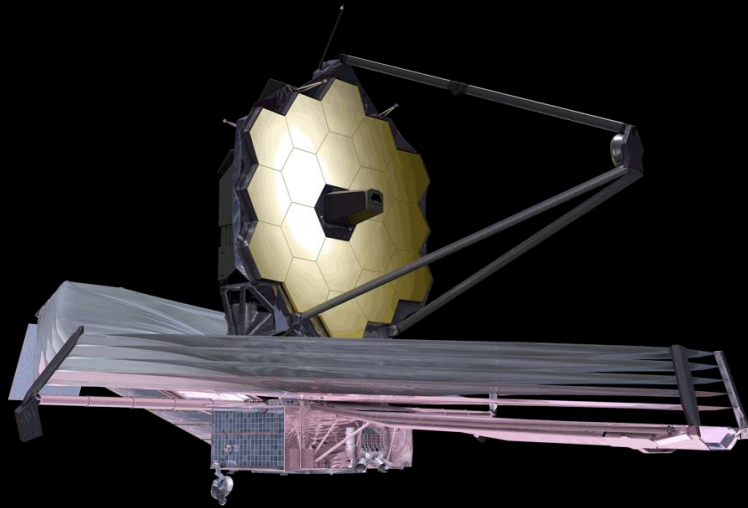


James Webb Space Telescope (JWST)



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.



credit: NASA

What is FIRST LIGHT?

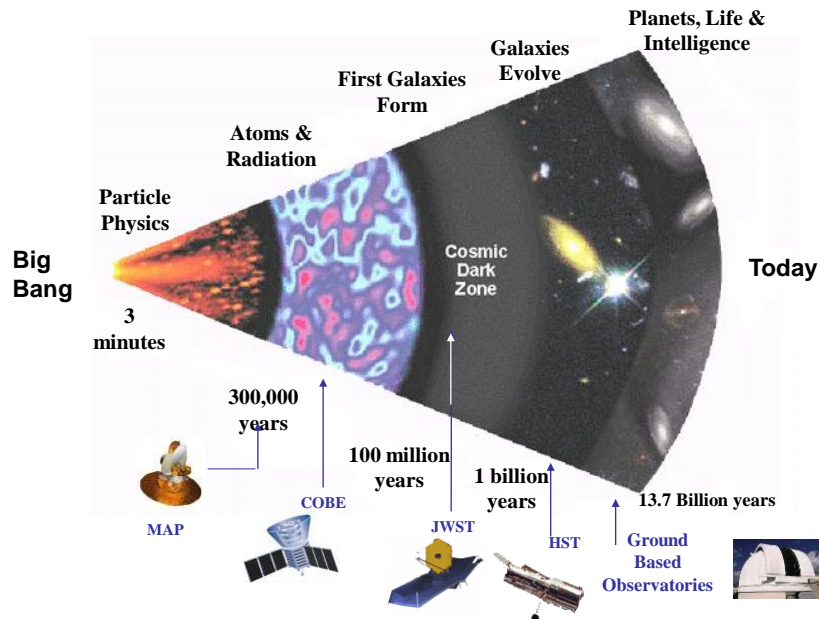
End of the dark ages: first light and reionization

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.

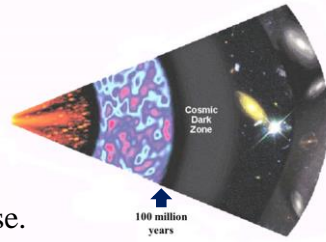
Hubble Ultra Deep Field

A Brief History of Time



First Light Stars

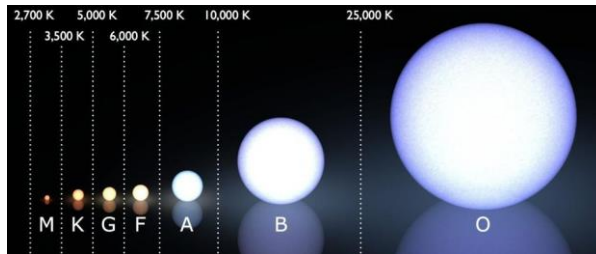
First stars (maybe 1000X larger than our own) formed from clouds of hydrogen 50-100 million years after the Big Bang.



These first stars helped ionize the universe.

Because they were so large, they quickly exploded supernova creating elements such as He or collapsed into black holes.

'O'-class stars are 25X larger than our 'G'-class Sun.



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

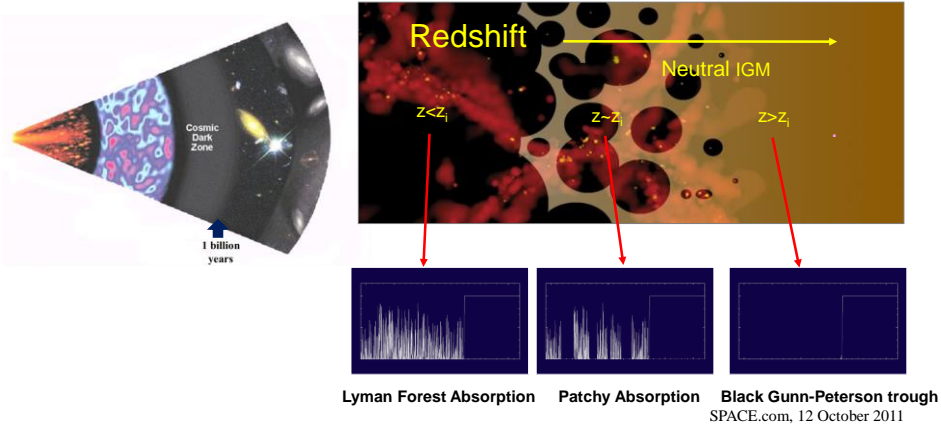
Ethan Siegel, FORBES.com, 24 Oct 2018

First Light: Reionization

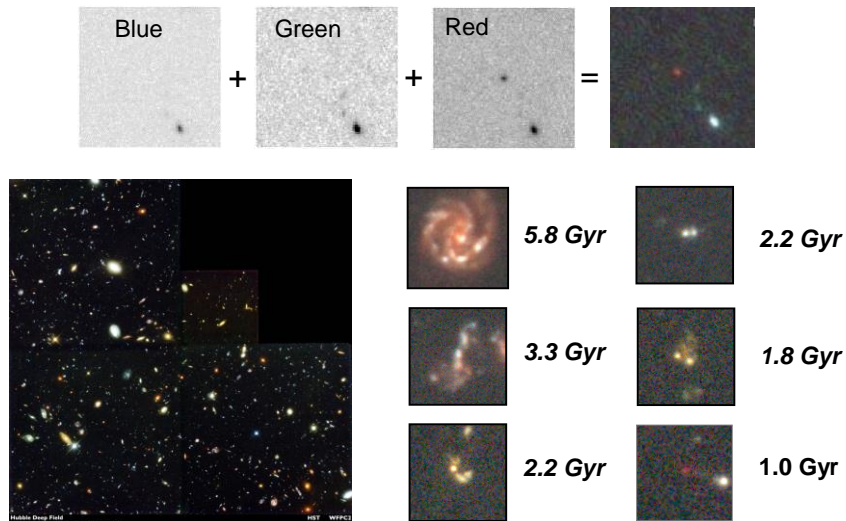
Neutral 'fog' was dissolved by very 1st Generation Stars.

As indicated by Neutral Hydrogen spectroscopy, 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.

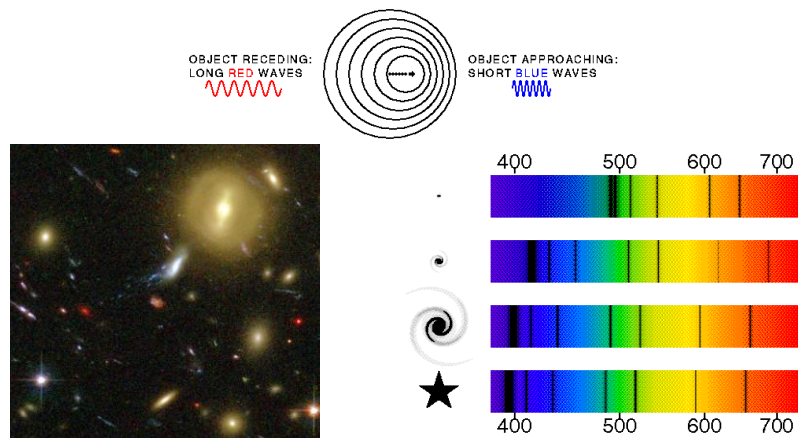


How do we see first light objects? Redshift



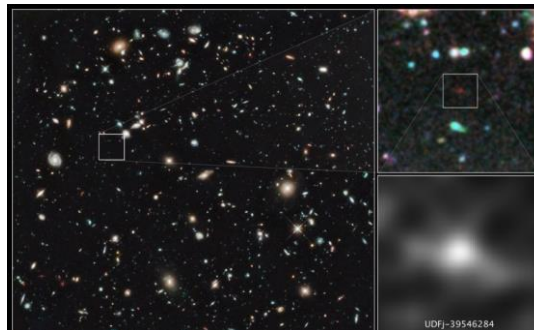
What is Redshift

The further away an object is, the more its light is **redshifted** from the visible into the infrared – because of space/time stretching.

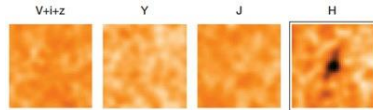


To see really far away, we need an **infrared** telescope.

First Galaxy in Hubble Deep Field



At 480 M yrs after big bang ($z \sim 10$) 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

• Mission Objective

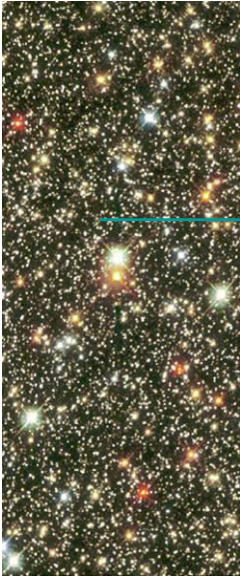
- Study origin & evolution of galaxies, stars & planetary systems
- Optimized for near infrared wavelength (0.6 –28 μm)
- 5 year Mission Life (10 year Goal)

• Organization

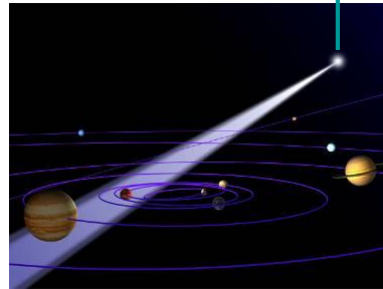
- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
 - Near Infrared Camera (NIRCam) – Univ. of Arizona
 - Near Infrared Spectrometer (NIRSpec) – ESA
 - Mid-Infrared Instrument (MIRI) – JPL/ESA
 - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute



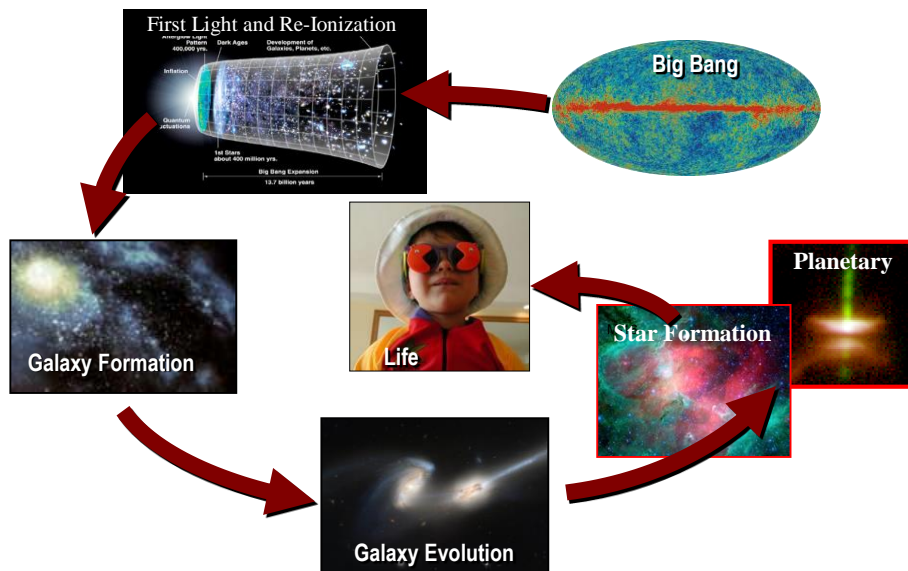
NASA's Fundamental Questions



- 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 its Science Mission:

It is a Space Telescope

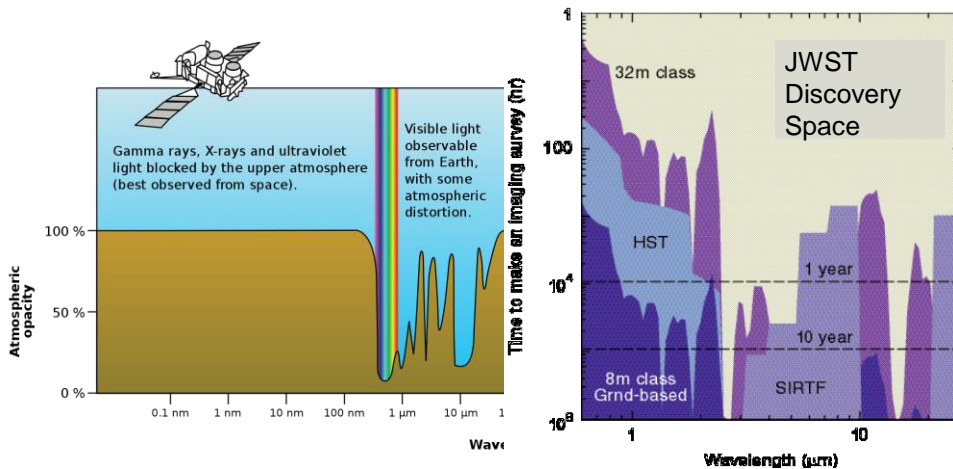
It is an Infrared Telescope

It has a Large Aperture

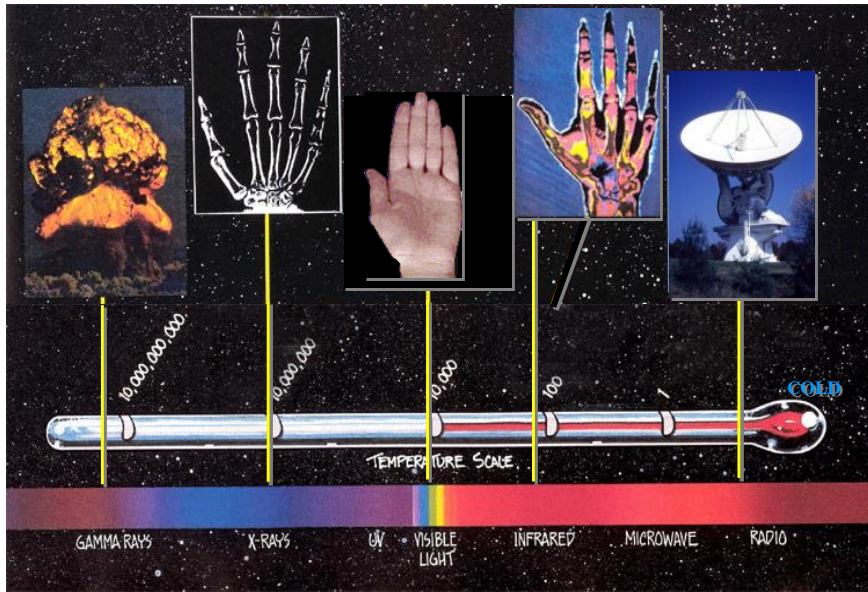
Why go to Space

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



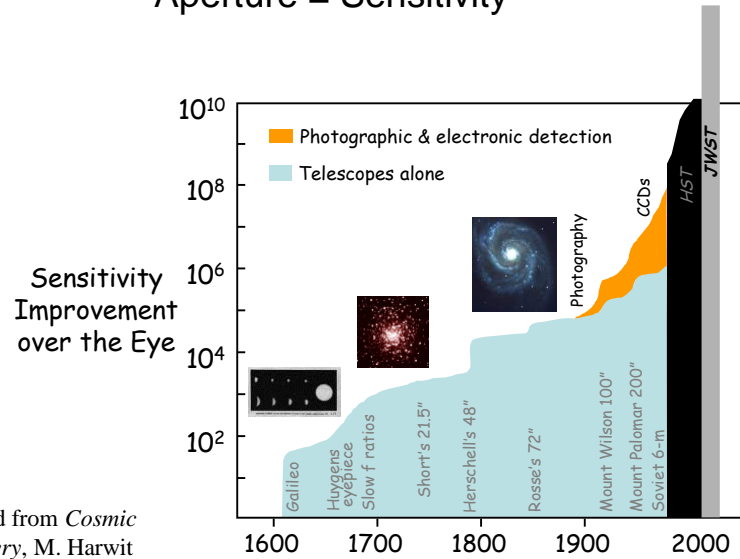
Infrared Light



Why Infrared ?



