the James Webb SPACE TELESCOPE THE FIRST LIGHT MACHINE

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Presentation by

Dr. H. Philip Stahl

Tuesday, March 12th

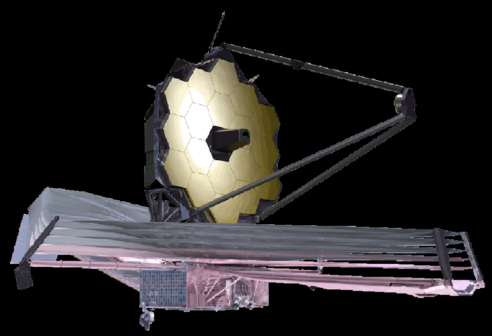
8:00 pm

1200 EECS Bldg,
U of M, North Campus

Scheduled to begin its 10 year mission after 2018, the James Webb Space Telescope (JWST) will search for the first luminous objects of the Universe to help answer fundamental questions about how the Universe came to look like it does today. At 6.5 meters in diameter, JWST will be the world's largest space telescope. This talk reviews science objectives for JWST and how they drive the JWST architecture, e.g. aperture, wavelength range and operating temperature. Additionally, the talk provides an overview of the JWST primary mirror technology development and fabrication status.

A²OSA
Ann Arbor Section of the Optical Society of America

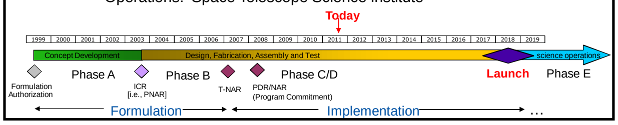
James Webb Space Telescope (JWST)



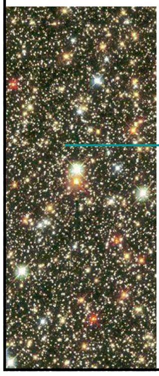
The First Light Machine

JWST Summary

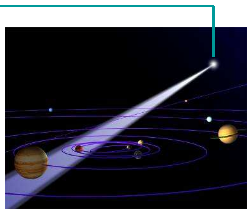
- **Mission Objective**
  - Study origin & evolution of galaxies, stars & planetary systems
  - Optimized for near infrared wavelength (0.6 –28 μm)
  - 5 year Mission Life (10 year Goal)
- **Organization**
  - Mission Lead: Goddard Space Flight Center
  - International collaboration with ESA & CSA
  - 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



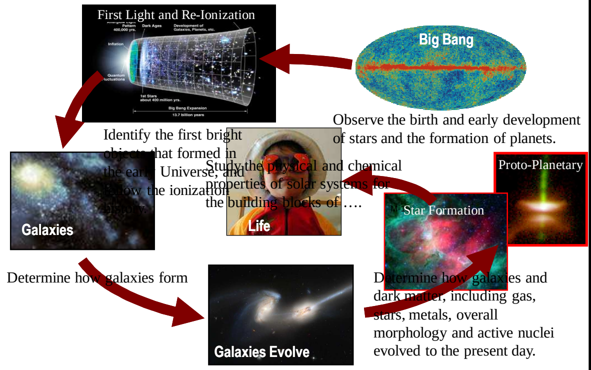
Origins Theme's ***Two*** Fundamental Questions



- 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

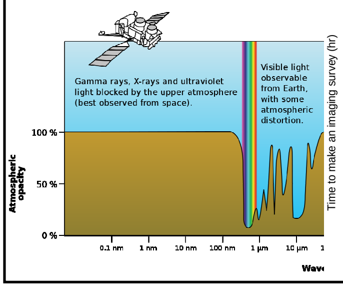
It is an Infrared Telescope

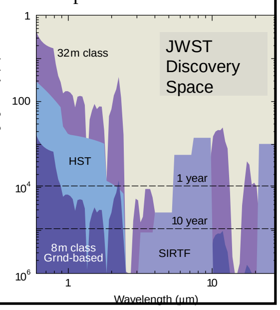
It has a Large Aperture

Why go to Space

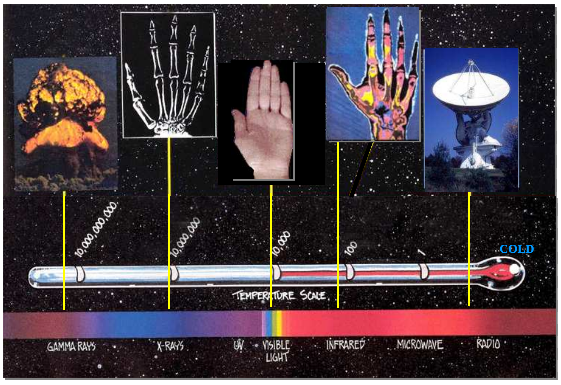
Atmospheric Transmission drives the need to go to space.

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





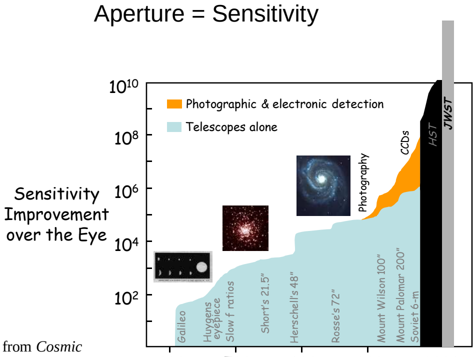
Infrared Light



Why Infrared ?

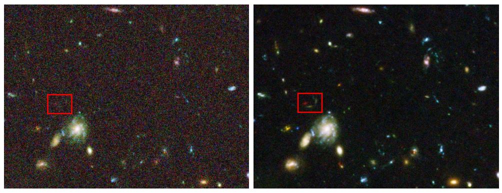
Why do we need Large Apertures?

Aperture = Sensitivity

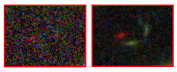


Adapted from *Cosmic Discovery*, M. Harwit

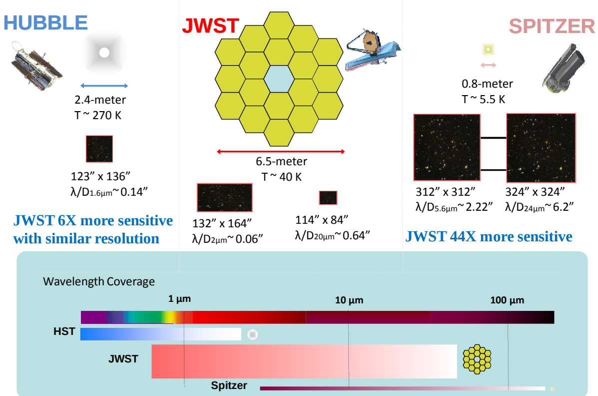
Sensitivity Matters



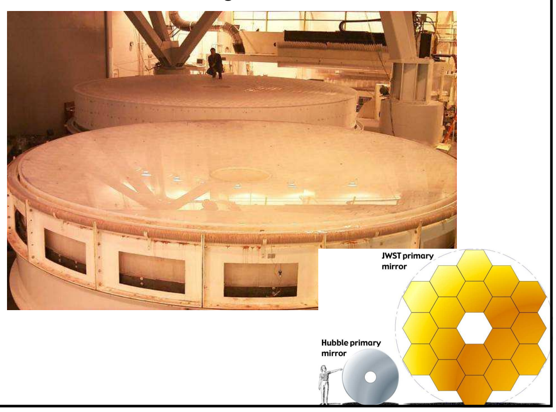
GOODS CDFS – 13 orbits HUDF – 400 orbits



JWST will be more Sensitive than Hubble or Spitzer



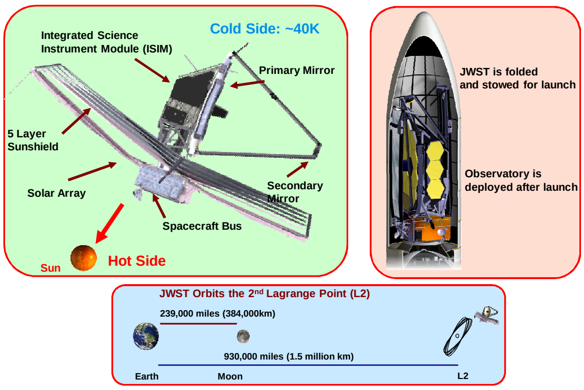
How big is JWST?



