

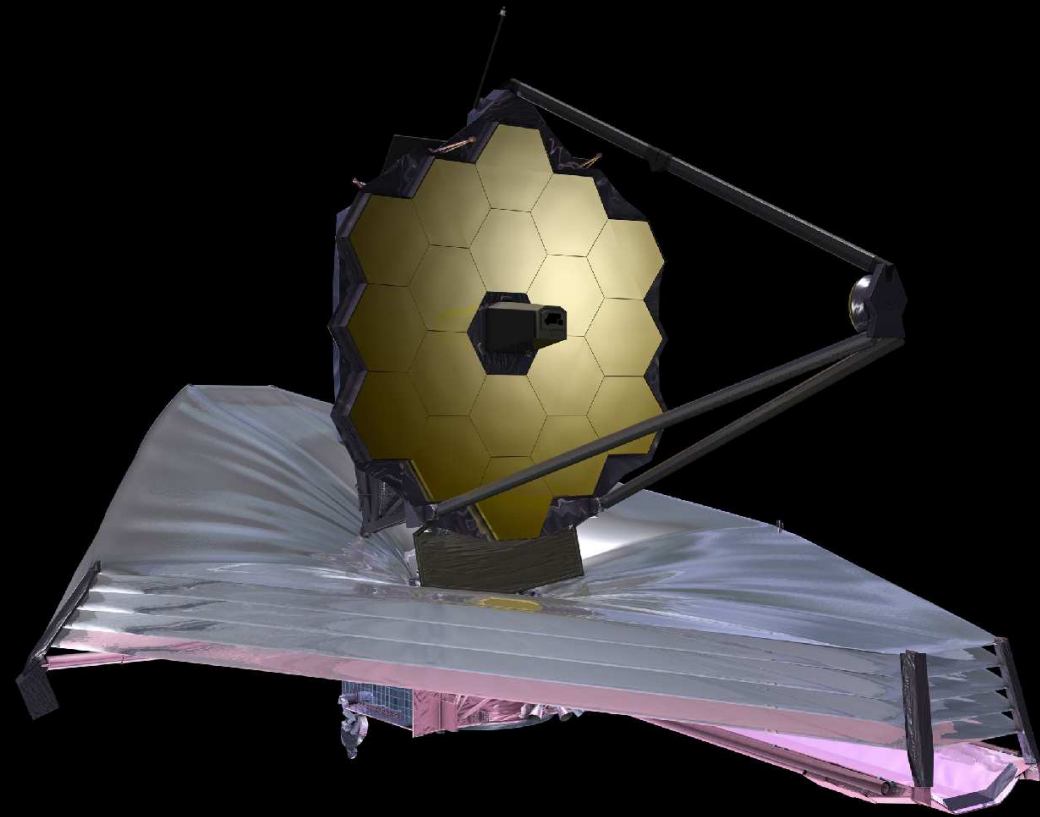
# How will JWST measure First Light, Galaxy Assembly & Supermassive Blackhole Growth: New Frontier after HST

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

*Collaborators: S. Cohen, L. Jiang, R. Jansen (ASU), C. Conselice (UK), S. Driver (OZ), & H. Yan (U-MO)*

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



*Review Talk at the "18<sup>th</sup> Paris Cosmology Colloquium 2014: Latest News from the Universe"*

*Observatoire de Paris, 25 July 2014, Paris, France. [All presented materials are ITAR-cleared].*

# Outline

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- (1) Brief Update on the James Webb Space Telescope (JWST), 2014.
- (2) What HST WFC3 has done: Measuring Galaxy Assembly and Supermassive Black-Hole Growth, including  $z \simeq 6$  QSO Host System Detection
- (3) How can JWST measure the Epochs of First Light & Galaxy Assembly, and Supermassive Black-Hole Growth?
- (4) Summary and Conclusions.



Sponsored by NASA/HST & JWST

Thank you, Europe & ESA, for your very significant work on JWST!



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

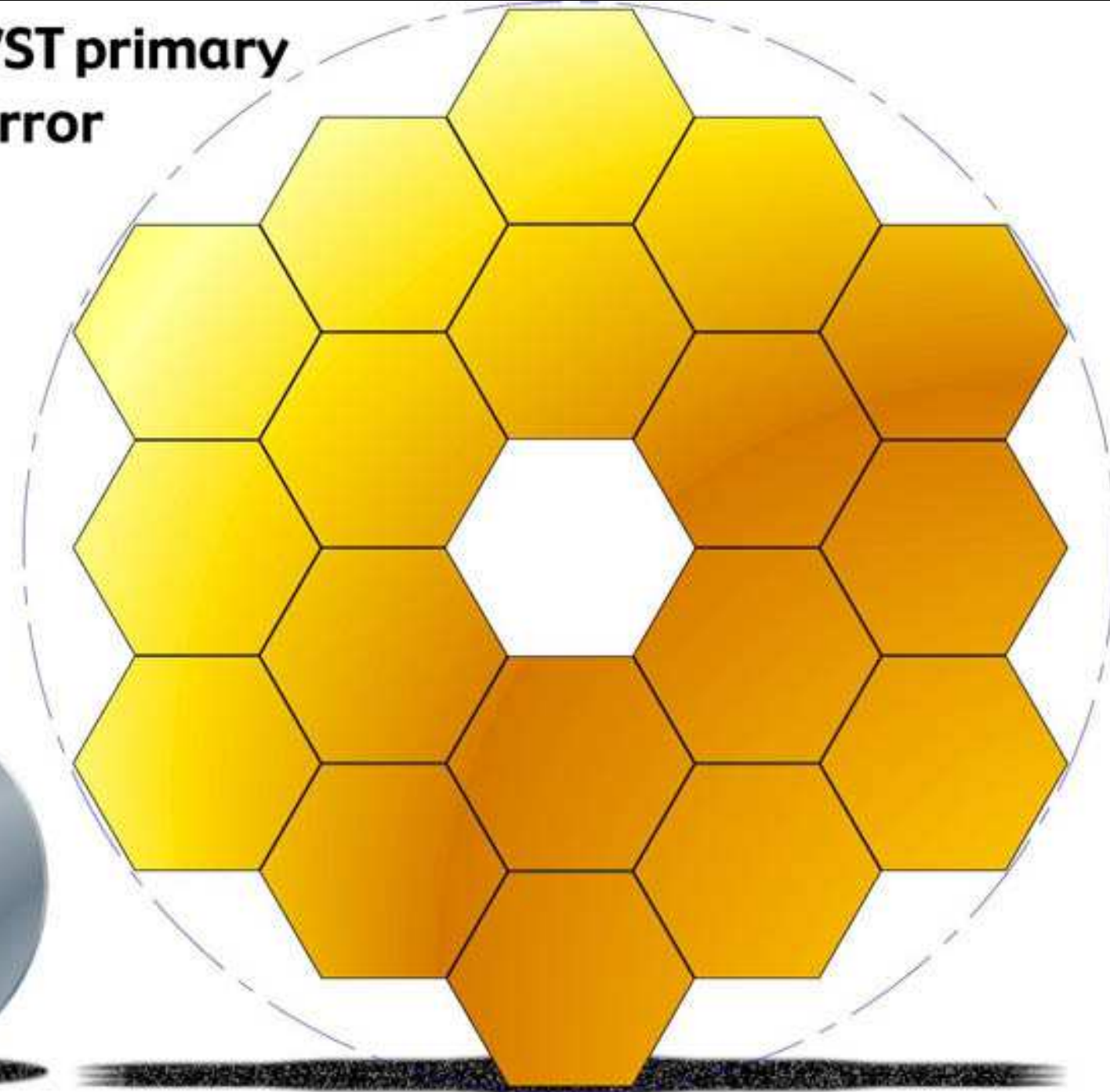


James E. Webb (1906–1992) — Second NASA Administrator

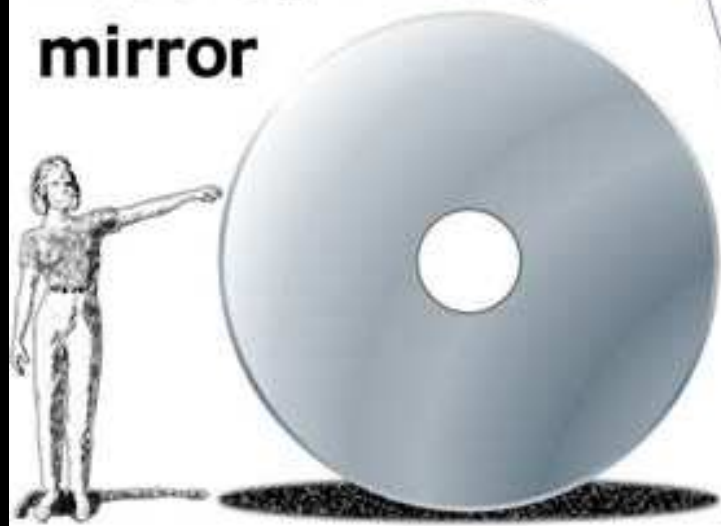
Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2014.

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

**JWST primary  
mirror**



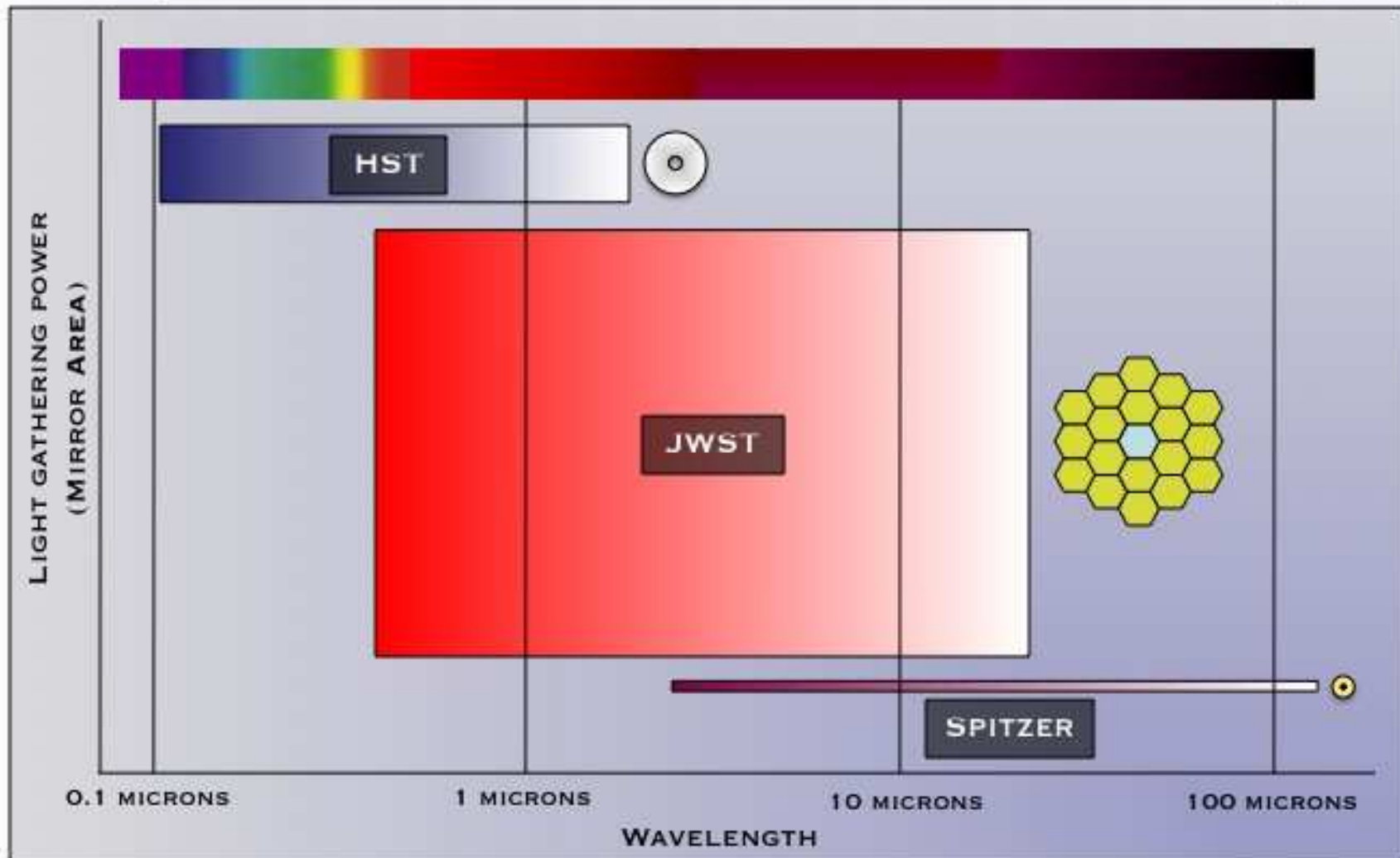
**Hubble primary  
mirror**



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

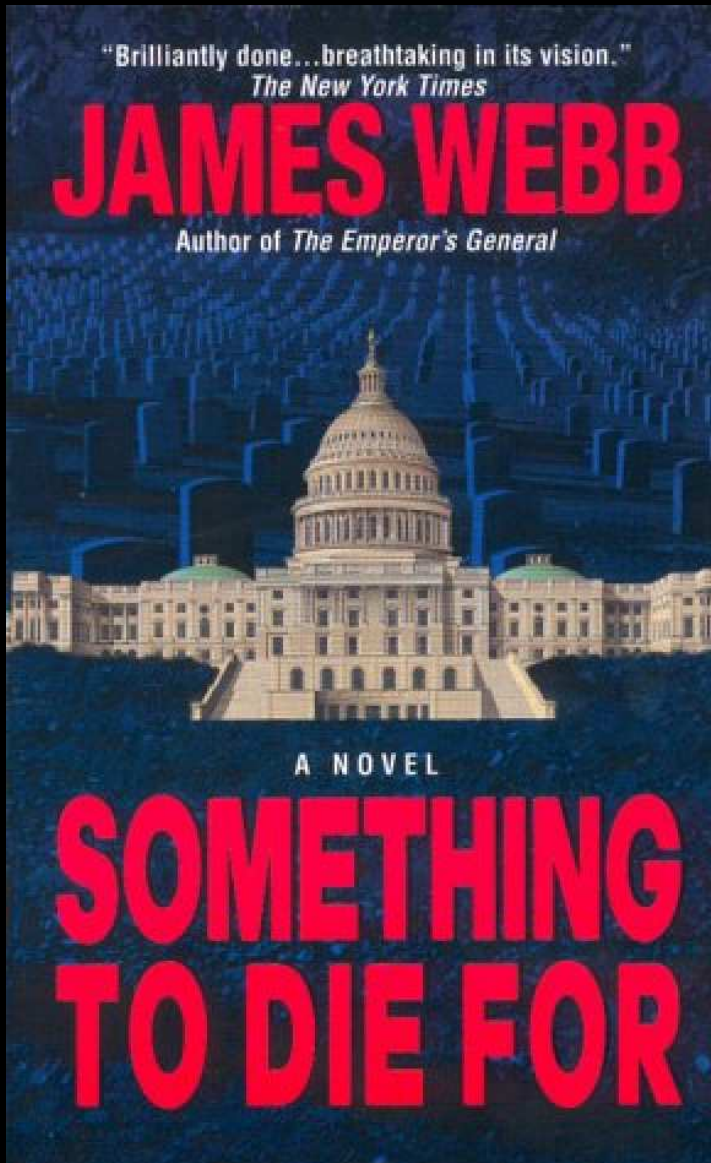


LIGHT GATHERING POWER  
JWST = 25 M<sup>2</sup> ; HUBBLE = 4.5 M<sup>2</sup> ; SPITZER = 0.6 M<sup>2</sup>

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.

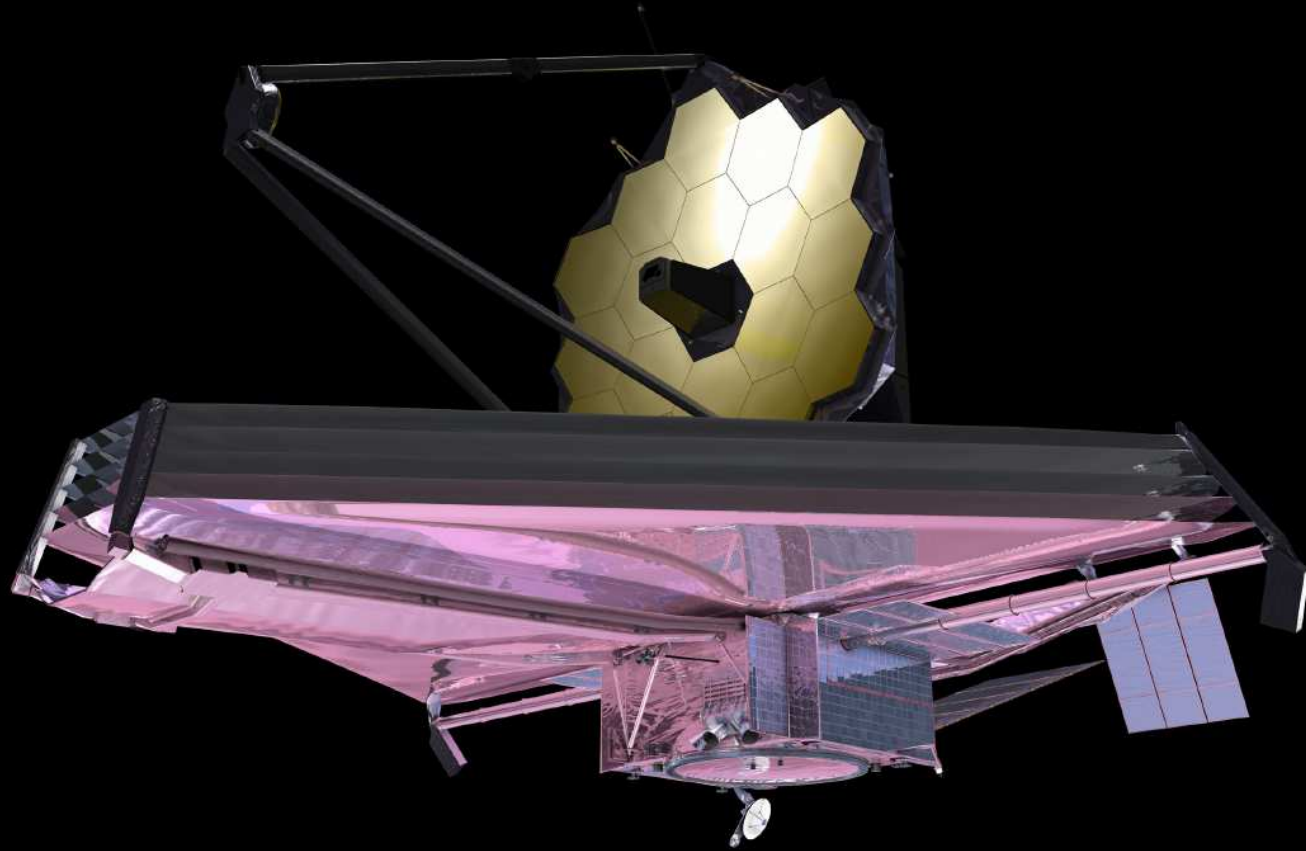
# (1) Brief Update of the James Webb Space Telescope (JWST).



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

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

# (1) 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

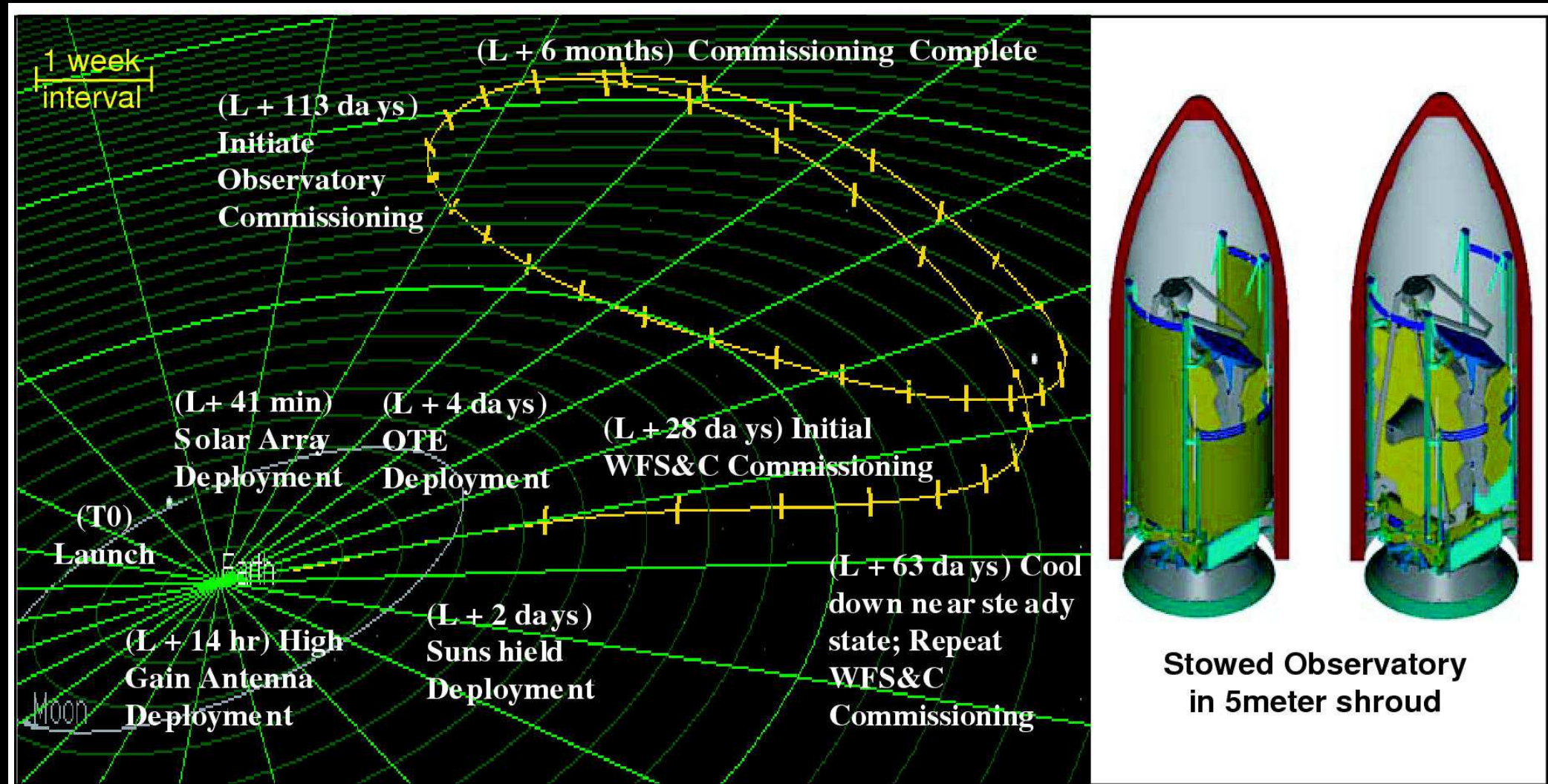


ARIANESPACE - ESA - NASA

- 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.

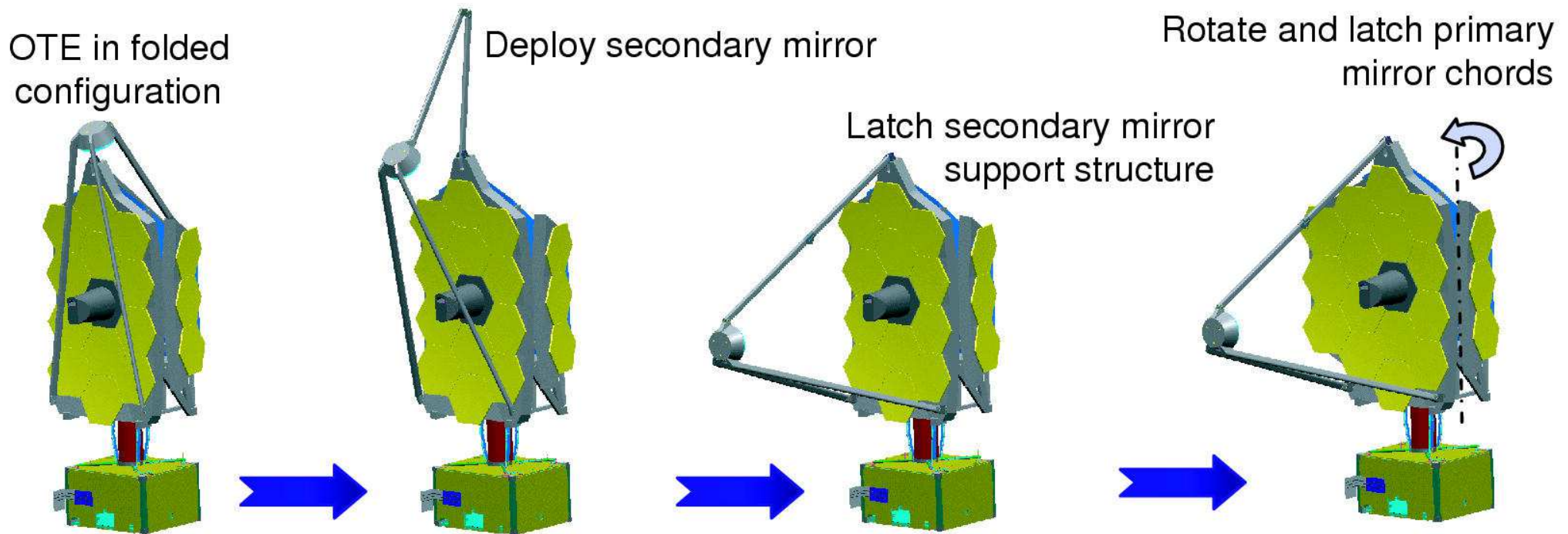


# (1a) How will JWST travel to its L2 orbit?



- After launch in (Oct.) 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.

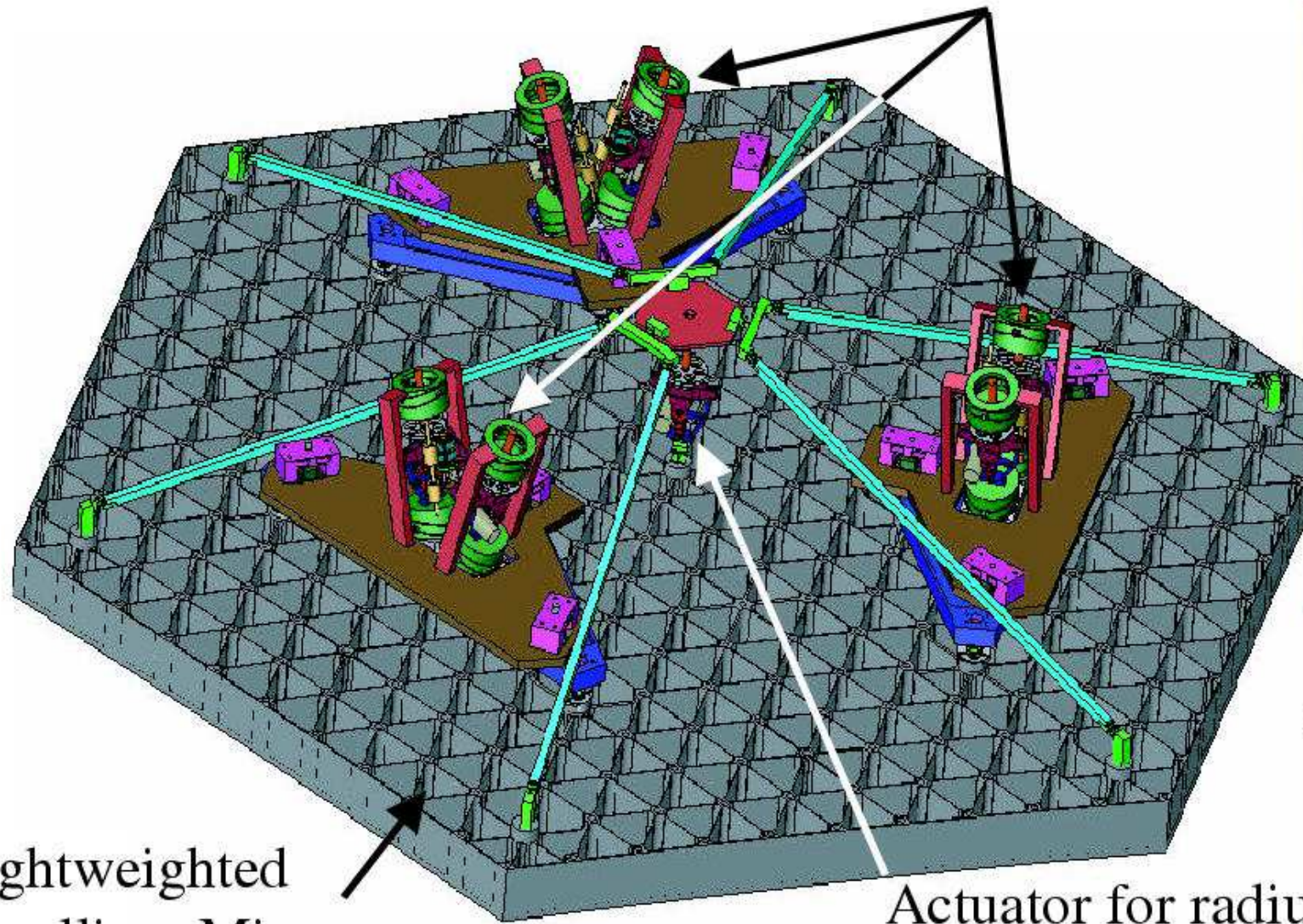
- (1b) How will JWST be automatically deployed?



