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

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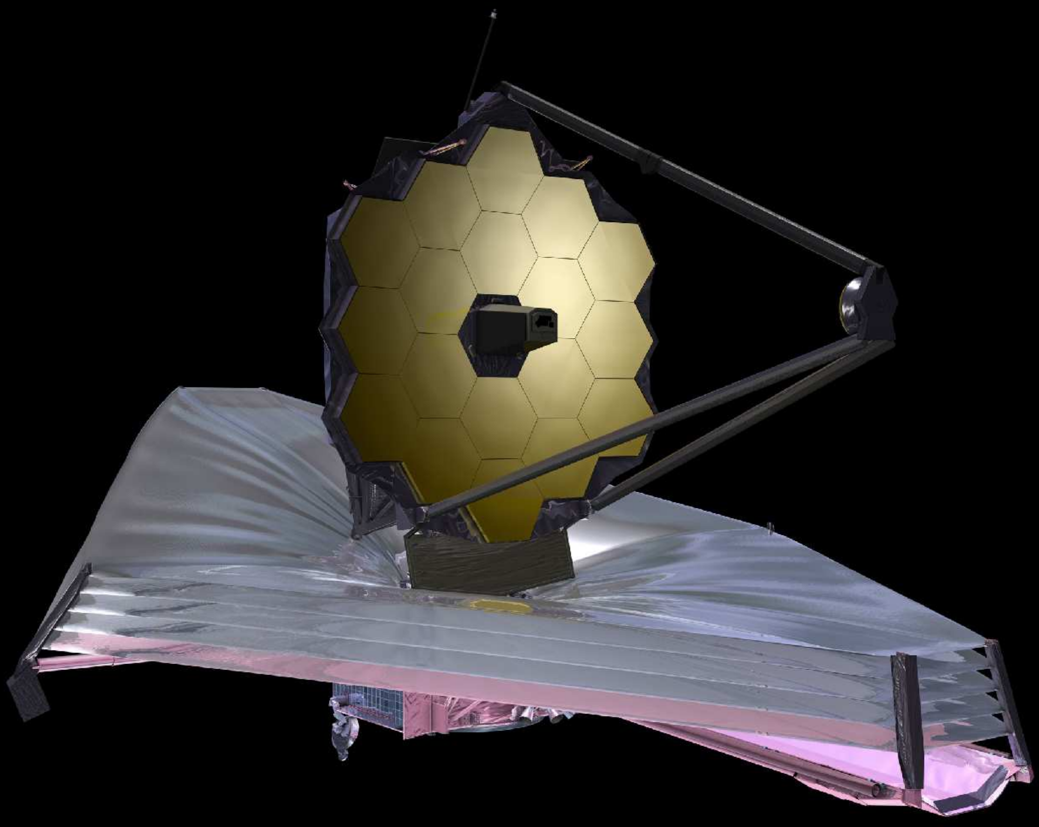


*Review Talk at the "18$^{th}$ Paris Cosmology Colloquium 2014: Latest News from the Universe"*

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

# Outline

- (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.

ARIZONA STATE UNIVERSITY

Sponsored by NASA/HST & JWST

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

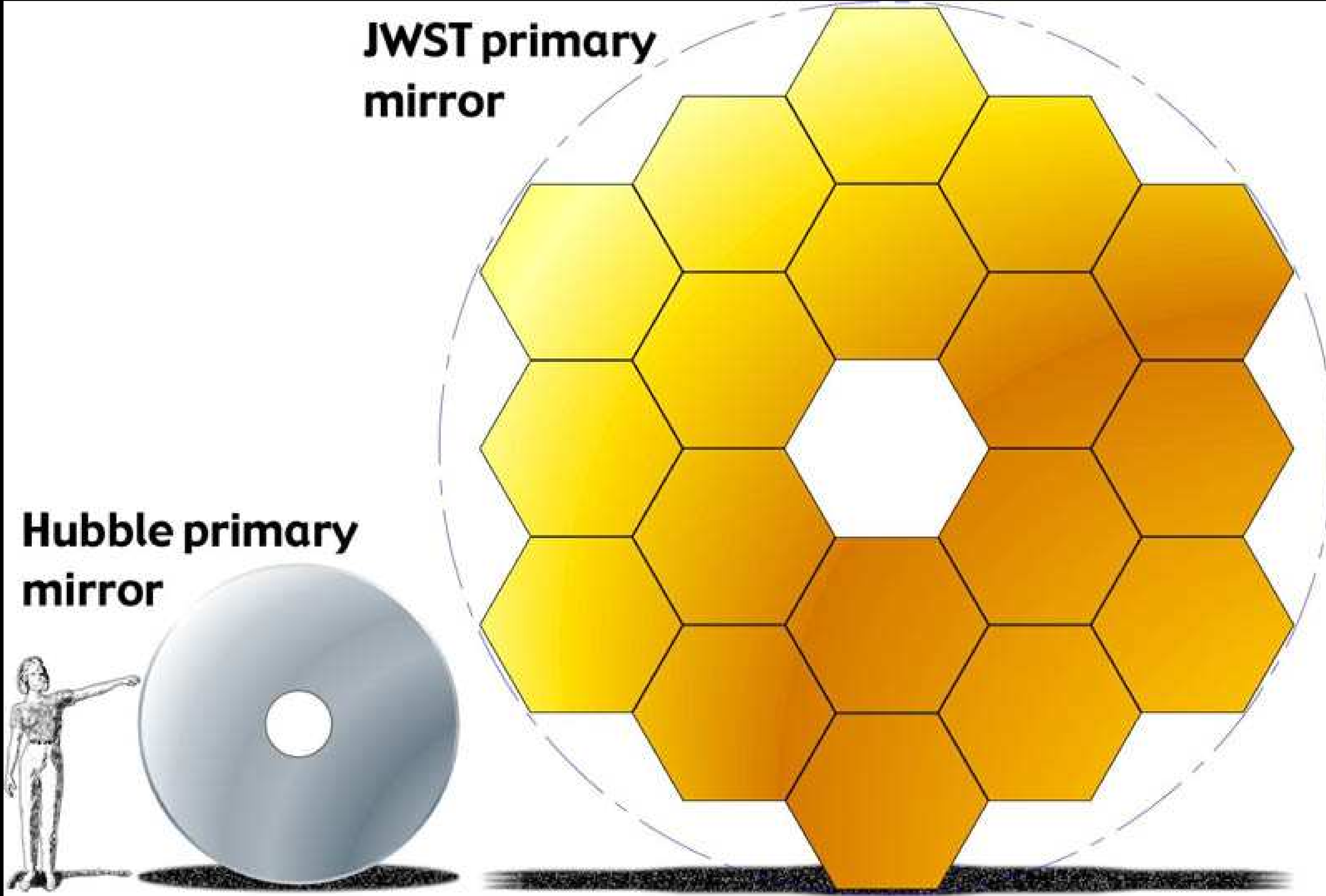
Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/paris14hstjwst.pdf`

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

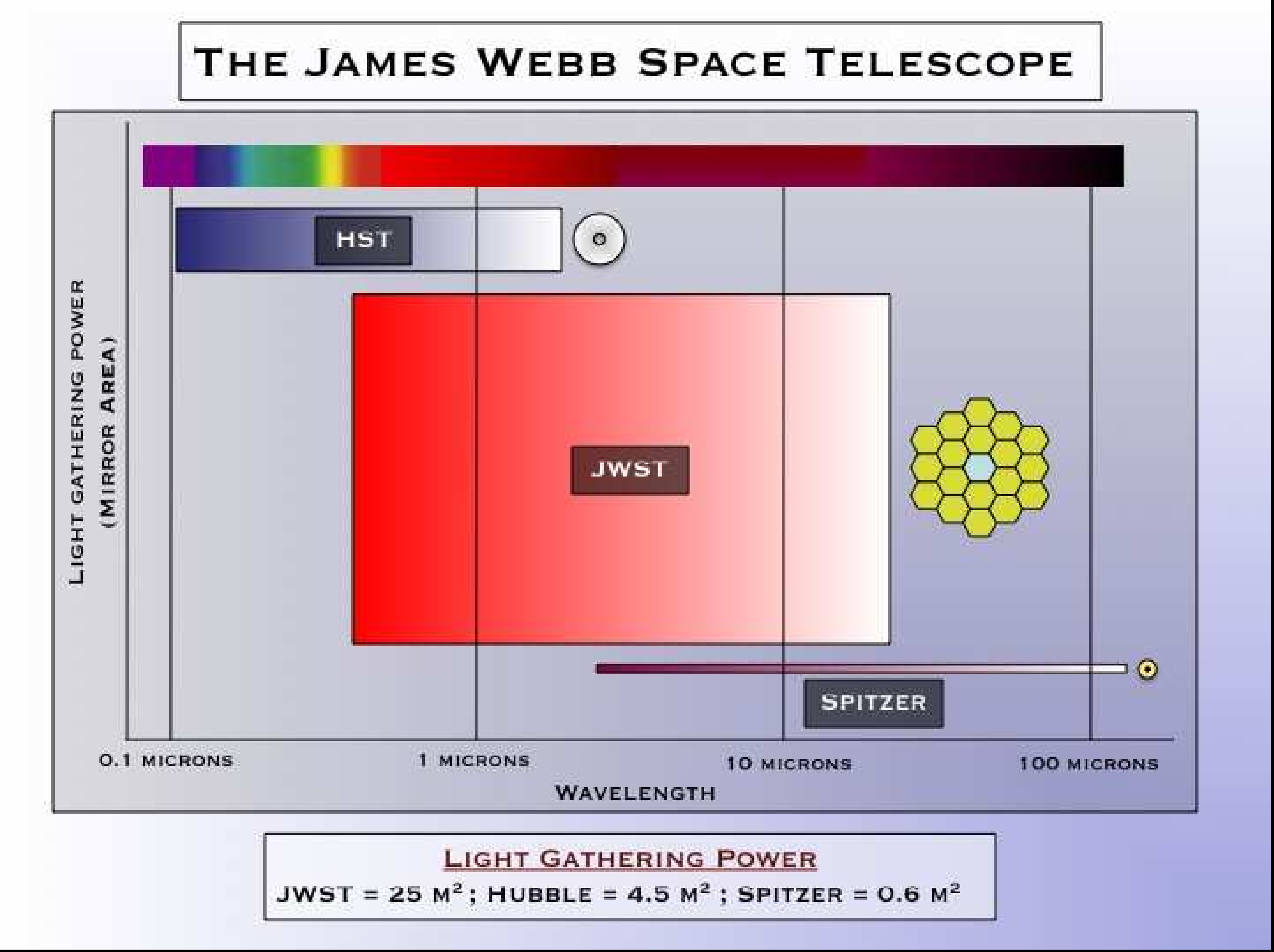
James E. Webb (1906–1992) — Second NASA Administrator

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

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



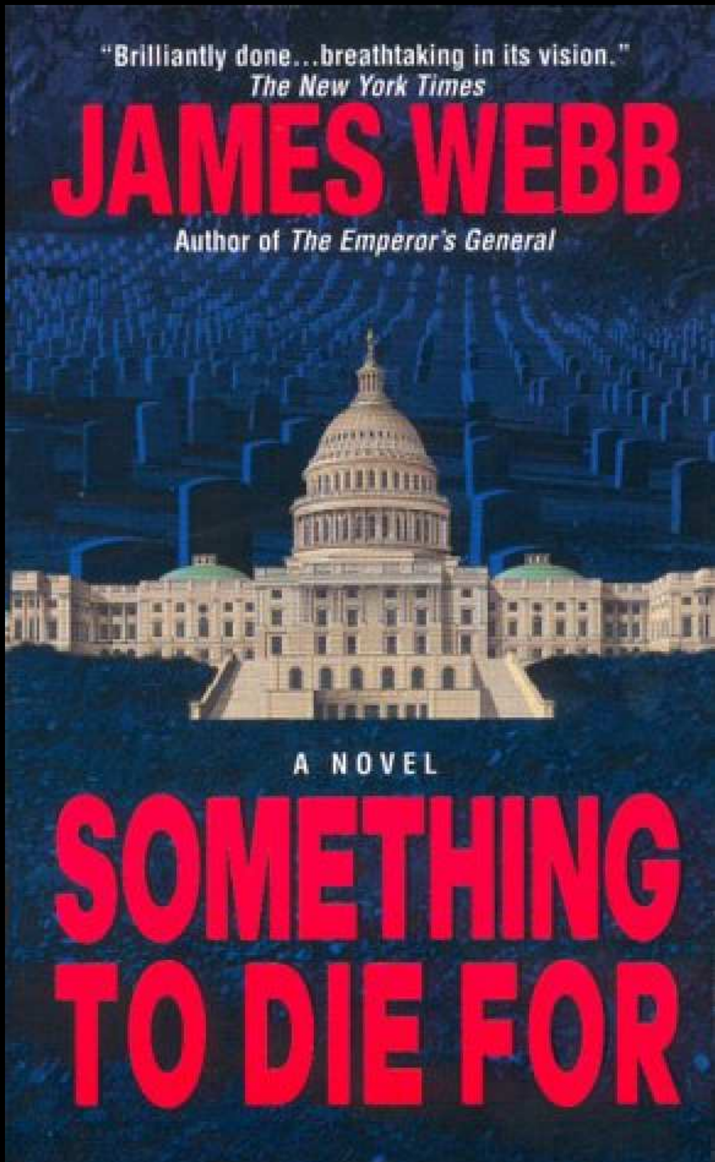

JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.




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

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

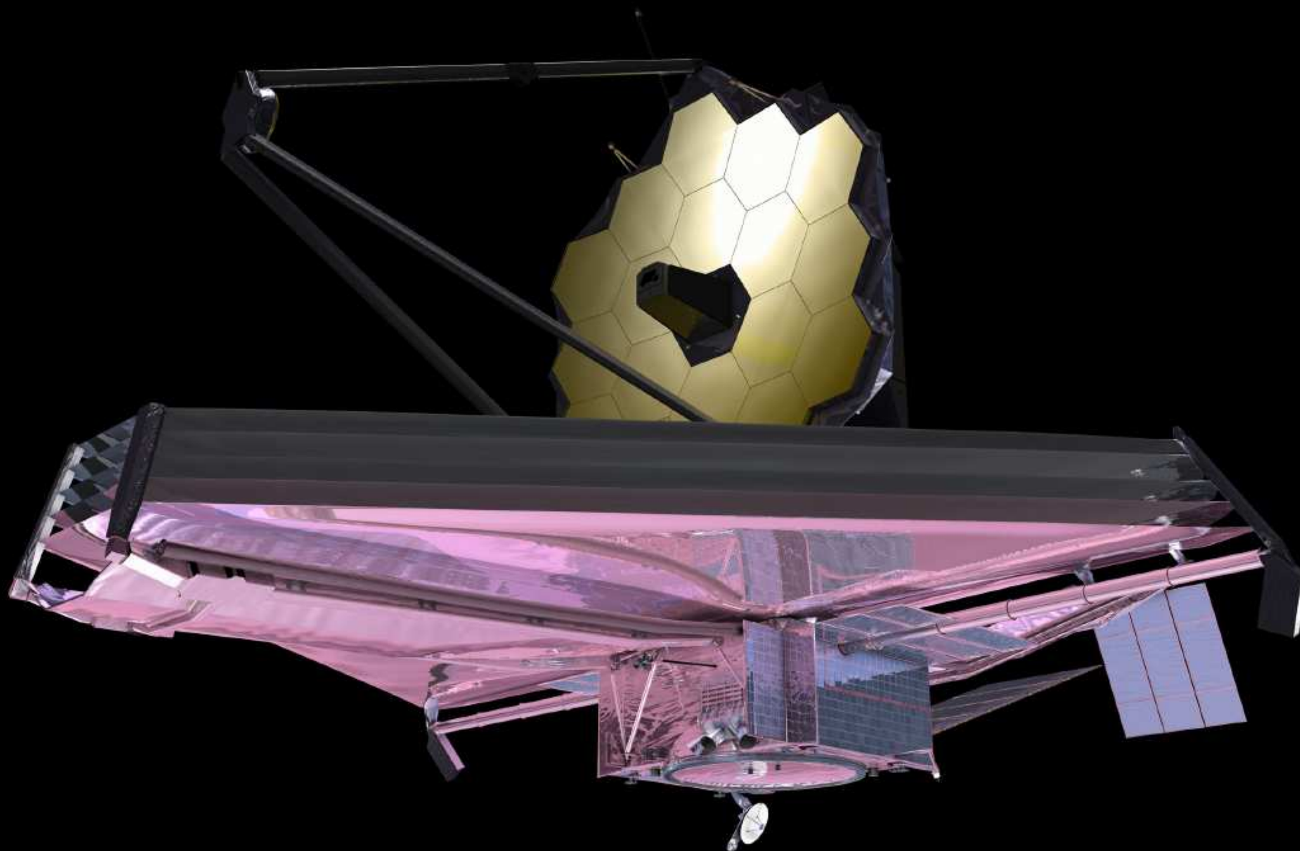
# (1) Brief Update of the James Webb Space Telescope (JWST).




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

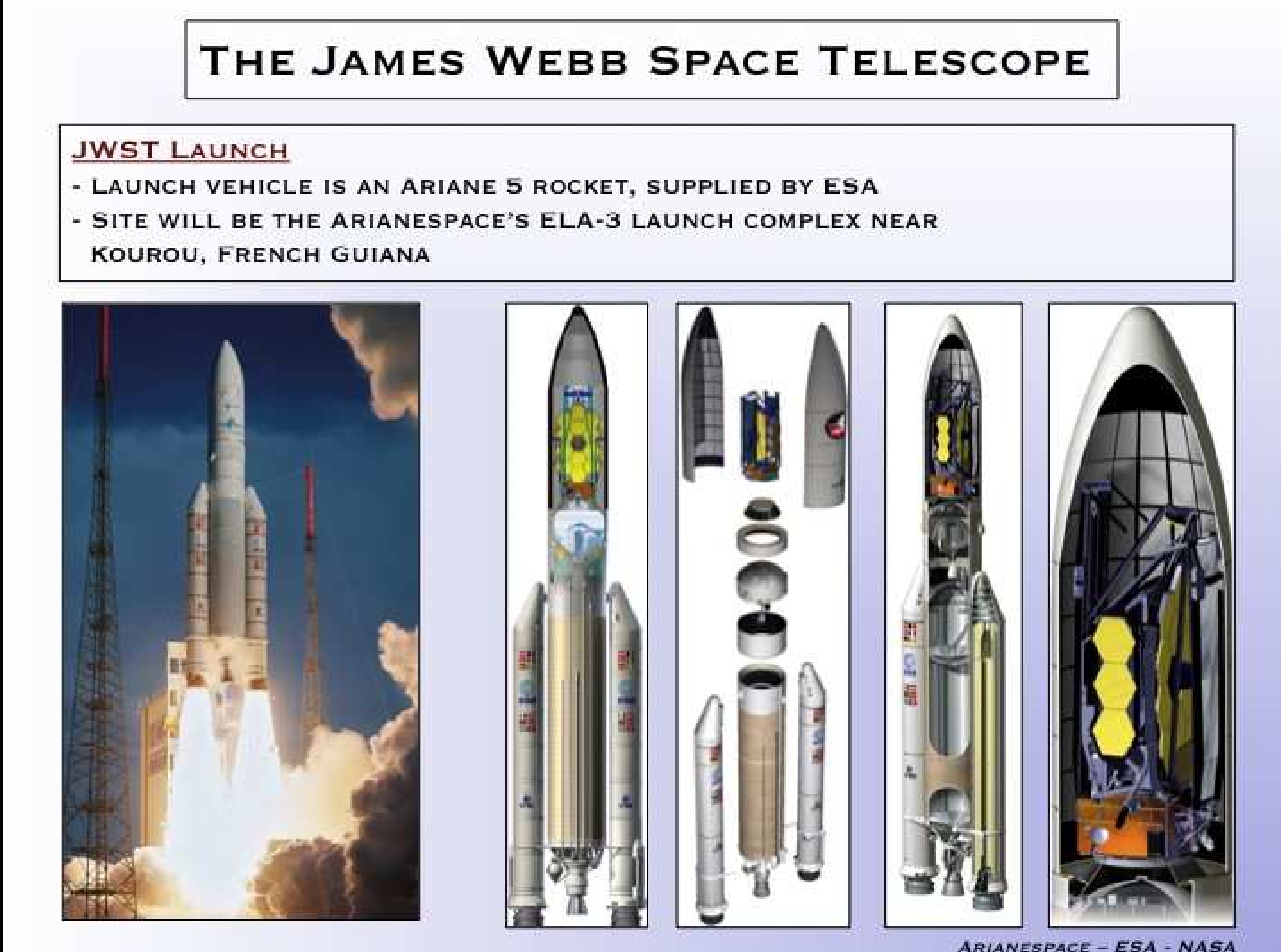
(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007.

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



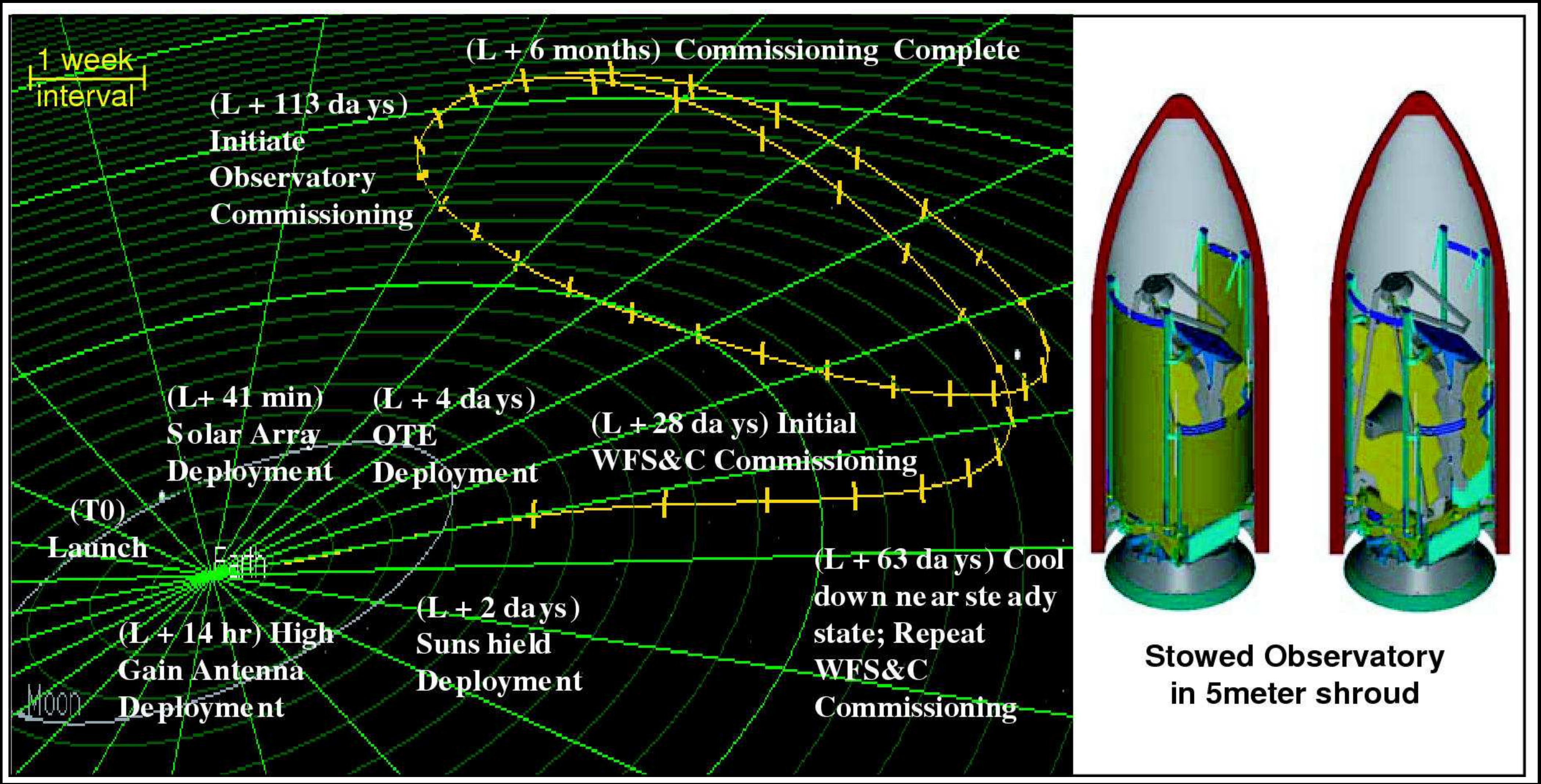
• A fully deployable 6.5 meter (25 $m^2$) segmented IR telescope for imaging and spectroscopy at 0.6–28 $\mu$m wavelength, to be launched in Fall 2018.

• Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.



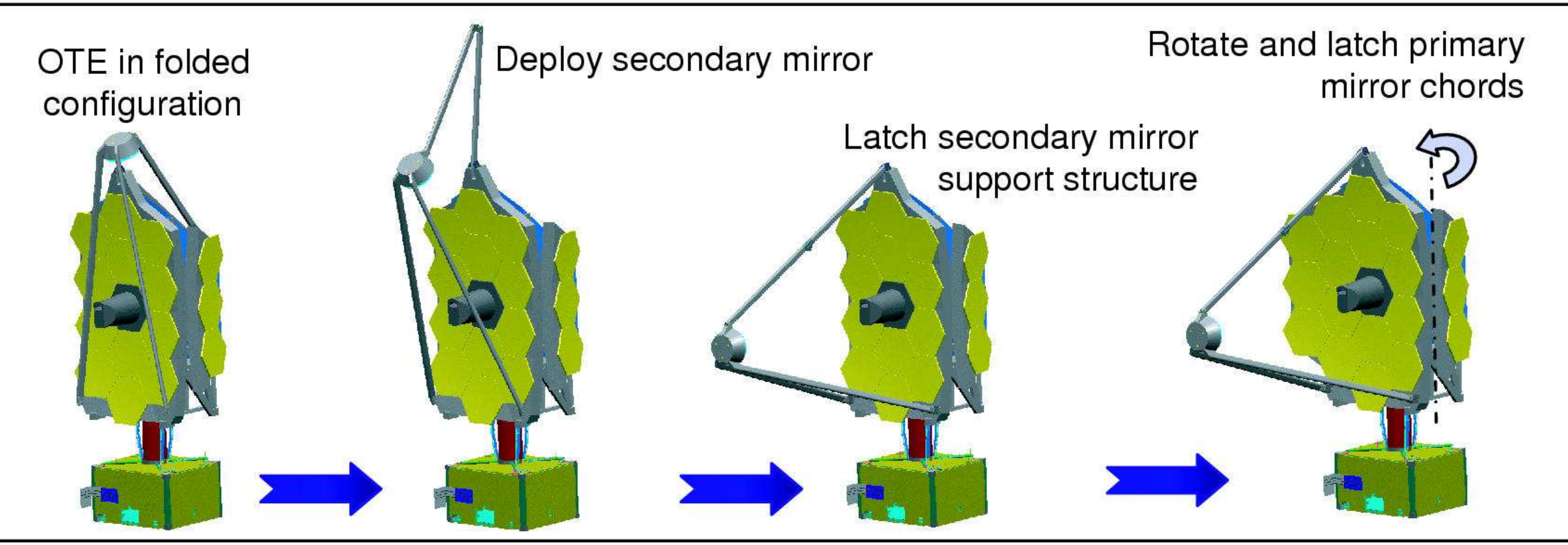

• The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

# (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.

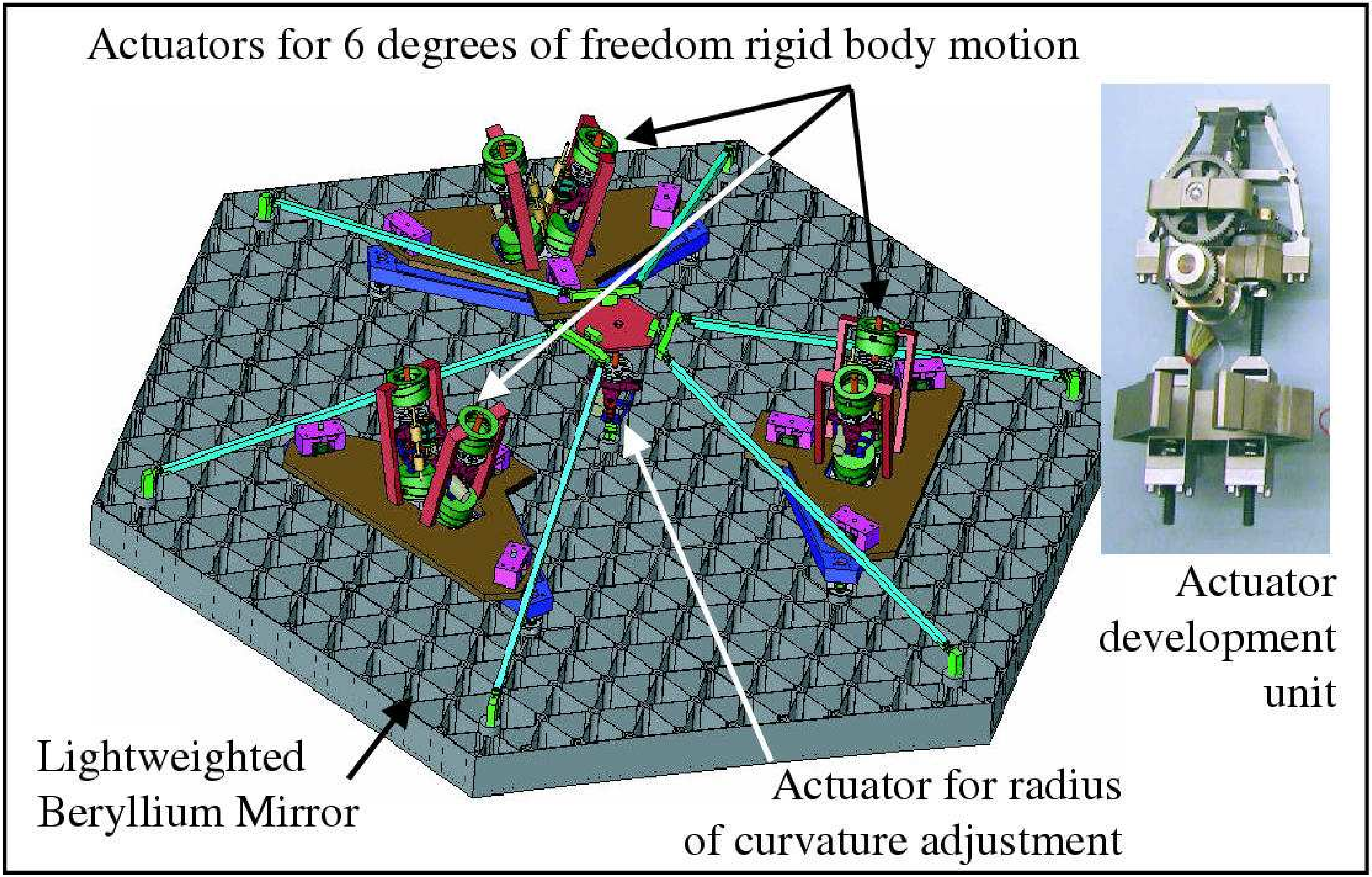
• (1b) How will JWST be automatically deployed?




