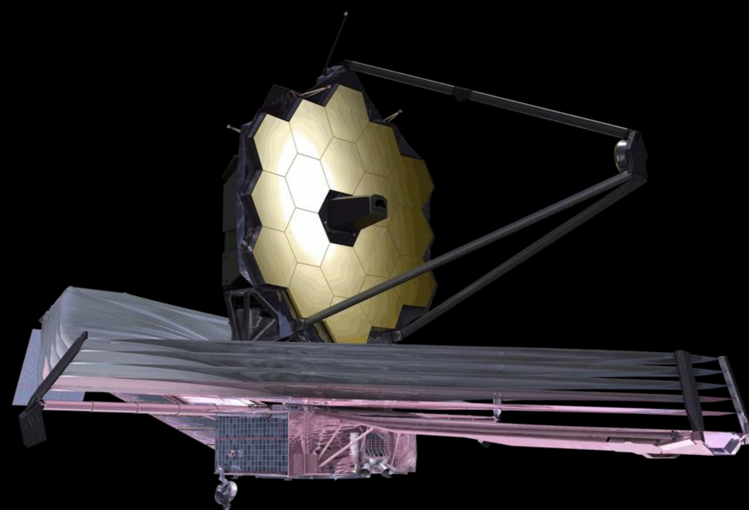
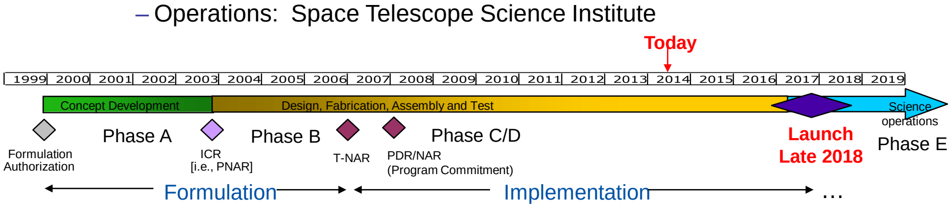
James Webb Space Telescope (JWST)



The First Light Machine

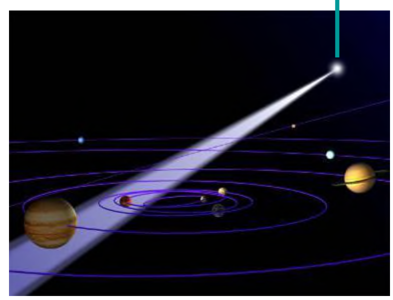
JWST Summary

- **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

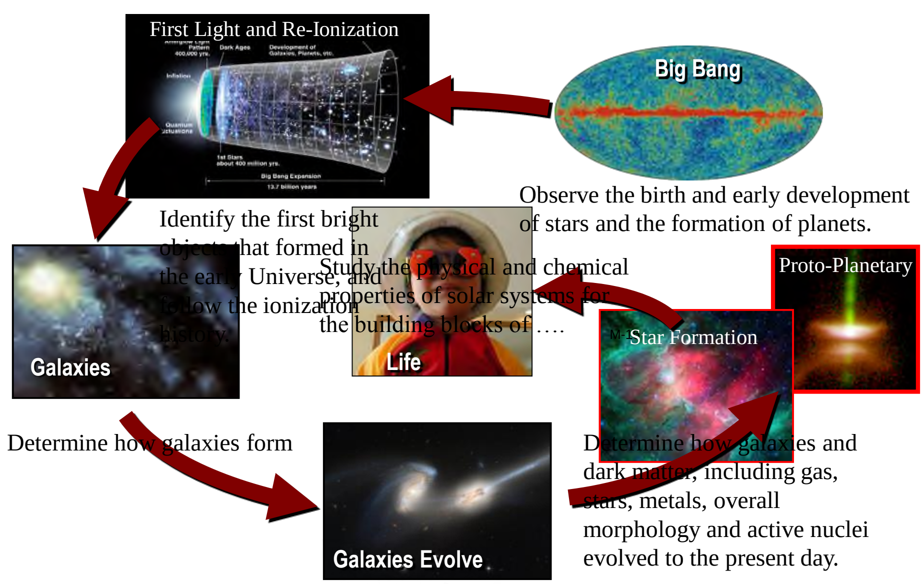


Origins Theme's ***Two*** Fundamental Questions

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



JWST Science Themes



Three Key Facts

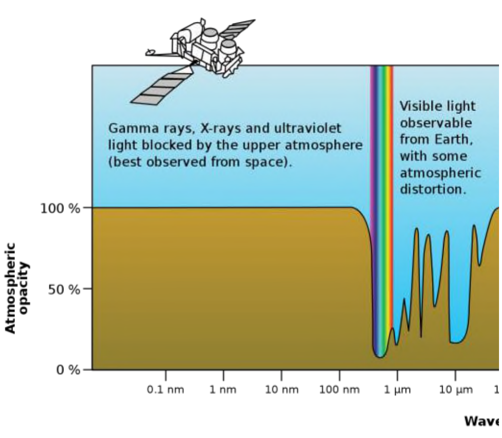
There are 3 key facts about JWST that enables it to perform is Science Mission:

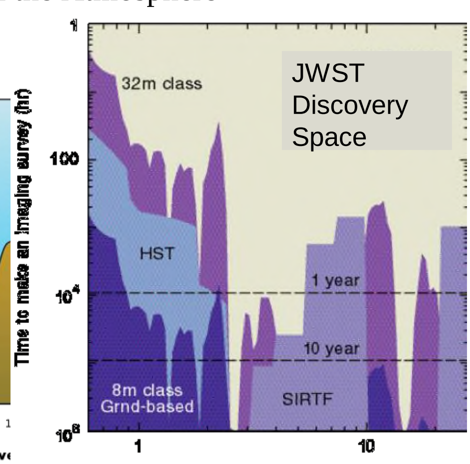
- It is a Space Telescope
- It is an Infrared Telescope
- It has a Large Aperture

Why go to Space

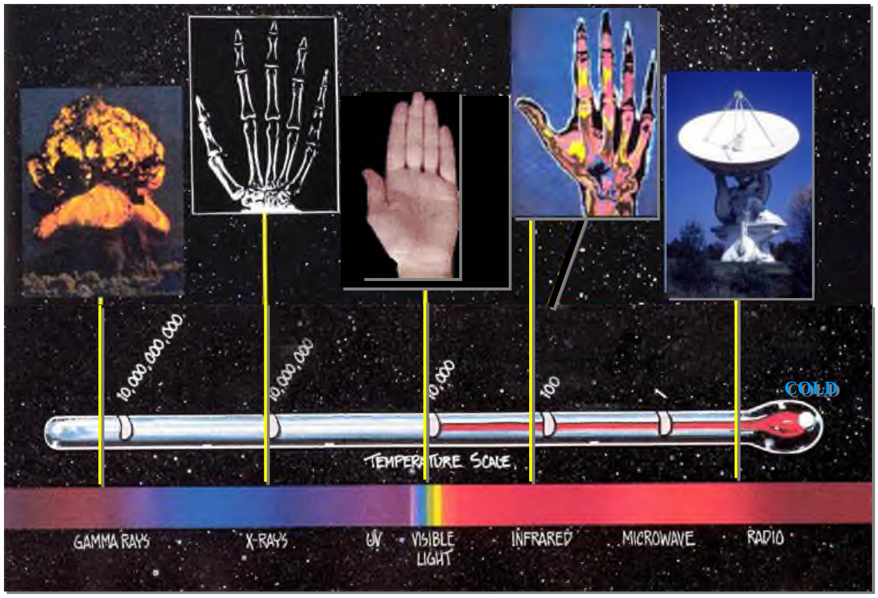
Atmospheric Transmission drives the need to go to space.

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



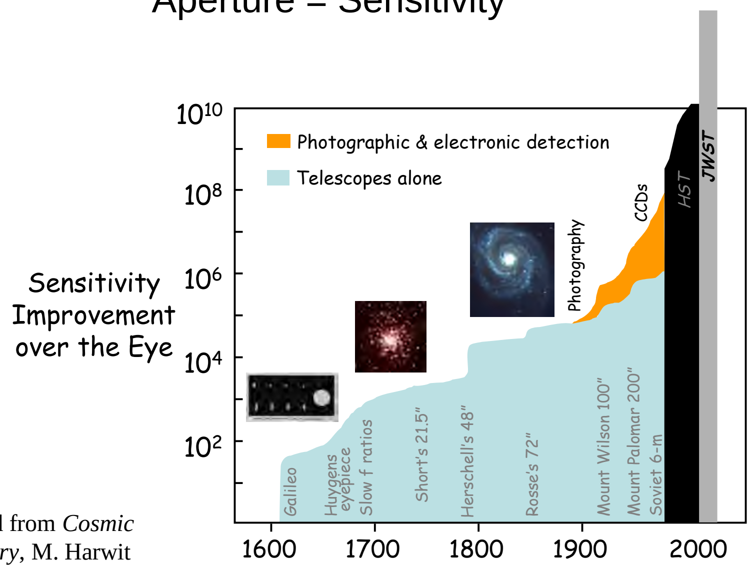


Infrared Light



Why Infrared ?

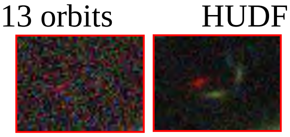
Why do we need Large Apertures?
Aperture = Sensitivity



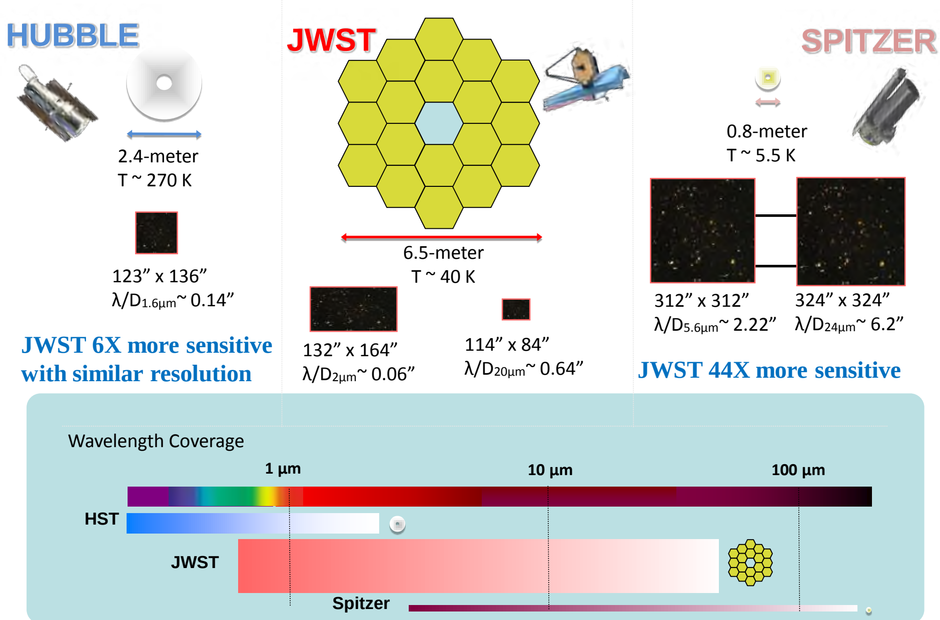
Adapted from *Cosmic Discovery*, M. Harwit

Sensitivity Matters

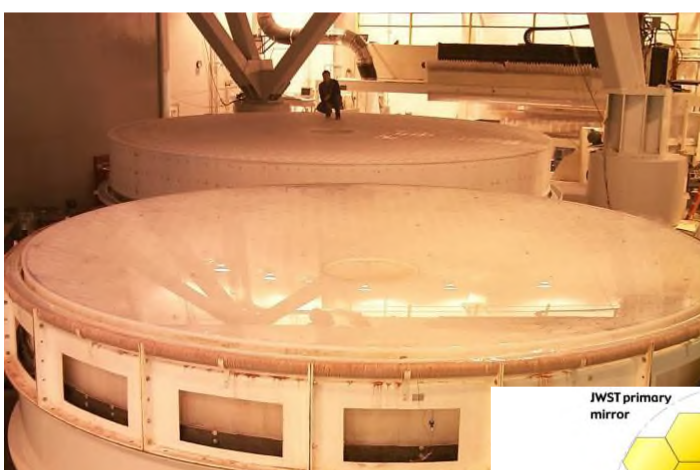
GOODS CDFS – 13 orbits HUDF – 400 orbits

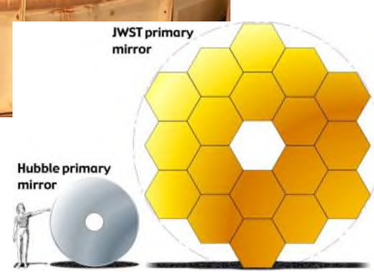


JWST will be more Sensitive than Hubble or Spitzer



How big is JWST?

