

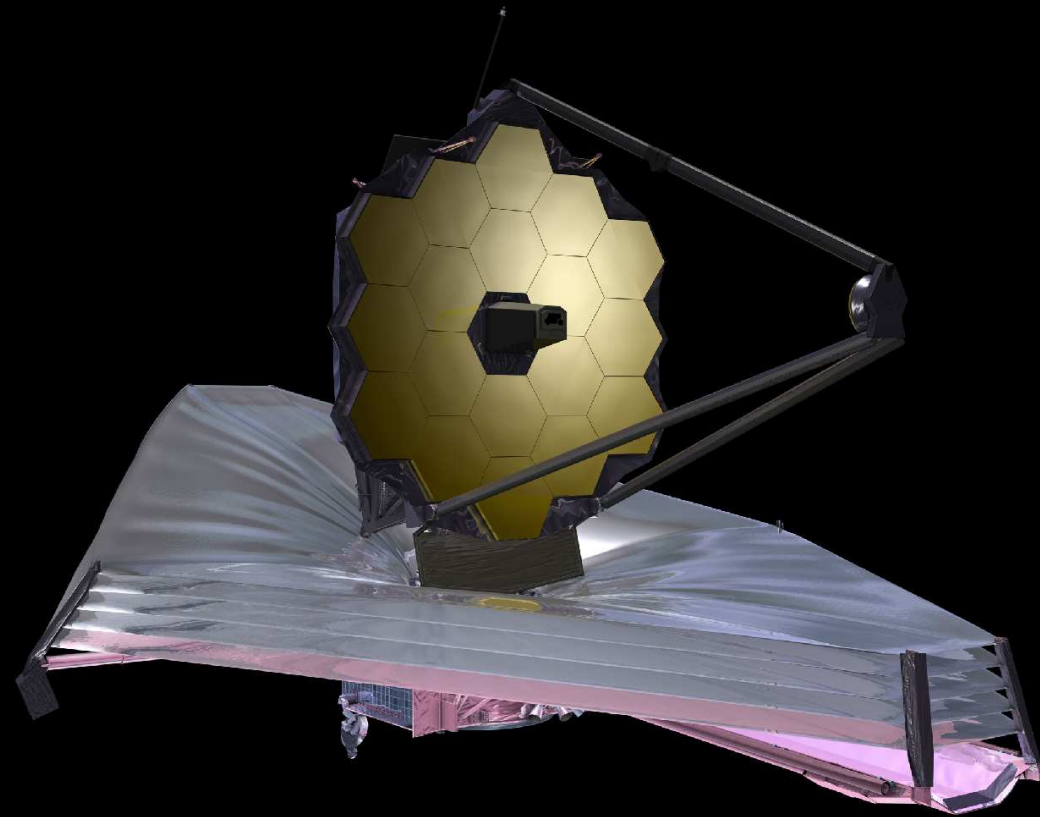
# How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

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**Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist**

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



*Colloquium at the School of Physics, The University of Melbourne, VIC, Australia*

*Tuesday, July 23, 2013. All presented materials are ITAR-cleared.*

# Outline

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- (1) Recent key aspects of the Hubble Space Telescope (HST) project.
- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth: including first WFC3  $z \simeq 6$  QSO host galaxy detection this month ...
- (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-formation & Earth-like exoplanets?]

Sponsored by NASA/HST & JWST



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

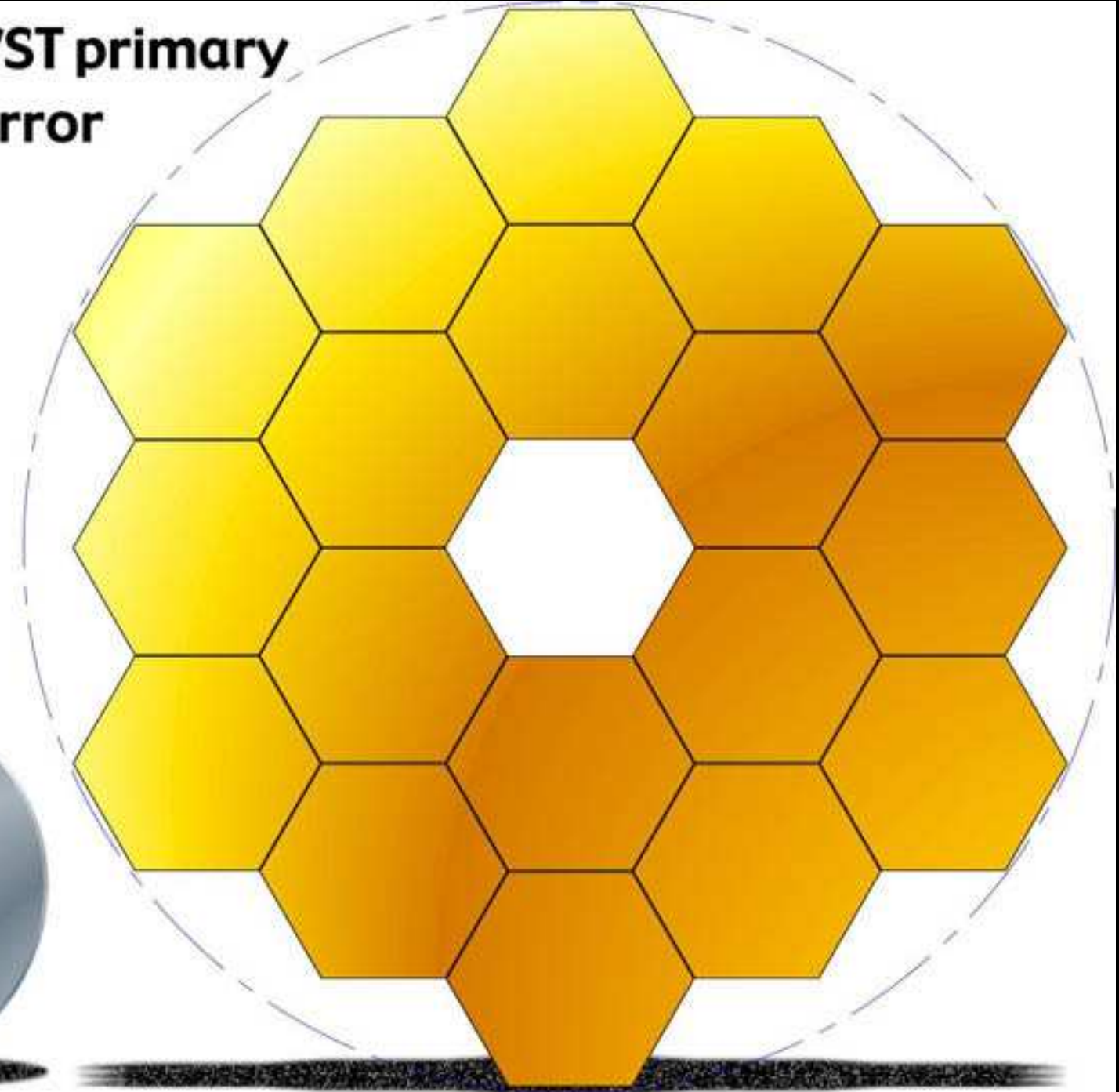


James E. Webb (1906–1992) — Second NASA Administrator

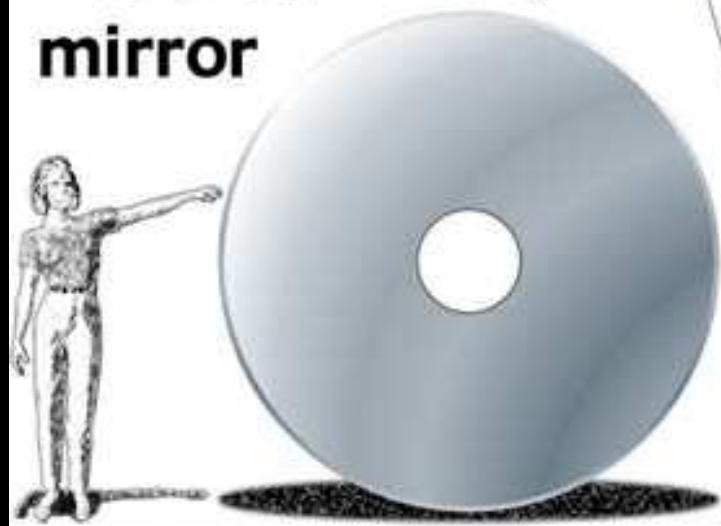
Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2014.

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

**JWST primary  
mirror**

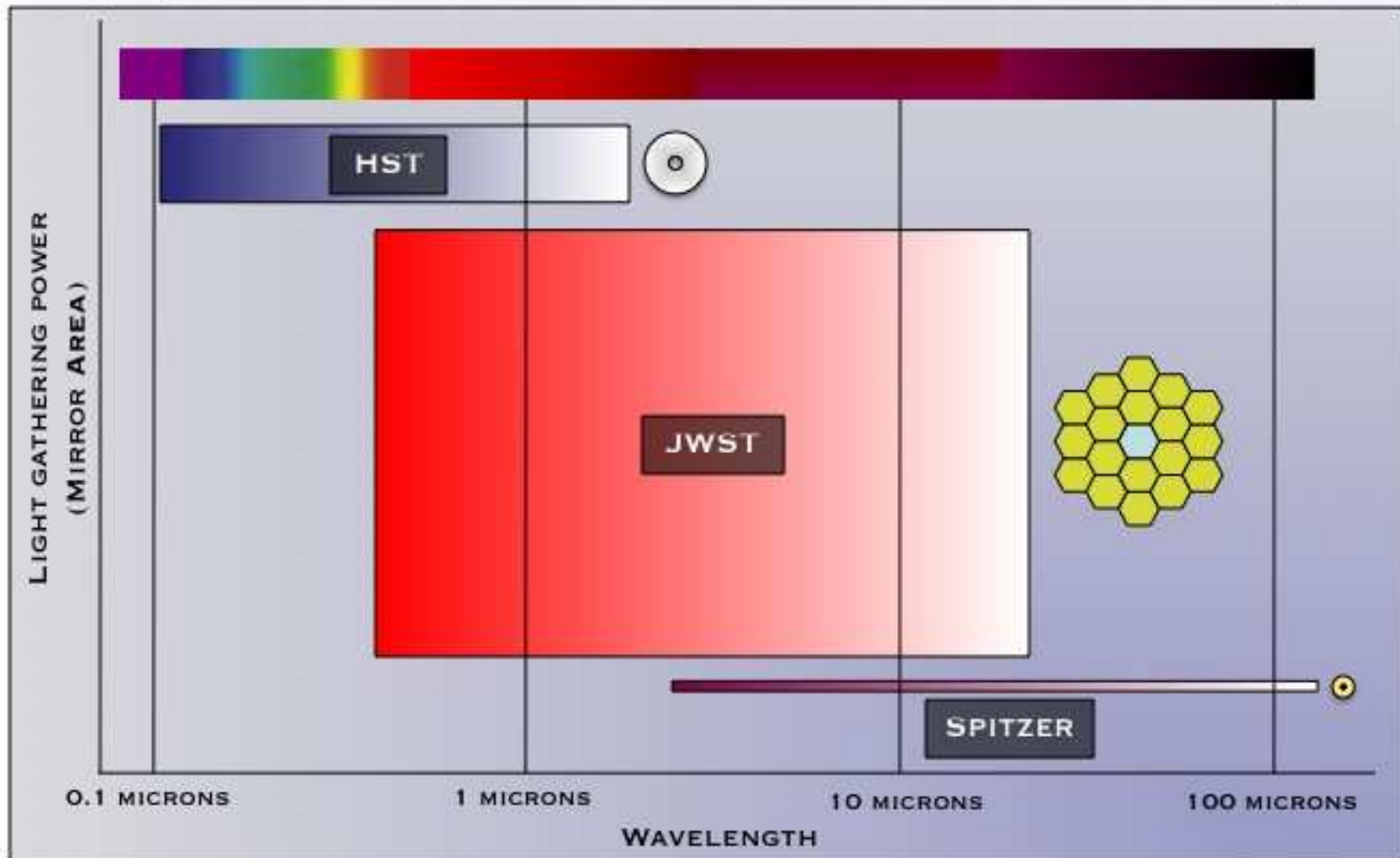


**Hubble primary  
mirror**



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.

# THE JAMES WEBB SPACE TELESCOPE



LIGHT GATHERING POWER  
JWST = 25 M<sup>2</sup> ; HUBBLE = 4.5 M<sup>2</sup> ; SPITZER = 0.6 M<sup>2</sup>

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

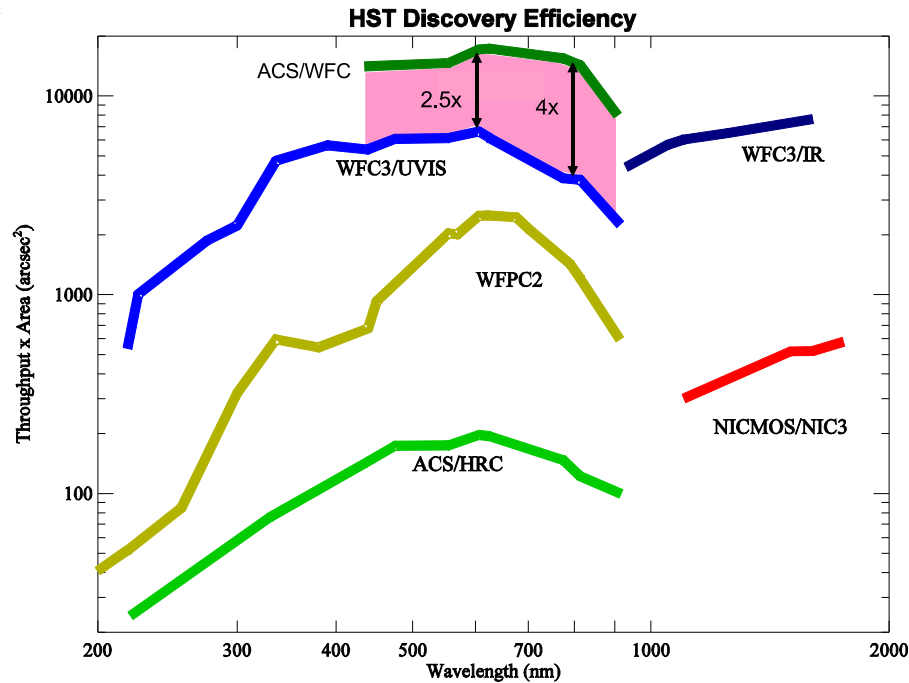
- Vastly larger  $A(\times\Omega)$  than HST in UV-optical and Spitzer in mid-IR.

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

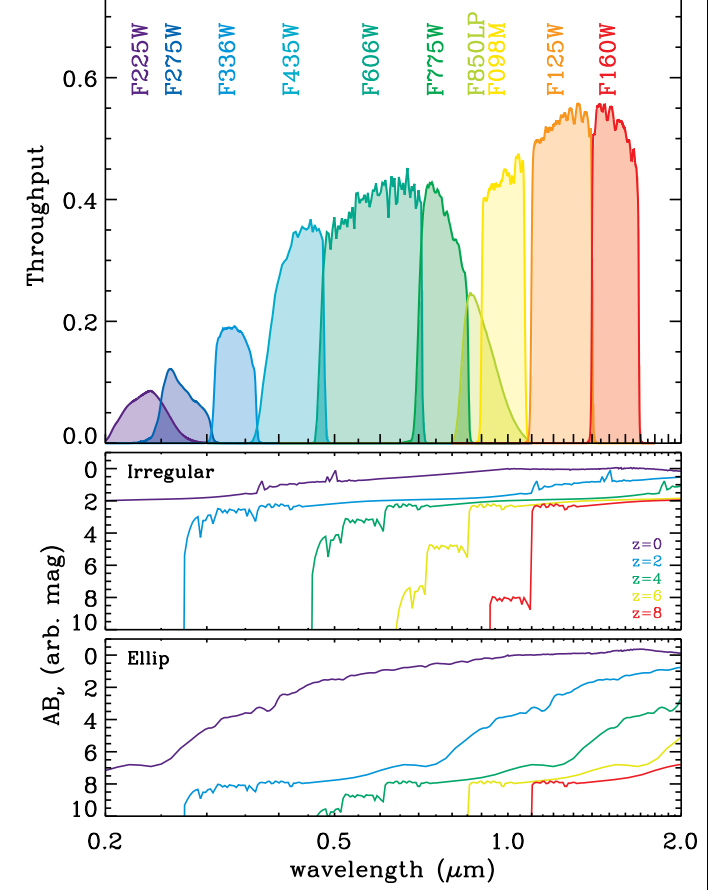


HST WFC3 and its **IR channel**: a critical pathfinder for JWST science.

# Role of ACS in HST Post-SM4 Imaging Capability



ACS/WFC superior to WFC3 survey efficiency at visible-red wavelengths



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:

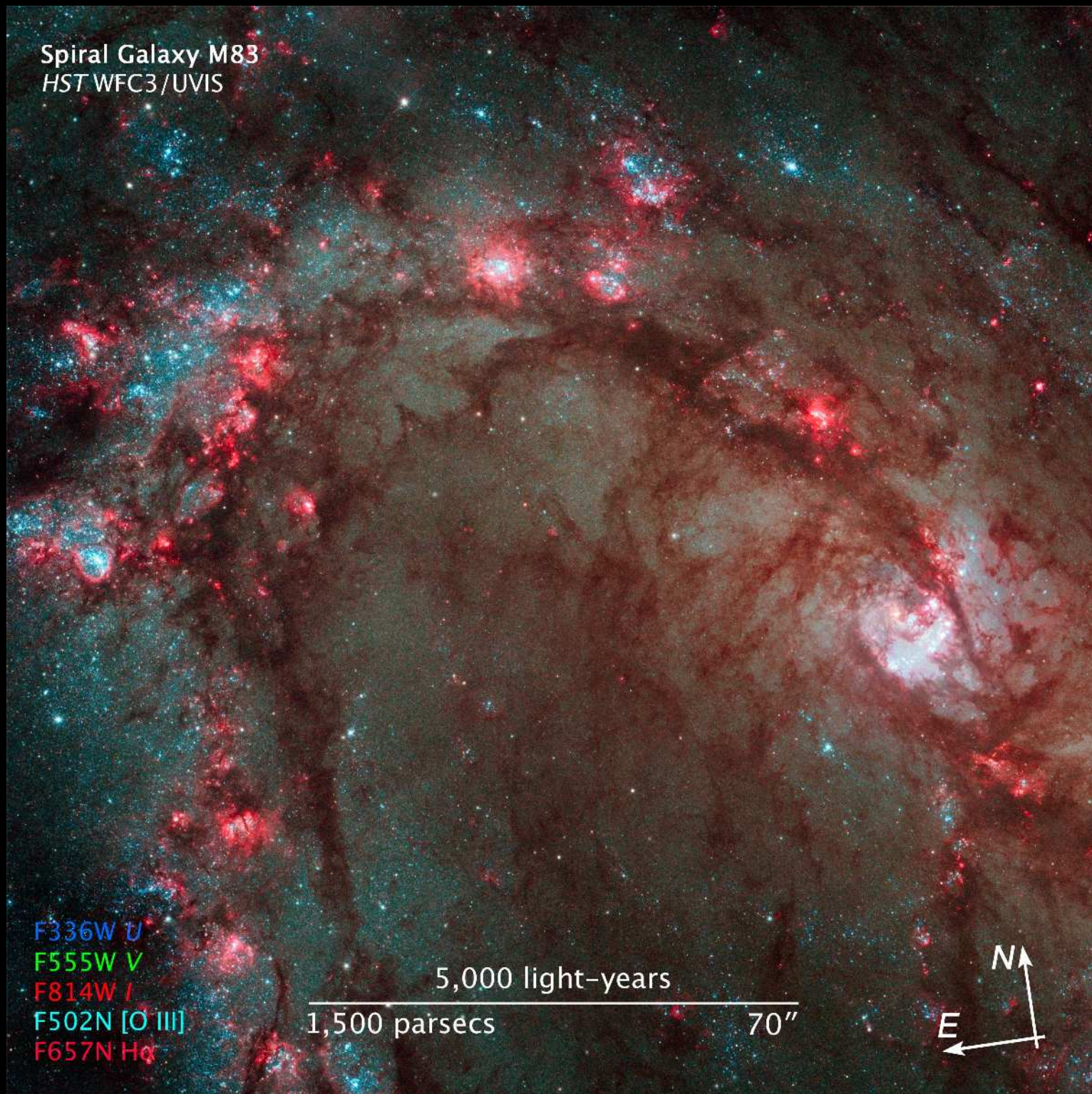
- $QE \gtrsim 70\%$ ,  $1k \times 1k$  array of  $0''.13$  pixel,  $FOV \simeq 2'.25 \times 2'.25$ .

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

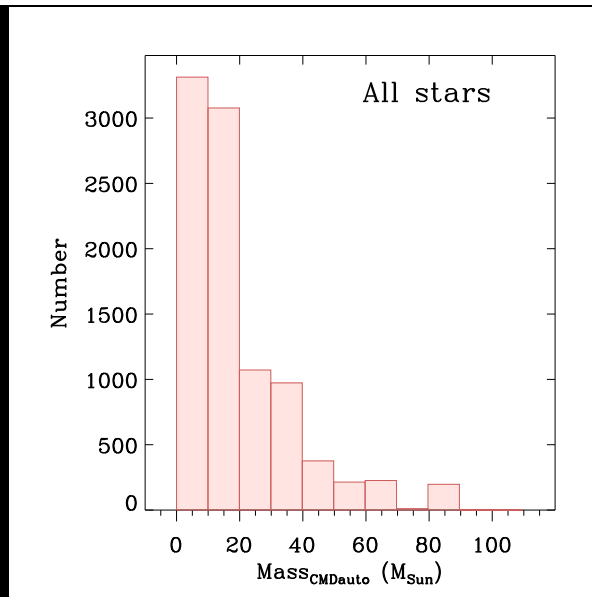
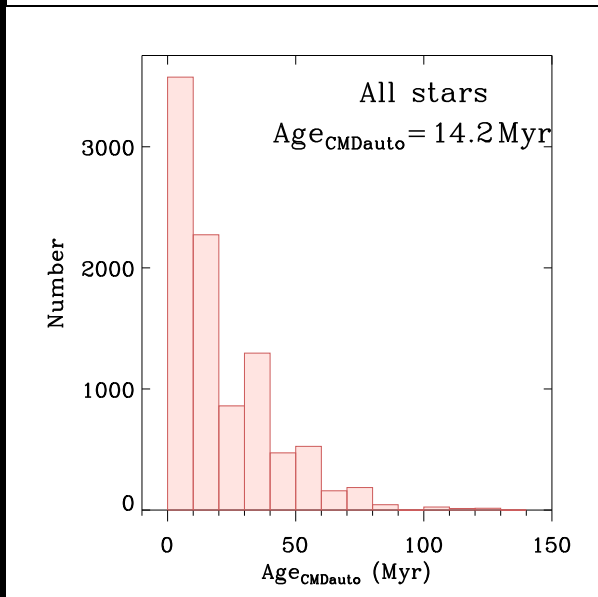
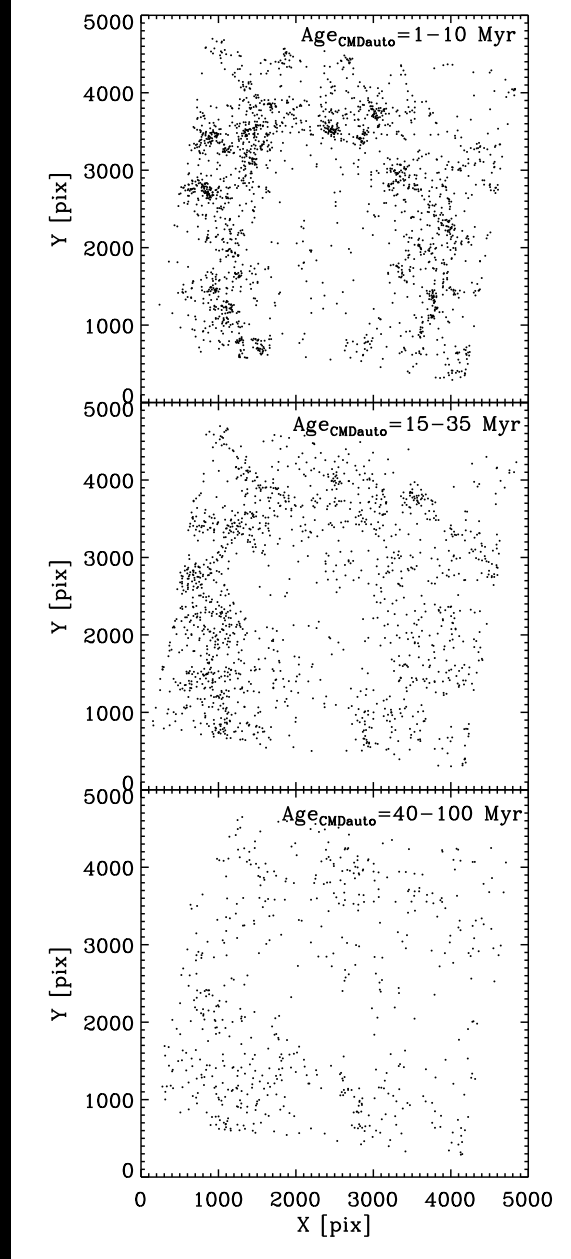
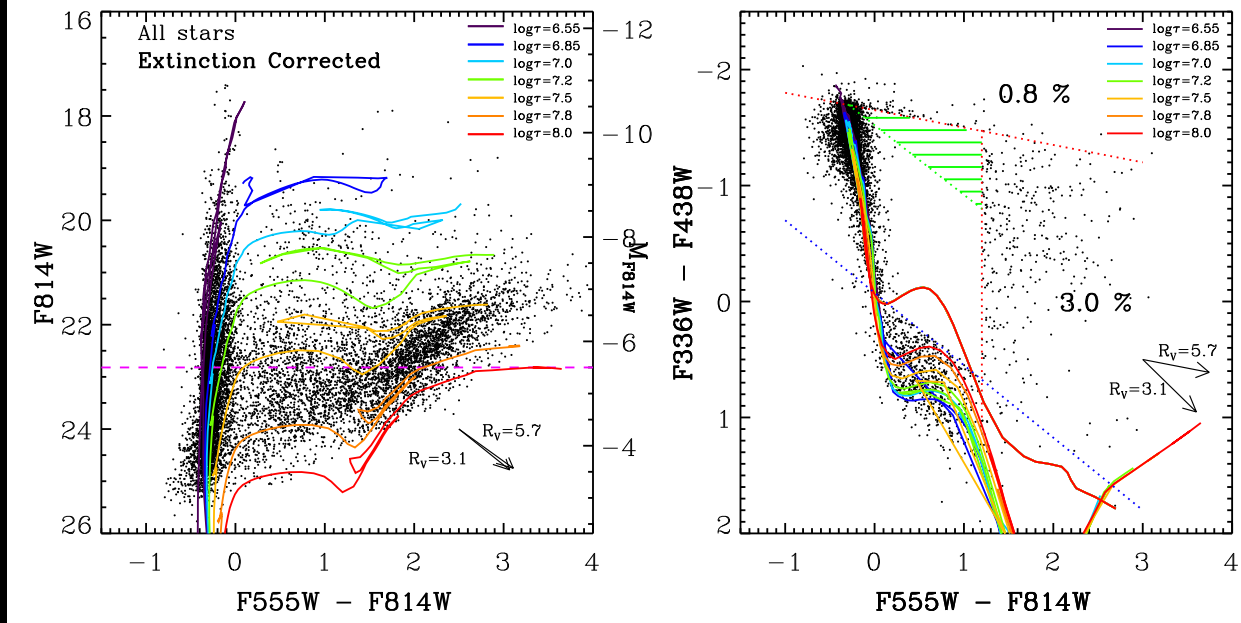
WFC3 filters designed for star-formation and galaxy assembly at  $z \simeq 1-8$ .

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

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







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!



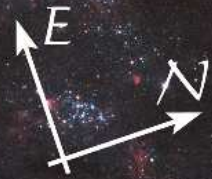
*"For God's sake, Edwards. Put the laser pointer away."*

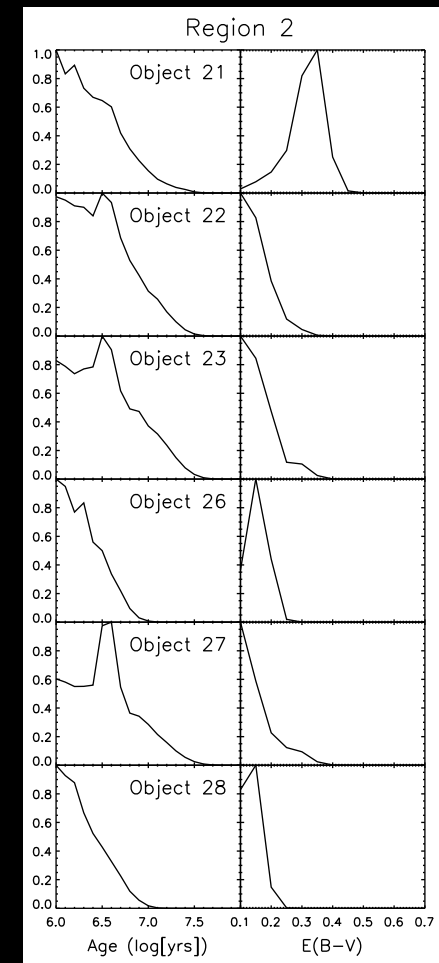
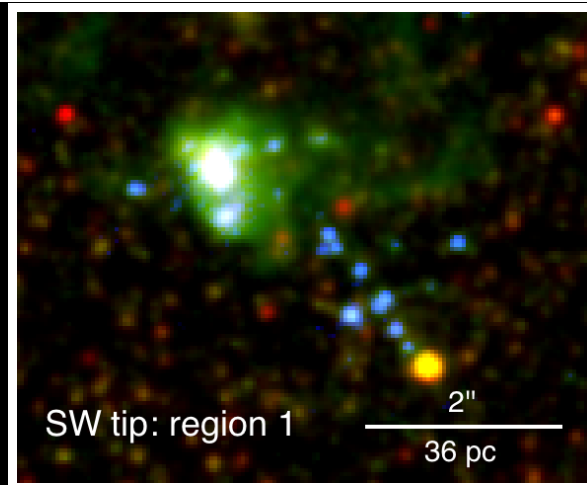
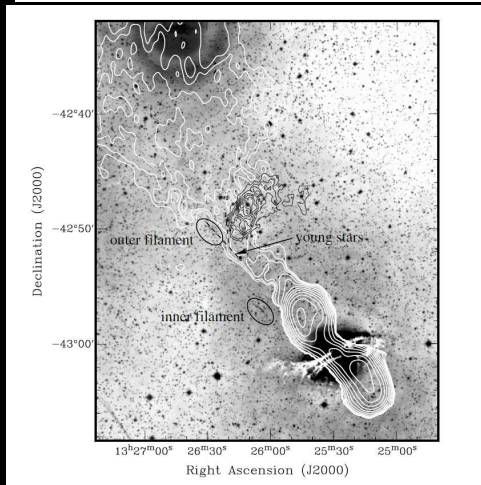
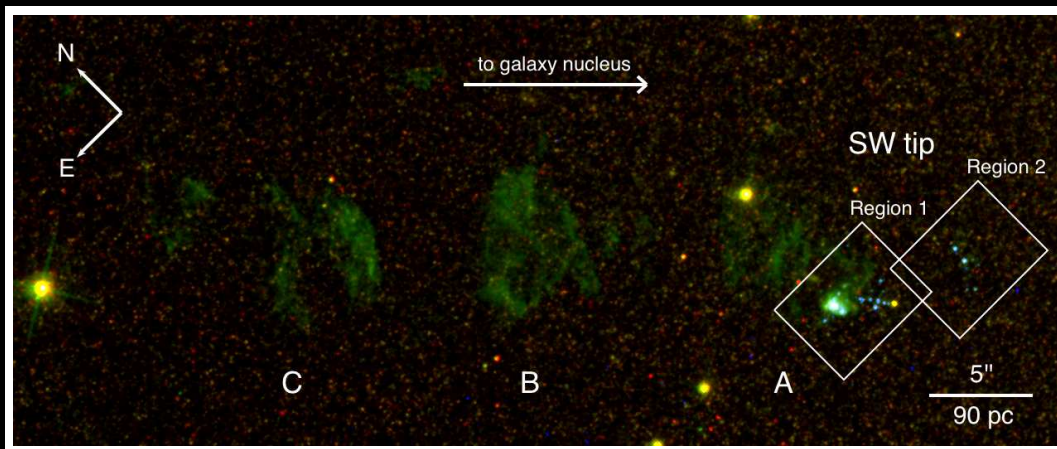
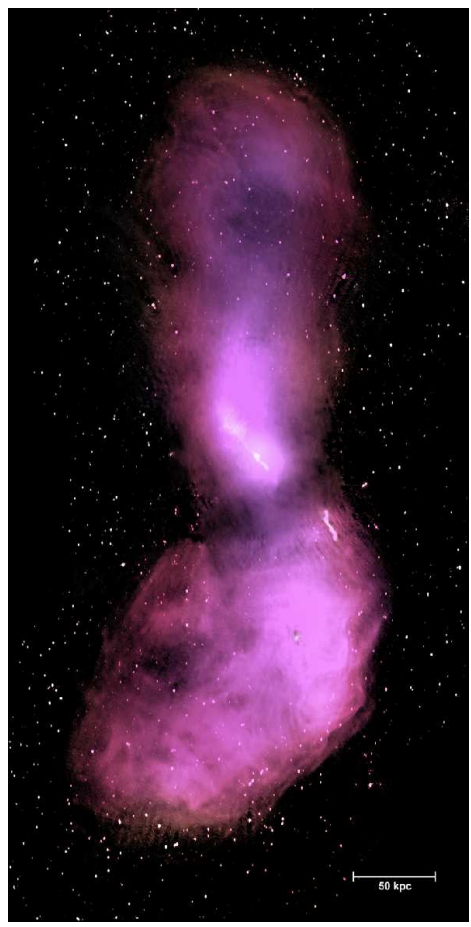
The danger of having Quasar-like devices too close to home ...

Centaurus A  
NGC 5128  
HST WFC3/UVIS

F225W+F336W+F438W  
F487N H $\beta$   
F502N [O III]  
F547M  $\gamma$   
F657N H $\alpha$ + [N II]  
F673N [S II]  
F814W I

3000 light-years  
1400 parsecs  
56''

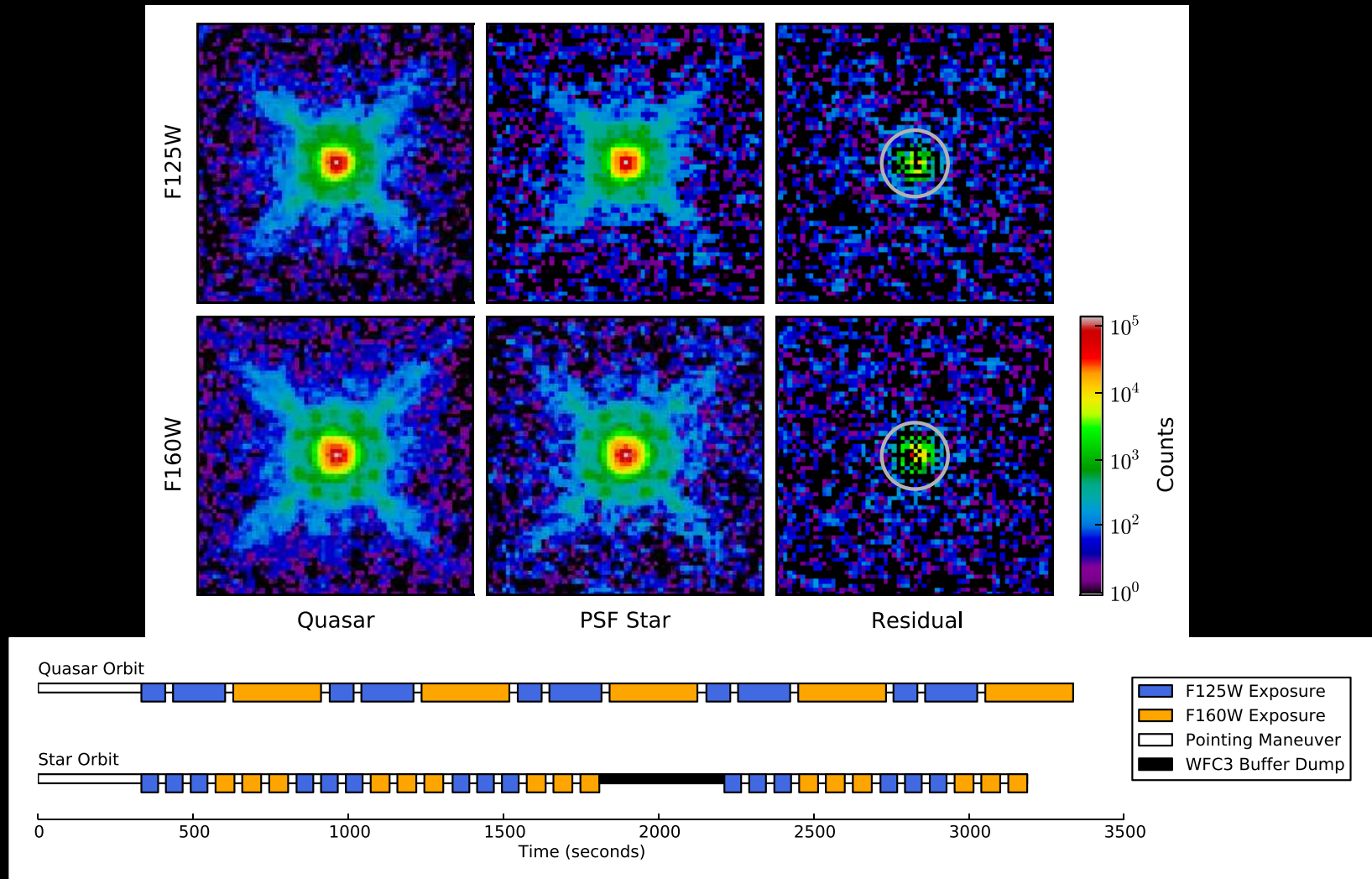




[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain, Cornwell & Ekers (2009). Fermi GeV source (Yang<sup>+</sup> 12); & Auger UHE Cosmic Rays (Abreu<sup>+</sup> 2010).  
 [Middle] SF in Cent A jet's wake (Crockett<sup>+</sup> 2012, MNRAS, 421, 1602).  
 [Right] Well determined ages for young ( $\sim 2$  Myr) stars near Cen A's jet.