• 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).

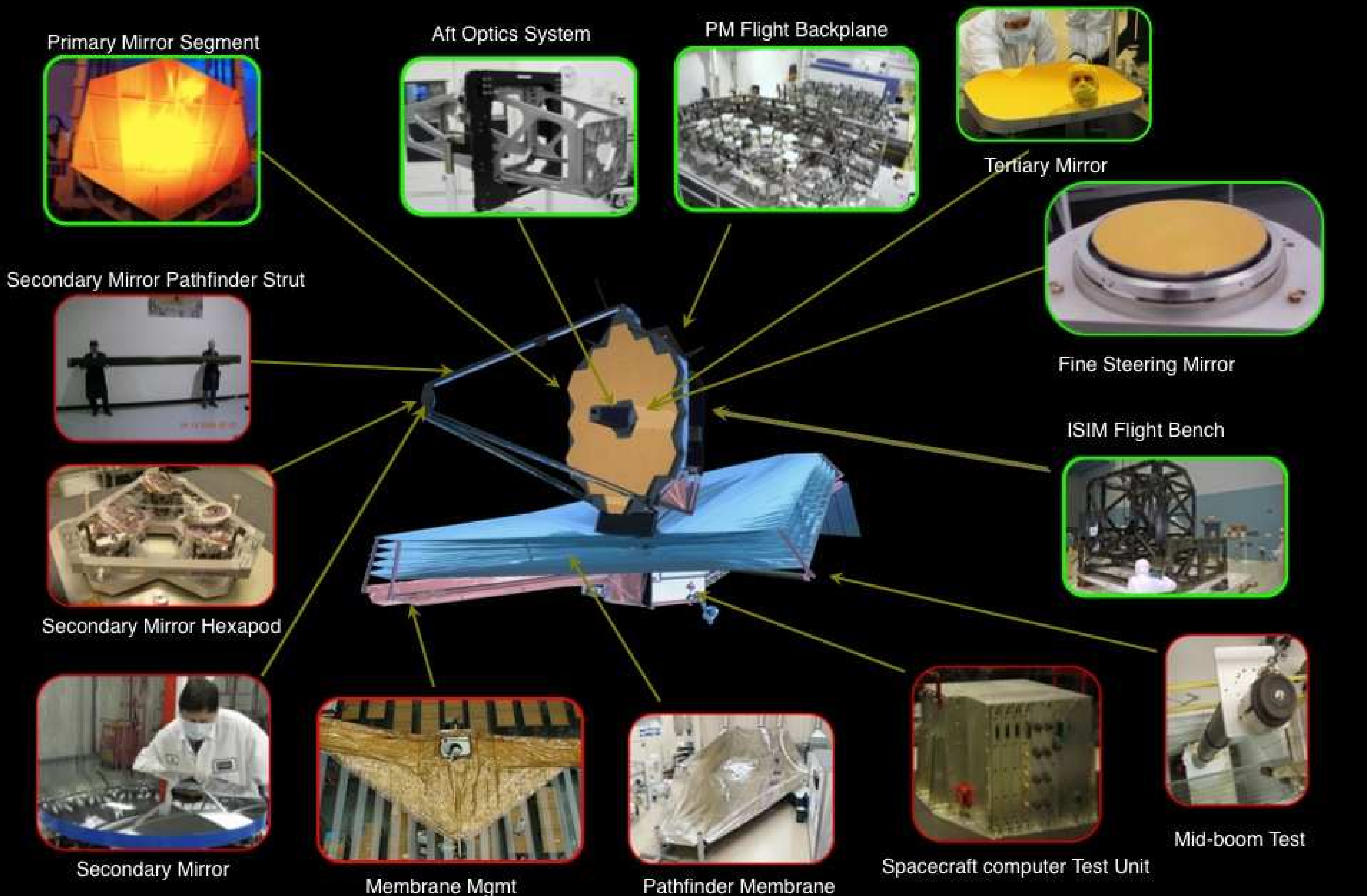
• Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.




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

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

# JWST Hardware Status

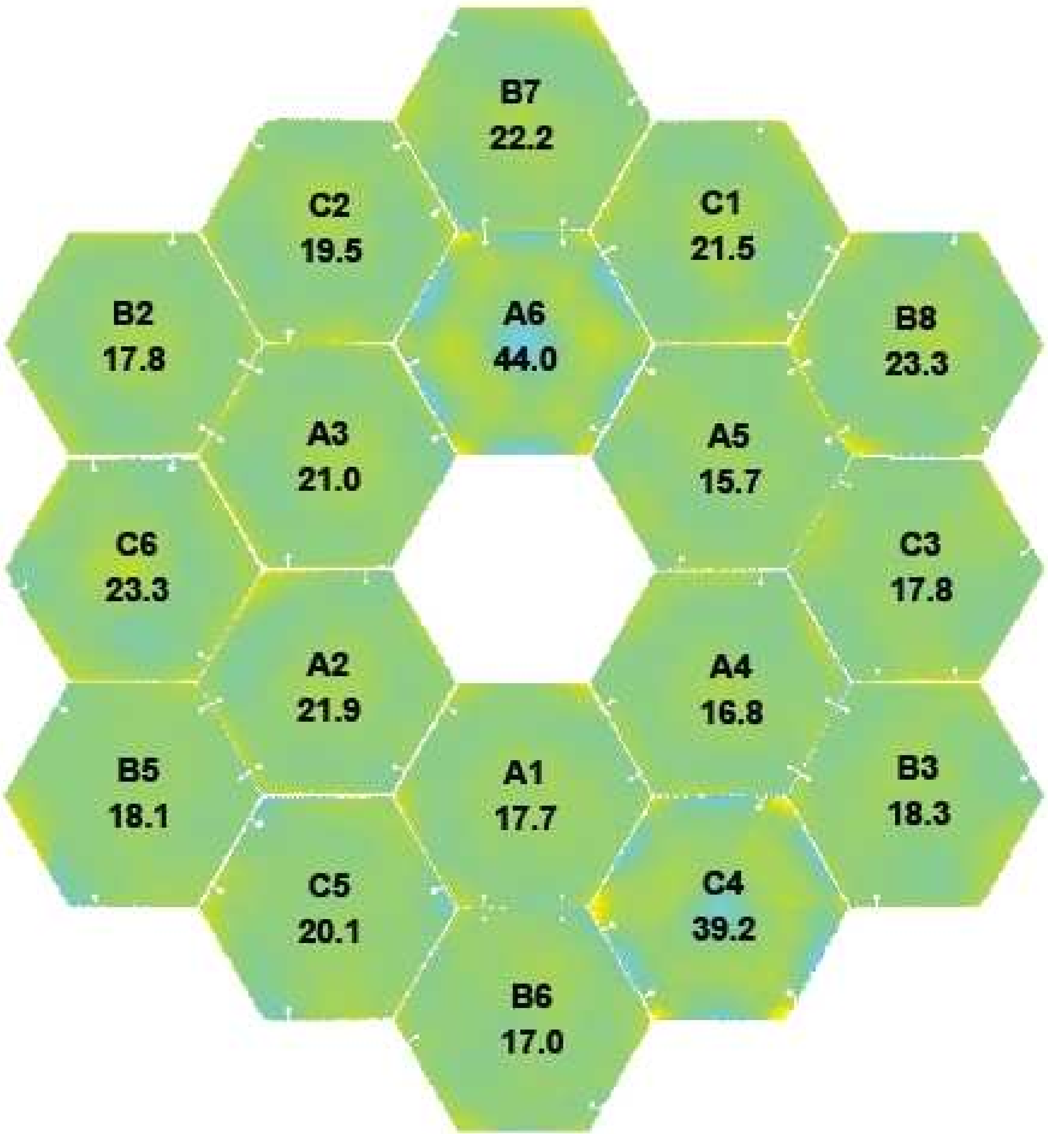



July 2014: $\gtrsim$97.4% of launch mass designed and built ($\gtrsim$60% weighed).

# Mirror Acceptance Testing

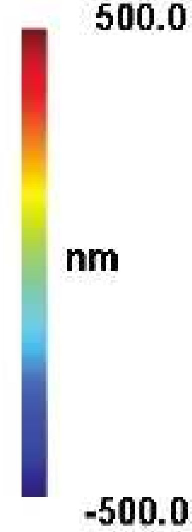

Ball

# Primary Mirror Composite




RMS: 23.2 nm

PV: 515.5 nm



# Mirror Status

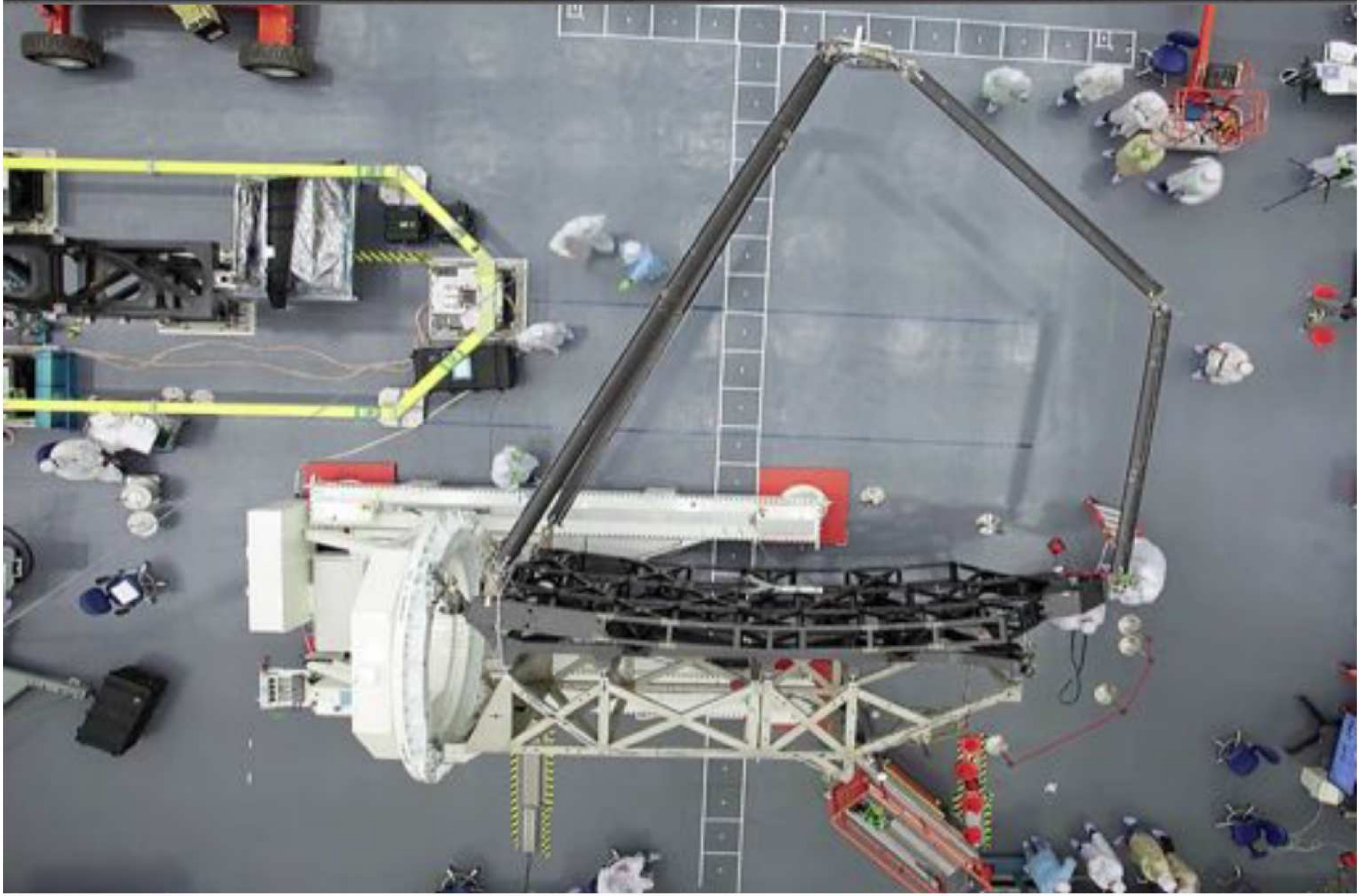
- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC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



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

**PROJECT STATUS:** November 2013

# 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.

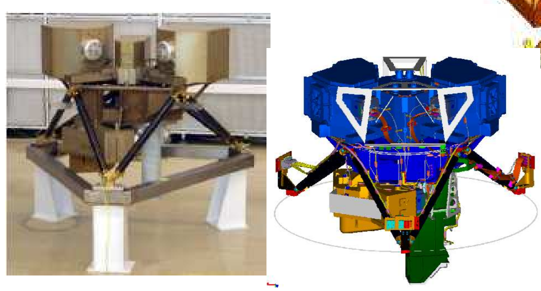
## Instrument Overview

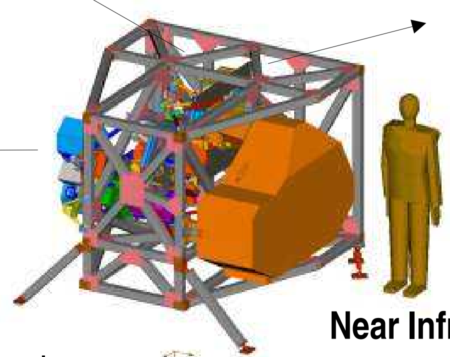
**Fine Guidance Sensor (FGS)**

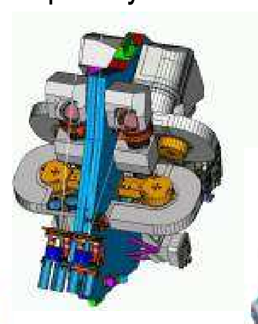
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

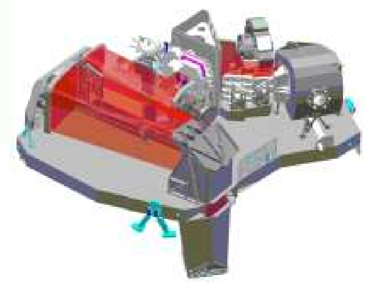
**Near Infra-Red Camera (NIRCam)**

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









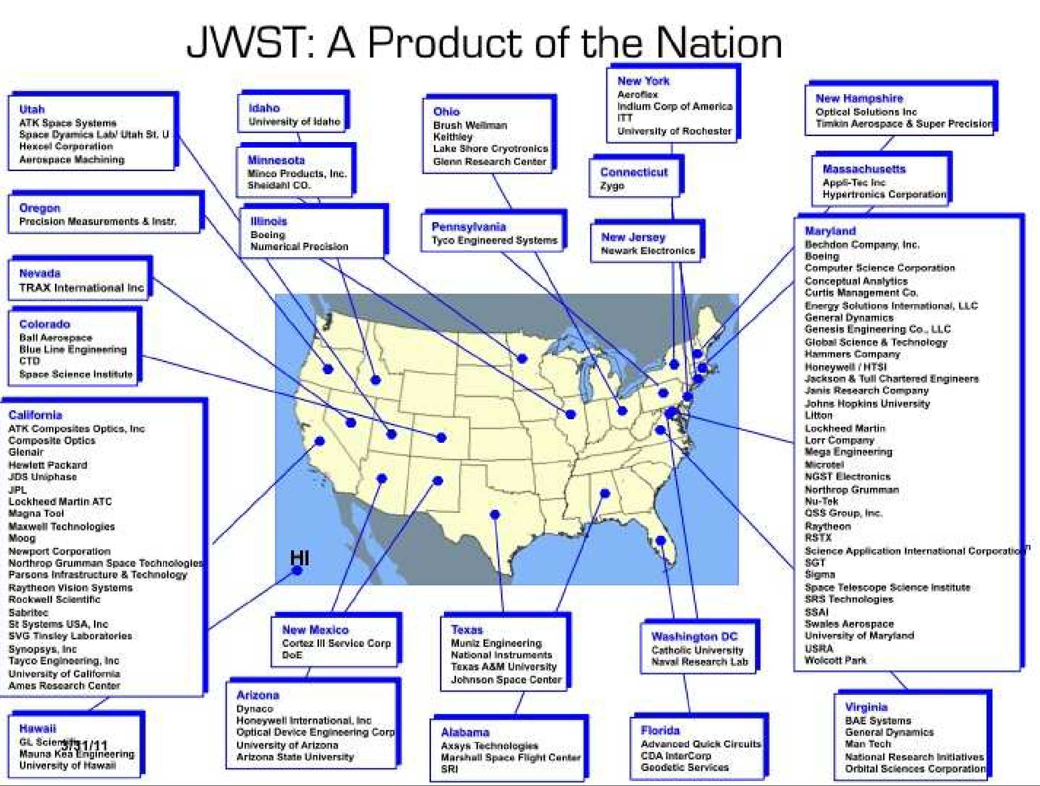
**Mid-Infra-Red Instrument (MIRI)**

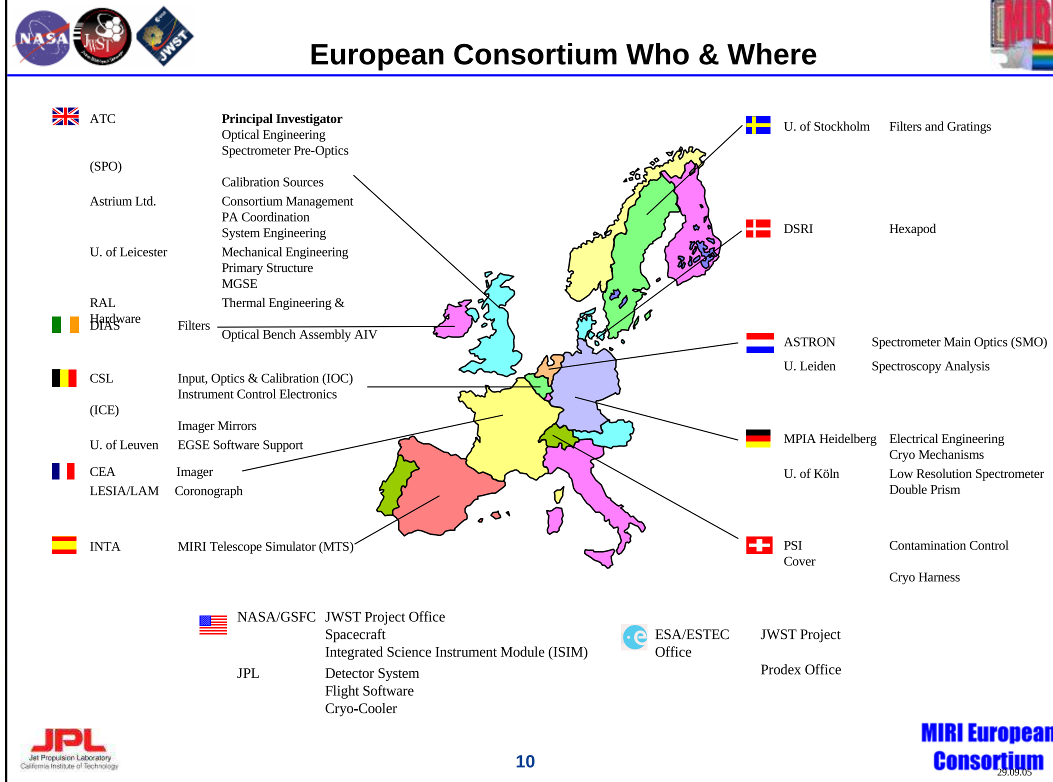
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

**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

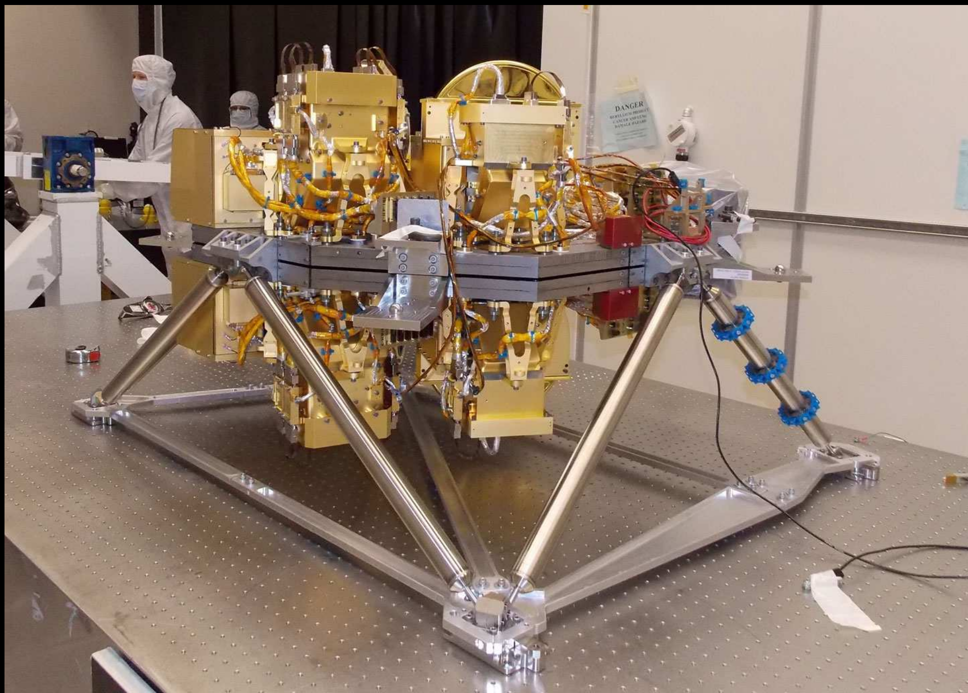
All delivered: MIRI 05/12; FGS 07/12; NIRCam 07/13, NIRSpec 9/13.



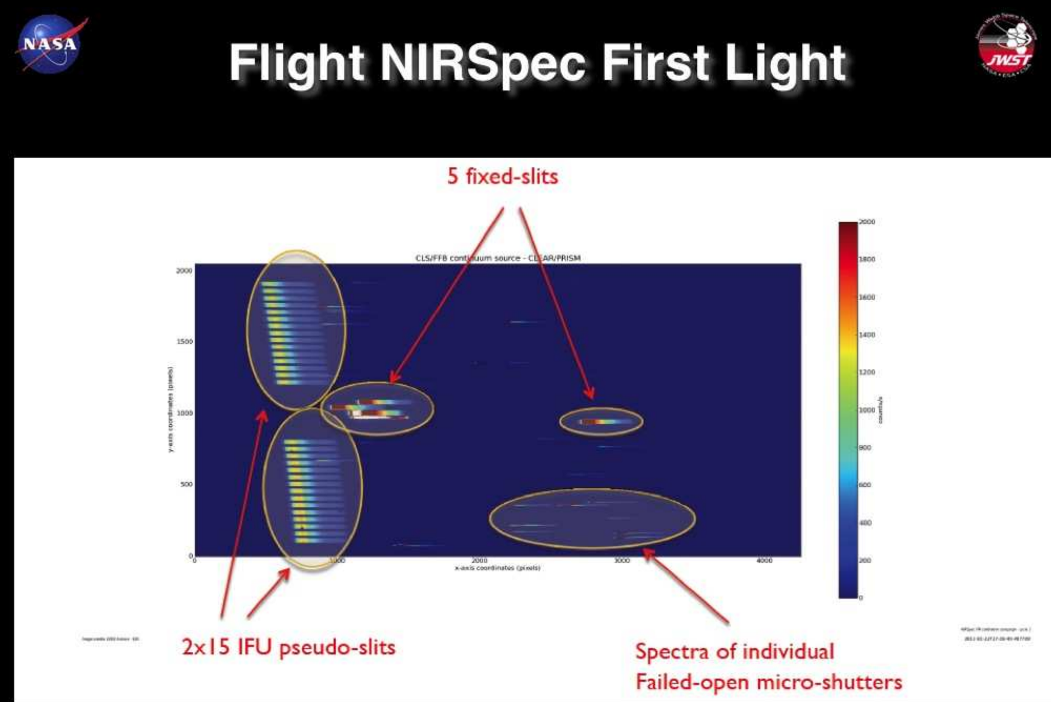

- JWST hardware made in 27 US States: $\gtrsim$97.4% of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

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



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

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

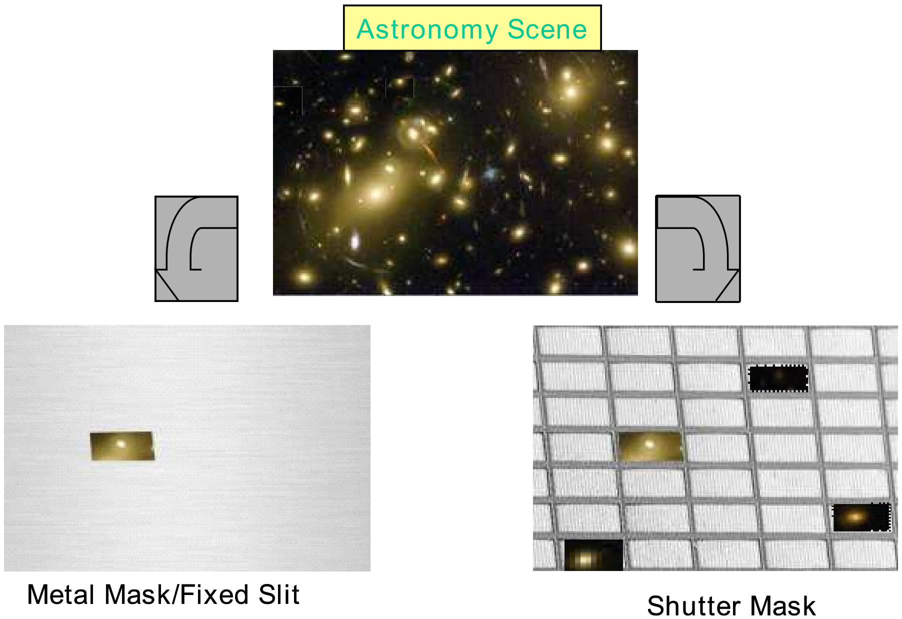



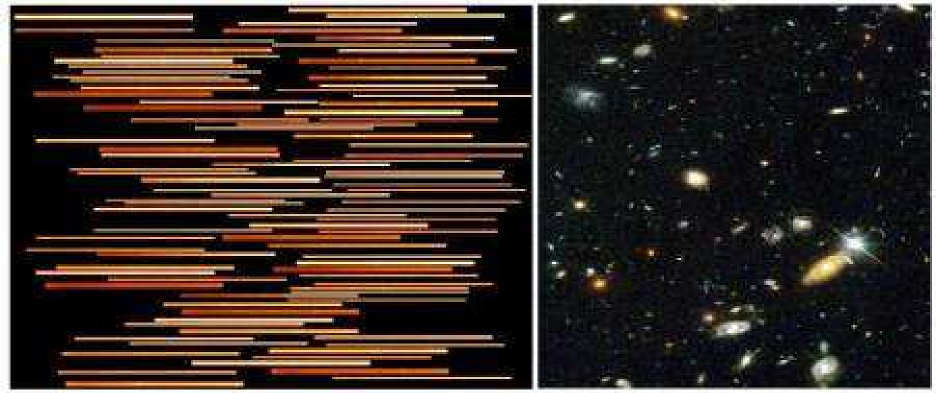

JWST's short-wavelength (0.6–5.0$\mu$m) spectrograph:

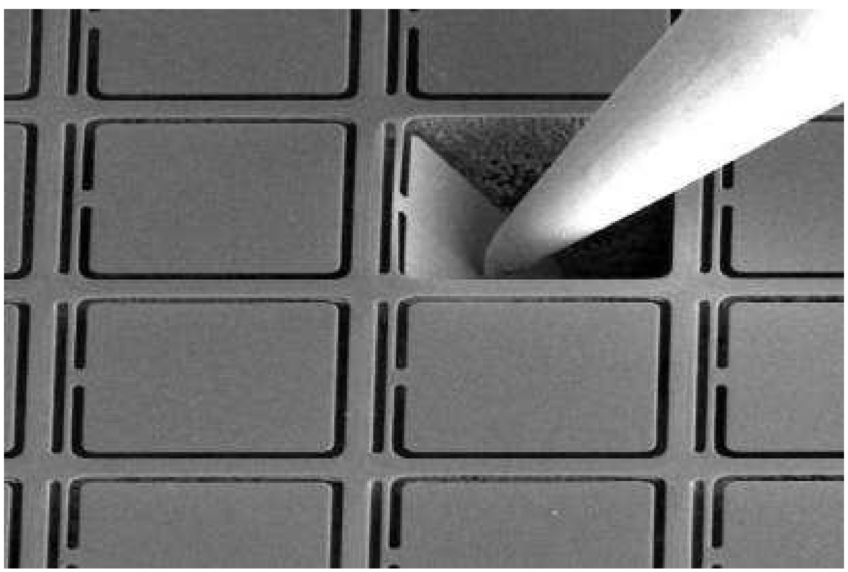
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

NIRSpec delivered to NASA/GSFC in Sept. 2013.

