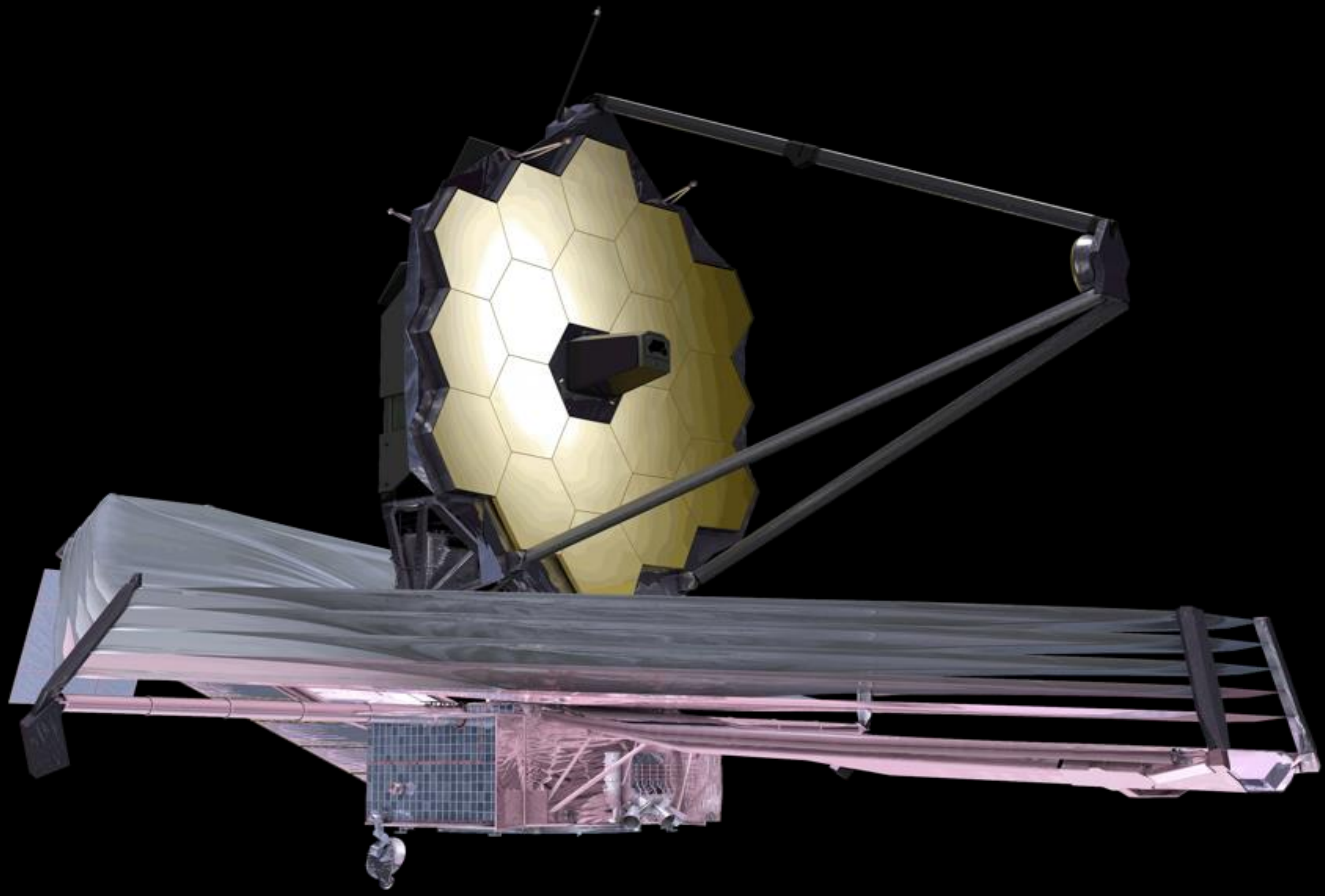
James Webb Space Telescope (JWST)



The First Light Machine

Who is James Webb?

James E Webb was the first administrator of NASA (1961 to 1968)

He supported a program balanced between Science and Human Exploration.

What is FIRST LIGHT?

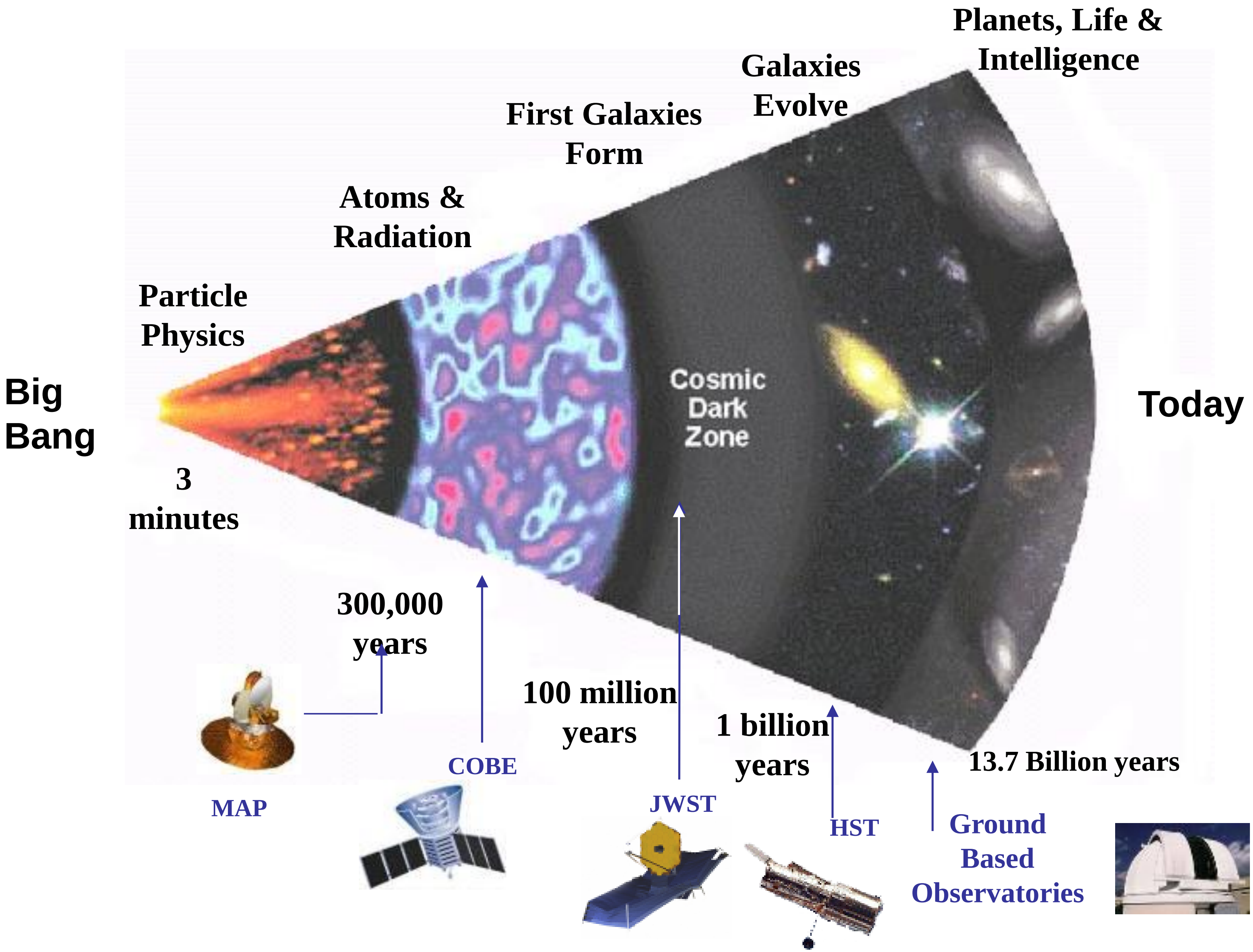
End of the dark ages: first light and reionization

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

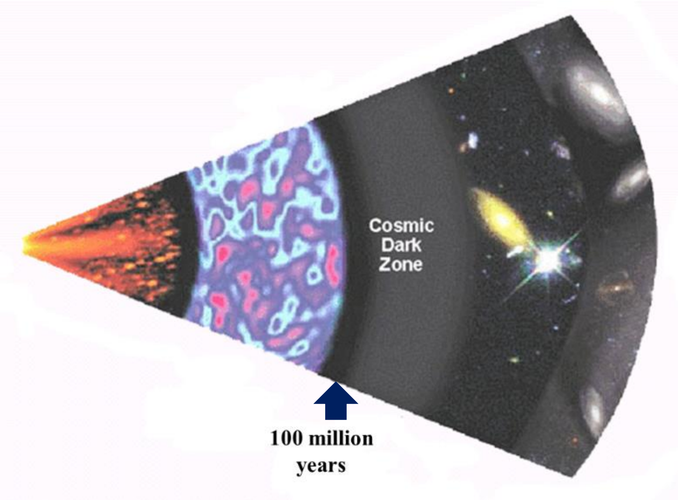


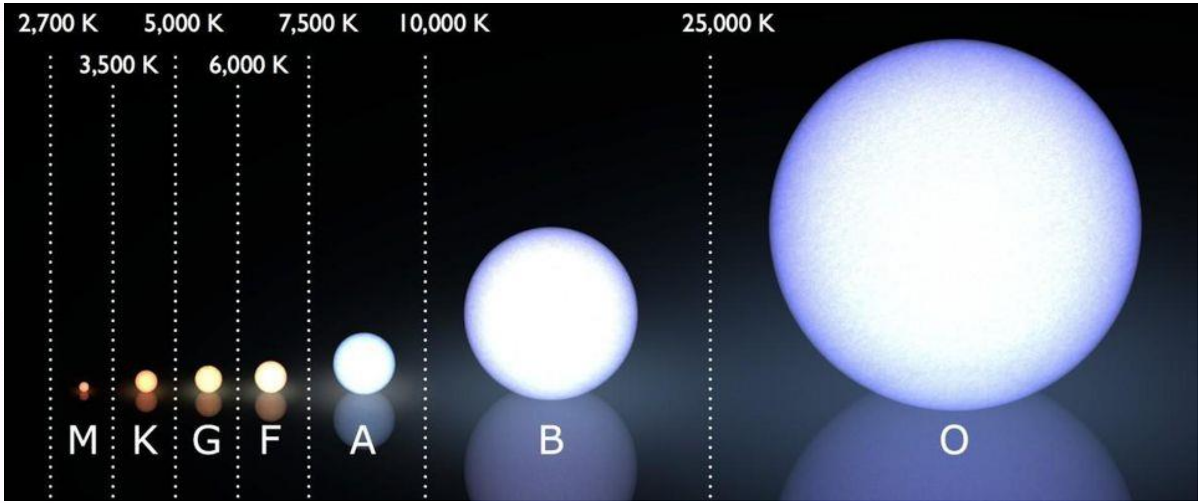
First Light Stars

50-to-100 million years after the Big Bang, the first massive stars started to form from clouds of hydrogen. But, because they were so large, they were unstable and either exploded supernova or collapsed into black holes.

These first stars helped ionize the universe and created elements such as He.

O-class stars are 25X larger than our sun. ‘First’ stars may have been 1000X larger.





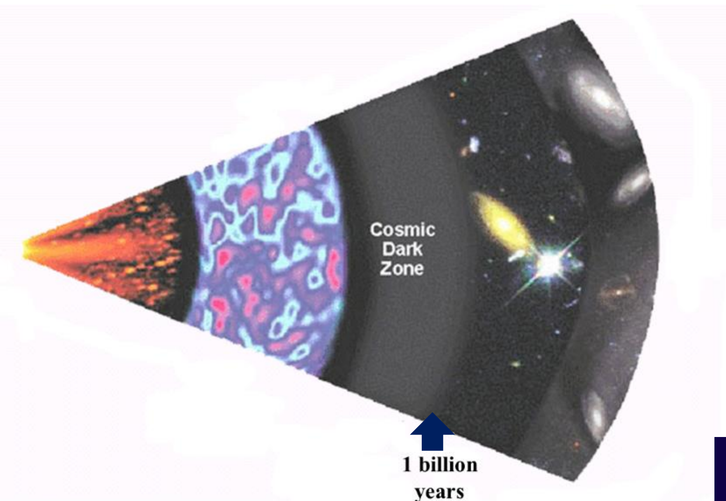
The (modern) Morgan–Keenan spectral classification system, with the temperature range of each star class shown above it, in kelvin. The overwhelming majority of stars today are M-class stars, with only 1 known O- or B-class star within 25 parsecs. Our Sun is a G-class star. However, in the early Universe, almost all of the stars were O or B-class stars, with an average mass 25 times greater than average stars today. Wikimedia Commons user LucasVB, additions by E. Siegel

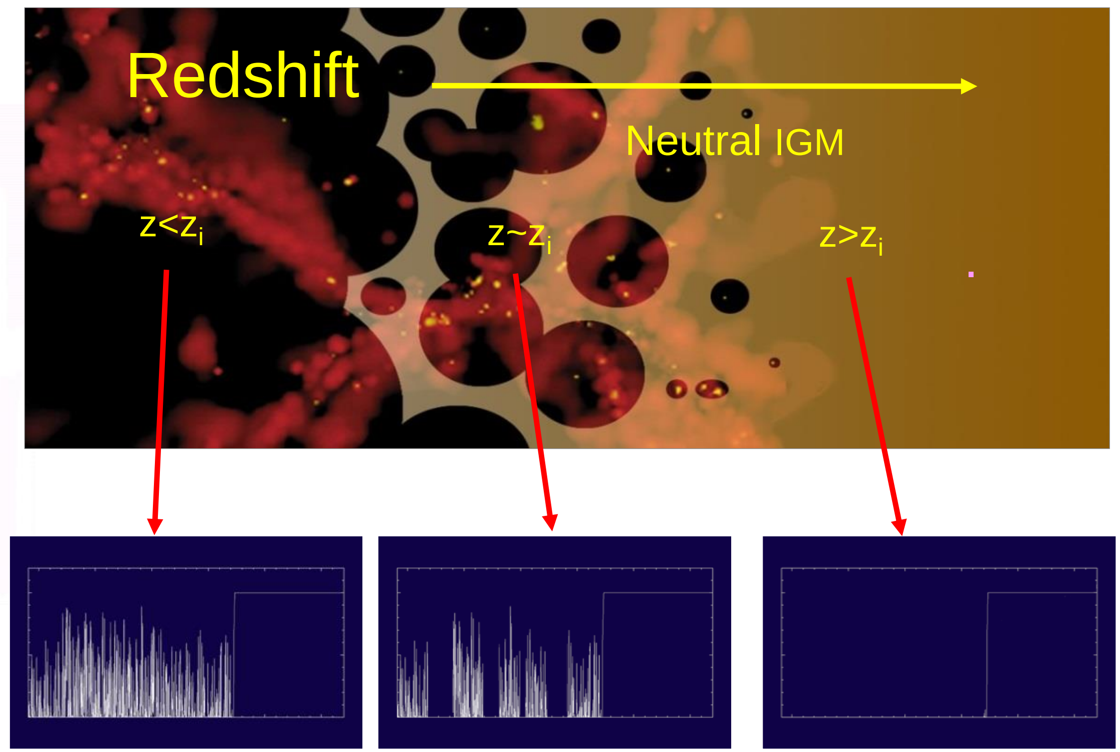
Ethan Siegel, FORBES.com, 24 Oct 2018

First Light: Reionization

Neutral ‘fog’ was dissolved by very bright 1st Generation Stars.

At 780 M yrs after BB the Universe was up to 50% Neutral. But, by 1 B years after BB is was as we see it today. 787 M yr Galaxy confirmed by Neutral Hydrogen method.

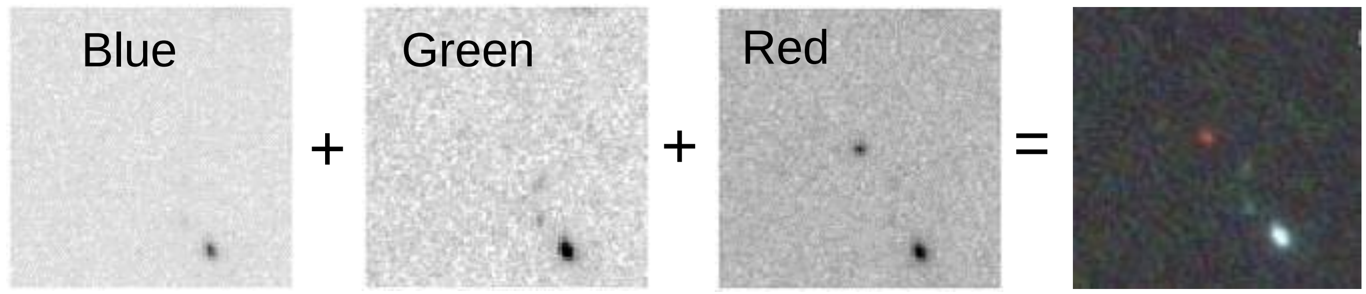


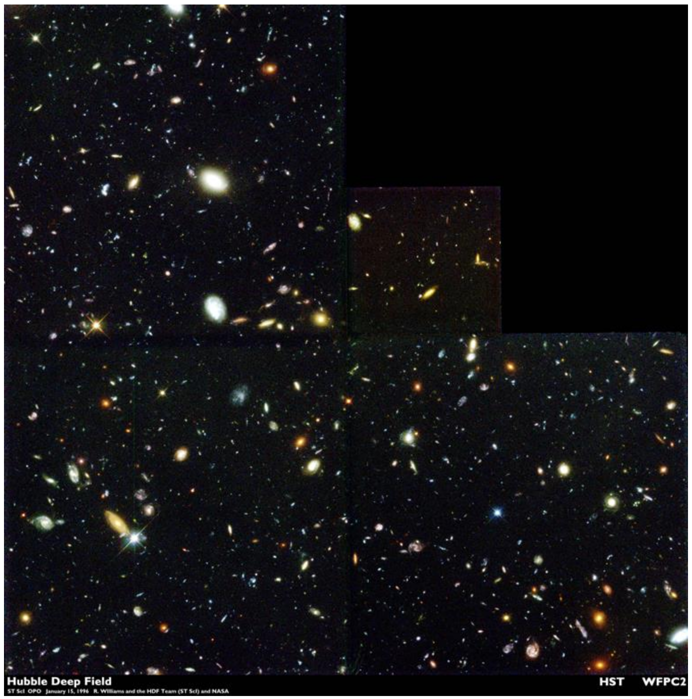


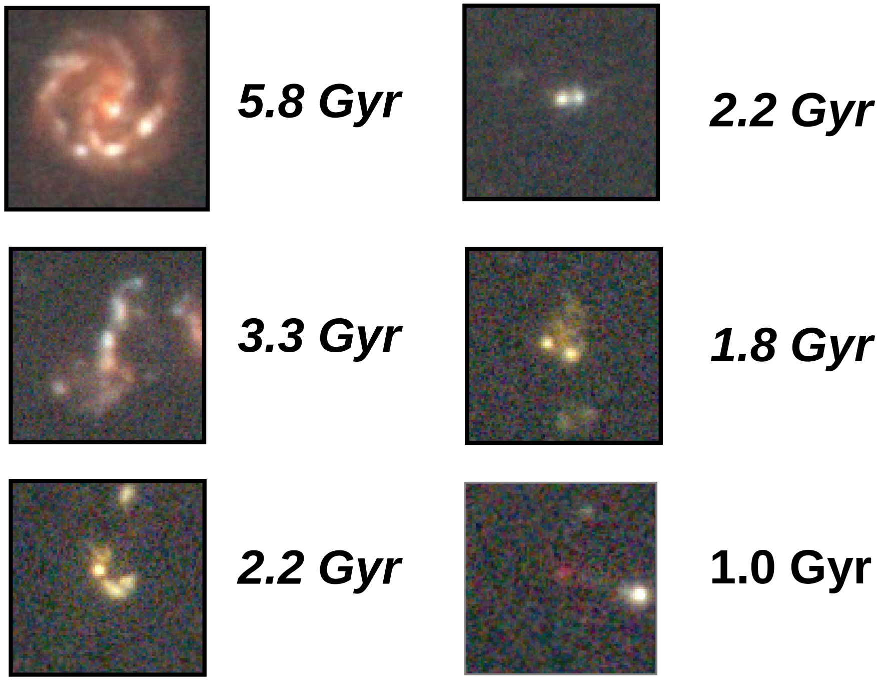
Lyman Forest Absorption   **Patchy Absorption**   **Black Gunn-Peterson trough**

SPACE.com, 12 October 2011

How do we see first light objects? Redshift

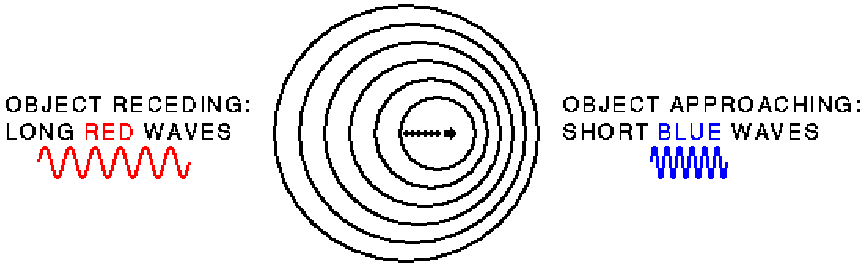


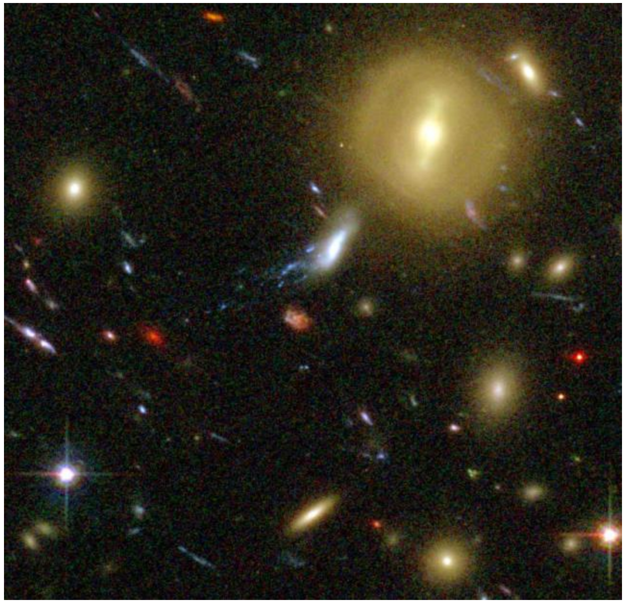


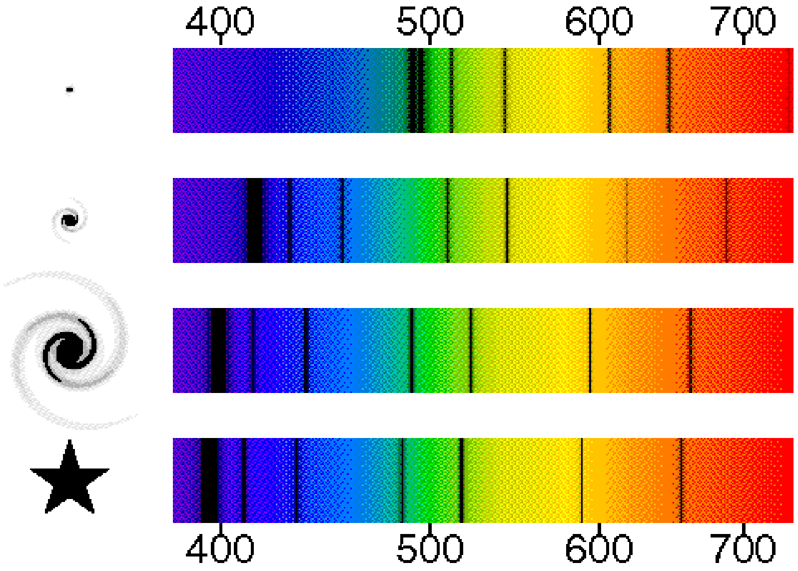


Redshift

The further away an object is, the more its light is redshifted from the visible into the infrared.

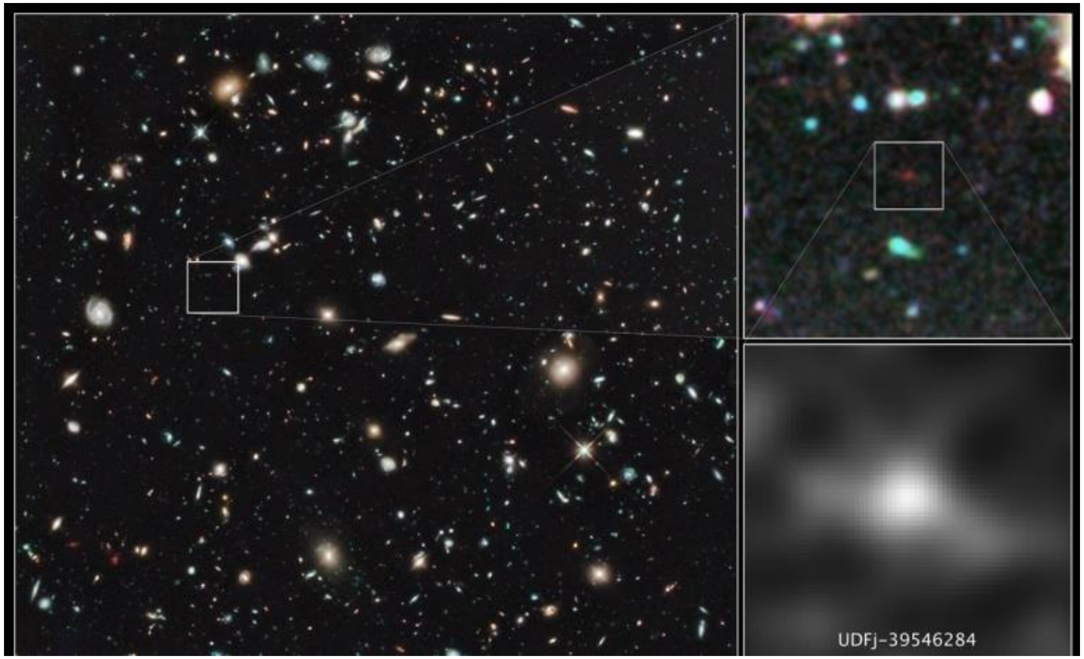




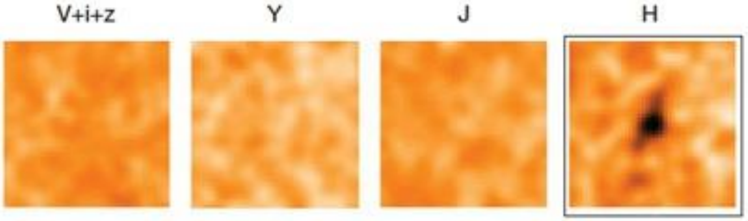


To see really far away, we need an **infrared** telescope.

First Galaxy in Hubble Deep Field



At 480 M yrs after big bang (z ~ 10) this one of oldest observed galaxy. Discovered using drop-out technique.
(current oldest is 420 M yrs after BB, maybe only 200 M yrs)

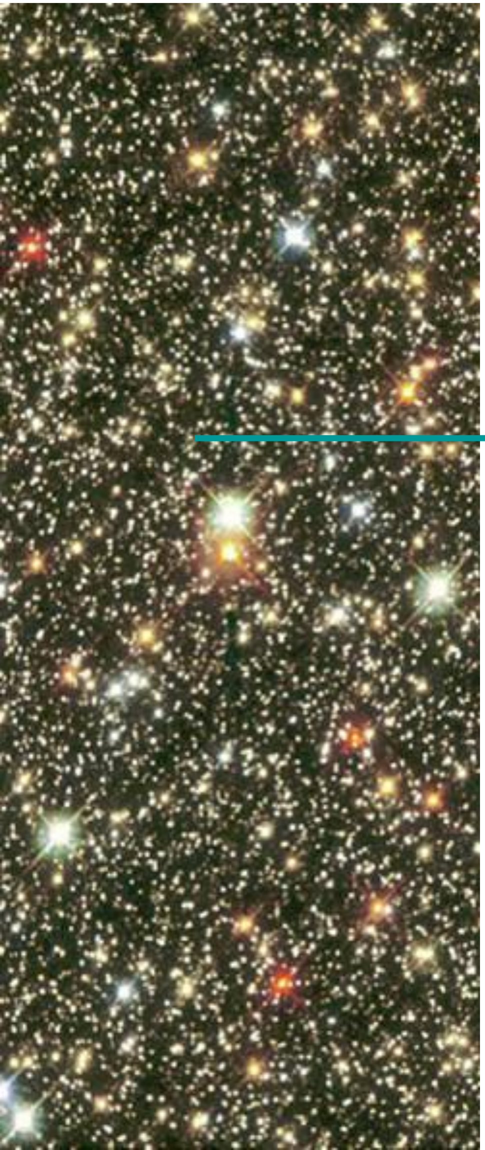


Left image is visible light, and the next three in near-infrared filters. The galaxy suddenly pop up in the H filter, at a wavelength of 1.6 microns (a little over twice the wavelength the eye can detect). (Discover, Bad Astronomy, 26 Jan 2011)

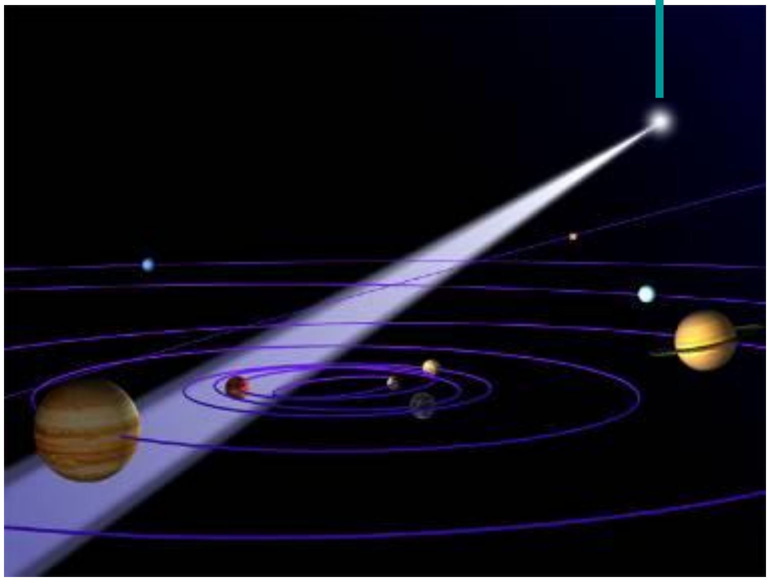
JWST Summary

- **<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

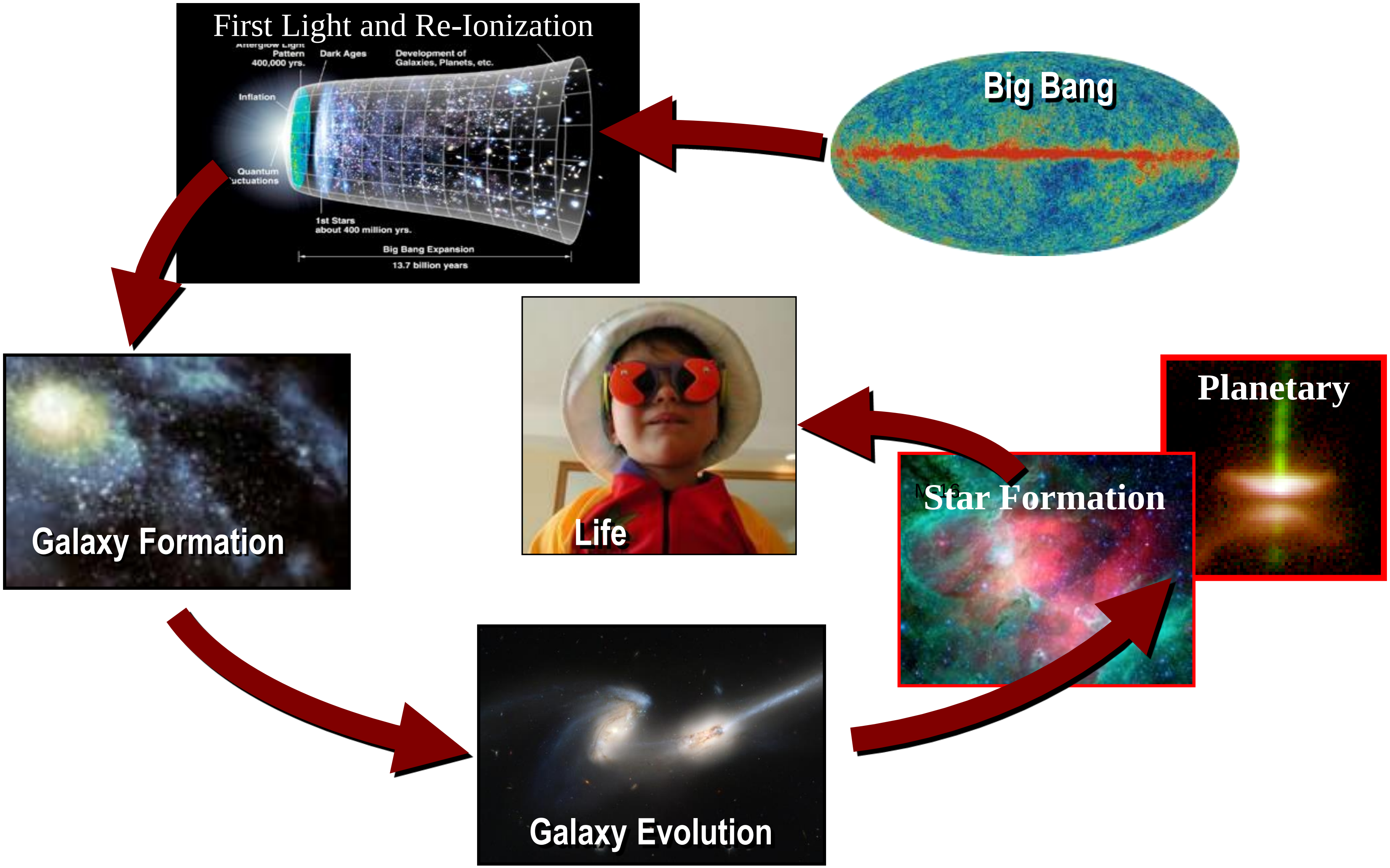
Origins Theme's Fundamental Questions



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



JWST Science Themes



Three Key Facts

There are 3 key facts about JWST that enables it to perform is Science Mission:

It is a Space Telescope

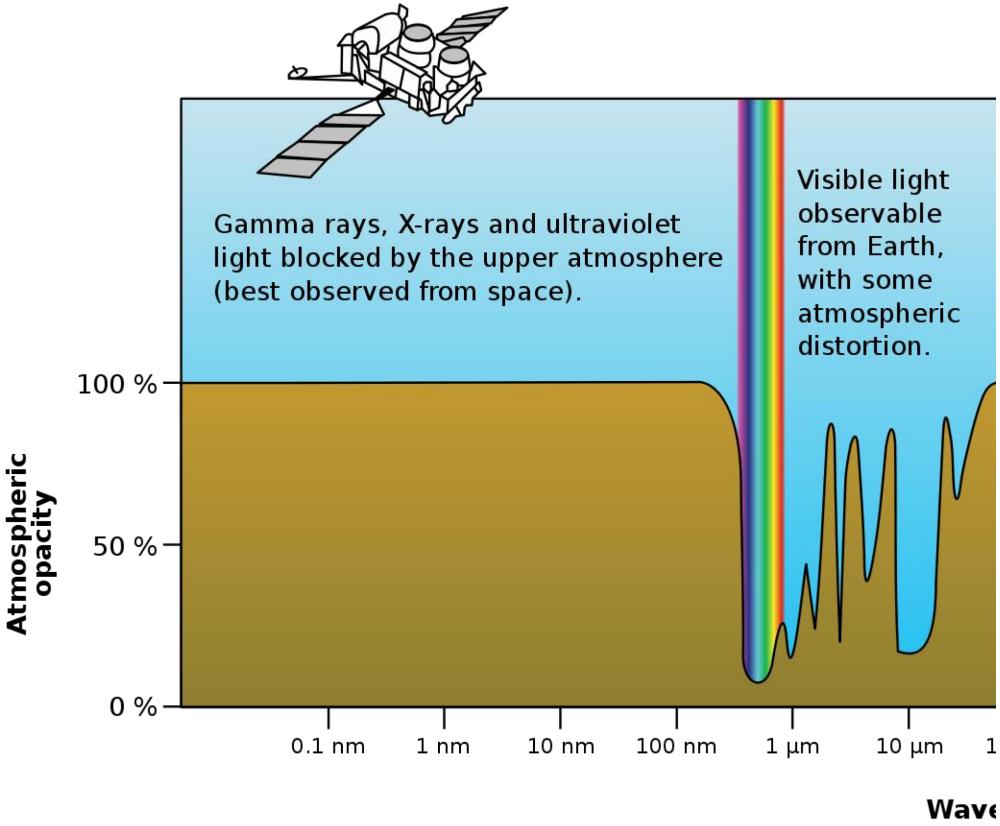
It is an Infrared Telescope

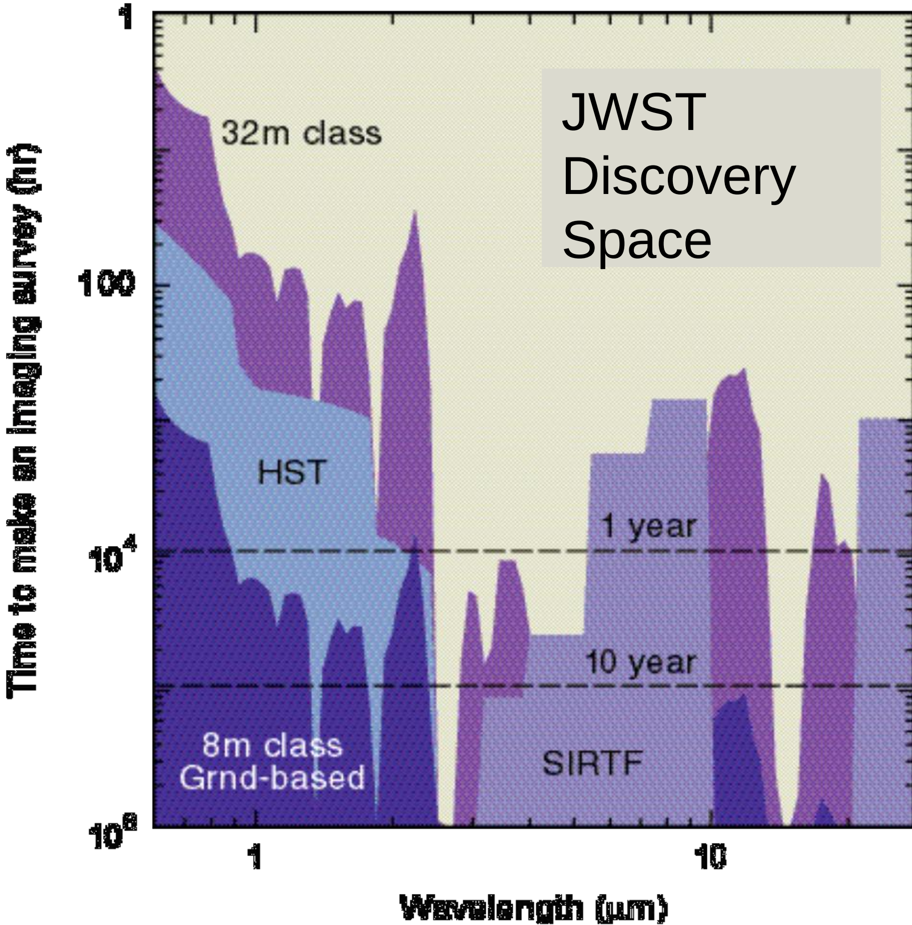
It has a Large Aperture

Why go to Space

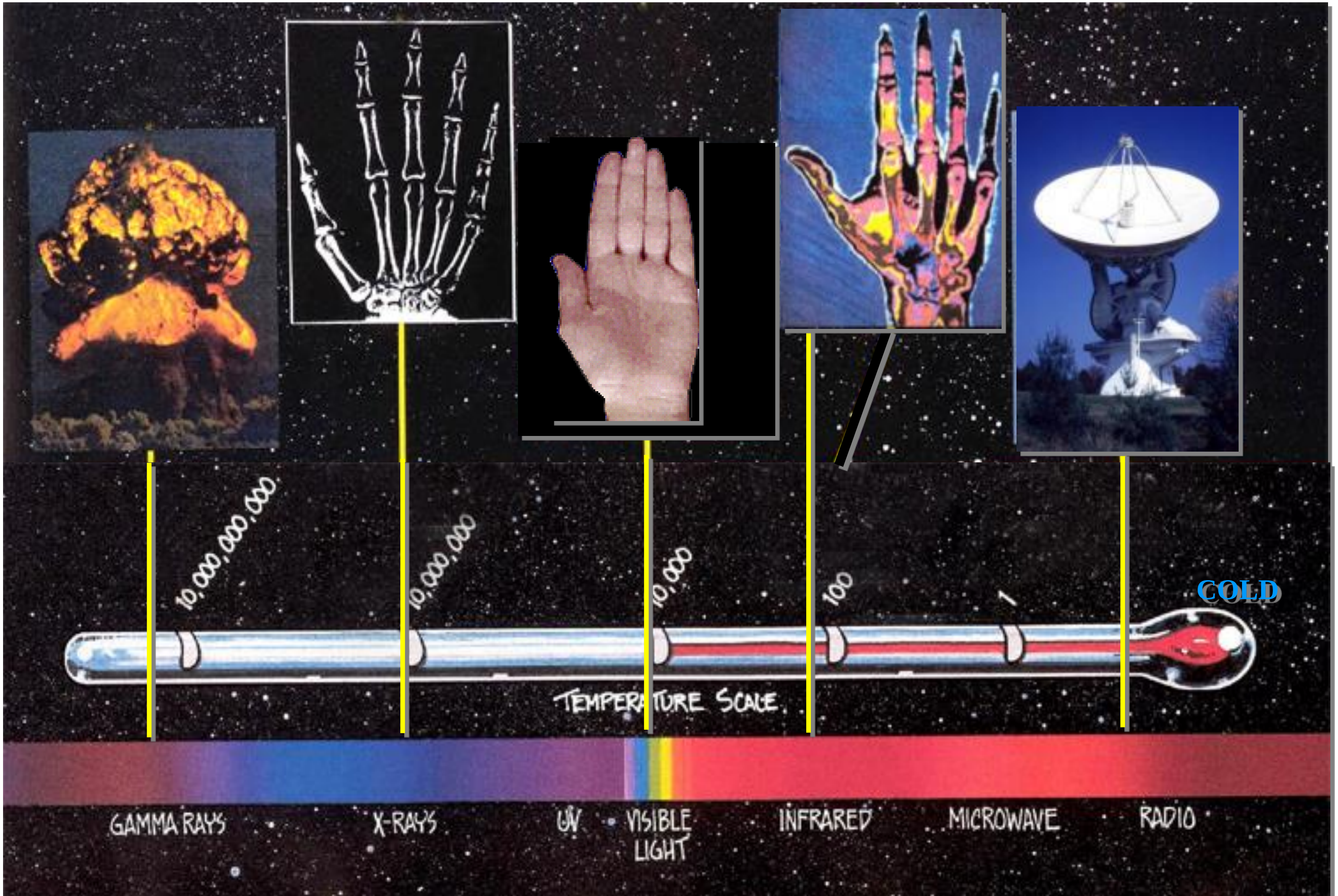
Atmospheric Transmission drives the need to go to space.

Infrared (mid and far/sub-mm) Telescopes (also uv, x-ray, and gamma-ray) cannot see through the Atmosphere





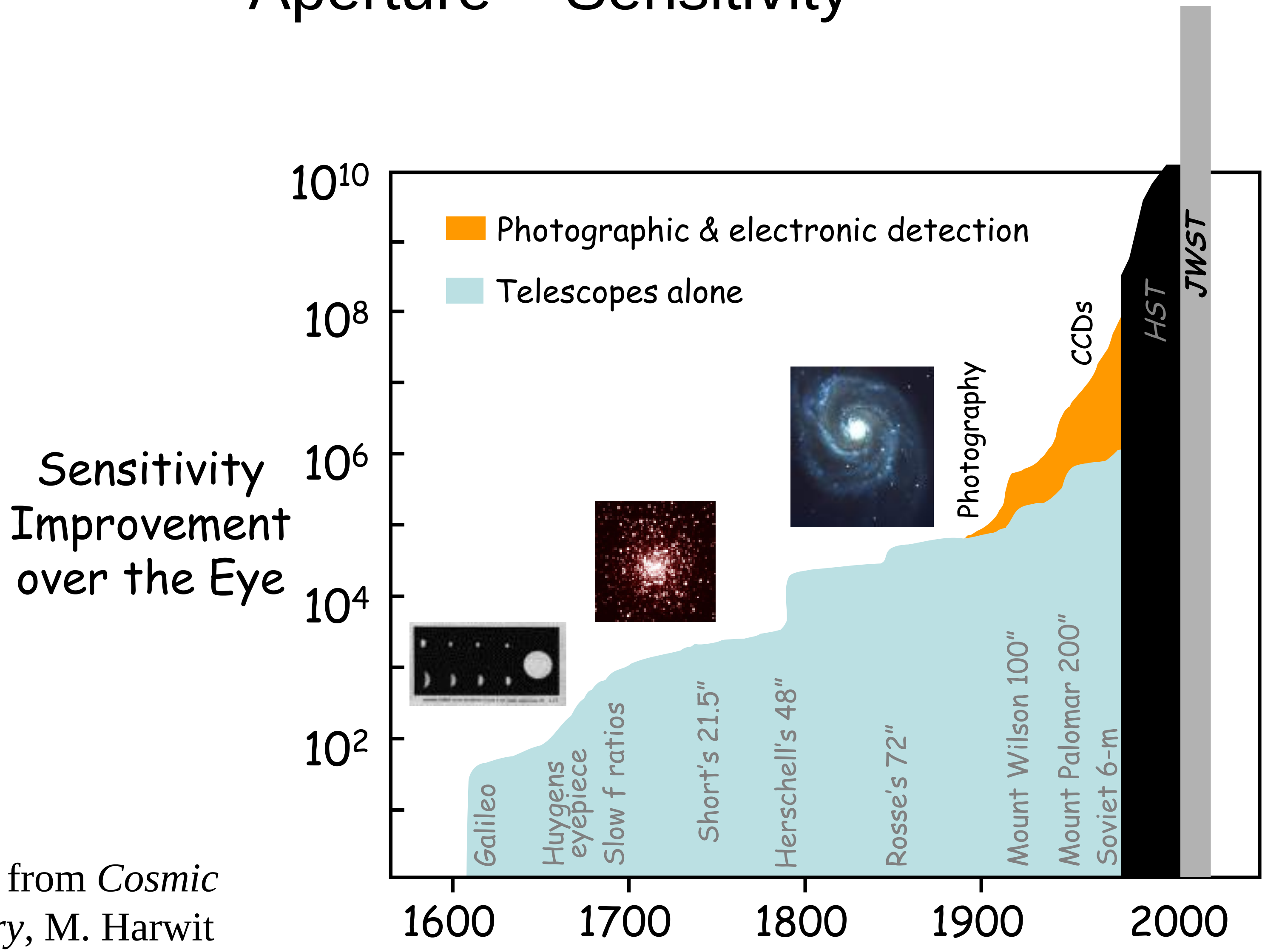
Infrared Light



Why Infrared ?

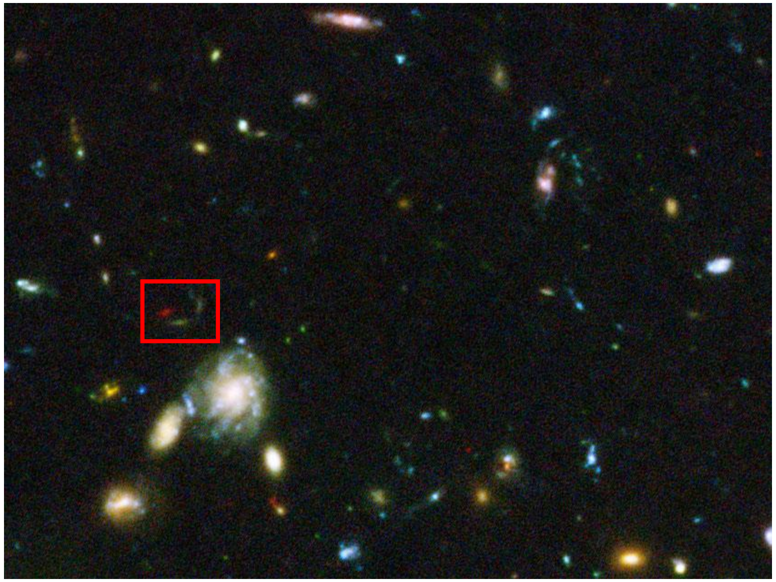
Why do we need Large Apertures?

Aperture = Sensitivity



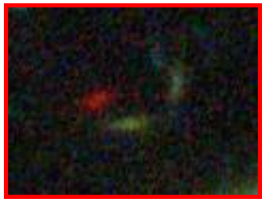
Adapted from *Cosmic Discovery*, M. Harwit

Sensitivity Matters

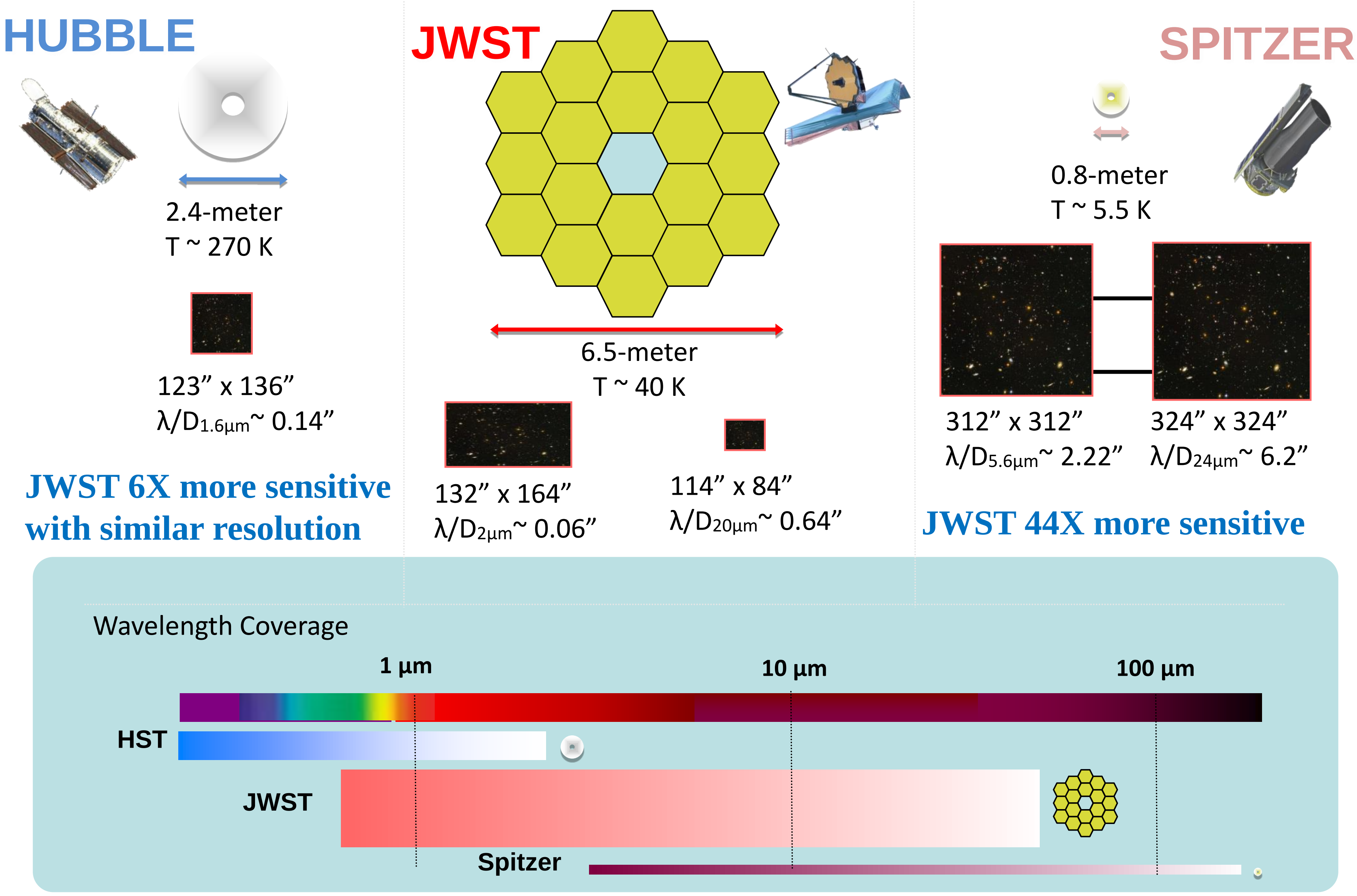


GOODS CDFS – 13 orbits

HUDF – 400 orbits

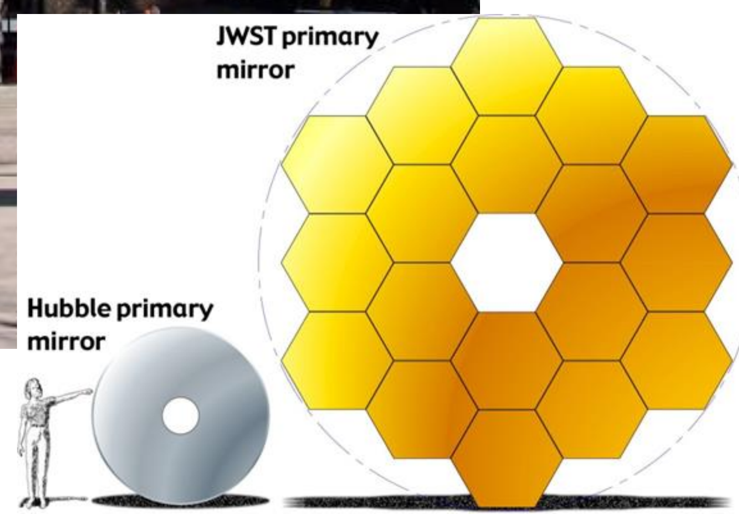


JWST will be more Sensitive than Hubble or Spitzer

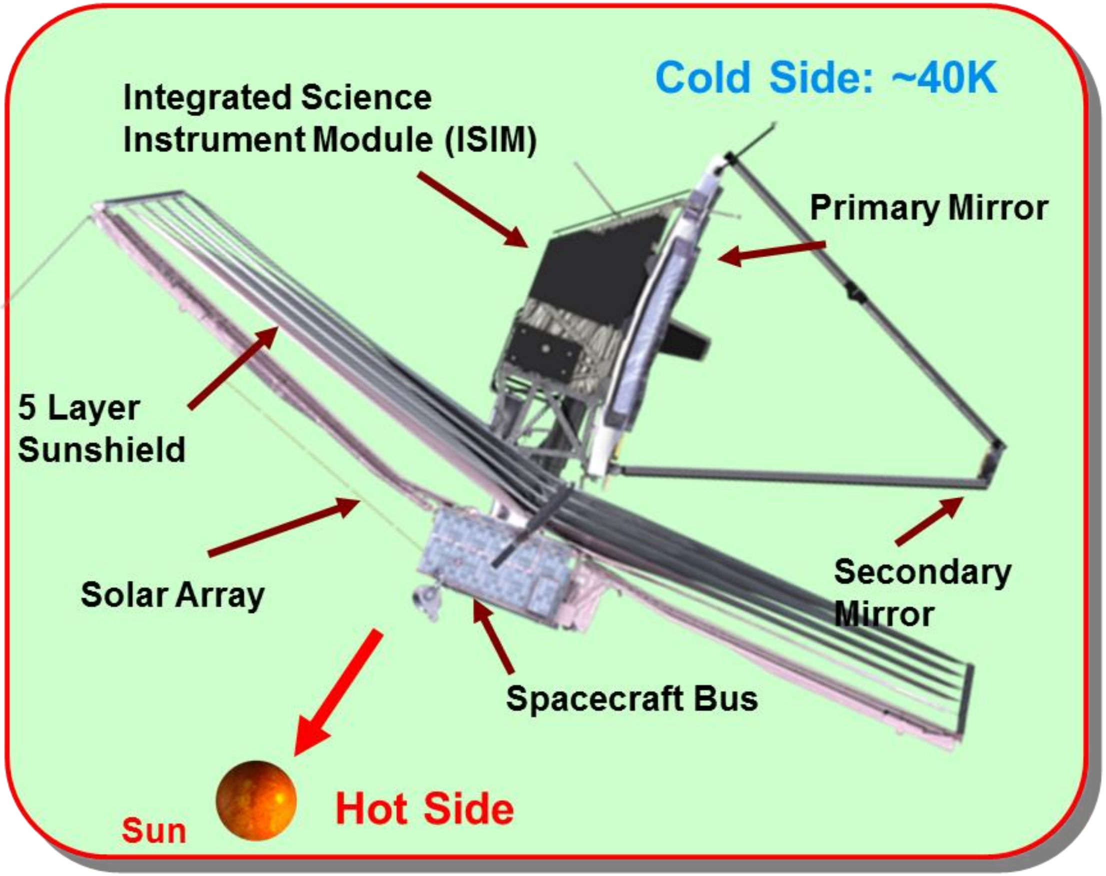


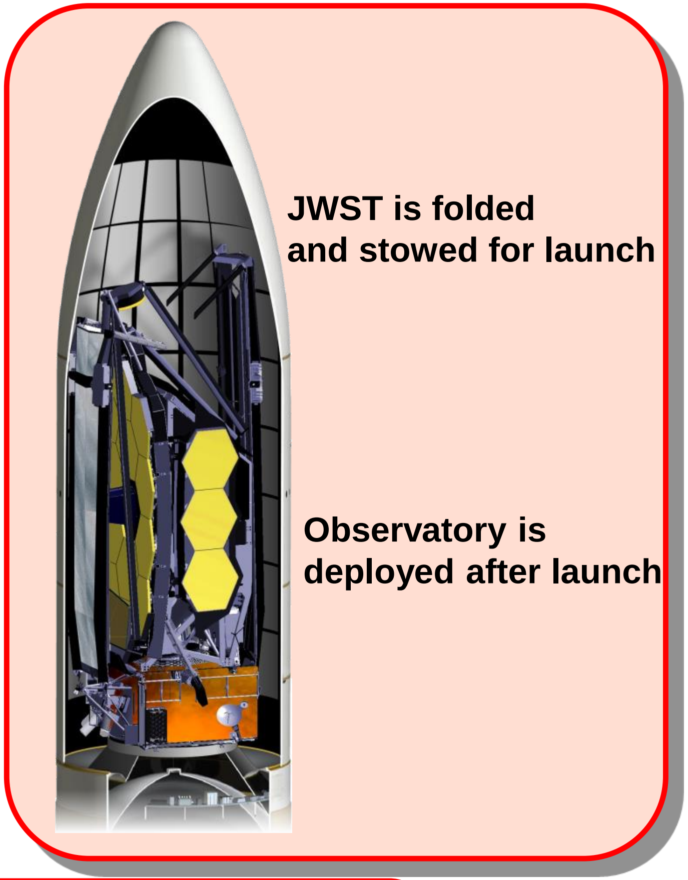
How big is JWST?