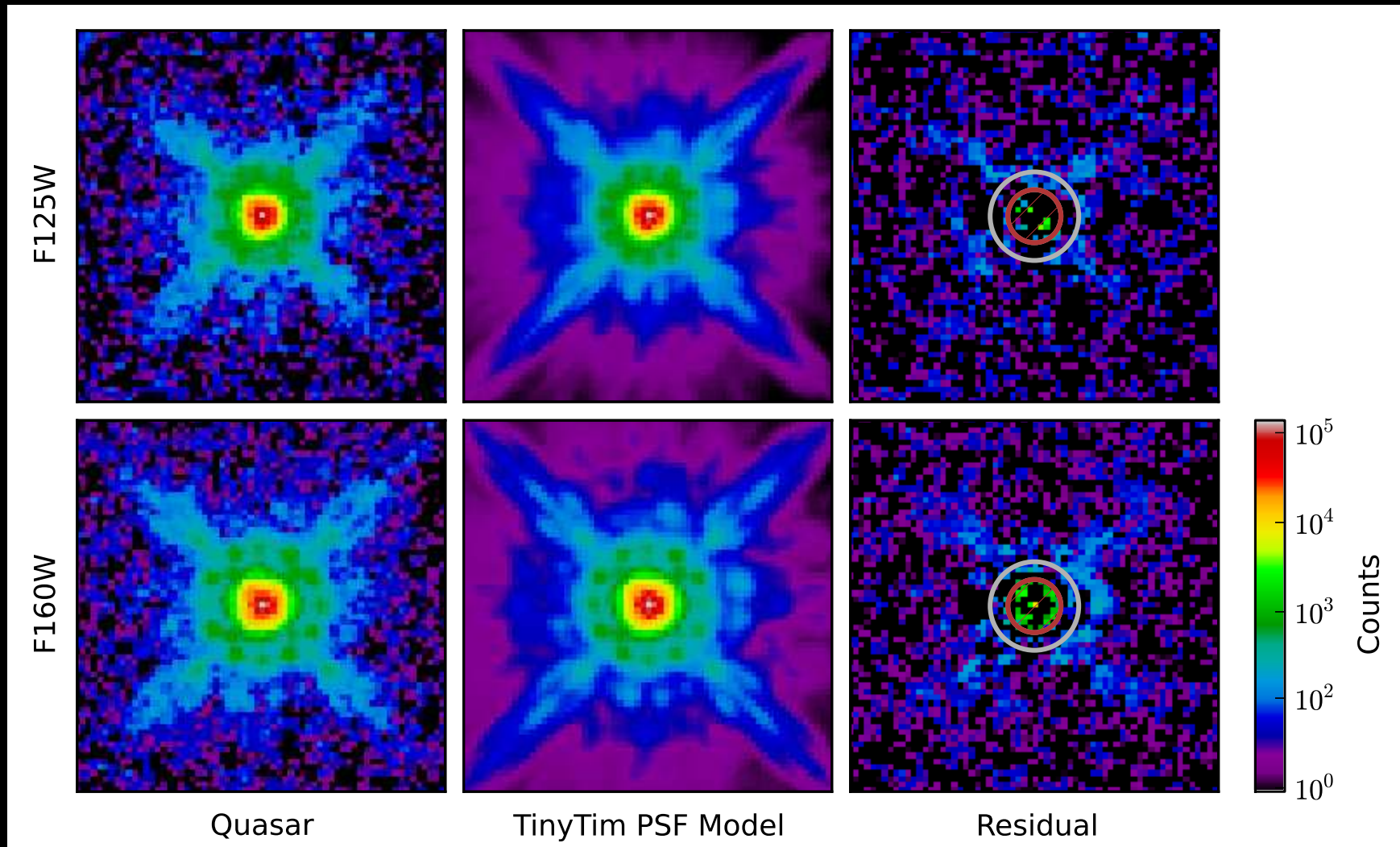
- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV-blue before JWST flies.

## (2) HST WFC3 observations of QSO host galaxies at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley et al 2012, ApJL, 756, L38).
- PSF-star ( $AB \simeq 15$  mag) subtracts  $z=6.42$  QSO ( $AB \simeq 18.5$ ) nearly to the noise limit: NO host galaxy detected  $100\times$  fainter ( $AB \gtrsim 23.5$  at  $r \gtrsim 0.3$ ).

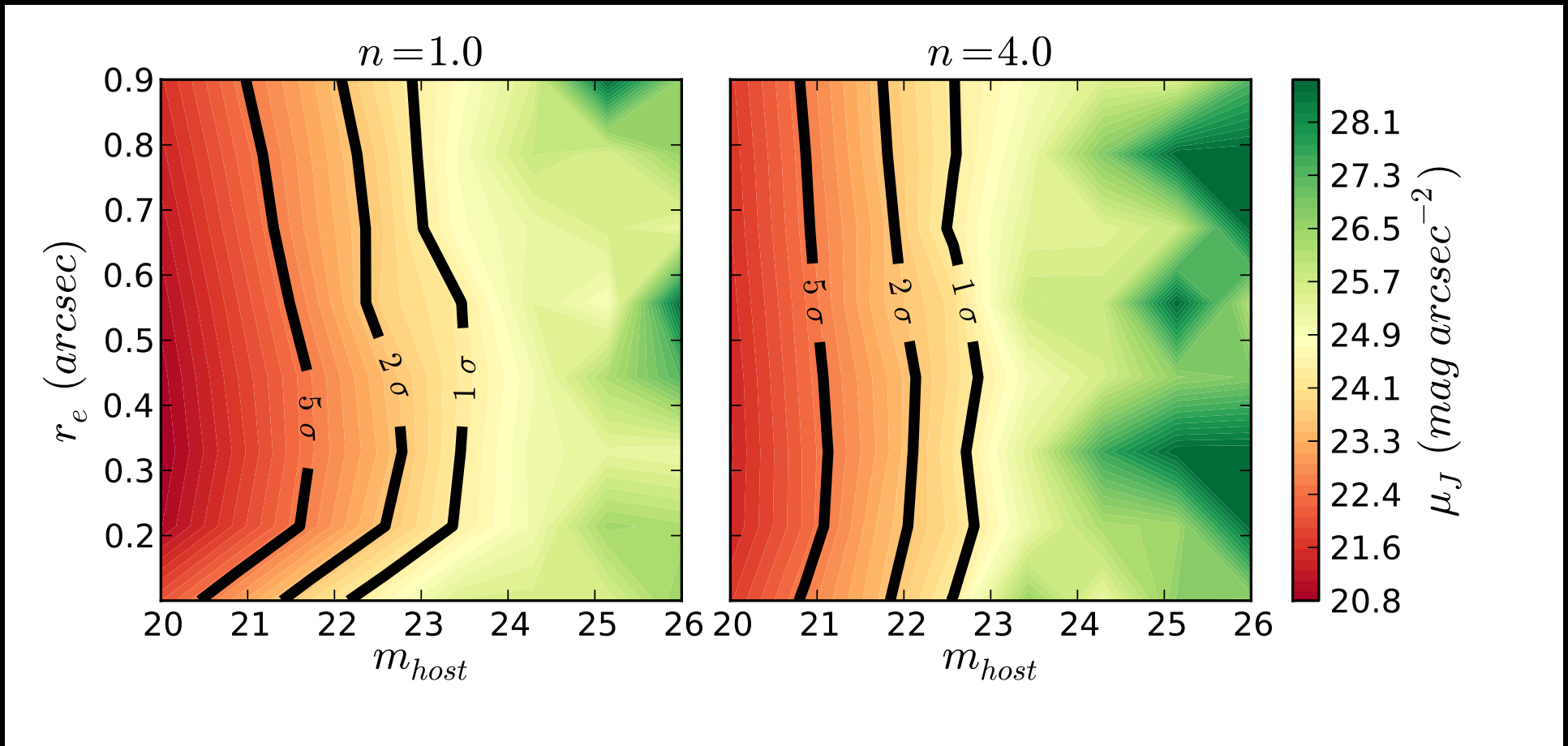
## (2) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- 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  $r \simeq 0''.3-0''.5$ .

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

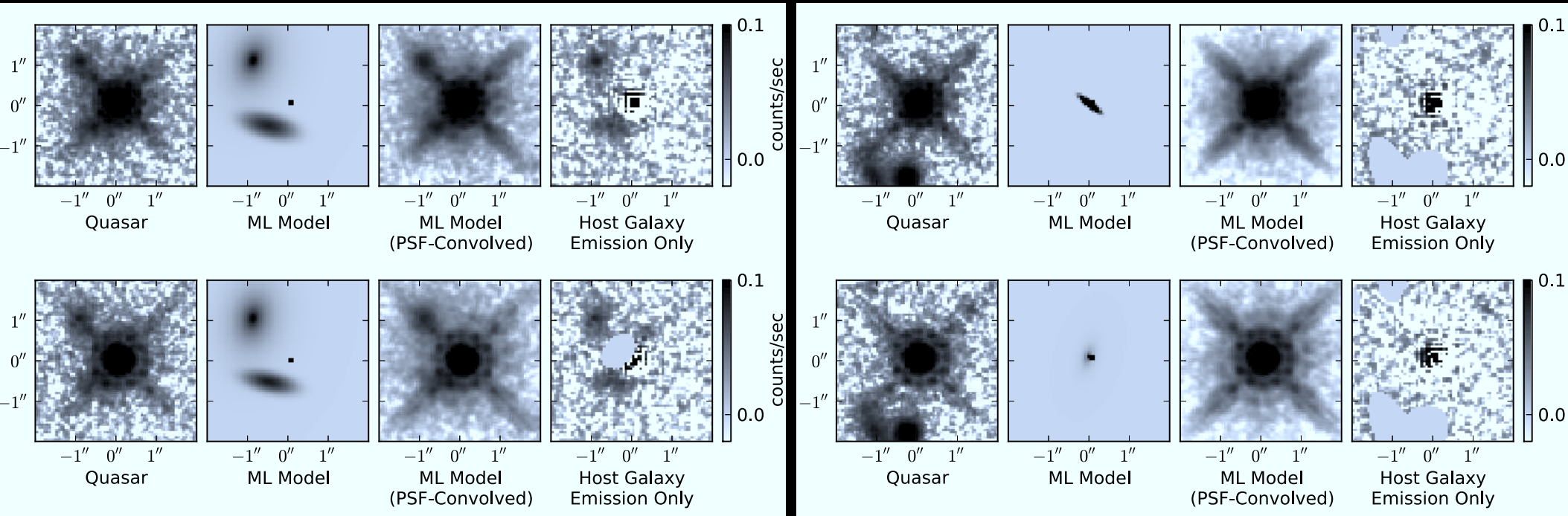
## (2) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$



- TinyTim fit of PSF-star + Sersic models of galaxy light-profile, nearly to the noise limit: NO host galaxy at  $AB \gtrsim 23.0$  mag with  $r_e \simeq 0.5$  (Mechtley et al. 2012, ApJL, 756, L23; astro-ph/1207.3283)

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

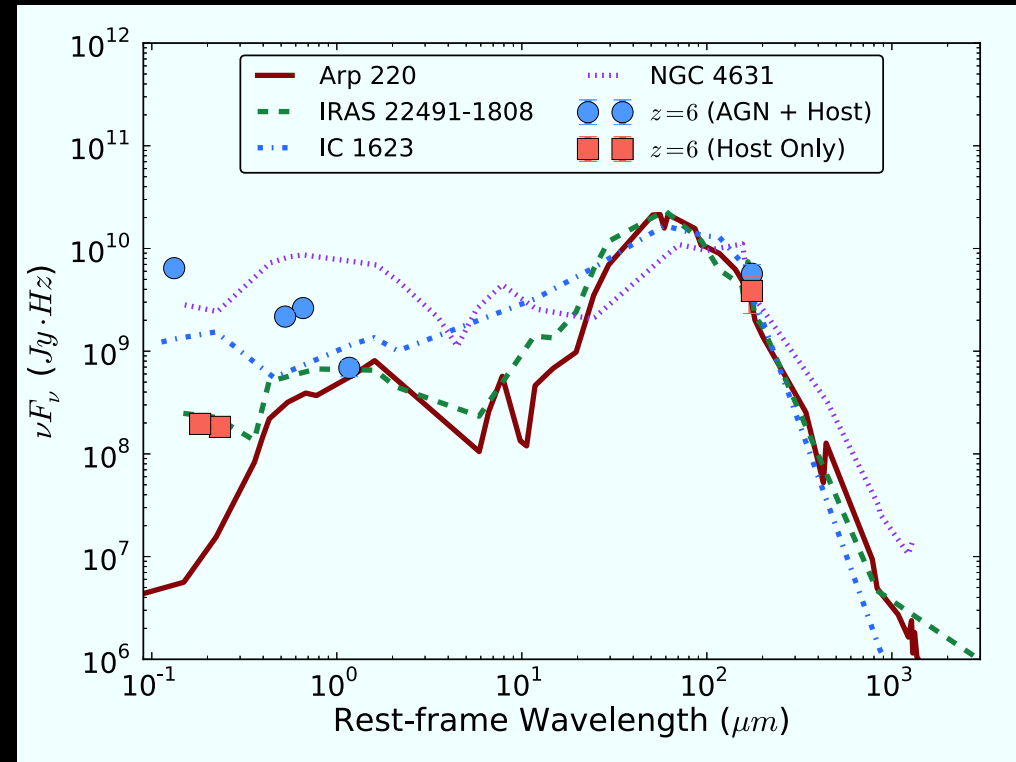
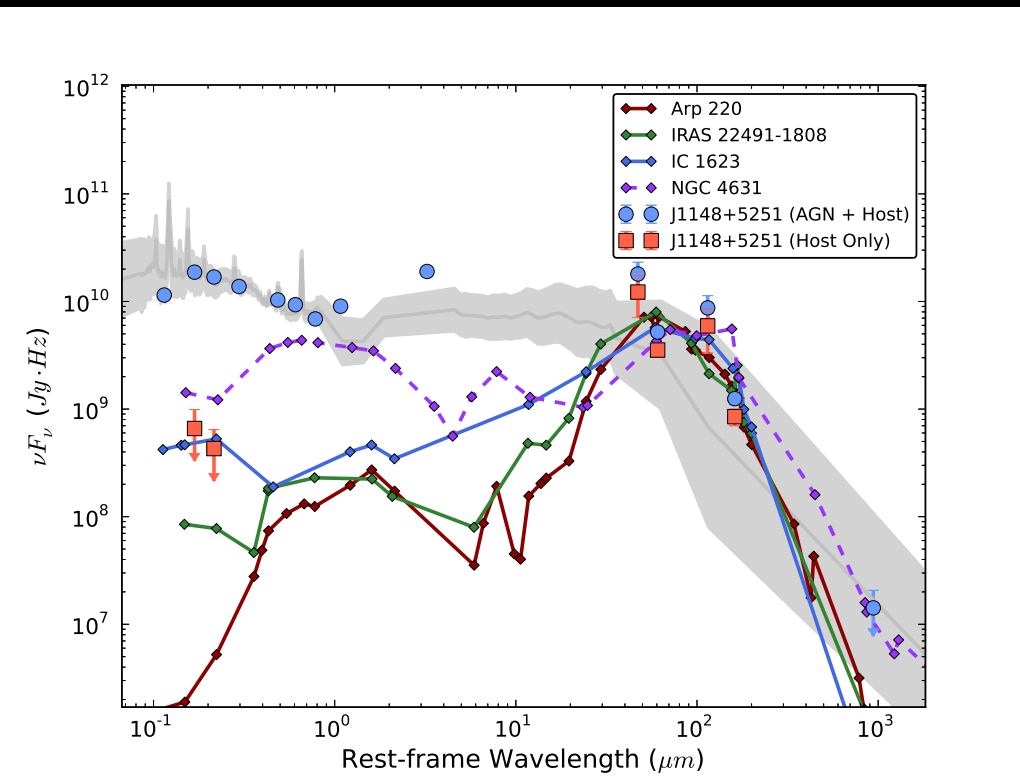
## (2) WFC3: First detection of one QSO Host Galaxy at $z \simeq 6$ (Giant merger?)



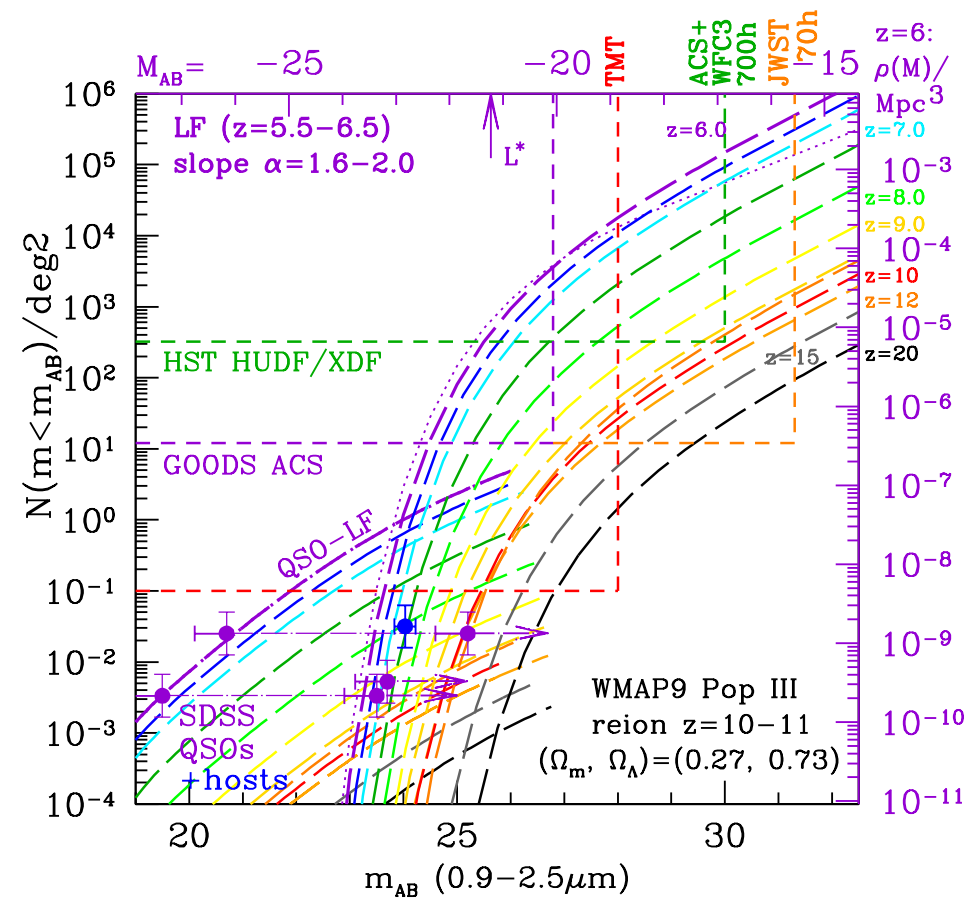
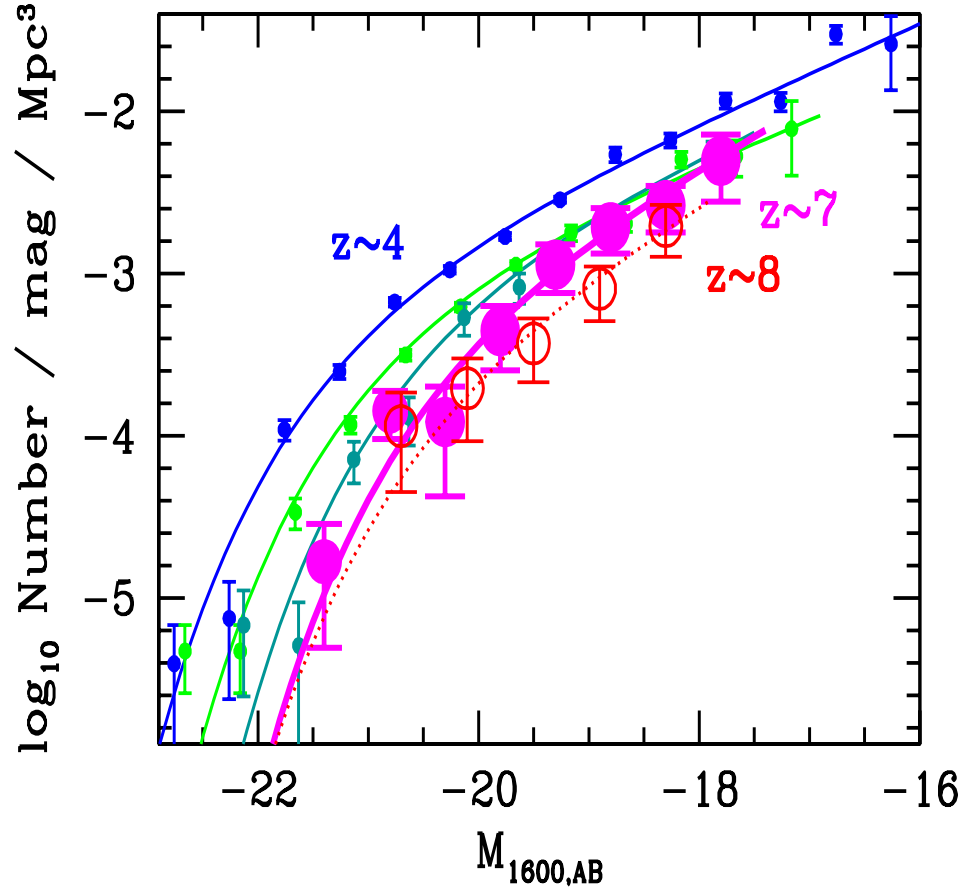
- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO data critical for PSF stars (Mechtley<sup>+</sup> 2013).
  - First solid detection out of four  $z \simeq 6$  QSOs [3 more to be observed].
  - One  $z \simeq 6$  QSO host galaxy: Giant merger morphology + tidal structure??
  - Same J+H structure! Blue UV-SED colors:  $(J-H) \simeq 0.19$ , constrains dust.
    - IRAS starburst-like SED from rest-frame UV–far-IR,  $A_{FUV} \sim 1$  mag.
  - $M_{AB}^{host}(z \simeq 6) \lesssim -23.0$  mag, i.e.,  $\sim 2$  mag brighter than  $L^*(z \simeq 6)$ !
- $\Rightarrow z \simeq 6$  QSO duty cycle  $\lesssim 10^{-2}$  ( $\lesssim 10$  Myrs); 1/4 QSO's close to Magorrian.



## (2) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$

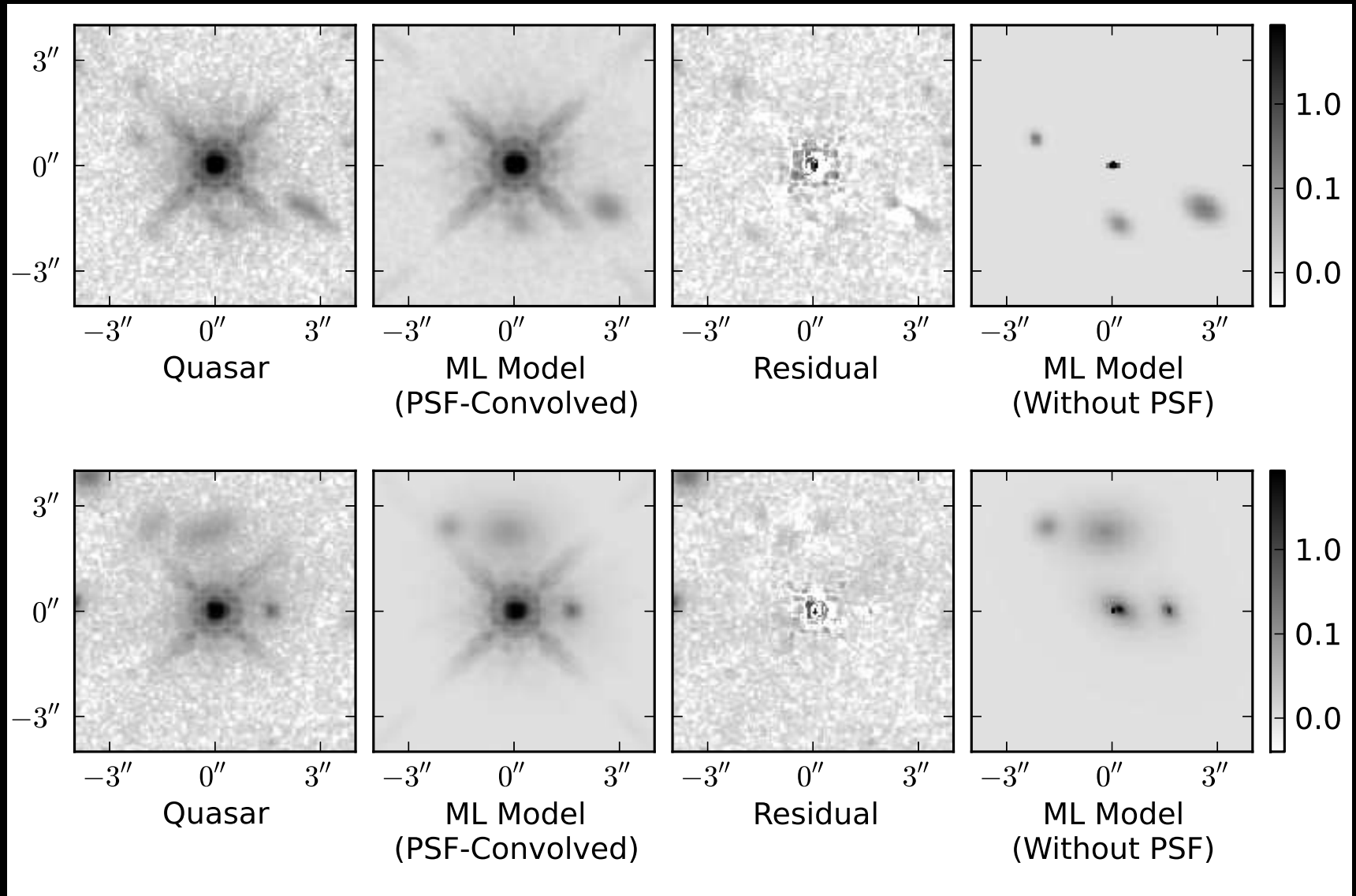


- Blue dots:  $z \simeq 6$  QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at  $z \gtrsim 1$  (normalized at  $0.5 \mu$ ). Red:  $z \simeq 6$  host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages  $\lesssim 1$  Gyr) normalized at  $100 \mu$ : [LEFT] Rules out  $z=6.42$  spiral or bluer host galaxy SEDs for 1148+5251. (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38).
- [RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR,  $A_{FUV}(\text{host}) \sim 1$  mag (Mechtley et al. 2013b).
- JWST Coronagraphs can do this  $10\text{--}100\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu$ ).



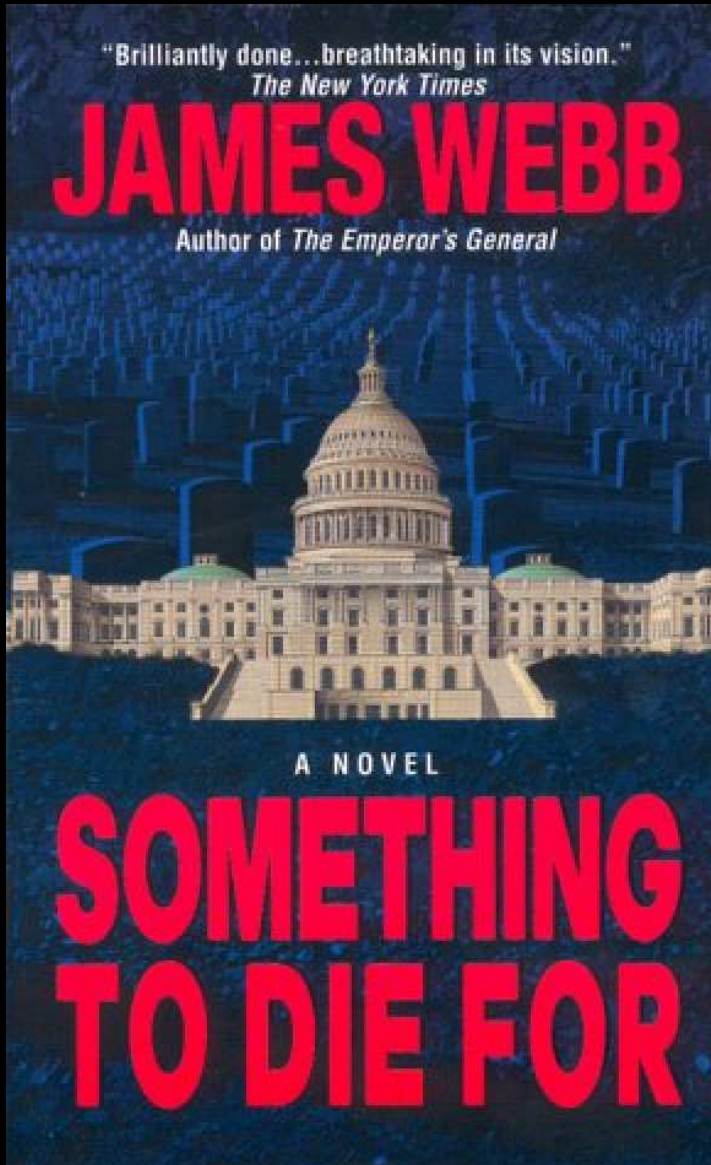
- $M_{AB}^{host}(z \simeq 6) \lesssim -23.0 \simeq M^* - 2 \text{ mag}$  at  $z \simeq 6$ ; 1/4 QSOs @ Magorrian.  
 $\Rightarrow z \simeq 6$  QSO duty cycle ( $A_{FUV} \simeq 0 \rightarrow 1$ )  $\lesssim 0.01 \rightarrow 1.0$  ( $\lesssim 10 \rightarrow 950$  Myrs).
- To study co-evolution of SMBH-growth & proto-bulge assembly for  $z \lesssim 10-15$  requires new AGN finding techniques for JWST (e.g., Mortlock).
- JWST Coronagraphs can also trace super-massive black-holes as faint quasars in young galaxies: JWST needs  $2.0 \mu\text{m}$  diffraction limit for this.

## (2) WFC3 observations of QSO host galaxies at $z \simeq 2$ (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 $\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu\text{m}$ ).

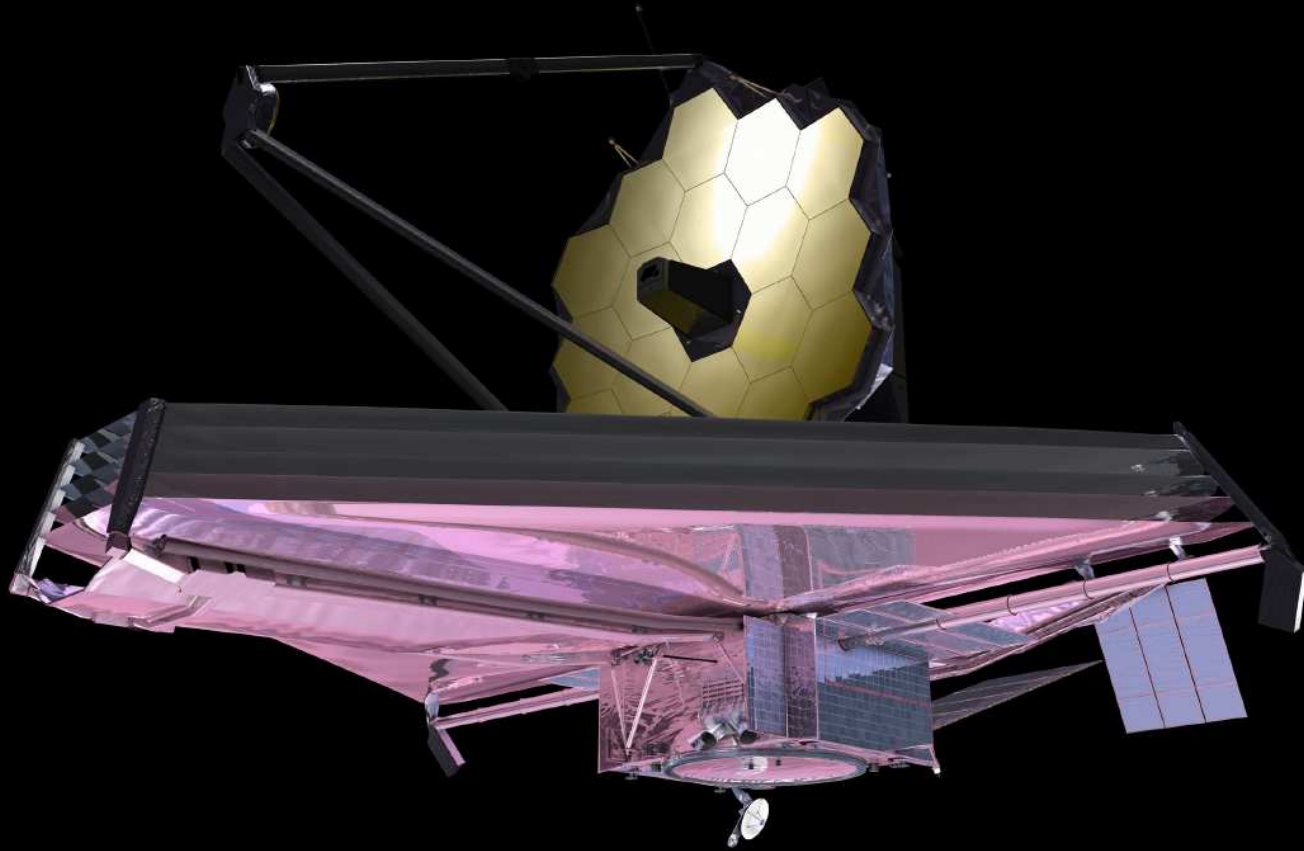
### (3) Brief Update of the James Webb Space Telescope (JWST).



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 ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy at  $0.6\text{--}28 \mu\text{m}$  wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging ( $\text{AB}=31.5 \text{ mag}$ ) and spectroscopy.

# THE JAMES WEBB SPACE TELESCOPE

## JWST LAUNCH

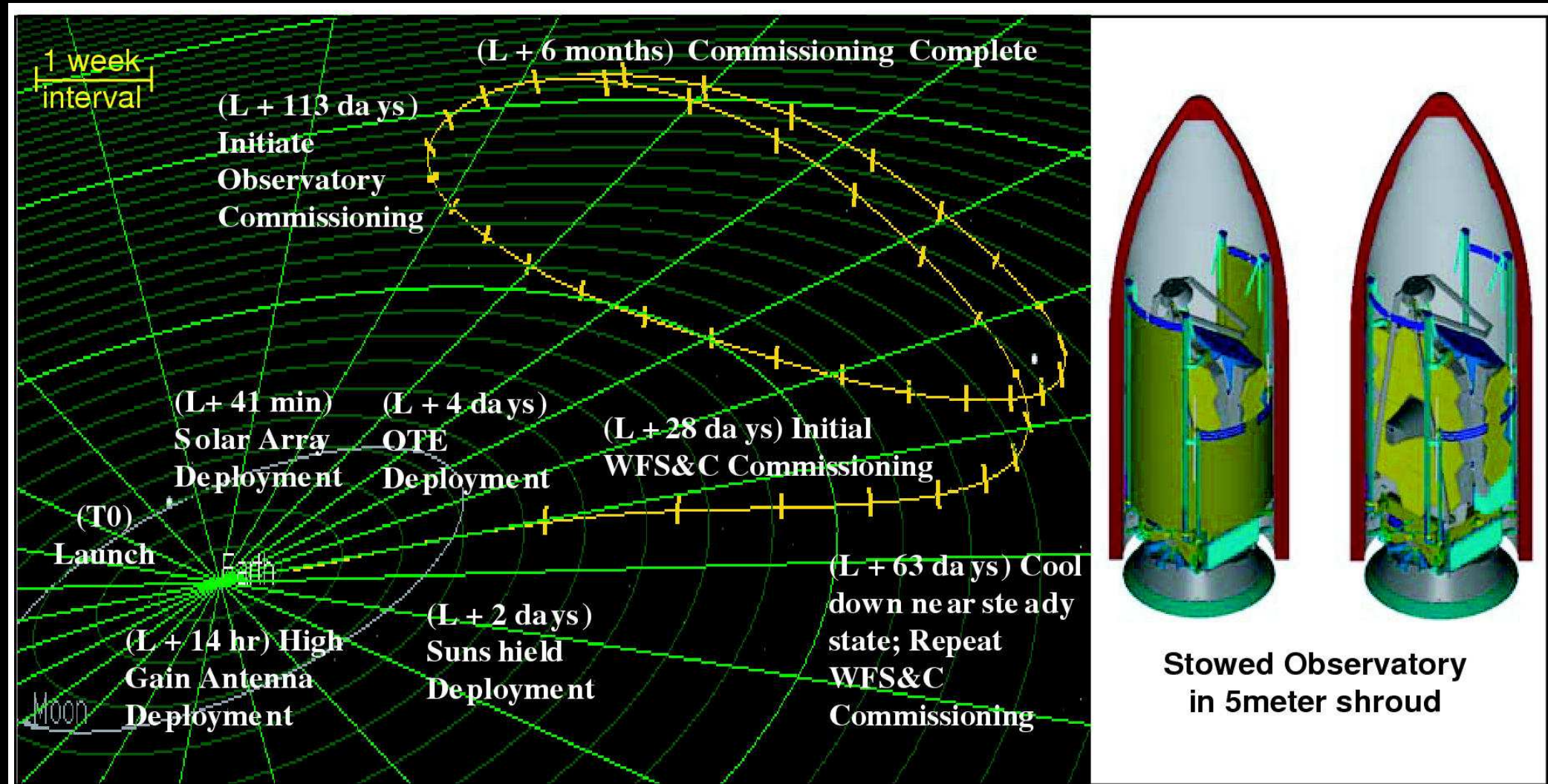
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



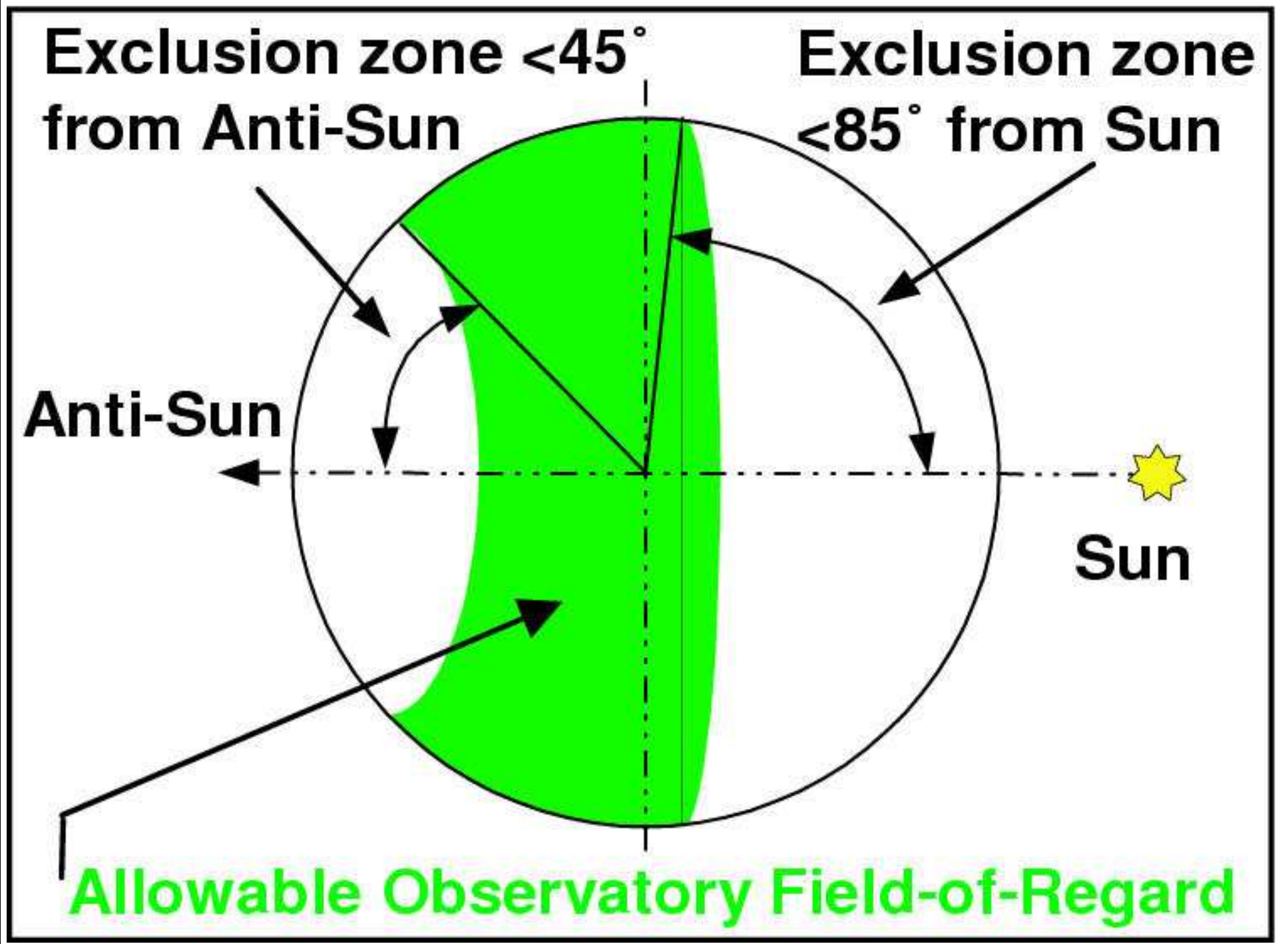
ARIANESPACE - ESA - NASA

- 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?