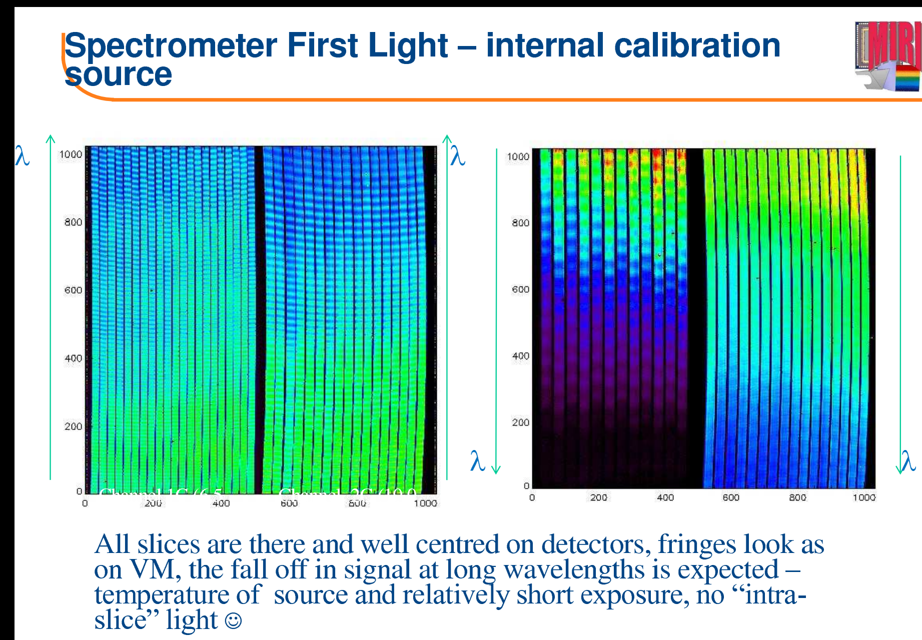
# Micro Shutters





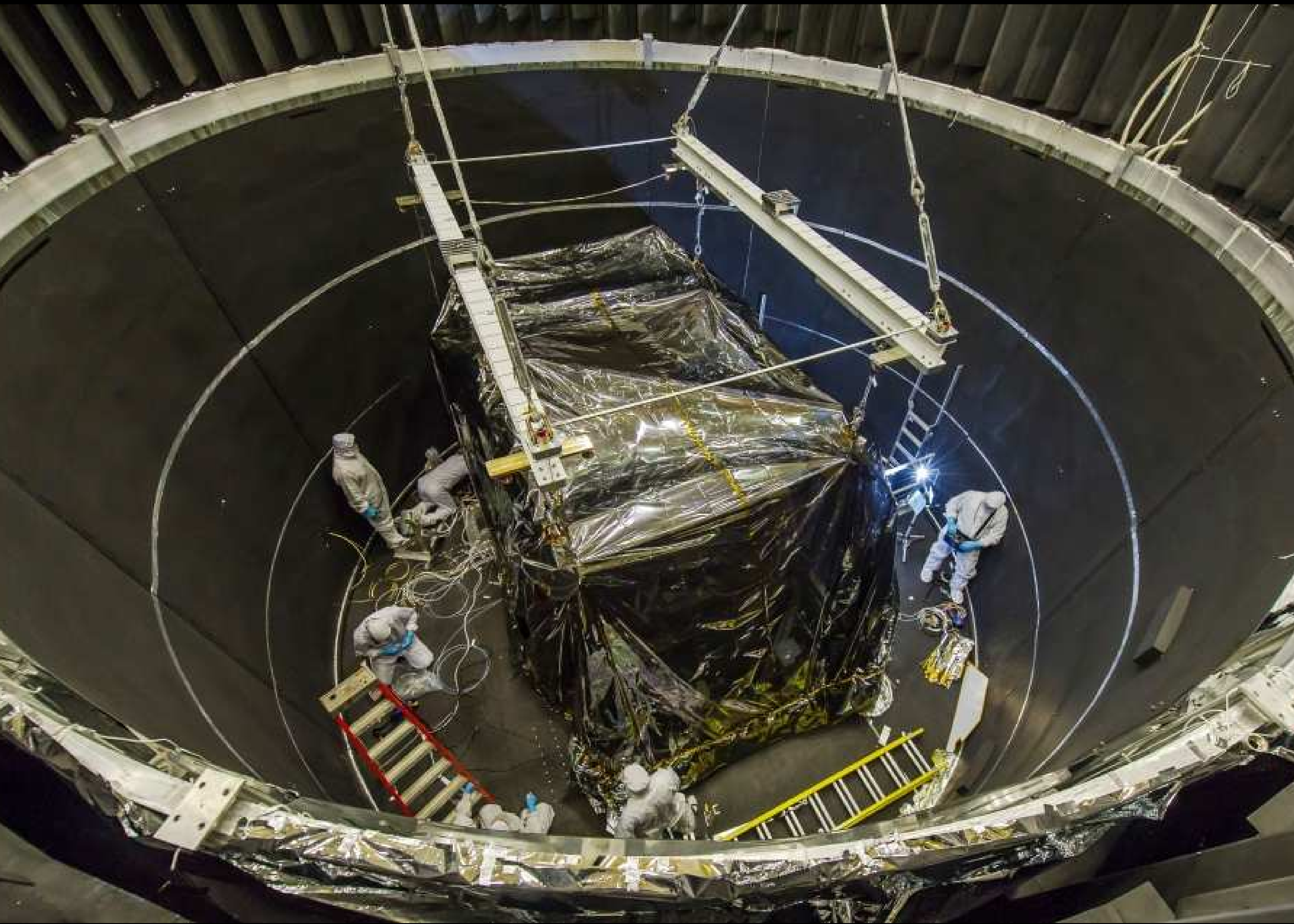
# Flight MIRI




JWST's mid-infrared (5–29$\mu$m) camera and spectrograph:

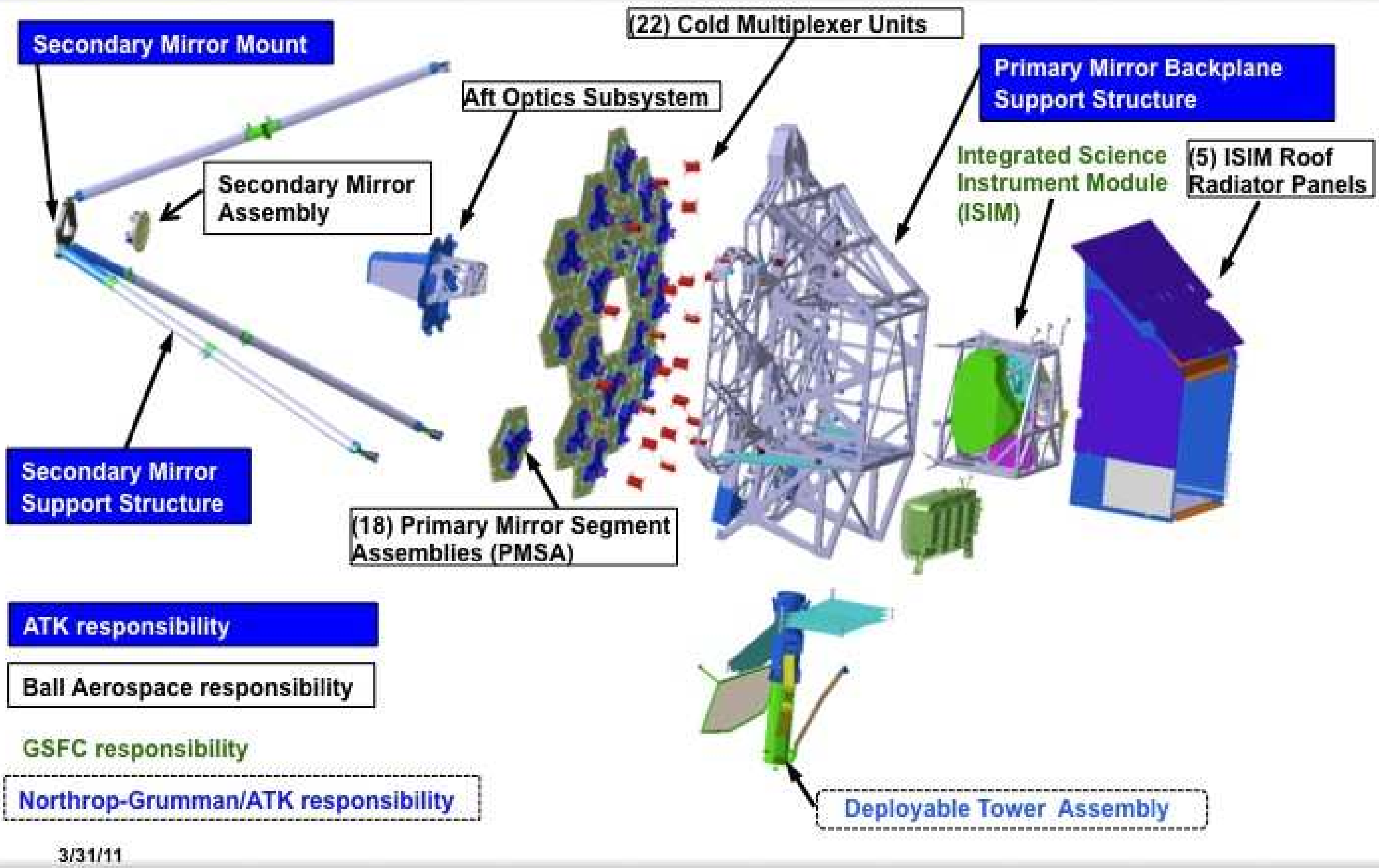
- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.

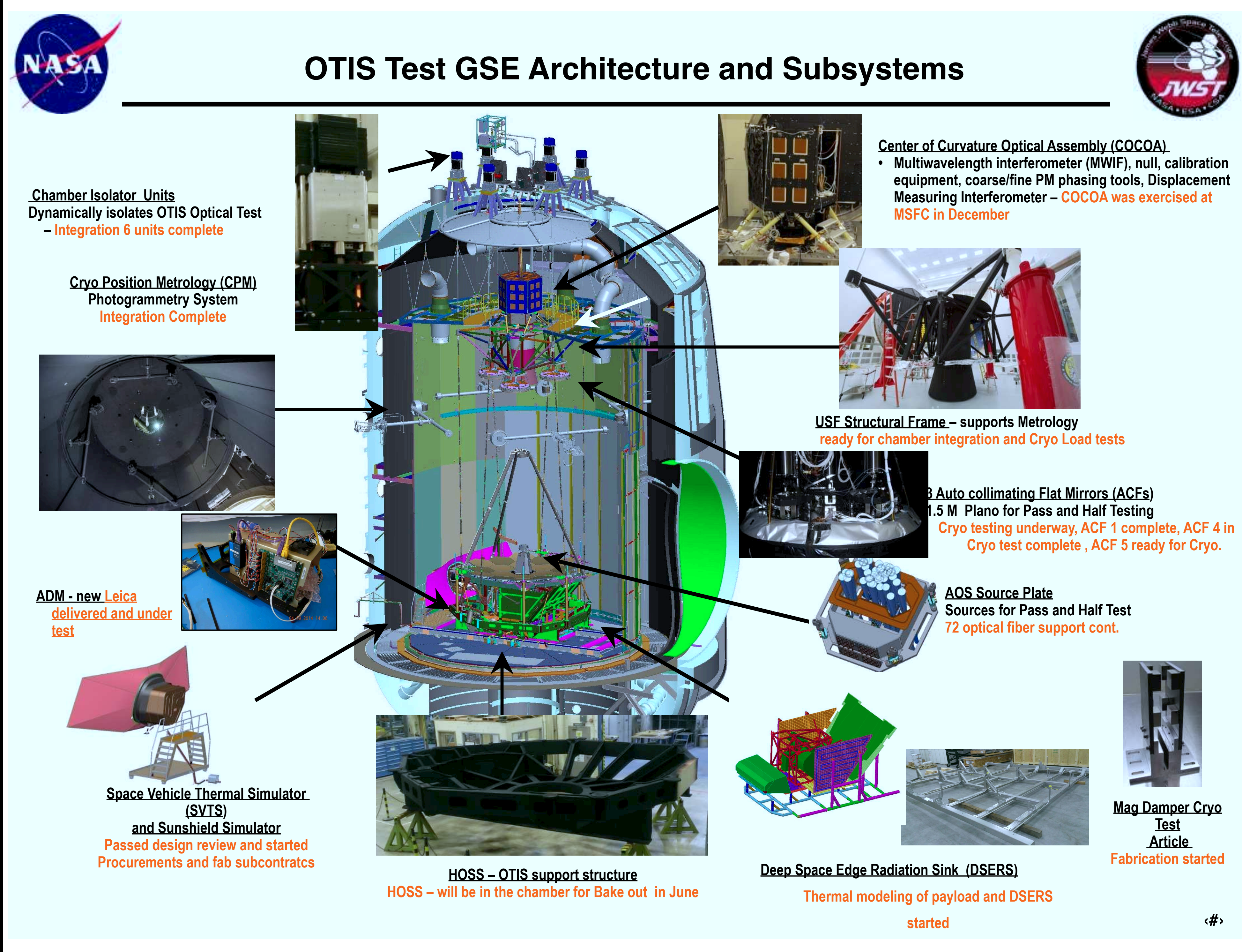


June 2014: Actual Flight ISIM (with all 4 instruments) lowered into OSIM.

# TELESCOPE ARCHITECTURE

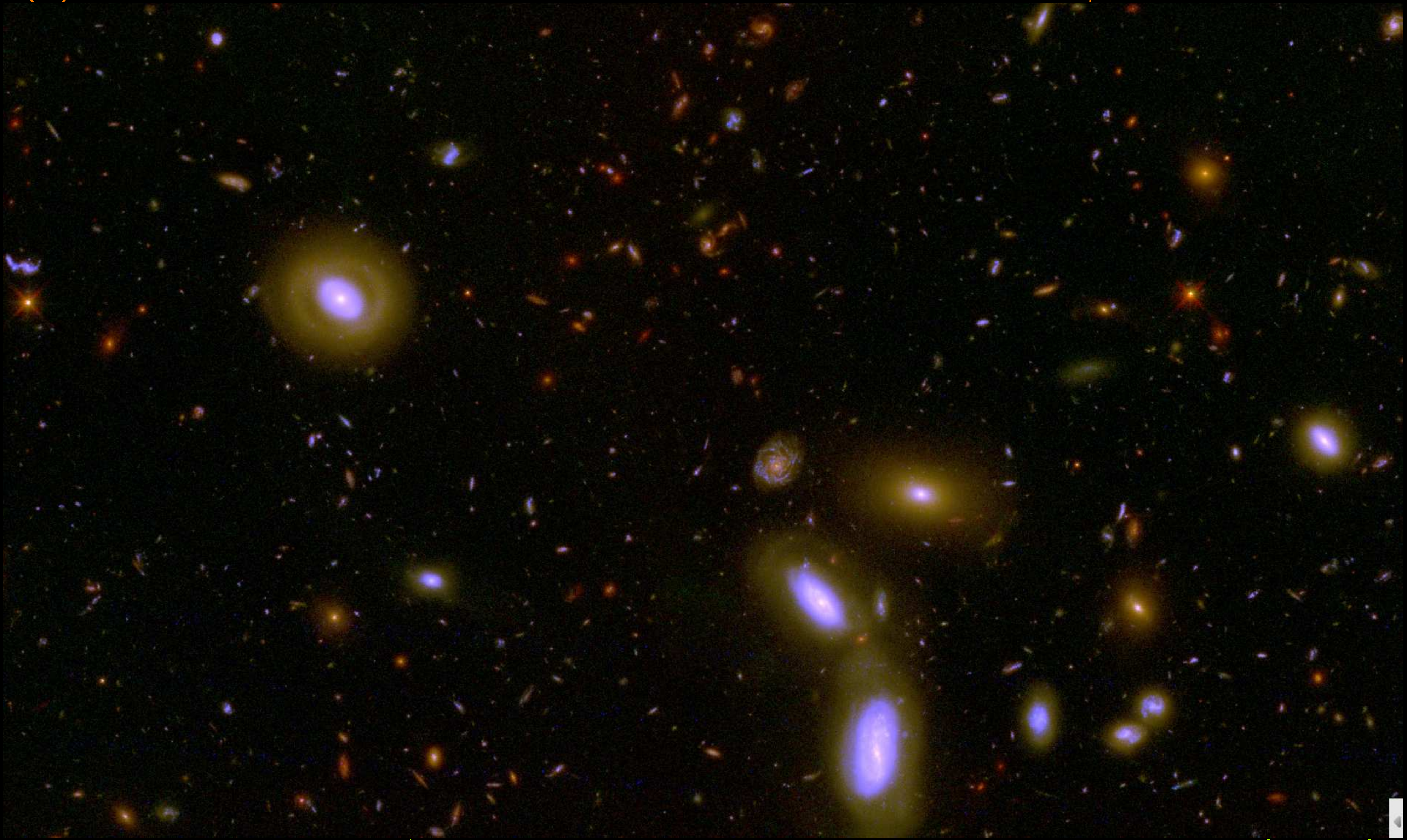



2014–2016: Complete system integration at GSFC and Northrop.




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

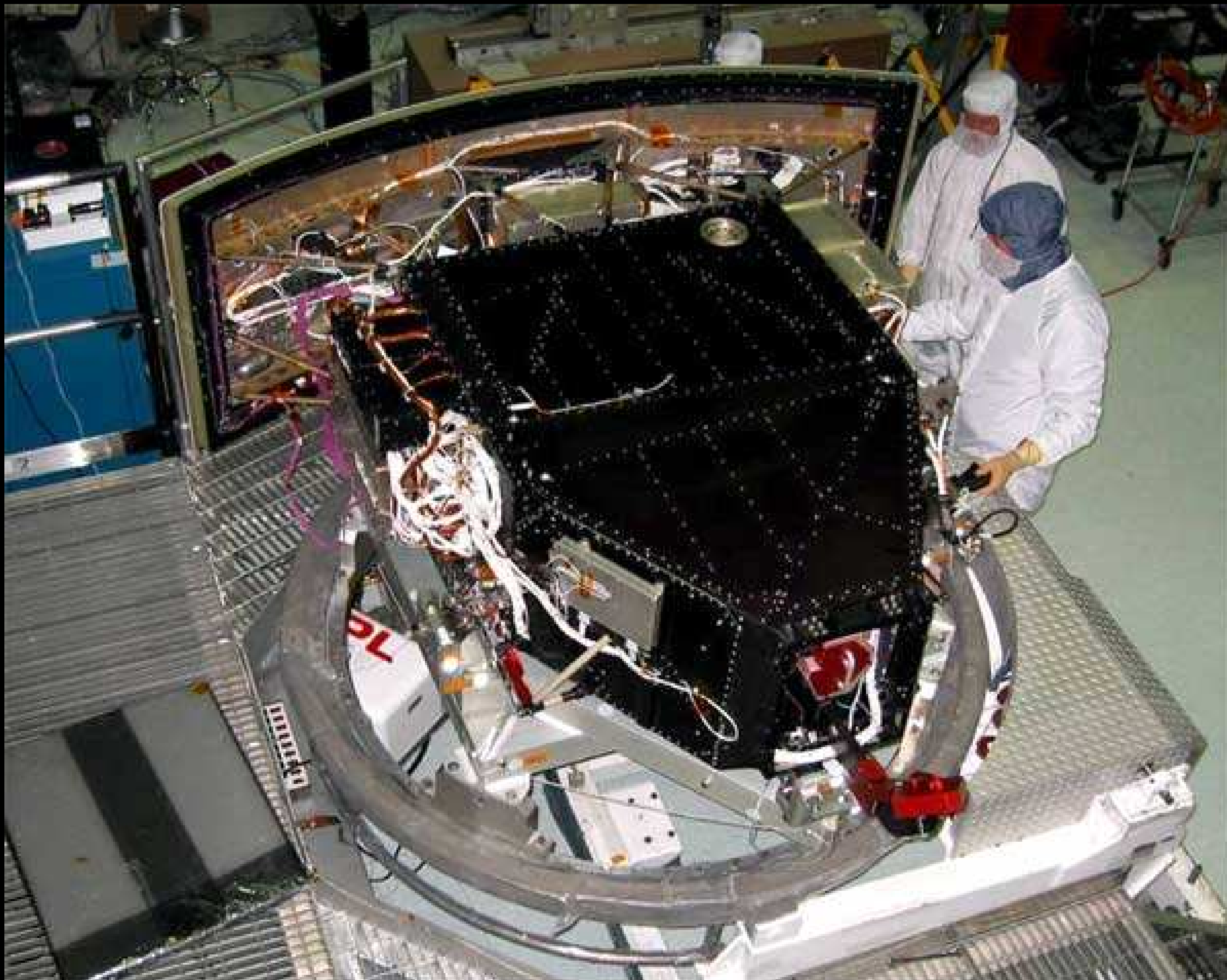
# (2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



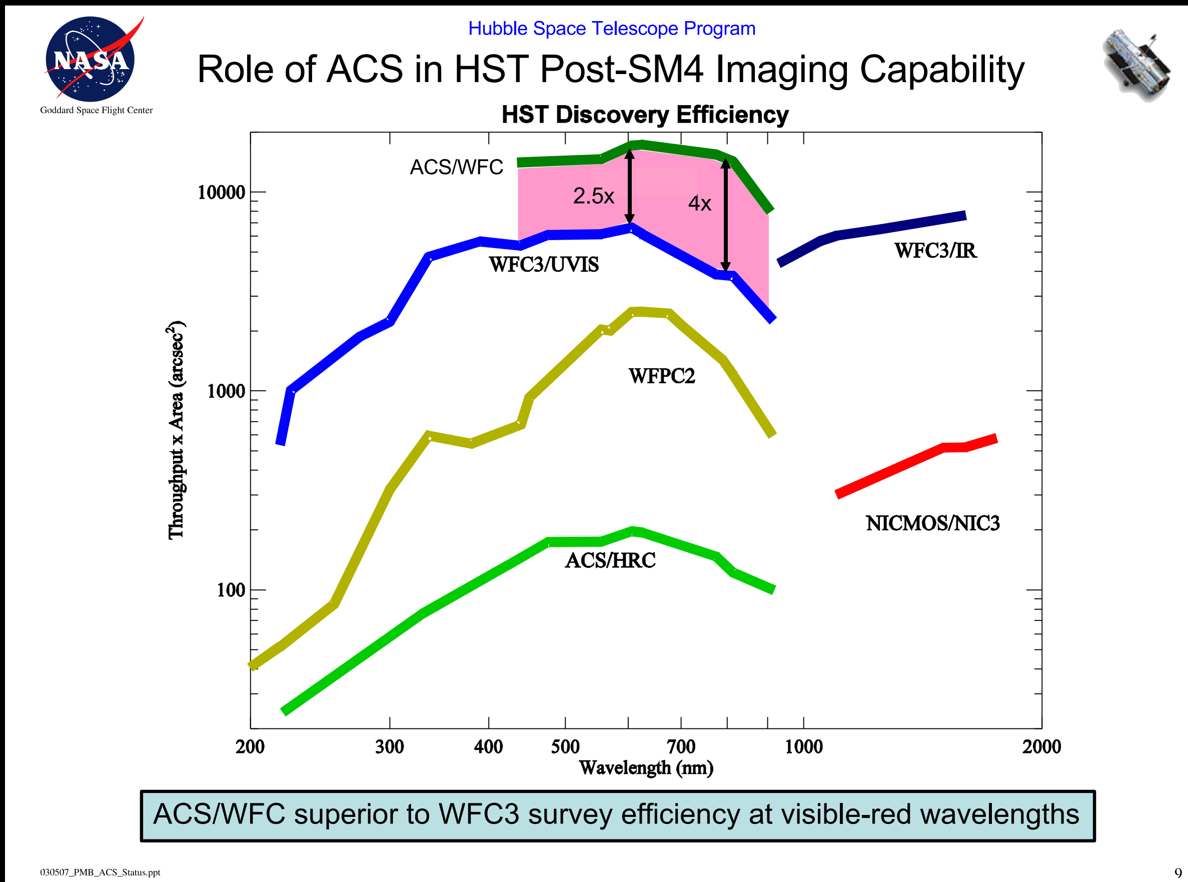
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-$\sigma$) over 40 arcmin$^2$ at 0.07–0.15" FWHM from 0.2–1.7$\mu$m (UVUBVizYJH).

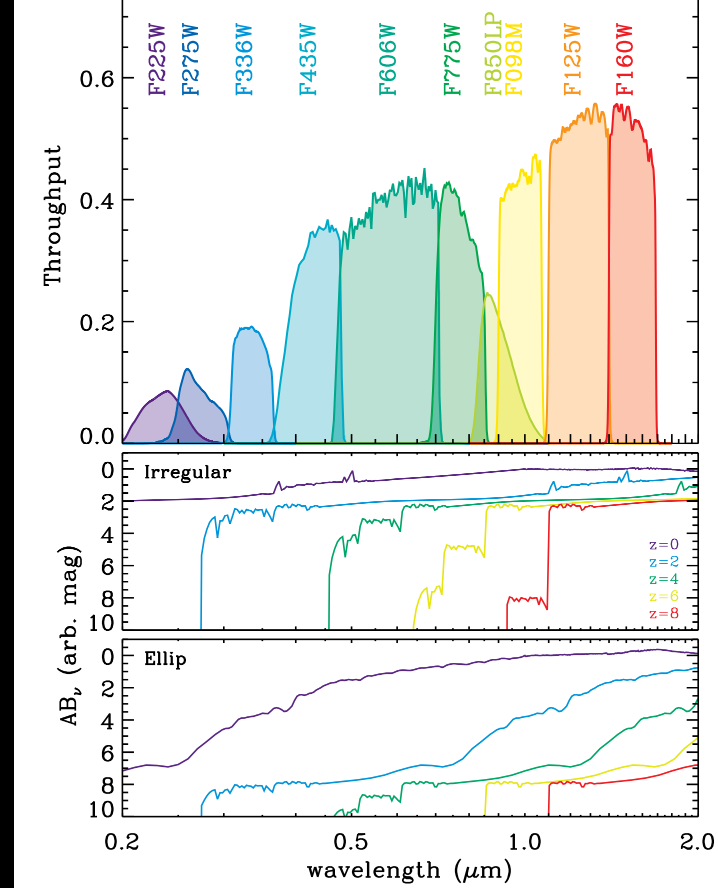
JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5$\mu$m, and 0.2–1.2" FWHM at 5–29$\mu$m, tracing young+old SEDs & dust.

