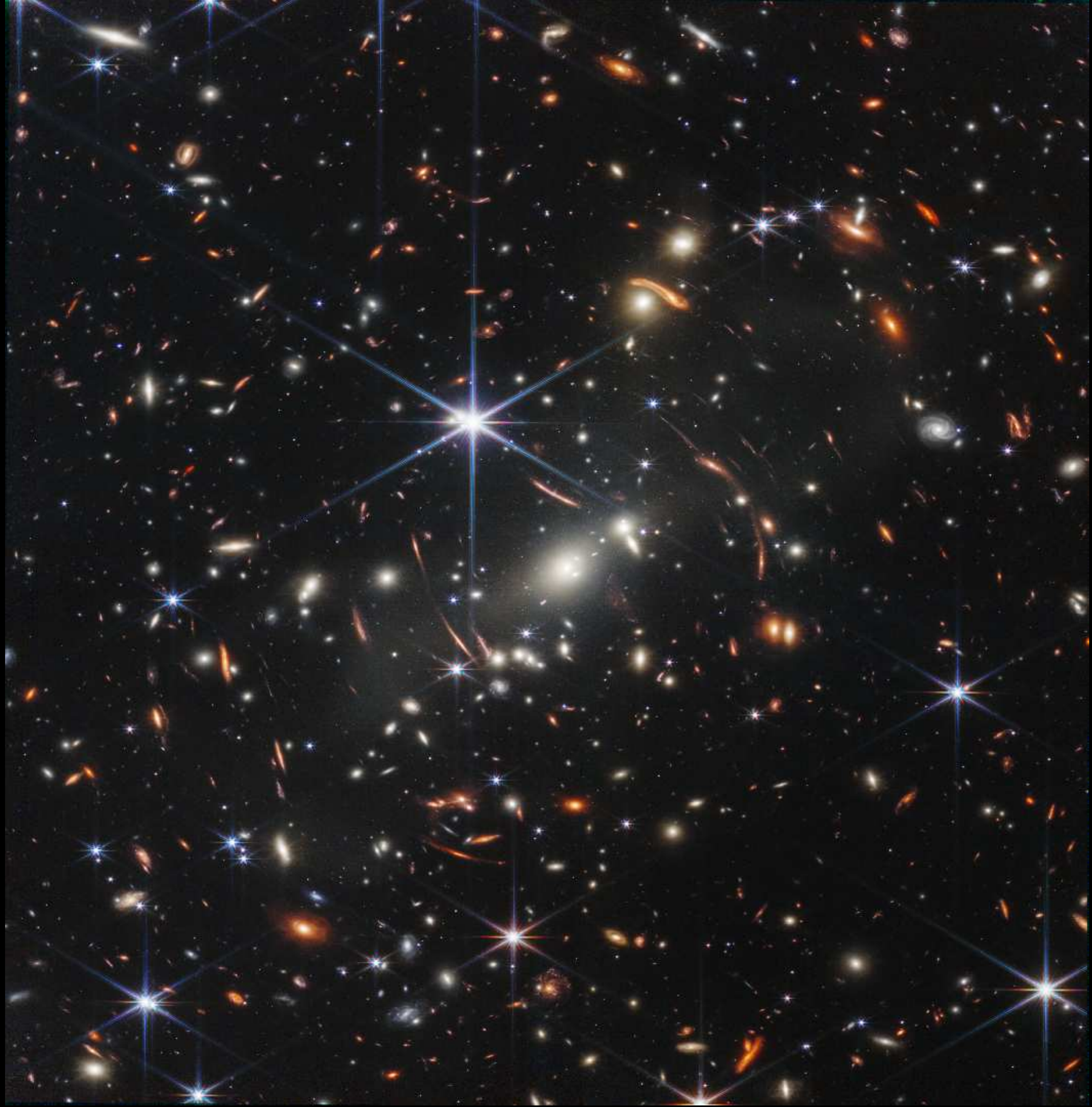
$\Longrightarrow$ Regular monitoring of several clusters can see stars at z$\gtrsim$1 directly!

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



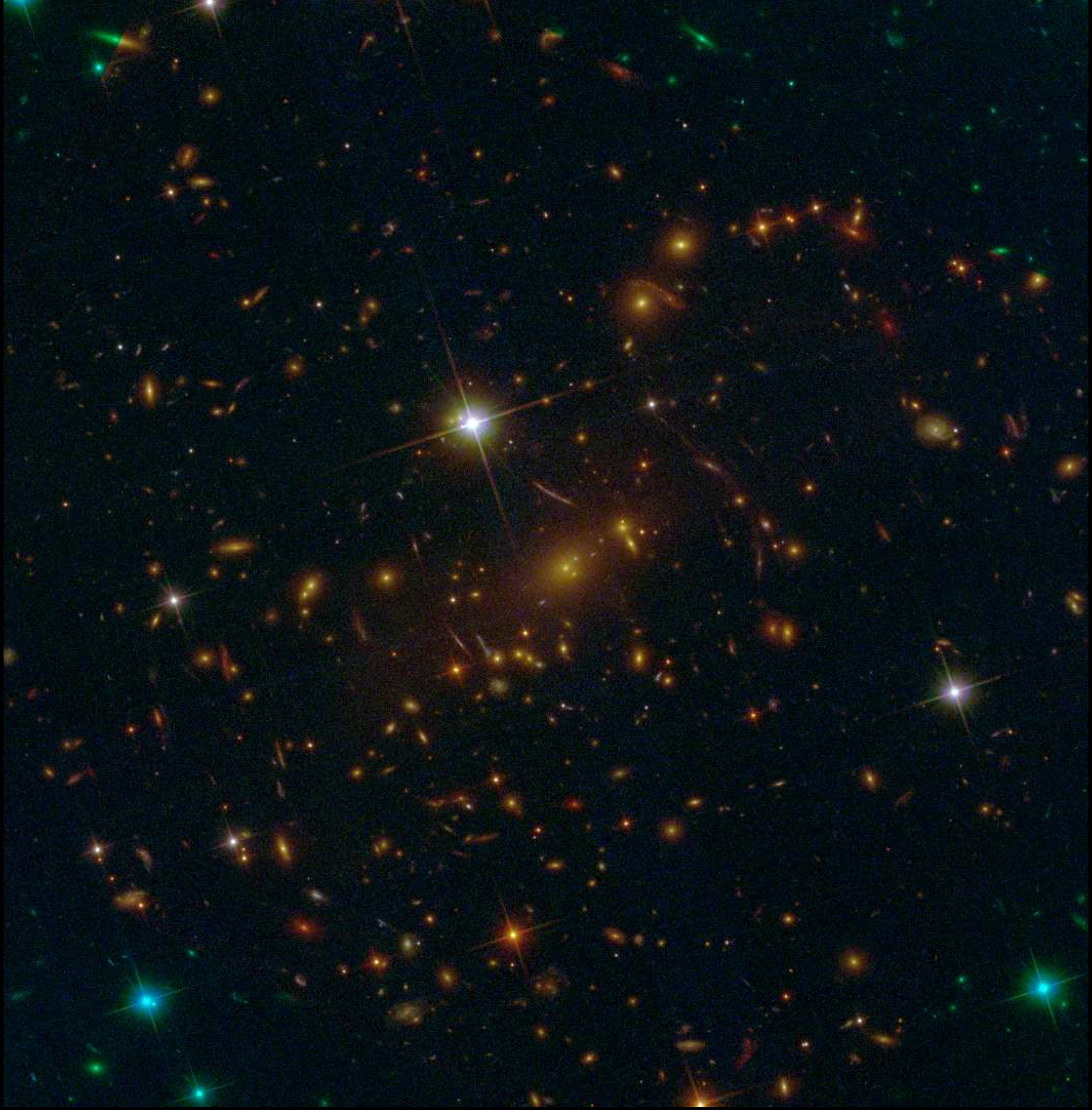
122 hr HST + 22 hr JWST on Frontier Field cluster MACS0416 (4.3 Blyr)

- 2900 Globular clusters in z=0.397 cluster MACS0416 (Berkheimer+ astro-ph/2508.03883)
  - Webb is measuring GC masses/ages at cosmological distances!



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

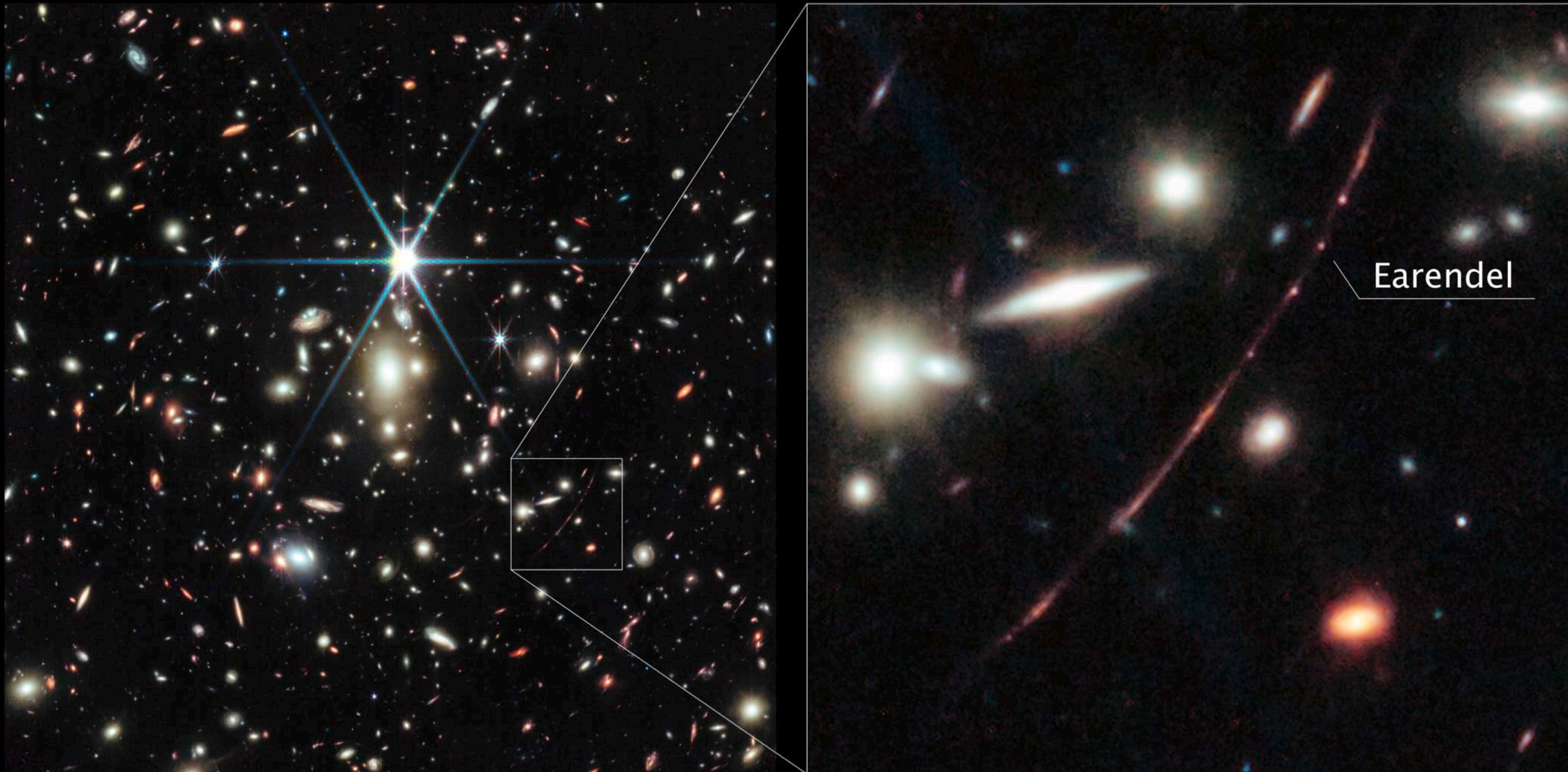
- Cluster galaxies already are $\sim$9 Byrs old, seen at 4.5 Blyr distance!



Hubble image of SMACS 0723: not the same depth and breadth as Webb!

- Cluster $3\times$older than the Earth today: we are cosmic late bloomers!

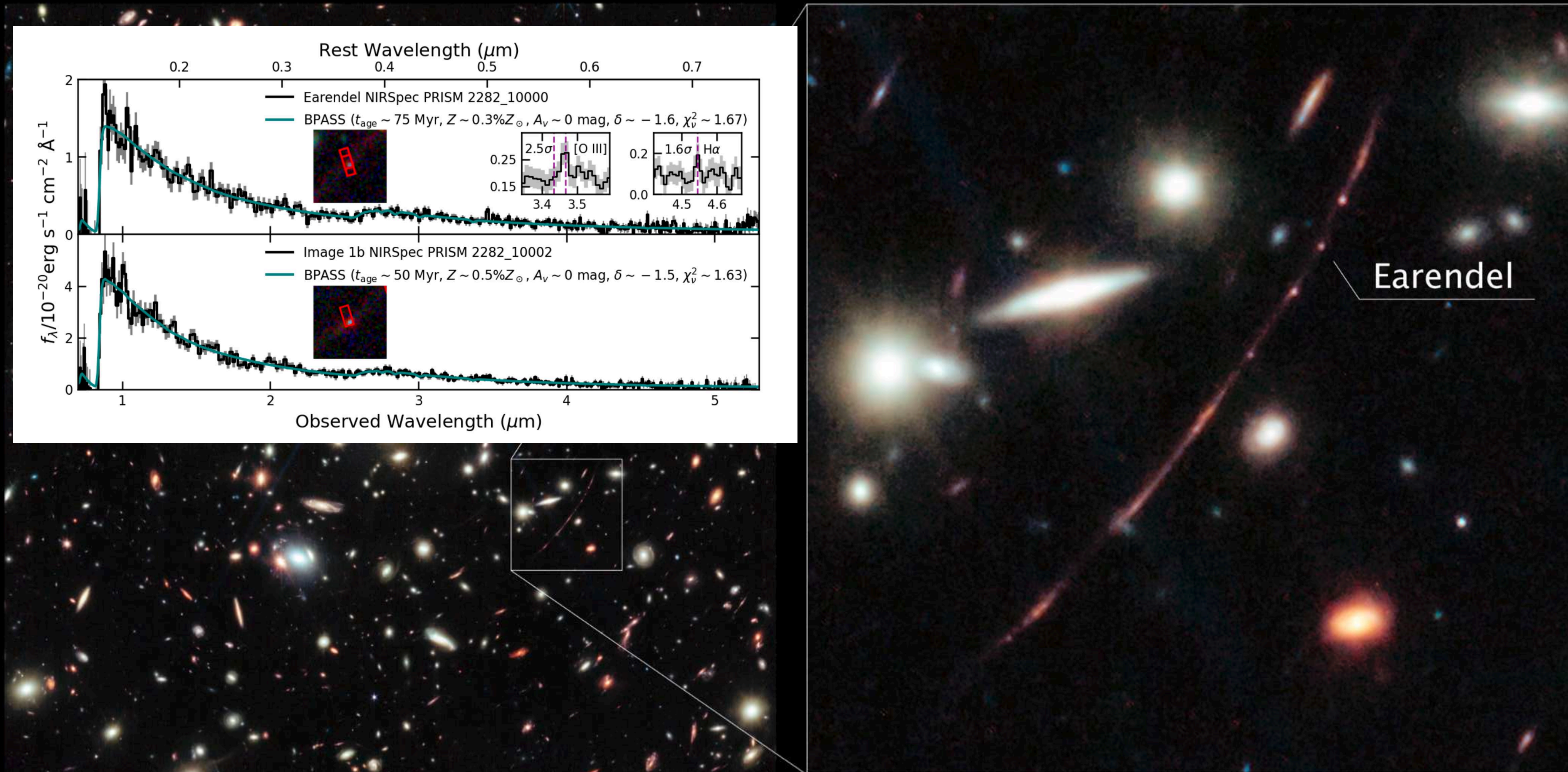
Cluster MACS0647 triply lensed a galaxy 0.4 Byrs after BB! (Hsiao, Coe^{+} 22)



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

- Earendel: a highly magnified $\mu\sim$9000 (double-)star seen in the first billion years after the Big Bang: the most distant star ever observed directly!

