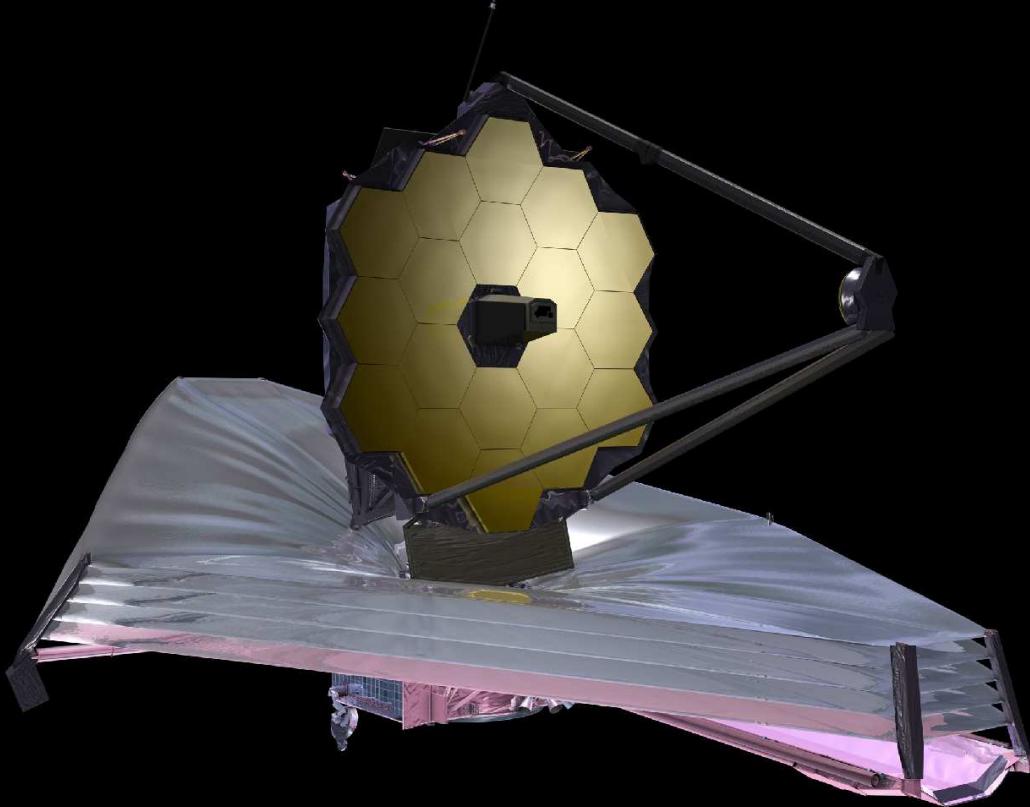


How will the Webb Telescope measure First Light and Galaxy Assembly: New Frontier in the Cosmos after Hubble

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, A. Straughn & K. Tamura



Talk at the ASU Undergraduate Seminar AST 394; ASU, Tempe, AZ

Friday May 2, 2014. All presented materials are ITAR-cleared.

Outline

- (1) Where do our students end-up? Possible NASA Careers
- (2) The Best of Hubble: Recent results from the Hubble Space Telescope (HST) and its Wide Field Camera 3 (WFC3).
- (3) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.
- (4) What is the James Webb Space Telescope (JWST)?
- (5) How can JWST measure the Epochs of First Light & Reionization?
- (6) Summary and Conclusions.
- Appendix: (7) Measuring Star-birth and Earth-like exoplanets

(1) What do our Astrophysics College Graduates do?

Future Careers at NASA:

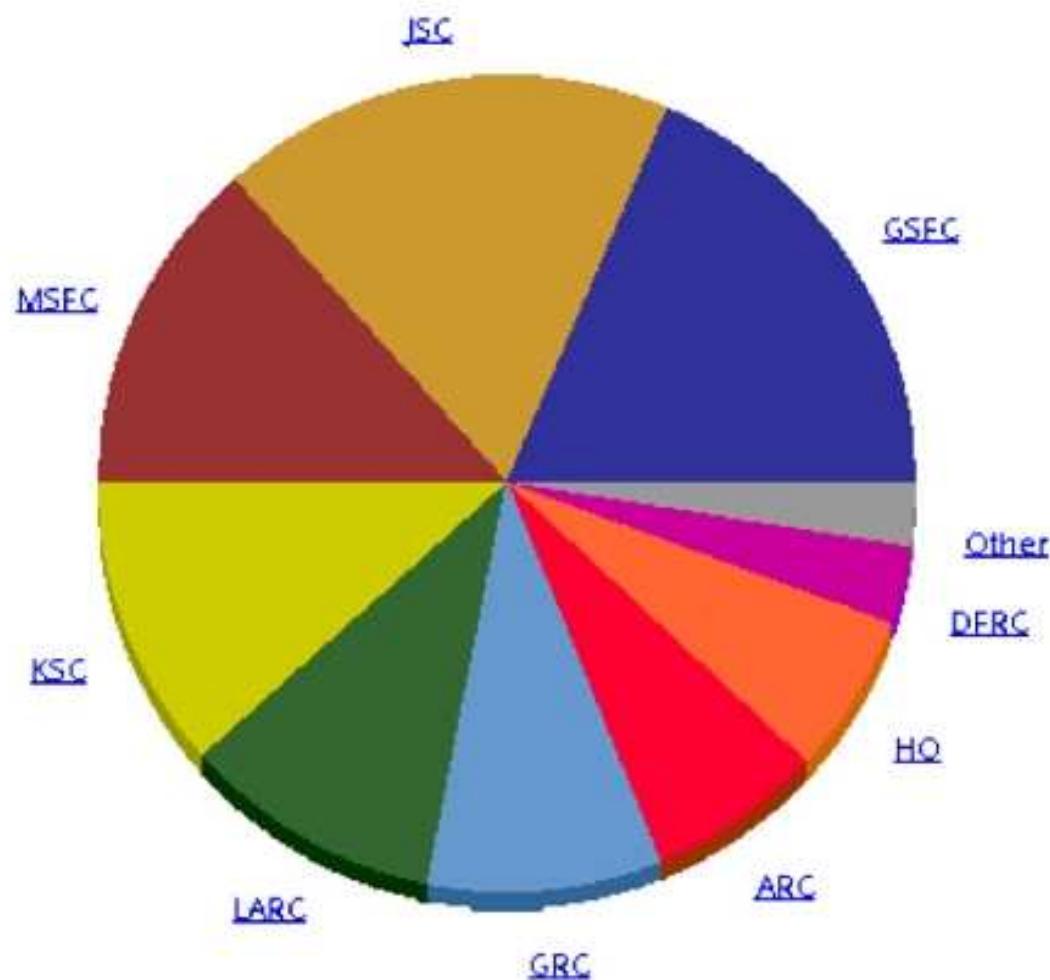
- Over the last 25 years, (ASU) Astrophysics College Graduates typically:
- (0) Have very low unemployment (\lesssim few %).
- (1) About 30% are faculty at Universities or 4-year colleges.
- (2) About 30% are researchers at NASA or other government centers.
- (3) About 20% work in Aerospace or related industries.
- (4) About 20% are faculty at Community Colleges or Highschools.

See: <http://aas.org/learn/careers-astronomy>

and: <http://www.aip.org/statistics/>

CS Head Count

as values



Centers & NSSC	CS Head Count
GSFC	3,354
JSC	3,203
MSFC	2,432
KSC	2,055
LARC	1,881
GRC	1,640
ARC	1,215
HQ	1,152
DFRC	558
Other	454

NASA workforce as pie-chart and in numbers — 2013 total: about 18,000).

Nation-wide NASA contractors (Northrup, Lockheed, Boeing, etc): 150,000.

See also: <https://wicn.nssc.nasa.gov/generic.html>

(2) The Best of Hubble: Recent results from the HST and its WFC3





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

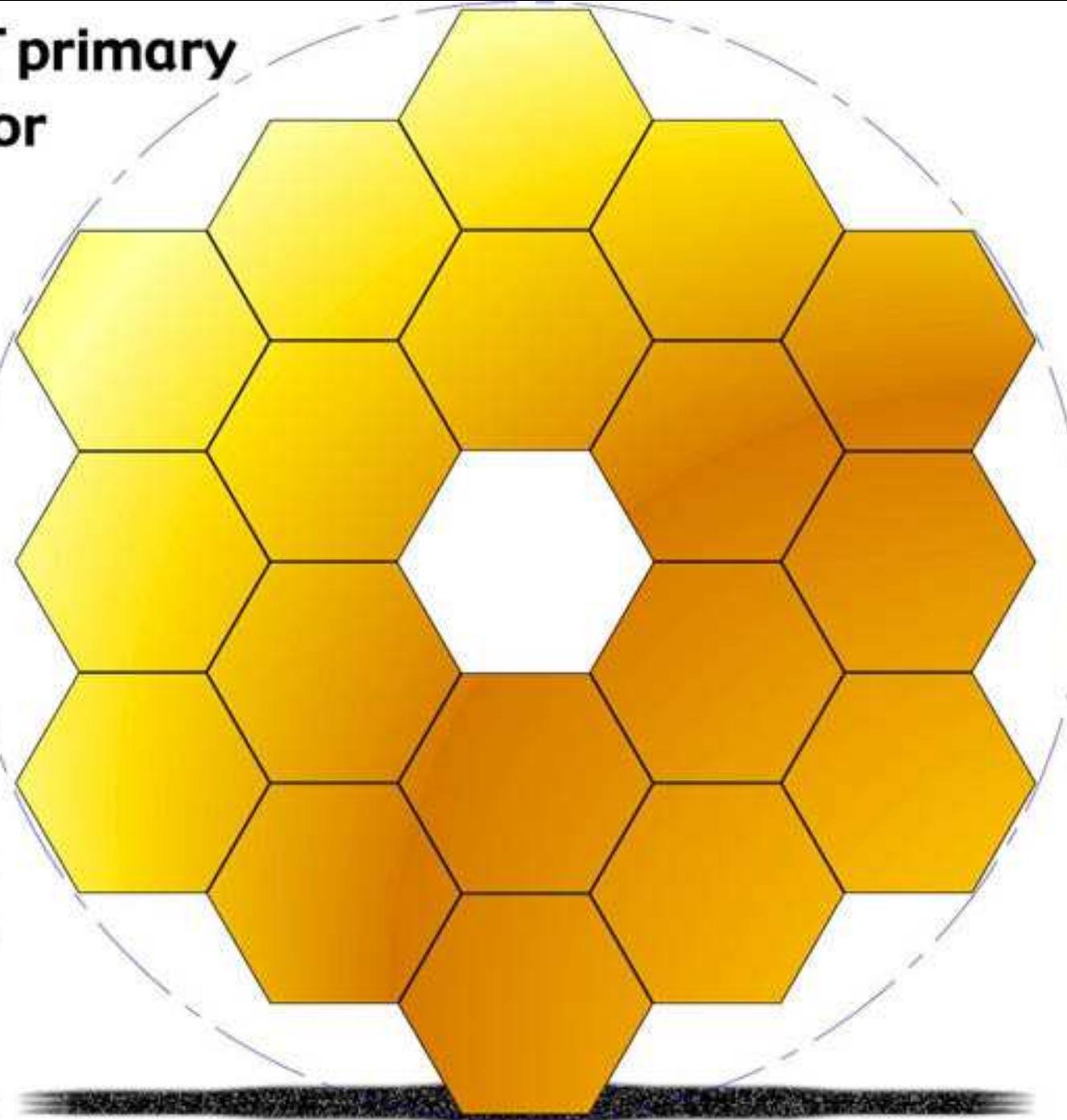


James E. Webb (1906–1992) — Second NASA Administrator

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**

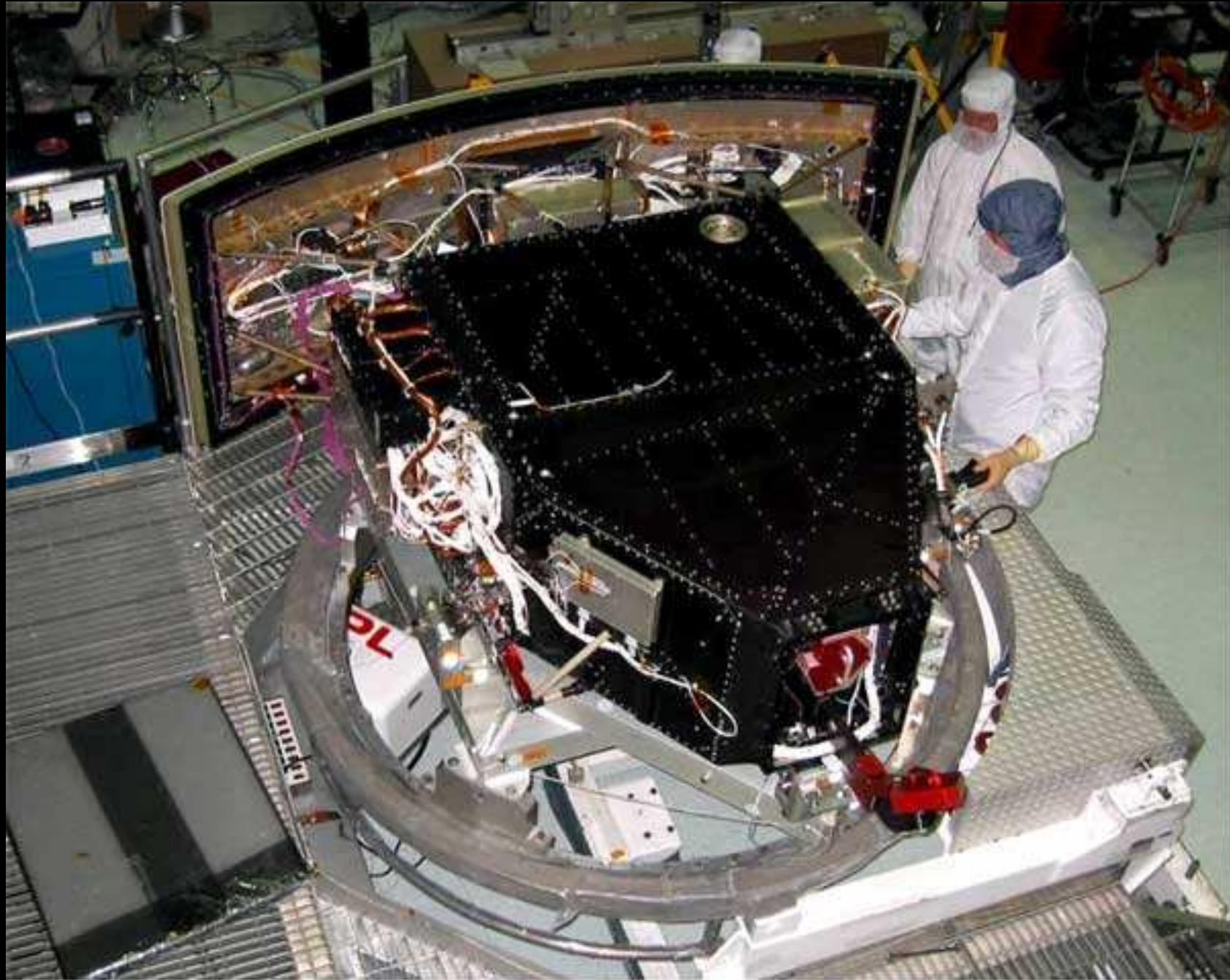


**Hubble primary
mirror**



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.

WFC3: Hubble's new Panchromatic High-Throughput Camera



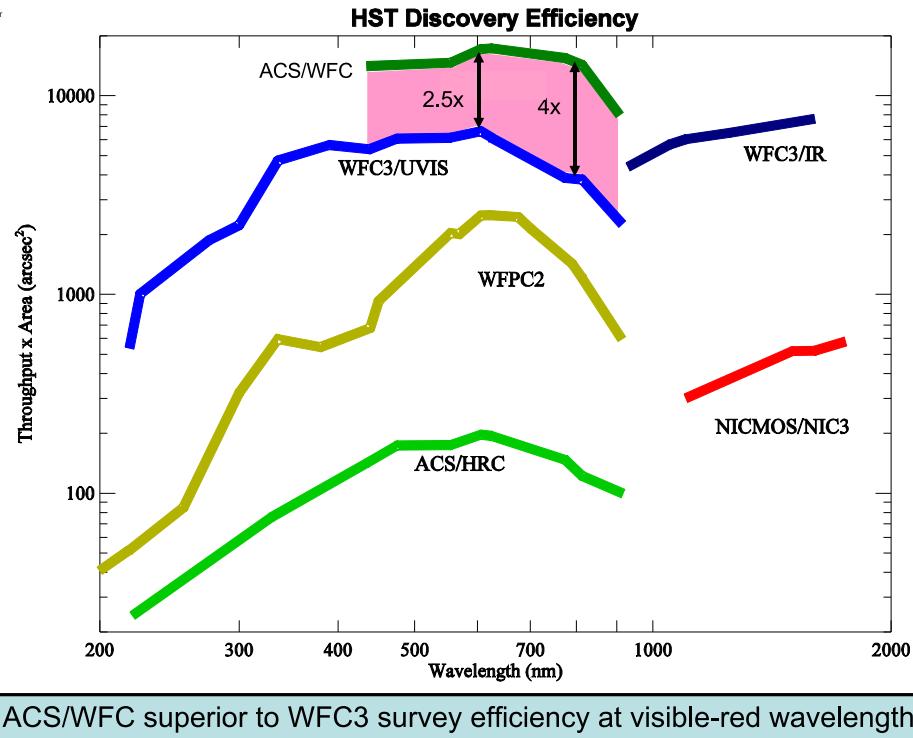
HST WFC3 and its IR channel: a critical pathfinder for JWST science.



Goddard Space Flight Center

Hubble Space Telescope Program

Role of ACS in HST Post-SM4 Imaging Capability



030607_PMB_ACS_Status.ppt

WFC3/UVIS channel unprecedented UV–blue throughput & area:

- QE $\gtrsim 70\%$, $4k \times 4k$ array of $0\farcs04$ pixel, FOV $\simeq 2\farcs67 \times 2\farcs67$.

WFC3/IR channel unprecedented near-IR throughput & area:

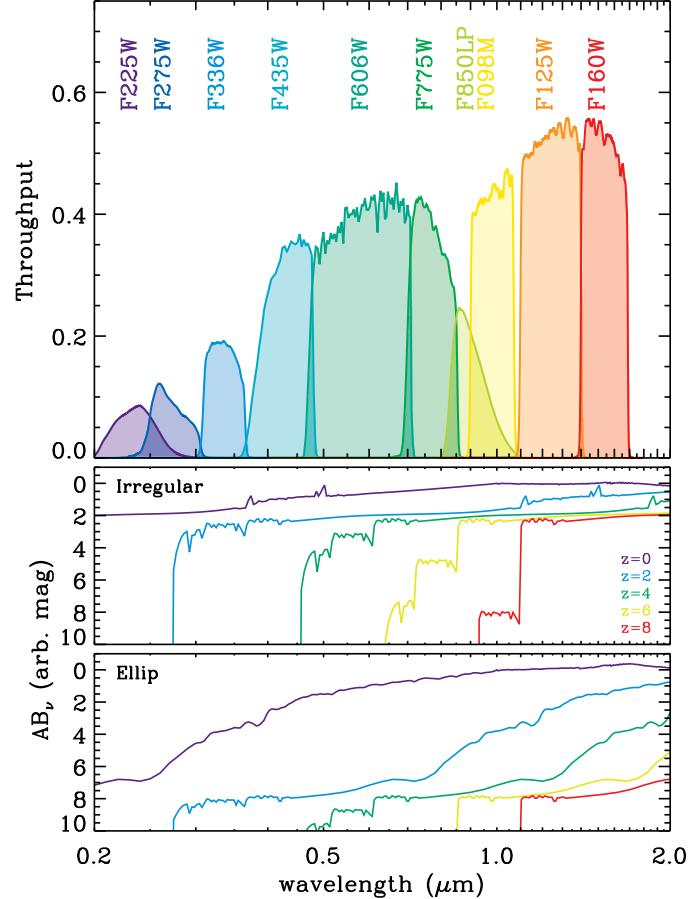
- QE $\gtrsim 70\%$, $1k \times 1k$ array of $0\farcs13$ pixel, FOV $\simeq 2\farcs25 \times 2\farcs25$.

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

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

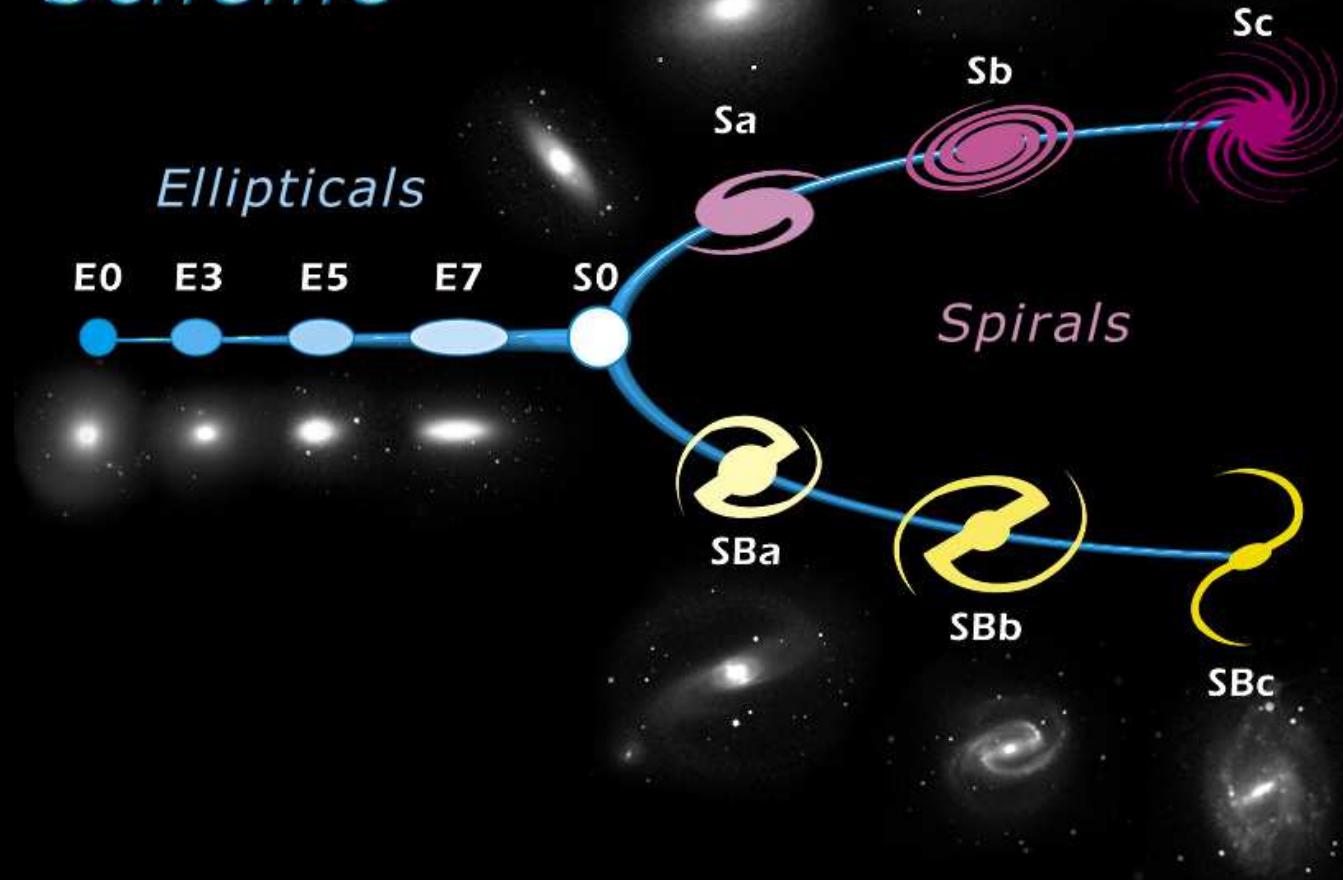
- HST WFC3 and its IR channel a critical pathfinder for JWST science.

