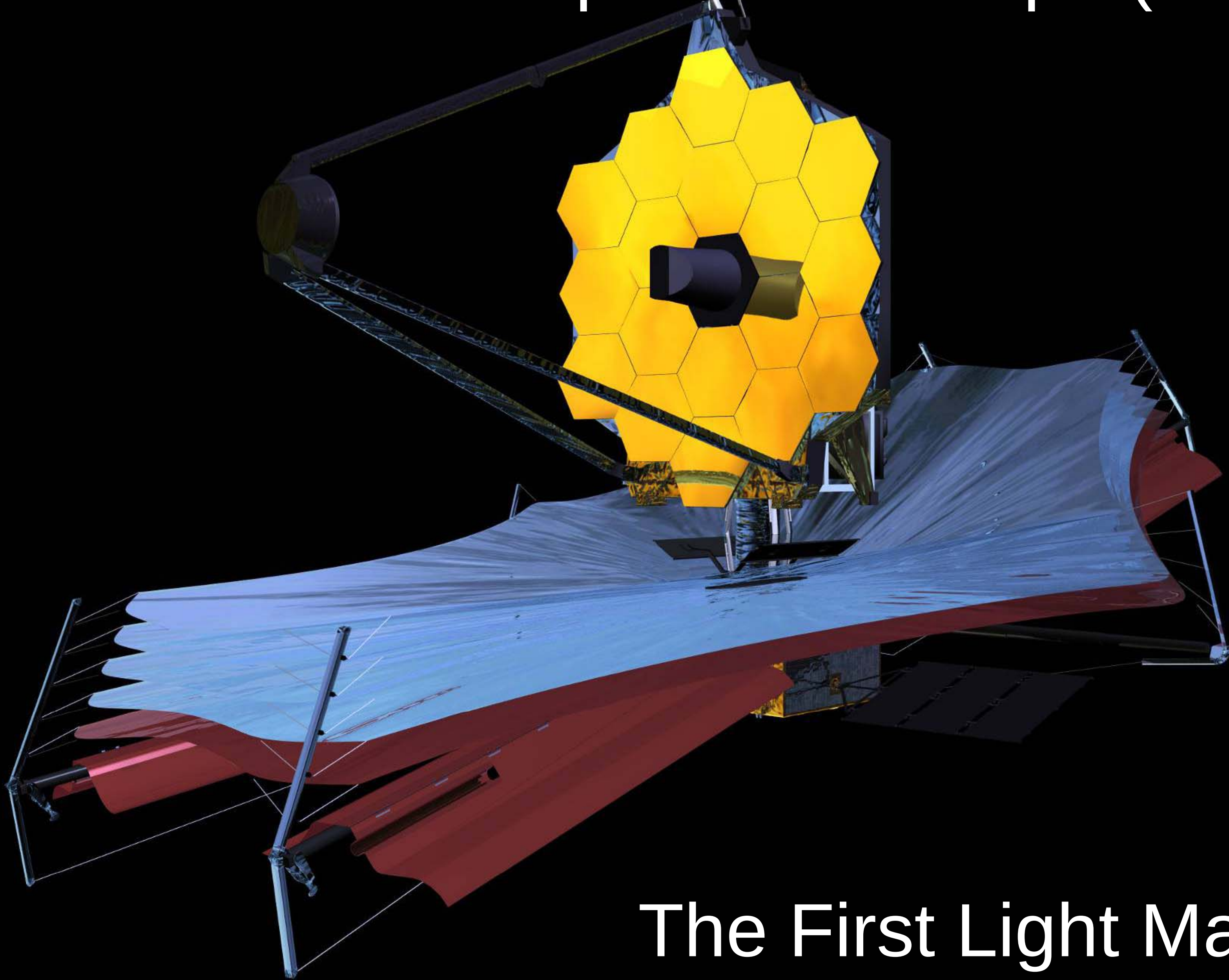
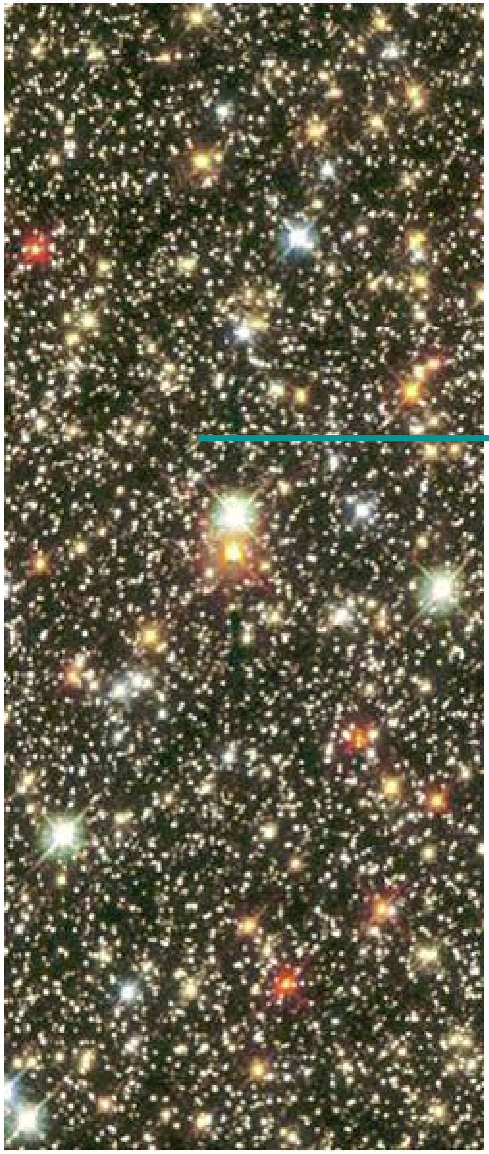
James Webb Space Telescope (JWST)

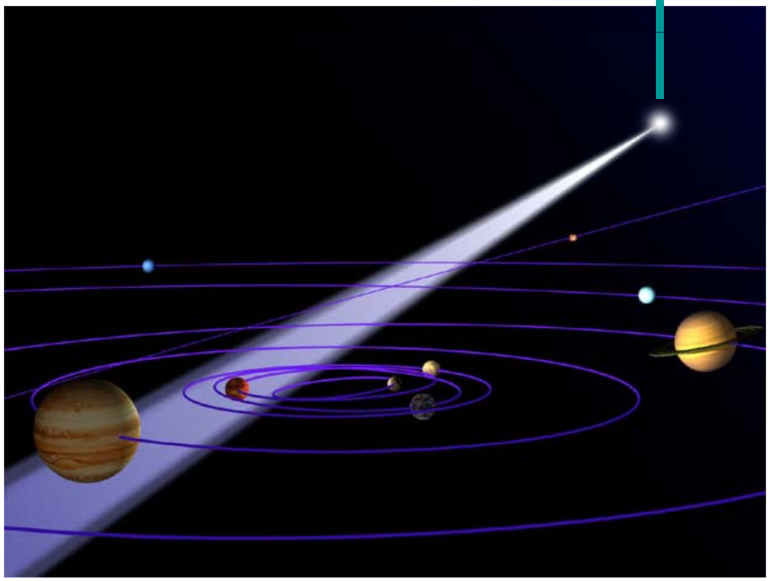


The First Light Machine

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

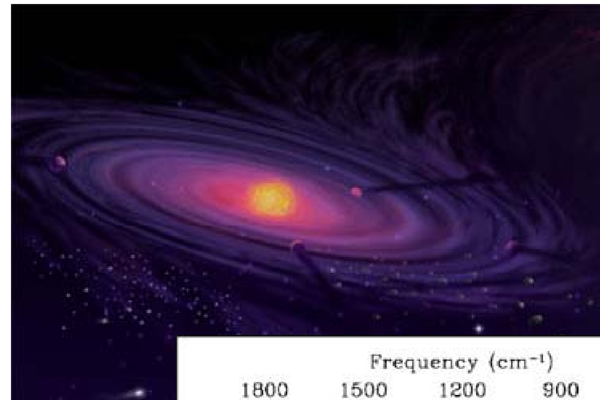
Formation of planetary systems

Formation of life on the early Earth

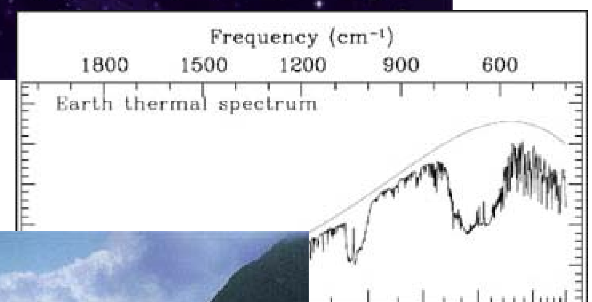
Are We Alone?

Search for life outside the solar system

Search for other planetary systems



Search for habitable planets

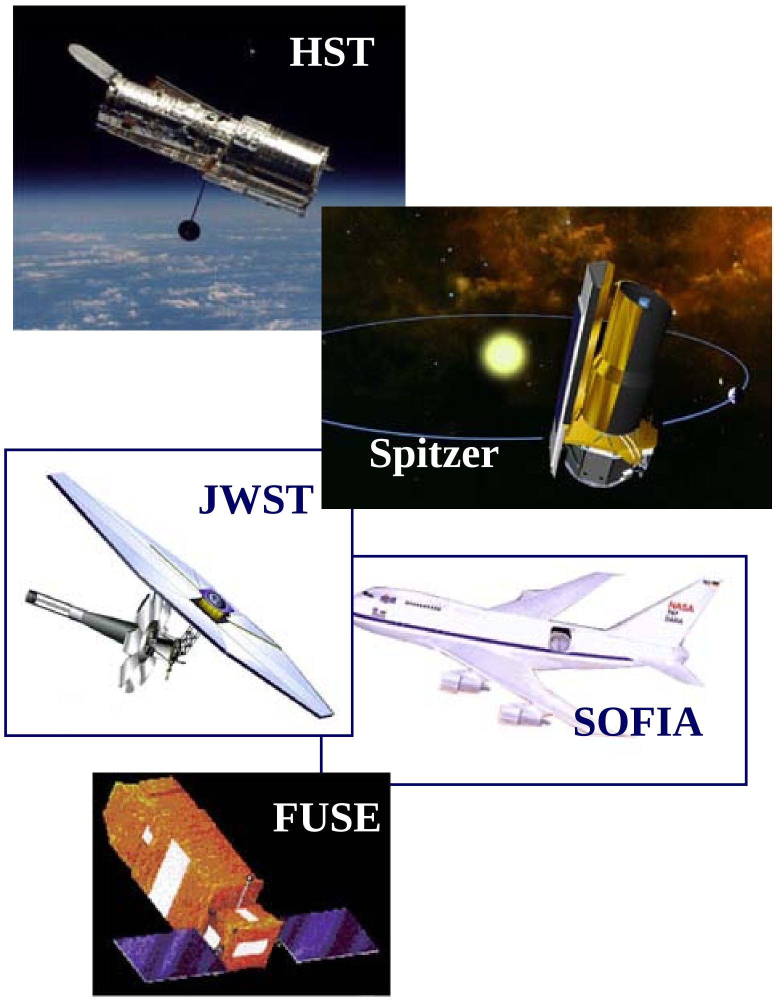


Identify remotely detectable bio-signatures

Search for “smoking guns” indicating biological activities

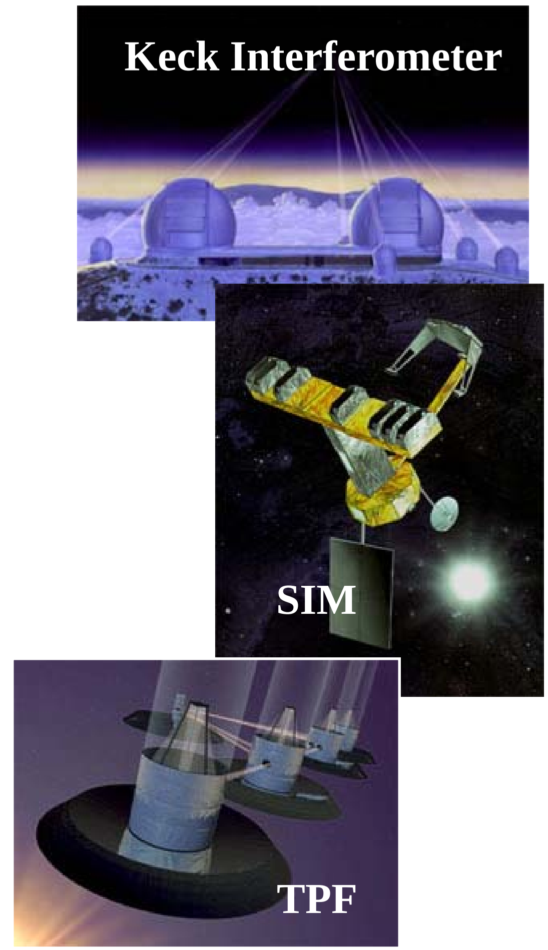
Missions Supporting the Origins Goals

How Did We Get Here?

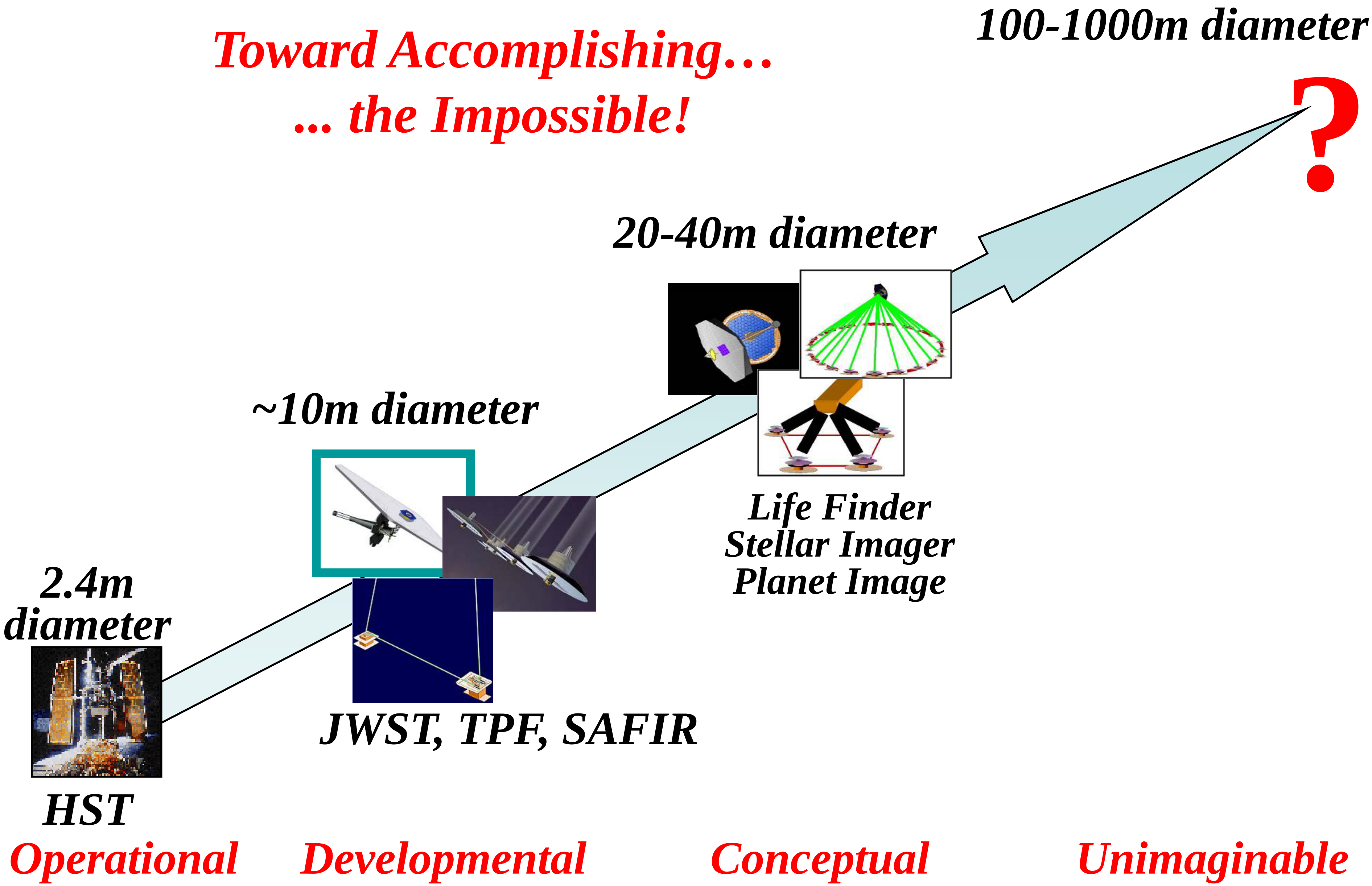


Cross Feed Science & Technology

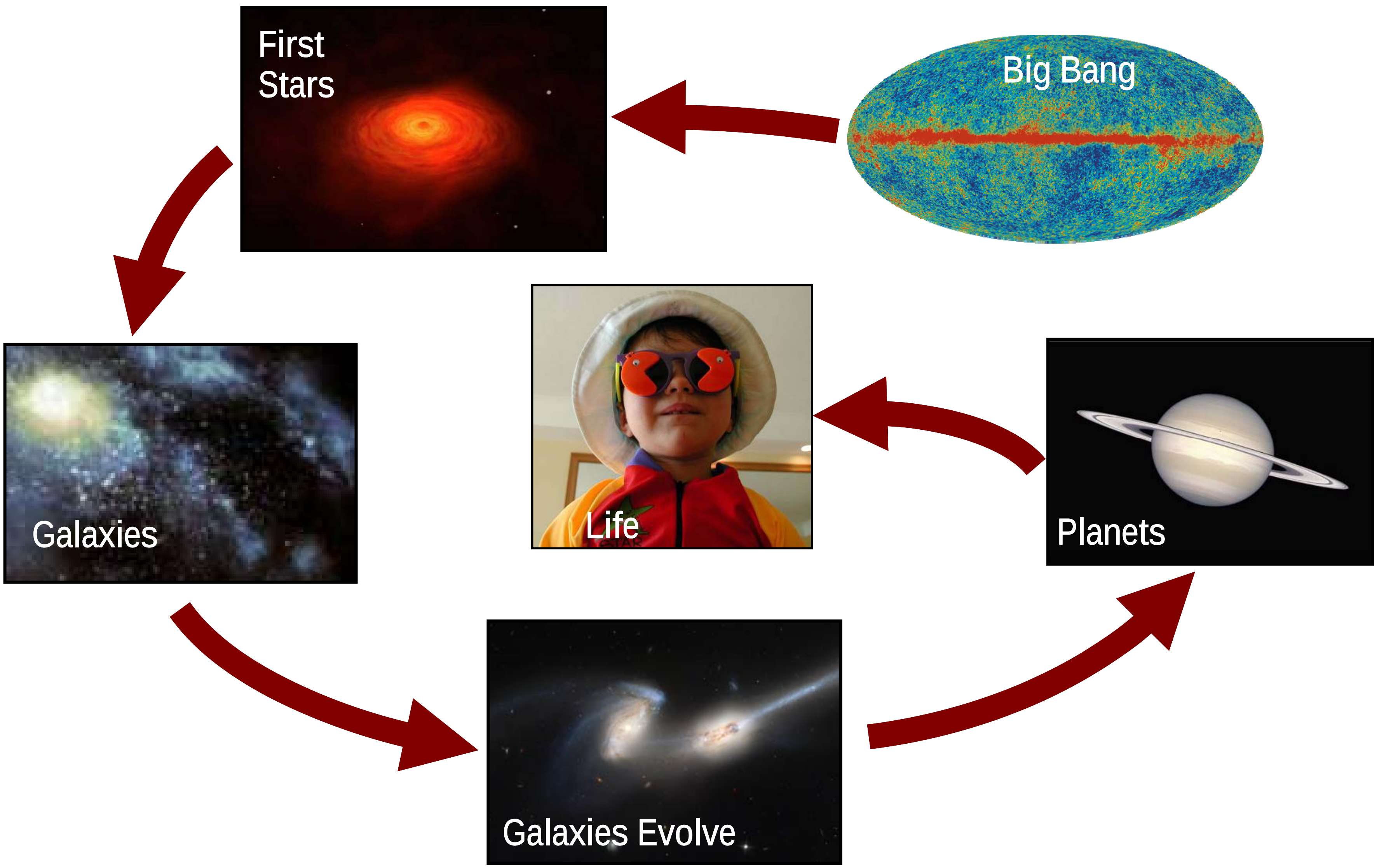
Are We Alone?



A Vision for Large Telescopes & Collectors

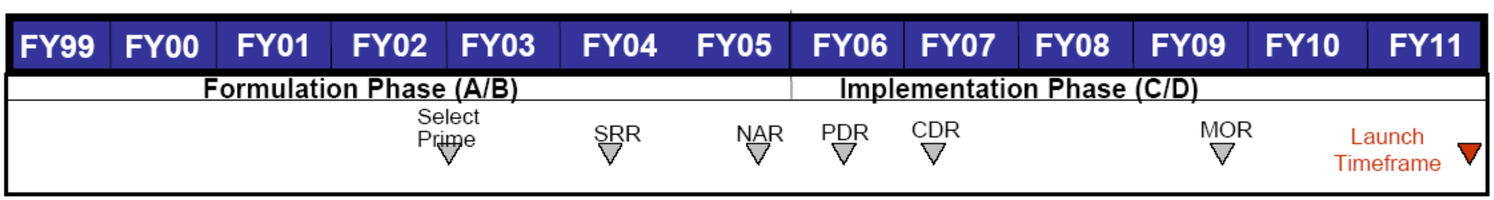


JWST Science Themes



JWST Summary

- **<u>Mission Objective</u>**
  - Study origin & evolution of galaxies, stars & planetary systems
  - Optimized for near infrared wavelength (0.6 –28 μm)
  - 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



JWST Requirements

Optical Telescope Element

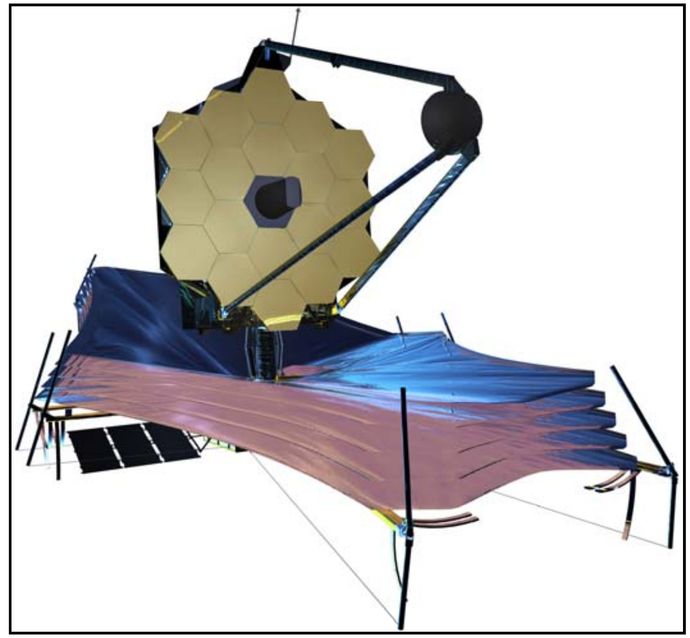
- 25 sq meter Collecting Area
- 2 micrometer Diffraction Limit
- < 50K (~35K) Operating Temp

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

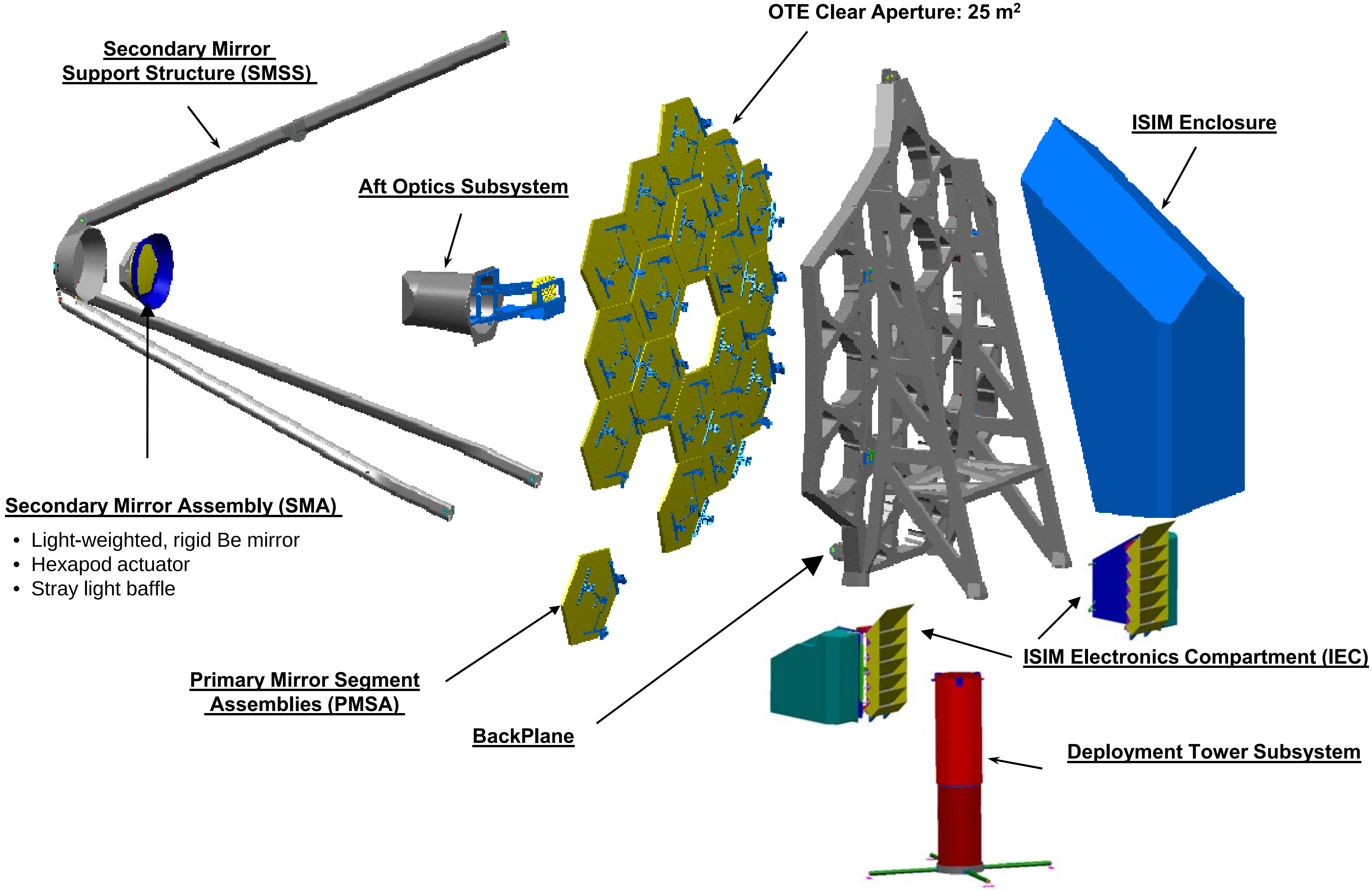
Segments

- 1.315 meter Flat to Flat Diameter
- < 20 nm rms Surface Figure Error

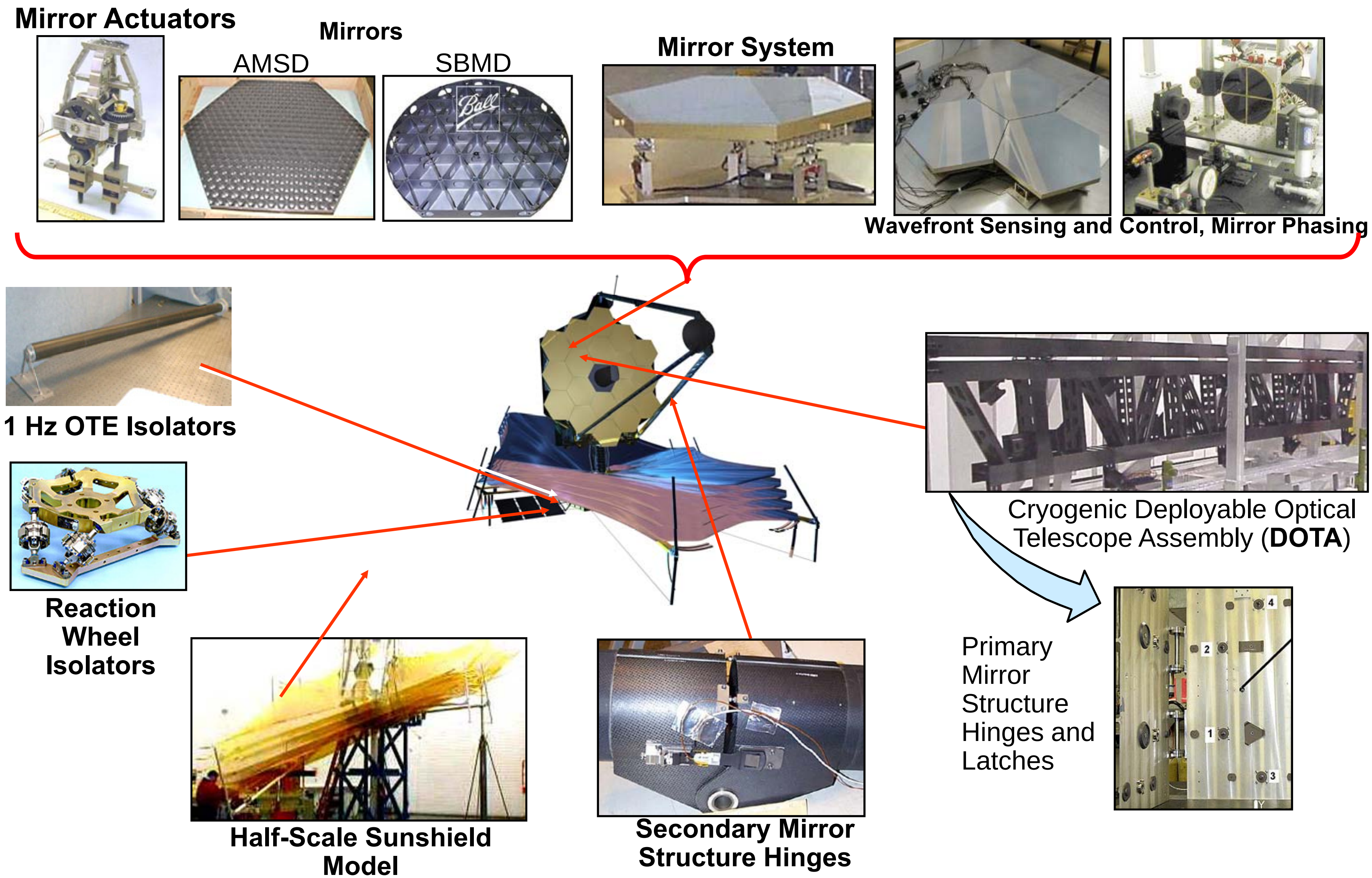


Low (0-5 cycles/aper)	4 nm rms
CSF (5-35 cycles/aper)	18 nm rms
Mid (35-65K cycles/aper)	7 nm rms
Micro-roughness	<4 nm rms

OTE Architecture Concept



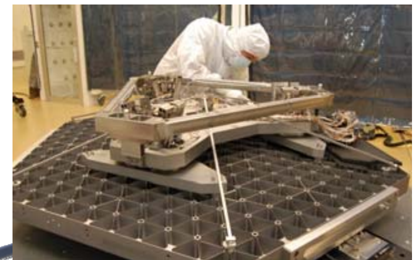
Investments Have Reduced Risk



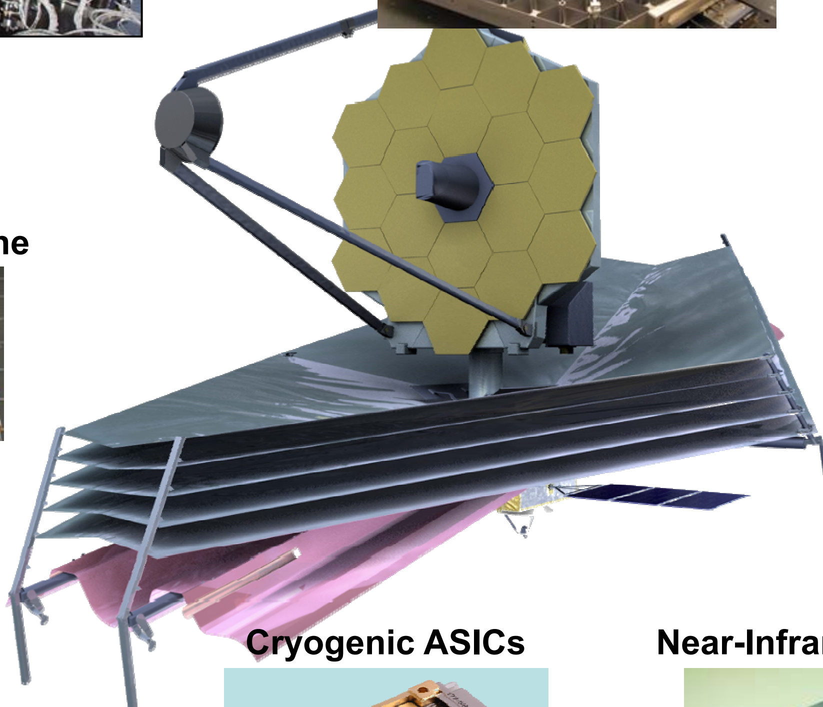
JWST Technology Demonstrations for TNAR

Mirror Phasing Algorithms

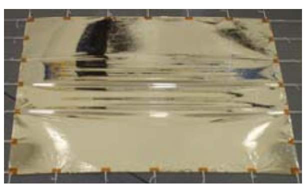
Beryllium Primary Mirror Segment



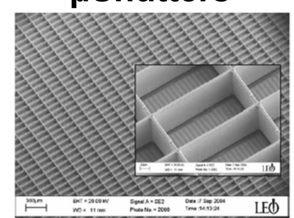
Backplane



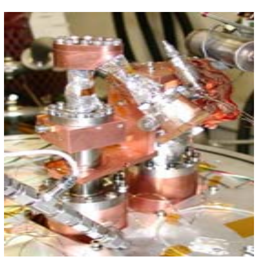
Sunshield Membrane



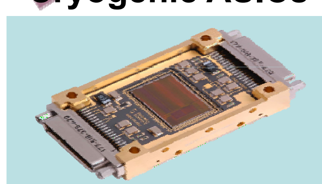
µShutters



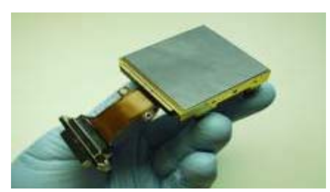
Cryocooler



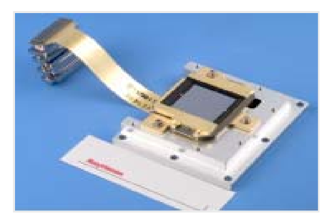
Cryogenic ASICs



Near-Infrared Detector

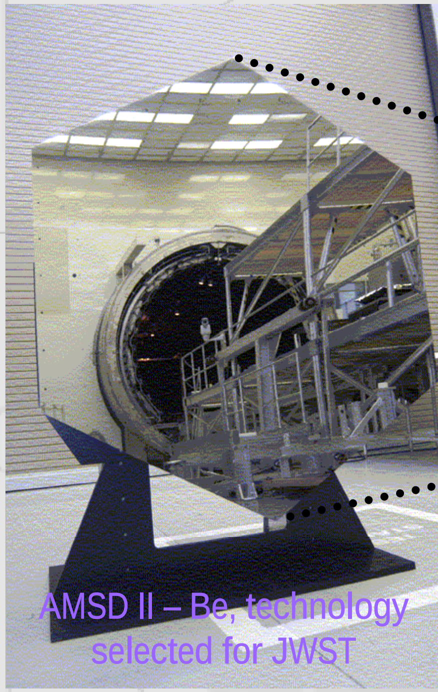


Mid-Infrared Detector

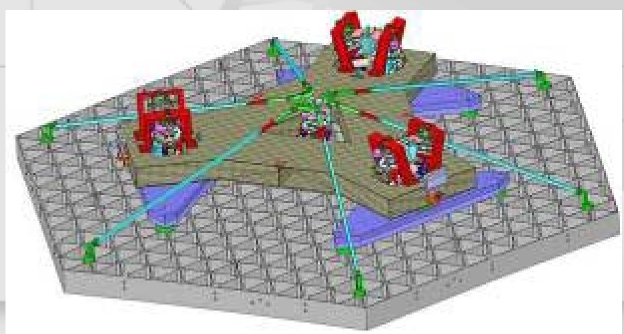


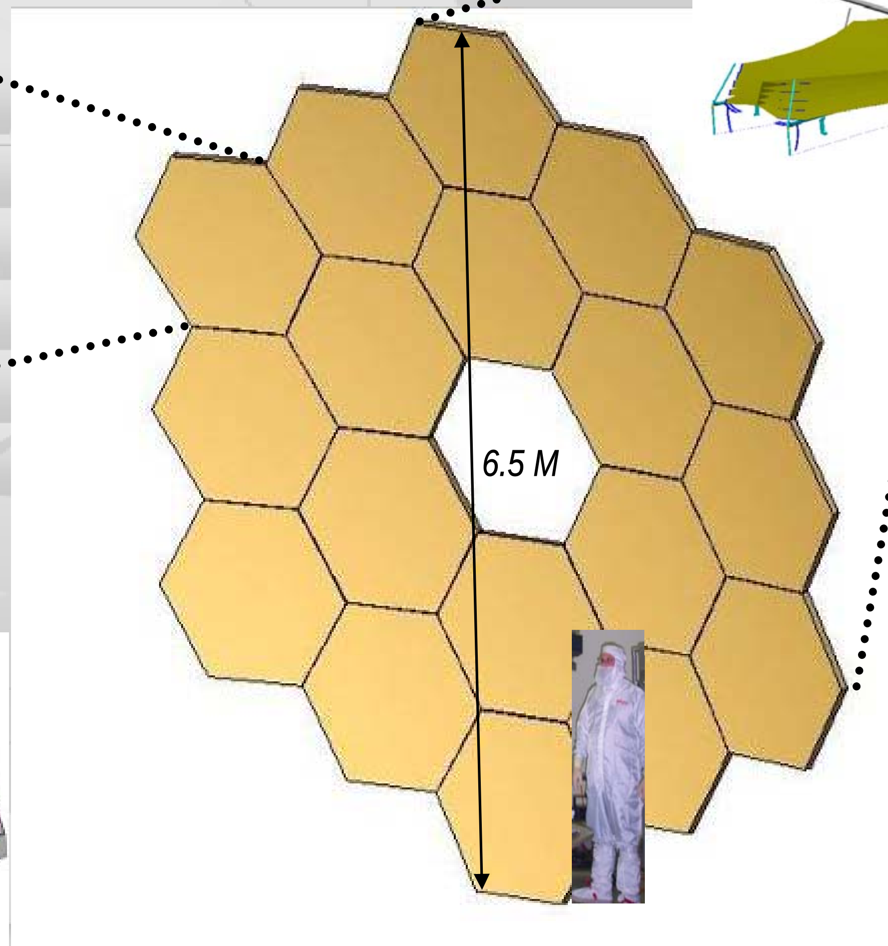
Technology Development of Large Optical Systems