Full Scale JWST Mockup

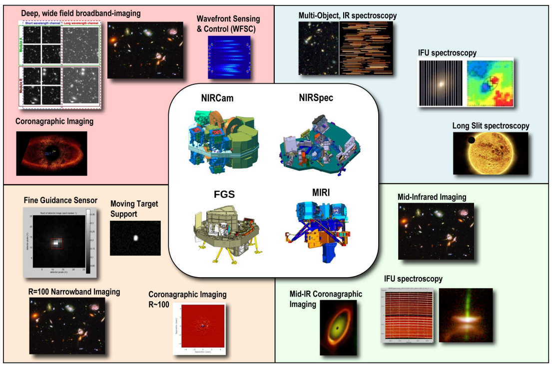
21st National Space Symposium, Colorado Springs, The Space Foundation

How JWST Works



JWST Science Instruments

enable imagery and spectroscopy over the 0.6 – 29 micron spectrum

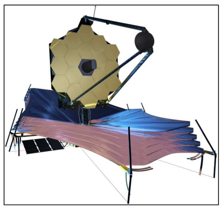


JWST Requirements

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

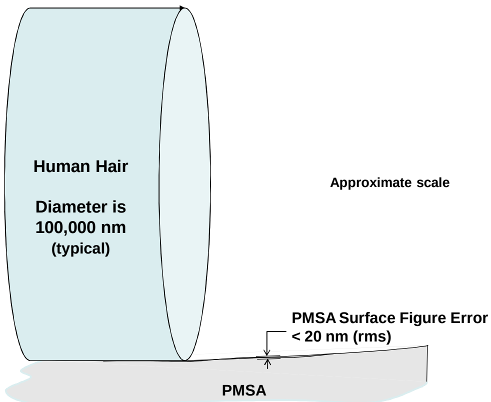
Primary Mirror
- 6.6 meter diameter (tip to tip)
- < 25 kg/m^2 Areal Density
- < $6 M/m^2 Areal Cost
- 18 Hex Segments in 2 Rings
- Drop Leaf Wing Deployment

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

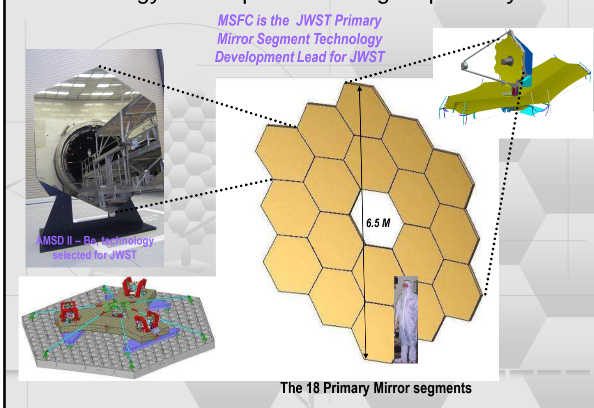


Low (0-5 cycles/aper)	4 nm rms
CSF (5-35 cycles/aper)	18 nm rms
Mid (35-65K cycles/aper)	7 nm rms
Micro-roughness	<4 nm rms

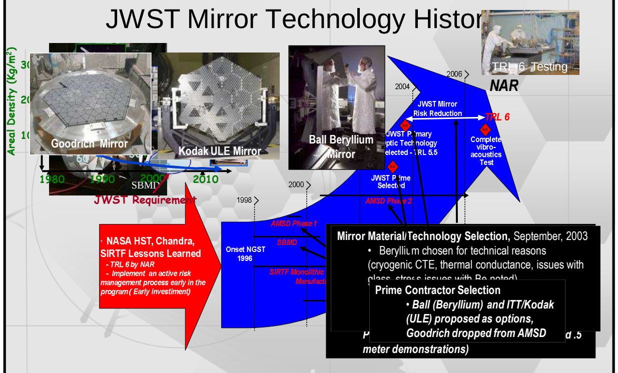
Fun Fact – Mirror Surface Tolerance



Technology Development of Large Optical Systems



JWST Mirror Technology History



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

Advantages of Beryllium

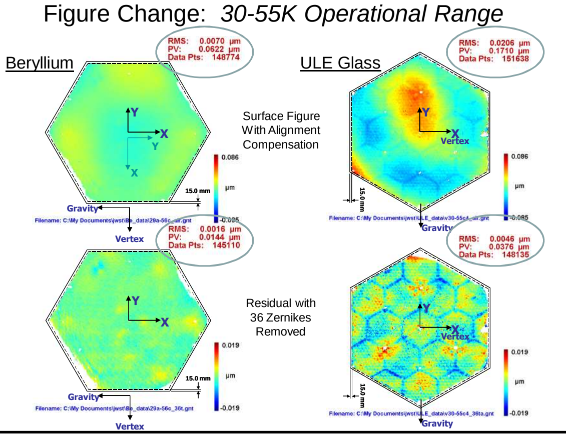
Very High Specific Stiffness – Modulus/Mass Ratio

Saves Mass – Saves Money

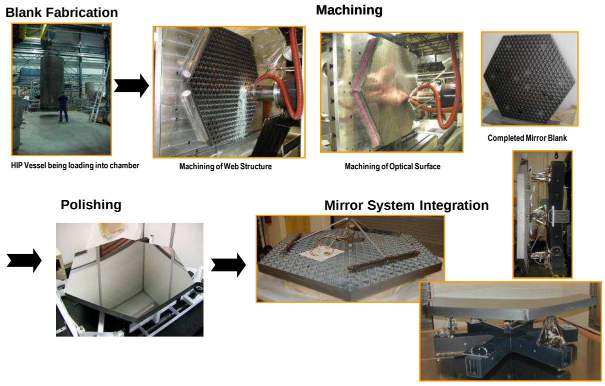
High Conductivity & Below 100K, CTE is virtually zero.

