The James Webb Space Telescope: Science and Mission Status

George Sonneborn
JWST Project Scientist for Operations
NASA Goddard Space Flight Center

5 October 2011 - FermiLab Colloquium

What is JWST ?

Description

- Cryogenic infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- General astrophysics mission for the astronomical community
- Launch on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

Organization

- **Mission Lead:** Goddard Space Flight Center
- Project Scientist: Dr John Mather (Nobel Laureate)
- **International collaboration:** ESA & CSA
- Prime Contractor: Northrop Grumman Aerospace
- **Instruments:**
  - Near Infrared Camera (NIRCam) – Univ. of AZ
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA
- **Operations:** Space Telescope Science Institute

JWST Science Drivers

"First Light" -
First luminous objects and hydrogen reionization

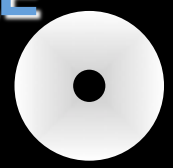
The assembly of galaxies: the origin of the Hubble sequence

Birth of stars and proto-planetary systems

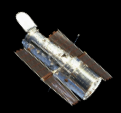
Planetary systems and the origin of life

JWST and its Precursors

HUBBLE

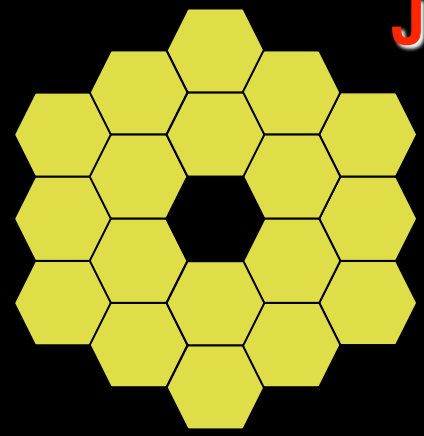


2.4-meter
T ~ 270 K

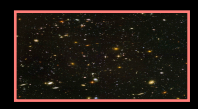


123” x 136”
$\lambda/D_{1.6\mu m}$~ 0.14”

JWST



6.5-meter
T ~ 40 K



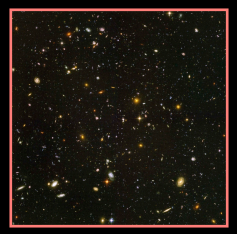
132” x 264”
$\lambda/D_{2\mu m}$~ 0.06”

114” x 84”
$\lambda/D_{20\mu m}$~ 0.64”

SPITZER

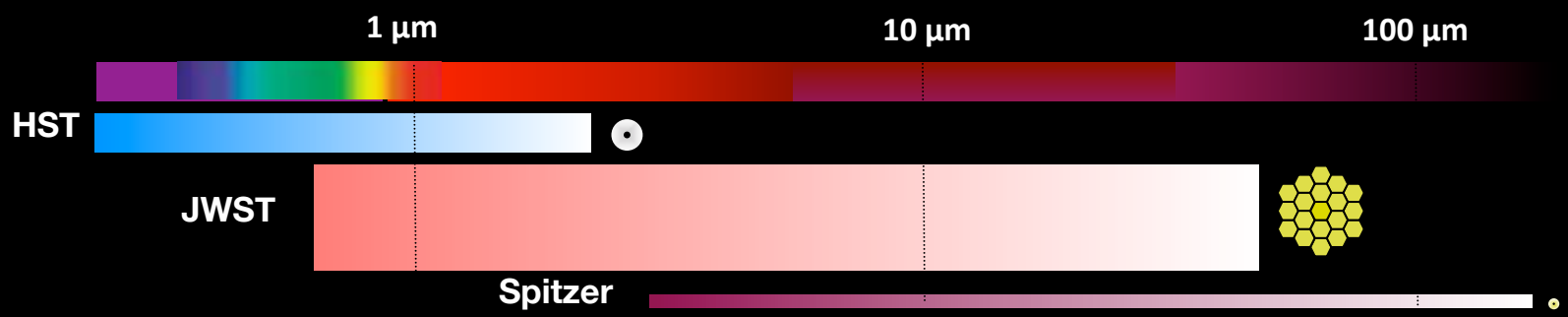
0.8-meter
T ~ 5.5 K

312” x 312”
$\lambda/D_{5.6\mu m}$~ 2.22”



324” x 324”
$\lambda/D_{24\mu m}$~ 6.2”

Wavelength Coverage



End of the dark ages: first light and reionization

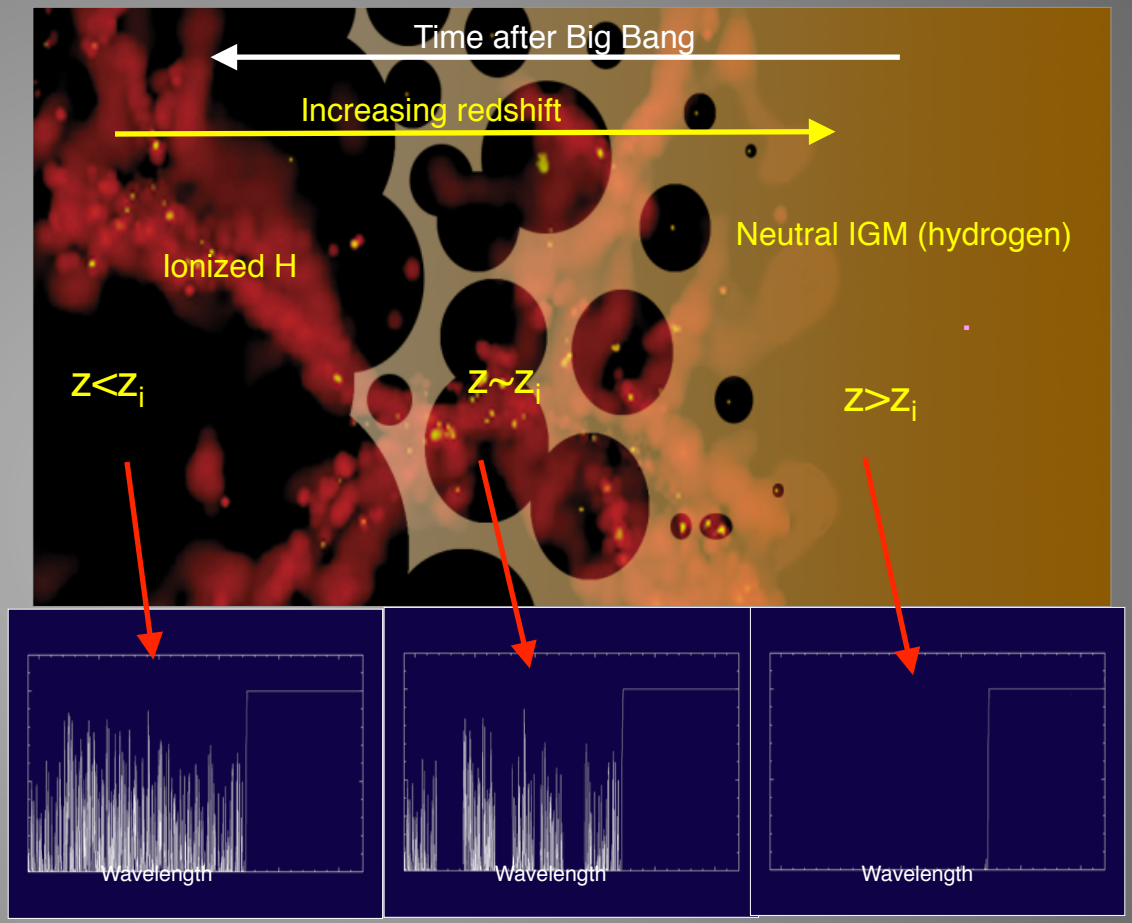
… to identify the first luminous sources to form and to determine the ionization history of the early universe.

Hubble Ultra Deep Field - 2006

Key questions about the "first light" & reionization era

- What is the nature of the first galaxies and other luminous objects?
- When did reionization of H in the intergalactic medium occur?
- What caused the H re-ionization?
- How did black holes form and interact with their host galaxies?

Redshift z	m_{AB}	Fν (nJy)	Lyman Break wavelength
10	30.3	2.8	1.34 μm
15	30.9	1.6	1.95 μm
20	31.3	1.1	2.55 μm

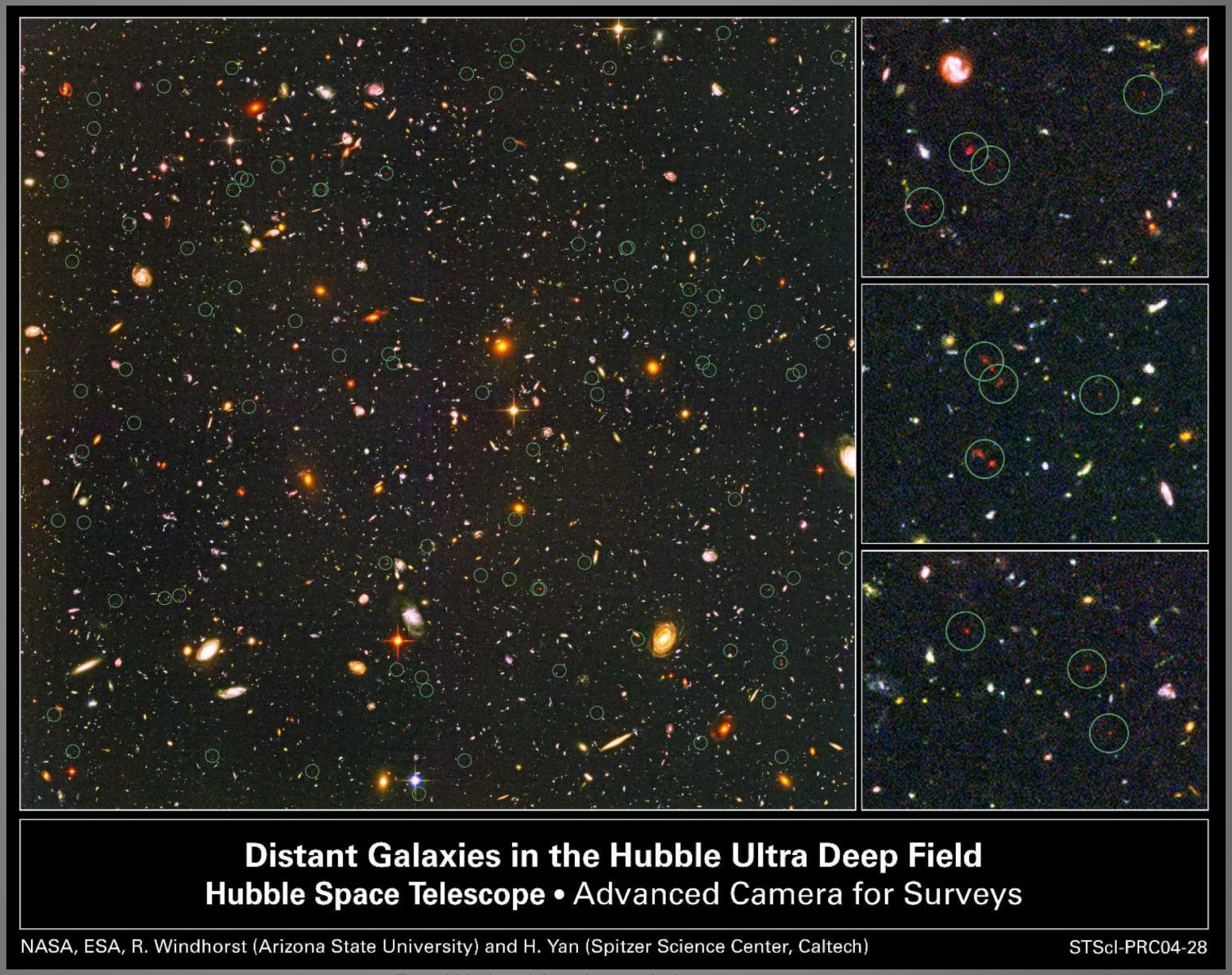


Key Enabling Design Requirments:

- Deep near-infrared imaging survey (1 nJy)
- Near-IR multi-object spectroscopy
- Mid-IR photometry and spectroscopy

Hubble Ultra-Deep Field i-band dropouts: faint galaxies at z~6 (Yan & Windhorst 2004)

HUDF
240 hours observing time with ACS



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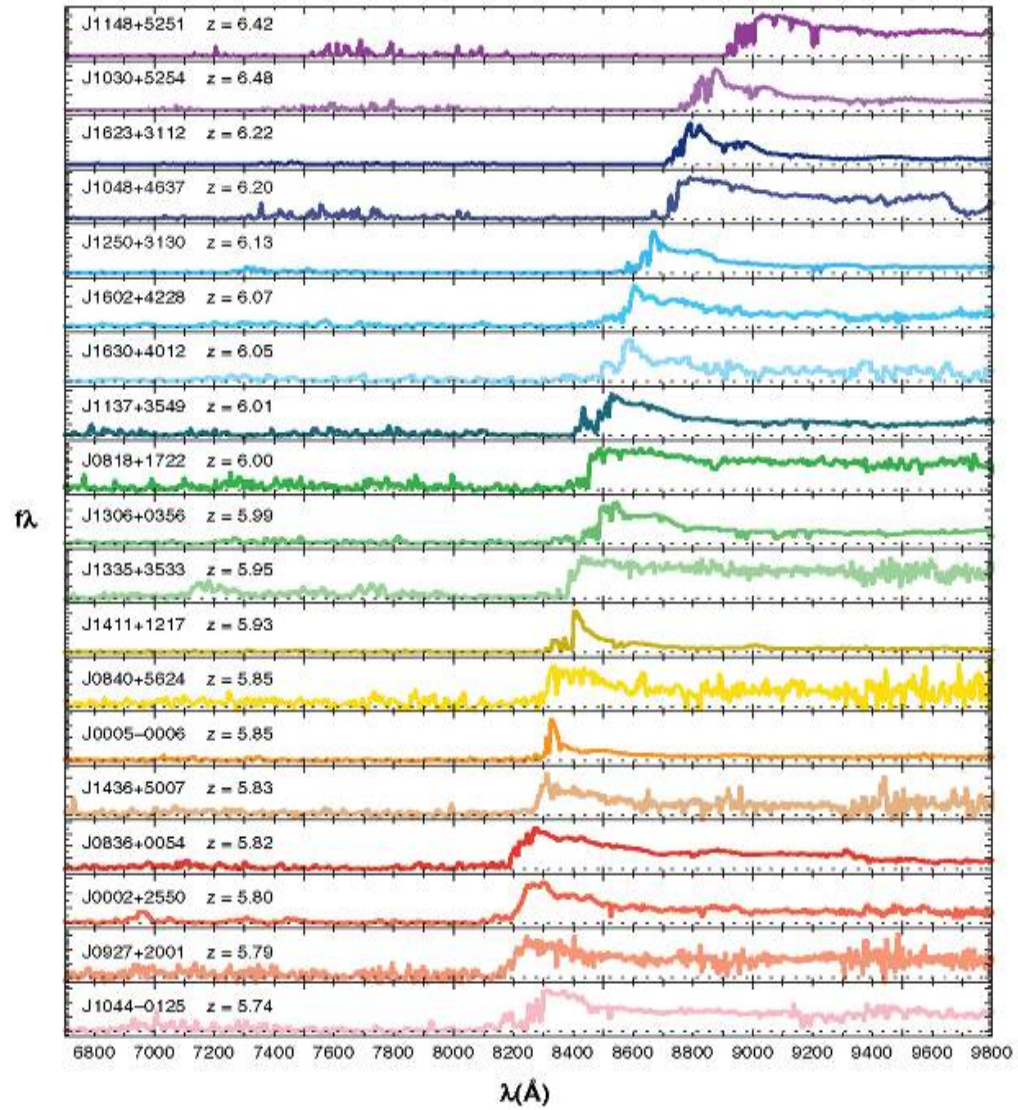
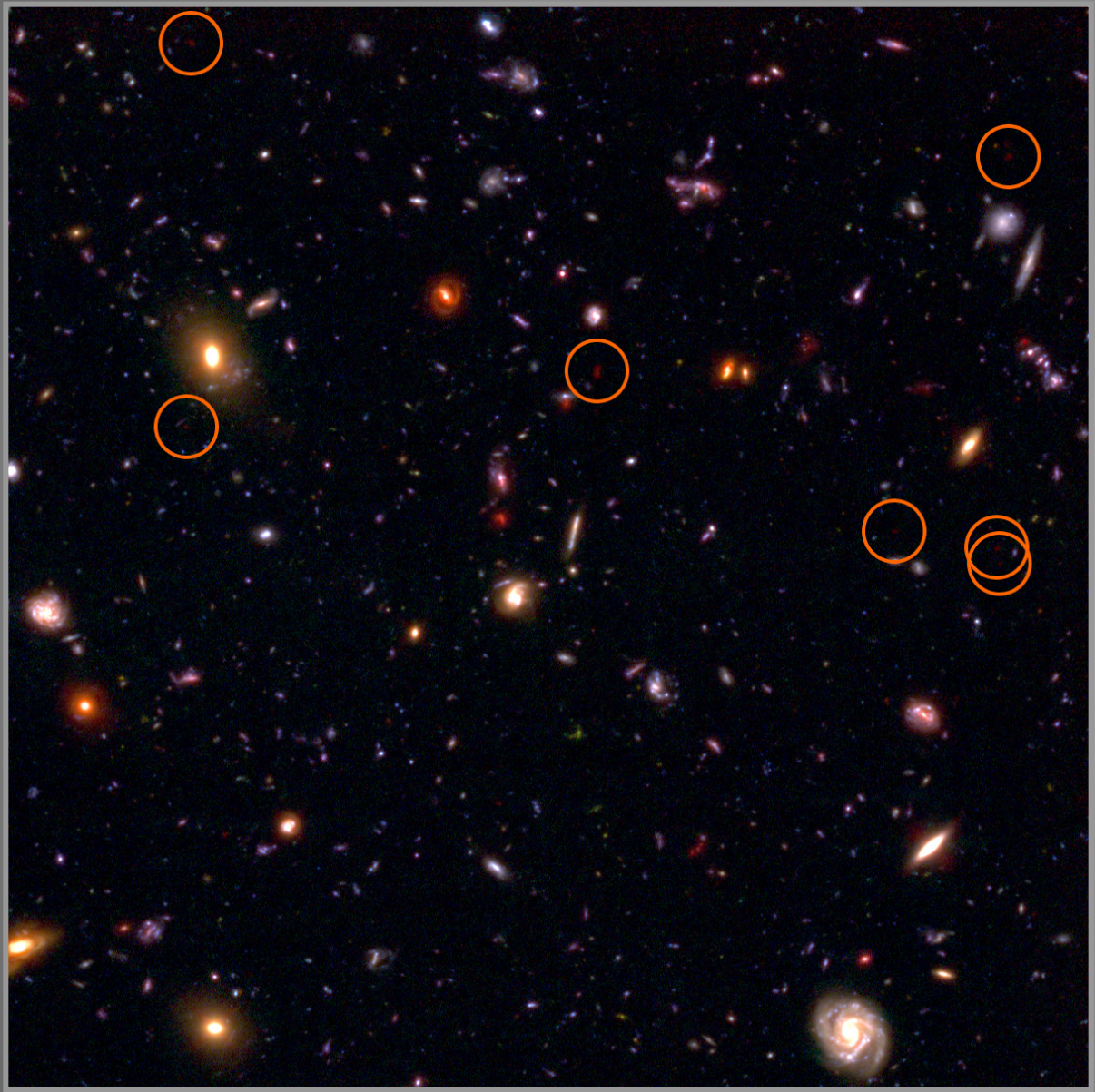
Fan, Carilli & Keating 2006, ARAA, 44, 415



HUDF: 40 hours with WFC3 in August 2009



New objects found at z~7-8 (z-band dropouts)

WFC3/IR F105W + F125W + F160W

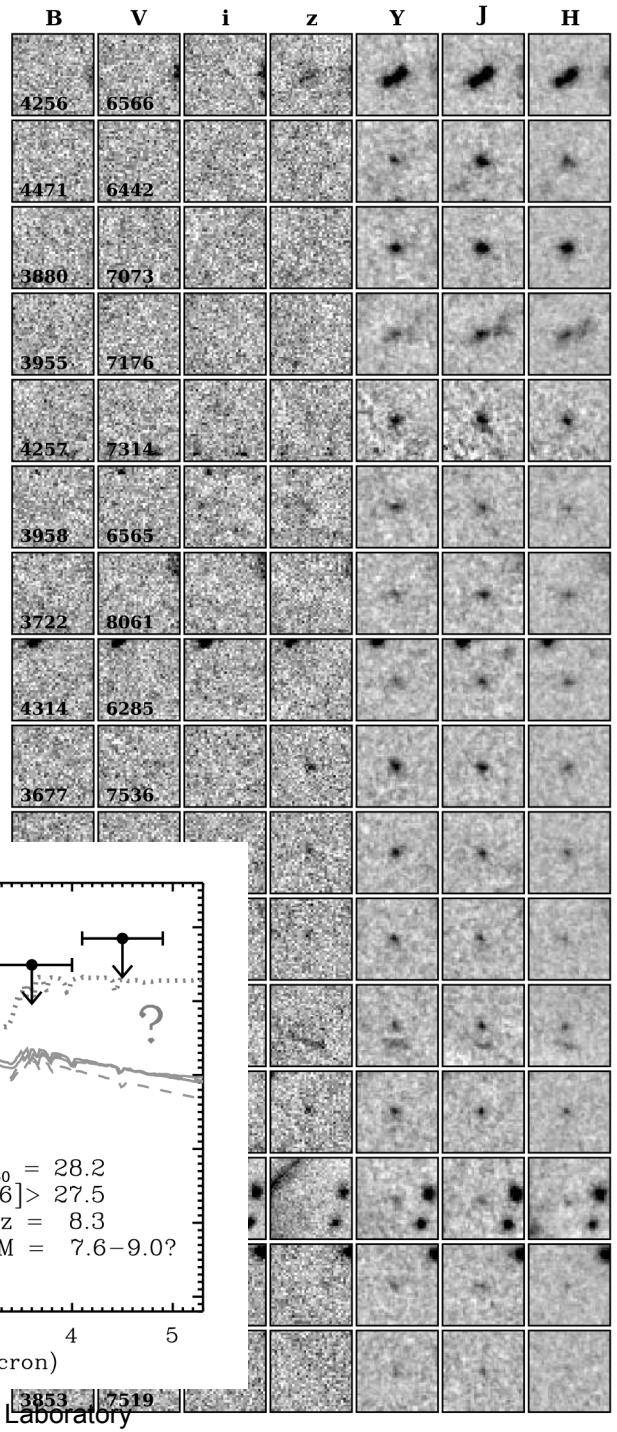
ACS F814W + F850LP

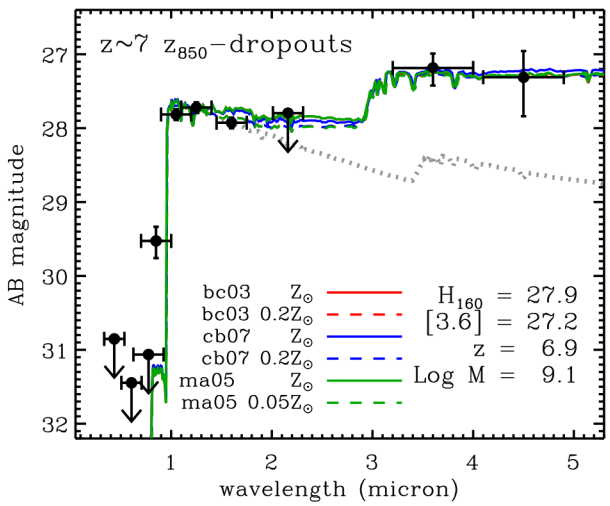
ACS F435W + F606W

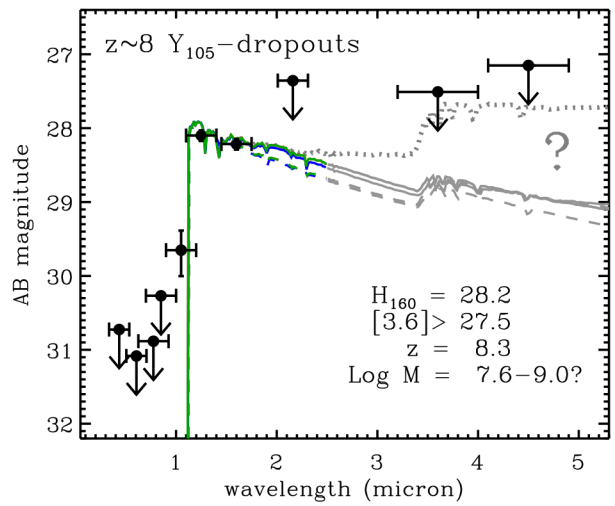
Courtesy of the HUDF09 team: Garth Illingworth (PI), Marcella Carollo, Rychard Bouwens, Marijn Franx, Ivo Labbe, Dan Magee, Pascal Oesch, Massimo Stiavelli, Michele Trenti, Pieter van Dokkum

z = 7-8 galaxies found in new HST/WFC3 images of HUDF

- **40 hours of observations in late August '09**
- **Vastly superior near-IR sensitivity (20-30X) over previous instruments**
  - 5σ detections at Y ~27.5 mag
- **Redshift from z-band (850 nm) and Y-band (1μm) dropouts (Oesch et al 2009, Bouwens et al 2009, Labbe et al 2009)**
- **JWST will provide a similar sensitivity gain over WFC3**

