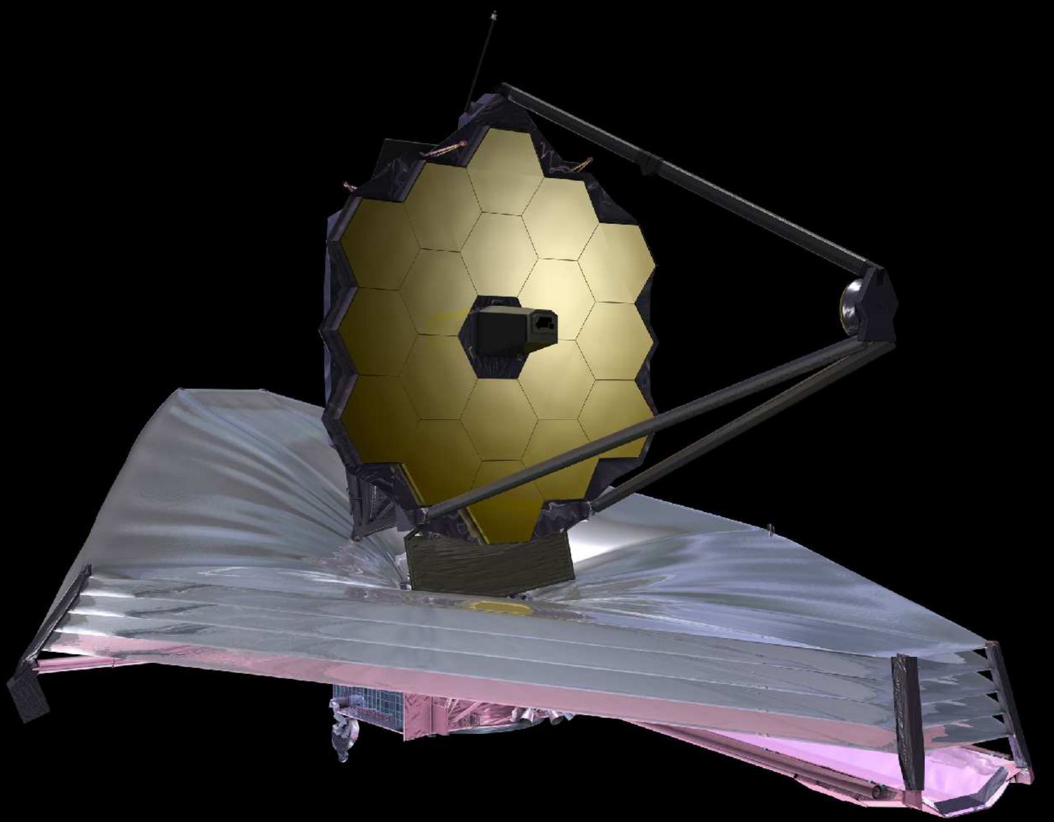
How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (Carnegie)

(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, B. Smith, & A. Straughn



Colloquium at Macquarie University, Physics Department, North Ryde, NSW, Australia

Thursday July 4, 2013. All presented materials are ITAR-cleared.

Outline

- (1) Recent key aspects of the Hubble Space Telescope (HST) project.
- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.
- (3) Brief Update on the James Webb Space Telescope (JWST)?
- (4) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?
- (5) Summary and Conclusions.

[• (6) How can JWST measure Star-birth and Earth-like exoplanets?]

Sponsored by NASA/HST & JWST

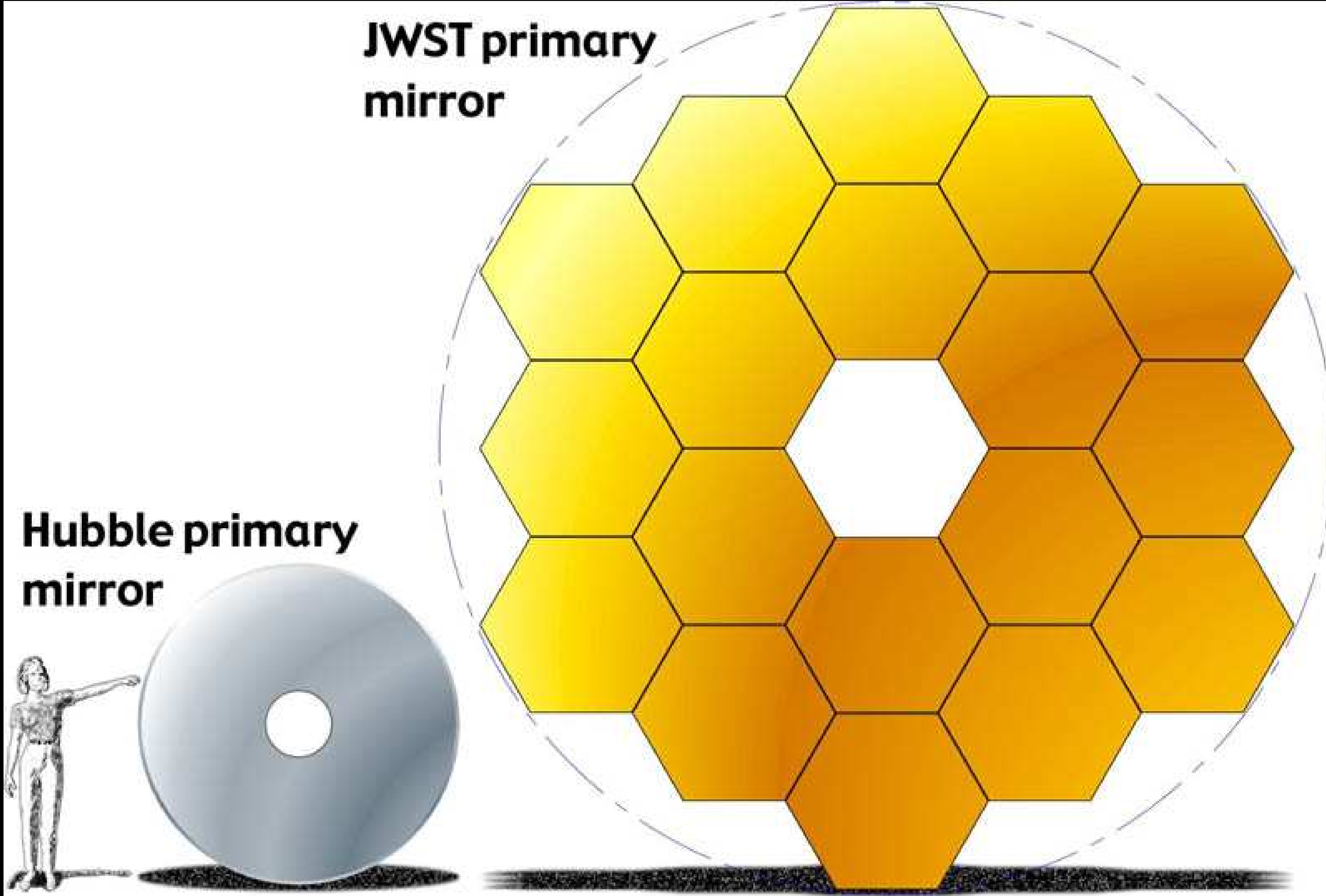
ARIZONA STATE UNIVERSITY

Edwin P. Hubble (1889–1953) — Carnegie astronomer

James E. Webb (1906–1992) — Second NASA Administrator

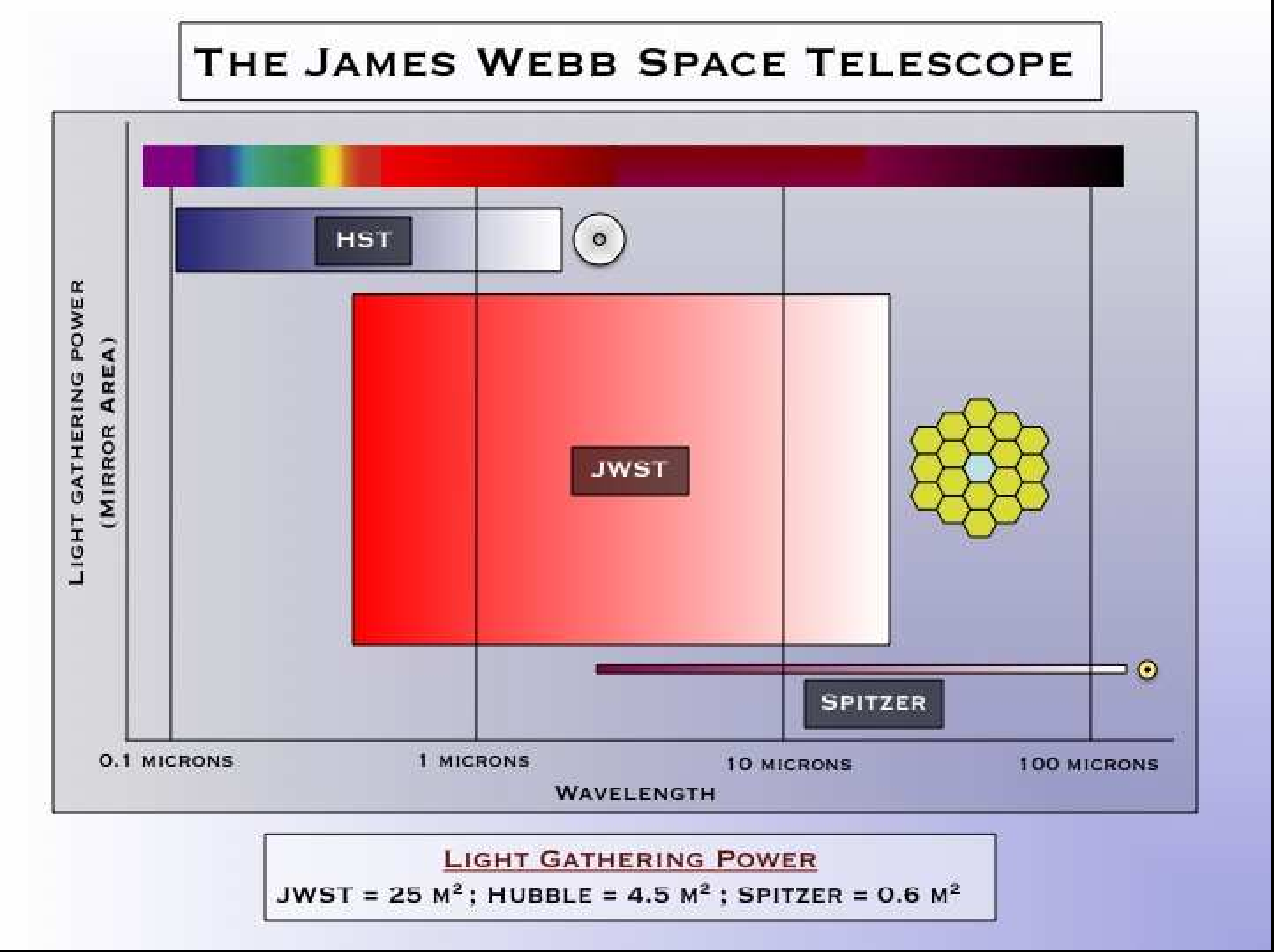
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2014.

JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).



JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:

JWST has the same resolution in the near-IR as Hubble in the optical.

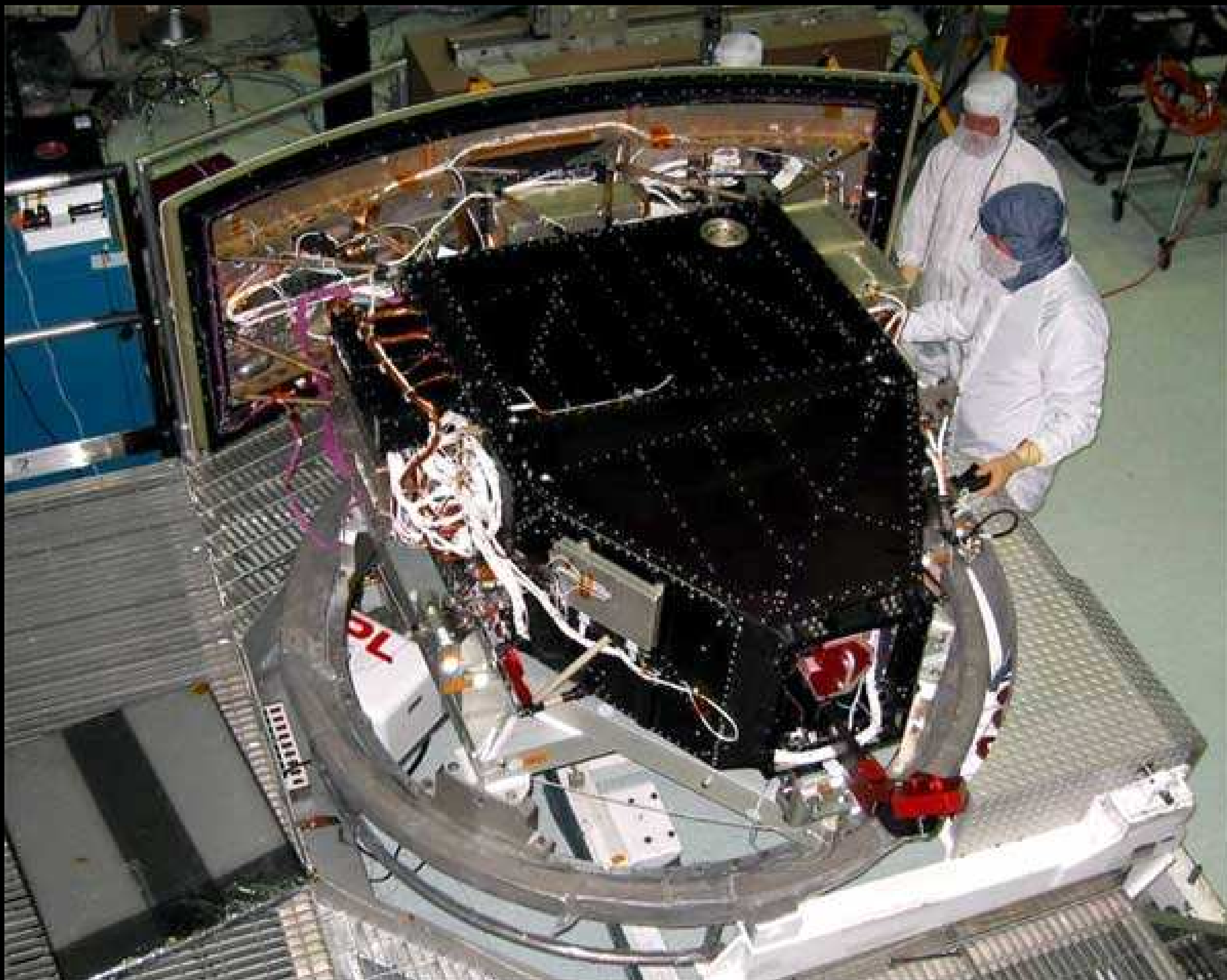


JWST is the perfect near–mid-IR sequel to HST and Spitzer:

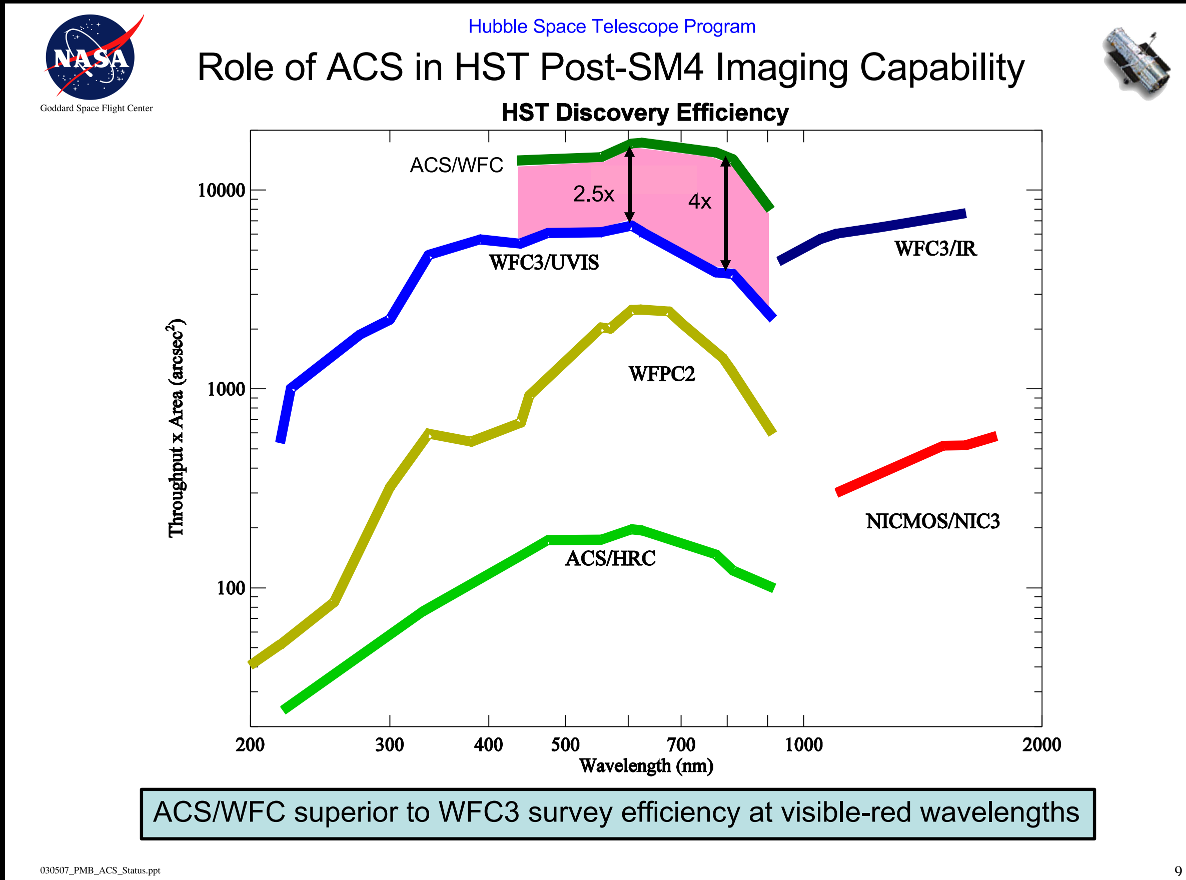
- Vastly larger $A(\times\Omega)$ than HST in UV-optical and Spitzer in mid-IR.

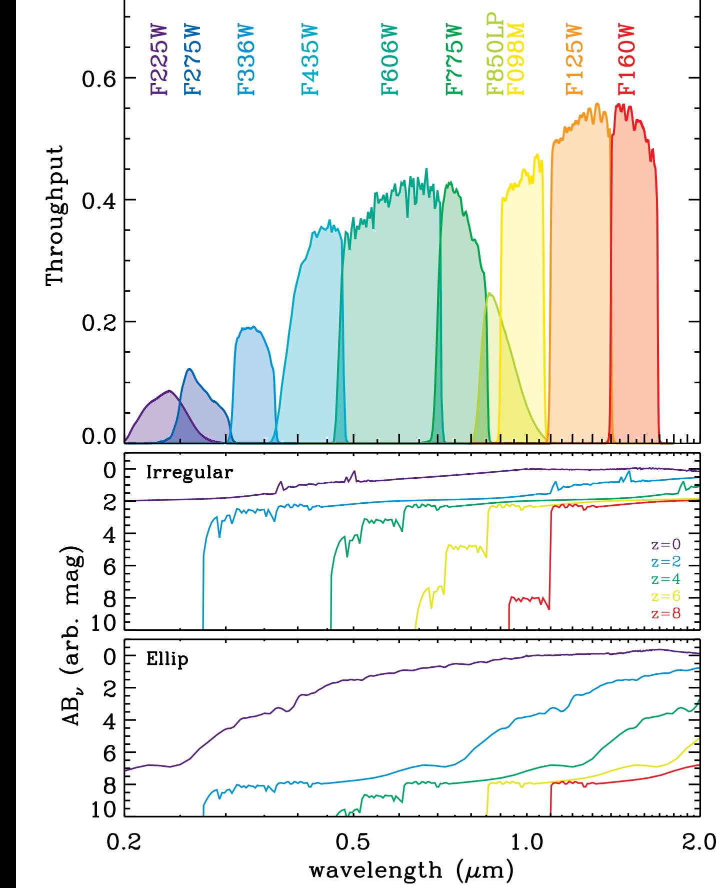
(1) Recent key aspects of the Hubble Space Telescope (HST) project:

(1) WFC3: Hubble's new Panchromatic High-Throughput Camera



HST WFC3 and its IR channel: a critical pathfinder for JWST science.





WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- QE$\gtrsim$70%, 4k$\times$4k array of 0.″04 pixel, FOV $\simeq$ 2.′67 $\times$ 2.′67.

WFC3/IR channel unprecedented near–IR throughput & areal coverage:

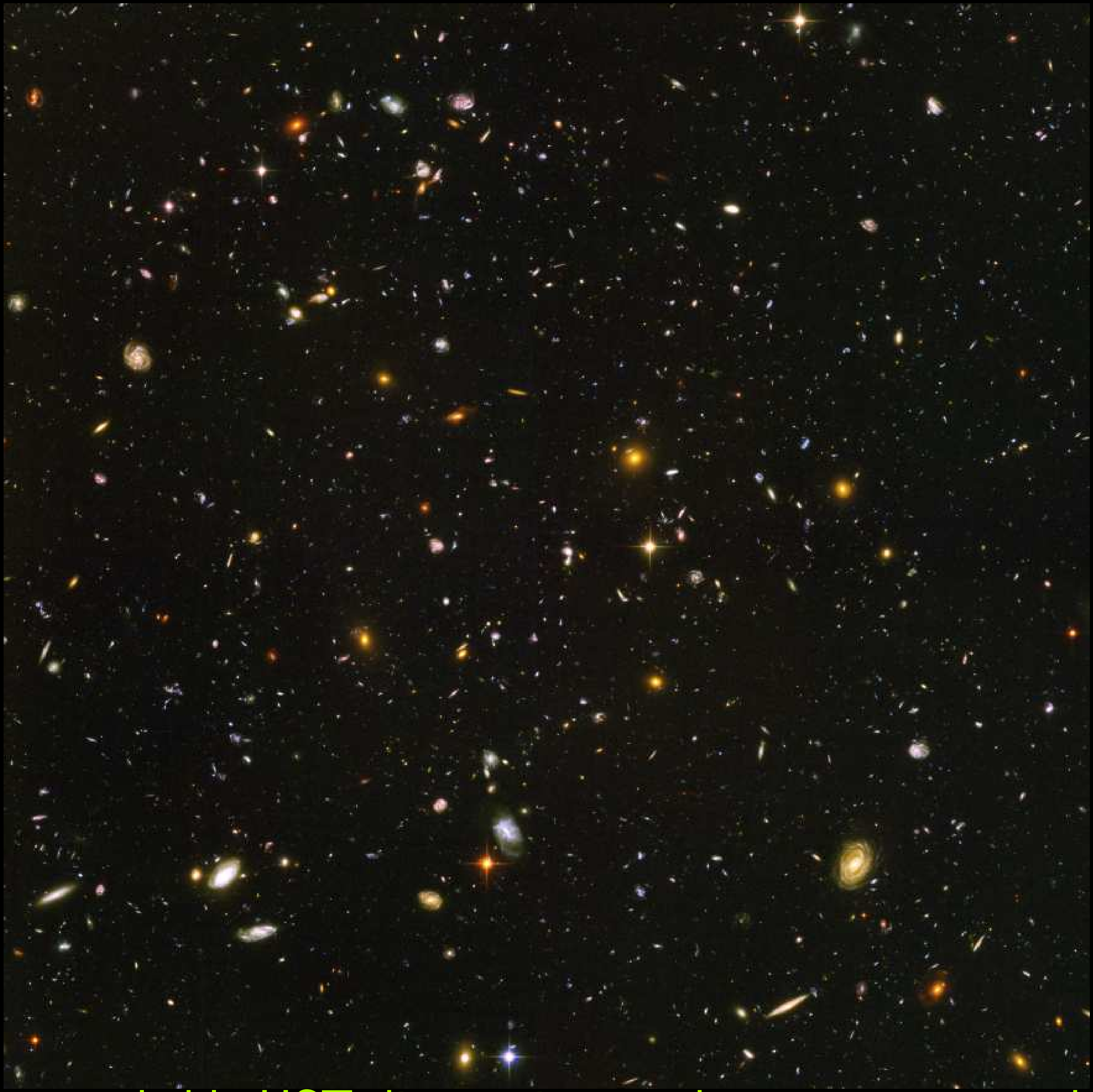
- QE$\gtrsim$70%, 1k$\times$1k array of 0.″13 pixel, FOV $\simeq$ 2.′25 $\times$2.′25.

$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

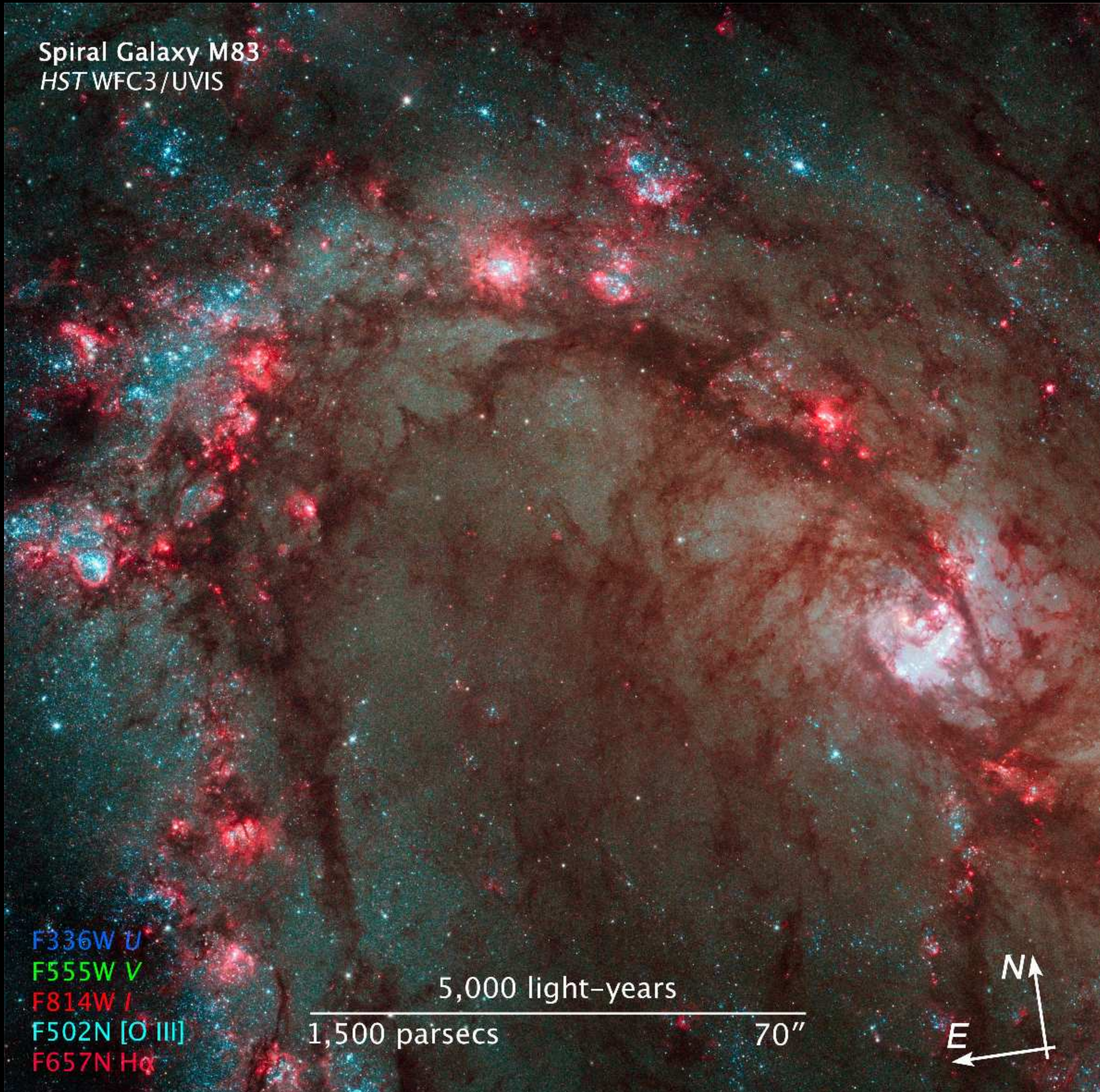
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

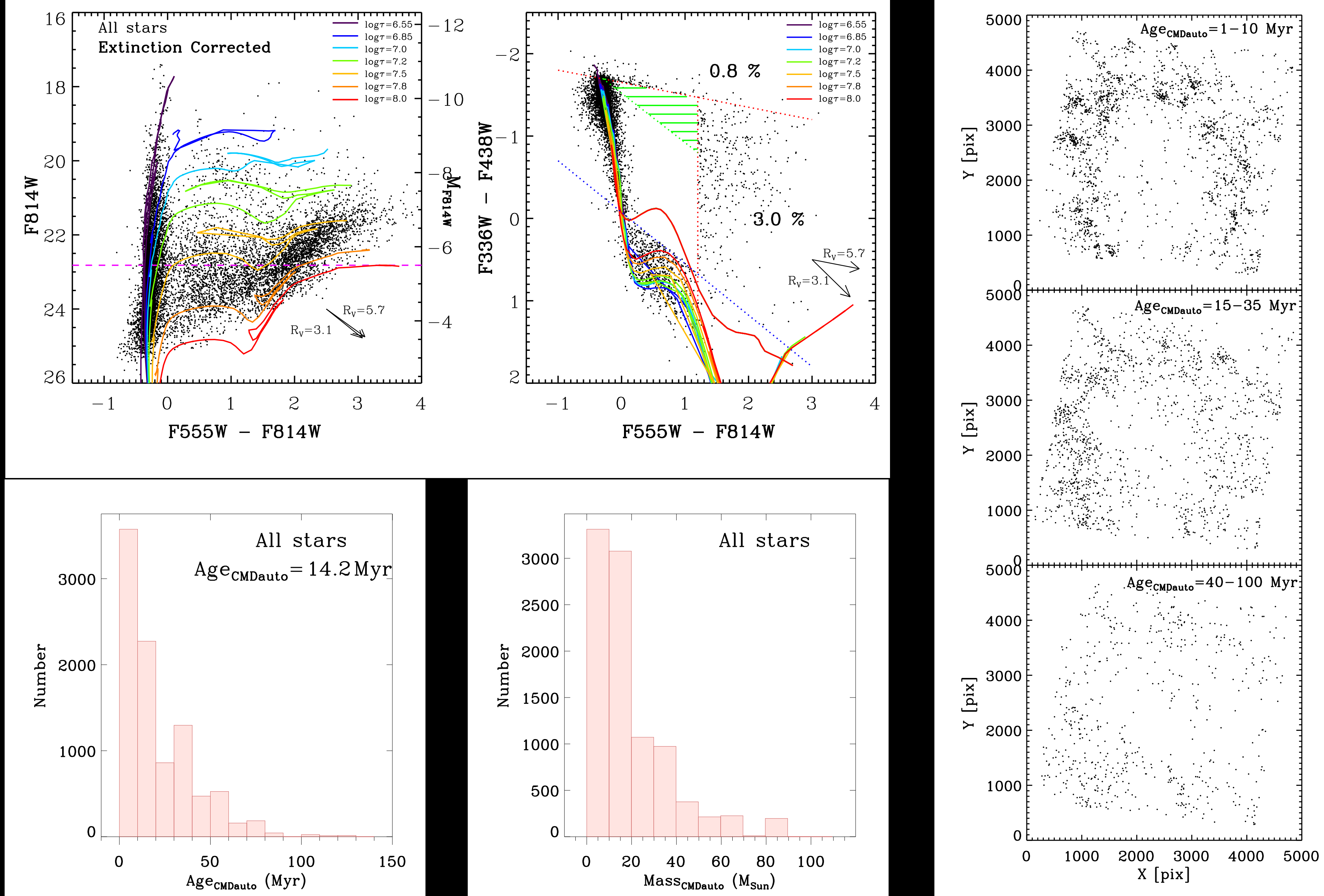
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

(2) Measuring (Nearby) Galaxy Assembly and Supermassive Black-Hole Growth.



One of the remarkable HST discoveries was how numerous and small faint galaxies are: The building blocks of giant galaxies seen today.


Spiral Galaxy M83
HST WFC3/UVIS
F336W U
F555W V
F814W I
F502N [O III]
F657N Hα
5,000 light-years
1,500 parsecs
70″
N
E



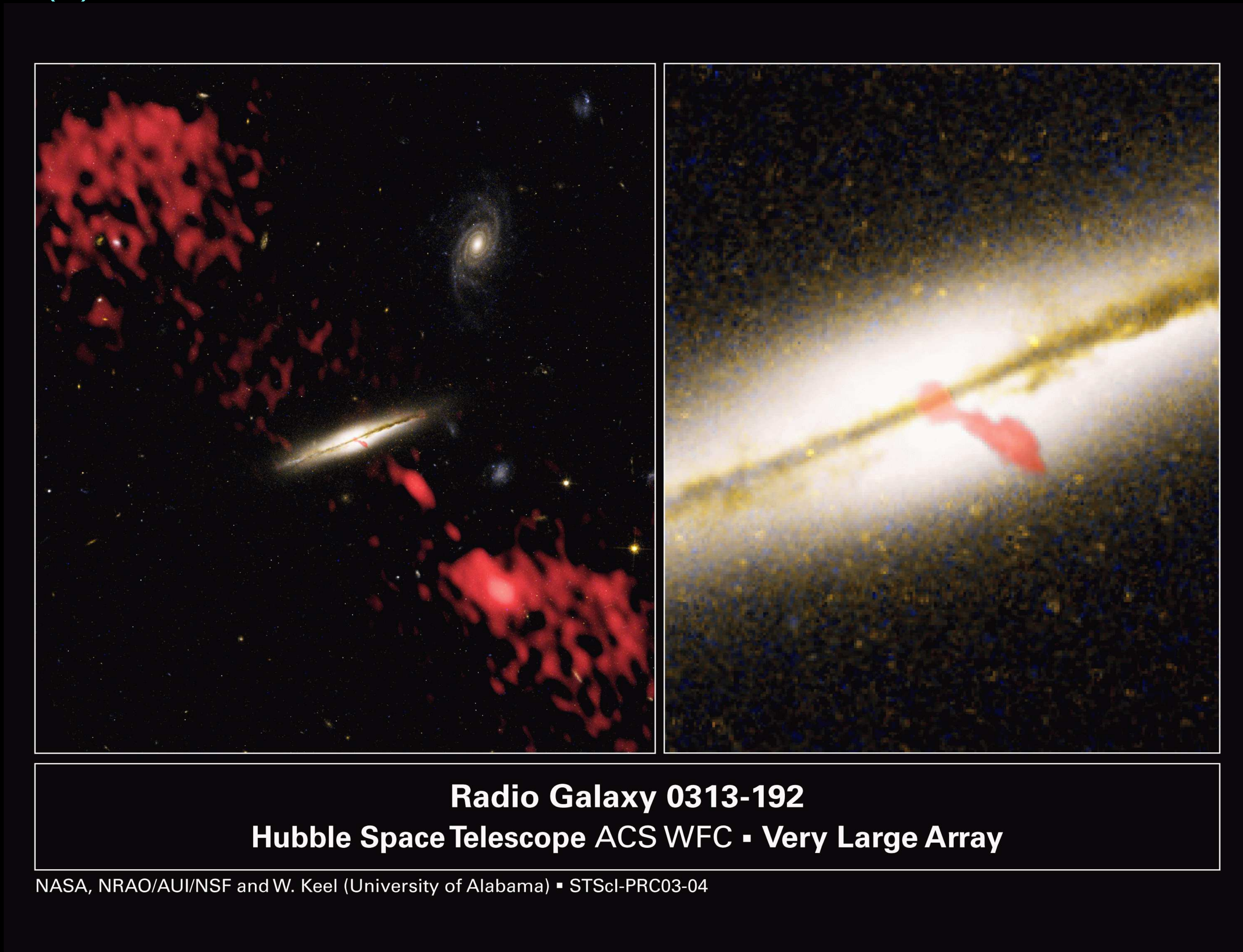
Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).

JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV–blue before JWST flies!

NGC 3032: “Boring old elliptical galaxy” with residual ongoing star-formation!

Central star-formation could be feeding central super-massive black-hole!