9



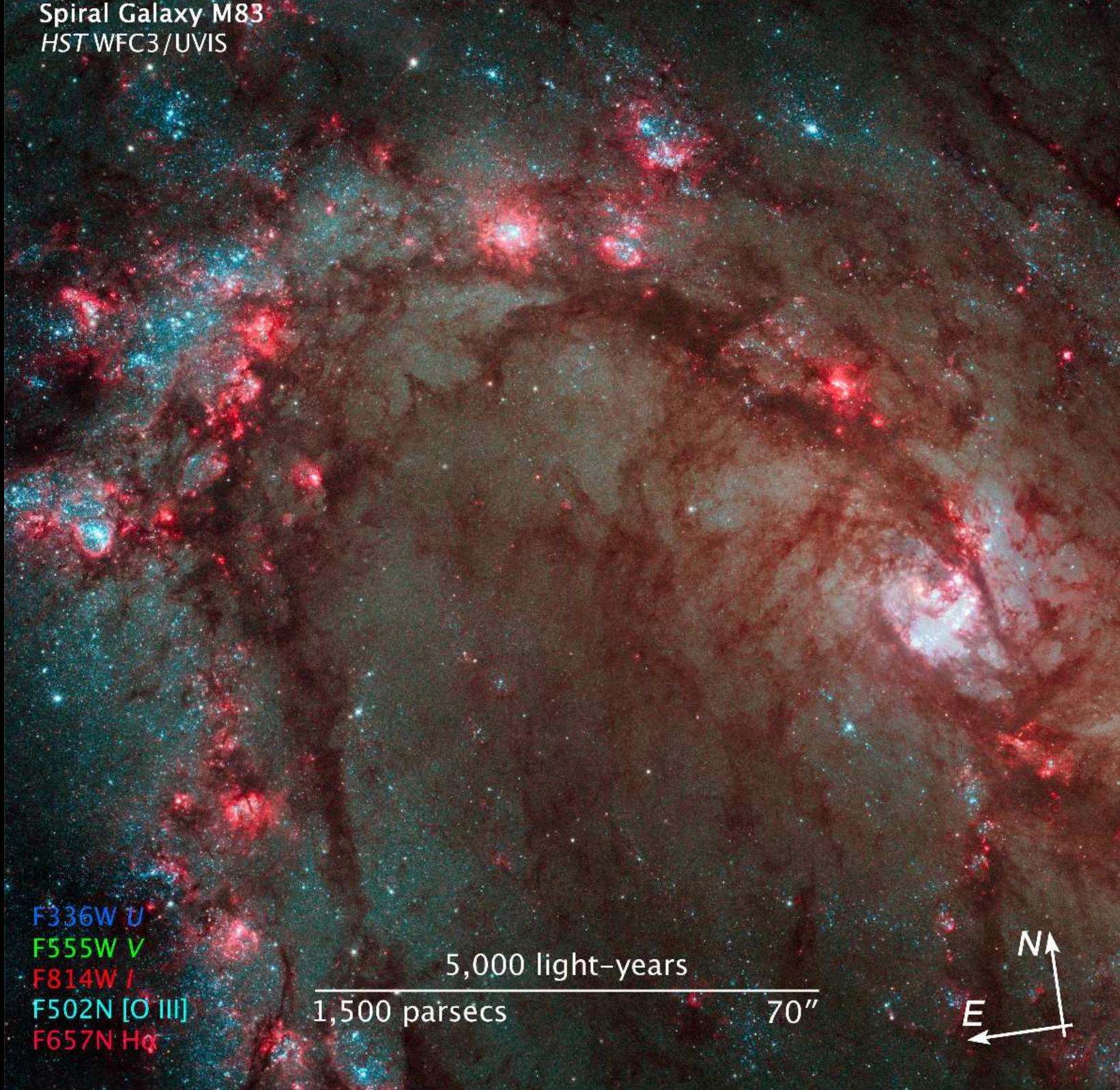
(2) HST turned the classical Hubble sequence upside down!

Edwin Hubble's Classification Scheme



Who (when)	Cosmic Epoch	Ellipticals	Spirals	Irr's/mergers
Hubble (1920's)	$z=0$ (13.73 Gyr)	$\sim 40\%$	$\gtrsim 50\%$	$\lesssim 10\%$
HST (1990's)	$z \approx 1-2$ (3–6 Gyr)	$\lesssim 15\%$	$\sim 30\%$	$\gtrsim 55\% !$

Spiral Galaxy M83
HST WFC3/UVIS







HST Antenna galaxy: Prototype of high redshift, star-forming, major merger?

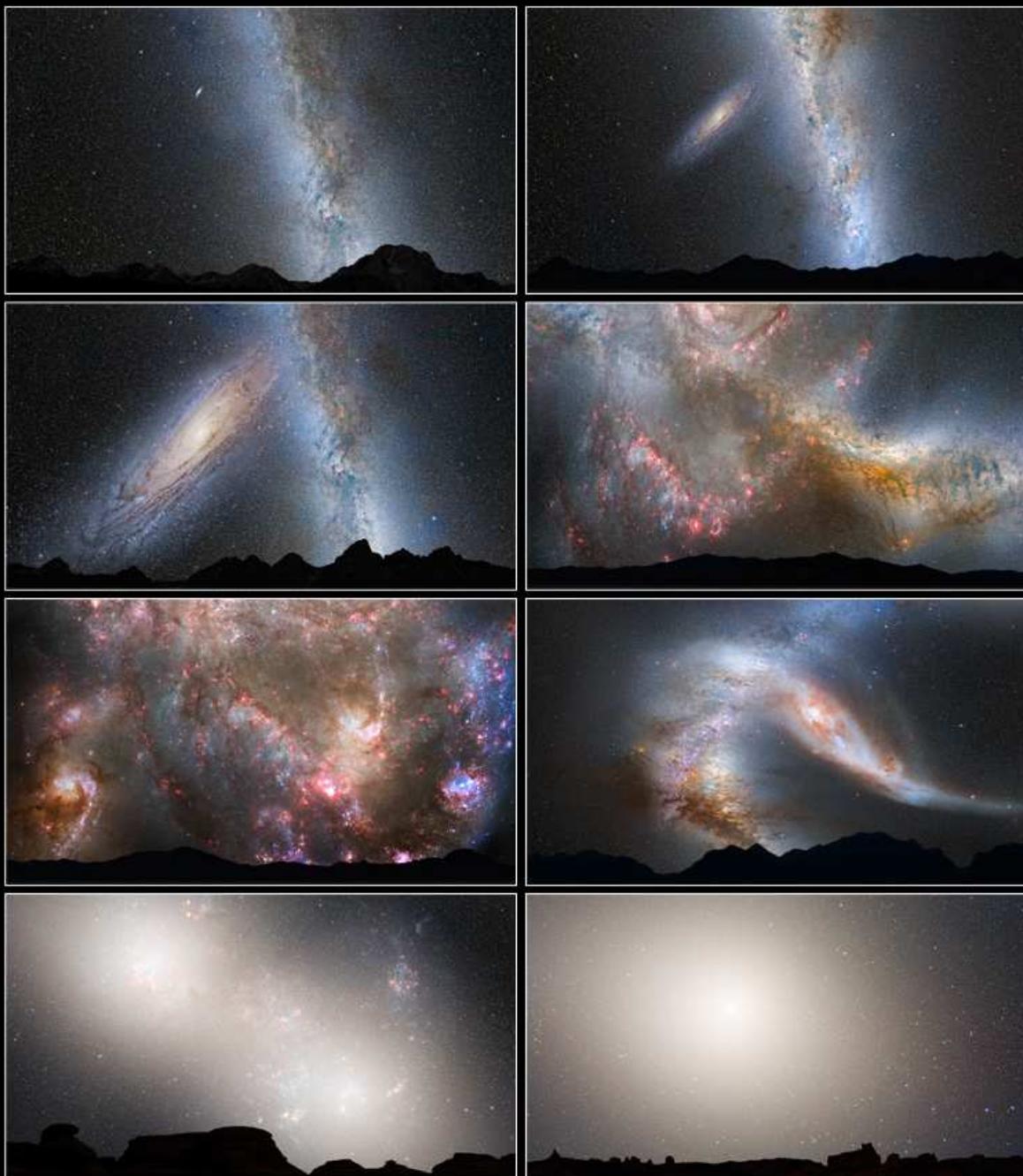


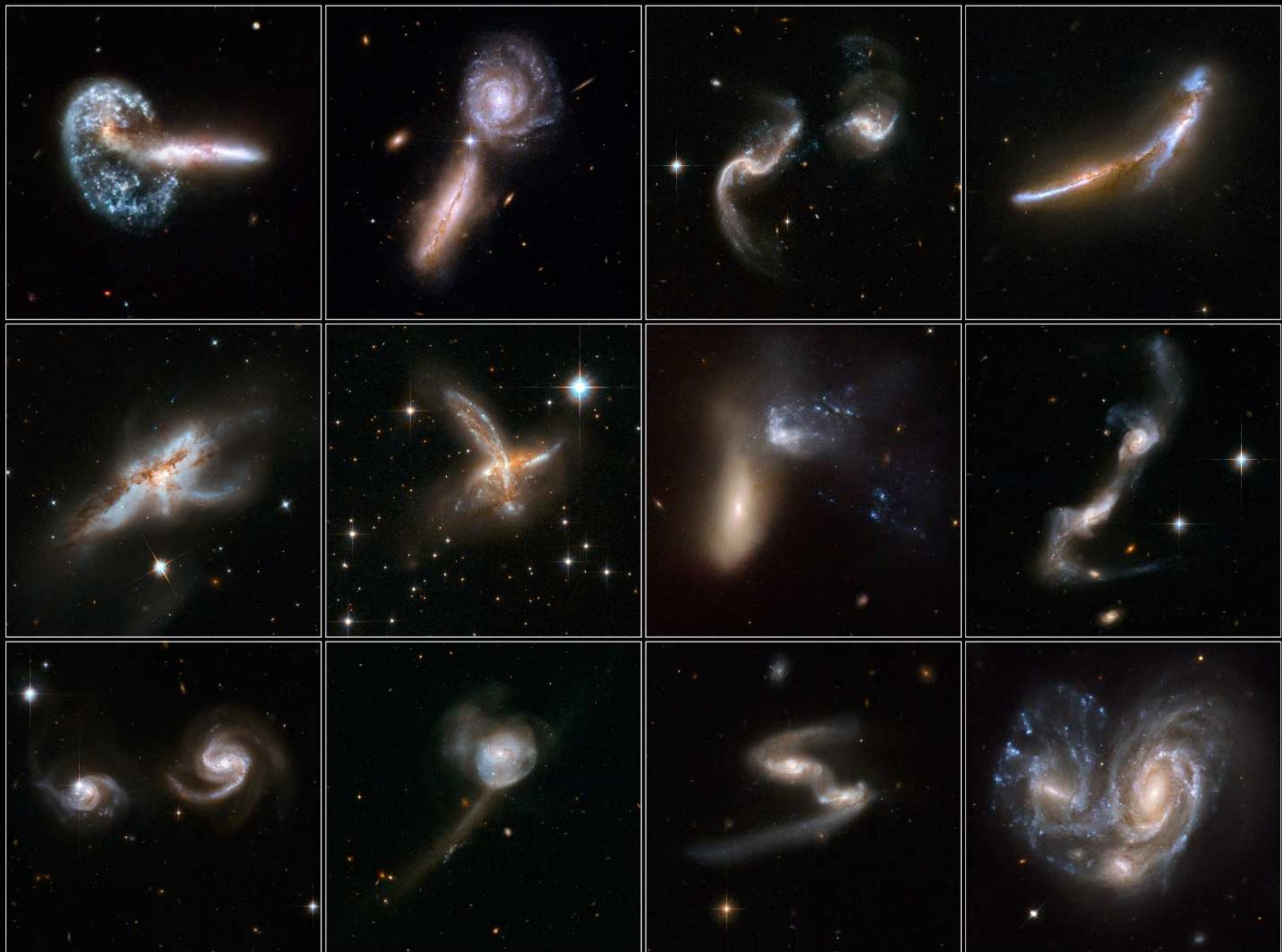
Illustration Sequence of the Milky Way
and Andromeda Galaxy Colliding

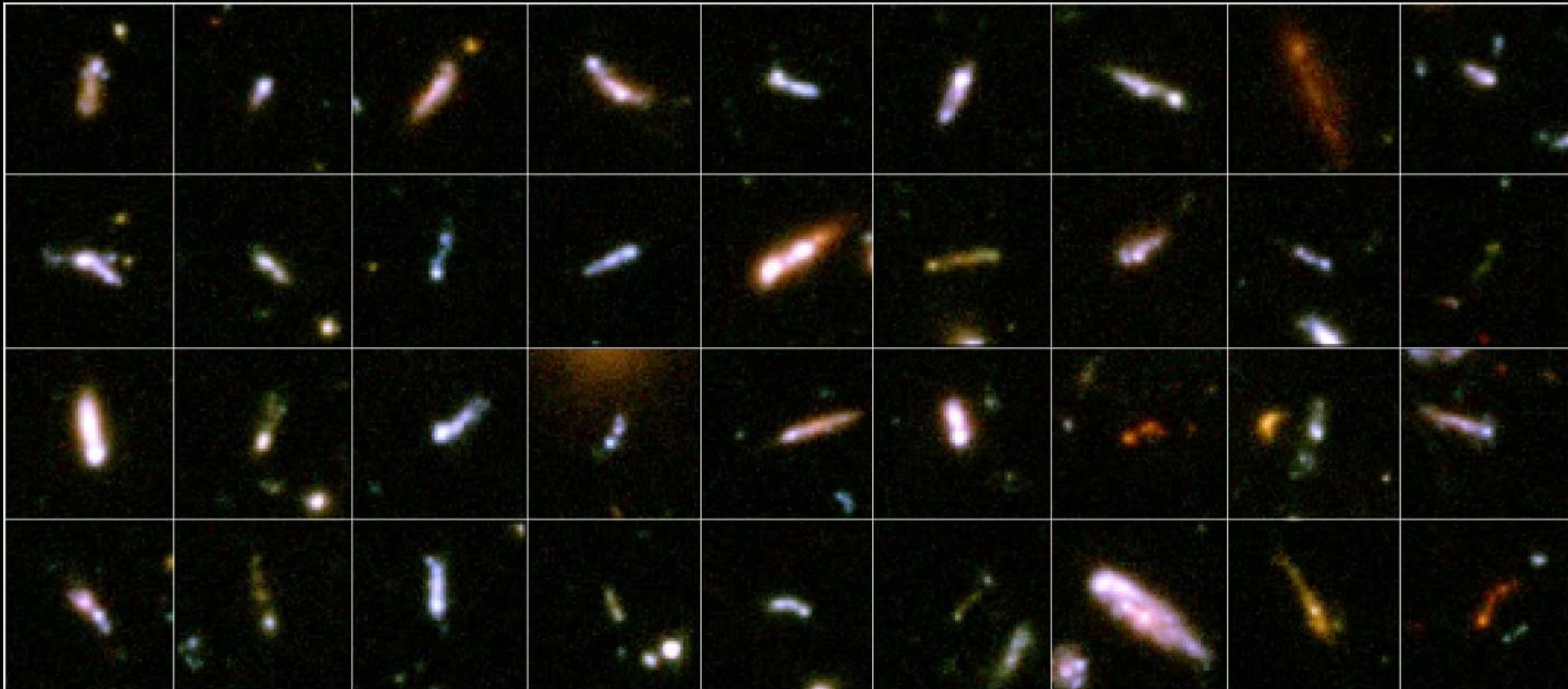
NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger • STScI-PRC12-20b

Merger of Andromeda galaxy (M31) with Milky Way about 4 Gyr from now.

Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2





“Tadpole” Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope ■ ACS/WFC

NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)

STScI-PRC06-04

Merging galaxies constitute $\lesssim 1\%$ of Hubble sequence TODAY (age $\gtrsim 12.5$ Gyr).

Tadpole galaxies are early stage mergers, very common at $z \gtrsim 2$ (age $\lesssim 3$ Gyr).

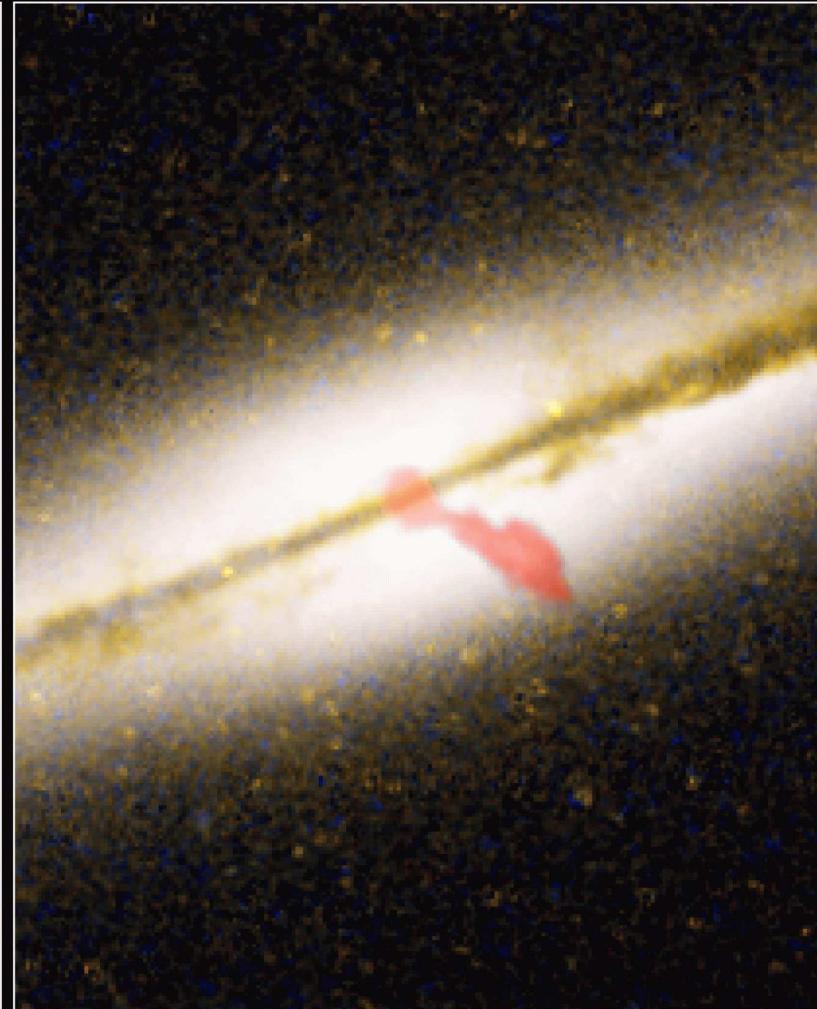
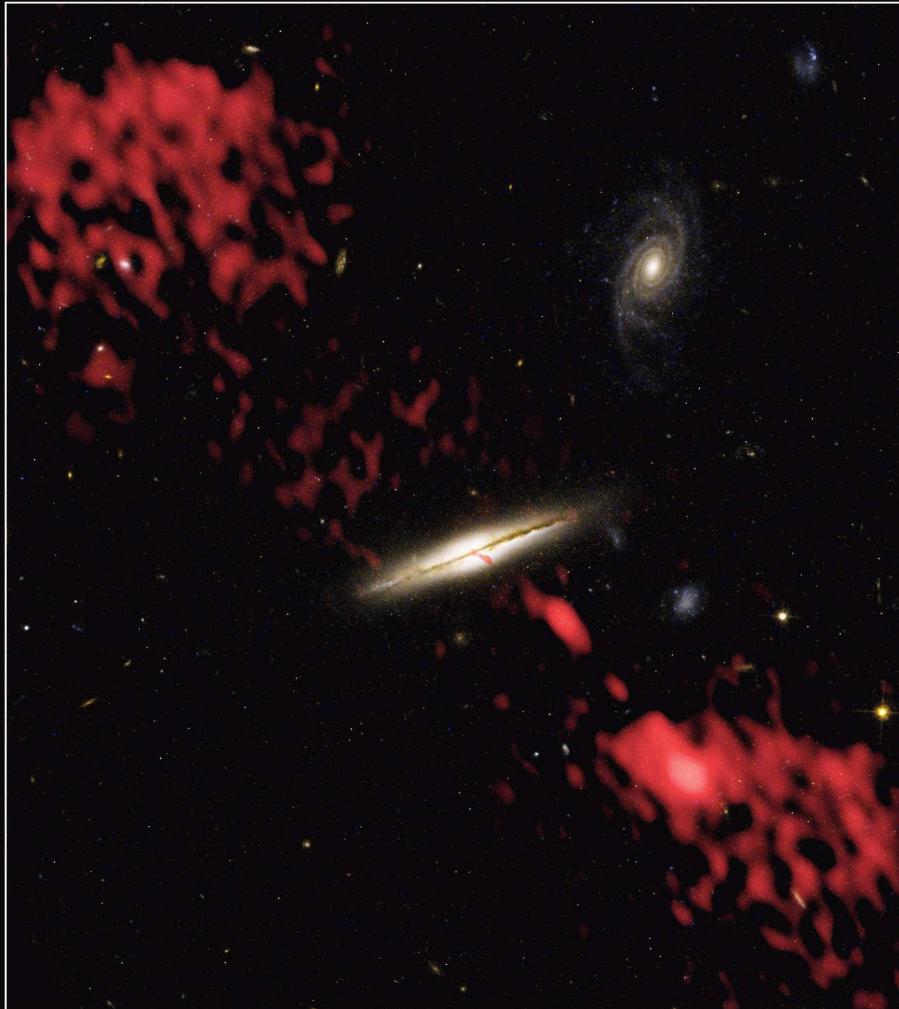
JWST will measure Galaxy Assembly to $z \lesssim 20$ (cosmic age $\gtrsim 0.2$ Gyr).



HST/WFC3 & ACS reach AB=26.5-27.0 mag (\sim 100 fireflies from Moon)
over 0.1 \times full Moon area in 10 filters from 0.2–2 μ m wavelength.

JWST has 3 \times sharper imaging to AB \simeq 31.5 mag (\sim 1 firefly from Moon)
at 1–5 μ m wavelengths, tracing young and old stars + dust.

