



Deciphering the Big Bang

(and the whole history of the universe from the beginning to the end)

John C. Mather

Senior Project Scientist, James Webb Space Telescope,
NASA's Goddard Space Flight Center

July 2, 2008



Rutgers Lusscroft Farm - Site of Early Nerds in Sussex County, NJ



July 2, 2008

Mather Crete 2008

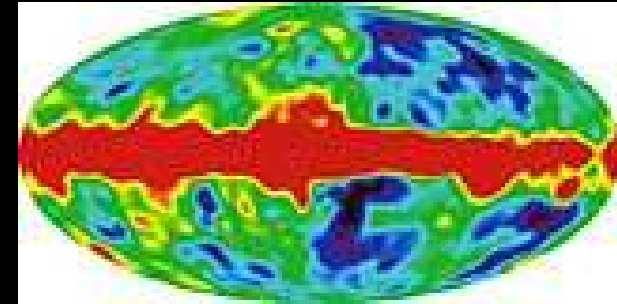
2



Astronomical Search For Origins



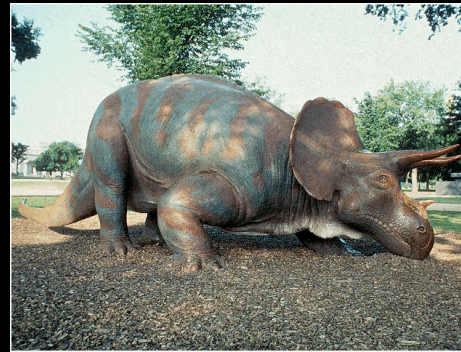
First Galaxies



Big Bang



Galaxies Evolve



Life



Planets



Stars







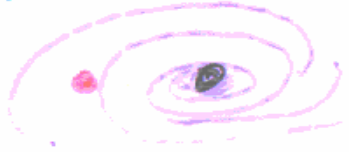



Can you imagine?

Your chin is made
of exploded stars!



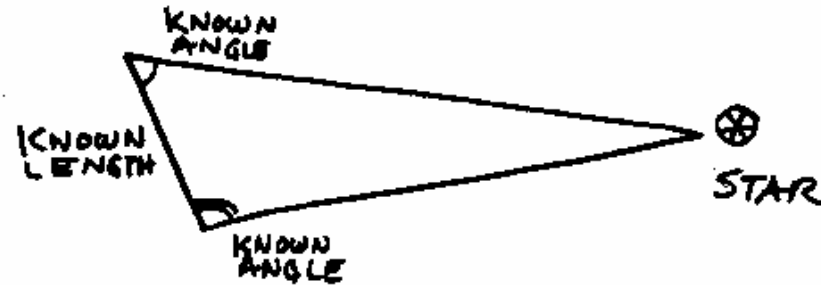
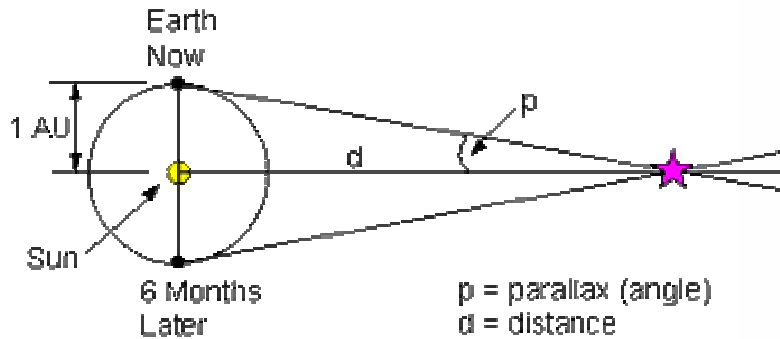
Looking Back in Time

HAND		1 m	0.000000003
EARTH		7000 km	0.02 sec
SUN		150,000,000 km	500 SE
STAR			4 YRS
GALAXY			25,000 YRS
BIG BANG			15,000,000,000 Y



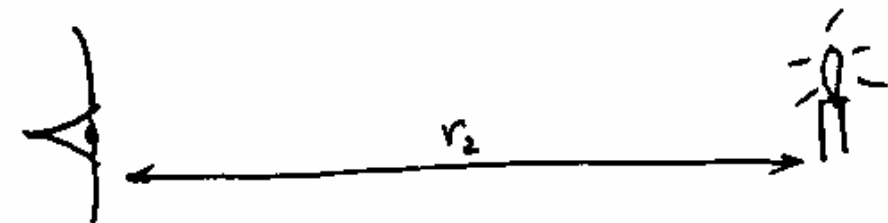
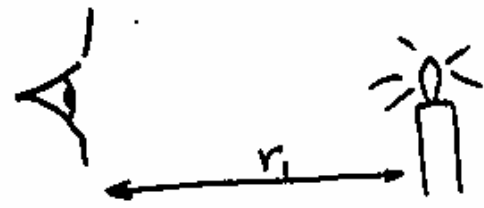
Measuring Distance