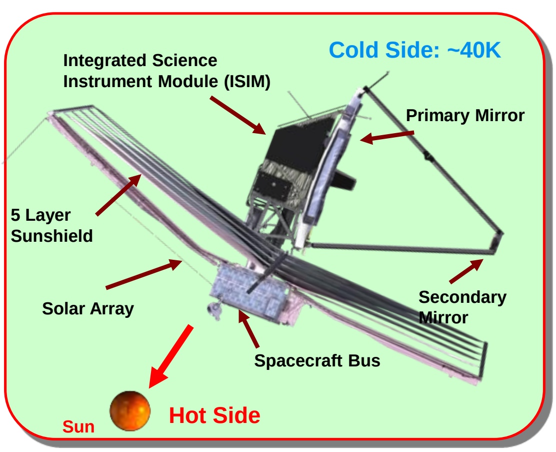


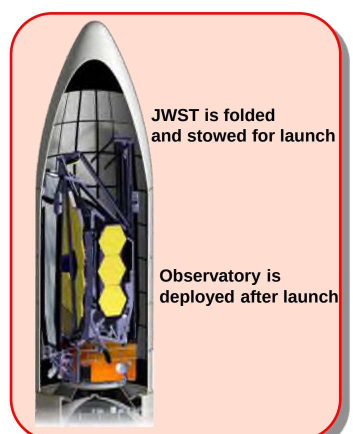


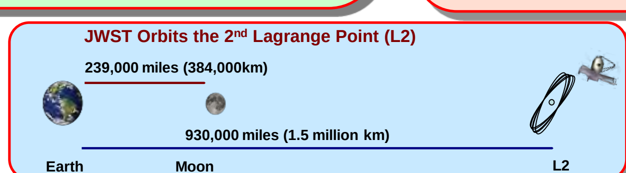
Full Scale JWST Mockup

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

How JWST Works

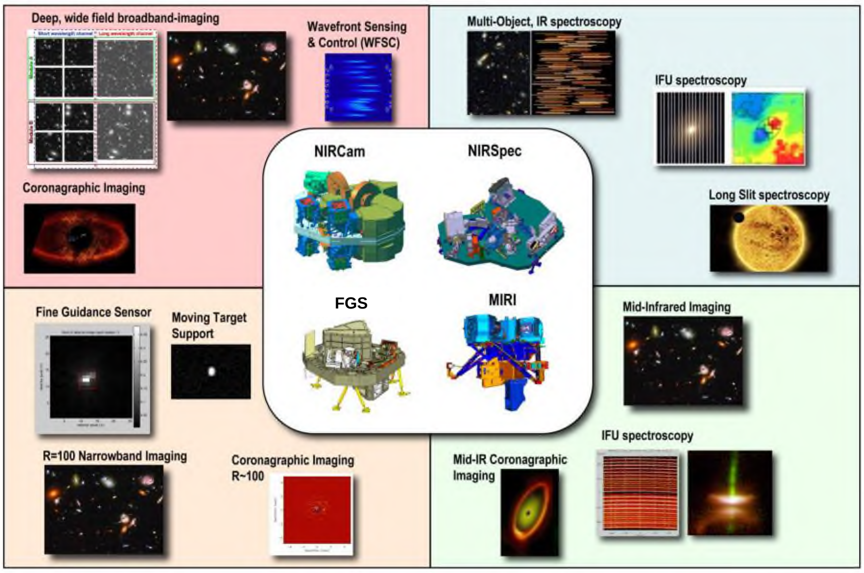






JWST Science Instruments

enable imagery and spectroscopy over the 0.6 – 29 micron spectrum

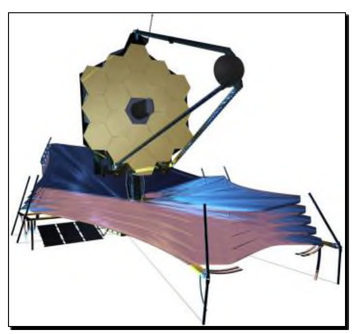


JWST Requirements

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

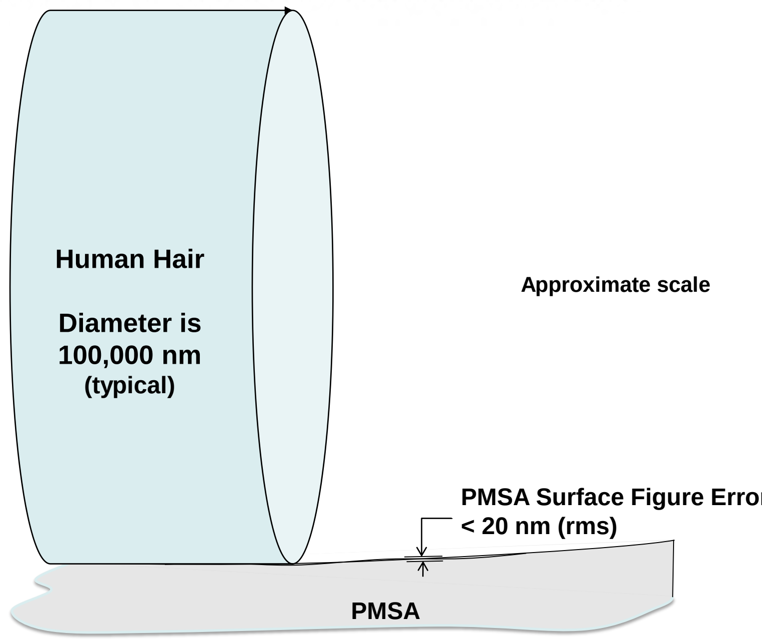
Primary Mirror
- 6.6 meter diameter (tip to tip)
- < 25 kg/m^2 Areal Density
- < \$6 M/m^2 Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

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

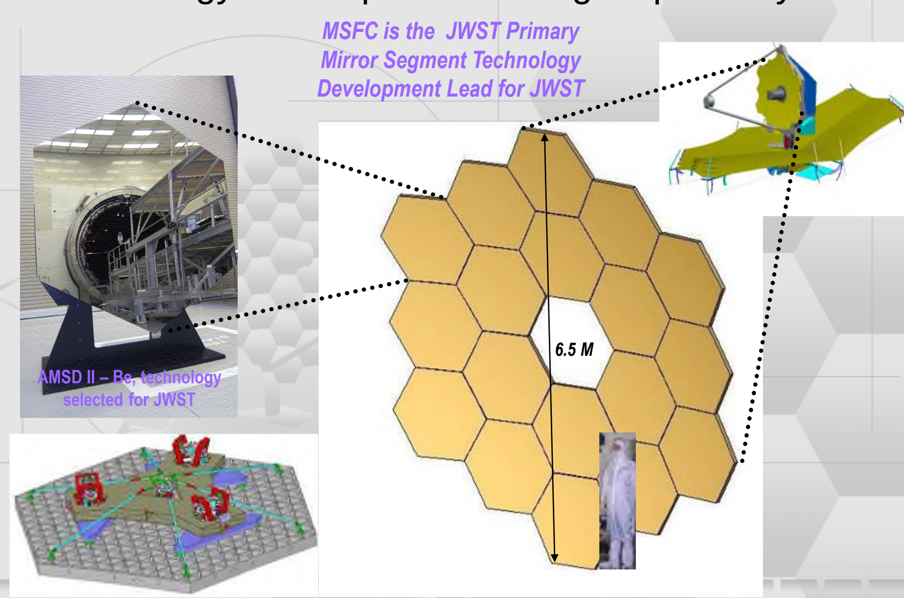


Low (0-5 cycles/aper)	4 nm rms
CSF (5-35 cycles/aper)	18 nm rms
Mid (35-65K cycles/aper)	7 nm rms
Micro-roughness	<4 nm rms

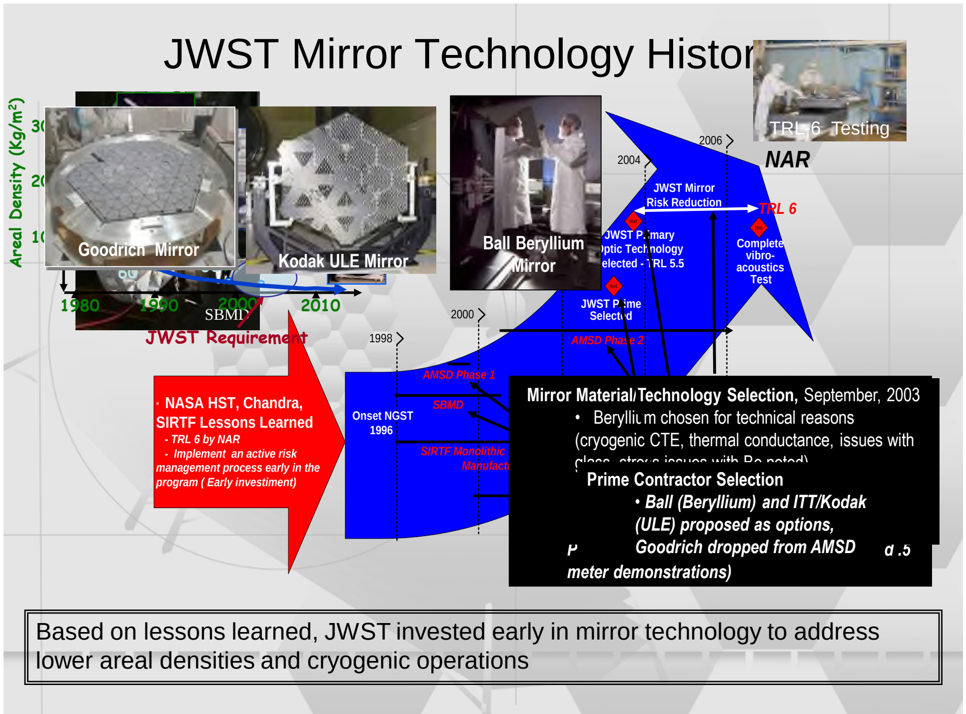
Fun Fact – Mirror Surface Tolerance



Technology Development of Large Optical Systems



The 18 Primary Mirror segments



Advantages of Beryllium

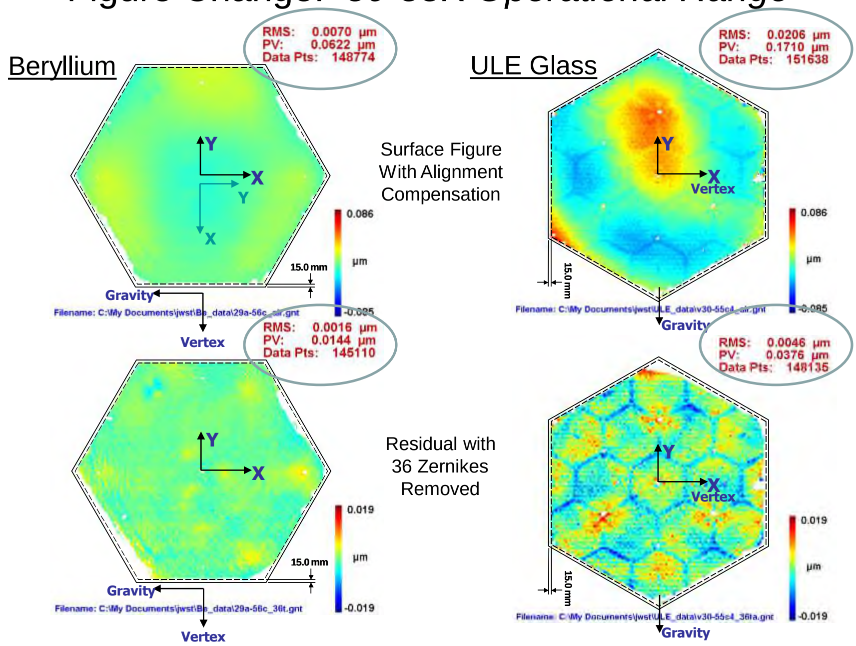
Very High Specific Stiffness – Modulus/Mass Ratio

Saves Mass – Saves Money

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

Thermal Stability

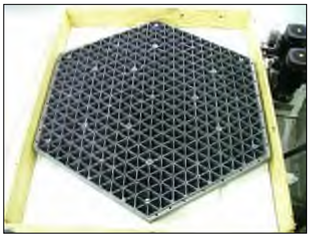
Figure Change: *30-55K Operational Range*



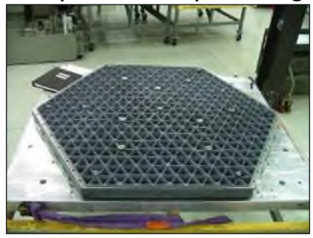
Brush Wellman

Axsys Technologies

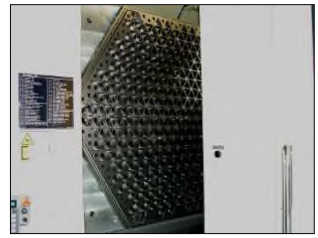
Batch #1 (Pathfinder) PM Segments



PMSA #1 (EDU-A / A1)



PMSA #2 (3 / B1)



PMSA #3 (4 / C1)

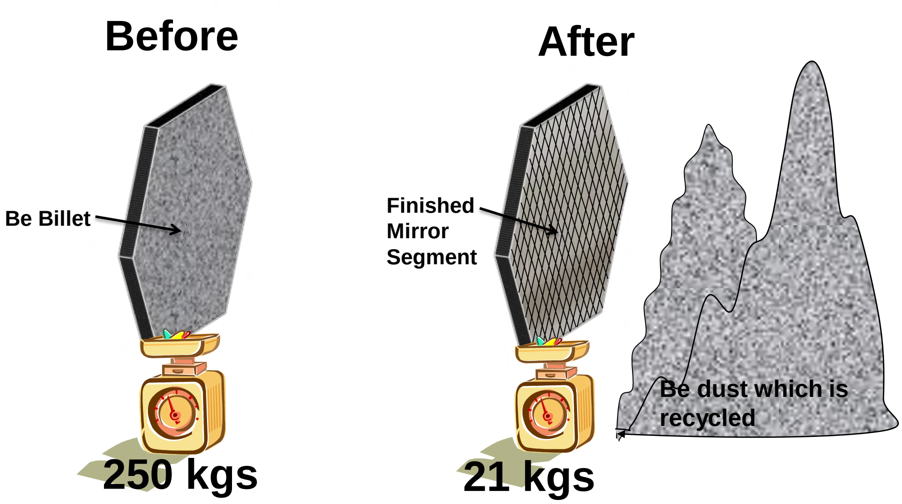
Batch #2 PM Segments

PMSA #4 (5 / A2)

PMSA #5 (6 / B2)

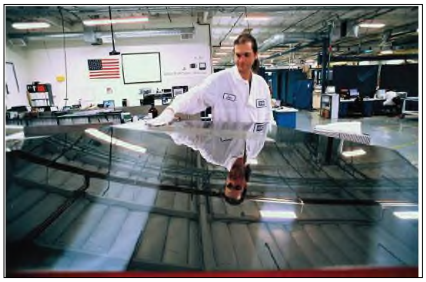
PMSA #6 (7 / C2)

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






Optical Testing Challenge

JWST

- In-Process Optical Testing
- Requirement Compliance Certification Verification & Validation

is probably the most difficult metrology job of our generation

But, the challenge has been met:

- by the hard work of dozens of optical metrologists,
- the development and qualification of multiple custom test setups, and
- several new inventions, including 4D PhaseCam and Leica ADM.

4-D PhaseCam & Leica ADM

PhaseCam

Simultaneous Phase-Measuring Interferometer enables ability to test 16 m ROC JWST PMSA.
Camera: 2k x 2k (1.3 mm/pixel at PMSA)
Precision: 0.5 nm rms

Absolute Distance Meter

Polarization Phase-Modulation
Beam can be interrupted
Range: 1.7 to 50 meters
Resolution: 1 μm
Absolute Accuracy: 25 to 50 μm
Reproducibility: 10 to 20 μm

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:

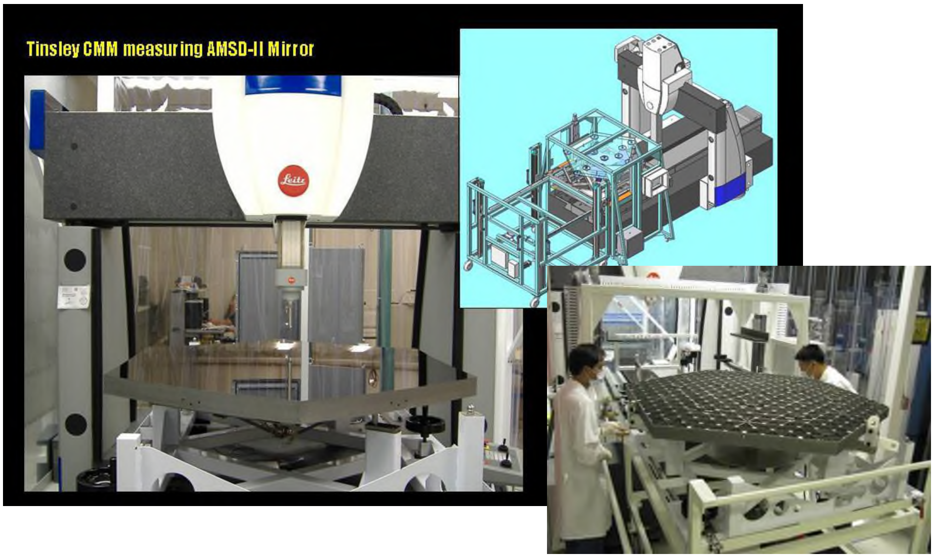
- 2 Center of Curvature CGH Optical Test Stations (OTS1 and OTS2)
- Auto-Collimation Test Station

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



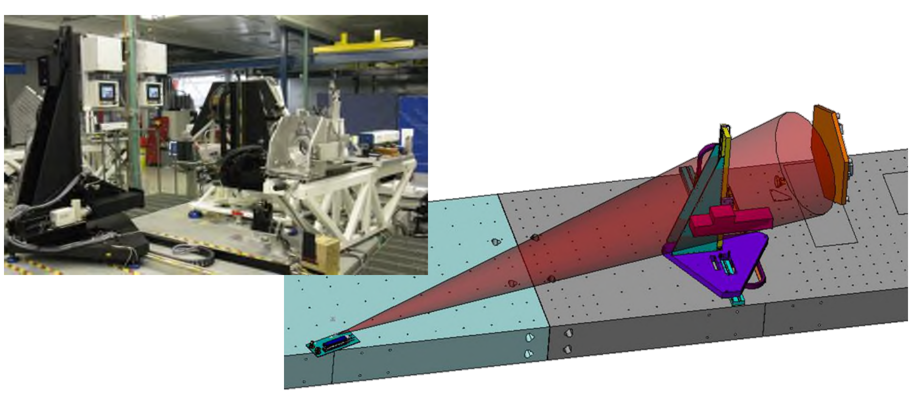
Wavefront Sciences Scanning Shack-Hartmann

