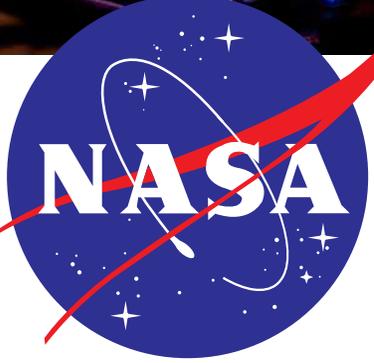




# the James Webb SPACE TELESCOPE

# THE FIRST LIGHT MACHINE



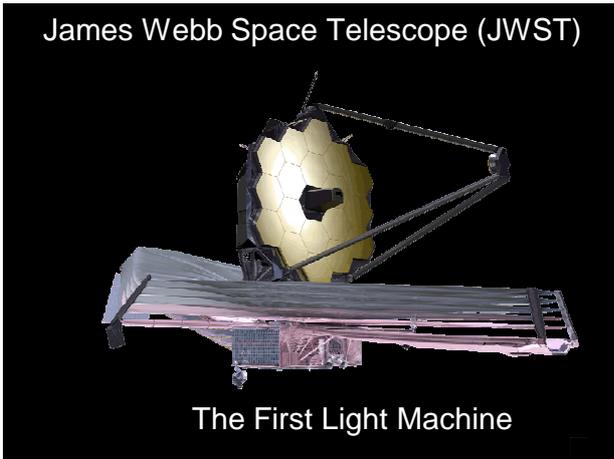
Dr. H. Philip Stahl is the James Webb Space Telescope Optical Telescope Element Mirror Optics Lead, responsible for its primary, secondary and tertiary mirrors. He is a Senior Optical Physicist at NASA Marshall Space Flight Center.



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.





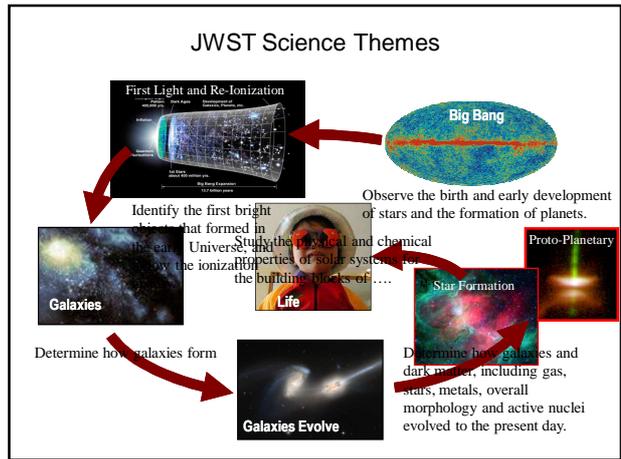
### JWST Summary

- 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

Timeline: 1999 (Formulation) - 2001 (Phase A) - 2002 (Phase B) - 2003 (Phase C/D) - 2007 (Launch) - 2018 (Phase E)

### Origins Theme's Two Fundamental Questions

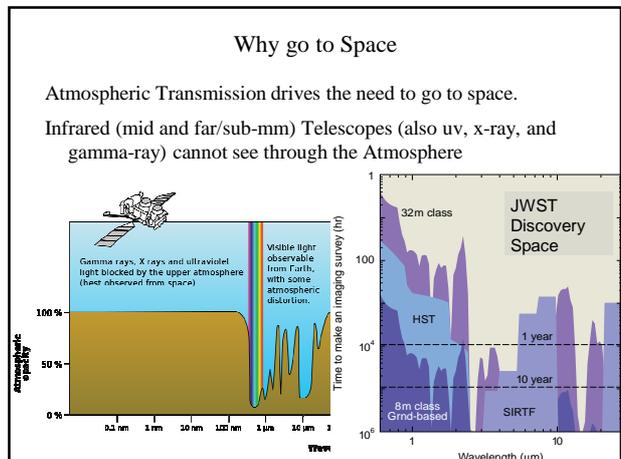
- How Did We Get Here?
- Are We Alone?

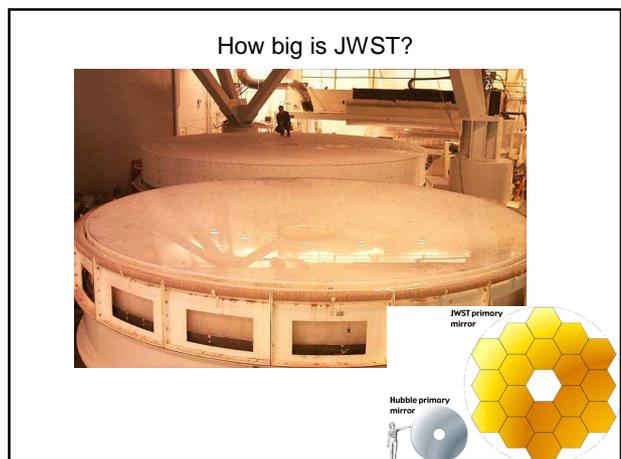
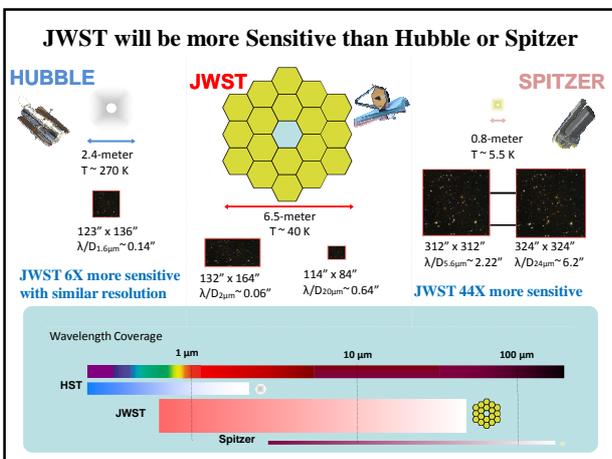
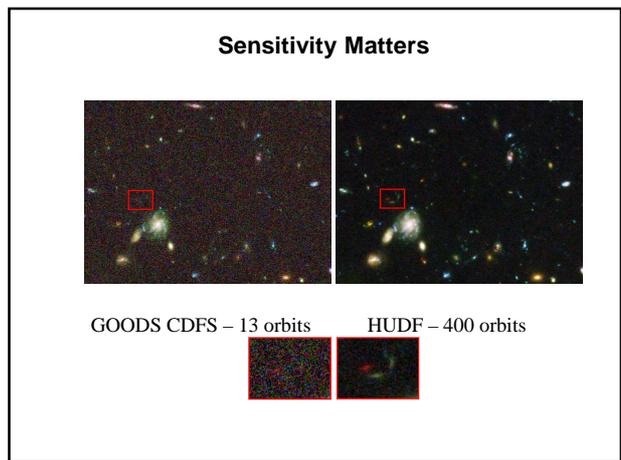
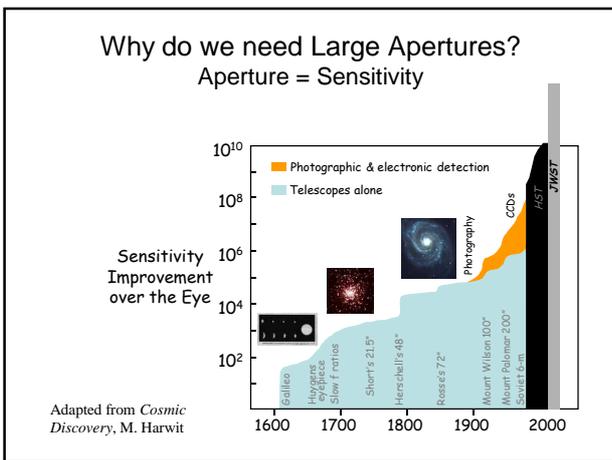
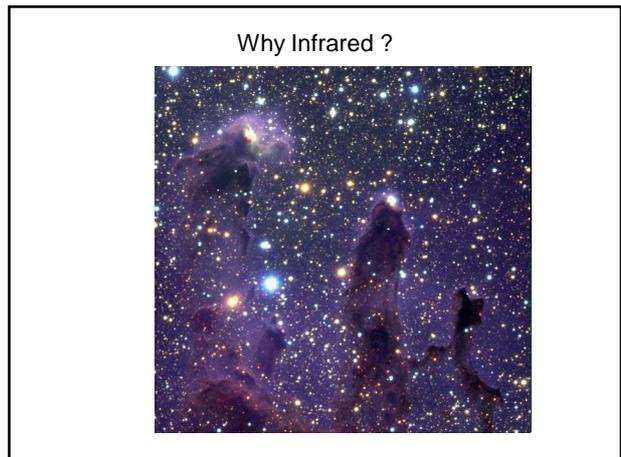
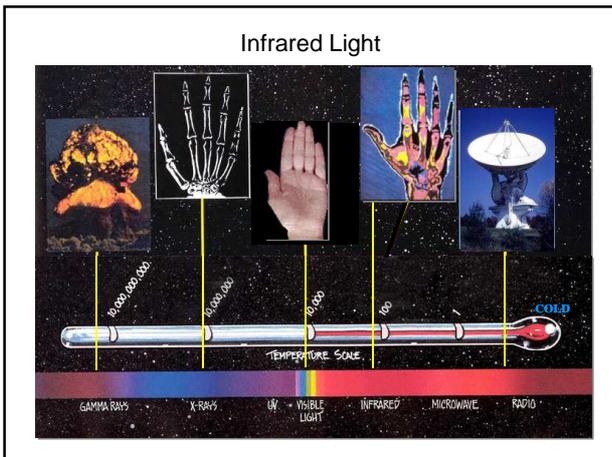