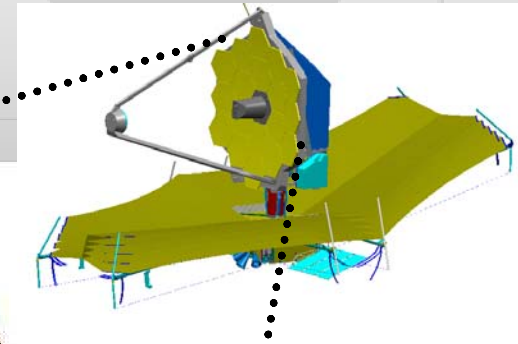
MSFC is the JWST Primary Mirror Segment Technology Development Lead for JWST



AMSD II – Be, technology selected for JWST







The 18 Primary Mirror segments

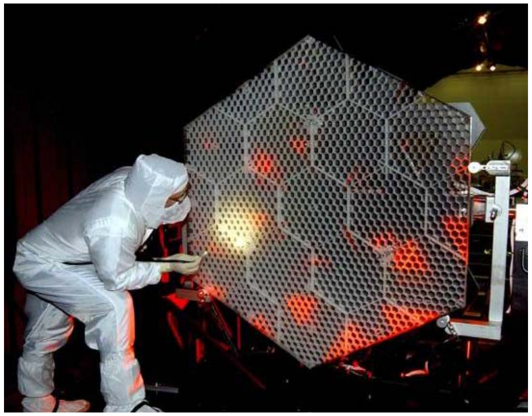
AMSD – Ball & Kodak

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

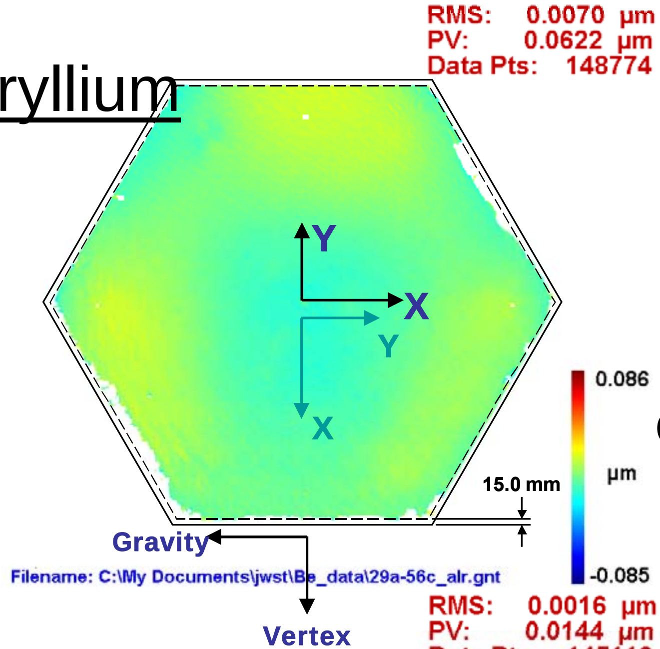
Saves Mass – Saves Money

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

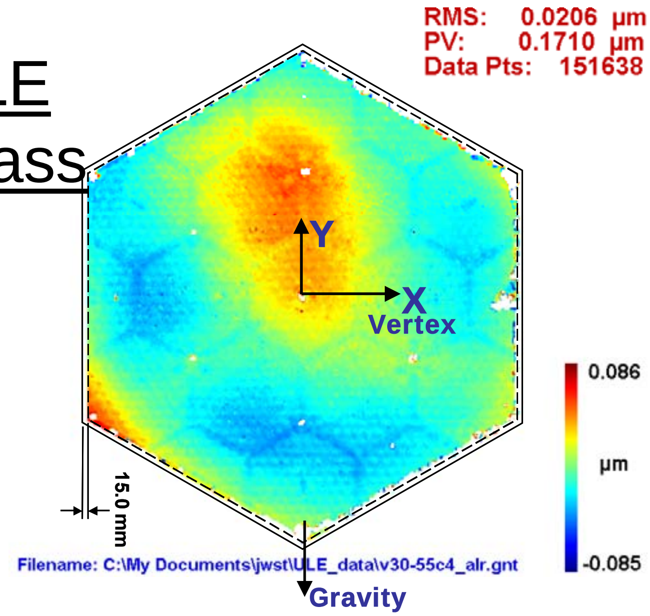
Thermal Stability

Figure Change: *30-55K Operational Range*

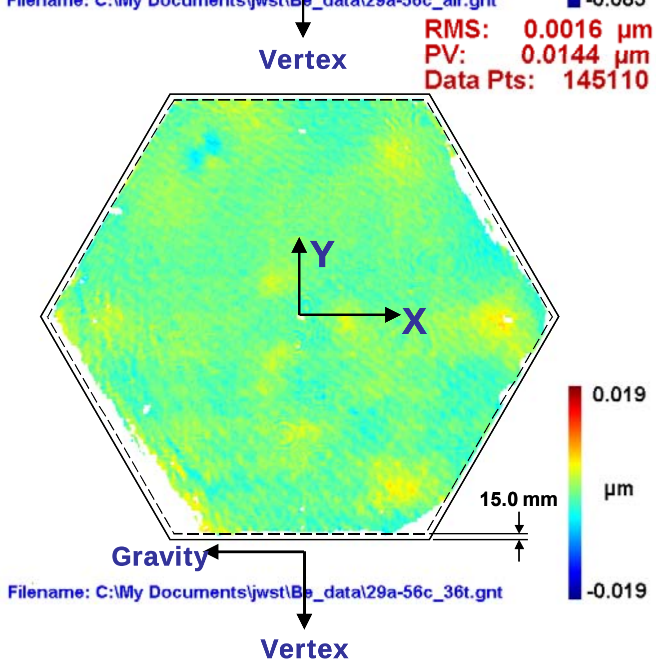
Beryllium

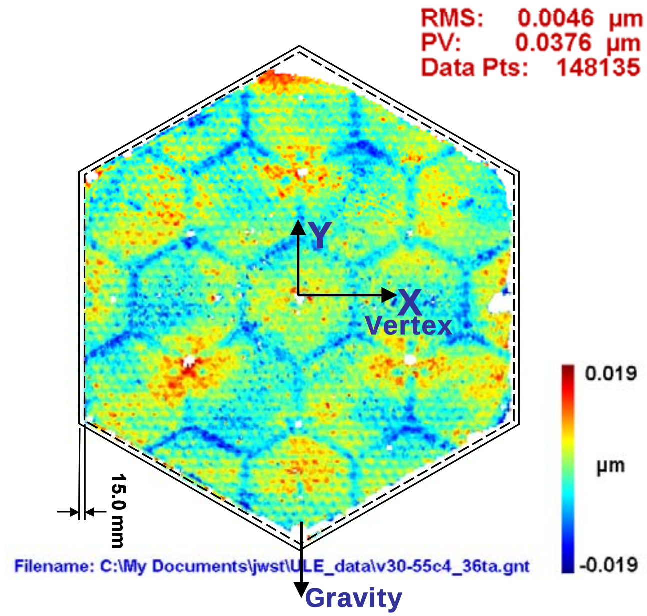


ULE Glass



Surface Figure With Alignment Compensation





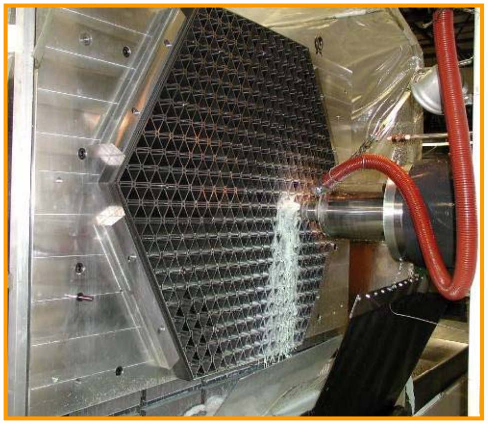
Residual with 36 Zernikes Removed

Mirror Manufacturing Process

Blank Fabrication

HIP Vessel being loading into chamber

Machining



Machining of Web Structure

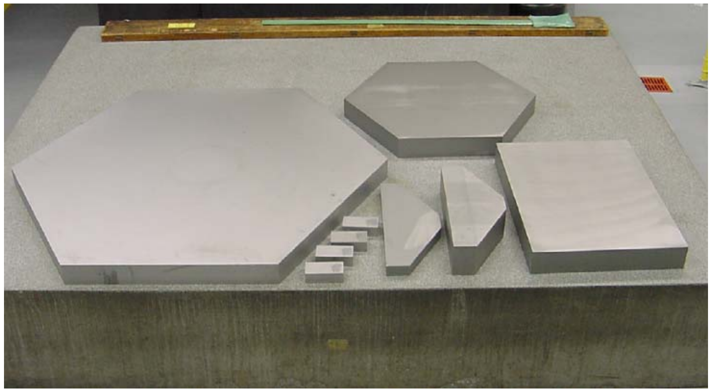
Machining of Optical Surface

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

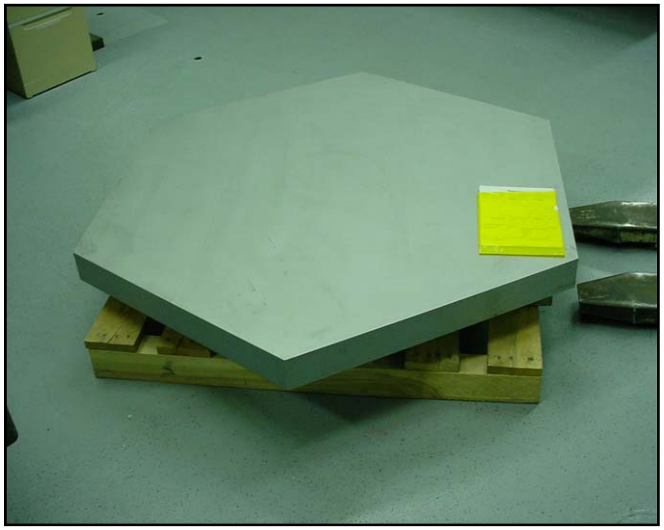
PM Segments SN 19-20
loaded HIP can in degas furnace

Fabrication Process

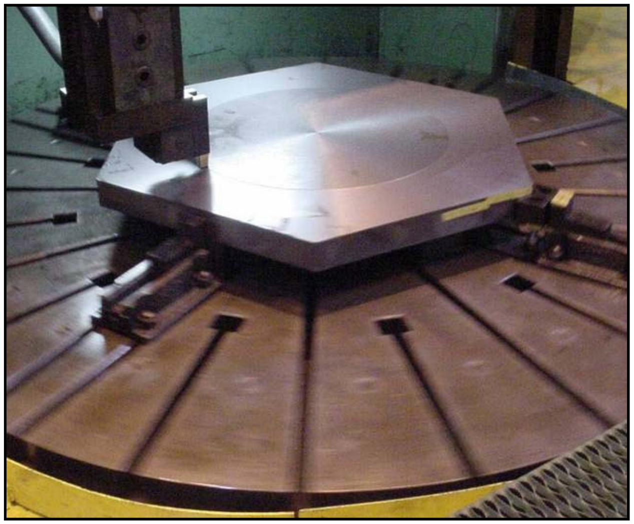
Movie

Quality Control X-Ray Inspection

PM Segment SN 17 after finish machining



PM Segment SN 17 after x-ray



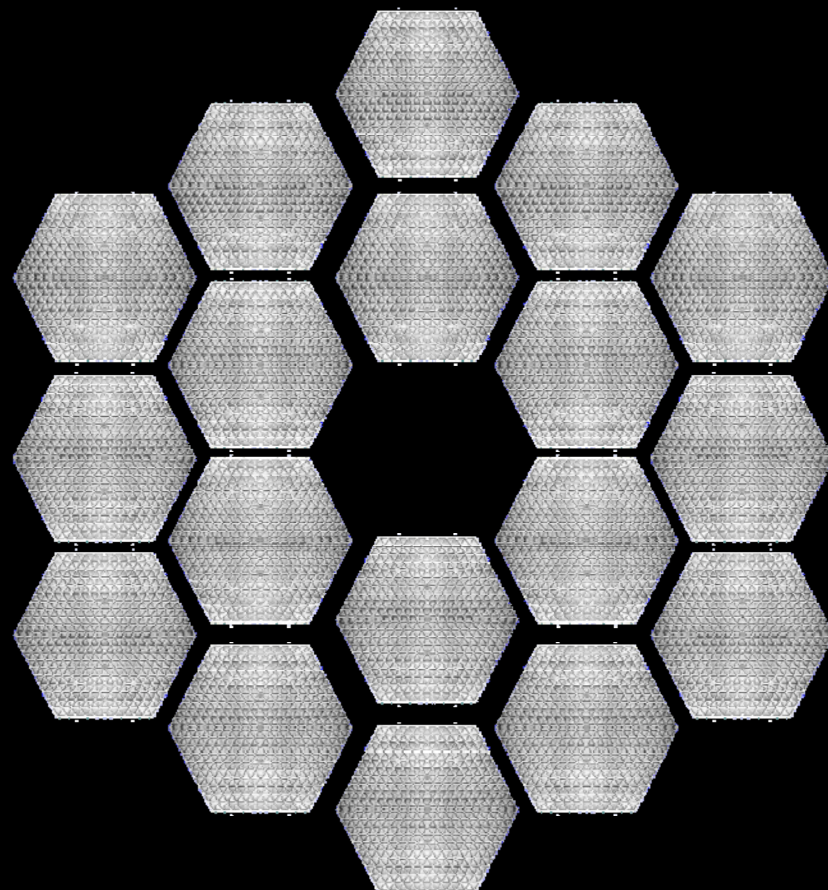
PM Segment SN 18 during finish machining

PM Segment SN 18 during x-ray

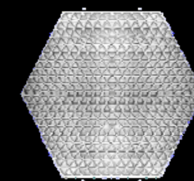
Status = Flight Mirror Blank Fabrication Complete

- **Be fabrication**
- **Brush-Wellman**

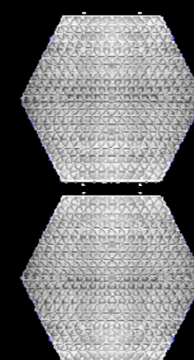
Secondary Mirror



Primary Mirror Segments



Pathfinder Mirror



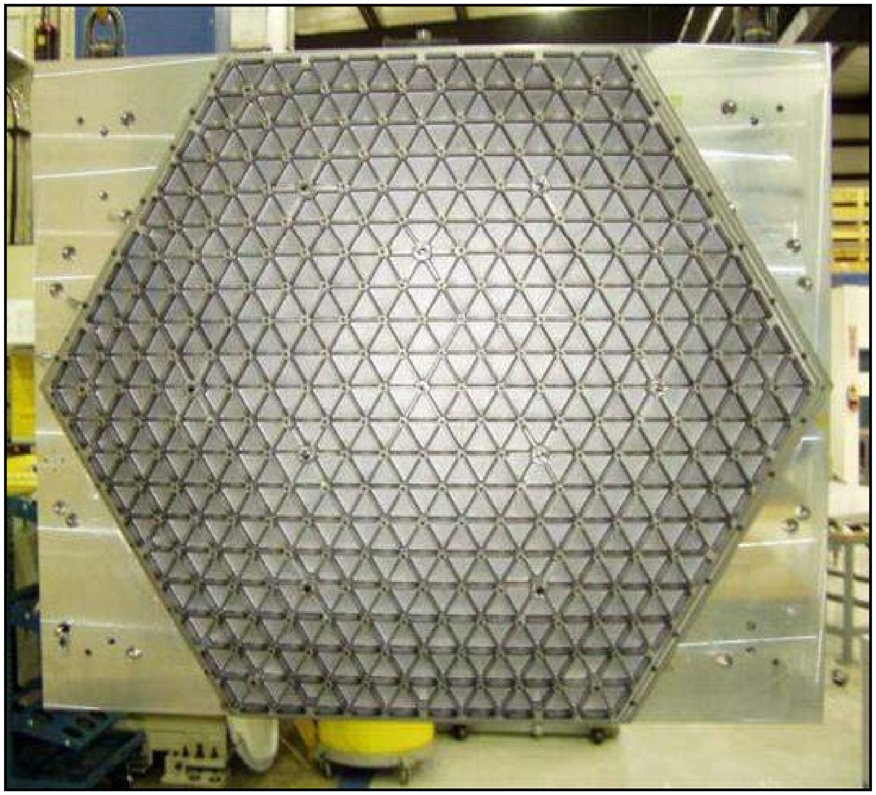
2 Flight Spares

Axsys Technologies

8 CNC Machining Centers

Axsys Technologies

PMSA Engineering Development Unit

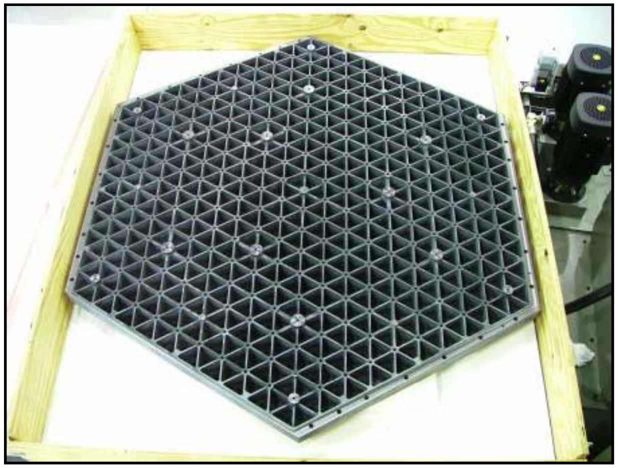


PMSA EDU rear side machined pockets

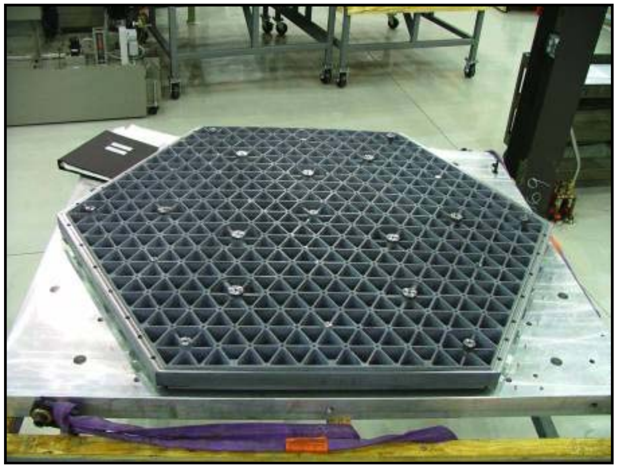
PMSA EDU front side machined optical surface

Axsys Technologies

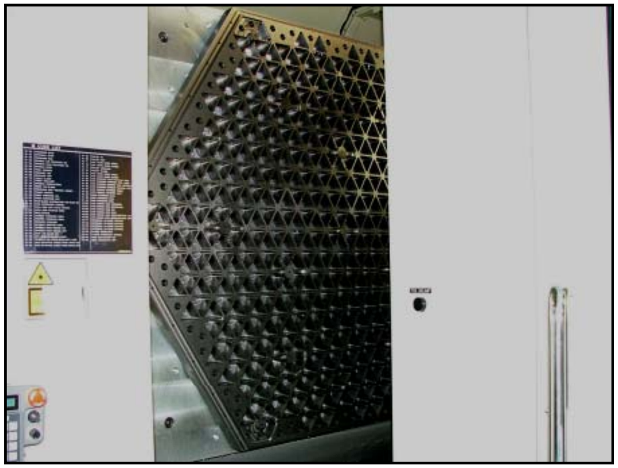
Batch #1 (Pathfinder) PM Segments



PMSA #1 (EDU-A / A1)



PMSA #2 (3 / B1)



PMSA #3 (4 / C1)

Batch #2 PM Segments

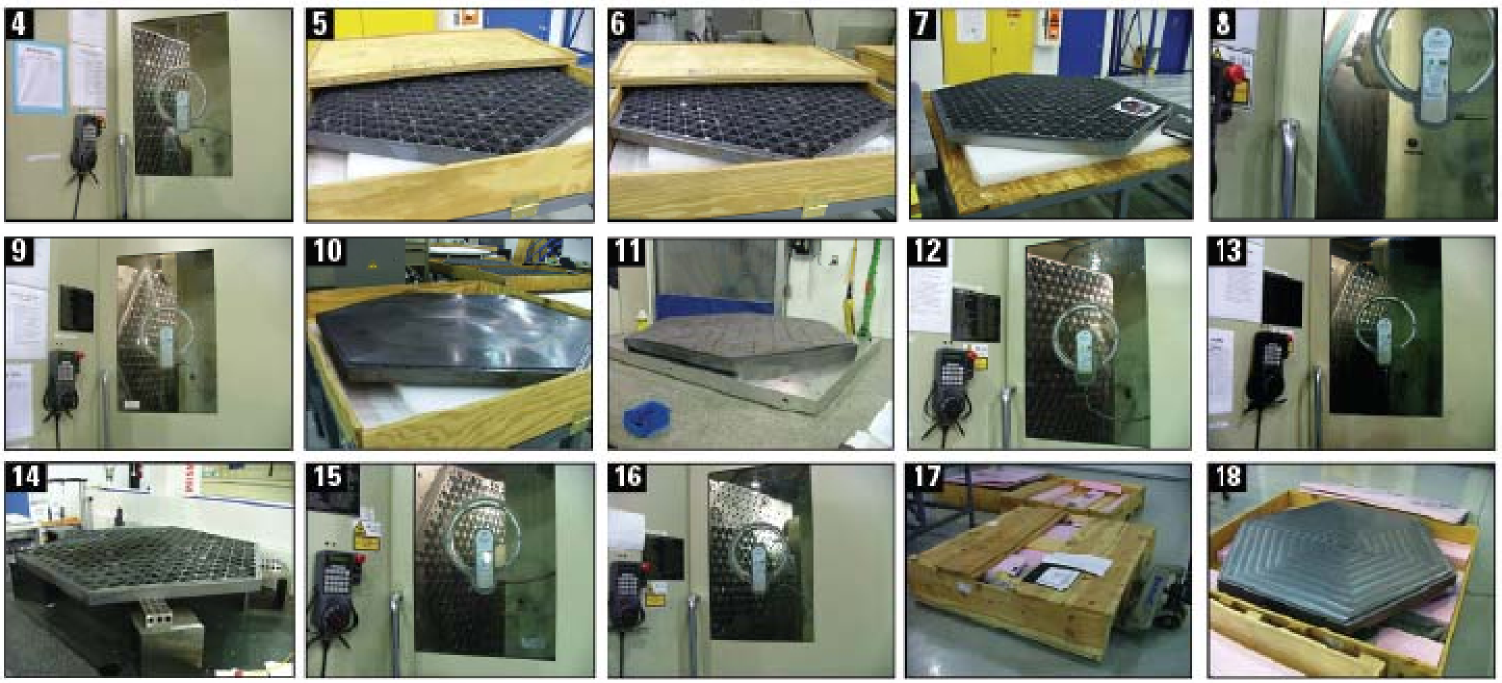
PMSA #4 (5 / A2)

PMSA #5 (6 / B2)

PMSA #6 (7 / C2)

17 OUT OF THE 18 SEGMENTS of the Primary Flight Mirrors are currently being machined at Axsys Technologies

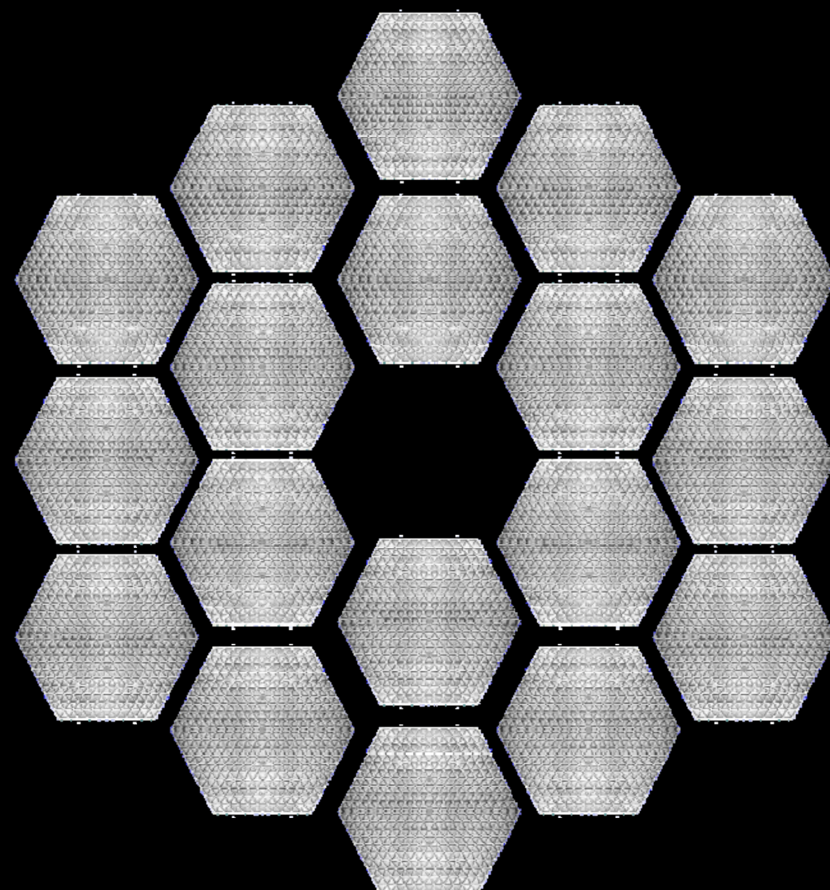
AXSYS JWST FACILITY



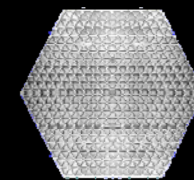
Status = Flight Mirror Lightweighting Complete

- Lightweighting
- Axsys

Secondary Mirror



Primary Mirror Segments



Pathfinder Mirror

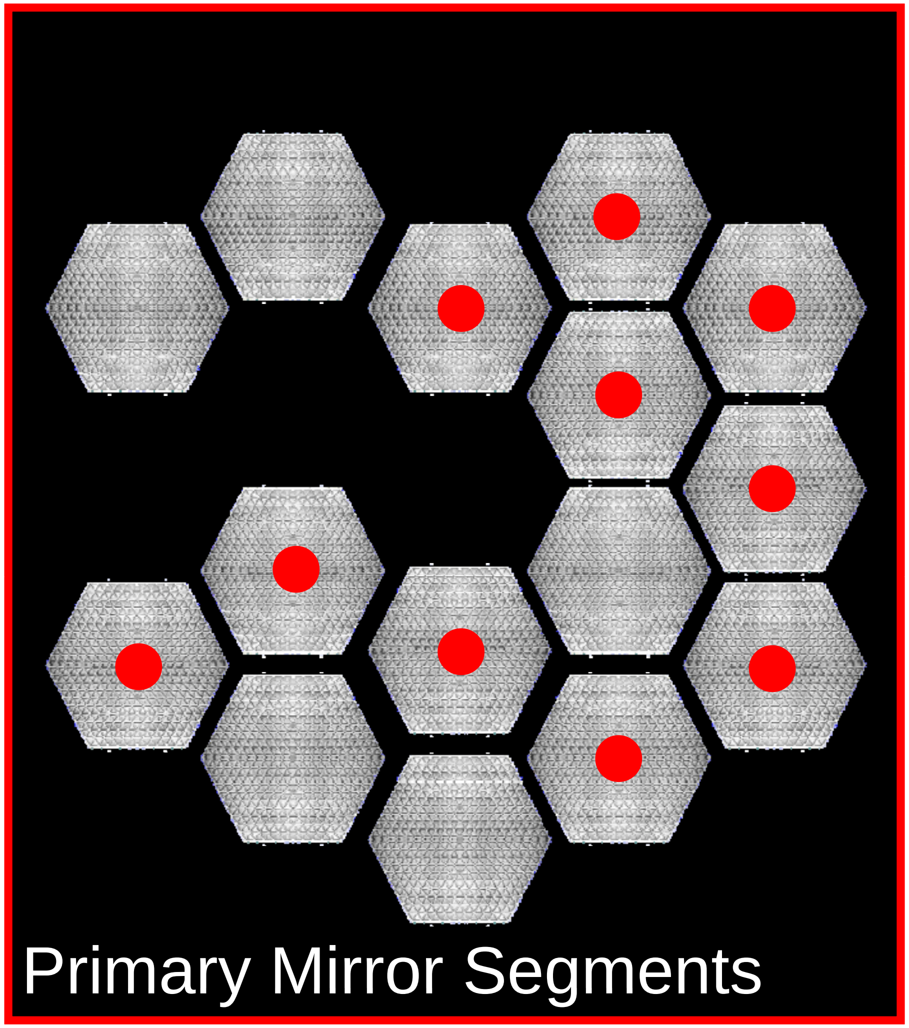
Tinsley Laboratories

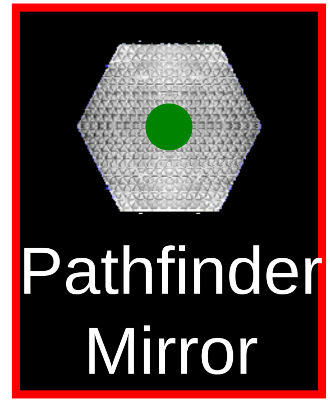
Production Preparation – CCOS Machines

- 1st – 4th CCOS machine bases assembled and operational
- 5th – 8th CCOS machines received and in storage – installation to start 4/4/05