1. TRIANGLES



2. STANDARD CANDLES

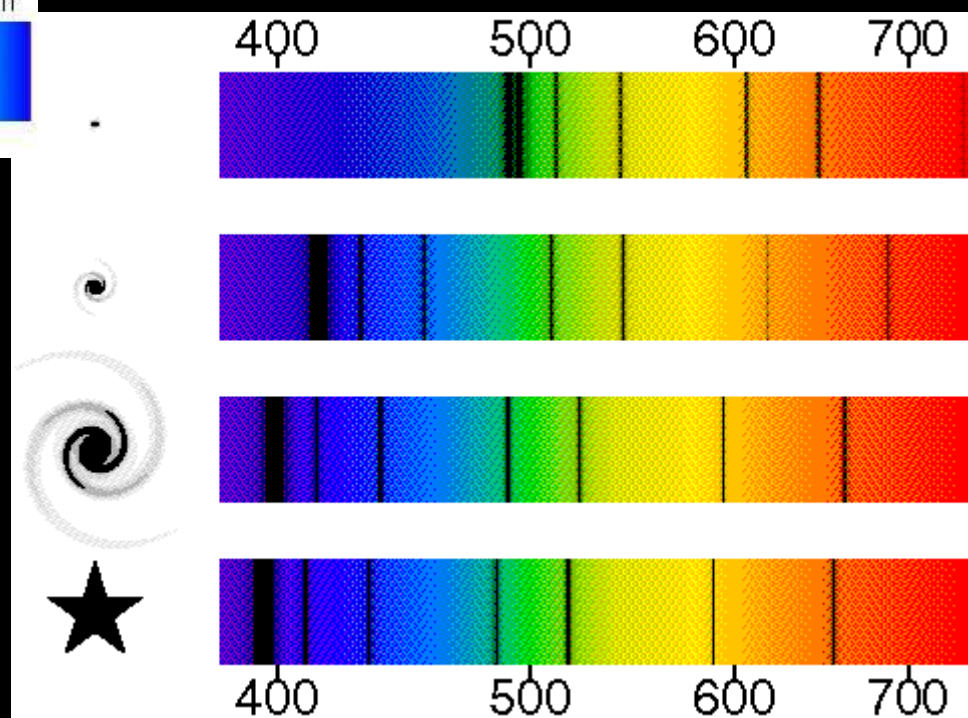
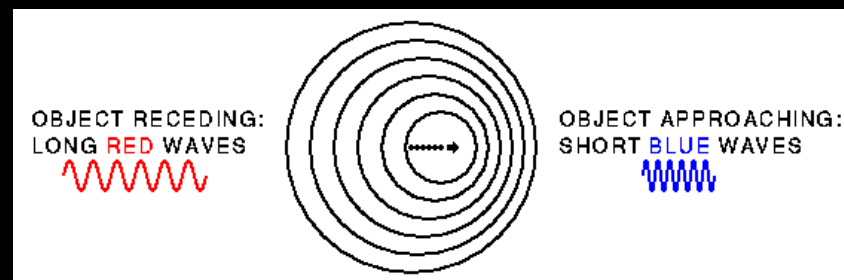
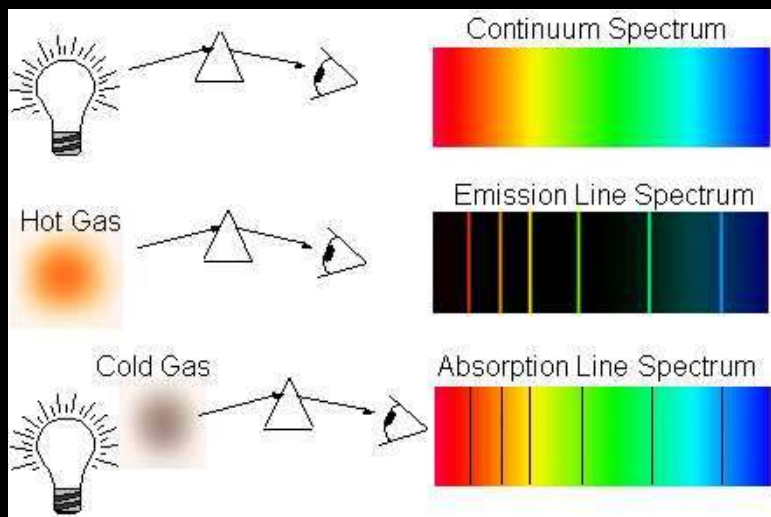
This technique enables measurement of enormous distances