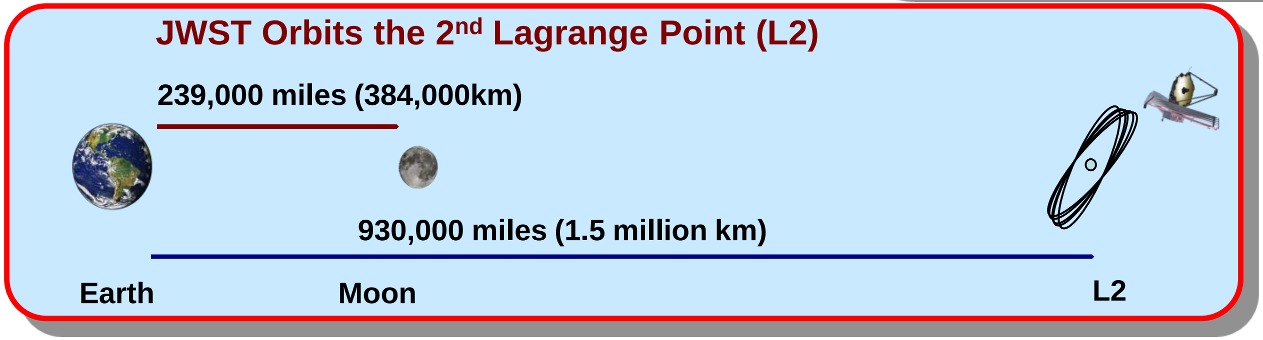
21st National Space Symposium, Colorado Springs, The Space Foundation



How JWST Works

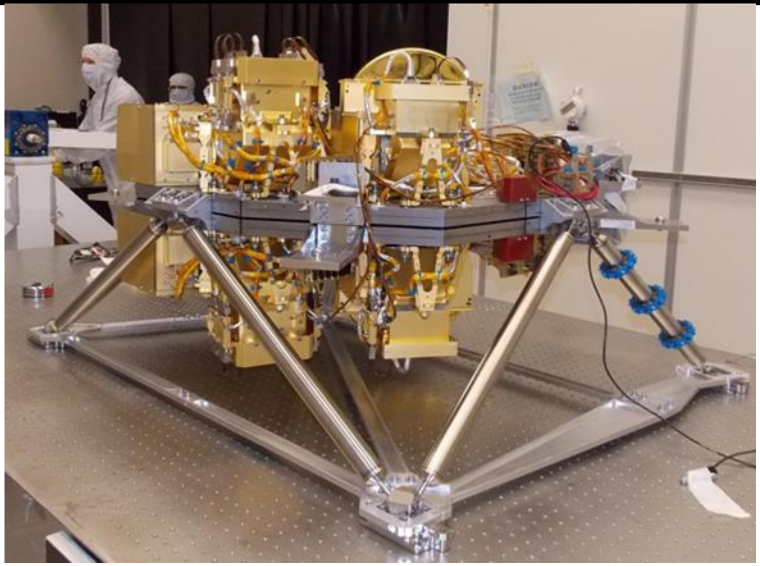




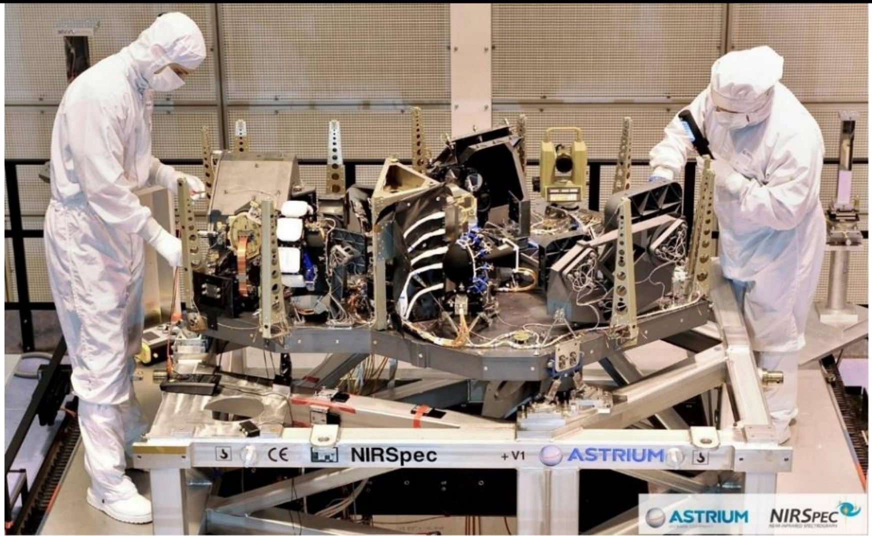


JWST has 4 Science Instruments (0.6 to 28 micrometers)

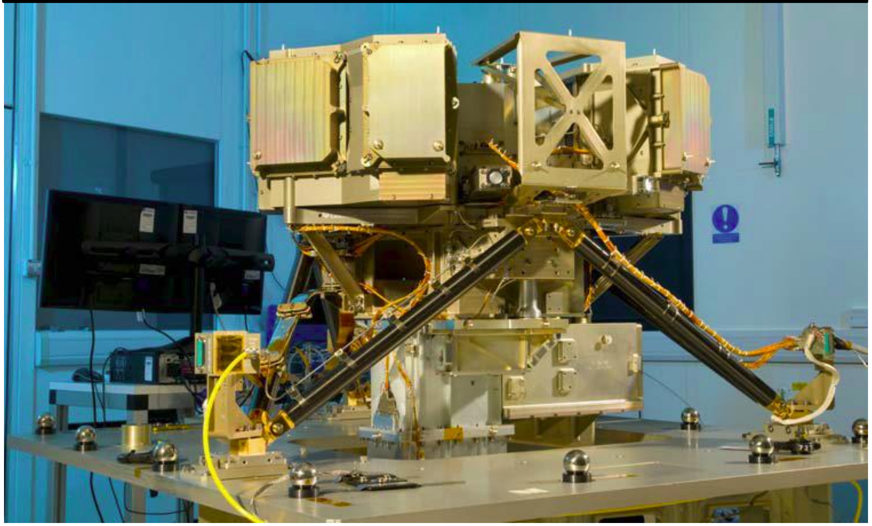
NIRCam: image the first galaxies



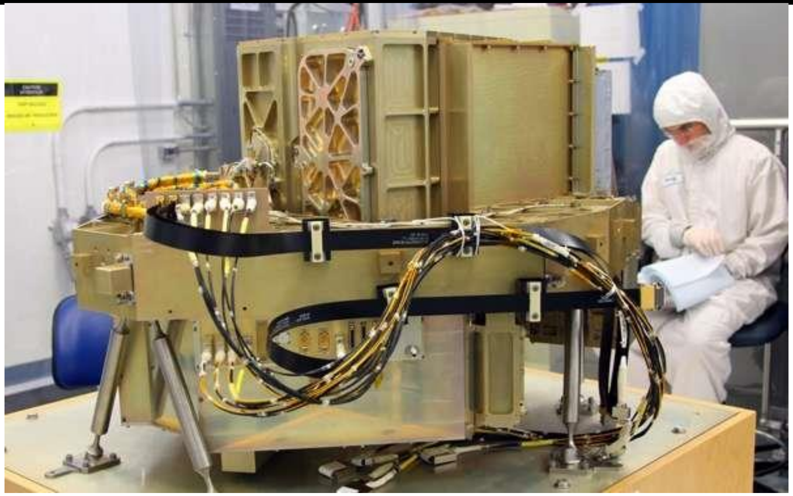
NIRSpec: simultaneous spectra of 100 galaxies



MIRI: first HD view of infrared universe



FGS: sense pointing to 1 millionth degree
NIRISS: imagery & spectra of exoplanets



JWST Telescope Requirements

Optical Telescope Element

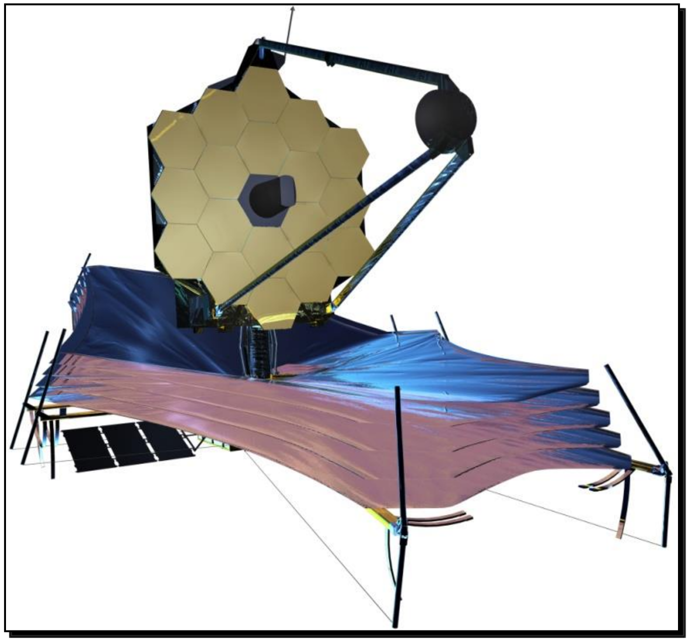
- 25 sq meter Collecting Area
- 2 micrometer Diffraction Limit
- < 50K (~35K) Operating Temp

Primary Mirror

- 6.6 meter diameter (tip to tip)
- < 25 kg/m^2 Areal Density
- < \$6 M/m^2 Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

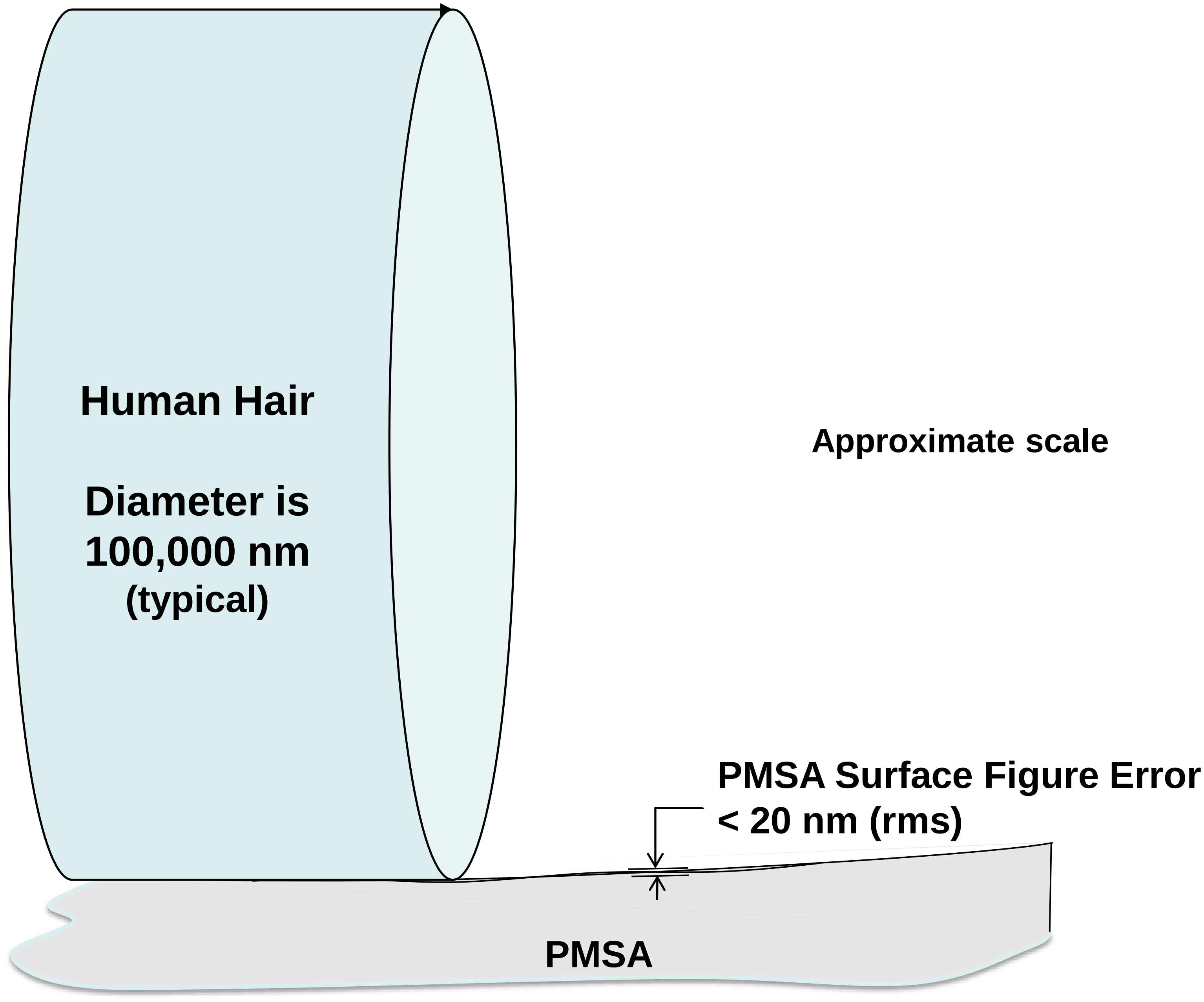
Segments

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

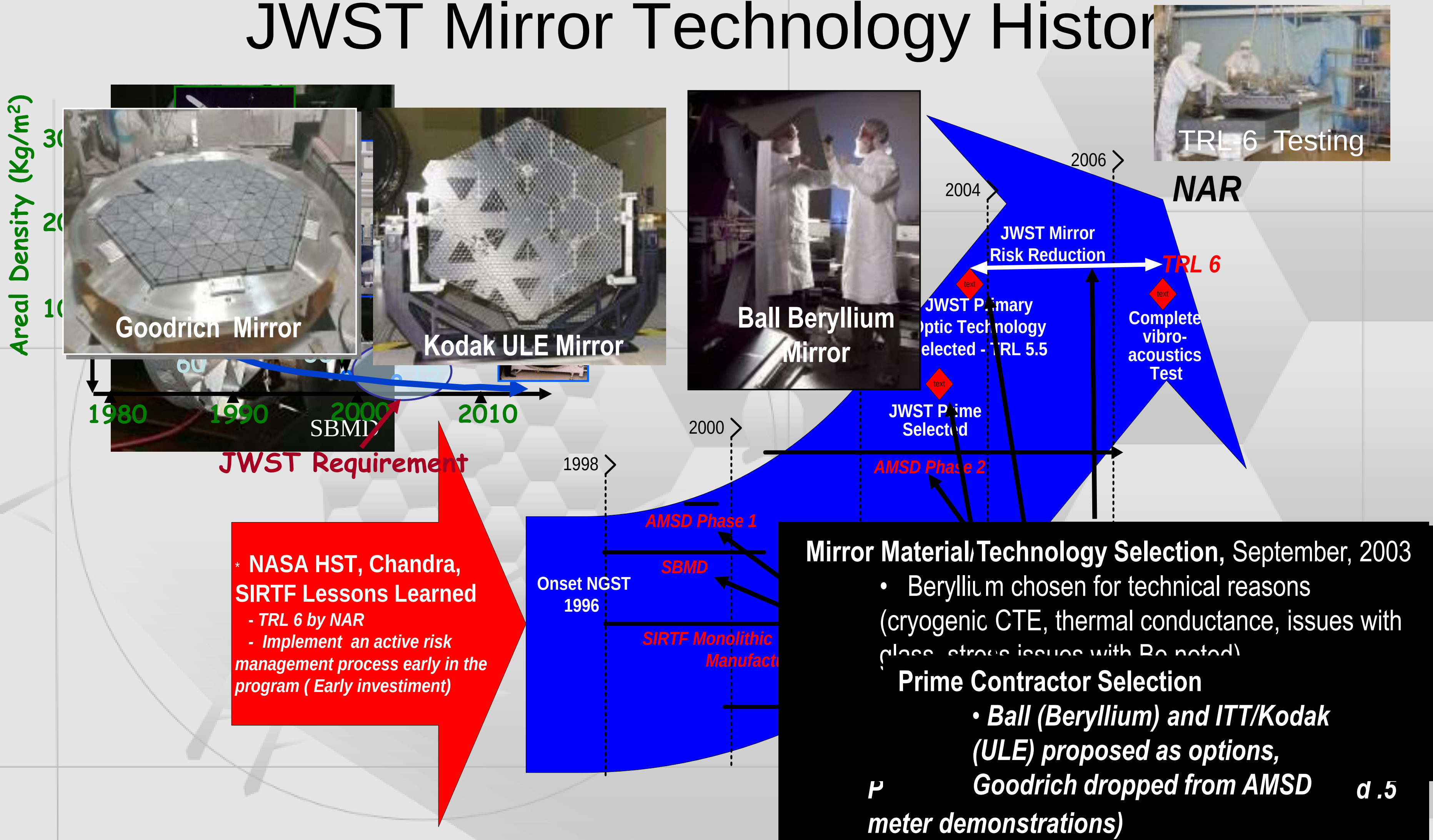


Low (0-5 cycles/aper)	4 nm rms
CSF (5-35 cycles/aper)	18 nm rms
Mid (35-65K cycles/aper)	7 nm rms
Micro-roughness	<4 nm rms

Fun Fact – Mirror Surface Tolerance



JWST Mirror Technology History



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

Advantages of Beryllium

Very High Specific Stiffness – Modulus/Mass Ratio

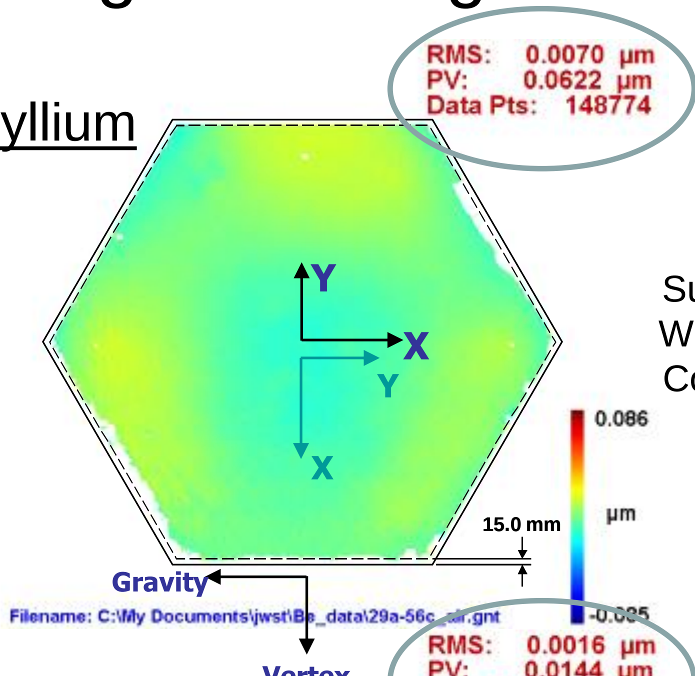
Saves Mass – Saves Money

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

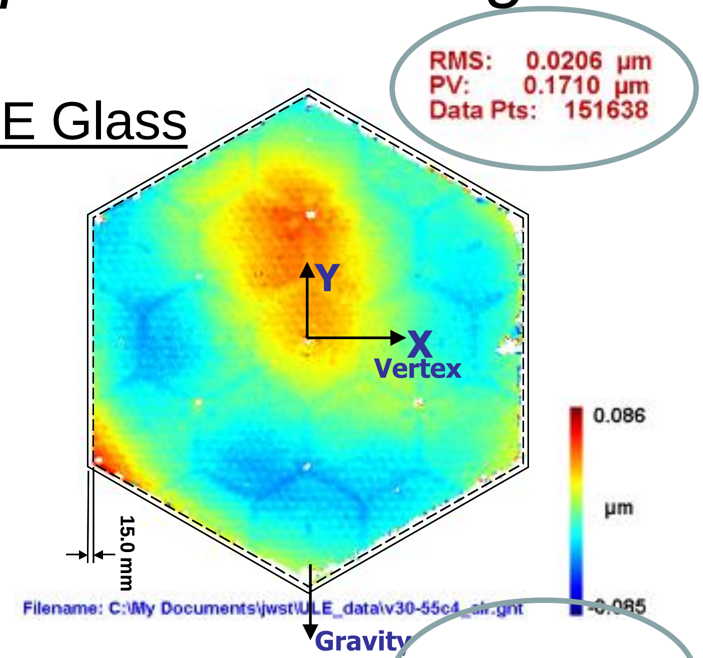
Thermal Stability

Figure Change: *30-55K Operational Range*

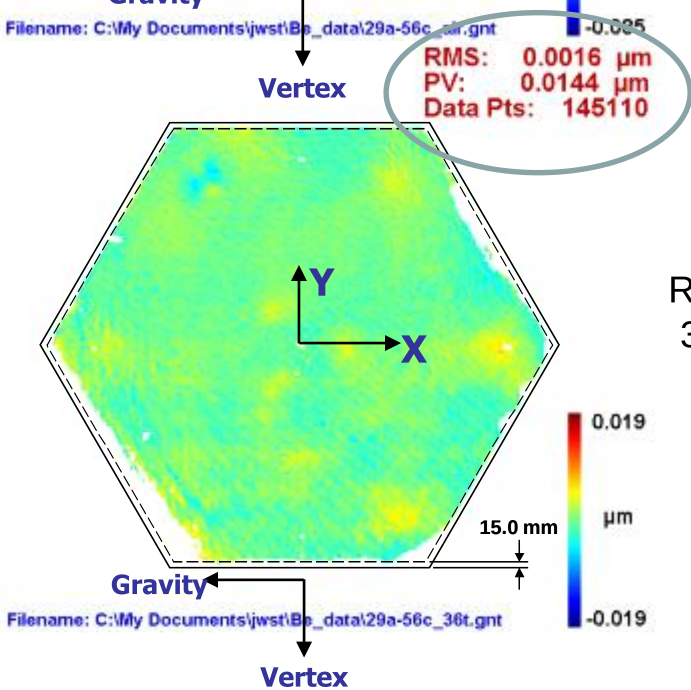
<u>Beryllium</u>



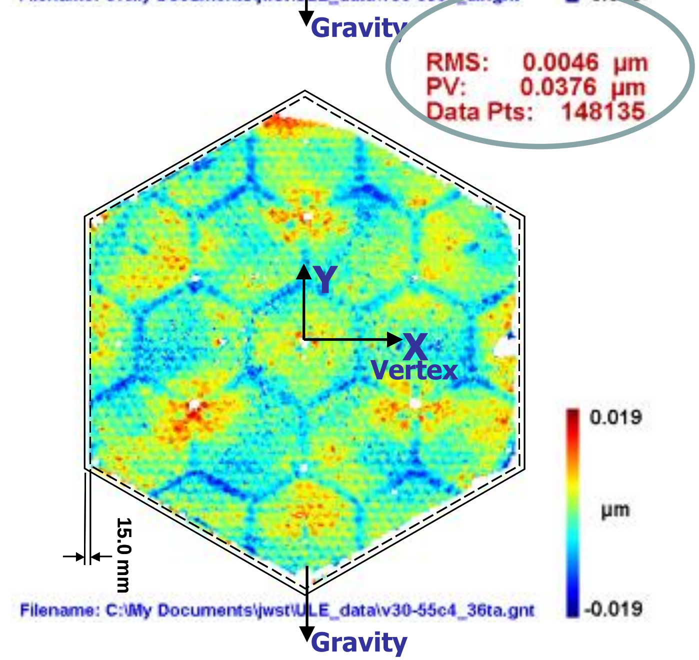
<u>ULE Glass</u>



Surface Figure With Alignment Compensation

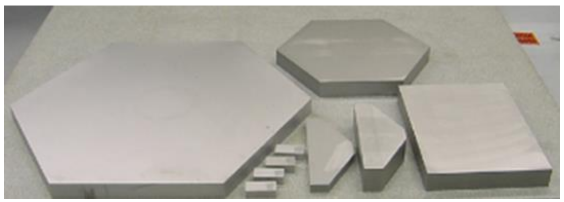


Residual with 36 Zernikes Removed

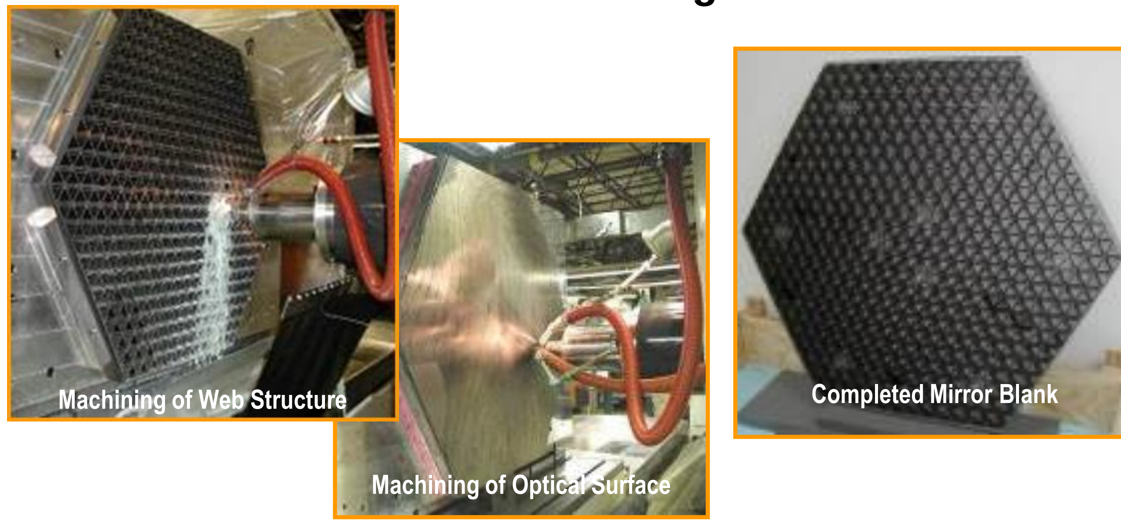


Mirror Manufacturing Process

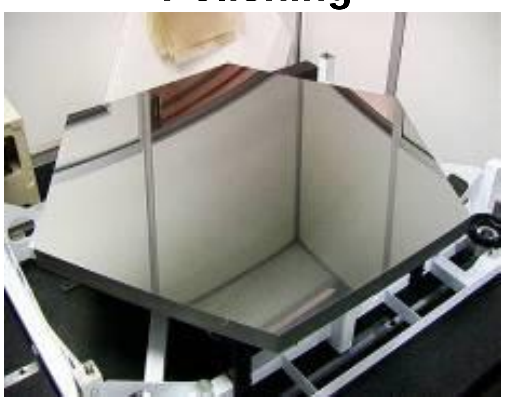
Blank Fabrication



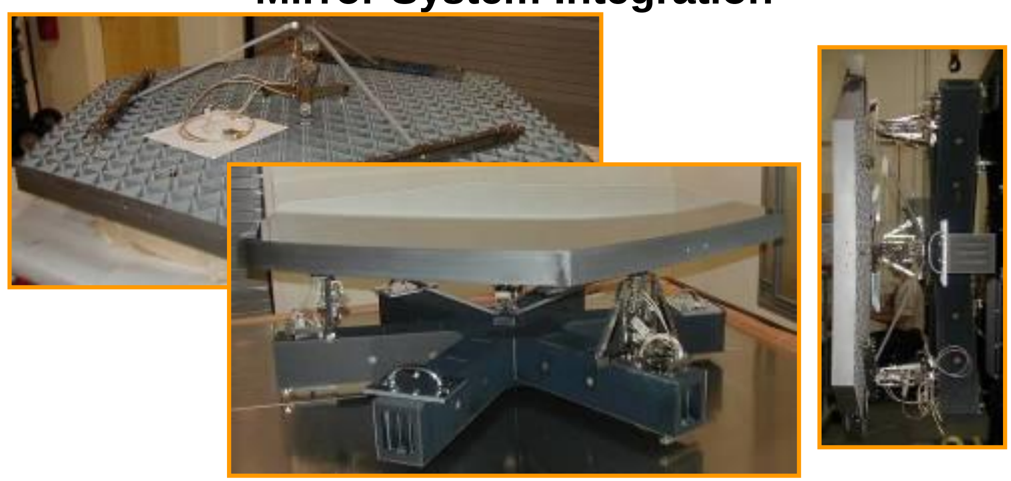
Machining



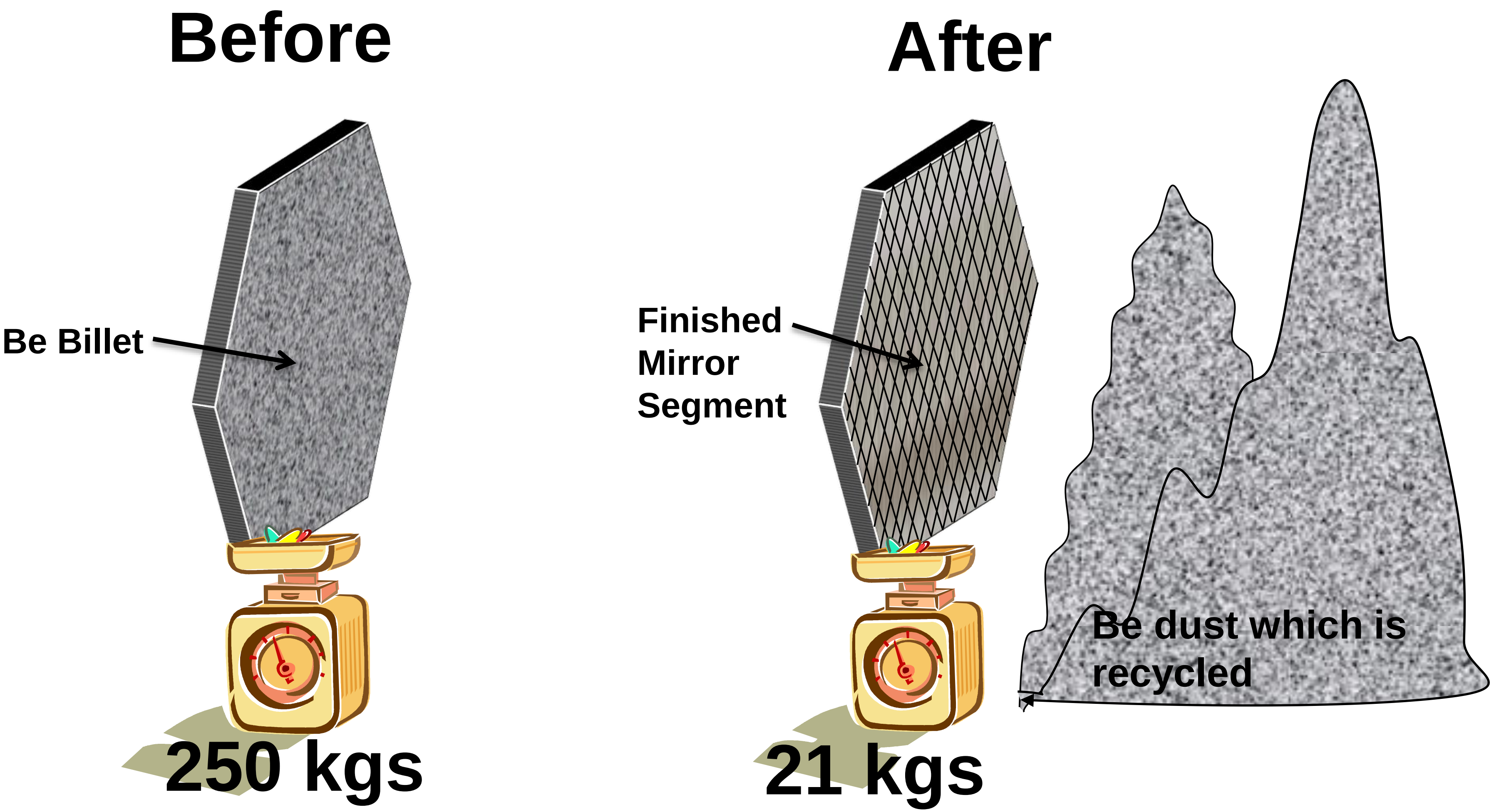
Polishing



Mirror System Integration

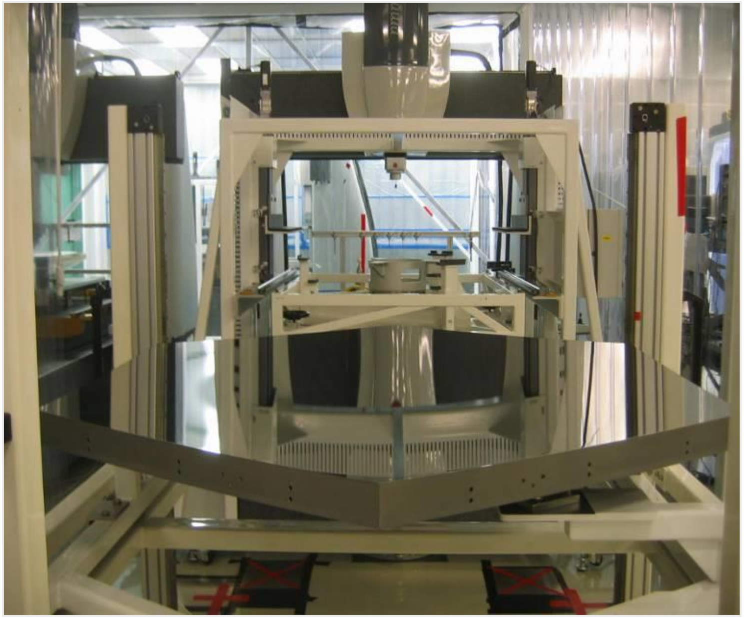


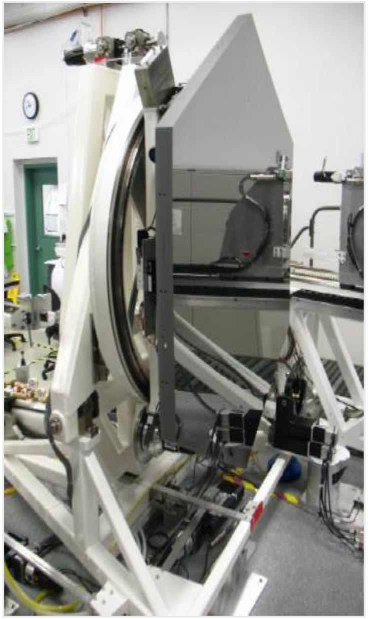
Fun Facts – Mirror Manufacturing



Over <u>90%</u> of material is removed to make each mirror segment – want a little mirror with your Be dust?

Mirror Processing at Tinsley





Tinsley In-Process Metrology Tools

Metrology tools provide feedback at every manufacturing stage:

Rough Grinding	CMM
Fine Grinding/Rough Polishing	Scanning Shack-Hartmann
Final Polishing/Figuring/CNF	Interferometry

PMSA Interferometer Test Stations included:

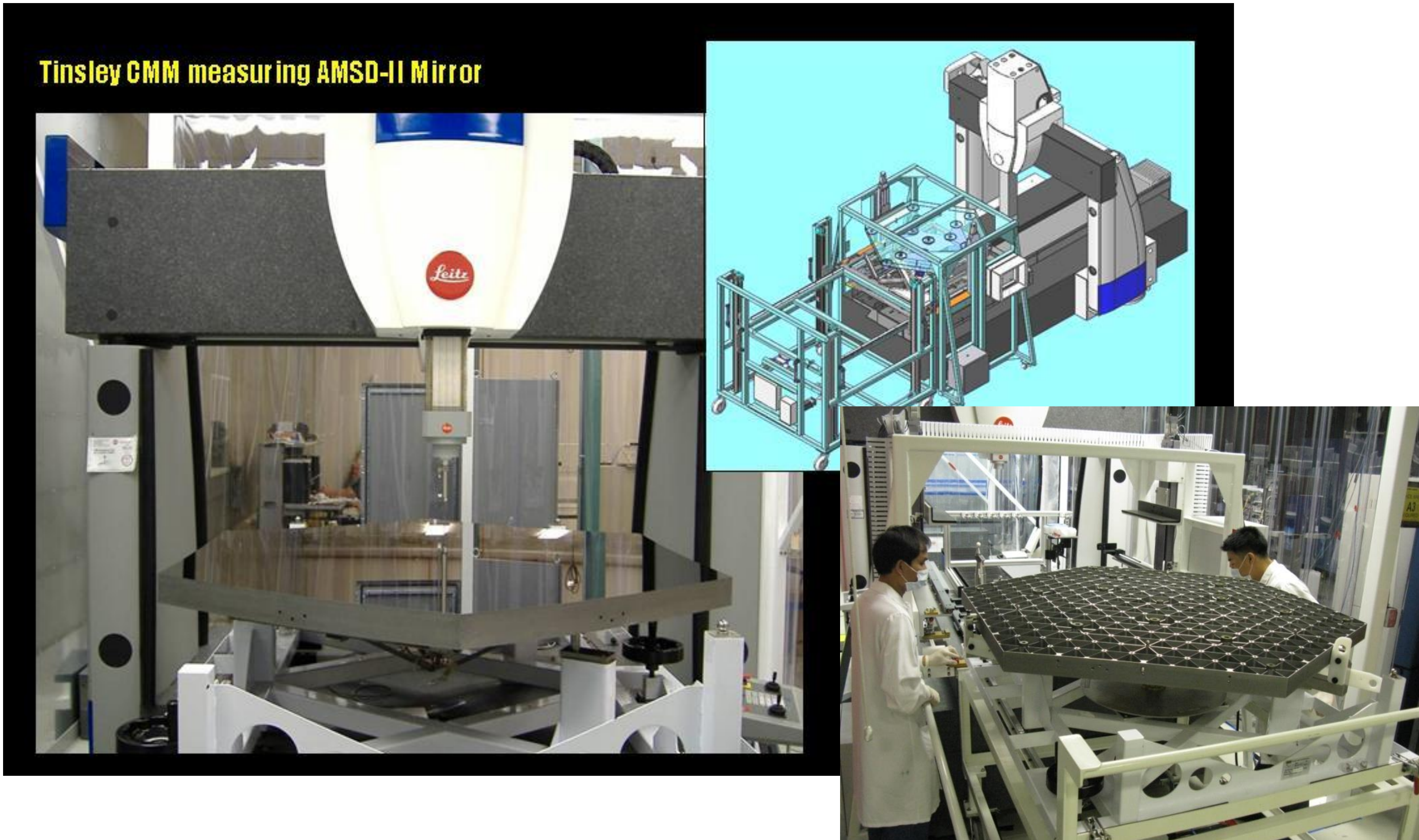
- 2 Center of Curvature CGH Optical Test Stations (OTS1 and OTS2)
- Auto-Collimation Test Station

Data was validated by comparing overlap between tools

Independent cross check tests were performed at Tinsley and between Tinsley, Ball and XRCF.

Leitz CMM

CMM was sized to test PMSA Full Aperture



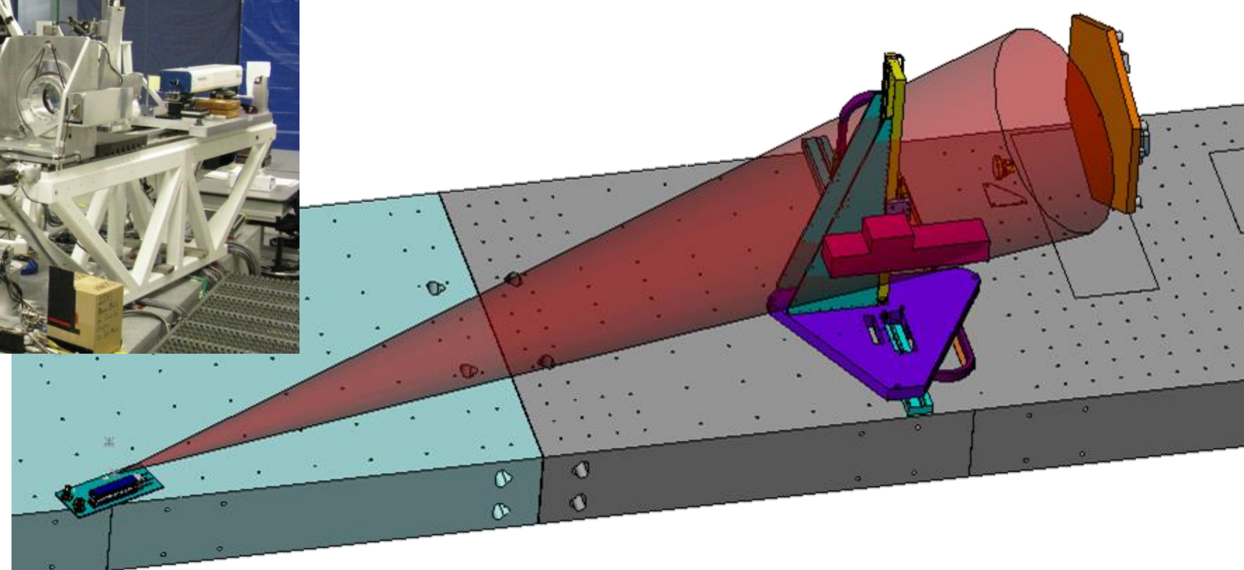
Wavefront Sciences Scanning Shack-Hartmann

SSHS provided bridge-data between grind and polish, used until PMSA surface was within capture range of interferometry

SSHS provide mid-spatial frequency control: 222 mm to 2 mm

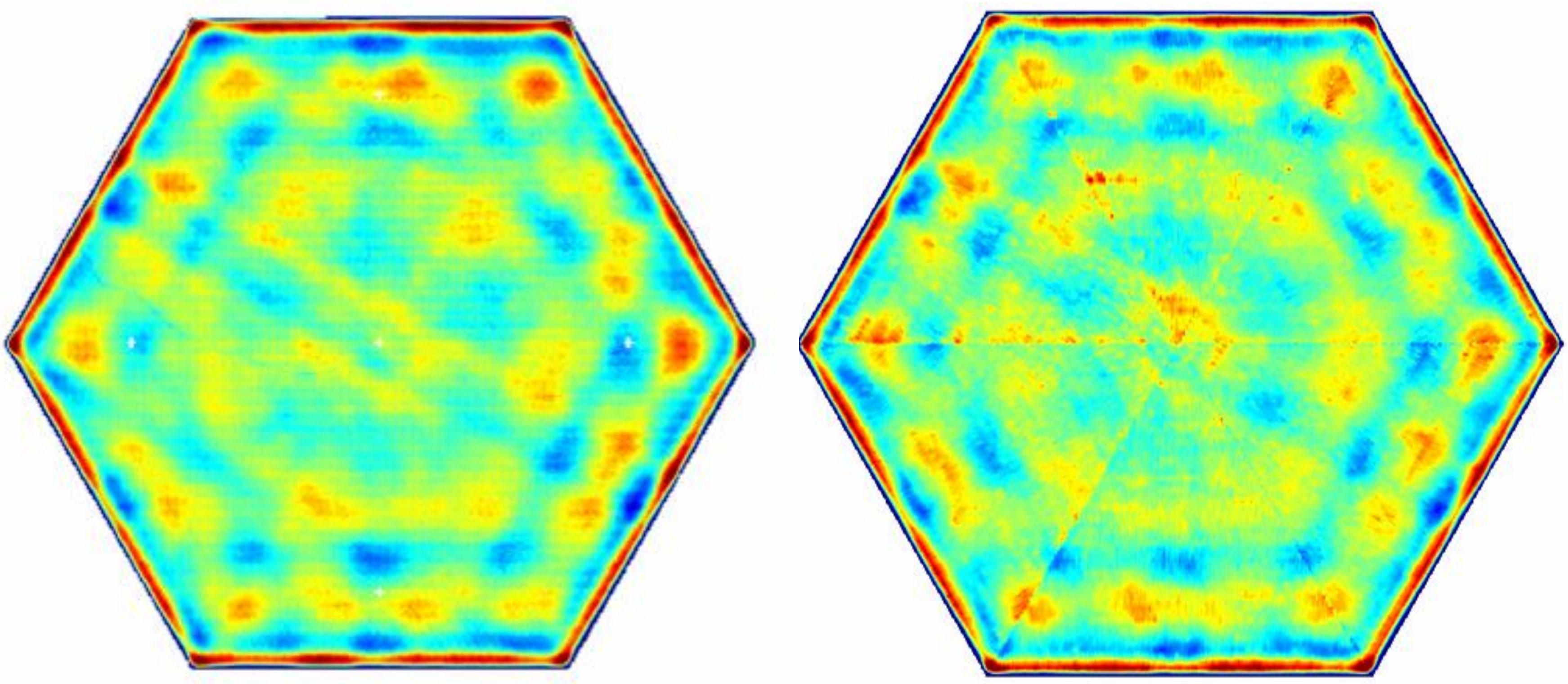
Large dynamic range (0 – 4.6 mr surface slope)

When not used, convergence rate was degraded.



Comparison to CMM (222 - 2 mm spatial periods)
8/1/2006 data

Smooth grind



SSHS
4.7 µm PV, 0.64 µm RMS

CMM
4.8 µm PV, 0.65 µm RMS

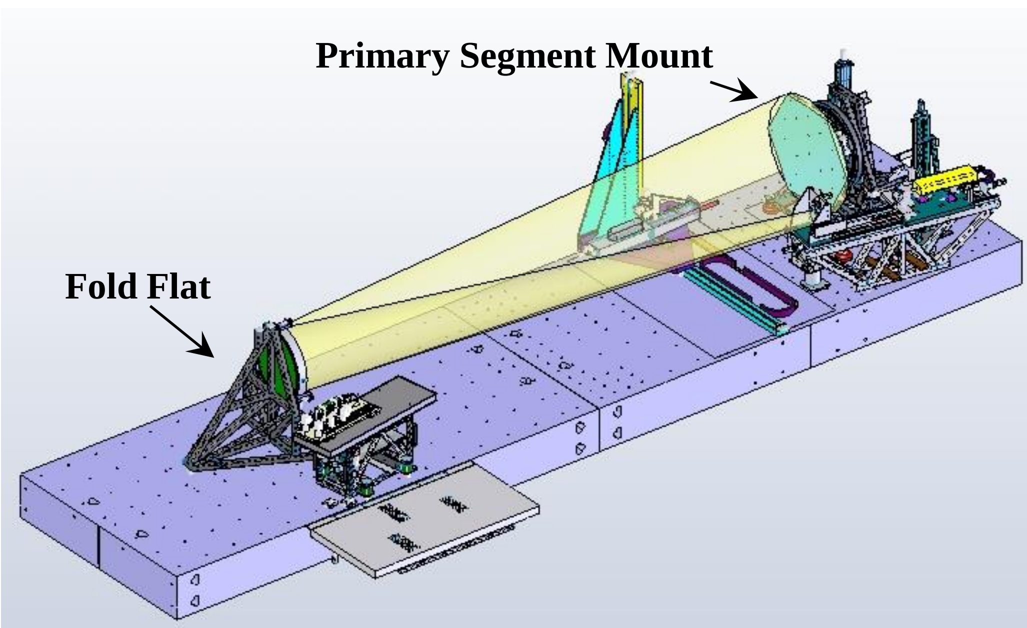
Point-to-Point Subtraction: SSHS - CMM = 0.27 µm RMS

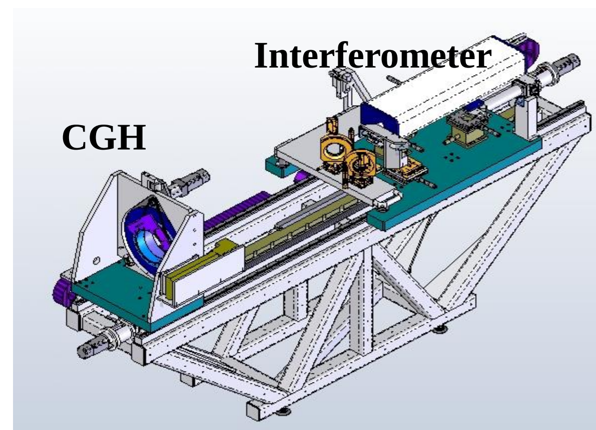
Full Aperture Optical Test Station (OTS)

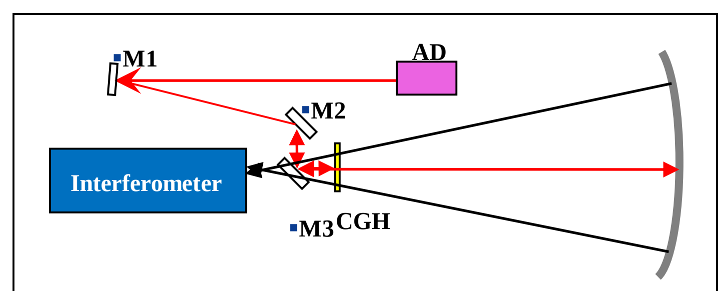
Center of Curvature Null Test measured & controlled:

- Prescription,
- Radius &
- Figure

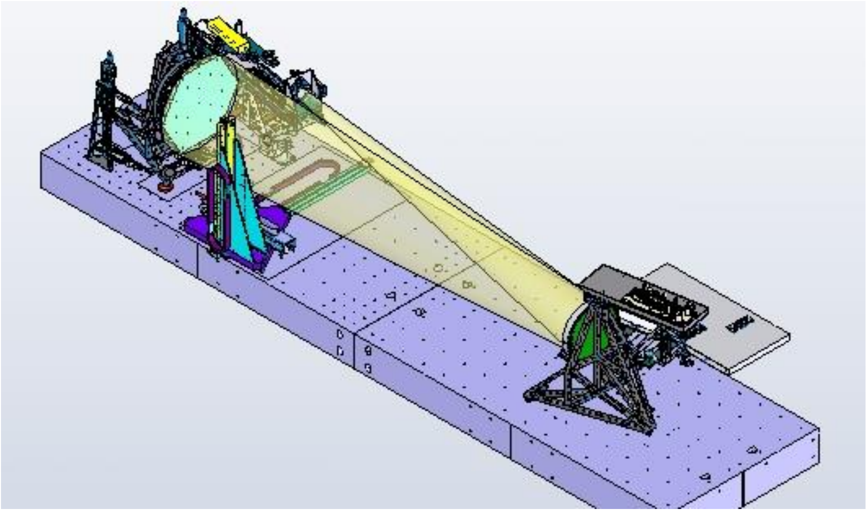
Results are cross-checked between 2 test stations.





