A field of Extragalactic PEARLS Studded with Galactic Diamonds

HST & JWST Explorations of a new Time–Domain and Deep Field

Dr. Rolf A. Jansen (ASU/SESE, Research Scientist)

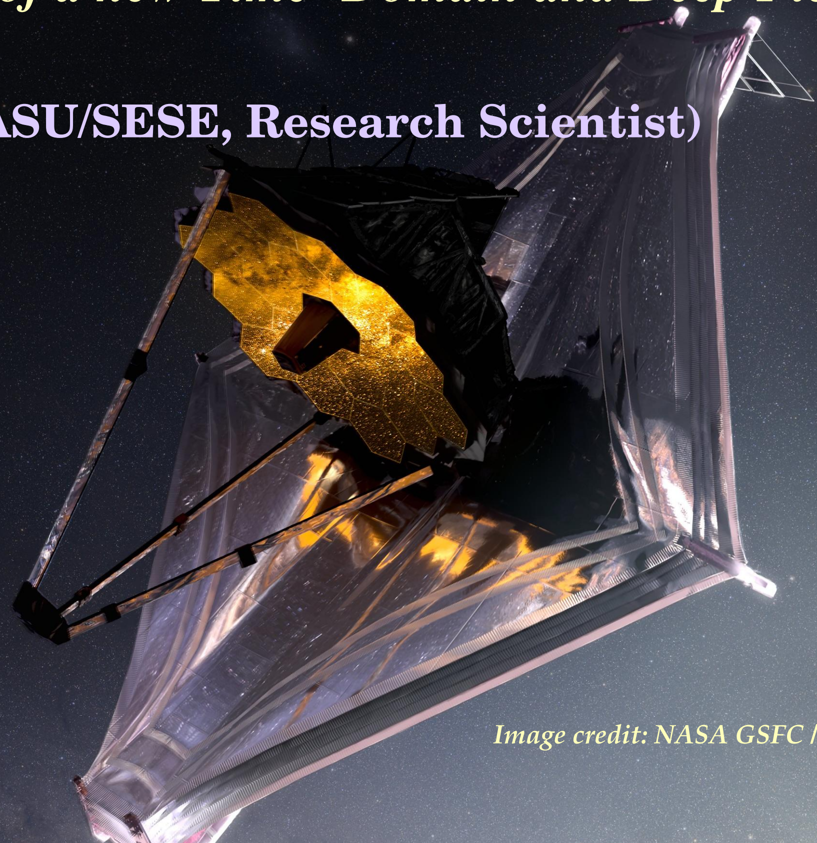


Image credit: NASA GSFC / CIL / A. Manrique Gutierrez

JWST NEP Time Domain Field – HST/ACS F606W

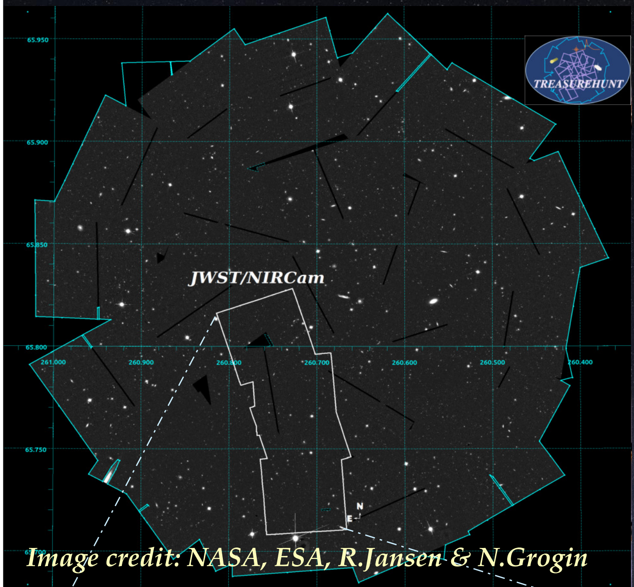
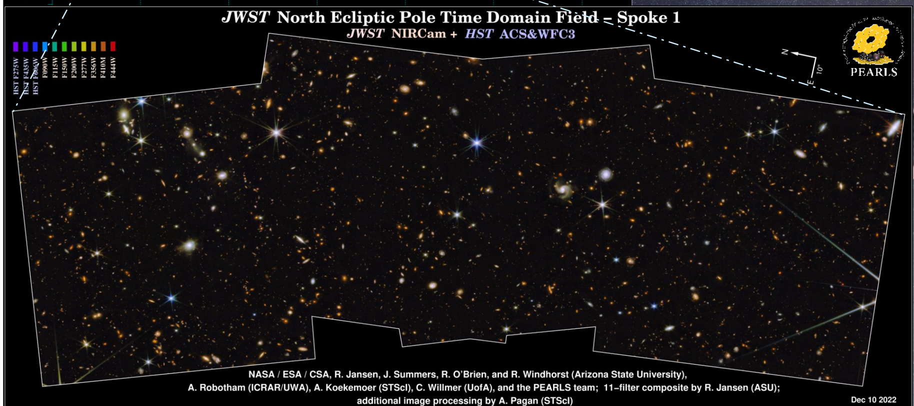


Image credit: NASA, ESA, R.Jansen & N.Grogin



East Valley Astronomy Club, Gilbert, Feb 17 2023

HST & JWST Explorations of a new Time-Domain and Deep Field

- **Outline:**
  - **The *James Webb* Space Telescope (What, Why, Where, Wow — *it works!*)**
  - **Time-domain Science with *JWST*? What and Why?**
  - **Where can *JWST* do Time-domain Science?**
  - **Development of the *JWST* NEP Time-Domain Field as a *Community Field***
  - **Multi-cycle UV–Visible Imaging Campaign with *Hubble***
  - **First Near-Infrared observations with *JWST***

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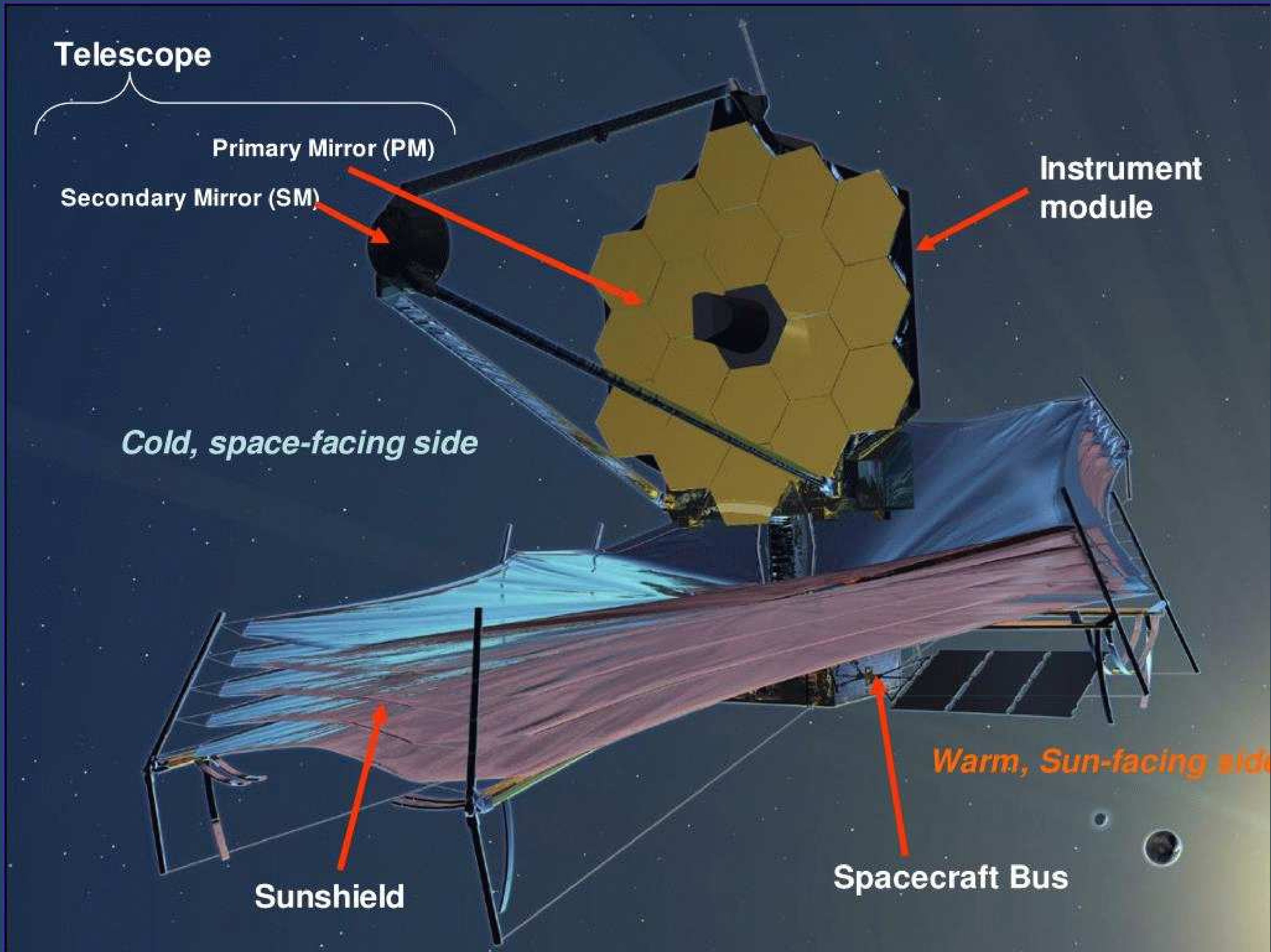
The *James Webb* Space Telescope – What is it?



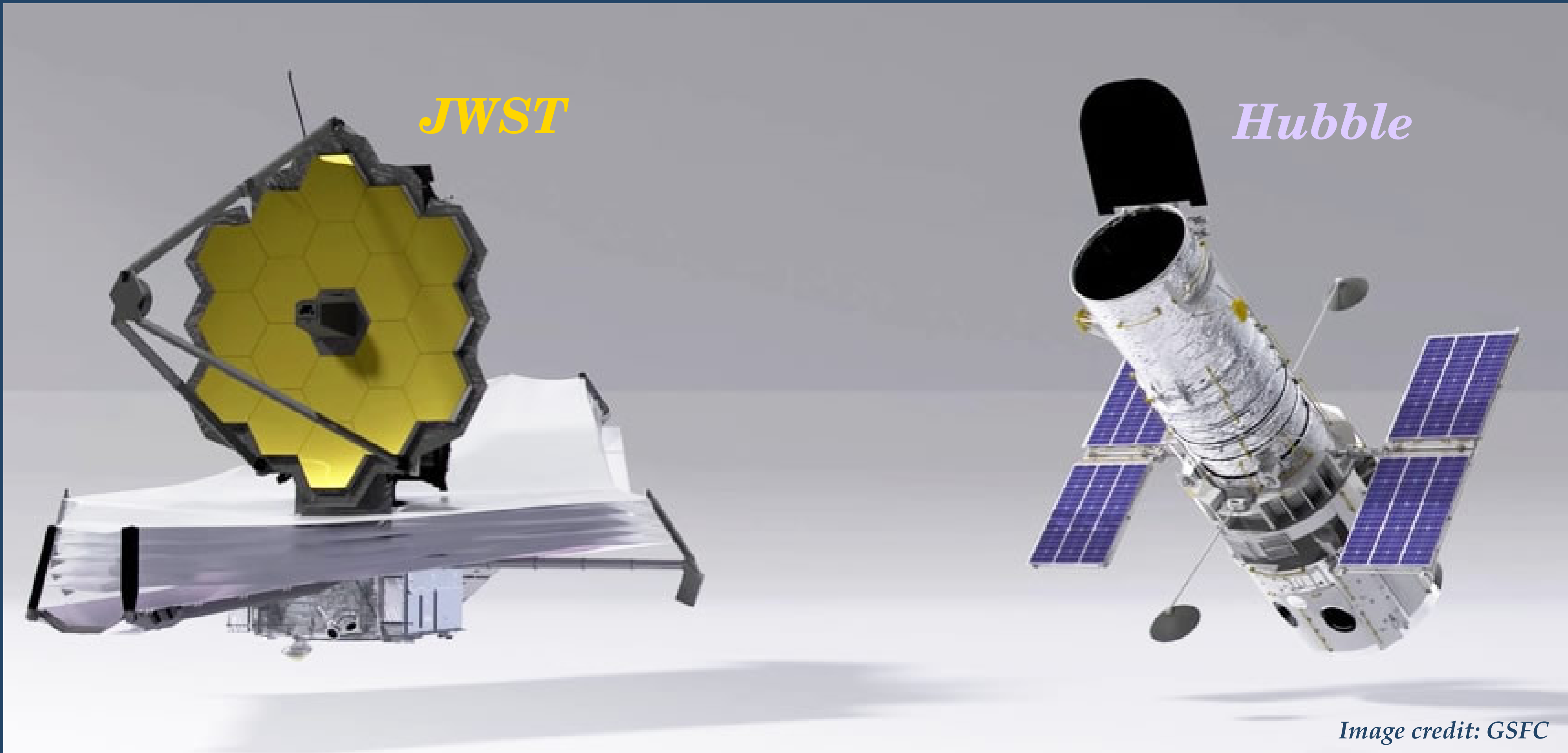
- **The *James Webb* Space Telescope, *JWST* for short, is a large infrared space telescope**

Image credit:

P. Stockman (STScI)

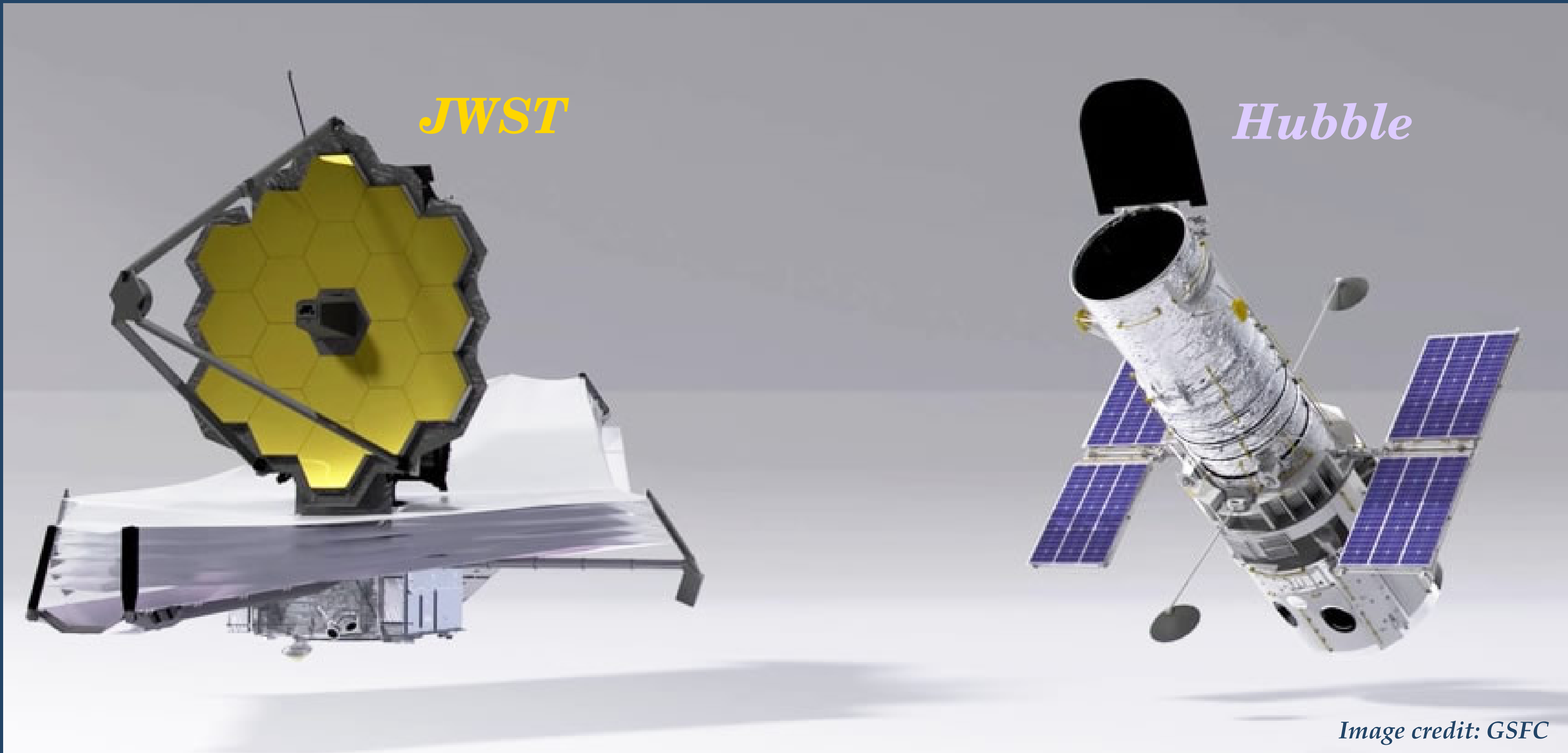
The *James Webb* Space Telescope – What is it?

- ***JWST* is the scientific successor of *Hubble***



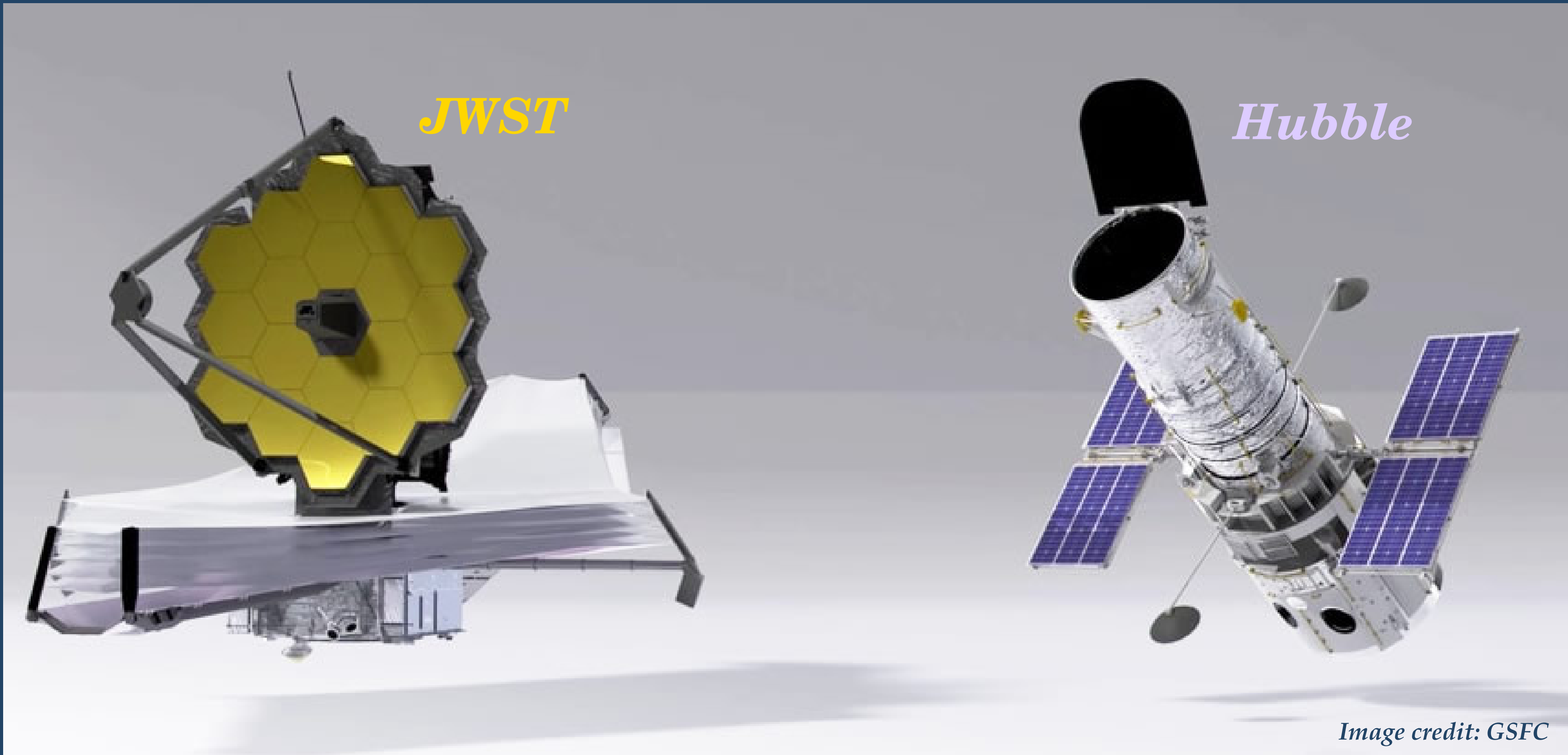
The *James Webb* Space Telescope – What is it?

- ***JWST*** **is unlike other space telescopes**
  - **open structure (no telescope tube)**



The *James Webb* Space Telescope – What is it?

- ***JWST*** **is unlike other space telescopes**
  - **segmented primary mirror (18 smaller hexagonal mirrors)**



The *James Webb* Space Telescope – What is it?

- **mirror segments made of *beryllium***
  - **the lightest possible metal**
  - **holds shape and strength at cryogenic temperatures**

A light-weighted 4.2 ft (1.3 m) bare beryllium primary mirror segment, seen from the rear
(July 20, 2010)

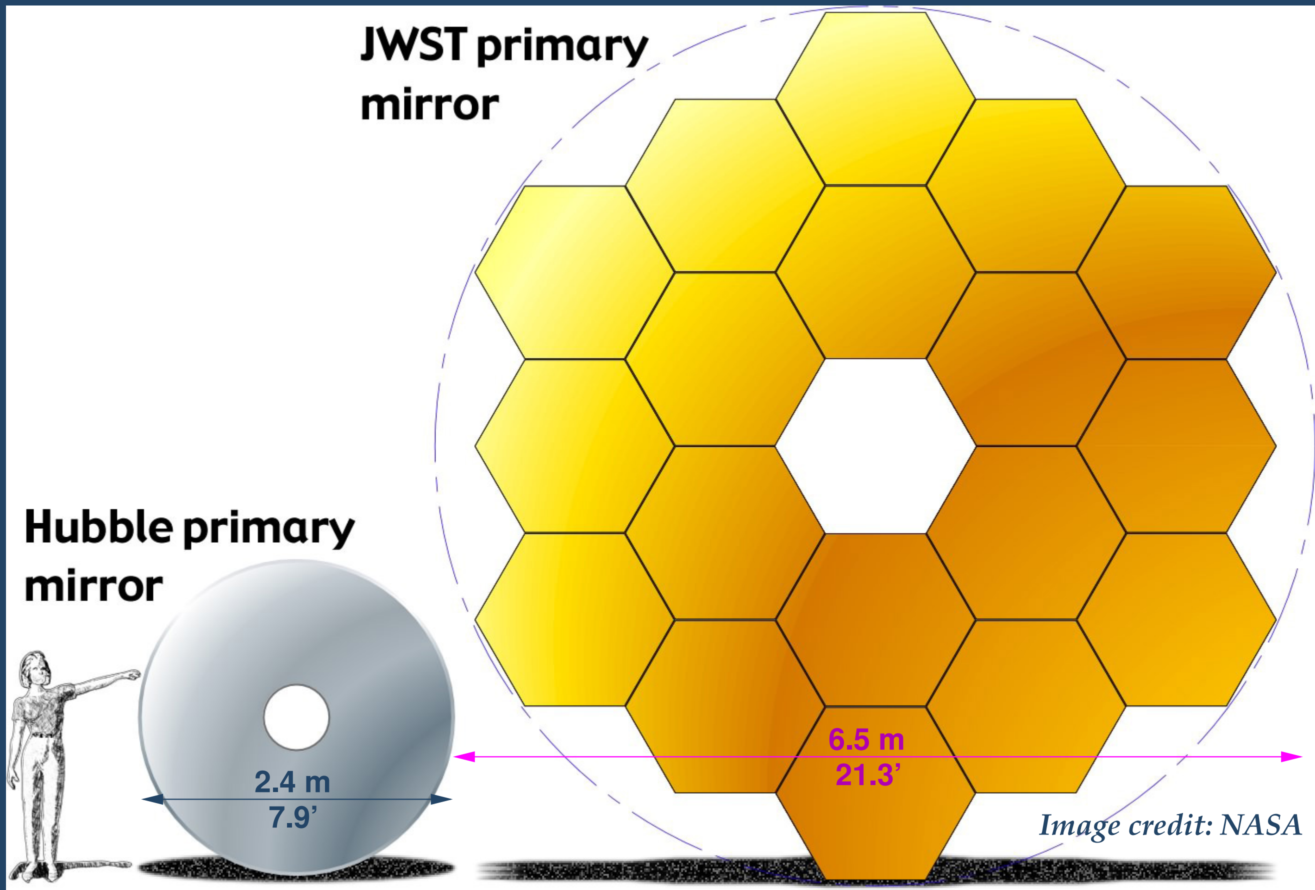
The *James Webb* Space Telescope – What is it?

