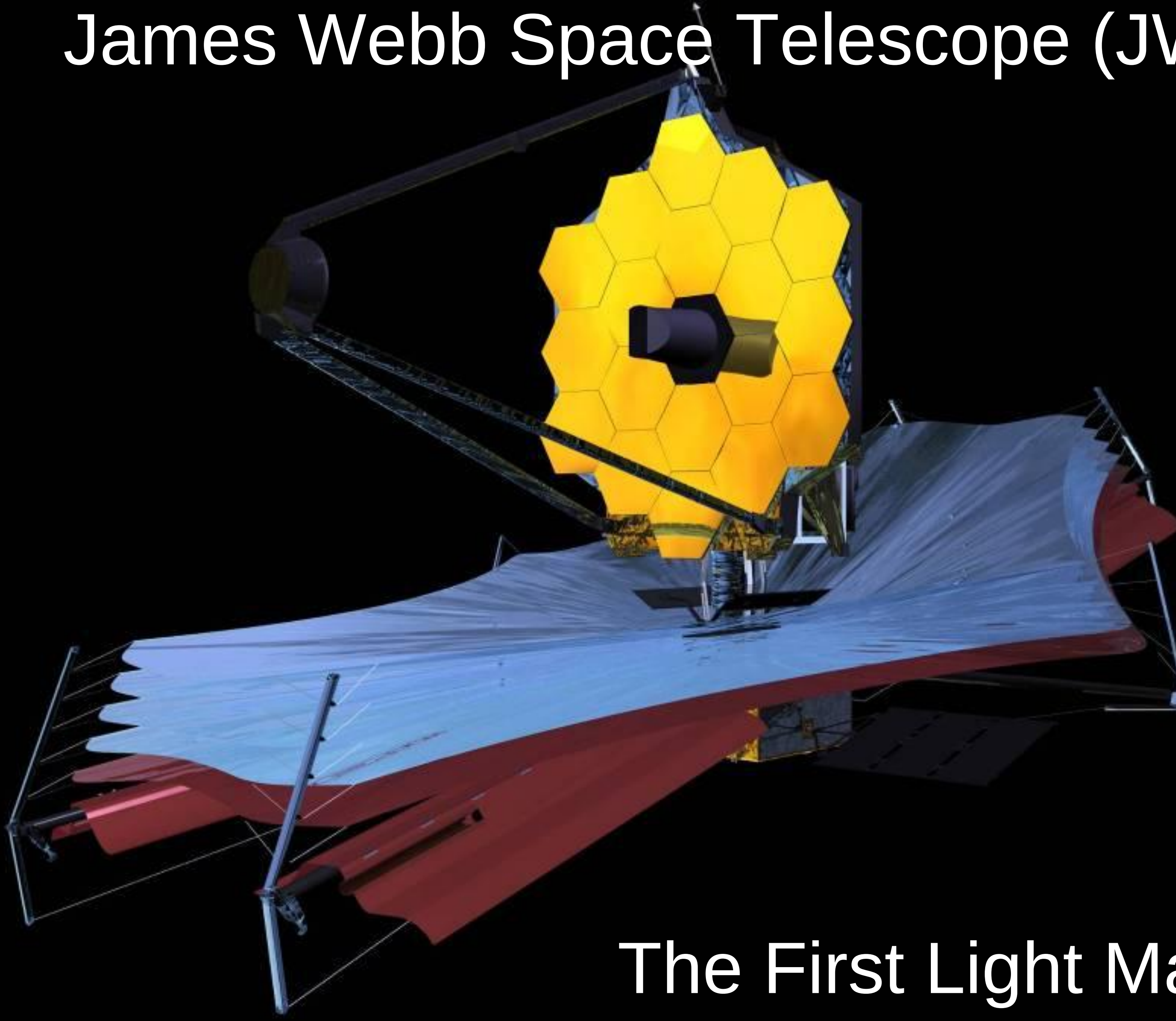
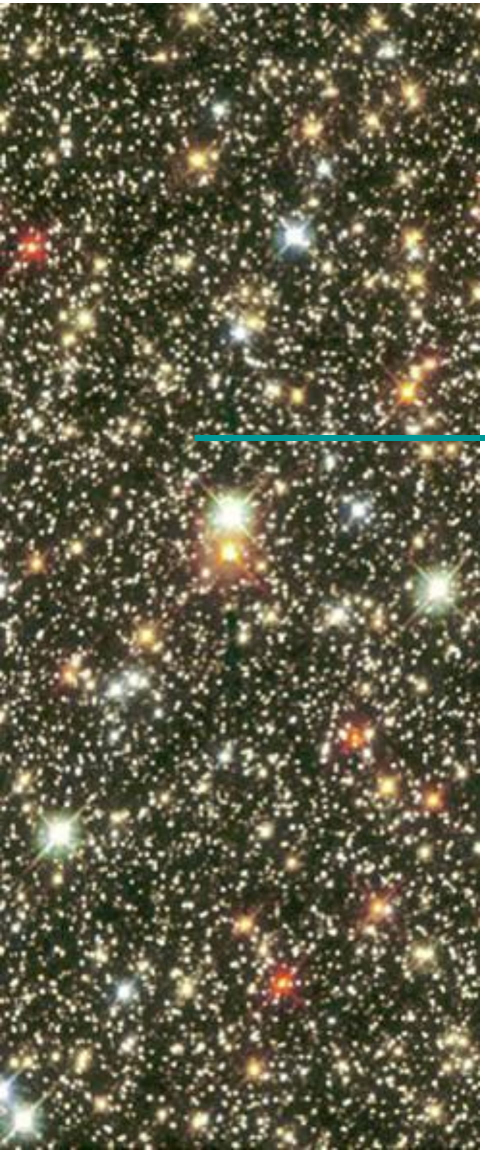
# James Webb Space Telescope (JWST)

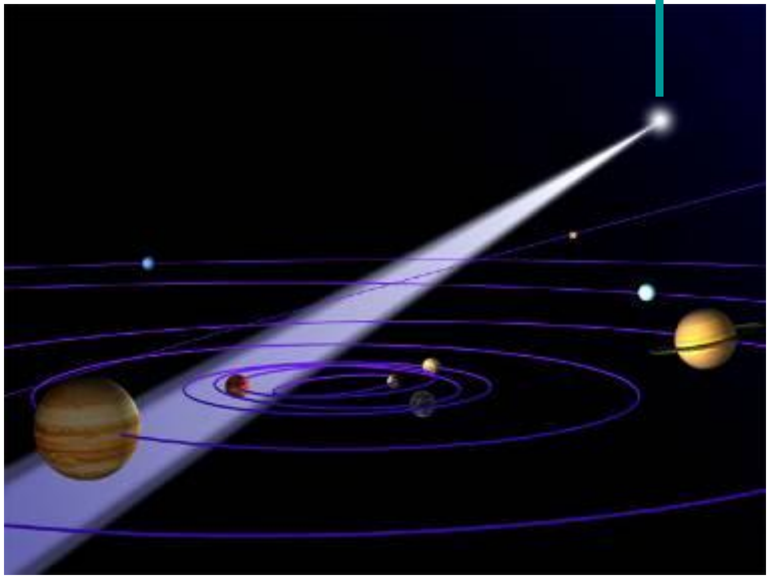


The First Light Machine

# Origins Theme's ***Two*** Fundamental Questions

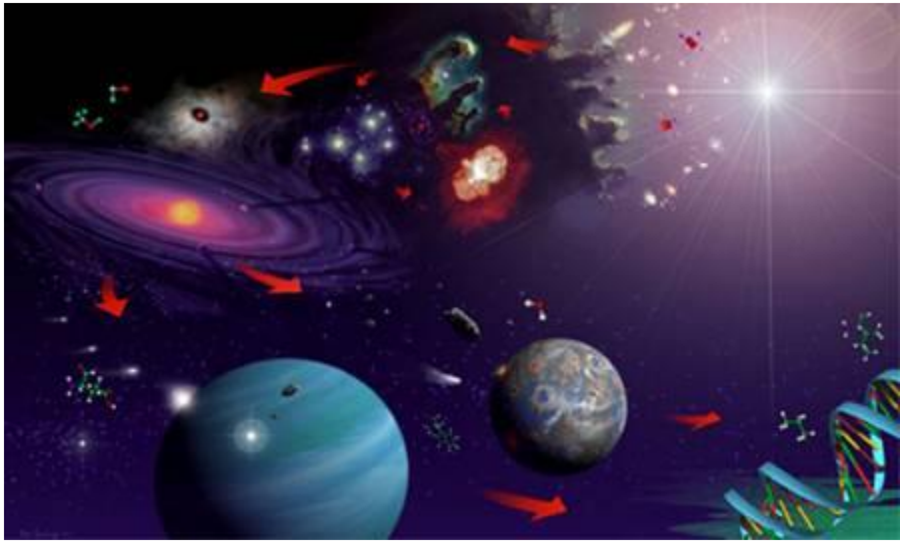


- How Did We Get Here?
- Are We Alone?



# How Did We Get Here?

***Trace Our Cosmic Roots***



Formation of galaxies

Formation of stars

Formation of heavy elements

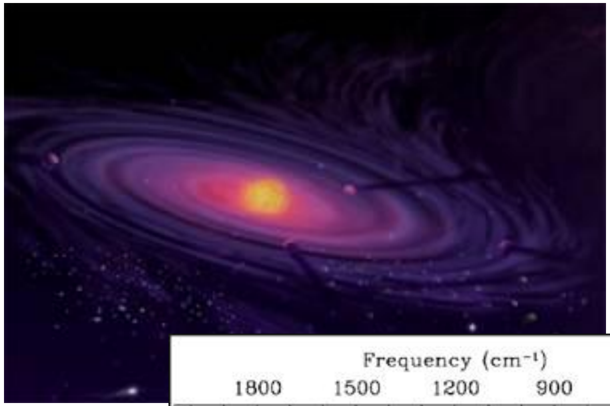
Formation of planetary systems

Formation of life on the early Earth

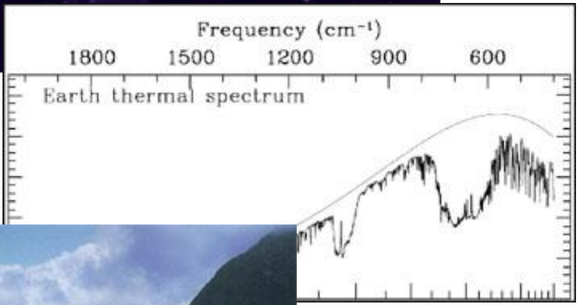
# Are We Alone?

## ***Search for life outside the solar system***

Search for other planetary systems



Search for habitable planets




Identify remotely detectable bio-signatures

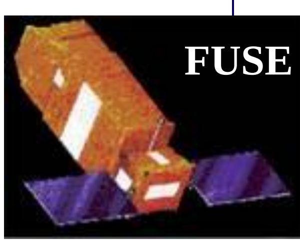
Search for “smoking guns” indicating biological activities

# Missions Supporting the Origins Goals

## ***How Did We Get Here?***





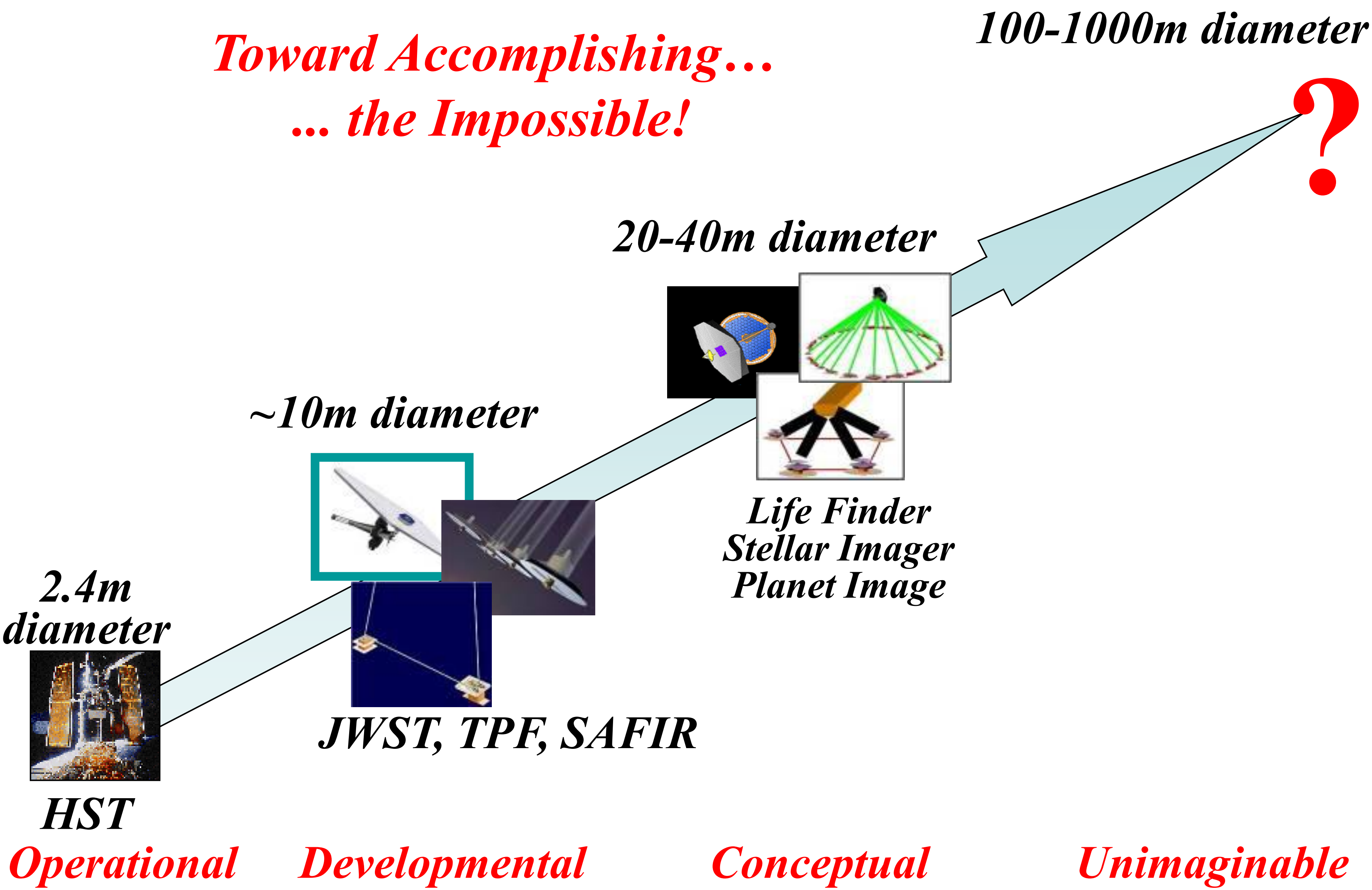



*Cross Feed Science & Technology*

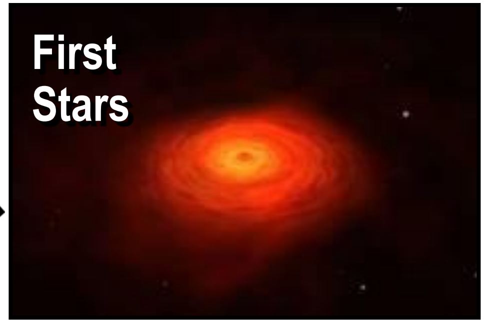
## ***Are We Alone?***

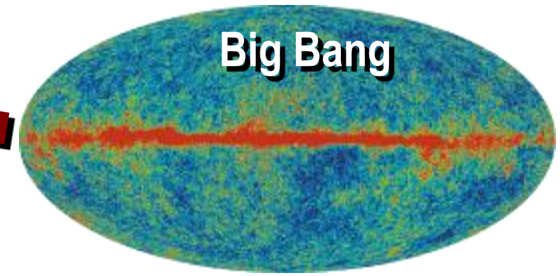


# A Vision for Large Telescopes & Collectors



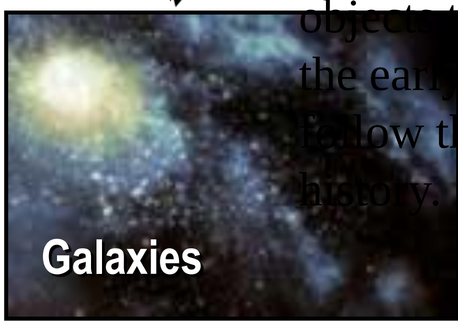
# JWST Science Themes

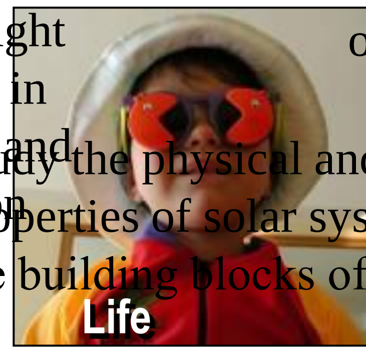



Observe the birth and early development of stars and the formation of planets.

Identify the first bright objects that formed in the early Universe, and follow the ionization history.



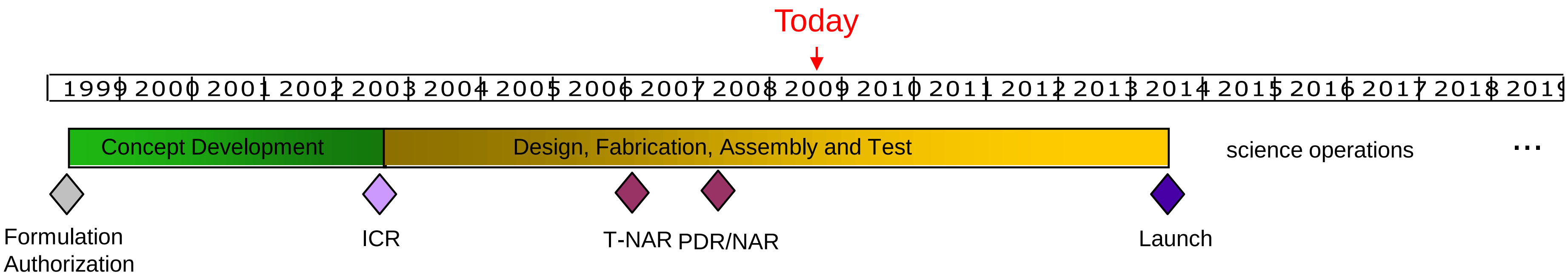

Study the physical and chemical properties of solar systems for the building blocks of ….


Determine how galaxies form

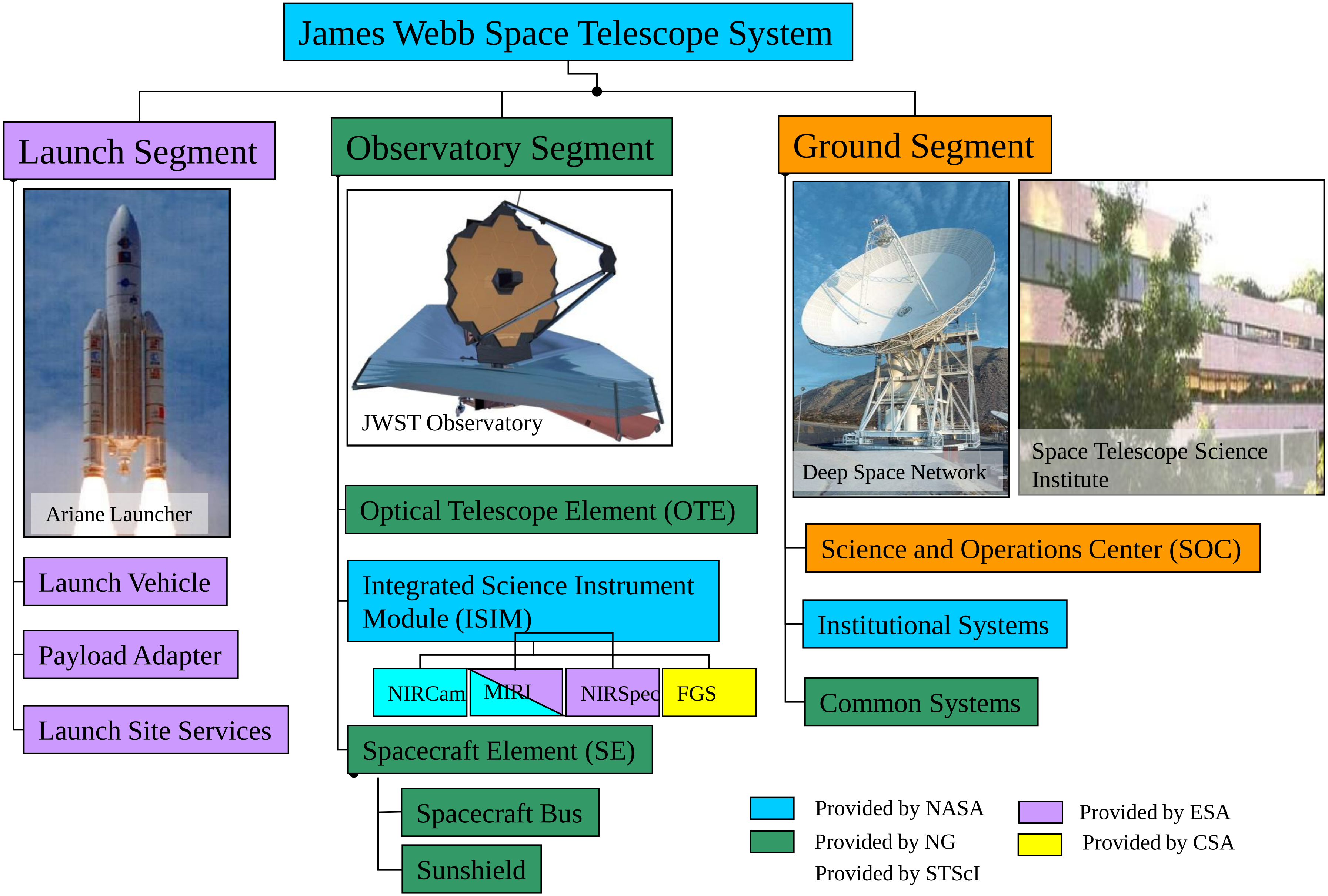

Determine how galaxies and dark matter, including gas, stars, metals, overall morphology and active nuclei evolved to the present day.

# JWST Summary

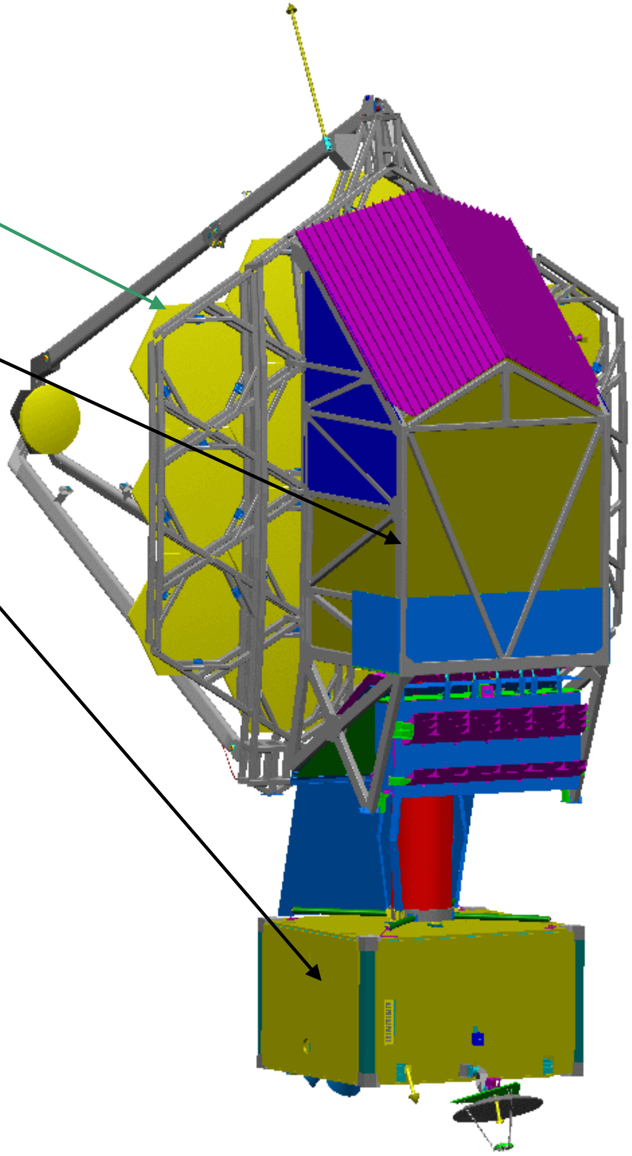
- **<u>Mission Objective</u>**
  - Study origin & evolution of galaxies, stars & planetary systems
  - Optimized for near infrared wavelength (0.6 –28 $\mu$m)
  - 5 year Mission Life (10 year Goal)
- **<u>Organization</u>**
  - Mission Lead: Goddard Space Flight Center
  - International collaboration with ESA & CSA
  - Prime Contractor: Northrop Grumman Space Technology
  - Instruments:
    - Near Infrared Camera (NIRCam) – Univ. of Arizona
    - Near Infrared Spectrometer (NIRSpec) – ESA
    - Mid-Infrared Instrument (MIRI) – JPL/ESA
    - Fine Guidance Sensor (FGS) – CSA
  - Operations: Space Telescope Science Institute



# The JWST system consists of three segments



# The observatory segment consists of three main elements



Optical Telescope Element (OTE)
- Collects star light from distant objects

Integrated Science Instrument Module (ISIM)
- Decodes physics information from star light and converts to digital data

Spacecraft
- Attitude control, telecom, power & other support systems

# JWST Requirements

Optical Telescope Element

25 sq meter Collecting Area

2 micrometer Diffraction Limit

< 50K (~35K) Operating Temp

Primary Mirror

6.6 meter diameter (tip to tip)

< 25 kg/m$^2$ Areal Density

< \$4 M/m$^2$ Areal Cost

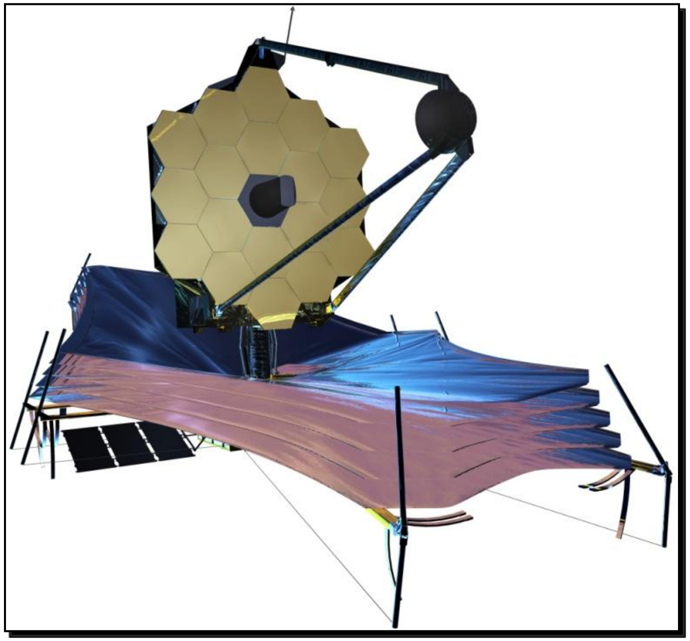
18 Hex Segments in 2 Rings

Drop Leaf Wing Deployment

Segments

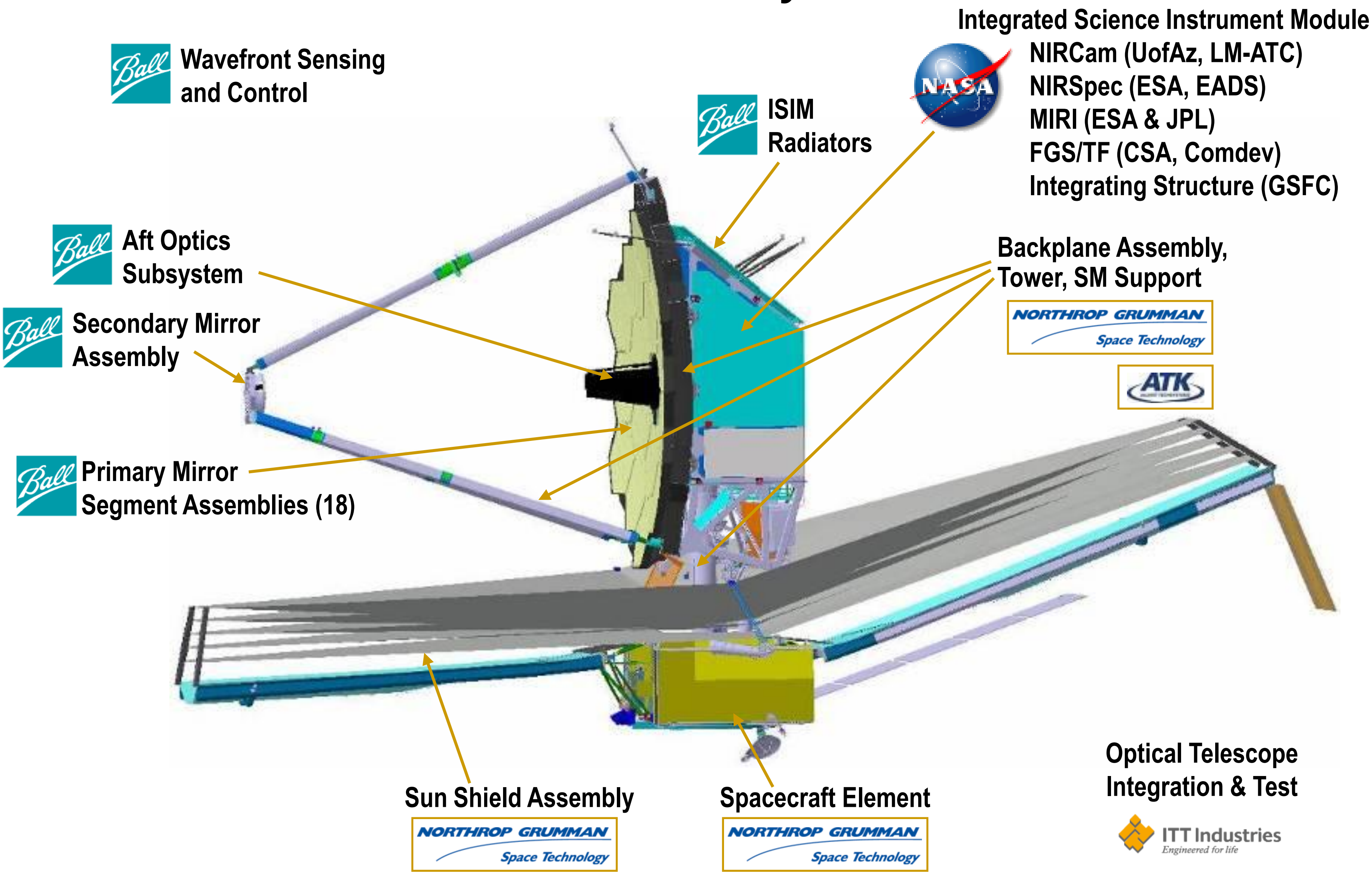
1.315 meter Flat to Flat Diameter

< 20 nm rms Surface Figure Error

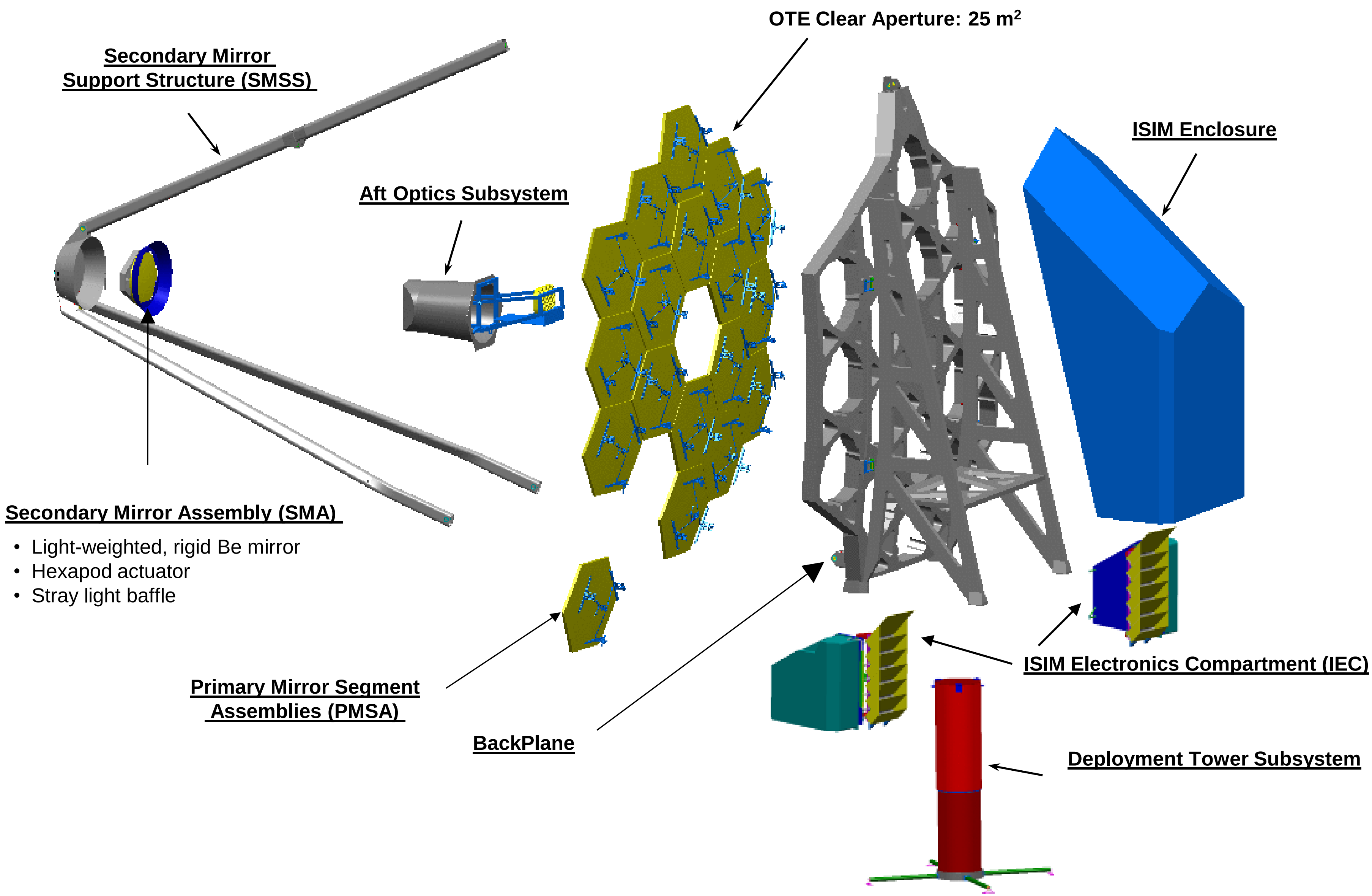


| | |
|---|---|
| Low (0-5 cycles/aper) | 4 nm rms |
| CSF (5-35 cycles/aper) | 18 nm rms |
| Mid (35-65K cycles/aper) | 7 nm rms |
| Micro-roughness | <4 nm rms |

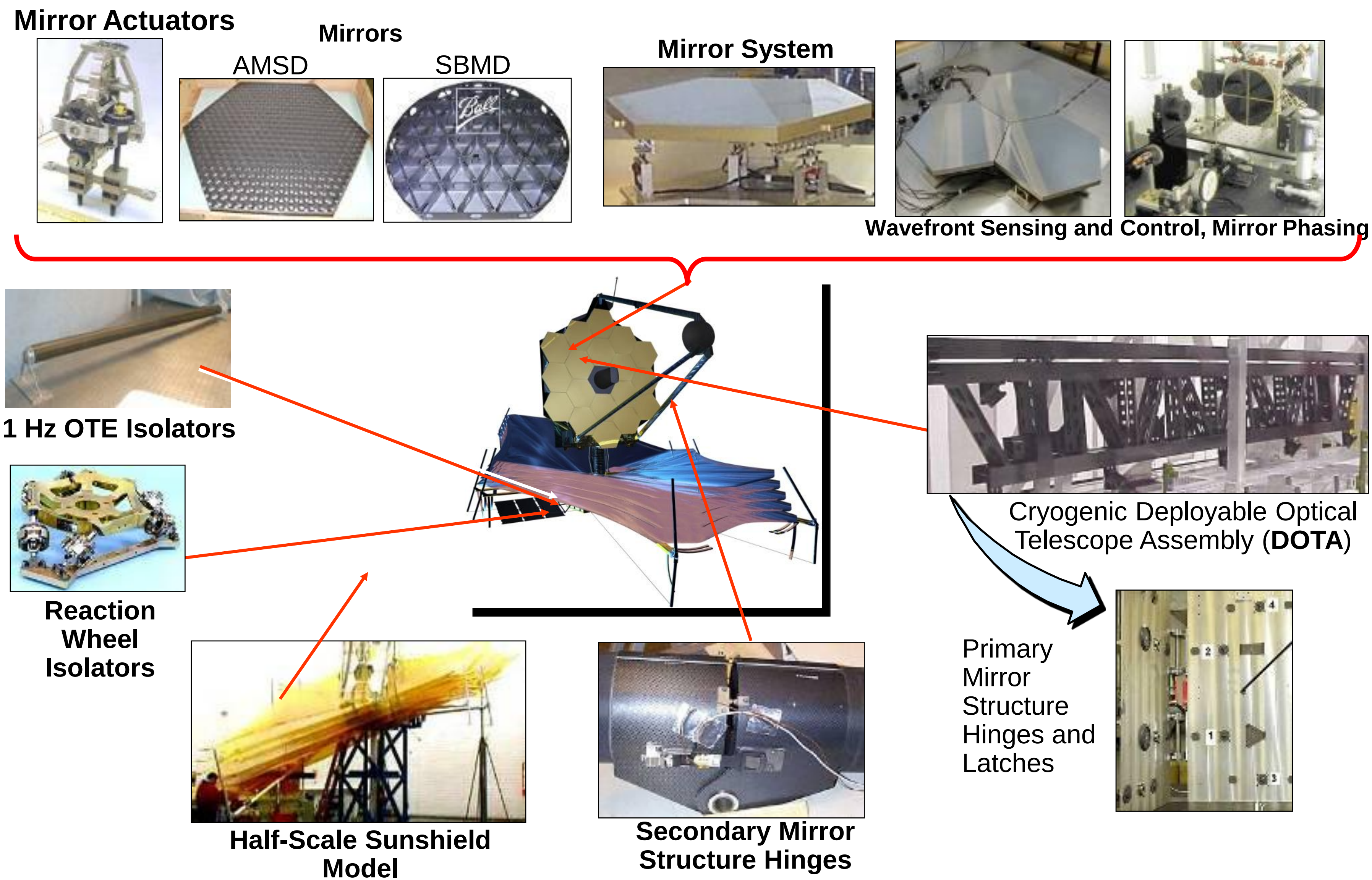
# JWST Observatory Elements



# OTE Architecture Concept

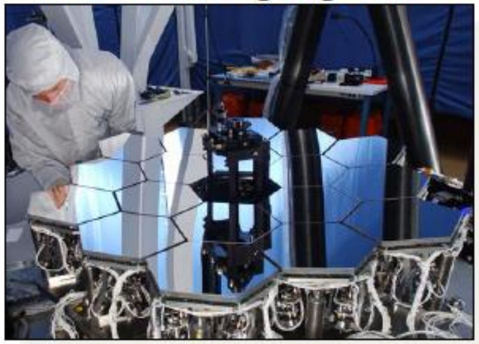


# Investments Have Reduced Risk

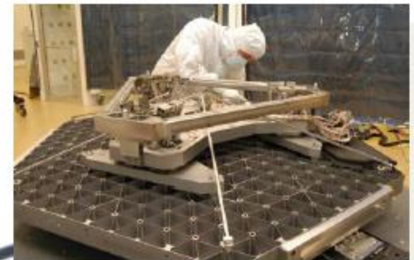


# JWST Technology Demonstrations for T-NAR

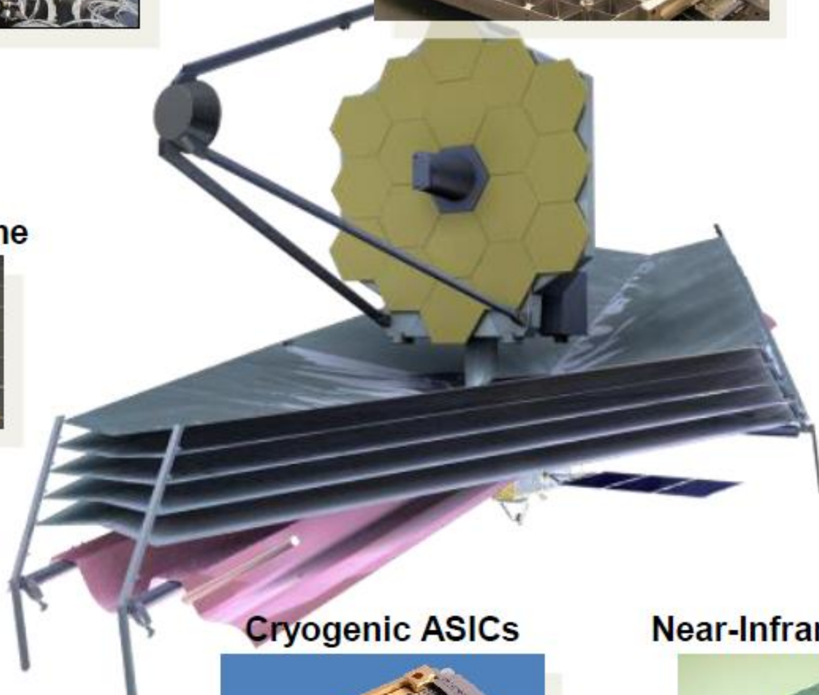
**Mirror Phasing Algorithms**



**Beryllium Primary Mirror Segment**

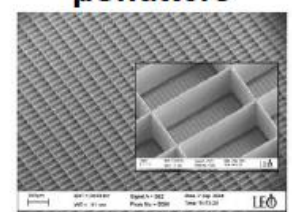


**Backplane**



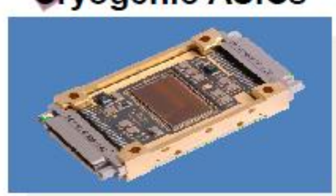
**Sunshield Membrane**

**µShutters**

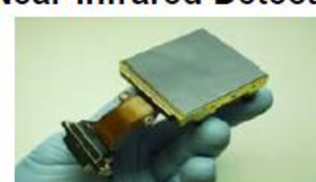


**Cryocooler**

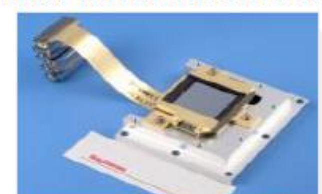
**Cryogenic ASICs**



**Near-Infrared Detector**

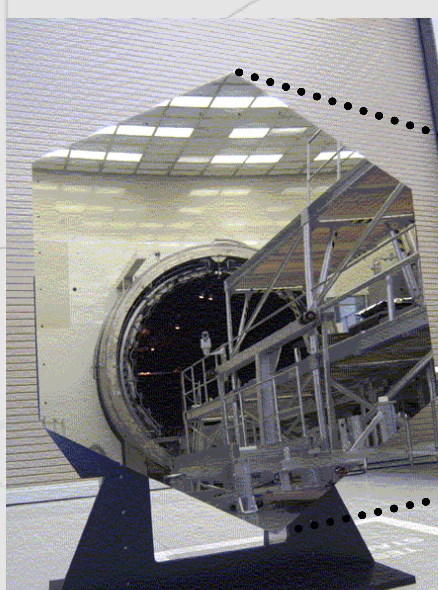


**Mid-Infrared Detector**

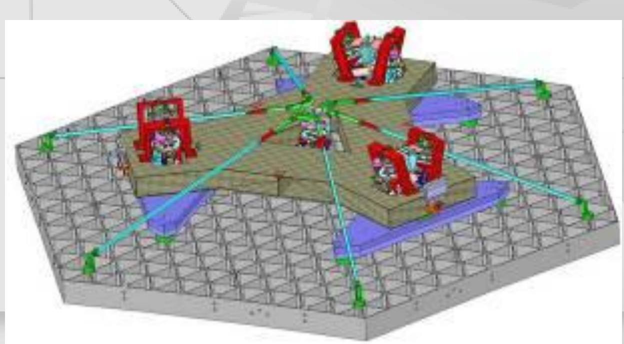


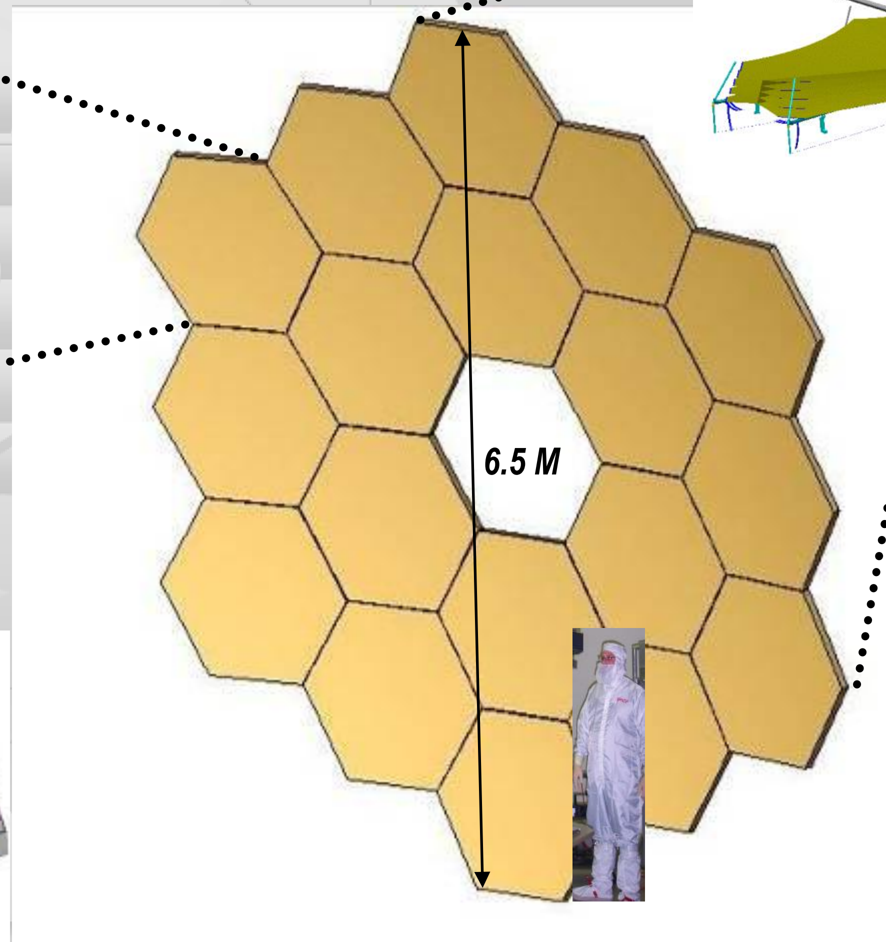
# Technology Development of Large Optical Systems