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



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




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.

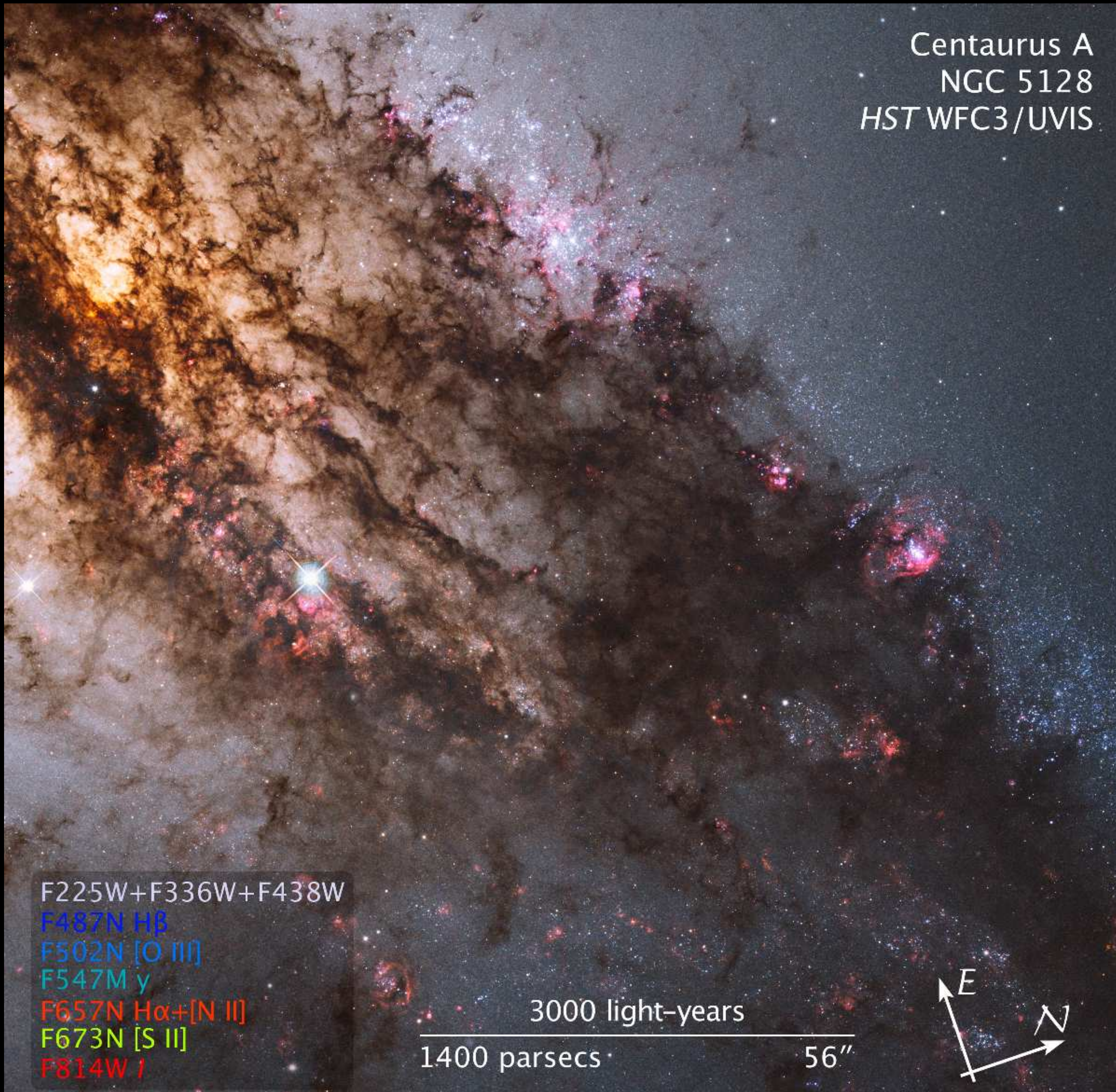
WFC3/IR channel unprecedented near–IR throughput & areal coverage:

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

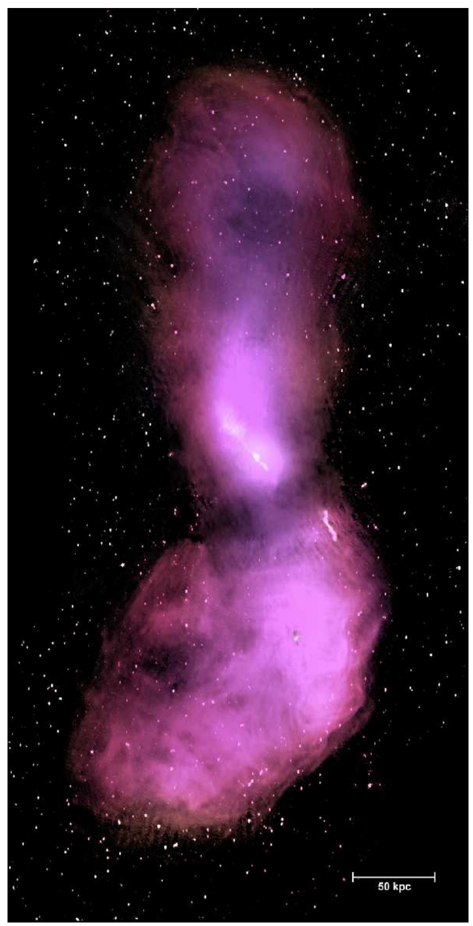
$\Rightarrow$ WFC3 opened major new parameter space for astrophysics in 2009:

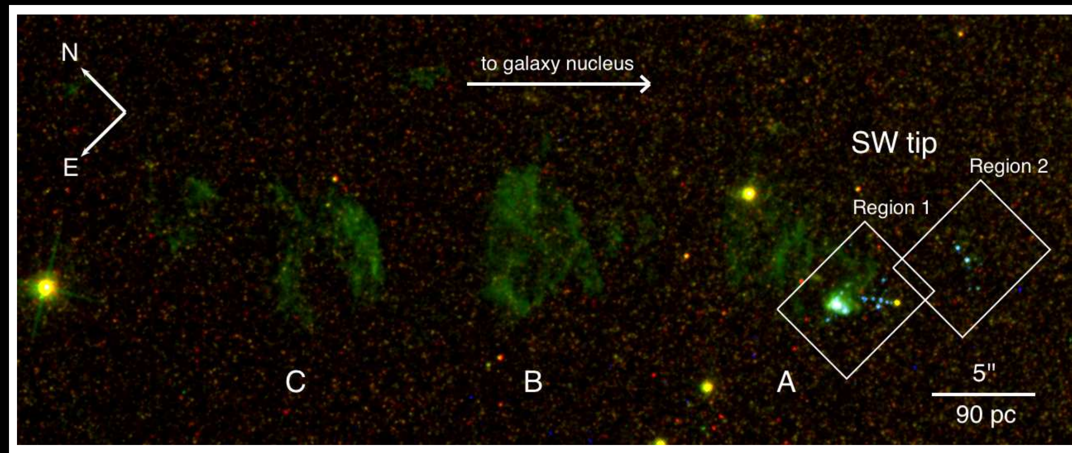
WFC3 filters designed for star-formation and galaxy assembly at z$\simeq$1–8.

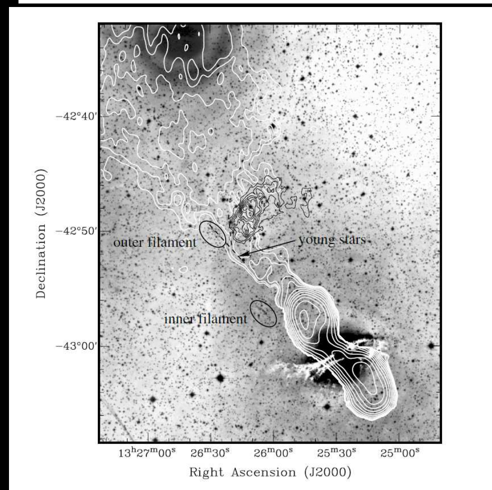
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

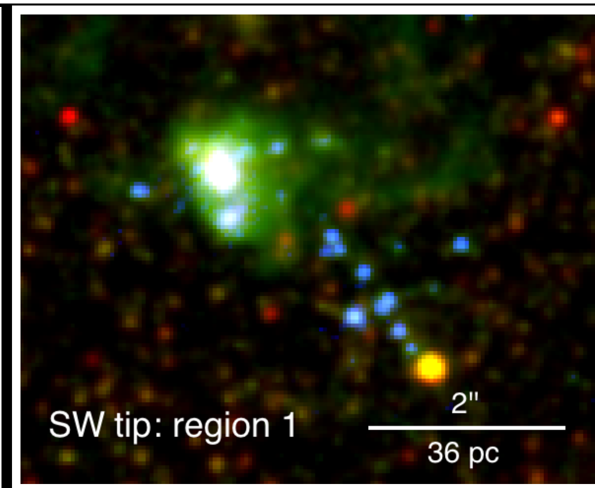


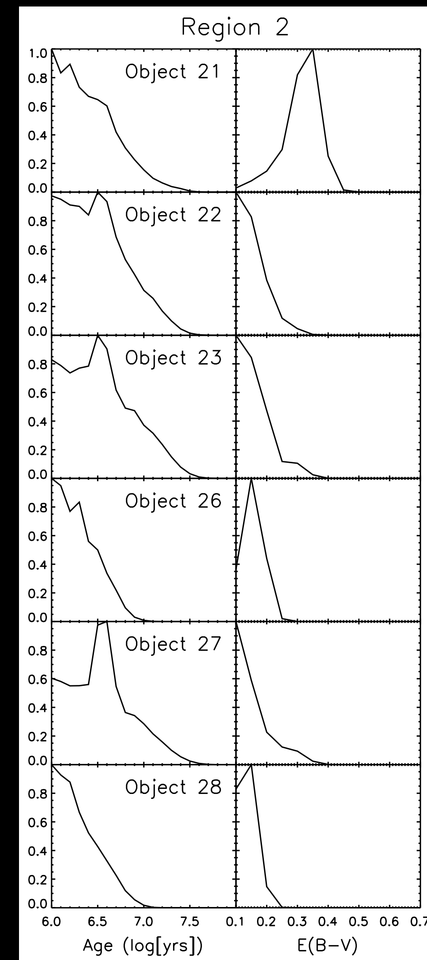
Centaurus A
NGC 5128
*HST* WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W I
3000 light-years
1400 parsecs
56″
E
N



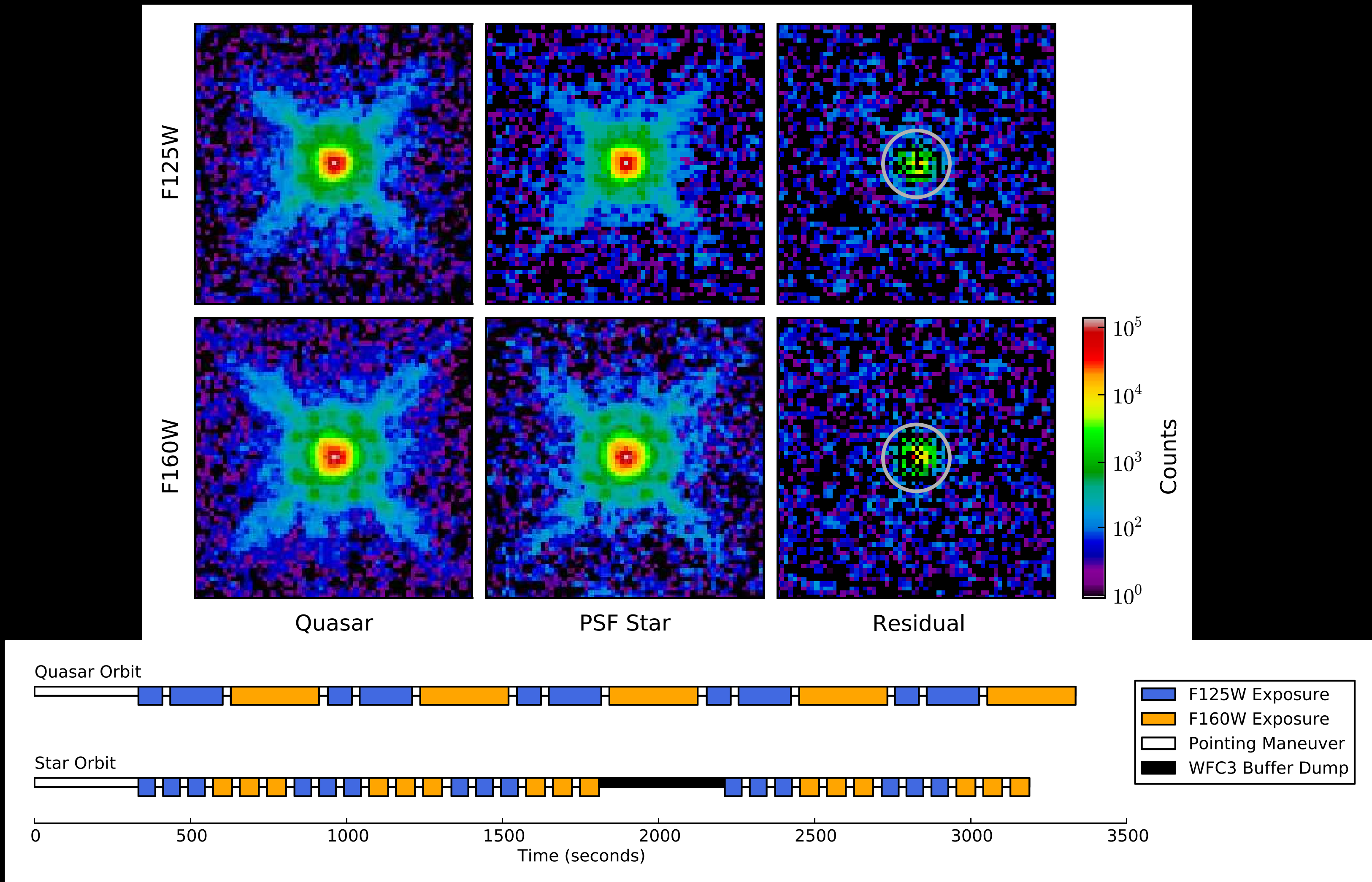

[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain$^{+}$ 2009).
Fermi GeV source (Yang$^{+}$ 12); & Auger UHE Cosmic Rays (Abreu$^{+}$ 2010).
[Middle] SF in Cent A jet's wake (Crockett$^{+}$ 2012, MNRAS, 421, 1602).
[Right] Well determined ages for young (∼2 Myr) stars near Cen A's jet.

- 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 properties of the medium.

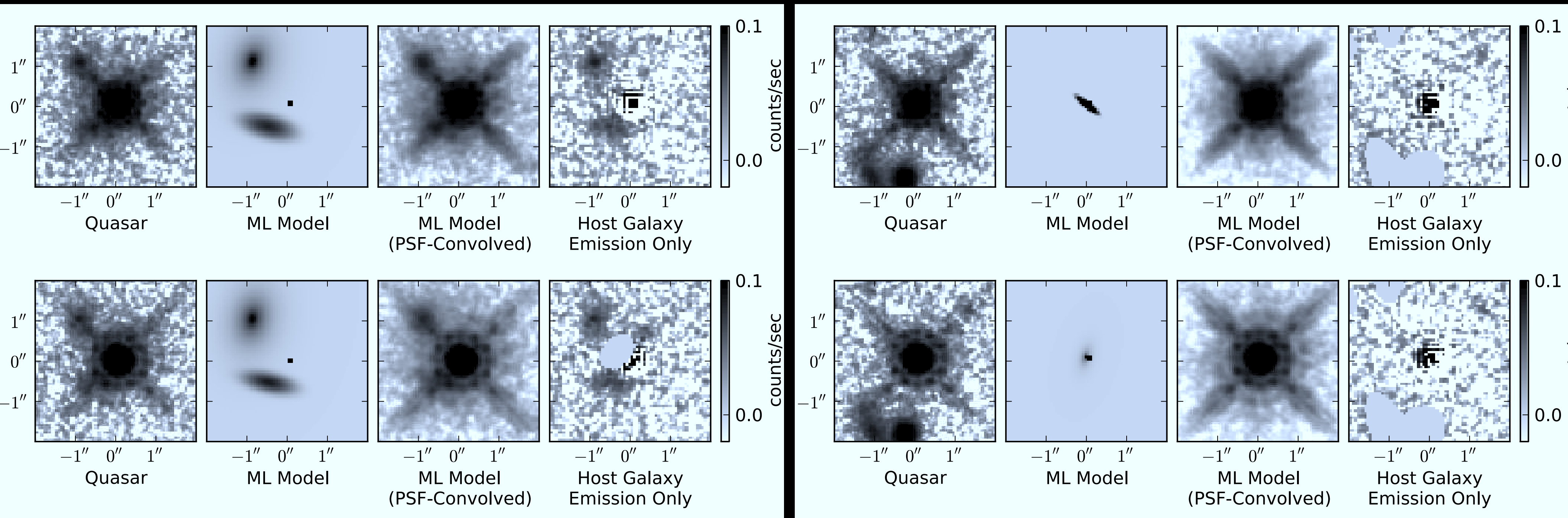
(See also Peter Biermann's talk).

# (2b) HST WFC3 observations of QSO host systems at z≃6 (age≲1 Gyr)




- Careful contemporaneous orbital PSF-star subtraction: Removes most of "OTA spacecraft breathing" effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star (AB≃15 mag) subtracts z=6.42 QSO (AB≃18.5) nearly to the noise limit: NO host galaxy detected 100× fainter (AB≳23.5 at r≳0.″3).

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

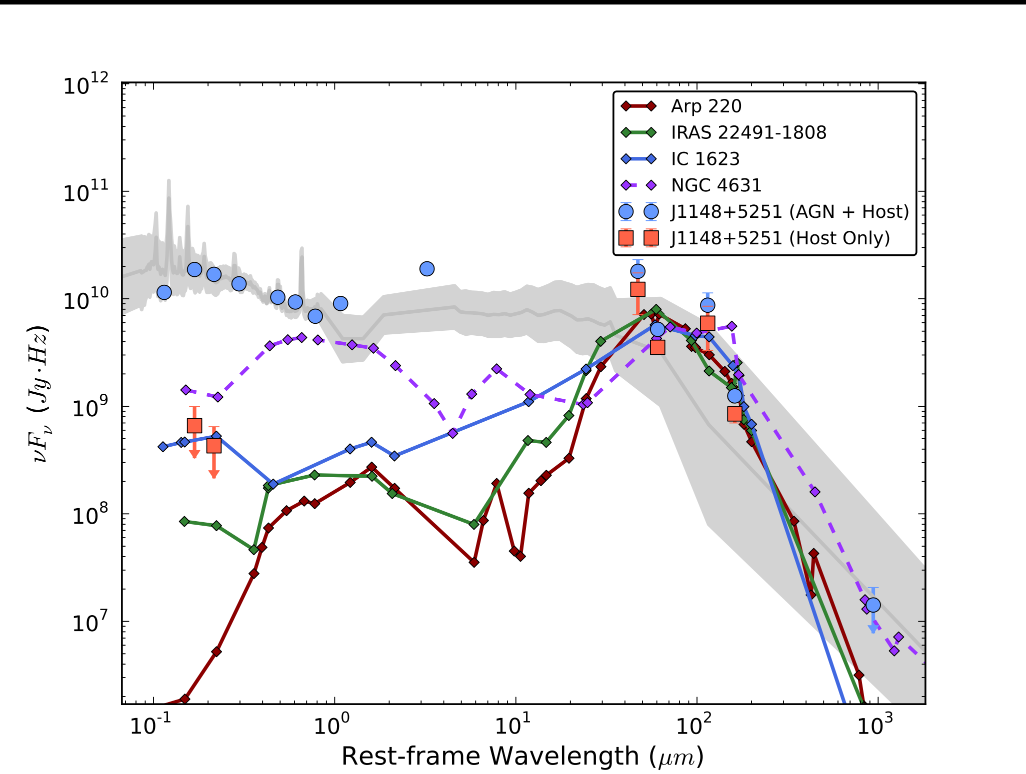


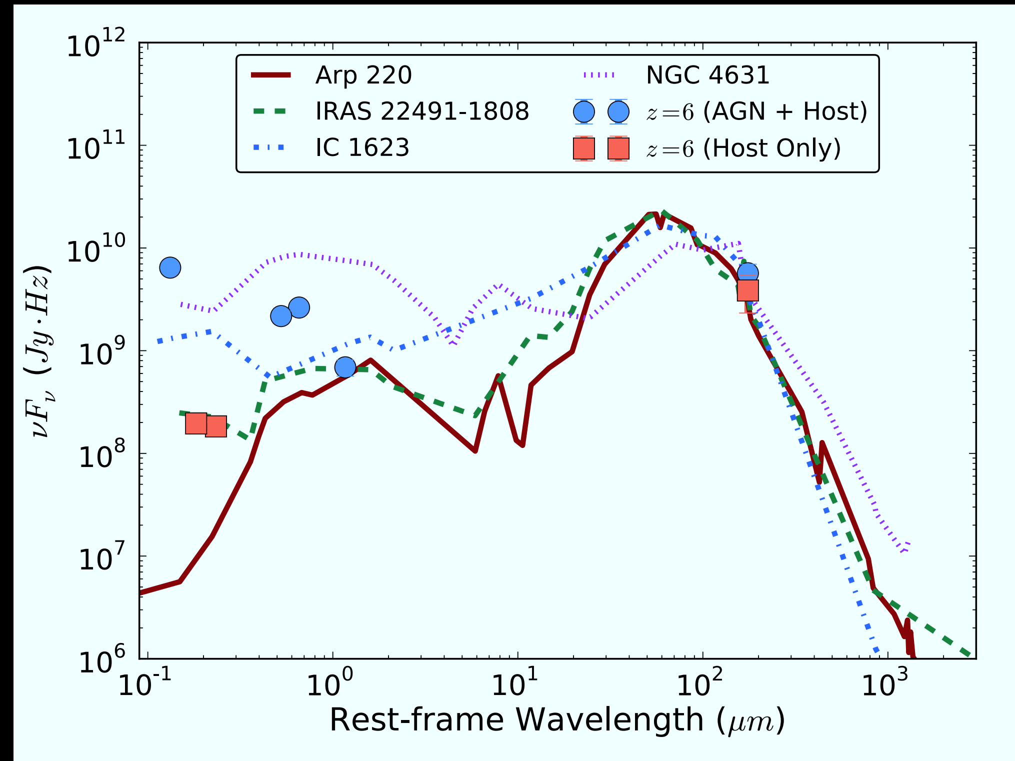

- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley$^{+}$ 2014).
- First detection out of four z≃6 QSOs [2 more to be observed].
- One z≃6 QSO host galaxy: Giant merger morphology + tidal structure??

- Same J+H structure! Blue UV-SED colors: (J–H)≃0.19, constrains dust.
  - IRAS starburst-like SED from rest-frame UV–far-IR, $A_{FUV}\sim 1$ mag.
- $M_{AB}^{host}$(z≃6)$\lesssim$–23.0 mag, i.e., ∼2 mag brighter than L*(z≃6)!

⇒ z≃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≃6



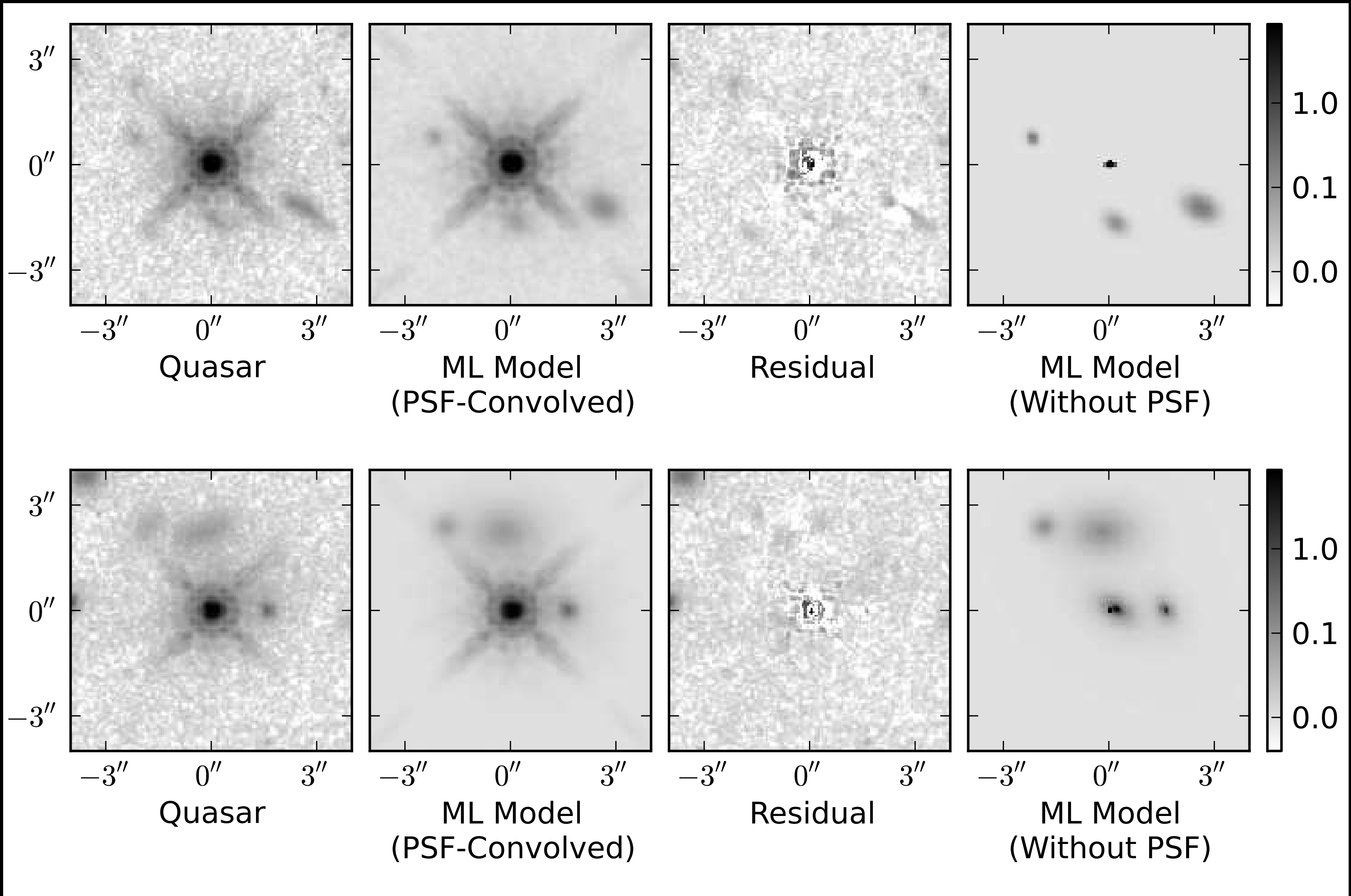

- Blue dots: z≃6 QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at z≳1 (normalized at 0.5$\mu$). Red: z≃6 host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages≲1 Gyr) normalized at 100$\mu$m:

[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).

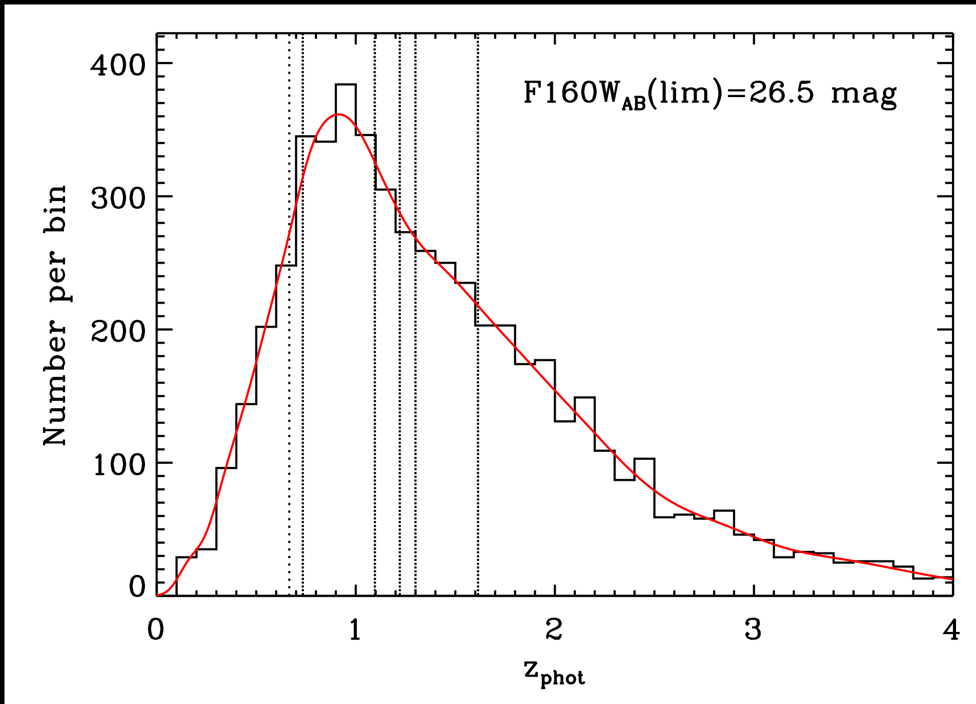
[RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR, $A_{FUV}$(host)∼1 mag (Mechtley 2013 PhD; et al. 2014).