$$\frac{\text{BRIGHTNESS}_1}{\text{BRIGHTNESS}_2} = \frac{r_2^2}{r_1^2}$$



Astronomer's Toolbox #2: Doppler Shift - Light



Atoms emit light at discrete wavelengths that can be seen with a spectroscope

This "line spectrum" identifies the atom and its velocity



Hubble's Law - 1929 Discovery

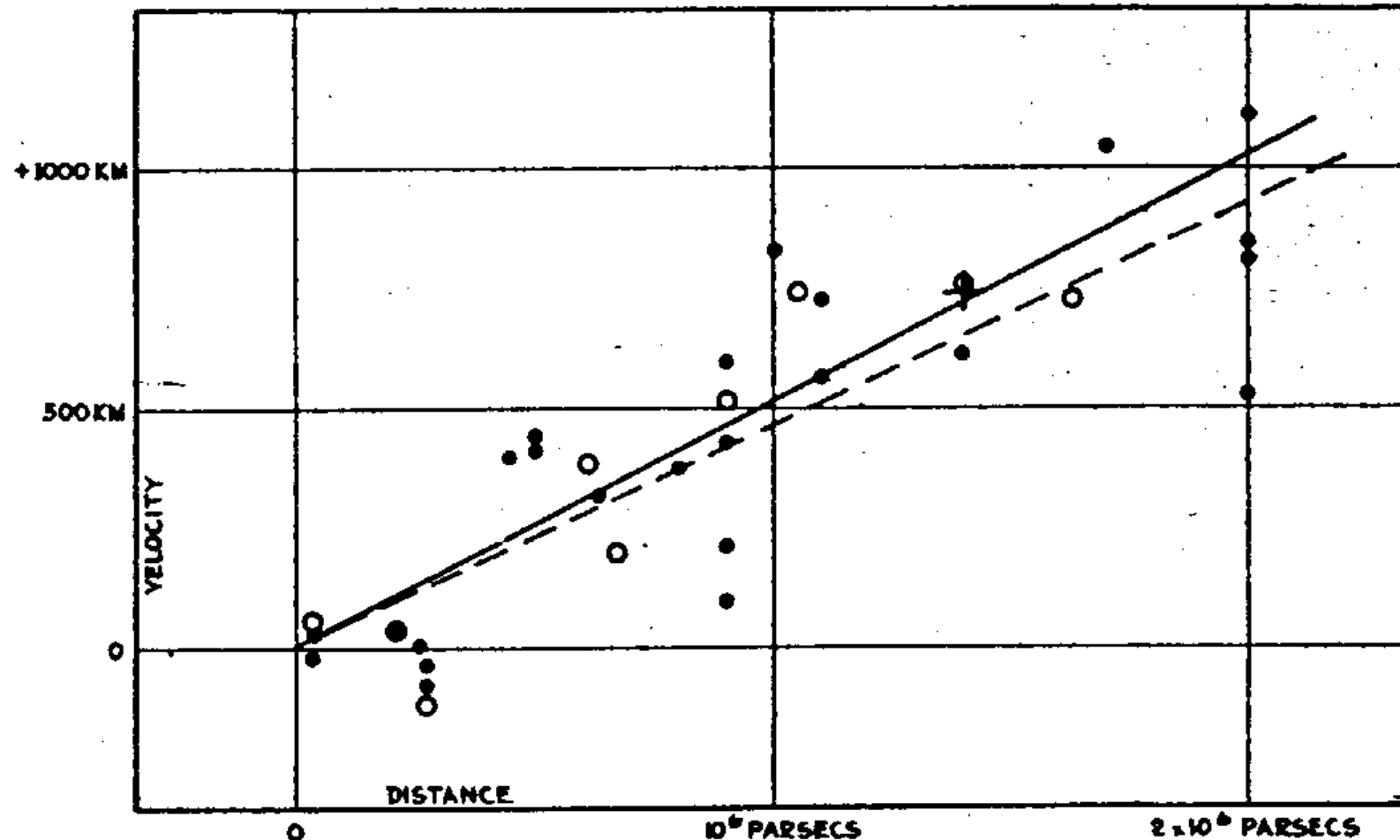
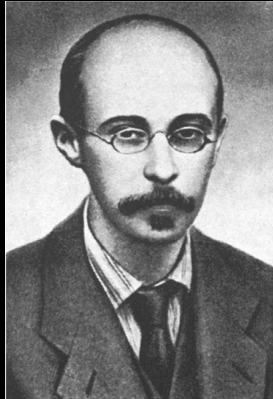