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

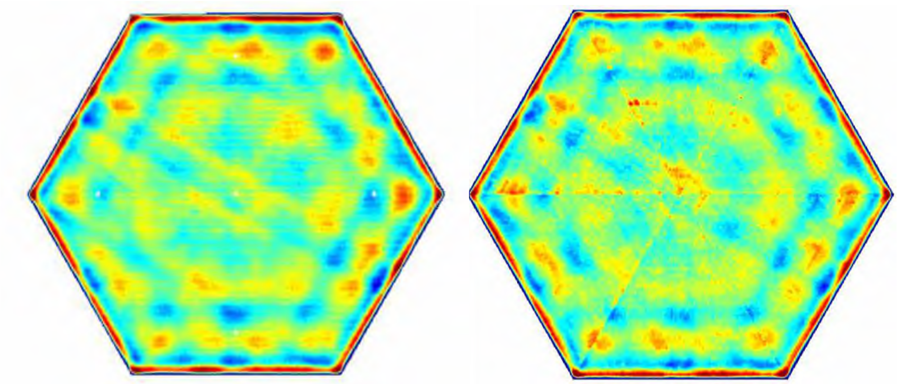
- Large dynamic range (0 – 4.6 mr surface slope)

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

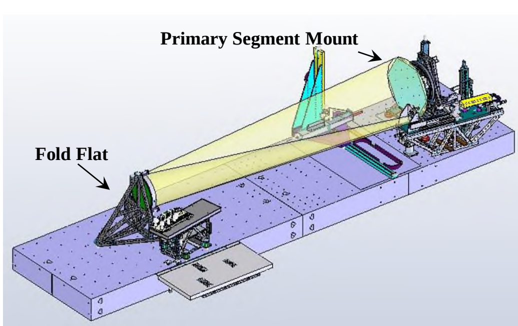
Point-to-Point Subtraction: SSHS - CMM = 0.27 µm RMS

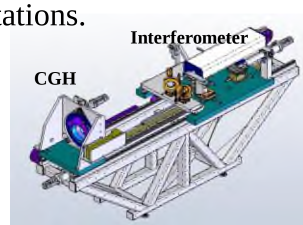
Full Aperture Optical Test Station (OTS)

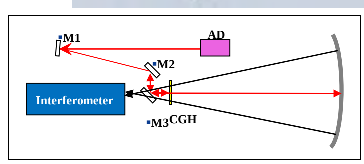
Center of Curvature Null Test (Prescription, Radius & Figure)

- PMSAs measured in 6 rotational positions to back-out gravity
- ADM – measures spacing between CGH and segment
- CGH – generates aberrated wavefront
- Quad cells – mounted to segments measure displacement of spots projected through CGH to determine parent vertex location

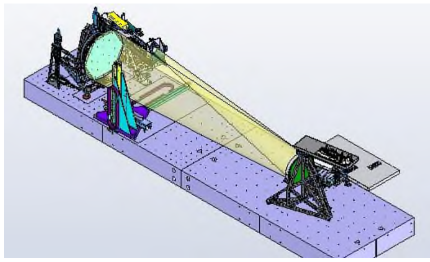
Results are cross-checked between 2 test stations.





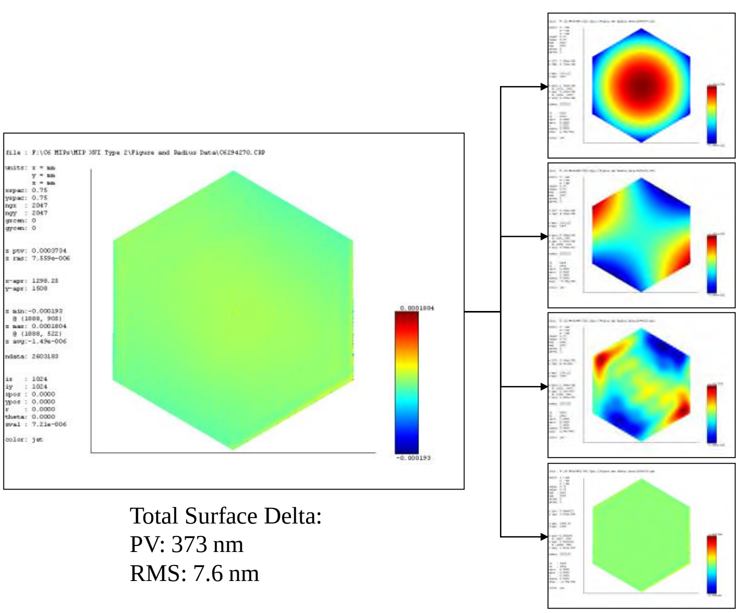


Full Aperture Optical Test Station (OTS)



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

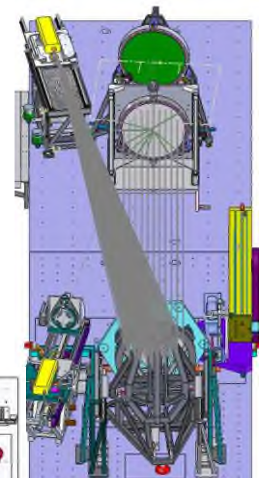
Total Surface Delta:
PV: 373 nm
RMS: 7.6 nm

Auto-Collimation Test

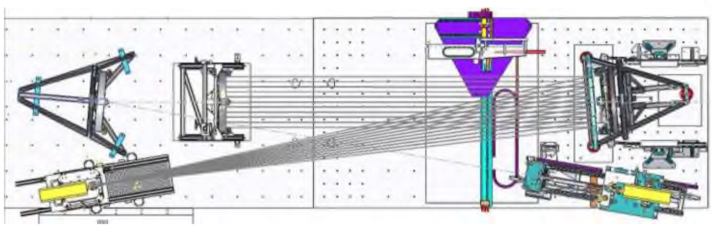
Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:

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

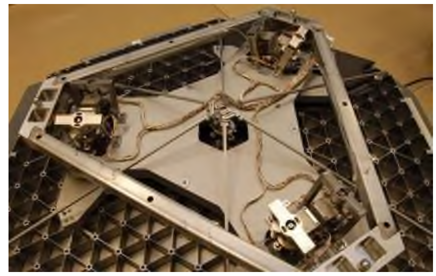


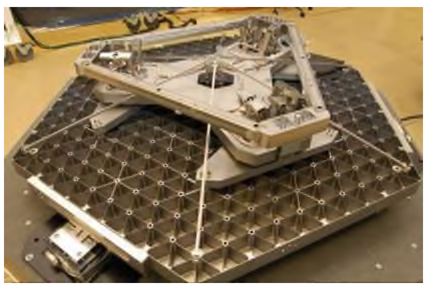
Note: is not a full-aperture figure verification test

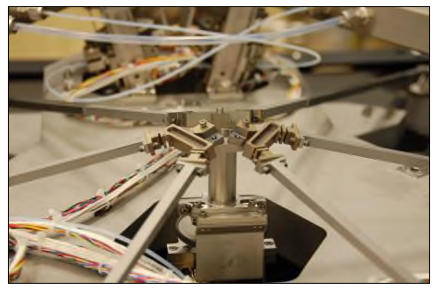


Tinsley Laboratory – Final Shipment

Primary Mirror Segment Assembly at BATC





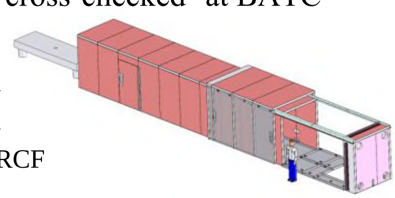


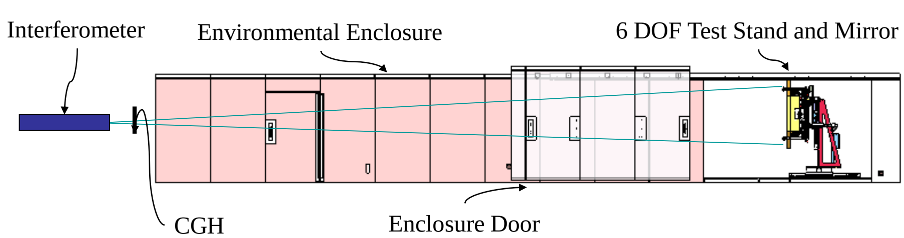
Ball Optical Test Station (BOTS)

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

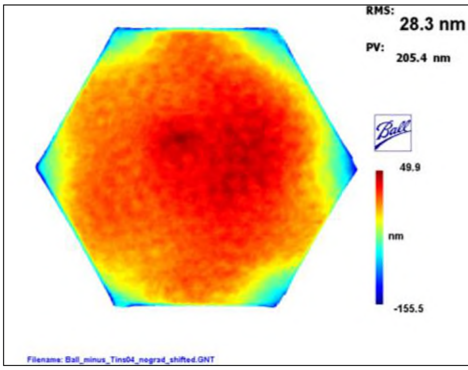
BOTS measurements:

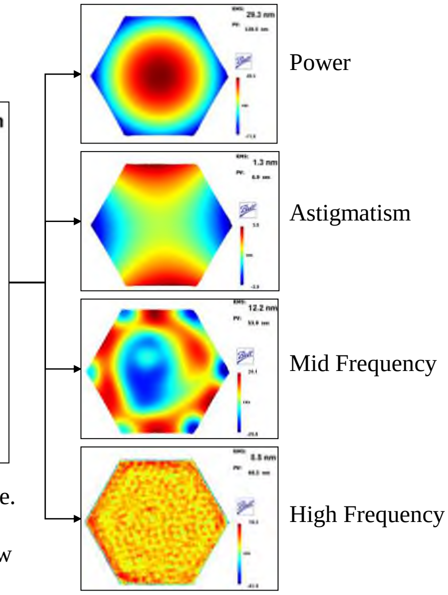
- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation





BOTS to Tinsley Initial Comparison

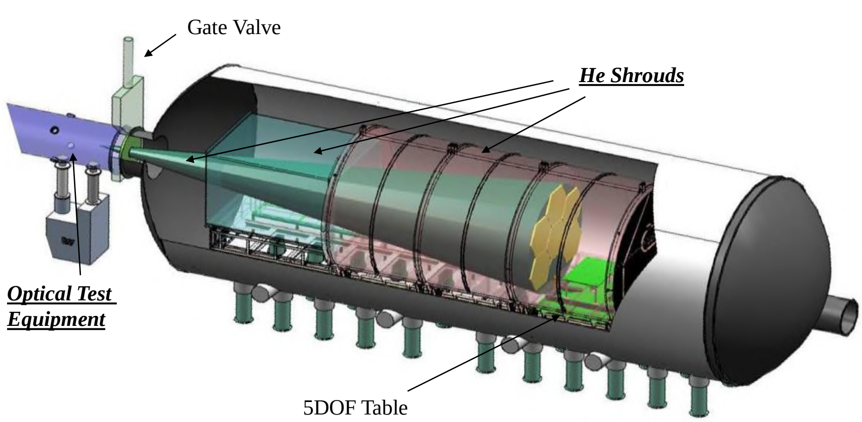




Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.

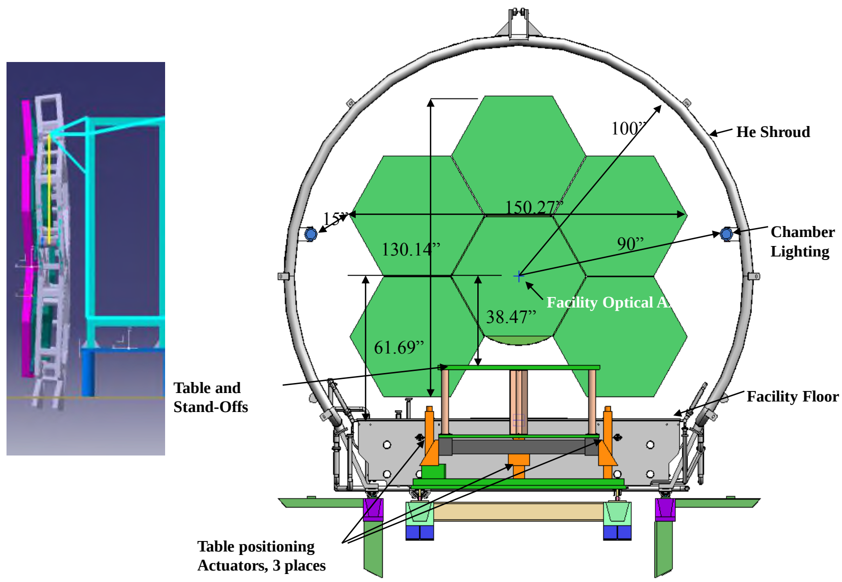
PMSA Flight Mirror Testing at MSFC XRCF

Cryogenic Performance Specifications are Certified at XRCF

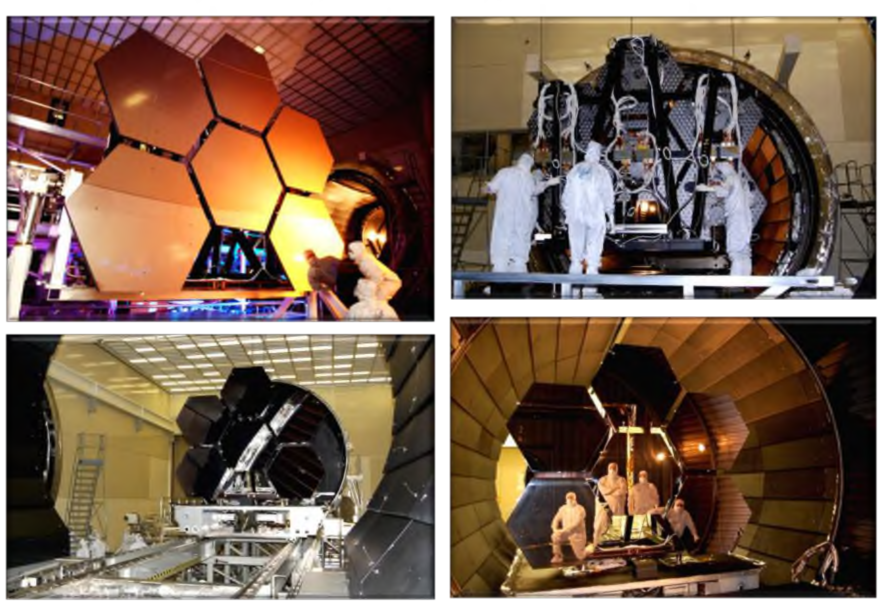


Cryo-Vacuum Chamber is 7 m dia x 23 m long

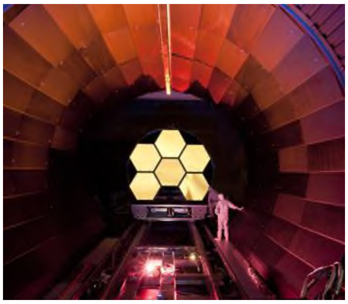
JWST Flight Mirror Test Configuration

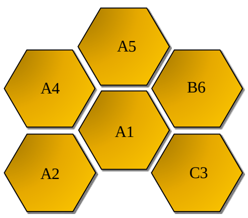


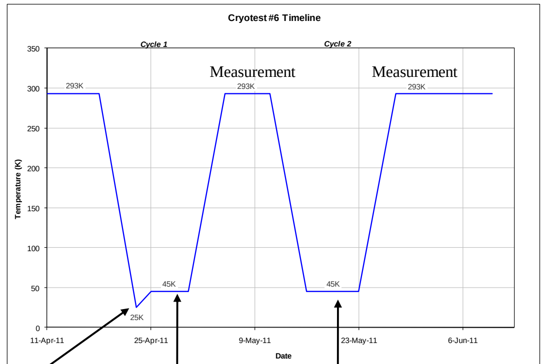
Primary Mirror Cryogenic Tests



XRCF Cryo Test







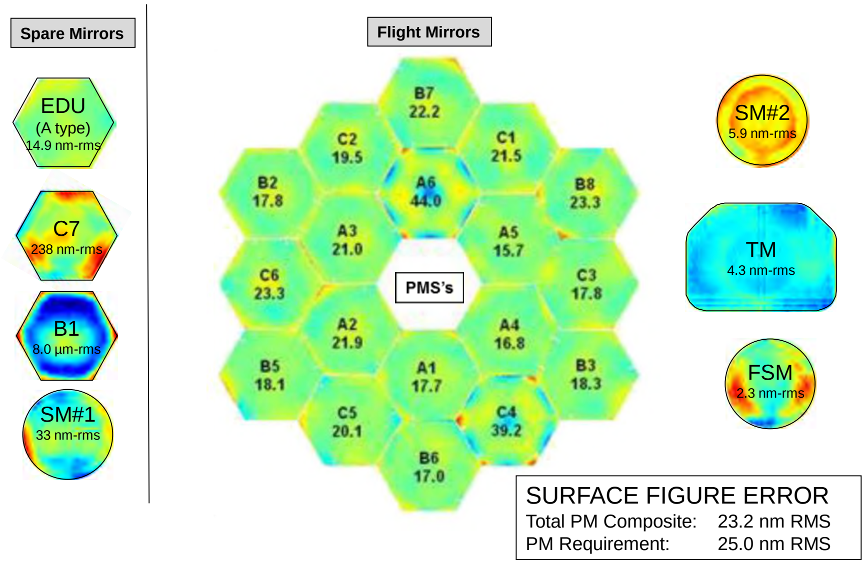
- Survival Temperature

- 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)