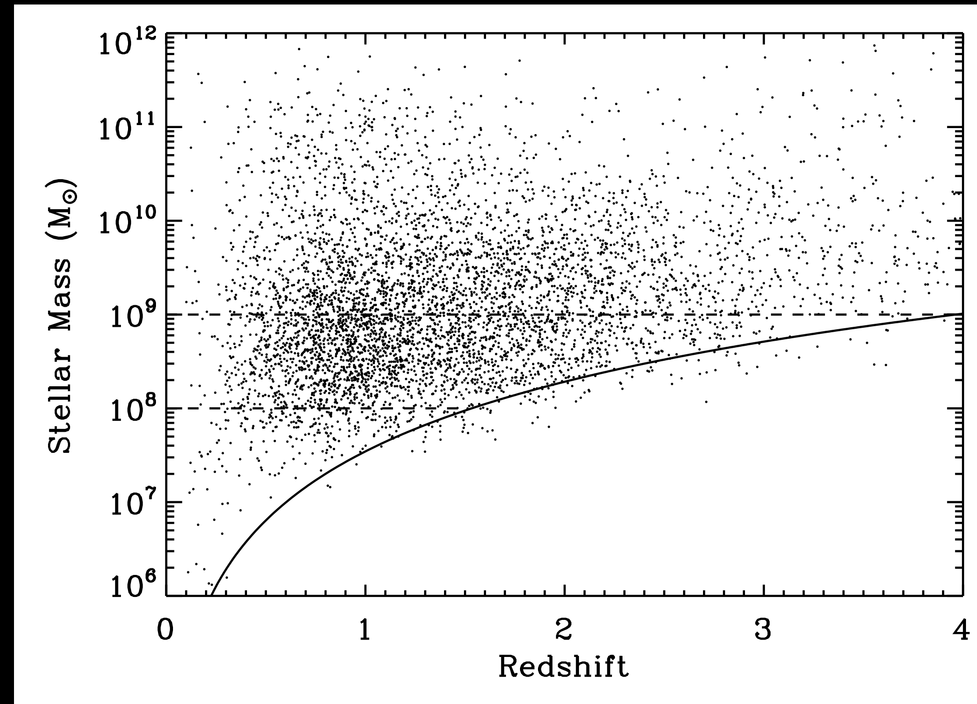
- JWST Coronagraphs can do this 10–100× fainter (& for z≲20, $\lambda$≲28$\mu$m).

# (2b) WFC3 observations of QSO host galaxies at z≃2 (evidence for mergers?)




- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, MPI, Koekemoer, Windhorst et al. 2014).
- JWST Coronagraphs can do this 10–100× fainter (& for z$\lesssim$20, $\lambda\lesssim 28\mu$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?).

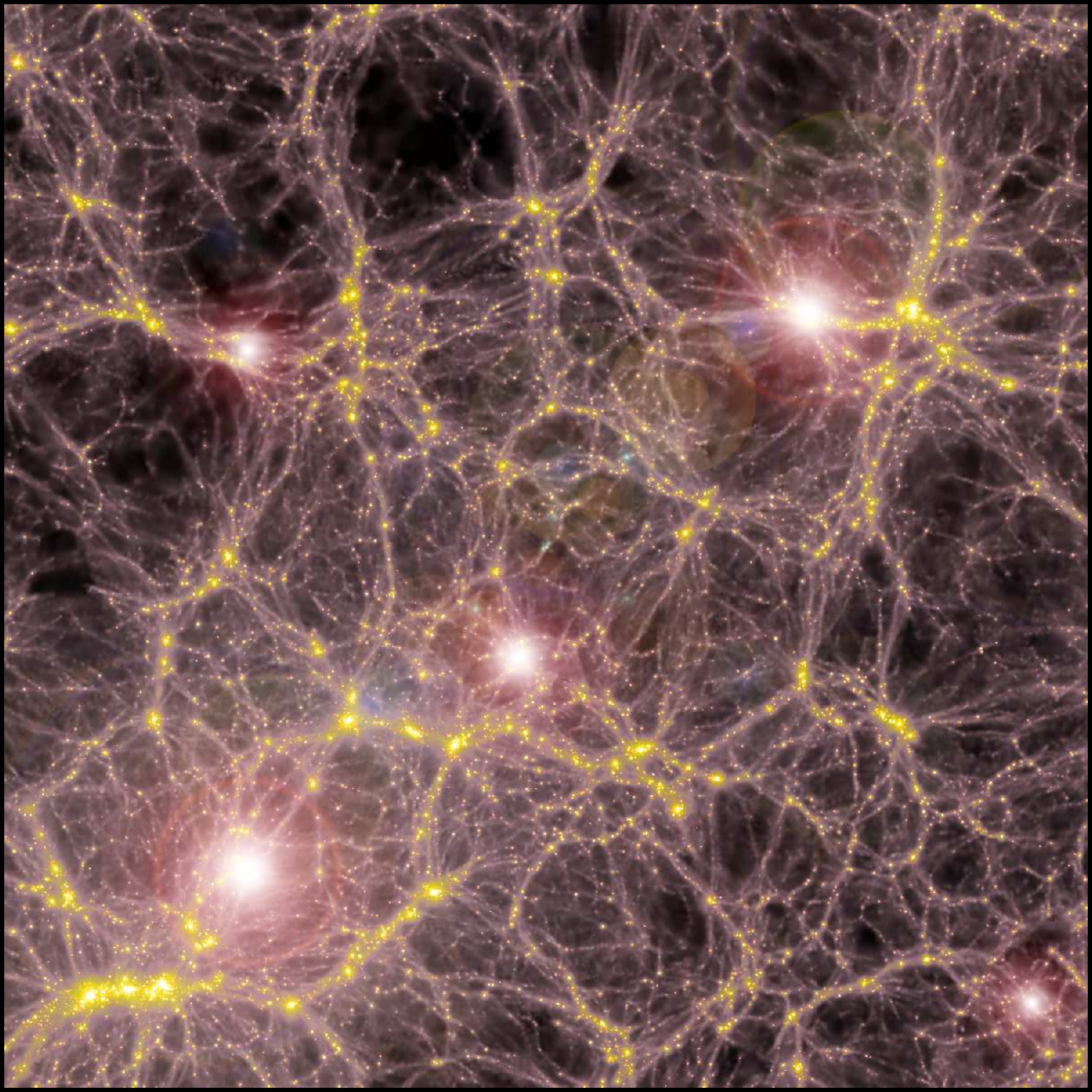
$\Rightarrow$ Median redshift in (medium-)deep fields is $z_{med}$ $\simeq$1.5–2.

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

- HUDF shows WFC3 z$\simeq$7–9 capabilities (Bouwens$^+$ 2010; Yan$^+$ 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$m.

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

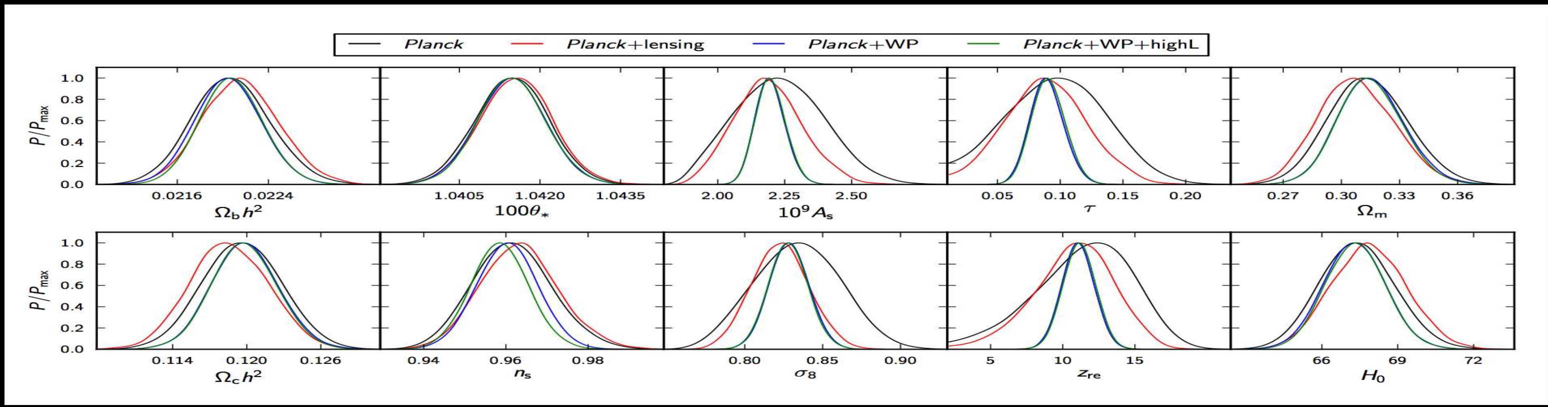


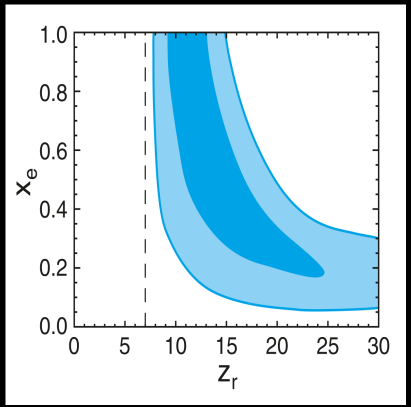
- Detailed Hydrodynamical models (e.g., V. Bromm) suggest that massive Pop III stars may have reionized universe at redshifts $z \lesssim 10$–30 (First Light).

- 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 $z \simeq 10 \longrightarrow 30$.

We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates, etc., with accurate predictions before JWST flies [See F. Mirabel's talk].

# Implications of the WMAP year-9 & Planck13 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$^+$ 2011; Hinshaw$^+$ 2012; Planck XVI 2013; see also A. Lasenby's talk):

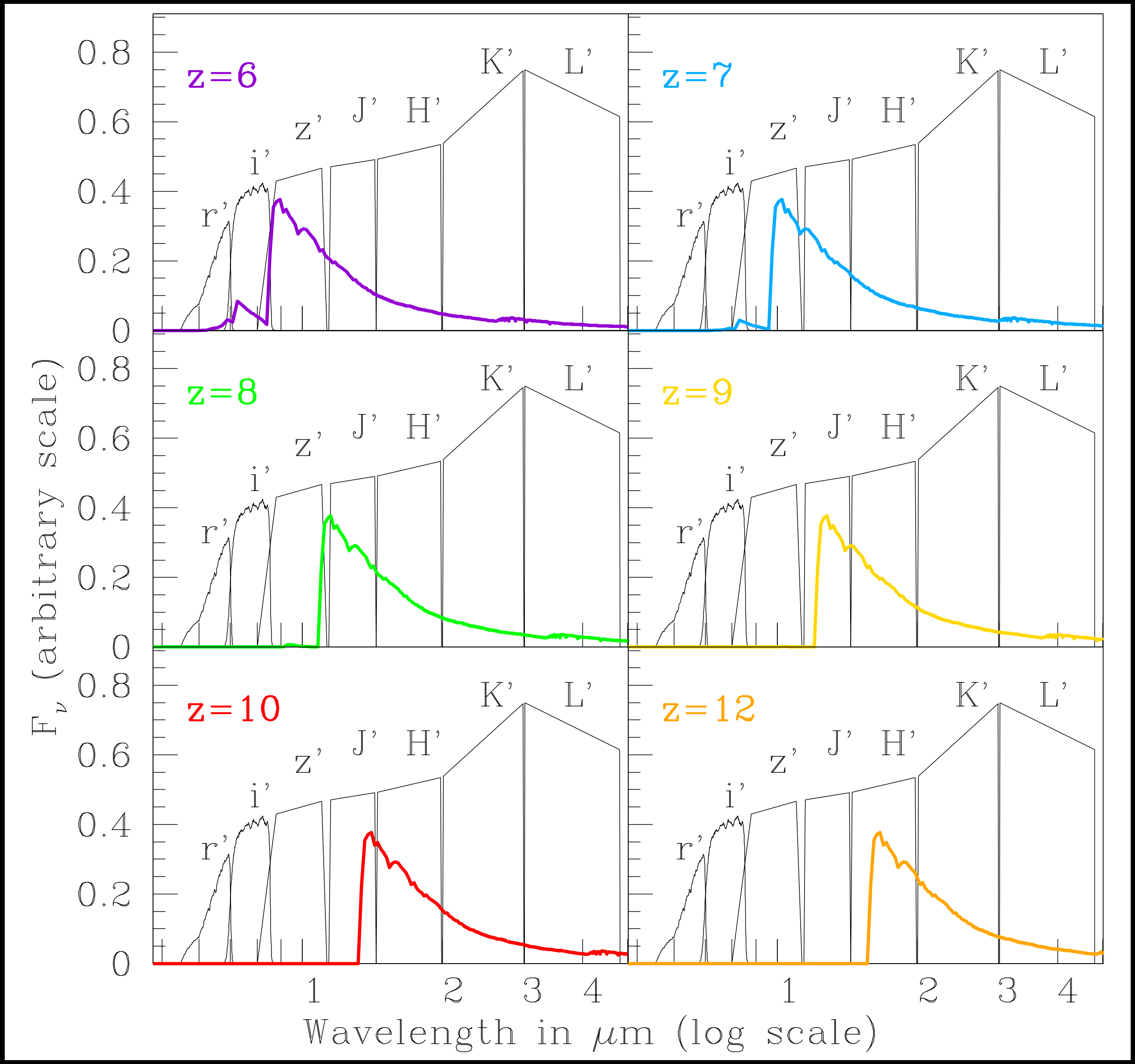
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (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.

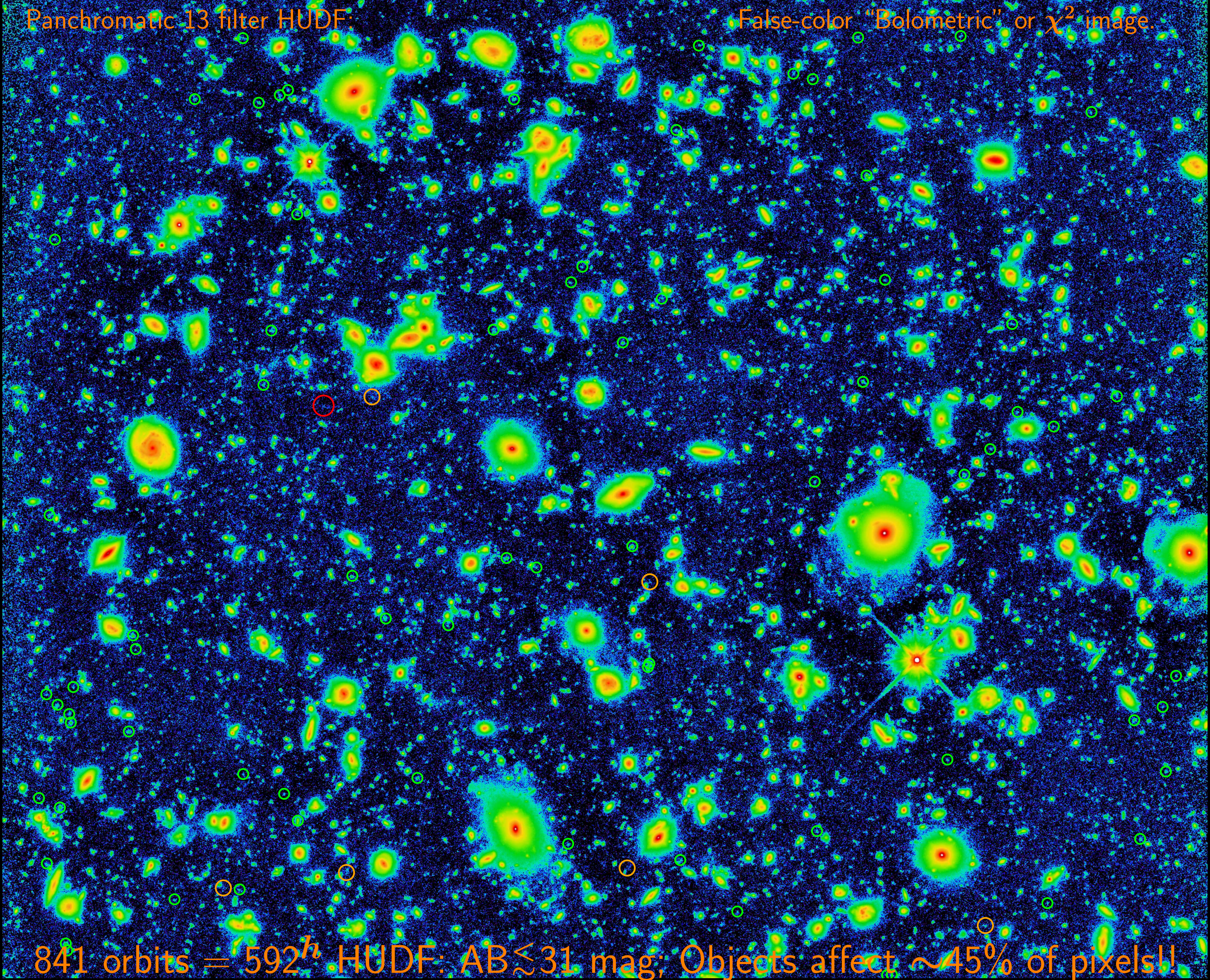
Question: If Planck-$\tau \downarrow \lesssim 0.08$ (TBD, Planck14), then how many reionizers will JWST see at $z \simeq 10$–20?

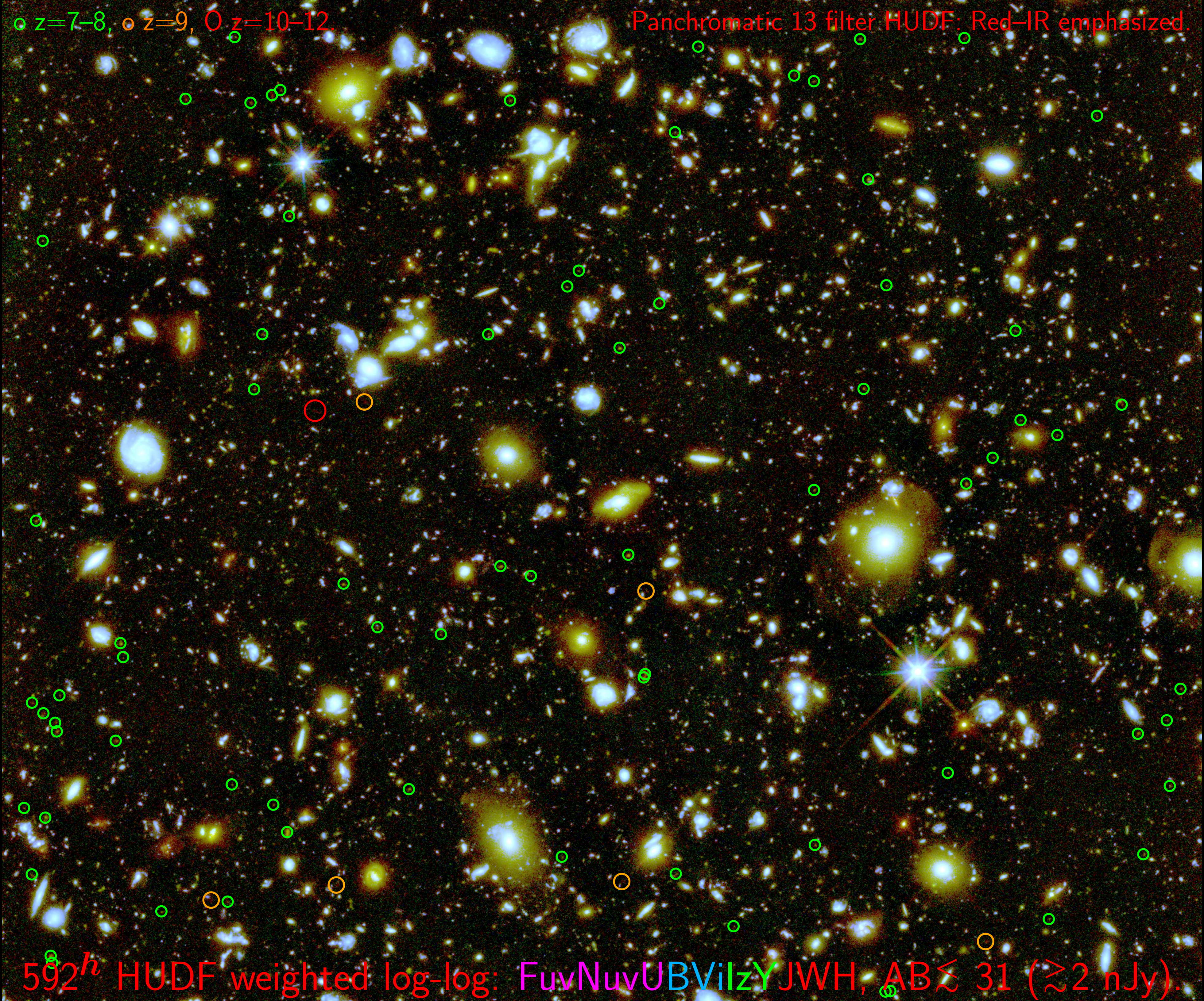
# 3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?




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

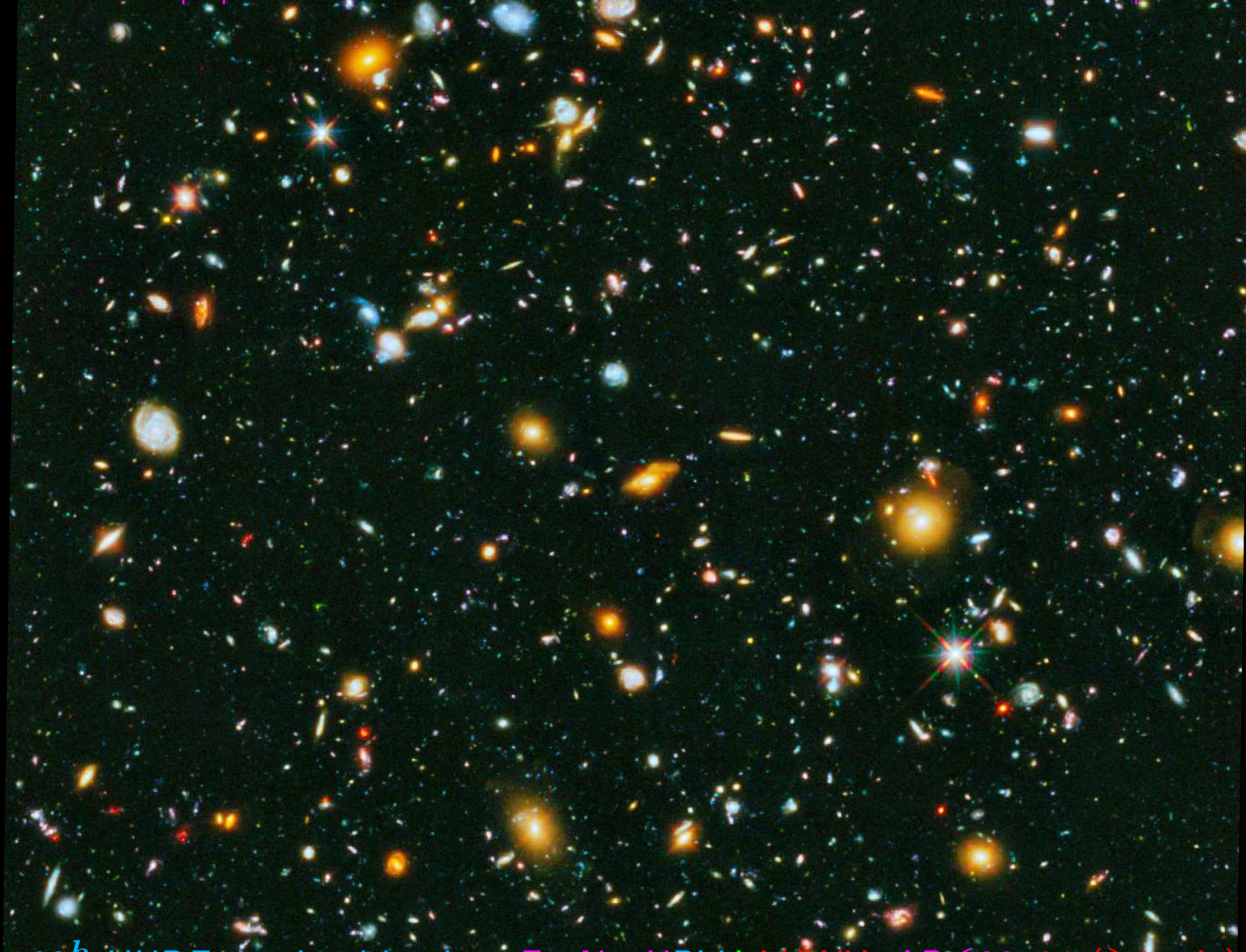
$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 $\mu$m and MIRI at 5–28 $\mu$m.


Panchromatic 13 filter HUDF:
False-color "Bolometric" or $\chi^2$ image.
841 orbits = $592^h$ HUDF: AB$\lesssim$31 mag; Objects affect $\sim$45% of pixels!!



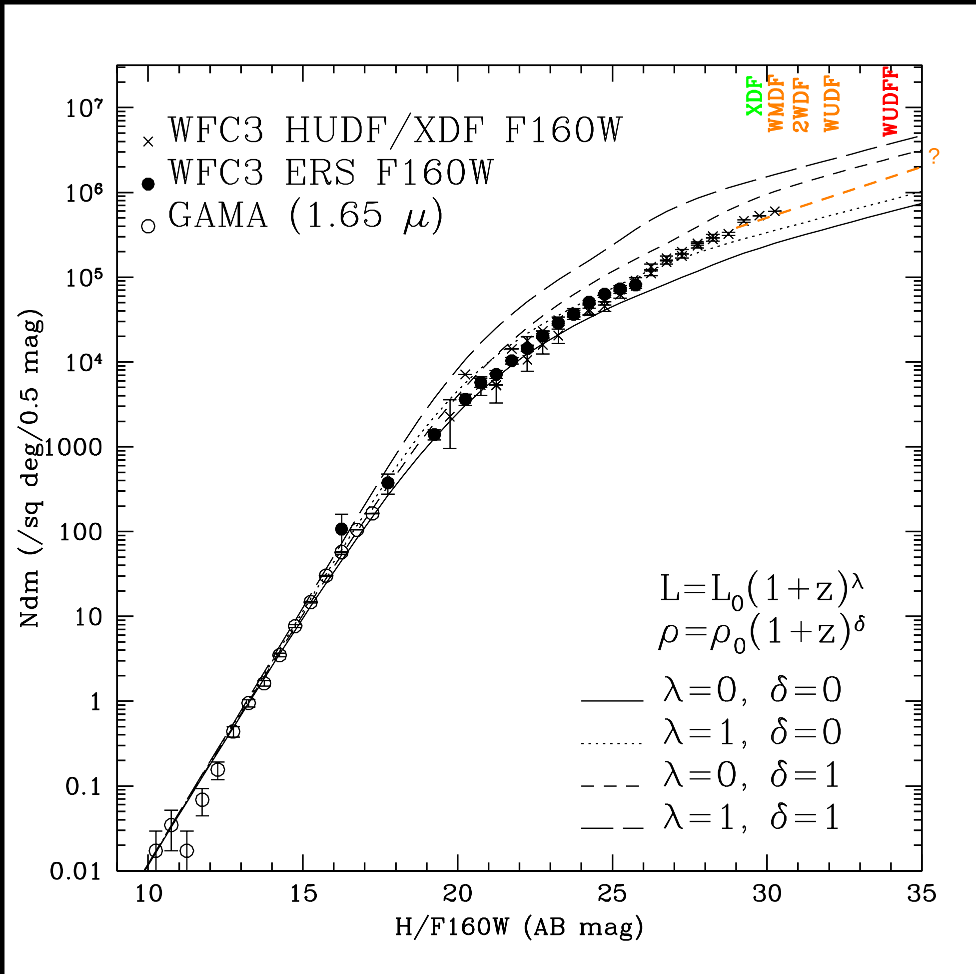
o z=7–8, o z=9, O z=10–12.
Panchromatic 13 filter HUDF: Red–IR emphasized.
592$^{h}$ HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$ 31 ($\gtrsim$2 nJy).