### Three Key Facts

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

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



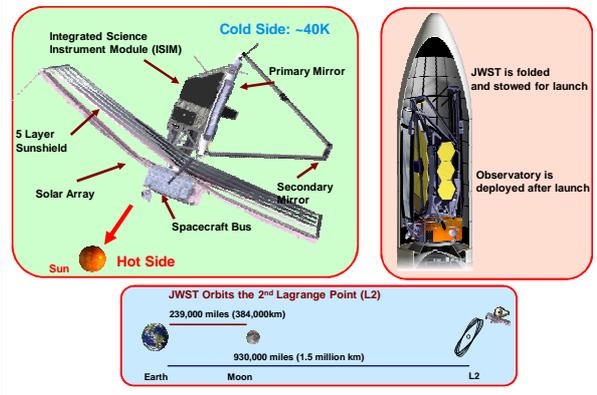


### Full Scale JWST Mockup



21<sup>st</sup> National Space Symposium, Colorado Springs, The Space Foundation

### How JWST Works

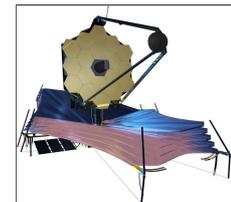


### JWST Science Instruments

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

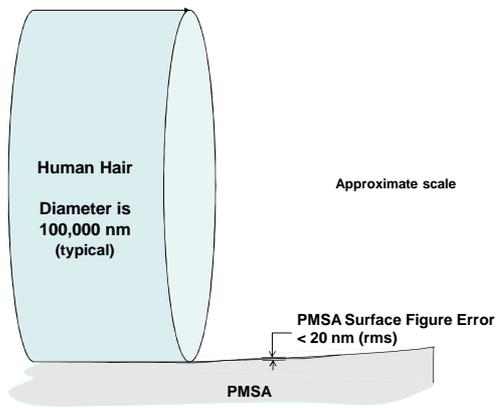


**Primary Mirror**  
 6.6 meter diameter (tip to tip)  
 < 25 kg/m<sup>2</sup> Areal Density  
 < \$6 M/m<sup>2</sup> Areal Cost  
 18 Hex Segments in 2 Rings  
 Drop Leaf Wing Deployment

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

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

### Fun Fact – Mirror Surface Tolerance



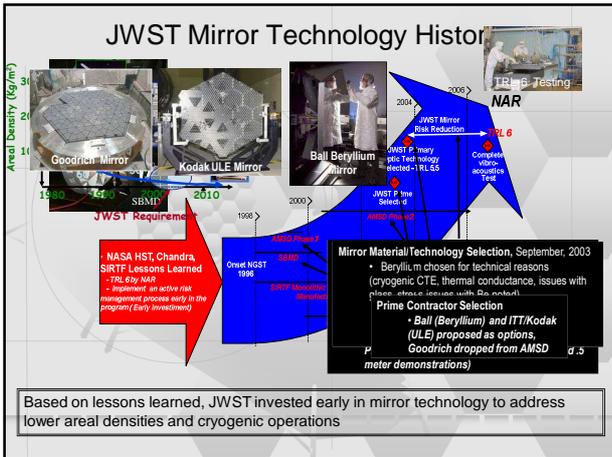
### Technology Development of Large Optical Systems