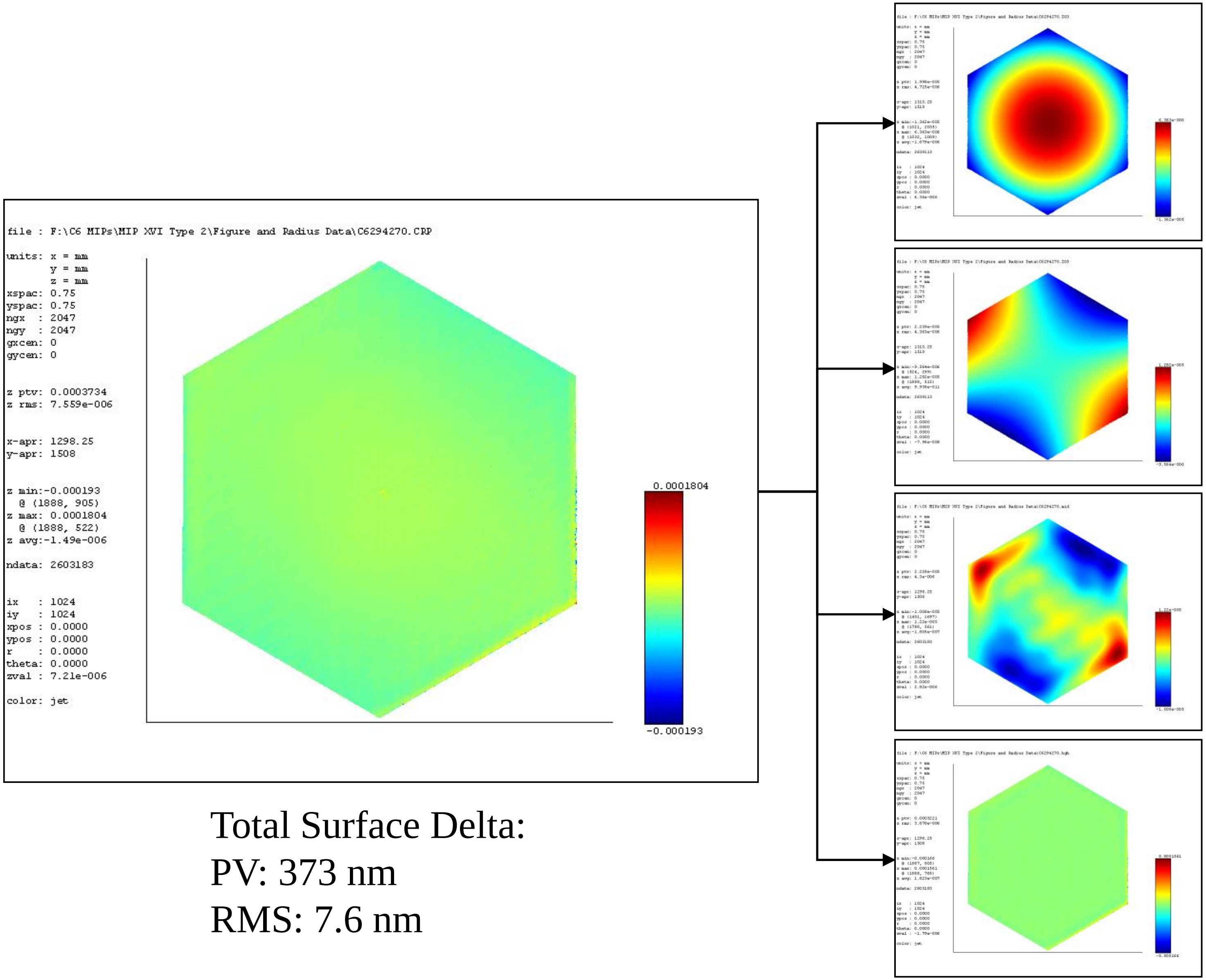


Full Aperture Optical Test Station (OTS)



Test Reproducibility

(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270



Power (Radius Delta: 0.02 mm)

Astigmatism: 4.4 nm RMS

Mid Frequency: 4.3 nm RMS

High Frequency: 3.9 nm RMS

Total Surface Delta:
PV: 373 nm
RMS: 7.6 nm

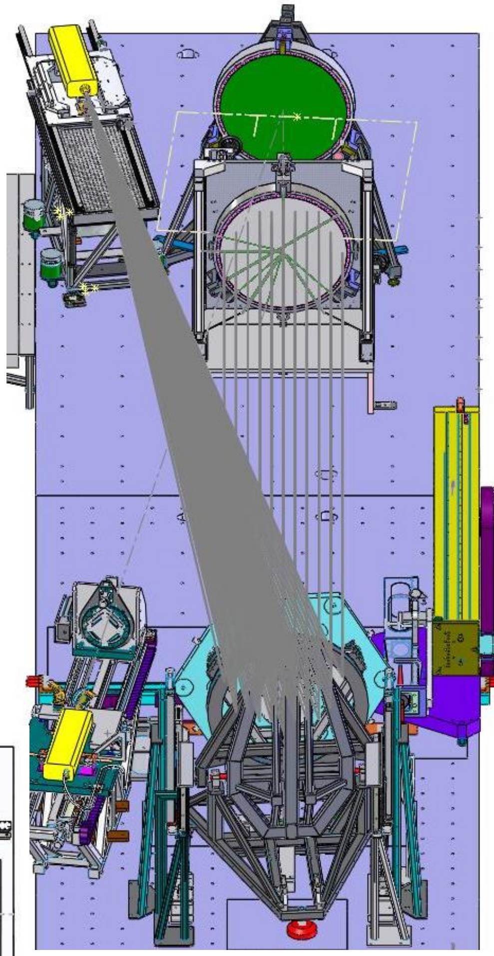
Auto-Collimation Test

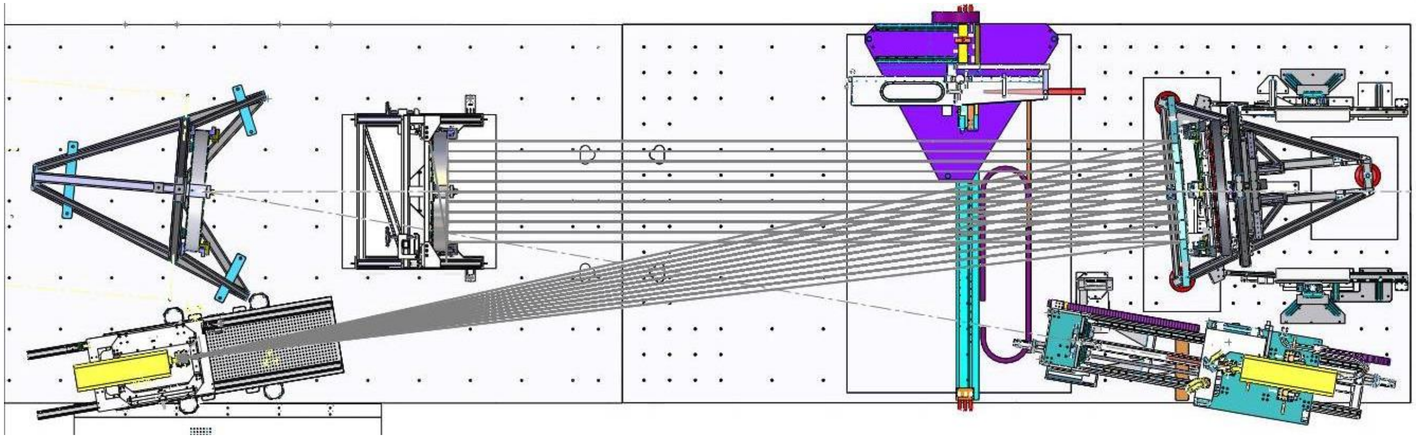
Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:

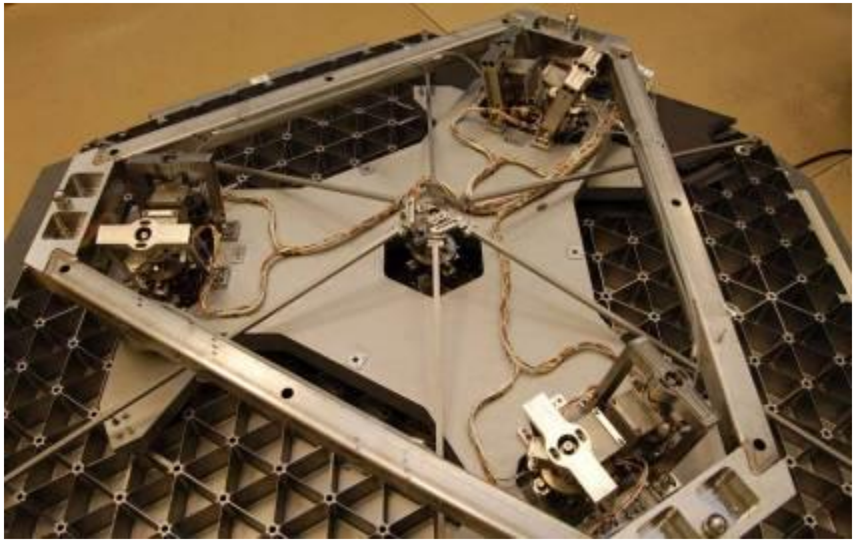
- Radius of Curvature
- Conic Constant
- Off-Axis Distance
- Clocking

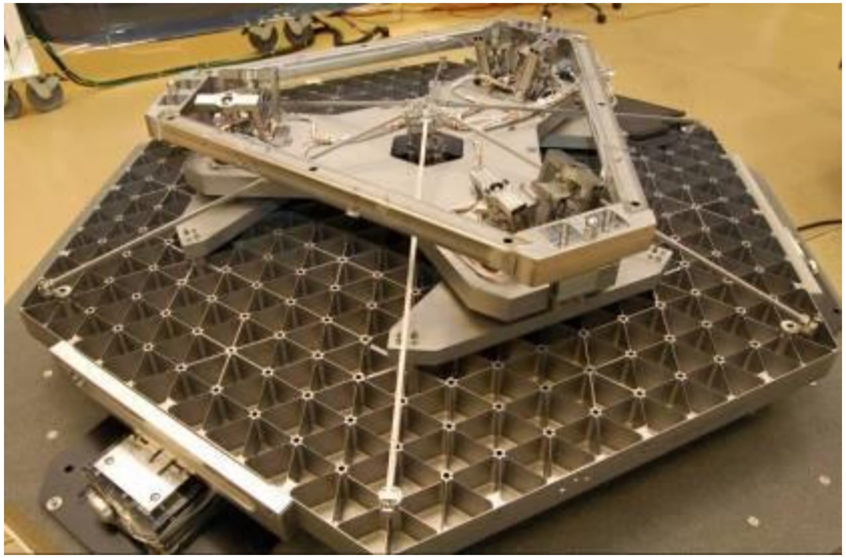
Note: is not a full-aperture figure verification test





Primary Mirror Segment Assembly at BATC



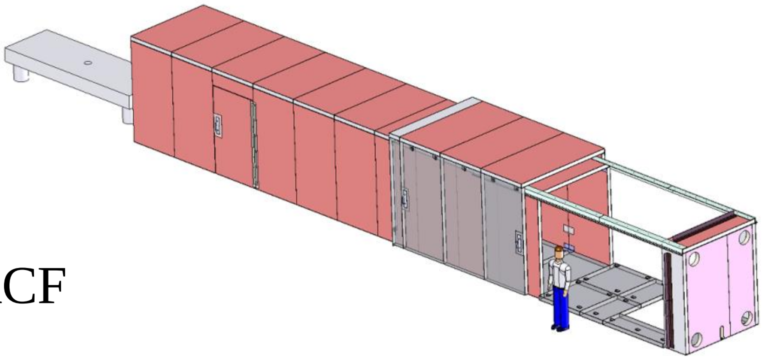


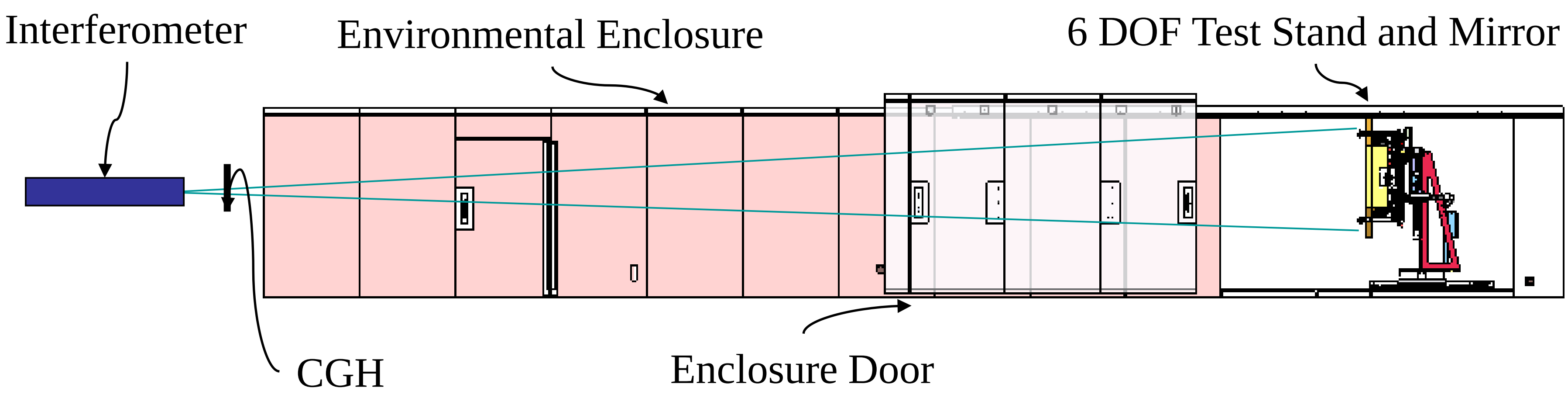
Ball Optical Test Station (BOTS)

Tinsley ambient metrology results are ‘cross-checked’ at BATC

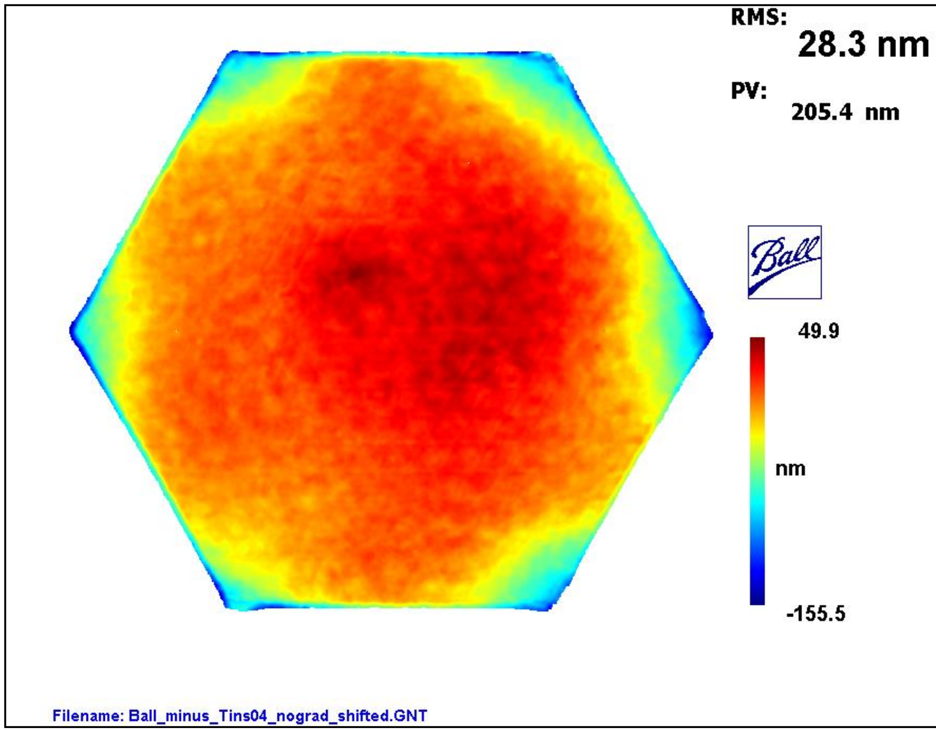
BOTS measurements:

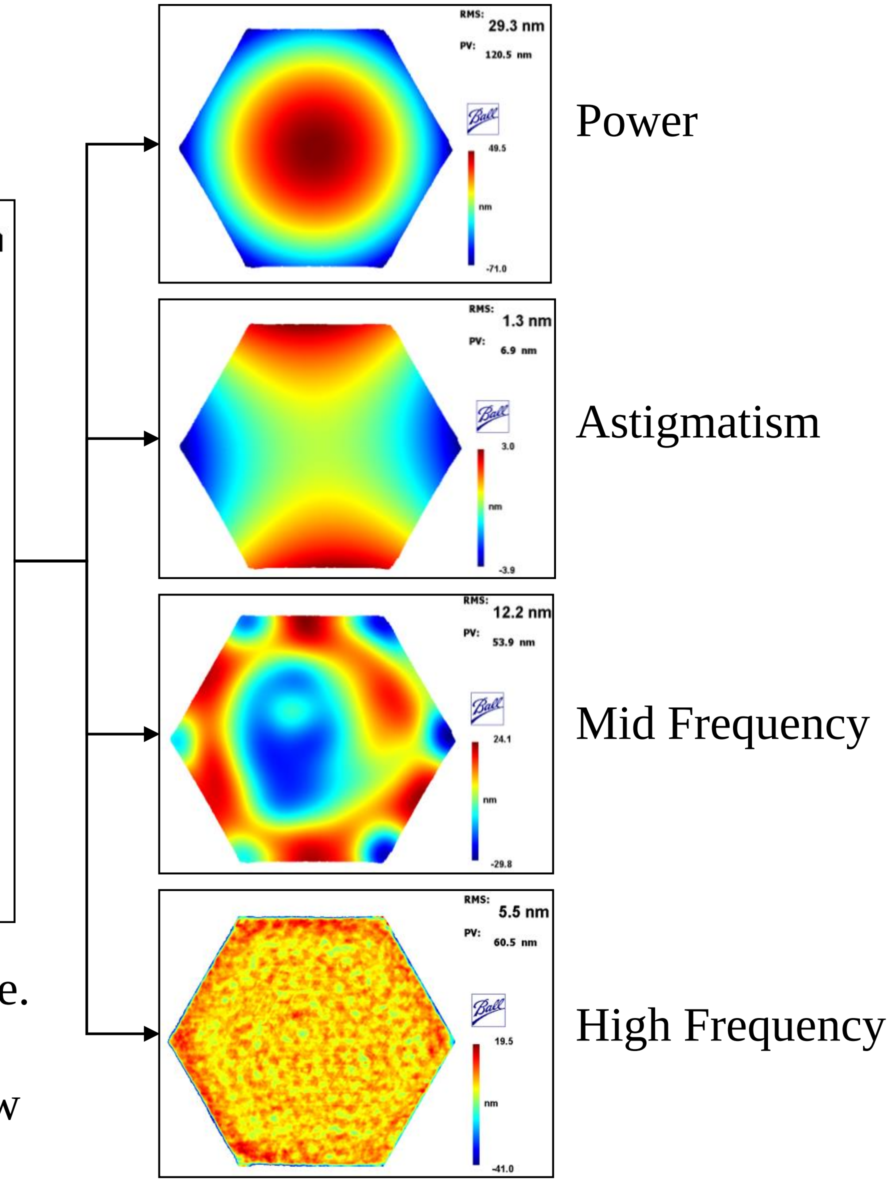
- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation





BOTS to Tinsley Initial Comparison

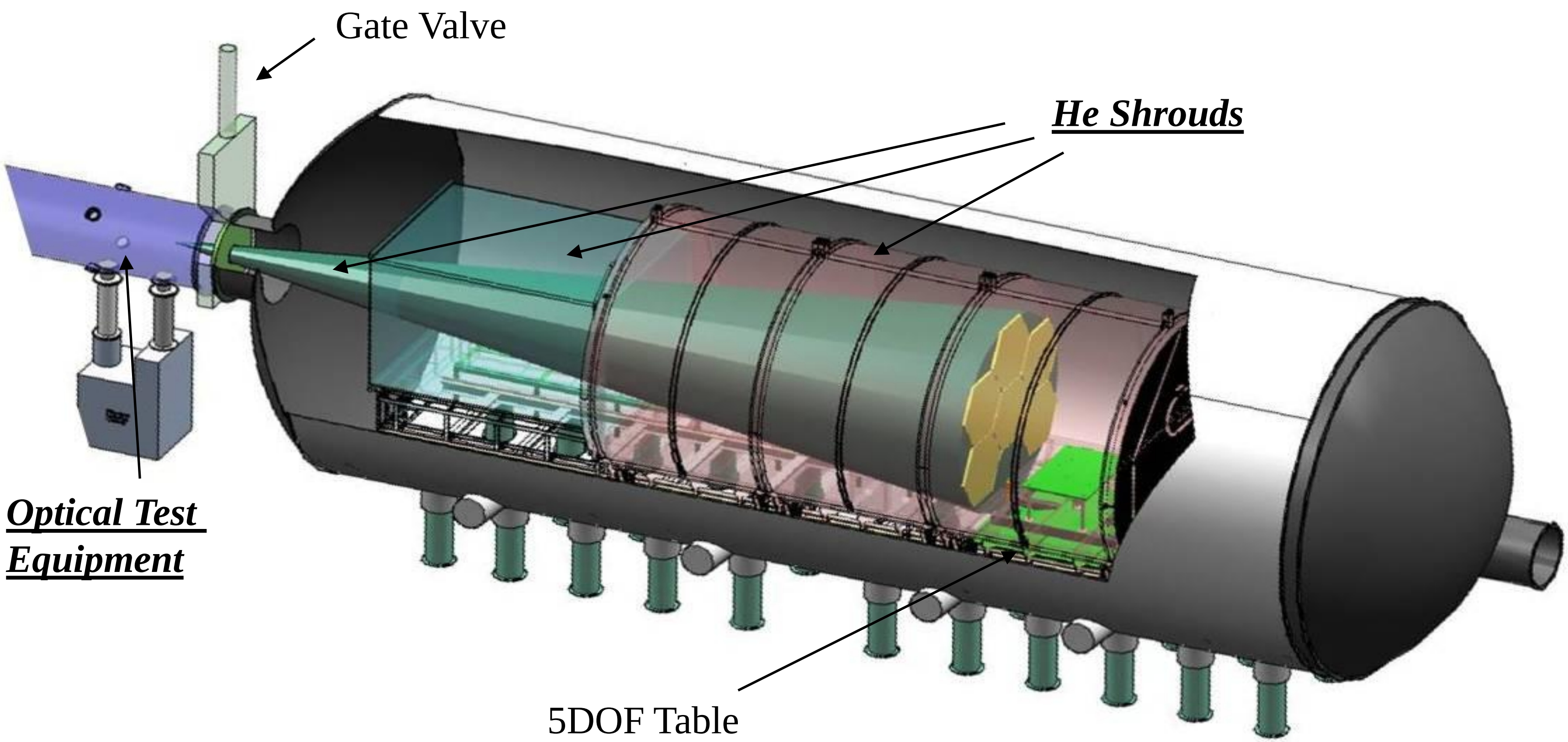




Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.

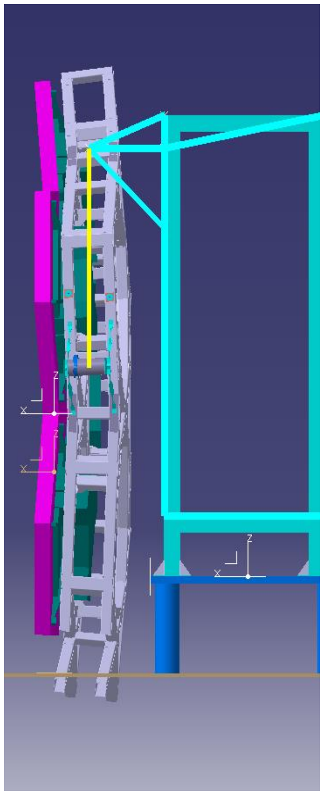
PMSA Flight Mirror Testing at MSFC XRCF

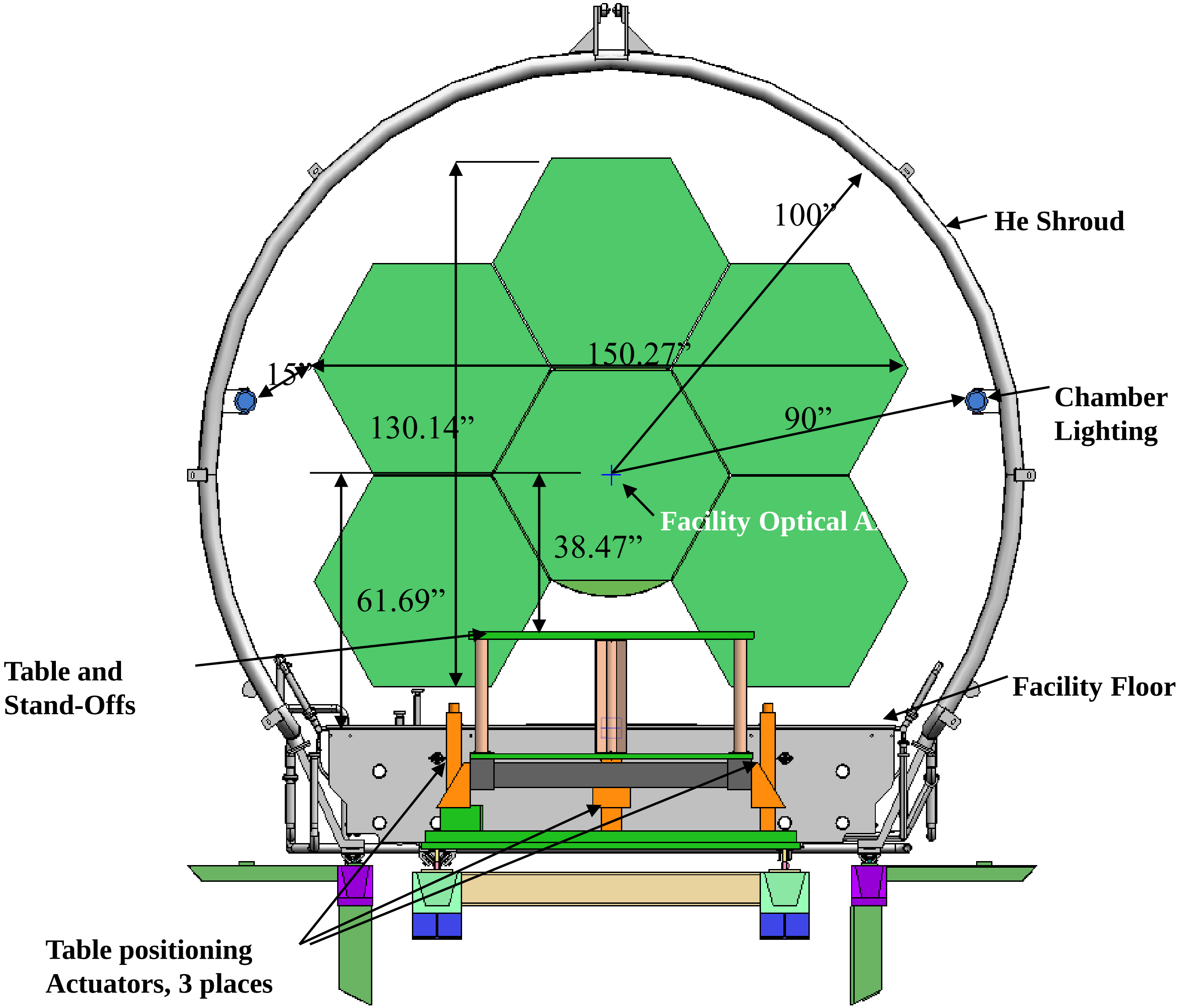
Cryogenic Performance Specifications are Certified at XRCF



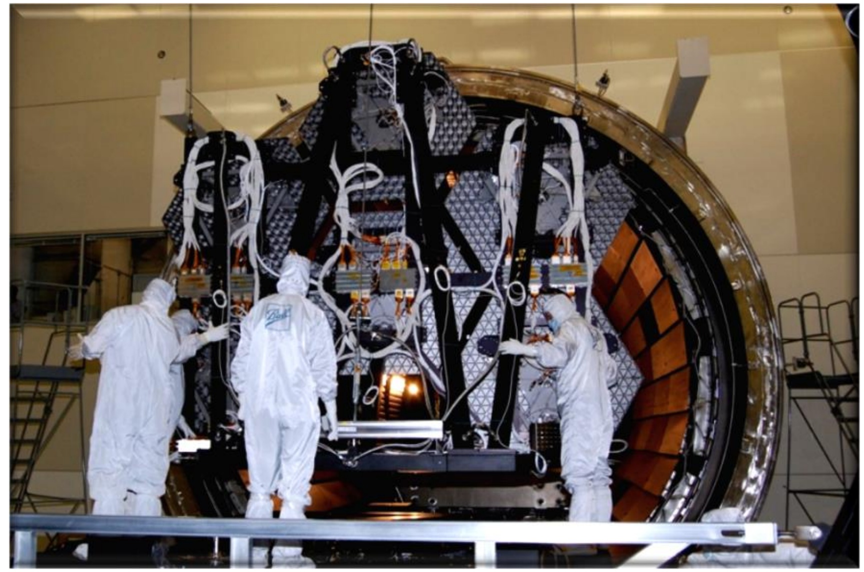
Cryo-Vacuum Chamber is 7 m dia x 23 m long

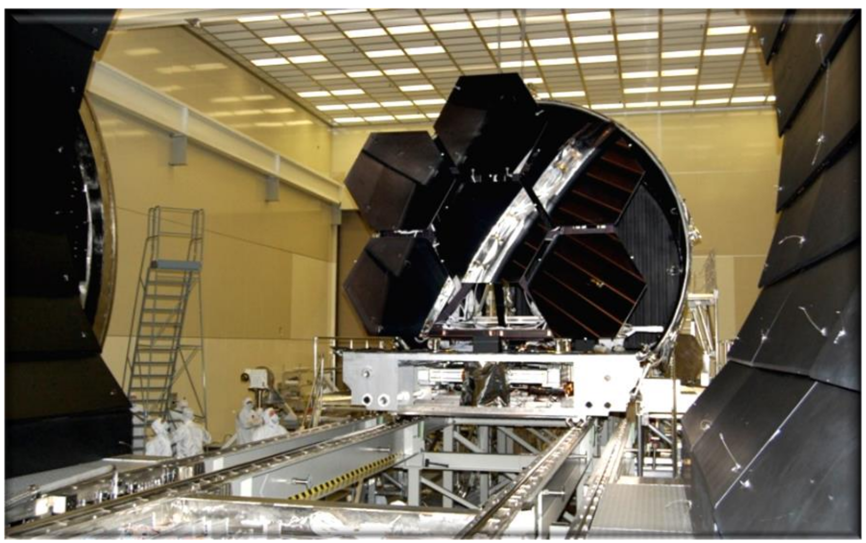
JWST Flight Mirror Test Configuration



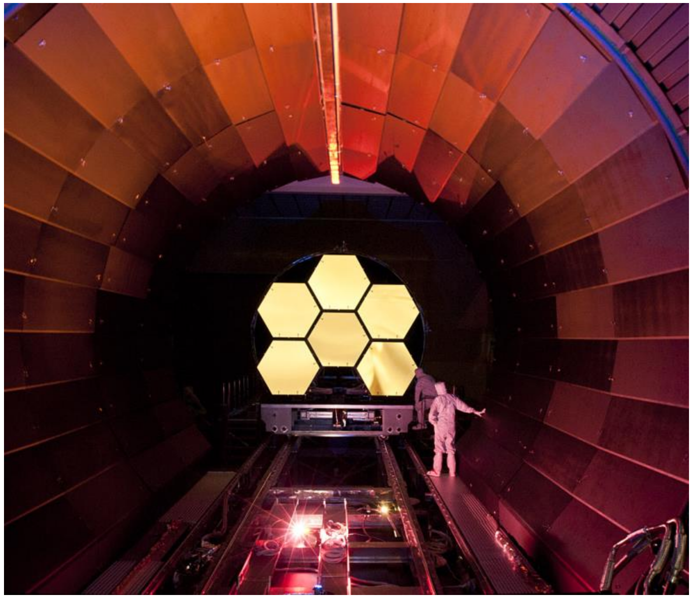


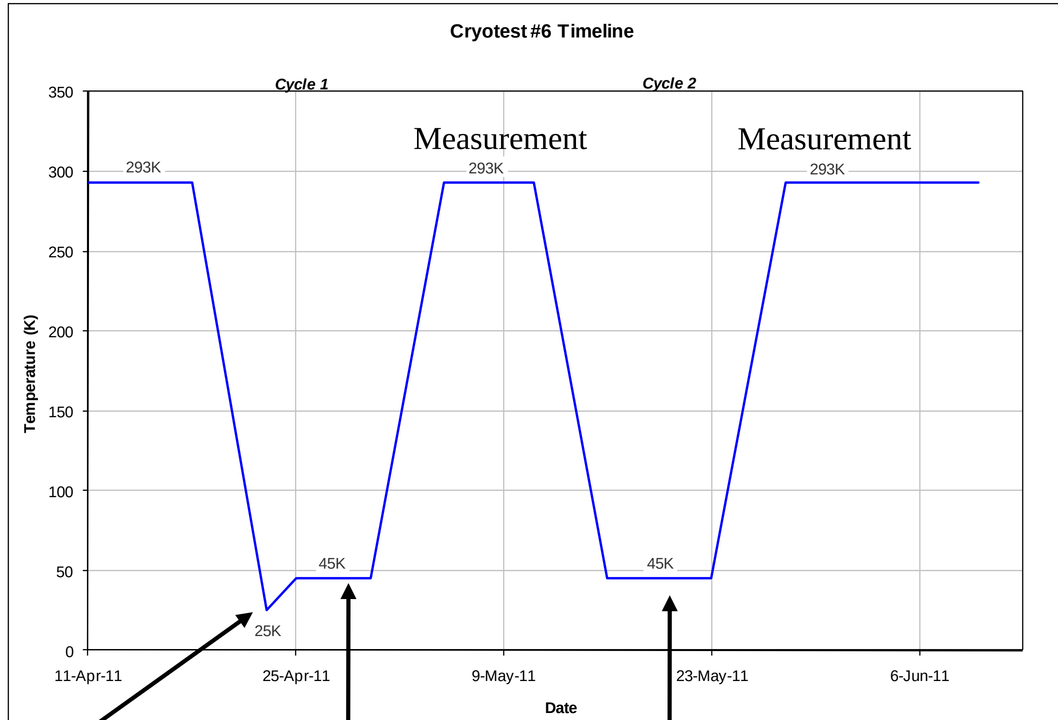
Primary Mirror Cryogenic Tests

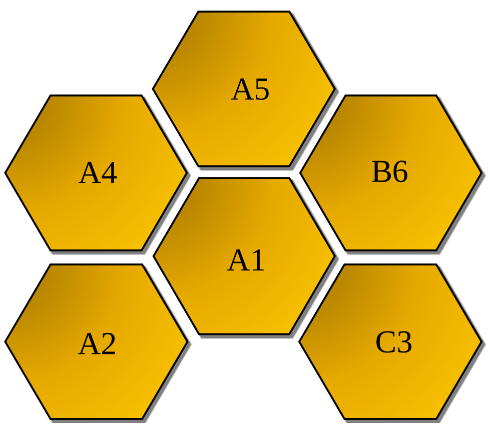




XRCF Cryo Test







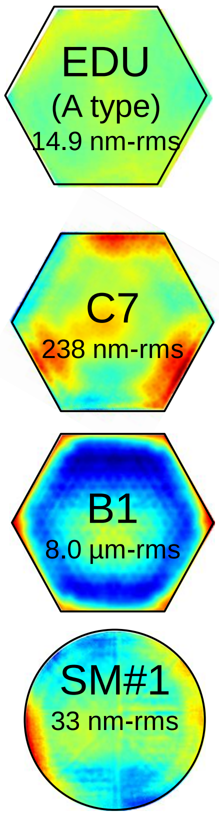
- Survival Temperature

- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

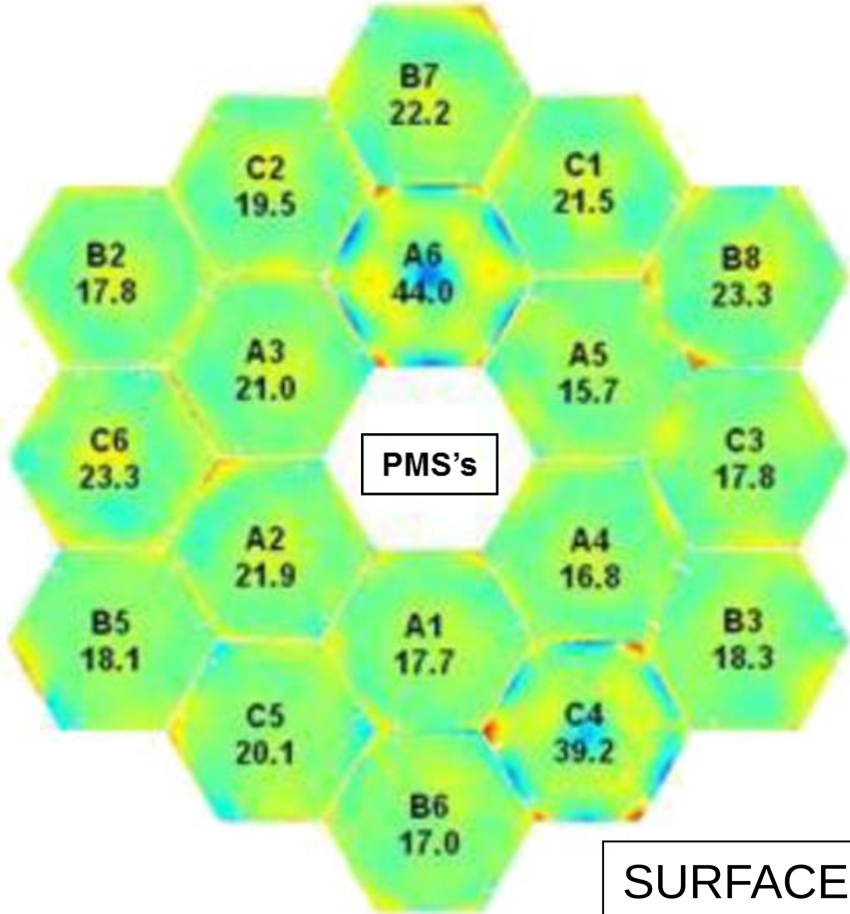
- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

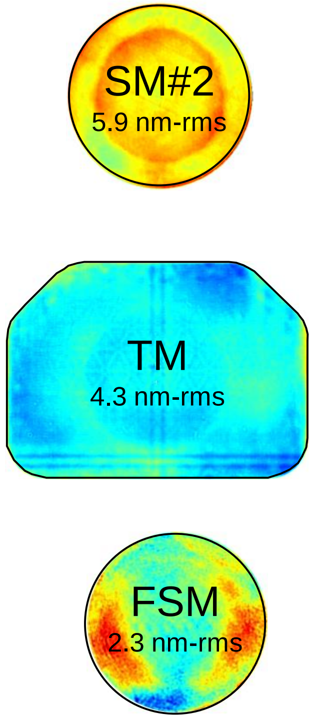
Mirror Fabrication

Spare Mirrors



Flight Mirrors



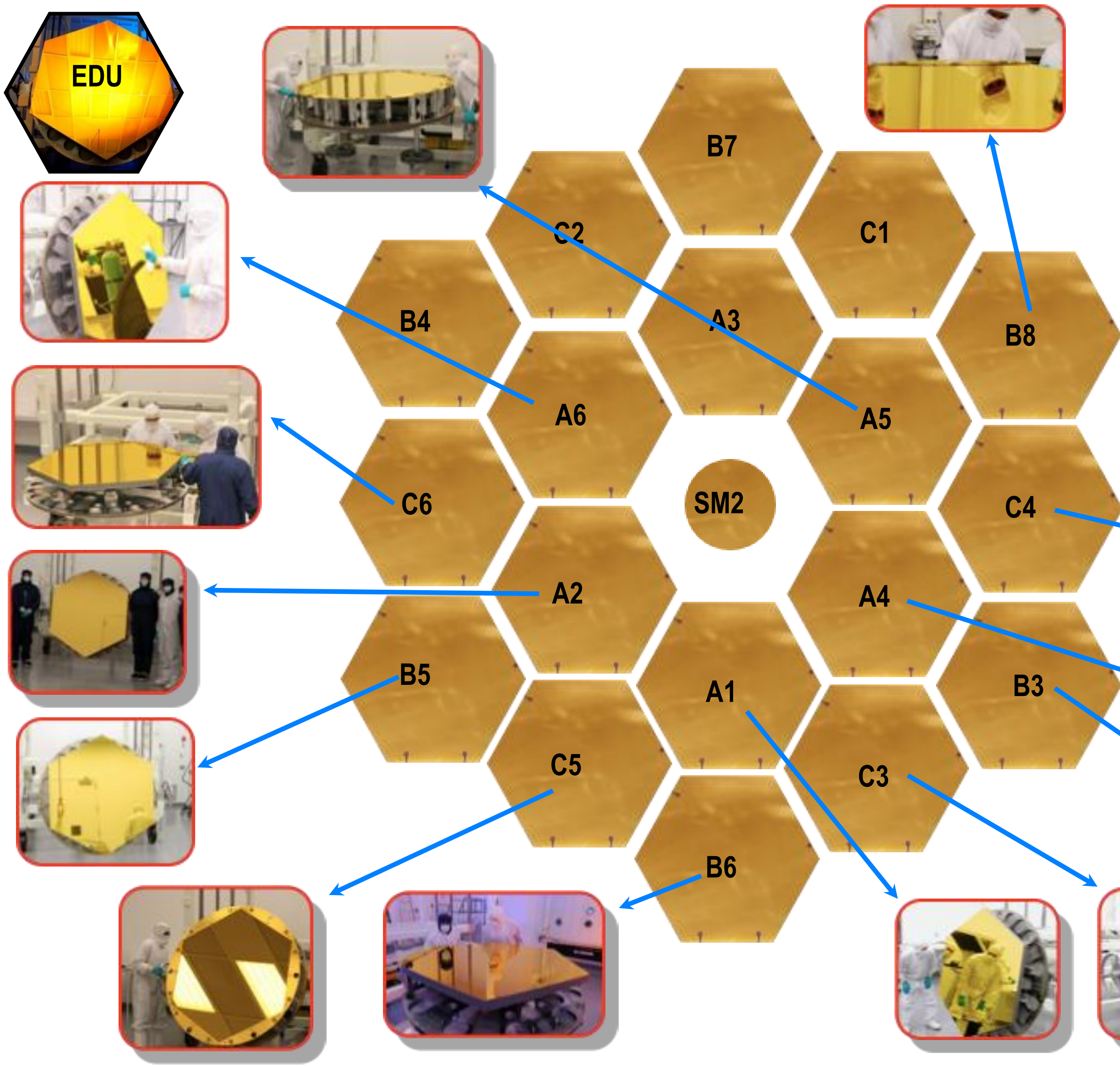


SURFACE FIGURE ERROR

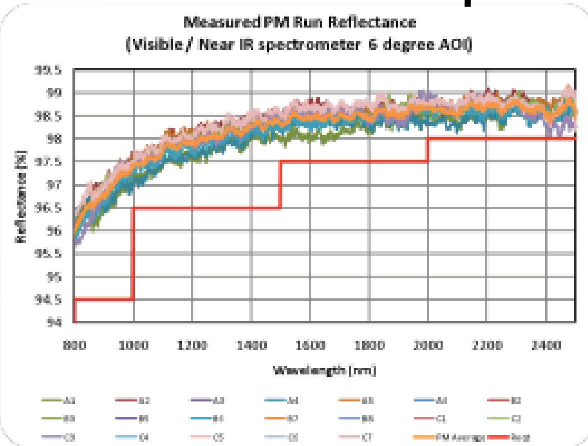
Total PM Composite:	23.2 nm RMS
PM Requirement:	25.0 nm RMS

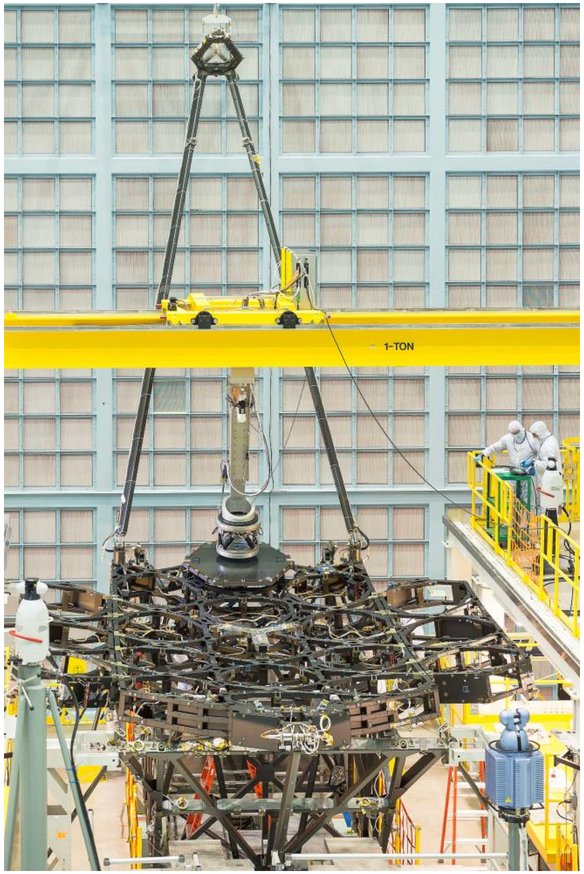
James Webb Space Telescope: large deployable cryogenic telescope in space. Lightsey, Atkinson, Clampin and Feinberg, Optical Engineering 51(1), 011003 (2012)

Gold Coated Mirror Assemblies

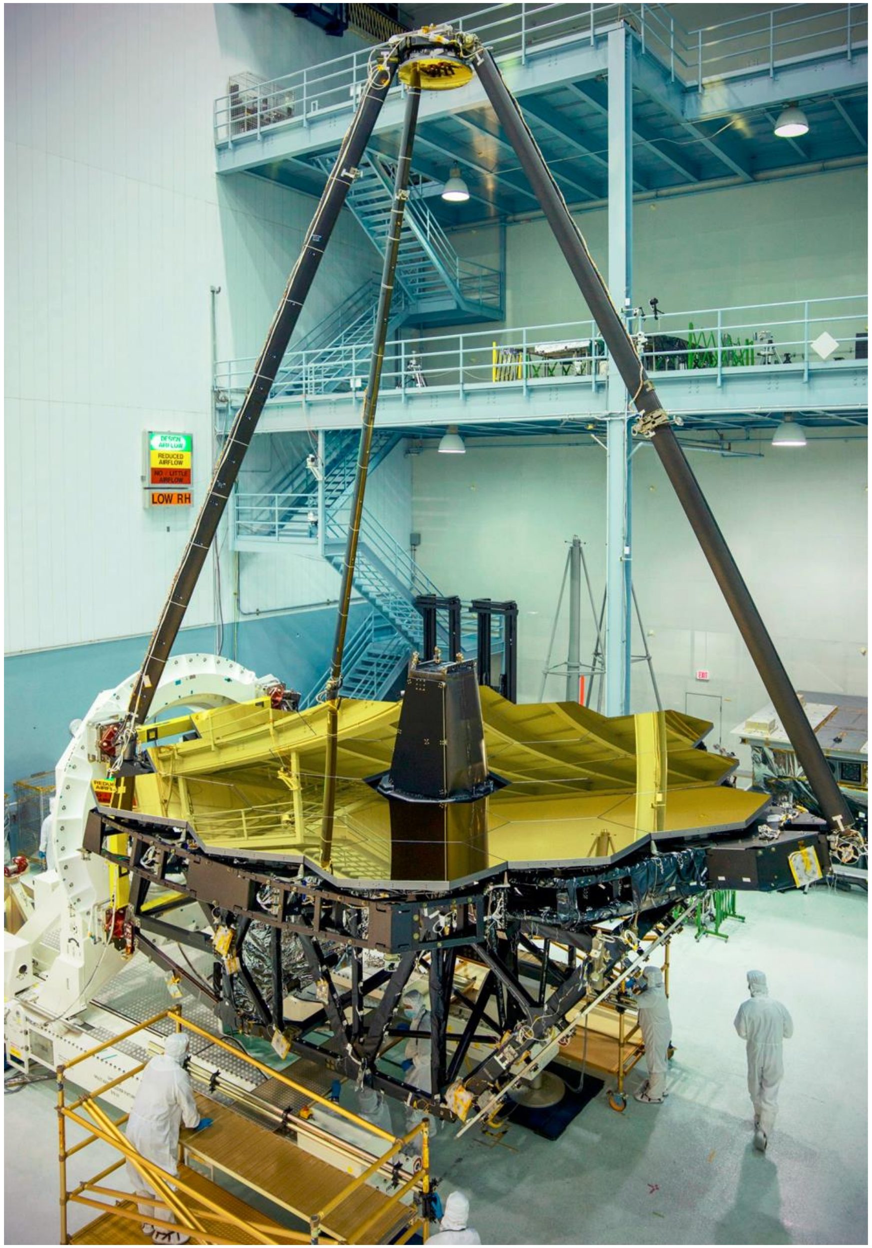


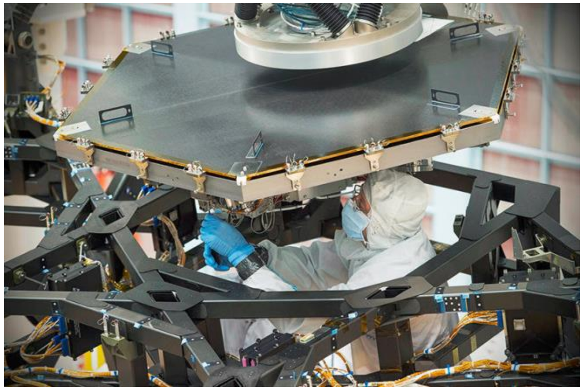
Mirrors ≥ 98% at 2 µm





Optical Telescope Assembly

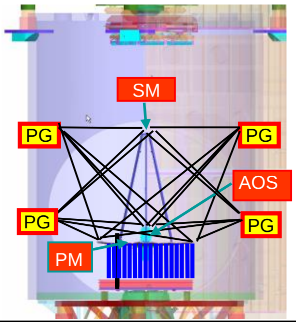




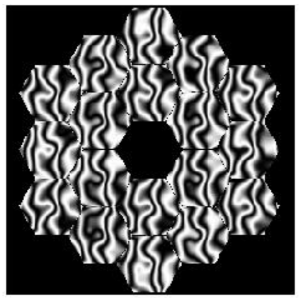
Observatory level testing occurs at JSC Chamber A

Verification Test Activities in JSC Chamber-A

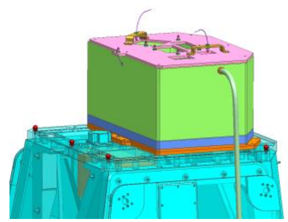
Cryo Position Metrology



Primary Mirror Stability Test

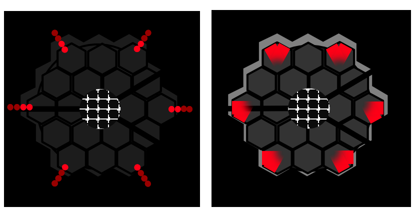


Focus Sweep Test (inward facing sources)