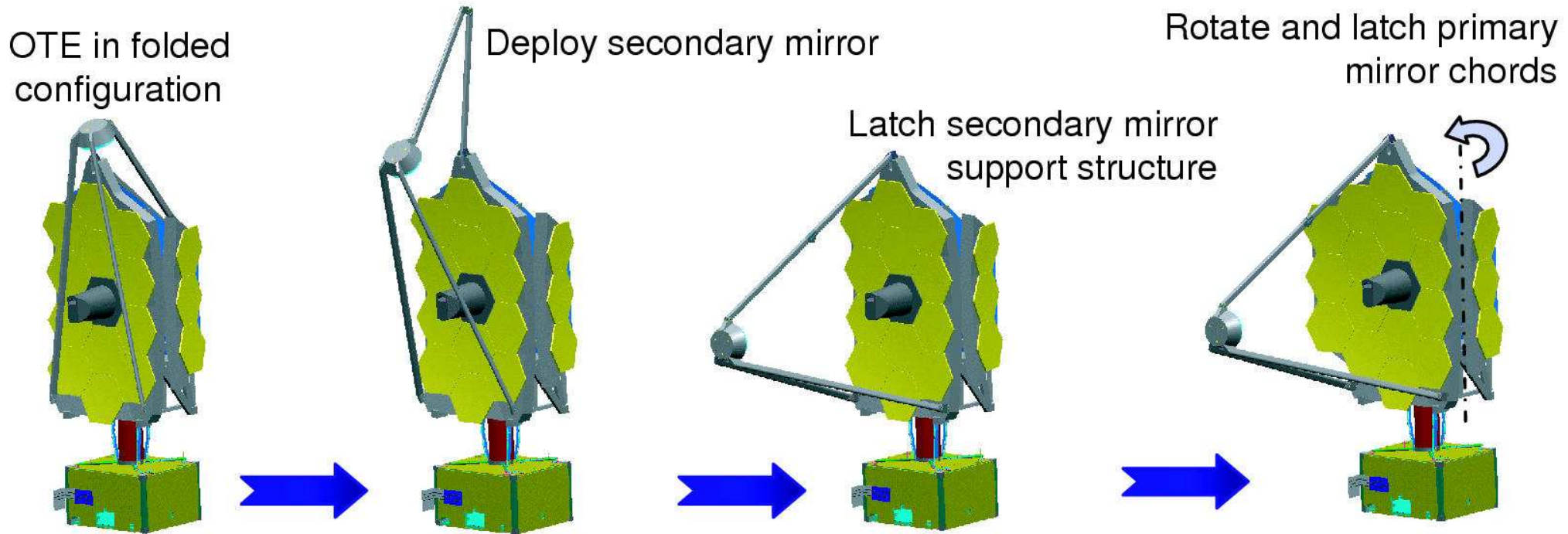
- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe  $\gtrsim 70\%$  of the time, and send data back to Earth every day.



JWST can observe NEP+SEP continuously: Think of 1000-hr proposals!

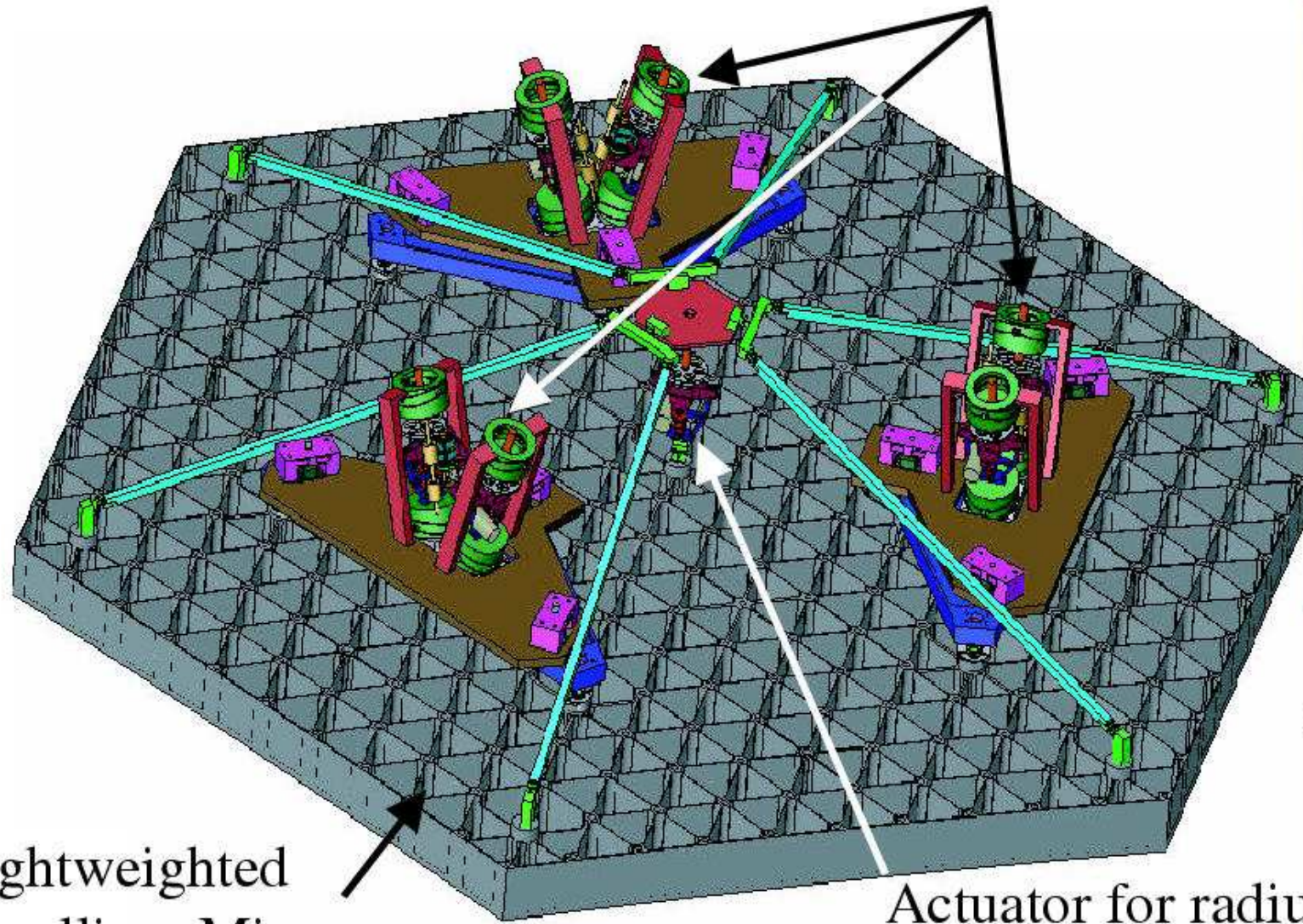


- (3b) How will JWST be automatically deployed?



- 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.

# Actuators for 6 degrees of freedom rigid body motion



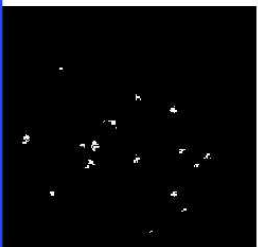
Actuator  
development  
unit

Lightweighted  
Beryllium Mirror

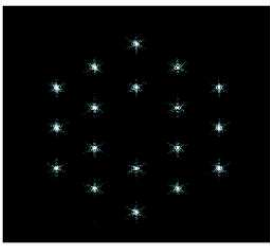
Actuator for radius  
of curvature adjustment

Active mirror segment support through "hexapods", similar to Keck.  
Redundant & doubly-redundant mechanisms, quite forgiving against failures.

**First light  
NIRCam**



1. Segment Image Capture



After Step 1

**Initial Capture**

18 individual 1.6-m diameter aberrated sub-telescope images  
 PM segments: < 1 mm, < 2 arcmin tilt  
 SM: < 3 mm, < 5 arcmin tilt

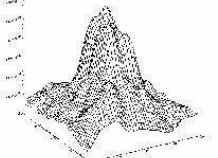
**Final Condition**

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

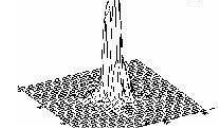


Primary Mirror segments:  
 < 1 mm, < 10 arcsec tilt  
 Secondary Mirror :  
 < 3 mm, < 5 arcmin tilt

WFE < 200 μm (rms)

**3. Coarse Phasing - Fine Guiding (PMSA piston)**

After Step 3

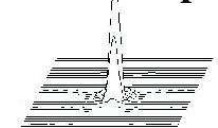


WFE: < 250 μm rms

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.



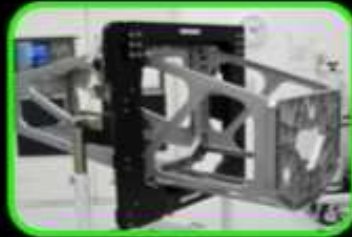
# JWST Hardware Status



Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror

Secondary Mirror Pathfinder Strut



Fine Steering Mirror



Secondary Mirror Hexapod

ISIM Flight Bench



Secondary Mirror



Membrane Mgmt



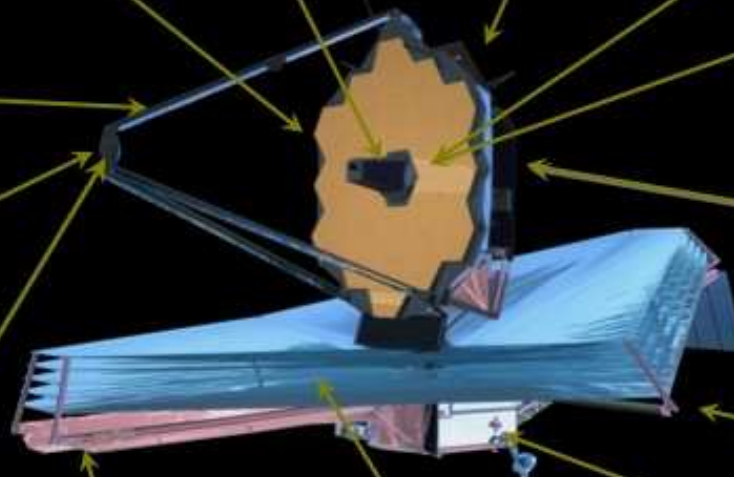
Pathfinder Membrane



Spacecraft computer Test Unit

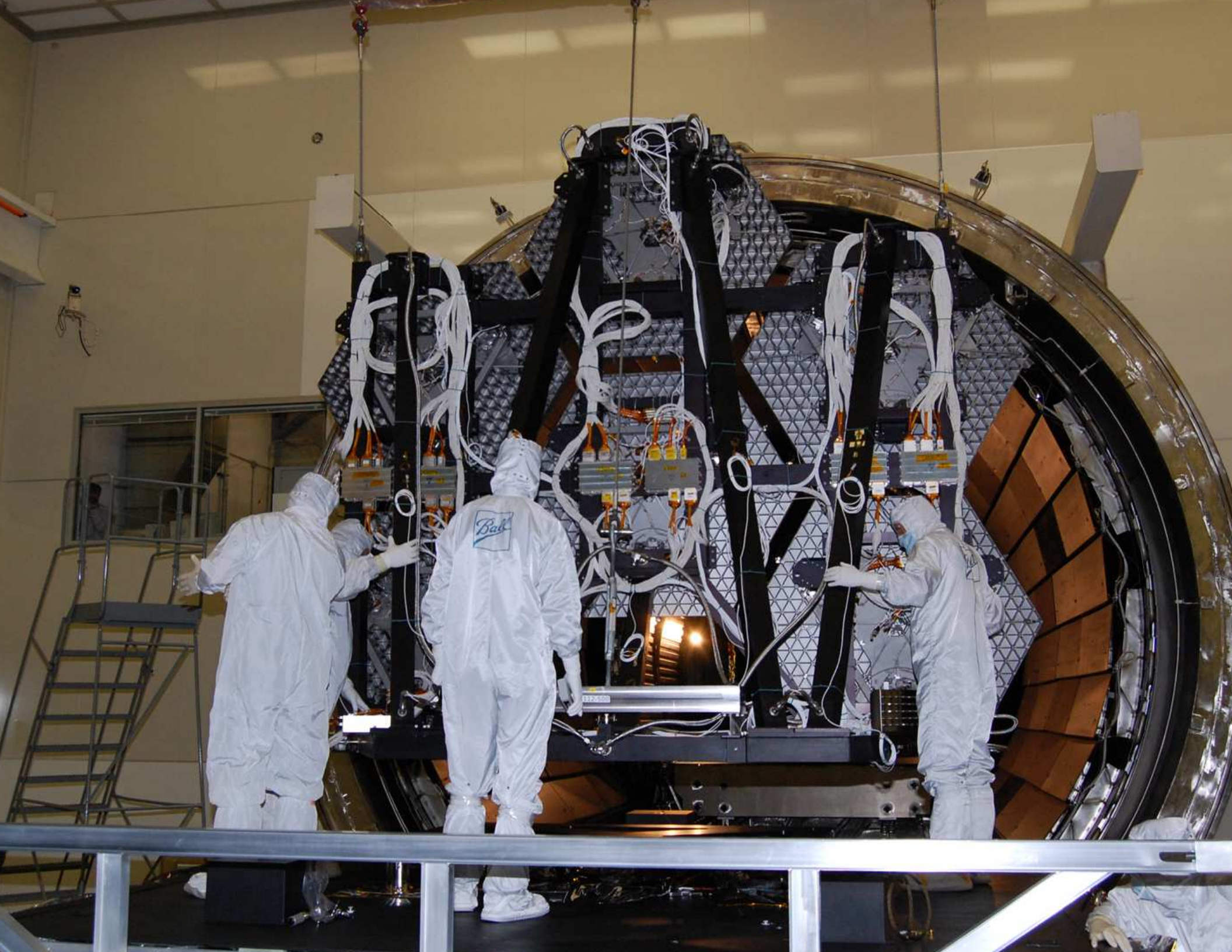


Mid-boom Test



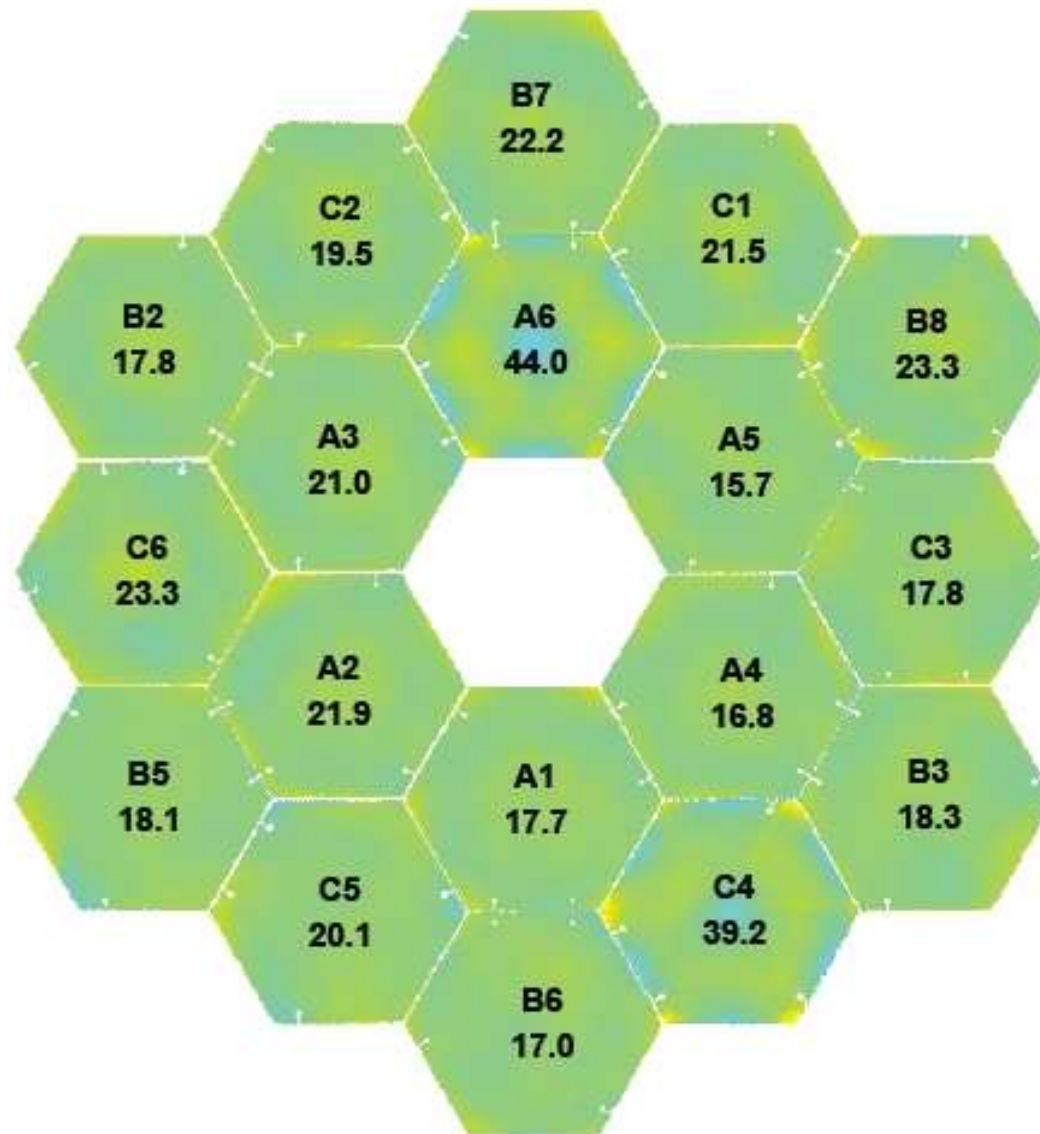
# Mirror Acceptance Testing







# Primary Mirror Composite



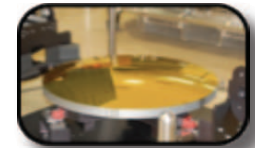
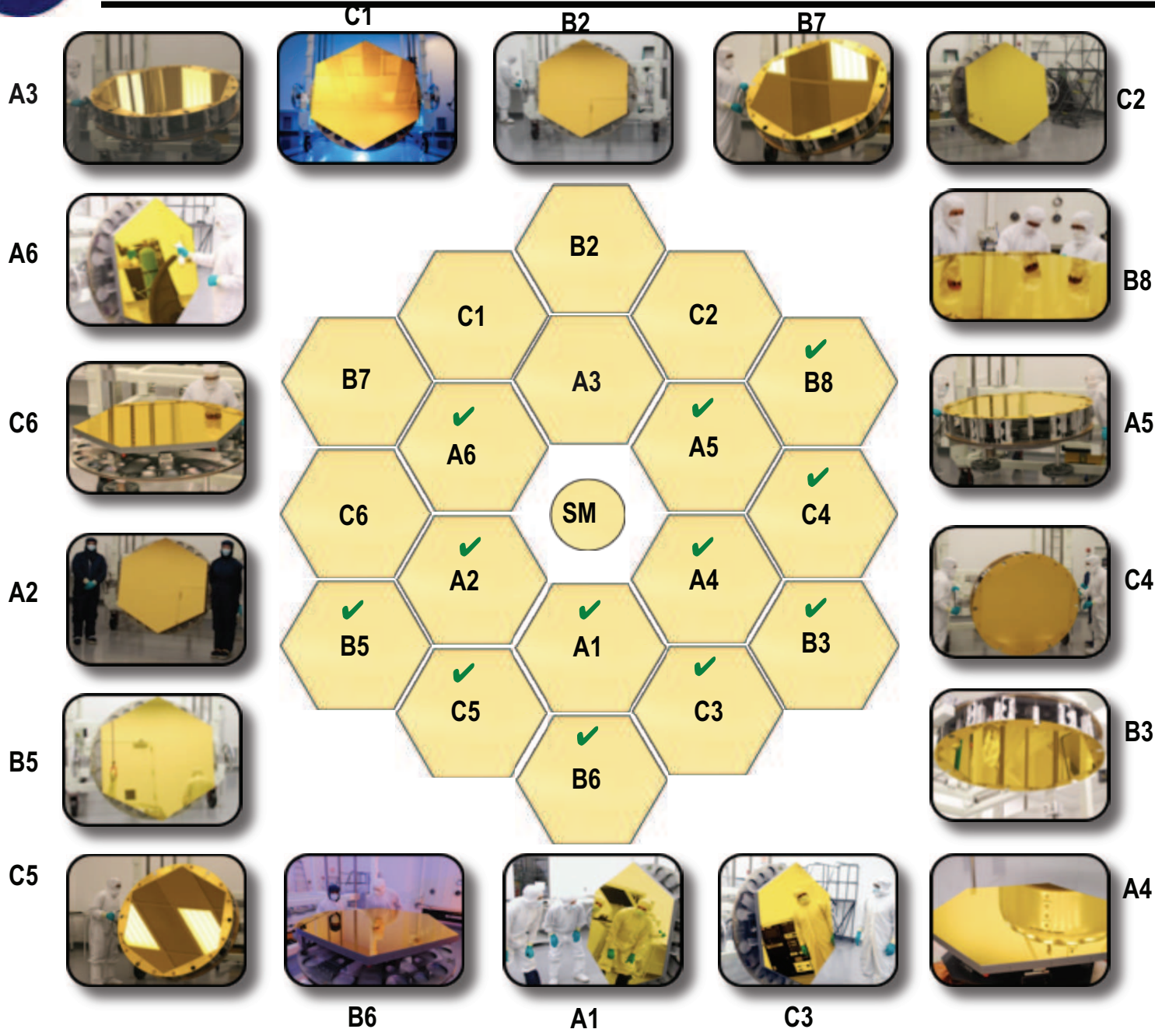
RMS: **23.2 nm**

PV: **515.5 nm**





# Family Portrait



Secondary



Tertiary



Fine Steering

✓ Mirror segment has completed all thermal testing

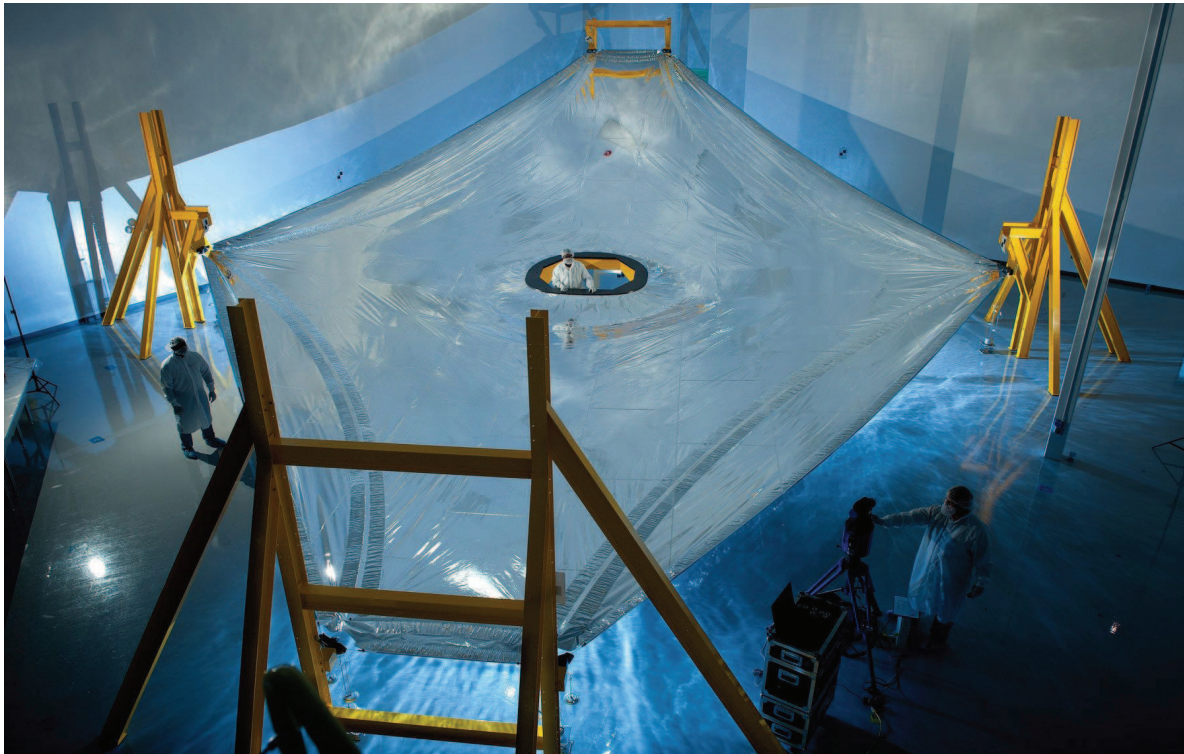




# Sunshield

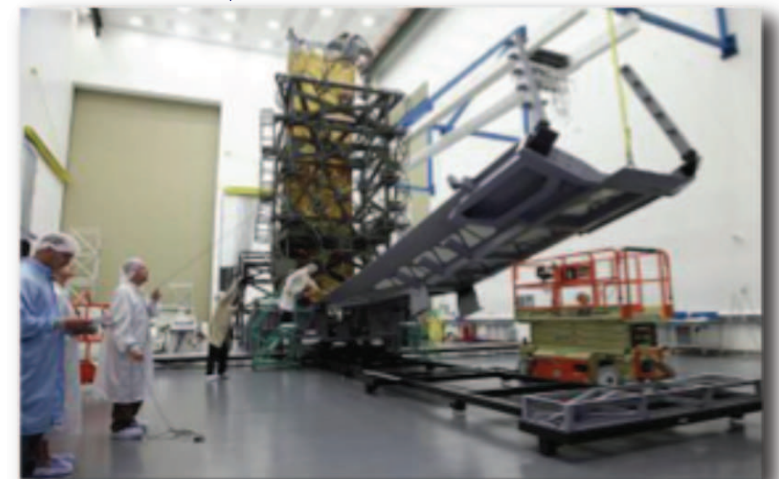


- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape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



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

**Full-scale JWST mockup with sunshield palette**



# Telescope Assembly Ground Support Equipment



Ambient Optical Alignment Stand



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



March 2012 NAC Science Meeting



Landing a mirror onto backplane simulator

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



## Instrument Overview

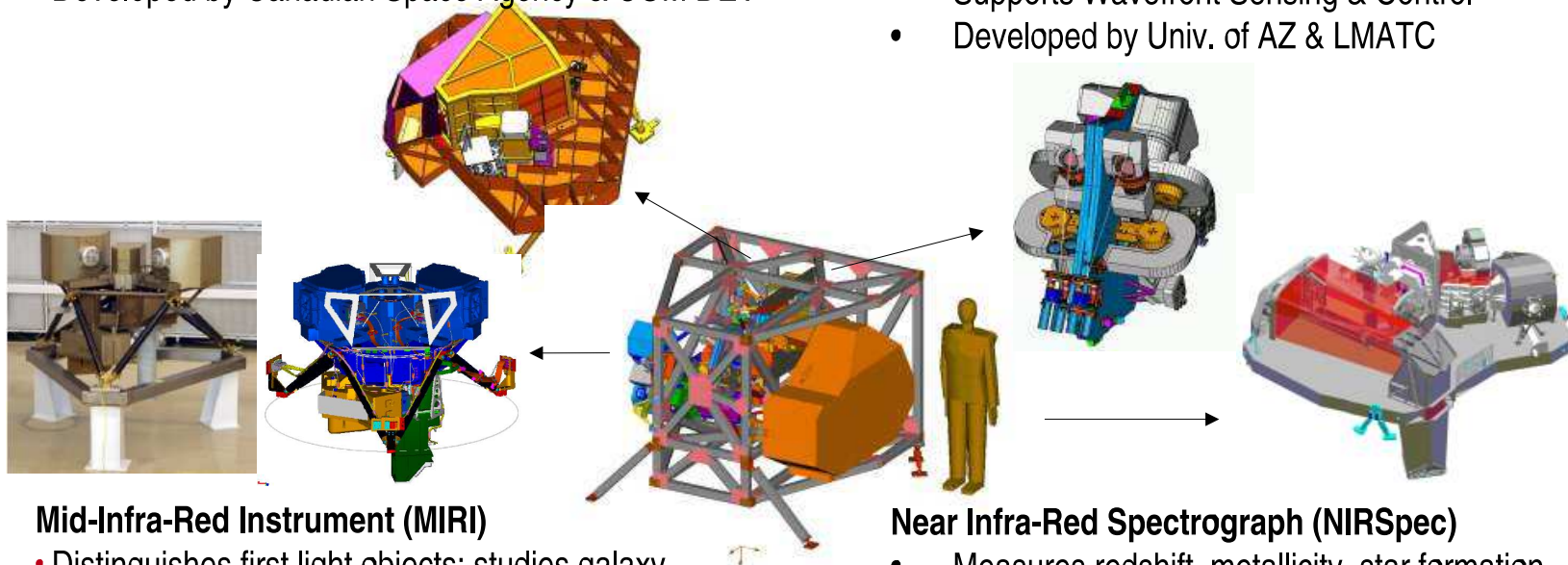


### Fine Guidance Sensor (FGS)

- 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)

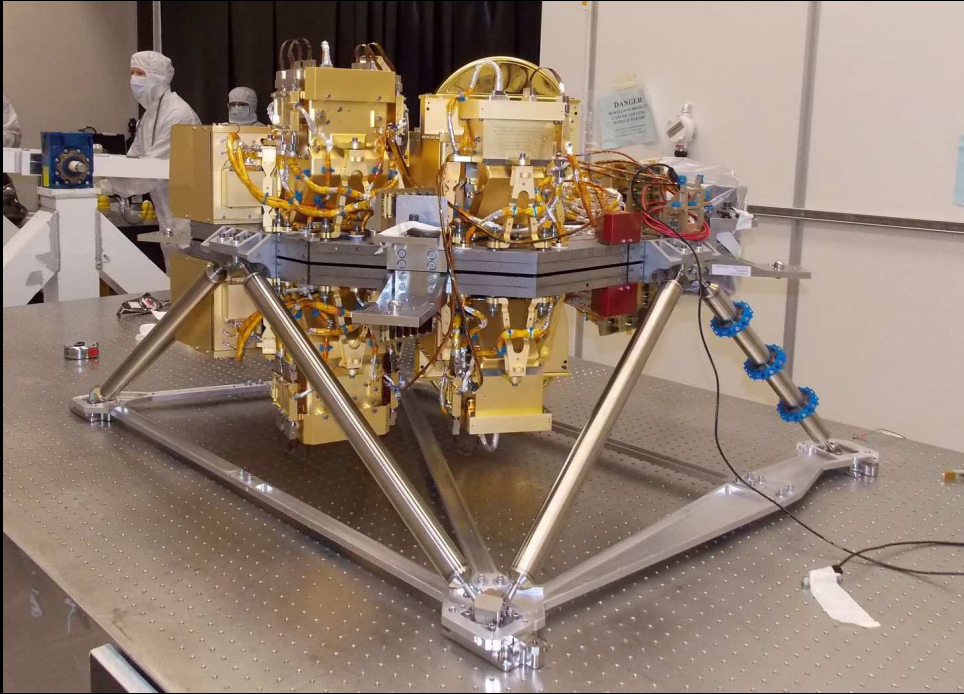
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

### 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.



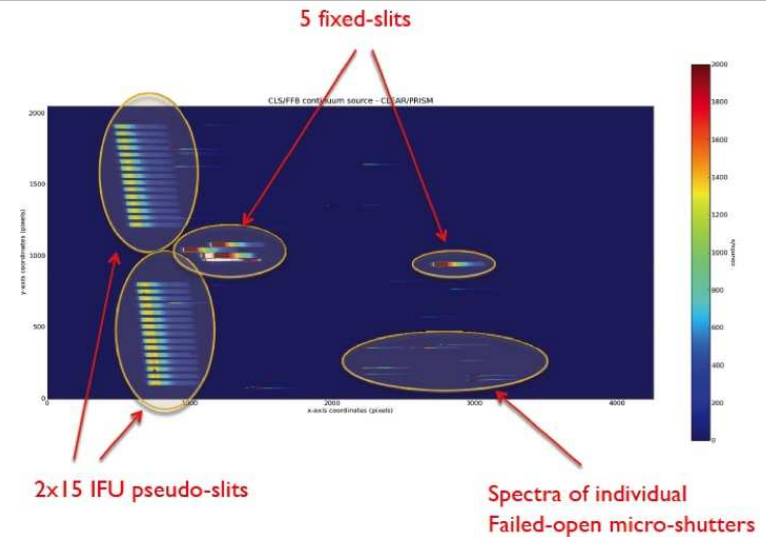


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (&  $1\text{--}5\ \mu\text{m}$  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.