Why do we need Large Apertures? Aperture = Sensitivity

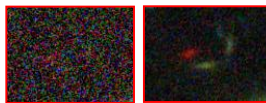


Sensitivity Matters



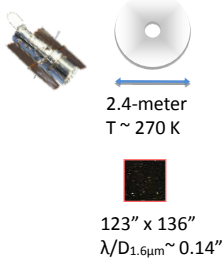
GOODS CDFS – 13 orbits

HUDF – 400 orbits



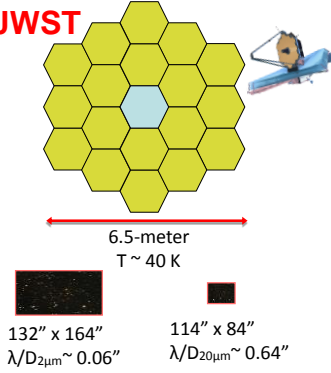
JWST will be more Sensitive than Hubble or Spitzer

HUBBLE

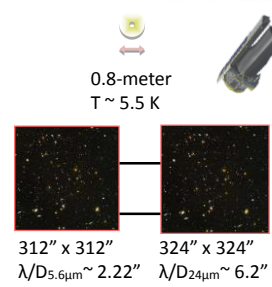


JWST 6X more sensitive with similar resolution

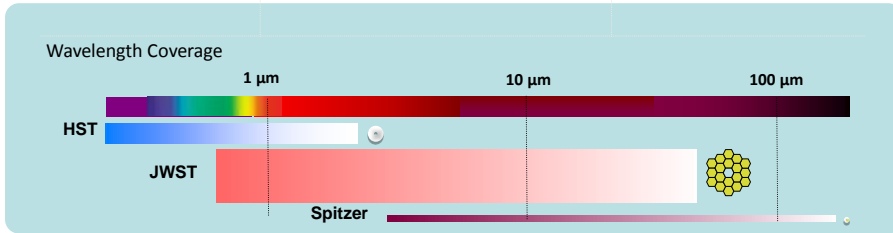
JWST



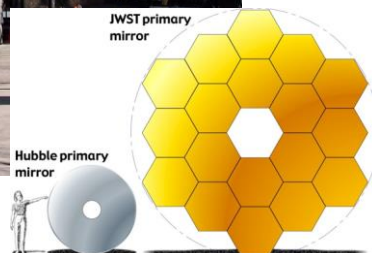
SPITZER



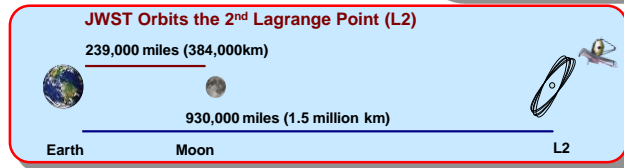
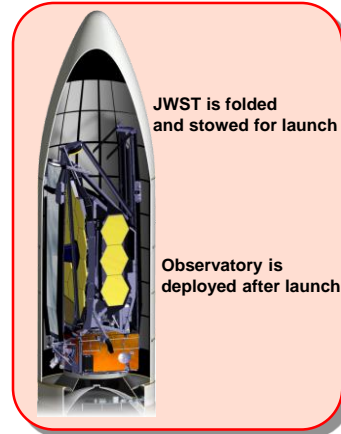
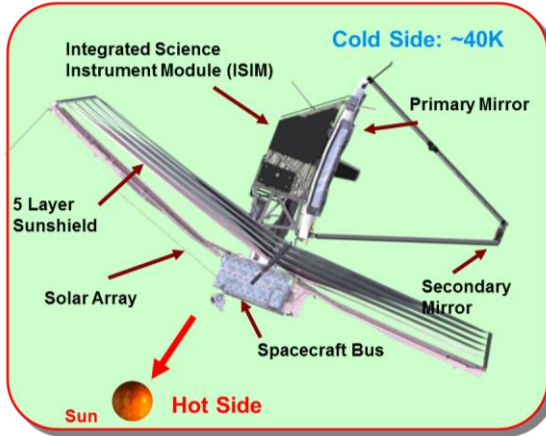
JWST 44X more sensitive



How big is JWST?

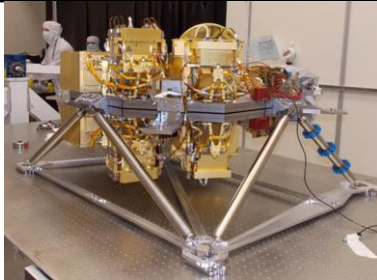


How JWST Works



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



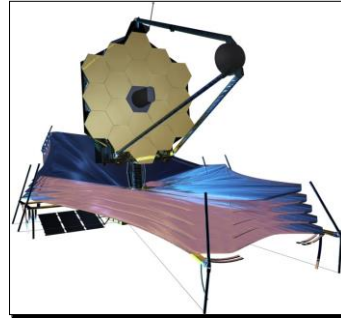
FGS: sense pointing to 1 millionth degree
NIRISS: imagery & spectra of exoplanets



JWST Telescope Requirements

Optical Telescope Element

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



Primary Mirror

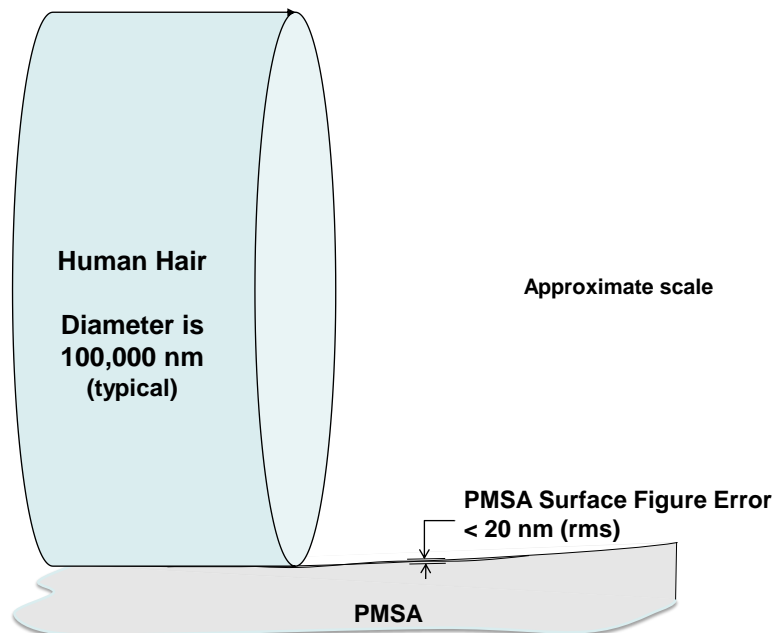
- 6.6 meter diameter (tip to tip)
- < 25 kg/m² Areal Density
- < \$6 M/m² Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

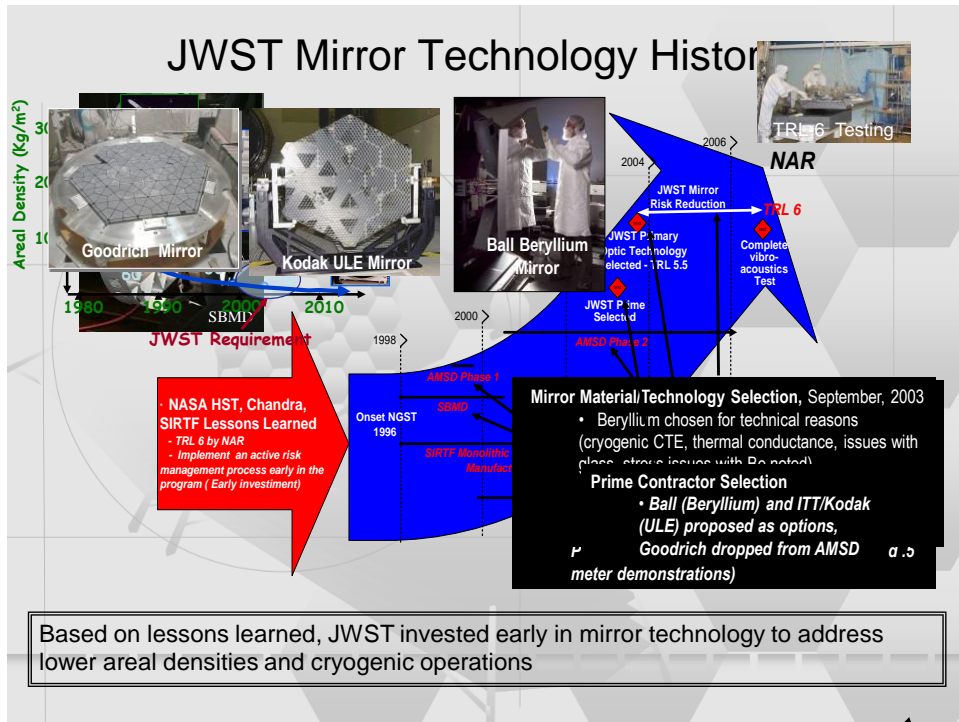
Segments

- 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





Advantages of Beryllium

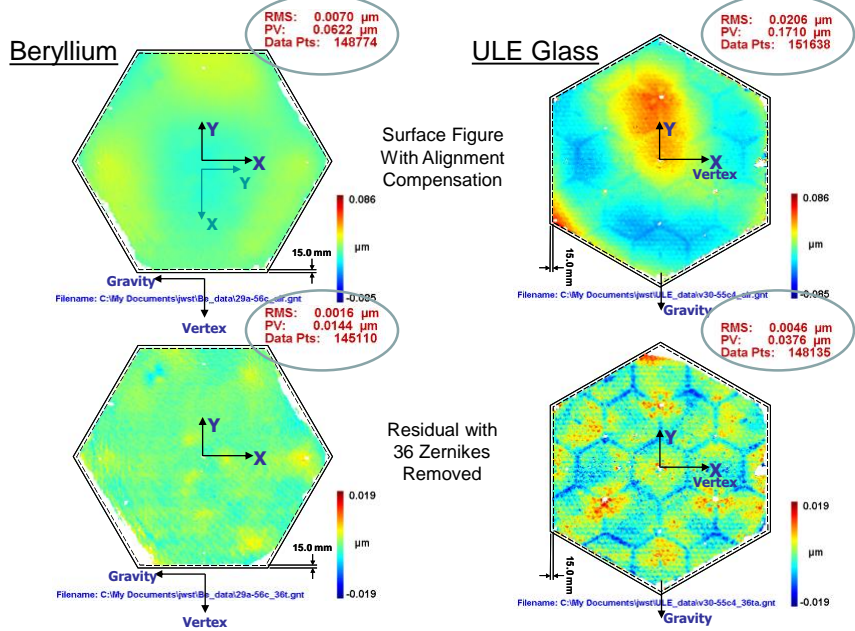
Very High Specific Stiffness – Modulus/Mass Ratio

Saves Mass – Saves Money

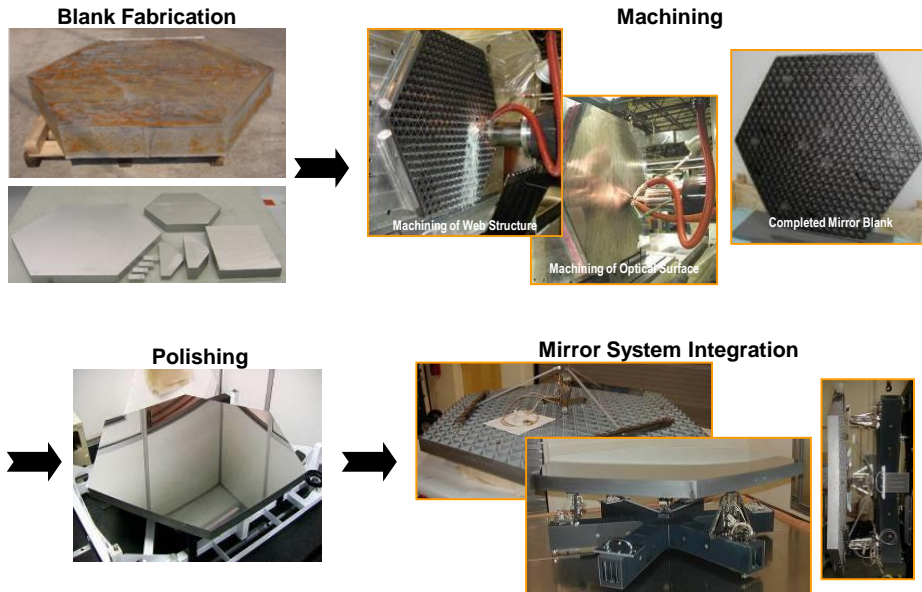
High Conductivity & Below 100K, CTE is virtually zero.

Thermal Stability

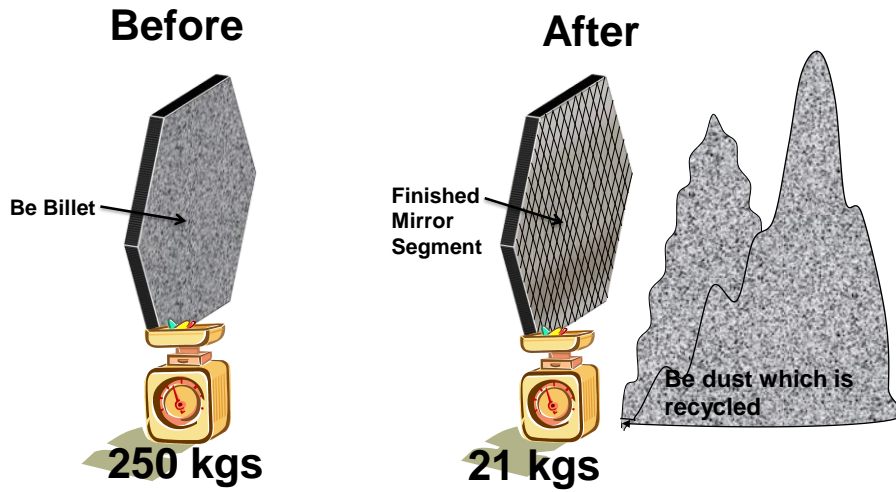
Figure Change: 30-55K Operational Range



Mirror Manufacturing Process

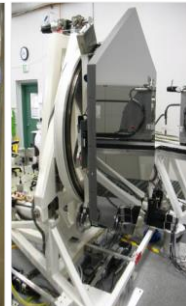
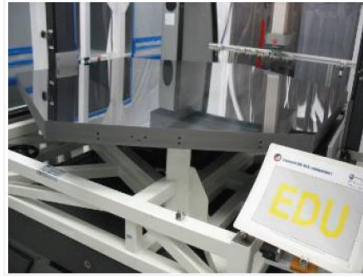


Fun Facts – Mirror Manufacturing



Over 90% 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:

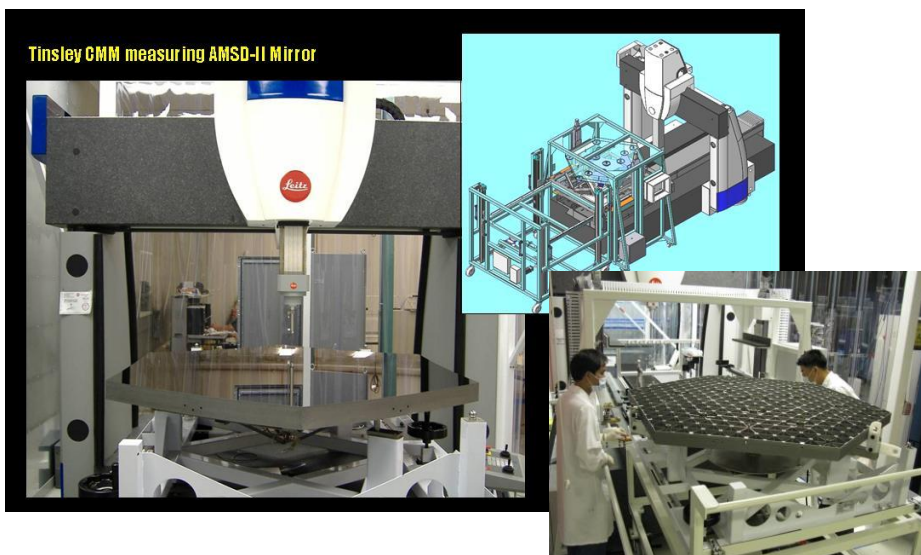
- 2 Center of Curvature CGH Optical Test Stations (OTS1 and OTS2)
- Auto-Collimation Test Station

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

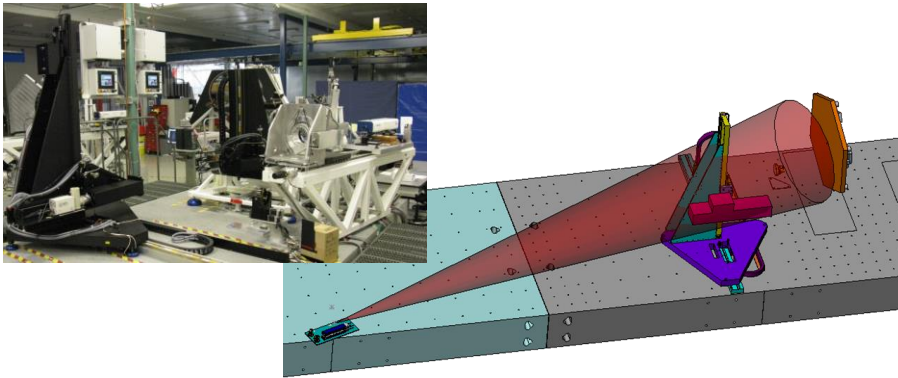
SSHS provided bridge-data between grind and polish, used until

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)

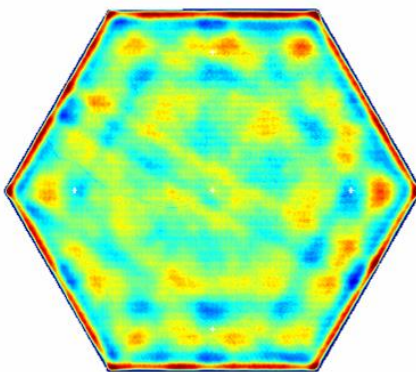
When not used, convergence rate was degraded.