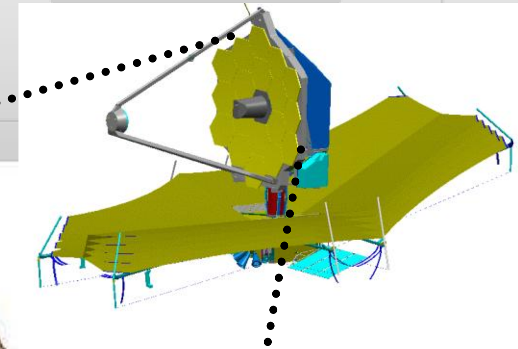
*MSFC is the JWST Primary Mirror Segment Technology Development Lead for JWST*



AMSD II – Be, technology selected for JWST





**The 18 Primary Mirror segments**

# Observatory Performance

Observatory Performance Requirements

- Strehl Ratio:
  - > 0.8 at $\lambda = 2\ \mu m$
  - > 0.8 at $\lambda = 5.6\ \mu m$
- Encircled Energy:
  - > 74% at $\lambda = 1\ \mu m$ within 150 milli-arcsec radius
- Encircled Energy Stability:
  - < 2.5% at $\lambda = 2\ \mu m$ within 80 milli-arcsec radius

Strehl Ratio requires 150 nm rms total WFE

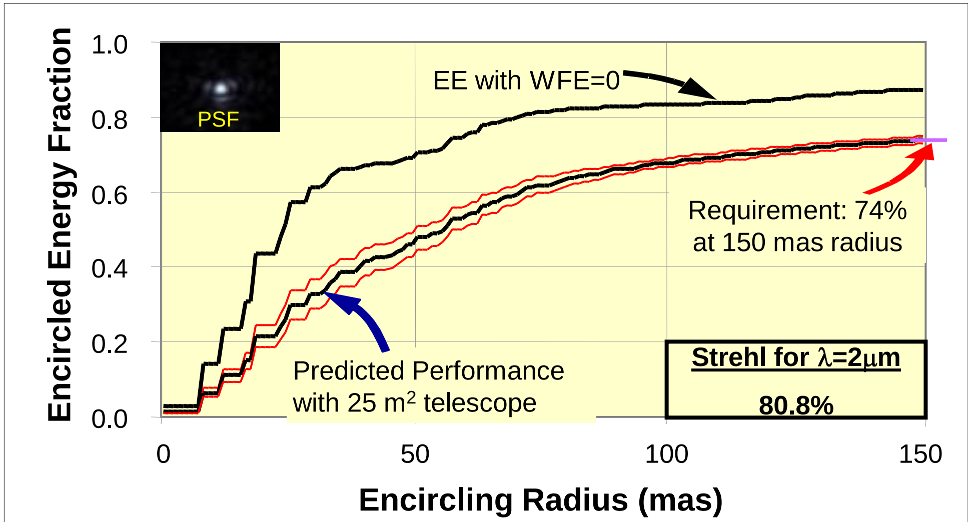
EE depends on 60 nm rms Mid & High Error

- WFE < ~ 5 cycles doesn't affect EE

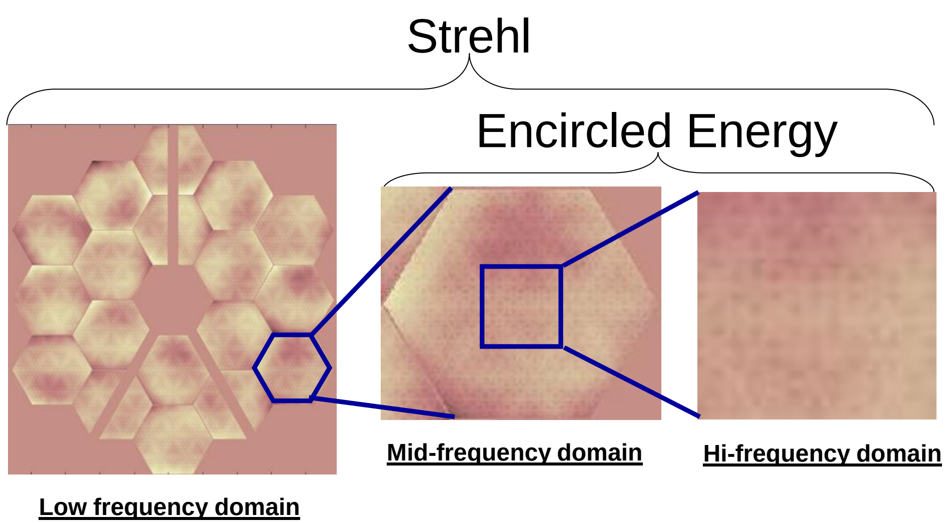
Active control of 18 hexagonal PM segments

- 6 DoF control of PM segment positions
- 1 DoF control of PM segment radius of curvature
- This provides active control of the low spatial frequencies up to nominally 5 c/a

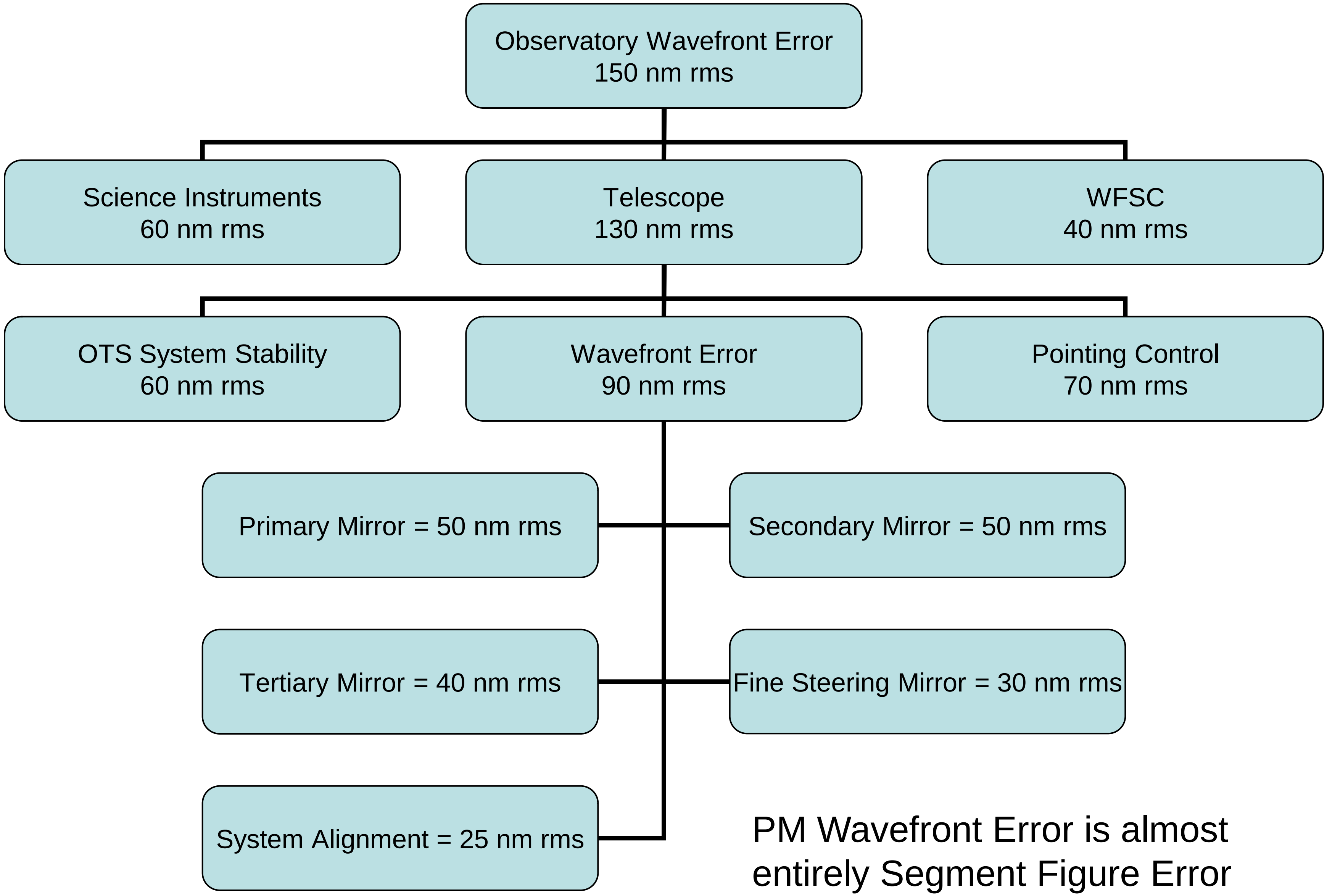
PMSA Phase Error effects both Strehl & EE




Curves show Mean ± 1$\sigma$ Encircled Energy Fraction for $\lambda$=1$\mu$m from Monte Carlo simulations of allocated WFE and LOS jitter

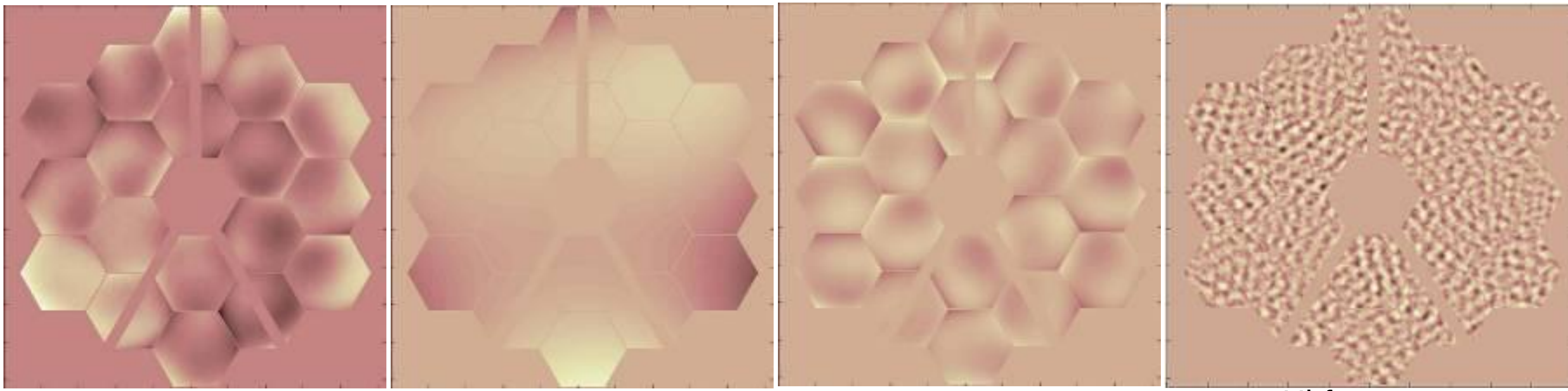


# Total WFE Error Budget




PM Wavefront Error is almost entirely Segment Figure Error

# Observatory Wavefront Error



Total OPD | Low frequency 0 to 5 cycles/aperture | Mid-frequency 5 to 30 cycles/aperture | Hi-frequency > 30 cycles/aperture

WFE is tracked by spatial frequency:

- Low spatial frequency = global aberrations
  - Controllable by SM 6DOF alignment and
  - PMSA piston, tilt, lateral adjust for Astigmatism & ROC adjust
- Mid spatial frequency
  - Individual PMSA positioning and low order aberrations
  - Partially controllable with PMSA 6DOF positioning & RoC control
- High spatial frequencies
  - Polishing residuals or local deformations at mounting locations
  - Not controllable by WFSC

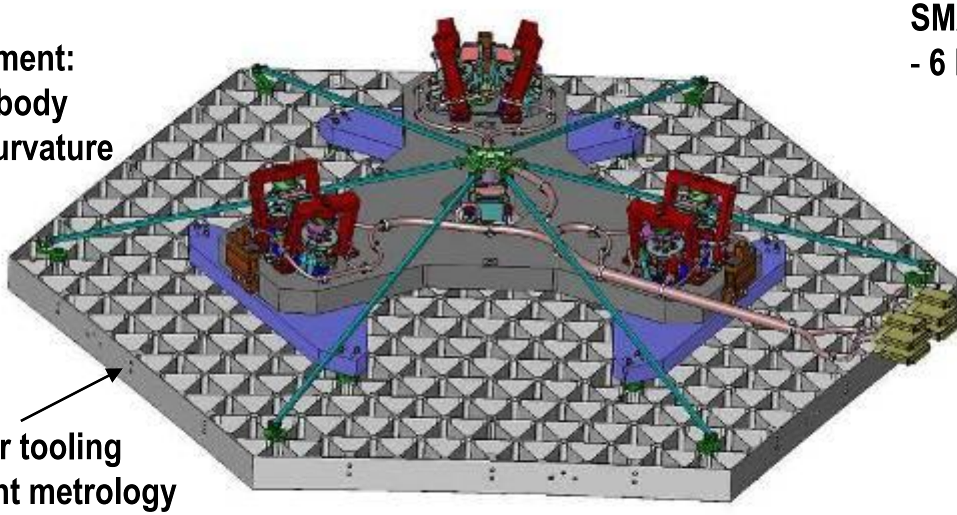
| nm | OTE WFC Residual | | | |
|---|---|---|---|---|
| rms | tot | lo | mid | hi |
| Req | 58 | 13 | 55 | 16 |
| EOL | 58 | 13 | 55 | 16 |

| Req | | | EOL | | |
|---|---|---|---|---|---|
| seg piston | 5 | nm | seg piston | 5 | nm |
| seg tilt | 7 | nr | seg tilt | 7 | nr |
| seg decent | 100 | nm | seg decent | 100 | nm |
| seg clock | 217 | nr | seg clock | 217 | nr |
| Seg Met. | 10 | nm | Seg Met. | 10 | nm |
| SM piston | 100 | nm | SM piston | 100 | nm |
| SM tilt | 2 | μr | SM tilt | 2 | μr |
| SM decent | 2 | μm | SM decent | 2 | μm |
| SM Met. | 10 | nm | SM Met. | 10 | nm |

| nm | Config. OTE Res | | | ote |
|---|---|---|---|---|
| rms | tot | lo | mid | hi |
| Req | 99 | 83 | 52 | 16 |
| EOL | 99 | 83 | 52 | 16 |

# PMSA & SMA Actively Controlled

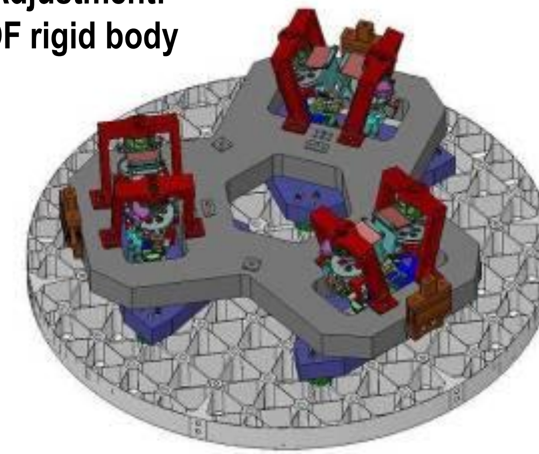
**PMSA Adjustment:**
- 6 DOF rigid body
- Radius of Curvature



Inserts for tooling
ball alignment metrology

**Primary Mirror Segment Assembly**

**SMA Adjustment:**
- 6 DOF rigid body



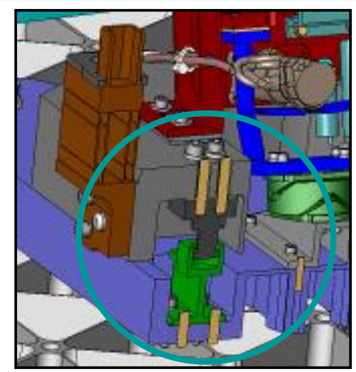
**Secondary Mirror Assembly**

**PMSAs and SMA are in fabrication**

**Common Design Features**

**Bipod Actuator**

**Interface Mount**



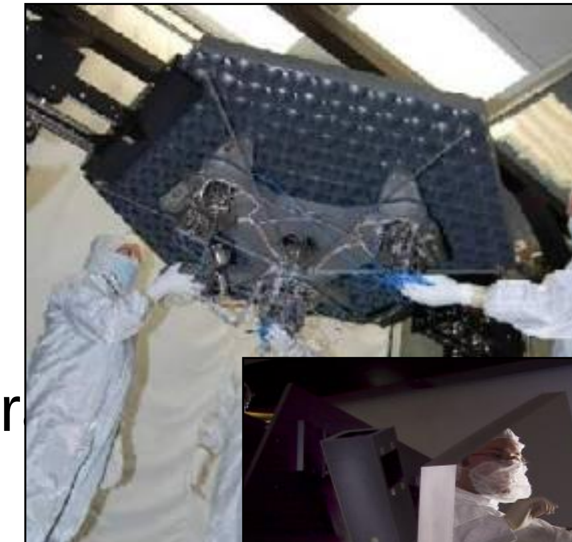
**Lateral Launch Restraint**
**In Stowed Position**

# Mirror Technology has been demonstrated

time and maturity

## Flight mirror demonstration

- Launch Load survival
- Acoustic tests



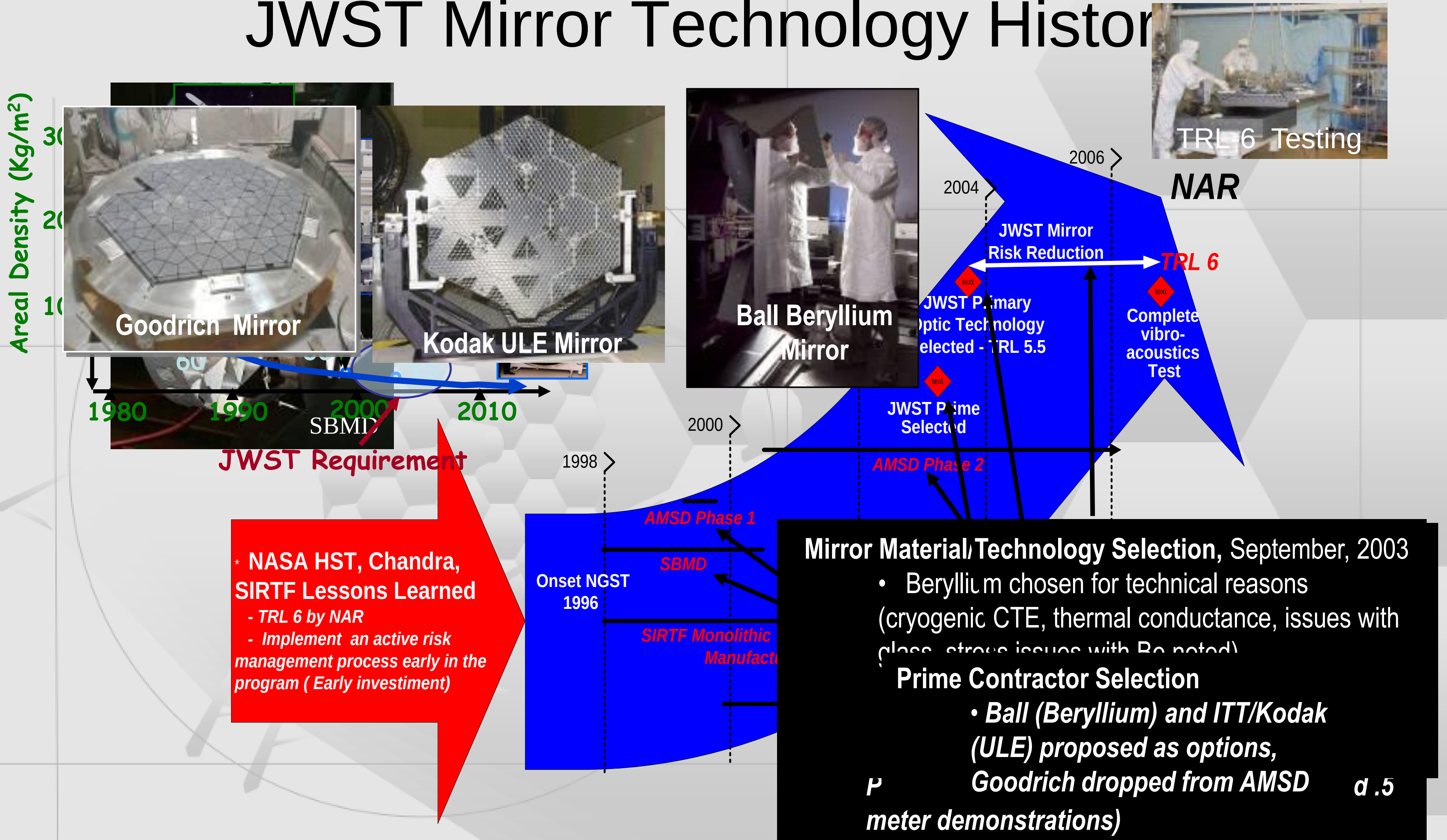
## Advanced Mirror System Demonstr

- Areal density, full scale asphere
- Surface figure requirements
- Radius of curvature control
- Cryo-repeatability

## Subscale Beryllium Mirror Demonstrator

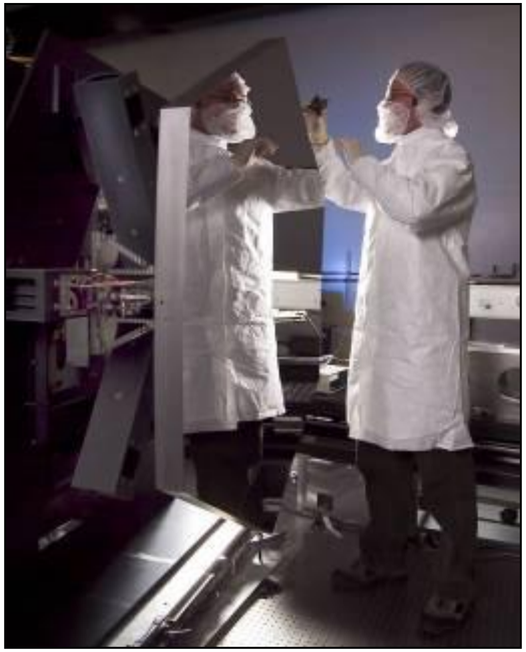
- Areal density
- Cryo-figuring
- Radius of curvature control
- Cryo-testing of protected gold coati

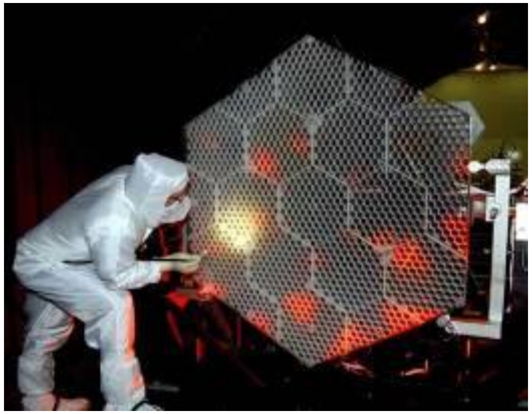
# JWST Mirror Technology History




Based on lessons learned, JWST invested early in mirror technology to address lower areal densities and cryogenic operations

# AMSD – Ball & Kodak





## Specifications

| | |
|---|---|
| Diameter | 1.4 meter point-to-point |
| Radius | 10 meter |
| Areal Density | < 20 kg/m2 |
| Areal Cost | < $4M/m2 |

## Beryllium Optical Performance

| | |
|---|---|
| Ambient Fig | 47 nm rms (initial) |
| Ambient Fig | 20 nm rms (final) |
| 290K – 30K | 77 nm rms |
| 55K – 30K | 7 nm rms |

## ULE Optical Performance

| | |
|---|---|
| Ambient Fig | 38 nm rms (initial) |
| 290K – 30K | 188 nm rms |
| 55K – 30K | 20 nm rms |

# Advantages of Beryllium

Very High Specific Stiffness – Modulus/Mass Ratio

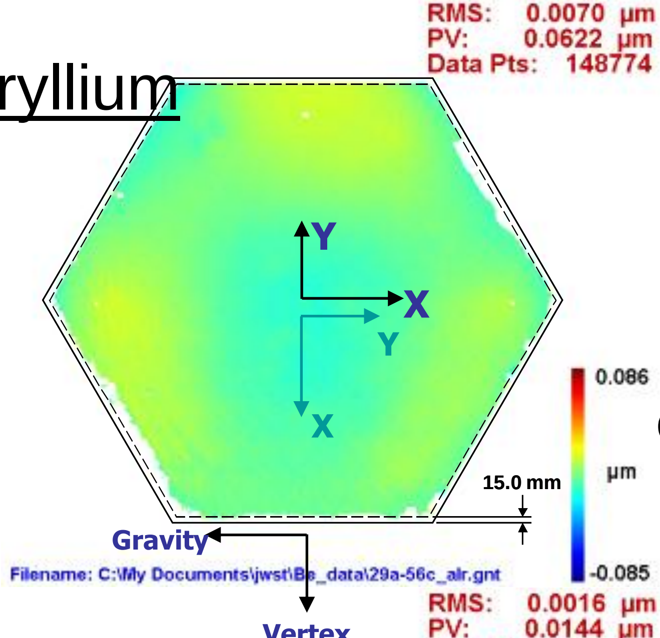
- Saves Mass – Saves Money

High Conductivity & Below 100K, CTE is virtually zero.

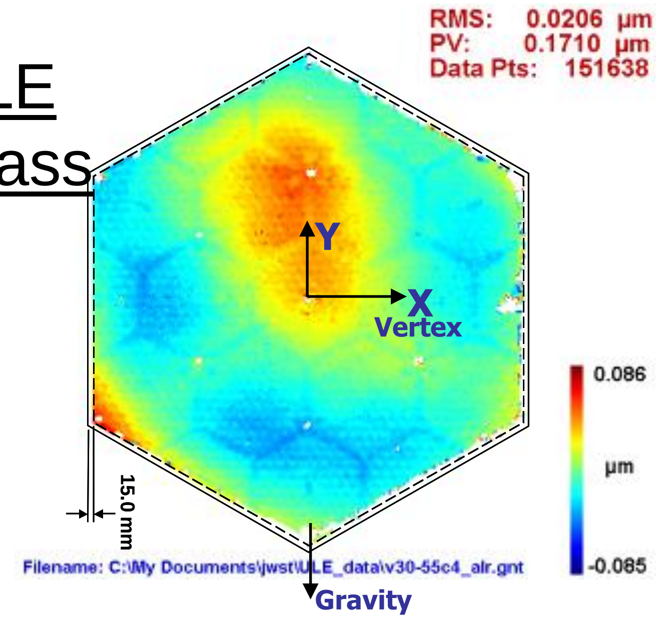
- Thermal Stability

# Figure Change: *30-55K Operational Range*

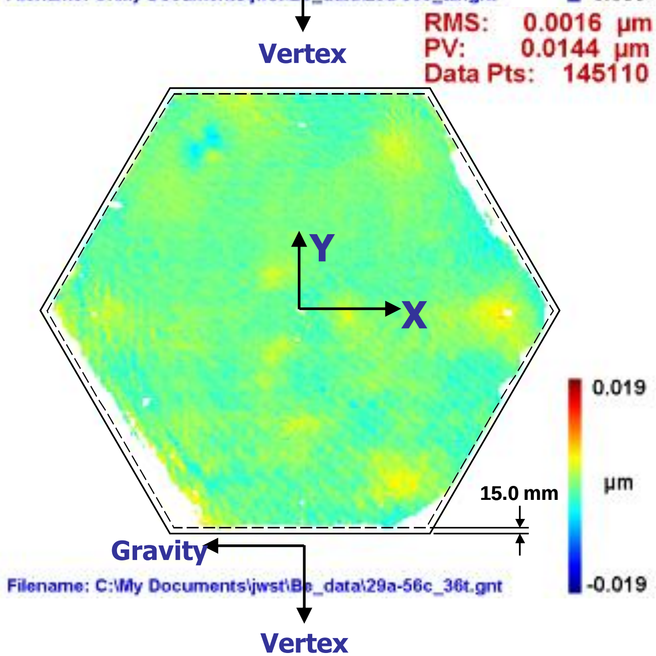
## Beryllium

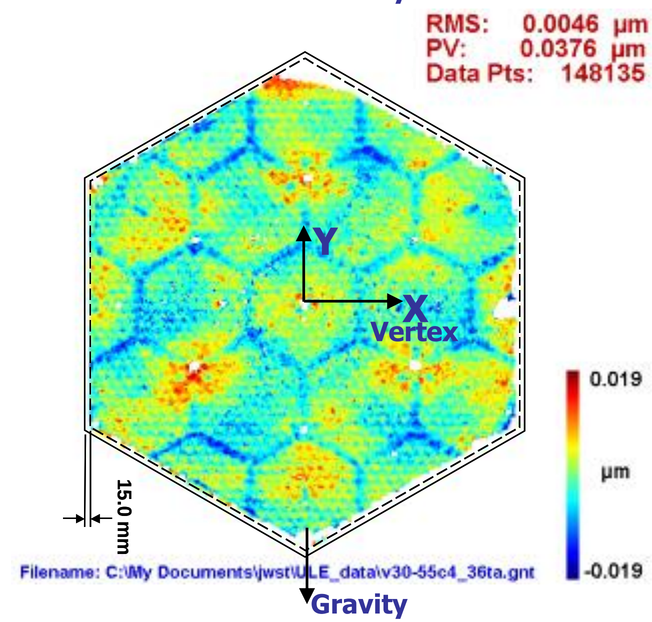



## ULE Glass




Surface Figure With Alignment Compensati on



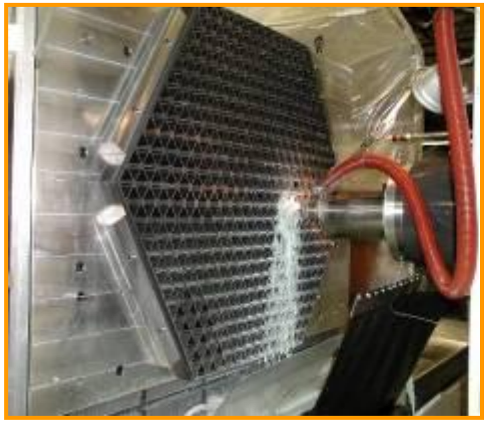




Residual with 36 Zernikes Removed

# Mirror Manufacturing Process

## Blank Fabrication

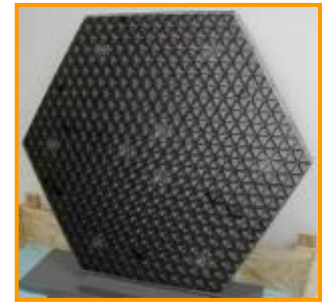
HIP Vessel being loading into chamber



Machining of Web Structure

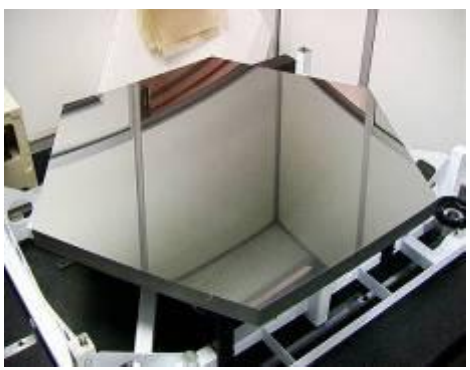
## Machining

Machining of Optical Surface



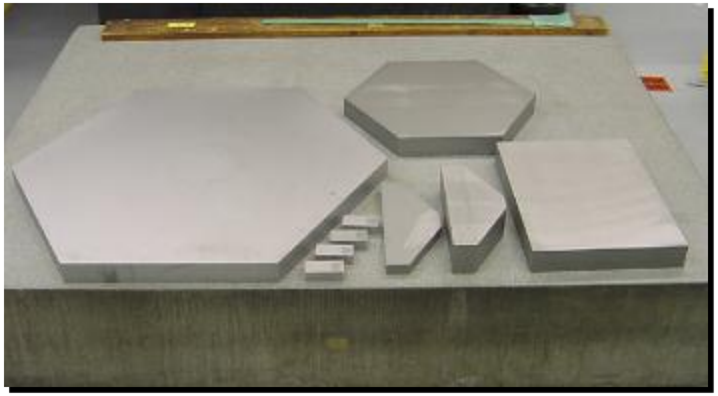
Completed Mirror Blank

## Polishing



## Mirror System Integration

# Brush Wellman

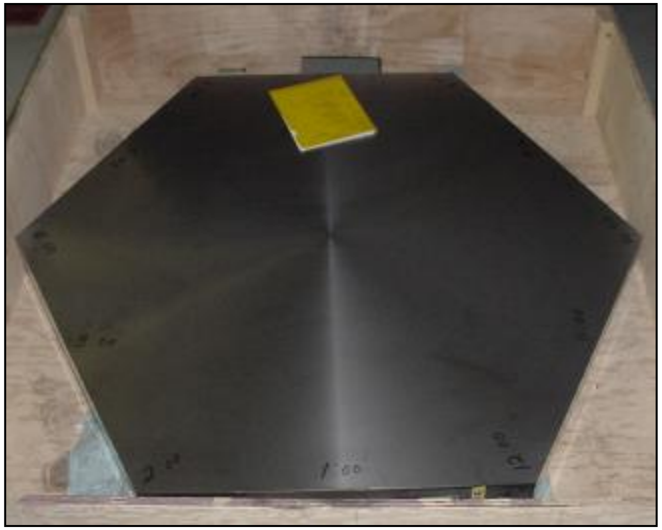
# Substrate Fabrication

**PM Segments SN 19-20**
**powder in loading container**

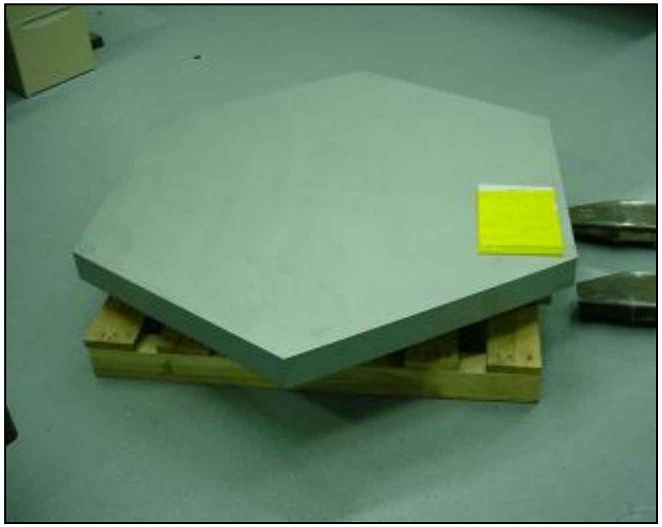
**PM Segments SN 19-20**
**HIP can prepared for powder loading**

**PM Segments SN 19-20**
**loaded HIP can in degas furnace**

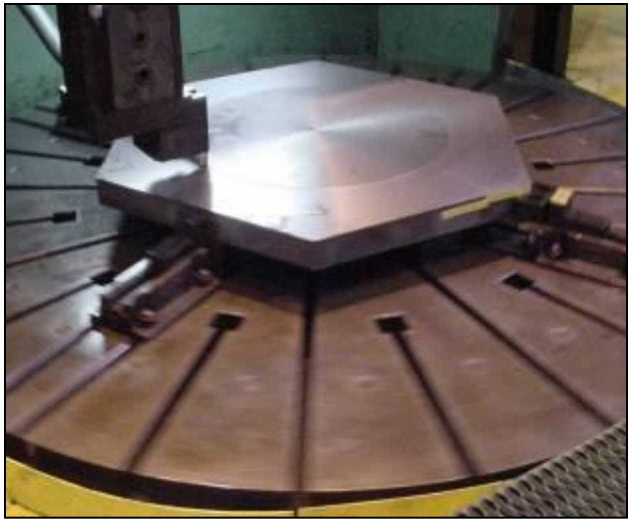
# Quality Control X-Ray Inspection



PM Segment SN 17 after finish machining



PM Segment SN 17 after x-ray



PM Segment SN 18 during finish machining

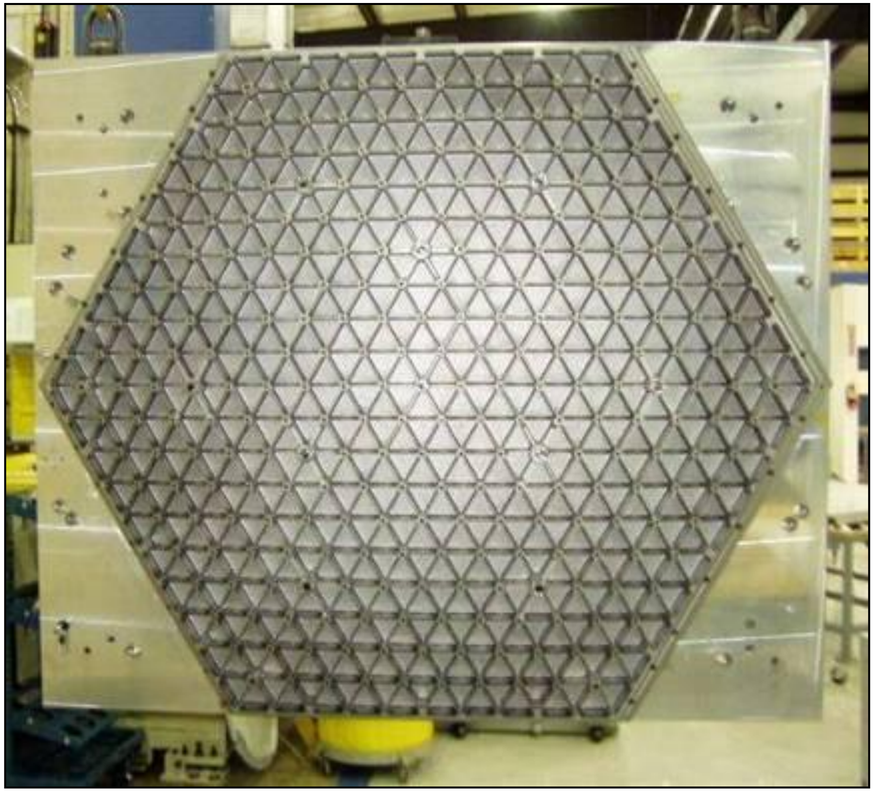
PM Segment SN 18 during x-ray

# Axsys Technologies

8 CNC Machining Centers

# Axsys Technologies

## PMSA Engineering Development Unit

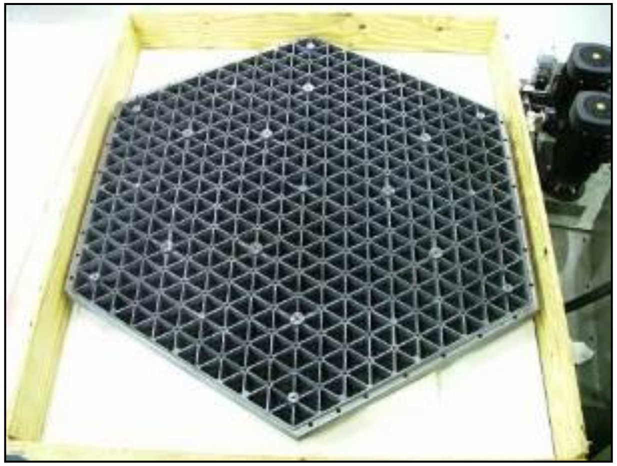


PMSA EDU rear side machined pockets

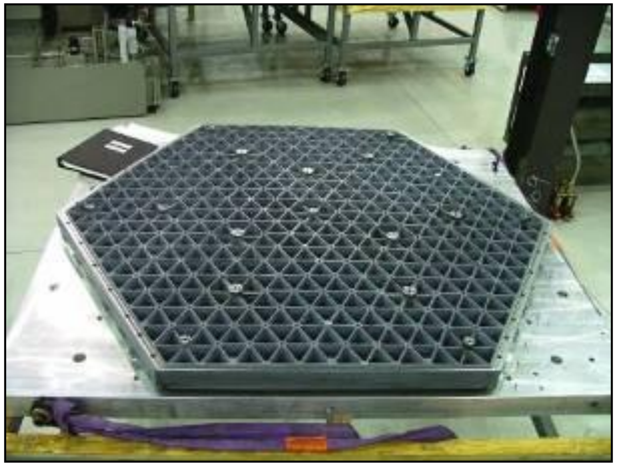
PMSA EDU front side machined optical surface

# Axsys Technologies

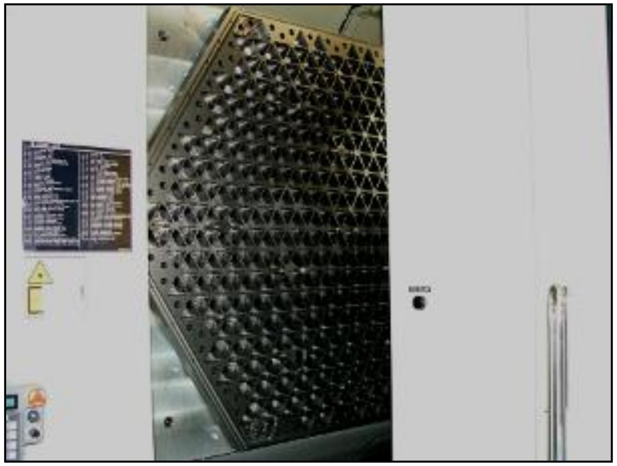
## Batch #1 (Pathfinder) PM Segments



PMSA #1 (EDU-A / A1)



PMSA #2 (3 / B1)



PMSA #3 (4 / C1)

## Batch #2 PM Segments

PMSA #4 (5 / A2)

PMSA #5 (6 / B2)

PMSA #6 (7 / C2)

# Tinsley Laboratories

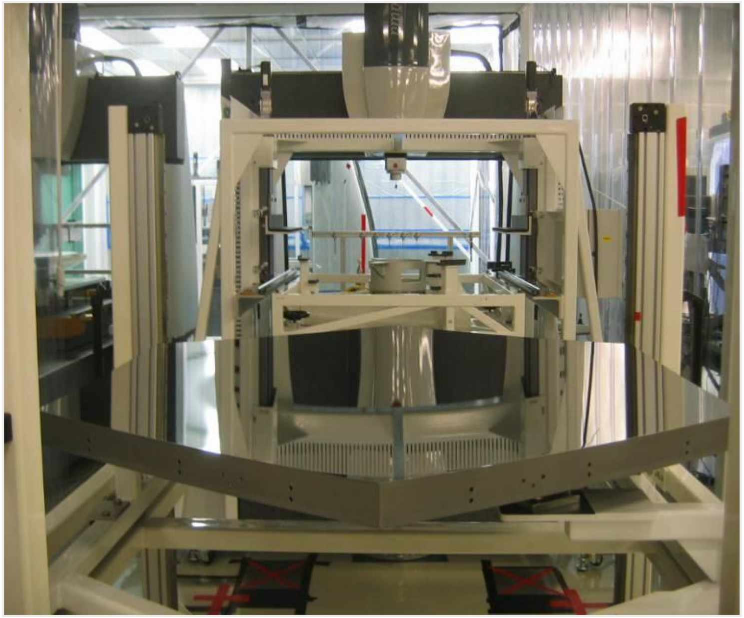
Production Preparation – CCOS Machines

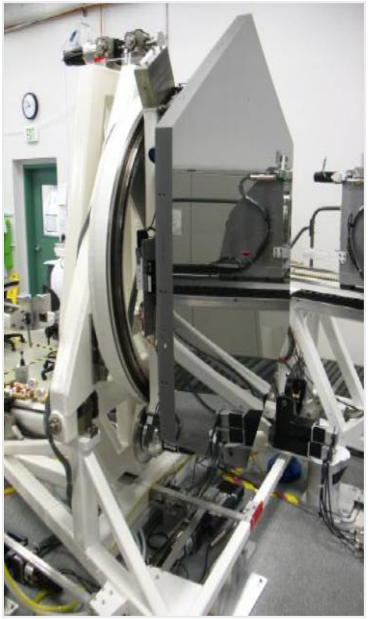
1$^{st}$ – 4$^{th}$ CCOS machine bases assembled and operational

5$^{th}$ – 8$^{th}$ CCOS machines received and in storage – installation to start 4/4/05