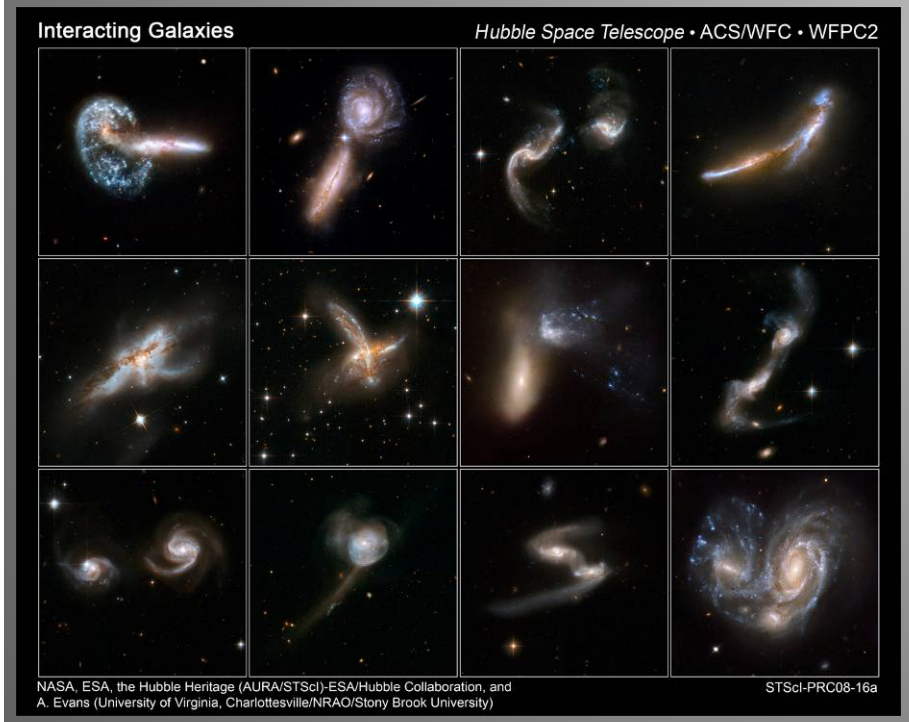


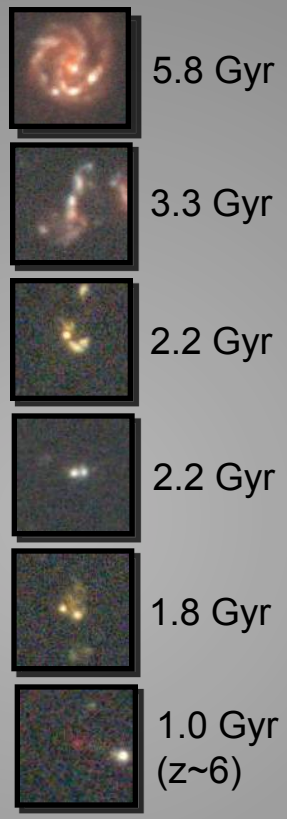


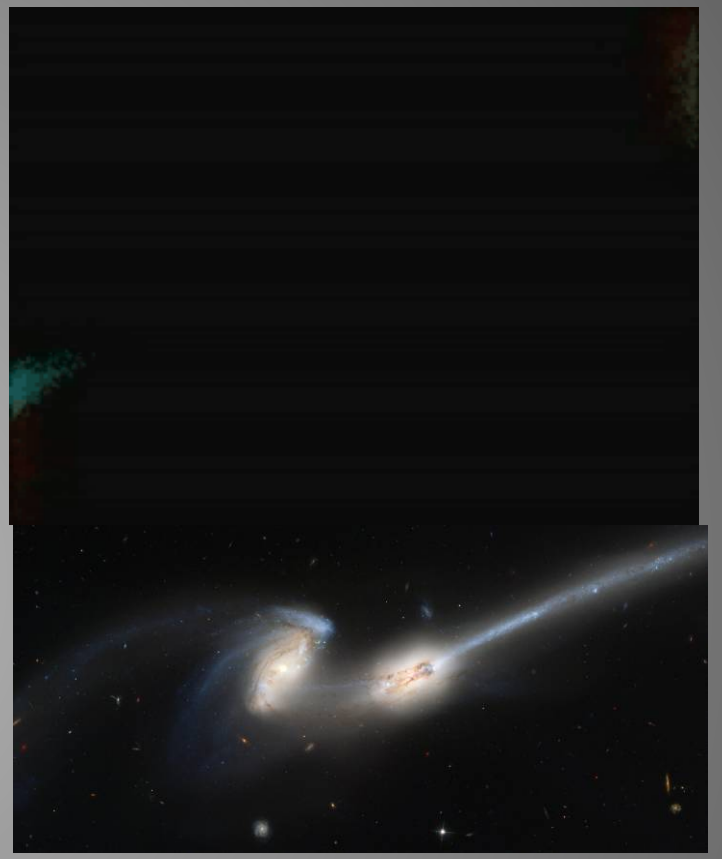


Key questions about galaxy evolution:

- When did the Hubble Sequence form?
- What role did galaxy collisions play in their evolution?
- How is the chemical evolution of the universe related to galaxy evolution?
- What powers emission from galaxy nuclei?





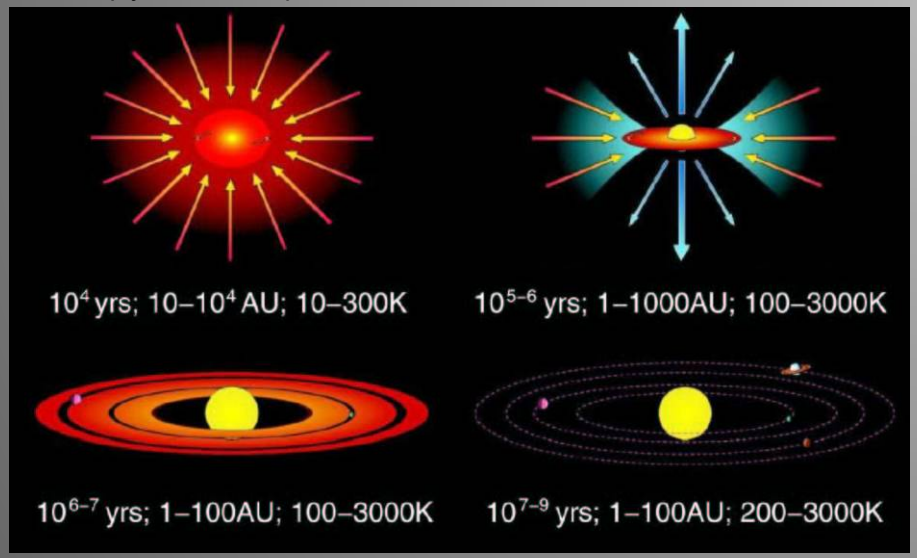


Key Enabling Design Requirments:

- Wide-area near-infrared imaging survey
- Low and medium resolution spectra of 1000s of galaxies at high redshift
- Targeted observations of galactic nuclei

Key questions about star formation:

- How do molecular clouds collapse?
- How does environment affect star-formation?
  - Vice-versa?
- What is the mass distribution of low-mass stars?
- What do debris disks reveal about the evolution of terrestrial planets?



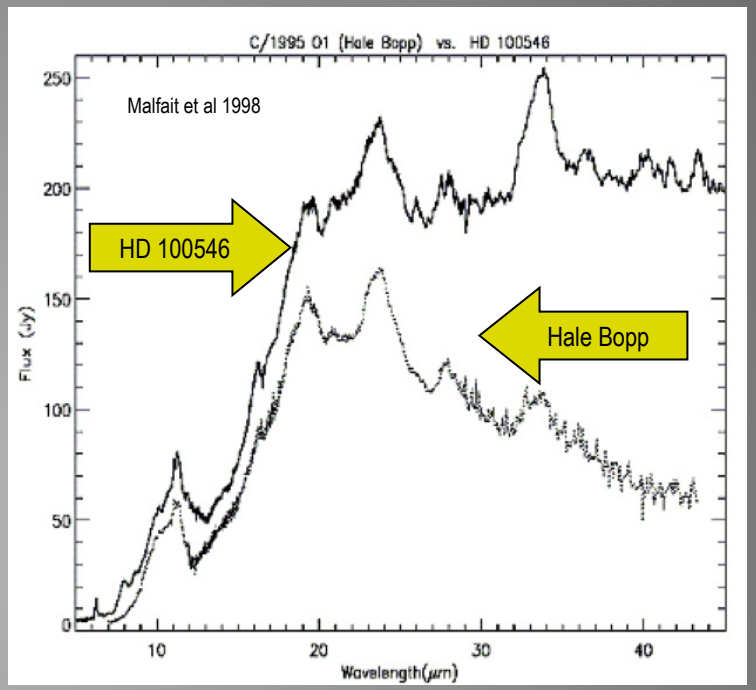
The Eagle Nebula as seen in the near-infrared

Key Enabling Design Requirments:

- High angular resolution near- and mid-IR imagery
- High angular resolution imaging spectroscopy

Key questions about planet formation:

- How do planets form?
- How are circumstellar disks like our Solar System?
- How are habitable zones established?



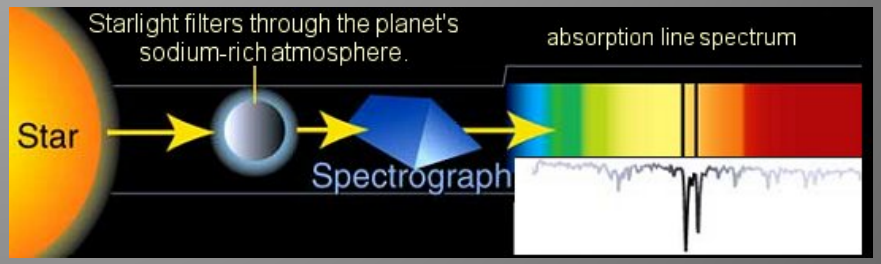
Key Enabling Design Requirements:

- Near- and mid-IR coronagraphic imaging
- Near- and mid-IR spectroscopy
- High time resolution sub-array imaging and spectroscopy for exoplanet transit studies

Two landmark discoveries in mid-1990s have become important science goals for JWST

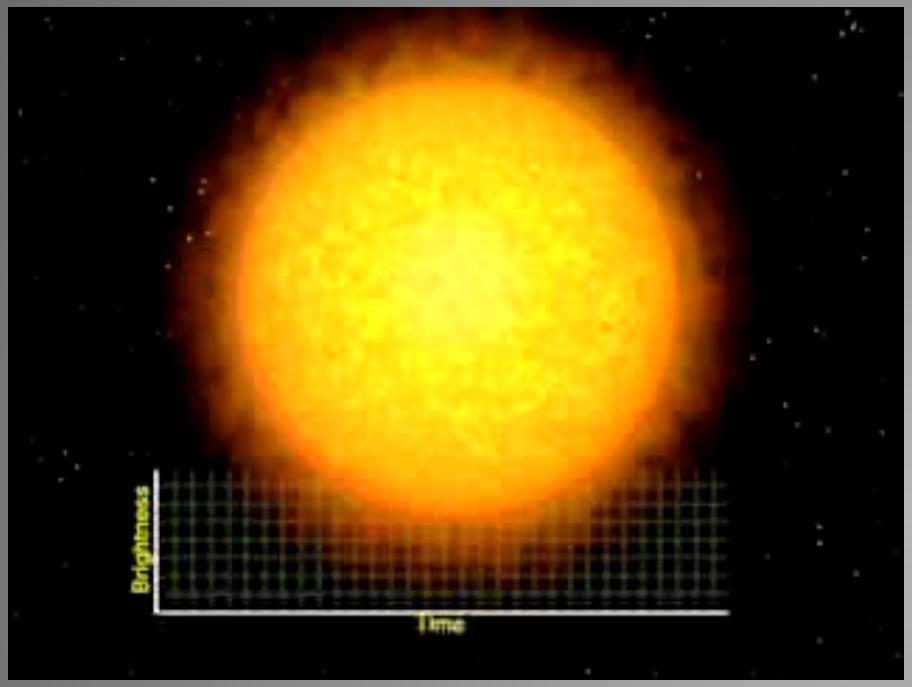
- Exoplanets

- Kuiper Belt Objects



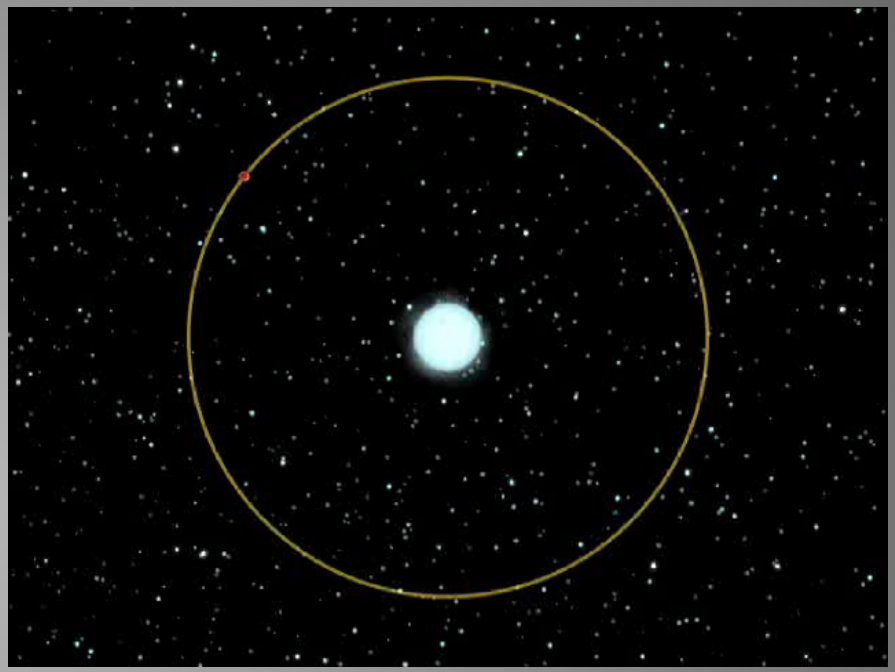
Transits

Primary



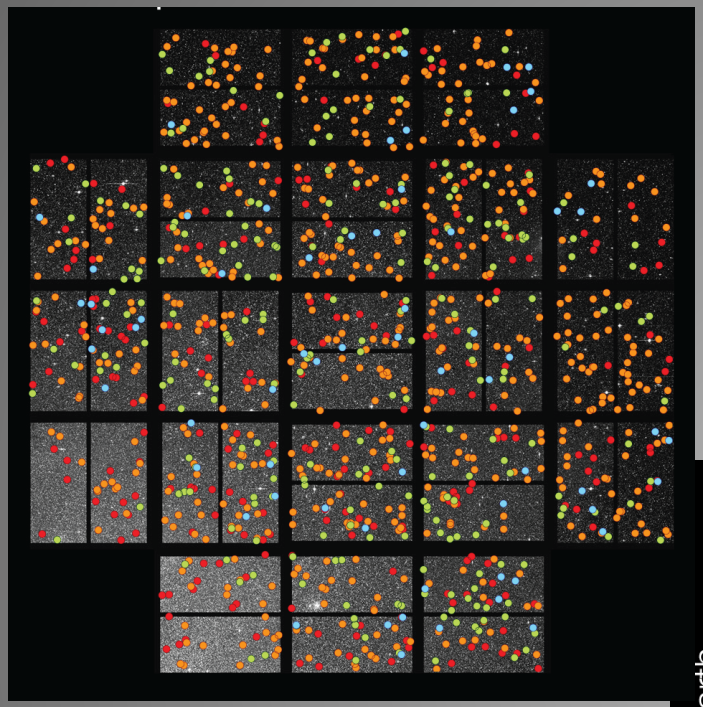
- Planet blocks light from star
- Visible/NIR light (Hubble/JWST)
- Radius of planet/star
- Absorption spectroscopy of planet's atmosphere
- JWST: Look for moons (by timing), constituents of atmosphere, Earth-like planets with water, weather

Secondary

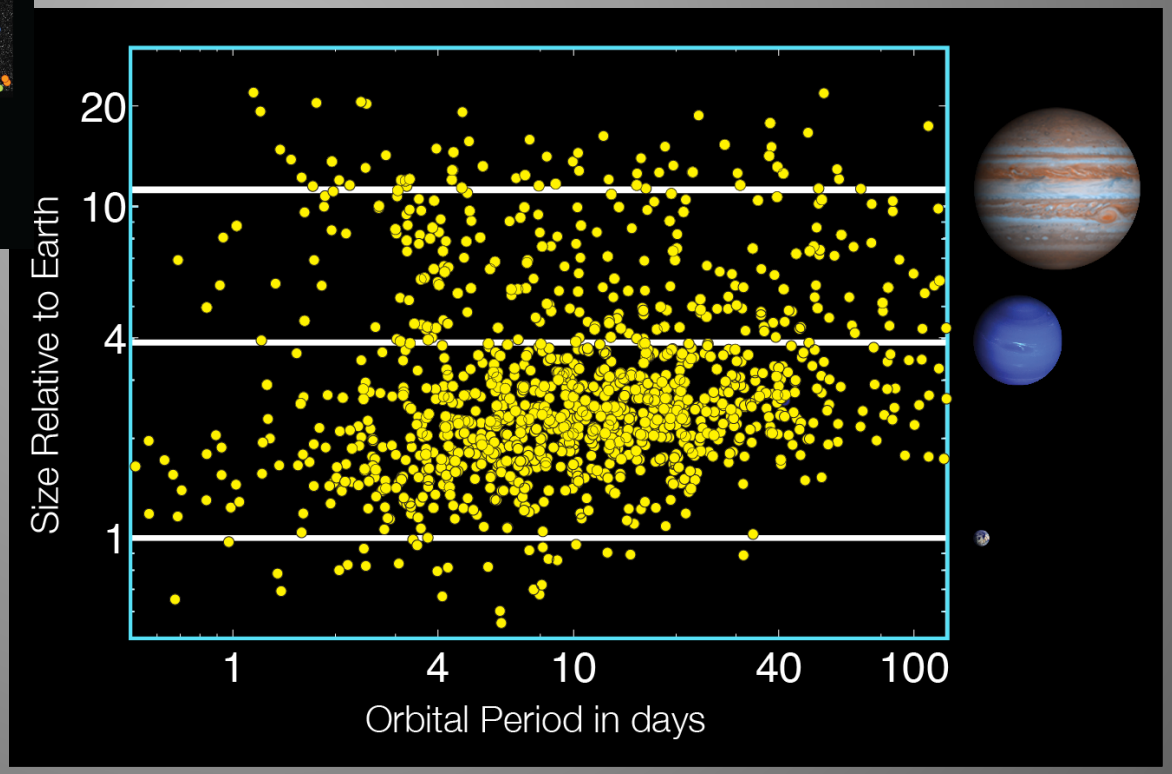


- Star blocks light from planet
- Mid-Infrared light (Spitzer/JWST)
- Direct detection of photons from planet
- Temperature of planet
- Emission from surface
- JWST: Atmospheric characteristics, constituents of atmosphere, map planets

Kepler Found over 1200 Planetary Candidates



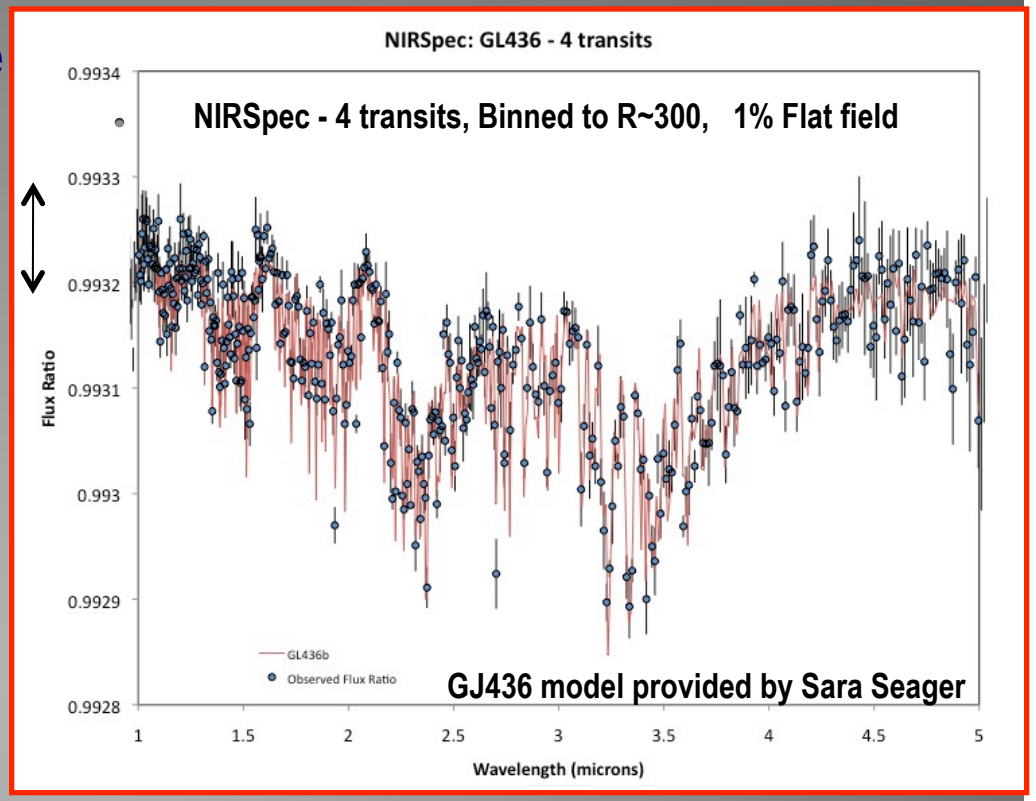
- **Data on 155,435 stars over 105 sq deg**
- **1235 planetary candidates as of Feb 2011**
  - 68 Earth size
  - 288 super-Earth size
  - 688 Neptune size
  - 165 Jupiter size

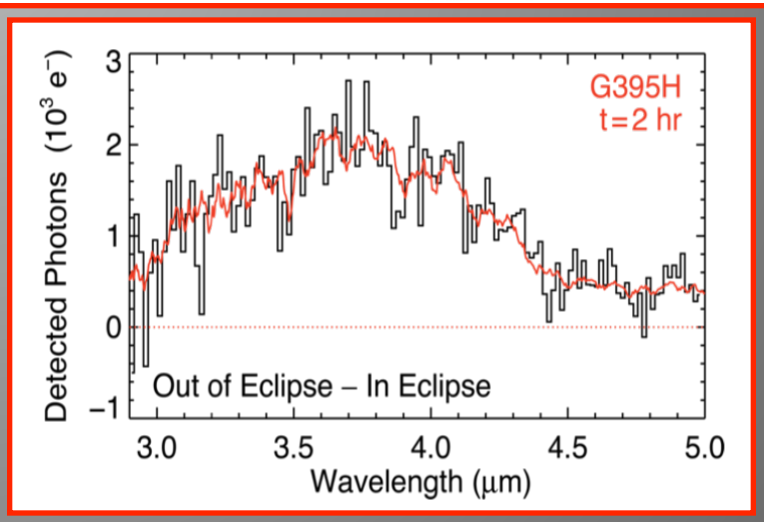


Exoplanet Transit Science

- Near-IR and Mid-IR spectroscopy
- Primary and secondary transits
- NIRSpec can obtain spectra at a range of spectral resolutions for hot Jupiters and hot Neptunes
- For the bright host stars JWST can conduct high precision transit spectroscopy (GKM stars) to characterize spectral features

0.01%





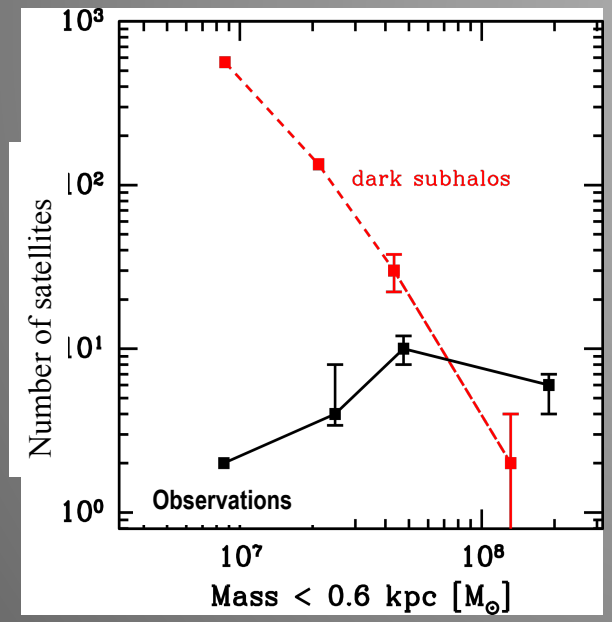
Simulation by Jeff Valenti (NIRSpec Science Team)

JWST Potential for Dark Matter and Dark Energy Studies

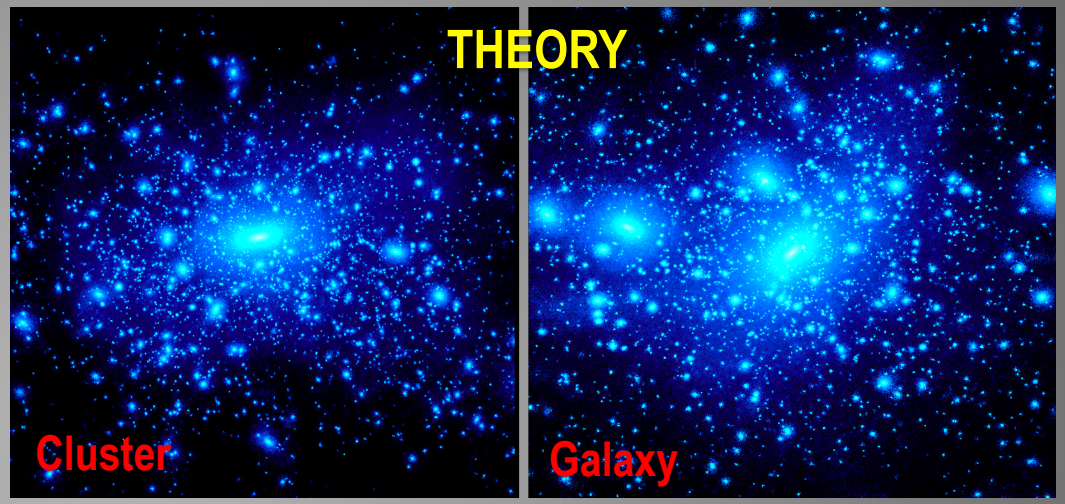
- **The combination of JWST's sensitivity, angular resolution, and wavelength coverage provide powerful new tools to address major questions related to Dark Matter and Dark Energy**
- **Two examples**
  - Dark Matter – Dark matter substructure and the presence of dark matter satellites around galaxies
  - Dark Energy – Cosmological constraints imposed by greater precision in the Hubble Constant
- **Based on invited talks presented at "Frontier Science Opportunities with the JWST" held June 6-8, 2011**
  - Tommaso Treu (UCSB) "Strong Lensing to Study the Evolution of Galaxies"
  - Adam Riess (JHU) "High Precision Measurements of H_o"
  - Visit https://webcast.stsci.edu/webcast/calendar.xhtml to listen to talks and download presentations

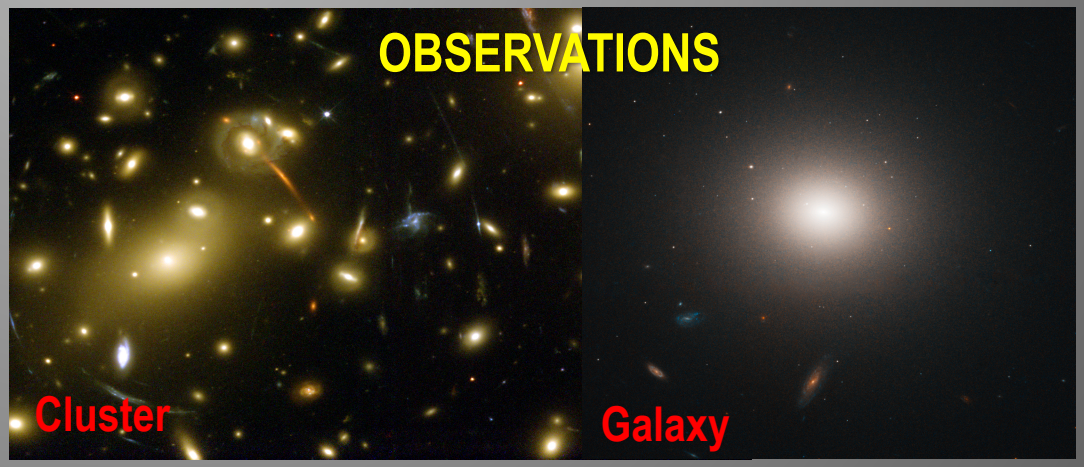
Is There Dark Matter Substructure?