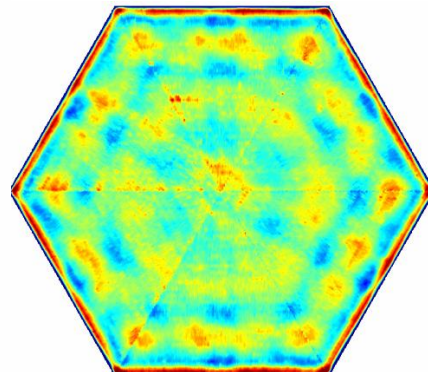
Comparison to CMM (222 - 2 mm spatial periods)

8/1/2006 data

Smooth grind



SSHS
4.7 μm PV, 0.64 μm RMS



CMM
4.8 μm PV, 0.65 μm RMS

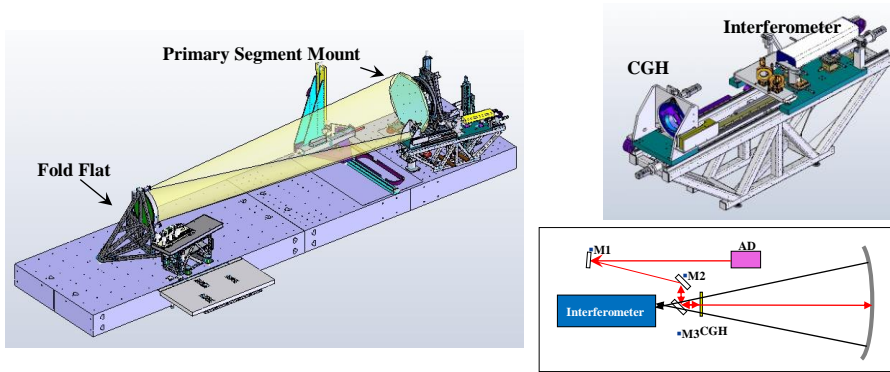
Point-to-Point Subtraction: SSHS - CMM = 0.27 μm RMS

Full Aperture Optical Test Station (OTS)

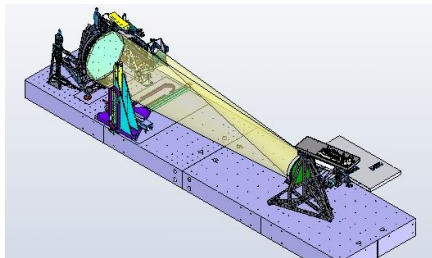
Center of Curvature Null Test measured & controlled:

Prescription,
Radius &
Figure

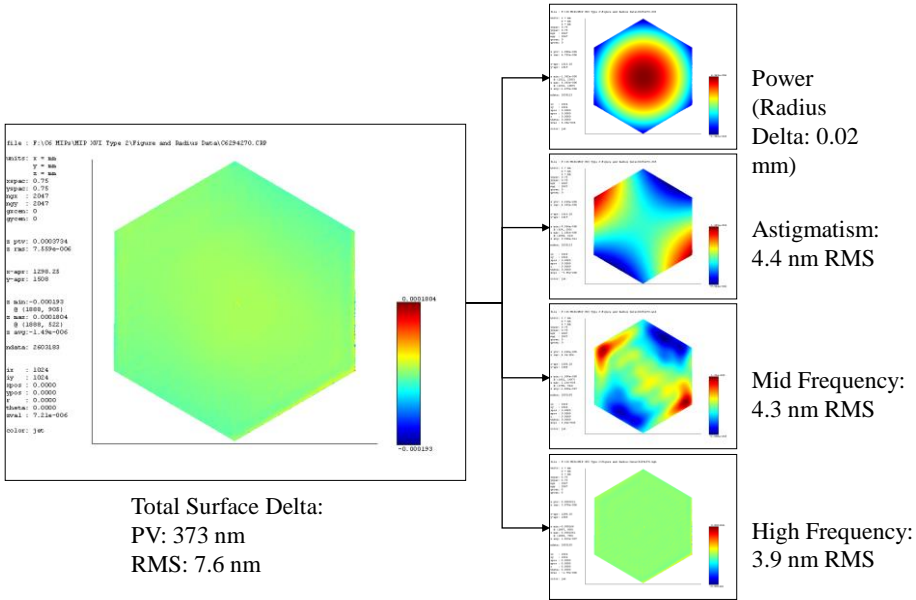
Results are cross-checked between 2 test stations.



Full Aperture Optical Test Station (OTS)



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



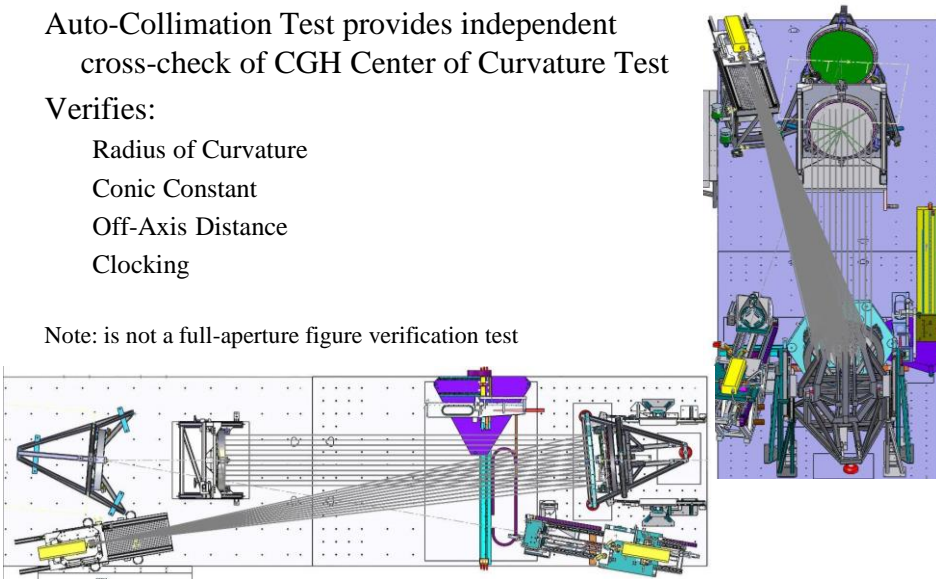
Auto-Collimation Test

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

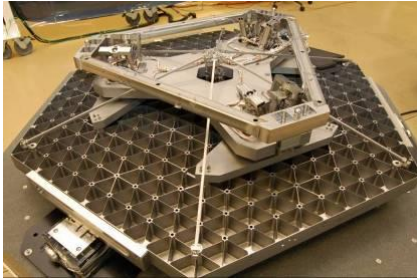
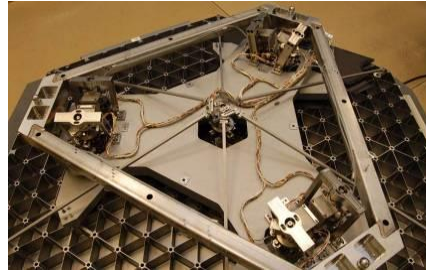
Verifies:

- 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

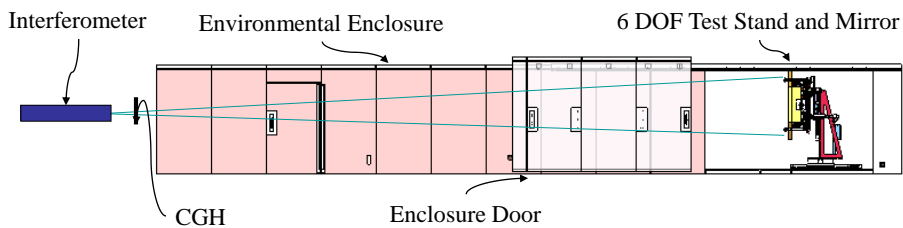
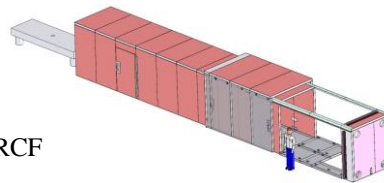
Measure Configuration 2 to 3 deformation

Create a Gravity Backout file for use at XRCF

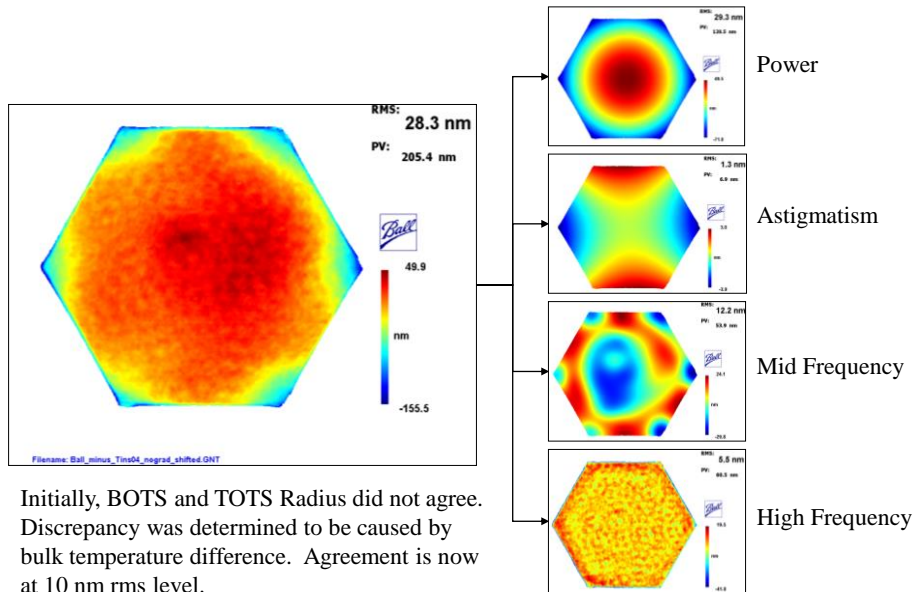
Measure Vibration Testing Deformation

Measure Vacuum Bakeout Deformation

Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation

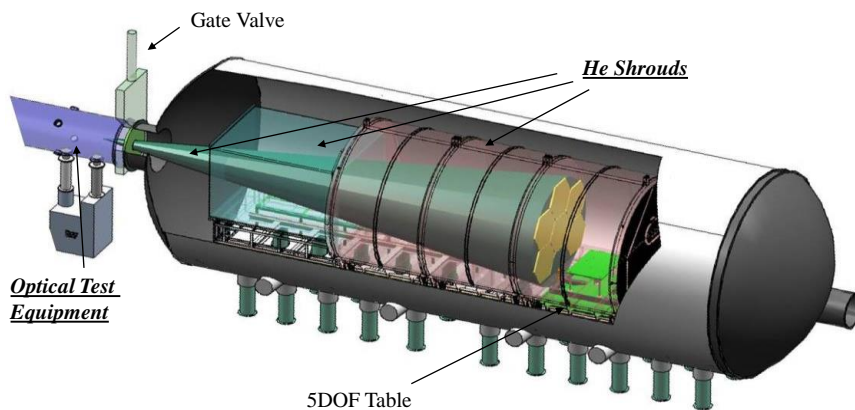


BOTS to Tinsley Initial Comparison



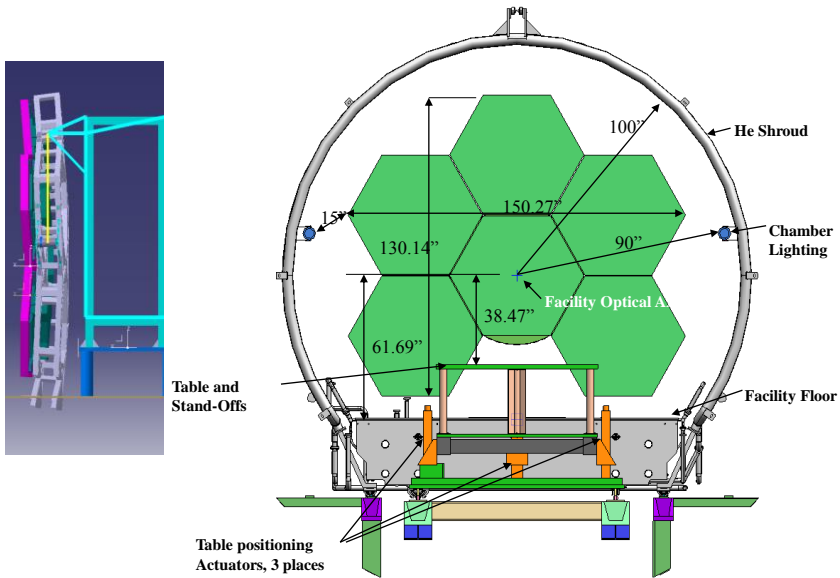
PMSA Flight Mirror Testing at MSFC XRCF

Cryogenic Performance Specifications are Certified at XRCF



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

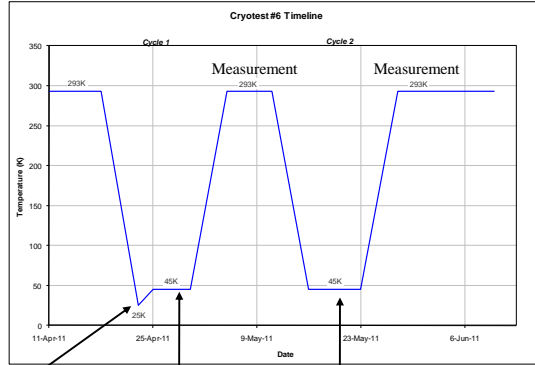
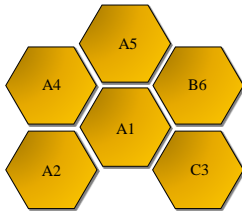
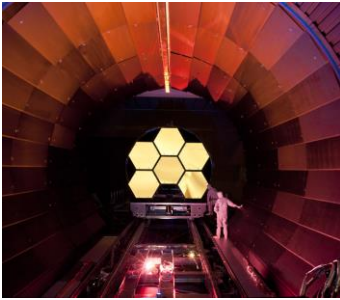
JWST Flight Mirror Test Configuration