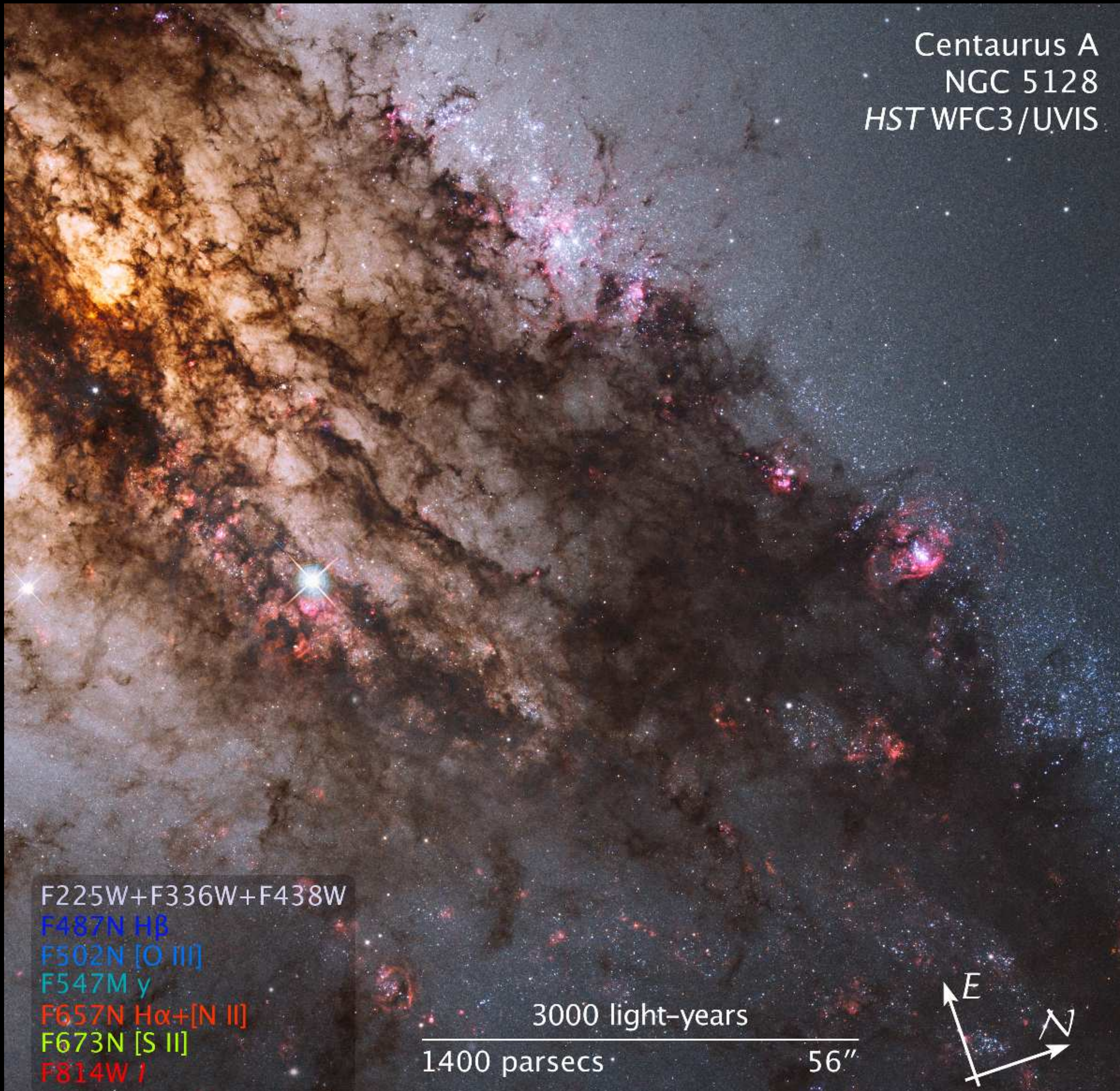
(2) Measuring Galaxy Assembly & Supermassive Blackhole Growth

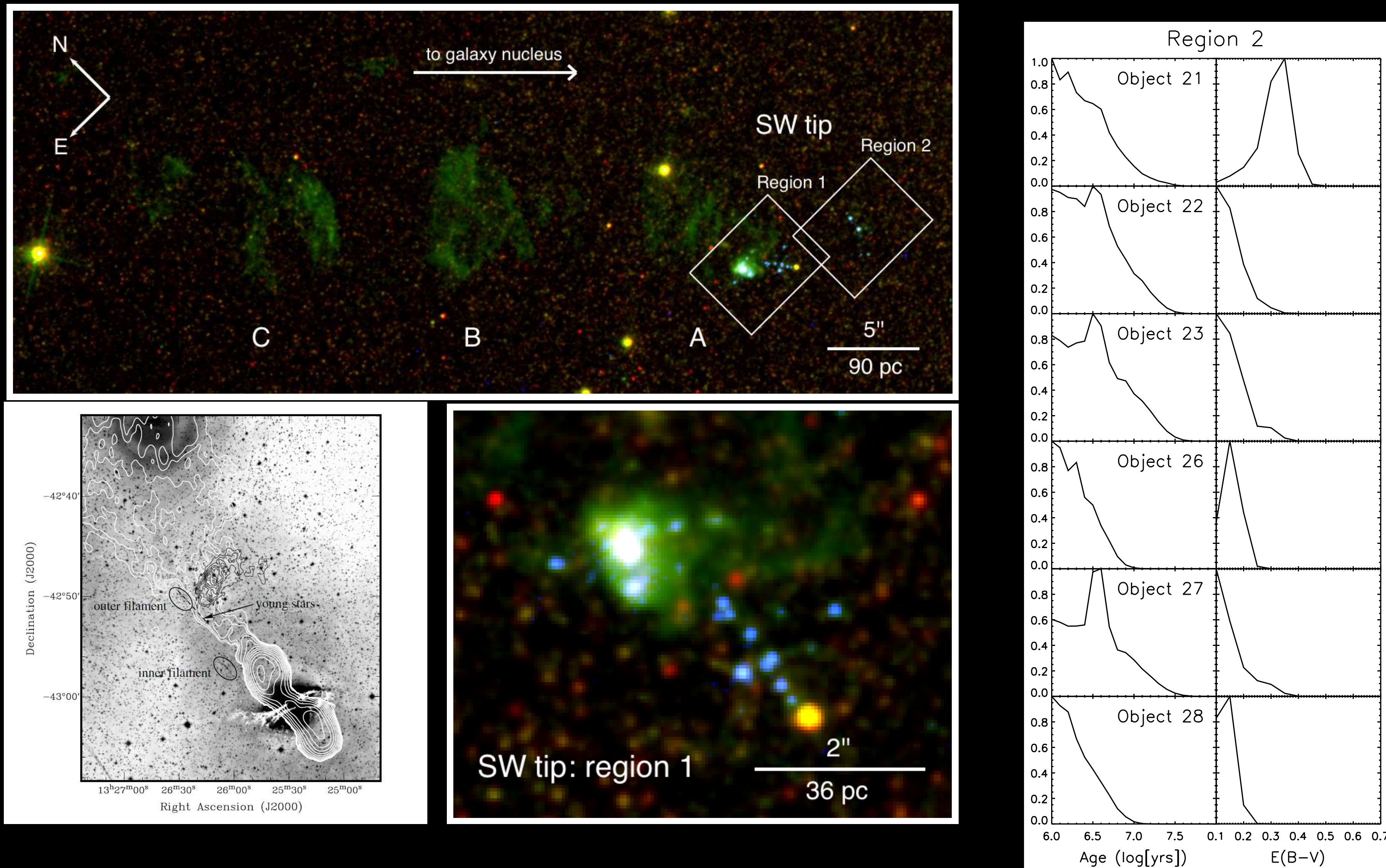


Does galaxy assembly go hand-in-hand with supermassive blackhole growth?

"For God's sake, Edwards. Put the laser pointer away."

The danger of having Quasar-like devices too close to home ...


Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N

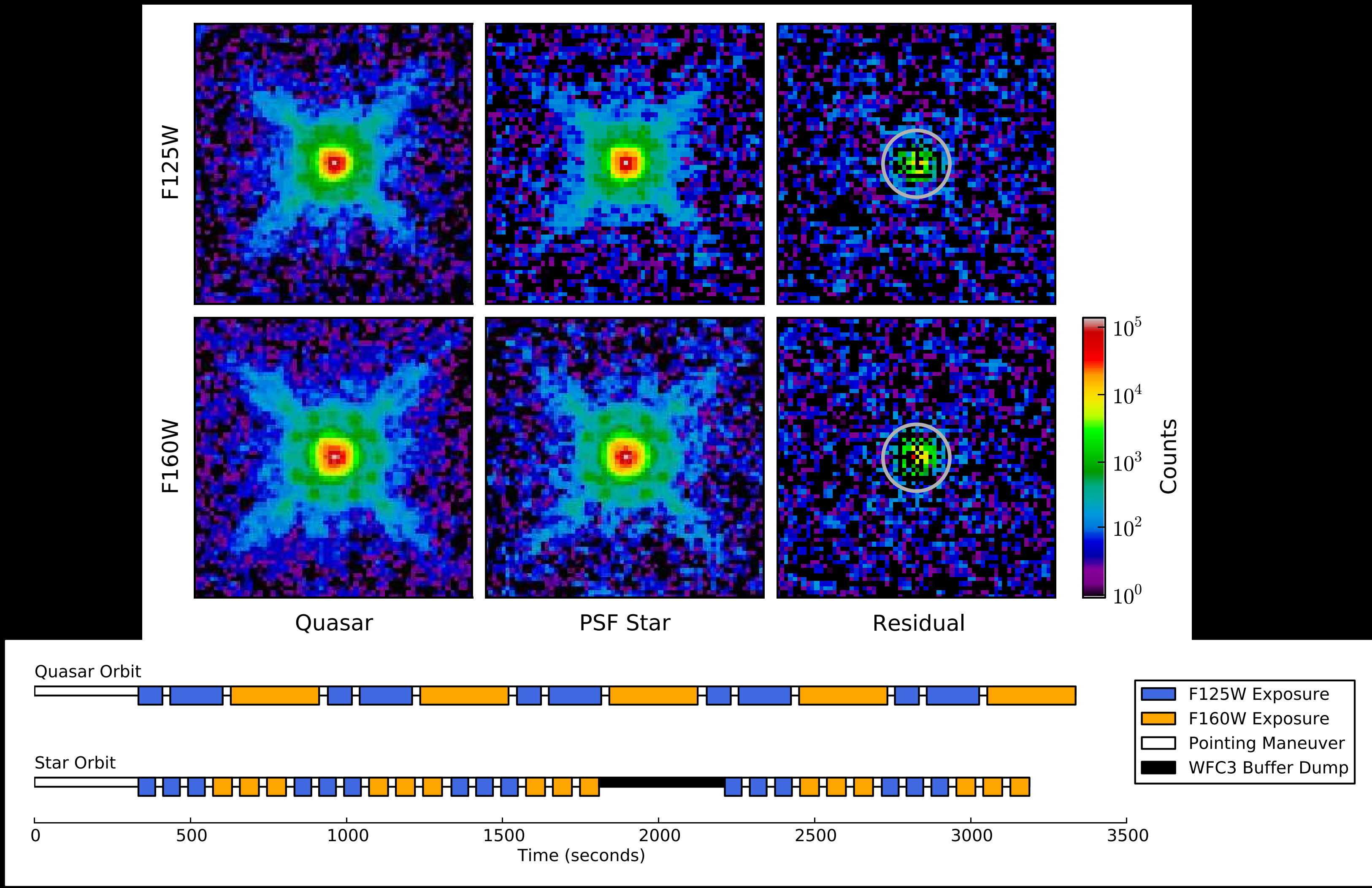


Well determined ages for young (∼2 Myr) stars in Centaurus A jet with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

JWST will trace older stellar pops and SF in much dustier environment.

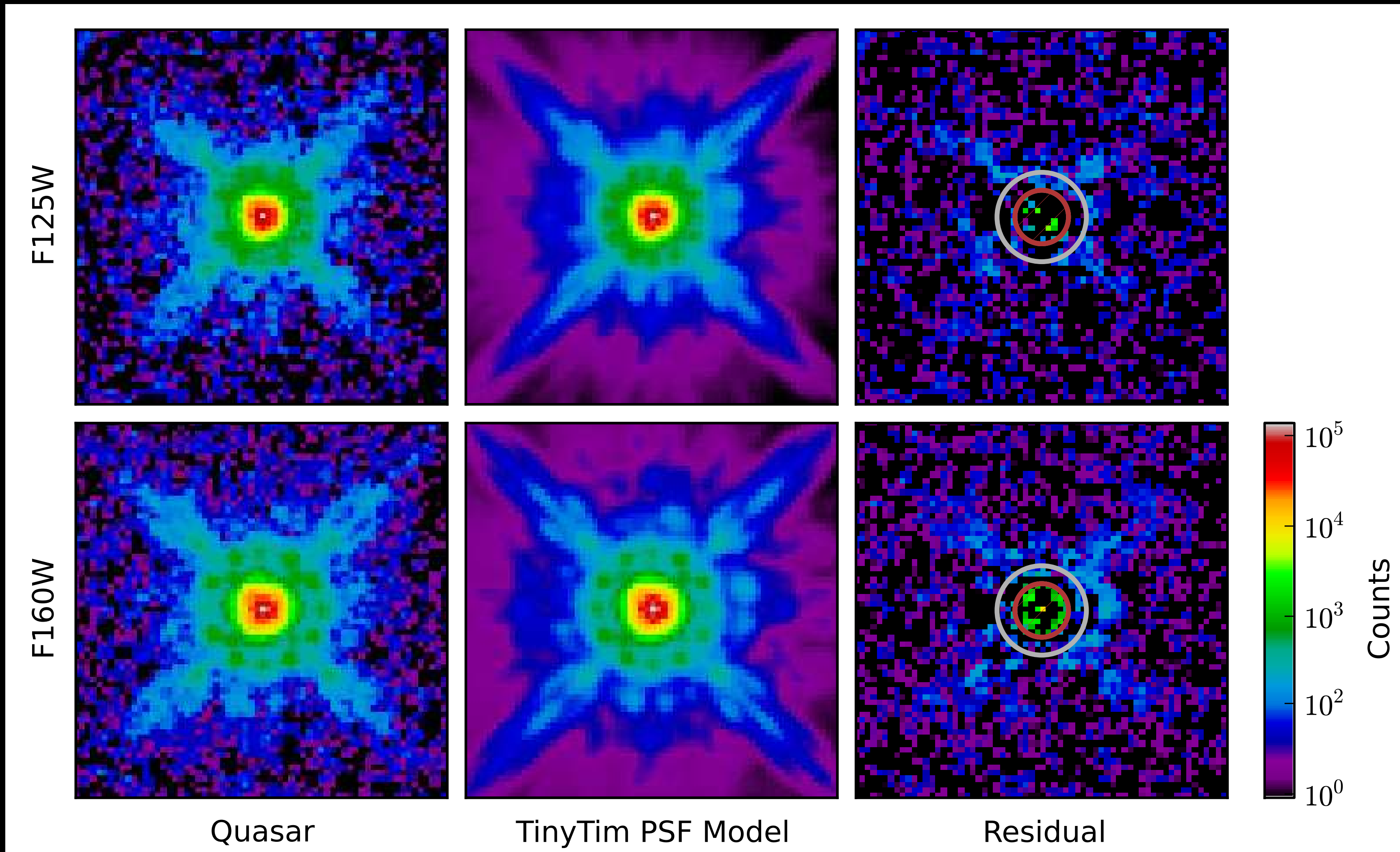
- We must do all we can with HST in the UV–blue before JWST flies.

(2) HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲1 Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38)
- PSF-star (AB=15 mag) subtracts z=6.42 QSO (AB=19) nearly to the noise limit: NO host galaxy detected 100× fainter (AB≳23.5 mag at r≳0.″3).

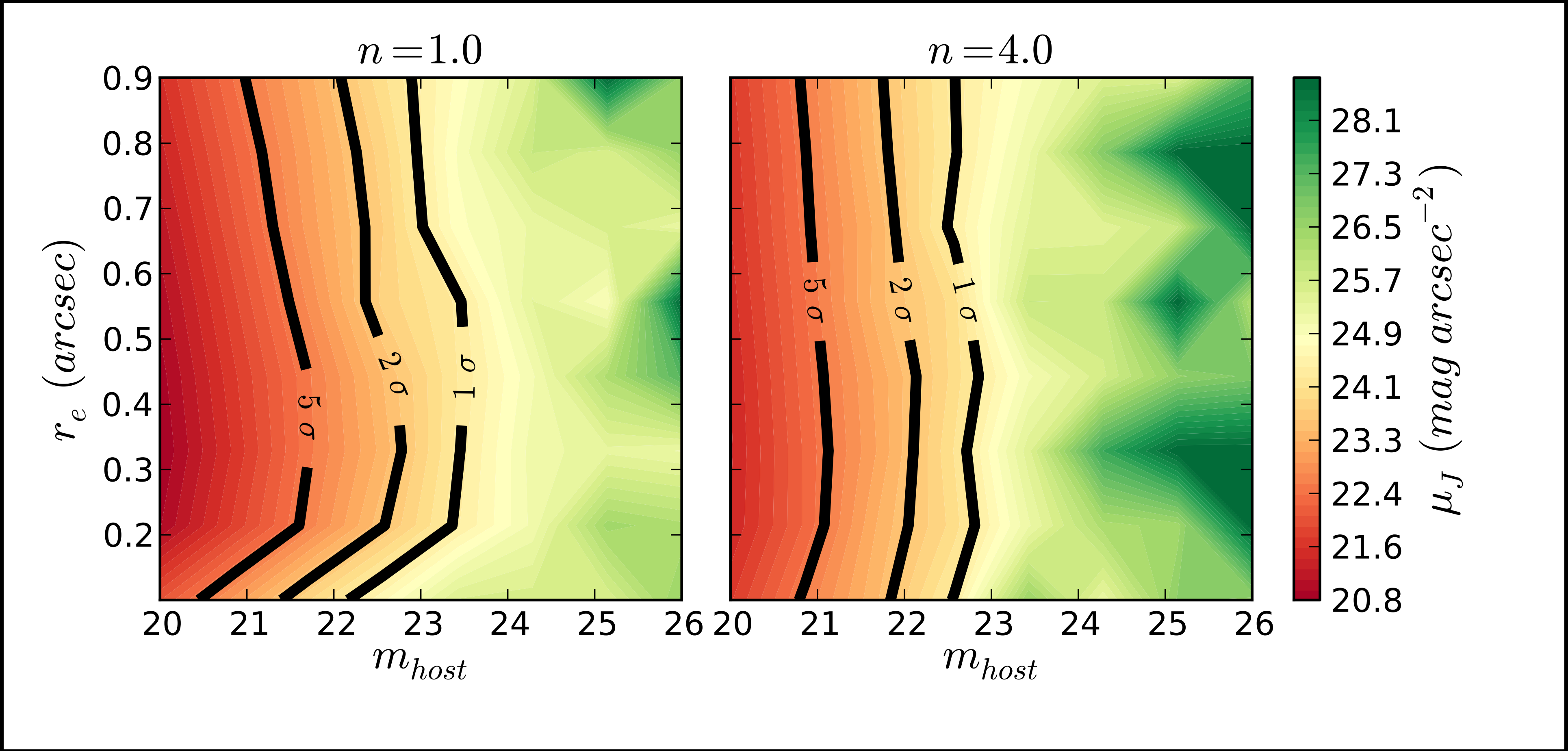
(2) HST WFC3 observations of Quasar Host Galaxies at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- TinyTim fit of PSF-star + Sersic models QSO nearly to the noise limit: NO z=6.42 host galaxy at AB$\gtrsim$23.5 mag at radius $r \simeq 0\farcs3$–$0\farcs5$.

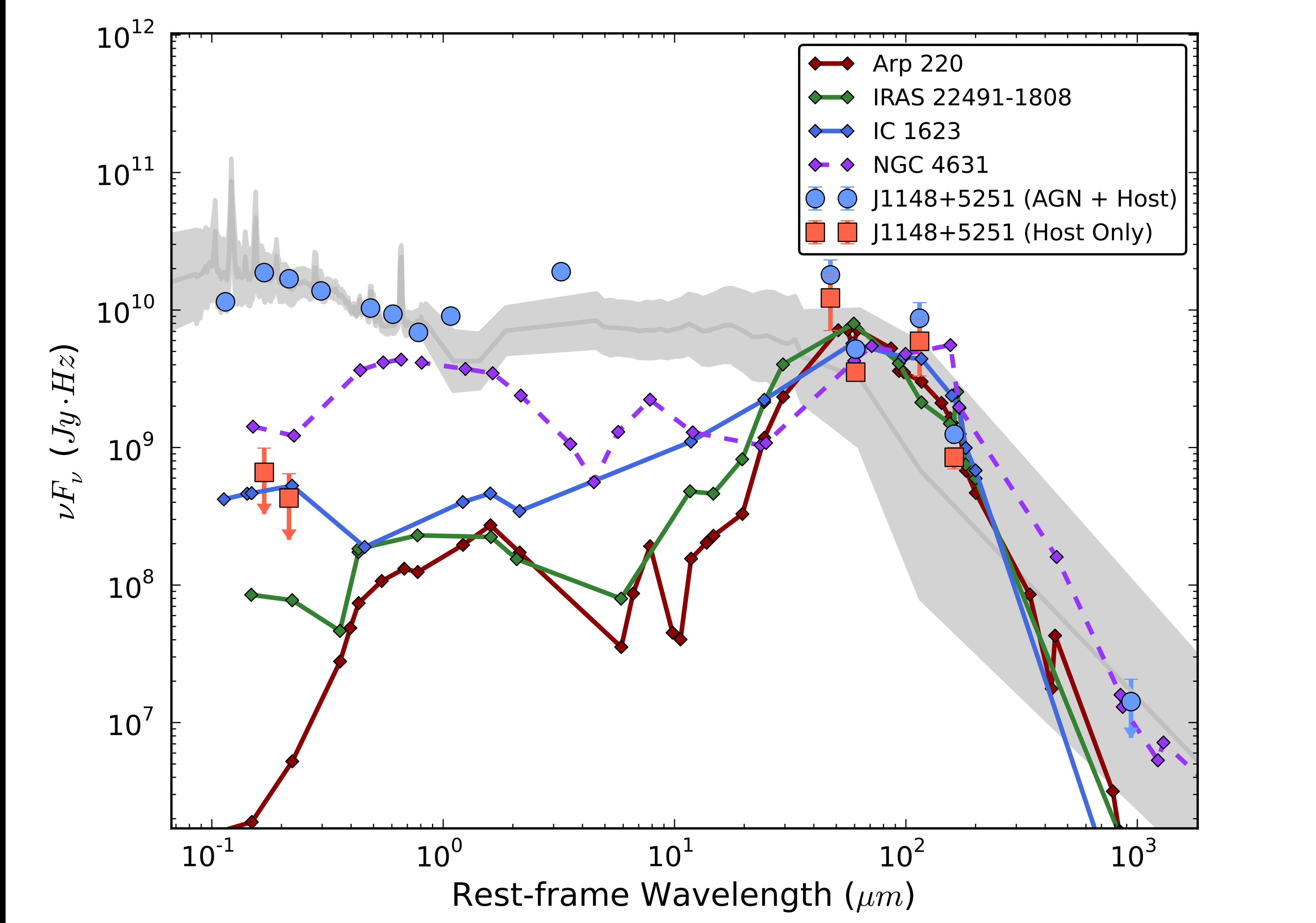
THE most luminous Quasars in the Universe: Are all their host galaxies faint (dusty)? $\Rightarrow$ Major implications for Galaxy Assembly–SMBH Growth.

(2) HST WFC3 observations of Quasar Host Galaxies at z≃6 (age≲1 Gyr)



- TinyTim fit of PSF-star + Sersic models of galaxy light-profile, nearly to the noise limit: NO host galaxy at AB≳23.0 mag with $r_e \simeq 0\farcs5$ (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283)

- JWST Coronagraphs can do this 10–100× fainter (and for z≲20, $\lambda \lesssim 28\mu$m) — but need JWST diffraction limit at 2.0μm and clean PSF to do this.

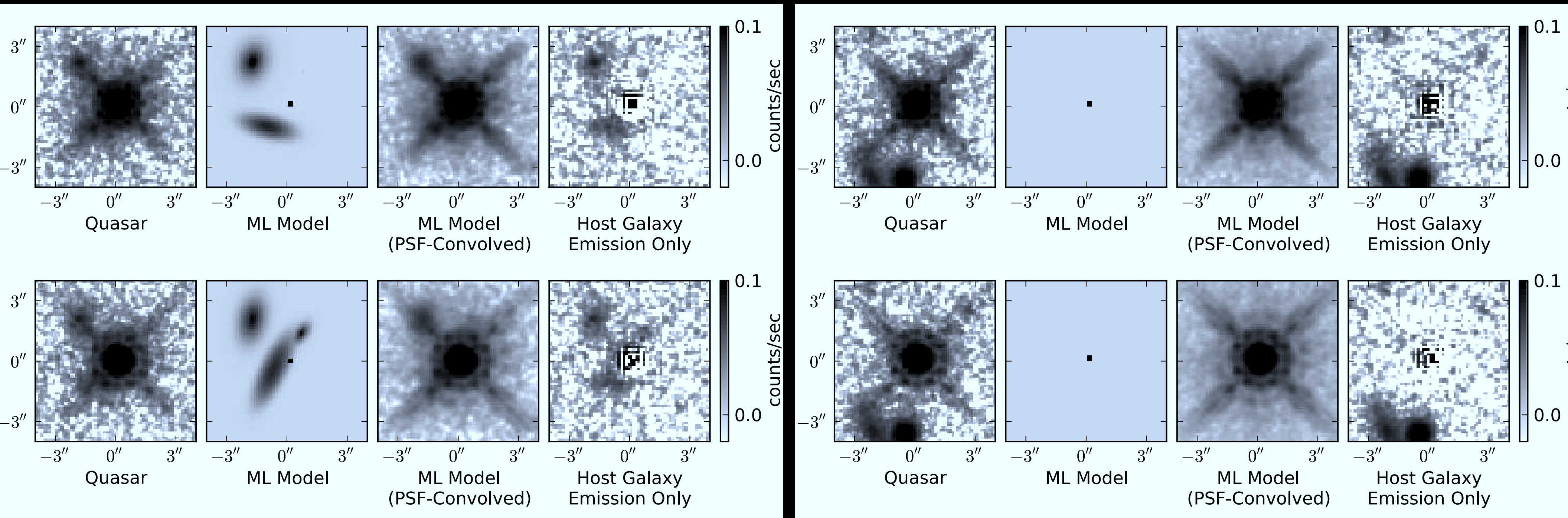


- Blue dots: z=6.42 QSO SED, Grey: Average radio-quiet QSO spectrum at z$\lesssim$1 (normalized at 0.5μ). Red: z=6.42 host galaxy (WFC3+submm).

- Nearby fiducial galaxies (starburst ages$\lesssim$1 Gyr) normalized at 100μm: Rules out z=6.42 spiral or bluer host galaxy SEDs. (U)LIRGs permitted.

- JWST Coronagraphs can do this 10–100$\times$ fainter (& for z$\lesssim$20, $\lambda\lesssim$28μm).

(2) WFC3: First detection of one Quasar Host Galaxy at z≃6 (Giant merger?)

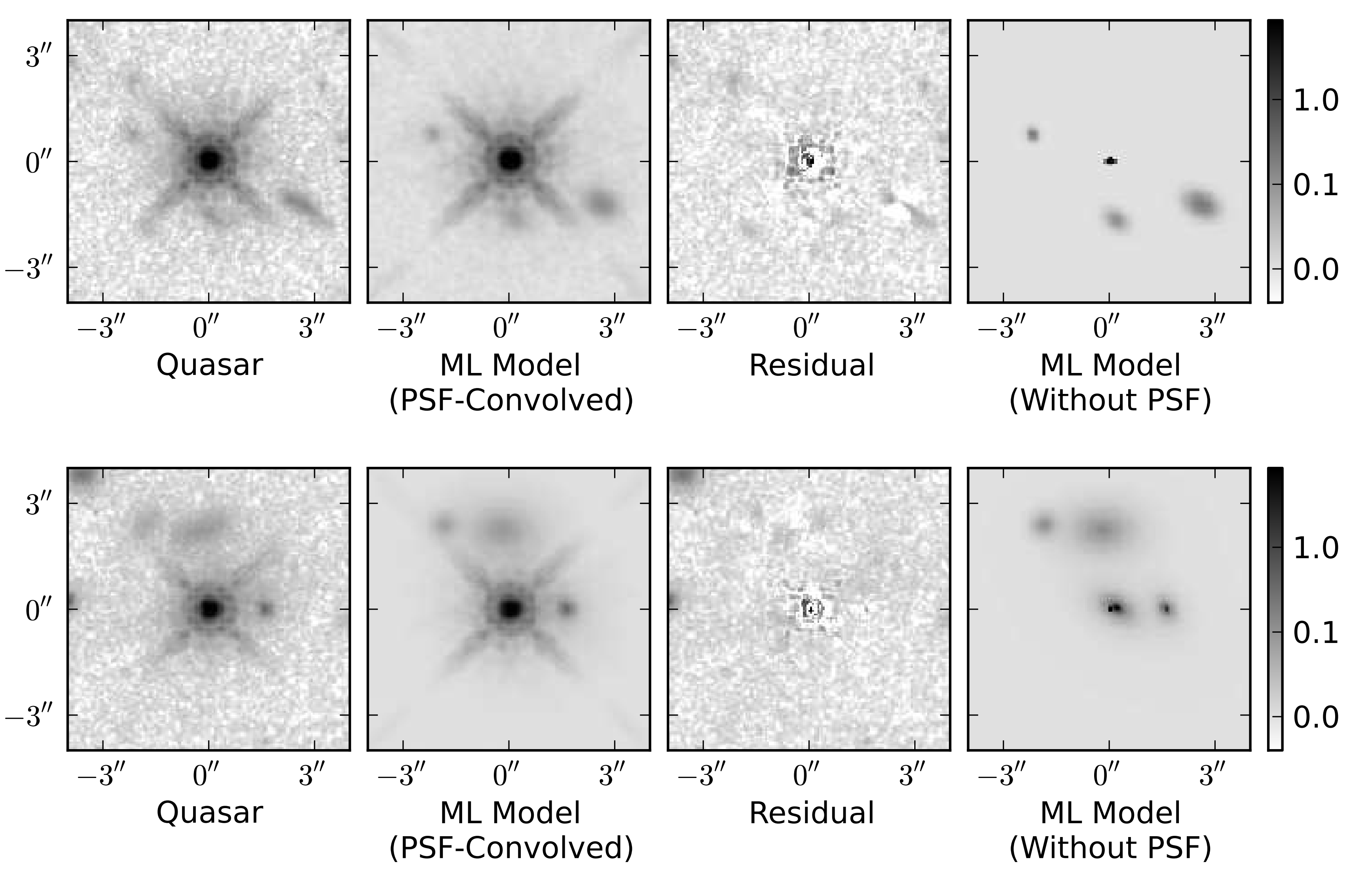


- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile: First z≃6 host galaxy detection (Mechtley, Windhorst+ 2013).
- First solid detection out of four z≃6 QSOs [3 more to be observed].
- 14hr QSO host galaxy: Giant merger morphology + tidal structure?
- Same J+H structure!: blue UV-SED colors at z≃6, constrains dust.

[IRAS starburst galaxy-like SED from rest-frame UV–far-IR, $A_V \gtrsim 1$ mag].

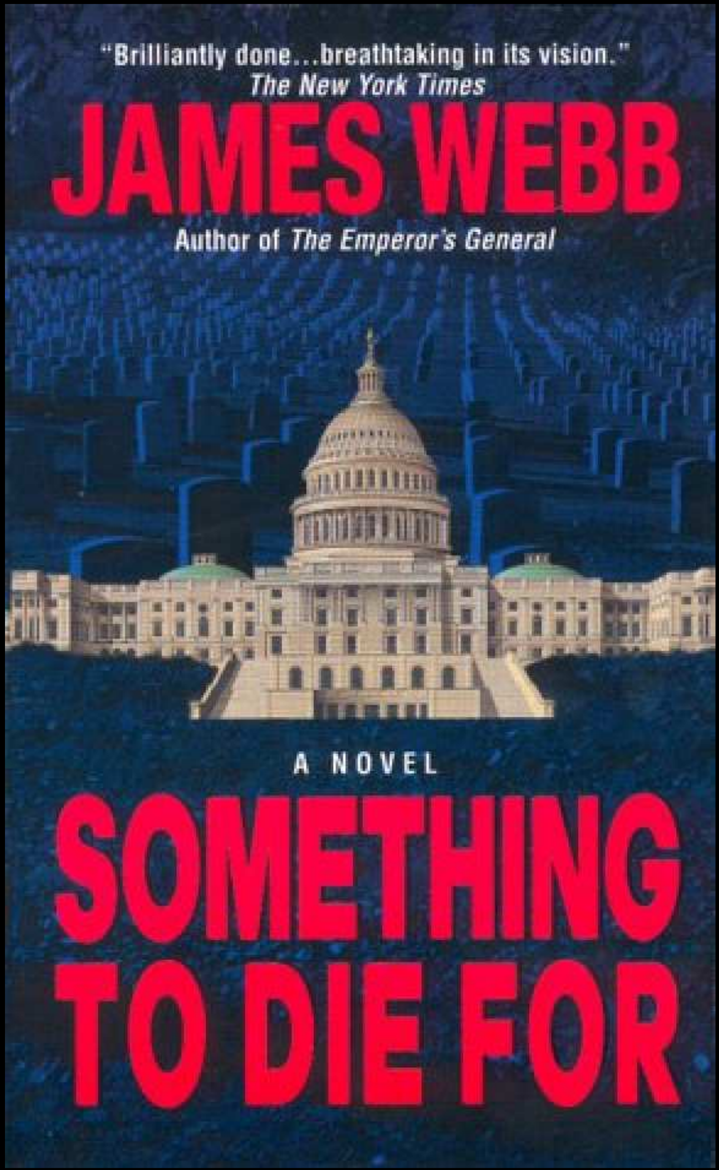
- M_{AB}^{host}(z≃6)$\lesssim$–22.5 mag, possibly $\gtrsim$–1 mag brighter than L*(z≃6)!
- JWST Coronagraphs can do this 10–100$\times$ fainter (& for z$\lesssim$20, $\lambda \lesssim 28\mu$m).

(2) WFC3 observations of Quasar Host Galaxies at z≃2 (evidence for mergers?)



- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, Koekemoer, Windhorst et al. 2013).
- JWST Coronagraphs can do this 10–100× fainter (& for $z \lesssim 20$, $\lambda \lesssim 28\mu m$).

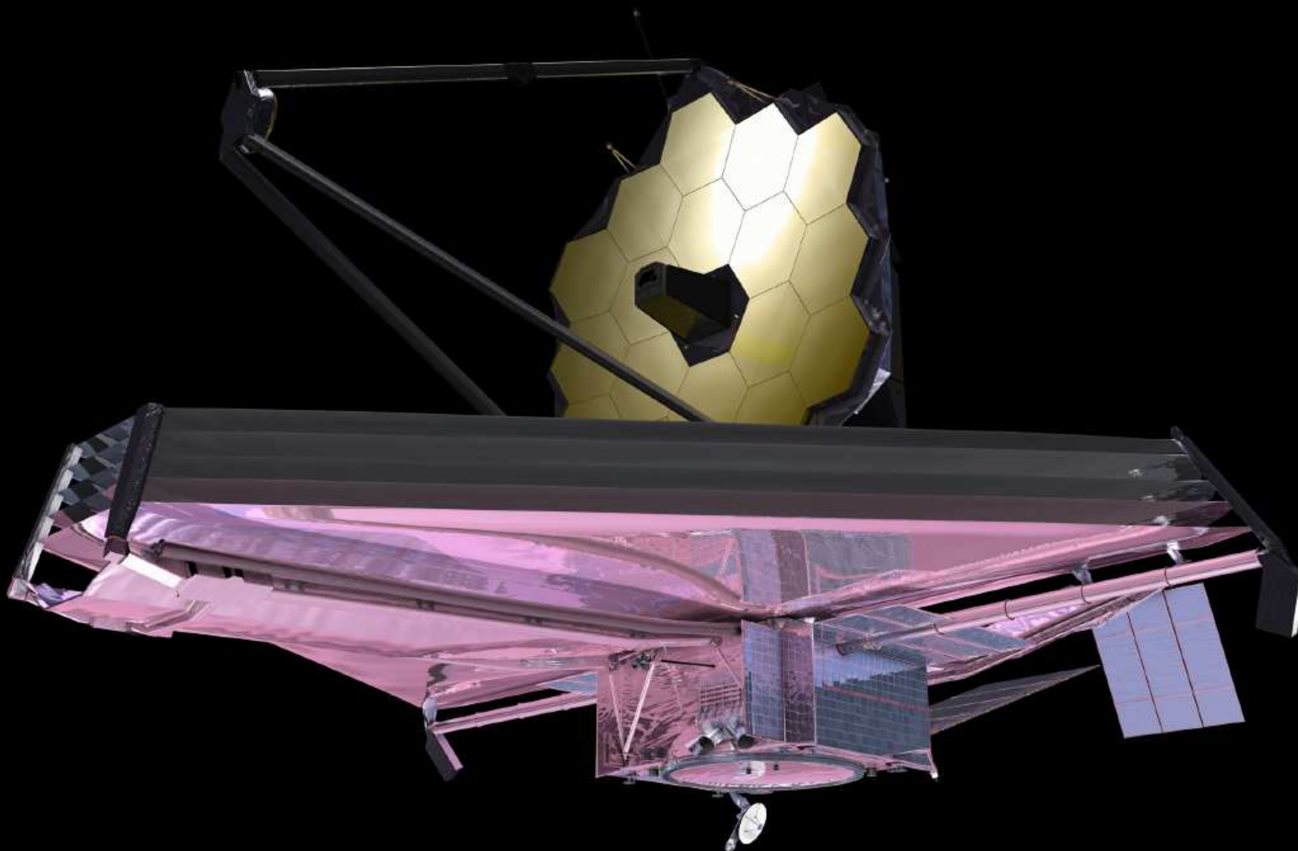
(3) Brief Update of the James Webb Space Telescope (JWST).



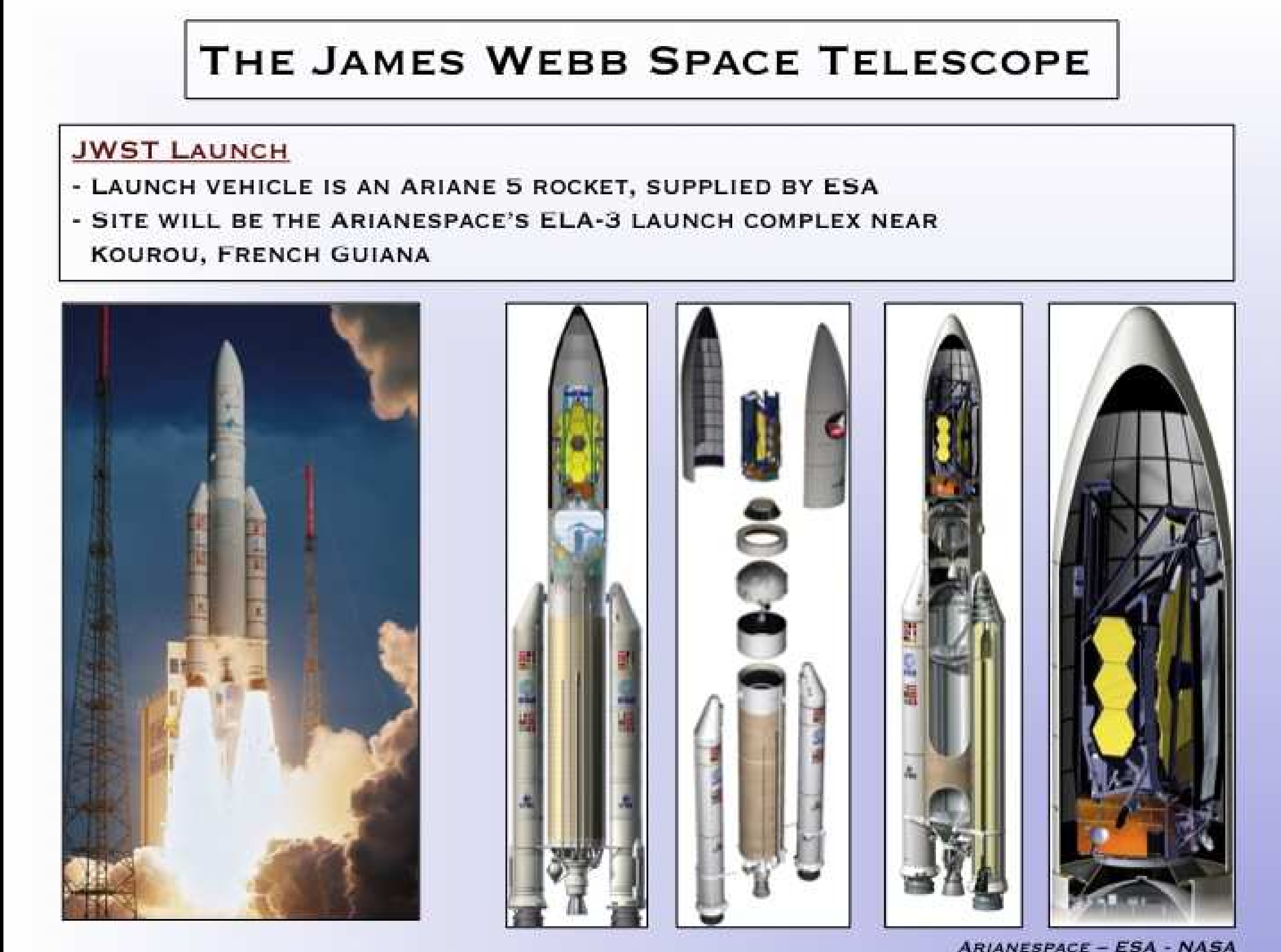
To be used by students & scientists after 2018 ... It'll be worth it.