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

MSFC II - Re-Technology facility for JWST

6.5 M

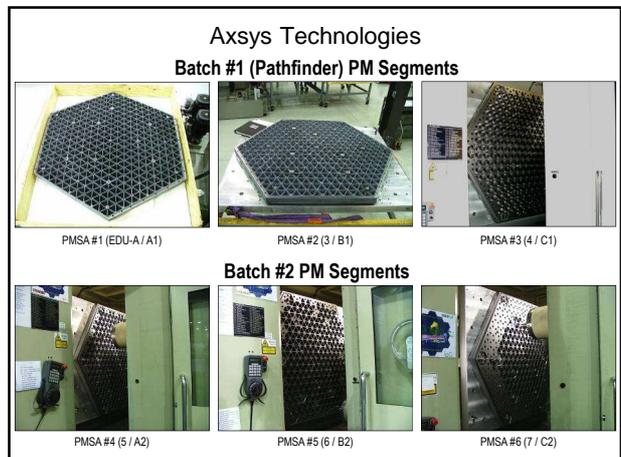
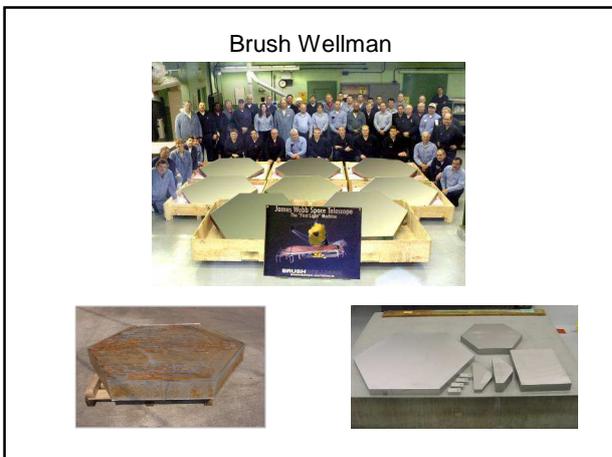
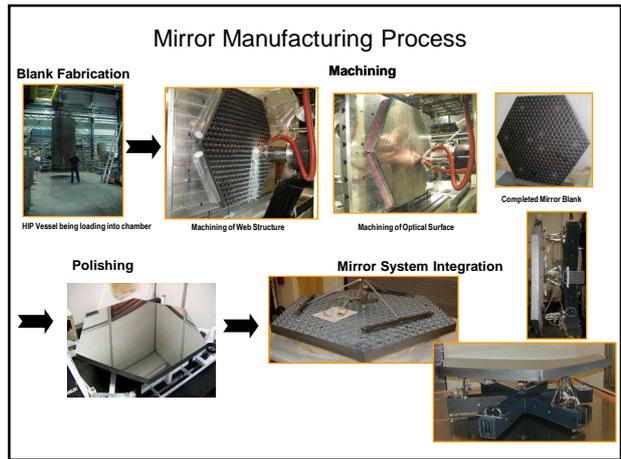
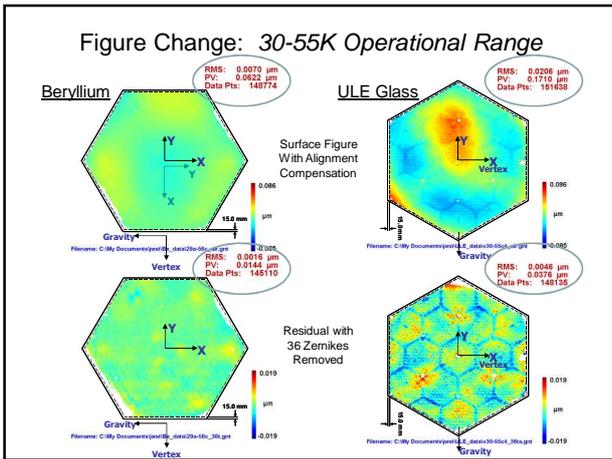
The 18 Primary Mirror segments



### Advantages of Beryllium

Very High Specific Stiffness – Modulus/Mass Ratio  
Saves Mass – Saves Money

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



### Fun Facts – Mirror Manufacturing

**Before**

Be Billet

**250 kgs**

**After**

Finished Mirror Segment

Be dust which is recycled

**21 kgs**

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

Congratulations to the JWST Mirror Team for successful program completion June 15, 2011

### Primary Mirror Segment Assembly at BATC

### MSFC Cryogenic Test Facility

- Remove Guide Tube Section, Add GSE Station
- Gate Valve
- Add Forward He Extension Module 1
- New XL Shrouds sections
- Add GSE Support System
- 5DOF Table - Upgrade
- East End Dome

### XRCF Cryo Test

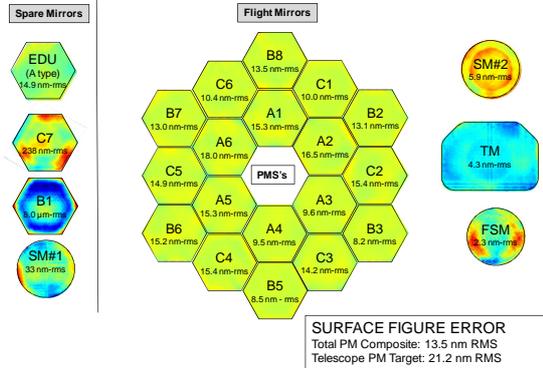
**Cryostat #6 Timeline**

Date	Temperature (K)	Event
11-Apr-11	200K	Survival Temperature
25-Apr-11	200K	Cryo Deployment
25-Apr-11	200K	Nominal Measurement
25-Apr-11	200K	Hexapod Deformation Pose
25-Apr-11	200K	RoC Actuation Test
25-Apr-11	200K	Hexapod Envelope Test
25-Apr-11	200K	Pullout Current & Redundant Test (3 of 6 PMSAs)
4-May-11	200K	Measurement
22-May-11	200K	Measurement
6-Jun-11	200K	Set RoC
6-Jun-11	200K	Nominal Measurement
6-Jun-11	200K	Hexapod Tilt Test
6-Jun-11	200K	Pullout Current & Redundant Test (3 of 6 PMSAs)

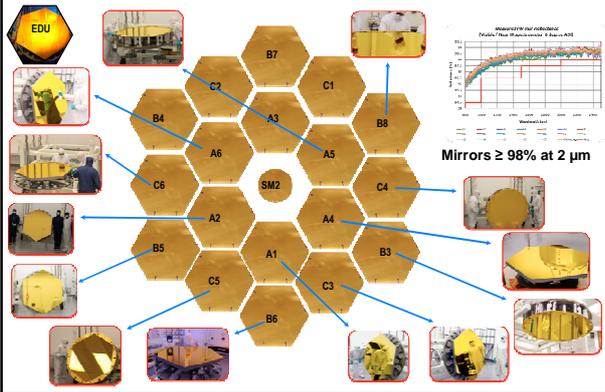
### Flight Mirrors in XRCF



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

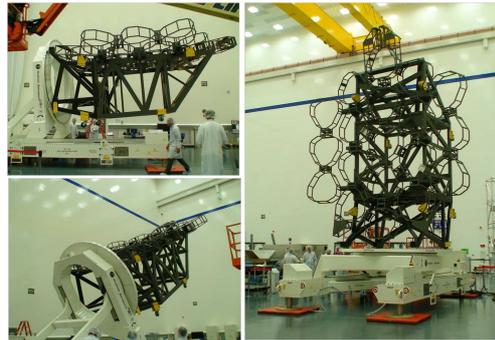


### Gold Coated Mirror Assemblies



### 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:**

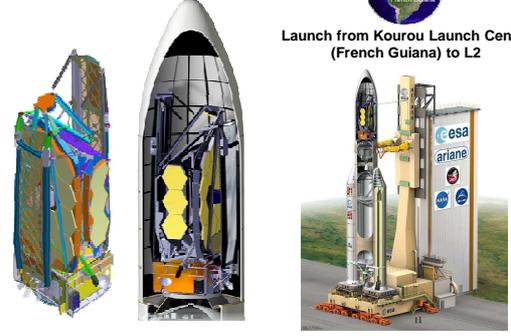
- 37m tall, 20m diameter, 12m door
- LN2 shroud and GHe panels