(Welch, B., Coe, D., et al. 2022, ApJ, 940, L1; astro-ph/2208.09007; — 2022, *Nature*, 603, 815; astro-ph/2209.14866).



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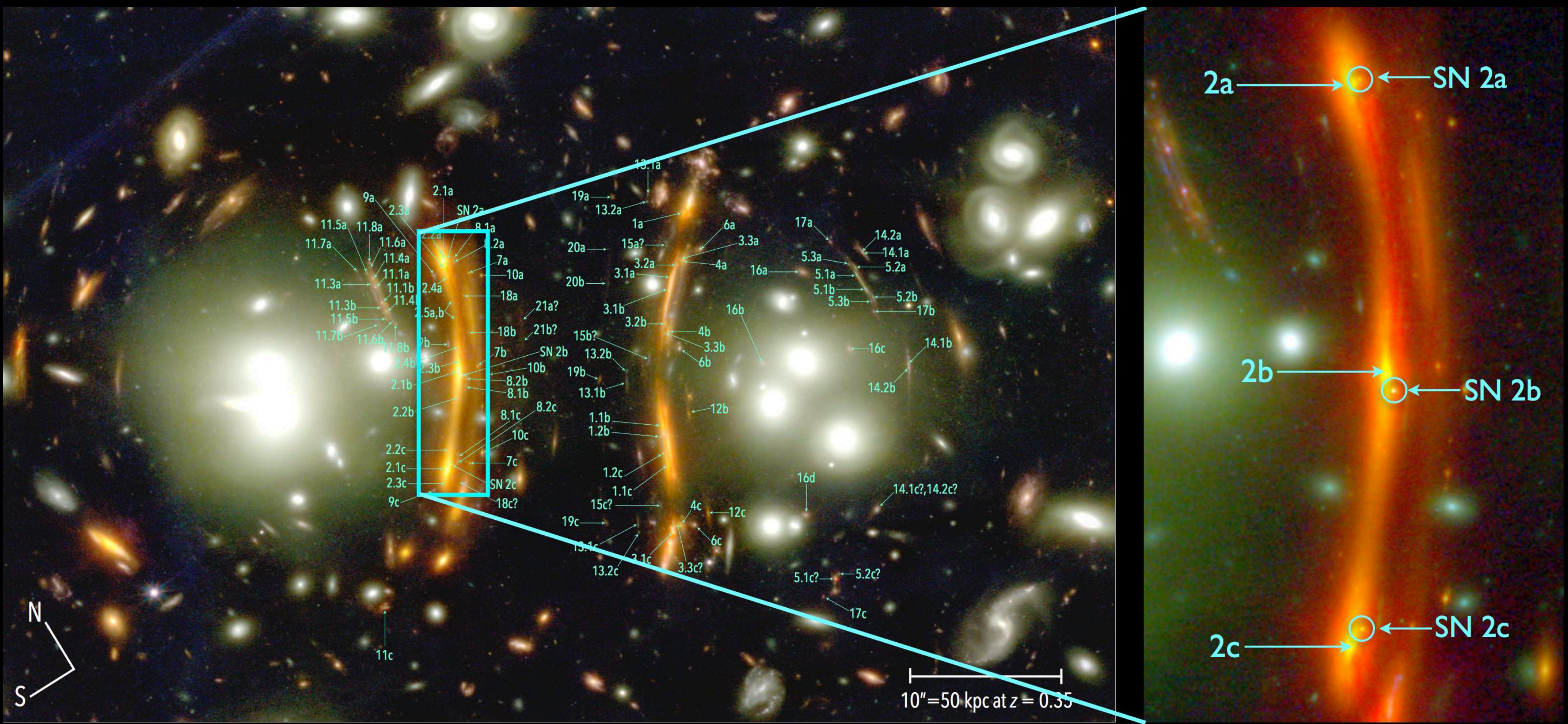
- NIRSpec: Earendel (part of) ~75 Myr, 0.003 Z_o Globular Cluster at z≃5.926 (Pascale$^+$ 2025, ApJL, 988, L76).

JWST image of most luminous far-IR Planck cluster G165 at z=0.35 found:
Lensed Supernova Ia "H0pe" at z=1.78 → $H_o = 75.4^{+8.1}_{-5.5}$, 10 Byrs ago!

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



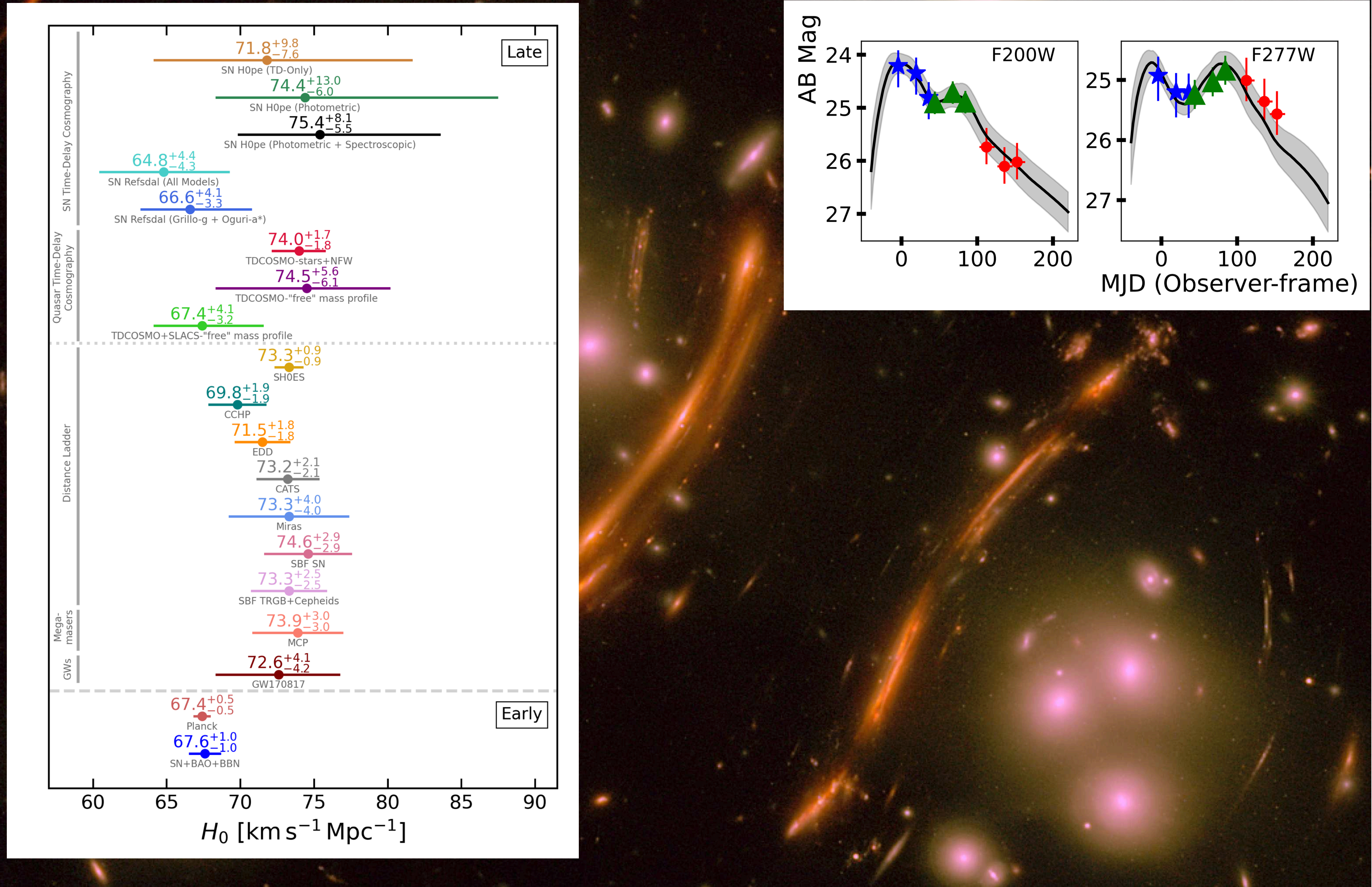
NIRCam in G165 shows: 3 bright point sources parity-flipped w.r.t. Arc-2:

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

(Polletta+ 2023, Frye+ 2024, Chen+ 2024, Kamieneski+ 2024, Pierel+ 2024, Pascale+ 2025); see also talks by Massimo Pascale & Brenda Frye).

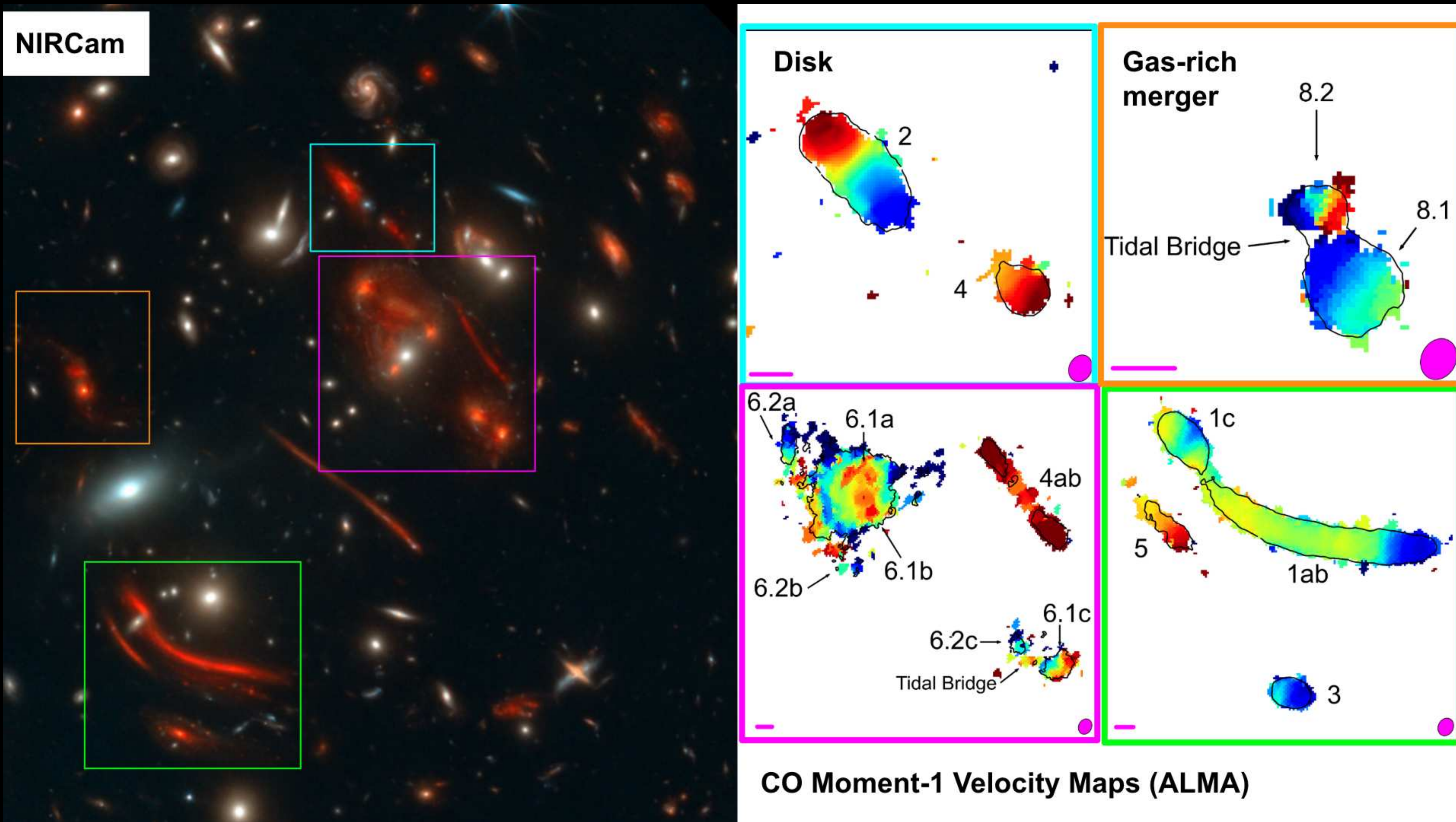
$\longrightarrow$ Regular monitoring of clusters with extreme SF to yield more lensed SNe!