Thermal Stability

Figure Change: *30-55K Operational Range*



Mirror Manufacturing Process



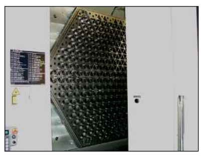
Brush Wellman

Axsys Technologies

Batch #1 (Pathfinder) PM Segments

PMSA #1 (EDU-A / A1)

PMSA #2 (3 / B1)



PMSA #3 (4 / C1)

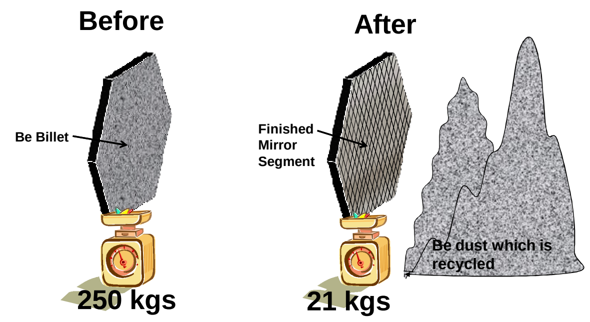
Batch #2 PM Segments

PMSA #4 (5 / A2)

PMSA #5 (6 / B2)

PMSA #6 (7 / C2)

Fun Facts – Mirror Manufacturing

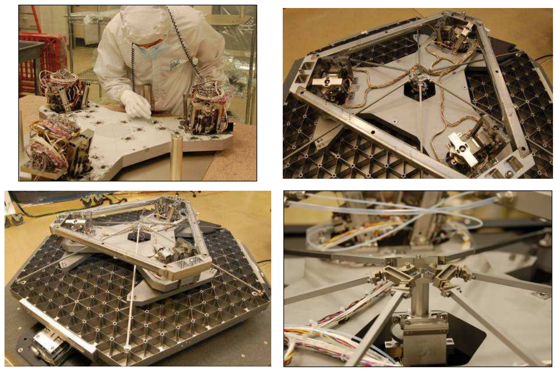


Over **90%** of material is removed to make each mirror segment – want a little mirror with your Be dust?

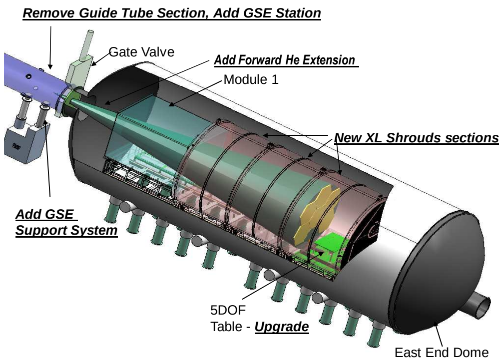
Mirror Processing at Tinsley

Tinsley Laboratory – Final Shipment

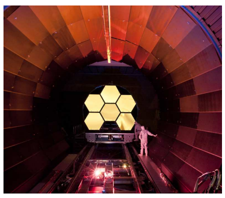
Primary Mirror Segment Assembly at BATC

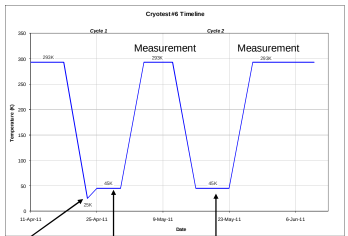


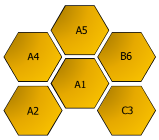
MSFC Cryogenic Test Facility



XRCF Cryo Test





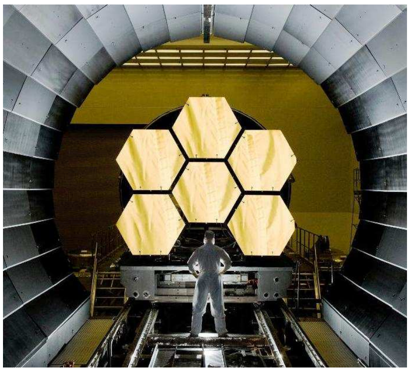


- Survival Temperature

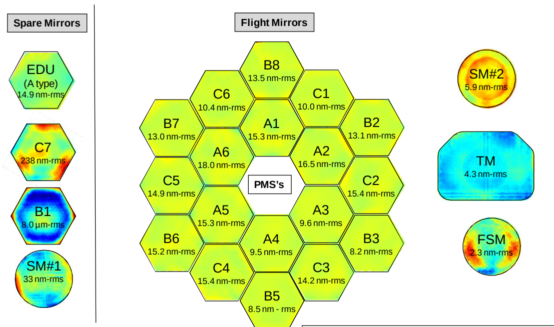
- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Envelope Test
- Pullout Current & Redundant Test (3 of 6 PMSAs)

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

Flight Mirrors in XRCF

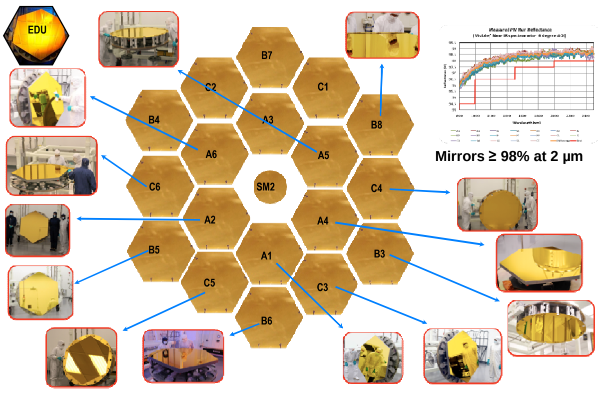


Mirror Fabrication Status at L-3 SSG-Tinsley – July 11 ALL DONE & DELIVERED



SURFACE FIGURE ERROR
Total PM Composite: 13.5 nm RMS
Telescope PM Target: 21.2 nm RMS