FIGURE 1

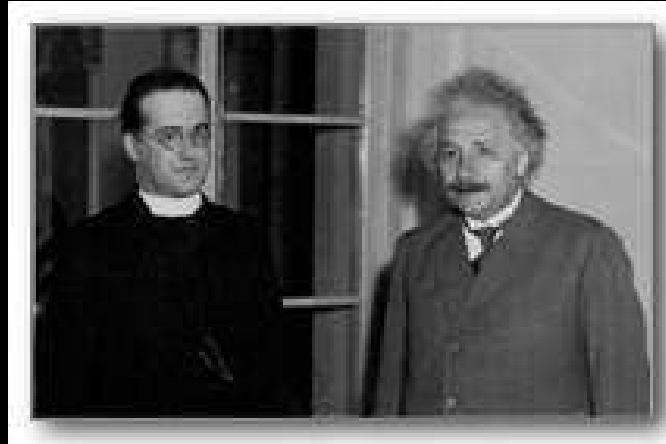


The Power of Thought



A. Friedman

Alexander Friedman



Georges Lemaître & Albert Einstein



Drawing by William Parker

George Gamow



Robert Herman & Ralph Alpher

July 2, 2008



Rashid Sunyaev

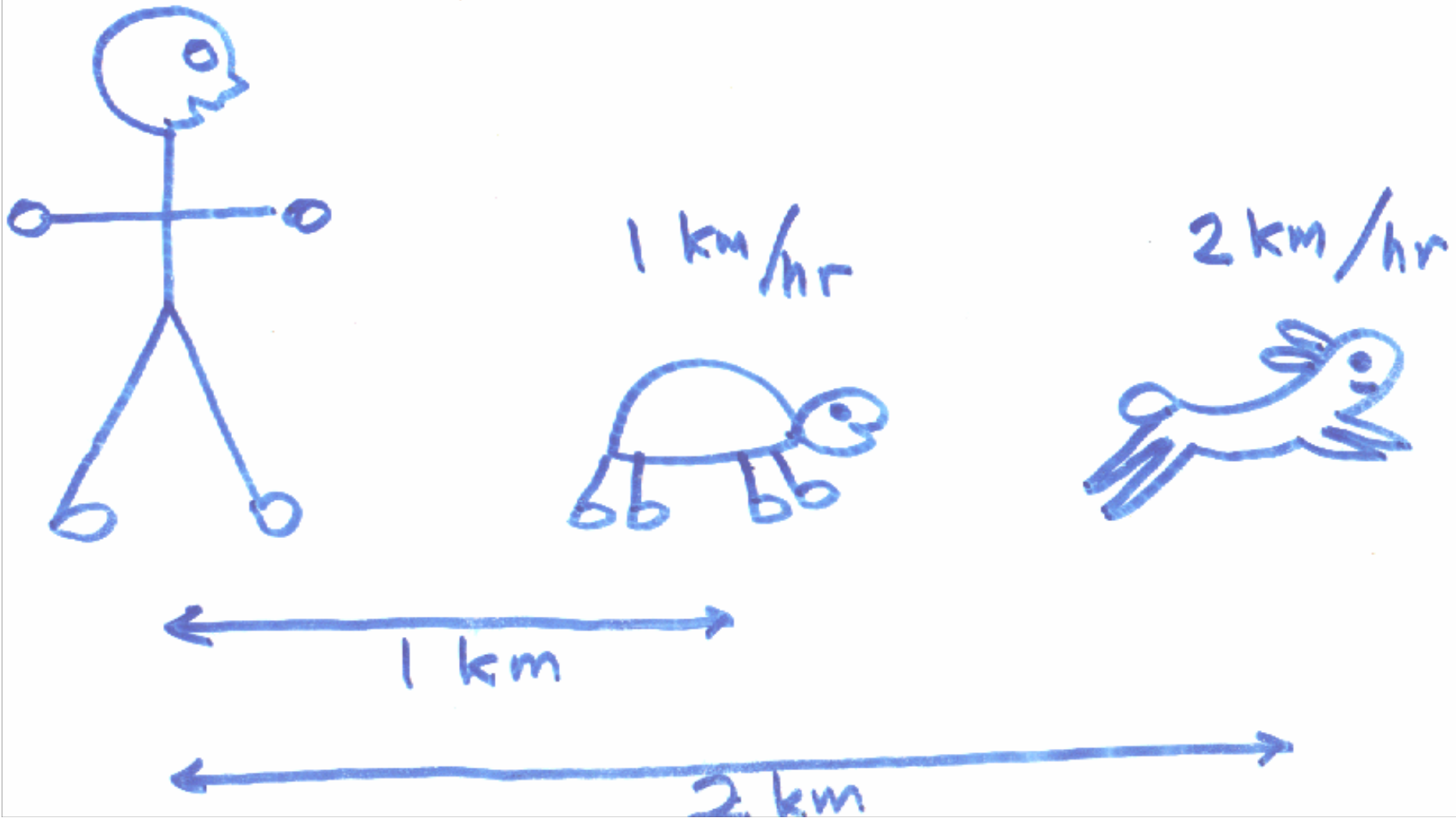
Mather Crete 2008



Jim Peebles

HUBBLE'S LAW

NO NECESSARY CENTER!





Big Bang - Cosmic Explosion 13.7 billion years ago

**IMPOSSIBLE TO
DRAW A PICTURE!**



So what happened?

- Primordial material, possibly infinite in every dimension
- Small piece of it (10 cm in size?) does something quantum mechanical with unknown physics
- Rapid expansion, faster than light can keep up with, stretches this little bit into whole observable universe (cosmic inflation)



How did the whole observable universe fit into that little ball?

