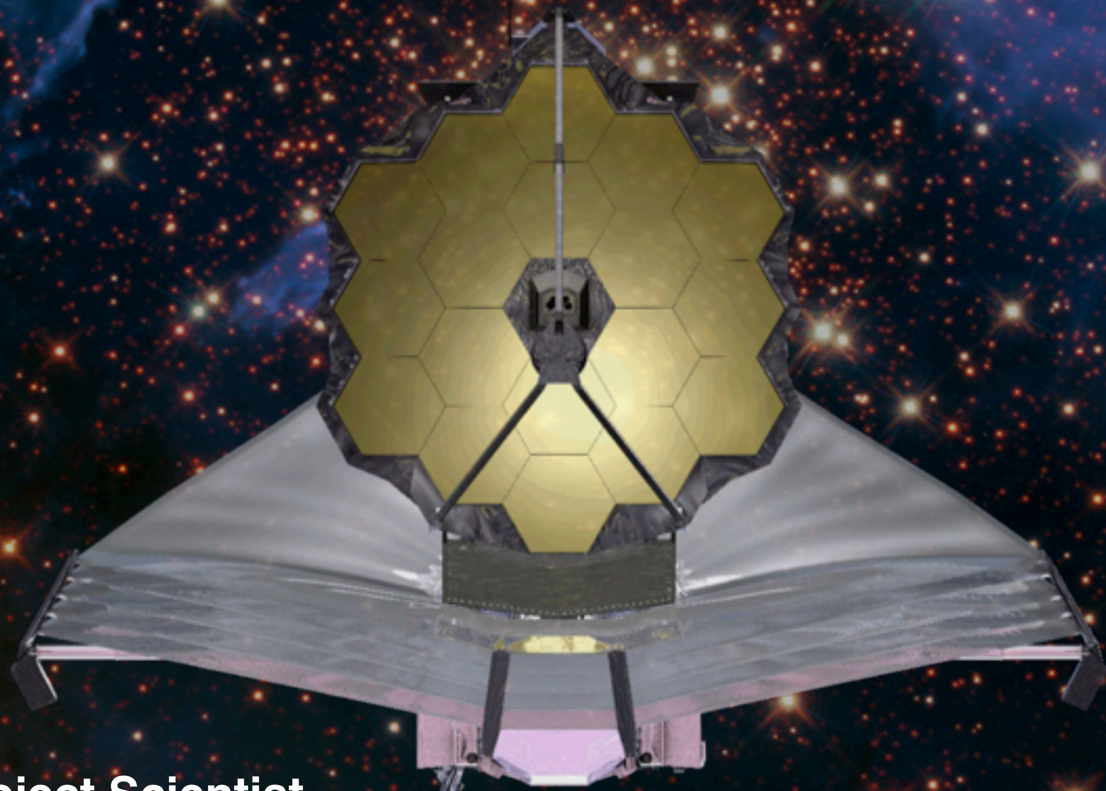
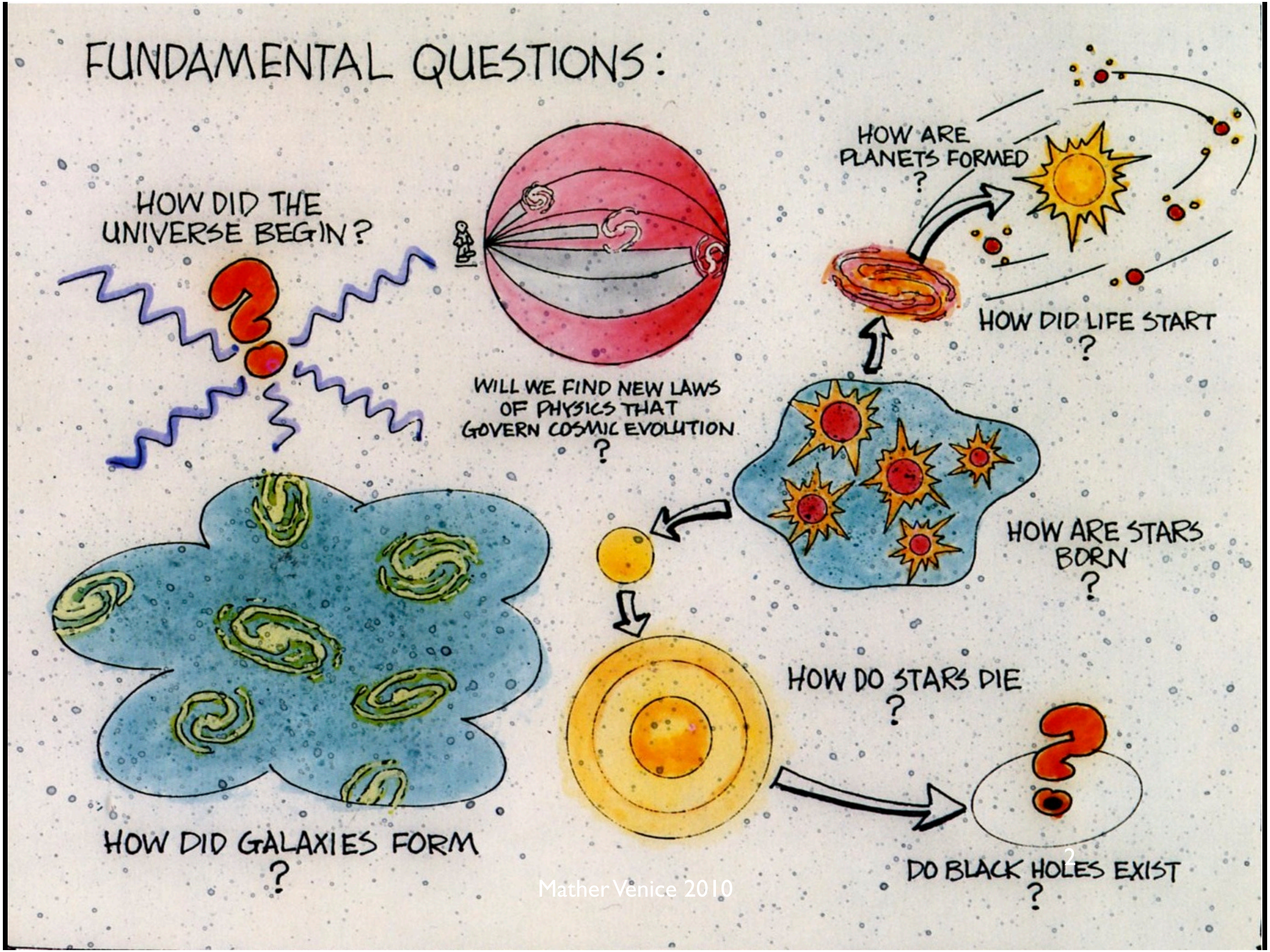
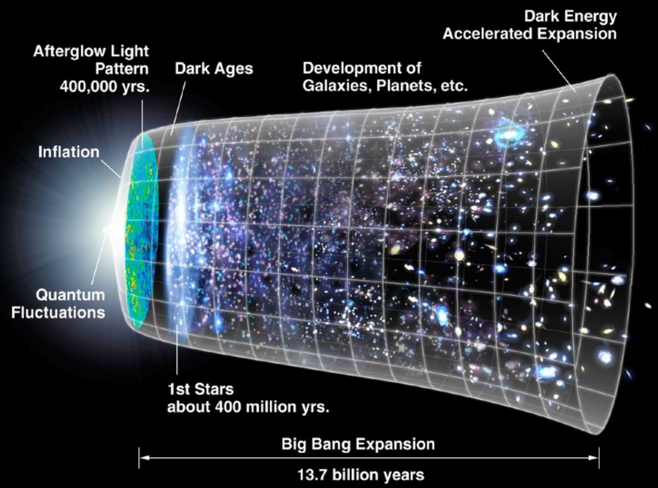
HST, JWST, and the Future



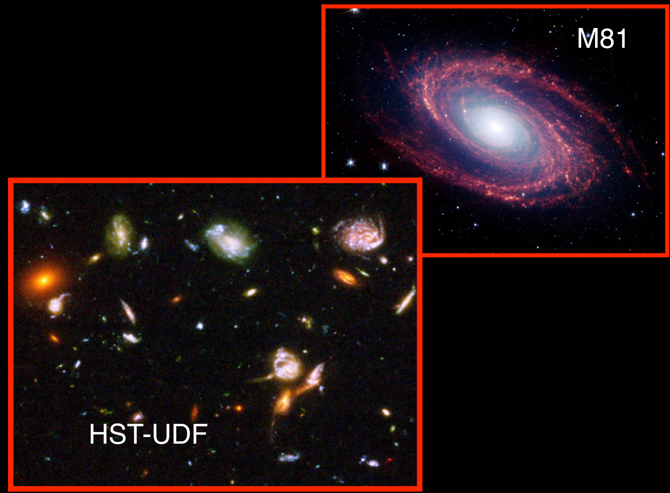
John Mather
JWST Senior Project Scientist
Goddard Space Flight Center


FUNDAMENTAL QUESTIONS:
HOW DID THE UNIVERSE BEGIN?
WILL WE FIND NEW LAWS OF PHYSICS THAT GOVERN COSMIC EVOLUTION ?
HOW ARE PLANETS FORMED ?
HOW DID LIFE START ?
HOW ARE STARS BORN ?
HOW DO STARS DIE ?
HOW DID GALAXIES FORM ?
DO BLACK HOLES EXIST ?

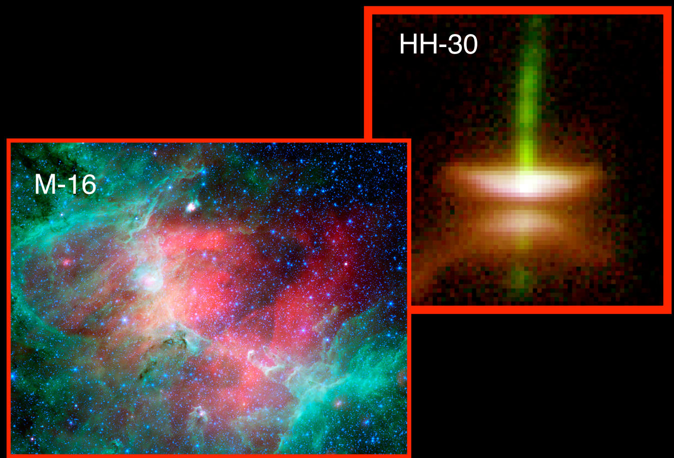
JWST Science



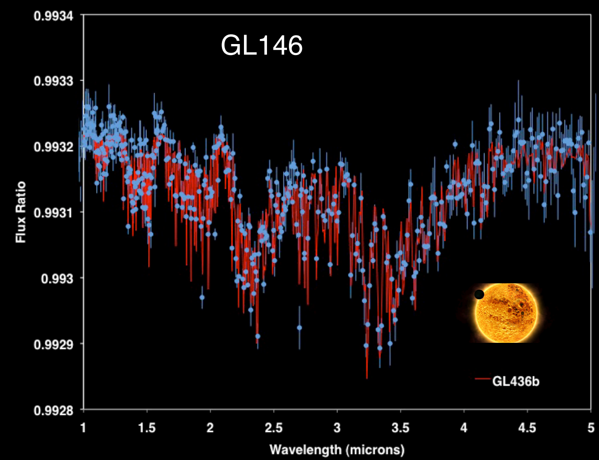
First Light and Re-Ionization



Assembly of Galaxies



Birth of stars and
proto-planetary systems

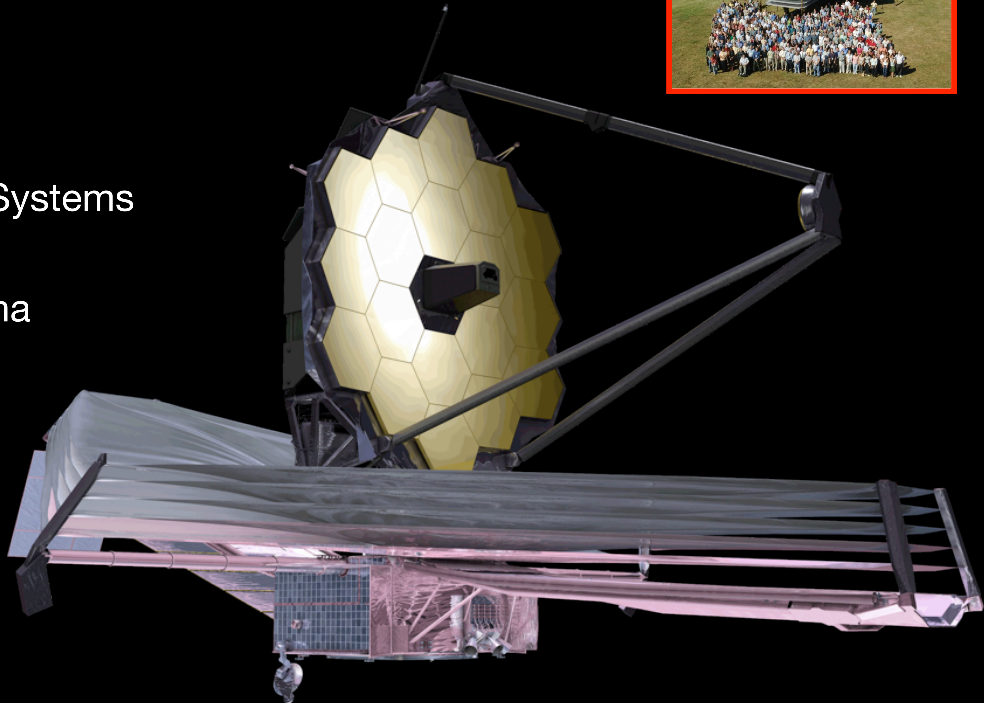


Planetary systems and the
origin of life

James Webb Space Telescope

Organization

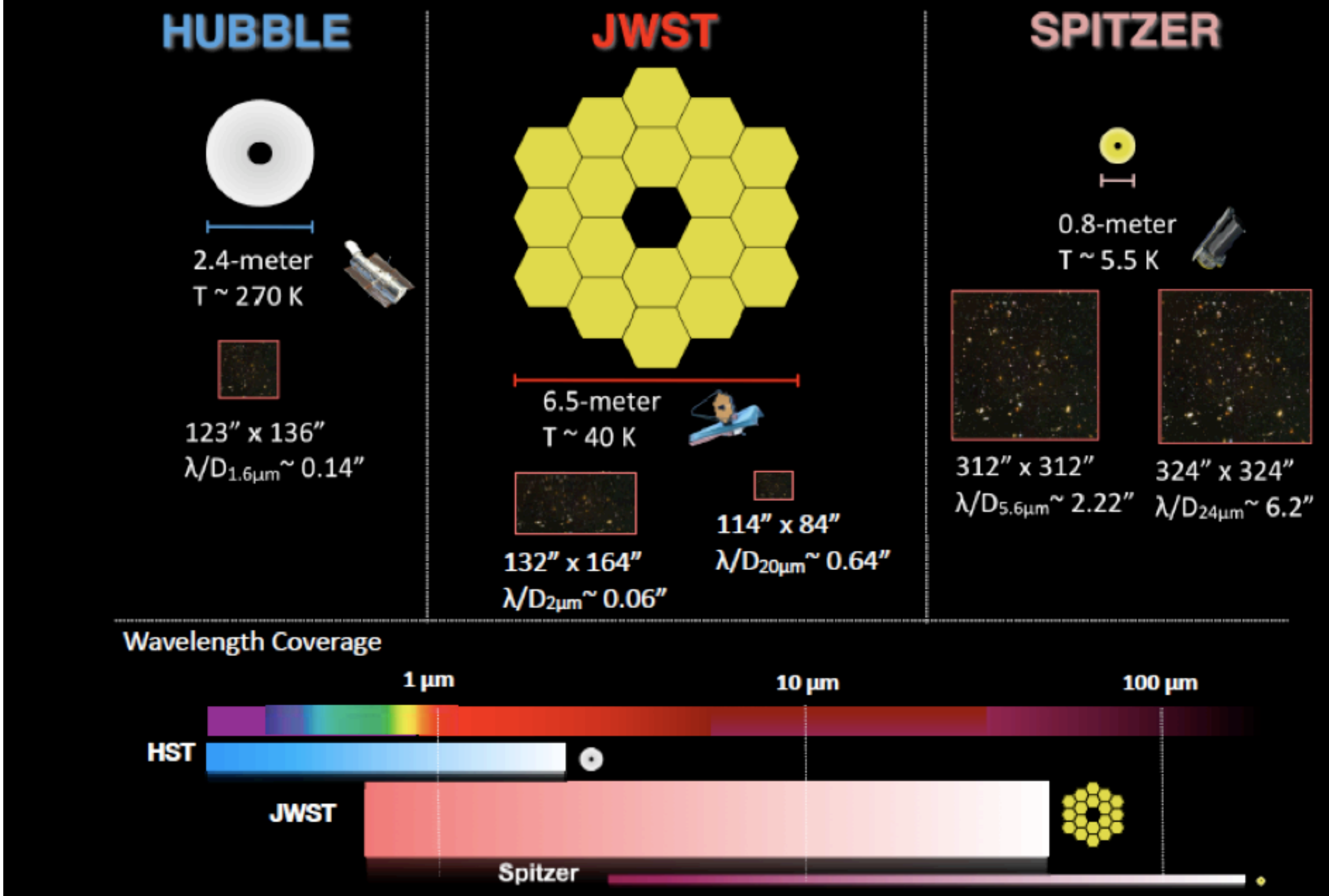
- **Mission Lead:** Goddard Space Flight Center
- Senior Project Scientist: Dr John Mather
- **International collaboration:** ESA & CSA
- **Prime Contractor:** Northrop Grumman Aerospace Systems
- **Instruments:**
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec)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



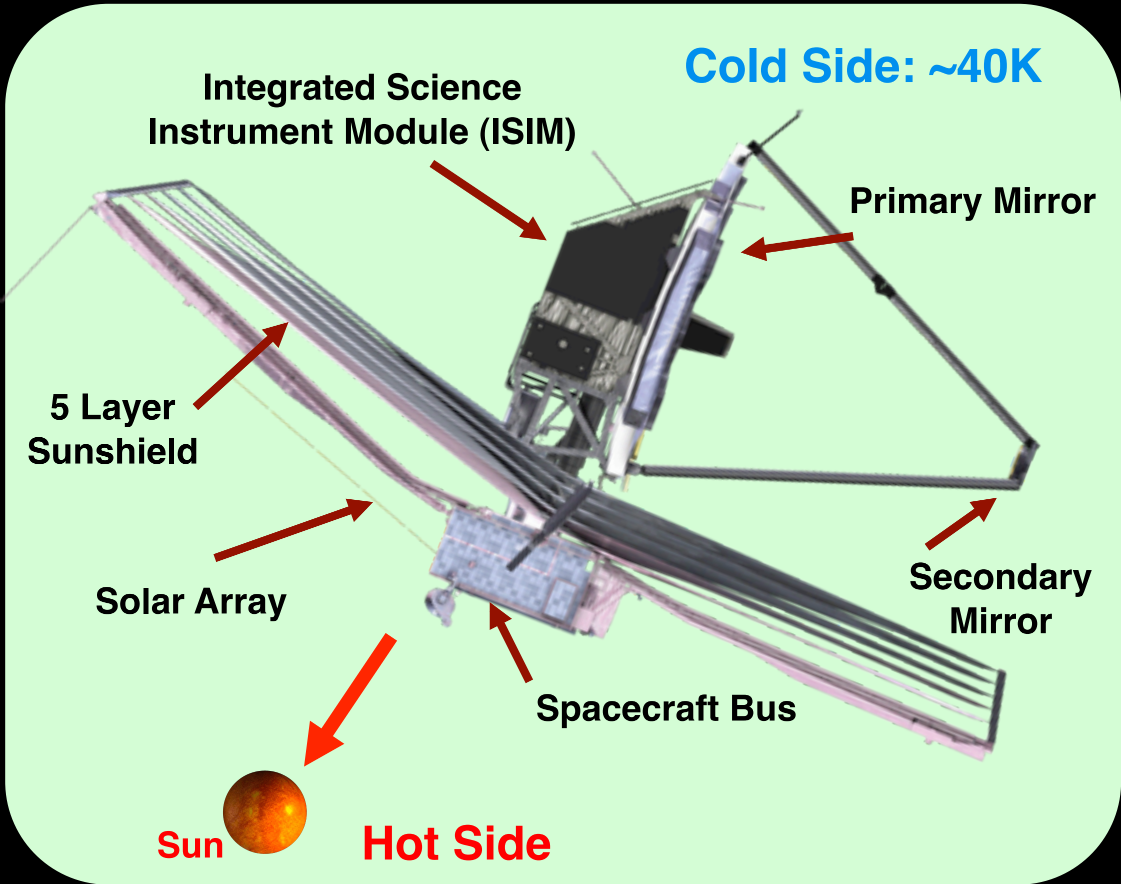
Description

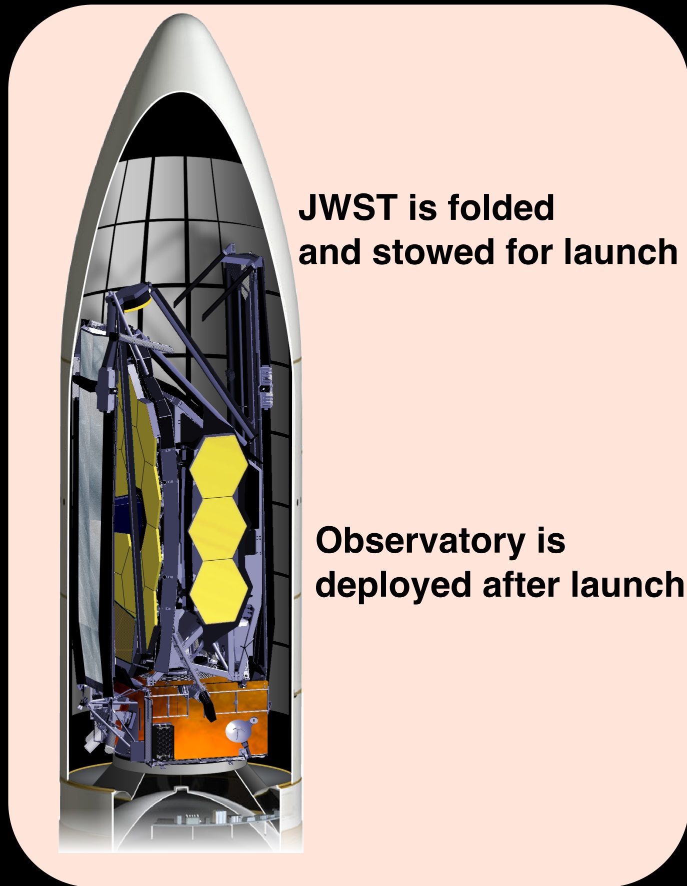
- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission requirement (10-year propellant lifetime)