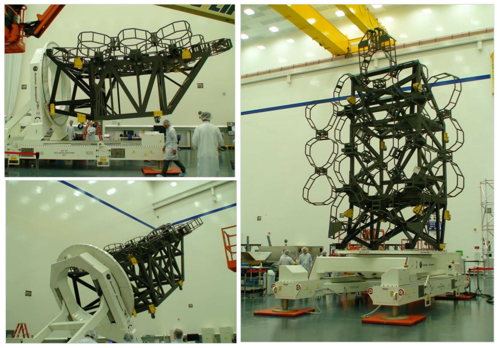
Gold Coated Mirror Assemblies



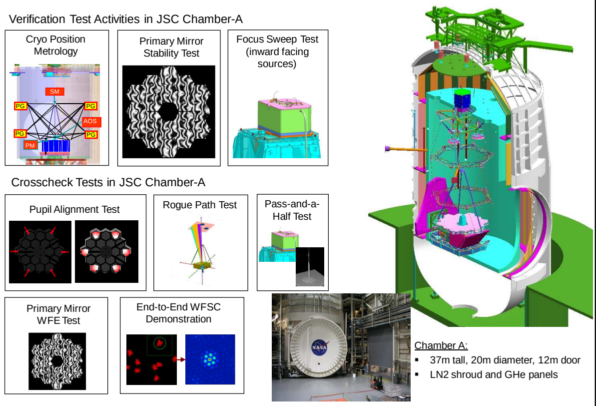
Primary Mirror Backplane

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

Flight Backplane under construction

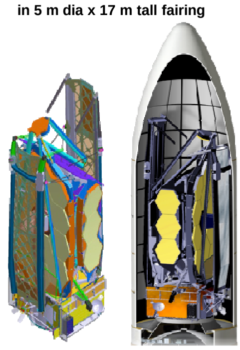


Observatory level testing occurs at JSC Chamber A

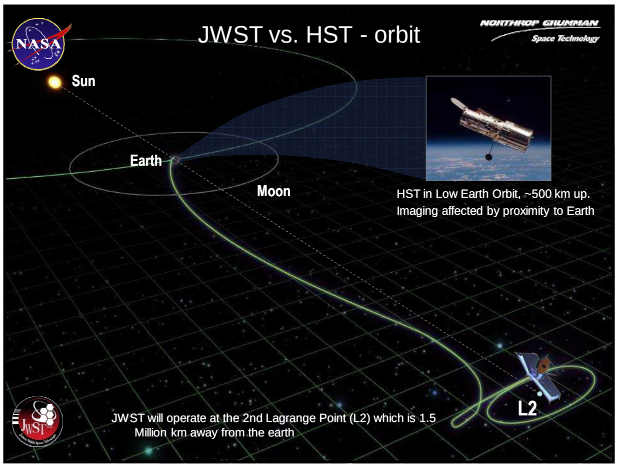


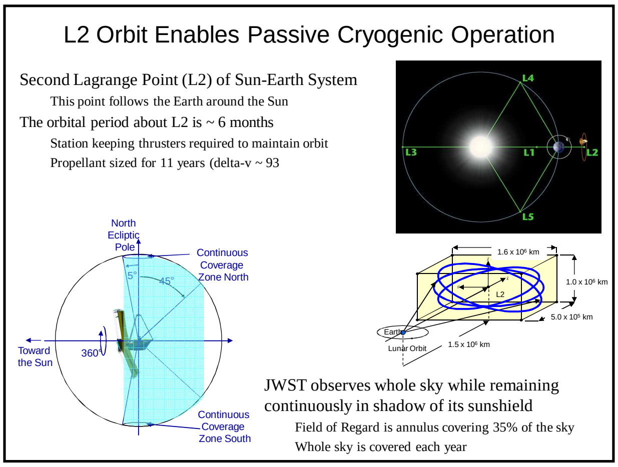
JWST Launched on Ariane 5 Heavy

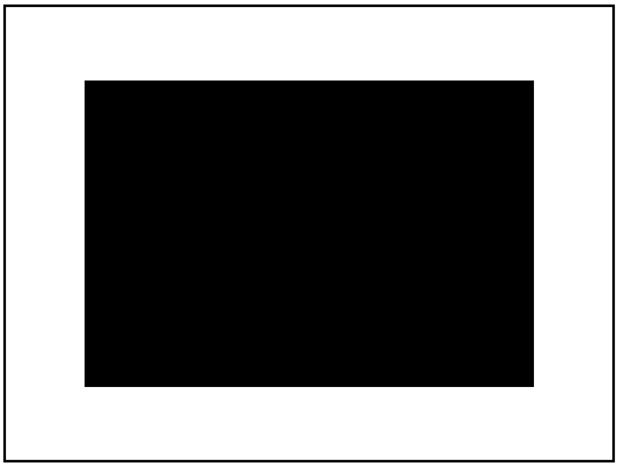
JWST folded and stowed for launch in 5 m dia x 17 m tall fairing

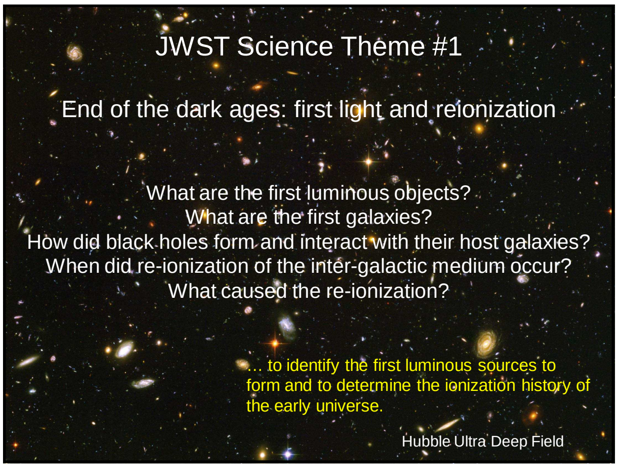


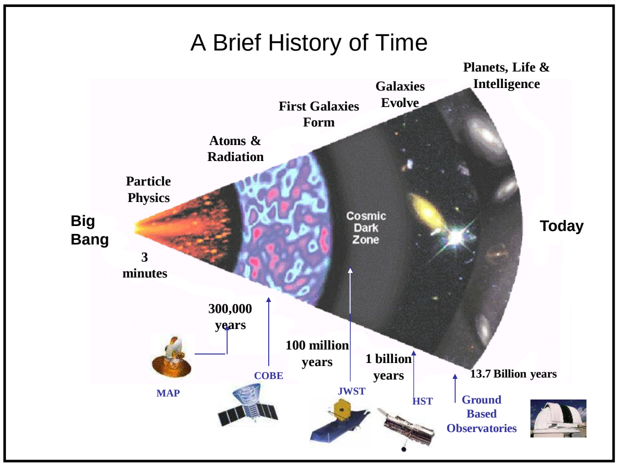
Launch from Kourou Launch Center (French Guiana) to L2

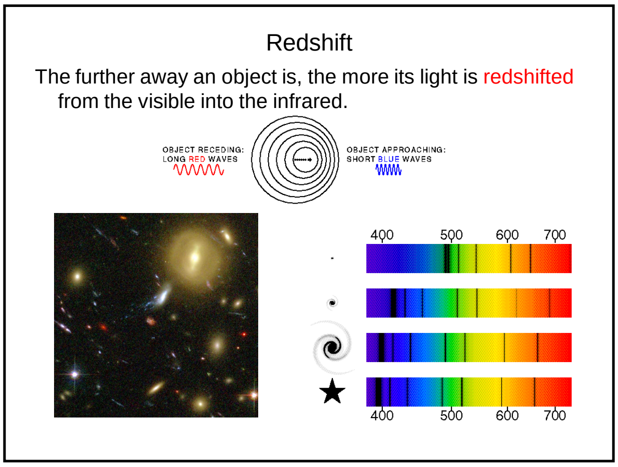

JWST vs. HST - orbit
NORTHROP GRUMMAN
Space Technology
Sun
Earth
Moon
HST in Low Earth Orbit, ~500 km up.
Imaging affected by proximity to Earth
L2
JWST will operate at the 2nd Lagrange Point (L2) which is 1.5
Million km away from the earth


L2 Orbit Enables Passive Cryogenic Operation
Second Lagrange Point (L2) of Sun-Earth System
This point follows the Earth around the Sun
The orbital period about L2 is ~ 6 months
Station keeping thrusters required to maintain orbit
Propellant sized for 11 years (delta-v ~ 93
L4
L3
L1
L2
L5
North
Ecliptic
Pole
Continuous
Coverage
Zone North
5°
45°
Toward
the Sun
360°
Continuous
Coverage
Zone South
Earth
Lunar Orbit
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 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
Planets, Life &
Intelligence
Galaxies
Evolve
First Galaxies
Form
Atoms &
Radiation
Particle
Physics
Big
Bang
3
minutes
Cosmic
Dark
Zone
Today
300,000
years
100 million
years
1 billion
years
13.7 Billion years
COBE
MAP
JWST
HST
Ground
Based
Observatories


Redshift
The further away an object is, the more its light is redshifted
from the visible into the infrared.
OBJECT RECEDING:
LONG RED WAVES
OBJECT APPROACHING:
SHORT BLUE WAVES
400
500
600
700
400
500
600
700

When and how did reionization occur?

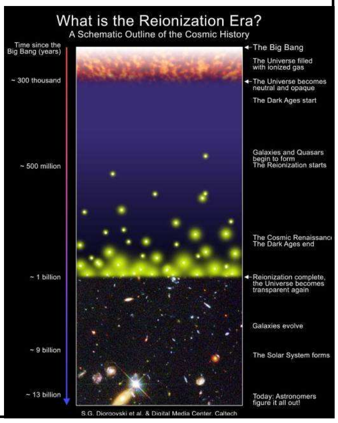
Re-ionization happened at z > 6 or < 1 B yrs after Big Bang.