- **mirror segments are coated with a thin layer of pure *gold***
  - **reflects infrared light extremely well**

Inspection of a gold-coated beryllium primary mirror segment at GSFC
(September 19, 2012)

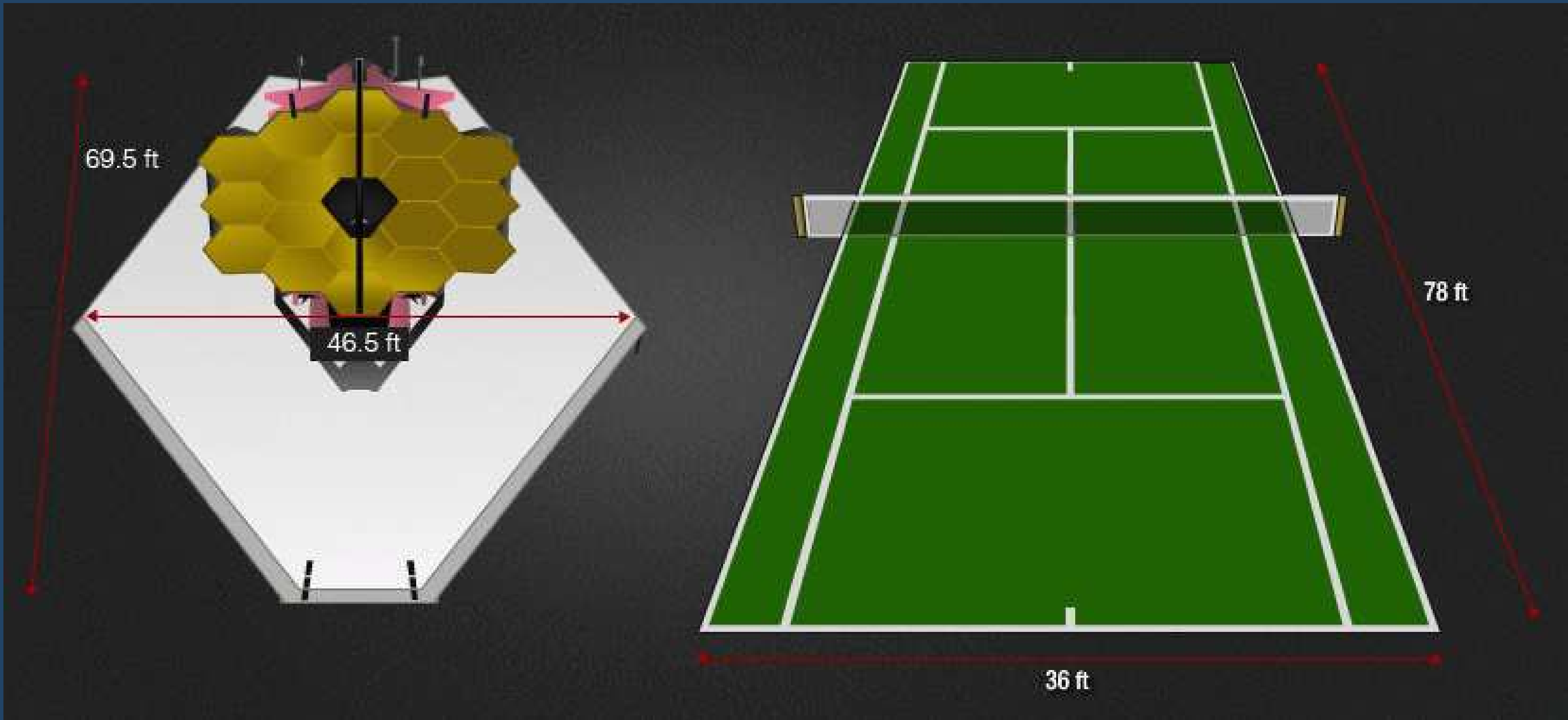
The *James Webb* Space Telescope – What is it?

- ***JWST***'s **primary mirror spans 6.5 m in diameter**
  - **2.7 times wider than *Hubble*'s mirror**
  - **6.25 times greater light collecting area**



The *James Webb* Space Telescope – What is it?

- ***JWST*'s 5-layer sunshield is roughly the size of a tennis court**
    - **keeps the telescope & instruments in perpetual shade at 40 K (−388°F); colder than the surface of Pluto!**



The *James Webb* Space Telescope – What is it?

- *JWST* was too big to launch as is
  - largest payload fairing, most reliable rocket: Ariane V
  - launched folded up like origami, then unfold in space

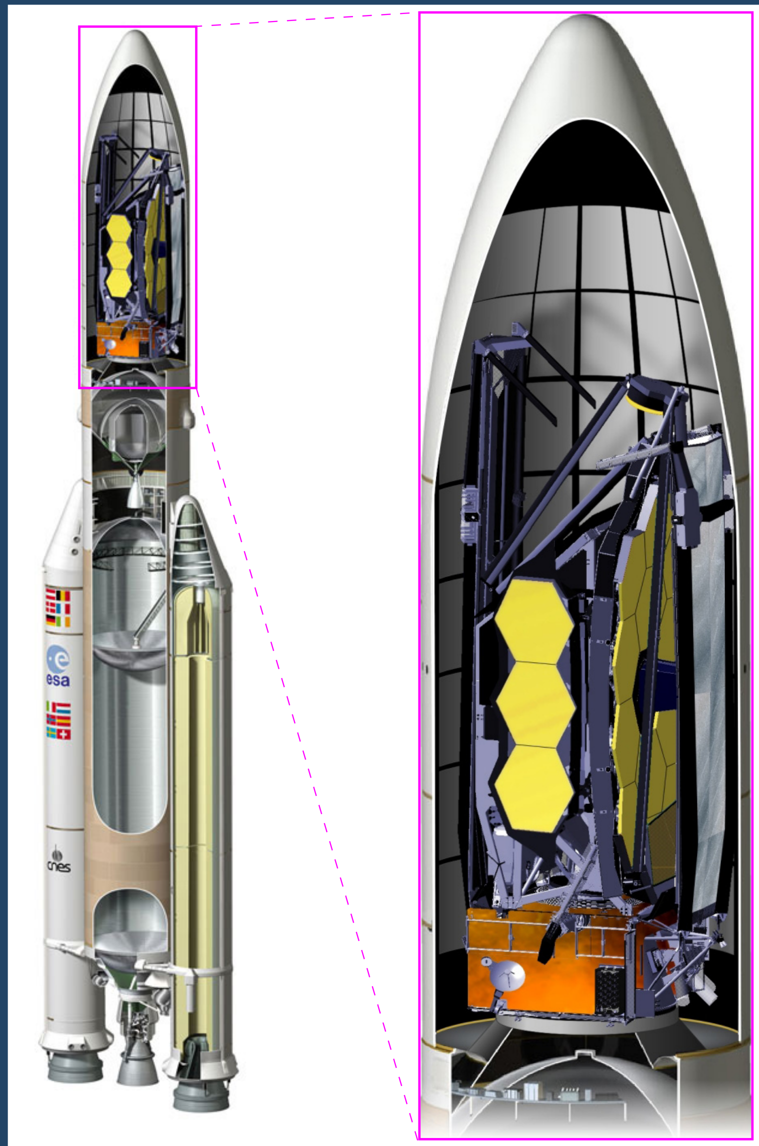
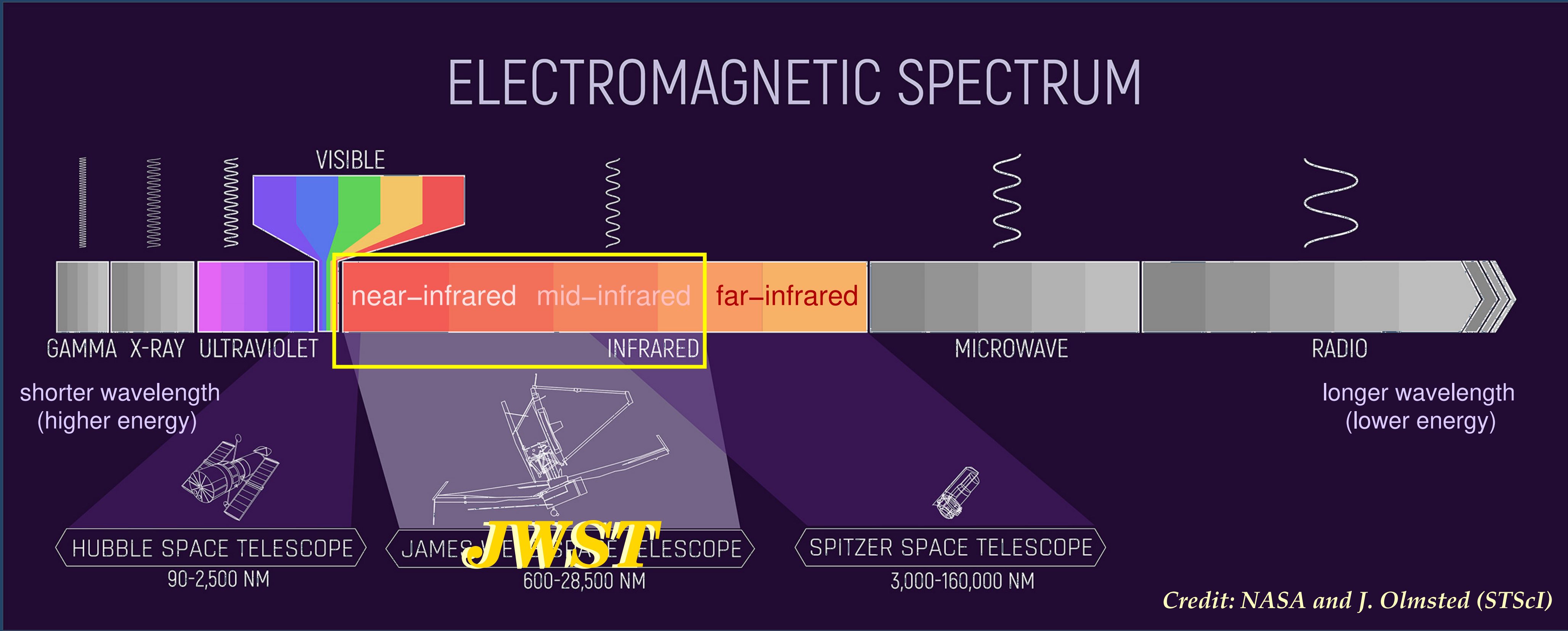


Image credit: ESA

The *James Webb* Space Telescope – What is it?

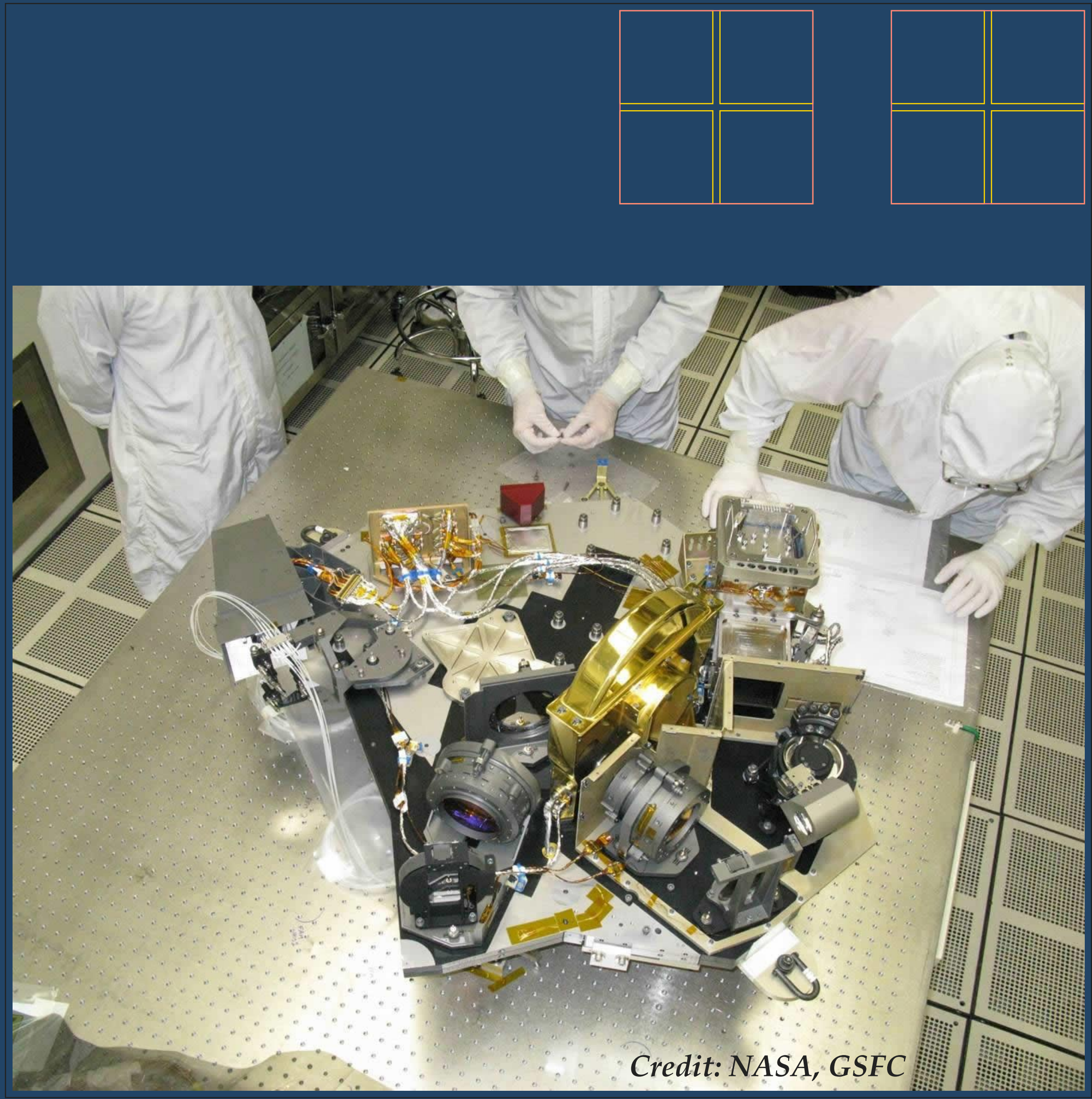
- ***JWST*** **is sensitive to the reddest visible light and invisible infrared light**
  - **0.6 – 28 microns; extending *Hubble*'s wavelength range**
  - **4 instruments, with redundant capabilities**



Credit: NASA and J. Olmsted (STScI)

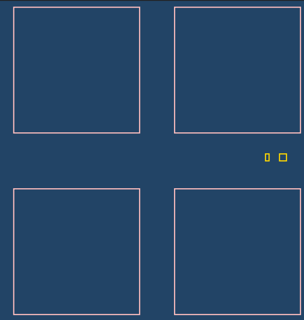
The *James Webb* Space Telescope – What is it?

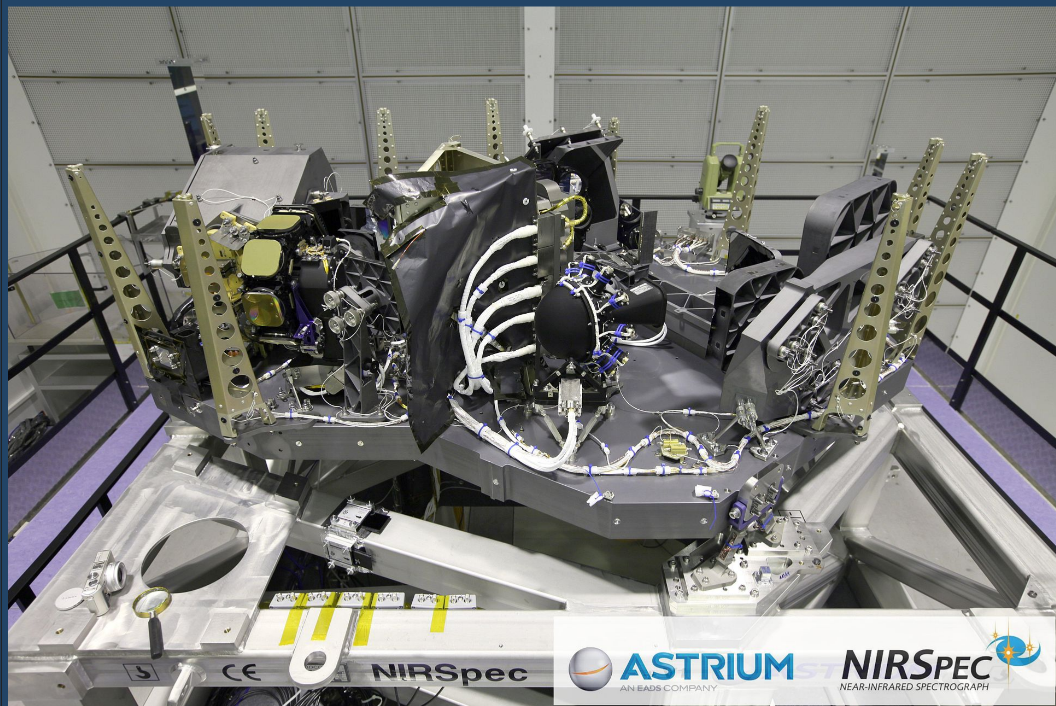
- **The Near Infrared Camera (NIRCam)**
  - **operating range: 0.6 – 5 micron**
    imaging area: $2 \times (2\overset{\prime}{.}2 \times 2\overset{\prime}{.}2)$
  - **2 independent optical systems (can operate at the same time, or separately)**
  - **simultaneous imaging in a short (SW) and in a long wavelength (LW) band**
  - **also a wavefront sensor to keep the 18 mirror segments aligned**
  - **both imaging and spectroscopic capabilities**



The *James Webb* Space Telescope – What is it?

- **The Near Infrared Spectrograph (NIRSpec)**
  - range: 0.6 – 5 micron
    area: $3' \times 3'$
  - multi-object spectroscopy (up to 100 objects at a time)
  - fixed slits + configurable slits and apertures using 4 micro-shutter arrays
  - integral field unit (IFU) mapping of velocities and spectral line strengths within extended objects

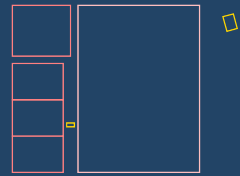


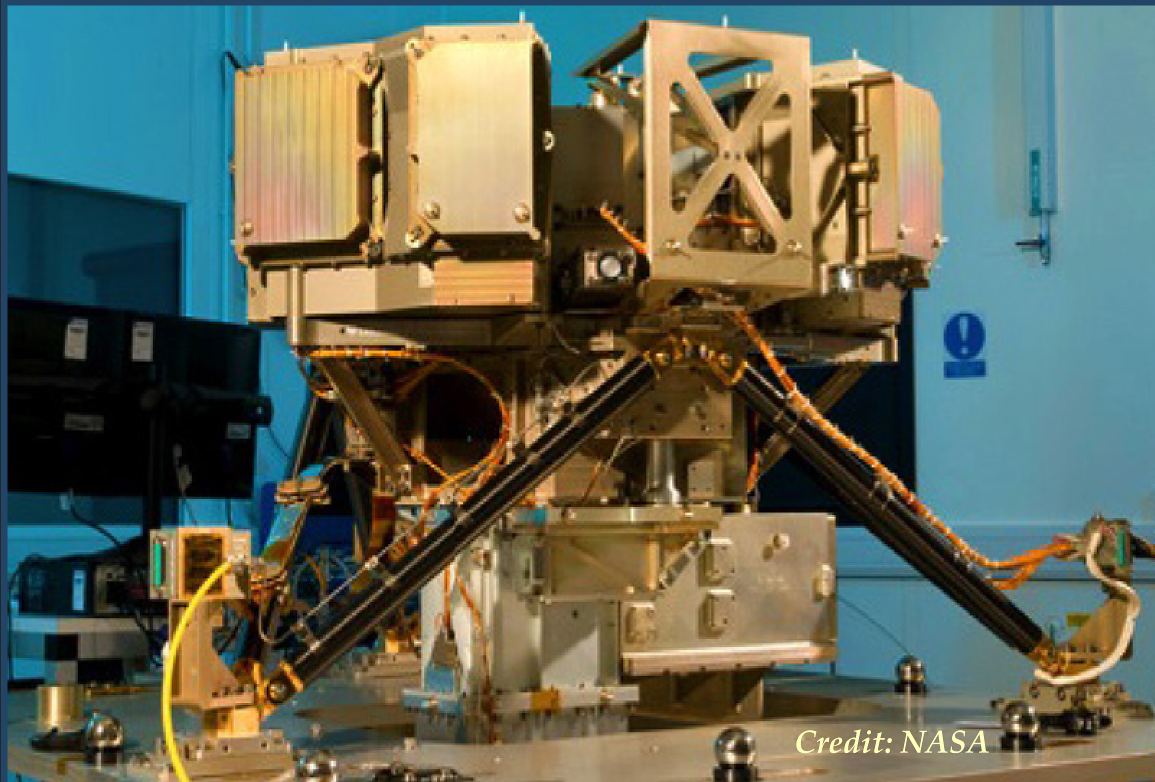


Credit: Astrium GmbH

The *James Webb* Space Telescope – What is it?

- **The Mid-InfraRed Instrument (MIRI)**
  - **5 – 28 micron imaging**
    area: $74'' \times 113''$
  - **5 – 28 micron fixed-aperture spectroscopy**
    area: $3.''5 \times 3.''5$
  - **5 – 12 micron low-resolution spectrometry**
  - **coronagraphic imaging**
    $24'' \times 24''$ or $30'' \times 30''$
  - **cooled deeper to 7 K (-447°F)**

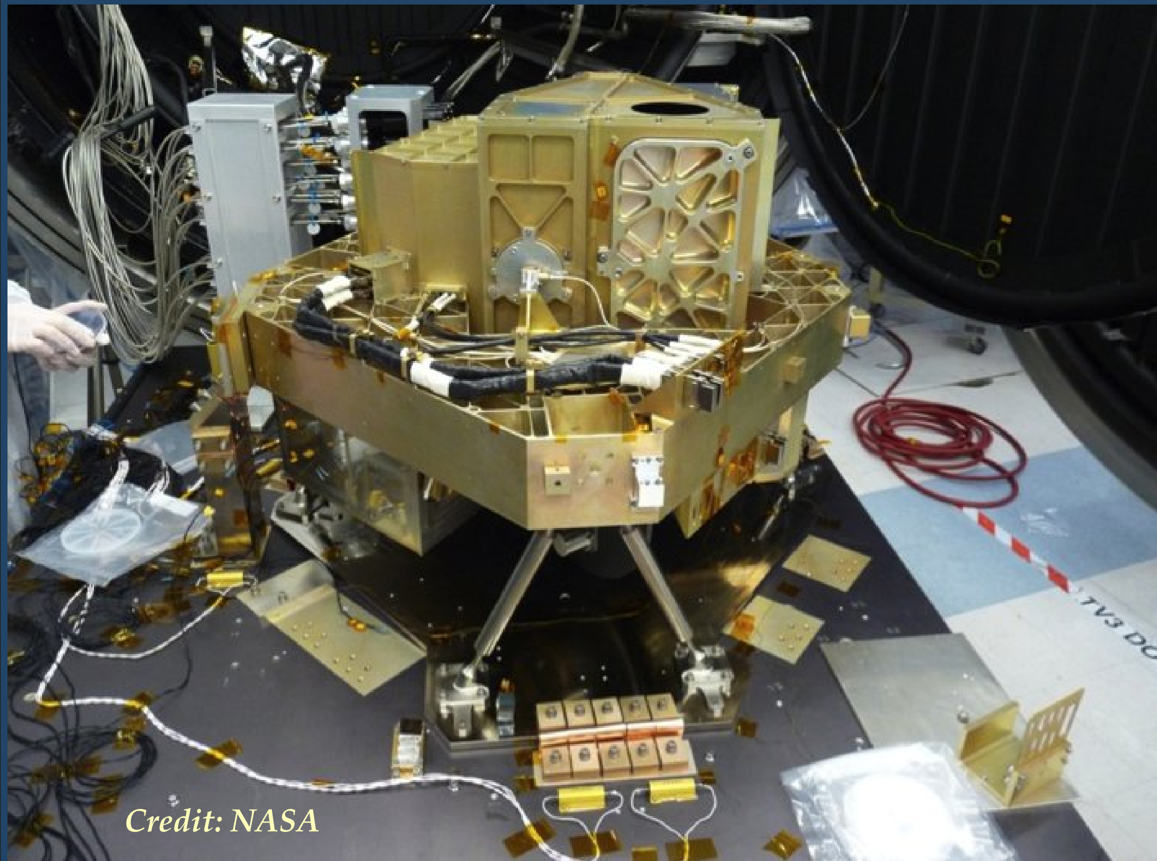




Credit: NASA

The *James Webb* Space Telescope – What is it?

- **The Fine Guidance Sensor (FGS) and Near-InfraRed Imager and Slitless Spectrograph (NIRISS)**
  - **0.8 – 5 micron imaging area: $2\overset{\prime}{.}2 \times 2\overset{\prime}{.}2$**
  - **redundancy with NIRCam**
  - **0.8 – 5 micron wide-field slitless spectroscopy**
  - **discovery potential; objects without accurately known positions**
  - **guide camera for *JWST***



Credit: NASA

Why do we need *JWST*?