(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007.

(3) Brief Update of the James Webb Space Telescope

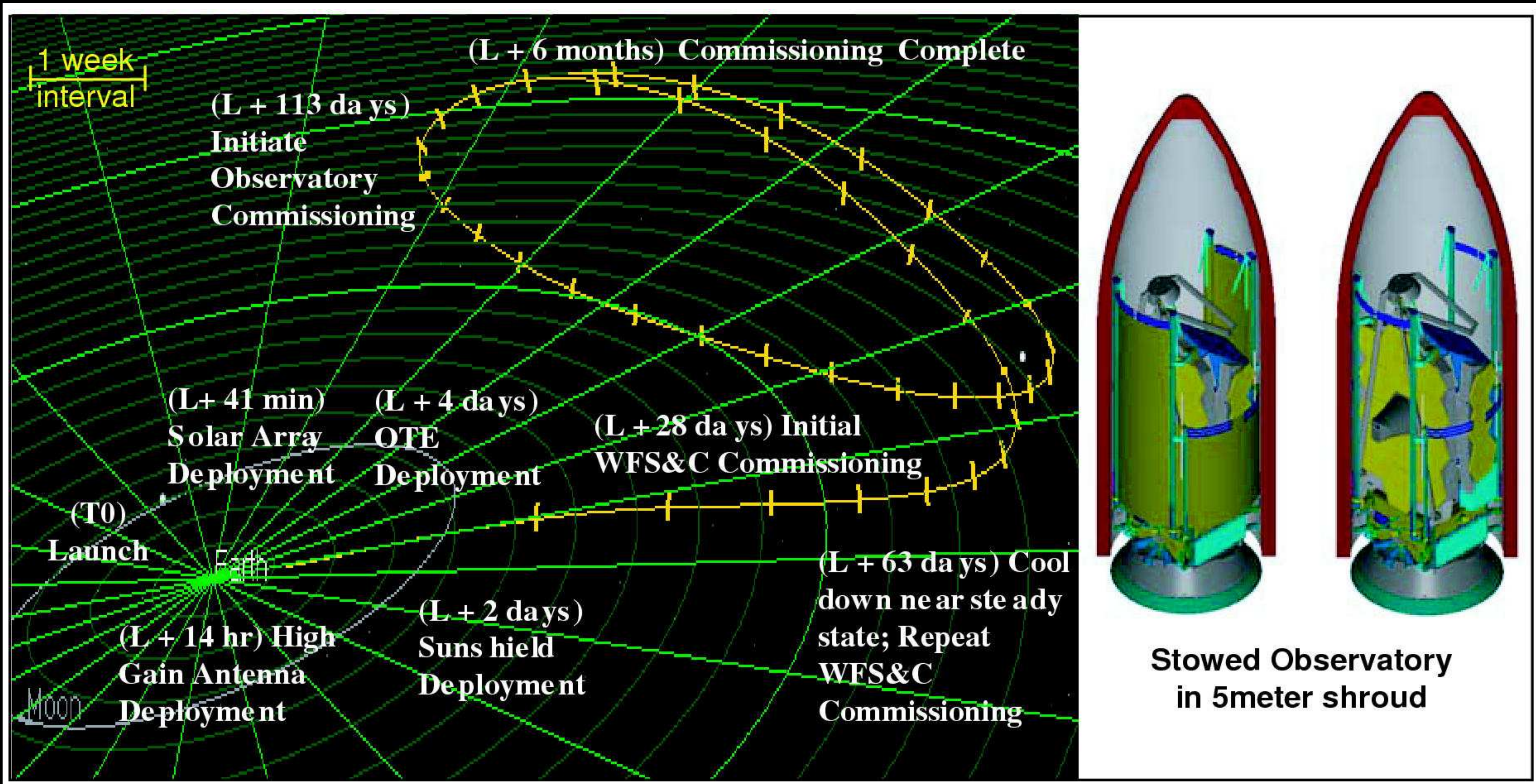


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.



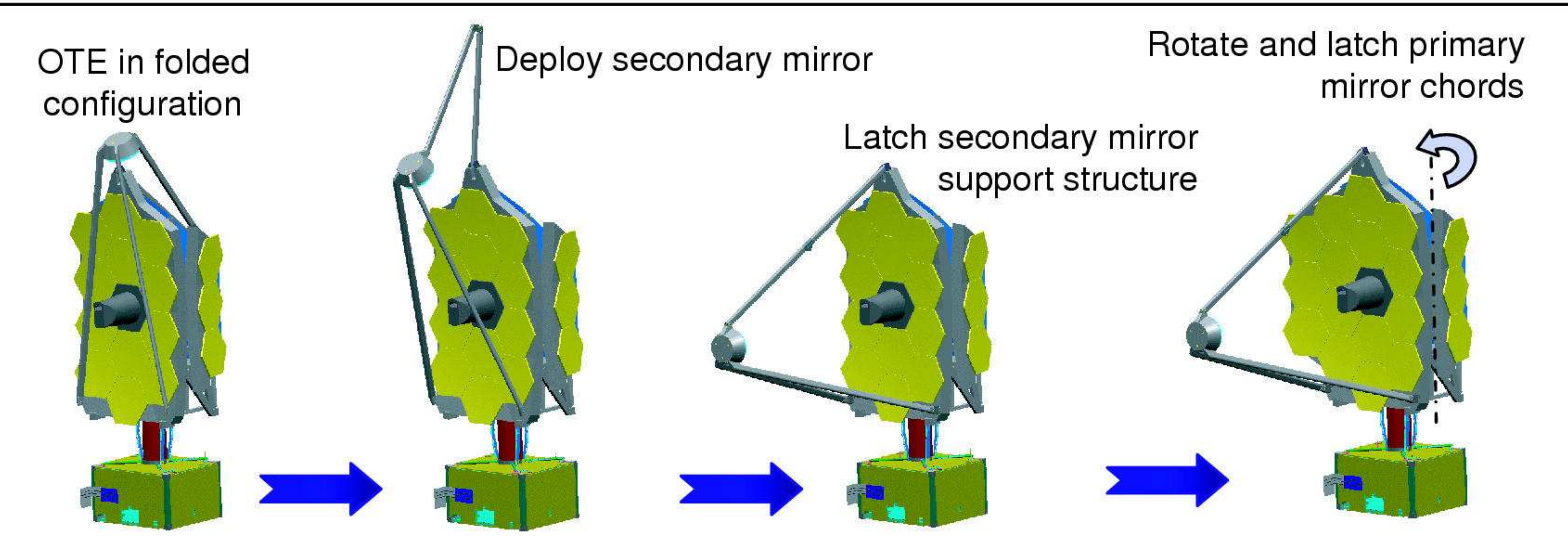
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(3a) How will JWST travel to its L2 orbit?



- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

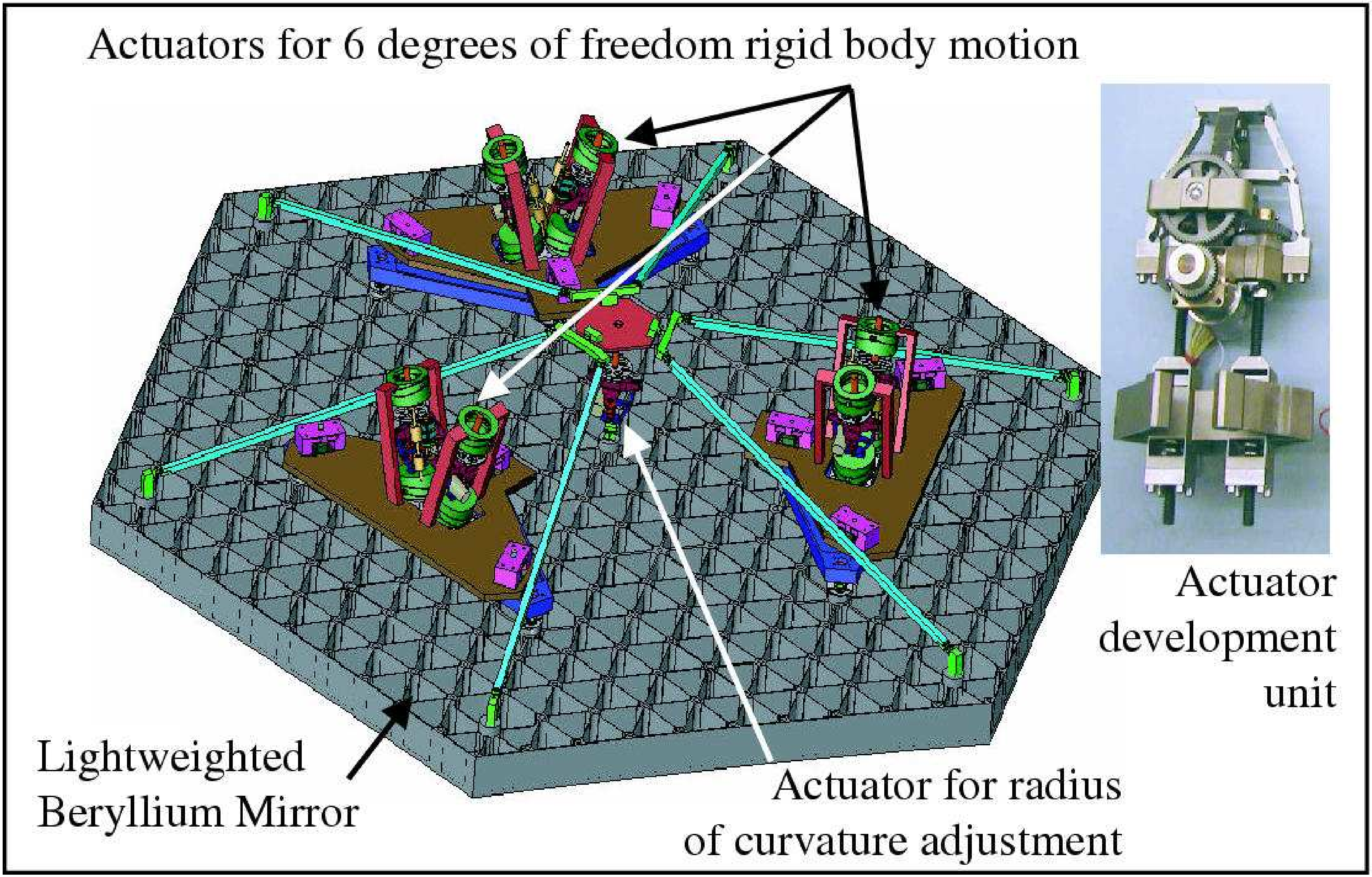
• (3b) How will JWST be automatically deployed?



- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.

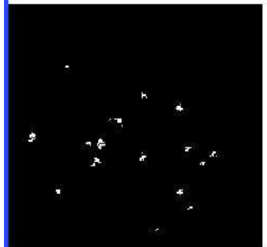
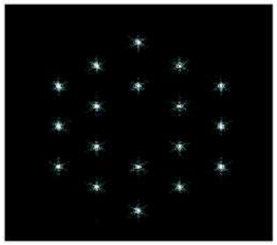
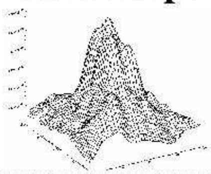
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.

- Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



Active mirror segment support through “hexapods”, similar to Keck.

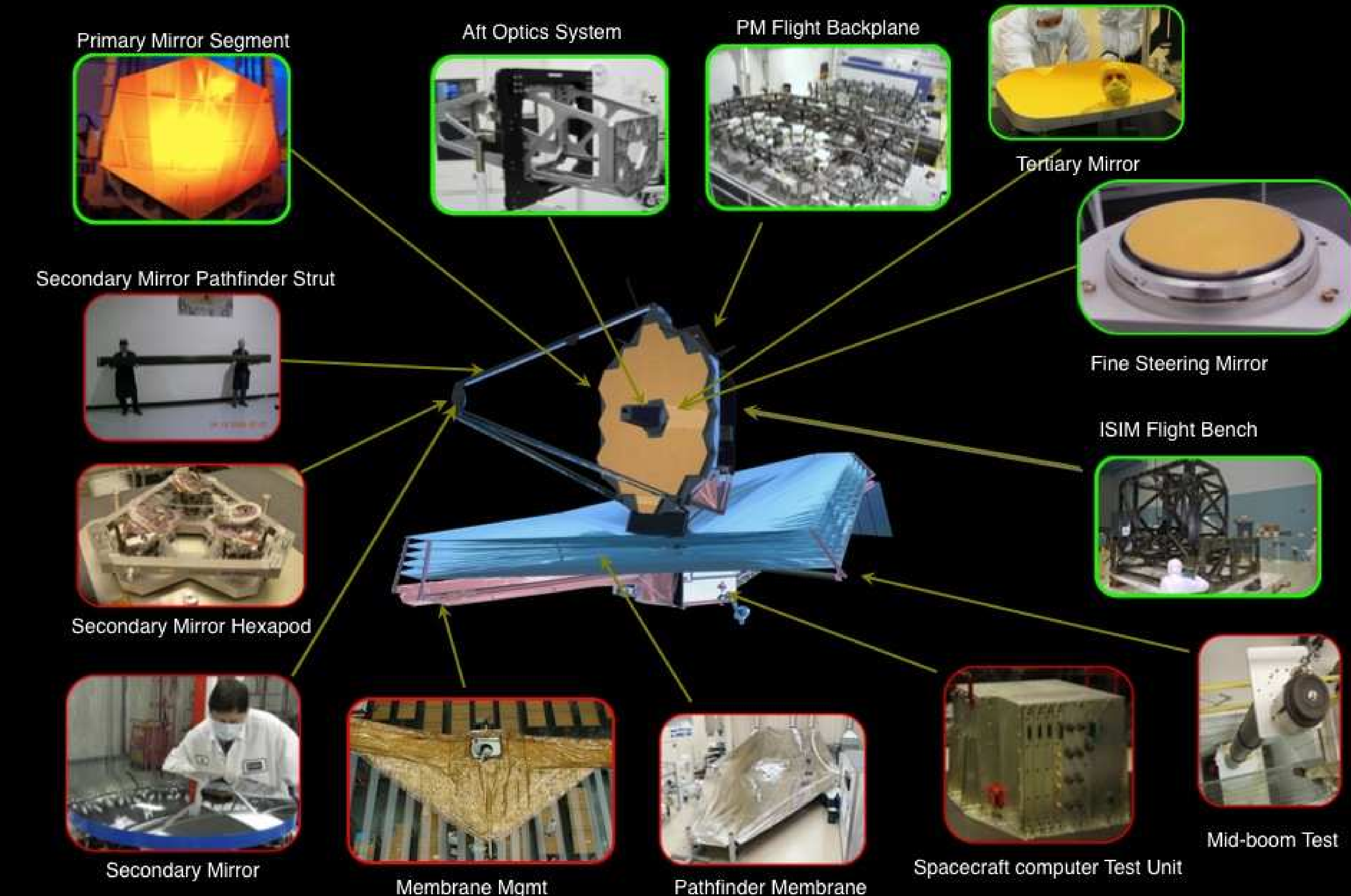
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	**After Step 1** 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	**After Step 2** 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	**After Step 3** 	WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing	**After Step 4** 	WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	**After Step 5** 	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

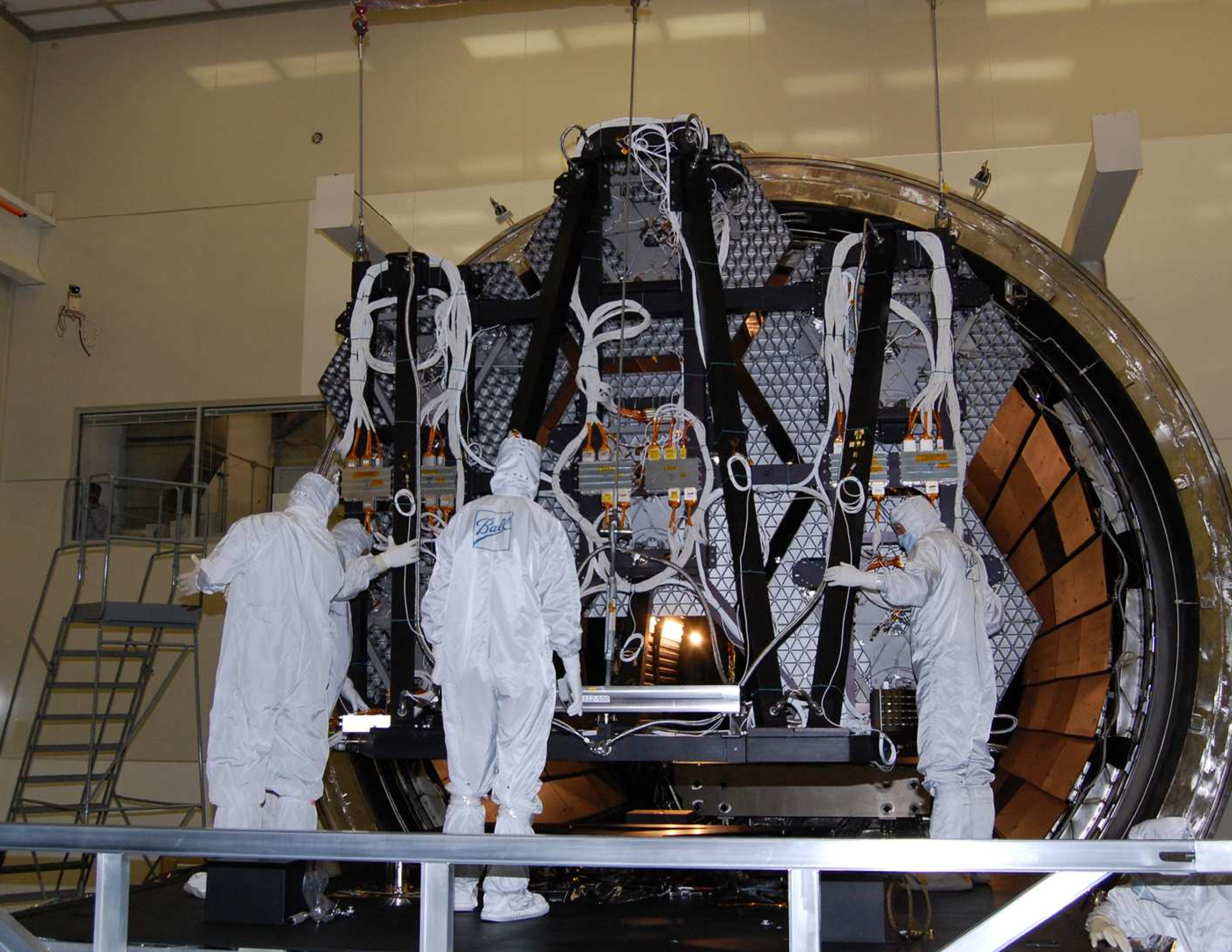
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

In L2, need WFS updates every 10 days depending on scheduling/illumination.

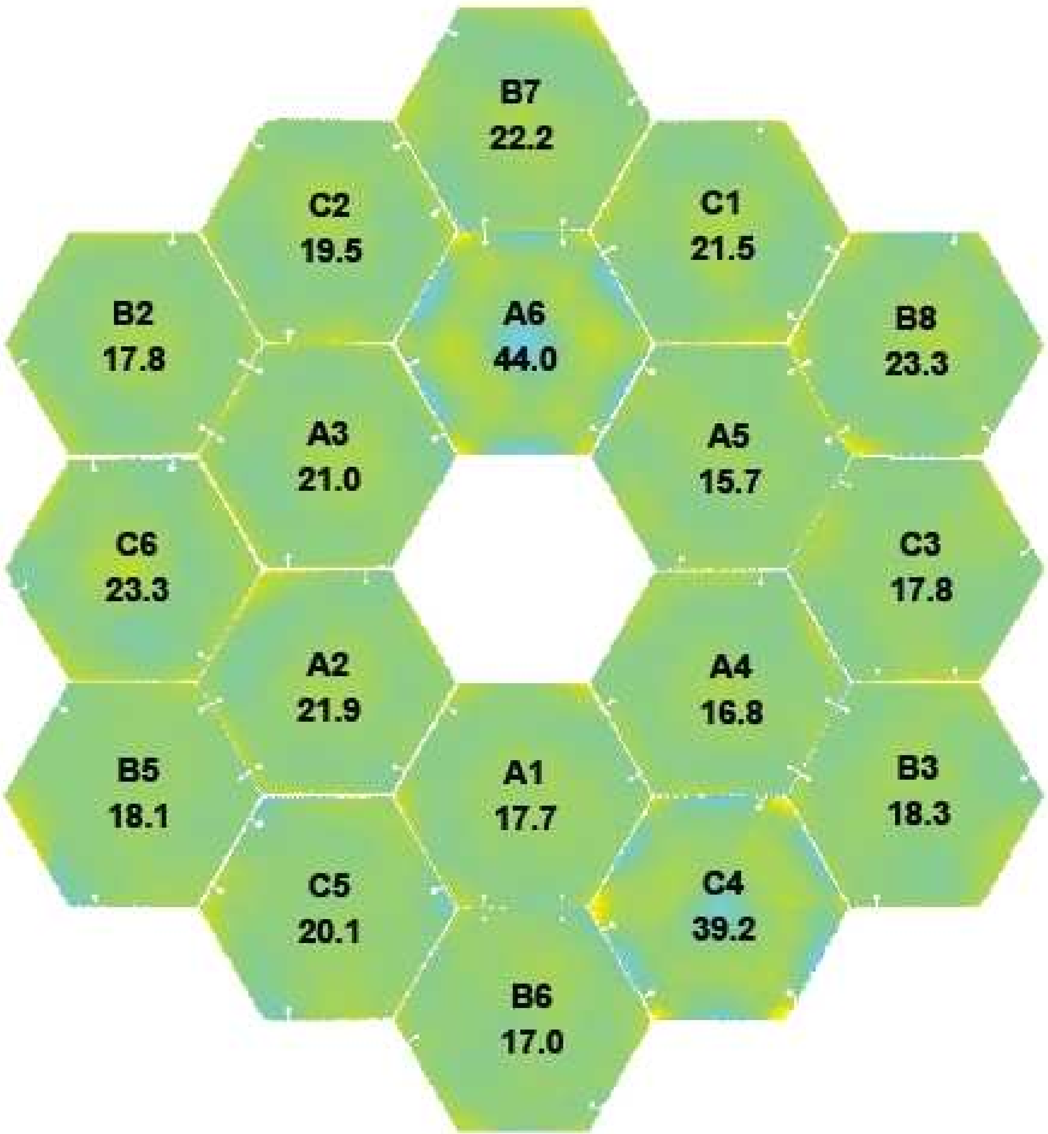
JWST Hardware Status



Mirror Acceptance Testing

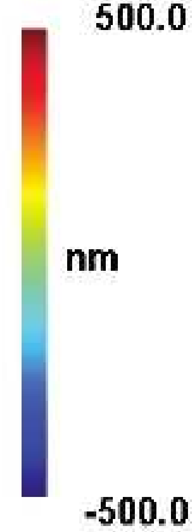


Primary Mirror Composite

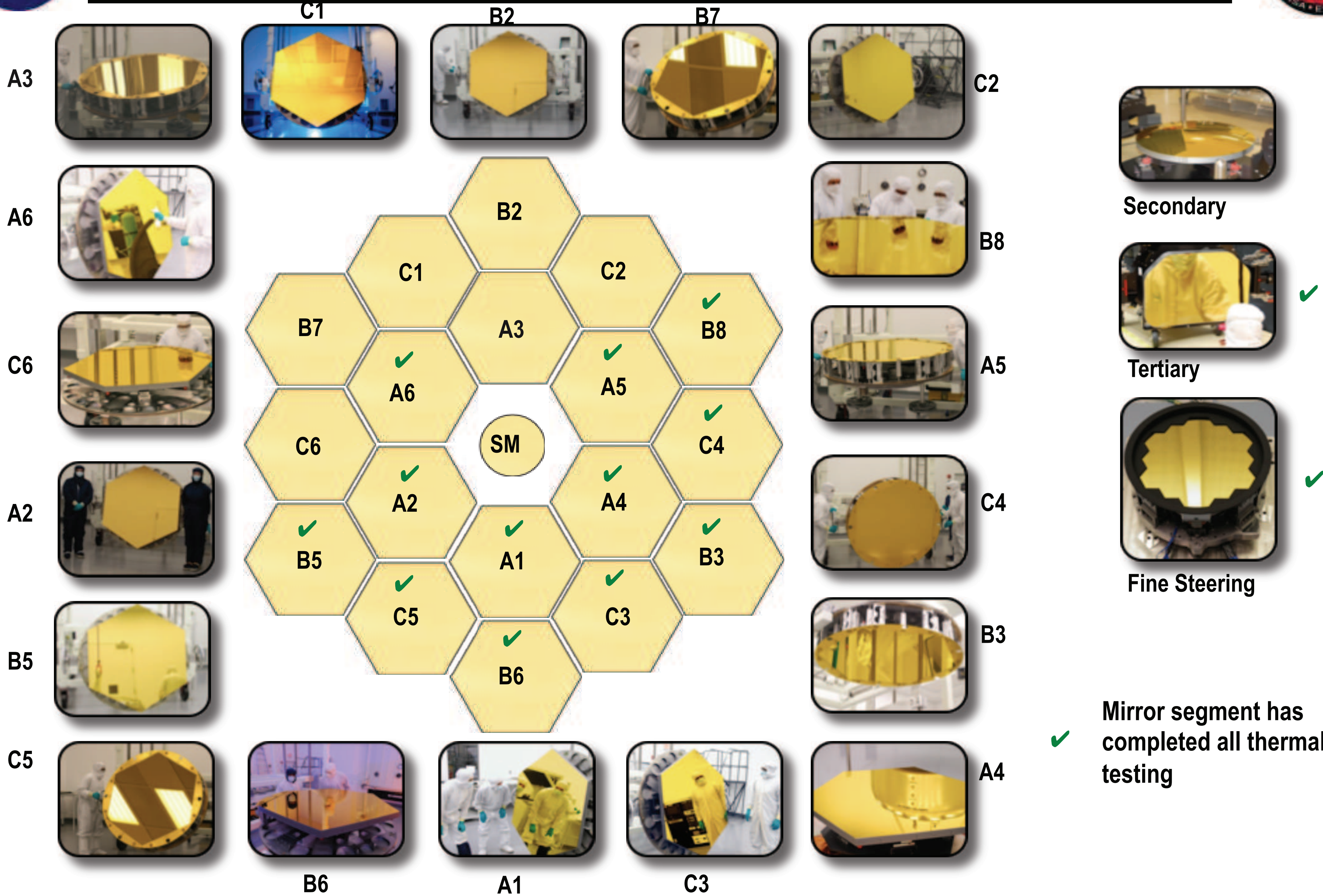


RMS: 23.2 nm

PV: 515.5 nm

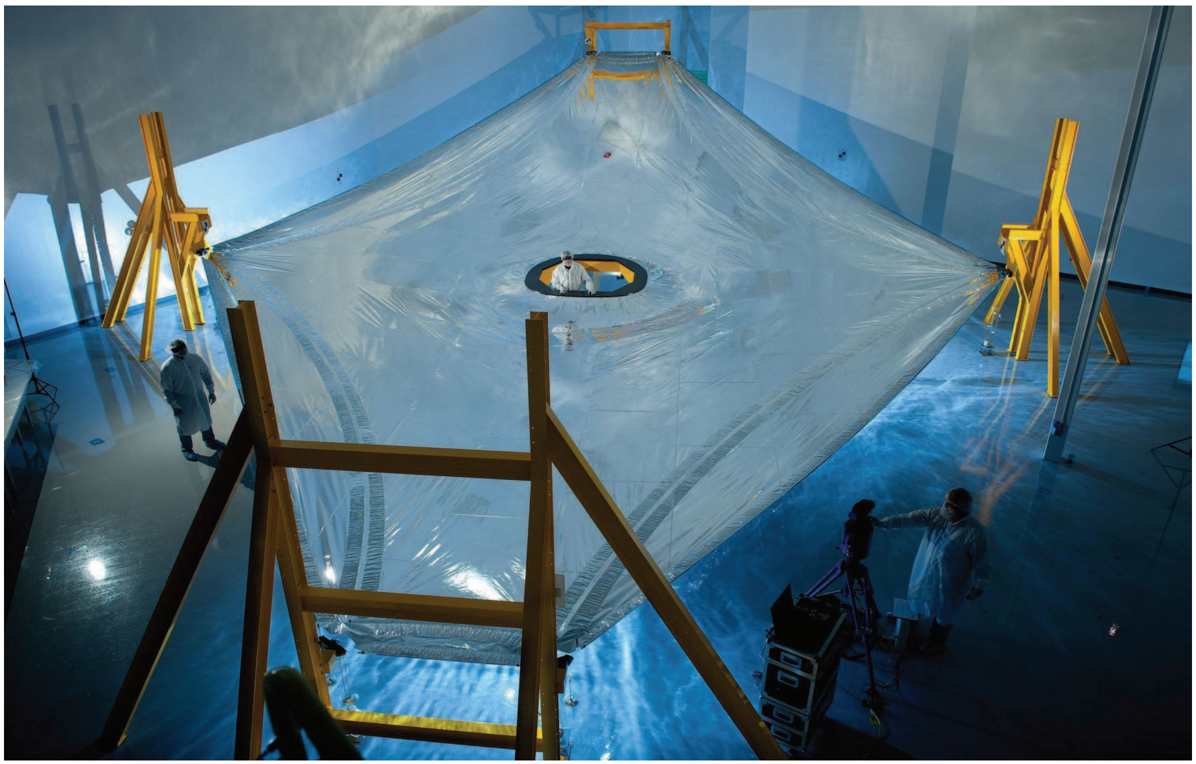


Family Portrait



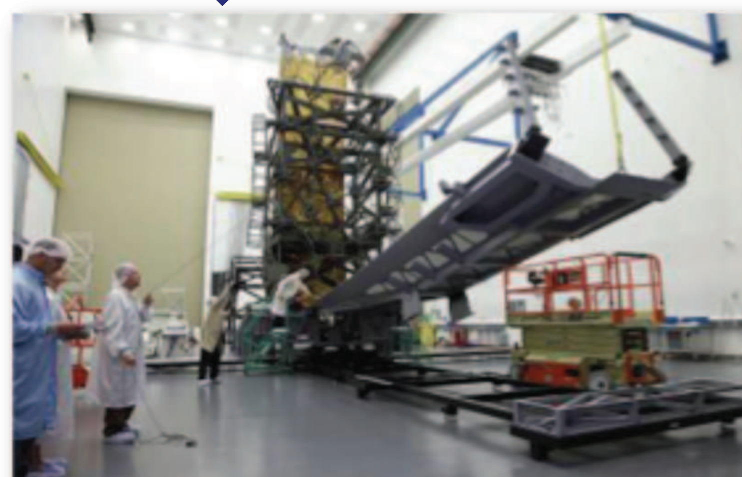
Sunshield

- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape measurements completed



←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette ↓



Telescope Assembly Ground Support Equipment

Ambient Optical Alignment Stand Complete

Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

Landing a mirror onto backplane simulator

(3b) JWST instrument update: US (UofA, JPL), ESA, & CSA.

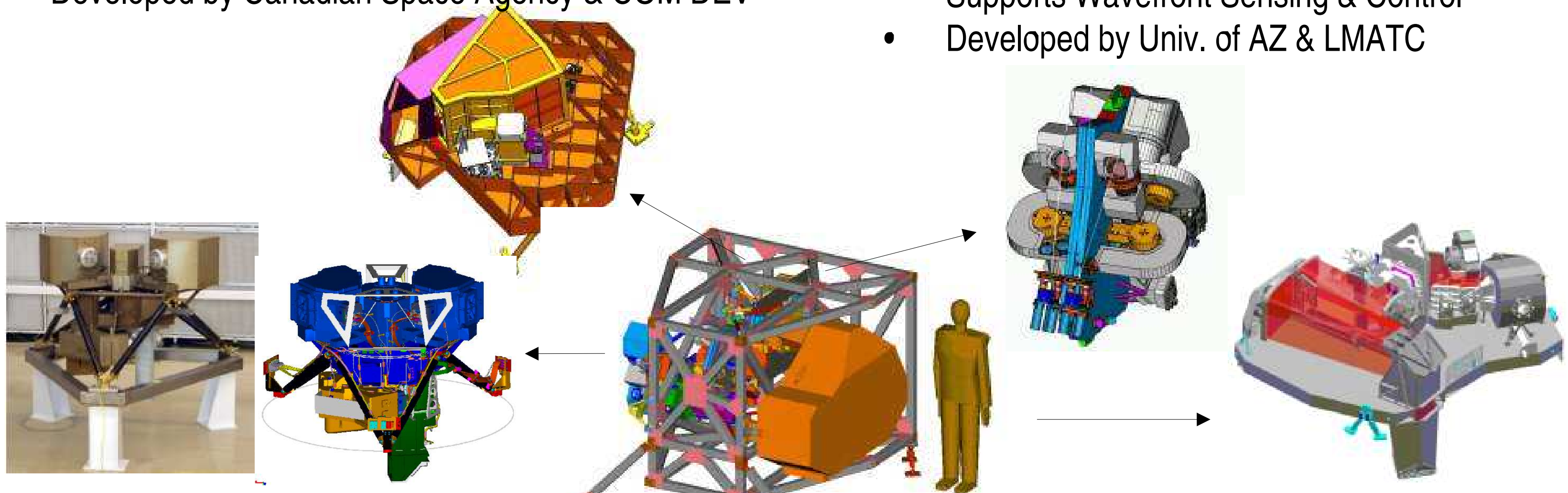
Instrument Overview

Fine Guidance Sensor (FGS)

- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

Near Infra-Red Camera (NIRCam)

- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



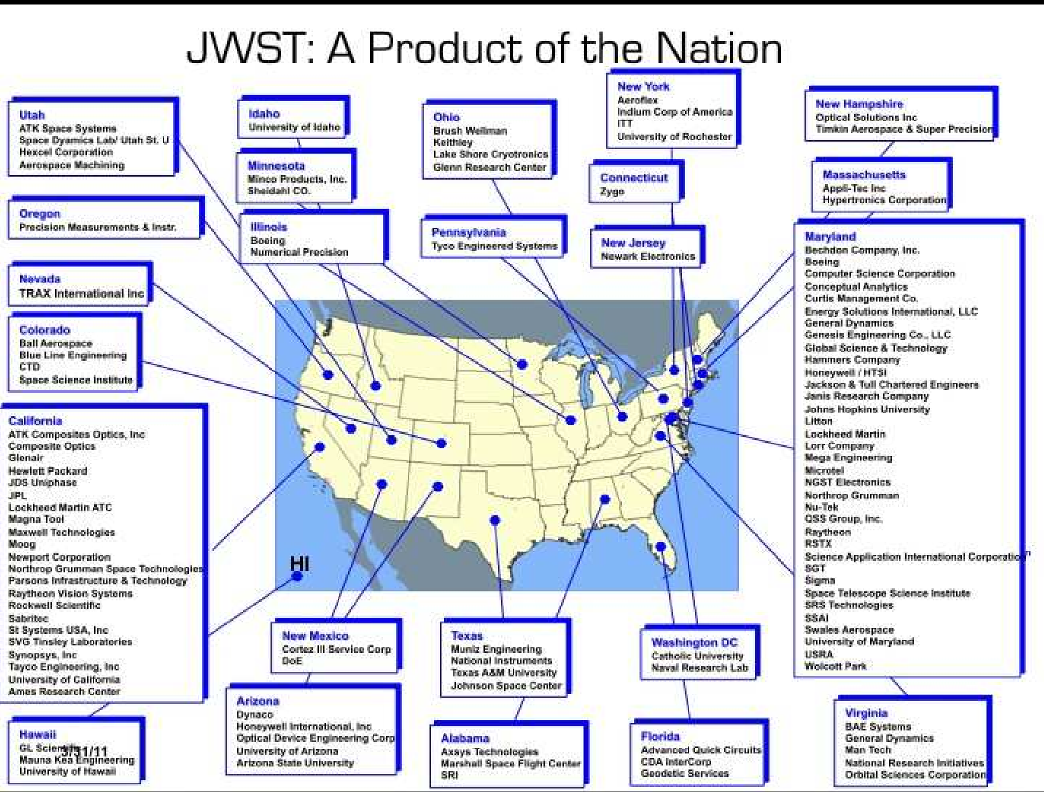
Mid-Infra-Red Instrument (MIRI)

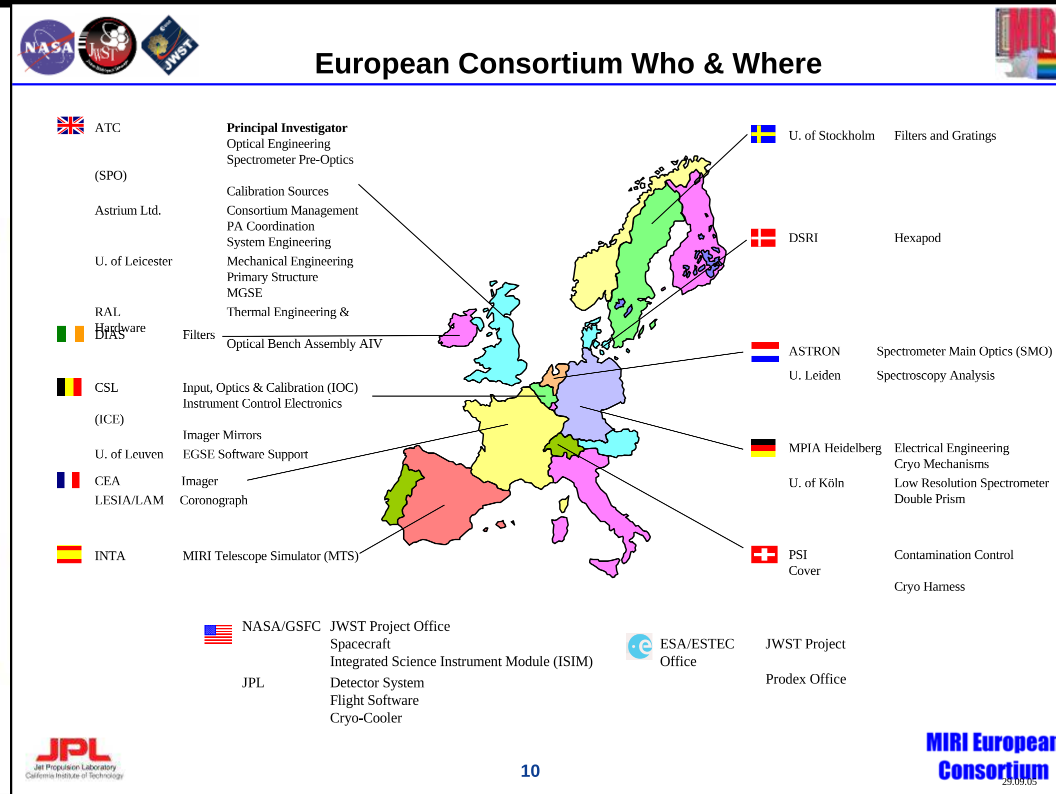
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)

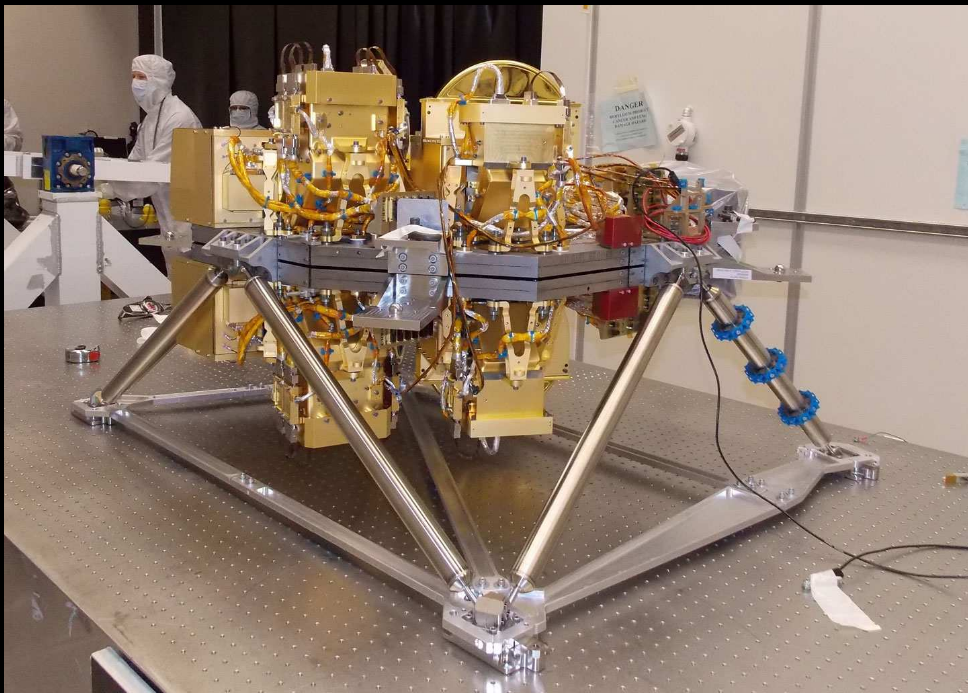
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

MIRI delivery 05/12; FGS 07/12; NIRCam and NIRSpec Fall 2013.