## Flight NIRSpec First Light

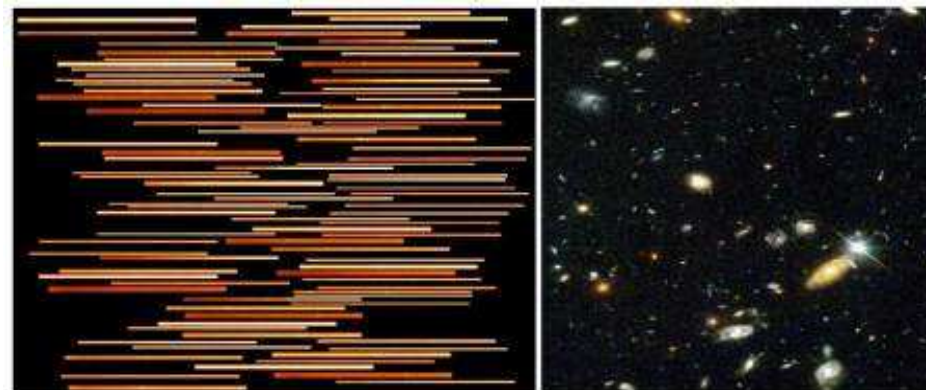
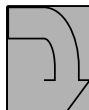
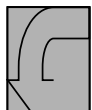


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) spectrograph:

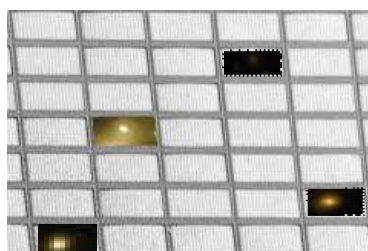
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

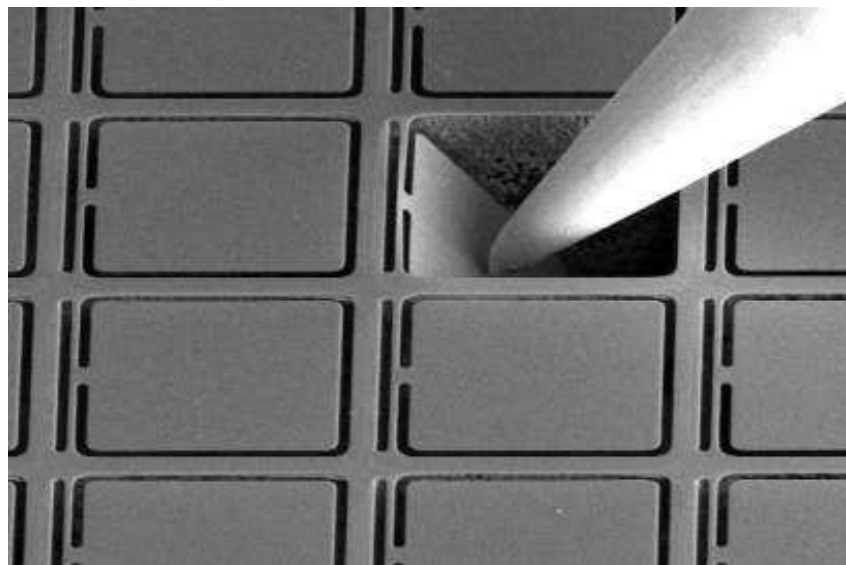
Astronomy Scene



Metal Mask/Fixed Slit



Shutter Mask

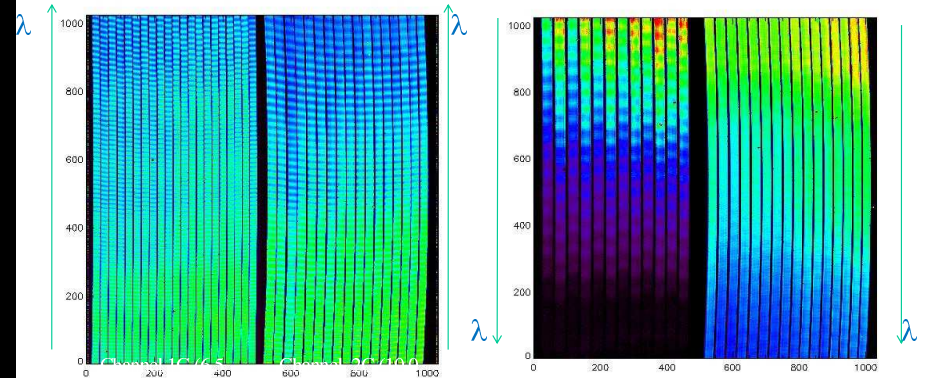




# Flight MIRI



## Spectrometer First Light – internal calibration source



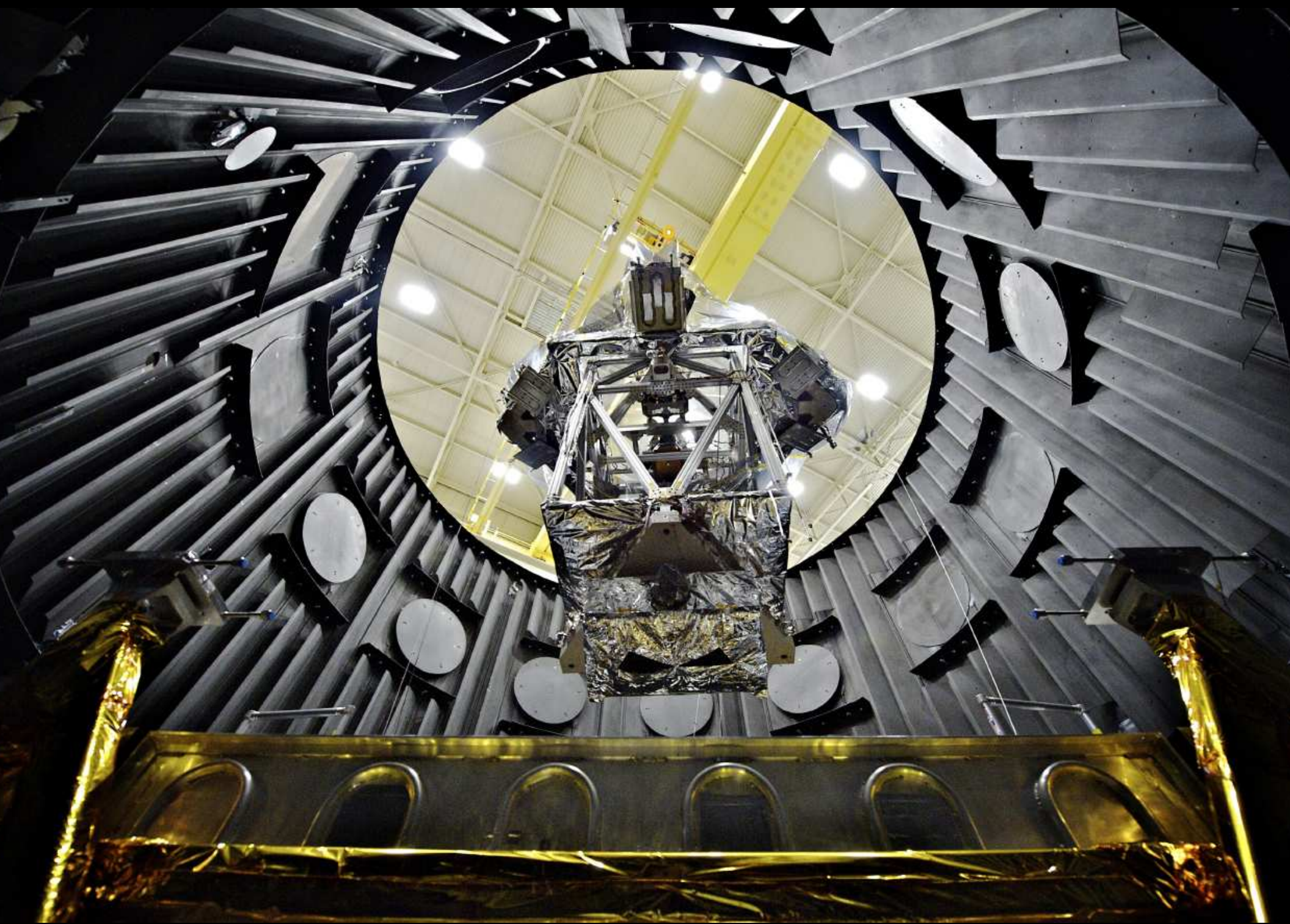
All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

JWST's mid-infrared (5–29 $\mu\text{m}$ ) 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!

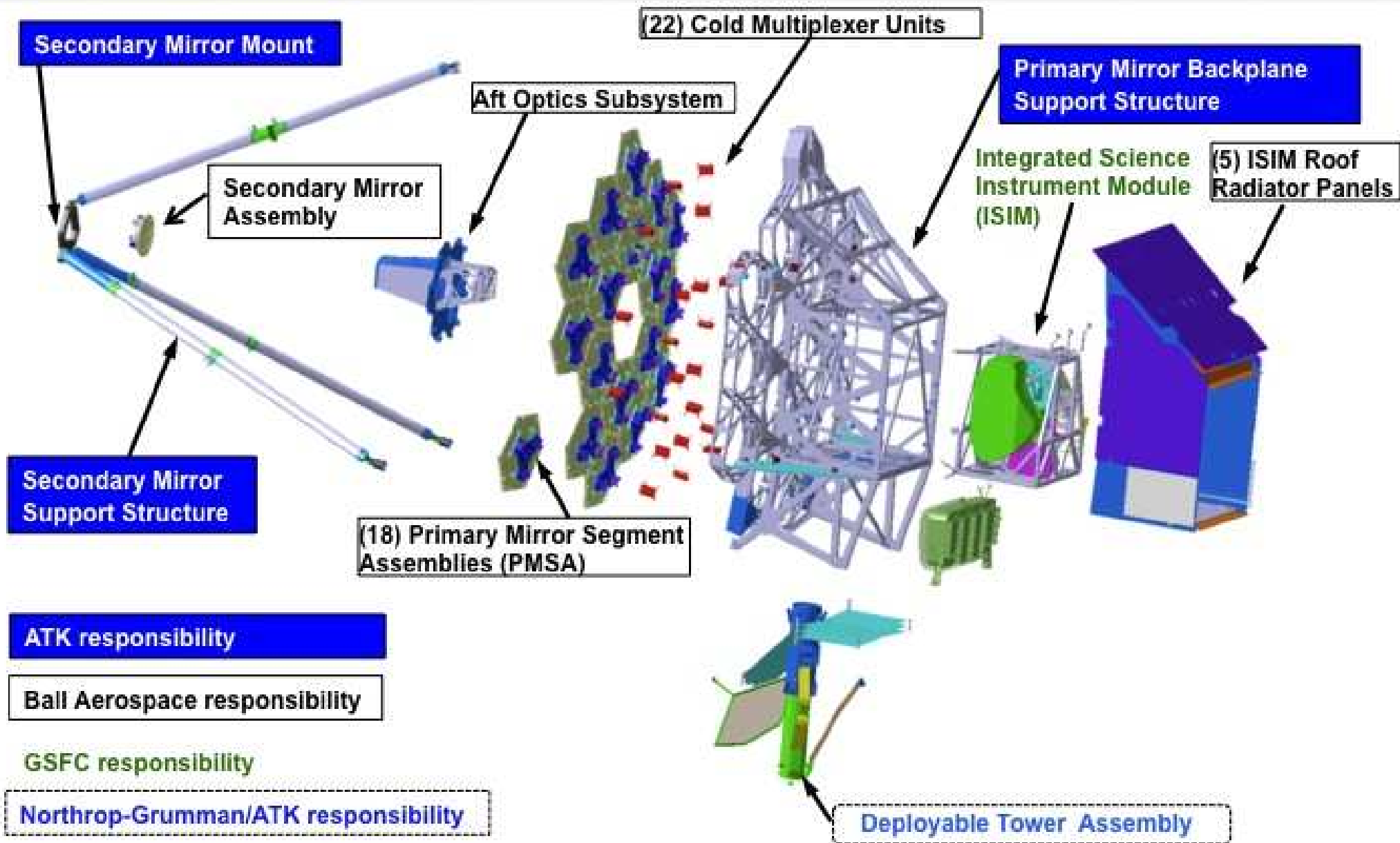




OSIM: Here is where JWST Instruments inside ISIM are being tested.

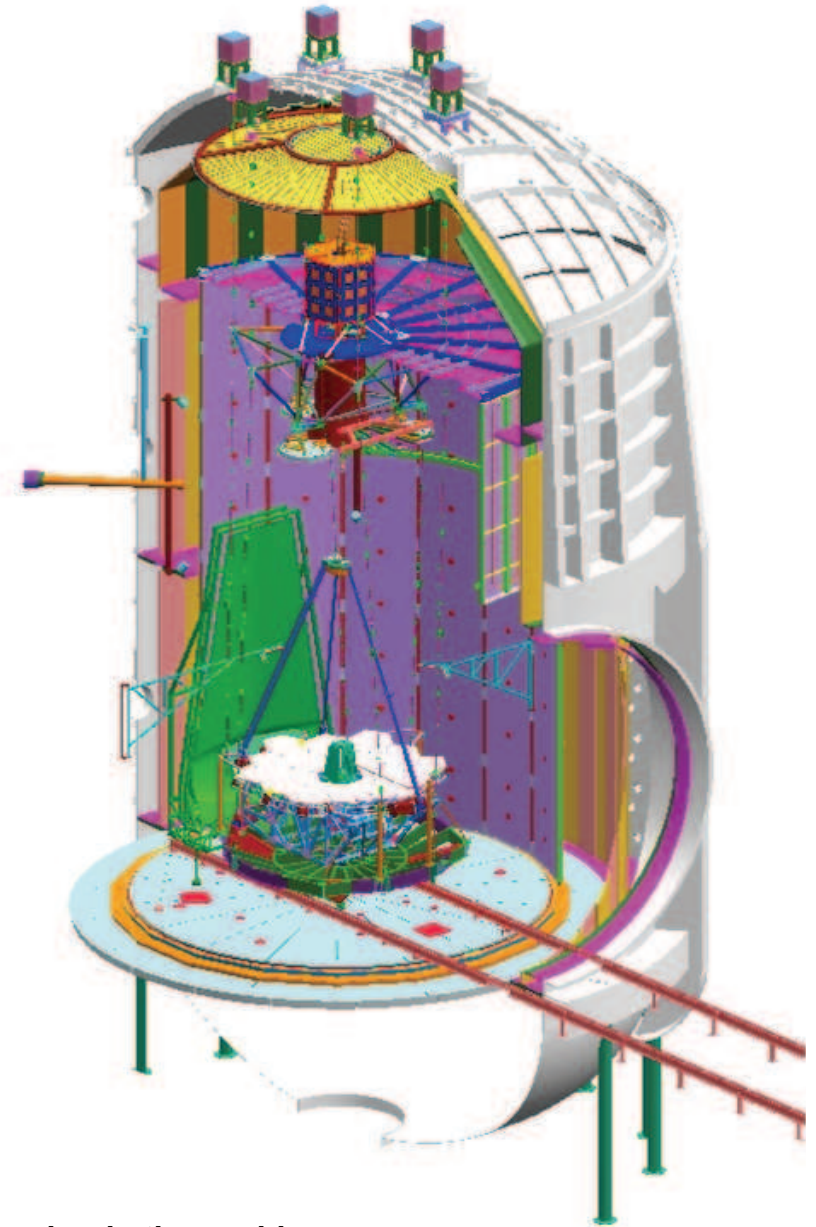
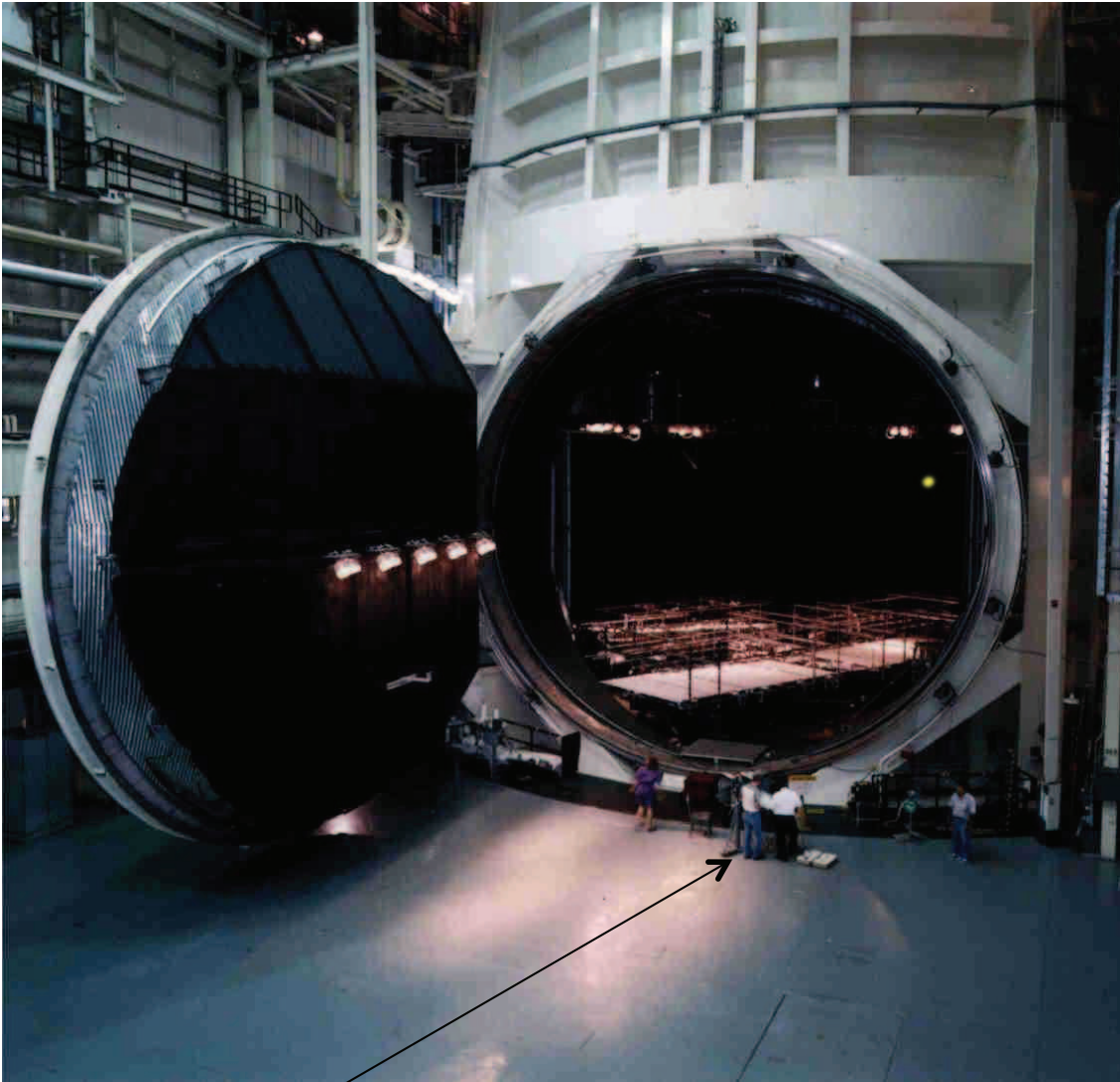


# TELESCOPE ARCHITECTURE





# OTE Testing – Chamber A at JSC

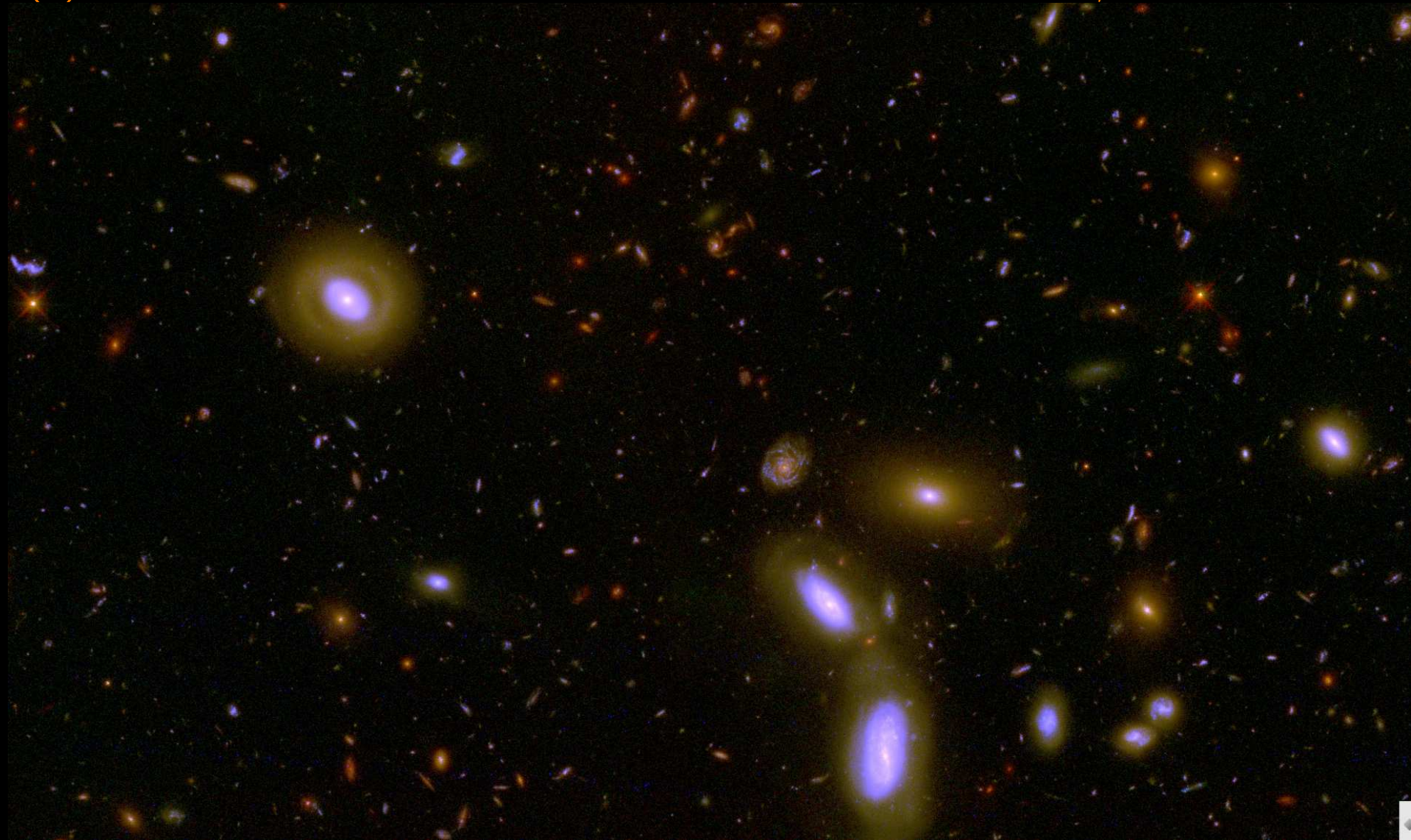


Notice people for scale

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 and SMBH/AGN Growth?

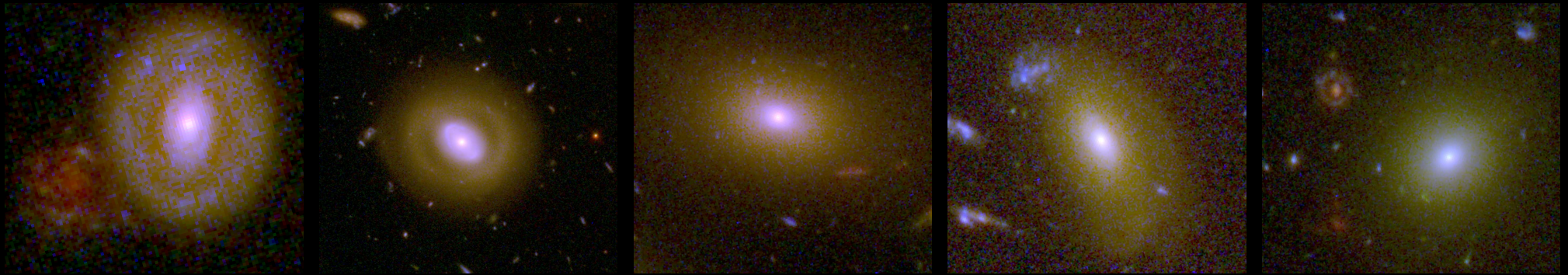


10 filters with HST/WFC3 & ACS reaching  $AB=26.5-27.0$  mag ( $10-\sigma$ ) over  $40 \text{ arcmin}^2$  at  $0.07-0.15''$  FWHM from  $0.2-1.7 \mu\text{m}$  (UVUBVizYJH). JWST adds  $0.05-0.2''$  FWHM imaging to  $AB \simeq 31.5$  mag (1 nJy) at  $1-5 \mu\text{m}$ , and  $0.2-1.2''$  FWHM at  $5-29 \mu\text{m}$ , 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  $H_0$ ,  $\Omega$ ,  $\rho_o$ ,  $w$ , and  $\Lambda$ , resp.

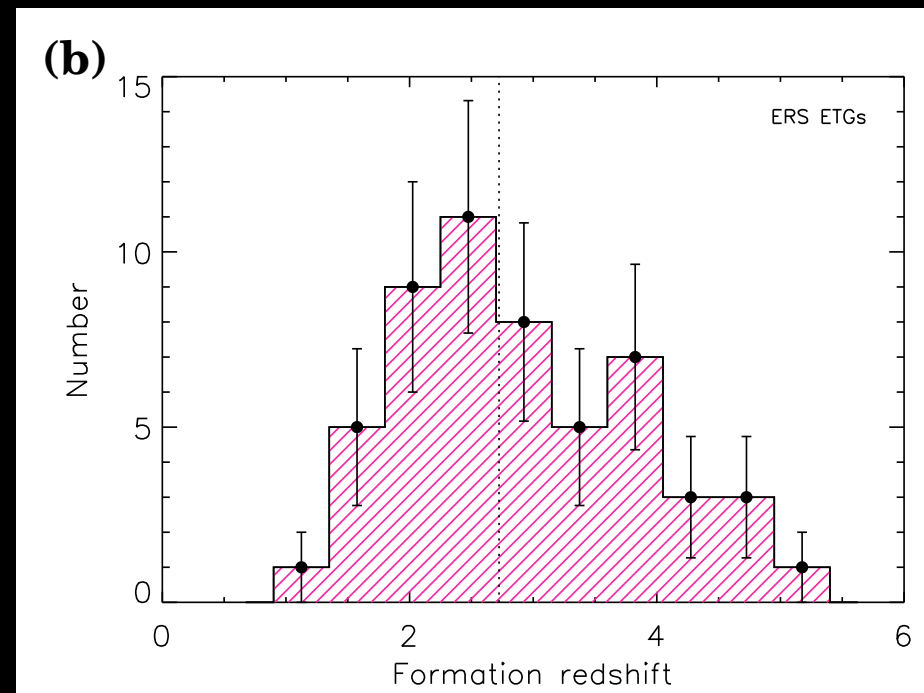
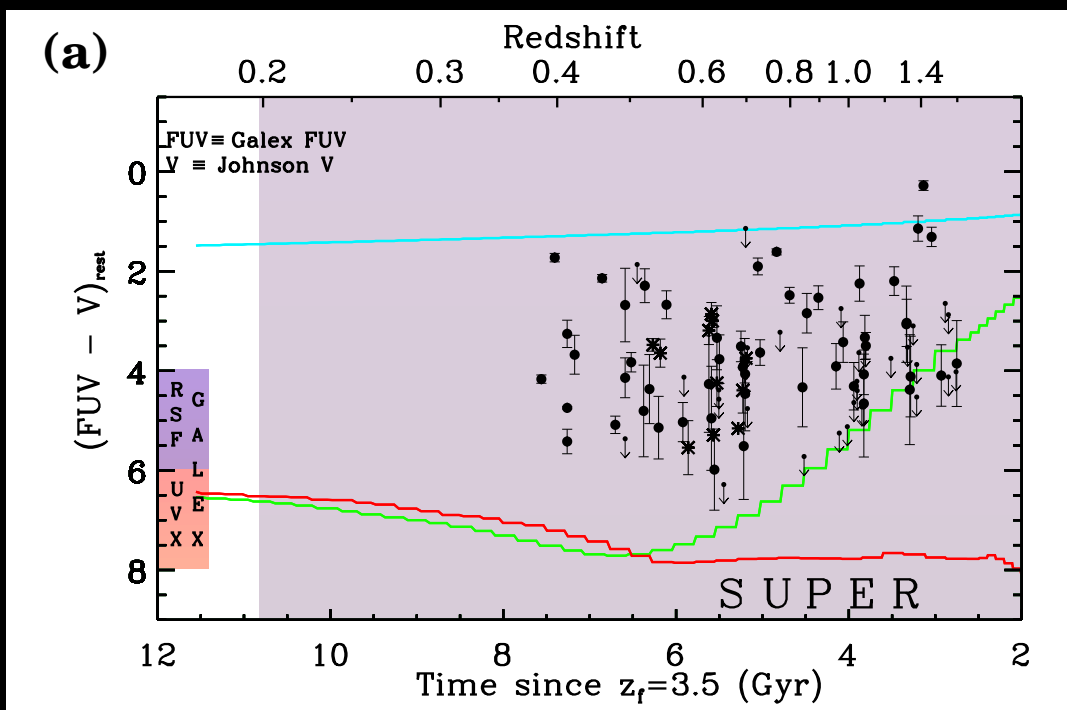


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(Rutkowski ea. 2012 ApJS 199, 4)  $\implies$  “Red & dead” galaxies aren’t dead!

- JWST will observe any such objects from 0.7–29  $\mu\text{m}$  wavelength.

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

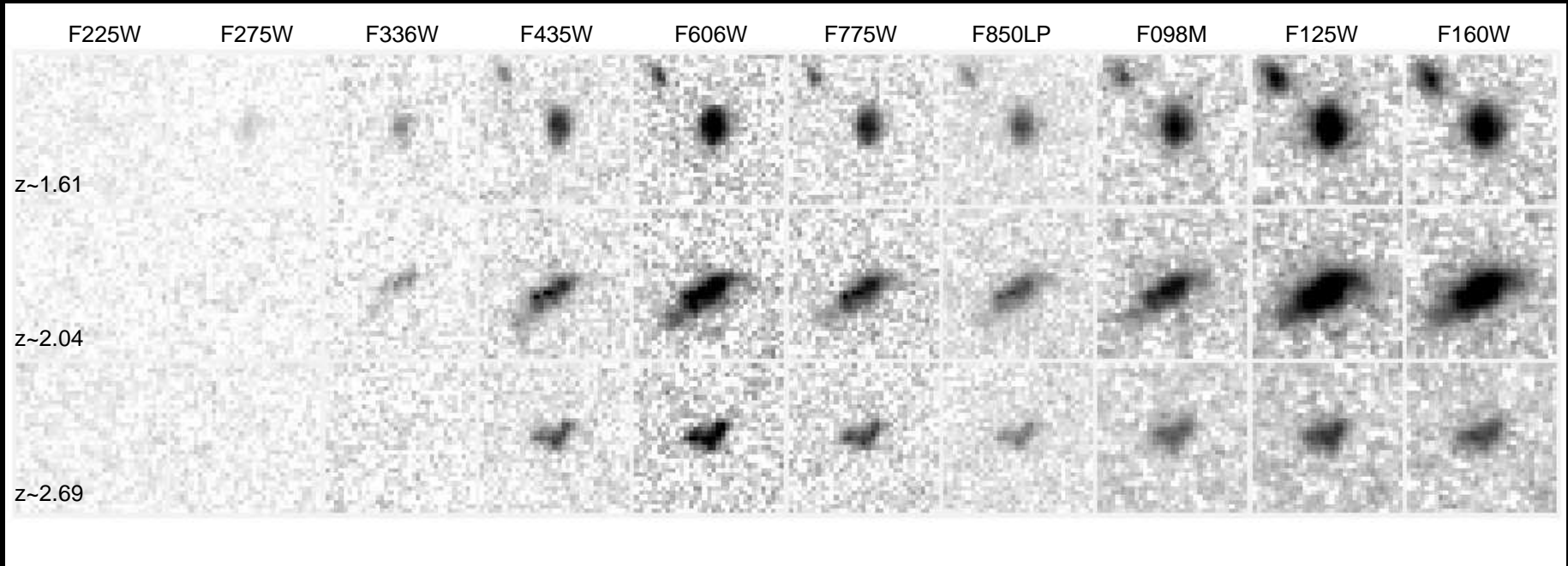


- 10-band WFC3 ERS data measured rest-frame UV-light in nearly all early-type galaxies at  $0.3 \lesssim z \lesssim 1.5$  (Rutkowski et al. 2012, ApJS, 199, 4).

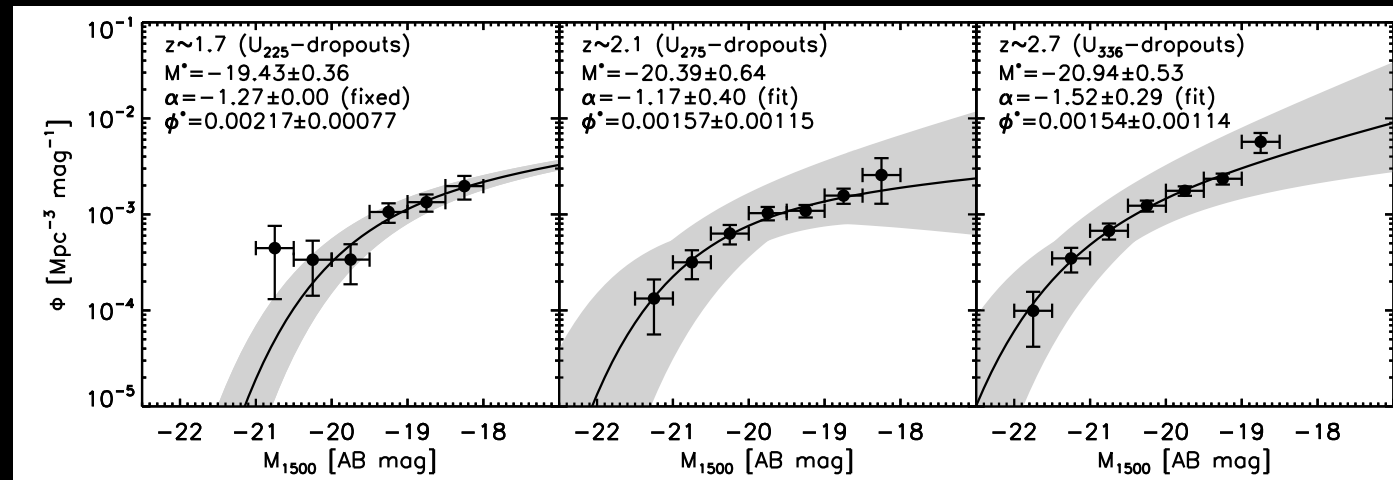
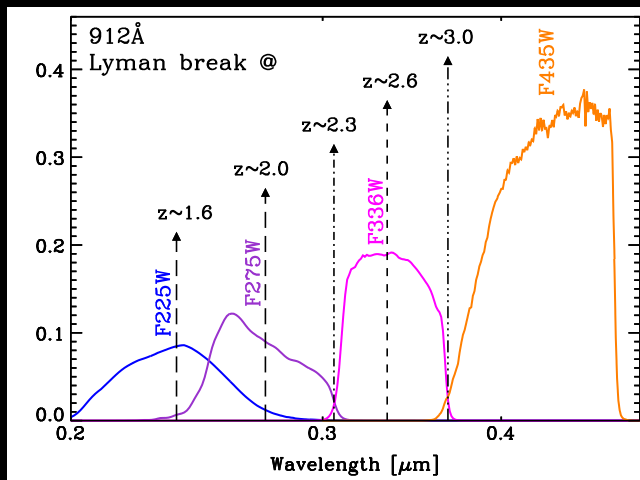
⇒ Most ETGs have continued residual star-formation after they form.

- 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.

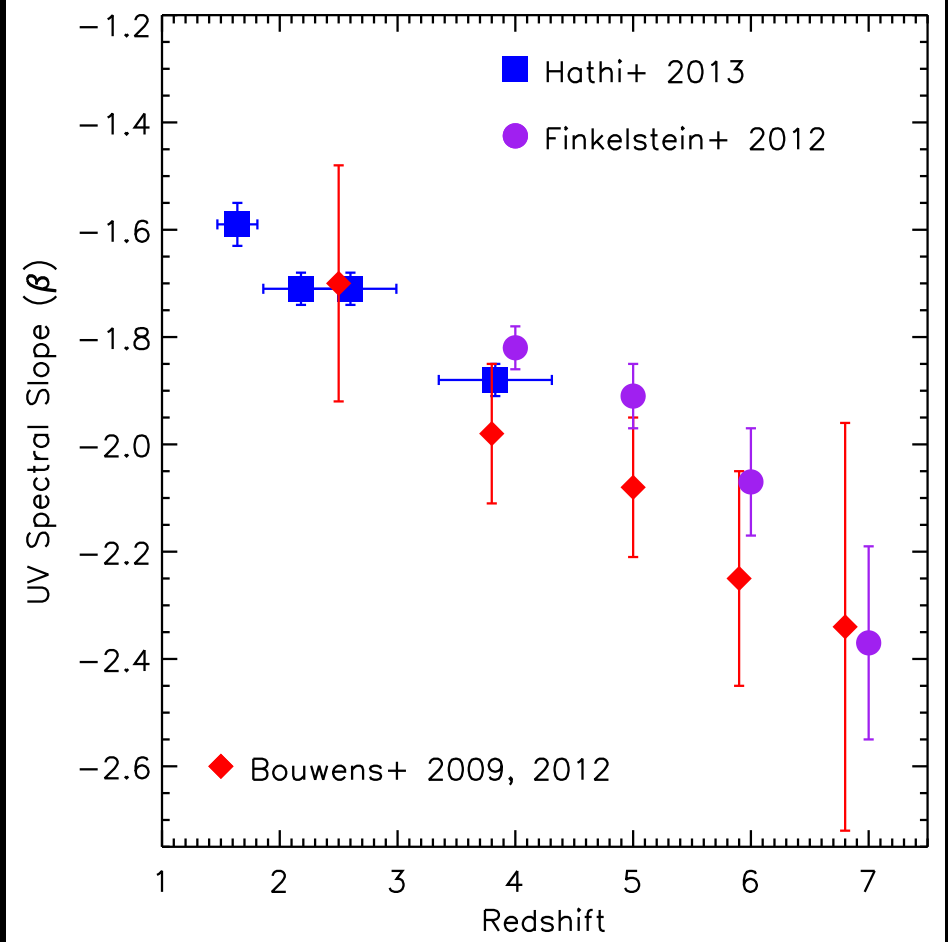
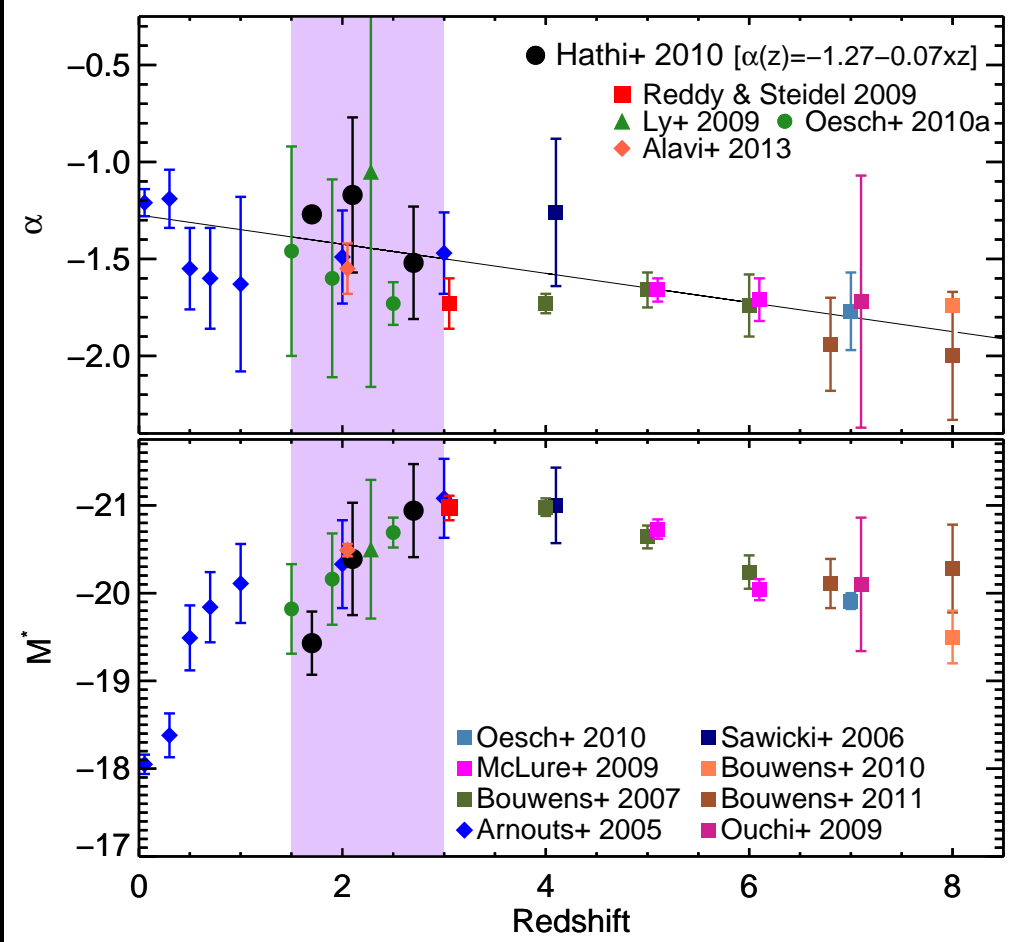


## Lyman break galaxies at the peak of cosmic SF ( $z \simeq 1-3$ ; Hathi<sup>+</sup> 2010, 2013)



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

(e.g., Bouwens<sup>+</sup> 2010, 2013; Hathi<sup>+</sup> 2010, 2013; Oesch<sup>+</sup> 2010; 2013; Ellis<sup>+</sup> 2012; Robinson<sup>+</sup> 2013).