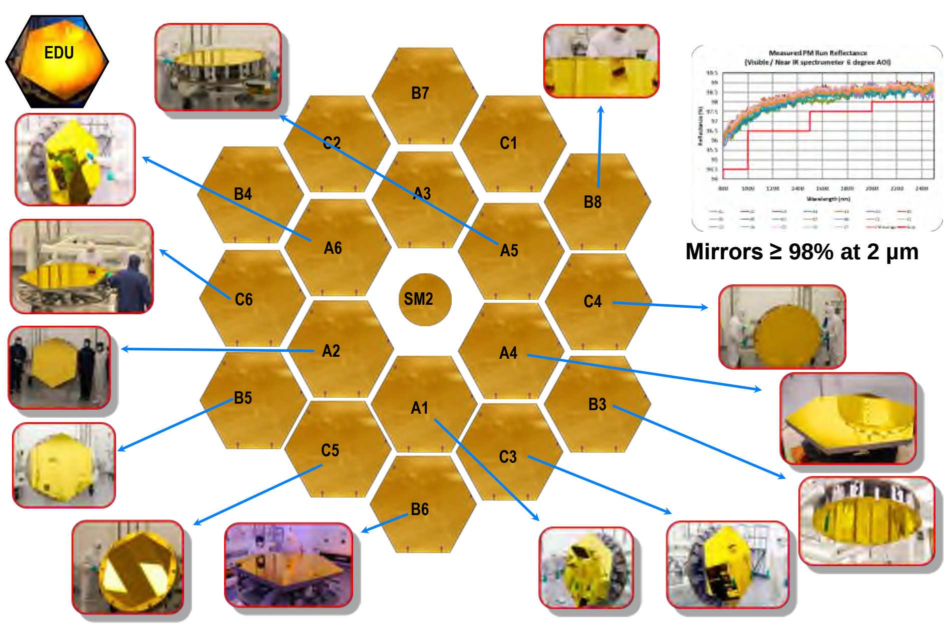
Flight Mirrors in XRCF

Mirror Fabrication Status
ALL DONE & DELIVERED



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

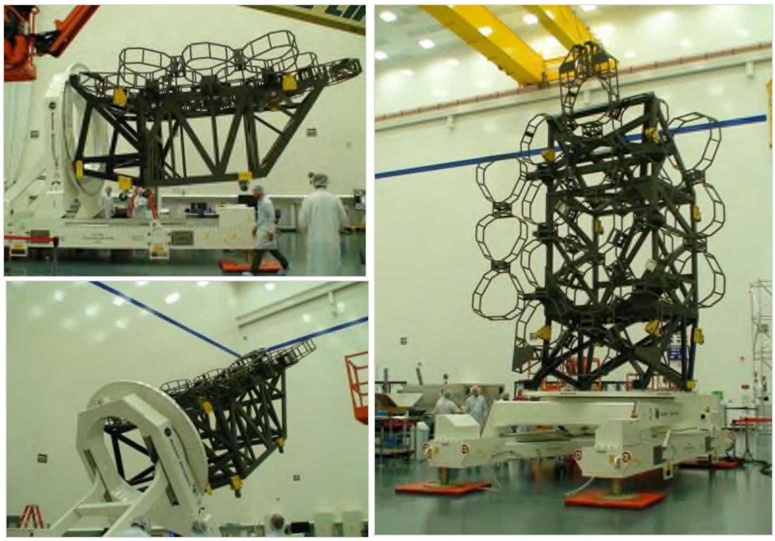
Gold Coated Mirror Assemblies



Primary Mirror Backplane

Pathfinder backplane (central section) is complete for test procedure verification at JSC

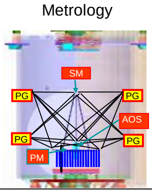
Flight Backplane under construction



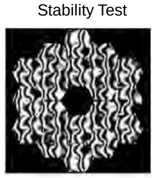
Observatory level testing occurs at JSC Chamber A

Verification Test Activities in JSC Chamber-A

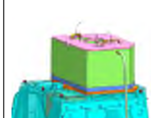
Cryo Position Metrology



Primary Mirror Stability Test

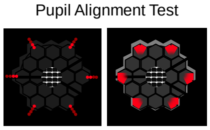


Focus Sweep Test (inward facing sources)



Crosscheck Tests in JSC Chamber-A

Pupil Alignment Test

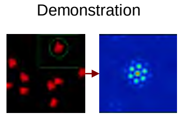


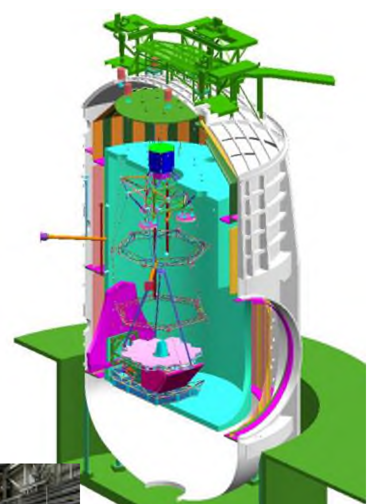
Rogue Path Test

Pass-and-a-Half Test

Primary Mirror WFE Test

End-to-End WFSC Demonstration





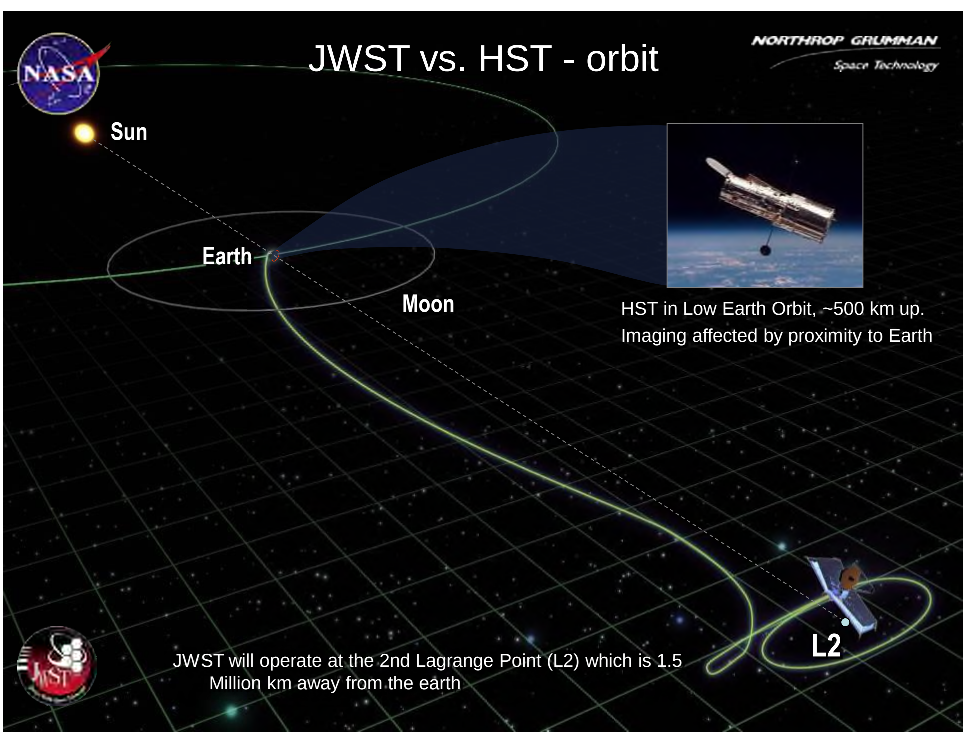
Chamber A:

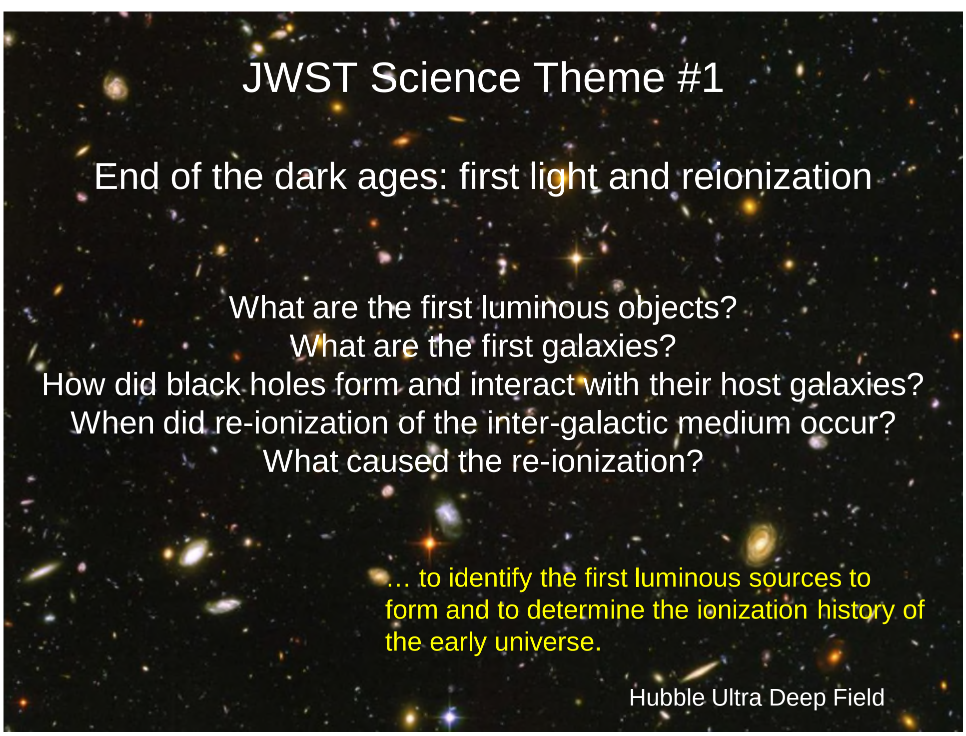
- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

JWST Launched on Ariane 5 Heavy

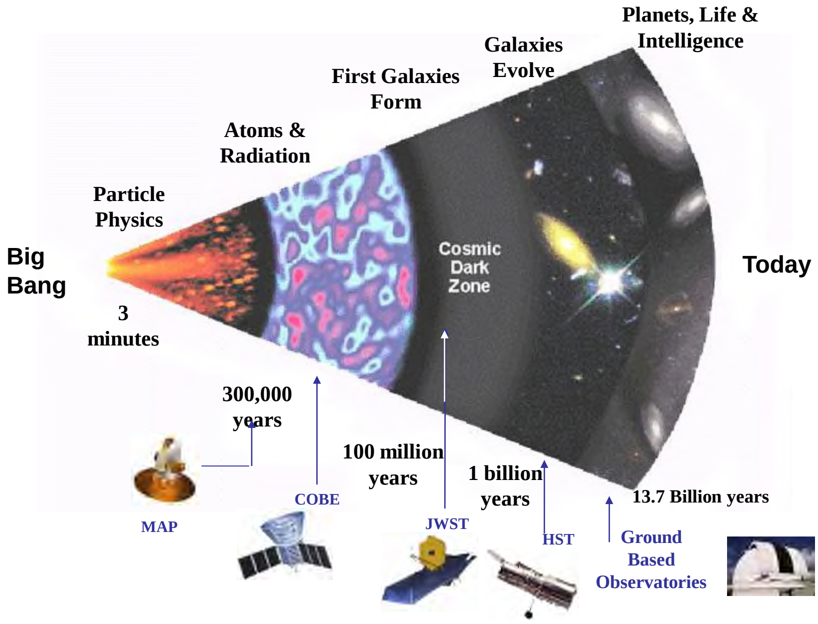
JWST folded and stowed for launch in 5 m dia x 17 m tall fairing

Launch from Kourou Launch Center (French Guiana) to L2



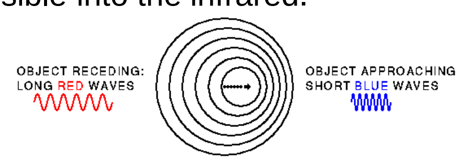

JWST Science Theme #1
End of the dark ages: first light and reionization
What are the first luminous objects?
What are the first galaxies?
How did black holes form and interact with their host galaxies?
When did re-ionization of the inter-galactic medium occur?
What caused the re-ionization?
… to identify the first luminous sources to form and to determine the ionization history of the early universe.
Hubble Ultra Deep Field

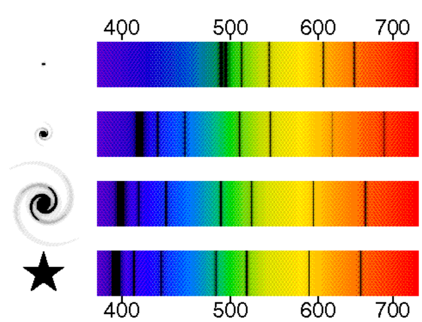
A Brief History of Time



Redshift

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





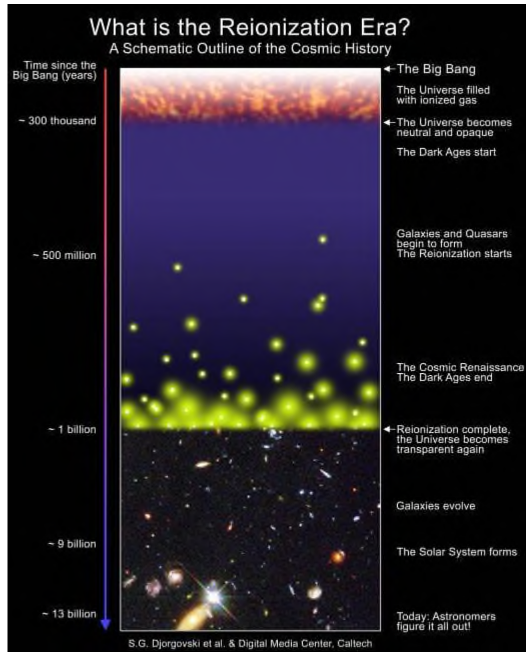
When and how did reionization occur?

Re-ionization happened at z > 6 or
< 1 B yrs after Big Bang.
- WMAP says maybe twice?