WMAP says maybe twice?

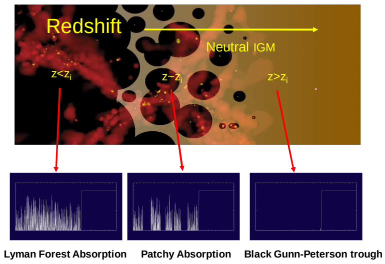
Probably galaxies, maybe quasar contribution

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

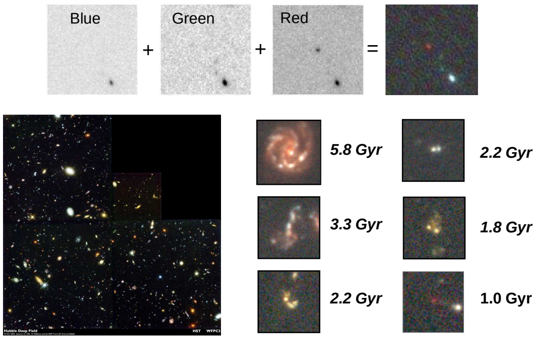


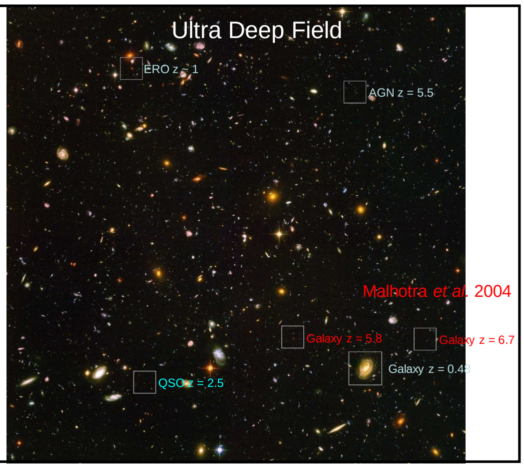
At 780 M yrs after Big Bang the Universe was up to 50% Neutral. But, by 1 B years after BB is was as we see it today.

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

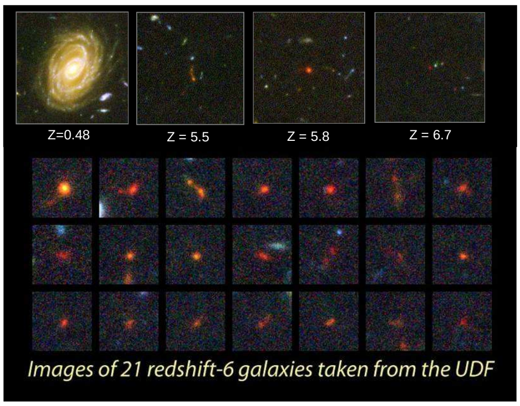
SPACE.com, 12 October 2011

How do we see first light objects?

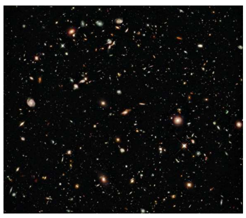




Results from UDF

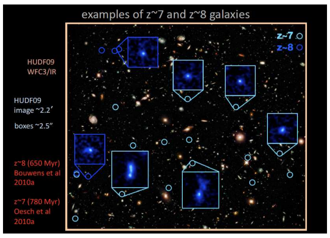


Hubble Ultra Deep Field – Near Infrared



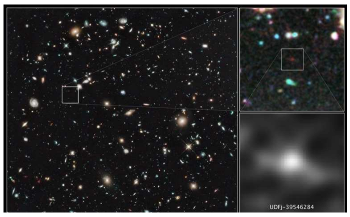
Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

Hubble Ultra Deep Field – Near Infrared

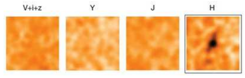


47 Galaxies have been observed at 600 to 650 Myrs after BB.

Hubble Ultra Deep Field – Near Infrared

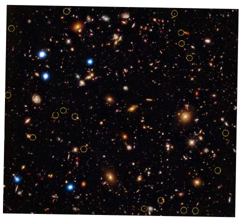


At 480 M yrs after big bang (z ~ 10) this is oldest observed galaxy. Discovered using drop-out technique.



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

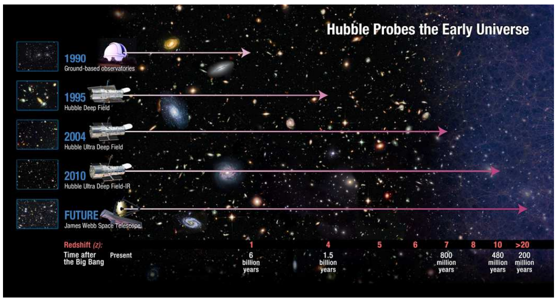
What came first – Galaxies or Black Holes?

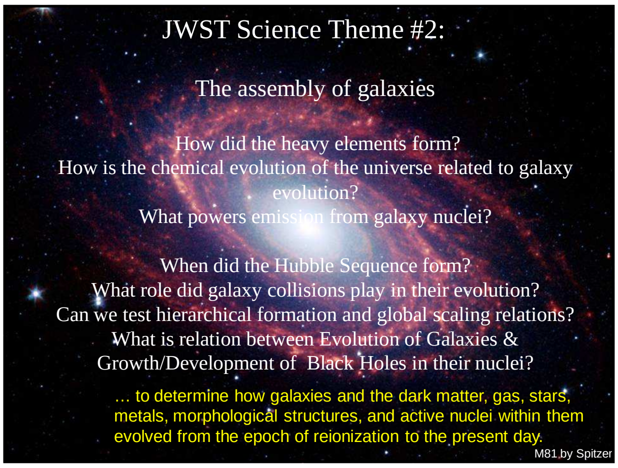
Each of these ancient 700 M yrs after BB galaxies has a black hole.

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

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?

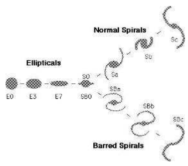
When did the Hubble Sequence form?
What role did galaxy collisions play in their evolution?
Can we test hierarchical formation and global scaling relations?
What is relation between Evolution of Galaxies & Growth/Development of Black Holes in their nuclei?

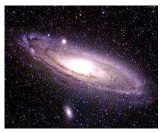
… to determine how galaxies and the dark matter, gas, stars, metals, morphological structures, and active nuclei within them evolved from the epoch of reionization to the present day.

M81 by Spitzer

The Hubble Sequence

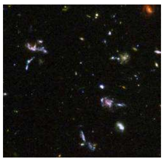
Hubble classified nearby (present-day) galaxies into Spirals and Ellipticals.

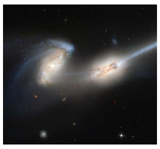


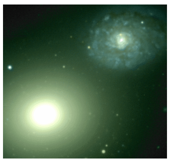


The Hubble Space Telescope has extended this to the distant past.