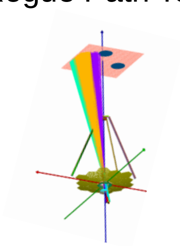


Crosscheck Tests in JSC Chamber-A

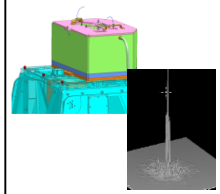
Pupil Alignment Test



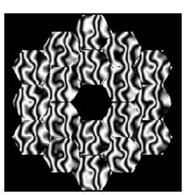
Rogue Path Test



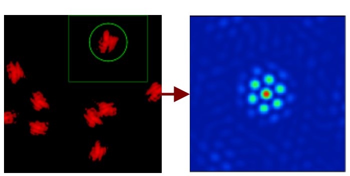
Pass-and-a-Half Test

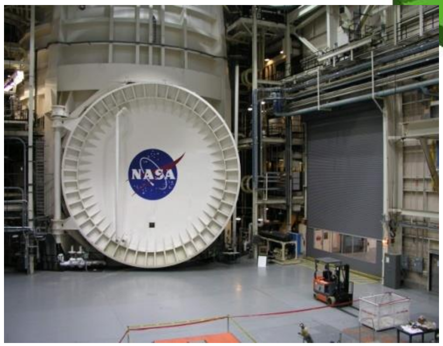


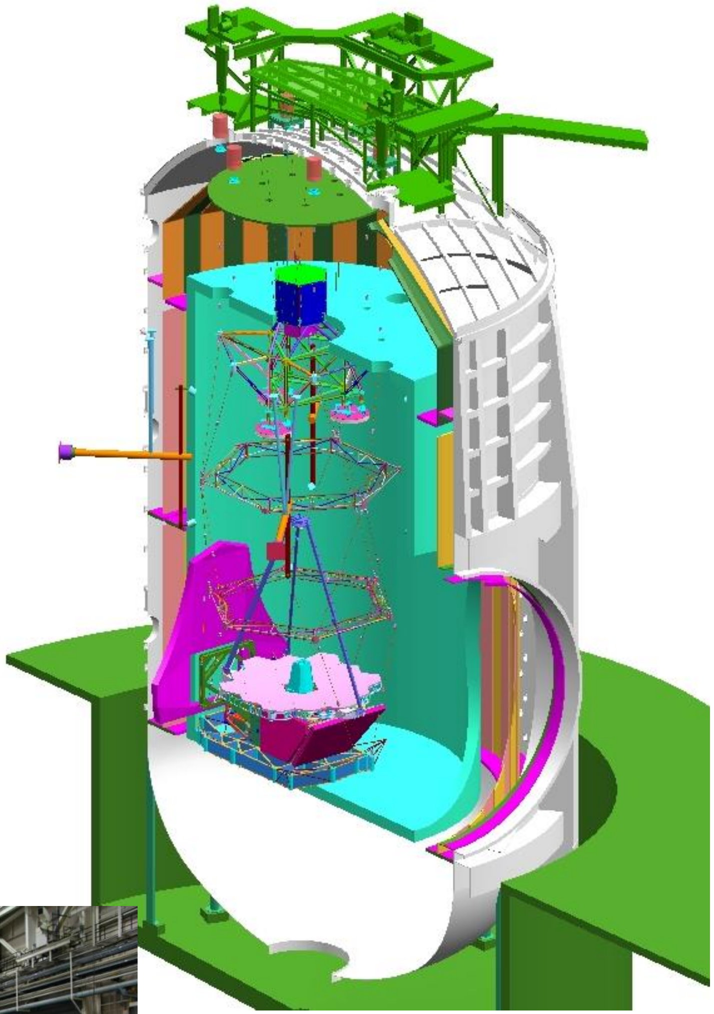
Primary Mirror WFE Test



End-to-End WFSC Demonstration



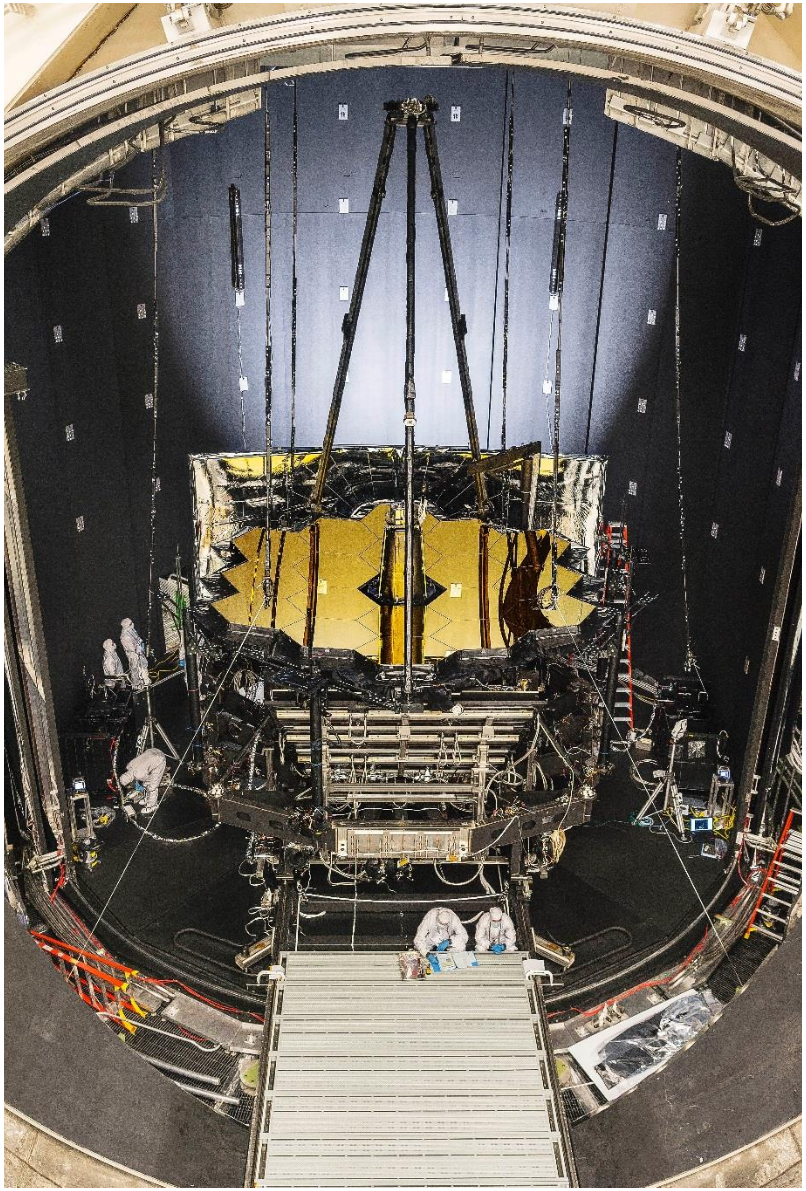


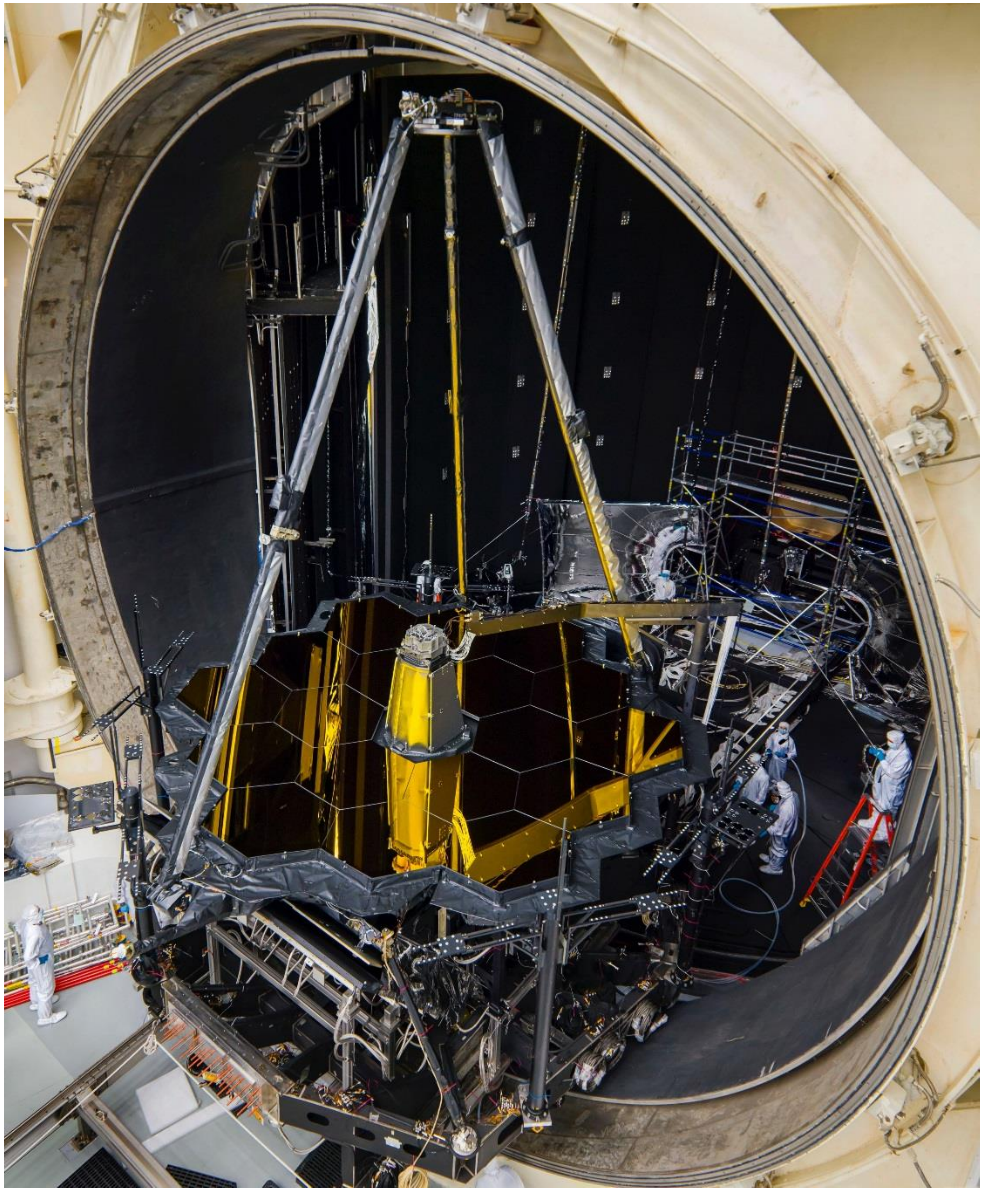


<u>Chamber A:</u>

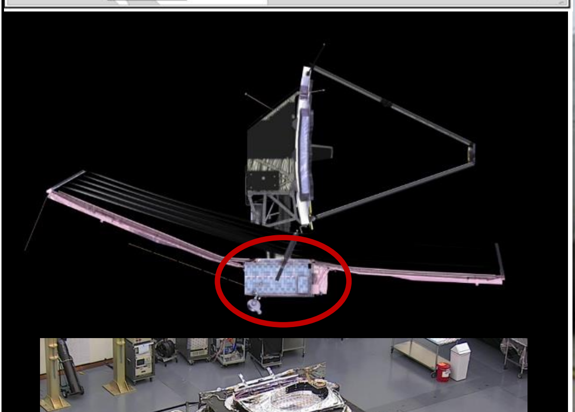
- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

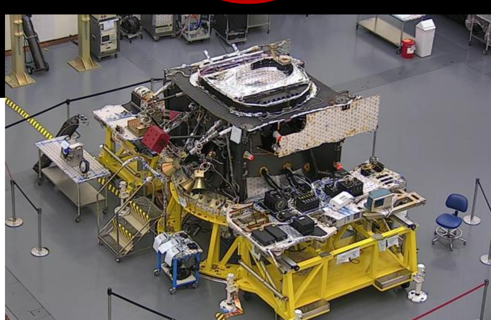
End-to-end optical testing at JSC July 2017 to Nov 2018





Telescope & instrument module now at Northrop Grumman for integration with the spacecraft bus and sunshield





Space Telescope Transporter for Air Road and Sea (STTARS)

Integration of Telescope with Spacecraft & Sunshade at Northrop

Mobile Cleanroom Moves JWST to Vibe Test at Northrop

JWST will be transported by ship through Panama Canal to French Guiana for launch during March 2021

6900 Nautical Miles
Approximately 20 days

Roll on roll off transport ship built in the Netherlands by Merwede Shipyards

- Length 116m
- Displacement about 4200 metric tons
- Garage deck length 95m (plenty of room for STTARS)
- Speed: 15 knots

Space Telescope Transporter for Air Road and Sea (STTARS)

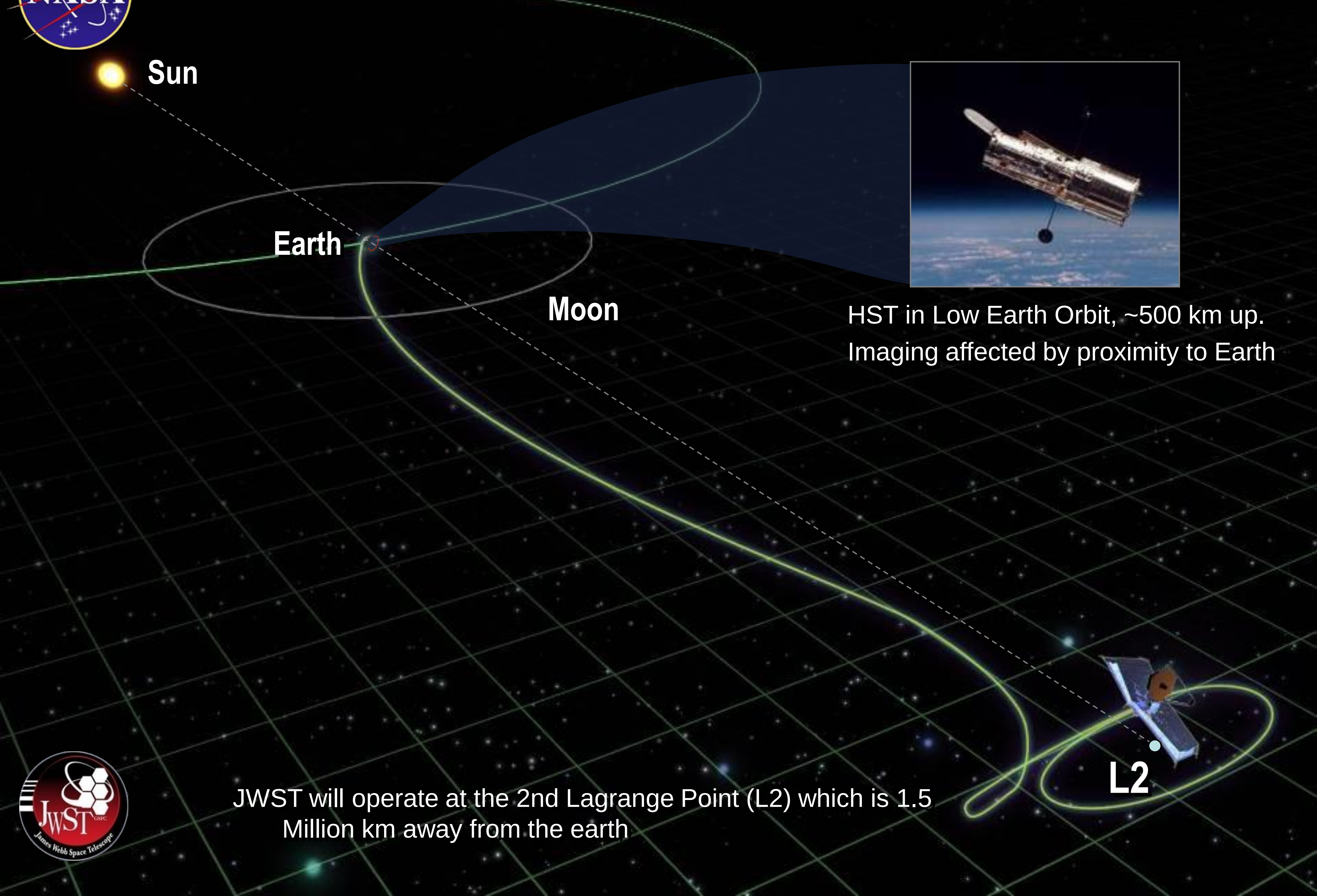
JWST Launched on Ariane 5 Heavy

JWST folded and stowed for launch in 5 m dia x 17 m tall fairing

Launch from Kourou Launch Center (French Guiana) to L2

JWST vs. HST - orbit

NORTHROP GRUMMAN Space Technology



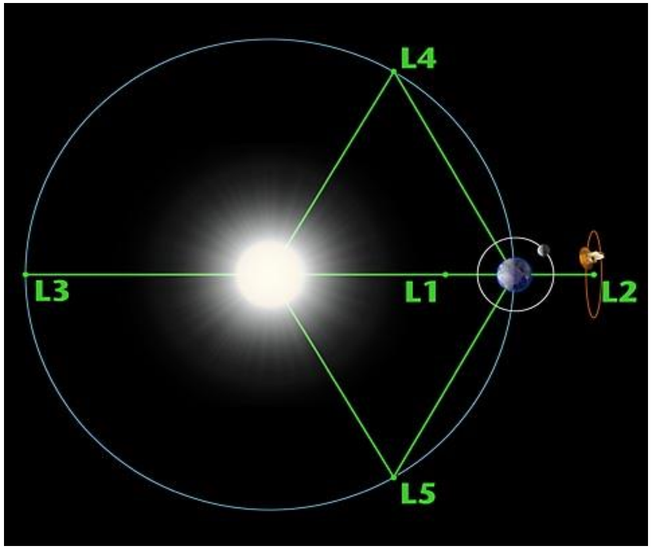
L2 Orbit Enables Passive Cryogenic Operation

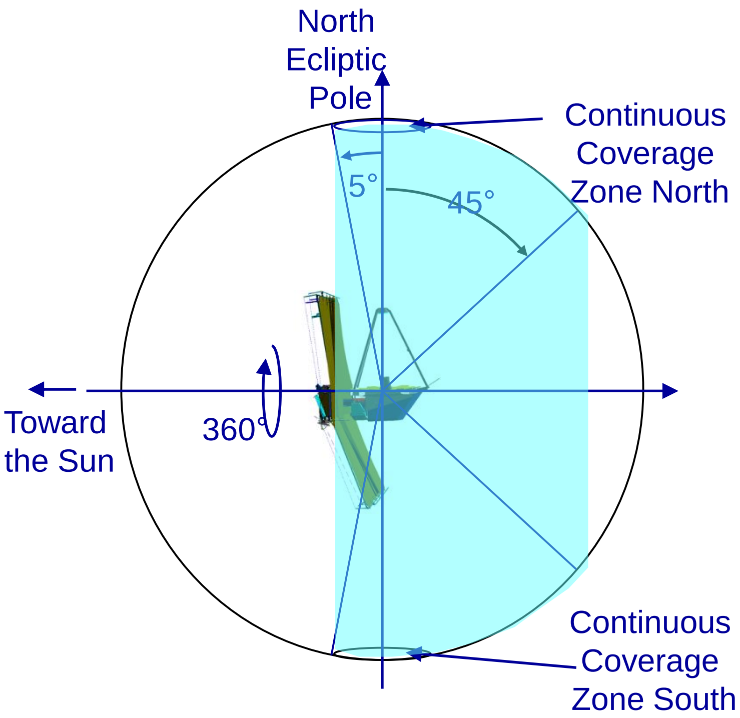
Second Lagrange Point (L2) of Sun-Earth System

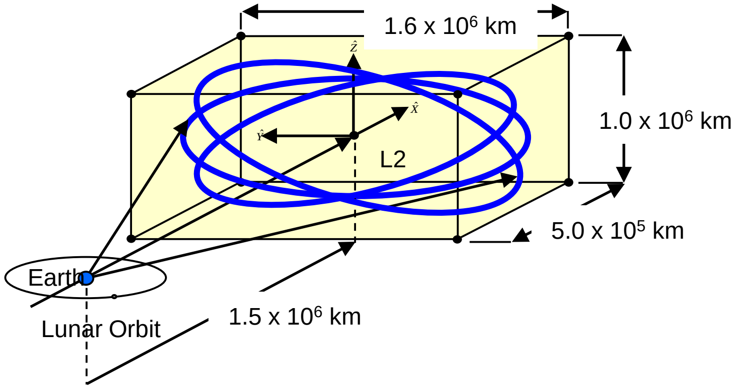
- This point follows the Earth around the Sun

The orbital period about L2 is ~ 6 months

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



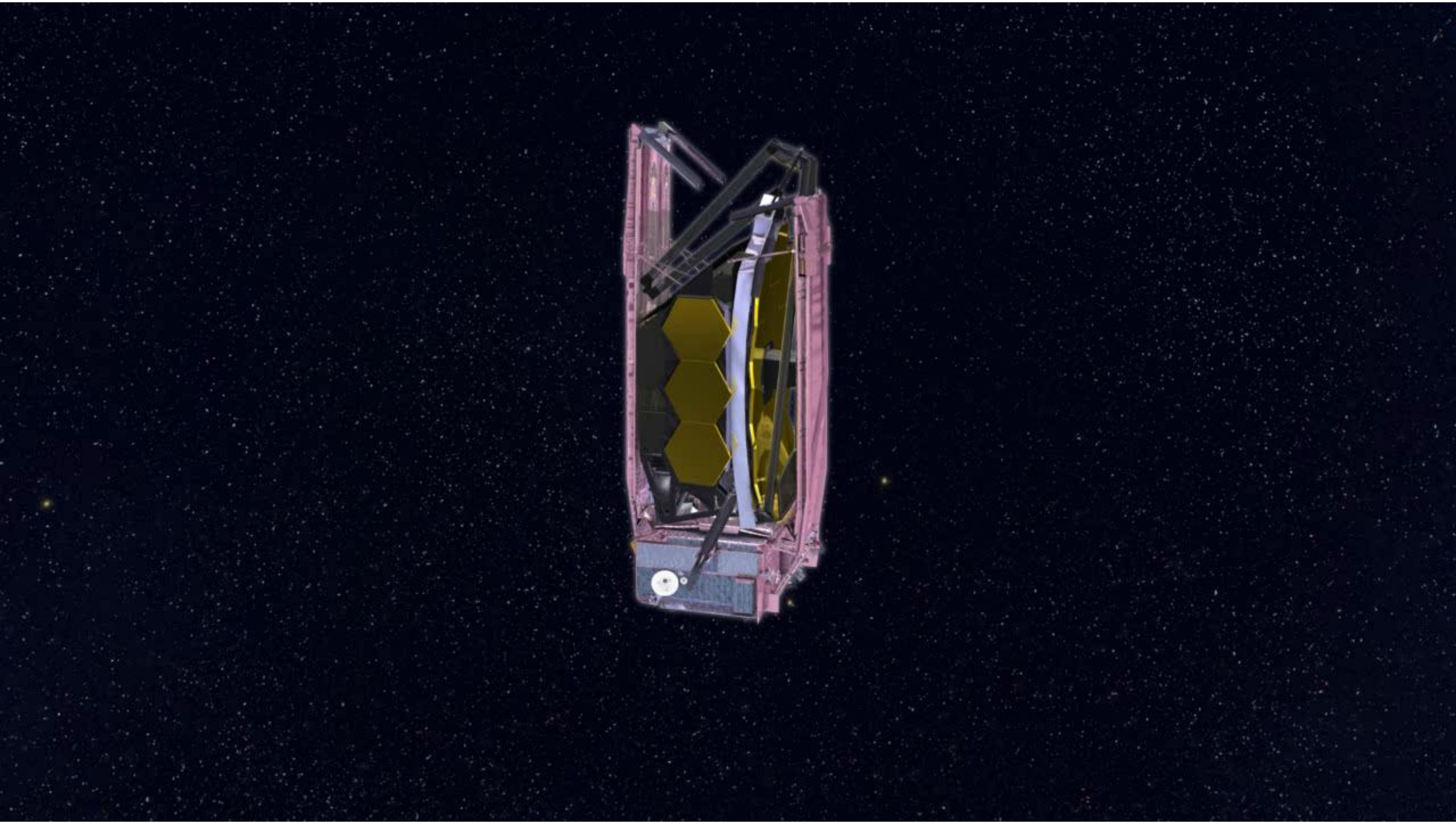




JWST observes whole sky while remaining continuously in shadow of its sunshield

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

JWST Deployment

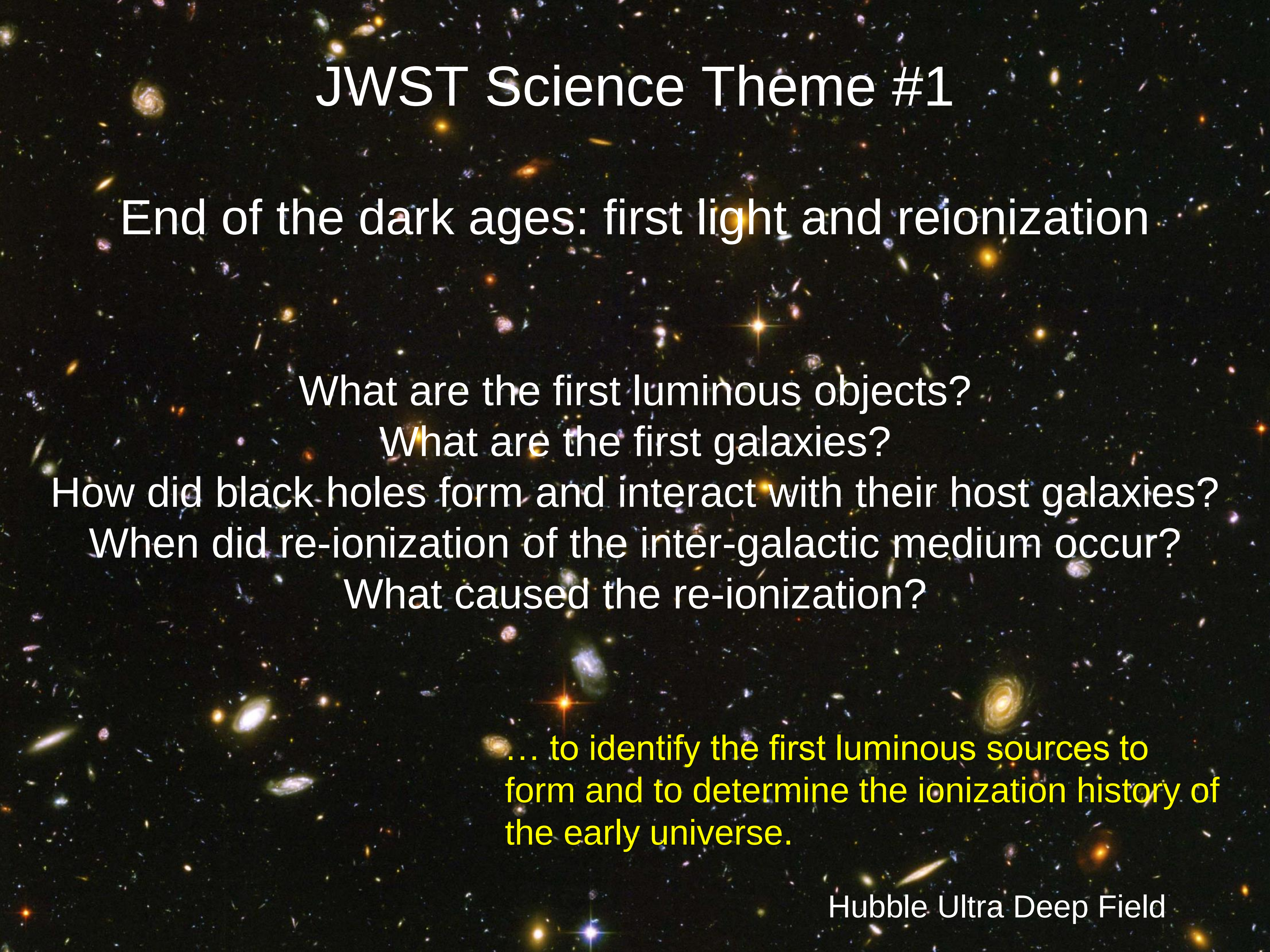


JWST Science Theme #1

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

When and how did reionization occur?

Reionization happened z > 6 or < 1 B yrs after Big Bang.

WMAP says maybe twice?

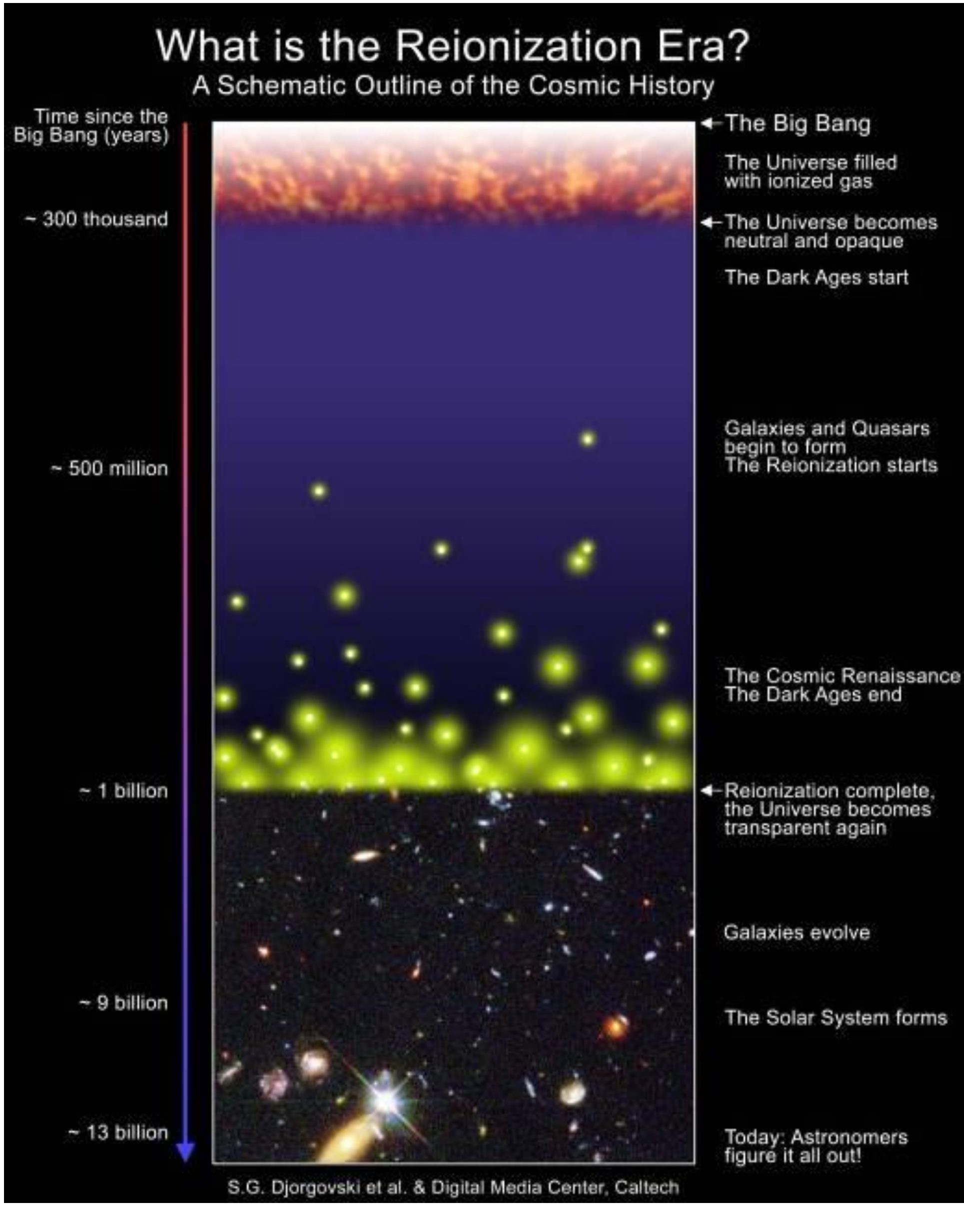
Probably **galaxies**, maybe quasar

Key Enabling Design Requirements:

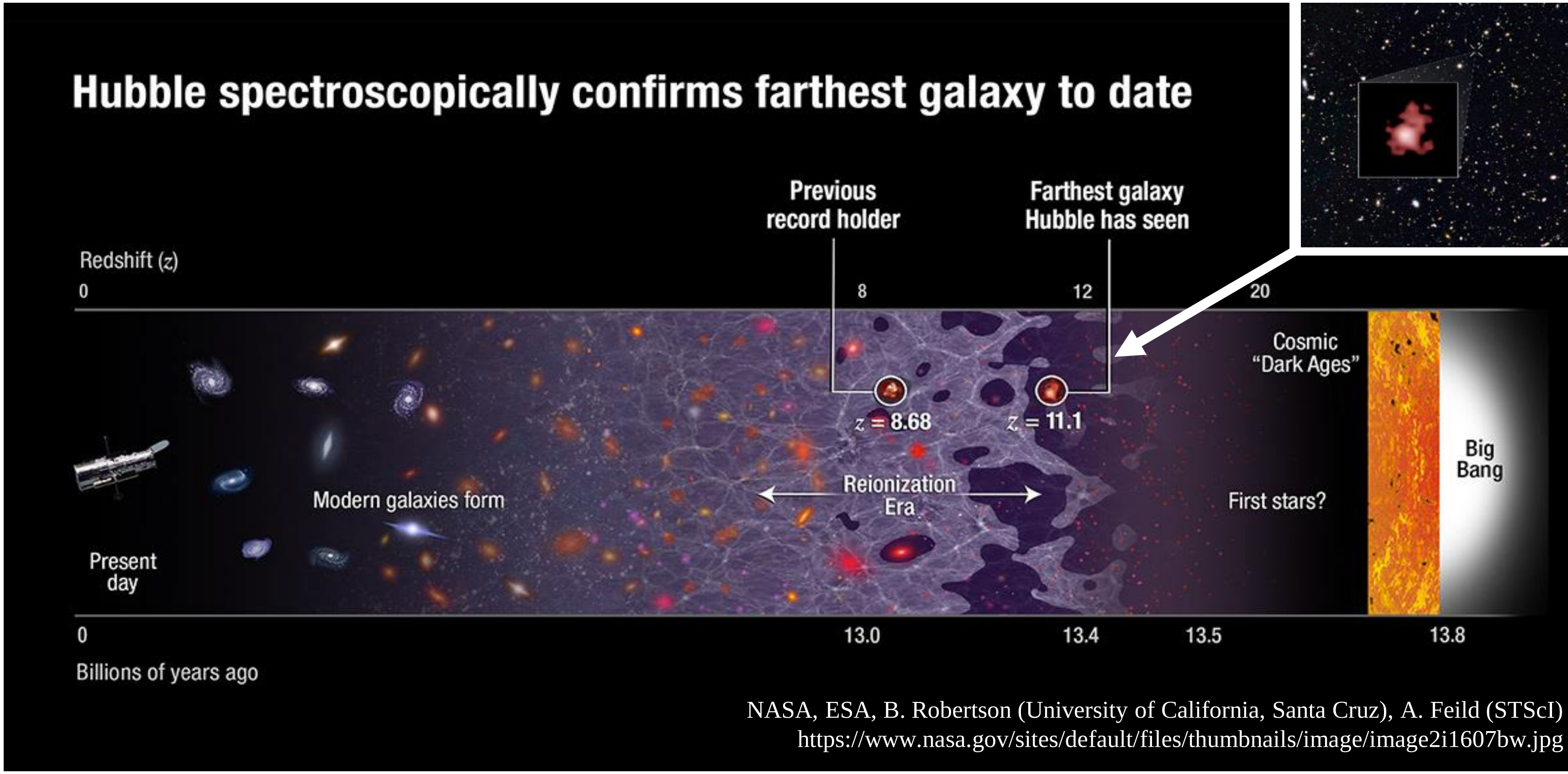
- Deep near-infrared imaging survey (1nJy)
- Near-IR multi-object spectroscopy
- Mid-IR photometry and spectroscopy

JWST Observations:

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



Studying Early Universe: 'First' Galaxies

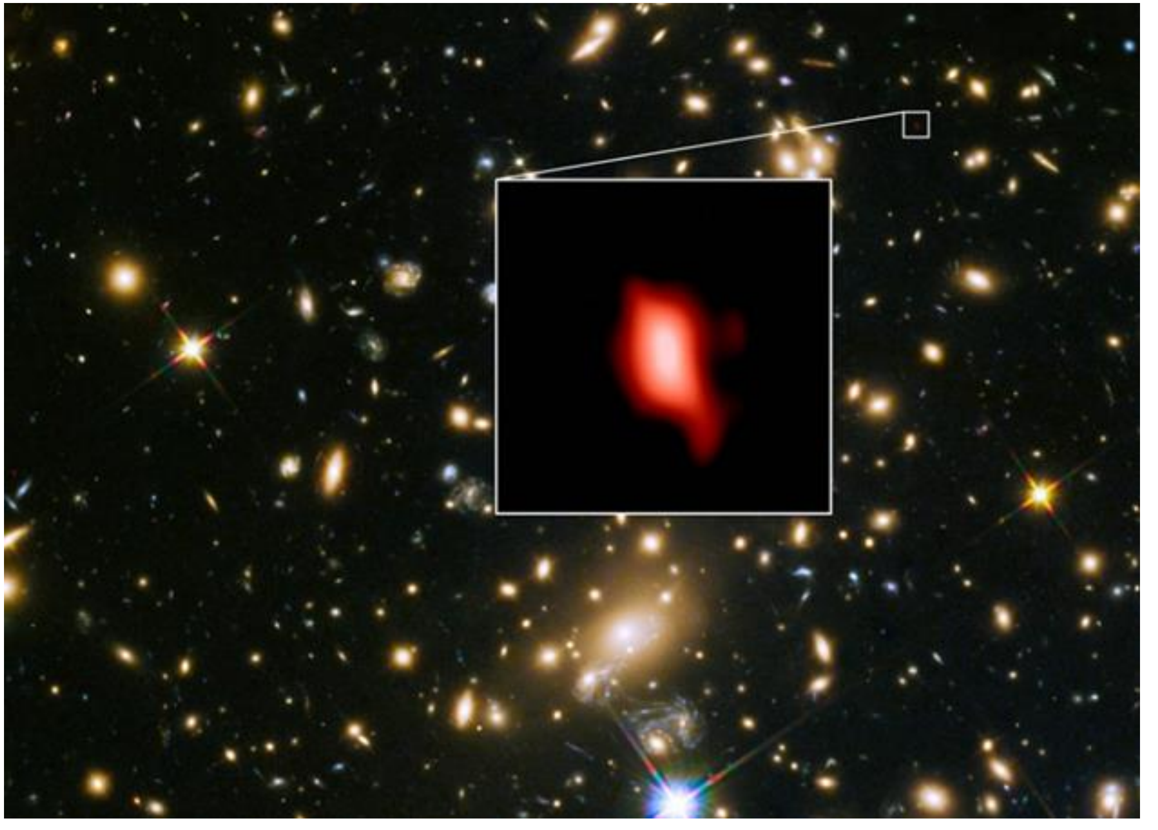


Galaxy GN-z11 is 13.4 B-yrs away, just 400 M-yrs after BB.

It is 25X smaller than and has only 1% the mass of Milky Way, but is forming stars 20X faster (produced by large gas inflow).

Other 'first' galaxies are forming stars 1000X faster.

Oldest Star Formation – 250M yrs after BB

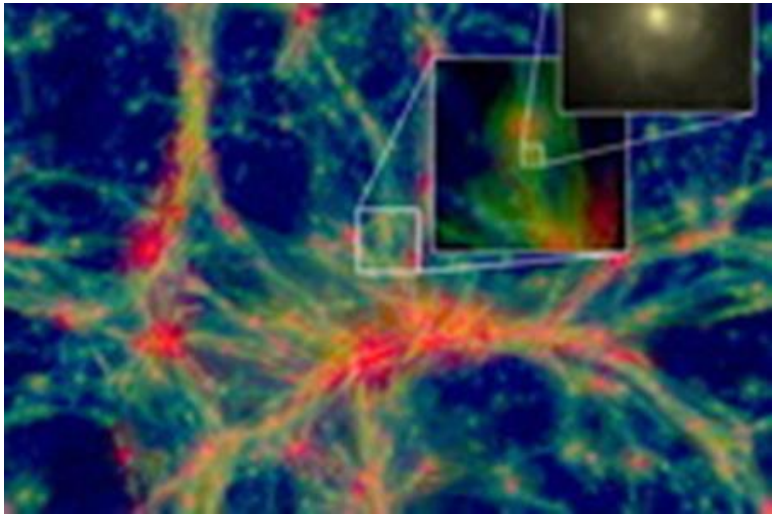


Oxygen was detected in the very distant galaxy MACS1149-JD1 using the Atacama Large Millimeter/submillimeter Array (APMA) and ESO's Very Large Telescope (VLT) to determine that star formation started at an unexpectedly early stage, only 250 million years after the Big Bang.

Keith Cowing, SPACEREF.com, 16 May 2018

First Galaxies form in Cosmic Web

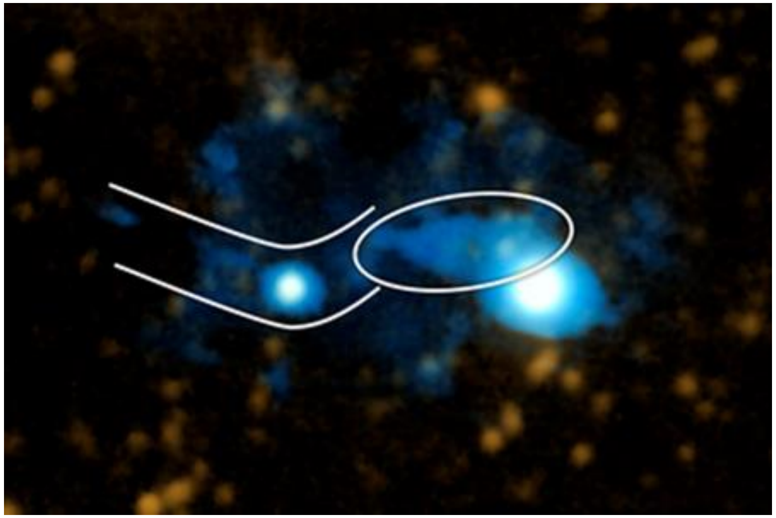
Ripples in the early universe formed long filaments of hydrogen gas surrounded by 'dark matter'.



Galaxies form at crossing points.

Most of universe's matter is in these filaments and dark matter.

This one is 10B light years away.

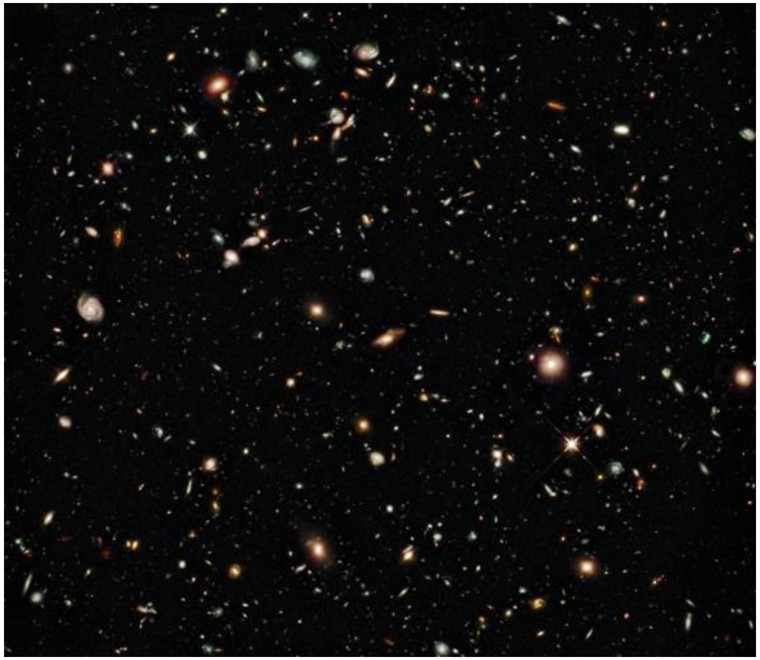


A filament of the universe's "cosmic web" is highlighted with parallel curved lines in this image, while a protogalaxy is outlined with an ellipse. The brightest spot (on the lower right side of the ellipse) is the quasar UM287. The other bright spot is a second quasar in the system. The image combines a visible light image with data from the Cosmic Web Imager.

CREDIT: Chris Martin/PCWI/Caltech

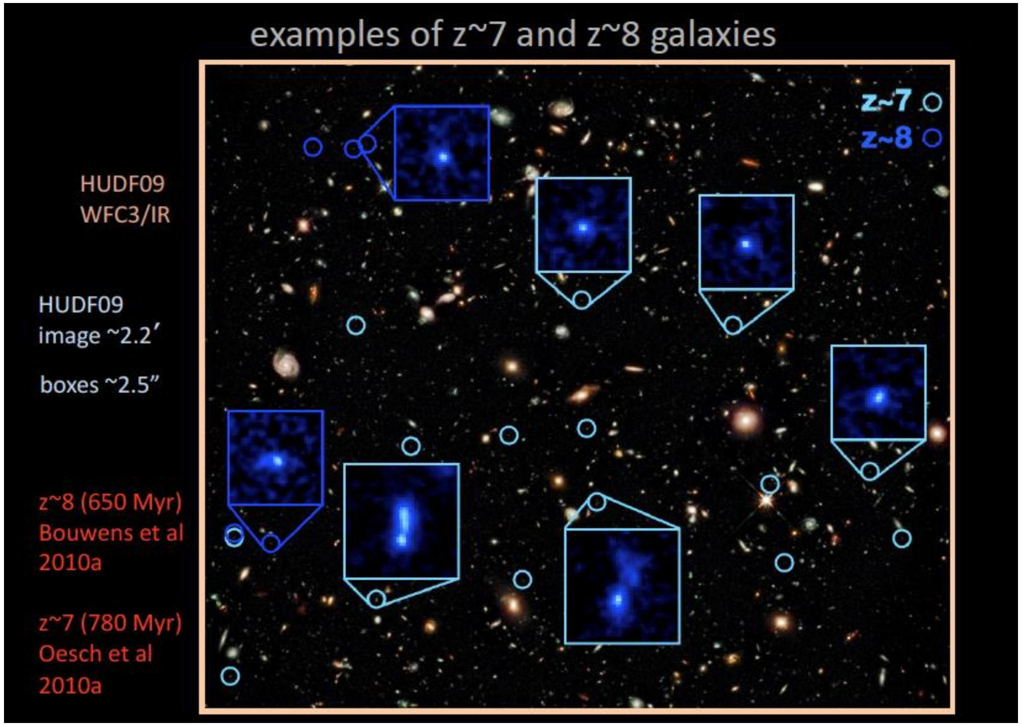
Charles Choi, Space.com, 5 Aug 2015.

Hubble Ultra Deep Field – Near Infrared



Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

Hubble Ultra Deep Field – Near Infrared



47 Galaxies have been observed at 600 to 650 Myrs after BB.

Hubble Ultra Deep Field – Near Infrared overlaid with Chandra Deep Field South

CREDIT: X-ray: NASA/CXC/U.Hawaii/E.Treister et al; Optical: NASA/STScI/S.Beckwith et al

Keith Cooper, Astronomy Now, 15 June 2011
Taylor Redd, SPACE.com, 15 June 2011

What came first – Galaxies or Black Holes?

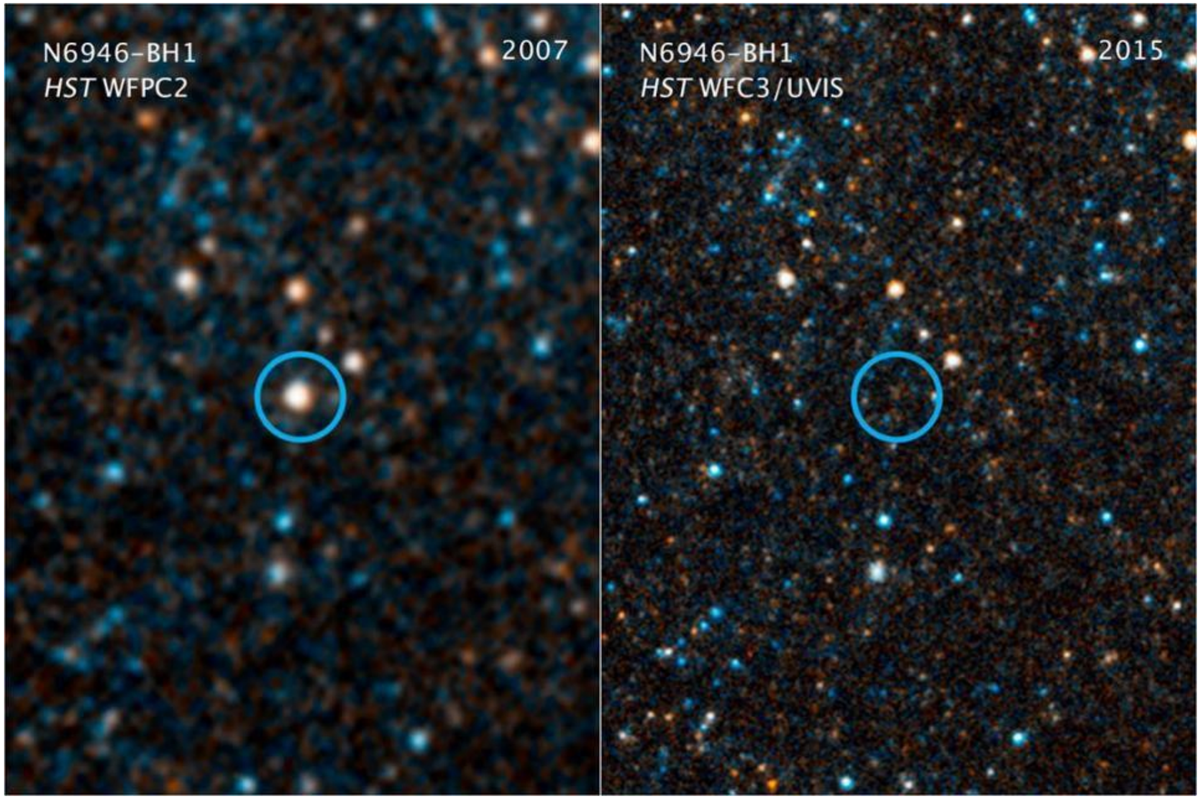
Each of these ancient 700 M yrs after BB galaxies has a black hole.

Only the most energetic x-rays are detected, indicating that the black-holes are inside very young galaxies with lots of gas.

First Black Holes

One theory for ‘first’ black holes is direct collapse of ‘first’ stars.

Below shows disappearance of 25X times our Sun star without a supernova.

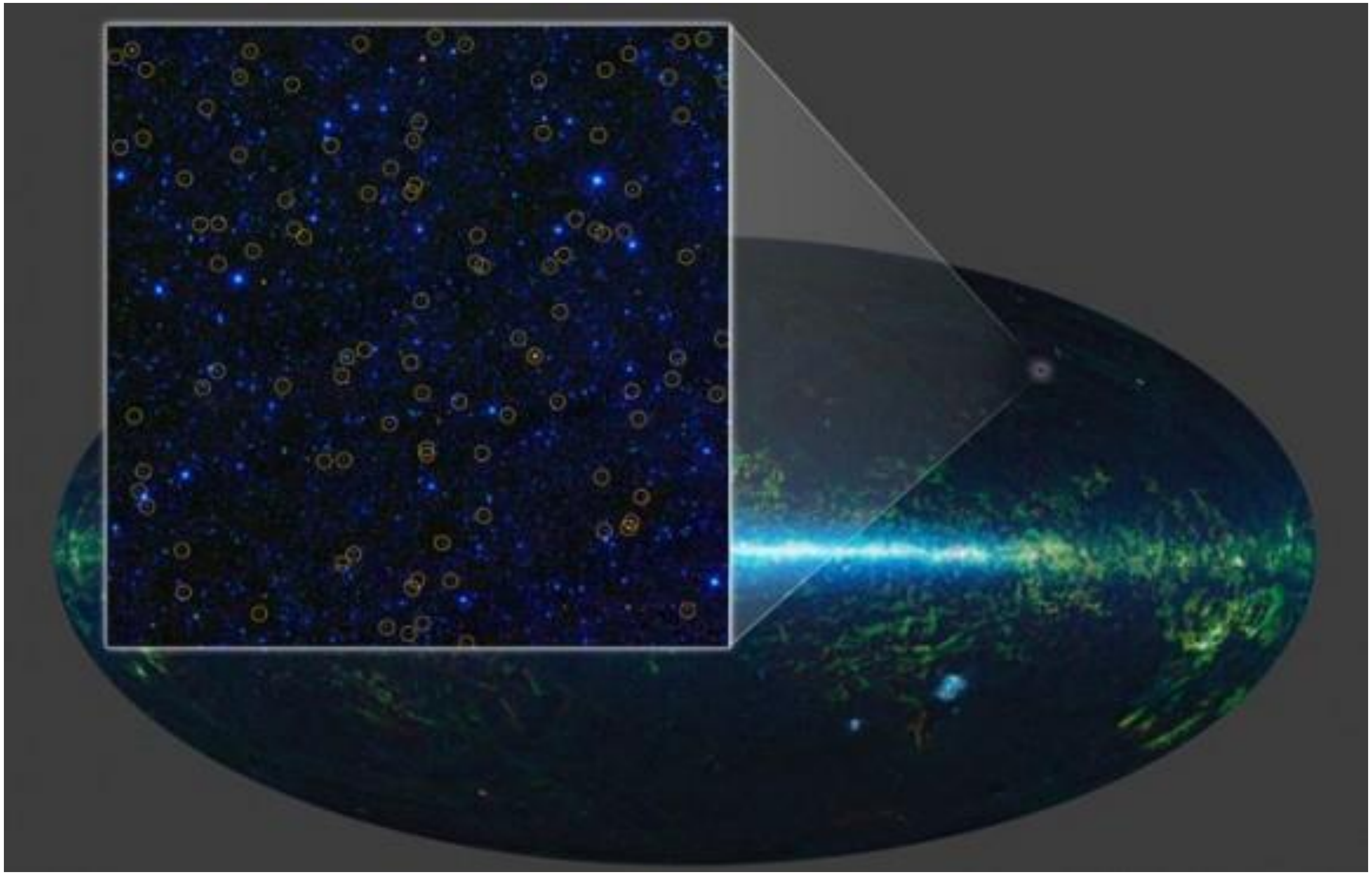


The visible/near-IR photos from Hubble show a massive star, about 25 times the mass of the Sun, that has winked out of existence, with no supernova or other explanation. Direct collapse is the only reasonable candidate explanation. NASA/ESA/C. Kochanek (OSU)

Ethan Siegel, FORBES.com, 24 Oct 2018

WISE is Wide-Field IR ‘finder scope’ for JWST

WISE has found millions of black holes in galaxies previously obscured by dust called hot DOGs, or dust-obscured galaxies.



Nancy Atkinson , Universe Today, on August 29, 2012

Oldest & Brightest Quasar – 770M yrs after BB

This Quasar is 770 million years after Big Bang, is powered by a black hole 2 billion times the mass of our Sun and emits 60 trillion times as much light as the sun. How a black hole became so massive so soon after the Big Bang is unknown.