- Are the satellites predicted by theory non-existent or just dark?
- If they don't exist, what's wrong with the standard cosmological model?
- If they exist and are dark, why are they not forming stars?



Strigari et al. 2007

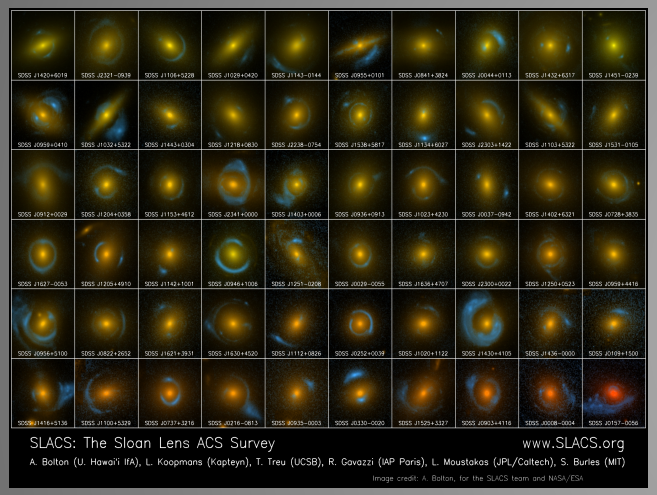


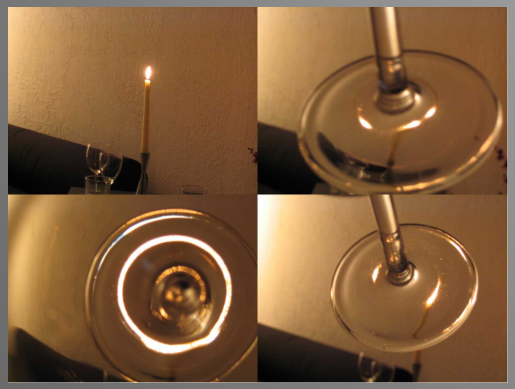


from Treu talk at JWST Fontiers Conference

Gravitationally Lensed QSOs are the Key Observations for Dark Matter Diagnostics

Strong lensing is rare (1/1000 galaxies): It's hard to find large samples!!





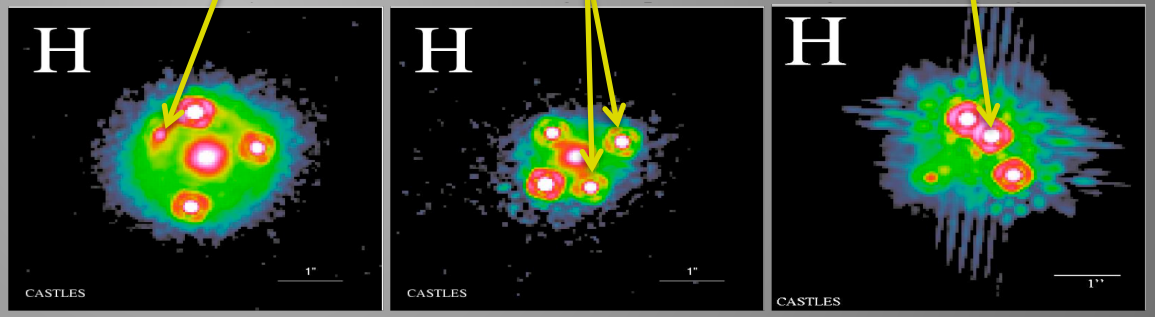
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2X brighter

This to be 10% brighter



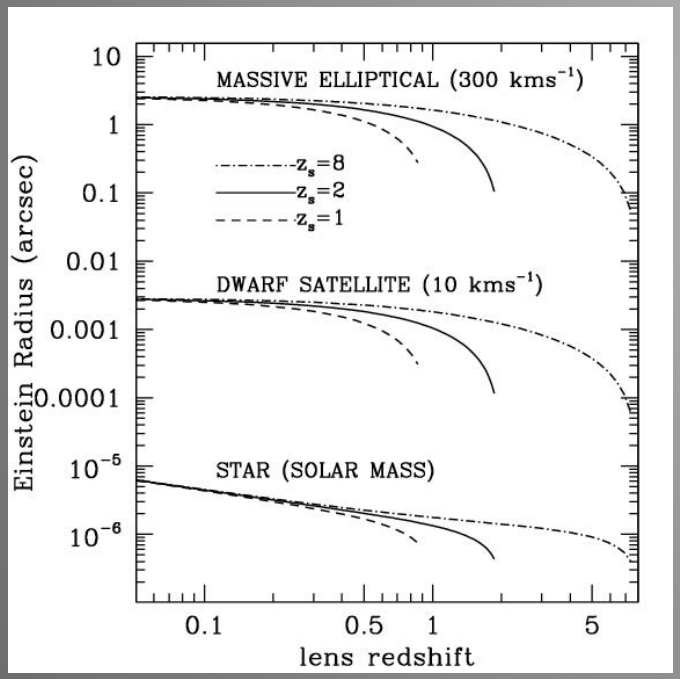
What causes these flux ratio anomalies?

1. Dark satellites?
2. Astrophysical noise (i.e. microlensing and dust)?
3. Small sample/sample selection?

from Treu talk at JWST Fontiers Conference

State of the Art vs. JWST

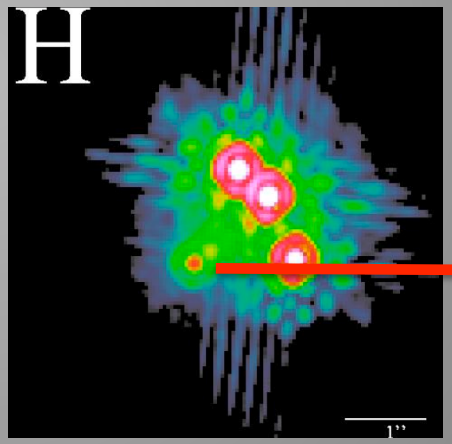
- Strong lensing detects satellites based on mass
- Satellites are detected as "anomalies" in the gravitational potential ψ
  - ψ'' = **magnification** (most visible effect)
  - ψ' = **astrometry**
  - ψ = **time delay** (least visible effect)



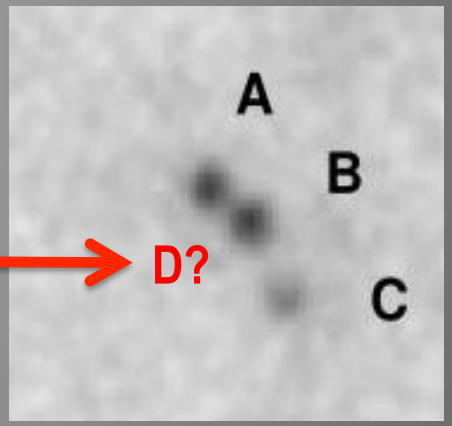
Treu 2010

Sensitivity at 11μm to detect dusty BH torus

- Image D ~0.2-0.3mJy
  - Undetected by Subaru
  - S/N~40-60 in 28s of JWST/MIRI
- Image B ~10mJy
  - S/N~5 in 3.1 hrs of Subaru
  - S/N~700 in 28sec with JWST/MIRI
- In 3 hrs JWST can reach 0.002 mJy (S/N=10)



H band (1.6 μm)



11 μm (Subaru)

Chiba et al. 2005

from Treu talk at JWST Fontiers Conference

Conclusions for Dark Matter Studies

JWST observations of gravitationally lensed QSOs can solve three open problems

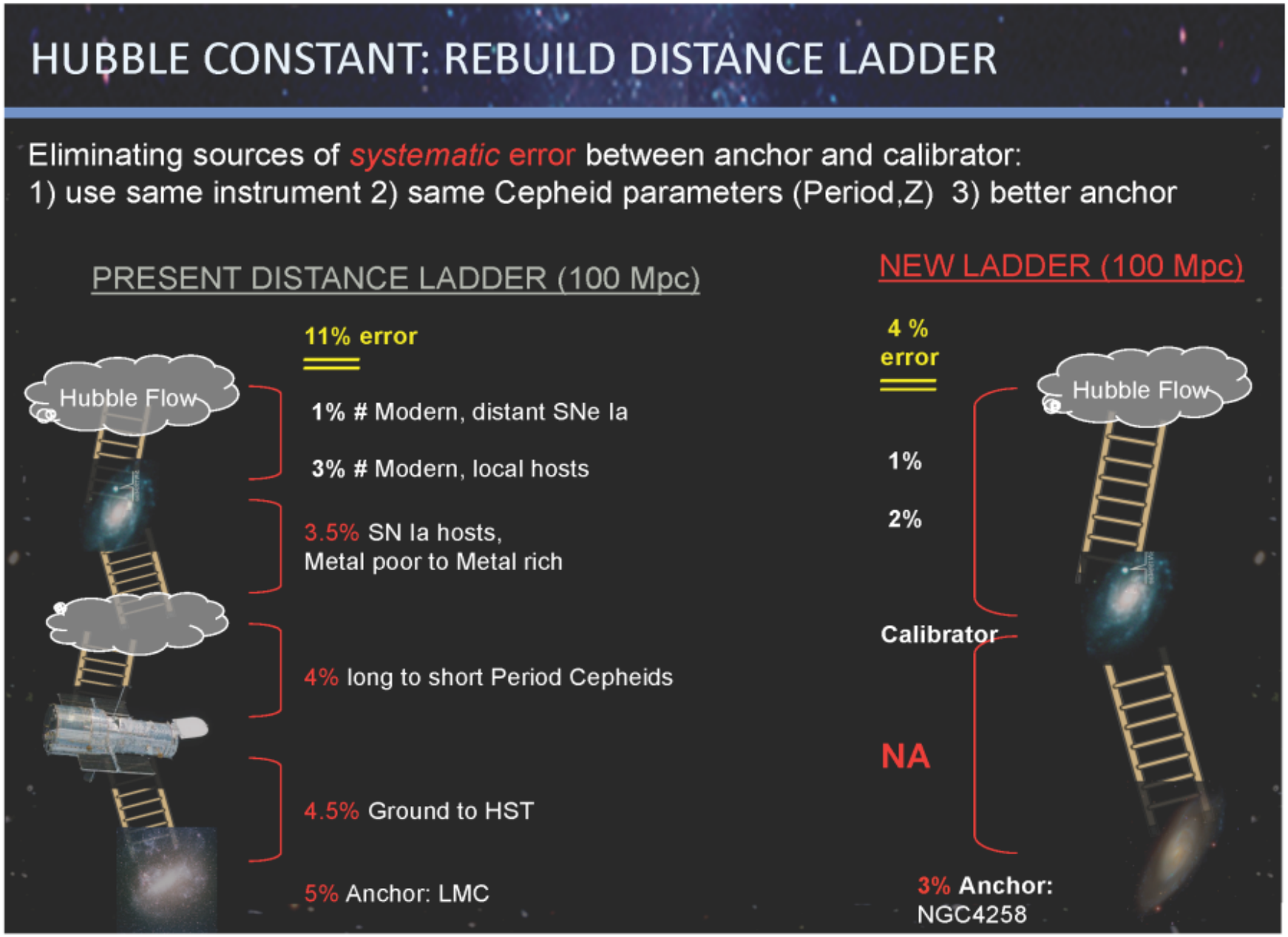
- Are there dark satellites around galaxies?
  - MIRI imaging of lensed dusty torus
- Which comes first, black hole or host spheroid?
  - NIRSPEC spectroscopy of lensed QSO hosts
- Are dark matter density profiles universal?
  - NIRSPEC spectroscopy of lensed QSO hosts
  - NIRSPEC spectroscopy of foreground deflector

BIG TASK FOR THE NEXT 5 YEARS IS FINDING TARGETS

Constraints on Dark Energy from Higher Precision Measurement of H_0

- **The expansion of the universe is currently accelerating.**
- **This is measured differentially – measure the velocity/distance relation at a range of epochs H(z).**
  - It must be anchored with the local value: H_0
- **To measure H_0, you need a distance ladder that extends into the Hubble Flow.**
  - Improve distances to P>10d Cepheids
  - Improve distance anchor: NGC 4258
    - Keplerian motion of masers around supermassive black hole
    - More P>10 day Cepheids than LMC (Macri+ 2006, 2008)

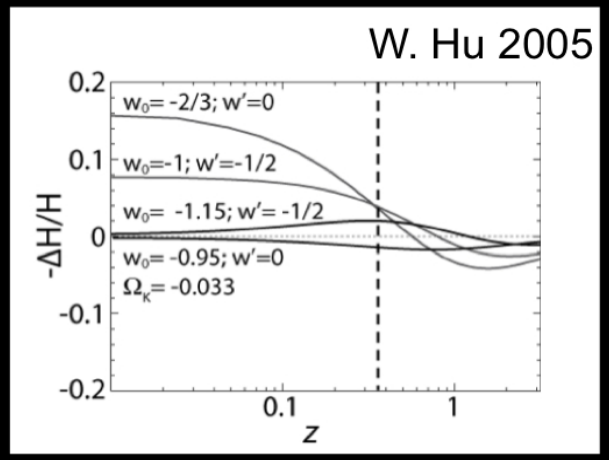
Material from Adam Riess talk at Frontiers Conference (June 2011)

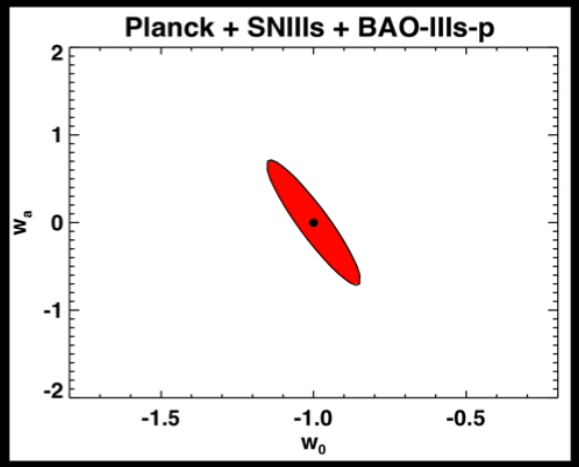


Riess Frontiers Conference talk

H_0, Also A Dark Energy Tool!

Fix CMB, vary w, w', Ω_k $\rightarrow \Delta H/H$

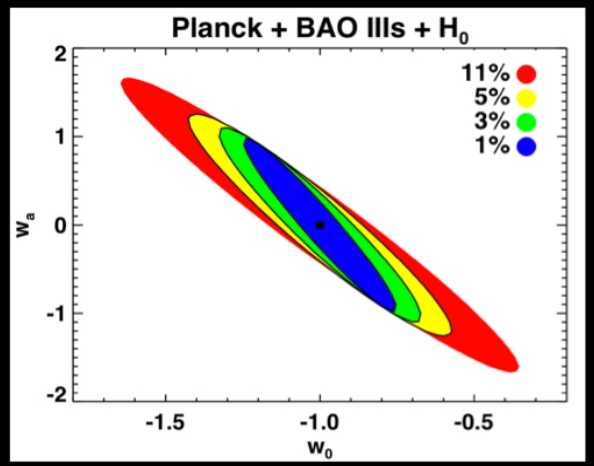


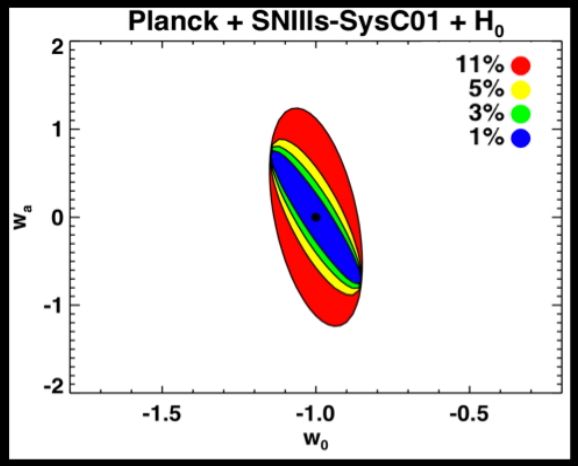


Gen III: ~2015 very *aggressive* BAO+SNe+ Planck.

We may not get here!

~2015 if hi-z Sne break (dust evolution), $+H_0$



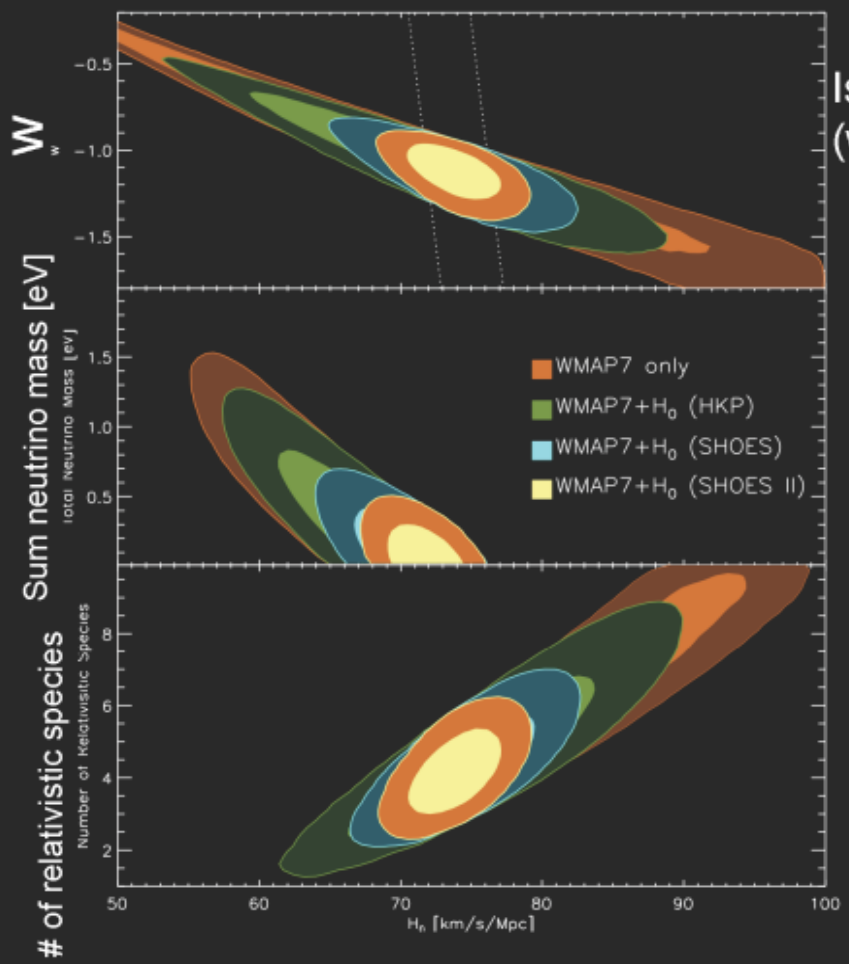


~2015 if BAO breaks, $+H_0$

Already some tension (CMB+BAO+SNe) today! So how do we improve H_0?

Riess Frontiers Conference talk

Dark Energy and Neutrinos



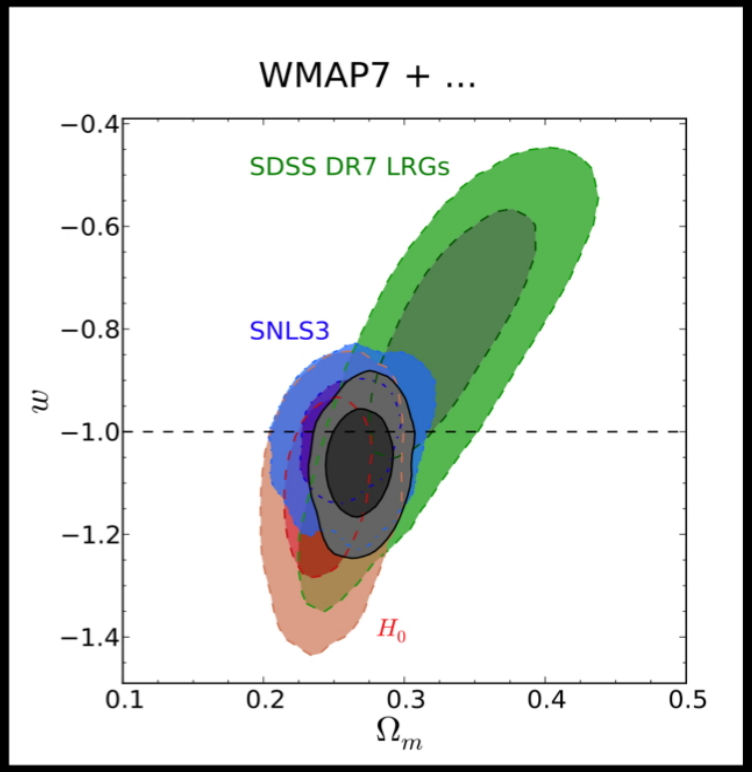
Is dark energy Λ?
(w=-1.08 +/-0.10 from *only* H_0, WMAP)

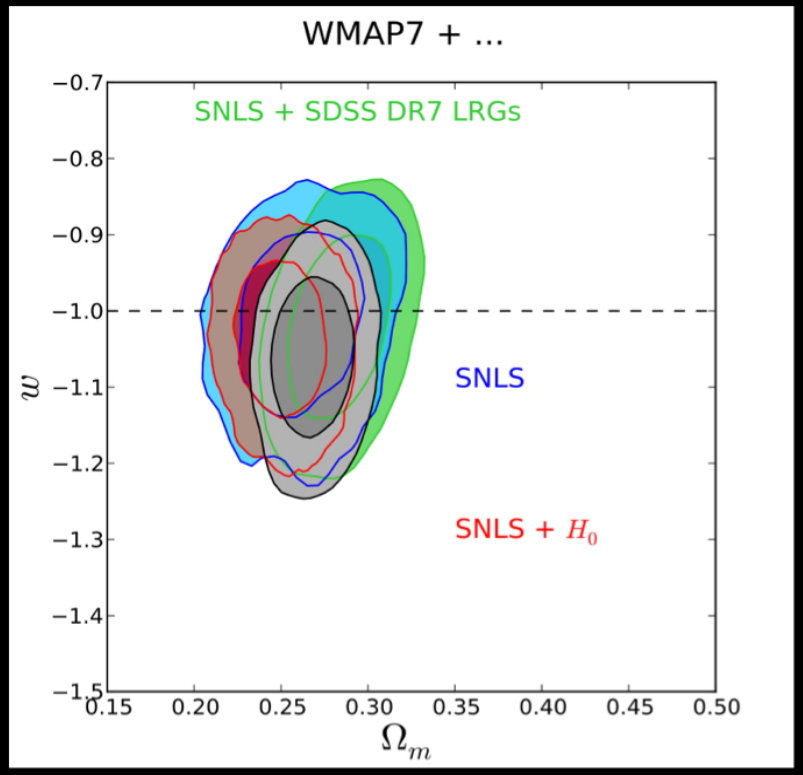
What do neutrinos weigh?
(Which hierarchy of mass eigenstates?)