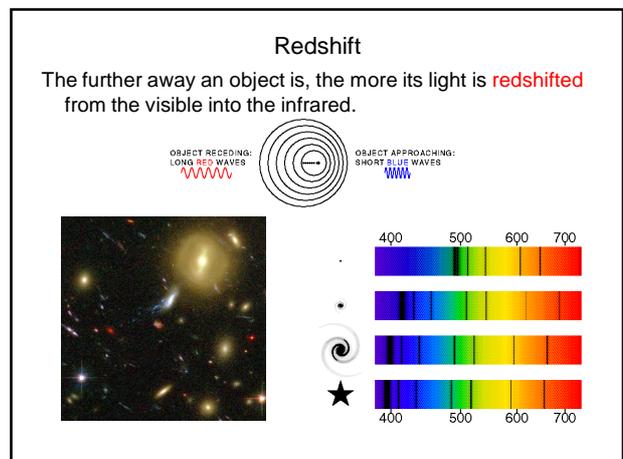
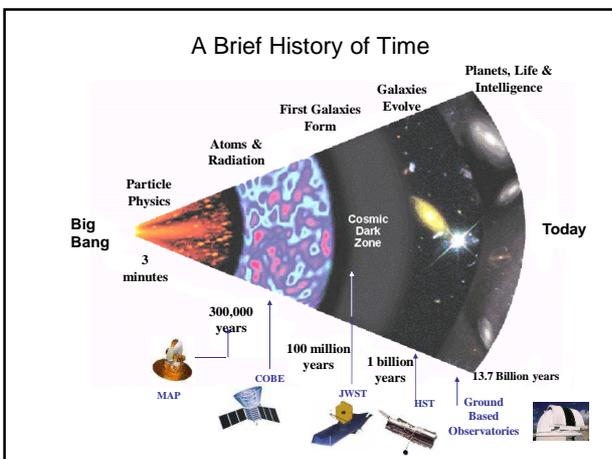
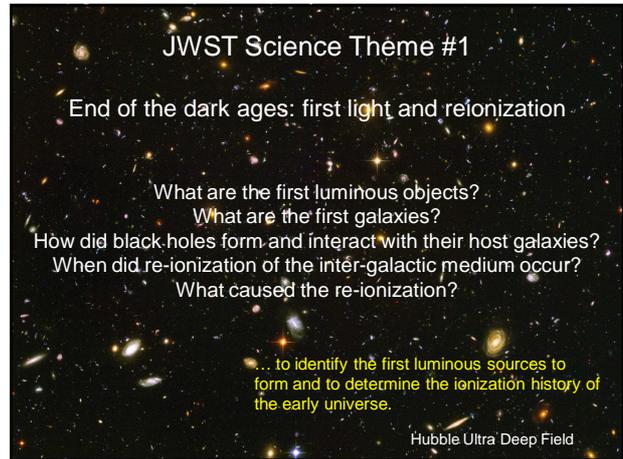
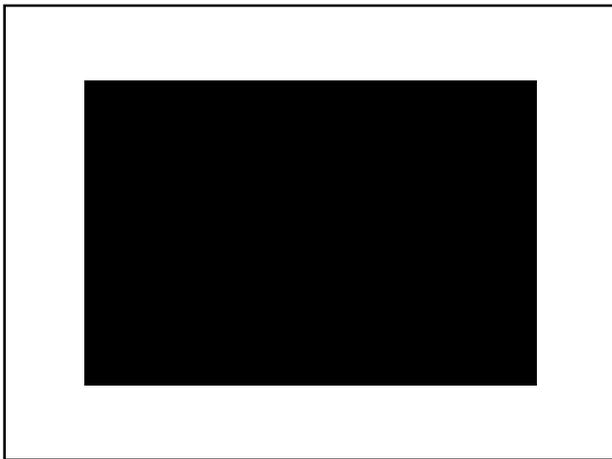
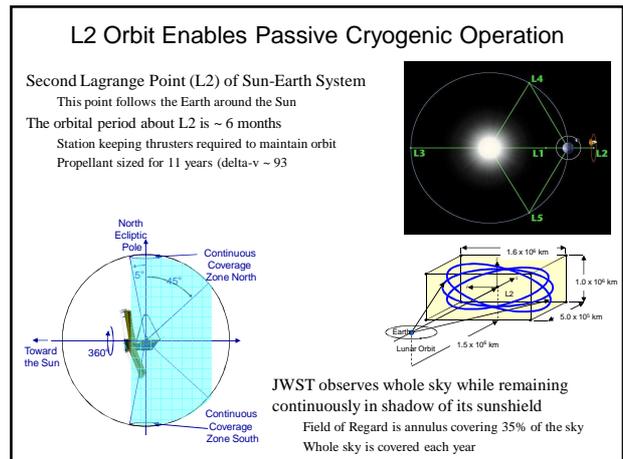
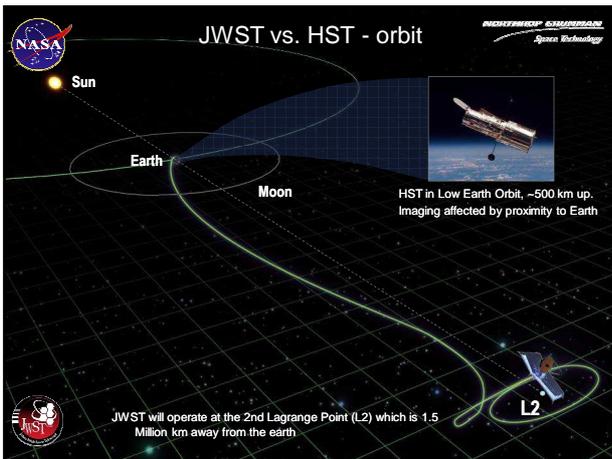
### JWST Launched on Ariane 5 Heavy

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



Launch from Kourou Launch Center (French Guiana) to L2





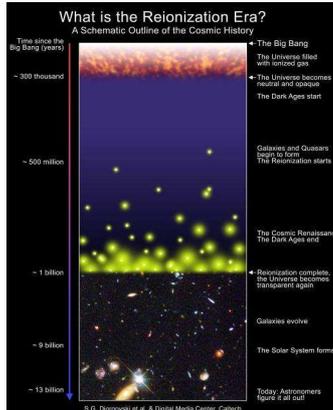
### When and how did reionization occur?

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

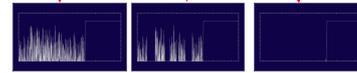
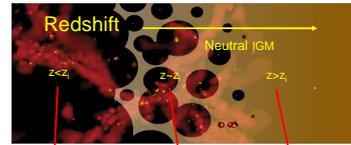
Probably galaxies, maybe quasar contribution

**Key Enabling Design Requirments:**  
 Deep near-infrared imaging survey (InJy)  
 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



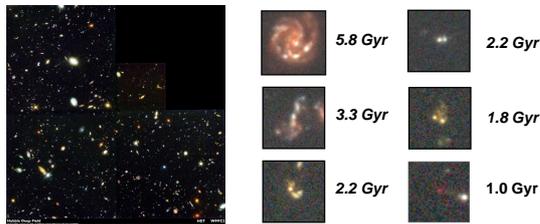
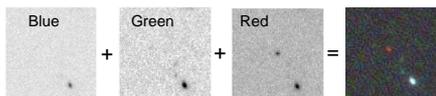
Lyman Forest Absorption Patchy Absorption Black Gunn-Peterson trough

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.

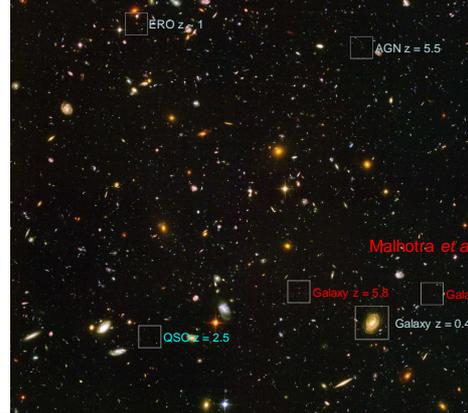
Neutral 'fog' was dissolved by very bright 1<sup>st</sup> Generation Stars (5000X younger & ~100X more massive than our sun).