(3) Measuring Galaxy Assembly & Supermassive Blackhole Growth

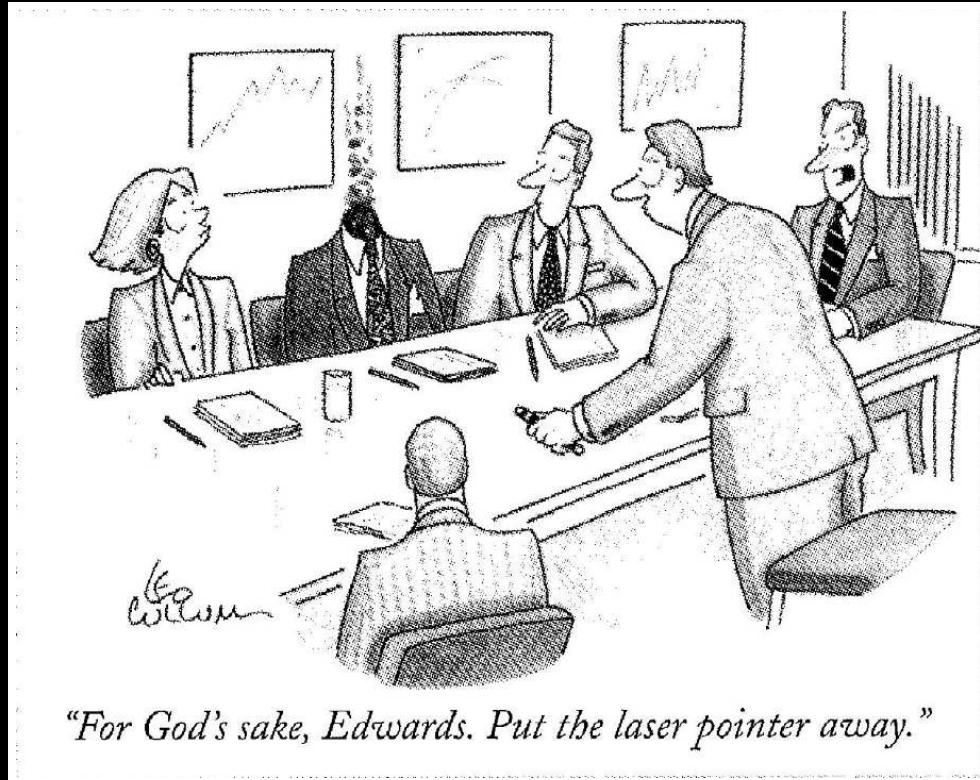
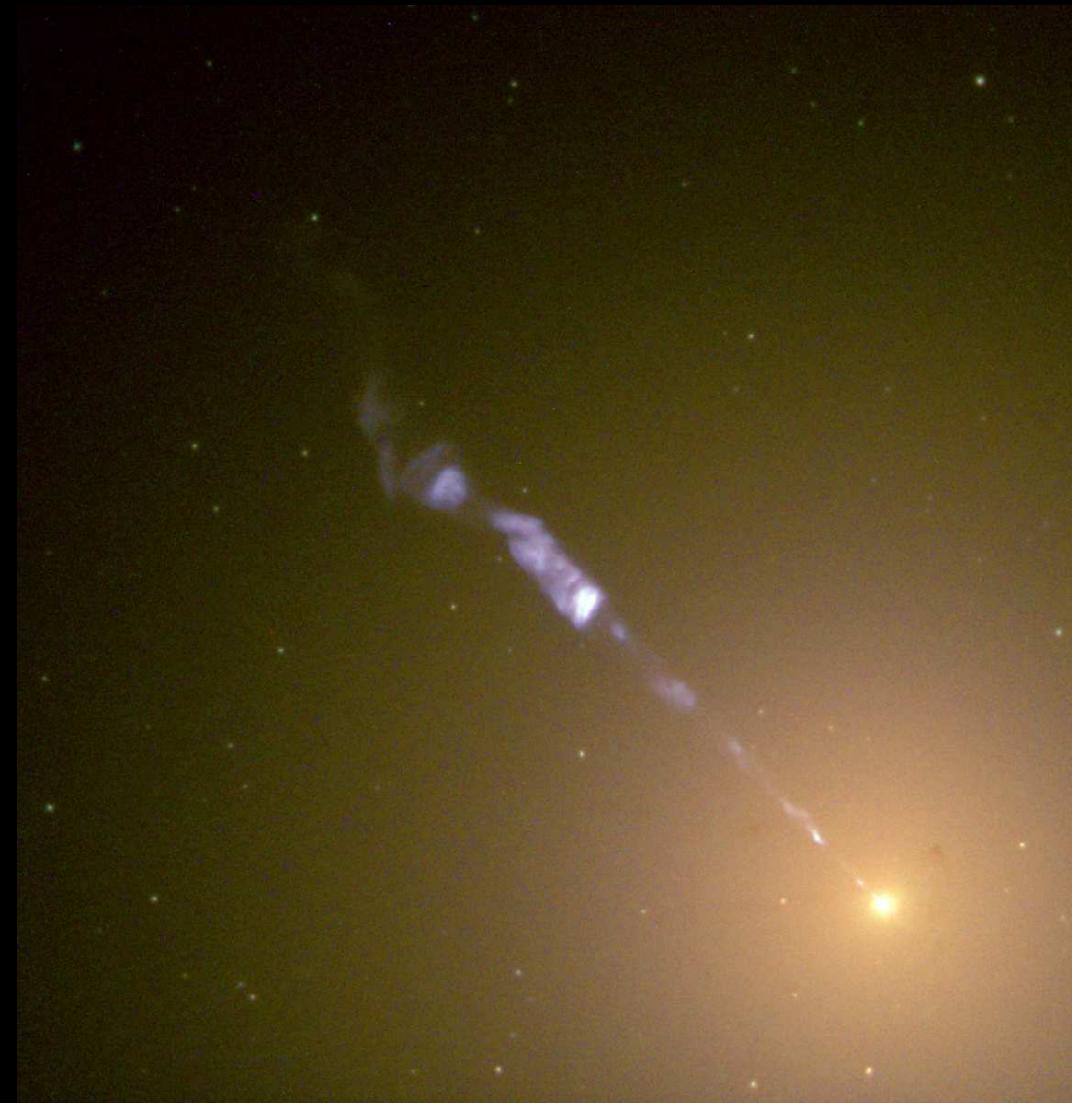


Radio Galaxy 0313-192
Hubble Space Telescope ACS WFC • Very Large Array

NASA, NRAO/AUI/NSF and W. Keel (University of Alabama) • STScI-PRC03-04

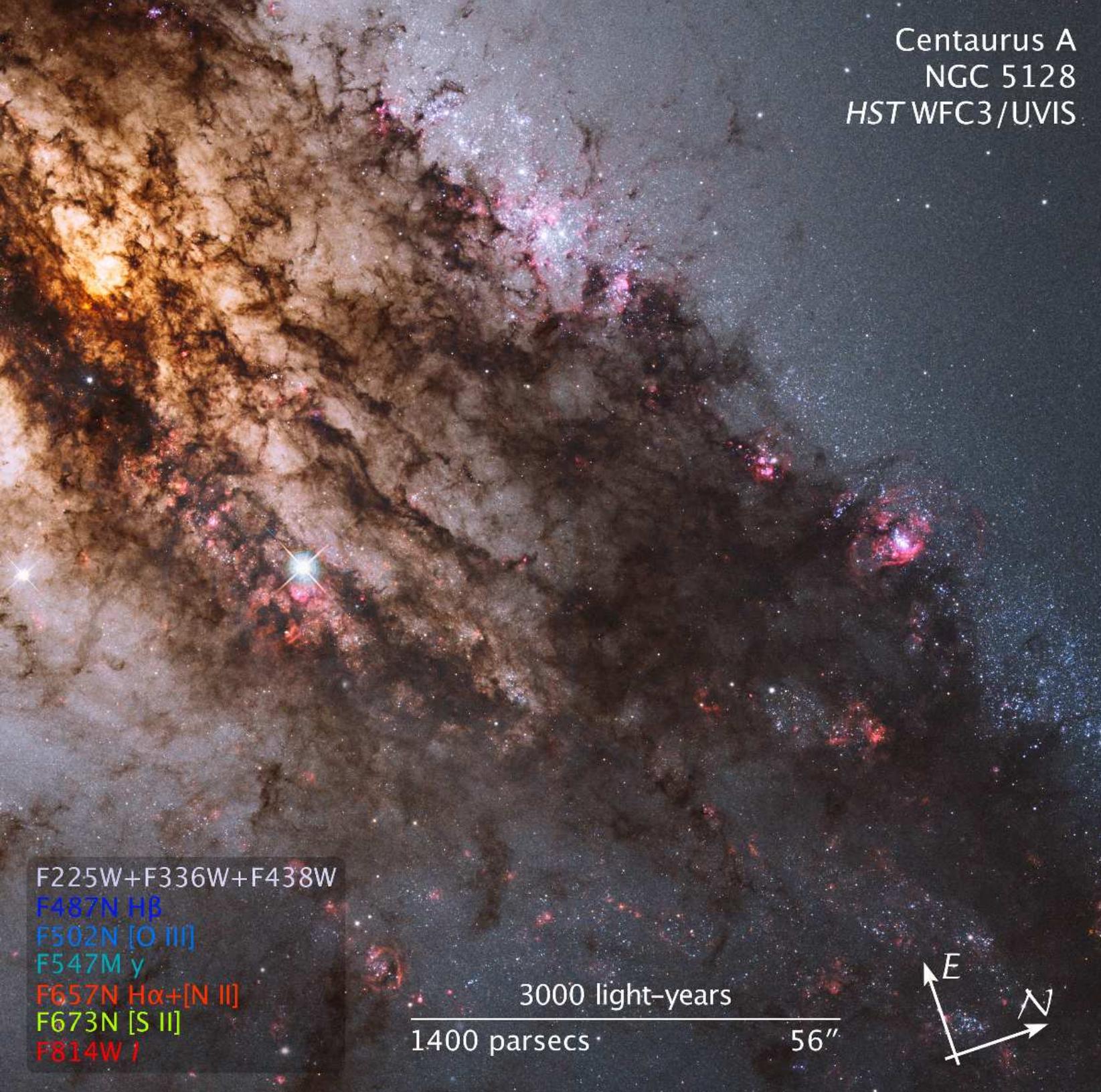
Does galaxy assembly go hand-in-hand with supermassive blackhole growth?

Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet:

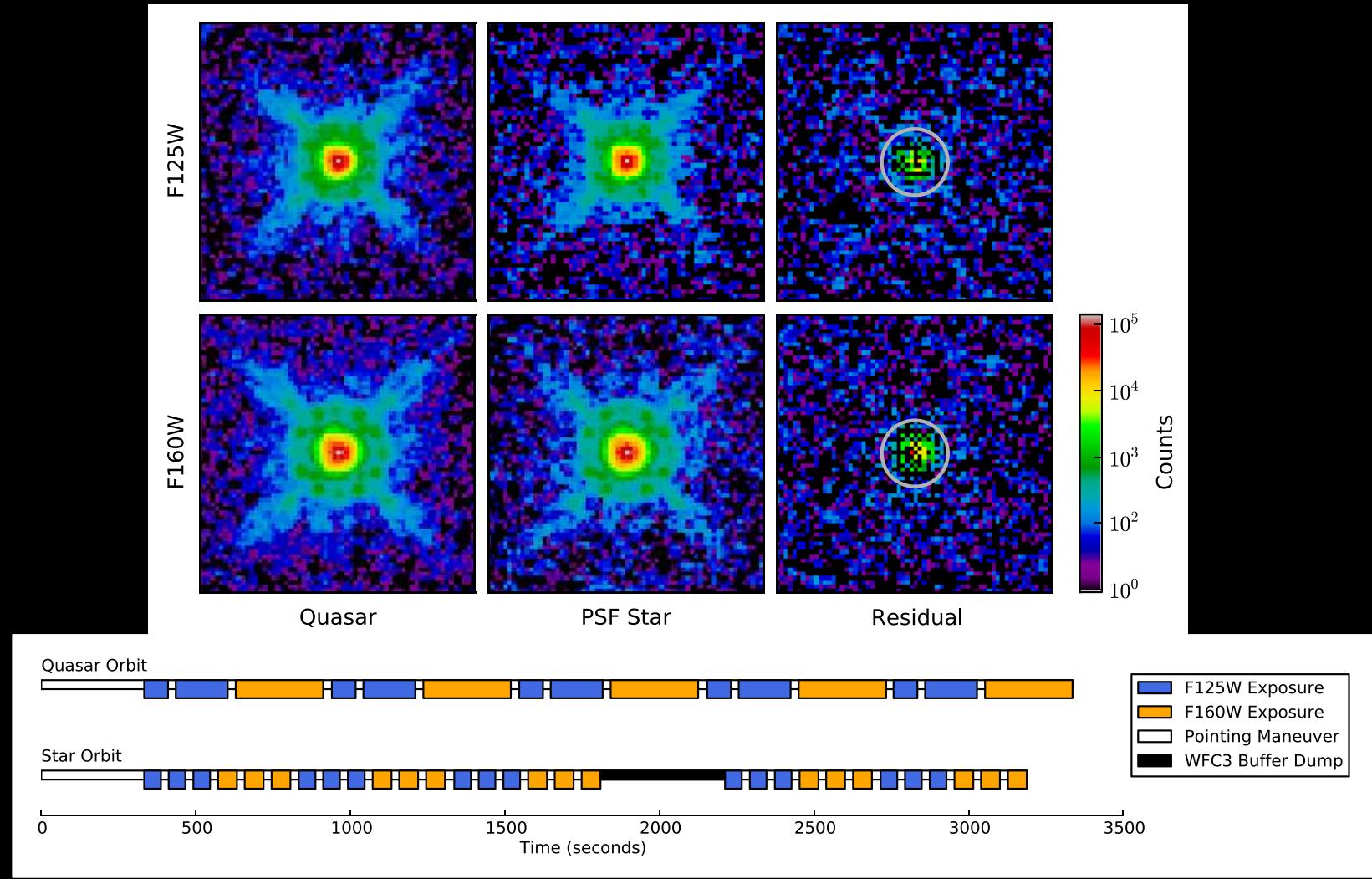


The danger of having Quasar-like devices too close to home ...

Centaurus A
NGC 5128
HST WFC3/UVIS

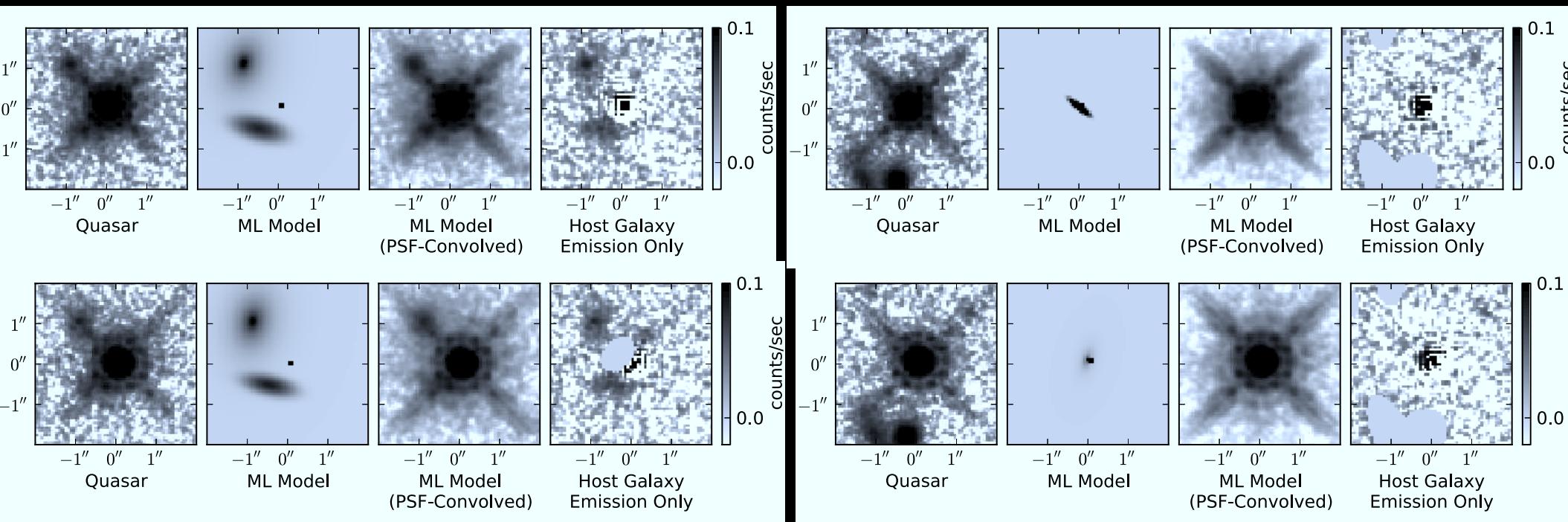


(3) HST WFC3 observations of QSO host galaxies at $z \simeq 6$ (age $\lesssim 1$ Gyr)



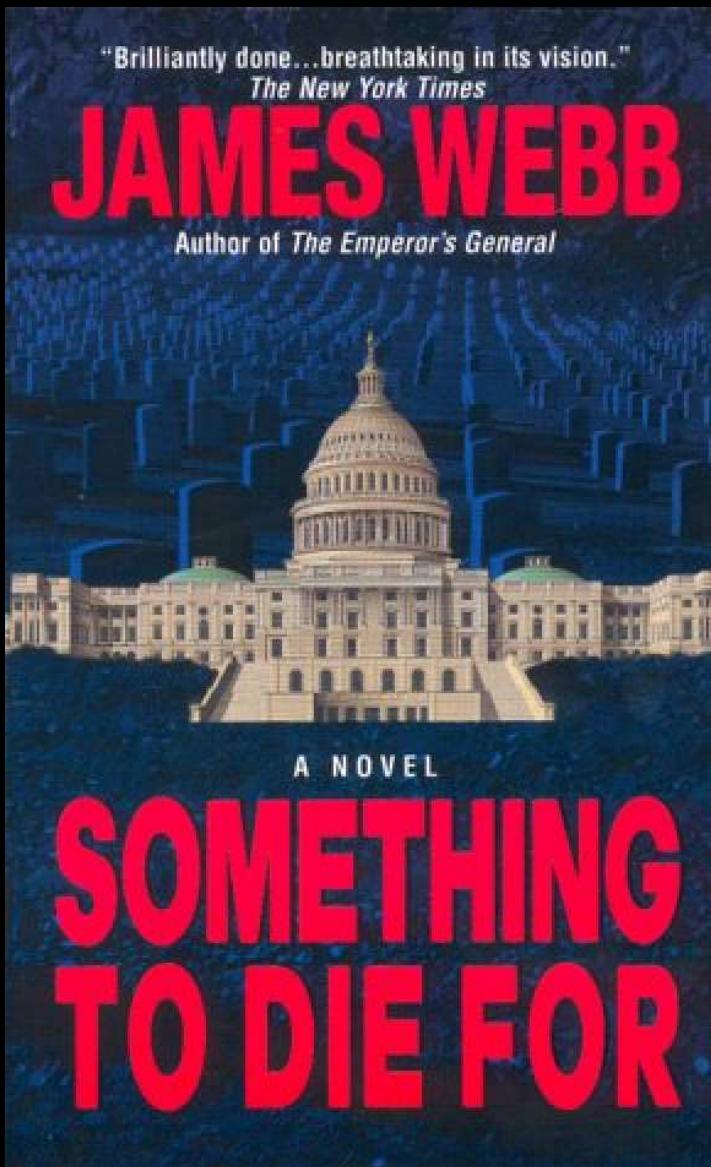
- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star ($AB \simeq 15$ mag) subtracts $z=6.42$ QSO ($AB \simeq 18.5$) nearly to the noise limit: NO host galaxy detected $100 \times$ fainter ($AB \gtrsim 23.5$ at $r \gtrsim 0\farcs3$).

(3) WFC3: First detection of one QSO Host Galaxy at $z \approx 6$ (Giant merger?)



- Monte Carlo Markov-Chain modeling of PSF-star + galaxy light-profile: (Mechtley, MPI, Jiang, Windhorst et al. 2014; Michtley 2013, PhD):
- FIRST solid detection out of four $z \approx 6$ QSOs [3 more to be observed].
- One $z \approx 6$ QSO host galaxy: Giant merger morphology + tidal structure??
- Same 1.2–1.6 μm structure! Blue UV-spectrum: Modest dust.
- L ($z \approx 6$ host system) brighter than typical galaxy: Monster!
- JWST Coronagraphs can do this 10–100× fainter (& for $z \lesssim 20$, $\lambda \lesssim 28 \mu\text{m}$).

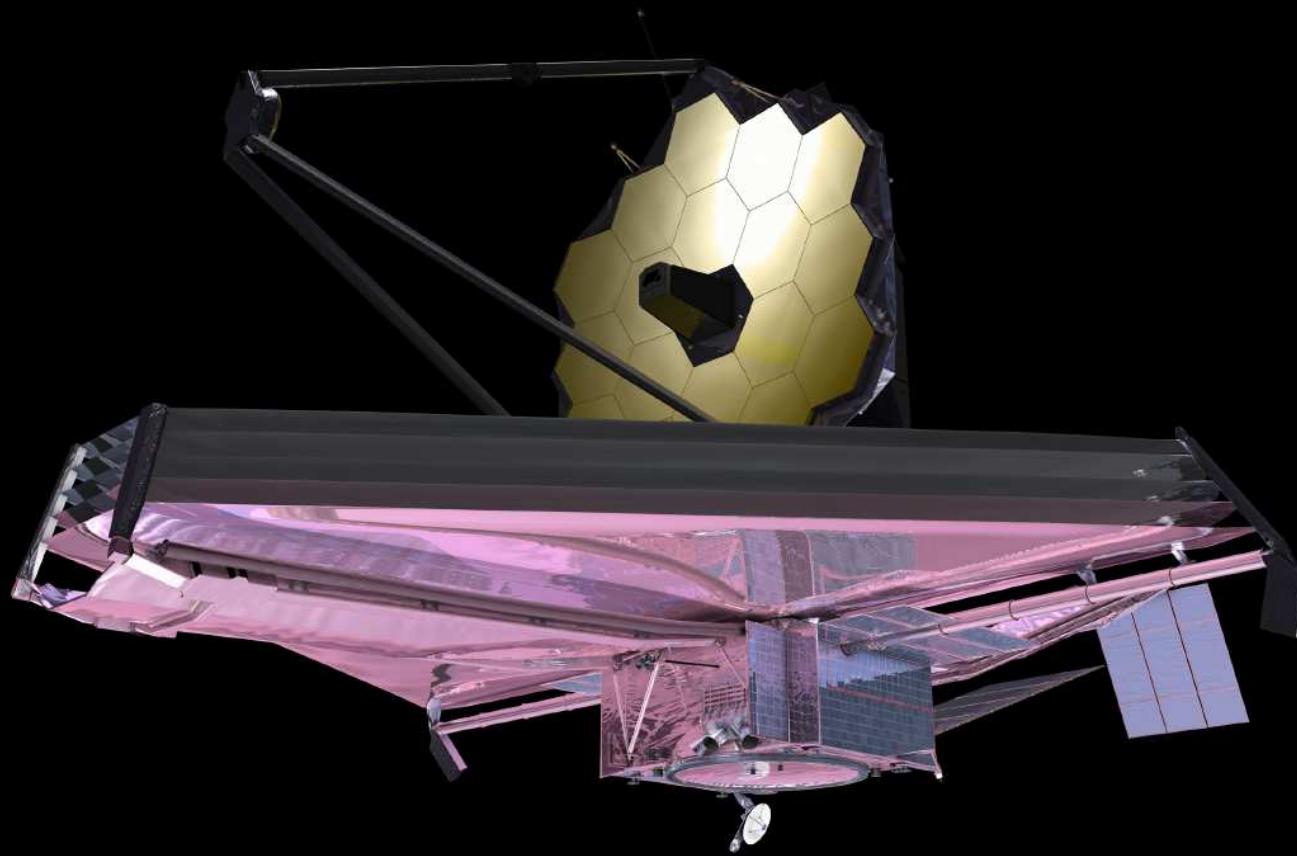
(4) What is the James Webb Space Telescope (JWST)?



Need young generation of students & scientists after 2018 ... It'll be worth it!

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

(4) What is the James Webb Space Telescope (JWST)?



- A fully deployable 6.5 meter (25 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 (31.5 mag = firefly from Moon!) and spectroscopy.

THE JAMES WEBB SPACE TELESCOPE

JWST LAUNCH

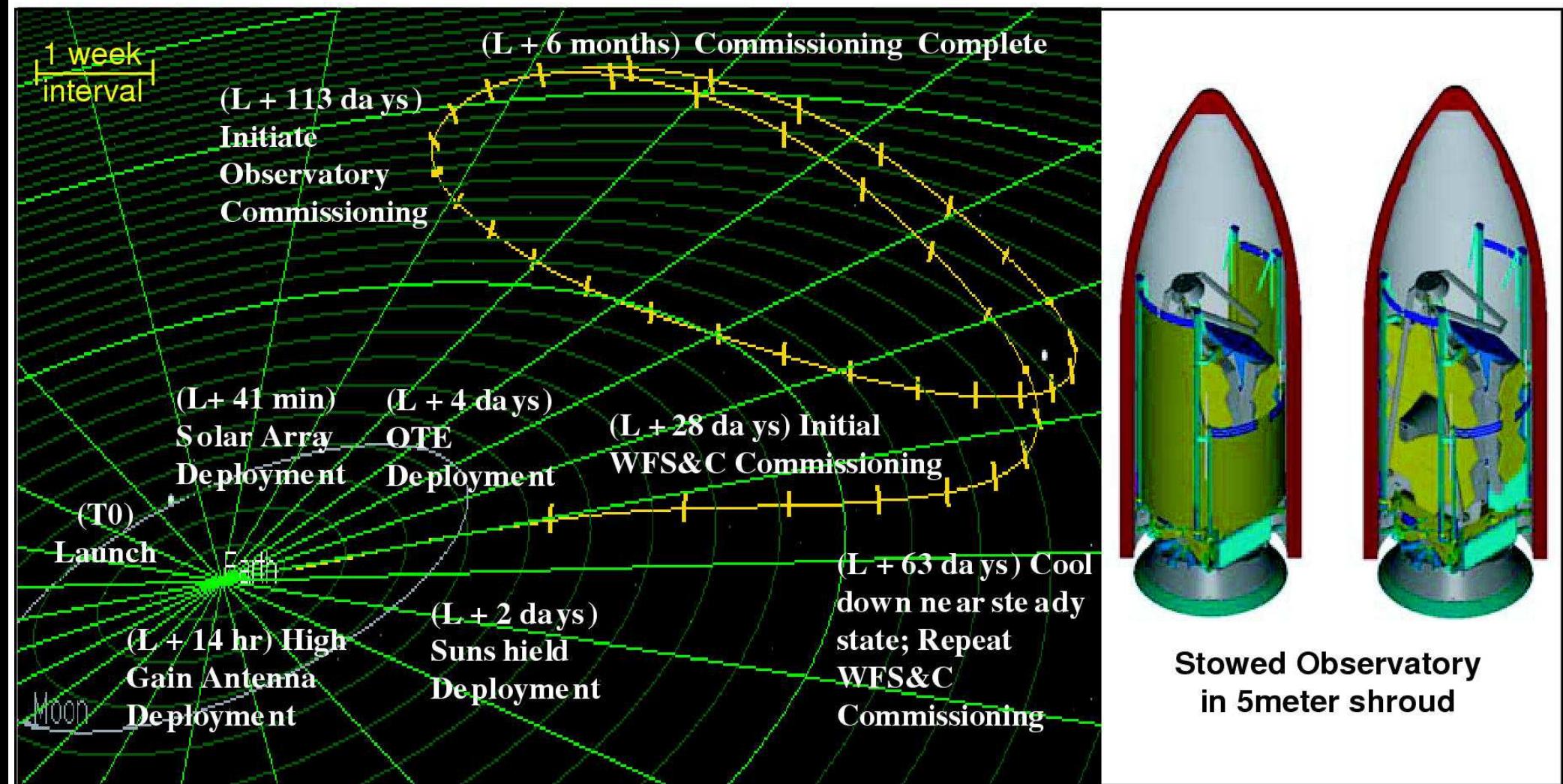
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



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.