Is their a species beyond known 3?
(present 4.2 +/- 0.7, & neutrino experiments have hints of a sterile neutrino)

Riess Frontiers Conference talk

And with other High-z probes…





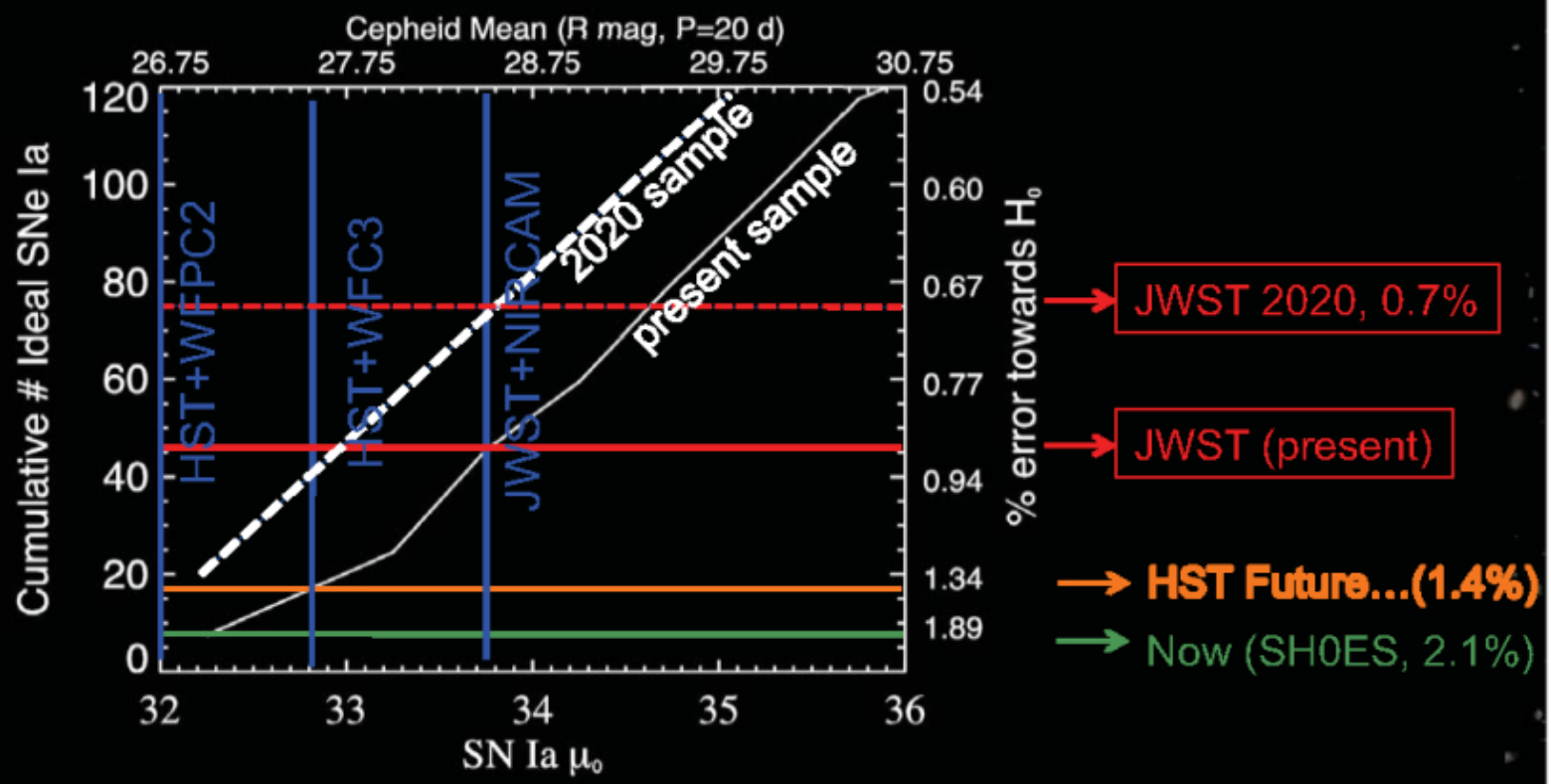
Sullivan et al. 2011 (SNLS3=SNLS+lowz+SDSS+HST)

H_0 now competitive, consistent with High-z Sne Ia, BAO+P(k)

Riess Frontiers Conference talk

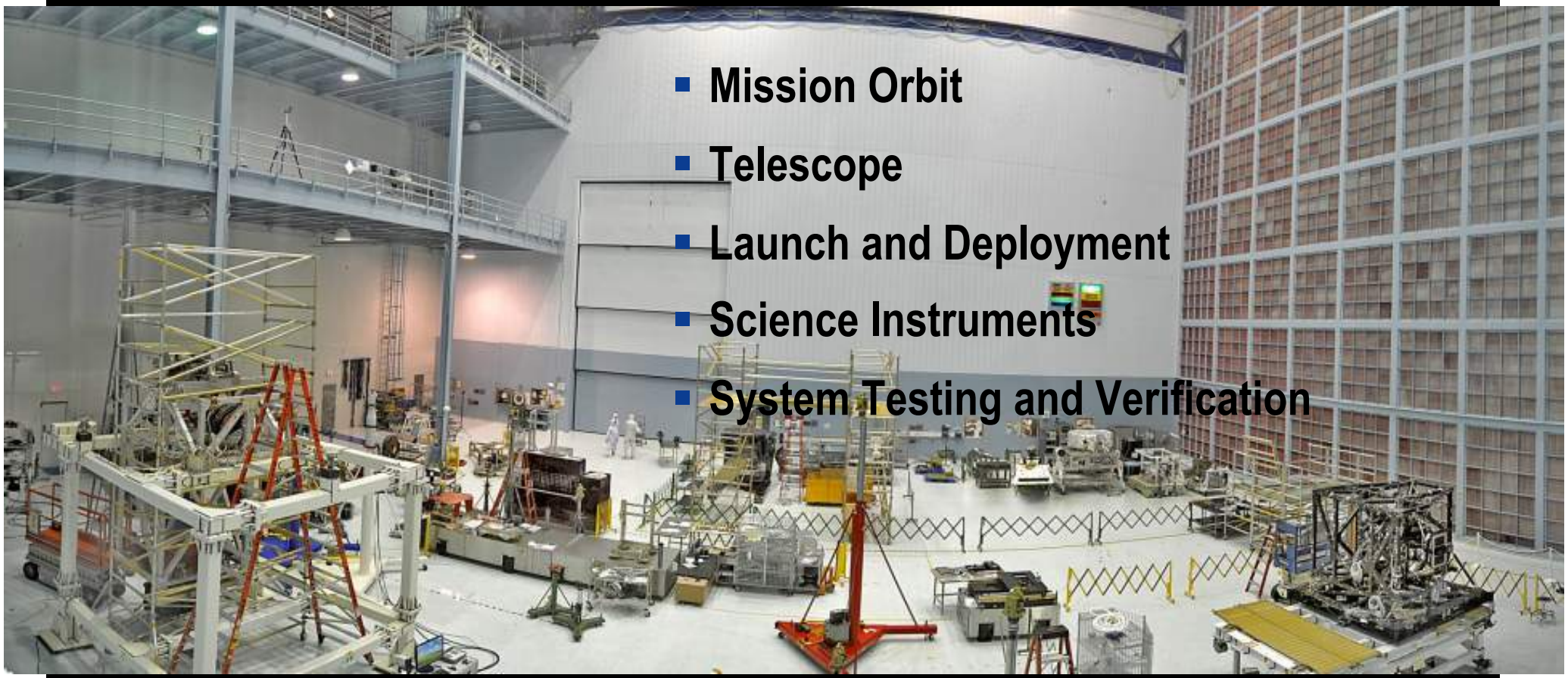
JWST Extends Volume, Sample for SN Ia Calibration

Assuming typical ~1.5 hour exposures/epoch on hosts



Riess Frontiers Conference talk

JWST Mission Design and Expected Performance

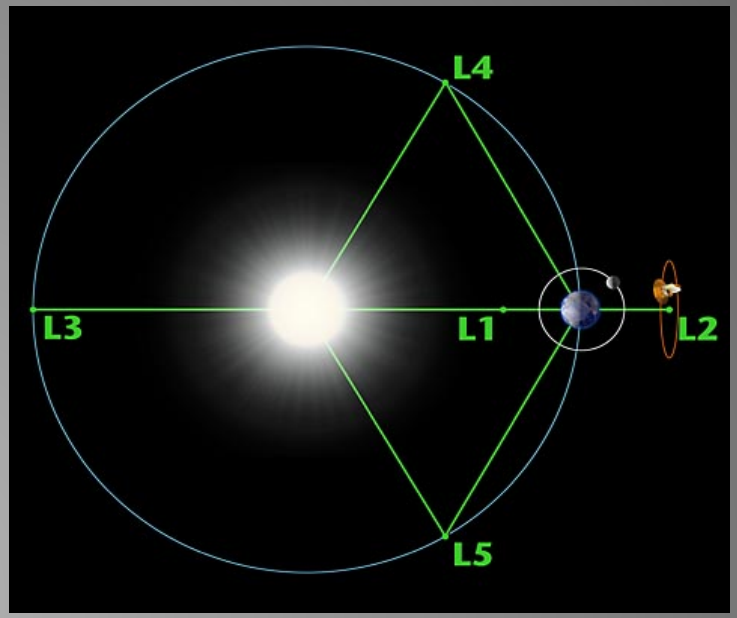


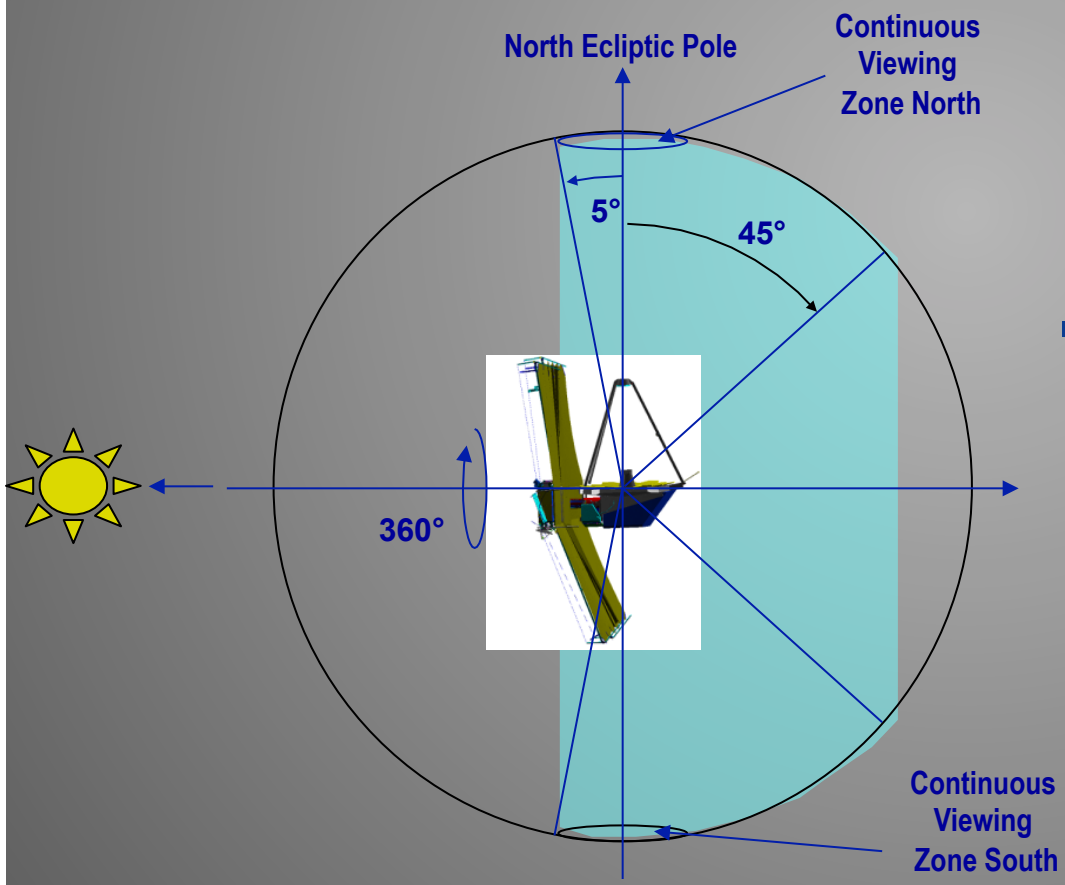
- Mission Orbit
- Telescope
- Launch and Deployment
- Science Instruments
- System Testing and Verification

JWST hardware in cleanroom at Goddard Space Flight Center

JWST science objectives require the largest cryogenic telescope ever constructed

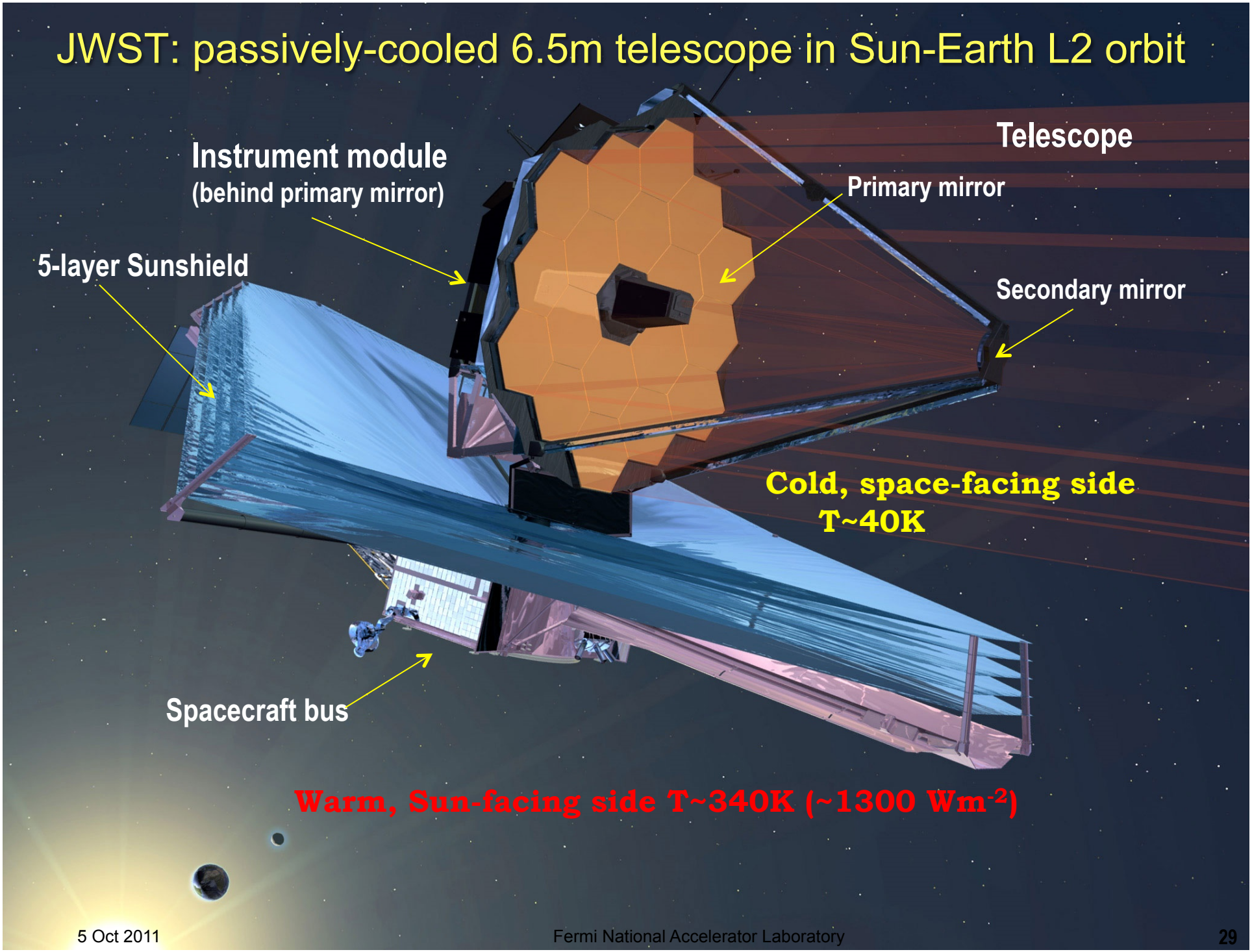
- L2 point orbit was selected for JWST to provide passive cryogenic cooling
  - Station keeping thrusters are required to maintain this orbit
  - Propellant sized for 11 years (delta-v ~ 93 m/s)



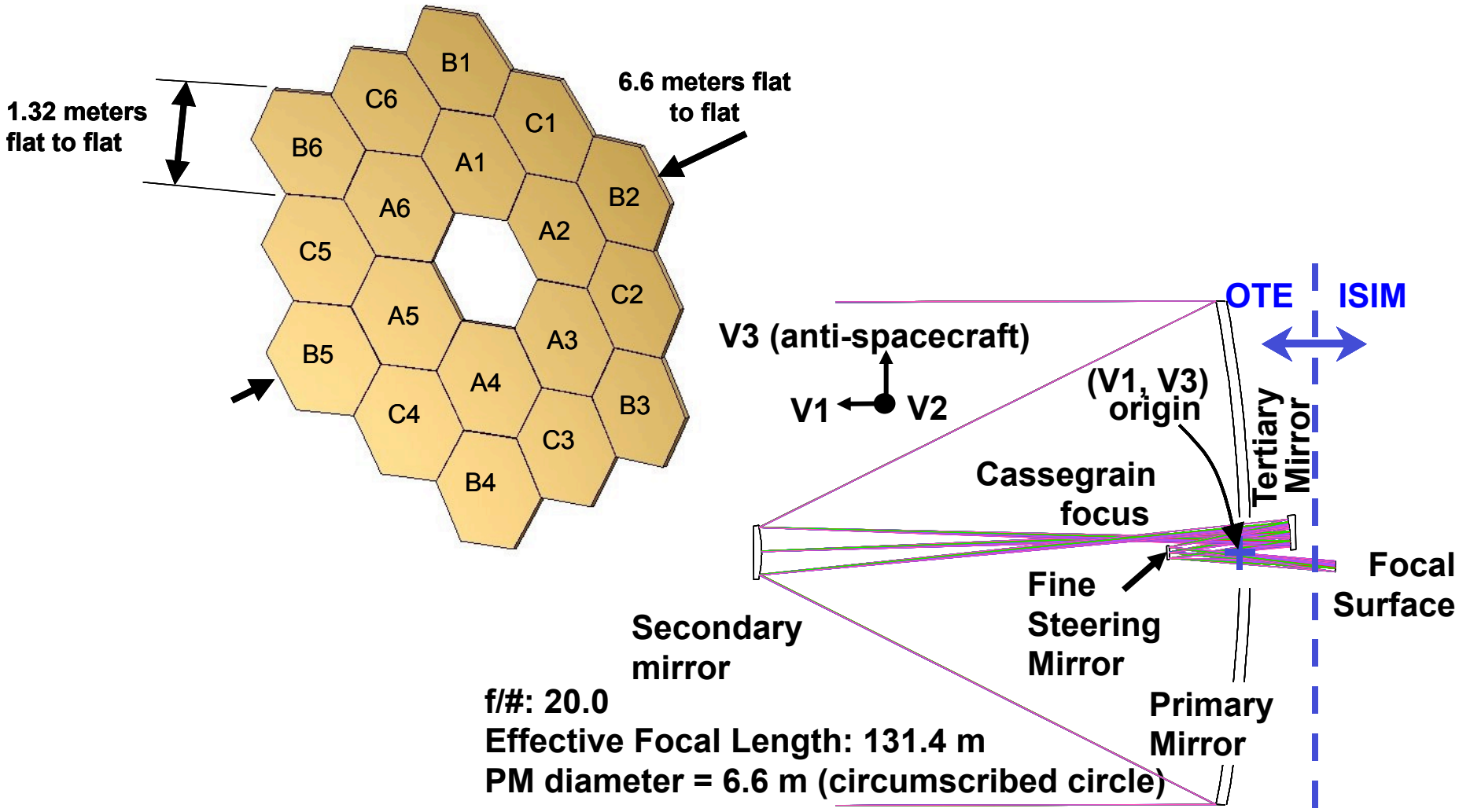


- The JWST can observe the whole sky while remaining continuously in the shadow of its sunshield
  - Field of Regard is an annulus covering 35% of the sky
  - The whole sky is covered each year with small continuous viewing zones at the Ecliptic poles

JWST: passively-cooled 6.5m telescope in Sun-Earth L2 orbit



Three Mirror Anastigmat Optical Design Provides a Wide Field-of-View



Beryllium telescope mirror segments

Key physical properties of Beryllium:

- low coefficient of thermal expansion at 50 K
- high thermal conductivity
- high stiffness to mass ratio

Primary mirror mass properties

- segments: 21.8 kg eg (>95% light weighted)
- Primary mirror area density: ~28 kg m^{-2}
- HST (ULE) ~ 180 kg m^{-2}
- Keck (Zerodur) ~ 2000 kg m^{-2}

Design & assembly by Ball Aerospace

Be blank fab by Axsys

Mirror polishing by Tinsley

Gold coating by QCI

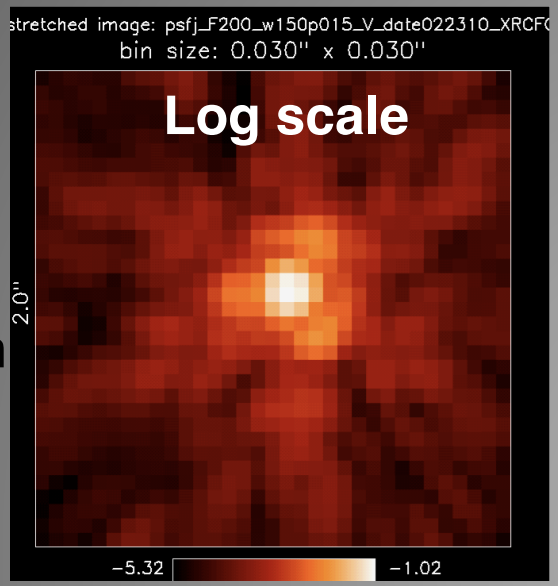
Flight Mirror Segments at MSFC for Final Cryo Tests

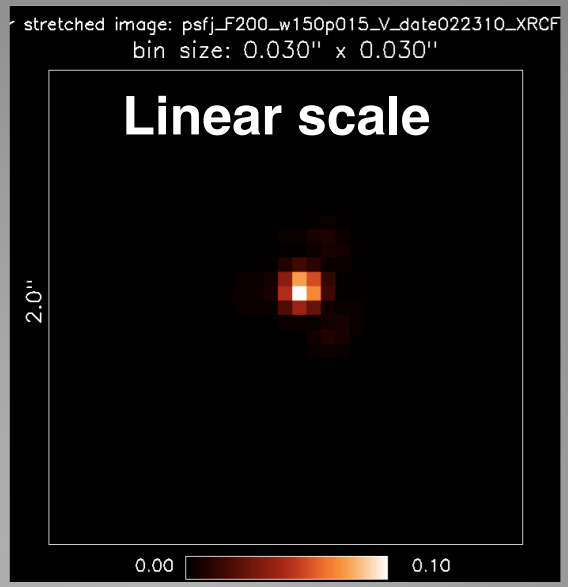
All JWST Telescope Mirror Optics Are Done!