- Before the *Hubble* revolution...
  - stark photographic images
  - Earth's atmosphere blocks light outside the visible range and blurs images

Image credit: seds.org

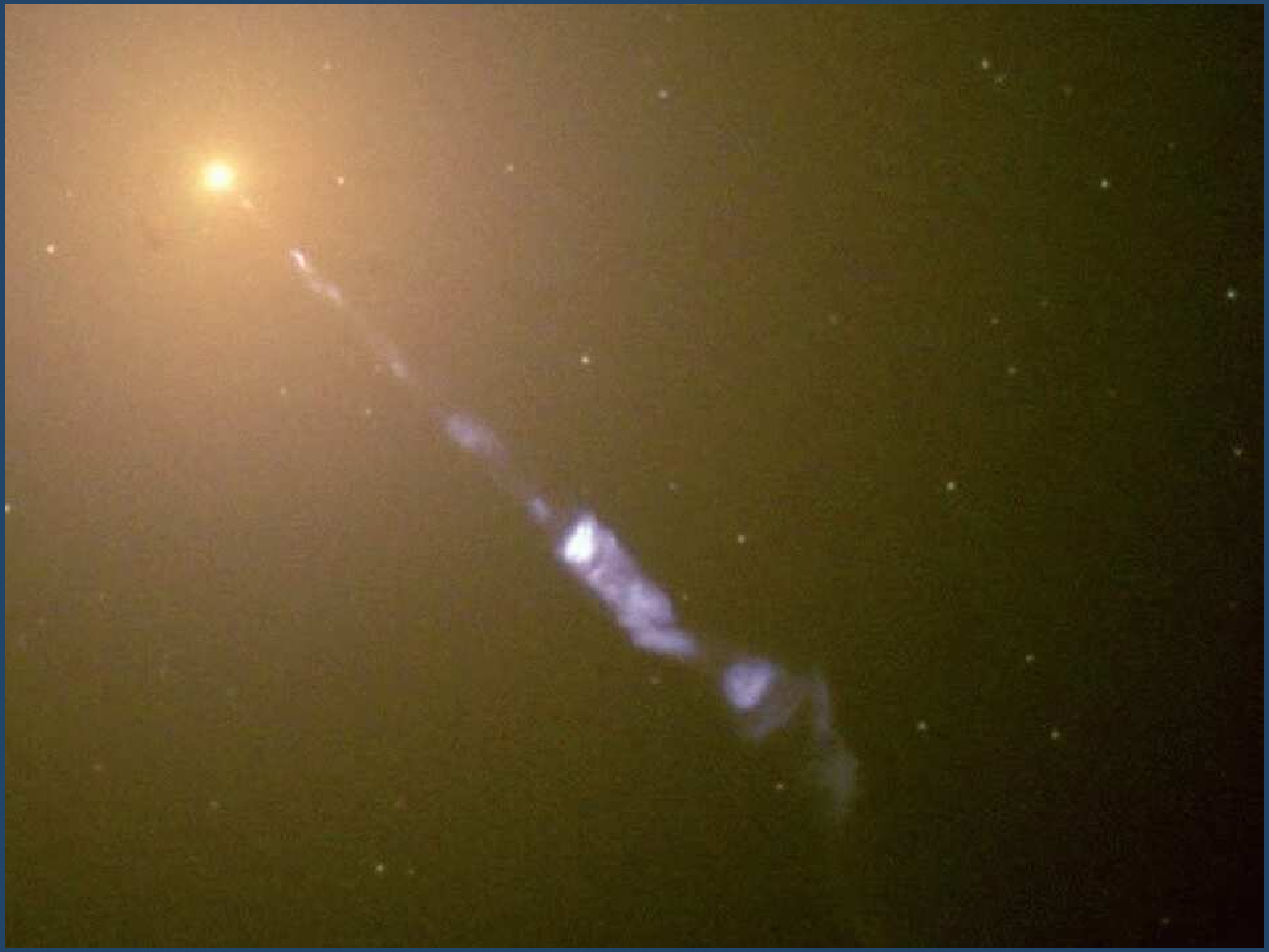
Why do we need *JWST*?

- After the *Hubble* revolution...
  - *Hubble* provides darker sky background
  - higher resolution
  - access to wavelengths of light inaccessible from the ground

Credit: NASA, ESA, Hubble Legacy Archive
Processing & Copyright: R. Bernal Andreo

Why do we need *JWST*?

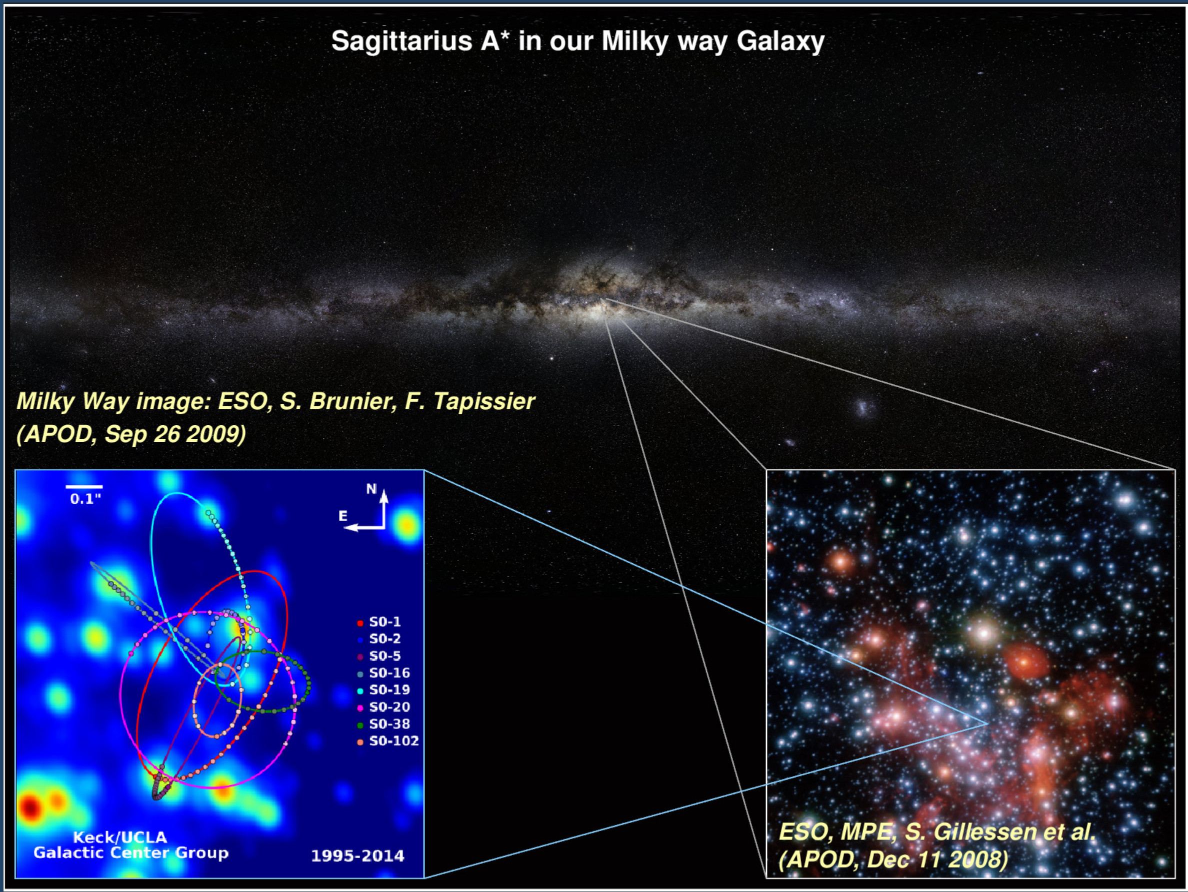
- **After the *Hubble* revolution...**
  - ***Hubble* discovered that all large galaxies have a supermassive black hole at their center...**

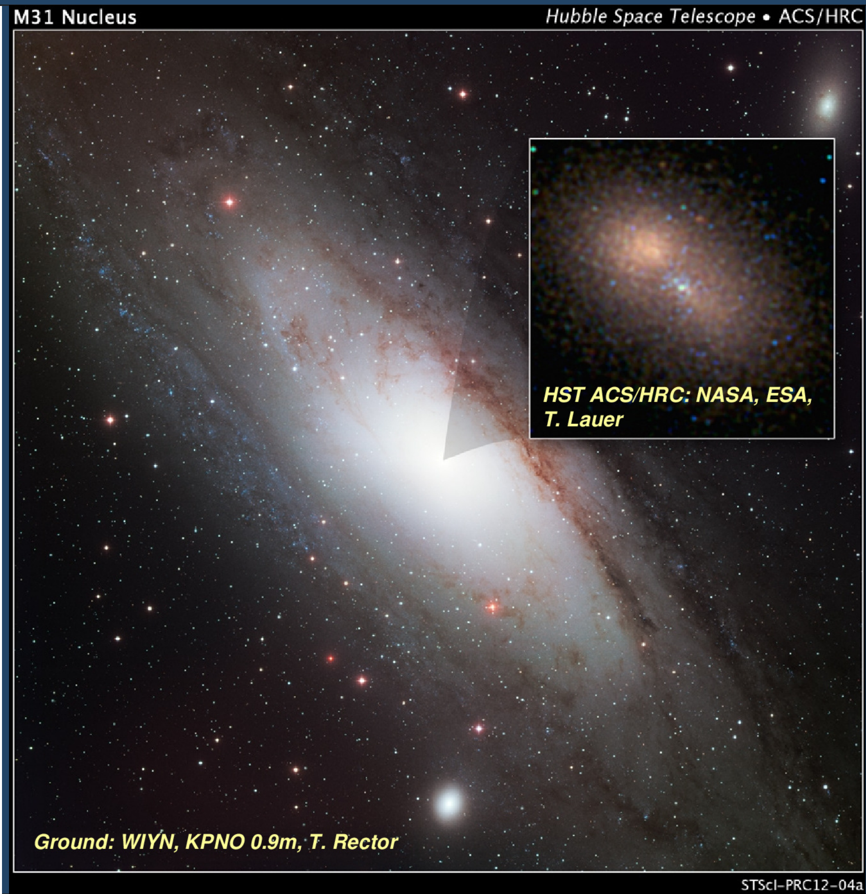


Credit: NASA, ESA, Hubble Heritage Team (STScI/AURA); J. Biretta et al.

Why do we need *JWST*?

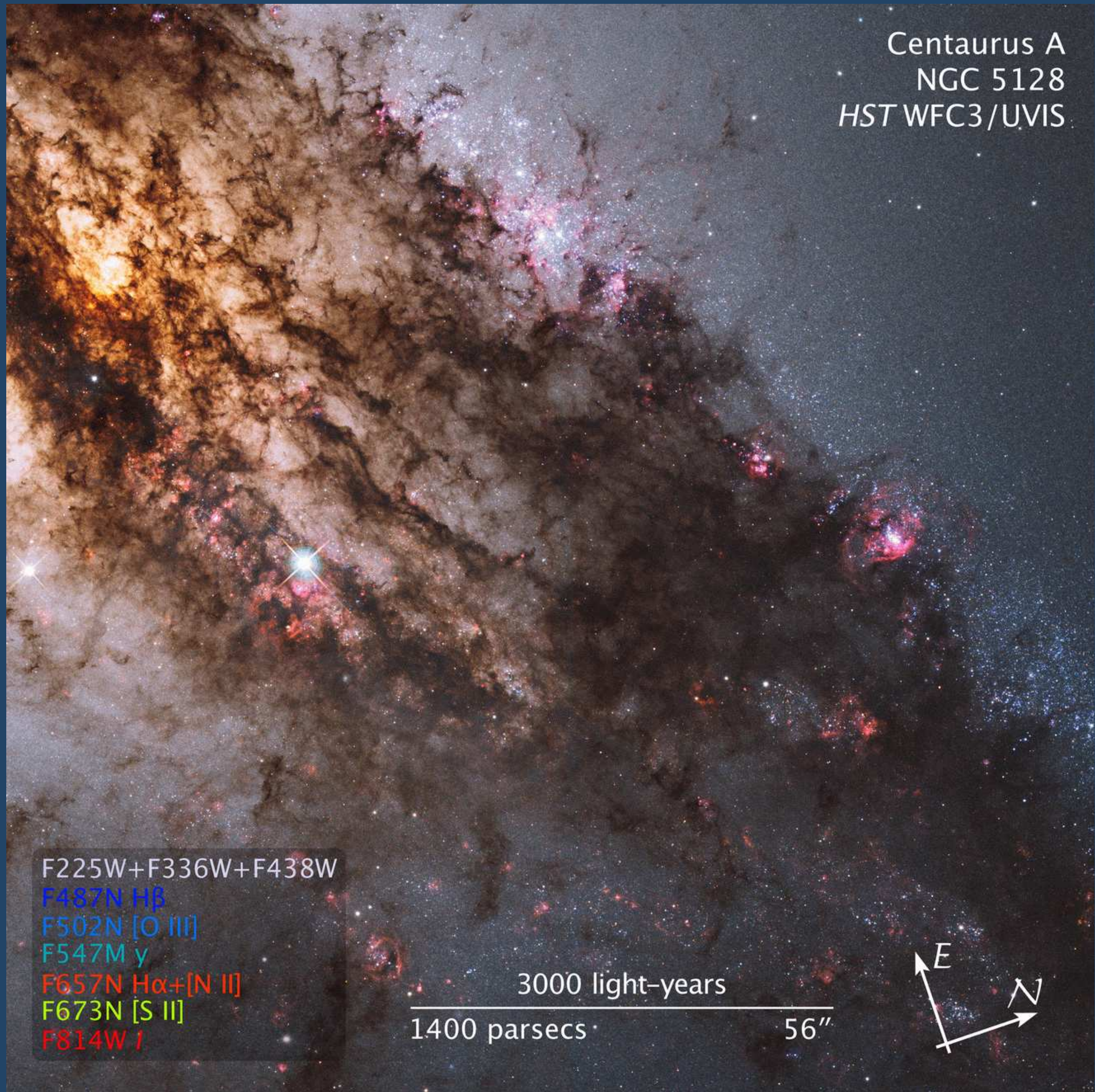
- **After the *Hubble* revolution...**
  - **... even our own Milky Way Galaxy and our nearest big neighbor, M 31, the Andromeda Galaxy**





Why do we need *JWST*?

- ***Hubble*** **gave us sharp views of starbursting galaxies...**



Credit: NASA, ESA, Hubble Heritage Team (STScI/AURA)–ESA/Hubble Collaboration; R. O'Connell et al.

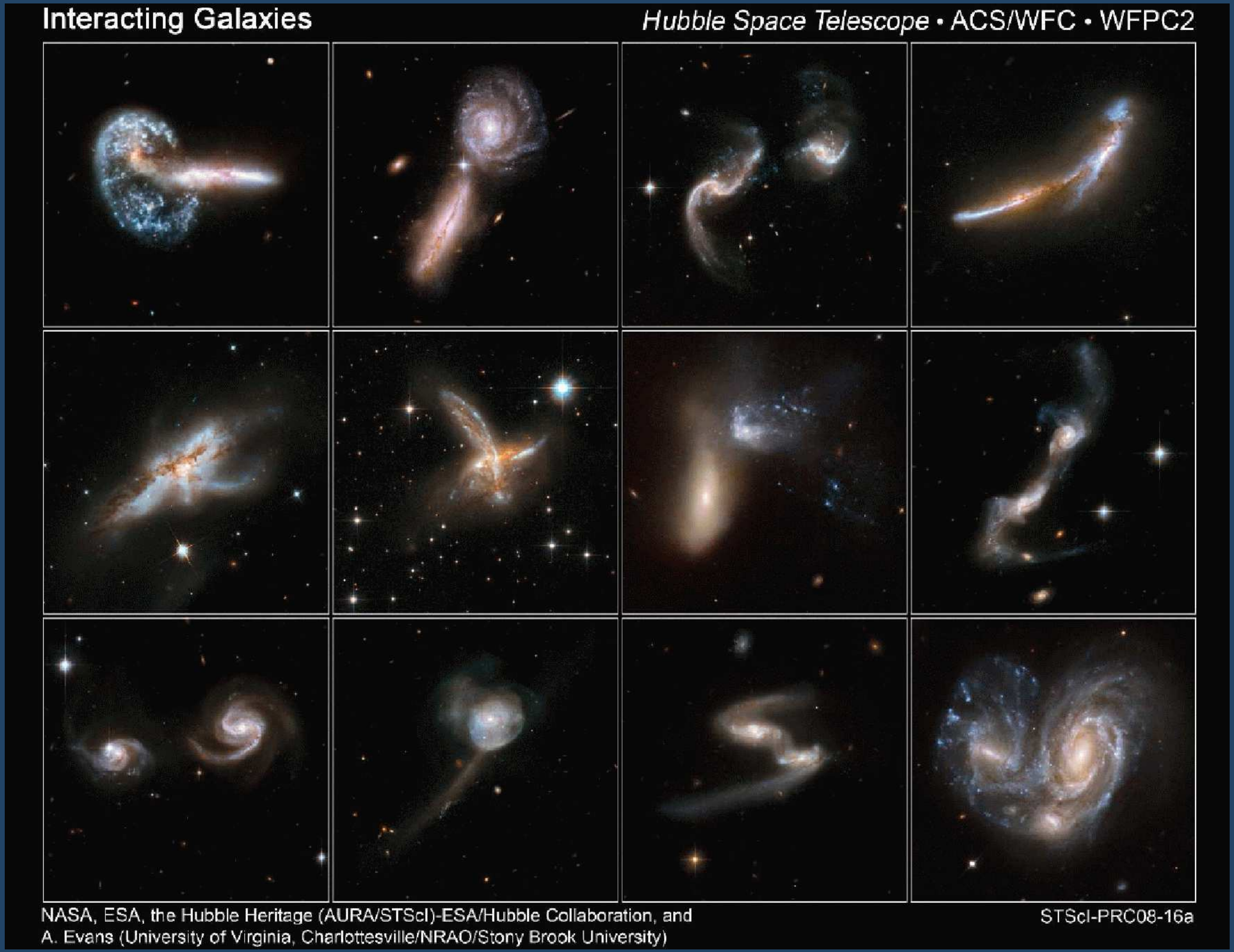
Why do we need *JWST*?

- *Hubble* gave us sharp views of interacting and merging galaxies...

Credit: NASA, ESA, Hubble Heritage Team (STScI/AURA)–ESA/Hubble Collaboration; B. Whitmore & J. Long

Why do we need *JWST*?

- **... and allowed us to trace galaxy assembly and subsequent evolution over the past 12 billion years**



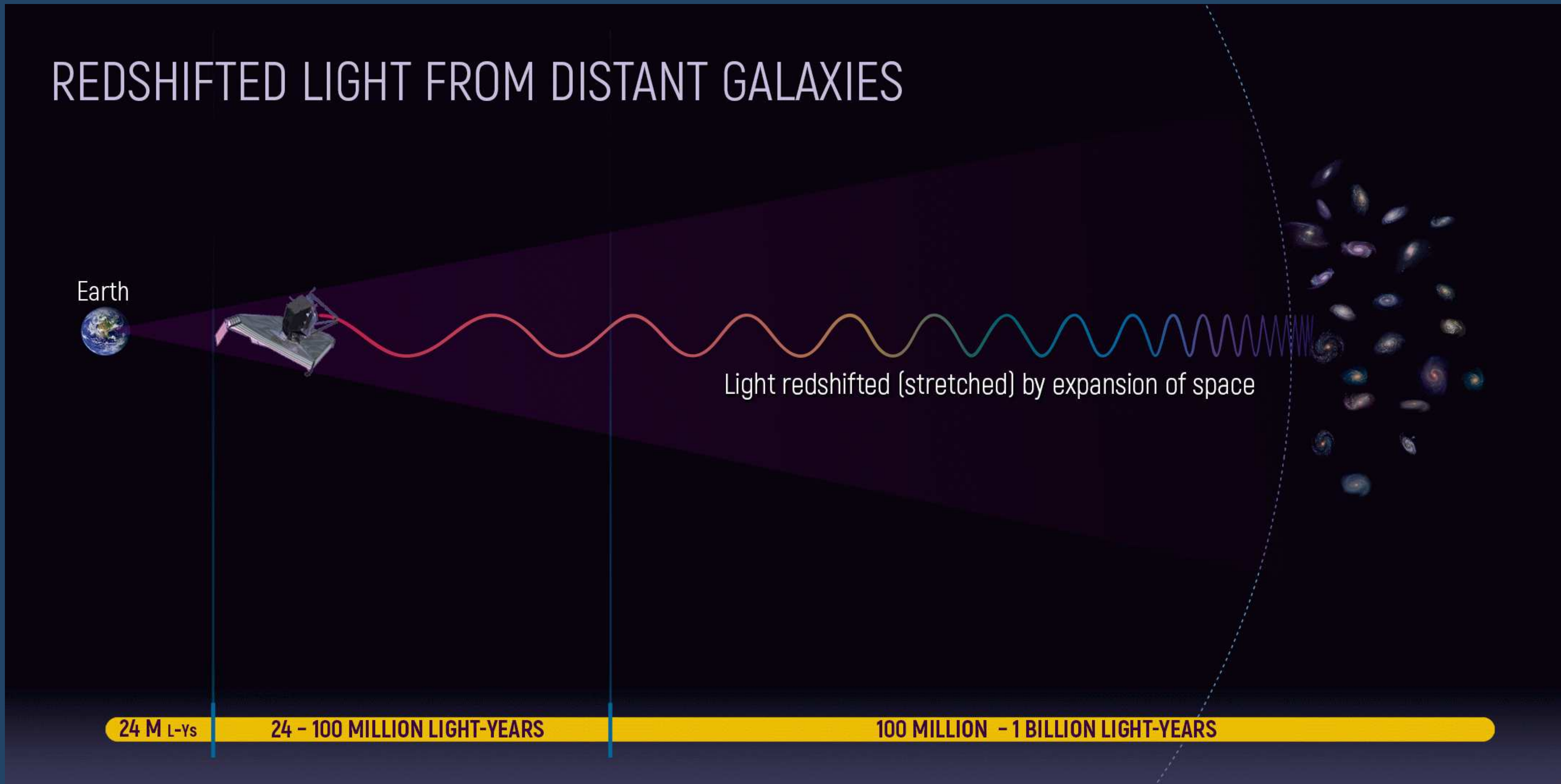
Why do we need *JWST*?

- **12 billion years of cosmic history in one *Hubble* picture**
  - **galaxies at redshifts larger than 7 are hard to find (dim, red, and tiny), and very rare**

Credit: NASA, ESA, R. Windhorst (ASU), P. McCarthy (CIW), & R. O'Connell (UVa); color composite by M. Mechtley (ASU)

Why do we need *JWST*?

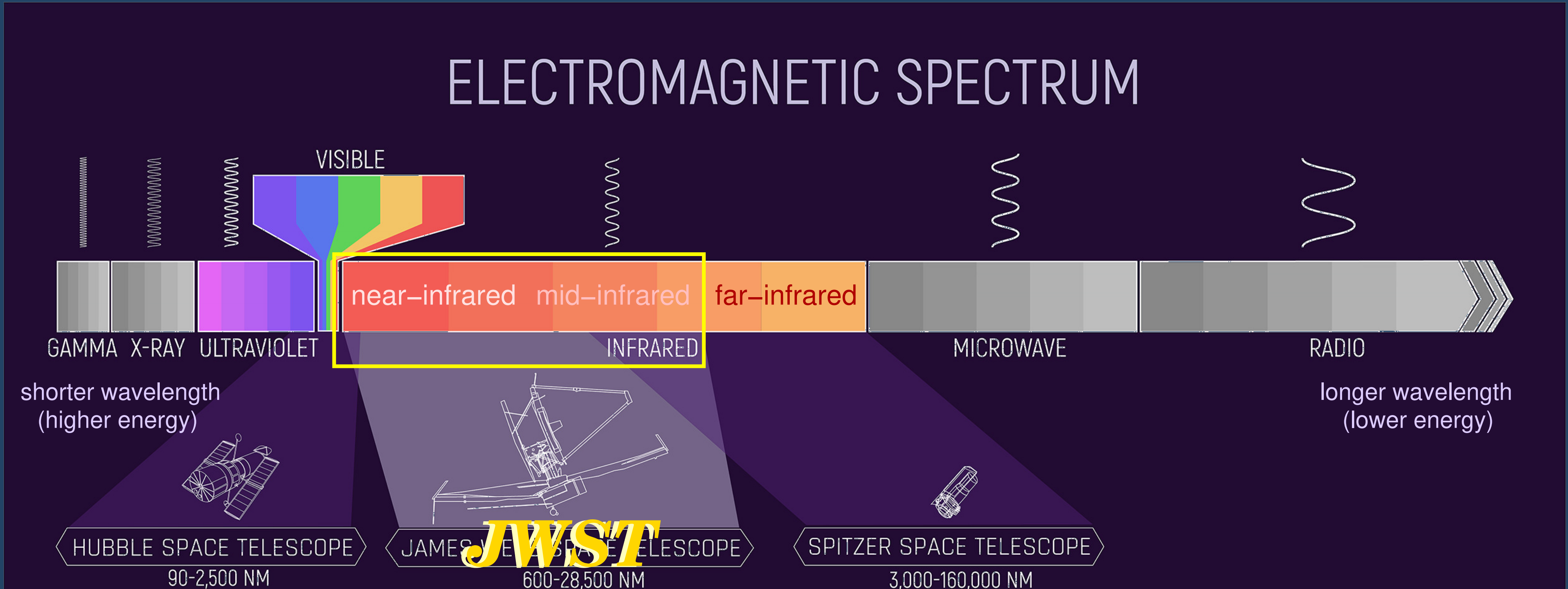
- **the wavelengths of light emitted by distant galaxies gets stretched as it travels to us.**
  - **ultraviolet–visible light from the first galaxies in the Universe arrives as *infrared* light**



Credit: NASA and A. Feild (STScI)

Why do we need *JWST*?