# Telescope mirror polishing is underway


PMSA EDU

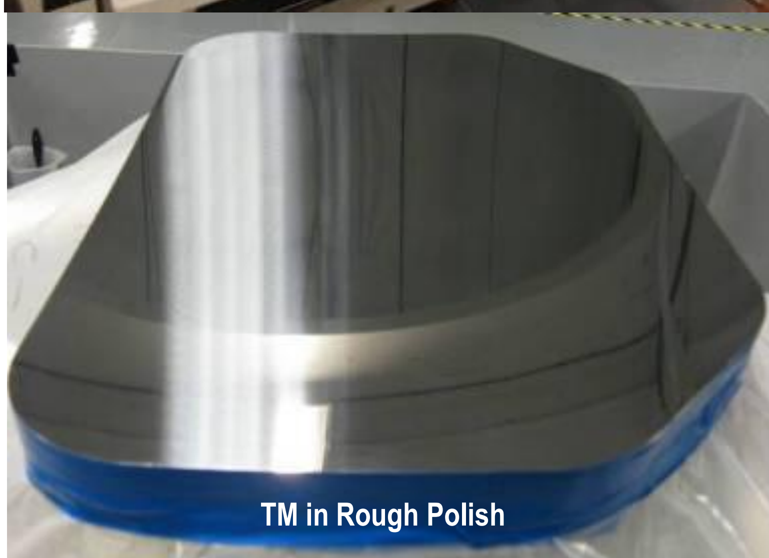




# Mirror Fabrication Status at L-3 SSG-Tinsley

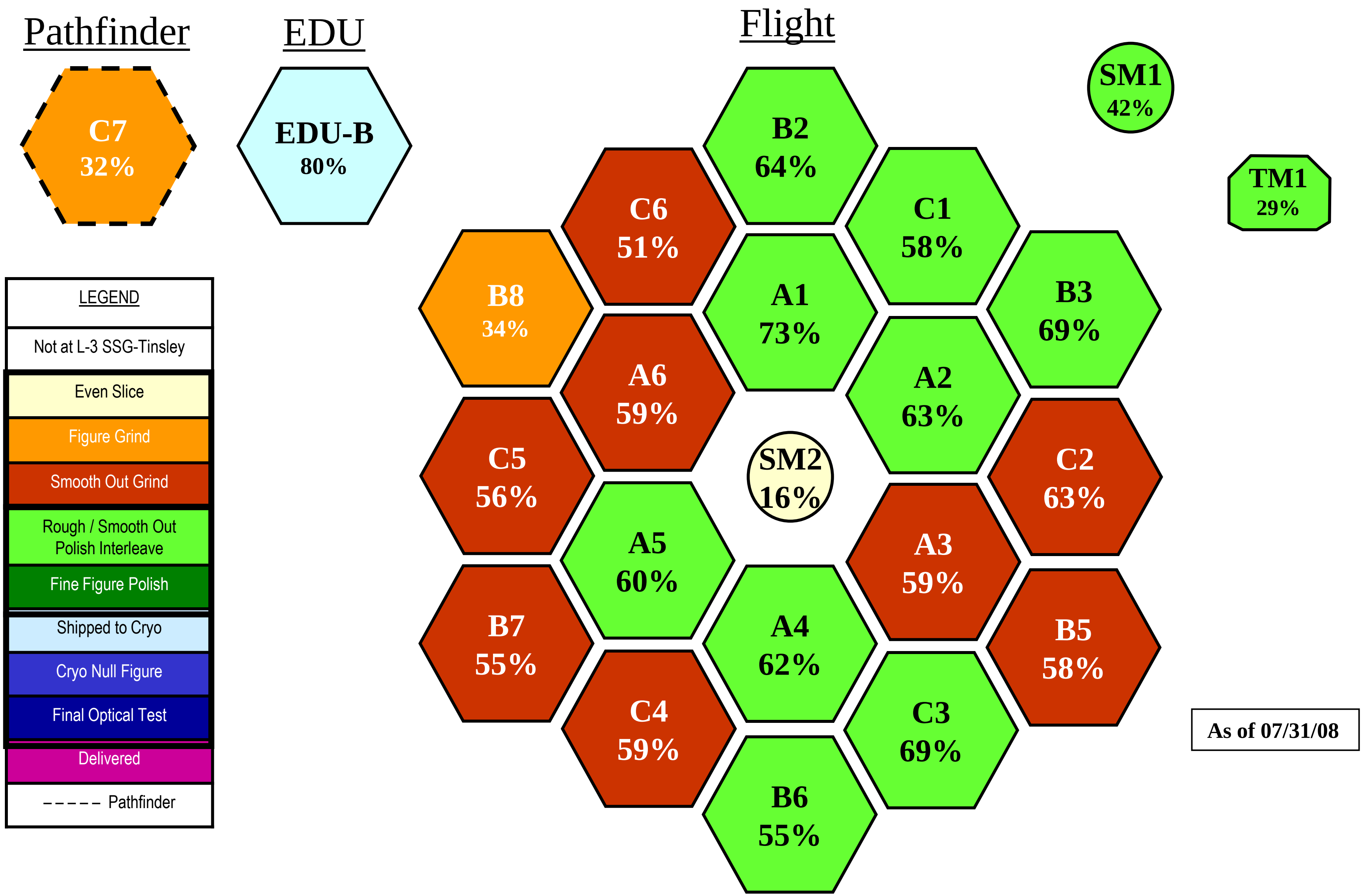

Primary Mirror EDU  Post Fine Polish


SM in Rough Polish

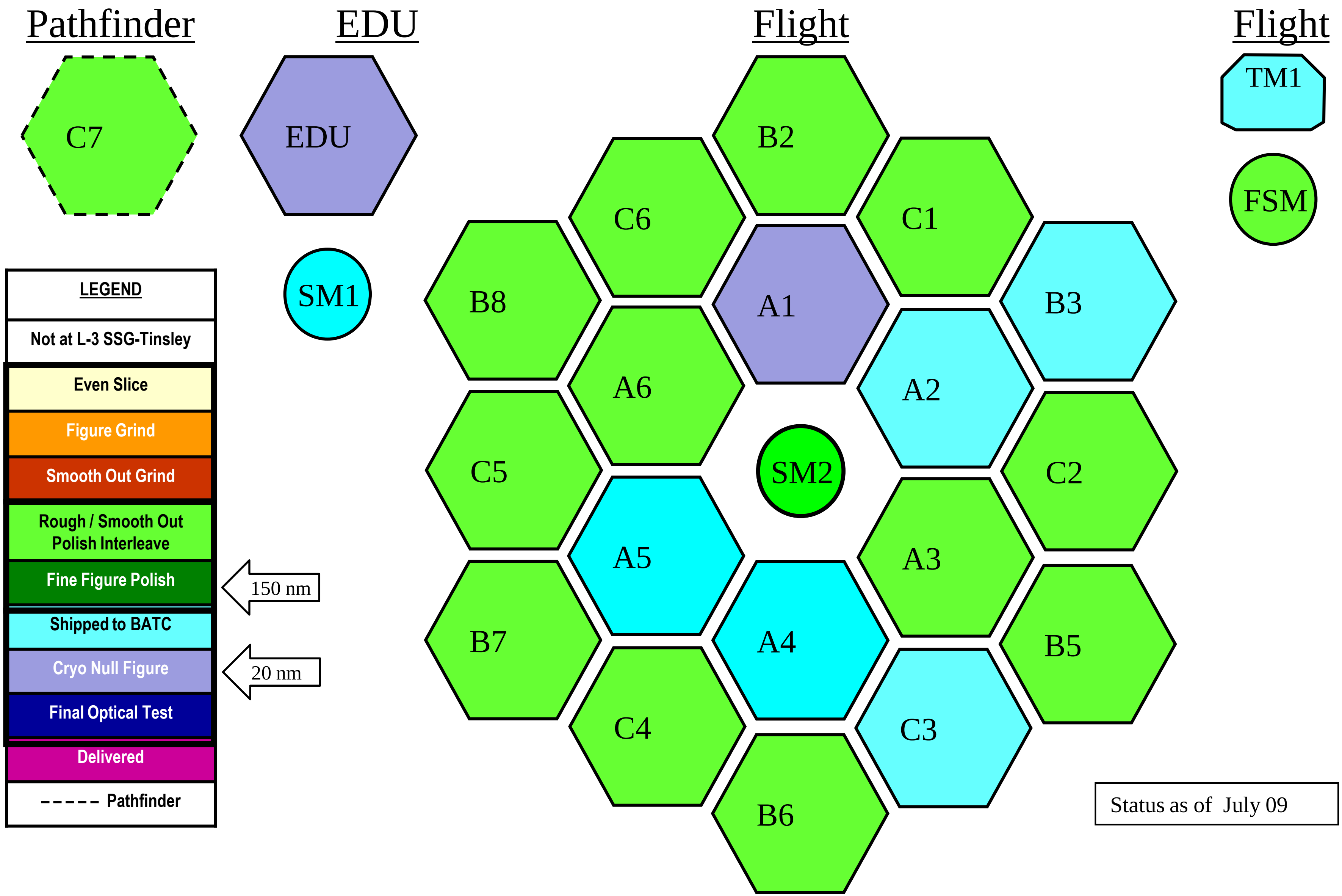

TM in Rough Polish


EDU Shipped to BATC for Cryo Testing

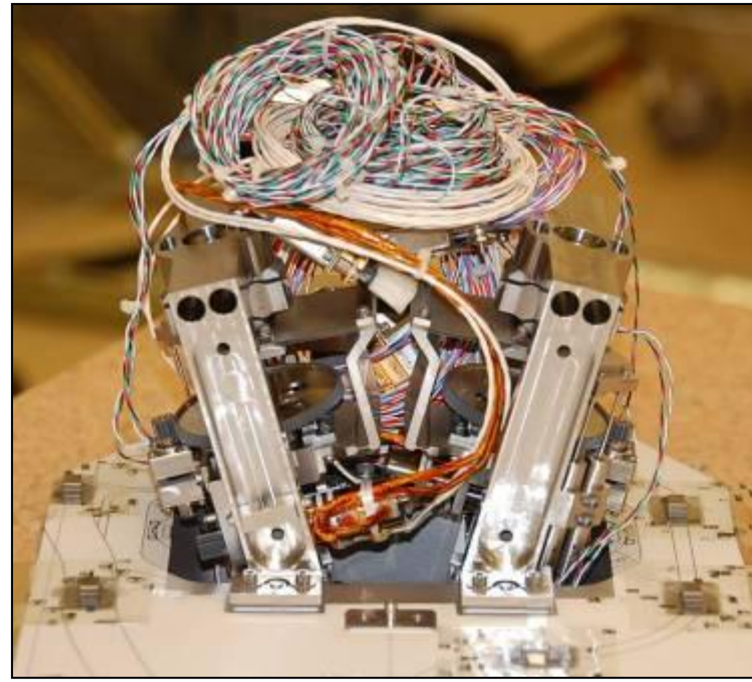
# Mirror Fabrication Status at L-3 SSG-Tinsley – July 08

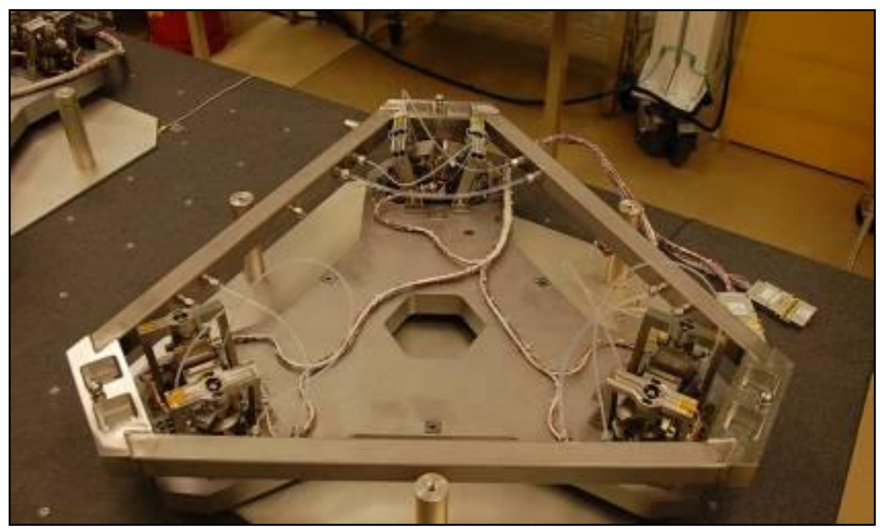


# Mirror Fabrication Status at L-3 SSG-Tinsley – July 09

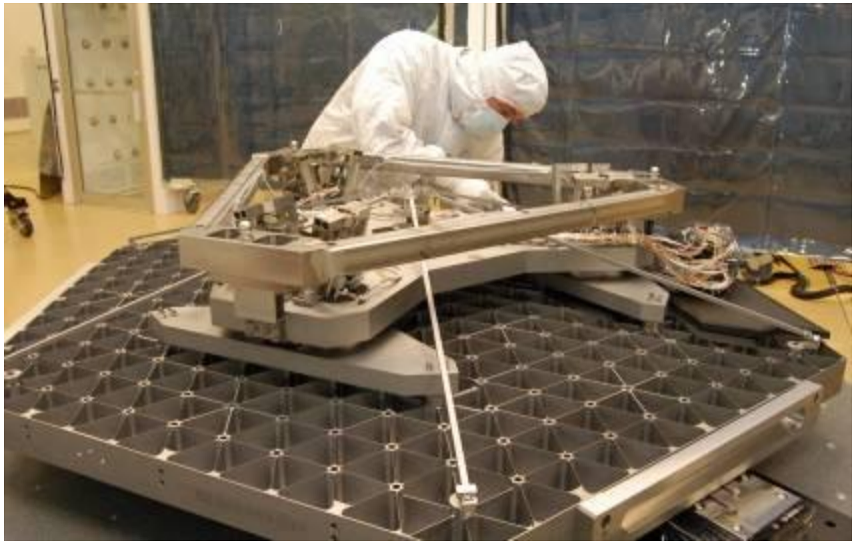


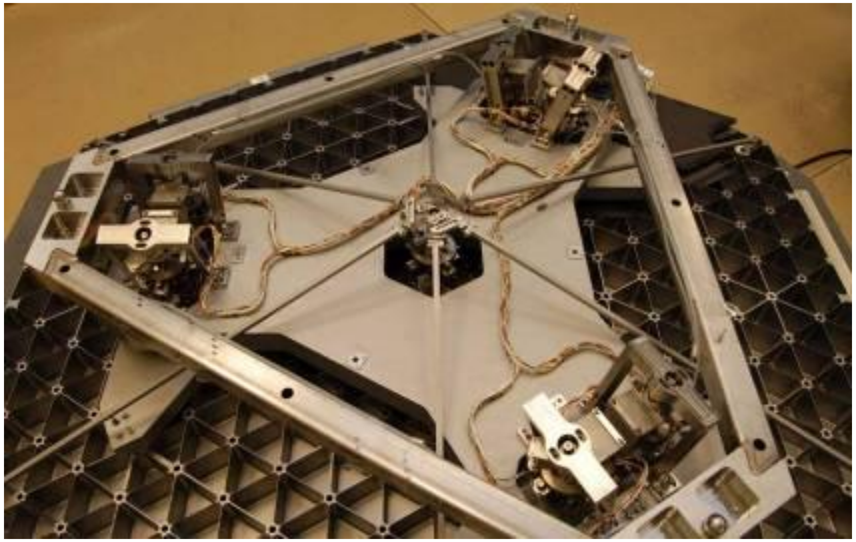
# Hexapod assemblies in manufacturing and on schedule

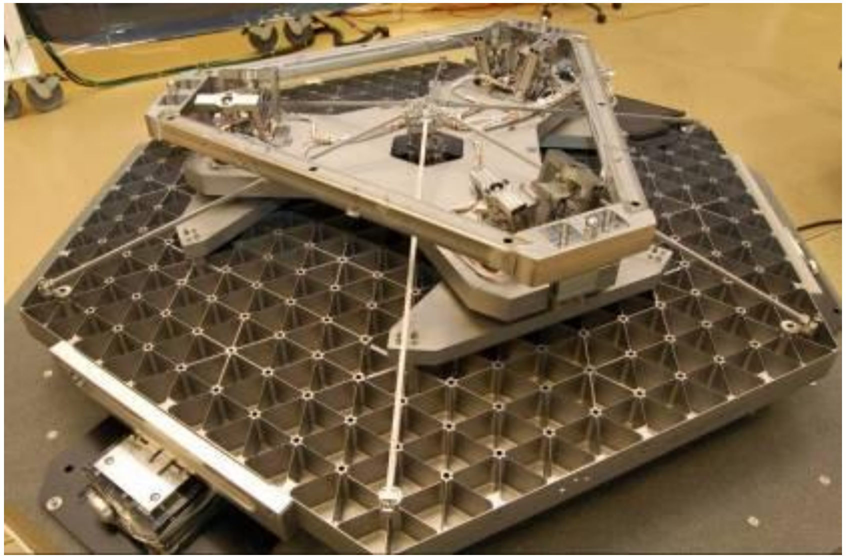


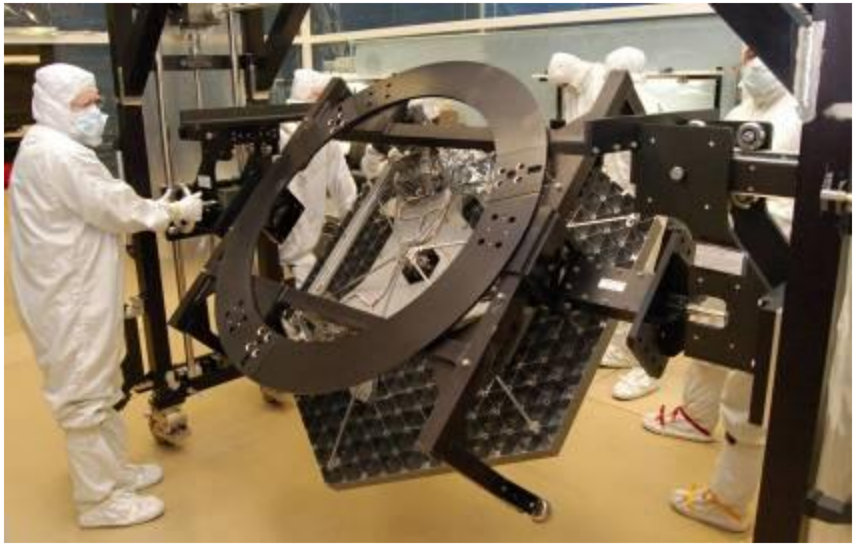


# Primary Mirror Segment Assembly (PMSA)

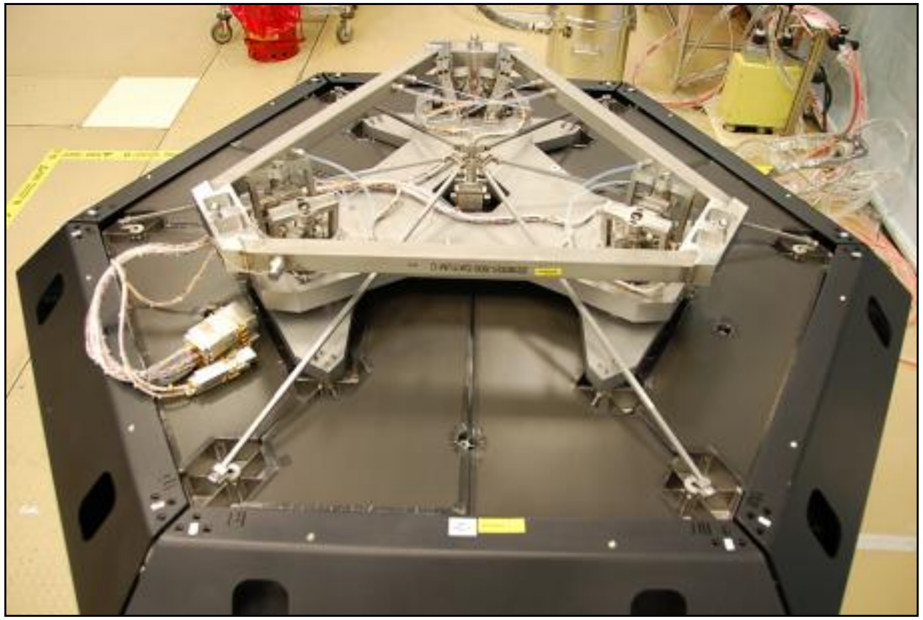


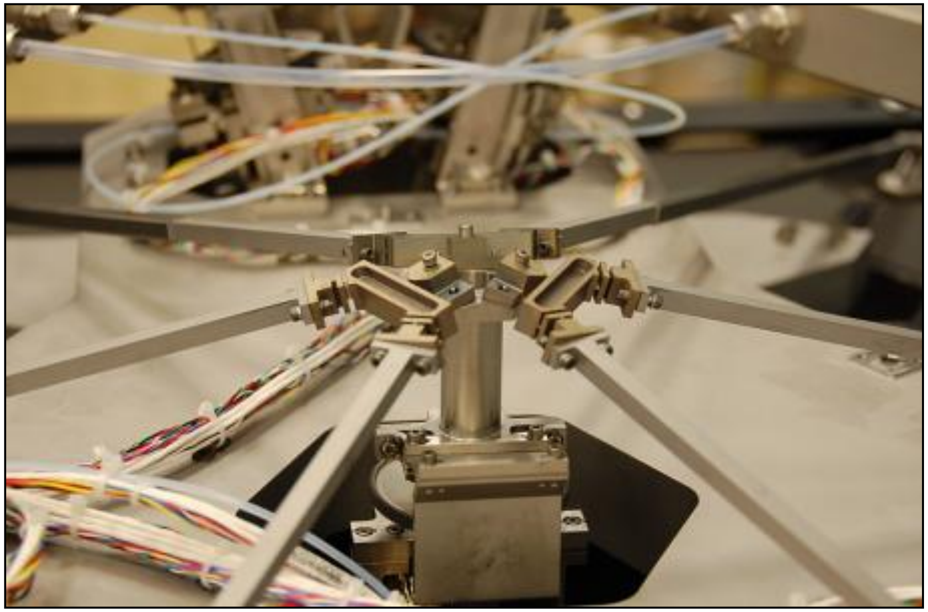




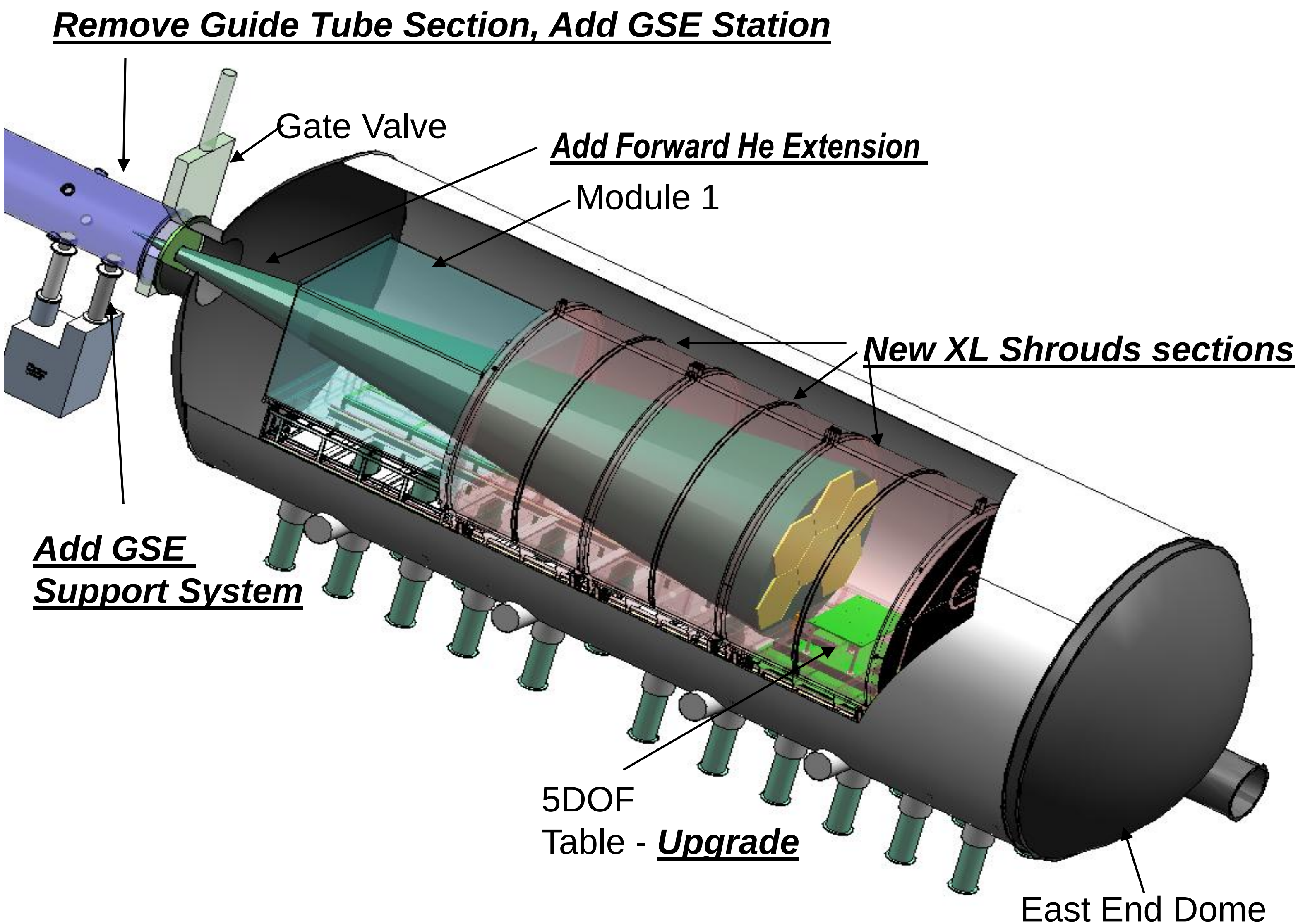


# EDU PMSA in assembly for cryo-testing

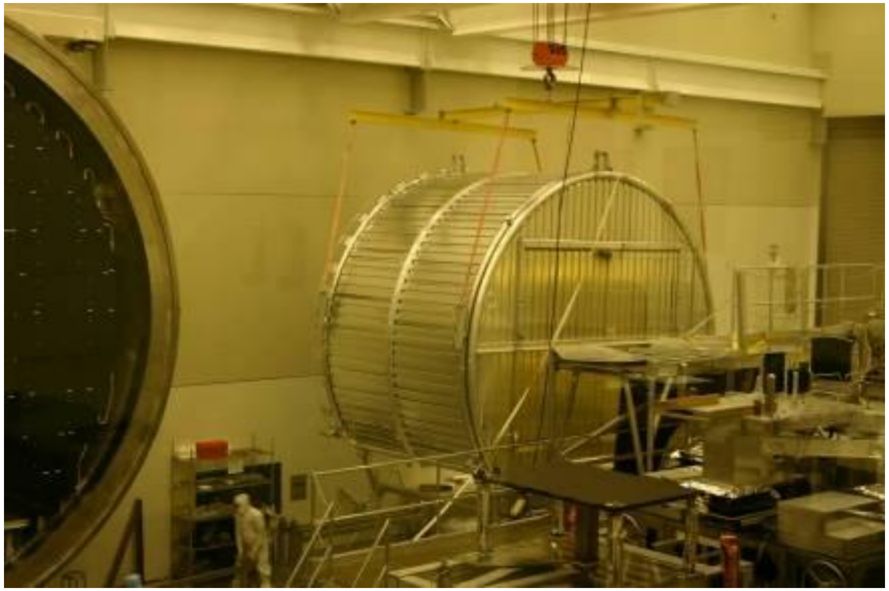


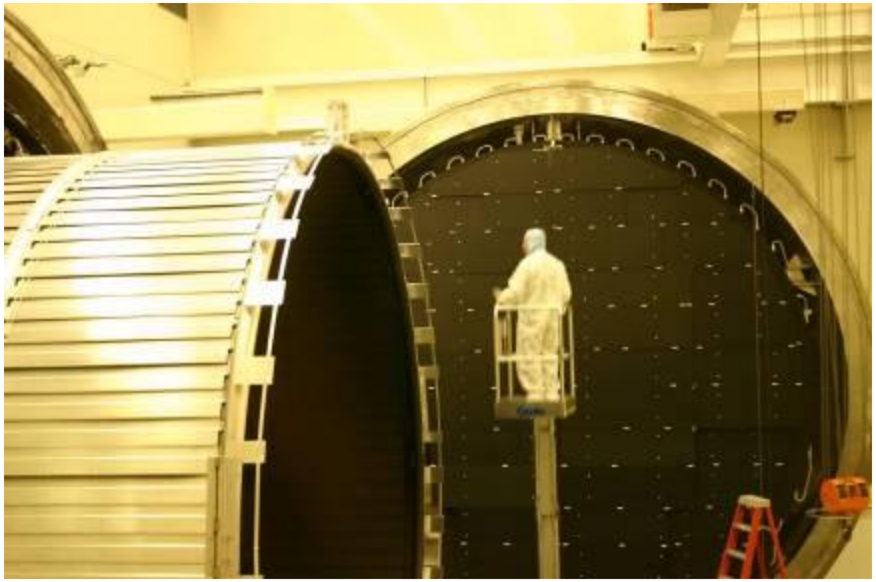


# MSFC Cryogenic Test Facility

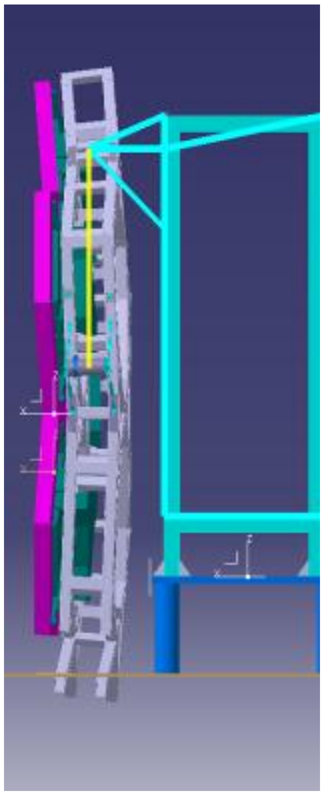


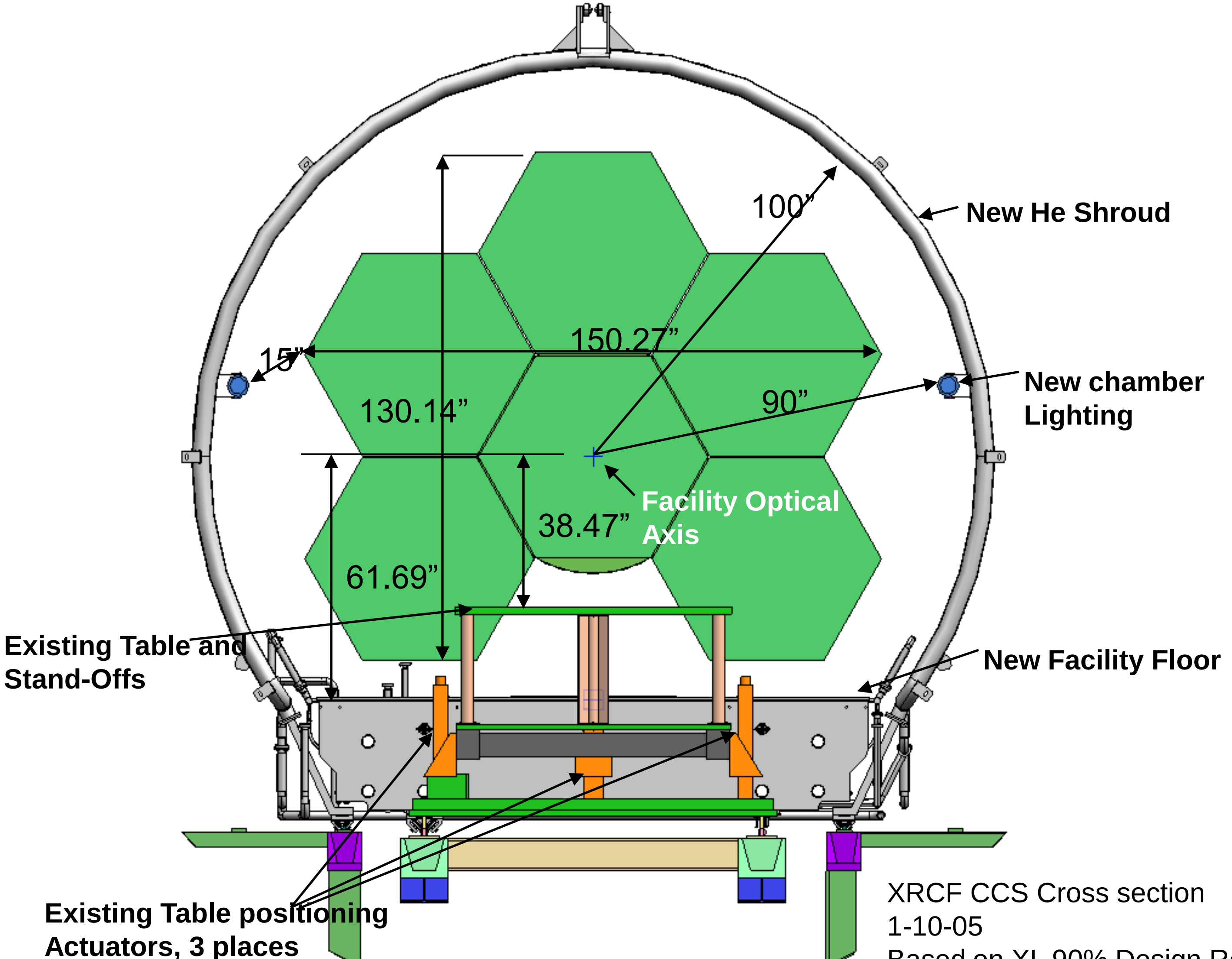
# XRCF Cryo-Shroud Fit- Check





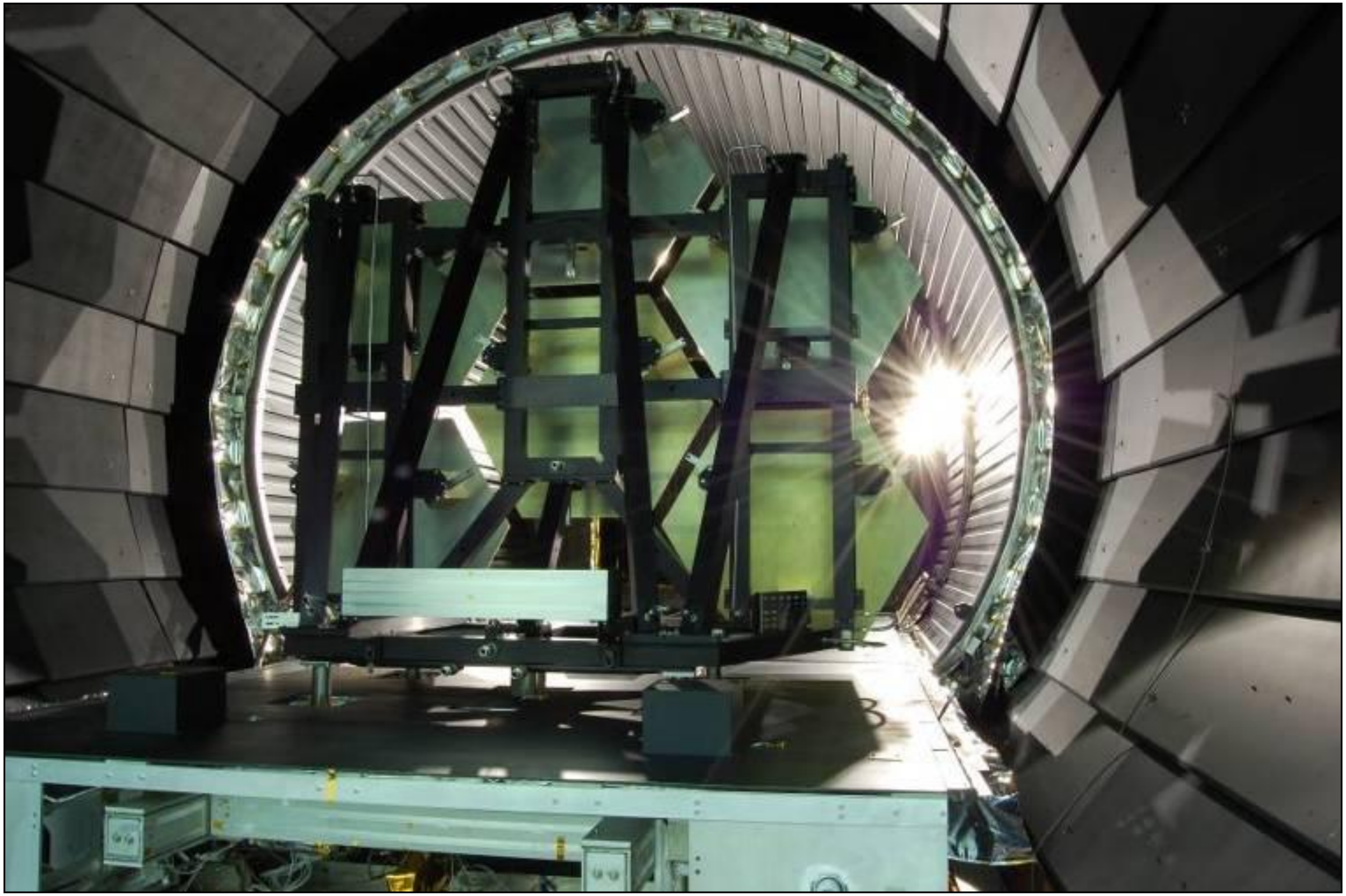
# MSFC Cryogenic Test Stand





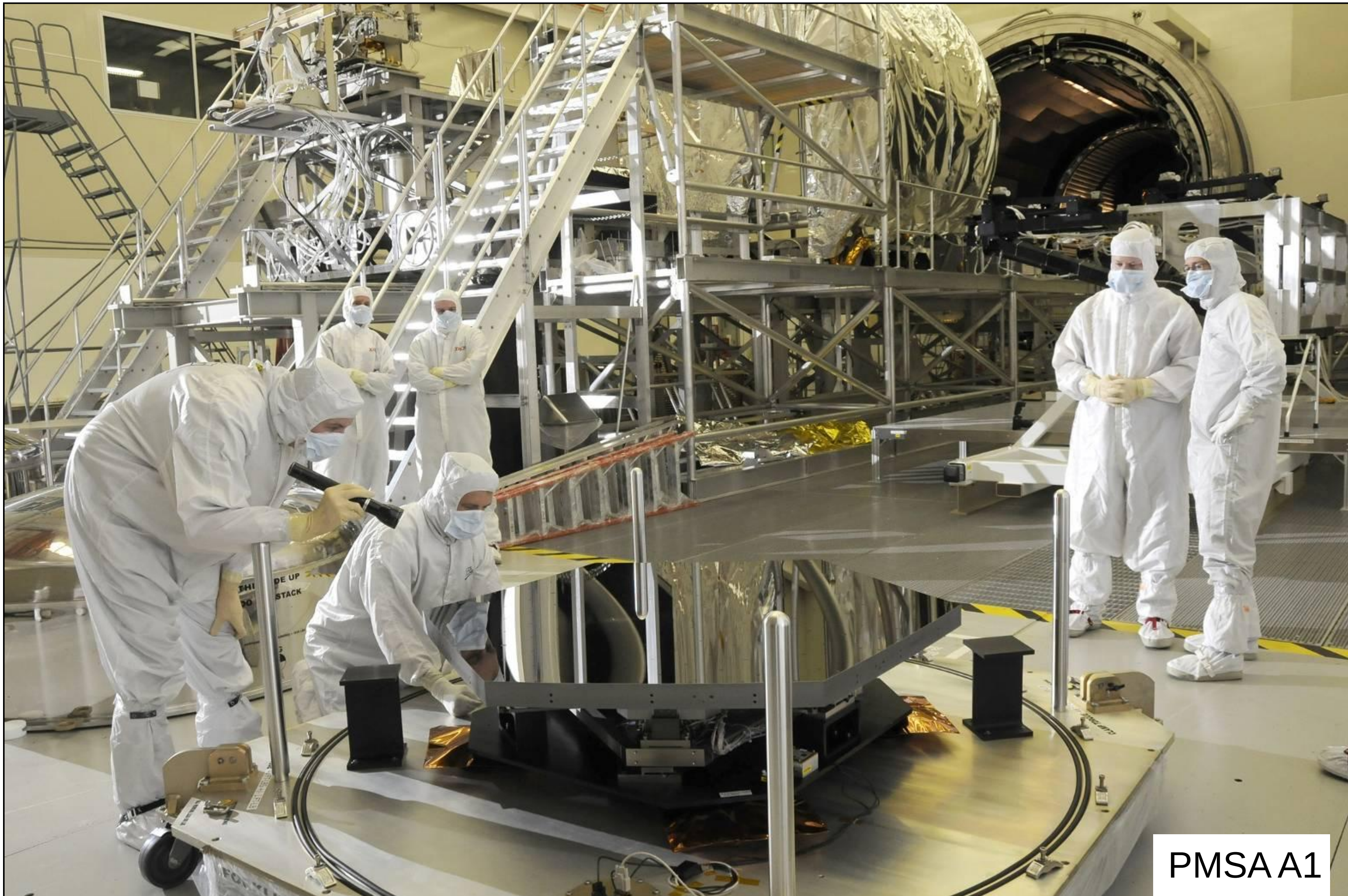

XRCF CCS Cross section
1-10-05
Based on XL 90% Design Review Data

# MSFC Cryo-Test

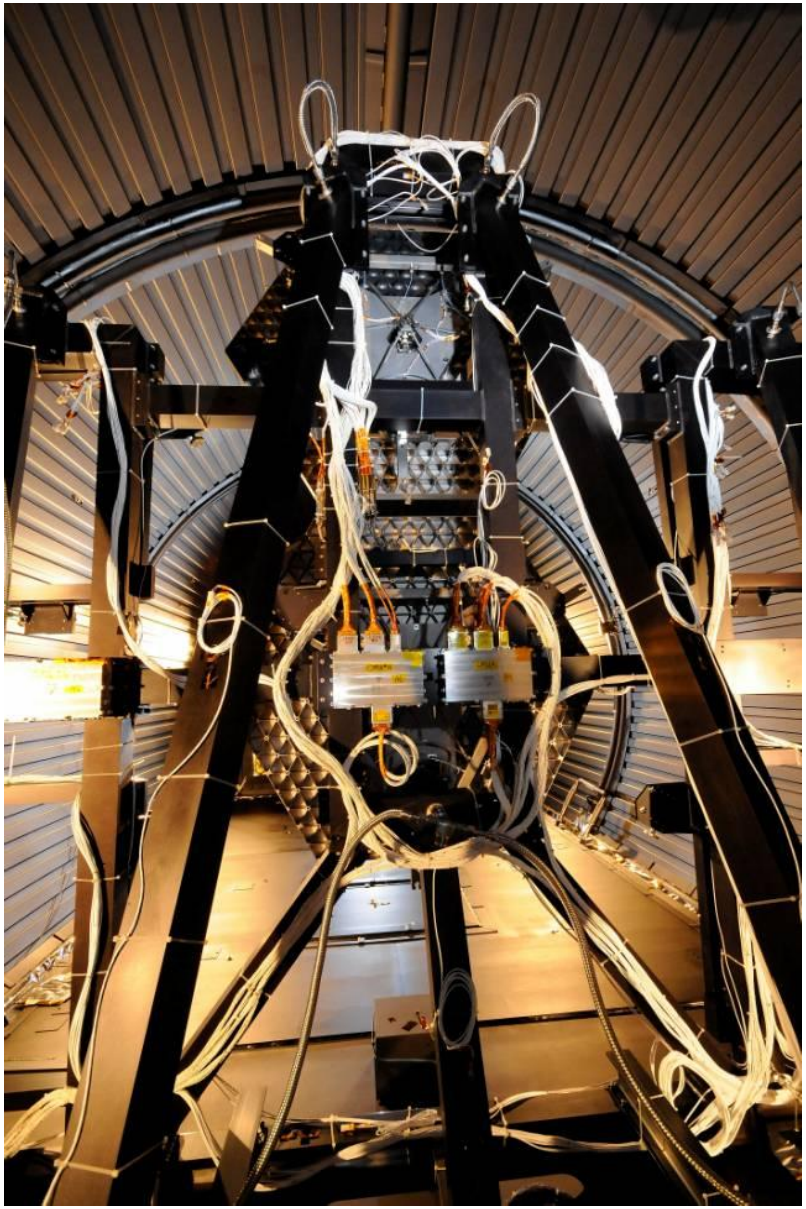


**GSE PMSA Test Stand Cryo Certification Testing at XRCF**

# The first flight mirror segment at the XRCF at MSFC

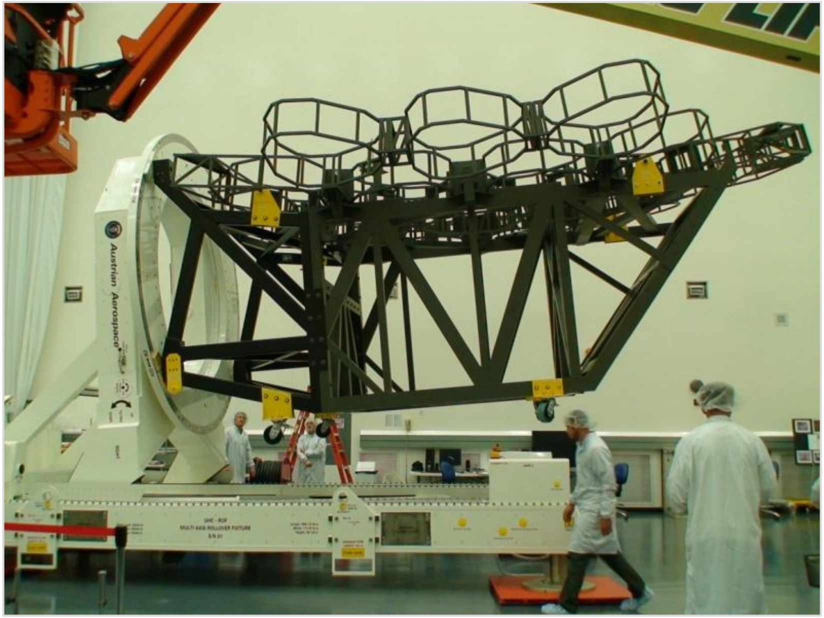


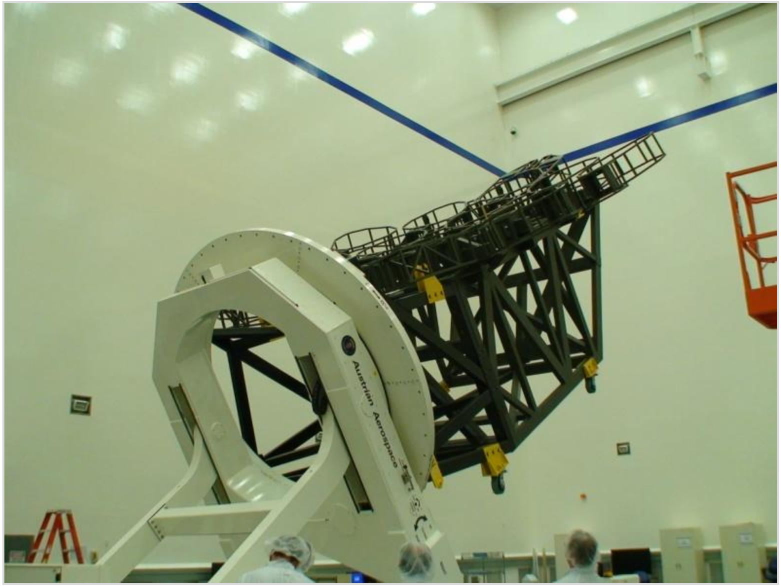
# EDU and A1 PMSAs in the XRCF chamber at MSFC