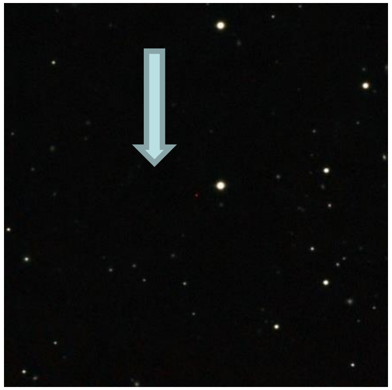


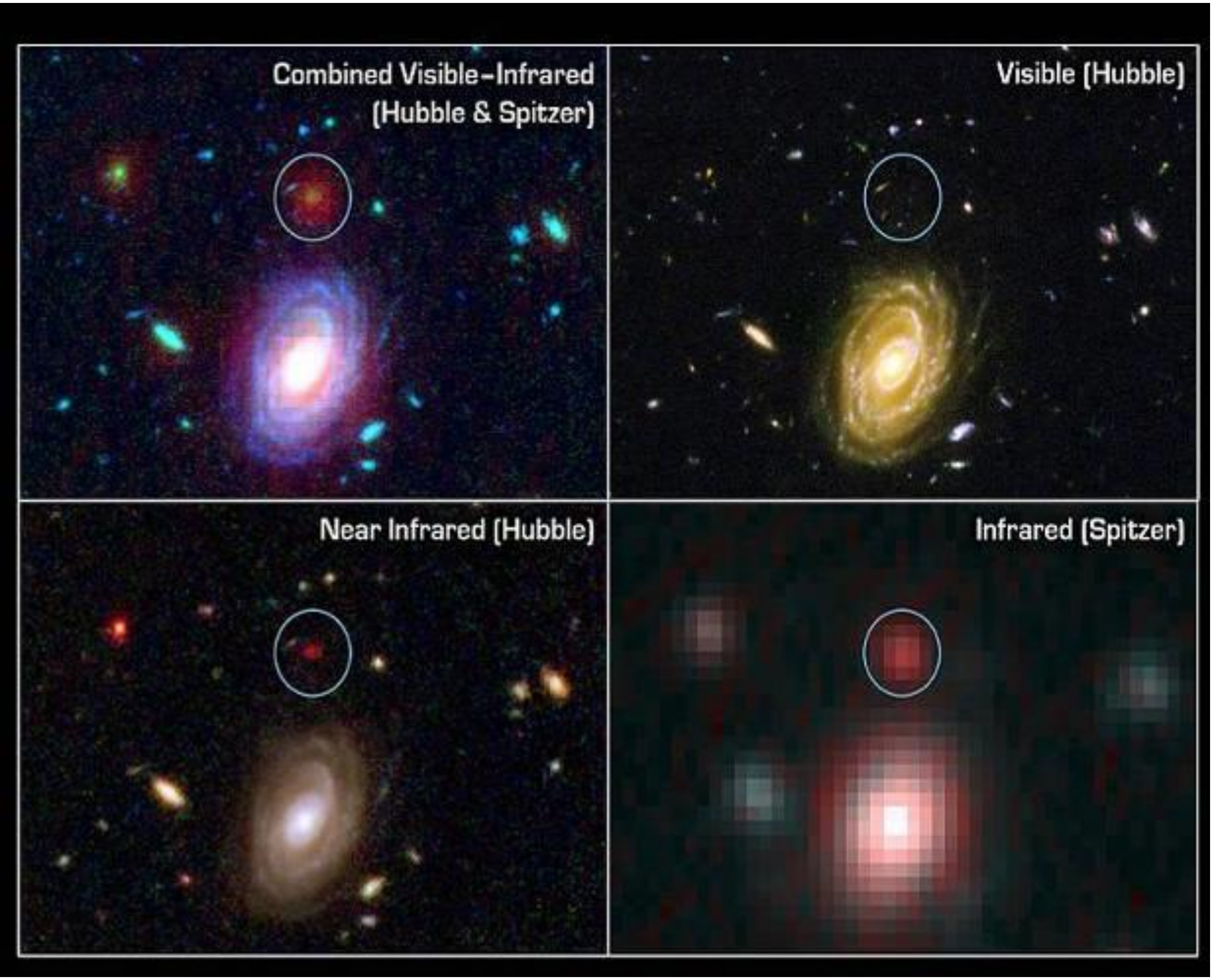
Image of ULAS J1120+0641, a very distant quasar powered by a black hole with a mass 2 billion times that of the sun, was created from images taken from surveys made by both the Sloan Digital Sky Survey and the UKIRT Infrared Deep Sky Survey. The quasar appears as a faint red dot close to the centre. CREDIT: ESO/UKIDSS/SDSS

"It is like finding a 6-foot-tall child in kindergarten," says astrophysicist Marta Volonteri, at the University of Michigan in Ann Arbor.

The spectra of the light from this (and other early light objects) indicate that the Universe was still filled with significant amounts of neutral hydrogen even 770 Myrs after big bang.

Nadia Drake , Science News, 29 June 2011
Charles Q. Choi, SPACE.com, 29 June 2011

Unexpected "Big Babies": 800M yrs after BB



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.

JWST Science Theme #2:

The assembly of galaxies

How did the heavy elements form?
How is the chemical evolution of the universe related to galaxy evolution?
What powers emission from galaxy nuclei?

When did the Hubble Sequence form?
What role did galaxy collisions play in their evolution?
Can we test hierarchical formation and global scaling relations?
What is relation between Evolution of Galaxies & Growth/Development of Black Holes in their nuclei?

… 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

Formation of Heavy Elements

Carl Sagan said that we are all ‘star dust’.

All of the heavy elements which exist in the universe were formed from Hydrogen inside of stars and distributed via supernova explosions. But observations in the visible couldn’t find enough dust.

Dust is cold, therefore, it can only be seen in IR.

Looking in the IR (with Herschel and Spitzer) at Supernova 1987A, 100,000X more dust was seen than in the visible – the total mass of this dust equals about half of our Sun.

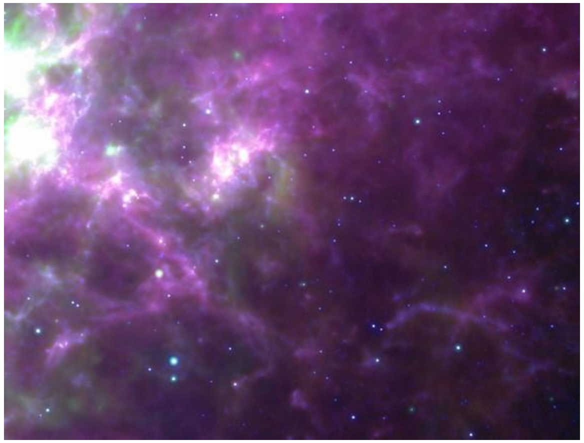
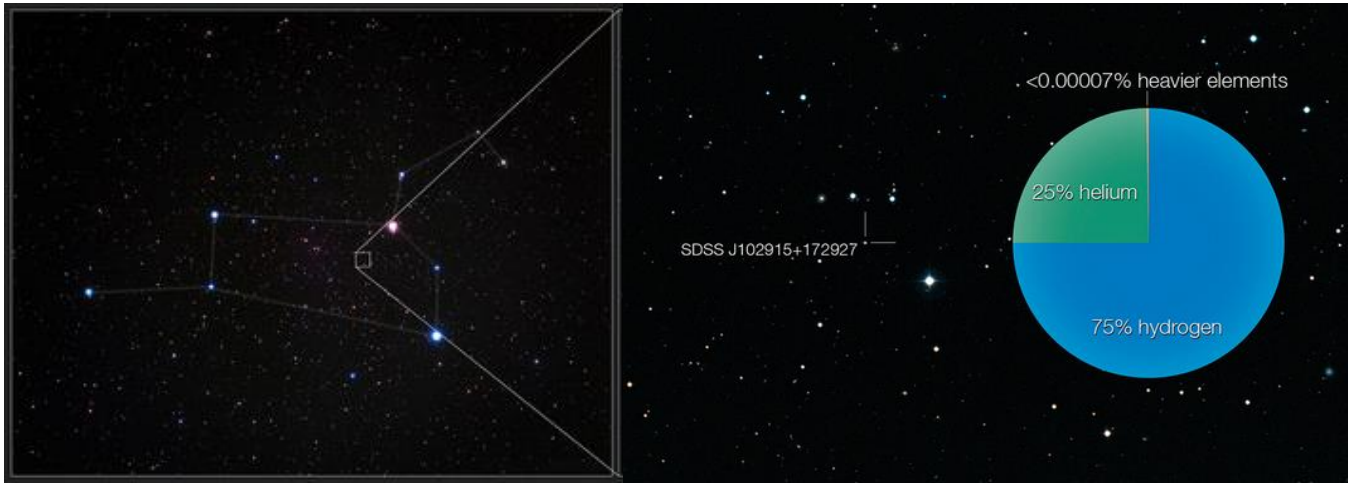


Image of Supernova 1987A, taken in the infrared by Herschel and Spitzer, shows some of the warm dust surrounding it.
CREDIT: Pasquale Panuzzo
SPACE.com, Taylor Redd, 7 July 2011

2nd Generation Stars – 700M yrs after BB

This star is a 2nd generation star after the big bang because it has trace amounts of heavy elements – meaning that at least one supernova had exploded before it was formed.

But its existence contradicts current theories because it has too much Hydrogen and too much Helium and not enough Carbon and other heavy elements.



Nola Taylor Redd, SPACE.com, 31 August 2011; CREDIT: ESO/Digitized Sky Survey 2

Chemical make-up of Early Universe

1.8 B yr after BB gamma-ray burst illuminates neighboring galaxies yielding spectra of their chemical makeup.

Metals in the early universe are higher than expected – indicating that star formation in the early universe was much higher than current theory.

GRB 090323 was first detected on 23 March 2009 by NASA's Fermi space telescope and then the Swift satellite, shortly followed by the ground-based GROND system (Gamma-Ray burst Optical and Near-infrared Detector) at the MPG/ESO 2.2-metre telescope in Chile, as well as ESO's Very Large Telescope (VLT). The VLT observations revealed that the gamma-ray burst injected light through its host galaxy and another nearby galaxy, which are both seen at a redshift of 3.57, equivalent to 12 billion years ago.

DR EMILY BALDWIN, ASTRONOMY NOW, 02 November 2011

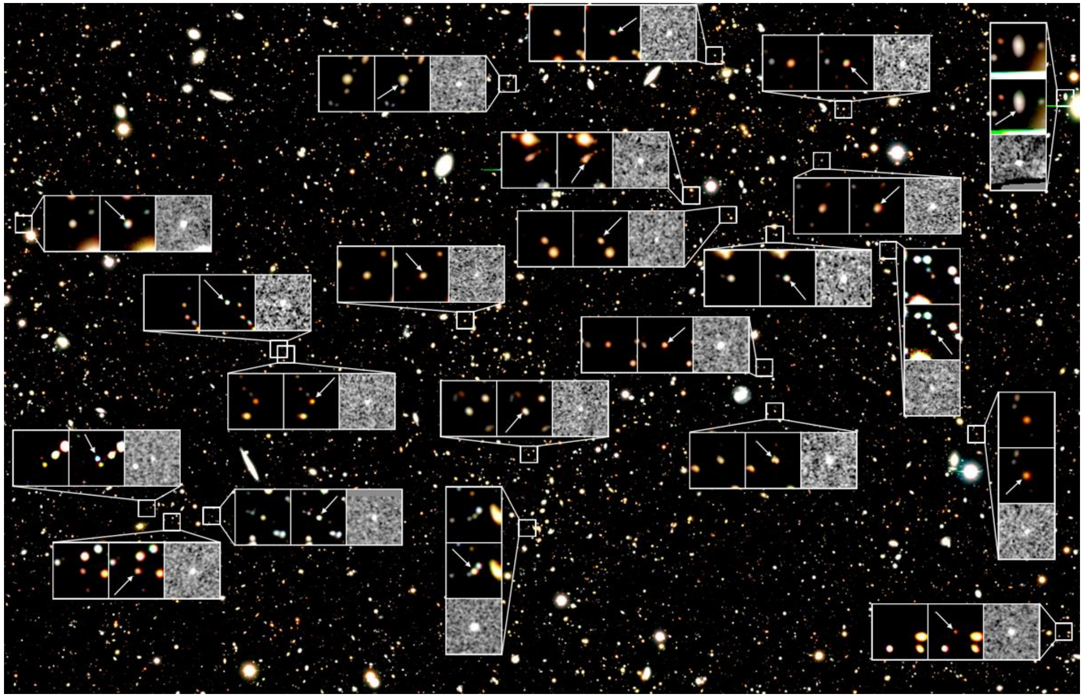
Subaru Deep Field: Ancient Supernova 3.7B yrs after BB

22 of 150 ancient supernovae in 10% of Subaru Deep Field

12 occurred around 3.7B yrs after big bang.

Supernova were 10X more frequent at this time than today.

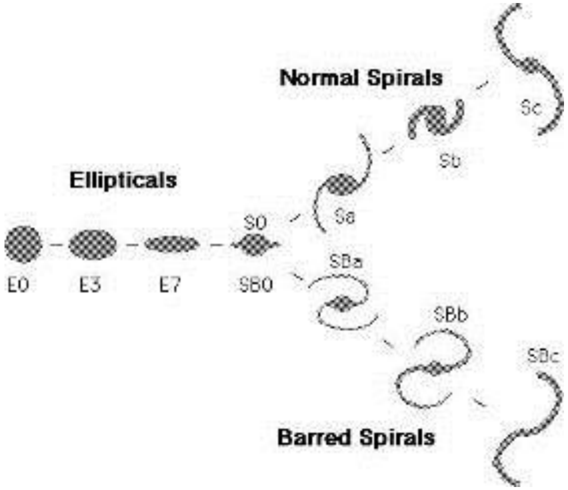
Supernova helped seed early universe with chemical elements.



Clara Moskowitz, SPACE.com, 05 October 2011

The Hubble Sequence

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



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

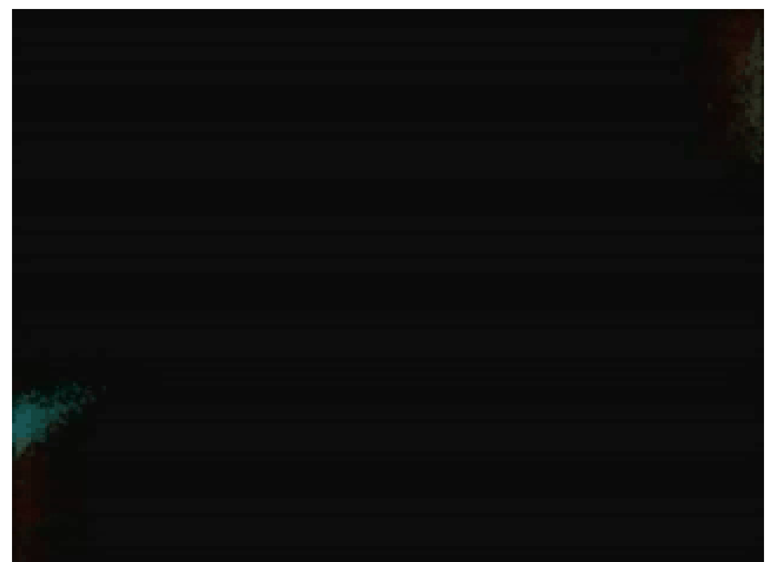
Where and when did the Hubble Sequence form?

Galaxy assembly is a process of hierarchical merging

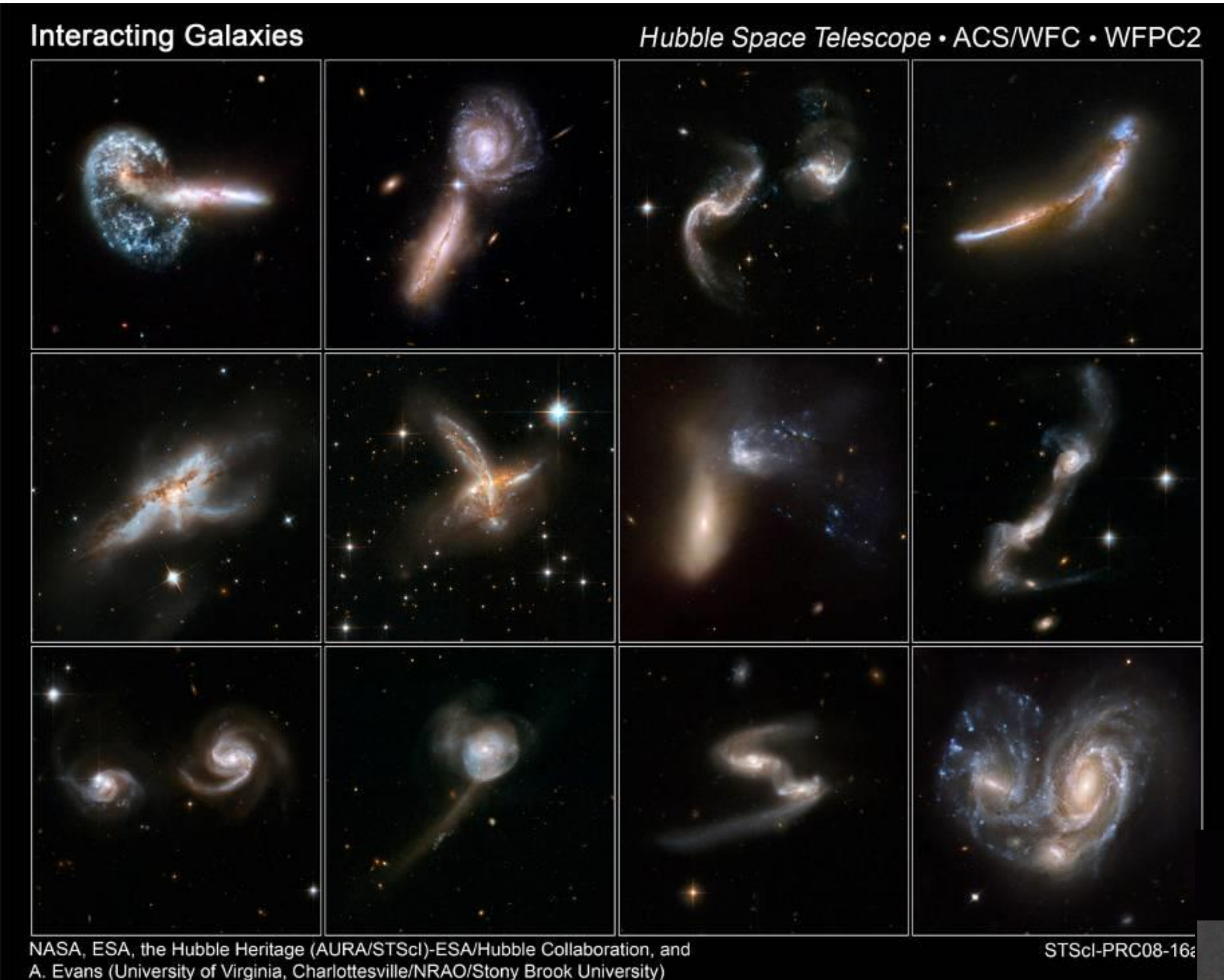
Components of galaxies have variety of ages & compositions

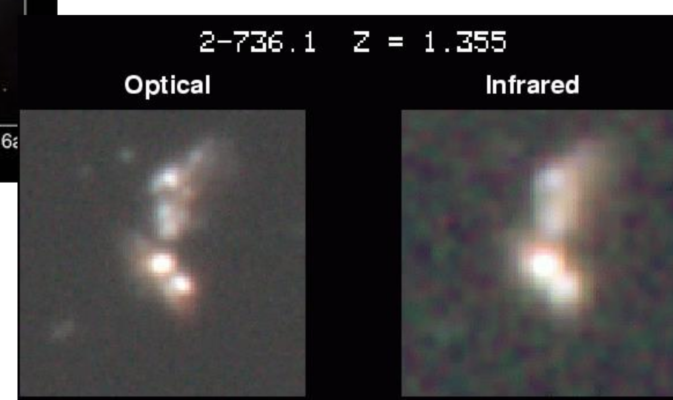
JWST Observations:

- 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"





Merging Galaxies = Merging Black Holes

Combined Chandra & Hubble data shows two black holes (one 30M & one 1M solar mass) orbiting each other – separated by 490 light-years. At 160 million light-years, these are the closest super massive black holes to Earth.

Theory says when galaxies collide there should be major disruption and new star formation.

This galaxy has regular spiral shape and the core is mostly old stars.

These two galaxies merged with minor perturbations.

Galaxy NGC3393 includes two active black holes
X-ray: NASA/CXC/SAO/G.Fabbiano et al; Optical: NASA/STScI

Charles Q. Choi, SPACE.com, 31 August 2011

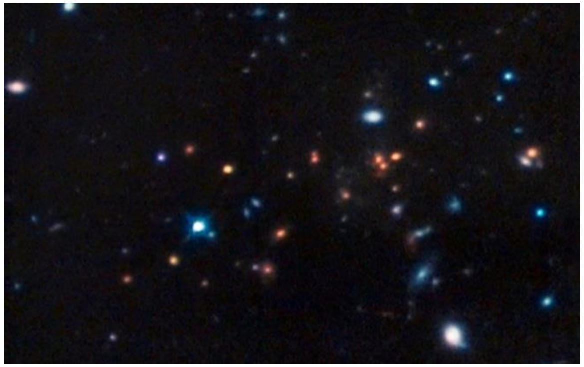
Galaxy Clusters

Galaxy clusters are the largest structures in the universe. Bound together by gravity, they require billions of years to form.

Galaxy Clusters have been detected as early at 0.6 B-yrs after big bang.

At 2.6 B-yrs old, this is not the oldest observed galaxy cluster. But, spectra indicates that stars in its constituent galaxies are 1 B-yrs old. Thus, may have started forming about 1.5 B-yrs after BB.

X-ray data (similar to image) shows glow from cloud of very hot gas that holds cluster together. Most of the mass of the cluster is in the gas.

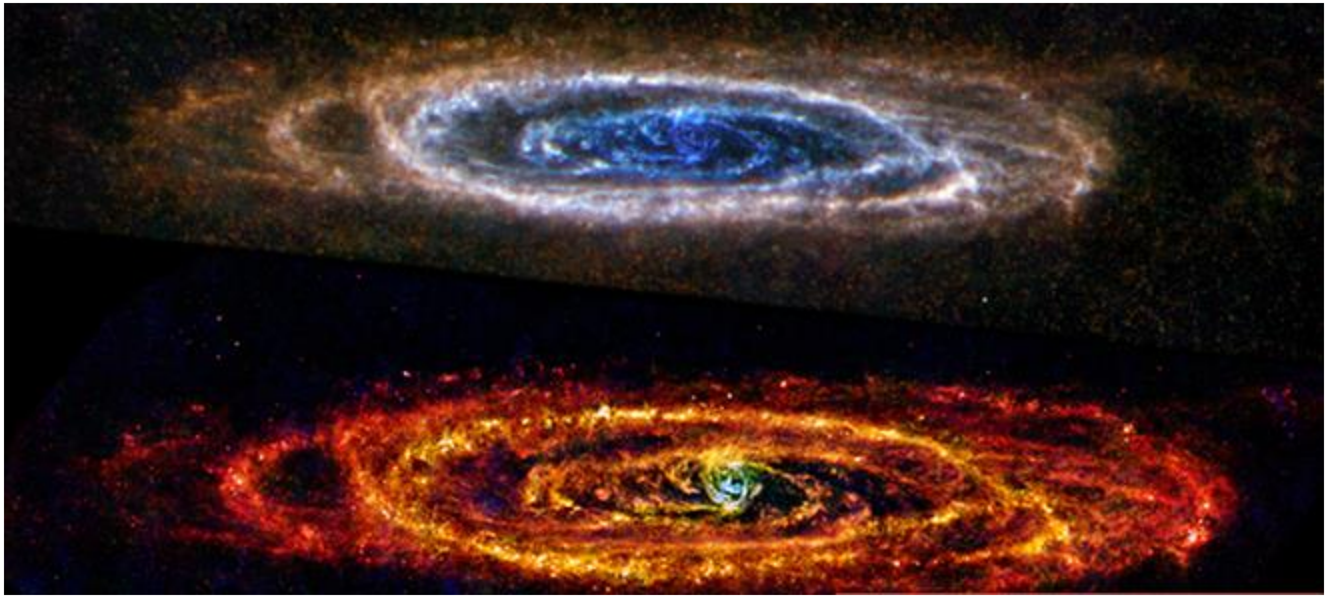


Hubble NIR Image of CL J1449+0856, the most distant mature cluster of galaxies found. Color added from ESO's VLT and NAOJ's Subaru Telescope. CREDIT: NASA, ESA, R. Gobat (SPACE.com 09 March 2011)

JKCS 041 at 3.7 B-yr after BB may be one of the Universe's oldest clusters. In Chandra image, X-ray emission is shown in blue. Image: NASA/CXC/INAF/S.Andreon (Astronomy Now, 10 May 2010)

Galaxy Formation

Rings of interstellar dust circulating around Andromeda's galactic core viewed in Far-IR by the Herschel space observatory.



The brighter the ring, the more active the star fomation.

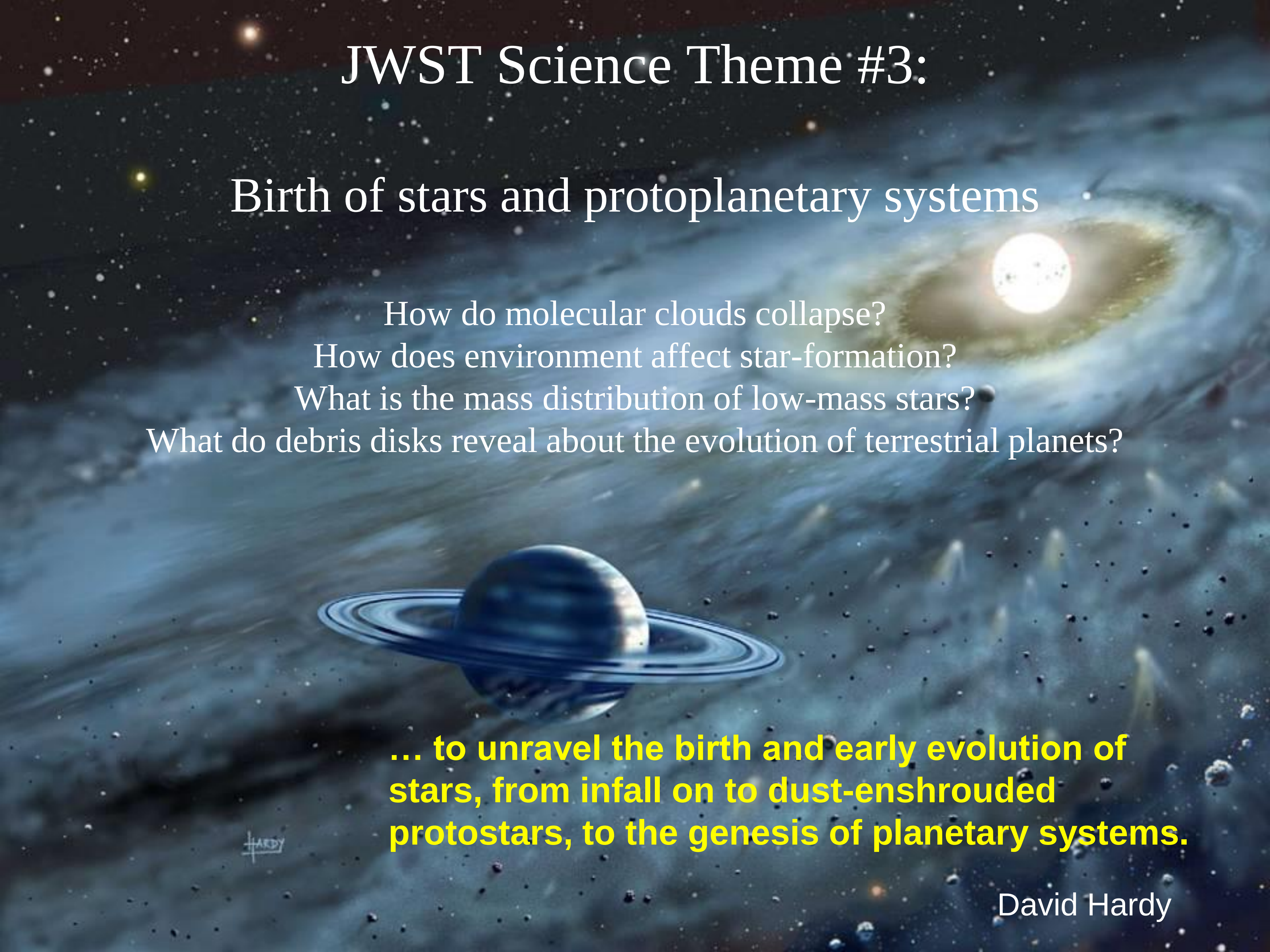
Further out rings are extremely cold, only a few tens of degrees warmer than absolute zero.

Discovery News; Jan 29, 2013 03:00 PM ET // by Ian O'Neill

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?



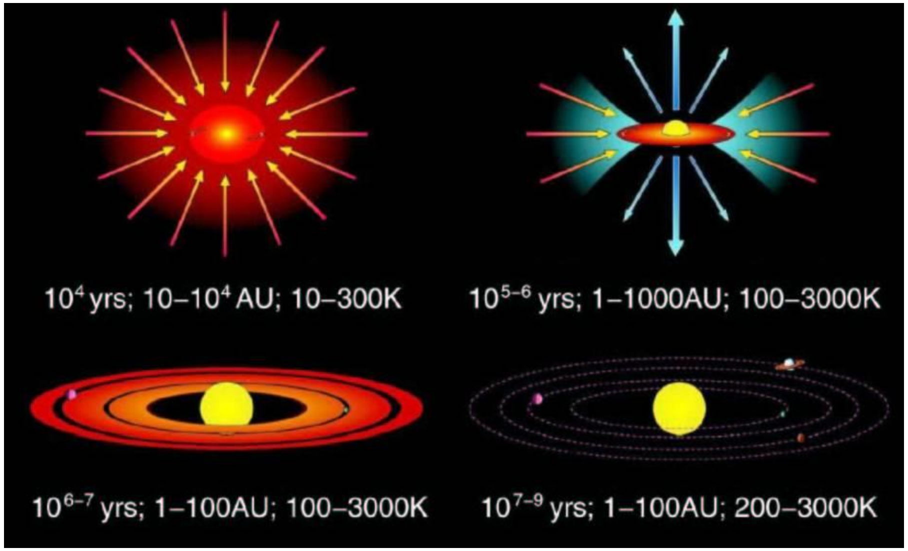
… to unravel the birth and early evolution of stars, from infall on to dust-enshrouded protostars, to the genesis of planetary systems.

David Hardy

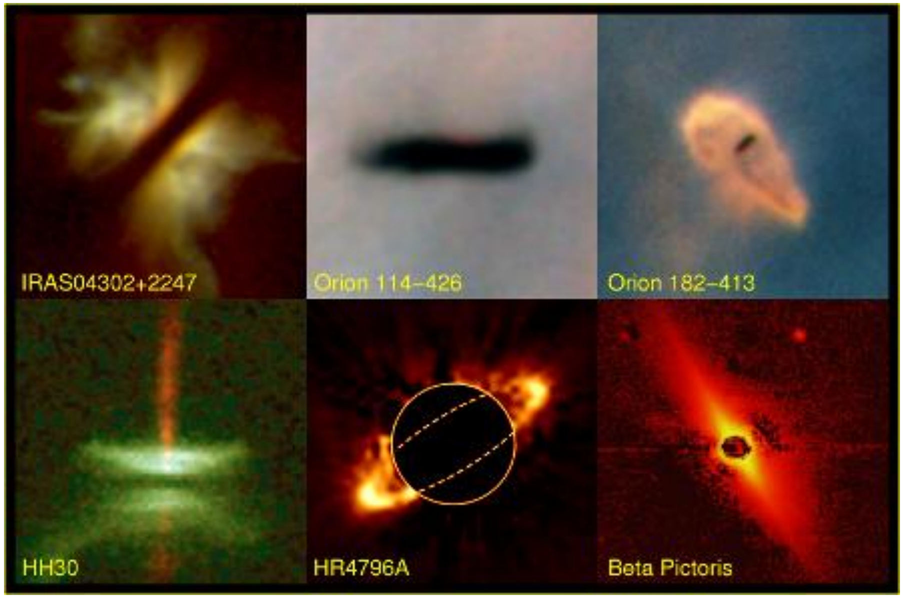
Birth of Stars and Proto-planetary Systems

- 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?

Deeply embedded protostar Circumstellar disk



Agglomeration & planetesimals Mature planetary system



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?

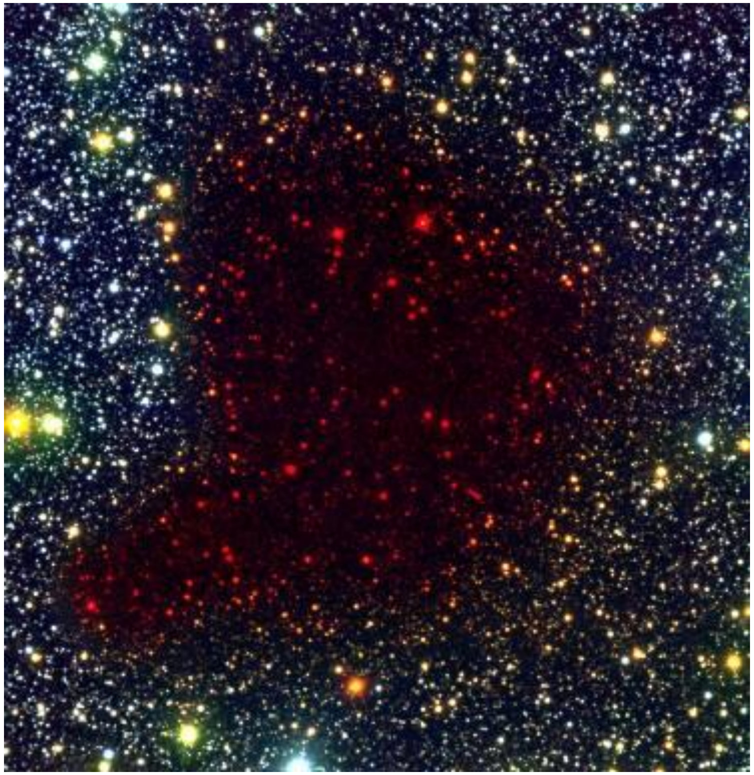
JWST Observations:

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

The Eagle Nebula
as seen in the infrared

How do proto-stellar clouds collapse?

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



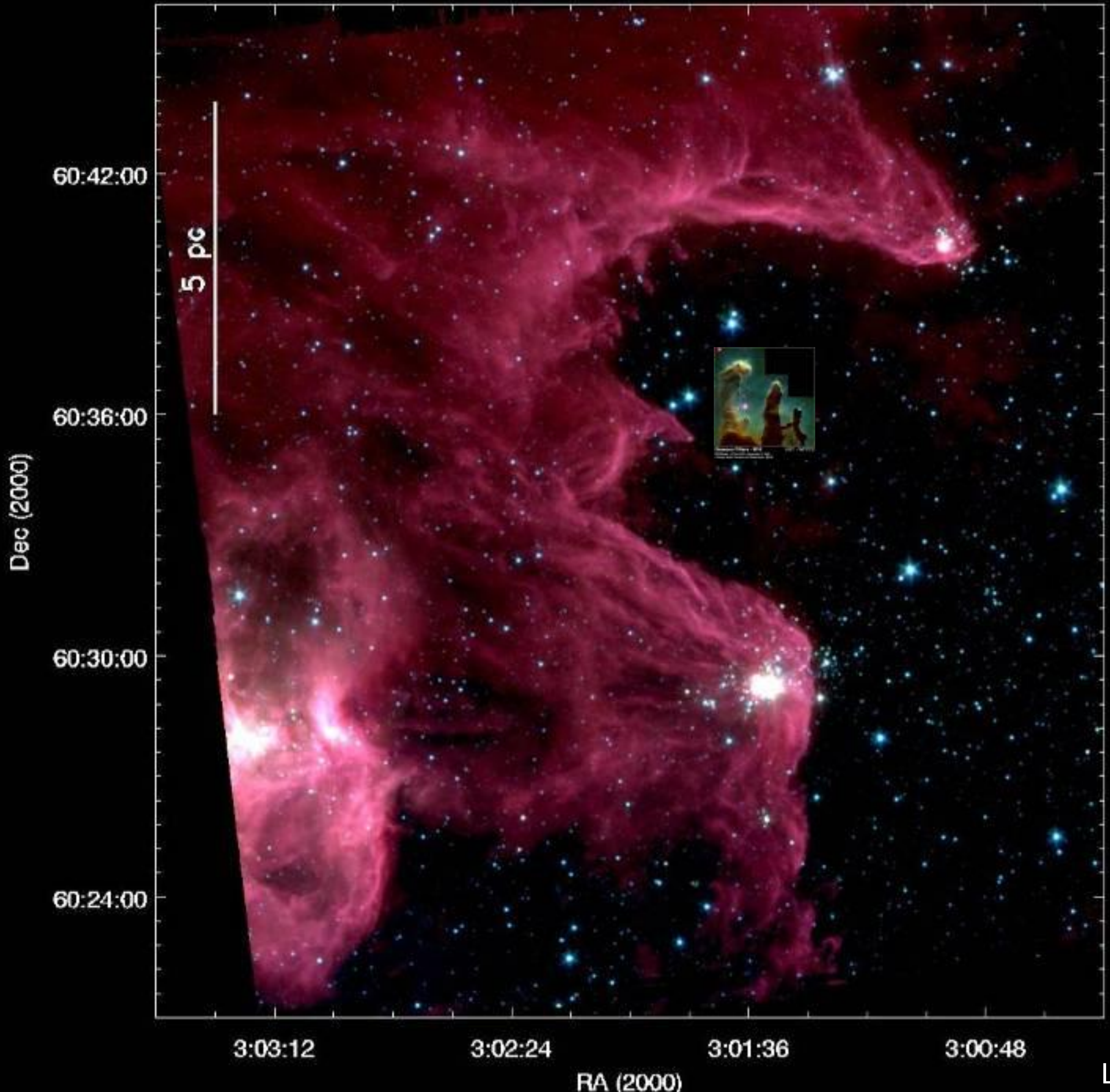
Barnard 68 in infrared

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



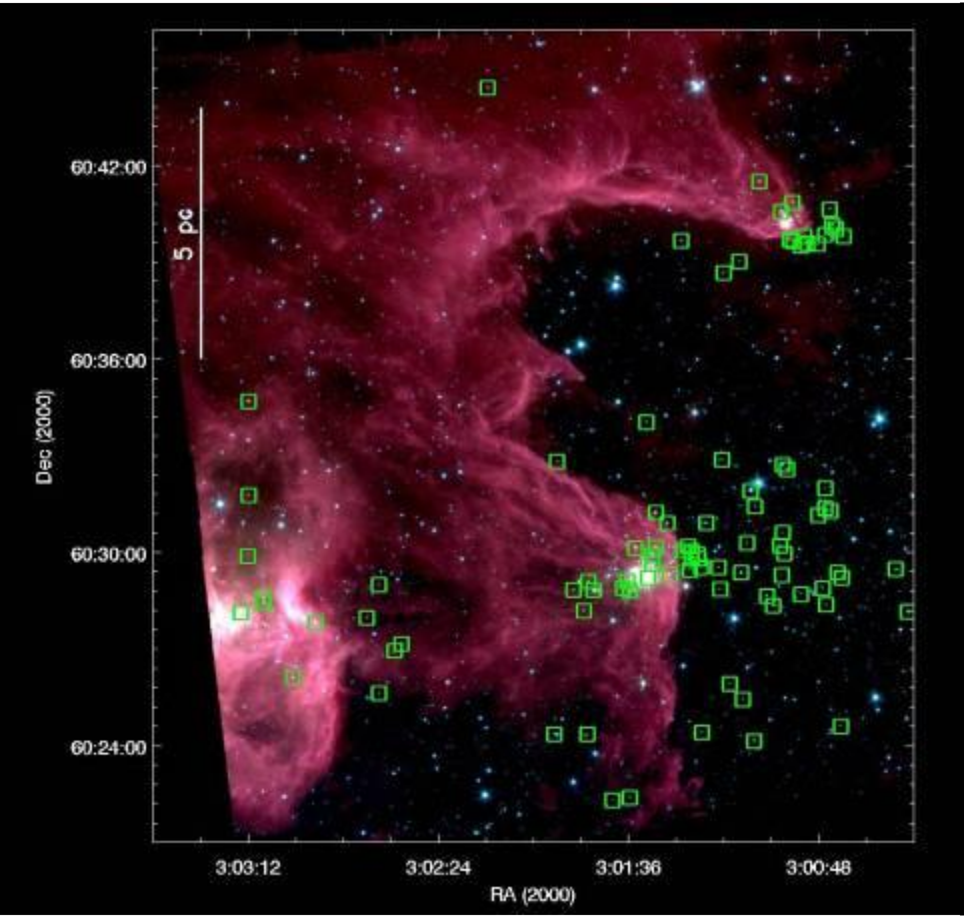
Spitzer has Found "The Mountains Of Creation"

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

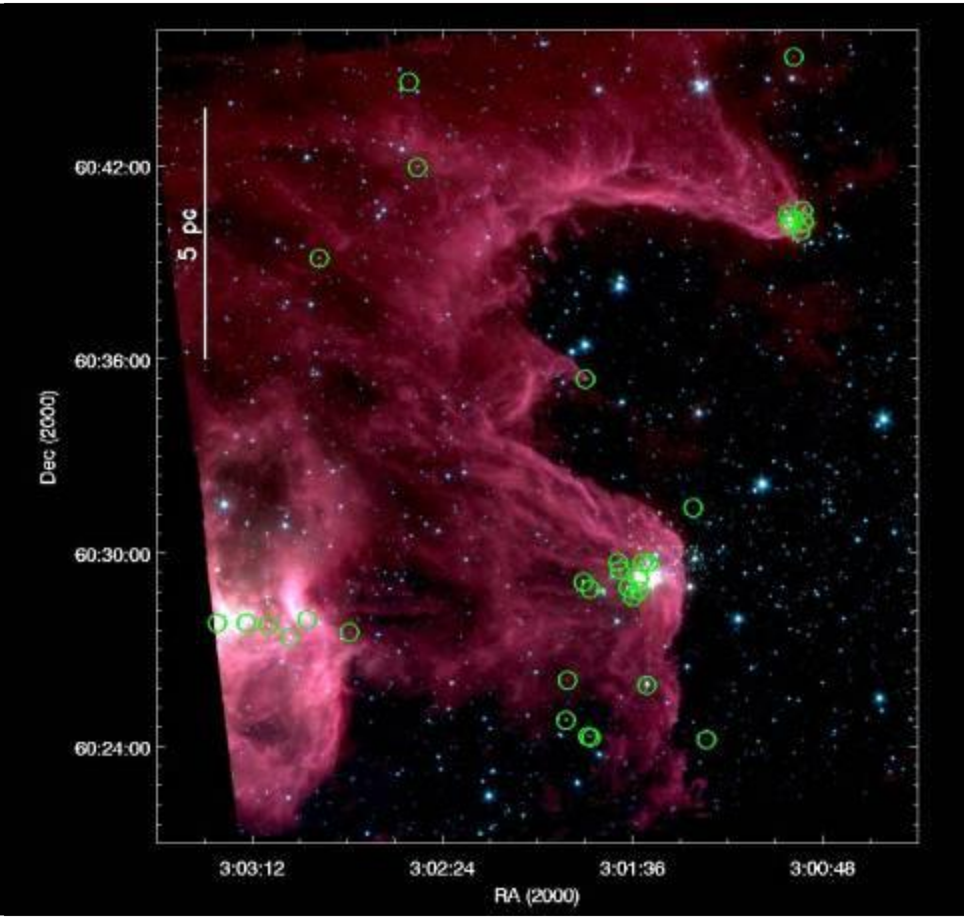
L. Allen, CfA [GTO]

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.

Stellar Shockwave

Shockwave created by Zeta Ophiuchi which is moving towards the left at about 24 kilometres per second.

STARSTUFF IMAGE by Stuart Gary, ABC Science, 20 July 2015

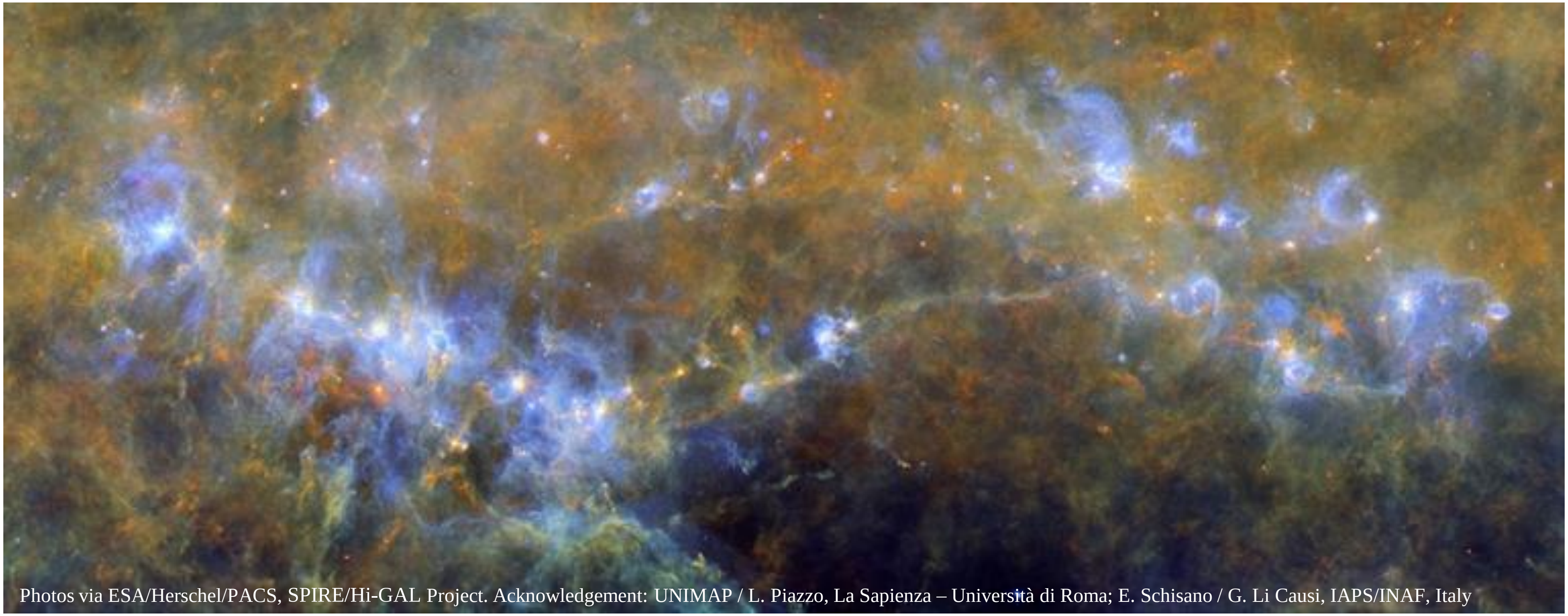
Star Formation in Dust/Gas Cloud

Herschel discovered 700 newly-forming stars condensing along filaments of dust in a never before penetrated dark cloud at the heart of Eagle Nebula.

Two areas glowing brightest in icy blue light are regions where large newborn stars are causing hydrogen gas to shine.

SPACE.com 16 December 2009

Cosmic Breeding Ground for Young Stars



Composite image of molecular cloud RCW106 using Herschel.

Cloud itself consists of (color coded) gases: hydrogen, oxygen, carbon.

Young stars are creating pockets in the cloud.

Blue is hot.

Cassie Kelly, Dope Space Pics, February 27, 2017

Impossible Stars

100 to 150 solar mass stars should not exist but they do.

When a star gets to 8 to 10 solar mass its wind blows away all gas and dust, creating a bubble and stopping its growth (see Herschel Image).

The bubble shock wave is creating a dense 2000 solar mass region in which an ‘impossible’ star is forming. It is already 10 solar mass and in a few 100 thousand years will be a massive 100 to 150 solar mass – making it one of the biggest and brightest in the galaxy.

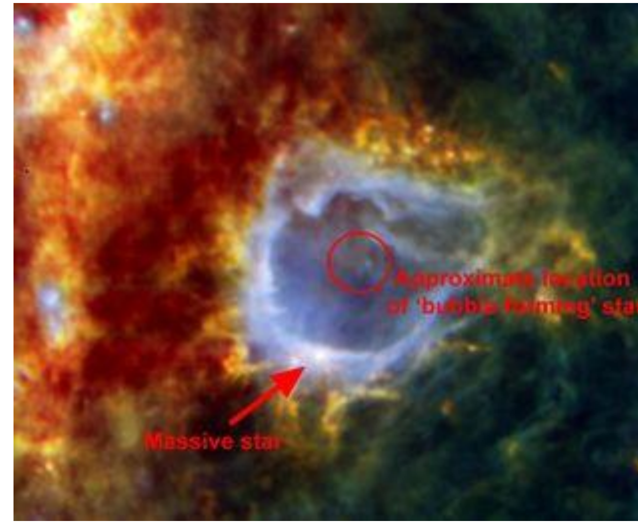


Image of RCW 120 (ESA), Discover.com, Ian O’Neill, 7 May 2010

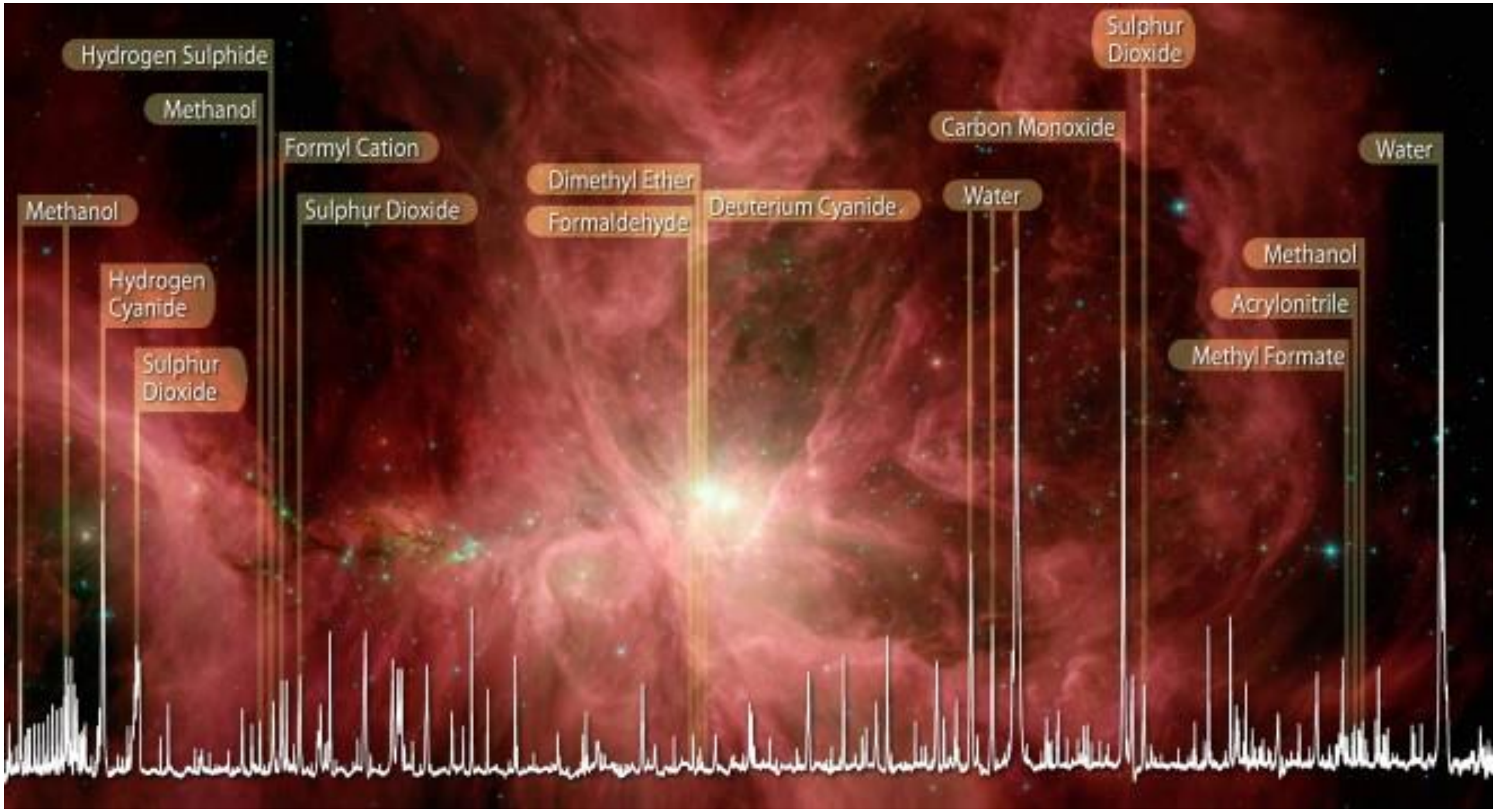
(Space.com, 6 May 2010)

Orion Nebula Protoplanetary Discs

Hubble has discovered 42 protoplanetary discs in the Orion Nebula

Credit: NASA/ESA and L. Ricci (ESO)

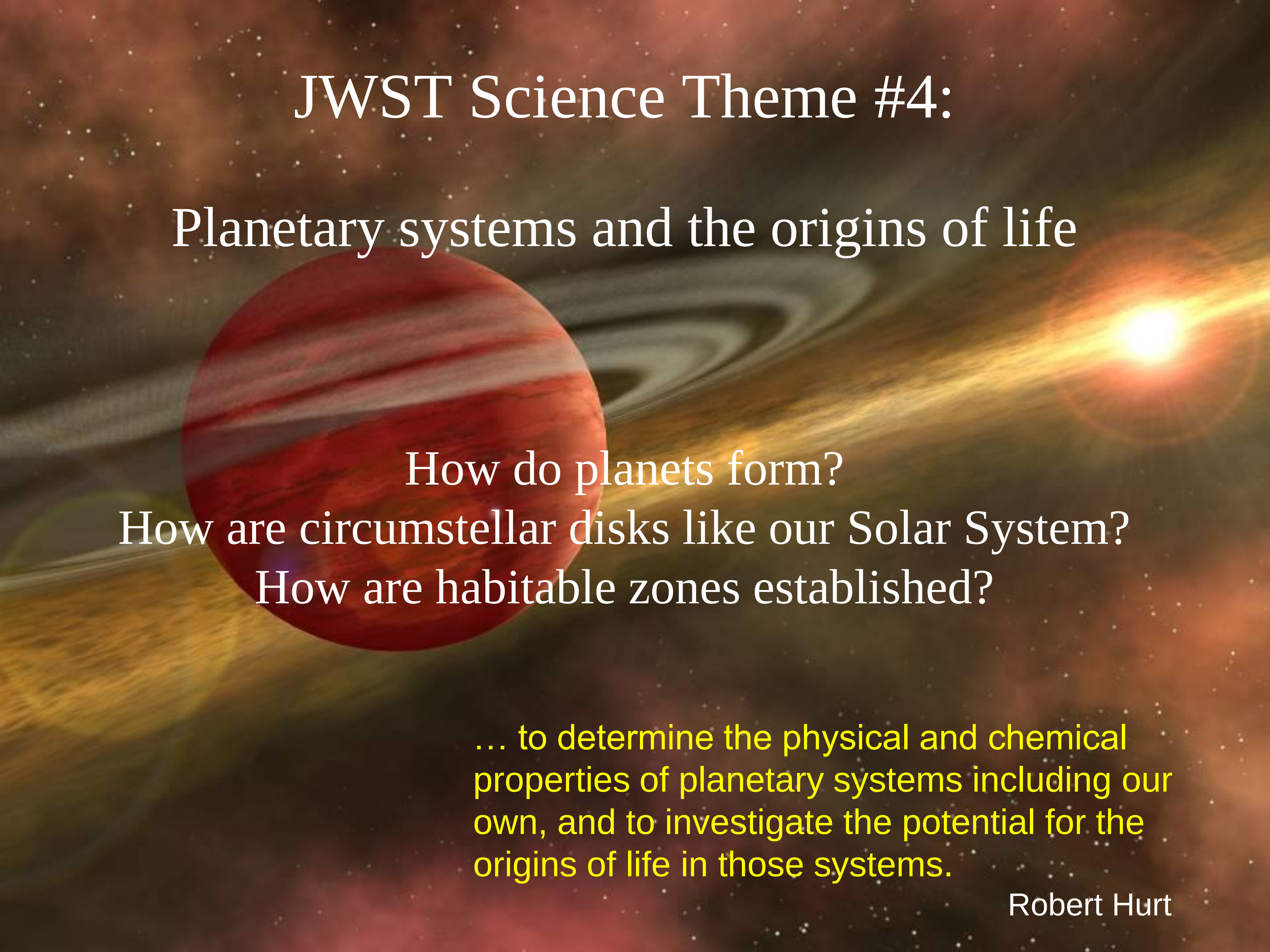
All of Life's Ingredients Found in Orion Nebula



Herschel Telescope has measured spectra for all the ingredients for life as we know them in the Orion Nebula.