- Space is mostly empty - stars are very very far apart
- Atoms are mostly empty - atomic nuclei are very tiny compared to size of atoms
- Squeeze very hard, and compression can create antimatter and rip quarks apart inside protons and neutrons
- Squeeze even harder, and the known laws of physics no longer apply - space and time may mix into higher dimensions?



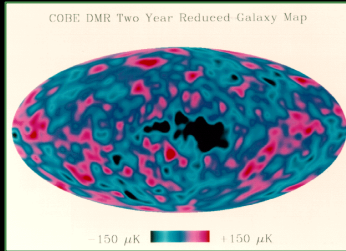
How did a smooth Big Bang make complicated things like us?

- Gravity is long range attractive force
 - Matter distribution is unstable
 - Remove heat, and system heats up more
 - Makes condensed objects (stars, galaxies, etc.)
 - Gravitational energy flows support complexity
- Stars release heat from nuclear reactions
 - Heat & light received by Earth support complexity, from weather to photosynthesis



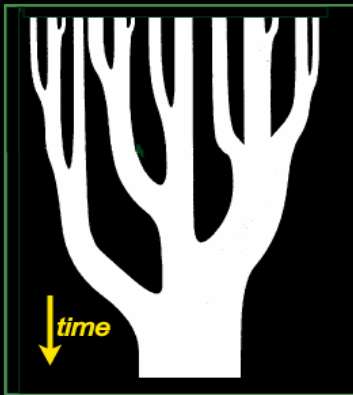
Brief History of the Universe

Big Bang
seen by
COBE &
WMAP



?

Galaxy
assembly



?

Galaxies,
stars,
planets,
life



- Horrendous Space Kablooney - exponential expansion, primordial fluctuations, matter/antimatter, dark matter, dark energy, 13.7 ± 0.2 billion years ago
- Annihilation of antiparticles, 1 part per billion matter remaining
- Formation of Helium nuclei, 3 minutes, redshift $z = 10^9$
 - $[1+z = \text{size of universe now} / \text{size then}]$
- Formation of neutral gas “recombination”, 389,000 yrs, $z=1089$
- Population III supermassive stars, super-supernovae, and black holes, $z=17$ (age ~ 200 Myr)
- Galaxy formation in small parts, star formation, merging and clustering of galaxy parts, until $z \sim 1$
- Earth and Sun form, 4.5 billion years ago
- Mammals dominant, ~ 55 million years ago
- Humans, lions, tigers, mammoths, 1-2 million years ago
- Telescopes, Galileo, 1609: ~ 400 yr
- Theory of Special Relativity, 100 yr
- NASA founded, Oct. 1, 1958
- Signs of life on other planets ...?
- Far future: we’re toast (1 billion yrs)
- Andromeda Nebula collides with Milky Way (5 billion years)
- Sun goes out (7.6 billion years)
- Universe continues to expand faster, we lose sight of other galaxies
- Universe goes dark?