Status = Flight Mirror Polishing Started

- **Mirror Polishing**
- **Tinsley**

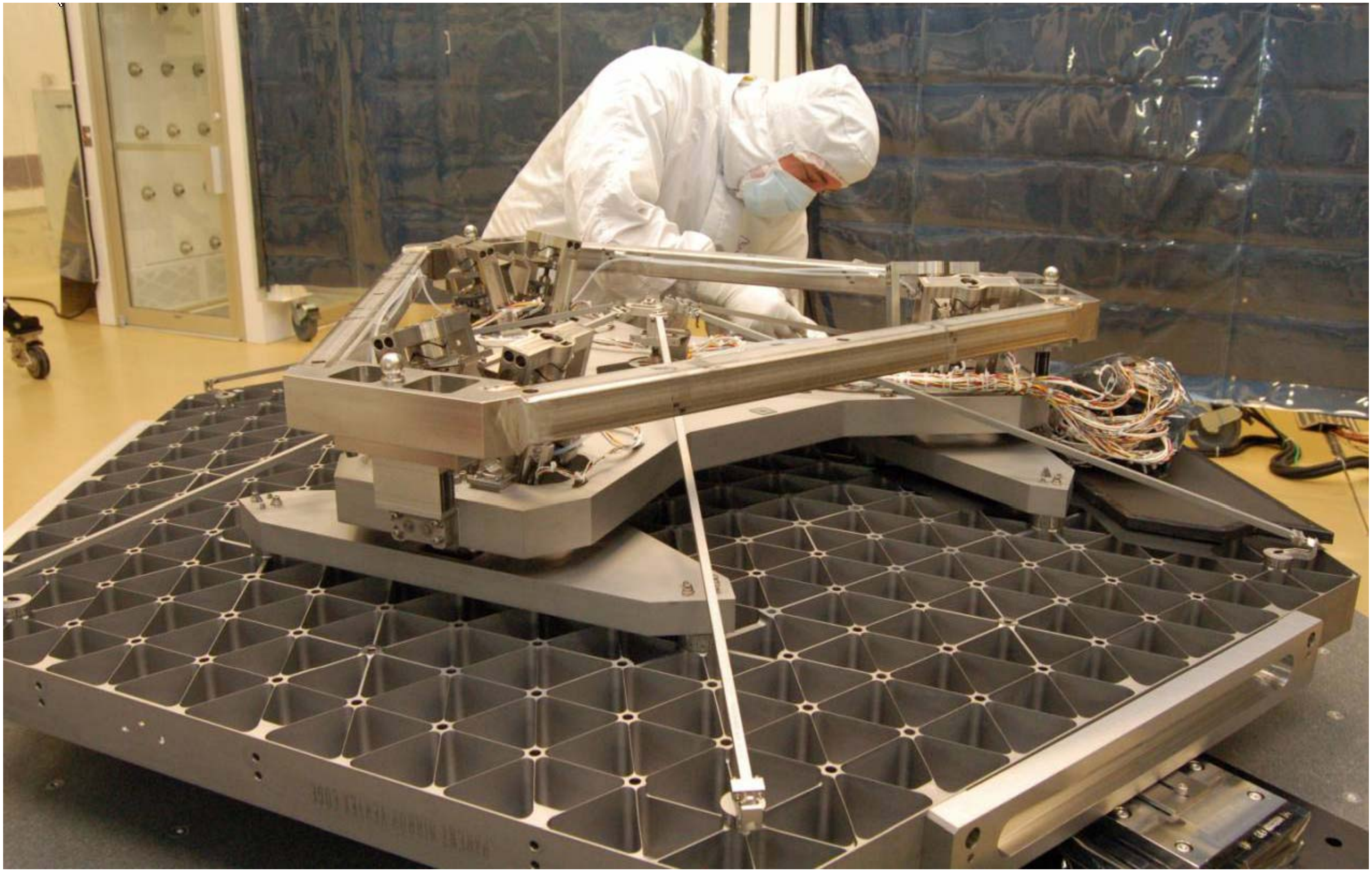




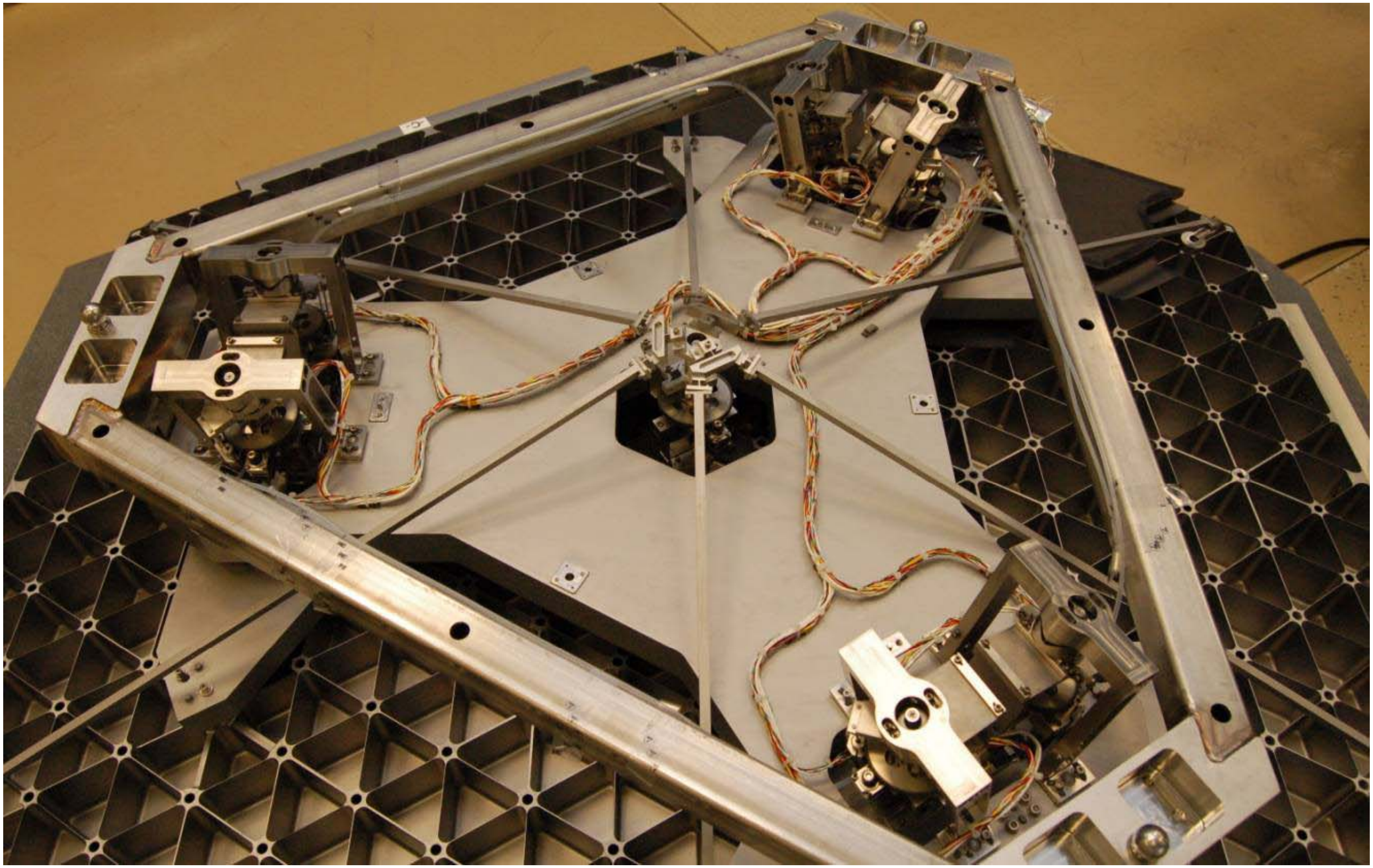
Coarse grind

fine grind

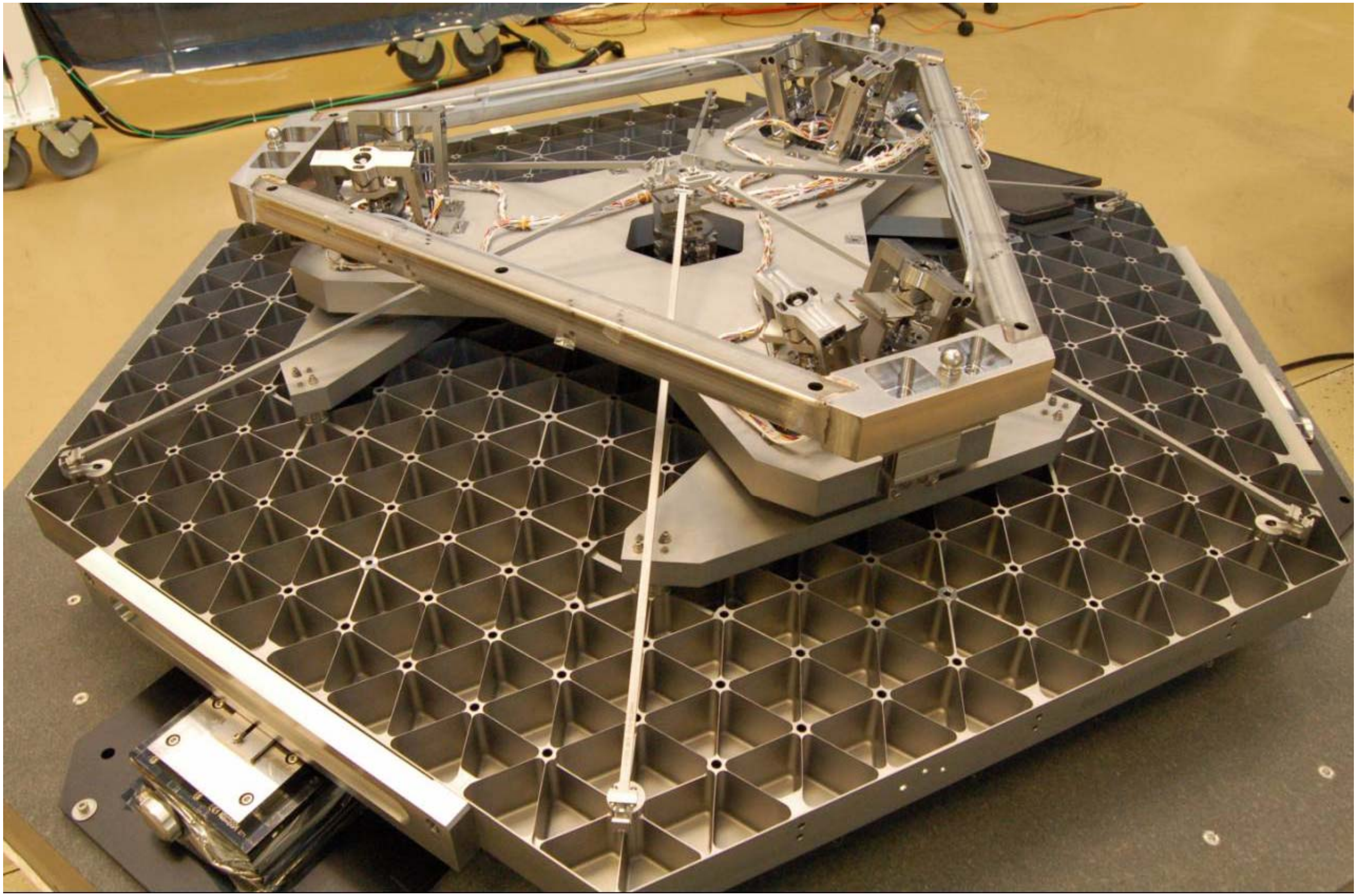
PMSA Assembly



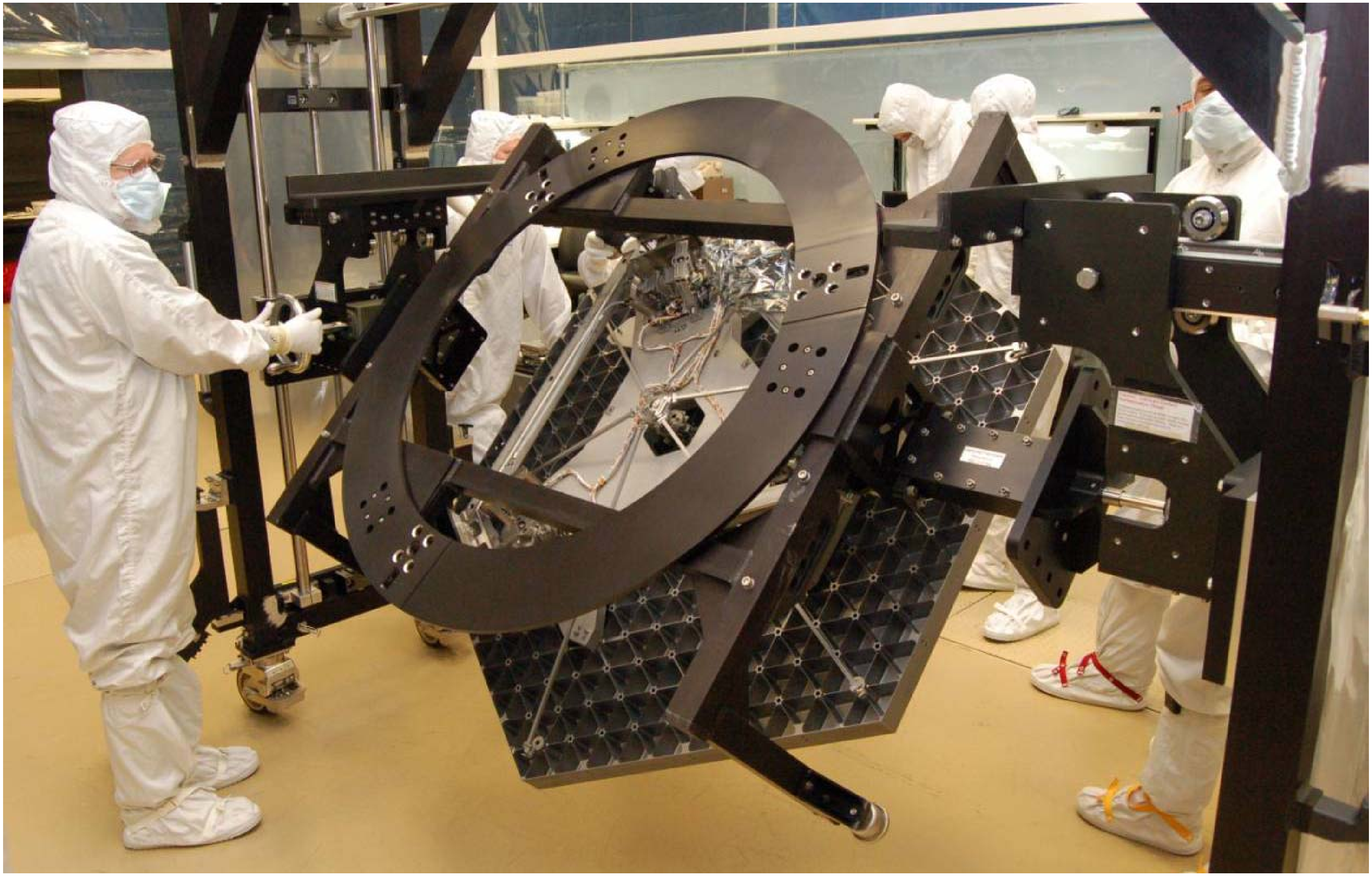
PMSA Assy



PMSA Assembly

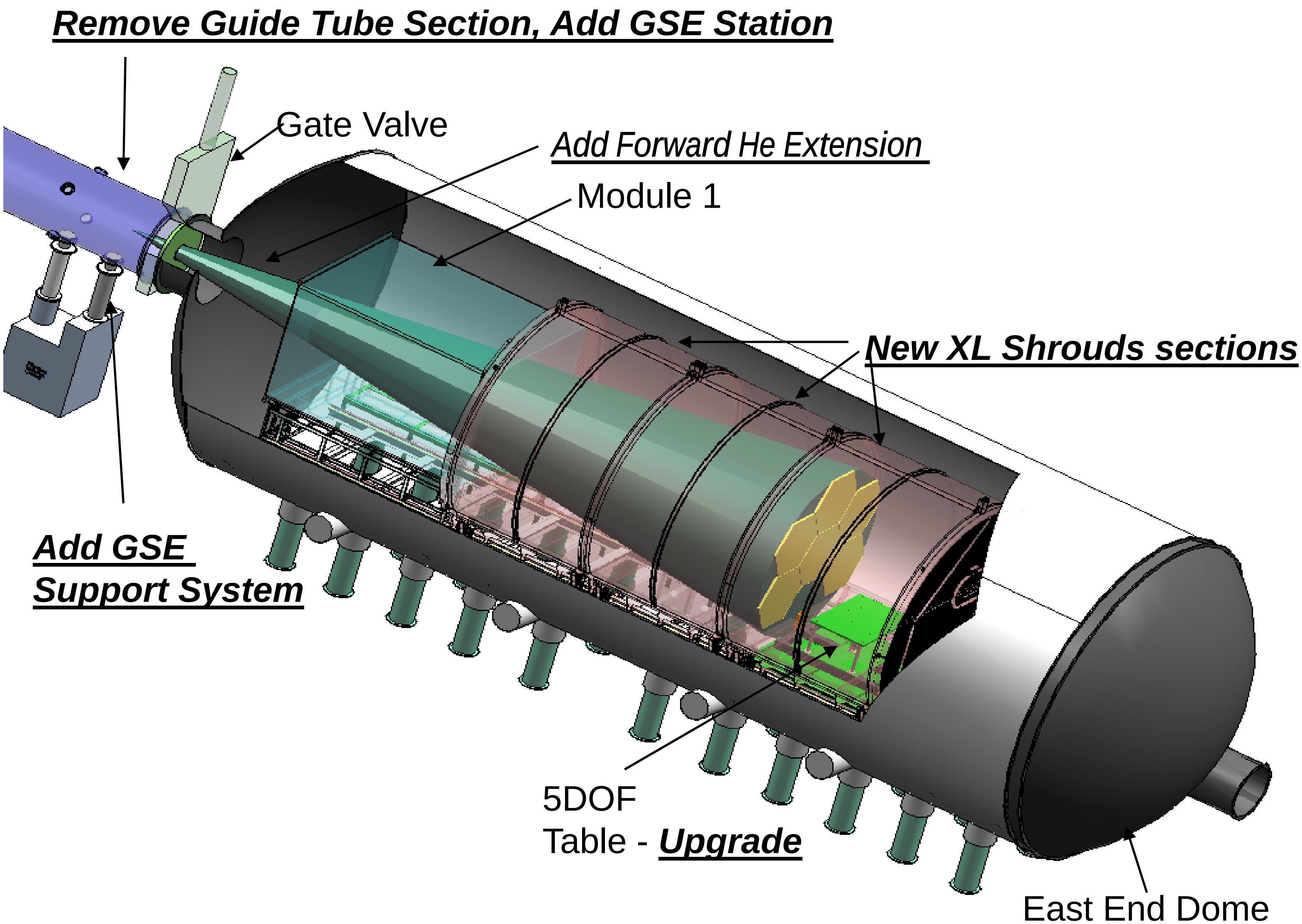


PMSA Assembly on its way to Optical Test

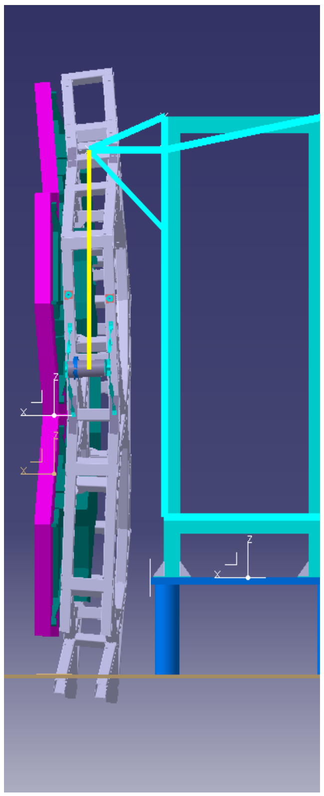


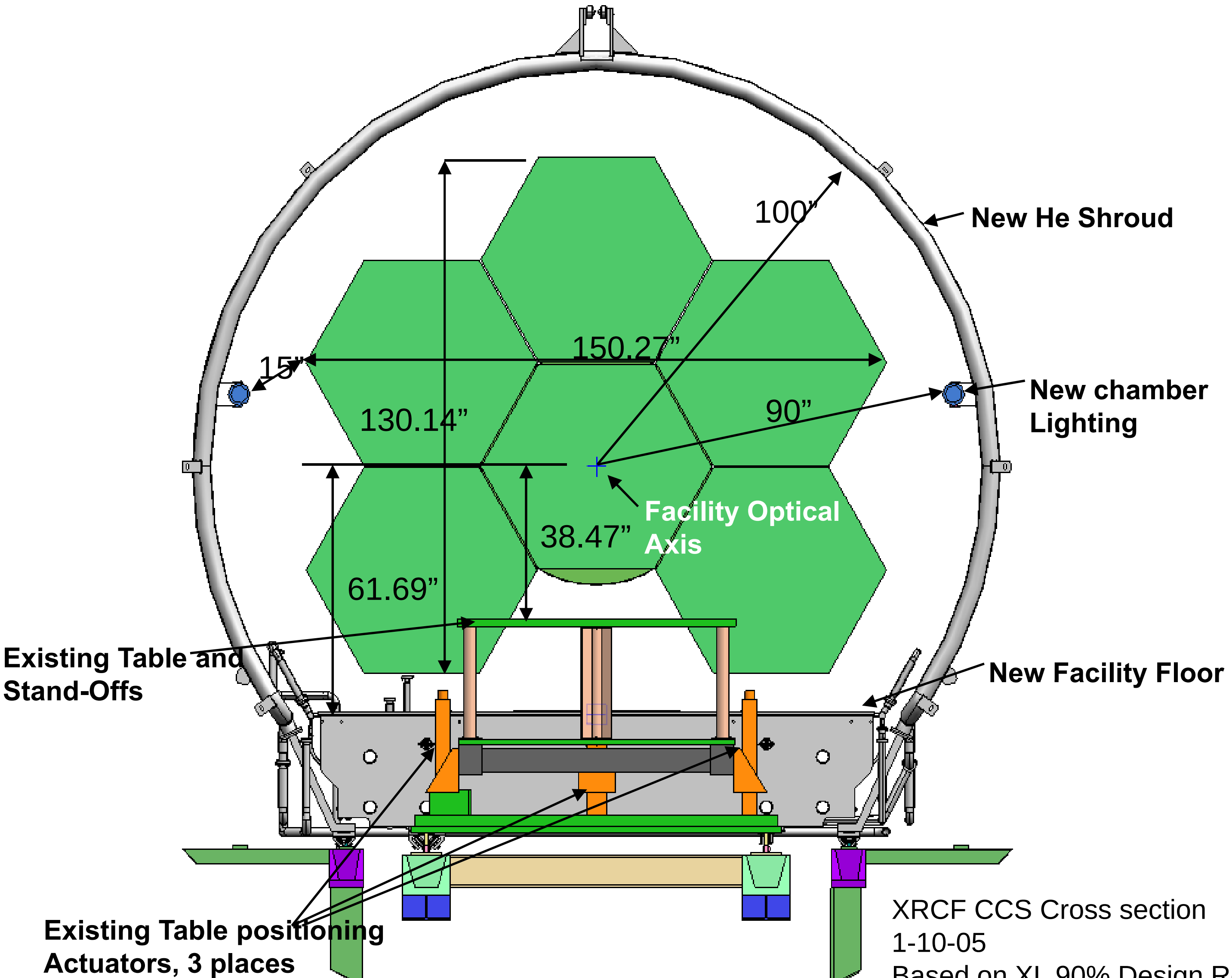
PMSA Assembly on its way to Optical Test

MSFC JWST Support Effort – Facility Upgrades



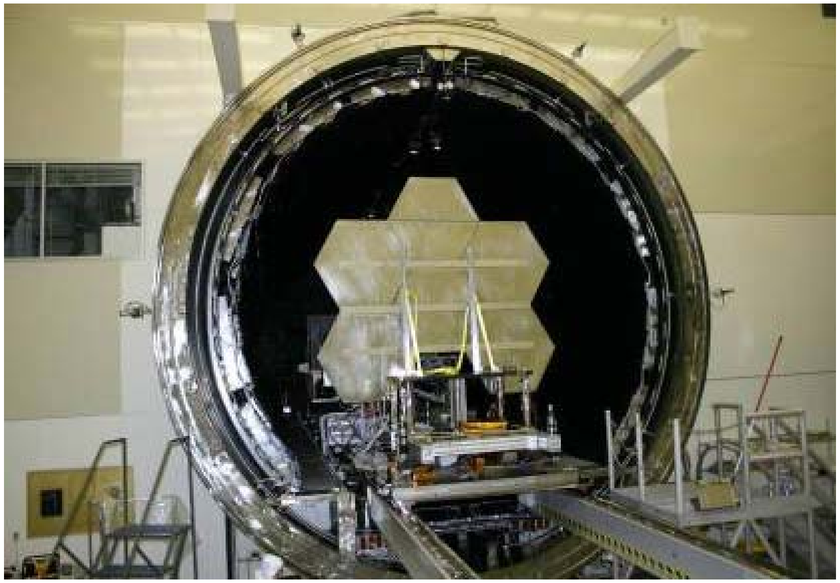
MSFC JWST Support Effort – BSTA Test Configuration





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

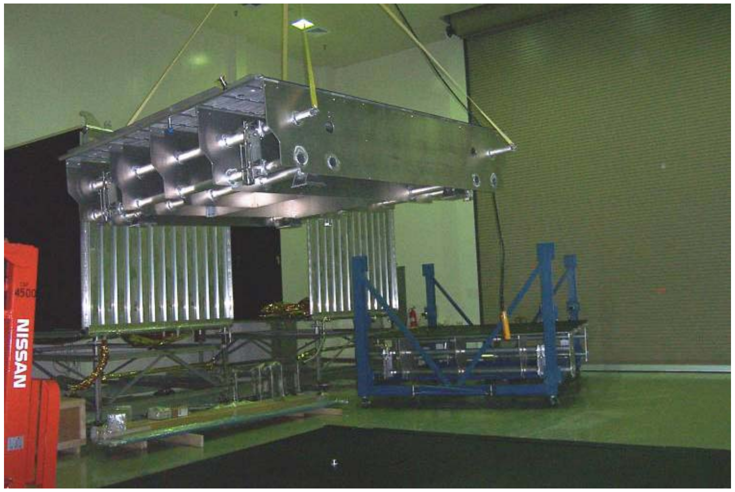
XRCF Facility Upgrades in FY ‘05-06




XRCF CCS Assembly

Shroud Reassembly

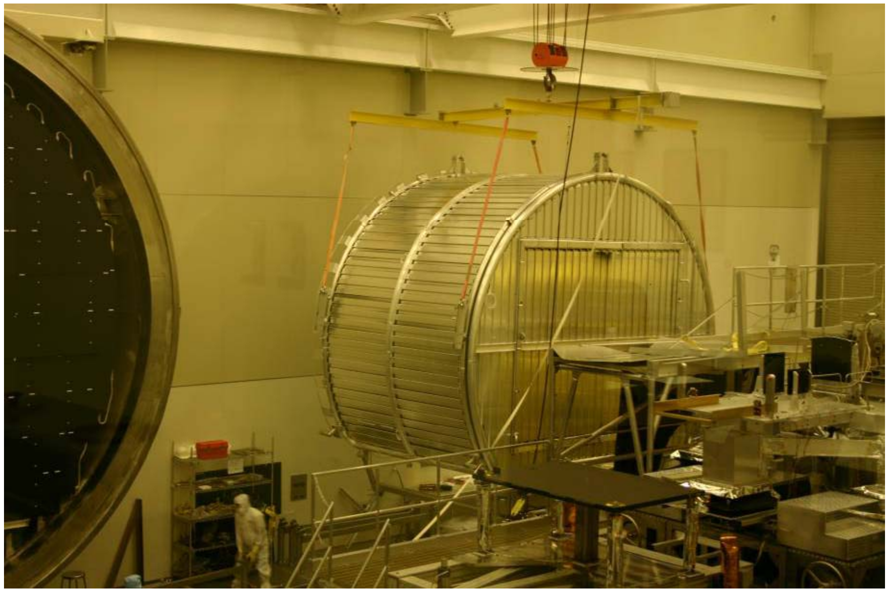
1 of 3 Shrouds rough cleaning

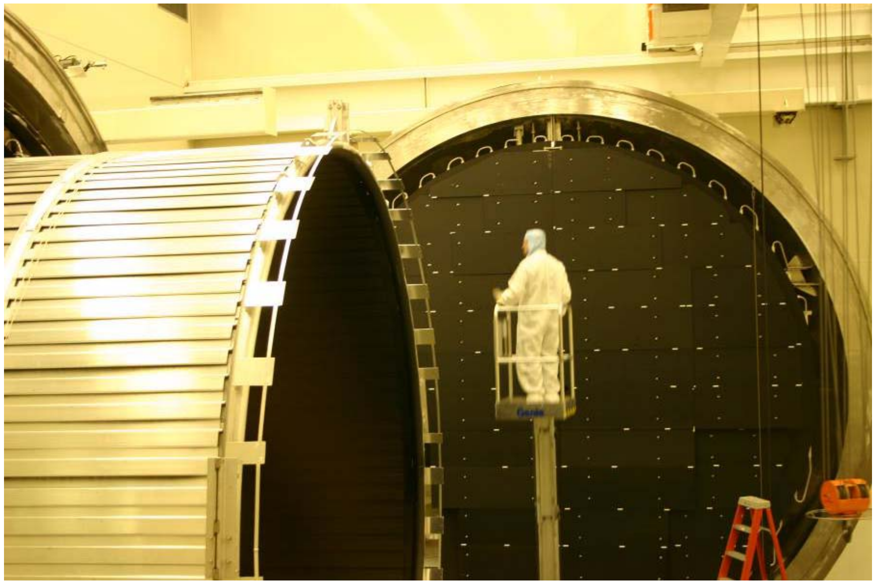


1 of 3 floors move into clean room

Shrouds move into clean room

XRCF CCS Fit- Check



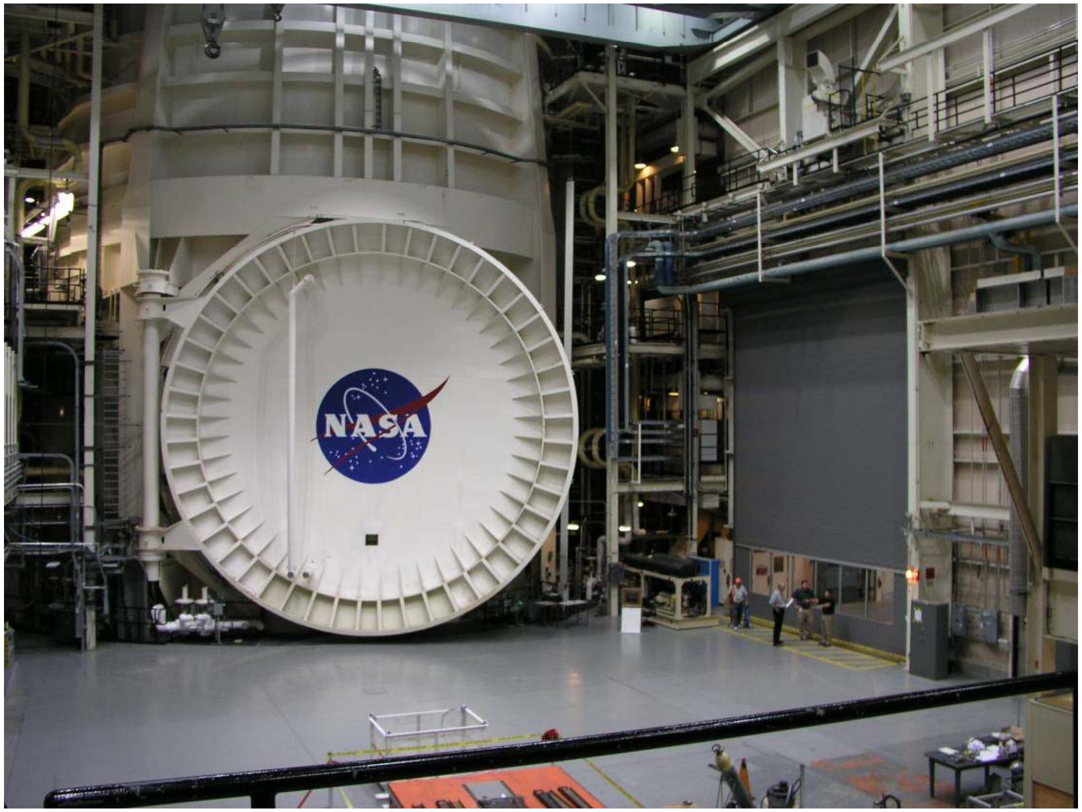


XRCF Facility With Be AMSD II Mirror

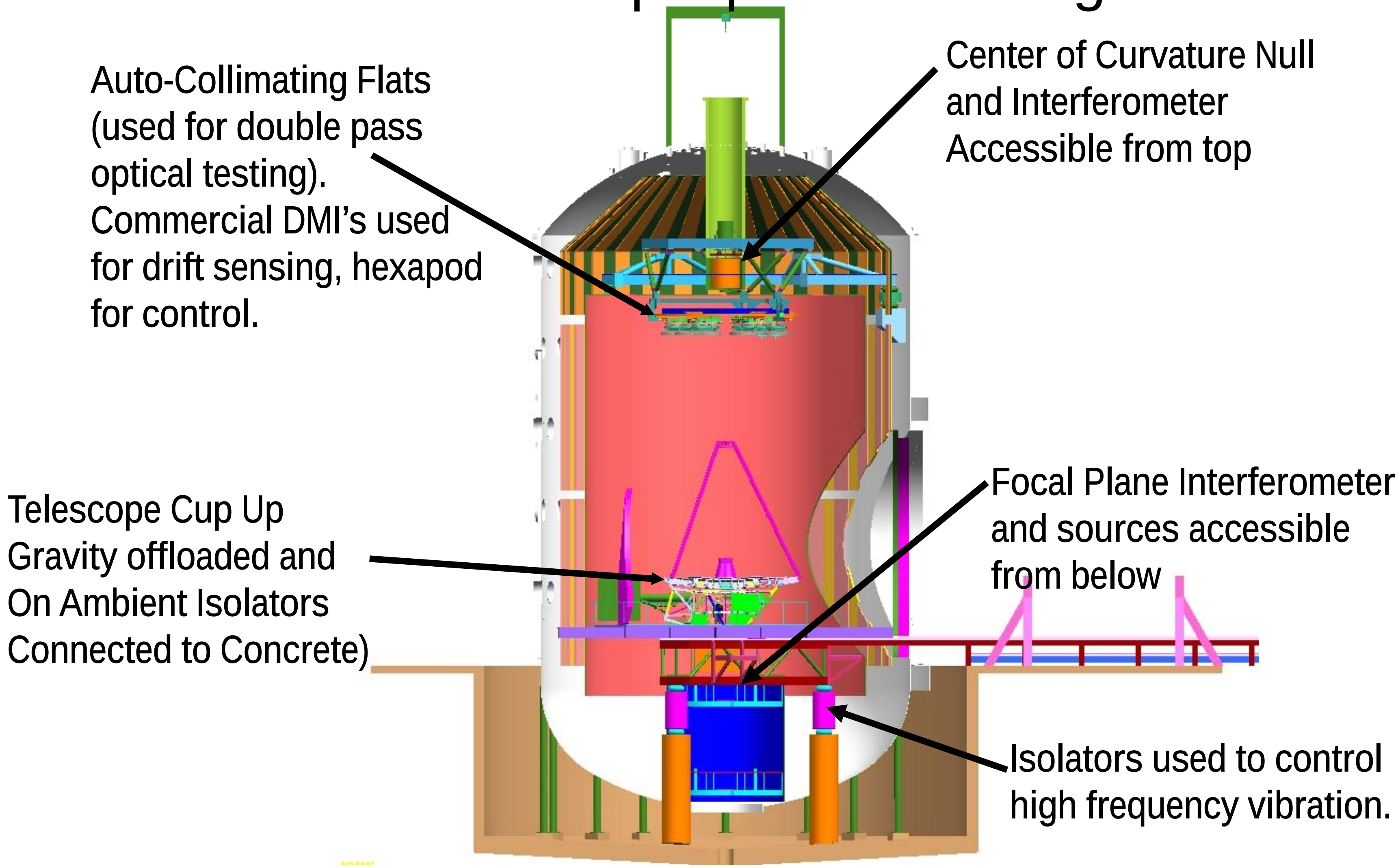
JWST I&T

JSC Chamber A

Chamber size	55' diam, 117' high
Existing Shrouds	LN2 shroud, GHe panels
Chamber Cranes	4x25t fixed, removable
Chamber Door	40' diam
High bay space	~102'Lx71'W



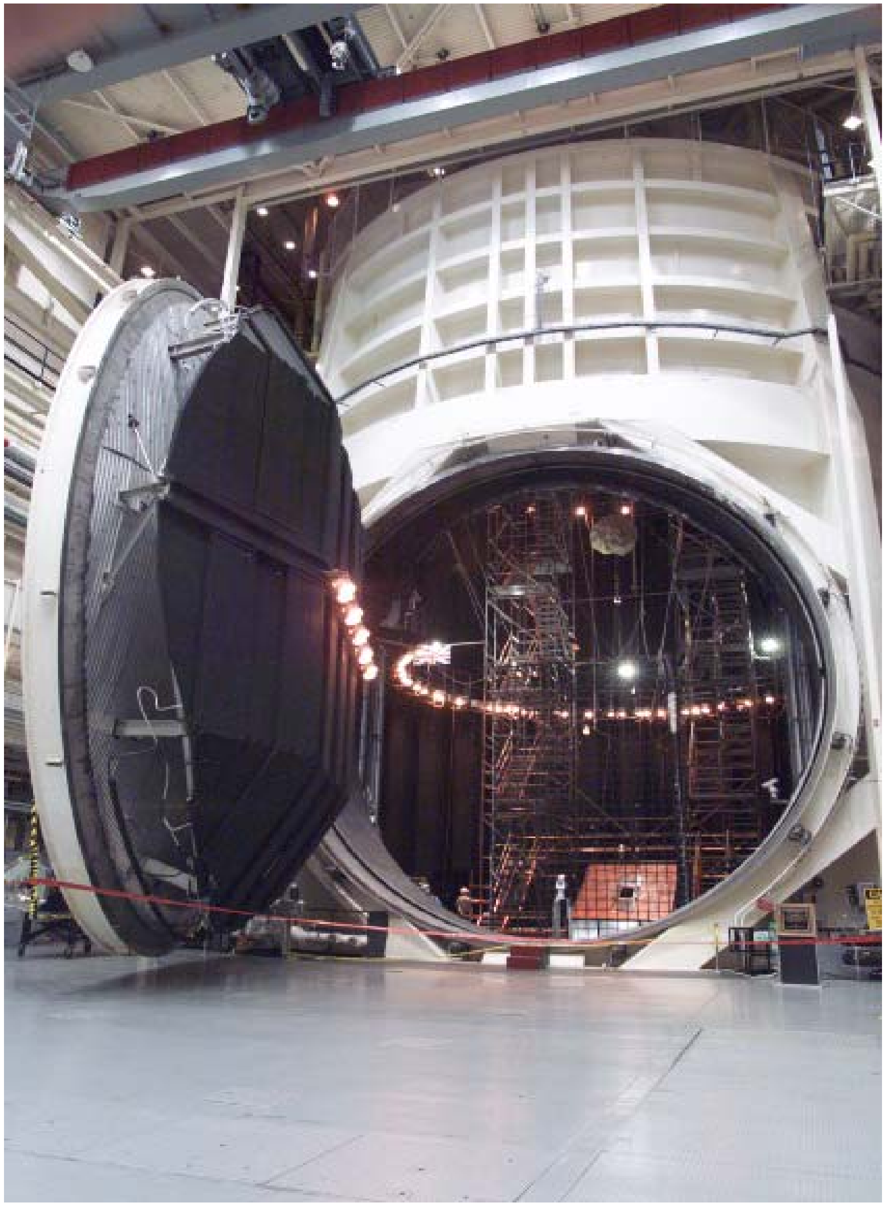
JSC “Cup Up” Test Configuration



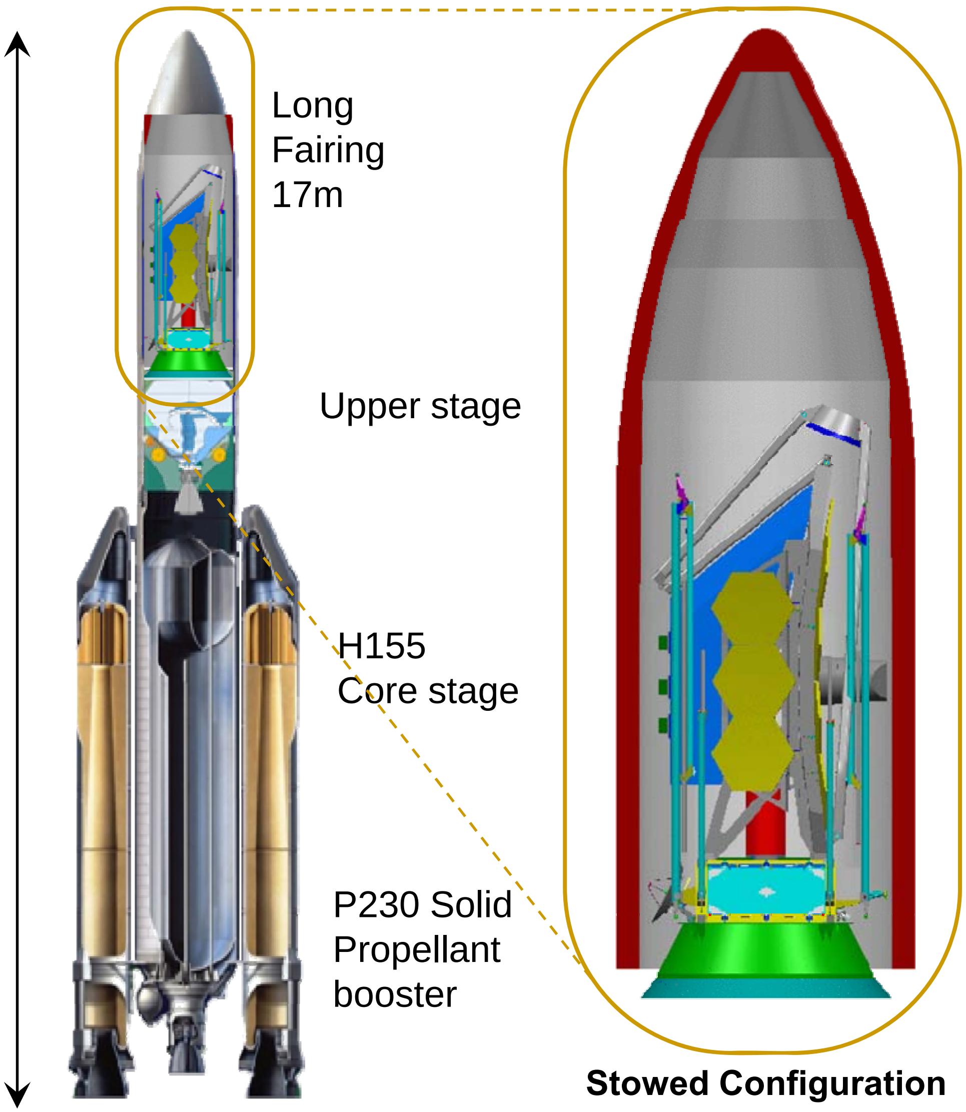
JSC Size, Accessibility, and Large Side Door Access Make it Well Suited for This Configuration

JSC Chamber A Thermal Vacuum Facility

Chamber A was used for Apollo landers and already includes Nitrogen and Helium systems. Plan is to upgrade it with a new Helium Inner Shroud and Helium refrigerators.