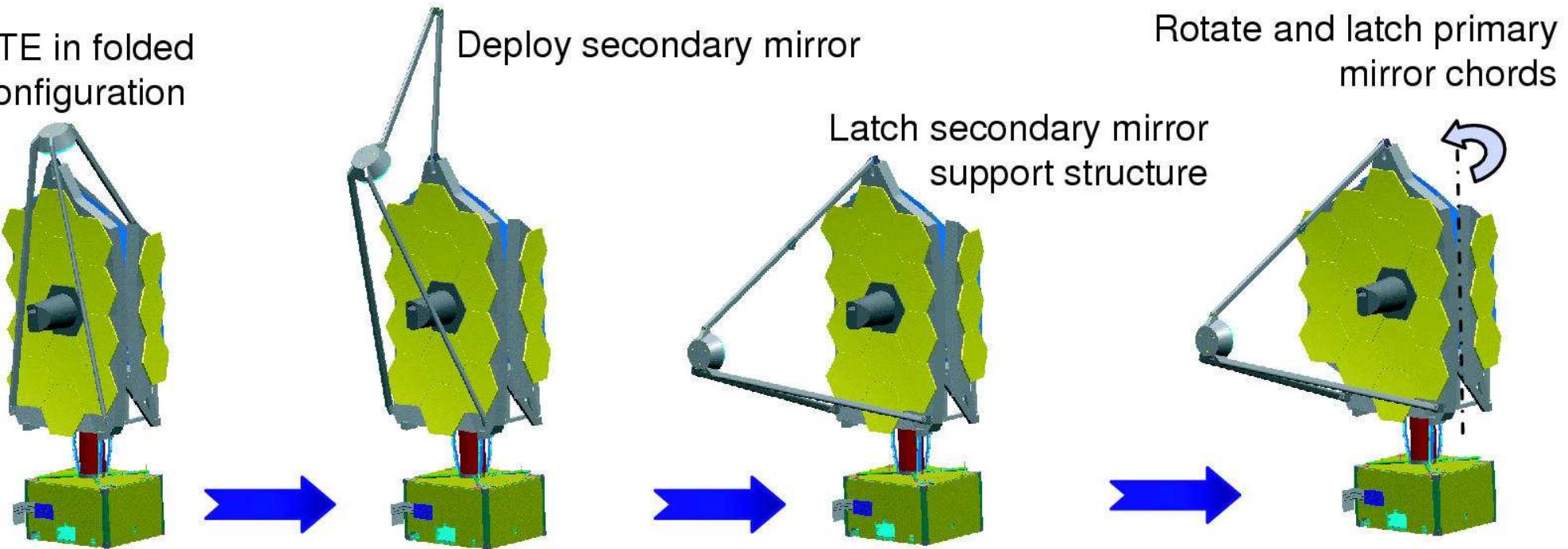
(4a) How will JWST travel to its L2 orbit?



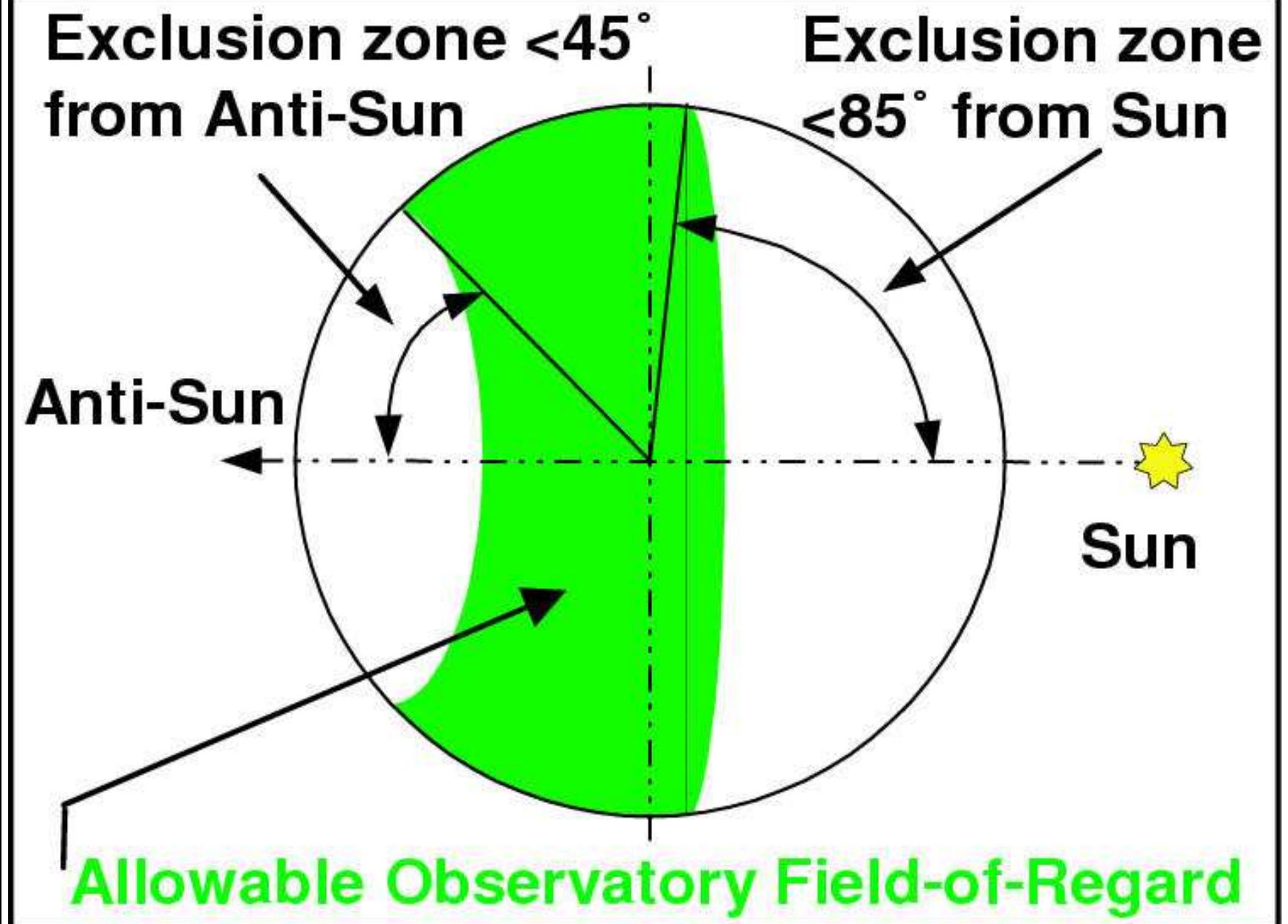
- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim 70\%$ of the time, and send data back to Earth every day.

- (4b) How will JWST be automatically deployed?

OTE in folded configuration



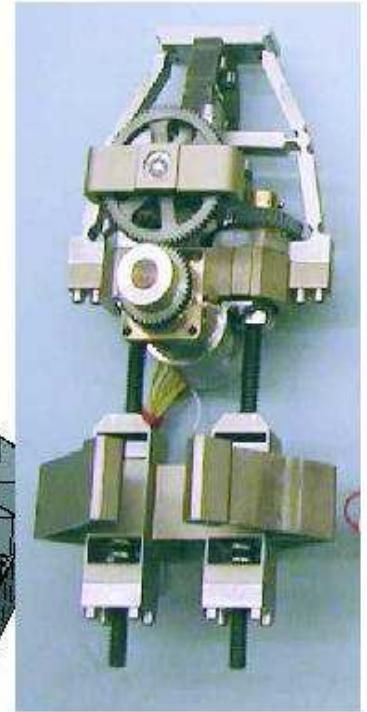
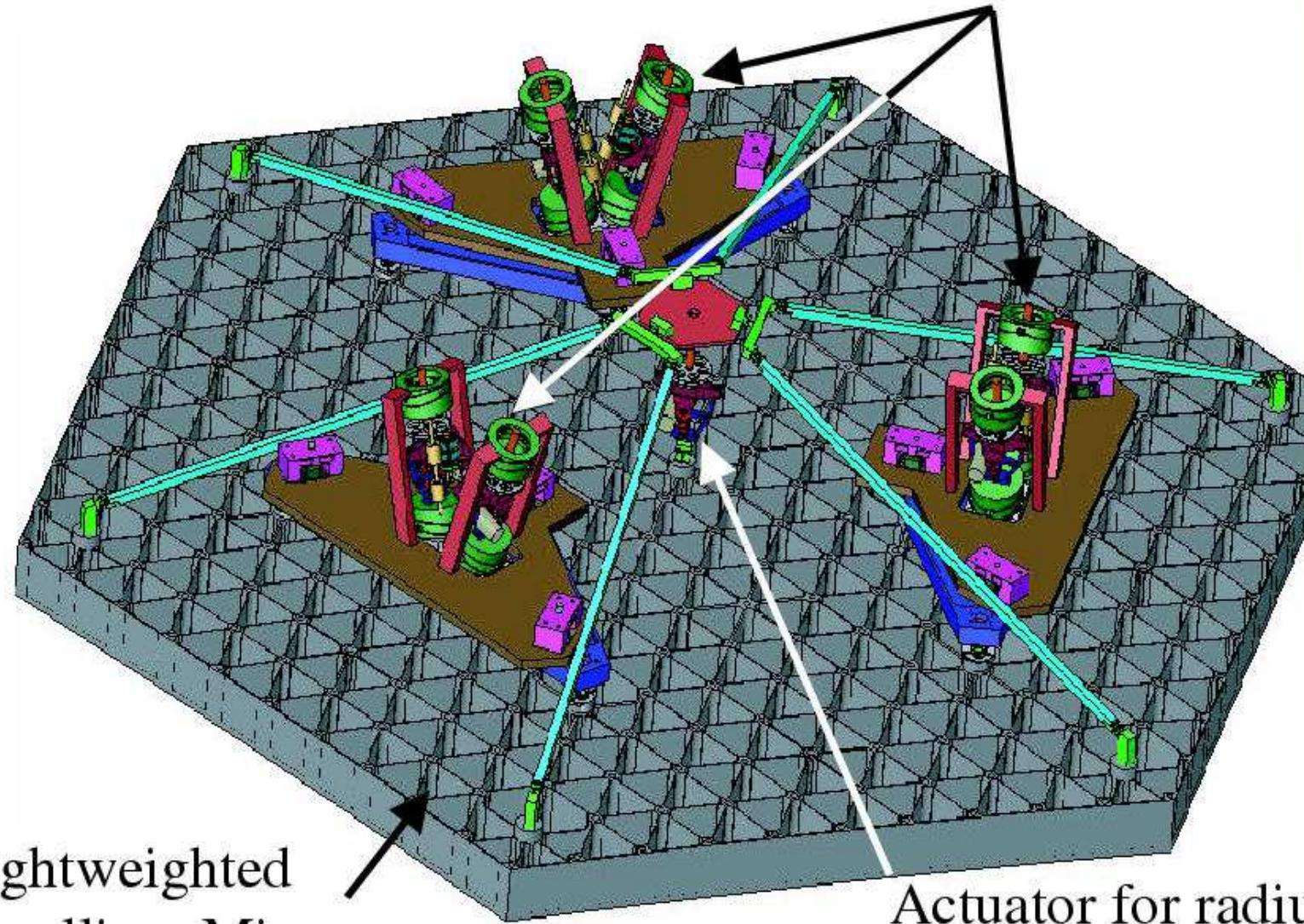
- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications!



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 its reaction wheels!

Actuators for 6 degrees of freedom rigid body motion



Actuator development unit

Lightweighted
Beryllium Mirror

Actuator for radius
of curvature adjustment

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

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

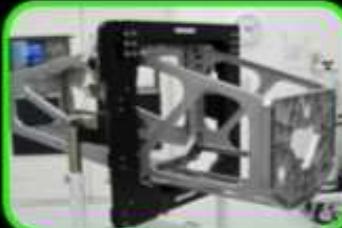


JWST Hardware Status

Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror



Fine Steering Mirror

Secondary Mirror Pathfinder Strut



Secondary Mirror Hexapod



Secondary Mirror

ISIM Flight Bench



Membrane Mgmt



Pathfinder Membrane



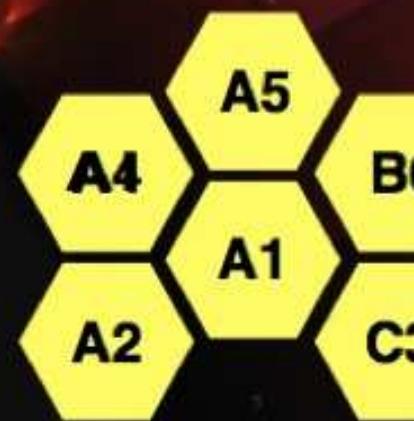
Spacecraft computer Test Unit



Mid-boom Test

80% of launch mass designed³ and built as of Jan. 2014.

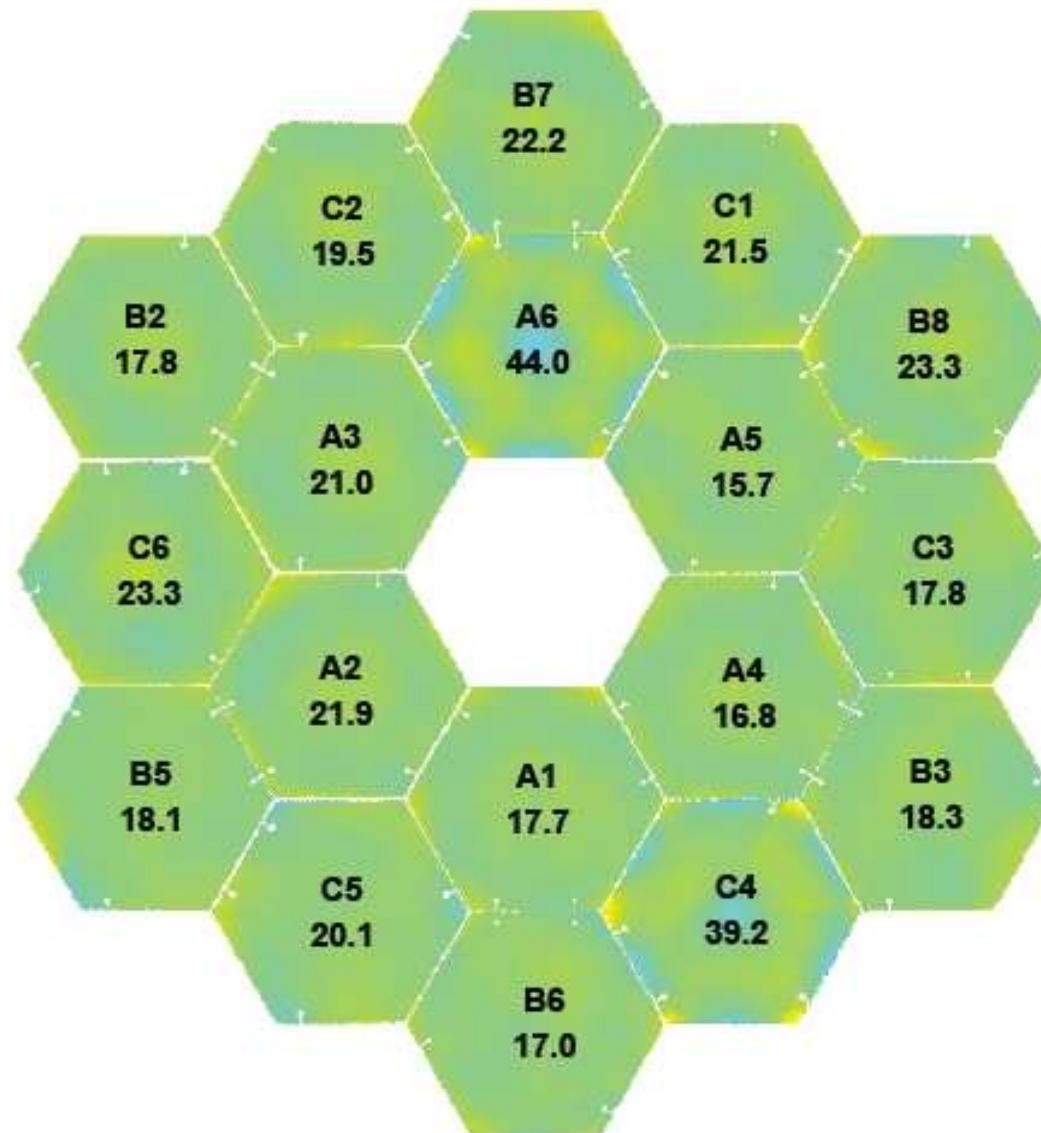
Mirror Acceptance Testing







Primary Mirror Composite



RMS:
23.2 nm

PV:
515.5 nm

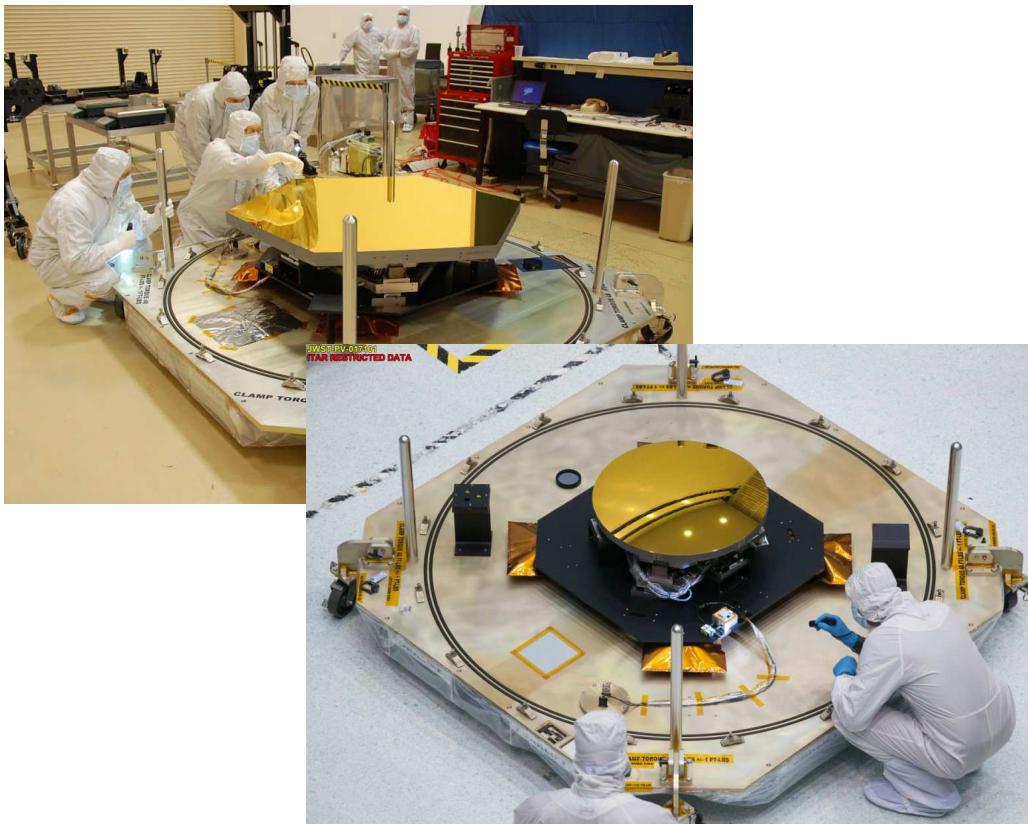




Mirror Status



- **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



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



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

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

Telescope Assembly Ground Support Equipment



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





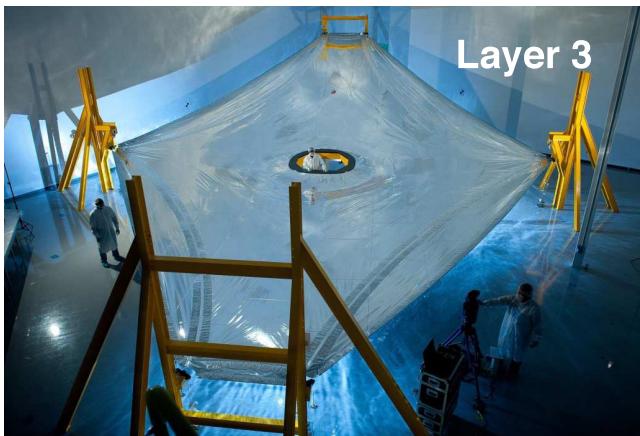
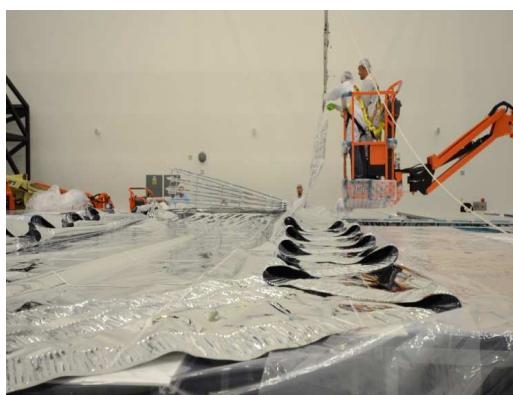
Sunshield Template Membrane Work Completed

Templates Verify Design/Manufacturing Prior to Flight Build

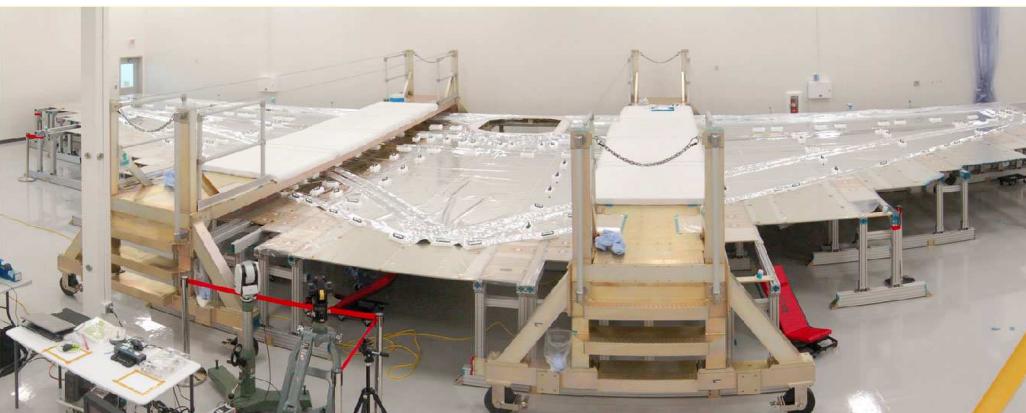


- All Template Layers Completed
- Preparing for flight article manufacturing
- First two Flight Manufacturing Readiness Reviews Completed
- Membrane pull out test complete