- 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 is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2016 at GSFC (MD), Northrop (CA), and JSC (Houston).
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.

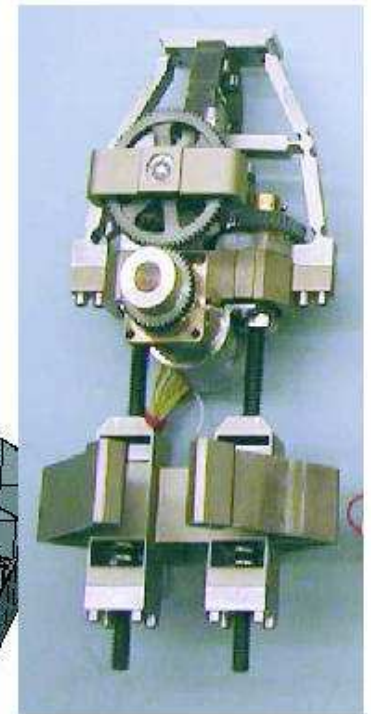


# Actuators for 6 degrees of freedom rigid body motion



Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment



Actuator  
development  
unit

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

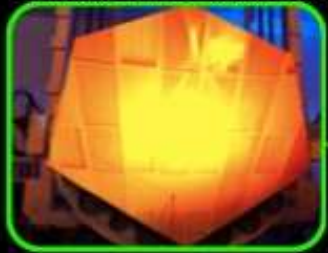




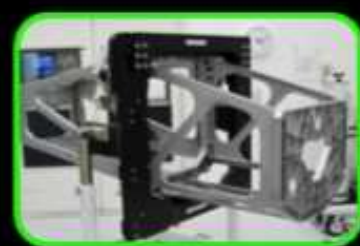
# JWST Hardware Status



Primary Mirror Segment



Aft Optics System



PM Flight Backplane

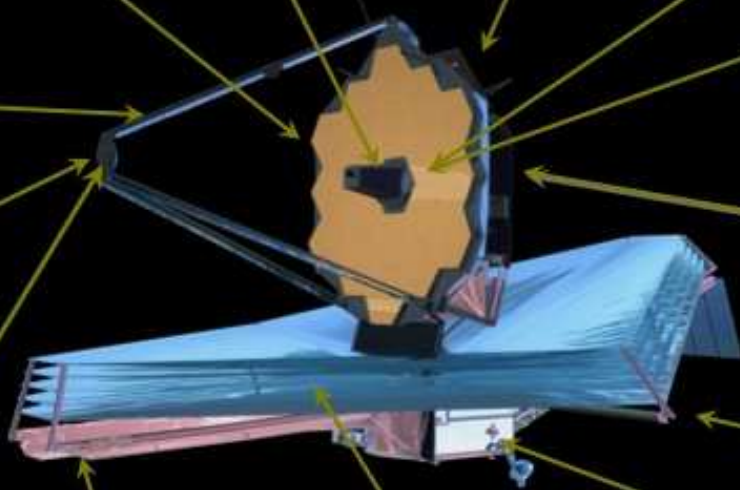


Tertiary Mirror

Secondary Mirror Pathfinder Strut



Fine Steering Mirror



ISIM Flight Bench



Secondary Mirror Hexapod



Secondary Mirror



Membrane Mgmt



Pathfinder Membrane



Spacecraft computer Test Unit

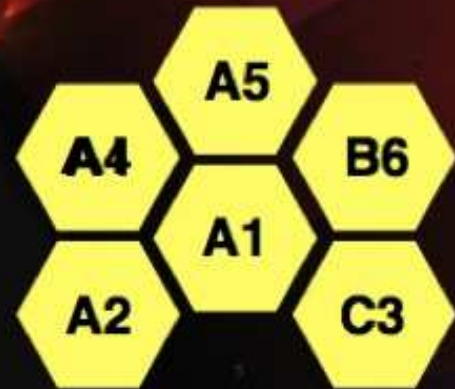
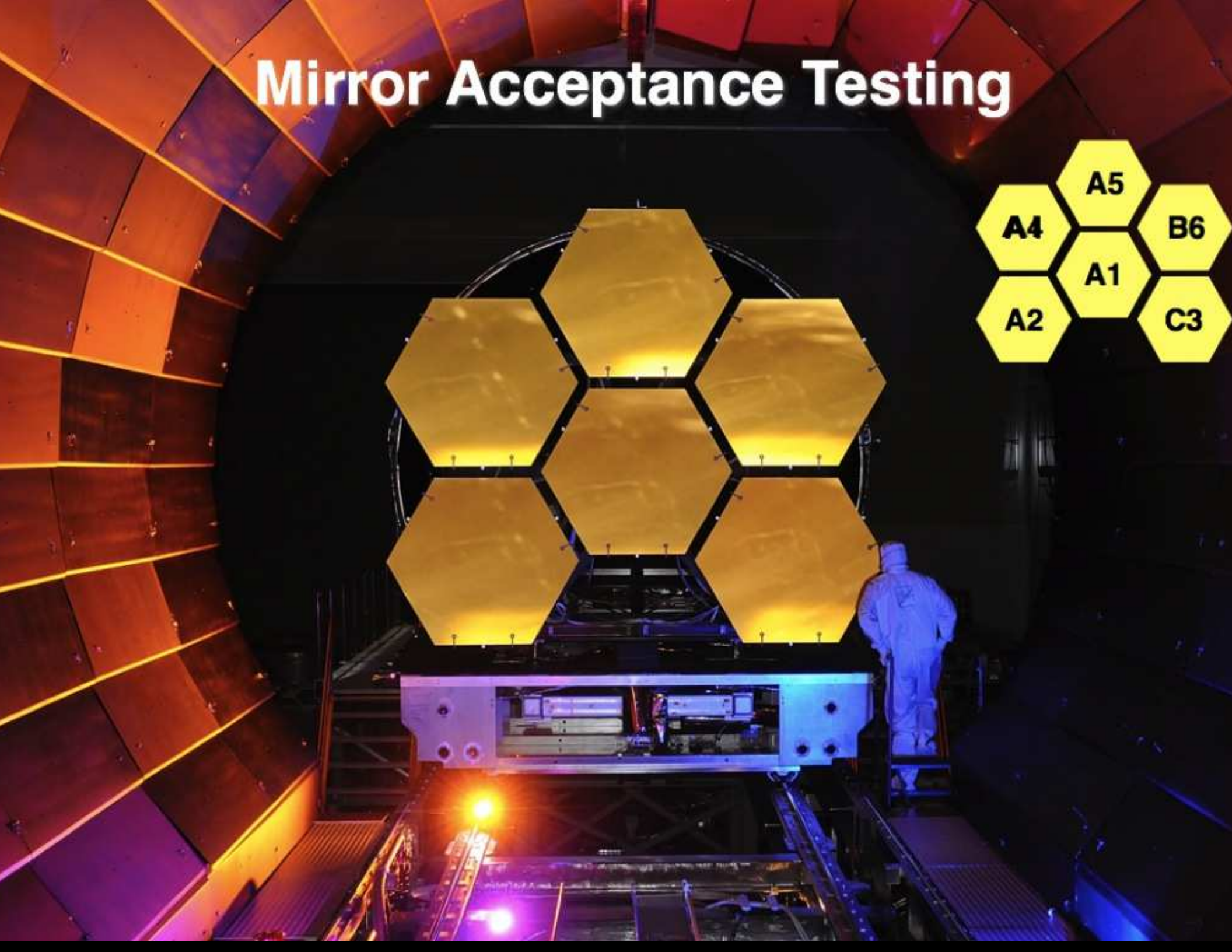


Mid-boom Test

July 2014:  $\approx 97.4\%$  of launch mass <sup>3</sup> designed and built ( $\approx 60\%$  weighed).



# Mirror Acceptance Testing

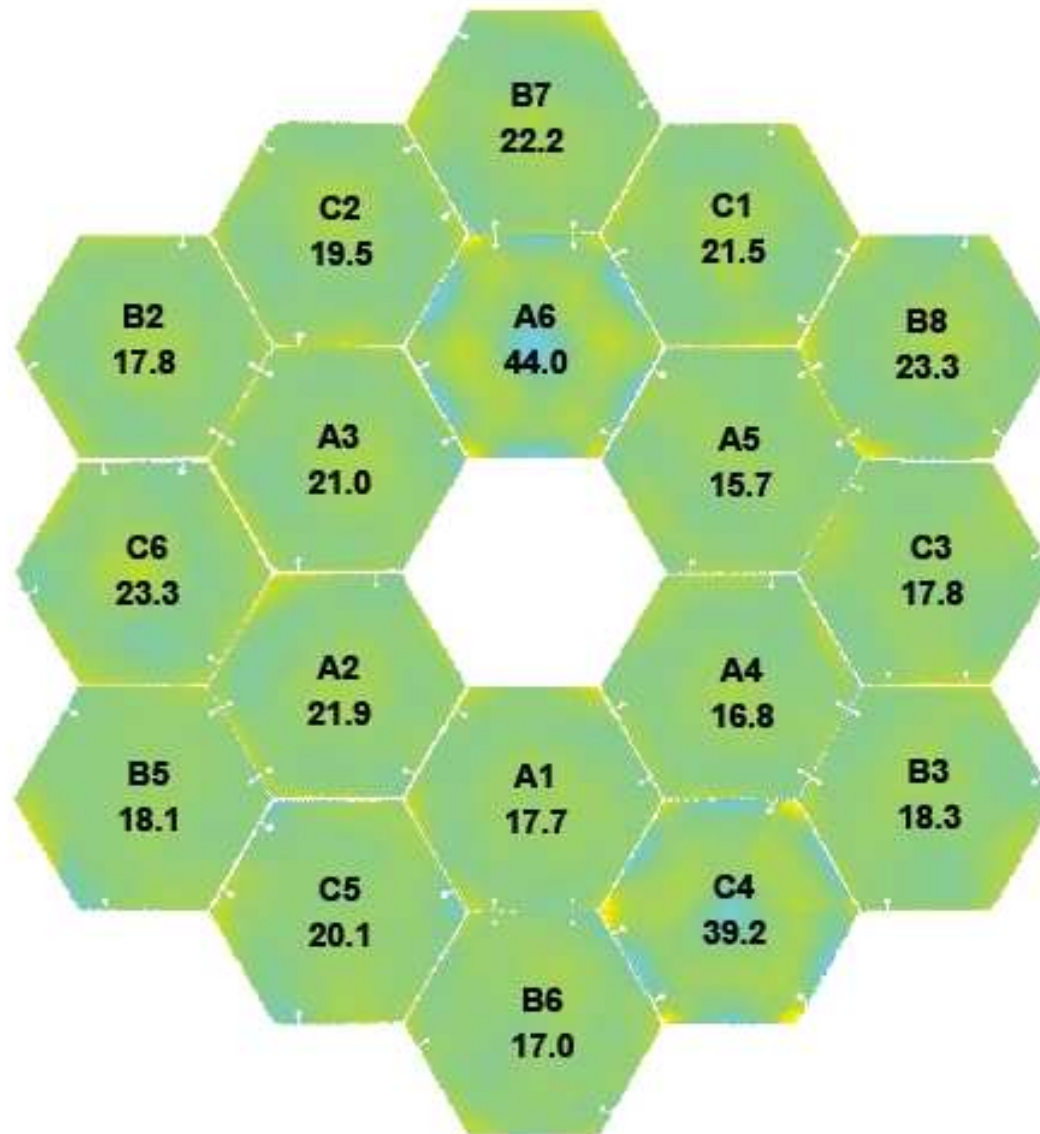








# Primary Mirror Composite



RMS: **23.2 nm**

PV: **515.5 nm**







# Mirror Status



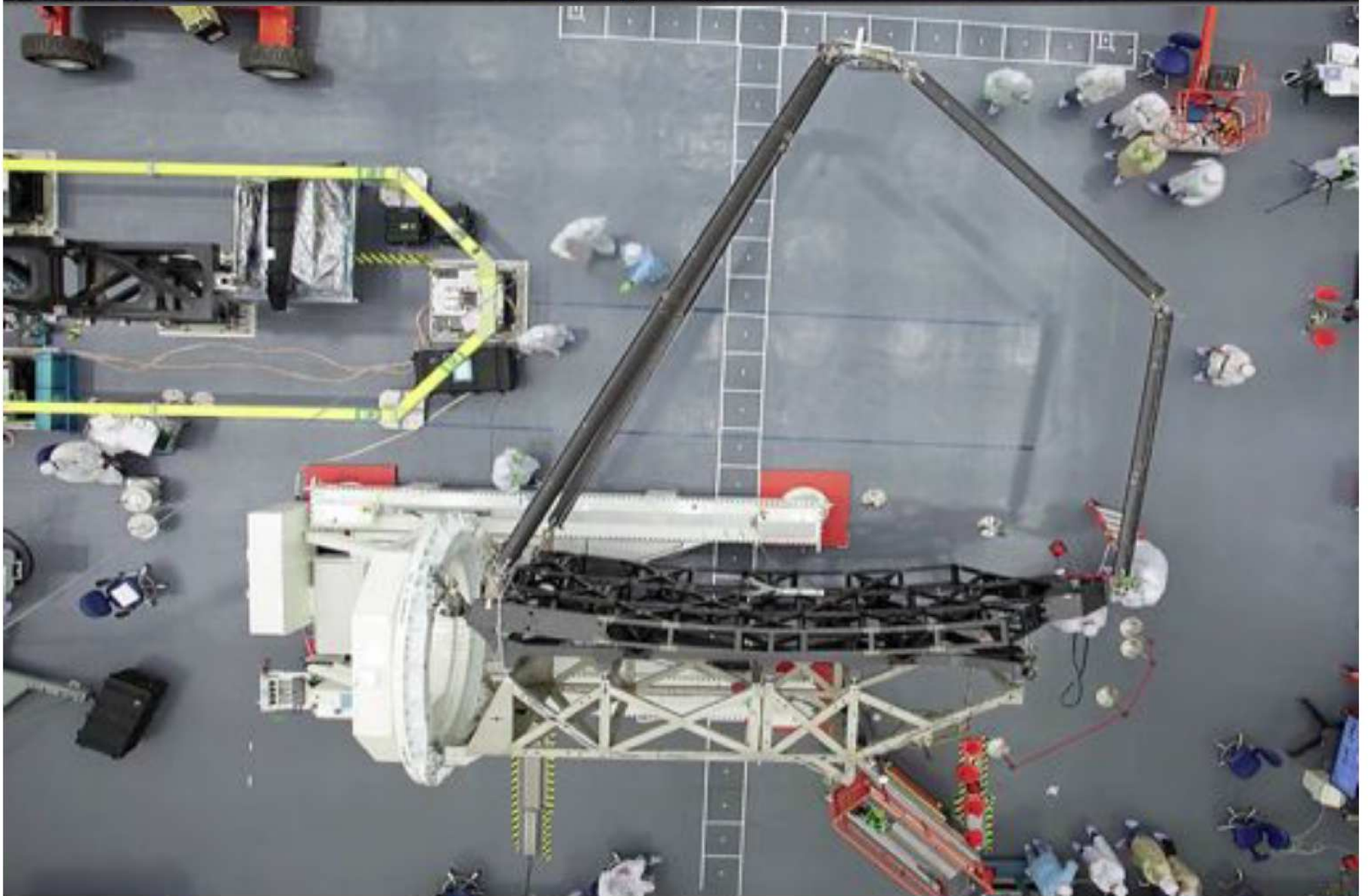
- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC by end of year, needed in 2015



Spring 2014: All 18 flight mirrors now delivered to NASA GSFC (MD).



# Pathfinder: Powered Deployment of SMSS



July 2014: Secondary Mirror Support deployment successfully tested.



# Sunshield Deployment



July 2014: Engineering sunshield successfully deployed at Northrop (CA).



# (1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.

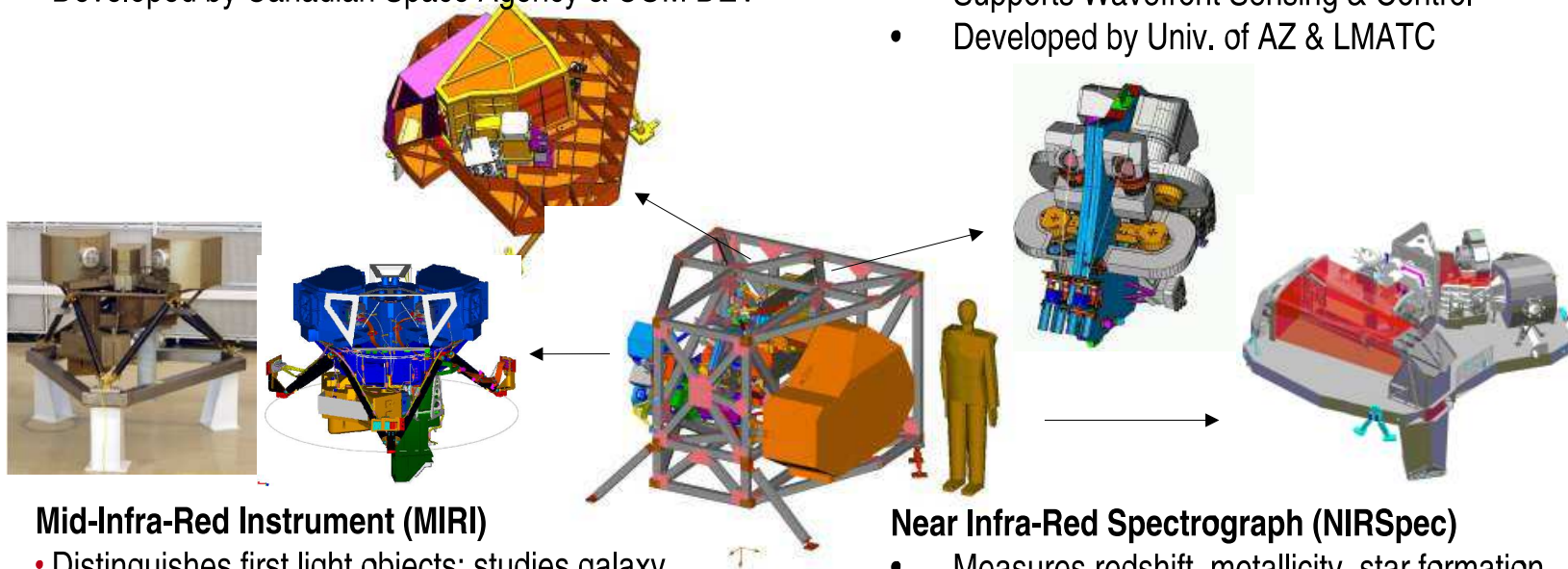


## Instrument Overview



### 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



### 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 Camera (NIRCam)

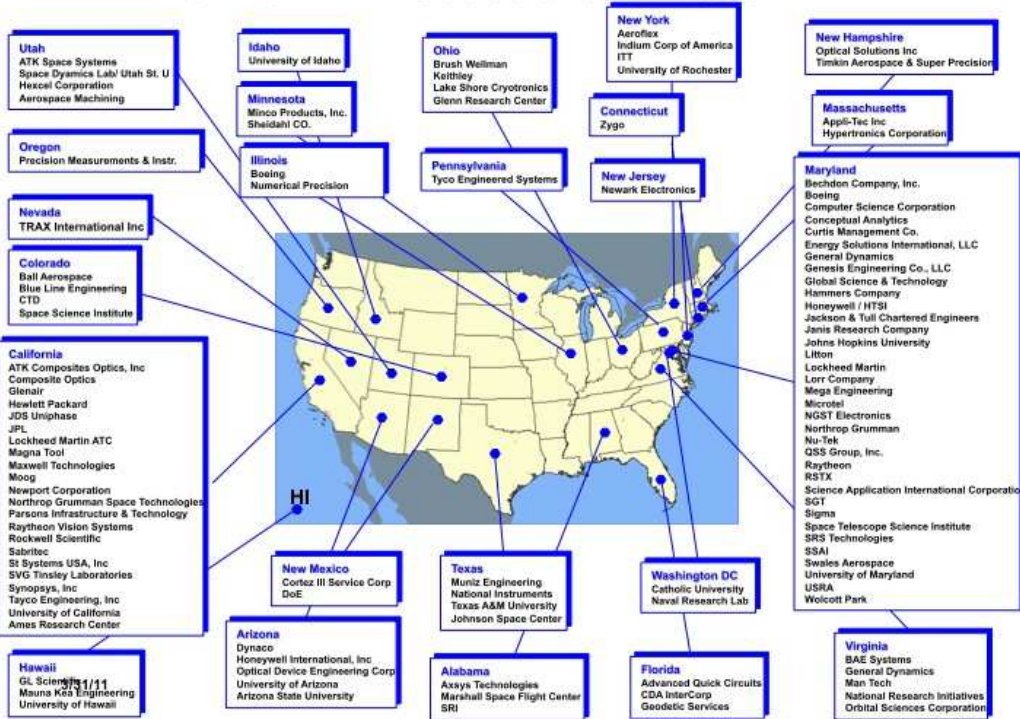
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

### Near Infra-Red Spectrograph (NIRSpec)

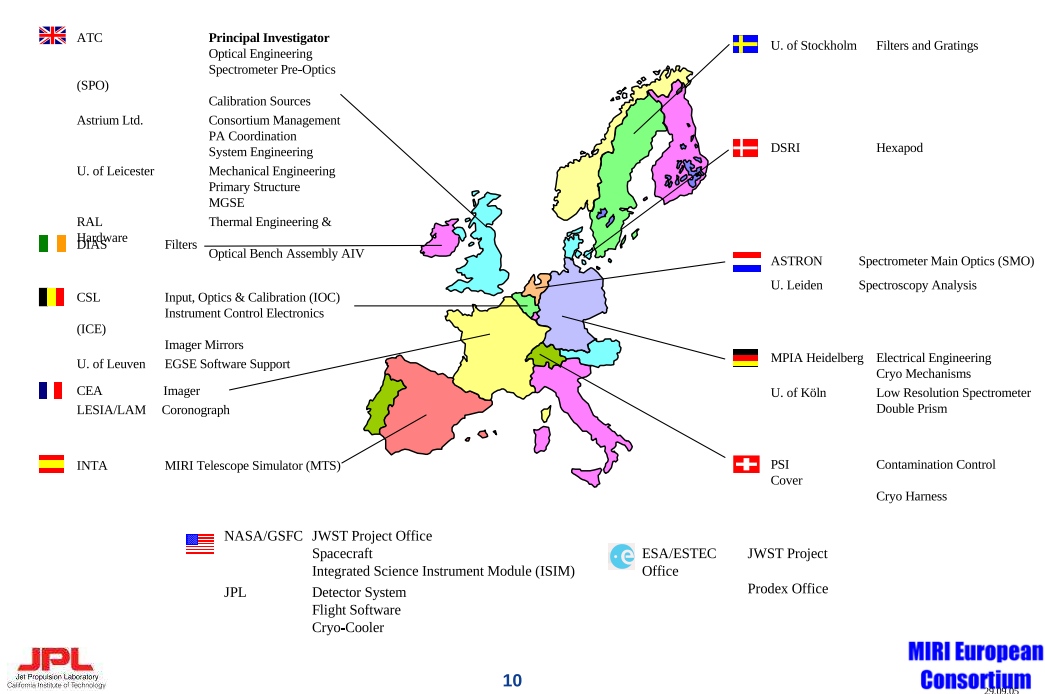
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

All delivered: MIRI 05/12; FGS 07/12; NIRCams 07/13, NIRSpec 9/13.

# JWST: A Product of the Nation



# European Consortium Who & Where

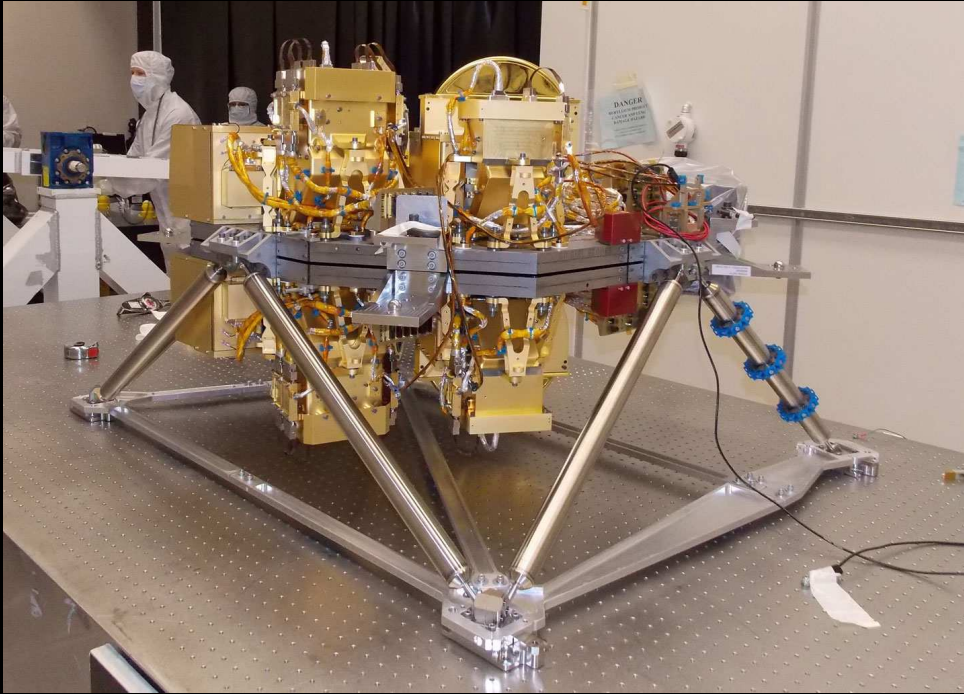


- JWST hardware made in 27 US States:  $\approx 97.4\%$  of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCам made by UofA and Lockheed.

Thank you, Europe & ESA, for your very significant work on JWST!





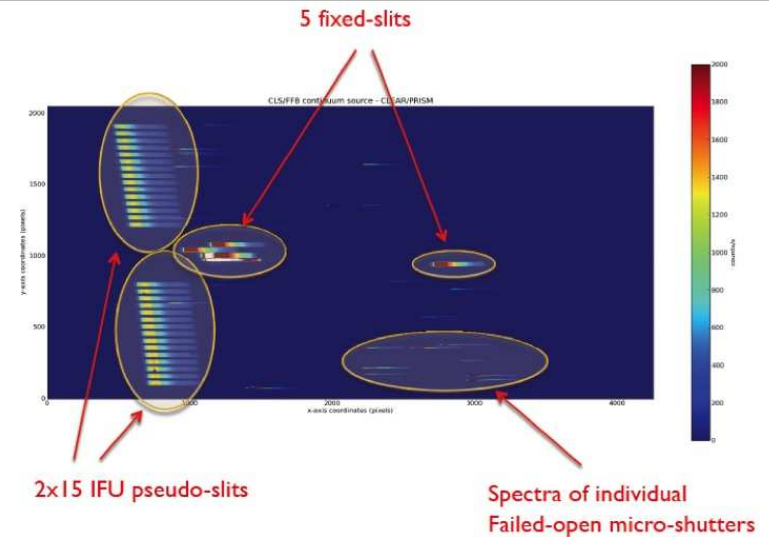


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) imagers:

- 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 delivered July 28, 2013.



## Flight NIRSpec First Light



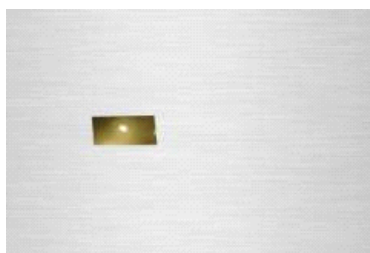
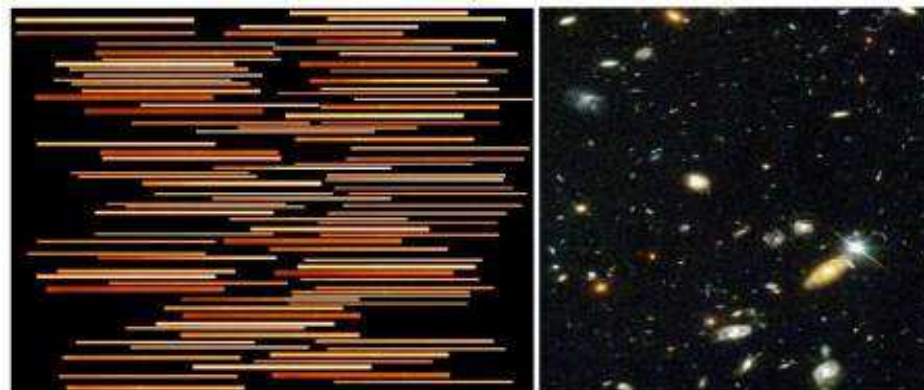
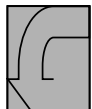
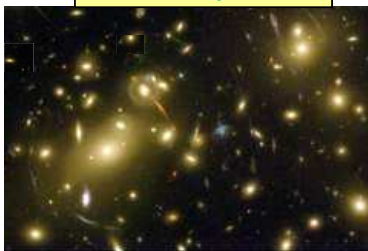
JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) spectrograph:

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

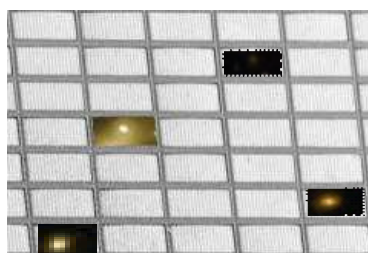
NIRSpec delivered to NASA/GSFC in Sept. 2013.