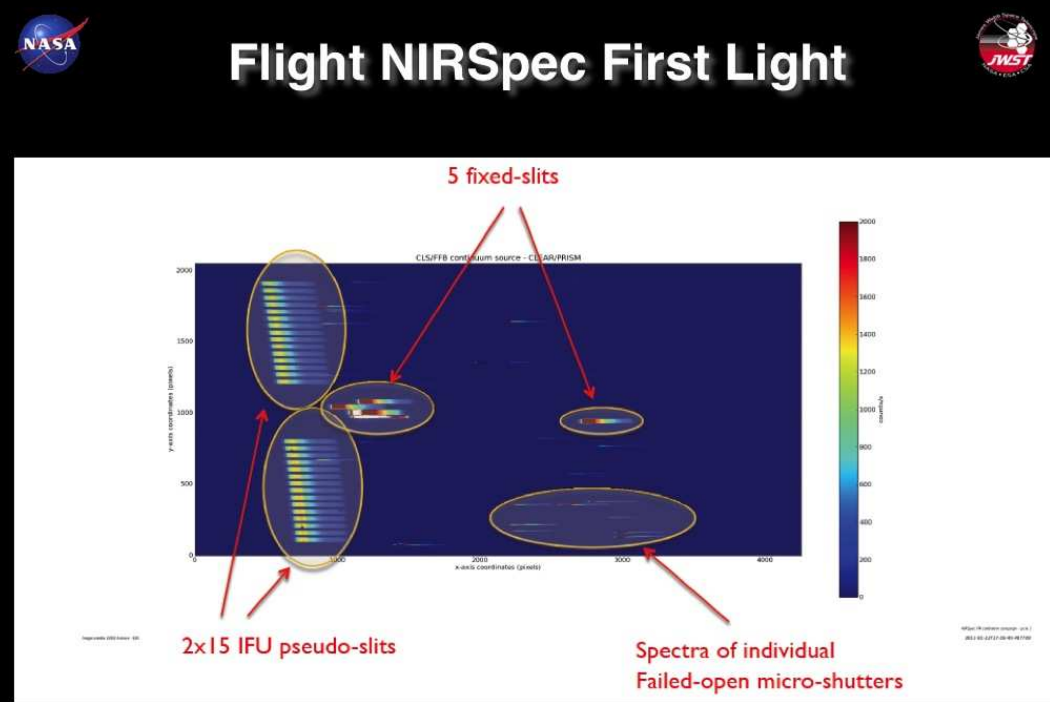


- JWST hardware made in 27 US States: $\gtrsim$75% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.



JWST's short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam scheduled for Fall 2013.

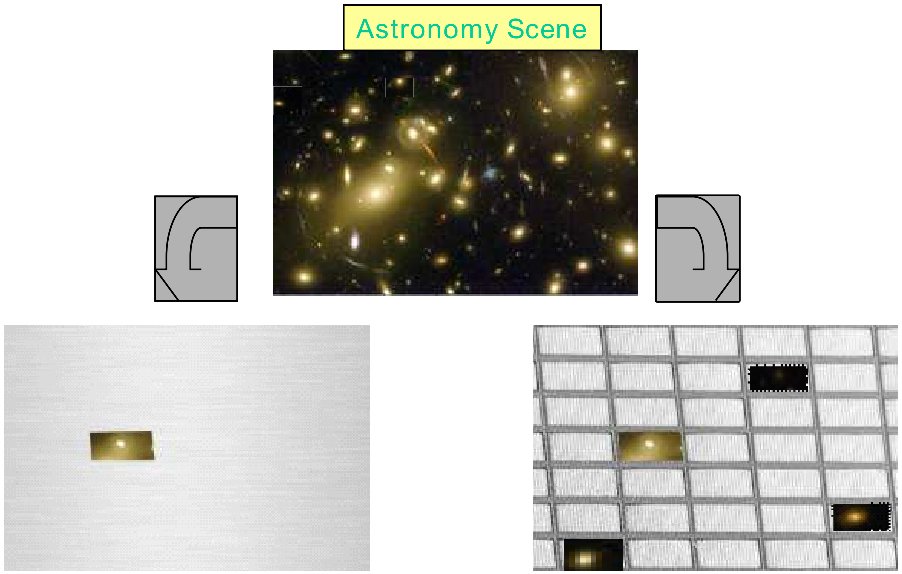


JWST's short-wavelength (0.6–5.0μm) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

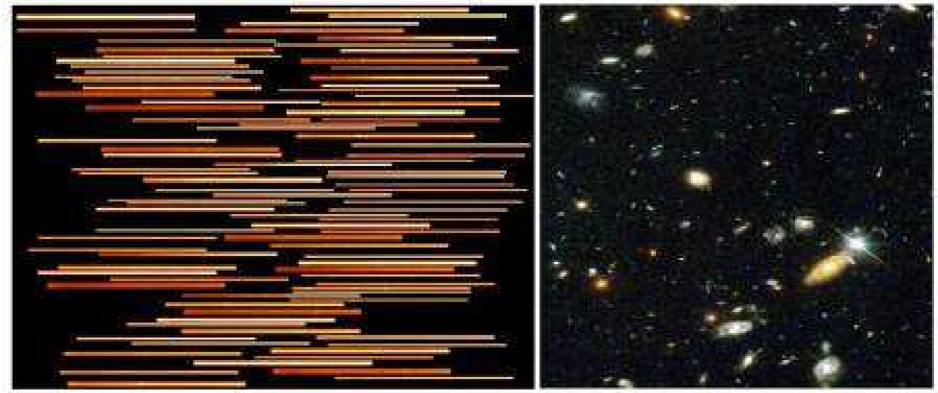
NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

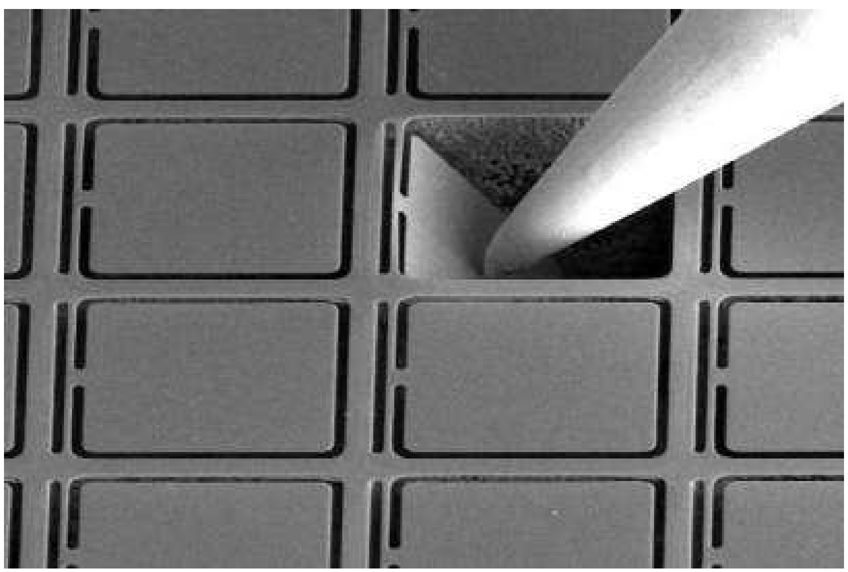
Micro Shutters



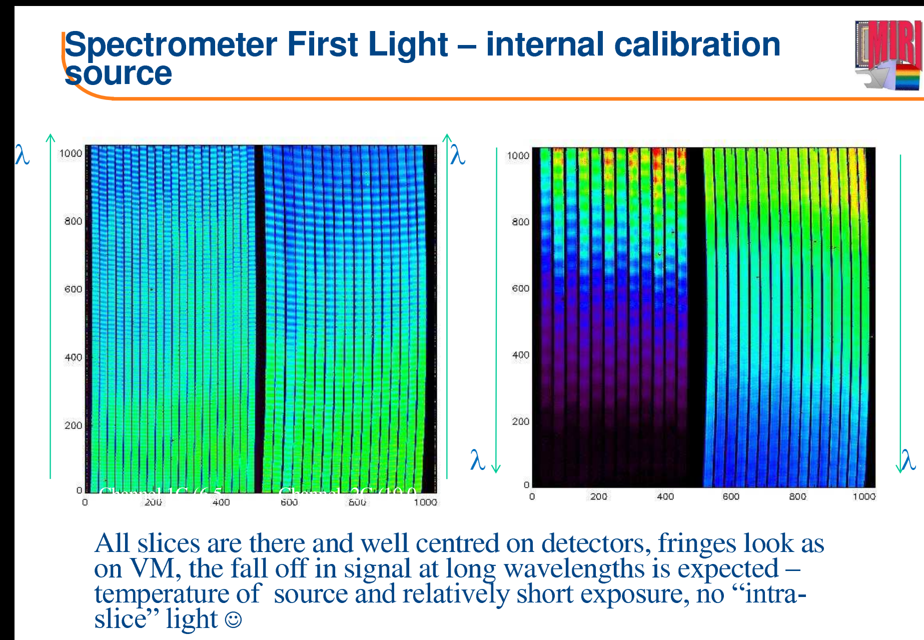
Metal Mask/Fixed Slit

Shutter Mask





Flight MIRI



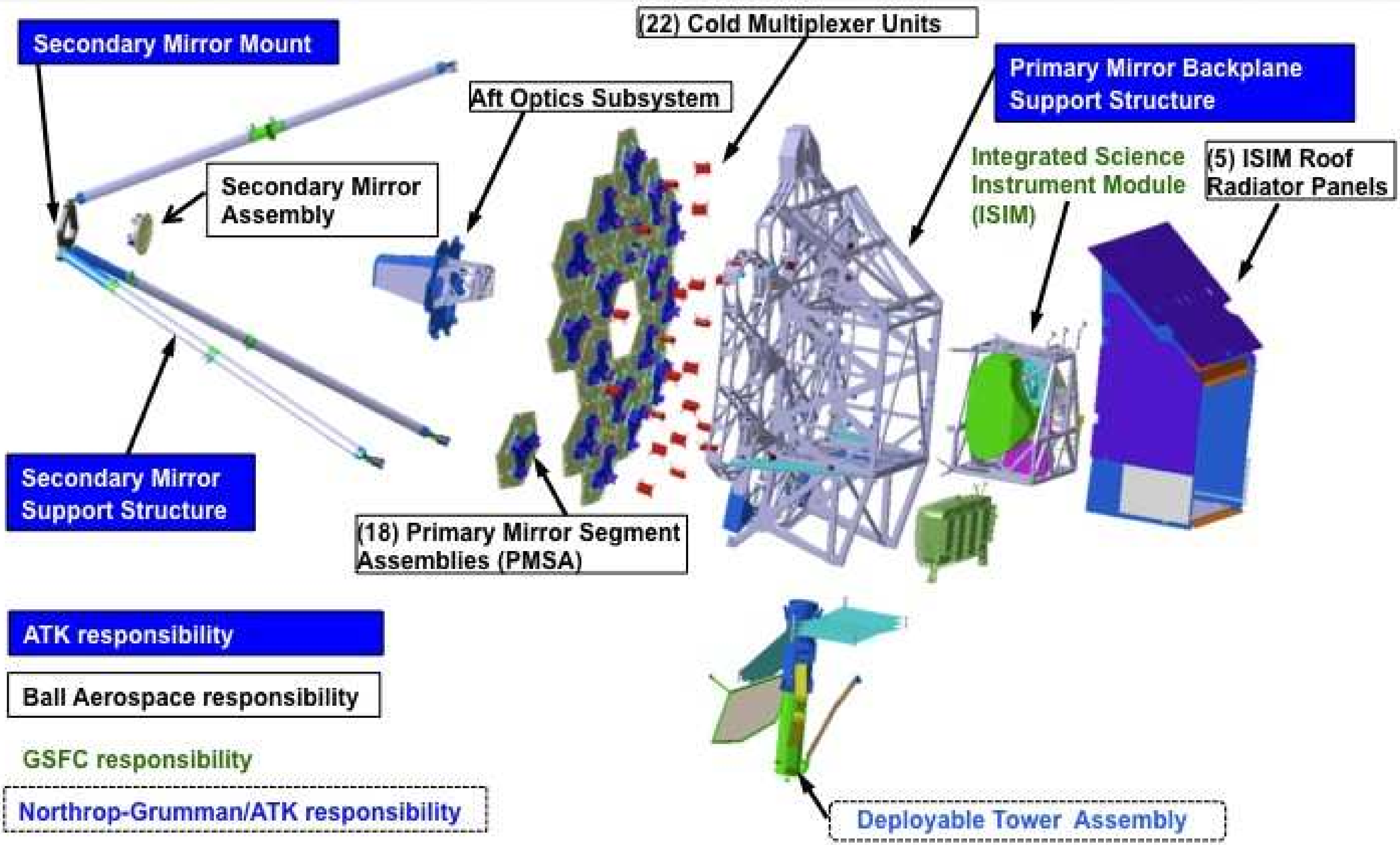
JWST's mid-infrared (5–29μm) camera and spectrograph:

- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012!

OSIM: Here is where JWST Instruments inside ISIM are being tested.

TELESCOPE ARCHITECTURE



ATK responsibility

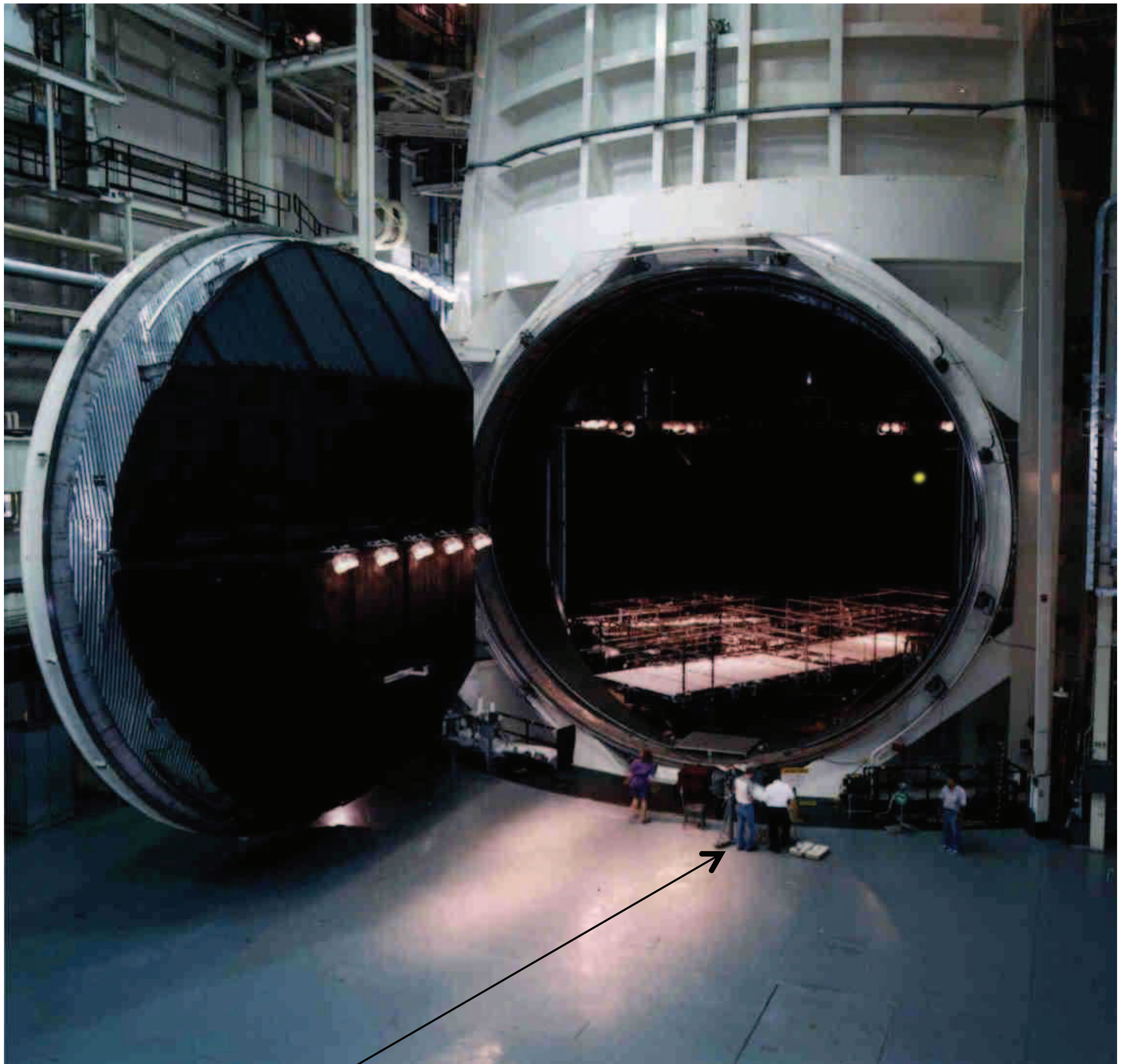
Ball Aerospace responsibility

GSFC responsibility

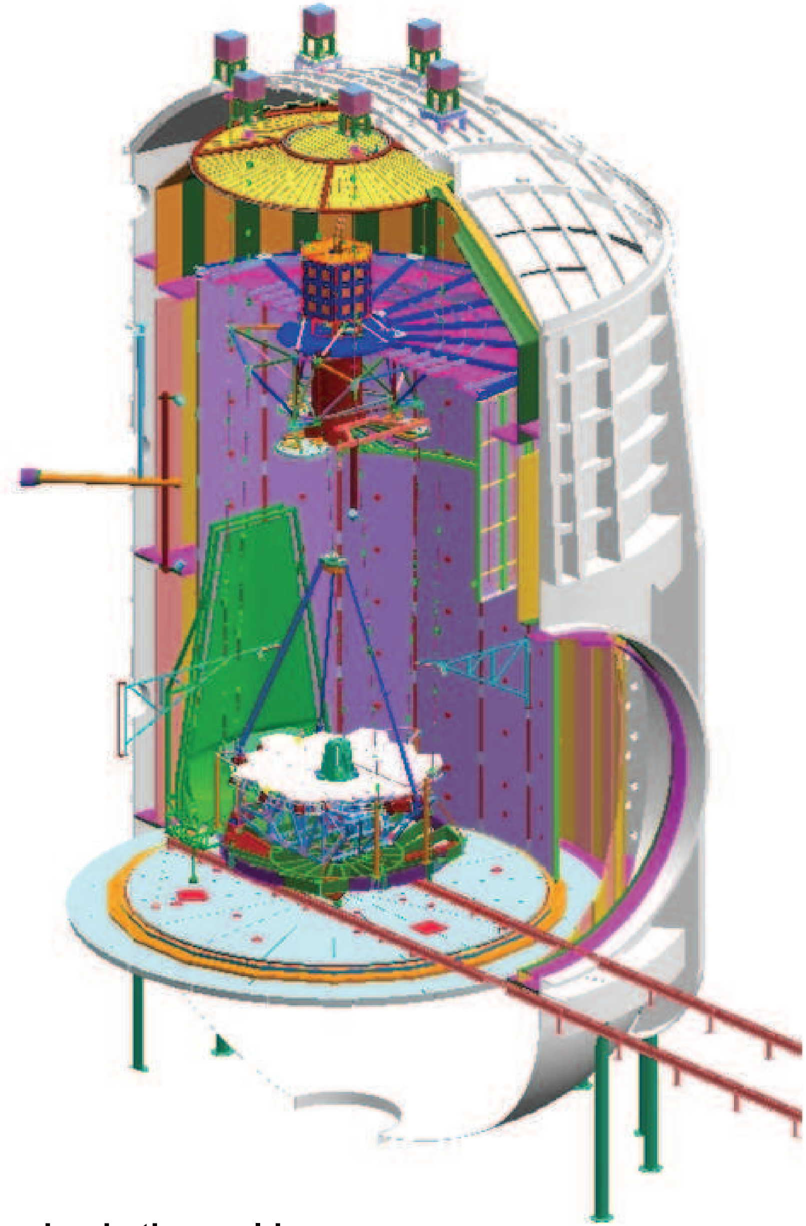
Northrop-Grumman/ATK responsibility

3/31/11

OTE Testing – Chamber A at JSC



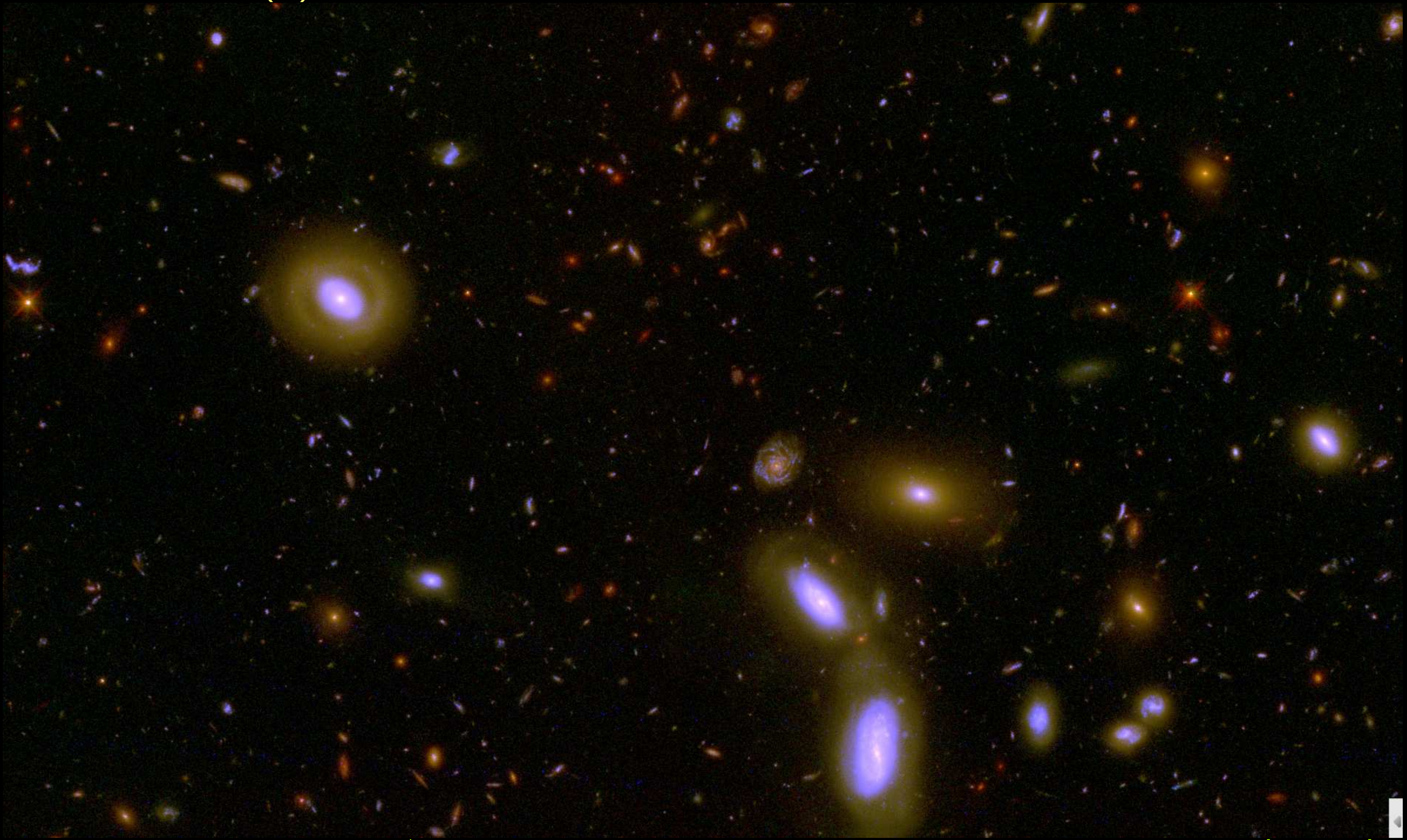
Notice people for scale



Will be the largest cryo vacuum test chamber in the world

OTIS: Largest TV chamber in world: will test whole JWST in 2015–2016.

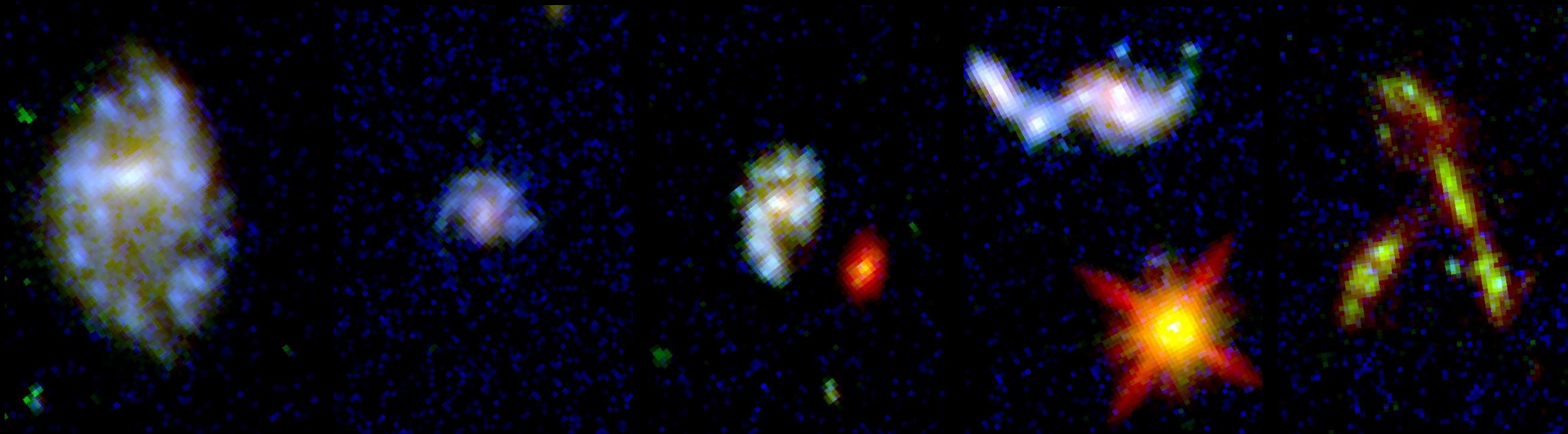
(4) How can JWST measure Galaxy Assembly?



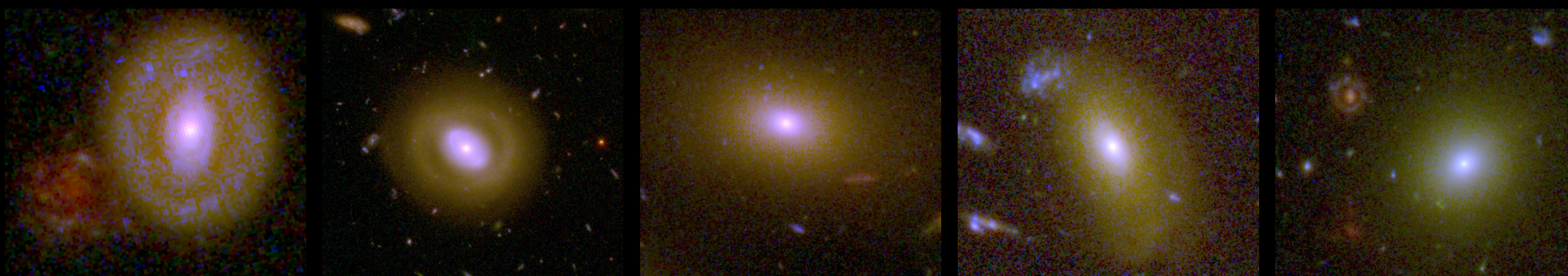
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

(4) Recent results of Hubble WFC3 on Galaxy Assembly & what JWST will do:



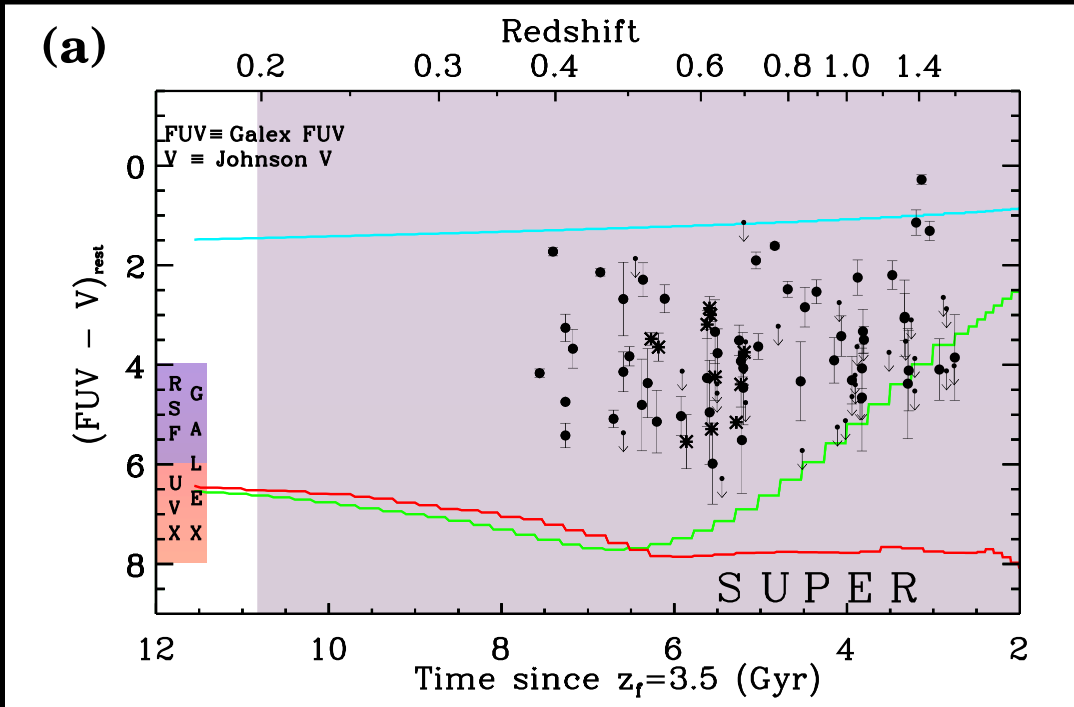
Galaxy structure at the peak of the merging epoch (z$\simeq$1–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$, $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.

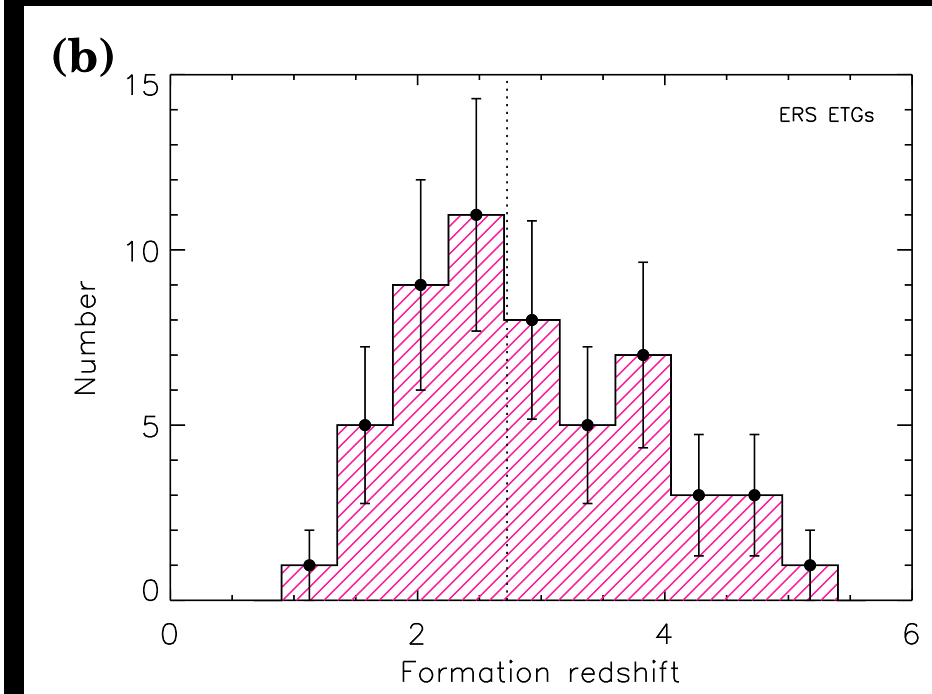


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure. (Rutkowski ea. 2012 ApJS 199, 4) $\Longrightarrow$ "Red & dead" galaxies aren't dead!

- JWST will observe any such objects from 0.7–29 μm wavelength.

Rest-frame UV-evolution of Early Type Galaxies since z$\lesssim$1.5.