- ***JWST* sees farther into the infrared than *Hubble***
- ***JWST* has a larger mirror to collect the dim light of the first galaxies**
- ***JWST* has a larger mirror to create sharper images of such small objects.**



Credit: NASA and J. Olmsted (STScI)

Where is *JWST*?

- ***JWST* was successfully launched from Kourou (French Guiana) on Dec 25 2021 by an Ariane V rocket**

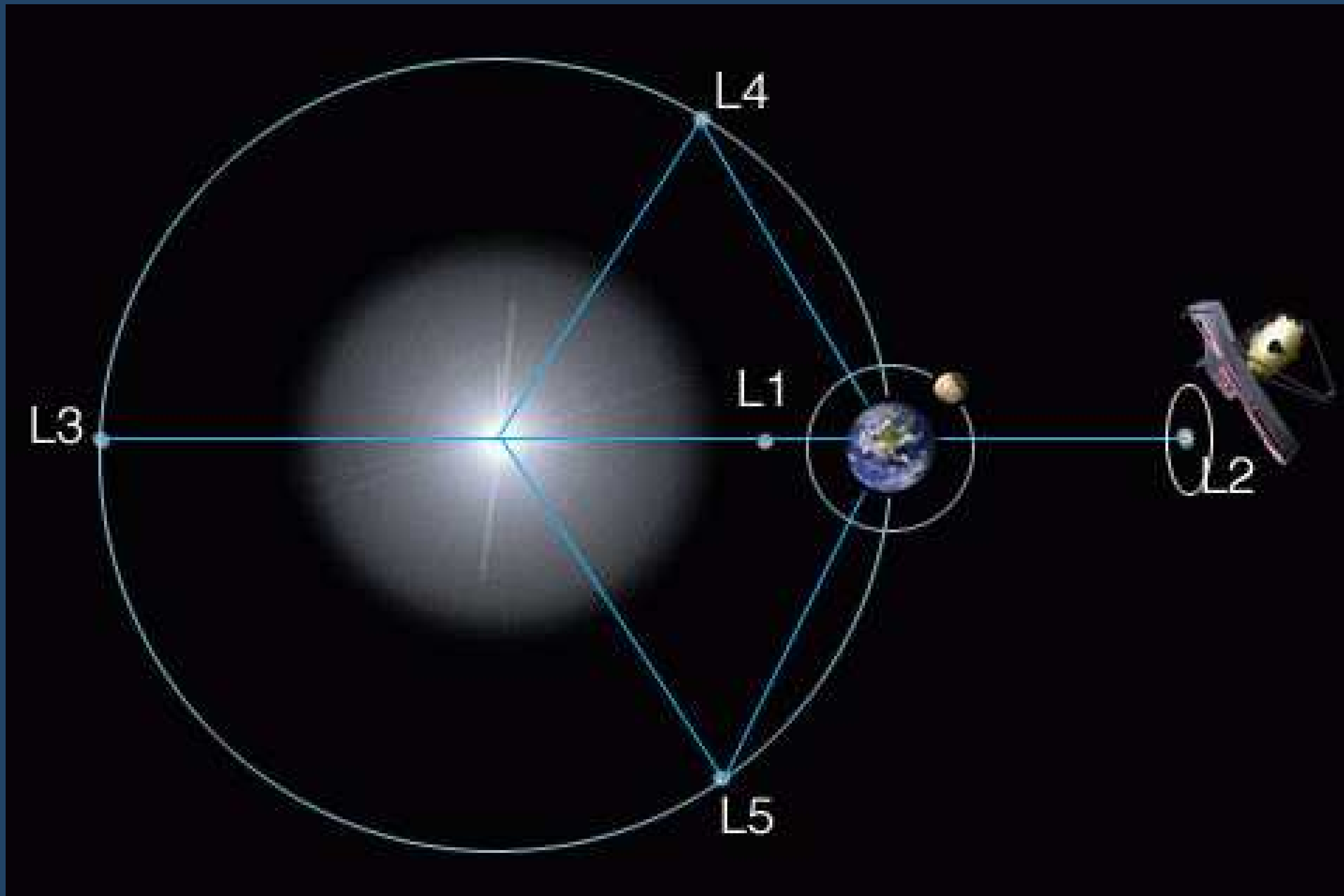
Photo courtesy of Arianespace + NASA

Where is *JWST*?

- *JWST* was successfully launched from Kourou (French Guiana) on Dec 25 2021 by an Ariane V rocket

Where is *JWST*?

- **Ariane V launched *JWST* extremely precisely into an orbit around a special point in space: the second Earth–Sun Lagrange point, L2**

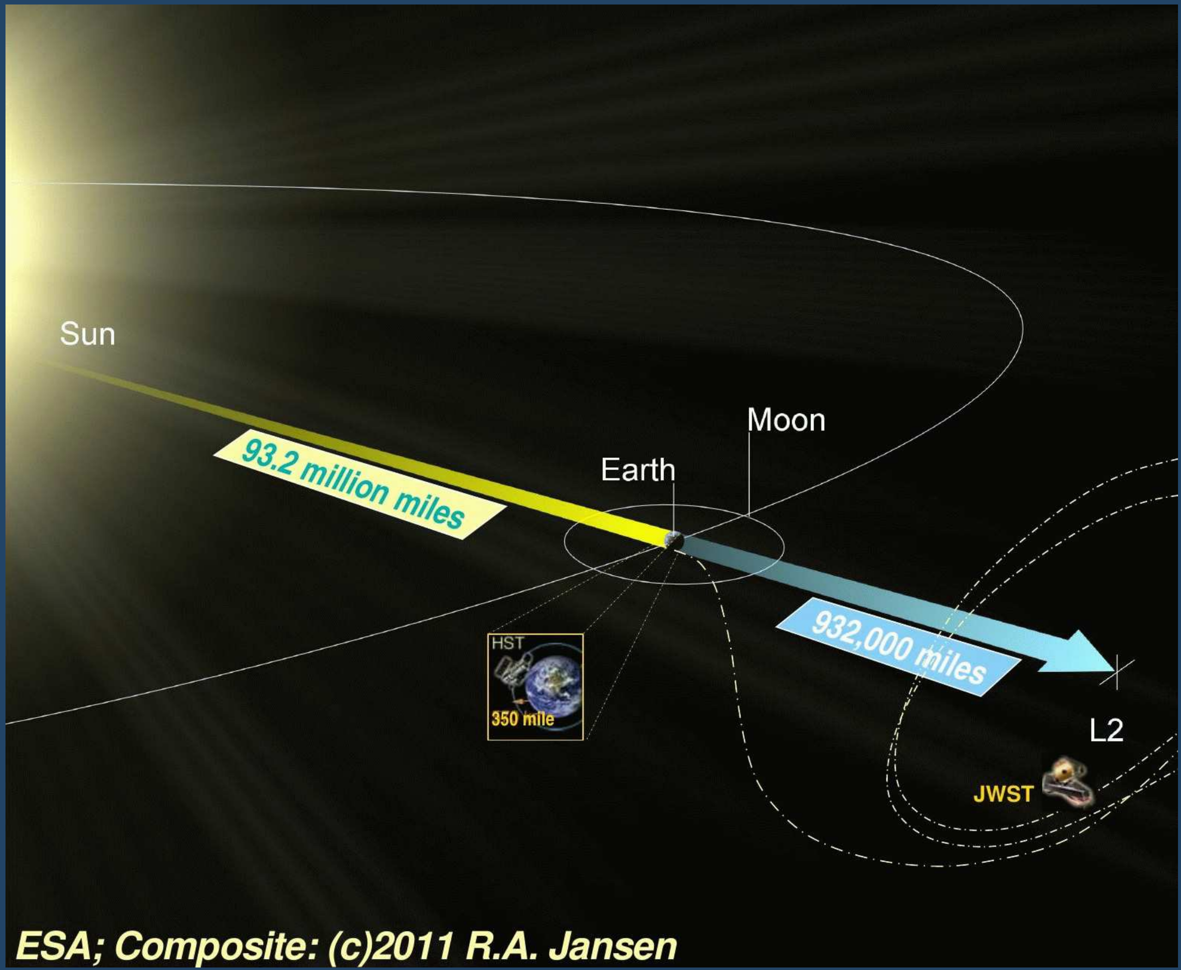


Note: Image not to scale

Where is *JWST*?

- In this L2 halo orbit:
  - always power, always possible to communicate with Earth
  - telescope never sees Sun, Earth, or Moon
  - fuel is expended for operation and to stay in this orbit

- L2 is too far away for astronauts to service *JWST*
  - built-in redundancy, overlap in instrumental capabilities



JWST: Wow — it *works*!

- **After 7 months of travel to L2, cool-down to $<$40 K, mirror alignment and on-orbit instrument commissioning activities, the first science image was released to the world on July 11 2022:**
  - **Galaxy cluster SMACS 0723.3−7327**
  - **Distorted images of background galaxies due to gravitational lensing by the cluster**
  - **Many infrared-bright galaxies that were invisible to *Hubble***

- **Image quality far exceeds requirements**

Credit: NASA, ESA, CSA, and STScI

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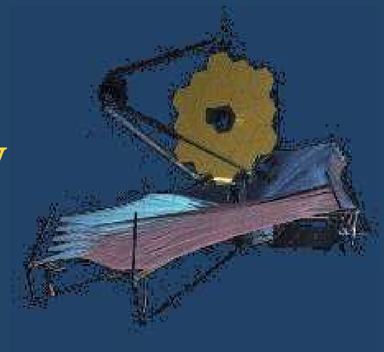
  - **First Near-Infrared observations with *JWST***

What is “Time-Domain Science”?

- **many phenomena cause the brightness or position of objects to change with time on a variety of time-scales.**
  - **variable stars — vary in brightness, some in very regular patterns**
  - **novae, supernovae, and gamma ray bursts — transients that appear and fade away again**
  - **active galactic nuclei — flicker as their supermassive black holes feed on infalling matter**
  - **asteroids, comets, interstellair visitors — orbital motion**
  - **nearby stars and brown dwarfs — move with respect to the background of more distant Galactic stars**

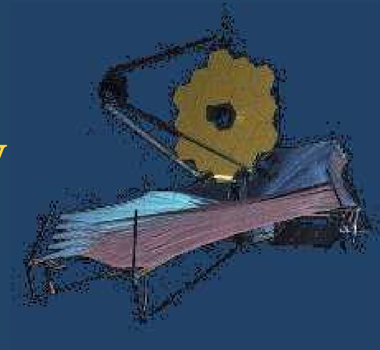
- **The study of all such objects and more, where important scientific information can be gleaned from their change over time, can be termed “time-domain science”.**

JWST as a Time-Domain Science Facility



- **Context: Advent of the era of deep, large area (survey) time-domain science (relatively faint objects with, e.g., PanSTARRS, *Rubin*/LSST, *Roman*)**
  - **Solar System**
  - **Galactic neighborhood (and beyond)**
  - **Objects at cosmological distances / large look-back times**

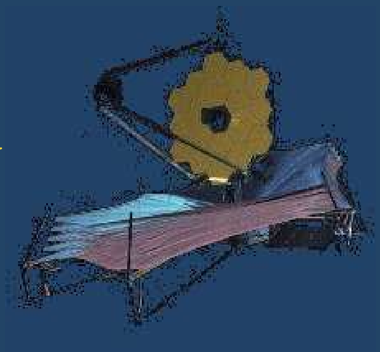
JWST as a Time-Domain Science Facility



- **Context: Advent of the era of deep, large area (survey) time-domain science (relatively faint objects with, e.g., PanSTARRS, *Rubin*/LSST, *Roman*)**

- **Question: can *JWST* do time-domain survey science? What would it add?**
  - ***Rubin* / LSST: $m_{\rm AB} \lesssim$ 23.8 mag (10σ per 2$\times$15 s visit; $\sim$15 min – 1 hr time-scales over large fraction of the sky)**
  - ***JWST*/NIRCam: $m_{\rm AB} \sim$ 26.8–28.3 mag (10σ per epoch; $\sim$15 min – 1 hr time-scales ... in a suitable survey field)**

JWST as a Time-Domain Science Facility



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▷ **Unexplored magnitude regime for variability studies: $m_{\mathrm{AB}} \gtrsim$ 24 mag**

- **Supernovae (Type Ia SNe to $z \sim 5$, Core Collapse SNe to $z \sim 1.5$, Pair Instability SNe to the Epoch of Reionization); (weak) AGN**

▷ **Unexplored regime for proper motion detections: $m_{\mathrm{AB}} \gtrsim$ 24 mag, $p \gtrsim$ 0.5 mas/yr**

- **Extreme outer Solar System objects; interstellar asteroids and comets (such as 1I/'Oumuamua or 2I/Borisov); nearby Galactic brown dwarfs and low-mass stars.**

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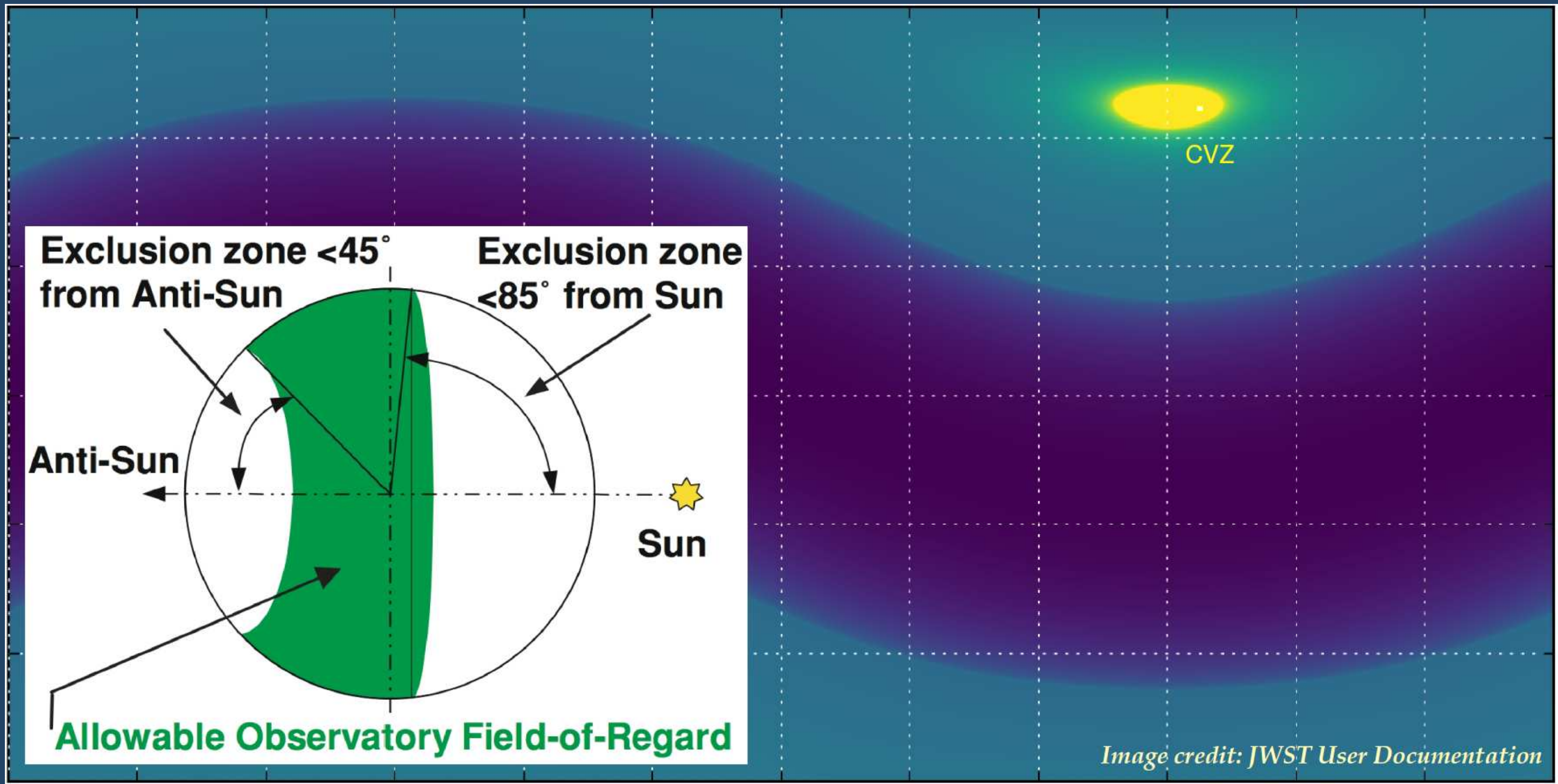
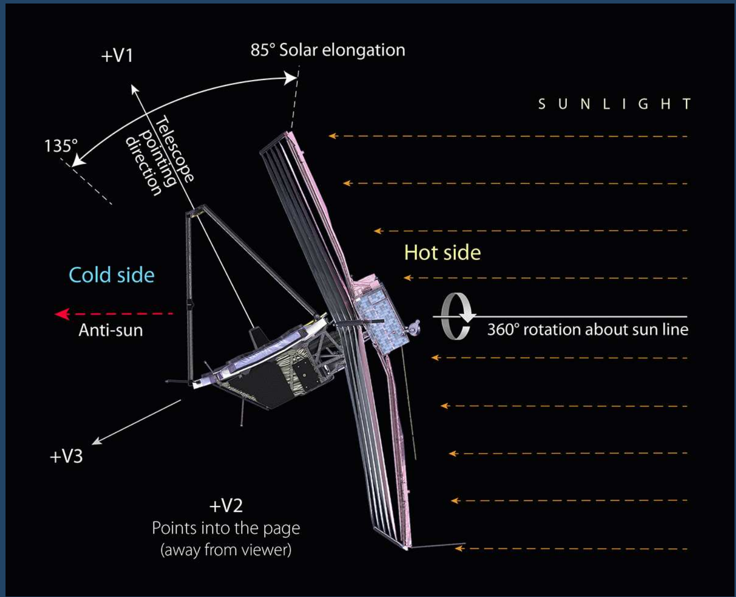
JWST Operational Restrictions = Orientation Restrictions

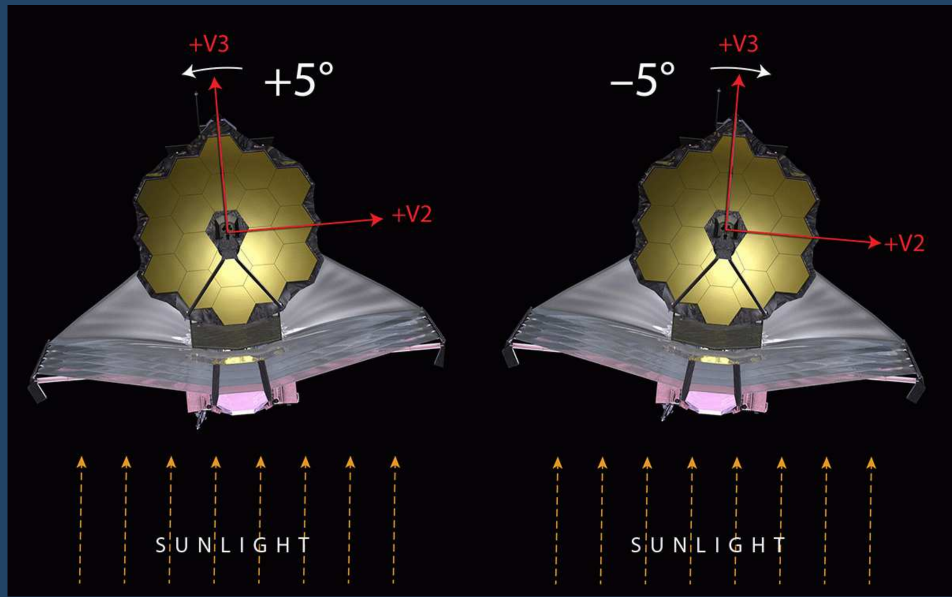


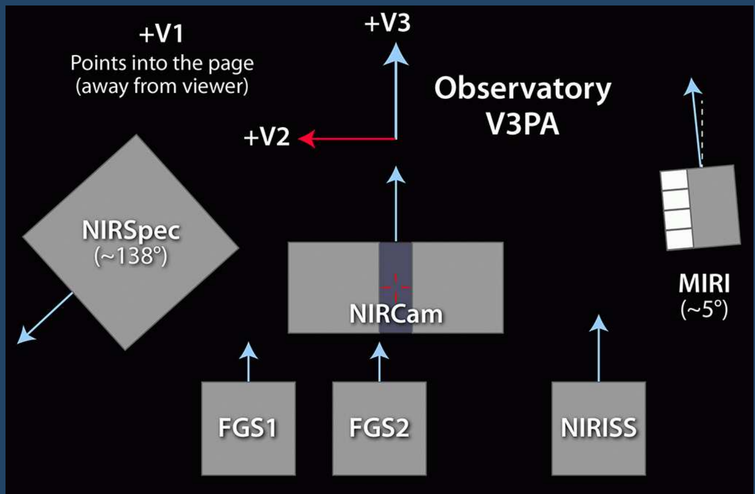
- Sun avoidance, power generation, and shielding requirements of the cryogenic telescope restricts object visibility to two time intervals per year *[also: avoid pointing into the meteor wind!]*

▷ Except for objects within two small ($r < 5°$) *continuous viewing zones* (CVZs) centered on the North Ecliptic Pole (NEP) and the South Ecliptic Pole (SEP).

JWST Operational Restrictions = Orientation Restrictions







- **Date of observation dictates orientation on the sky. Observers cannot freely choose orientations, limiting efficient use of instruments in parallel.**

▷ **Except for objects located within *JWST*'s Continuous Viewing Zones (CVZs).**

NASA / JWST User Documentation

JWST's Northern and Southern CVZs

- *JWST* Time-Domain Science on time-scales of minutes to years implies a survey field that *must* be located within one of *JWST*'s Continuous Viewing Zones.

  ▷ Existing, well-established, fields (e.g., from *HST*, *Chandra*, *XMM*, VLA) won't do.

- So let's take a closer look at these two special areas on the sky...

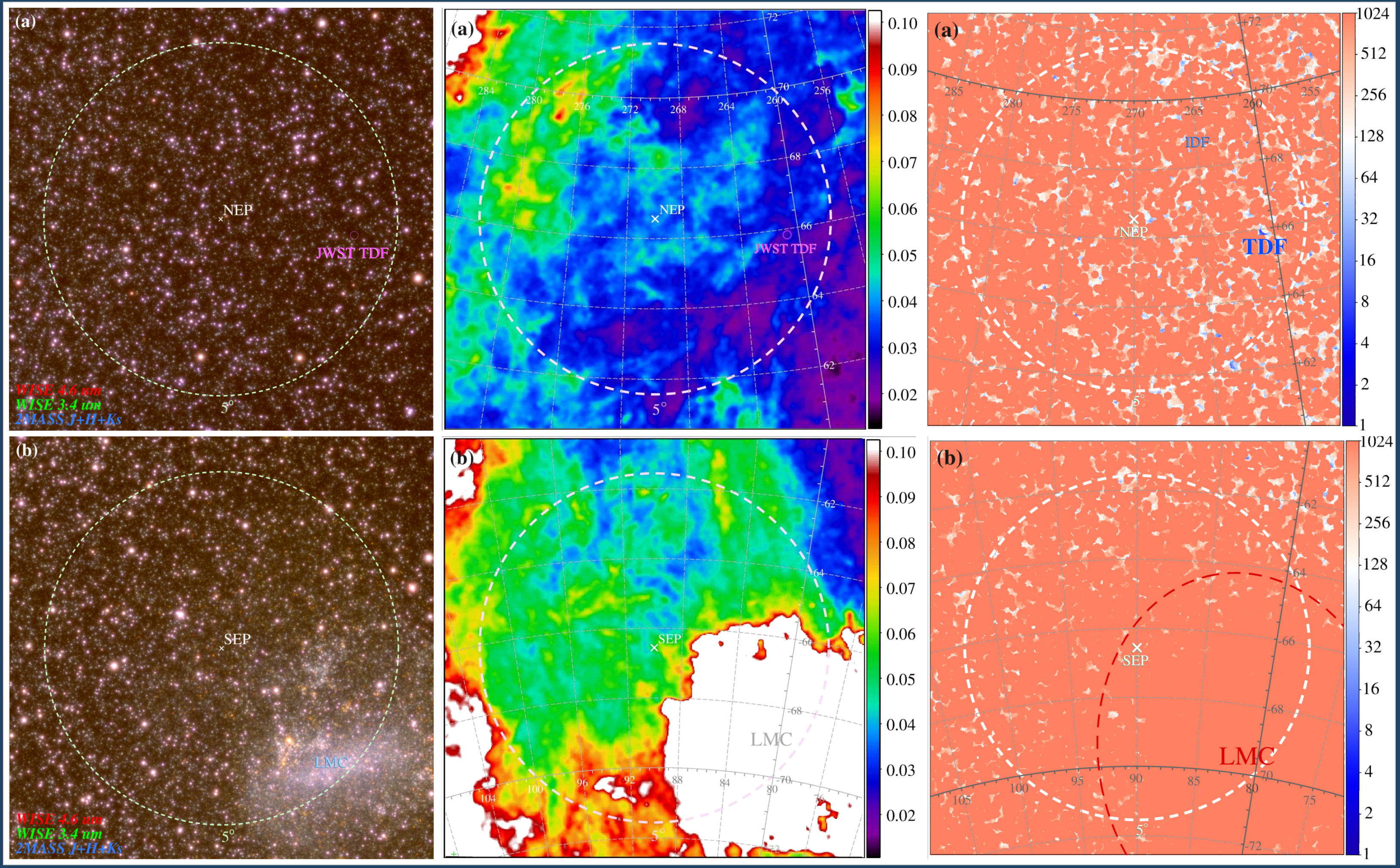
  ○ at near-infrared wavelengths (1.2 – 4.8 μm),

  ○ at foreground Galactic extinction $E(B{-}V)$, and

  ○ at density of sources brighter than $m_{\mathrm{AB}} \sim 15.5$ mag

  ▷ Can we find suitably clean locations for a *JWST* time-domain survey?