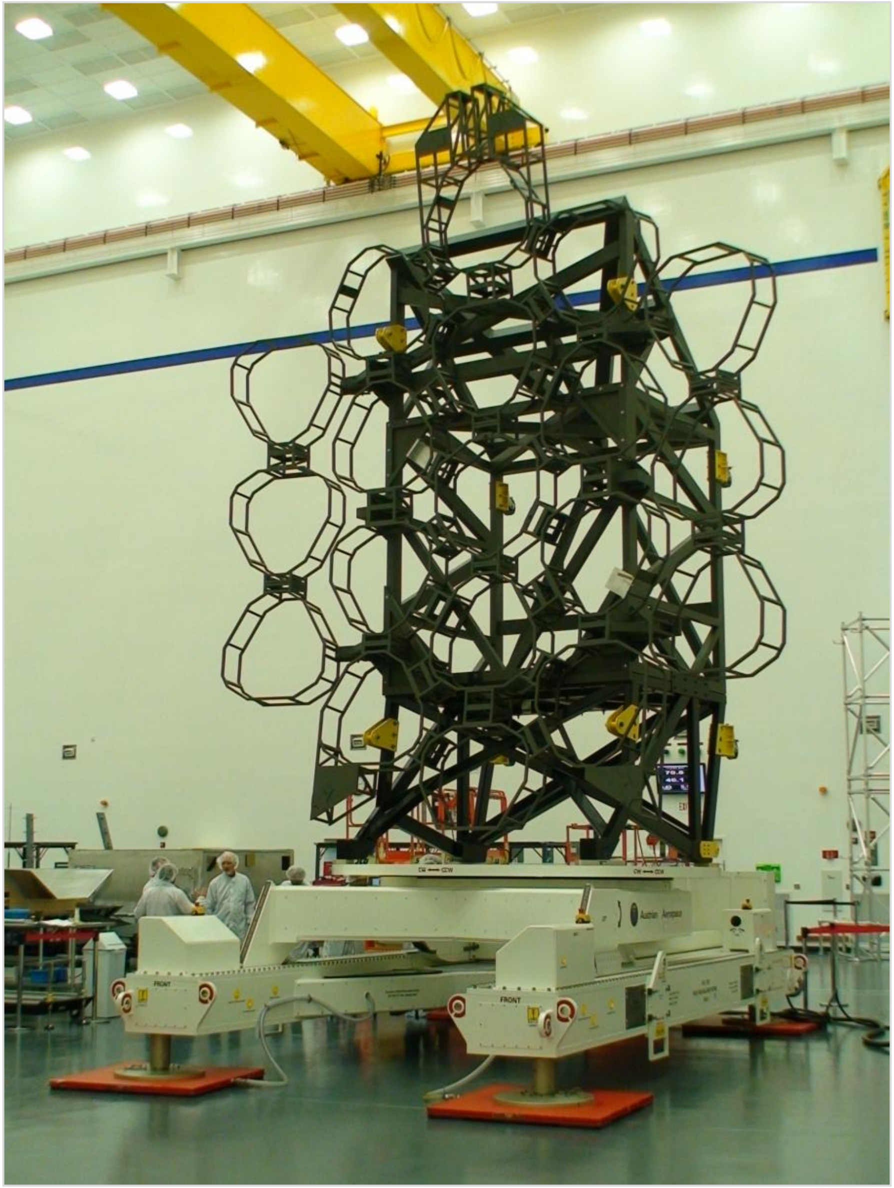


# Buildup of telescope flight structure underway at ATK

# Full scale OTE mockup in handling test at NGAS



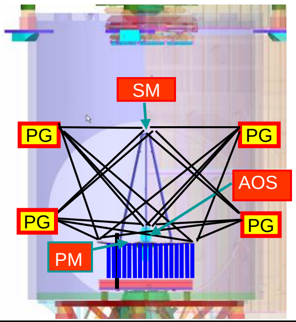



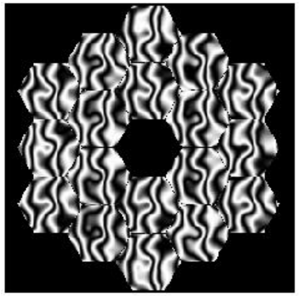
# Observatory level testing occurs at JSC Chamber A

## Verification Test Activities in JSC Chamber-A

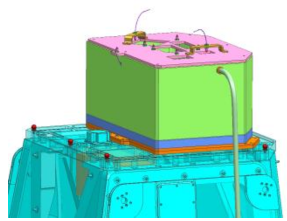
Cryo Position Metrology




Primary Mirror Stability Test

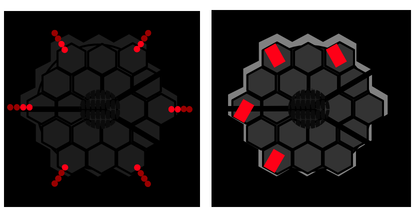


Focus Sweep Test (inward facing sources)

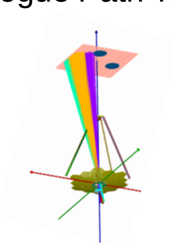


## Crosscheck Tests in JSC Chamber-A

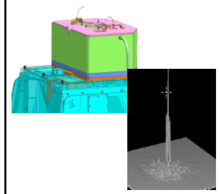
Pupil Alignment Test



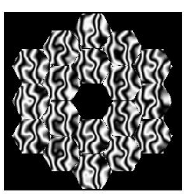
Rogue Path Test



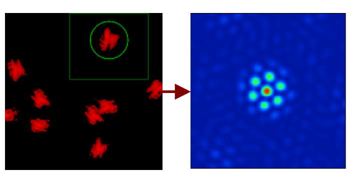
Pass-and-a-Half Test

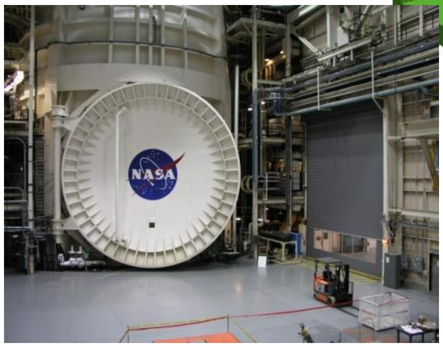


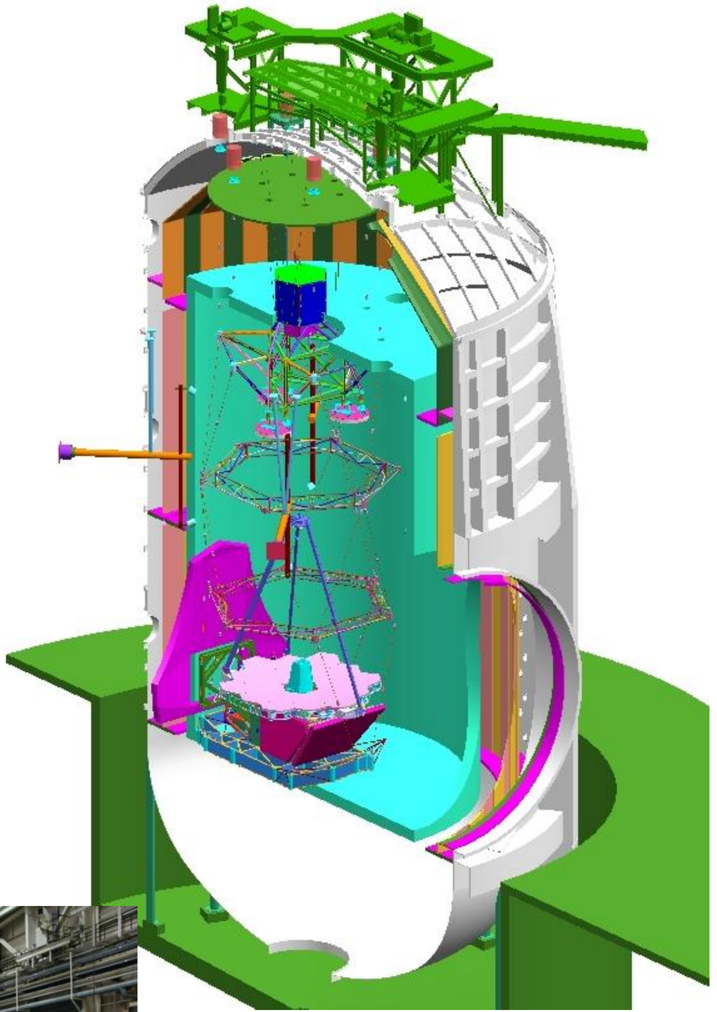
Primary Mirror WFE Test



End-to-End WFSC Demonstration





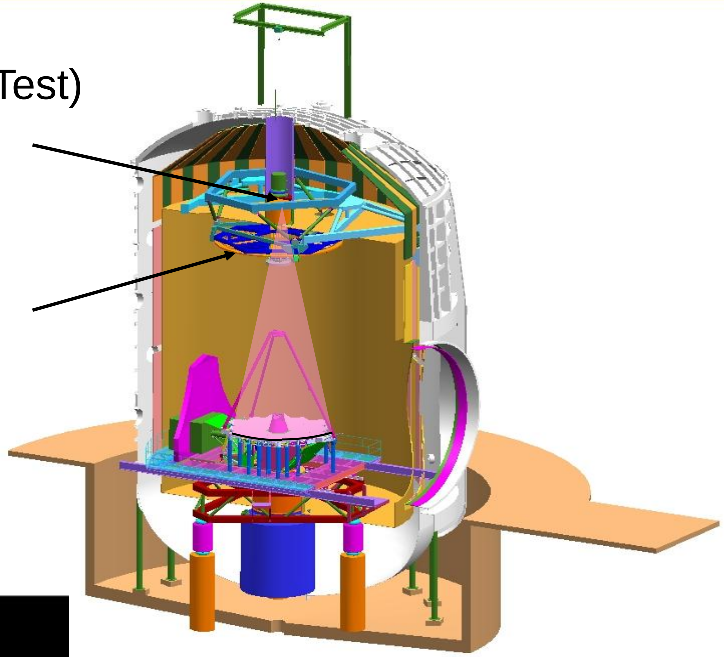
Chamber A:

- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

# Primary Mirror Testing

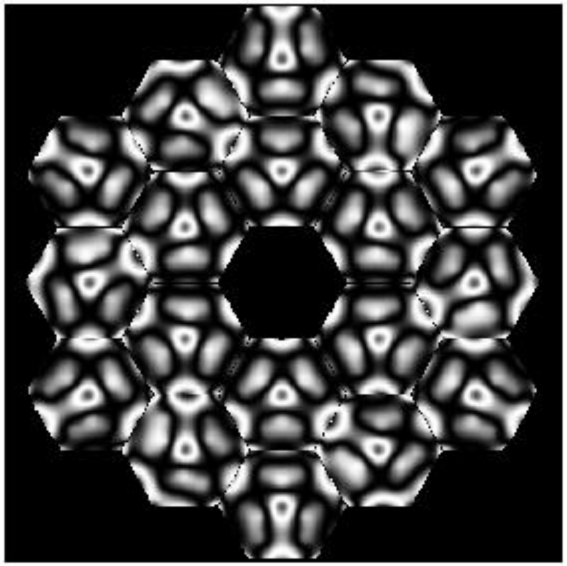
Center of Curvature Optical Assembly (COCOA) (PM Test)
- Multi Wavelength Interferometer
- Reflective Null Lens
- 6 DOF Position Drive

Object Surface Optical Assembly (OSOA) (ACFs)

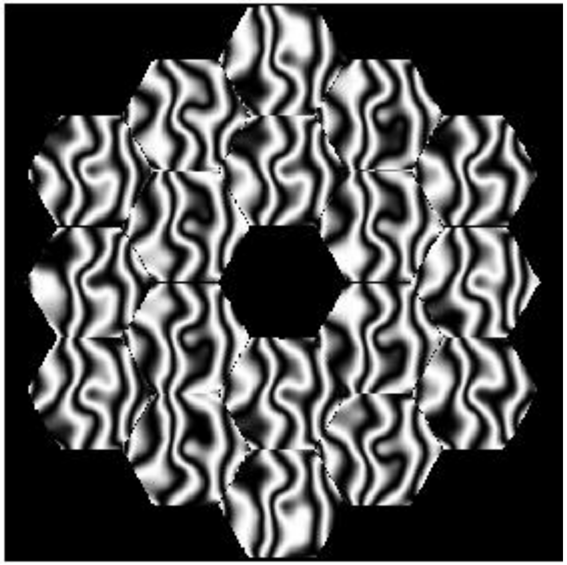


## Predicted PM 1g Gravity Deformation

~200 nm rms WFE (~1.5 λ PV @ 632 nm)



**Nulled Interferogram (λ=632 nm)**



**Interferogram with 20 Tilt Fringes**

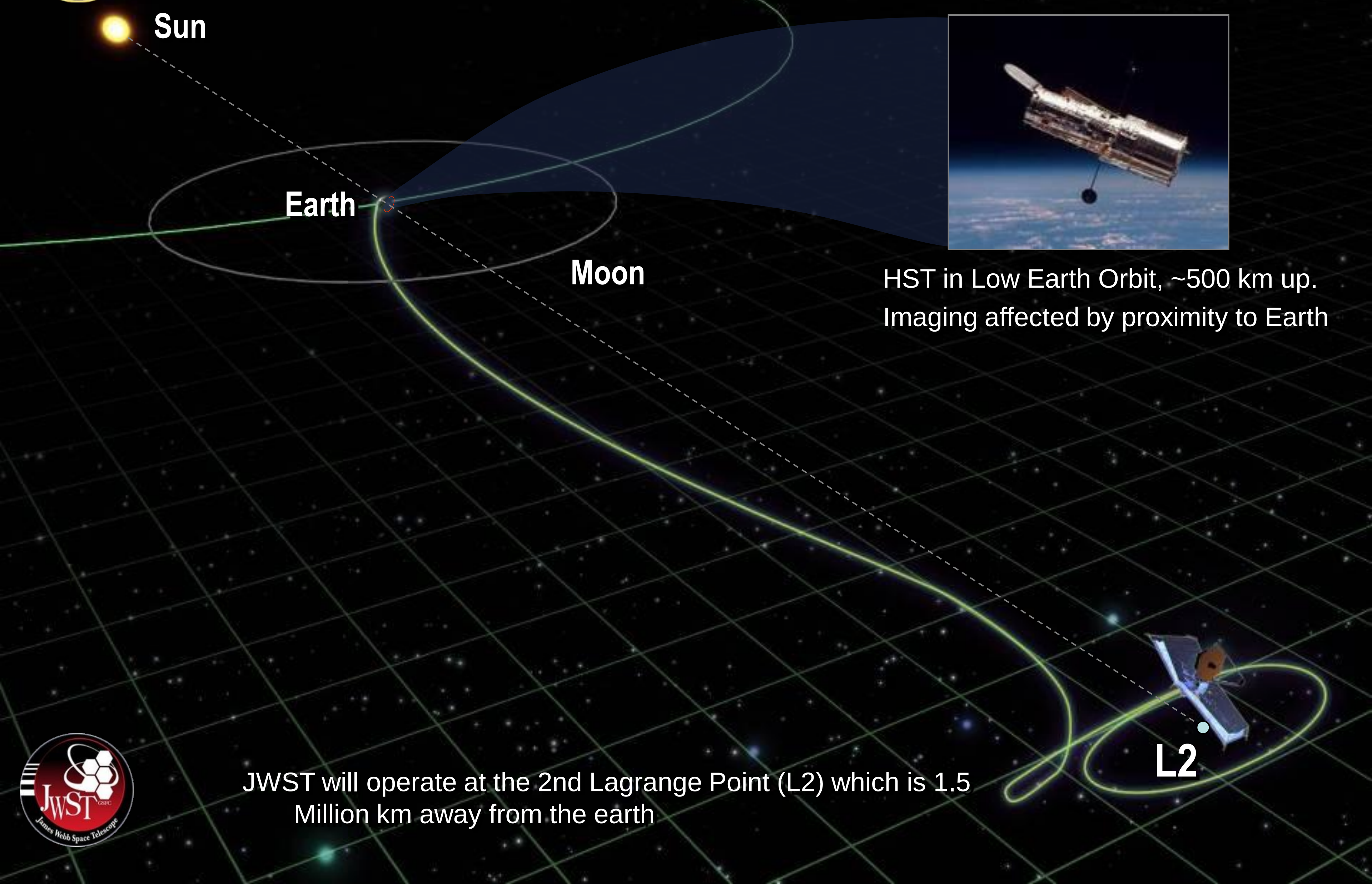
# JWST Launch Configuration


Ariane 5 ECA


- JWST is folded and stowed into Arian V with 5 m diameter x 17 m tall fairing
- Launch from Kourou Launch Center (French Guiana) with direct transfer to L2 point.
- Payload launched at ambient temperature with on orbit cooling to 50 K via passive thermal radiators
- JWST payload: 6330 kg

# JWST vs. HST - orbit






HST in Low Earth Orbit, ~500 km up.
Imaging affected by proximity to Earth

JWST will operate at the 2nd Lagrange Point (L2) which is 1.5 Million km away from the earth

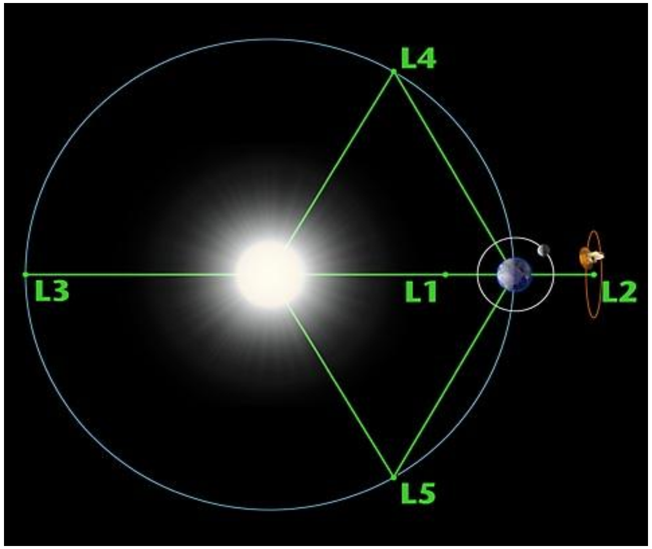
# L2 Orbit Enables Passive Cryogenic Operation

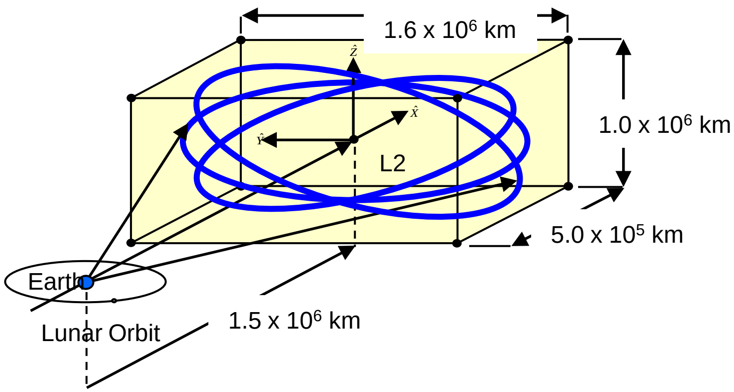
Second Lagrange Point (L2) of Sun-Earth System

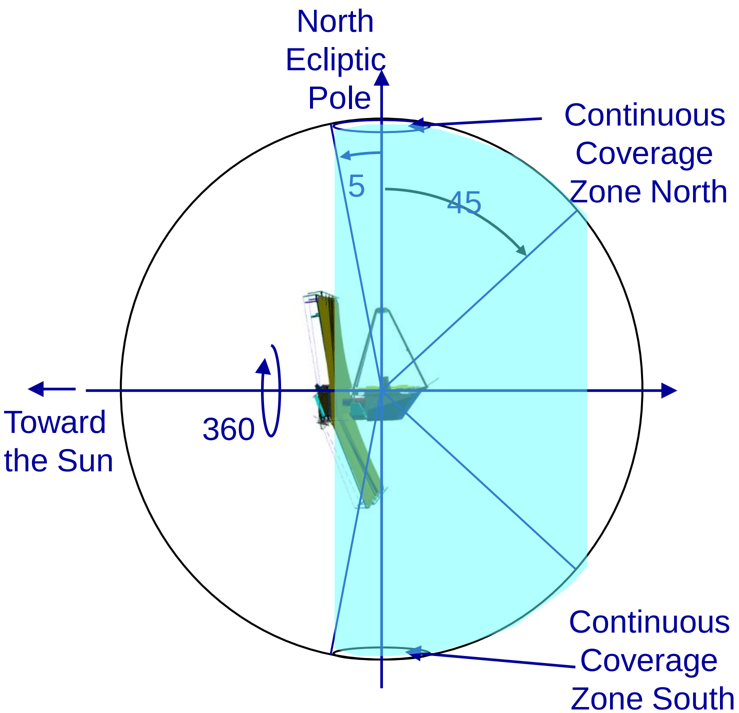
- This point follows the Earth around the Sun

The orbital period about L2 is ~ 6 months

- Station keeping thrusters required to maintain orbit
- Propellant sized for 11 years (delta-v ~ 93



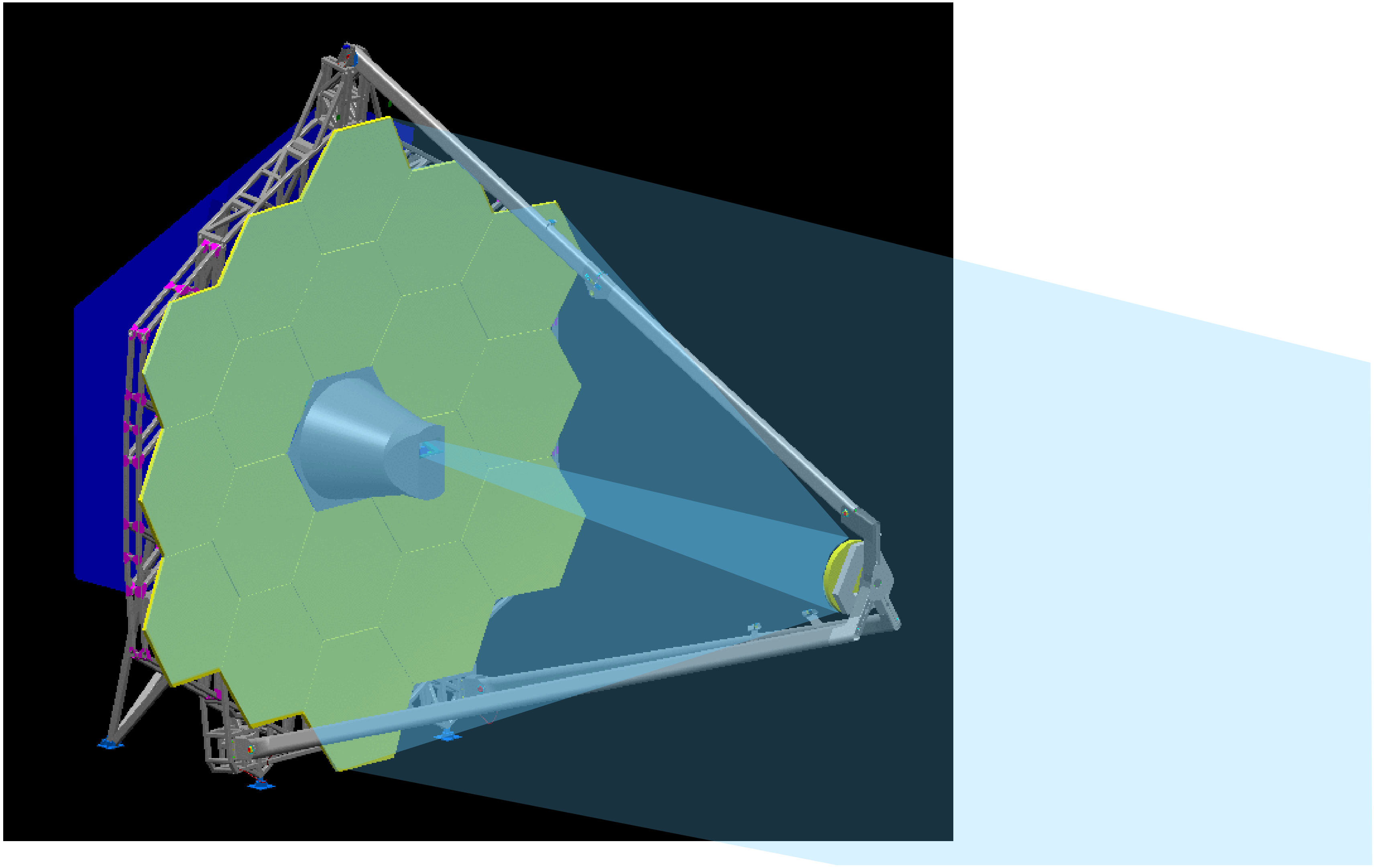




JWST observes whole sky while remaining continuously in shadow of its sunshield

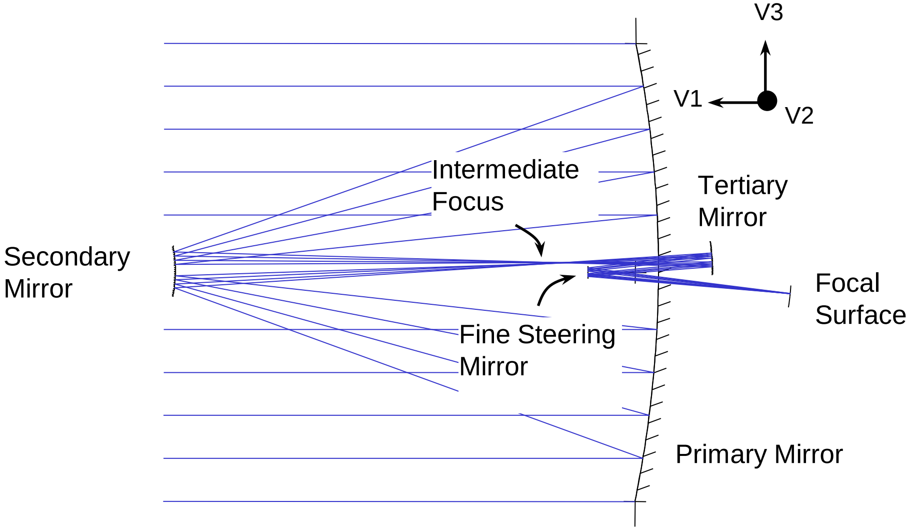
- Field of Regard is annulus covering 35% of the sky
- Whole sky is covered each year

[redacted]

# JWST Optical Path

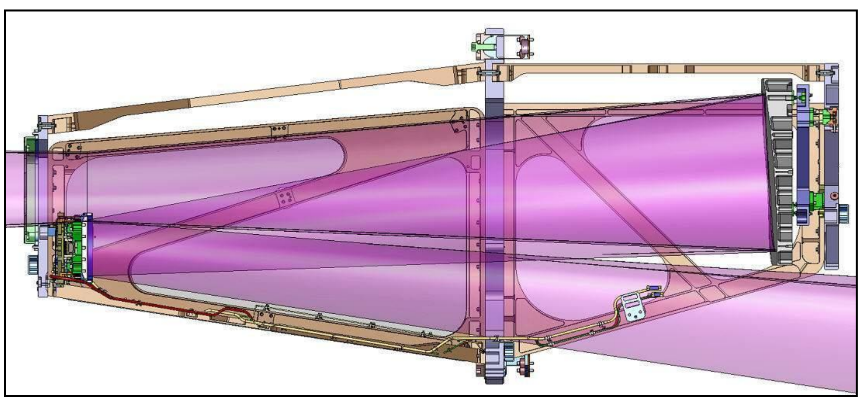


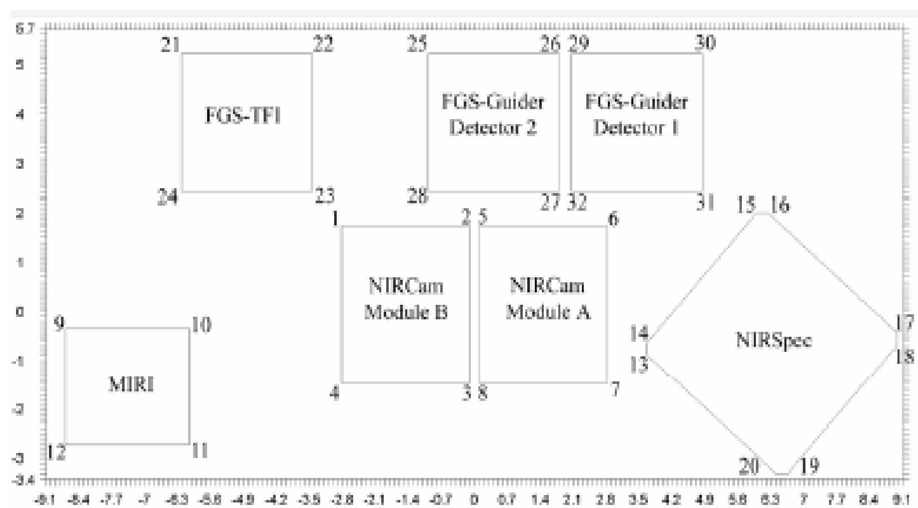
# The JWST telescope is a three mirror anastigmat equipped with a fine steering mirror




JWST's is a Three Mirror Anistigmat (TMA)

- Optical design: f/20
- Diameter of PM: 6.6 m
- Effective focal length: 131.4 m
- Clear aperture area: 25 $m^2$
- Field of view: 18.2 x 9.1 arcmin
- Elliptical f/1.2 Primary Mirror
- Hyperbolic Secondary Mirror creates f/9 intermediate image
- Elliptical Tertiary Mirror images pupil at Fine Steering Mirror
- Transmitted Wavefront Error is 131 nm rms



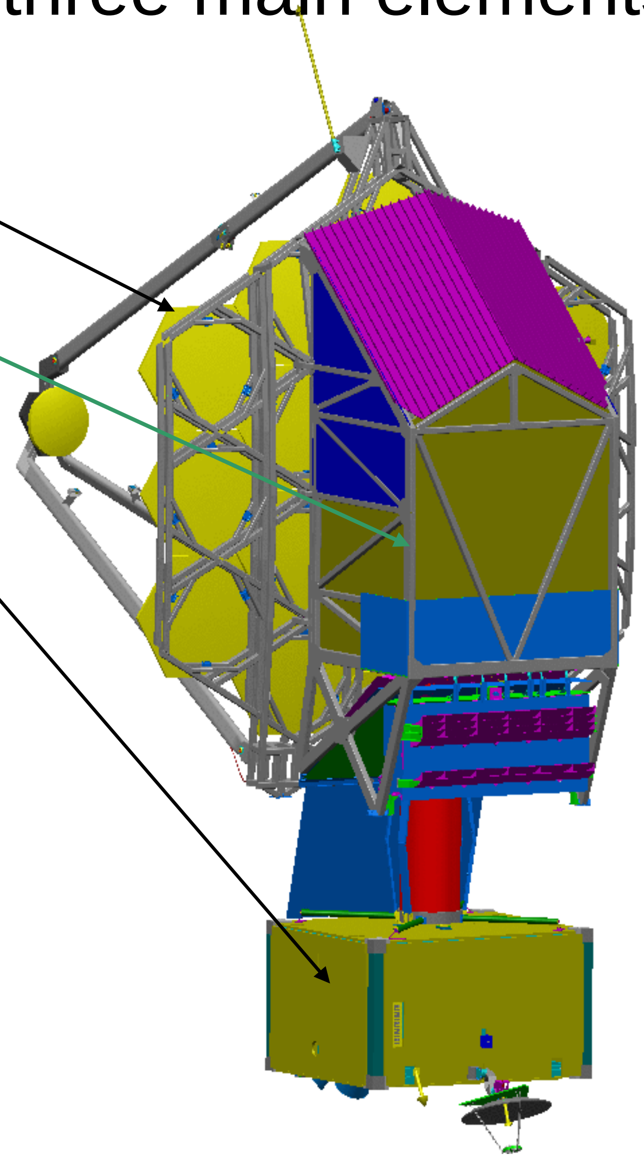


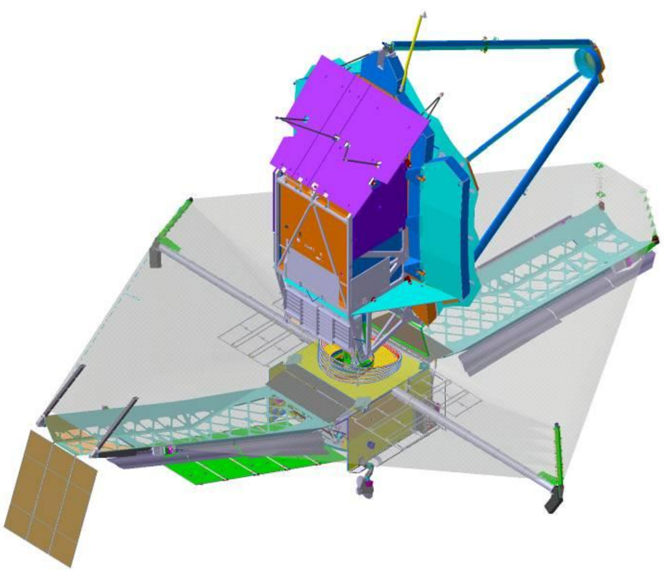
# JWST space vehicle consists of three main elements

**Optical Telescope Element (OTE)**
- Collects star light from distant objects

**Integrated Science Instrument Module (ISIM)**
- Decodes physics information from star light and converts to digital data

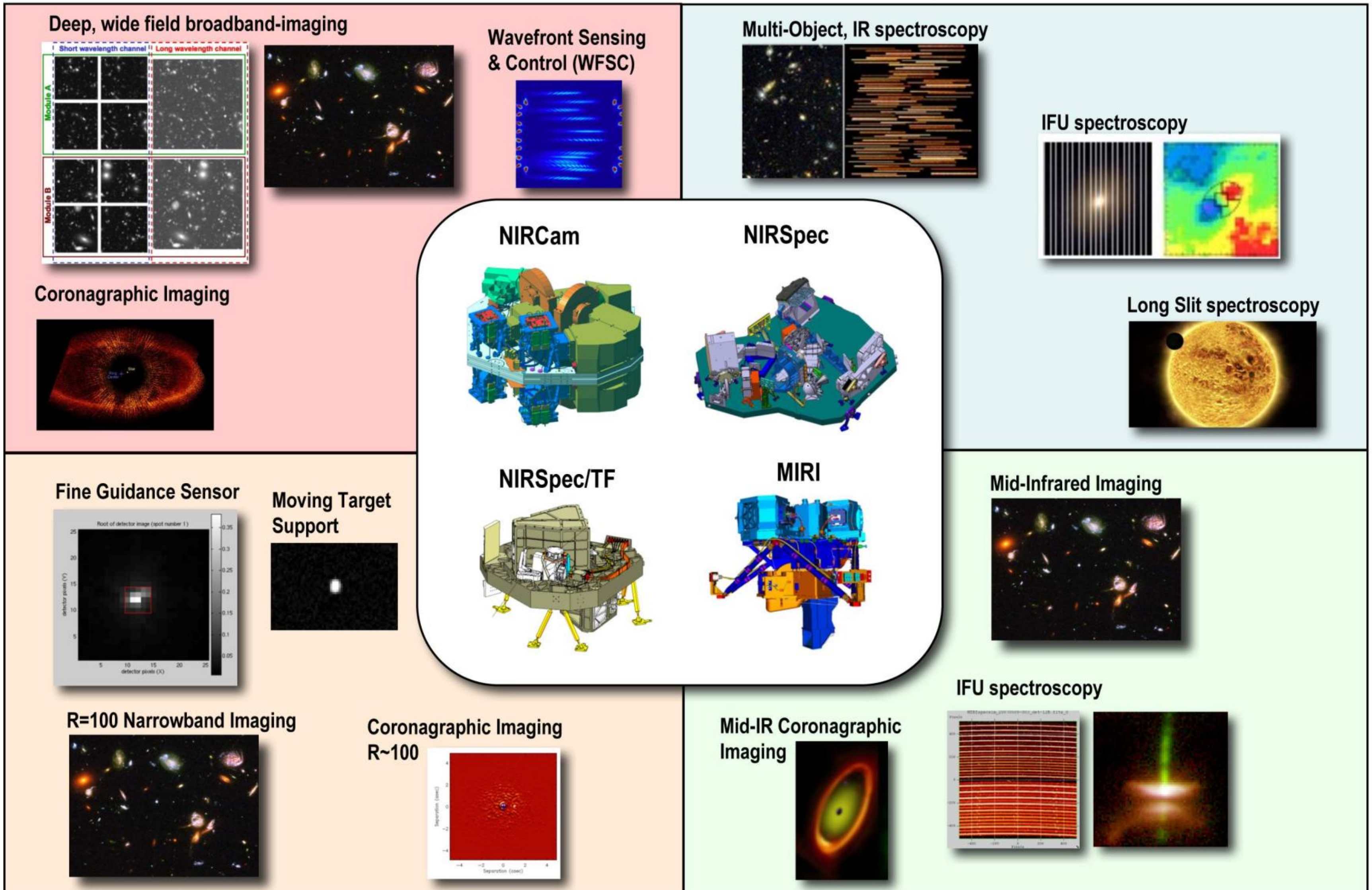
**Spacecraft**
- Attitude control, telecom, power & other support systems



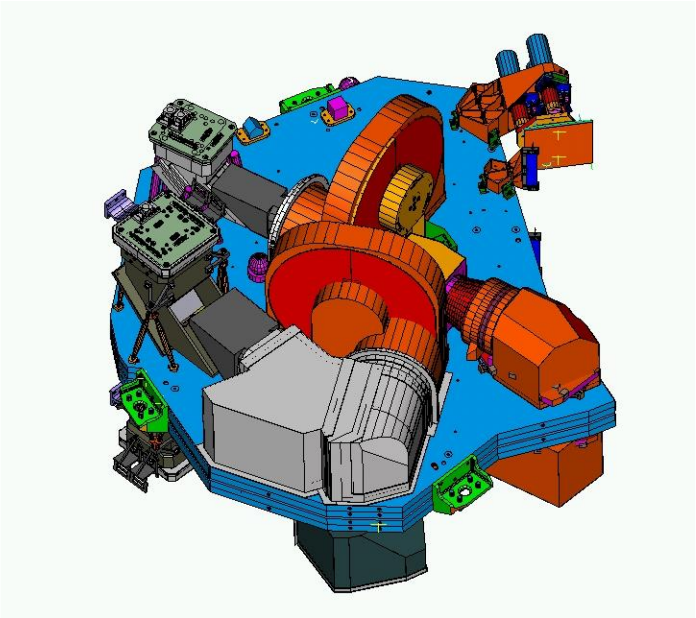


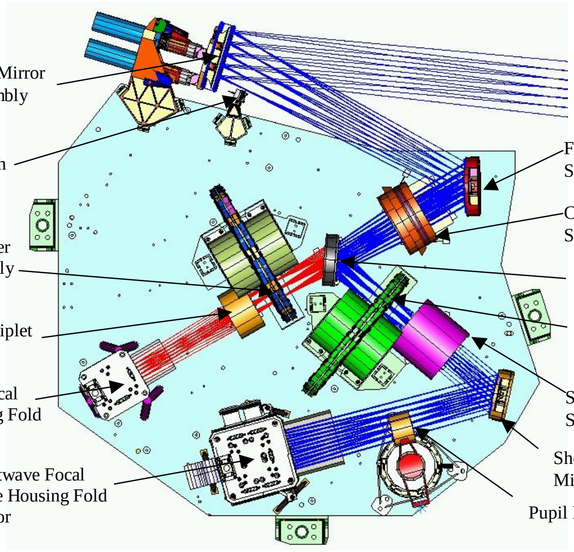
# JWST Science Instruments

enable imagery and spectroscopy over the 0.6 – 29 micron spectrum



# NIRCam images large portions of the sky identifying primeval galaxy targets for the other instruments





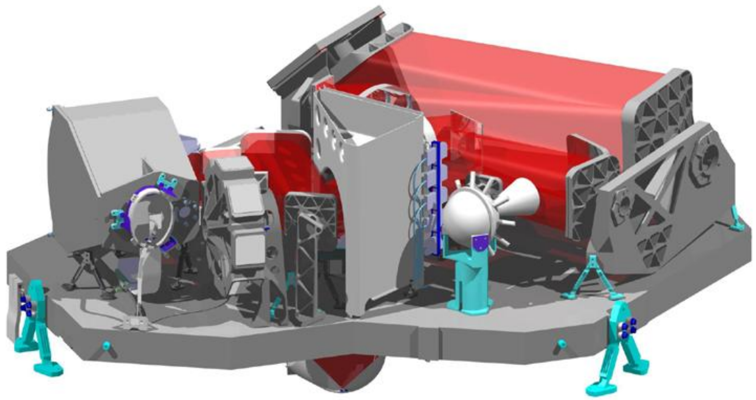

Developed by the University of Arizona with Lockheed Martin ATC

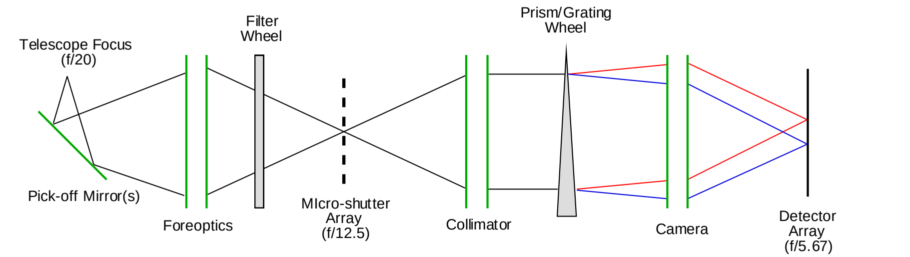
- Operating wavelength: 0.6 – 5.0 microns
- Spectral resolution: 4, 10, 100
- Field of view: 2.2 x 4.4 arc minutes
- Angular resolution (1 pixel): 32 mas < 2.3 microns, 65 mas > 2.4 microns
- Detector type: HgCdTe, 2048 x 2048 pixel format, 10 detectors, 40 K passive cooling
- Refractive optics, Beryllium structure

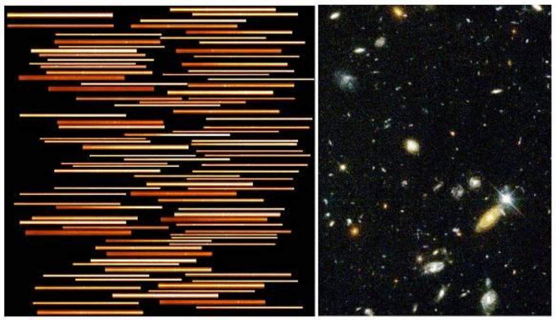
Supports OTE wavefront sensing

NIRCam ETU in integration now

# NIRSpec obtains spectra of 100 galaxies per exposure

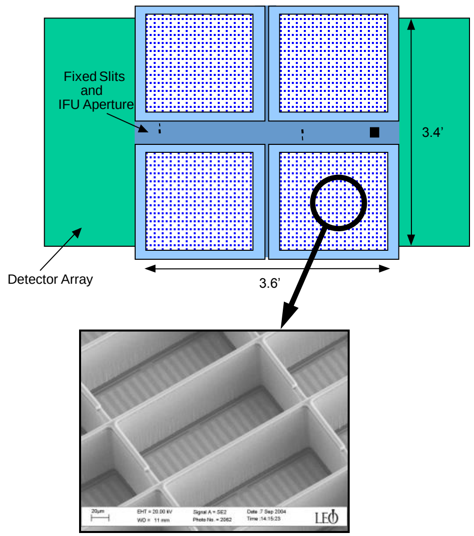




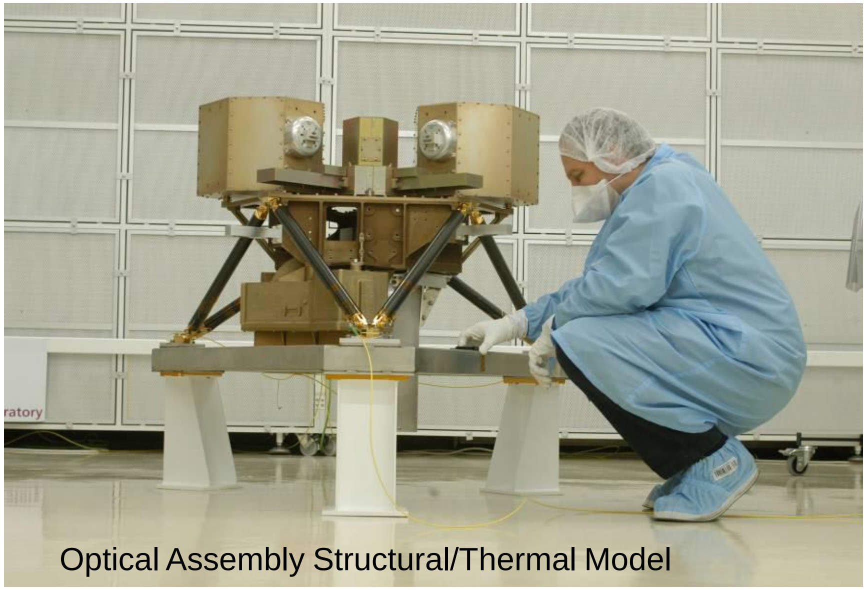
Developed by the European Space Technology Center (ESTEC) with Astrium GmbH and Goddard Space Flight Ctr

- Operating wavelength: 0.6 – 5.0 microns
- Spectral resolution: 100, 1000, 3000
- Field of view: 3.4 x 3.4 arc minutes
  - Aperture control: programmable micro-shutters, 250,000 pixels
  - Angular resolution: shutter open area 203 x 463 mas, pitch 267 x 528 mas
- Detector type: HgCdTe, 2048 x 2048 pixel format, 2 detectors, 37 K passive cooling
- Reflective optics, SiC structure and optics

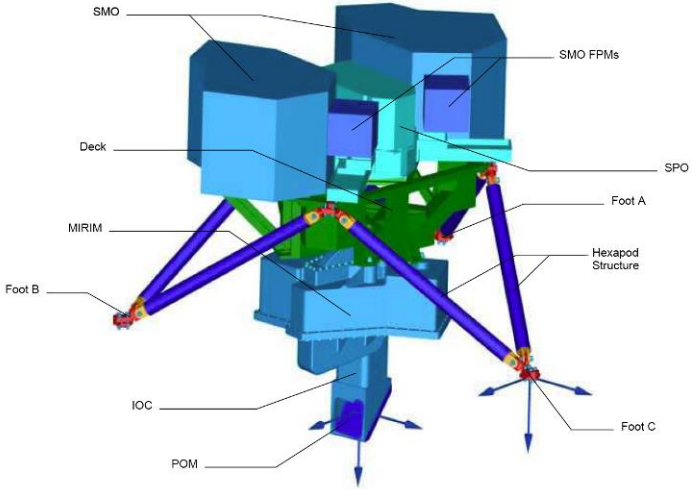



ETU Testing & FM Integration Underway Now

# MIRI studies galaxy evolution



Optical Assembly Structural/Thermal Model

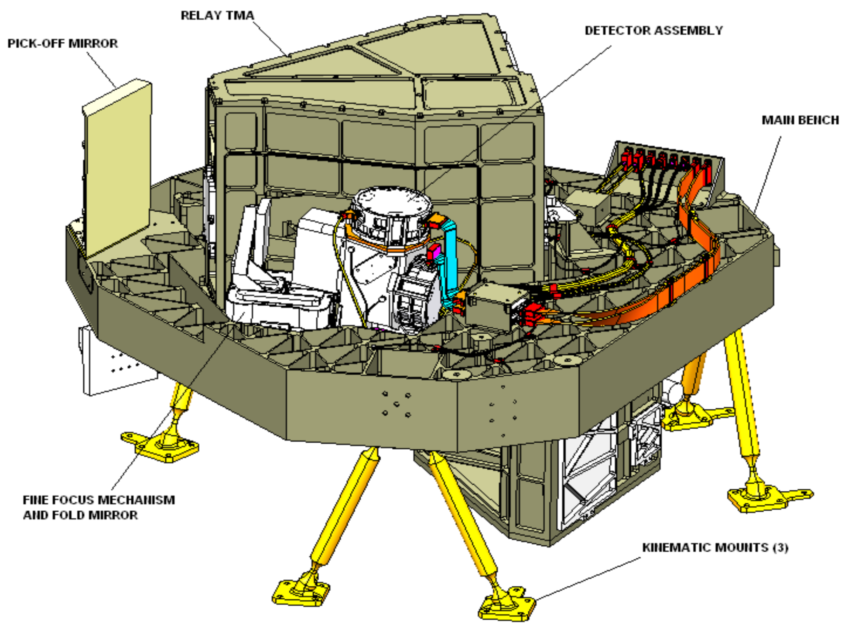


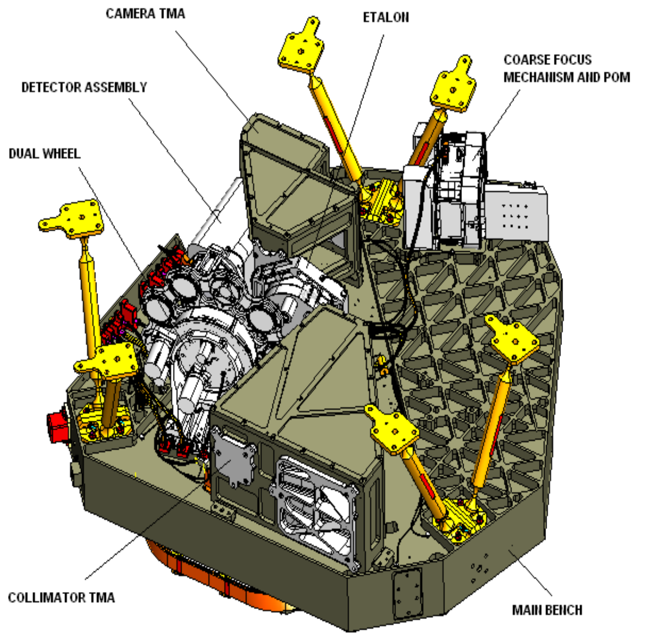

Developed by the United Kingdom Advanced Technology Center and JPL

- Operating wavelength: 5 - 29 microns
- Spectral resolution: 5, 100, 2000
- Field of view: 1.9 x 1.4 arc minutes broad-band imagery
  - R100 spectroscopy 5 x 0.2 arc sec slit
  - R2000 spectroscopy 3.5 x 3.5 and 7 x 7 arc sec integral field units
- Detector type: Si:As, 1024 x 1024 pixel format, 3 detectors, 7 K cryo-cooler
- Reflective optics, Aluminum structure and optics