- Total SFR$\simeq$200–350 $M_{\odot}$/yr predicts $\gtrsim$1 lensed SN/yr (Kamieneski+ 2024, ApJ, 973, 25)



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

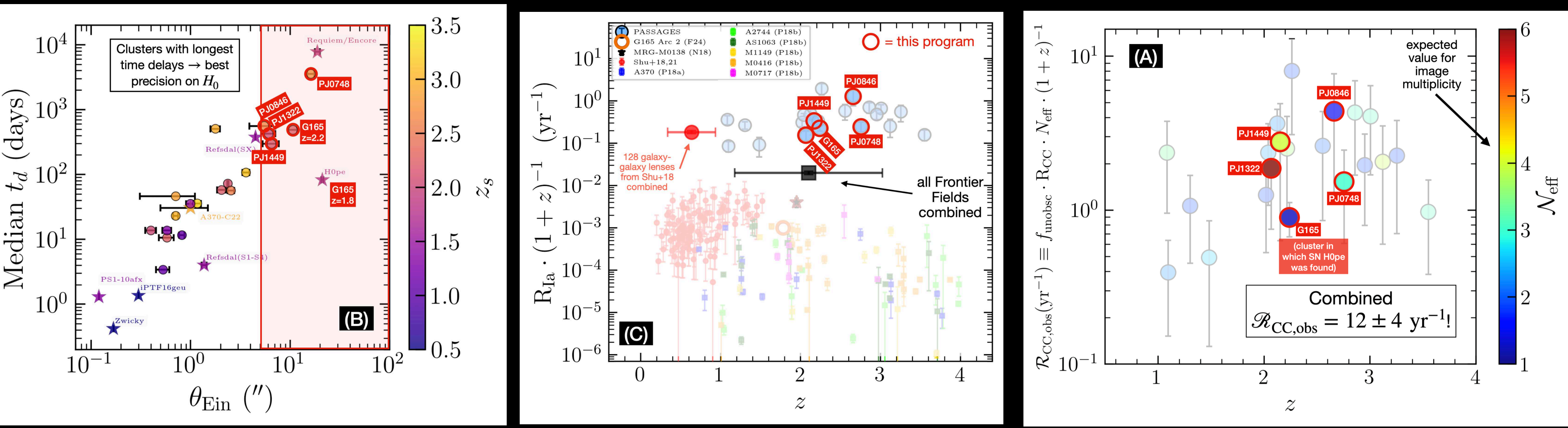
- Monitoring G165 predicts $\gtrsim$1 lensed SN-Ia/yr ! (Kamieneski+ 2024, ApJ, 973, 25)



How to find clusters with highest lensed Supernova rate to improve $\boldsymbol{H_0}$?:

- Use the brightest Planck clusters with regular, merger-driven & chaotic star-formation, as seen by JWST (left) and ALMA velocity maps (right);

(Foo, N. et al. 2025, ApJ, in press, astro-ph/2504.05617; Kamieneski, P. et al. ApJ, submitted, astro-ph/2510.00923)



How to find clusters with highest lensed Supernova rate to improve $\boldsymbol{H_0}$?:

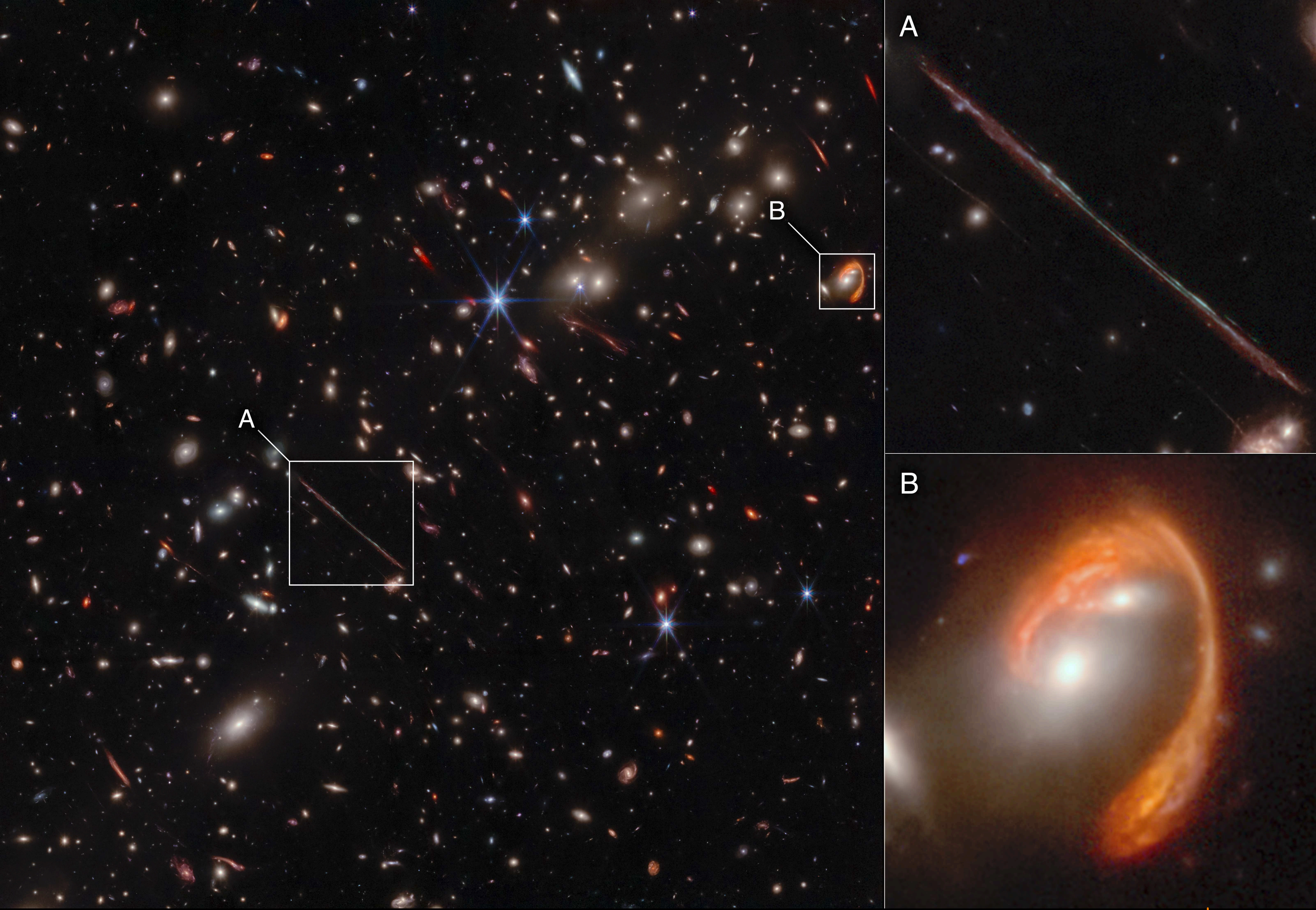
- Select the most massive clusters to get the largest Einstein angles and largest relativistic time-delays (within reason);

- Select the brightest Planck clusters with highest lensed SFR at z≃2–3;

- Observe a few times yearly with JWST to find gravitationally lensed SNe (SN rate ∼0.3–3/year for Type Ia SNe to Core Collapse SNe!);

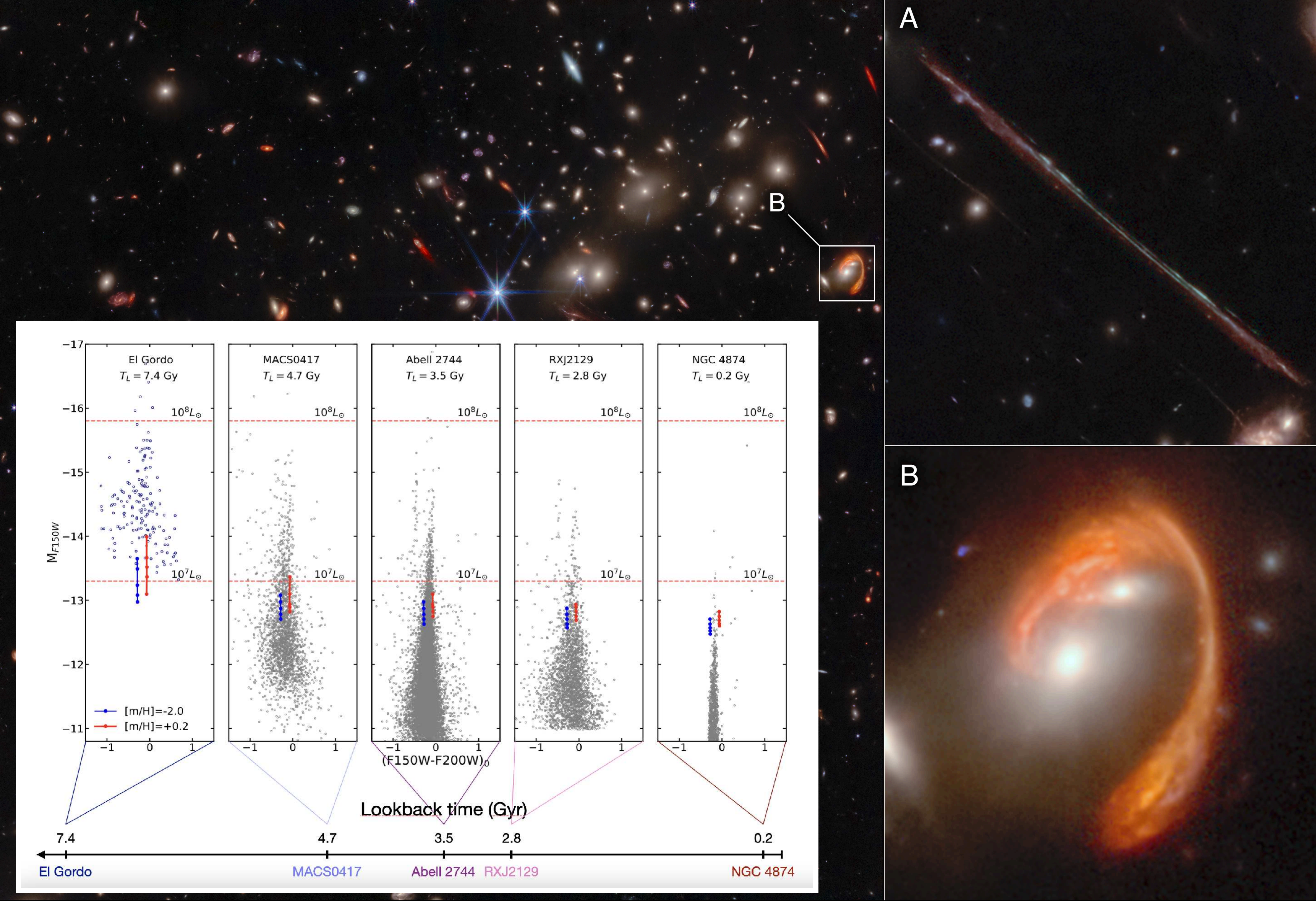
- Measure relativistic time-delays from multiple images, & improve on $\boldsymbol{H_0}$

(Kamieneski, P. et al. ApJ, submitted; astro-ph/2510.00923)



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



- Webb yields direct Globular Cluster ages/masses over half the Hubble time!

(Harris, W., Reina-Campos, M., et al. 2025, ApJ, 991, 7; astro-ph/2508.12862)

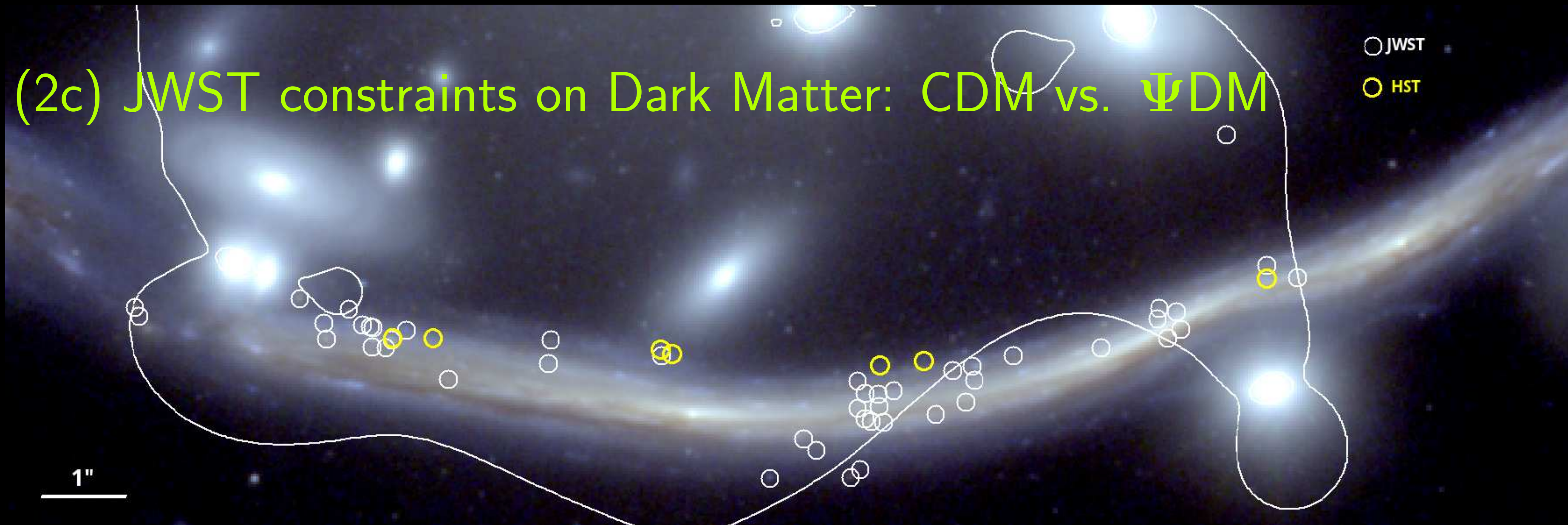
(Kamieneski+ 2023, ApJ, 955, 91)

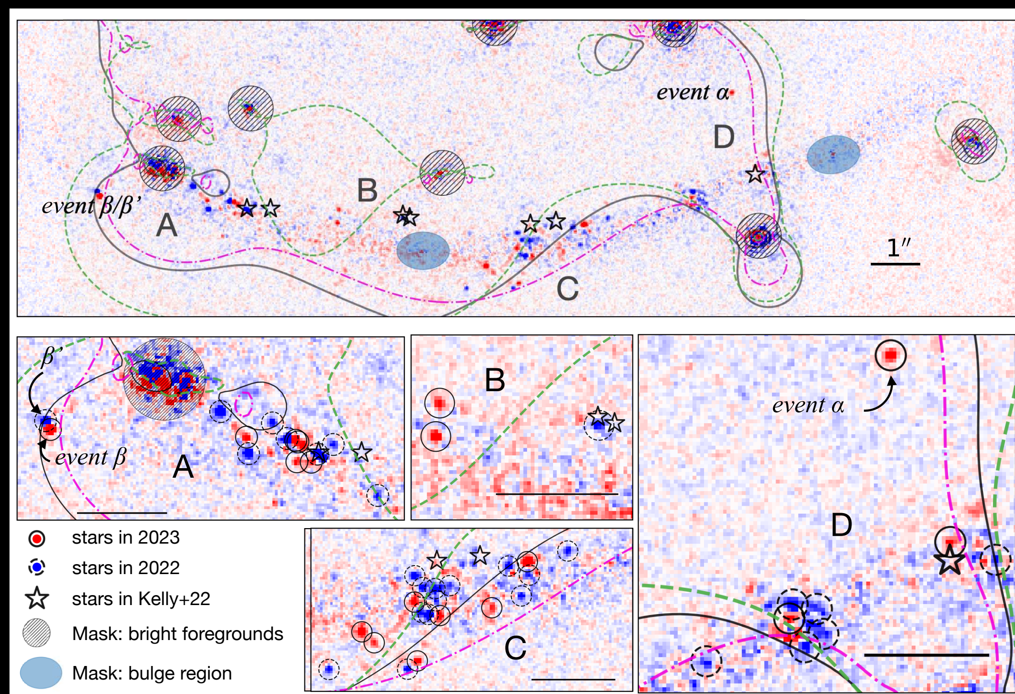
and El Gordo makes a super-lens “El Anzuelo” — Einstein’s fishhook!