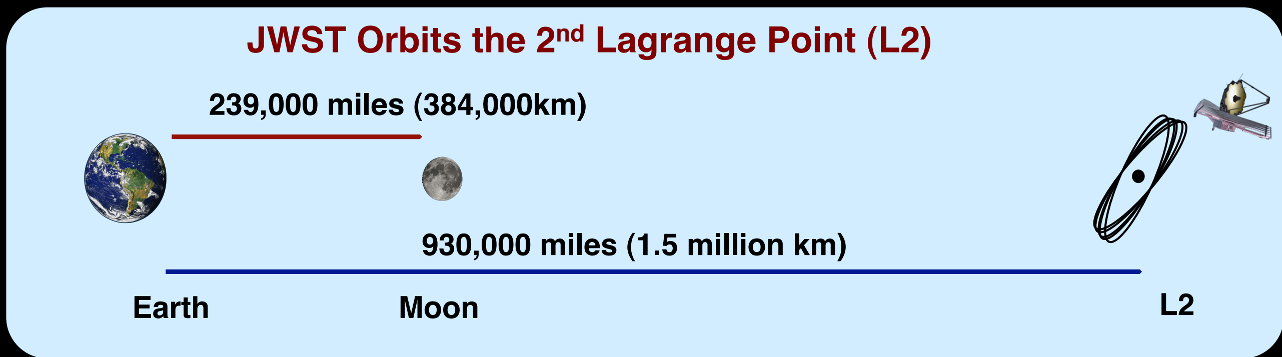
JWST and its Precursors



HOW JWST WORKS

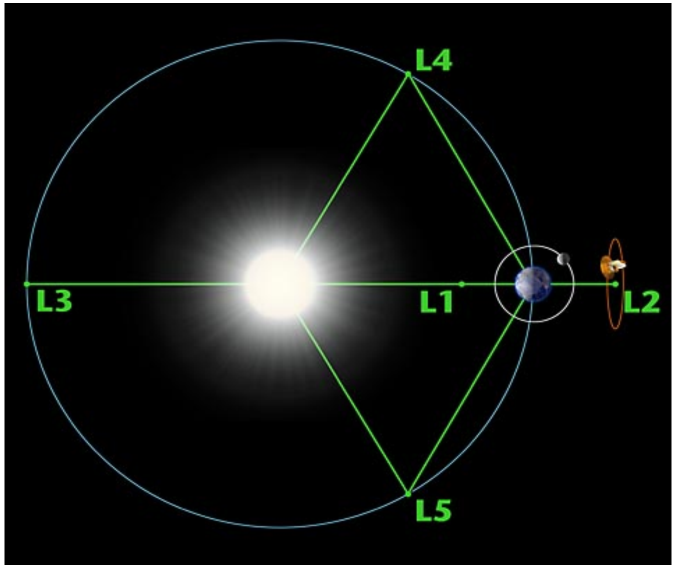


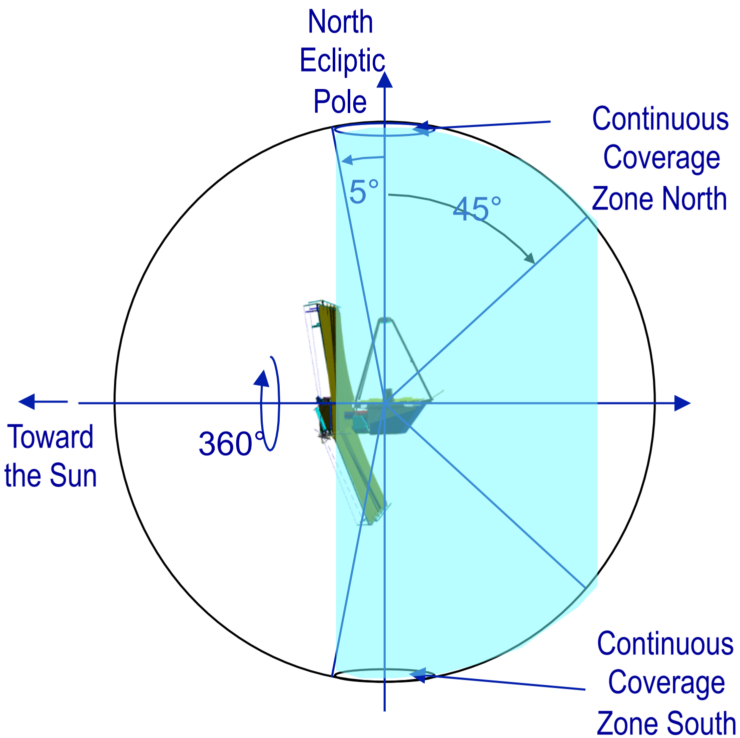




JWST science objectives require the largest cryogenic telescope ever constructed

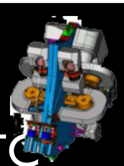
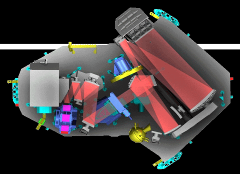
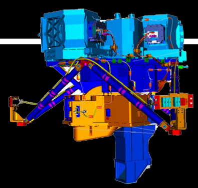
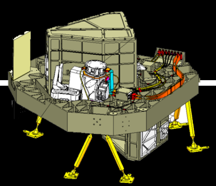
- An L2 point orbit was selected for JWST to enable passive cryogenic cooling
  - Station keeping thrusters fire ~ every 3 weeks to maintain this orbit
  - Propellant sized for 11 years (delta-v ~ 93 m/s)





- 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 Instrumentation

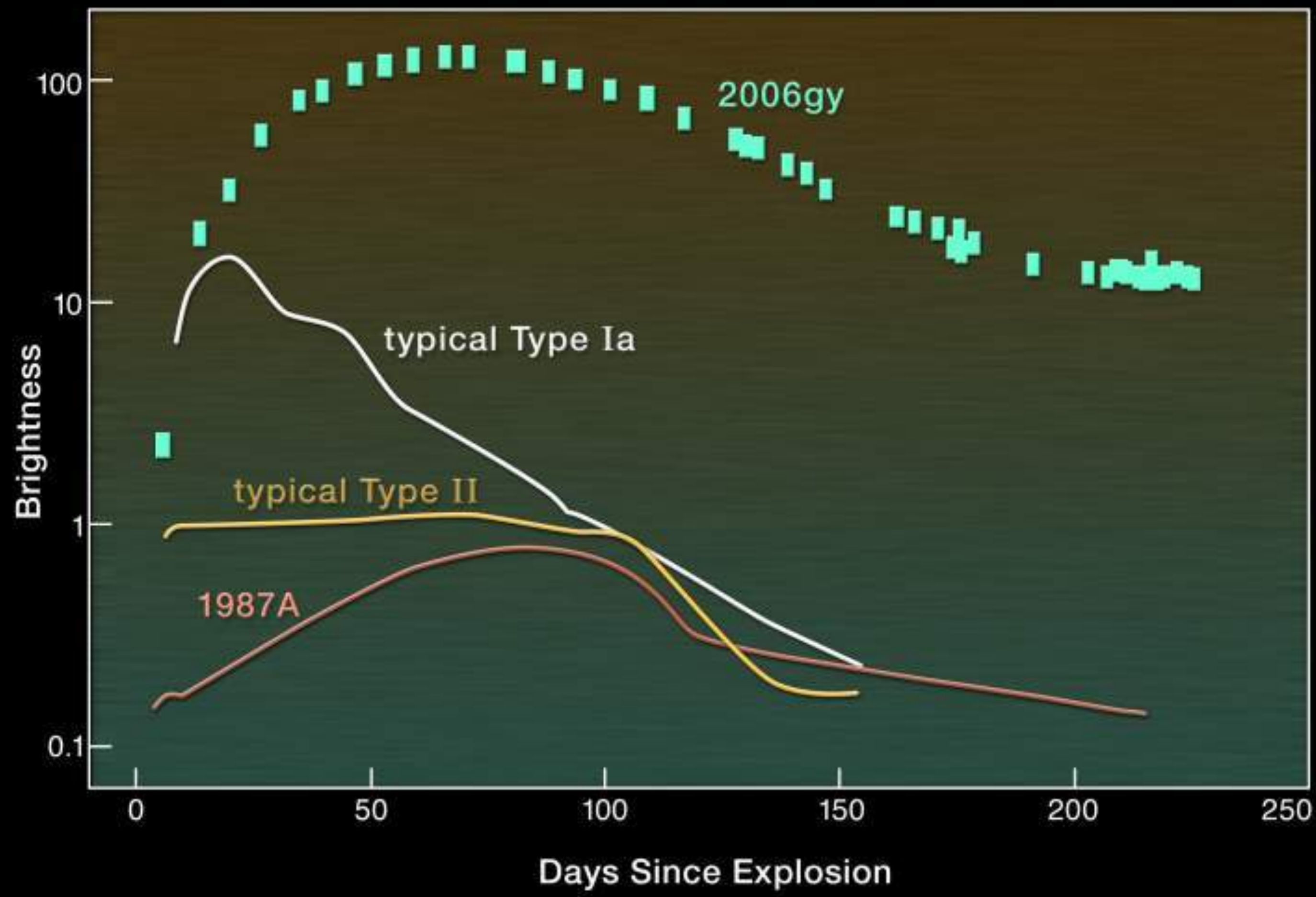
Instrument	Science Requirement	Capability
NIRCam Univ. Az/LMATC 	Wide field, deep imaging ‣0.6 μm - 2.3 μm (SW) ‣2.4 μm - 5.0 μm (LW)	Two 2.2' x 2.2' SW Two 2.2' x 2.2' LW Coronagraph
 **NIRSpec** ESA/Astrium	Multi-object spectroscopy ‣0.6 μm - 5.0 μm	9.7 Sq arcmin Ω + IFU + slits 100 selectable targets: MSA R=100, 1000, 3000
 **MIRI** ESA/UKATC/JPL	Mid-infrared imaging ‣ 5 μm - 27 μm Mid-infrared spectroscopy ‣ 4.9 μm - 28.8 μm	1.9' x1.4' with coronagraph 3.7"x3.7" – 7.1"x7.7" IFU R=3000 - 2250
 **FGS/TFI** CSA	Fine Guidance Sensor 0.8 μm - 5.0 μm Tunable Filter Imager ‣1.6 μm - 4.9 μm	Two 2.3' x 2.3' 2.2' x 2.2' R=100 with coronagraph

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.

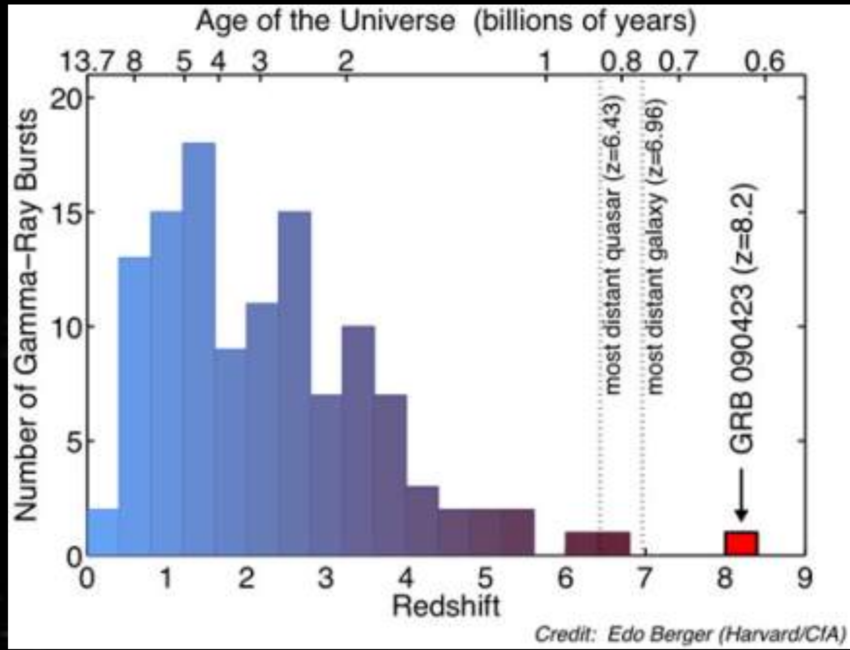
Hubble Ultra Deep Field

Pair-production SNe as First Stars



- Good news: JWST can easily detect these when stars first formed (but not as transients).
- Interesting news: pair-production instability doesn't necessarily require primordial composition.

Gamma Ray Burst 4/23/09 was one of the most distant objects yet found (z = 8.2) – supernova jet aimed at us!

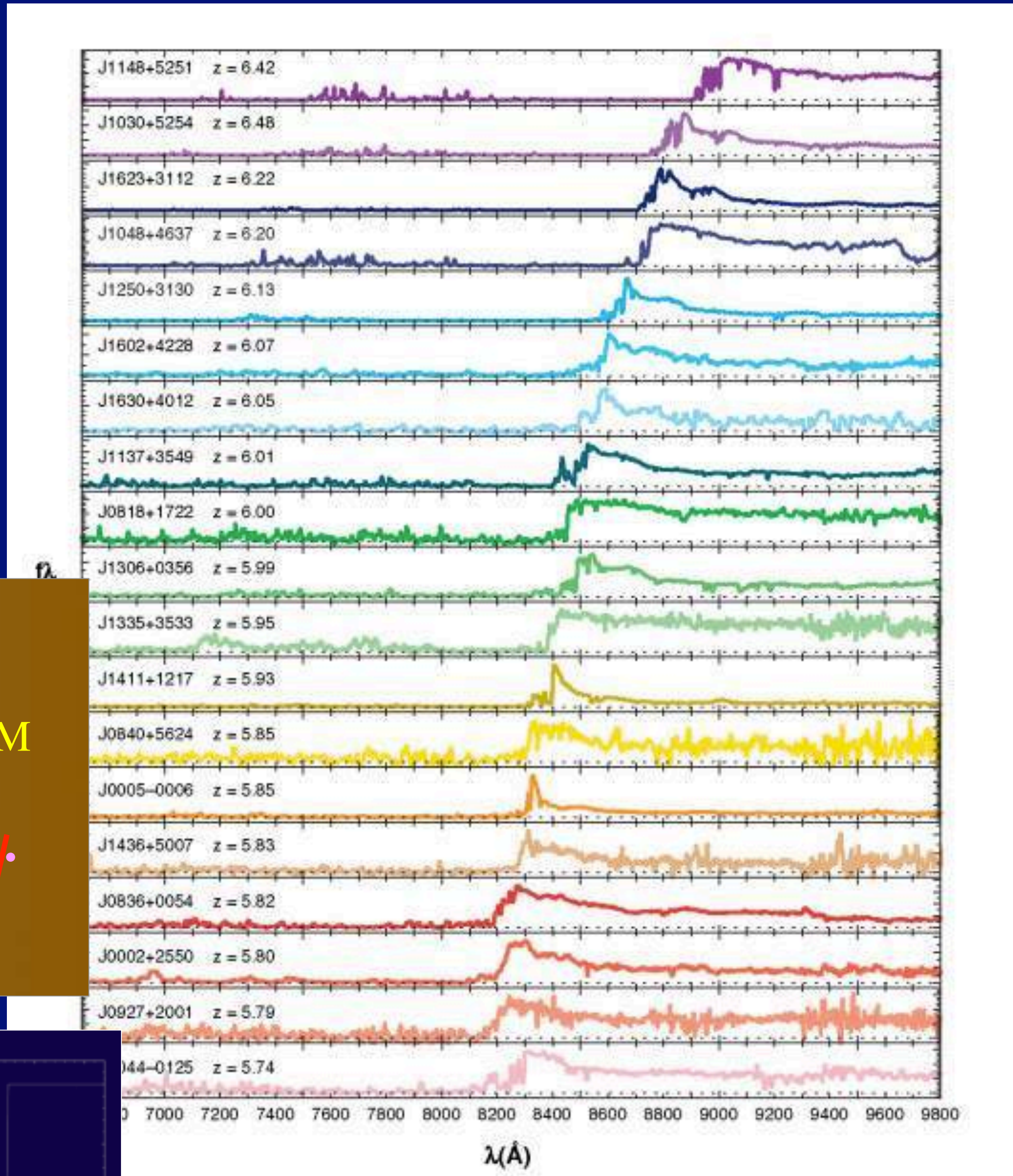


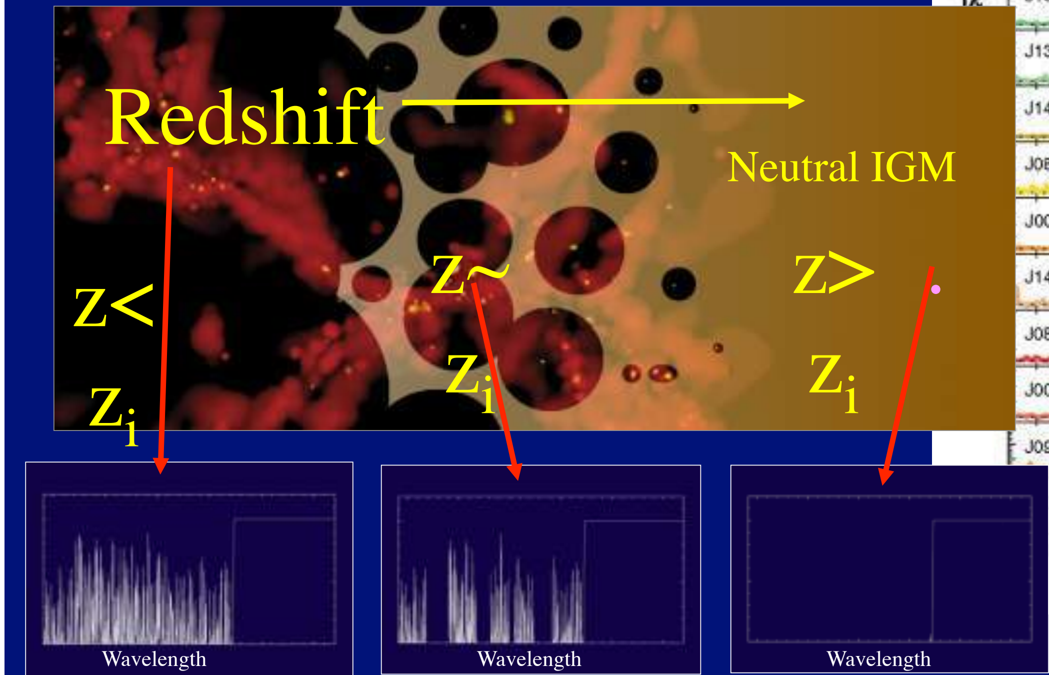
JANUS GRB (SMEX) search proposed, could see to z = 12

When was re-ionization?