(Methanol is a particularly important molecule)

Wired.com Mar 2010

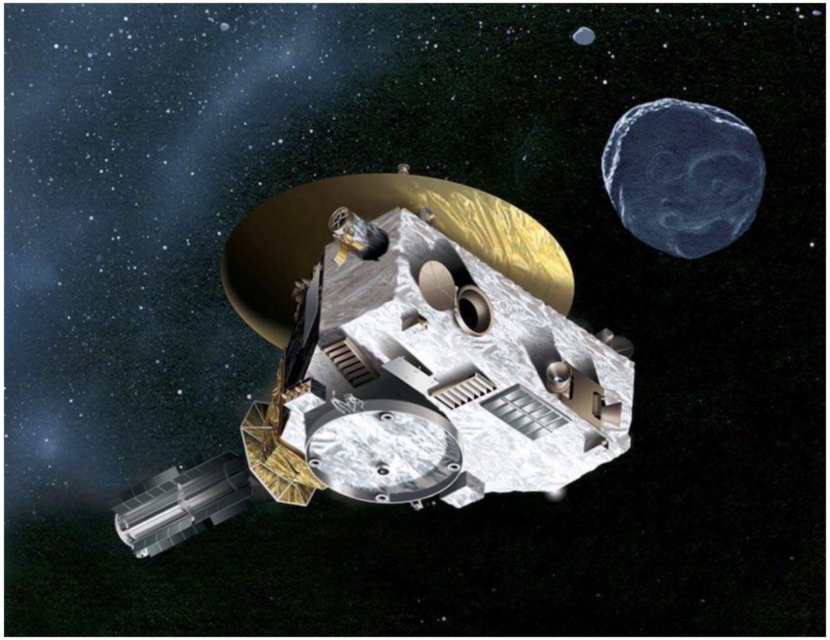

JWST Science Theme #4:
Planetary systems and the origins of life
How do planets form?
How are circumstellar disks like our Solar System?
How are habitable zones established?
… to determine the physical and chemical properties of planetary systems including our own, and to investigate the potential for the origins of life in those systems.
Robert Hurt

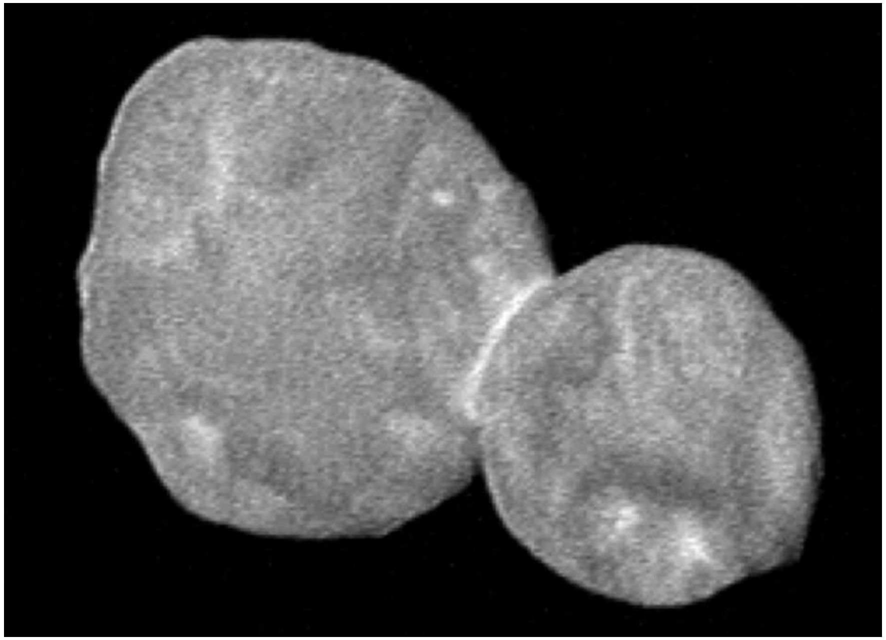
Planetary Formation Questions and 2 Models

- 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?

Ultima Thule

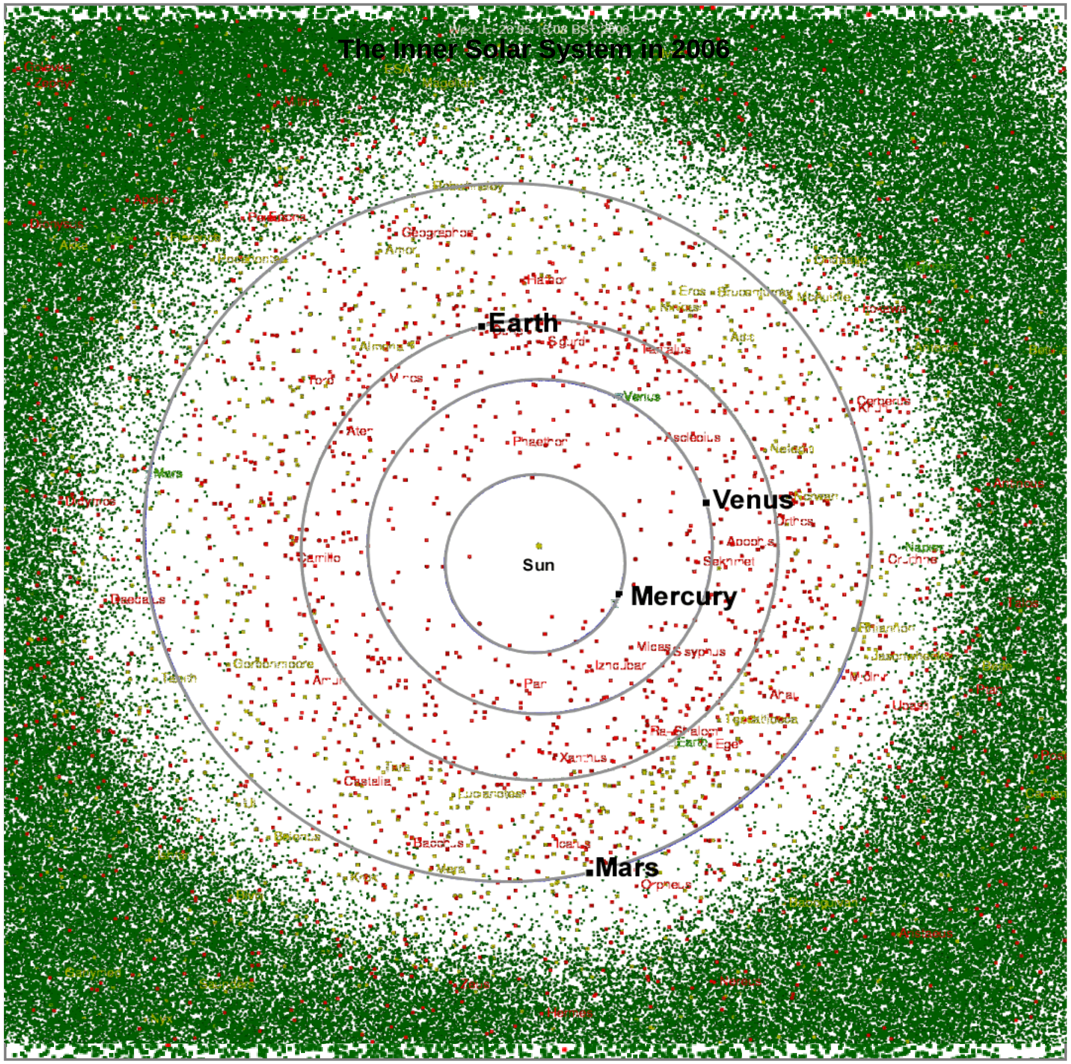
New Horizons' imaging of Ultima Thule on 1 Jan 2019 appears to support the Accretion Model of Planetary System Formation.





History of Known (current) NEO Population

2006



Earth Crossing

Outside Earth's Orbit

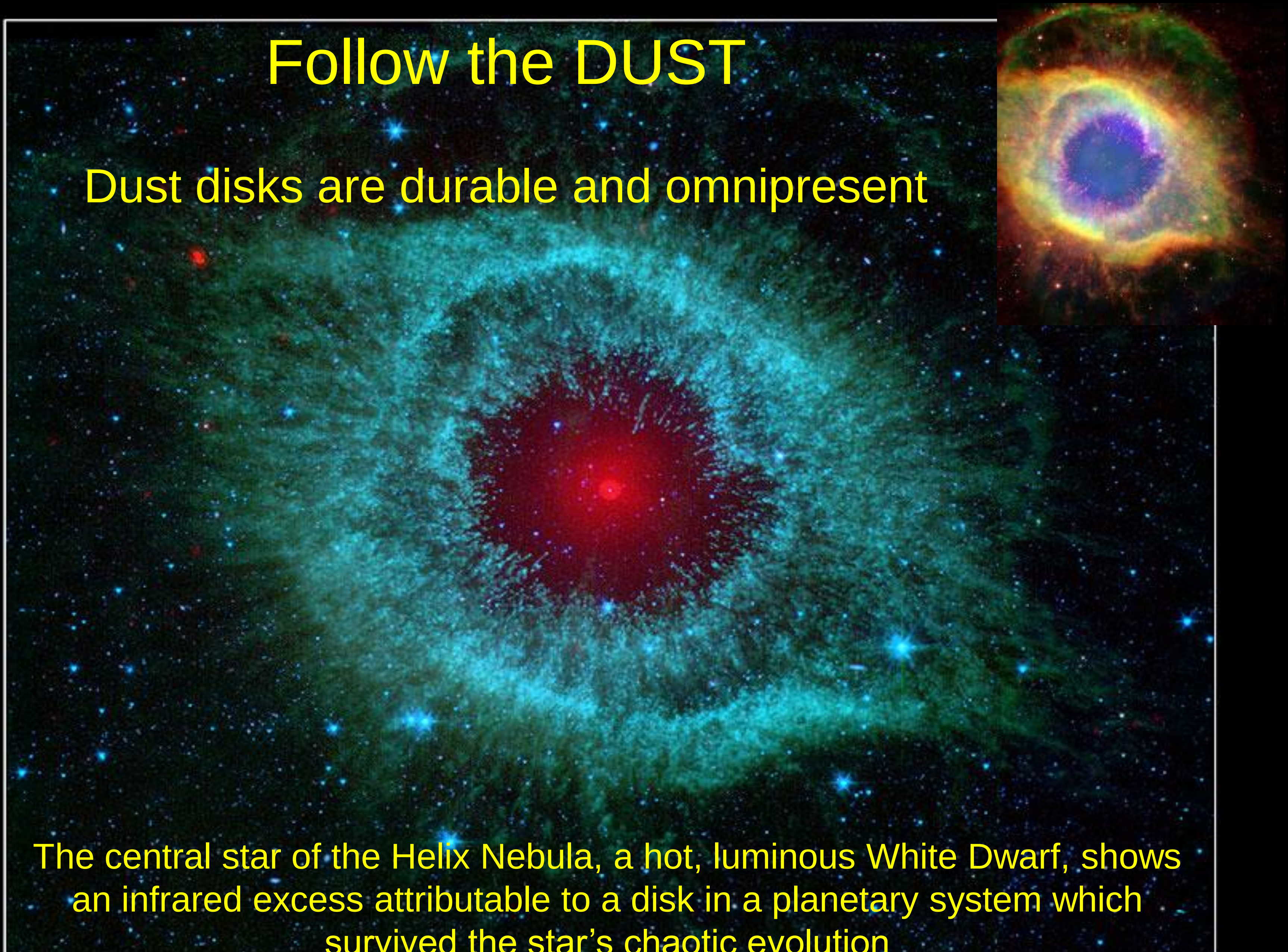
Known
- **340,000 minor planets**
- **~4500 NEOs**
- **~850 Potentially Hazardous Objects (PHOs)**

Scott Manley

Armagh Observatory

Follow the DUST

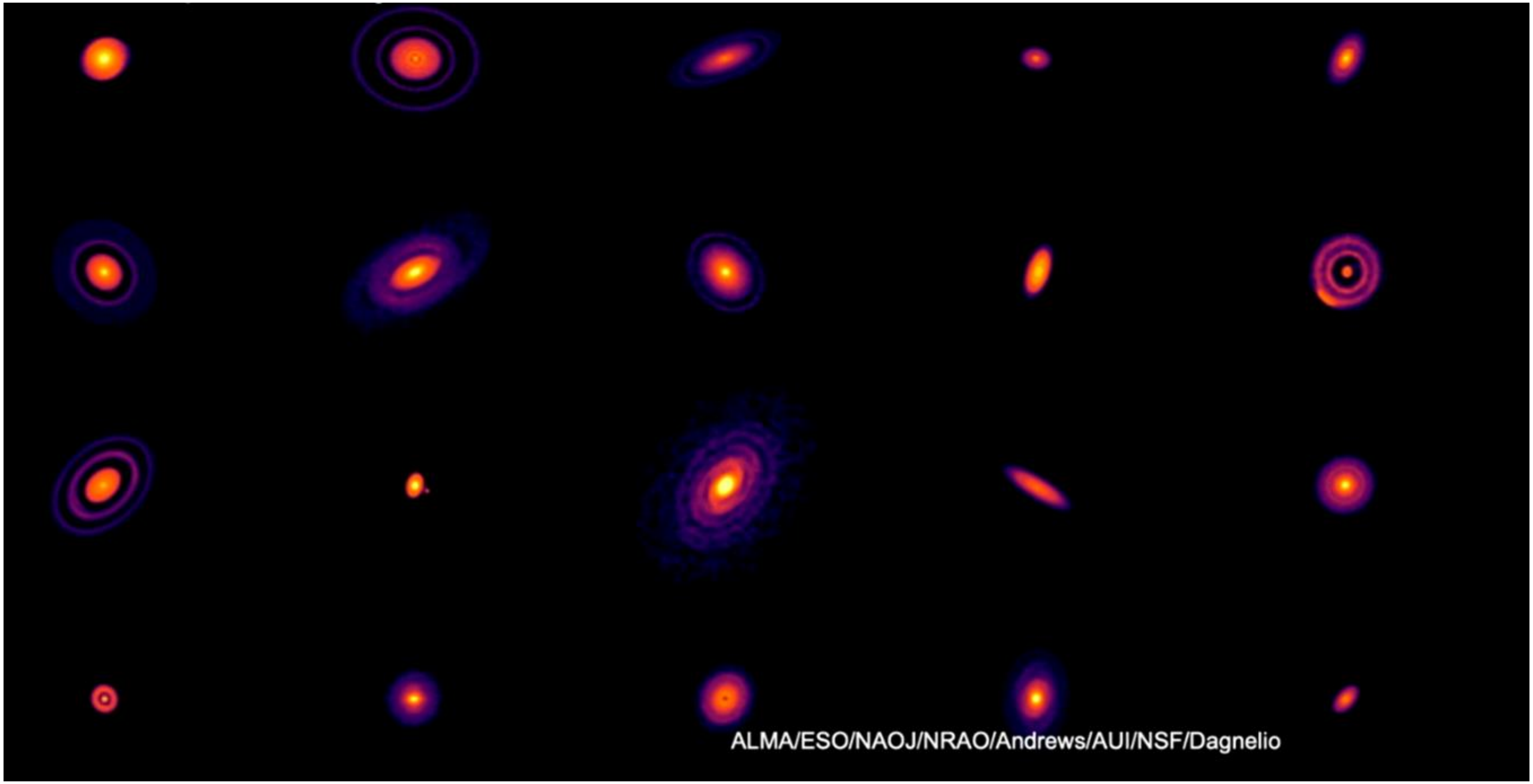
Dust disks are durable and omnipresent



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.

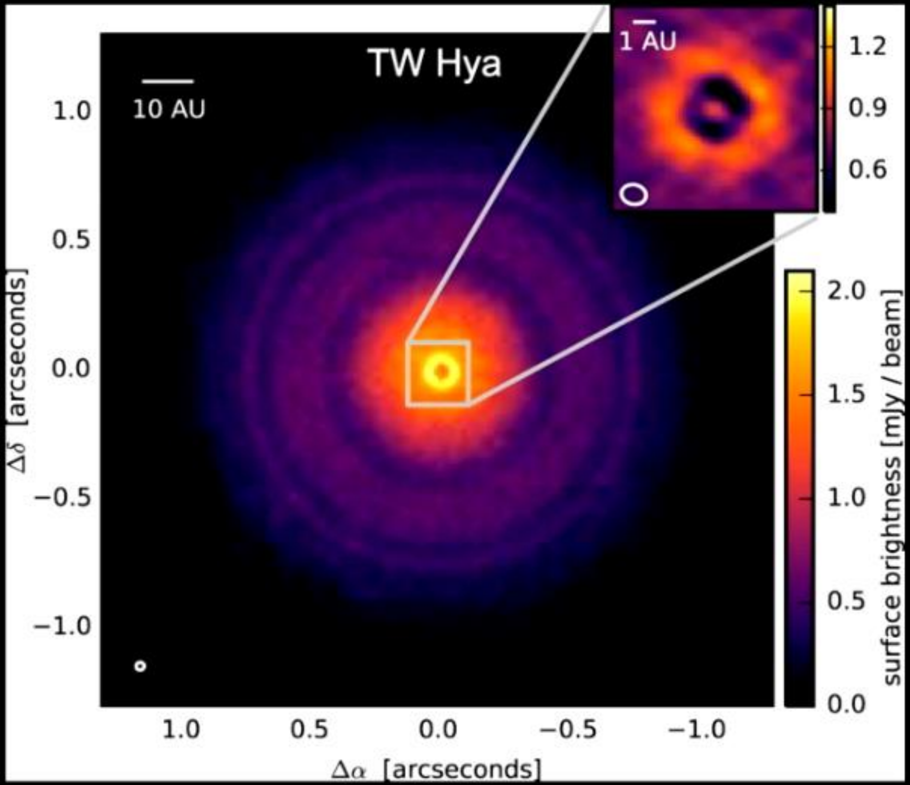
Protoplanetary Disks are Ubiquitous & Diverse



Planets form in the gaps and spiral arms.

Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

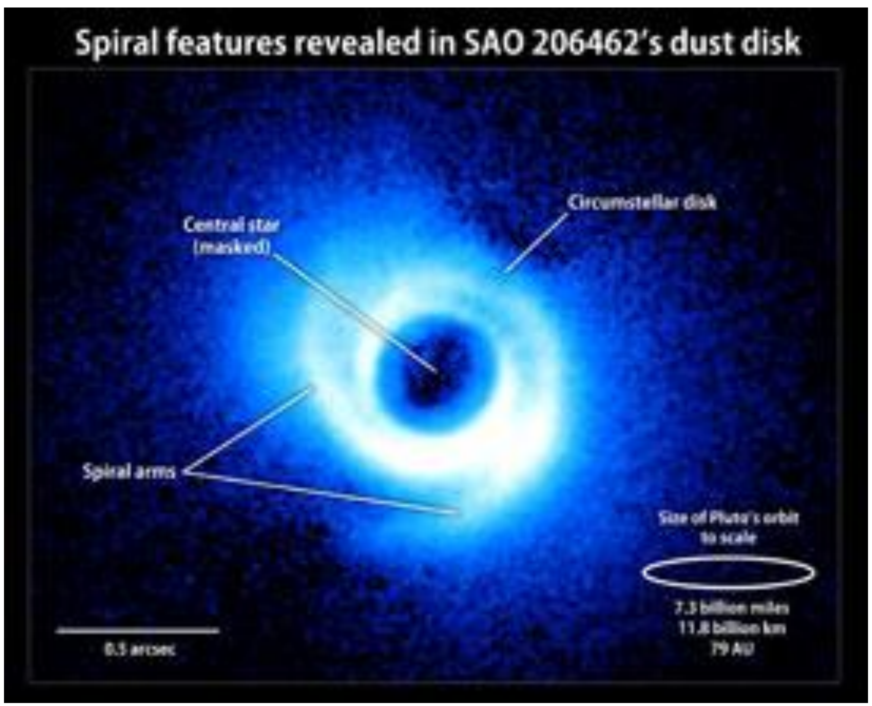
ALMA has shown that small ~au-sized disk gaps may be common



Andrews et al. 2016

Spiral Arms Hint At The Presence Of Planets

Disk of gas and dust around a sun-like star has spiral-arm-like structures. These features may provide clues to the presence of embedded but as-yet-unseen planets.



Near Infrared image from Subaru Telescope shows disk surrounding SAO 206462, a star located about 456 light-years away in the constellation Lupus. Astronomers estimate that the system is only about 9 million years old. The gas-rich disk spans some 14 billion miles, which is more than twice the size of Pluto's orbit in our own solar system.

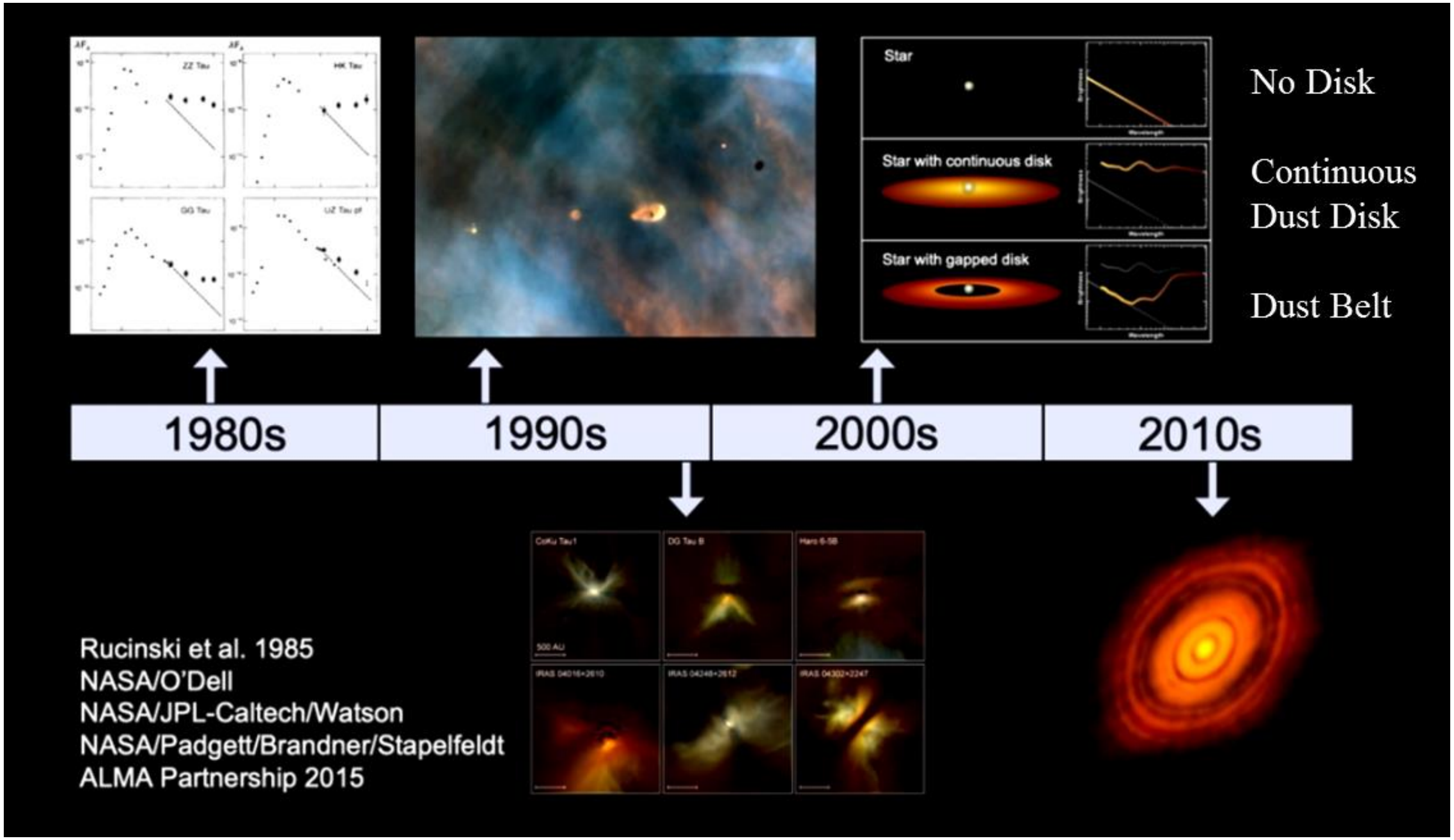
Photonics Online 20 Oct 2011

A protoplanet within a large disk gap has been imaged in the infrared

10 Jupiter Mass
20 AU from star

Keppler et al. 2018

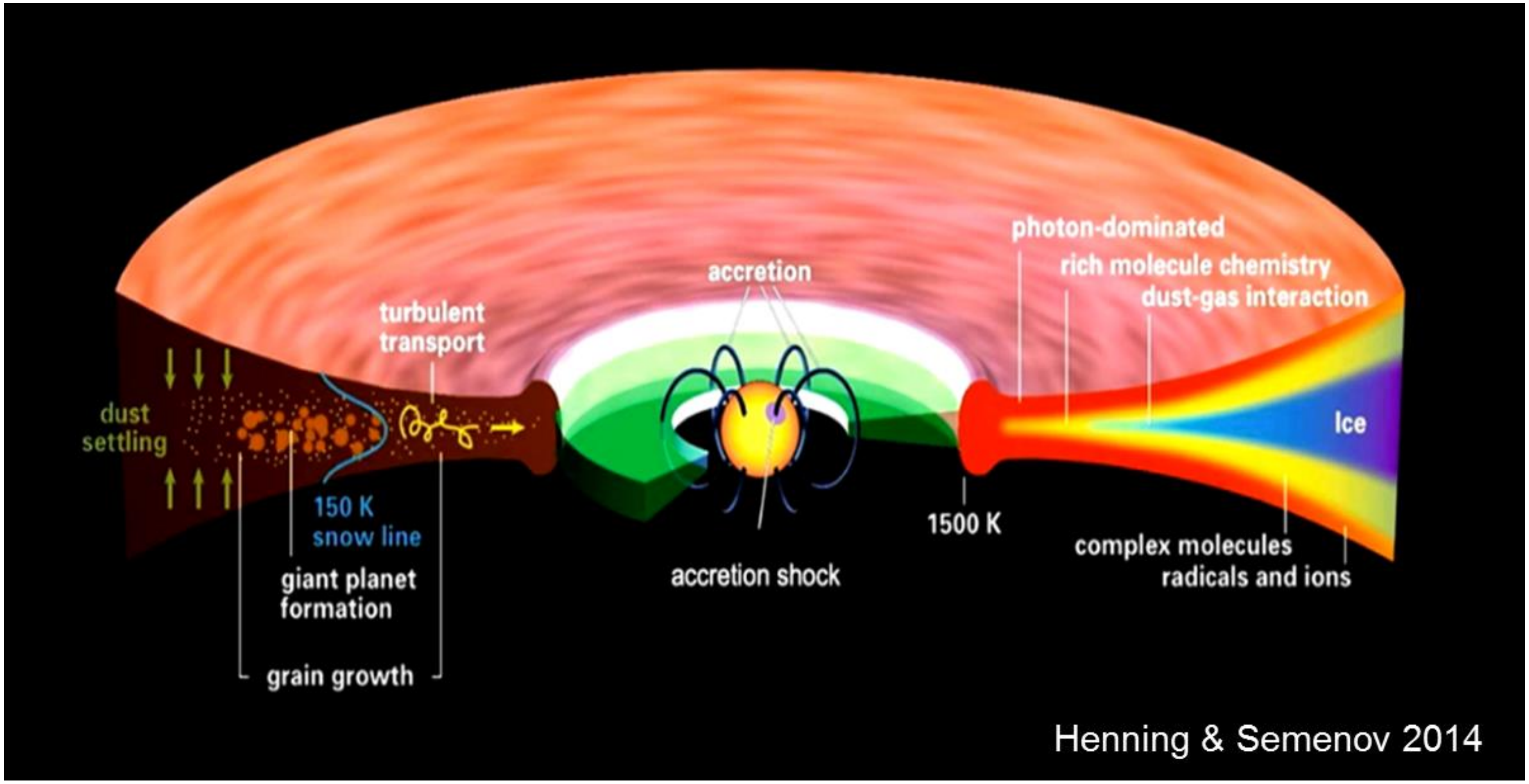
~ 40 years of Protoplanetary Disk research



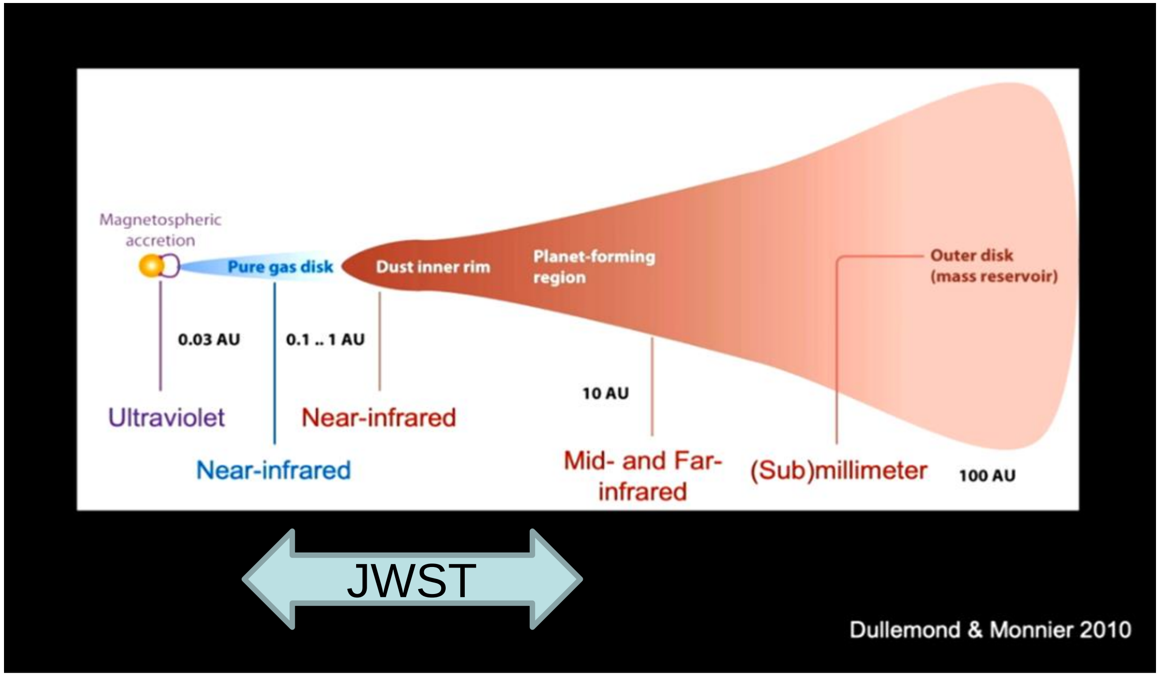
Photometric measurement as function of wavelength shows gaps.

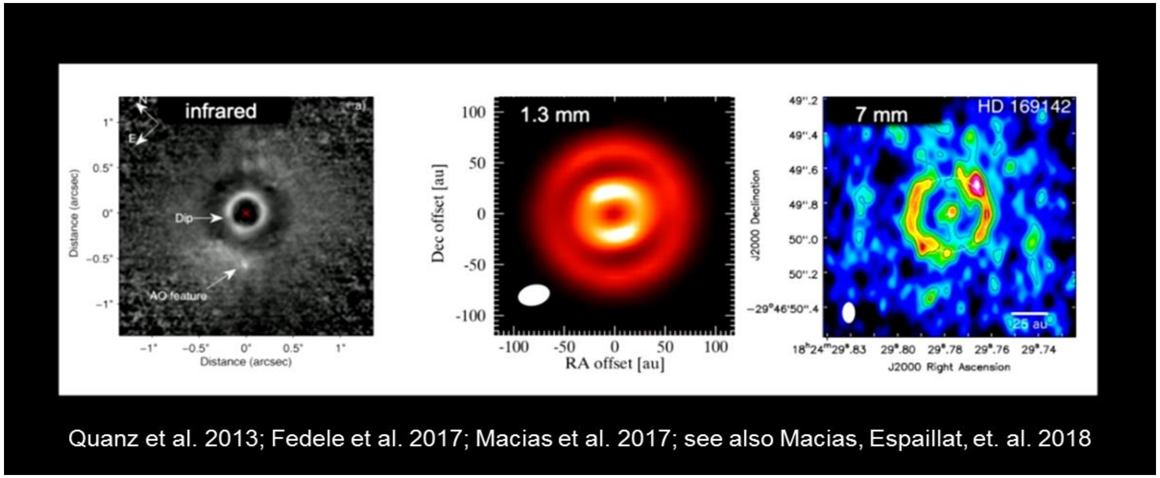
Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

Protoplanetary disks are complex and dynamic



Protoplanetary disk observations require multiple wavlengths





Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

Direct Imaging of Planet Formation

ALMA is mm/sub-mm 15-km baseline array telescope producing a 35 mas resolution image. (10 m telescope at 500 nm has 10 mas)

HL Tau is 1 million year old 'sun-like' start 450 light-years from Earth in constellation Taurus.

Concentric rings separated by gaps suggest planet formation.

HL Tau is hidden in visible light behind a massive envelope of dust and gas. ALMA wavelength sees through dust.

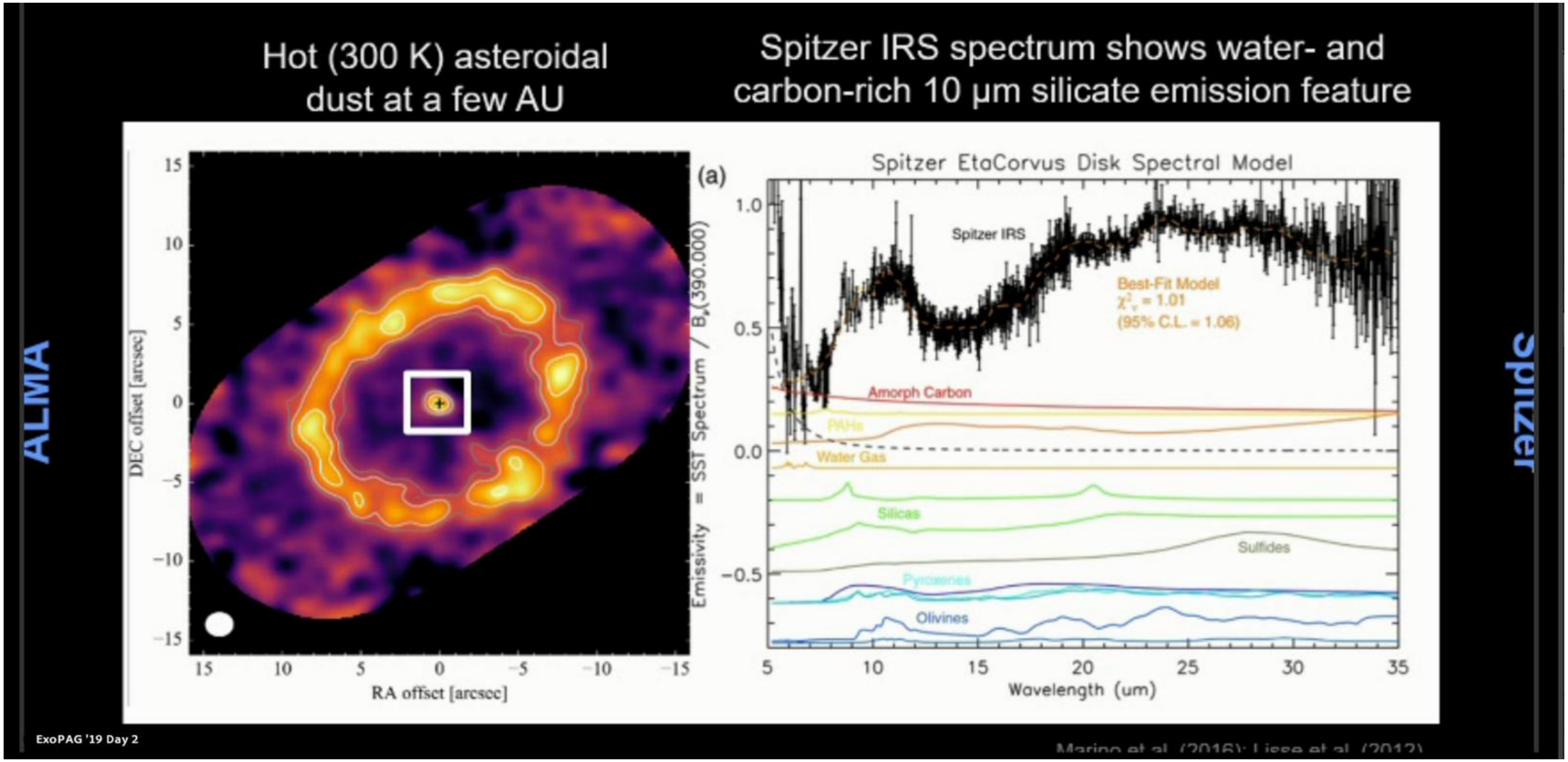
ALMA image of the young star HL Tau and its protoplanetary disk. This best image ever of planet formation reveals multiple rings and gaps that herald the presence of emerging planets as they sweep their orbits clear of dust and gas. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

Eta Corvi System

ALMA measures 'cold' Kuiper belt debris.

Spitzer measures 'warm' asteroid belt debris.

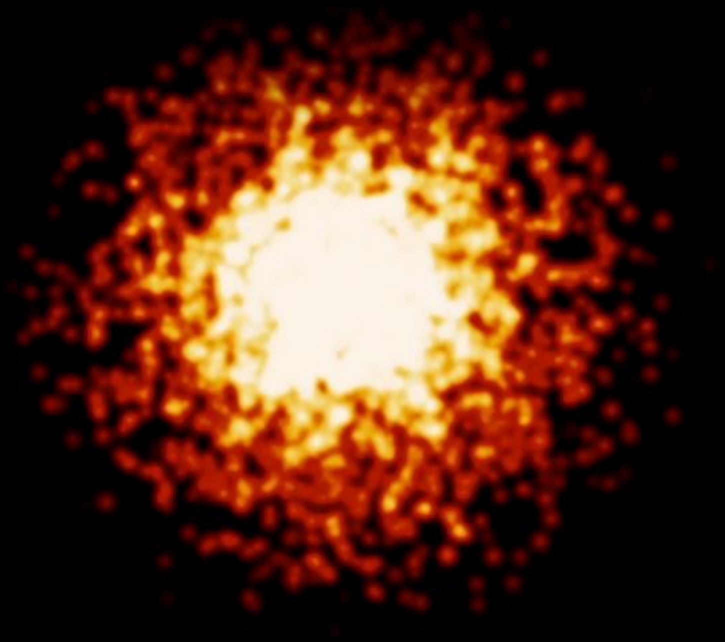
JWST will provide higher resolution image of asteroid belt.



MacGregor, Disks in Nearby Planetary Systems with JWST and ALMA, AAS 2019

Techniques to Detect Exoplanets

Direct Imaging

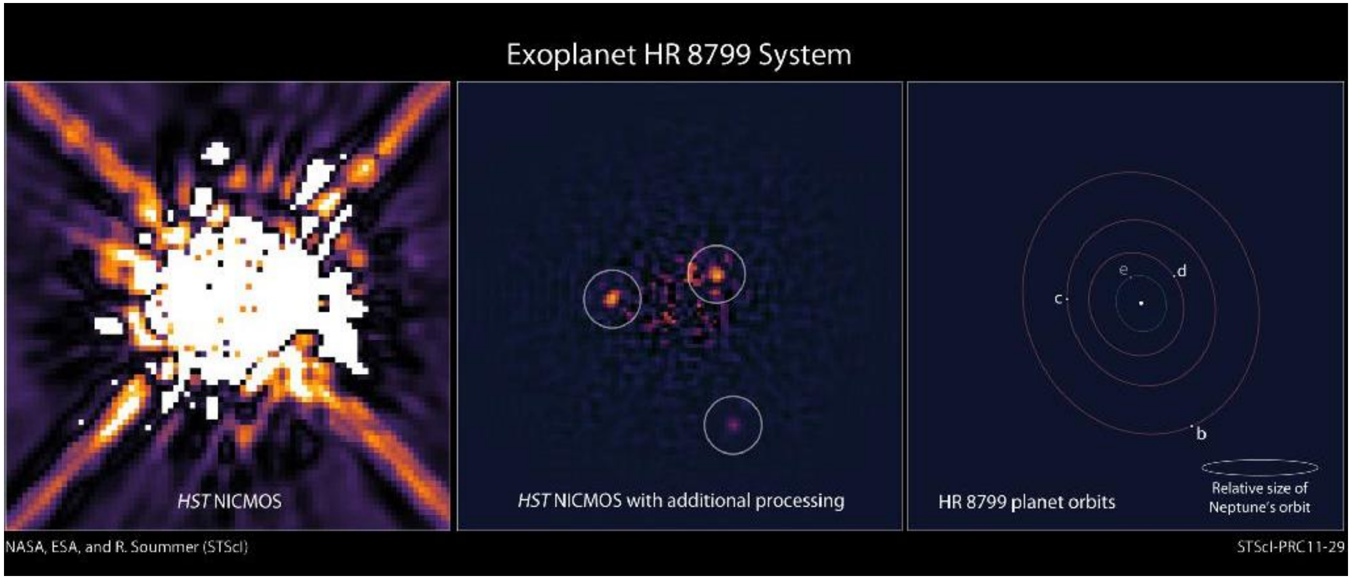


Direct Imaging detects planets far from their star

HR 8799 has at least 4 planets

3 planets ('c' has Neptune orbit) were first imaged by Hubble in 1998. Image reanalyzed because of a 2007 Keck discovery.

3 outer planets have very long orbits or 100, 200 & 400 years. Multiple detections are required to see this motion.

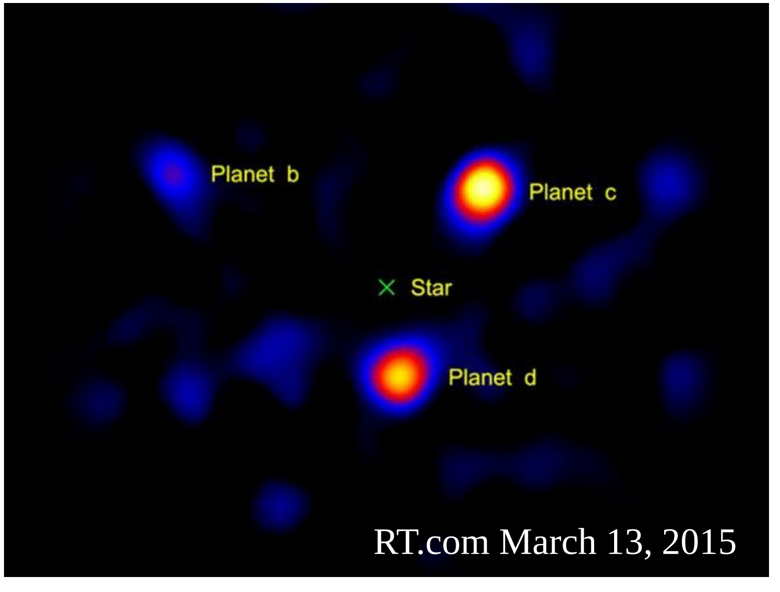


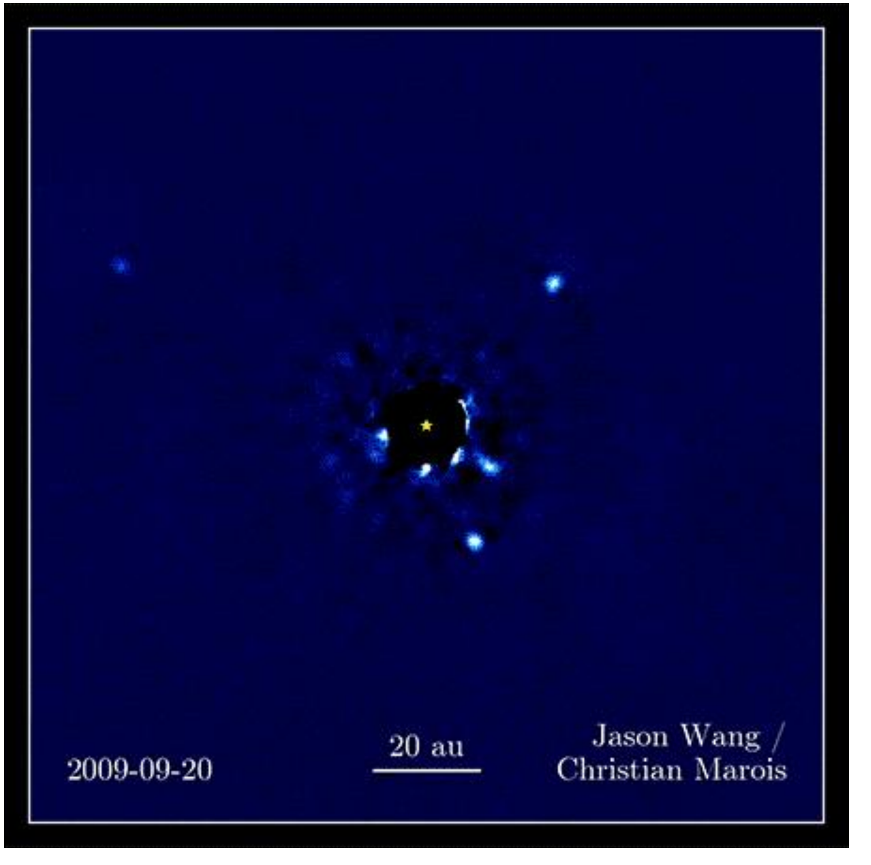
Denise Chow, SPACE.com; 06 October 2011

HR 8799 Planet (b)

HR 8799 is 129 light-years from earth, 1.5X the size of our sun in the constellation Pegasus, and has at least 4 planets.

HR 8799 Planet (b) is 7X the mass of Jupiter and has water, methane and carbon monoxide in its atmosphere.

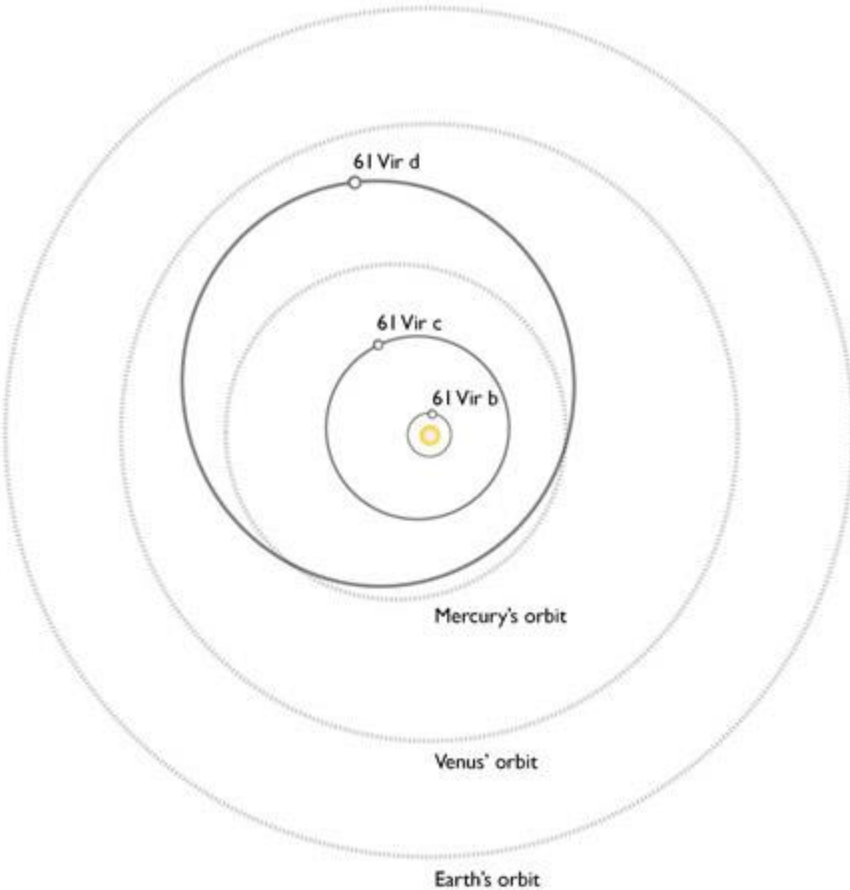




Techniques to Detect Exoplanets

Doppler Spectroscopy or Radial Velocity Method

Radial Velocity Method finds planets close to stars



61 Virginis (61 Vir) has 3 planets inside of Venus's orbit.

From their star, the planets have masses of ~5X, 18X & 24X Earth's mass.

They orbit 61 Virginis in 4, 38 & 124 day periods.

Also,direct Spitzer observations indicate a ring of dust at twice the distance of Neptune from the star.

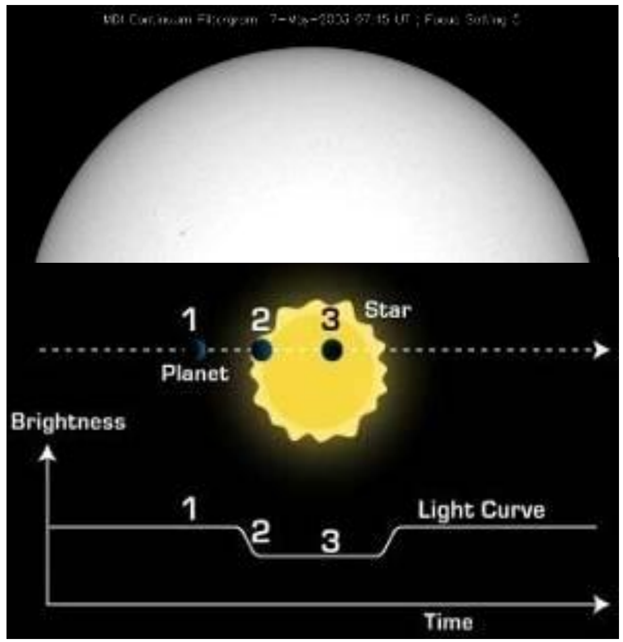
Bad Astronomy
Orbital schematic credit: Chris Tinney

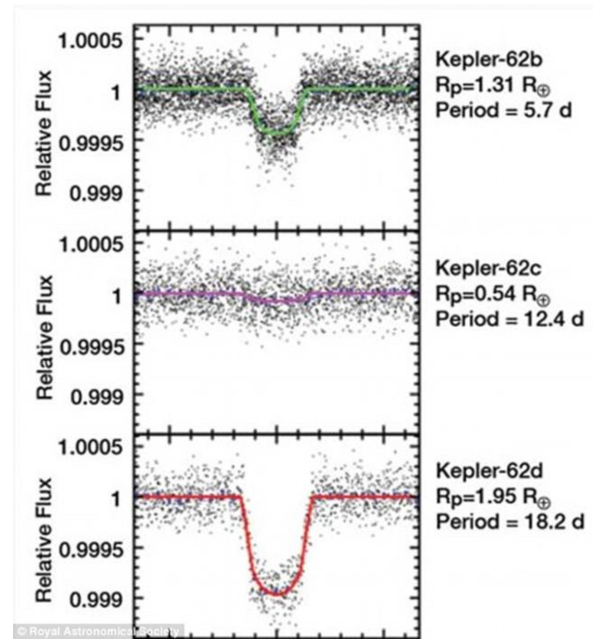
Techniques to Detect Exoplanets

Transit Method

Transit Method Finds Planets

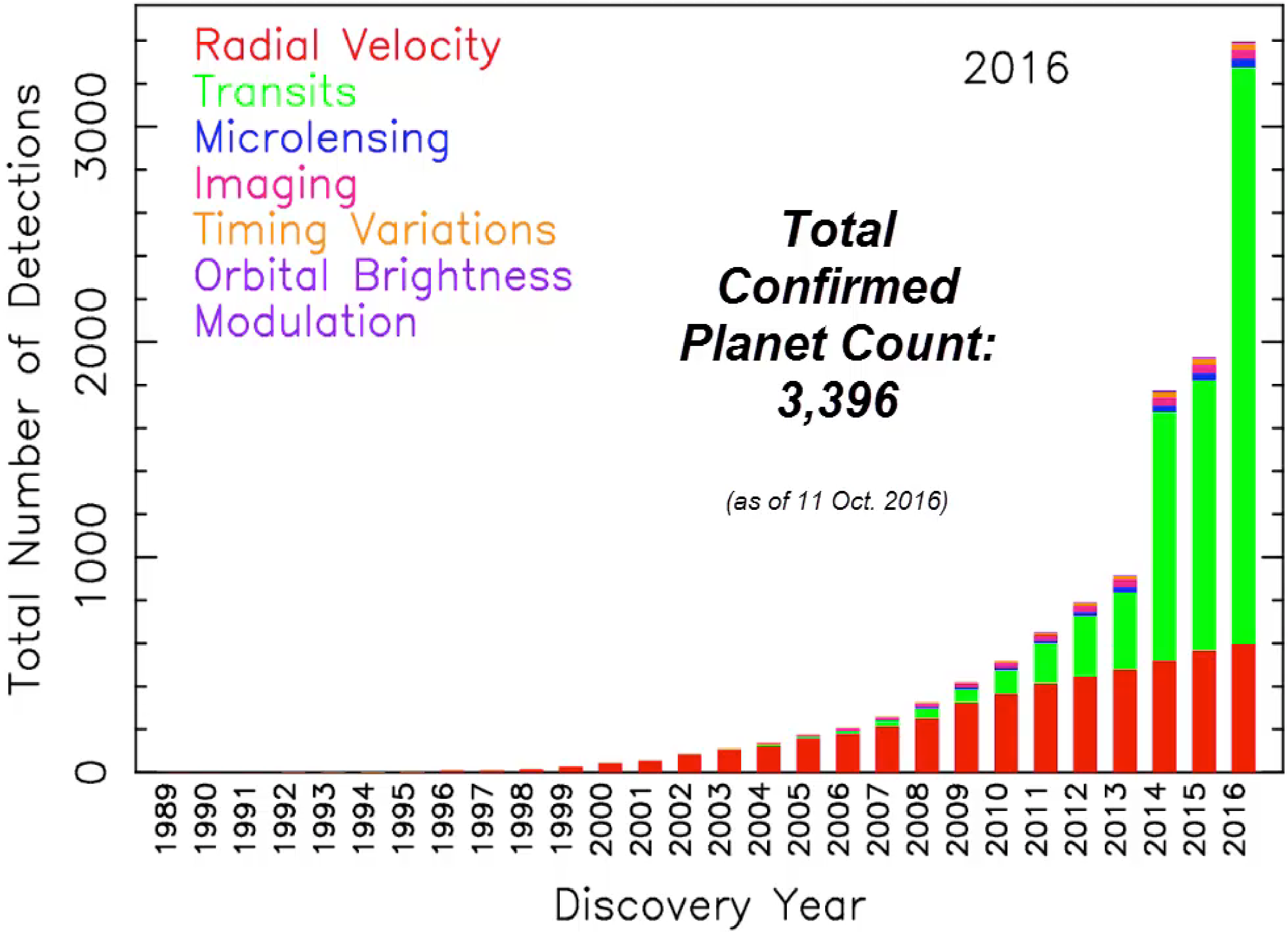
Kepler (launched in 2009) searched for planets by staring at 165,000 stars looking for dips in their light caused when a planet crosses in front of the star.