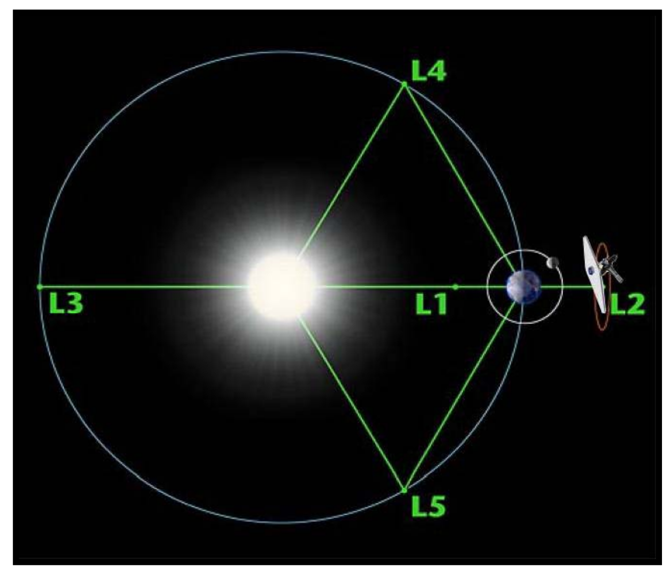


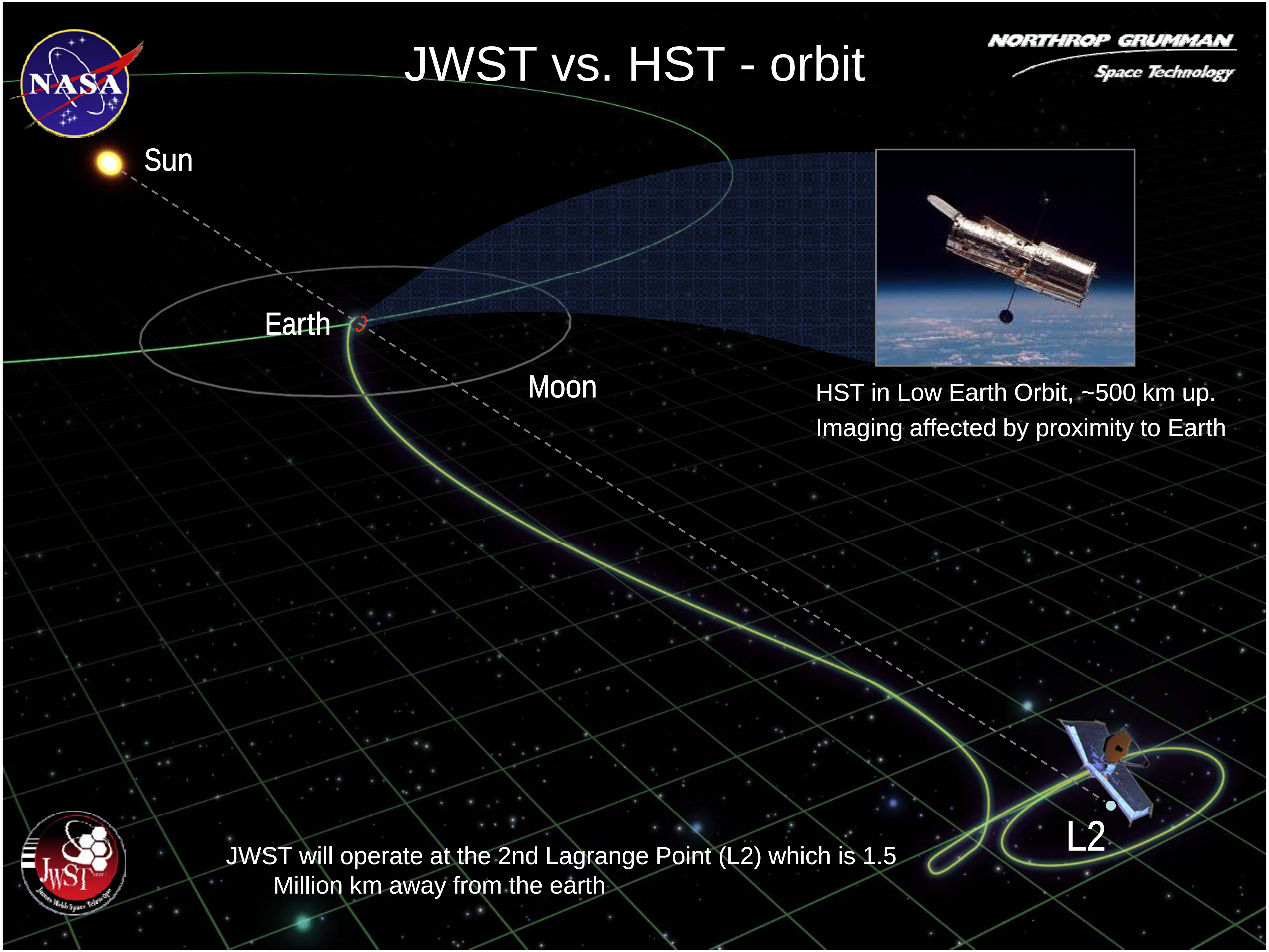
JWST Launch and Deployment



Stowed Configuration

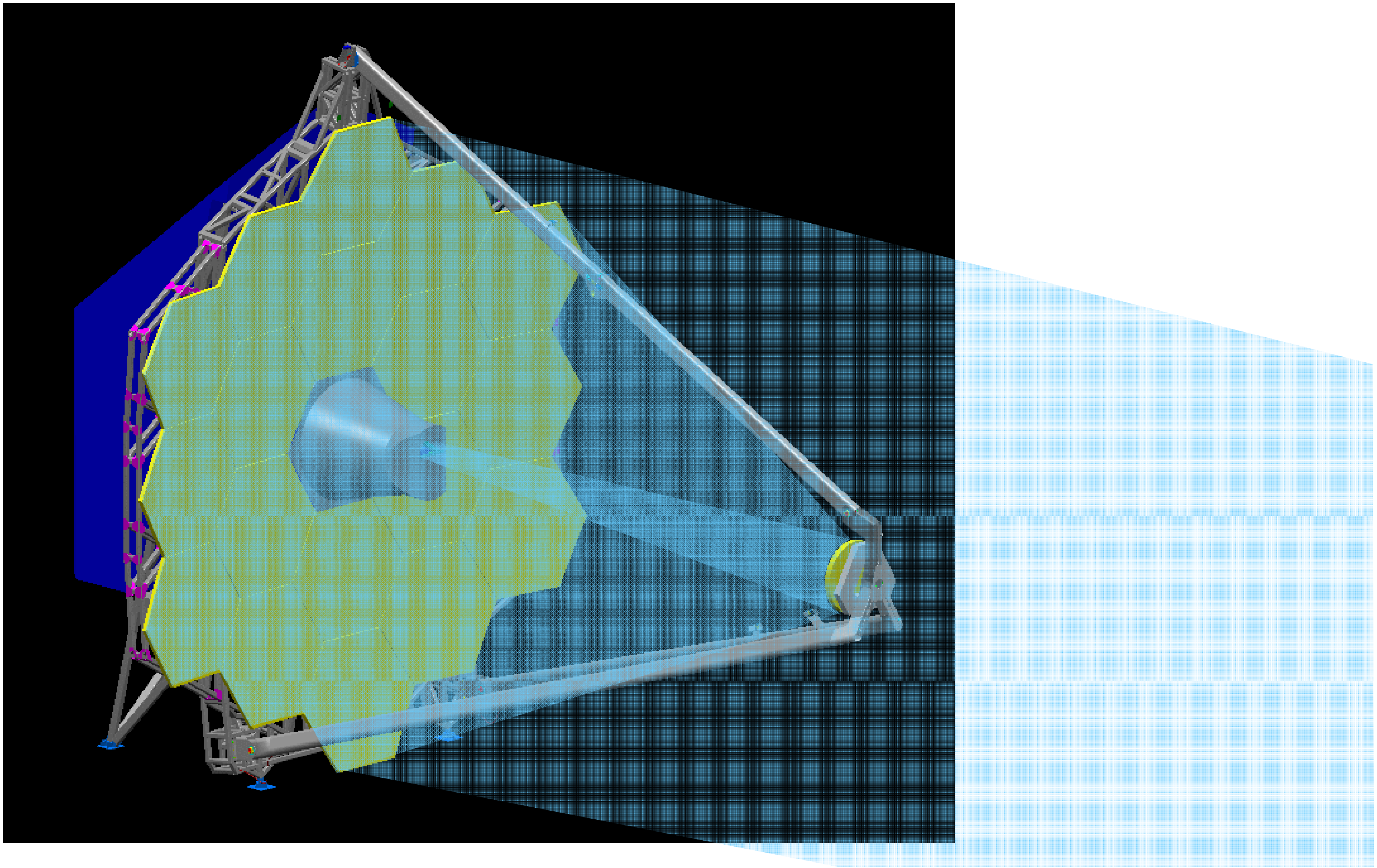
- **JWST is folded into stowed position to fit into the payload fairing of the Ariane V launch vehicle**
- **Several subsystems deploy during transit to its L2 orbit**




JWST vs. HST - orbit
NORTHROP GRUMMAN
Space Technology
NASA
Sun
Earth
Moon
HST in Low Earth Orbit, ~500 km up.
Imaging affected by proximity to Earth
L2
JWST will operate at the 2nd Lagrange Point (L2) which is 1.5 Million km away from the earth

[redacted]

JWST Optical Path

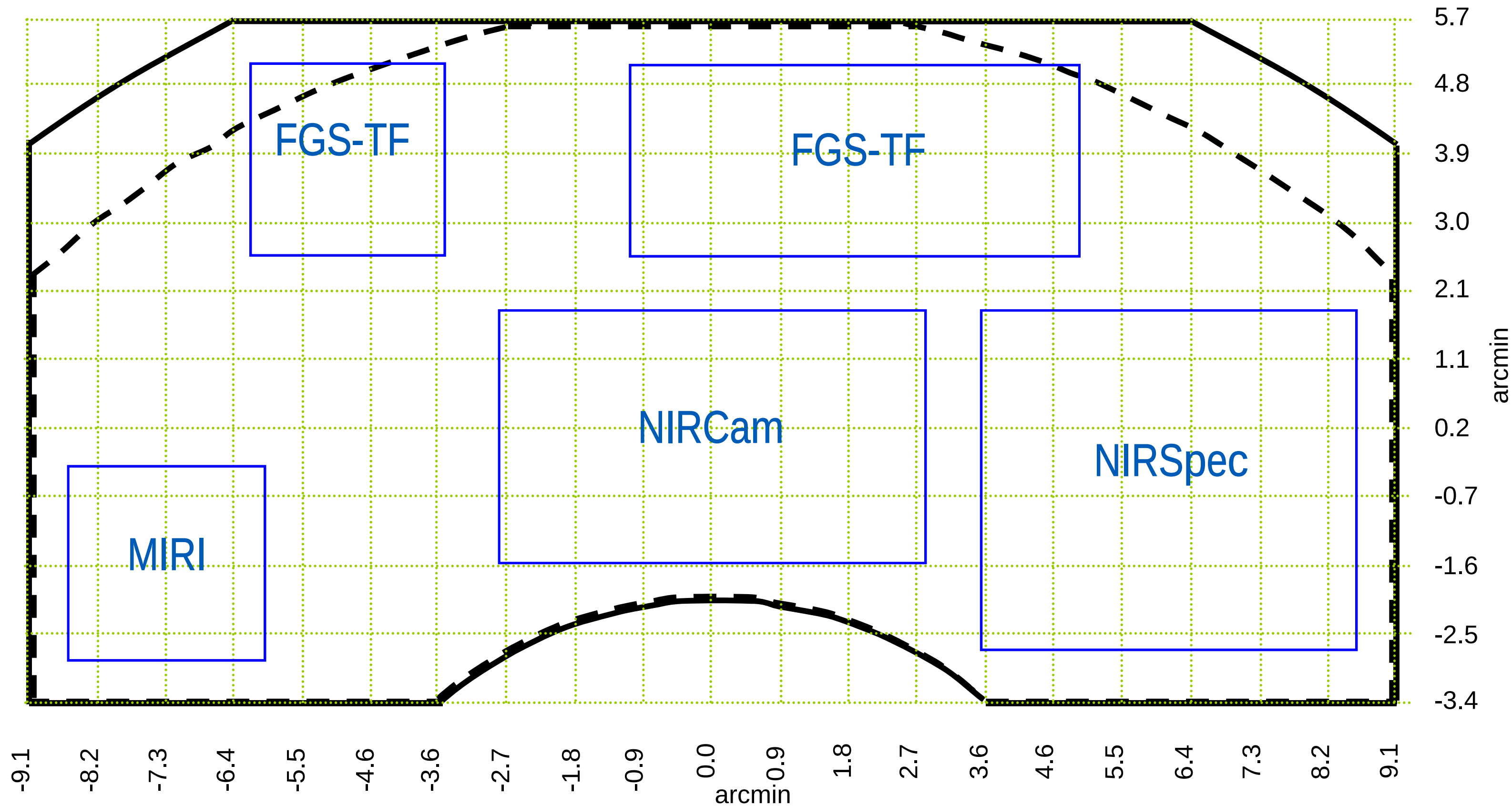


Off-Axis Annular FOV

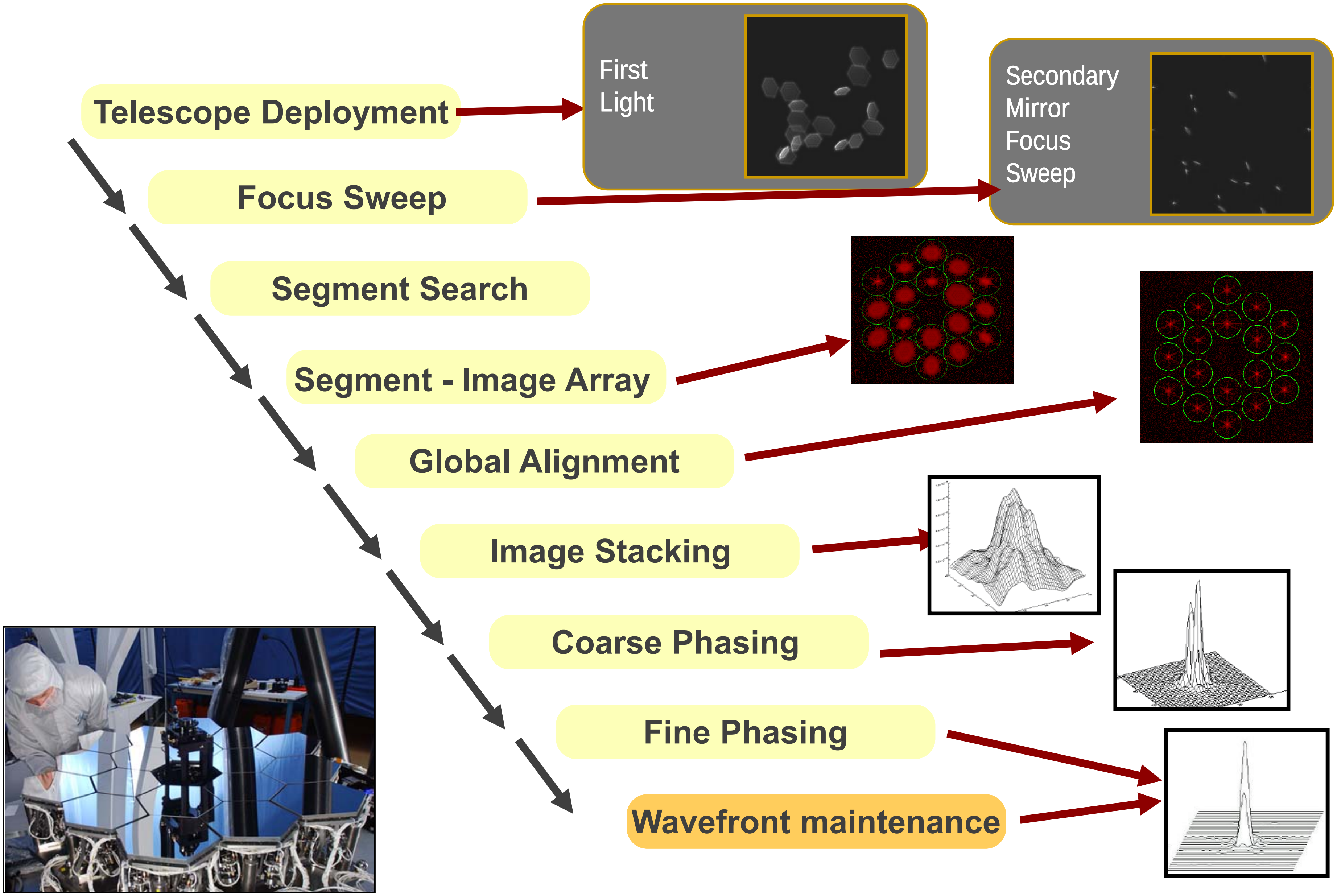
Unvignetted FOV shown in black

OTE WFE < 131 nm rms within area bounded by black dashed line

The science instrument placement allocations are shown in blue

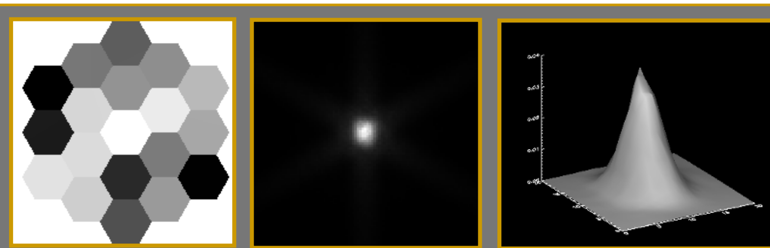


JWST Mirror Phasing



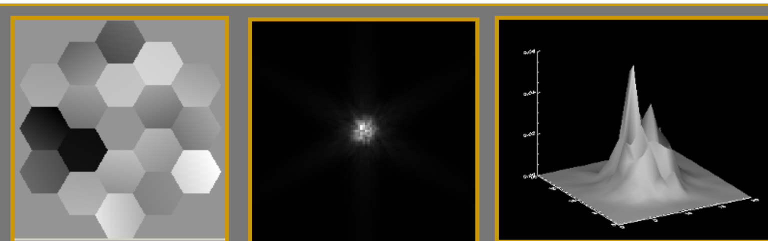
Wavefront Sensing & Control (WFS&C)

Global Alignment



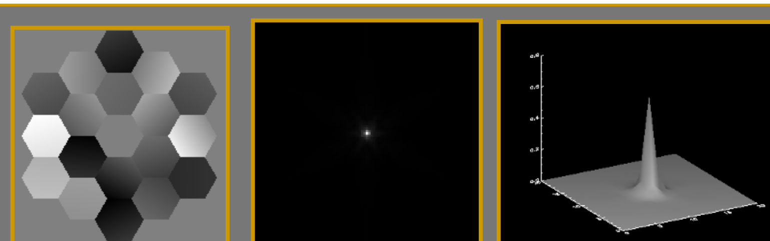
Segment WFE<200 nm rms *and* <100 μm rms segment-to-segment piston after Global Alignment

Coarse Phasing (Fine Guiding)



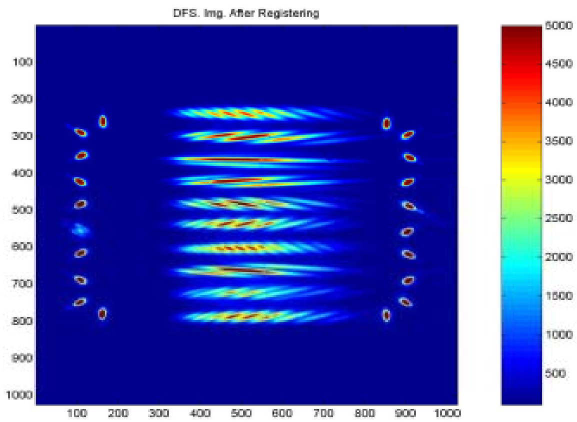
Total PM WFE<1000 nm rms after Coarse Phasing

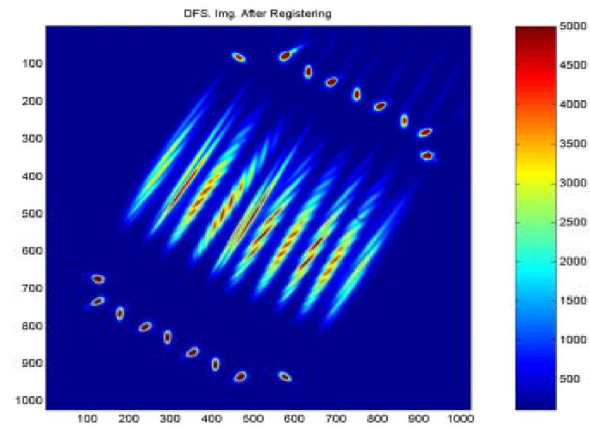
Fine Phasing



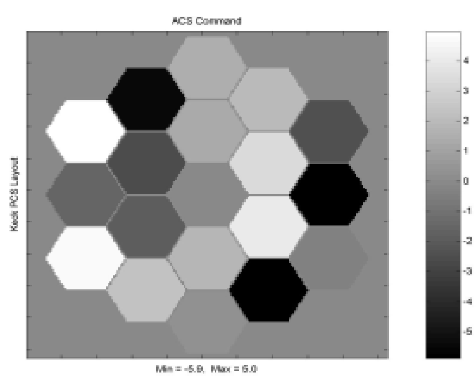
Total WFE <117 nm rms after Fine Phasing; re-phase every 30 days

Keck Demonstration of WFS&C

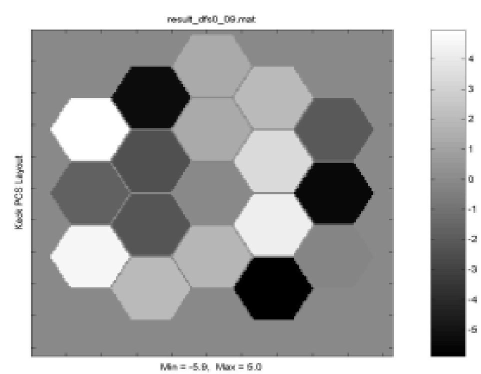




ACS Commands



Measured



Preliminary results compared with PCS:
Peak-to-valley edge detection error = 0.45 microns
Rms detection error = 0.12 microns

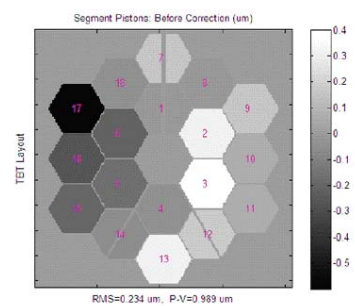
JWST Phasing Algorithms Demonstrated

Coarse Phasing

(Segment to segment piston)

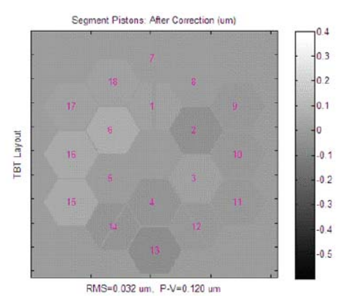
Fine Phasing

Before Coarse Phasing

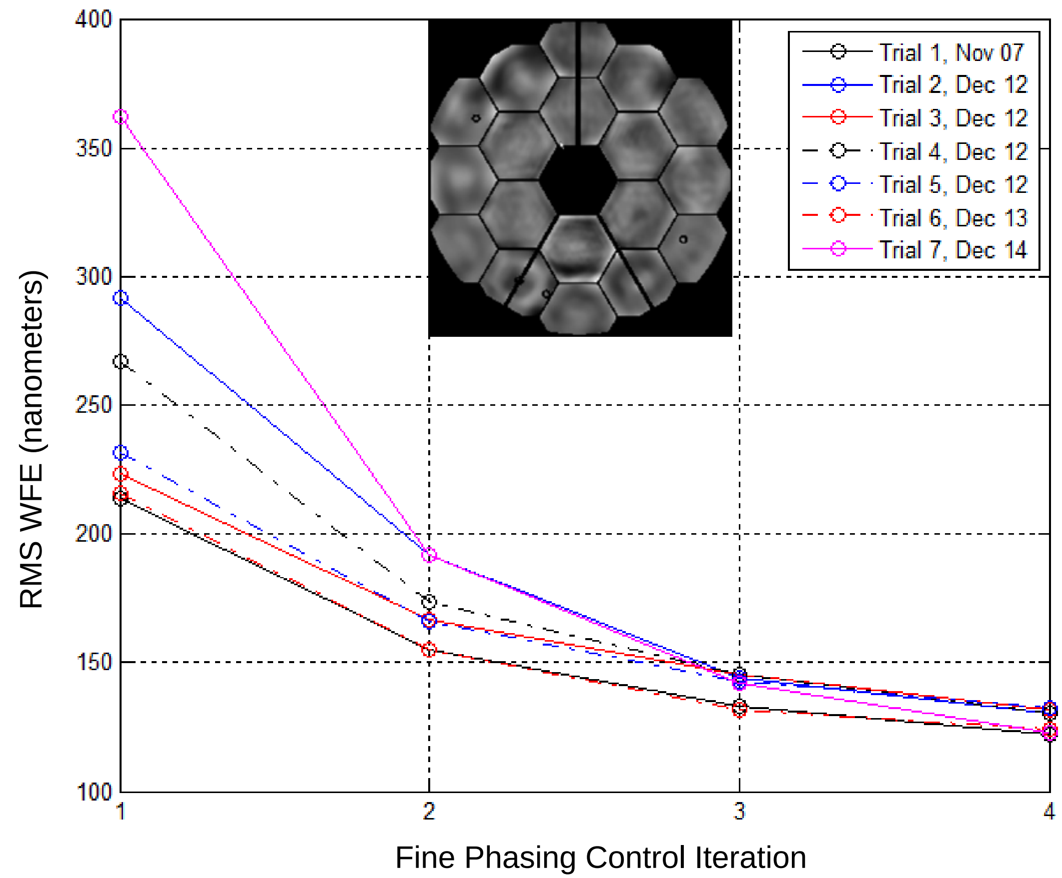


piston:
rms=234nm p/v=989nm

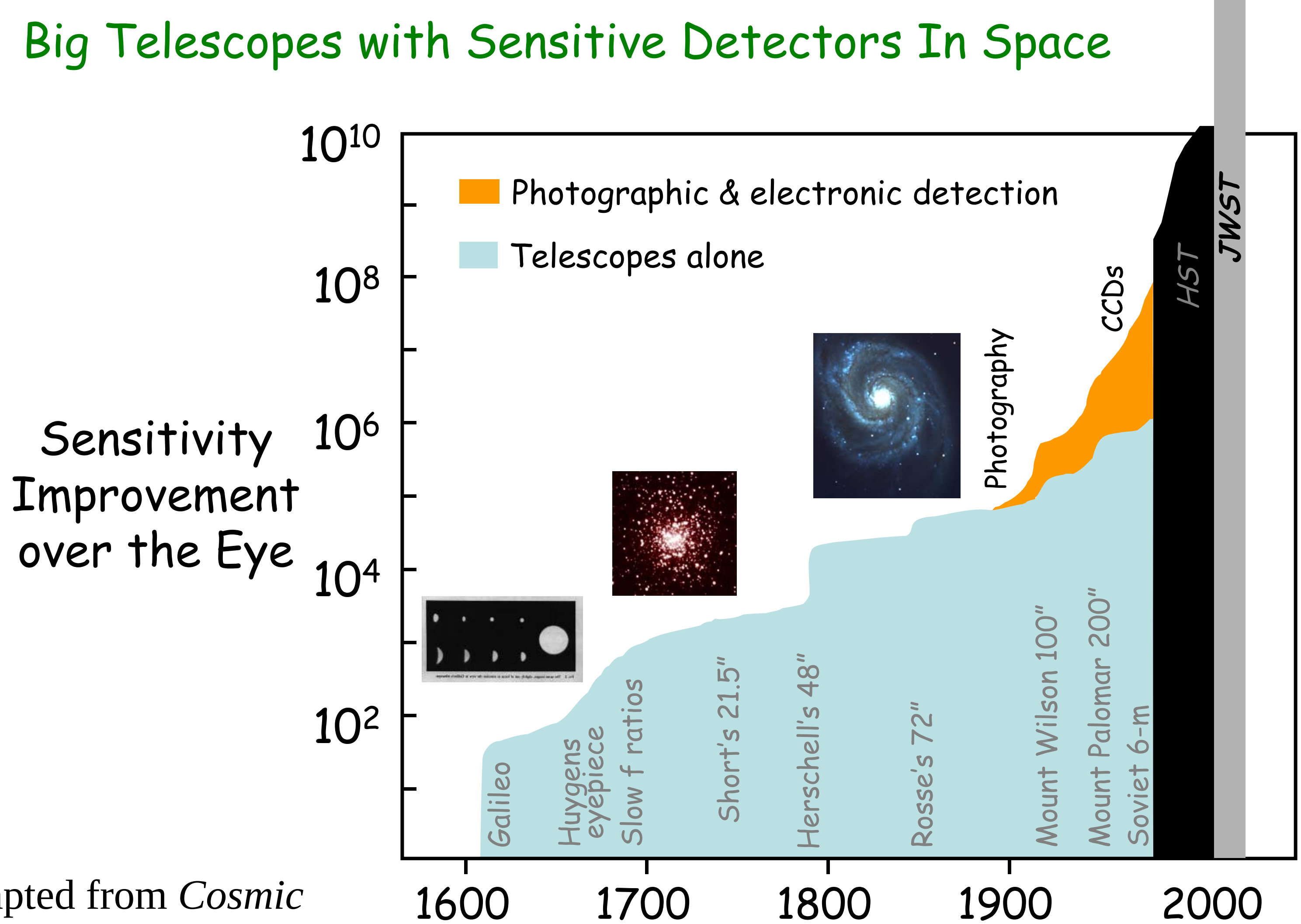
After Coarse Phasing



piston:
rms=32nm p/v=120nm



How to win at Astronomy
Aperture = Sensitivity



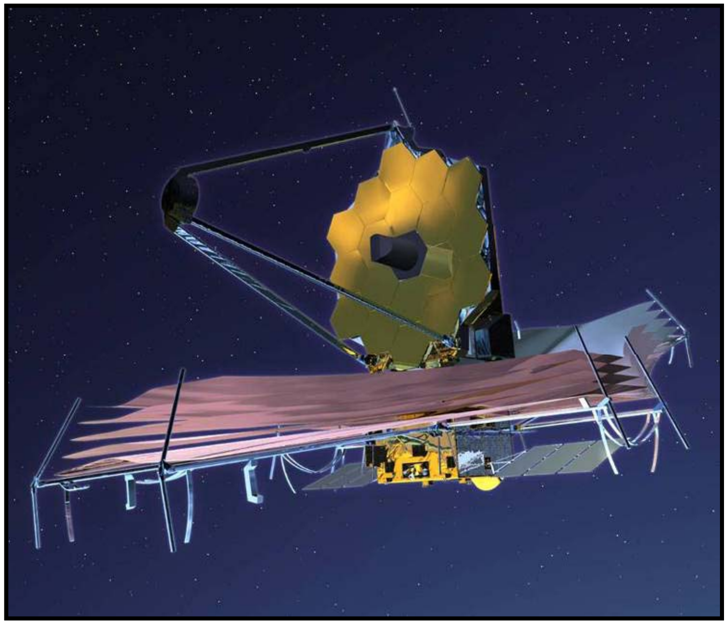
Adapted from *Cosmic Discovery*, M. Harwit

JWST Expands on HST Capabilities

HST: 2.4 m diameter Primary Mirror

Room Temperature

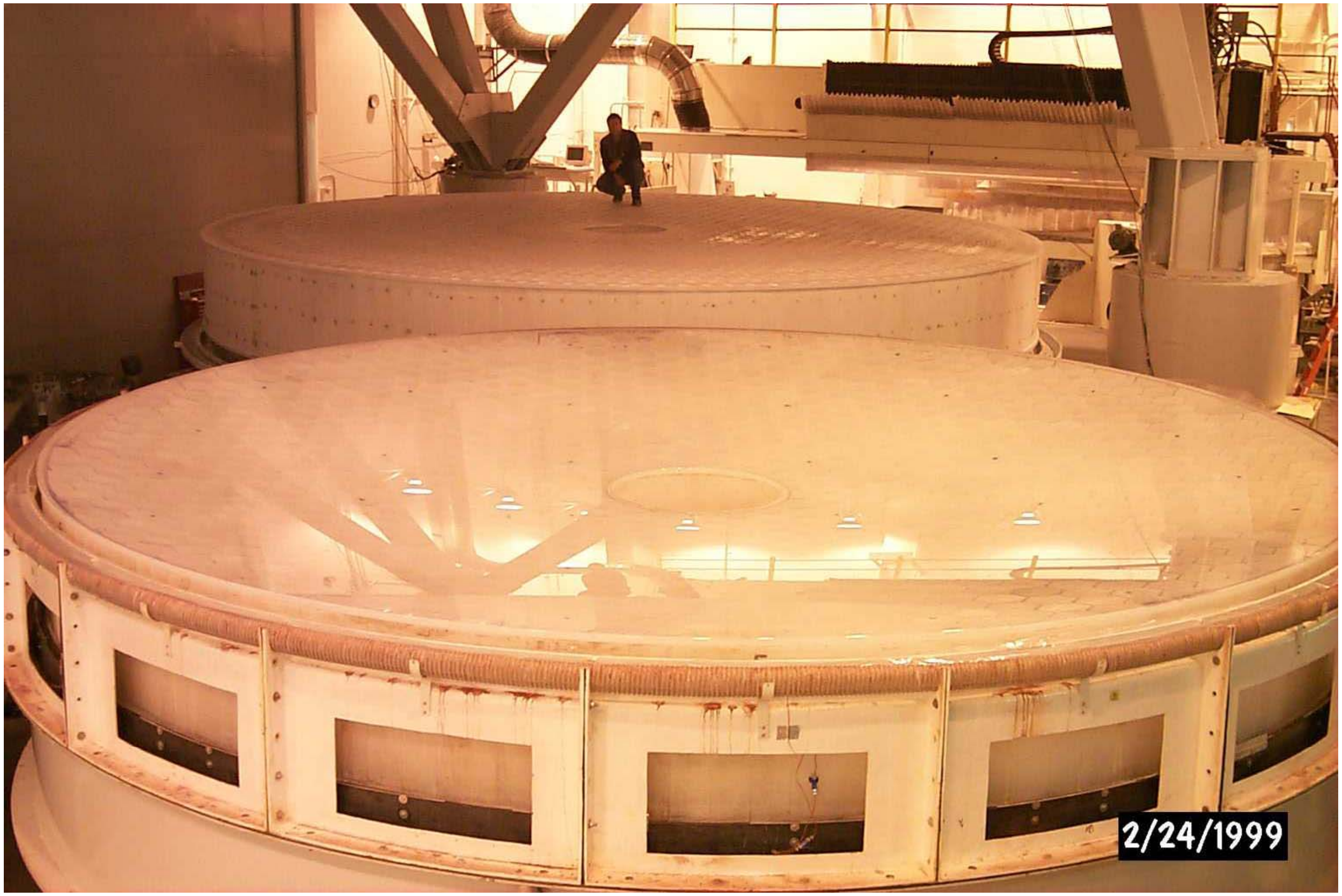
JWST: 6.5 m diameter Primary Mirror



< 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**

How big is JWST?



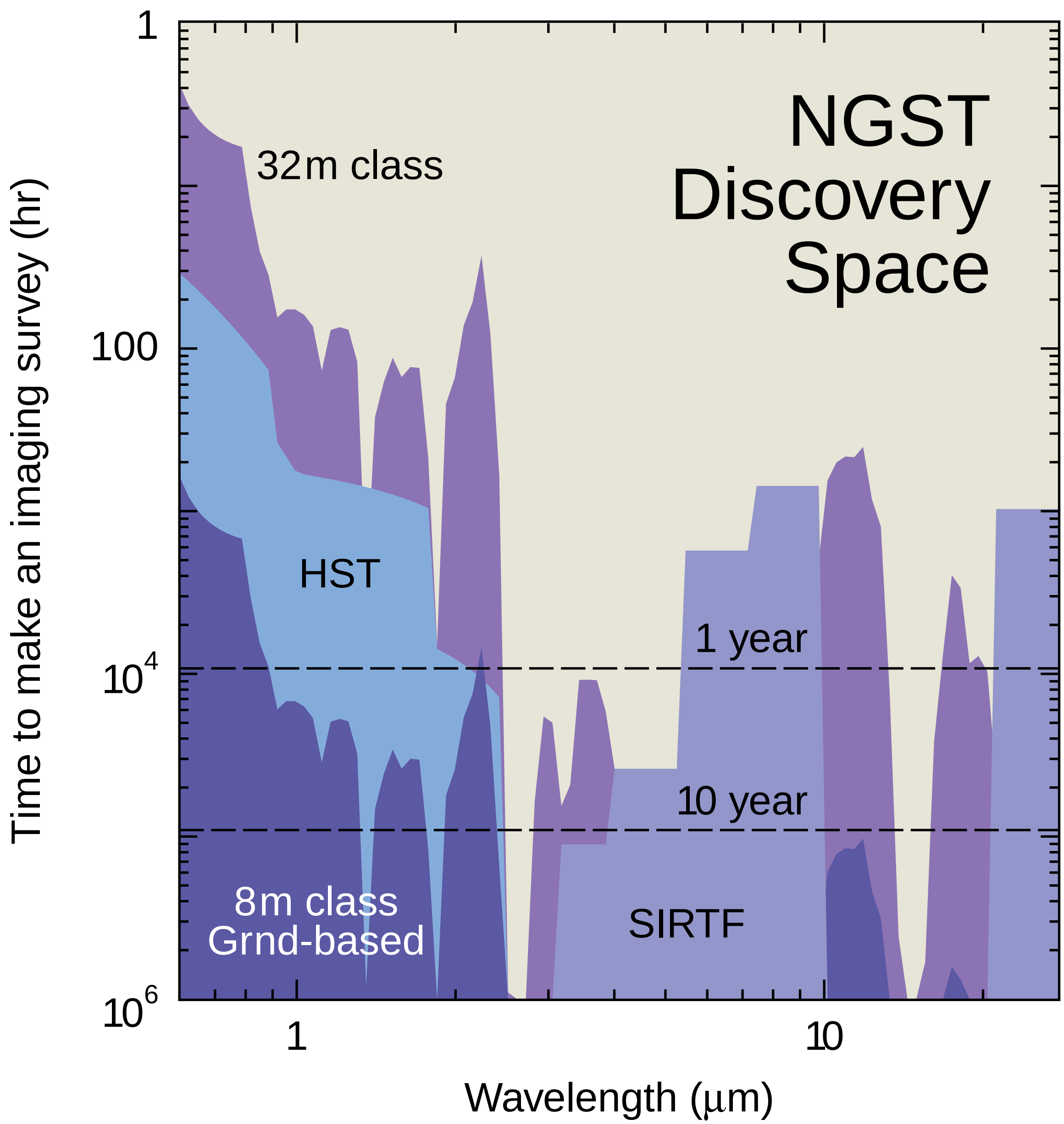
Full Scale JWST Mockup

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

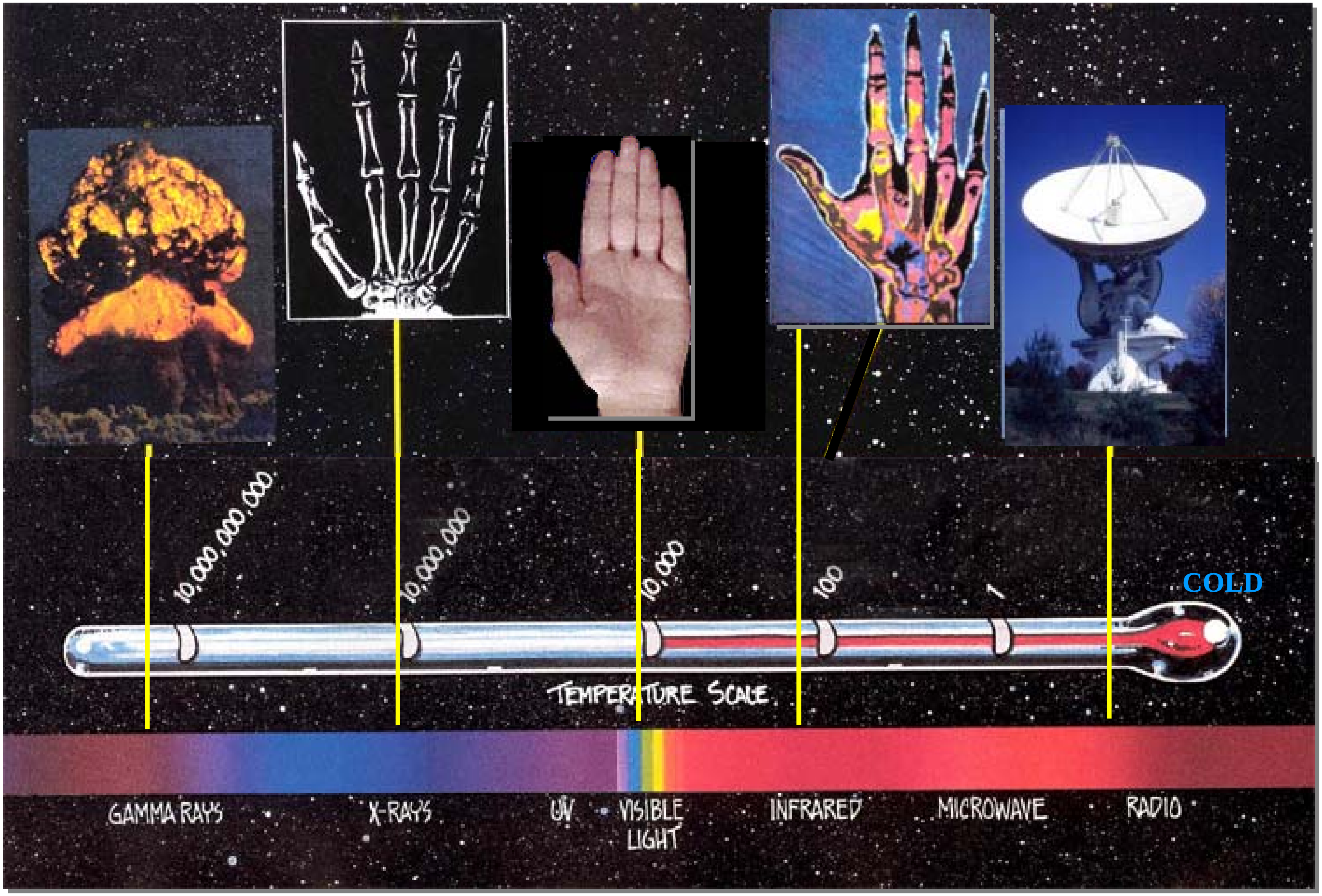
Full Scale JWST Mockup

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

Why go to Space – Wavelength Coverage



Infrared Light



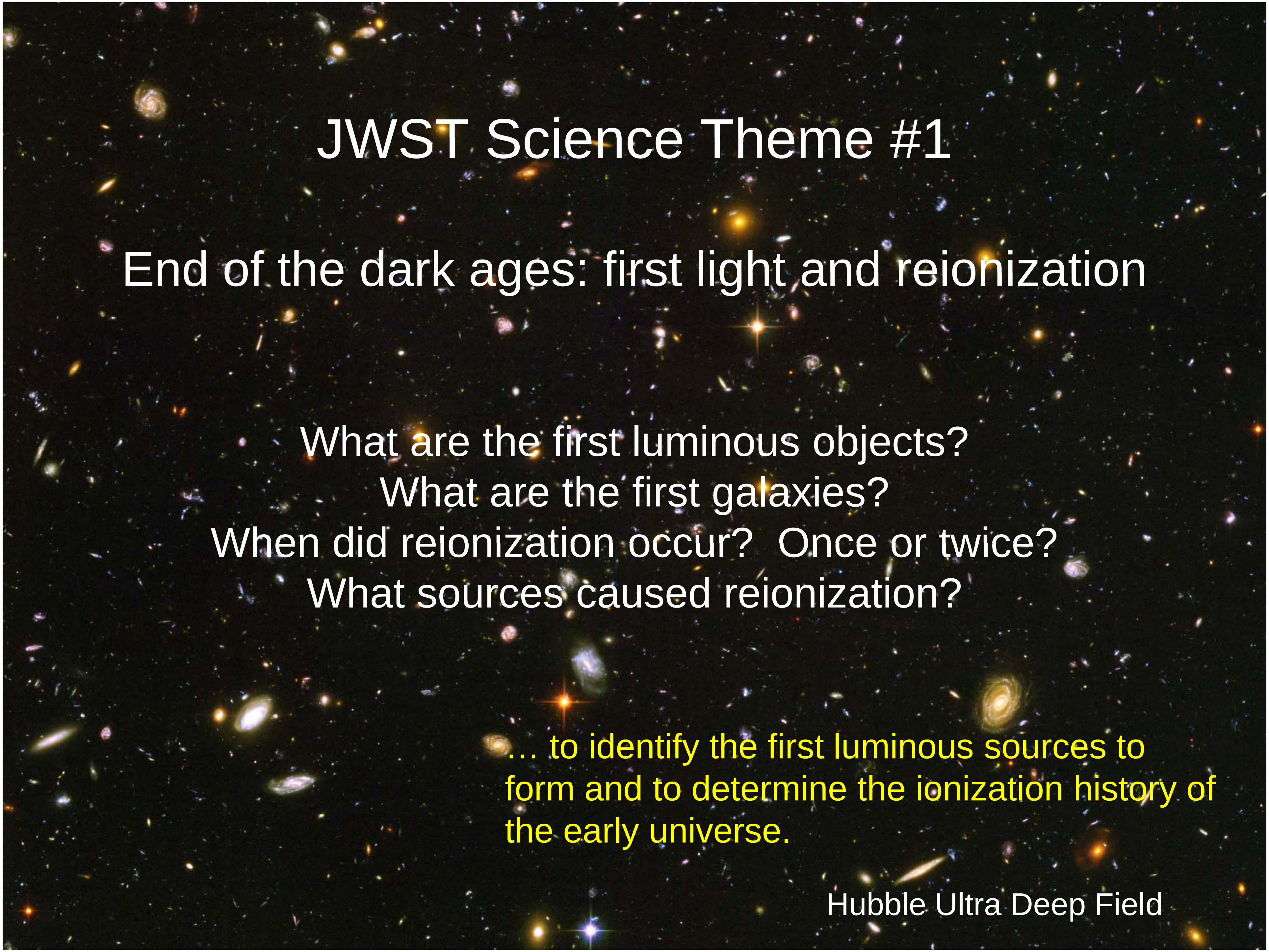
Why Infrared ?