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

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

(2c) JWST constraints on Dark Matter: CDM vs. ΨDM



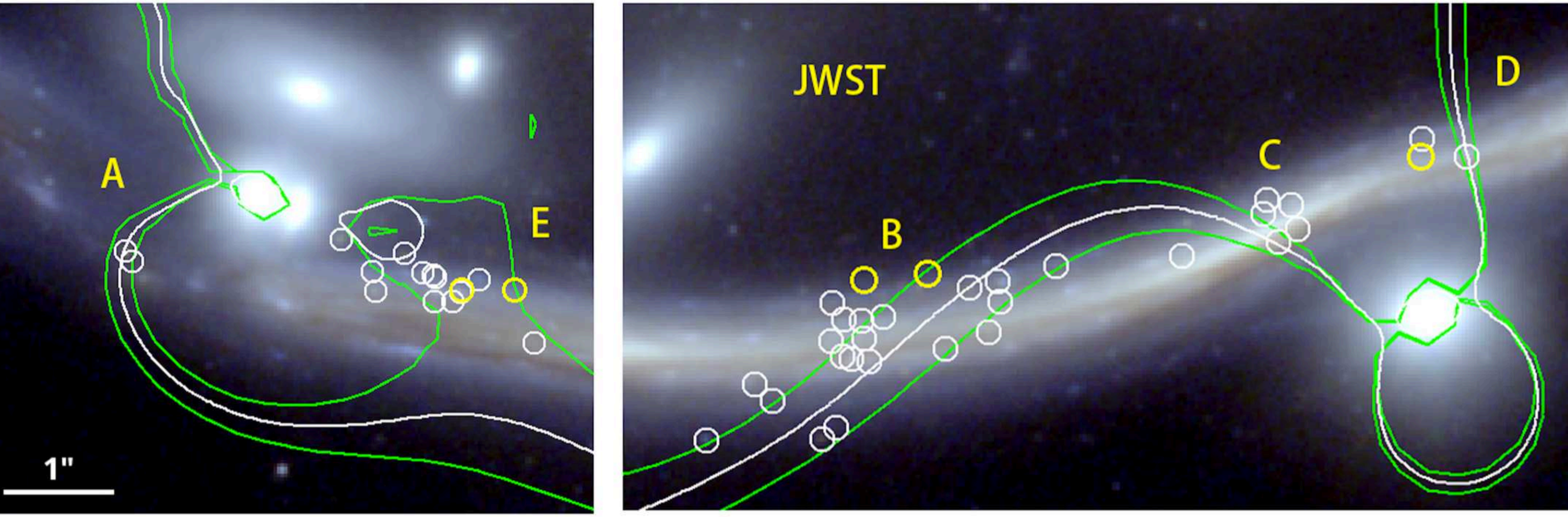


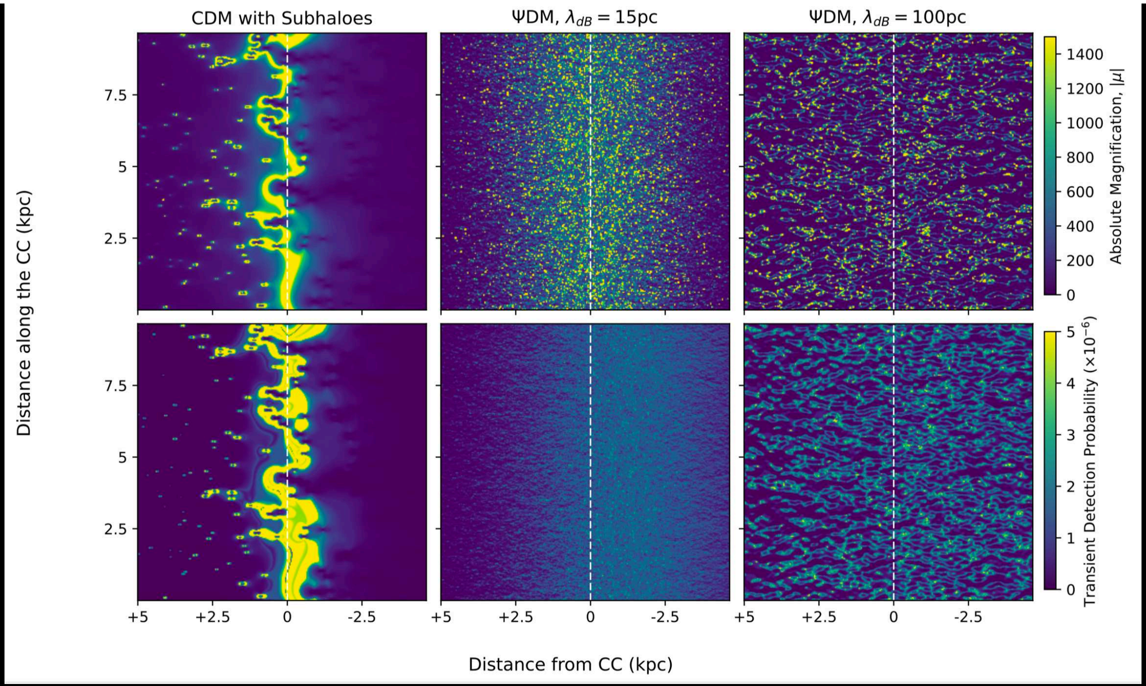
(see talks by L. Dai & H. Williams).

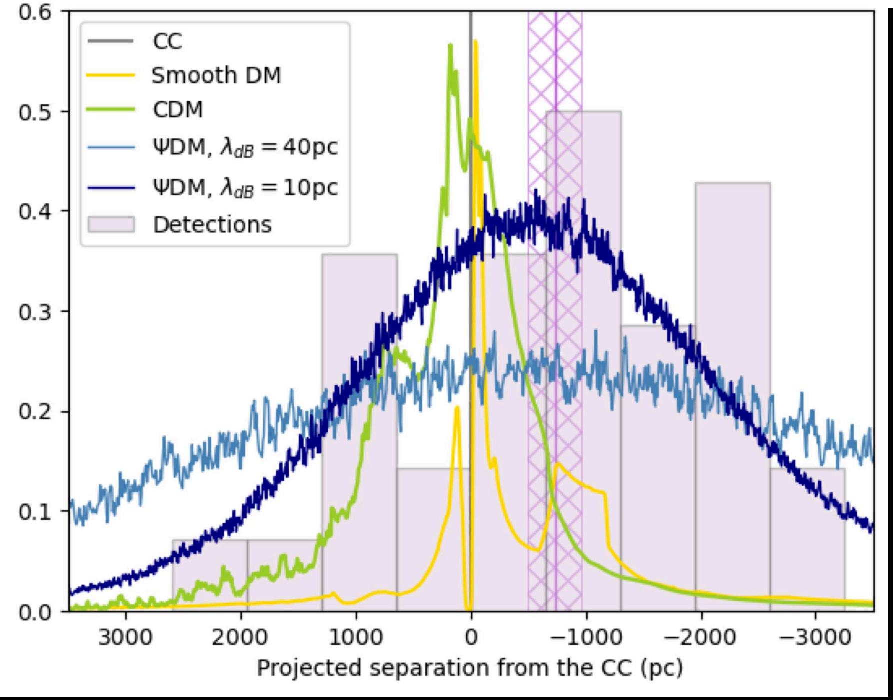
Abell 370 Dragon’s arc: 44 individual caustic-transiting stars at z=0.73!

$\longrightarrow$ Detect stars at z$\gtrsim$0.7 directly, going across infinity lines! (Y. Fudamoto[+], *Nat. Astr. 9, 428*).

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







A370 z=0.73 caustic transits asymmetric around C.C. (Broadhurst+ 2025, ApJL, 978, L5)

Explained better by ΨDM than CDM: $\sim 10^{-22}$ eV particle with $\lambda_{dB} \sim 10$ pc

A smooth filament origin for distant prolate galaxies seen by JWST and Hubble.

Alvaro Pozo[1,*], Tom Broadhurst[1,2,3], Razieh Emami[4], Philip Mocz[5], Mark Vogelsberger[6], Lars Hernquist[4], Christopher J. Conselice[7], Hoang Nhan Luu[1], George F. Smoot[1,8,9,10], and Rogier Windhorst[11]

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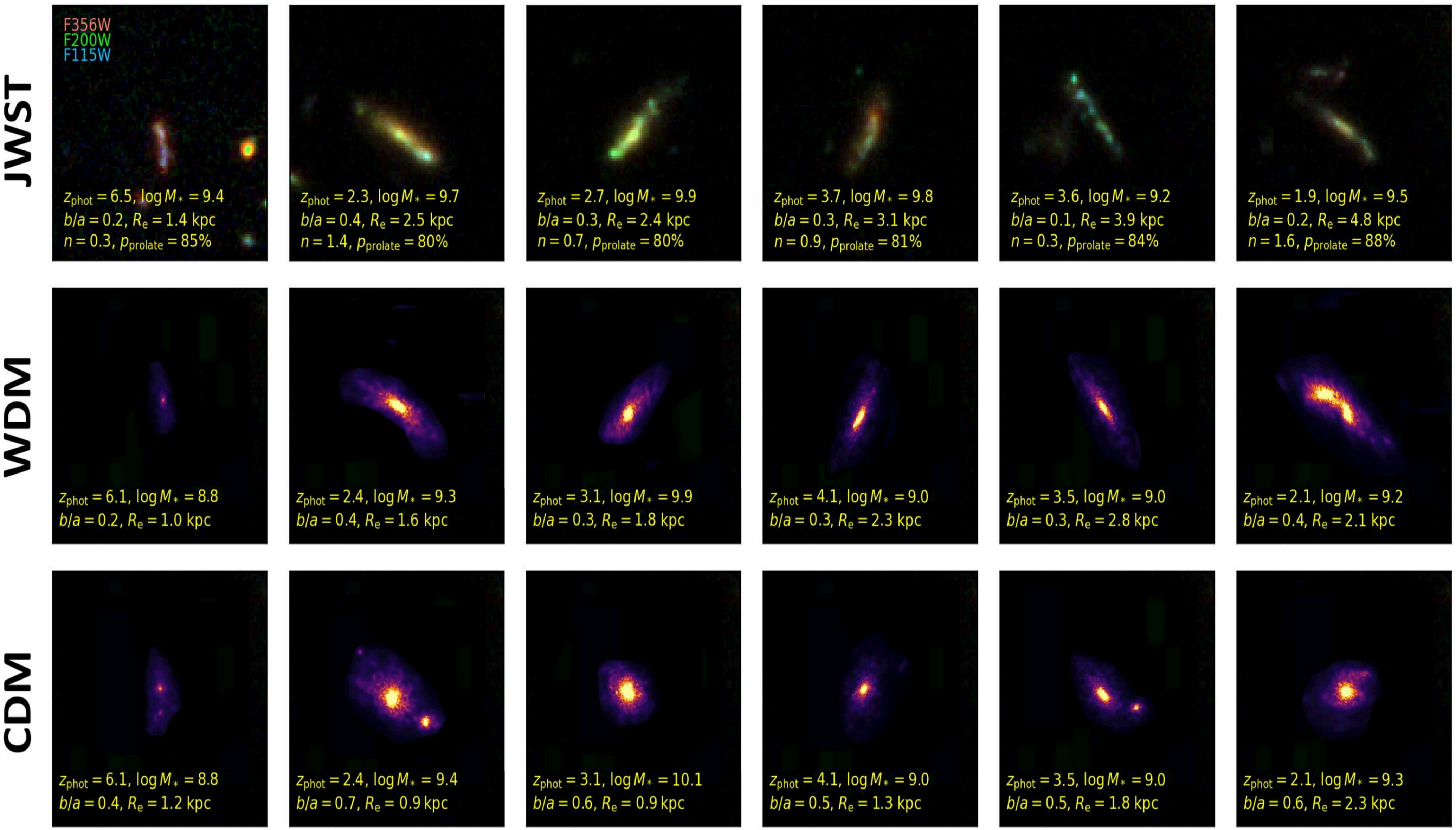
ABSTRACT

We compare the abundance of prolate-shaped galaxies reported in deep surveys with the predicted stellar morphology of young galaxies in high resolution hydrodynamical simulations of Cold Dark Matter (CDM), Warm Dark Matter (WDM) and Wave/Fuzzy Dark Matter, ψDM. For both CDM and WDM we have sufficient volume, $10^3 Mpc^3$, to yield galaxies with stellar masses over $> 10^9 M_\odot$ at $z > 2$, allowing comparison with the CEERS and CANDELS surveys. We find the observed elongation of young galaxies is well matched by WDM, during the first $\simeq$ 500Myr when material steadily accretes along smooth filaments, with little dependence on stellar mass over the range $10^{8-10} M_\odot$ in our simulations. The dark matter halos of WDM and ψDM both show prolate elongation, similar to that of the stars, indicating a shared, triaxial equilibrium. This contrasts with CDM where the early stellar morphology is mainly spheroidal, formed from fragmented filaments with frequent merging, resulting in modest triaxiality. For CDM, several visible subhalos are typically predicted to orbit within the virial radius of each galaxy, whereas sub-halos are absent for WDM and ψDM, as early merging is rare. Long, smooth filaments may be traced with JWST by alignment of neighbouring elongated galaxies on a predicted scale of $\simeq$ 150 kpc, set by the DM particle mass.

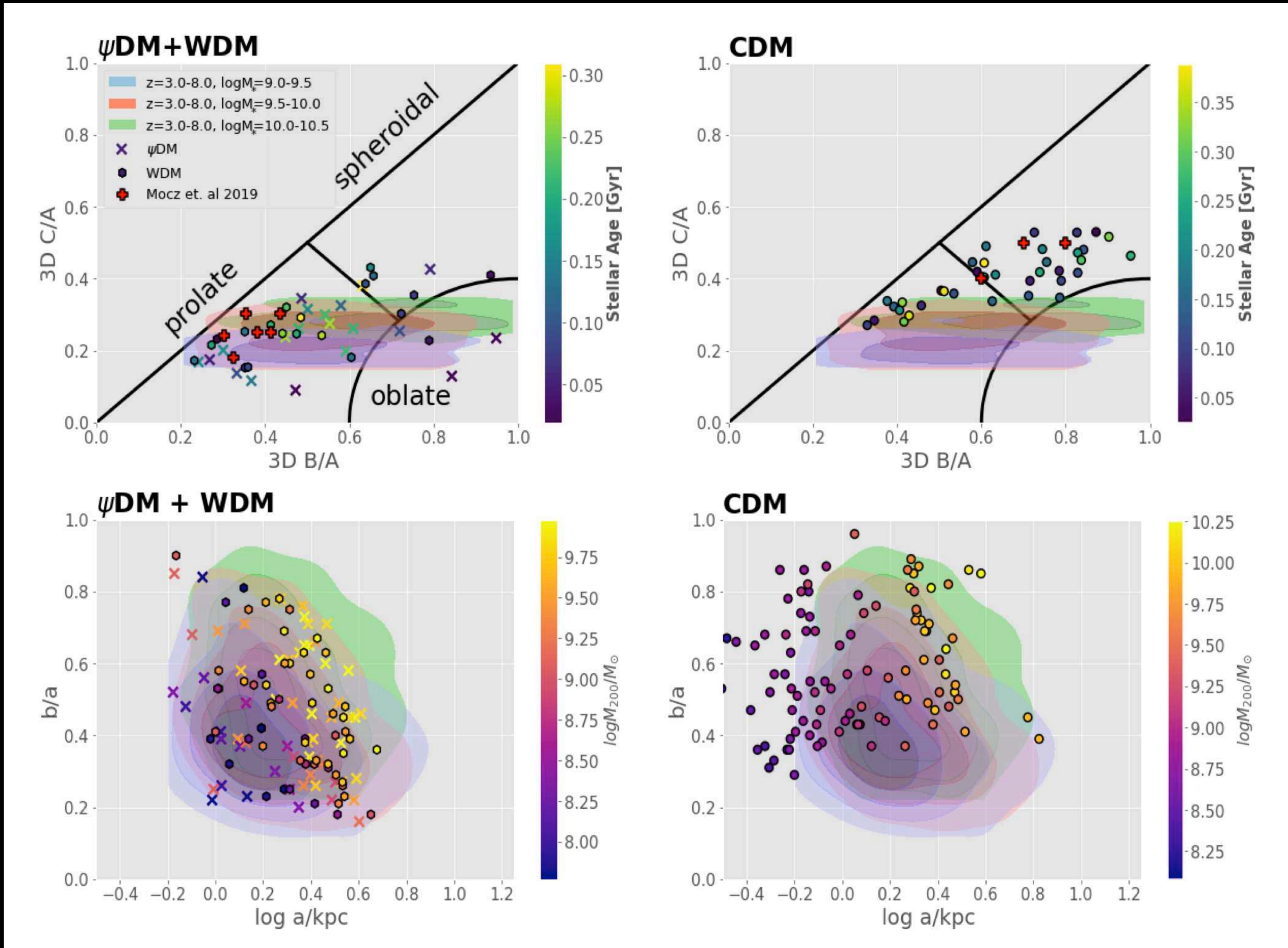
A. Pozo et al. 2025, Nature Astronomy (see also his Mon Dec 8 talk):
JWST & HST galaxies often elongated (prolate) $\Longleftarrow$ smooth WDM filaments

In honor of George F. Smoot (20 Feb 1945–18 Sept. 2025).