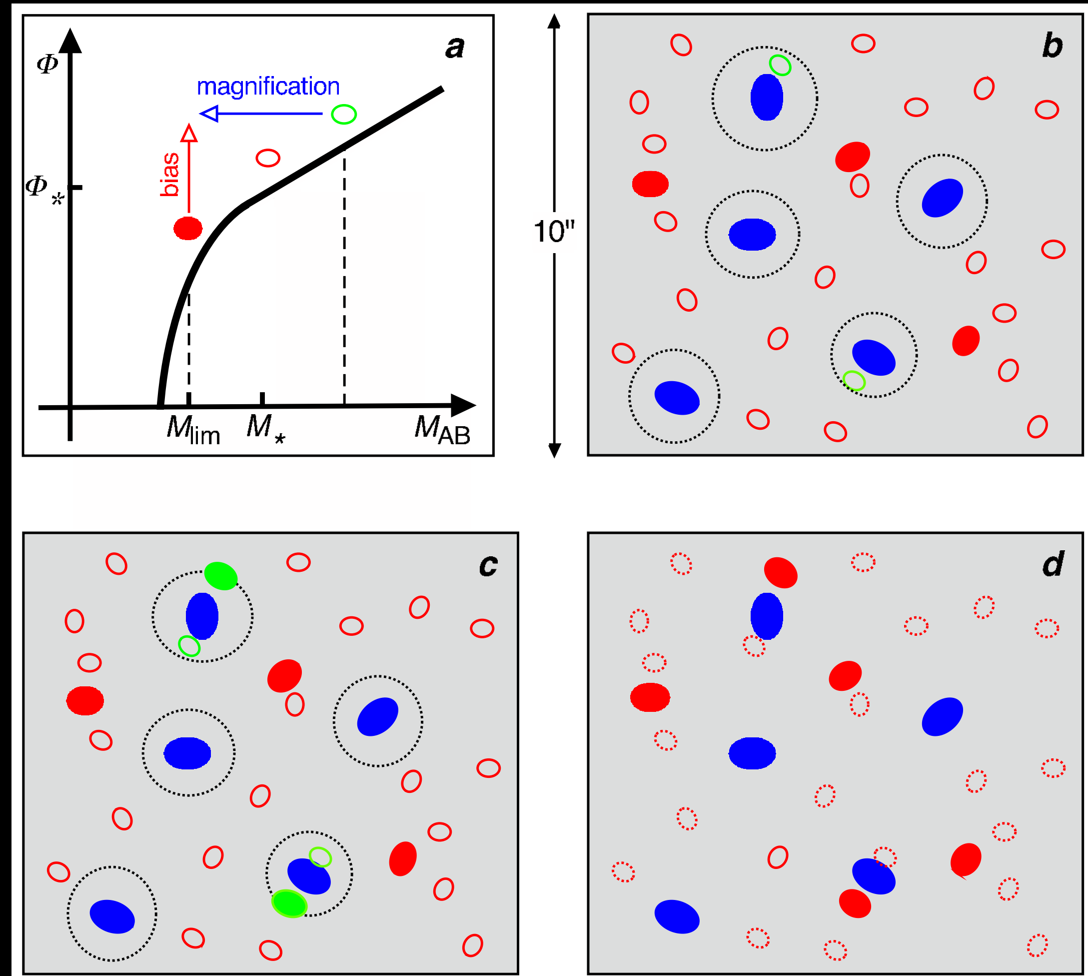
The HST-unique part for JWST: Panchromatic 13 filter HUDF: UV–Blue emphasized.



$592^h$ HUDF weighted log-log: FuvNuvUBViIzYJWH, AB$\lesssim$28–31 ($\gtrsim$2 nJy).

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



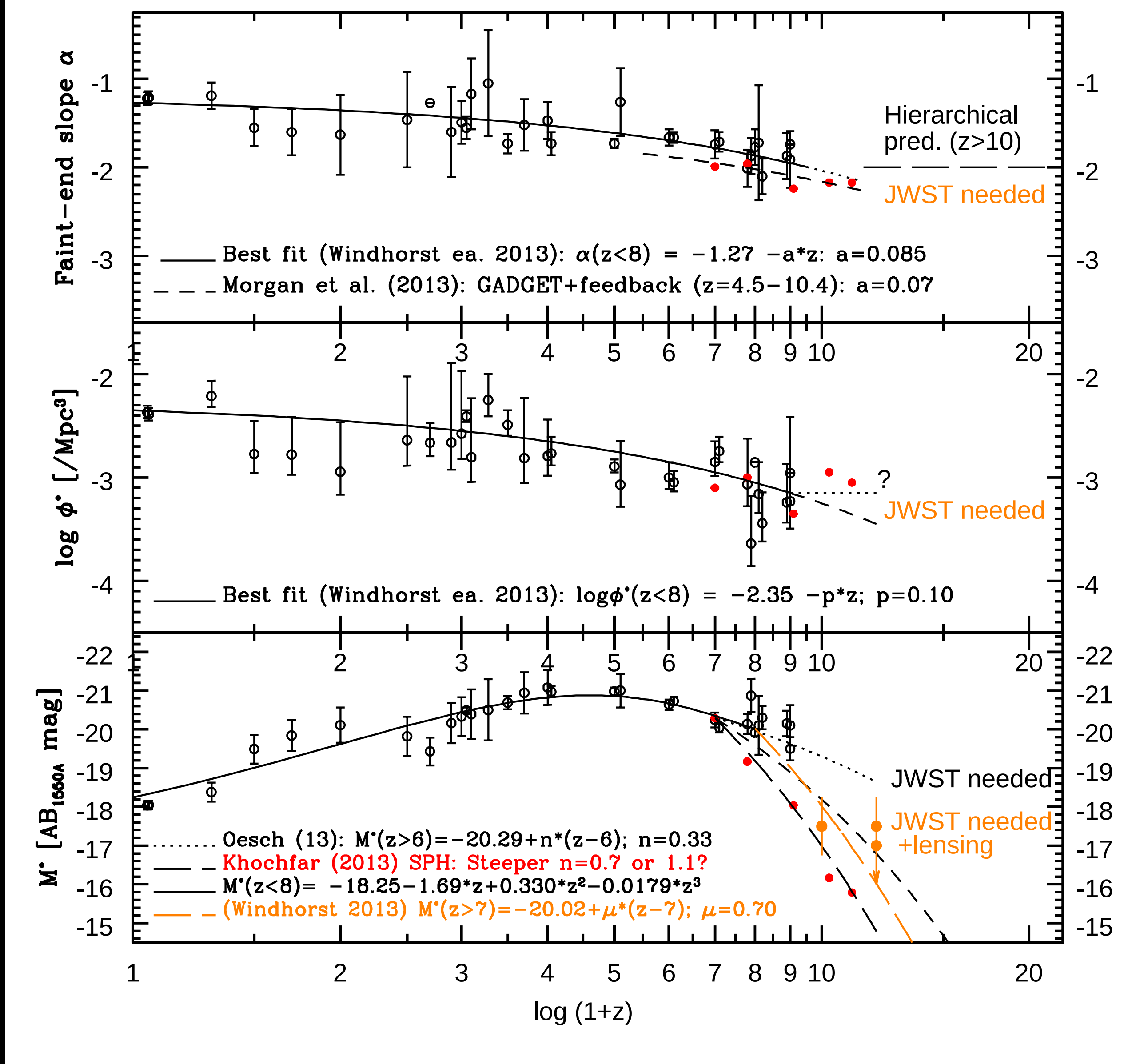




1.6$\mu$m counts (Windhorst[+]2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end near-IR count-slope$\simeq$0.12$\pm$0.02 dex/mag $\Longleftrightarrow$

Faint-end LF-slope($z_{med}$ $\simeq$1.6) $\alpha\simeq$–1.4 $\Rightarrow$ reach $M_{AB}\simeq$–14 mag.

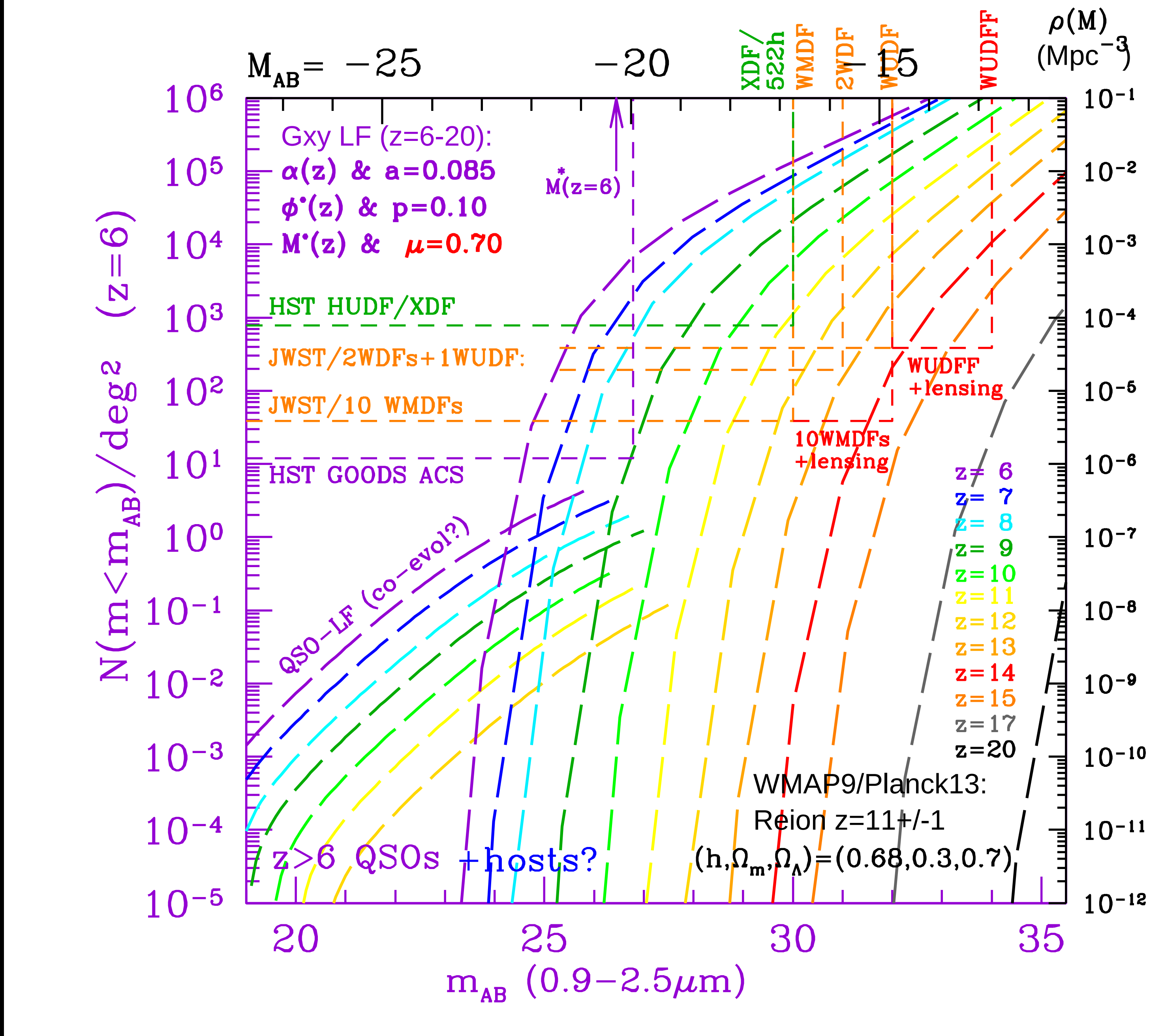
- WUDF (- - -) can see AB$\lesssim$32 objects: $M_{AB}$ $\simeq$–15 (LMCs) at z$\simeq$11.
- Lensing will change the landscape for JWST observing strategies (WUDFF).




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$^{-3}$) (Oesch$^+$ 11).
- HUDF: Characteristic $M^*$ may drop below –18 or –17.5 mag at z$\gtrsim$10.

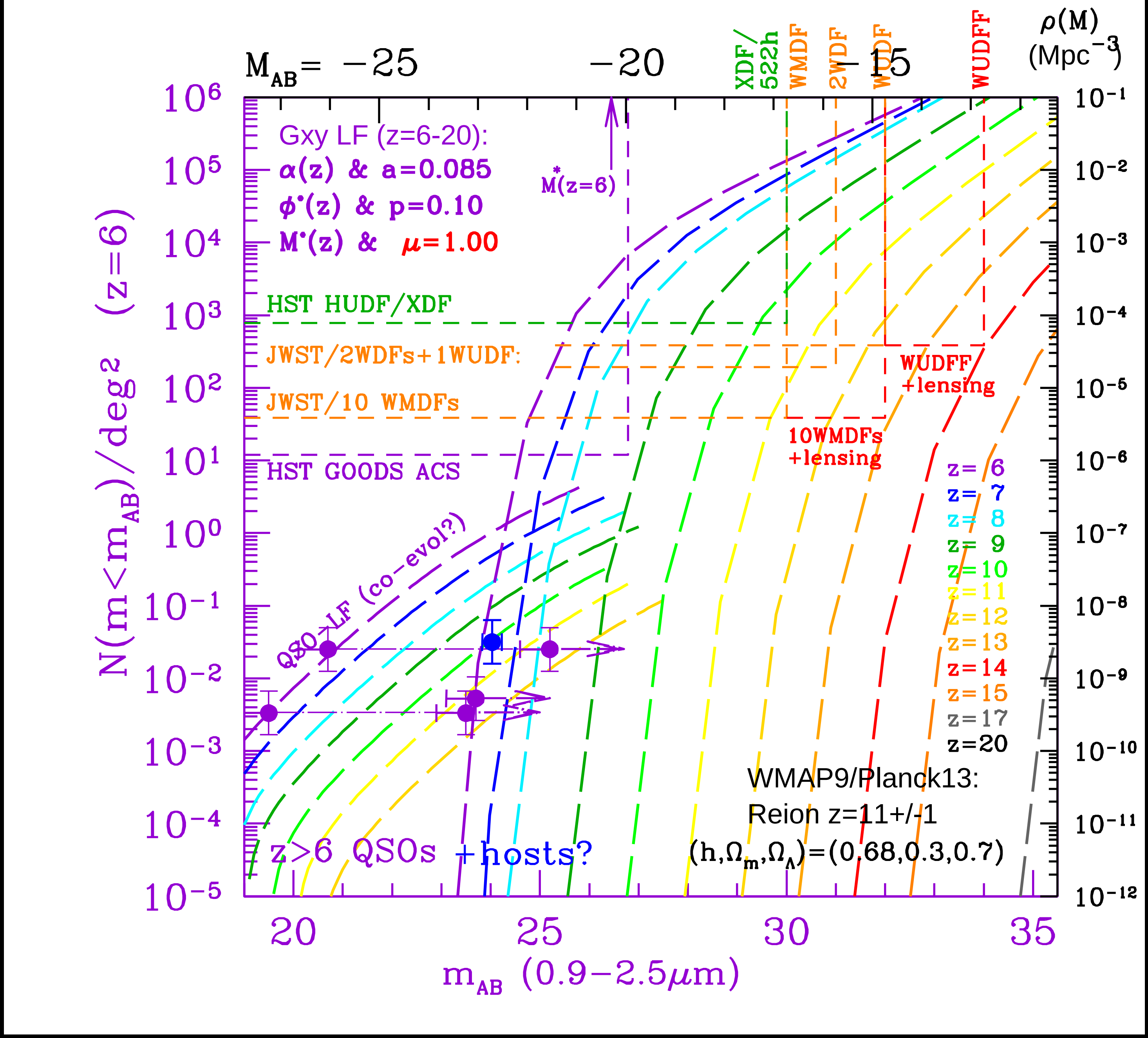
⇒ Will have significant consequences for JWST survey strategy.




Schechter LF (z≲6≲20) with $\alpha$(z), $\Phi^*$ (z), $M^*$ (z) above & $\mu$=0.70.

Area/Sensitivity for: HUDF/XDF, 10 WMDFs, 2 WDFs, & 1 WUDF.

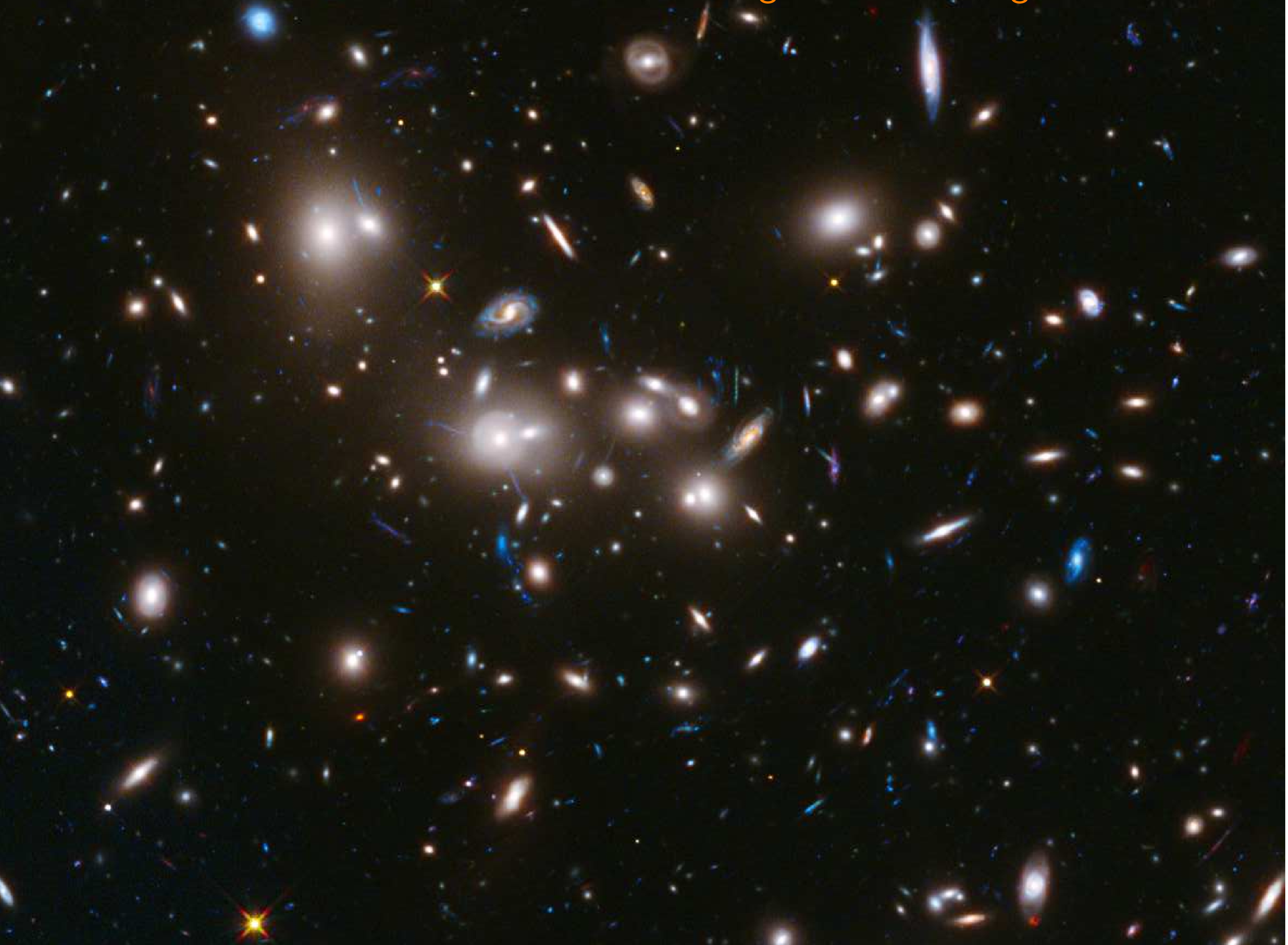
- Will need lensing targets for WMDF–WUDFF to see z≃14–16 objects.



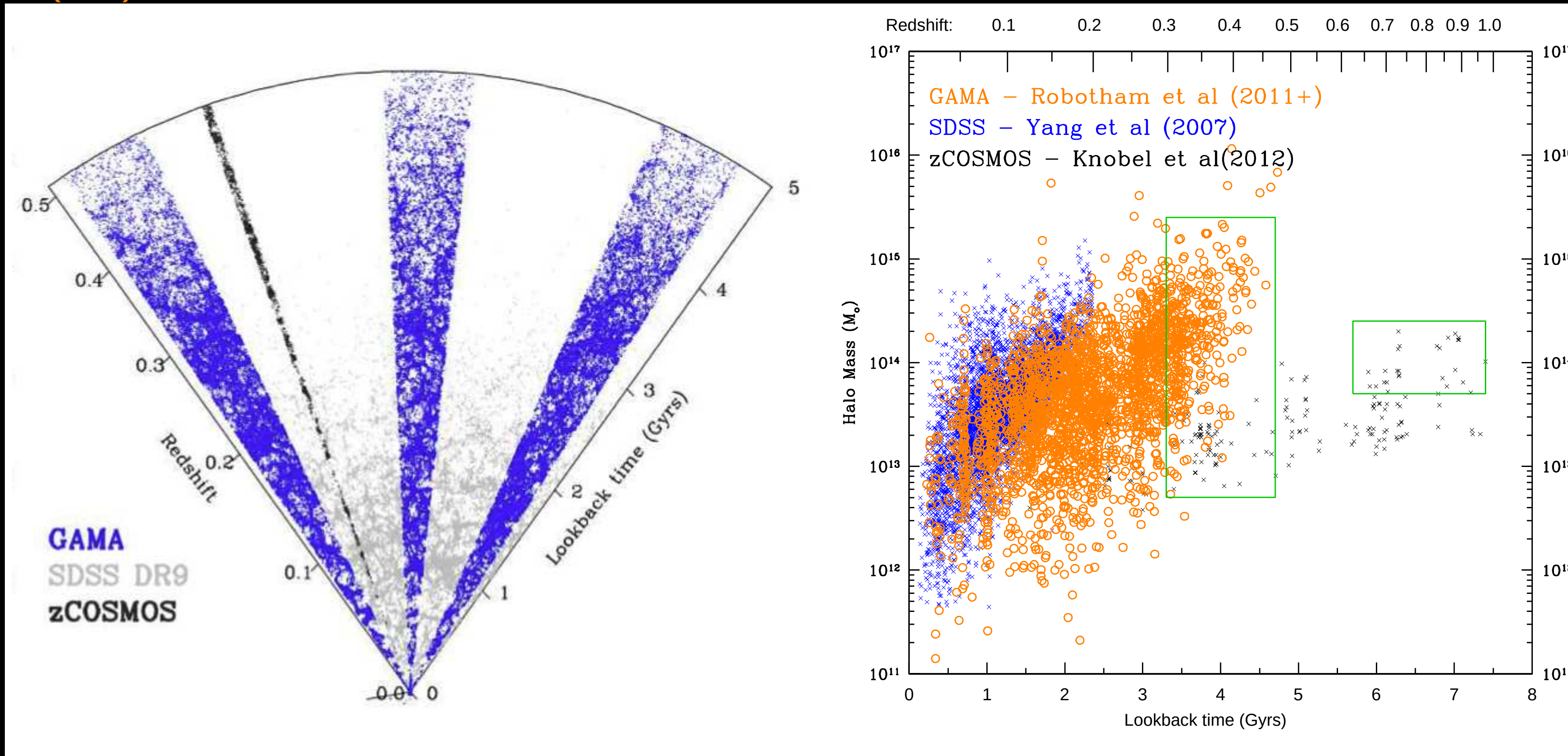

Same as before, but pessimistic $M^*$ (z) evolution parameter: $\mu$=1.0.

- 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[+] (2012, 2013).

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



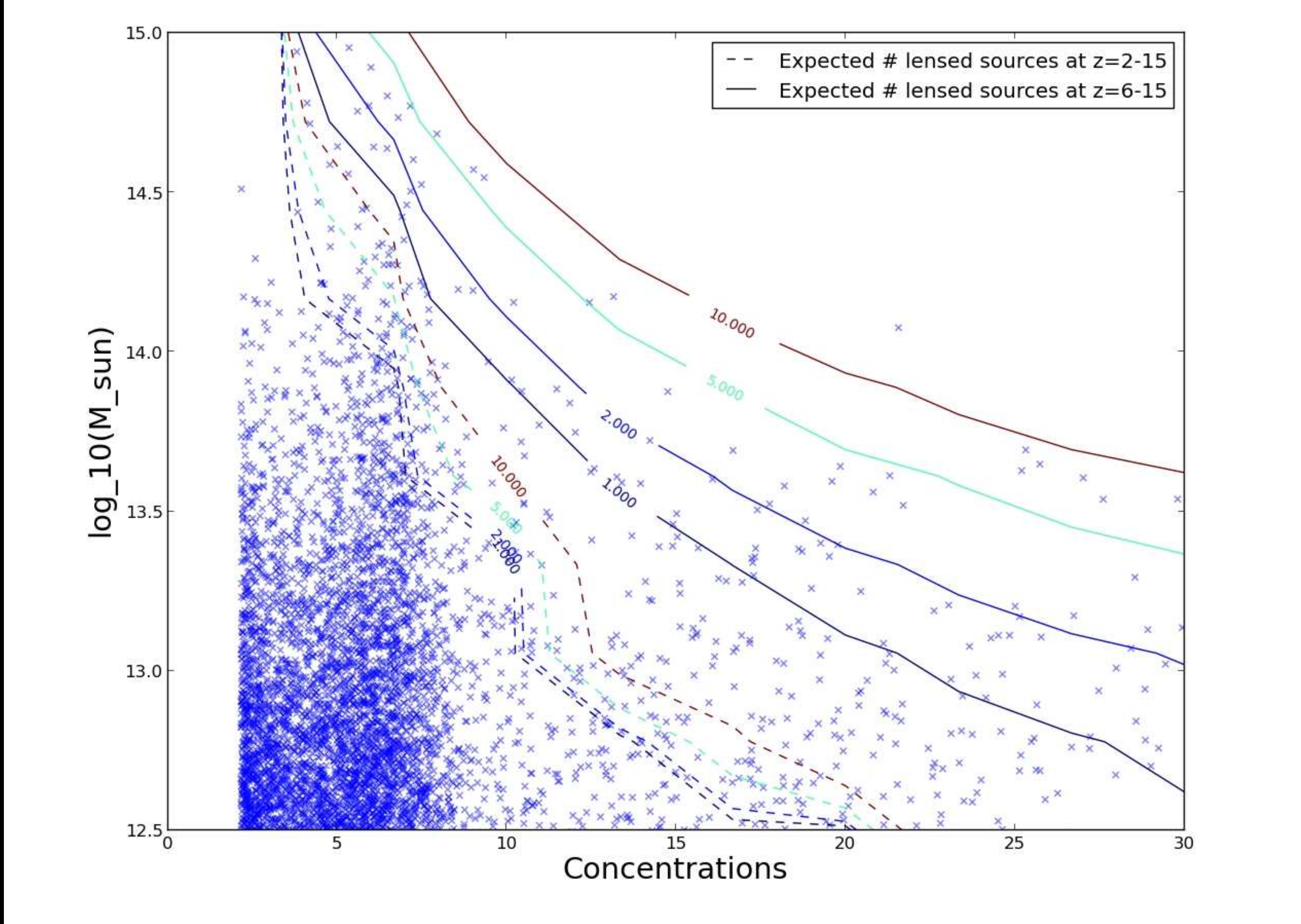
# (3b) Gravitational Lensing to see First Light population at z$\gtrsim$10.




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

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

- GAMA: 22,000 groups z$\lesssim$0.45; 2400 with $N_{spec}\gtrsim$5 (Robotham$^+$ 11).
  - $\lesssim$10% of GAMA groups compact for lensing (Konstantopoulos$^+$ 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$^{+}$ 13).

- 10 WMDFs on best GAMA groups add ∼50–100 z≃6–15 sources (AB≲30).
- Also get ≳10× more (≳500) lensed sources at ≃2–15.

WUDFF if pointed at clusters adds ∼6× more (≳3000) sources at 6≲z≲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
$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ 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.

$\Rightarrow$ Need multi-$\boldsymbol{\lambda}$ object-finder that works on sloped backgrounds.