JWST Science Theme #1

End of the dark ages: first light and reionization

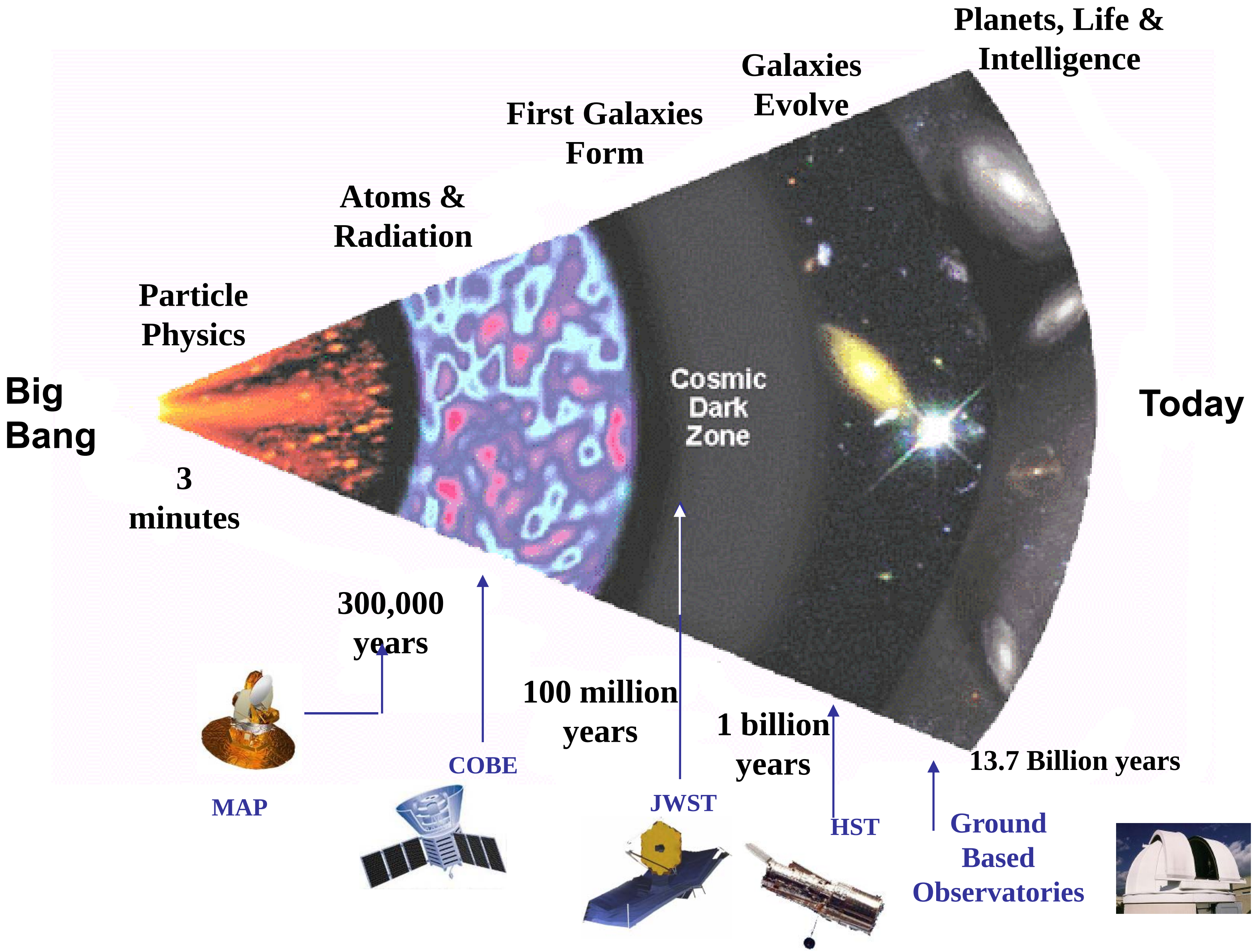
What are the first luminous objects?
What are the first galaxies?
When did reionization occur? Once or twice?
What sources caused reionization?

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

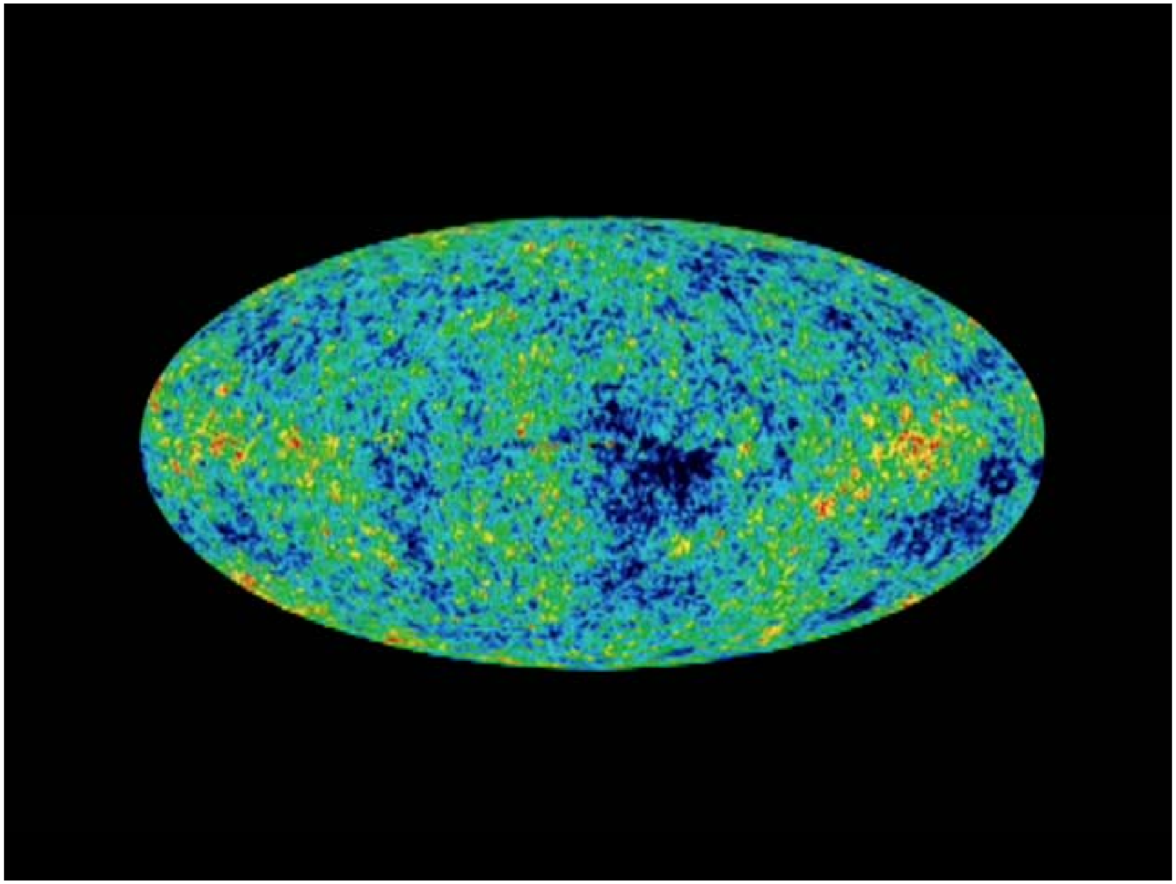


Hubble Ultra Deep Field

A Brief History of Time



History of Time?



WMAP Results		
Parameter	WMAP Value	What is it ?
Ωtotal	1.02 +/- 0.02	Total Density
Ω_{lambda}	0.73 +/- 0.04	Dark Energy
Ω_{matter}	0.27 +/- 0.04	Matter Density
Ω_{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

When and how did reionization occur?

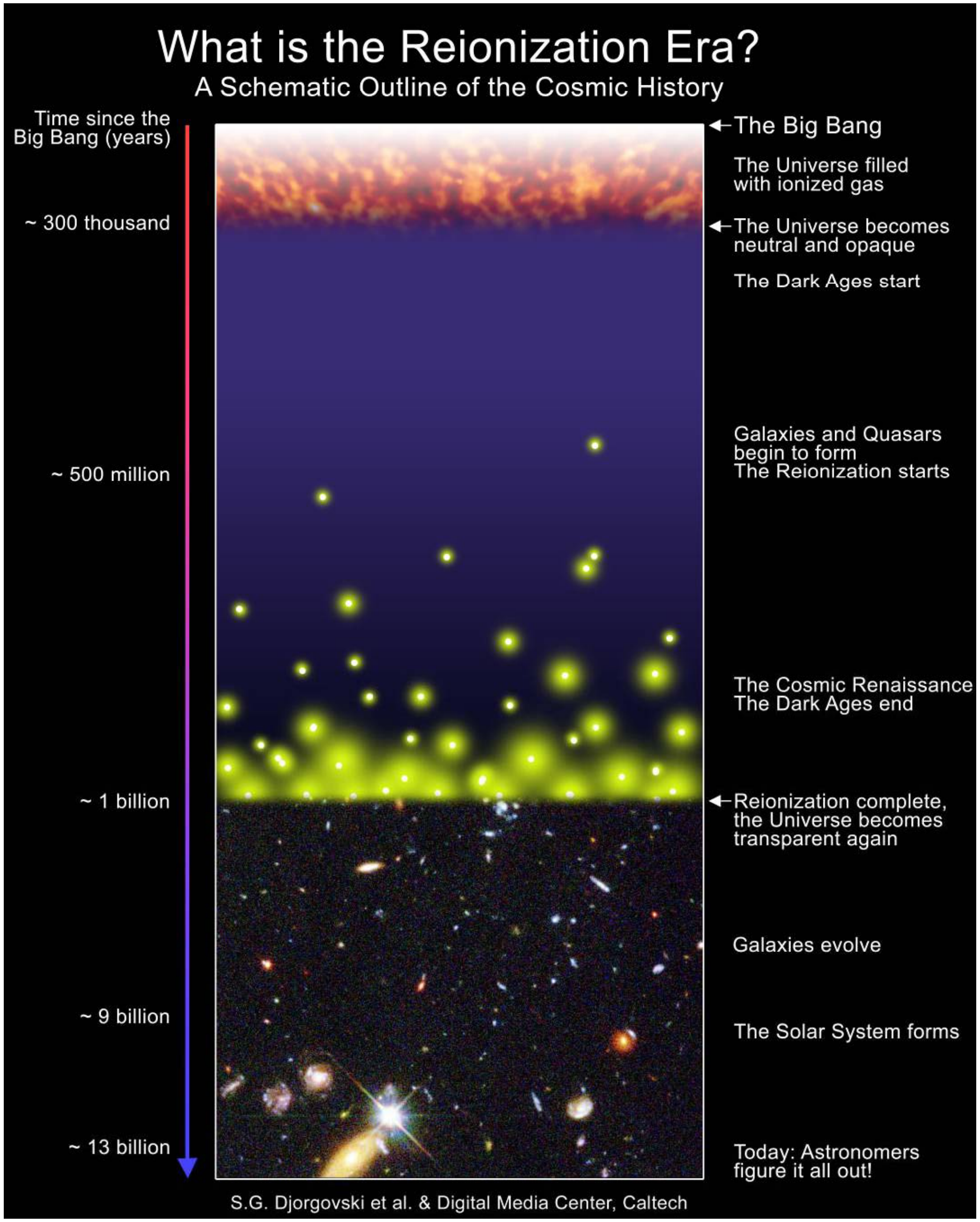
Reionization happened at z>6 or 1 billion years after Big Bang.

WMAP says maybe twice?

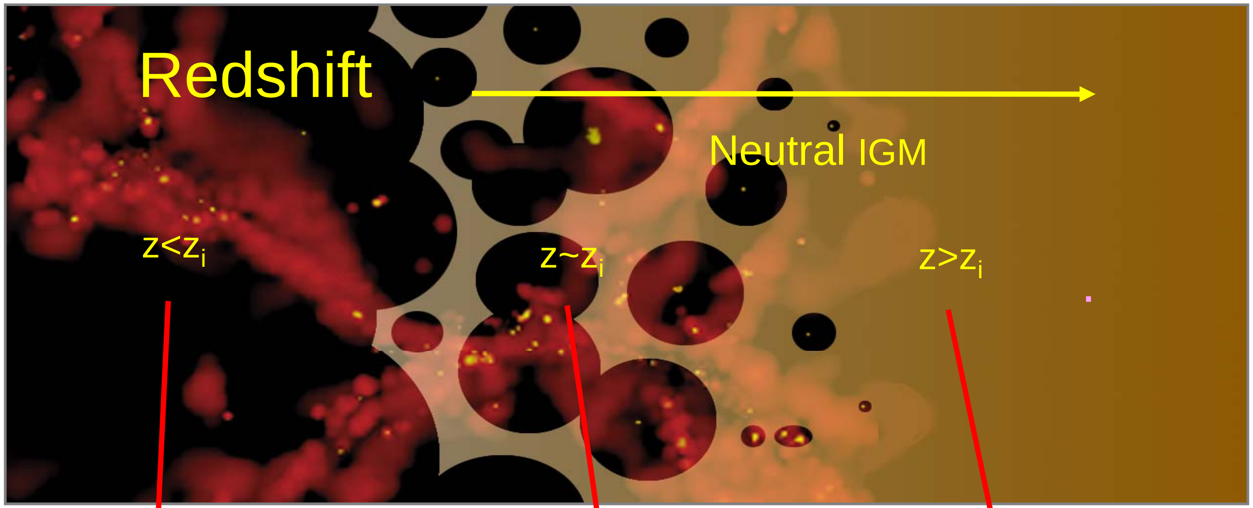
Probably galaxies, maybe quasar contribution

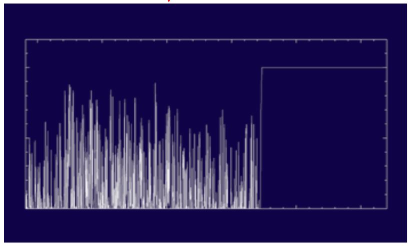
JWST Observations:

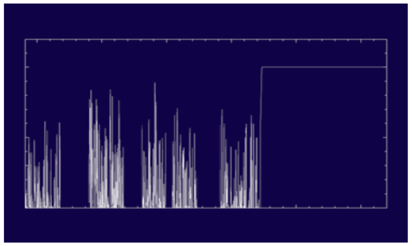
- Spectra of the most distant quasars
- Spectra of faint galaxies

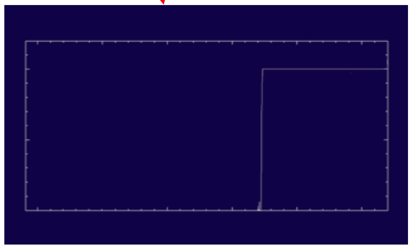


First Light: Observing Reionization Edge









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

End of the dark ages: first light and reionization

First galaxies are small & faint

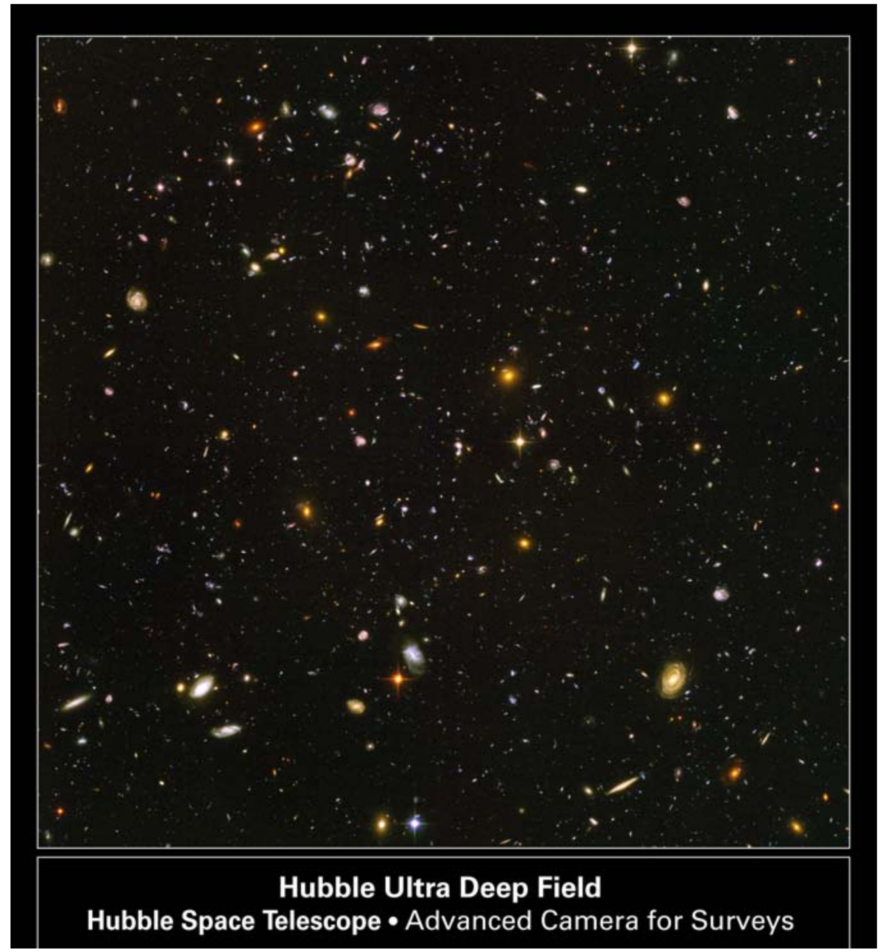
Light is redshifted into infrared.

Low-metallicity, massive stars.

- SNe! GRBs!

JWST Observations

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



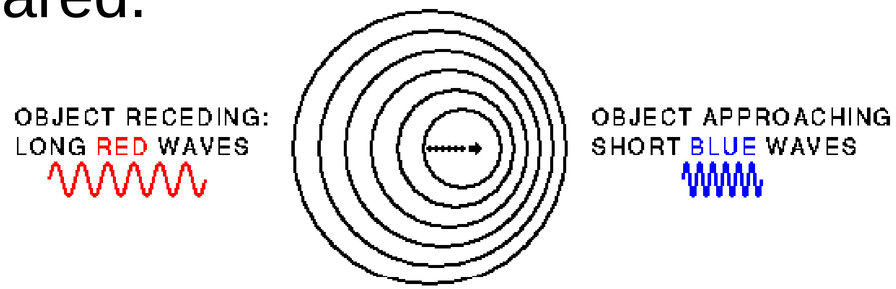
First Light

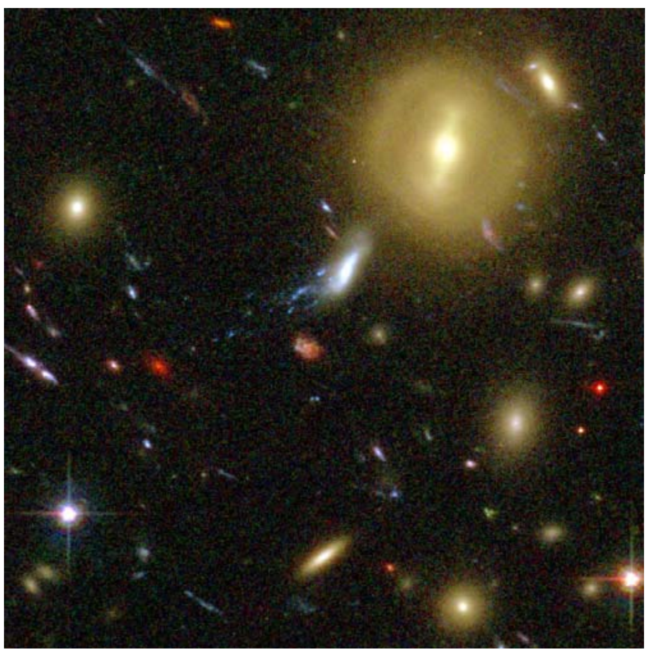
What did the first stars galaxies to form look like?

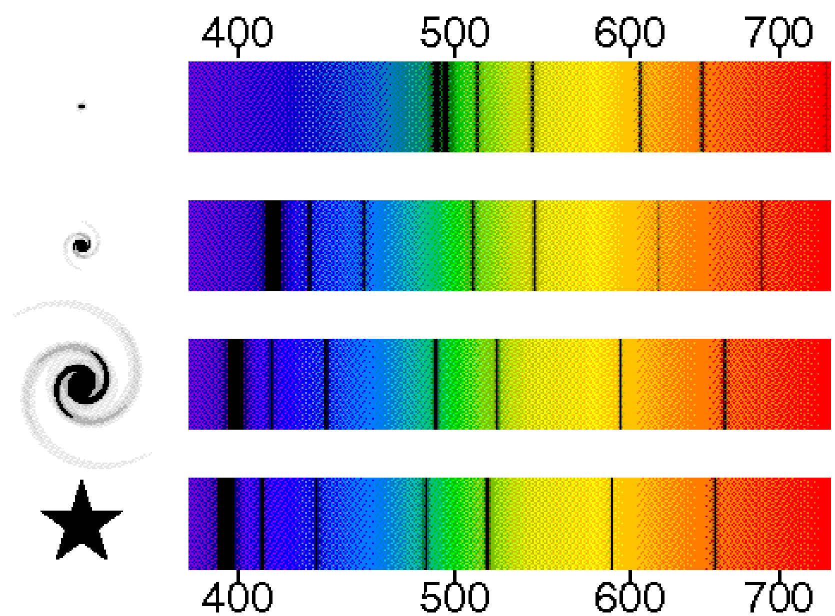
We don't know, but models suggest first stars were very massive!

Infrared Light

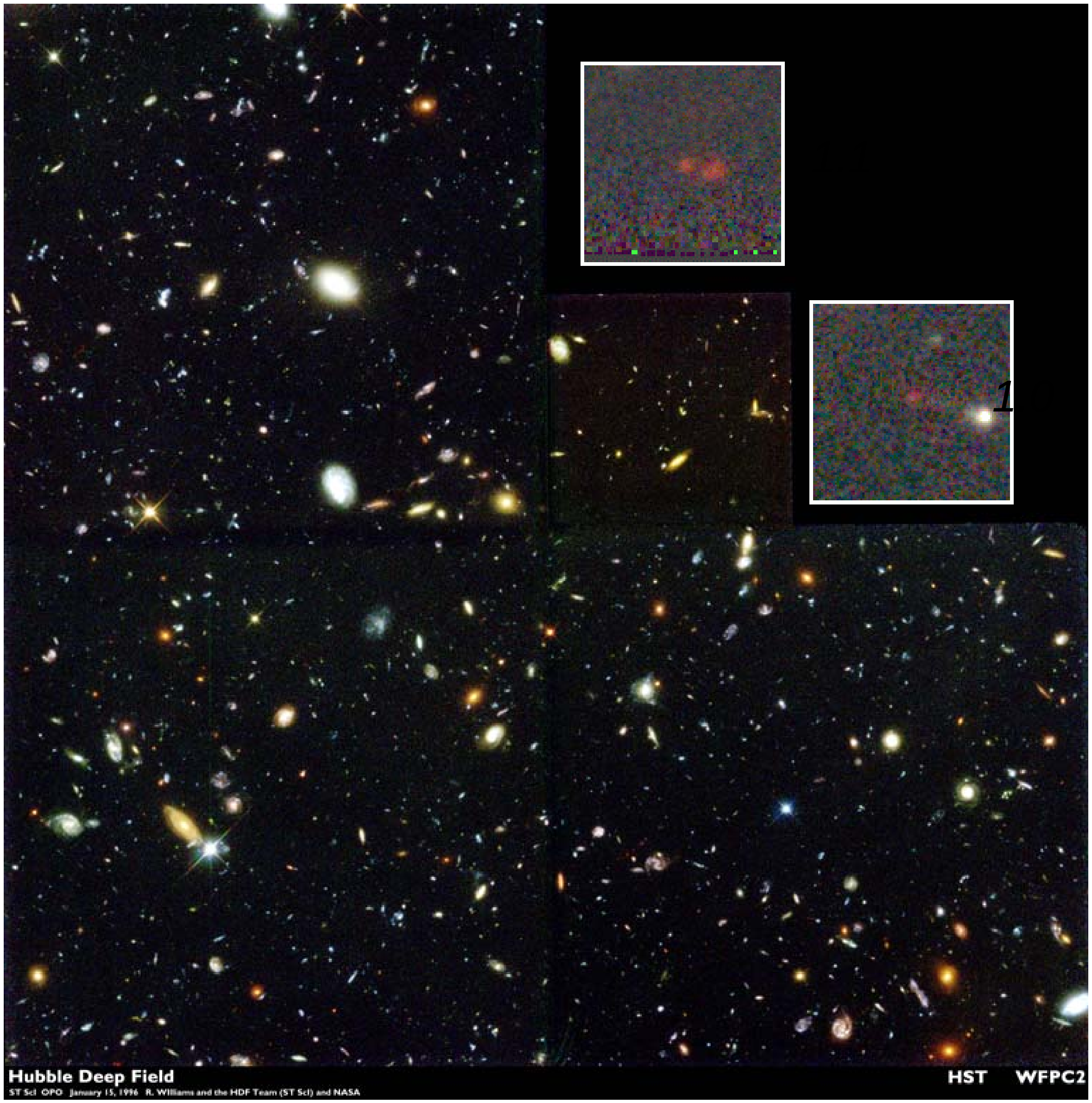
Light from the first galaxies is redshifted from the visible into the infrared.

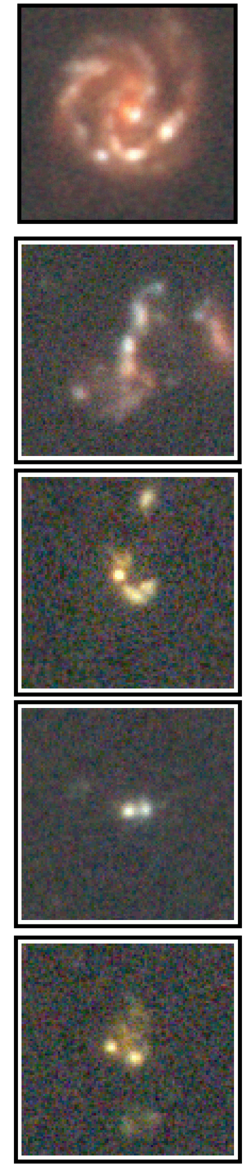






The Hubble Deep Field





5.8

3.3

2.2

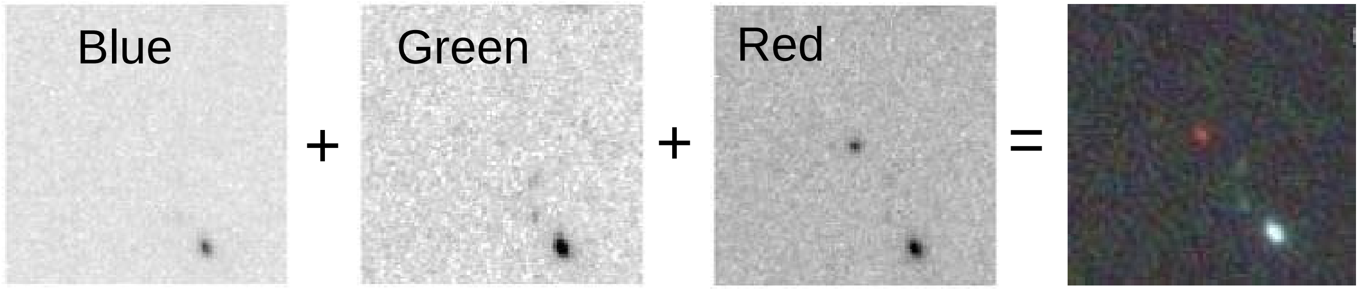
2.2

1.8

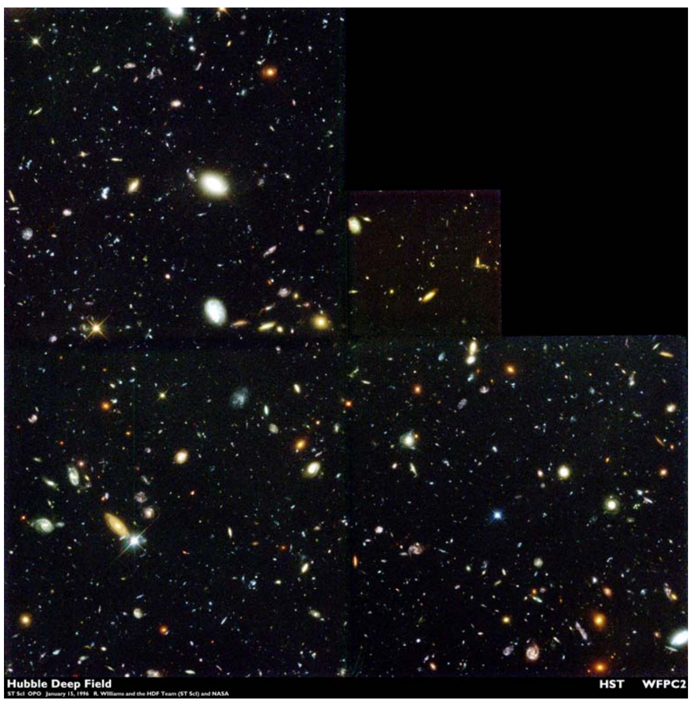
Age (Gyr)

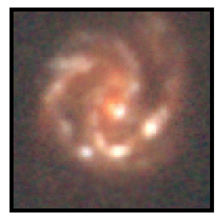
STScI Science Project: Robert Williams. et al. (1997)

How do we see first light objects?