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

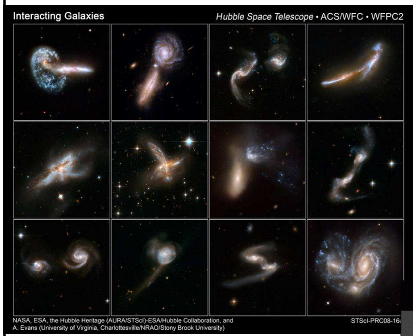


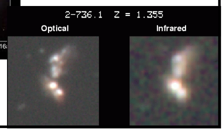




- Galaxy assembly is a process of hierarchical merging
- Components of galaxies have variety of ages & compositions
- JWST Observations:
  - Wide-area near-infrared imaging survey
  - Low and medium resolution spectra of 1000s of galaxies at high redshift
  - Targeted observations of galactic nuclei

Distant Galaxies are "Train Wrecks"



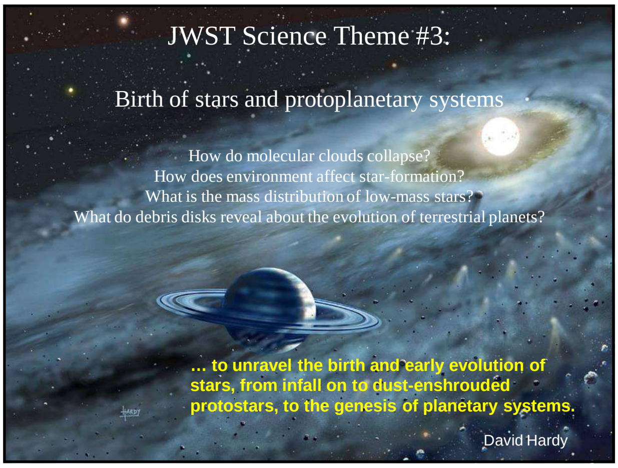


Merging Galaxies = Merging Black Holes

- 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

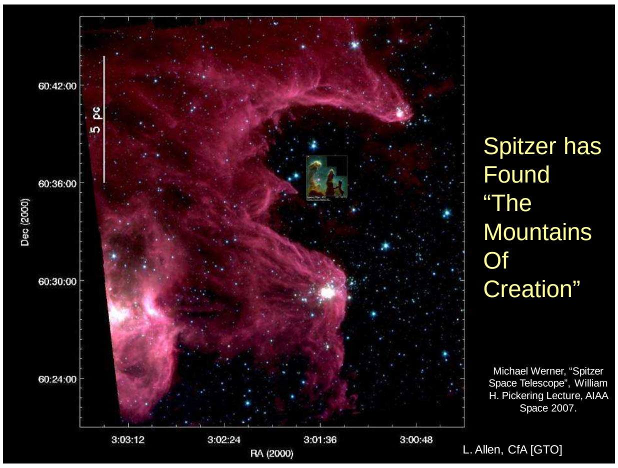
Charles Q. Choi, SPACE.com, 31 August 2011



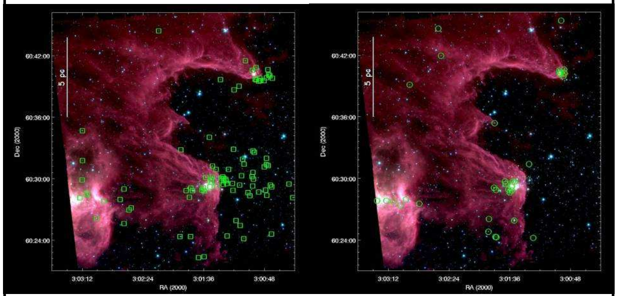
How does environment affect star-formation?

- 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



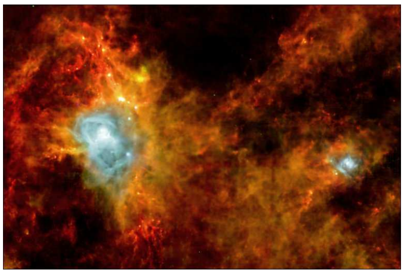
The Mountains Tell Their Tale
Interstellar erosion & star formation propagate through the cloud



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

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

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

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

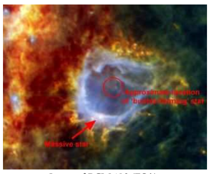
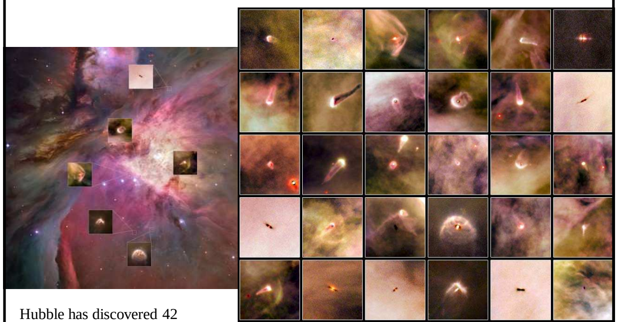


Image of RCW 120 (ESA), Discover.com, Ian O'Neill, 7 May 2010

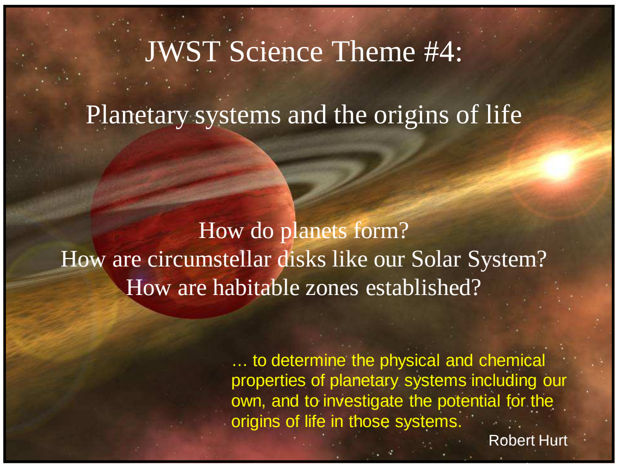
(Space.com, 6 May 2010)

Orion Nebula Protoplanetary Discs



Hubble has discovered 42 protoplanetary discs in the Orion Nebula

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



Planetary Formation Questions and 2 Models

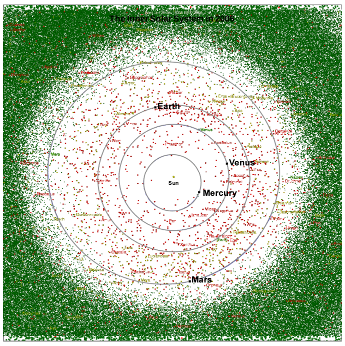
- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems)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



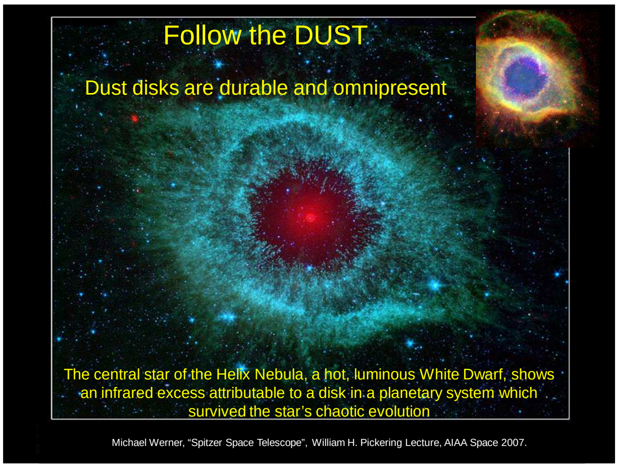
Known
- 340,000 minor planets
- ~4500 NEOs
- ~850 Potentially Hazardous Objects (PHOs)

Scott Manley
Armagh Observatory

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

Follow the DUST

Dust disks are durable and omnipresent

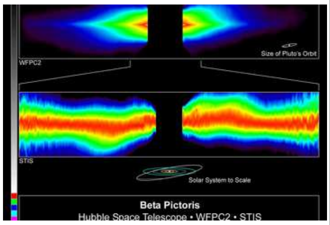


The central star of the Helix Nebula, a hot, luminous White Dwarf, shows an infrared excess attributable to a disk in a planetary system which survived the star's chaotic evolution

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

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.