6.42

6.00





Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

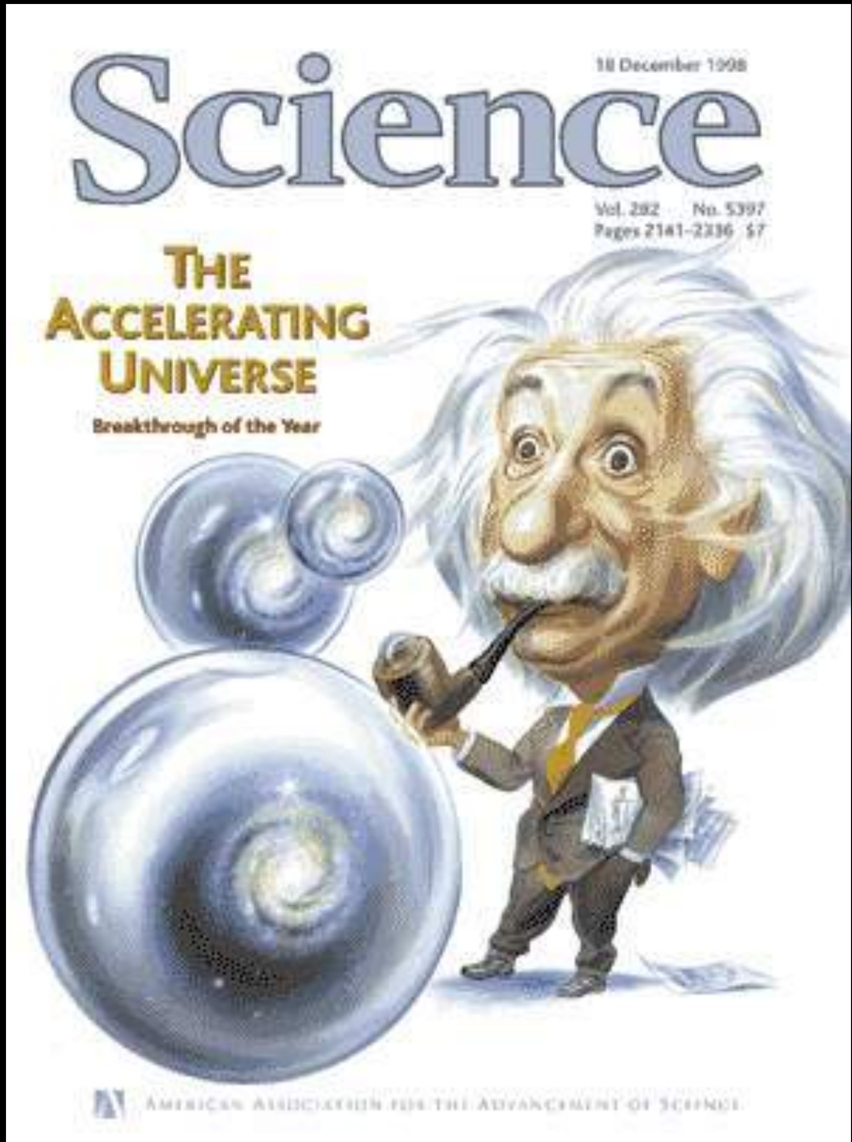
5.74

Mather Venice 2010

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

Dark Energy!

MacArthur Fellow
2008 - Adam Riess



S. Perlmutter, A. Riess, B. Schmidt

JWST, Dark Energy, Dark Matter

- Problem: determine acceleration parameter now and in the past
- Multiple techniques required due to likely systematic errors
- JDEM/IDECS wide-field surveys will find targets for JWST
- JWST contributes by
  - Measuring very distant supernovae (standard candles?)
  - SNe rest-frame IR light curves – maybe better standard candles?
  - Measuring effects of dark matter too (distorted images of distant objects, masses of galaxies and clusters out to high redshift, rotation curves, etc.)
  - Cosmic archeology at high redshift (prior to acceleration, formation of galaxies and clusters)
  - Measuring Cepheids in galaxies with maser distances

How does environment affect star-formation and vice-versa?
What is the sub-stellar initial mass function?

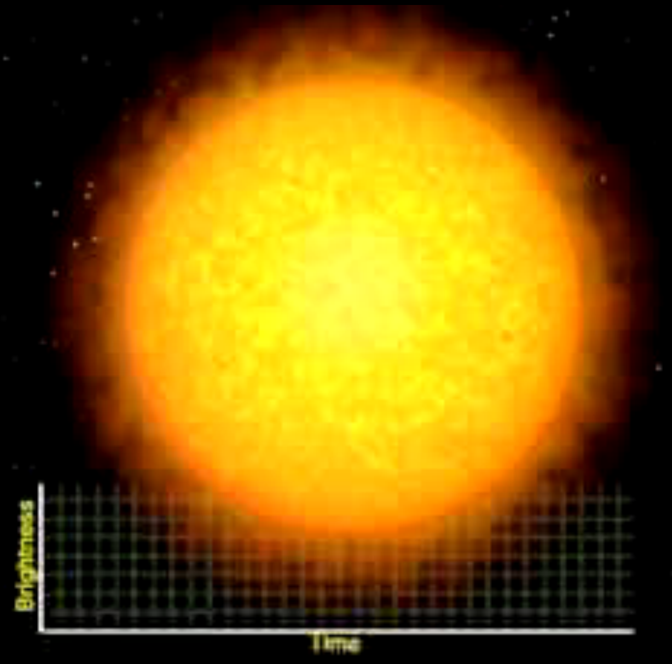
- Massive stars produce winds and radiation
  - Either disrupt star formation, or causes it.
- The boundary between the smallest brown dwarf stars and planets is unknown
  - Different processes? Or continuum?
- Observations:
  - Survey dark clouds, “elephant trunks” and star-forming regions

The Eagle Nebula
as seen in the infrared

Exoplanets

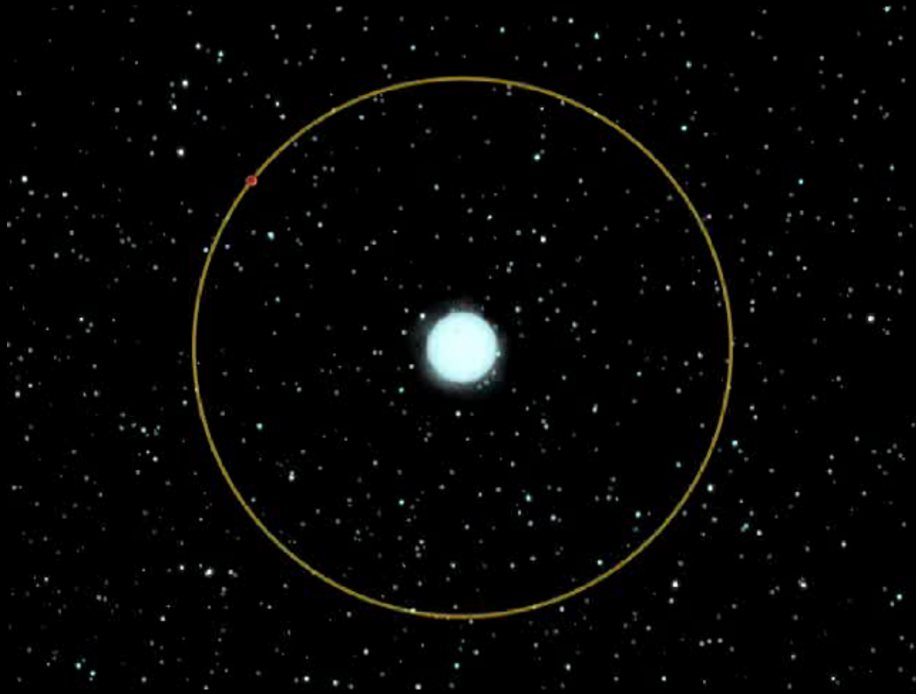
- As of Sept. 9, 2010, 490 total:
  - Radial velocity: 459 planets, 45 multiple planet systems
  - Transiting: 101 planets, including 6 multiples (most good JWST targets)
  - Microlensing: 10 planets, 1 multiple system
  - Imaging: 13 planets, 1 system (a triple) (JWST has 3 coronagraphs)
  - Timing: 8 planets, 2 multiple planet systems
  - + predictions from dust disk structures
- Kepler launched Mar. 6, 2009, monitors ~ 100,000 stars, to find handful of Earths, thousands of others
- TESS (Transiting Exoplanet Survey Satellite), proposed SMEX, would survey nearest stars, best candidates for detailed follow-up with JWST
- JWST Transits Working Group established – M. Clampin

Primary



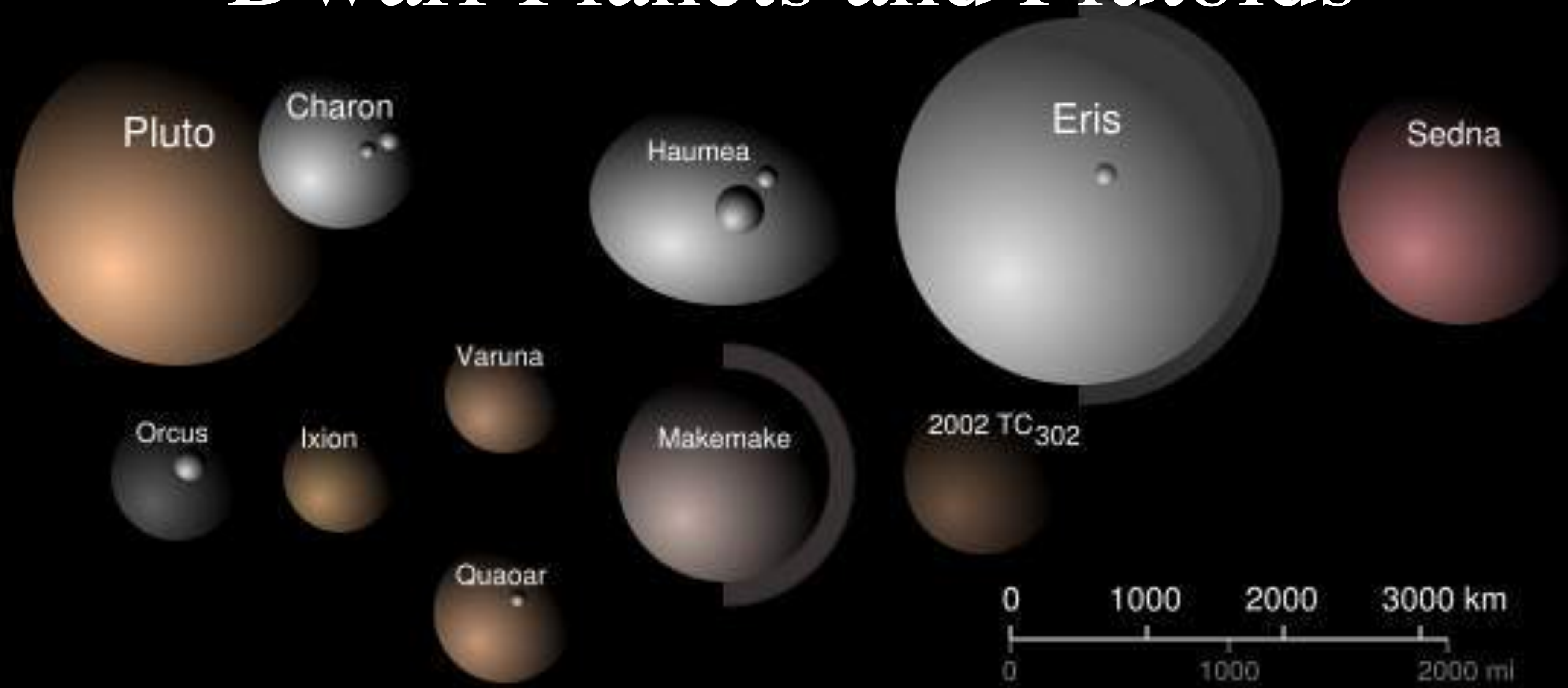
- Planet blocks light from star
- Visible/NIR light (Hubble/JWST)
- Radius of planet/star
- Absorption spectroscopy of planet's atmosphere
- JWST: Look for moons (by timing), constituents of atmosphere, Earth-like planets with water, weather

Secondary

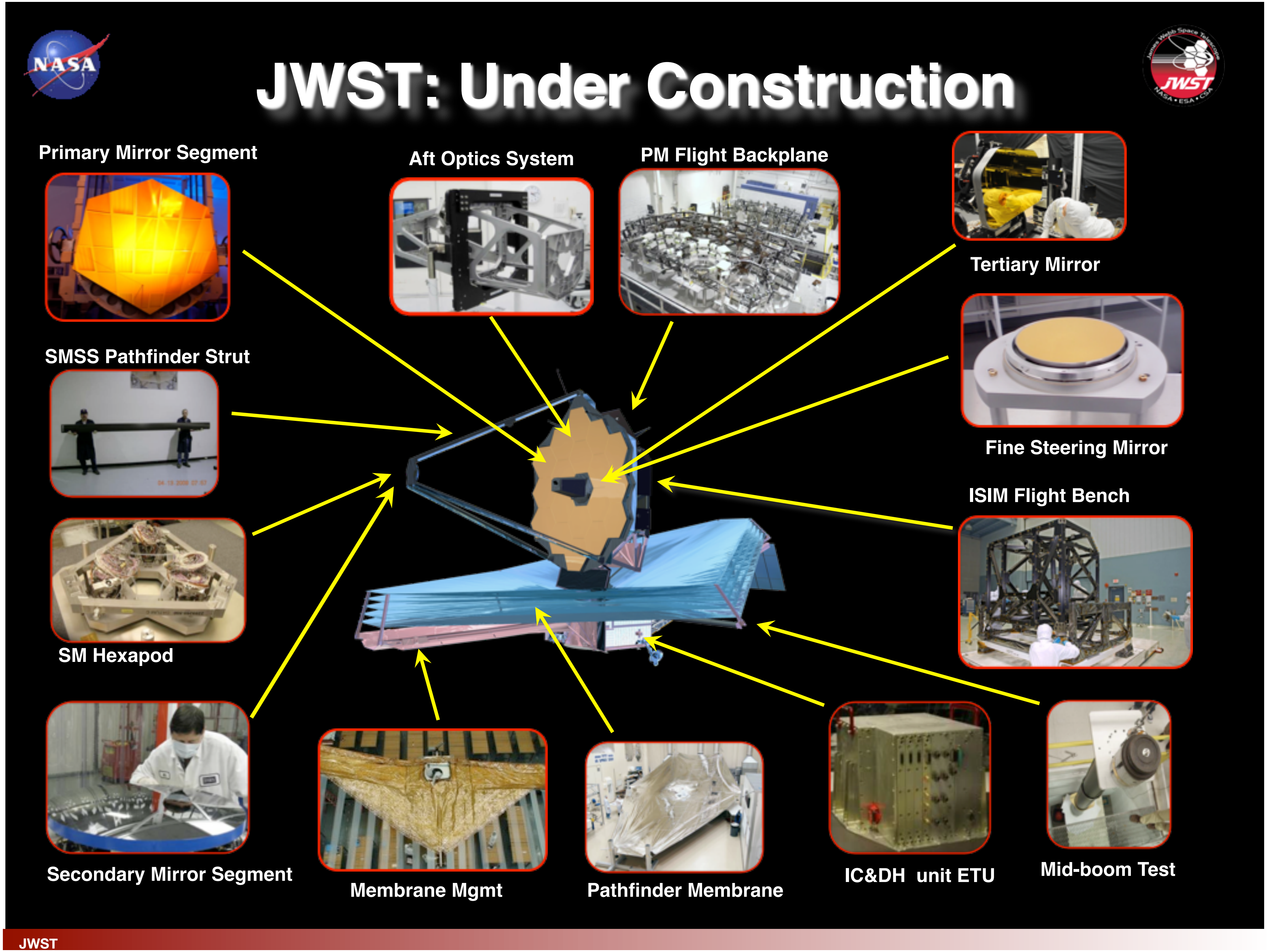


- Star blocks light from planet
- Mid-Infrared light (Spitzer/JWST)
- Direct detection of photons from planet
- Temperature of planet
- Emission from surface
- JWST: Atmospheric characteristics, constituents of atmosphere, map planets

Dwarf Planets and Plutoids



May be 2000 more when whole sky is surveyed
With moving object tracking JWST is perfect tool

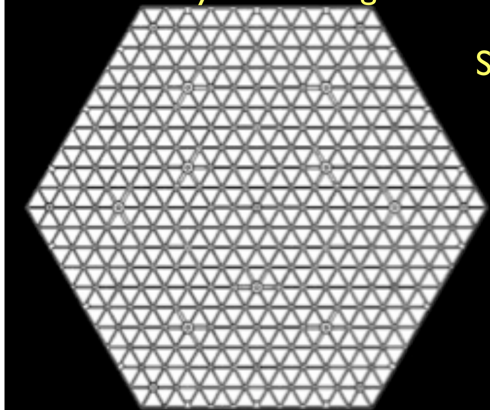

JWST: Under Construction
Primary Mirror Segment
Aft Optics System
PM Flight Backplane
Tertiary Mirror
SMSS Pathfinder Strut
Fine Steering Mirror
ISIM Flight Bench
SM Hexapod
Secondary Mirror Segment
Membrane Mgmt
Pathfinder Membrane
IC&DH unit ETU
Mid-boom Test
JWST

JWST Mirror Fabrication

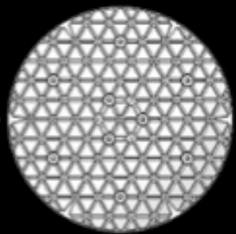
- JWST Mirrors made of beryllium
- Lightweight and stable at 40 K
- Brush-Wellman

Raw Be billet (two mirrors)

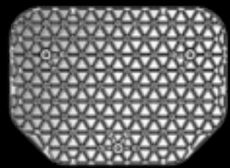
Primary mirror segment



Secondary mirror

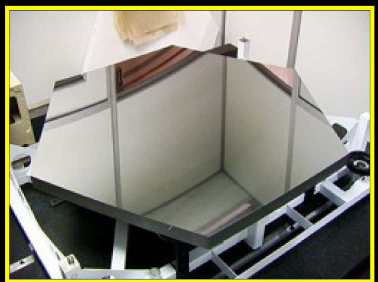


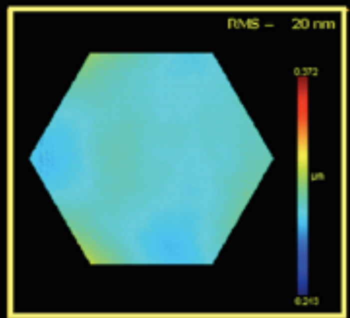
Tertiary mirror



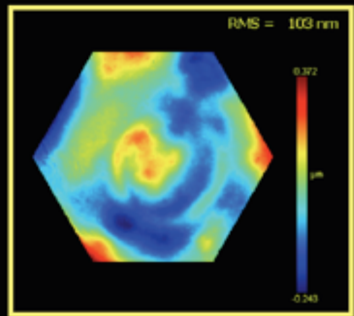
- Machined & lightweighted by Axsys
- 92% material is removed