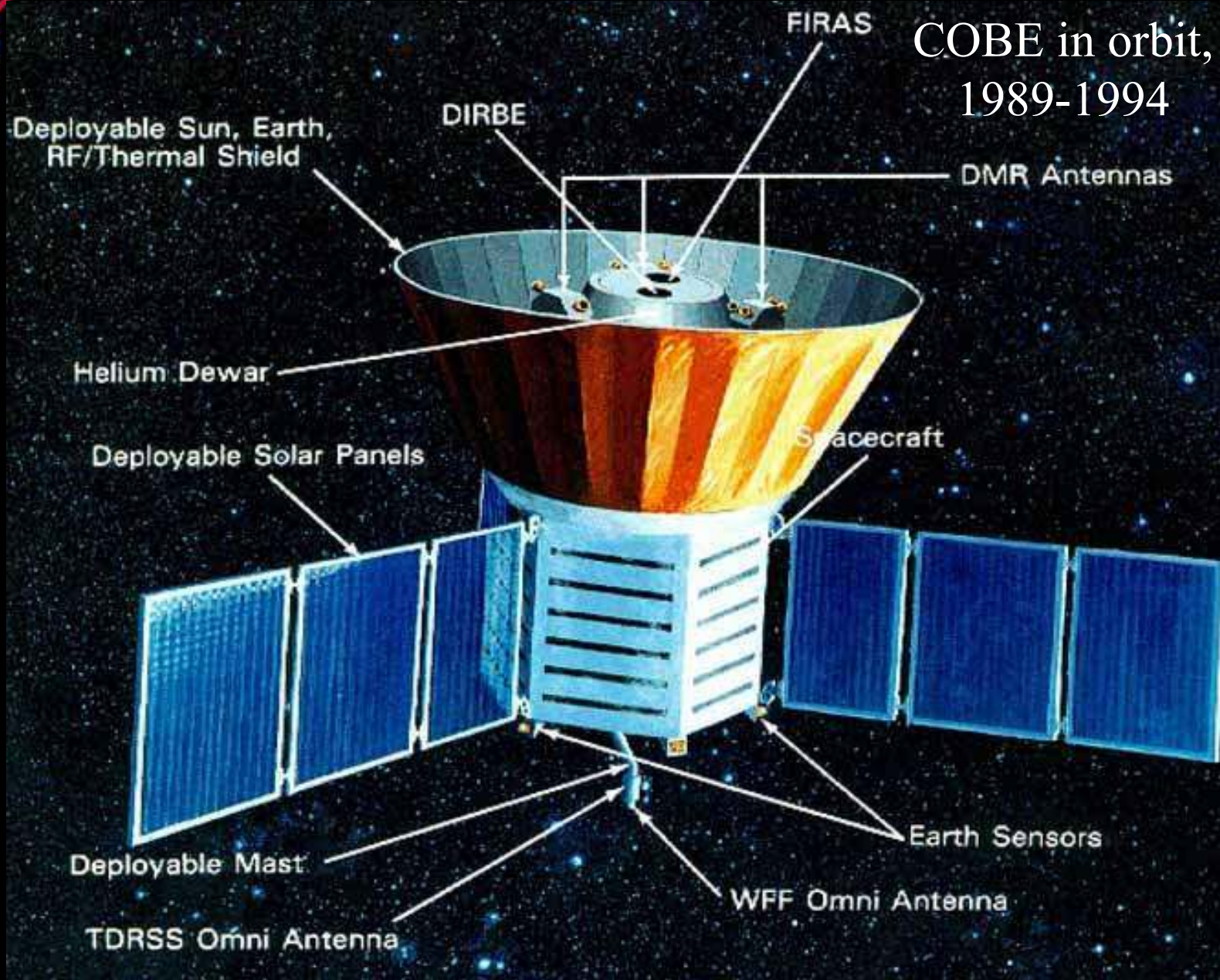


COBE (Cosmic Background Explorer) History

- 1976, Mission Definition Science Team selected by NASA HQ (Nancy Boggess, Program Scientist); PI's chosen
- ~ 1979, decision to build COBE in-house at Goddard Space Flight Center
- 1982, approval to construct for flight
- 1986, Challenger explosion, start COBE redesign for Delta launch
- 1989, Nov. 18, launch
- 1990, first spectrum results; helium ends in 10 mo
- 1992, first anisotropy results
- 1994, end operations
- 1998, major cosmic IR background results