Primary Mirror Cryogenic Tests

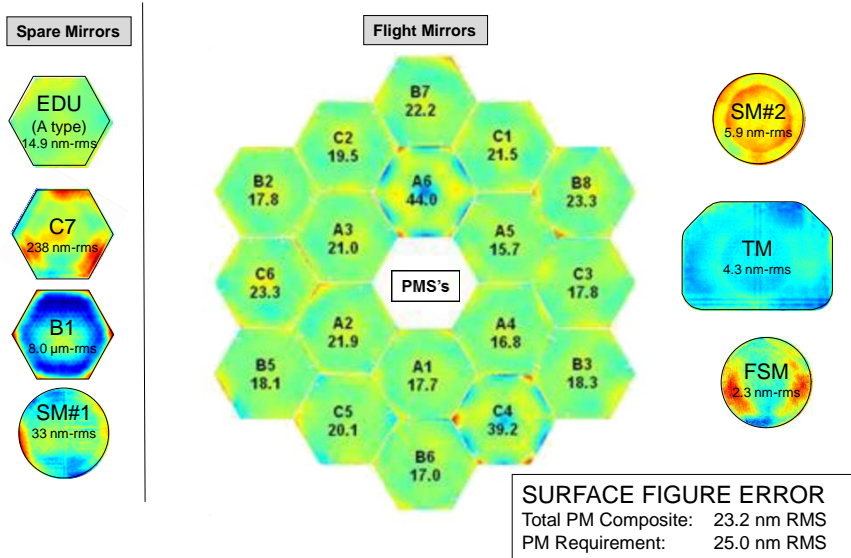


XRCF Cryo Test



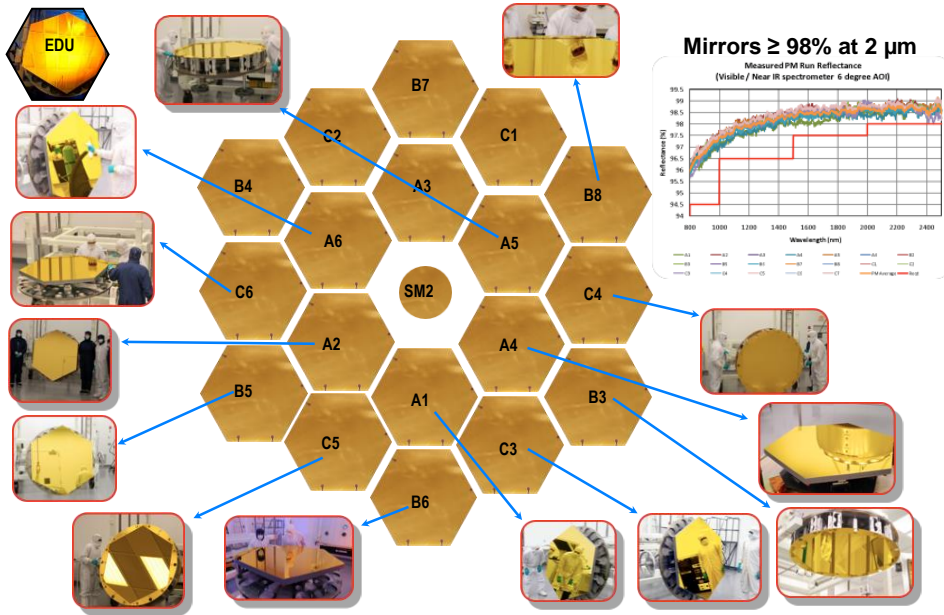
- Survival Temperature
- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)
- Set RoC
- Nominal Measurement
- Hexapod Tilt Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

Mirror Fabrication



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

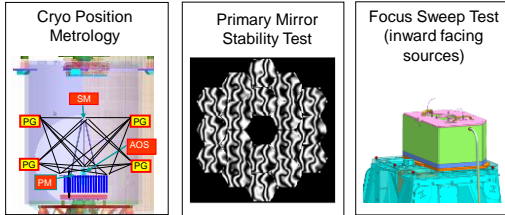


Optical Telescope Assembly

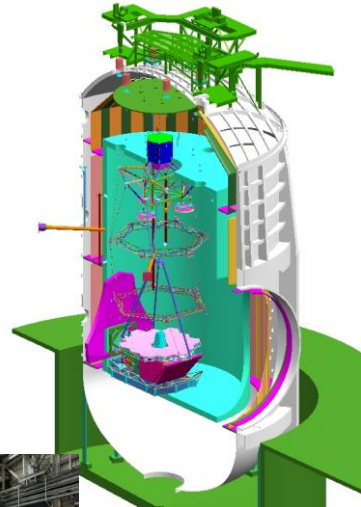
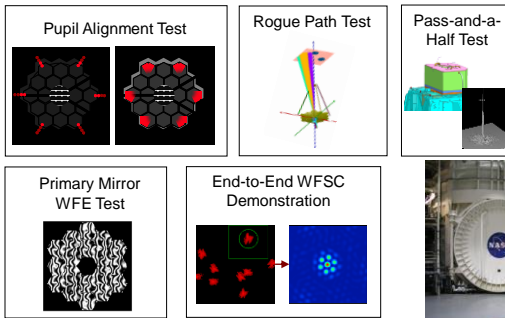


Observatory level testing occurs at JSC Chamber A

Verification Test Activities in JSC Chamber-A



Crosscheck Tests in JSC Chamber-A



Chamber A:

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



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

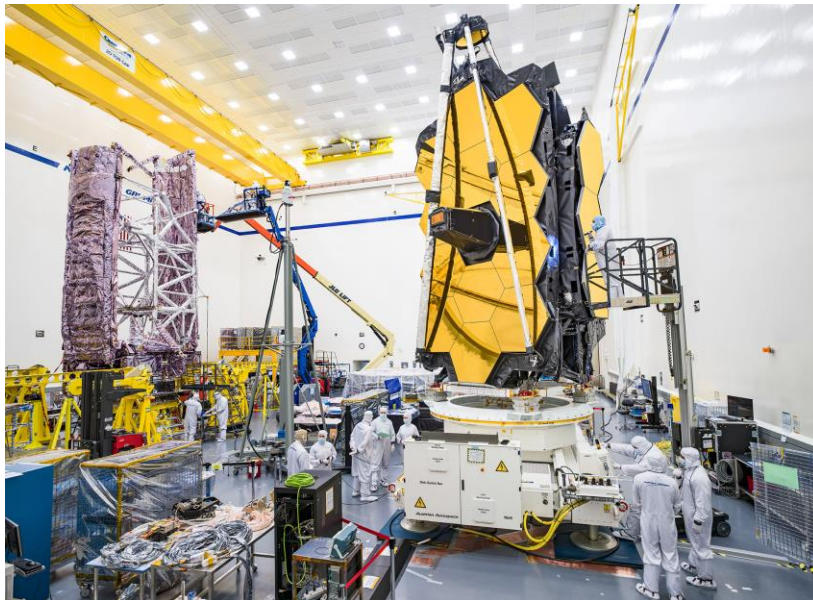


Telescope & instrument module now at Northrop Grumman for integration with the spacecraft bus and sunshield



5

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



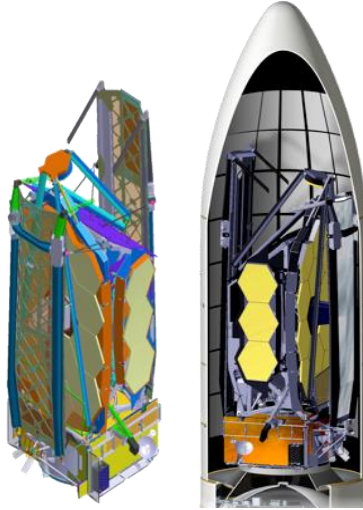
Roll on roll off transport ship built in the Netherlands by Merwede Shipyards

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

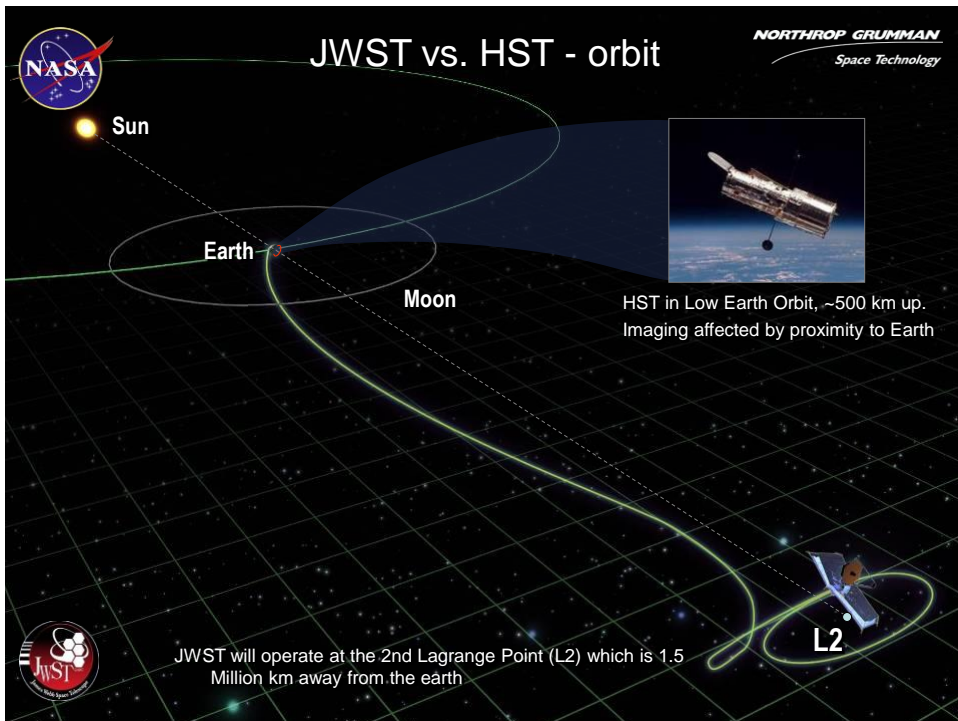


JWST Launched on Ariane 5 Heavy

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



Launch from Kourou Launch Center
(French Guiana) to L2



L2 Orbit Enables Passive Cryogenic Operation

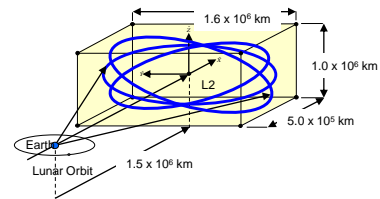
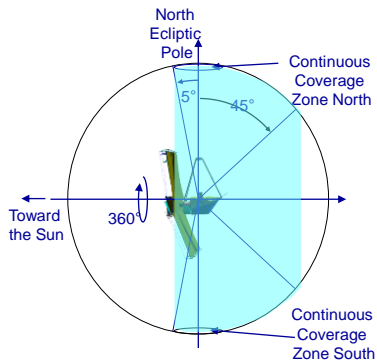
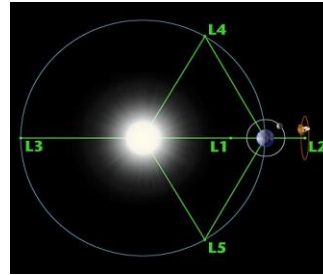
Second Lagrange Point (L2) of Sun-Earth System

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 ($\Delta v \sim 93$)



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

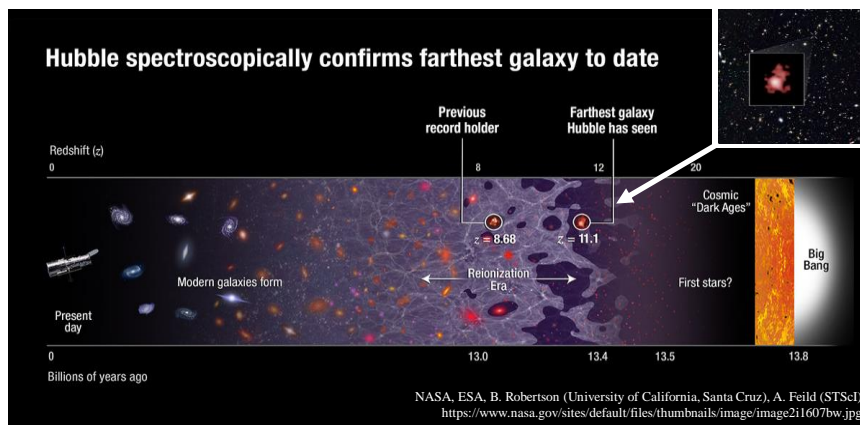
End of the dark ages: first light and reionization

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

Studying Early Universe: 'First' Galaxies



Galaxy GN-z11 is 13.4 B-yr away, just 400 M-yr 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).

Some 'first' galaxies formed stars 1000X faster than today.

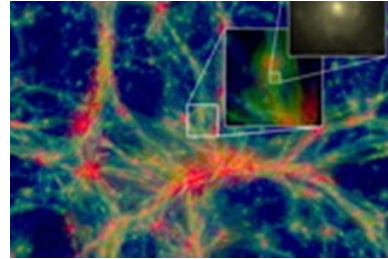
First Galaxies form in Cosmic Web

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

Galaxies form at crossing points.

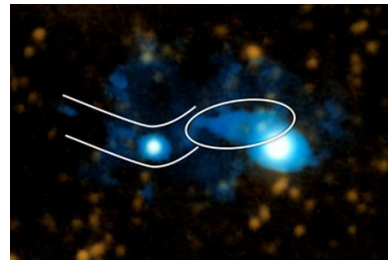
Most of universe's matter is in these filaments and dark matter.

This one is 10B light years away.

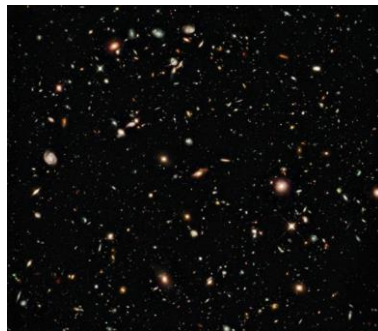


A filament of the universe's "cosmic web" is highlighted with parallel curved lines in this image, while a protogalaxy is outlined with an ellipse. The brightest spot (on the lower right side of the ellipse) is the quasar UM287. The other bright spot is a second quasar in the system. The image combines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

CREDIT: Chris Martin/PCWI/Caltech
Charles Choi, Space.com, 5 Aug 2015.

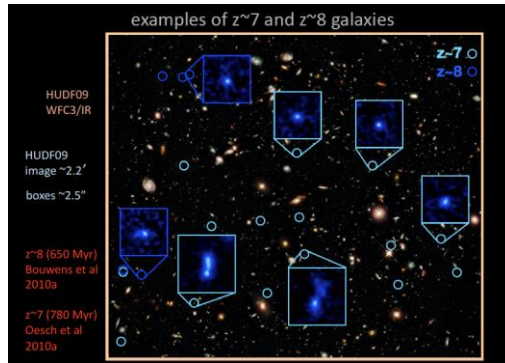


Hubble Ultra Deep Field – Near Infrared



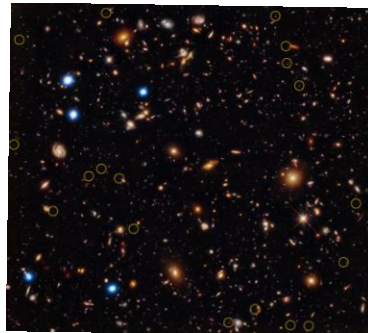
Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

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?

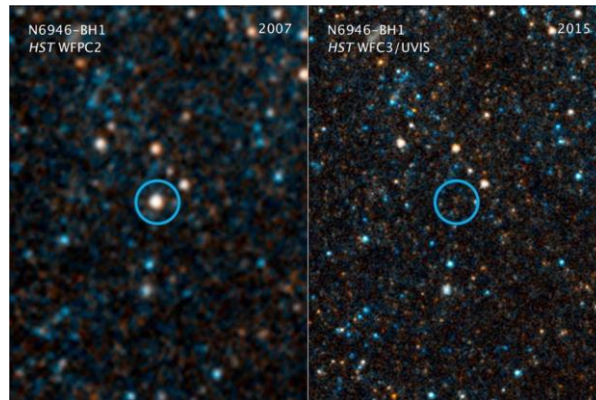
Each of these ancient 700 M yrs after BB galaxies has a black hole.

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.