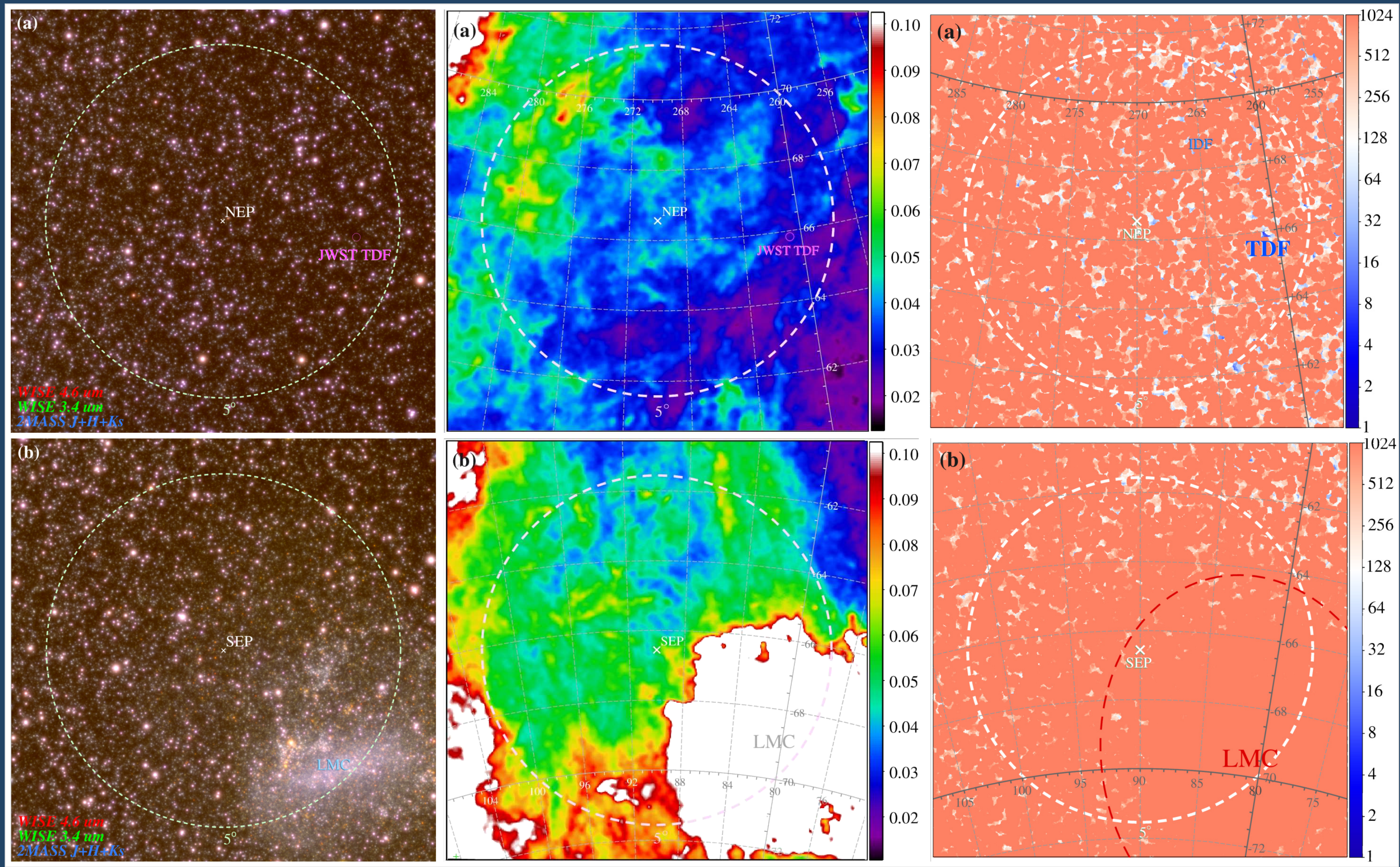
JWST's Northern and Southern CVZs



Jansen & Windhorst (2018)

▷ Northern CVZ contains emptier sky than Southern CVZ (due to LMC and Galactic structures)

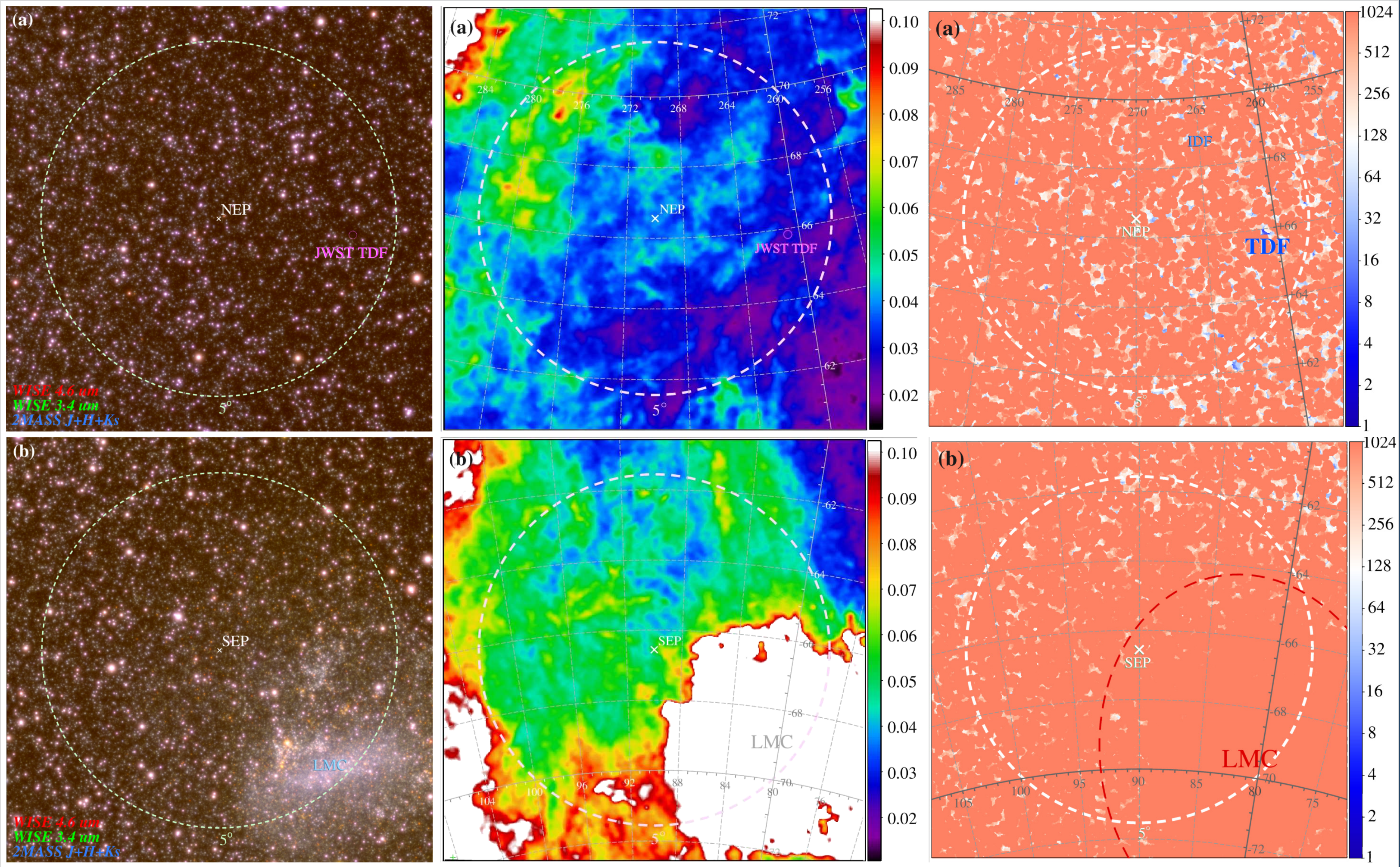
JWST's Northern and Southern CVZs



Jansen & Windhorst (2018)

- **Northern CVZ has a cleaner sight-line (less foreground extinction by Galactic dust) than Southern CVZ (due to LMC and Galactic structures)**

JWST's Northern and Southern CVZs



Jansen & Windhorst (2018)

- Only the Northern CVZ accommodates any clean $\gtrsim 14'$ diameter areas free of 2–4 μm-bright ($m_{\rm AB} \lesssim 15.5$ mag) stars.

Where can *JWST* do Time-Domain Survey Science?

▷ No solutions found in *JWST*'s Southern CVZ

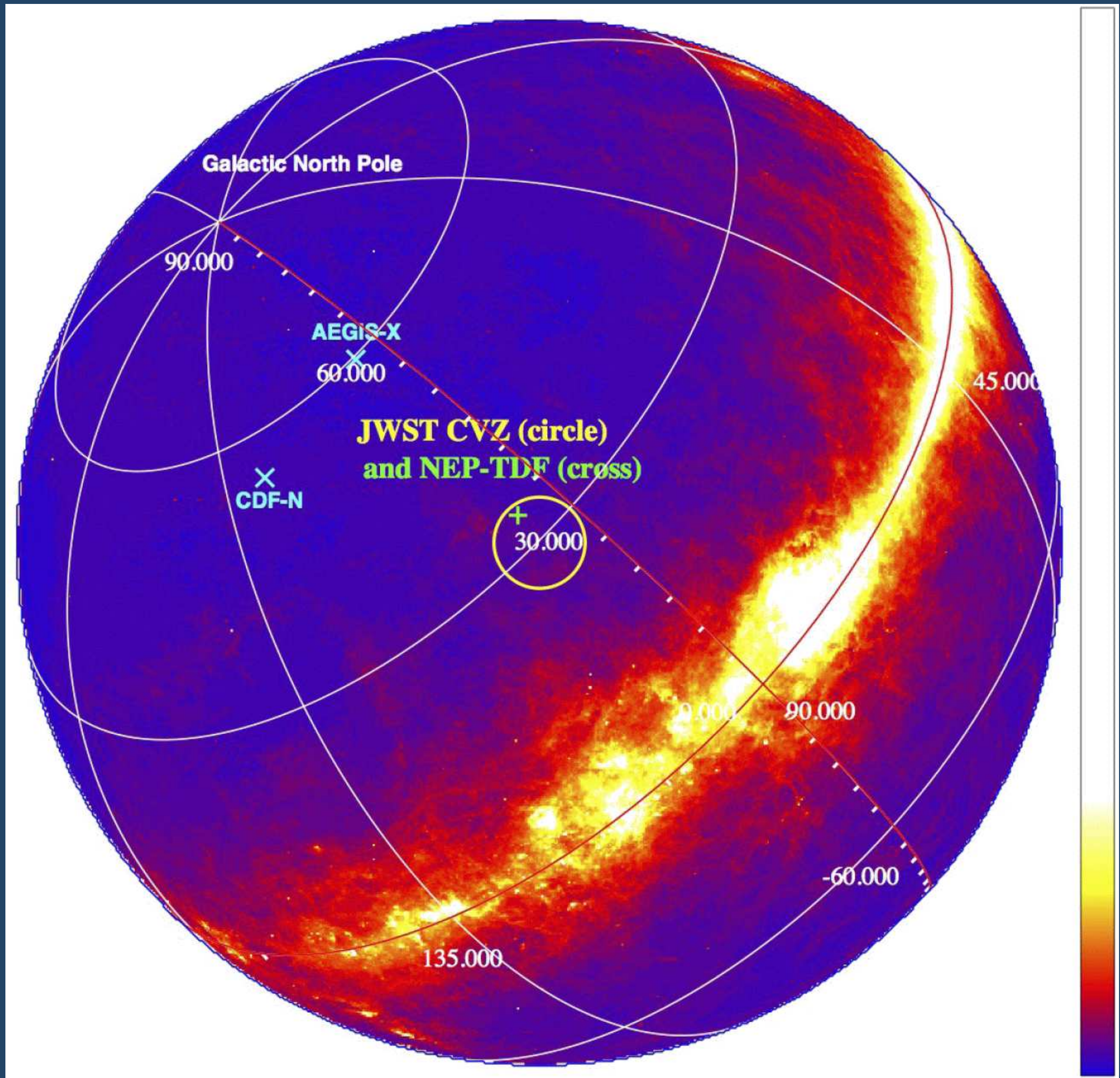
- The very best region in *JWST*'s Northern CVZ also has:
  - guide star solutions for *Hubble*, and it is just within *Hubble*'s CVZ as well
  - a bright quasar that can serve as a phase calibrator for radio interferometric observations,
  - low Galactic foreground extinction $E(B-V) \lesssim 0.03$, i.e., a clean sightline out of our Galaxy for extragalactic surveys.

▷ Selected *JWST North Ecliptic Pole (NEP) Time-Domain Field* centered at:

$$(\text{RA, Dec})_{\text{J2000}} = (17{:}22{:}47.896,\ +65{:}49{:}21.54)$$

- NEP and SEP always have lowest Zodiacal foreground emission

Selected field for *JWST* Time-Domain Surveys



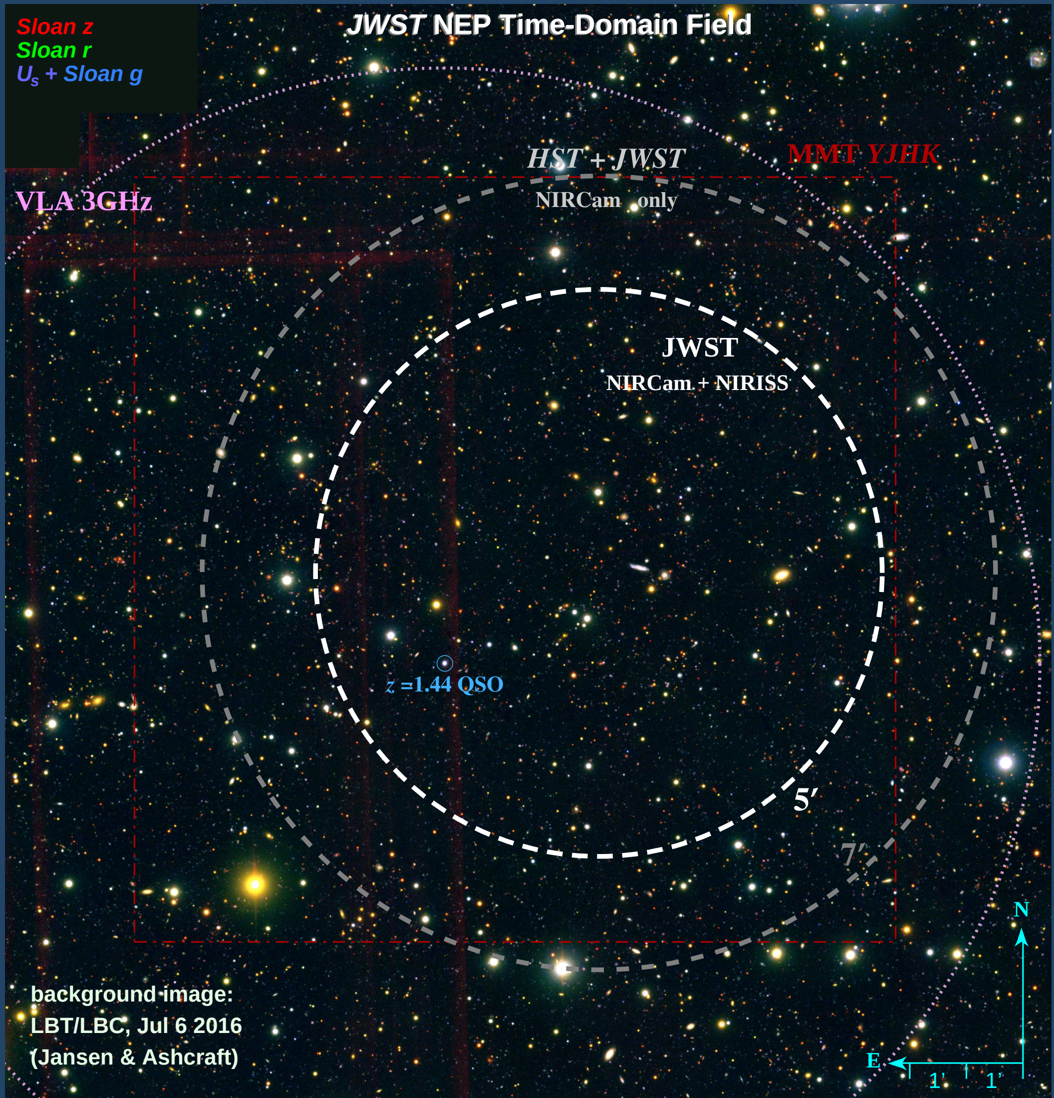
Maksym et al. (2019)

- **Relatively long but clear sight-line through our Galaxy**

  $(l^{II}, b^{II}) \simeq (96°, +33°)$

▷ **also good for Galactic time-domain science!**

Selected field for *JWST* Time-Domain Surveys



Jansen & Windhorst (2018)

- **Verified using 2×8.4 m Large Binocular Telescope / LBC *Ugriz* imaging to $m_{\rm AB} \sim$ 26.5 mag at $\sim$0.″95 FWHM**
  (PI: R. Jansen)

▷ **No bright *red* stars & excellent for deep extragalactic science**

- **Verified using 6.5 m MMT/-MMIRS *YJHK* imaging to $m_{\rm AB} \sim$ 24–22 mag**
  (PI: C. Willmer)

- **Verified using VLA A+B configuration 3 GHz ($\lambda \sim$ 10 cm) observations to 0.9 μJy**
  (PI: R. Windhorst; see M. Hyun et al. 2022)

HST & *JWST* Explorations of a new Time-Domain and Deep Field

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Development as a *JWST Community Field*: Ancillary X-ray through Radio Observations in the *JWST* NEP Time-Domain Field

- *JWST* NEP Time-Domain Field multiwavelength community investment

Telescope	PI	Status	Depth
NuSTAR 3–24 keV	F. Civano	extant (33 sources)	1467 ks; $>$50 cts
″	″	approved	855 ks ; ″
Chandra/ACIS-I 0.2–10 keV	W.P. Maksym	extant; 238 sources	1300 ks; $\sim$1$\times$10^{-16} cgs
″	″	in progress	500 ks; ″
XMM-Newton 0.5–2.0 keV	F. Civano	extant / approved	40 ks / 30 ks; 1$\times$10^{-15} cgs
AstroSat/UVIT F154W,F172M	K. Saha	approved	97.78 hrs; $m\sim$27 mag
GALEX NUV+FUV	MIS+AIS	extant	2$\times$2.8 ks; $m\sim$24.1 mag
HST/WFC3+ACS *F275W,F435W,F606W*	R. Jansen / R. Jansen & N. Grogin	extant GO 15278, GO 16252, GO 16793	96 CVZ orbits; $r\lesssim$7.′5 $m\sim$27.3, 28.2, 29 mag
LBT/LBC U_{sp}*griz*	R.A. Jansen	extant; wide-field (2 epochs)	11 hrs; $m\sim$26.8–26.0 mag
Subaru/HSC *giz*,nb816,nb921	G. Hasinger / E. Hu	extant; wide-field	5 hrs; $m\sim$25.5–25.1 mag
GTC/HiPERCAM *ugriz*	V. Dhillon	extant; $r<5'$	16$\times$1 hr; $m\sim$27 mag
TESS (0.6–1.0μm bandpass)	G. Berriman & B. Holwerda	in progress; ultra wide-field	357 days; low-SB xtd
MMT/MMIRS *YJHK*$_s$	C.N.A. Willmer	extant	68 hrs; $m\sim$24.5–23.5 mag
JWST/NIRCam+NIRISS 0.8–5 μm + 1.75–2.23 μm	R.A. Windhorst / H.B. Hammel	*guaranteed time* GTO #2738	$\sim$49 hrs; 54.7 arcmin^2 $m<$29–28.5 mag
JCMT/SCUBA-2 850μm	I. Smail / M. Im	extant; 113 sources (82 at $>4\sigma$)	43.4 hrs; rms$\sim$0.8 mJy
″	″	approved	20.0 hrs; rms$\sim$0.7 mJy
SMA 0.87 mm	G. Fazio	extant; 11 sources	66 hrs; rms$\sim$0.85 mJy/beam
IRAM/Nika2 1.2, 2 mm	S.H. Cohen	extant (pilot)	30 hrs; rms$\sim$2 mJy
VLA 3(2–4) GHz	R.A. Windhorst / W. Cotton	extant; $\sim$2500 sources	47 hrs; rms$\sim$0.9 μJy
VLBA 4.7 GHz	W. Brisken	extant; $\sim$128 targets	147 hrs; rms$\sim$3 μJy
eMERLIN 1.5 GHz	A. Thomson	extant	40 hrs
″	″	in progress	100 hrs; rms$\sim$3 μJy/beam
LOFAR 150 MHz	R. van Weeren	extant; ultra-wide field	72 hrs; rms$\sim$0.12 mJy
mini-JPAS (56 narrow-bands)	S. Bonoli / R. Dupke	extant; ultra-wide field	48 hrs; $m\sim$21.5–22.5 mag
MMT/Binospec (mos)	C.N.A. Willmer	extant; 1378 spectra/1000 redshifts	26 hrs; $m\sim$22.5–24 mag
MMT/MMIRS (mos)	C.N.A. Willmer	approved	$m<22$, $z>0.4$