- Mirrors polished at Tinsley Segment cryo-figure: 20 nm

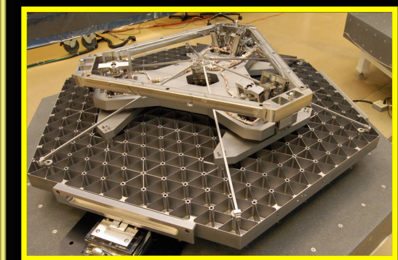




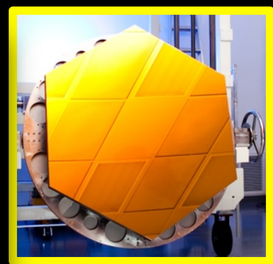
Cryo-surface figure



Ambient



Actuators & Strongback

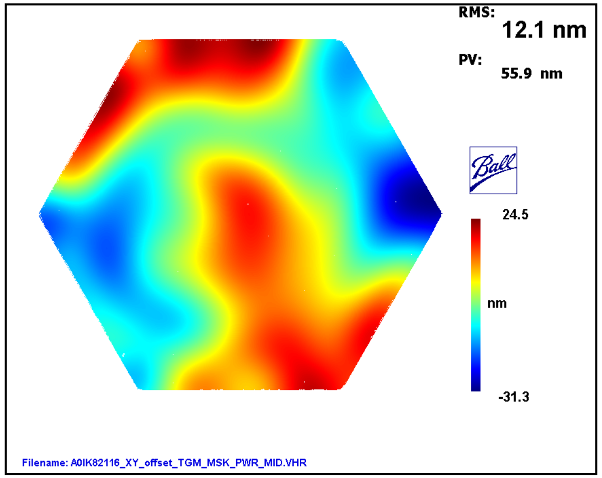


Gold Coating

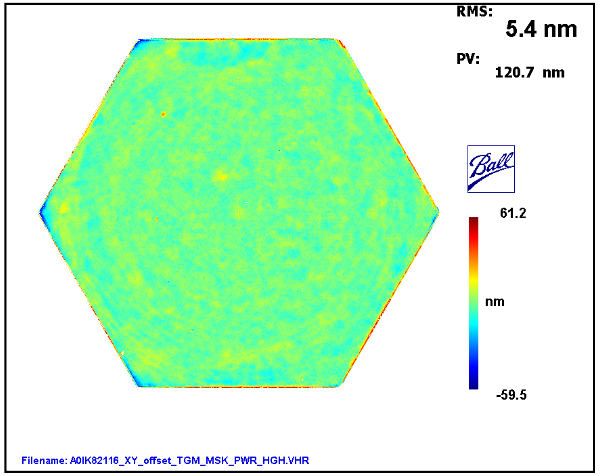
Flight Mirror Cryogenic Testing

First Flight Mirrors Complete

Mid Frequency: RMS 12.1nm, P-V 56nm

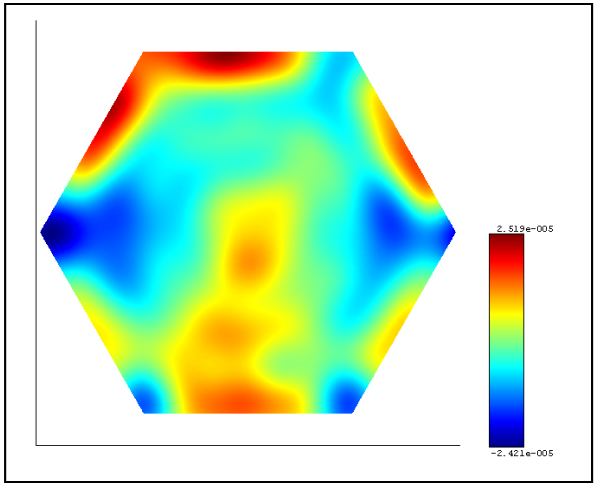


High Frequency: RMS 5.4nm, P-V 121nm

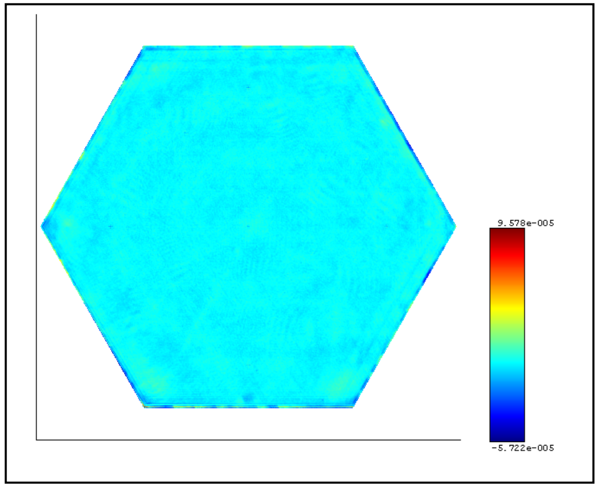


EDU

Mid Frequency: RMS 8.2nm, P-V 49nm



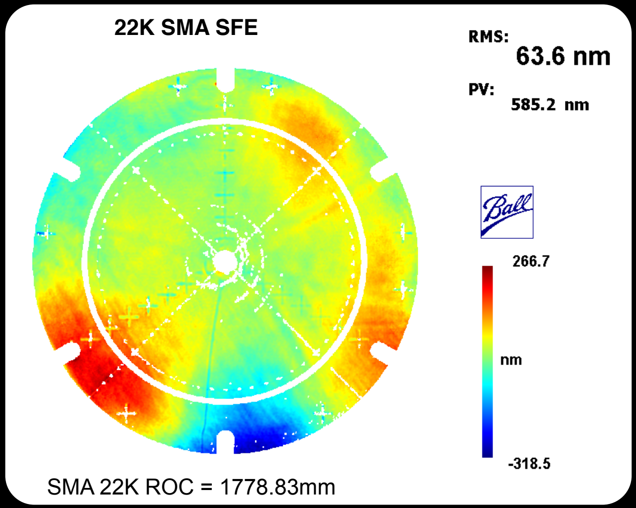
High Frequency: RMS 3.2nm, P-V 153nm

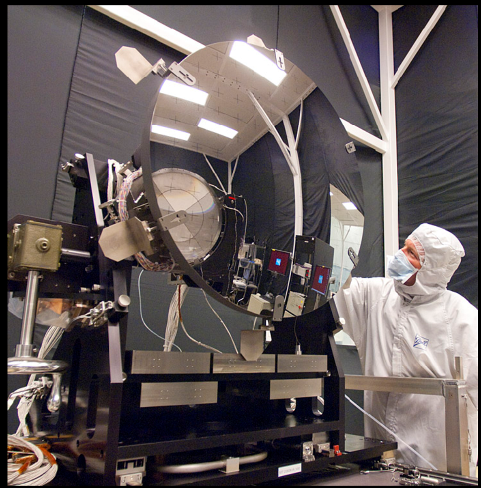


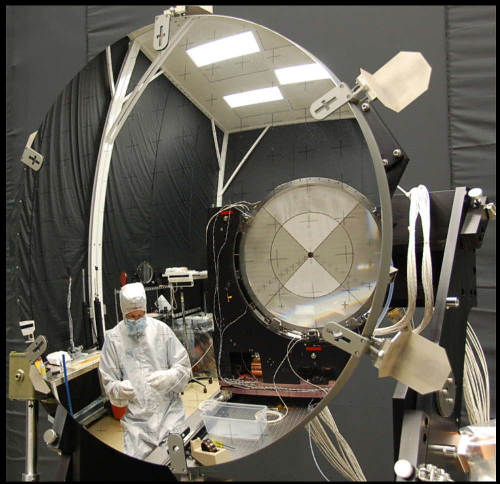
A4

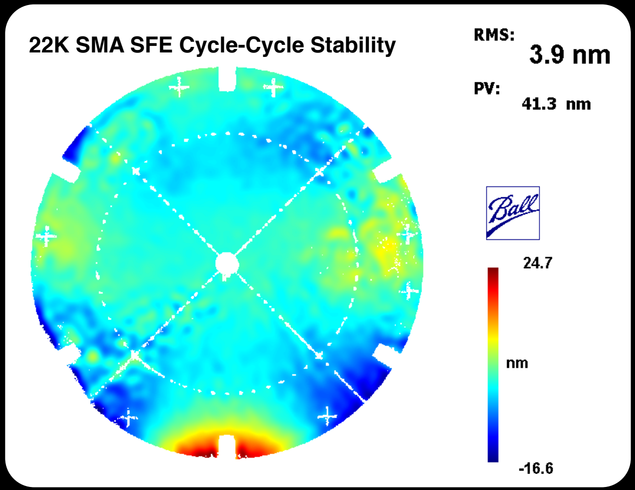
Secondary Mirror

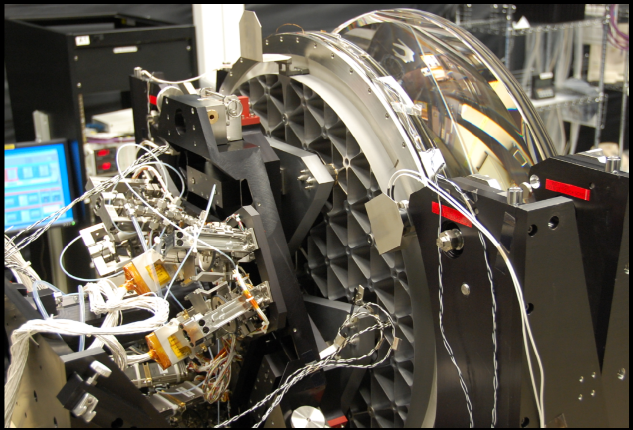
- SM flight spare meets requirements



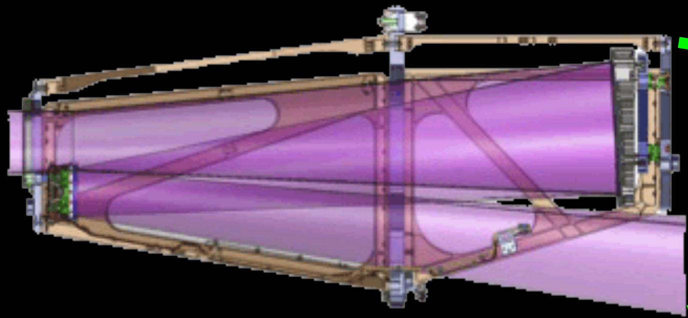


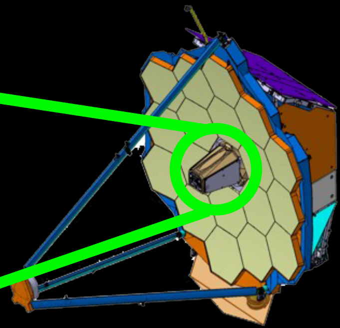


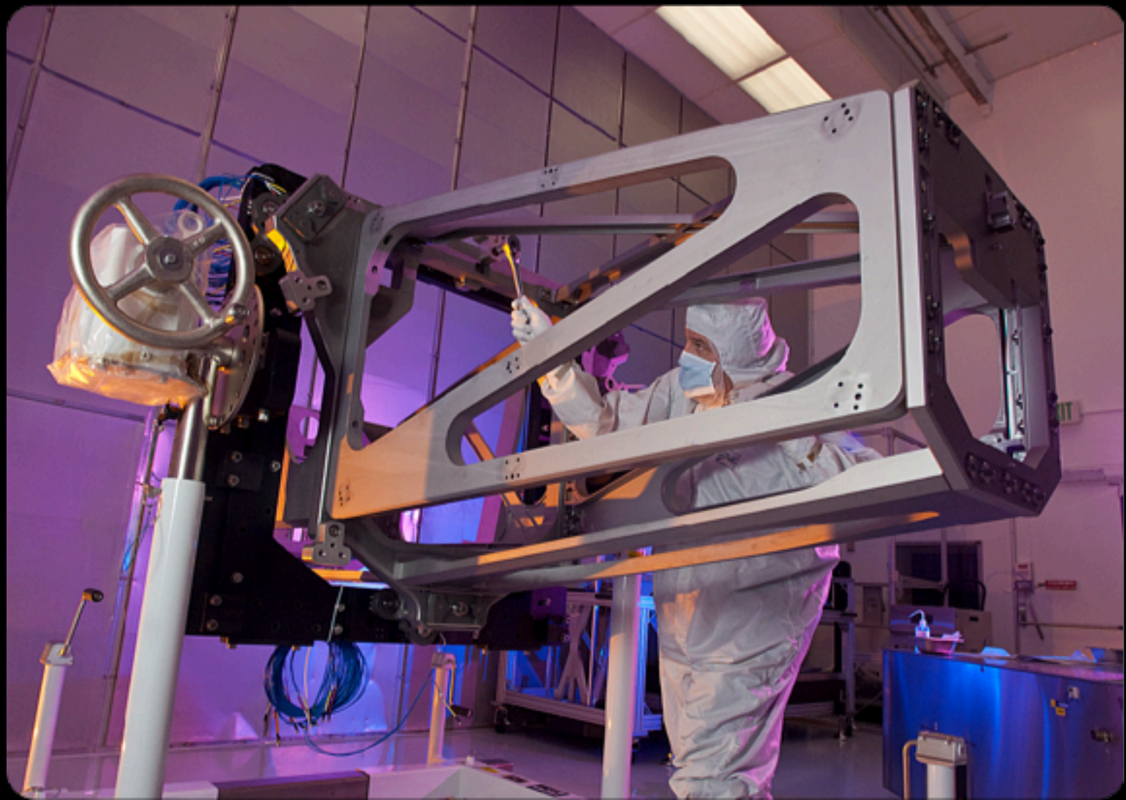




JWST Telescope Aft Optics

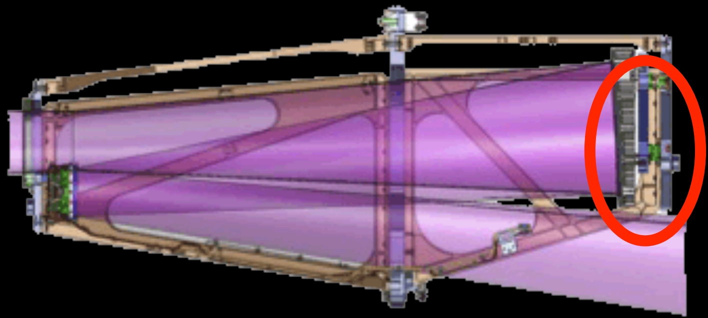




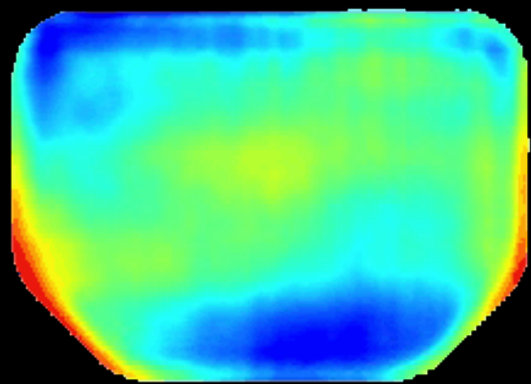


- Aft optics and Aft optics bench complete

JWST Telescope Optics

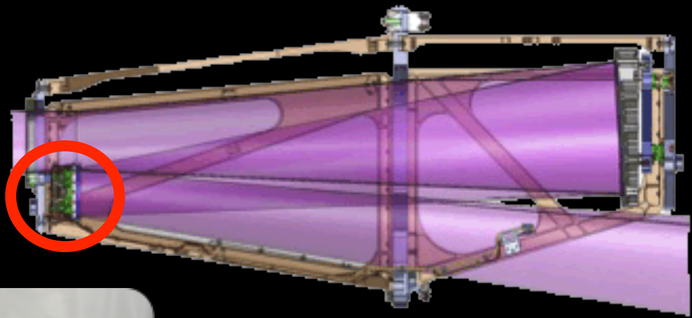


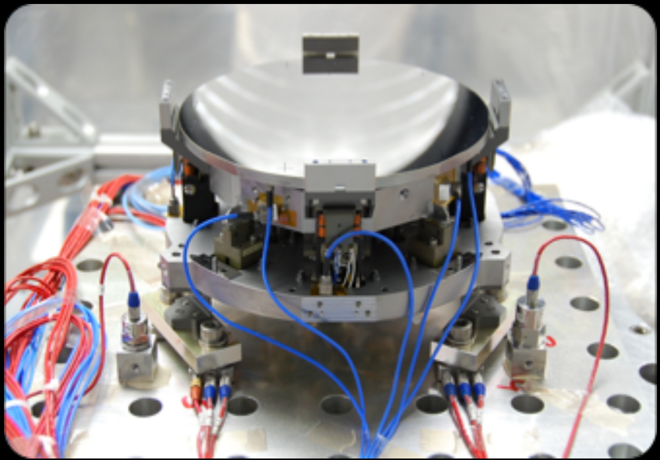
Tertiary Mirror

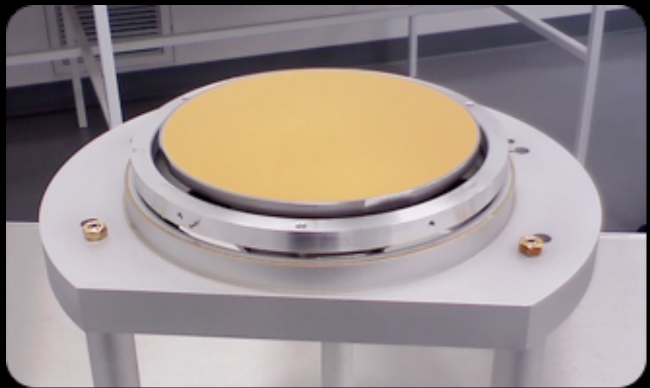


58 nm RMS
(-Tilt, -Power)