Clampin/JWST Observatory

Predicted telescope image quality meets requirements

2 µm

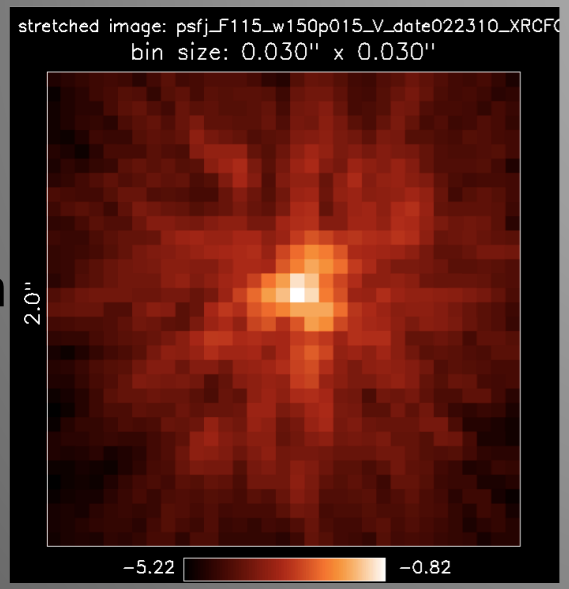


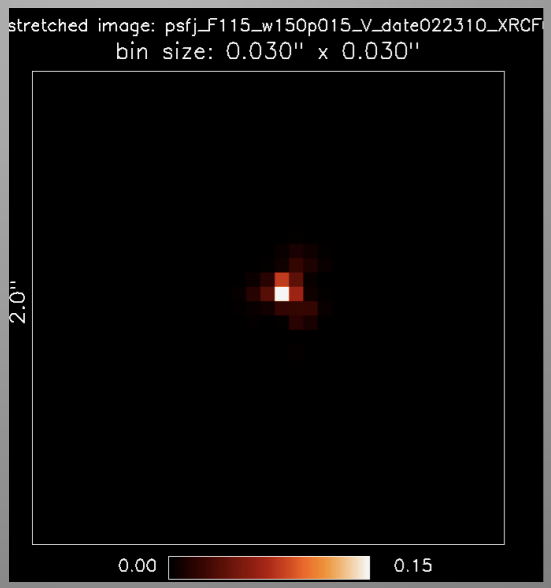


2 µm (diffraction limited, Nyquist sampled by NIRCam)

2.0” x 2.0” box

1 µm

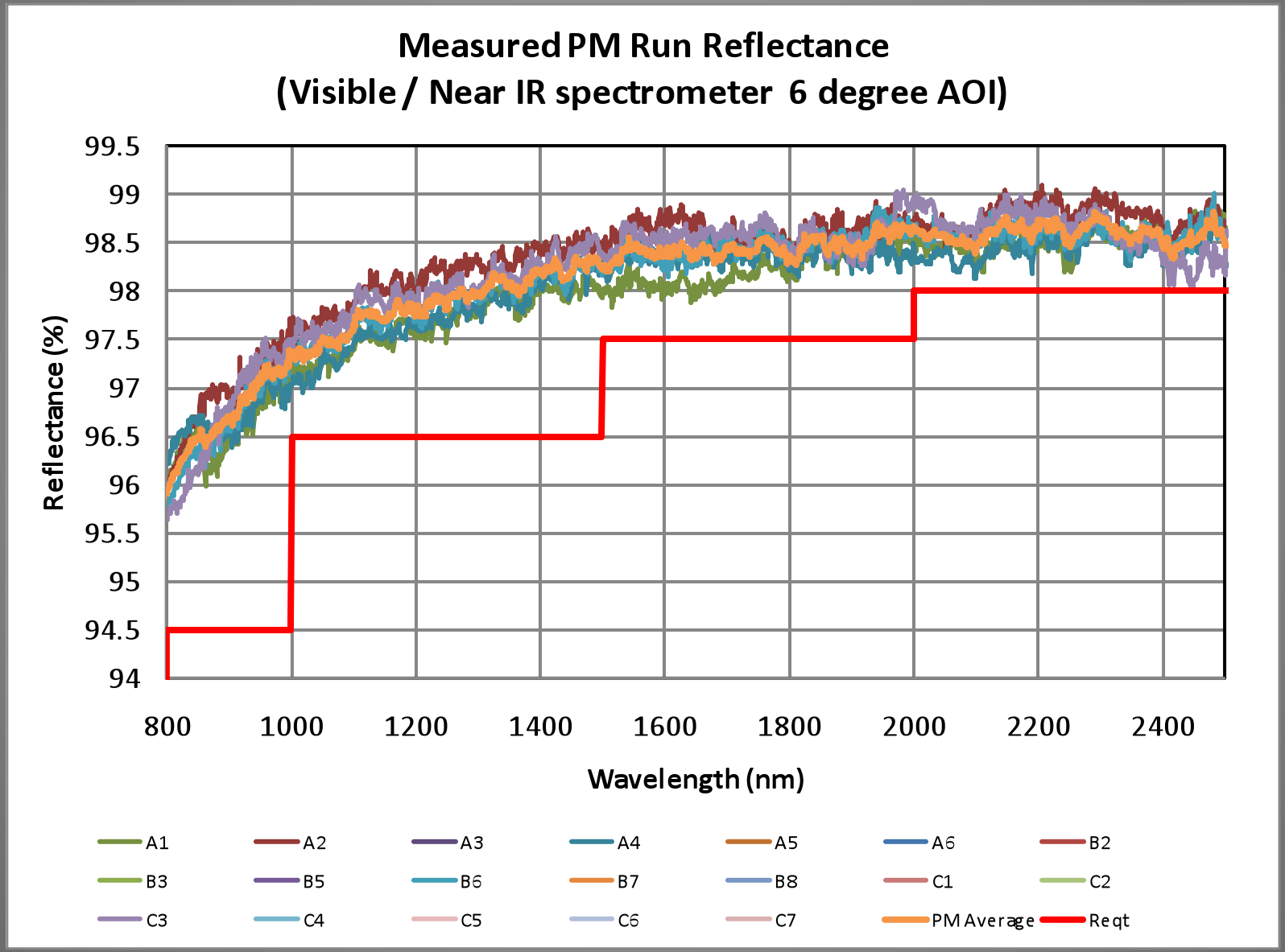




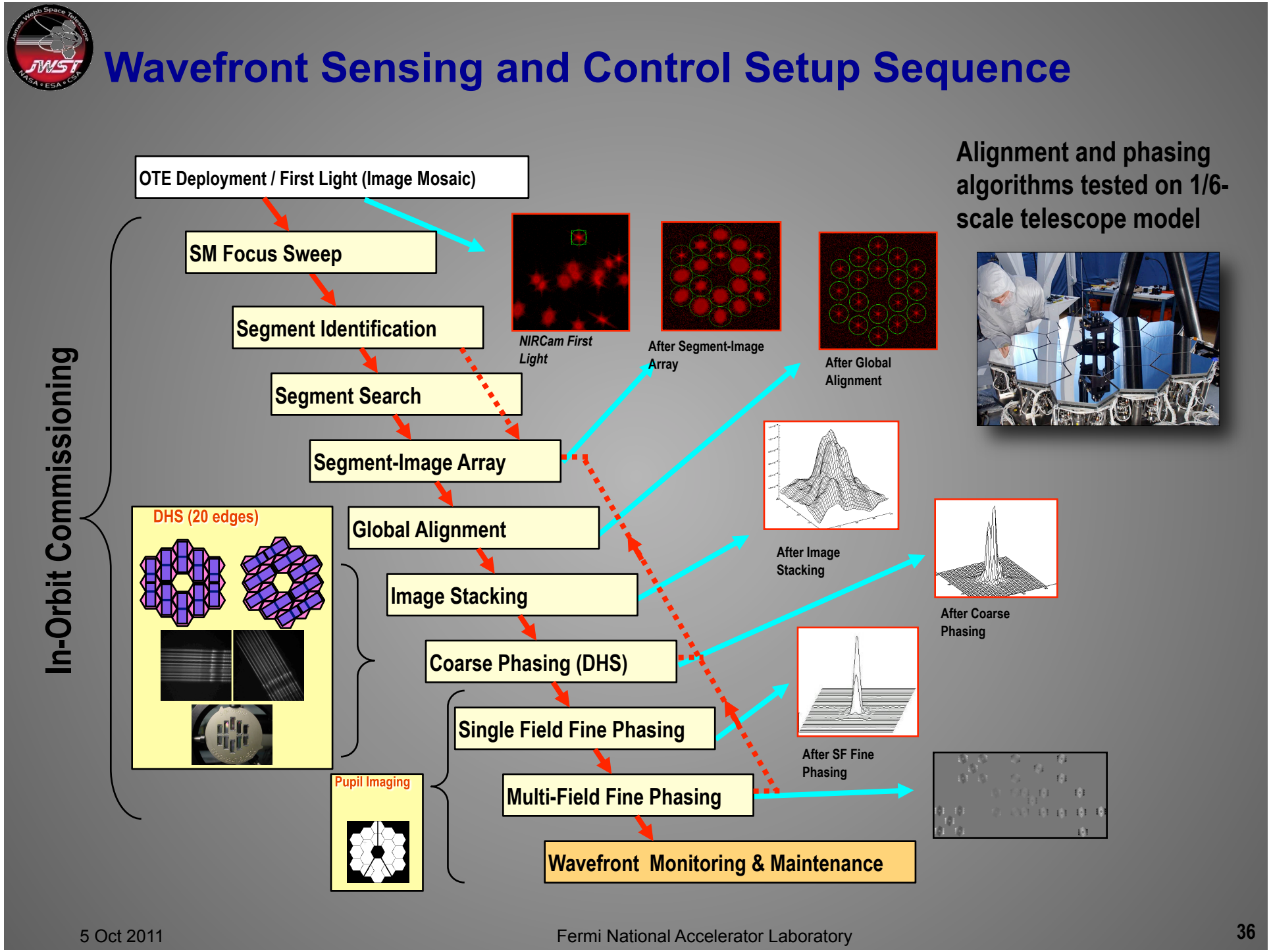
1 µm (Sub-Nyquist sharp core 0.03 arcsec, requires dithering)

2.0” x 2.0” box

Telescope Mirrors Have Excellent Reflectivity

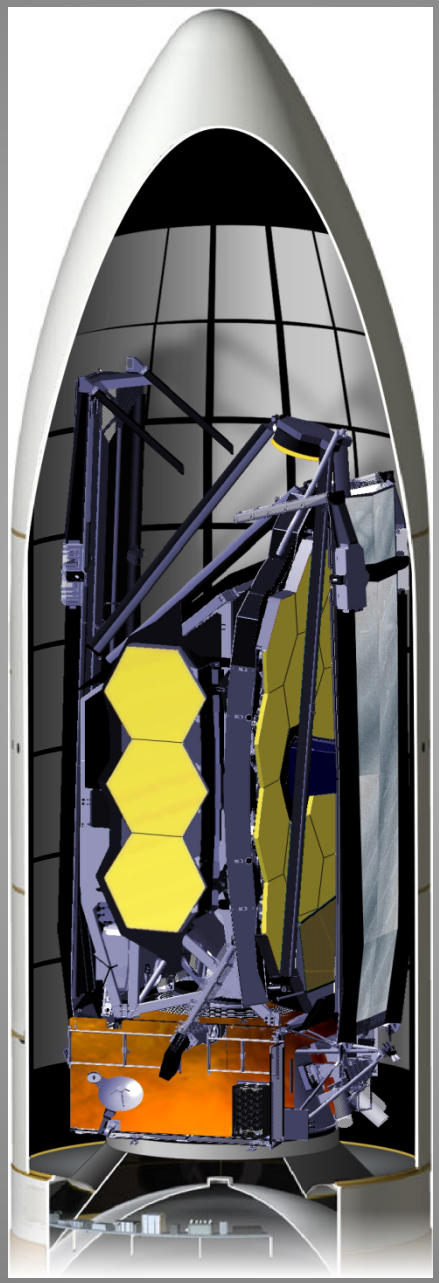


Wavefront Sensing and Control Setup Sequence

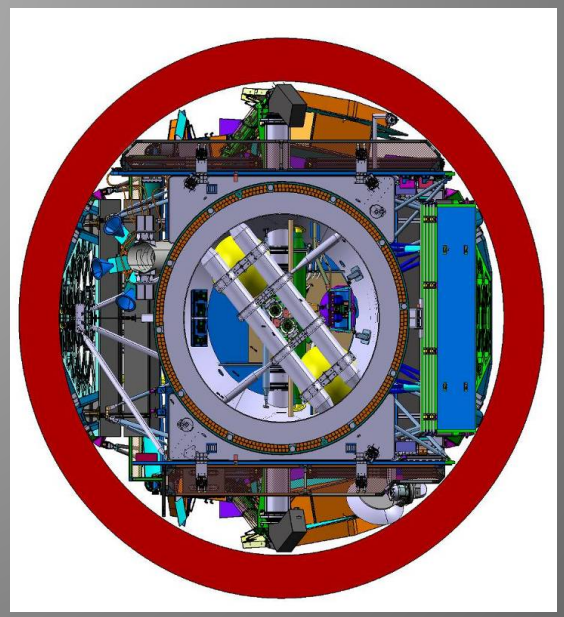


JWST Observatory Requires a Deployable Design

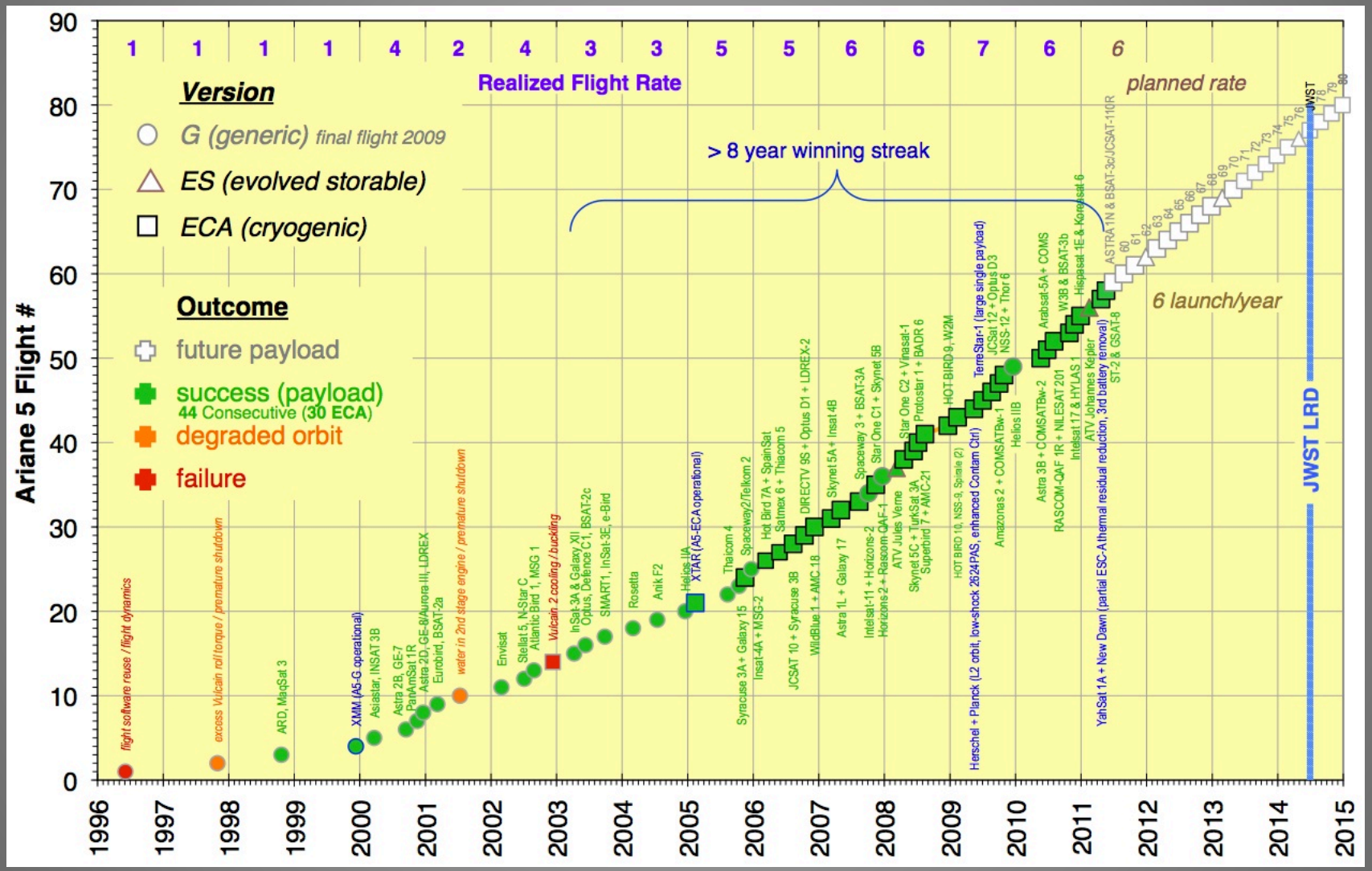
Ariane 5 ECA



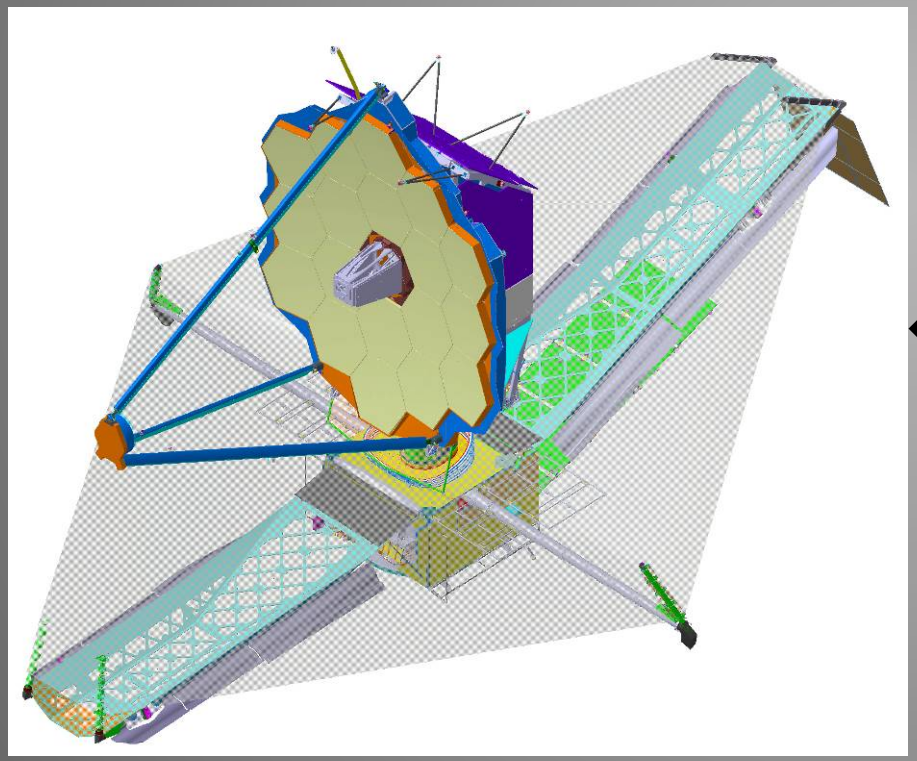
- JWST is designed to integrate with an Ariane 5 launch vehicle and 5 m diameter fairing
- Launch from Kourou Launch Center (French Guiana) with direct transfer to L2 point.
- Payload launched at ambient temperature with on orbit cooling to ~40 K via passive thermal radiators
- JWST payload: 6330 kg

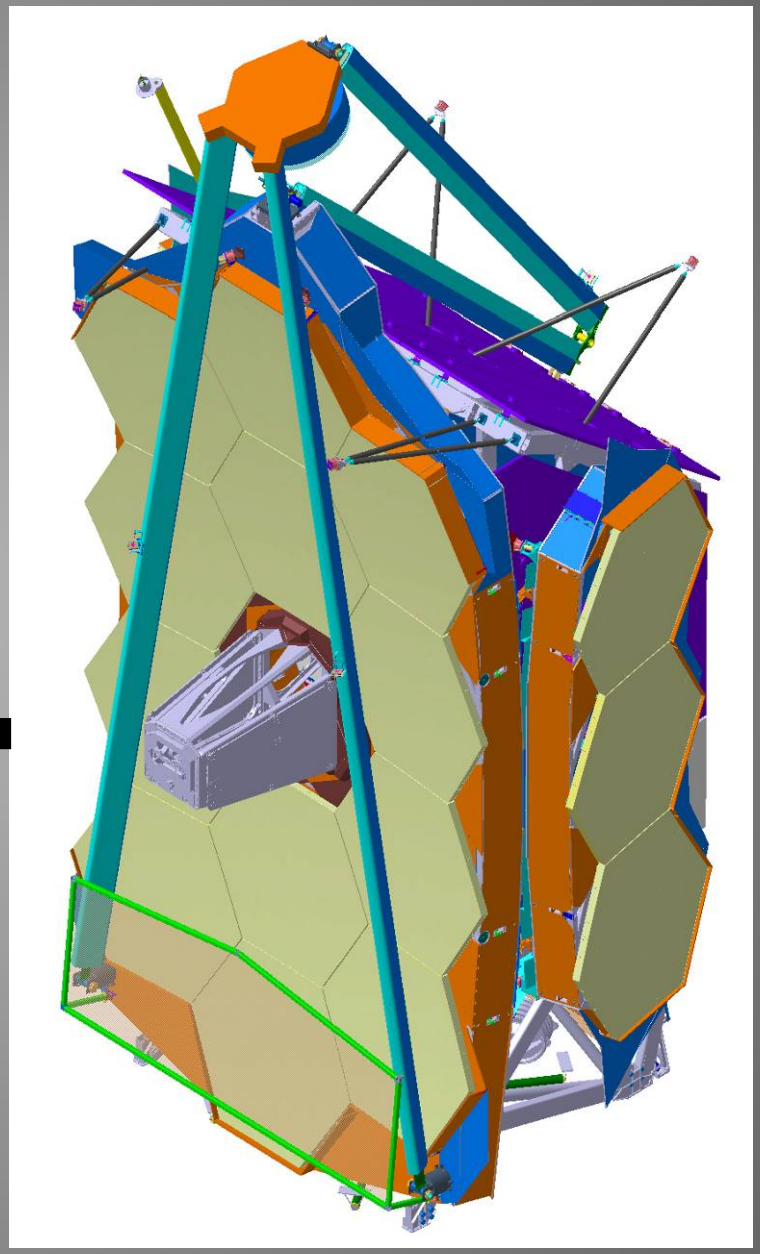


Ariane 5 ECA configuration is mature and reliable

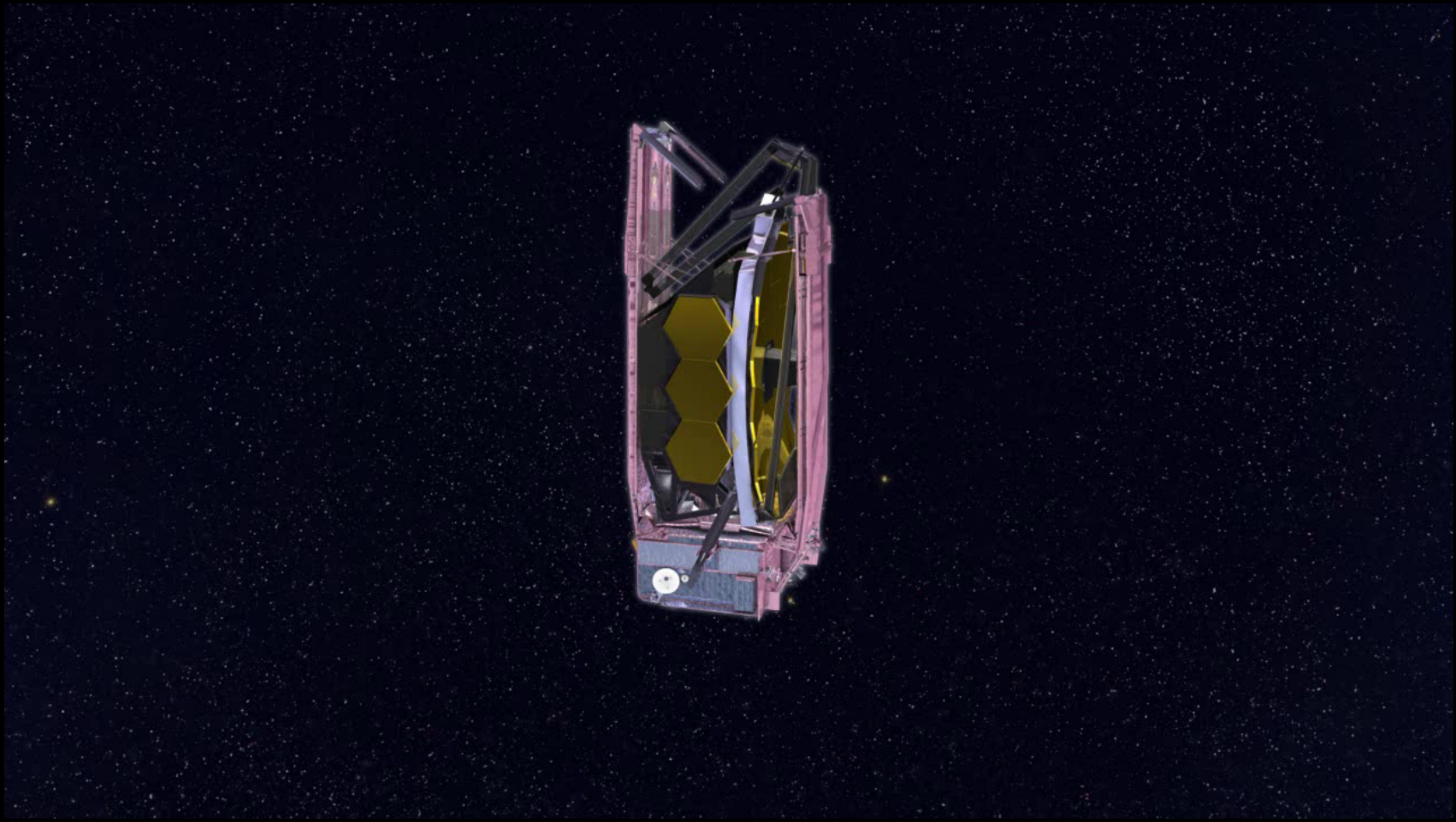


Deployment Sequence Overview





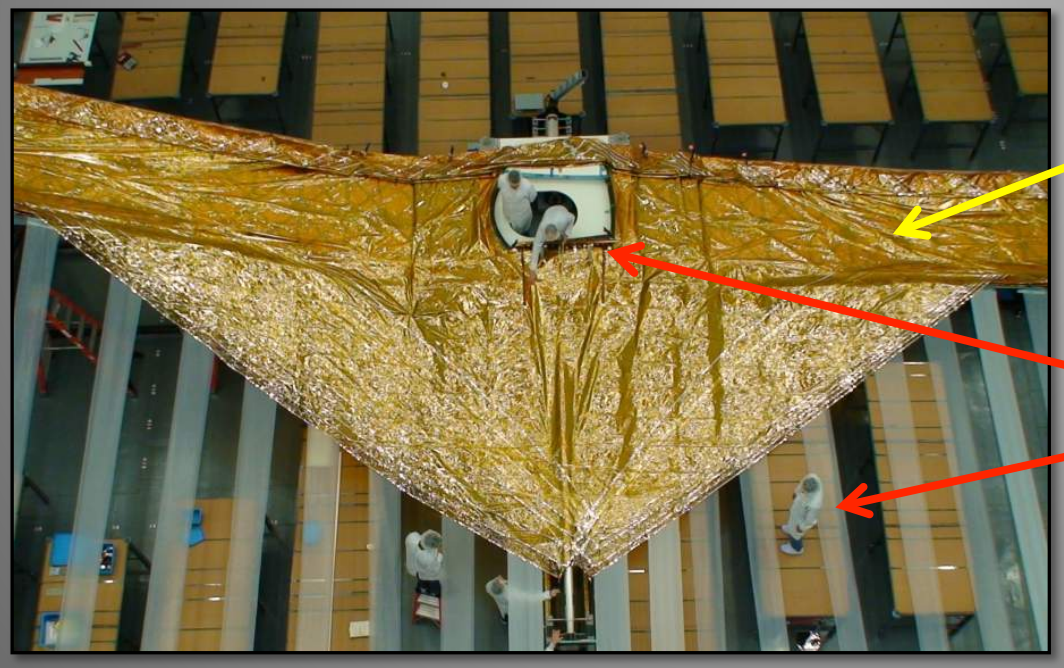
JWST Deployment, 10,000X faster than real time