Stringing Operations



Template
Layers 3-5



Hole Tool Operations

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

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

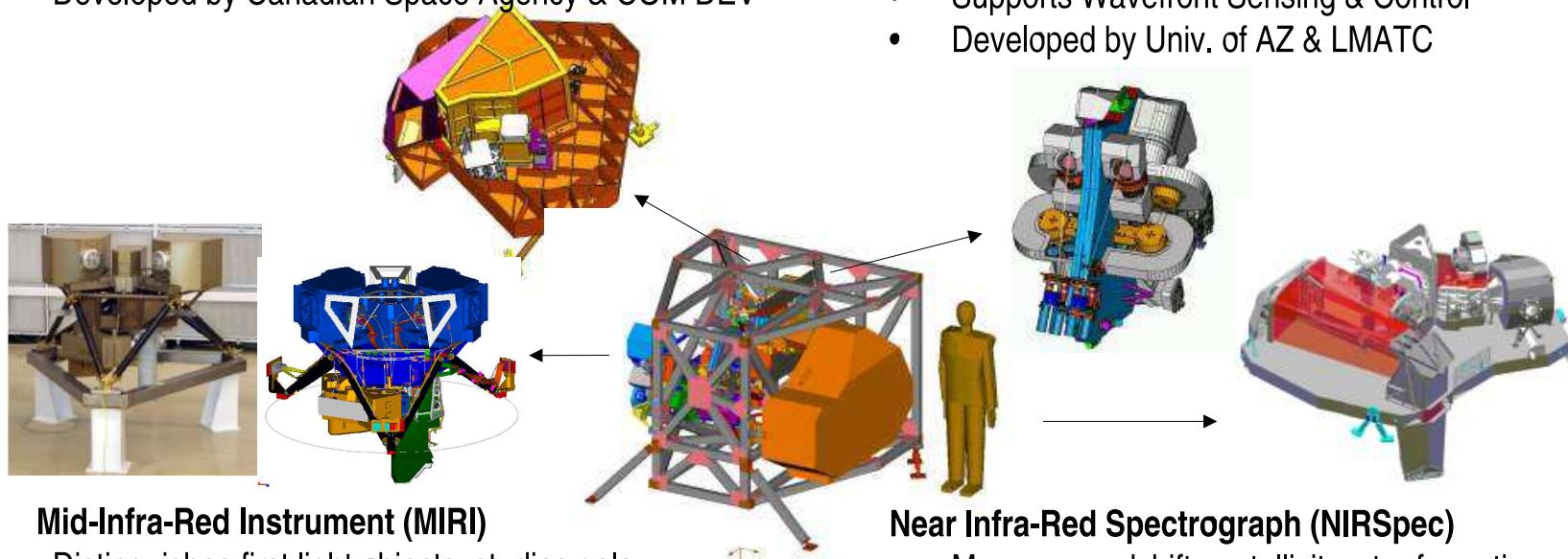


Instrument Overview



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

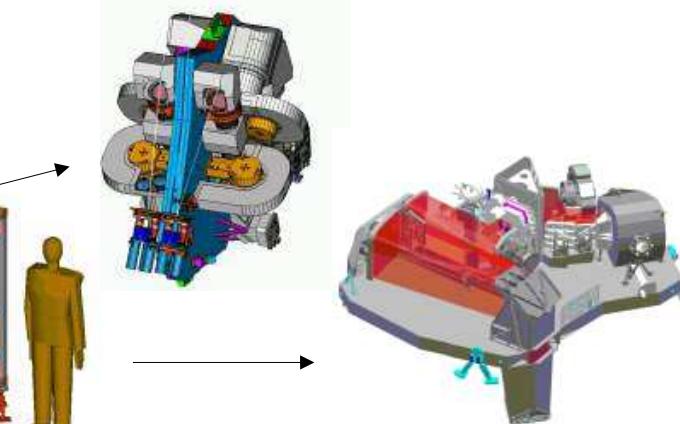


Mid-Infra-Red Instrument (MIRI)

- 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

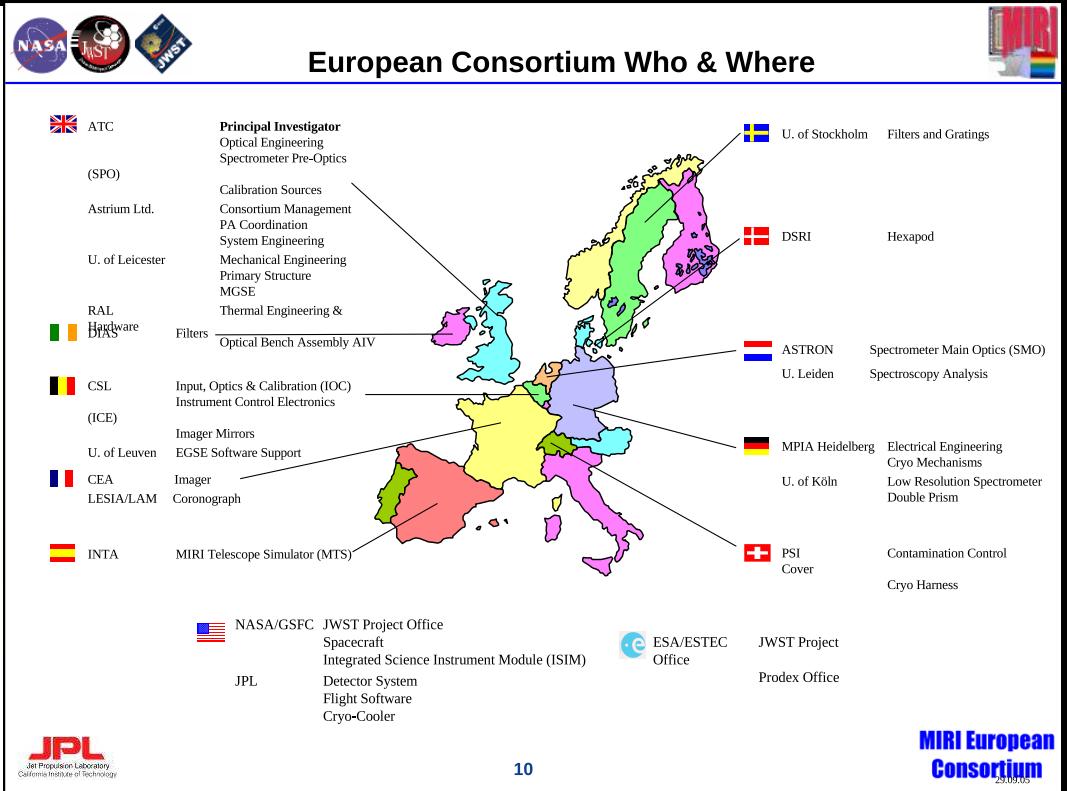
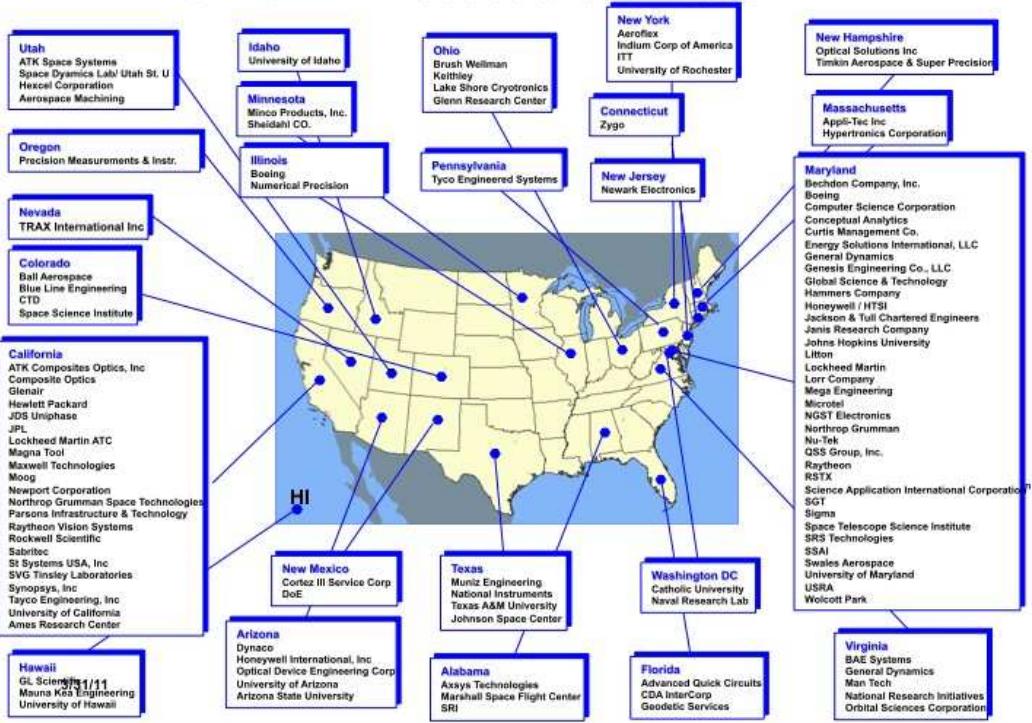


Near Infra-Red Spectrograph (NIRSpec)

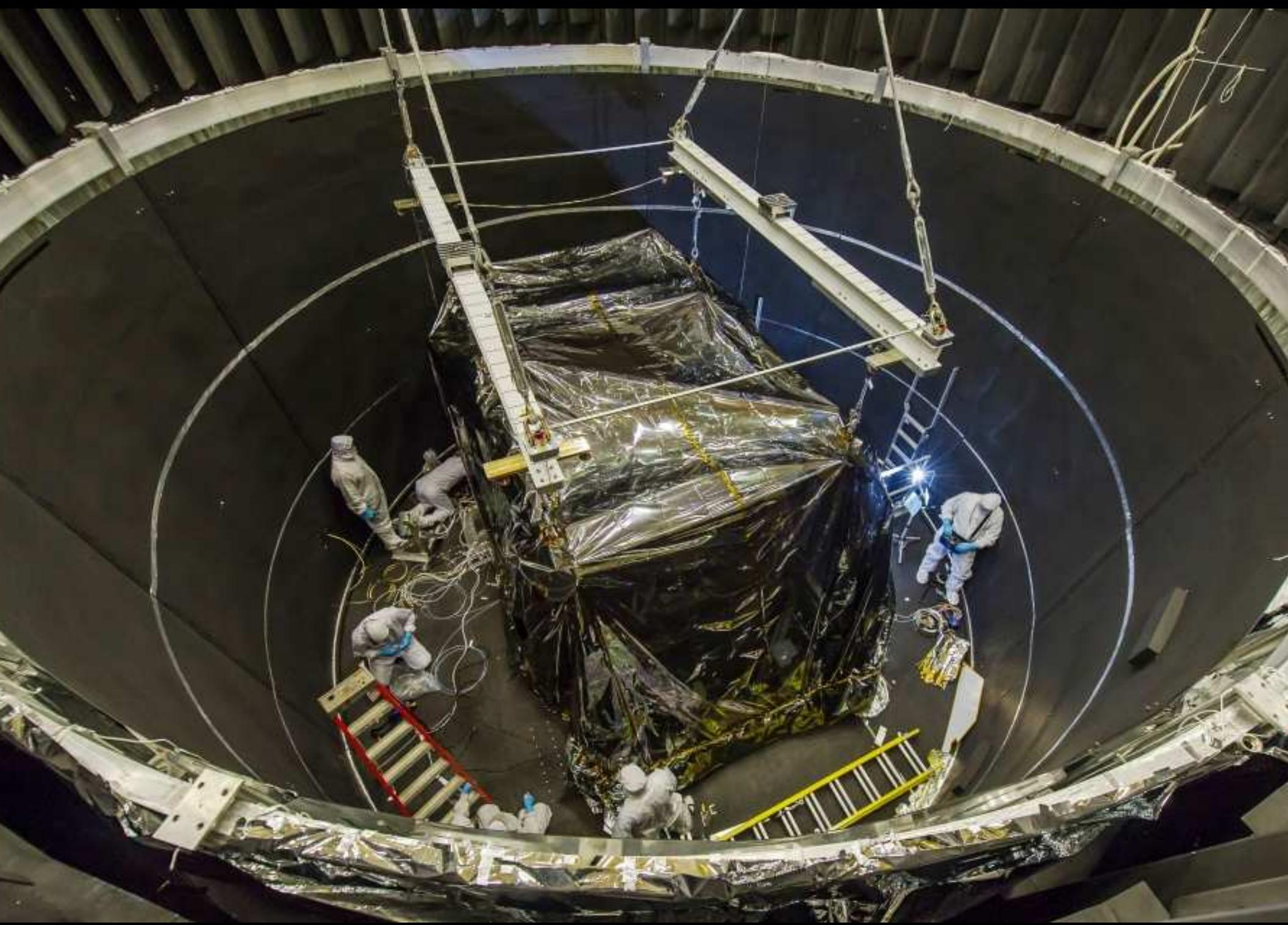
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

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

JWST: A Product of the Nation



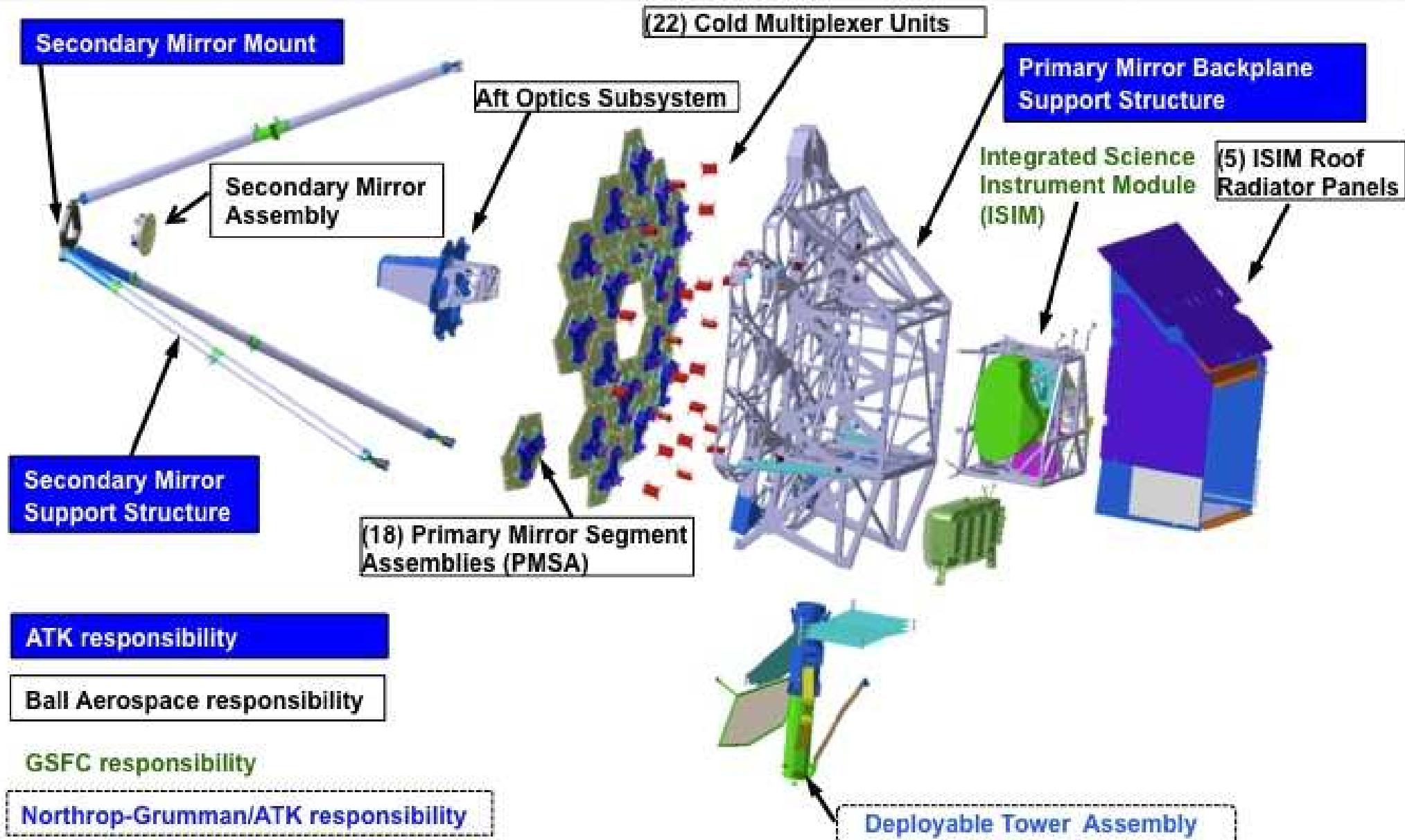
- JWST hardware made in 27 US States: $\gtrsim 80\%$ of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.



Aug. 2013: Actual Flight ISIM (with MIRI and FGS) lowered into OSIM.

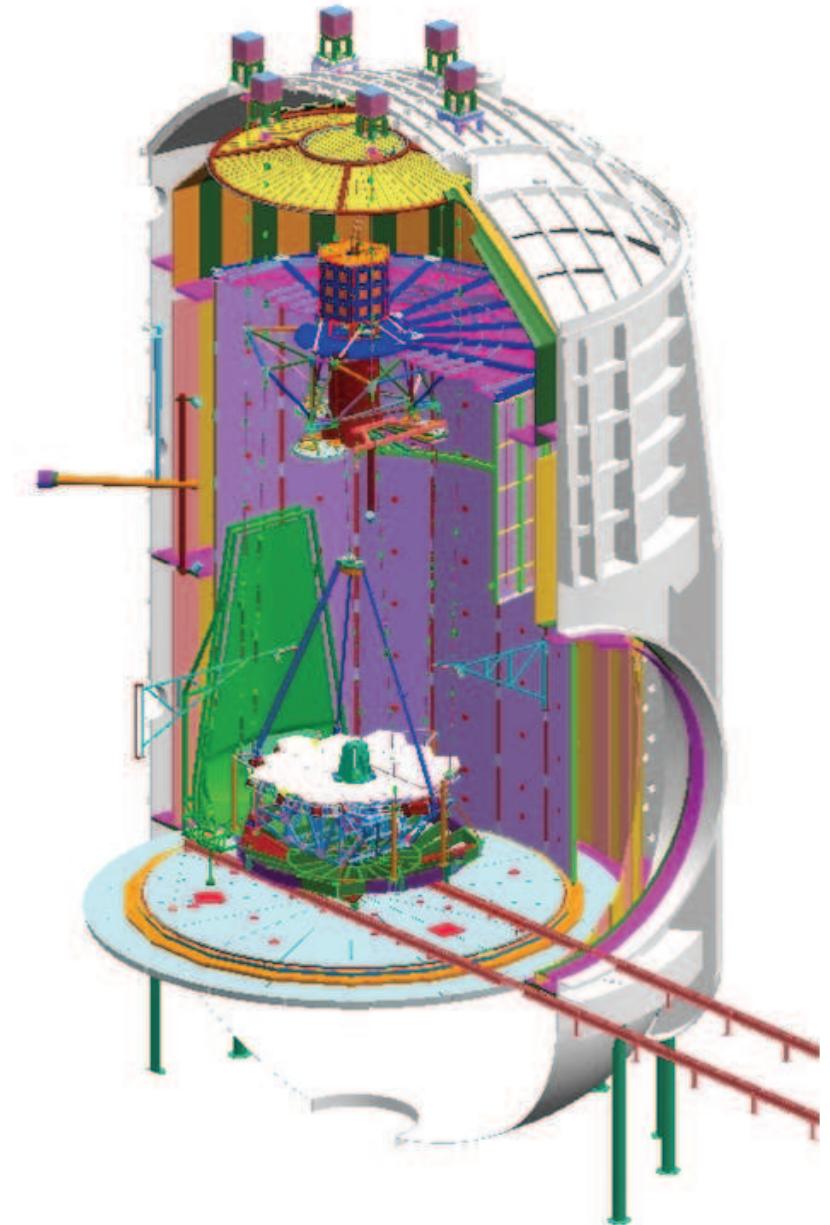
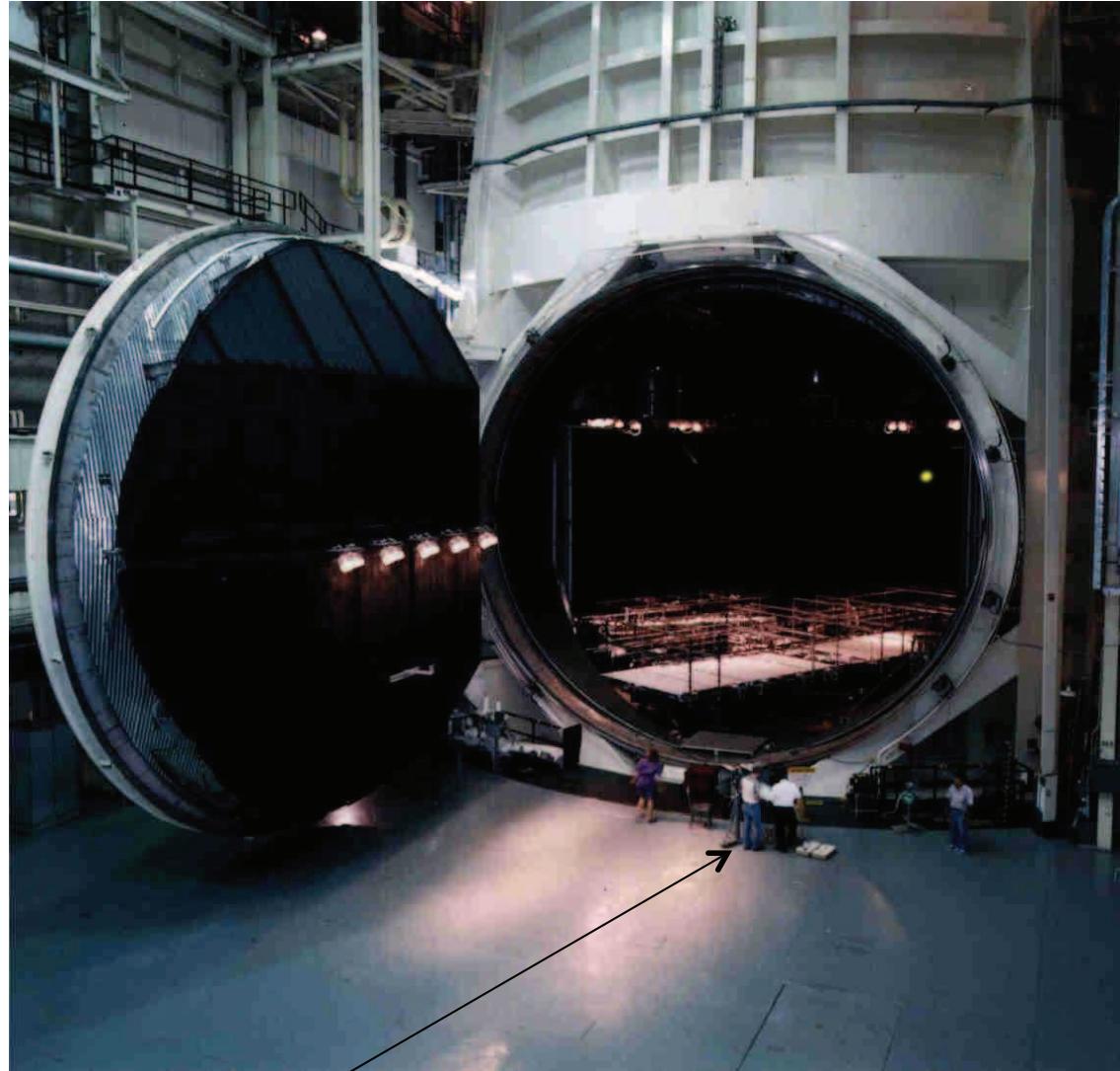