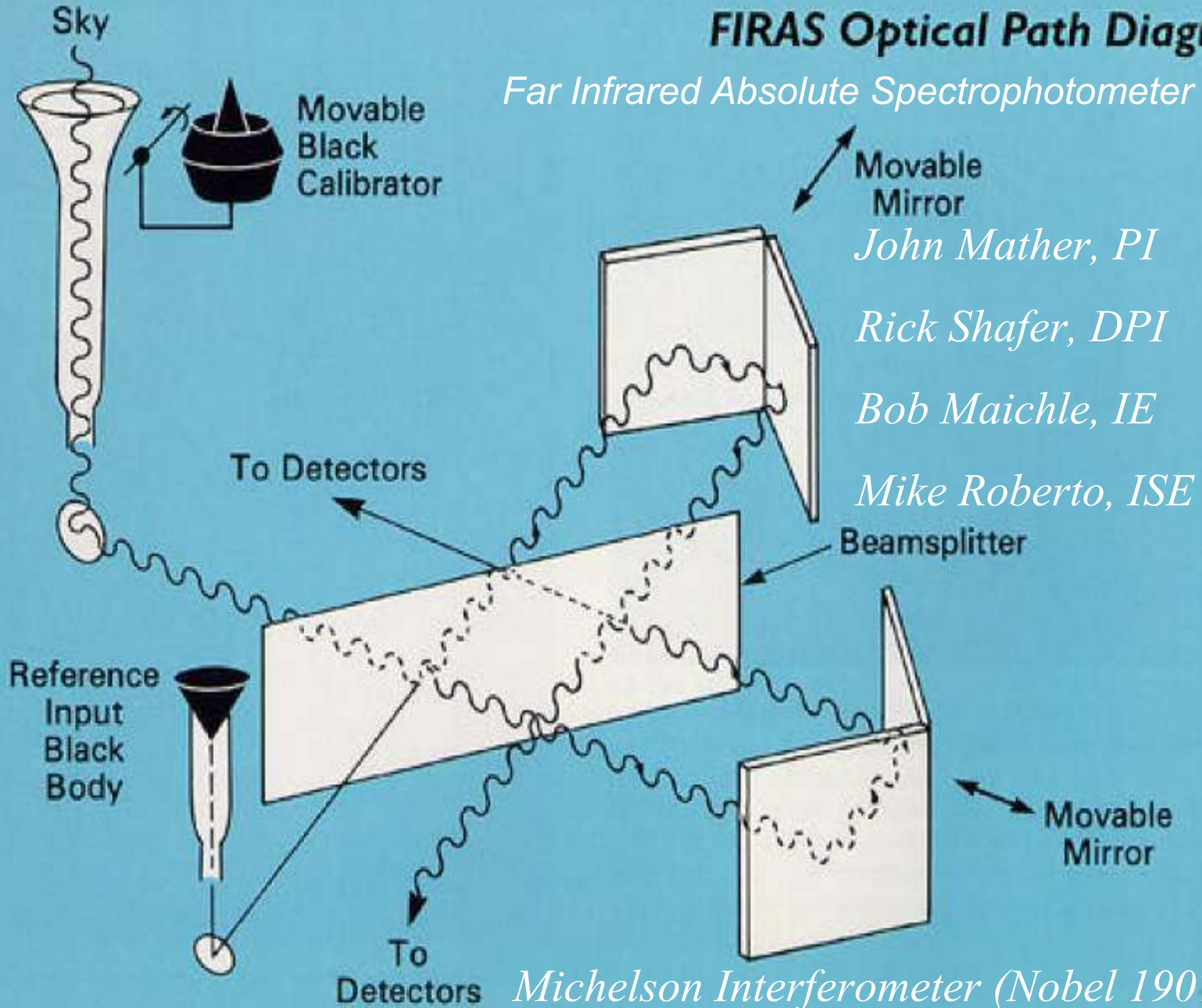


COBE in orbit, 1989-1994



FIRAS Optical Path Diagram

Far Infrared Absolute Spectrophotometer



John Mather, PI

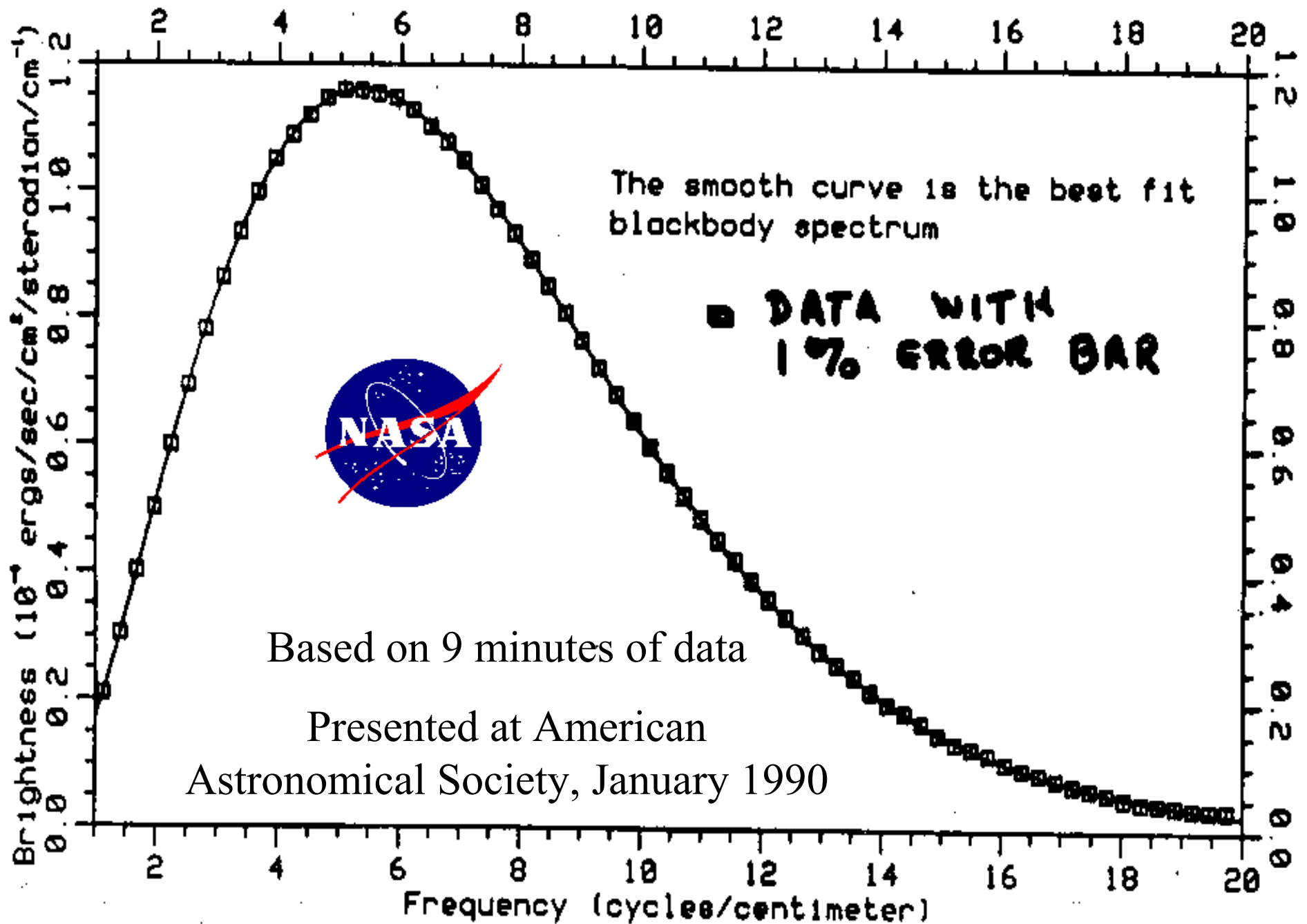
Rick Shafer, DPI

Bob Maichle, IE

Mike Roberto, ISE

Michelson Interferometer (Nobel 1907)