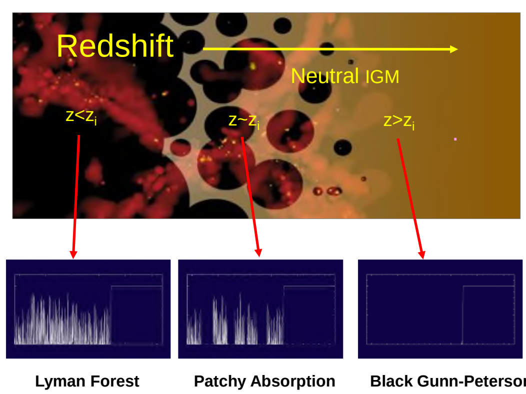
Probably galaxies, maybe quasar contribution

Key Enabling Design Requirments:
- Deep near-infrared imaging survey (1nJy)
- Near-IR multi-object spectroscopy
- Mid-IR photometry and spectroscopy

JWST Observations:
- Spectra of the most distant quasars
- Spectra of faint galaxies



First Light: Observing Reionization Edge

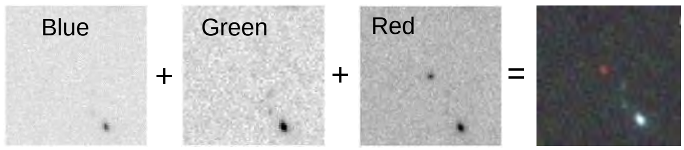


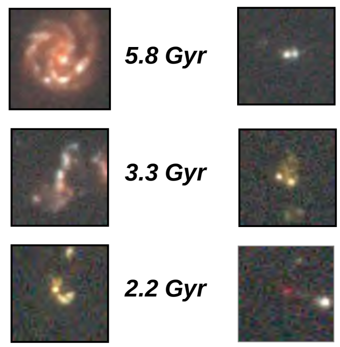
Reionization started at about 600 M yrs after Big Bang. At 780 M yrs after BB the Universe was up to 50% Neutral. But, by 1 B years after BB is was as we see it today. 787 M yr Galaxy confirmed by Neutral Hydrogen method.

Neutral 'fog' was dissolved by very bright 1st Generation Stars (5000X younger & ~100X more massive than our sun).

SPACE.com, 12 October 2011

How do we see first light objects?





Oldest Gamma Ray Burst – 520M yrs after BB

29 Apr 2009, SWIFT detected 5 sec gamma ray burst.

Afterglow in Gemini image has no visible light.

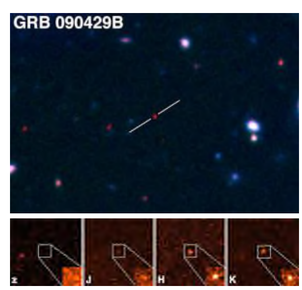
Also, no red-shifted Lyman 'forest' was detected.

Once afterglow faded, nothing was visible

TOO FAR

Estimated Age is 520 million years after big bang, 13.14 billion light-years from Earth (Red Shift 9.4).

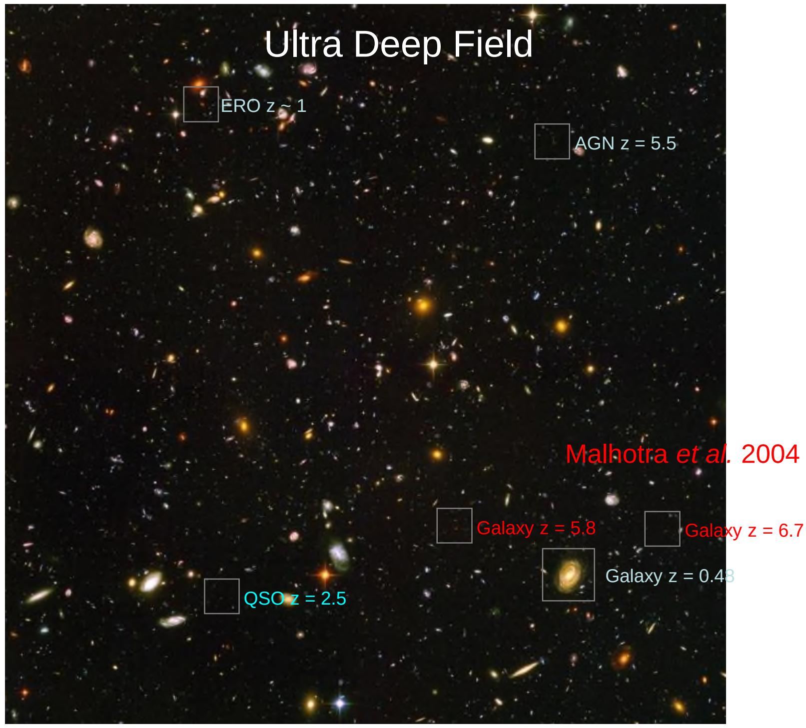
These first light objects are TOO RED SHIFTED for current telescopes. JWST will study them.



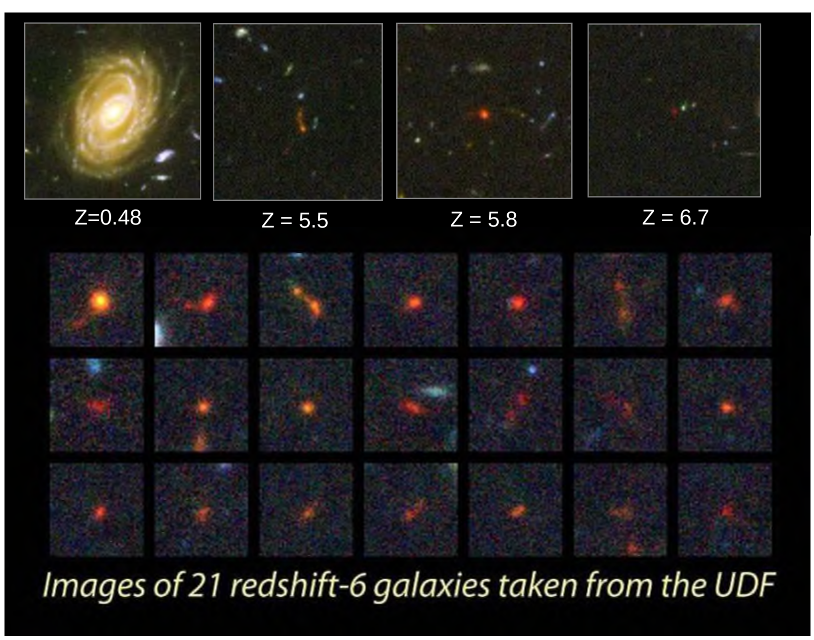
Credit: Gemini Observatory

Jonathan Amos Science correspondent, BBC News

Tammy Plotner, Universe Today, May 26, 2011



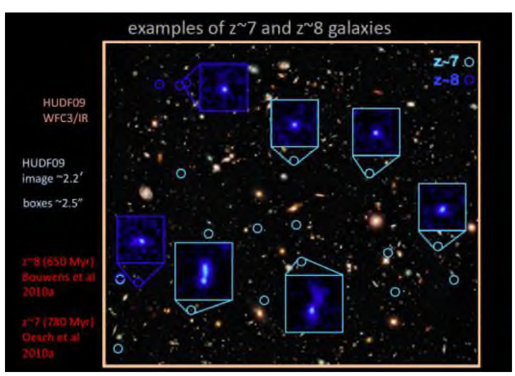
Results from UDF



Hubble Ultra Deep Field – Near Infrared

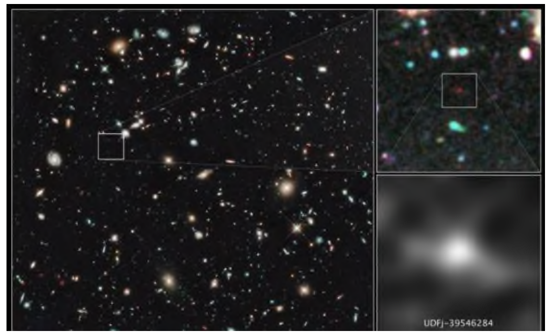
Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

Hubble Ultra Deep Field – Near Infrared

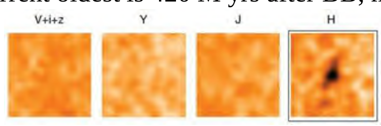


47 Galaxies have been observed at 600 to 650 Myrs after BB.

Hubble Ultra Deep Field – Near Infrared



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)

Hubble Ultra Deep Field – Near Infrared
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

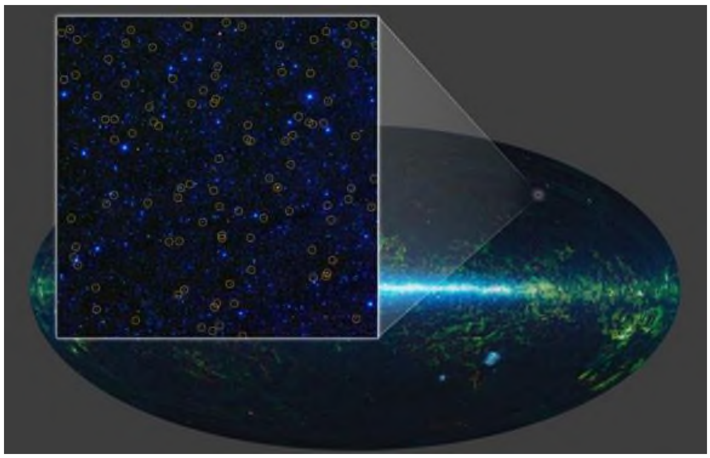
What came first – Galaxies or Black Holes?

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.

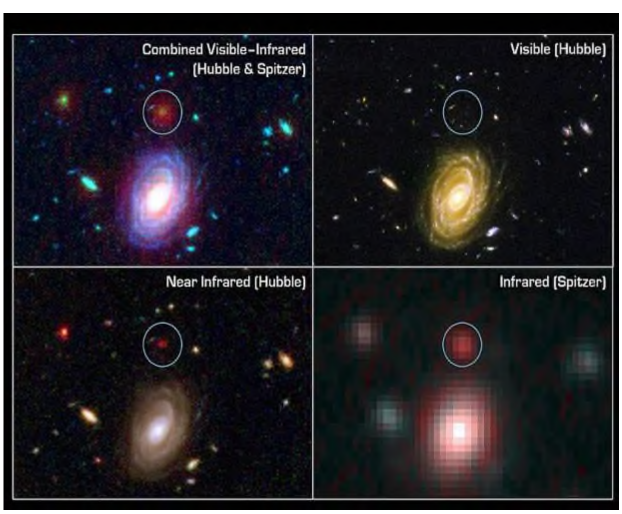
WISE is Wide-Field IR ‘finder scope’ for JWST

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

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.

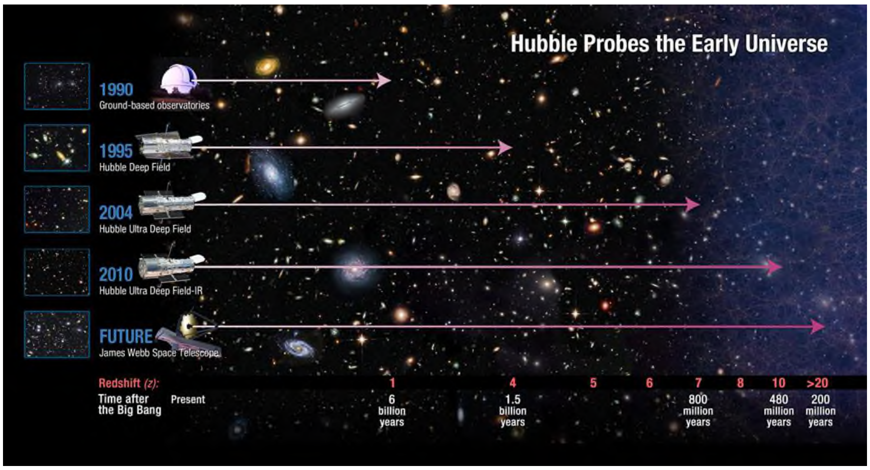
At an epoch when the Universe was only ~15% of its present size, and ~7% of its current age.

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

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

JWST – 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.



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.

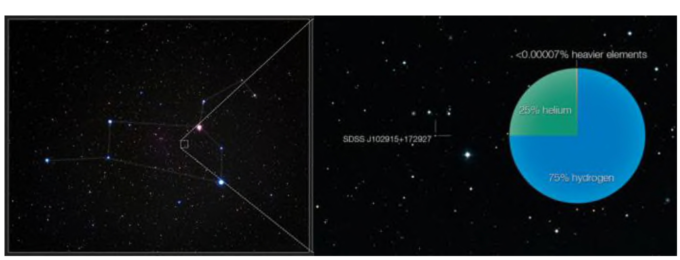
Looking in the IR (with Herschel and Spitzer) at Supernova 1987A, 100,000X more dust was seen than in the visible – the total mass of this dust equals about half of our Sun.

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

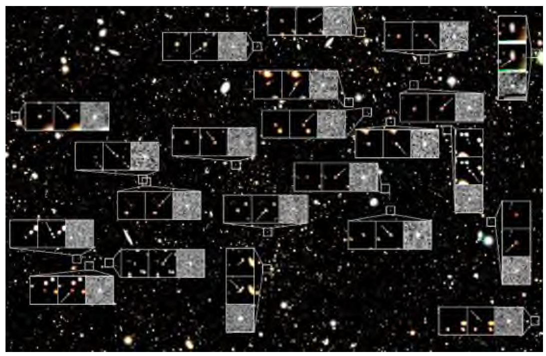
Subaru Deep Field: Ancient Supernova 3.7B yrs after BB

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.

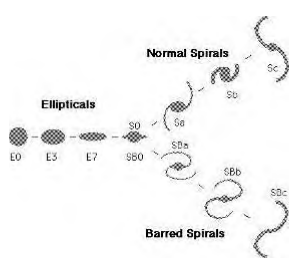
Supernova helped seed early universe with chemical elements.



Clara Moskowitz, SPACE.com, 05 October 2011

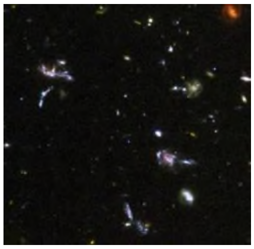
The Hubble Sequence

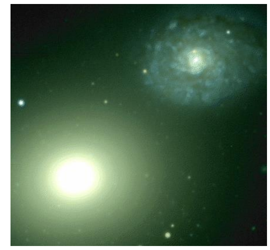
Hubble classified nearby (present-day) galaxies into Spirals and Ellipticals.



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

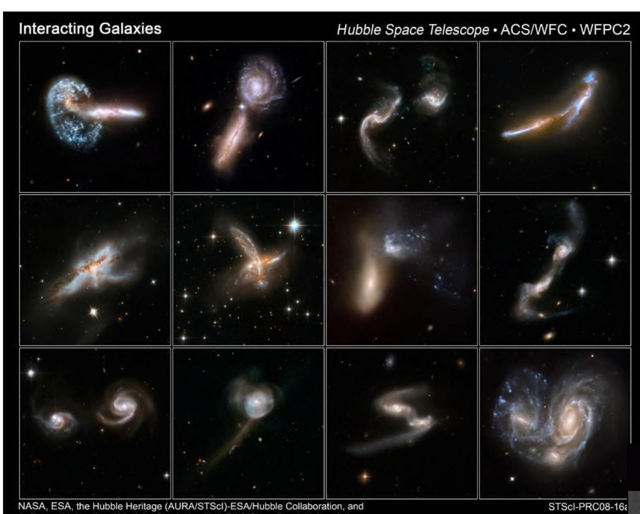
Where and when did the Hubble Sequence form?
How did the heavy elements form?

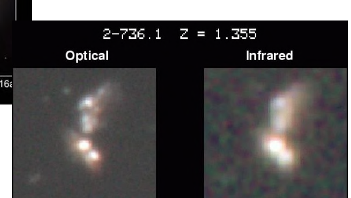




- Galaxy assembly is a process of hierarchical merging
- Components of galaxies have variety of ages & compositions
- JWST Observations:
  - Wide-area near-infrared imaging survey
  - Low and medium resolution spectra of 1000s of galaxies at high redshift
  - Targeted observations of galactic nuclei

Distant Galaxies are "Train Wrecks"





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 Formation – 0.6 B yrs after BB

The early universe was smooth and without structure. Clumping began small and grew to form large galaxies. But how and when?

At 600 Myrs after big bang, these 5 tiny galaxies (circled) are the youngest galaxy cluster yet observed.