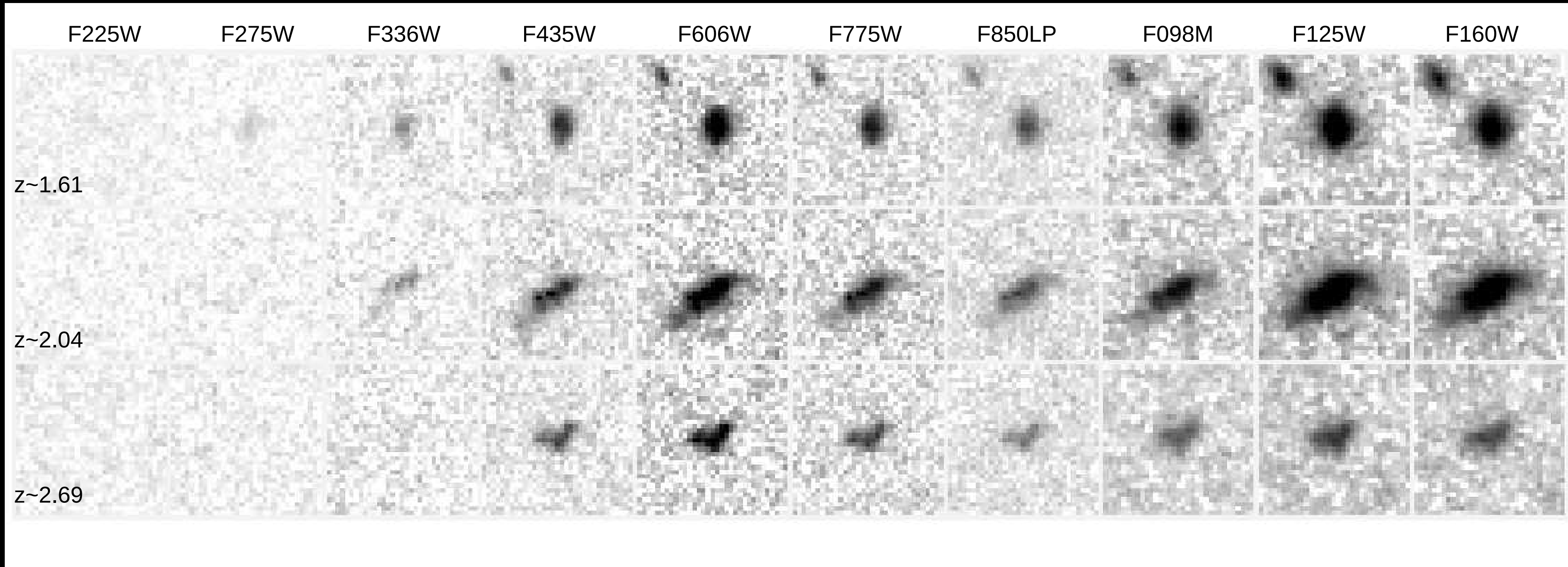


- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at 0.3$\lesssim$z$\lesssim$1.5 (Rutkowski et al. 2012, ApJS, 199, 4).

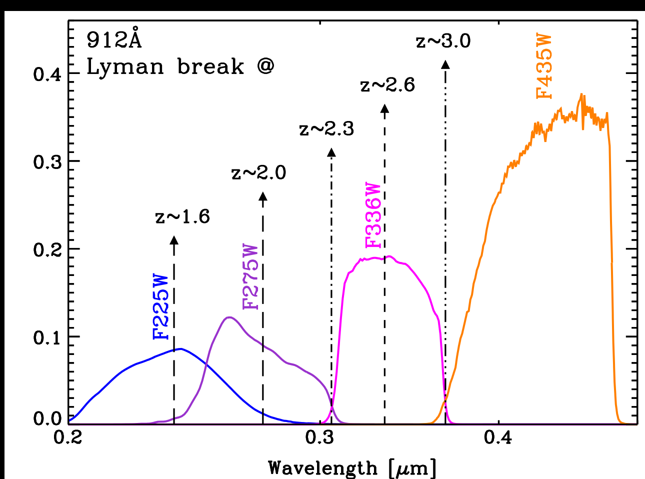
$\Longrightarrow$ Most ETGs have continued residual star-formation after they form.

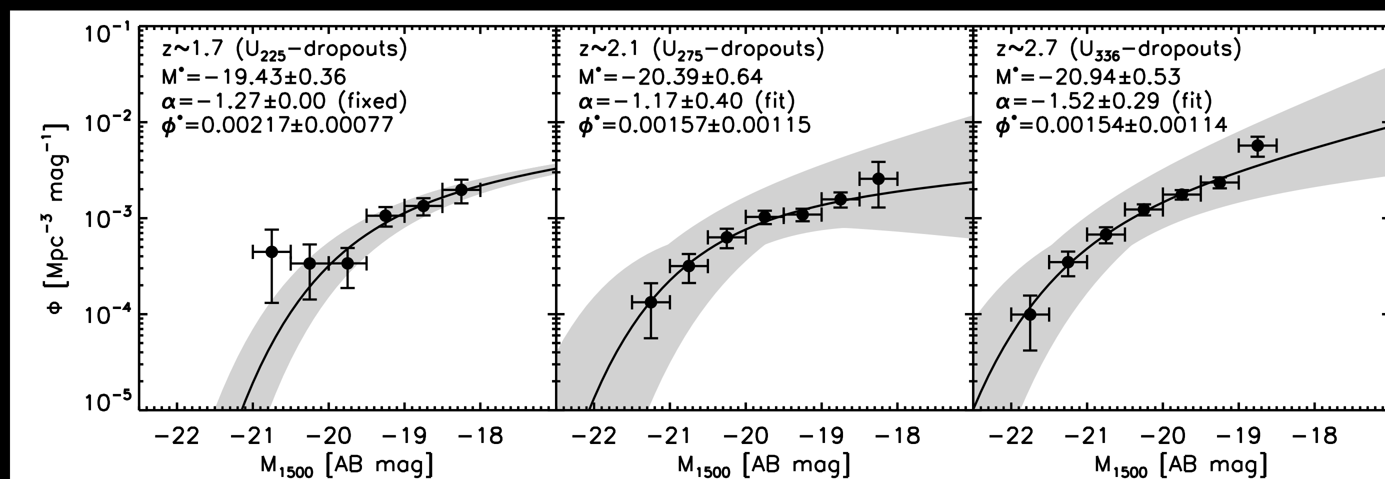
- Can determine their N(z_{form}), which resembles the cosmic SFH diagram (*e.g.*, Madau et al. 1996). This can directly constrain the process of galaxy assembly and down-sizing (Kaviraj, Rutkowski et al. 2012, MNRAS).

- JWST will extend this to all redshifts with Balmer+4000Å-break ages.



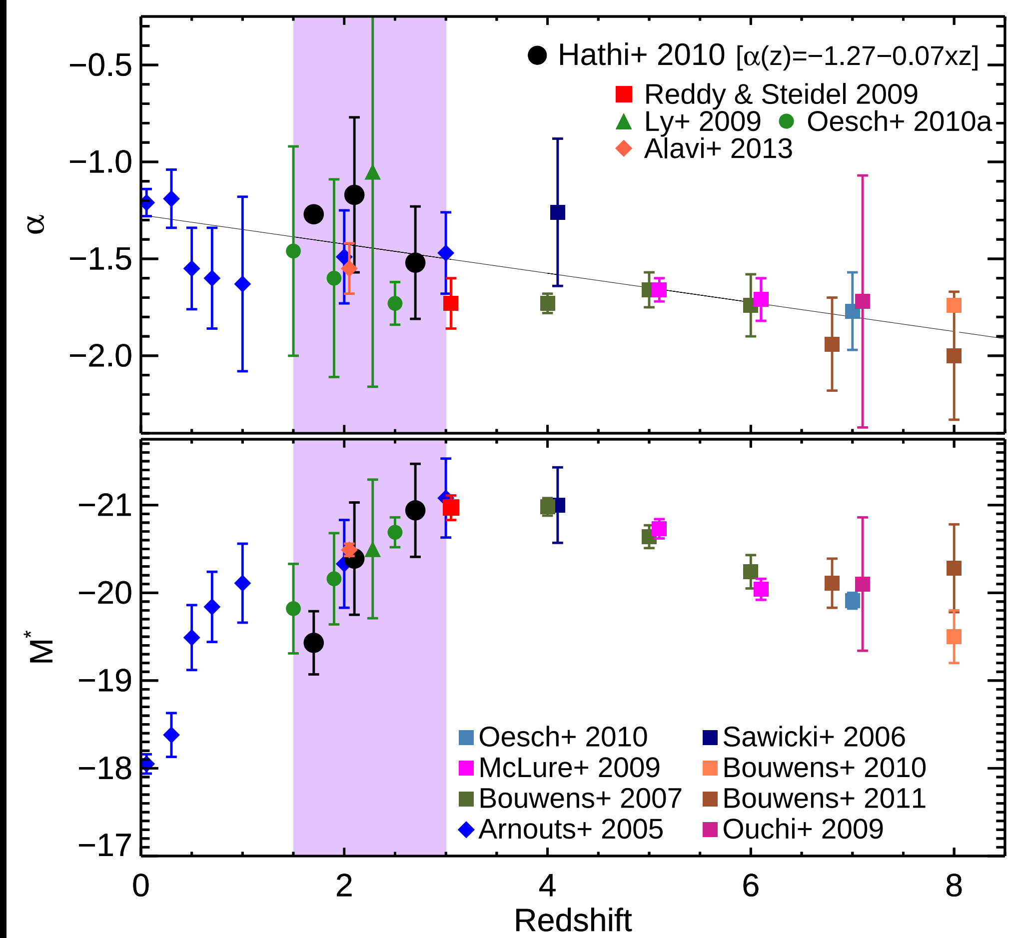
Lyman break galaxies at the peak of cosmic SF ($z \simeq 1$-3; Hathi ea. 2010)

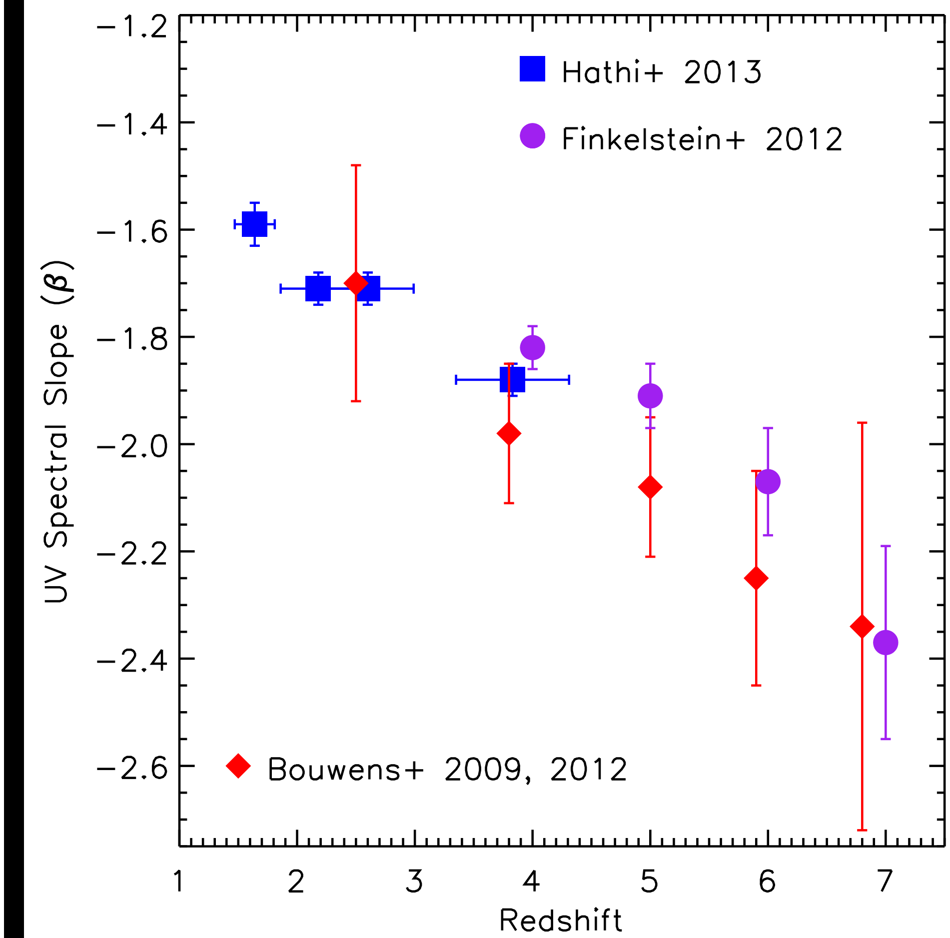




- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.

(e.g., Bouwens et al. 2010; Hathi et al. 2010, 2013; Oesch et al. 2010).





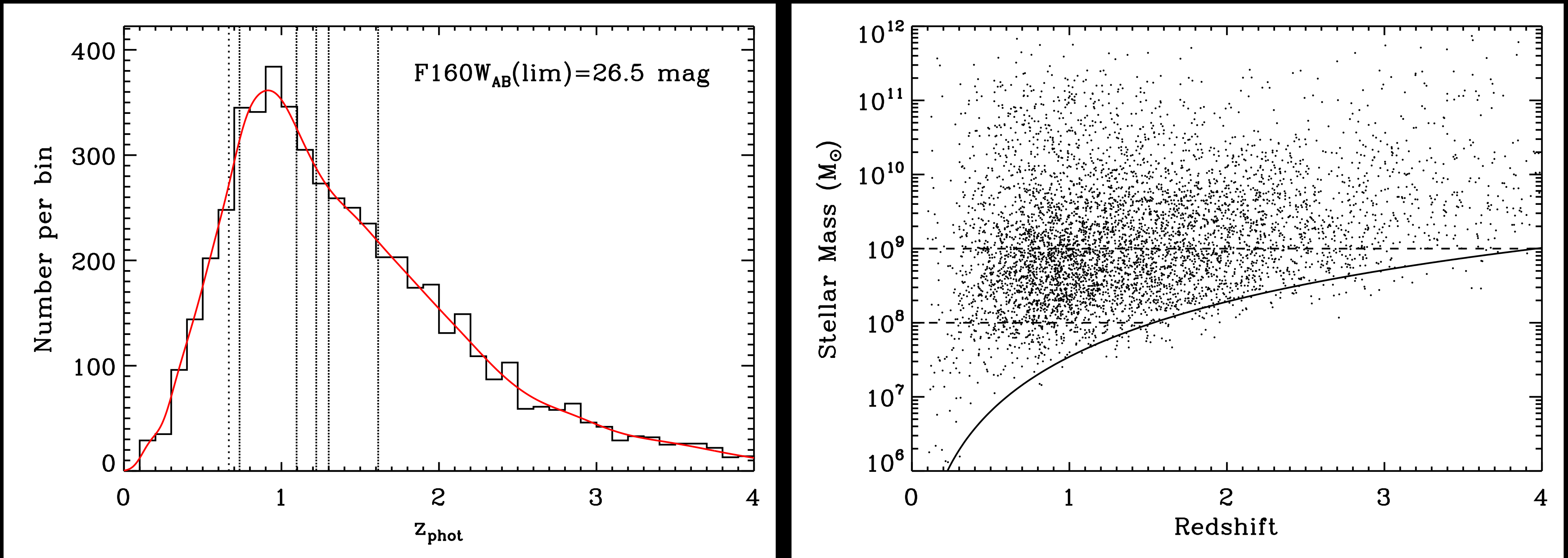
Measured evolution of faint-end LF slope α (top), characteristic luminosity M^* (bottom), and UV SED-slope β (Hathi et al. 2010, 2013).

- In the JWST regime at $z \gtrsim 8$, expect faint-end LF slope $\alpha \simeq 2.0$.
- In the JWST regime at $z \gtrsim 8$, expect UV SED-slope $\beta \lesssim -2.5$.

$\Rightarrow$ Significant consequences for cosmic reionization at $z \gtrsim 6$ by dwarf galaxies.

- In the JWST regime at $z \gtrsim 8$, expect characteristic luminosity $M^* \gtrsim -19$.

$\Rightarrow$ Could have critical consequences for gravitational lensing bias at $z \gtrsim 10$.



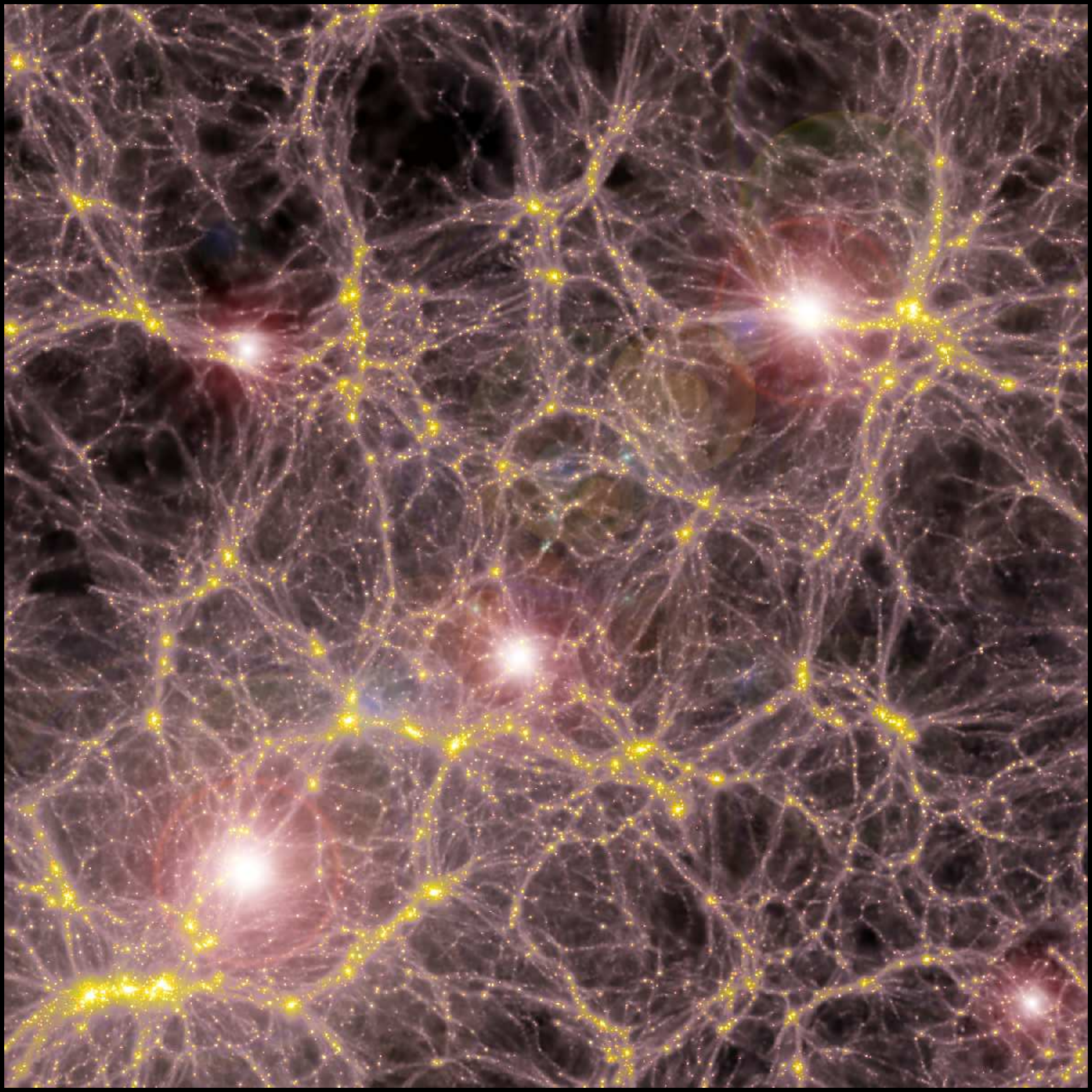
WFC3 ERS 10-band redshift estimates accurate to $\lesssim$4% with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable N(z).

- Measure masses of faint galaxies to AB=26.5 mag, tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

ERS shows WFC3's new panchromatic capabilities on galaxies at z$\simeq$0–7.

- HUDF shows WFC3 z$\simeq$7–9 capabilities (Bouwens$^+$ 2010; Yan$^+$ 2010).
- WFC3 is an essential pathfinder at z$\lesssim$8 for JWST (0.7–29 μm) at z$\gtrsim$9.
- JWST will trace mass assembly and dust content 3–4 mags deeper from z$\simeq$1–12, with nanoJy sensitivity from 0.7–5μm.

(4a) How will JWST Observe First Light and Reionization?



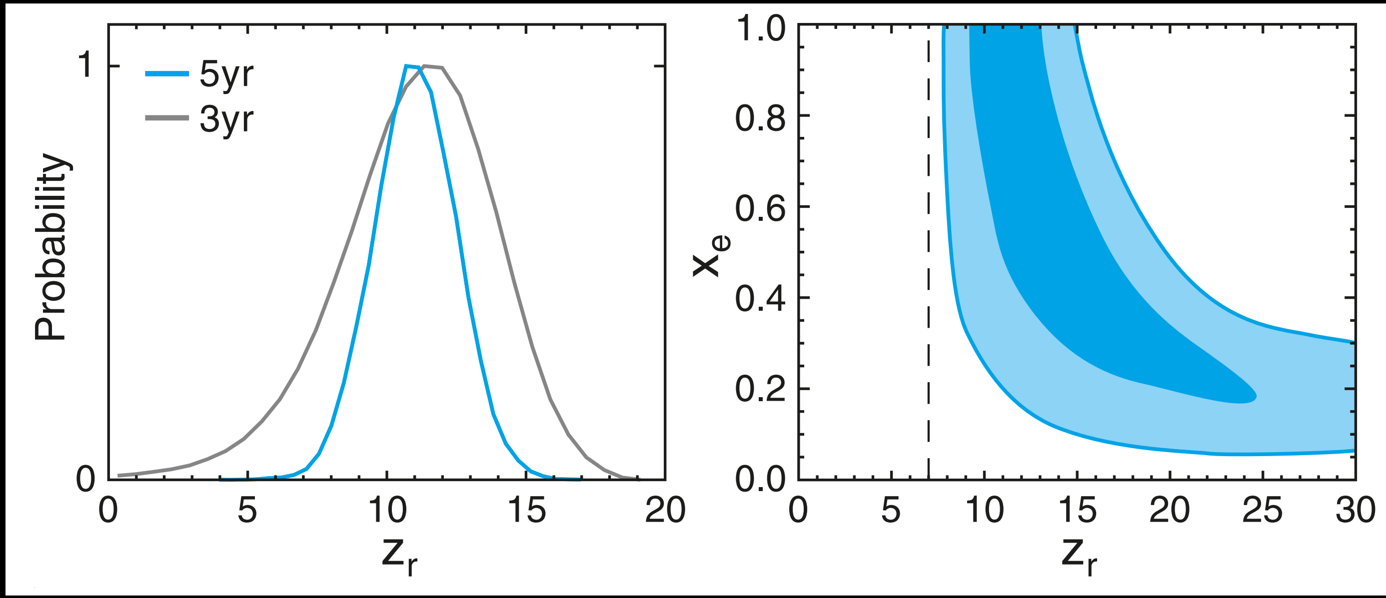
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10$–30 (First Light).

- A this should be visible to JWST as the first Pop III stars and surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.

We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc.

Implications of the WMAP year-9 & Planck results for JWST science:

HST/WFC3 $z \lesssim 7$–9 $\longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25



The year-7 WMAP data provided much better foreground removal (Dunkley$^+$ 2009; Komatsu$^+$ 2011; Hinshaw$^+$ 2012; Planck Collab. 2013):

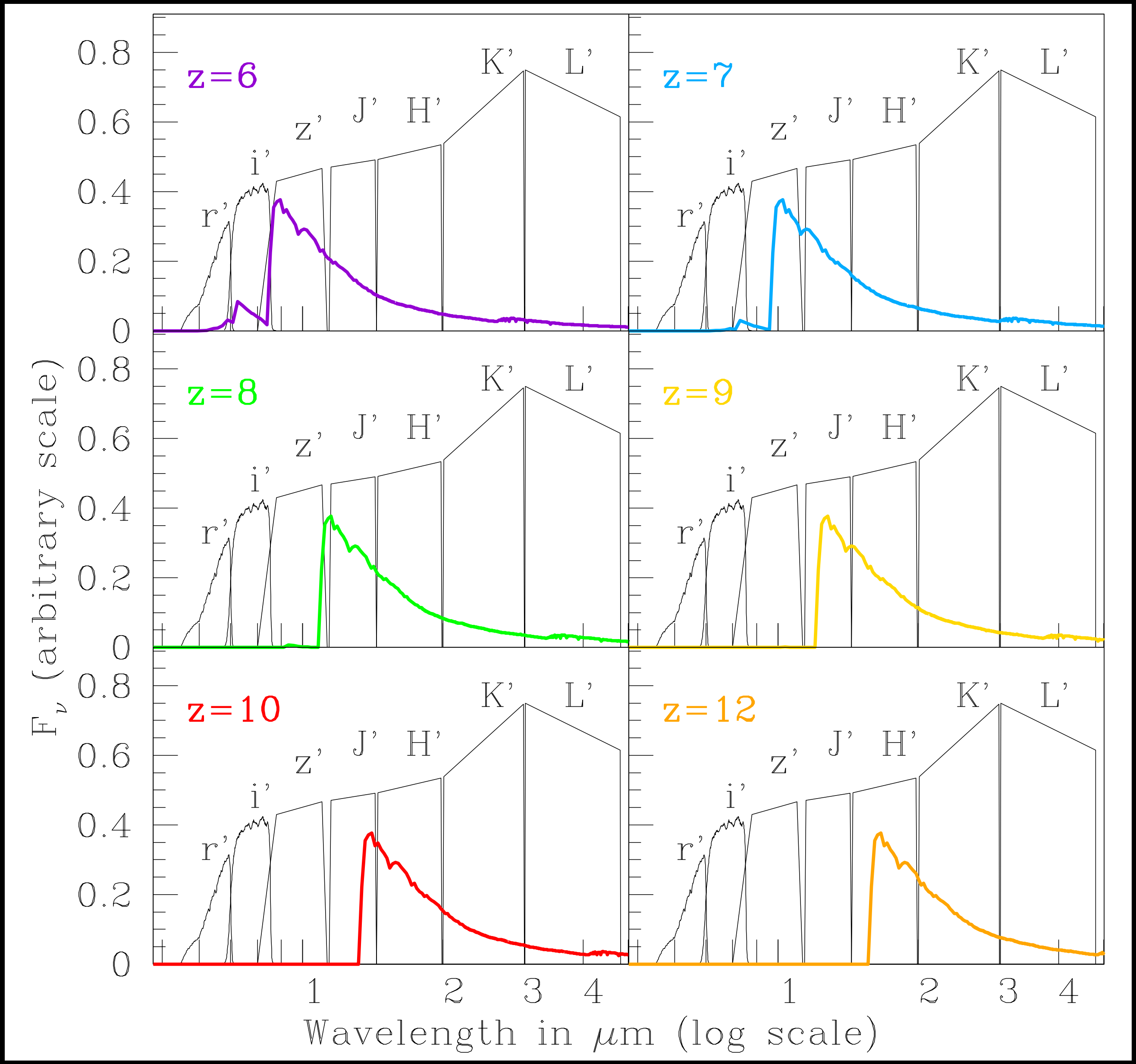
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at $z \simeq 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, more likely:
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. The implications for HST and JWST are:

- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15$–20.

$\Rightarrow$ JWST must cover λ=0.7–29 μm, with its diffraction limit at 2.0 μm.

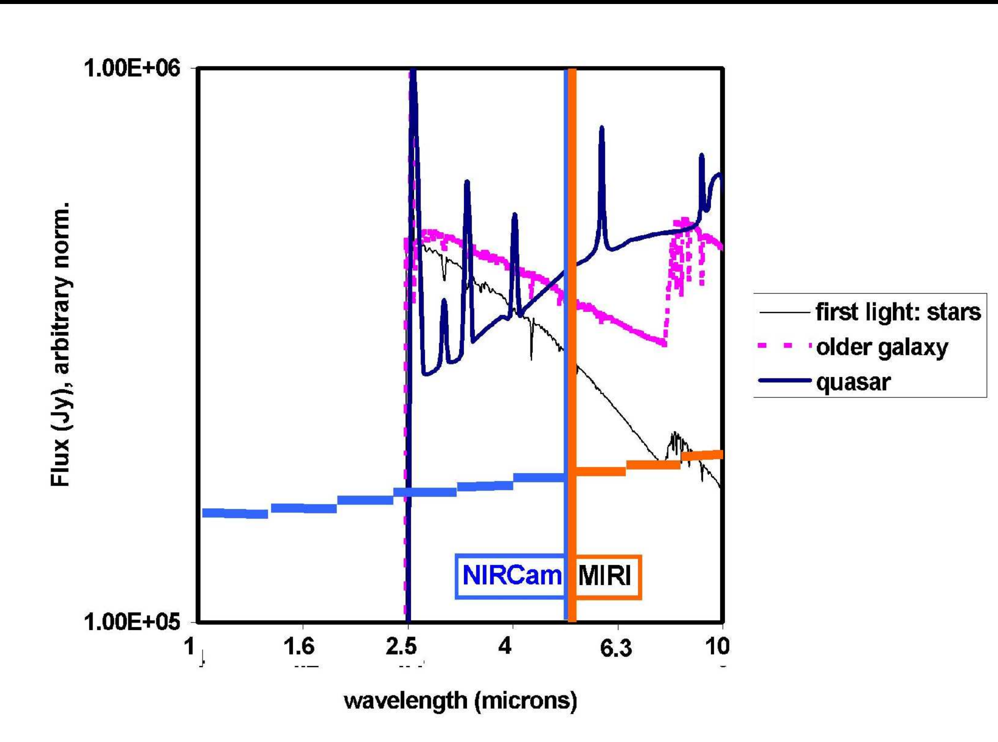
(4) How will JWST measure First Light & Reionization?

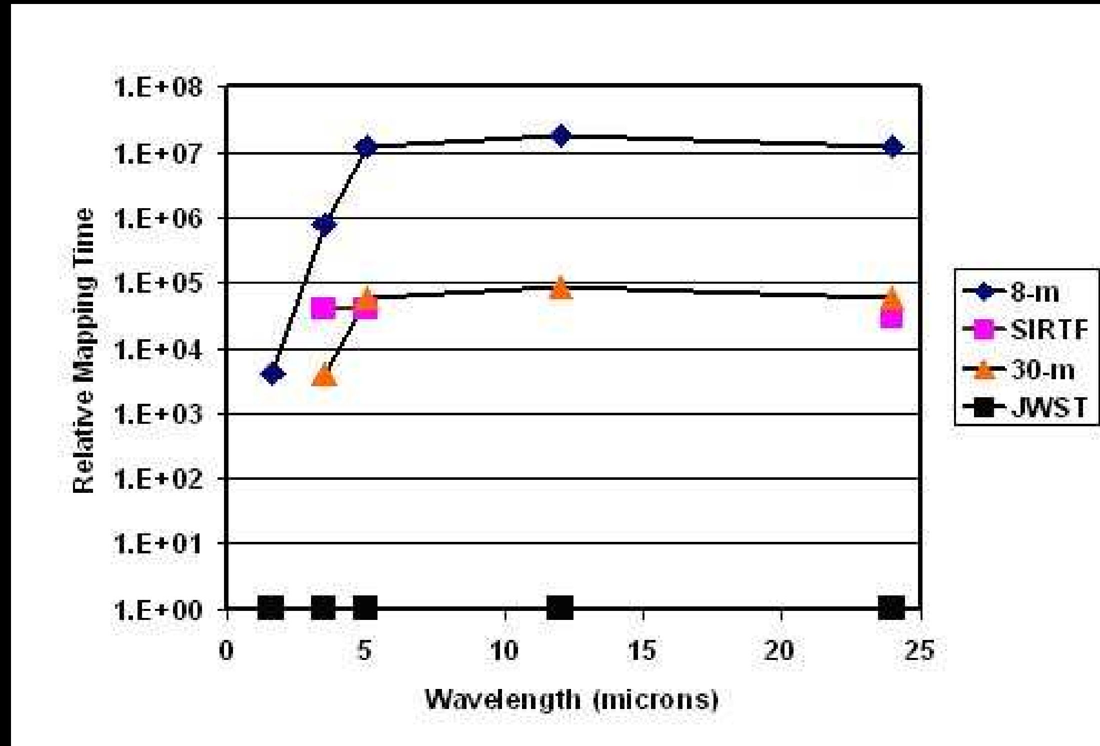


- Can't beat redshift: to see First Light, must observe near–mid IR.

$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

• (4) What sensitivity will JWST have?



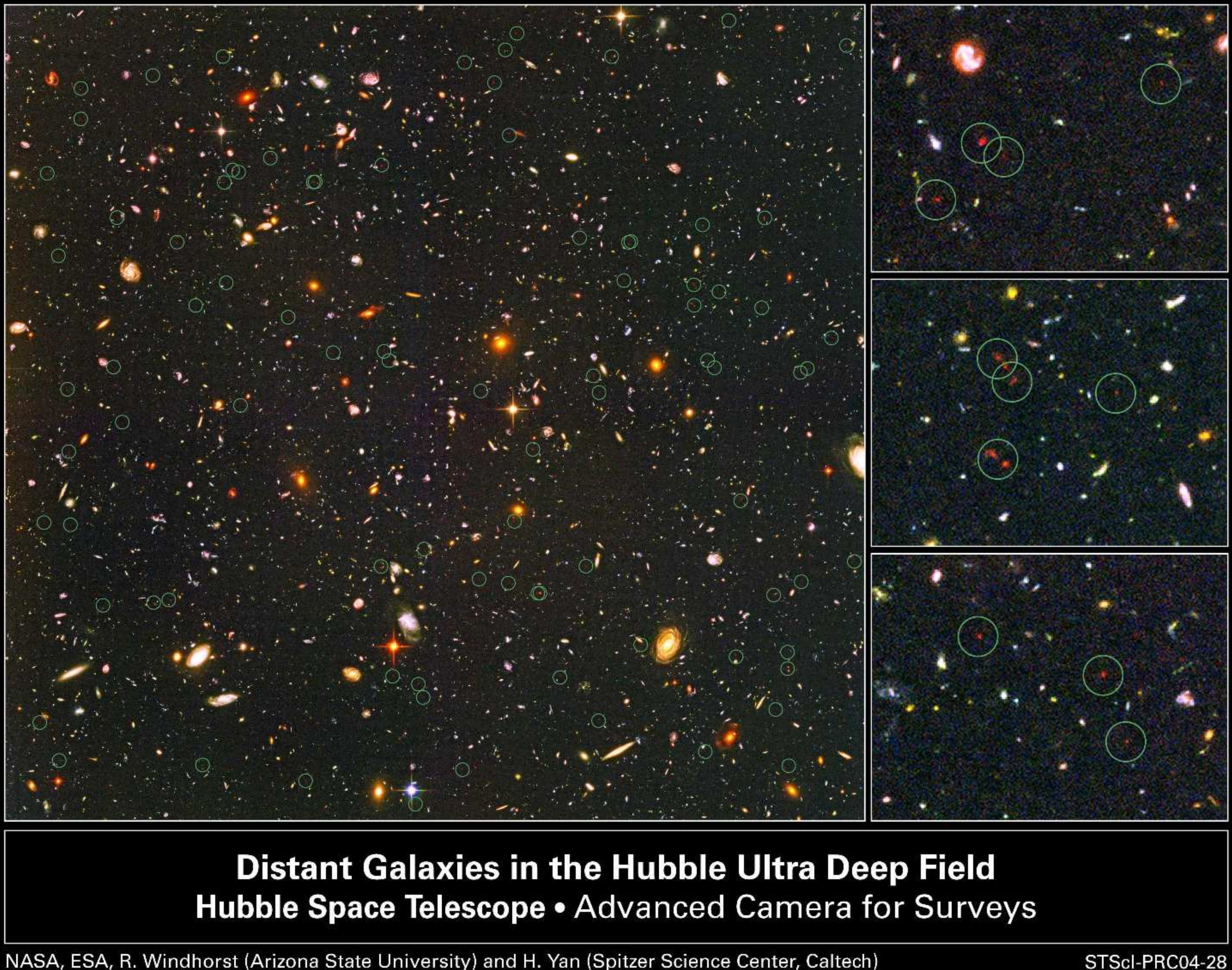


NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m.

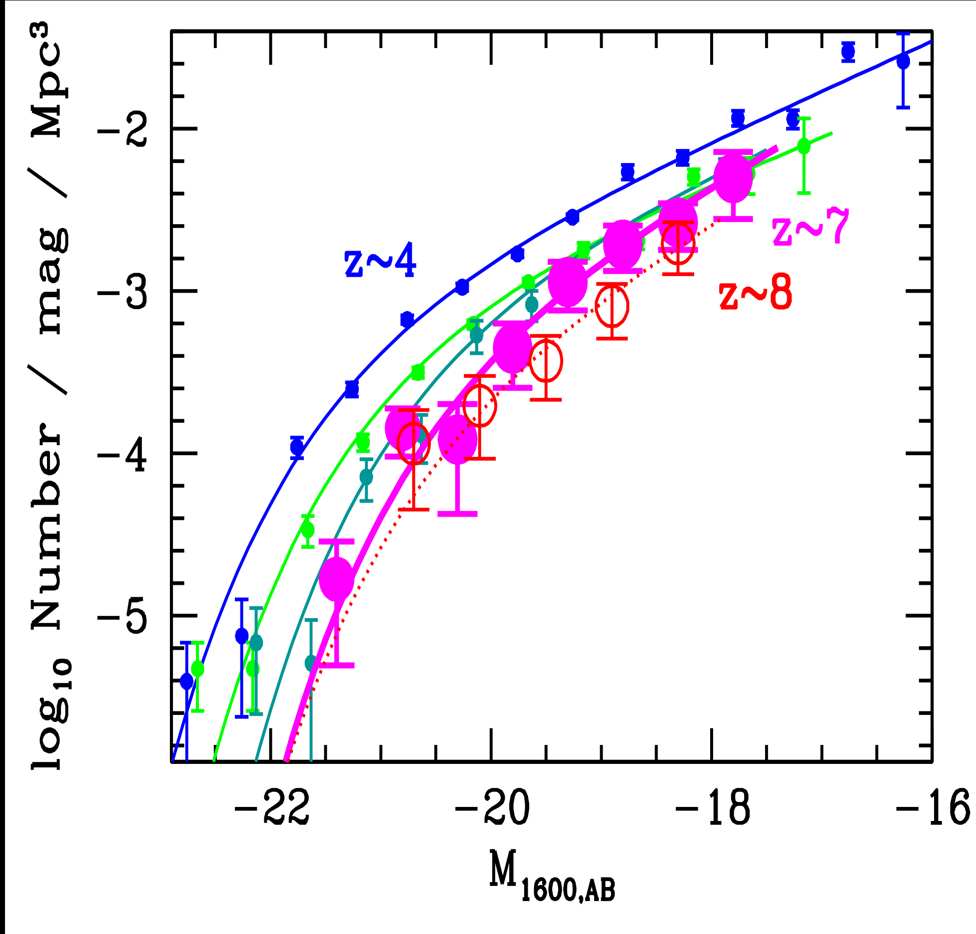
Together, they allow objects to be found to z=15–20 in $\sim 10^5$ sec (28 hrs).