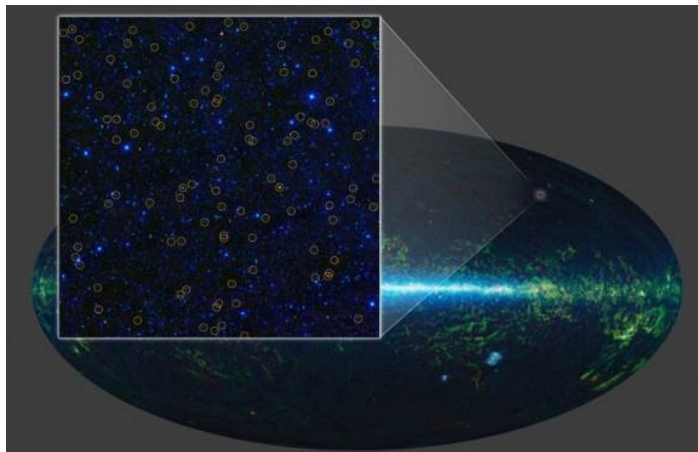


The visible/near-IR photos from Hubble show a massive star, about 25 times the mass of the Sun, that has winked out of existence, with no supernova or other explanation. Direct collapse is the only reasonable candidate explanation. NASA/ESA/C. Kochanek (OSU)

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.



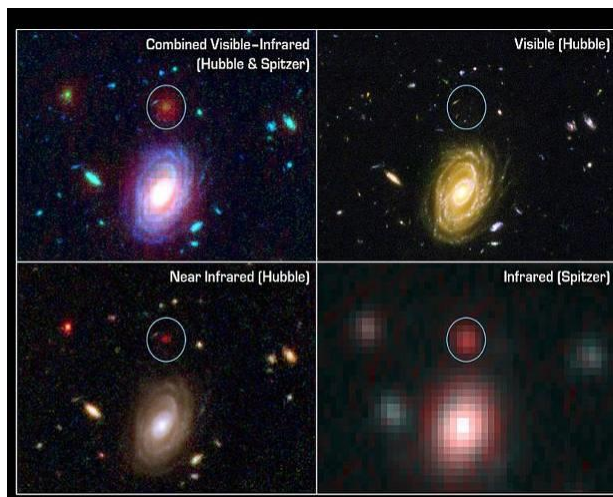
“It is like finding a 6-foot-tall child in kindergarten,” says astrophysicist Marta Volonteri, at the University of Michigan in Ann Arbor.

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.

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

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.



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

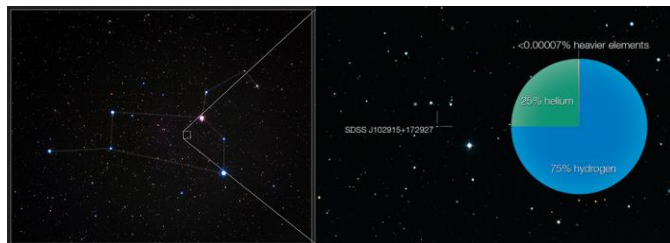
Dust is cold, therefore, it can only be seen in IR.

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.

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

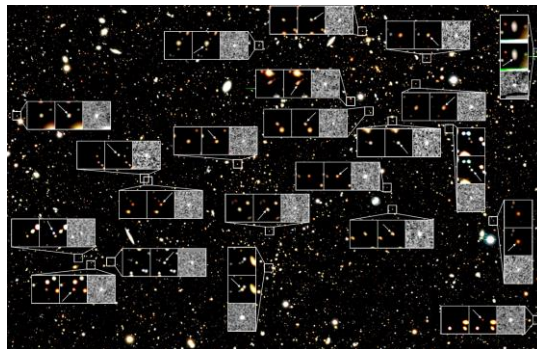
Subaru Deep Field: Ancient Supernova 3.7B yrs after BB

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.

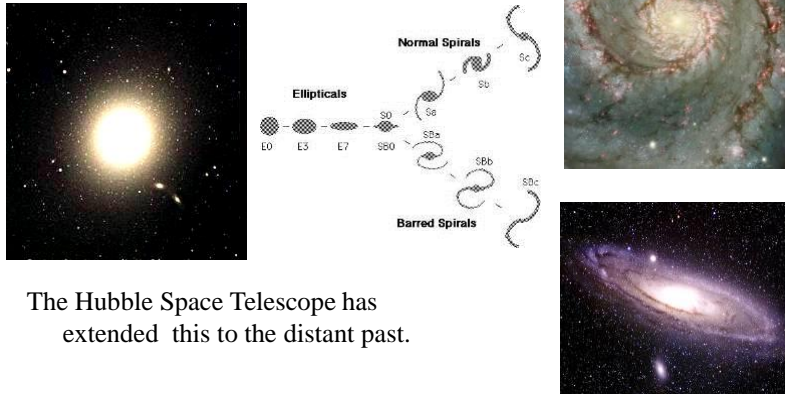
Supernova helped seed early universe with chemical elements.



Clara Moskowitz, SPACE.com, 05 October 2011

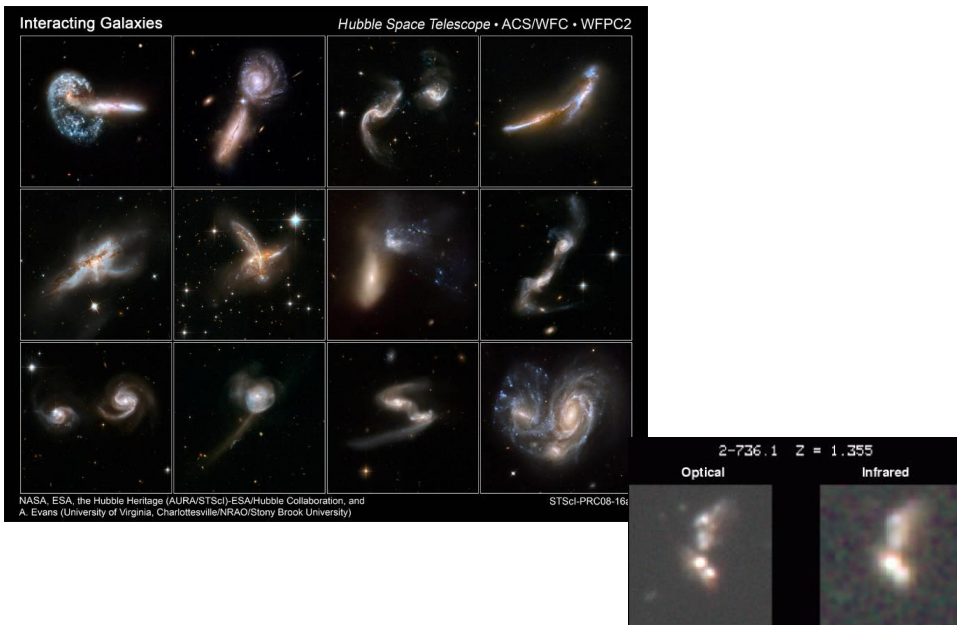
The Hubble Sequence

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



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

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 as 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)

JWST Science Theme #3:

Birth of stars and protoplanetary systems

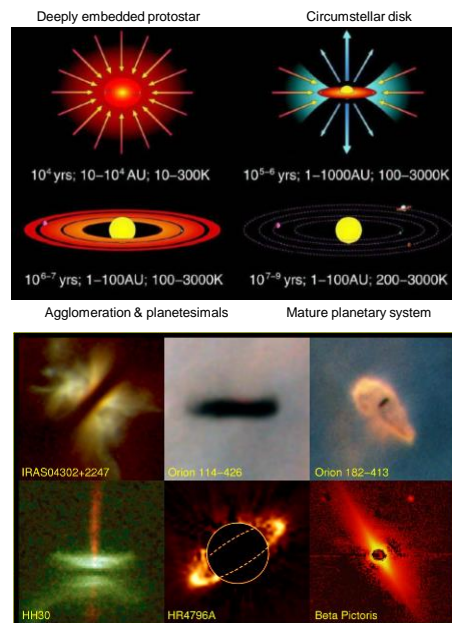
How do molecular clouds collapse?
How does environment affect star-formation?
What is the mass distribution of low-mass stars?
What do debris disks reveal about the evolution of terrestrial planets?

... 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?



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

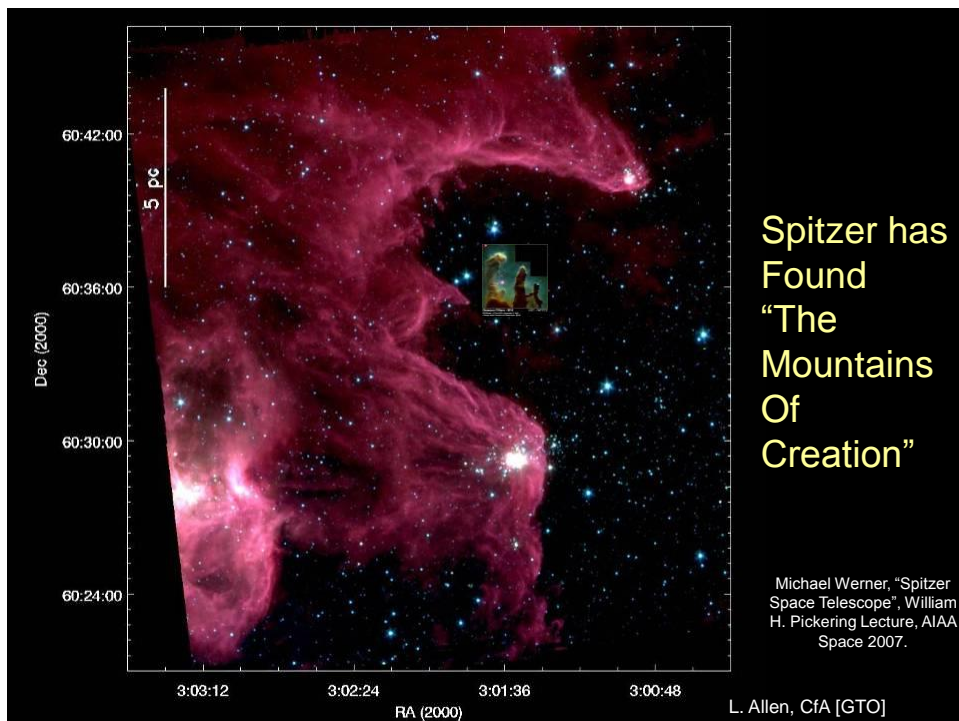
Different processes? Or continuum?

JWST Observations:

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

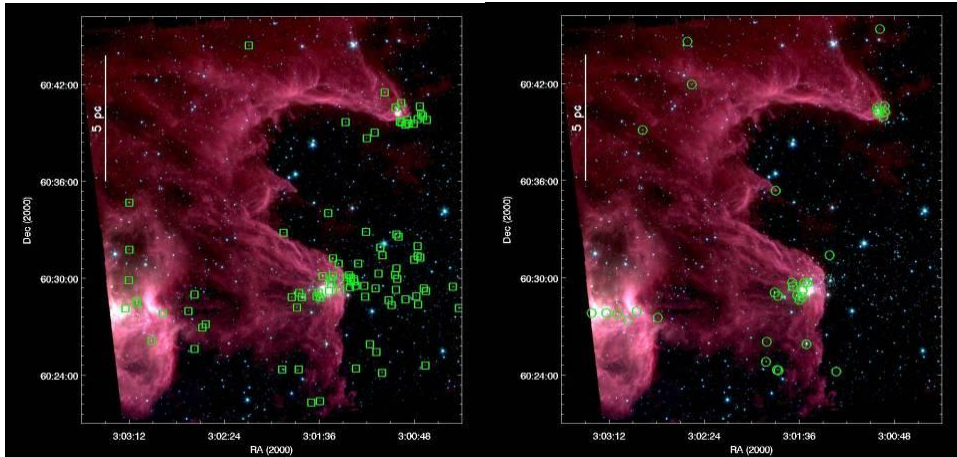


The Eagle Nebula
as seen in the infrared



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

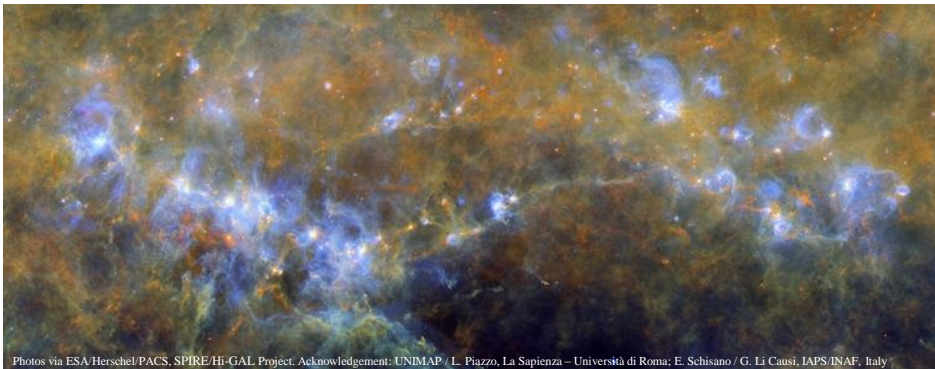
Star Formation in Dust/Gas Cloud



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



Photos via ESA/Herschel/PACS, SPIRE/Hi-GAL Project. Acknowledgement: UNIMAP / L. Pizzato, La Sapienza – Università di Roma; E. Schisano / G. Li Causi, IAPS/INAF, Italy

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).

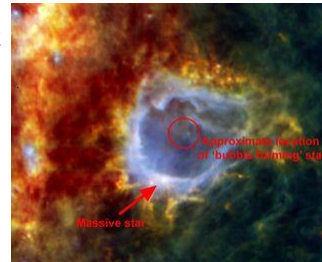
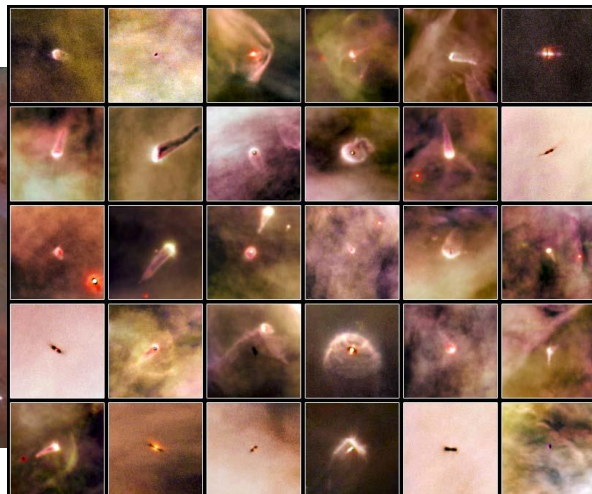


Image of RCW 120 (ESA),
Discover.com, Ian O'Neill, 7 May 2010

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.

(Space.com, 6 May 2010)

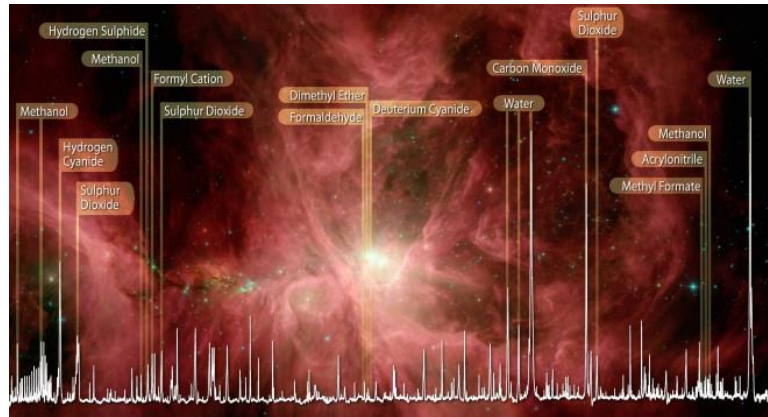
Orion Nebula Protoplanetary Discs



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

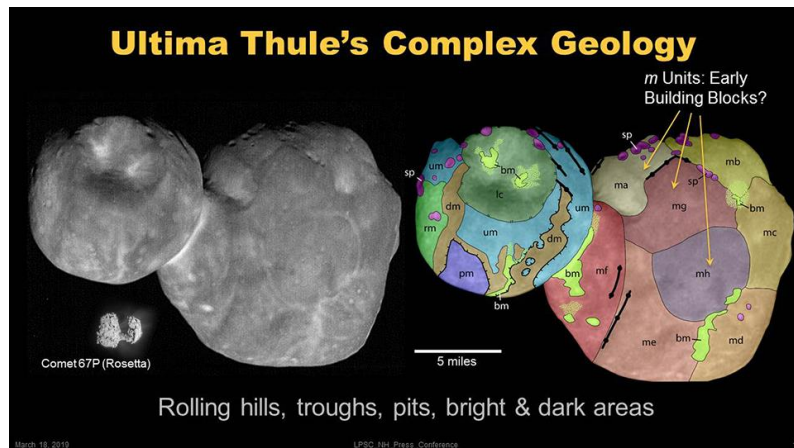
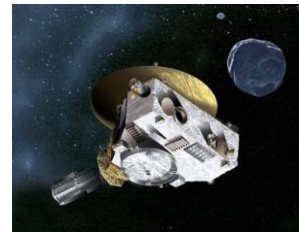
Planetary Formation Questions and 2 Models

- 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 terrestrial 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?