They ranging from 10% to 50% the size of our own Milky Way. But they're about as bright as the Milky Way, because they're feasting on huge amounts of gas via mergers with other galaxies.

Since this time, they may have merged to form a giant galaxy.

Borg 58 galaxy field: composite image taken in visible and near-infrared light, reveals the location of five tiny galaxies clustered together 13.1 billion light-years away. The circles pinpoint the galaxies.

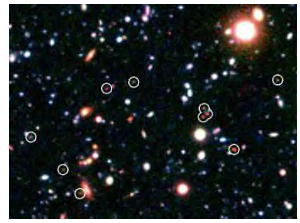
(Space.com 10 Jan 2012)

Galaxy Formation – 1.1B yrs after BB

Previous oldest cluster is 1.1 B-yrs after BB.

Cluster contains 11 min-galaxies which are all much smaller than the Milky Way. One has a 30 million solar mass black hole.

These too may have merged to form a galaxy.



Cluster COSMOS-AzTEC3, located in the Sextans, contains 11 mini-galaxies (circled red dots). Cluster is 1.1 billion yrs after Big Bang.
Subaru / NASA / JPL-Caltech

Discovery required observations from: Chandra X-ray, James Clerk Maxwell Sub-MM, Hubble, Subaru, Keck, Spitzer & several Radio Telescopes

(Sky and Telescope, Robert Naeye, 13 Jan 2011)

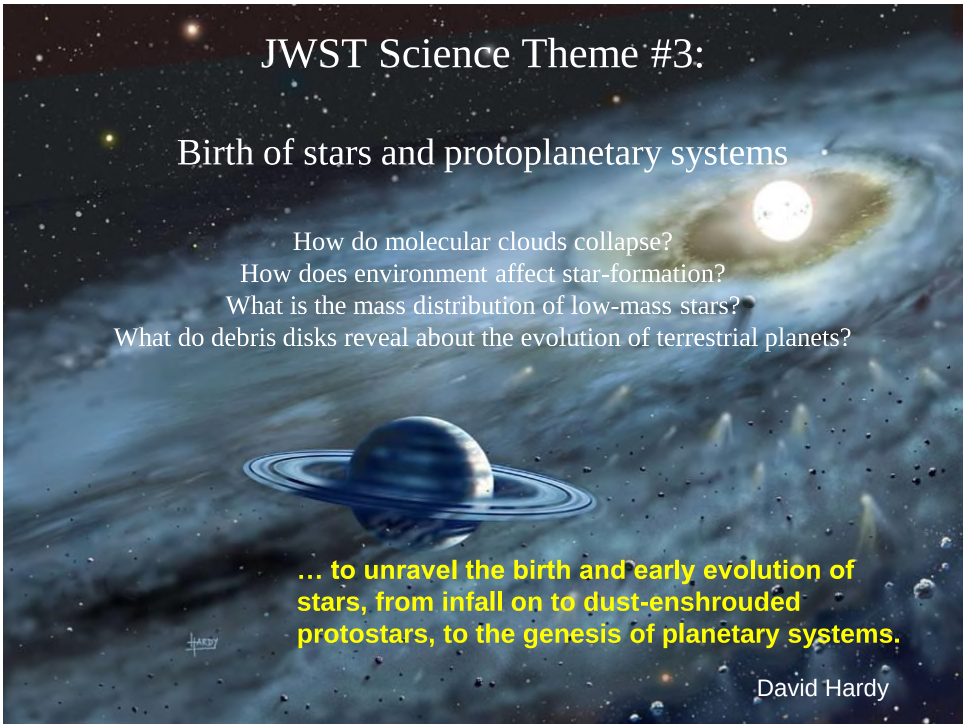
Galaxy Formation

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.

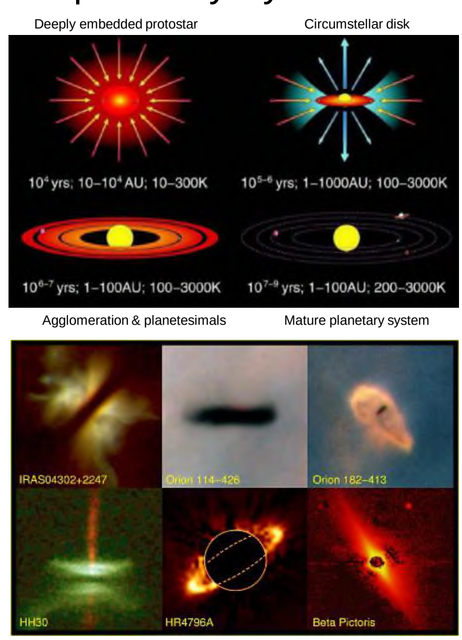
Further out rings are extremely cold, only a few tens of degrees warmer than absolute zero.

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



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.

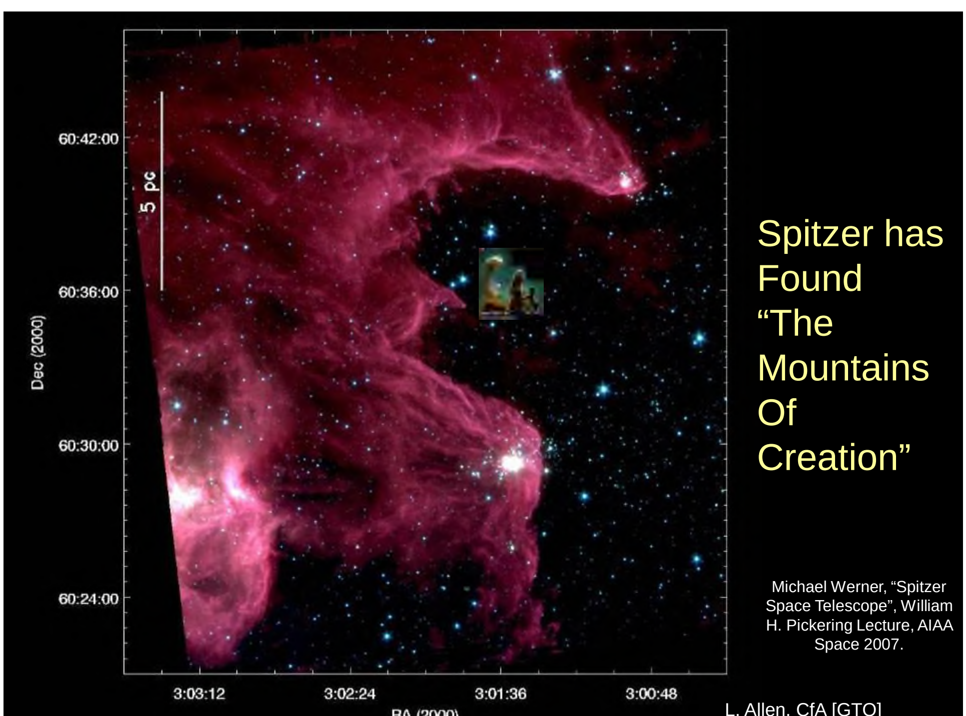
Boundary between smallest brown dwarf stars & planets is unknown

- Different processes? Or continuum?

JWST Observations:

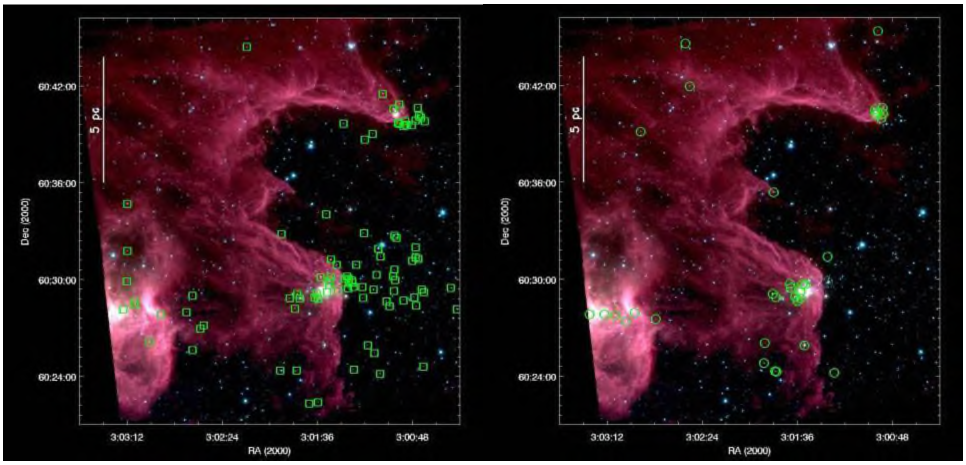
- Survey dark clouds, "elephant trunks" or "pillars of creation" star-forming regions

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.

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

Impossible Stars

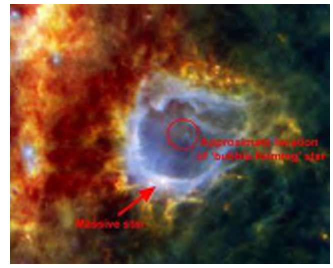


Image of RCW 120 (ESA), Discover.com, Ian O'Neill, 7 May 2010

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).

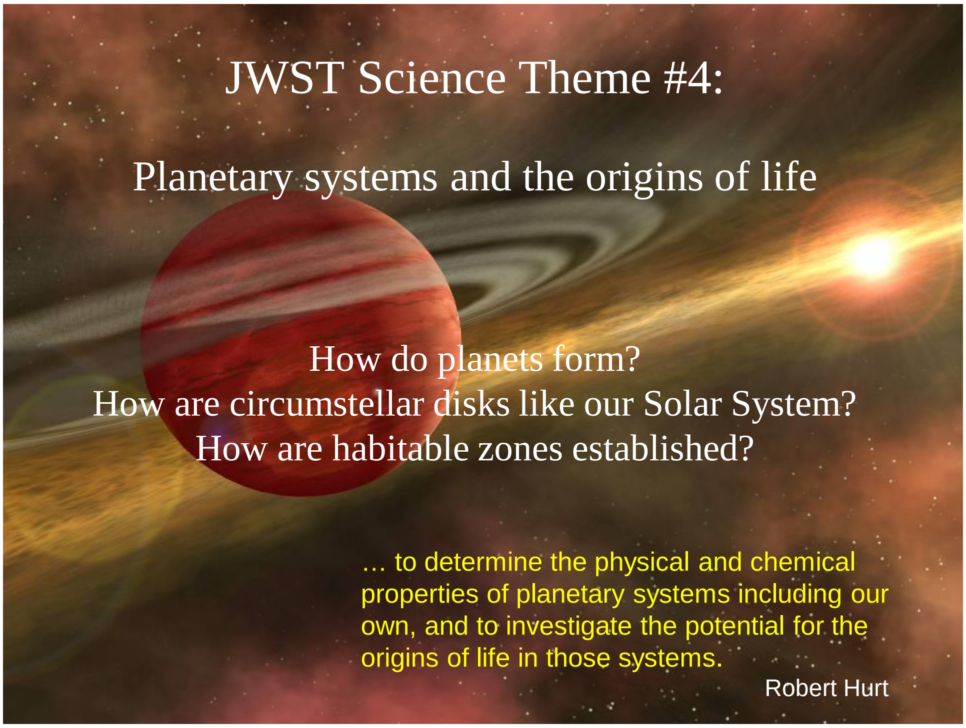
The bubble shock wave is creating a dense 2000 solar mass region in which an 'impossible' star is forming. It is already 10 solar mass and in a few 100 thousand years will be a massive 100 to 150 solar mass – making it one of the biggest and brightest in the galaxy.

(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)



Planetary Formation Questions and 2 Models

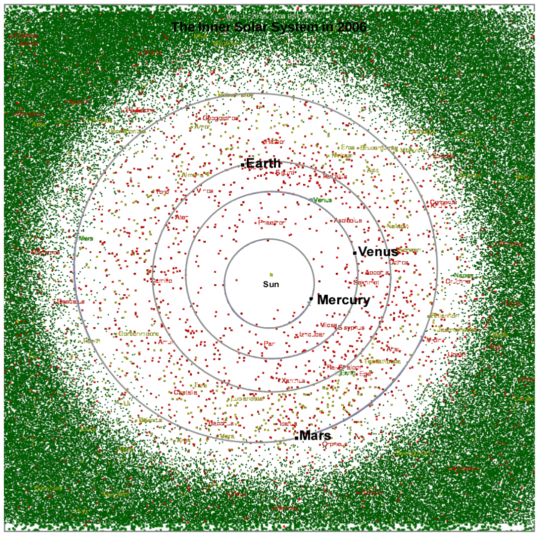
- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems) 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?

History of Known (current) NEO Population

2006

Earth Crossing

Outside Earth's Orbit

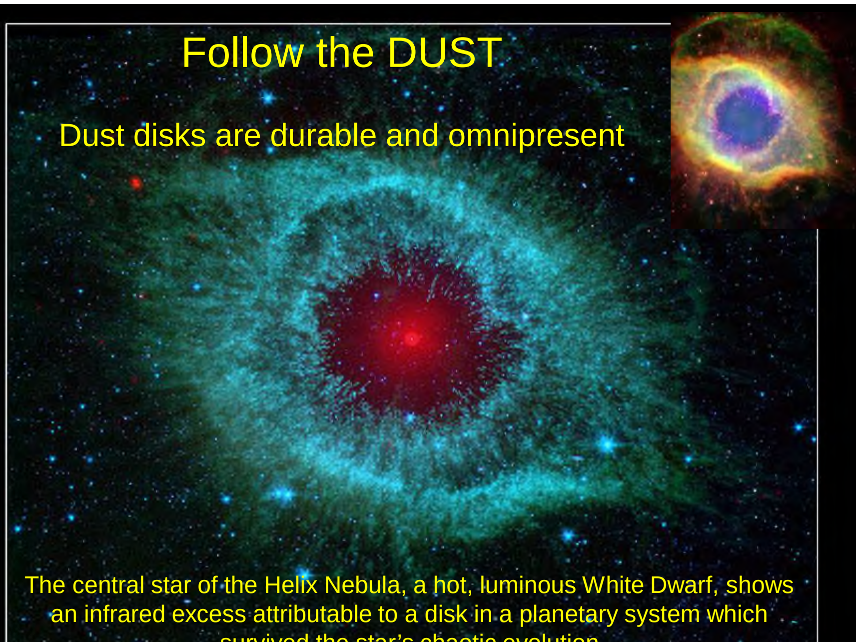


Known
- **340,000 minor planets**
- **~4500 NEOs**
- **~850 Potentially Hazardous Objects (PHOs)**

Scott Manley

Armagh Observatory

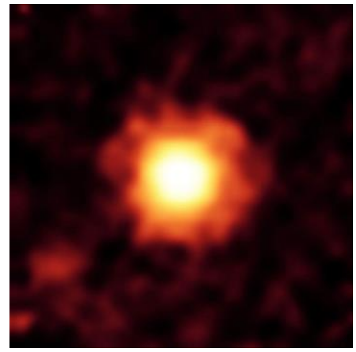
Landis, "Piloted Flight to a Near-Earth Object", AIAA Conference 19 Sep 07



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

Planetary System Formation effects Dust

This star has 3 large (10X Jupiter mass) planets (observed by Hubble, Keck & Gemini North) which are causing a huge halo of fine dust particles (indicating lots of colliding objects) around the star. Dust which can be detected by an infrared telescope.

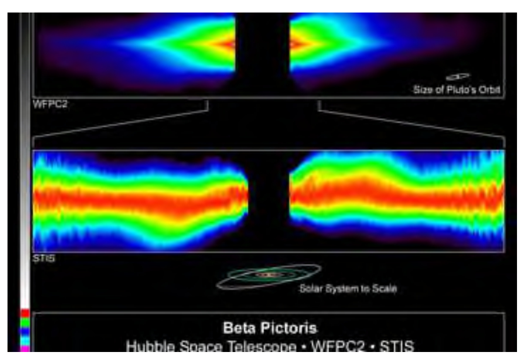


NASA's Spitzer Space Telescope captured this infrared image of a giant halo of very fine dust around the young star HR 8799, located 129 light-years away in the constellation Pegasus. The brightest parts of this dust cloud (yellow-white) likely come from the outer cold disk similar to our own Kuiper belt (beyond Neptune's orbit). The huge extended dust halo is seen as orange-red. Credit: NASA/JPL-Caltech/Univ. of Ariz.