Evol of LF-slope  $\alpha$  (top),  $M^*$  (bottom), & UV-slope  $\beta$  (right; Hathi<sup>+</sup> 10,13)

- JWST  $z \gtrsim 8$ , expect faint-end slope  $\alpha \simeq -2.0$  (Bouwens 2012).

- JWST  $z \gtrsim 8$ , expect UV  $\beta \lesssim -2.2$  (Finkelstein<sup>+</sup>12; Jiang 2013).

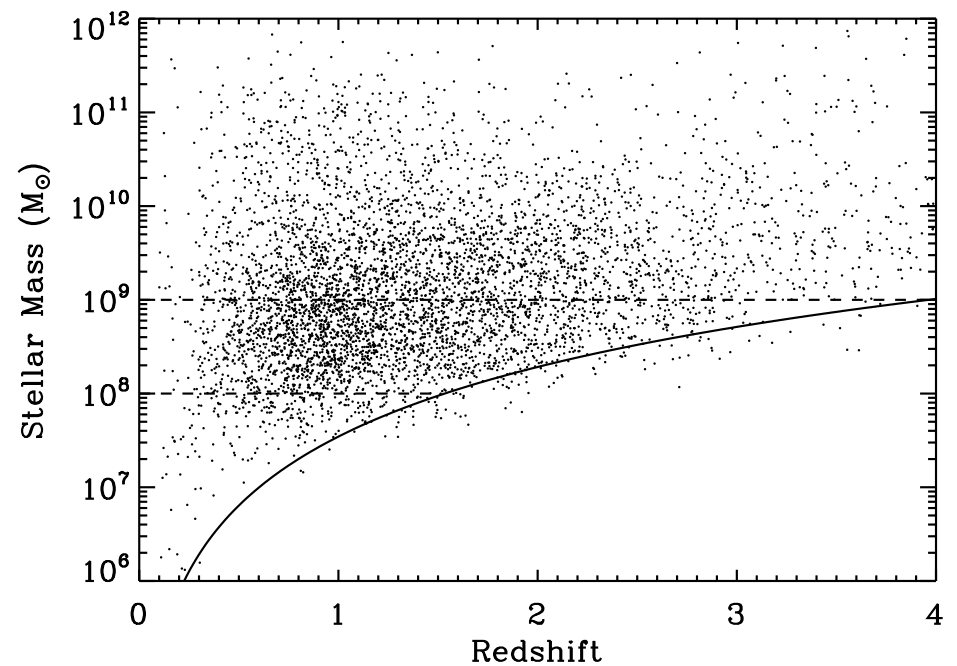
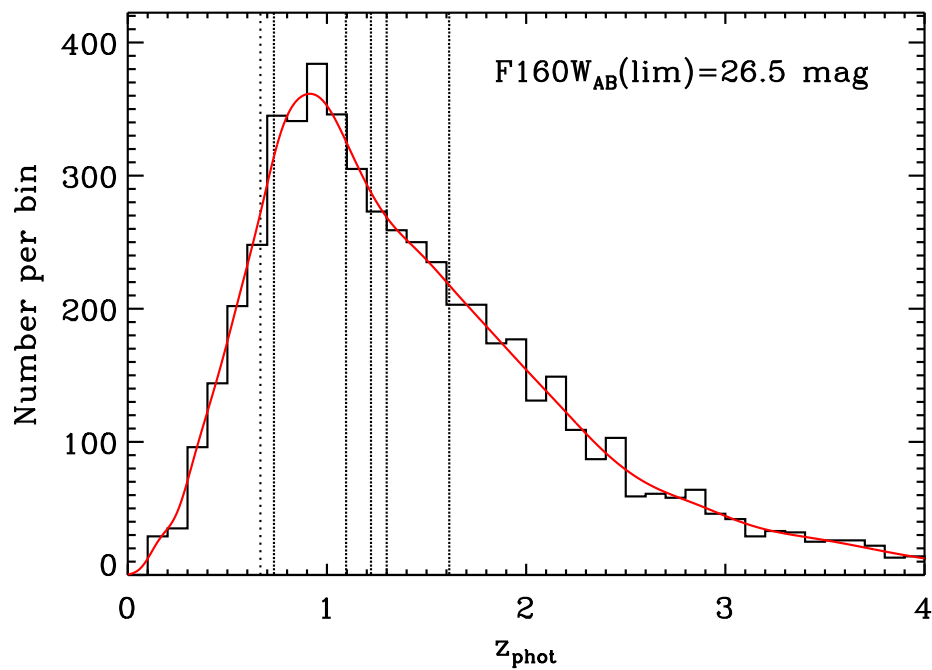
⇒ Both important for cosmic reionization at  $z \gtrsim 6$  by dwarf galaxies.

NOTE: Faint-end slope  $\alpha -1.5$  to  $-1.6$  at  $z \simeq 1.5-2$  (also Siana 2012).

- JWST at  $z \gtrsim 8$ : see if characteristic luminosity  $M^* \gtrsim -19$  mag.

⇒ Could cause significant gravitational lensing bias at  $z \gtrsim 8-10$ .





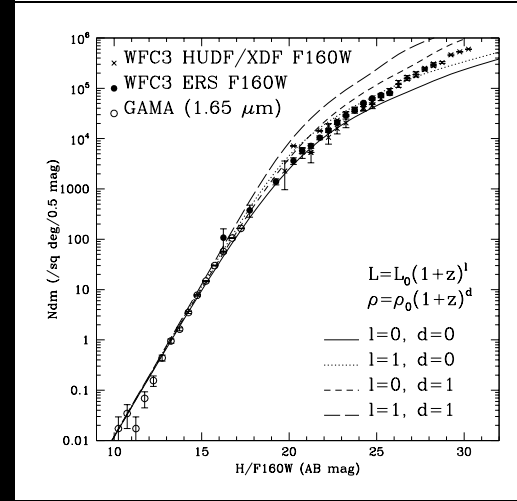
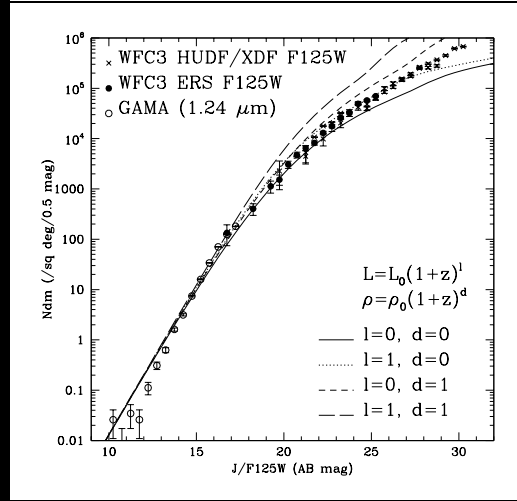
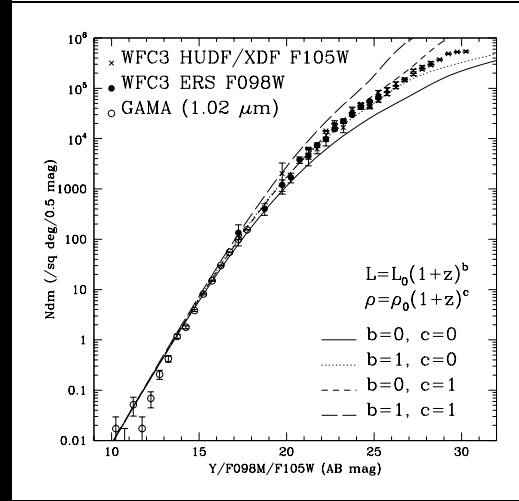
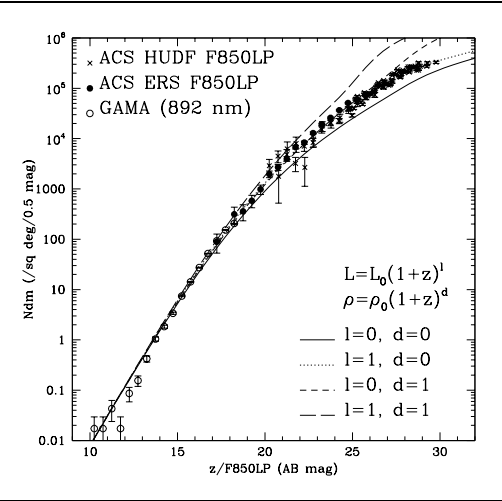
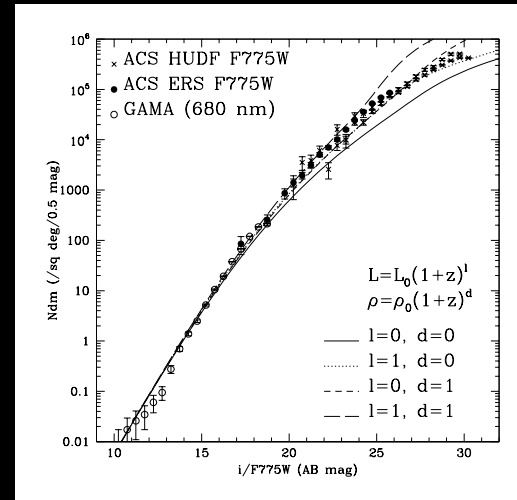
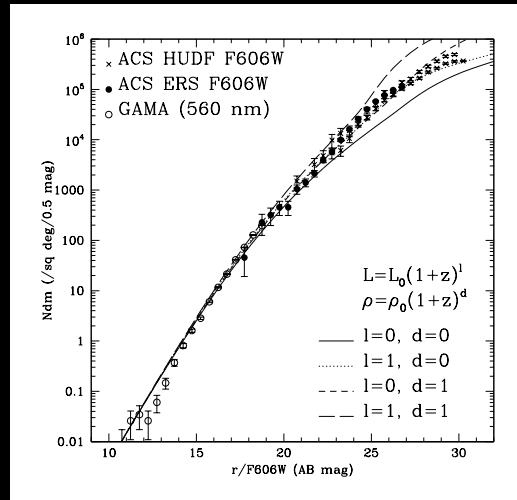
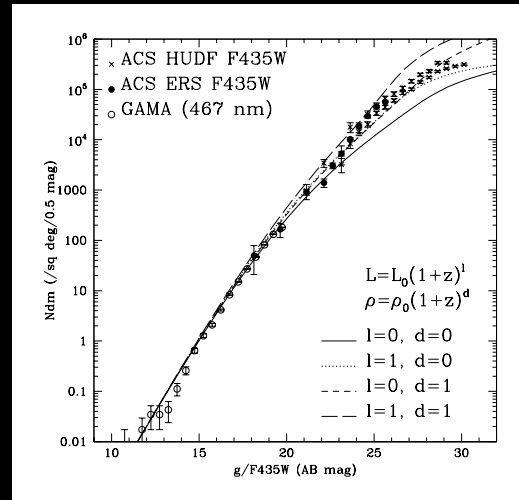
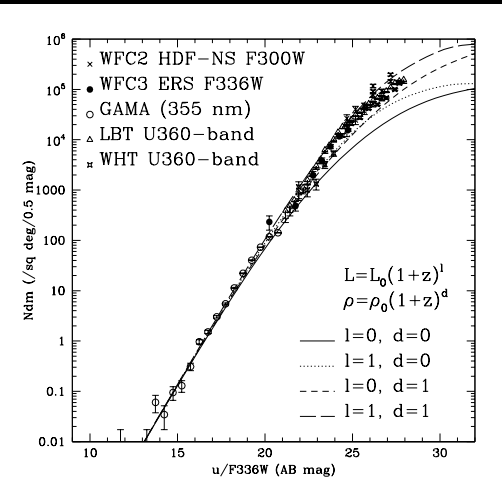
WFC3 ERS 10-band redshift estimates accurate to  $\lesssim 4\%$  with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable  $N(z)$ .

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

$\Rightarrow$  Median redshift in (medium-)deep fields is  $z_{med} \simeq 1.5-2$ .

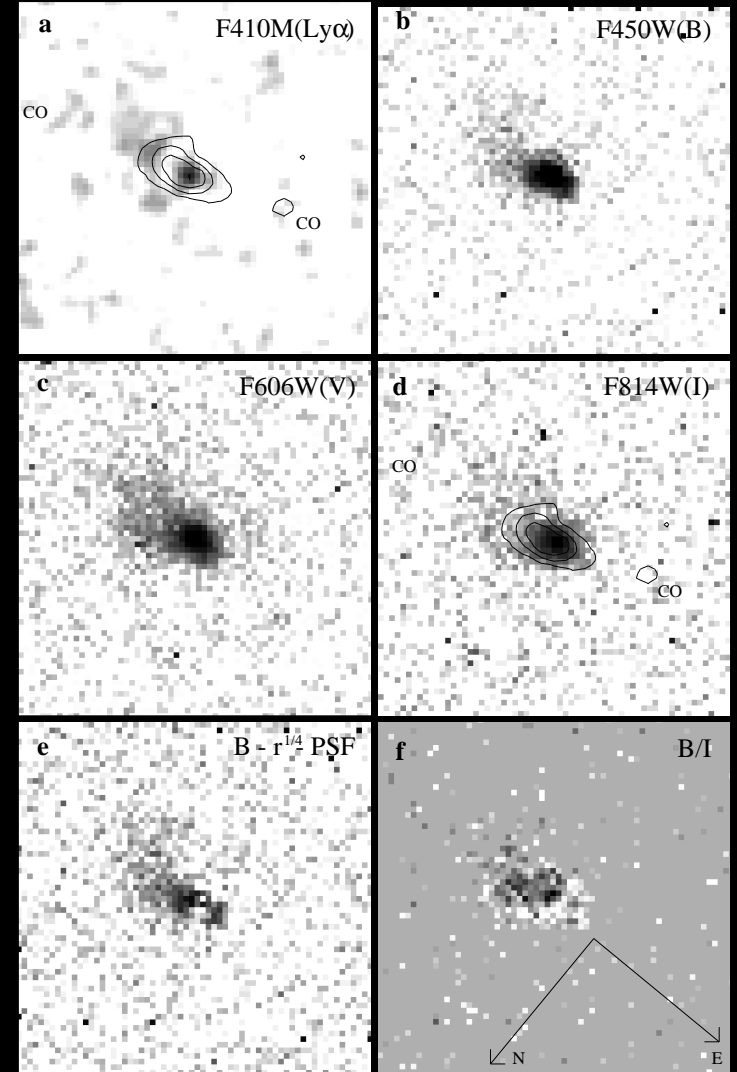
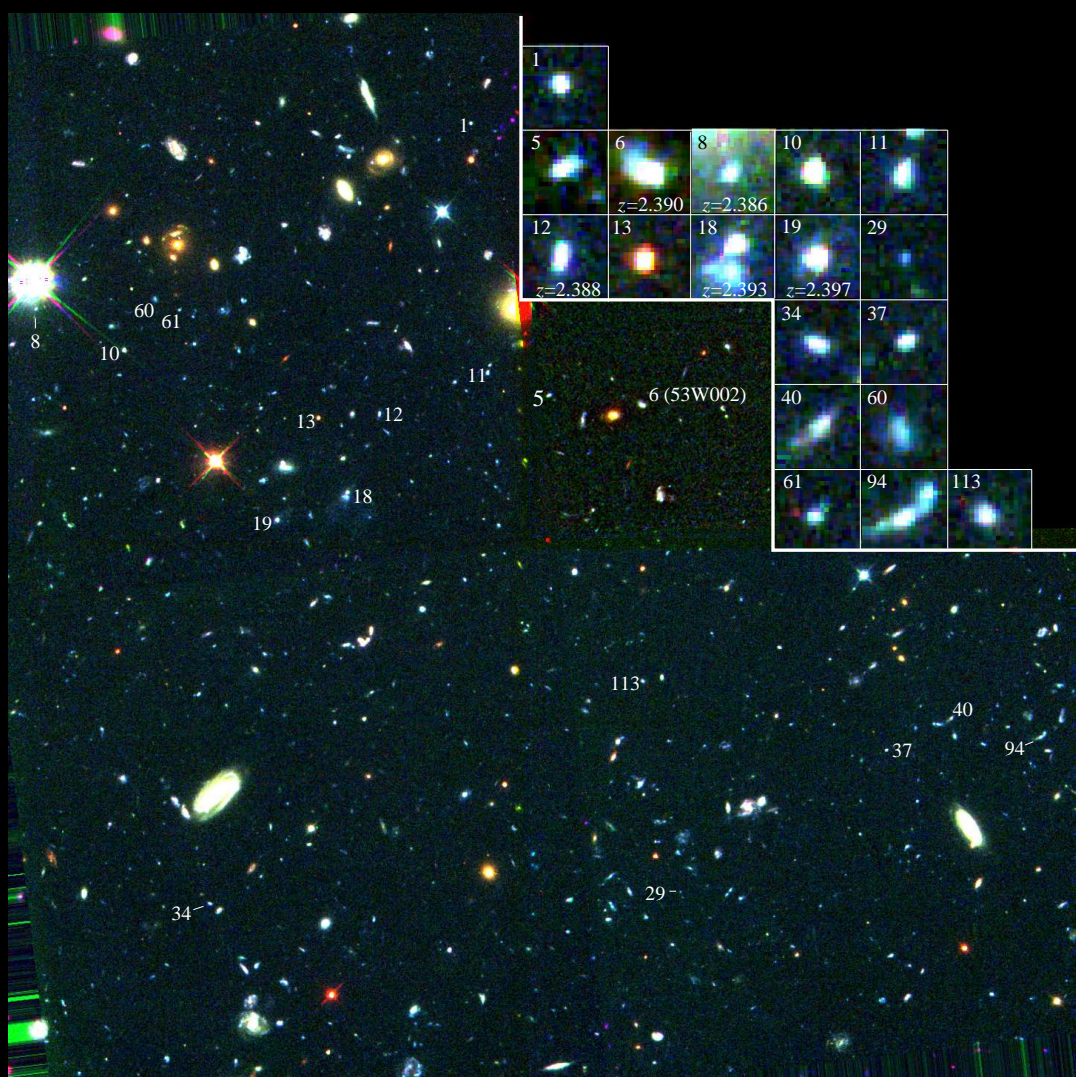
- JWST will trace mass assembly and dust content  $\lesssim 5 \text{ mag}$  deeper from  $z \simeq 1-12$ , with nanoJy sensitivity from  $0.7-5 \mu\text{m}$ .

# Panchromatic Galaxy Counts from $\lambda \simeq 0.2\text{--}2\mu\text{m}$ for $AB \simeq 10\text{--}31$ mag



Data: GALEX, GAMA, HST ERS + HUDF/XDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011; Ellis<sup>+</sup> 2012; Illingworth<sup>+</sup> 2012; Teplitz<sup>+</sup>2013): F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F140W, F160W.

- HUDF: Faint-end near-IR mag-slopes  $\simeq 0.22 \pm 0.02$  to  $AB \lesssim 31$  mag  $\iff$
- At  $z_{med} \simeq 1.6$ , faint-end LF-slope  $\alpha \simeq -1.5\text{--}1.6$  to  $M_{AB} \simeq -14$  mag !
- $\Rightarrow$  Extrapolation of LF( $z \gtrsim 2$ ) to  $AB \simeq -10$  is entirely plausible.
- JWST can see objects at  $AB \gtrsim 32$  mag. Confusion limit at  $AB \lesssim 34$  mag.



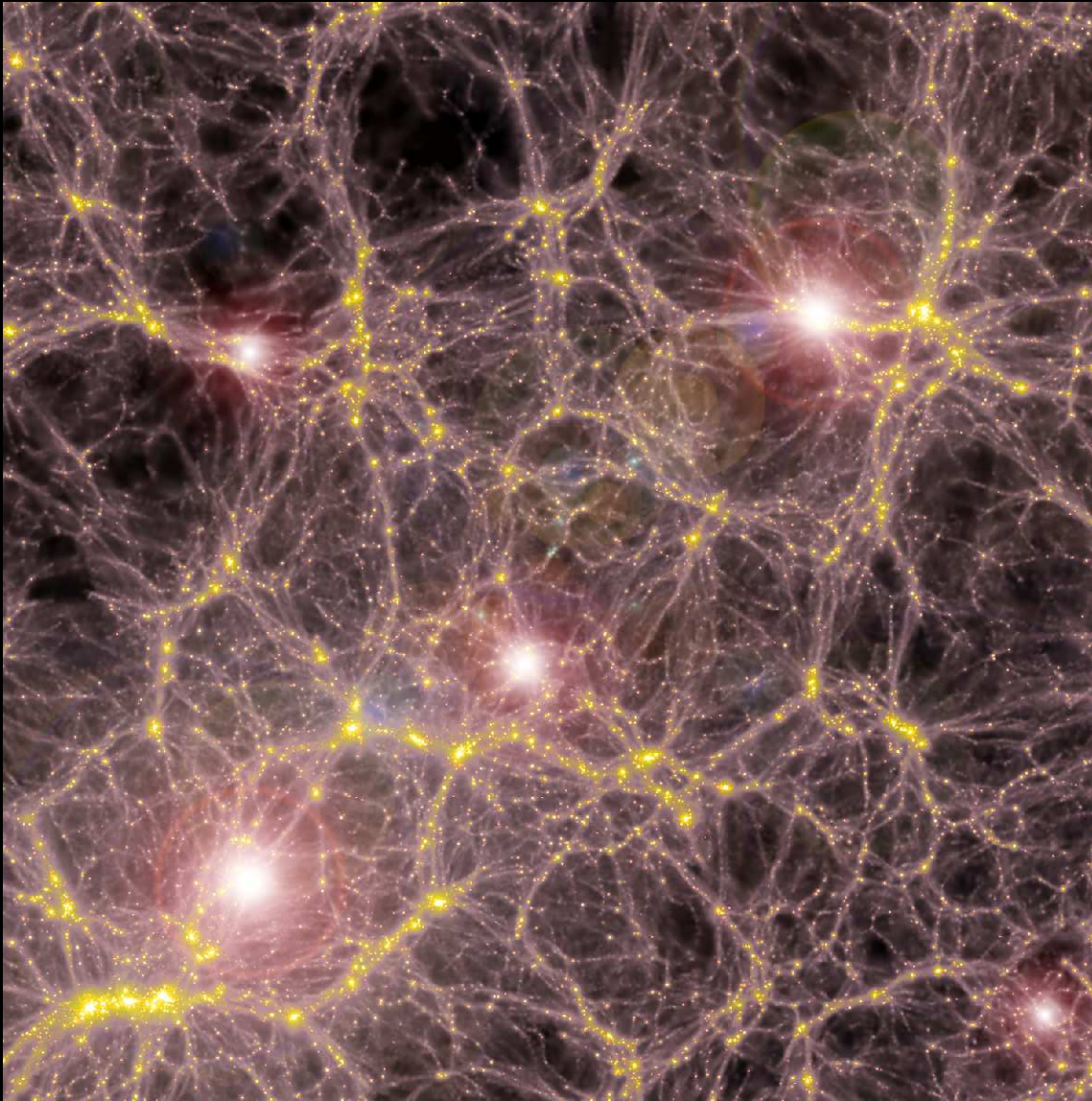
(Left): WFPC2 BVI + F410M ( $\text{Ly}\alpha$ ) on 53W002 + surrounding group of 17  $z=2.39$   $\text{Ly}\alpha$  candidates (Pascarelle et al. 1996, Nature, 383, 45).

(Right): HST/PC of radio galaxy 53W002 at  $z=2.390$  (Windhorst et al. 1998, ApJL): stellar  $r^{1/4}$ -law +  $\text{Ly}\alpha$  & blue continuum AGN-cloud.

$\implies$  Ly escape fraction should be measured *outside* LBGs with outflows!

- JWST can measure AGN hosts 4–6 mag fainter in restframe UV-Opt to  $z \lesssim 20$

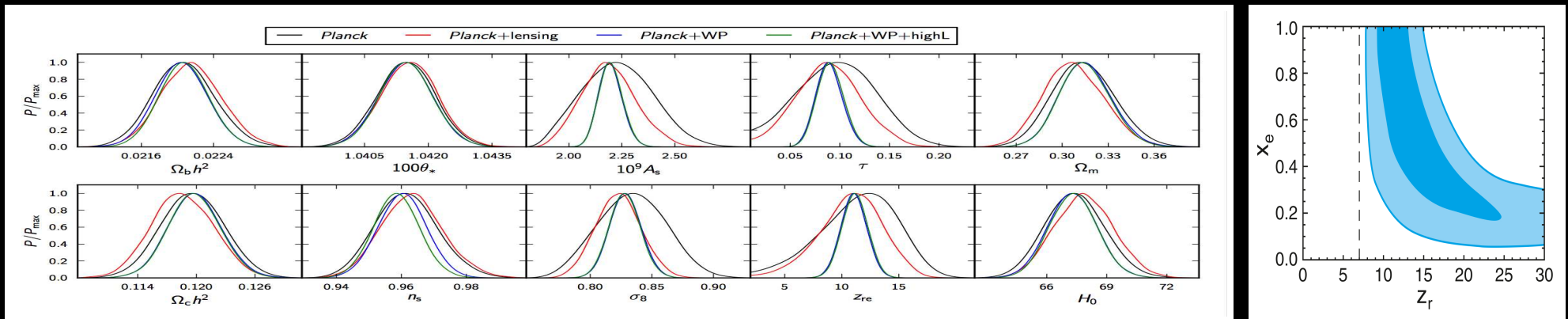
## (4a) How will JWST Observe First Light and Reionization?



- 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  $z \simeq 10 \rightarrow 30$ .

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-9 WMAP data provided better foreground removal (Komatsu<sup>+</sup> 2011; Hinshaw<sup>+</sup> 2012; but see: Planck XVI 2013.)

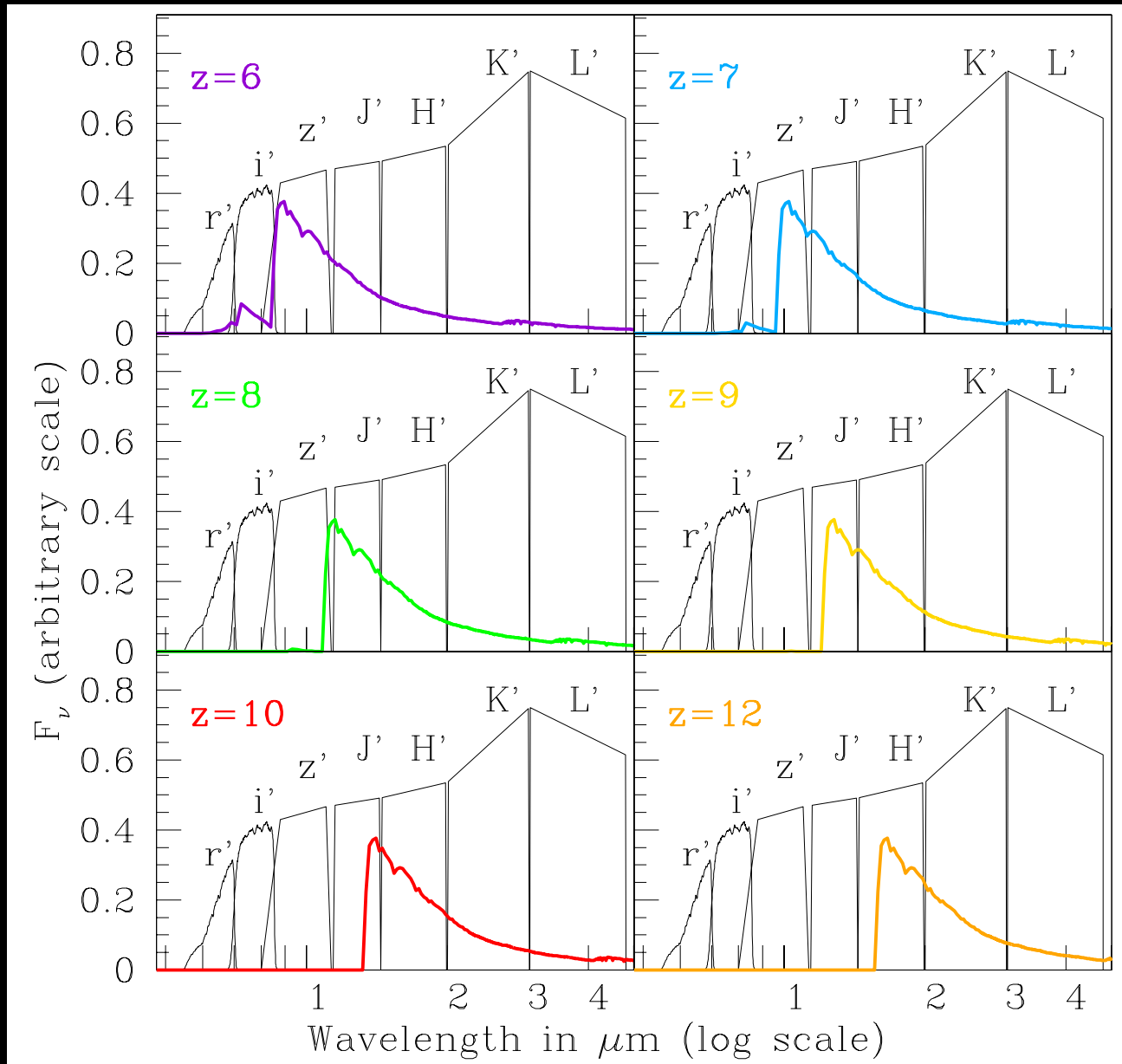
$\implies$  First Light & Reionization occurred between these extremes:

- (1) Instantaneous at  $z \simeq 11.1 \pm 1.1$  ( $\tau = 0.089 \pm 0.013$ ), or, more likely:
- (2) Inhomogeneous & drawn out: starting at  $z \gtrsim 20$ , peaking at  $z \lesssim 11$ , ending at  $z \simeq 7$ . The implications for HST and JWST are:

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

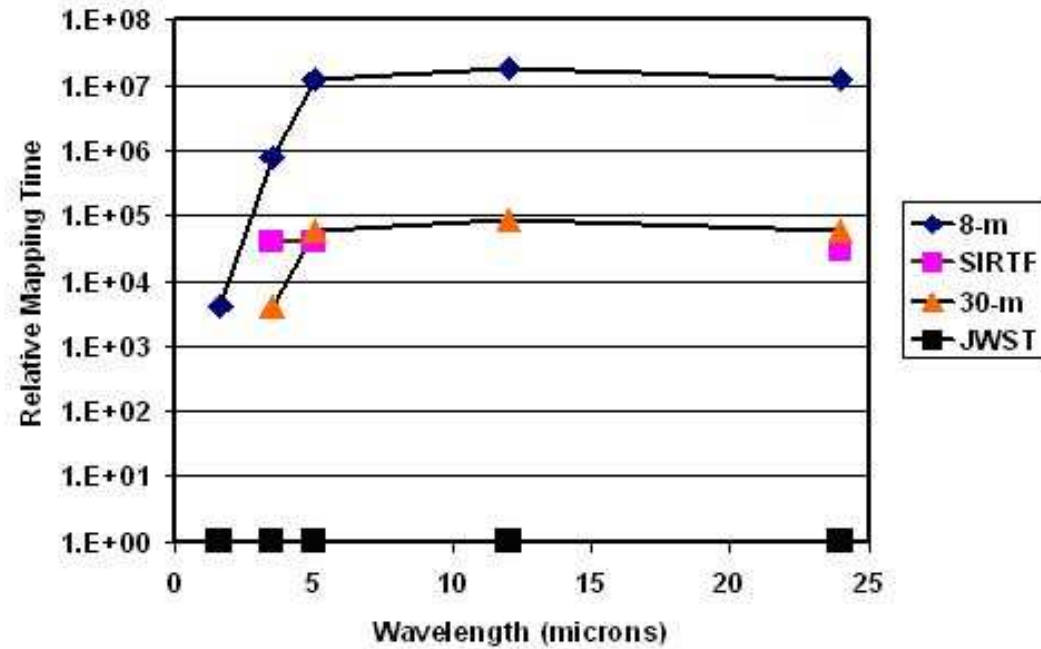
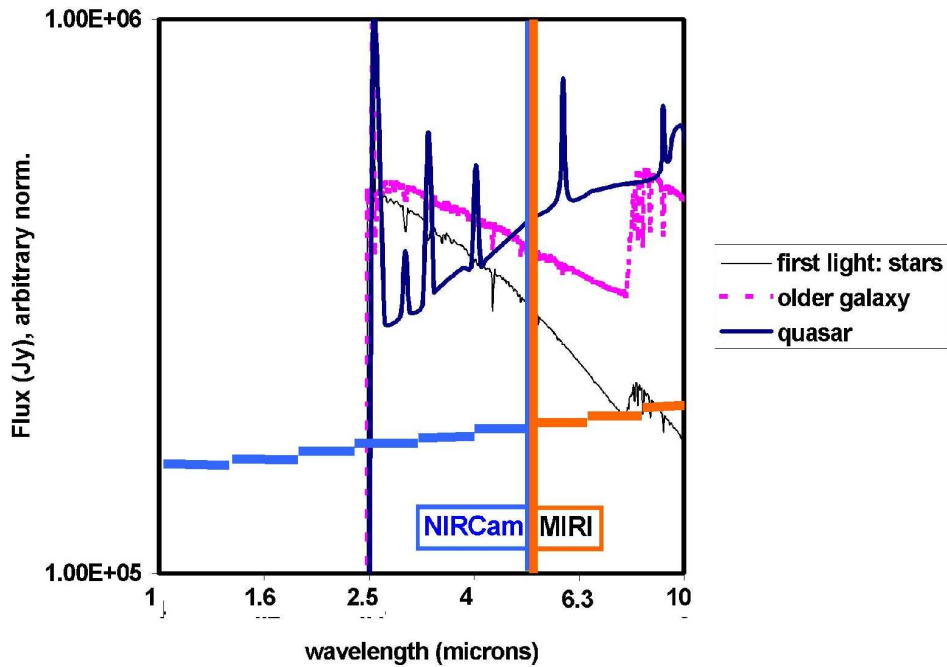
Question: If Planck- $\tau \downarrow \lesssim 0.08$  (TBD), then how many reionizers will JWST see at  $z \simeq 10-20$ ?

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



- Can't beat redshift: to see First Light, must observe near-mid IR.
- ⇒ This is why JWST needs NIRC*am* at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .

- (4) What sensitivity will JWST have?

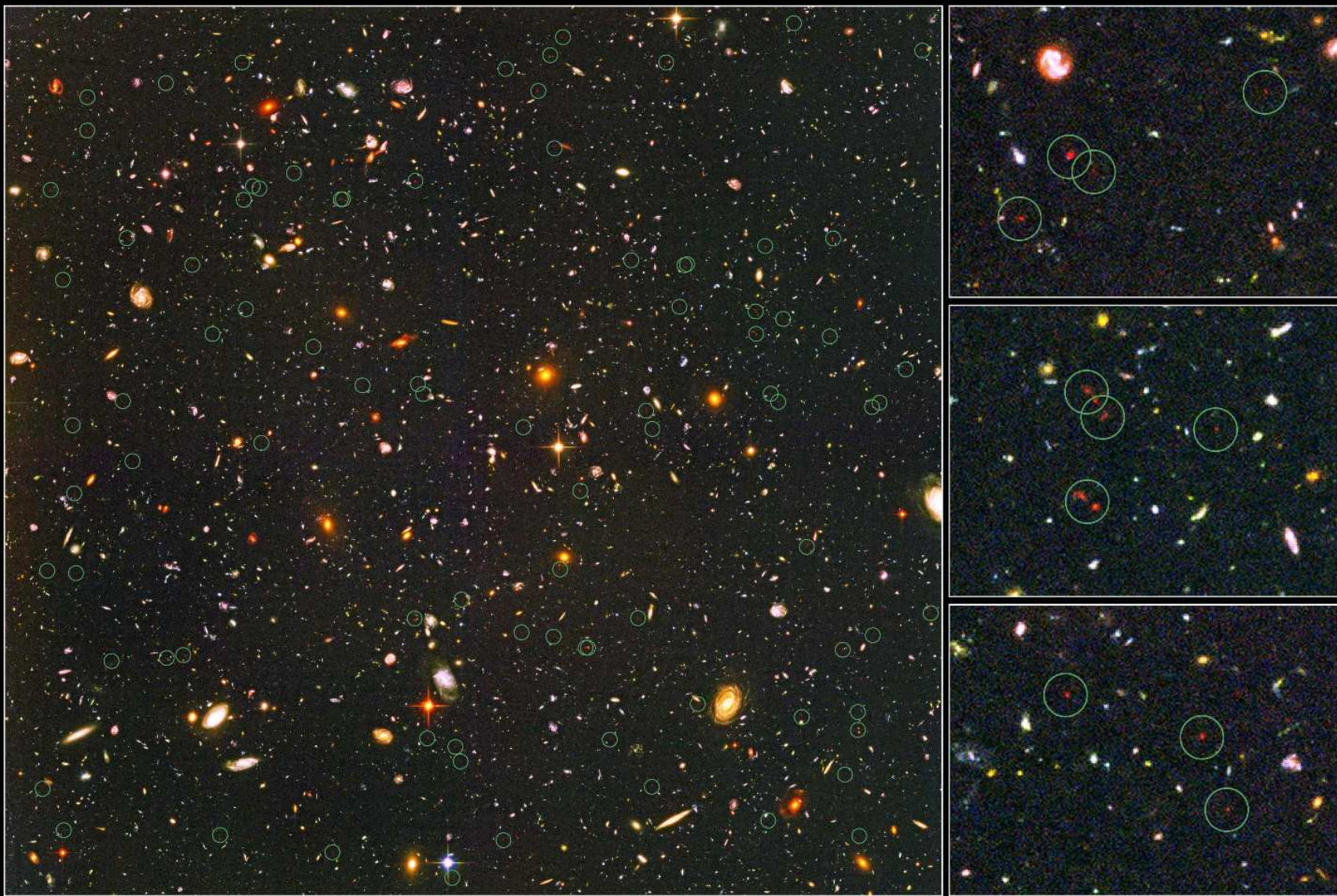


NIRCam and MIRI sensitivity complement each other, straddling  $\lambda \simeq 5 \mu\text{m}$ .