SPACE.com, 12 October 2011

### How do we see first light objects?

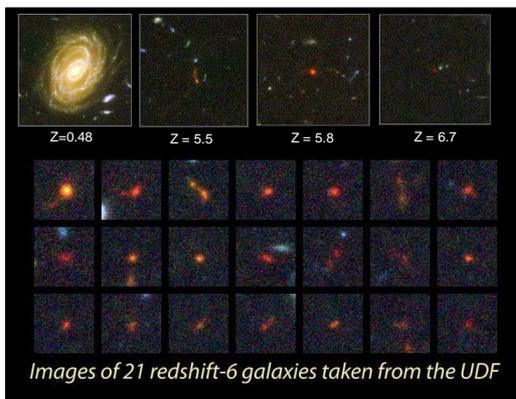


### Ultra Deep Field



*Malkotra et al. 2004*

### Results from UDF

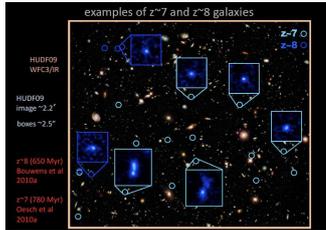


### Hubble Ultra Deep Field – Near Infrared



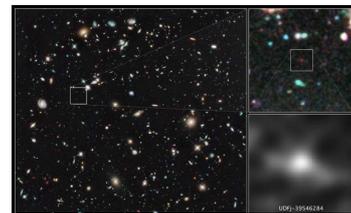
Near-Infrared image taken with new Wide-Field Camera 3 was acquired over 4 days with a 173,000 second exposure.

### Hubble Ultra Deep Field – Near Infrared

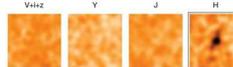


47 Galaxies have been observed at 600 to 650 Myrs after BB.

### Hubble Ultra Deep Field – Near Infrared

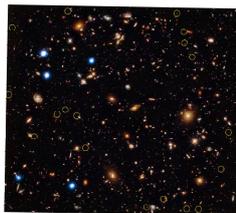


At 480 M yrs after big bang ( $z \sim 10$ ) this is oldest observed galaxy. Discovered using drop-out technique.



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/UC/Hawaii/E.Tsister et al.  
Optical: NASA/STScI/S.Beckwith et al.  
Keith Cooper, Astronomy Now, 15 June 2011  
Taylor Reel, SPACE.com, 15 June 2011

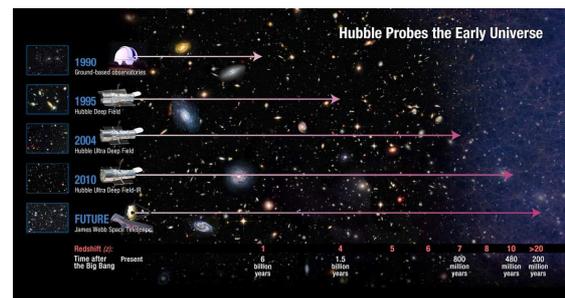
What came first – Galaxies or Black Holes?

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?

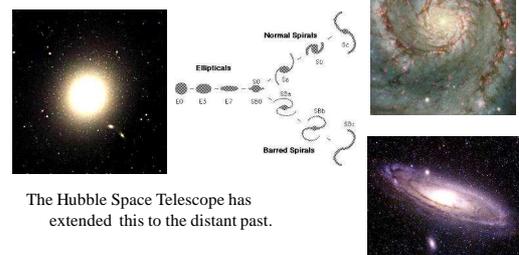
- When did the Hubble Sequence form?
- What role did galaxy collisions play in their evolution?
- Can we test hierarchical formation and global scaling relations?
- What is relation between Evolution of Galaxies & Growth/Development of Black Holes in their nuclei?

... 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.

MB1 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

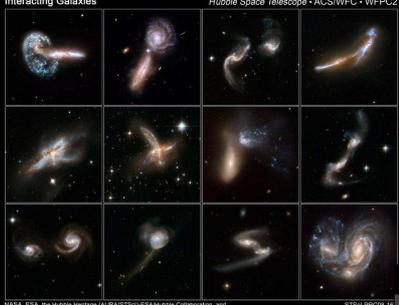
Components of galaxies have variety of ages & compositions

**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"



Hubble Space Telescope • ACS/WFC • WFPC2

2-736 1 z = 1.355

Optical      Infrared

NASA, ESA, the Hubble Heritage (AURA/STScI)/ESA/Hubble Corporation, and A. Evans (University of Virginia, Charlottesville)/NOAO/Ohio State University

### 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

### JWST Science Theme #3: Birth of stars and protoplanetary systems

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



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

David Hardy

### How does environment affect star-formation?

Massive stars produce wind & radiation  
Either disrupt star formation, or causes it.

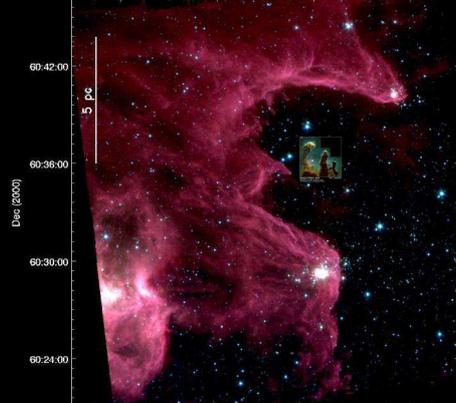
Boundary between smallest brown dwarf stars & planets is unknown  
Different processes? Or continuum?

**JWST Observations:**

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



The Eagle Nebula as seen in the infrared

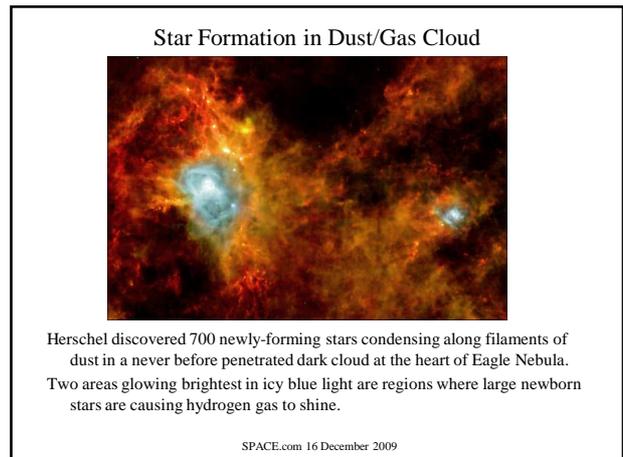
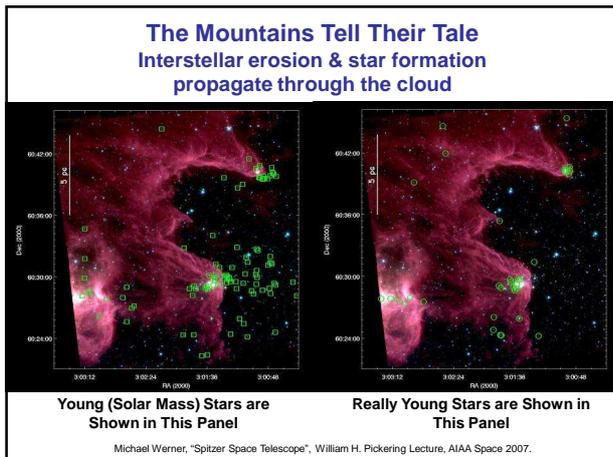