TELESCOPE ARCHITECTURE





OTE Testing – Chamber A at JSC

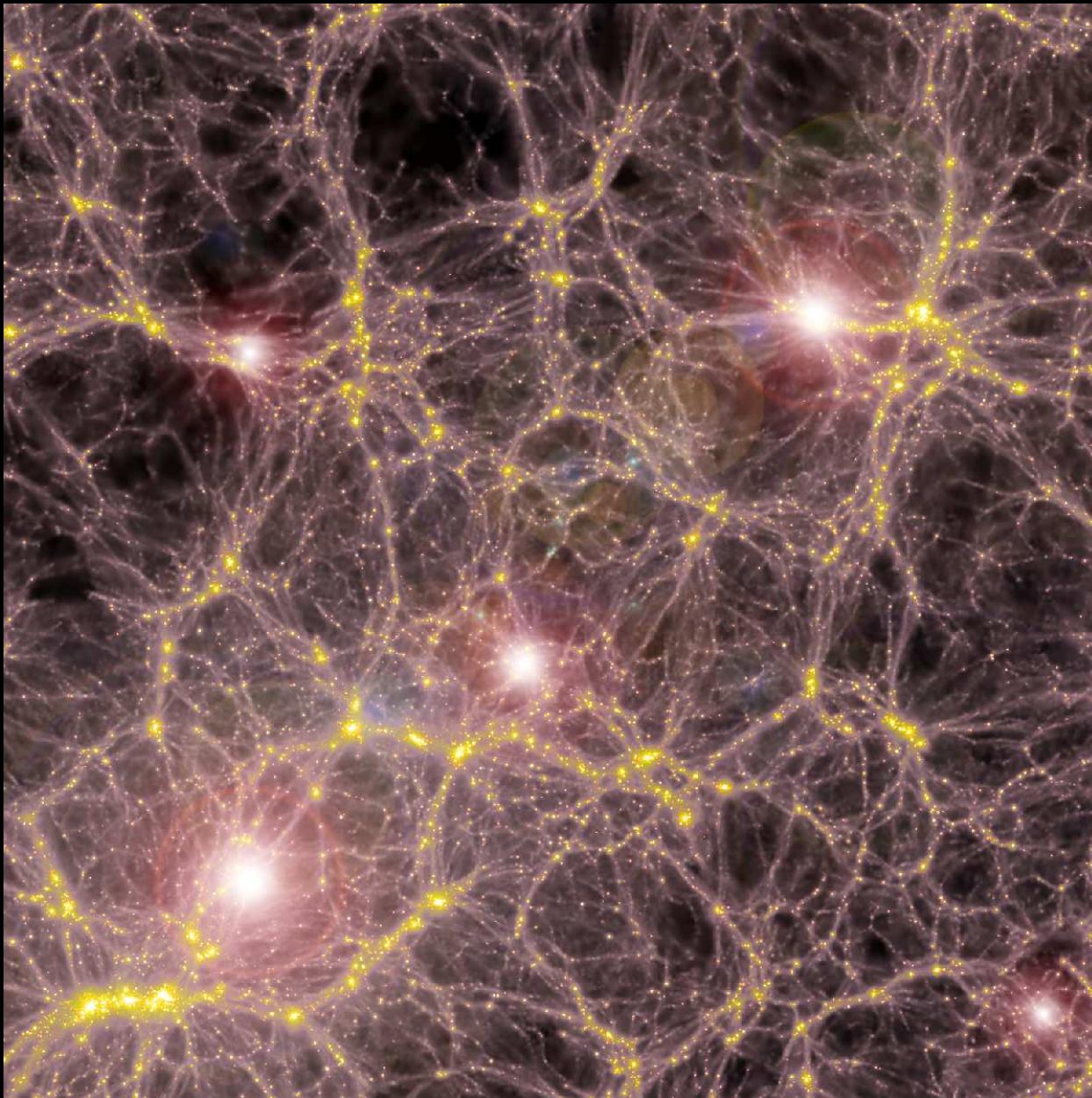


Notice people for scale

Will be the largest cryo vacuum test chamber in the world

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

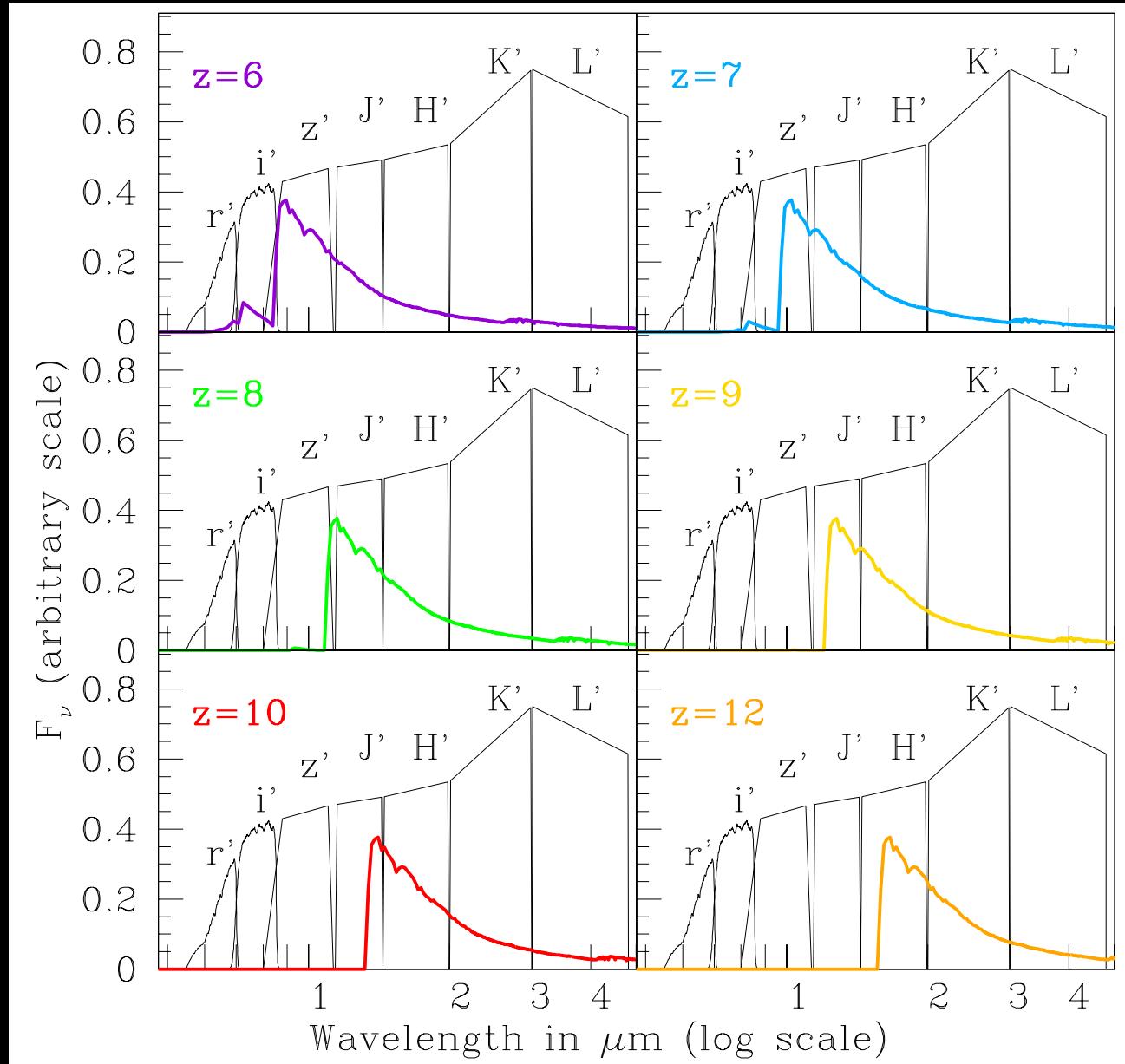
(5a) How will JWST Observe First Light and Reionization?



- Detailed hierarchical models (Dr. V. Bromm) show that formation of Pop III stars reionized universe for the first time at $z \simeq 10-30$ (First Light, age $\simeq 500-100$ Myr).
- This should be visible to JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10-30$.

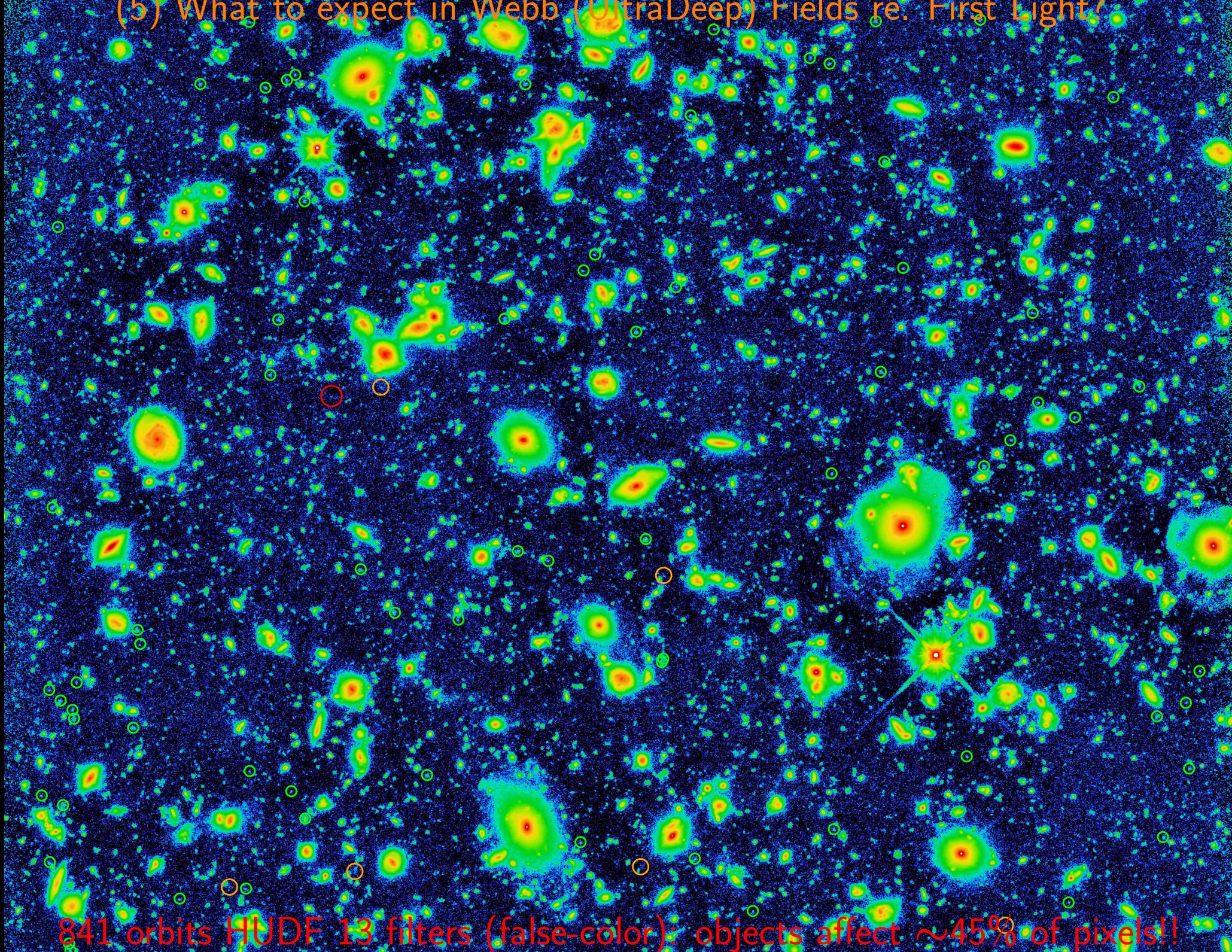
We must make sure we theoretically understand the likely Pop III mass-range, their IMF, their duplicity and clustering properties, their SN-rates.

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



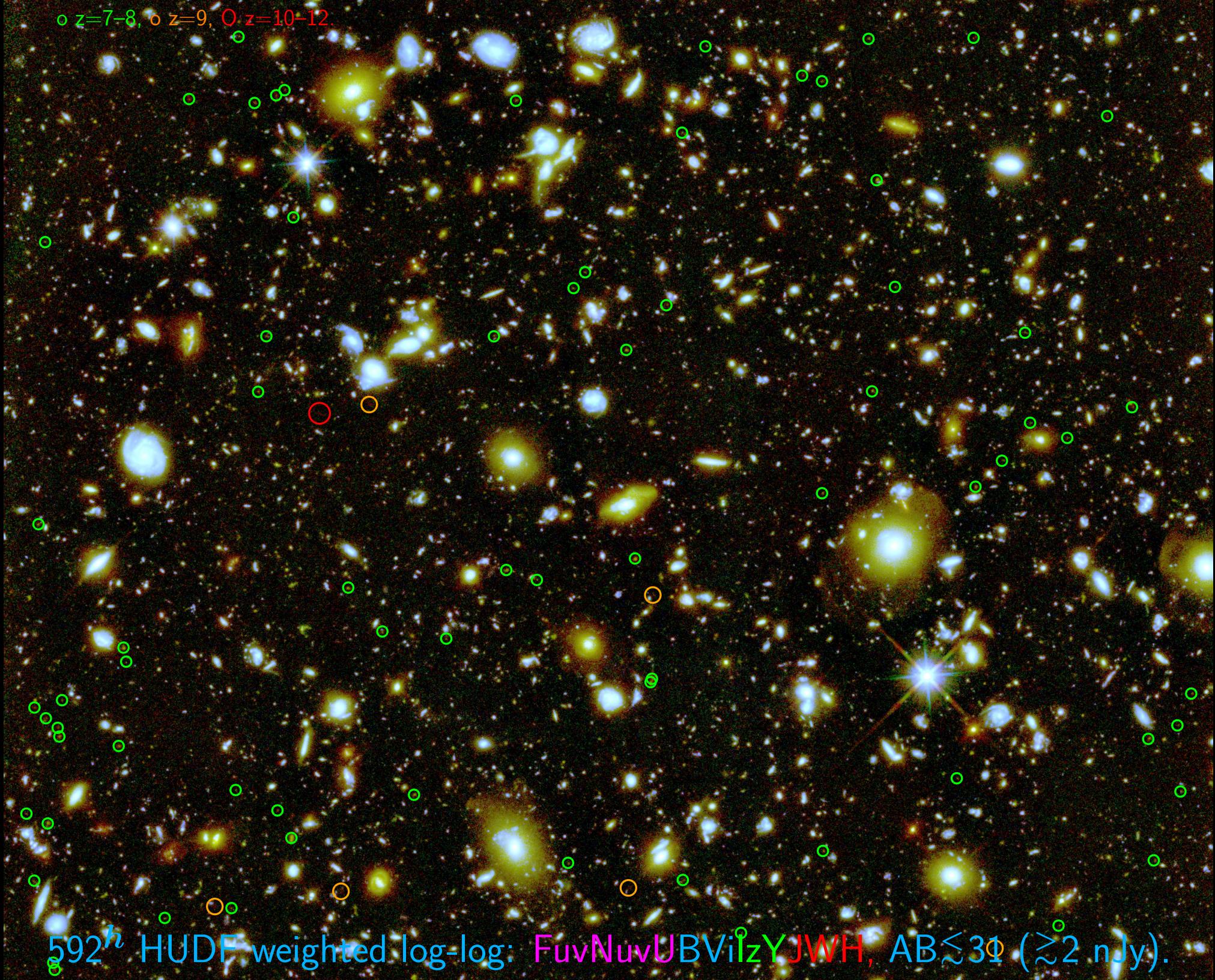
- Can't beat redshift: to see First Light, must observe near-mid IR.
⇒ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm .

(5) What to expect in Webb (UltraDeep) Fields re: First Light?



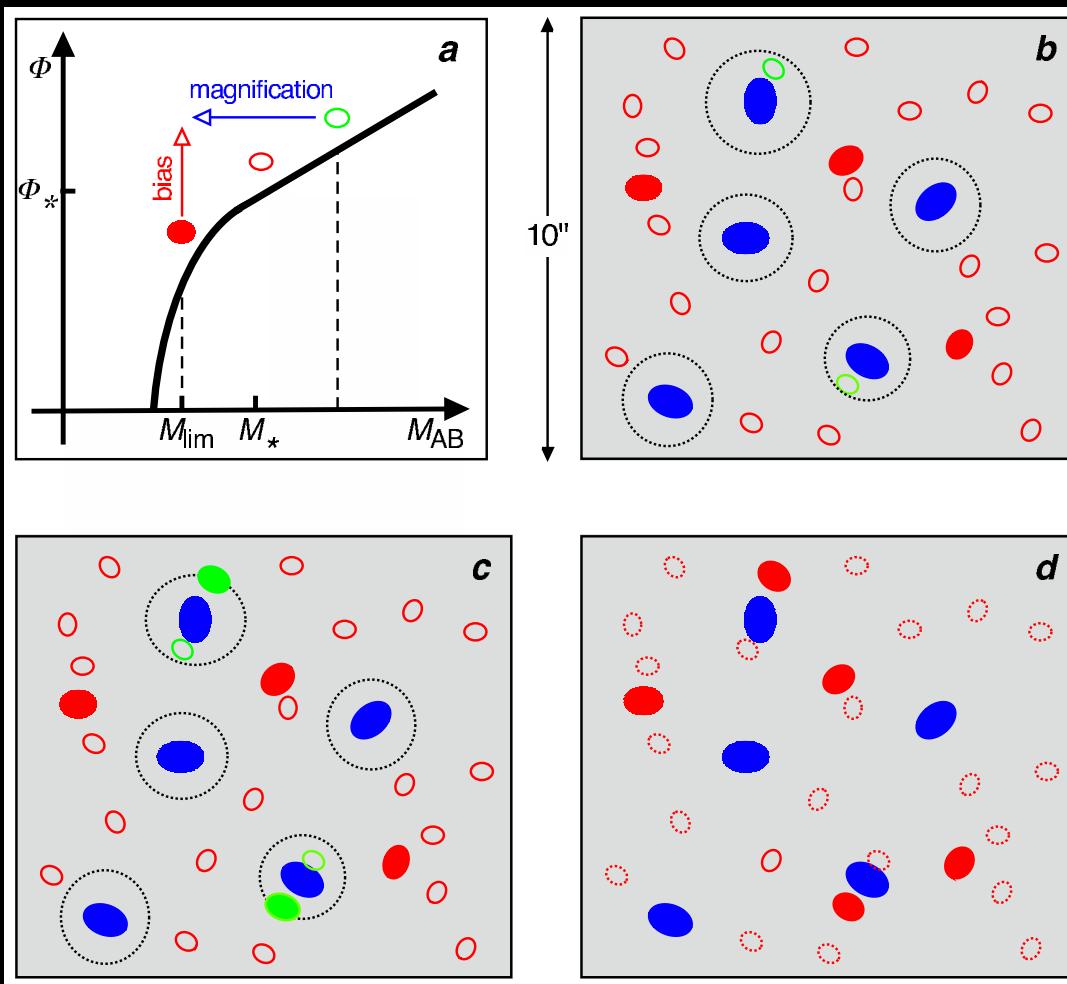
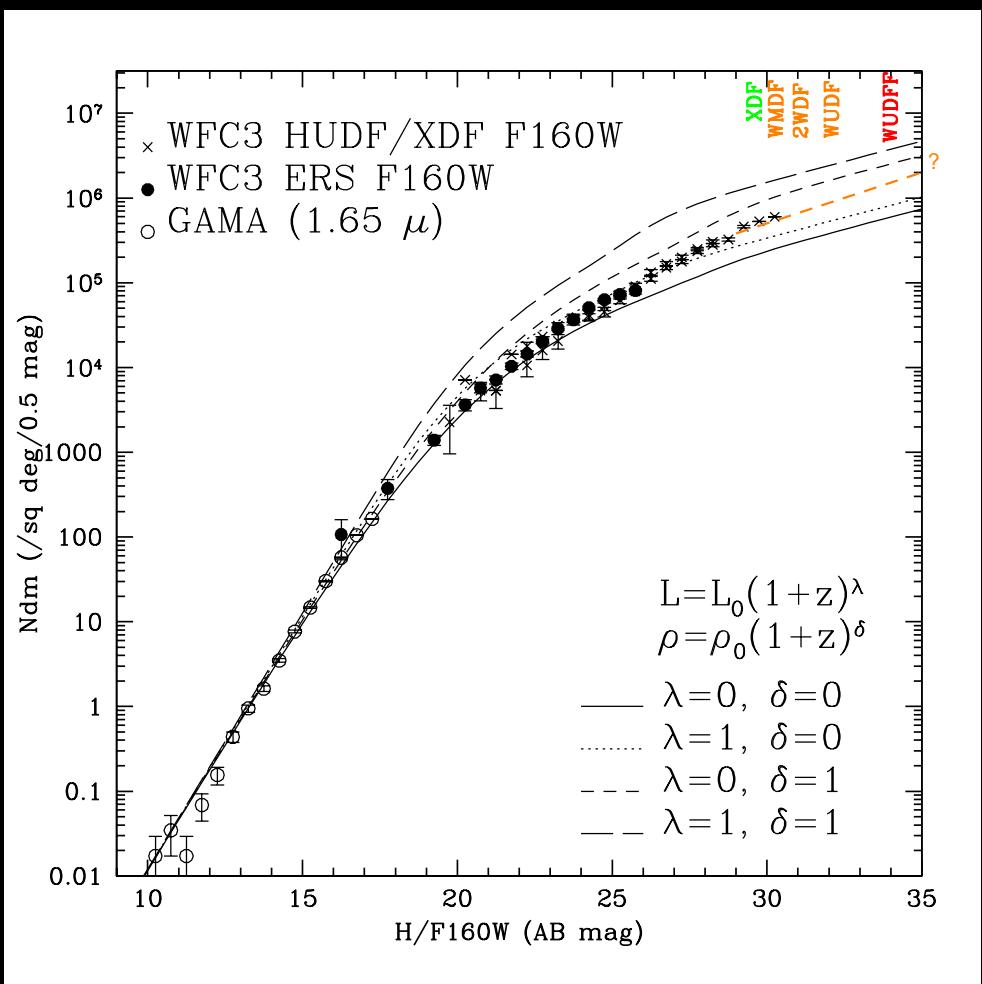
841 orbits HUDF 13 filters (false-color): objects affect $\sim 45\%$ of pixels!!

○ $z=7-8$, ○ $z=9$, ○ $z=10-12$.



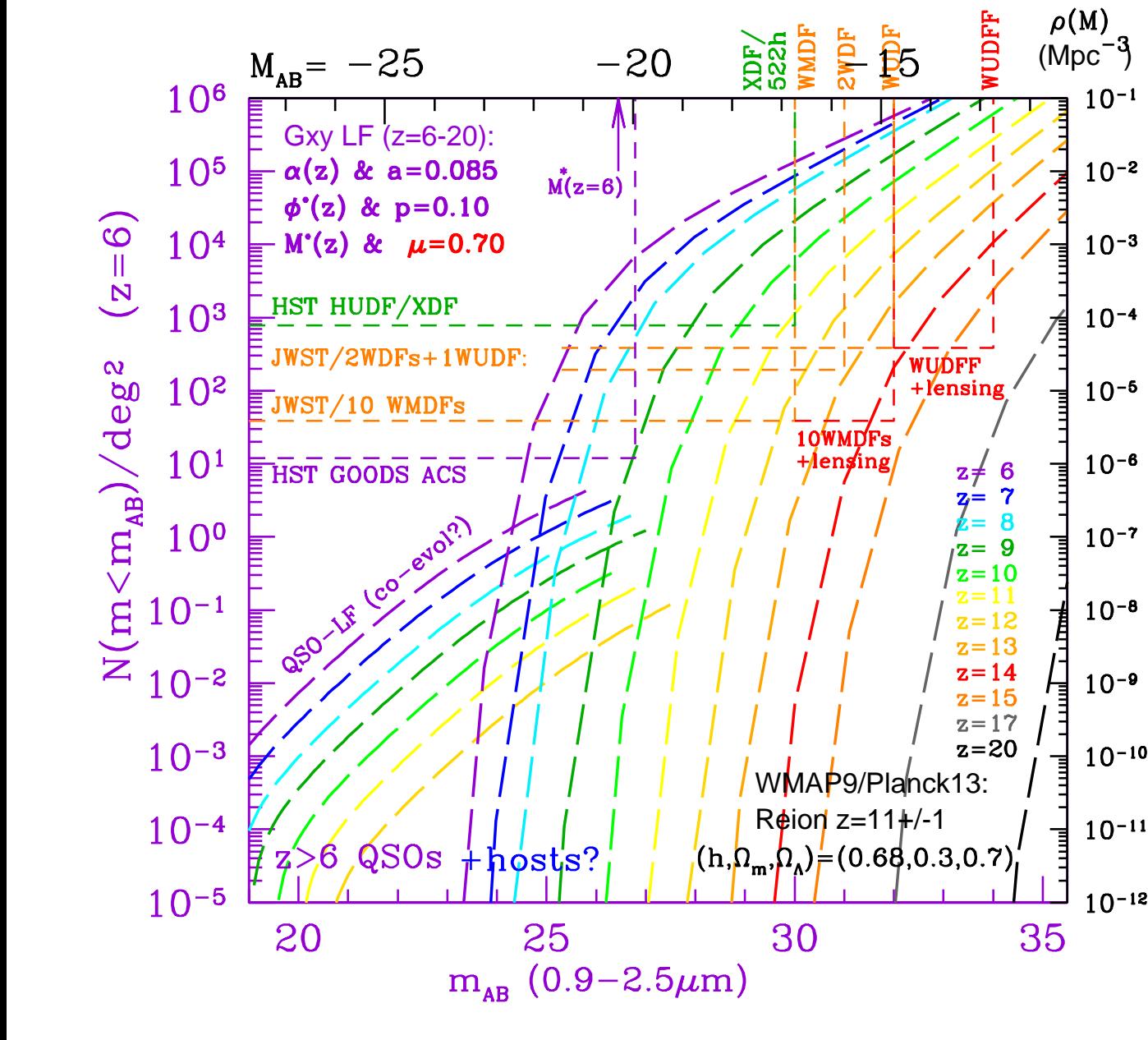
592^h HUDF weighted log-log: FuvNuvUBVi^zYJWH, AB $\lesssim 3\Phi$ ($\gtrsim 2$ nJy).