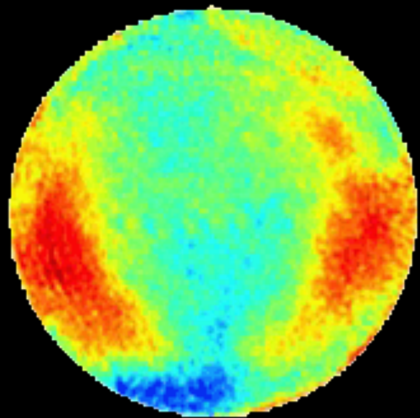
JWST Telescope Optics





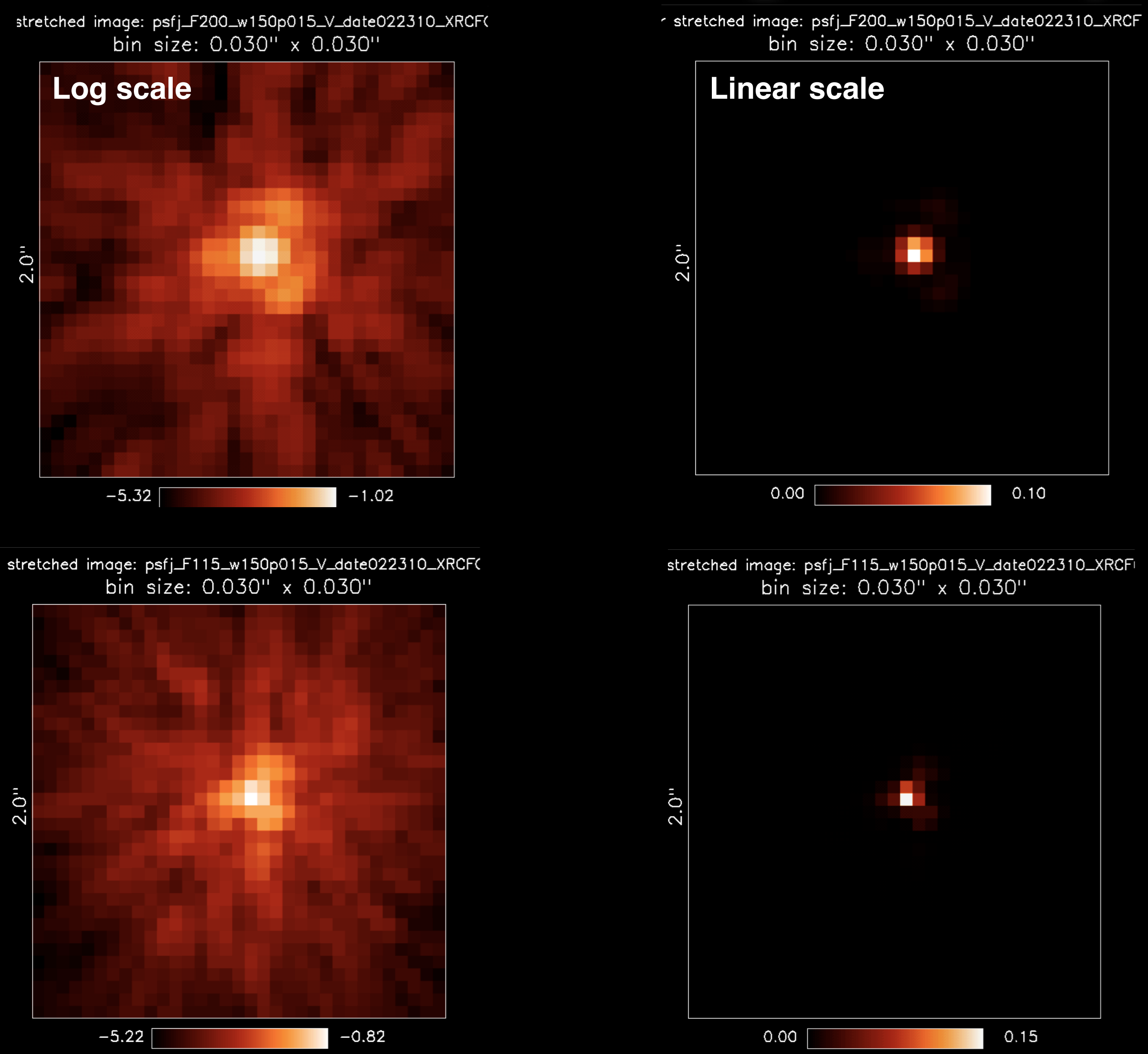


Fine Steering Mirror



2.3 nm RMS

Predicted Image Quality



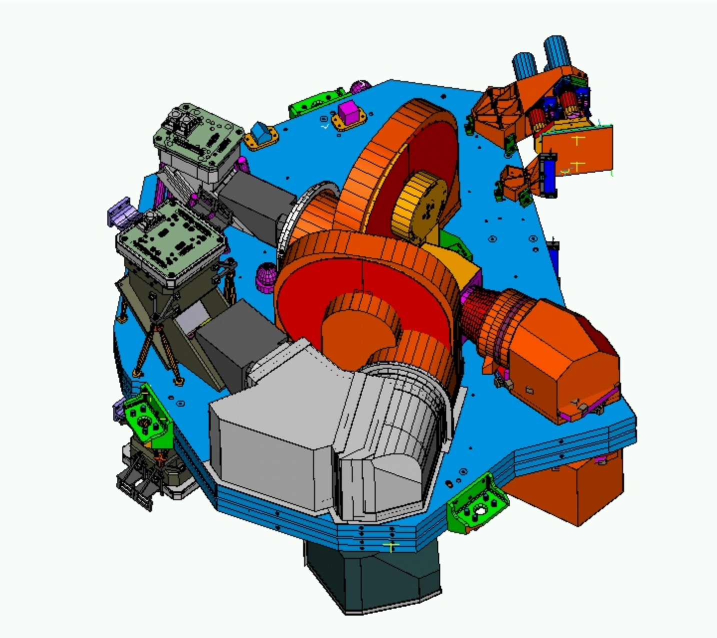
2 µm

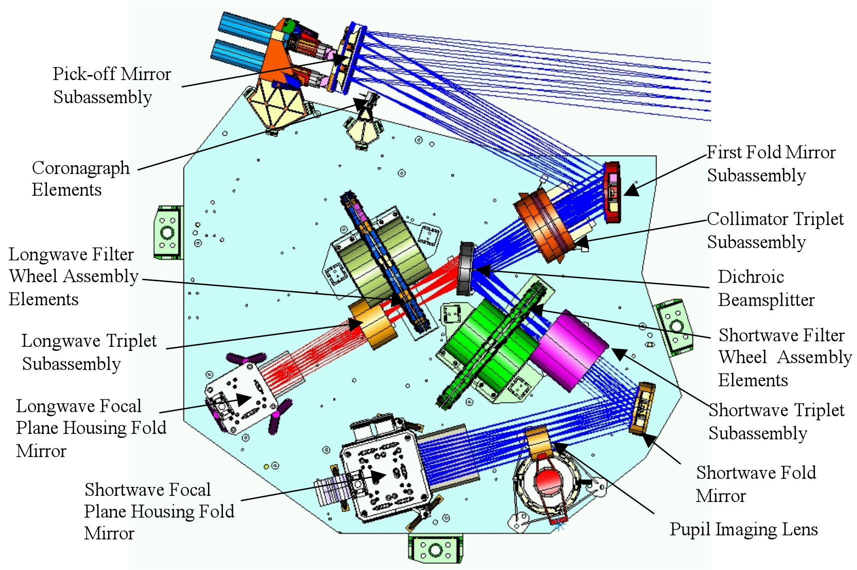
2.0" x 2.0"

1 µm

2.0" x 2.0"

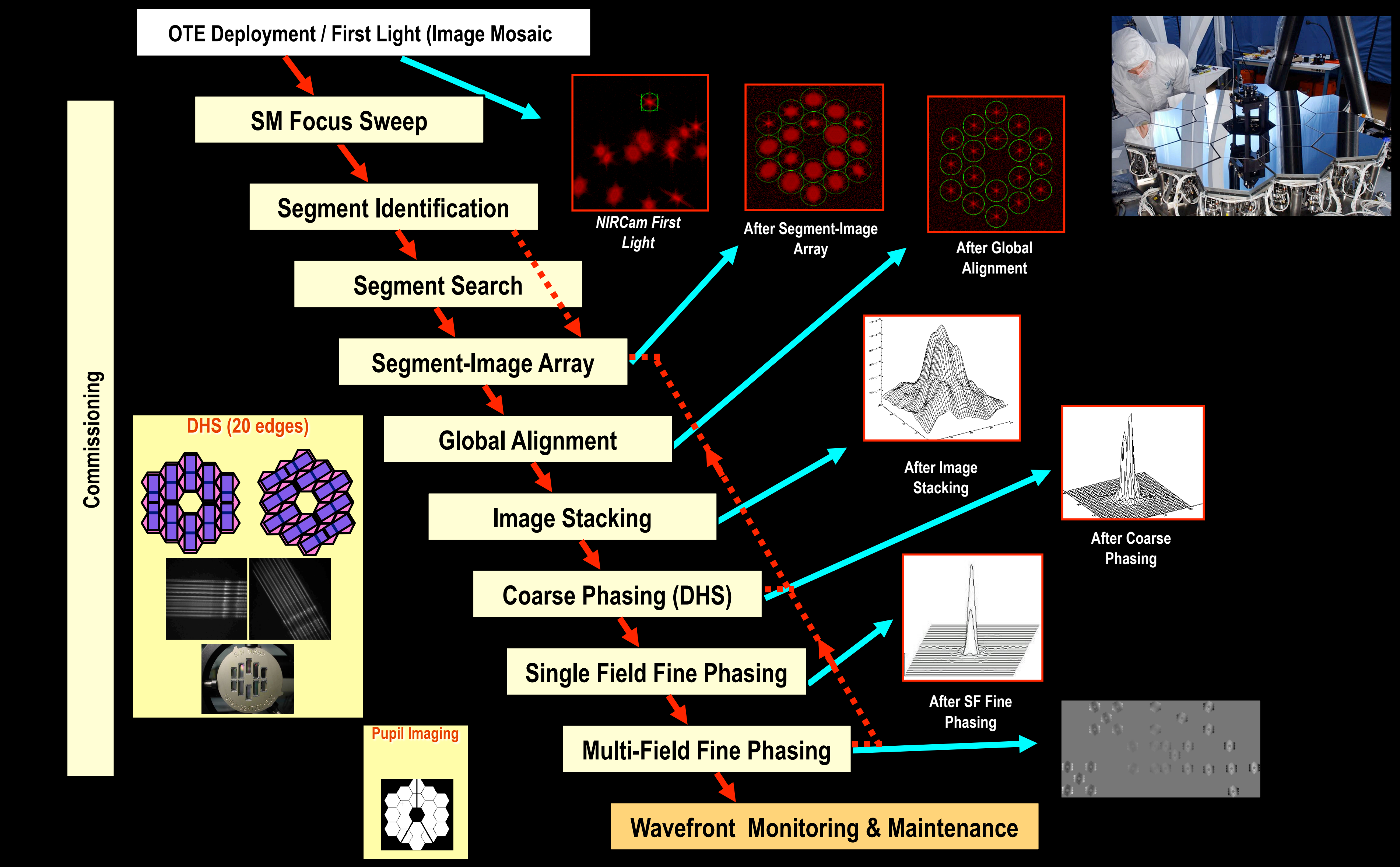
The NIRCam instrument will image large portions of the sky identifying primeval galaxy targets for the other instruments



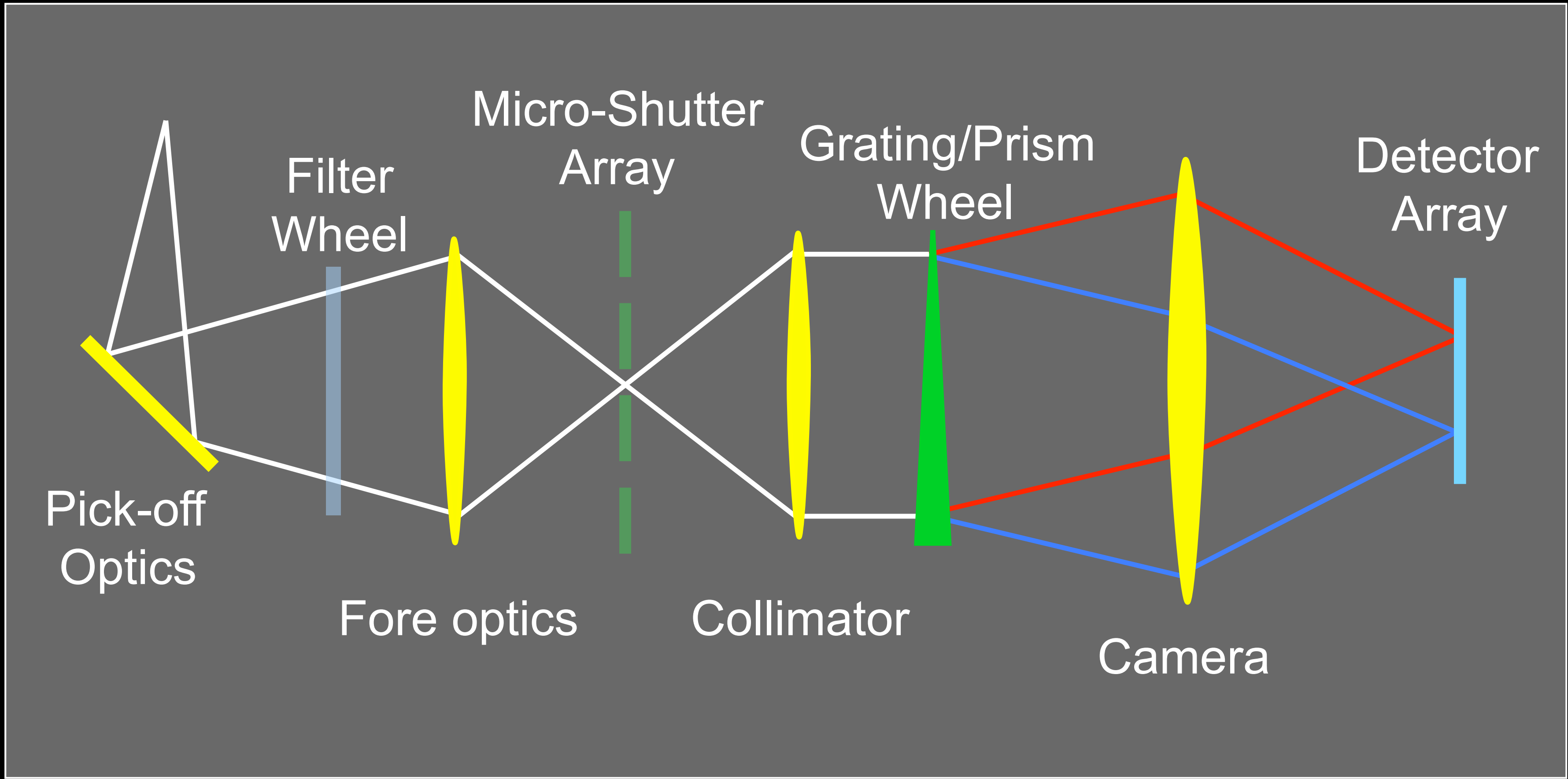


- Developed by the University of Arizona with Lockheed Martin ATC
  - Operating wavelength: 0.6 – 5.0 microns
  - Spectral resolution: 4, 10, 100
  - Field of view: 2.2 x 4.4 arc minutes
  - Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
  - Detector type: HgCdTe, 2048 x 2048 pixel format, 10 detectors, 40 K passive cooling
  - Refractive optics, Beryllium structure
  - Simple coronagraph with choice of Lyot masks in wheel
- Supports OTE wavefront sensing

Wavefront Sensing and Control Setup Sequence

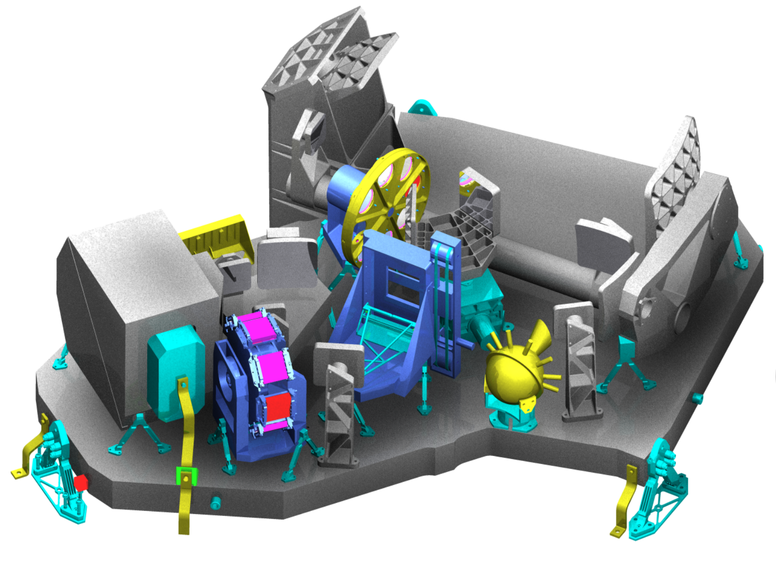


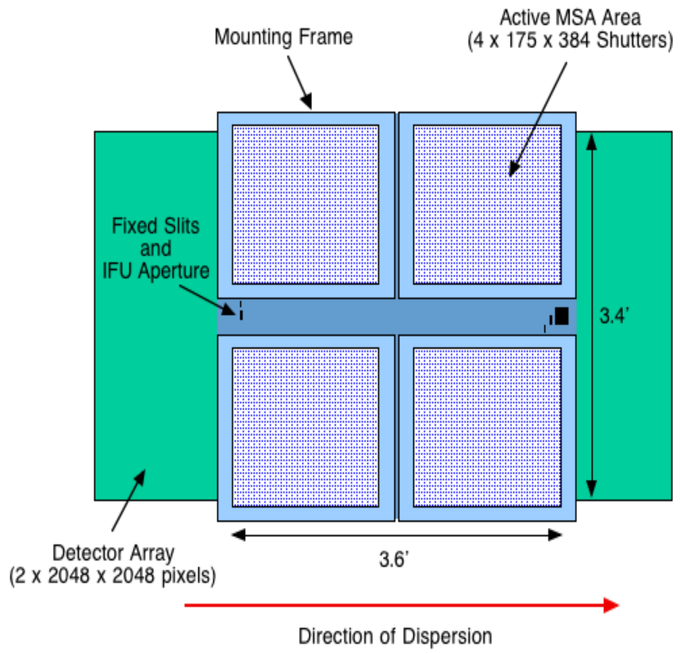
NIRSpec Schematic
0.6-5.0 μm, R = 100, 1000, 3000



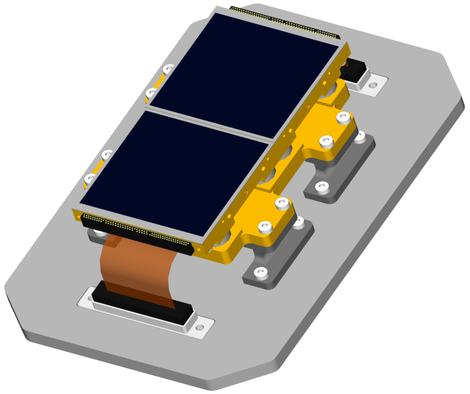
NIRSpec: ESA & Astrium

- > 100 Objects Simultaneously
- 10 square arcminute FOV

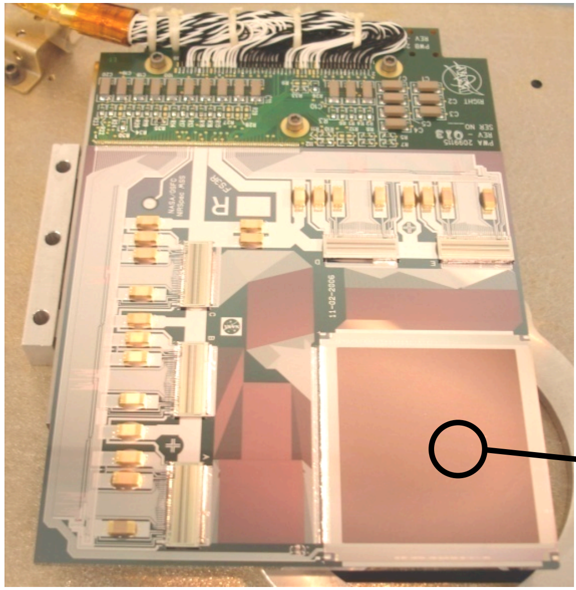


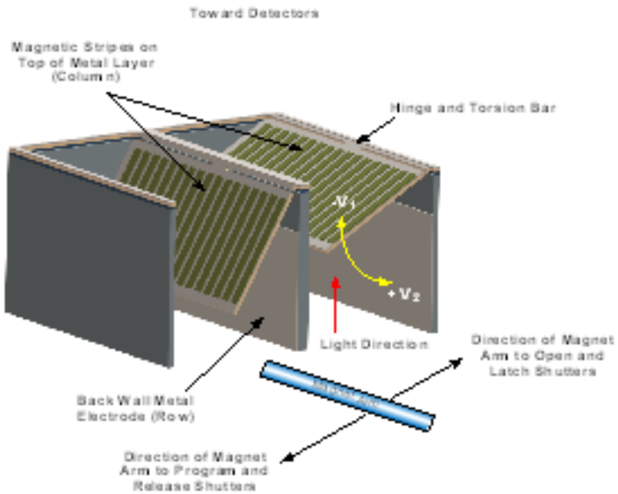


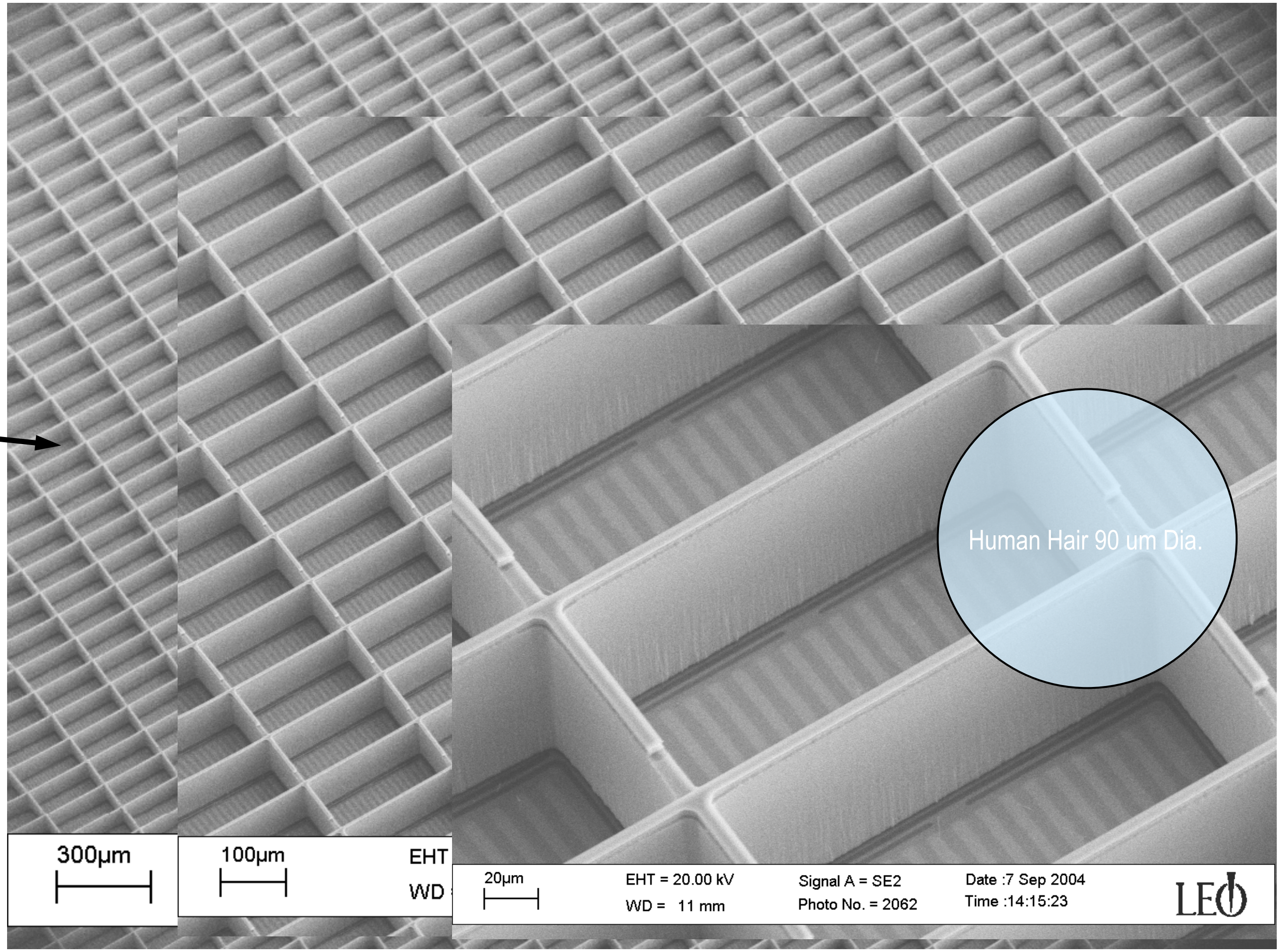
- **Implementation:**
  - 3.4' Large FOV Imaging Spectrograph
  - 4 x 175 x 384 element Micro-Shutter Array
    - 250,000 pixels, 203 x 463 mas, pitch 267 x 528 mas
  - 2 x 2k x 2k HgCdTe Detector Arrays
  - Fixed slits and IFU for backup, contrast
  - SiC optical bench & optics