ETU Testing Completed Dec 08
Flight Model in Integration Now

# FGS provides imagery for telescope pointing control & imaging spectroscopy to reveal primeval galaxies and extra-solar planets



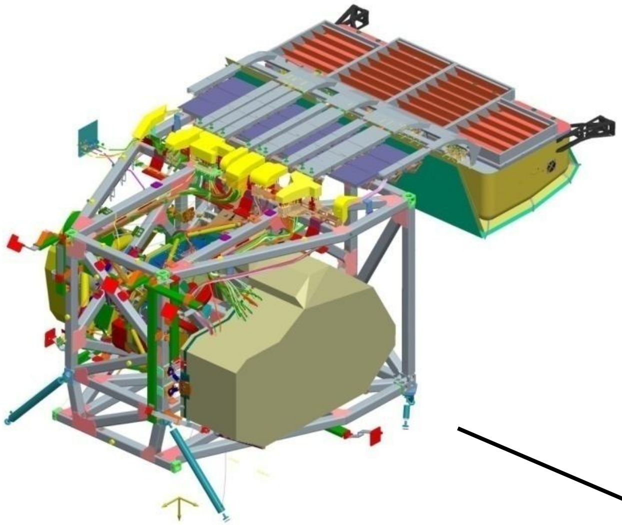




## Developed by the Canadian Space Agency with ComDev

- Operating wavelength: 0.8 – 4.8 microns
- Spectral resolution: Broad-band guider and R=100 science imagery
- Field of view: 2.3 x 2.3 arc minutes
  - R=100 imagery with Fabry-Perot tunable filter and coronagraph
- Angular resolution (1 pixel): 68 mas
- Detector type: HgCdTe, 2048 x 2048 pixel format, 3 detectors, 40 K passive cooling
- Reflective optics, Aluminum structure and optics

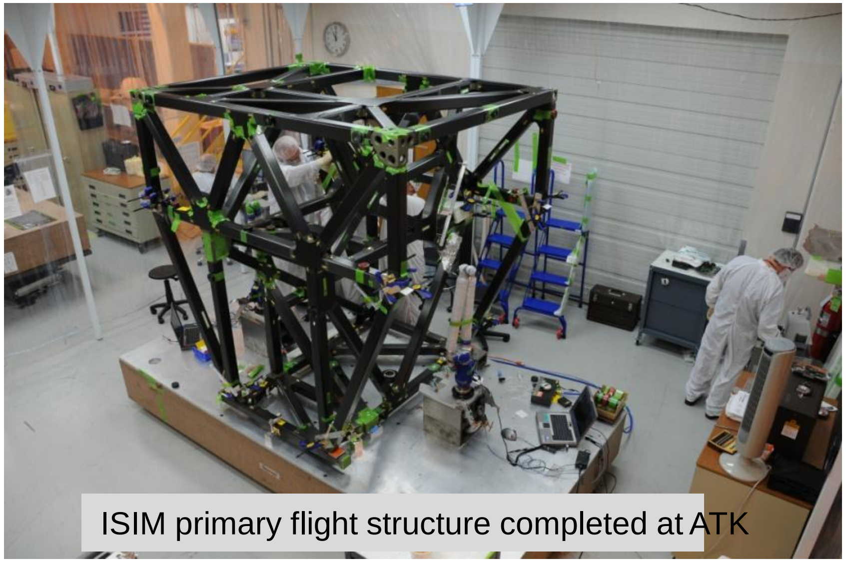
FGS ETU in Test Now

# All Science Instruments integrate into ISIM

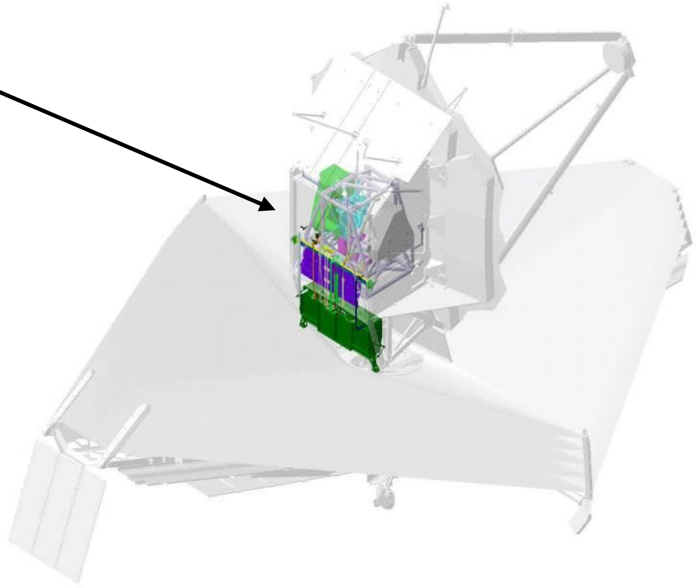


Integrated Science Instrument Module (ISIM) contains:

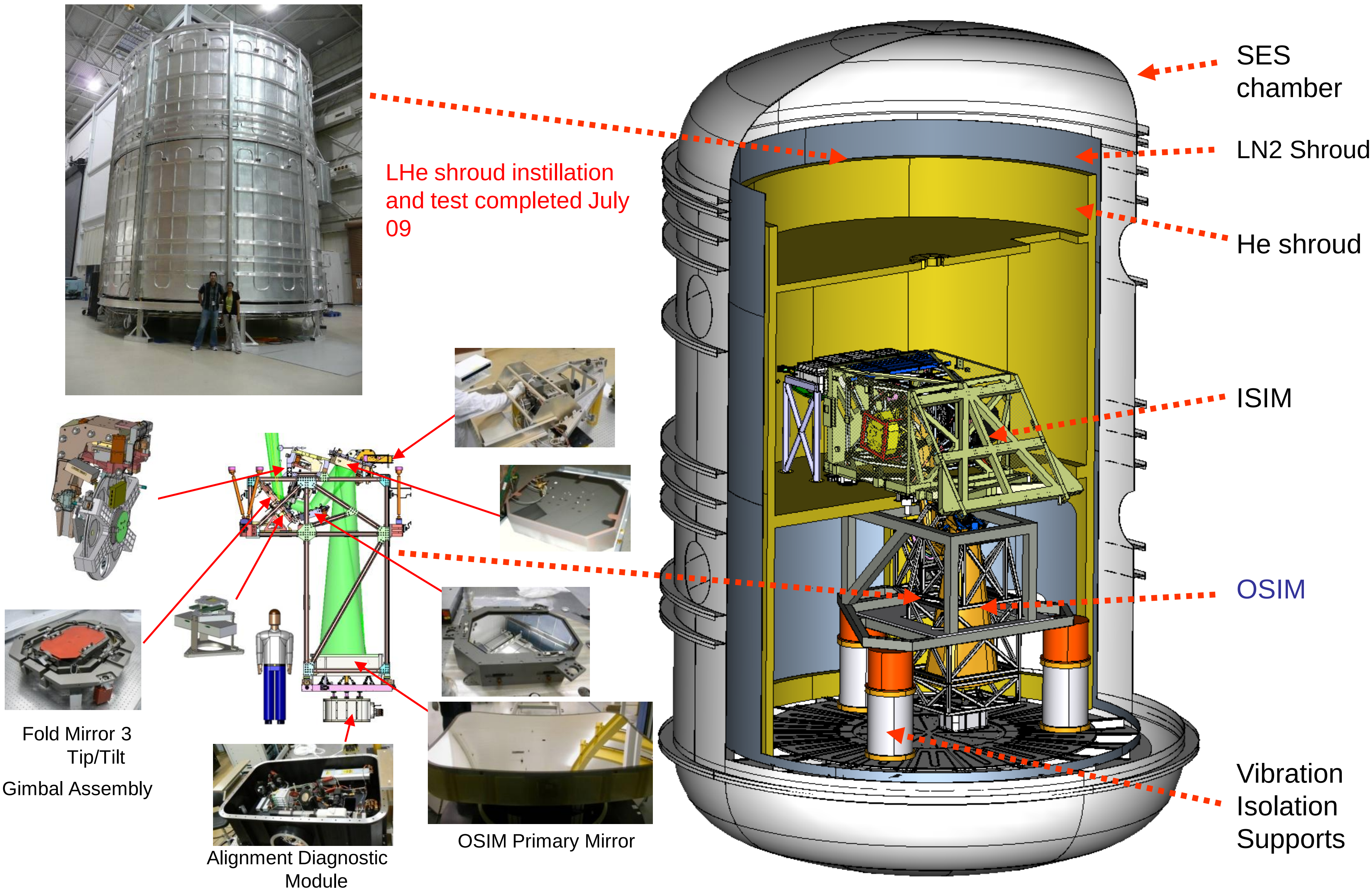
- Four science instruments
- Command and data handling system
- Flight software system
- Passive cryogenic thermal control system
- Optical metering structure system
- Science instrument control electronics
- Electrical harness system



ISIM primary flight structure completed at ATK

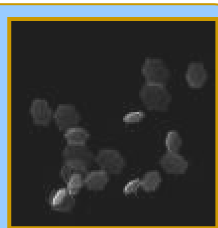


# ISIM will be tested in the GSFC SES chamber using an Optical Telescope Simulator (OSIM)



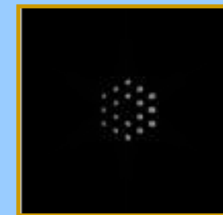
# Deployed Telescope Phasing

First Image

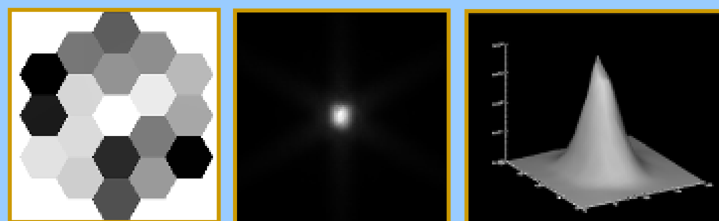


Secondary Mirror Focus Sweep

Segment ID and Image Array

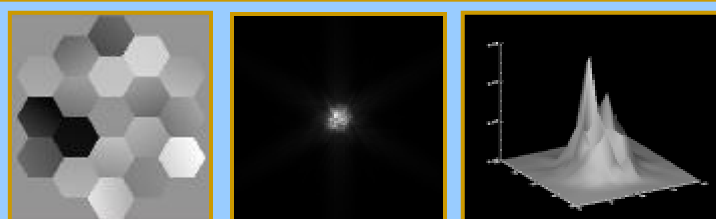


Global Alignment



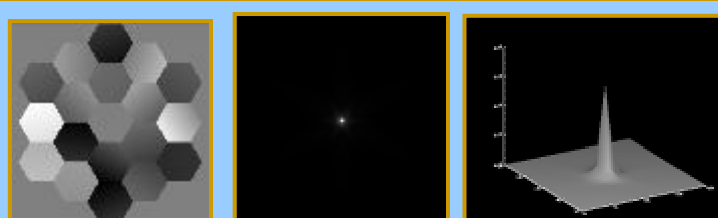
Segment wave front error <200nm and segment-to-segment piston <100μm rms after Global Alignment

Coarse Phasing (Fine Guiding)



PM wave front error < 1000 nm rms after Coarse Phasing

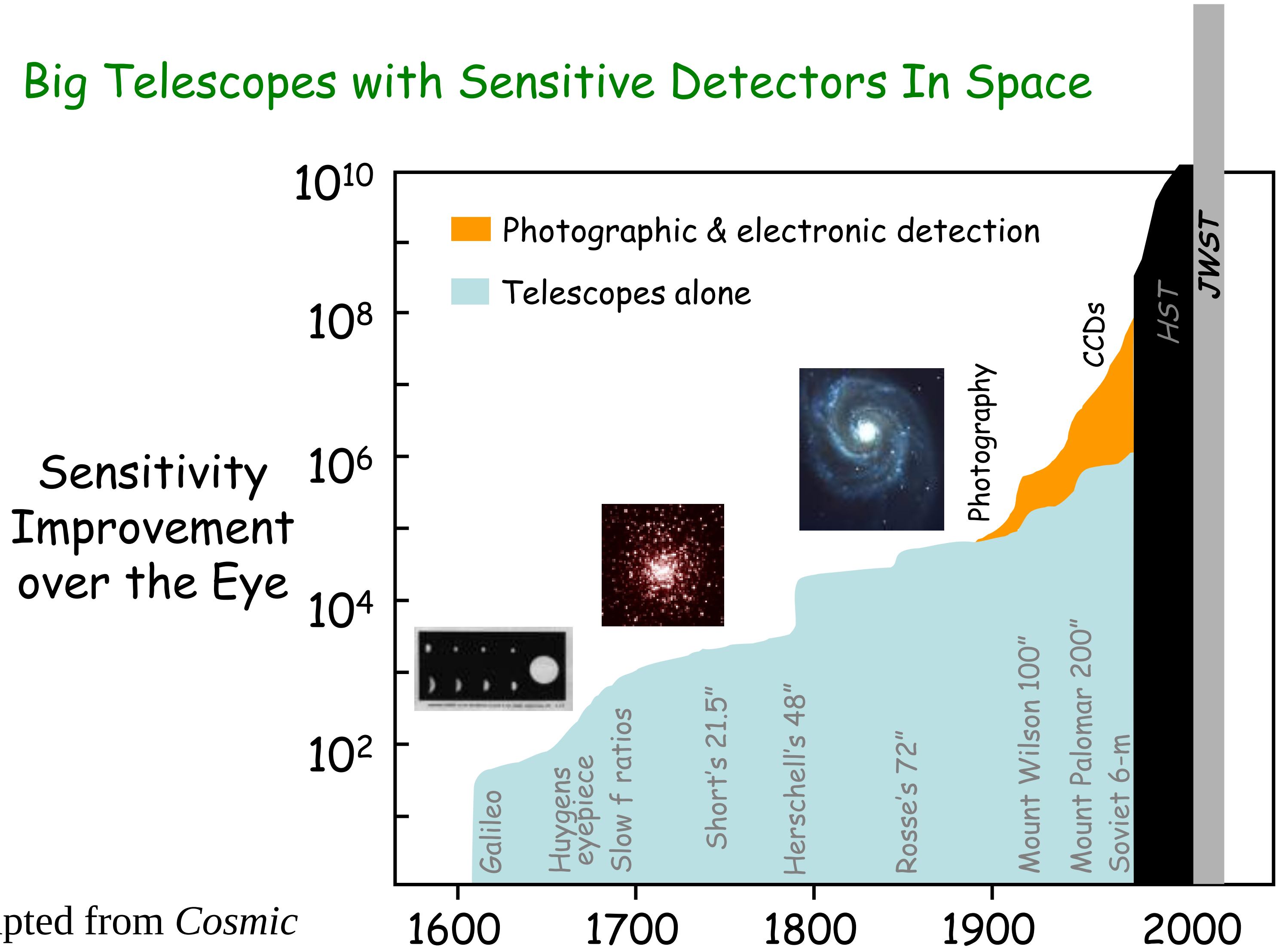
Fine Phasing (SP & MIMF)



OTE wave front error < 131 nm rms after Fine Phasing; stability > 14 days

Processes have been demonstrated on the Test Bed Telescope as part of TRL-6 development

# How to win at Astronomy
# Aperture = Sensitivity



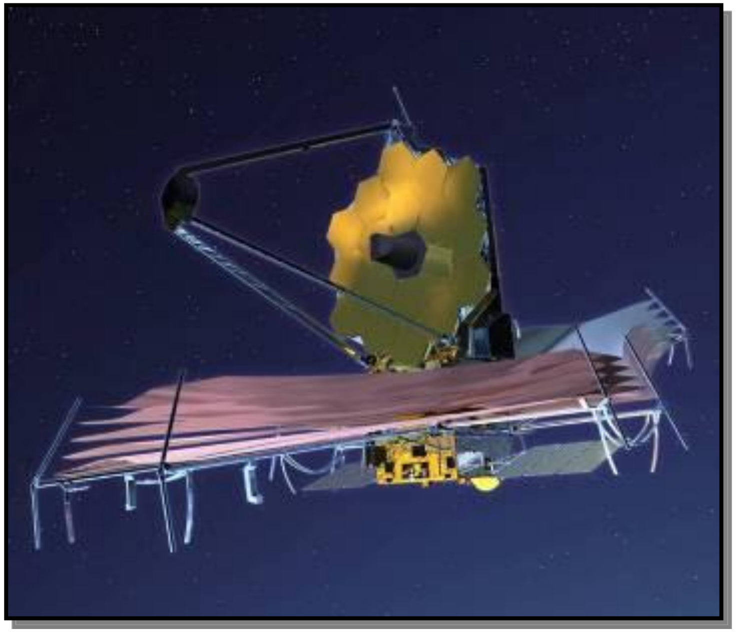

Adapted from *Cosmic Discovery*, M. Harwit

# JWST Expands on HST Capabilities

HST: 2.4 m diameter Primary Mirror

Room Temperature

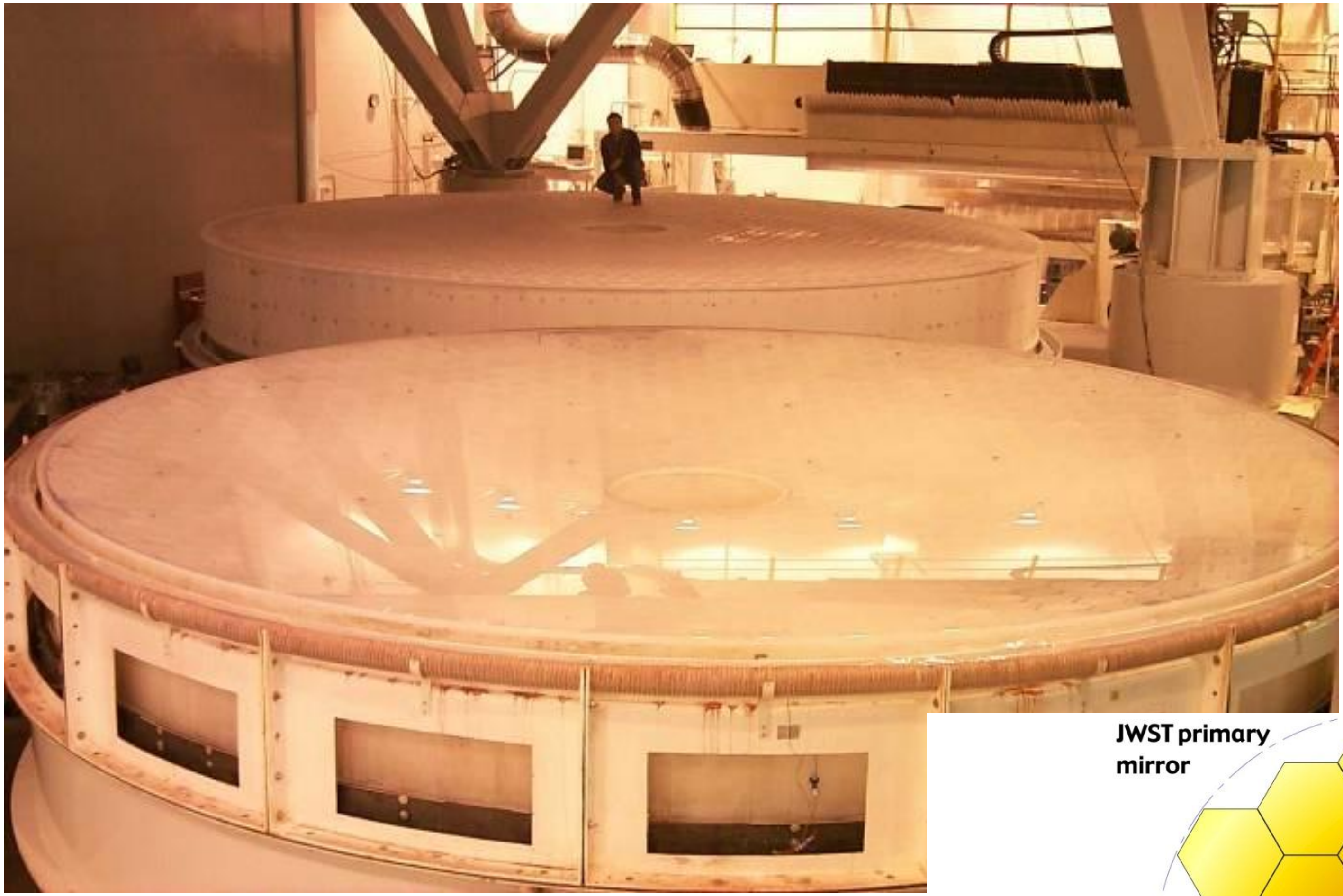
JWST: 6.5 m diameter Primary Mirror

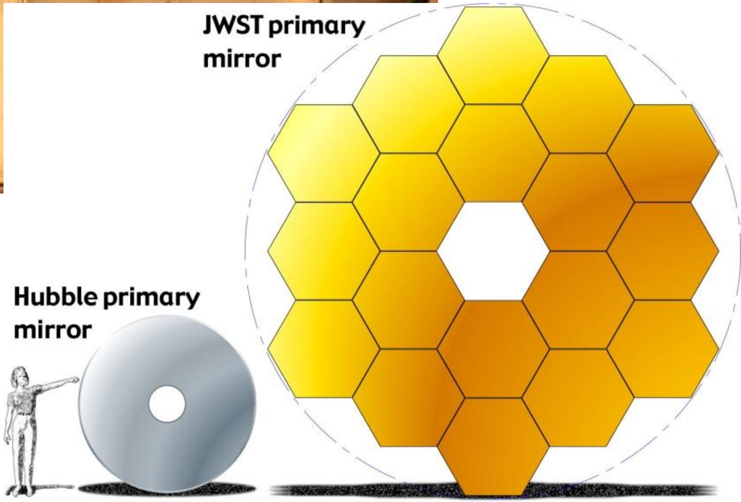


< 50 K (~ -223 C or -370 F)

- **JWST has 7x the light gathering capability of the Hubble Space Telescope**
- **JWST operates in extreme cold to enable sensitive infrared light collection**
- **JWST has same angular resolution in the near-IR as HST in visible**

# How big is JWST?





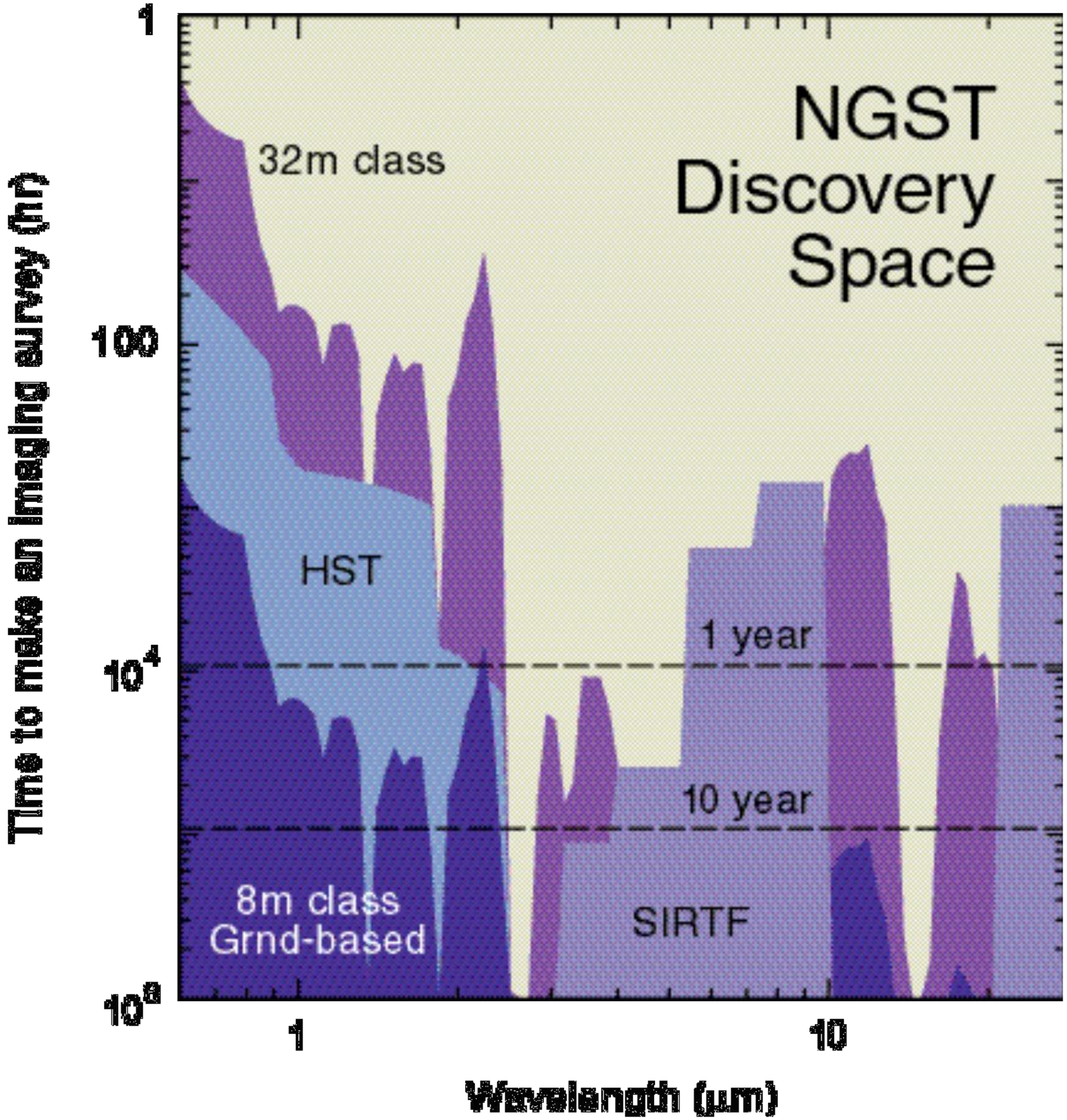
# Full Scale JWST Mockup

21st National Space Symposium, Colorado Springs, The Space Foundation

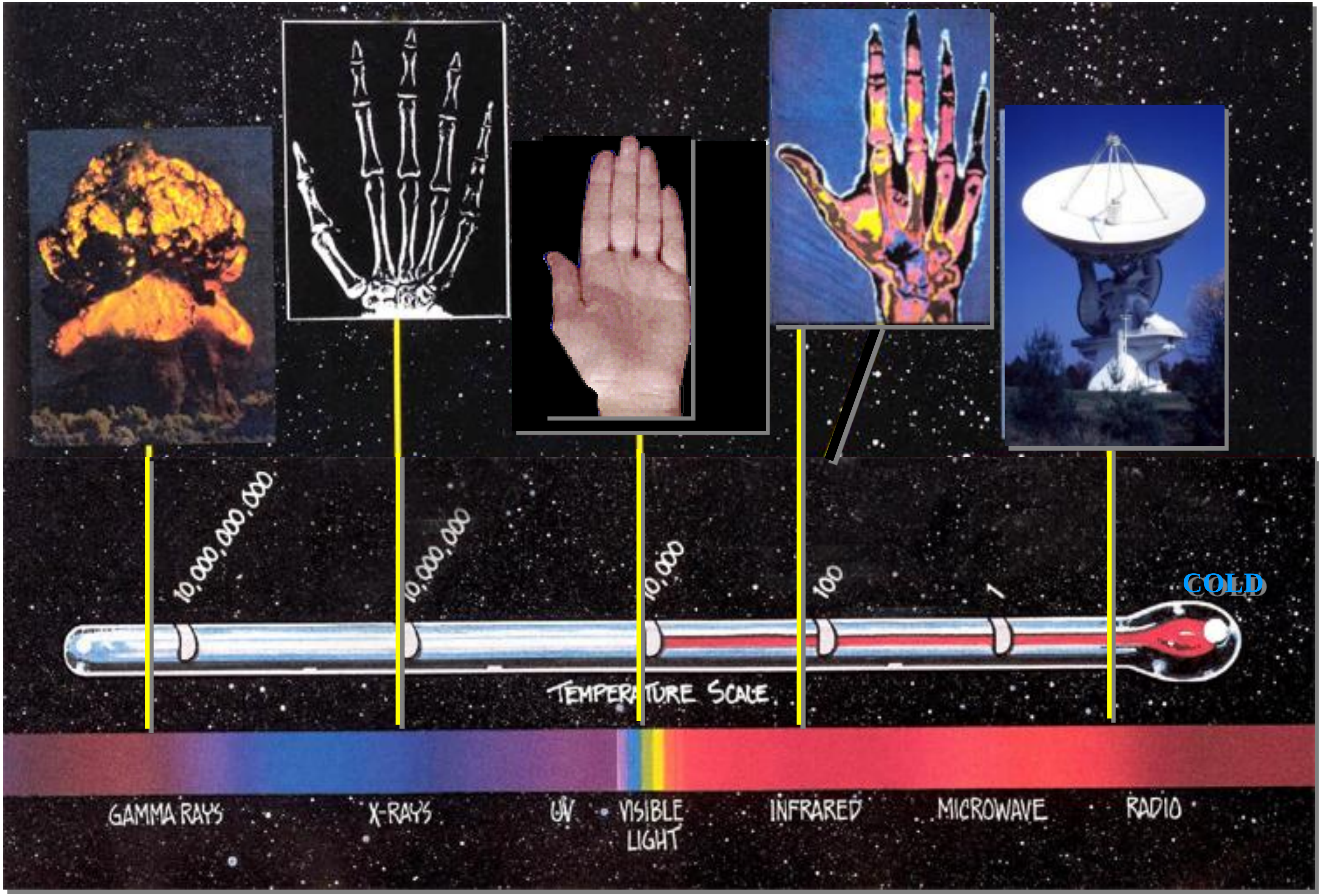
# Full Scale JWST Mockup

21st National Space Symposium, Colorado Springs, The Space Foundation

# Why go to Space – Wavelength Coverage



# Infrared Light



# Why Infrared ?

# JWST Science Theme #1

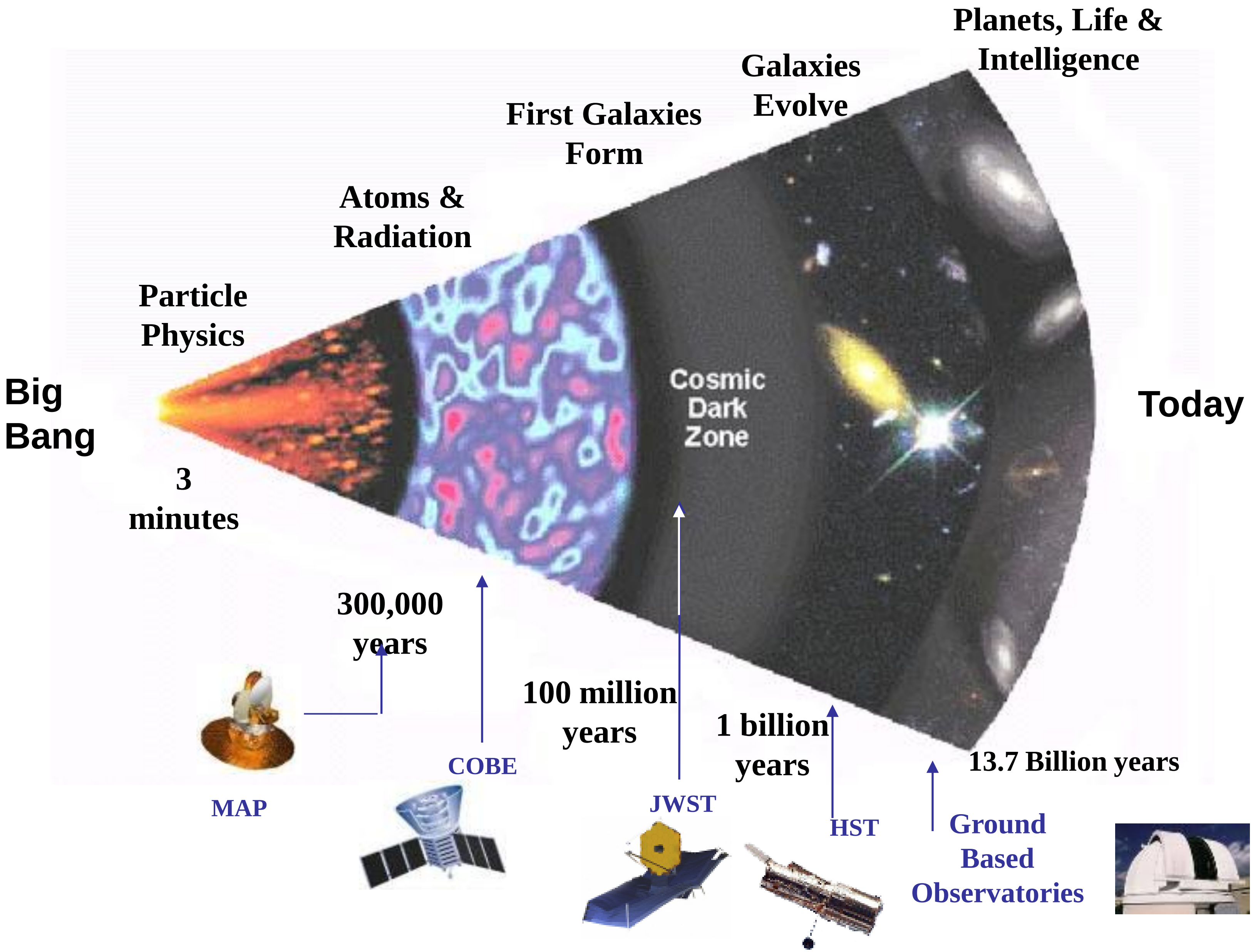
## End of the dark ages: first light and reionization

What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did re-ionization of the inter-galactic medium occur?
What caused the re-ionization?

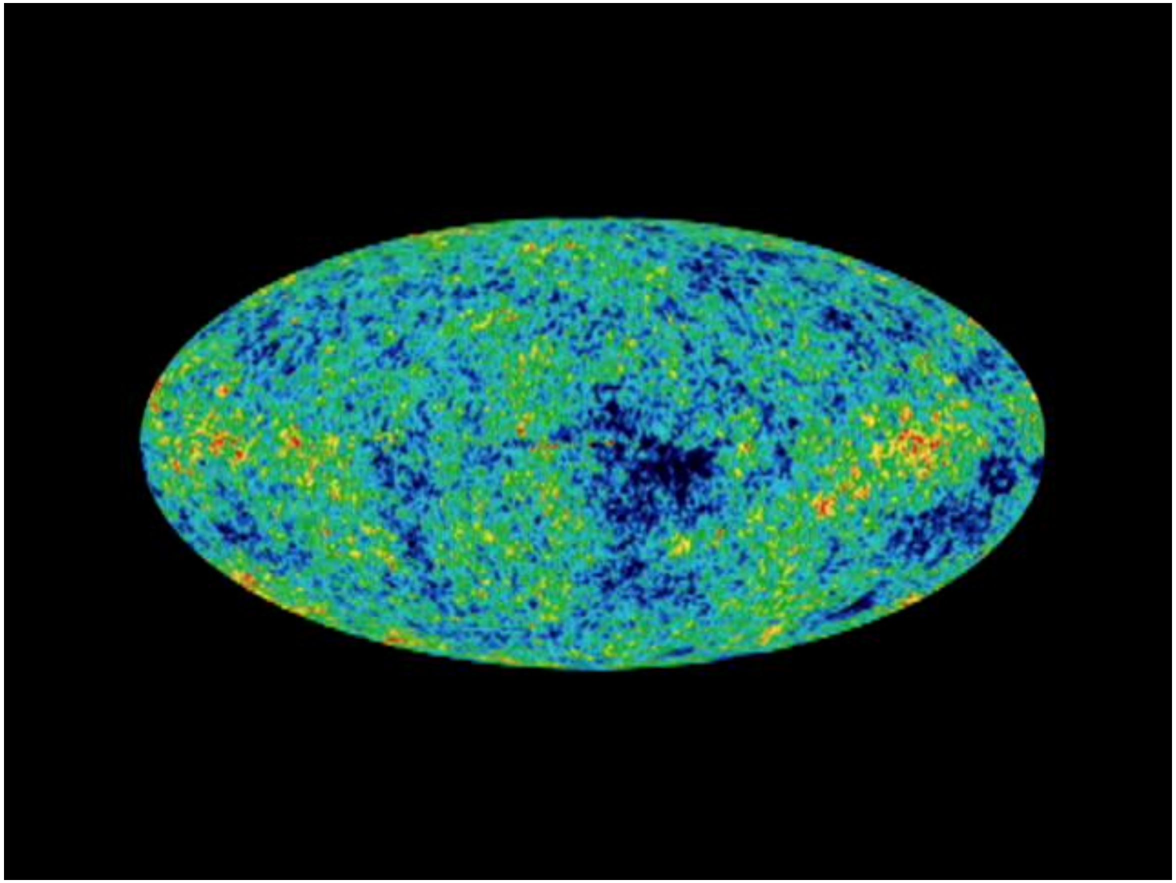
… to identify the first luminous sources to form and to determine the ionization history of the early universe.

Hubble Ultra Deep Field

# A Brief History of Time

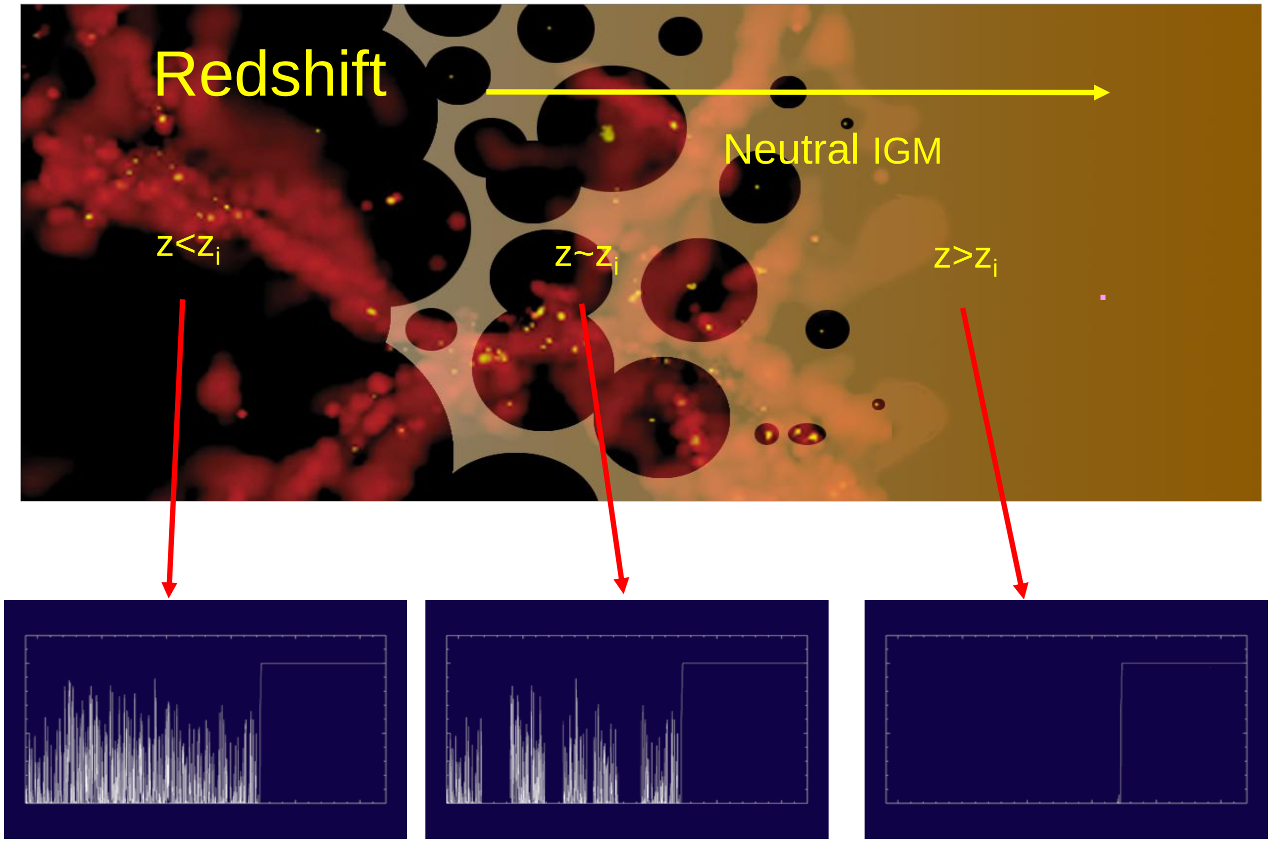


# History of Time?



| WMAP Results | | |
|---|---|---|
| Parameter | WMAP Value | What is it ? |
| Ototal | 1.02 +/- 0.02 | Total Density |
| $\Omega_{lambda}$ | 0.73 +/- 0.04 | Dark Energy |
| $\Omega_{matter}$ | 0.27 +/- 0.04 | Matter Density |
| $\Omega_{baryon}$ | 0.044 +/- 0.004 | Baryon Density |
| $H_o$ | 71 +/- 4 km/s/Mpc | Hubble Constant |
| $t_o$ | 13.7 +/- 0.2 Gyr | Age of the universe |

# First Light:  Observing Reionization Edge




**Lyman Forest Absorption** **Patchy Absorption** **Black Gunn-Peterson trough**

# When and how did reionization occur?

Re-ionization happened at z>6 or 1 billion years after Big Bang.

- WMAP says maybe twice?

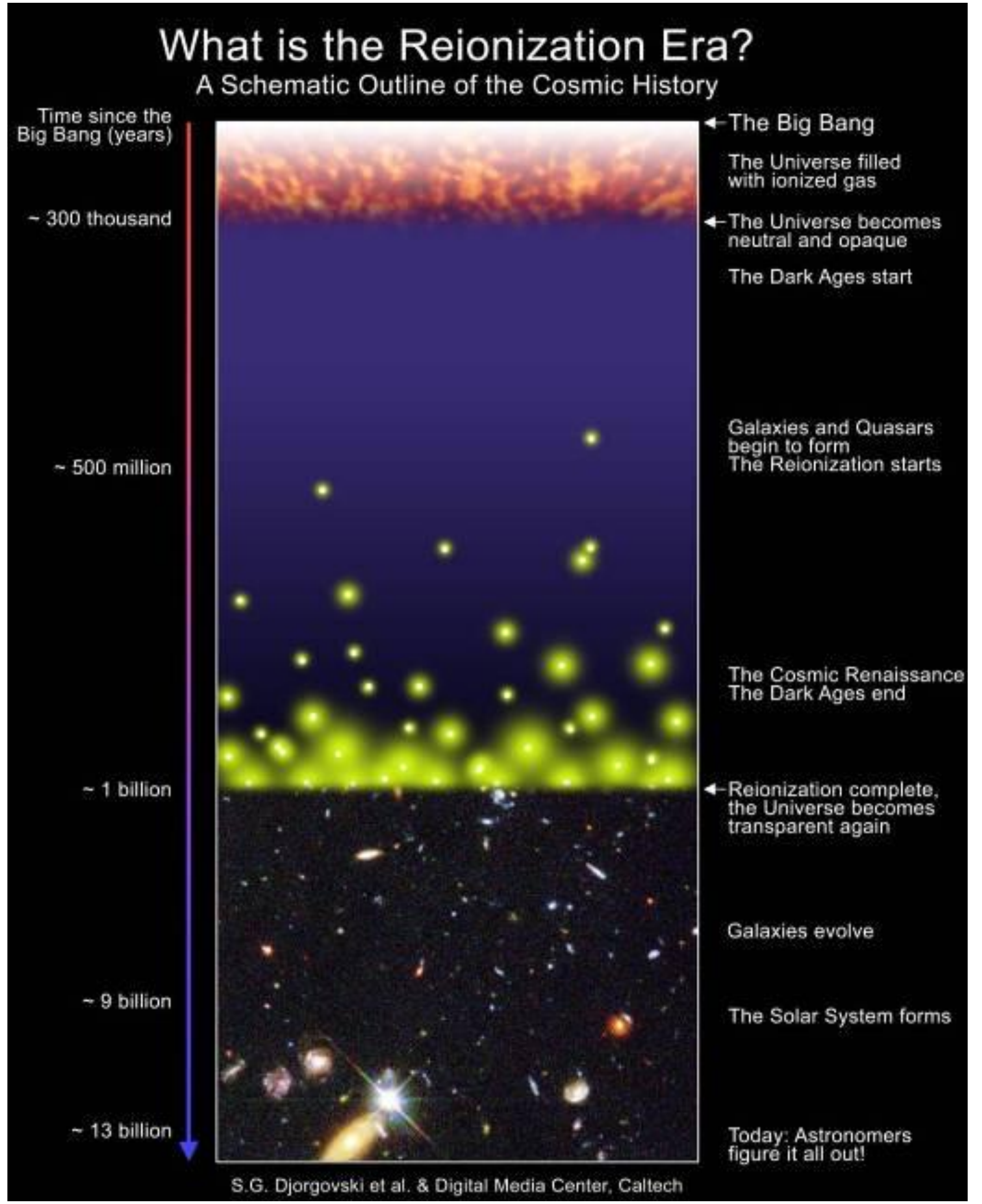
Probably galaxies, maybe quasar contribution

Key Enabling Design Requirments:

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

JWST Observations:

- Spectra of the most distant quasars
- Spectra of faint galaxies



# End of the dark ages: first light and reionization

First galaxies are small & faint

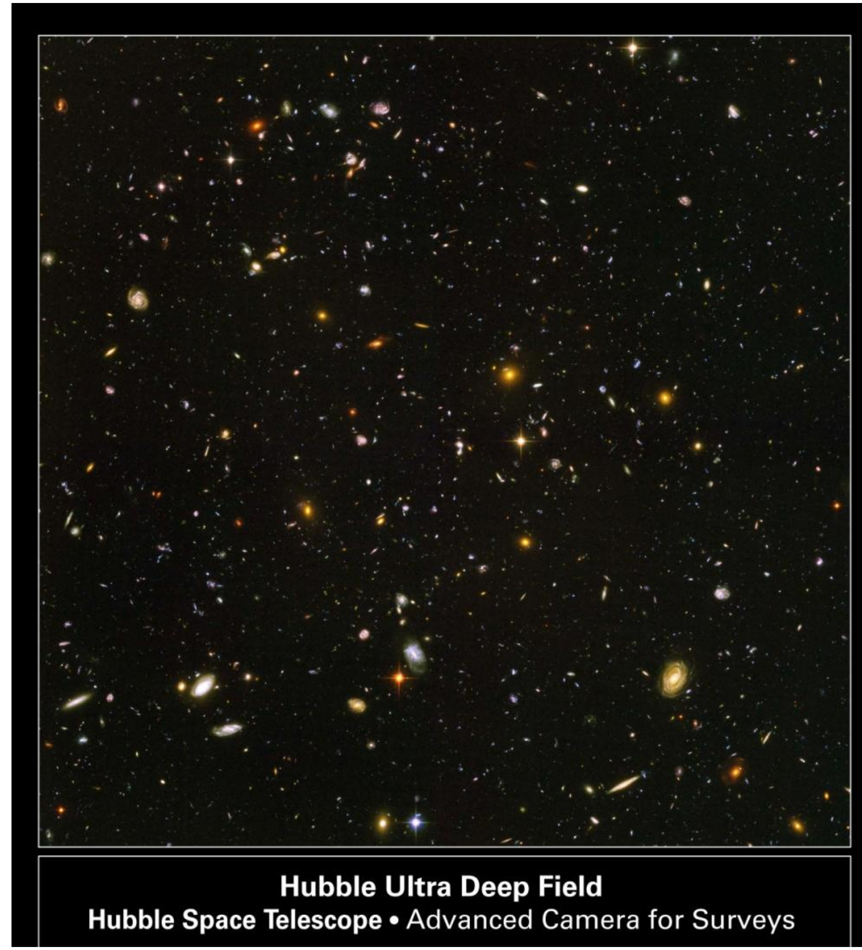
Light is redshifted into infrared.