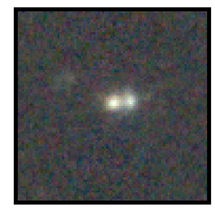


Deep Imaging: Look for *near-IR drop-outs*

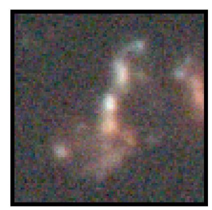




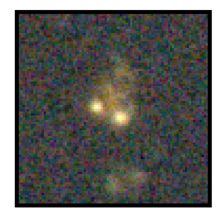
5.8 Gyr



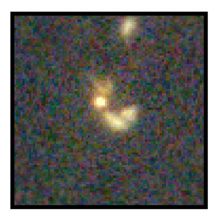
2.2 Gyr



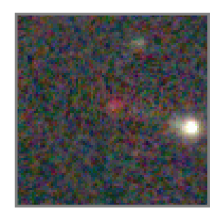
3.3 Gyr



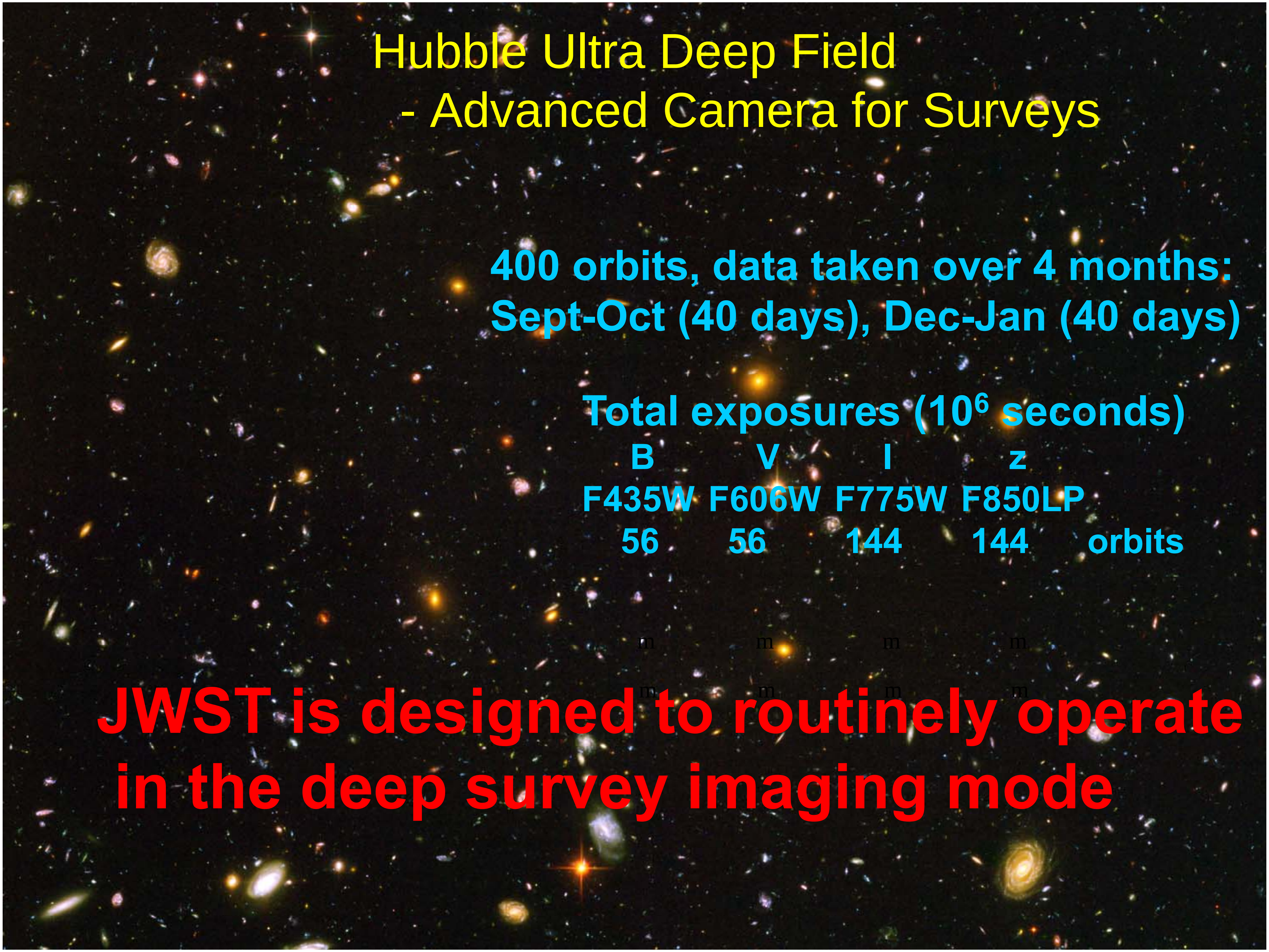
1.8 Gyr



2.2 Gyr



1.0 Gyr



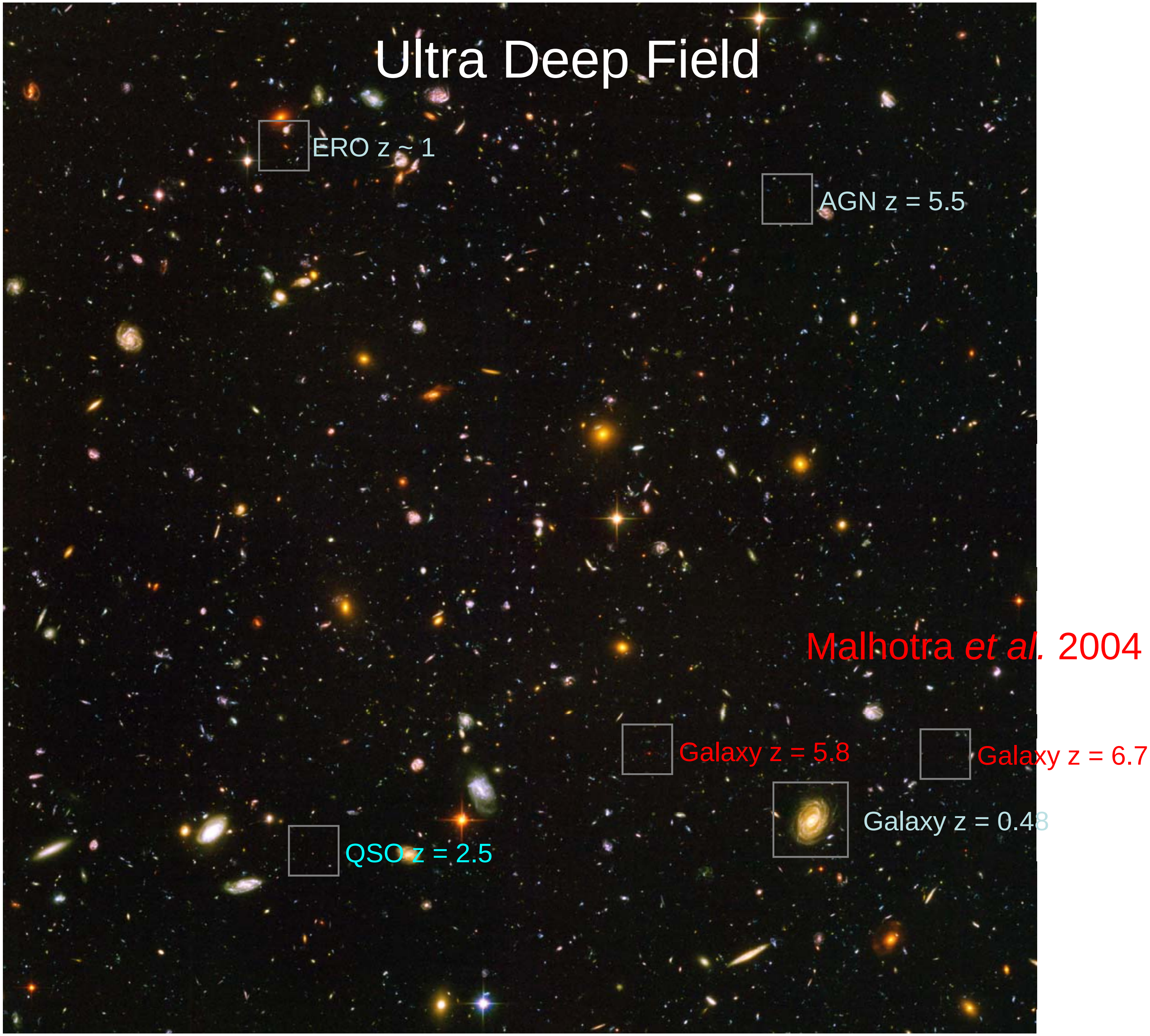
Hubble Ultra Deep Field
- Advanced Camera for Surveys

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

Total exposures (10^6 seconds)

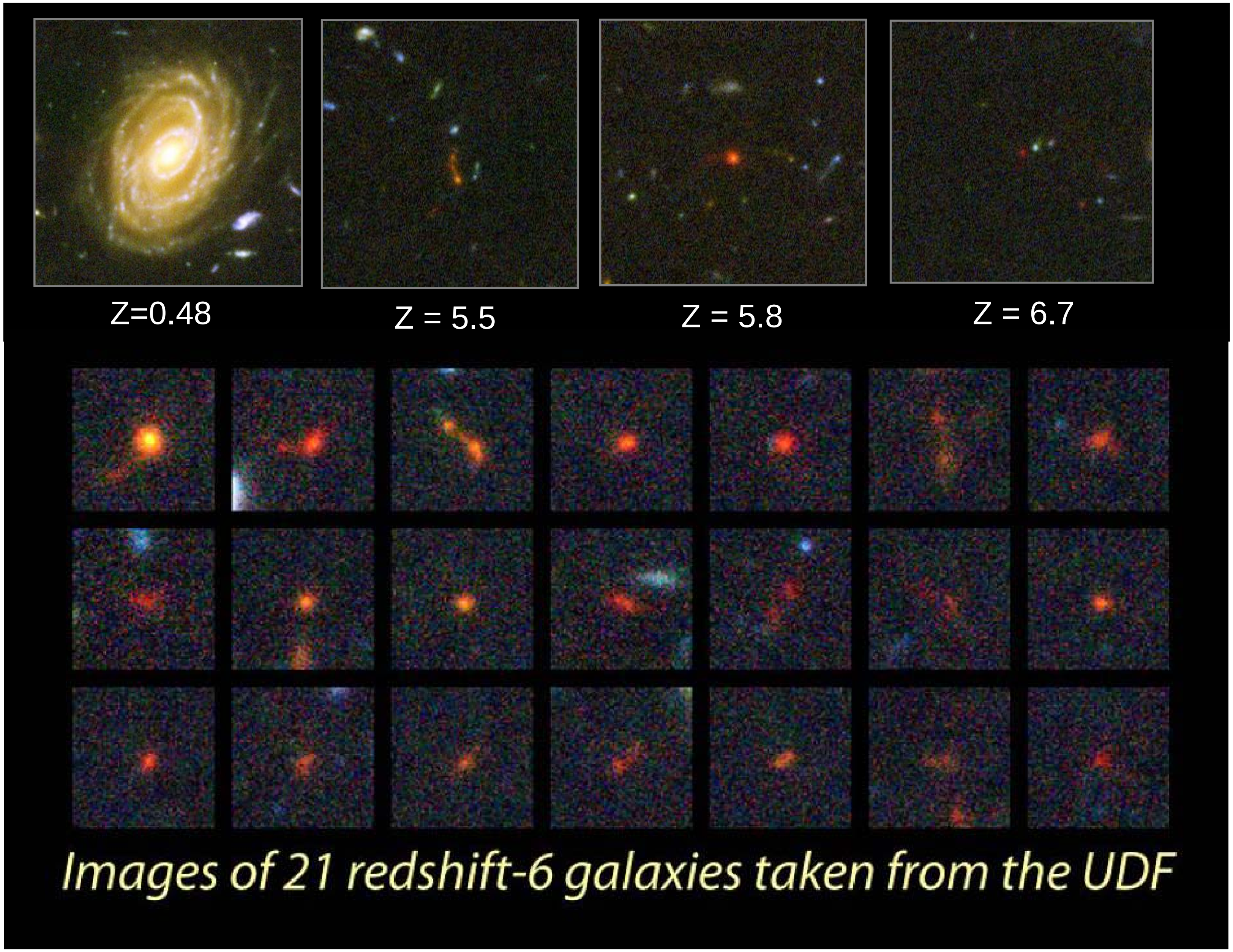
	B	V	I	z	
	F435W	F606W	F775W	F850LP	
	56	56	144	144	orbits

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



Ultra Deep Field
ERO z ~ 1
AGN z = 5.5
Malhotra et al. 2004
Galaxy z = 5.8
Galaxy z = 6.7
Galaxy z = 0.48
QSO z = 2.5

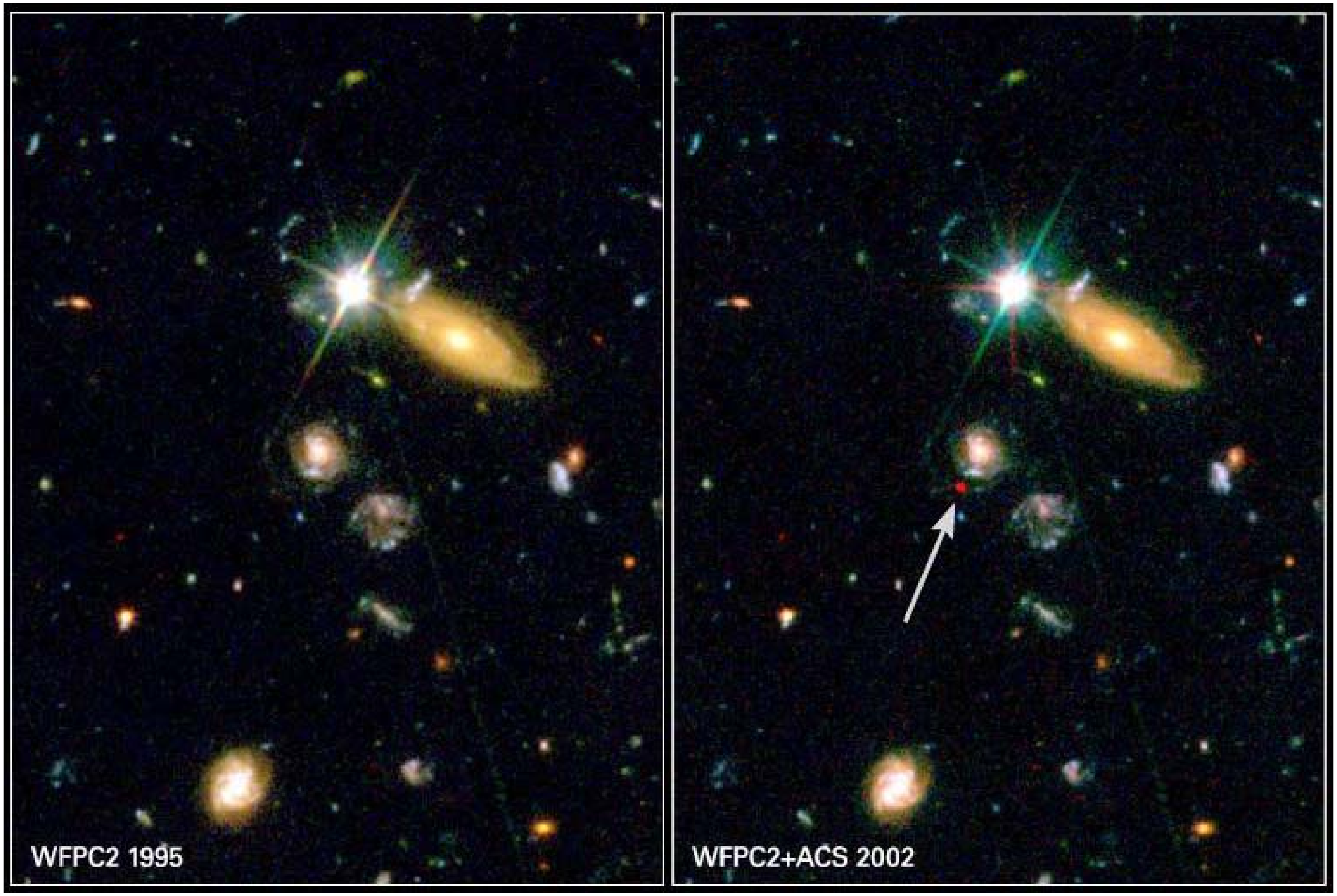
New Results from UDF



Images of 21 redshift-6 galaxies taken from the UDF

How do we see first light objects?

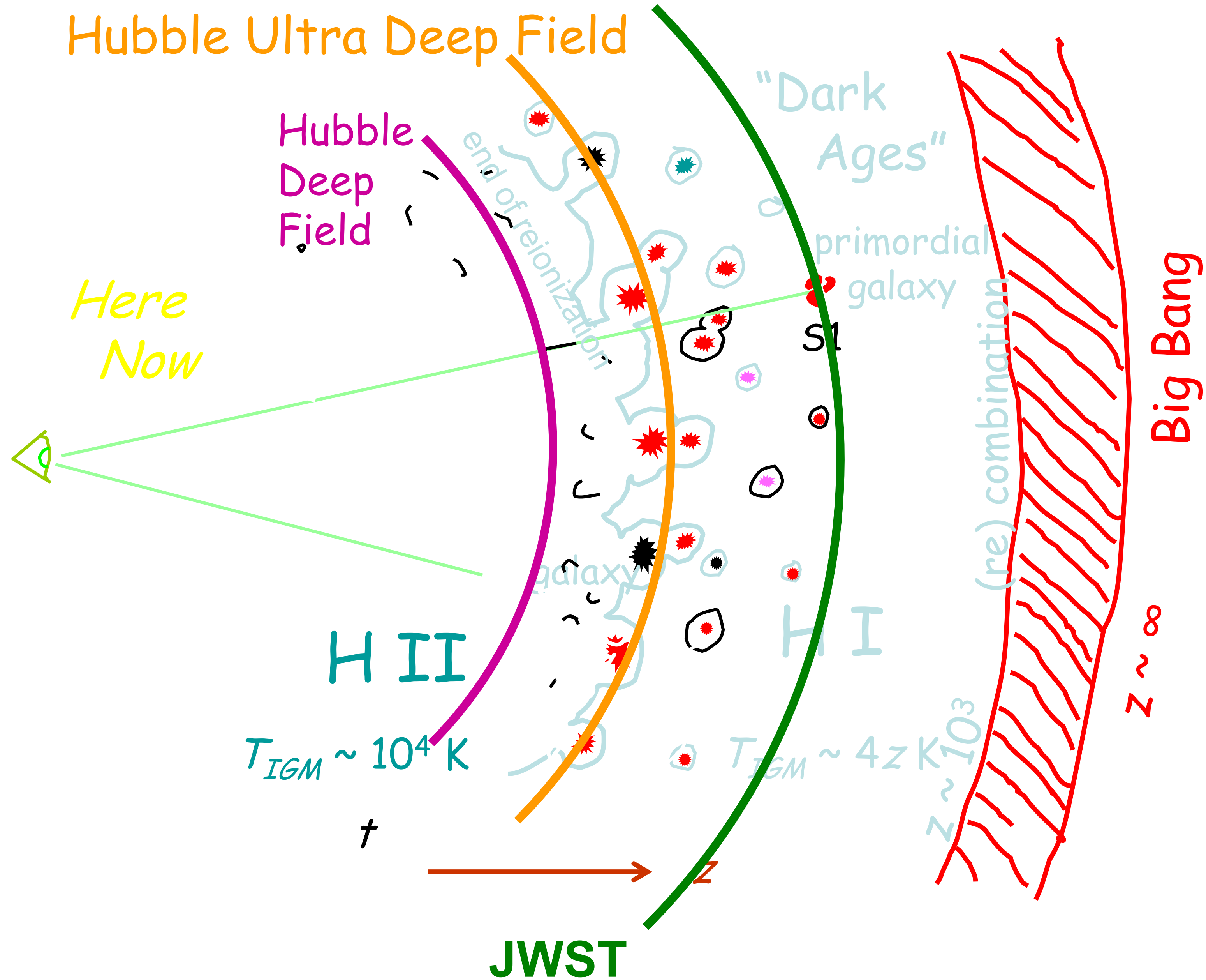
The first stars may be detected when they became bright supernovae. But, they will be very rare objects!



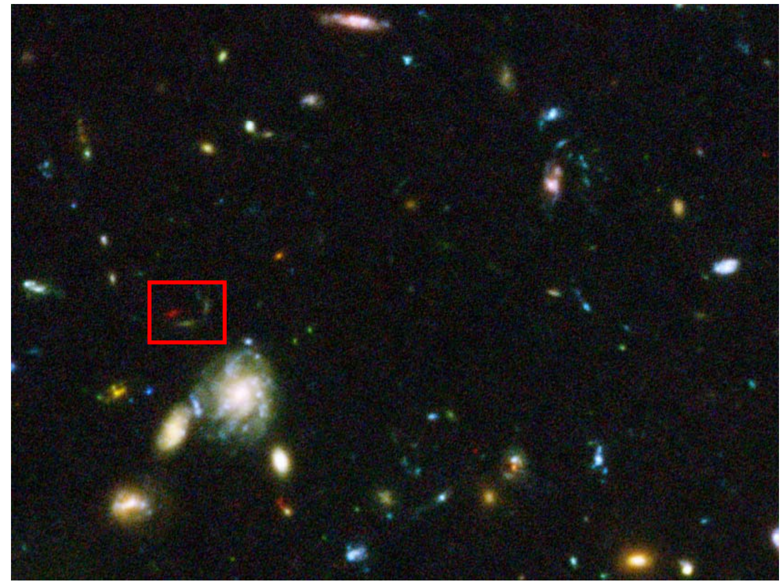
How do we see first light objects?

Use a magnifying glass !

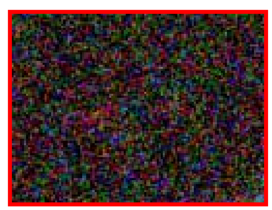
The Renaissance after the Dark Ages



Sensitivity Matters



GOODS CDFS – 13 orbits HUDF – 400 orbits

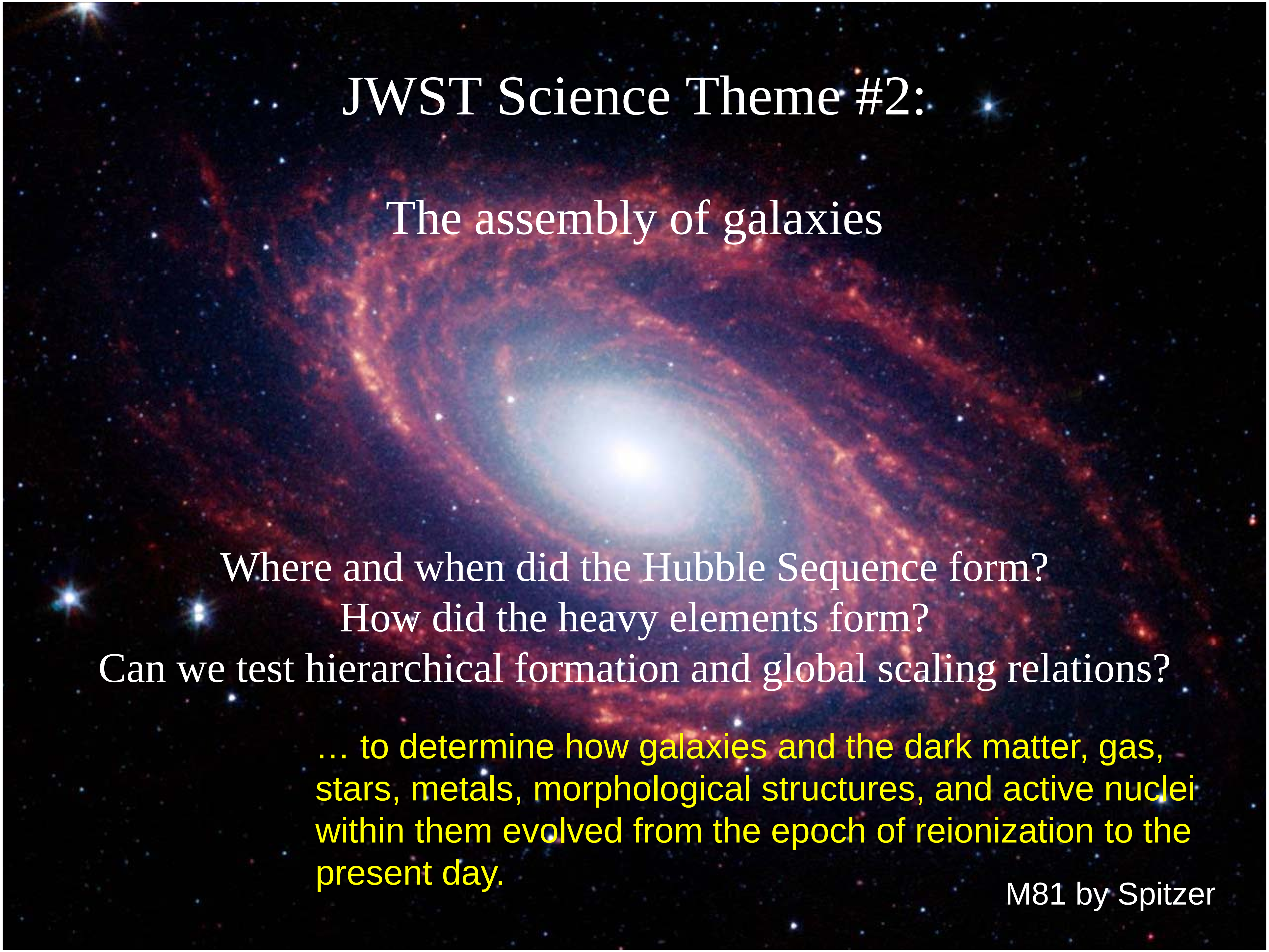


JWST Science Theme #2:

The assembly of galaxies

Where and when did the Hubble Sequence form?
How did the heavy elements form?
Can we test hierarchical formation and global scaling relations?

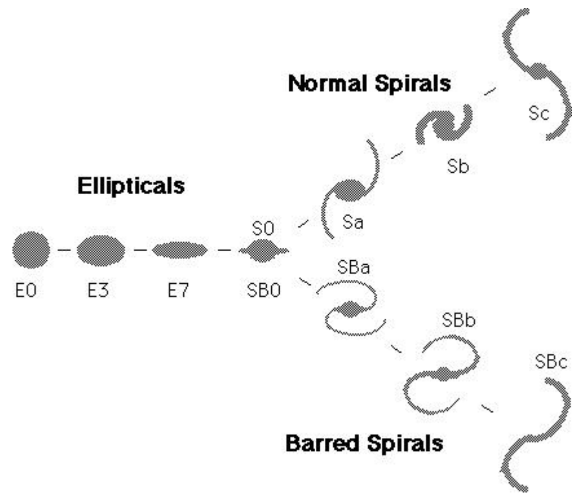
… to determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.

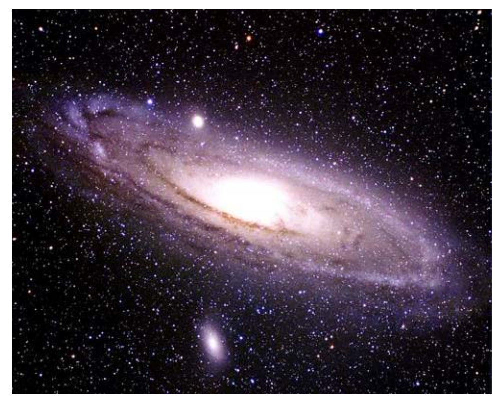


M81 by Spitzer

The Hubble Sequence

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



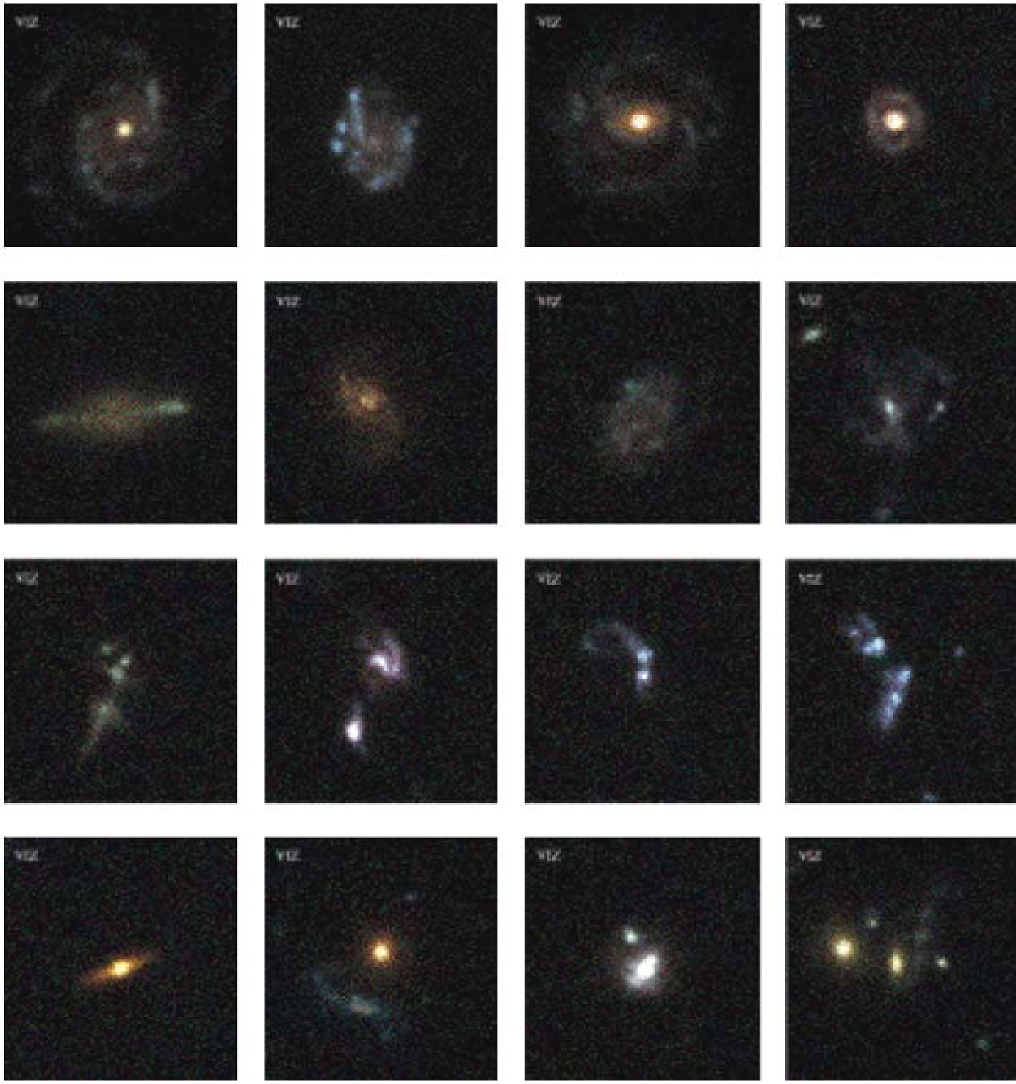


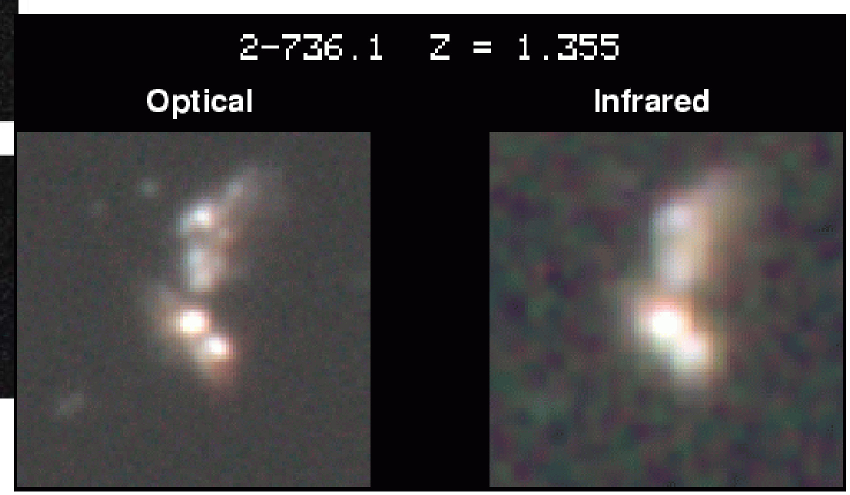
The Hubble Space Telescope has extended this to the distant past.

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

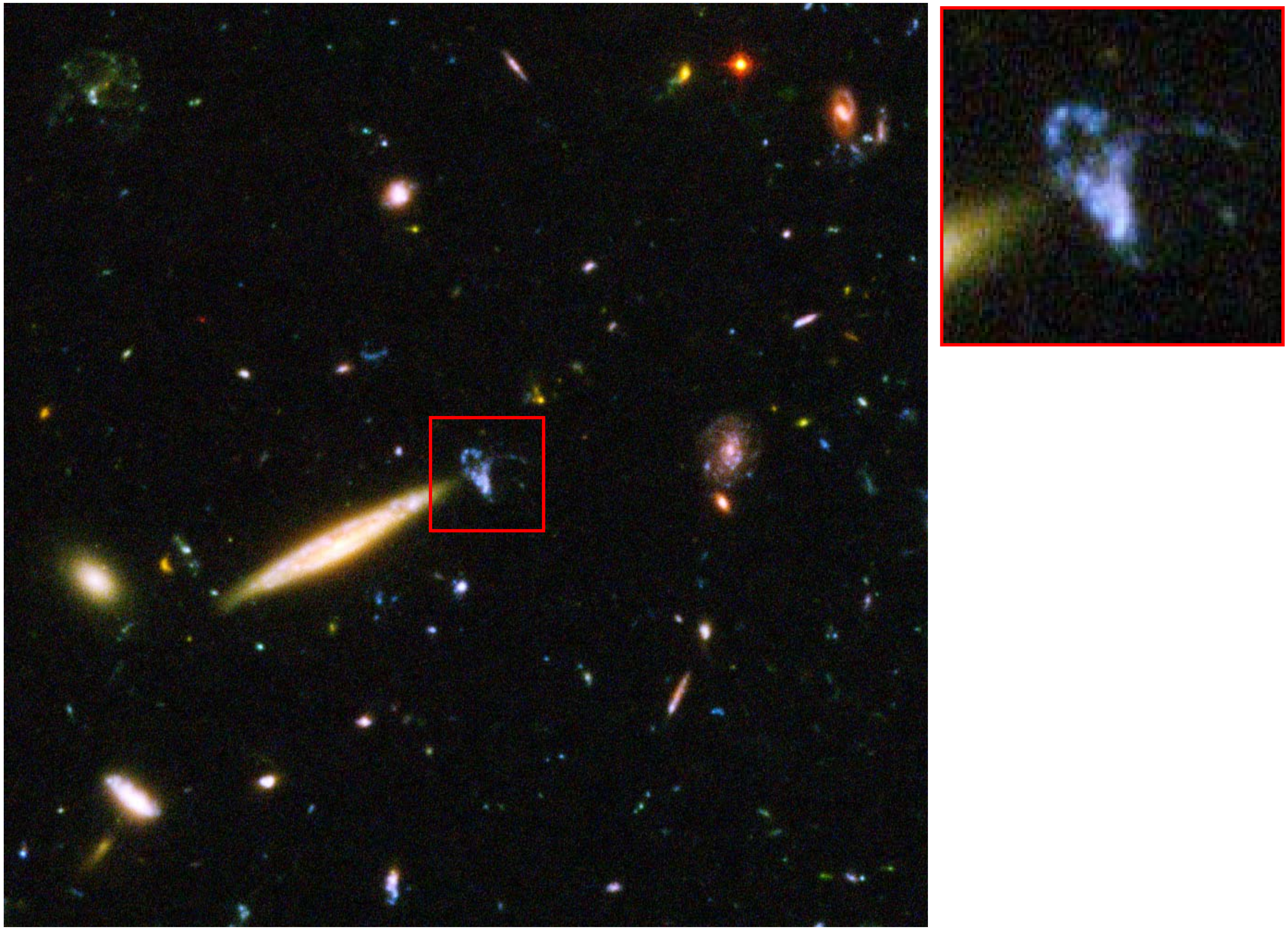
- Galaxy assembly is a process of hierarchical merging
- Components of galaxies have variety of ages & compositions
- JWST Observations:
  - NIRCam imaging
  - Spectra of 1000s of galaxies

Distant Galaxies are “Train Wrecks”



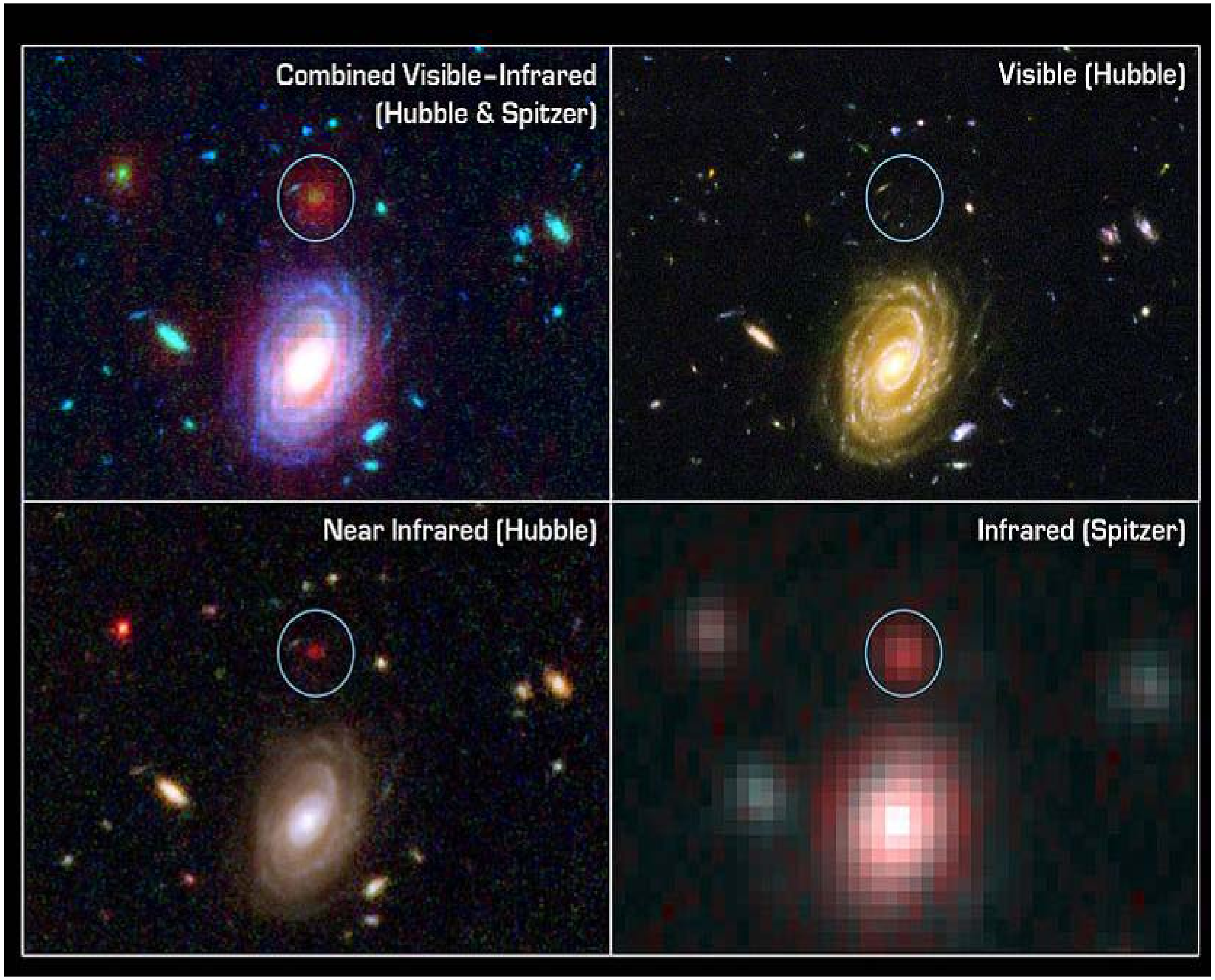


Unusual objects



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.

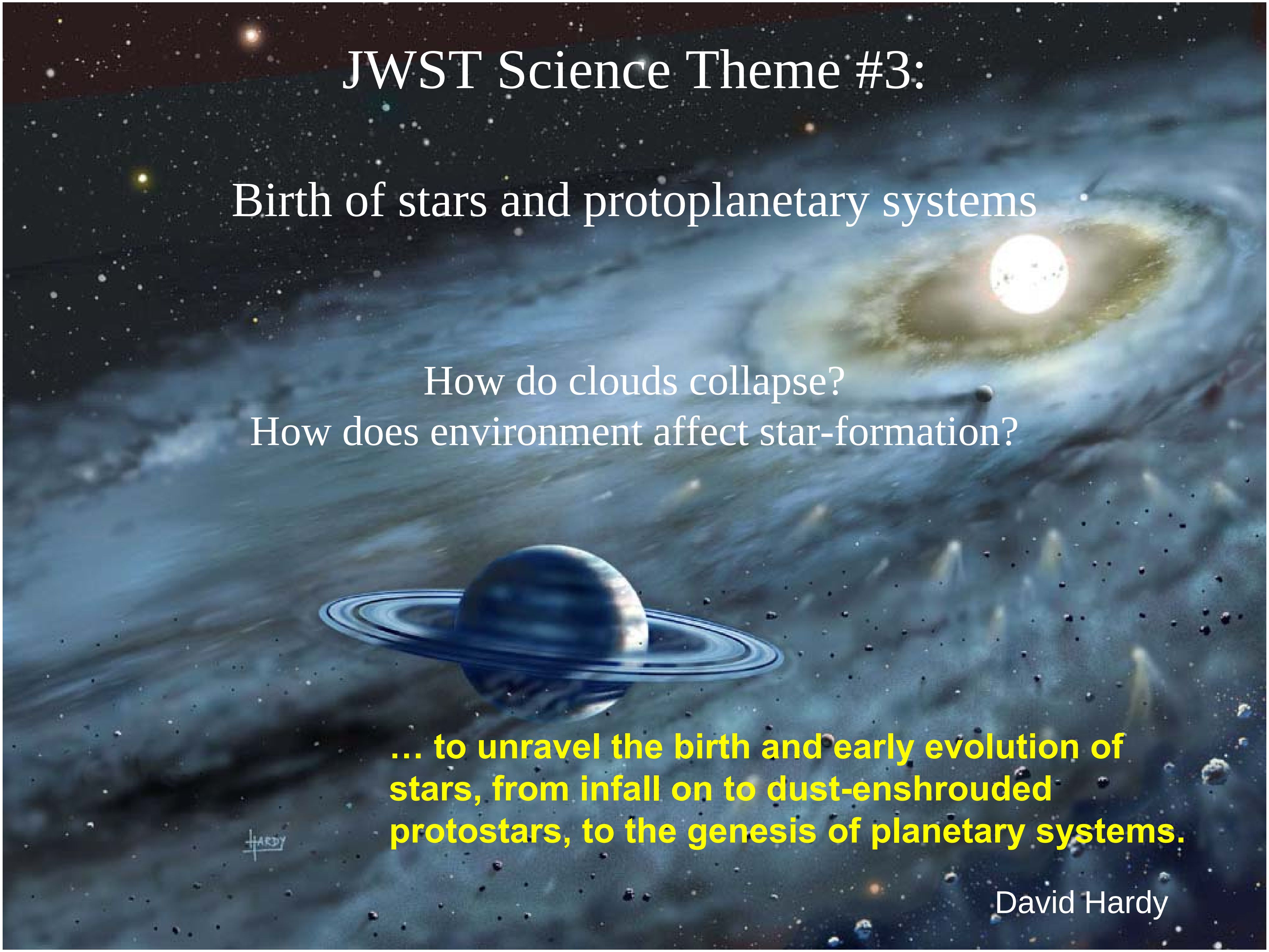
At an epoch when the Universe was only ~15% of its present size, and ~7% of its current age.