A. Pozo et al. 2025, Nature Astronomy (https://www.nature.com/articles/s41550-025-02721-5):
Prolate JWST and HST morphology better explained by WDM than CDM !

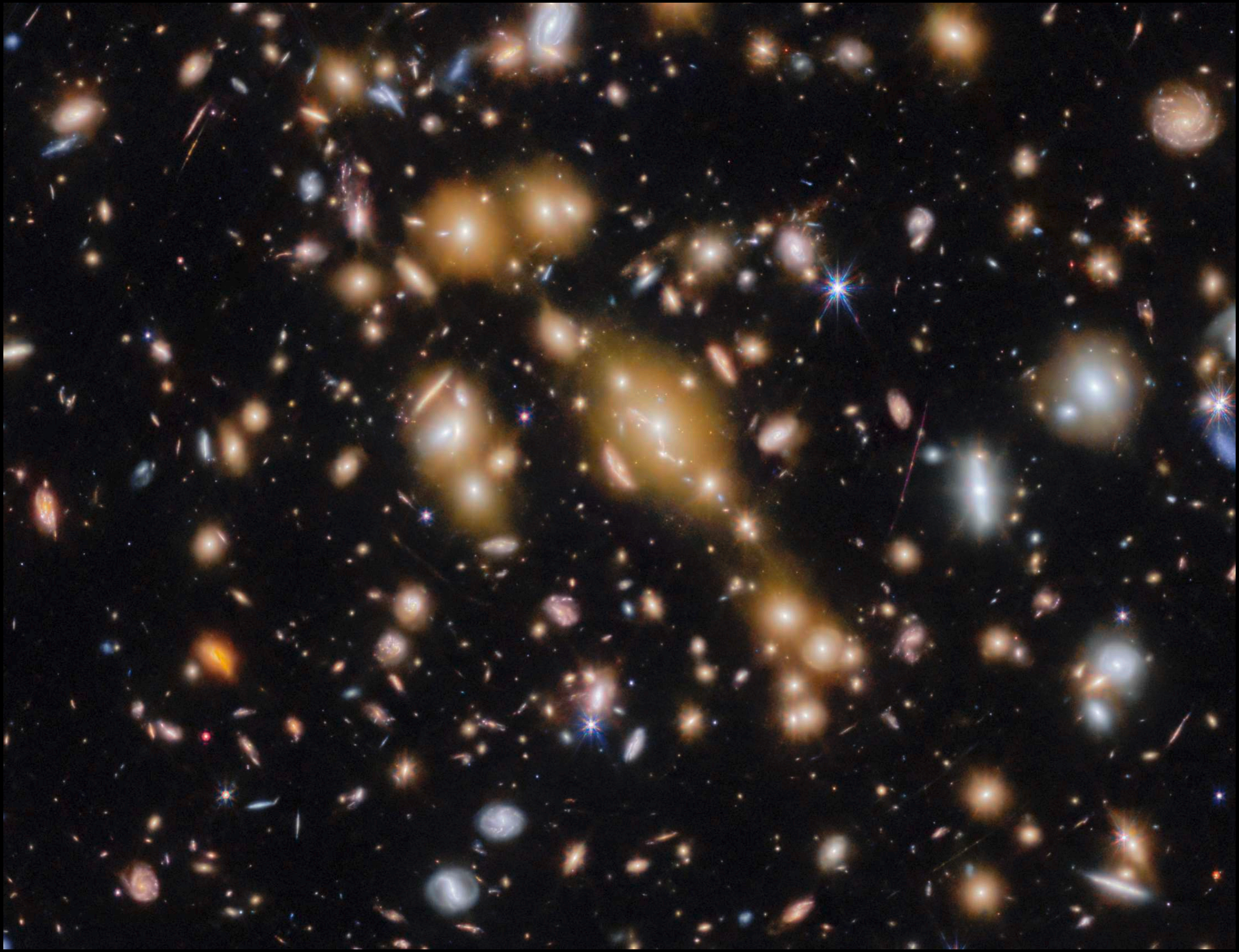
https://news.asu.edu/20251209-science-and-technology-james-webb-space-telescope-opens-new-window-hidden-world-dark



A. Pozo et al. 2025, Nature Astronomy, in press (and Mo Dec 8 talk):

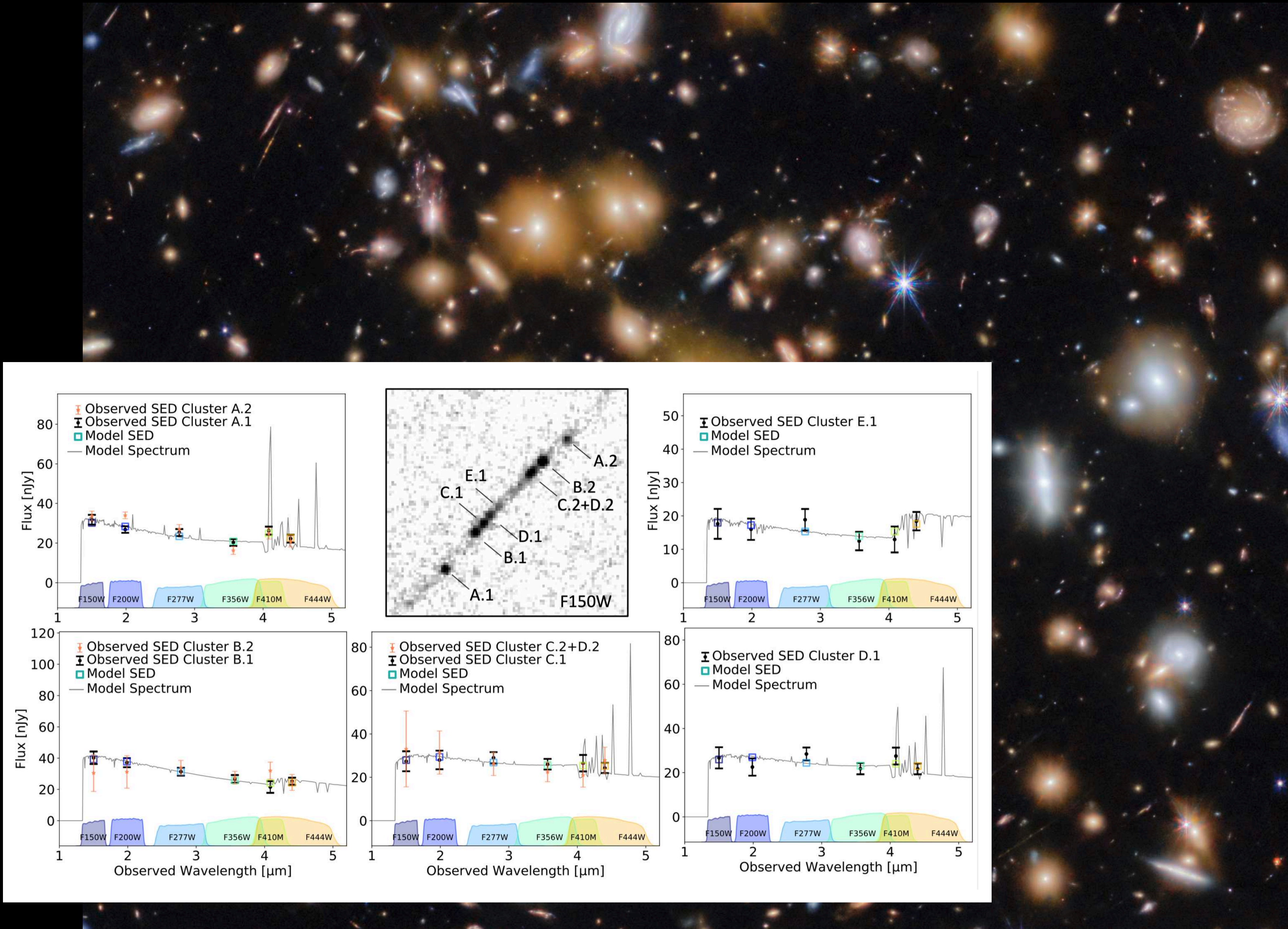
CDM predictions too round & too small; ΨDM+WDM model follows the data

Contours trace the JWST & HST data (CANDELS & CEERS); Dots are the model predictions.



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

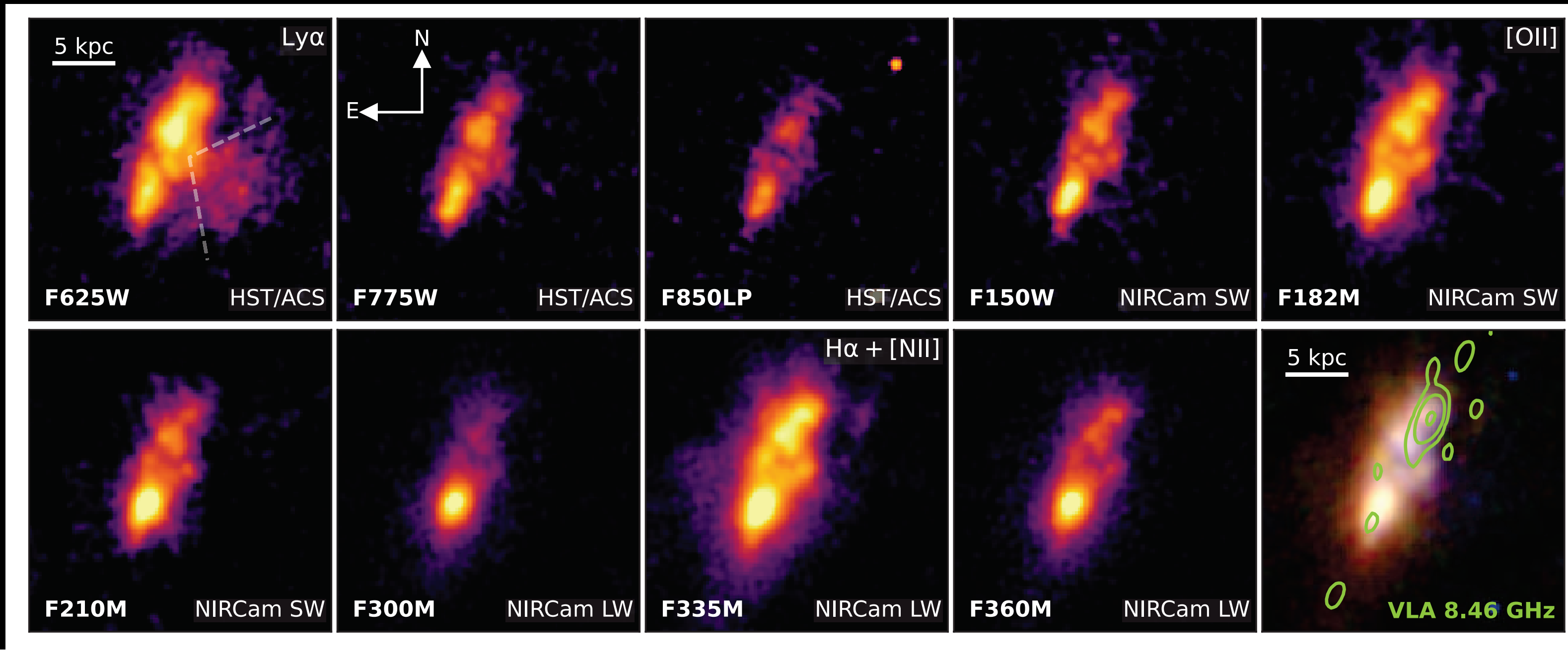
Adamo+ (Nature; astro-ph/2401.03224): ∼50 Myr old, formed at z∼11! `https://esawebb.org/news/weic2418/`

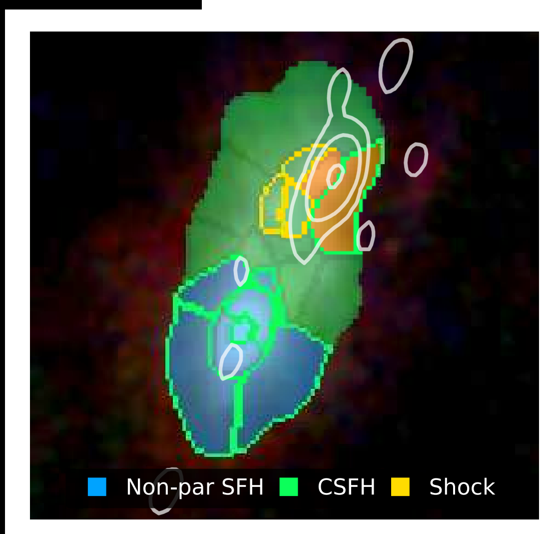


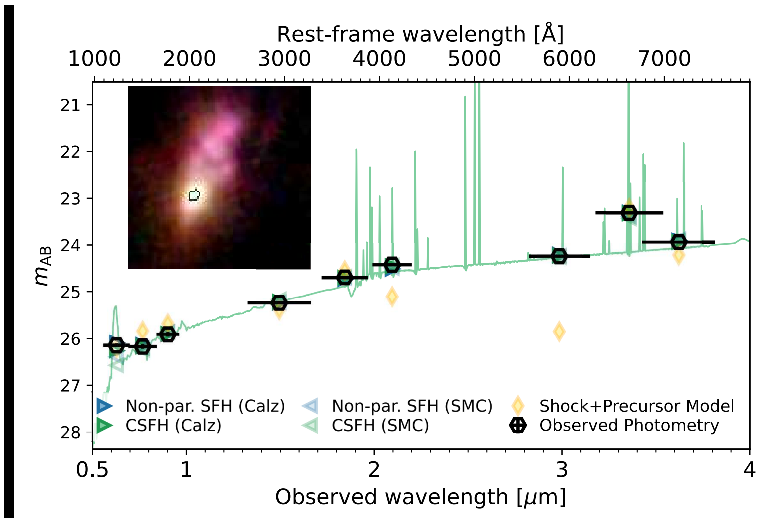
z=0.97 cluster SPT0615: lenses young globular clusters at z=10.2 !