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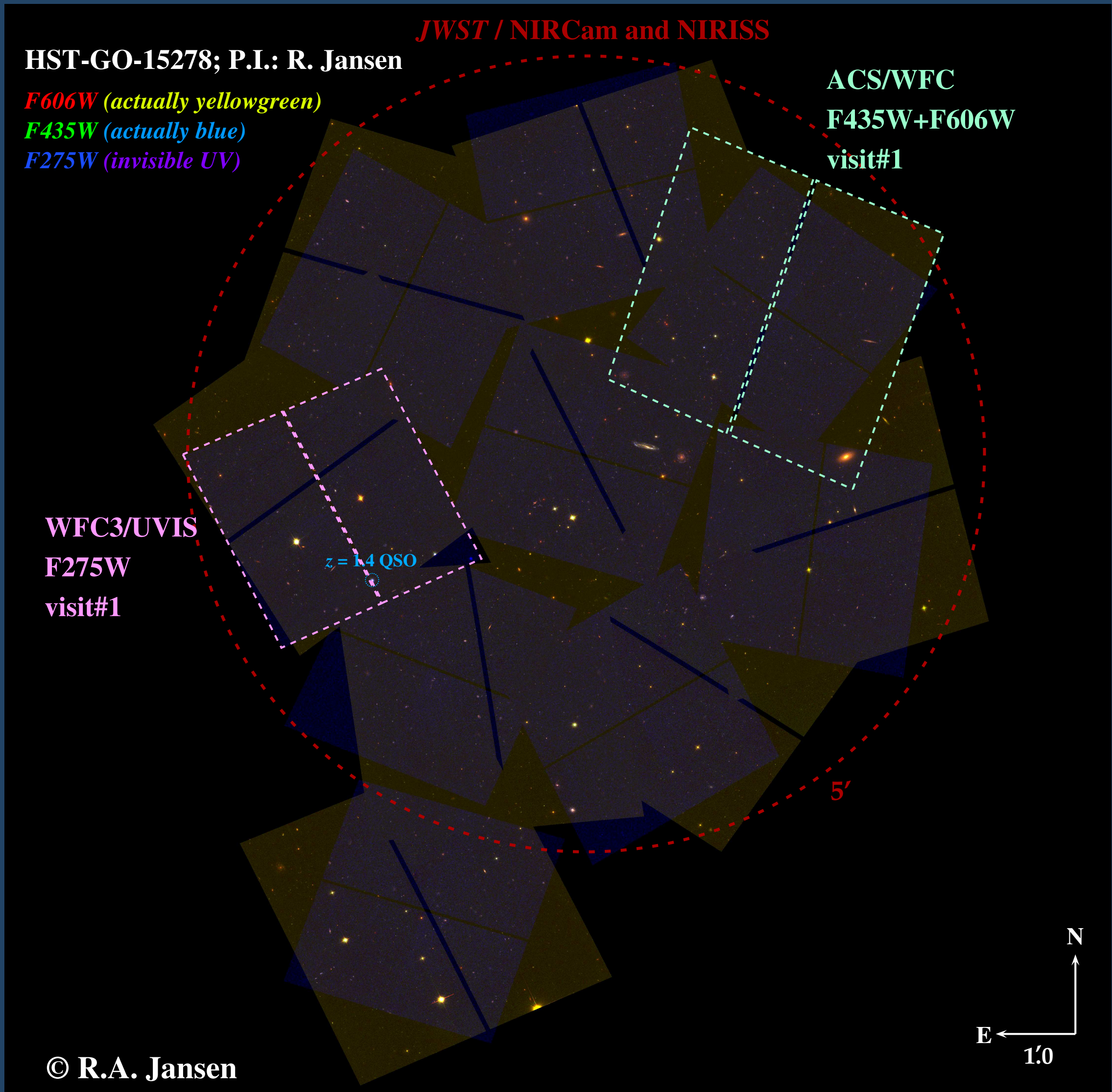
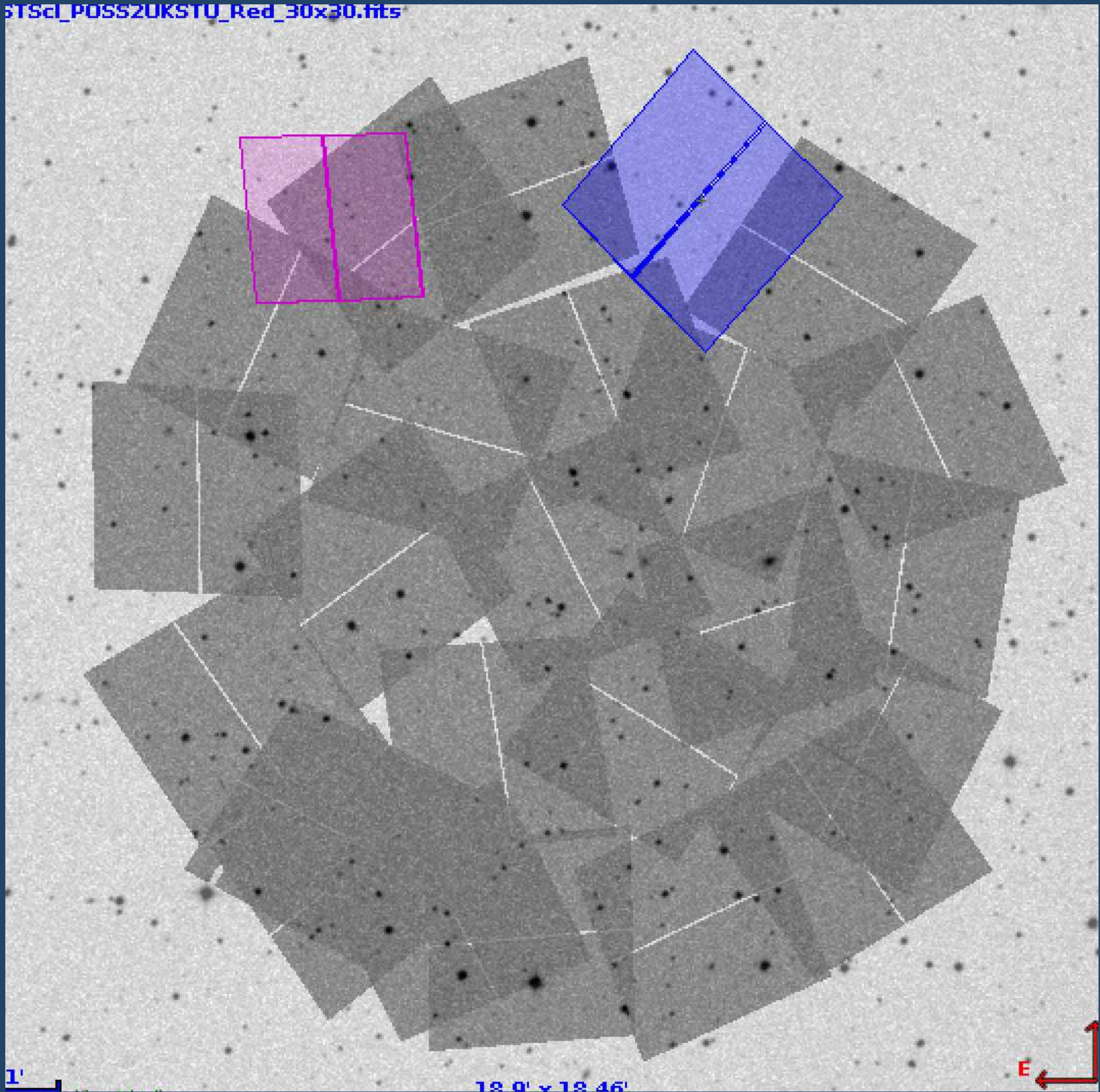
Multi-cycle UV–Visible Imaging with *Hubble*



- **36 CVZ orbits (9 visits) in Cycle 25 (GO-15278; PI: R. Jansen)**
- **Mosaic of the *Hubble* observations of Cycle 25. The dark red circle (radius = 5′) indicates where NIRCam and NIRISS GTO observations can overlap.**
- **Preliminary analyses resulted in Senior Theses by C. White (2019), V. Jones (2019), and S. Bechel (2020), and in ASU/NASA Space Grant presentations by T. Tyburczy (2019) and L. Nolan (2020, 2021).**

Multi-cycle UV–Visible Imaging with *Hubble*



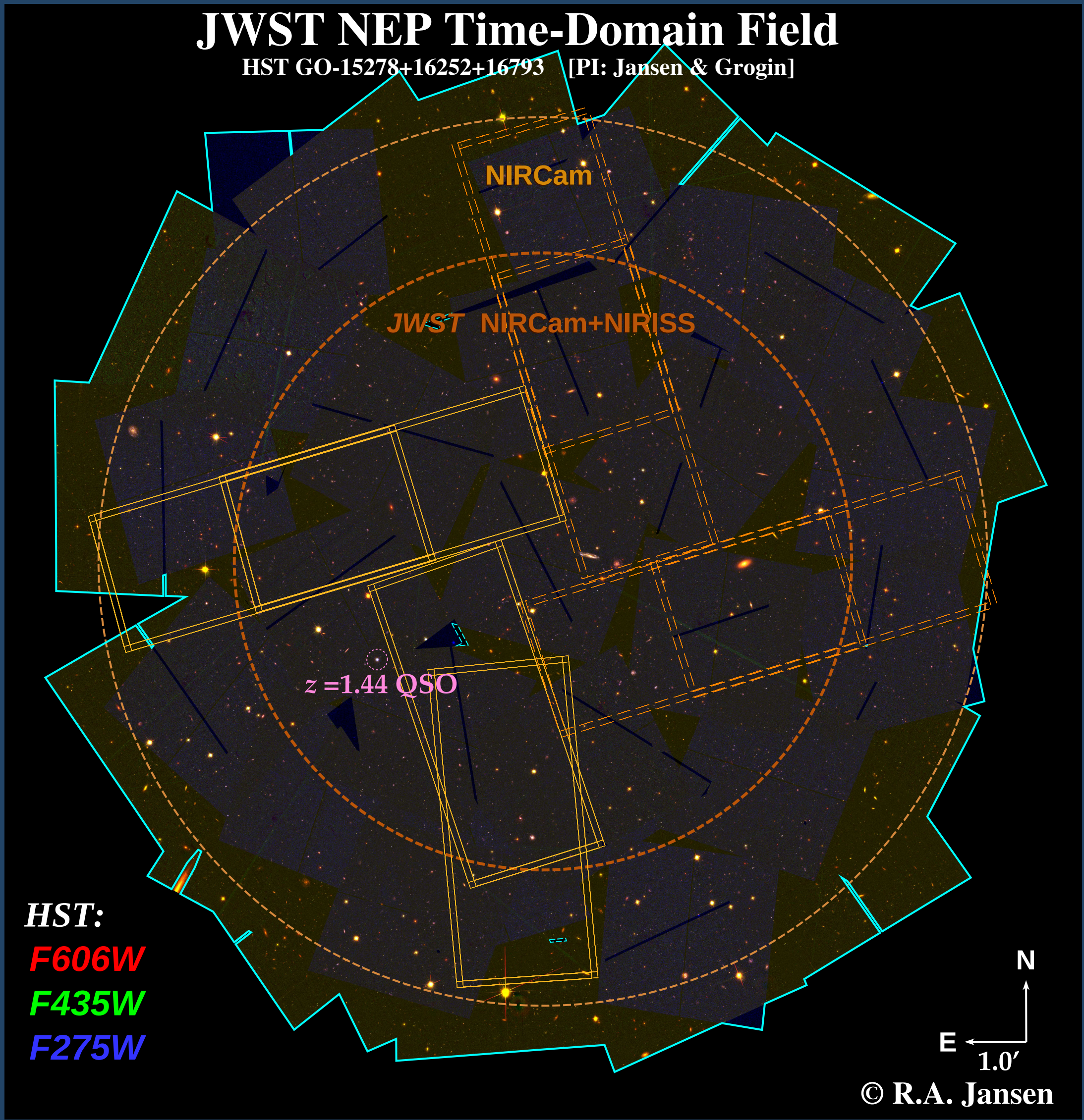
R.A. Jansen

- ‘TREASUREHUNT’ program: 60 CVZ orbits (15 visits) in Cycle 28 + 29 (GO-16252, 16793; PI: R. Jansen & N. Grogin)

- Mosaic of the *Hubble* ACS/WFC coverage of Cycle 25+28+29 combined, with the final visit (Oct 31 2022) highlighted. Near-contiguous F275W, F435W, and F606W imaging to $m_{\rm AB} \sim 27.3$, 28.2, and 29.0 mag ($5\,\sigma$), now exists for the entire $\sim 14'$ diameter *JWST* NEP Time Domain Field.

- Detailed analysis by ASU graduate student R. O’Brien is in progress.

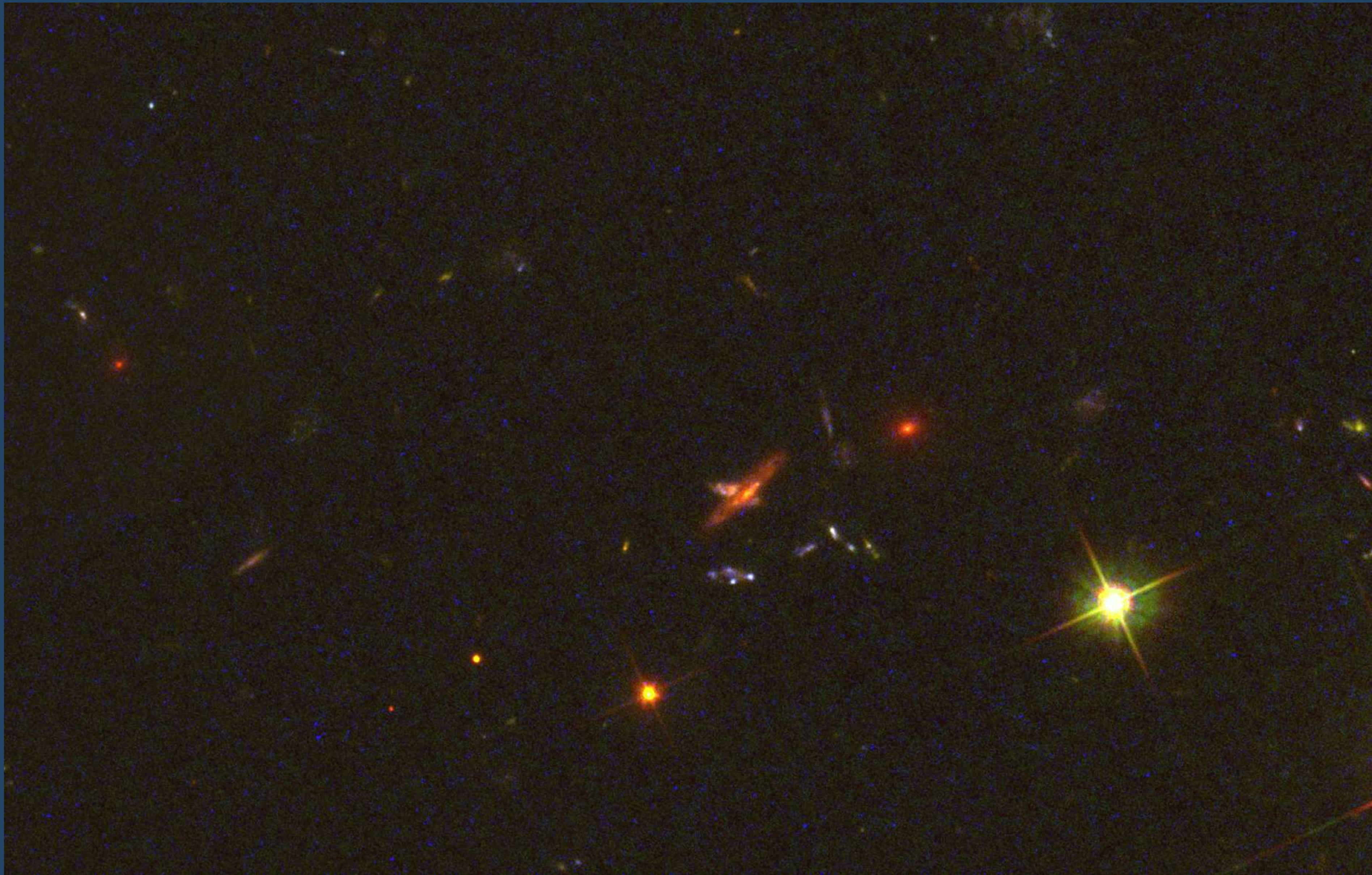
Multi-cycle UV–Visible Imaging with *Hubble*



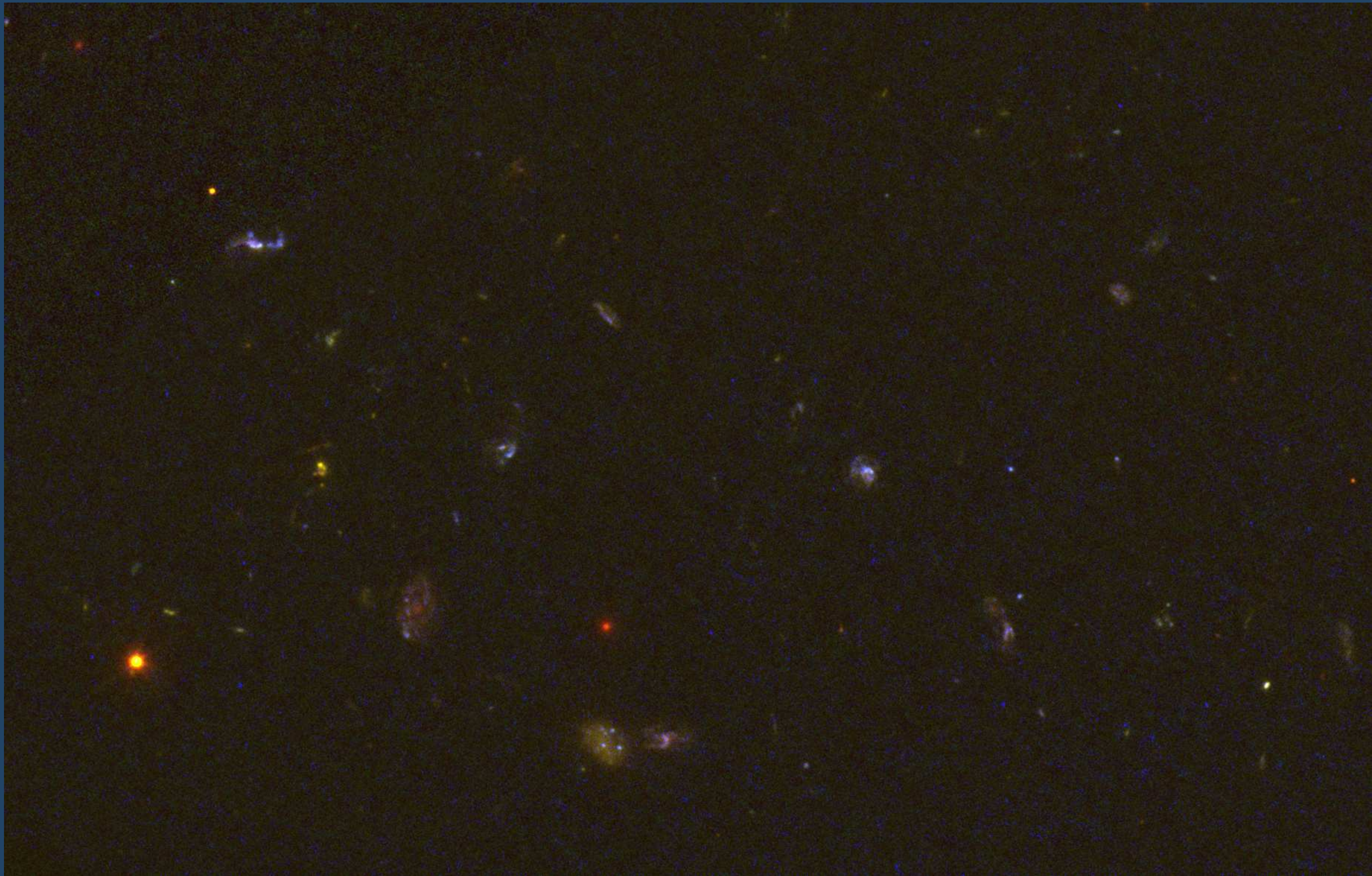
- **UV–Visible *HST* survey of the *JWST* NEP Time-Domain Field in 3 filters (WFC3/UVIS F275W [*UV*], ACS/WFC F435W [*blue*] and F606W [*yellowgreen light*]) is now ready for *JWST*.**
- **Orange outlines indicate the PEARLS *JWST* GTO coverage as executed (bright) and planned (dim, dashed), with four NIRCam "Spokes" extending to ∼7′, and parallel NIRISS coverage extending to ∼5′.**

Multi-cycle UV–Visible Imaging with *Hubble* – highlights

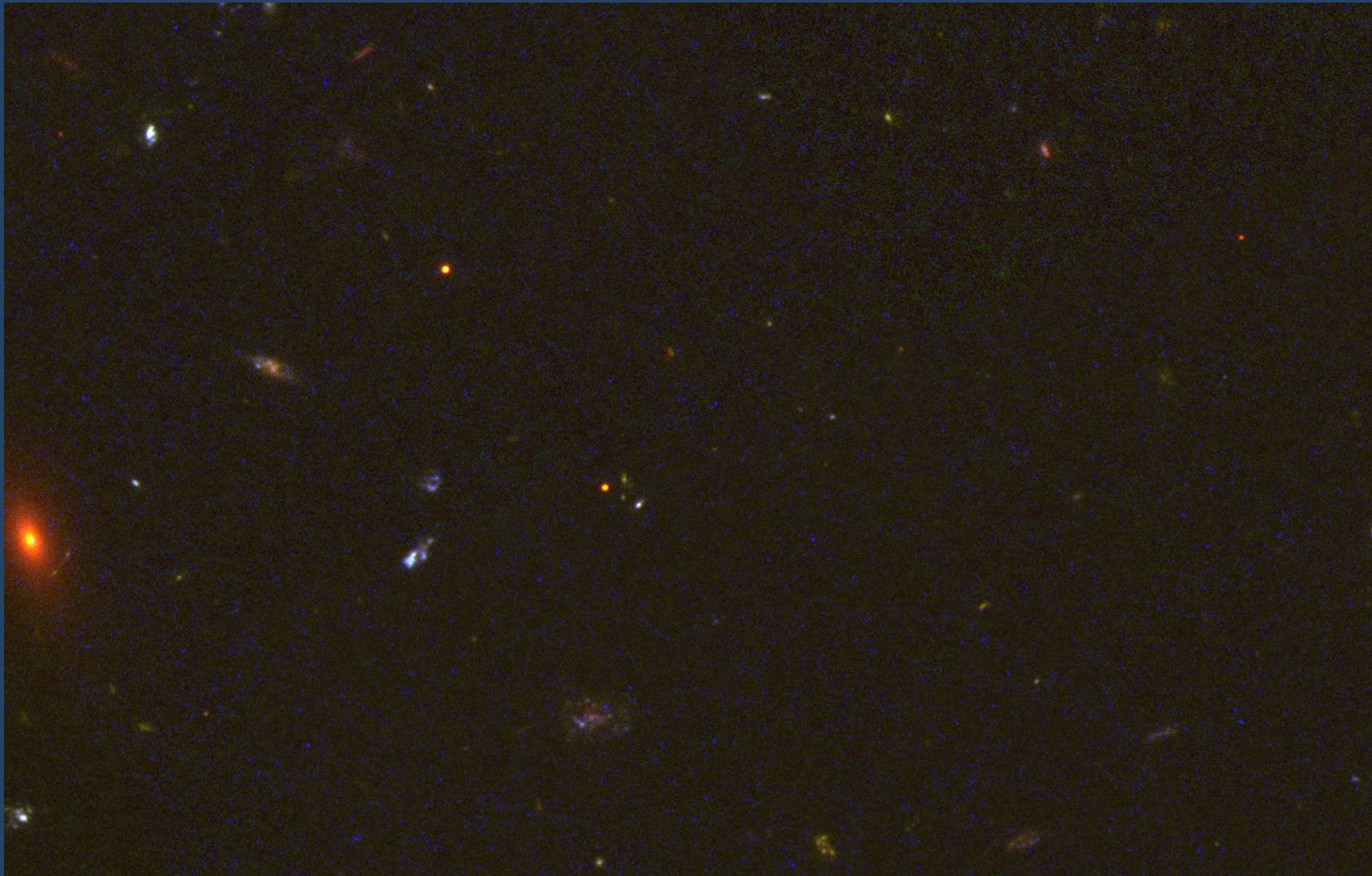
Multi-cycle UV–Visible Imaging with *Hubble* – highlights



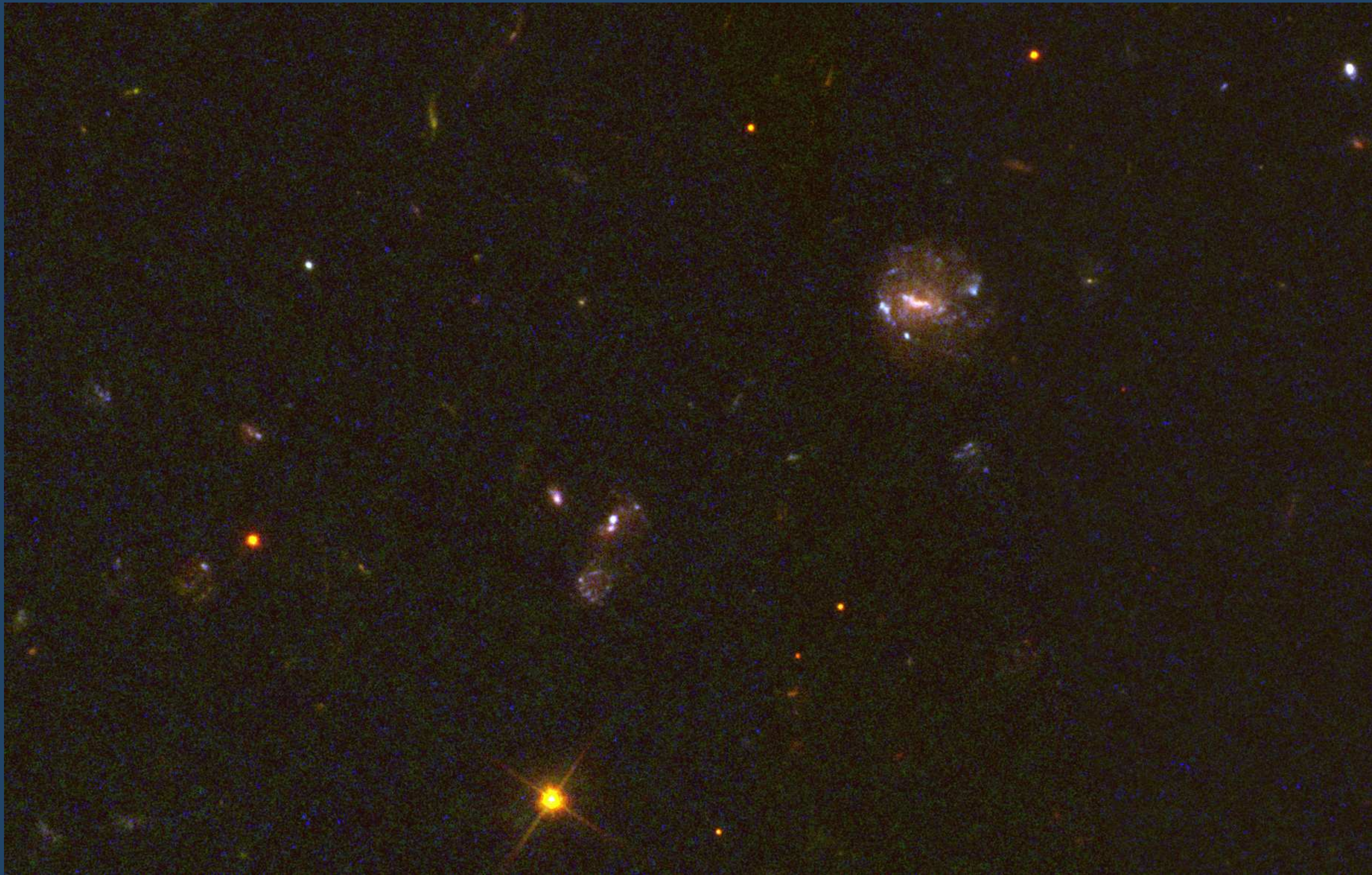
Multi-cycle UV–Visible Imaging with *Hubble* – highlights