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**Spitzer has Found "The Mountains Of Creation"**

Michael Werner, "Spitzer Space Telescope", William H. Pickering Lecture, AAS Space 2007.  
L. Allen, CFA (GTO)



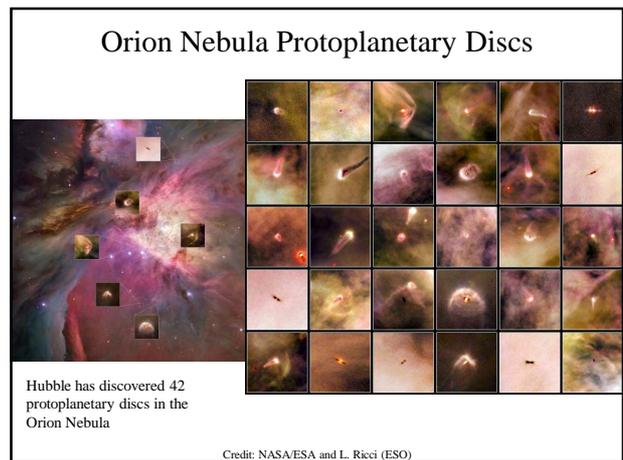
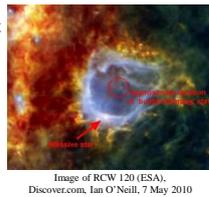
### Impossible Stars

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.

(Space.com, 6 May 2010)



## JWST Science Theme #4: Planetary systems and the origins of life

How do planets form?  
 How are circumstellar disks like our Solar System?  
 How are habitable zones established?

... to determine the physical and chemical properties of planetary systems including our own, and to investigate the potential for the origins of life in those systems.

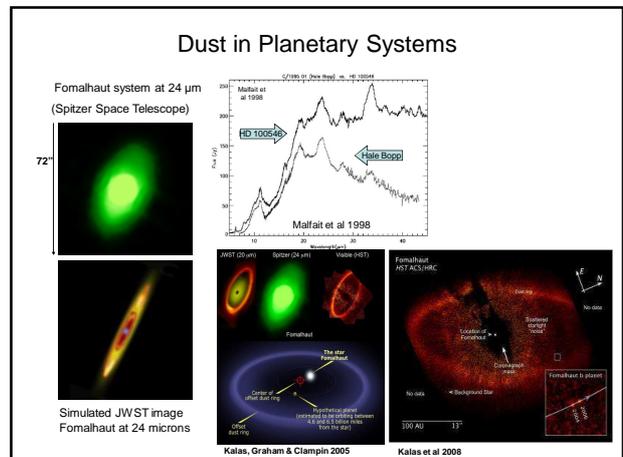
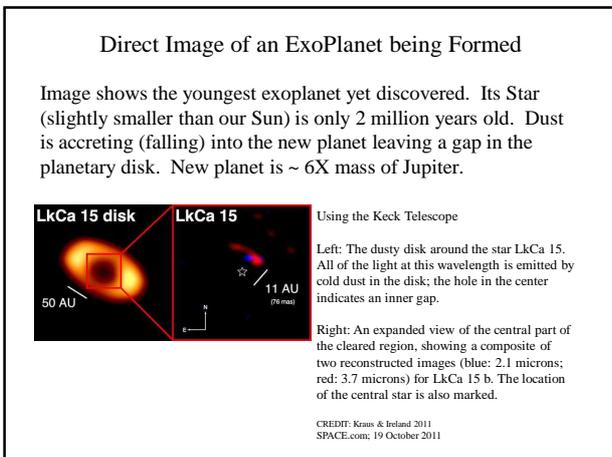
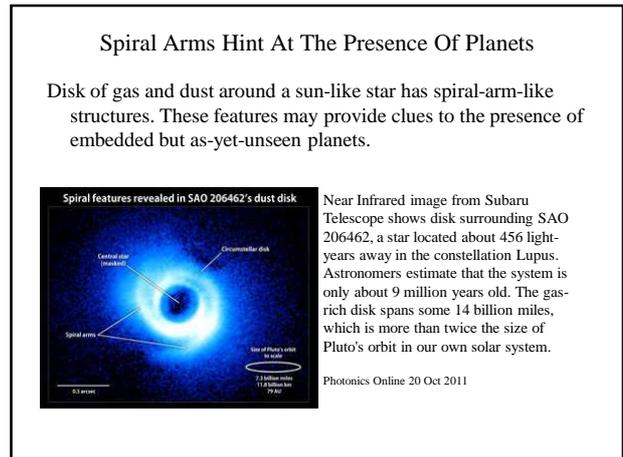
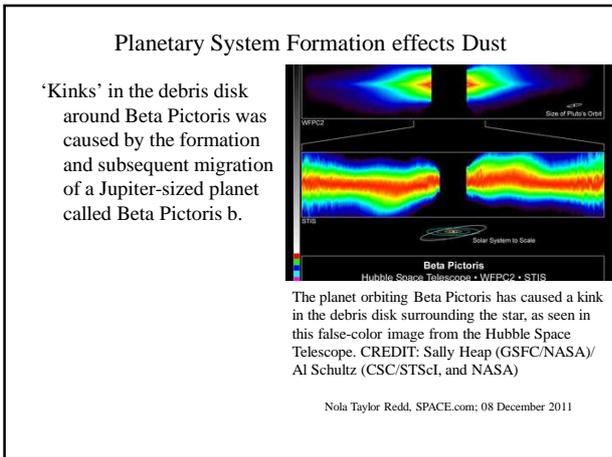
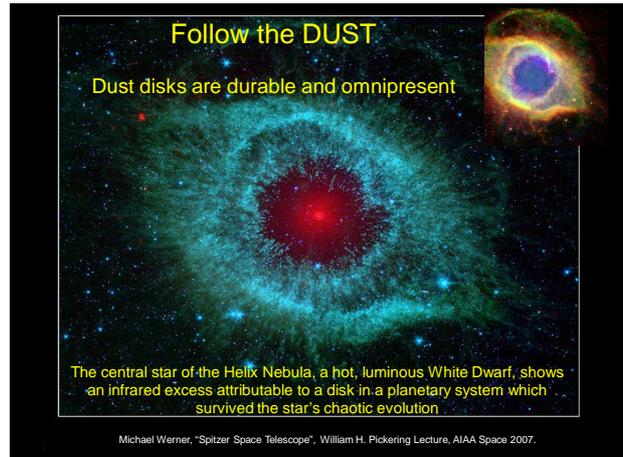
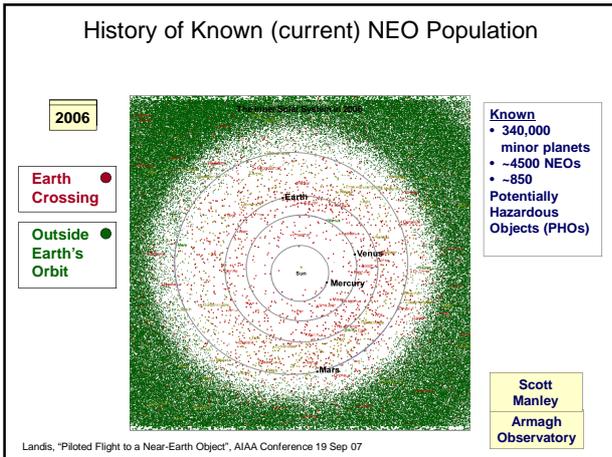
Robert Hurt

### Planetary Formation Questions and 2 Models

- How do planets and brown dwarfs form?
- How common are giant planets and what is their distribution of orbits?
- How do giant planets affect the formation of terrestrial planets?
- What comparisons, direct or indirect, can be made between our Solar System and circumstellar disks (forming solar systems) and remnant disks?
- What is the source of water and organics for planets in habitable zones?
- How are systems cleared of small bodies?
- What are the planetary evolutionary pathways by which habitability is established or lost?
- Does our solar system harbor evidence for steps on these pathways?