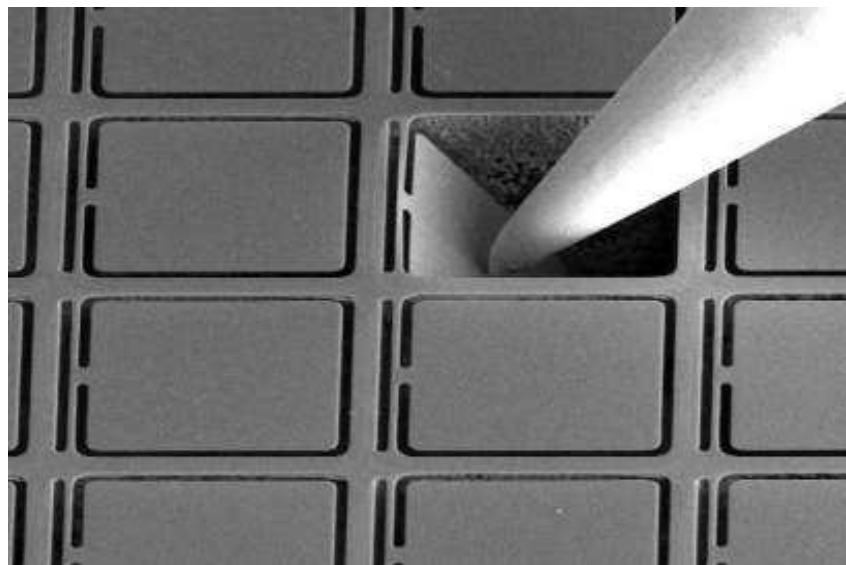
Astronomy Scene



Metal Mask/Fixed Slit



Shutter Mask

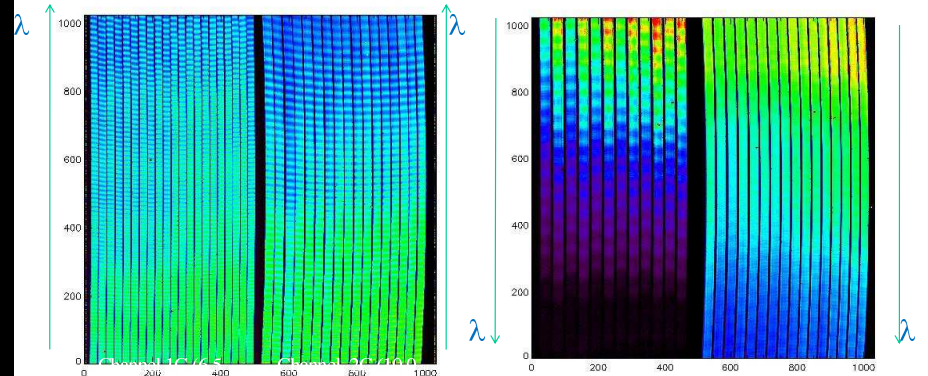




# Flight MIRI



## Spectrometer First Light – internal calibration source



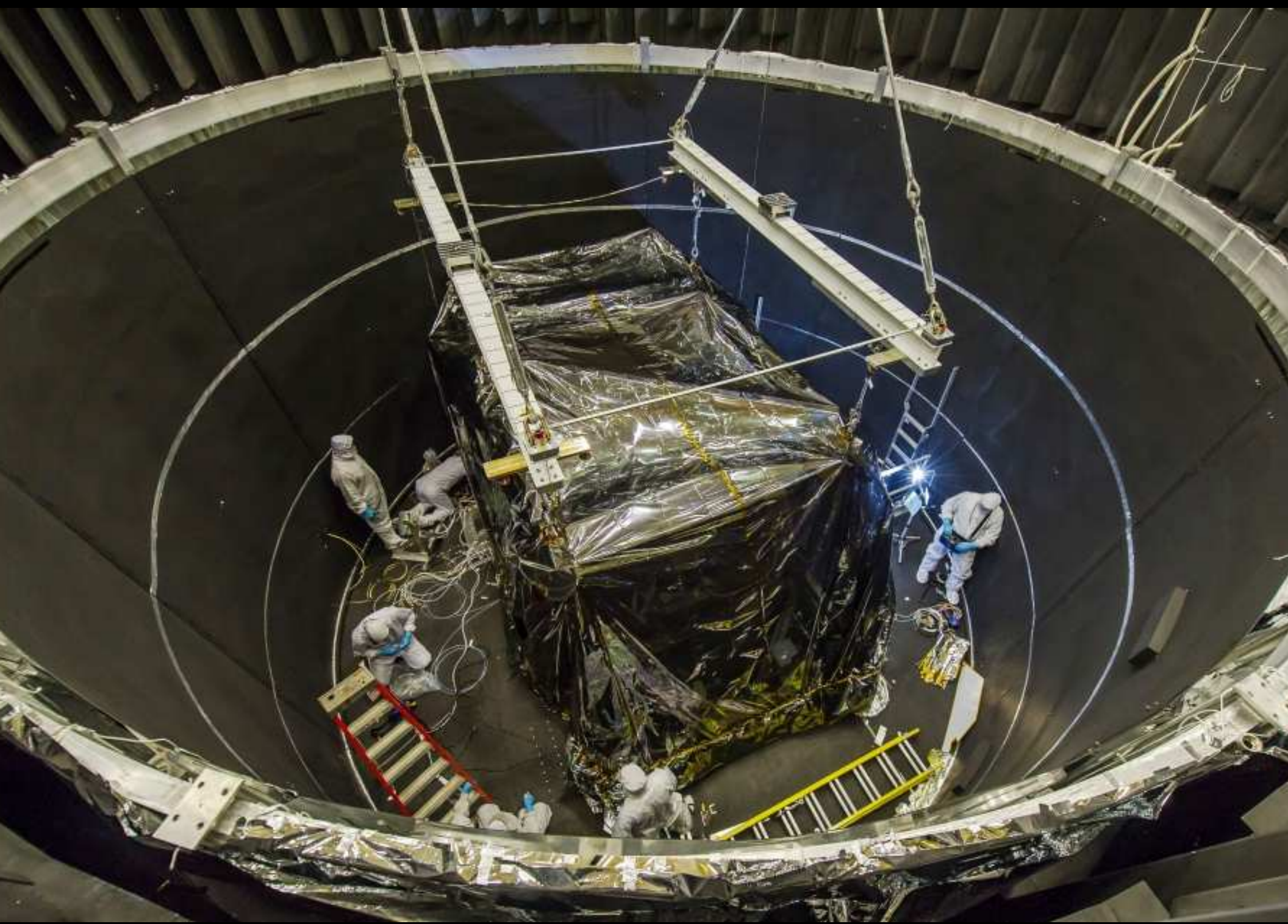
All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

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.

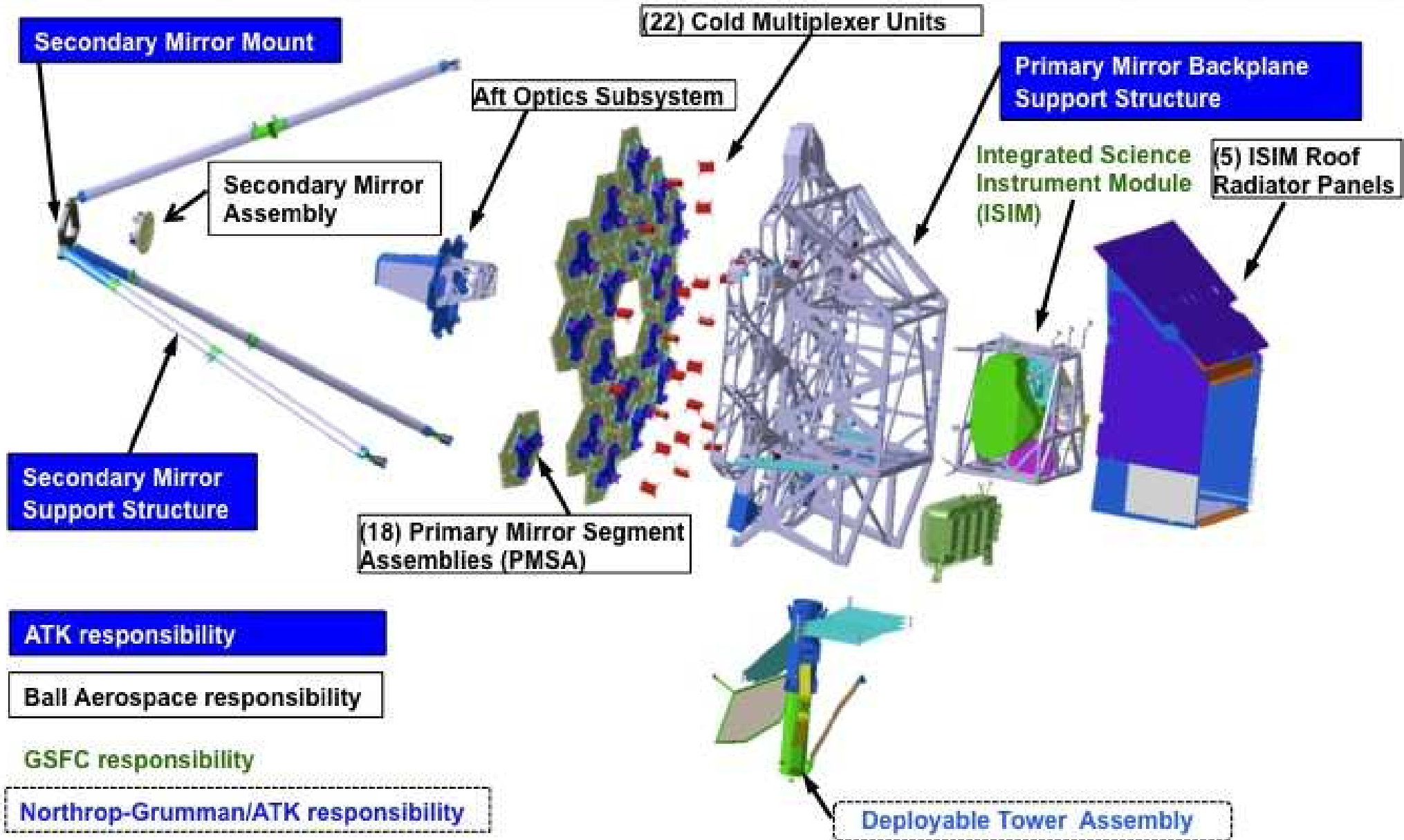




June 2014: Actual Flight ISIM (with all 4 instruments) lowered into OSIM.



# TELESCOPE ARCHITECTURE



3/31/11

2014–2016: Complete system integration at GSFC and Northrop.



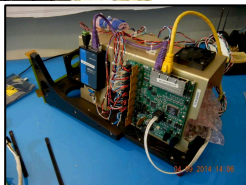
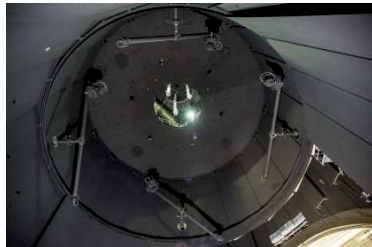


# OTIS Test GSE Architecture and Subsystems

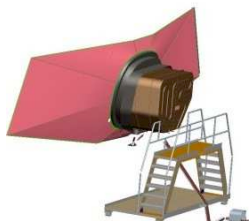


**Chamber Isolator Units**  
Dynamically isolates OTIS Optical Test  
– Integration 6 units complete

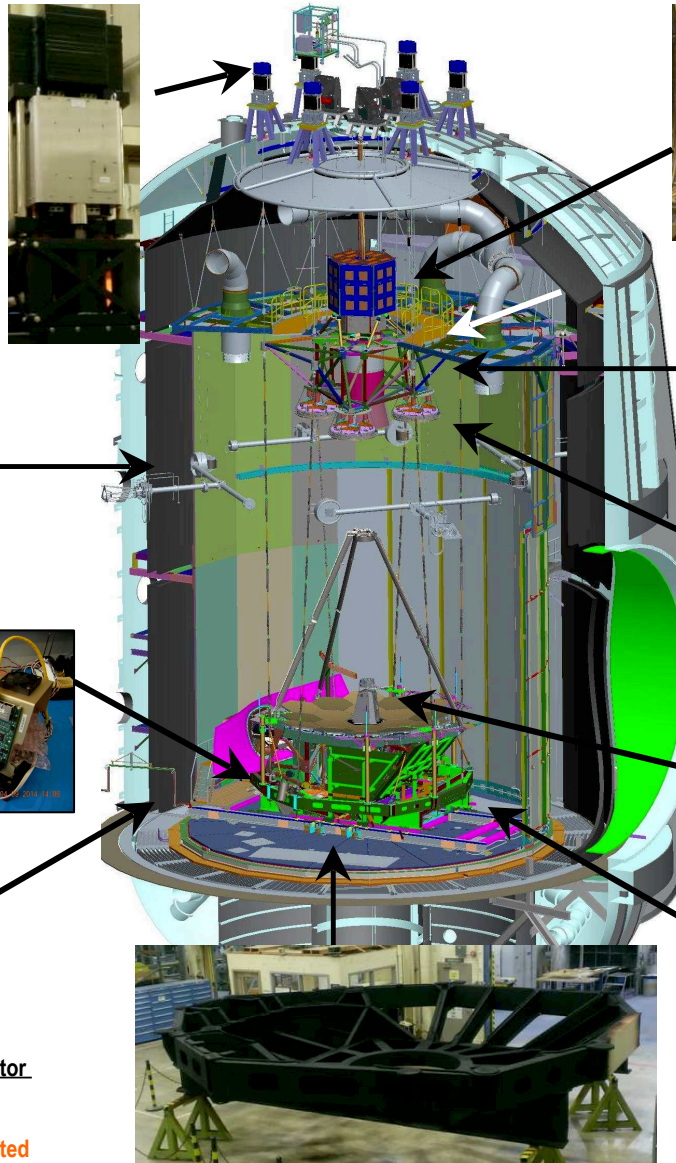
**Cryo Position Metrology (CPM) Photogrammetry System**  
Integration Complete



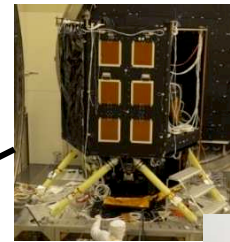
**ADM - new Leica**  
delivered and under test



**Space Vehicle Thermal Simulator (SVTS) and Sunshield Simulator**  
Passed design review and started Procurements and fab subcontracts



**HOSS – OTIS support structure**  
HOSS – will be in the chamber for Bake out in June



**Center of Curvature Optical Assembly (COCO)**  
• Multiwavelength interferometer (MWIF), null, calibration equipment, coarse/fine PM phasing tools, Displacement Measuring Interferometer – COCOA was exercised at MSFC in December



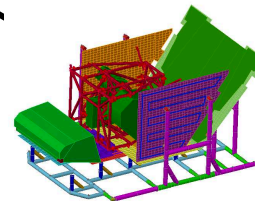
**USF Structural Frame** – supports Metrology ready for chamber integration and Cryo Load tests



**3 Auto collimating Flat Mirrors (ACFs)**  
1.5 M Plano for Pass and Half Testing  
Cryo testing underway, ACF 1 complete, ACF 4 in Cryo test complete, ACF 5 ready for Cryo.



**AOS Source Plate**  
Sources for Pass and Half Test  
72 optical fiber support cont.



**Deep Space Edge Radiation Sink (DSERS)**  
Thermal modeling of payload and DSERS started

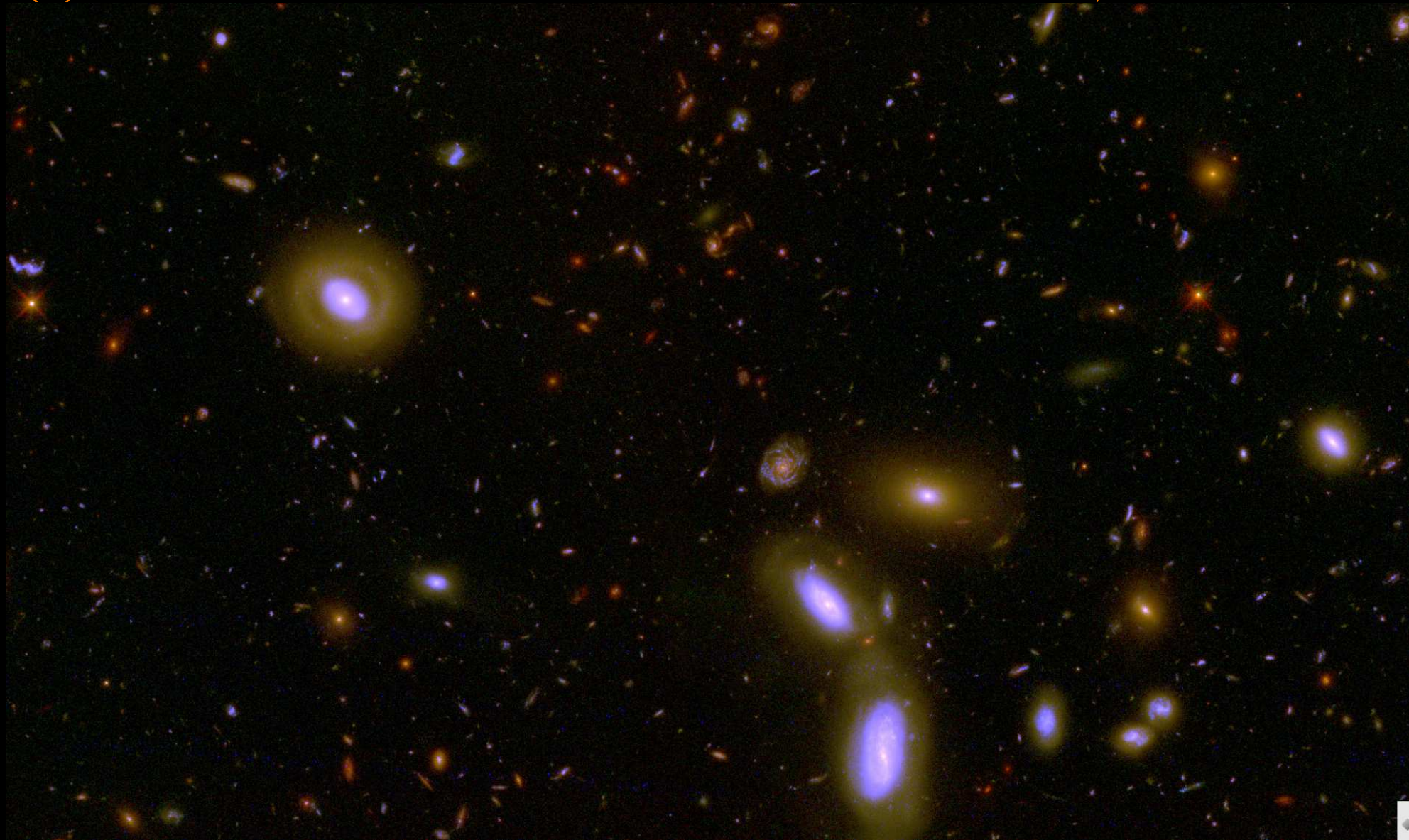


**Mag Damper Cryo Test Article**  
Fabrication started

World's largest TV chamber OTIS: will test whole JWST in 2016–2017.



## (2) 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.

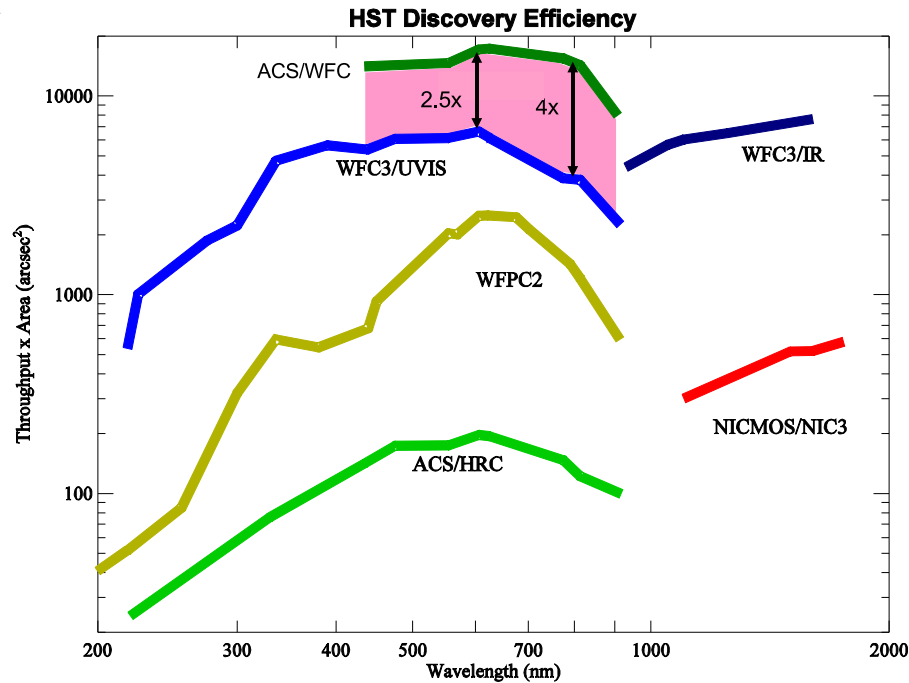


## (2a) WFC3: Hubble's new Panchromatic High-Throughput Camera

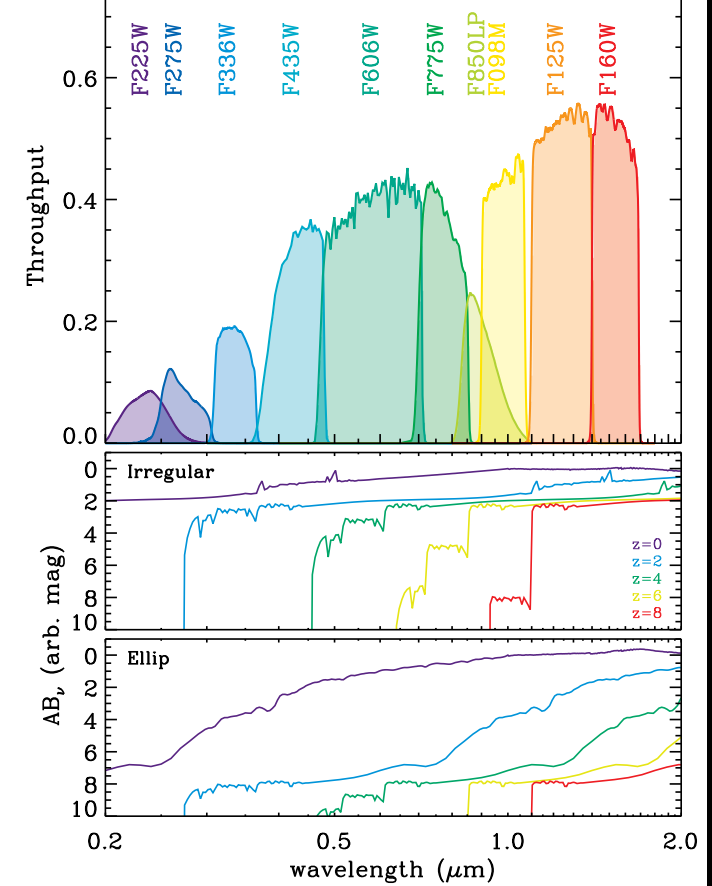


HST WFC3 and its **IR channel**: a critical pathfinder for JWST science.

# 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,  $FOV \simeq 2'.25 \times 2'.25$ .

⇒ 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.



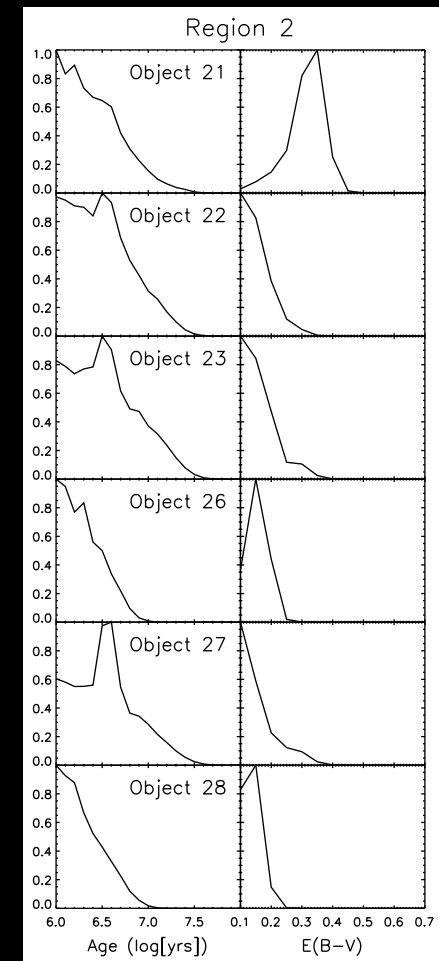
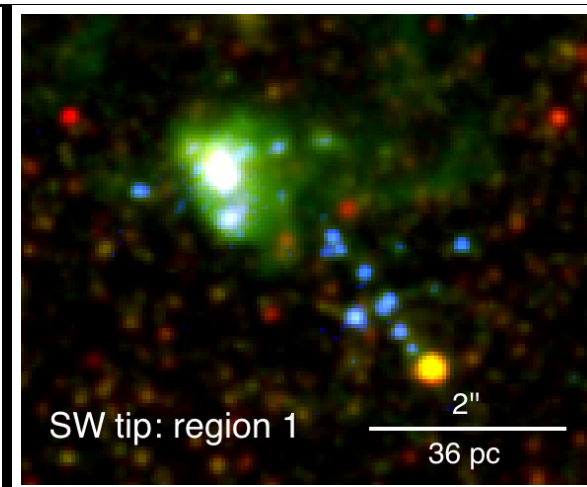
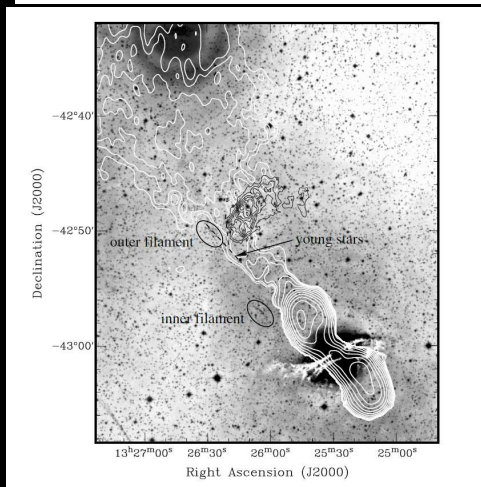
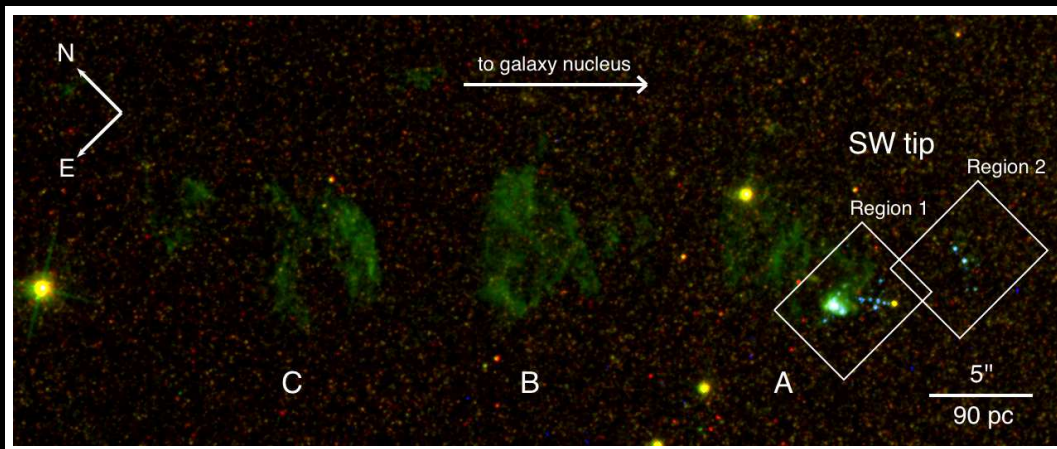
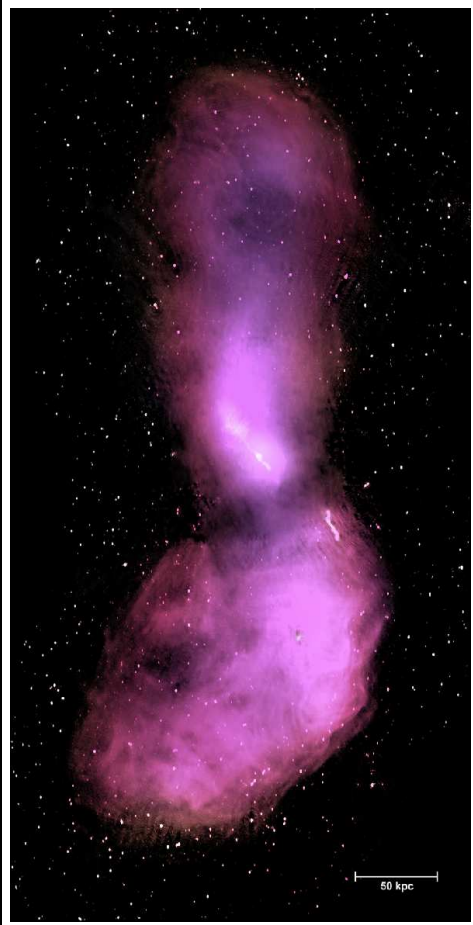
Centaurus A  
NGC 5128  
HST WFC3/UVIS

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<sup>+</sup> 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.