Astrophysical Journal, Nov 2009

Planetary System Formation effects Dust

'Kinks' in the debris disk around Beta Pictoris was caused by the formation and subsequent migration of a Jupiter-sized planet called Beta Pictoris b.

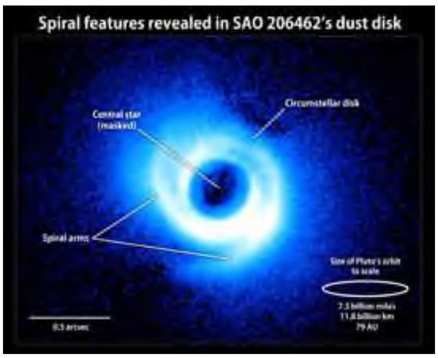


The planet orbiting Beta Pictoris has caused a kink in the debris disk surrounding the star, as seen in this false-color image from the Hubble Space Telescope. CREDIT: Sally Heap (GSFC/NASA)/ Al Schultz (CSC/STScI, and NASA)

Nola Taylor Redd, SPACE.com; 08 December 2011

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

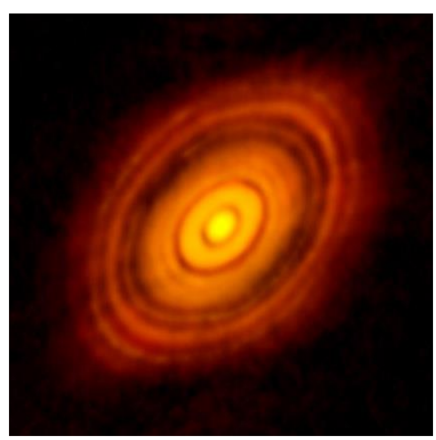
Direct Imaging of Planet Formation

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.

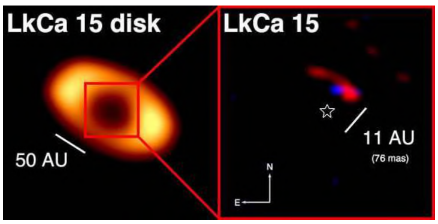
HL Tau is hidden in visible light behind a massive envelope of dust and gas. ALMA wavelength sees through dust.



ALMA image of the young star HL Tau and its protoplanetarydisk. 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)

Direct Image of an ExoPlanet being Formed

Image shows the youngest exoplanet yet discovered. Its Star (slightly smaller than our Sun) is only 2 million years old. Dust is accreting (falling) into the new planet leaving a gap in the planetary disk. New planet is ~ 6X mass of Jupiter.



Using the Keck Telescope

Left: The dusty disk around the star LkCa 15. All of the light at this wavelength is emitted by cold dust in the disk; the hole in the center indicates an inner gap.

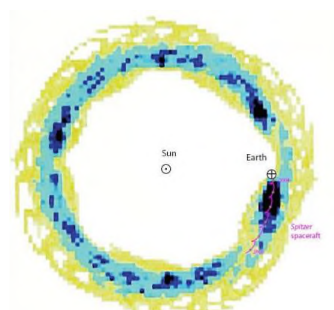
Right: An expanded view of the central part of the cleared region, showing a composite of two reconstructed images (blue: 2.1 microns; red: 3.7 microns) for LkCa 15 b. The location of the central star is also marked.

CREDIT: Kraus & Ireland 2011
SPACE.com; 19 October 2011

Planets and Dust

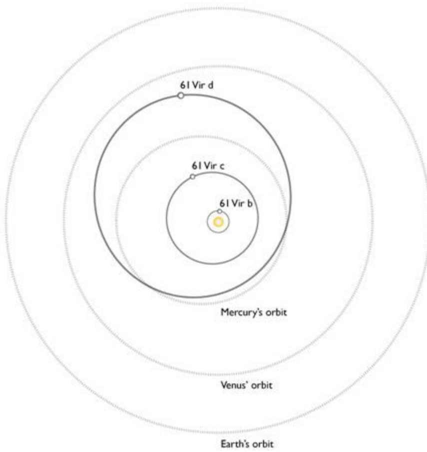
Earth has a 'tail' of dust particles.

10 to 20 micrometer size particles are slowed or captured by Earth's gravity and trail behind Earth. The cloud of particles is about 10 million km wide and 40 million km long.



(Wired.com, Lisa Grossman, 8 July 2010)

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.

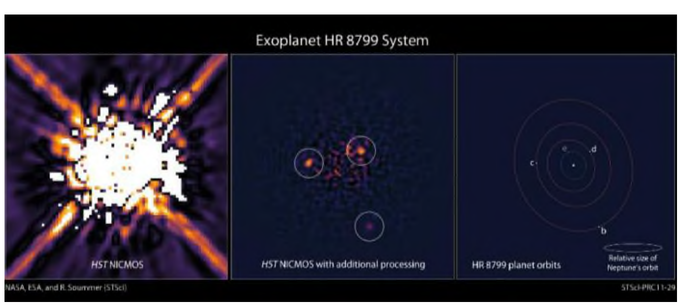
Bad Astronomy
Orbital schematic credit: Chris Tinney

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.

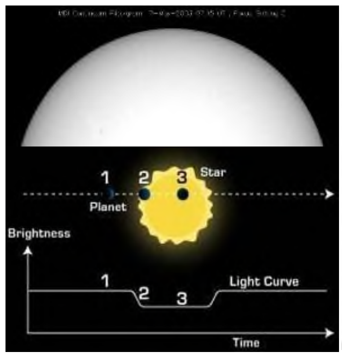


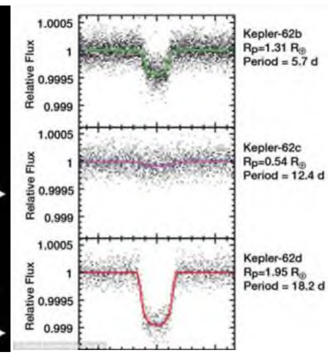
Denise Chow, SPACE.com; 06 October 2011

Transit Method Finds Planets

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

As of Dec 2011, Kepler found 2326 planets

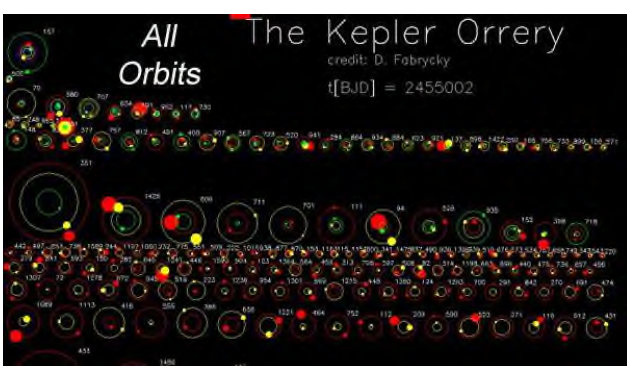




Kepler Planetary Systems – Dec 11

Of the 2326 planets which Kepler discovered:

- > 800 in single planet systems,
- > 400 in 170 systems with 2 to 6 transiting planets, and
- 207 potential Earth size; 680 super-Earth size; 48 in Habitable Zone



Graphic shows multiple-planet systems as of 2/2/2011. Hot colors to cool colors (red to yellow to green to cyan to blue to gray) indicate big planets to smaller planets. CREDIT: Daniel Fabrycky (SPACE.com, 23 May 2011)

Kepler's planet candidates by size. CREDIT: NASA/Wendy Stenzel (SPACE.com 2 Feb 2011)

Kepler Update – Jan 2013

Kepler has discovered 461 new potential planets, boosting total to 2,740 including 4 slightly larger than Earth in Habitable Zone.

114 are confirmed; > 2500 are probable; 350 are Earth Size

467 stars have more than 1 planet

Mike Wall, SPACE.com Senior Writer; 07 January 2013

Kepler Pipeline results – Nov 2013

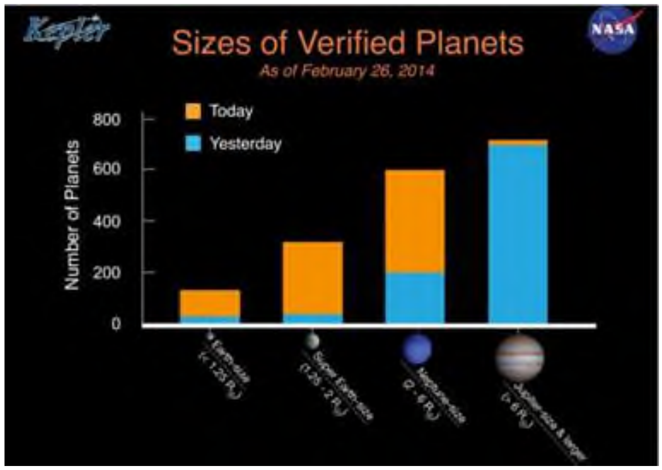
Summary

- 3,553 candidates associated with 2,658 stars discovered from analysis of 34 months of data.
- > 600 are earth-size or smaller
- 104 candidates are in the HZ; 24 are smaller than 2 R_e
- 22% of stars have more than one candidate
- Flat radius distribution within 3 R_e
- 17% of main sequence stars have an earth-size planet within P = 85 days
- At least 70% of main sequence stars have a planet within P = 400 days
- **~ 50% of M dwarfs harbor a planet smaller than 2 Re in the HZ**
- 170 confirmed/characterized planets, including many rocky planets.

Batalha, Kepler Conference Nov 2013

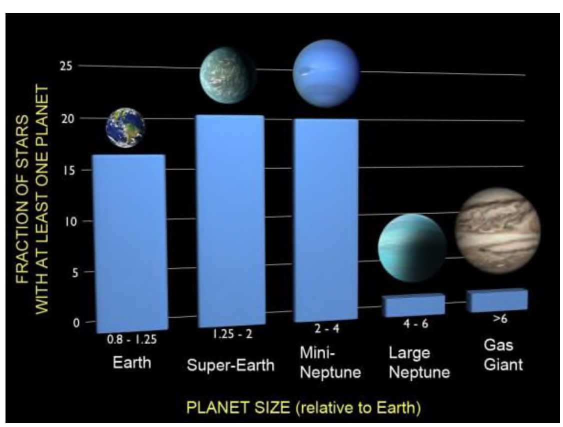
Kepler Update – 26 Feb 2014

NASA announced 715 new confirmed planets, increasing the total to over 1000.



Elizabeth Howell, Universe Today; 26 Feb 2014

Nearly All Stars have Planets



Our galaxy has 100B stars, so could be 17B Earth size planets.

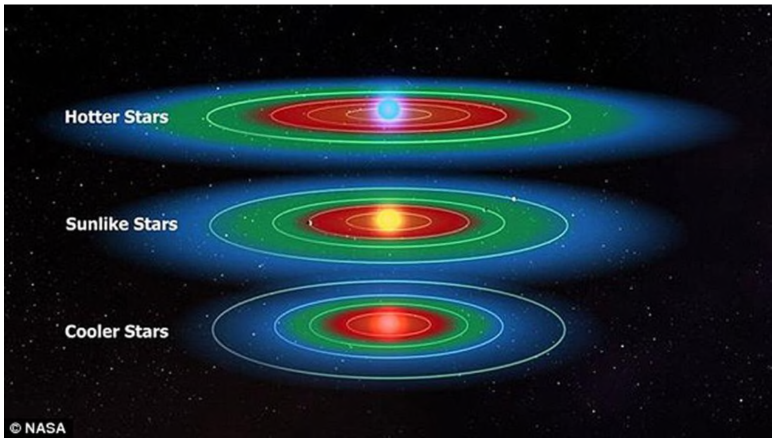
But only a few will be in Habitable Zone

Also, need a moon.

Nancy Atkinson; Universe Today; January 7, 2013

Habitable Zone

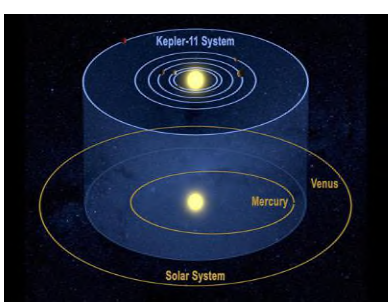
Life requires water. Liquid water can only exist in the 'Goldilocks'' Zone. The hotter the star, the further away the zone.



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

Kepler Mission

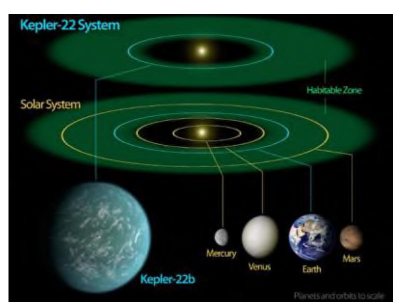
Kepler-11has a star like ours & 6 mini-Neptune size planets



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.)

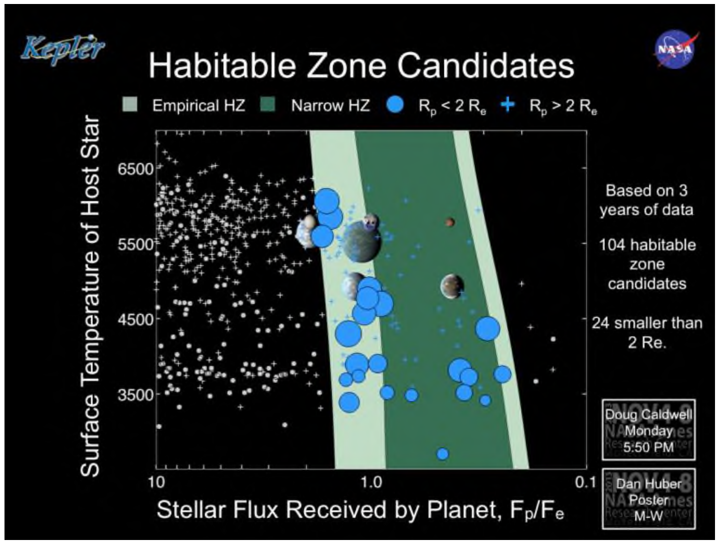
Kepler 22b is the first in the habitable zone.



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

> 100 Habitable Zone Planet Candidates
> 24 smaller than 2 Earth Radii



Batalha, Kepler Conference Nov 2013

All Stars may have 1 to 3 HZ Planets

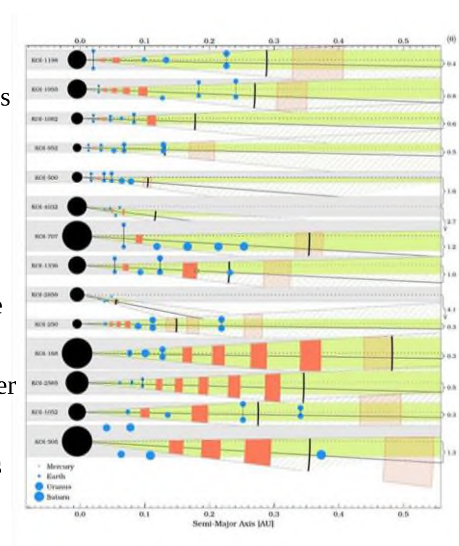
Titius-Bode law (used to predict Uranus) states that ratio between the orbital period of the first and second planet is the same as the ratio between the second and the third planet and so on.