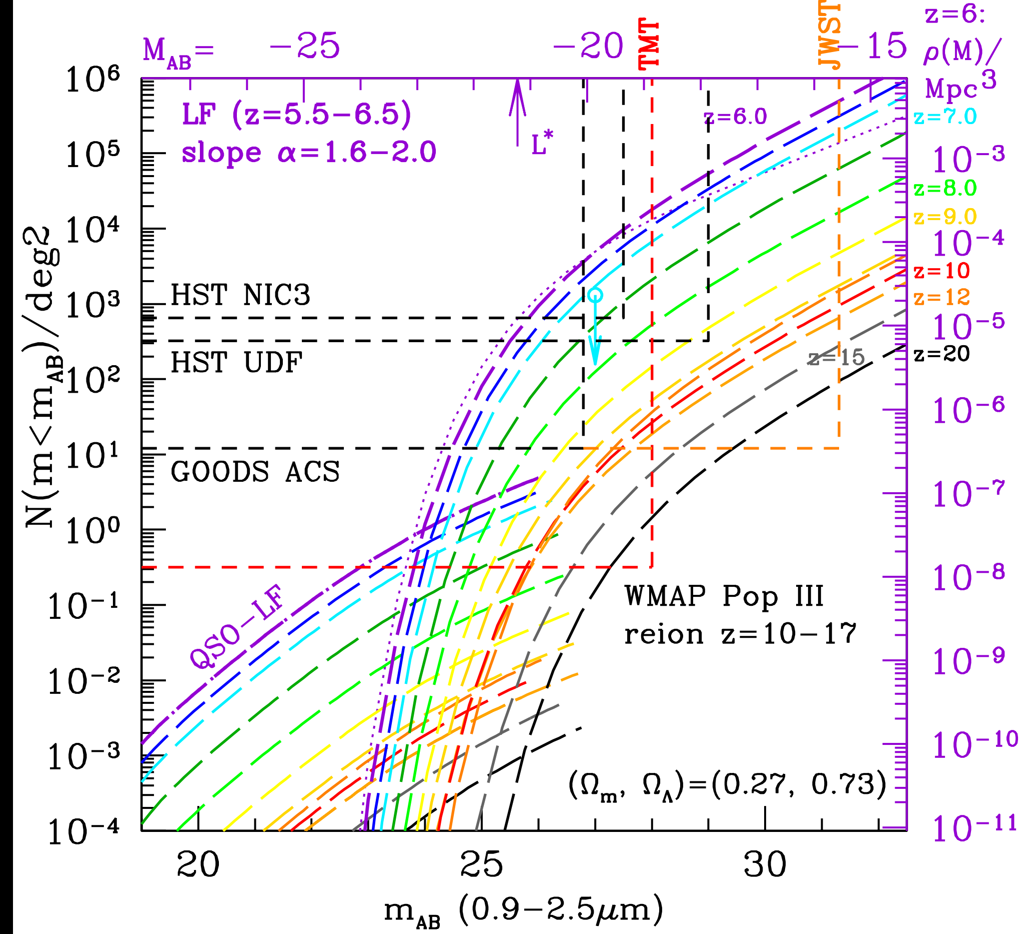
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.



Hubble UltraDeep Field: Dwarf galaxies at z≃6 (age≃1 Gyr; Yan & Windhorst 2004), many confirmed by spectra at z≃6 (Malhotra et al. 2005).

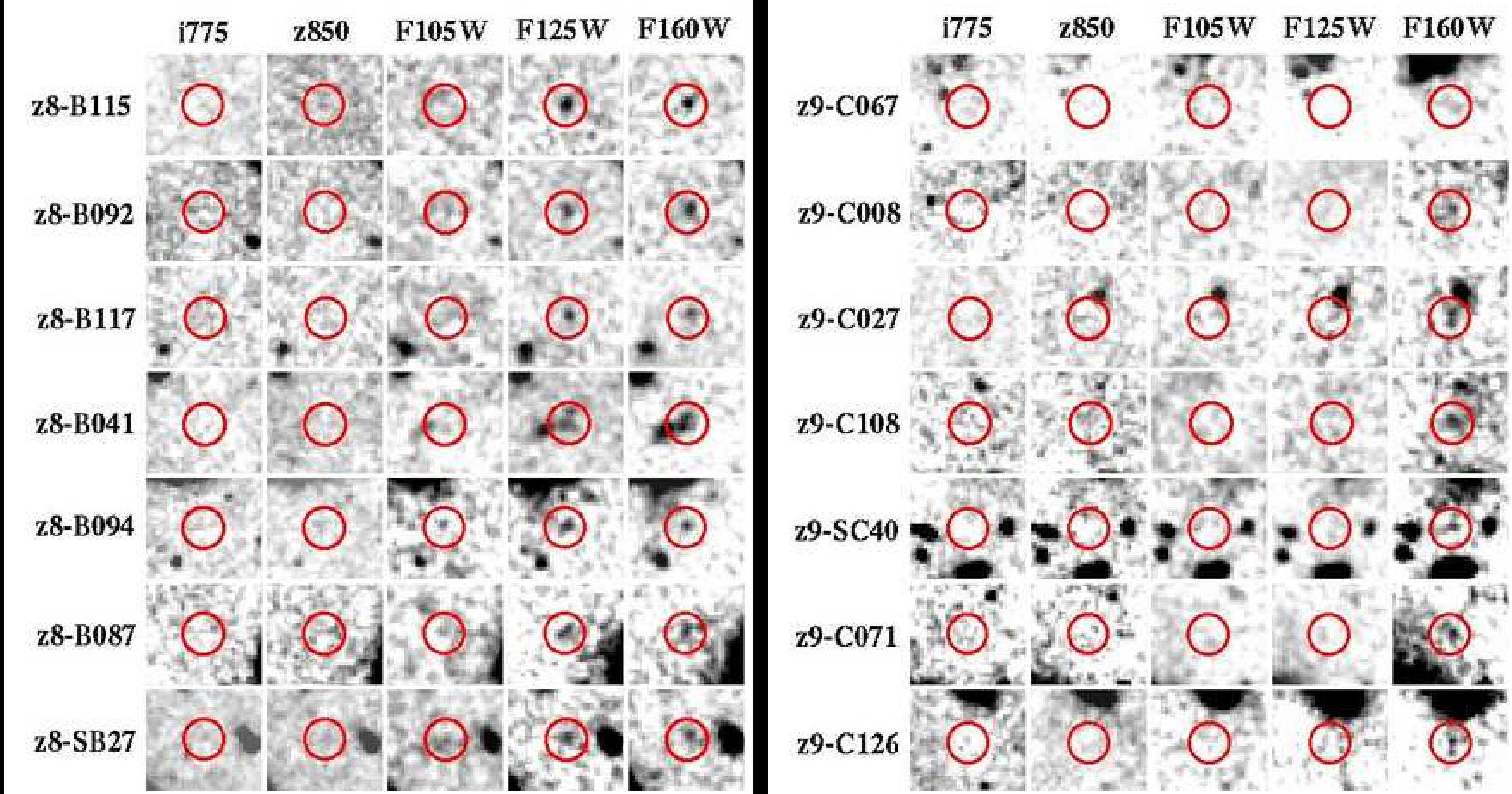




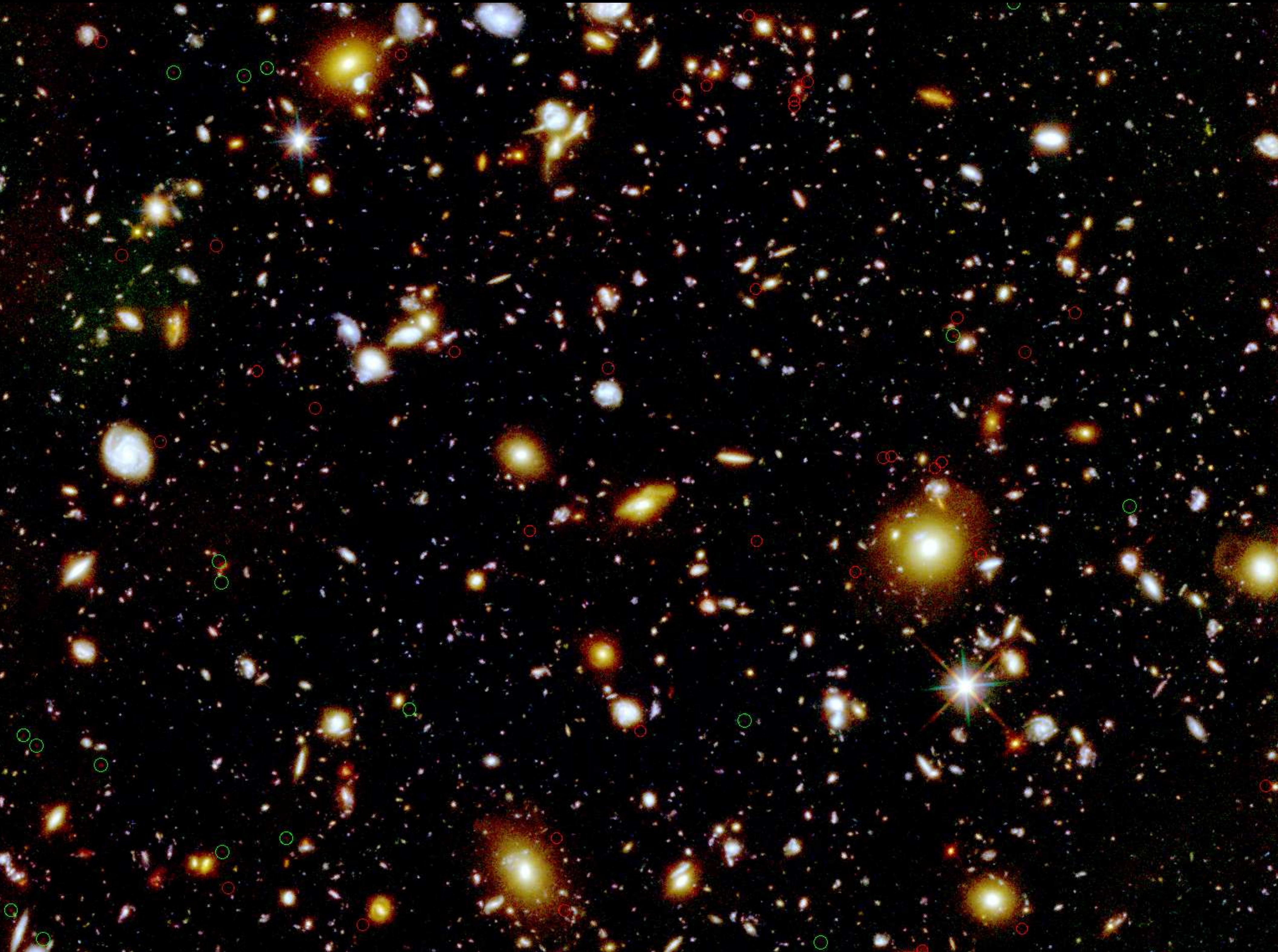
• Objects at z$\gtrsim$9 are rare (Bouwens$^+$ 10; Trenti,$^+$ 10; Yan$^+$ 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).

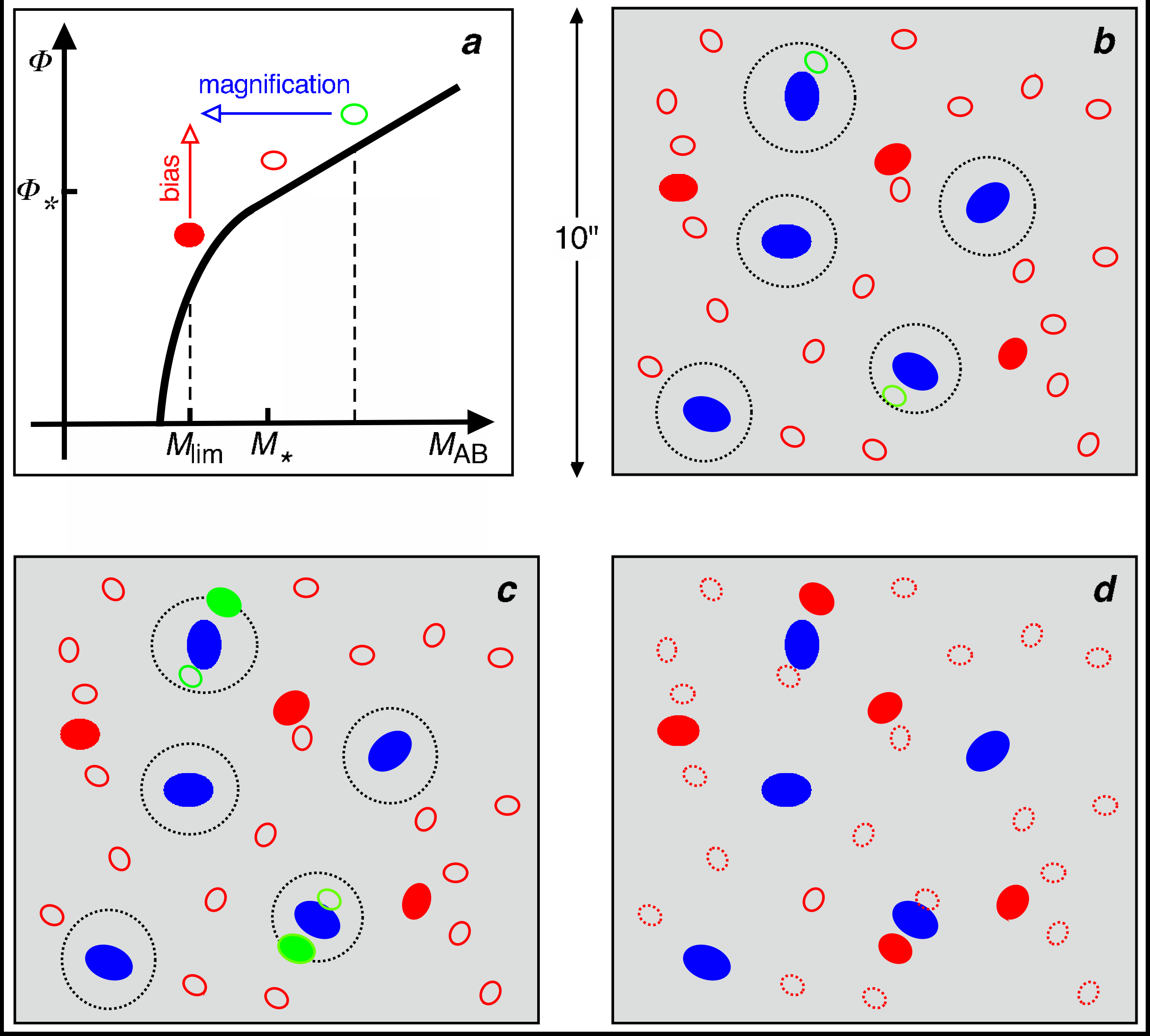
• With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.

• JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs 2.0μm diffraction limit for this.



- $\sim$10–40% of the HUDF Y-drops and J-drops appear close to bright galaxies (Yan et al. 2010, Res. Astr. & Ap., 10, 867).
- This is expected from gravitational lensing bias by galaxy dark matter halo distribution at z$\simeq$1–2 (Wyithe et al. 2011, Nature, 469, 181).
- Need JWST to measure z$\simeq$9–15 LFs, and see if fundamentally different from z$\lesssim$8. Does gravitational lensing bias boost LF bright-end?





Hard to see the forest for the trees in the first 0.5 Gyrs?:

- Foreground galaxies ($z \simeq 1$–2 or age$\simeq$3–6 Gyr) may gravitationally lens or amplify galaxies at $z \gtrsim 8$–10 (cosmic age$\lesssim$0.5 Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.

Two fundamental limitations determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect: Background objects blend into foreground neighbors $\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ deblending algorithms!

(2) House-of-mirrors effect: (Many?) First Light objects can be gravitationally lensed by foreground galaxies $\Rightarrow$ Must model/correct for this!

- Proper JWST 2.0μm PSF and straylight specs essential to handle this.

(5) Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.

- Today's Hubble sequence formed 7–10 Gyrs ago.

(2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 75% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.

(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.
- JWST will define the next frontier to explore: the Dark Ages at z$\gtrsim$20.

SPARE CHARTS

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java–tool]

http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/ [Clickable HUDF map]

http://www.jwst.nasa.gov/ & http://www.stsci.edu/jwst/

http://ircamera.as.arizona.edu/nircam/

http://ircamera.as.arizona.edu/MIRI/

http://www.stsci.edu/jwst/instruments/nirspec/

http://www.stsci.edu/jwst/instruments/fgs

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

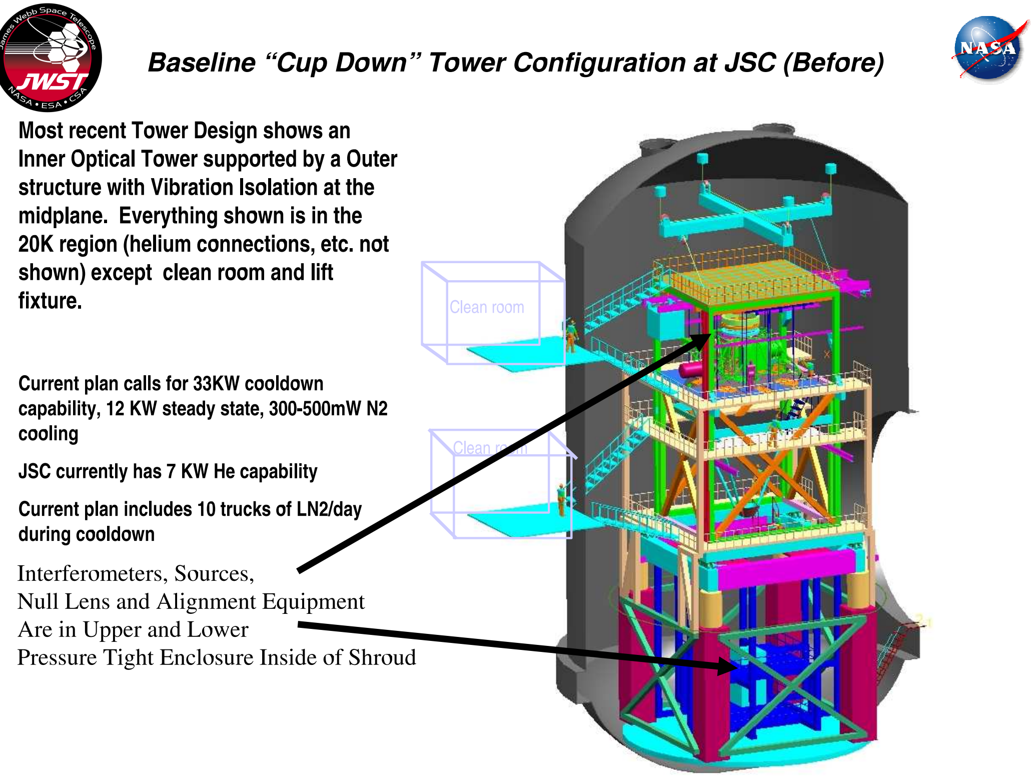
Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

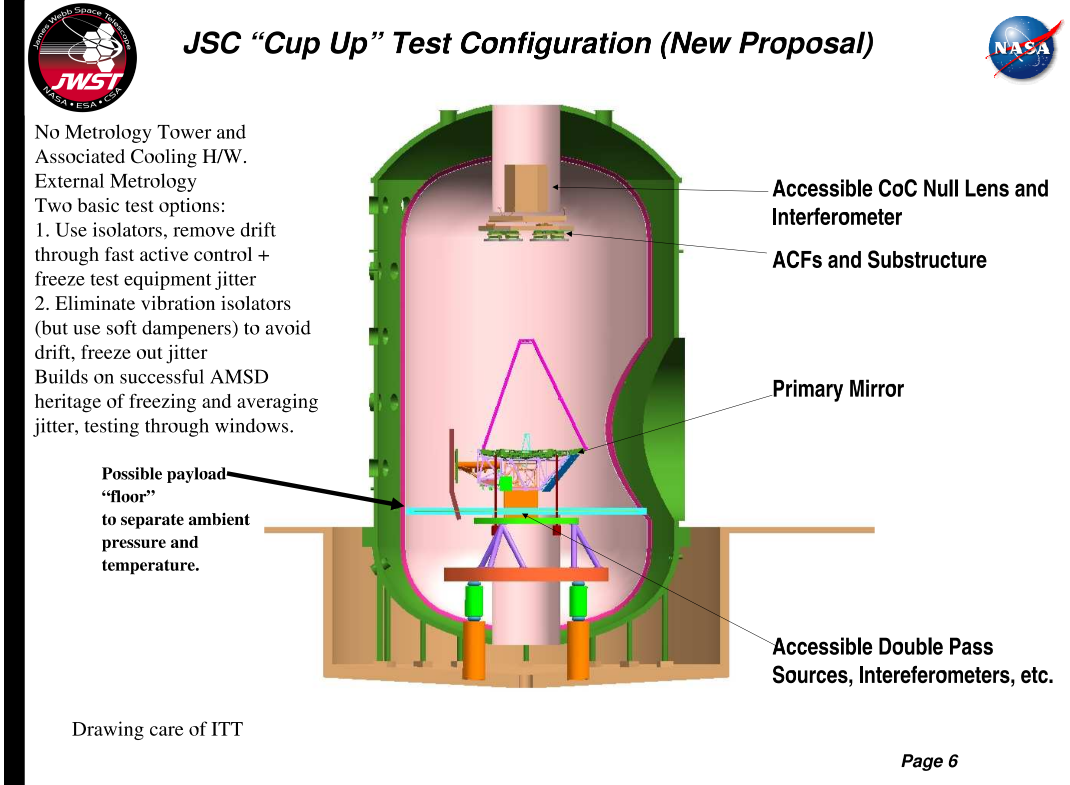
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements

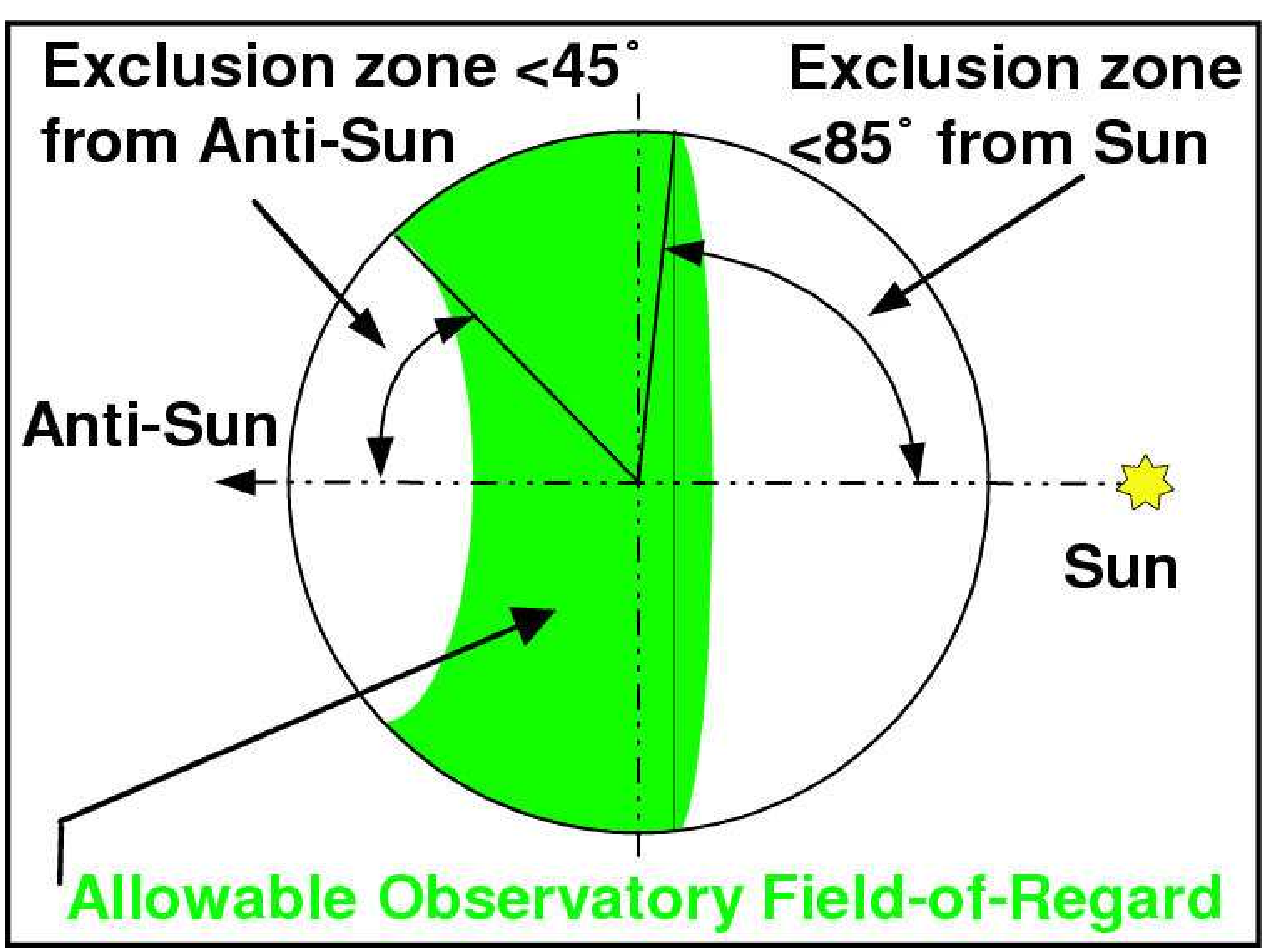




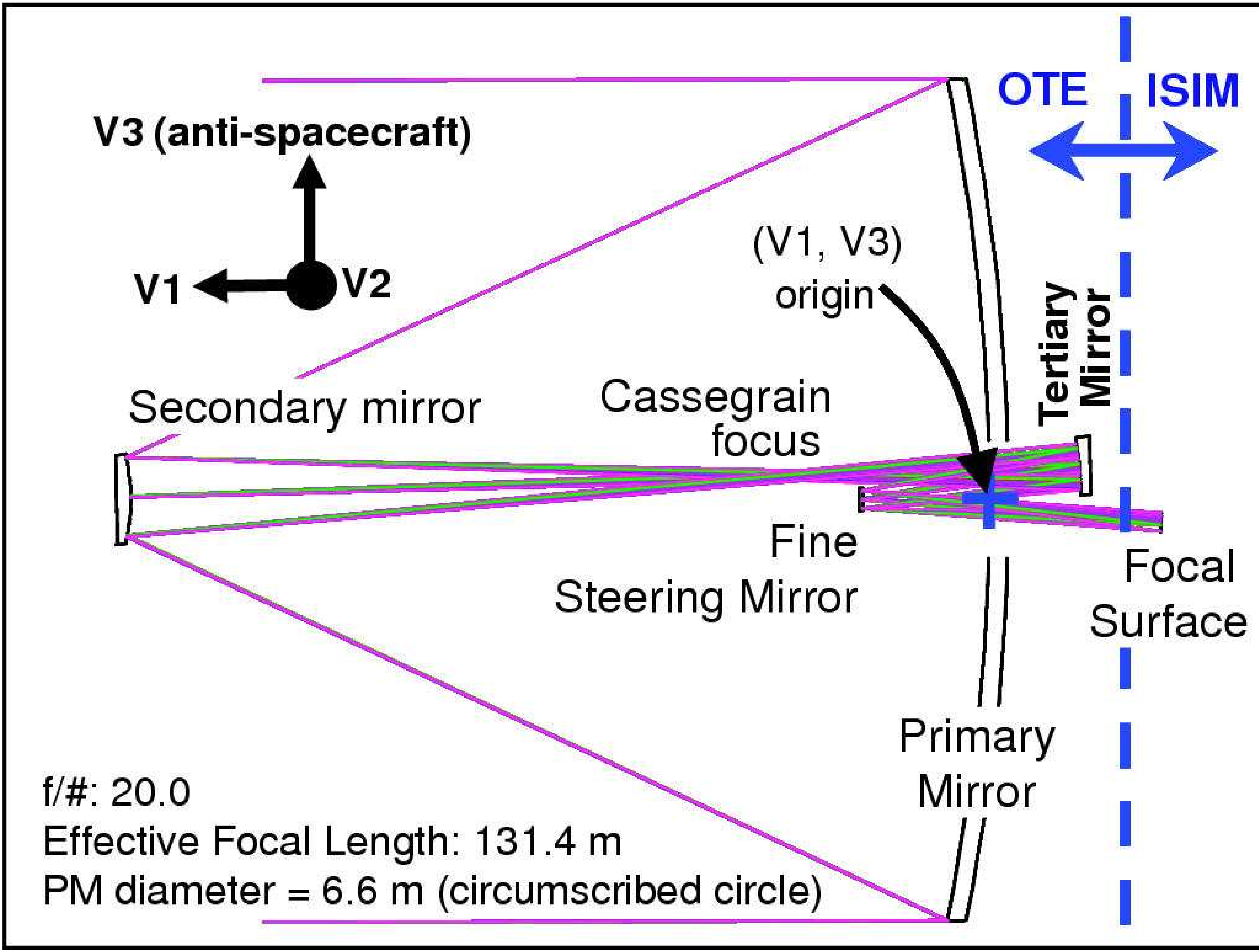


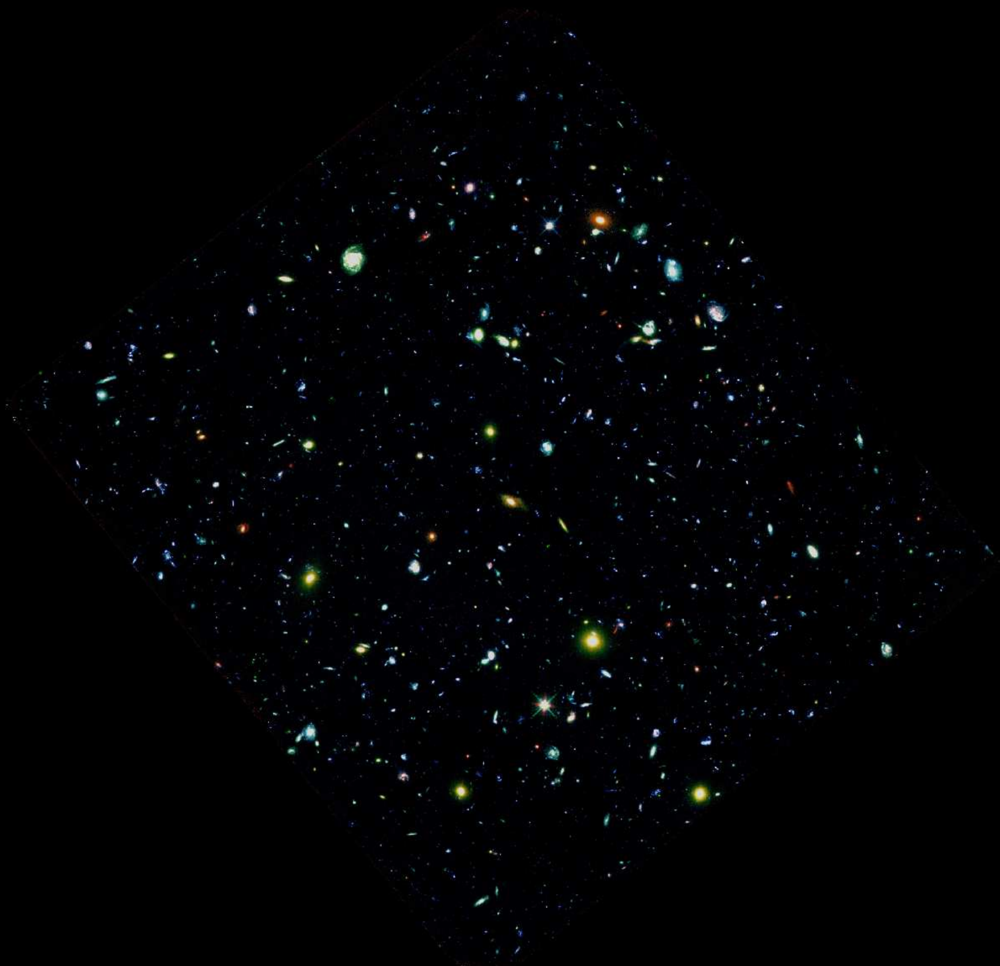
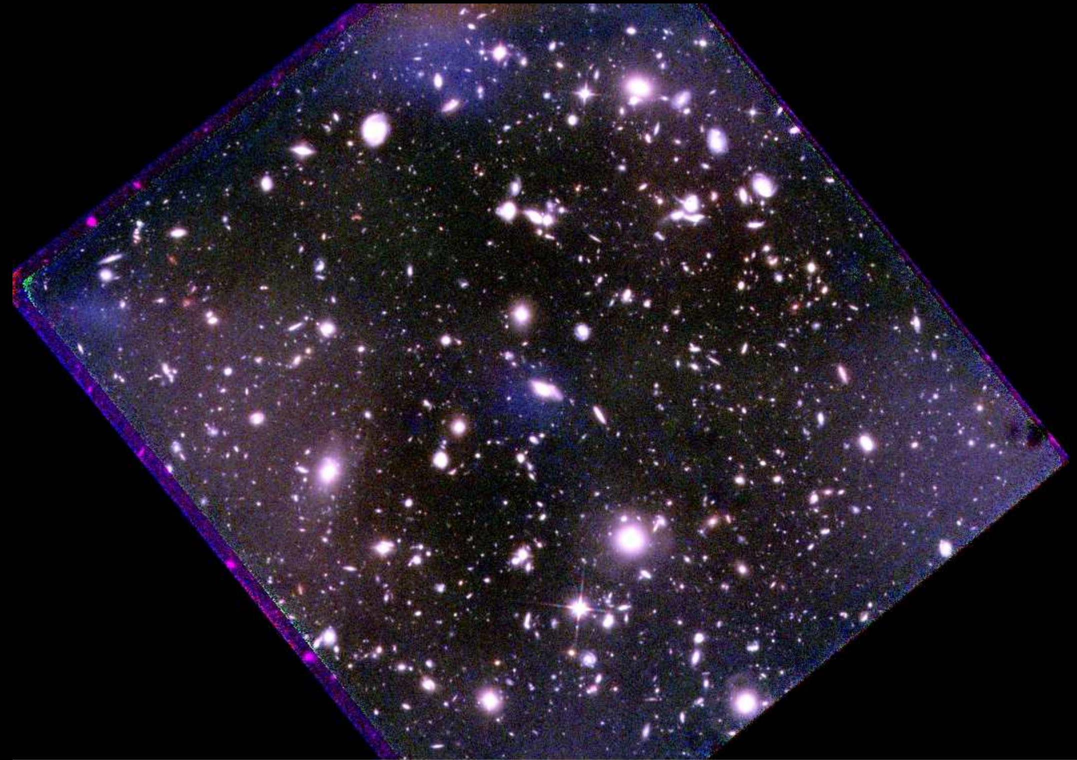
JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.



JWST can observe segments of sky that move around as it orbits the Sun.


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)

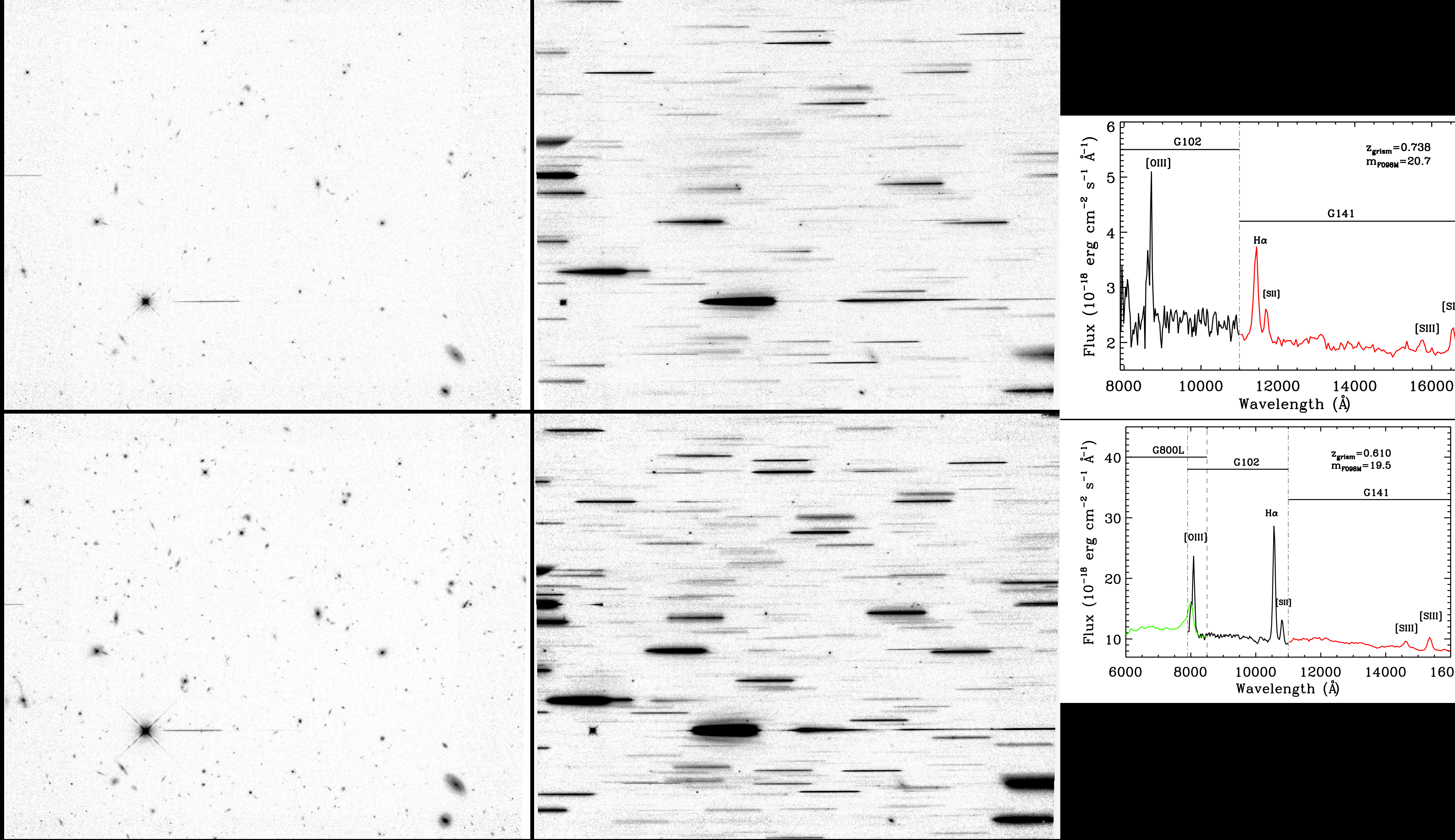
 

(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at 1–1.6μm (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodical sky!