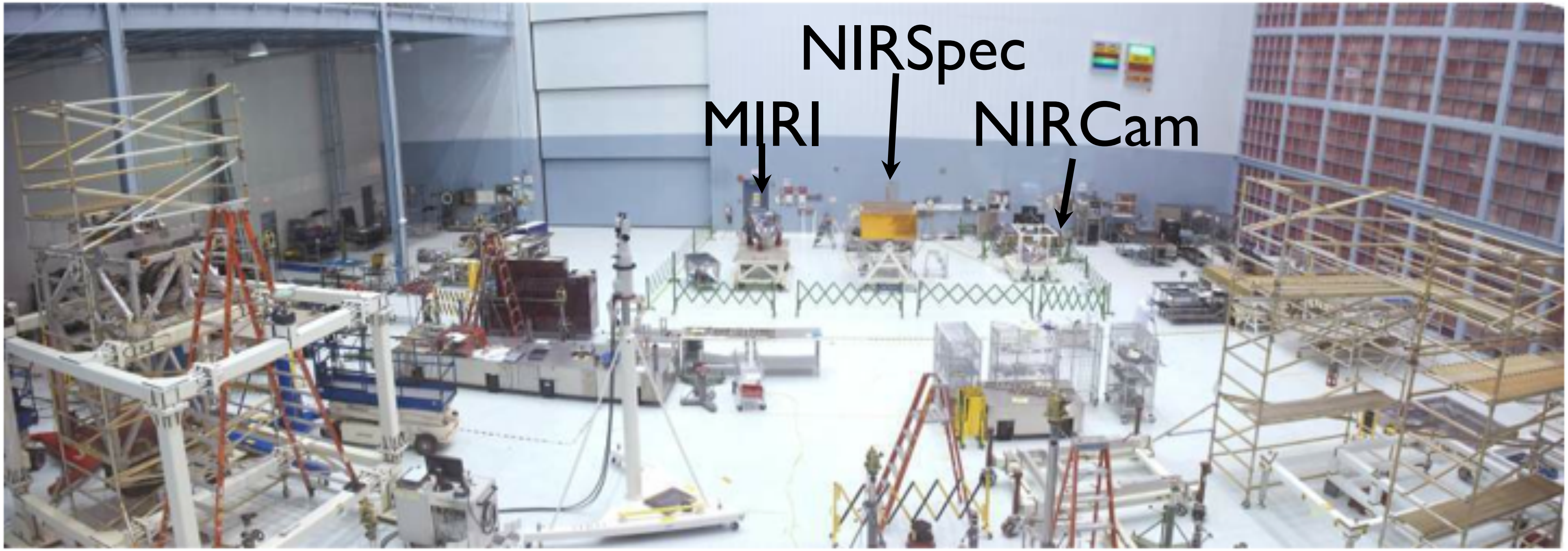
250,000 pixel cryogenic microshutter array system







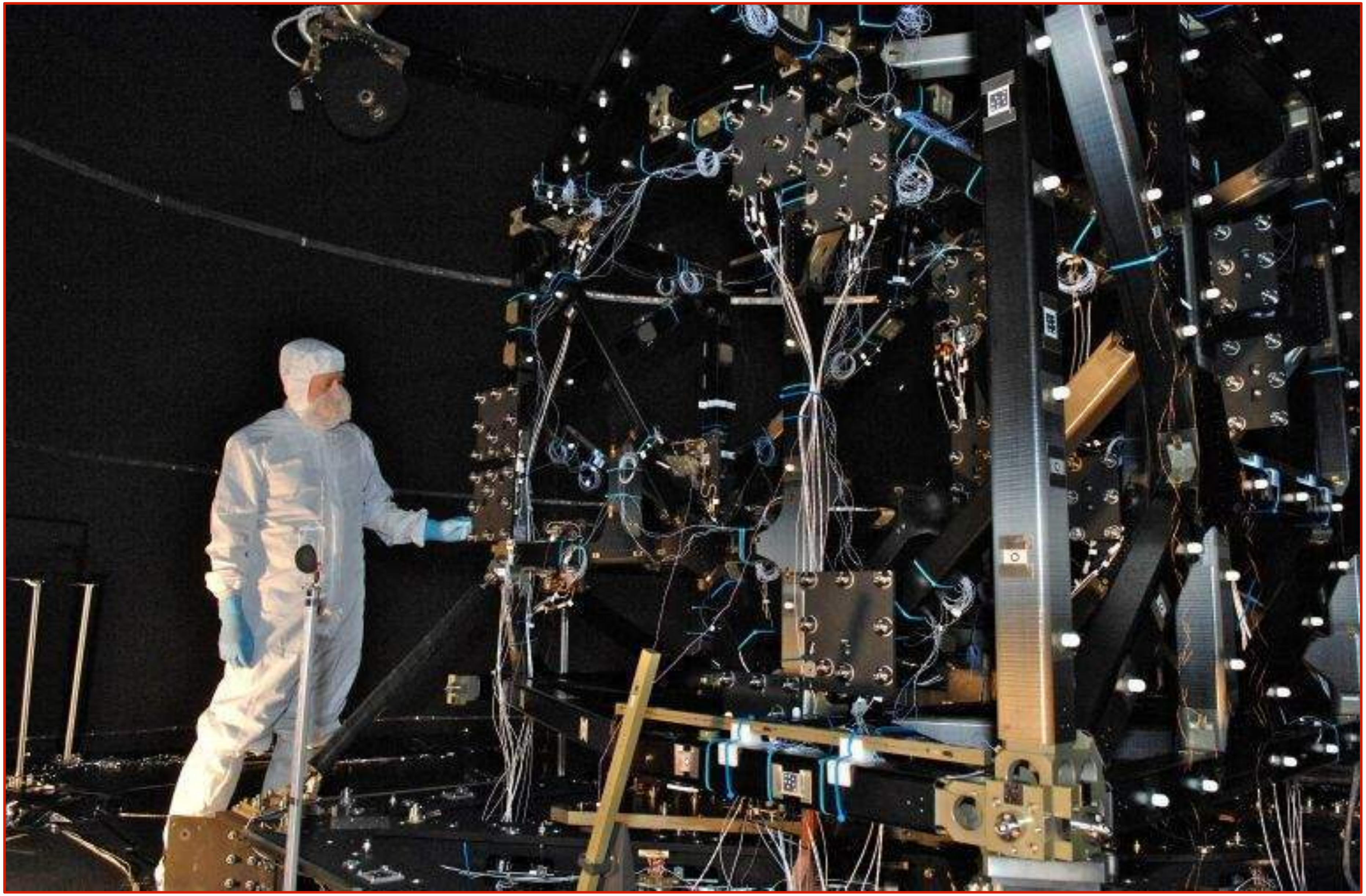
Engineering Test Units Instruments at GSFC



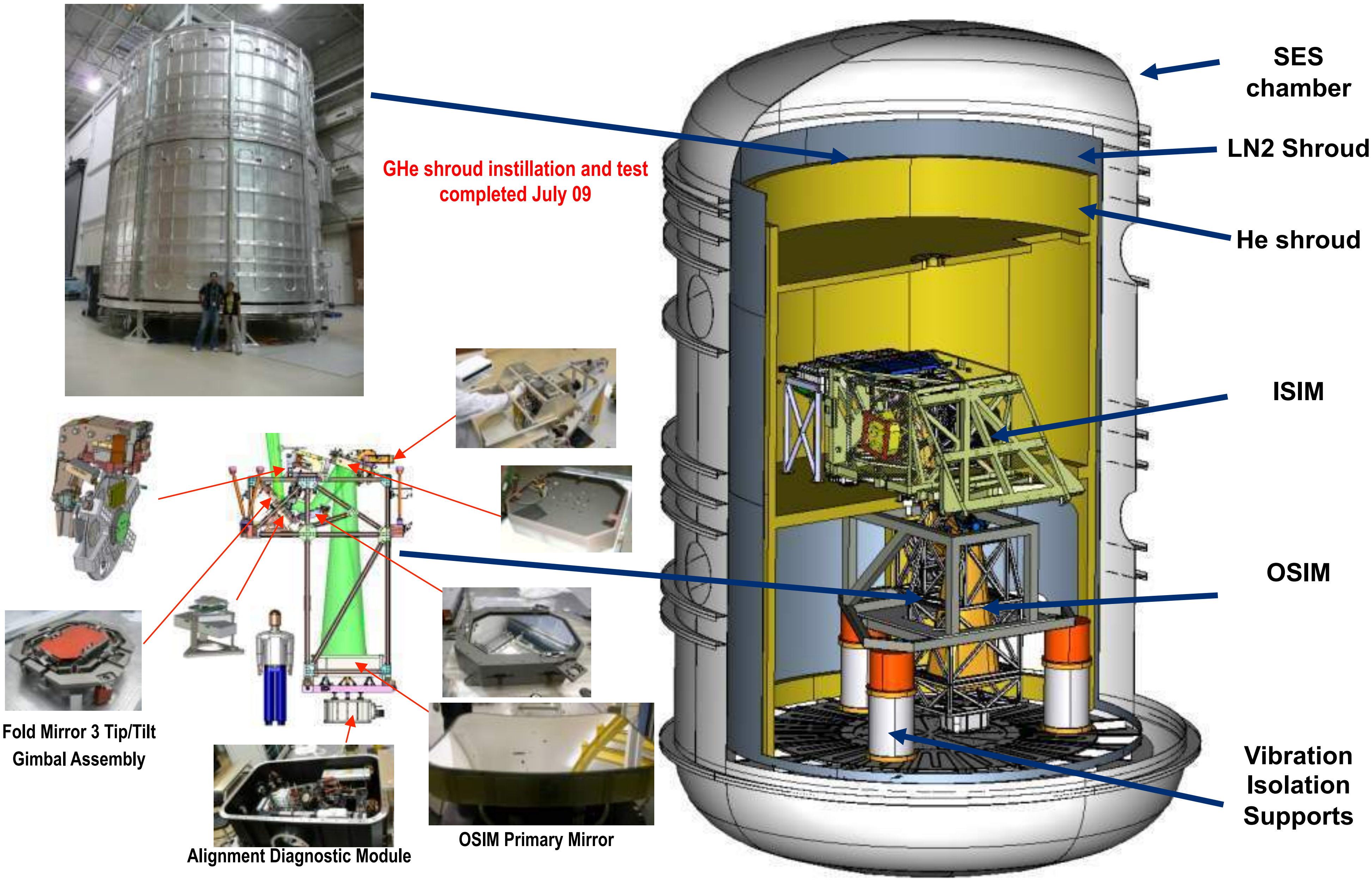
OSIM

http://www.jwst.nasa.gov/webcam.html

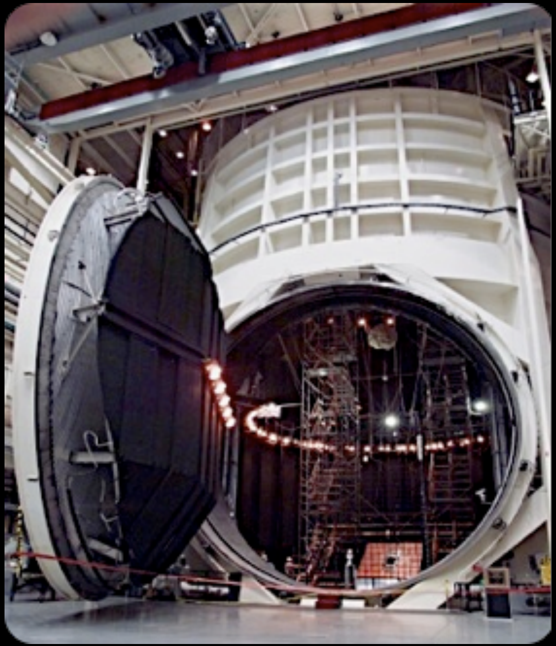
ISIM Structure Cryoset Test



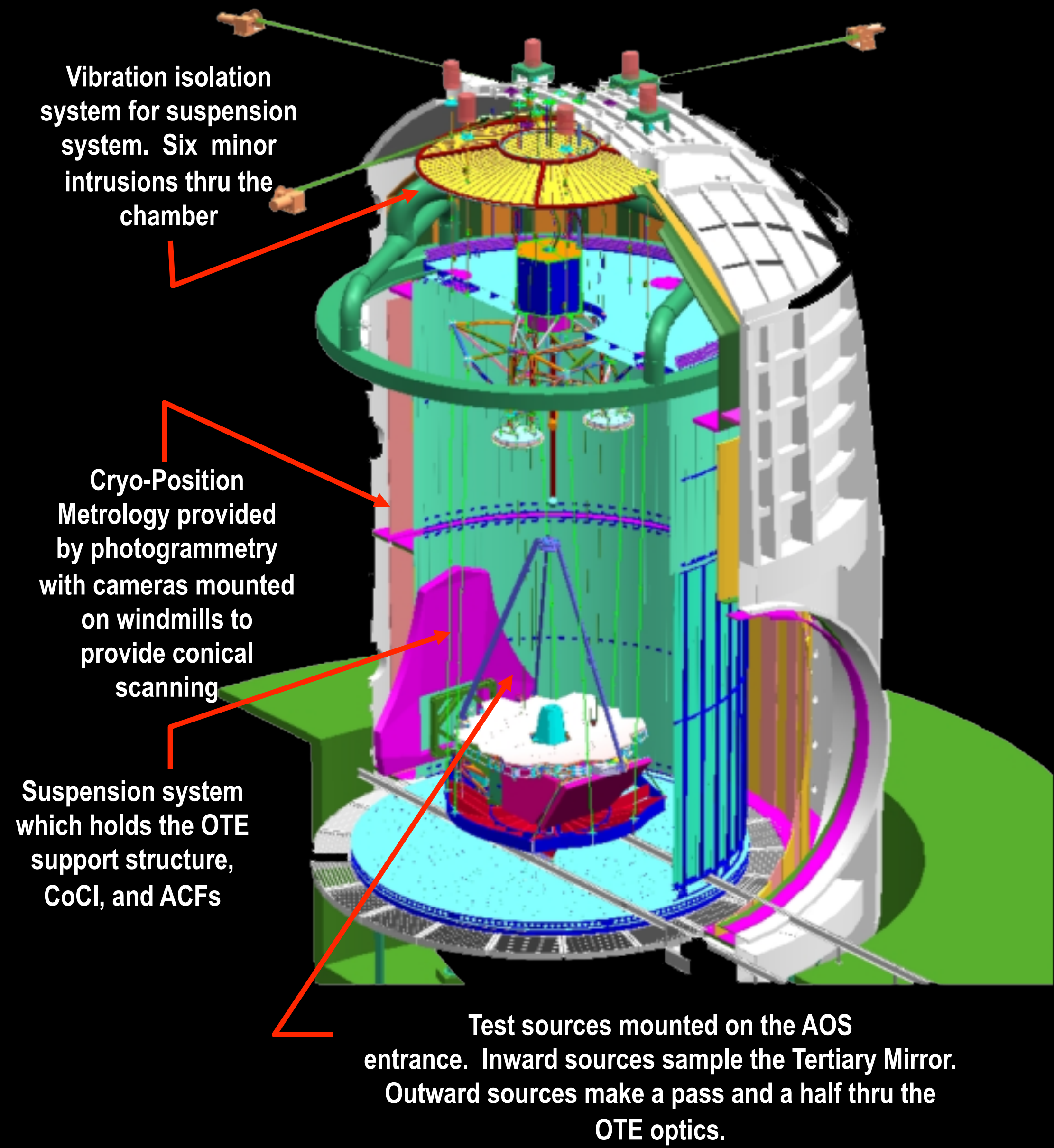
ISIM Test Configuration



Optical End-to-End Test @ JSC



- Goals of Test
  - ➡ Verify Optical alignment
  - ➡ Verify workmanship
  - ➡ Thermal balance

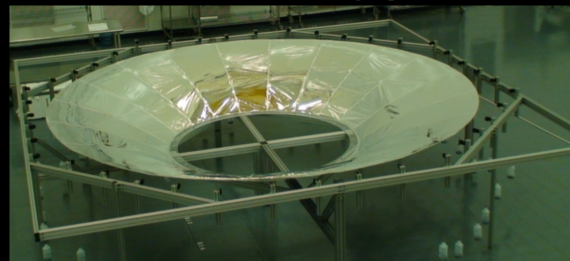


Sunshield Development

- JWST's sunshield is the key element that allows passive cooling to 40K
- The size of a tennis court, the five-layer sunshield is deployed after launch
- Key sunshield technical challenges have been addressed using pathfinders

Membrane folding strategy
Membrane covers

Packaging for launch



Membrane shape

Deployment

Membrane Deployment

- NGAS have developed a managed approach to sunshield deployment
- Full scale models validate deployment approach, membrane folding and deployment boom performance

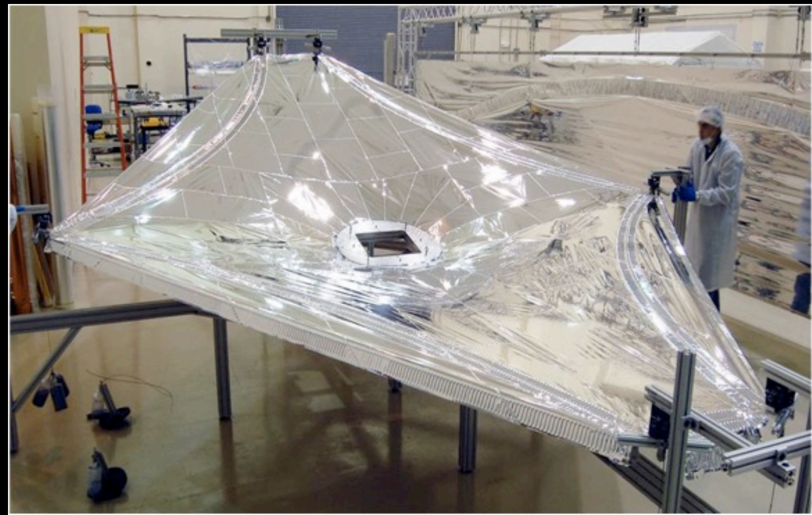
Folded membrane

Deploying membrane

Mid-Boom

Backplane/Sunshield Mockup

• Sunshield systems testing



• 1/3rd scale Sunshield thermal performance test

Spacecraft Bus Engineering Model Hardware

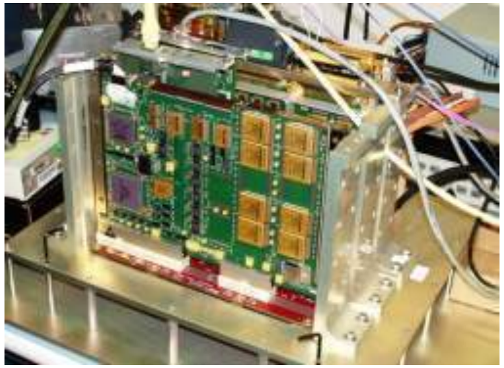
- **Successfully Completed Spacecraft Preliminary Design Review (PDR) in 2009**
- **Successfully completed & delivered SC Sim 1A**
- **Spacecraft Critical Design Audit: June 2012**