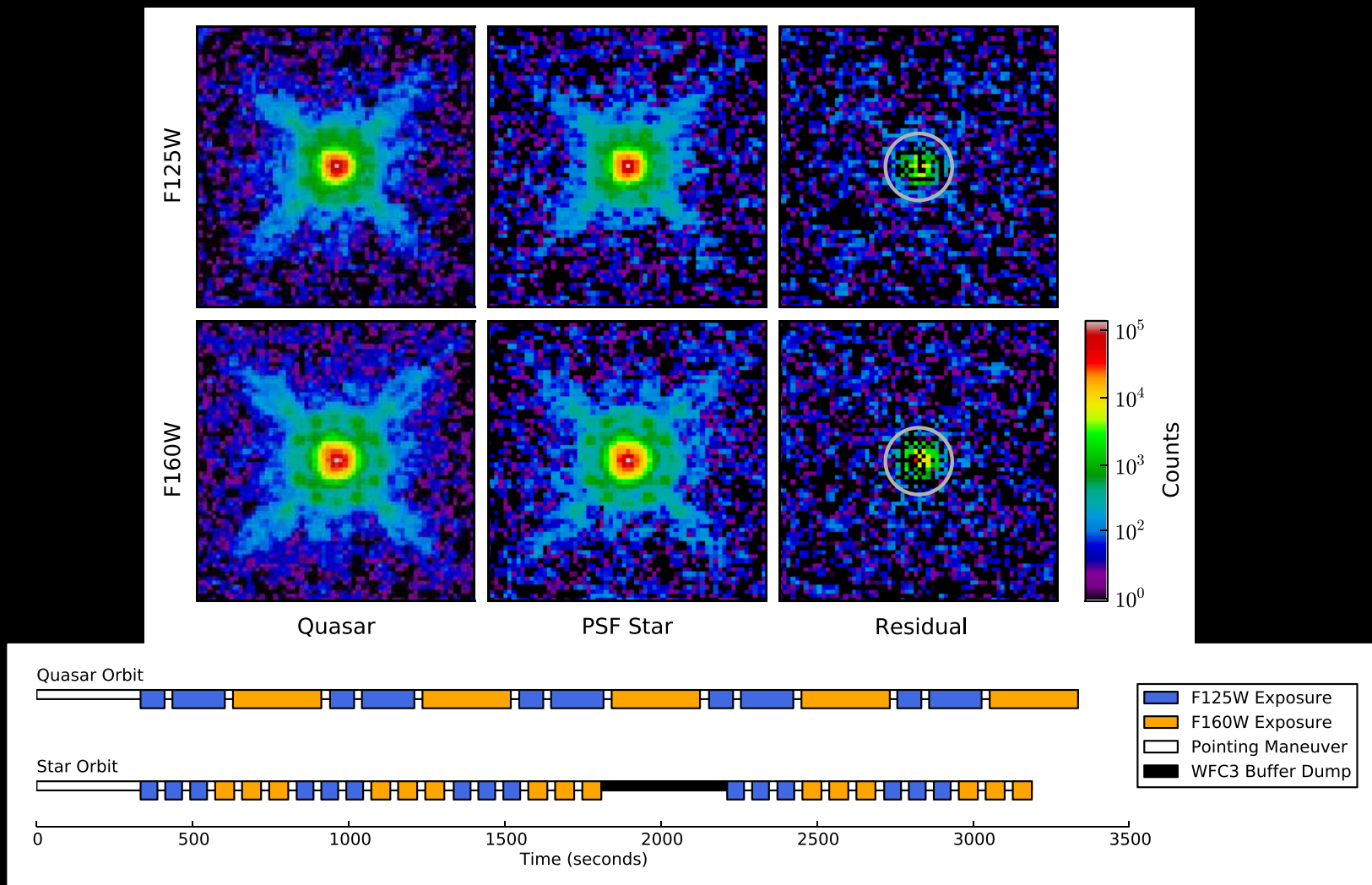


In what follows,  
remember that objects  
emitting two-sided  
and equally bright  
relativistic jets  
may look *different*,  
depending, e.g. on  
viewing angle, dust,  
and scattering proper-  
ties of the medium.

(See also Peter  
Biermann's talk).



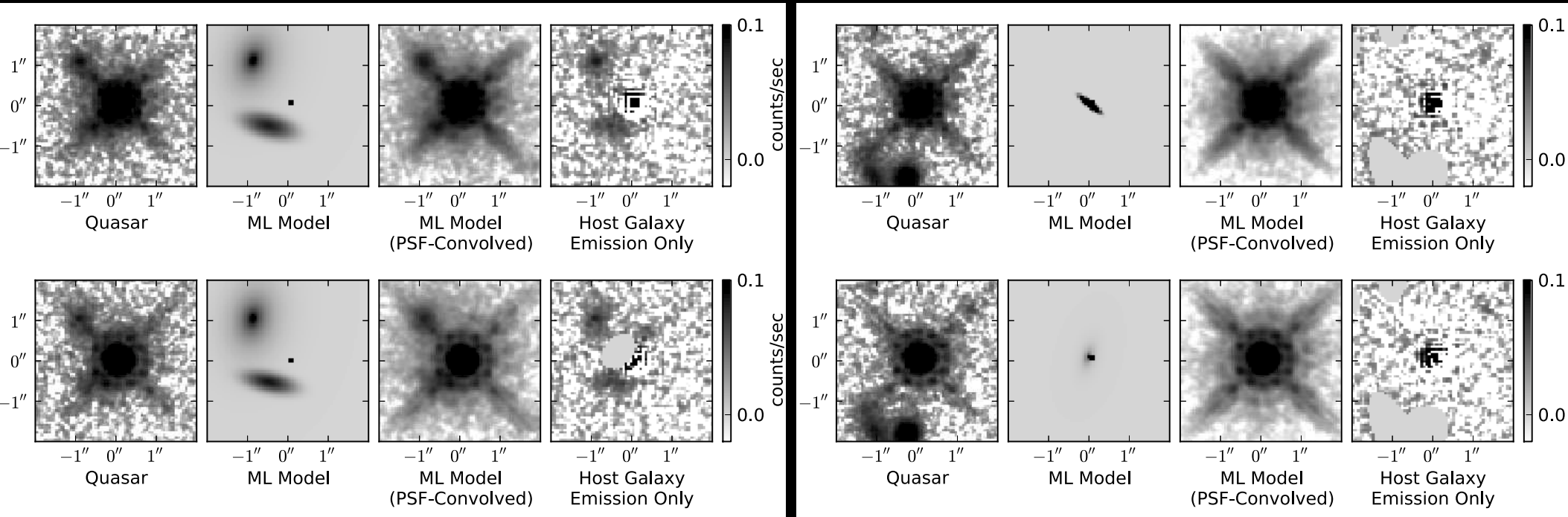
## (2b) HST WFC3 observations of QSO host systems at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- 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  $r \gtrsim 0.3$ ).

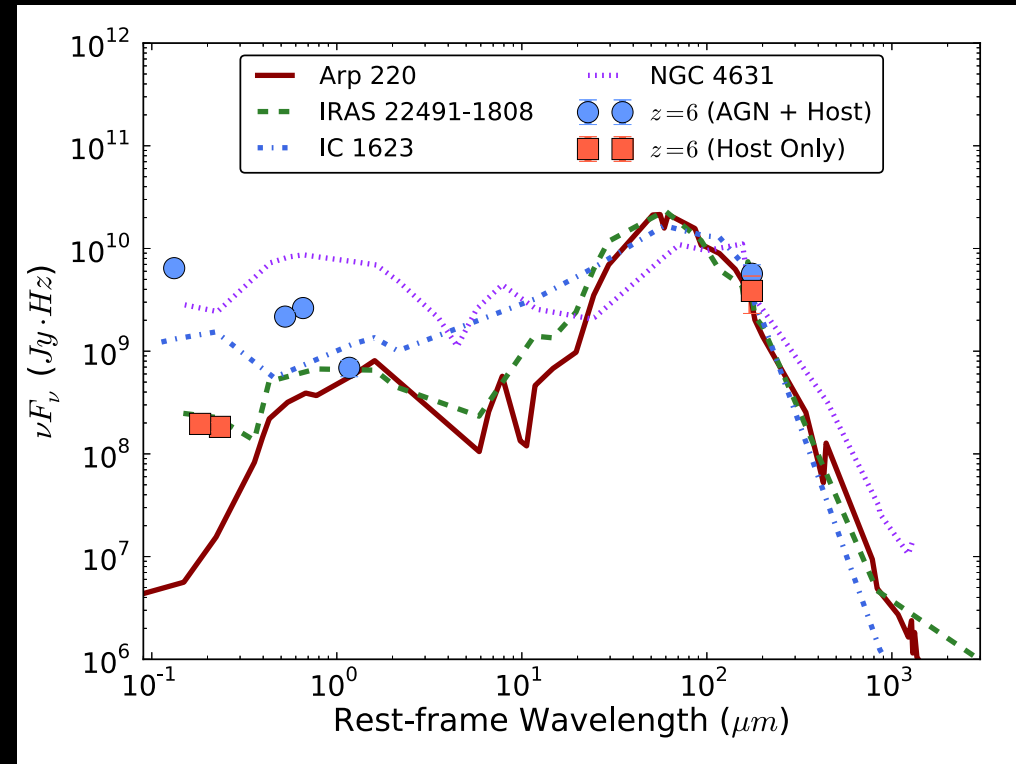
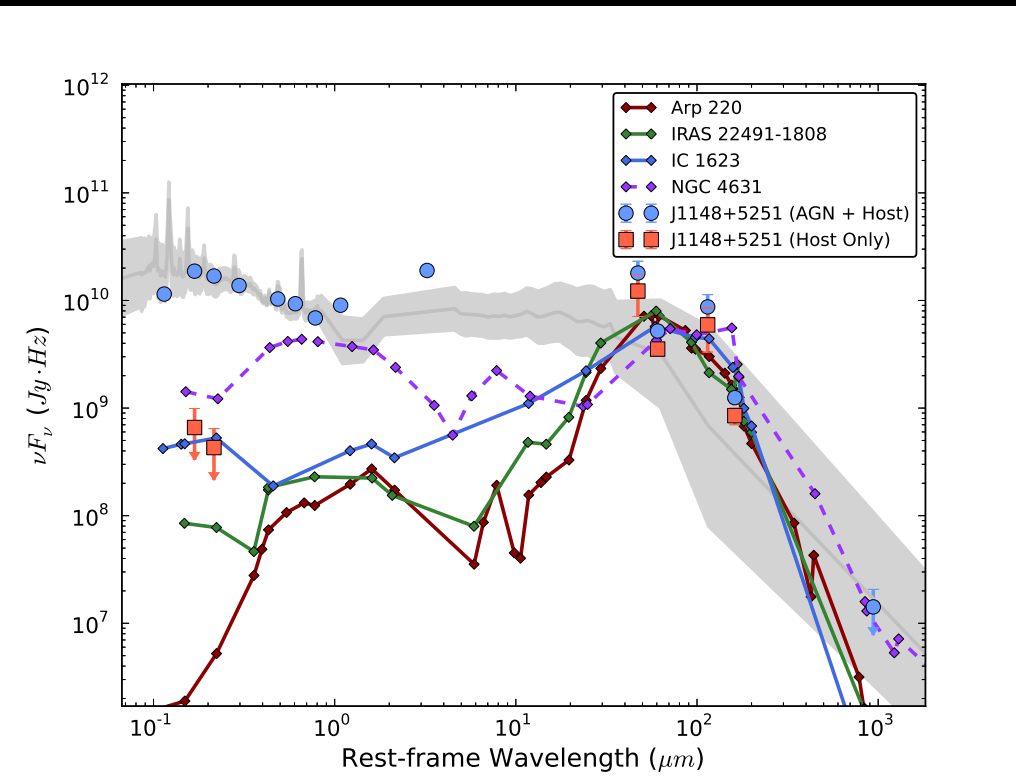


## (2b) WFC3: Detection of one QSO Host System at $z \simeq 6$ (Giant merger?)



- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley<sup>+</sup> 2014).
  - First detection out of four  $z \simeq 6$  QSOs [2 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.

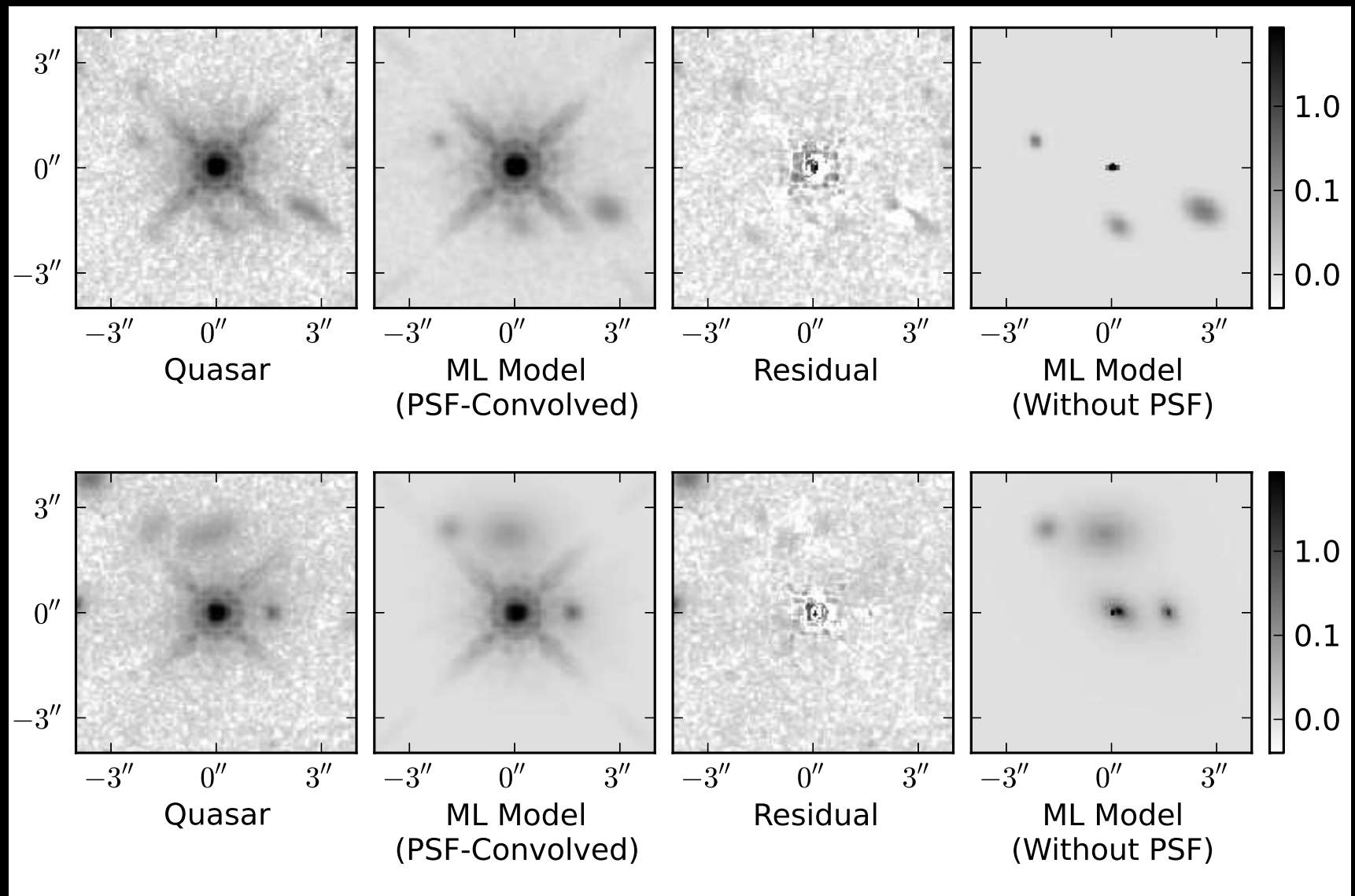
## (2b) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$



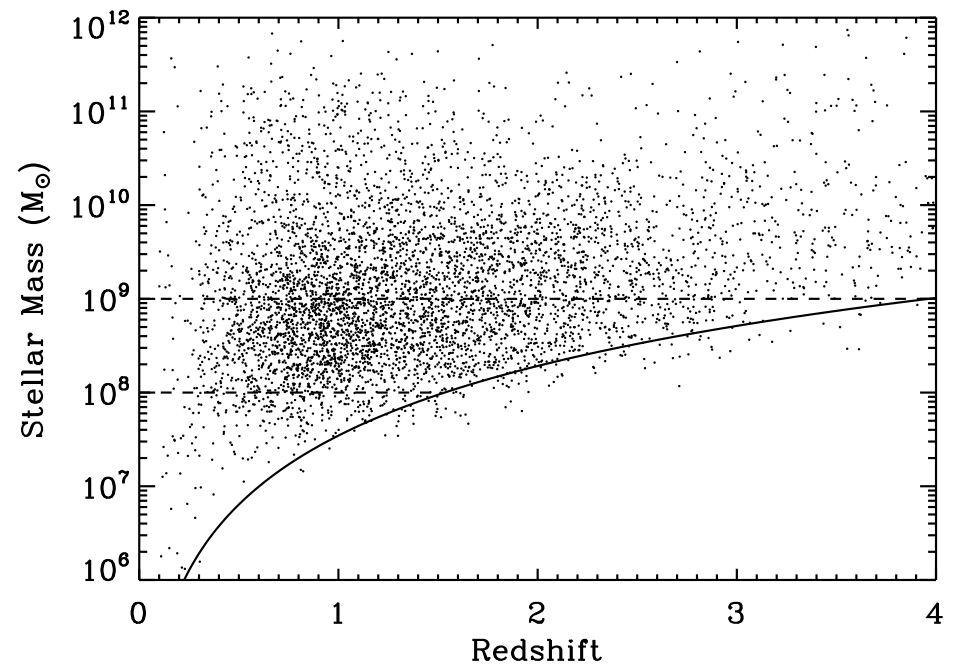
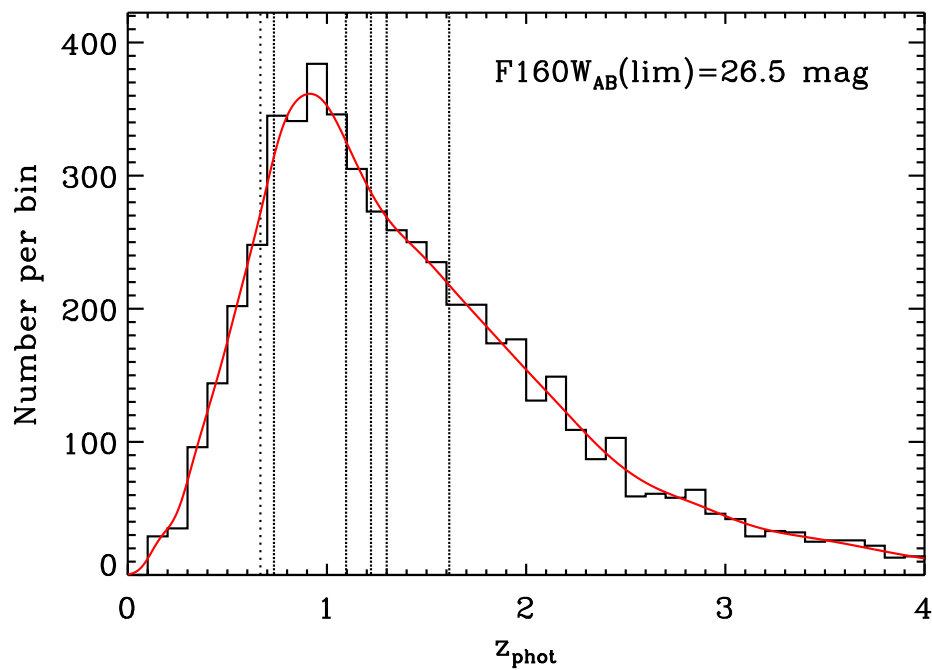
- Blue dots:  $z \simeq 6$  QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at  $z \gtrsim 1$  (normalized at  $0.5 \mu$ ). Red:  $z \simeq 6$  host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages  $\lesssim 1$  Gyr) normalized at  $100 \mu\text{m}$ :  
[LEFT] Rules out  $z=6.42$  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 2013 PhD; et al. 2014).
- JWST Coronagraphs can do this  $10\text{--}100 \times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu\text{m}$ ).



## (2b) 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, MPI, Koekemoer, Windhorst et al. 2014).
- JWST Coronagraphs can do this 10–100 $\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu\text{m}$ ).



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?).

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

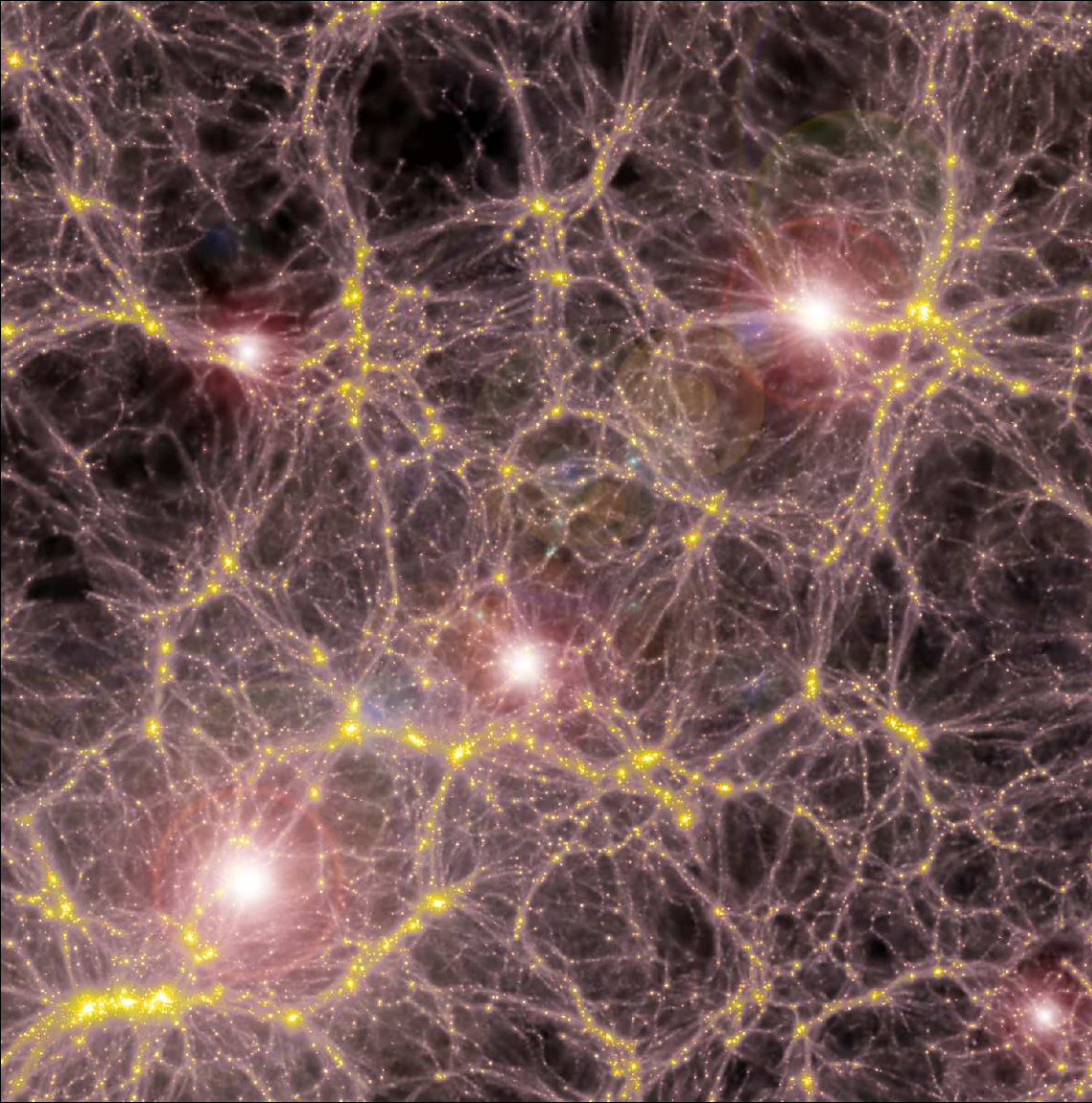
For WFC3's panchromatic capabilities at  $z \simeq 0-7$ , see Chris Conselice's talk.

- HUDF shows WFC3  $z \simeq 7-9$  capabilities (Bouwens<sup>+</sup> 2010; Yan<sup>+</sup> 2010).

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



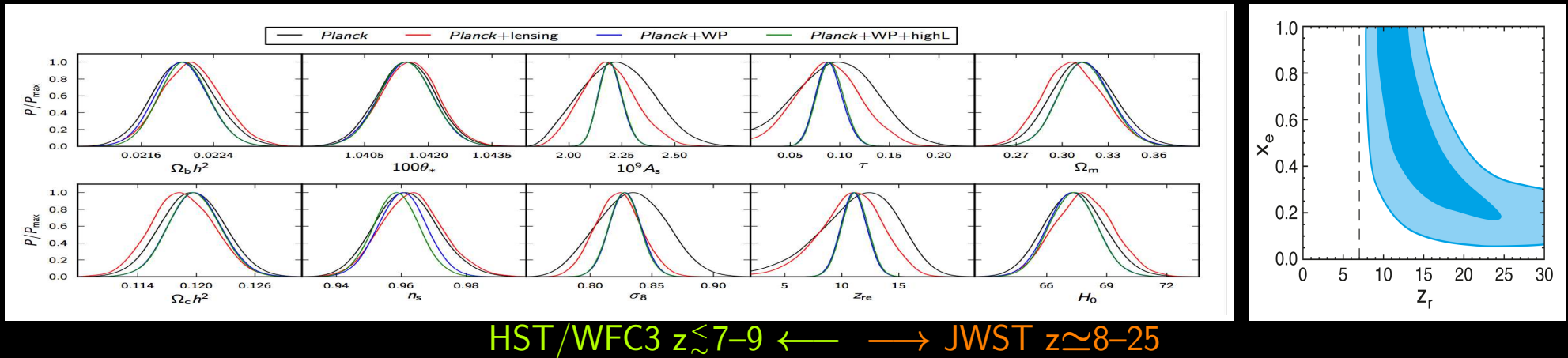
### (3) How will JWST Observe First Light and Reionization?



- 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., with accurate predictions before JWST flies [See F. Mirabel's talk].