- The CLOSED-TUBE HST has residual low-level systematics: Imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.

$\Rightarrow$ The open JWST architecture needs very good baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

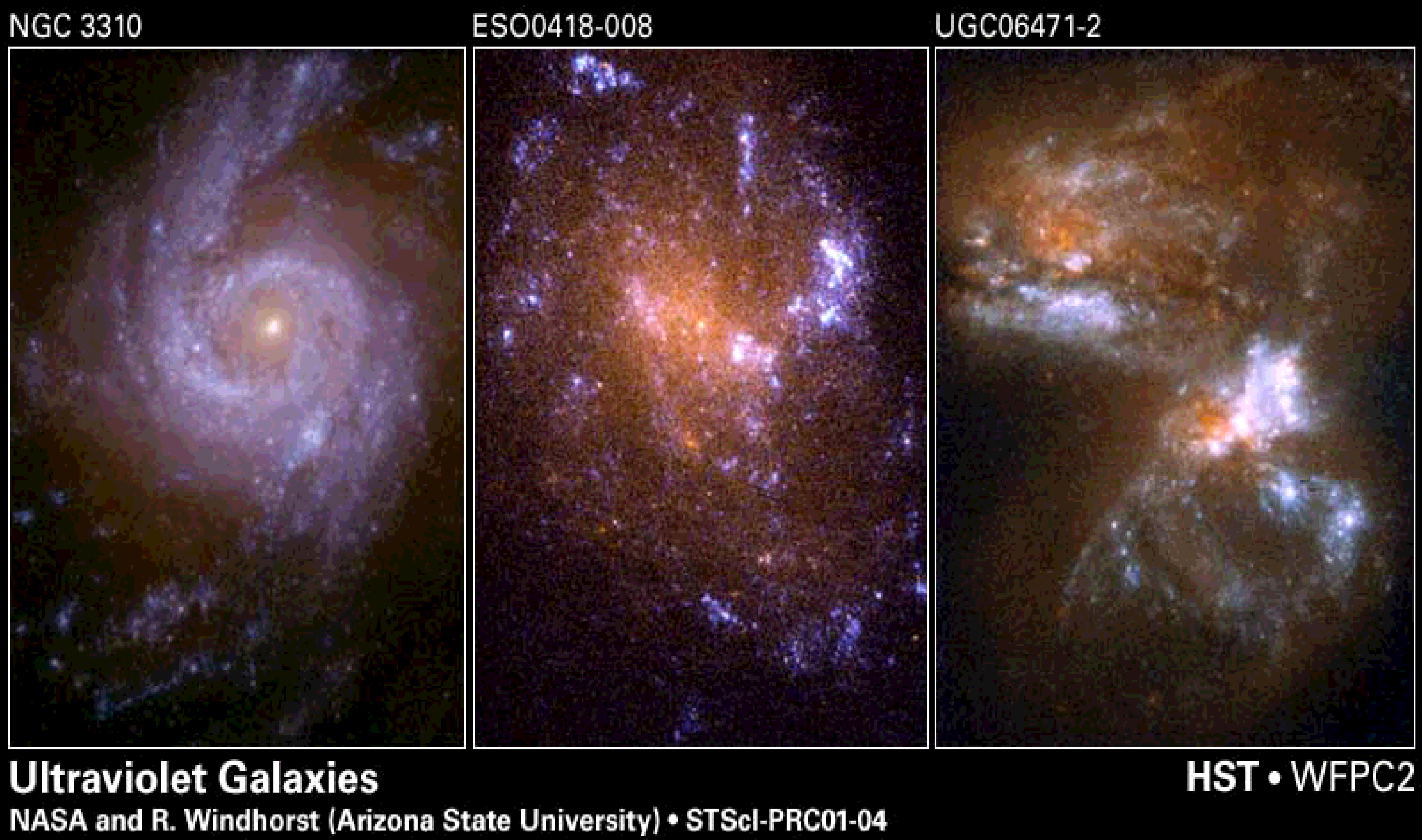


HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn^{+} 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to AB$\lesssim$29 mag from 2–5.0 μm.

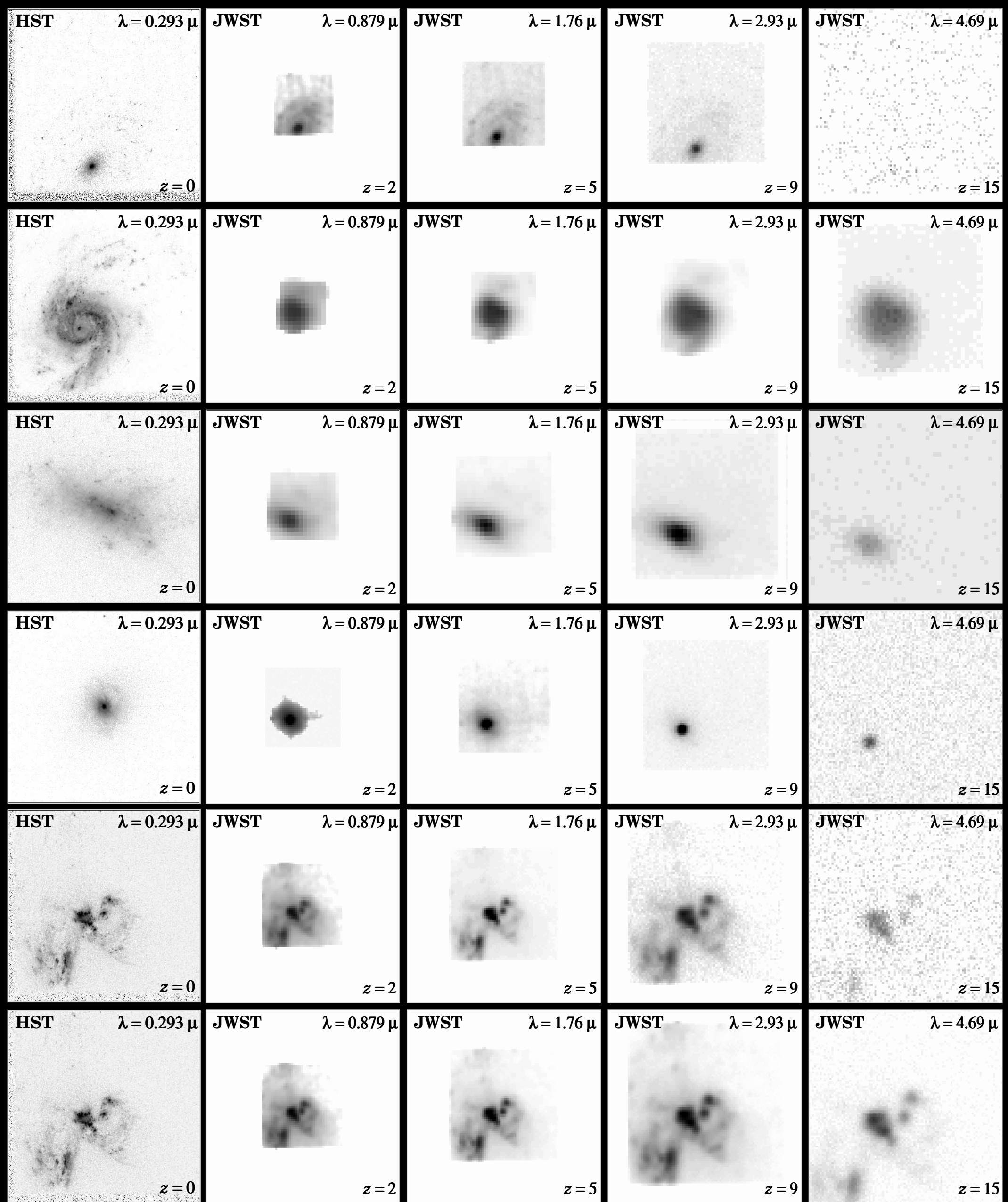
(4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1$–15



- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).
- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

(4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15

HST z=0   JWST z=2   z=5   z=9   z=15



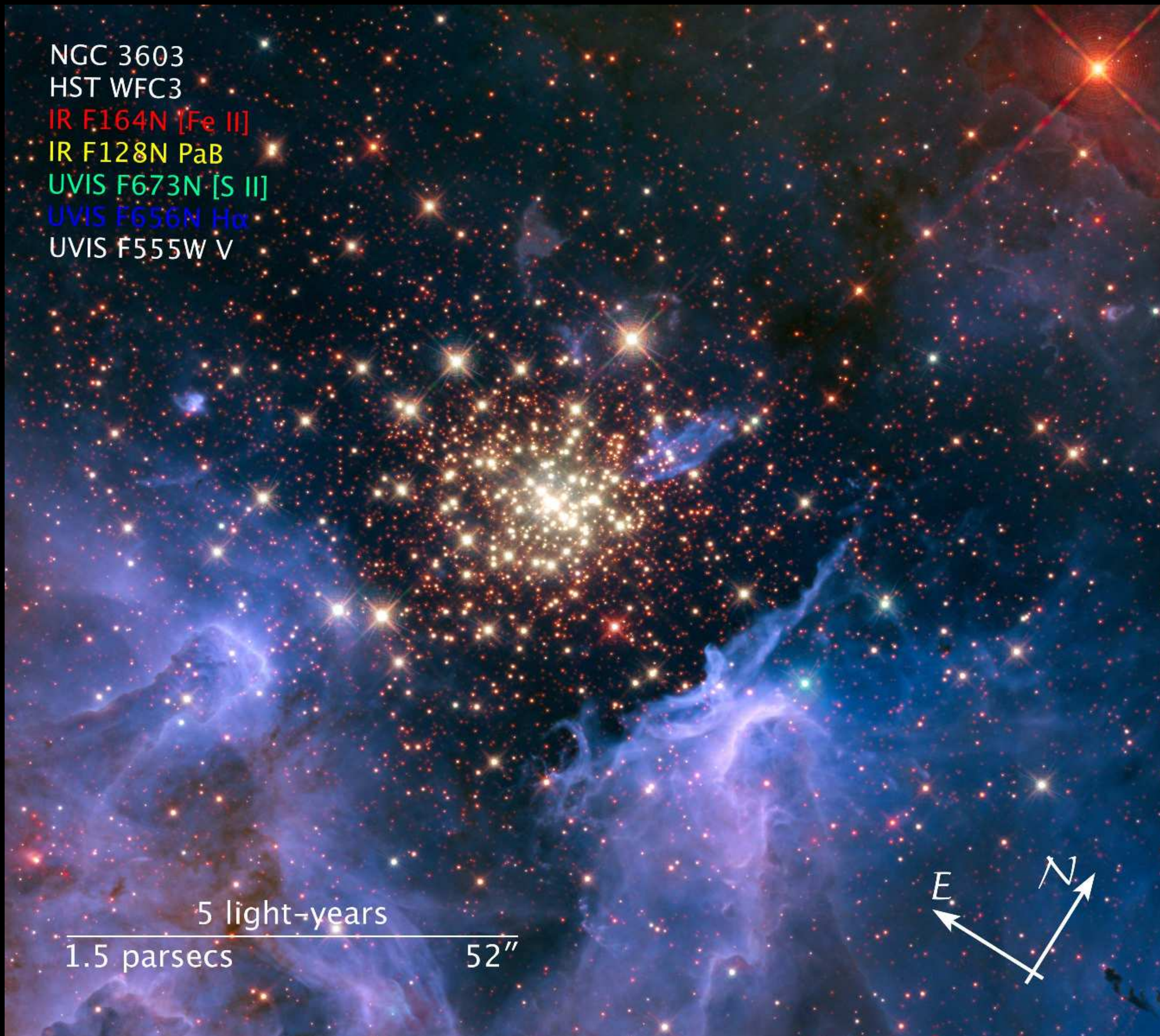
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at z≲1–2.

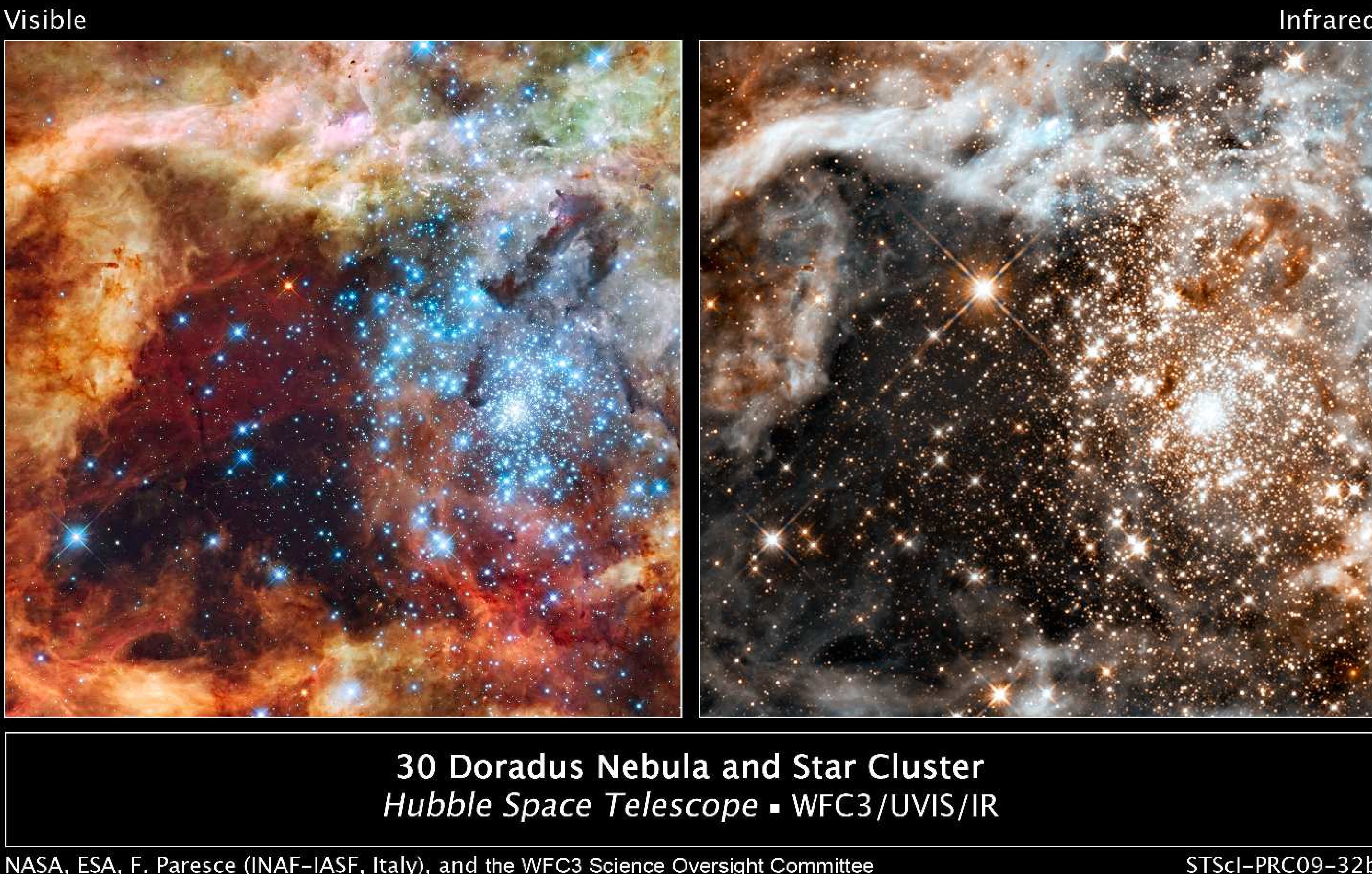
Visible to JWST at very high z are:

- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

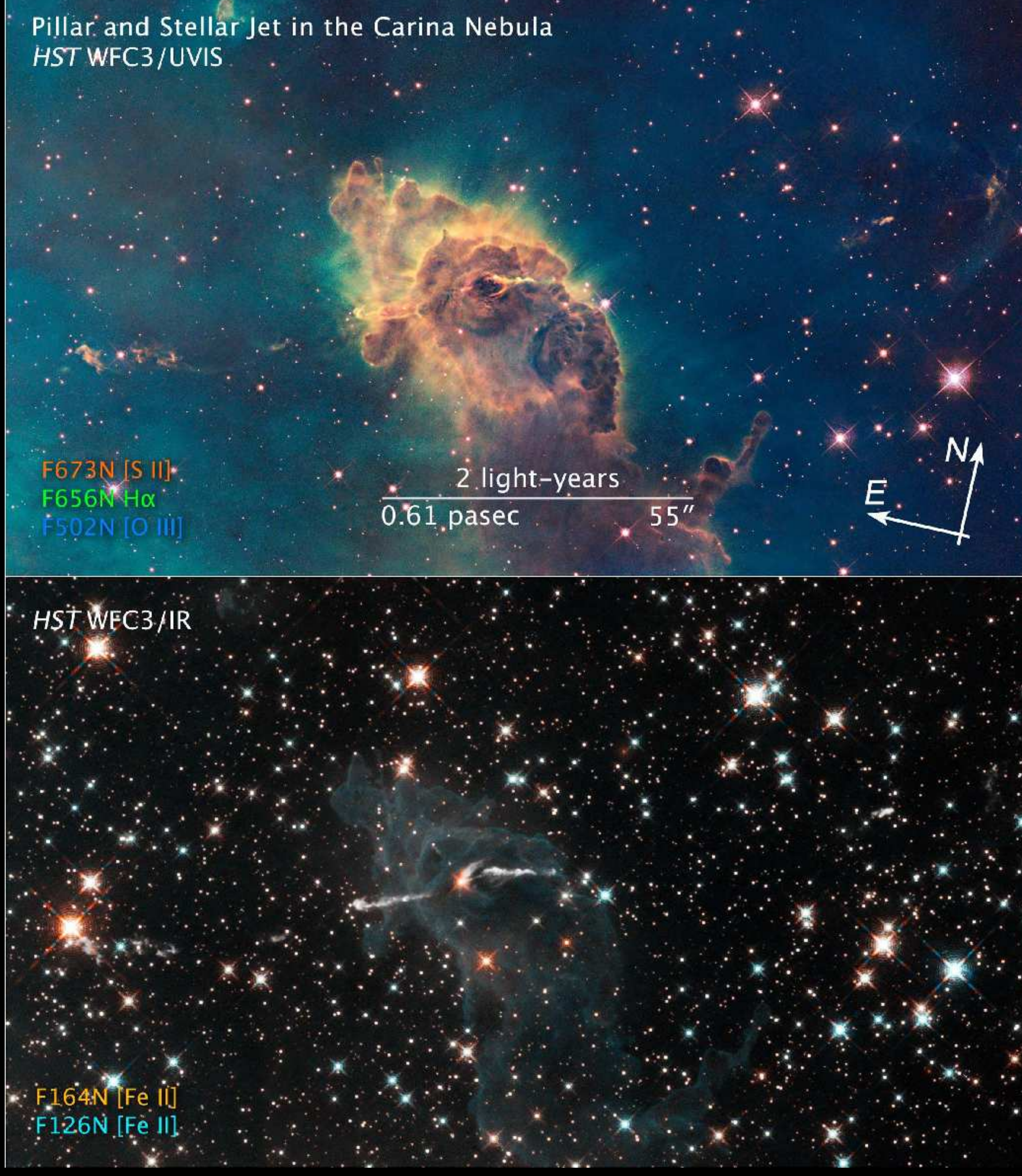
(6) How can JWST measure Earth-like exoplanets?

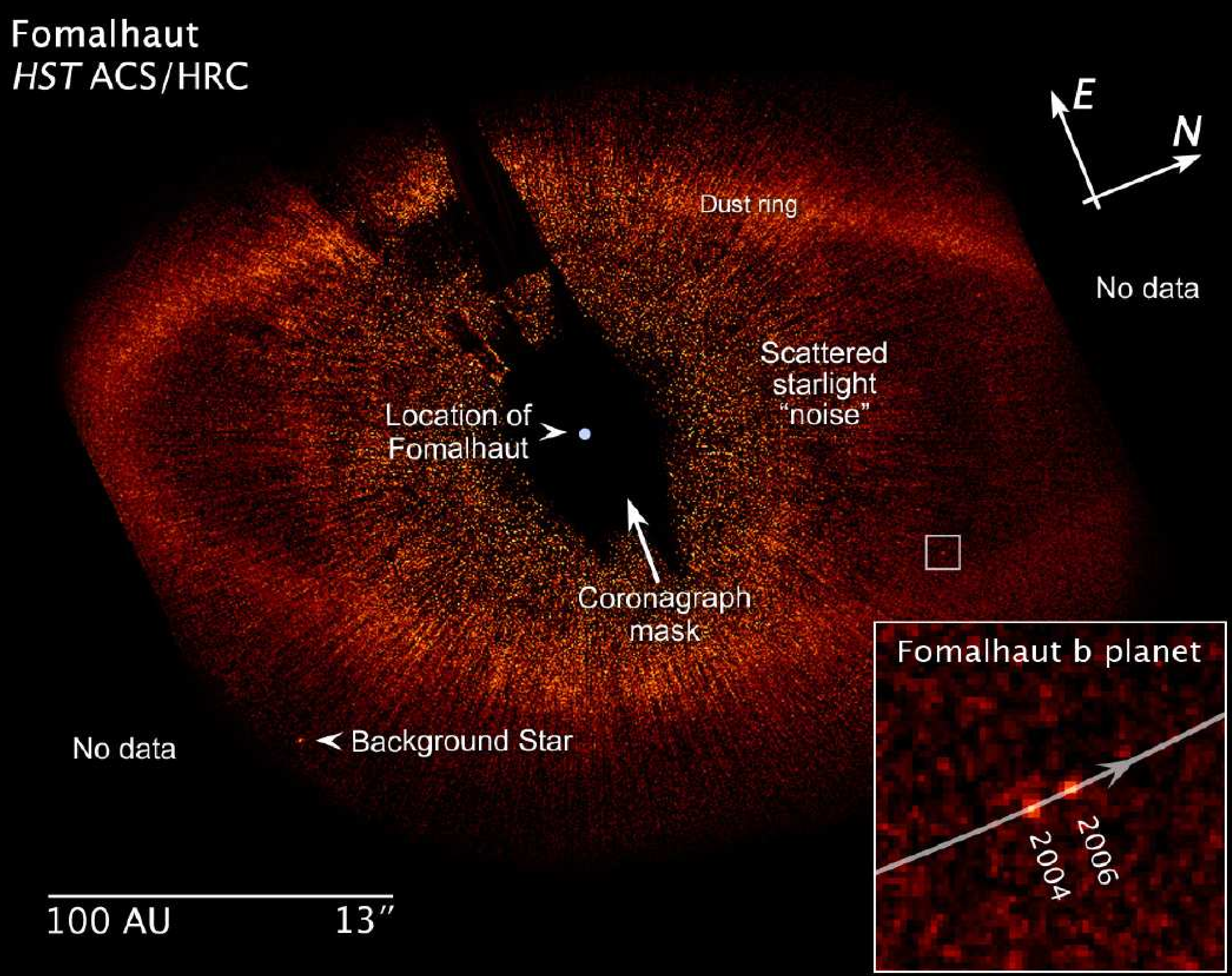


NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"



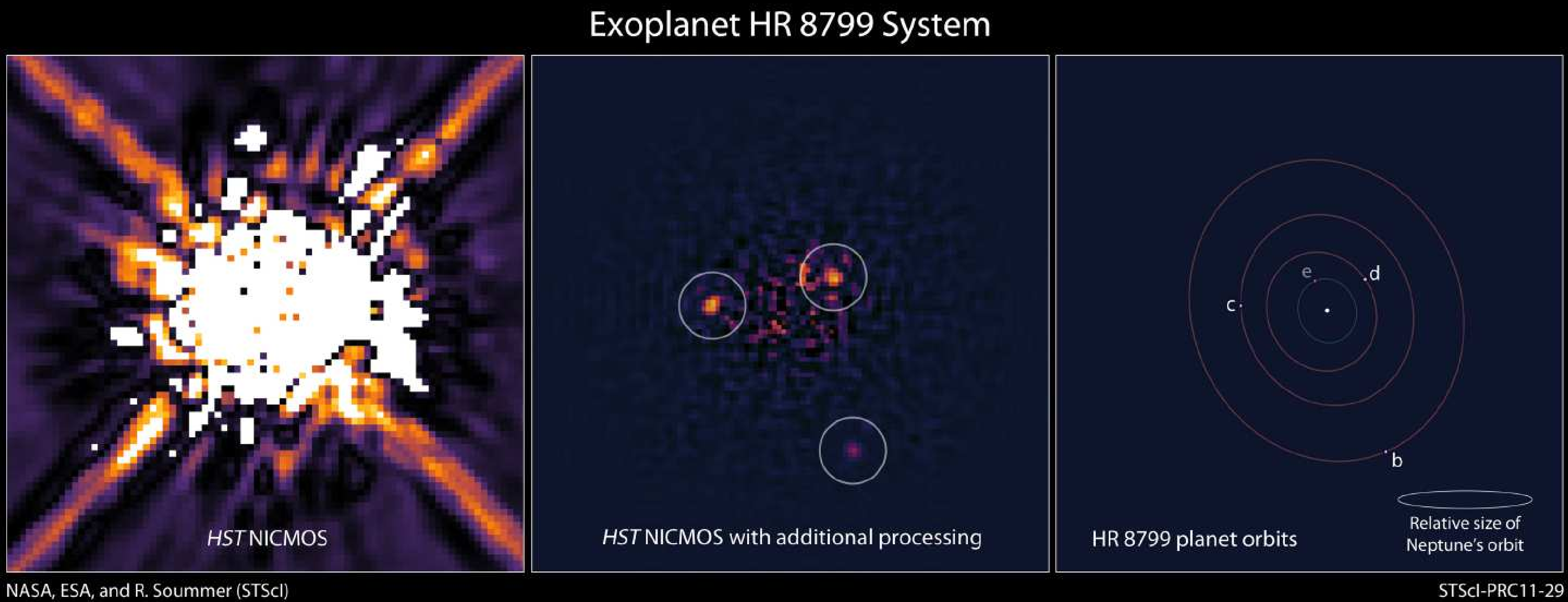
30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:
First direct imaging of a moving planet forming around a nearby star!

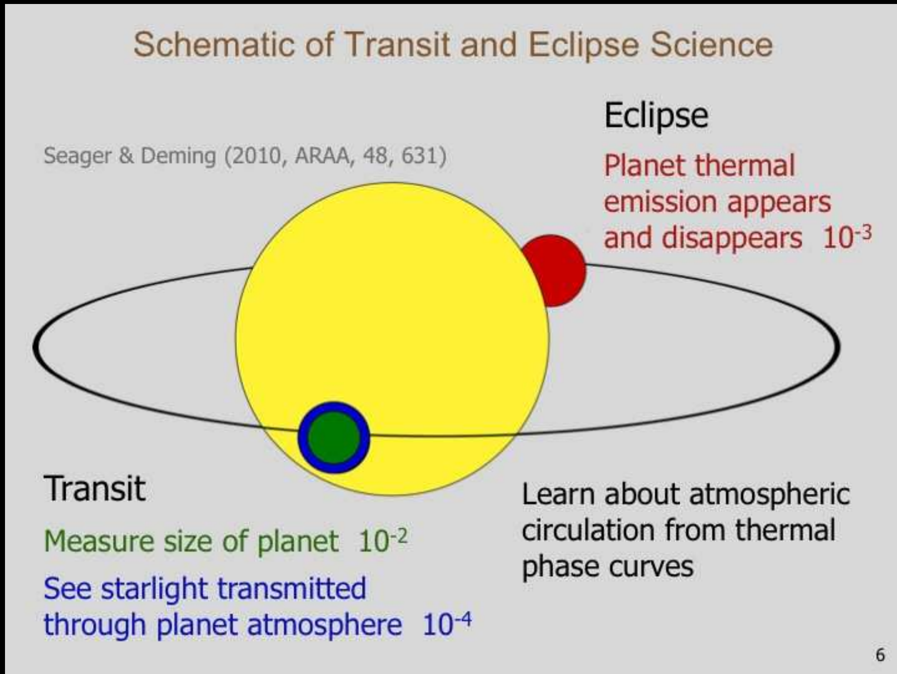
JWST can find such planets much closer in for much farther stars.

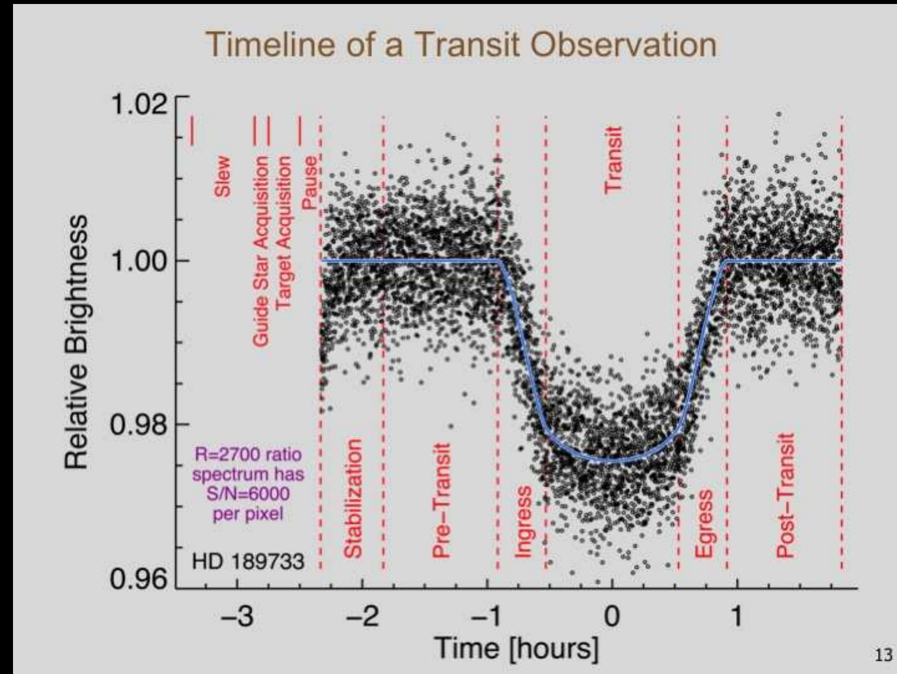


HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

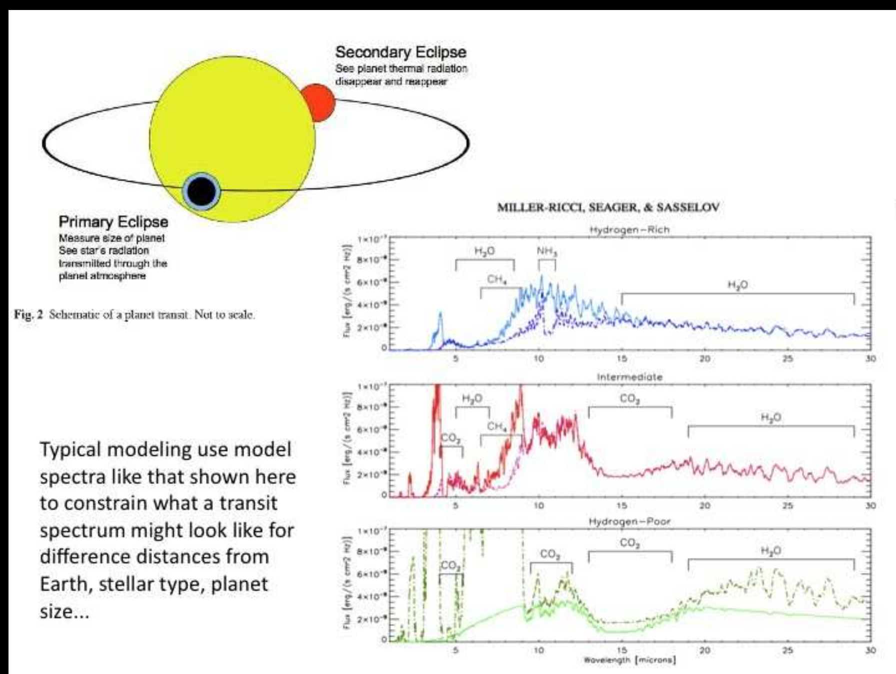
Press release: http://hubblesite.org/newscenter/archive/releases/2011/29/

JWST can find such planets much closer in for much farther-away stars.

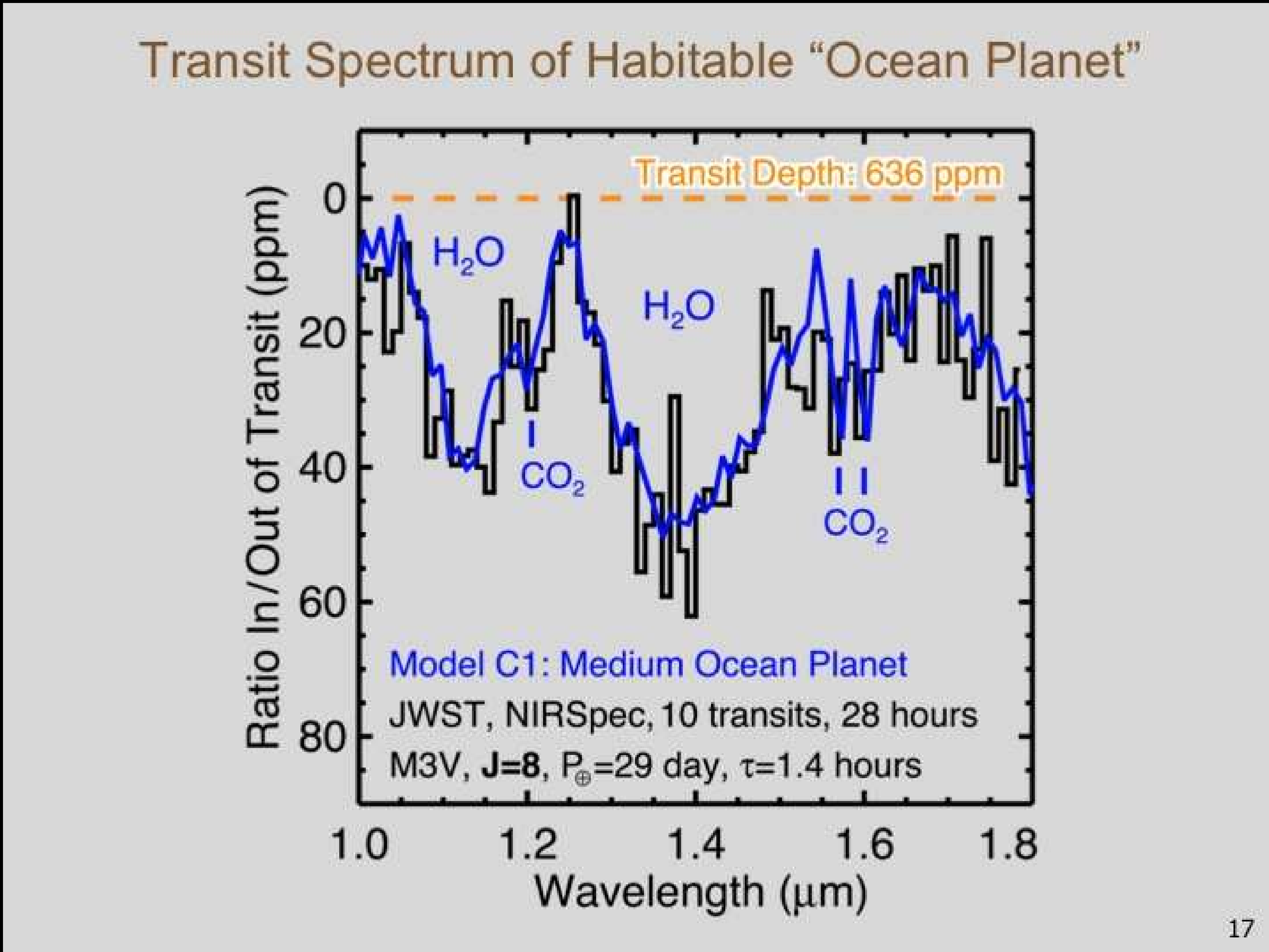




JWST can do very precise photometry of transiting Earth-like exoplanets.

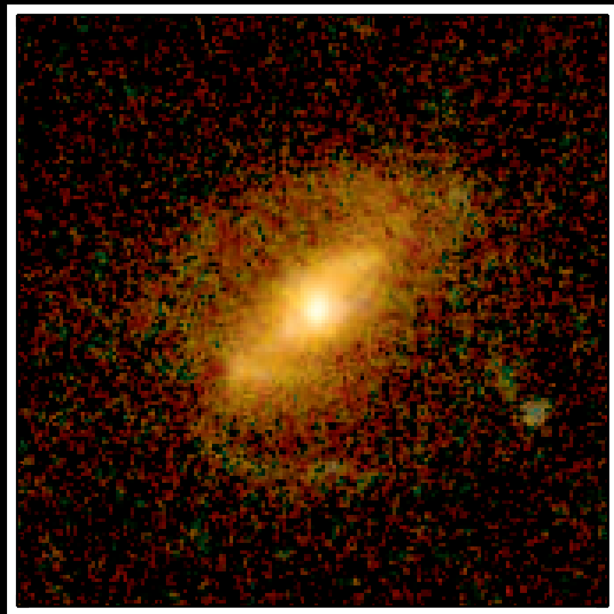


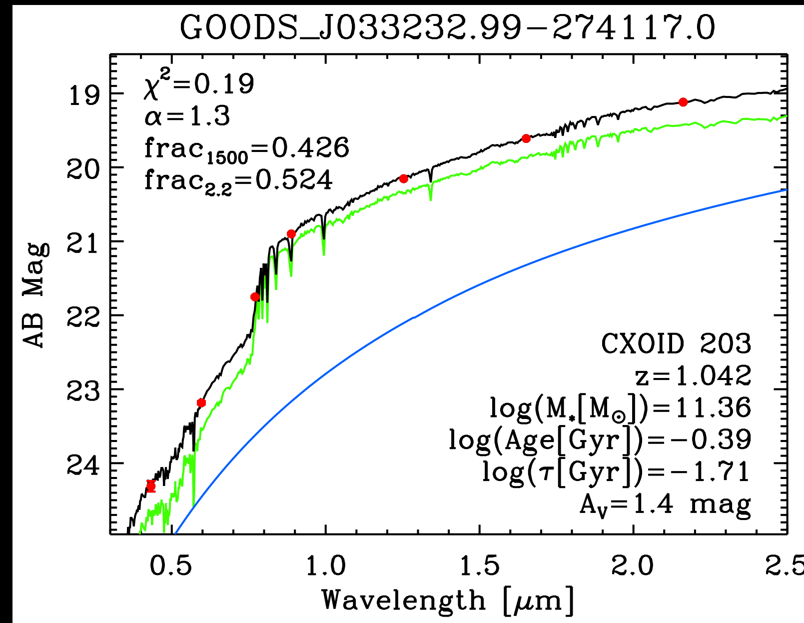
JWST IR spectra can find water and CO_2 in (super-)Earth-like exoplanets.