#### TWO PLANET FORMATION SCENARIOS

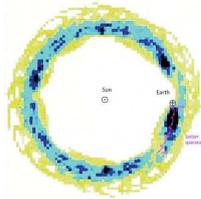
Accretion model	Gas-collapse model
 Central star Dust disk Orbiting dust grains accrete, and planetesimals form through non-gravitational forces.	 A protoplanetary disk of gas and dust forms around a young star.
 Planetesimals grow, moving in near-coplanar orbits, to form planetary embryos.	 Gravitational disk instabilities form a clump of gas that becomes a self-gravitating planet.
 Gas-giant planets accrete gas envelopes before disk gas disappears.	 Dust grains coagulate and sediment to the center of the protoplanet, forming a core.
 Gas-giant planets scatter or accrete remaining planetesimals and embryos.	 The planet sweeps out a wide gap as it continues to feed on gas in the disk.



### Planets and Dust

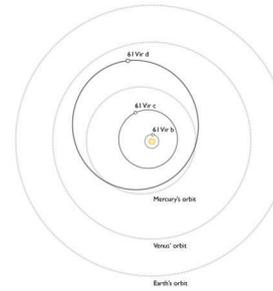
Earth has a 'tail' of dust particles.

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.

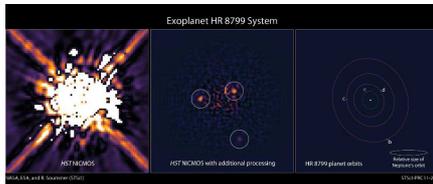
Bad Astronomy  
Orbital schematic credit: Chris Tinney

### 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.

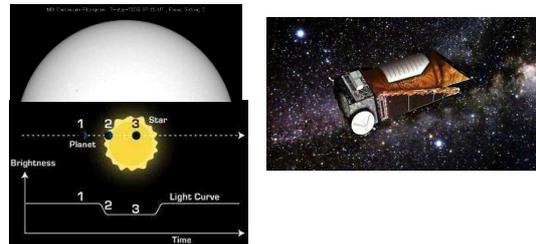


Denise Chow, SPACE.com; 06 October 2011

### 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.

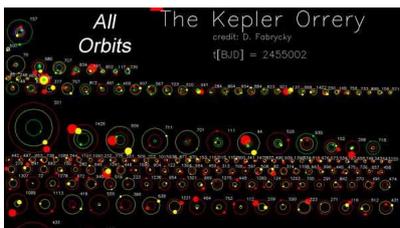
As of Dec 2011, Kepler has found 2326 planets



### Kepler Planetary Systems

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

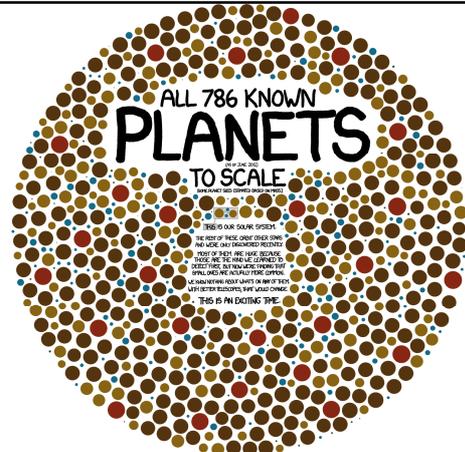
- > 800 in single planet systems,
- > 400 in 170 systems with 2 to 6 transiting planets, and
- 207 potential Earth size; 680 super-Earth size; 48 in Habitable Zone



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)

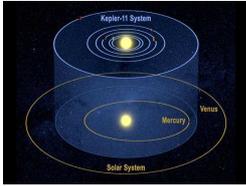


Kepler's planet candidates by size. CREDIT: NASA/Wendy Stenzel (SPACE.com 2 Feb 2011)



### Kepler Mission

Kepler-1 has a star like ours & 6 mini-Neptune size planets



Five of six Kepler-1 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. It is 2.4 times that of Earth, and the two planets have roughly similar temperatures (maybe 22C).

CREDIT: NASA/Ames/JPL-Caltech

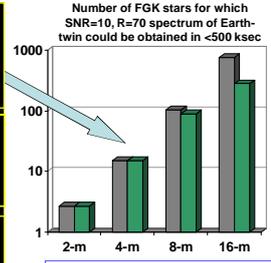
### Is There Life Elsewhere in the Galaxy?

Need to multiply these values by  $\eta_{Earth} \times f_B$  to get the number of potentially life-bearing planets detected by a space telescope.  
 $\eta_{Earth}$  = 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  $D_{Tel} \sim 8m$   
 $\eta_{Earth} \times f_B \ll 1$  then  $D_{Tel} \sim 16m$

Kepler is finding that  $\eta_{Earth}$  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.

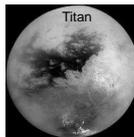


Green bars show the number of FGK stars that could be observed 3x each in a 5-year mission without exceeding 20% of total observing time available to community.

Marc Postman, "ATLAST", Barcelona, 2009; Modified by Stahl, 2011

### How are habitable zones established?

Source of Earth's H<sub>2</sub>O and organics is not known  
 Comets? Asteroids?

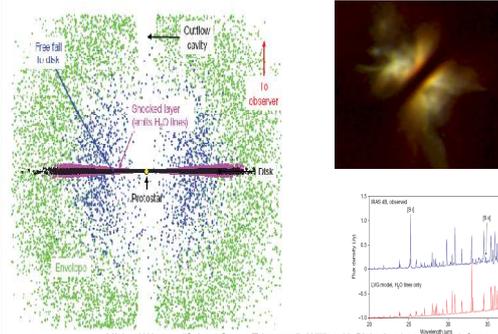


History of clearing the disk of gas and small bodies  
 Role of giant planets?

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.



A Protostar and its Polar Jets NASA/Caltech

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

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

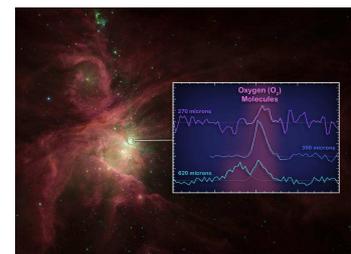
(National Geographic, Clay Dillow, 16 June 2011)

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

### Molecular Oxygen discovered in space

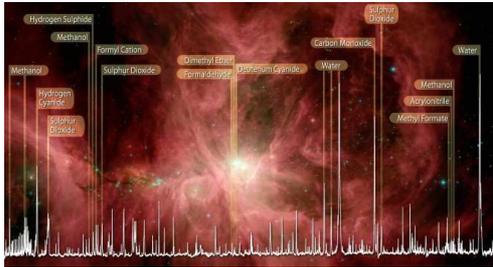
Herschel found molecular oxygen in a dense patch of gas and dust adjacent to star-forming regions in the Orion nebula.