Multi-cycle UV–Visible Imaging with *Hubble* – highlights



Multi-cycle UV–Visible Imaging with *Hubble* – highlights



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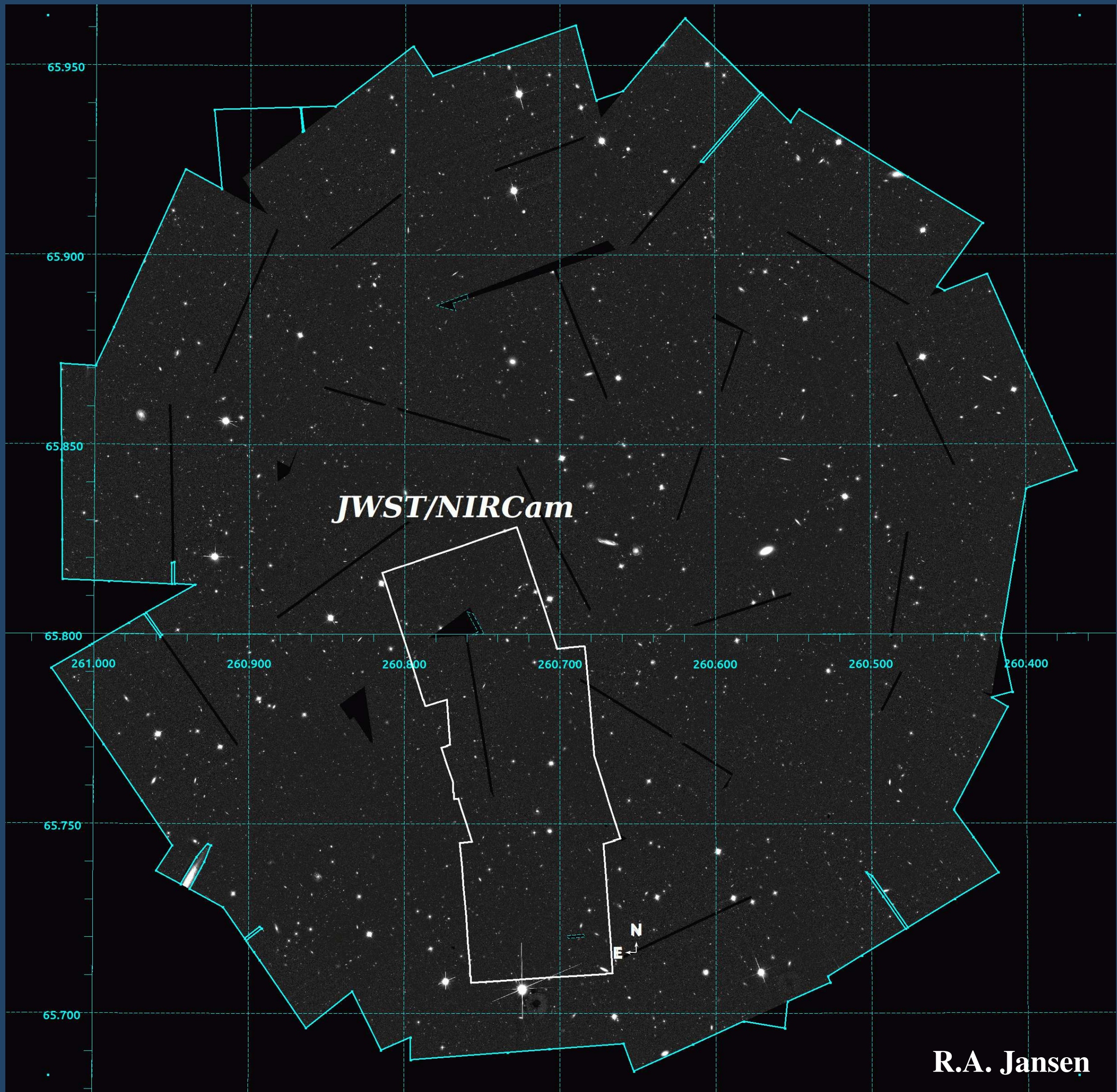
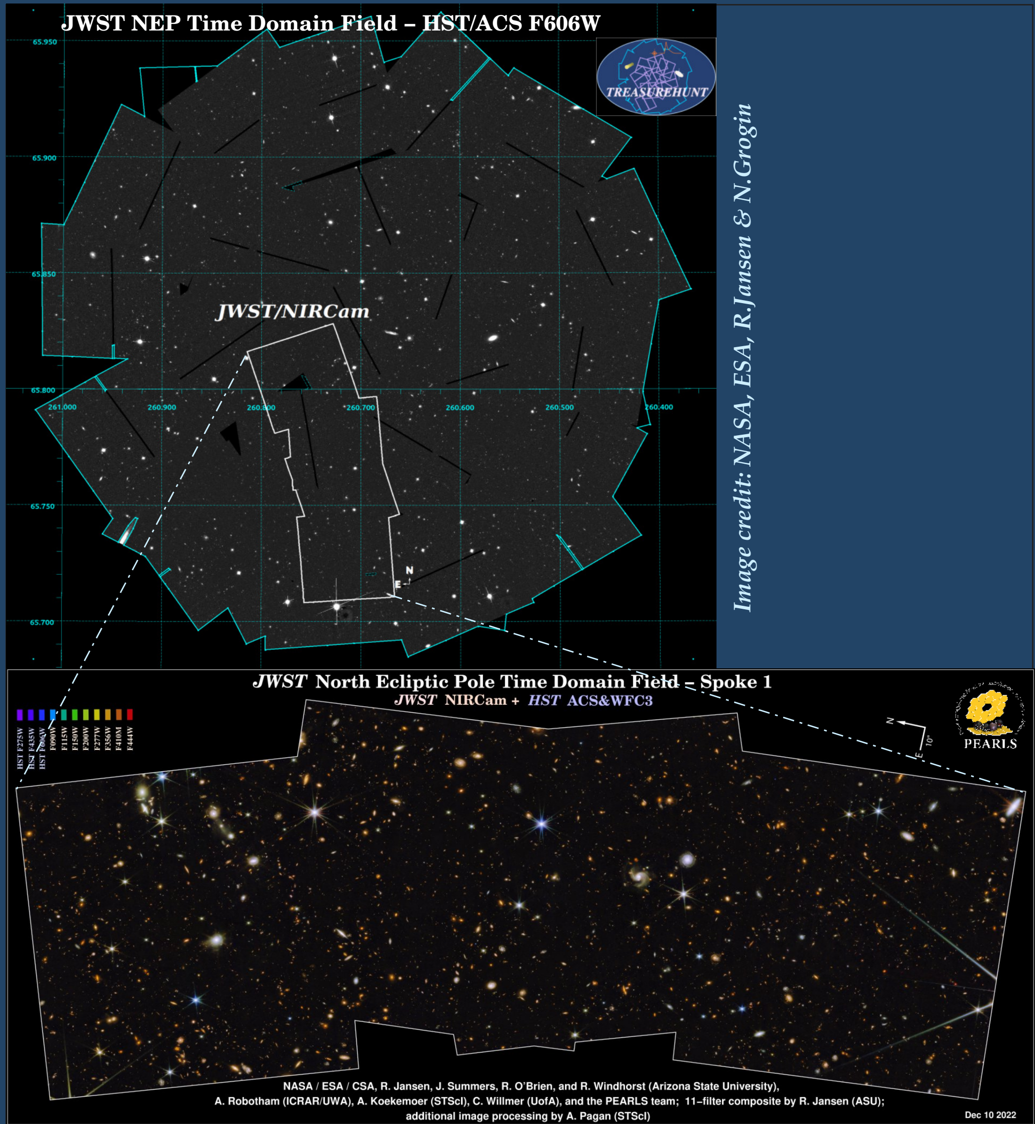
First Near-Infrared observations in the NEP TDF with *JWST*



- **Footprint of *JWST*/NIRCam "Spoke 1" in the *JWST* NEP Time-Domain Field as executed Aug 28 and Sep 14 2022 in 8 broad-band filters (F090W through F444W) as part of *JWST* PEARLS program GTO 2738 (PI: R. Windhorst), overlaid on a *HST* ACS/WFC F606W mosaic from the TREASUREHUNT program.**

- **Loss of guide star resulted in a difference in orientation between the first and second pointing in the 2×1 mosaic.**

First Near-Infrared observations in the NEP TDF with *JWST*



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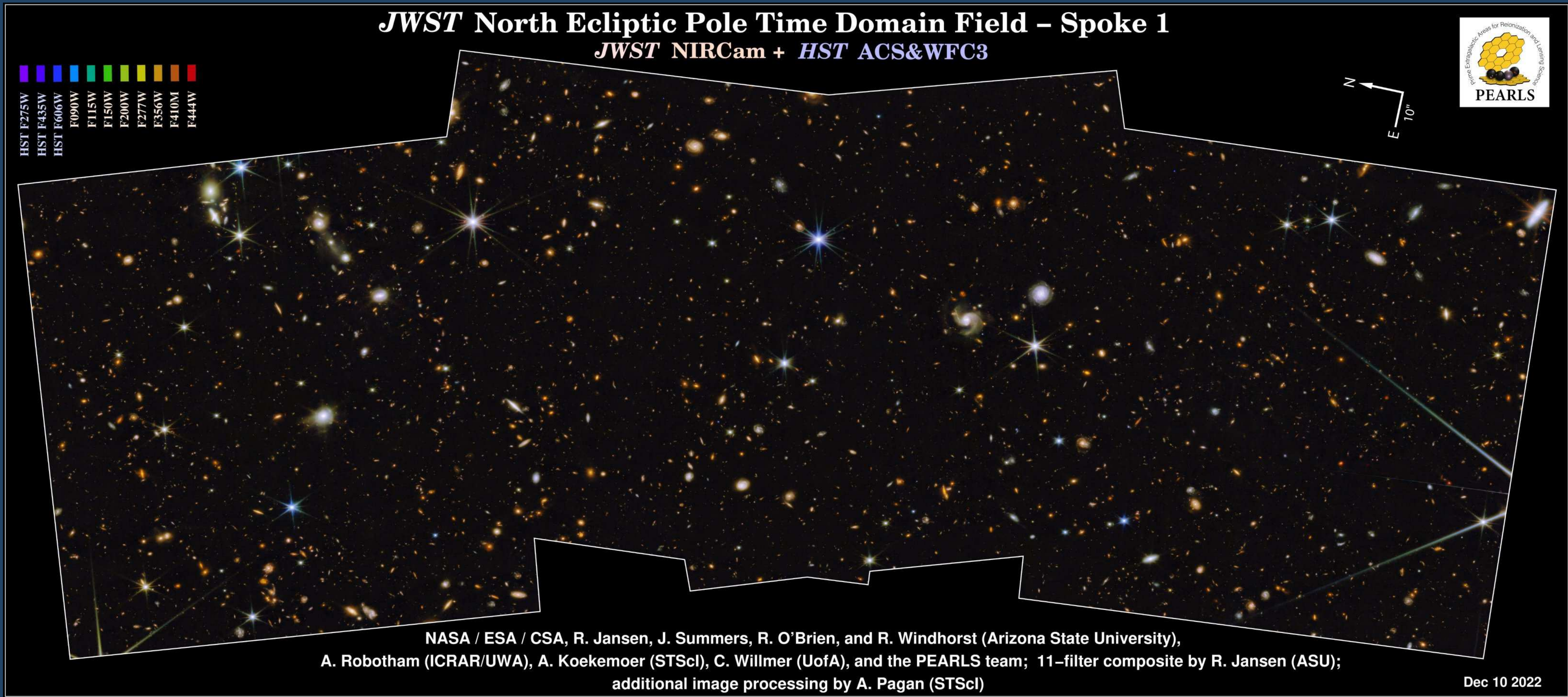
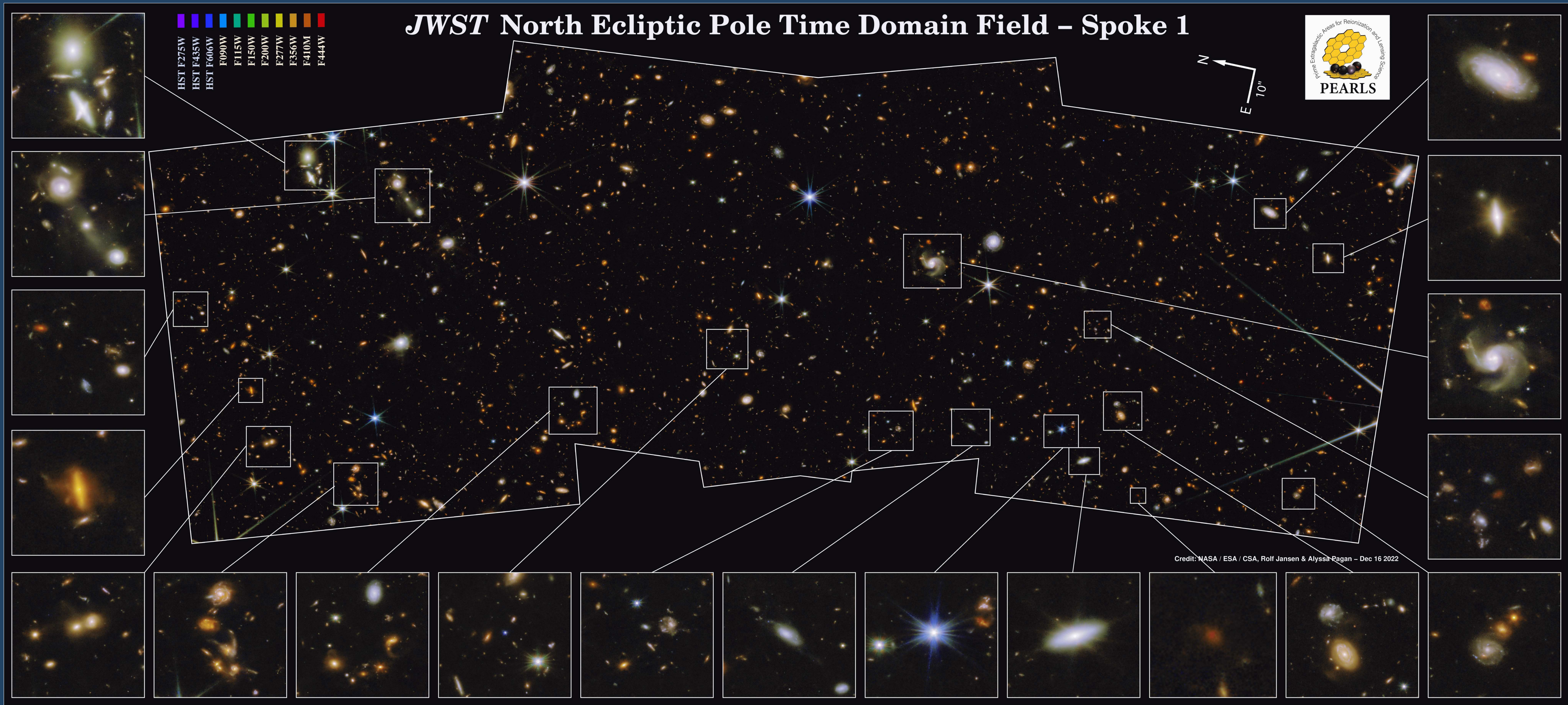
- Rotating vertical "Spoke 1" to a horizontal orientation...

First Near-Infrared observations with *JWST*



- ‘*A Field of Extragalactic PEARLS studded with Galactic Diamonds*’ – NASA Webb Blog dd. Dec 14 2022.

First Near-Infrared observations with *JWST*



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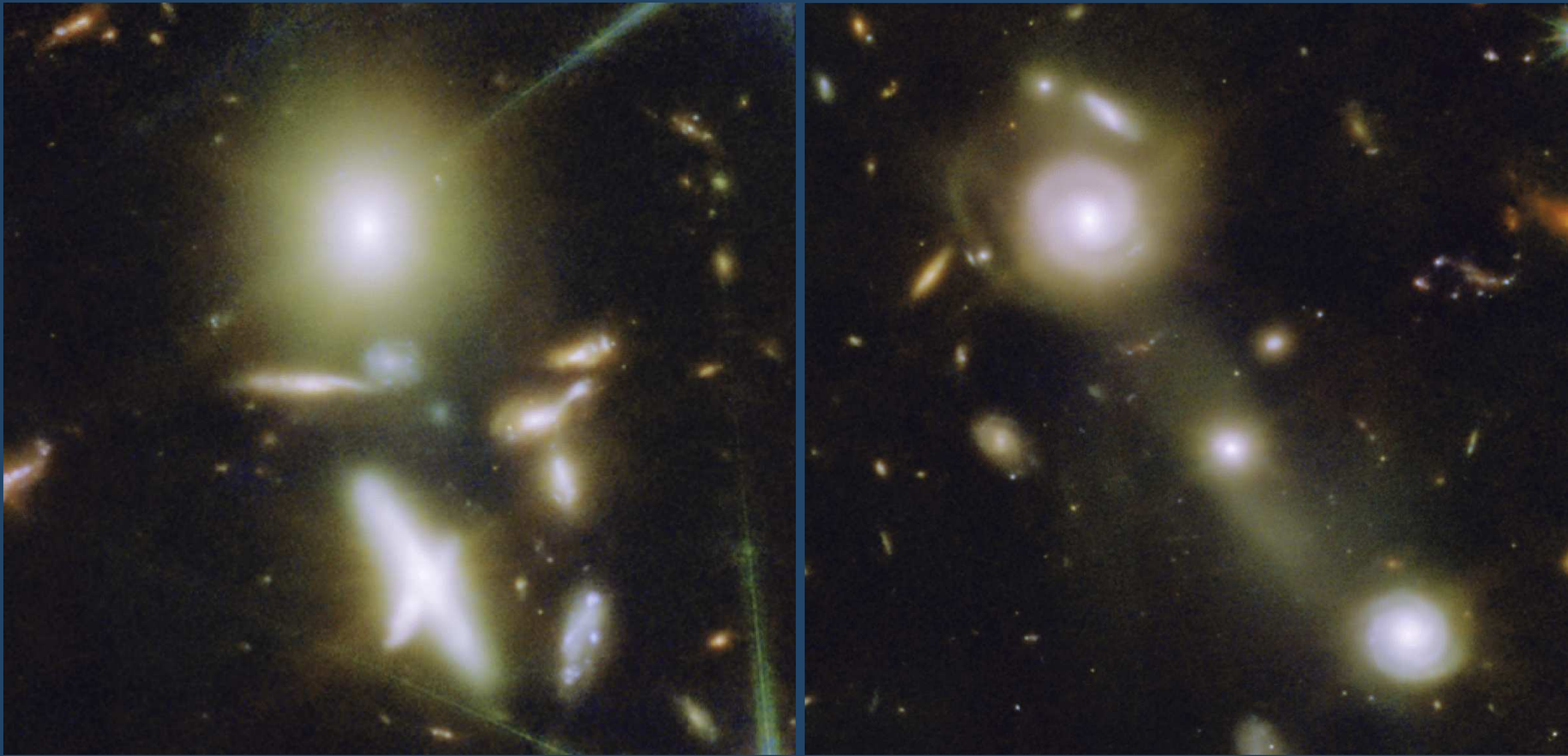
HST & JWST Explorations of a new Time-Domain and Deep Field



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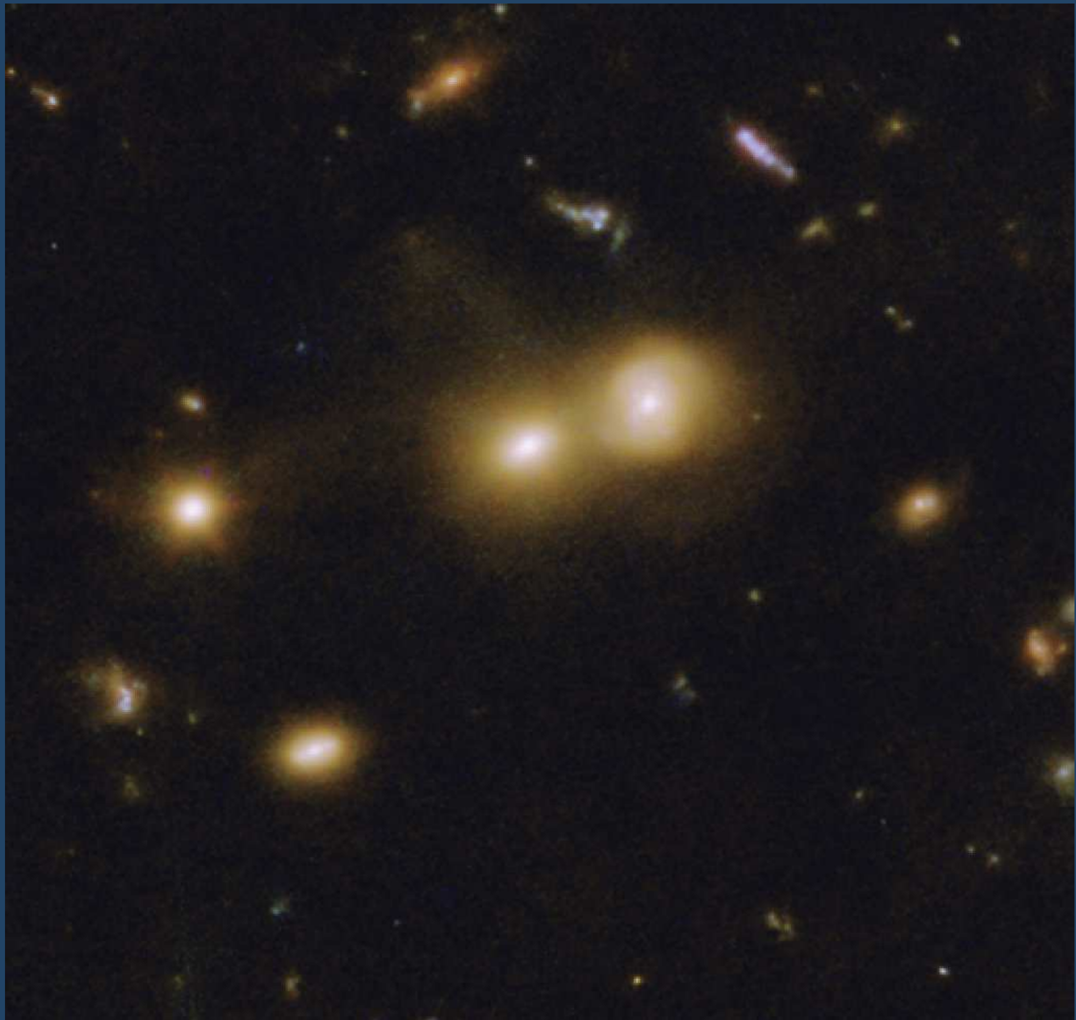