Sunshield Deployment

- Northrop Grumman's small and full-scale models validate deployment approach, membrane folding and deployment boom performance

Folded membrane



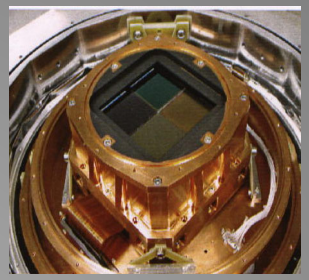
Deploying membrane

People

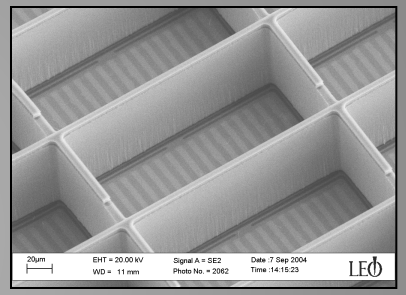
Sunshield membrane Layer 3 engineering unit under tension; ready for shape measurements (Sept 2011)

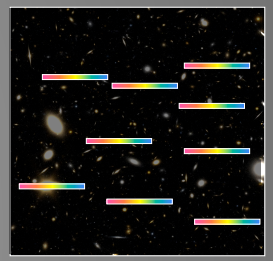
JWST Science Instruments Will be Delivered in 2012

- **NIRCam (Univ. Arizona):**
  - 6000Å - 5 μm imaging and coronography
  - Two channel 2.2'x2.2' FOV
  - Wave front sensing system for telescope

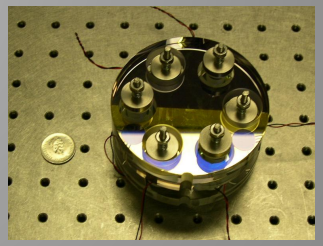


- **NIRSpec (ESA)**
  - 6000Å - 5 μm multi-object, long slit, and integral-field spectroscopy (IFS)
  - $\lambda/\Delta\lambda$ = 100, 1000, 2700

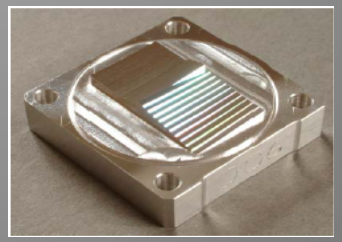


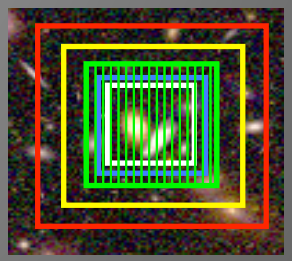


- **Fine Guidance Sensor and Near-IR Imager and Slitless Spectrograph (CSA)**
  - 0.9 – 4.4 μm broad-band imaging (same filters as NIRCam)
  - Wide-field and single object slitless spectroscopy
  - Sparse-aperture interferometric imaging (4-5 μm)

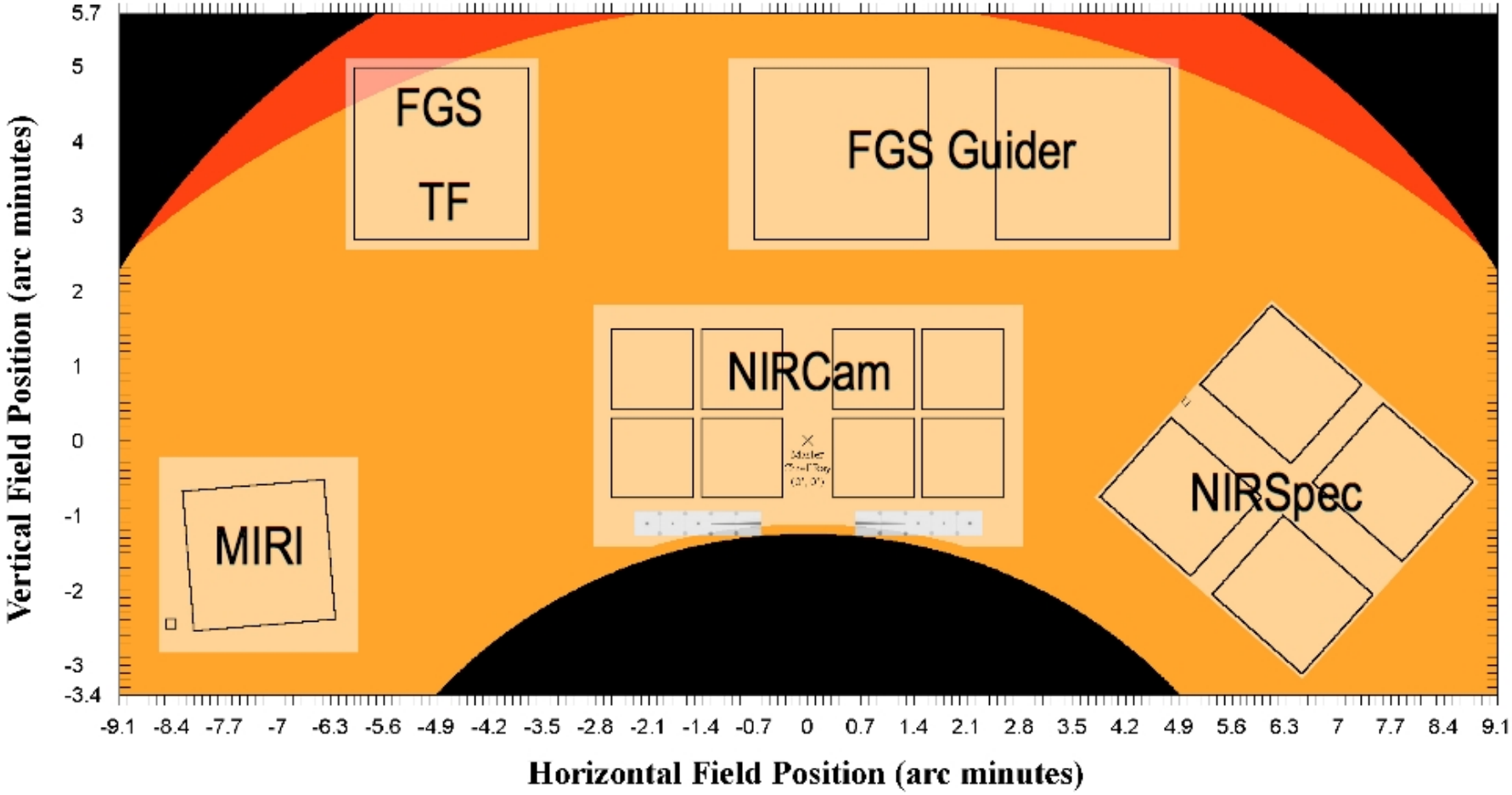


- **MIRI (Europe/ESA/NASA)**
  - 5- 29 μm imaging and coronography
  - Slit ($\lambda/\Delta\lambda$~100) and IFU spectroscopy ($\lambda/\Delta\lambda$~3000)



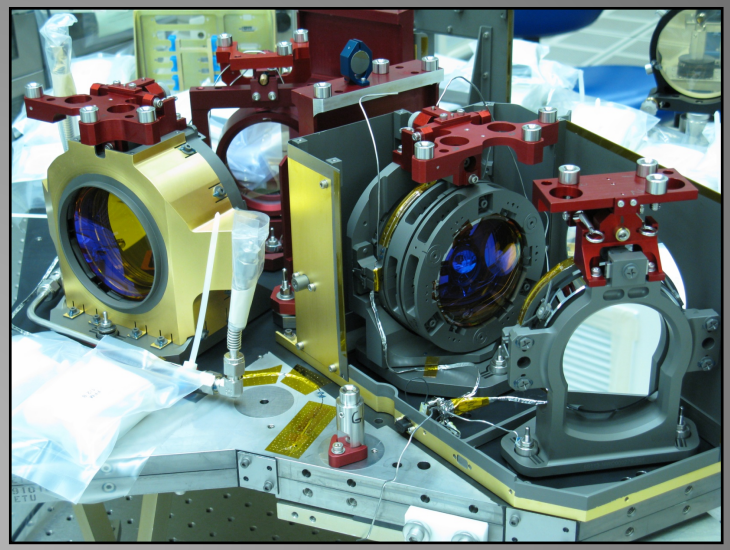


Instrument Layout in Telescope Focal Plane

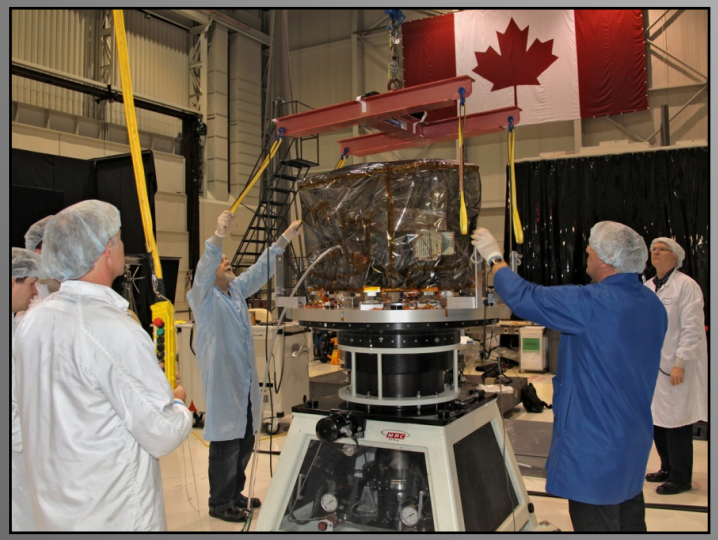


All flight science instruments are in various stages of integration or testing

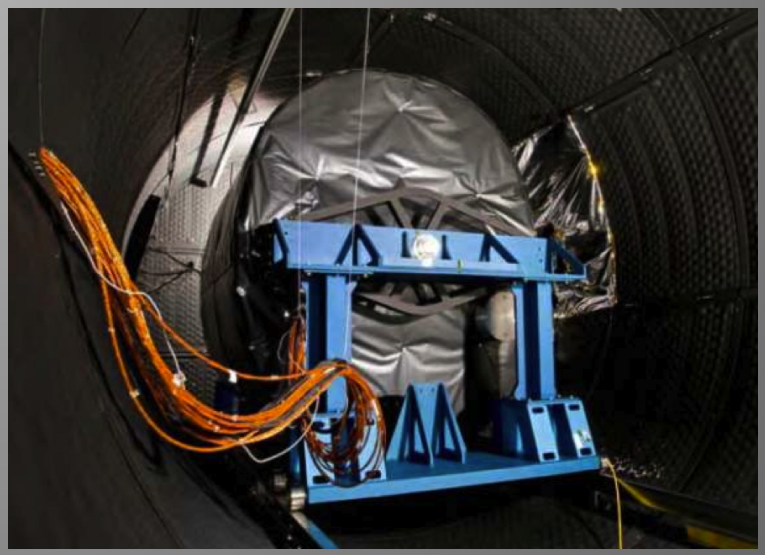
NIRSpec Flight Model Integration



NIRCam module B Flight Optics



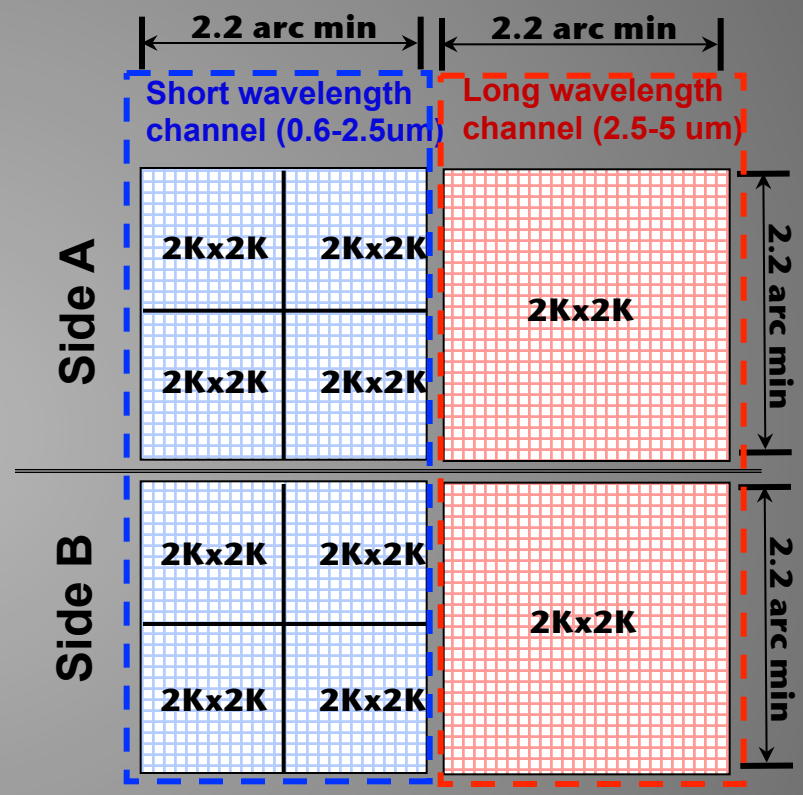
FGS Flight Model



MIRI Flight Model Cryo Test

NIRCam: Wide-Field Near-IR Imaging and Coronography

- **Developed by Univ. of Arizona**
  - PI: Marcia Rieke, Univ. of Arizona
- **Wavelength range: 6000Å – 5.0 μm (two channels, dichroic beamsplitter)**
- **Field of view: 2.2 x 2.2 arc min, each channel**
- **Angular resolution (1 pixel):**
  - 32 mas at $\lambda < 2.4$ μm
  - 65 mas at $\lambda > 2.4$ μm
- **Filter bandpasses ($\lambda/\Delta\lambda$): 4, 10, 100**
- **Coronography: occulters and Lyot stops**
- **Wide-field grism spectroscopy**
  - 2.4 – 5 μm with ($\lambda/\Delta\lambda$) ~ 1600
- **Wavefront sensing for telescope alignment and figure control**

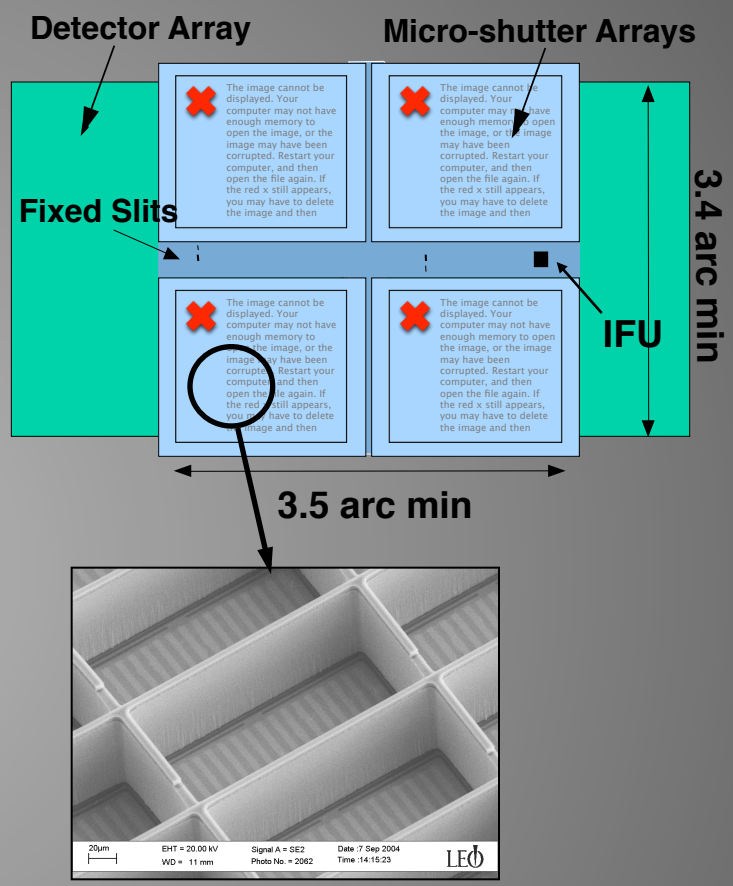


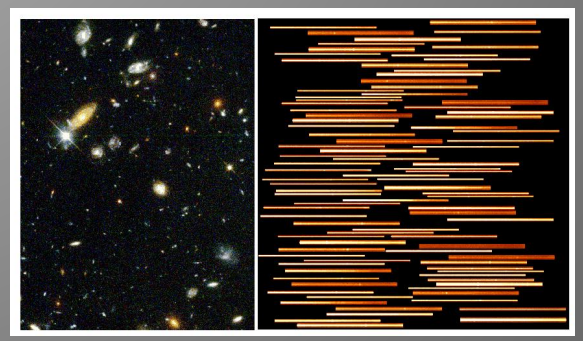
Two adjacent fields of view (2.2 arcminute)

Both fields in SW and LW bands

NIRSpec: Multi-Object Spectroscopy

- **Built by European Space Agency**
  - PI: Peter Jakobsen, ESTEC
- **Operating wavelength: 6000Å – 5.0 μm**
- **Multi-object spectroscopy with micro-shutter array (4 x [171x365]) developed by NASA/GSFC (Harvey Moseley)**
- **HgCdTe 2Kx2K detectors**
- **Spectral resolution: 100, 1000, 2700**
- **MSA field of view: 3.4 x 3.5 arc min**
  - 62,415 programmable micro-shutters in each array
  - Shutter open area 200 x 465 mas on sky
- **IFU: 3x3 arc sec, 0.1 arc sec slices**
- **Slits: 4.0x0.4, 3.5x0.2, 1.6x1.6 arc sec**





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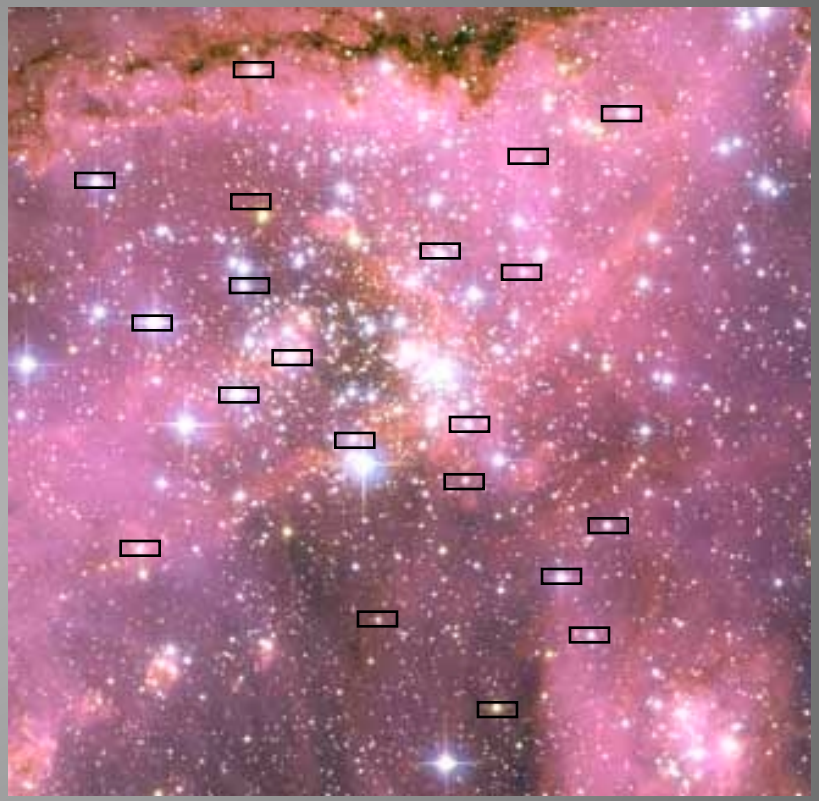
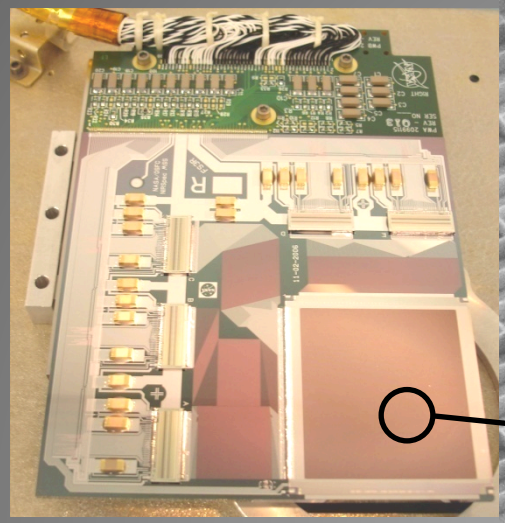
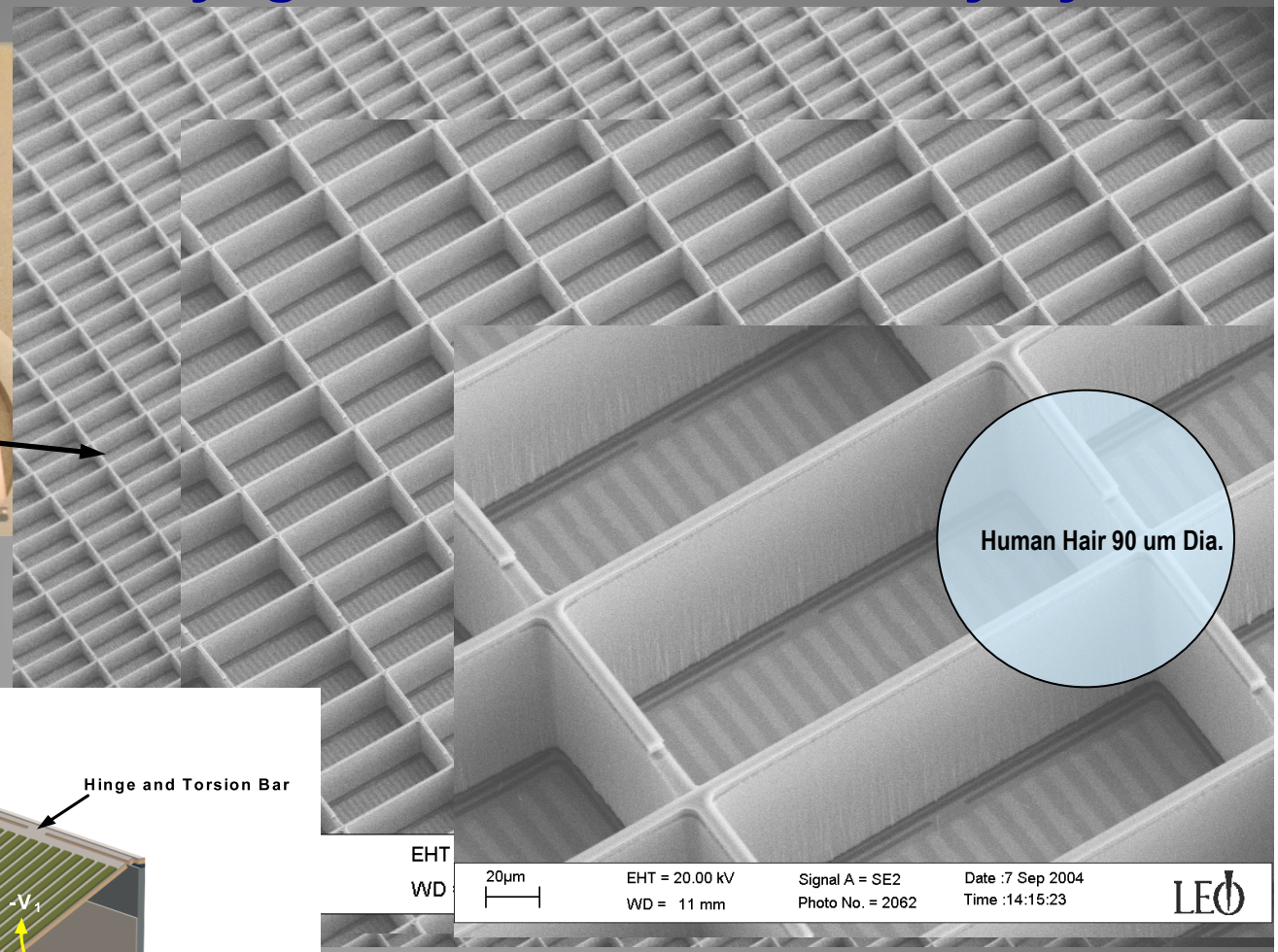
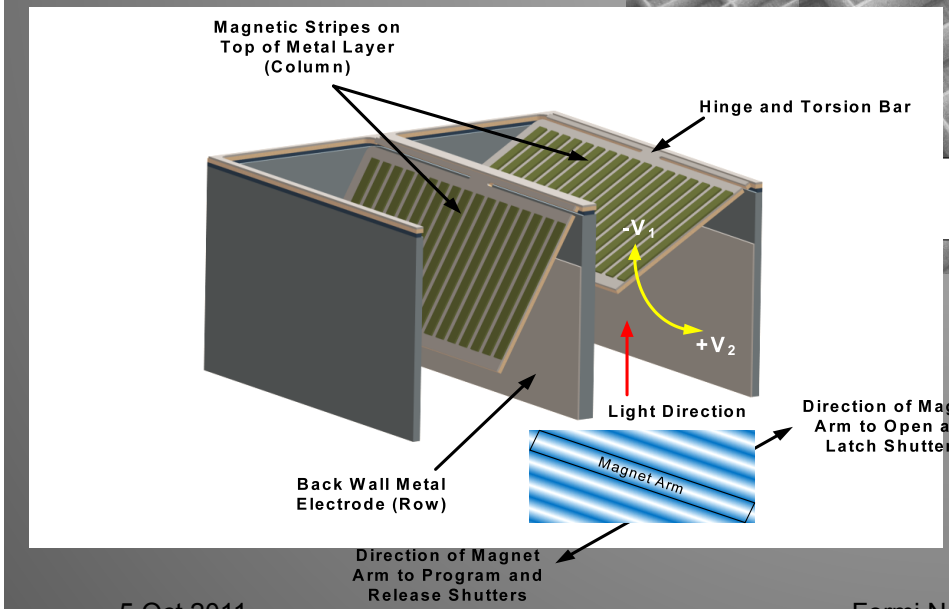