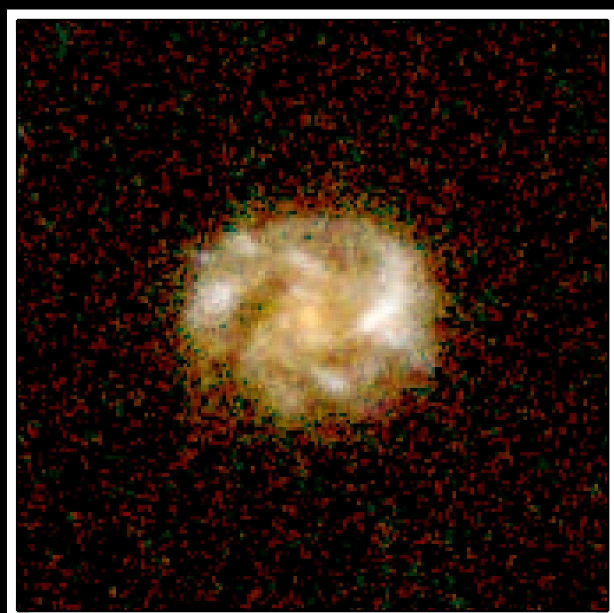


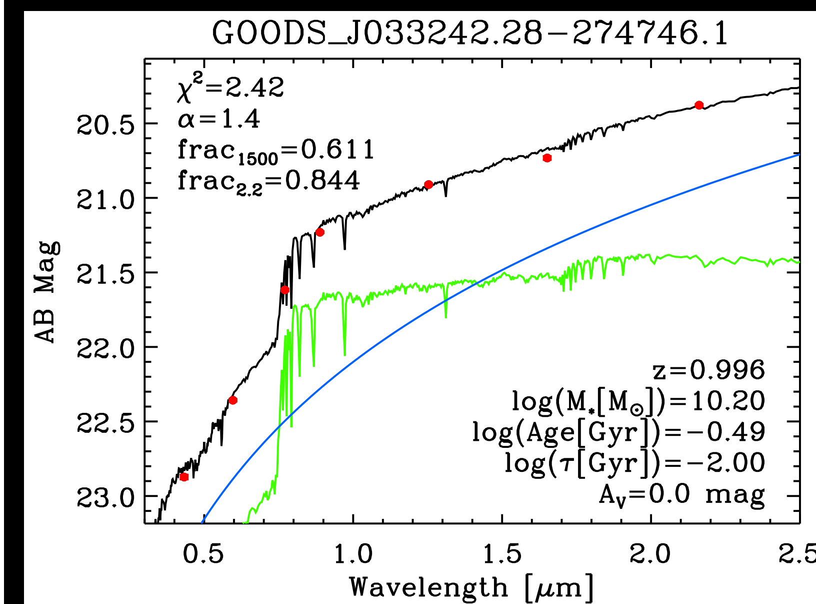
JWST IR spectra can find water and CO_2 in transiting Earth-like exoplanets.

(2b) Radio & X-ray host SED-ages: trace AGN growth directly?





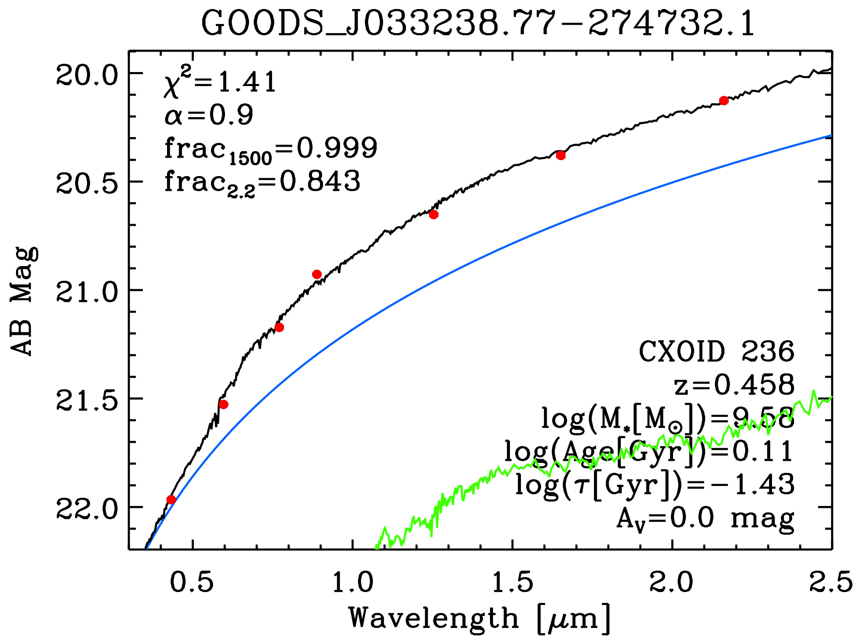


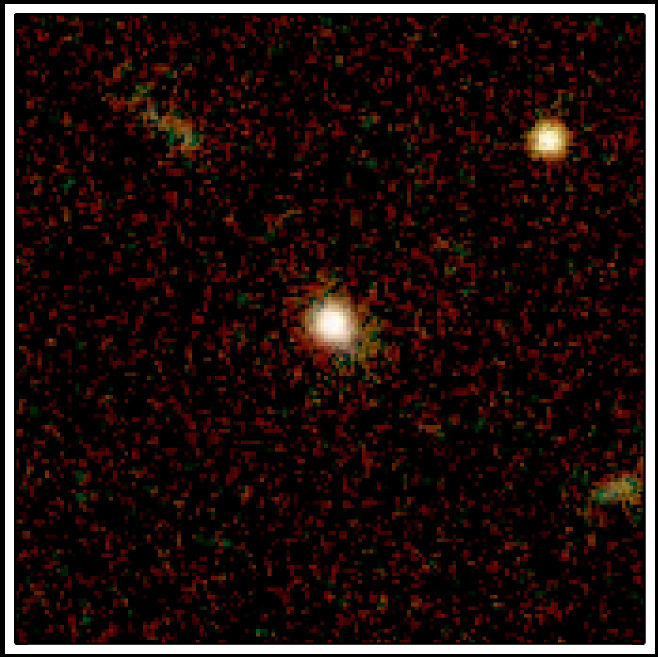


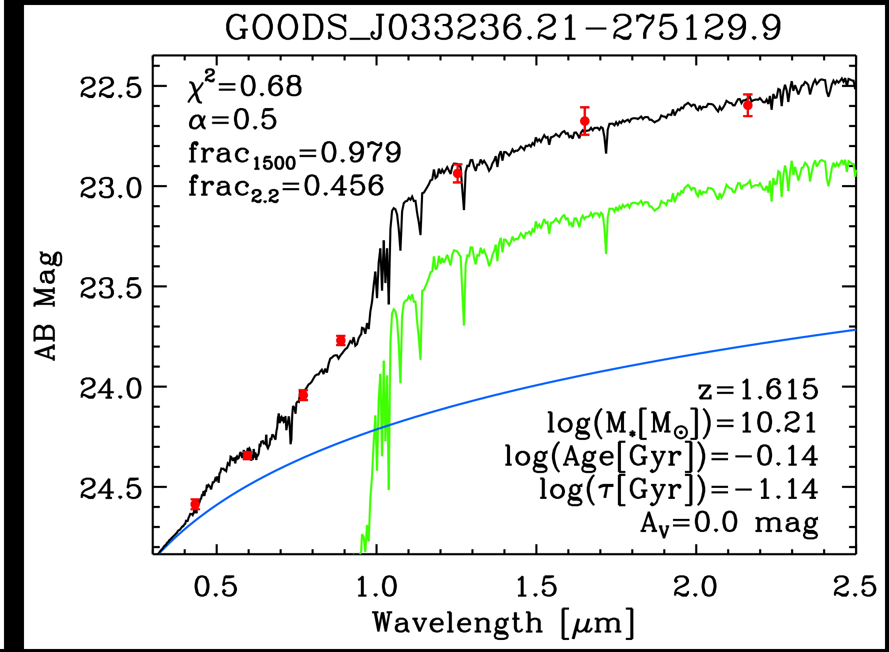
Cohen+ (2013): GOODS/VLT UV+BVizJHK images + 1549 VLT redshifts.

Best fit Bruzual-Charlot (2003) SED + power law AGN.

Method: Multi-component SED fits (see spare charts & Jeff Newman's talk).







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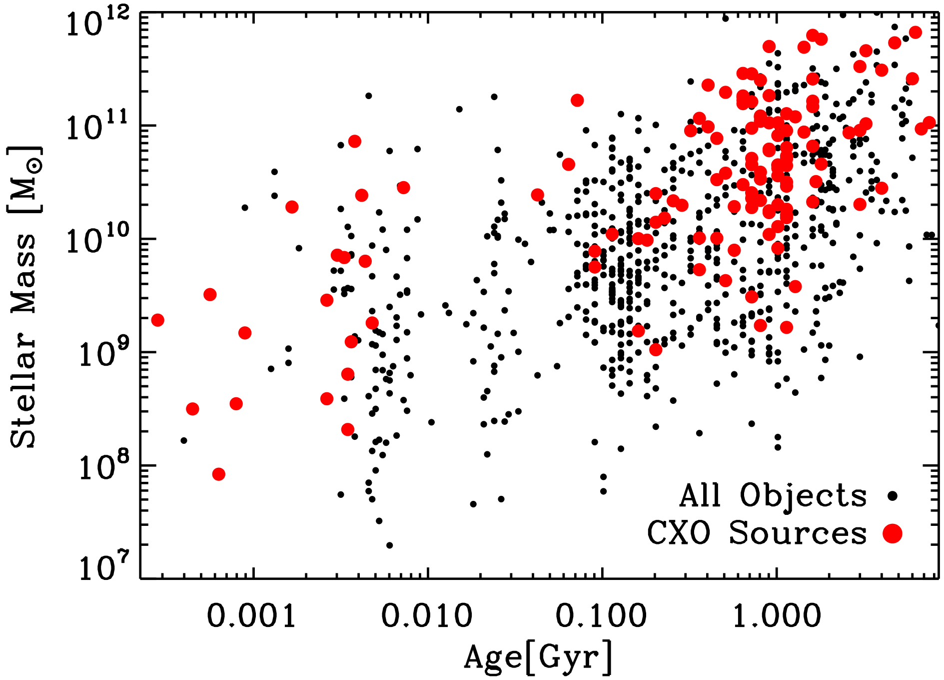
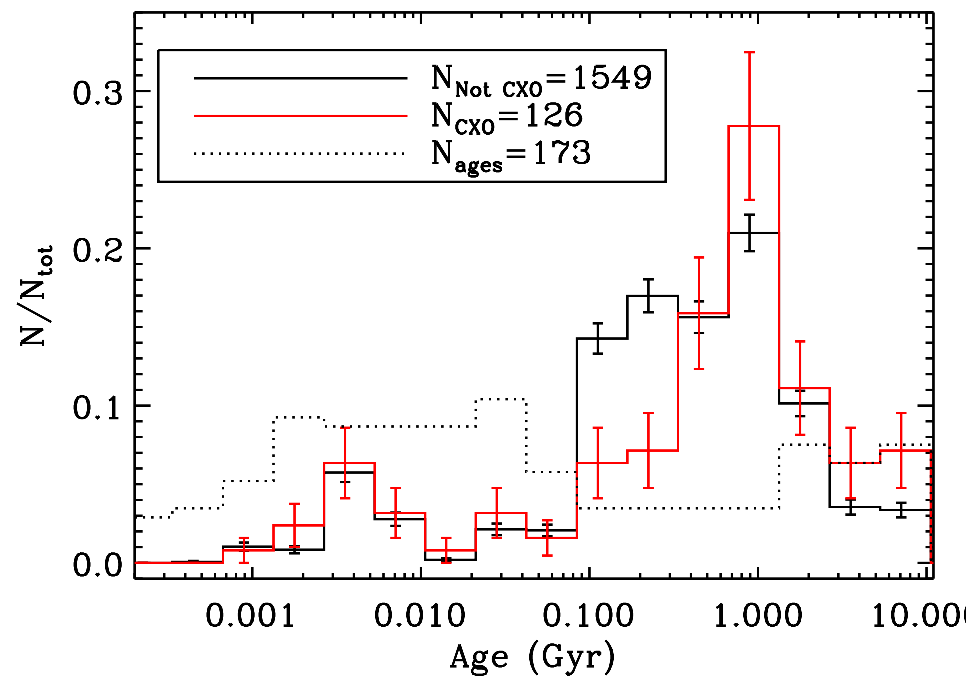
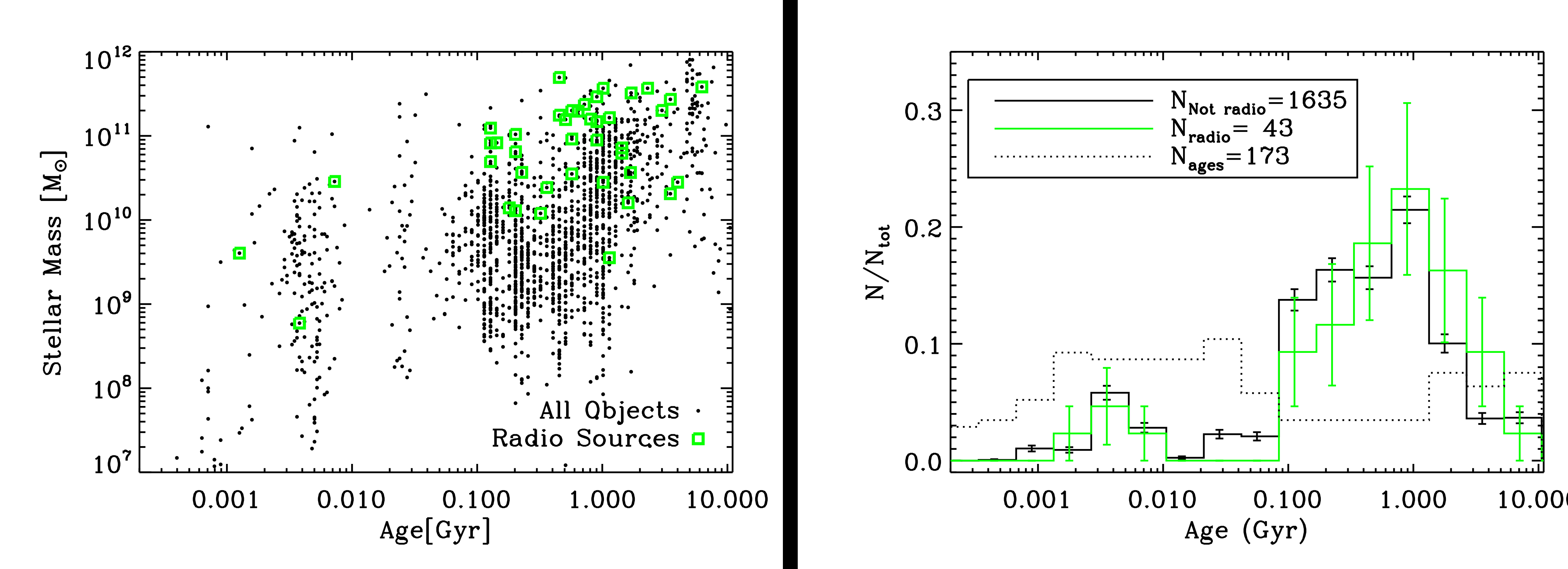




Cohen et al. (2013): Best fit Stellar Mass vs. Age: X-ray and field galaxies.

Field galaxies have: Blue cloud of ∼100-200 Myr, Red cloud of $\gtrsim$1–2 Gyr.

- X-ray sources reside in galaxies that are a bit older than the general field population, but by no more than $\lesssim$0.5–1 Gyr on average.
- JWST+WFC3 can disentangle multiple SED + AGN power-law from 15-band photometry to AB=30 mag for z$\lesssim$10.
- JWST can trace AGN-growth, host galaxy masses and ages since z∼10.



Cohen et al. (2013): Best fit Stellar Mass vs. Age: Radio and field galaxies.

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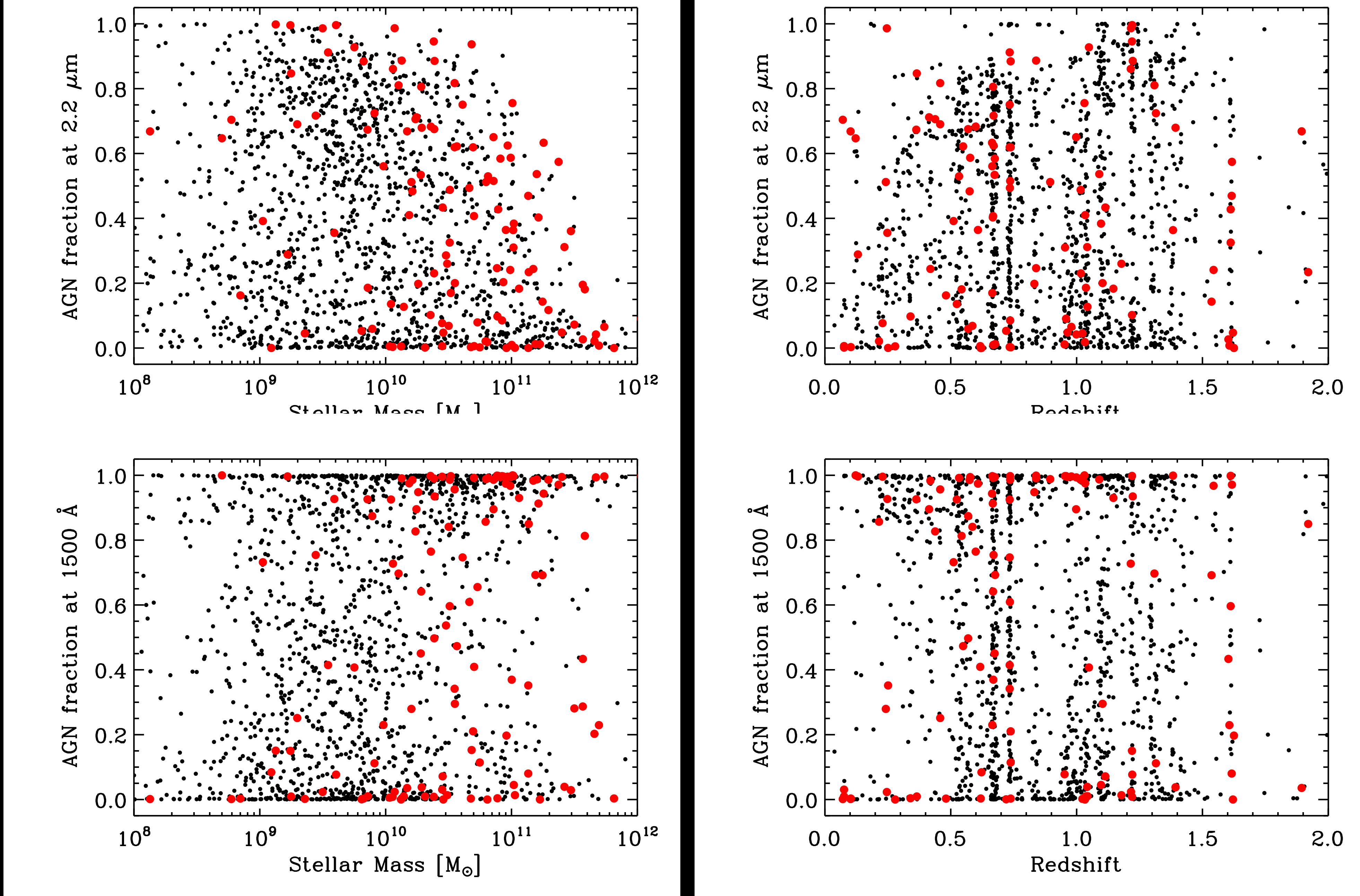
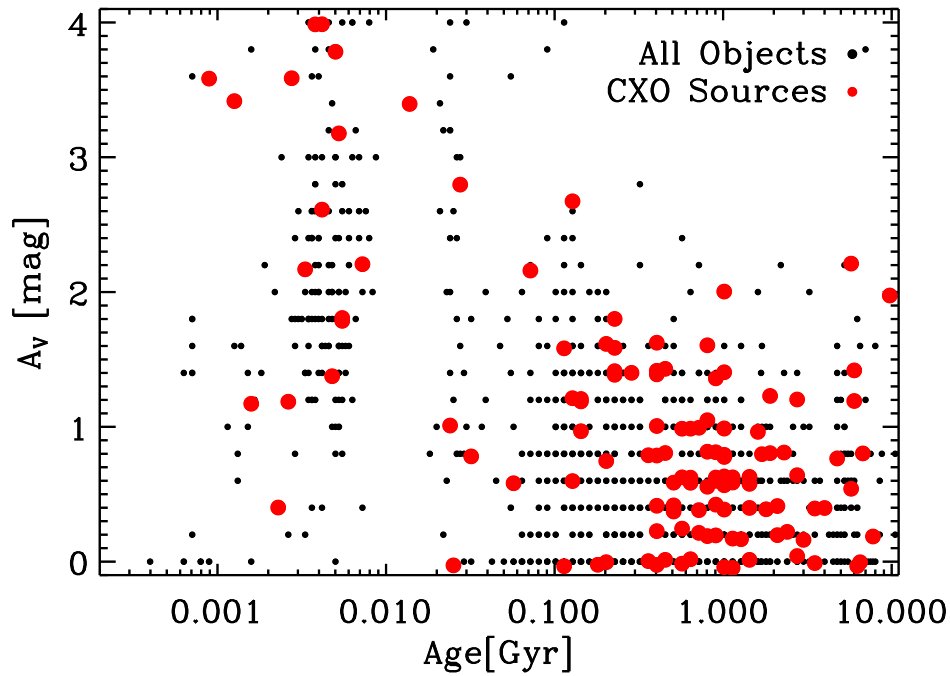
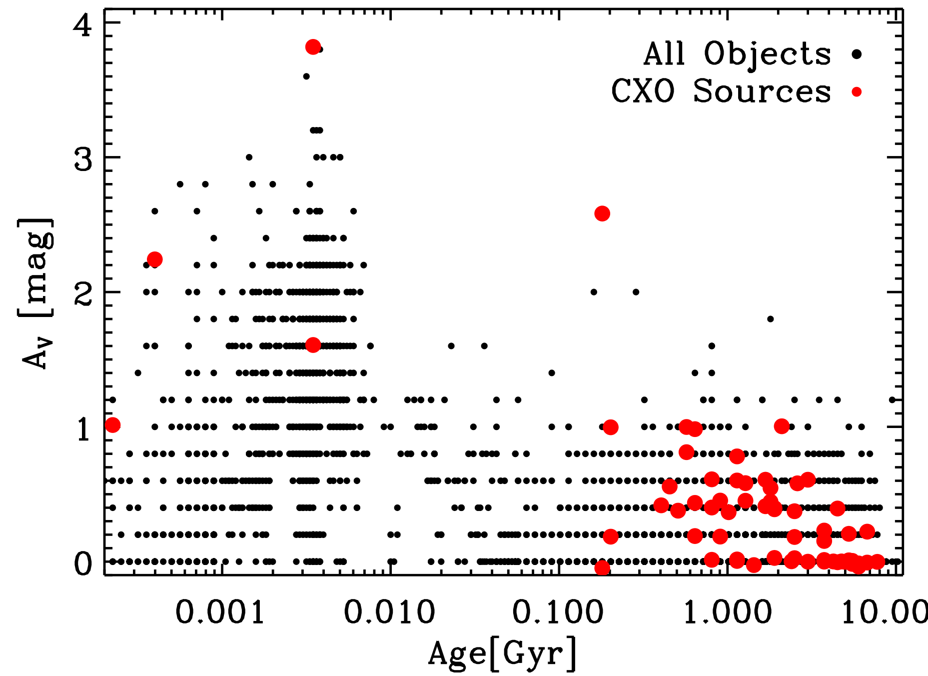


Cohen+ (2013): "AGN" fraction vs. stellar mass & z: X-ray and field gxys.

$\Rightarrow$ Many more with best-fit f(AGN)$\gtrsim$50% to be detected by IXO or SKA!

- JWST can trace power-law SED-fraction for M$\gtrsim 10^8$ $M_\odot$ and z$\lesssim$10.



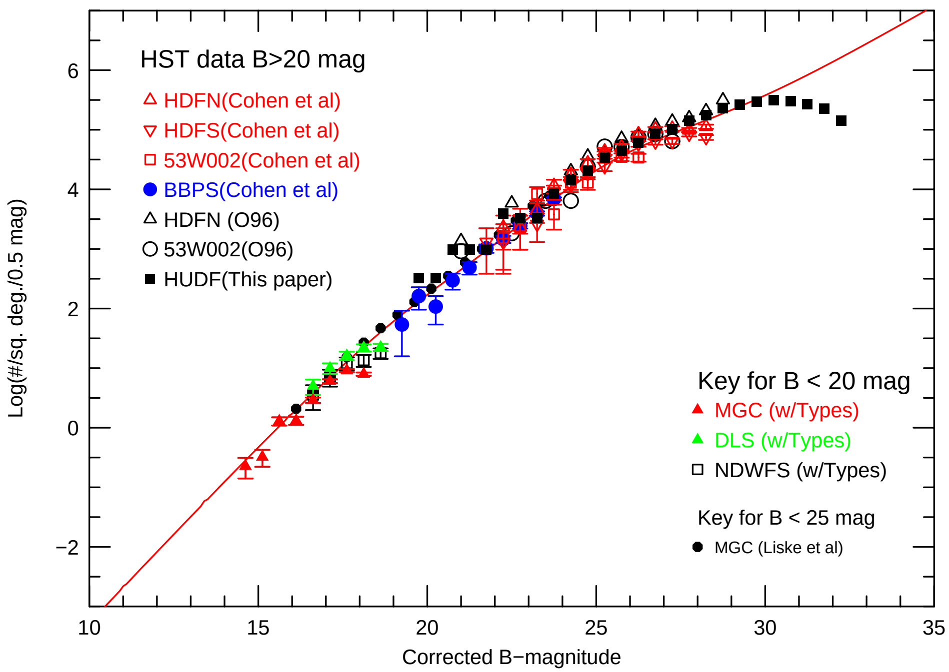


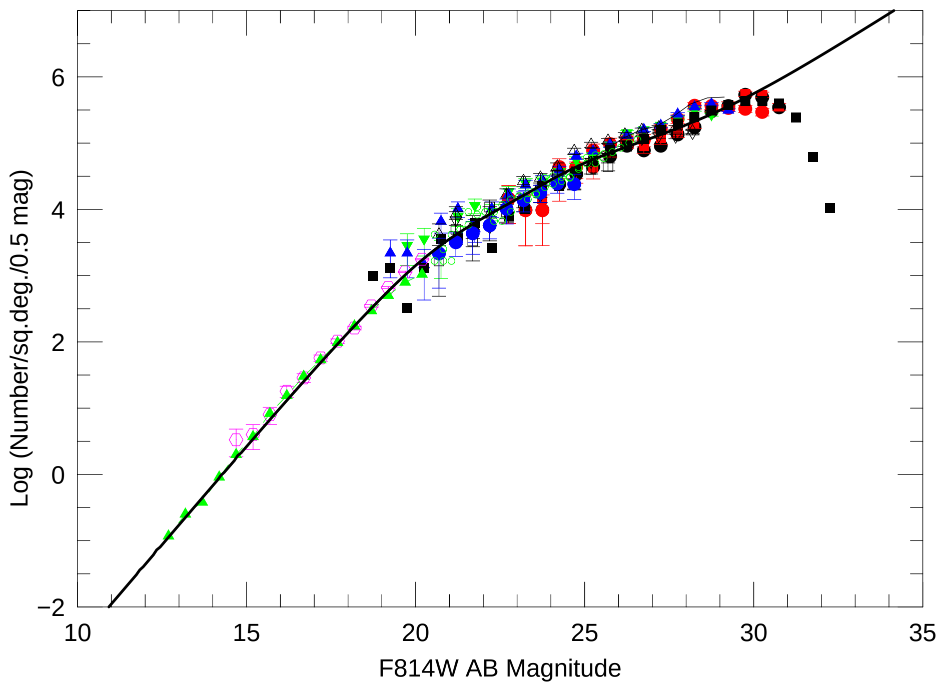
LEFT: 1549 CDF-S objects with z's. RIGHT: 7000 CDF-S ERS with spz's.

Cohen et al. (2013): Best fit extinction A_V distribution: X-ray and field.

- In Hopkins et al. (2006, ApJS, 163, 1) scenario, dust and gas are expelled *after* the starburst peaks and *before* before the AGN becomes visible.
- Older galaxies have less dust after merger/starburst/outflow.
- But the age-metallicity relation may complicate this.

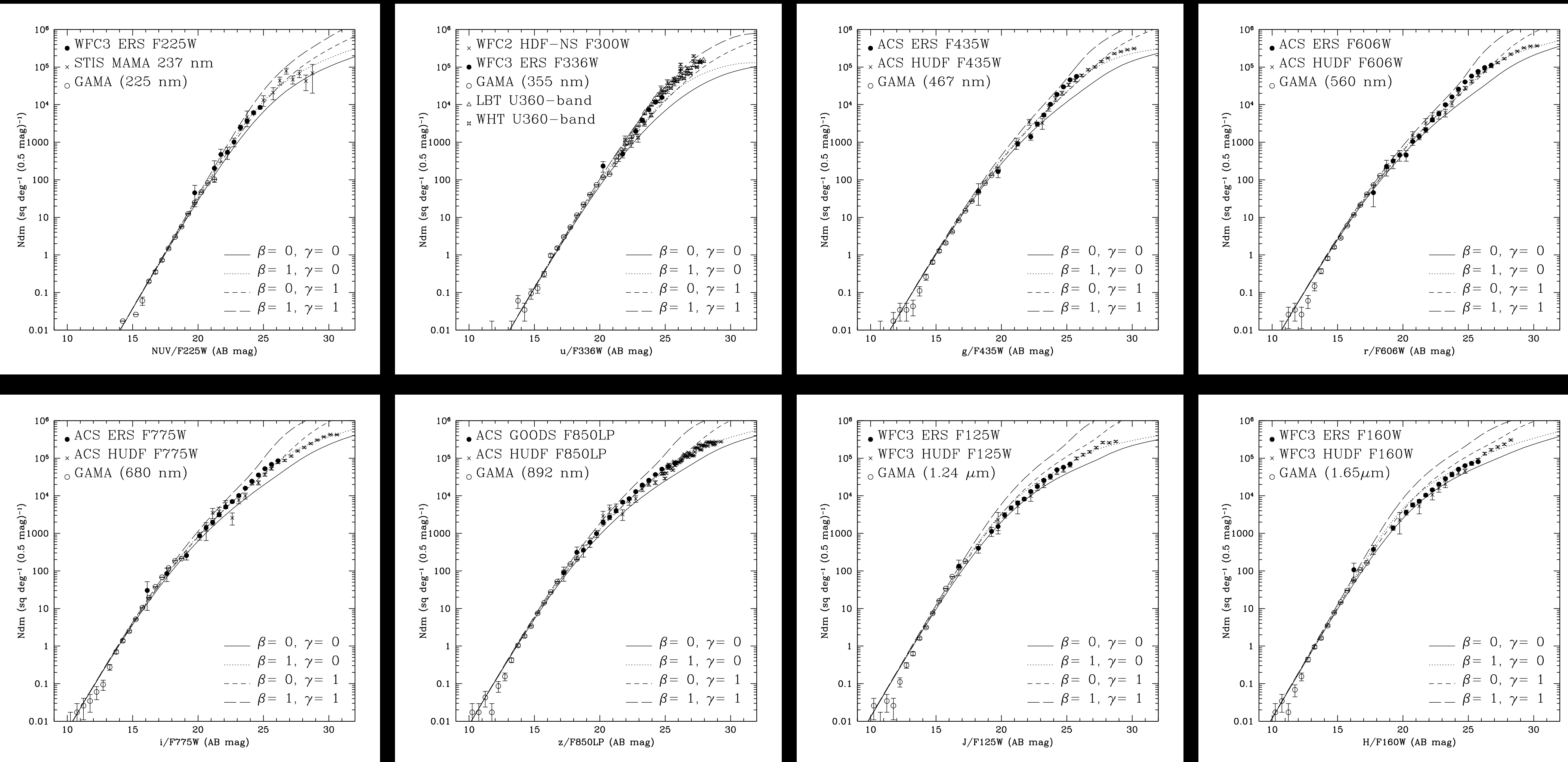
Appendix 1: Will JWST (& SKA) reach the Natural Confusion Limit?





- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times10^6$ galaxies/deg^2 to AB=31.5 mag ($\simeq$ 1 nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq$1 and 10 nJy, resp.
- $\Rightarrow$ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM$\lesssim$0.″08).
- $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.

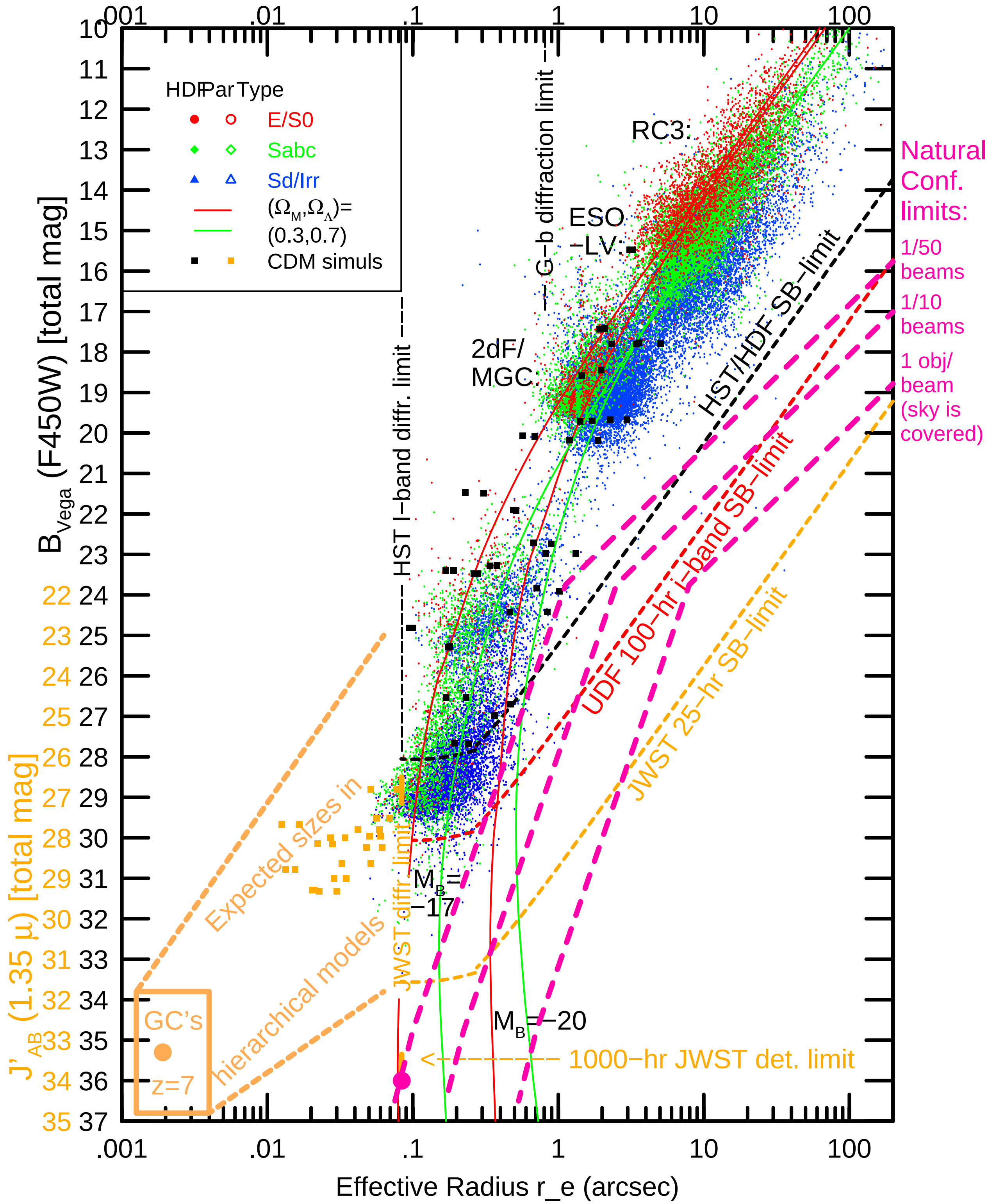
Panchromatic Galaxy Counts from $\lambda \simeq 0.2$–$2\mu m$ for AB$\simeq$10–30 mag



Data: GALEX, ground-based GAMA, HST ERS ACS+WFC3 + HUDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011, ApJS 193, 27):

Filters: F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F160W.

- No single Lum.+Dens evol model fits over 1 dex in λ and 8 dex in flux.



HDF Par Type
E/S0
Sabc
Sd/Irr
(Ω_M,Ω_Λ)=
(0.3,0.7)
CDM simuls
RC3
ESO
–LV
2dF/
MGC
HST/HDF SB–limit
G–b diffraction limit
HST I–band diffr. limit
UDF 100–hr I–band SB–limit
JWST 25–hr SB–limit
JWST diffr. limit
Expected sizes in hierarchical models
GC's
z=7
M_B=
–17
M_B=–20
<--------- 1000–hr JWST det. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)
B_{Vega} (F450W) [total mag]
J'_{AB} (1.35 μ) [total mag]
Effective Radius r_e (arcsec)

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$\gtrsim$30 mag, JWST and at $\gtrsim$10 nJy, SKA will see more than 2×10^6 galaxies/deg^2. Most of these will be unresolved ($r_{hl} \lesssim 0\farcs1$ FWHM (Kawata et al. 2006). Since $z_{med}\simeq1.5$, this influences the balance of how $(1+z)^4$-dimming & object overlap affects the catalog completeness.

- For details, see Windhorst, R. A., et al. 2008, Advances in Space Research, Vol. 41, 1965, (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"