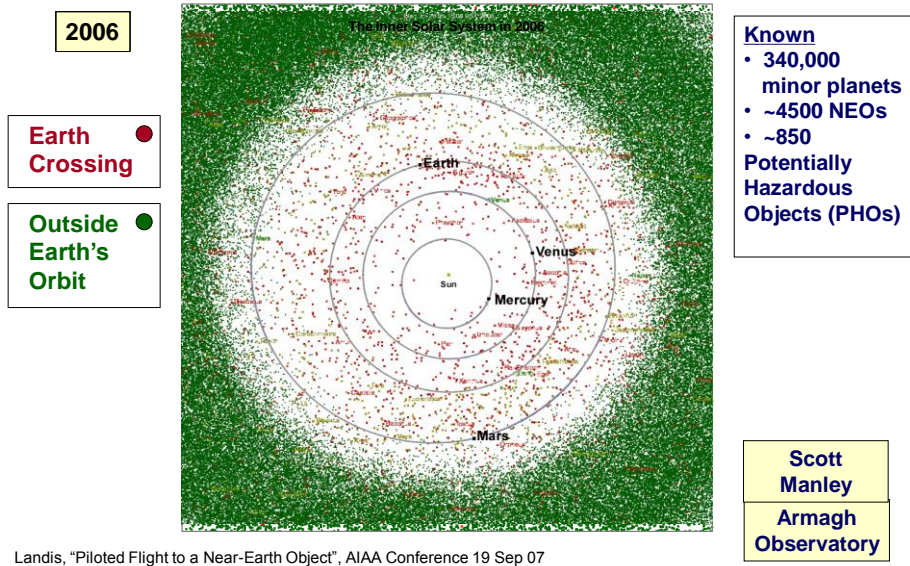


Ultima Thule

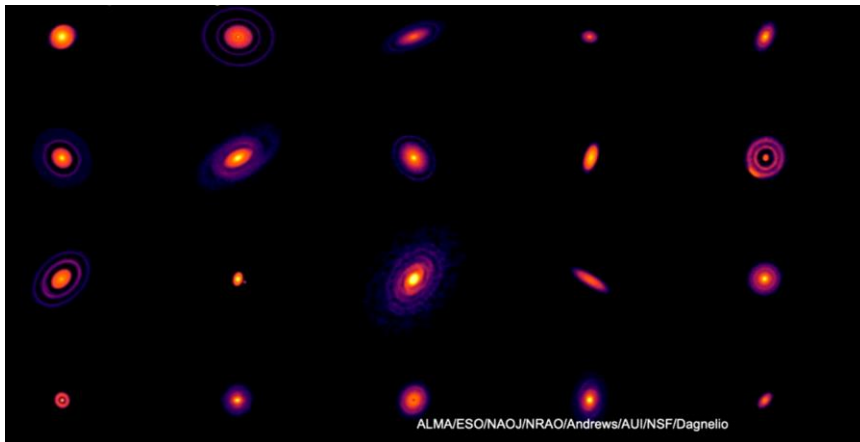
New Horizons' image of Ultima Thule on 1 Jan 2019 supports the Accretion Model of Planetary System Formation.



History of Known (current) NEO Population



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

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' star 450 light-years from Earth in constellation Taurus.

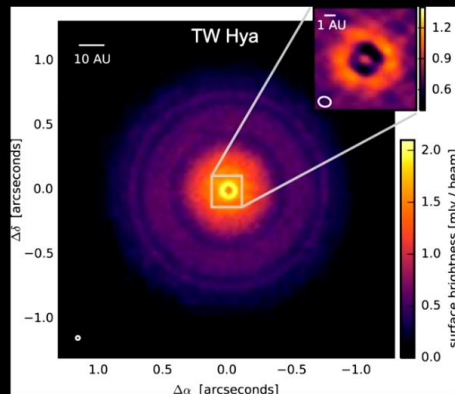
Concentric rings separated by gaps suggest planet formation.

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)

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

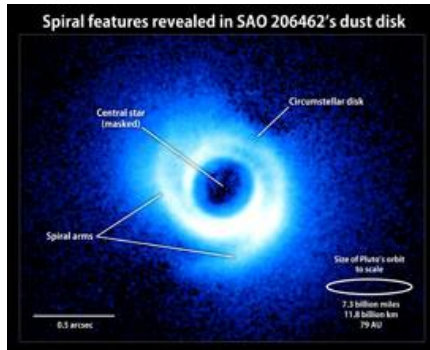


Andrews et al. 2016

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

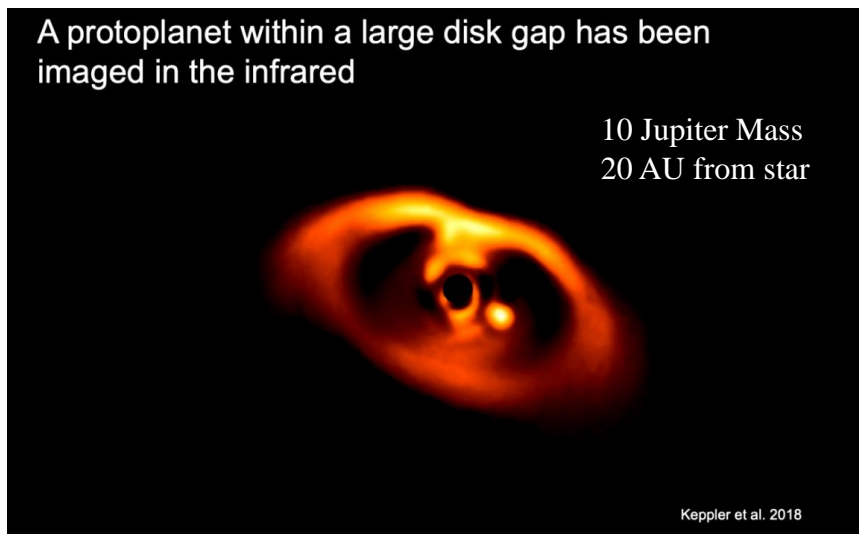
Spiral Arms Hint At The Presence Of Planets

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.



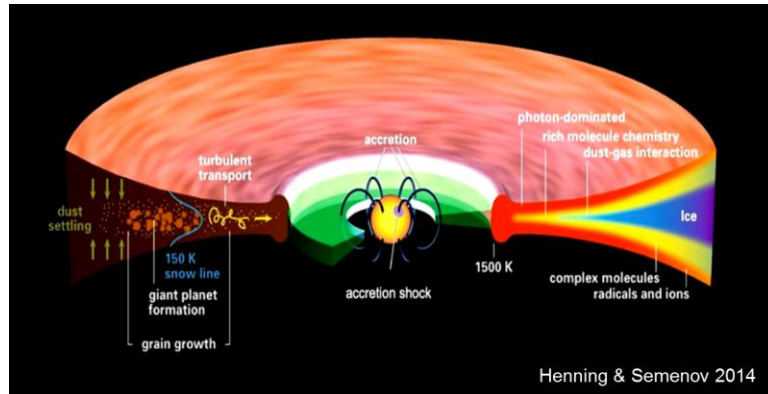
Near Infrared image from Subaru Telescope shows disk surrounding SAO 206462, a star located about 456 light-years away in the constellation Lupus. Astronomers estimate that the system is only about 9 million years old. The gas-rich disk spans some 14 billion miles, which is more than twice the size of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

Photonics Online 20 Oct 2011



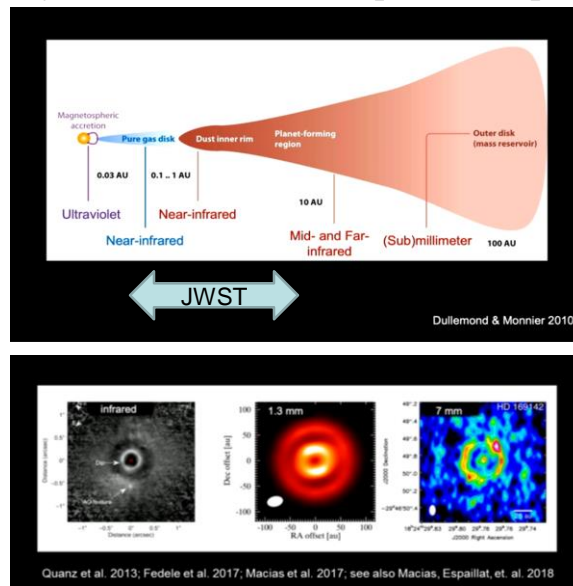
Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

Protoplanetary disks are complex and dynamic



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

Protoplanetary disk observations require multiple wavelengths



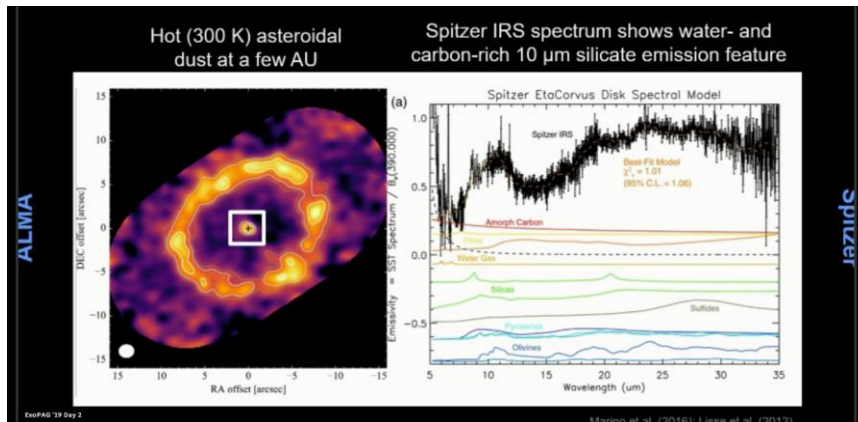
Catherine Espaillat (Boston University), Disks to Planets: Observing Planet Formation in Disks Around Young Stars, AAS 2019

Eta Corvi System

ALMA measures ‘cold’ Kuiper belt debris.

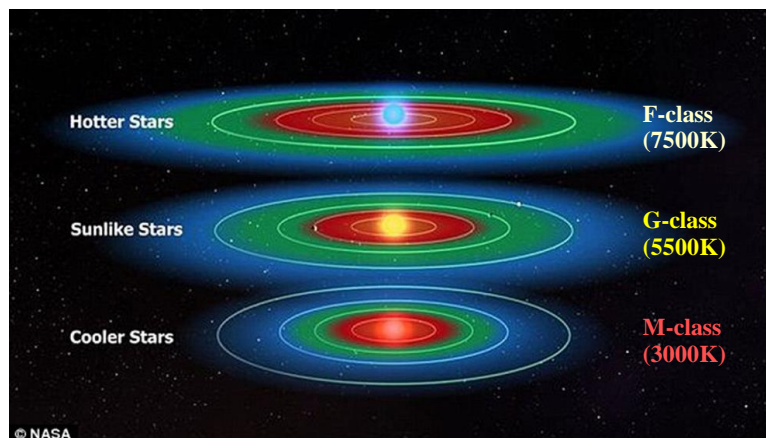
Spitzer measures ‘warm’ asteroid belt debris.

JWST will provide higher resolution image of asteroid belt.



Habitable Zone

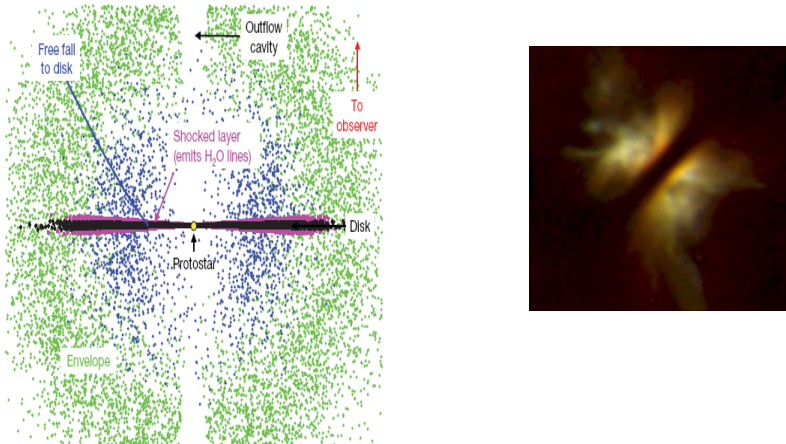
Life requires water. Liquid water can only exist in the ‘Goldilocks’ Zone. The hotter the star, the further away the zone.



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

Where does the water come from?

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk



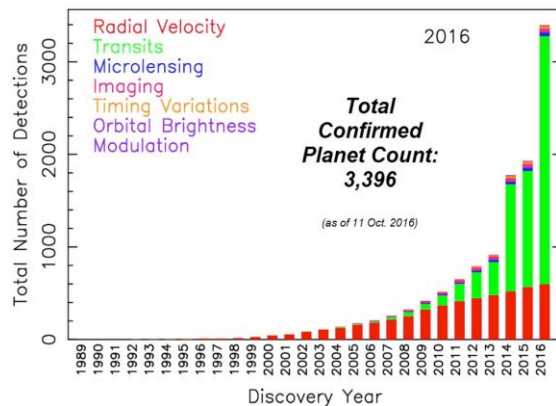
Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AIAA Space 2007.

EXOPLANETS

First Exo-Planet (51 Pegasi) orbiting a 'Sun-like' Star was observed in 1995 using Radial Velocity method.

Since then, 1000s of exo-planets have been discovered including 100's of Earth size exoplanets – mostly via Transit Method.

But what we really want is direct detection with spectroscopy.



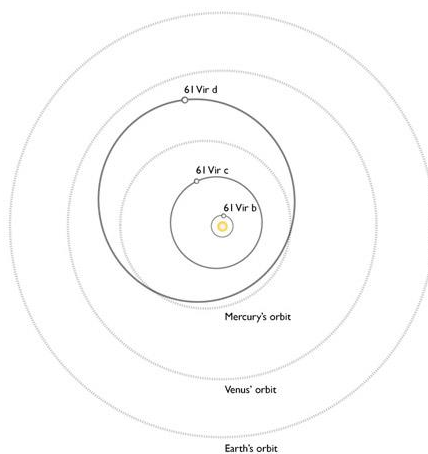
Techniques to Detect Exoplanets

**Doppler
Spectroscopy
or Radial
Velocity
Method**



103

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.

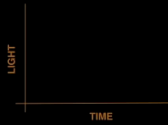
They orbit 61 Virginis in 4, 38 & 124 day periods.

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

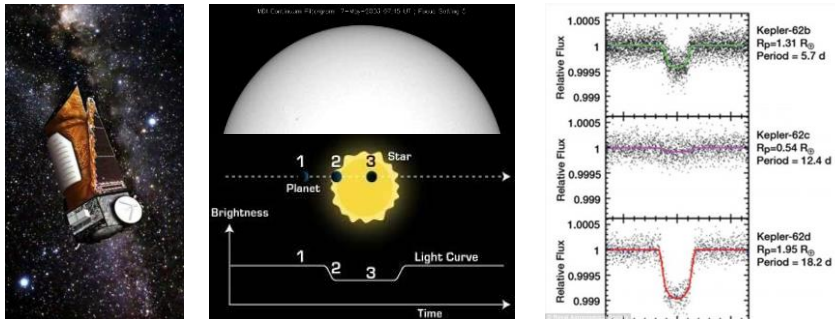
Transit Method



105

Transit Method Finds Planets

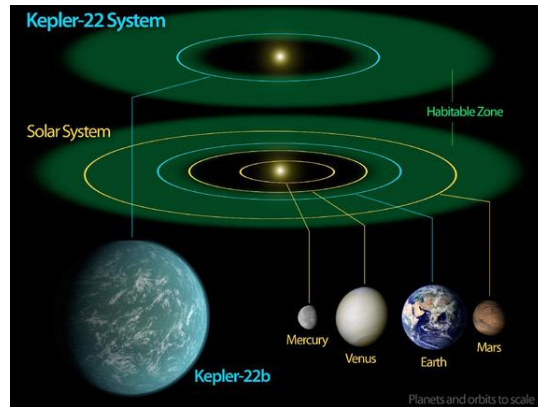
Kepler (launched in 2009) searched for planets by staring at 165,000 stars looking for dips in their light caused when a planet crosses in front of the star.