NGC 346

~250,000 Element Cryogenic Microshutter Array System

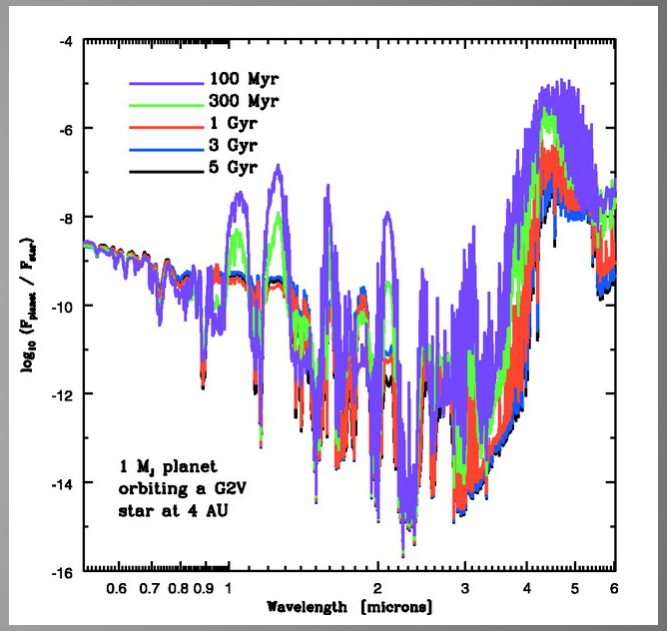




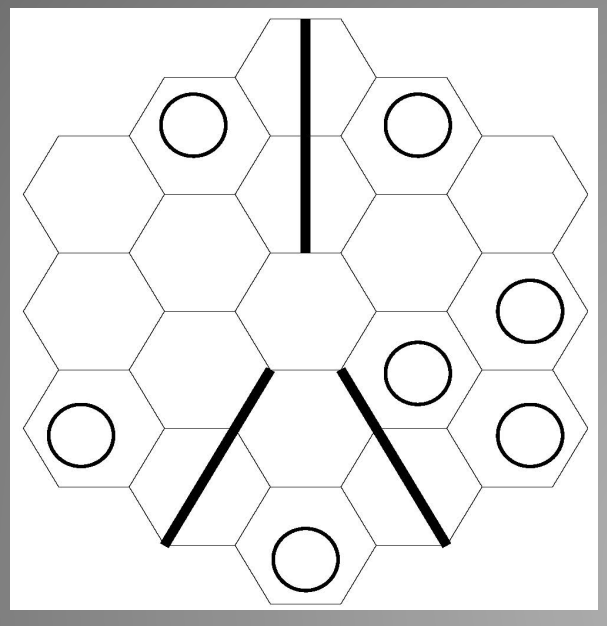


FGS Near-IR Imager and Slitless Spectrograph

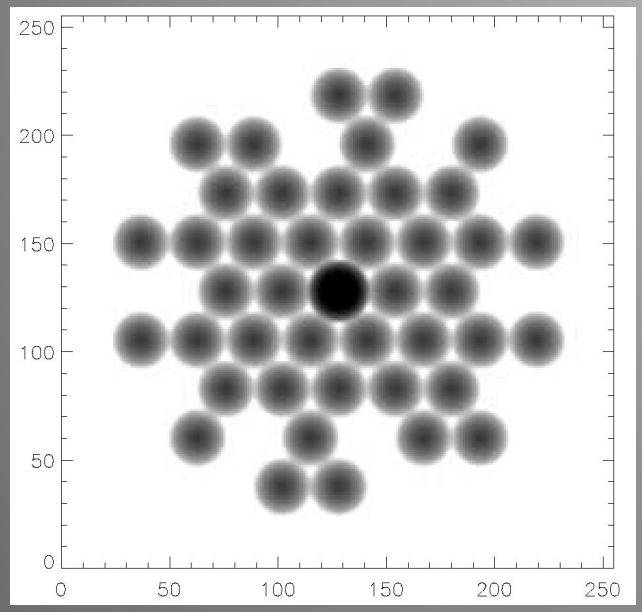
- **Built by the Canadian Space Agency**
  - PI: René Doyon, Université de Montreal
- **Field of view: 2.2 x 2.2 arc min**
- **Angular resolution: 65 mas/pixel**
- **Detector: HgCdTe, 2048 x 2048 format, T= 40 K passive cooling**
- **Wide-field slitless spectroscopy**
  - 1 – 2.5 μm, $\lambda/\Delta\lambda$ ~ 150
  - Two grisms with orthogonal dispersions
- **Single-object slitless spectroscopy**
  - 7000Å – 2.5 μm, $\lambda/\Delta\lambda$ =700 at 1.25 μm
  - Optimized exoplanet transit spectra of relatively bright stars
- **Sparse aperture interferometric imaging:**
  - 3.8 – 4.8 um, bandpass 5-8%
  - Contrast 10^{-4} between 70 and 500 mas

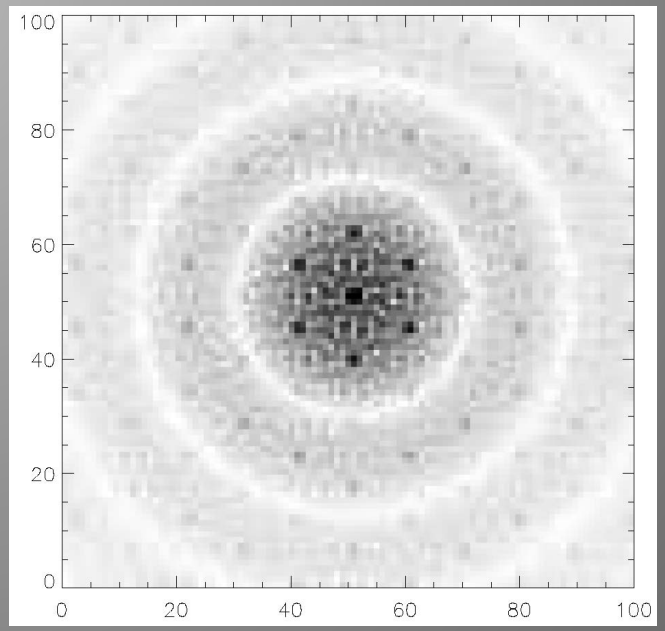


FGS Non-Redundant Mask Imaging



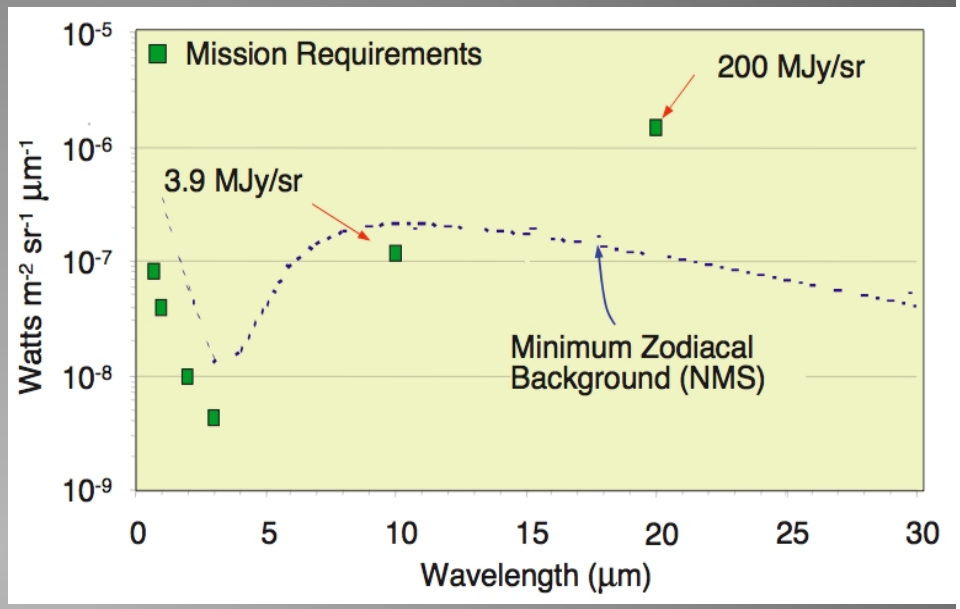
- Utilizes “interferometric” mask producing 21 baselines and a narrow PSF (0.5λ/D)
- Ground-based contrast limits ~5 mag, in space > 10 mag possible at small inner working angle
- Flat fielding issues may be problem (>>Photon noise) for bright stars

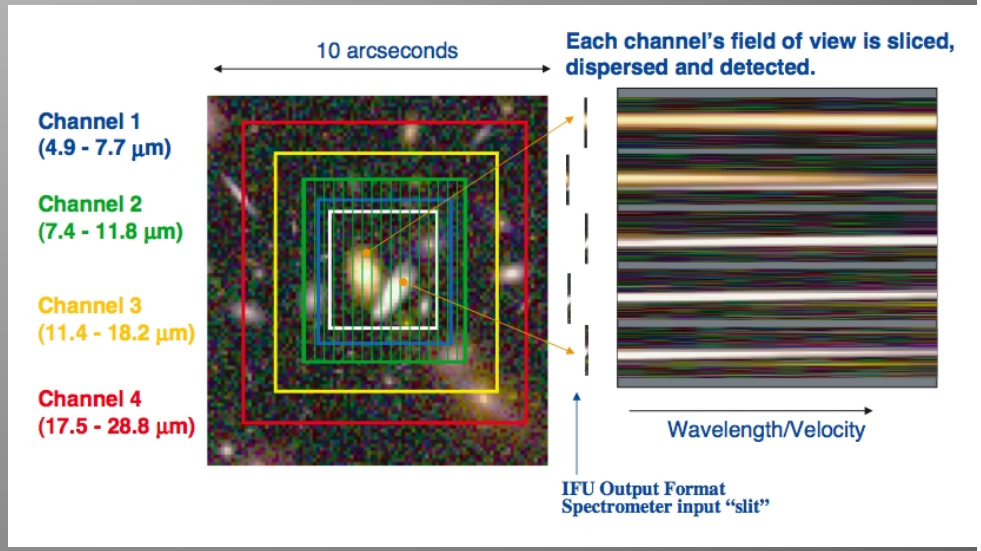




Mid-Infrared Instrument (MIRI): Zodiacal-Light-Limited Imaging at λ < ~15 μm

- **Built by European institutes & JPL**
  - PIs: Gillian Wright, U. Edinburgh, George Rieke, U. Arizona
- **Wavelength range: 5 - 29 μm**
- **Imaging FOV: 1.9 x 1.4 arc min**
- **R=100 spectroscopy (5 - 11 μm)**
  - 5 x 0.6 arc sec slit
- **R~3000 spectroscopy, ~5 x ~5 arc sec integral field unit**
- **Coronography: quadrant phase masks (10.6, 11.4, 15.5 μm) and Lyot mask (23 μm)**
- **Si:Ar 1024x1024 detector cooled to 6K**
- **MIRI detector actively cooler to 6.7K by two-stage mechanical cooler system.**
  - The MIRI Cooler will be the first long life, 7K mechanical cooler for space flight
  - Developed by Northrop Grumman and JPL

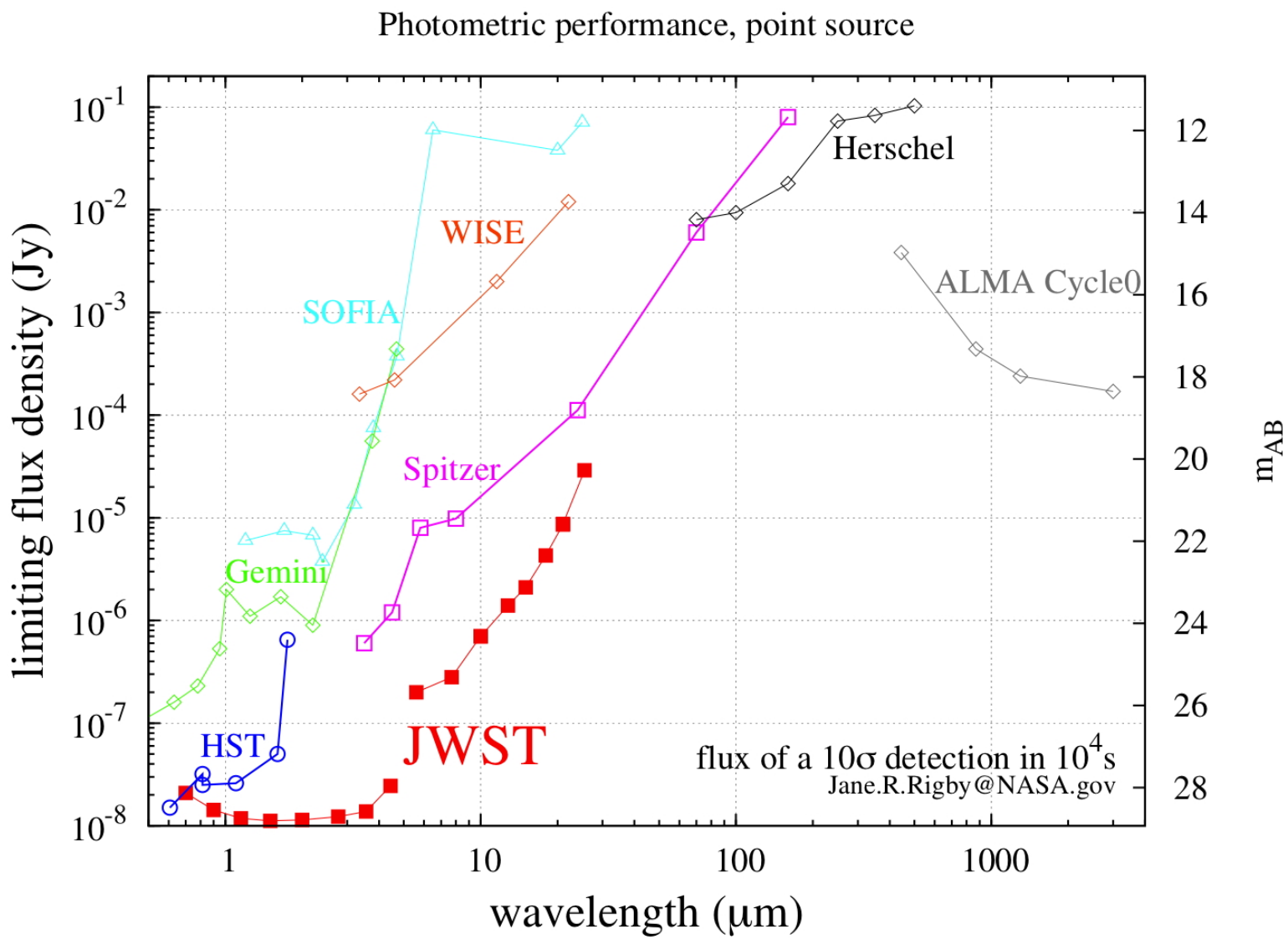




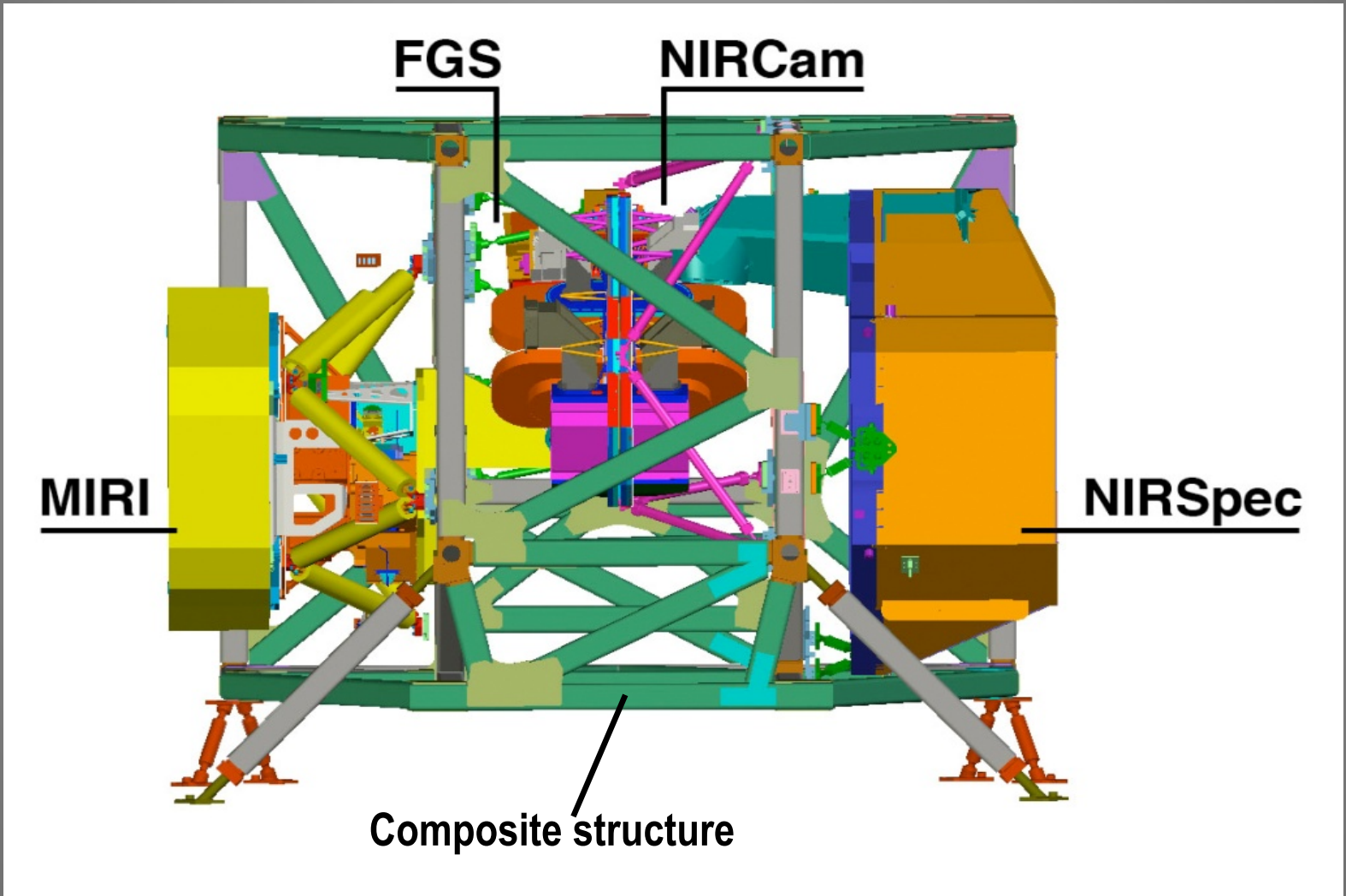
JWST Point-Source Sensitivity (10σ, 10,000 sec)

	Instrument	λ (μm)	$\Delta\lambda/\lambda$	Flux	m_{AB}
Continuum Source	NIRCam	2	4	12 nJy	28.8
	MIRI	10	5	700 nJy	24.3
	MIRI	21	5	8700 nJy	21.6
	TFI	3.5	100	126 nJy	26.2
	NIRSpec	3	100	132 nJy	26.1
Emission Line	NIRSpec	2	1000	1.6E-18 erg $s^{-1}cm^{-2}$	
	MIRI	9	3000	1.0E-17 erg $s^{-1}cm^{-2}$	
	MIRI	22	1200	5.6E-17 erg $s^{-1}cm^{-2}$	

JWST Point-Source Sensitivity (10σ, 10,000 sec)

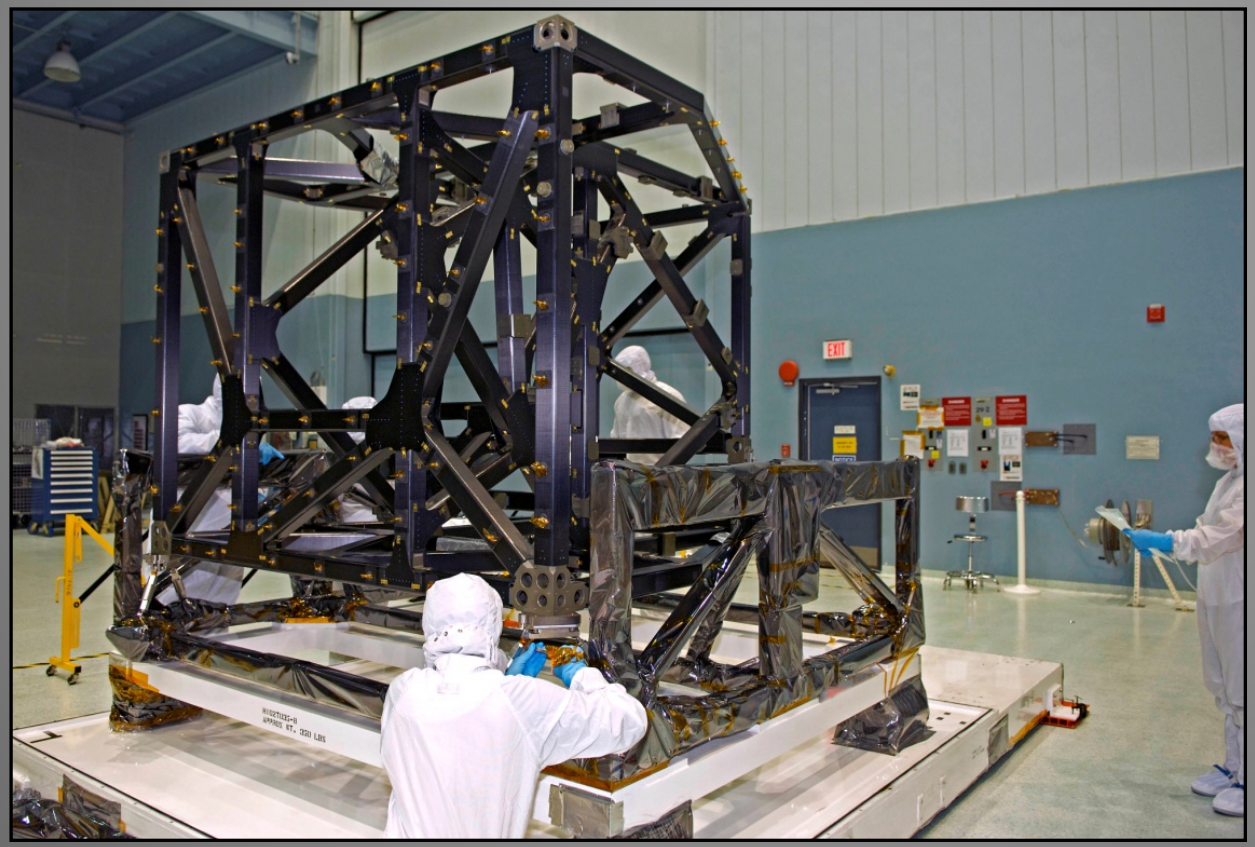


Precision composite structure maintains instrument alignment and wavefront error



Instrument module flight structure

- **Carbon-fiber/cyanate-ester composite material**
  - Primary launch-load bearing structure (warm launch)
  - High precision optical requirements
- **Key dimensional requirements (80 µm) for thermal cycling (300 to 30 K) verified to better than 25 µm precision.**



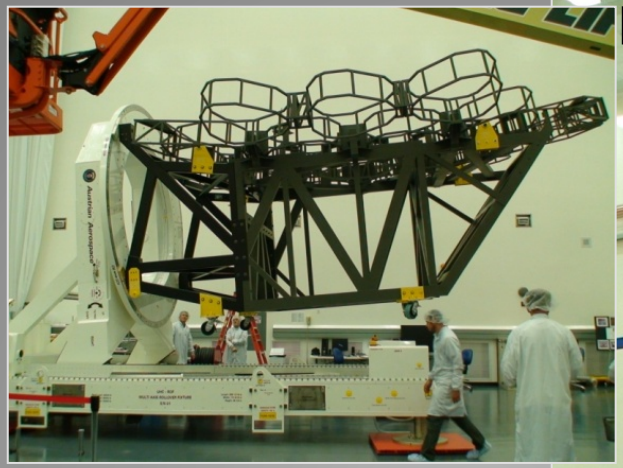
Whats Left?