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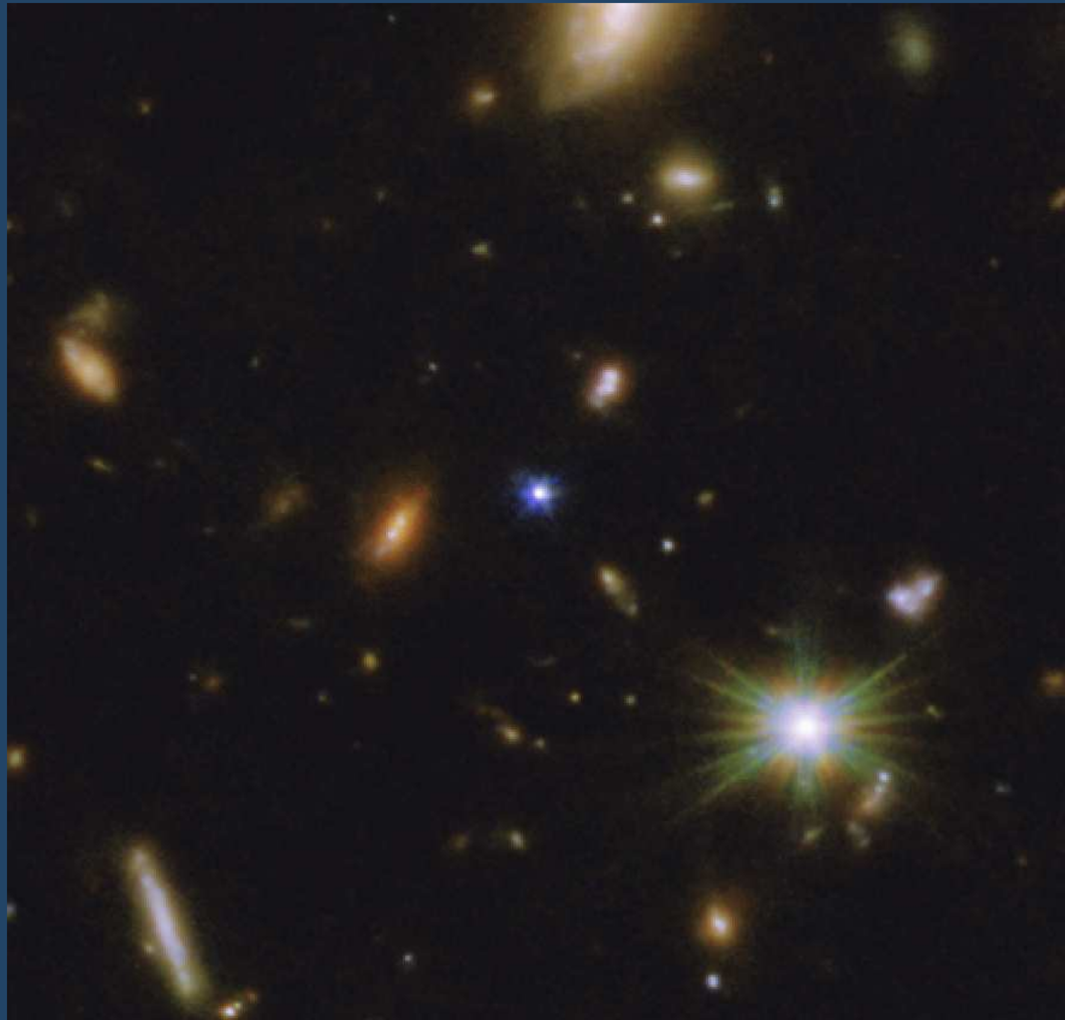

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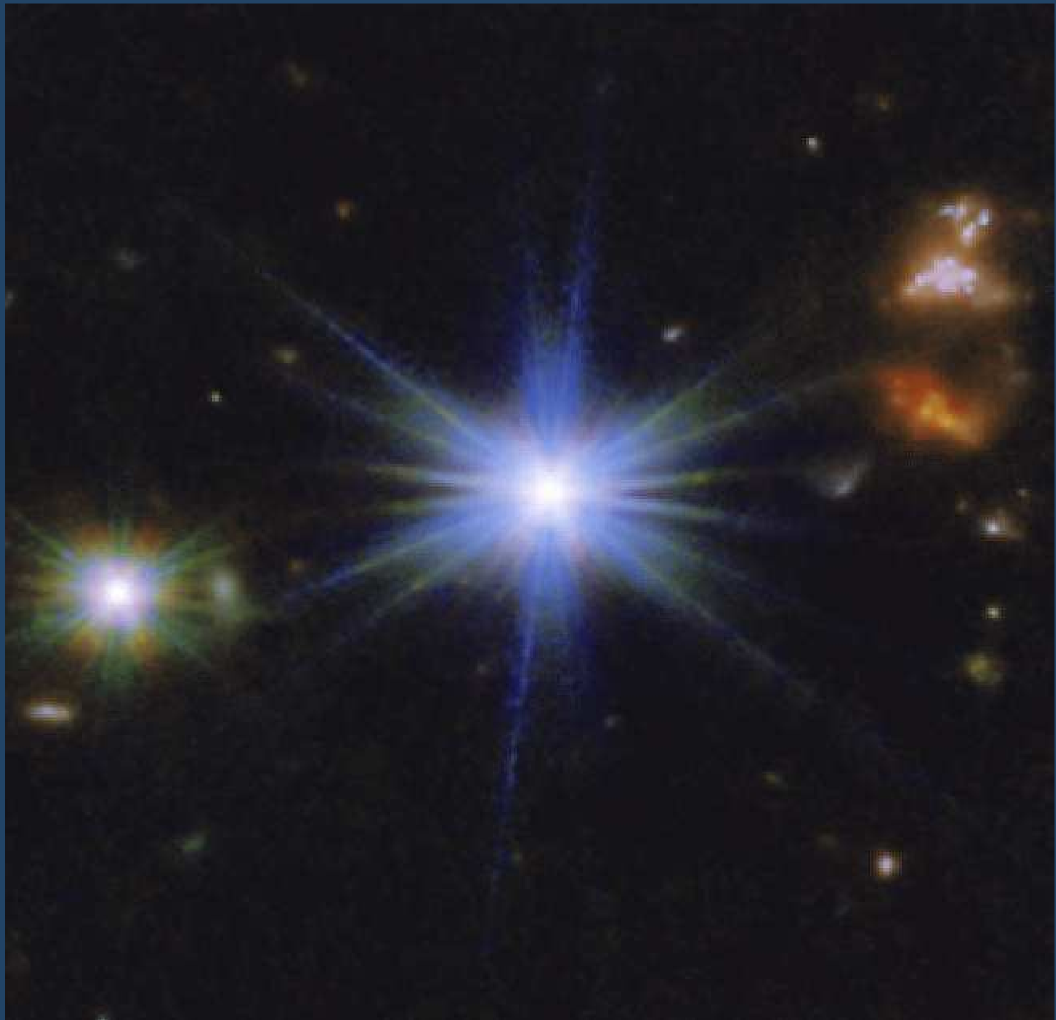

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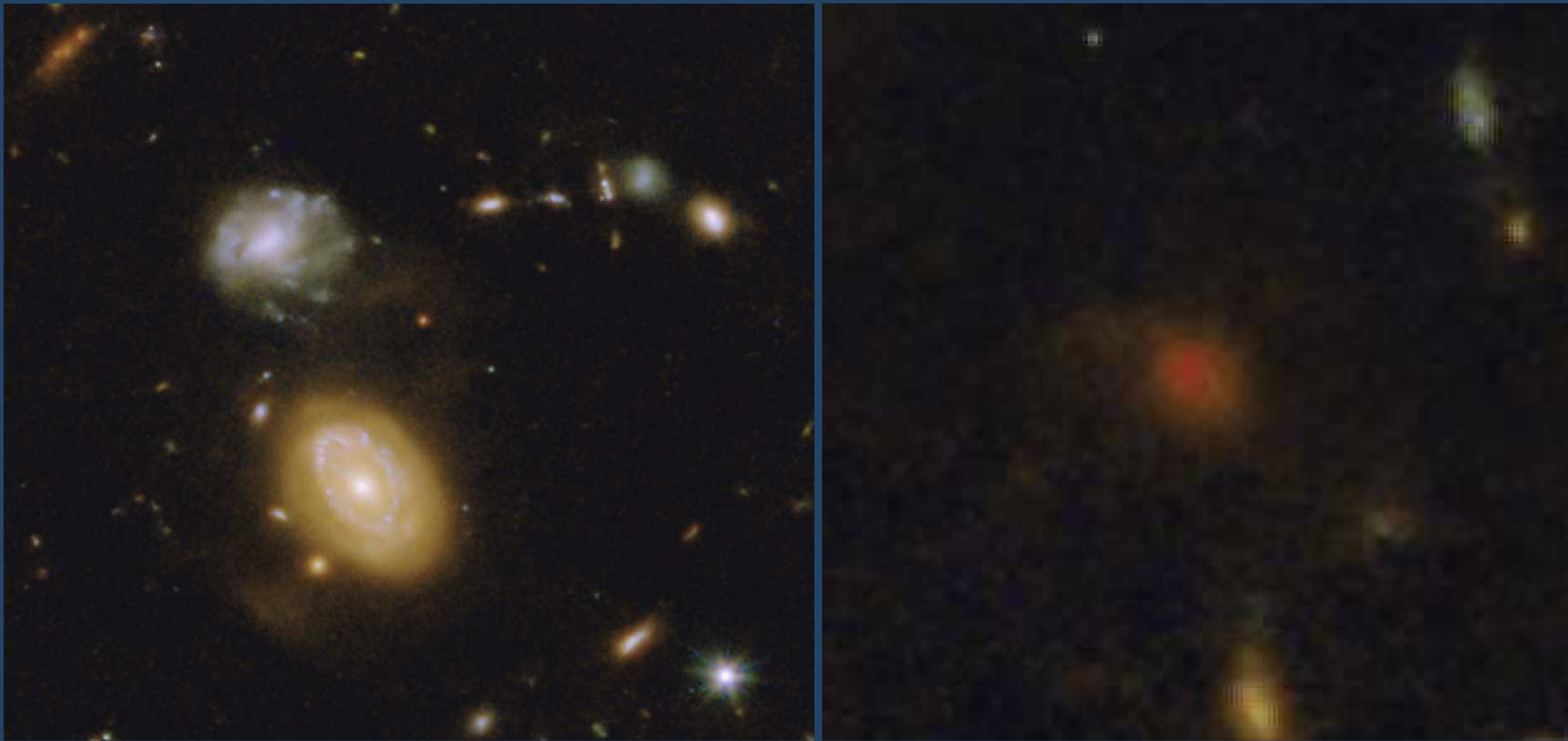

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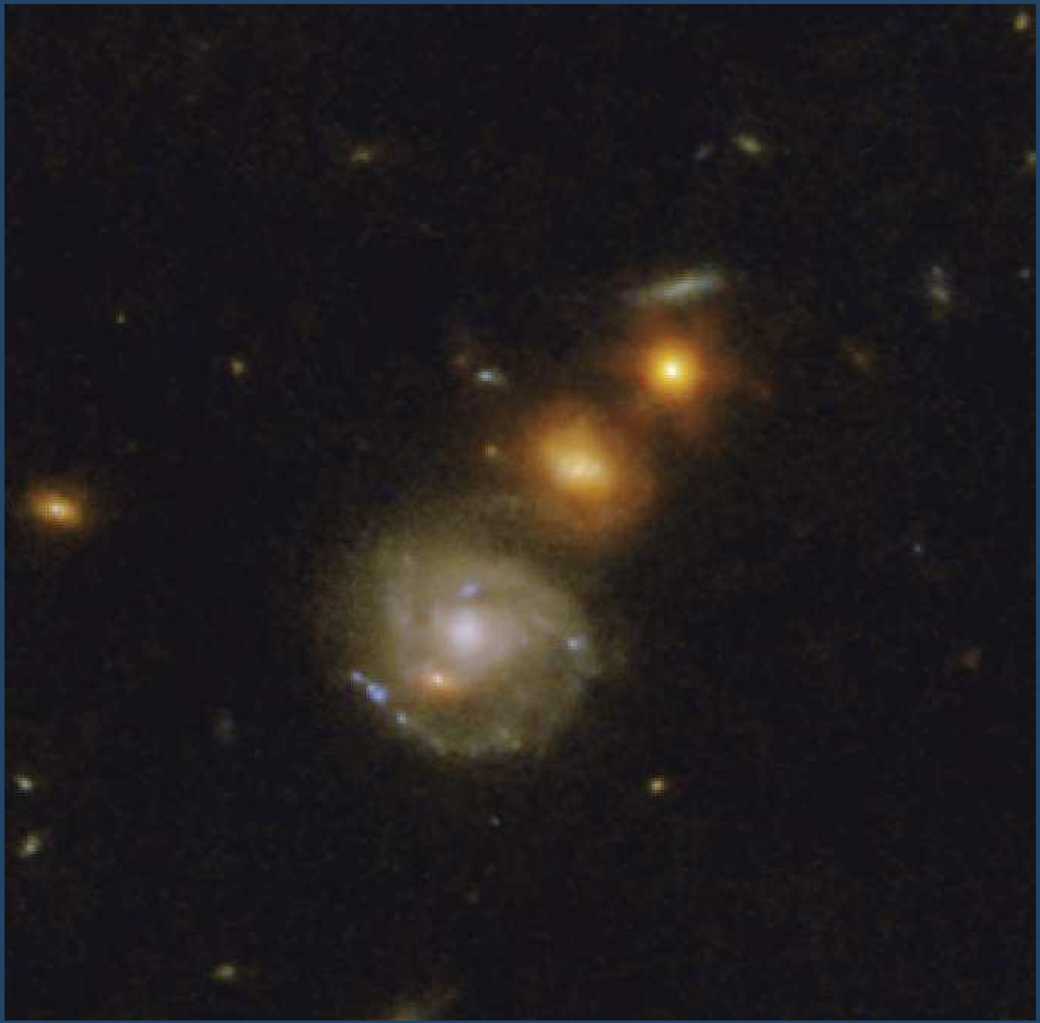

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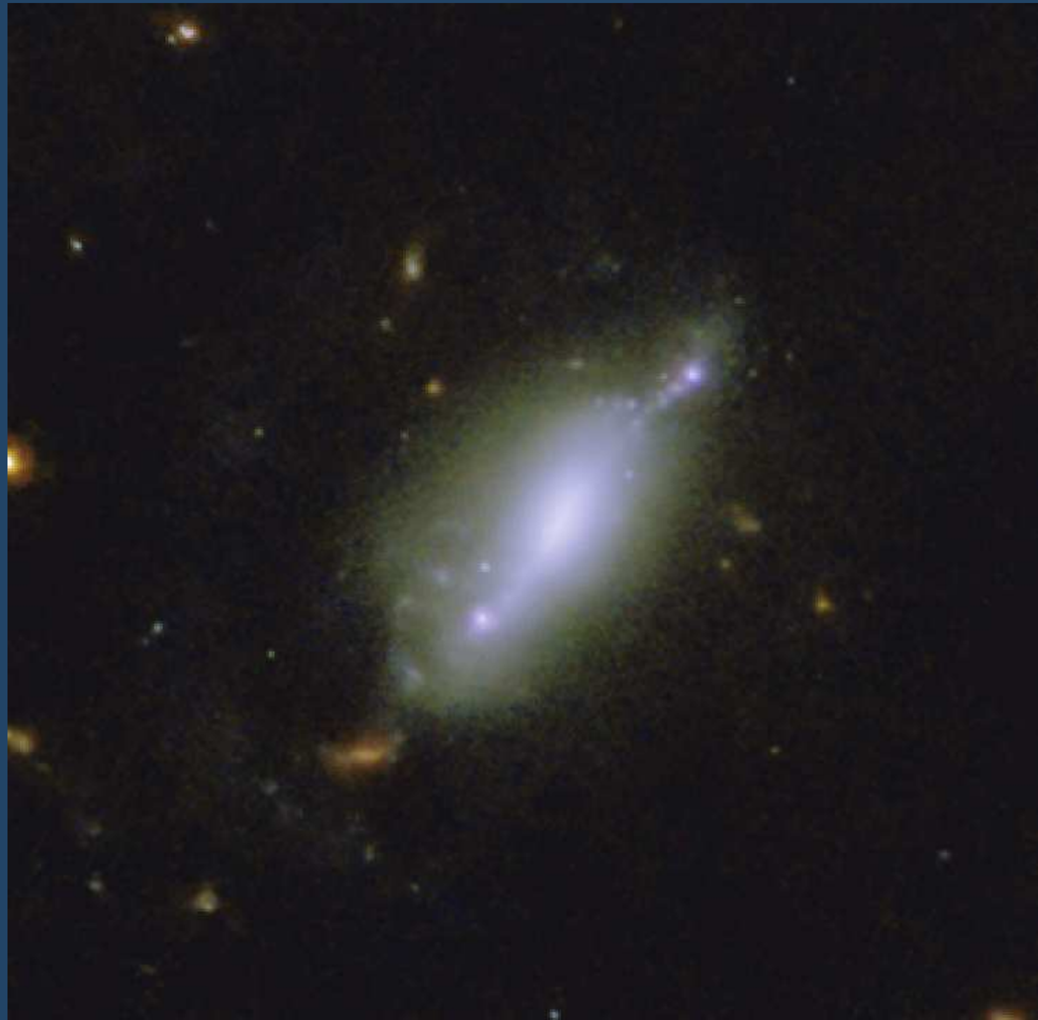

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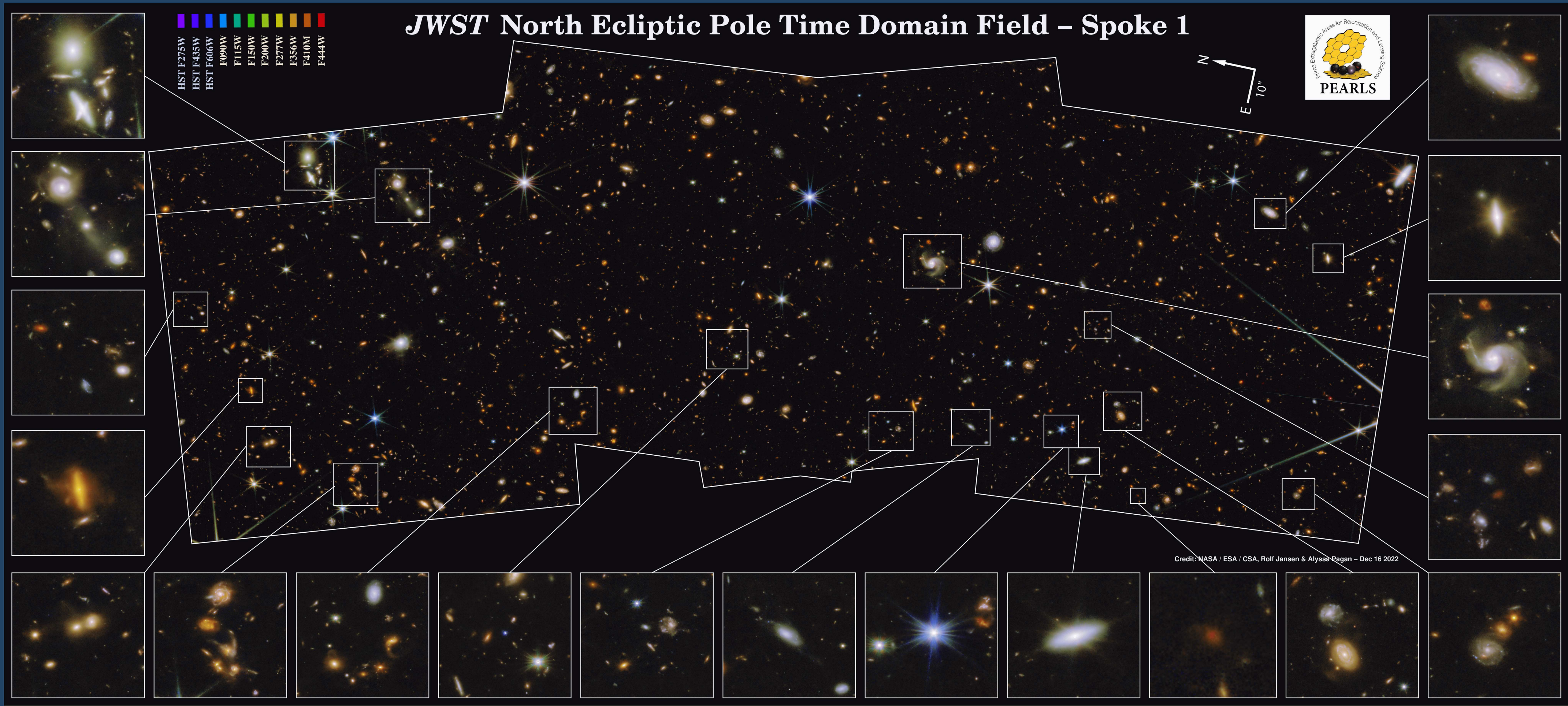

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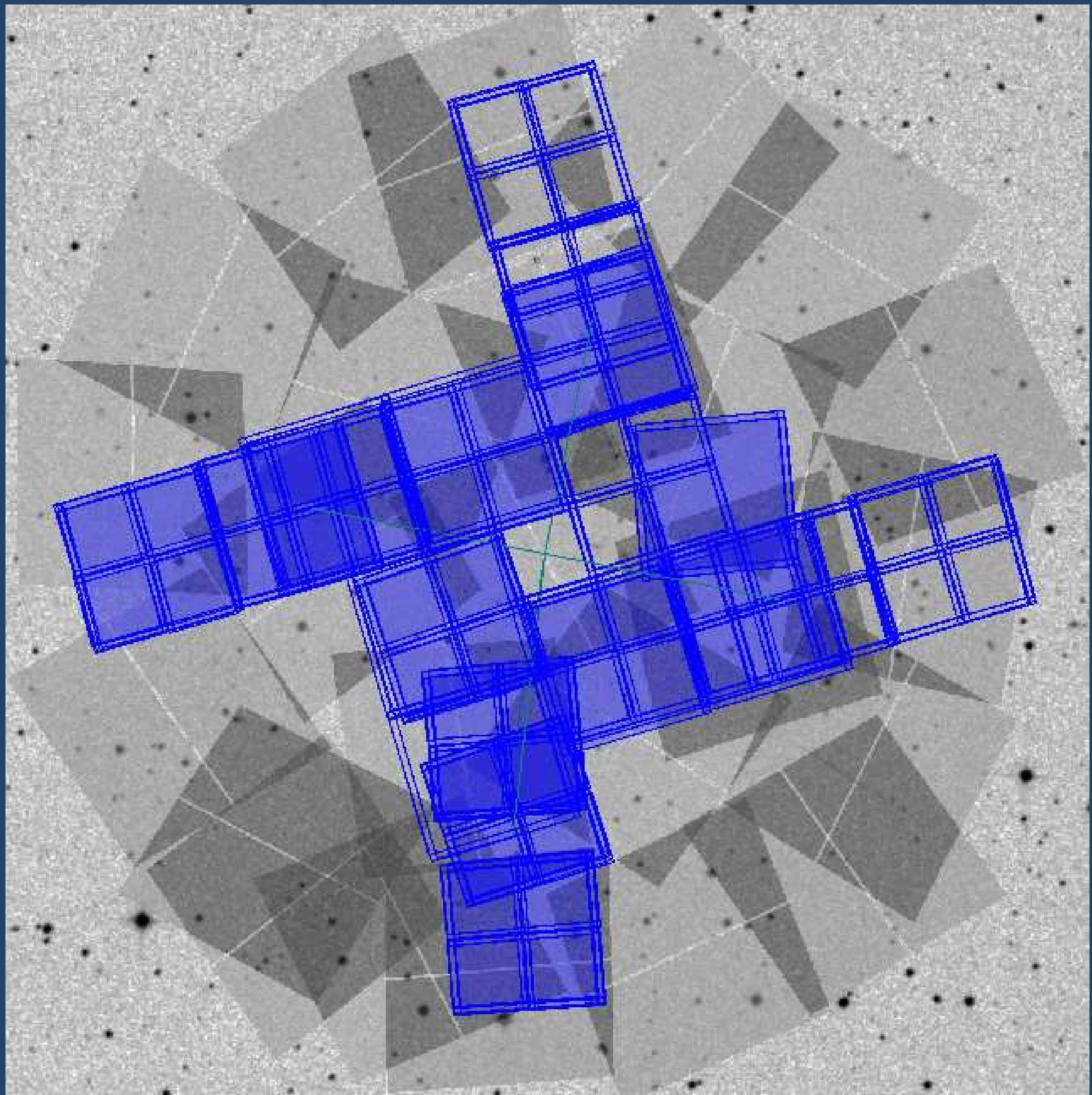

- Footprints of *JWST*/NIRCam "Spoke 1" (pointing south) + "Spoke 2" (pointing east [left]) as executed, overlaid on the HST ACS/WFC footprints (in grey) and a DSS-II Red image.

- NIRISS WFSS parallel footprints are indicated along with the NIRCam ones. Open wire-frame blue outlines correspond to the two GTO2738 spokes to be executed in 2023.

- "Spoke 2" executed as designed on Nov 26/27 2022.

- And observations of "Spoke 3" are scheduled for Feb 20/21 2023!

R.A. Jansen

A field of Extragalactic PEARLS Studded with Galactic Diamonds

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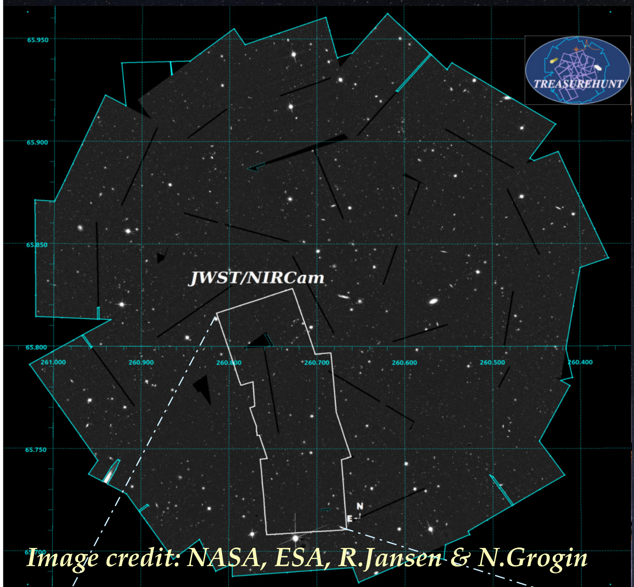

Image credit: NASA, ESA, R.Jansen & N.Grogin

Thanks!

(with more to come in 2023)

Image credit: NASA GSFC / CIL / A. Manrique Gutierrez