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.  $\lambda$  that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.



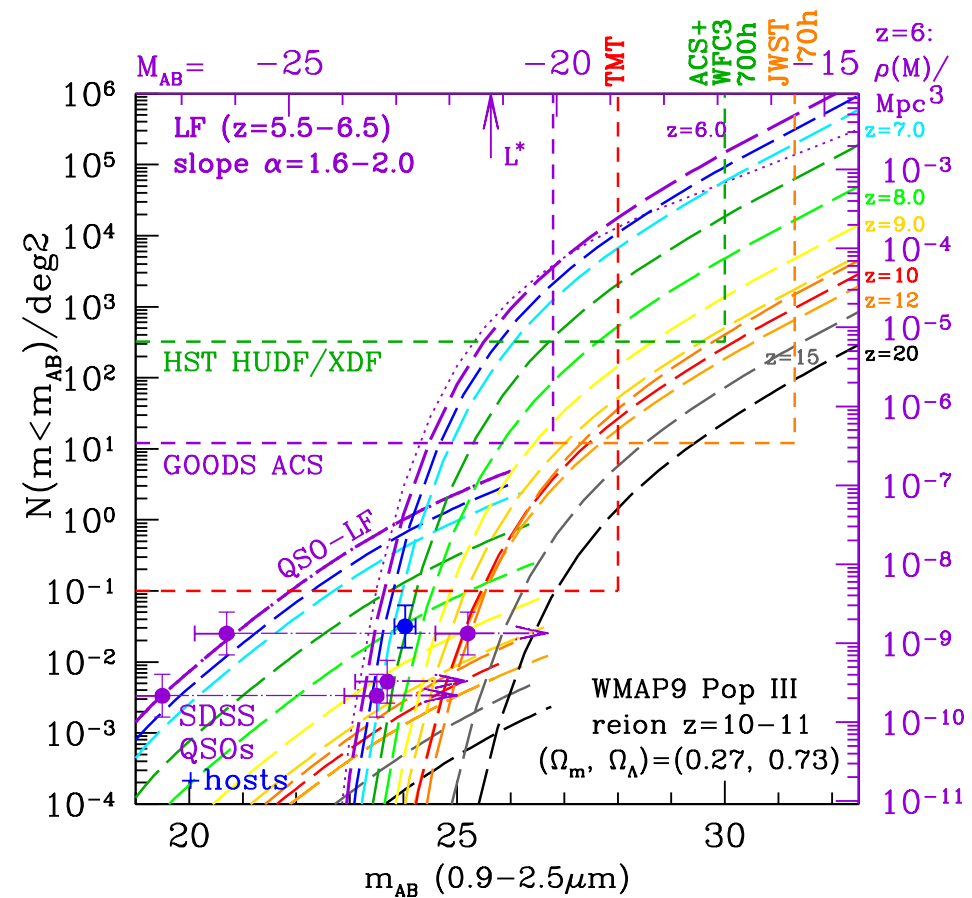
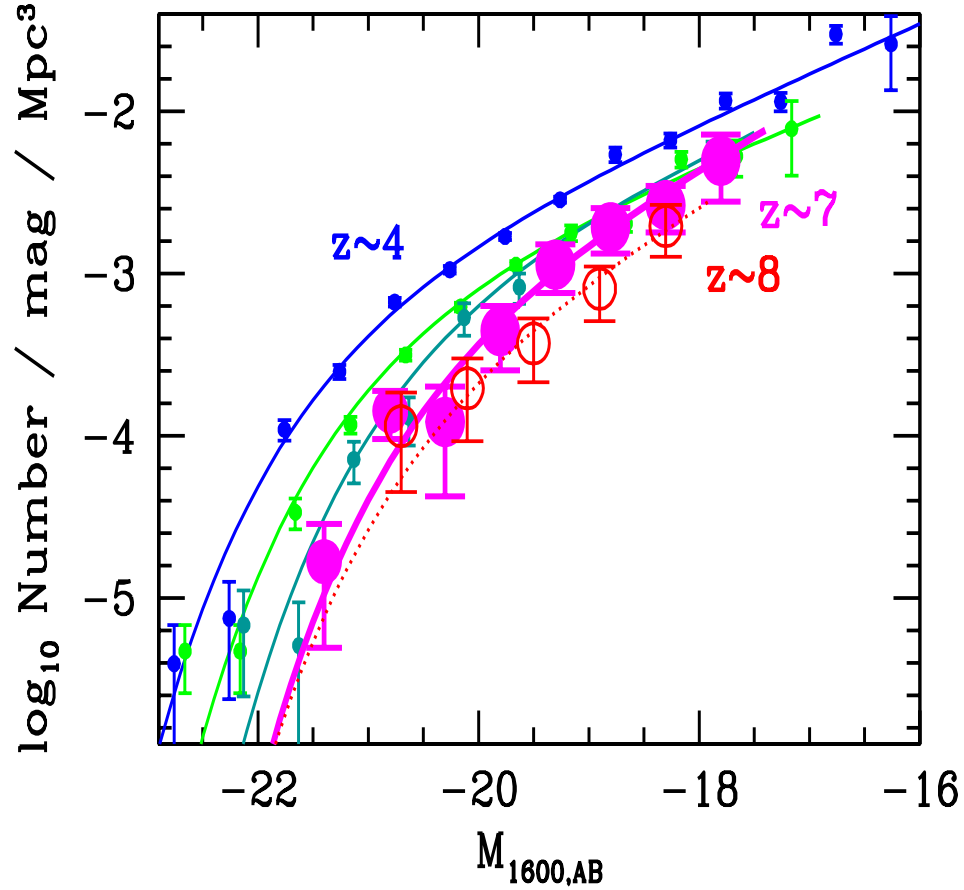
**Distant Galaxies in the Hubble Ultra Deep Field**  
**Hubble Space Telescope • Advanced Camera for Surveys**

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

STScI-PRC04-28

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



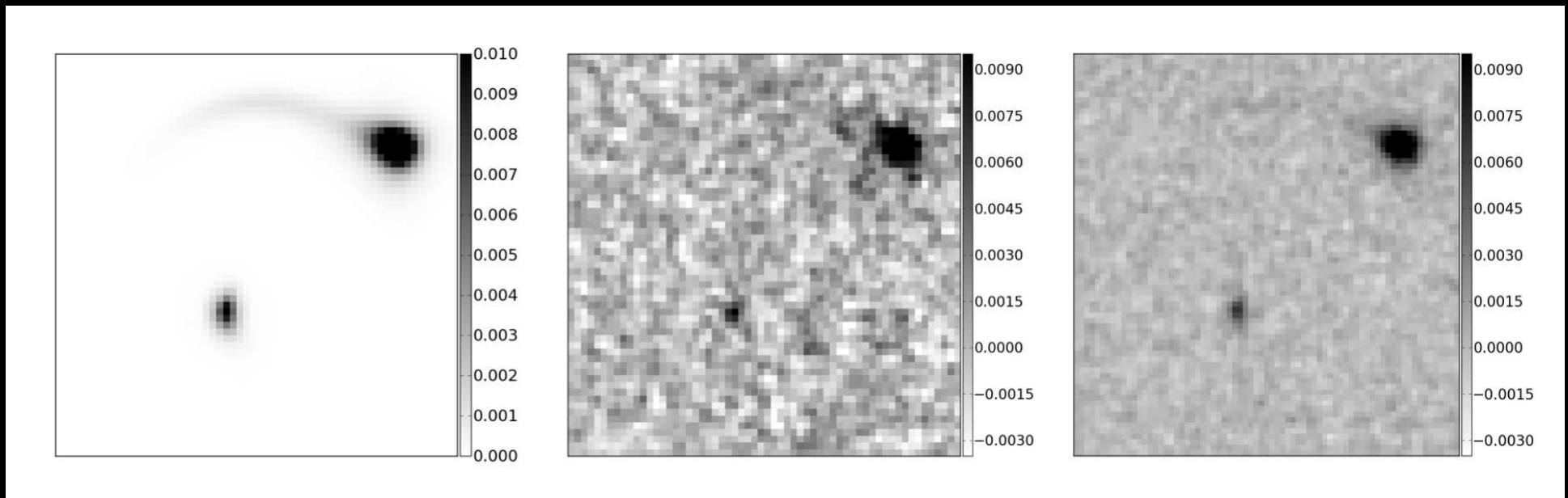
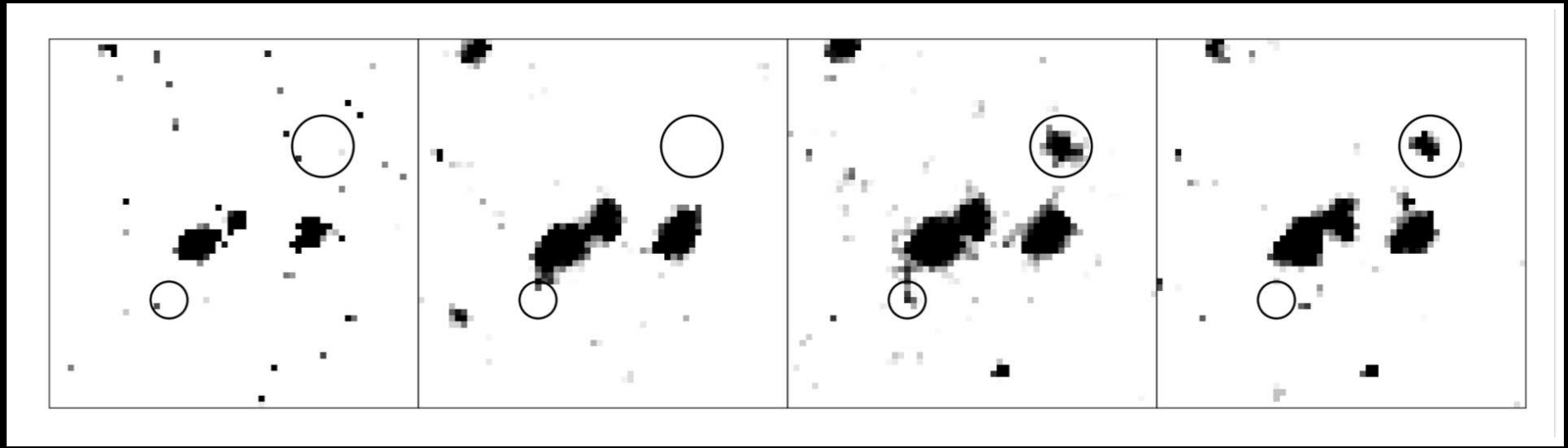


- Objects at  $z \gtrsim 9$  are rare (Bouwens<sup>+</sup> 12; Trenti,<sup>+</sup> 10; Yan<sup>+</sup> 10), since volume elt is small, and JWST samples brighter part of LF. JWST needs its sensitivity/aperture ( $A$ ), field-of-view ( $\Omega$ ), and  $\lambda$ -range ( $0.7\text{-}29 \mu\text{m}$ ).
- 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  $2.0 \mu\text{m}$  diffraction limit for this.

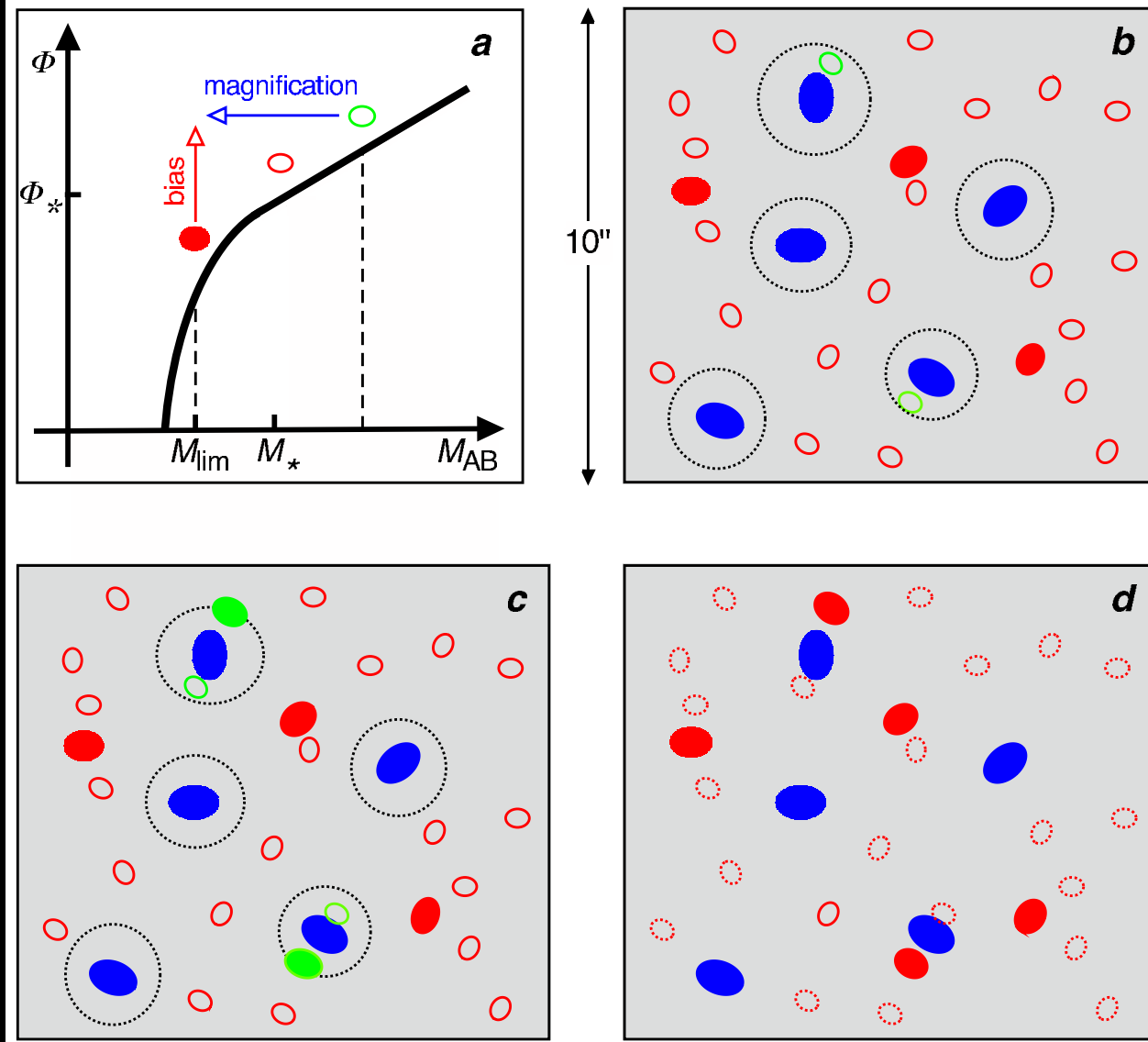
(4) Gravitational Lensing to see the Reionizing population at  $z \gtrsim 8$ .



## (4) Gravitational Lensing to see the Reionizing population at $z \gtrsim 8$ .



- Barone-Nugent<sup>+</sup> (2012): Possible  $z=8$  galaxy in WFC3 BoRG survey (Trenti<sup>+</sup> 2011) lensed by foreground group: Foreground halos ( $z \simeq 1-2$ ) may gravitationally lens or amplify galaxies at  $z \gtrsim 8-10$  (Wyithe et al. 2011).
- If common, this could change the landscape for JWST observing strategies.



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

- Foreground galaxies ( $z \simeq 1-2$  or  $\text{age} \simeq 3-6$  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.
- Strength of effect at  $z \gtrsim 8-10$  depends on how fast  $M^*$  declines with  $z$ .



Two fundamental limitations may determine ultimate JWST image depth:

(1) Cannot-see-the-forest-for-the-trees effect [Natural Confusion limit]:  
Background objects blend into foreground neighbors because of their own diameter  $\Rightarrow$  Need multi- $\lambda$  deblending algorithms!

(2) House-of-mirrors effect [“Gravitational Confusion”]: First Light objects at  $z \gtrsim 8-10$  may be gravitationally lensed by foreground halos.

$\Rightarrow$  May need multi- $\lambda$  SExtractor that works on sloped backgrounds!

$\Rightarrow$  If  $M^*(z \gtrsim 10) \gtrsim -19$ , may need to model entire gravitational foreground.

● Proper JWST  $2.0\mu\text{m}$  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.
- Most  $z \simeq 6$  QSO host galaxies faint (dusty?), with 1 exception:  $L \gg L^*$ .

(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

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- 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





### Baseline "Cup Down" Tower Configuration at JSC (Before)



### JSC "Cup Up" Test Configuration (New Proposal)



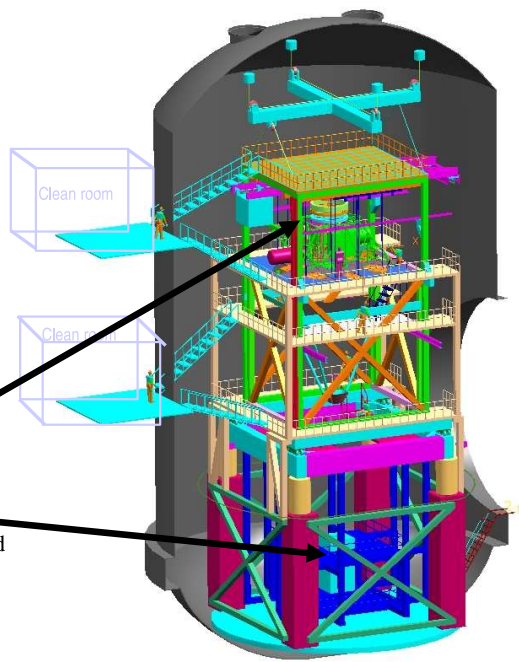
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

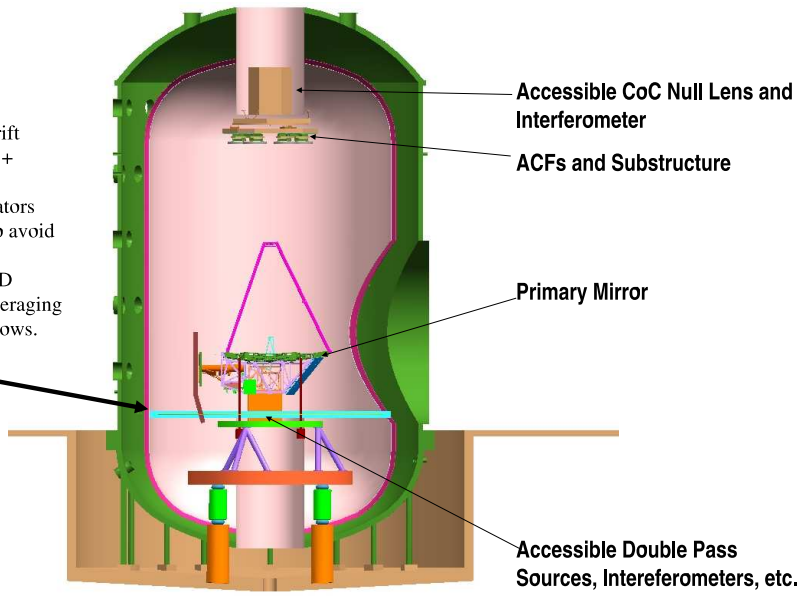
Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



No Metrology Tower and Associated Cooling H/W. External Metrology  
Two basic test options:  
1. Use isolators, remove drift through fast active control + freeze test equipment jitter  
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter  
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload "floor" to separate ambient pressure and temperature.

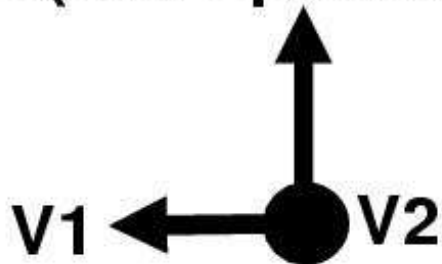


Drawing care of ITT

## 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  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 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.

V3 (anti-spacecraft)



OTE ISIM



(V1, V3)  
origin

Tertiary  
Mirror

Secondary mirror

Cassegrain  
focus

Fine  
Steering Mirror

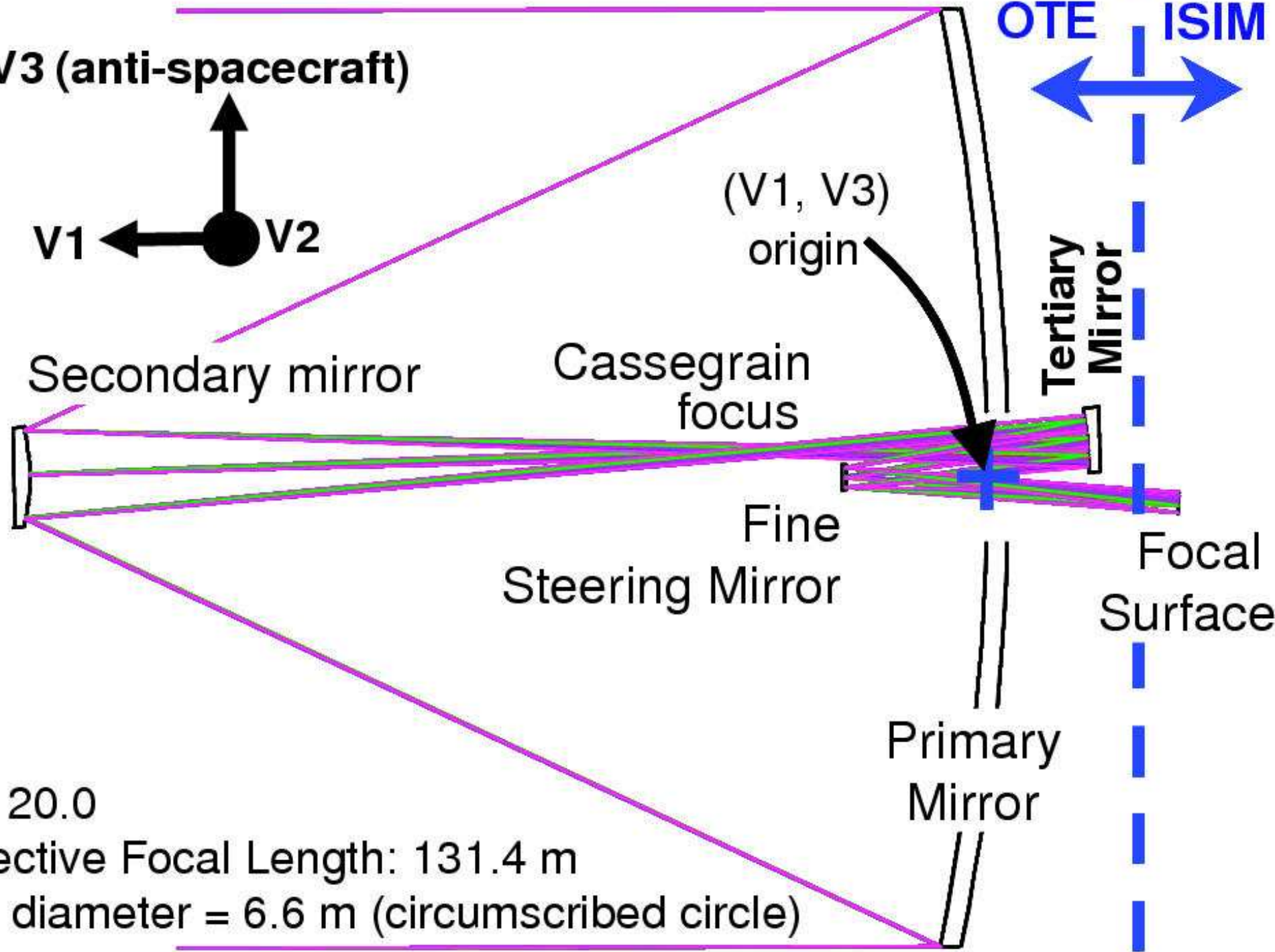
Focal  
Surface

Primary  
Mirror

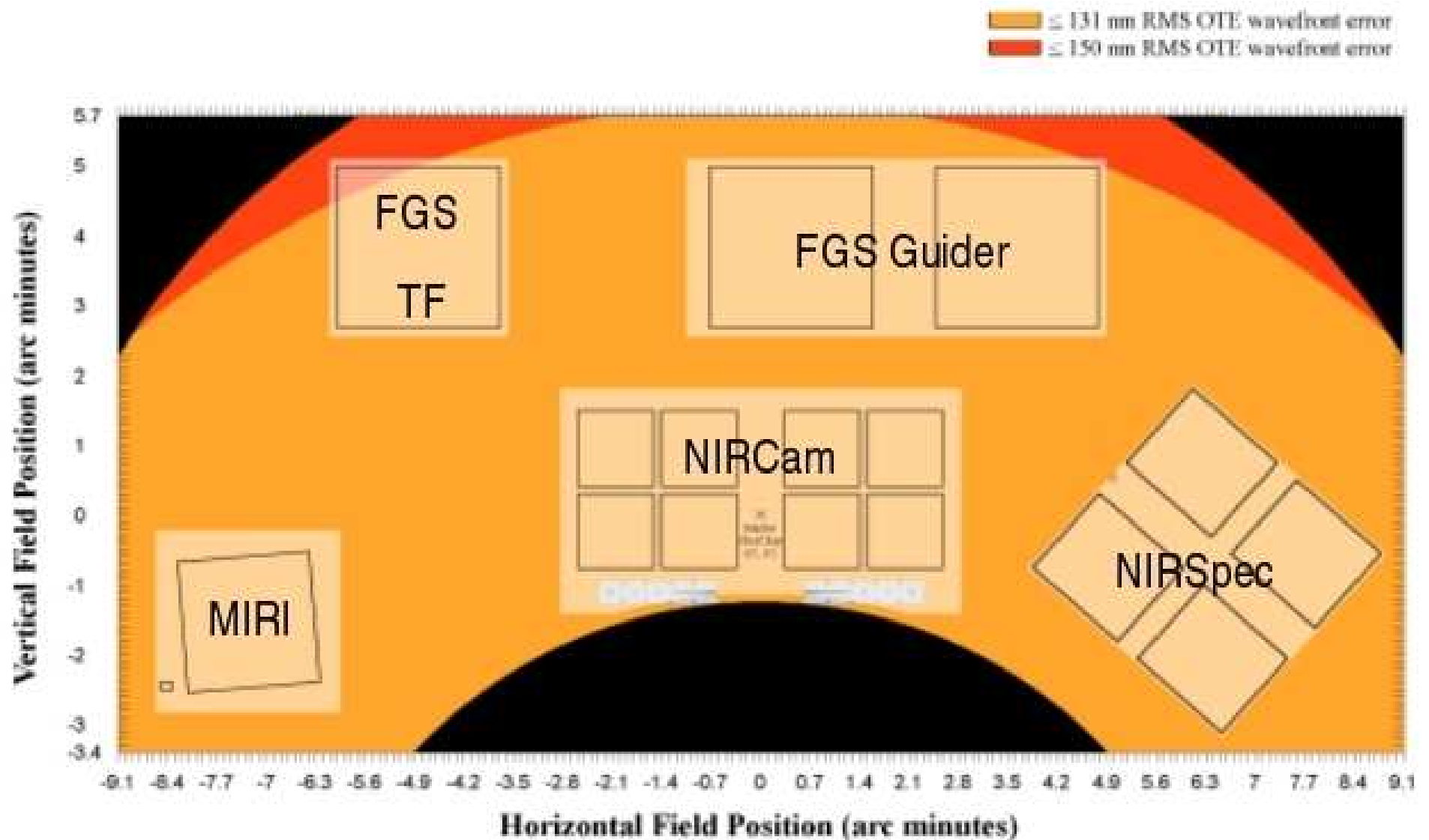
f/#: 20.0

Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)



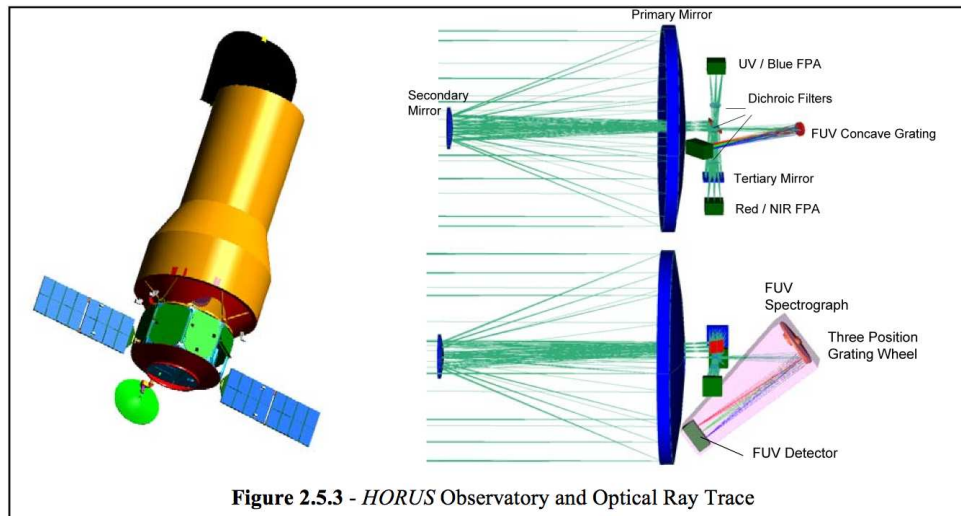
- (3c) What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations*.

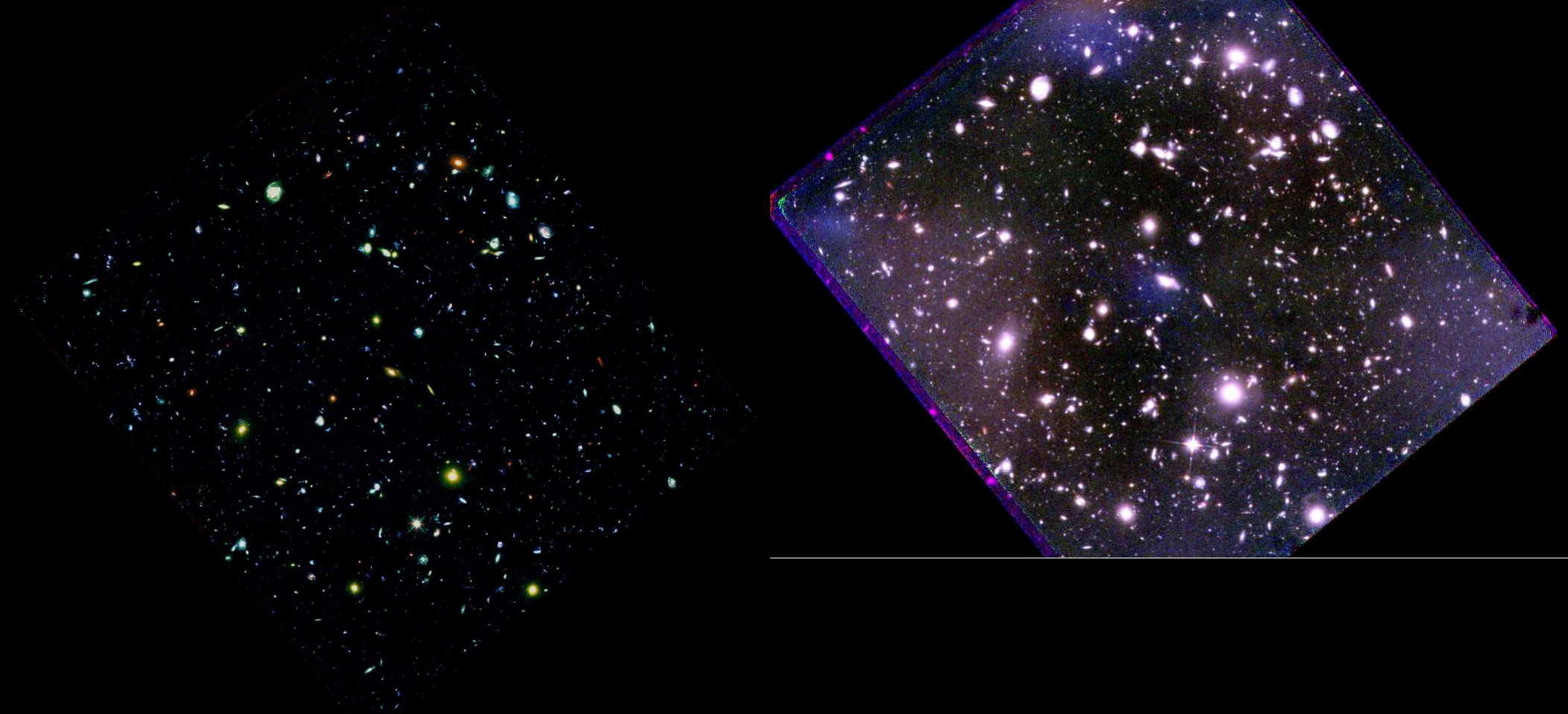
# One day we will need a UV-optical sequel to Hubble:



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.  
● NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.  
● Can do wide-field ( $\sim 0.25$  deg) UV-opt  $0''.06$  FWHM imaging to  $AB \lesssim 29-30$  mag, and high sensitivity (on-axis) UV-spectroscopy.

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.  
● Can do same at 9 m.a.s. FWHM routinely to  $AB \lesssim 32-34$  mag, [and an ATLAST-UDF to  $AB \lesssim 38$  mag  $\sim 1$  pico-Jy].

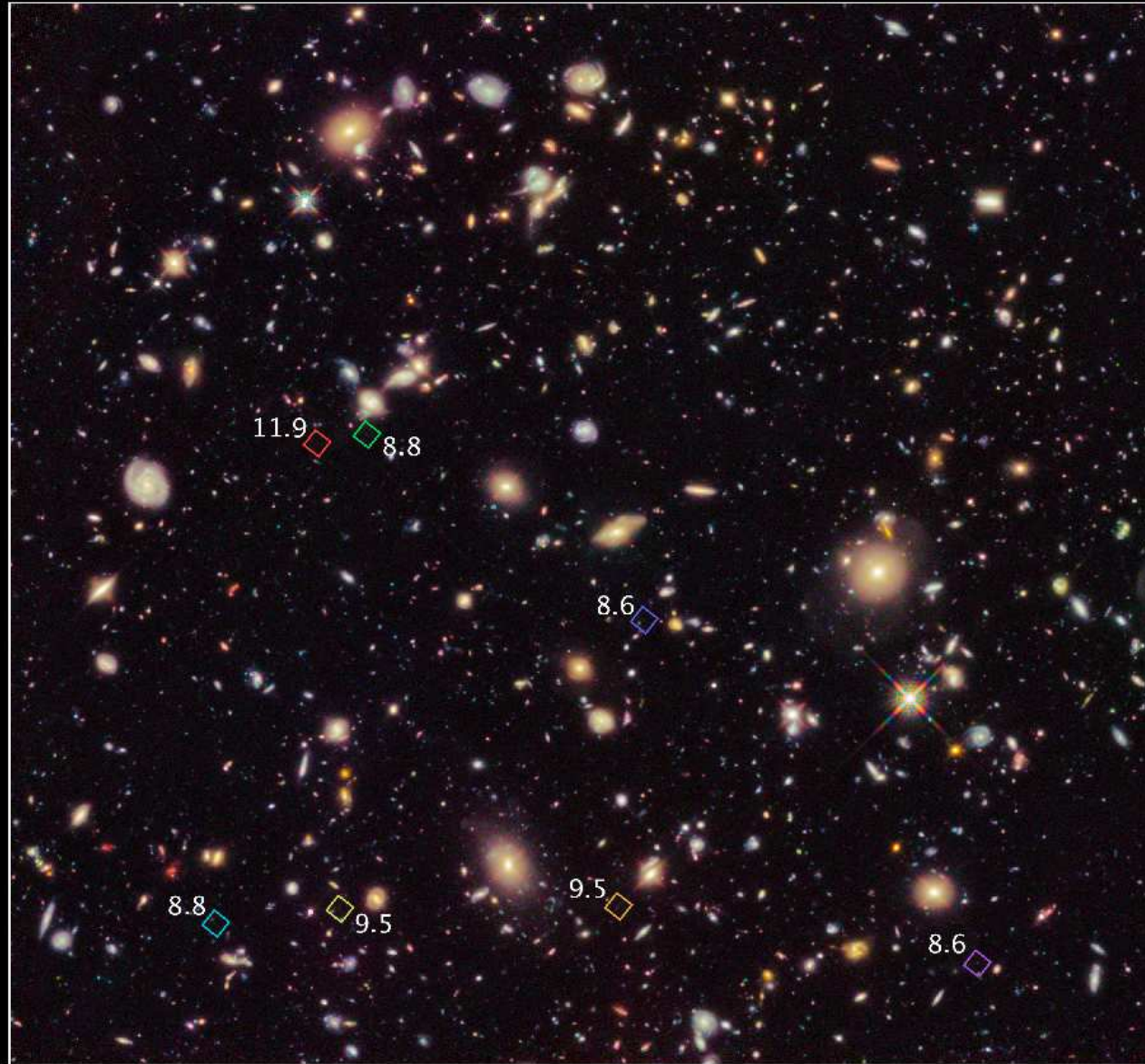
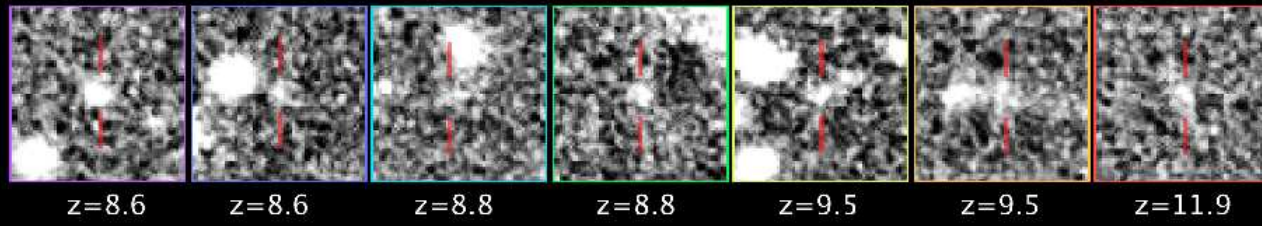


(Left) 128-hr HST/WFC3 IR-mosaic in HUDF at  $1\text{--}1.6\mu\text{m}$  (YJH filters; Bouwens et al 2010, Yan et al. 2010; +85-hr by R. Ellis in 09/2012).