Low-metallicity, massive stars.

- SNe! GRBs!

JWST Observations

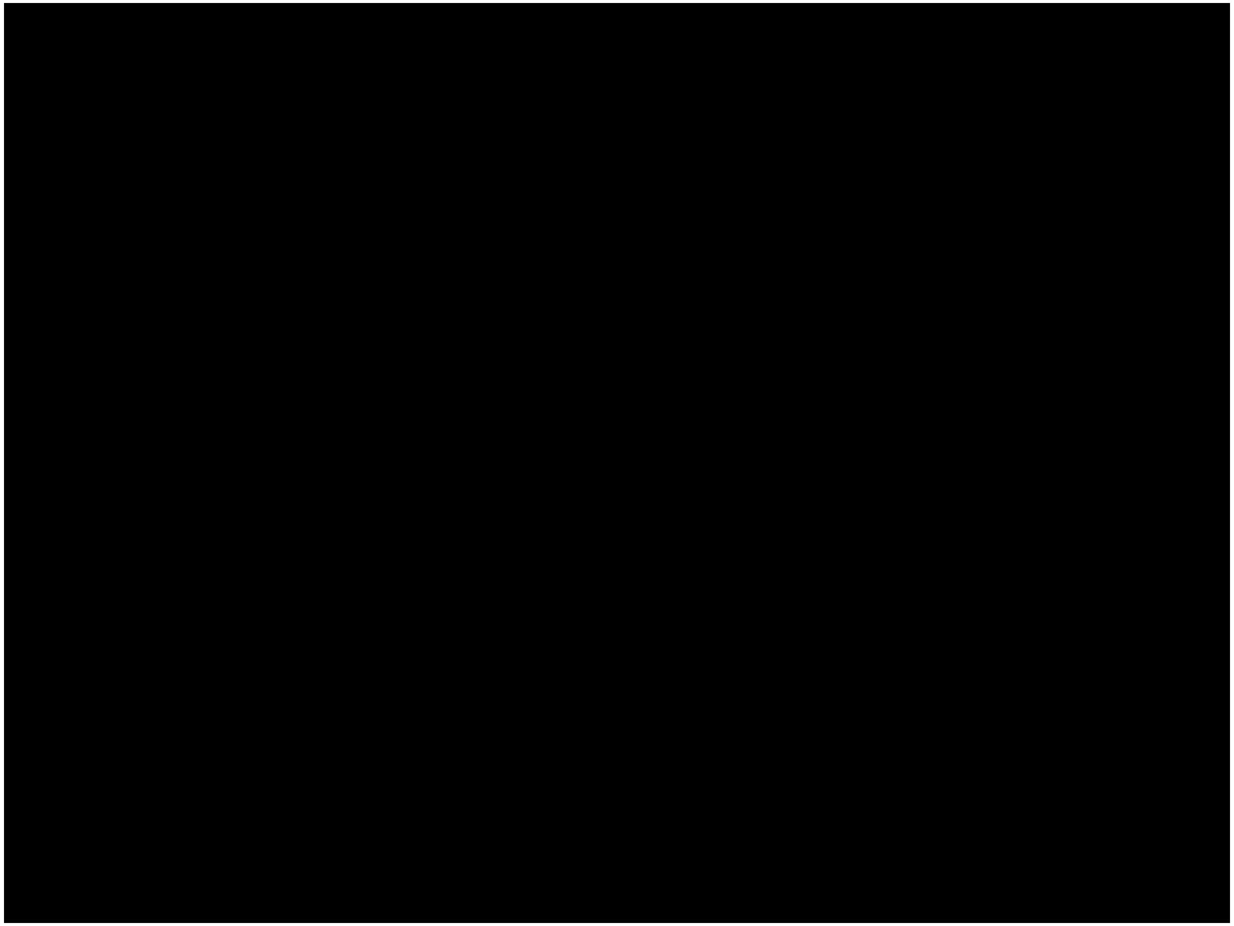
- Ultra-Deep NIR survey (1.4 nJy), spectroscopic & Mid-IR confirmation.



# First Light

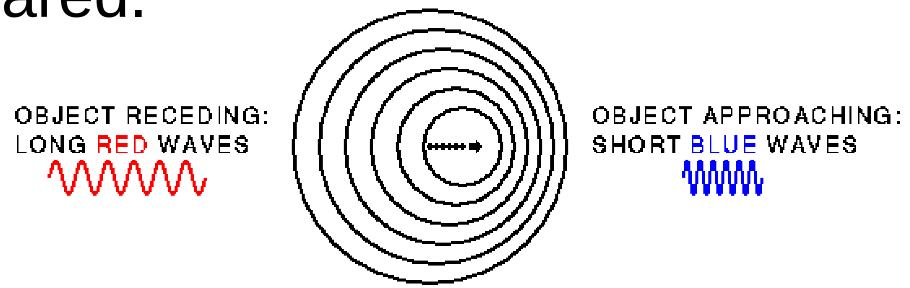
What did the first stars galaxies to form look like?

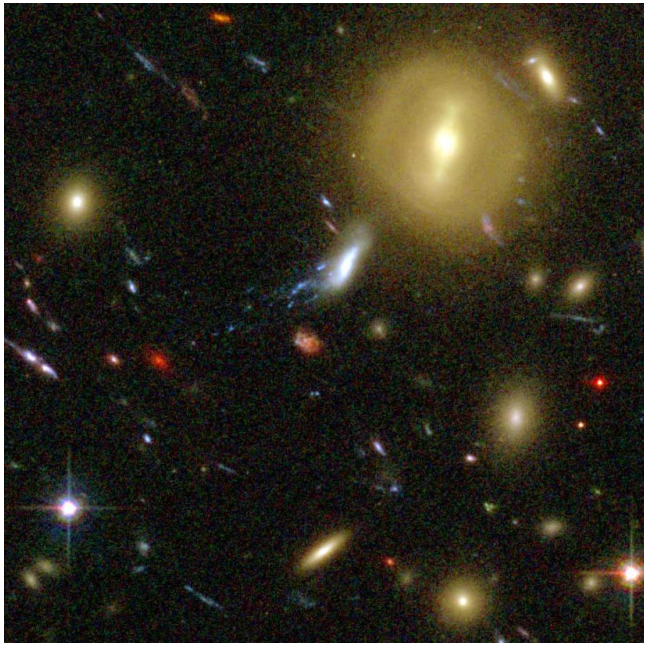
We don’t know, but models suggest first stars were very massive!

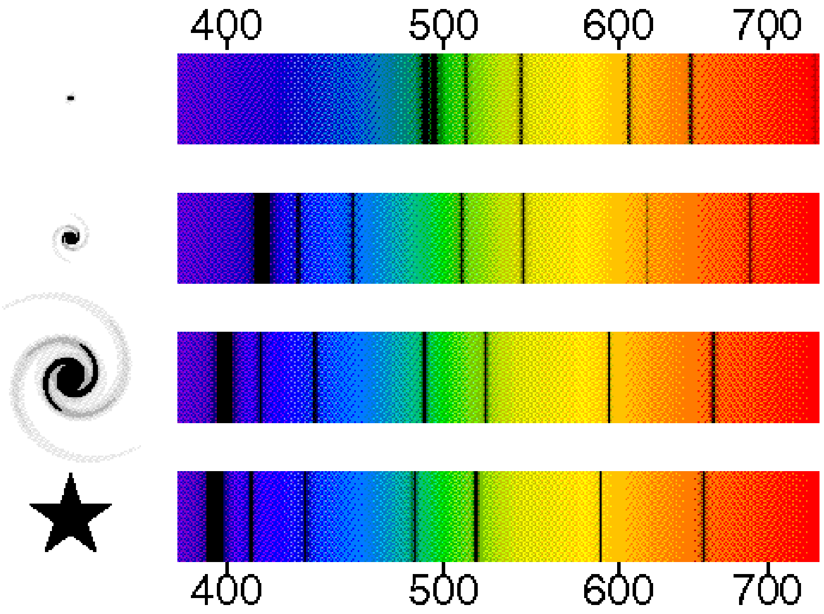


# Infrared Light

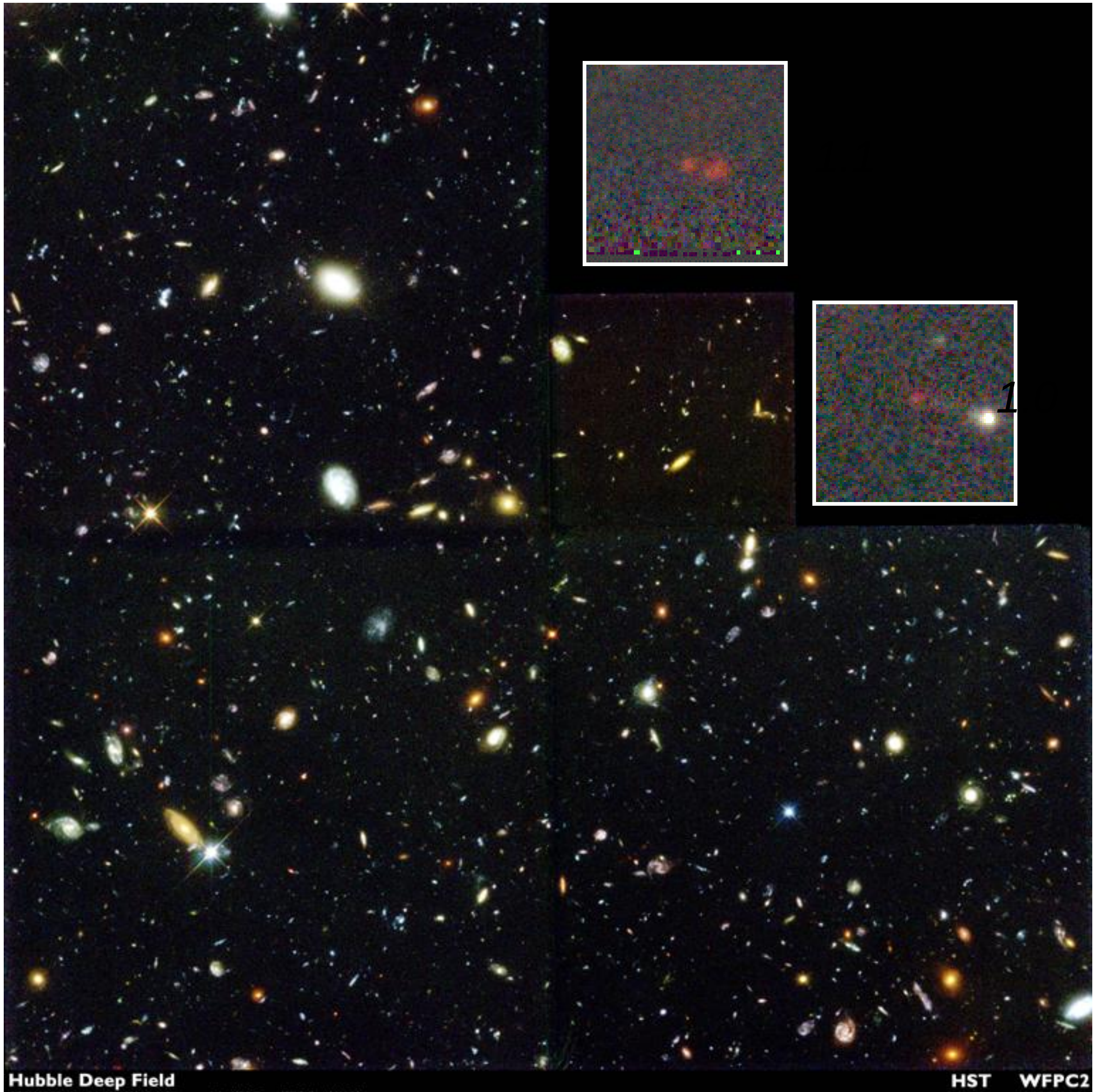
Light from the first galaxies is redshifted from the visible into the infrared.





# The Hubble Deep Field




5.8

3.3

2.2

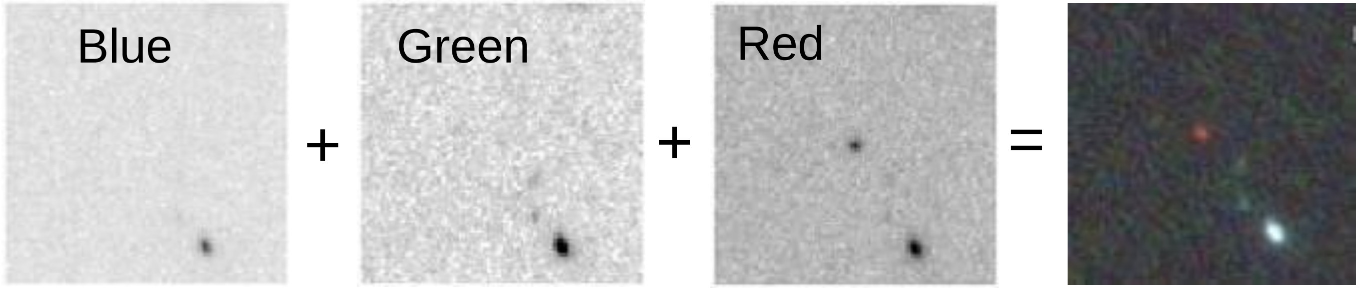
2.2

1.8

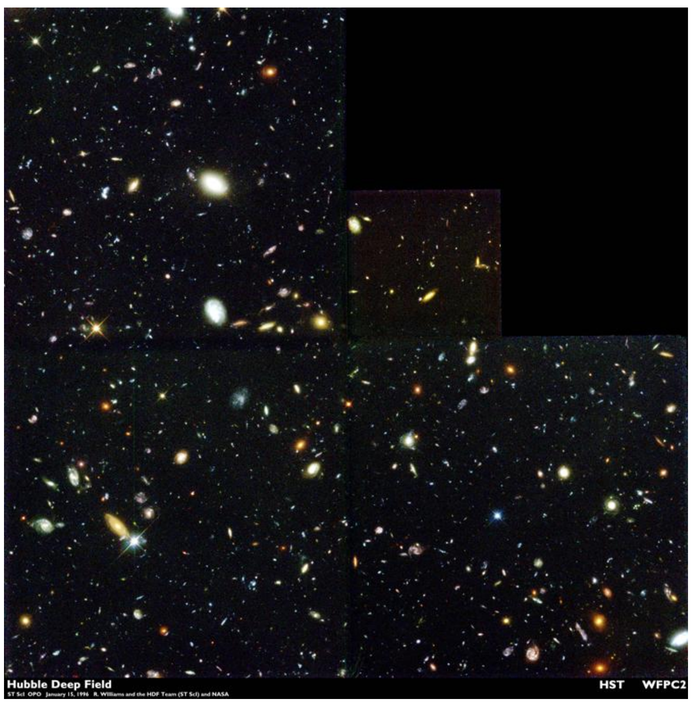
Age (Gyr)

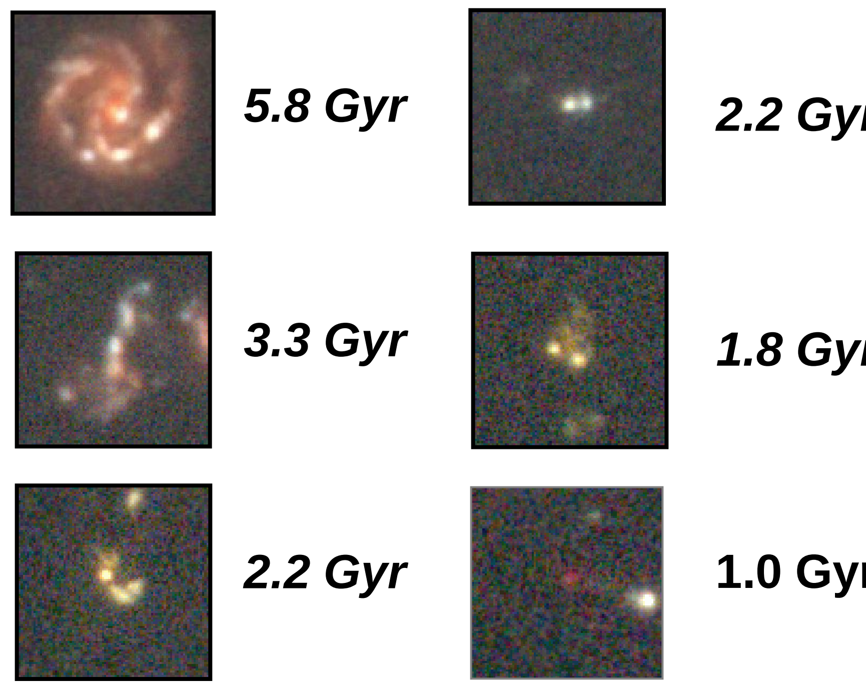
STScI Science Project: Robert Williams. et al. (1997)

# How do we see first light objects?




## Deep Imaging: Look for *near-IR drop-outs*



# Hubble Ultra Deep Field
## - Advanced Camera for Surveys

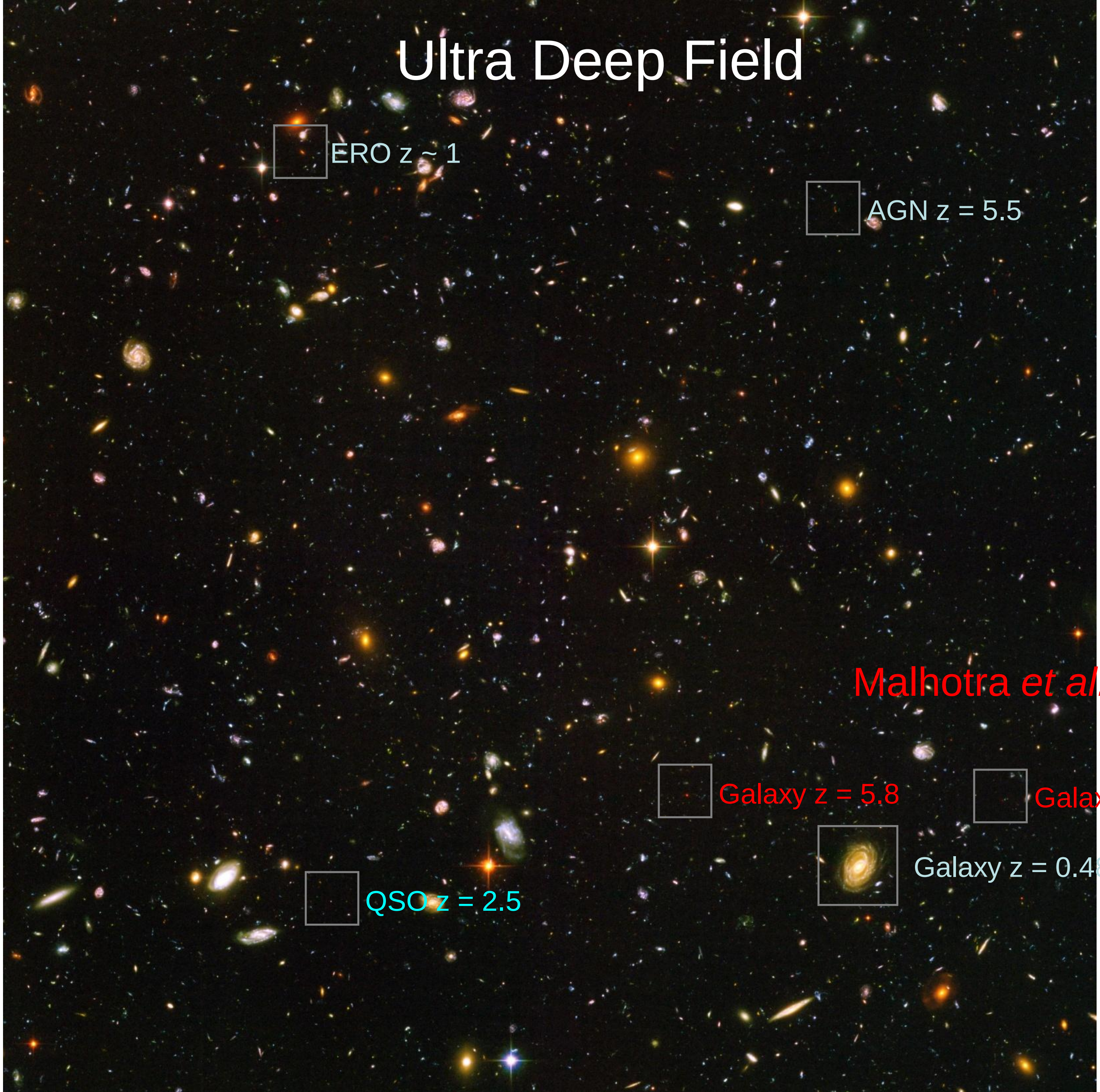
**400 orbits, data taken over 4 months:**
**Sept-Oct (40 days), Dec-Jan (40 days)**

**Total exposures ($10^6$ seconds)**

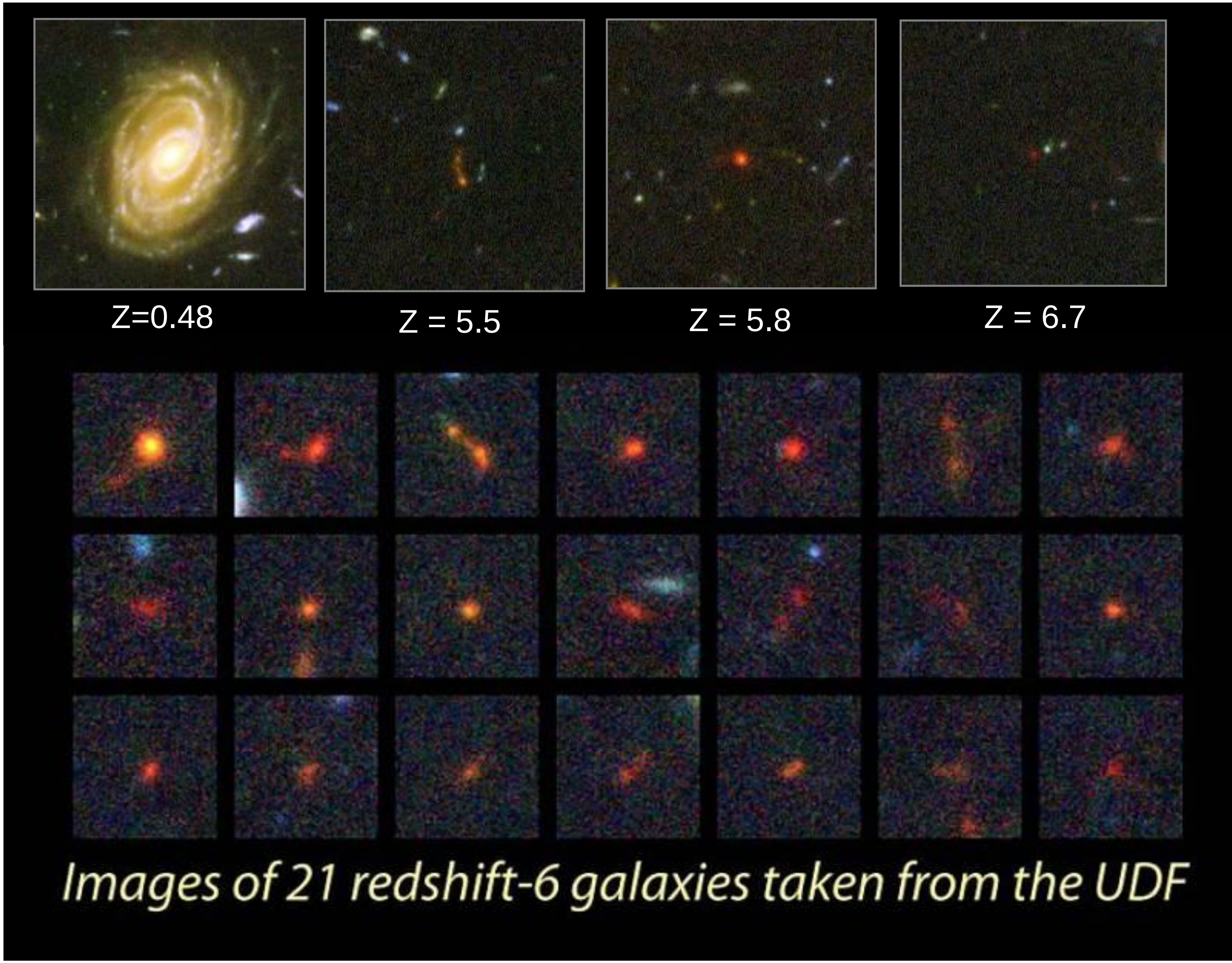
| B | V | I | z | |
|---|---|---|---|---|
| F435W | F606W | F775W | F850LP | |
| 56 | 56 | 144 | 144 | orbits |

**JWST is designed to routinely operate in the deep survey imaging mode**

# Ultra Deep Field

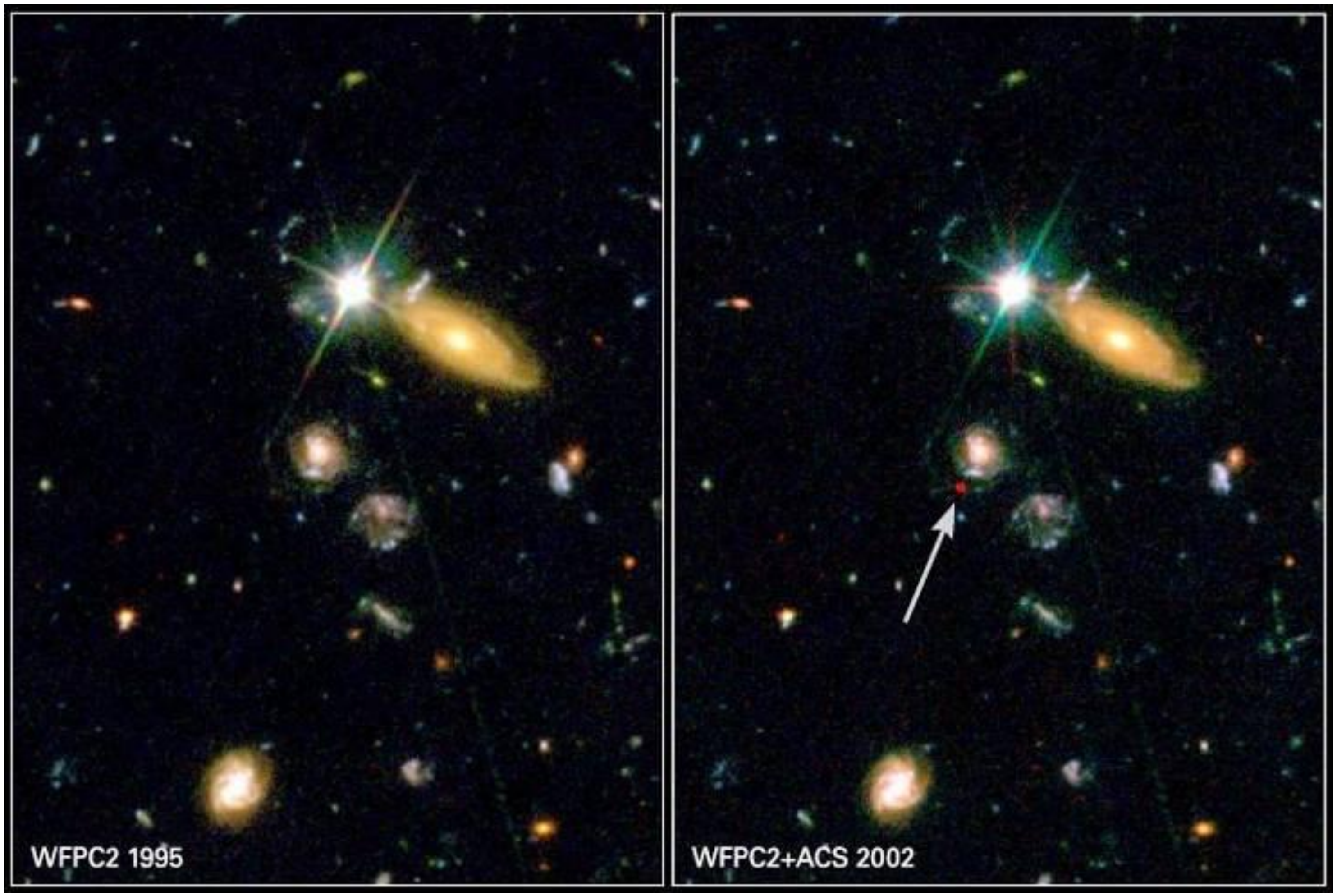


# New Results from UDF



# How do we see first light objects?

The first stars may be detected when they became bright supernovae. But, they will be very rare objects!

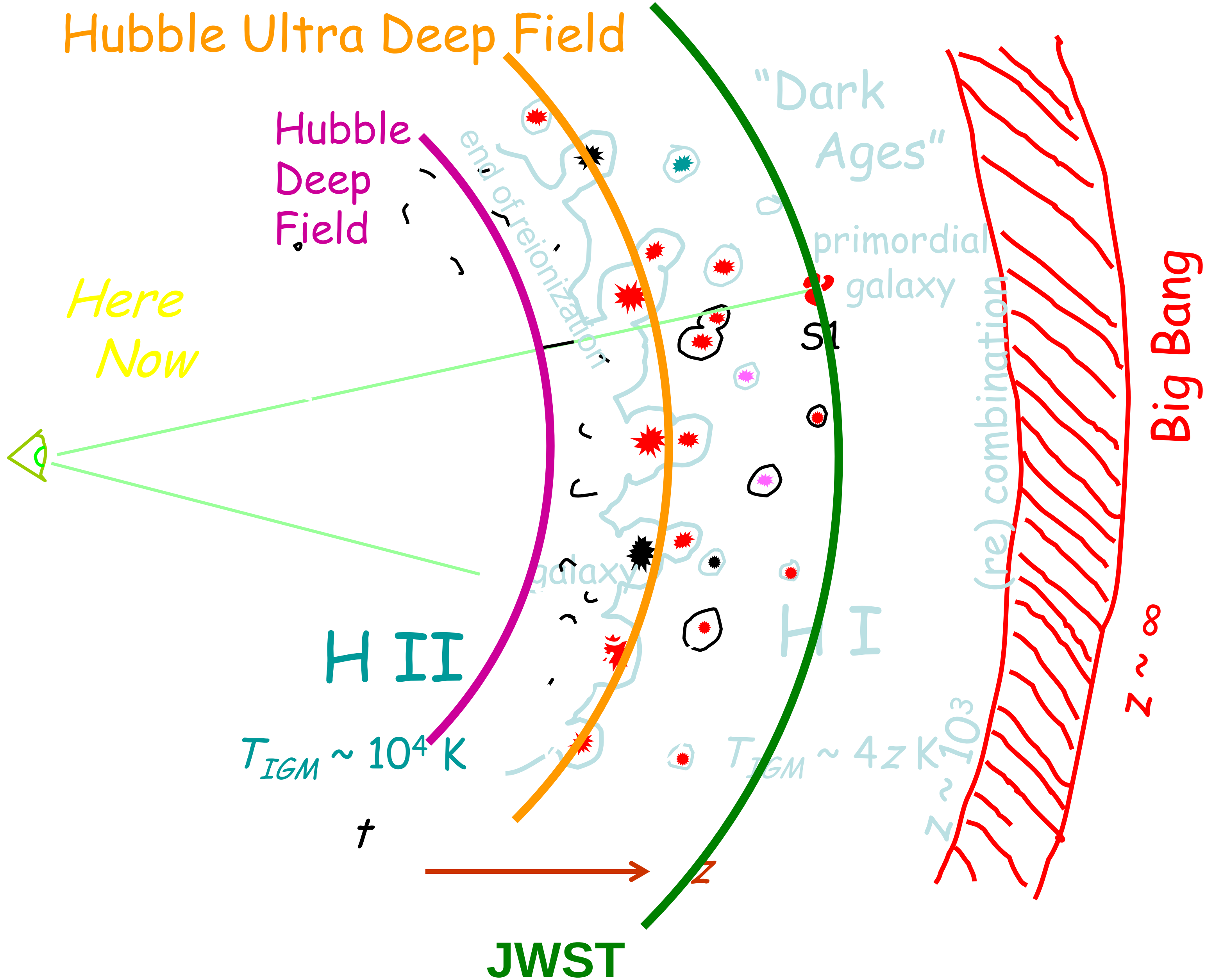


# How do we see first light objects?

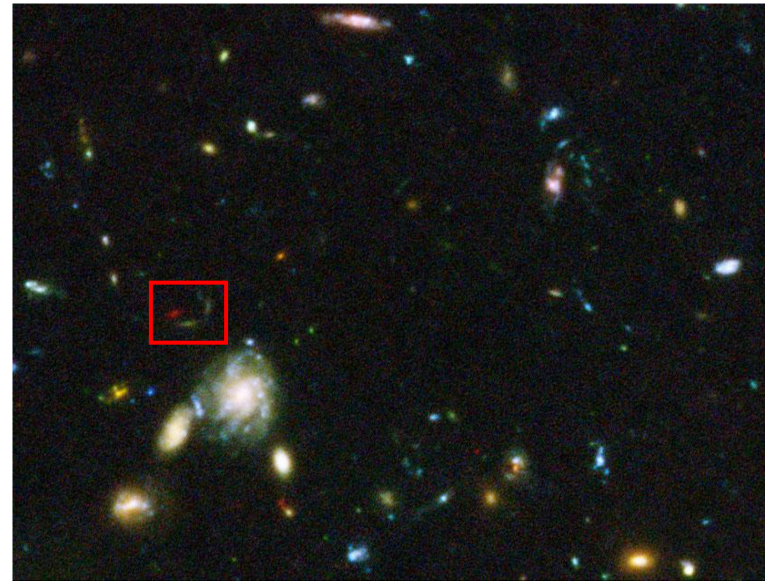


Use a magnifying glass !

# The Renaissance after the Dark Ages

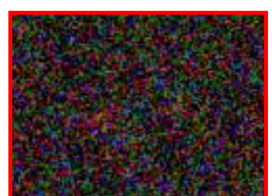


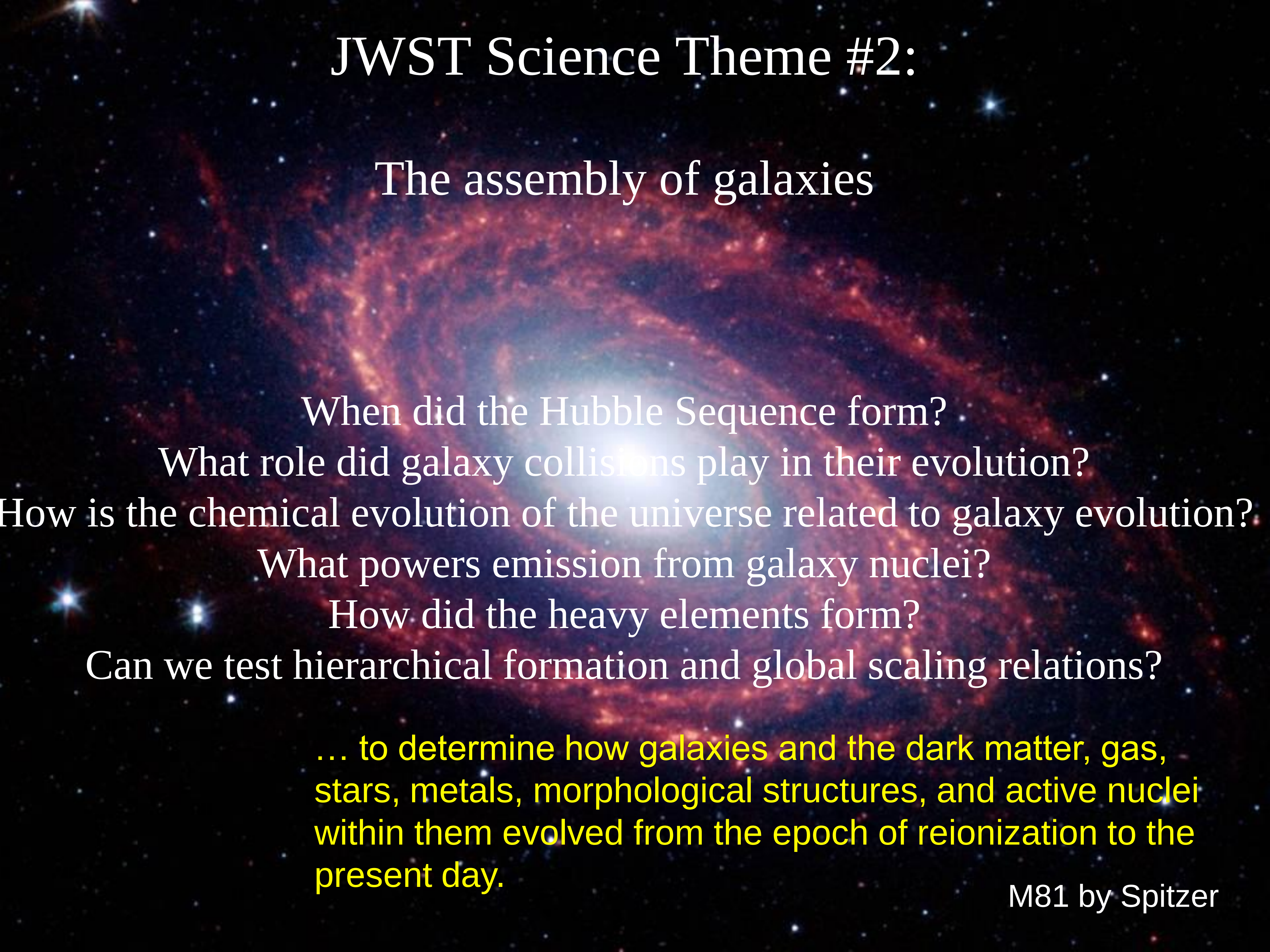
# Sensitivity Matters



GOODS CDFS – 13 orbits

HUDF – 400 orbits





# JWST Science Theme #2:

## The assembly of galaxies

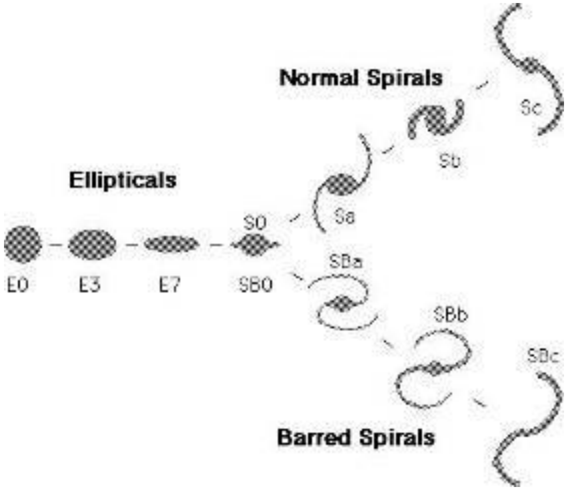
When did the Hubble Sequence form?
What role did galaxy collisions play in their evolution?
How is the chemical evolution of the universe related to galaxy evolution?
What powers emission from galaxy nuclei?
How did the heavy elements form?
Can we test hierarchical formation and global scaling relations?

… to determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.

M81 by Spitzer

# The Hubble Sequence

Hubble classified nearby (present-day) galaxies into Spirals and Ellipticals.




The Hubble Space Telescope has extended this to the distant past.

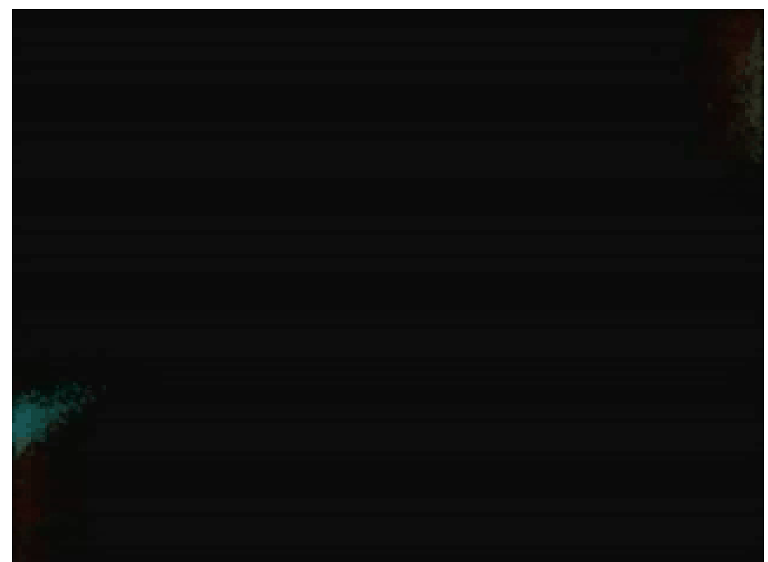
# Where and when did the Hubble Sequence form?
# How did the heavy elements form?