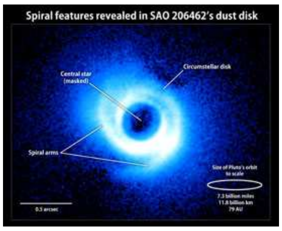


The planet orbiting Beta Pictoris has caused a kink in the debris disk surrounding the star, as seen in this false-color image from the Hubble Space Telescope. CREDIT: Sally Heap (GSFC/NASA)/ Al Schultz (CSC/STScI, and NASA)

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.

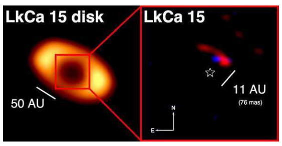


Near Infrared image from Subaru Telescope shows disk surrounding SAO 206462, a star located about 456 light-years away in the constellation Lupus. Astronomers estimate that the system is only about 9 million years old. The gas-rich disk spans some 14 billion miles, which is more than twice the size of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

Photonics Online 20 Oct 2011

Direct 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

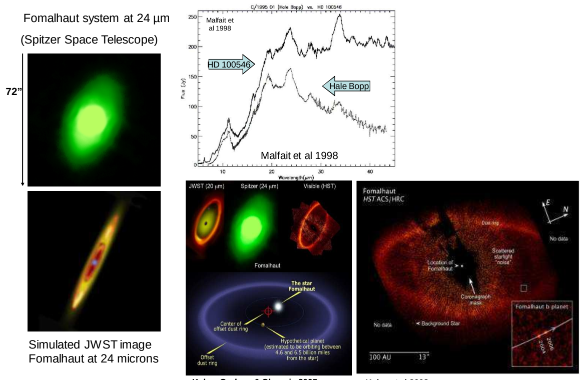
Left: The dusty disk around the star LkCa 15. All of the light at this wavelength is emitted by cold dust in the disk; the hole in the center indicates an inner gap.

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

Dust in Planetary Systems

Fomalhaut system at 24 µm
(Spitzer Space Telescope)



Simulated JWST image Fomalhaut at 24 microns

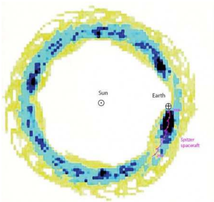
Kalas, Graham & Clampin 2005

Kalas et al 2008

Planets and Dust

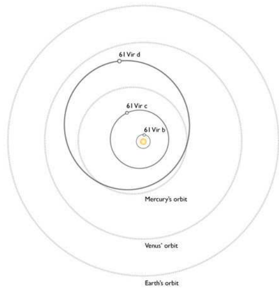
Earth has a 'tail' of dust particles.

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.

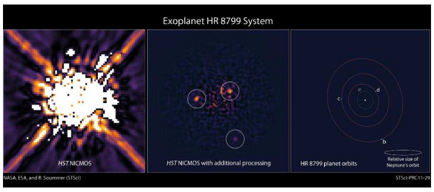
Bad Astronomy
Orbital schematic credit: Chris Tinney

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.

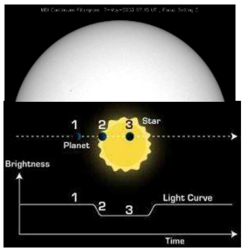


Denise Chow, SPACE.com; 06 October 2011

Transit Method Finds Planets

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

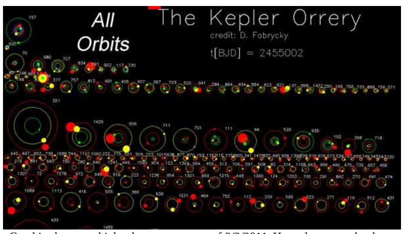
As of Dec 2011, Kepler has found 2326 planets



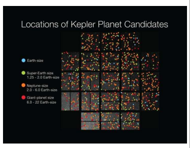
Kepler Planetary Systems

Of the 2326 planets which Kepler has discovered (Dec 11):

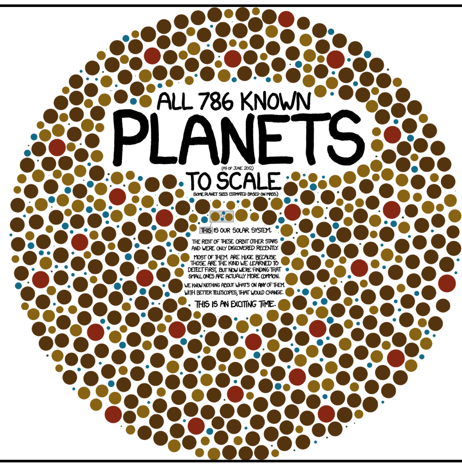
- > 800 in single planet systems,
- > 400 in 170 systems with 2 to 6 transiting planets, and
- 207 potential Earth size; 680 super-Earth size; 48 in Habitable Zone



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)

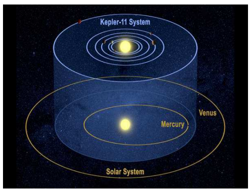


Kepler's planet candidates by size. CREDIT: NASA/Wendy Stenzel (SPACE.com 2 Feb 2011)



Kepler Mission

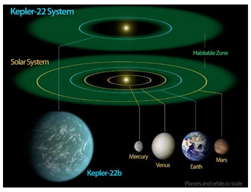
Kepler-11has a star like ours & 6 mini-Neptune size planets



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

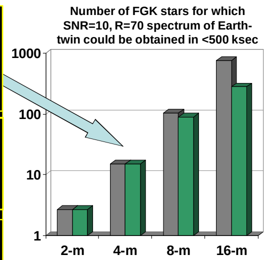
Is There Life Elsewhere in the Galaxy?

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

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

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.



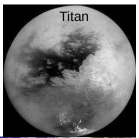
Green bars show the number of FGK stars that could be observed 3x each in a 5-year mission without exceeding 20% of total observing time available to community.

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

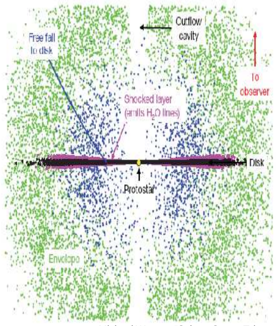
Role of giant planets?

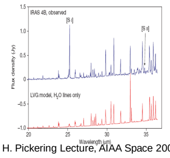
JWST Observations:

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

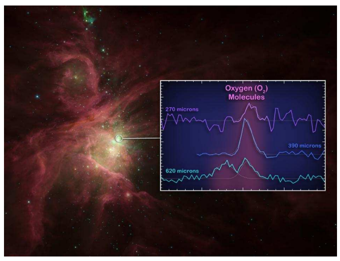
Other Herschel Data finds enough water in the outer reaches of the young star TW Hydrae (175 light-yrs from Earth) to fill Earth's oceans several thousand times over.

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

Molecular Oxygen discovered in space

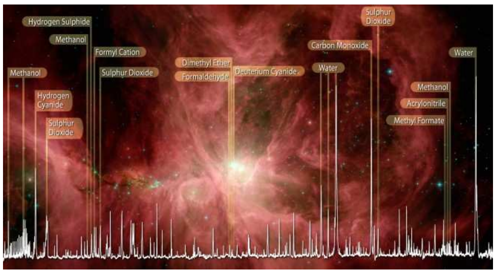
Herschel found molecular oxygen in a dense patch of gas and dust adjacent to star-forming regions in the Orion nebula.