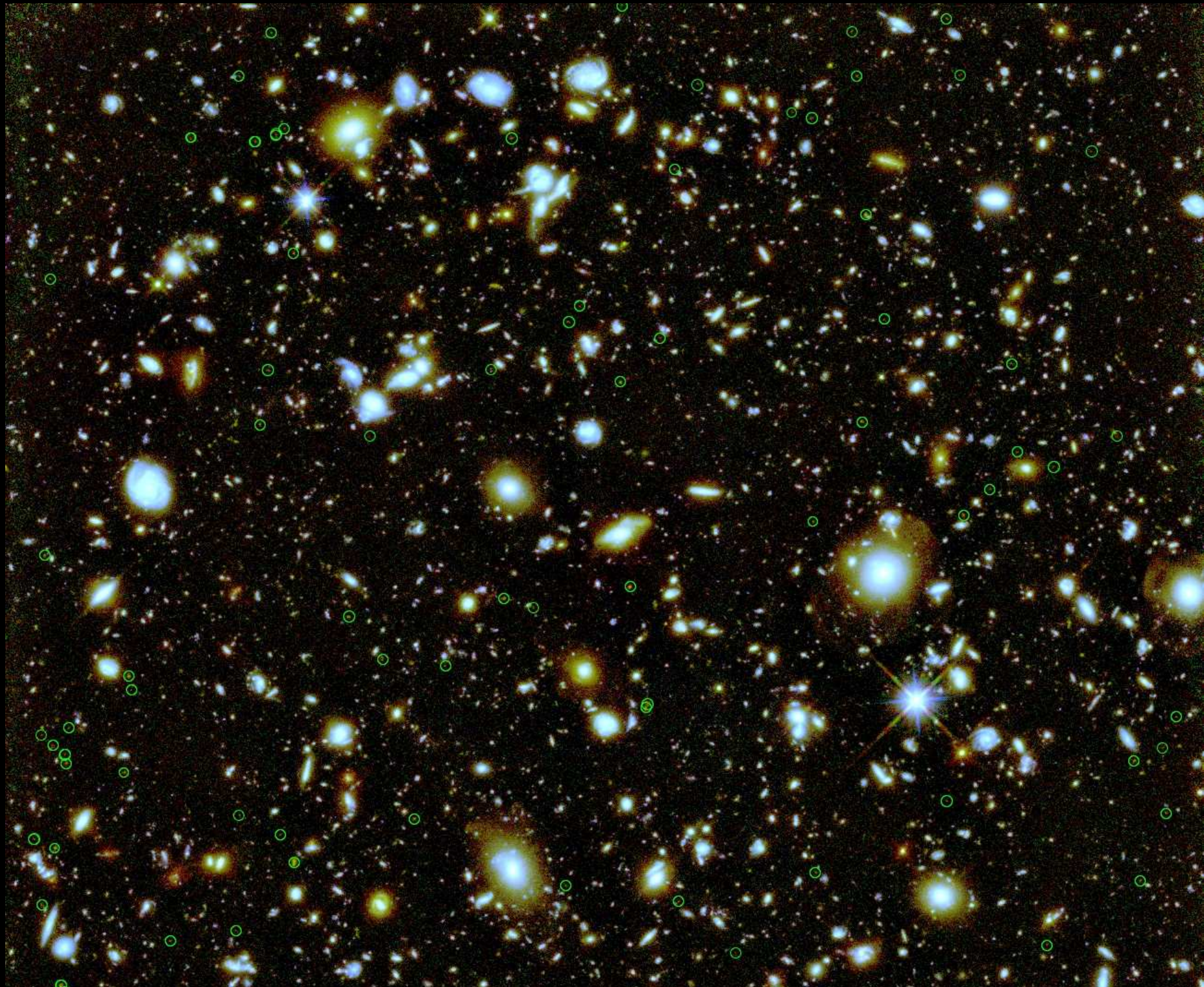
(Right) Same WFC3 IR-mosaic, but stretched to  $\lesssim 10^{-3}$  of Zodiacal sky!

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

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

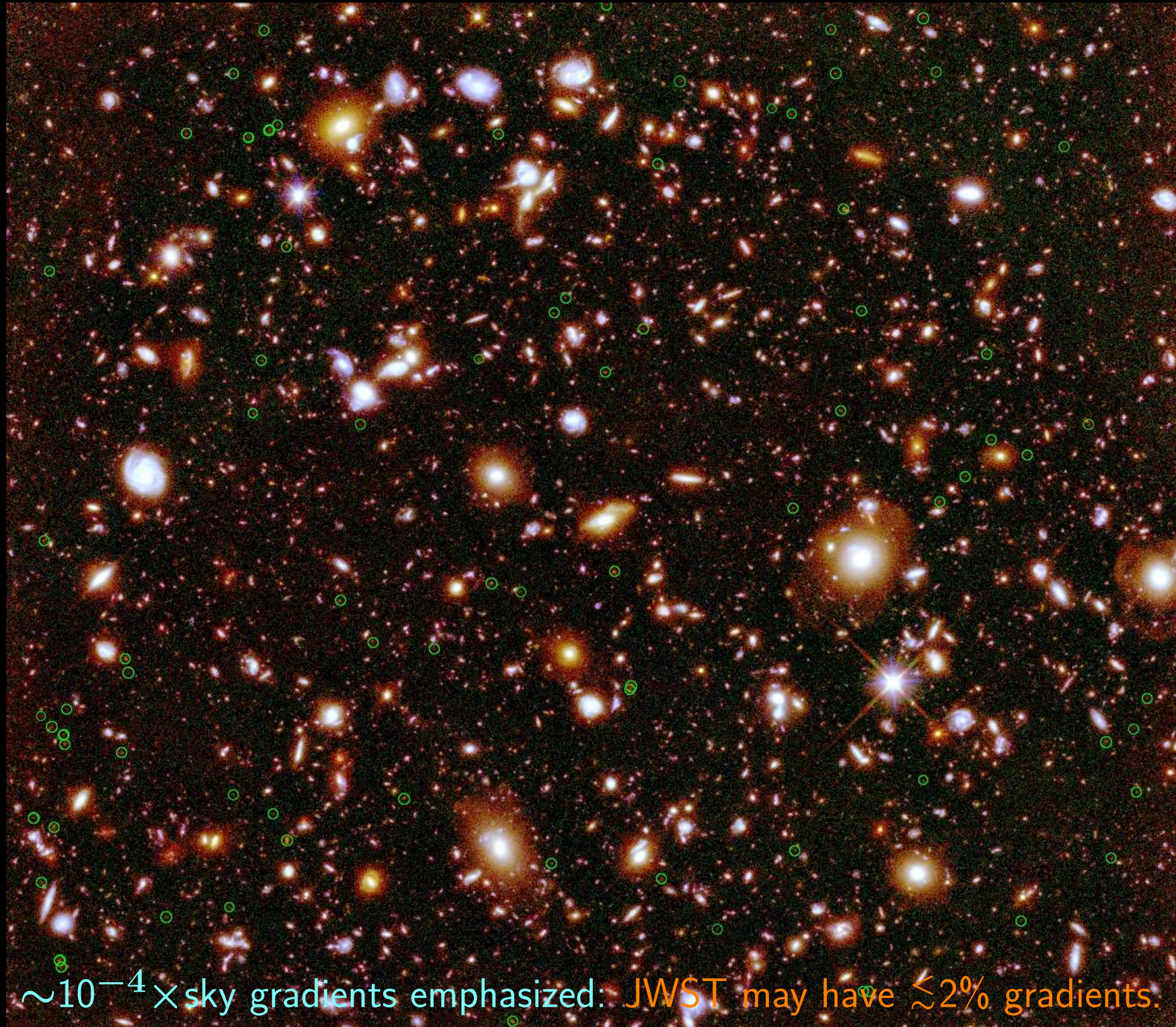


**Hubble Ultra Deep Field 2012**  
*Hubble Space Telescope WFC3/IR*

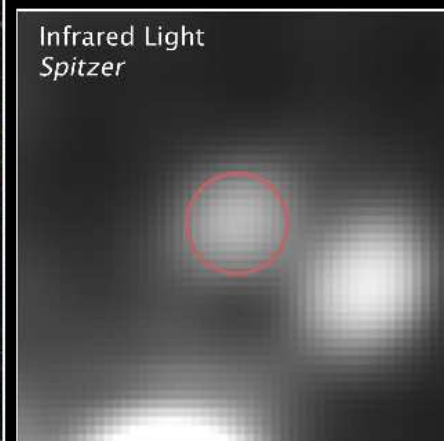
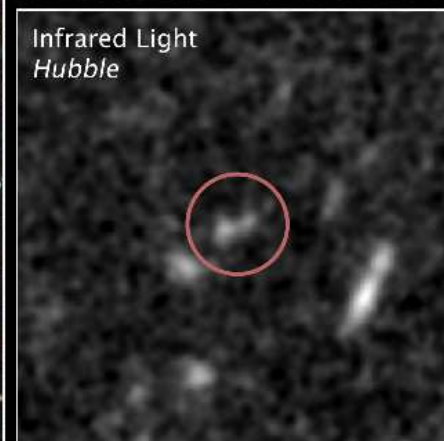
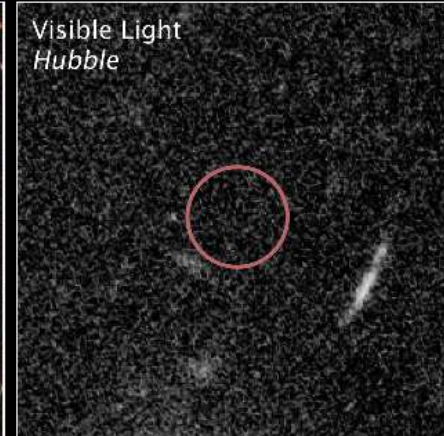
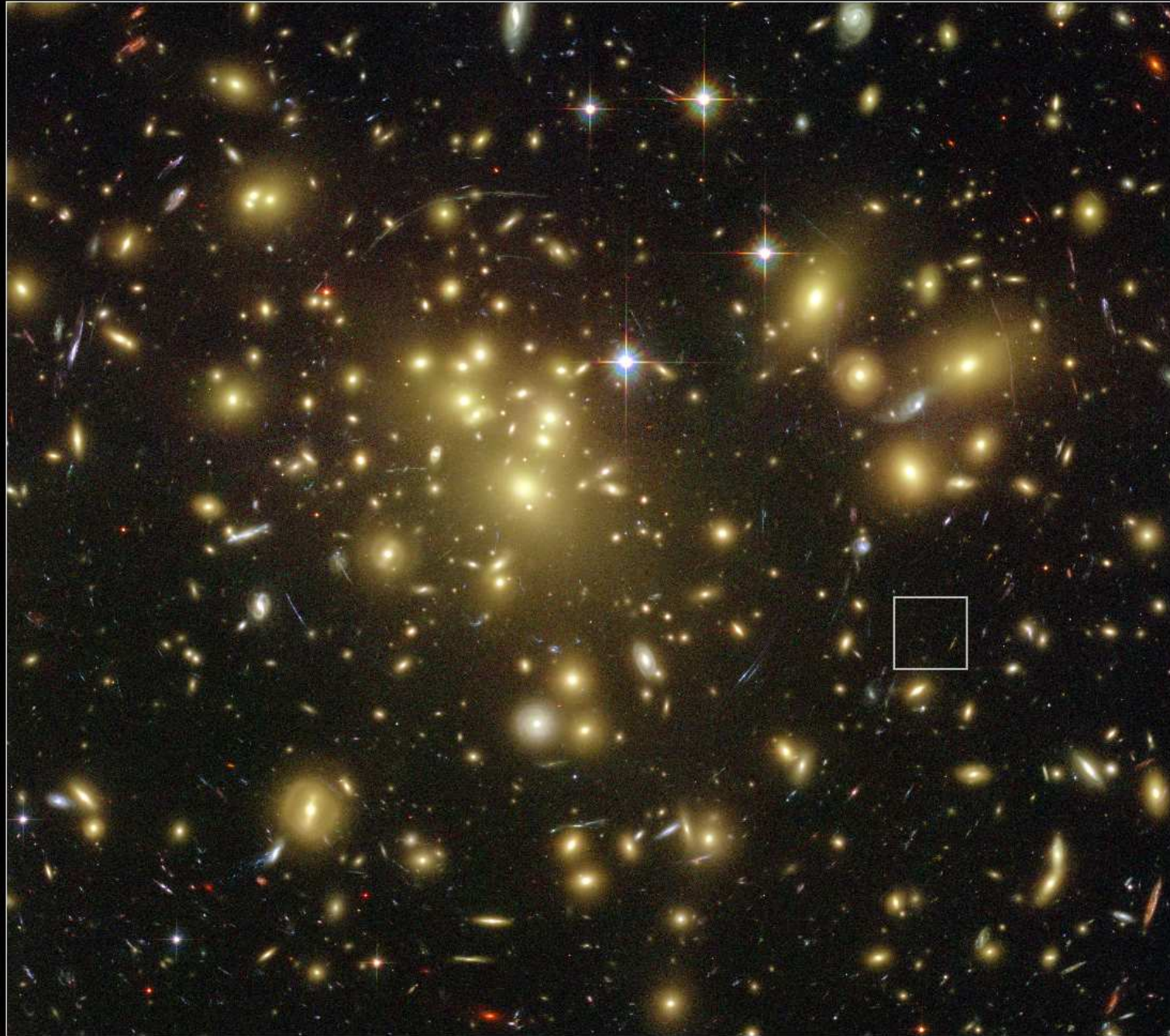


Best HUDF reduction (log-stretch): 700 ACS/WFC3 orbs **B**V*i***l****z****Y****J****W****H**.

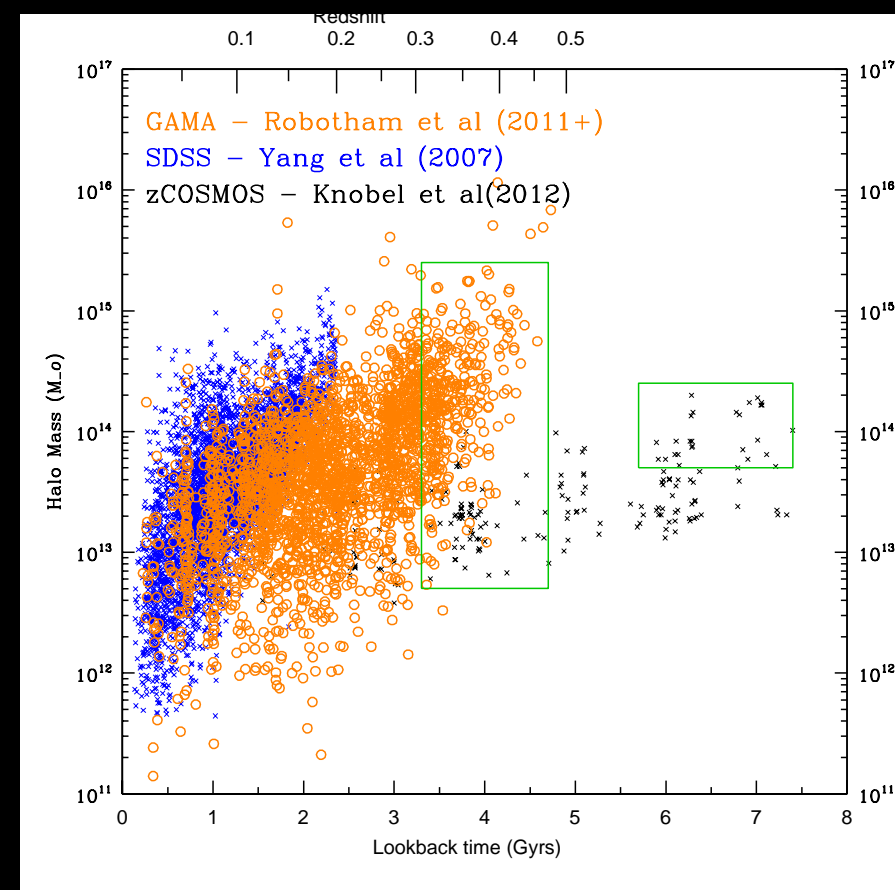
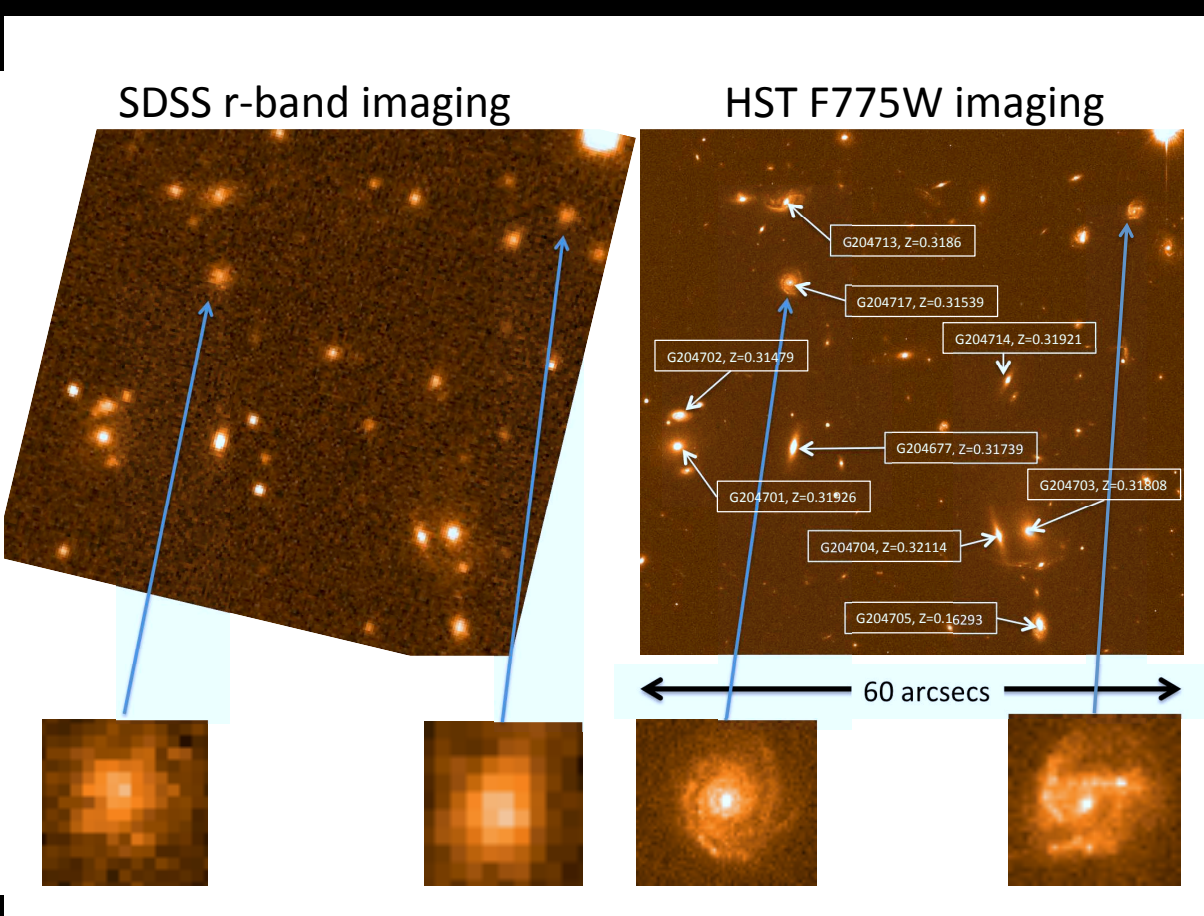




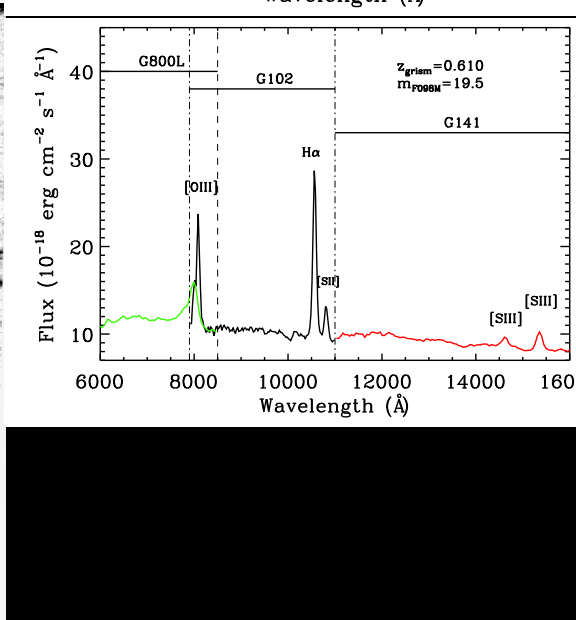
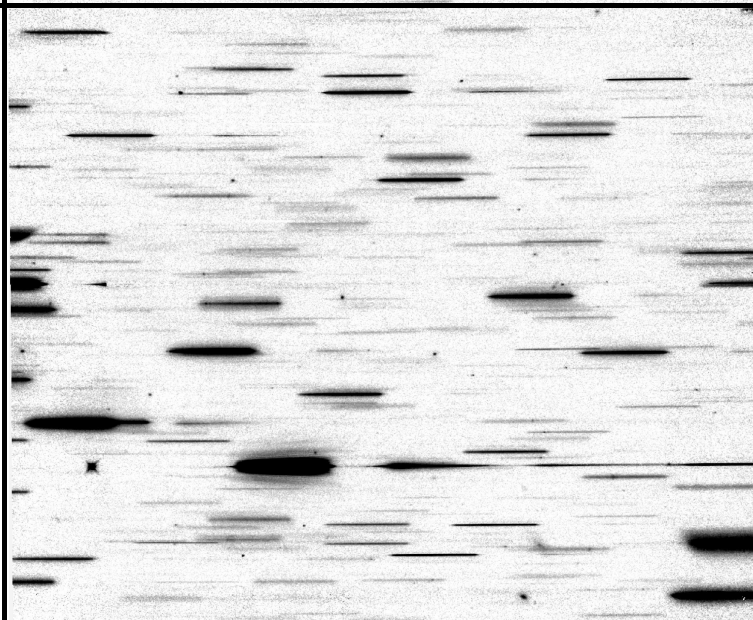
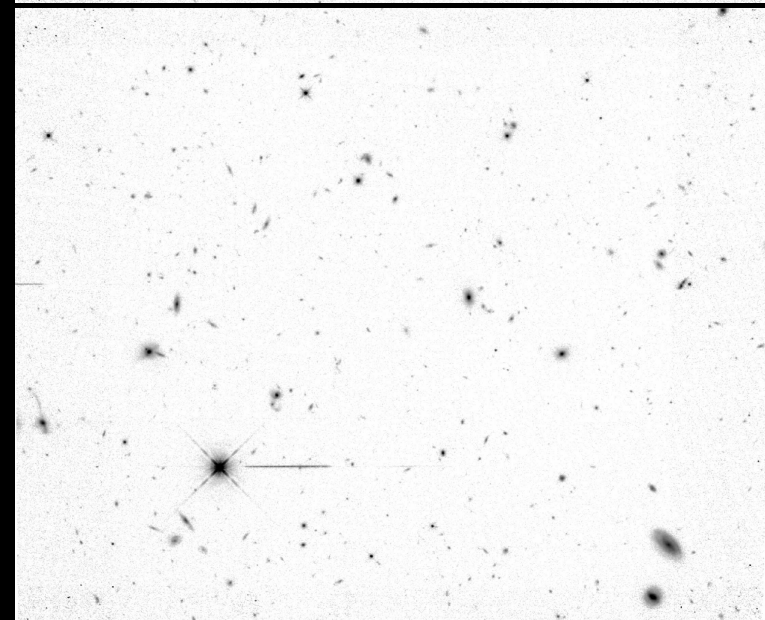
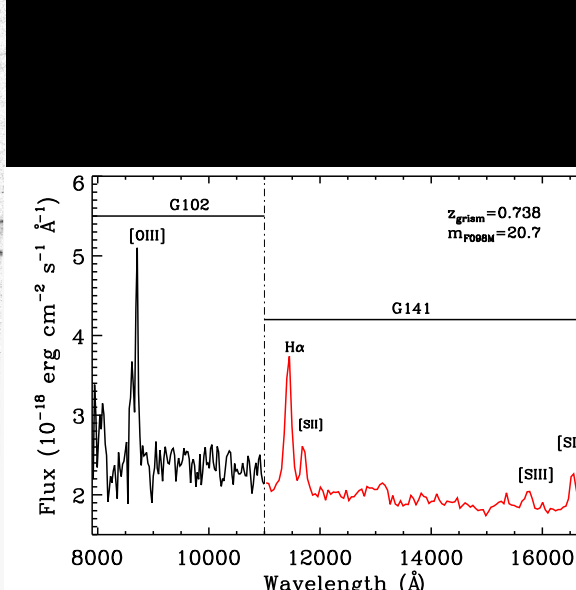
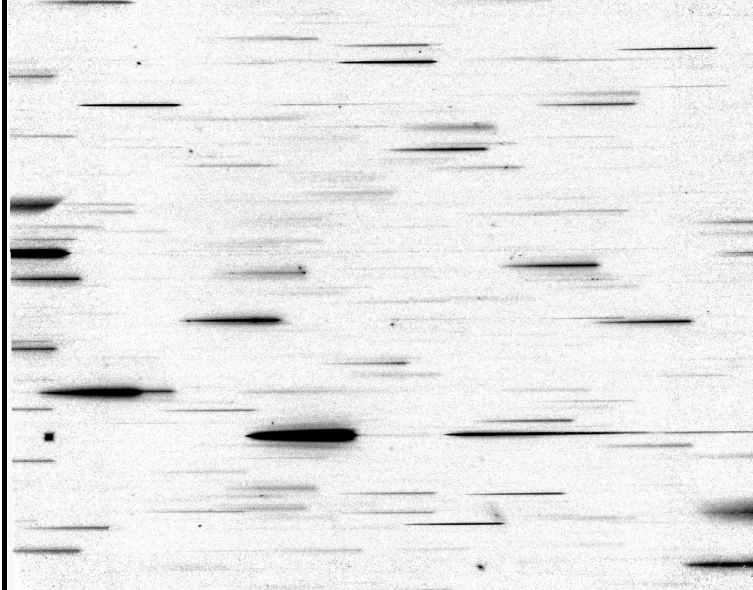
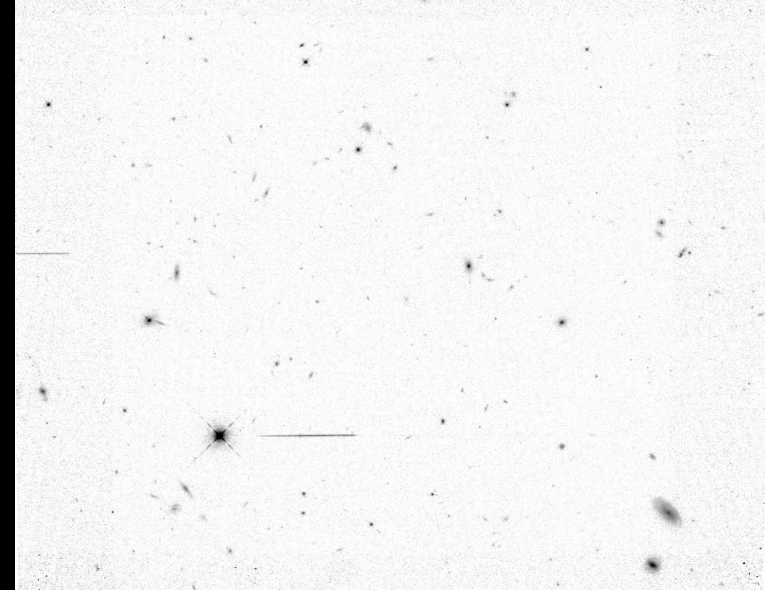
$\sim 10^{-4} \times$  sky gradients emphasized: JWST may have  $\lesssim 2\%$  gradients.



Distant Gravitationally Lensed Galaxy ■ Galaxy Cluster Abell 1689  
*Hubble Space Telescope* ■ ACS/WFC NICMOS



- (Left) Select the most massive known galaxy groups from GAMA at  $z \gtrsim 0.35$  as gravitational lensing-bias targets for JWST studies at  $z \gtrsim 2-15$ .
- In rich clusters, it may be much harder to separate intra-cluster light (ICL) from out-of-field or rogue path straylight in ultradeep JWST images.
- (Right) The most massive ( $\sim 10^{15} M_{\odot}$ ) GAMA groups at  $z \gtrsim 0.4$  have a  $\sim 16\times$  higher lensing cross section for  $z \simeq 3-15$  candidates than the most massive COSMOS groups ( $\sim 10^{14} M_{\odot}$ ) at  $z \sim 0.75$  (R. Barone-Nugent, priv. comm) — group compactness is critical here.



HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn<sup>+</sup> 2010)

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

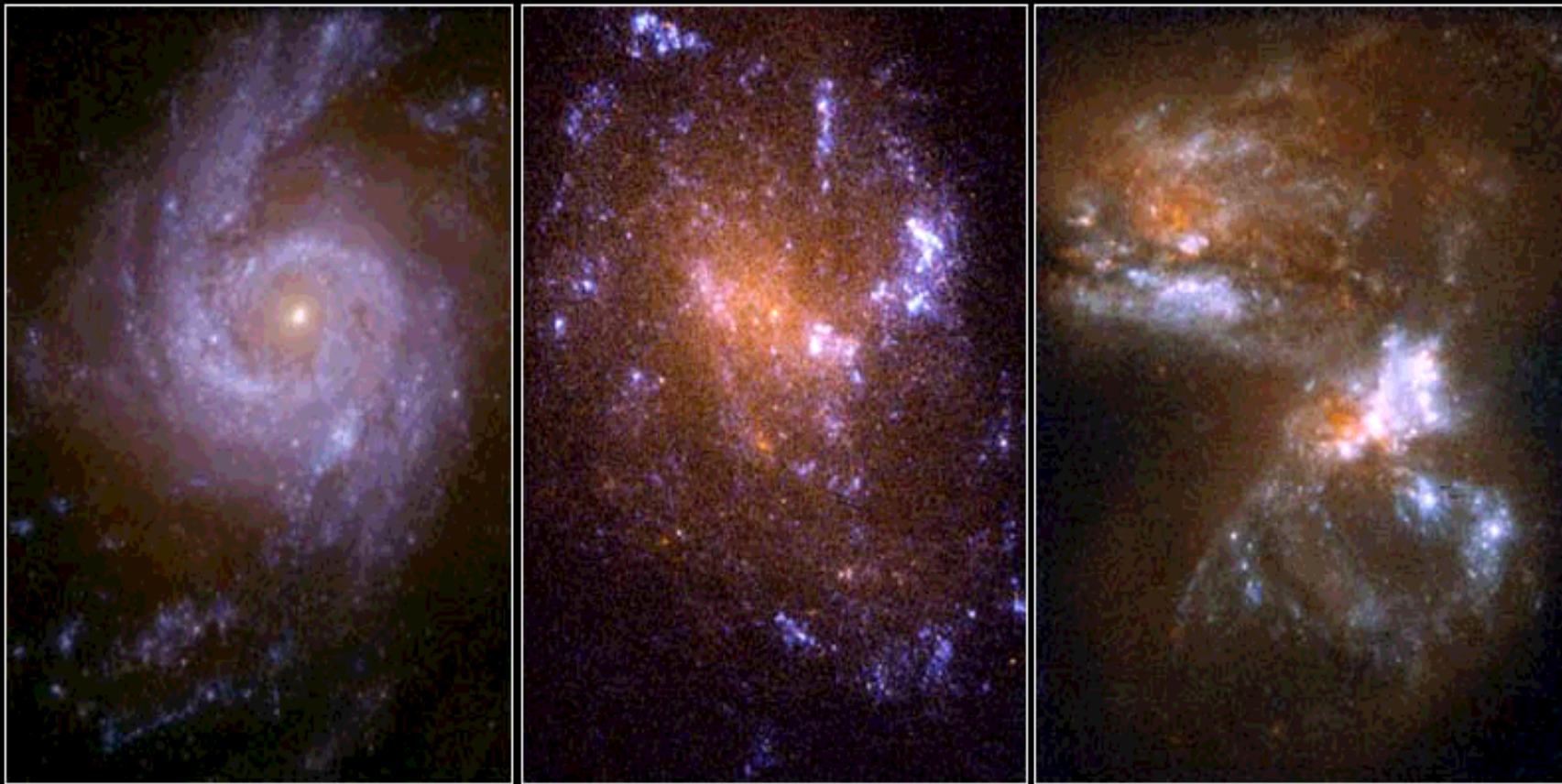
- JWST will provide near-IR grism spectra to  $AB \lesssim 29$  mag from 2–5.0  $\mu\text{m}$ .