Kepler has found over 1000 ‘confirmed’ planets and over 4000 potential planets.

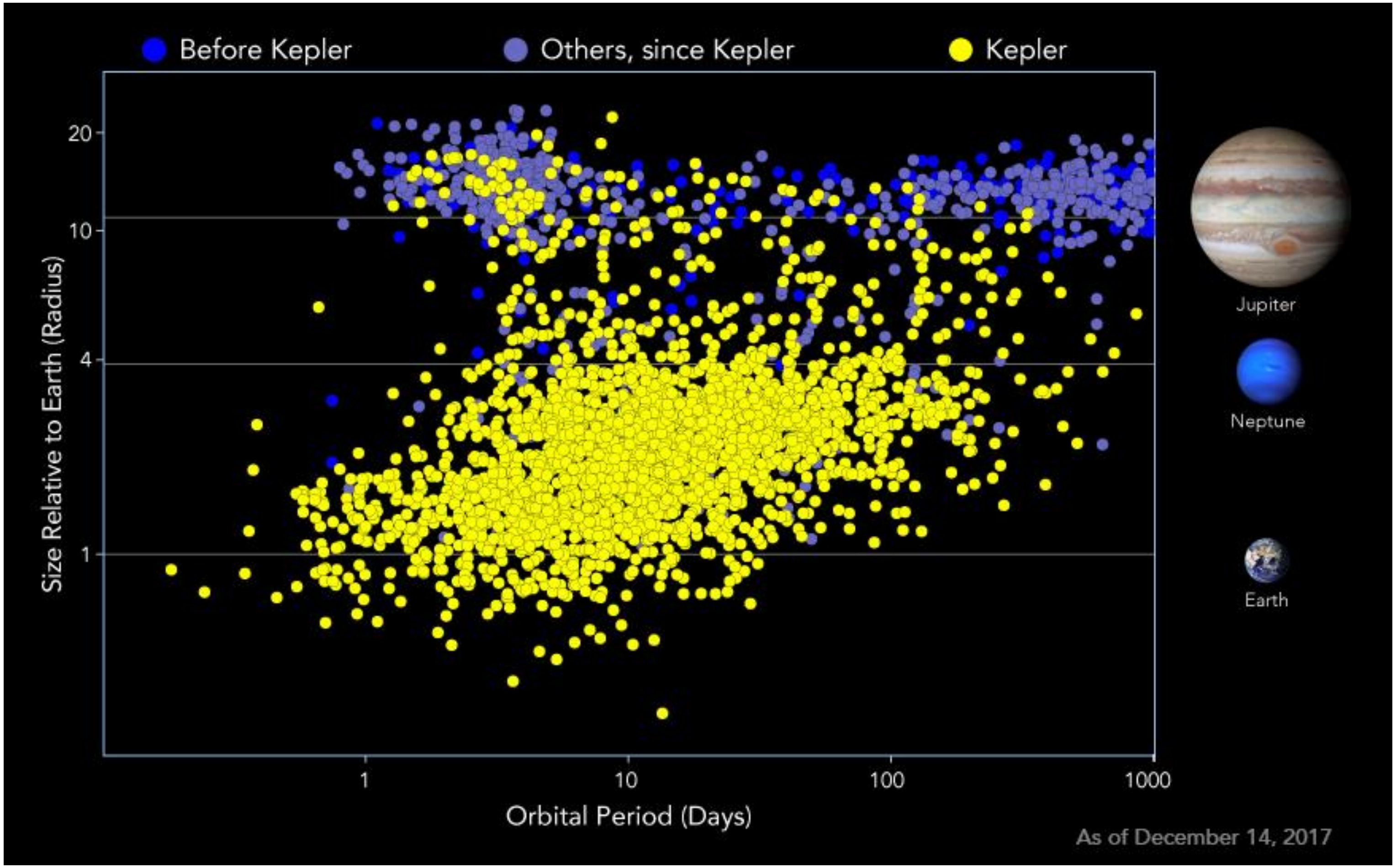
Confirmed Exoplanets versus Time



Exoplanet Census as of 14 Dec 2017

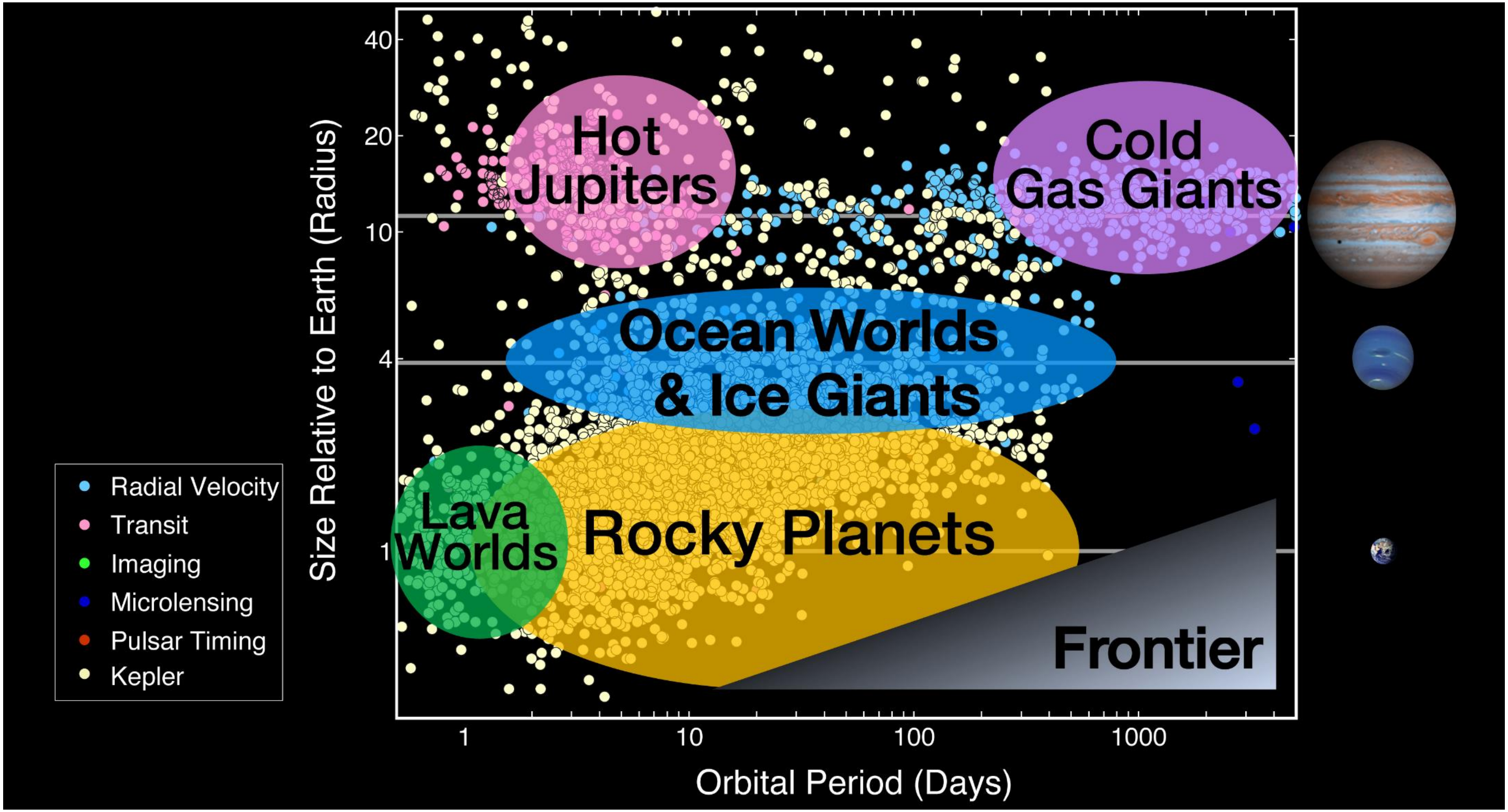
Total Confirmed Exoplanets = 3567

Total found by Kepler = 2525



https://www.nasa.gov/sites/default/files/thumbnails/image/fig10-exoplanetdisc-dec14.jpg

Exoplanet Populations & Discovery Method

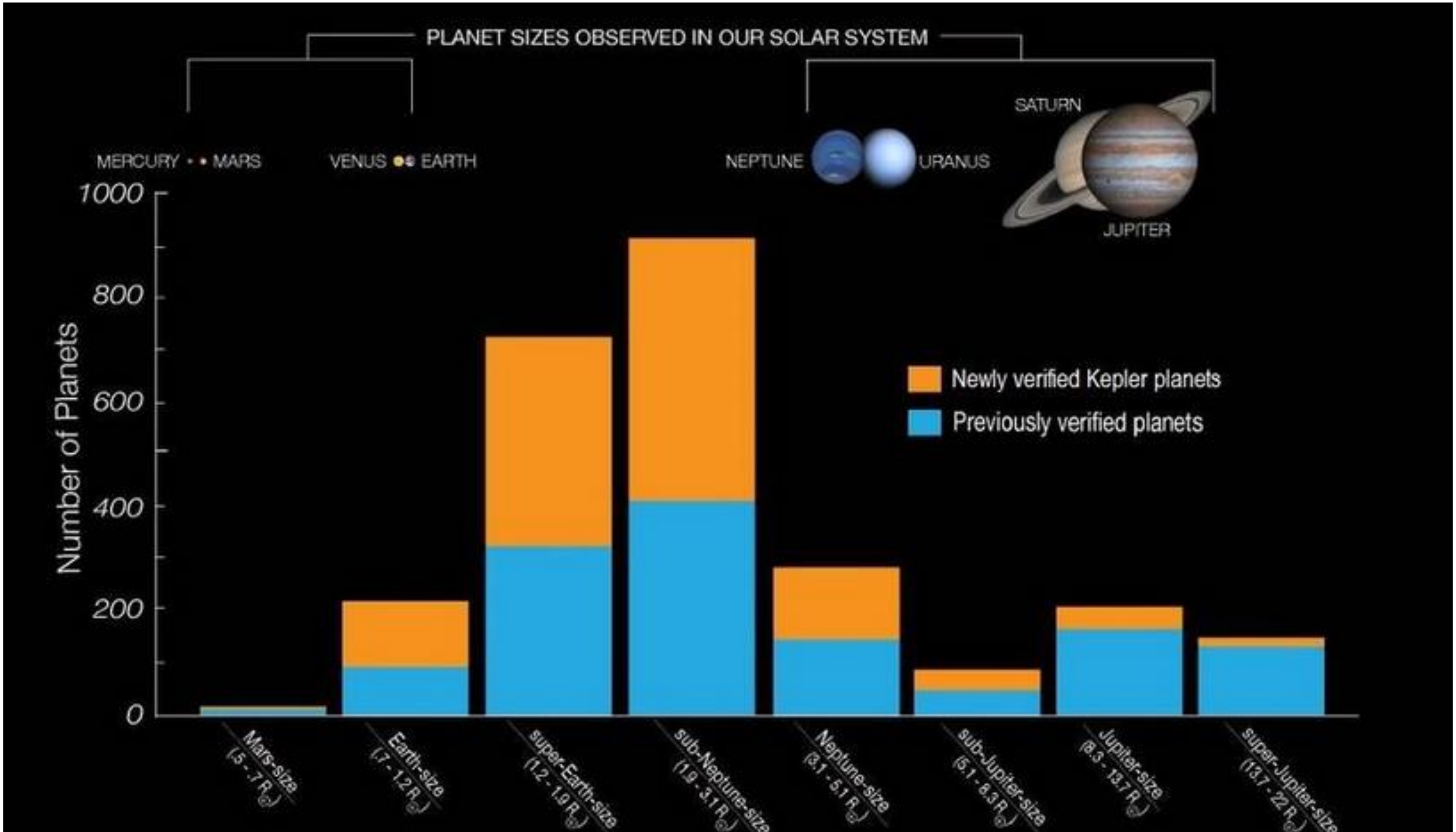


https://www.nasa.gov/sites/default/files/thumbnails/image/press-web25_exoplanet_populations.jpg

Kepler's Verified Planets, by Size

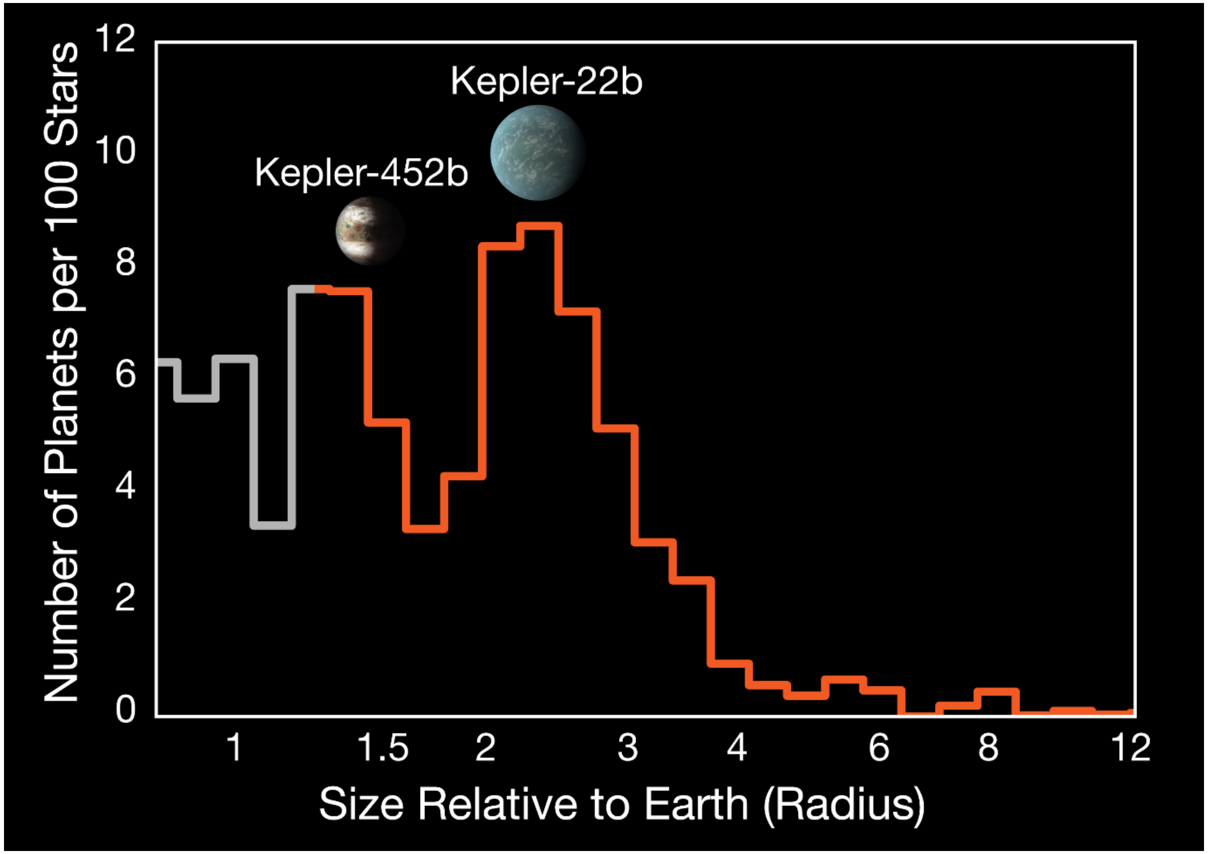
As of May 10, 2016

Final data release: spring 2017



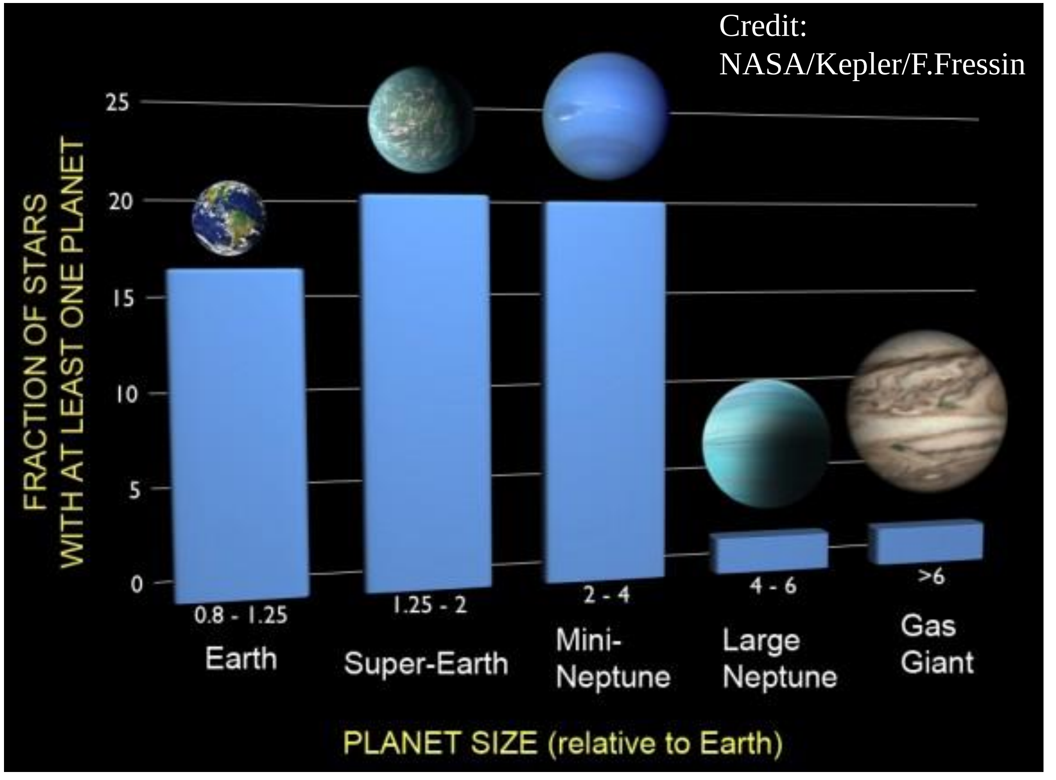
Courtesy: NASA/ARC

Small Planets come in Two Sizes



https://www.nasa.gov/sites/default/files/thumbnails/image/press-web19_small_planets_two_sizes-edit.jpg

Nearly All Stars have Planets



Our galaxy has 100B stars of which 17B are like ours, so our galaxy could have 17B Earth size planets.

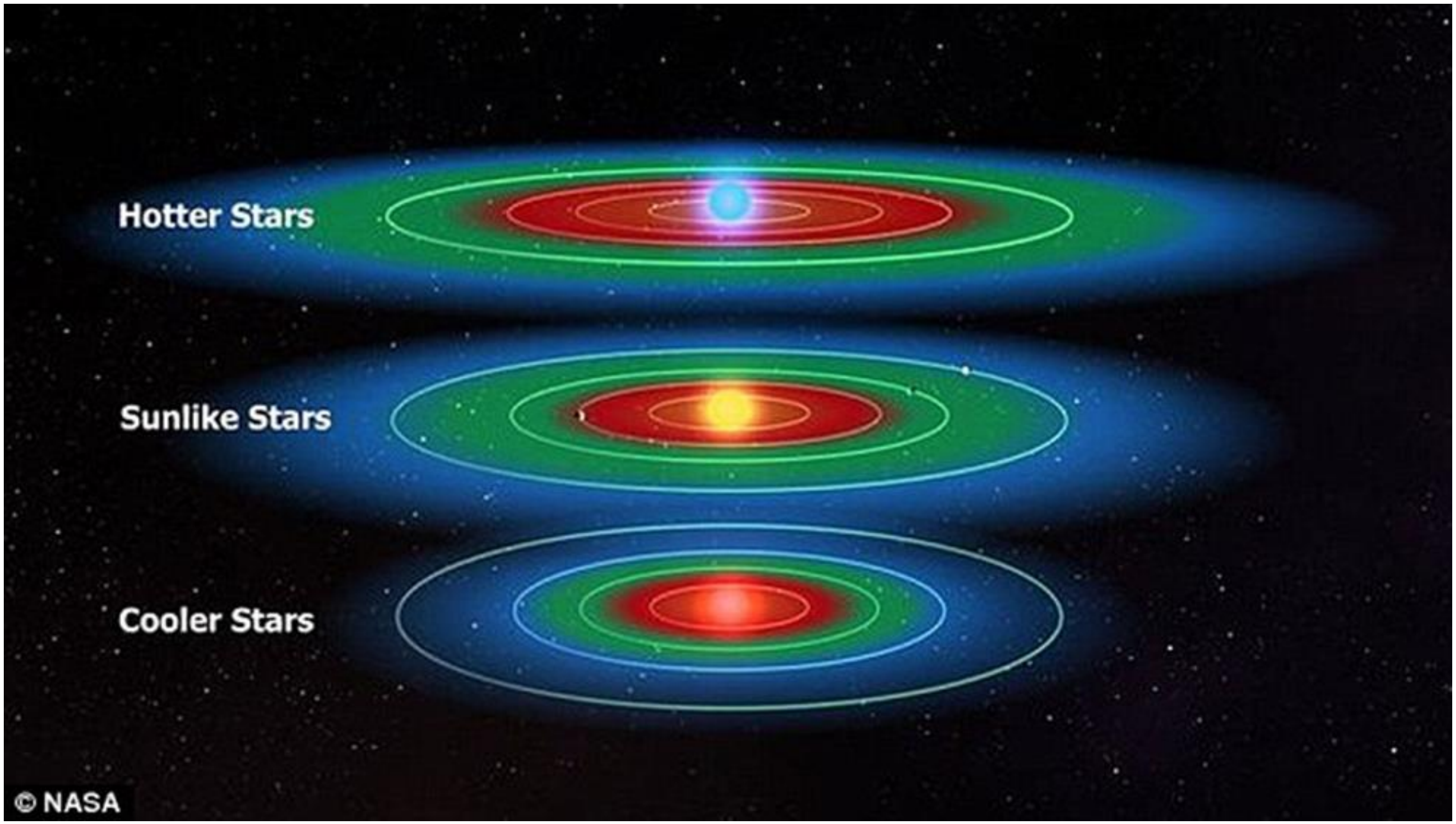
But only a few will be in Habitable Zone

Also, need a moon.

Nancy Atkinson; Universe Today; January 7, 2013

Habitable Zone

Life requires water. Liquid water can only exist in the 'Goldilocks'' Zone. The hotter the star, the further away the zone.



'Billions of stars' in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com, 18 March 2015

All Stars may have 1 to 3 HZ Planets

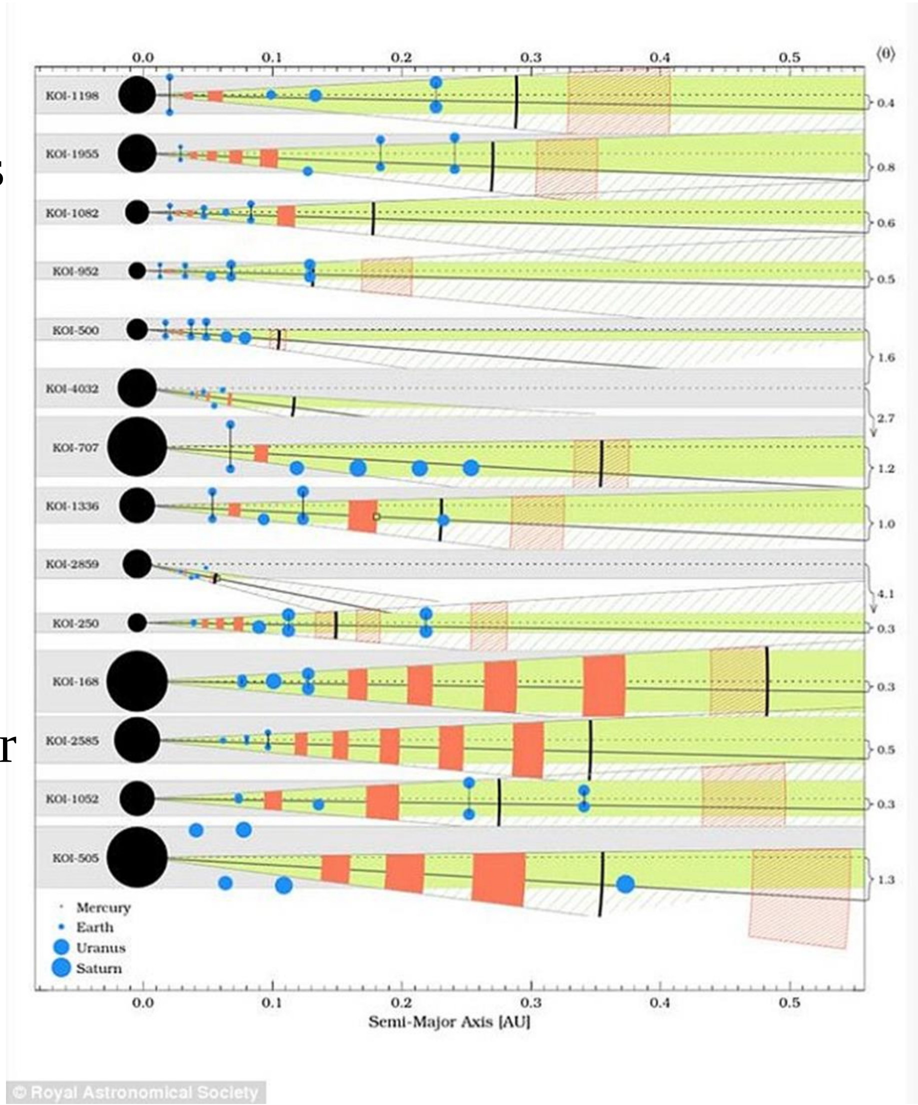
Titius-Bode law (used to predict Uranus) states that ratio between the orbital period of the first and second planet is the same as the ratio between the second and the third planet and so on.

Thus, if you know how long it takes for some planets to orbit a star, you can calculate how long it takes for others to orbit and can calculate their position in the planetary system.

Blue dots show planets measured by Kepler in 151 systems.

Red boxes predicted ‘missing’ 228 planets

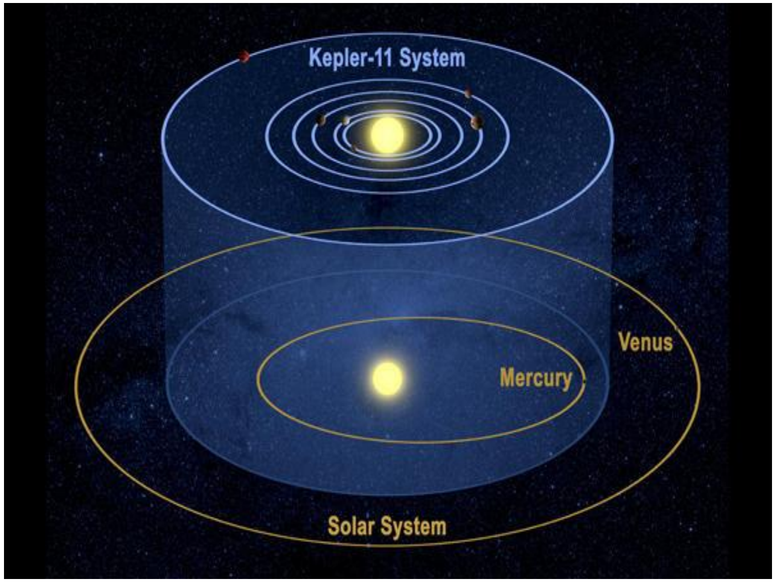
Average of 1 to 3 HZ planets per star.



'Billions of stars' in the Milky Way may have planets that contain alien life, Ellie Zolfagharifard, Dailymail.com, 18 March 2015

Kepler Mission

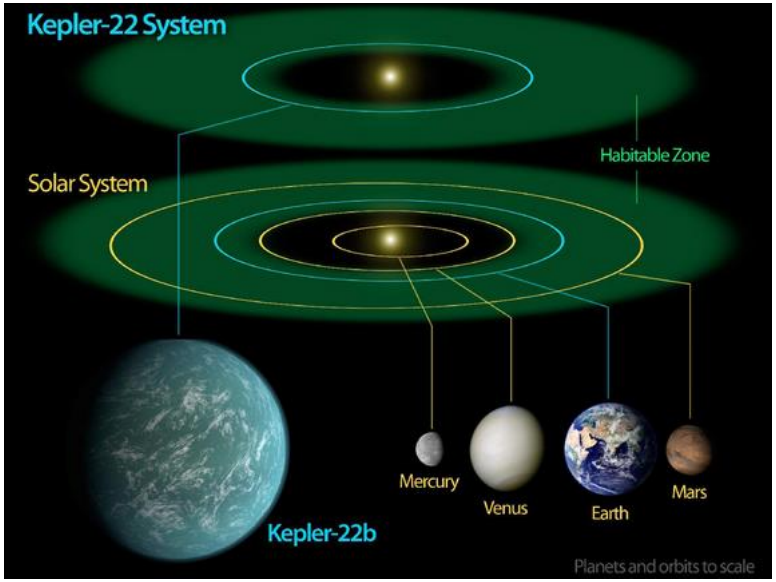
Kepler-11has a star like ours & 6 mini-Neptune size planets



Five of six Kepler-11 exoplanets (all larger than Earth) orbit their star closer than Mercury orbits the sun. One orbits inside Venus.

Credit: NASA/AP (Pete Spotts, Christian Science Monitor.com, 23 May 2011.)

Kepler 22b is the first in the habitable zone.



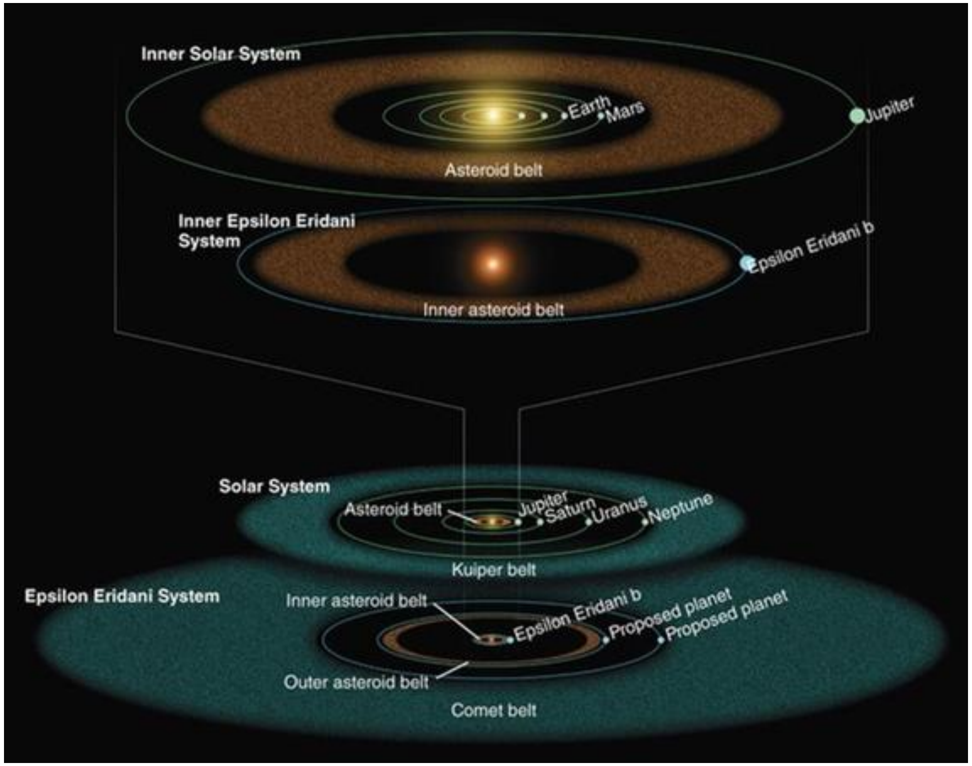
Kepler-22b is located about 600 light-years away, orbiting a sun-like star. Its is 2.4 times that of Earth, and the two planets have roughly similar temperatures (maybe 22C).

CREDIT: NASA/Ames/JPL-Caltech

Spitzer Mission: Epsilon Eridani

Epsilon Eridani is a young planetary system only 10.5 light-years away with a structure similar to ours.

Observed with both Spitzer and SOFIA.



Credit: NASA/JPL-Caltech/R. Hurt (SSC)

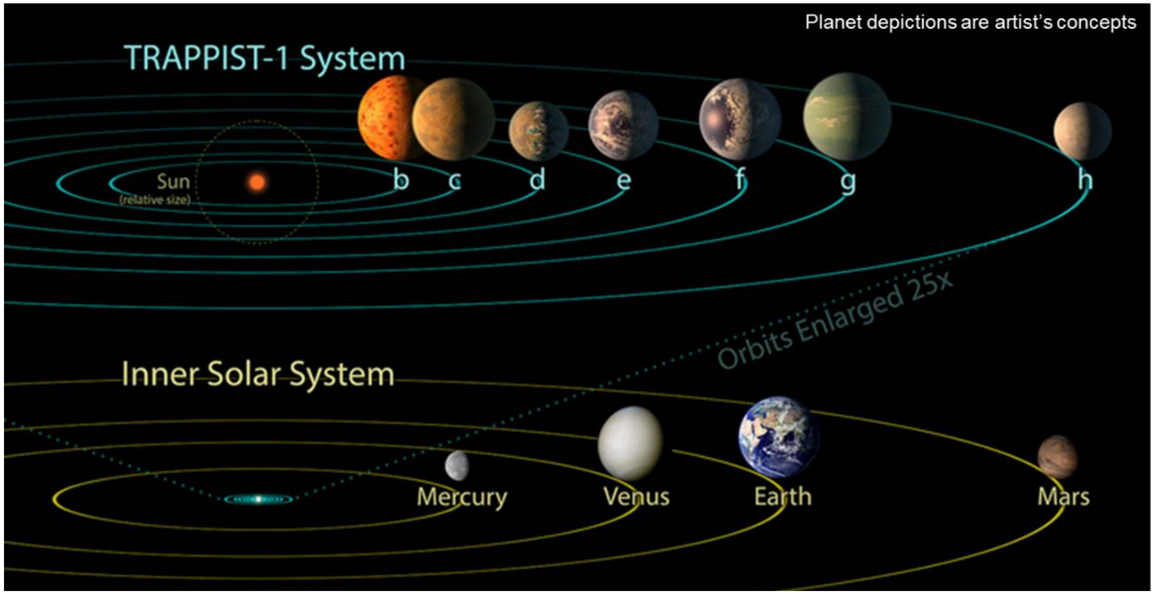
Samantha Mathewson, Space.com | May 4, 2017

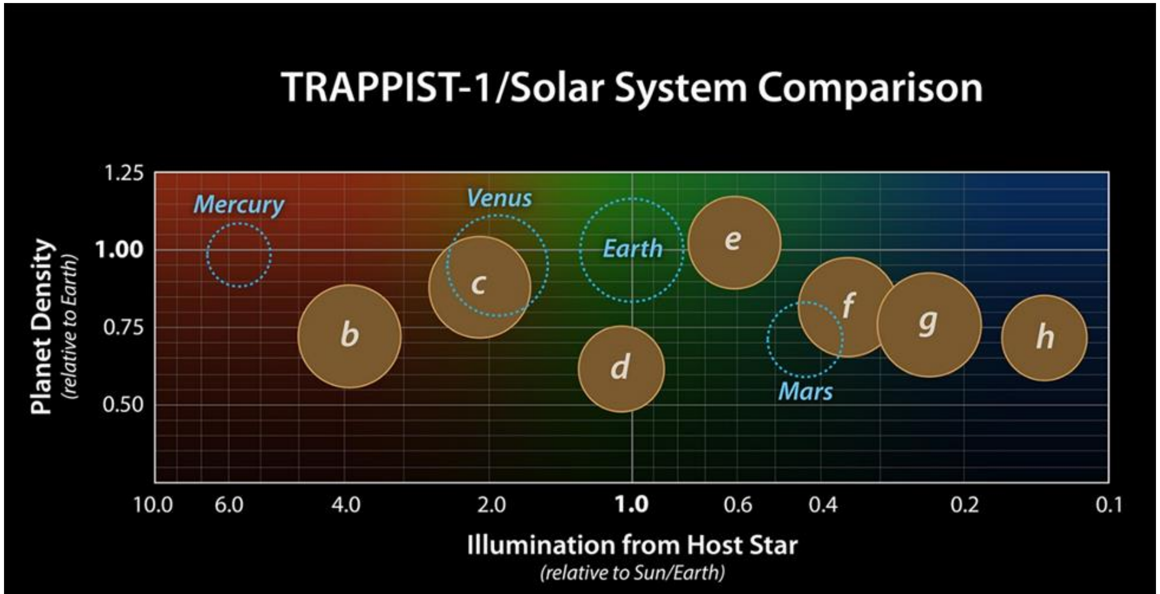
Spitzer Mission: Trappist-1

Trappist-1 is M-class star – i.e. much cooler than our G-class star.

Thus, the Trappist habitable zone is much closer to its star.

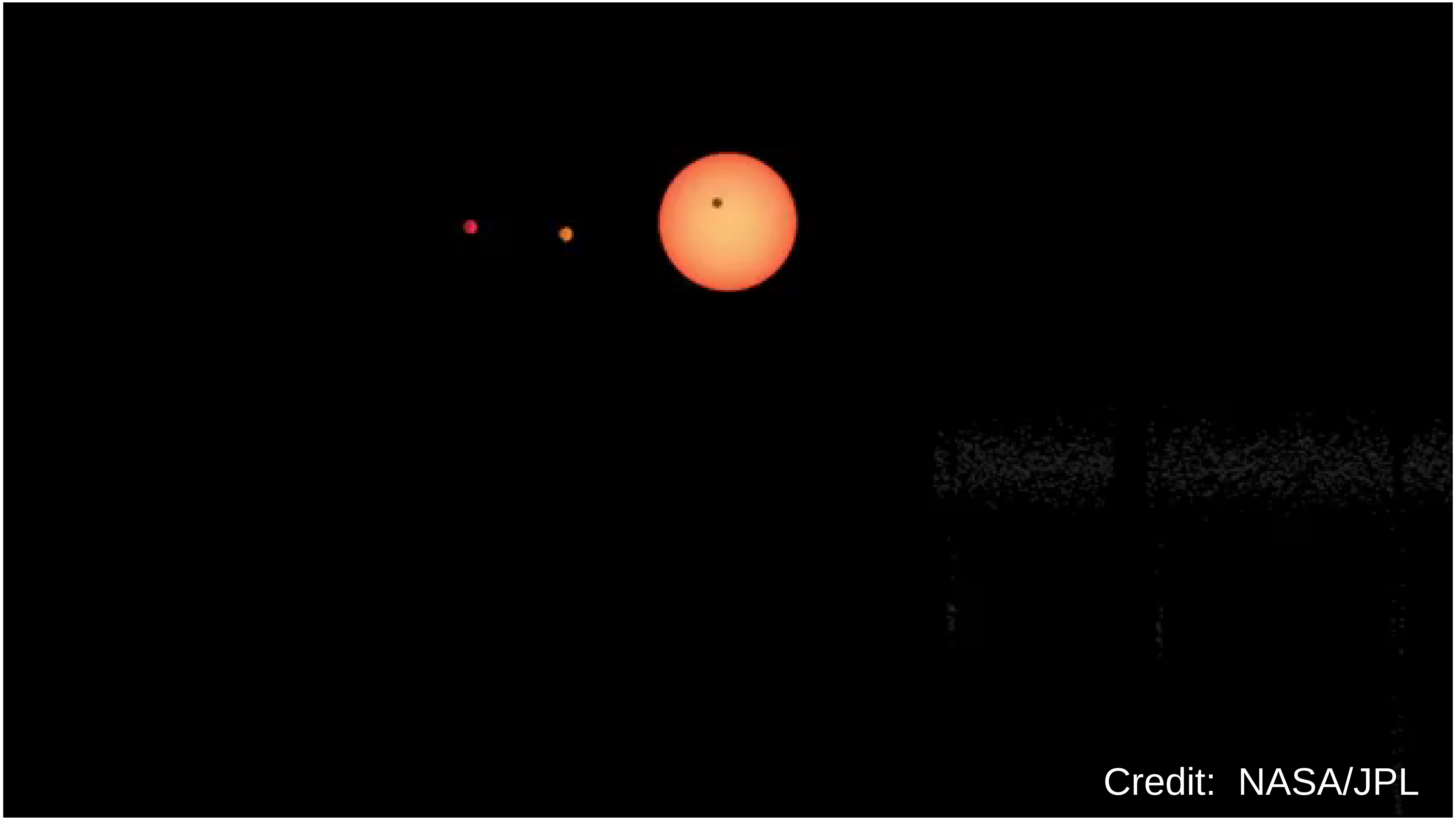
M-class stars may not be friendly to life because they have higher radiation environment than our G-class star.



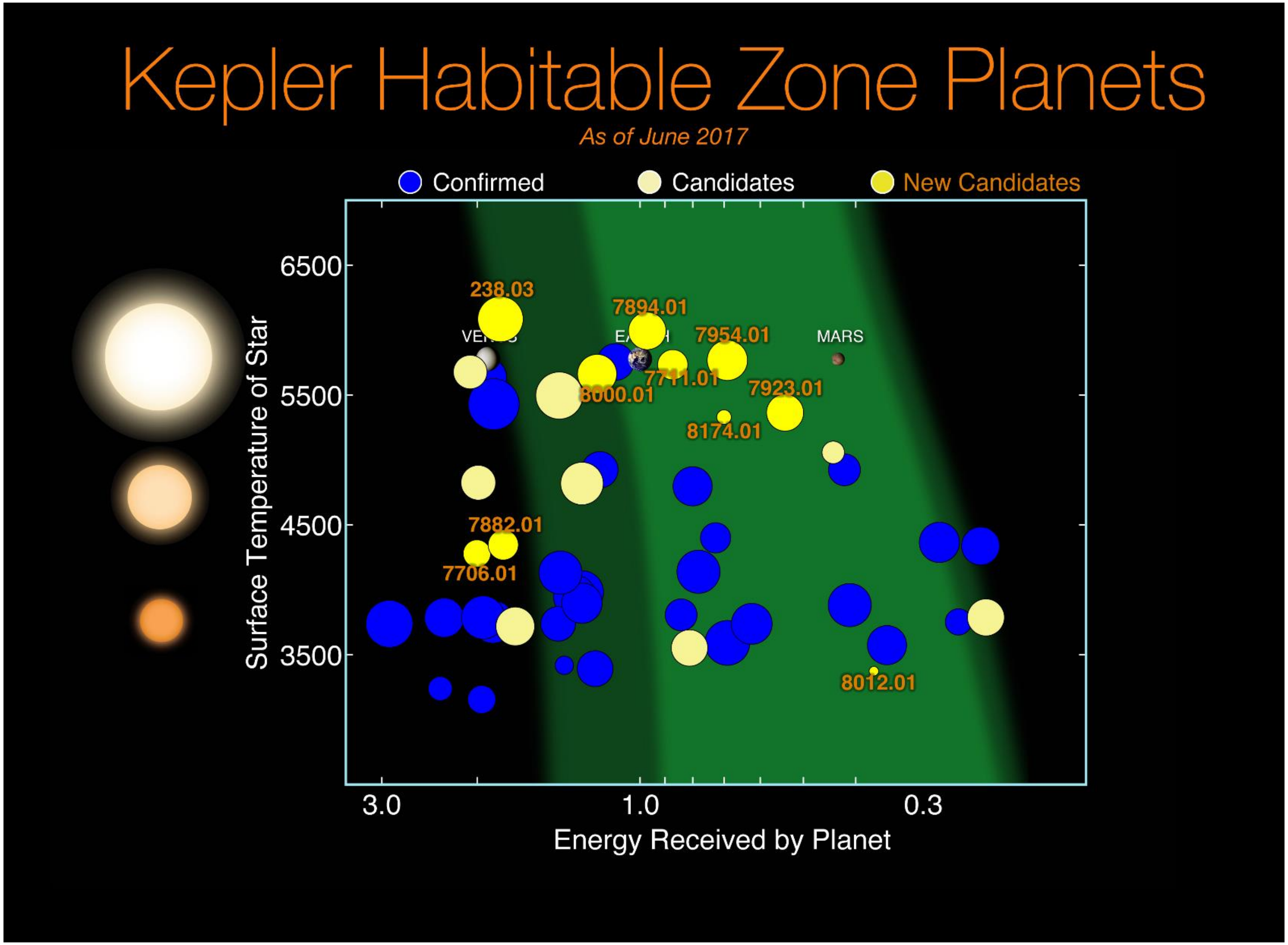


Credit: NASA/JPL

How Spitzer Observed the Trappist-1 System



> 100 Habitable Zone Planet Candidates
> 25 smaller than 2 Earth Radii



https://www.nasa.gov/sites/default/files/thumbnails/image/press-web15_kepler_hz_planets_edit.jpg

Is There Life Elsewhere in the Galaxy?

Need to multiply these values by η_{Earth} x f_B to get the number of potentially life-bearing planets detected by a space telescope.

η_{Earth} = fraction of stars with Earth-mass planets in HZ

f_B = fraction of the Earth-mass planets that have detectable biosignatures

Earth-mass planets within these HZ will be very

If: $\eta_{Earth} \times f_B \sim 1$ then $D_{Tel} \sim 4m$

$\eta_{Earth} \times f_B < 1$ then $D_{Tel} \sim 8m$

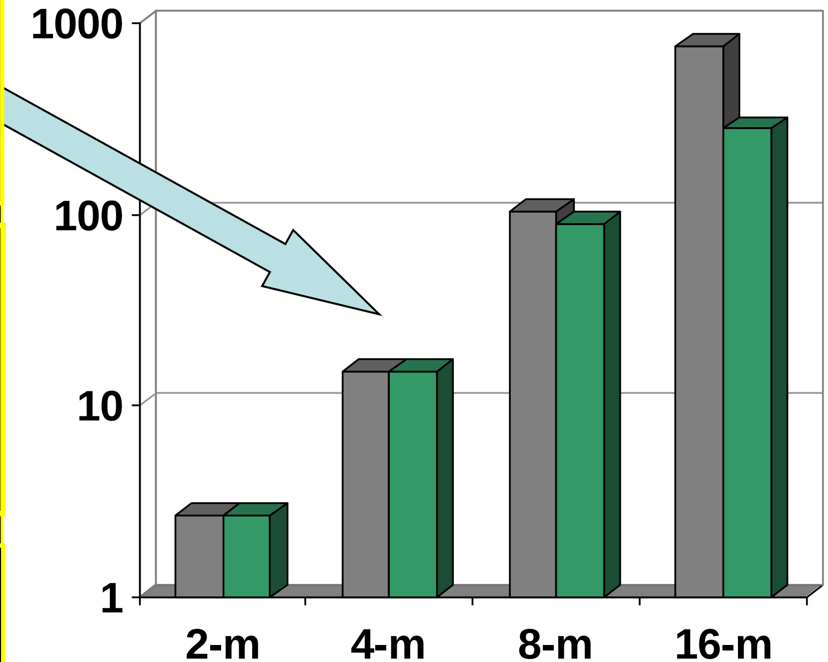
$\eta_{Earth} \times f_B << 1$ then $D_{Tel} \sim 16m$

Number of nearby stars capable of hosting

Kepler is finding that η_{Earth} maybe 1.5% to 2.5% (SPACE.COM, 21 Mar 2011)

Thus, an 8-m telescope might find 1 to 3 Earth twins and an 16-m telescope might find 10 to 20 Earth twins.

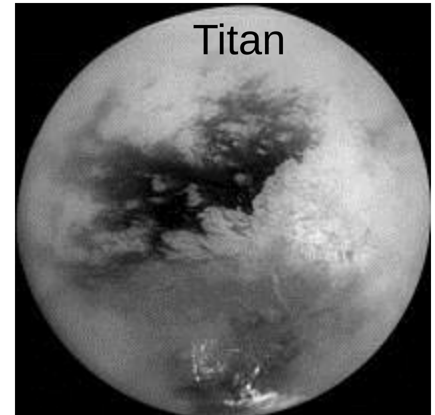
Number of FGK stars for which SNR=10, R=70 spectrum of Earth-twin could be obtained in <500 ksec



Green bars show the number of FGK stars that could be observed 3x each in a 5-year mission without exceeding 20% of total observing time available to community.

Marc Postman, “ATLAST”, Barcelona, 2009; Modified by Stahl, 2011

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?

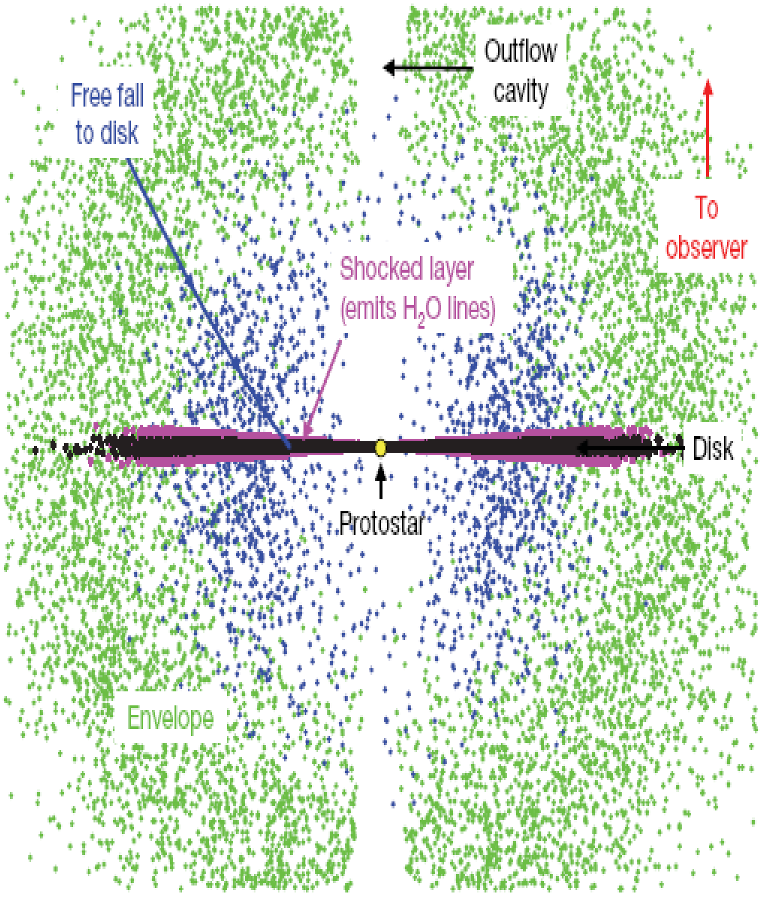
JWST Observations:

Comets, Kuiper Belt Objects

Icy moons in outer solar system

Where does the water come from?

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk



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

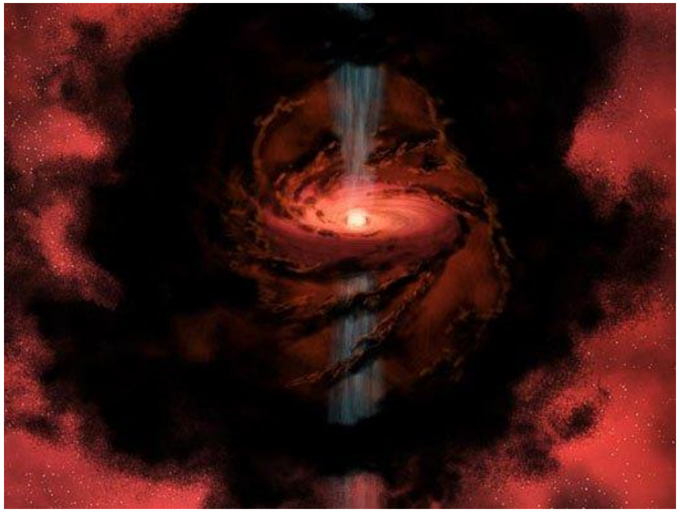
Proto-Stars produce Water

In a proto-star 750 light-years away, Herschel detected:

- Spectra of Atomic Hydrogen and Oxygen are being pulled into the star, and
- Water vapor being spewed at 200,000 km per hour from the poles.
- The water vapor freezes and falls back onto the proto-planetary disk.

Discovery is because Herschel's infrared sensors can pierce the dense cloud of gas and dust feeding the star's formation.