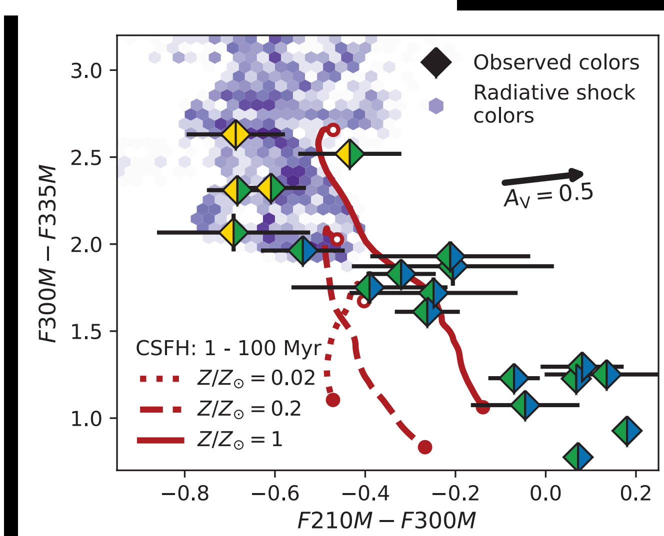
- Webb yields Globular Cluster ages/masses at z=10.2 $\longrightarrow z_{form} \lesssim 11$!

• (2d) Supermassive Black Hole Growth and its role in Galaxy Assembly







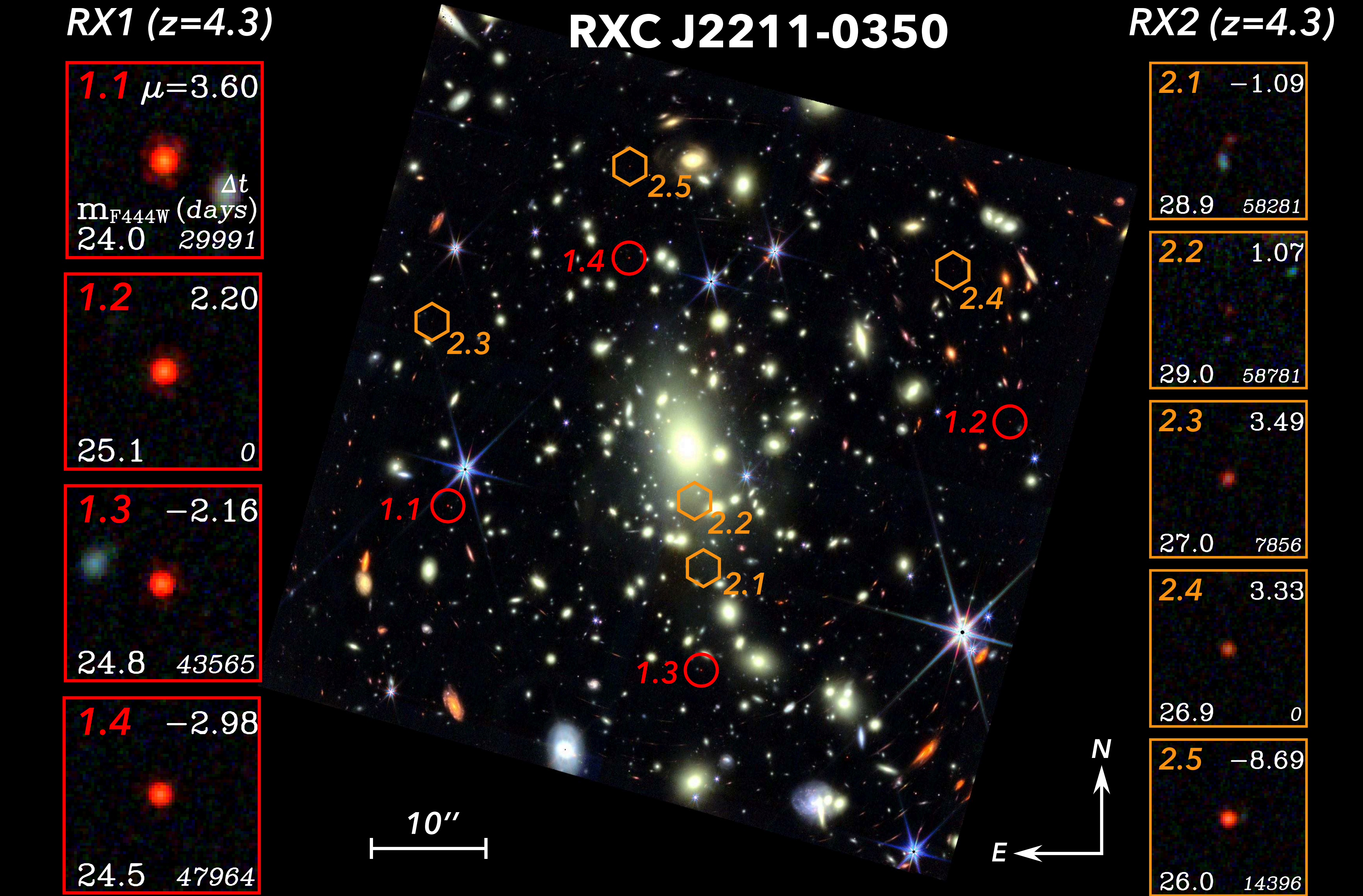


A massive ($10^{10.9}\ M_\odot$) high-z radio galaxy at z=4.11 (Duncan+ 2023, MNRAS, 522, 4548):

- TNJ1338: NIRCam medium-band SFR∼1800 $M_\odot$/yr; extreme jet-induced SFR≳500 $M_\odot$/yr, $t_{SFR}\simeq$44 Myr.

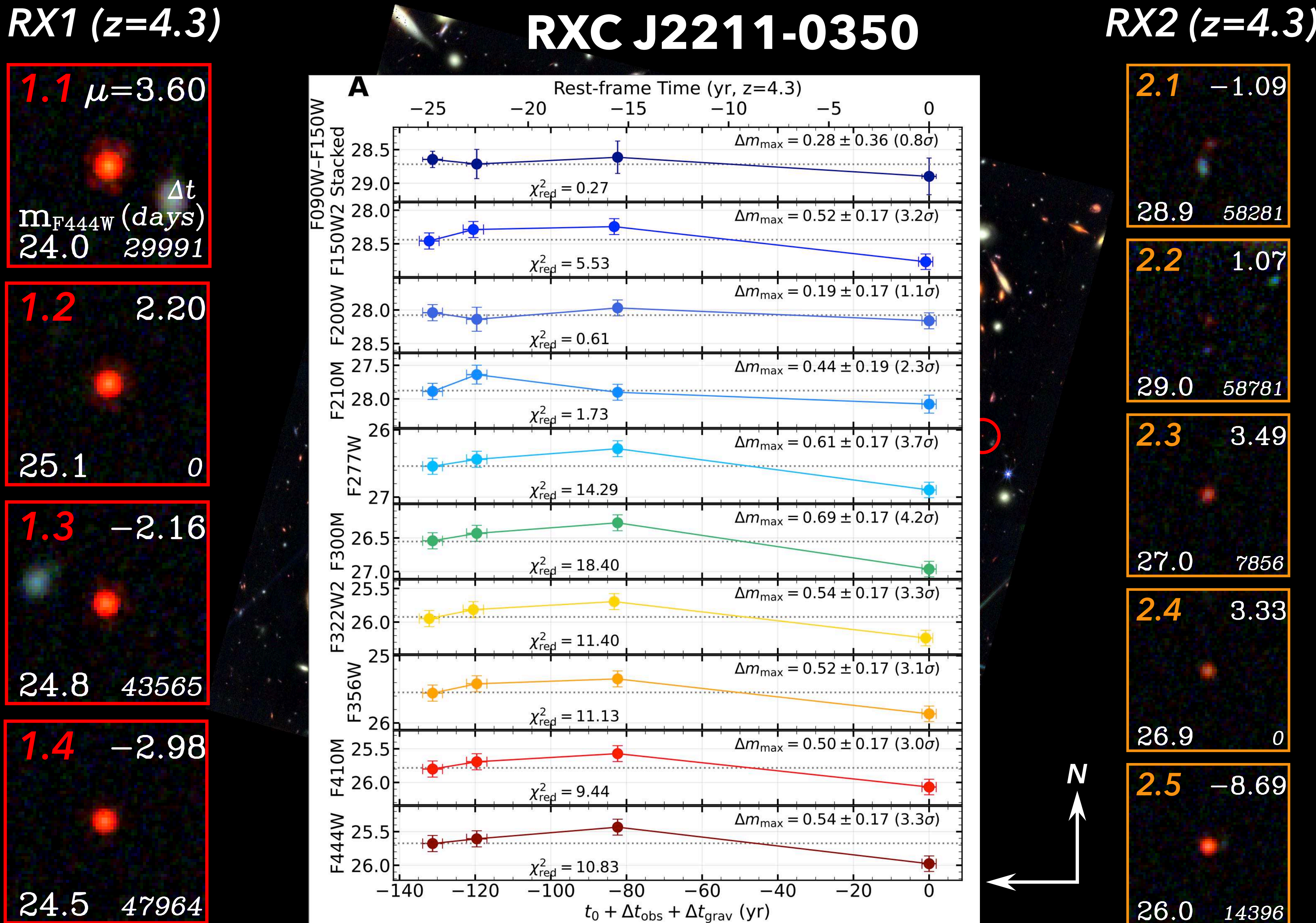
- The $\sim 10^9\ M_\odot$ SMBH triggered its (main?) galaxy growth at z≳4.2!

(see also talks by Roger Blandford, Sanch Borthakur, Skylar Grayson, Martijn Oei, and Evan Scannapieco)



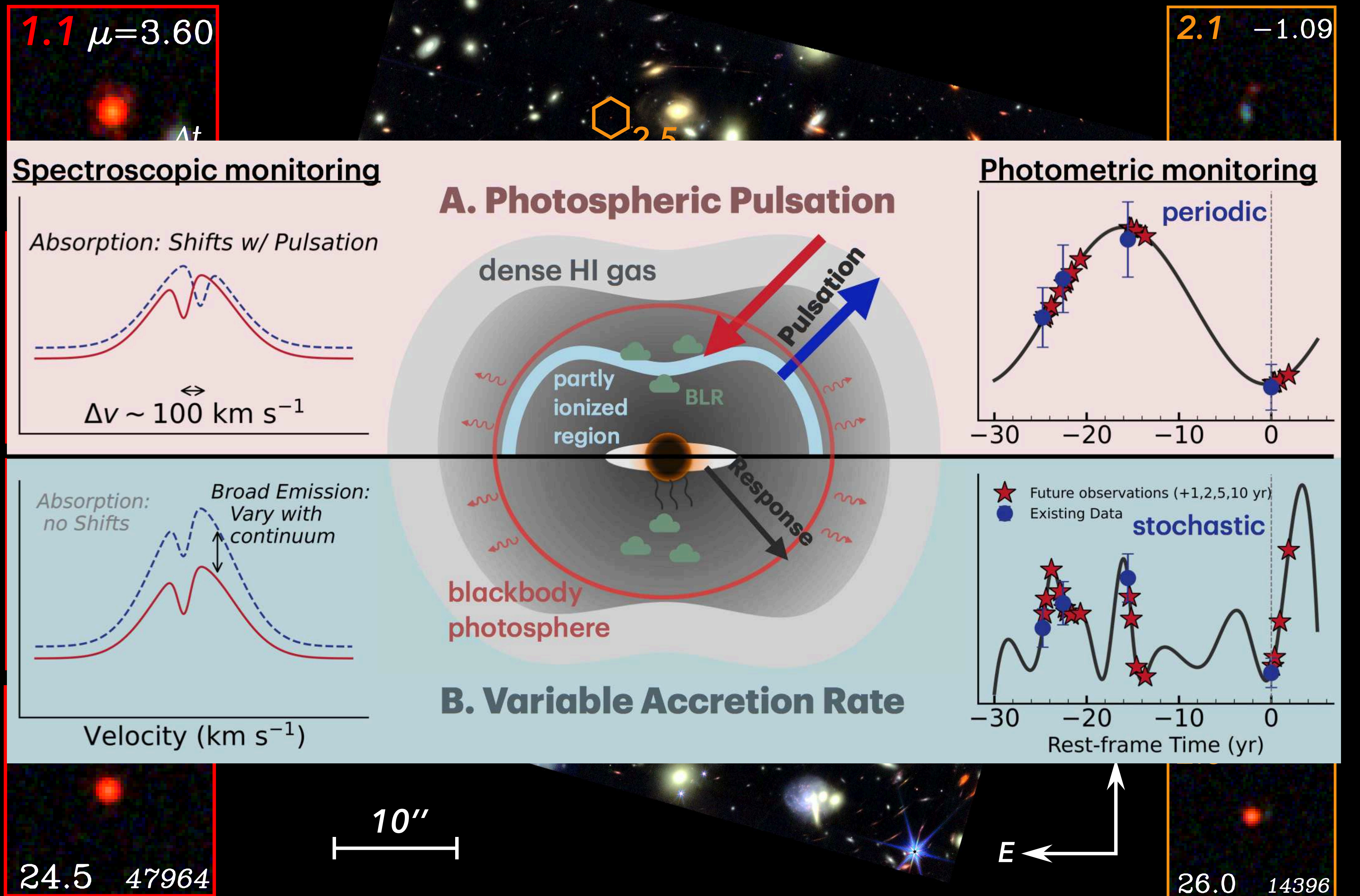
- VENUS: Two Einstein-cross LRD's at $z\simeq4.3$ (Zhang$^+$ 2025):
- Relativistic time delay: LRD's vary at $\lesssim$130 yrs! (https://arxiv.org/abs/2512.05180)