HUDF WFC3 IR Galaxy Counts: What to expect in Webb (UltraDeep) Fields?



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

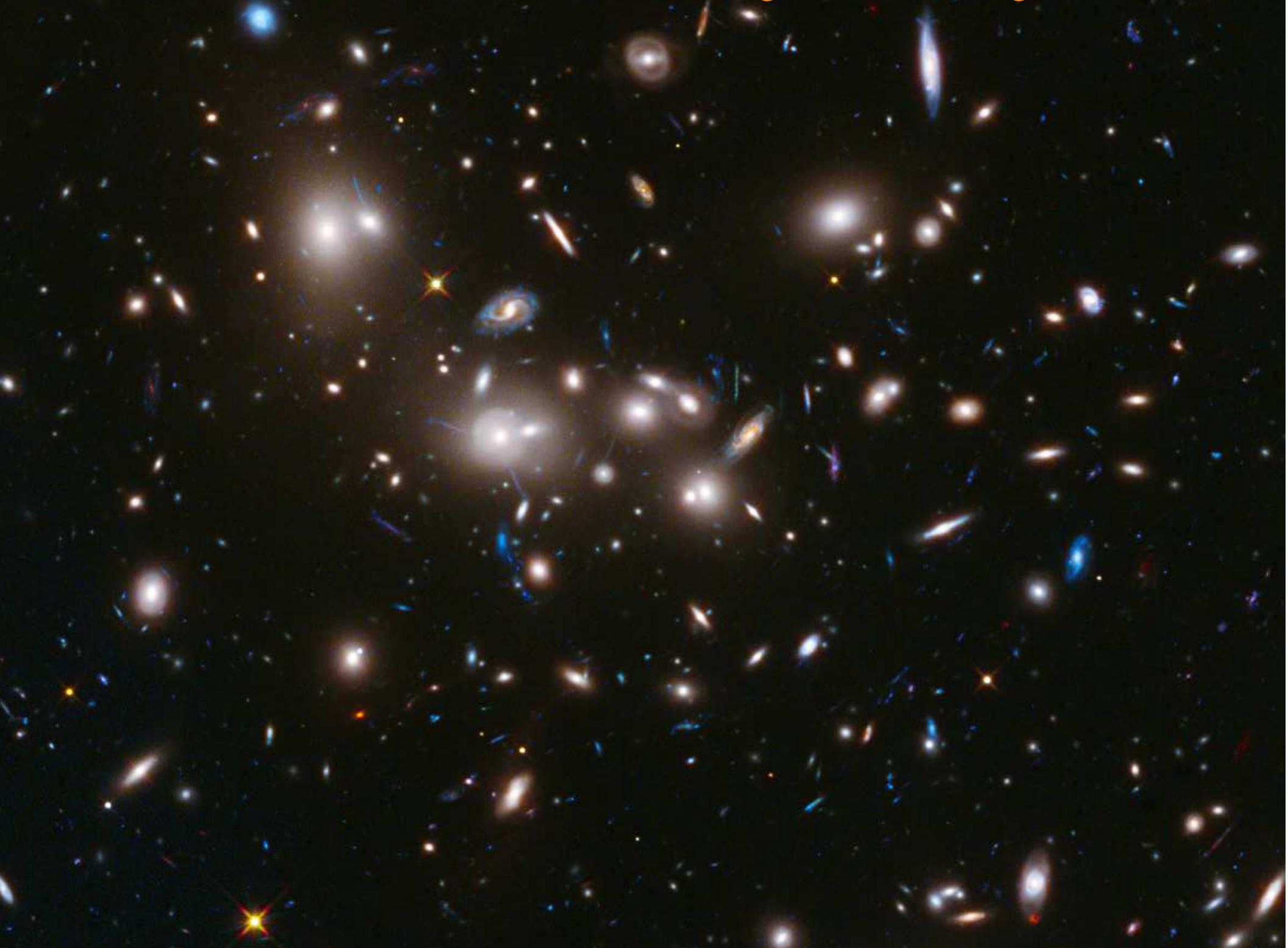
- Faint-end near-IR galaxy counts have $\gtrsim 2 \times 10^6$ galaxies/deg² !
- Webb UltraDeep Field (WUDF) can see Large Magellanic Cloud at $z \simeq 11$.
- Lensing will change the landscape for JWST observing strategies.



The “Cosmic Stock Market chart of galaxies: Very few big bright objects in the first Gyr, but lots of dwarf galaxies at $z \gtrsim 6$ (age $\lesssim 1$ Gyr).

- With proper survey strategy (area + depth), JWST can trace the entire reionization epoch and detect the first star-forming objects at $z \gtrsim 14$.

HST Frontier Field A2744: JWST needs lensing to see First Light at $z \gtrsim 10-15$!





Two fundamental limitations determine ultimate JWST image depth:

- (1) Cannot-see-the-forest-for-the-trees effect: Background objects blend into foreground neighbors \Rightarrow Need multi- λ deblending algorithms!
- (2) House-of-mirrors effect: (Many?) First Light objects can be gravitationally lensed by foreground galaxies \Rightarrow Must model/correct for this!
- Proper JWST $2.0\mu\text{m}$ PSF and straylight specs essential to handle this!

(6) Conclusions

- (1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.
- (2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.
Budget and Management replan in 2011. No technical showstoppers!
 - More than 80% 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>

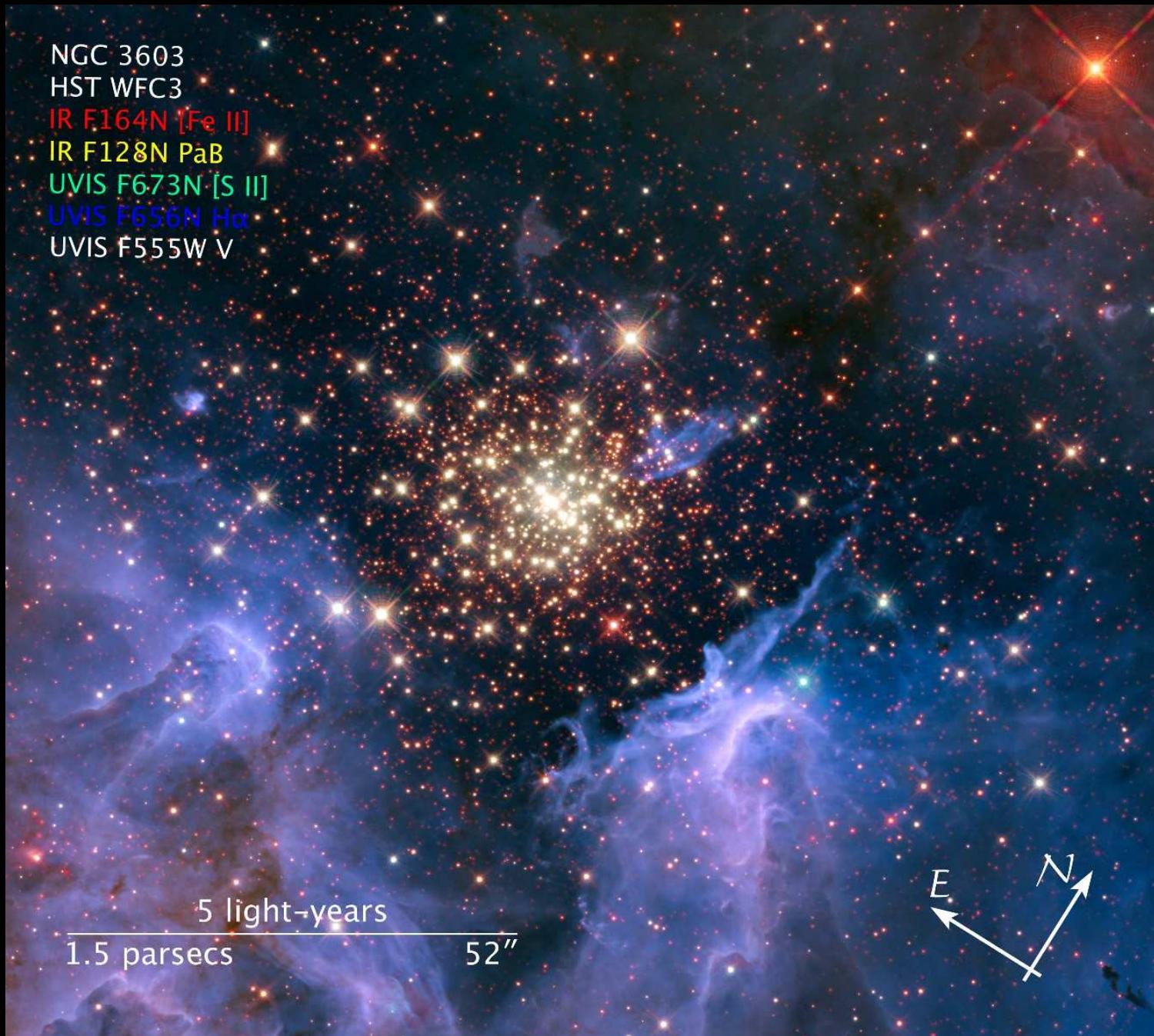
Gardner, J. P., et al. 2006, *Space Science Reviews*, 123, 485–606

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

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

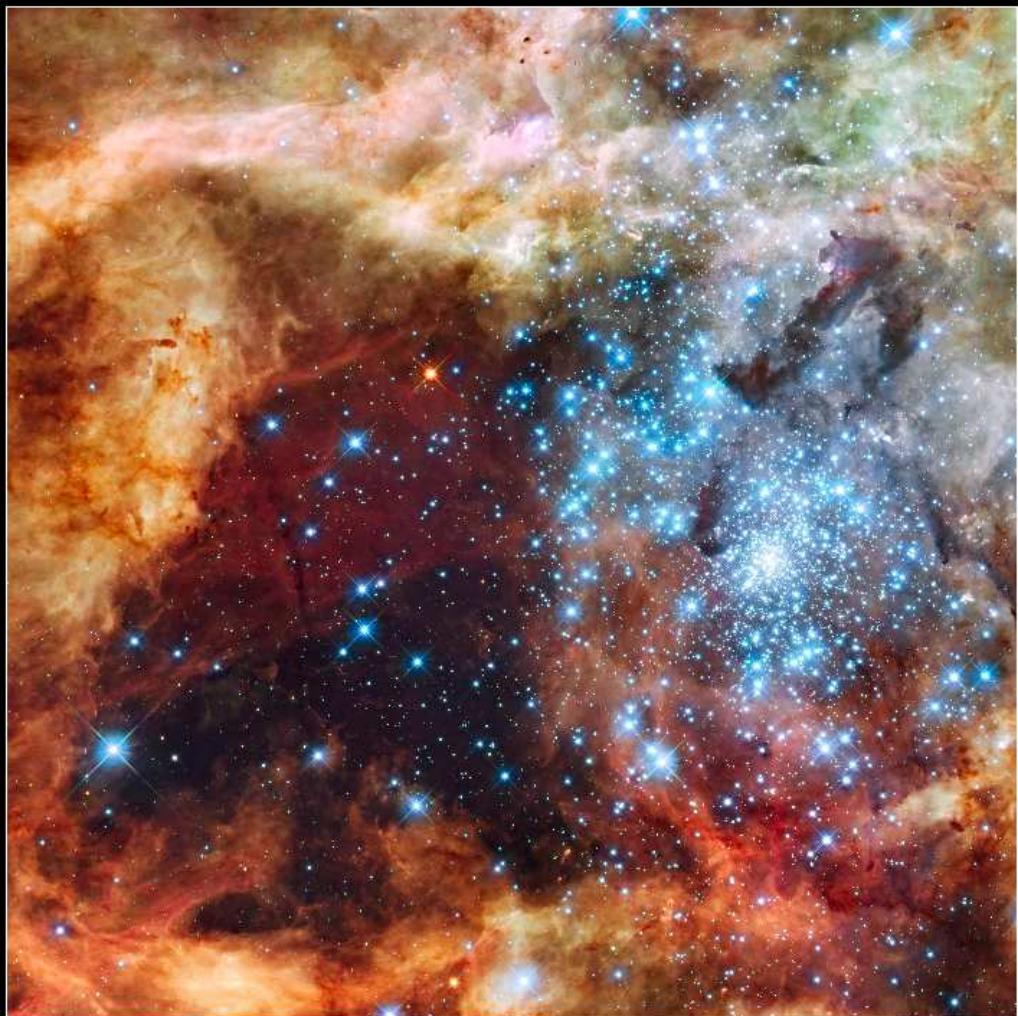
Windhorst, R., et al., 2011, *ApJS*, 193, 27 ([astro-ph/1005.2776](#))

(7) Measuring Star-birth and Earth-like exoplanets

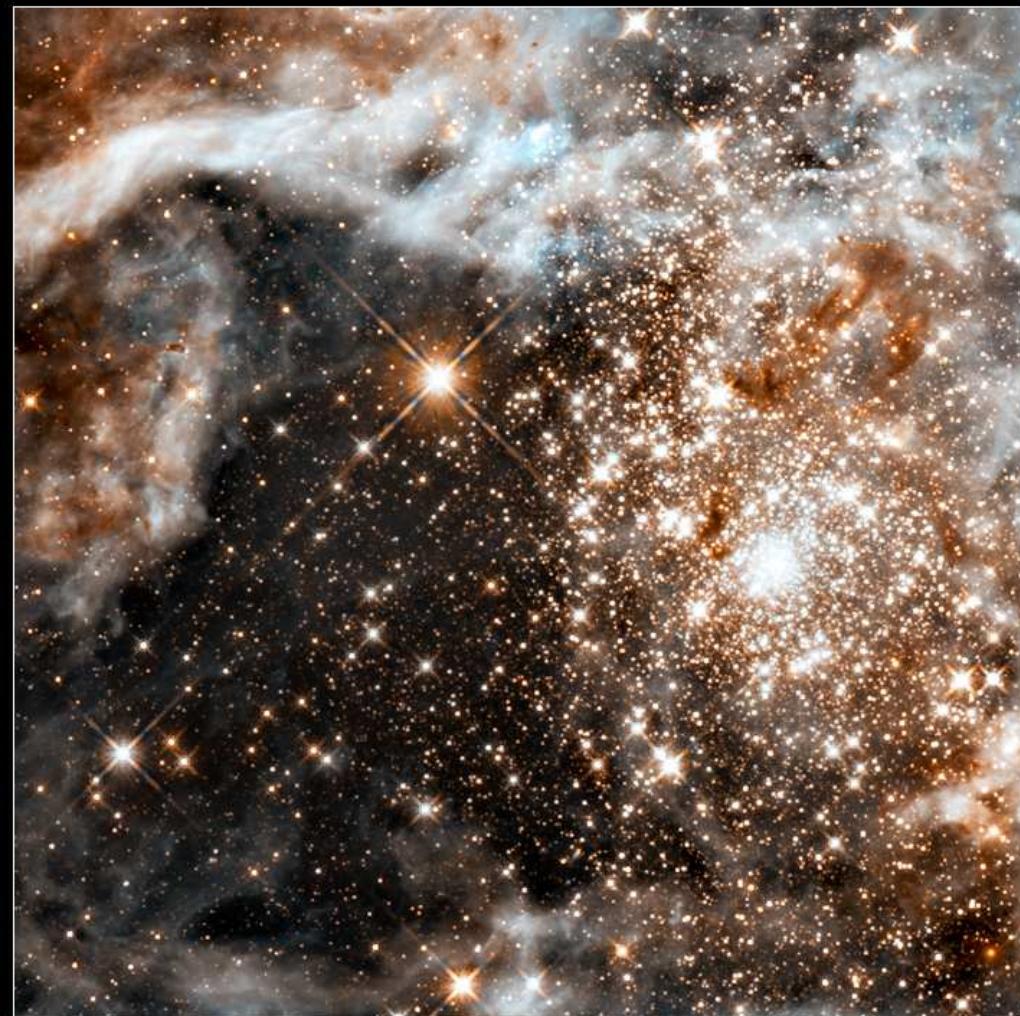


NGC 3603: Young star-cluster triggering star-birth in “Pillars of Creation”

Visible



Infrared



30 Doradus Nebula and Star Cluster

Hubble Space Telescope • WFC3/UVIS/IR

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

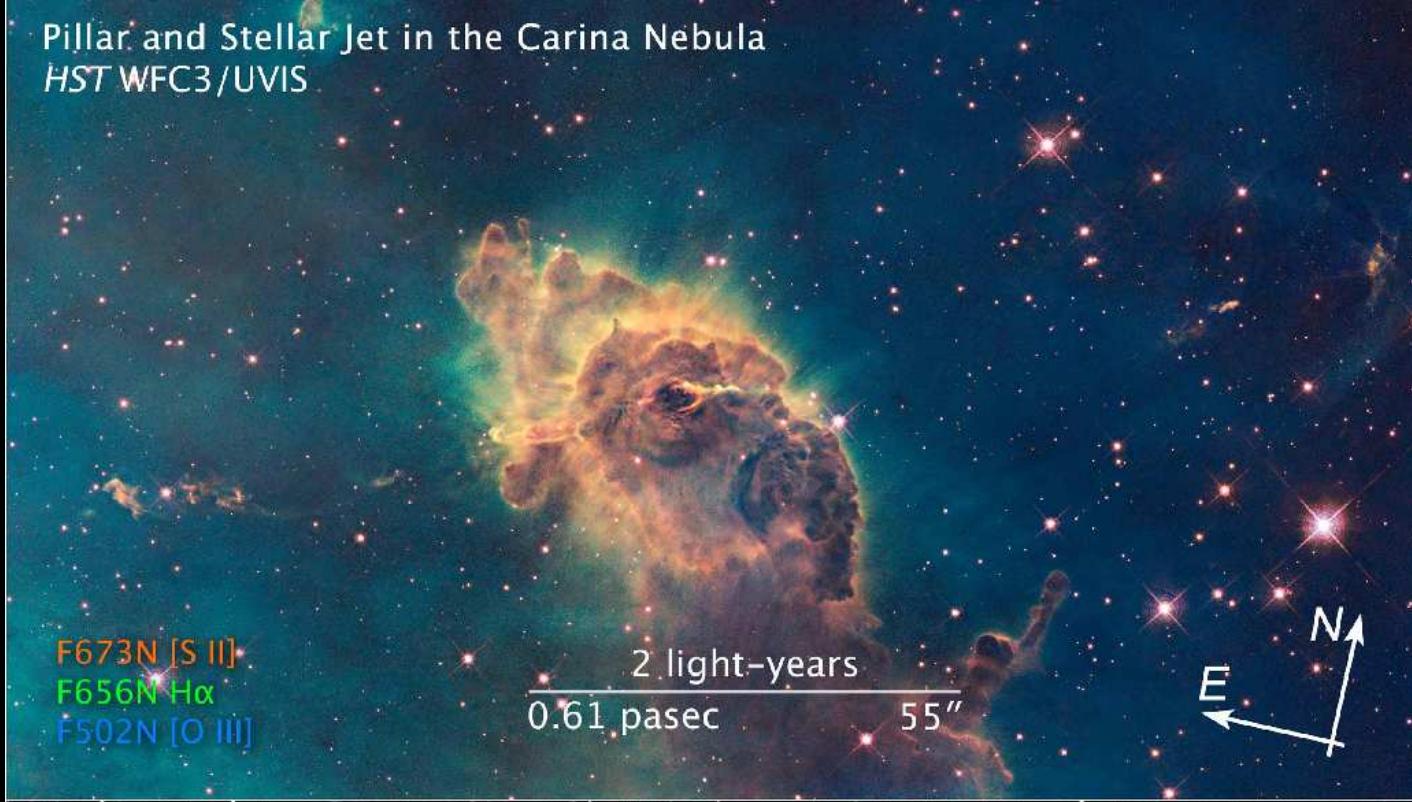
STScI-PRC09-32b

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

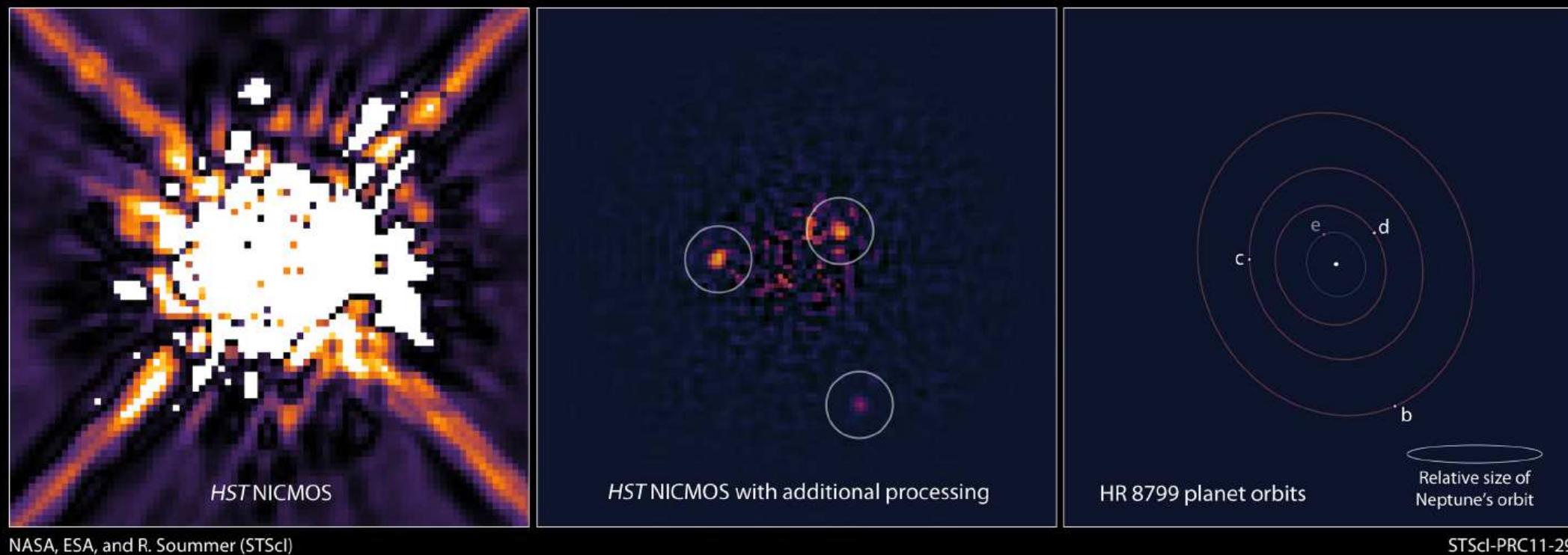




Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS



Exoplanet HR 8799 System



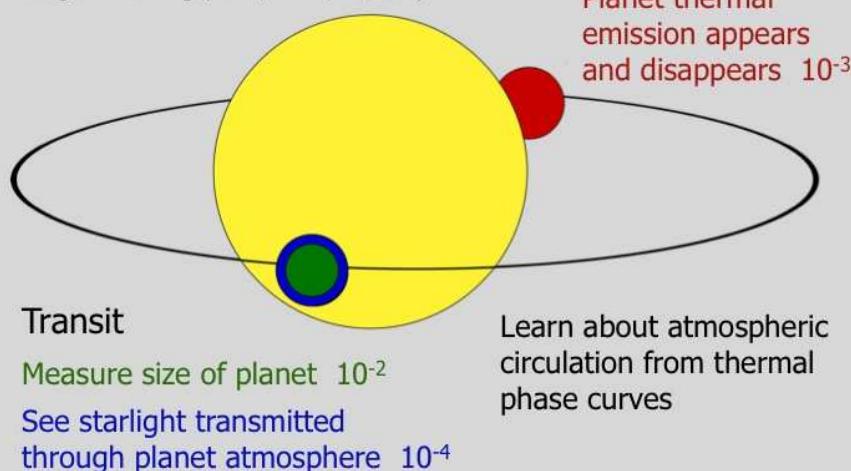
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

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

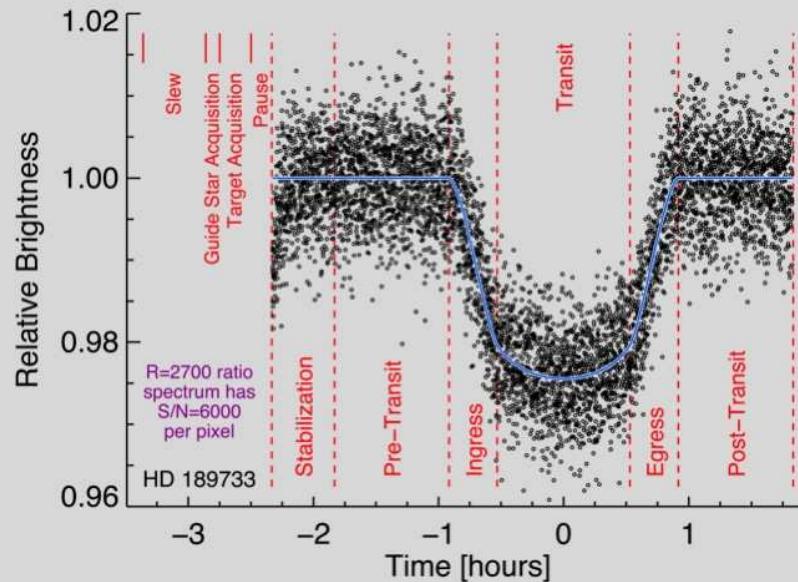
JWST can find such planets much closer in for much farther-away stars!