(National Geographic, Clay Dillow, 16 June 2011)



A Protostar and its Polar Jets NASA/Caltech

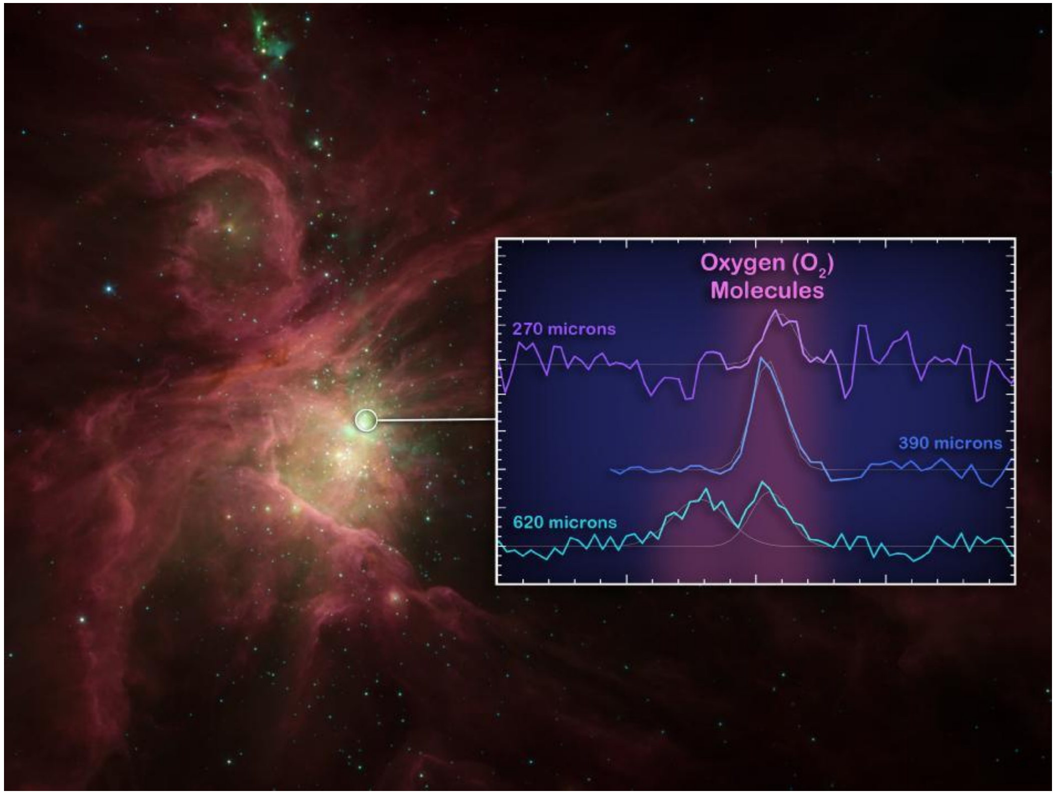
Other Herschel Data finds enough water in the outer reaches of the young star TW Hydrae (175 light-yrs from Earth) to fill Earth's oceans several thousand times over.

Mike Wall, SPACE.com; Date: 20 October 2011

Molecular Oxygen discovered in space

Herschel found molecular oxygen in a dense patch of gas and dust adjacent to star-forming regions in the Orion nebula.

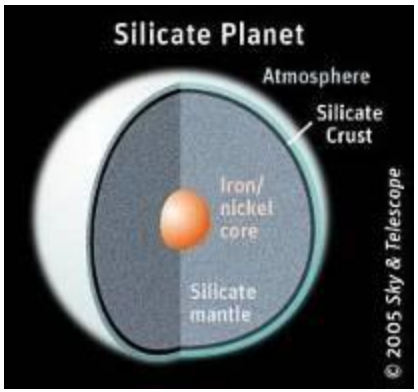
The oxygen maybe water ice that coats tiny dust grains.

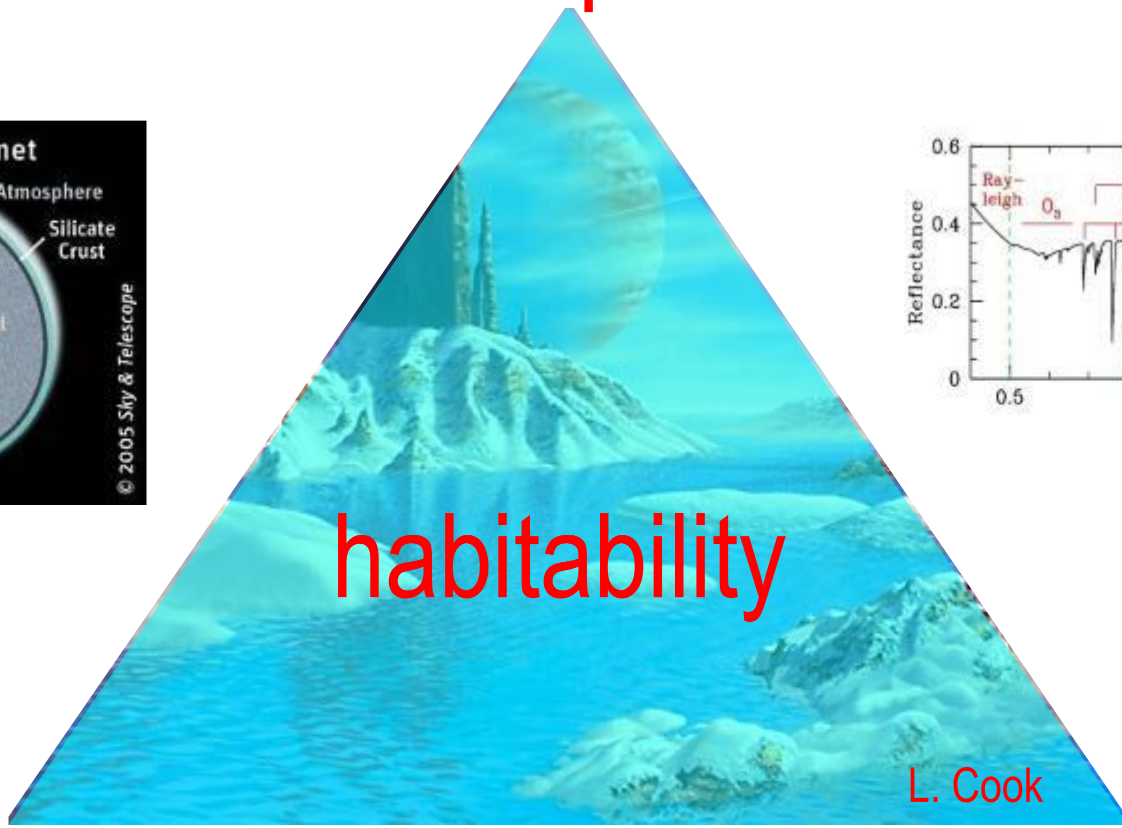


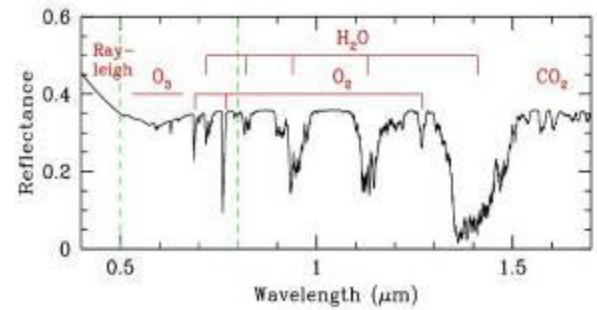
SPACE.com, 01 August 2011

Search for Habitable Planets

atmosphere







interior

surface

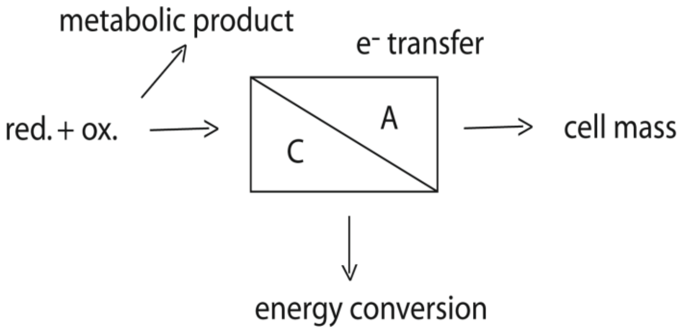
Sara Seager (2006)

Search for Life

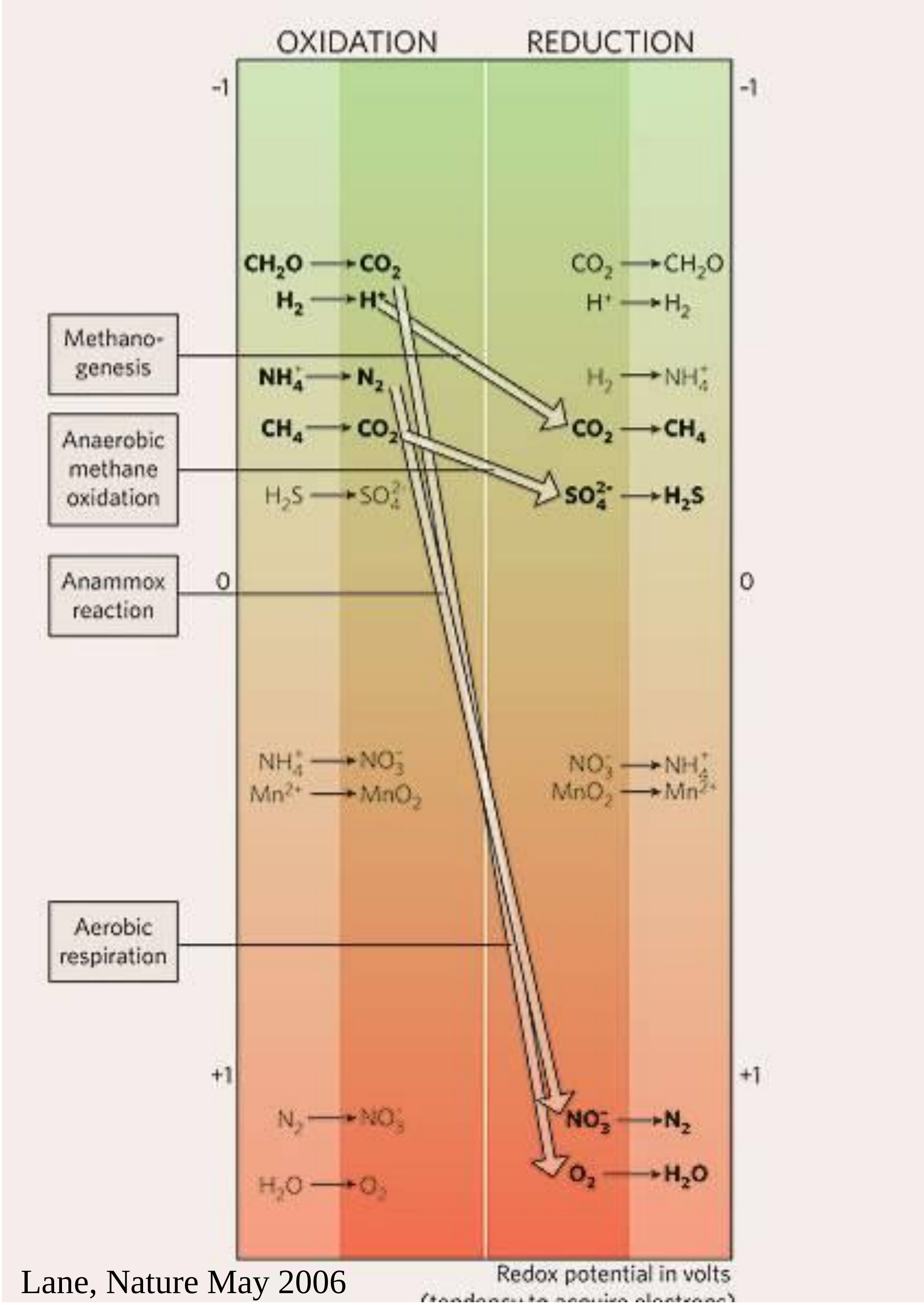
What is life?

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

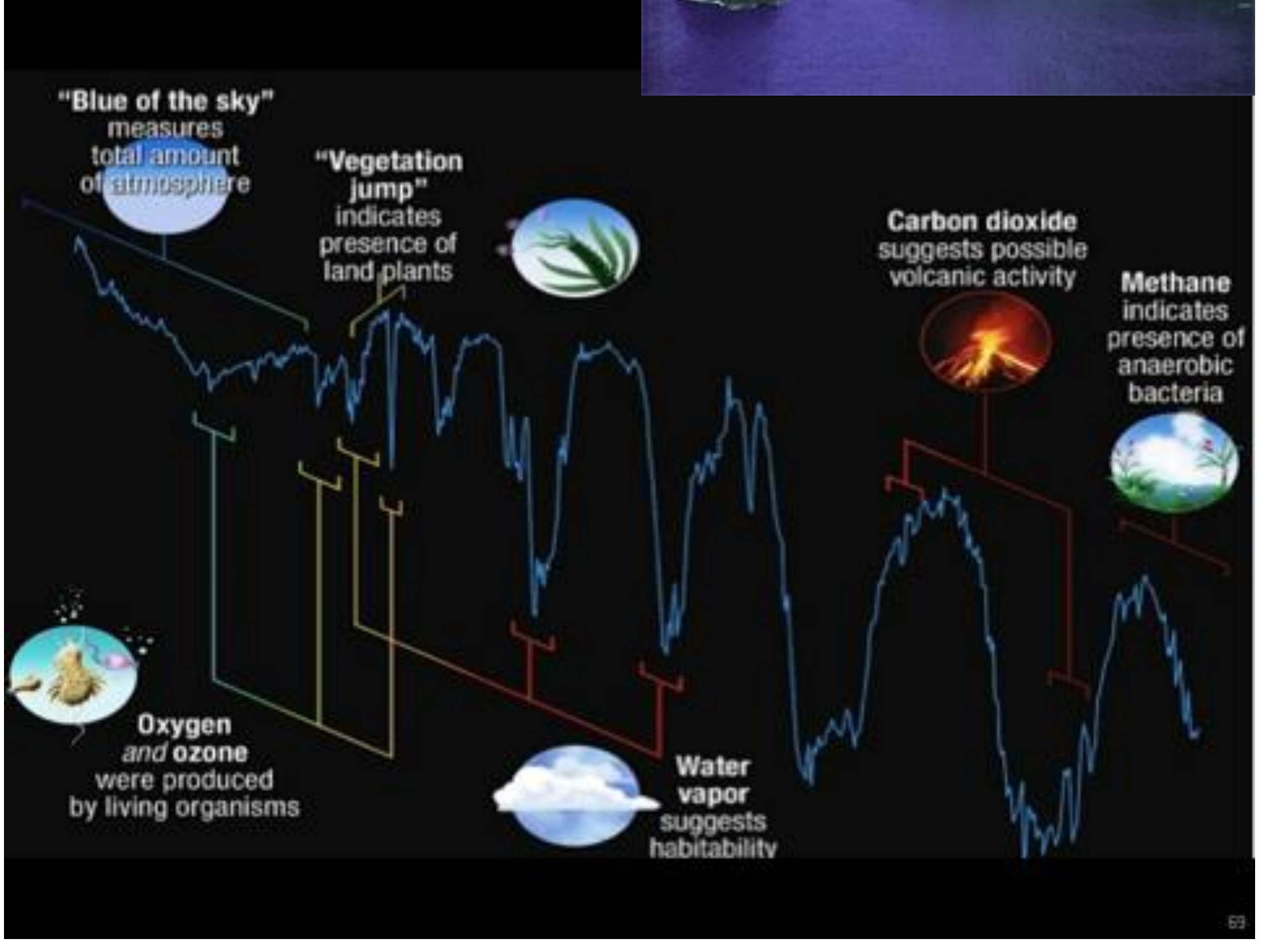
Sara Seager (2006)

Bio Markers

Spectroscopic Indicators of Life

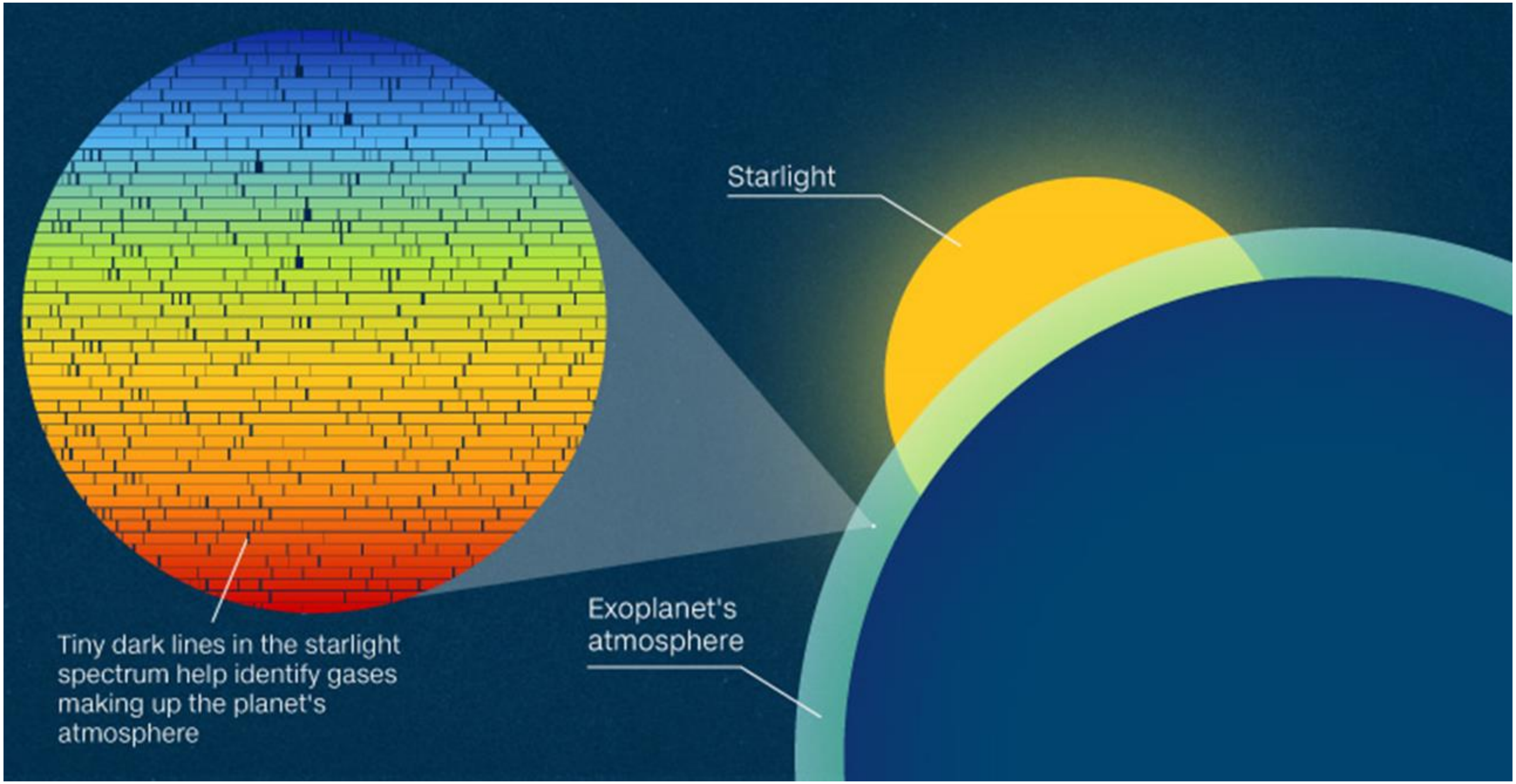
Absorption Lines

- Water
- Oxygen & Ozone
- CO2
- Methane
- “Red” Edge
- “Blue” Haze

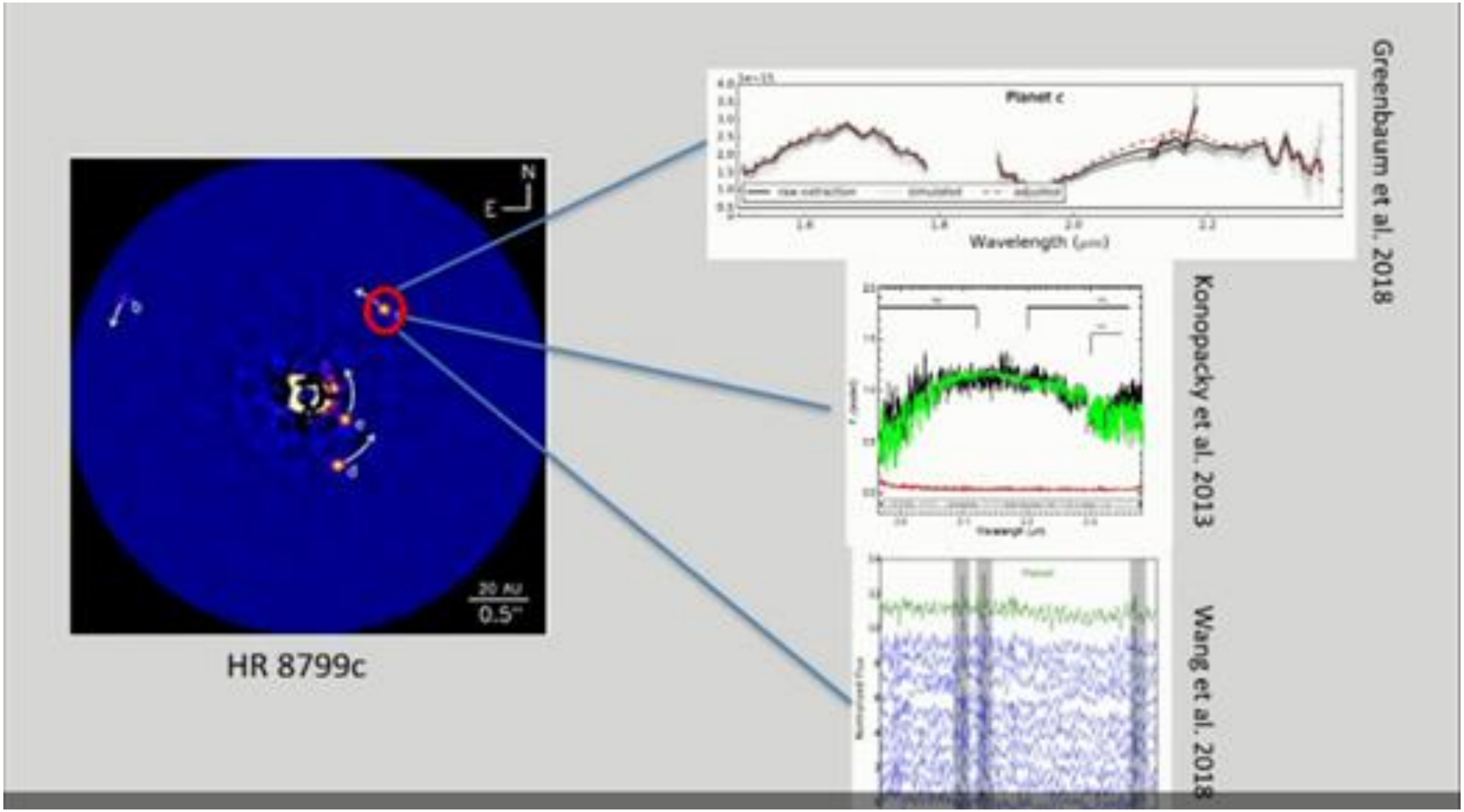


How to see an Exoplanet's Atmosphere

One method is absorption spectroscopy during transits.

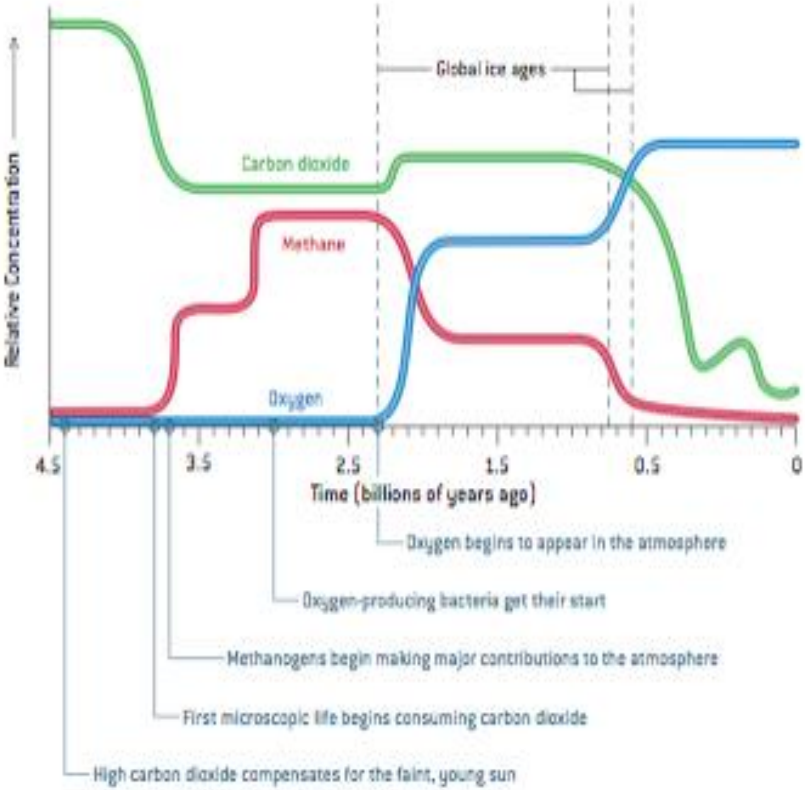


Another is reflected light spectroscopy

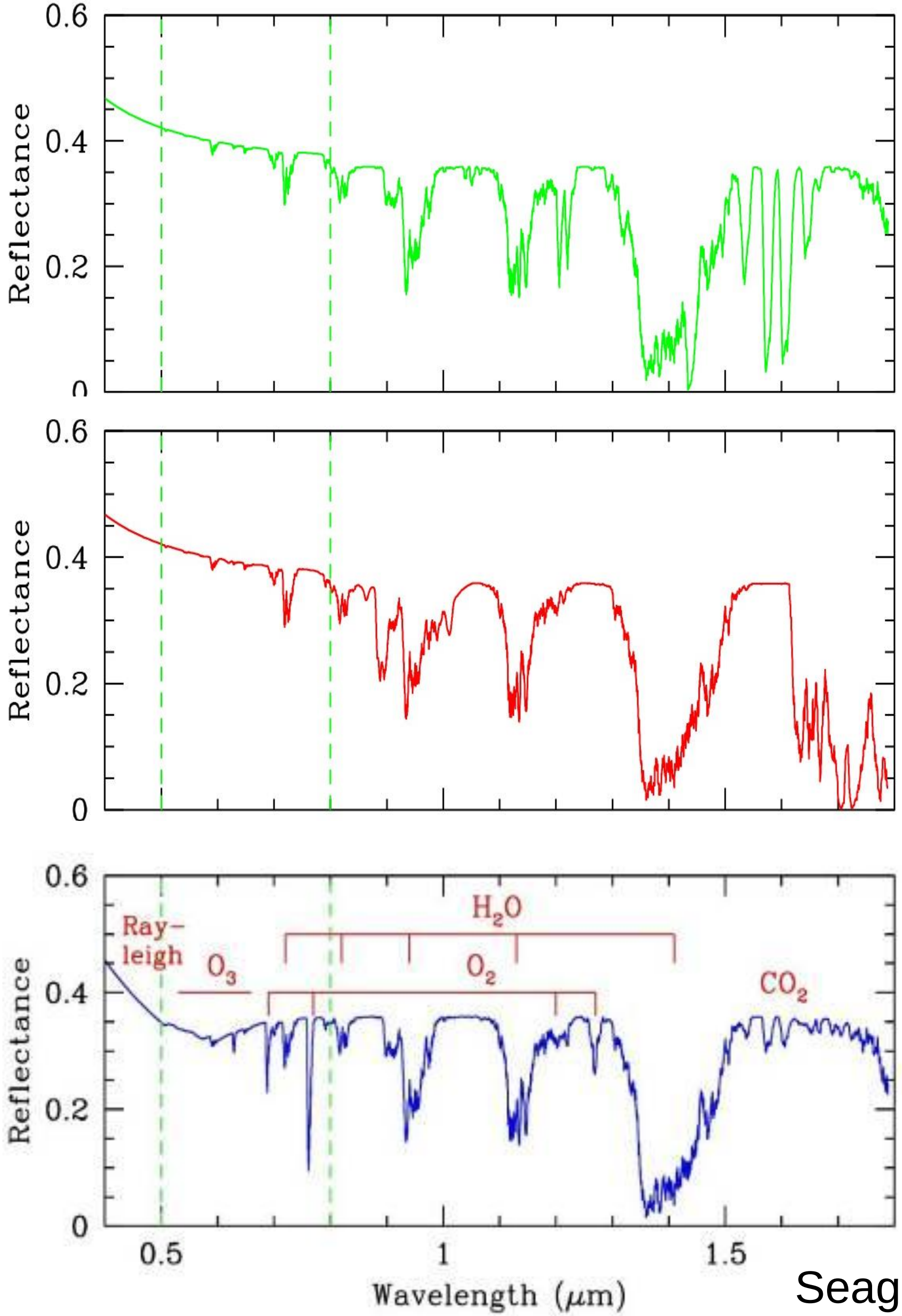


Konopacky, High Contrast Imaging and Adaptive Optics for Nearby Stars and Planetary Systems, AAS 2019

Earth Through Time



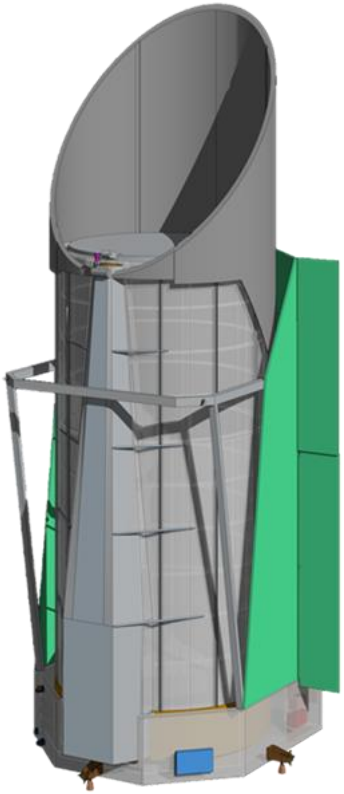
Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon

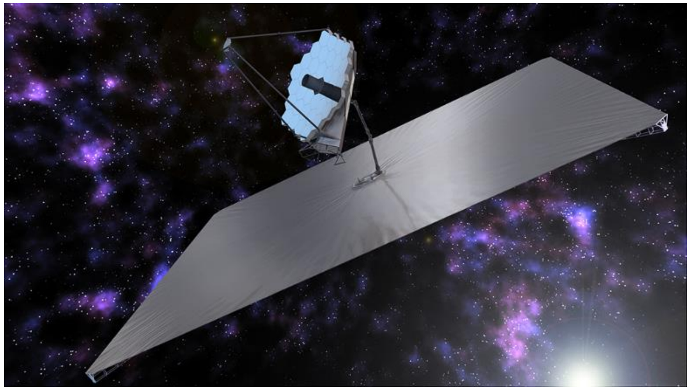


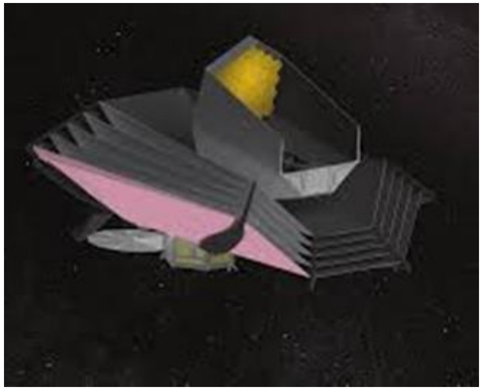
Seager

Beyond JWST

SLS enables even larger telescope Concepts:

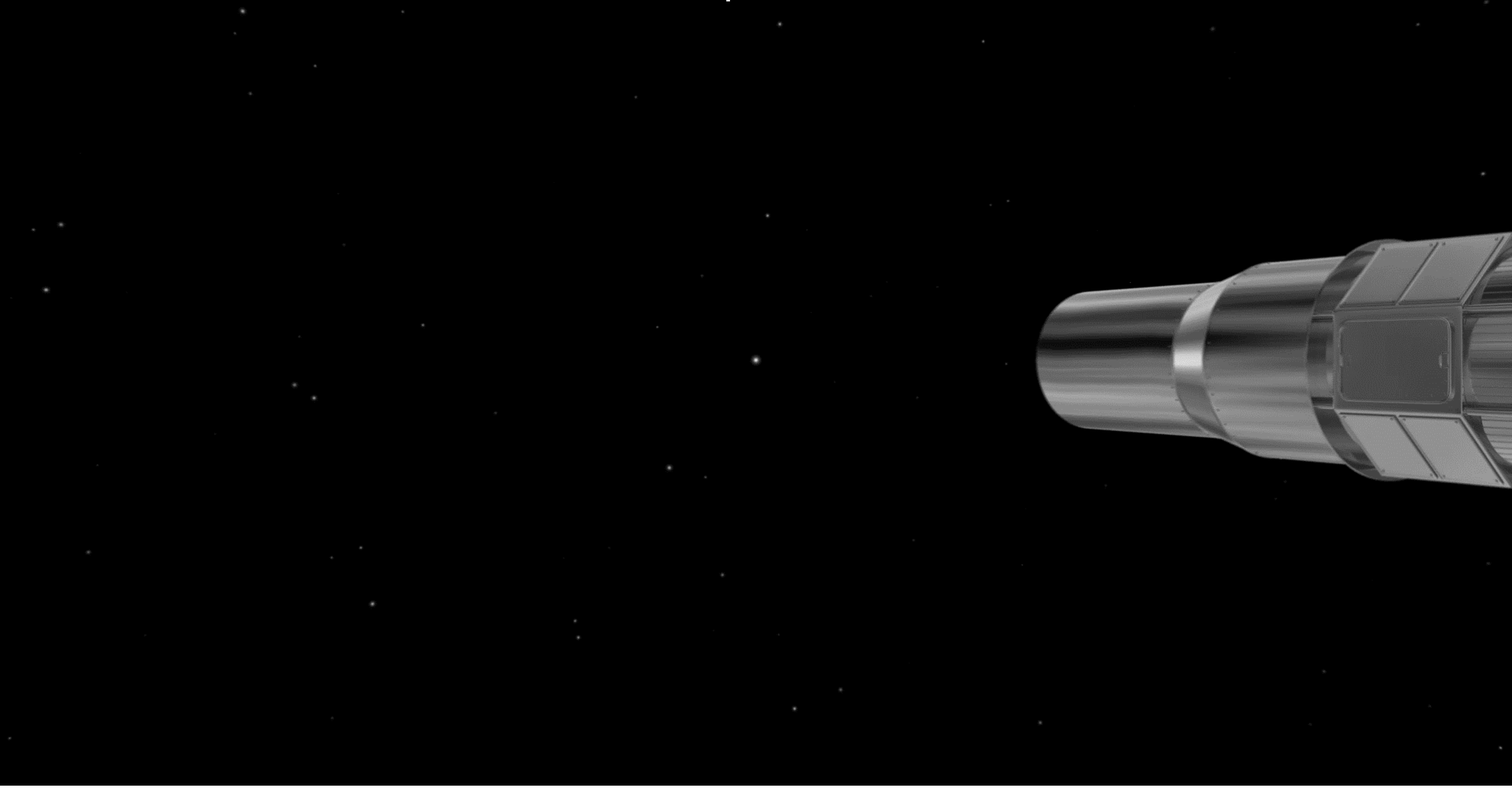


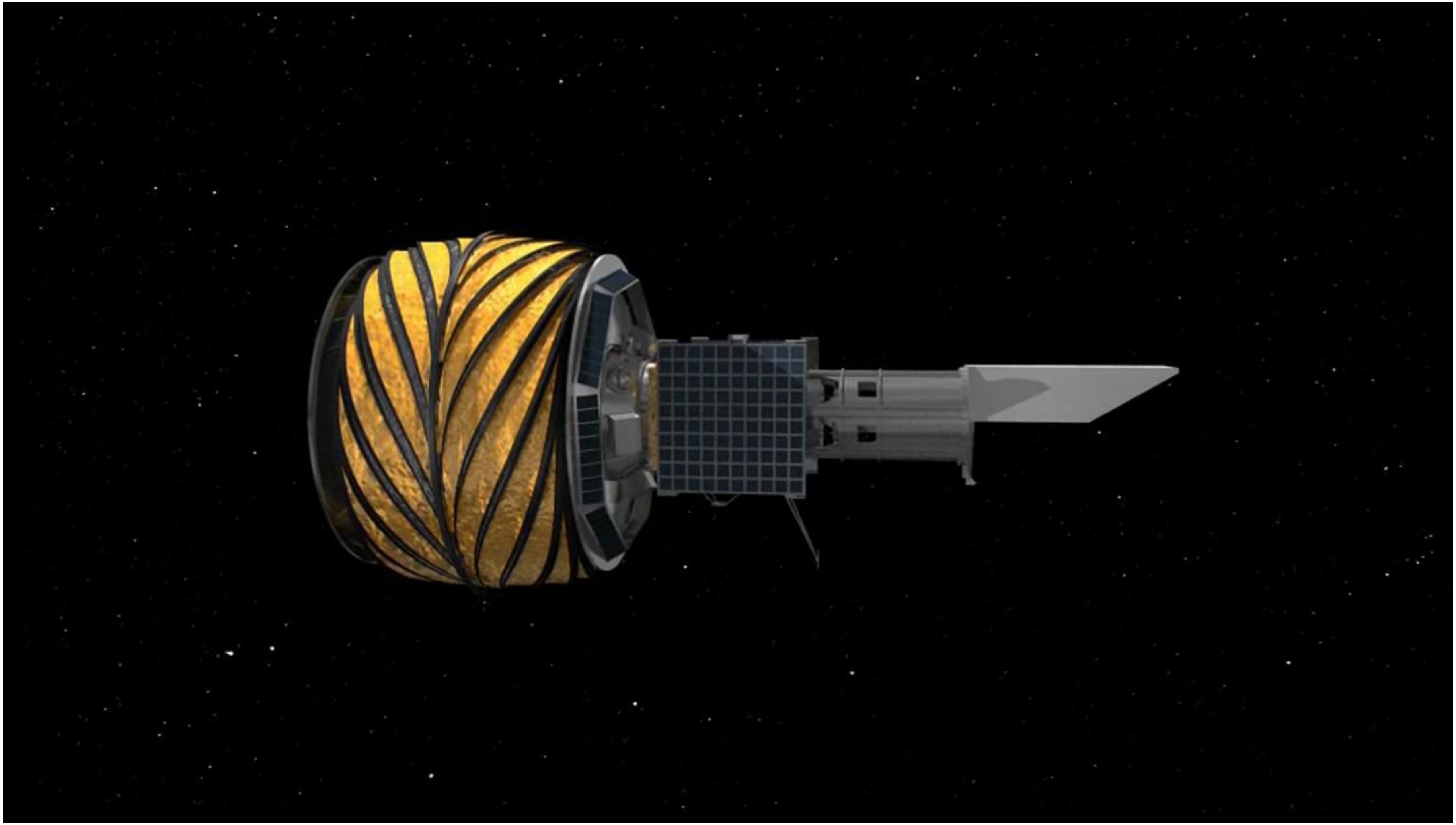




HabEx LUVOIR OST Far-IR

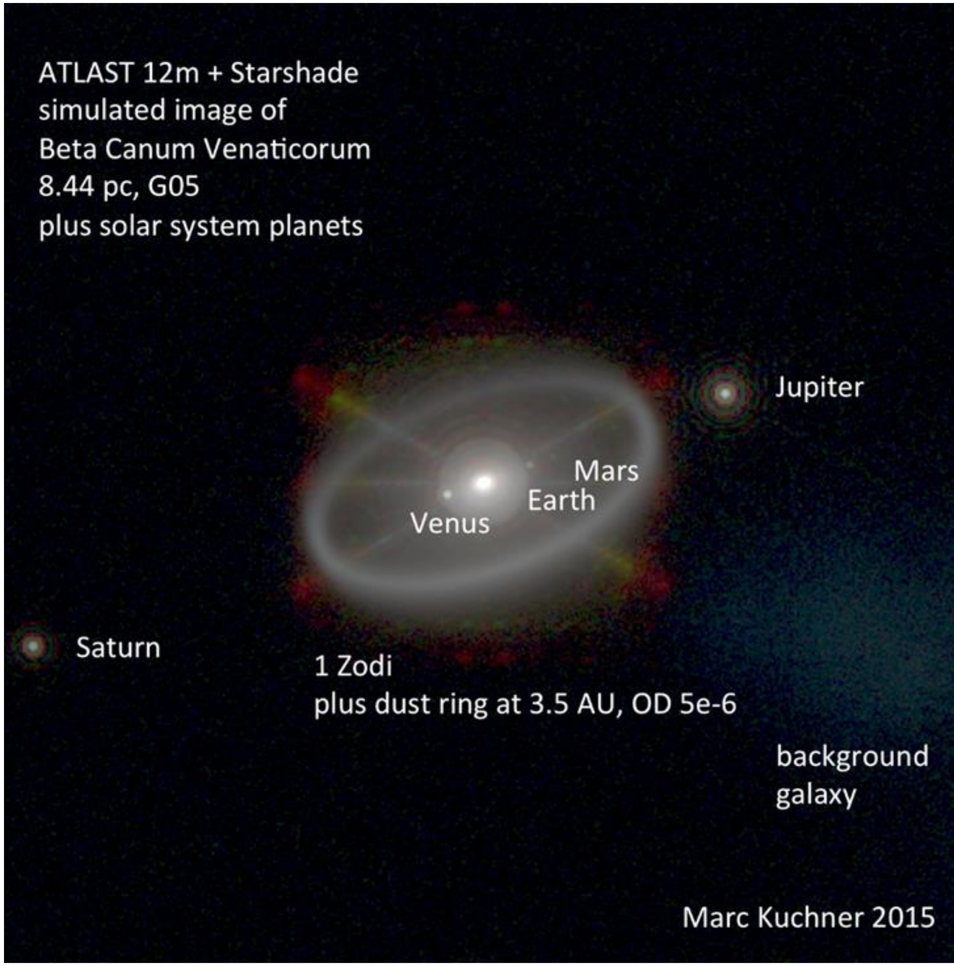
Controls Diffraction to Reveal Exoplanets in “Dark Hole”





Direct Imaging

Giant Space Telescopes will be able to directly image Planetary Systems using either internal coronagraphs or external star shades.



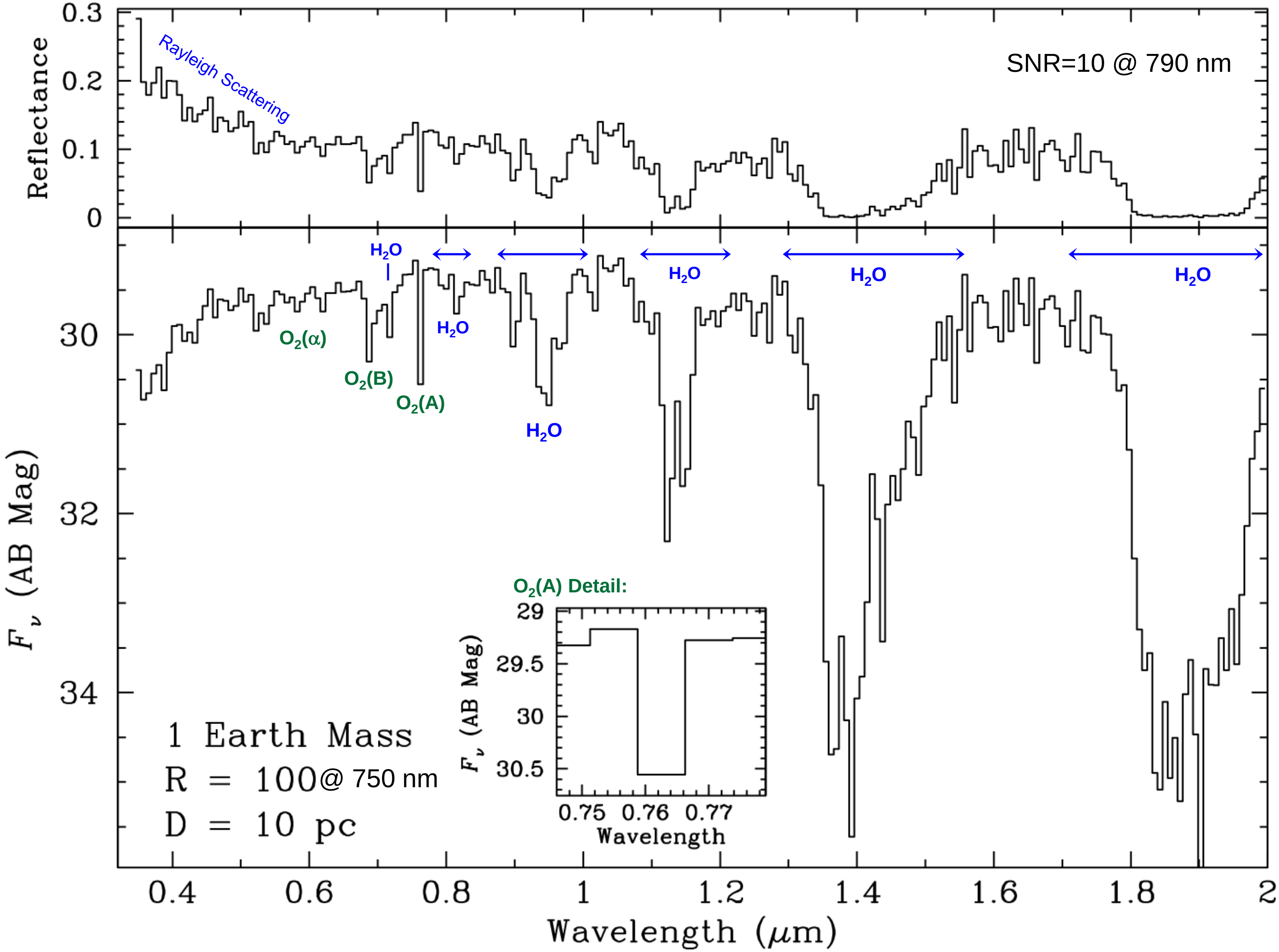
Simulated image for a 12-m telescope, a 100-m star shade, and 1 day exposure.

R=100 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc

Exposure: 51 ksec on 8-m
4.3 ksec on 16-m

Reflectance ∝ (Planet Mass)$^{2/3}$
5 Earth-mass: 8.5 ksec on 8-m

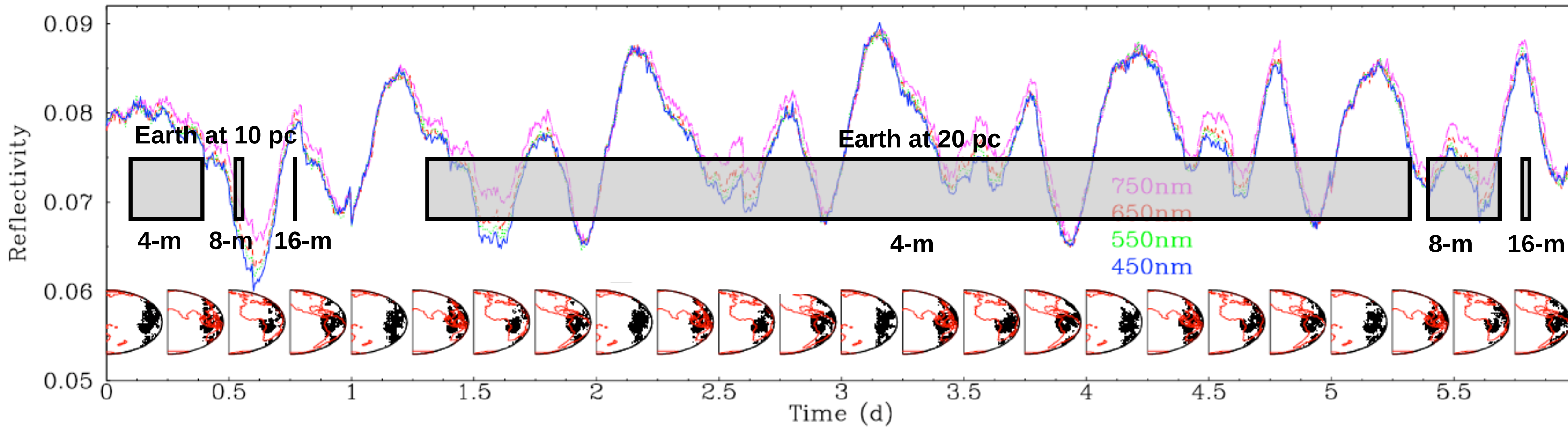
Bkgd: 3 zodi



Marc Postman, “ATLAST”, Barcelona, 2009

Detecting Photometric Variability in Exoplanets

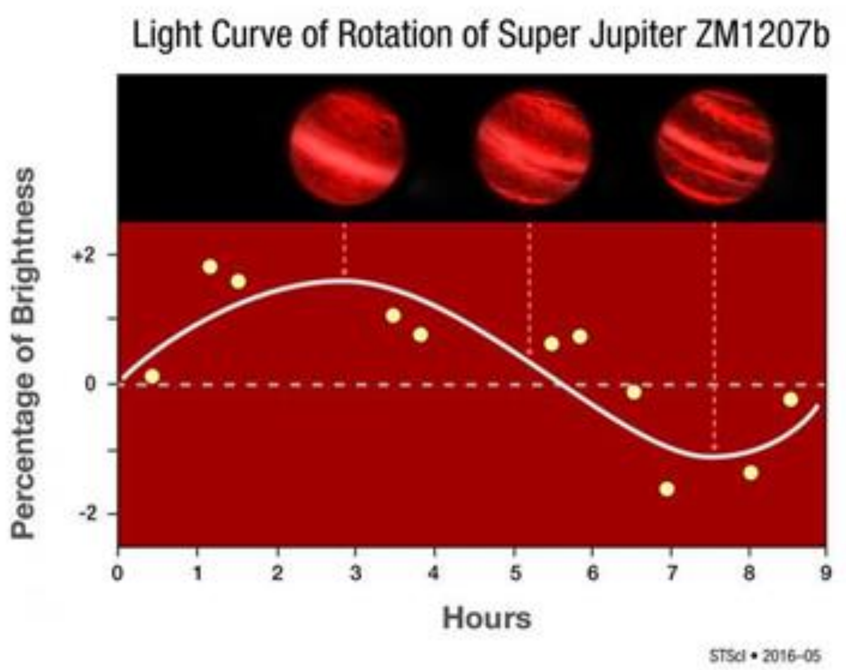
Ford et al. 2003: Model of broadband photometric temporal variability of Earth



Require S/N ~ 20 (5% photometry) to detect ~20% temporal variations in reflectivity.

Need to achieve a single observation at this S/N in < 0.25 day of exposure time in order to sample the variability with at least 4 independent observations per rotation period.

Detecting Photometric Variability in Exoplanets



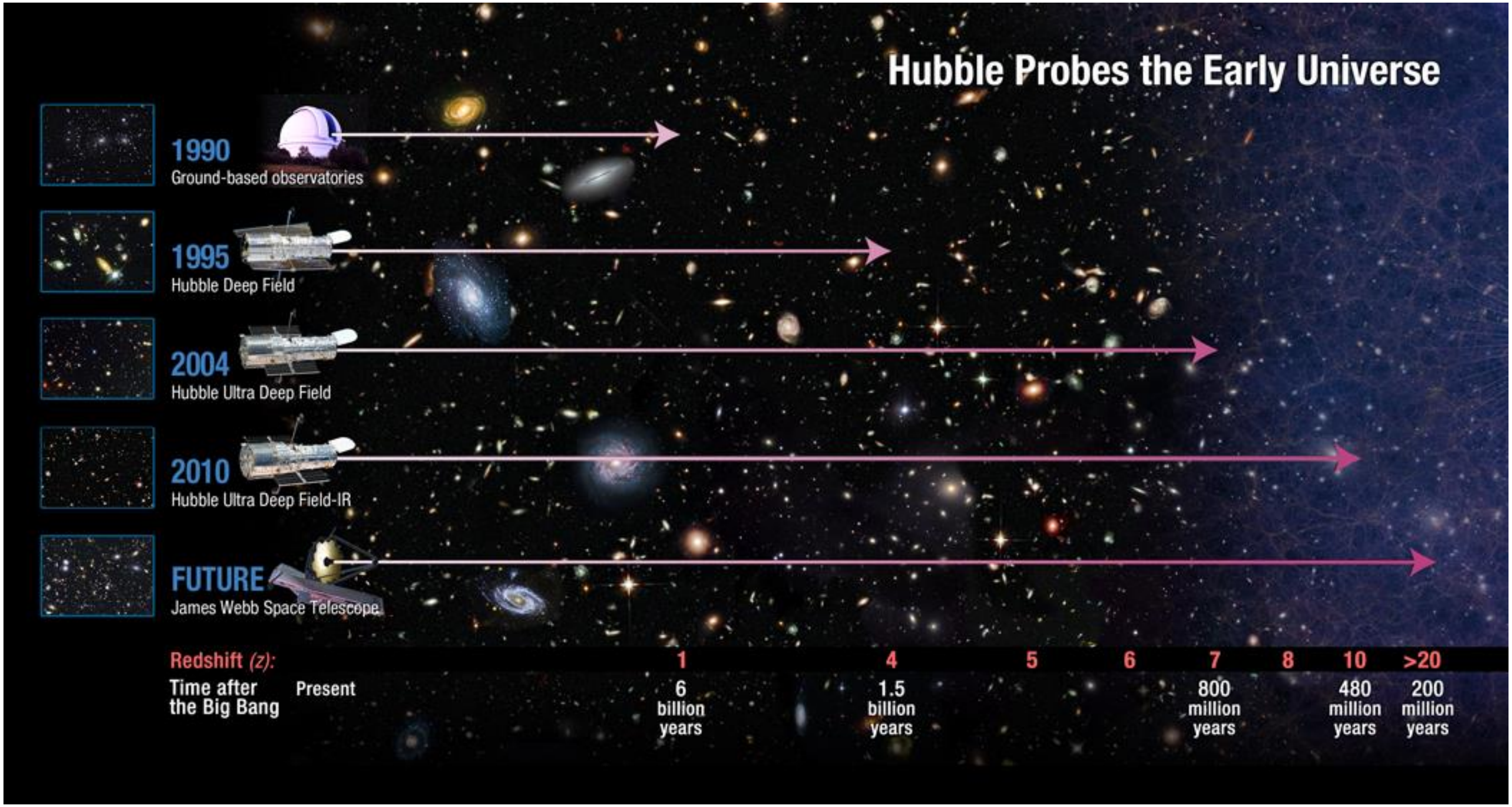
Graph shows changes in infrared brightness of 2M1207b as measured by Hubble over the course of a 10-hr observation.

Change in brightness suggests presence of clouds that influence amount of infrared radiation observed as the planet rotates.

CREDIT NASA, ESA, Y. Zhou (University of Arizona), and P. Jeffries (STScI)

JWST – the First Light Machine

With its 6X larger collecting aperture, JWST will see back in time further than Hubble and explore the Universe's first light.



Countdown to Launch

JWST is

- making excellent technical progress
- will be ready for launch in 2021
- will be the dominant astronomical facility for a decade undertaking a broad range of scientific investigations

1000s of Scientists and Engineers in USA and around the world are working to make JWST.

Any Questions?