$\Rightarrow$ If $M^*(z\gtrsim10)\gtrsim-18$, 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>>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

- 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

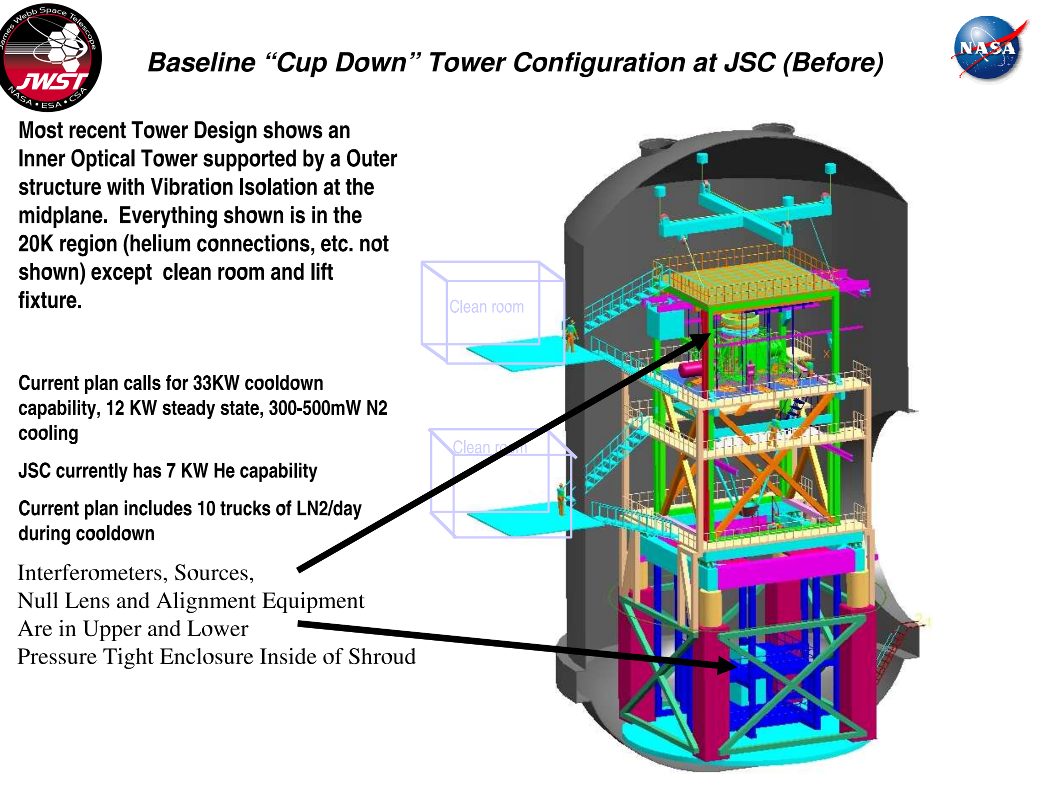
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).

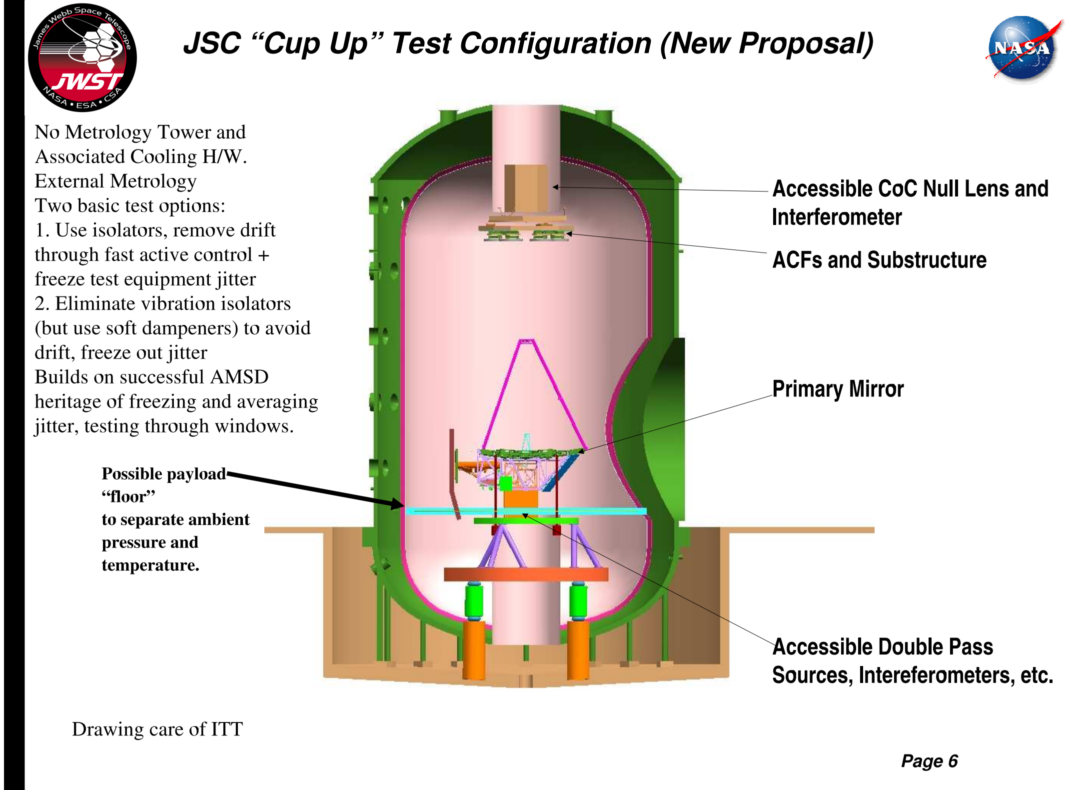

Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).

# 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






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 $\mu$m performance specs (kept 2.0 $\mu$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 |
| | 4 | Johnson Space Center (JSC) Telescope and ISIM support structure fabrication complete | Completed 11/4 |
| Dec-13 | 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] |
| | 8 | Complete ISIM cryogenic-vacuum risk reduction test | Concluded 11/13/2013, but not all tests completed because of shutdown |
| Jan-14 | 9 | Delivery of last Primary Mirror Segment to GSFC | Completed 12/16 |
| | 10 | Observatory Operations software scripts Build 3 Complete | |
| | 11 | New detector focal plane arrays for NIRCam ready for integration into instrument | Completed 11/20 |
| Feb-14 | 12 | Secondary Mirror Mount delivery | |
| | 13 | MIRI Cryocooler flight electronics delivered to JPL | |
| | 14 | Final Data Management Subsystem Design Review | Completed 11/22 |
| | 15 | Flight NIRCam and NIRSpec ready for integration into ISIM | Delayed to 3/14 [shutdown] |
| Mar-14 | 16 | Spacecraft Solar Array Manufacturing Readiness Review | |
| | 17 | JSC Chamber A Telescope ground support equipment test #1 design review | |
| Apr-14 | 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 | |
| | 21 | Sunshield Membrane Cover Assembly Manufacturing Readiness Review | |
| | 22 | MIRI cryocooler Test Readiness Review | |
| May-14 | 23 | Updated Observatory Commissionning Plan (rev C) delivery | |
| | 24 | Start acceptance testing of flight cryocooler assembly and associated electronics | |
| | 25 | Start cryo-vacuum test with fully integrated ISIM ("CV2") | Delayed to 6/14 [shutdown] |
| Jun-14 | 26 | Flight spare MIRI cryocooler assembly delivered to JPL | |
| | 27 | JSC Chamber A bake-out and cryogenic proof testing complete | |
| | 28 | Hardware ready for MIRI cryo cooler test #3: checkout complete | |
| Jul-14 | 29 | Spacecraft Mid-Course Correction Thruster Final Assembly complete | |
| | 30 | Proprosal Planning Subsystem build 9 complete | |
| Aug-14 | 31 | Sunshield Mid-boom and Stem assembly Manufacturing Readiness Review | |
| | 32 | Spacecraft Flight Software Build 2.2 Test Readiness Review | |
| | 33 | NIRSpec and FGS/NIRISS new Focal Plane Arrays ready for integration | Delayed to 9/14 [shutdown] |
| Sep-14 | 34 | JSC cryogenic test telescope and ISIM test ground support equipment integration complete | |
| | 35 | Complete cryo-vacuum test of fully integrated ISIM ("CV2")plete | 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

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

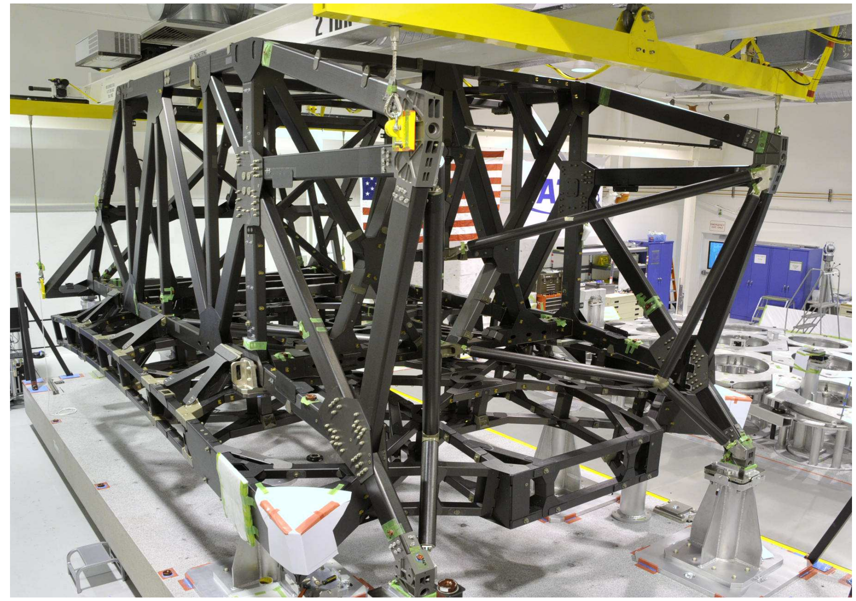
*Late milestones have been or are forecast to complete within the year. Shutdown related delayed milestones included in this tally

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

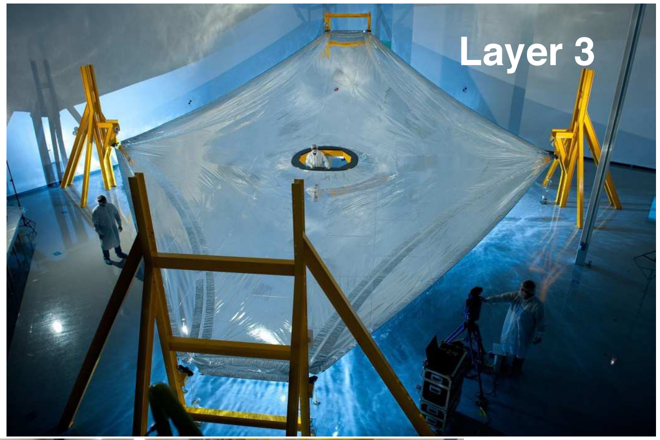


2014: Flight back-plane ready to receive mirrors starting in Aug. 2014.

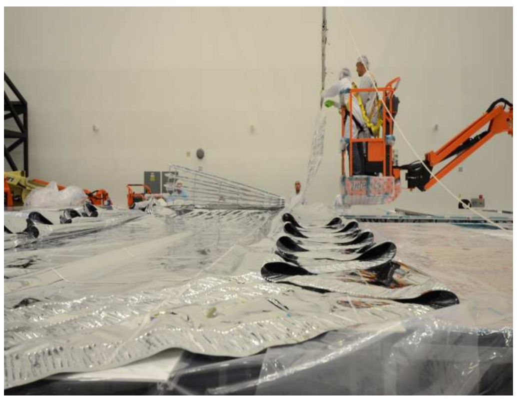
# Sunshield Template Membrane Work Completed

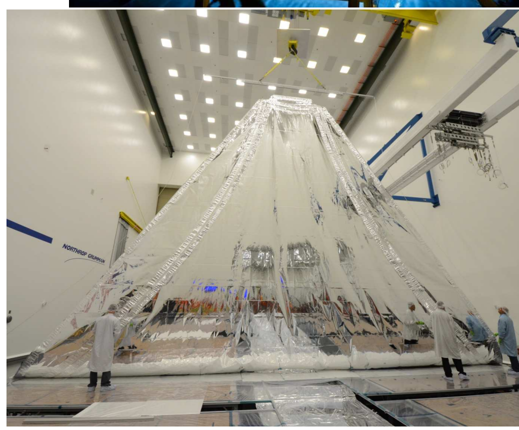
## Templates Verify Design/Manufacturing Prior to Flight Build

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

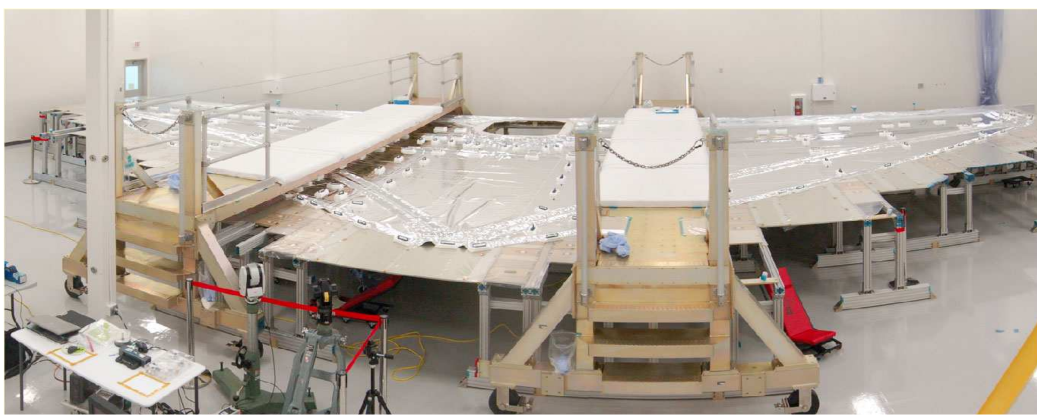



Stringing Operations





Template Layers 3-5



Hole Tool Operations



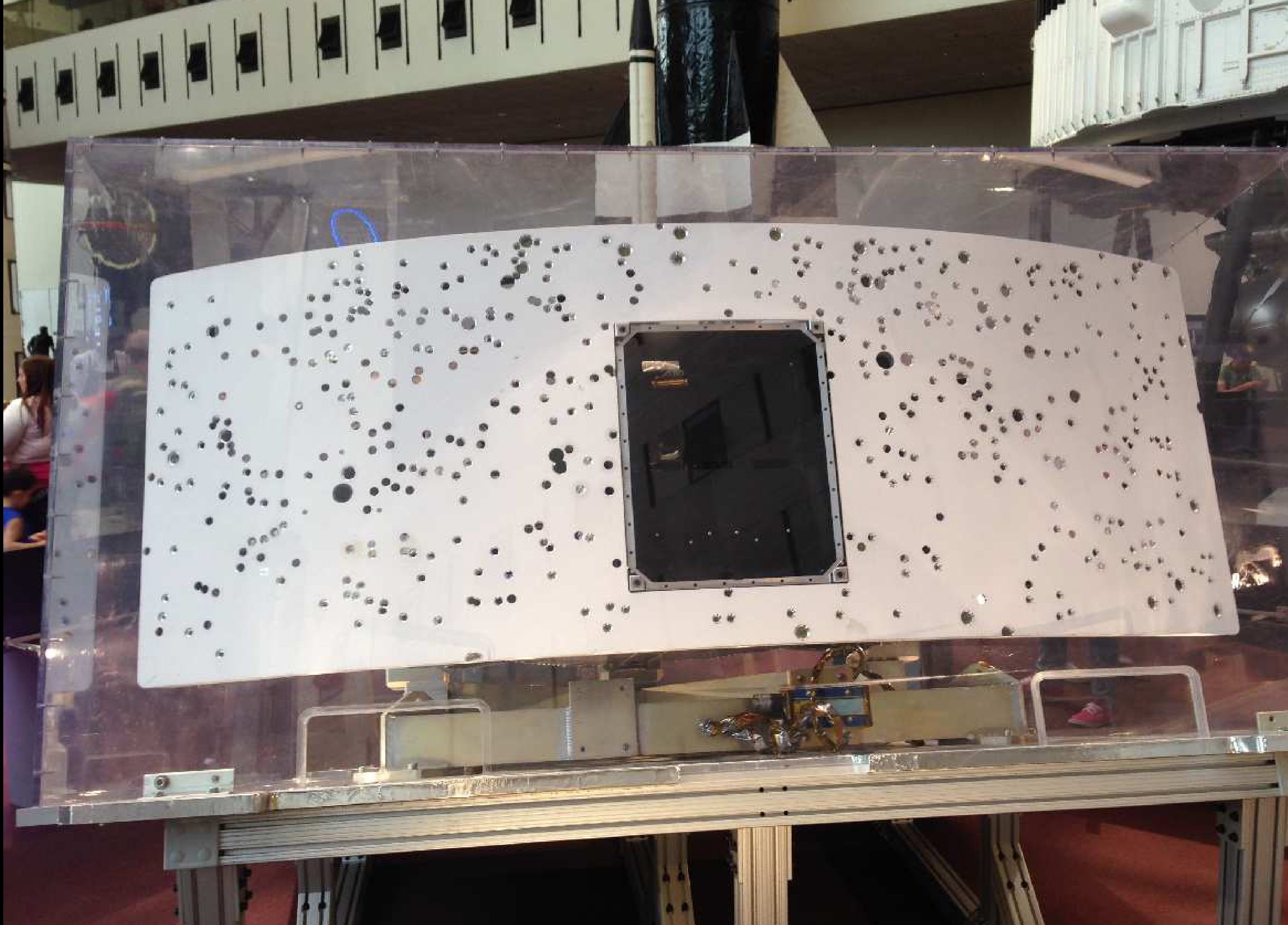
Flight sunshield to be completed & tested by 2015 at Northrop (CA).

# Telescope Assembly Ground Support Equipment

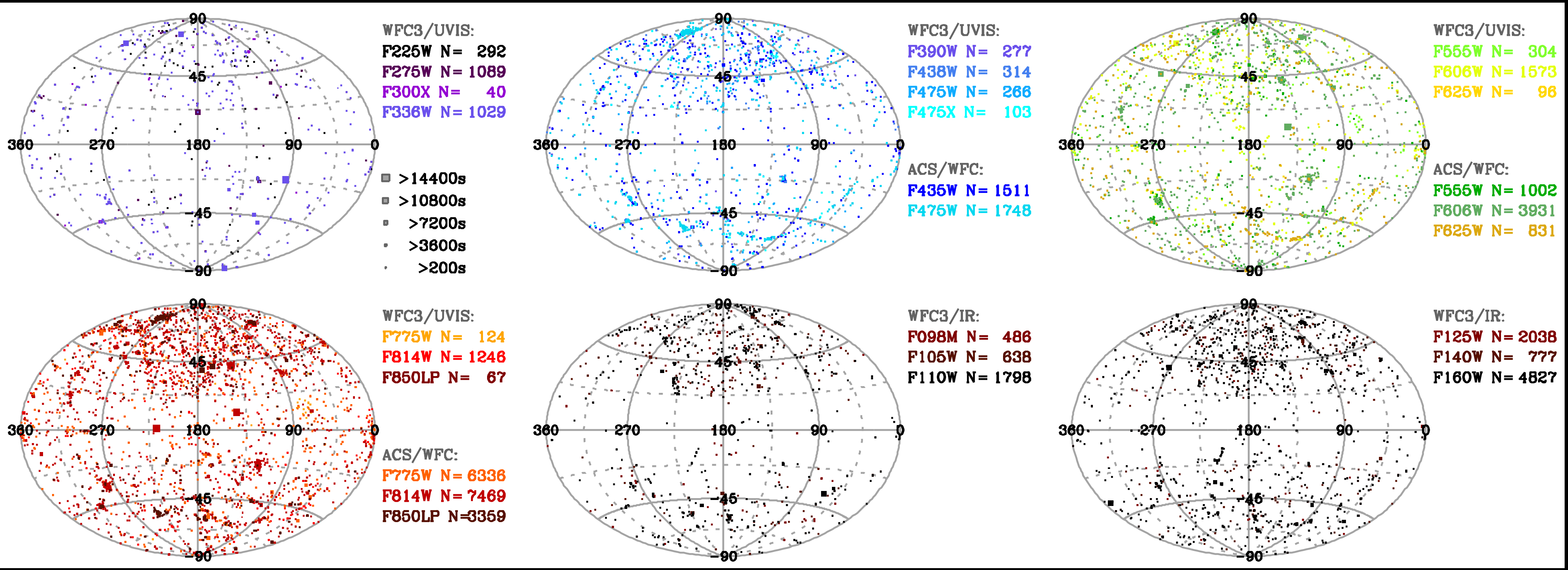
Ambient Optical Alignment Stand Complete


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

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).

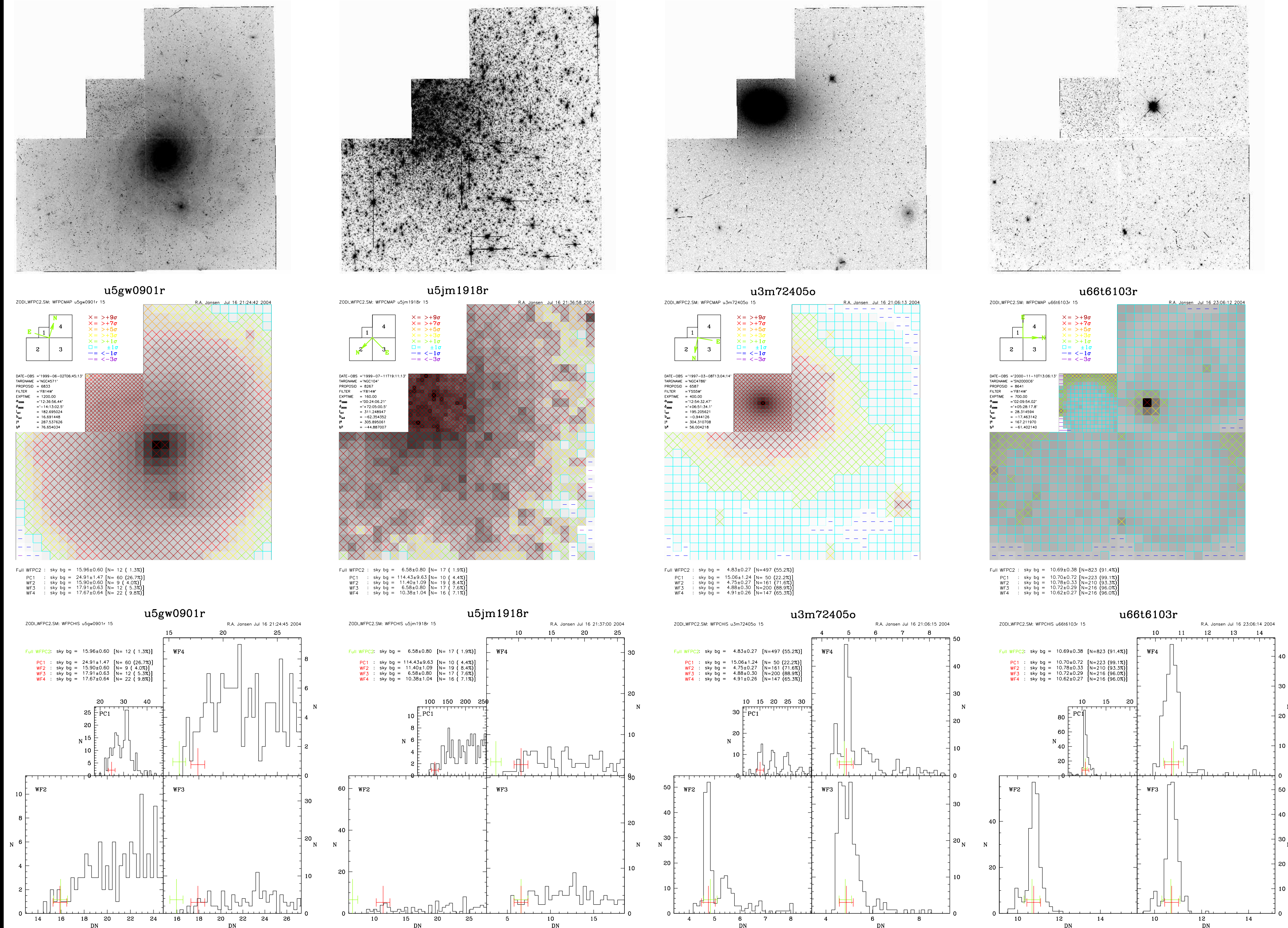



Summary of 21 years of HST WFPC2, ACS and WFC3 Zodi measurements:

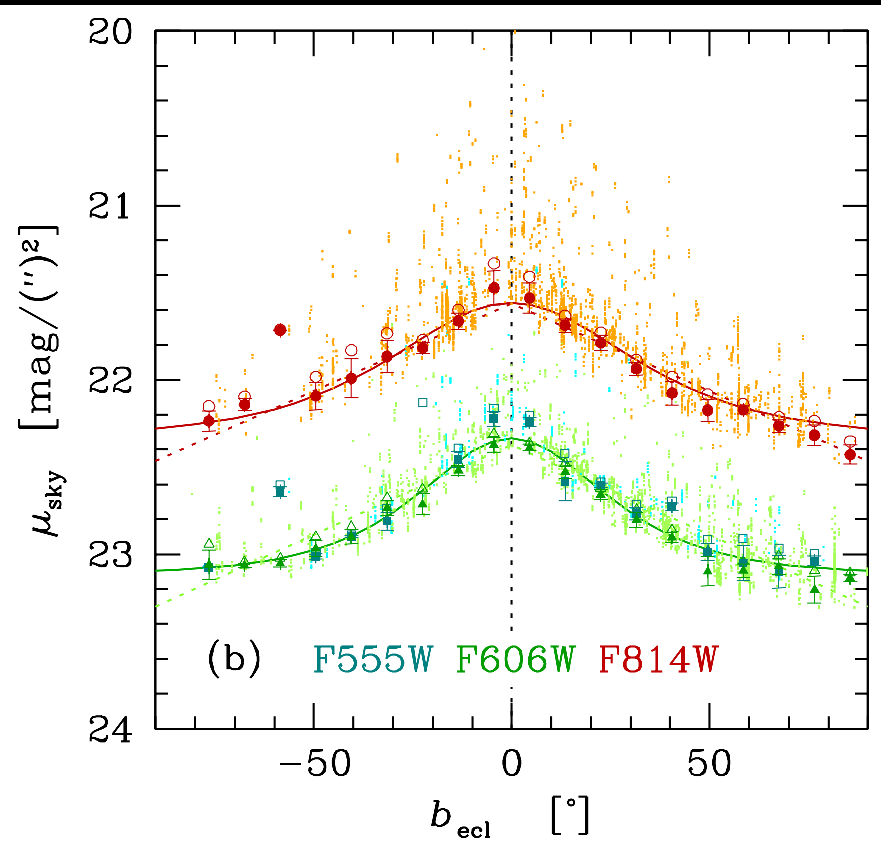
- Ecliptic distribution of 43,571 ACS/WFC and WFC3/UVIS+IR targets as of Spring 2014: Use to measure Zodi sky SB($l^{Ecl}$ , $b^{Ecl}$ ).

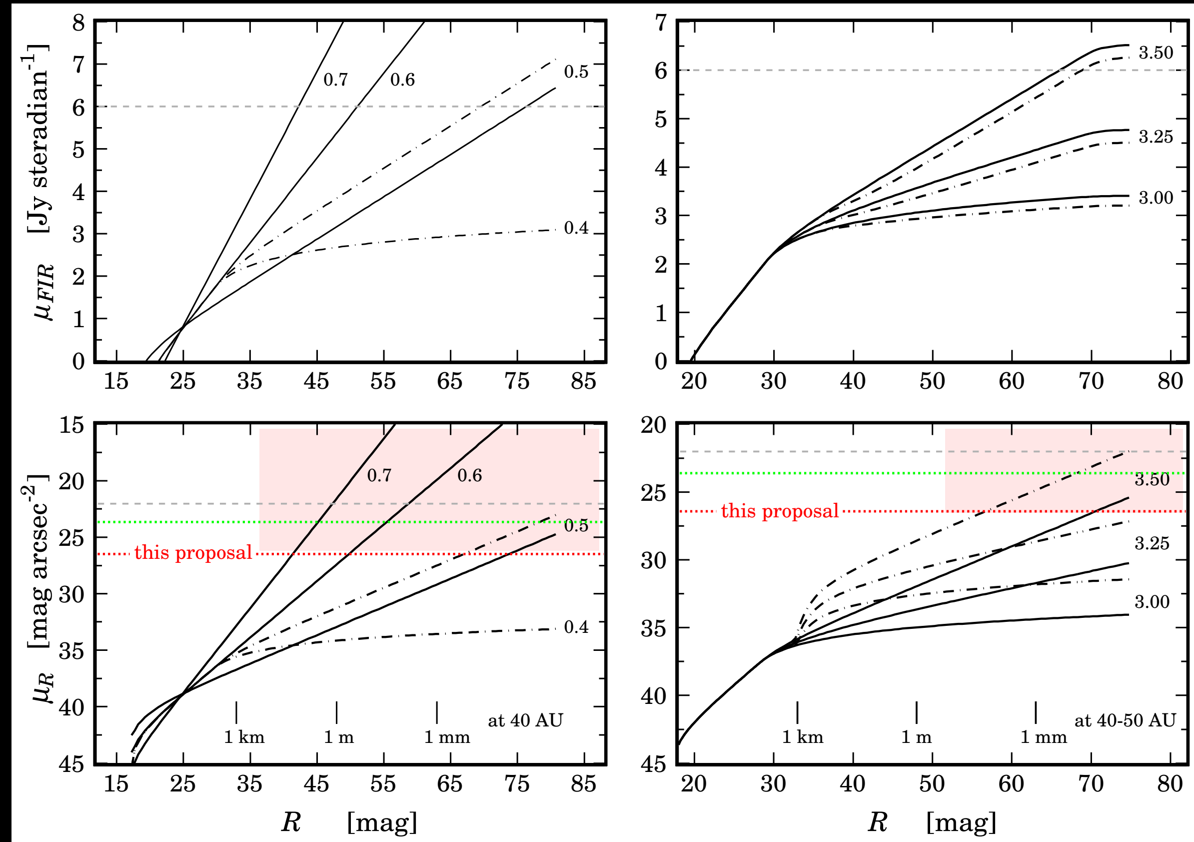
- WFPC2 Zodi measurements on next pages (Jansen et al. 2014).