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

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

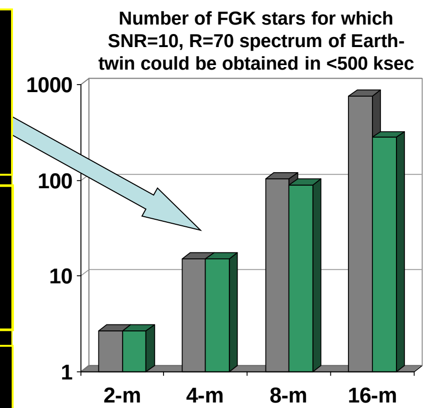
$\eta_{Earth} \times f_B < 1$ then $D_{Tel} \sim$ 8m

$\eta_{Earth} \times f_B << 1$ 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)

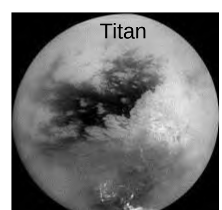
Thus, an 8-m telescope might find 1 to 3 Earth twins and an 16-m telescope might find 10 to 20 Earth twins.



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

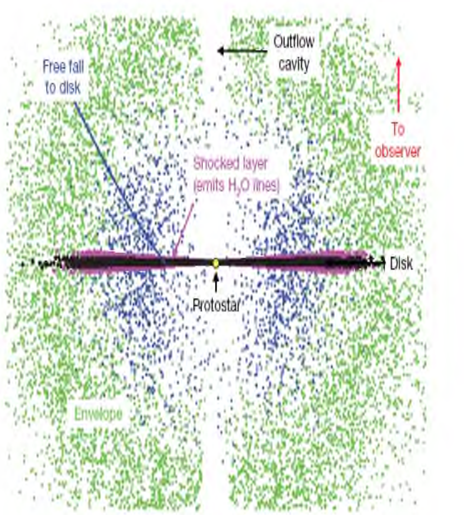
Role of giant planets?

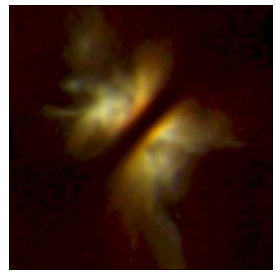
JWST Observations:

Comets, Kuiper Belt Objects

Icy moons in outer solar system

Spitzer Spectrum Shows Water Vapor Falling onto Protoplanetary Disk





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

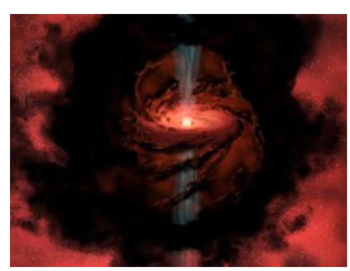
Proto-Stars produce Water

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.

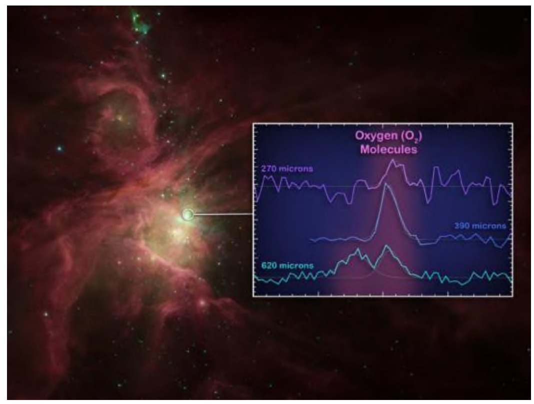
Mike Wall, SPACE.com; Date: 20 October 2011

Molecular Oxygen discovered in space

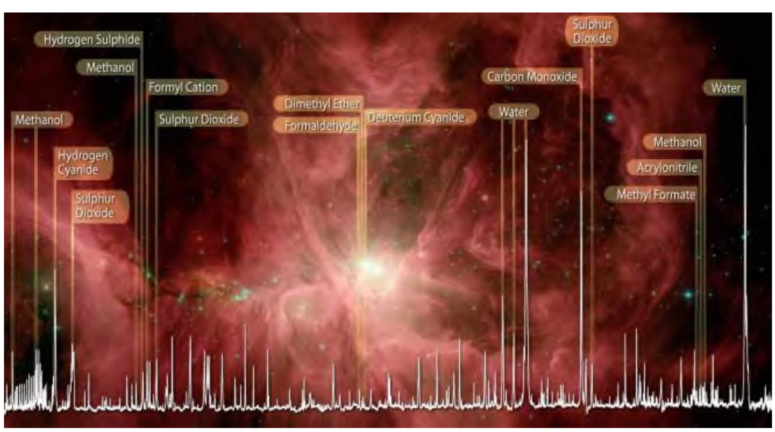
Herschel found molecular oxygen in a dense patch of gas and dust adjacent to star-forming regions in the Orion nebula.

The oxygen maybe water ice that coats tiny dust grains.

SPACE.com, 01 August 2011



All of Life's Ingredients Found in Orion Nebula



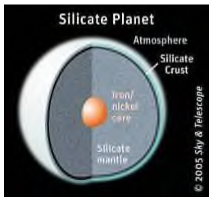
Herschel Telescope has measured spectra for all the ingredients for life as we know them in the Orion Nebula.

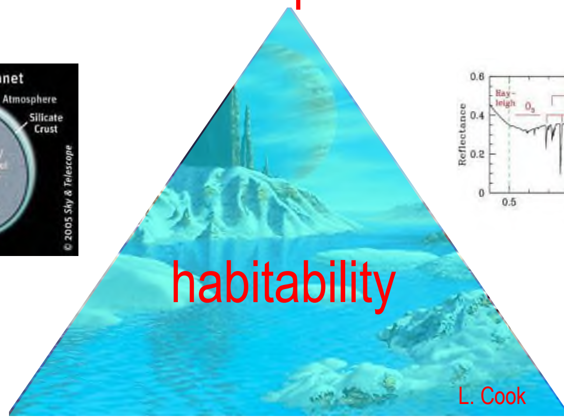
(Methanol is a particularly important molecule)

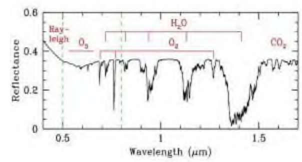
Wired.com Mar 2010

Search for Habitable Planets

atmosphere







interior

surface

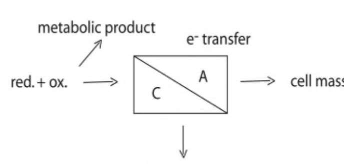
Sara Seager (2006)

Search for Life

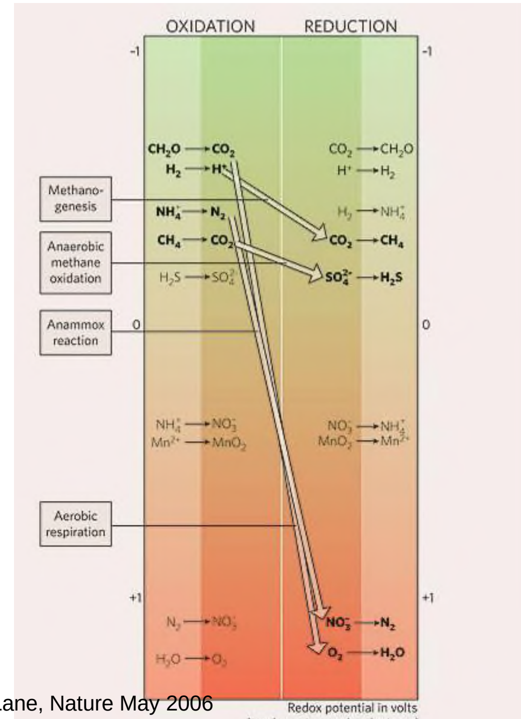
What is life?

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

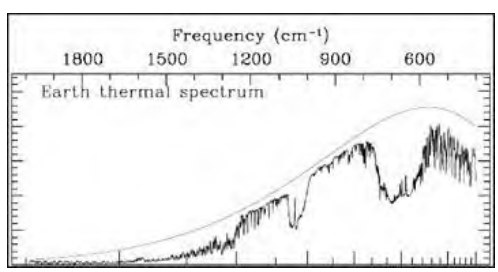
Diversity of metabolisms rivals diversity of exoplanets

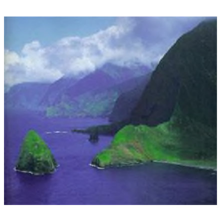
Sara Seager (2006)

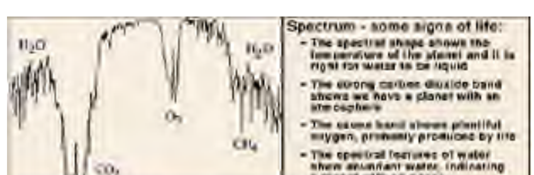
Bio Markers

Spectroscopic Indicators of Life

Absorption Lines
- CO2
- Ozone
- Water
- “Red” Edge

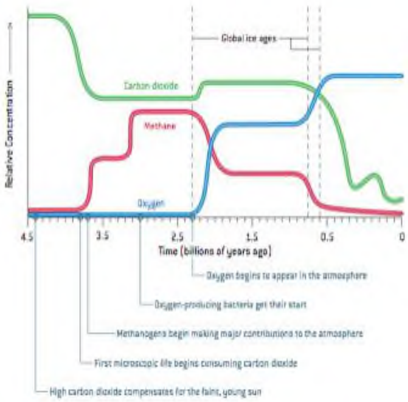




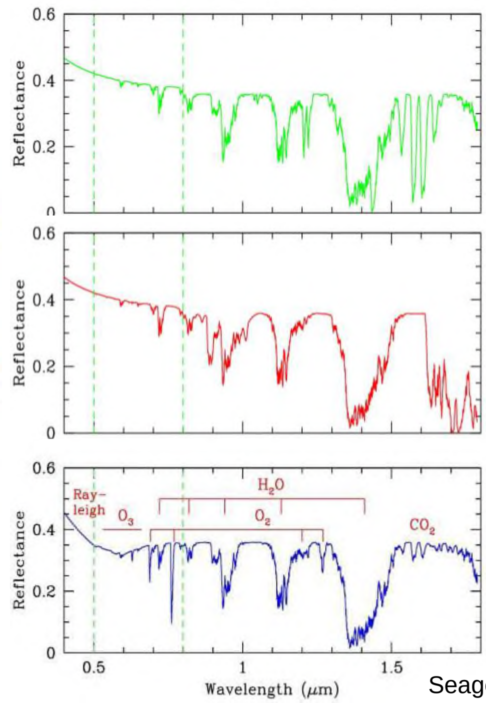


Example signs of life from chemical spectra.
Credit: NASA JPL

Earth Through Time



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



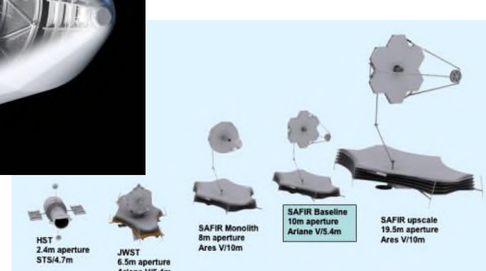
Seager

Beyond JWST

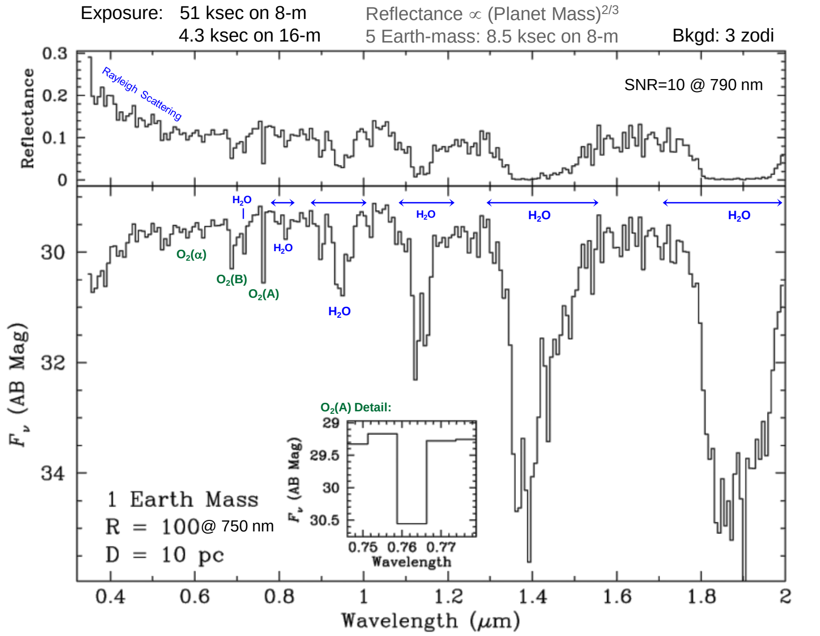
Heavy Lift Launch Vehicle enables even larger telescopes

8-m UV/Optical Telescope or

24-m Far-IR Telescope

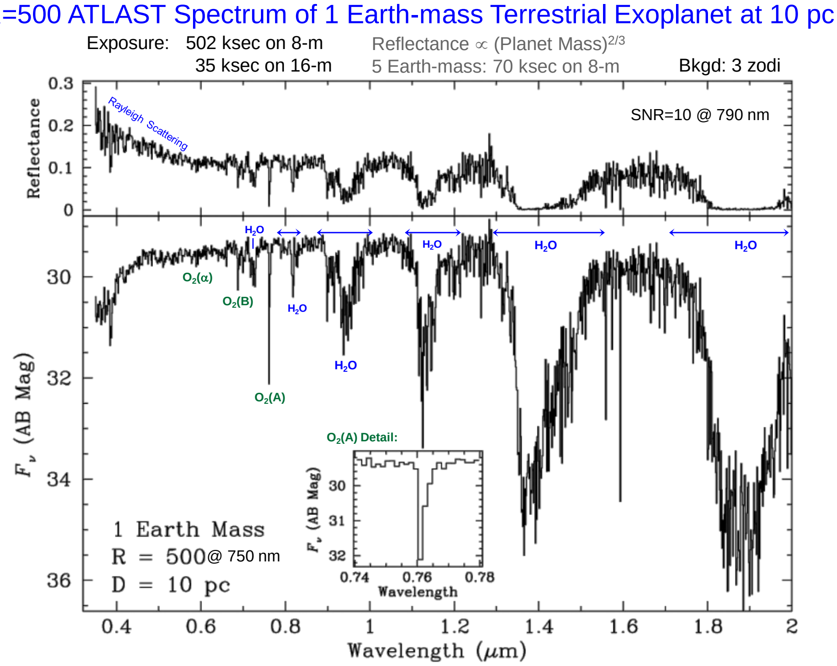


R=100 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc



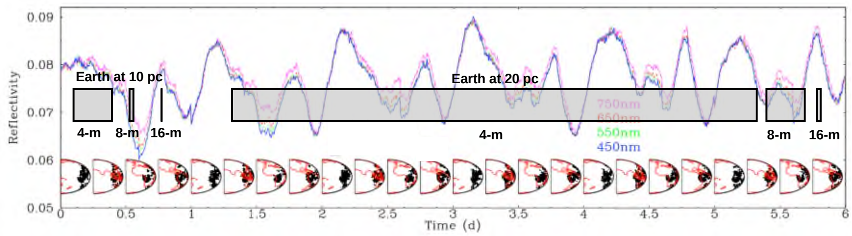
Marc Postman, "ATLAST", Barcelona, 2009

R=500 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc



Marc Postman, "ATLAST", Barcelona, 2009

Detecting Photometric Variability in Exoplanets

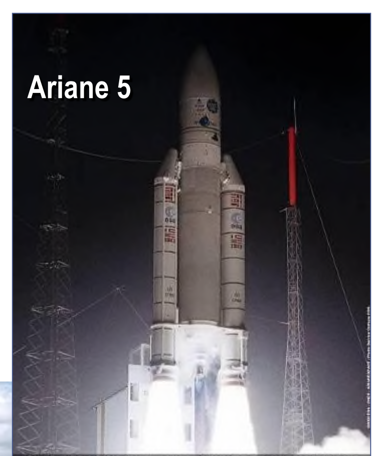


Marc Postman, "ATLAST", Barcelona, 2009

Countdown to Launch

JWST is

- making excellent technical progress
- will be ready for launch late 2018
- 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.