Kepler has found over 1000 'confirmed' planets and over 4000 potential planets.

Kepler – Habitable Zone Planet

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 has a temperature of maybe 20C

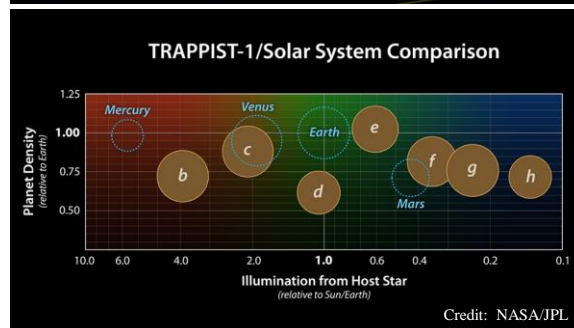
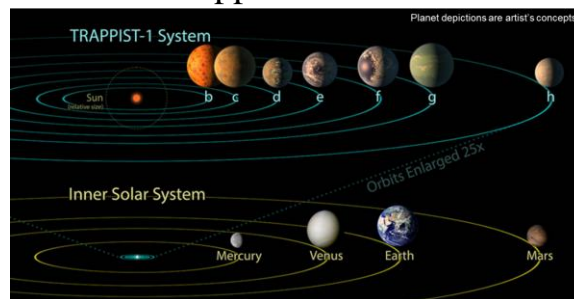
CREDIT: NASA/Ames/JPL-Caltech

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.

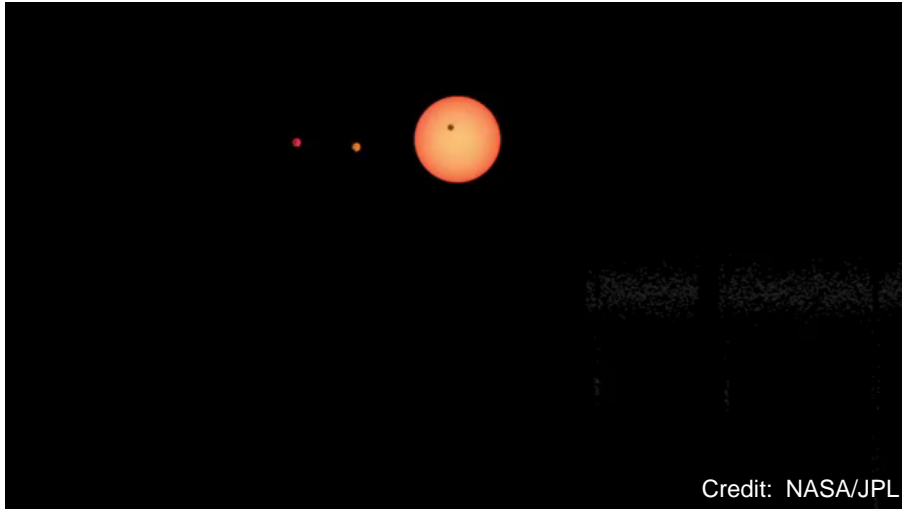
M-class stars may not be friendly to life because they have higher radiation environment than our G-class star.



Credit: NASA/JPL

108

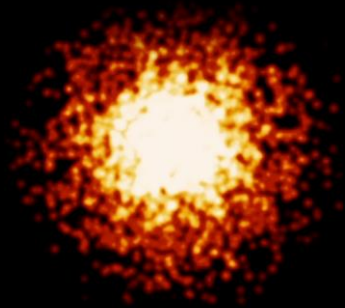
How Spitzer Observed the Trappist-1 System



109

Techniques to Detect Exoplanets

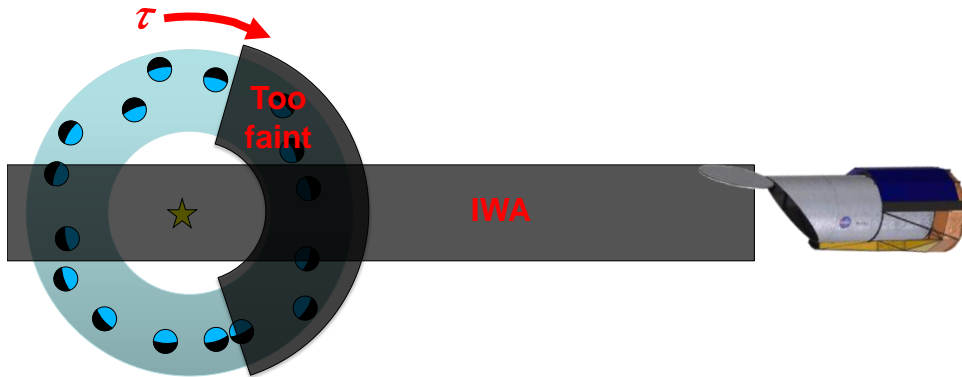
**Direct
Imaging**



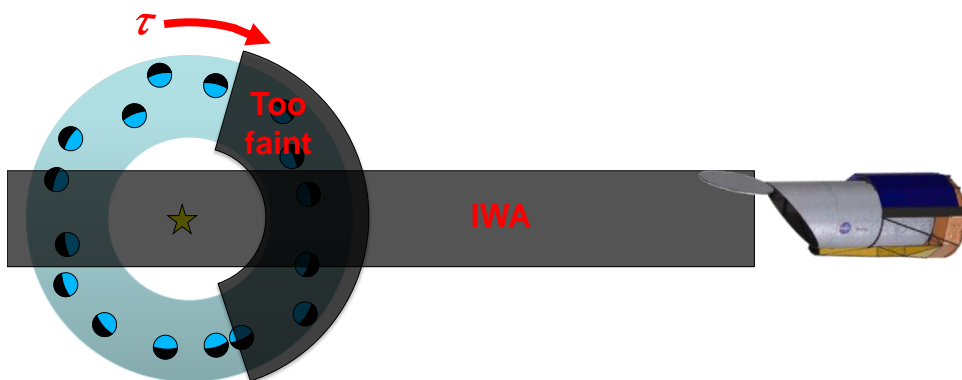
Detecting an exo-Earth is like looking for a firefly next to a search light on top of the Empire State Building from Los Angeles.

110

Detection depends on where Planet is relative to its Star



Revisiting multiple times increases Detection

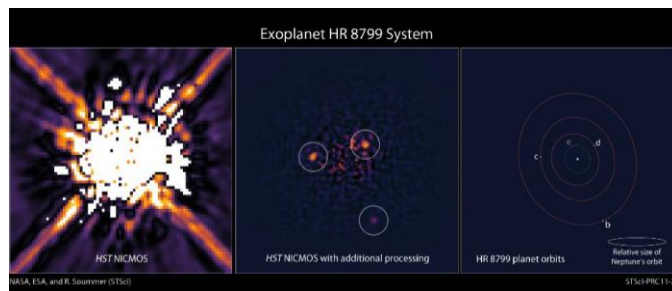


Hubble can detect planets far from their star

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.

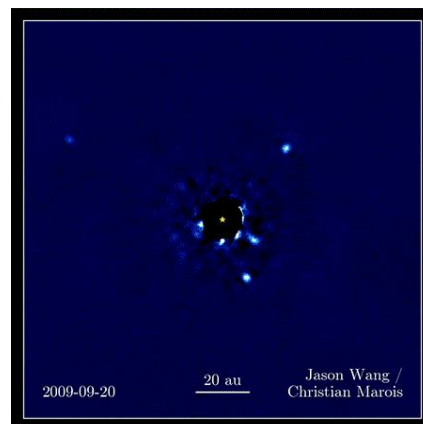
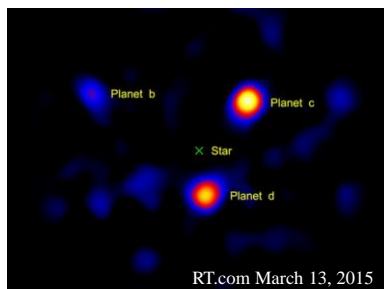


Denise Chow, SPACE.com; 06 October 2011

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.

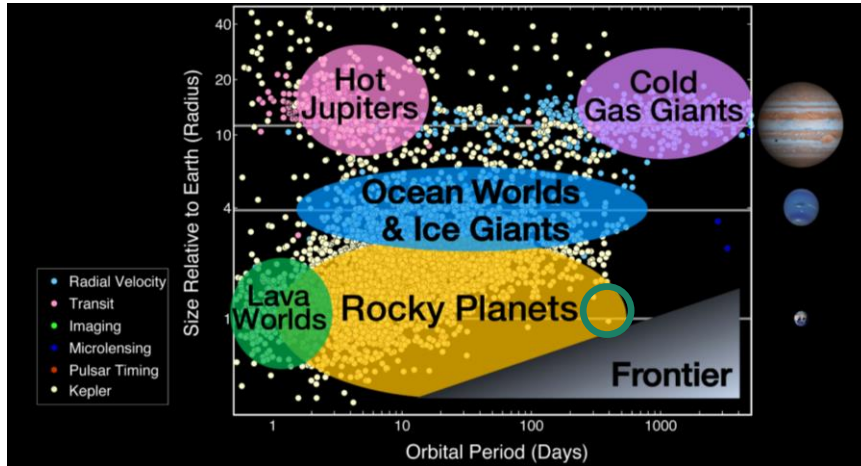
HR 8799 Planet (b) is 7X the mass of Jupiter and has water, methane and carbon monoxide in its atmosphere.



Exoplanet Populations & Discovery Method

As of 14 December 2017

- Total Confirmed Exoplanets = 3567
- Total found by Kepler = 2525

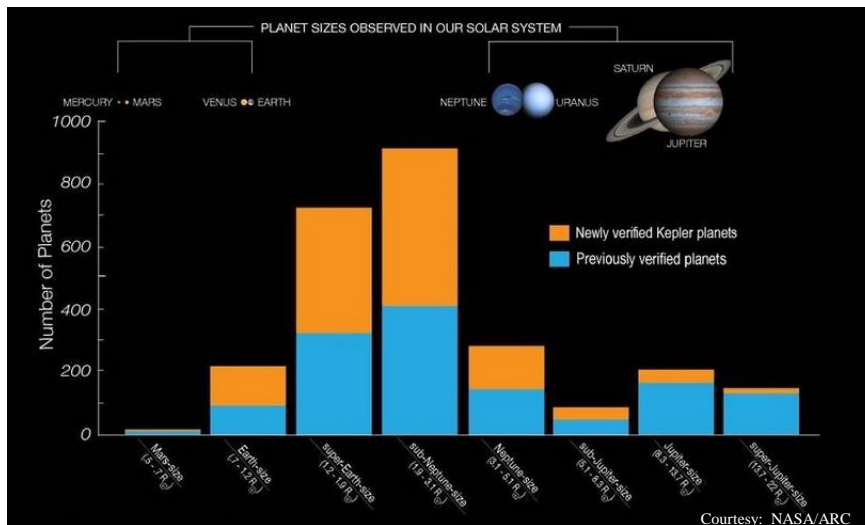


https://www.nasa.gov/sites/default/files/thumbnails/image/press-web25_exoplanet_populations.jpg

Kepler's Verified Planets, by Size

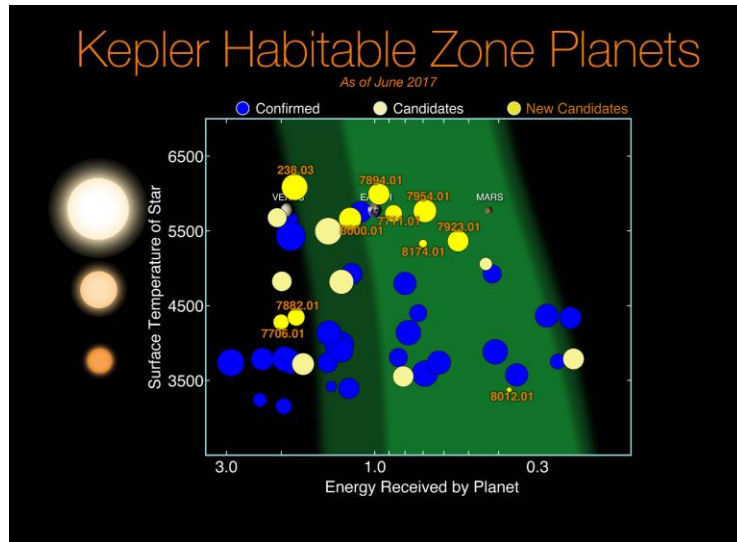
As of May 10, 2016

Final data release: spring 2017



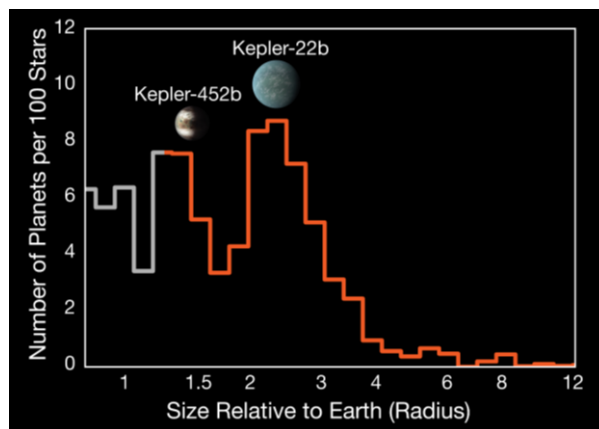
Courtesy: NASA/ARC

- > 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

Small Planets come in Two Sizes



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

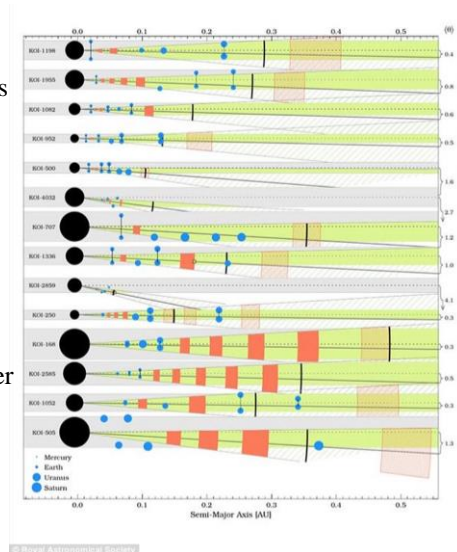
All Stars may have 1 to 3 HZ Planets

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.

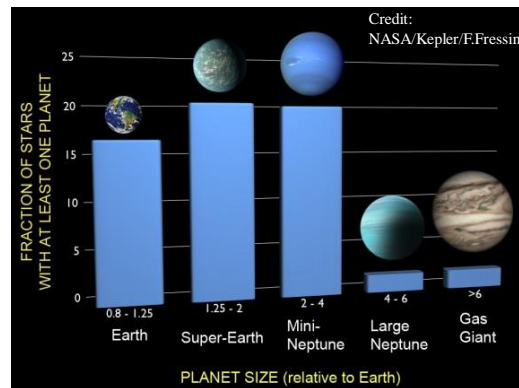
Blue dots show planets measured by Kepler in 151 systems.

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

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.

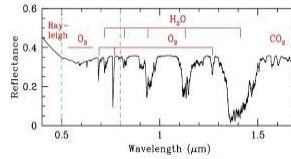
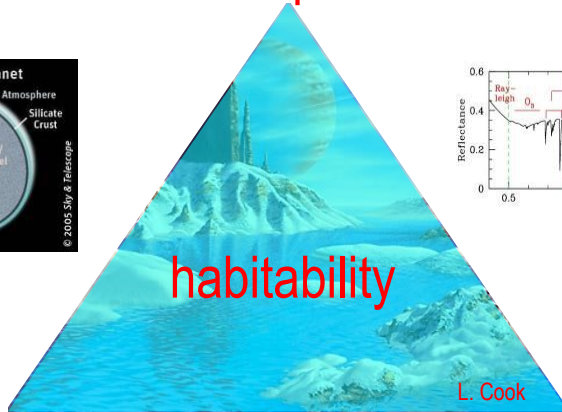
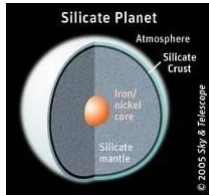
But only a few will be in Habitable Zone

Also, need a moon.