Completed HGA STM

CTP in Lab testing FSW Release 1.x

SC Sim 1A upgrade

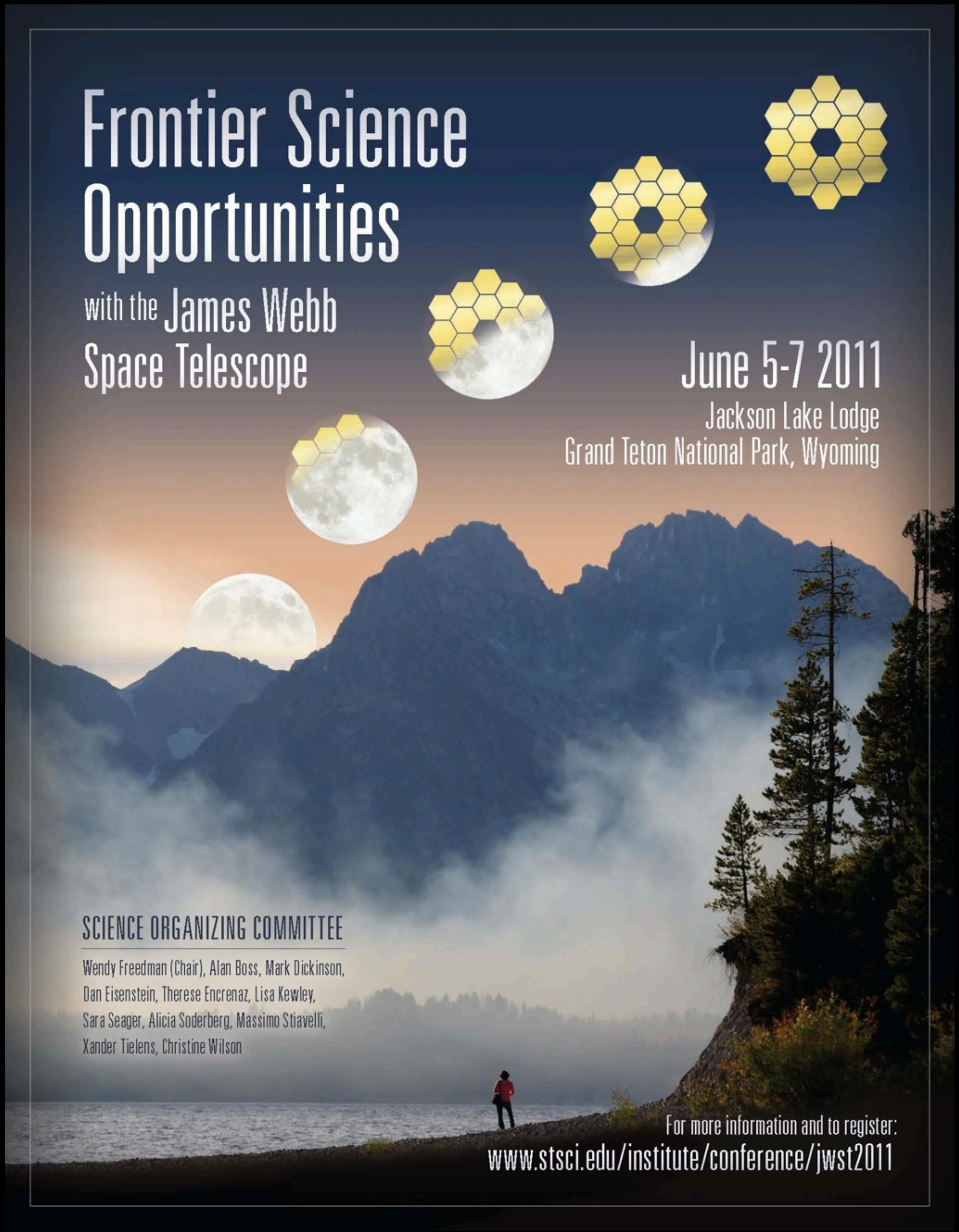
Transponder Transmitter Slice (in progress)



Software Development Lab CTP EM

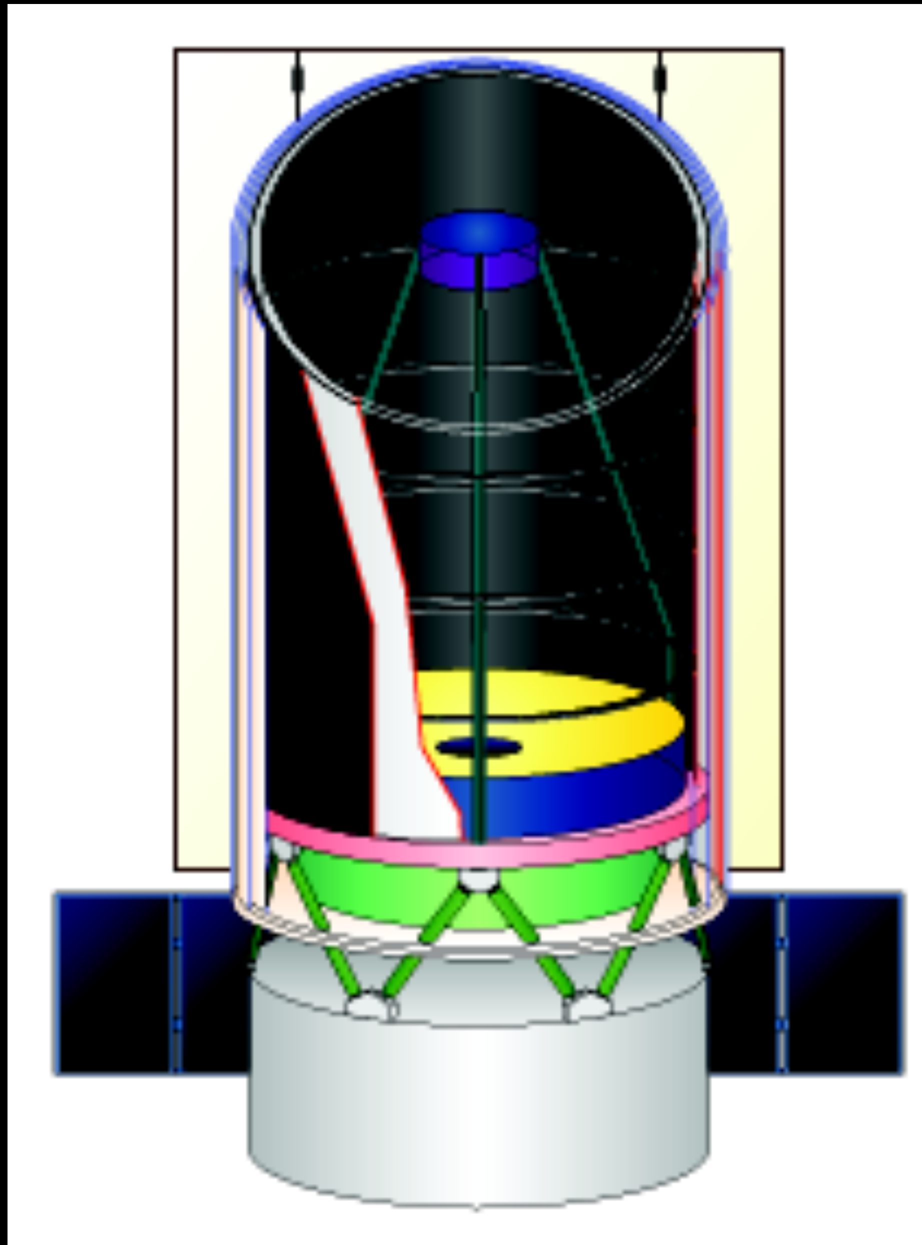
JWST Flight SCAT at Test Site

Transponder Receiver Slice

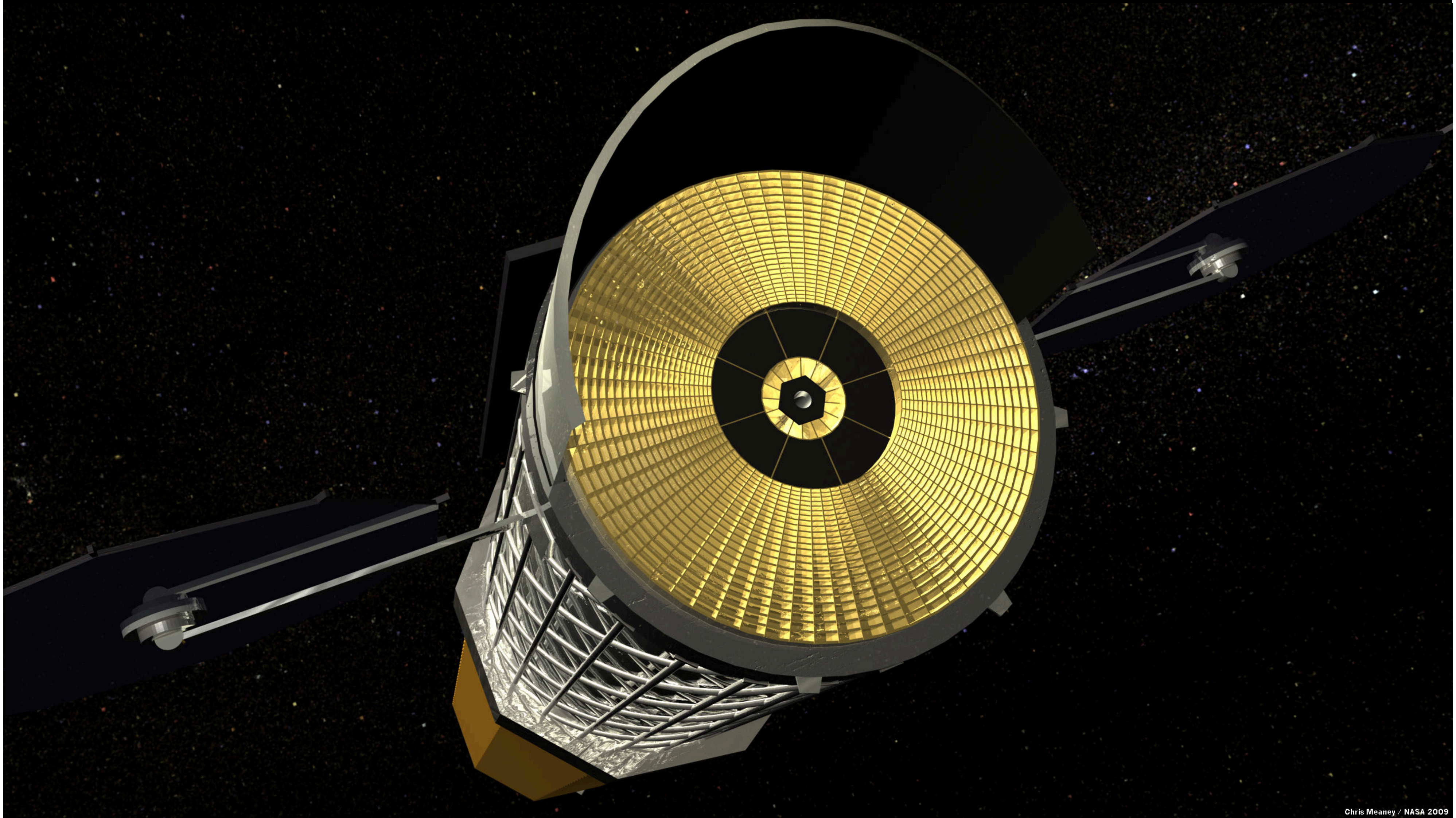

Frontier Science Opportunities
with the James Webb Space Telescope
June 5-7 2011
Jackson Lake Lodge
Grand Teton National Park, Wyoming
SCIENCE ORGANIZING COMMITTEE
Wendy Freedman (Chair), Alan Boss, Mark Dickinson,
Dan Eisenstein, Therese Encrenaz, Lisa Kewley,
Sara Seager, Alicia Soderberg, Massimo Stiavelli,
Xander Tielens, Christine Wilson
For more information and to register:
www.stsci.edu/institute/conference/jwst2011

SPICA

- Japanese 3.5 m 4.5 K actively cooled telescope, launched on H-II rocket to L_2
- Cooling design mature
- 5-200 μm with cameras and spectrometers
- Seeking international partnership



Con-X + XEUS → IXO



Advanced Technology Large Space Telescope

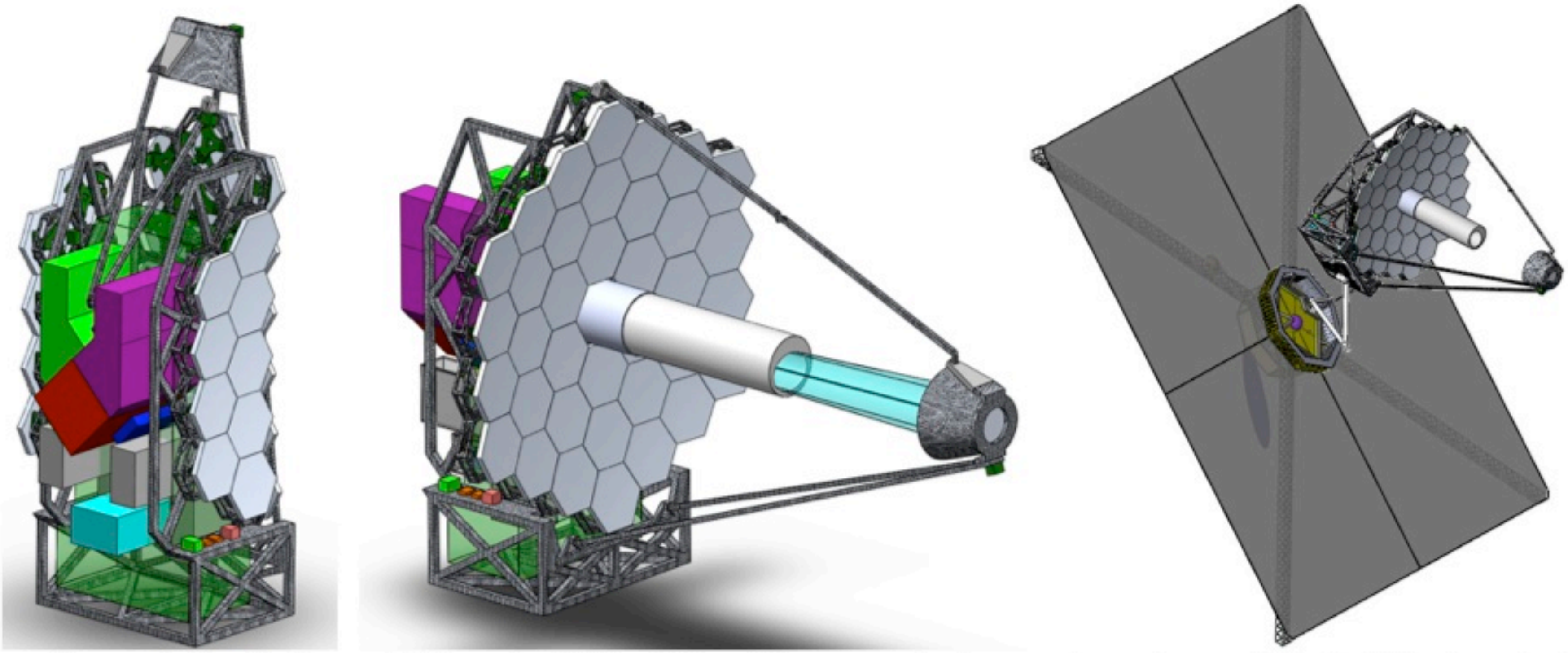
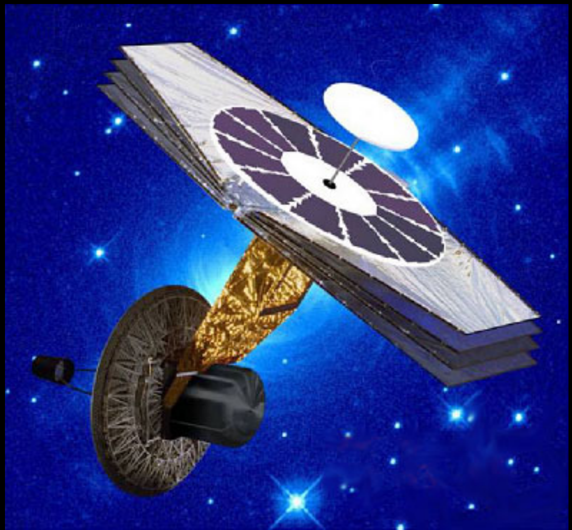
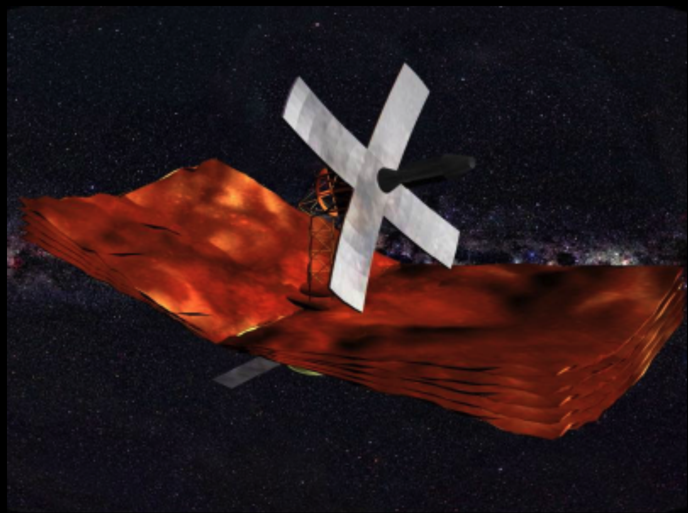


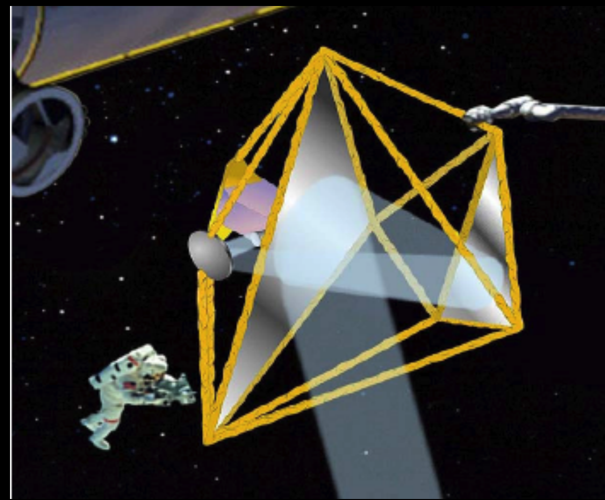
Figure 6: (Left) Stowed 9.2-meter OTA. Colored boxes are instrument envelopes. (Center) Deployed. (Right) Sunshield and arm-mounted OTA. Spacecraft bus is on sun side of sunshield.