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

NGC 3310

ESO0418-008

UGC06471-2



**Ultraviolet Galaxies**

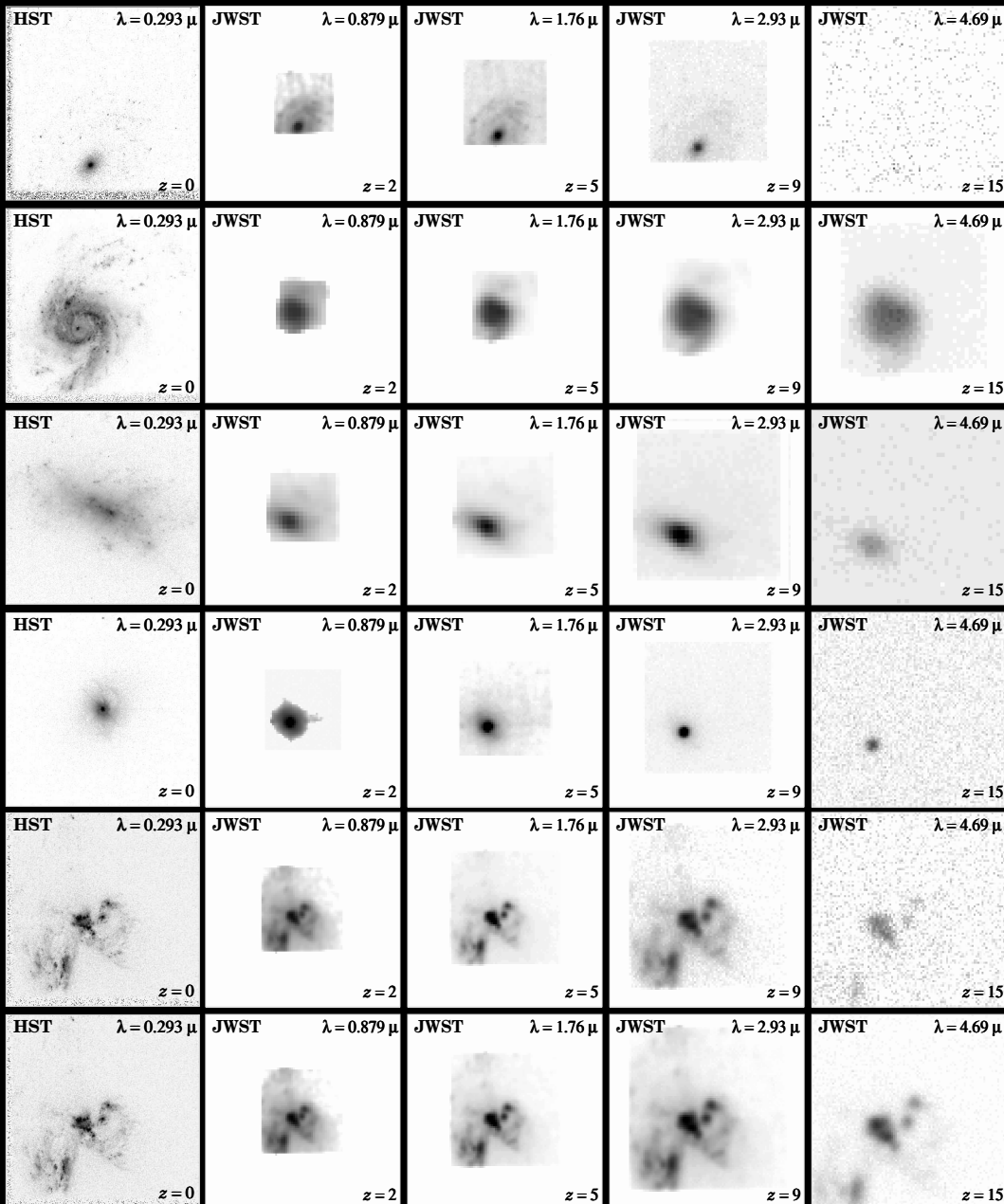
**HST • WFPC2**

NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

- 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 $z \simeq 1-15$

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



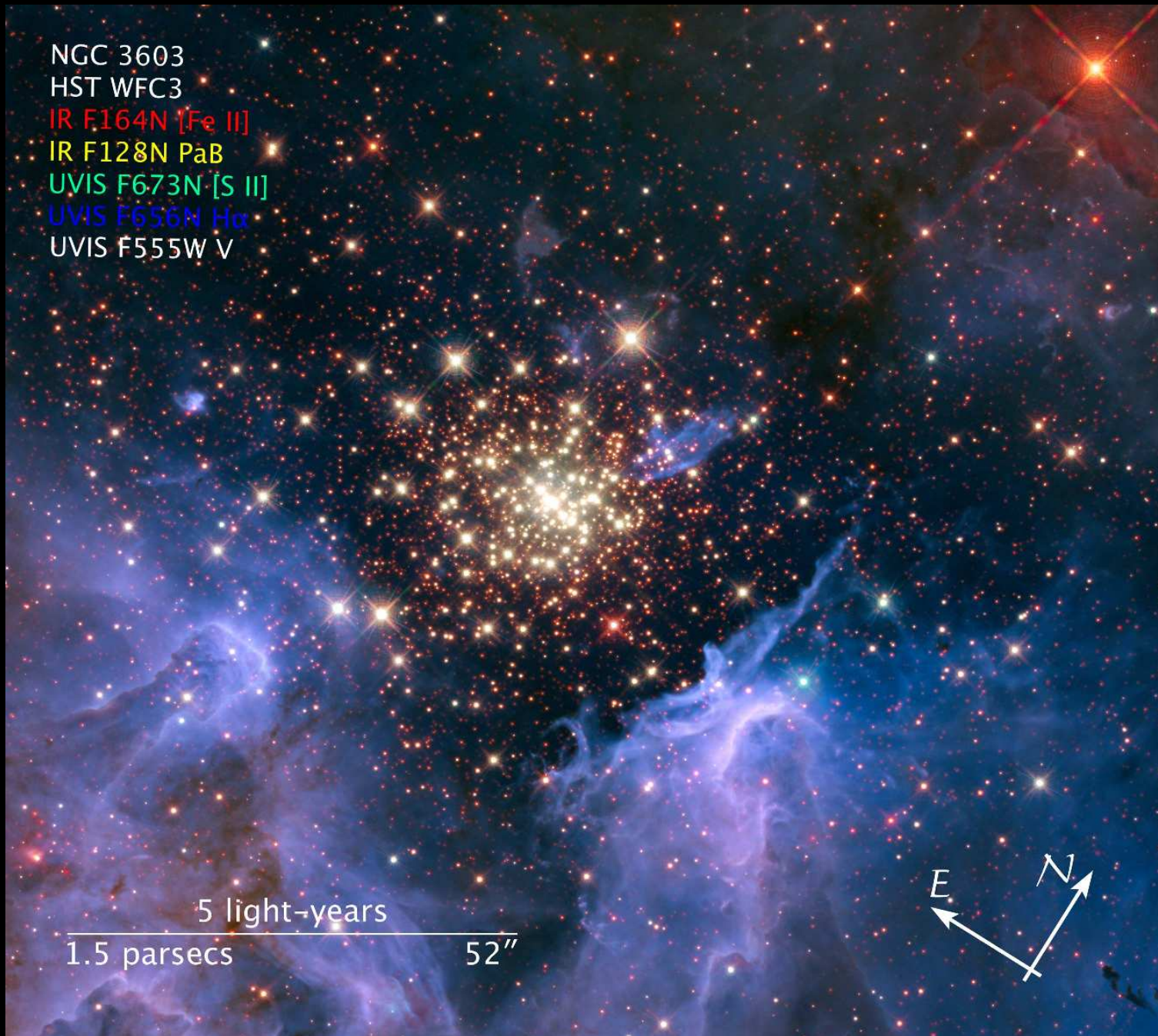
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

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

Visible to JWST at very high  $z$  are:

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

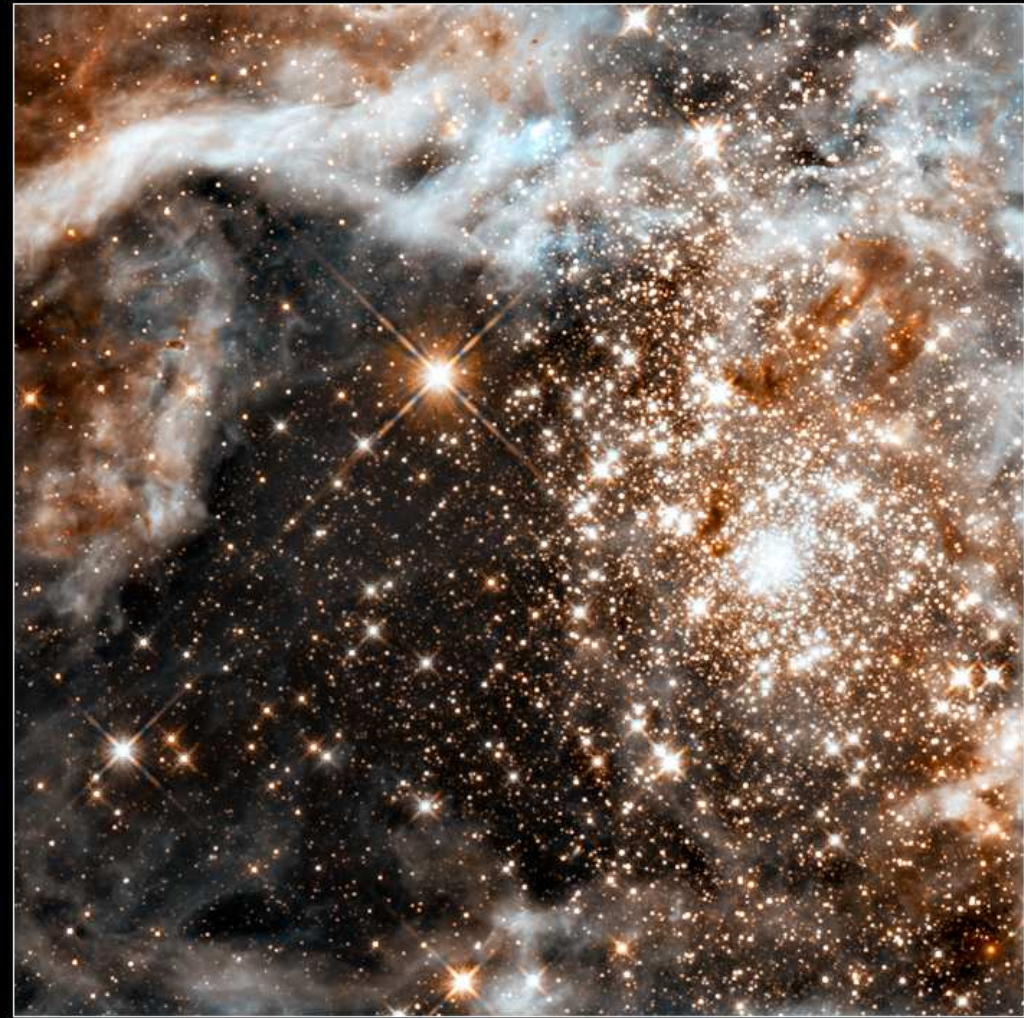
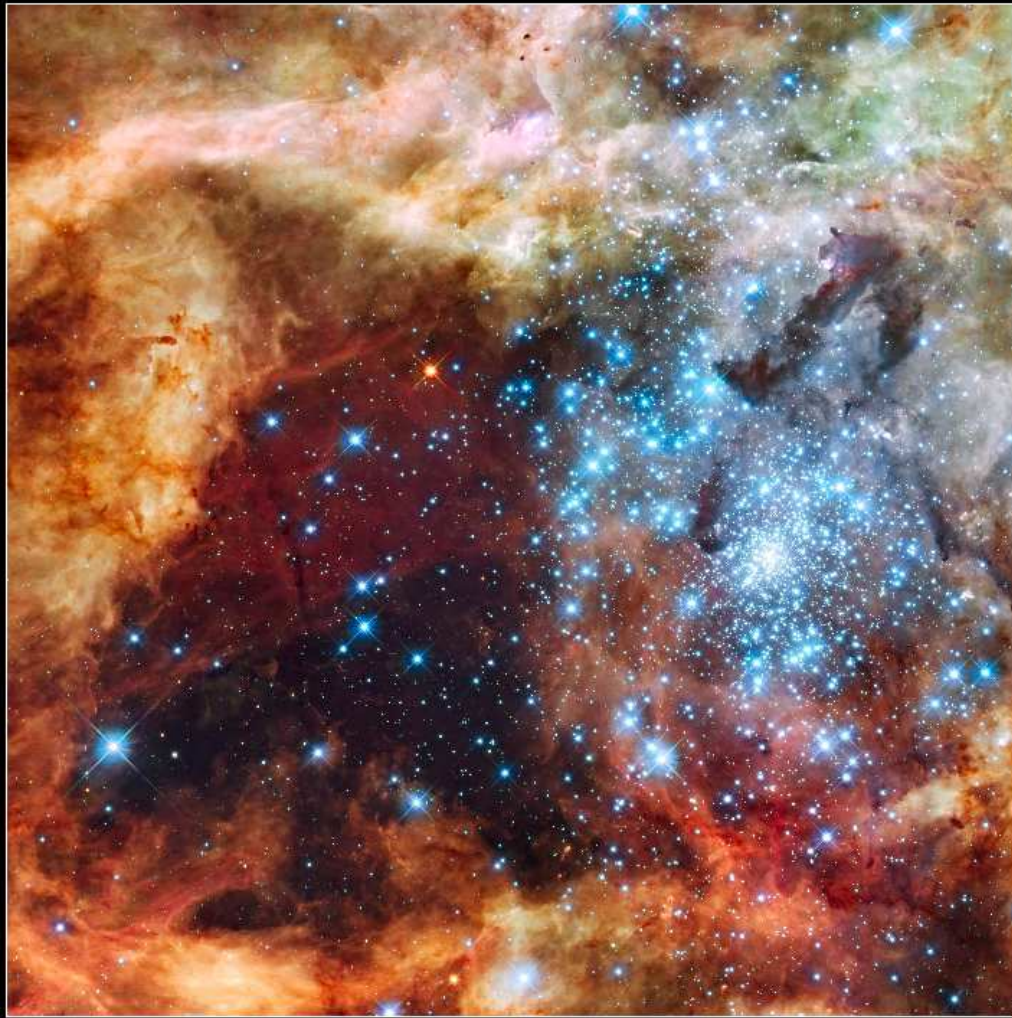
## (6) How can JWST measure Star-Formation and Earth-like exoplanets?



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

Visible

Infrared



**30 Doradus Nebula and Star Cluster**  
*Hubble Space Telescope* ■ WFC3/UVIS/IR

NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee

STScI-PRC09-32b

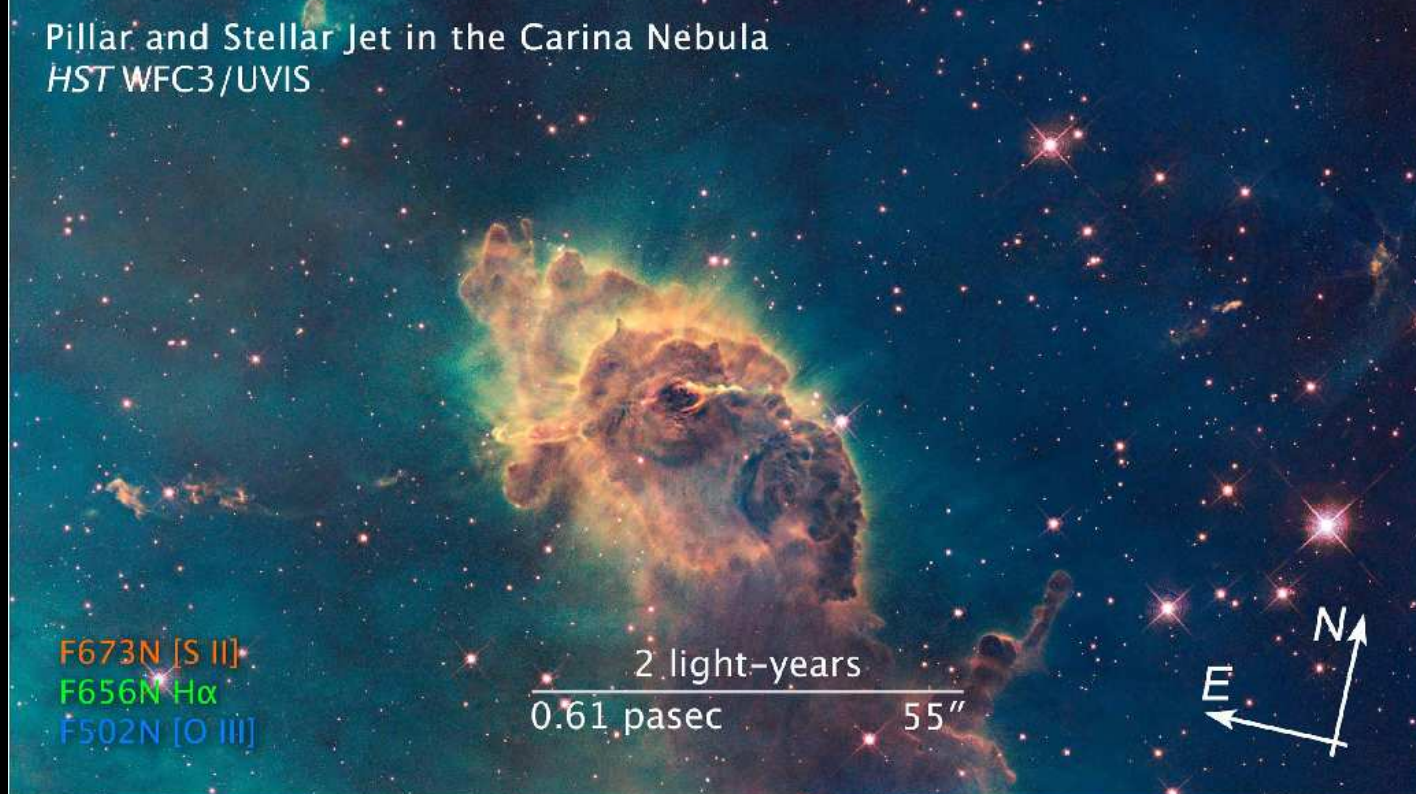
30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).







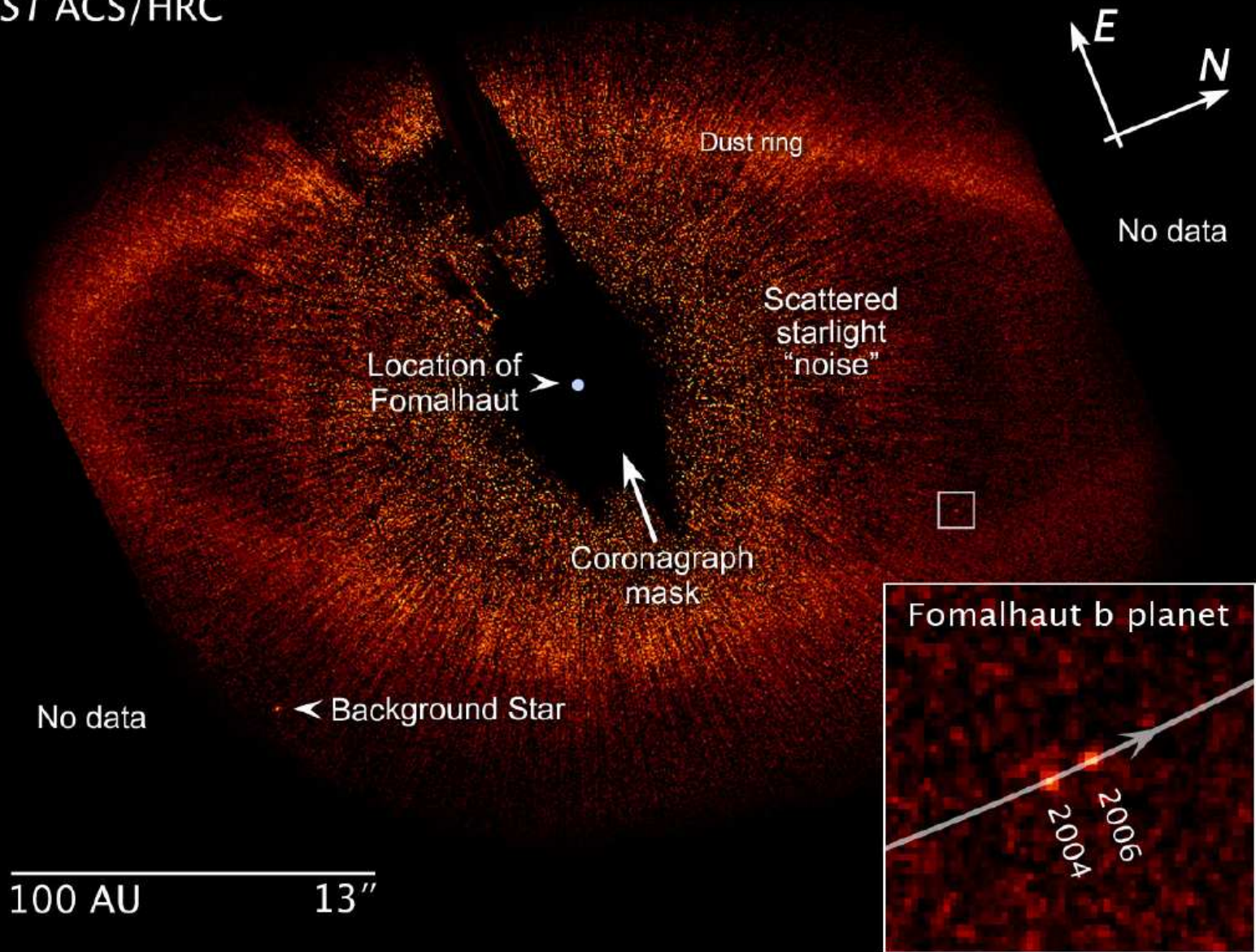
Pillar and Stellar Jet in the Carina Nebula  
HST WFC3/UVIS



HST WFC3/IR



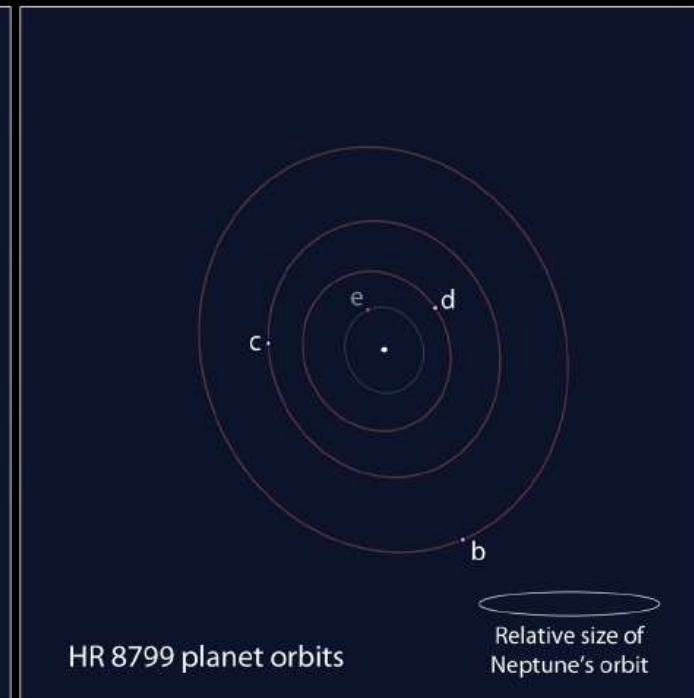
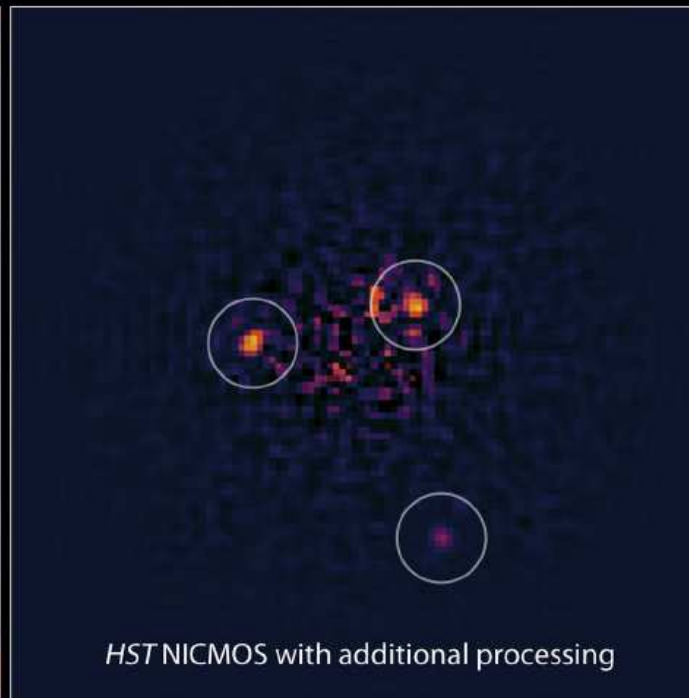
Fomalhaut  
HST ACS/HRC



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.

## Exoplanet HR 8799 System



NASA, ESA, and R. Soummer (STScI)

STScI-PRC11-29

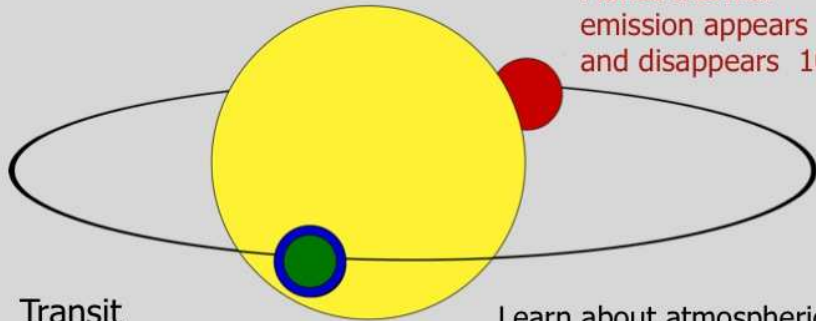
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

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

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

## Schematic of Transit and Eclipse Science

Seager & Deming (2010, ARAA, 48, 631)



### Eclipse

Planet thermal emission appears and disappears  $10^{-3}$

### Transit

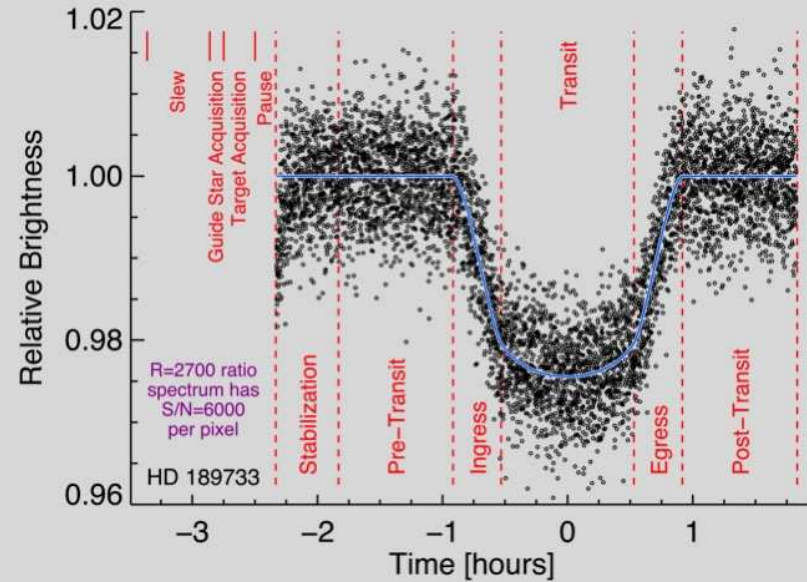
Measure size of planet  $10^{-2}$

See starlight transmitted through planet atmosphere  $10^{-4}$

Learn about atmospheric circulation from thermal phase curves

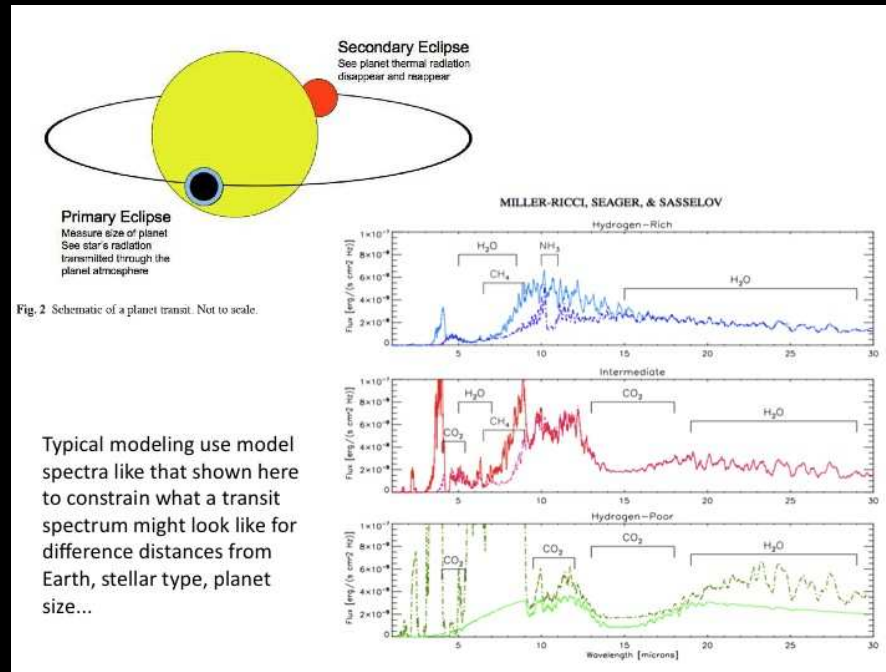
6

## Timeline of a Transit Observation



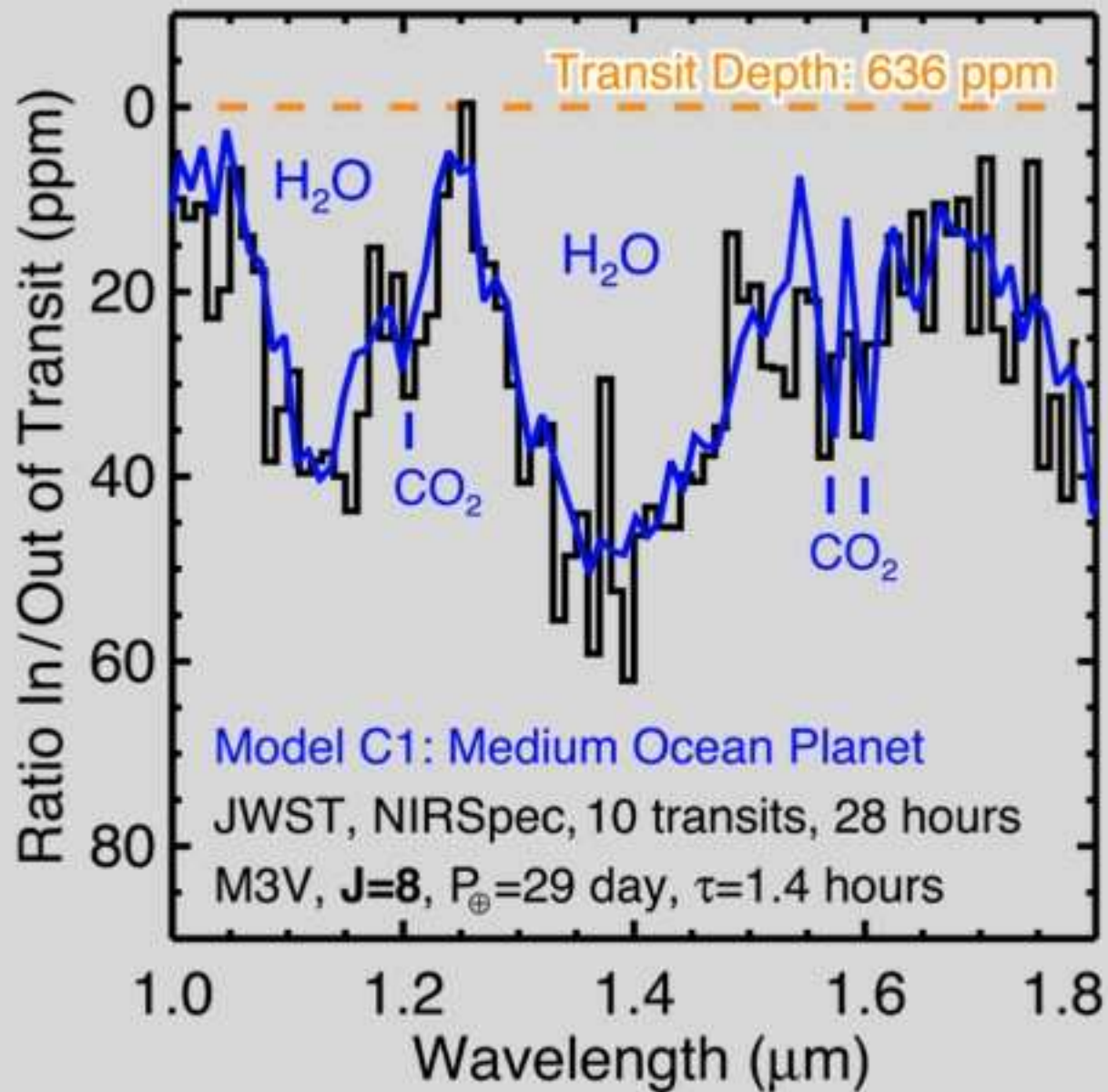
13

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



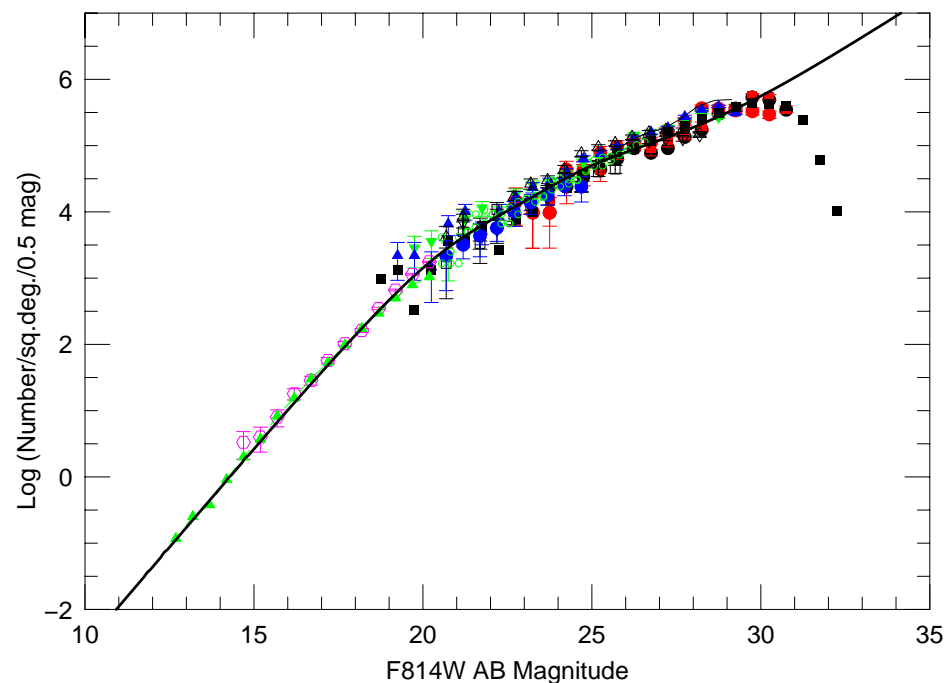
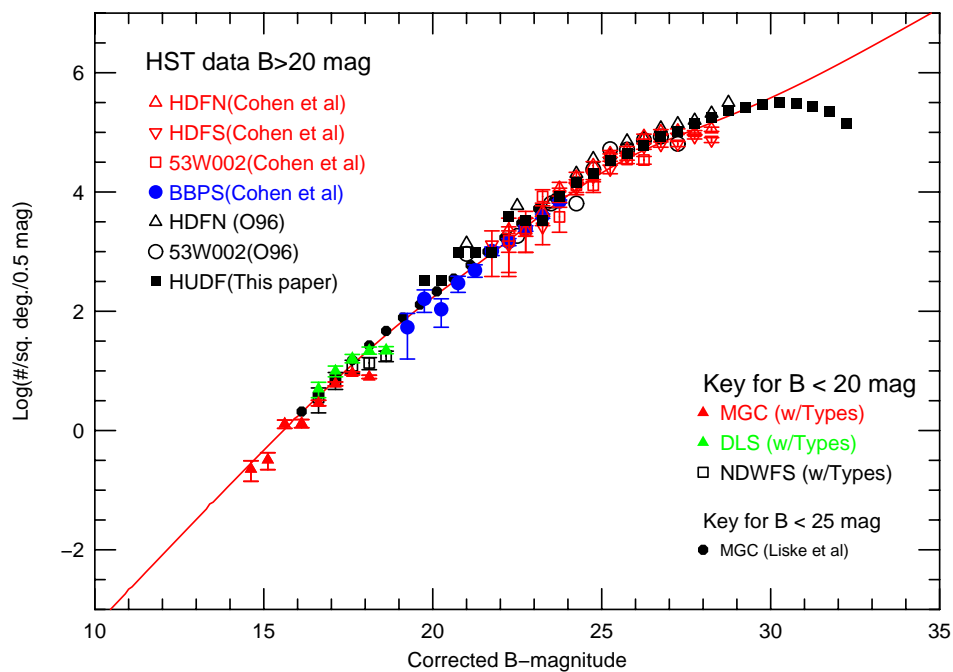
JWST IR spectra can find water and CO<sub>2</sub> in (super-)Earth-like exoplanets.

# Transit Spectrum of Habitable "Ocean Planet"



JWST IR spectra can find water and CO<sub>2</sub> in transiting Earth-like exoplanets.

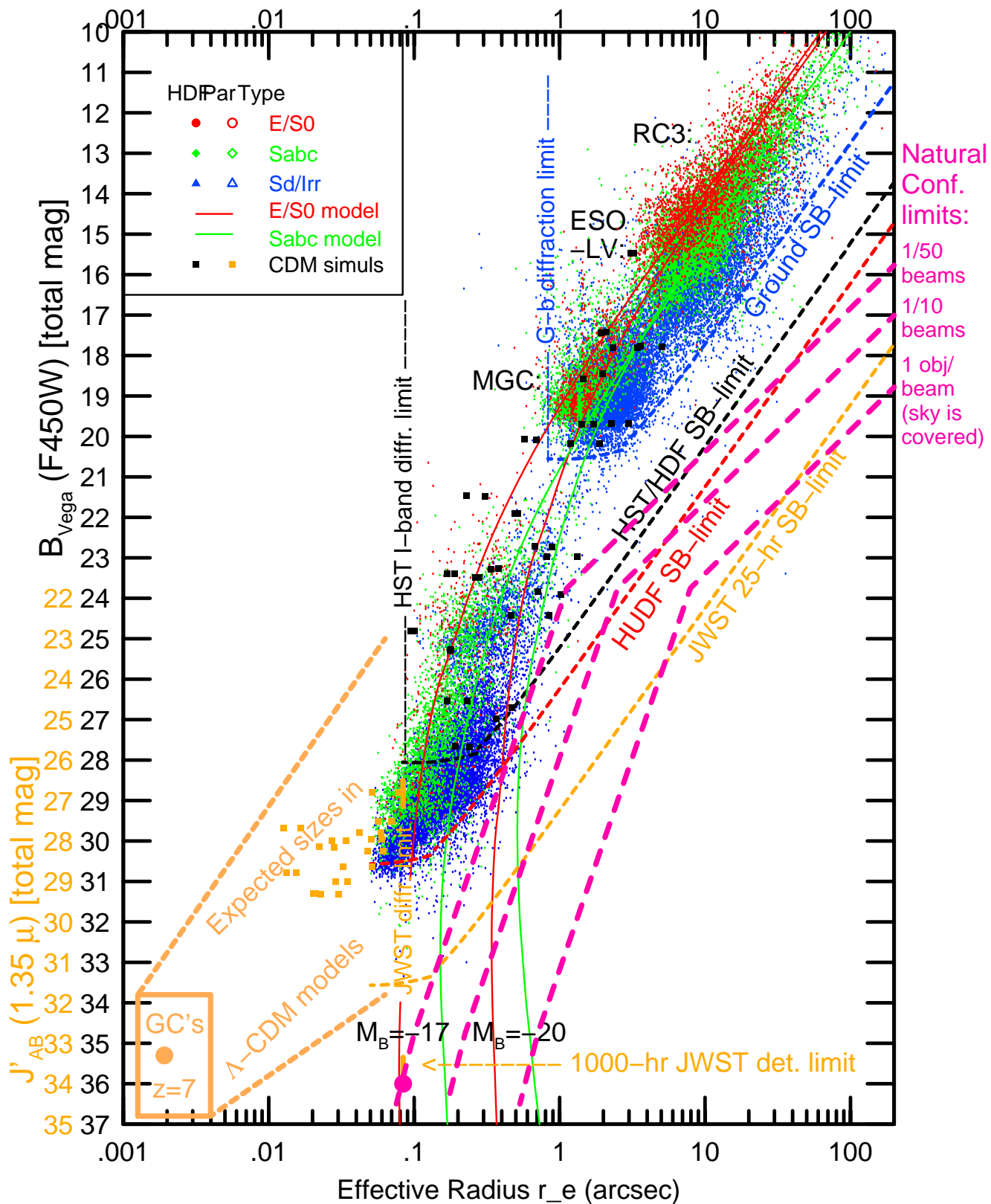
# Appendix 1: Will JWST (& SKA) reach the Natural Confusion Limit?



- HUDF galaxy counts (Cohen et al. 2006): expect an integral of  $\gtrsim 2 \times 10^6$  galaxies/deg<sup>2</sup> 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.



The natural confusion limit slowly sets in for  $AB \lesssim 25$ .



## 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  $2 \times 10^6$  galaxies/deg<sup>2</sup>. Most of these will be unresolved ( $r_{hl} \lesssim 0''.1$  FWHM (Kawata et al. 2006). Since  $z_{\text{med}} \simeq 1.5$ , 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”