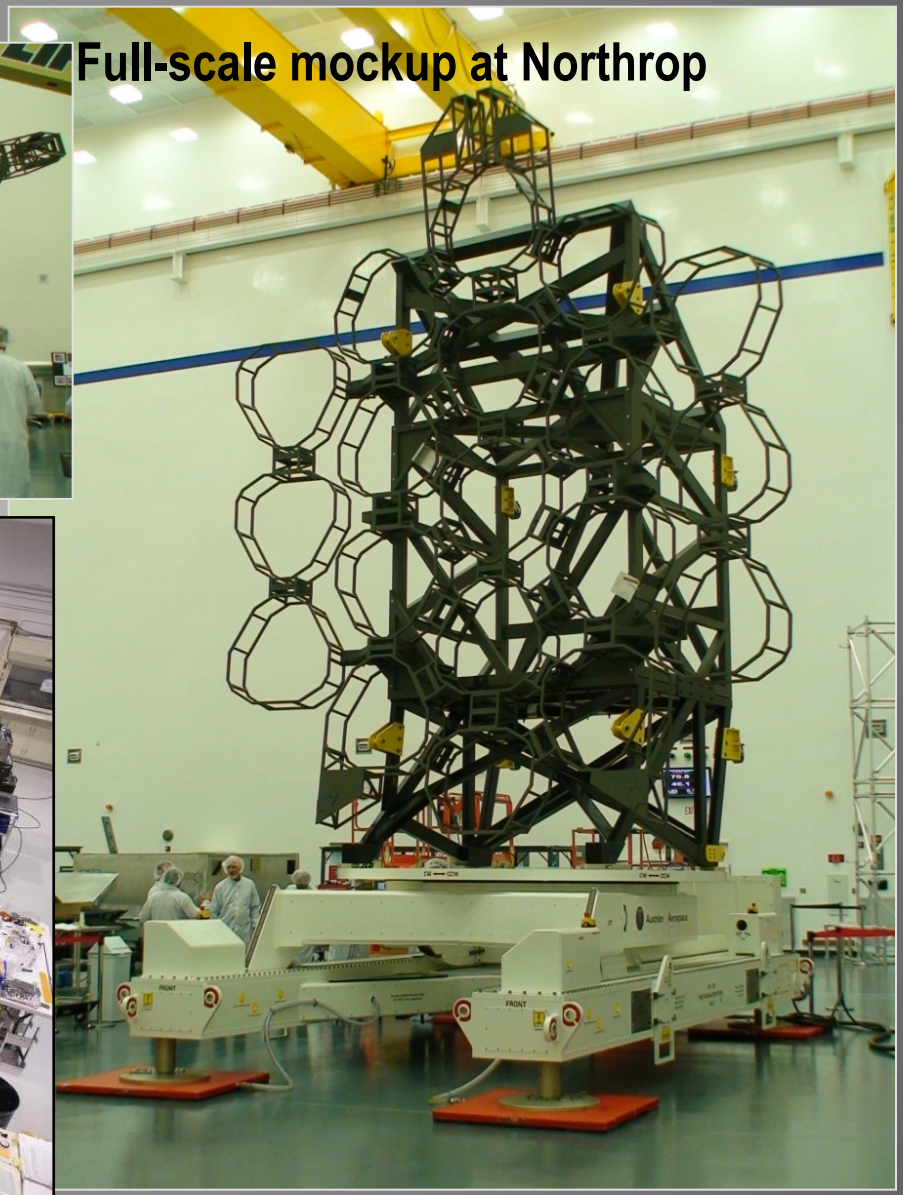
- Build and test spacecraft
- Build and test sunshield
- Assemble and test instrument module
- Assemble and test telescope (plus instruments)

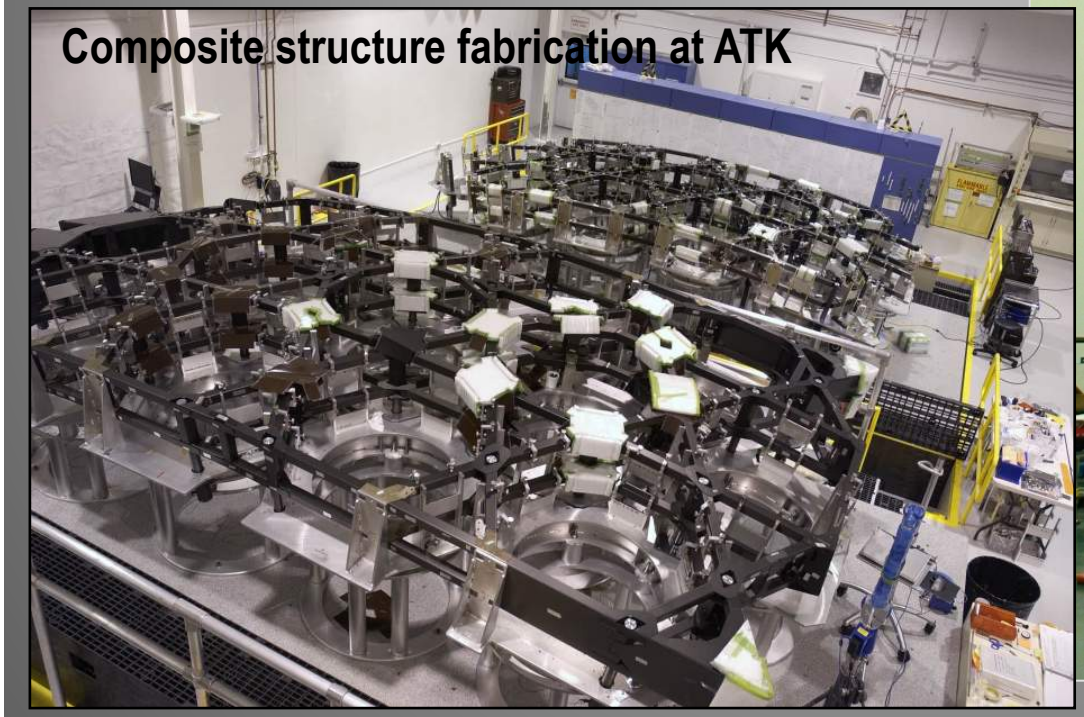
ISIM structure on Goddard centrifuge

- Integrate and test telescope-instrument system with spacecraft and sunshield
- Transport to Fr Guiana for launch
- Develop and test ground system and Science & Operations Center

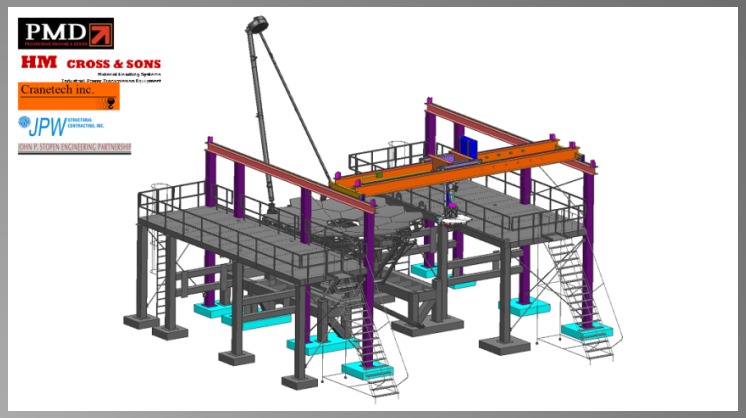
Telescope backplane and support structure



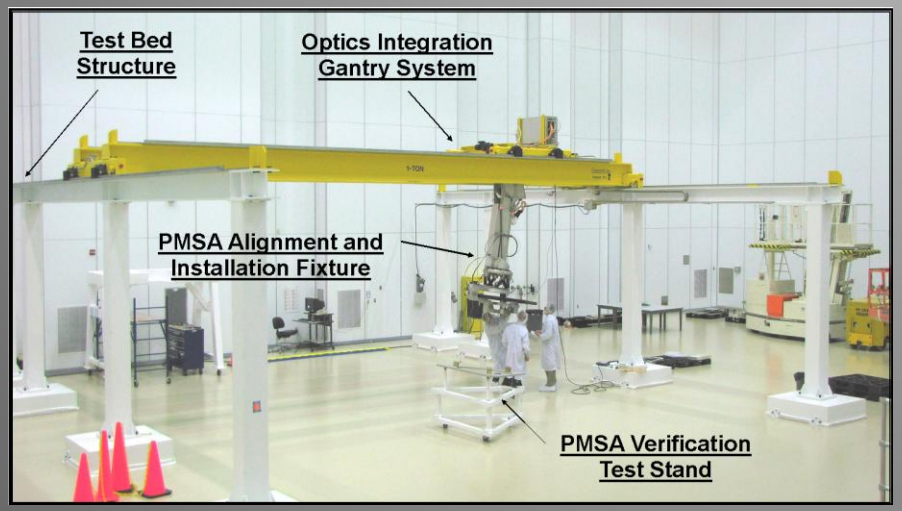




Telescope assembly equipment



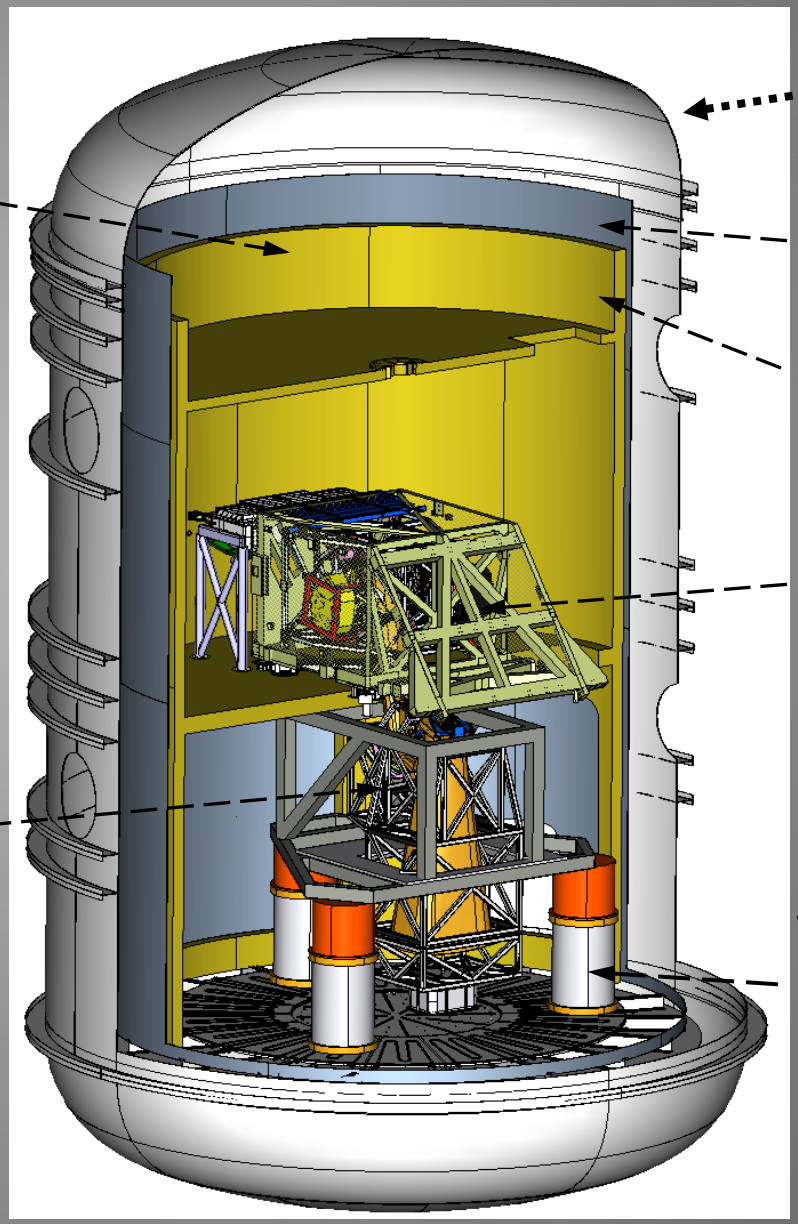
Hardware is completed and being readied for assembly at GSFC this month.



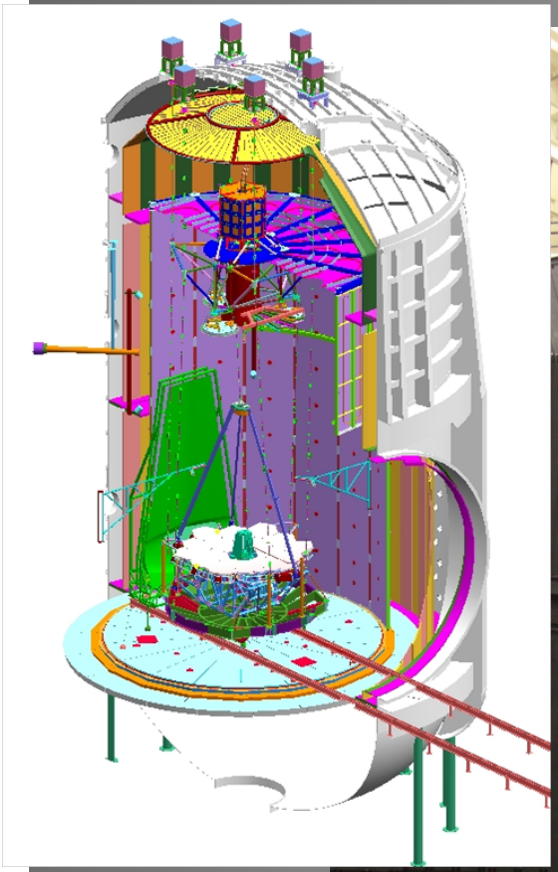
ISIM will be tested in the GSFC SES chamber using an Optical Telescope Simulator

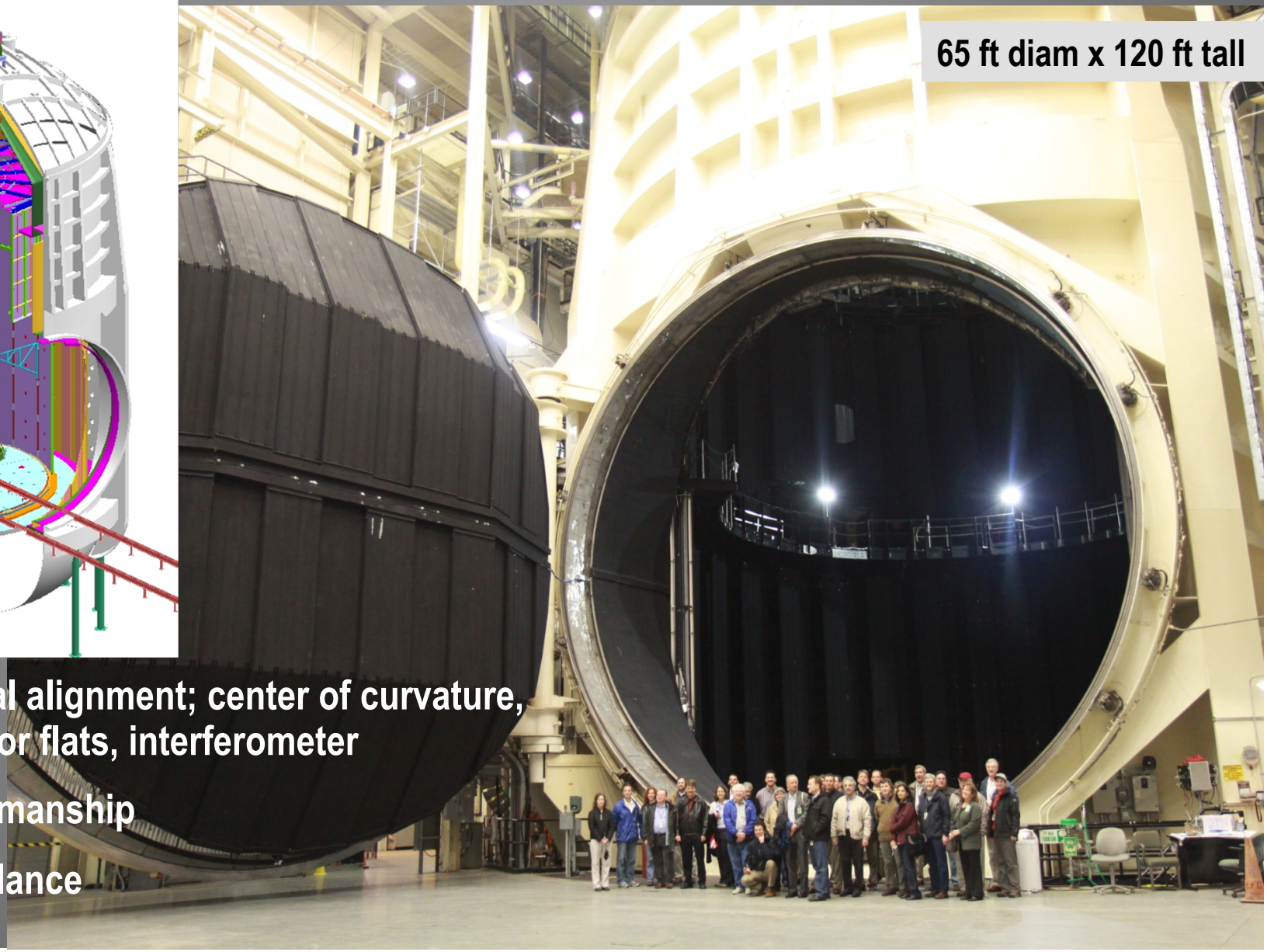
Liquid He shroud installation and test completed July 2009

JWST telescope simulator



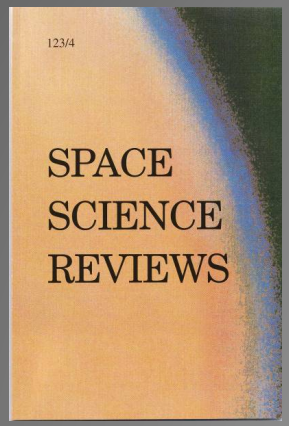
Then …. The telescope + ISIM will be tested in a larger space simulation chamber at Johnson Space Center



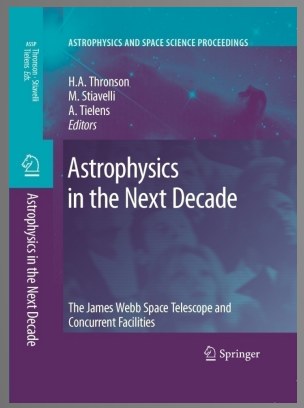


- Verify optical alignment; center of curvature, autocollimator flats, interferometer
- ➡ Verify workmanship
- ➡ Thermal balance

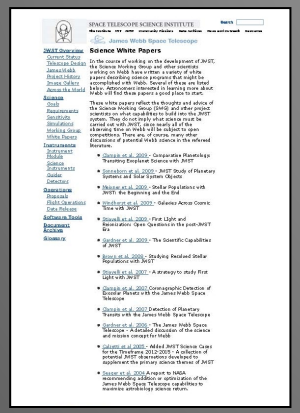
Learn more about JWST science ….



JWST science paper (Gardner et al.2006)
Download 120-page paper for free:
www.jwst.nasa.gov/science.html

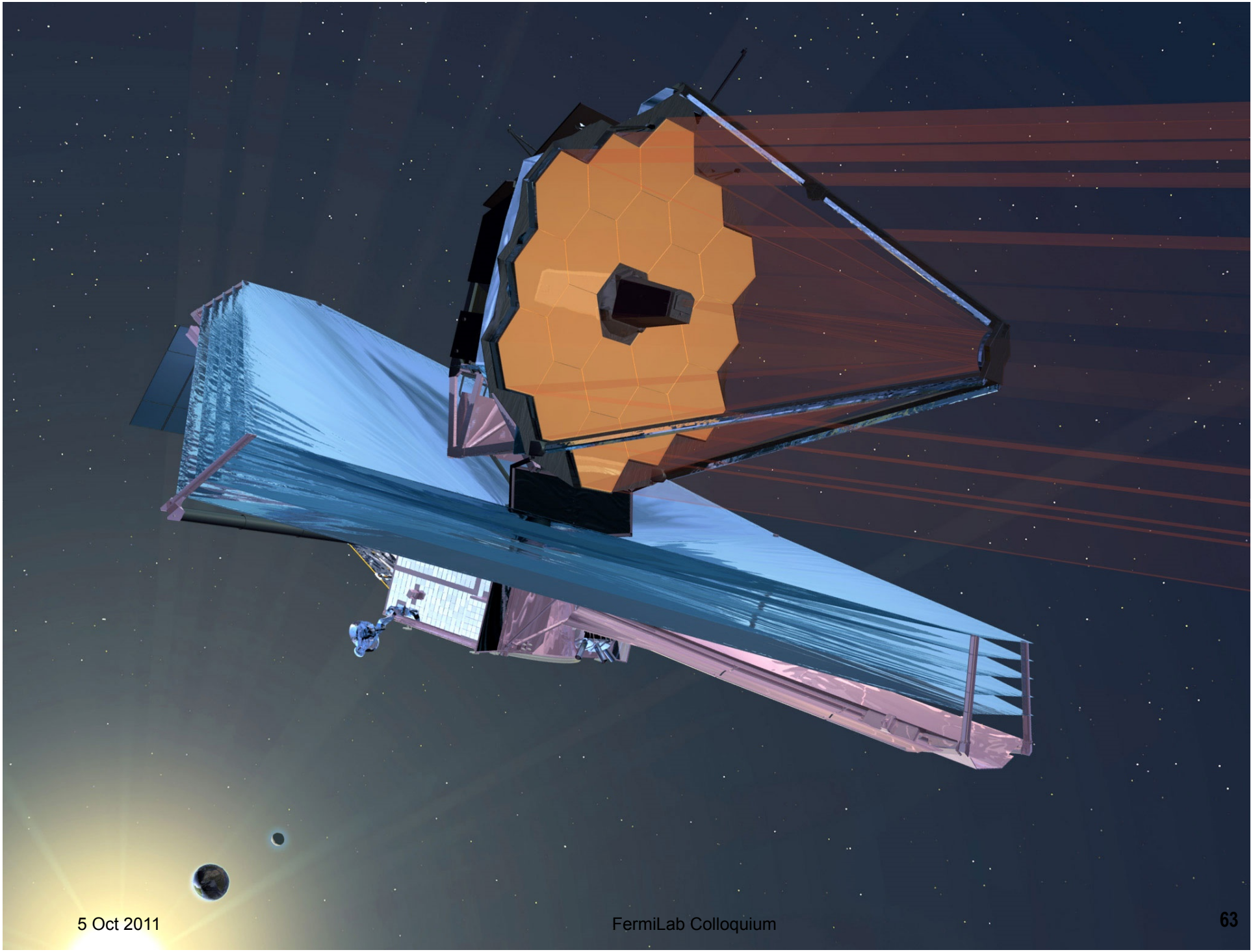


2007 conference in Tucson
Available from publisher.



Science white papers
www.stsci.edu/jwst/science/whitepapers/

New

All talks recorded and available on line

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