# Implications of the WMAP year-9 & Planck13 results for JWST science:



The year-9 WMAP data provided better foreground removal (Komatsu<sup>+</sup> 2011; Hinshaw<sup>+</sup> 2012; Planck XVI 2013; see also A. Lasenby's talk):

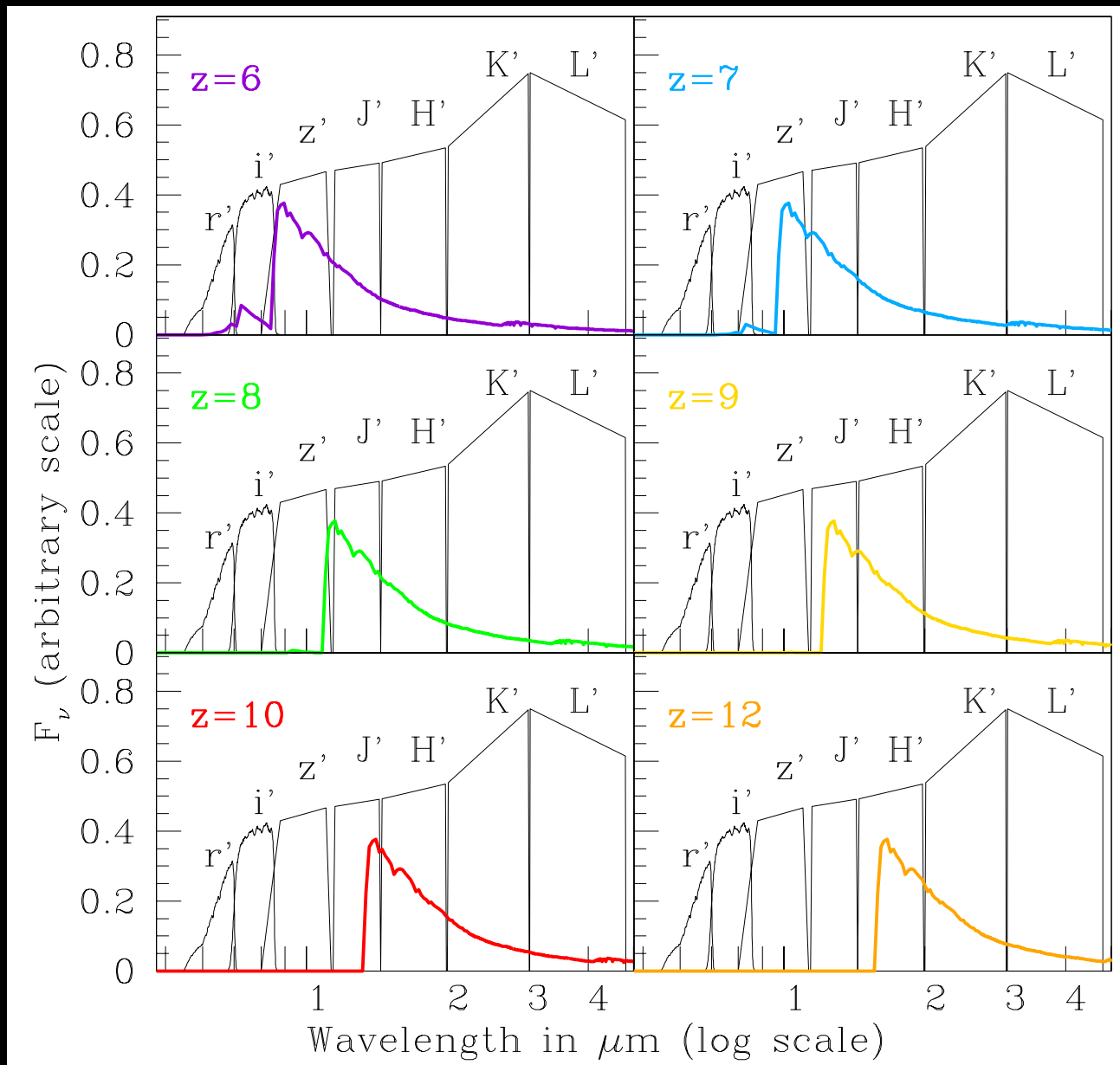
$\implies$  First Light & Reionization occurred between these extremes:

- (1) Instantaneous at  $z \simeq 11.1 \pm 1.1$  ( $\tau = 0.089 \pm 0.013$ ), or:
- (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, Planck14), then how many reionizers will JWST see at  $z \simeq 10-20$ ?



### 3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



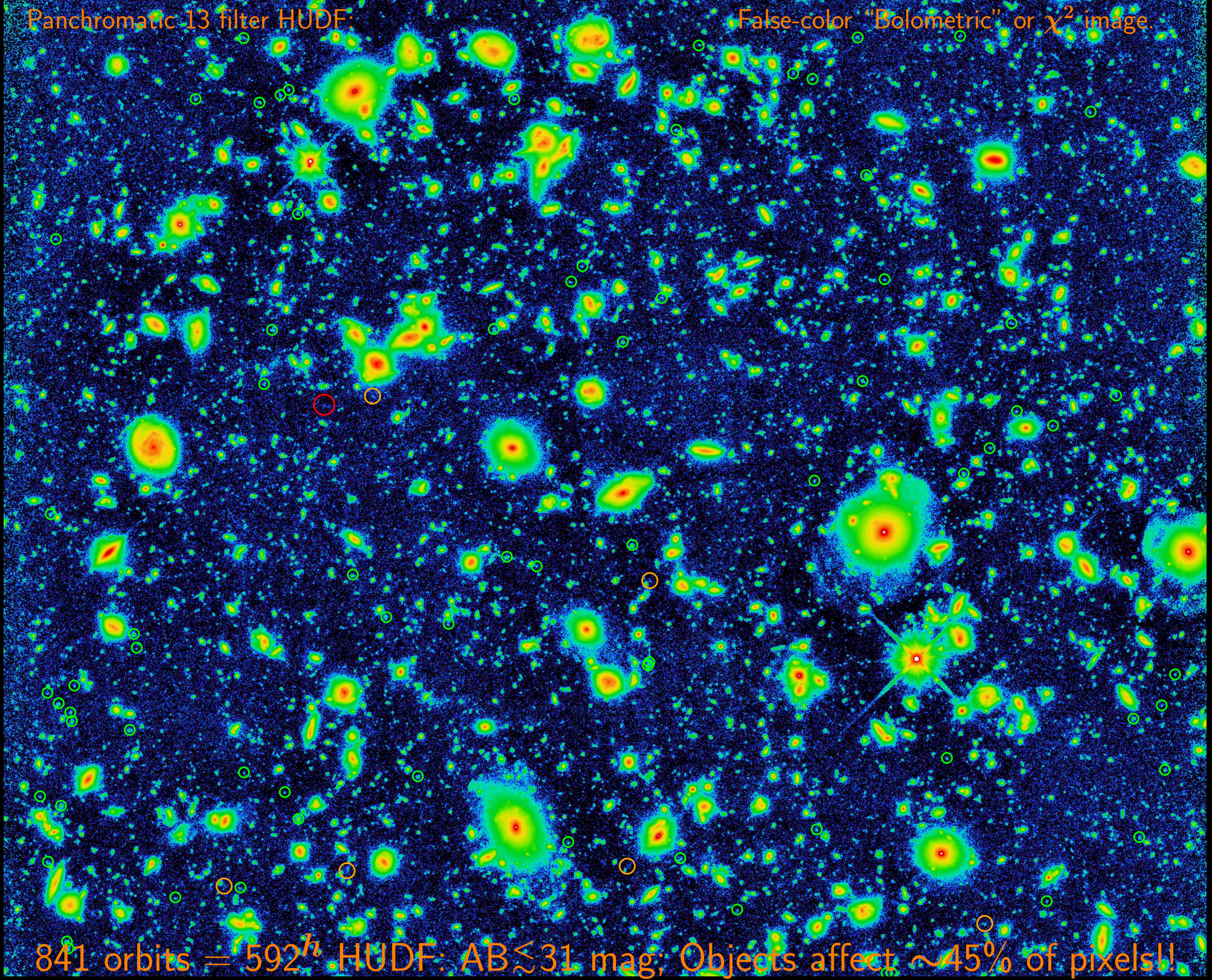
● Can't beat redshift: to see First Light, must observe near-mid IR.

⇒ This is why JWST needs NIRCам at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .



Panchromatic 13 filter HUDF:

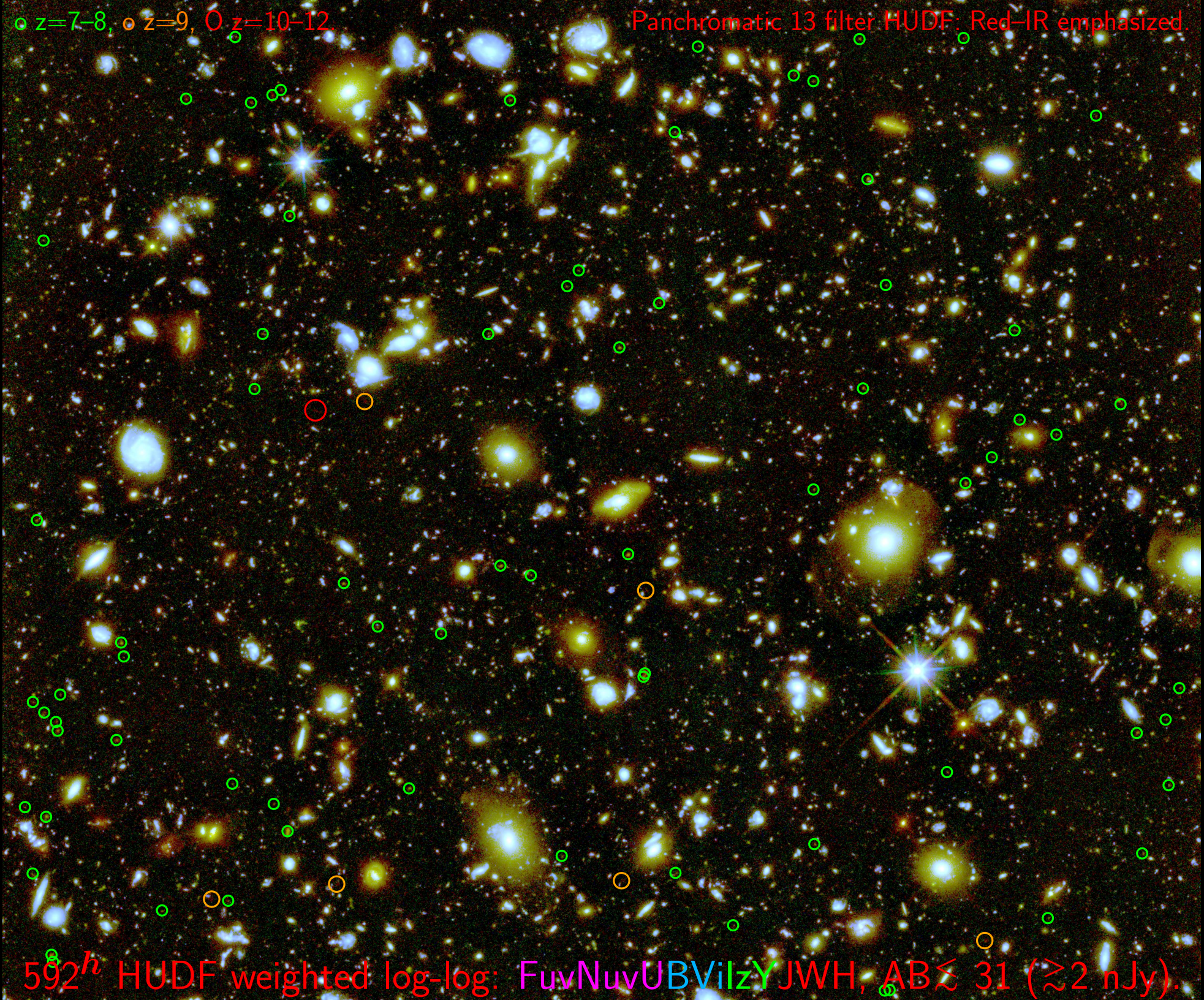
False-color "Bolometric" or  $\chi^2$  image.



841 orbits = 592<sup>h</sup> HUDF: AB  $\lesssim$  31 mag; Objects affect  $\sim 45\%$  of pixels!!



○  $z=7-8$ , ○  $z=9$ , ○  $z=10-12$ . Panchromatic 13 filter HUDF: Red-IR emphasized.



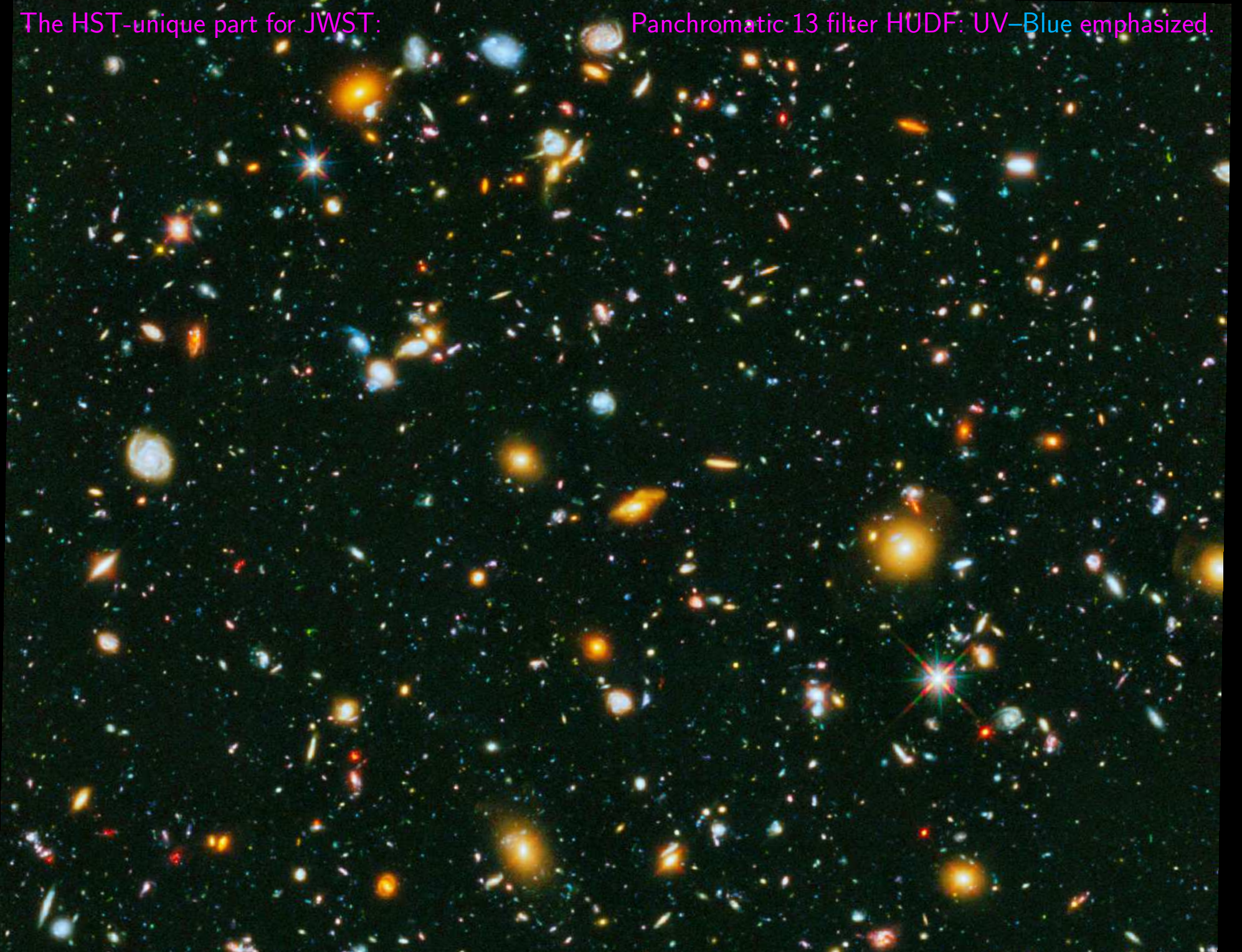
592<sup>h</sup> HUDF weighted log-log: FuvNuvUBViIzYJWH, AB  $\lesssim 31$  ( $\gtrsim 2$  nJy).



The HST-unique part for JWST:

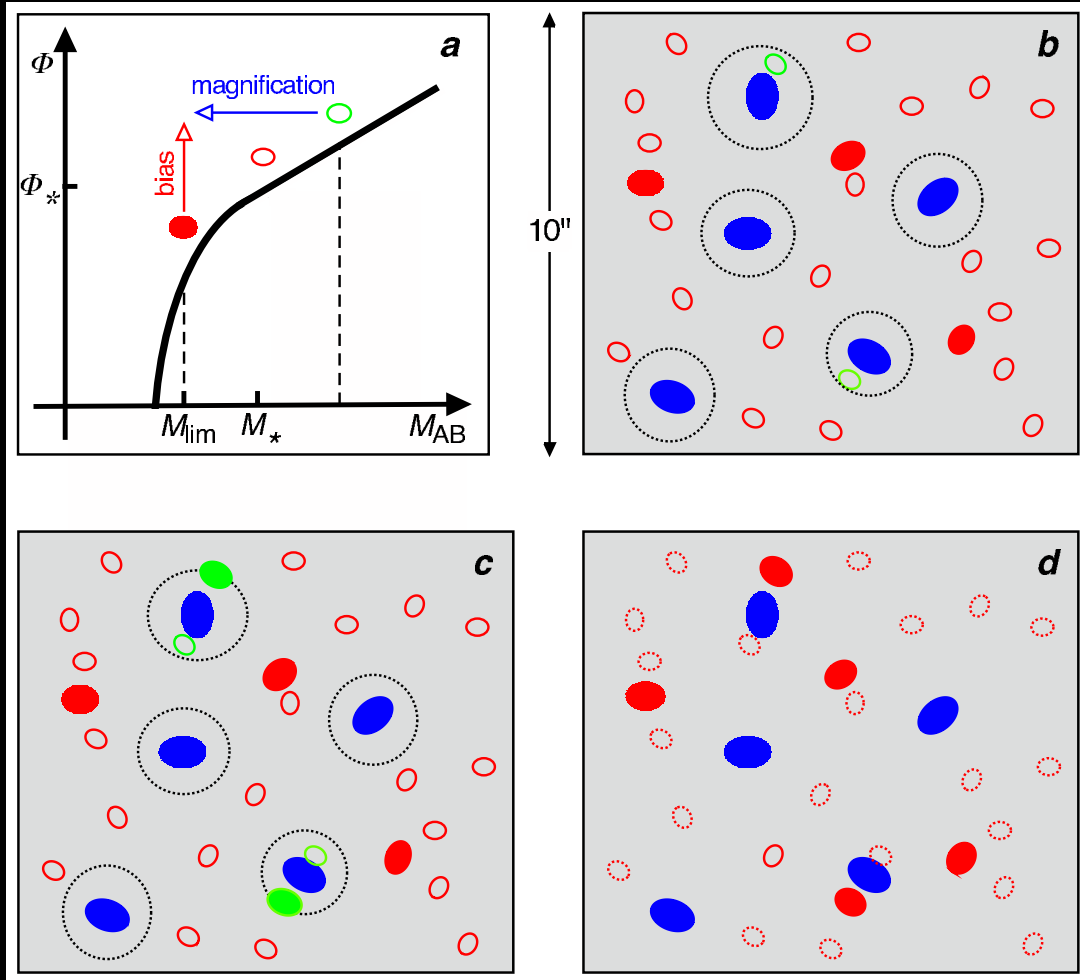
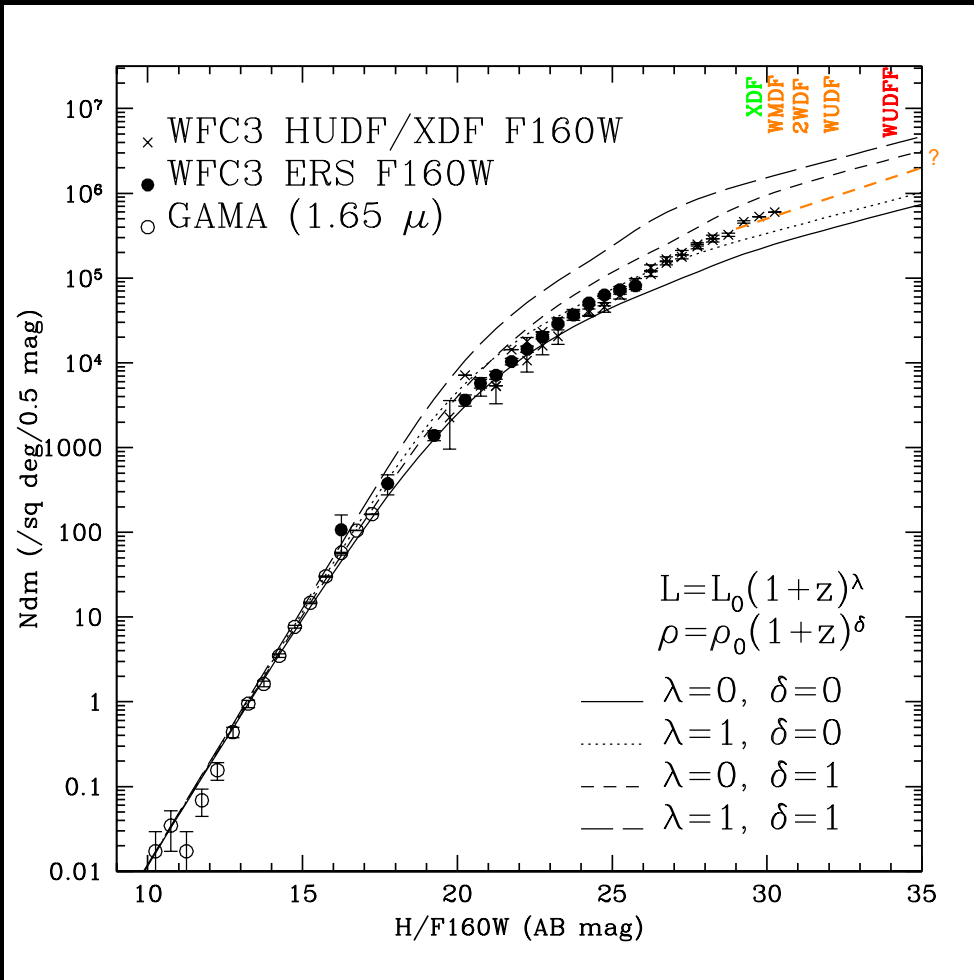
Panchromatic 13 filter HUDF: UV-Blue emphasized.

592<sup>h</sup> HUDF weighted log-log: FuvNuvUBVilzYJWH, AB  $\lesssim 28-31$  ( $\gtrsim 2$  nJy).



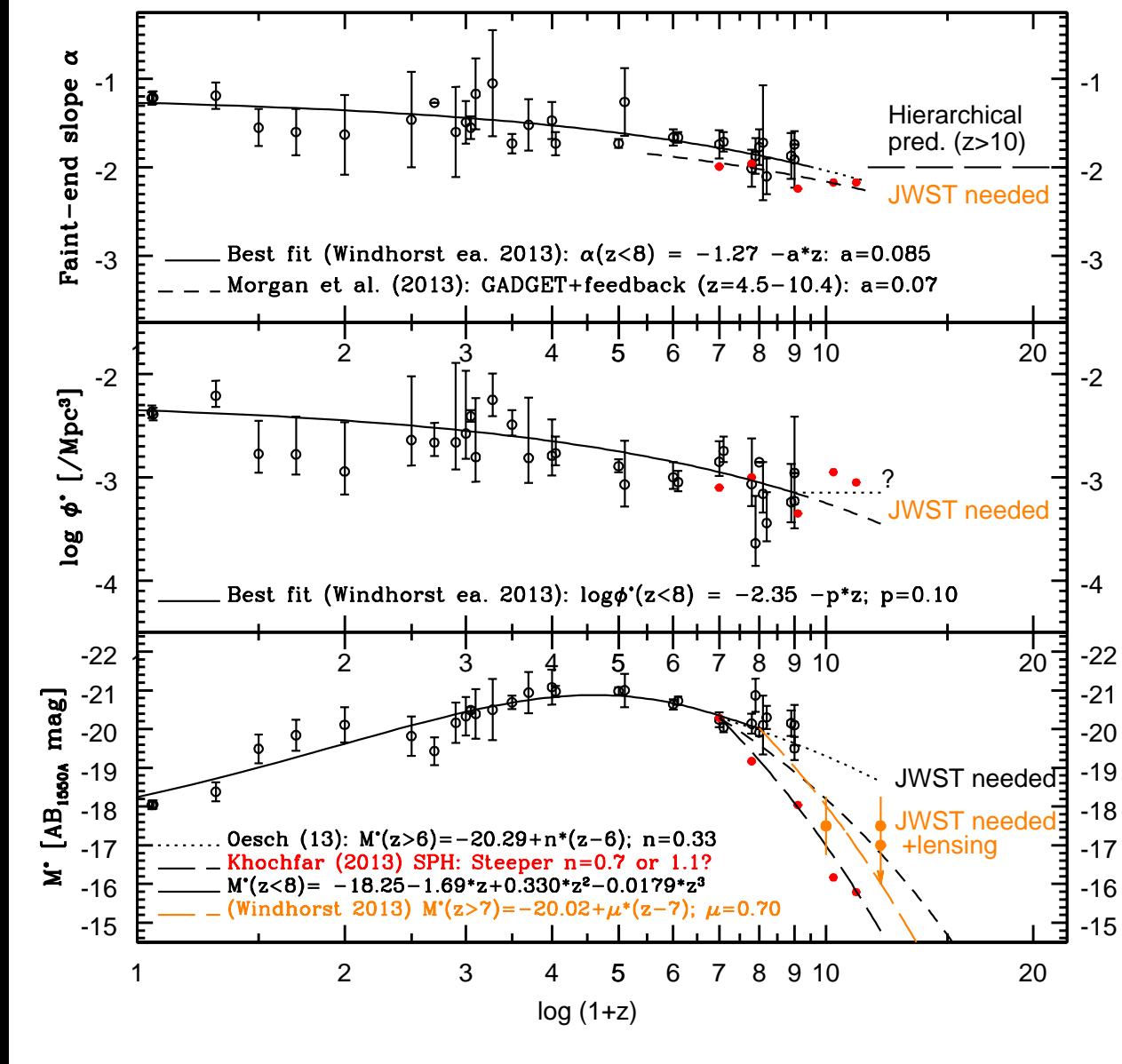


# HUDF WFC3 IR Galaxy Counts: What to expect in its (Ultra)Deep Fields?



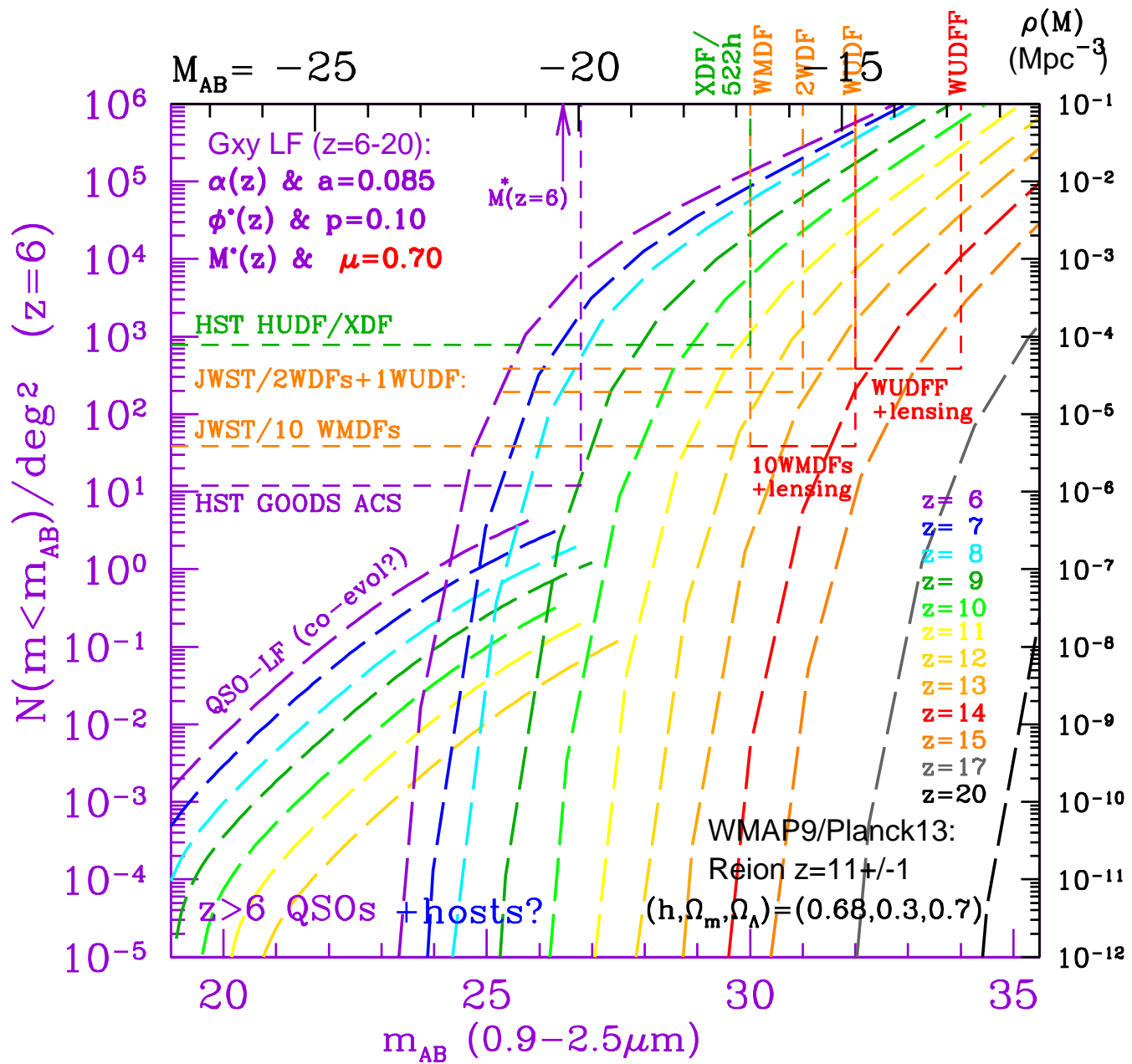
$1.6 \mu m$  counts (Windhorst<sup>+</sup>2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end near-IR count-slope  $\simeq 0.12 \pm 0.02$  dex/mag  $\iff$  Faint-end LF-slope ( $z_{med} \simeq 1.6$ )  $\alpha \simeq -1.4 \Rightarrow$  reach  $M_{AB} \simeq -14$  mag.
- WUDF (- - -) can see  $AB \lesssim 32$  objects:  $M_{AB} \simeq -15$  (LMCs) at  $z \simeq 11$ .
- Lensing will change the landscape for JWST observing strategies (WUDFF).