RXC J2211-0350

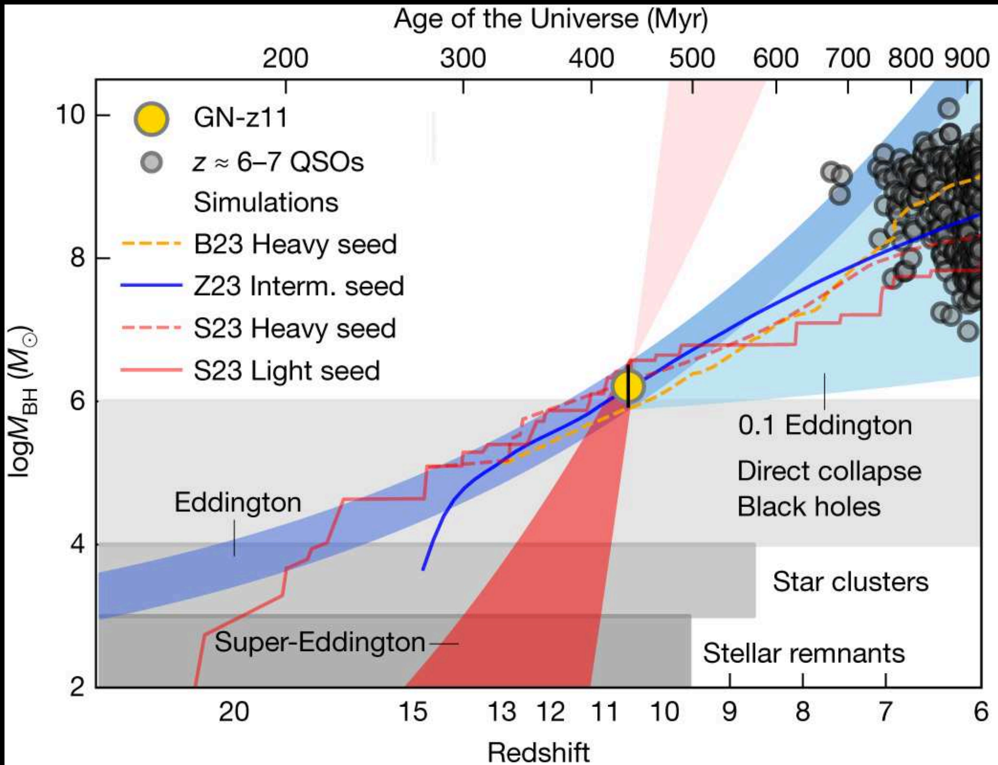


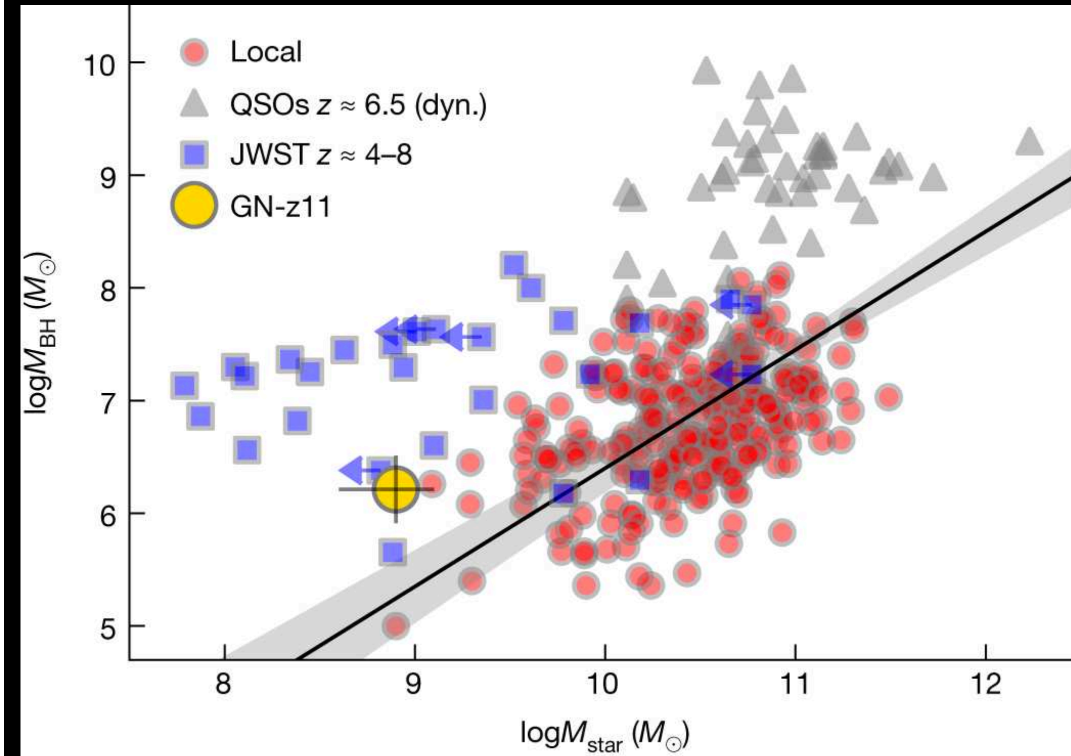
- VENUS: Two Einstein-cross LRD's at z≃4.3 (Zhang^{+} 2025):
- Relativistic time delay: LRD's vary at ≲130 yrs! (https://arxiv.org/abs/2512.05180)

RXC J2211-0350



- VENUS: Two Einstein-cross LRD's at z≃4.3 (Zhang^{+} 2025):
- LRD's SMBH thermosphere may pulsate like a Cepheid or Mira?!





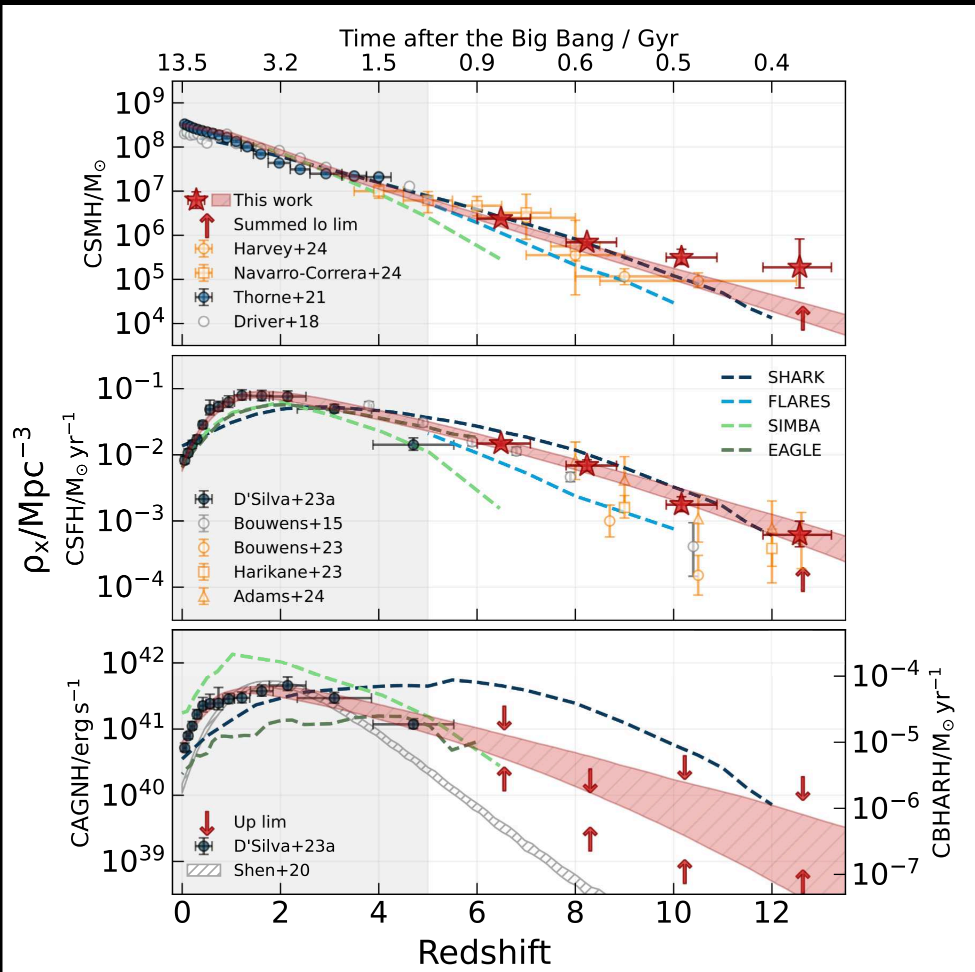
[Left] (Super Massive) Black Hole growth may start before z≃20 (175 Myr).

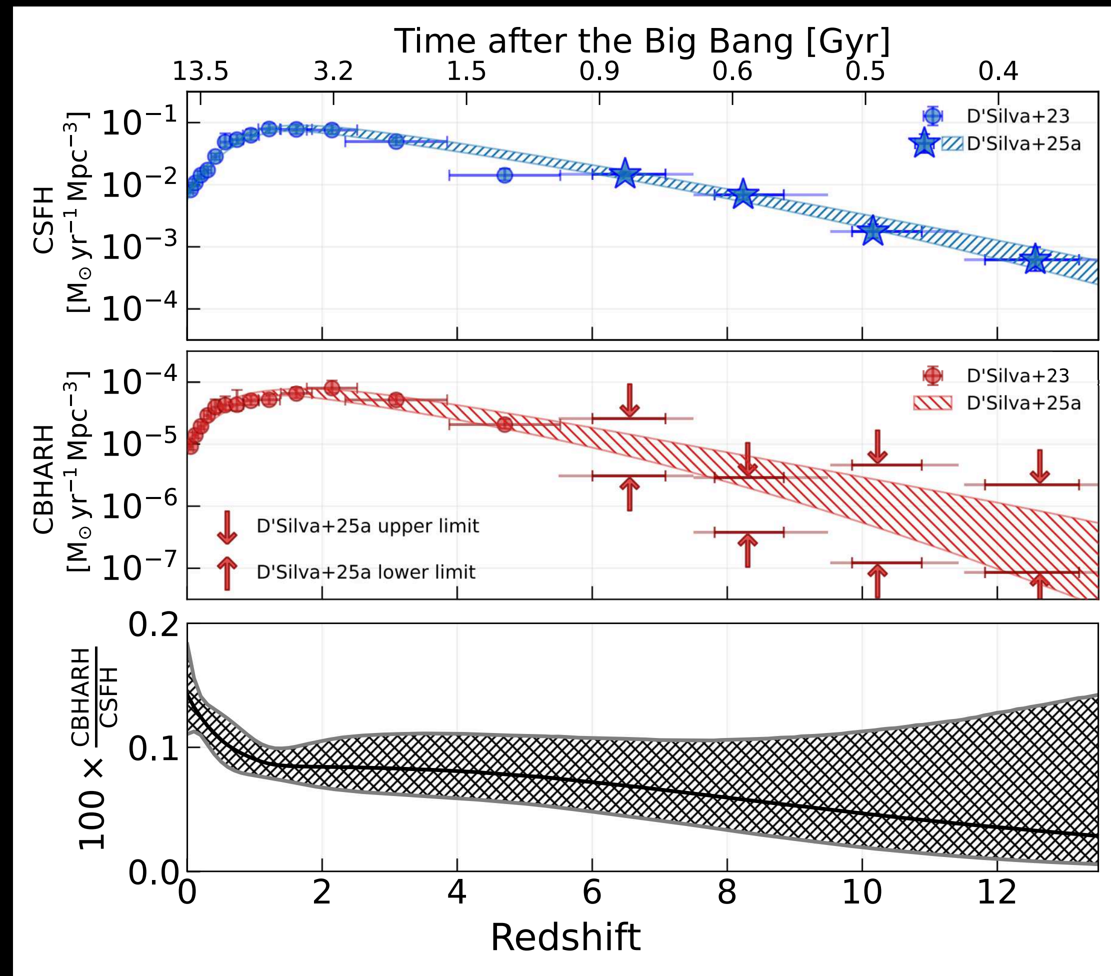
[Right] This results in overweight SMBHs compared to their host galaxies at z≃4–8 ($i.e.$, in the first 0.6–1.5 Byr)! (Maiolino+2024, Nature, 627, 59)

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

(see also Xiaohui Fan's talk).

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





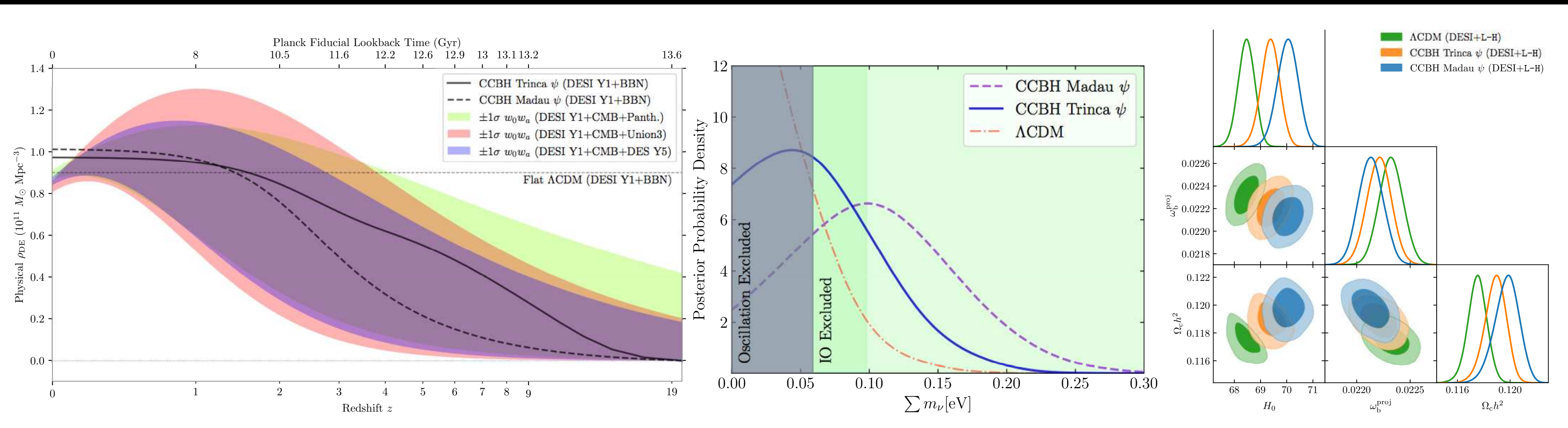
- Cosmic SFH & AGN-FH derived from multi-band HST+JWST data:
- Use ProSpect to decompose into objects stellar & AGN SEDs.

(J. D'Silva[+] 2023, MNRAS, 524, 1448; — 2024, ApJL, 959, L18; — 2025, A&A, 990, 44; astro-ph/2503.03431).

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

However, the large number of red, dusty AGN that JWST now sees at $z \gtrsim 4$ suggests that SMBH's started growing very fast, before the first galaxies.

(2e) Possible JWST constraints on nature of Dark Energy evolution



CCBH model: Explains DESI DE(z) with same nr. of parameters as ΛCDM!

- Key of new CCBH model: Base CCBH-FH on observed JWST AGN FH.
- Gets positive neutrino masses ($\Sigma m_\nu \lesssim 0.1$ eV) for JWST CSFH/BH-FH!
- Resolves ~half of the Hubble tension compared to none in ΛCDM.

(Croker+ 2024, JCAP, 10, 094, astro-ph/2405.12282; Ahlen+ 2025, Phys. Rev. Lett., 125, 081003, astro-ph/2504.20338v2)

(Please see Kevin Croker's DESI DR2 version in his Fr. Dec. 12, ~2:15 pm talk — Bronze room)

(3) 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.

- HST maps (unobscured) SF in the last 10 Gyr,

complementing Webb's great advantage in the (dusty!) first 3 Gyr:

(2) 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 assembled over 13.6 Billion years (triggered by SMBHs?!)