Schematic of Transit and Eclipse Science

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



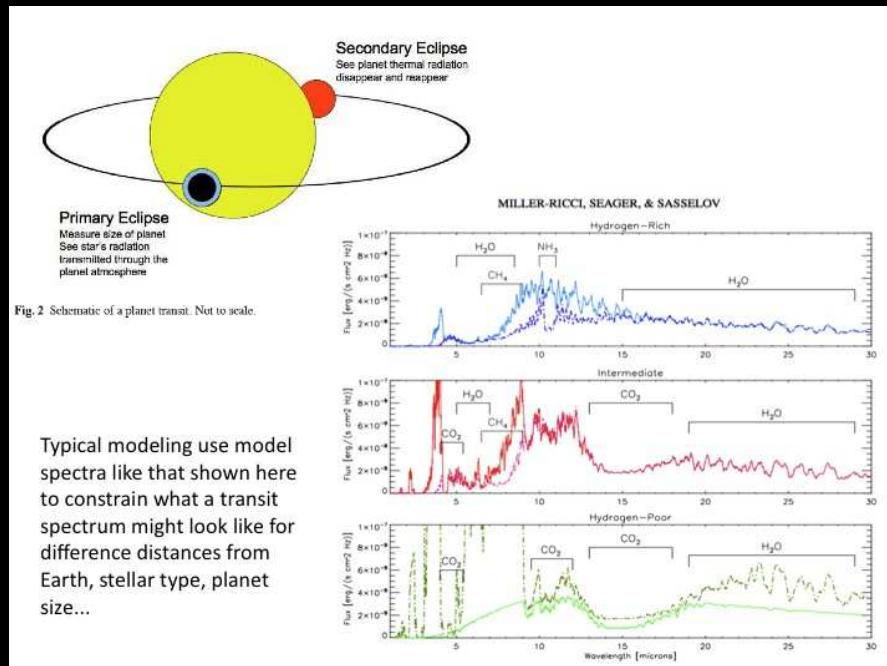
Timeline of a Transit Observation



6

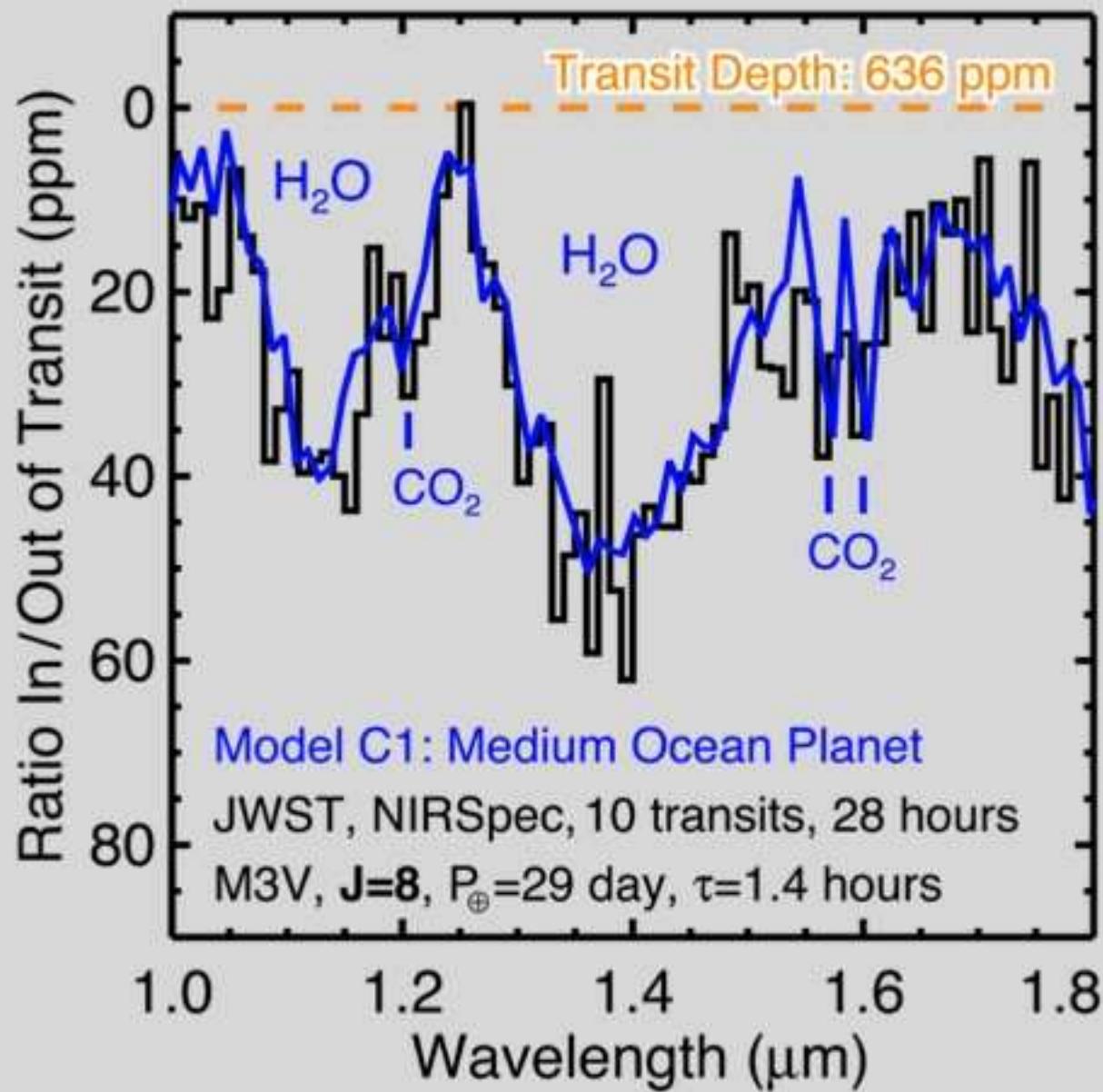
13

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



JWST IR spectra can find water and CO₂ in (super-)Earth-like exoplanets.

Transit Spectrum of Habitable “Ocean Planet”



17

JWST IR spectra can find water and CO₂ in transiting Earth-like exoplanets.

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

NGC 3310



ESO0418-008



UGC06471-2



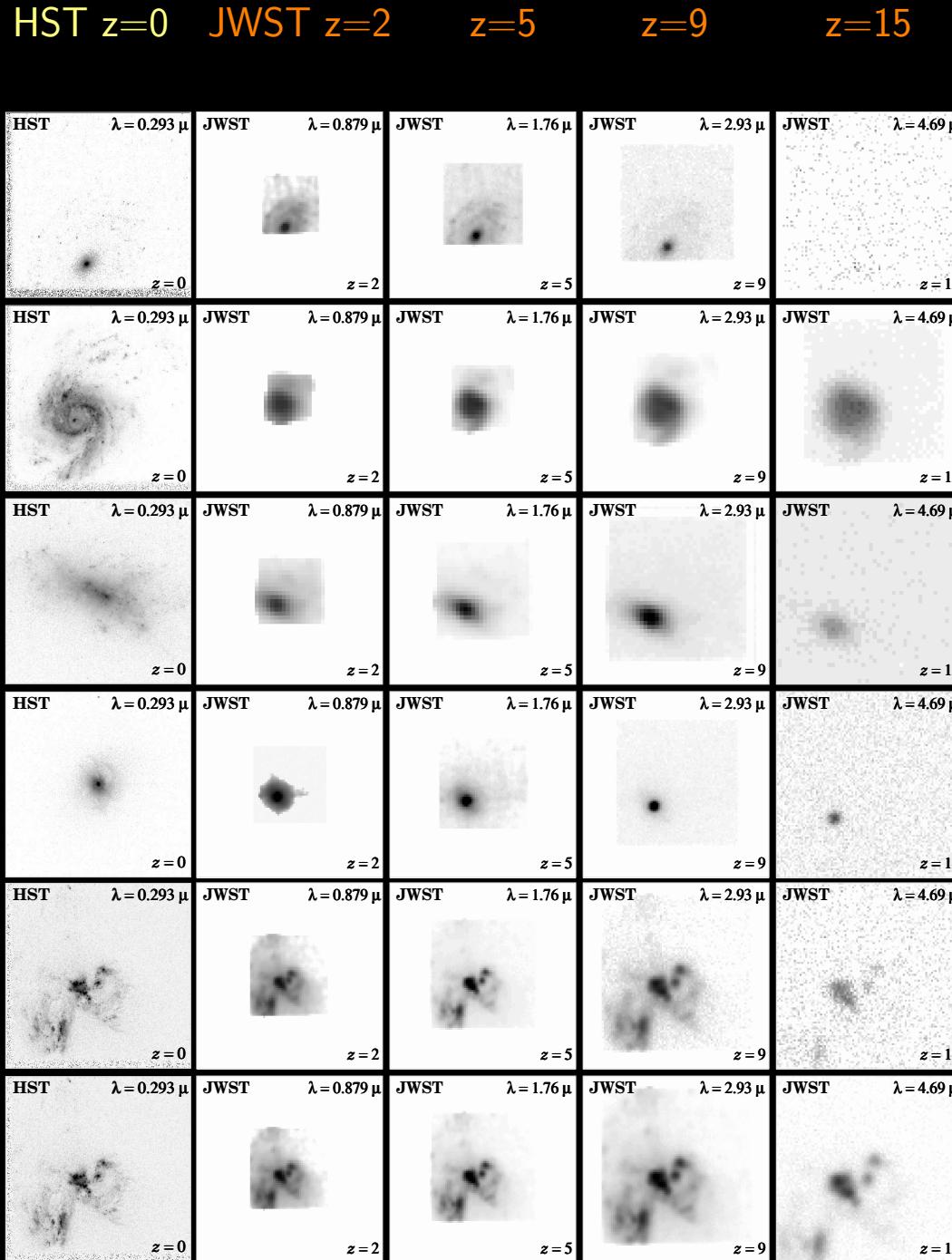
Ultraviolet Galaxies

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

HST • WFPC2

- 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



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.

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)



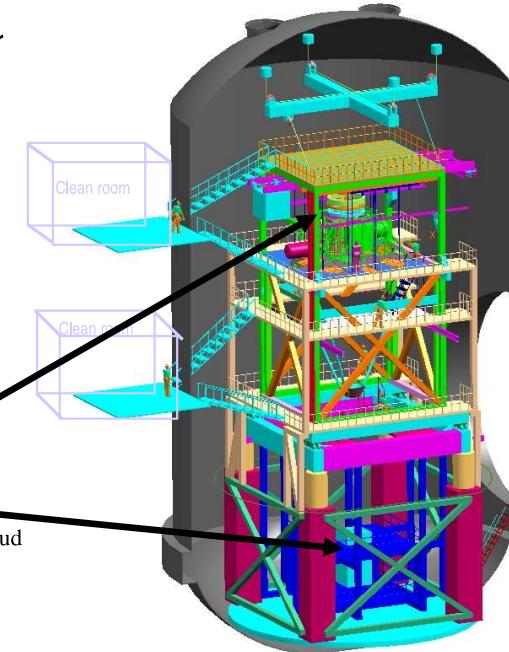
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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



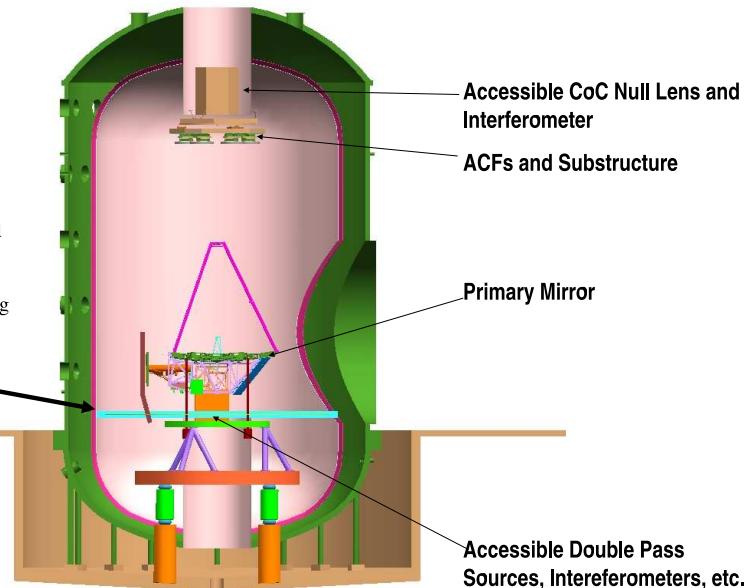
JSC "Cup Up" Test Configuration (New Proposal)



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.



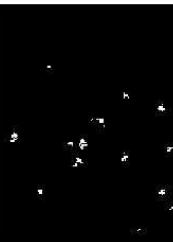
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

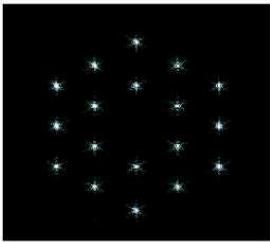
- ≈2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further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

*First light
NIRCam*



After Step 1

1.
Segment
Image
Capture



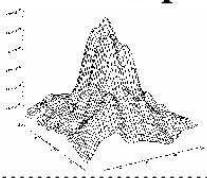
Initial Capture

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

2. Coarse Alignment

Secondary mirror aligned
Primary RoC adjusted

After Step 2



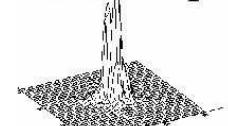
Primary Mirror segments:
< 1 mm, < 10 arcsec tilt
Secondary Mirror :
< 3 mm, < 5 arcmin tilt

Final Condition

PM segments:
< 100 μm ,
< 2 arcsec tilt
SM: < 3 mm,
< 5 arcmin tilt

3. Coarse Phasing - Fine Guiding (PMSA piston)

After Step 3

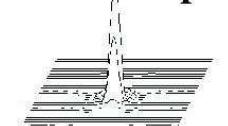


WFE: < 250 μm rms

WFE < 200 μm (rms)

4. Fine Phasing

After Step 4

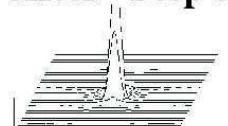


WFE: < 5 μm (rms)

WFE < 1 μm (rms)

5. Image-Based Wavefront Monitoring

After Step 5

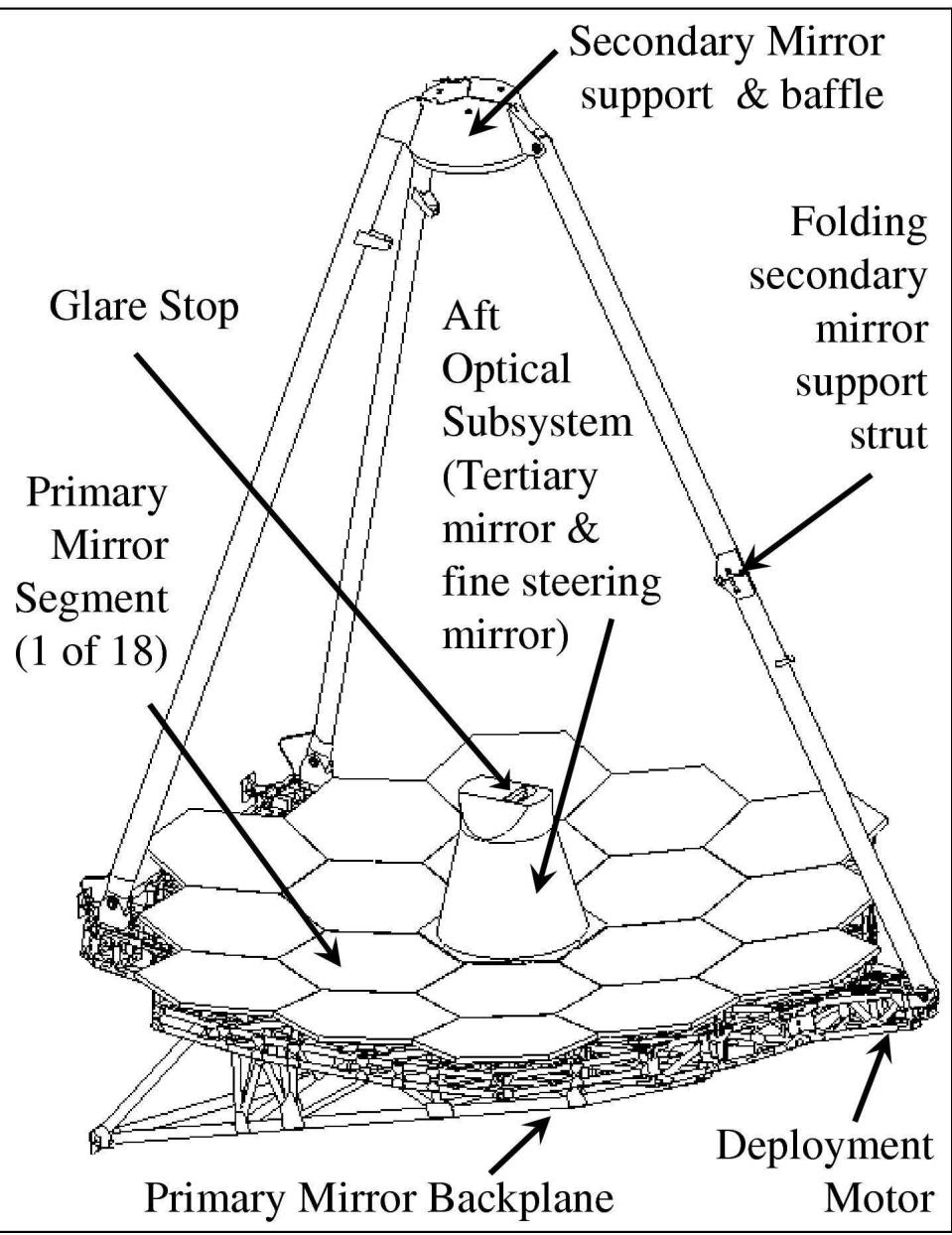


WFE: < 150 nm (rms)

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 μm images.

V3 (anti-spacecraft)

V1
V2

Secondary mirror

Cassegrain focus

Fine Steering Mirror

Primary Mirror

Tertiary Mirror

Focal Surface

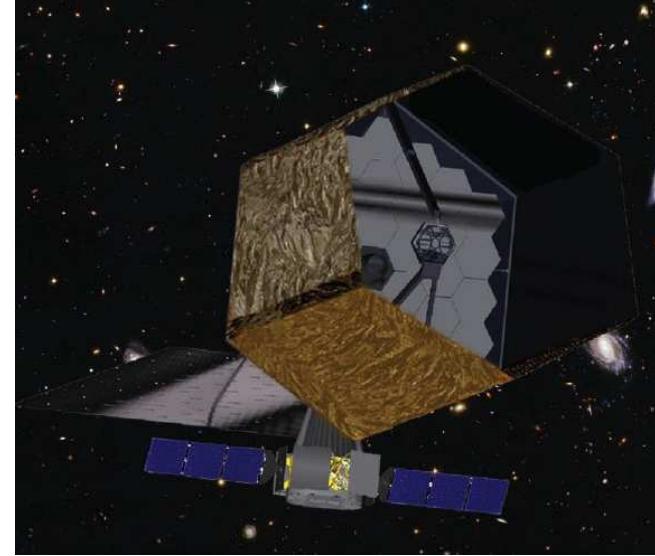
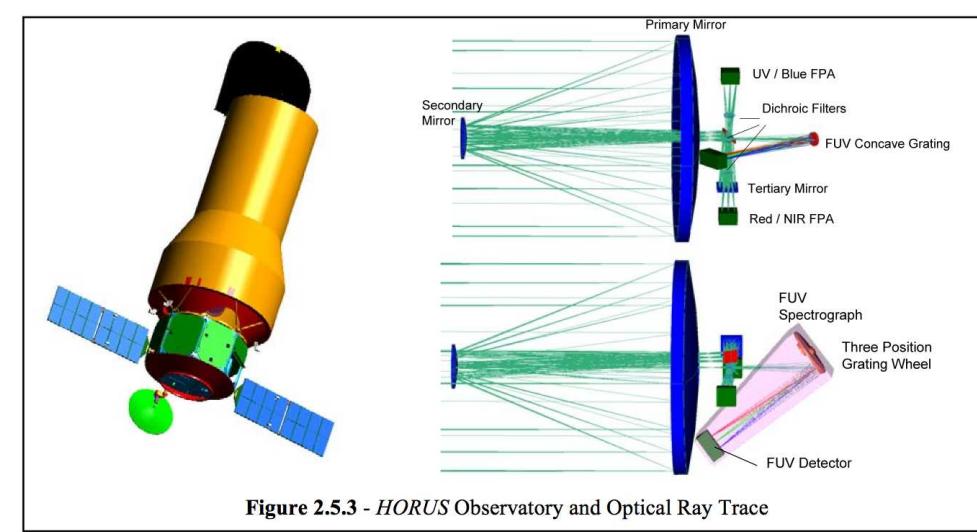
f/#: 20.0

Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)

OTE ISIM

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



[Left] One of two spare 2.4 m NRO mirrors: one will become WFIRST.

- NASA may look for partners to turn 2nd NRO into UV-opt HST sequel.

[Middle] HORUS: 3-mirror anastigmat NRO as UV-opt HST sequel.

- Can do wide-field (~ 0.25 deg) UV-opt $0\text{''}06$ FWHM imaging to $\text{AB} \lesssim 30$ mag, and high sensitivity (on-axis) UV-spectroscopy (Scowen et al. 2012).

[Right] ATLAST: 8–16 m UV-opt HST sequel, with JWST heritage.

- Can do same at 9 m.a.s. FWHM routinely to $\text{AB} \lesssim 32$ -34 mag, [and an ATLAST-UDF to $\text{AB} \lesssim 38$ mag ~ 1 pico-Jy].



Life-sized JWST model, at NASA/GSFC with the whole JWST Project ...



Life-sized JWST model, at NASA/GSFC Friday afternoon after 5 pm ...