Single Aperture Far IR Telescope

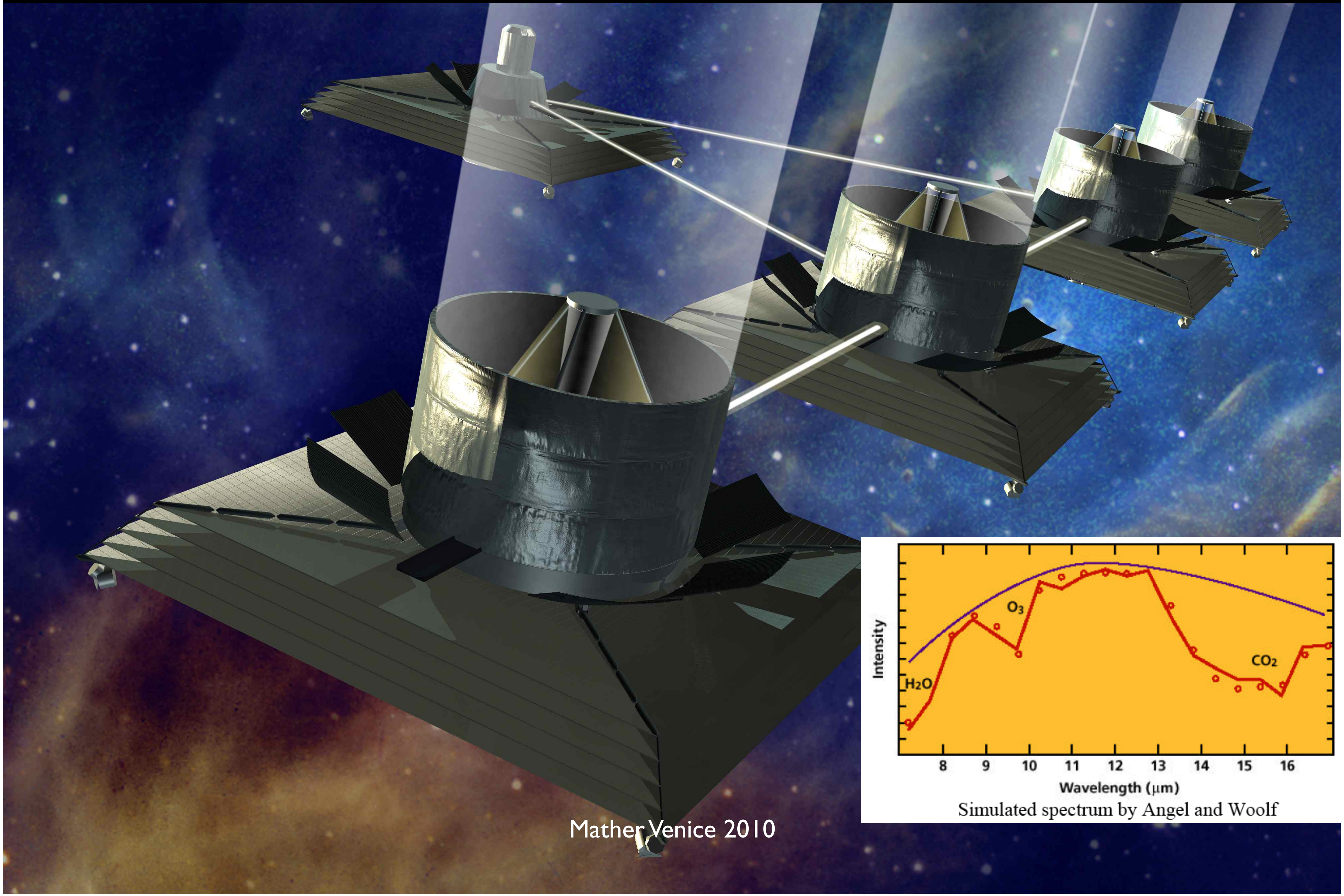
- 20 - 500 microns wavelength, cooled to ~ 4 K, operating at L2, 8 - 10 m aperture







TPF-Interferometer

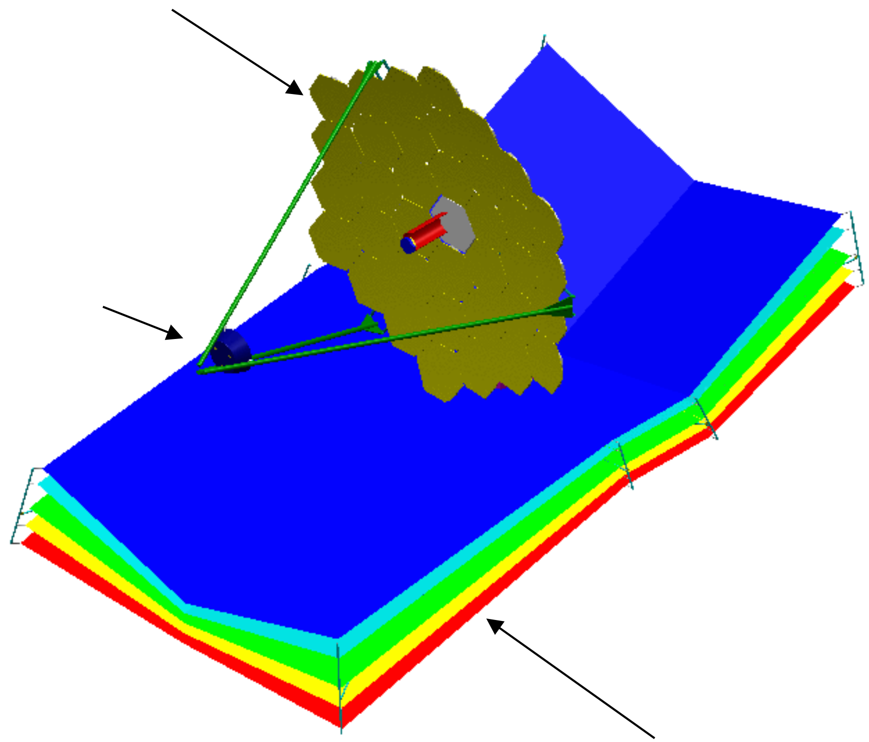


Simulated spectrum by Angel and Woolf

IR Coronagraph Design Concept

TRW

- 28-meter filled aperture telescope
  - Three-mirror anastigmat
  - 36 segments, 4-meter flat-flat
  - Composite replica optics
  - Gold mirror coatings
- Multi-layer sunshade
  - Passive cooling to ~30K
- IR Coronagraph for planetary detection/ characterization
  - 10^7 contrast at 100 mas
- IR camera and spectrograph for general imaging/spectroscopy
  - 2 x 2 arcmin FOV
- Launched with EELV heavy to L2
  - On-orbit assembly option



Why astronomy doesn’t pay for everything

Summary

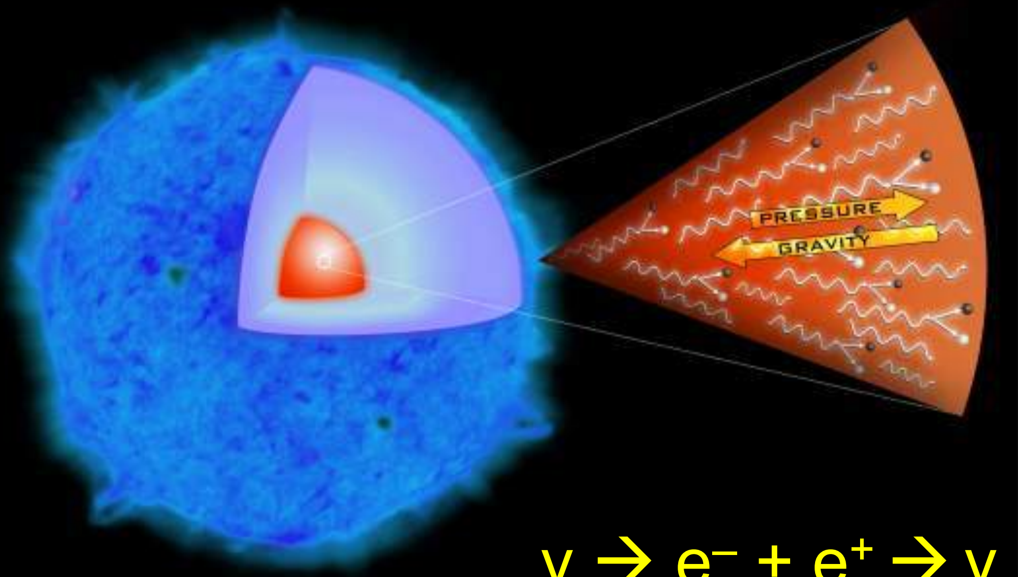
- JWST is making excellent technical progress

- JWST will be the dominant astronomical facility for a decade, and will undertake a broad range of investigations by the astronomical community

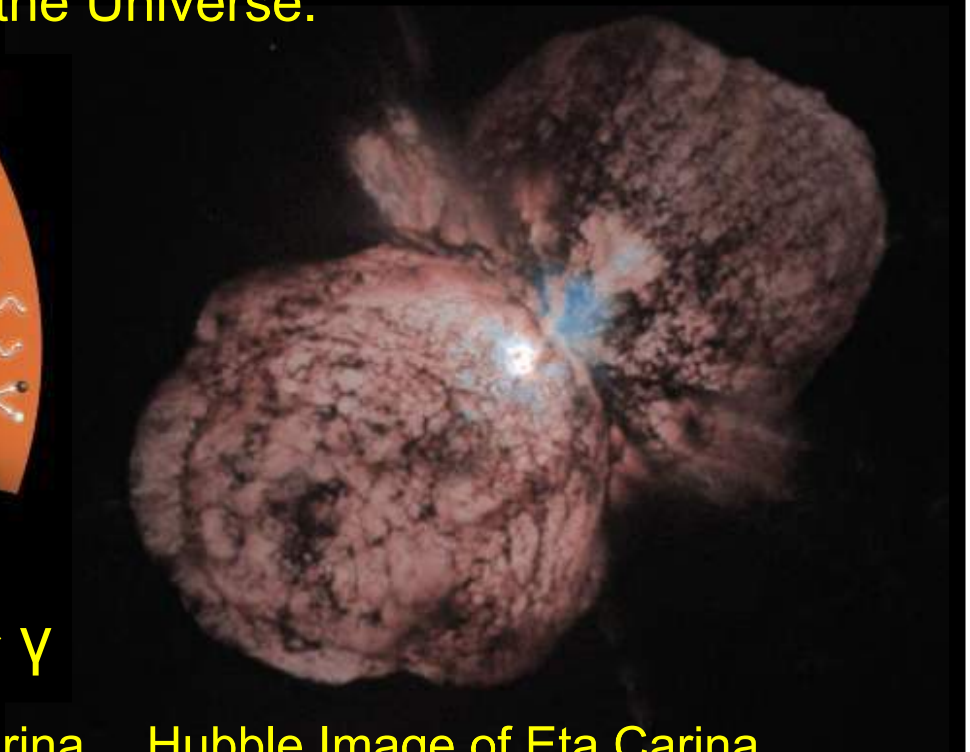
- JWST remains the brilliant advance recommended by the 2000 Decadal Survey
  - JWST science underpins the science recommended by the 2010 Decadal Survey
  - JWST has the capability to address new observing opportunities such as exoplanet characterization......

SN 2006 gy – brightest supernova

- Could be the first observation of a pair-production instability, from the death of a very massive star.
  - Stars are normally held up by the balance of light pressure and gravity
  - Gamma rays producing electron/positron pairs scatters light, reducing pressure. Instability creates runaway collapse.
- A nearby analog for the first stars in the Universe.



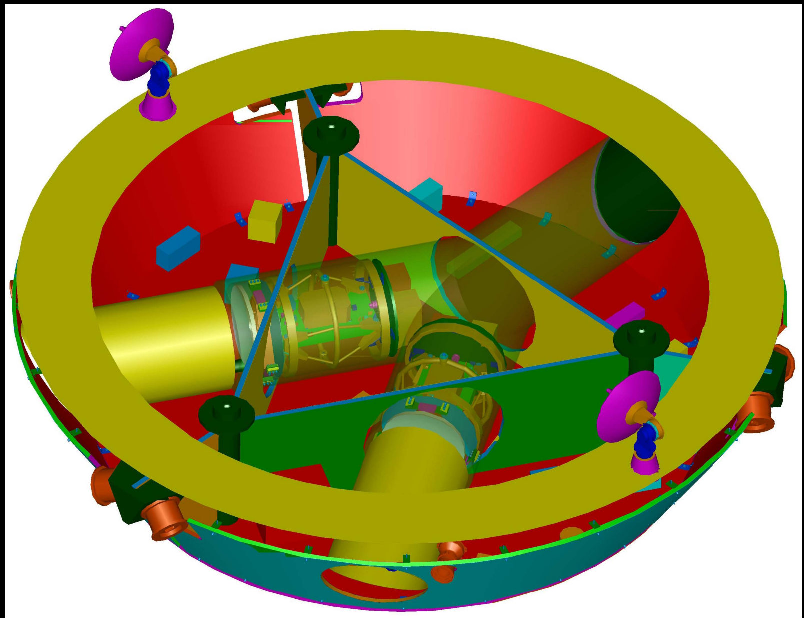
$$\gamma \rightarrow e^{-} + e^{+} \rightarrow \gamma$$



- Progenitor was similar to Eta Carina.

Hubble Image of Eta Carina

The Laser Interferometer Space Antenna (LISA)



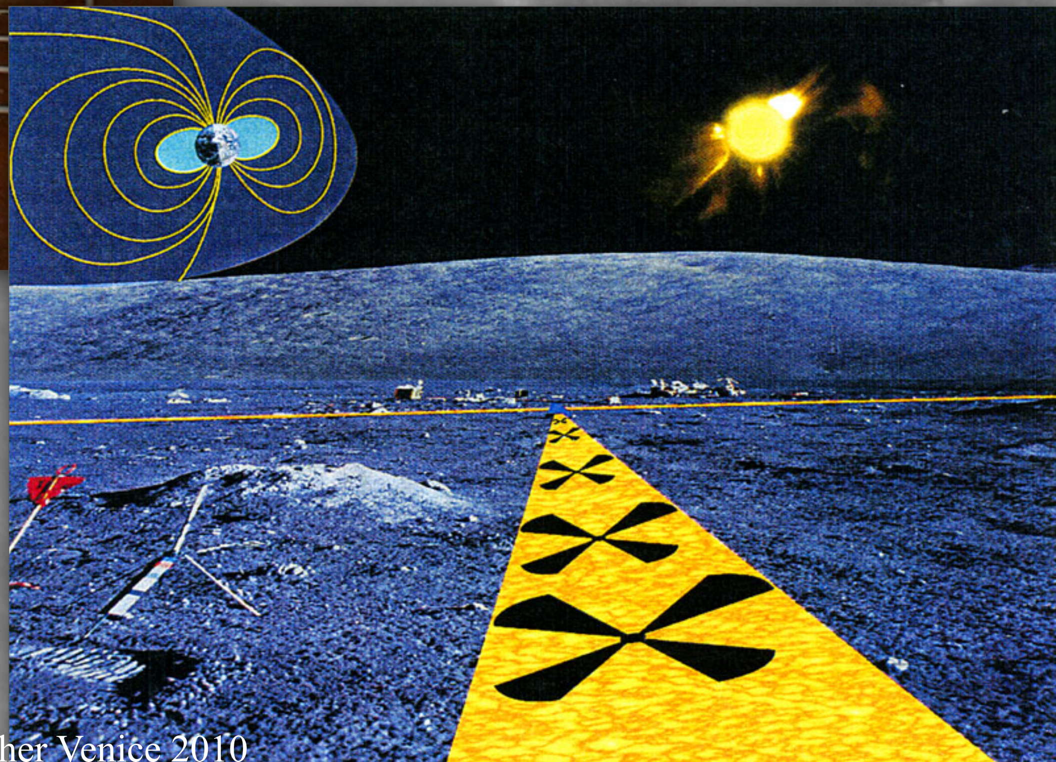
- New branch of astronomy!
- Space-based gravitational wave detector
- 3 spacecraft in 5,000,000 km equilateral triangle
- Laser interferometer senses changes of 1/100 size of an atom

Sensitivity & Resolution

- Cameras and R ~ 100 spectroscopy background limited at all wavelengths
  - 6.5 m mirror much larger than HST, Spitzer - big gains
  - Background dominated by zodi light, and at > 12 μm from thermal emission from sunshield
  - Other stray light from galaxy, sometimes Earth or Moon
- NIRSpec sensitivity detector limited at R ~ 1000
- Image quality
  - Diffraction limited (λ/14 rms wavefront) at 2 μm (better than ground AO in Strehl and much better Field of View)
  - 0.032 arcsec pixels in NIRCam short band (Nyquist @ 2 μm)
  - 0.065 arcsec in NIRCam long band and .068 in Fine Guider
  - 0.2 x 0.45 arcsec shutters for NIRSpec
  - 0.11 arcsec pixels for MIRI camera
  - 0.19 - 0.28 arcsec pixels for MIRI image slicer integral field unit

30 - 300 m Wavelength Radio Telescope on Far Side of Moon

Low frequency radio observations require only lightweight dipoles



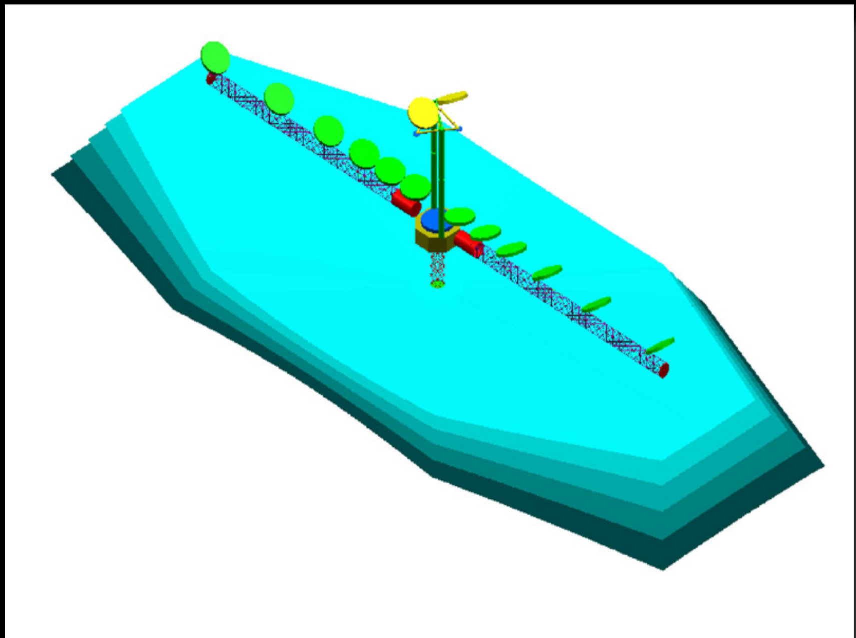
Ionosphere blocks access from Earth surface

Mather Venice 2010

SPIRIT and SPECS

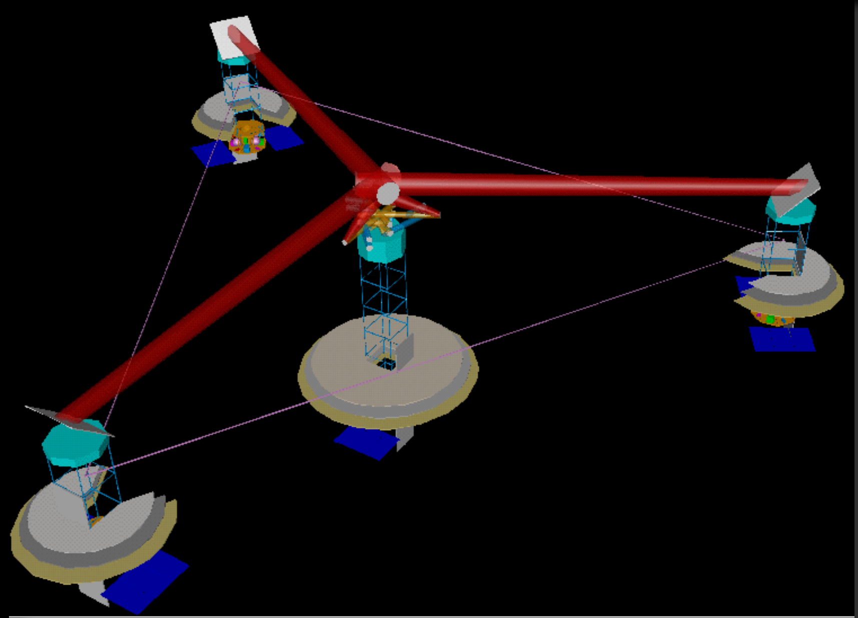
SPIRIT

Space Infrared Interferometric Telescope



SPECS

Submillimeter Probe of the Evolution of Cosmic Structure



SPIRIT - deployed boom linear array, rotating to fill (u,v) plane

SPECS - separated spacecraft array, with tethers for faster rotation

Where they are