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




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).

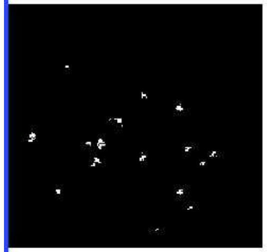
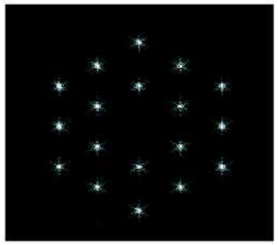
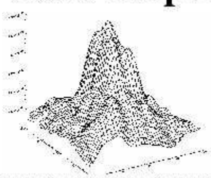
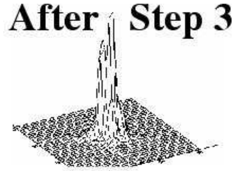
If L2 meteoroid size *distribution* same as in Kuiper belt (also have $\alpha \lesssim$3.3 to avoid Olbers paradox!), then L2 meteoroid impact rate predictable.

# Chamber doesn't look so big anymore!



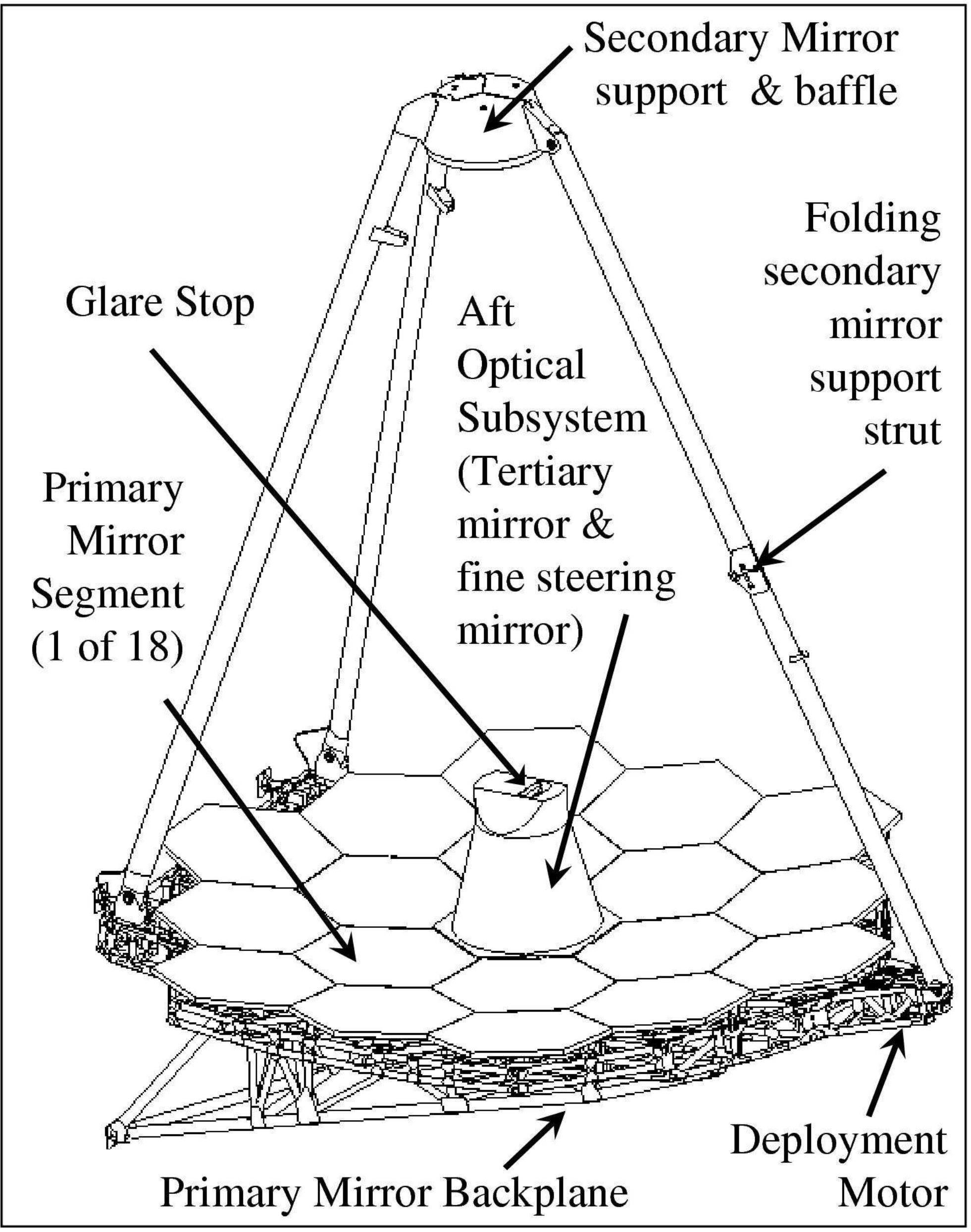


July 2014: OTIS — World's largest TV chamber readied to test JWST.

| Step | | Initial Capture | Final Condition |
|---|---|---|---|
| *First light NIRCam*  1. Segment Image Capture | After Step 1  | 18 individual 1.6-m diameter aberrated sub-telescope images<br>PM segments: < 1 mm, < 2 arcmin tilt<br>SM: < 3 mm, < 5 arcmin tilt | PM segments: < 100 µm, < 2 arcsec tilt<br>SM: < 3 mm, < 5 arcmin tilt |
| **2. Coarse Alignment**<br>Secondary mirror aligned<br>Primary RoC adjusted | After Step 2  | Primary Mirror segments: < 1 mm, < 10 arcsec tilt<br>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) |

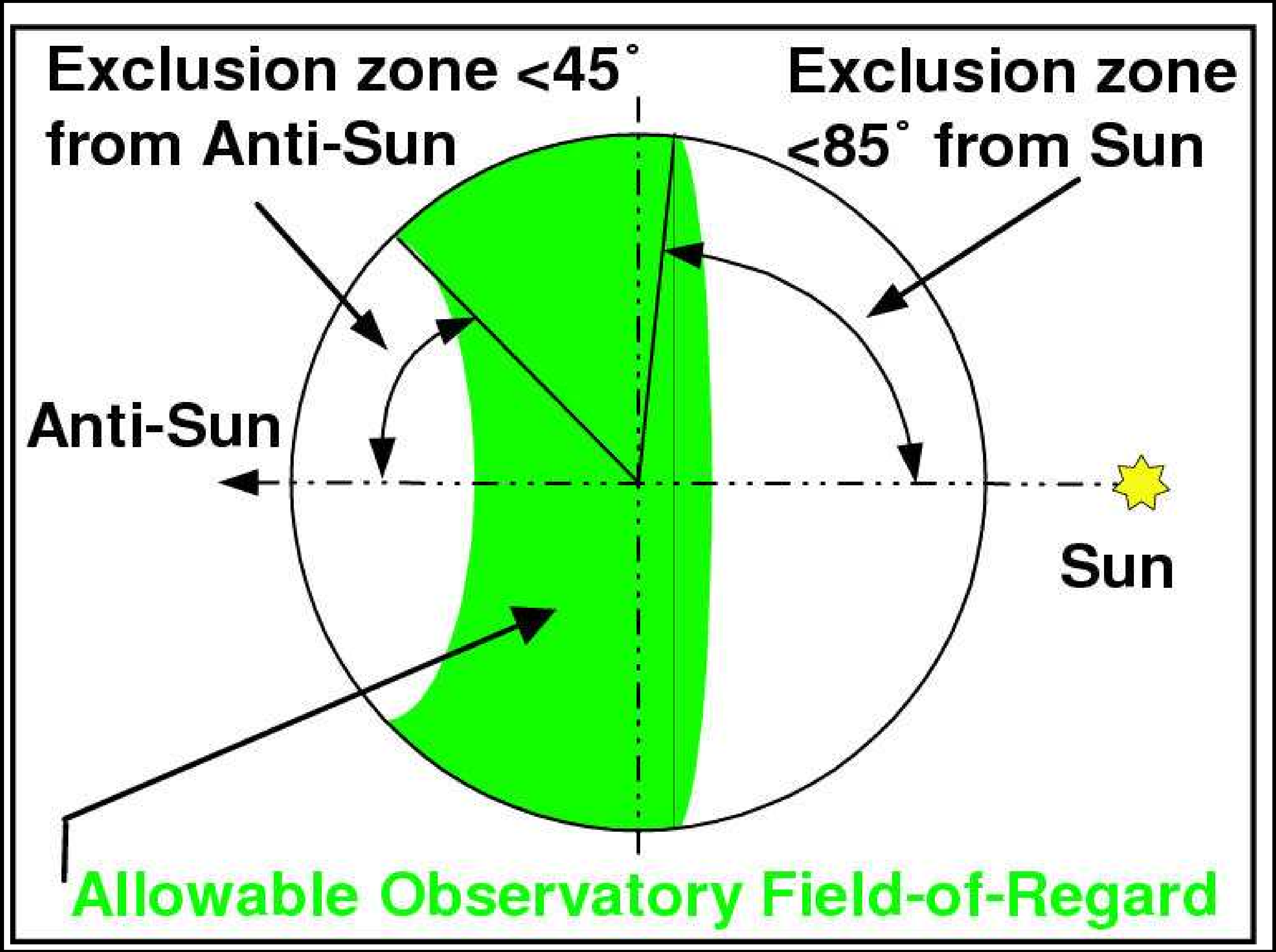
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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




Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

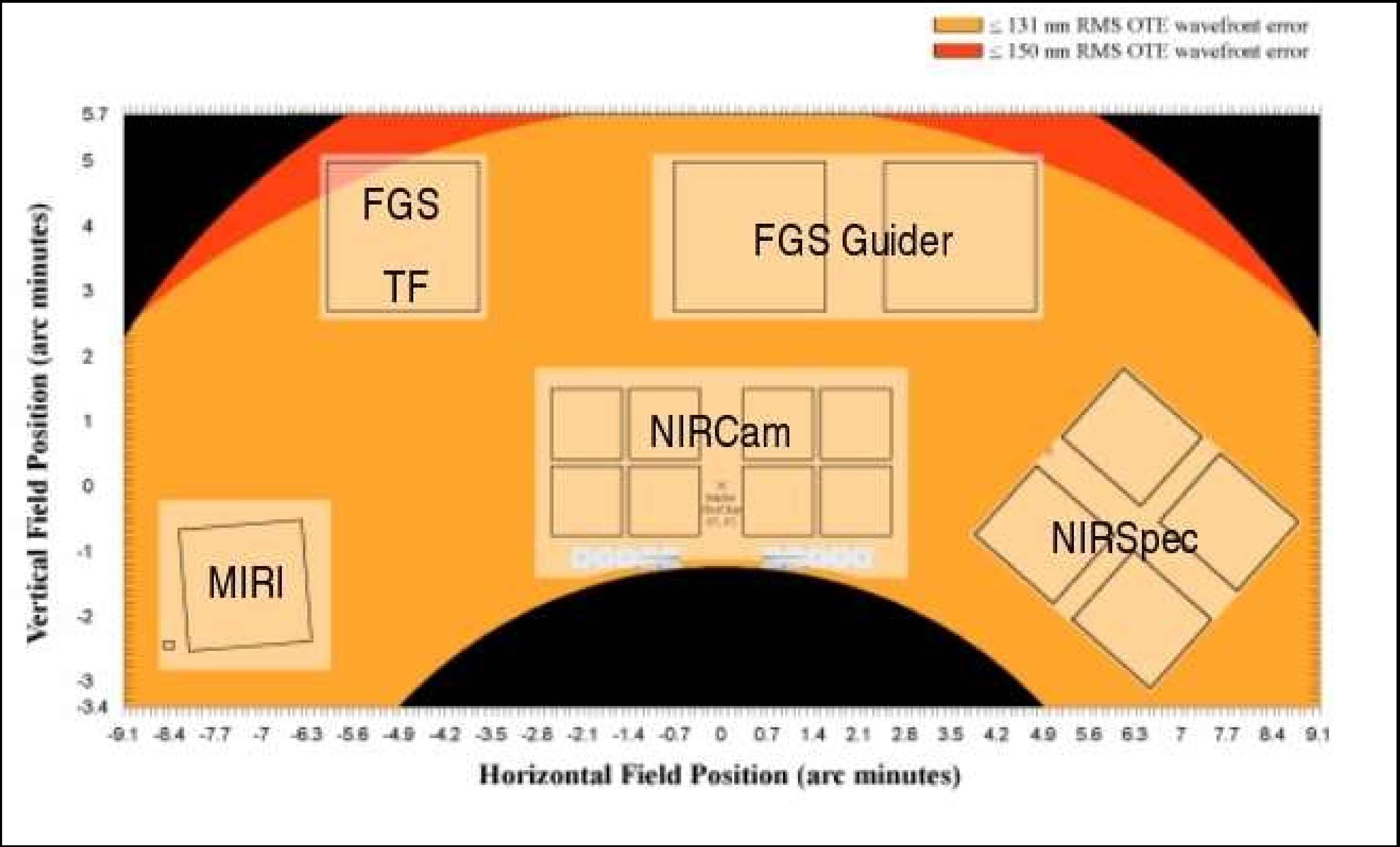
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 $\mu$m images.




JWST can observe North/South Ecliptic pole targets continuously:

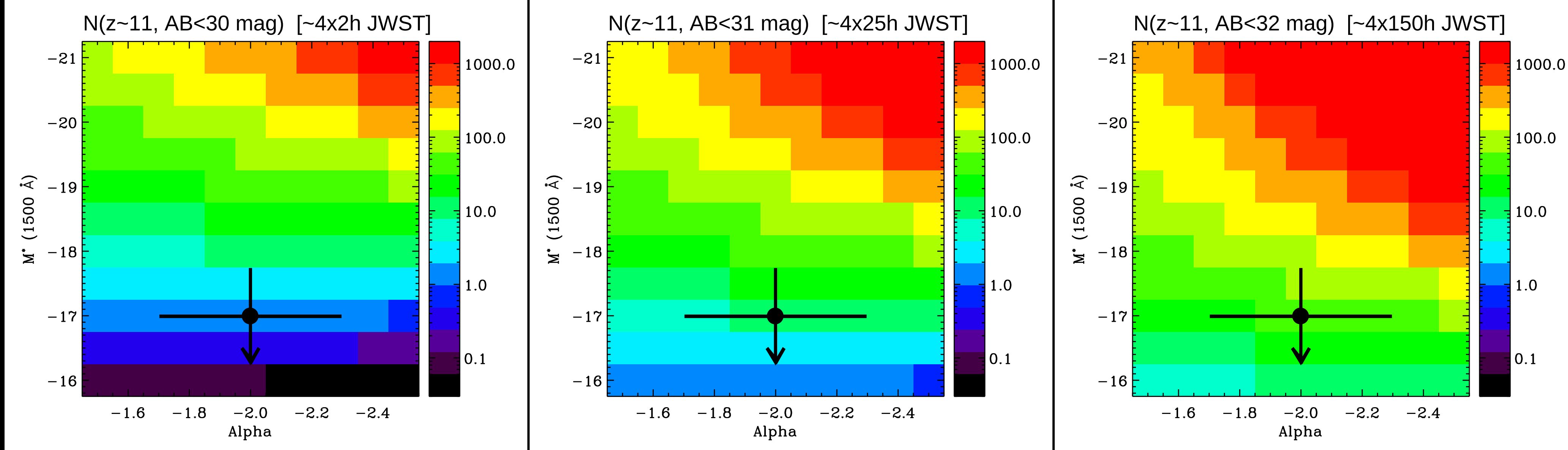
- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

• (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?

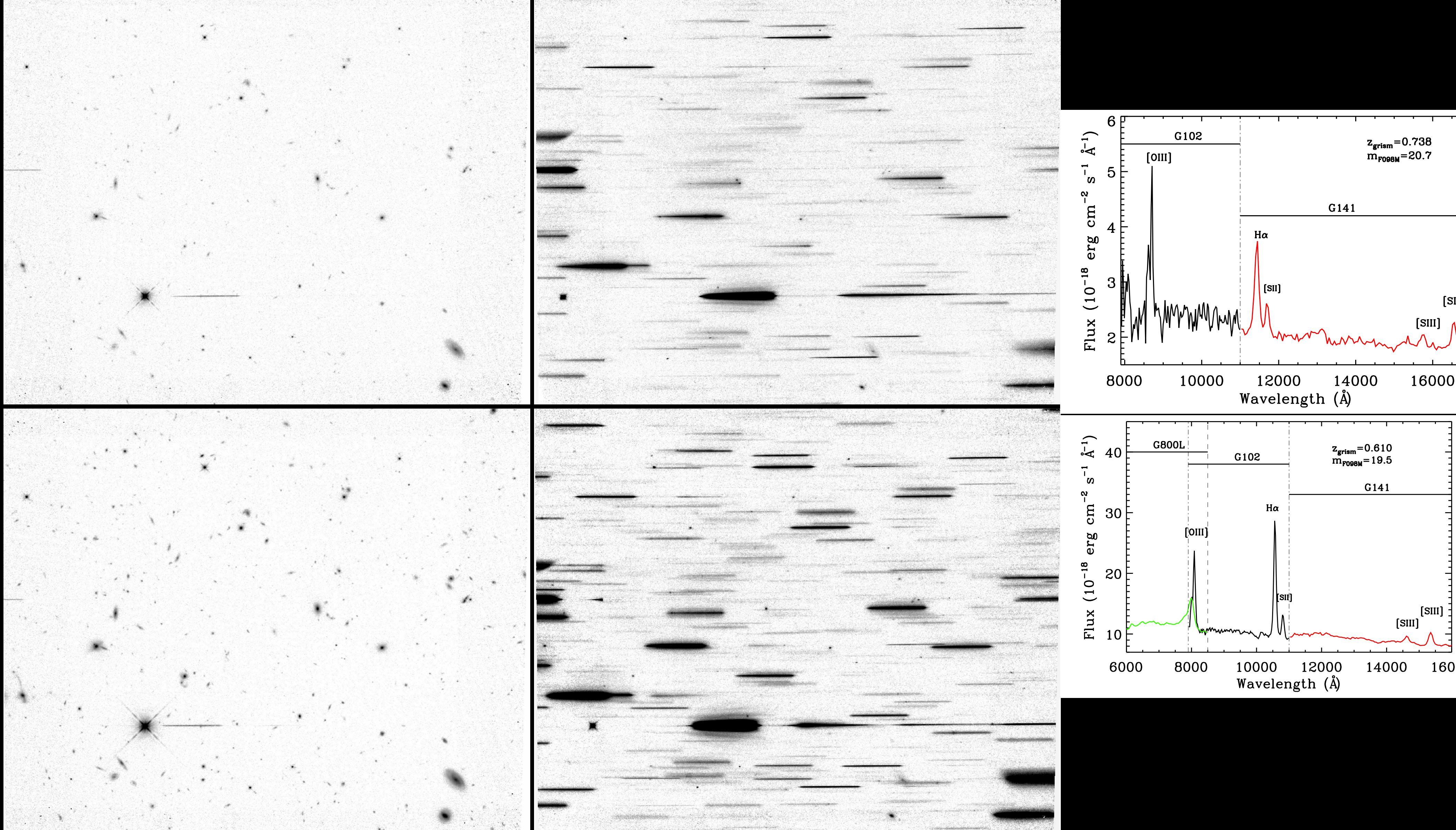
Integrate Schechter LFs with $\alpha$(z), $\Phi^*$ (z) and $M^*$ (z): $\lesssim$45% sky-coverage by AB$\lesssim$30 objects (Koekemoer$^+$13). Cosmic Variance $\gtrsim$30%.

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$2h RAW): Expect few z$\simeq$10–12 objects to AB$\lesssim$30 mag, so plan lensing targets.

- (2) [Middle] Webb Deep Field (**WDF**) (4$\times$25h 7-filt NIRCam GTO): Expect 8–25 objects at z$\simeq$10–12 to AB$\lesssim$31 mag.

- (3) [Right] Webb UltraDeep Field (**WUDF**) (4$\times$150h; NIRCam DD?]: Expect 30–90 objects to AB$\lesssim$32 mag, many more if lensing targets.

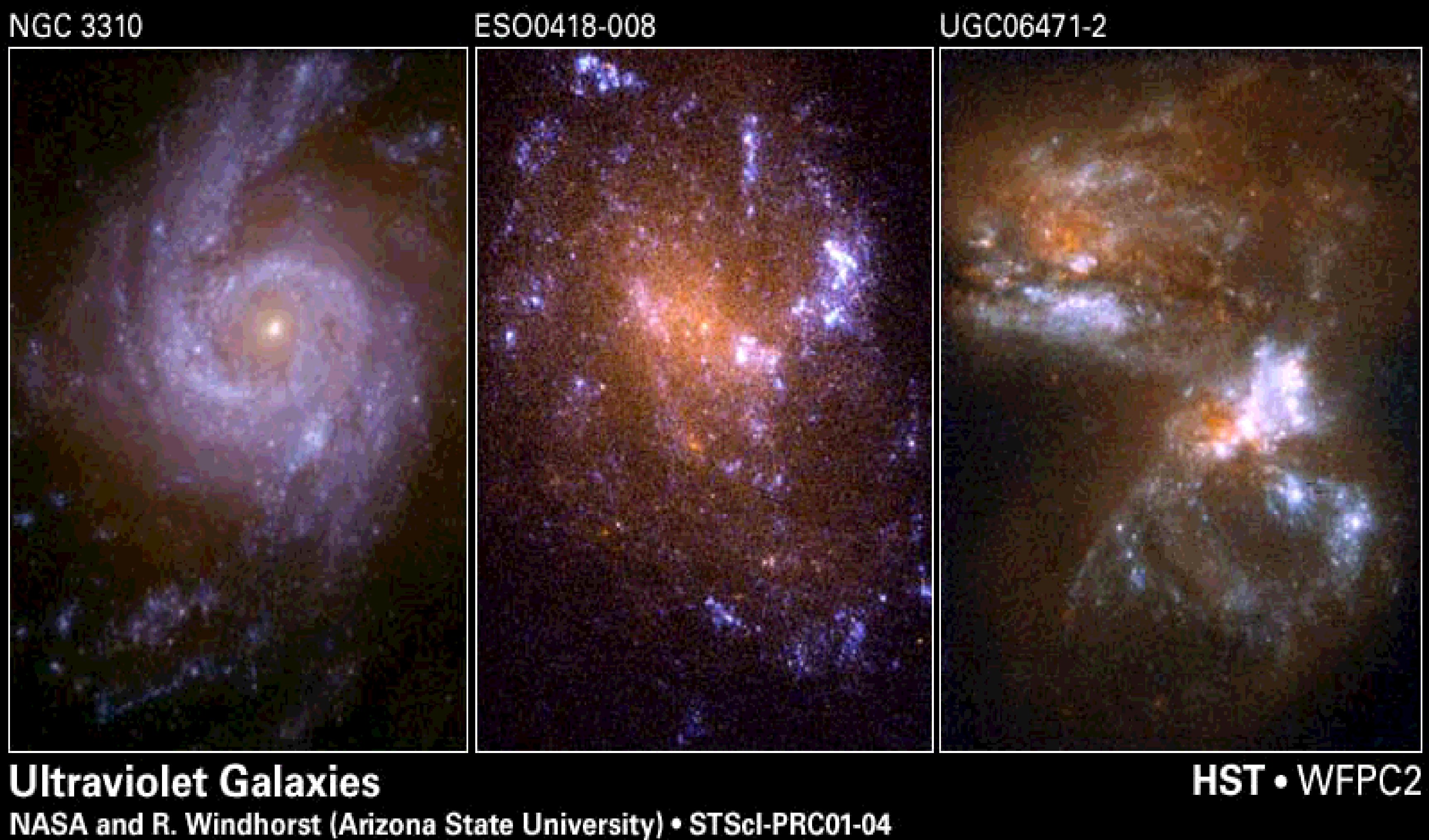



HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn+ 2010)

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 $\mu$m.

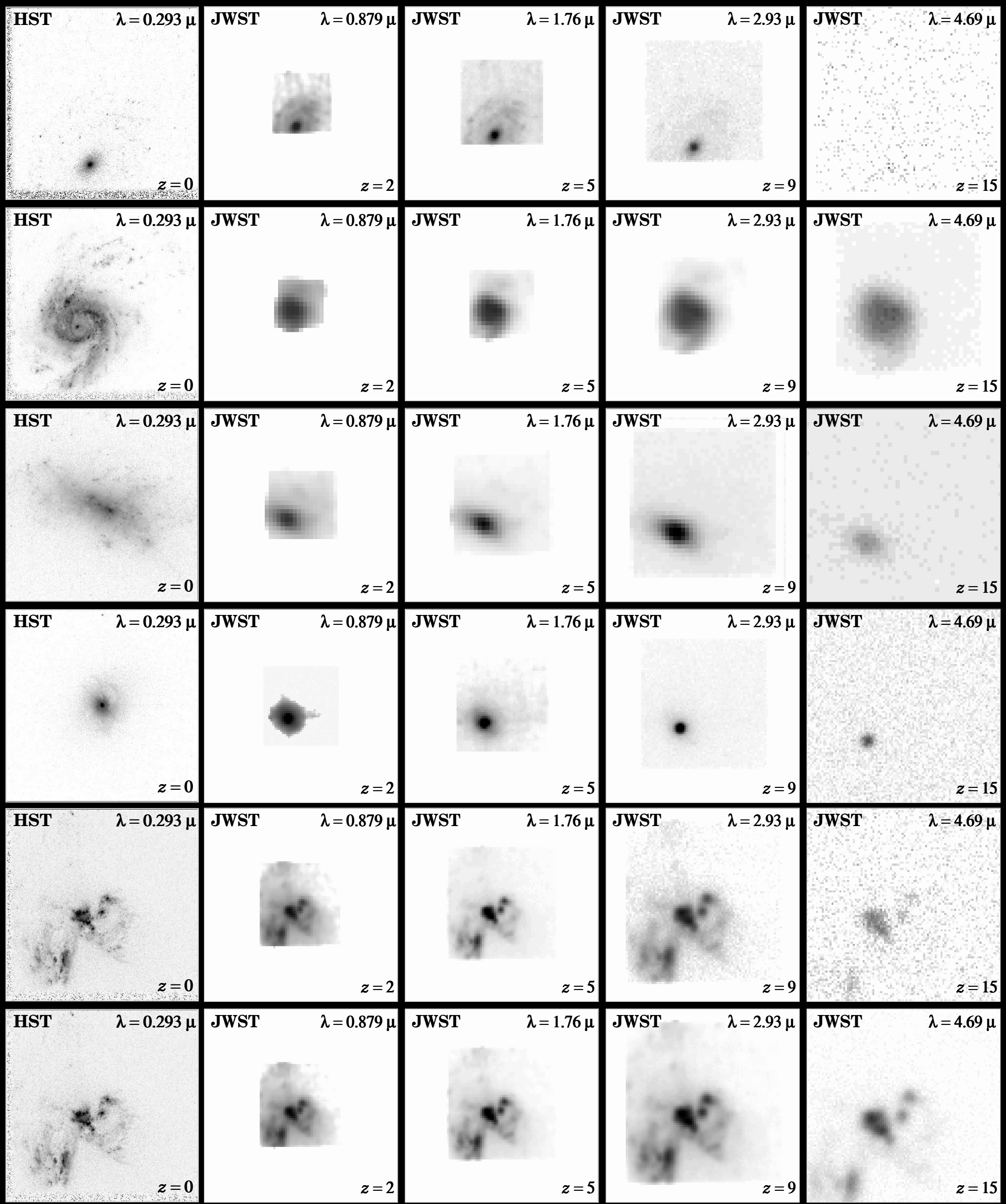
# (4b) Predicted Galaxy Appearance for JWST at redshifts z≃1–15




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

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

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




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

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

Visible to JWST at very high z are:

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

B, I, J AB-mag vs. half-light radii $r_e$ from RC3 to HUDF limit are shown.

All surveys limited by by SB (+5 mag dash)

Deep surveys bounded also by object density.

Violet lines are gxy counts converted to to natural conf limits.

Natural confusion sets in for faintest surveys (AB≳25). Will update for JWST.