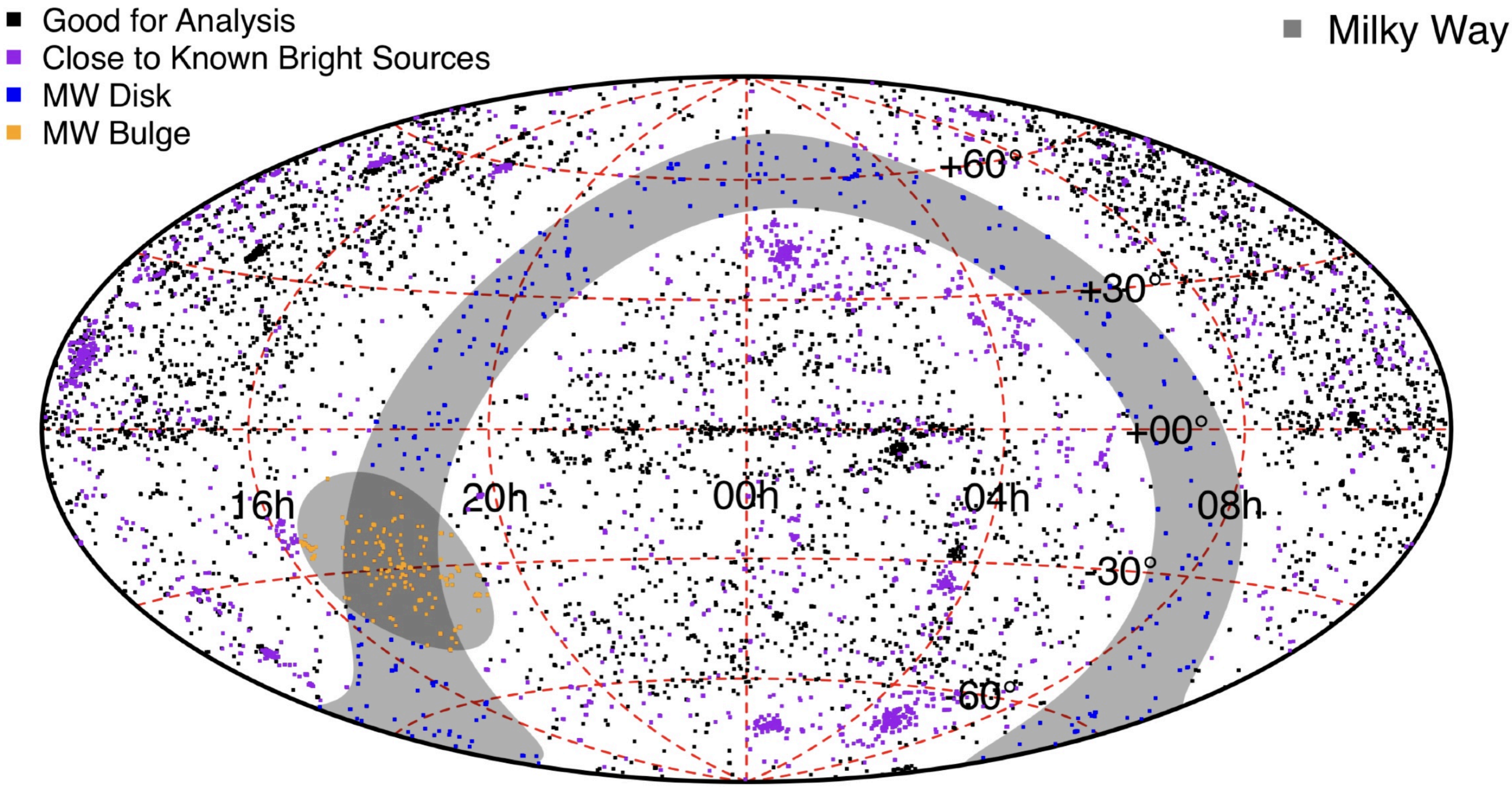
(3) Webb is observing stellar populations in a cosmological context:

- Constrain Globular Cluster ages/masses directly over most of the Hubble time!

- Detect lensed stars at cosmological distances: direct IMF constraints!

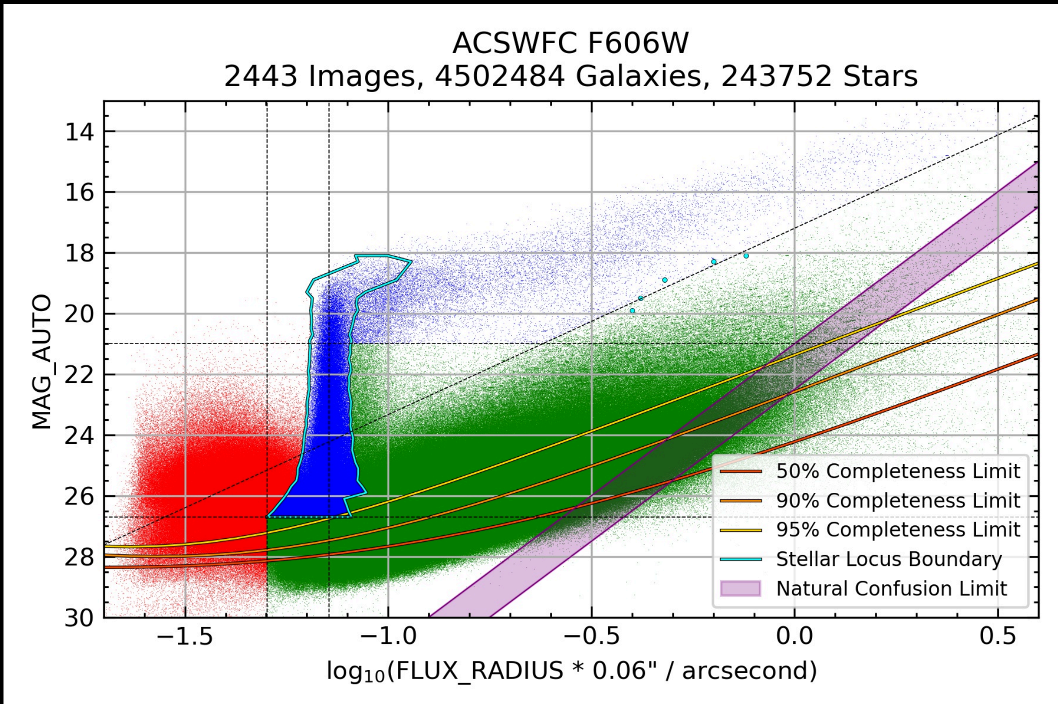
(4) Spare Charts

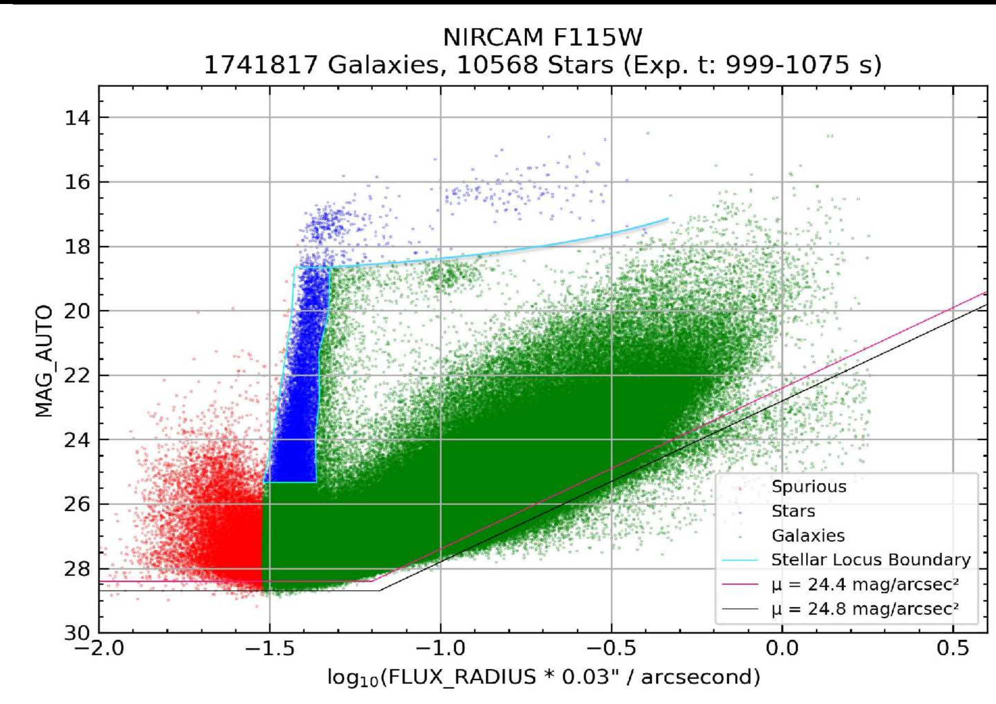
SKYSURF Sky Coverage



HST Project SKYSURF: 20 years of ACS + 13 years of WFC3: 249,000 images, 47,000 mosaics in 28 filters:

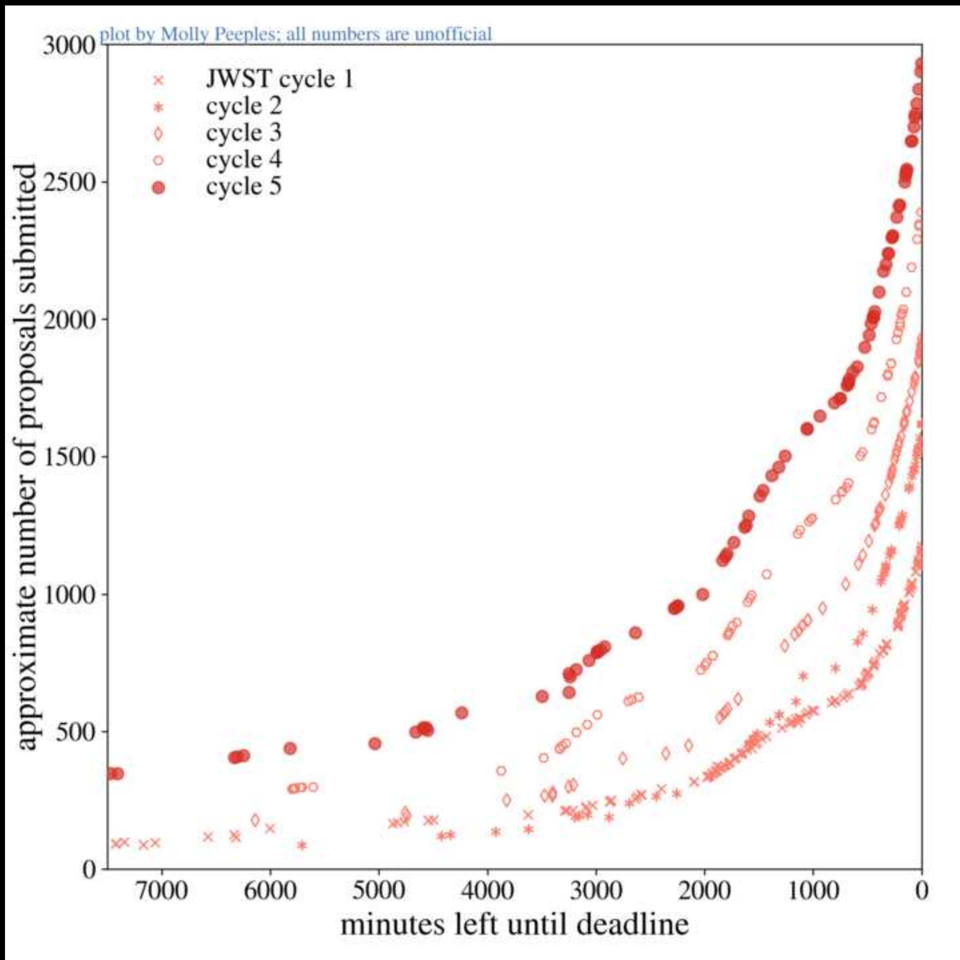
Carter+ 2025, ApJS, (astro-ph/2507.05323); Tompkins+ 2025, MNRAS, (astro-ph/2507.03412); O'Brien+ 2025, ApJ, submitted (astro-ph/2510.18231); O'Brien+ 2023, AJ, 165, 237; Goisman+ 2025, PASP, 137, 094501; McIntyre+ 2025, AJ, 169, 136; Kramer+ 2022, ApJL, 940, L15; Carleton+ 2022, AJ, 164, 170; Windhorst+ et al. 2022, AJ, 164, 141.

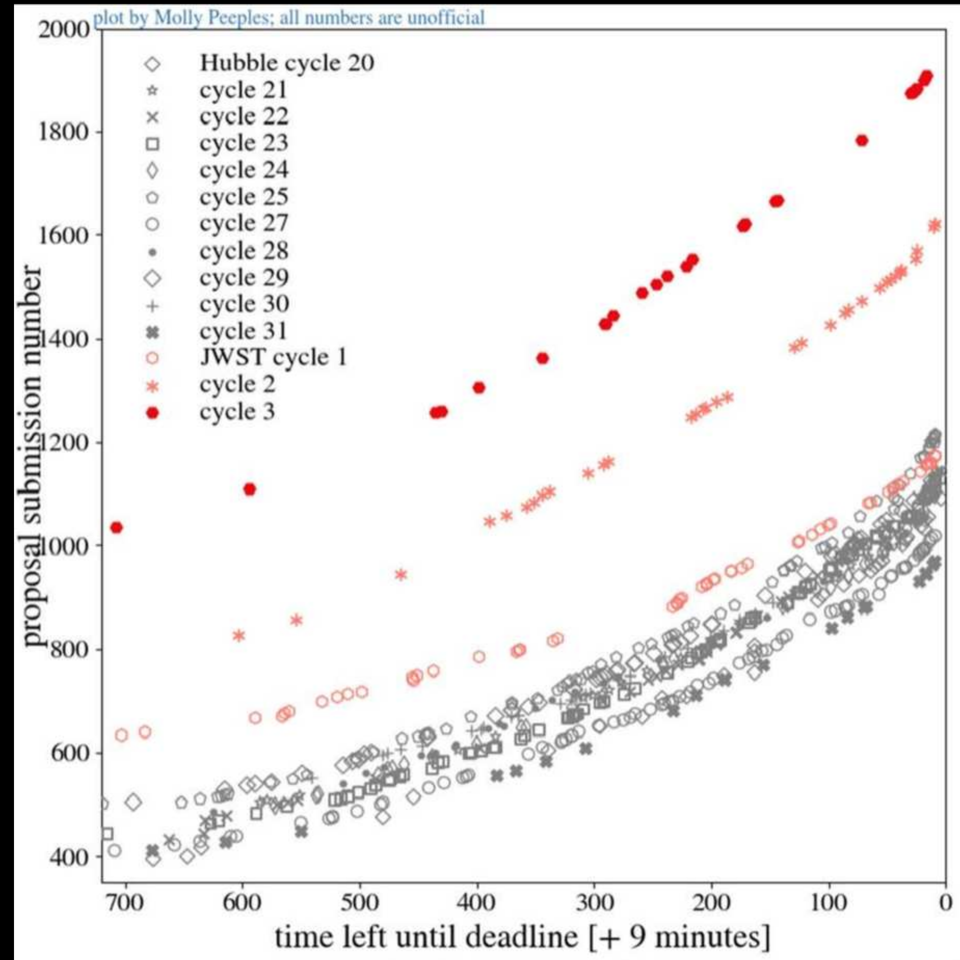




[Left] HST SKYSURF: $\sim$47,000 mosaics, $\gtrsim 4.5\times10^{6}$ galaxies, $\gtrsim 2.4\times10^{5}$ stars to AB$\lesssim$27-29 in each of 9 main ACS & WFC3 filters: (Carter^{+} 2025, ApJS, astro-ph/2507.05323; Tompkins^{+} 2025, MNRAS, astro-ph/2507.03412).

[Right] JWST SKYSURF-IR: $\sim$64,000 Cycle 1–3 images, $\sim$2700 mosaics, $\gtrsim 1.7\times10^{6}$ galaxies, $\gtrsim 1.1\times10^{4}$ stars to AB$\lesssim$28–30 mag in 16 main NIRCam & NIRISS filters: (Berkheimer, J.$^{+}$ 2026; Ortiz, R. $^{+}$ 2026, in prep).





- Webb is now THE highest-in-demand NASA Flagship mission ever: $\sim$3000 JWST proposals for Cycle 5; Oversubscription 13.5/1 !

but Hubble remains in at least as high a demand as it was $\sim$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://lambda.la.asu.edu/raw/jwst/talks/texas25_jwst_v2.pdf` Data: `https://sites.google.com/view/jwstpearls`

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

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`https://blogs.nasa.gov/webb/2024/10/01/` & `https://bigthink.com/starts-with-a-bang/triple-lens-supernova-jwst/`

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