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 clouds collapse?
How does environment affect star-formation?
… to unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.
HARDY
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.

JWST Observations:

Deep NIR and MIR imaging of dark clouds and proto-stars

Barnard 68 in infrared

How does environment affect star-formation?

Massive stars produce wind & radiation

Either disrupt star formation, or causes it.

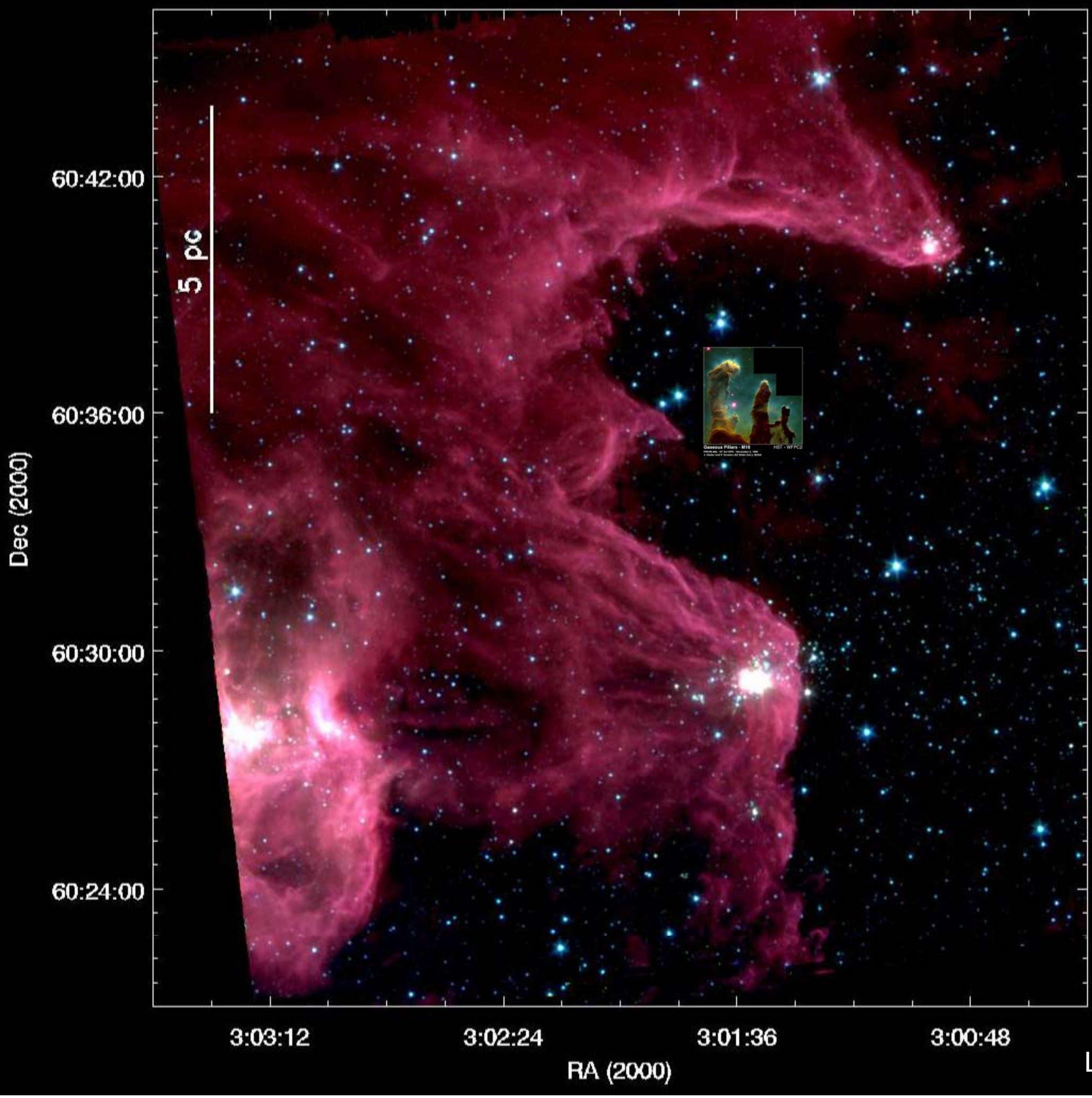
Boundary between smallest brown dwarf stars & planets is unknown

Different processes? Or continuum?

JWST Observations:

Survey dark clouds, “elephant trunks” and star-forming regions

The Eagle Nebula
as seen in the infrared



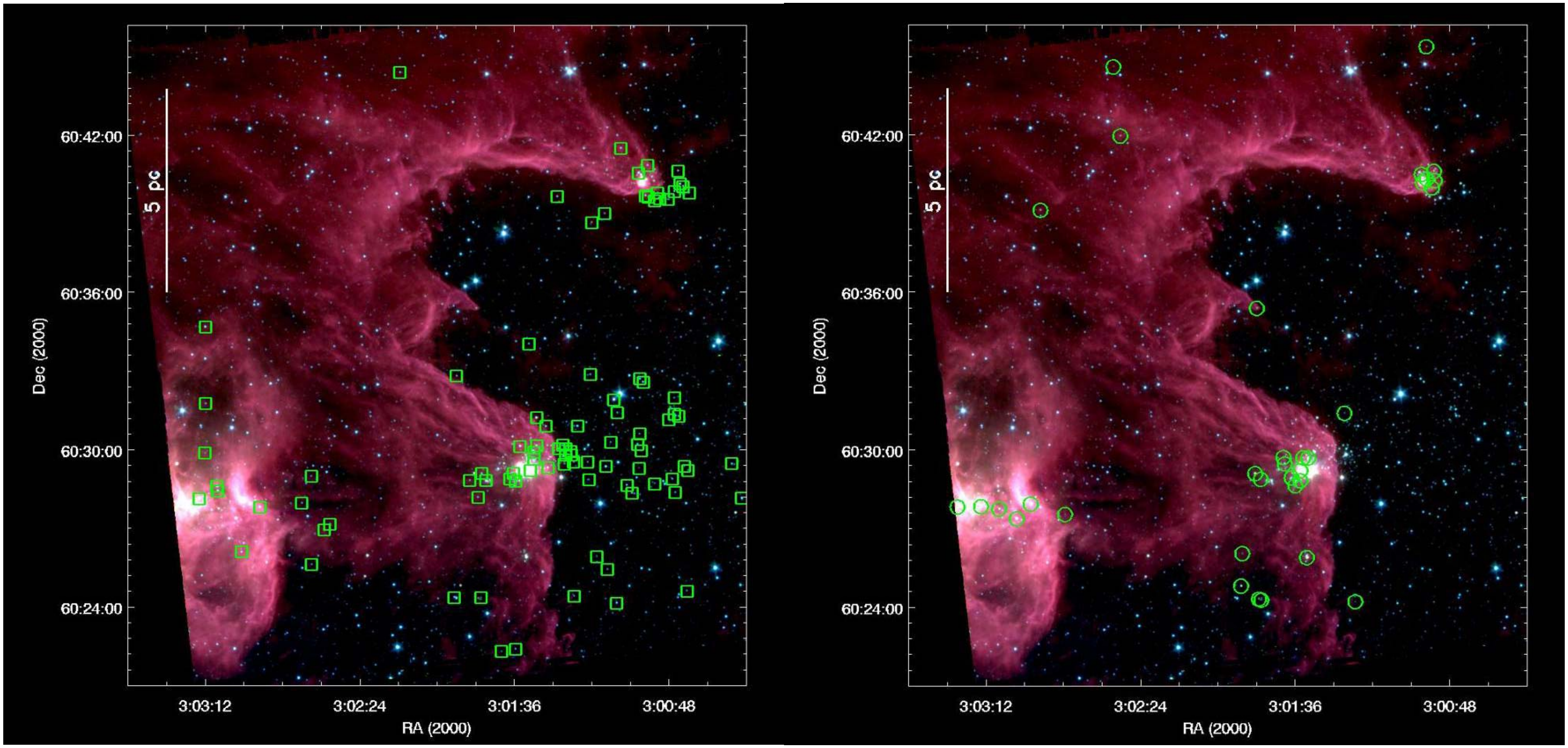
Spitzer has Found "The Mountains Of Creation"

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



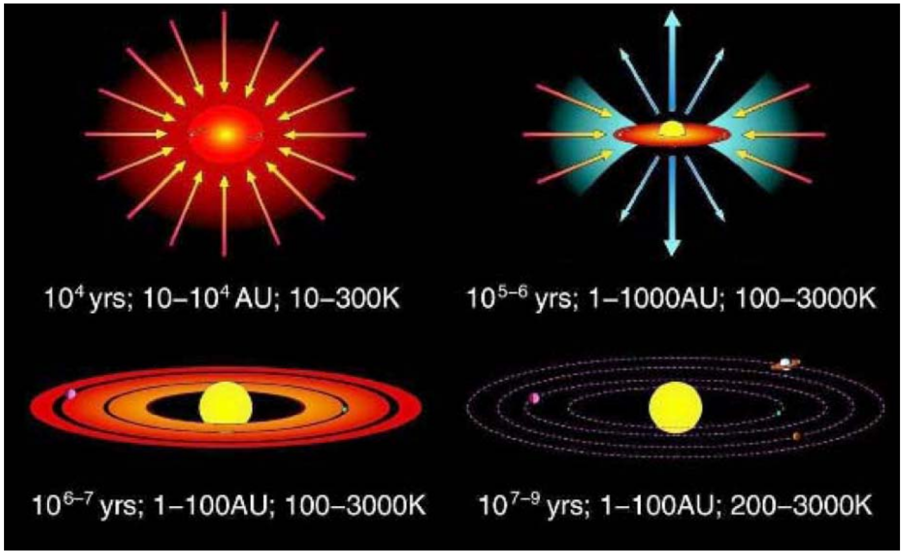
Young (Solar Mass) Stars are Shown in This Panel

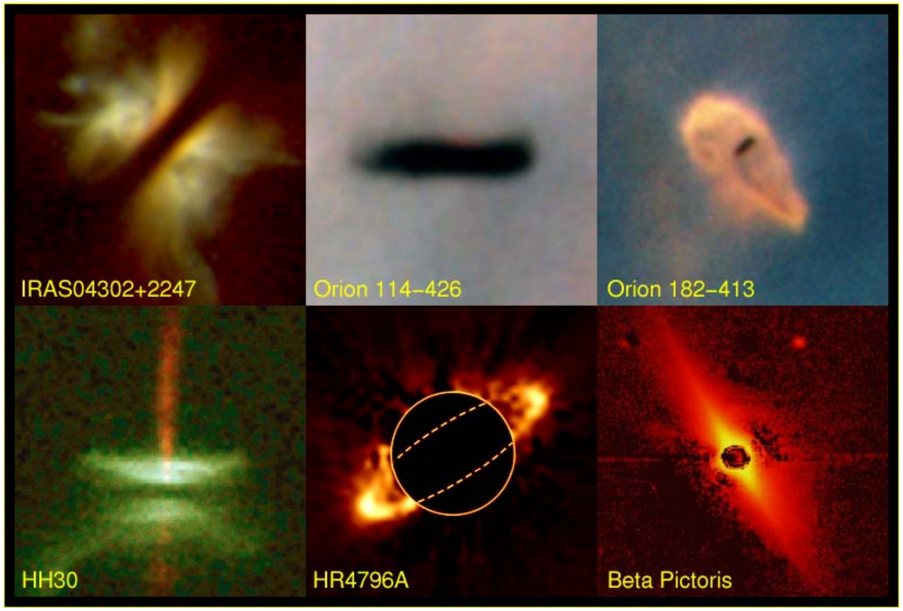
Really Young Stars are Shown in This Panel

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

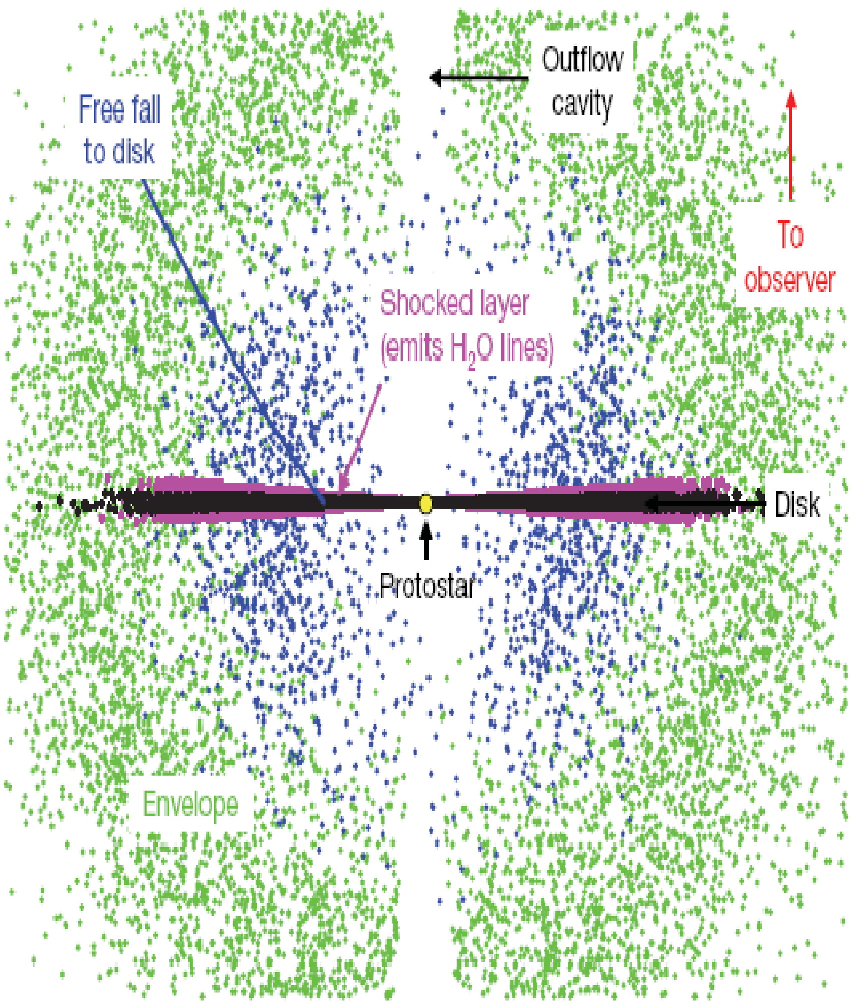
Birth of Stars and Proto-planetary Systems

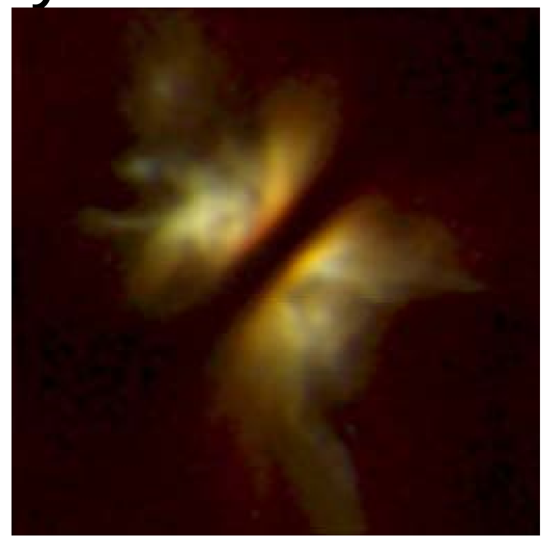
- What is the role of molecular clouds, cores and their collapse in the evolution of stars and planetary systems?
- How do protostars form and evolve?
- How do massive stars form and interact with their environment?
- How do massive stars impact their environment by halting or triggering further star 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?

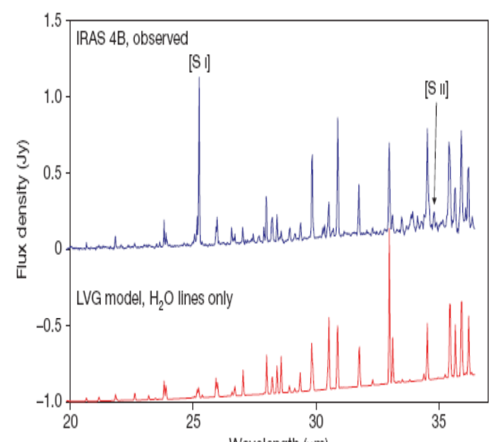




How are Planets Assembled? Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk

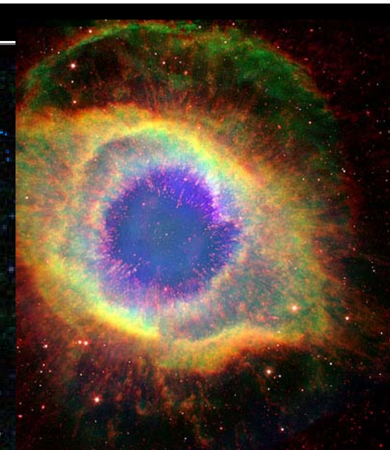






Michael Werner, “Spitzer Space Telescope”, William H. Pickering Lecture, AIAA Space 2007.

Dust disks are durable and omnipresent



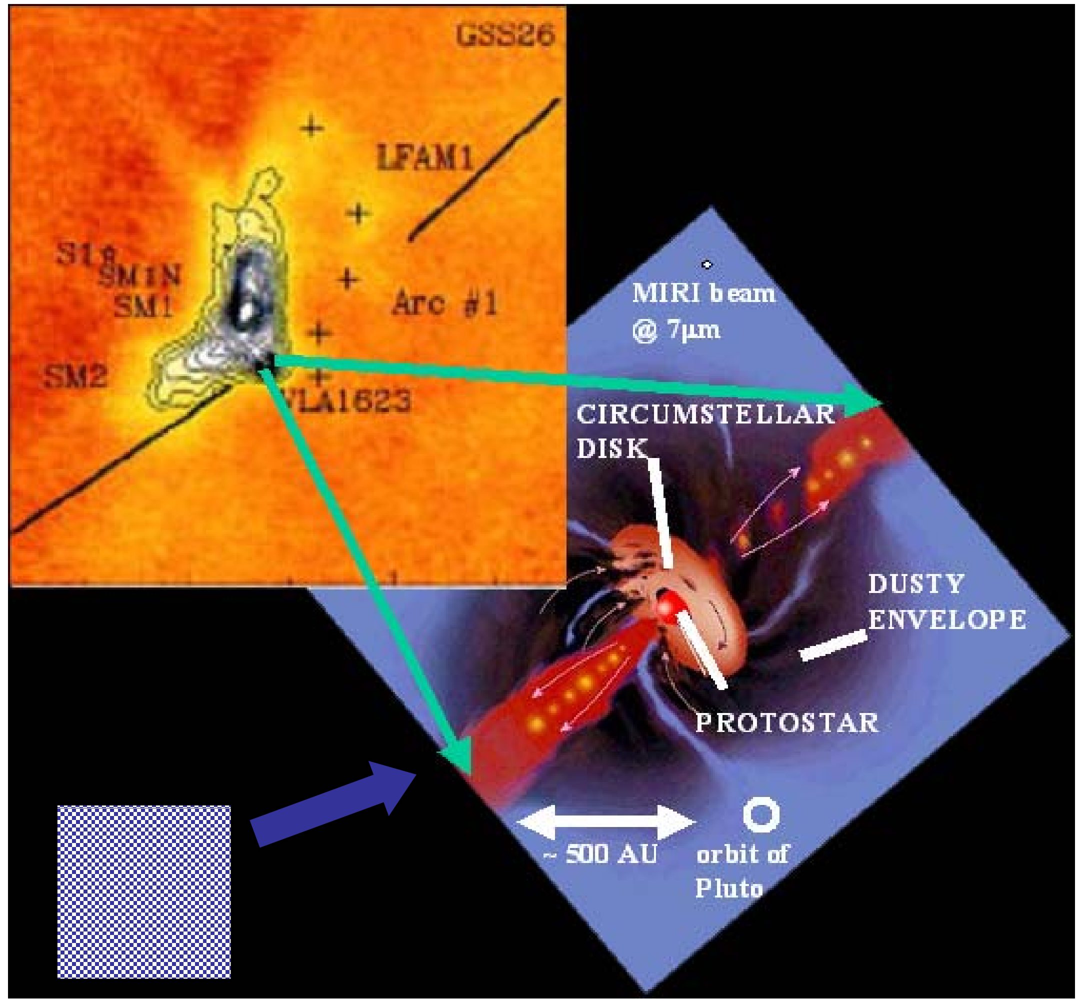
The central star of the Helix Nebula, a hot, luminous White Dwarf, shows an infrared excess attributable to a disk in a planetary system which survived the star's chaotic evolution

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

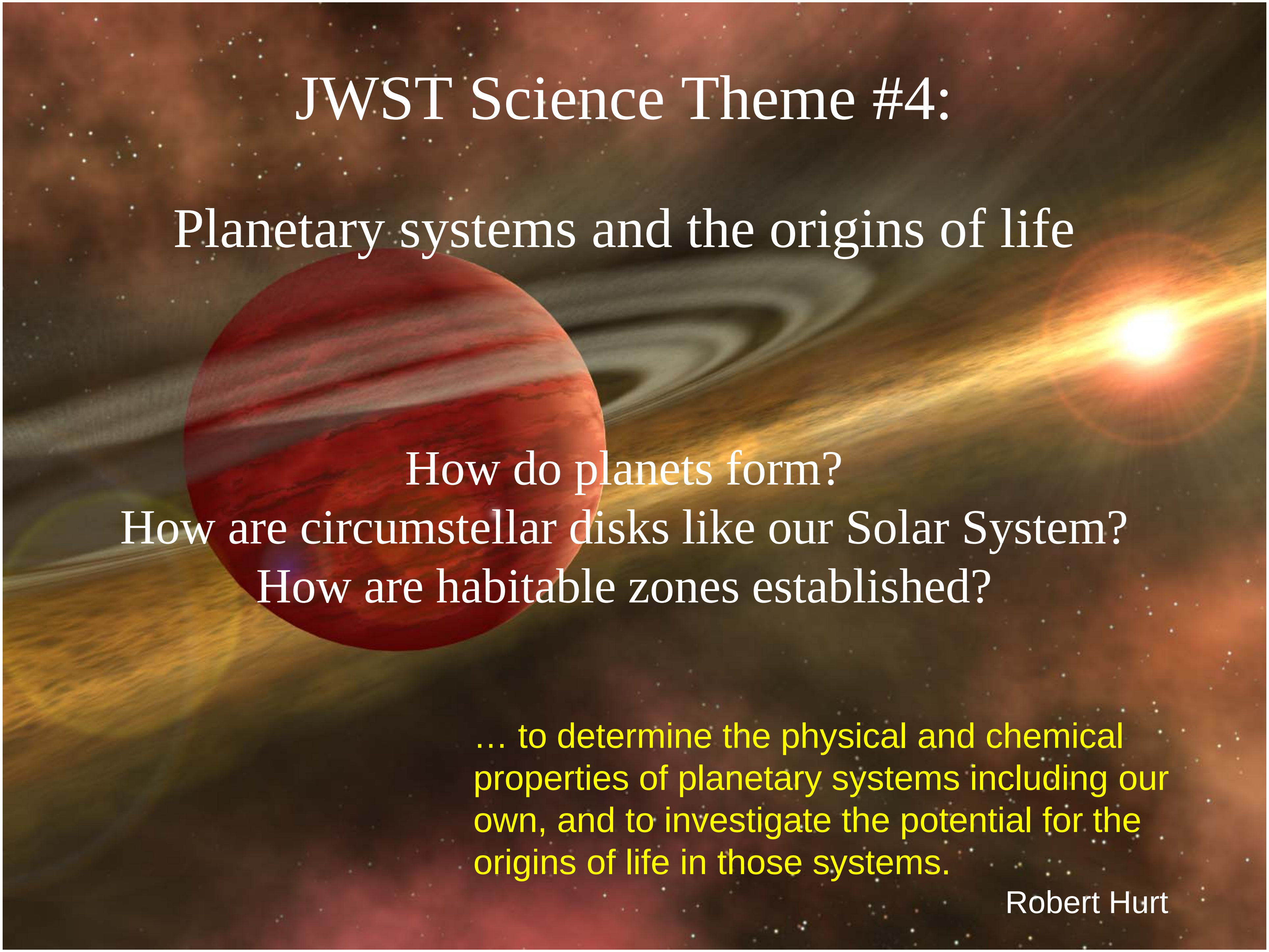
How are circumstellar disks like our Solar System?

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

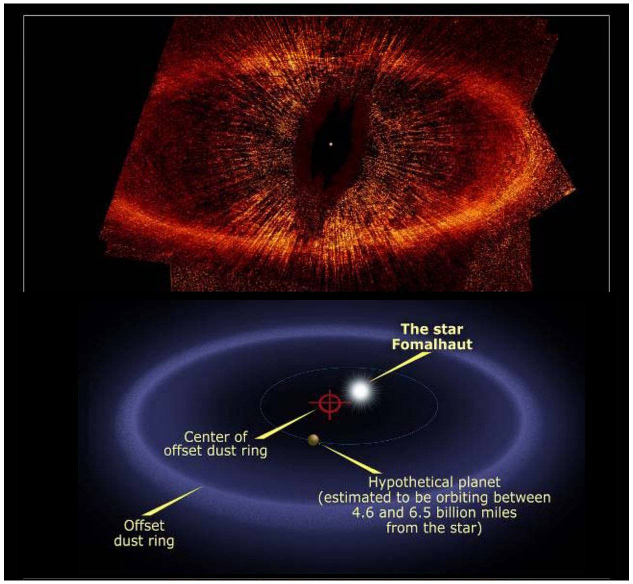
How do planets form?

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

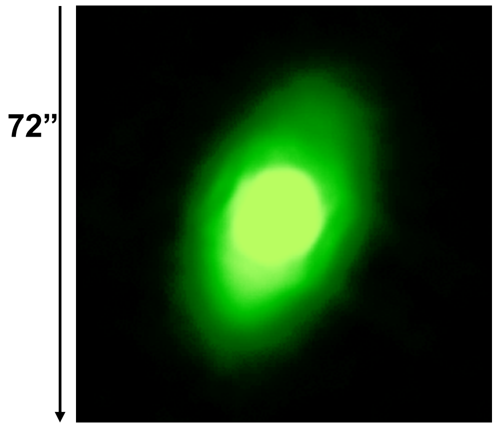


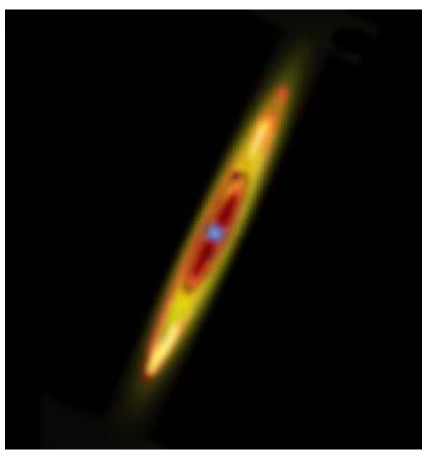
Fomalhaut (ACS): Kalas, Graham & Clampin 2005

Planetary systems and the Origins of Life

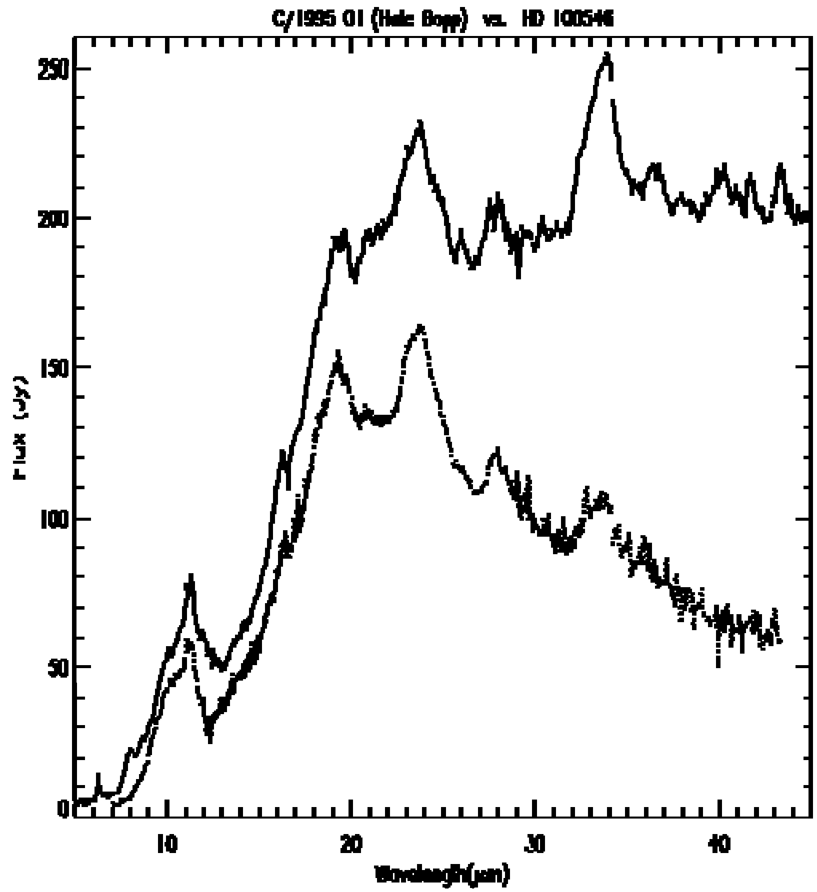
Fomalhaut system at 24 μm

(Spitzer Space Telescope)





Simulated JWST image
Fomalhaut at 24 microns



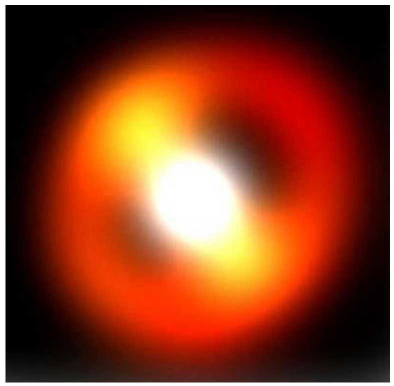
Malfait et al 1998

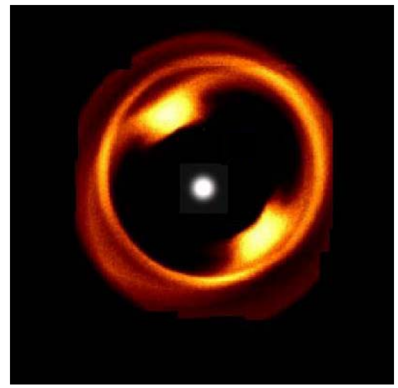
Planetary Systems and the Origins of Life

- 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)



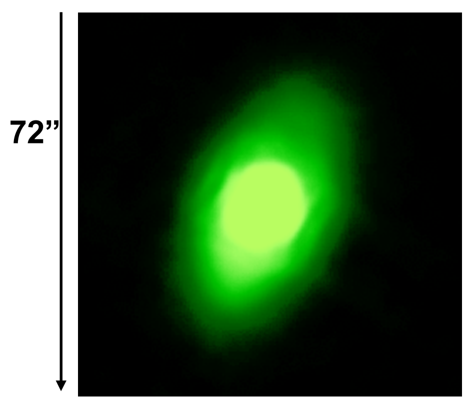


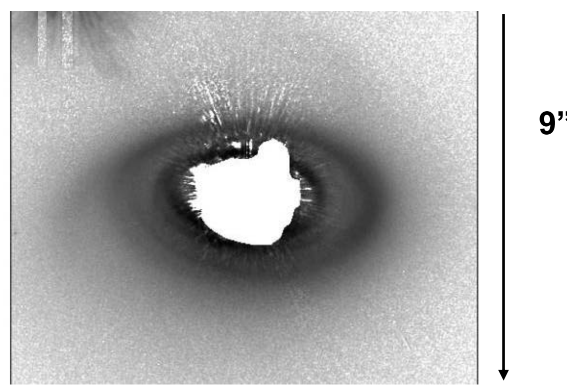
Formalhaut system at 24 µm

(Spitzer Space Telescope)

HD141569 (606 nm)

(HST/ACS)



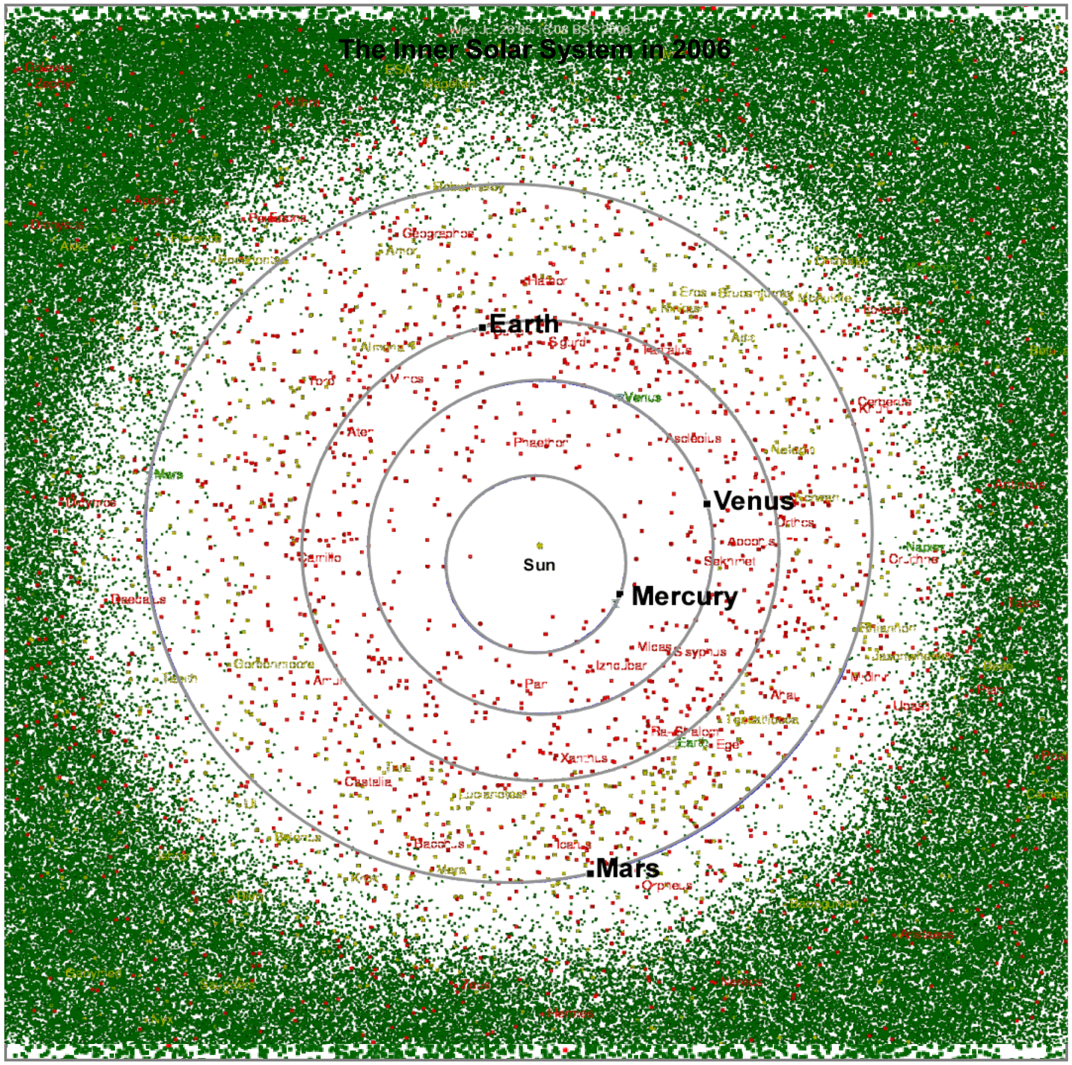


History of Known (current) NEO Population

2006

Earth Crossing

Outside Earth's Orbit



Known

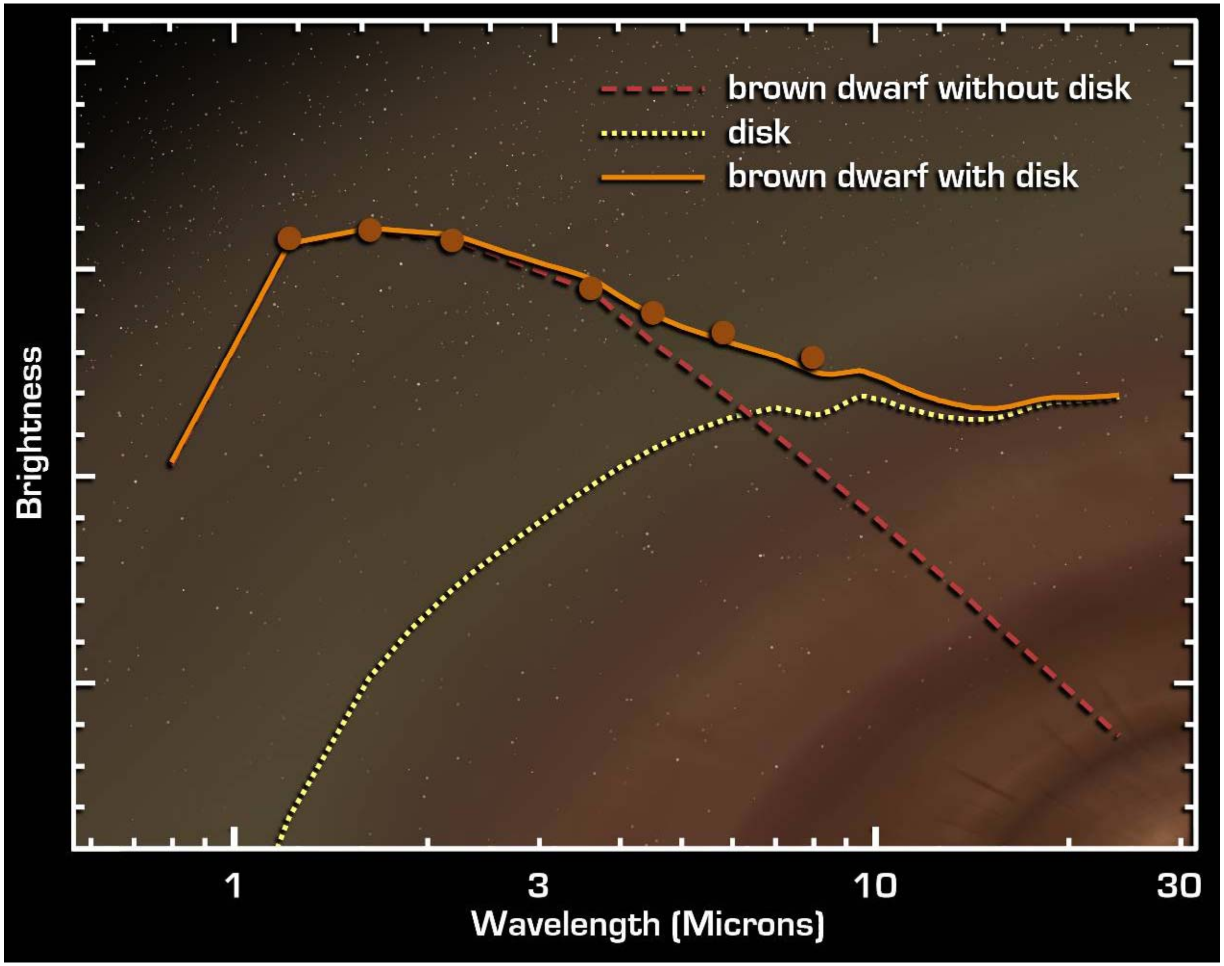
- **340,000 minor planets**
- **~4500 NEOs**
- **~850 Potentially Hazardous Objects (PHOs)**

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?