Galaxy assembly is a process of hierarchical merging

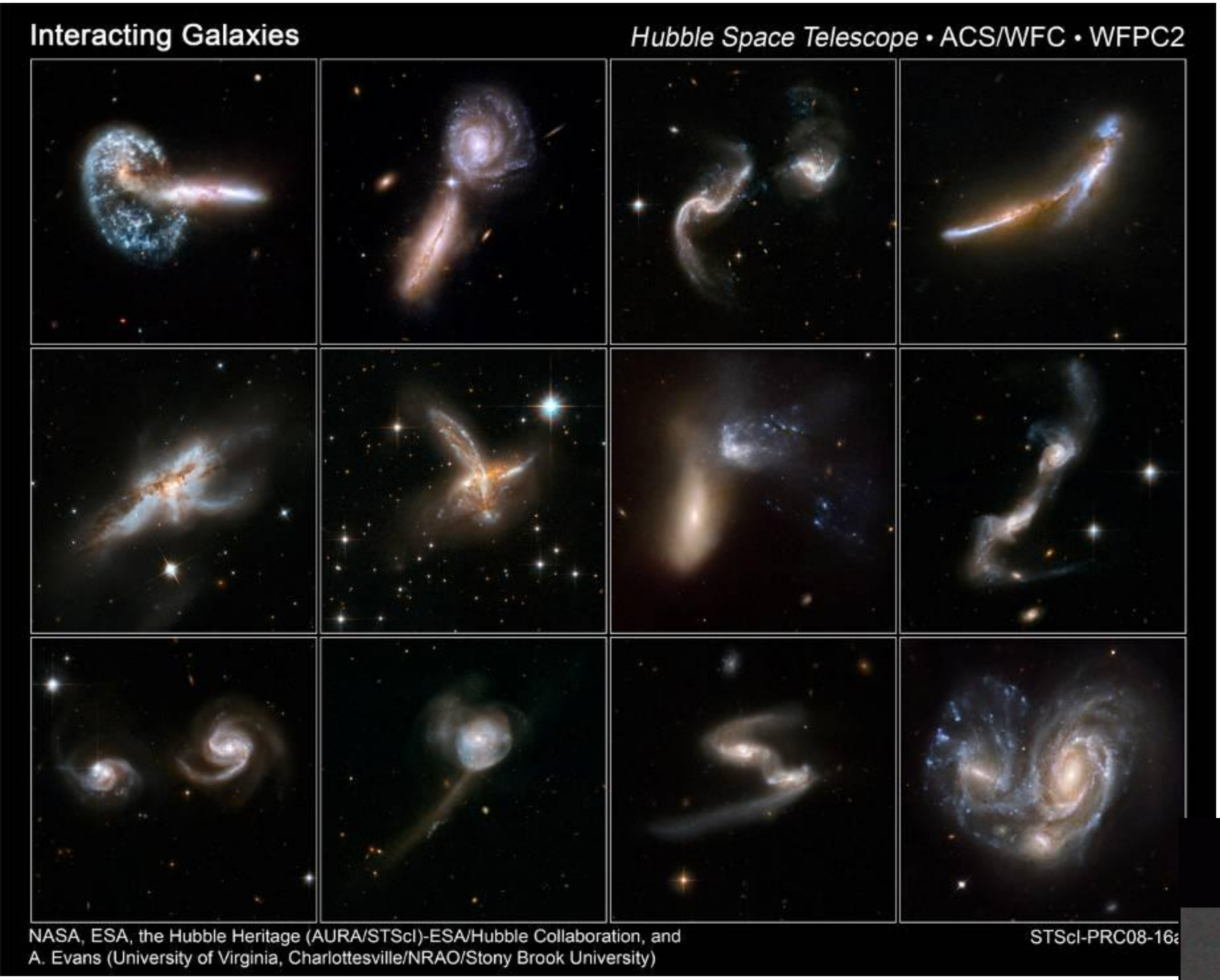
Components of galaxies have variety of ages & compositions

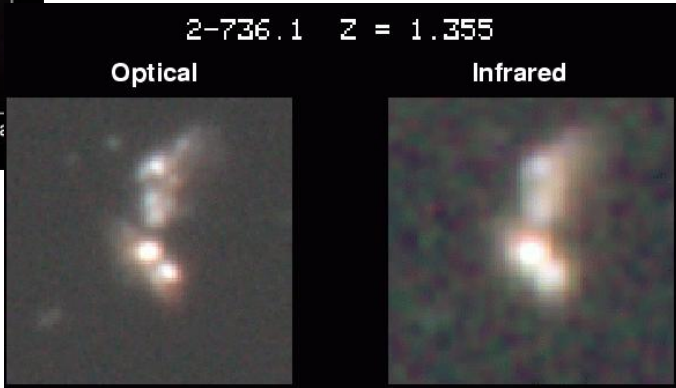
JWST Observations:

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

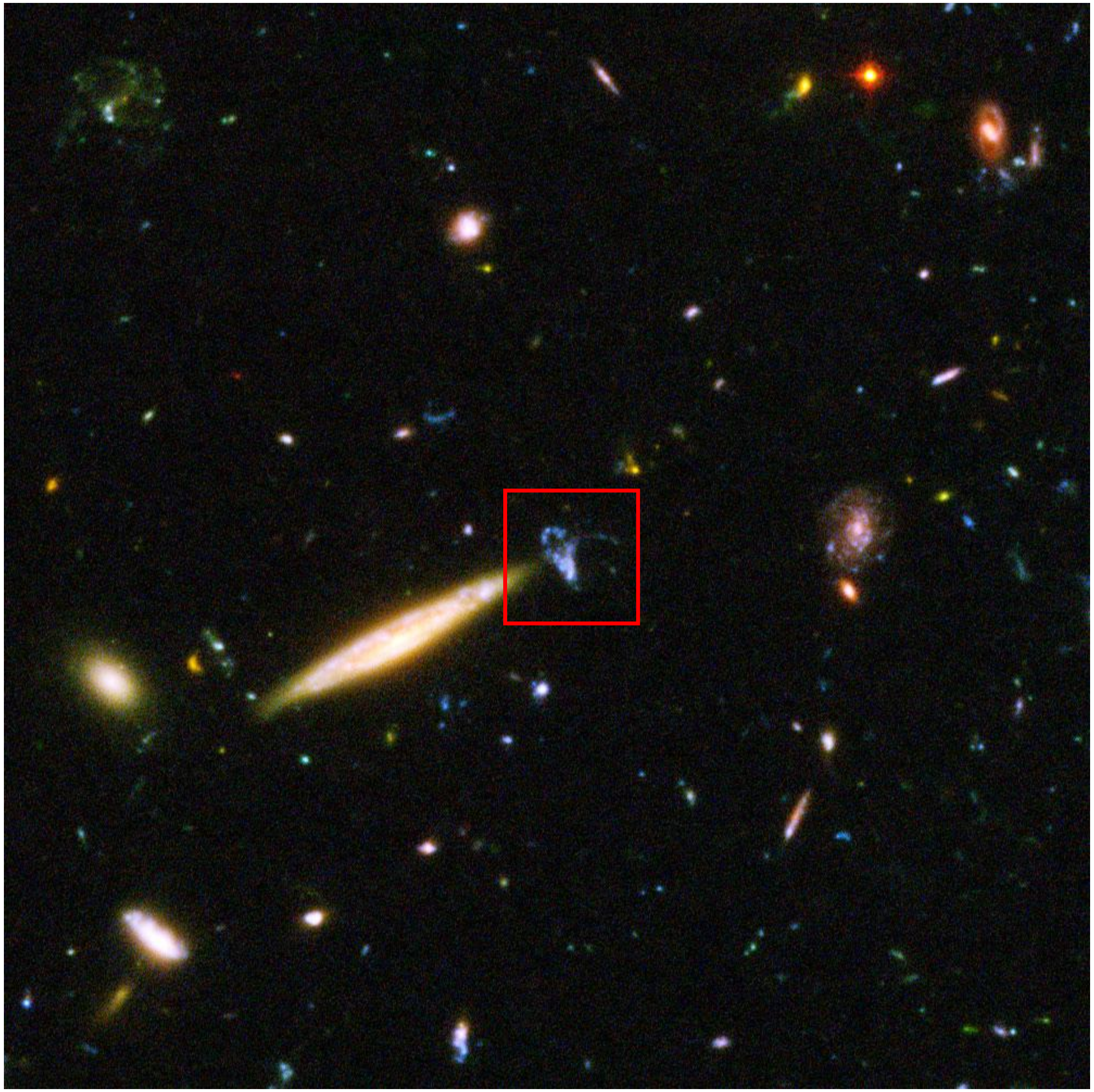


# Distant Galaxies are "Train Wrecks"



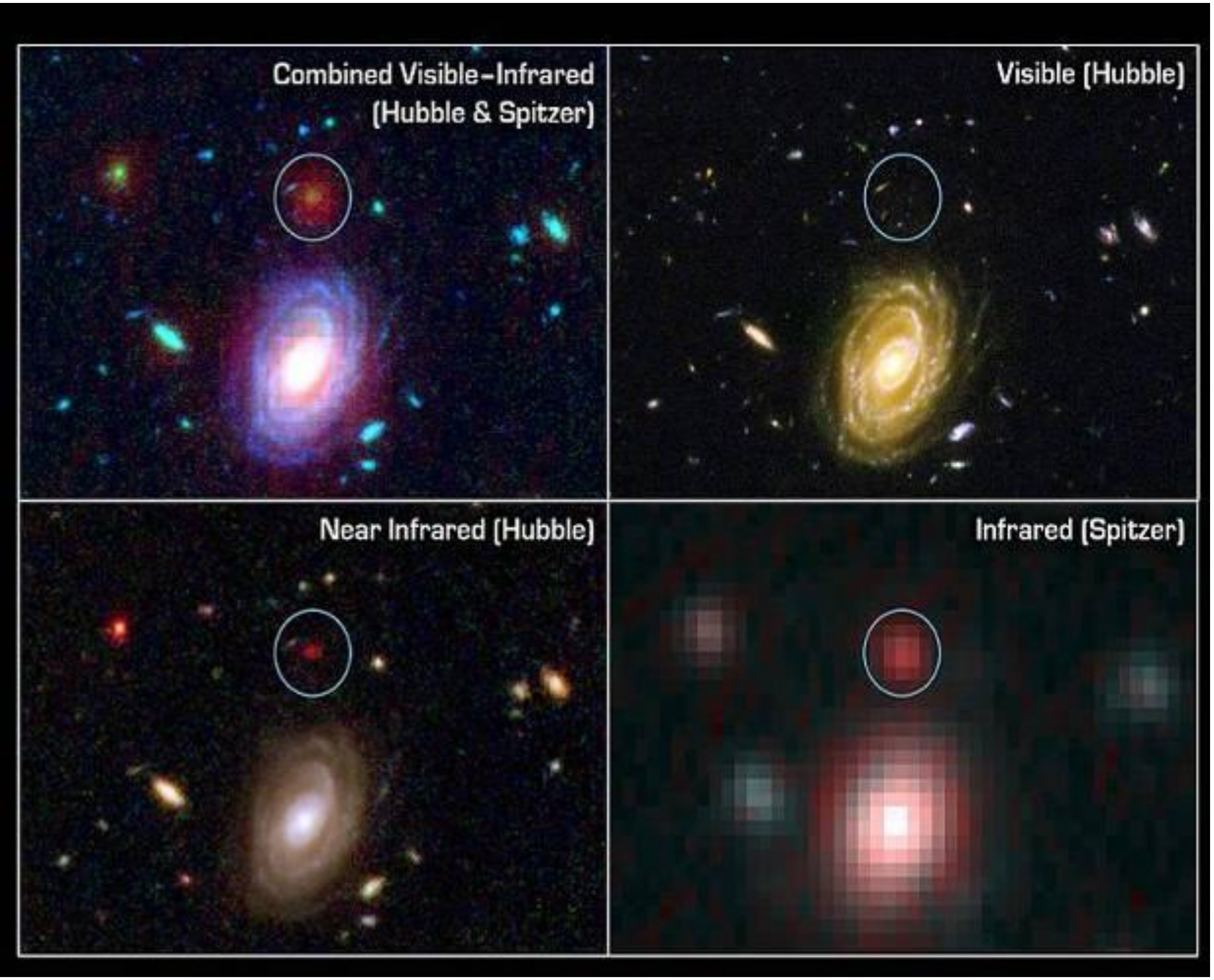



# Unusual objects



# Clusters of Galaxies

# Unexpected “Big Babies”




Spitzer and Hubble have identified a dozen very old (almost 13 Billion light years away) very massive (up to 10X larger than our Milky Way) galaxies.

At an epoch when the Universe was only ~15% of its present size, and ~7% of its current age.

This is a surprising result unexpected in current galaxy formation models.

Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.


….Hence Science News reports that Spitzer and Hubble posed a Cosmic Conundrum by finding these very massive galaxies in the early Universe….This challenges theories of structure formation

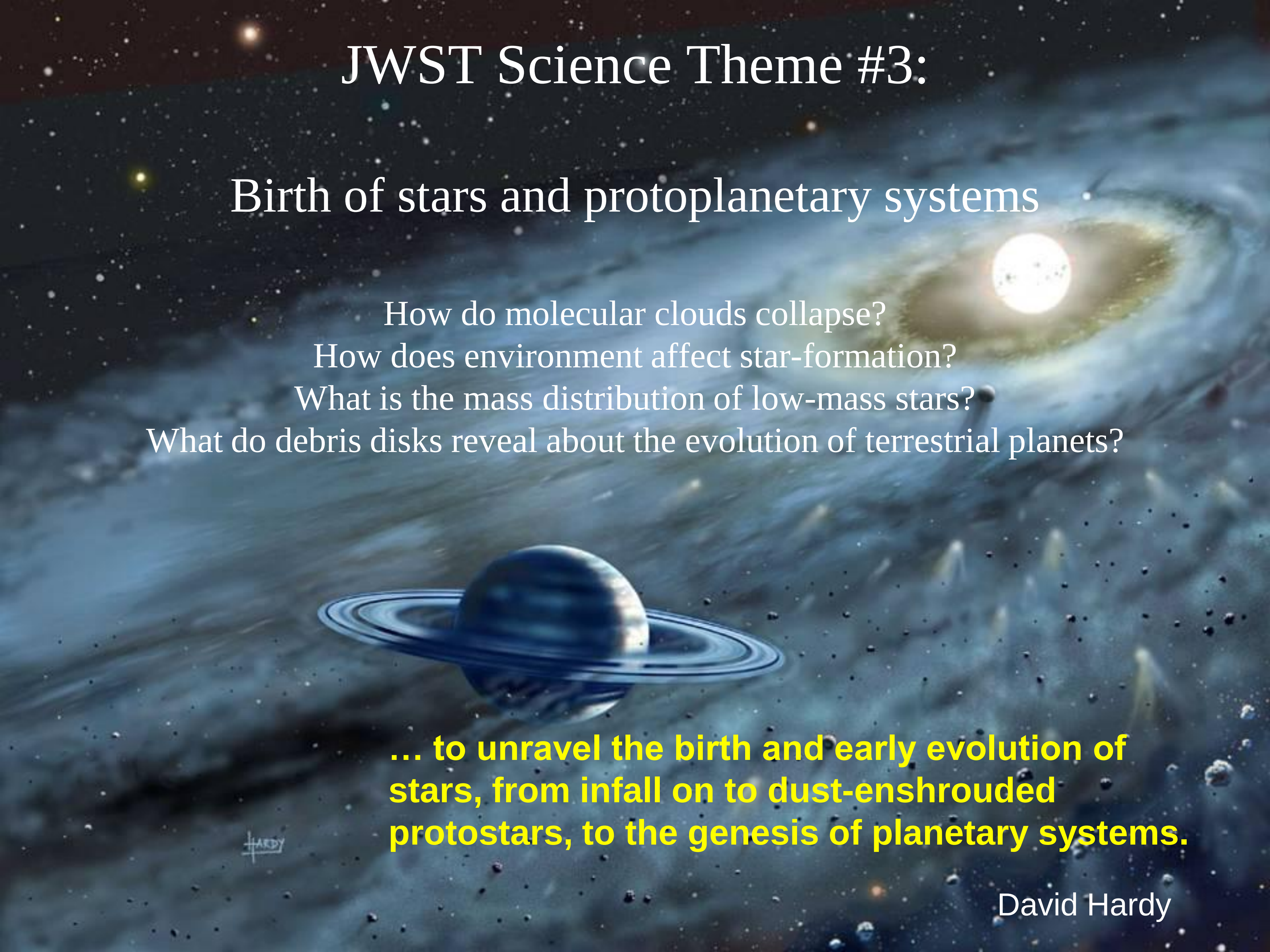
Mich[illegible]ner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

# JWST Science Theme #3:

## Birth of stars and protoplanetary systems

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

**… to unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.**



David Hardy

# How do proto-stellar clouds collapse?

Stars form in small regions collapsing gravitationally within larger molecular clouds.

Infrared sees through thick, dusty clouds

Proto-stars begin to shine within the clouds, revealing temperature and density structure.

Key JWST Enabling Requirements:

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

Barnard 68 in infrared

# How does environment affect star-formation?

Massive stars produce wind & radiation

Either disrupt star formation, or causes it.

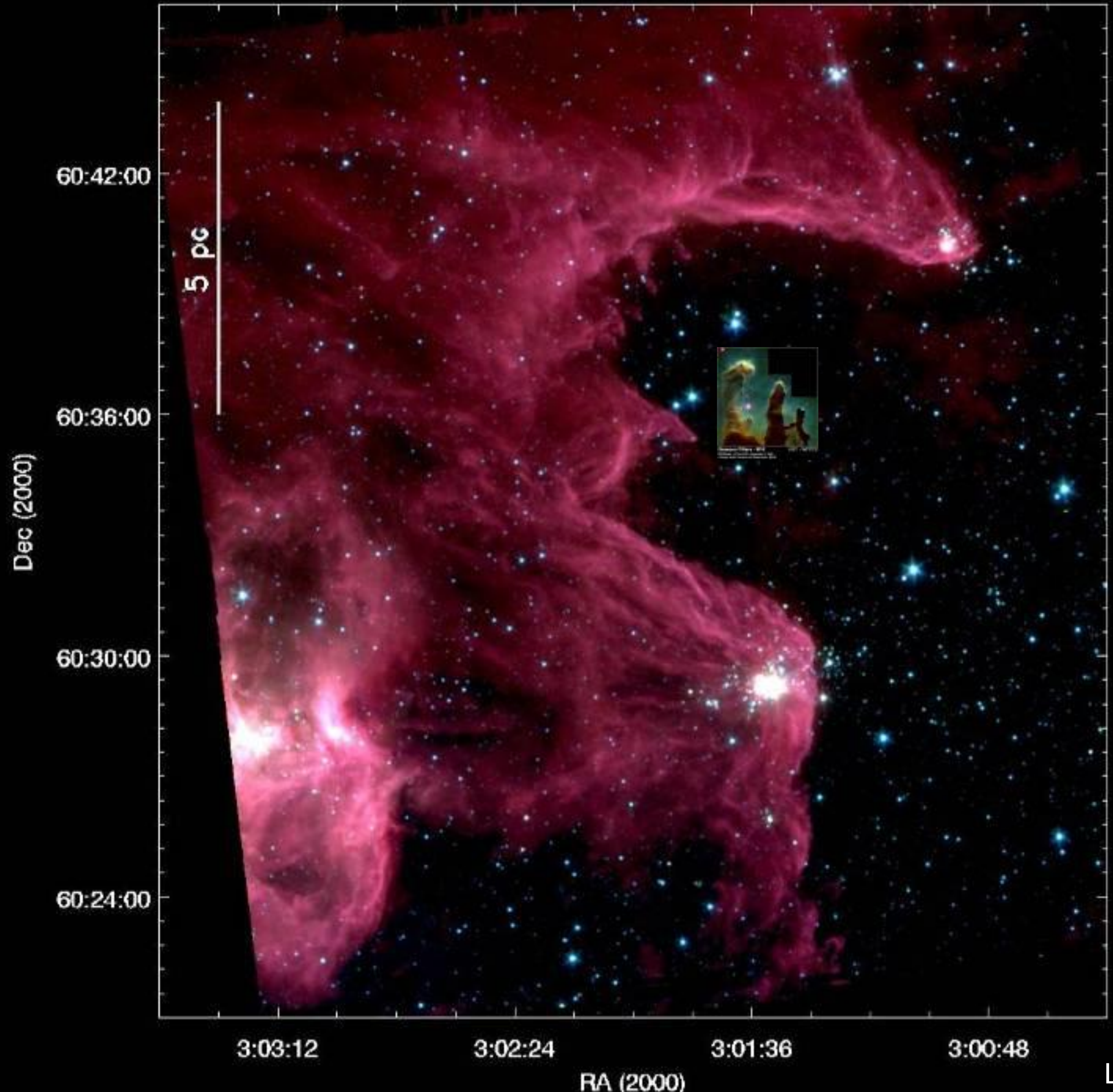
Boundary between smallest brown dwarf stars & planets is unknown

Different processes? Or continuum?

JWST Observations:

Survey dark clouds, “elephant trunks” or “pillars of creation” star-forming regions

The Eagle Nebula
as seen in the infrared



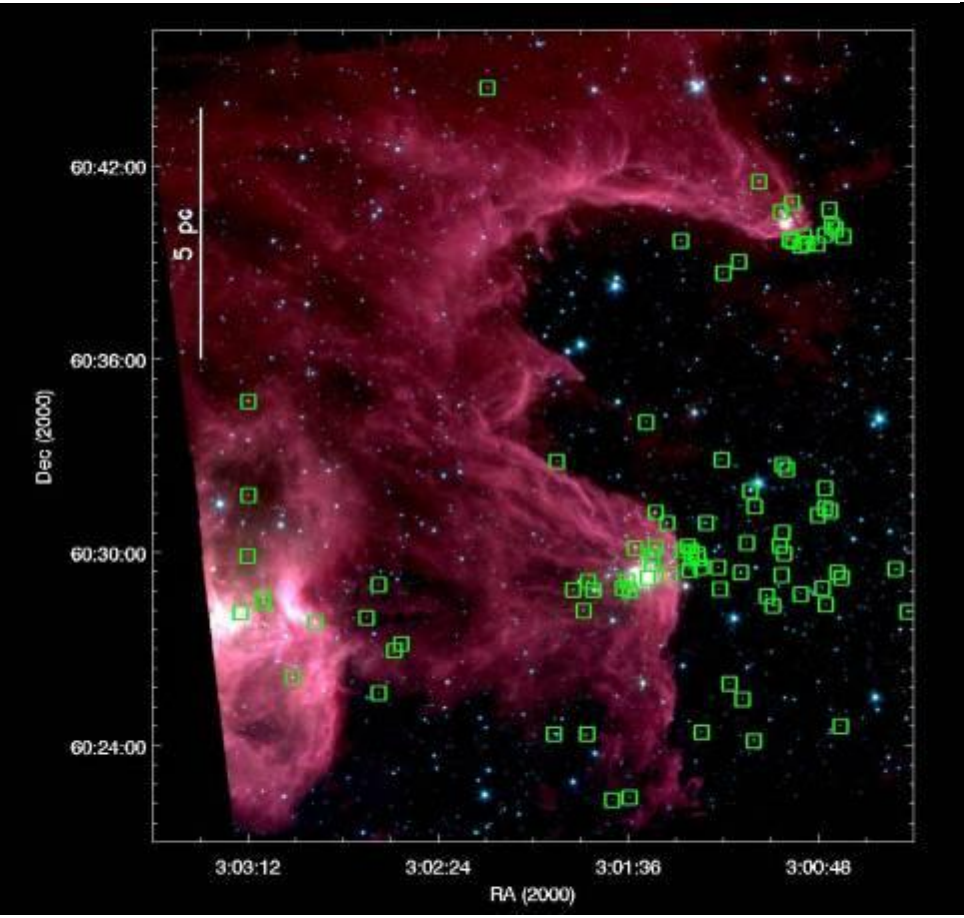

Spitzer has Found “The Mountains Of Creation”

Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

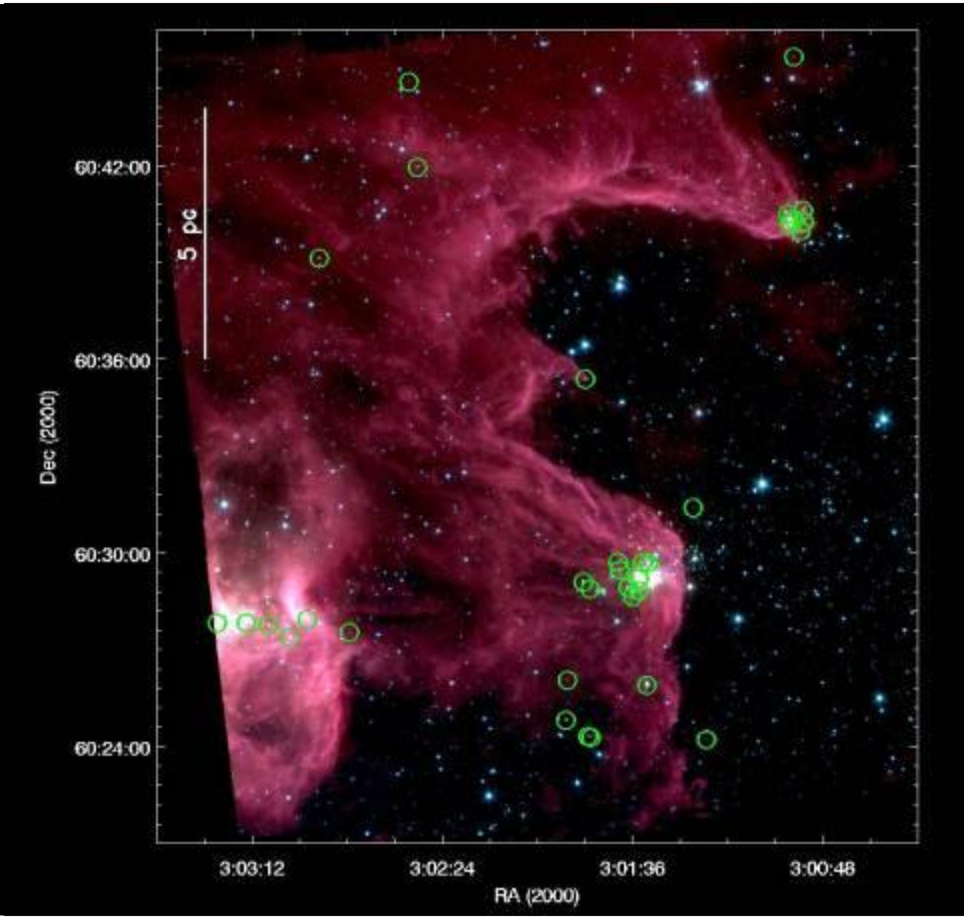
L. Allen, CfA [GTO]

# The Mountains Tell Their Tale

## Interstellar erosion & star formation propagate through the cloud




**Young (Solar Mass) Stars are Shown in This Panel**

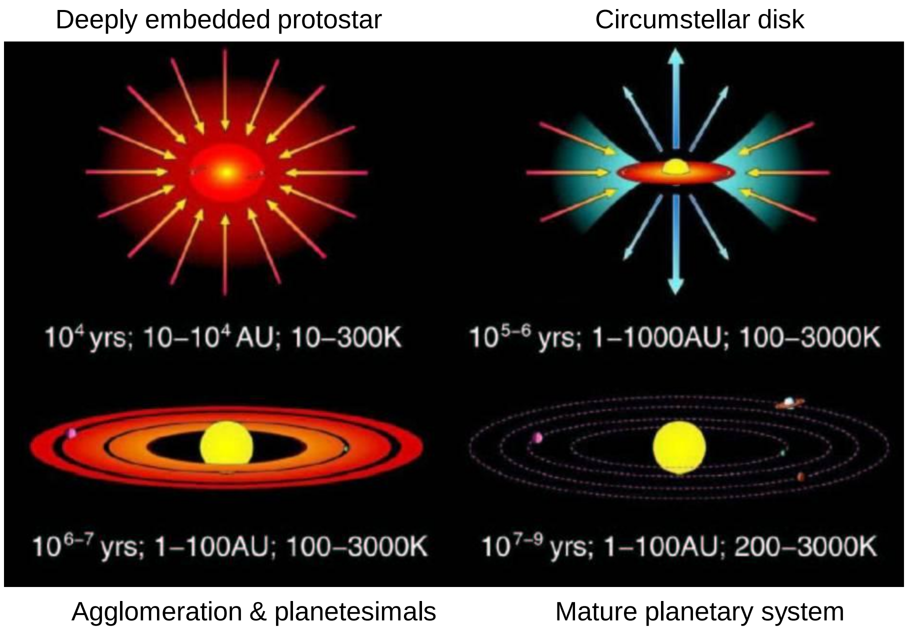


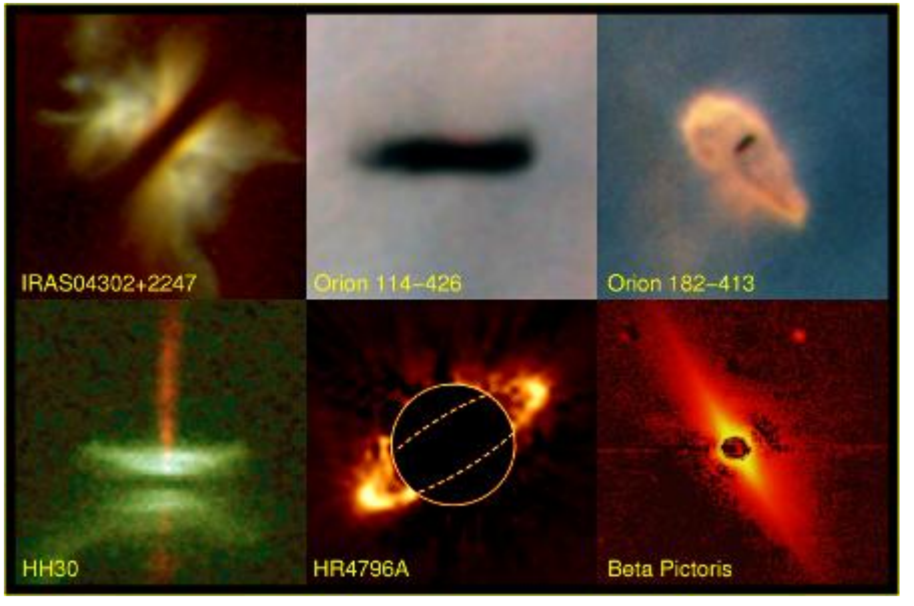

**Really Young Stars are Shown in This Panel**

Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

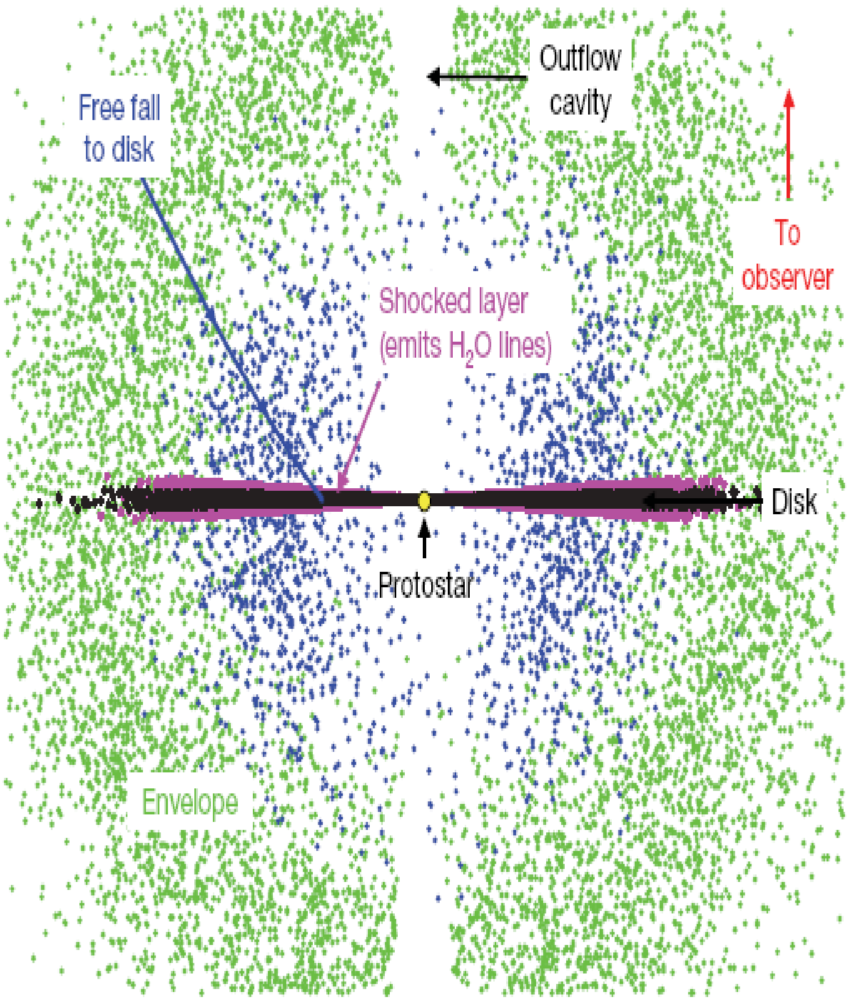
# Birth of Stars and Proto-planetary Systems

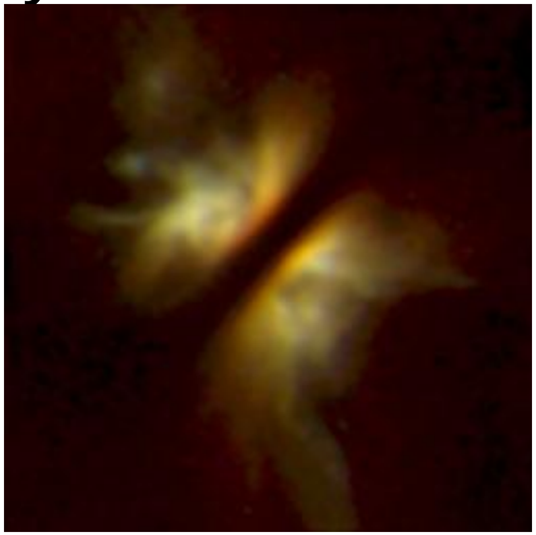
- What is the role of molecular clouds, cores and their collapse in the evolution of stars and planetary systems?
- How do protostars form and evolve?
- How do massive stars form and interact with their environment?
- How do massive stars impact their environment by halting or triggering further star formation. How do they impact the evolution of disks?
- What is the initial mass function down to planetary masses?
- How do protoplanetary systems form and evolve?
- How do astrochemical tracers track star formation and the evolution of protoplanetary systems?

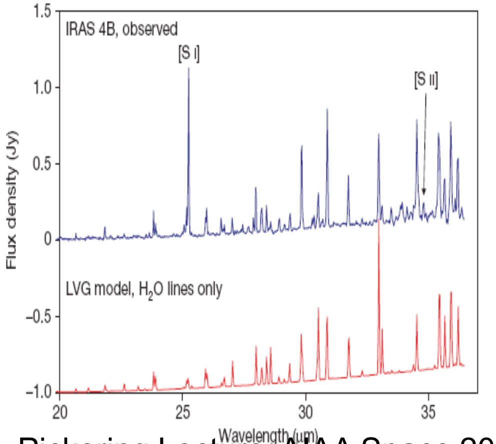


# How are Planets Assembled?
# Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk






Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

# Dust disks are durable and omnipresent

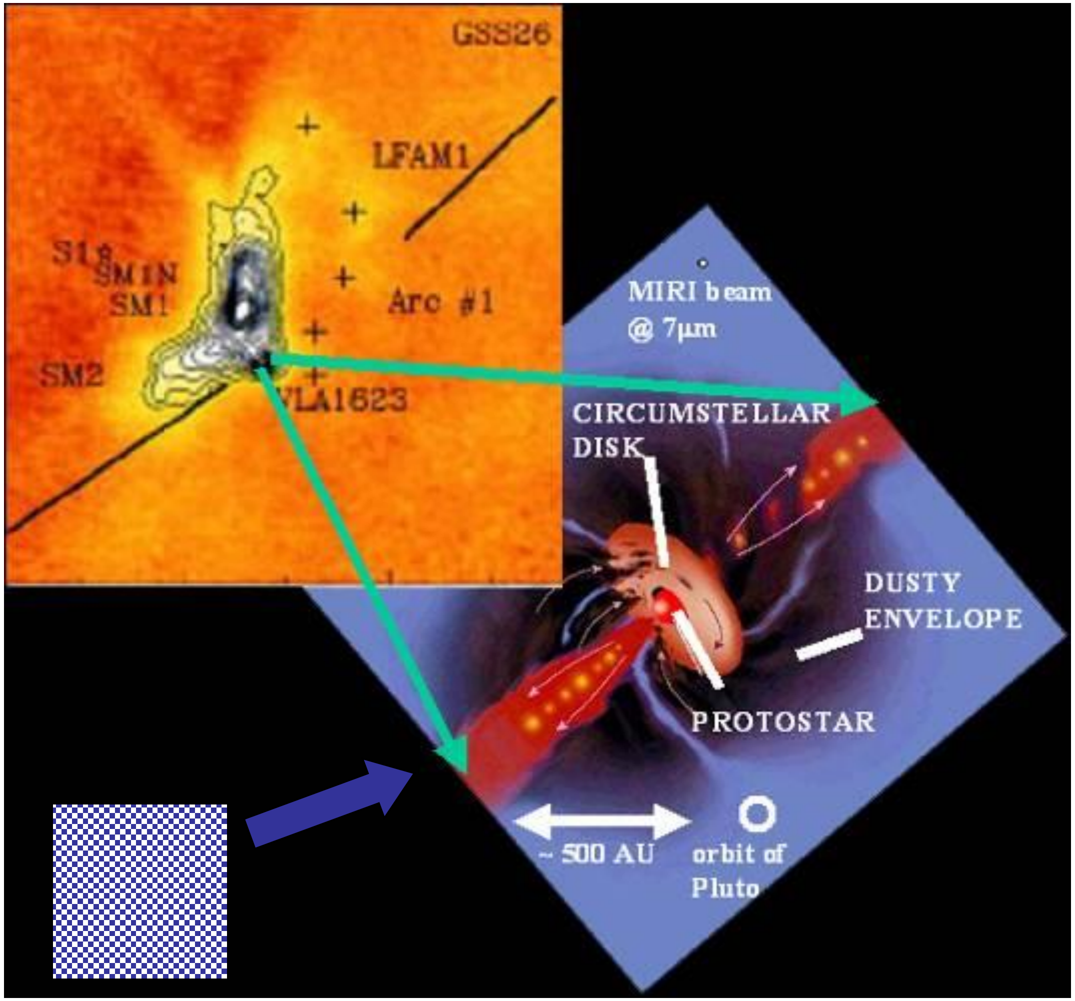
The central star of the Helix Nebula, a hot, luminous White Dwarf, shows an infrared excess attributable to a disk in a planetary system which survived the star's chaotic evolution

Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

# How are circumstellar disks like our Solar System?

**Here is an illustration of what MIRI might find within the very young core in Ophiuchus, VLA 1623**

**artist's concept of protostellar disk from T. Greene, Am. Scientist**




**approximate field for JWST NIRSpec & MIRI integral field spectroscopy**

# JWST Science Theme #4:

## Planetary systems and the origins of life

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

… to determine the physical and chemical properties of planetary systems including our own, and to investigate the potential for the origins of life in those systems.

Robert Hurt

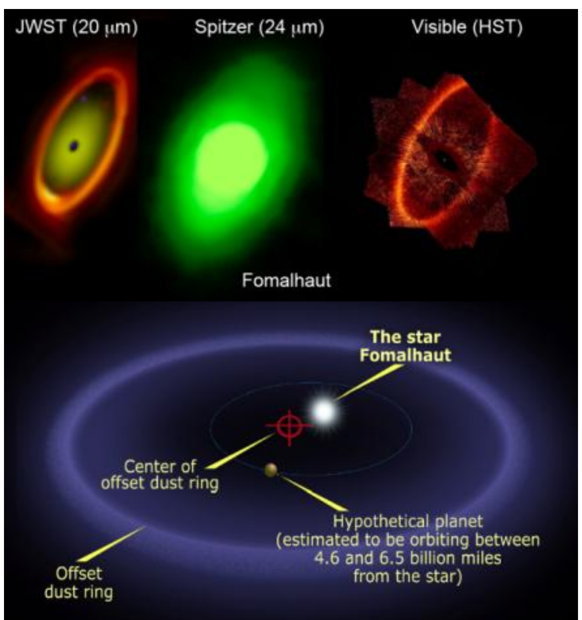
# How do planets form?

Giant planets could be signpost of process that create Earth-like planets

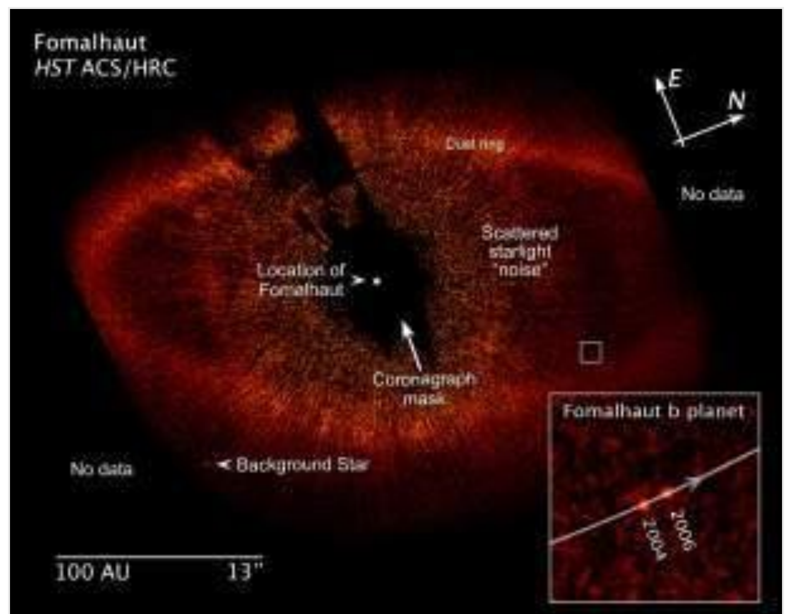
Solar System primordial disk is now in small planets, moons, asteroids and comets

JWST Observations:

- Coronagraphy of exosolar planets
- Compare spectra of comets & circumstellar disks




Kalas, Graham & Clampin 2005

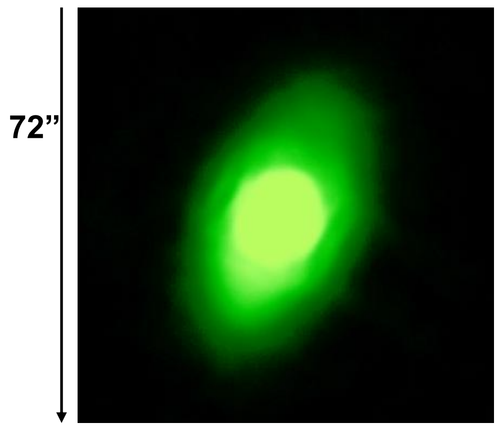


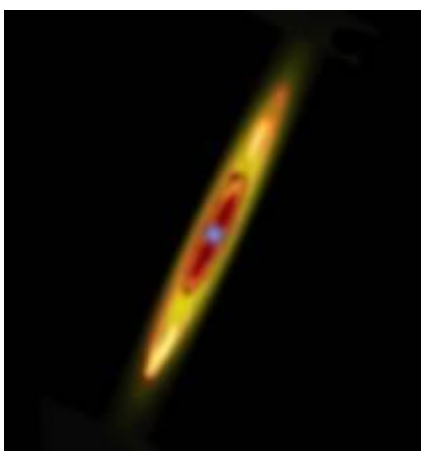

Kalas et al 2008

# Planetary systems and the Origins of Life

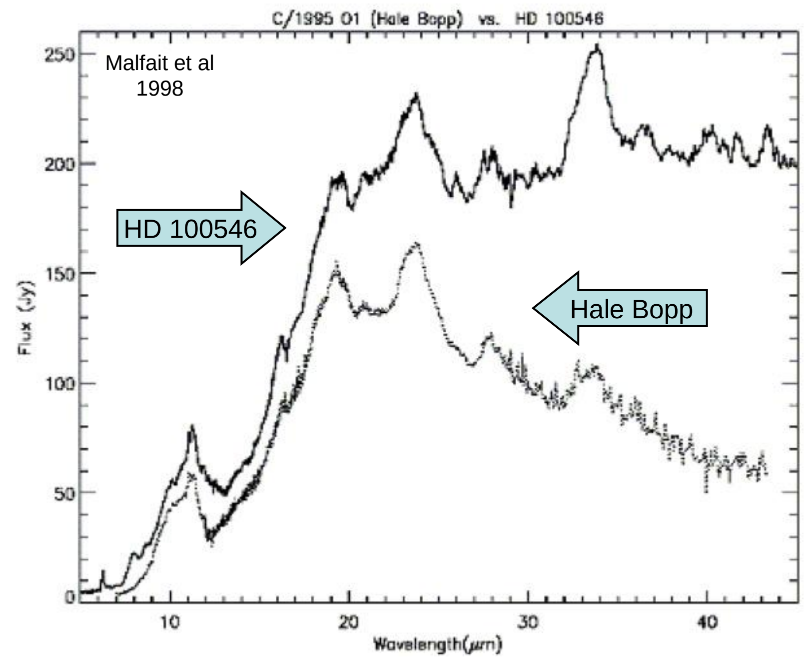
Fomalhaut system at 24 µm

(Spitzer Space Telescope)



Simulated JWST image
Fomalhaut at 24 microns



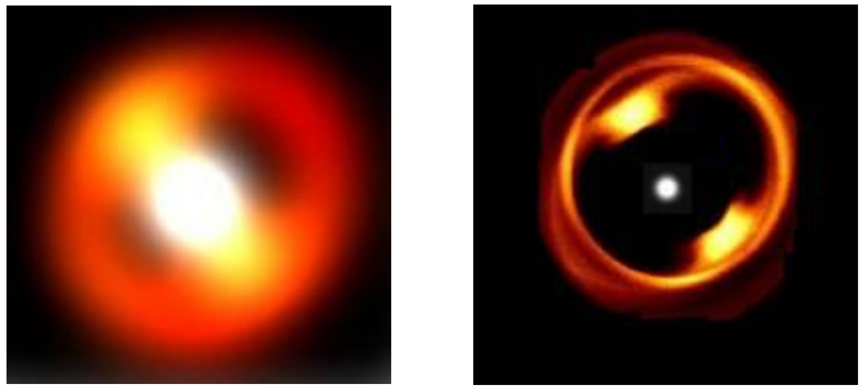

Malfait et al 1998

# Planetary Systems and the Origins of Life

- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems) and remnant disks?
- What is the source of water and organics for planets in habitable zones?
- How are systems cleared of small bodies?
- What are the planetary evolutionary pathways by which habitability is established or lost?
- Does our solar system harbor evidence for steps on these pathways?