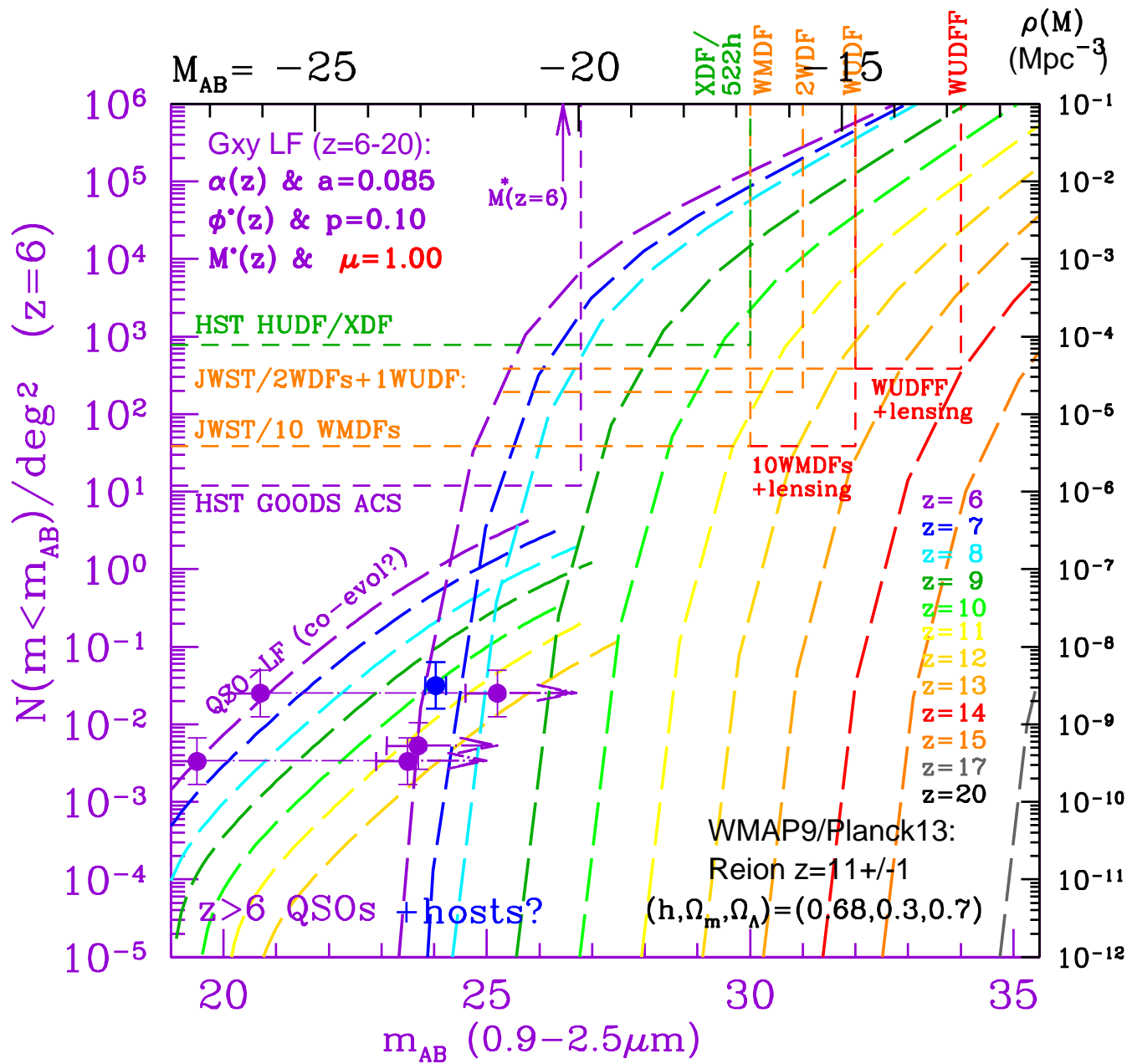


- Evolution of Schechter UV-LF: faint-end LF-slope  $\alpha(z)$ ,  $\Phi^*(z)$  &  $M^*(z)$ :
- For JWST  $z \gtrsim 8$ , expect  $\alpha \lesssim -2.0$ ;  $\Phi^* \lesssim 10^{-3}$  (Mpc<sup>-3</sup>) (Oesch<sup>+</sup> 11).
  - HUDF: Characteristic  $M^*$  may drop below  $-18$  or  $-17.5$  mag at  $z \gtrsim 10$ .
- ⇒ Will have significant consequences for JWST survey strategy.





- Schechter LF ( $z \lesssim 6 \lesssim 20$ ) with  $\alpha(z)$ ,  $\Phi^*(z)$ ,  $M^*(z)$  above &  $\mu=0.70$ .  
 Area/Sensitivity for: HUDF/XDF, 10 WMDFs, 2 WDFs, & 1 WUDF.
- Will need lensing targets for WMDF–WUDFF to see  $z \simeq 14-16$  objects.



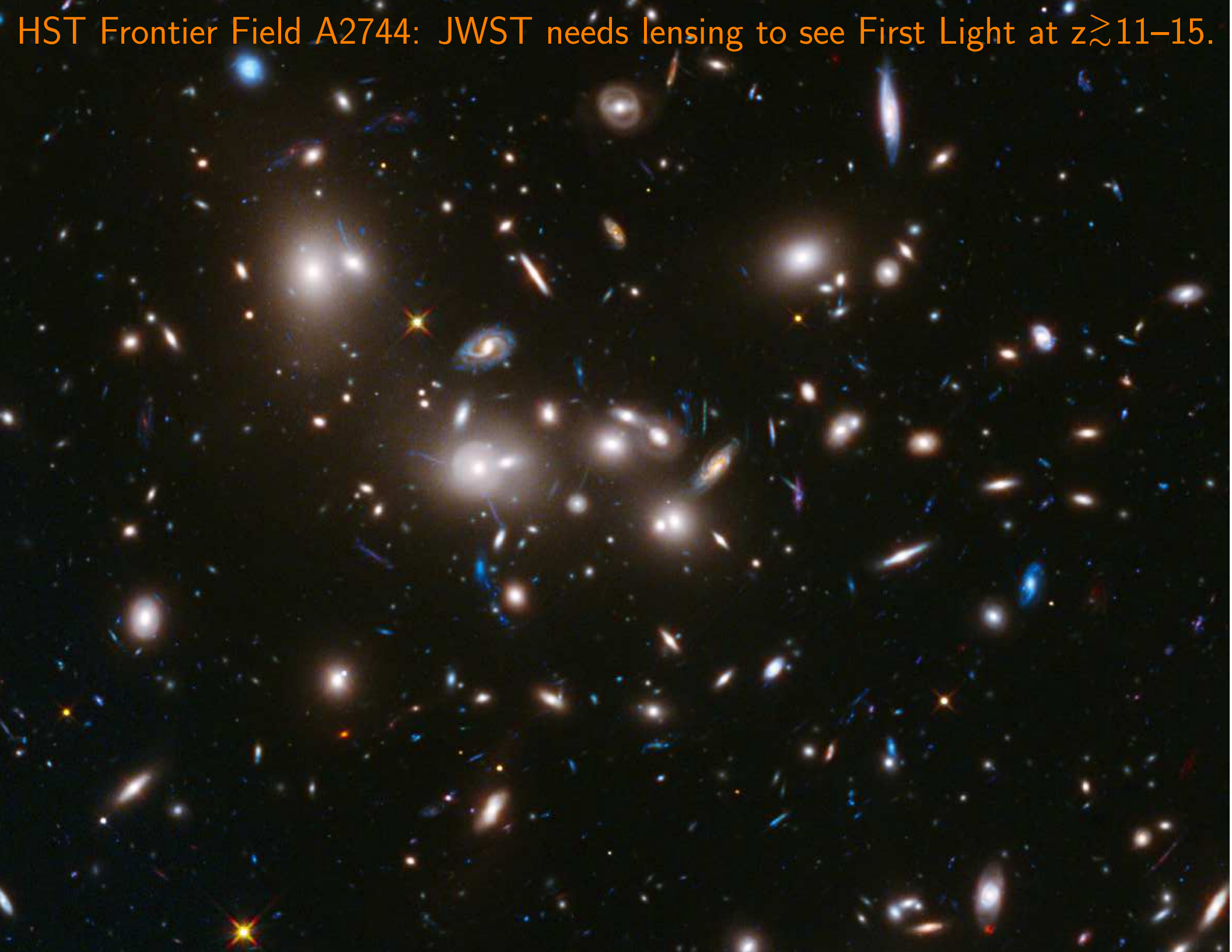
Same as before, but pessimistic  $M^*(z)$  evolution parameter:  $\mu=1.0$ .

- If so, JWST surveys would need lensing to see most  $\gtrsim 11$  objects.

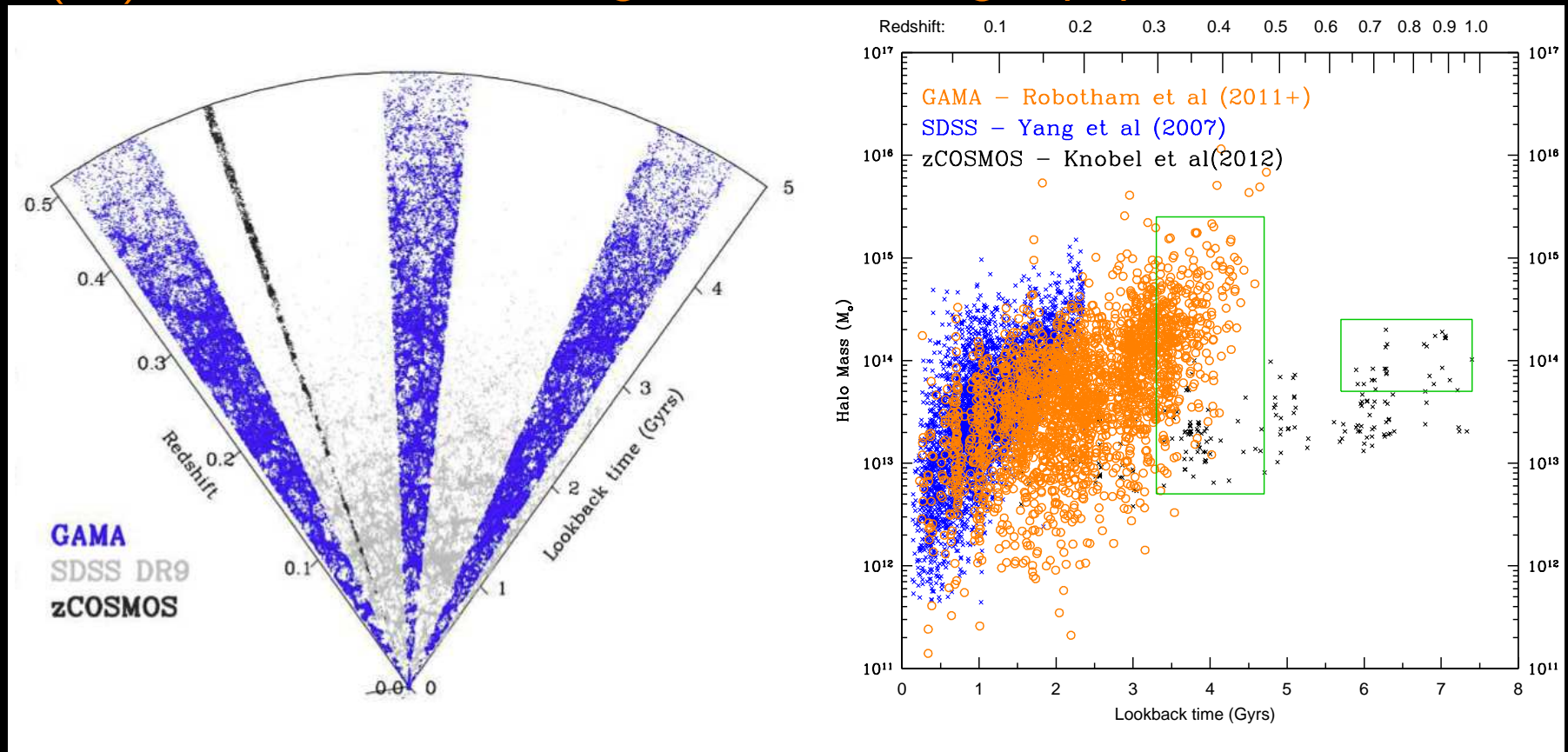
- Add  $z \simeq 6$  QSO host galaxy limits (or fluxes) by Mechtley<sup>+</sup> (2012, 2013).



HST Frontier Field A2744: JWST needs lensing to see First Light at  $z \gtrsim 11-15$ .



## (3b) Gravitational Lensing to see First Light population at $z \gtrsim 10$ .

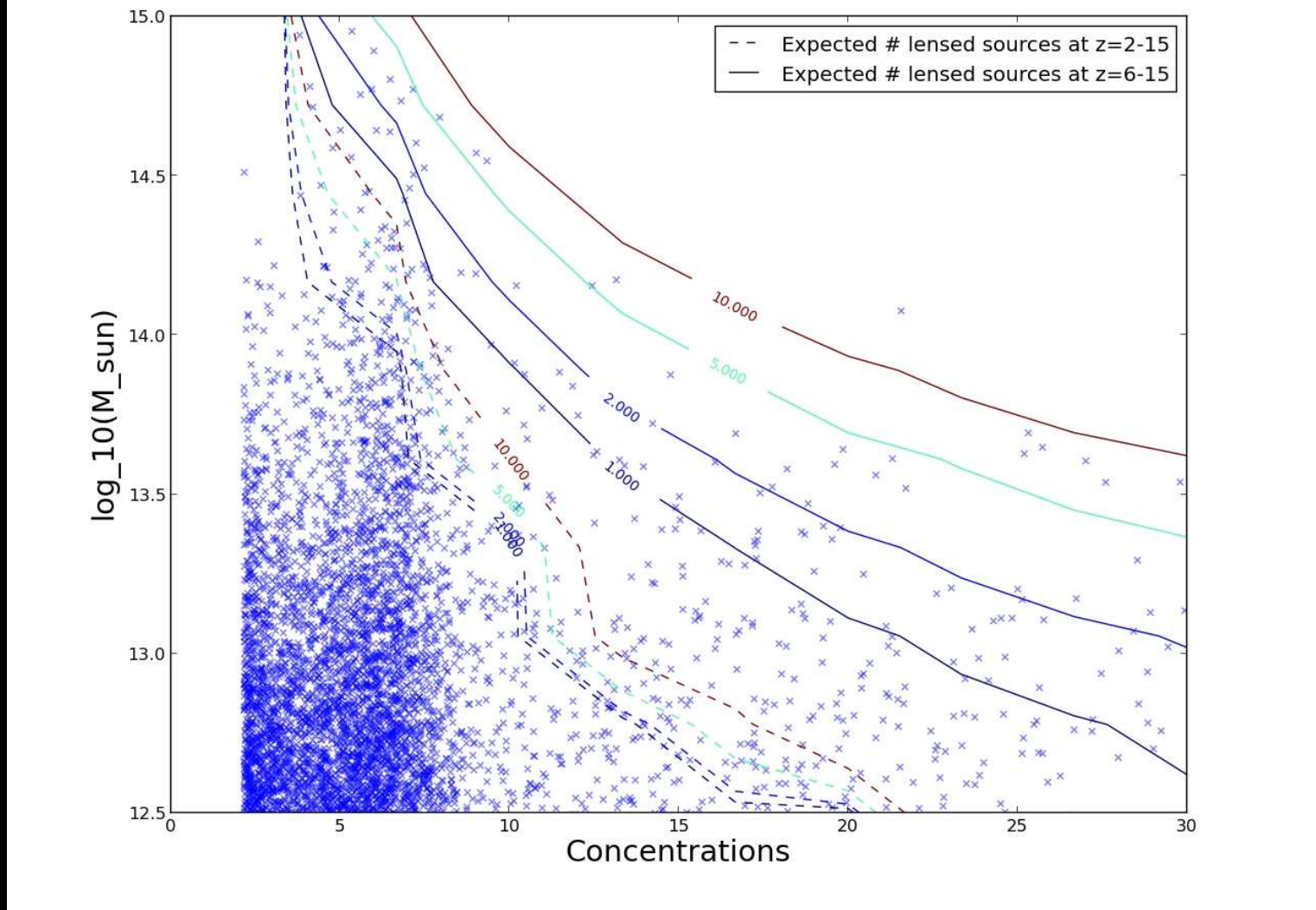


What are the best lenses in 2018: Rich clusters or (compact) galaxy groups?

[Left] Redshift surveys: SDSS  $z \lesssim 0.25$  (Yang<sup>+</sup> 2007), GAMA  $z \lesssim 0.45$  (Robotham<sup>+</sup> 2011), and zCOSMOS  $z \lesssim 1.0$  (Knobel<sup>+</sup> 2012).

- GAMA: 22,000 groups  $z \lesssim 0.45$ ; 2400 with  $N_{spec} \gtrsim 5$  (Robotham<sup>+</sup> 11).
- $\lesssim 10\%$  of GAMA groups compact for lensing (Konstantopoulos<sup>+</sup> 13).
- Large group sample to identify optimal lens-candidates for  $z \gtrsim 6$  sources.

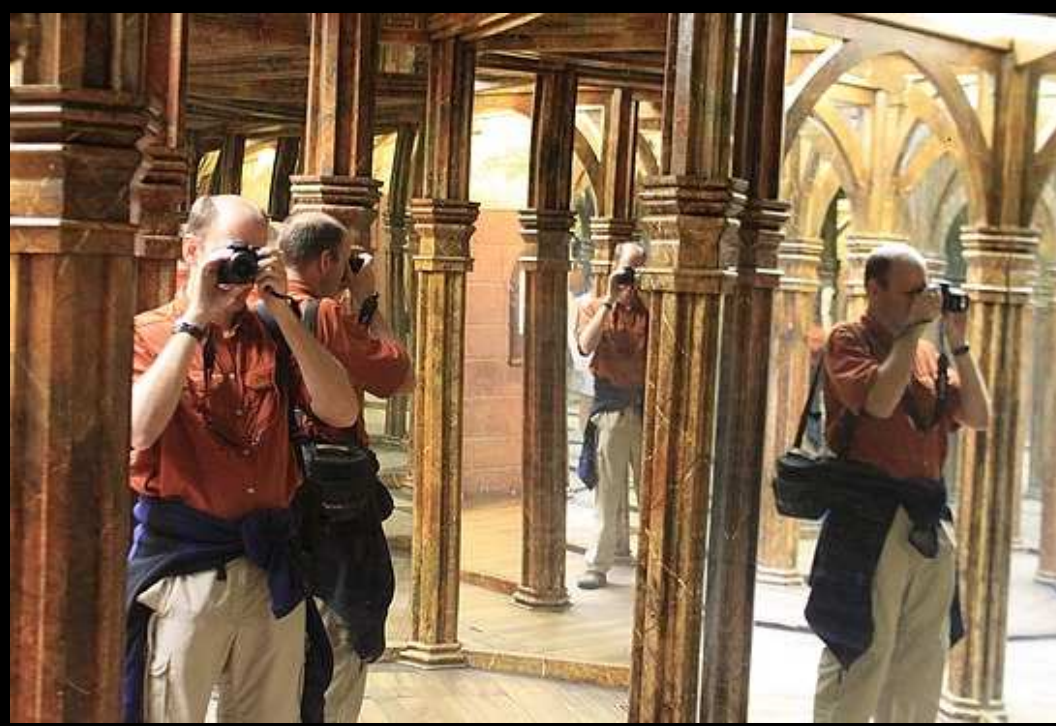




GAMA group mass versus concentration assuming NFW DM halo profiles.  
 Contours = Nr of expected lensed sources ( $\Delta z=1$ ; Barone-Nugent<sup>+</sup> 13).

- 10 WMDFs on best GAMA groups add  $\sim 50-100$   $z \simeq 6-15$  sources ( $AB \lesssim 30$ ).
- Also get  $\gtrsim 10\times$  more ( $\gtrsim 500$ ) lensed sources at  $\simeq 2-15$ .

WUDFF if pointed at clusters adds  $\sim 6\times$  more ( $\gtrsim 3000$ ) sources at  $6 \lesssim z \lesssim 15$ .



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 because of their own diameter  
⇒ Need multi- $\lambda$  deblending algorithms.

(2) House-of-mirrors effect [“Gravitational Confusion”]: Most First Light objects at  $z \gtrsim 12-14$  may need to be found by cluster or group lensing.

⇒ Need multi- $\lambda$  object-finder that works on sloped backgrounds.

⇒ If  $M^*(z \gtrsim 10) \gtrsim -18$ , need to use & model gravitational foreground.



## (4) Conclusions

- (1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.
  - 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 97% 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).

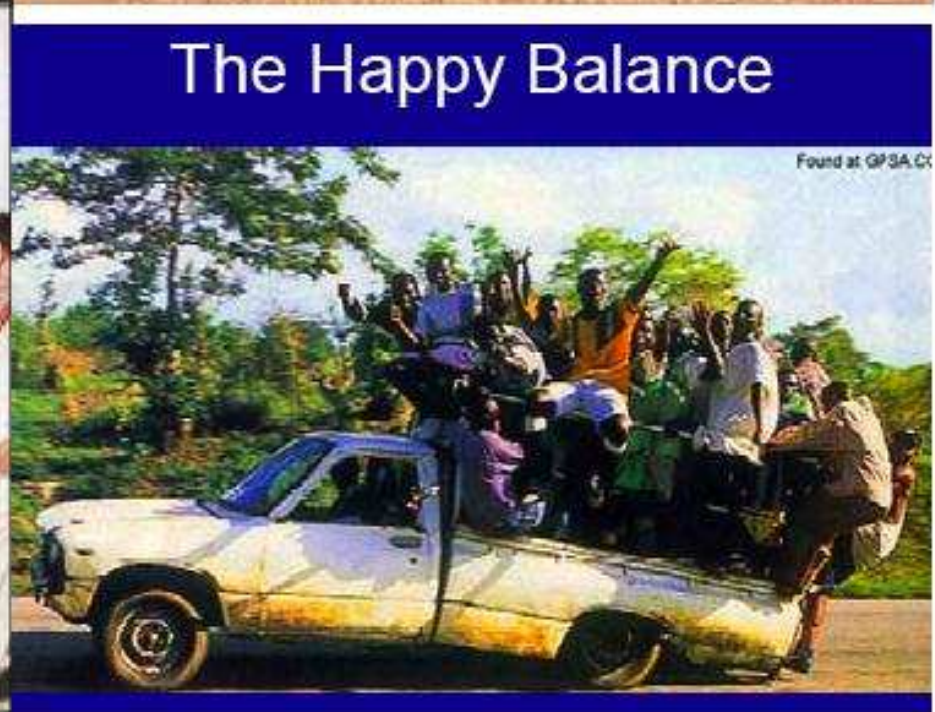
What the Scientists See:



What the Project Manager Sees:



The Happy Balance



Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).



# 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)



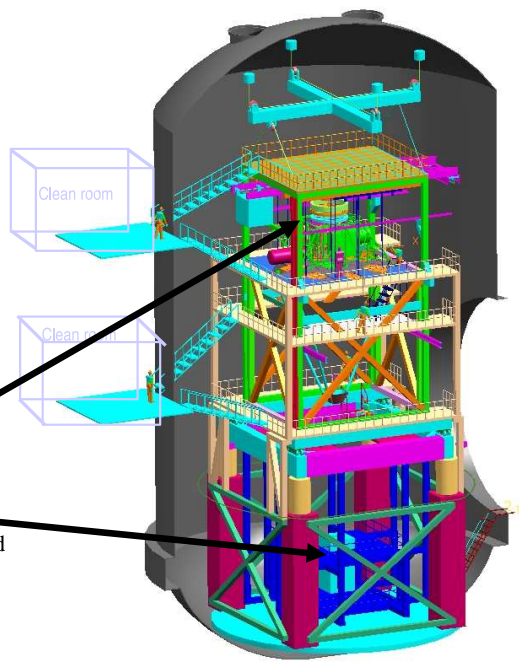
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

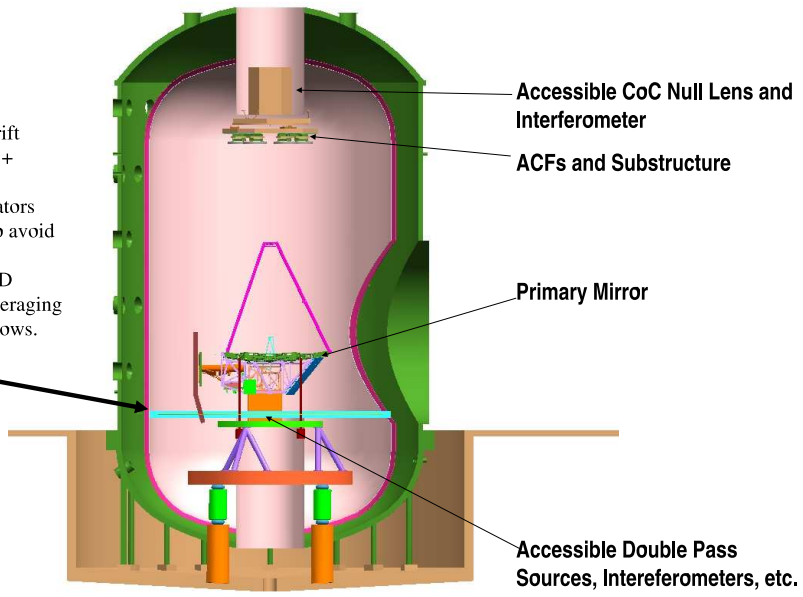
Current plan includes 10 trucks of LN2/day during cooldown

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.



# Fiscal Year 2014 HQ Milestones

Assumes JWST is appropriated in FY2014 the full President's budget request of new obligation authority (NOA).

Month	Milestone	Comment
Oct-13	1 Primary Mirror Backplane Support Structure Cryogenic Testing Readiness Review	Completed 9/10
Nov-13	2 Mirror Deployment Electronics Unit Manufacturing Readiness Review	Completed 10/8
	3 Jet Propulsion Lab. (JPL) Cryogenic Test Chamber Readiness Review	Delayed: pulse tube, cooler shield issues
Dec-13	4 Johnson Space Center (JSC) Telescope and ISIM support structure fabrication complete	Completed 11/4
	5 Spacecraft Critical Design Review Complete	Delayed to 1/14 [shutdown]
	6 MIRI Cryocooler Flight Cold Head Assembly delivered to ISIM	Delayed 1/21/2014
	7 JSC Clean Room ready to receive ground support equipment	Delayed to 1/14 [shutdown]
Jan-14	8 Complete ISIM cryogenic-vacuum risk reduction test	Concluded 11/13/2013, but not all tests completed because of shutdown
	9 Delivery of last Primary Mirror Segment to GSFC	Completed 12/16
	10 Observatory Operations software scripts Build 3 Complete	
Feb-14	11 New detector focal plane arrays for NIRCcam ready for integration into instrument	Completed 11/20
	12 Secondary Mirror Mount delivery	
	13 MIRI Cryocooler flight electronics delivered to JPL	
	14 Final Data Management Subsystem Design Review	Completed 11/22
Mar-14	15 Flight NIRCcam and NIRSpec ready for integration into ISIM	Delayed to 3/14 [shutdown]
	16 Spacecraft Solar Array Manufacturing Readiness Review	
Apr-14	17 JSC Chamber A Telescope ground support equipment test #1 design review	
	18 Telescope actuators electronics drive unit delivery	
	19 Flight MIRI cryocooler assembly delivered to JPL	
	20 MIRI Cryocooler Flight Refrigerant Line Deployment Assembly delivered to integration and testing	
May-14	21 Sunshield Membrane Cover Assembly Manufacturing Readiness Review	
	22 MIRI cryocooler Test Readiness Review	
	23 Updated Observatory Commissioning Plan (rev C) delivery	
Jun-14	24 Start acceptance testing of flight cryocooler assembly and associated electronics	Delayed to 6/14 [shutdown]
	25 Start cryo-vacuum test with fully integrated ISIM ("CV2")	
Jul-14	26 Flight spare MIRI cryocooler assembly delivered to JPL	
	27 JSC Chamber A bake-out and cryogenic proof testing complete	
Aug-14	28 Hardware ready for MIRI cryo cooler test #3: checkout complete	
	29 Spacecraft Mid-Course Correction Thruster Final Assembly complete	
	30 Proposal Planning Subsystem build 9 complete	
Sep-14	31 Sunshield Mid-boom and Stem assembly Manufacturing Readiness Review	
	32 Spacecraft Flight Software Build 2.2 Test Readiness Review	
Oct-14	33 NIRSpec and FGS/NIRISS new Focal Plane Arrays ready for integration	Delayed to 9/14 [shutdown]
	34 JSC cryogenic test telescope and ISIM test ground support equipment integration complete	
	35 Complete cryo-vacuum test of fully integrated ISIM ("CV2")	Delayed to 10/14 [shutdown]
	36 NIRSpec new microshutters ready for integration	Delayed to 10/14 [shutdown]

Blue font denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late.

Milestones: How the Project reports its progress monthly to Congress.