The oxygen maybe water ice that coats tiny dust grains.



SPACE.com, 01 August 2011

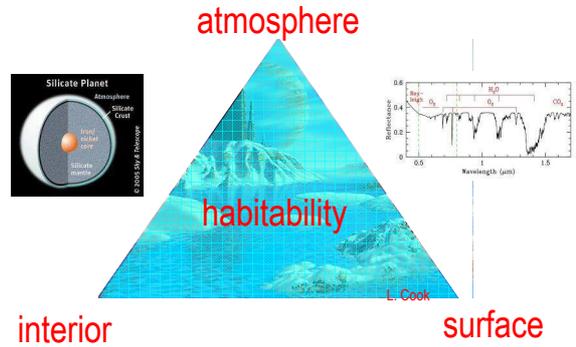
All of Life's Ingredients Found in Orion Nebula



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



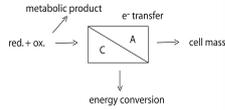
Sara Seager (2006)

Search for Life

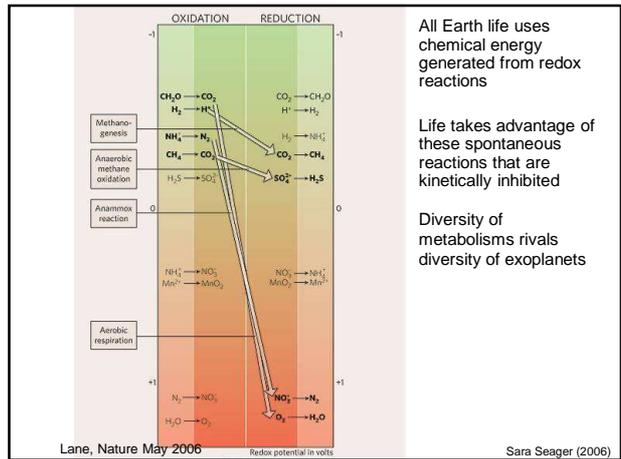
What is life?

What does life do?

Life Metabolizes



Sara Seager (2006)



All Earth life uses chemical energy generated from redox reactions

Life takes advantage of these spontaneous reactions that are kinetically inhibited

Diversity of metabolisms rivals diversity of exoplanets

Lane, Nature May 2006

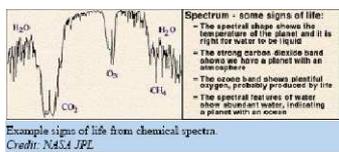
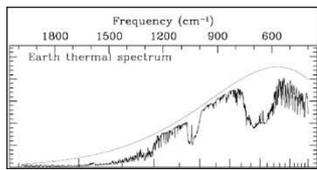
Sara Seager (2006)

Bio Markers

Spectroscopic Indicators of Life

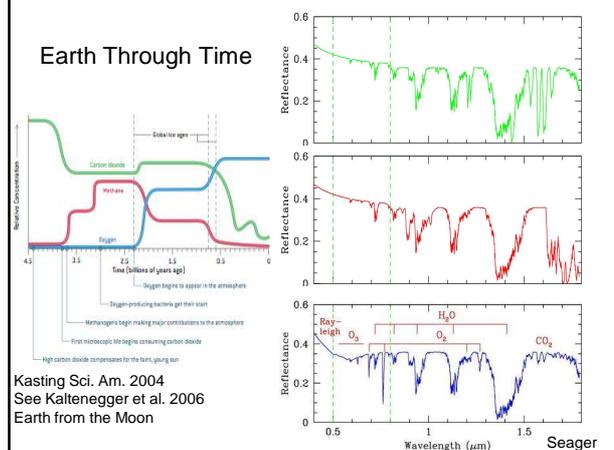
Absorption Lines

- CO2
- Ozone
- Water
- "Red" Edge



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

Earth Through Time



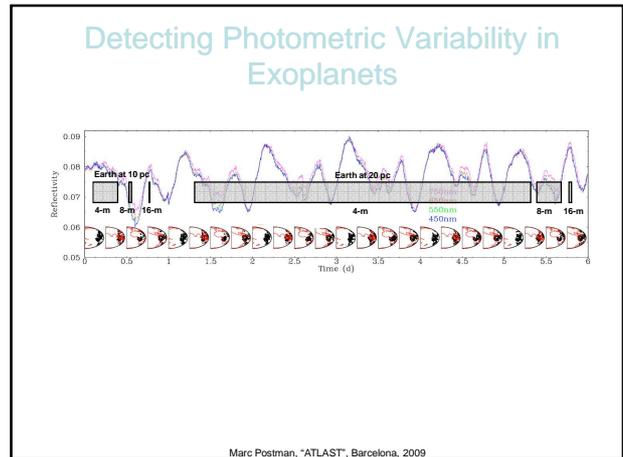
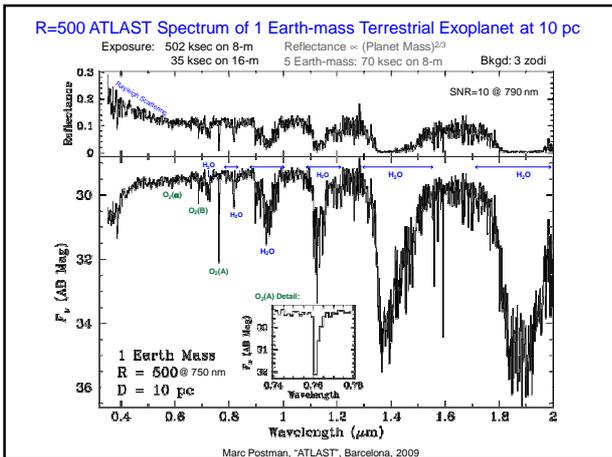
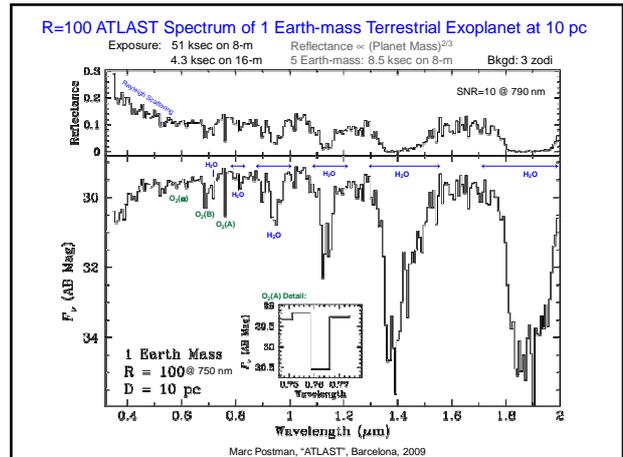
Kasting Sci. Am. 2004  
See Kaltenegger et al. 2006  
Earth from the Moon

Seager

### Beyond JWST

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

Ariane 5 ES  
 Ariane 5 ES  
 Ariane 5 ES  
 Ariane 5 ES



### 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

Ariane 5  
 Ariane Vol 139 - ASTRA 20, GE 8 & LDREX - 1012/20000

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

Full Scale Model