# Planetary Systems and the Origins of Life

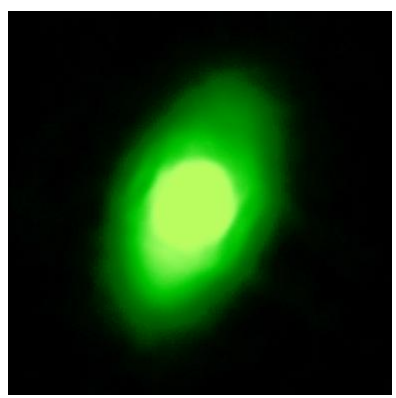
Model of Vega system at 24 µm (Wilner et al. 2000)



Formalhaut system at 24 µm

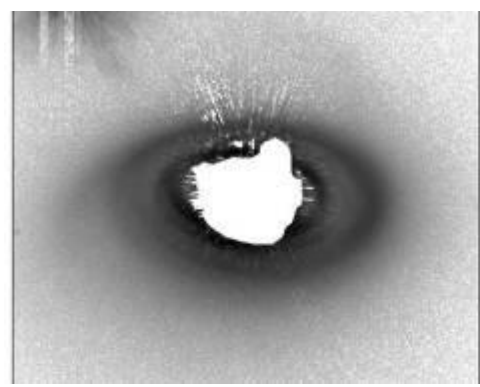
(Spitzer Space Telescope)

72”



HD141569 (606 nm)

(HST/ACS)



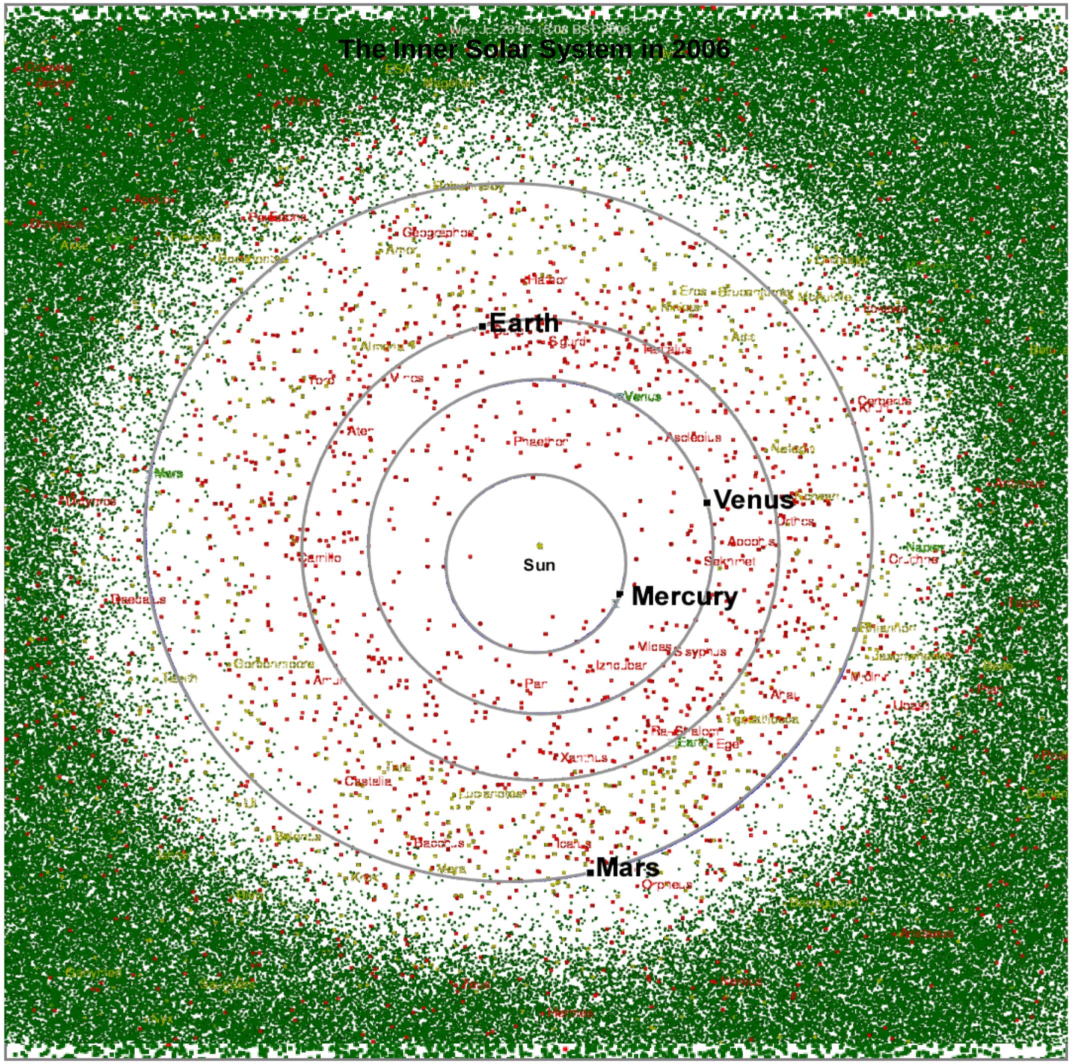
9”

# History of Known (current) NEO Population

2006

Earth Crossing

Outside Earth's Orbit



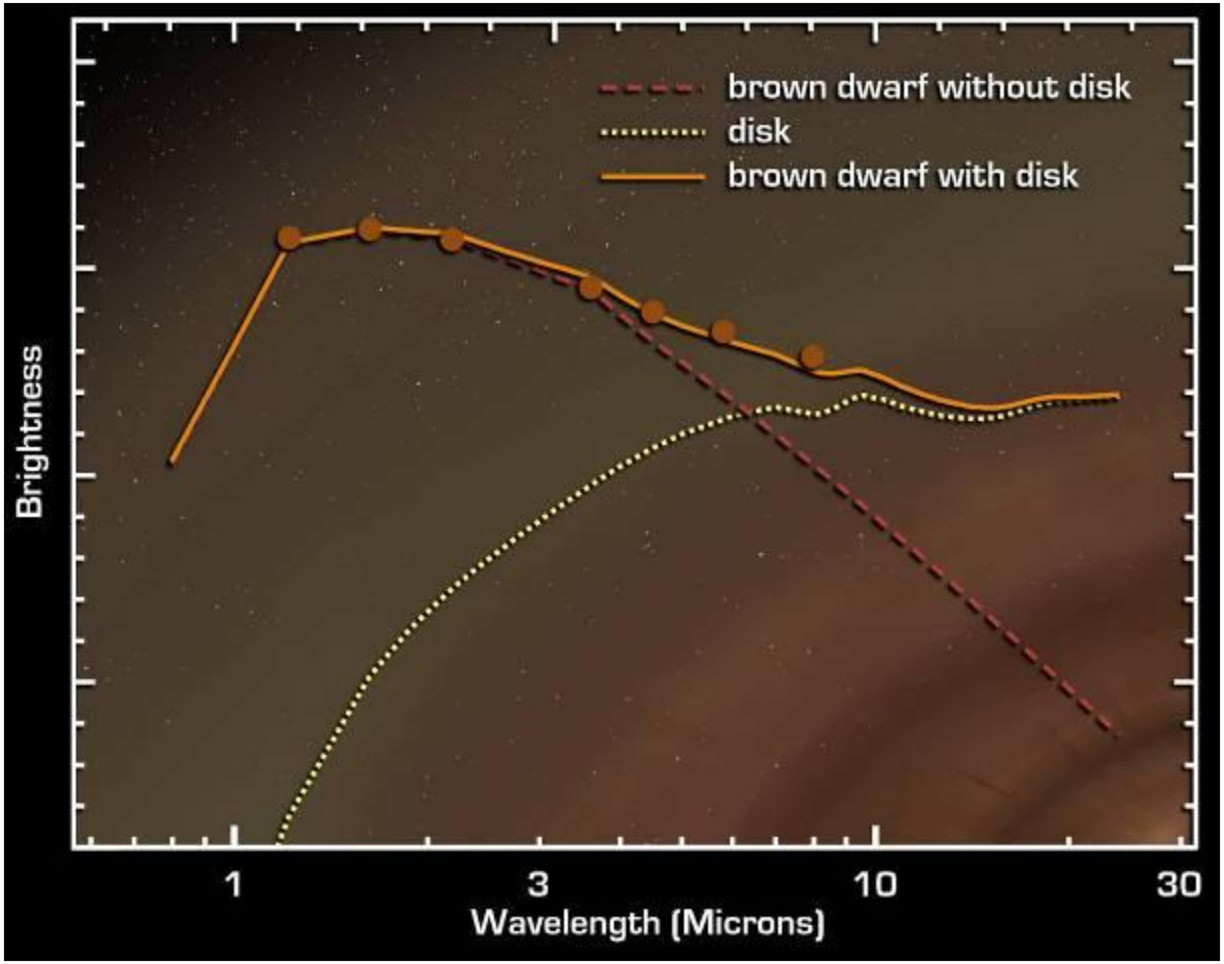

**Known**
- 340,000 minor planets
- ~4500 NEOs
- ~850 Potentially Hazardous Objects (PHOs)

Scott Manley

Armagh Observatory

Landis, "Piloted Flight to a Near-Earth Object", AIAA Conference 19 Sep 07

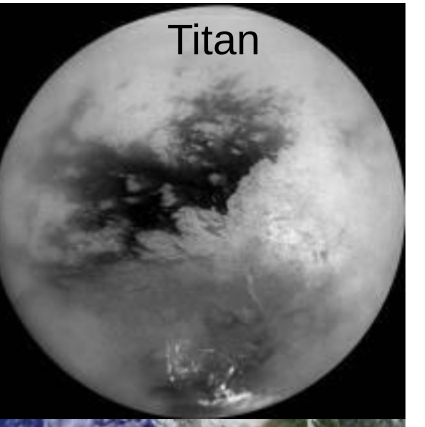
# Brown Dwarfs Form Like Stars: Can “Planets” have Planets?




A Brown Dwarf With a Planet-Forming Disk

Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

# How are habitable zones established?




Source of Earth's $H_20$ and organics is not known

Comets? Asteroids?

History of clearing the disk of gas and small bodies

Role of giant planets?

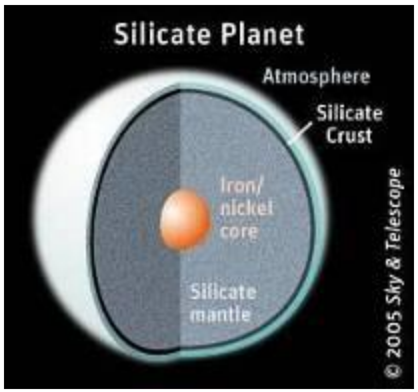
JWST Observations:

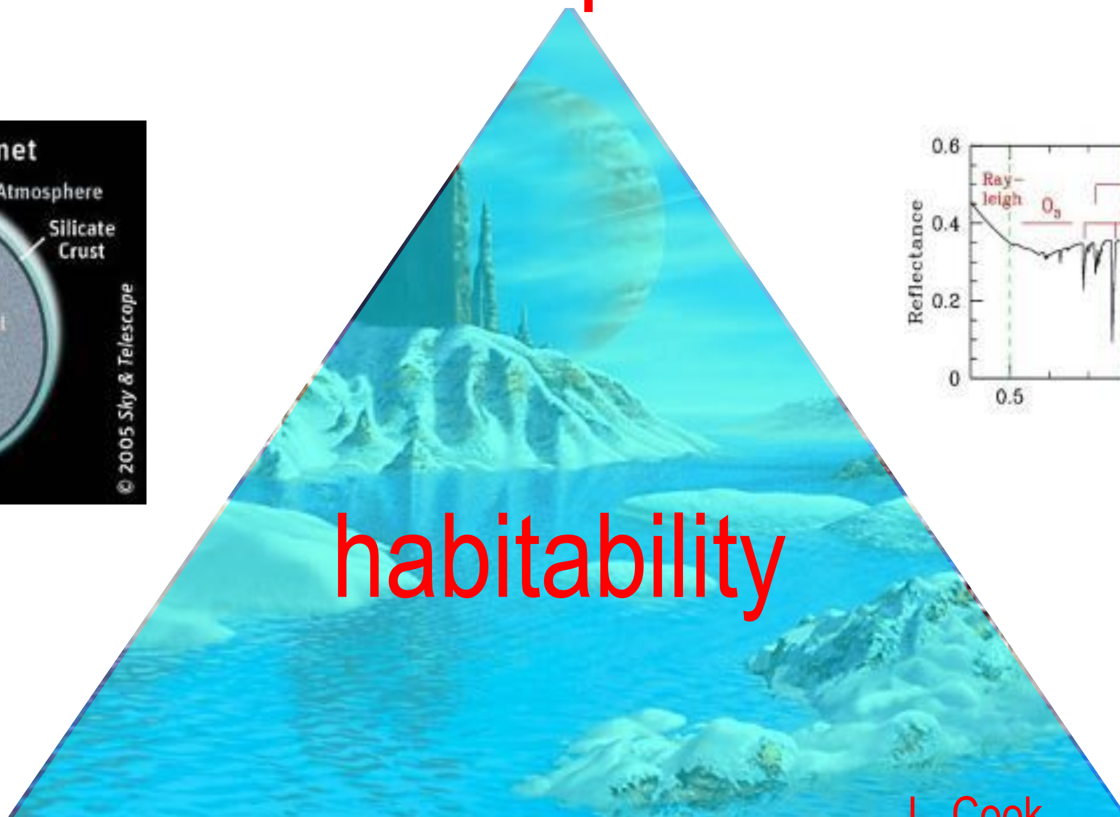
Comets, Kuiper Belt Objects

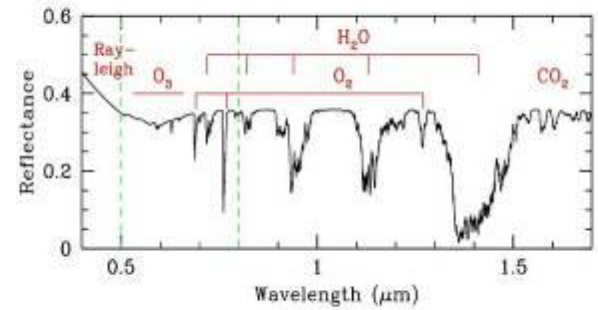
Icy moons in outer solar system

# Search for Habitable Planets

atmosphere



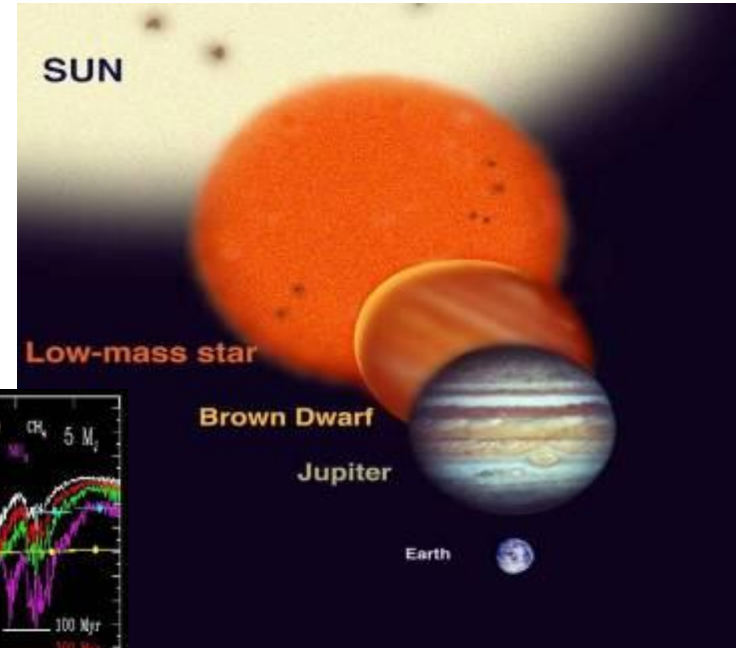




interior

surface

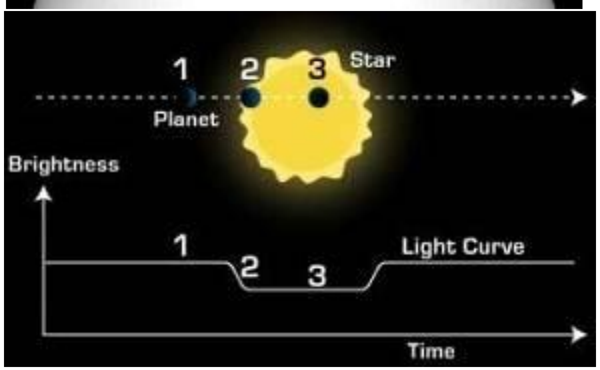
Sara Seager (2006)

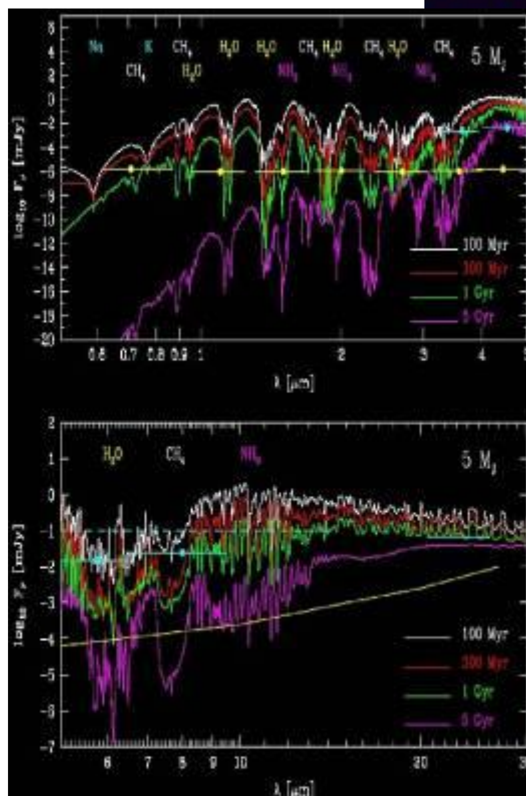
# Atmospheres of Extrasolar Planets




Extrasolar Planet Transits

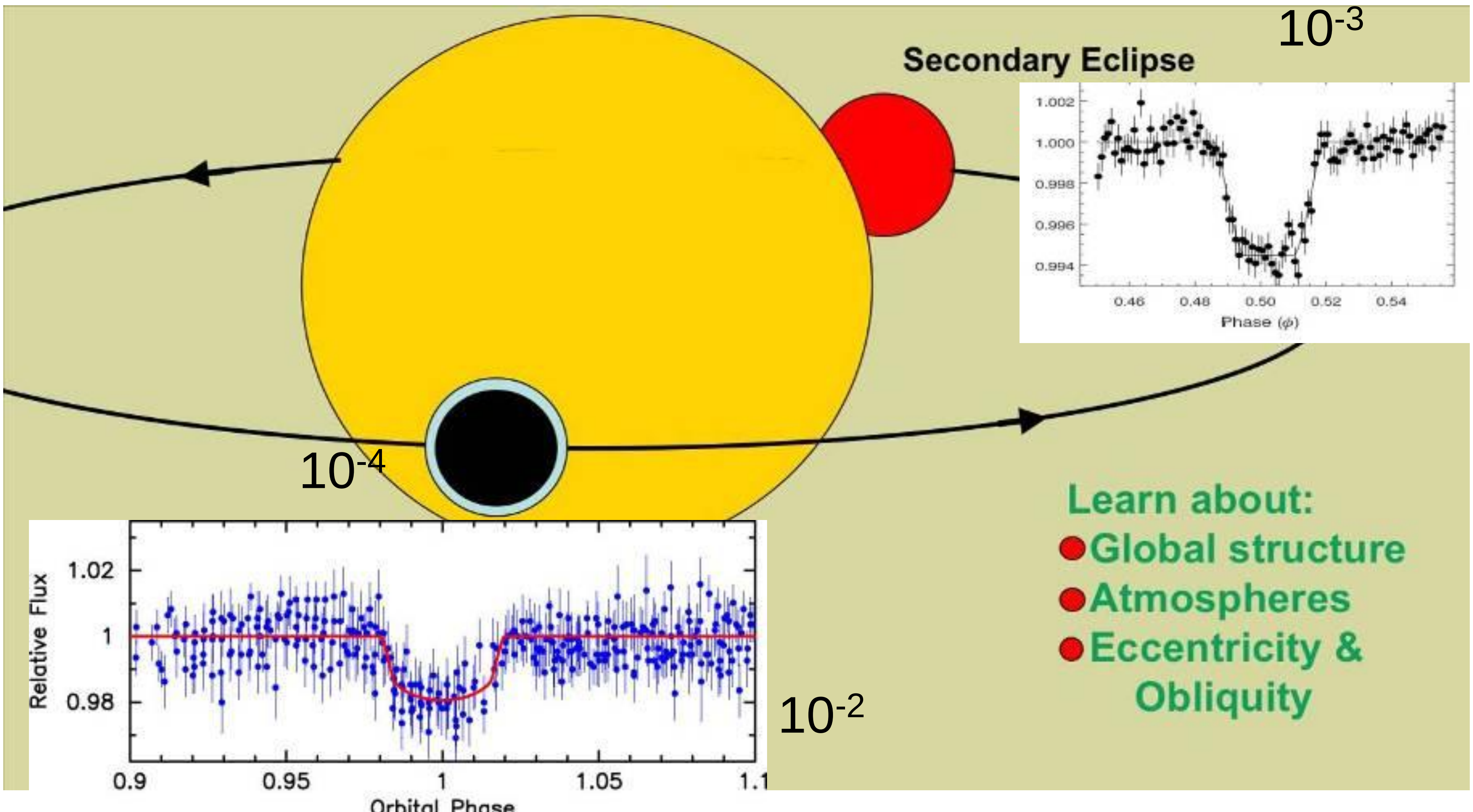
Detecting terrestrial planet atmospheres




Burrows, Sudarsky and Lunine (2003)

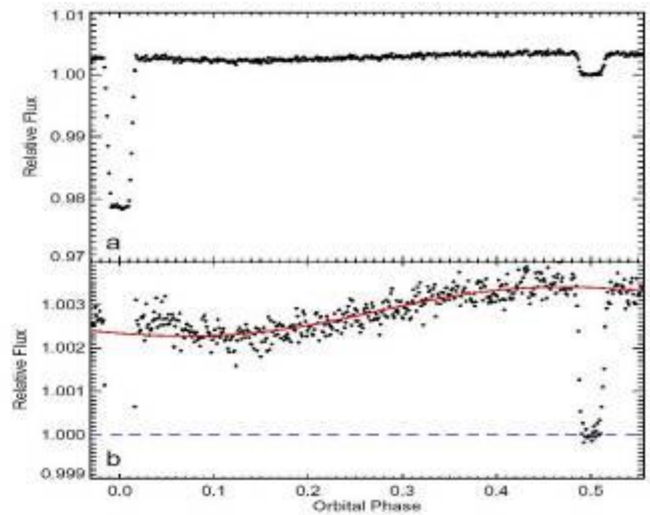
# Transiting Planet Science



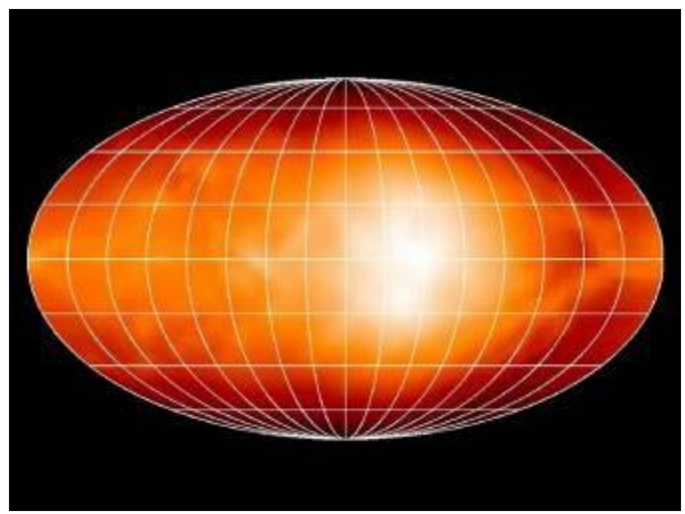

Courtesy Lori Allen

# HD 189733b: First [one-dimensional] temperature map of an exoplanet

- 970K on night side; 1210K on day side
- "warm spot" 30 degrees E of high-noon point.
- High "easterly" winds, 6000 mph, carry heat around planet
- Precise Spitzer observations indicate elliptical orbit => unseen planet, could be as small as Earth?




Data – flux at 8um over more than half an orbit



Model: Assumes tidal locking of planet to star and extrapolates in latitude.

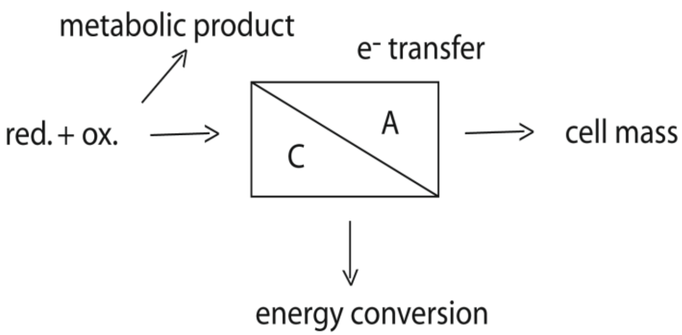
Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

# Search for Life

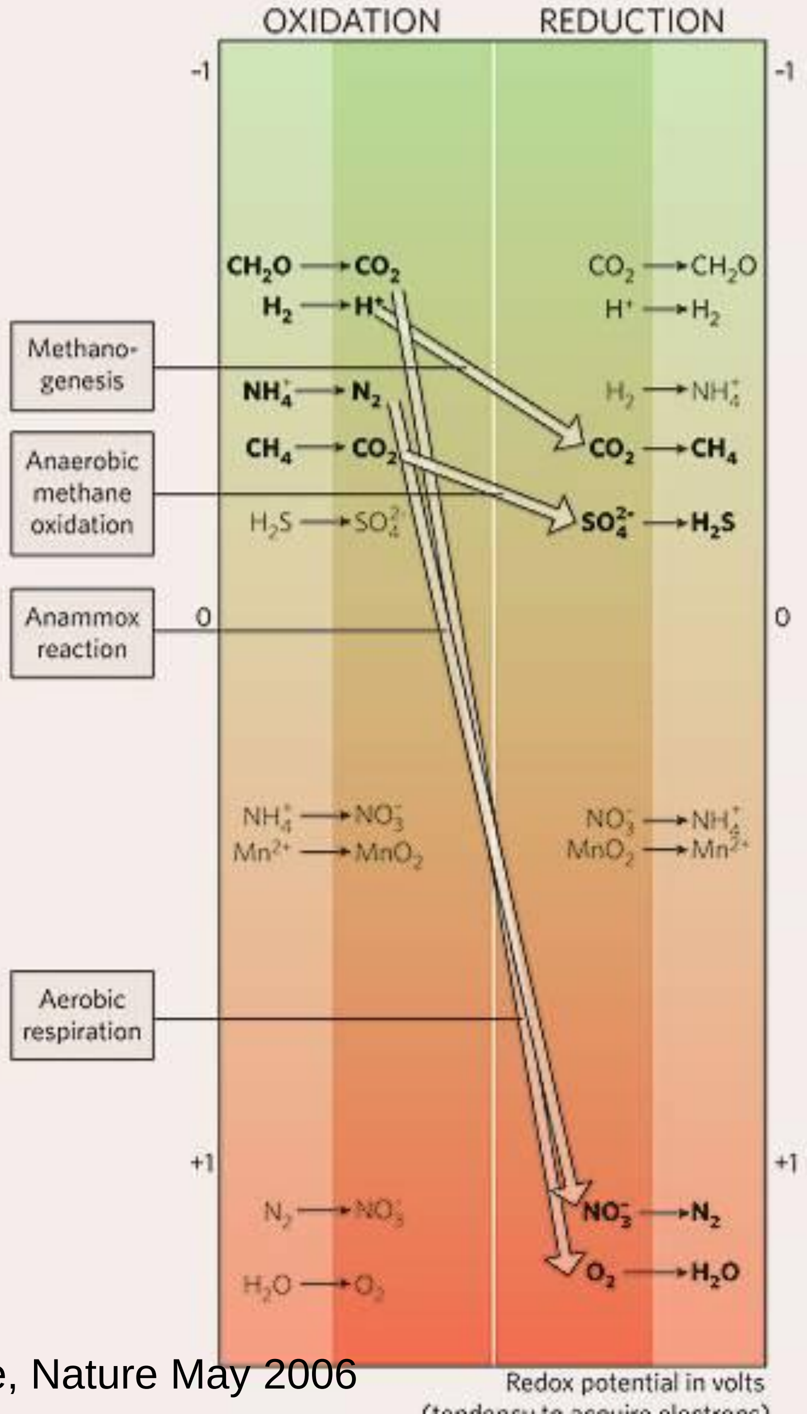
## What is life?

## What does life do?

### Life Metabolizes




Sara Seager (2006)




Lane, Nature May 2006

All Earth life uses chemical energy generated from redox reactions

Life takes advantage of these spontaneous reactions that are kinetically inhibited

Diversity of metabolisms rivals diversity of exoplanets

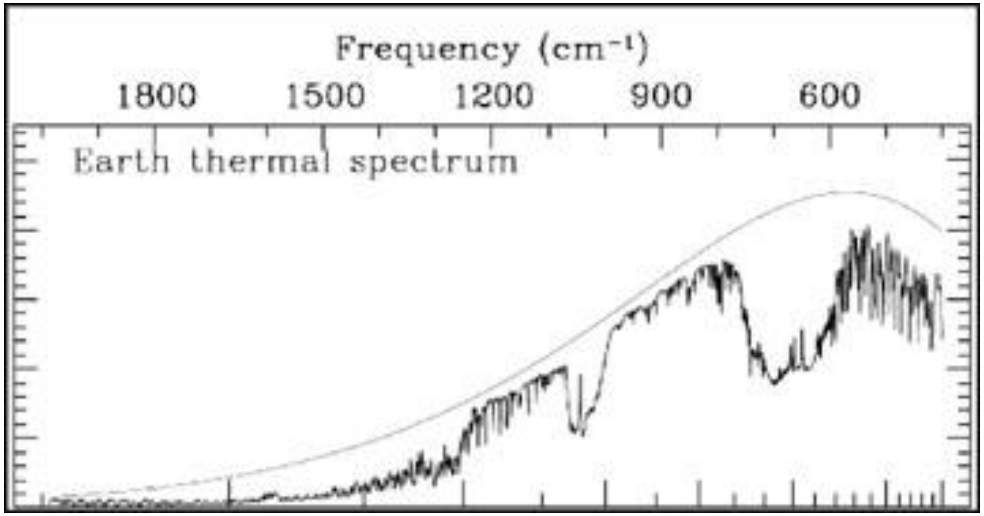
Sara Seager (2006)

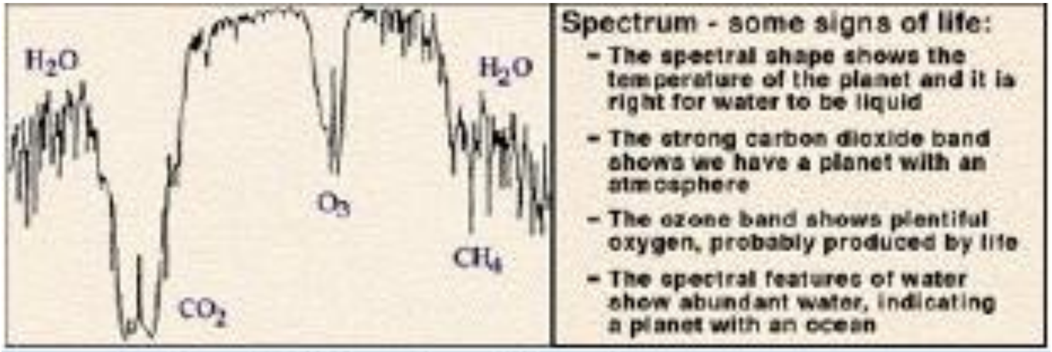
# Bio Markers

## Spectroscopic Indicators of Life

### Absorption Lines

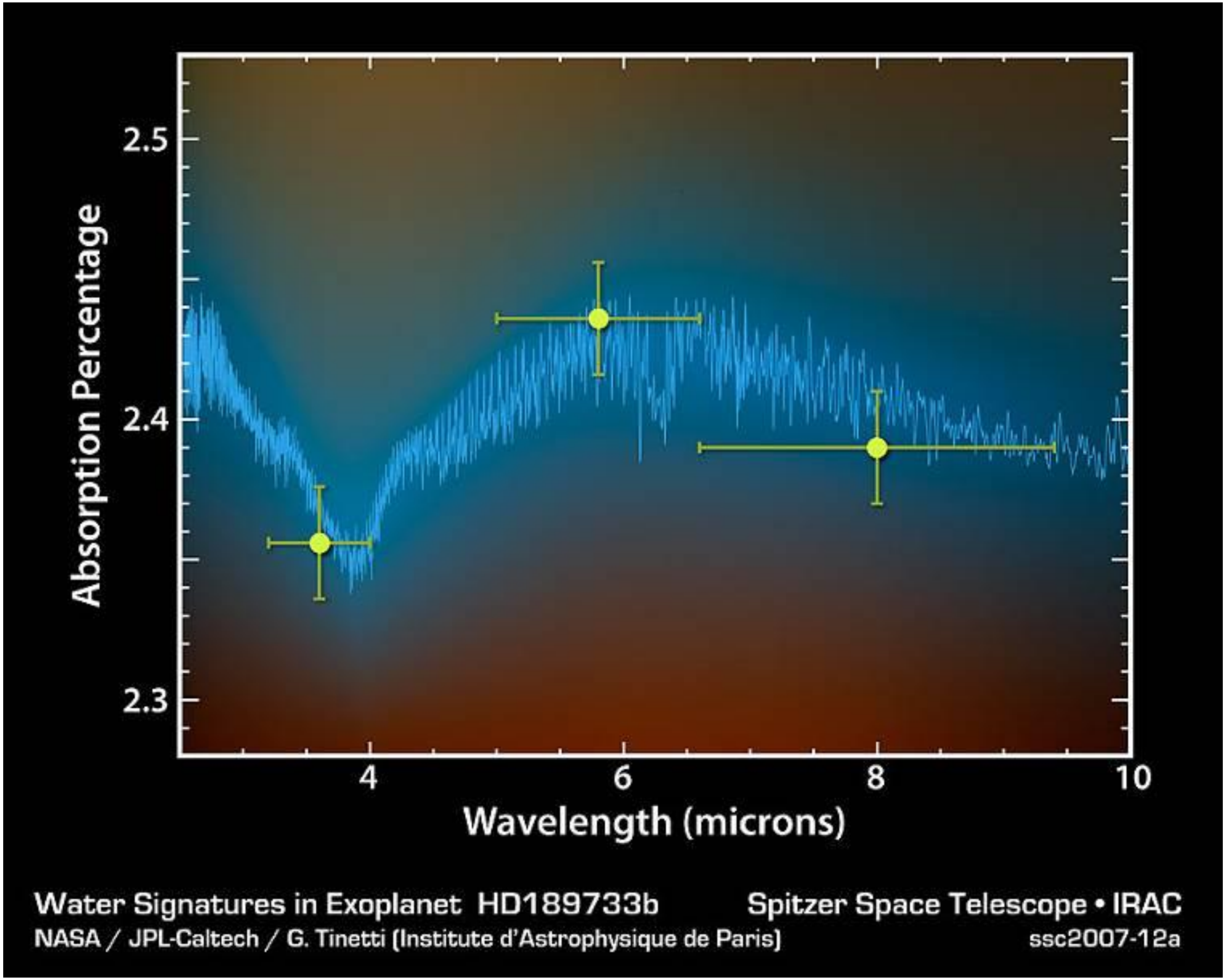
- $CO_2$
- Ozone
- Water
- "Red" Edge



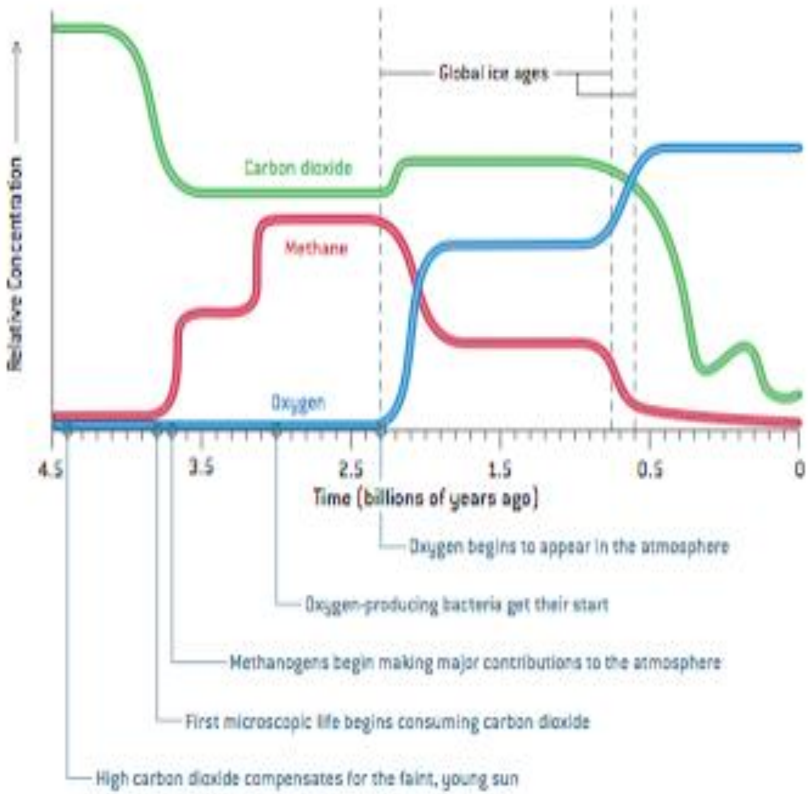

Example signs of life from chemical spectra.
*Credit: NASA JPL*

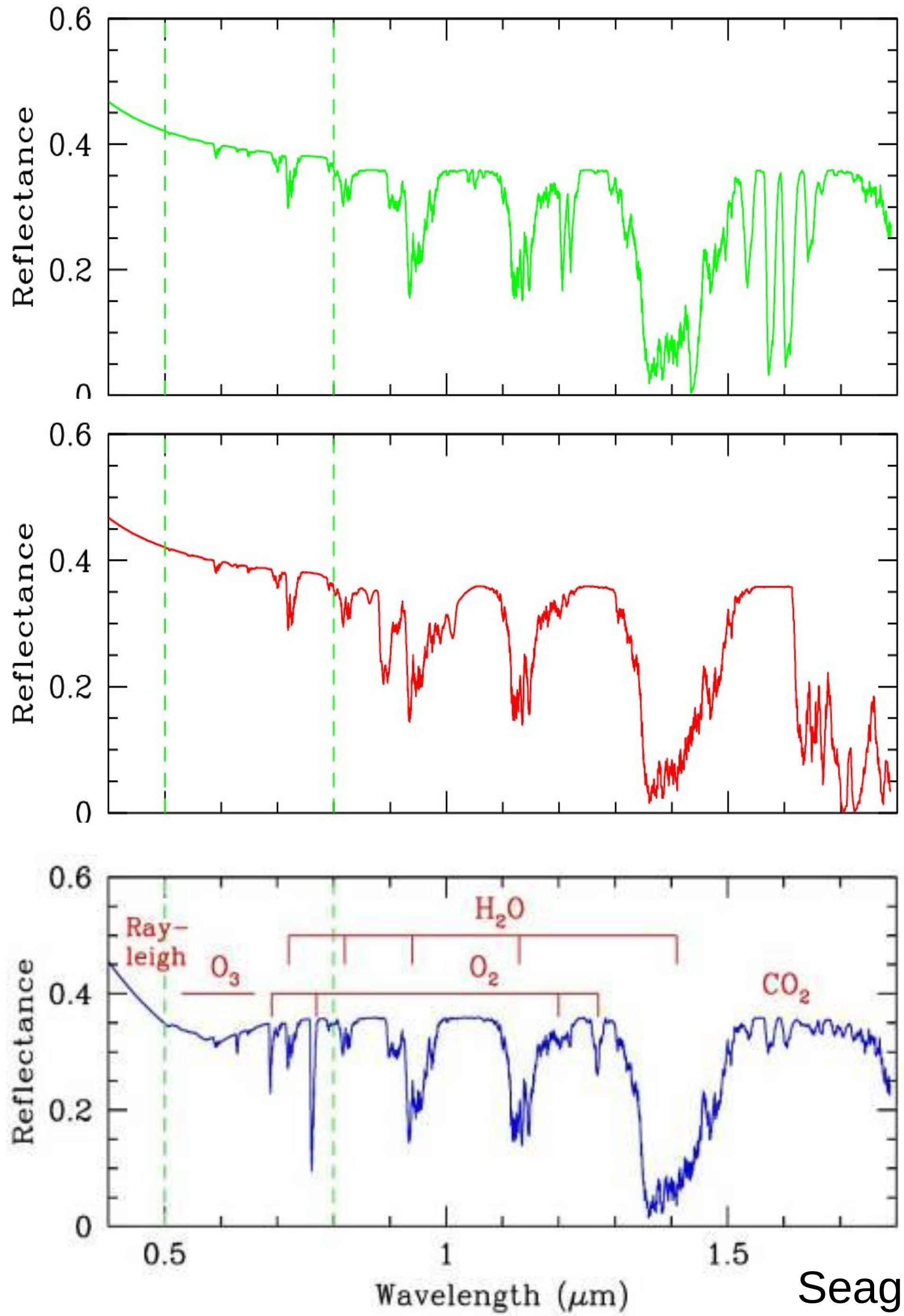
# Is there water in an Exoplanet?




Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

# Earth Through Time



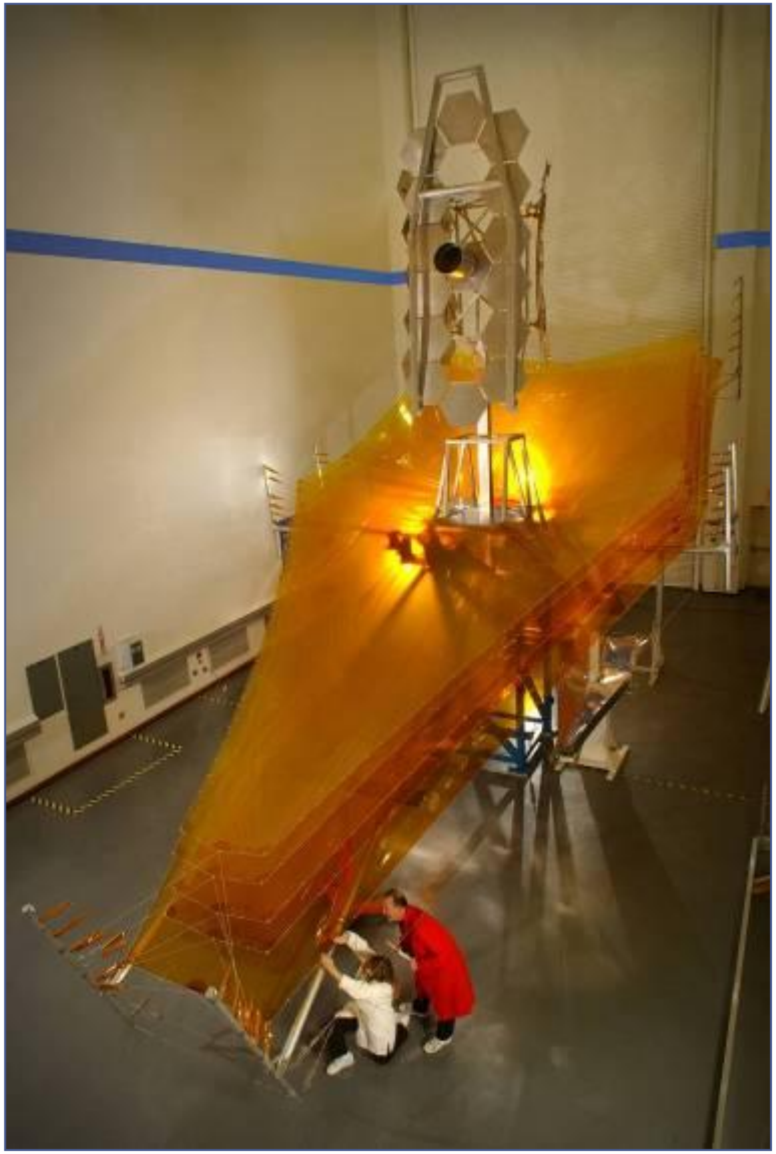




Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon

Seager

# Countdown to Launch

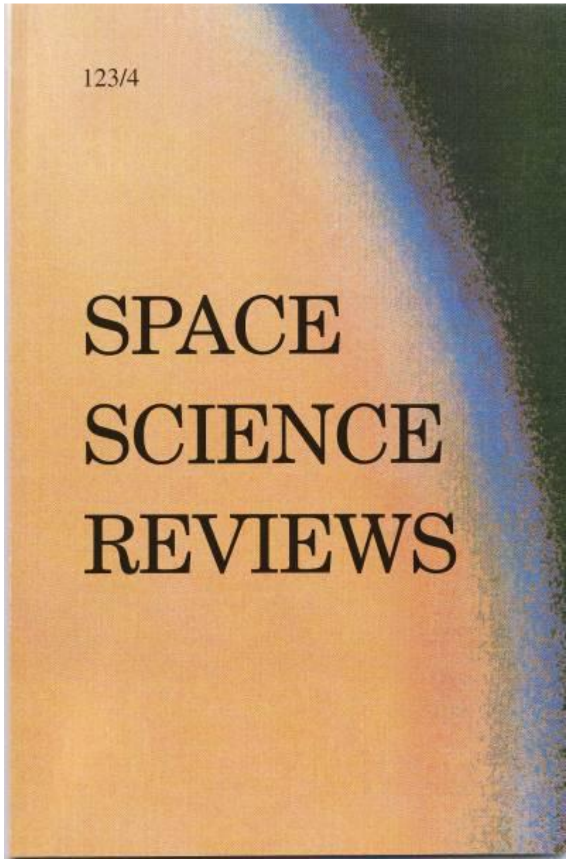
Planned for 2014 Launch

# Learn more at: www.jwst.nasa.gov

New

New

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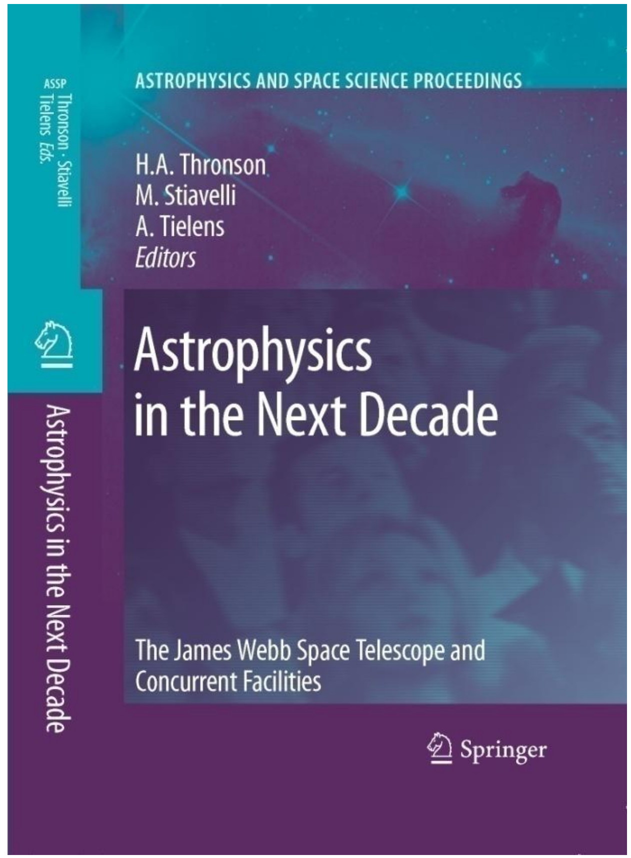
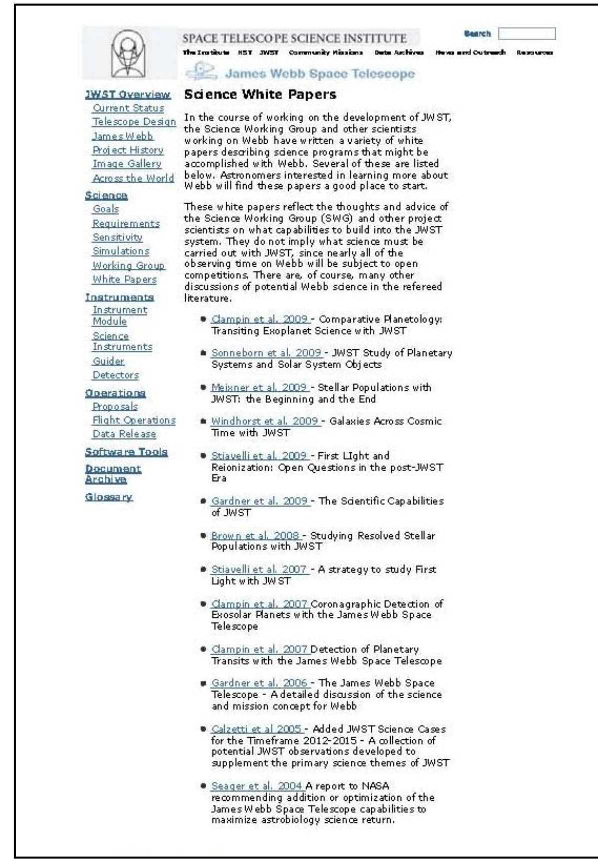



Available Now




www.stsci.edu/jwst/science/whitepapers/

# Any Questions?