# Milestone Performance

- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	<b>Total Milestones</b>	<b>Total Milestones Completed</b>	<b>Number Completed Early</b>	<b>Number Completed Late</b>	<b>Deferred to Next Year</b>
FY2011	21	21	6	3	0
FY2012	37	34	16	2	3
FY2013	41	38	20	5	3
FY2014	36	7	5	10*	0

\*Late milestones have been or are forecast to complete within the year.  
Shutdown related delayed milestones included in this tally

7 out of 10 FY14 milestones late by 1 month due to Government shutdown.  
None of these are on the critical path, so caused no launch delay.

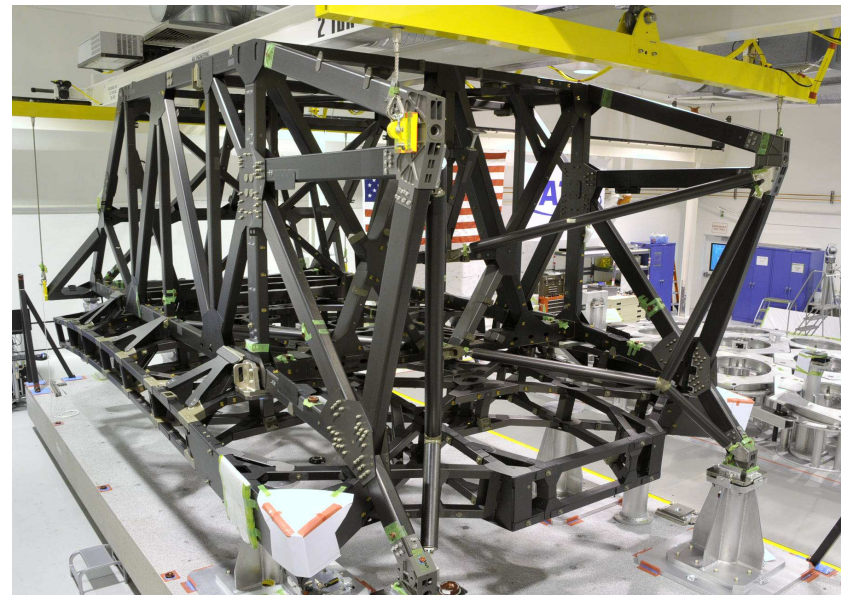




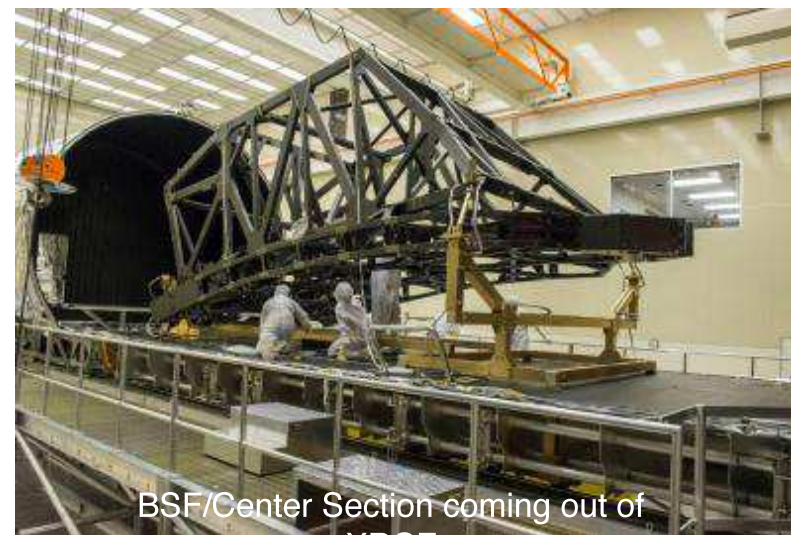
# Backplane Support Frame, Center Section, & Wings



- Center Section is complete
- Wings and cryo cycling is complete
- BSF assembly is complete
- Integration of the BSF to Center Section Complete
  - Cryo Cycling at MSFC XRCF complete



BSF and Center Section



BSF/Center Section coming out of XRCF

2014: Flight back-plane ready to receive mirrors starting in Aug. 2014.





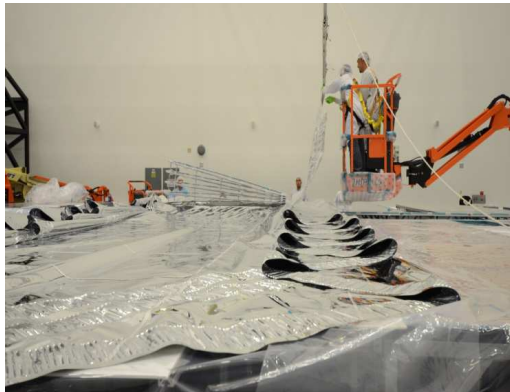
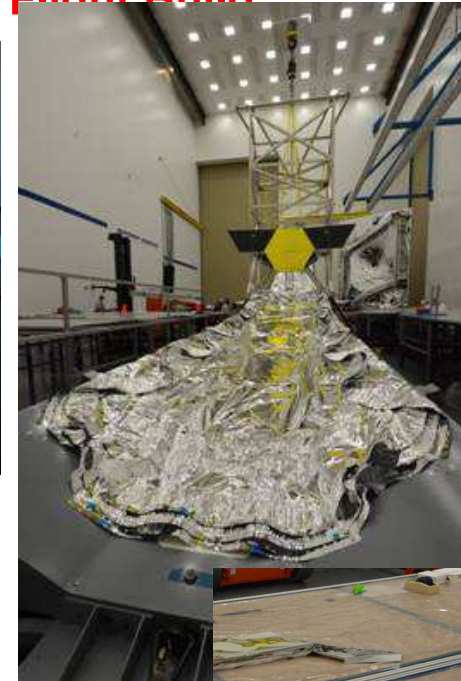
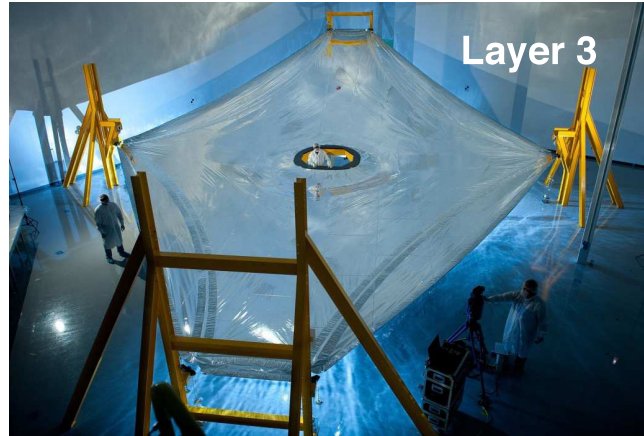
# Sunshield Template Membrane Work Completed

**Templates Verify Design/Manufacturing Prior to Flight Build**



- All Template Layers Completed
- Preparing for flight article manufacturing
- First two Flight Manufacturing Readiness Reviews Completed
- Membrane pull out test complete

Stringing Operations



Template Layers 3-5



Hole Tool Operations

Flight sunshield to be completed & tested by 2015 at Northrop (CA).



# Telescope Assembly Ground Support Equipment



PMD  
HVI CROSS & SONS  
Crested Air  
JPW



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

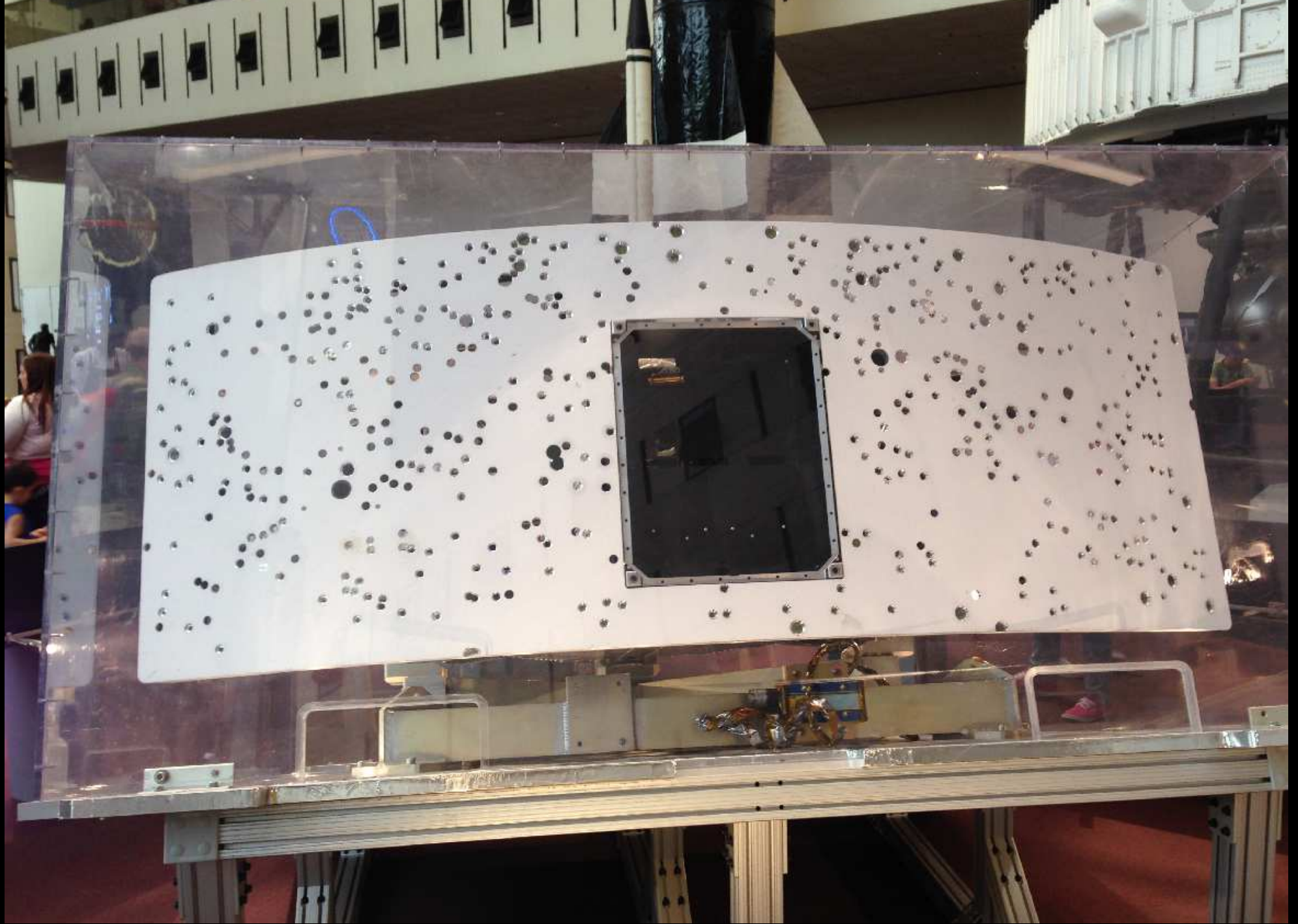


March 2012 NAC  
Science Meeting



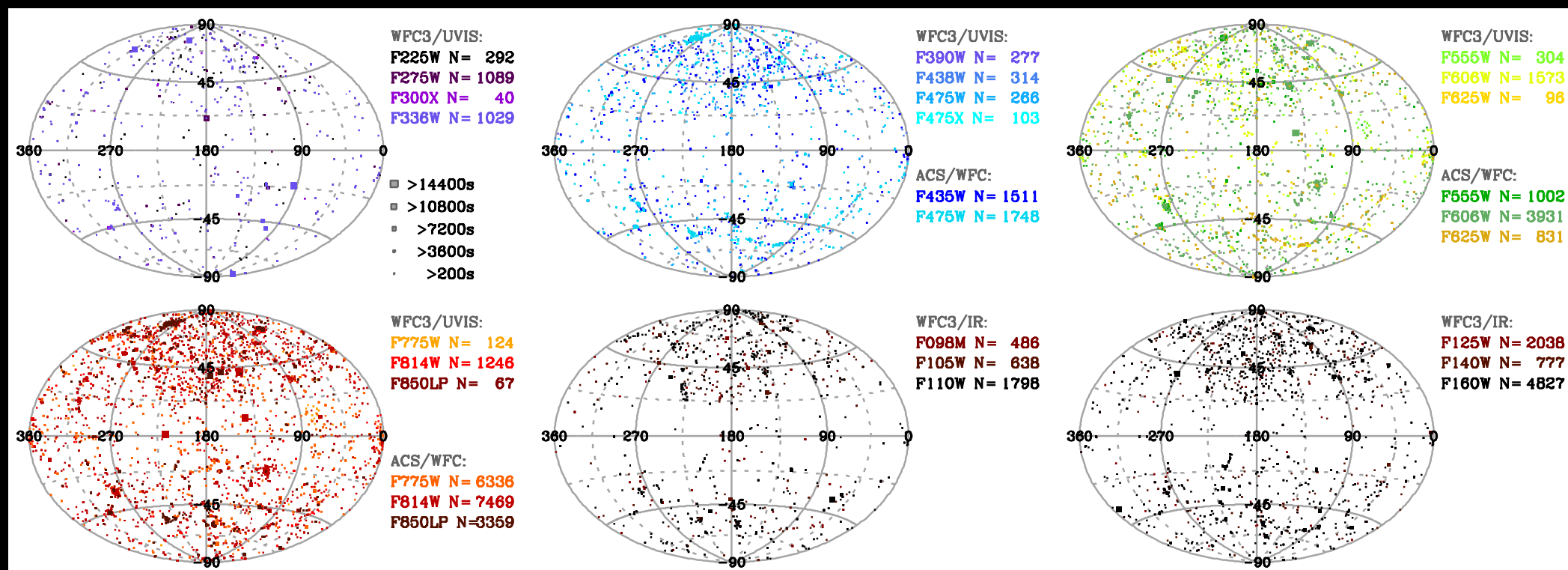
Landing a mirror onto  
backplane simulator





Hubble's WFPC2 returned to Smithsonian in 2009: Results from 16 years of micro-meteorite hits ... (holes drilled in shield for sample analysis).

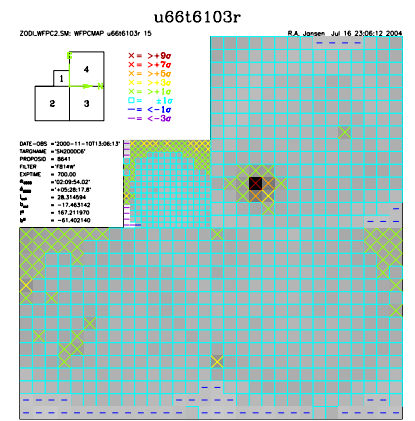
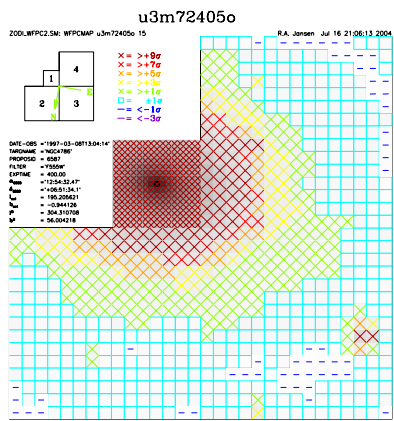
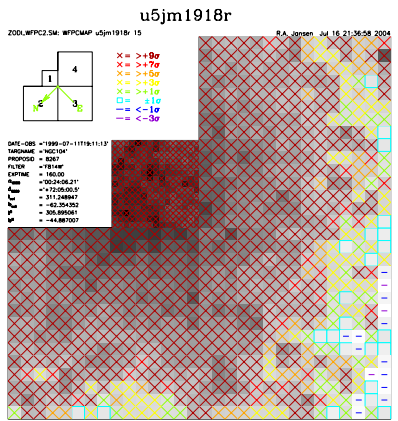
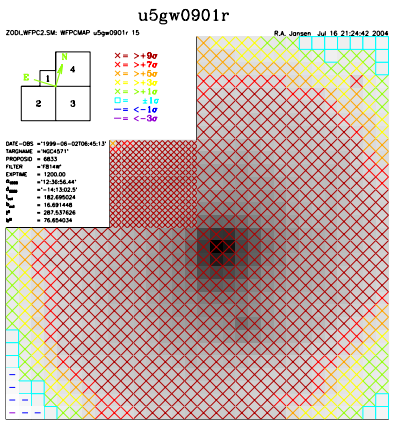
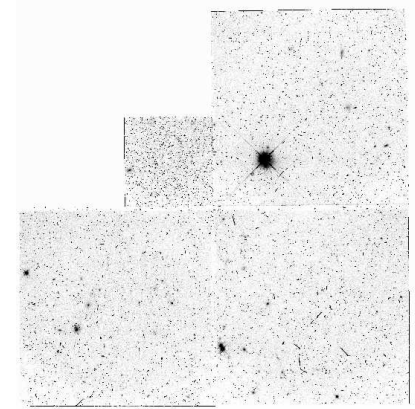
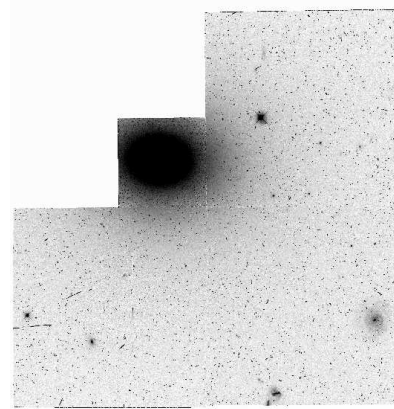
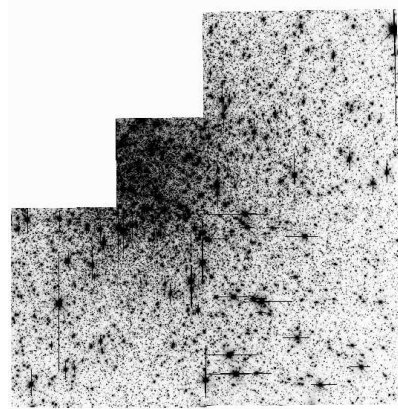
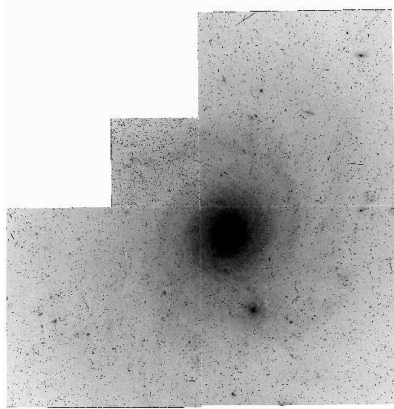




## Summary of 21 years of HST WFC2, ACS and WFC3 Zodi measurements:

- Ecliptic distribution of 43,571 ACS/WFC and WFC3/UVIS+IR targets as of Spring 2014: Use to measure Zodi sky  $SB(l^{Ecl}, b^{Ecl})$ .
- WFC2 Zodi measurements on next pages (Jansen et al. 2014).

This analysis will help address micro-meteorite hit-rate for JWST in L2, which could be substantial (see Gerry Gilmore's GAIA talk).

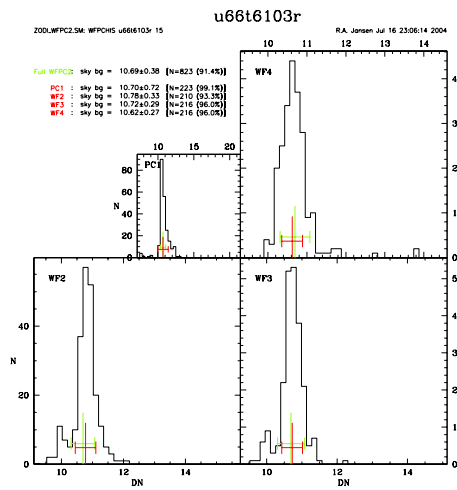
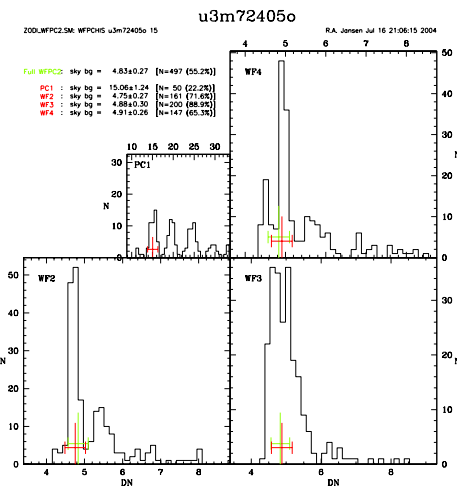
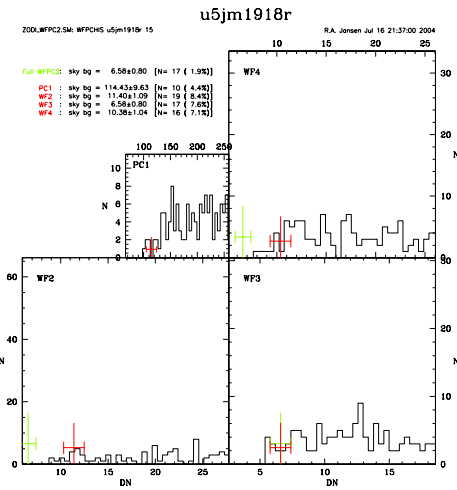
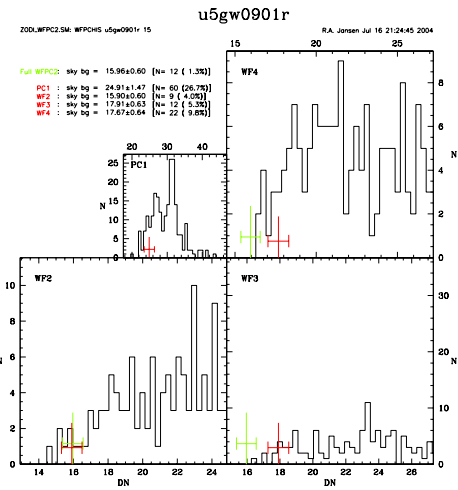


Full WFPC2: sky bg = 15.96±0.60 [N=12 (1.3%)]  
 PC1: sky bg = 24.91±1.47 [N=50 (26.7%)]  
 WF2: sky bg = 15.90±0.60 [N=9 (4.0%)]  
 WF3: sky bg = 17.91±0.63 [N=12 (1.3%)]  
 WF4: sky bg = 17.87±0.64 [N=22 (9.8%)]

Full WFPC2: sky bg = 6.58±0.80 [N=17 (1.9%)]  
 PC1: sky bg = 114.43±9.63 [N=10 (4.4%)]  
 WF2: sky bg = 11.40±1.09 [N=19 (8.4%)]  
 WF3: sky bg = 6.58±0.80 [N=17 (7.8%)]  
 WF4: sky bg = 10.38±1.04 [N=16 (7.1%)]

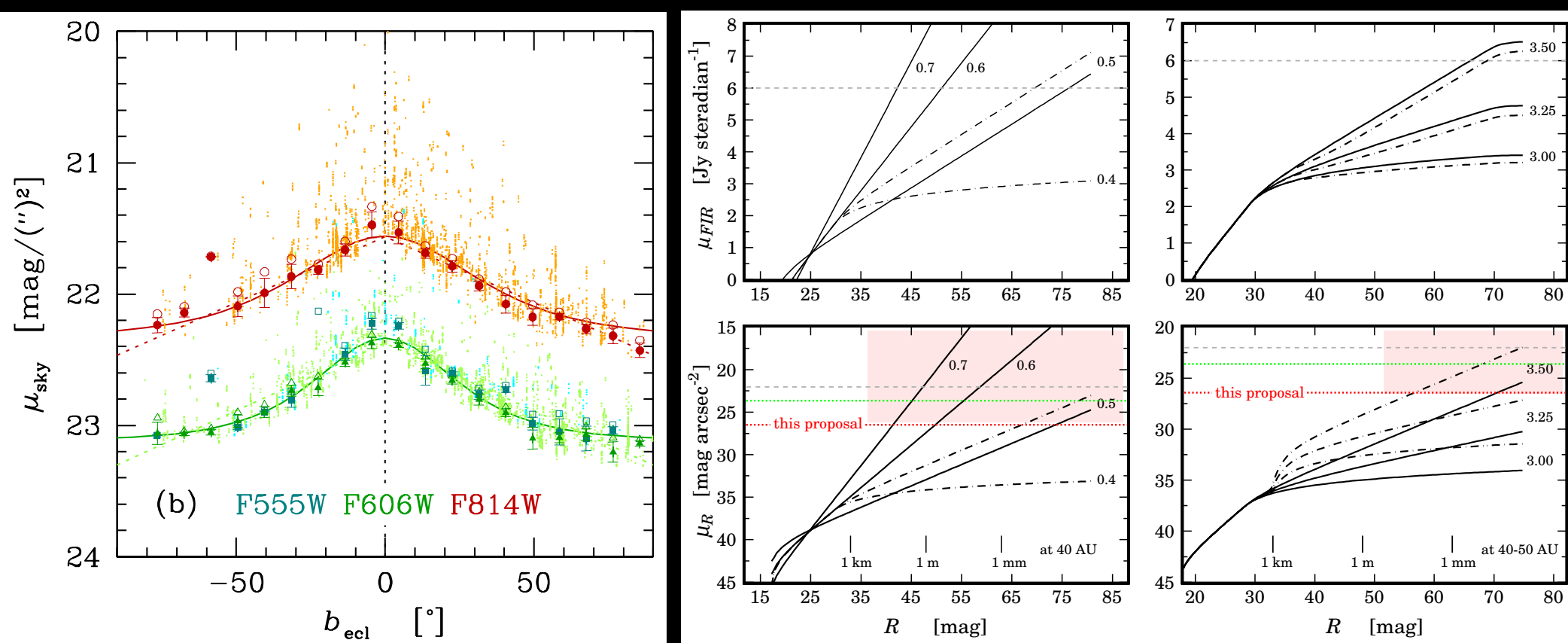
Full WFPC2: sky bg = 4.83±0.27 [N=497 (55.2%)]  
 PC1: sky bg = 15.06±1.24 [N=55 (22.2%)]  
 WF2: sky bg = 4.75±0.27 [N=161 (71.6%)]  
 WF3: sky bg = 4.86±0.30 [N=208 (88.9%)]  
 WF4: sky bg = 4.91±0.26 [N=147 (65.3%)]

Full WFPC2: sky bg = 10.69±0.38 [N=823 (91.4%)]  
 PC1: sky bg = 10.70±0.72 [N=223 (89.1%)]  
 WF2: sky bg = 10.78±0.33 [N=210 (83.3%)]  
 WF3: sky bg = 10.72±0.29 [N=16 (96.0%)]  
 WF4: sky bg = 10.62±0.27 [N=216 (96.0%)]



Measuring the Zodi modal sky-SB for *all* HST WFPC2 targets over 16.3 years in orbit, rejecting those where target overfills FOV.





[LEFT]: Measured Zodi sky-SB( $b^{Ecl}$ ) in HST V555/V606 and I814.

[RIGHT]: Constrains KBO sky-integral at  $\gtrsim 40$  AU (Kenyon & Windhorst, 2001, ApJL, 547, L69) beyond  $AB \sim 29$  (where it is measured):

To avoid Olbers paradox, KBO size distribution must have  $N(r) \propto r^{-\alpha}$ , with  $\alpha \lesssim 3.3$  at  $AB \gtrsim 29$  mag (due to solar system collisional history).

If L2 meteoroid size *distribution* same as in Kuiper belt (also have  $\alpha \lesssim 3.3$  to avoid Olbers paradox!), then L2 meteoroid impact rate predictable.