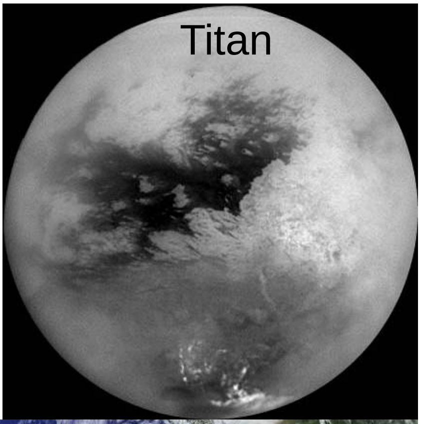
A Brown Dwarf With a Planet-Forming Disk

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

How are habitable zones established?

Source of Earth's $H_2$0 and organics is not known

Comets? Asteroids?



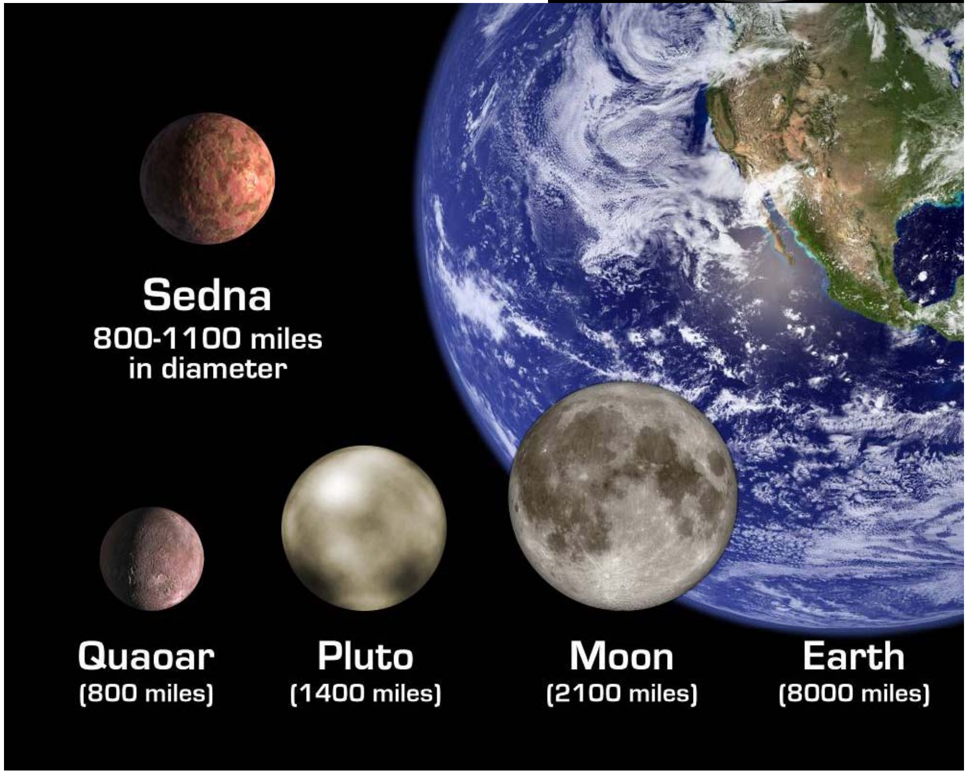
History of clearing the disk of gas and small bodies

Role of giant planets?

JWST Observations:

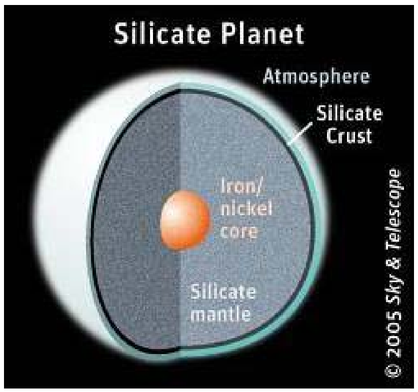
Comets, Kuiper Belt Objects

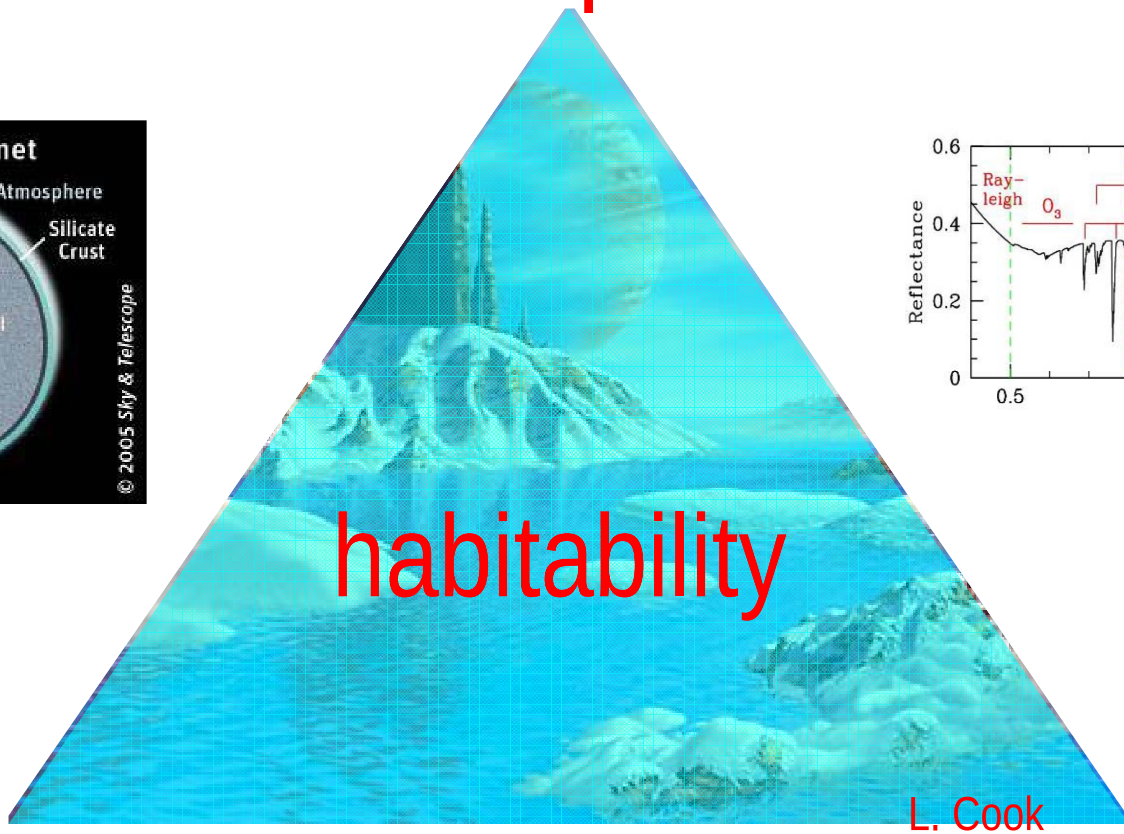
Icy moons in outer solar system

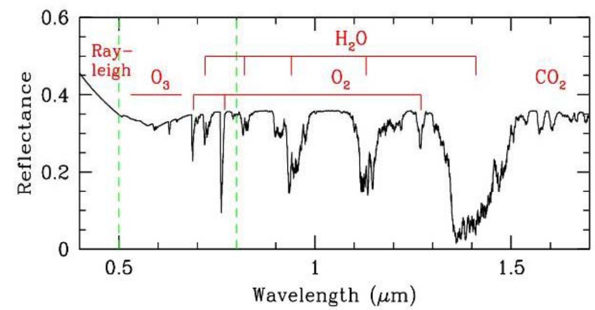


Search for Habitable Planets

atmosphere







interior

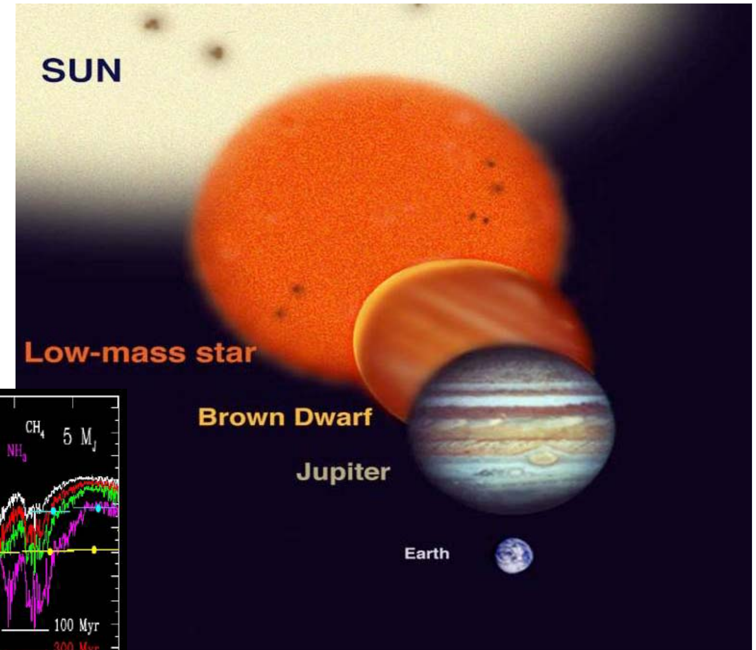
surface

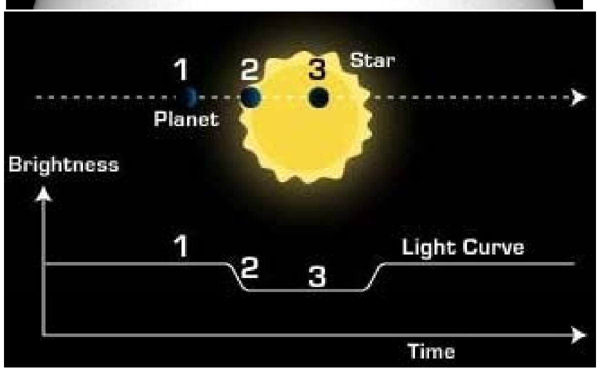
Sara Seager (2006)

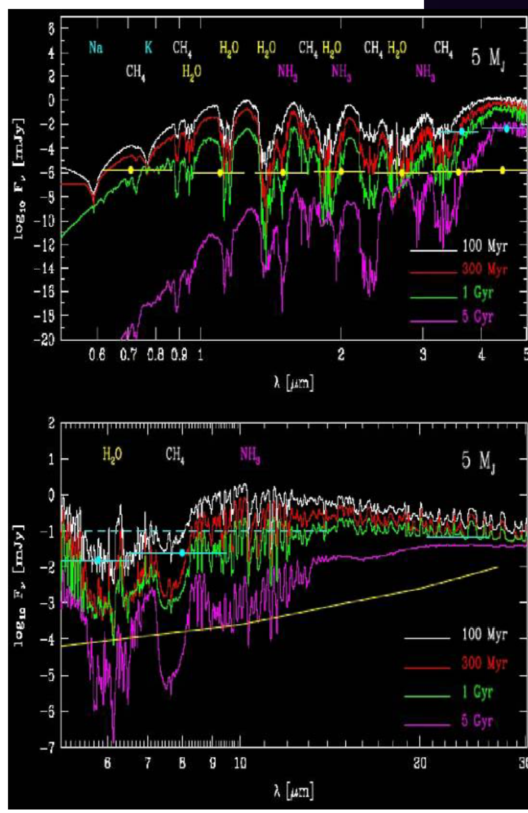
Atmospheres of Extrasolar Planets

Extrasolar Planet Transits

Detecting terrestrial planet atmospheres

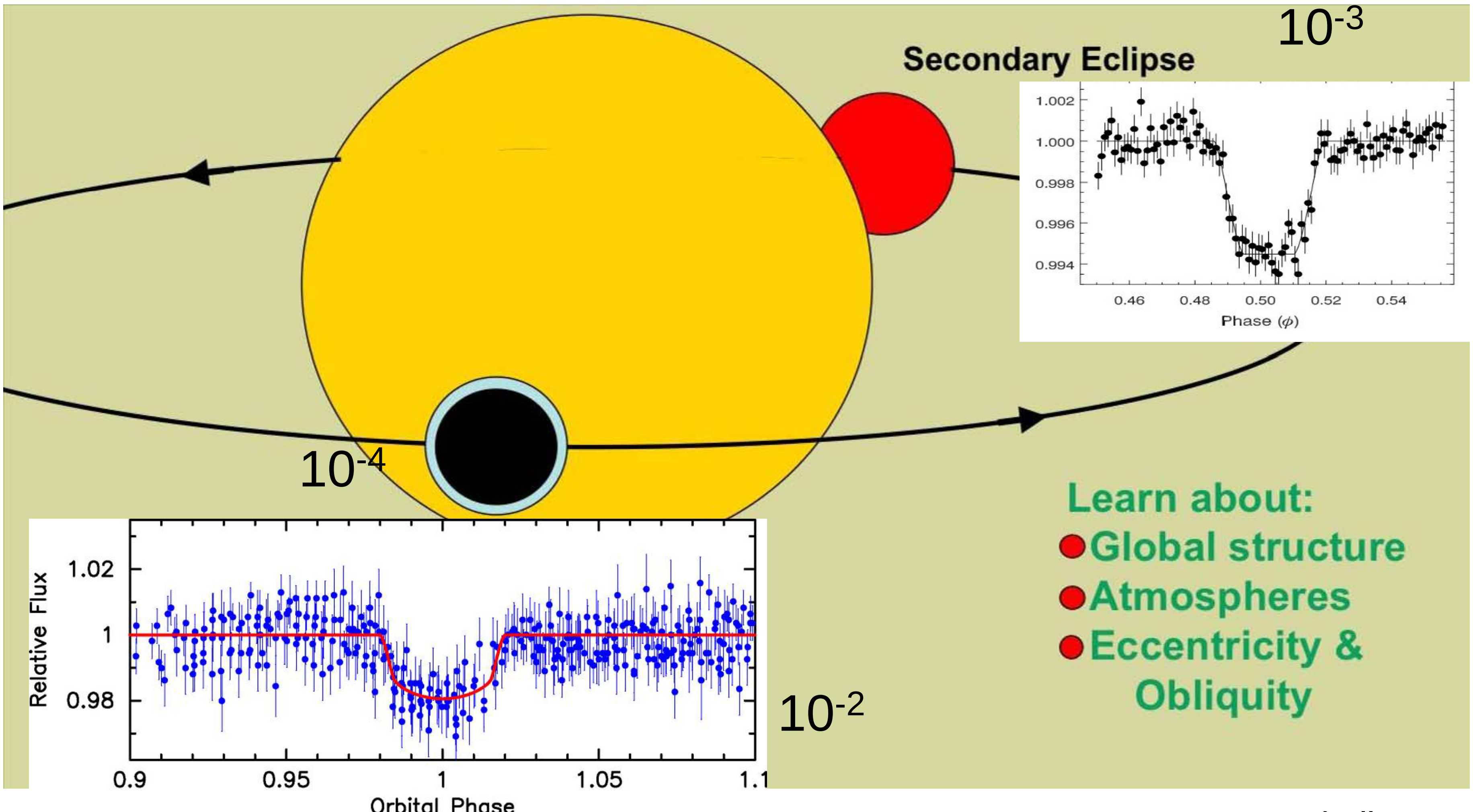






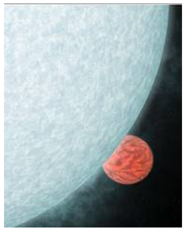
Burrows, Sudarsky and Lunine (2003)

Transiting Planet Science

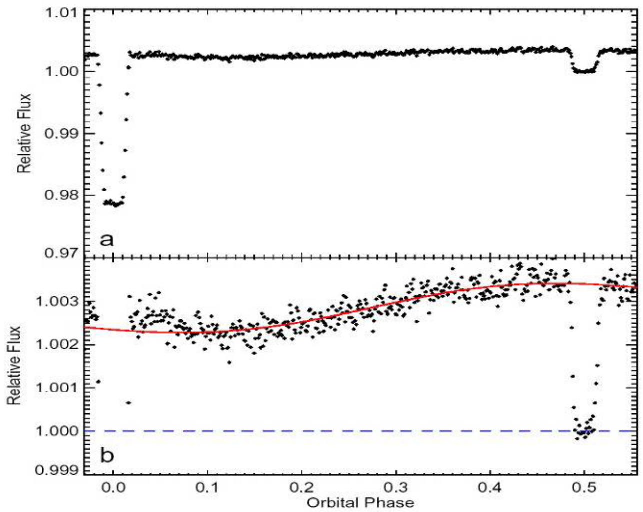


Courtesy Lori Allen

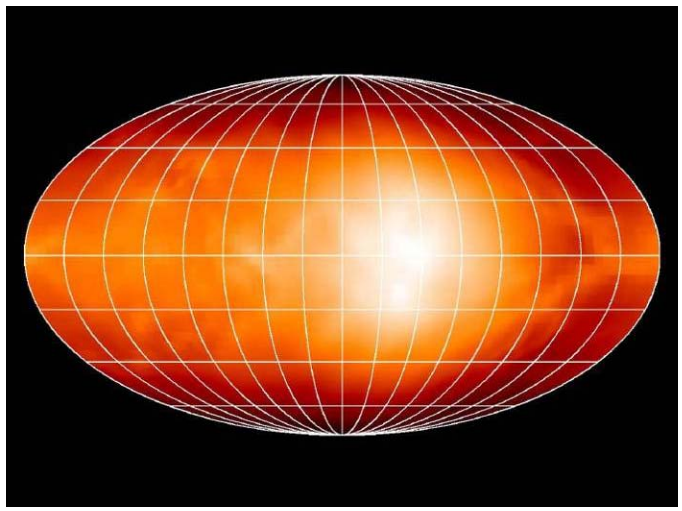
HD 189733b: First [one-dimensional] temperature map of an exoplanet



- **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.

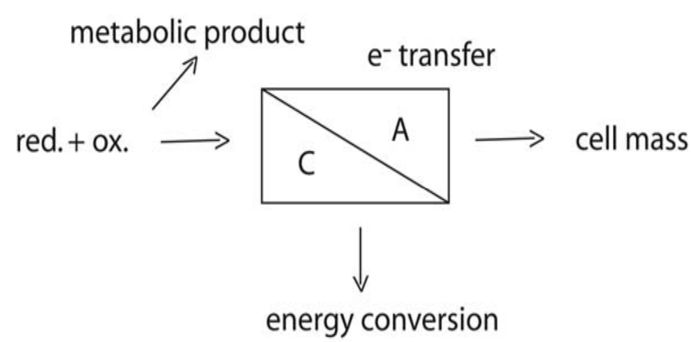
Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

Search for Life

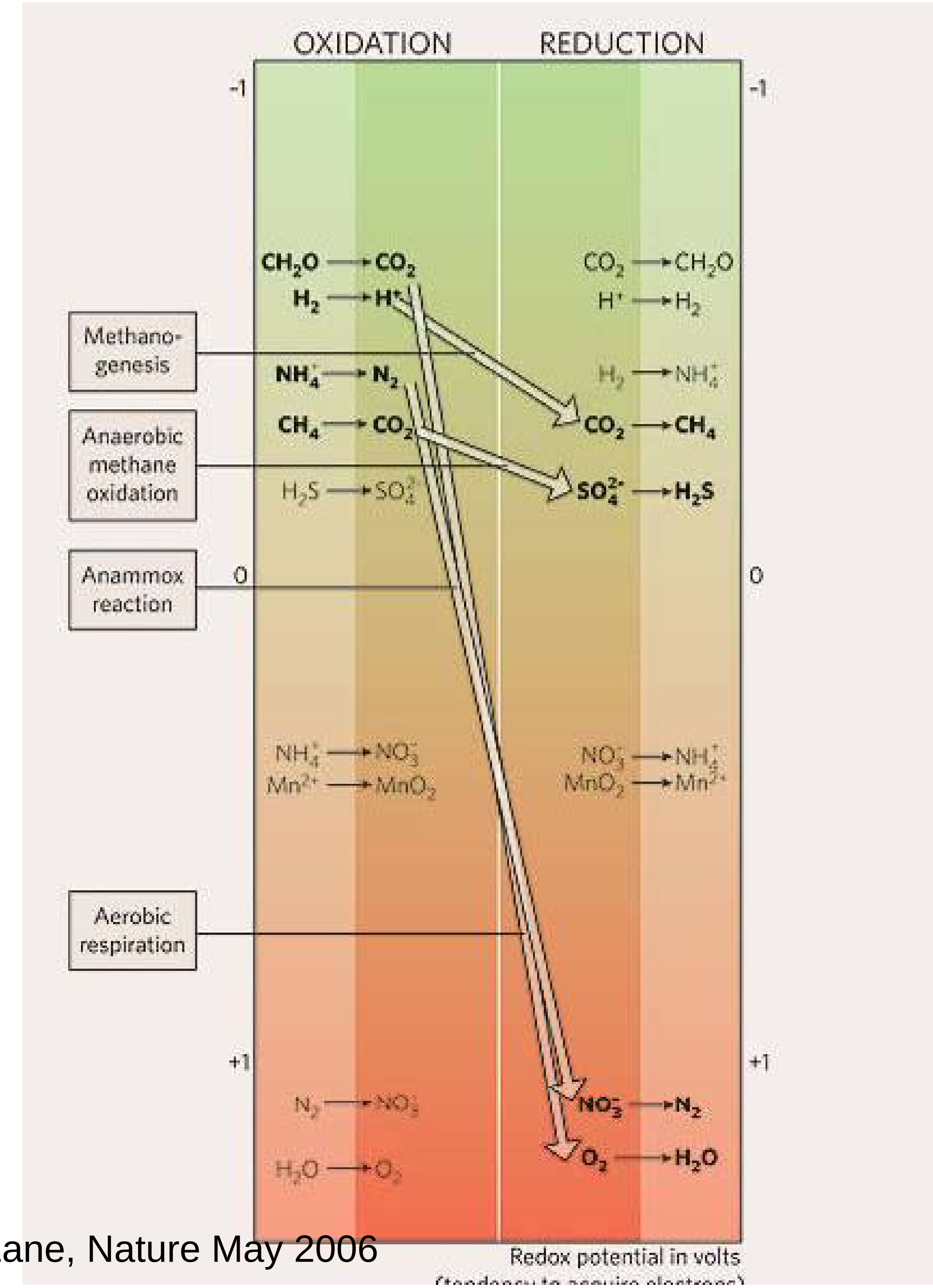
~~What is life?~~

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

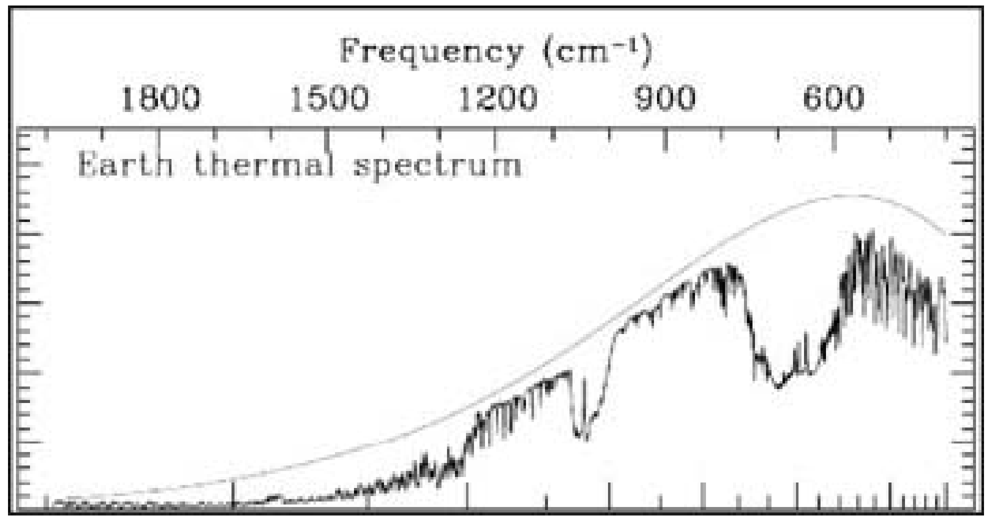
Diversity of metabolisms rivals diversity of exoplanets

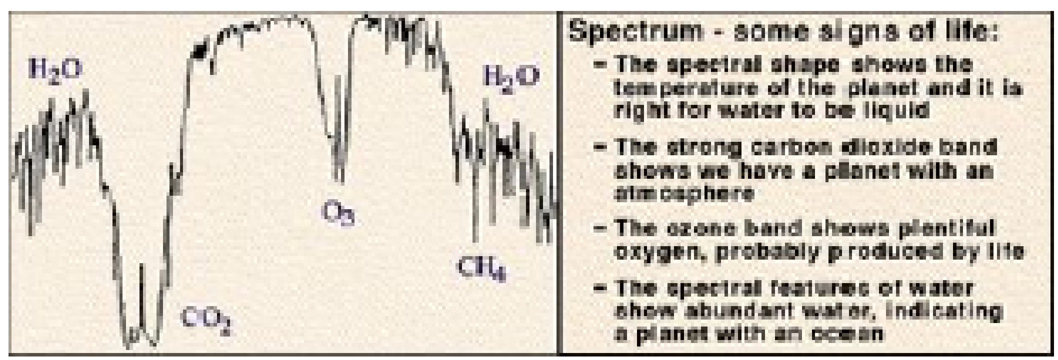
Bio Markers

Spectroscopic Indicators of Life

Absorption Lines

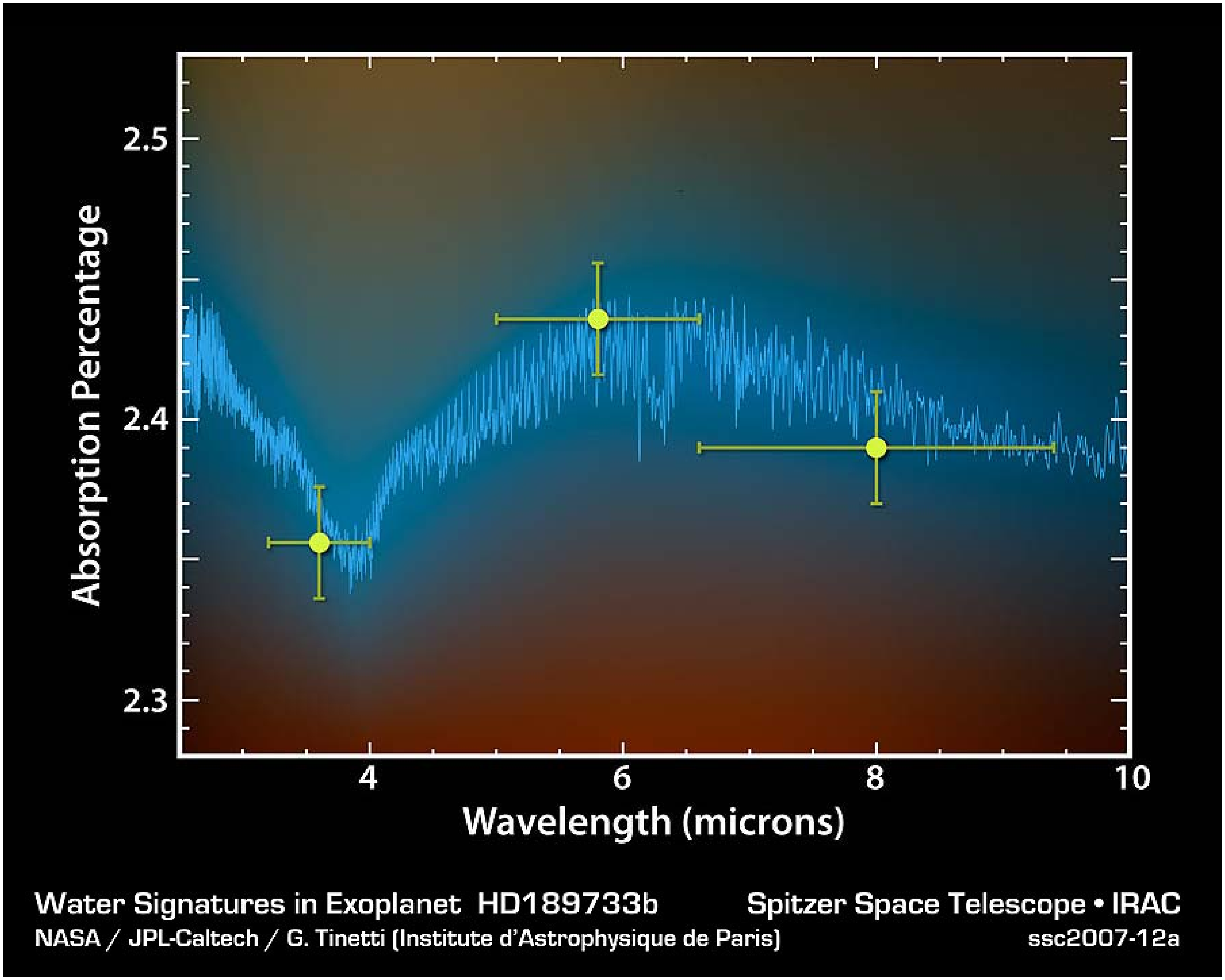
- CO2
- Ozone
- Water
- “Red” Edge





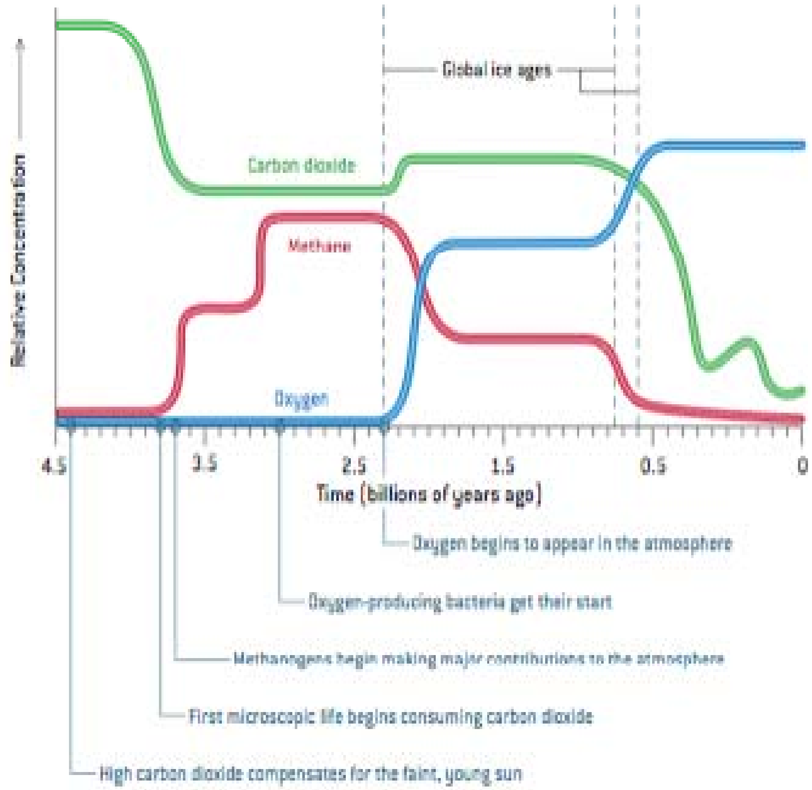
Example signs of life from chemical spectra.
Credit: NASA JPL

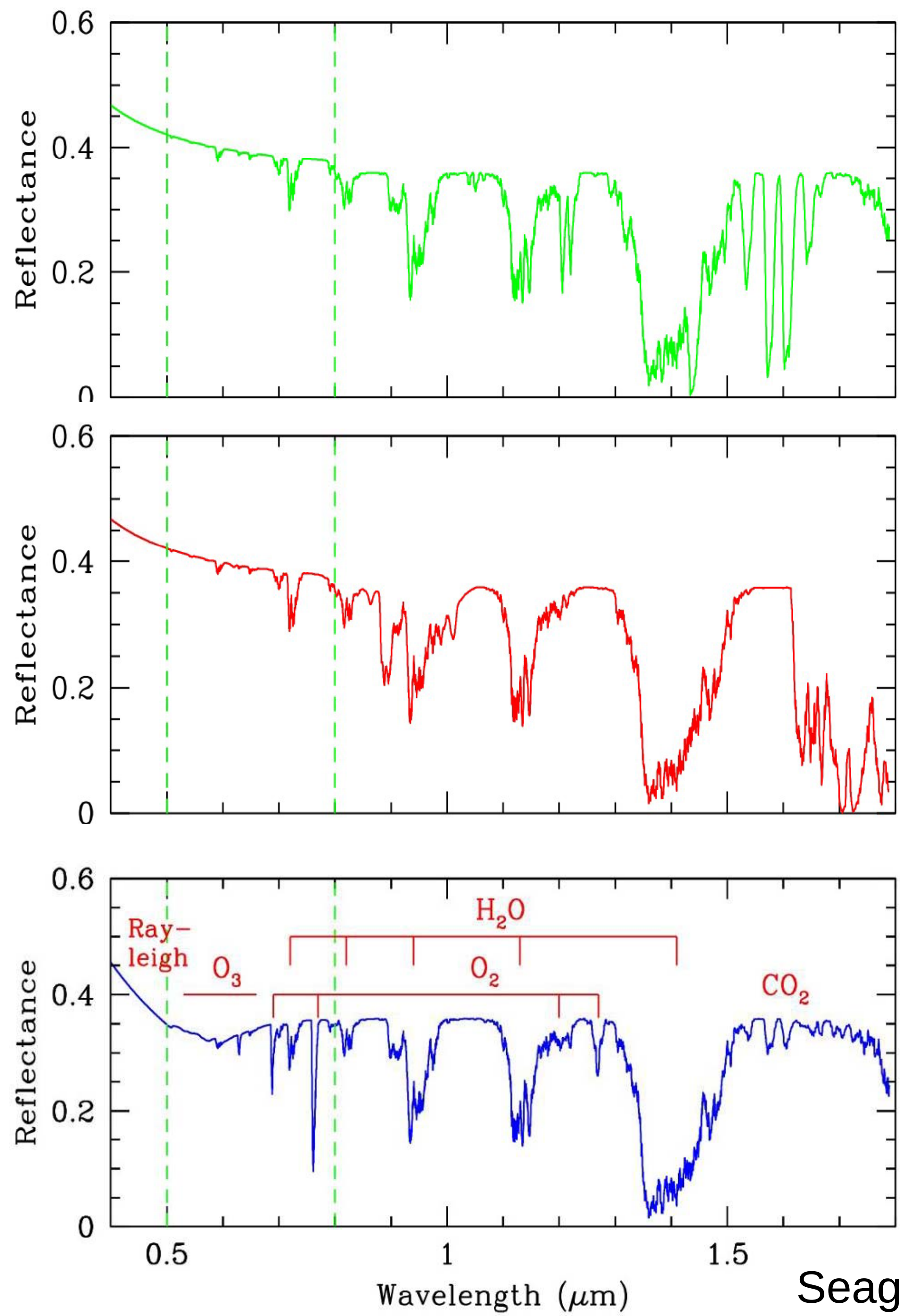
Is there water in an Exoplanet?



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

Earth Through Time



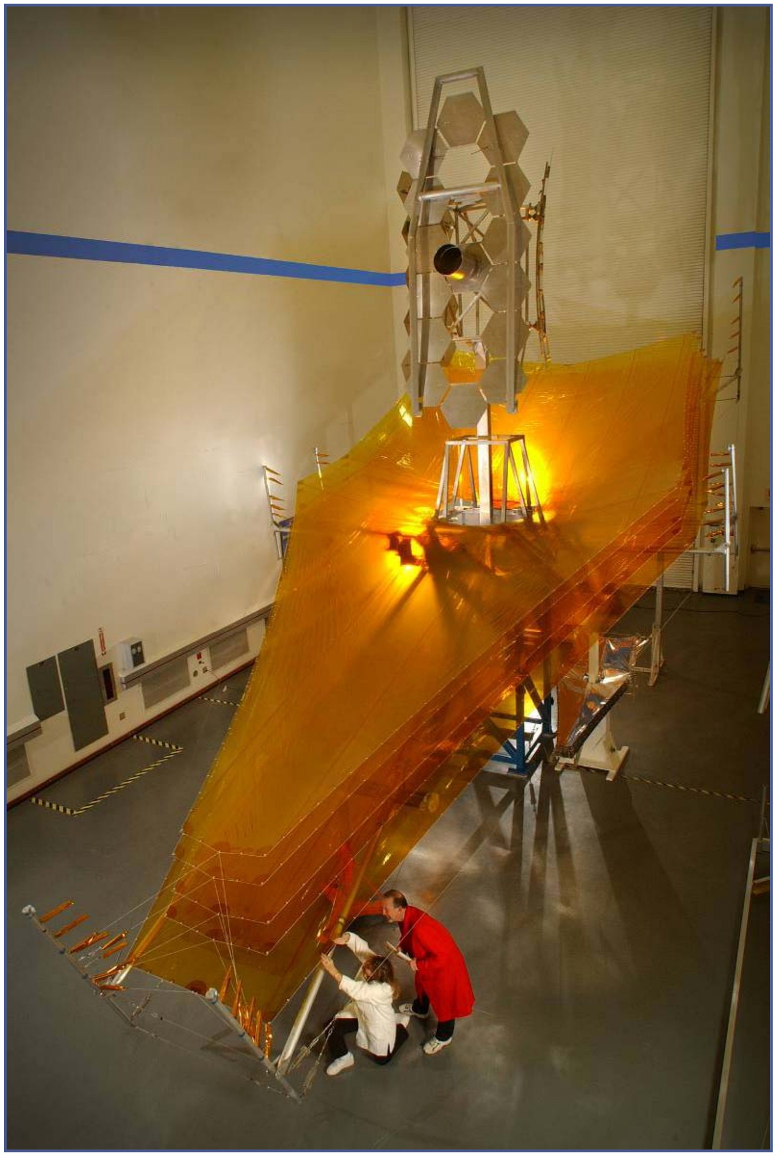


Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon

Seager

Countdown to Launch

Planned for 2013 Launch



Any Questions?