Nancy Atkinson; Universe Today; January 7, 2013

Search for Habitable Planets

atmosphere



interior

surface

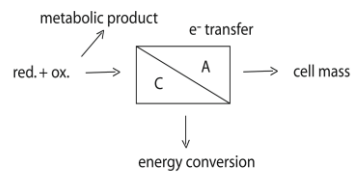
Sara Seager (2006)

Search for Life

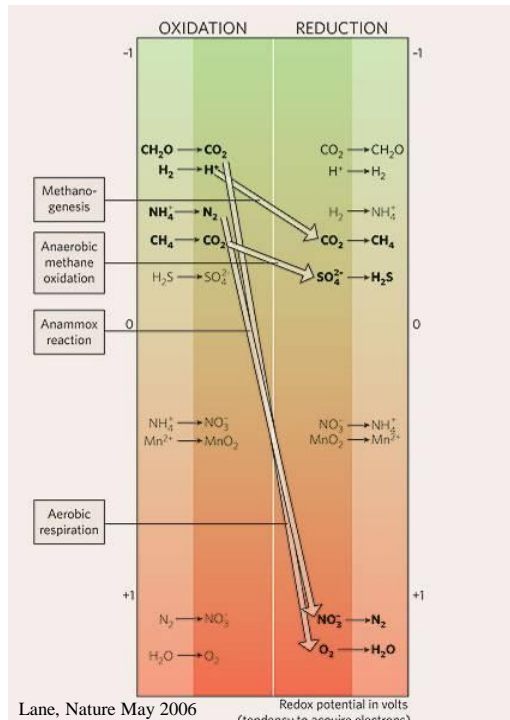
What is life?

What does life do?

Life Metabolizes



Sara Seager (2006)



All Earth life uses chemical energy generated from redox reactions

Life takes advantage of these spontaneous reactions that are kinetically inhibited

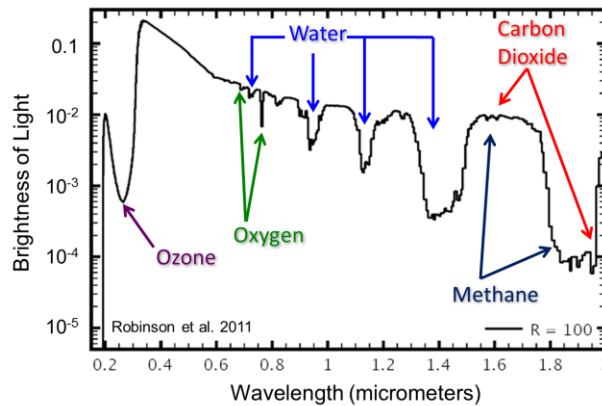
Diversity of metabolisms rivals diversity of exoplanets

Sara Seager (2006)

Atmospheric Spectrum

Spectral Bio-Markers:

- Water (900 nm) easy
- CO₂ (1570 nm) harder
- Oxygen (680 nm) hard
- Methane (1800 nm) hardest

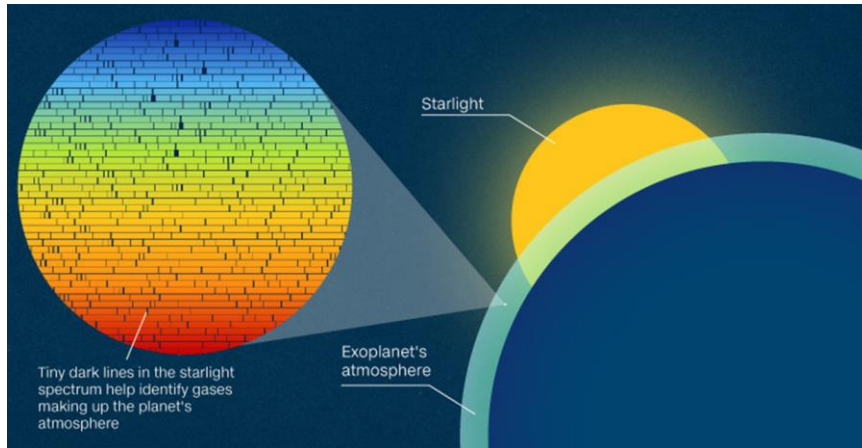


Methane is 'smoking gun'.
Other indicators are 'red-edge' and 'blue-haze'

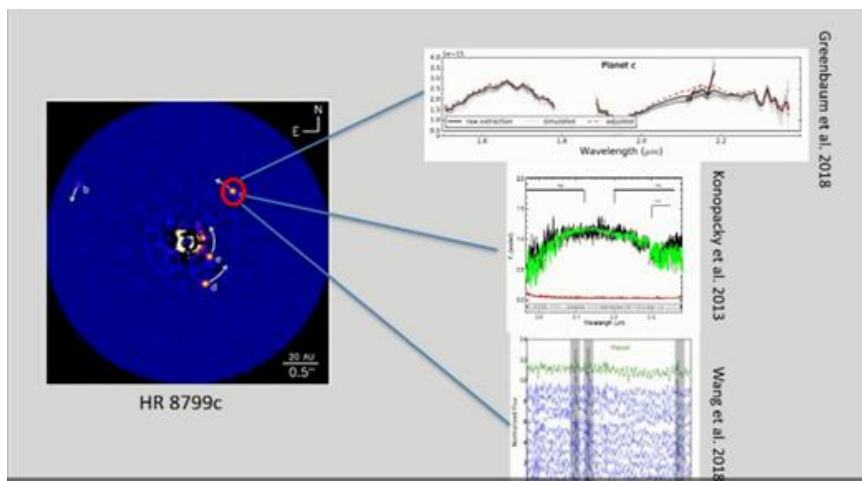


How to see an Exoplanet's Atmosphere

One method is absorption spectroscopy during transits.

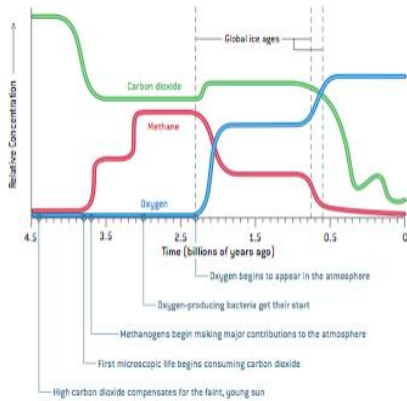


Another is reflected light spectroscopy

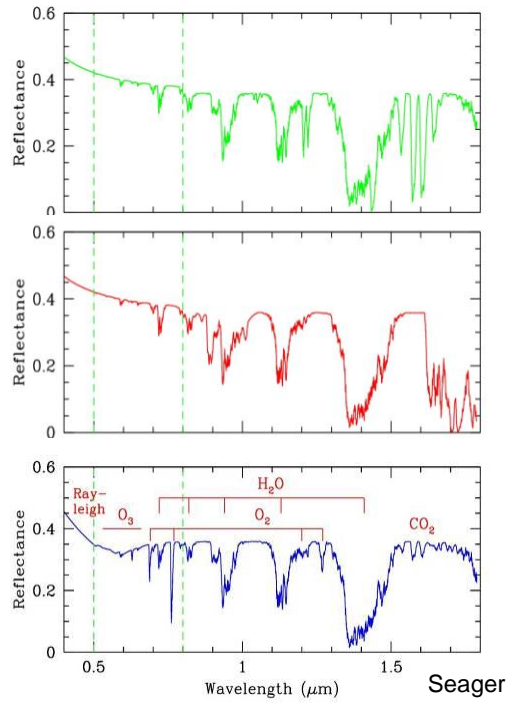


Konopacky, High Contrast Imaging and Adaptive Optics for Nearby Stars and Planetary Systems, AAS 2019

Earth Through Time



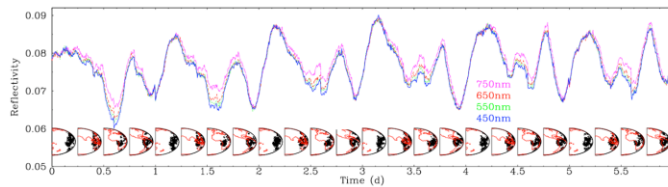
Kasting Sci. Am. 2004
 See Kaltenegger et al. 2006
 Earth from the Moon



Photometric Variability in Exoplanets

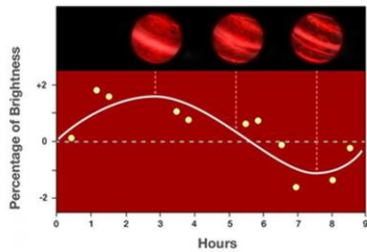
Photometry (brightness or polarization) from planet can vary as it rotations due to:

- Land Mass
- Clouds
- Water



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

Light Curve of Rotation of Super Jupiter ZM1207b



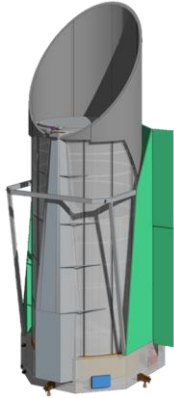
CREDIT NASA, ESA, Y. Zhou (University of Arizona), and P. Jeffries (STScI) STScI • 2016-05

Change in infrared brightness of 2M1207b as measured by Hubble over a 10-hr observation.

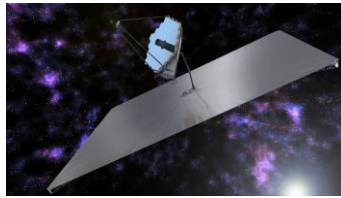
Change in brightness suggests presence of clouds that influence amount of infrared radiation observed as the planet rotates.

Beyond JWST

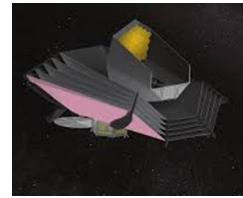
SLS enables even larger telescope Concepts:



HabEx



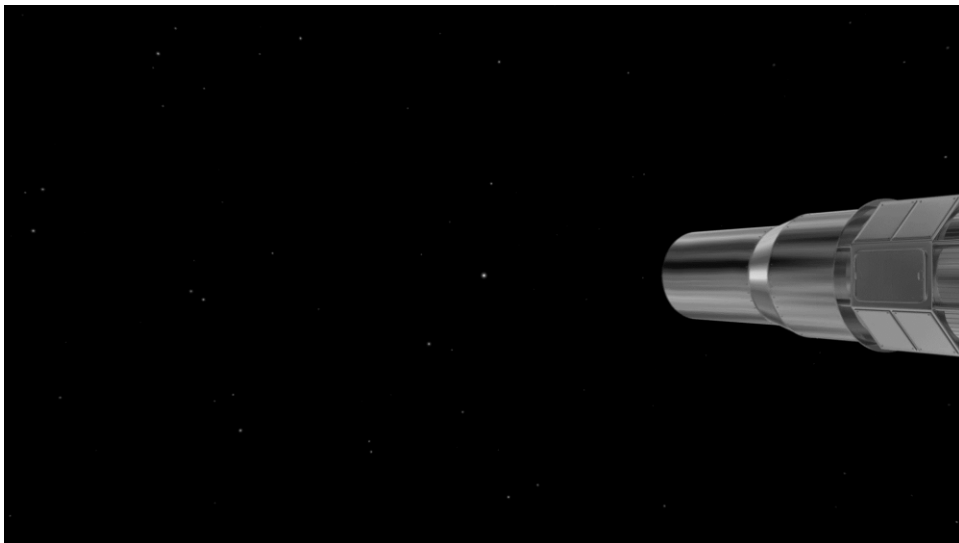
LUVOIR



OST Far-IR

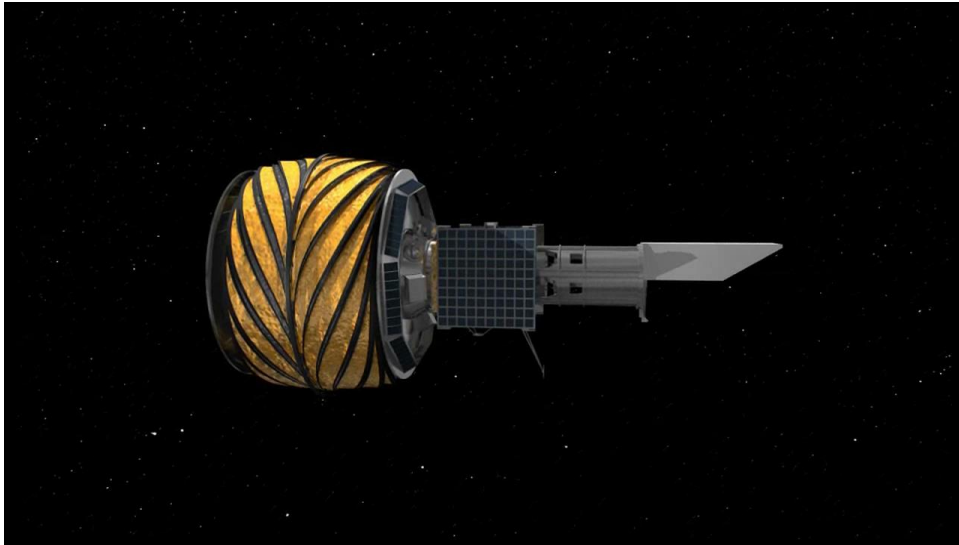
Internal Coronagraph

Controls Diffraction to Reveal Exoplanets in “Dark Hole”



Starshade (External Occulter)

Blocks Starlight, Controls Diffraction prior to entering Telescope

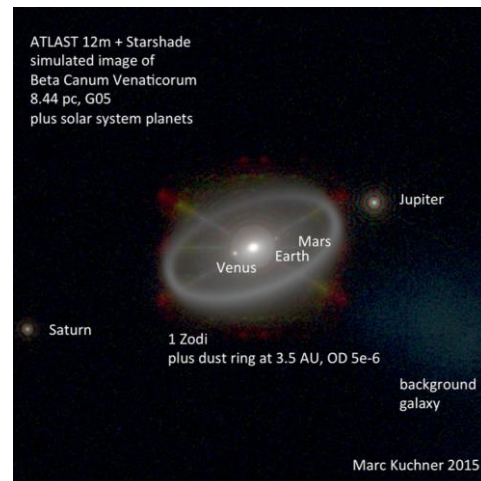


131

Direct Imaging

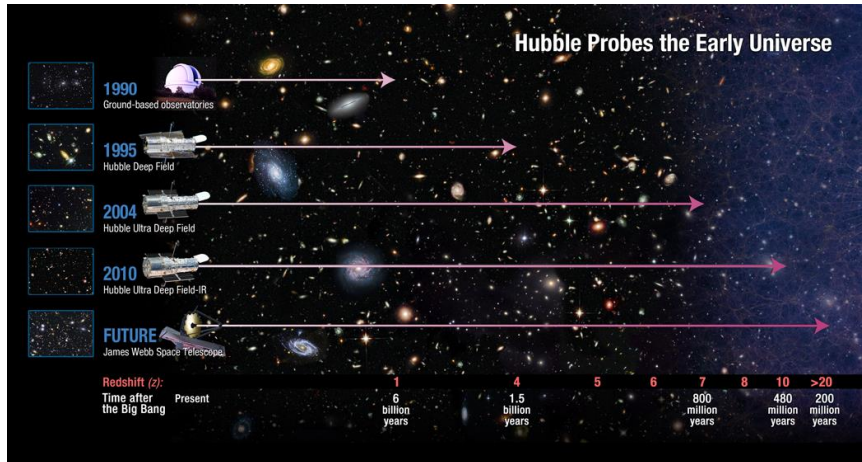
Giant Space Telescopes will be able to directly image Planetary Systems using either internal coronagraphs or external star shades.

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



Webb: Seeing Farther

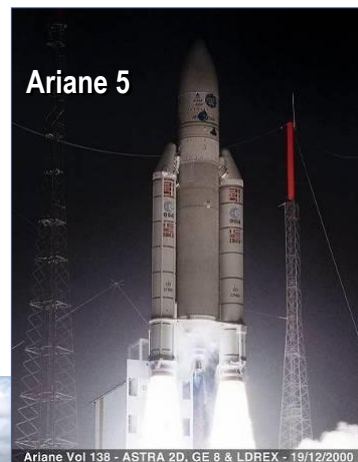
With its 6X larger collecting aperture, the Webb telescope will see farther back in time than Hubble to seek the universe's first light & explore distant worlds.



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.