The oxygen maybe water ice that coats tiny dust grains.



SPACE.com, 01 August 2011

All of Life's Ingredients Found in Orion Nebula



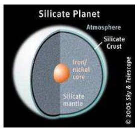
Herschel Telescope has measured spectra for all the ingredients for life as we know them in the Orion Nebula.

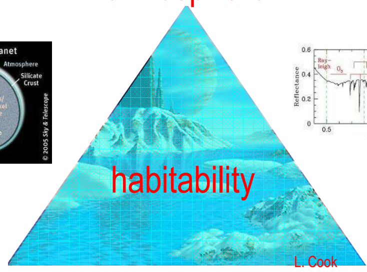
(Methanol is a particularly important molecule)

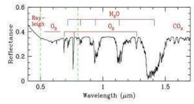
Wired.com Mar 2010

Search for Habitable Planets

atmosphere







interior

surface

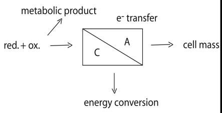
Sara Seager (2006)

Search for Life

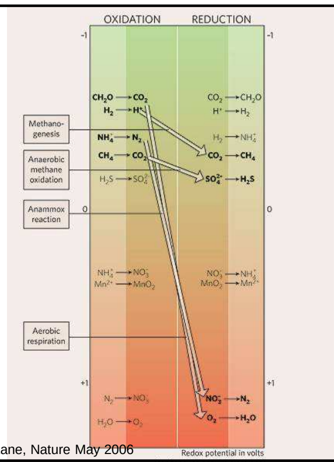
What is life?

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

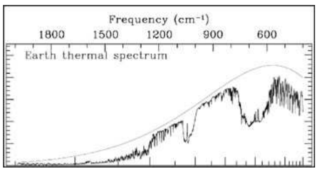
Diversity of metabolisms rivals diversity of exoplanets

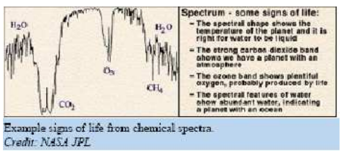
Sara Seager (2006)

Bio Markers

Spectroscopic Indicators of Life

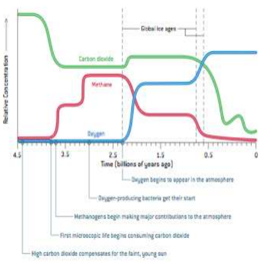
Absorption Lines
- CO2
- Ozone
- Water
- "Red" Edge



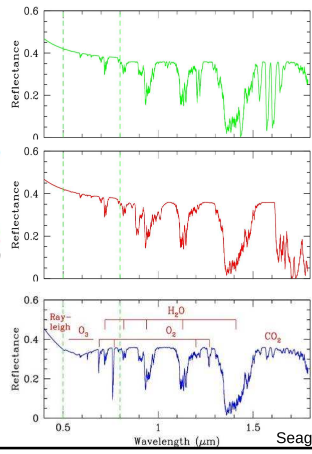


Example signs of life from chemical spectra.
Credit: NASA JPL

Earth Through Time



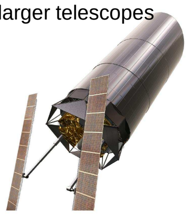
Kasting Sci. Am. 2004
See Kaltenegger et al. 2006
Earth from the Moon

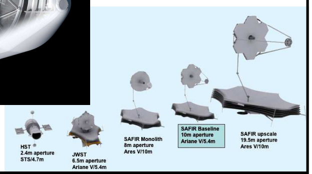


Seager

Beyond JWST

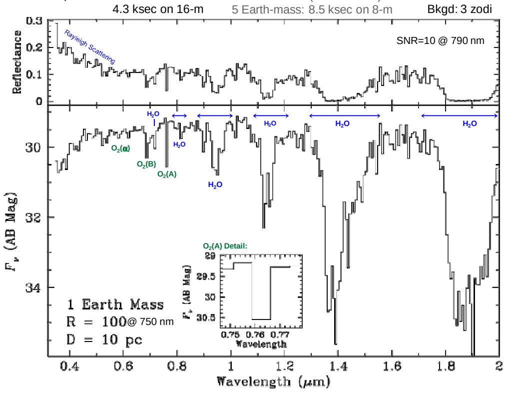
Heavy Lift Launch Vehicle enables even larger telescopes
8-m UV/Optical Telescope or
24-m Far-IR Telescope





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

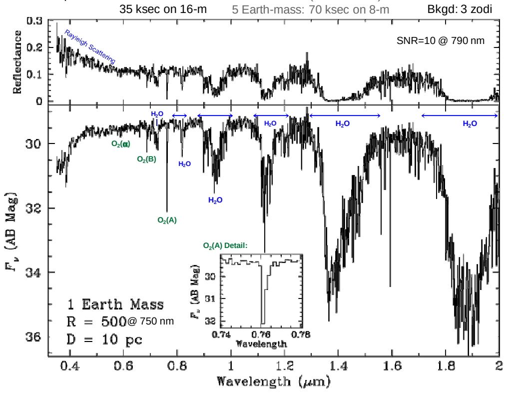
Exposure: 51 ksec on 8-m
4.3 ksec on 16-m
Reflectance ∝ (Planet Mass)$^{2/3}$
5 Earth-mass: 8.5 ksec on 8-m
Bkgd: 3 zodi



Marc Postman, "ATLAST", Barcelona, 2009

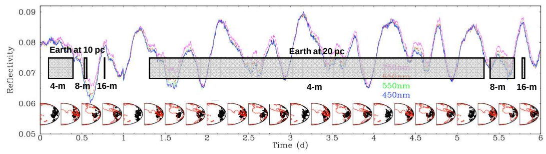
R=500 ATLAST Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc

Exposure: 502 ksec on 8-m
35 ksec on 16-m
Reflectance ∝ (Planet Mass)$^{2/3}$
5 Earth-mass: 70 ksec on 8-m
Bkgd: 3 zodi



Marc Postman, "ATLAST", Barcelona, 2009

Detecting Photometric Variability in Exoplanets



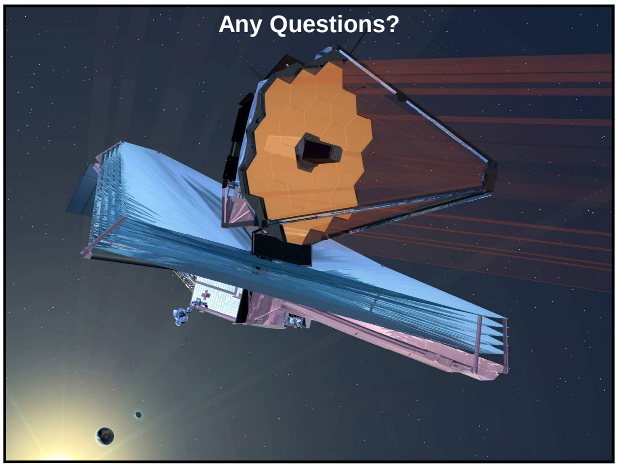
Marc Postman, "ATLAST", Barcelona, 2009

Countdown to Launch

JWST is

- making excellent technical progress
- will be ready for launch ~2017-2019
- will be the dominant astronomical facility for a decade undertaking a broad range of scientific investigations

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


Any Questions?