# Chamber doesn't look so big anymore!

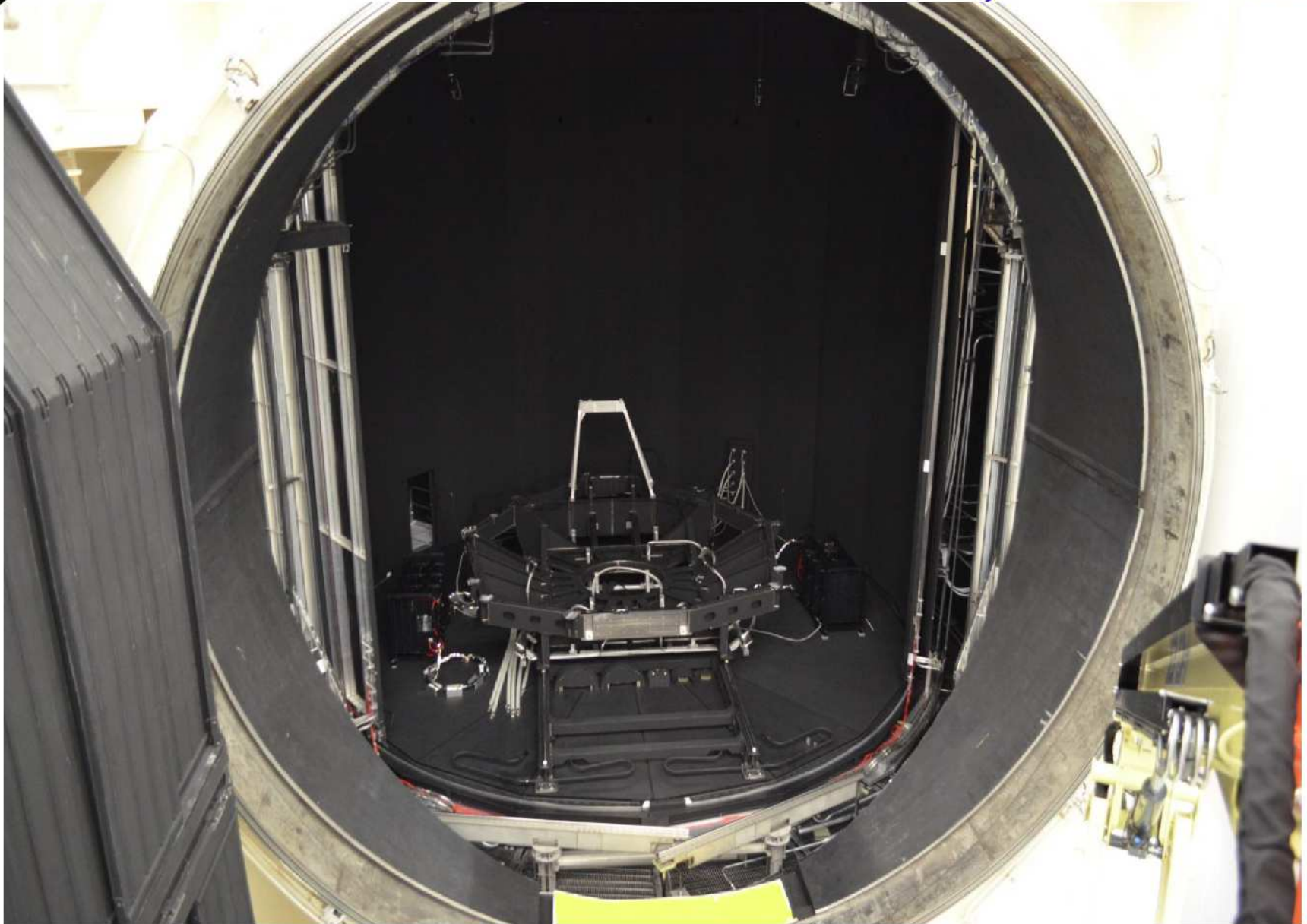


**NORTHROP GRUMMAN**

*Ball*

**EXELIS**

**ATK**  
ARMED TECHNOLOGIES



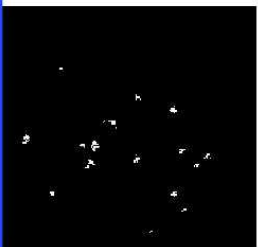
This document is not subject to the controls of the International Traffic in Arms Regulations (ITAR) or the Export Administration Regulations (EAR).

Page 14

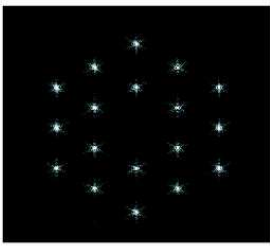
July 2014: OTIS — World's largest TV chamber readied to test JWST.



**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

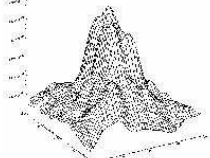
**Final Condition**

PM segments:  
 < 100  $\mu\text{m}$ ,  
 < 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  $\mu\text{m}$  (rms)

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

After Step 3



WFE: < 250  $\mu\text{m}$  rms

WFE < 1  $\mu\text{m}$  (rms)

**4. Fine Phasing**

After Step 4



WFE: < 5  $\mu\text{m}$  (rms)

WFE < 110 nm (rms)

**5. Image-Based Wavefront Monitoring**

After Step 5

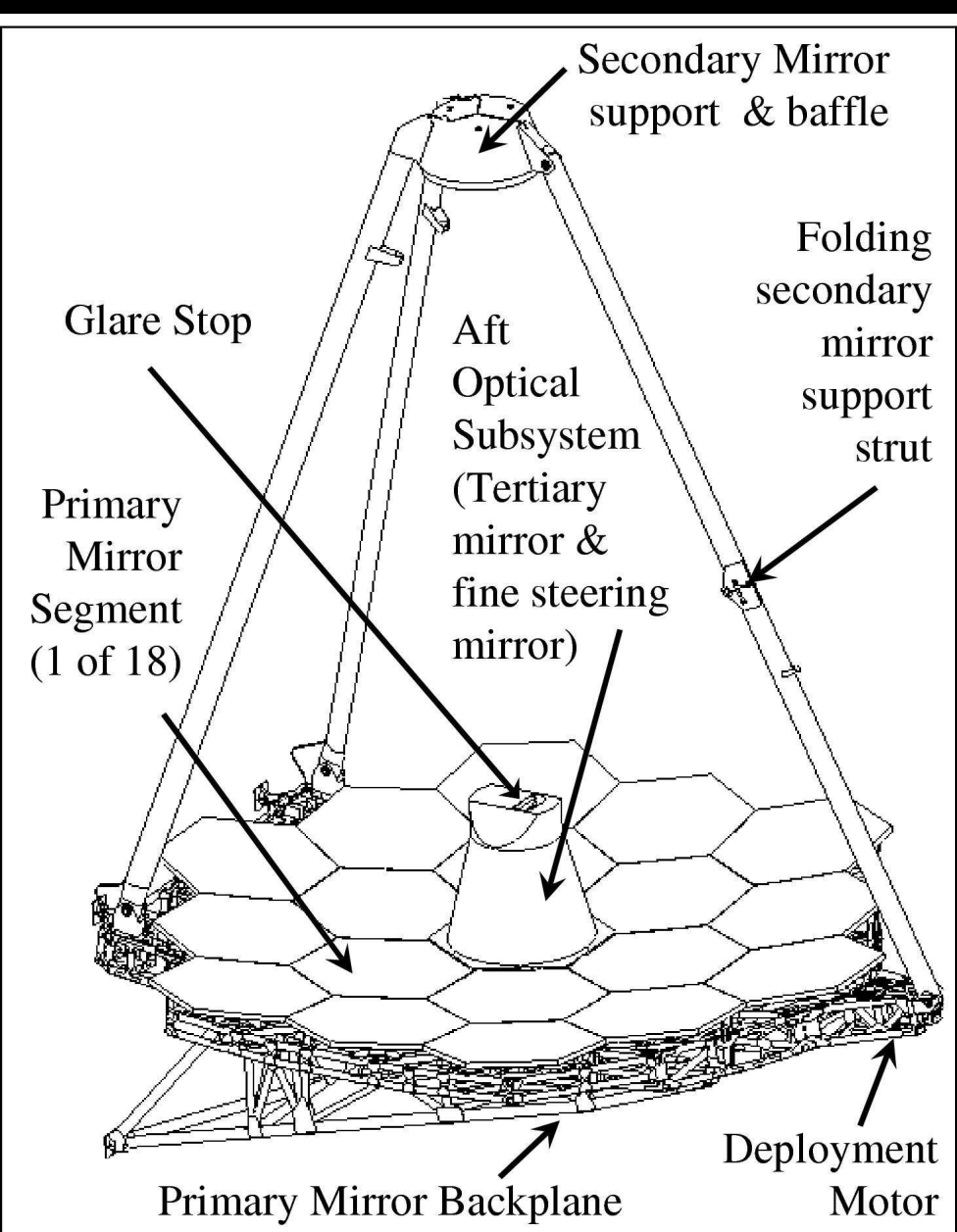


WFE: < 150 nm (rms)

WFE < 110 nm (rms)

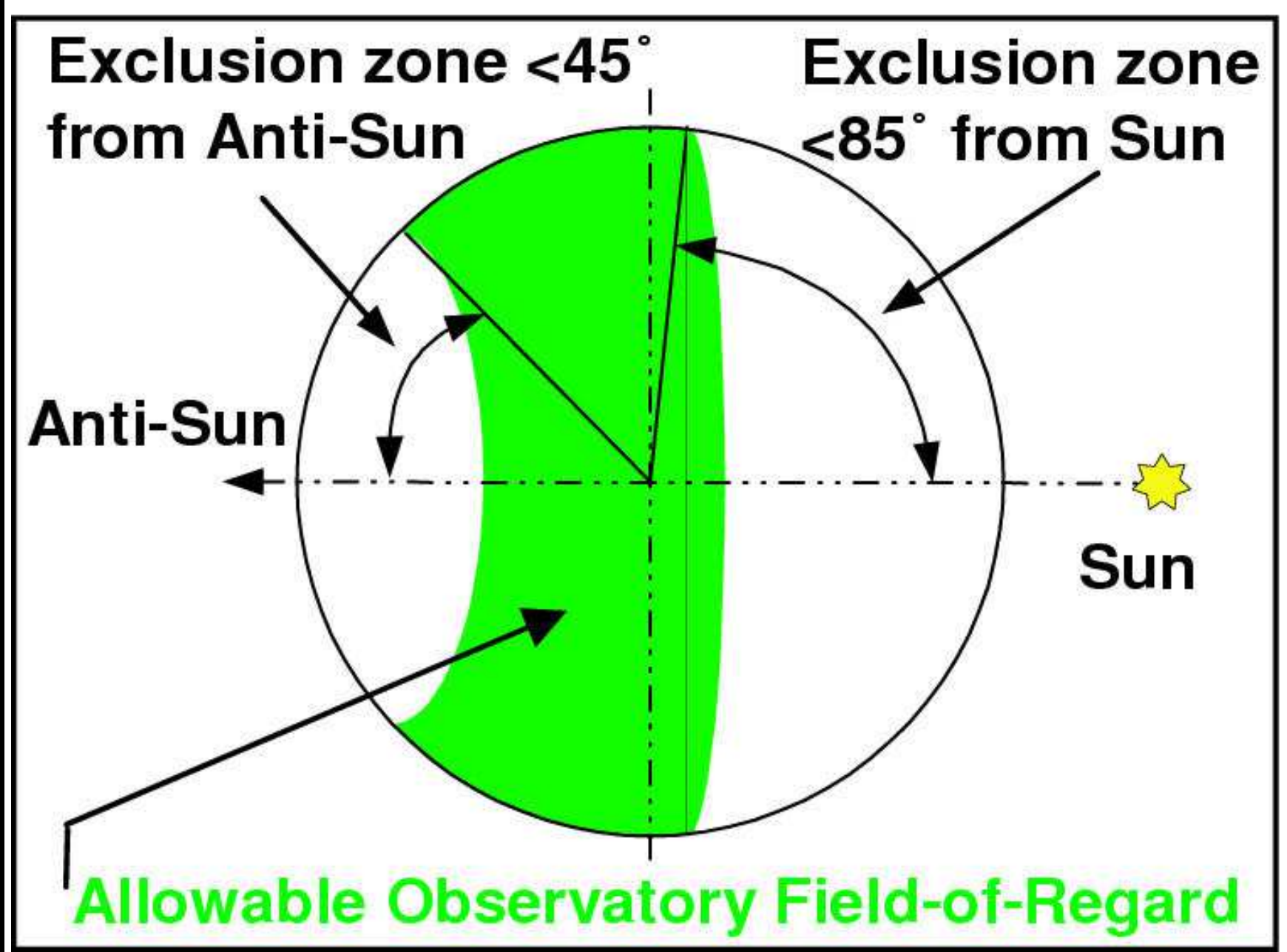
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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



Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.  
Ball 1/6 scale-model for WFS: produces diffraction-limited  $2.0 \mu\text{m}$  images.

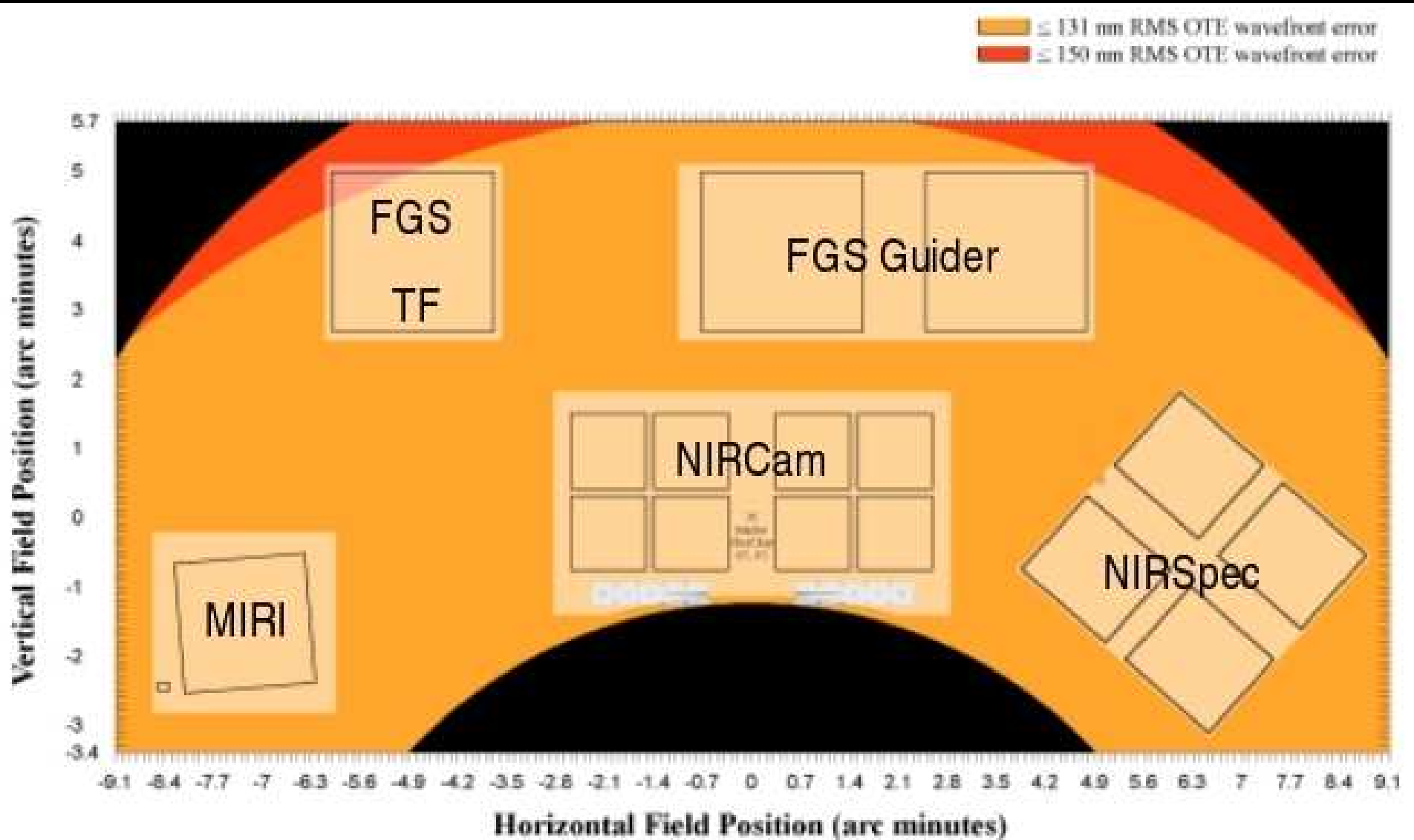




JWST can observe North/South Ecliptic pole targets continuously:

- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

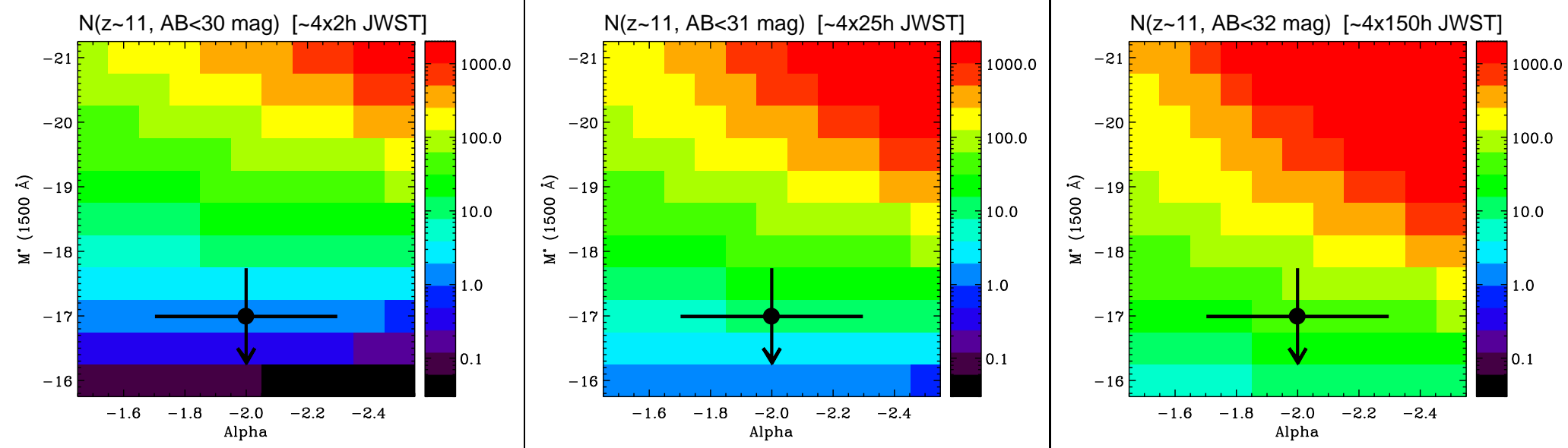
- (3c) What instruments will JWST have?



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

- Currently only being implemented for parallel *calibrations*.



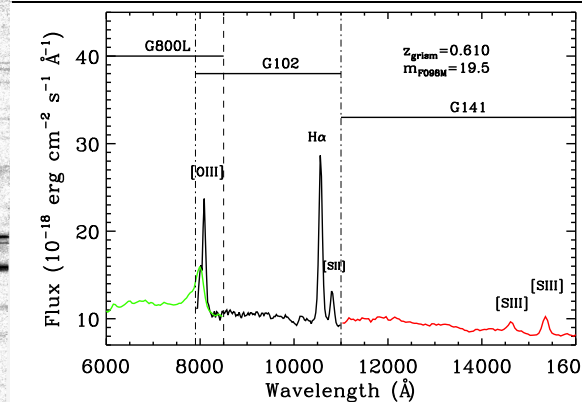
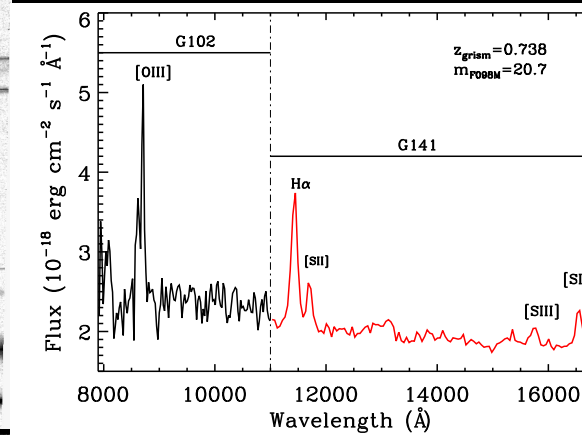
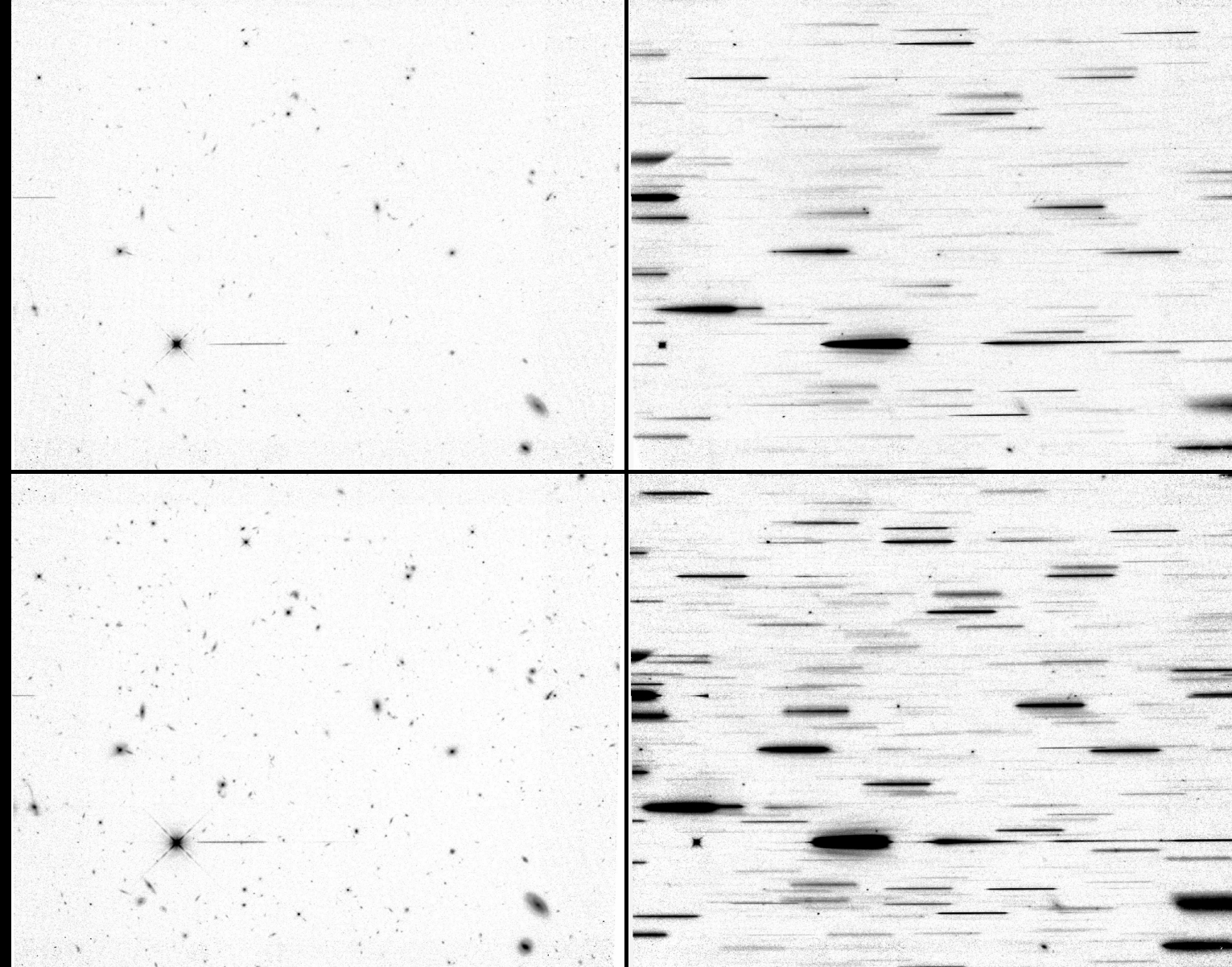


What do the 6 possible  $z \simeq 9$  and single  $z \gtrsim 10$  HUDF candidate mean?

Integrate Schechter LFs with  $\alpha(z)$ ,  $\Phi^*(z)$  and  $M^*(z)$ :  $\lesssim 45\%$  sky-coverage by  $AB \lesssim 30$  objects (Koekemoer<sup>+</sup>13). Cosmic Variance  $\gtrsim 30\%$ .

For any  $\alpha(z \gtrsim 9-10)$ , implies  $M^*(z \gtrsim 10) \gtrsim -17.5$  mag (fainter!), so plan:

- (1) [Left] Webb “Medium-Deep” Fields (**WMDF**) ( $10 \times 4 \times 2 \text{ h RAW}$ ): Expect few  $z \simeq 10-12$  objects to  $AB \lesssim 30$  mag, so plan lensing targets.
- (2) [Middle] Webb Deep Field (**WDF**) ( $4 \times 25 \text{ h 7-filt NIRCcam GTO}$ ): Expect 8–25 objects at  $z \simeq 10-12$  to  $AB \lesssim 31$  mag.
- (3) [Right] Webb UltraDeep Field (**WUDF**) ( $4 \times 150 \text{ h; NIRCcam DD?}$ ): Expect 30–90 objects to  $AB \lesssim 32$  mag, many more if lensing targets.



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  $\mu\text{m}$ .

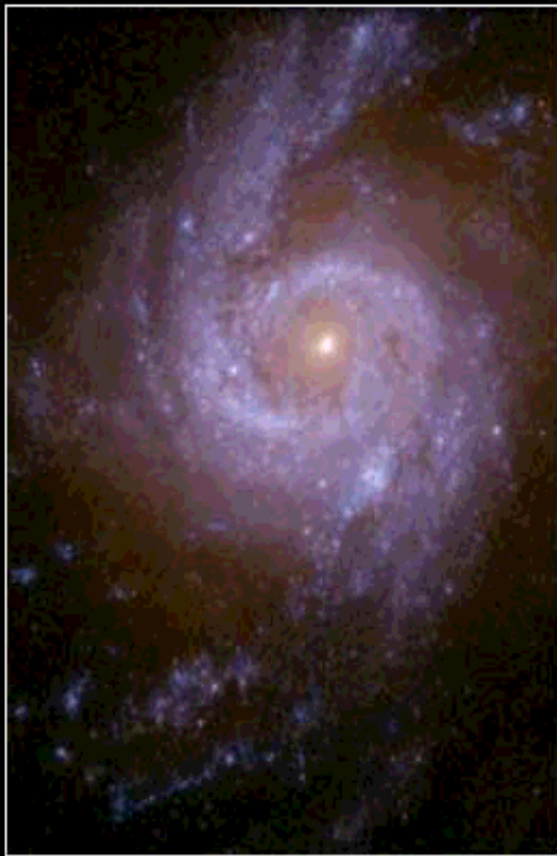


## (4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

NGC 3310

ESO0418-008

UGC06471-2



### Ultraviolet Galaxies

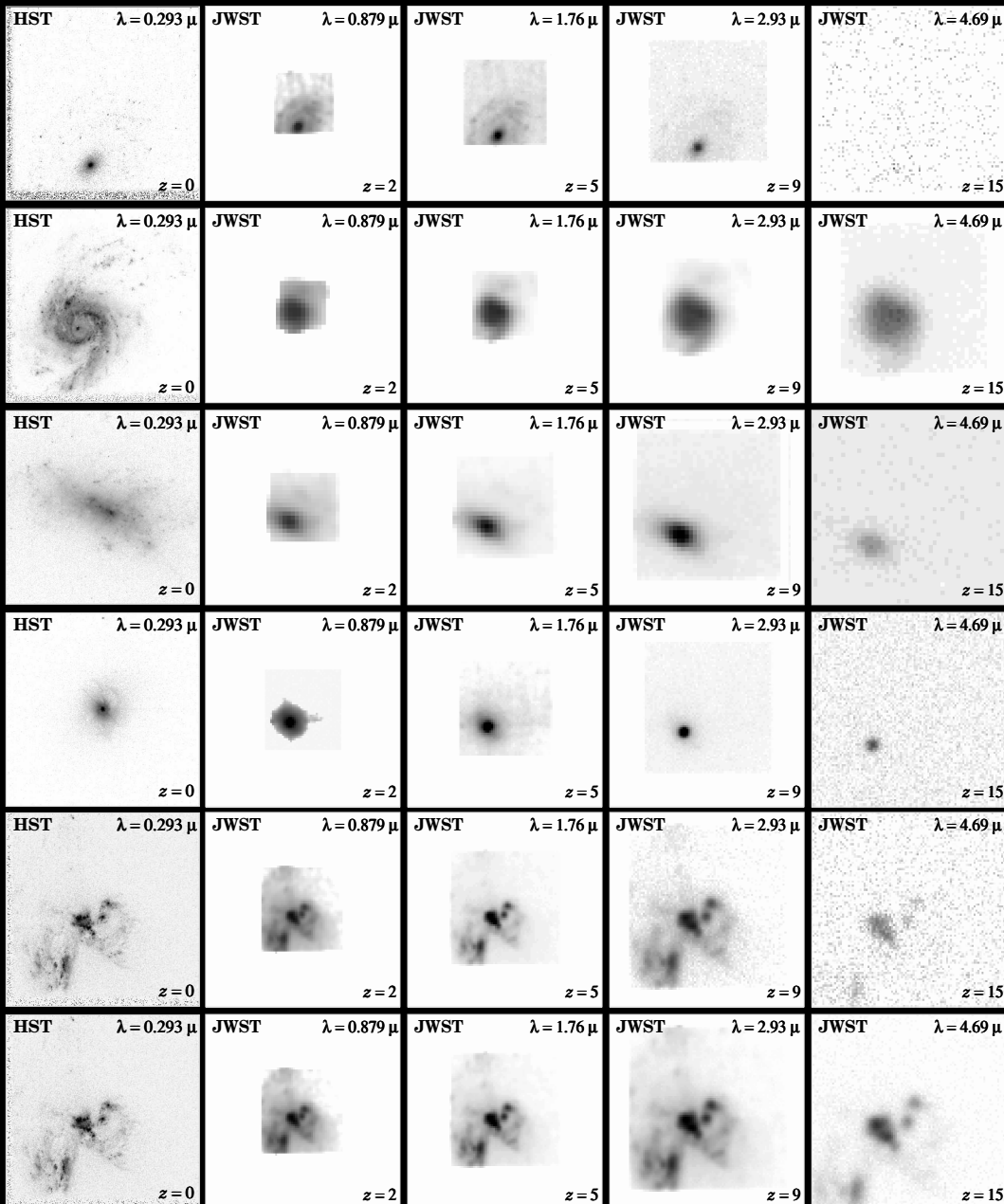
HST • WFPC2

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.