Cosmic Background Spectrum at the North Galactic Pole





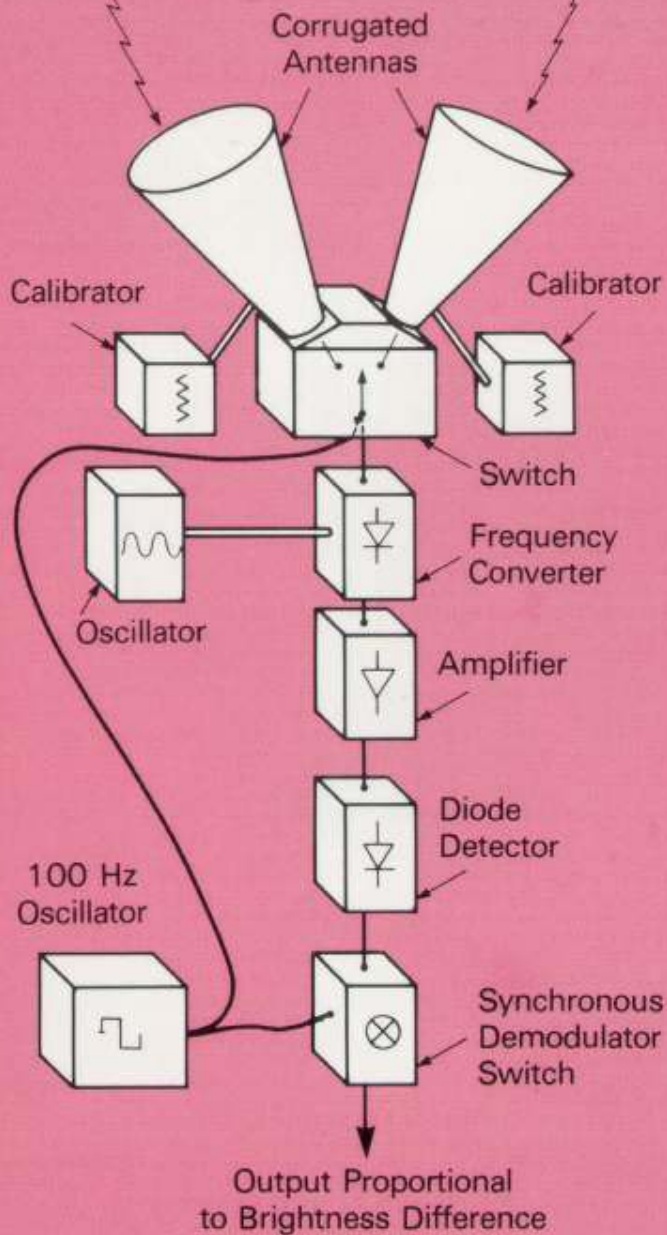
Significance of Spectrum

- Old data were wrong! Old theories explaining bad data were wrong too!
- Hot Big Bang explains everything here. Steady State theory (main alternative) doesn't.
- It was all very “simple” - just a single giant, very uniform “explosion” of the whole universe!



DMR Signal Flow Diagram

Differential Microwave Radiometers



George Smoot

Chuck Bennett

Bernie Klein

Steve Leete



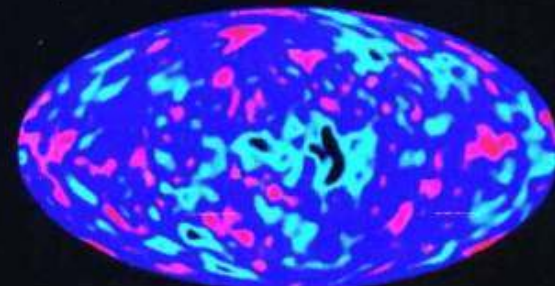
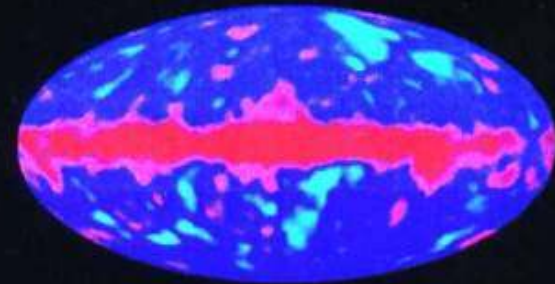
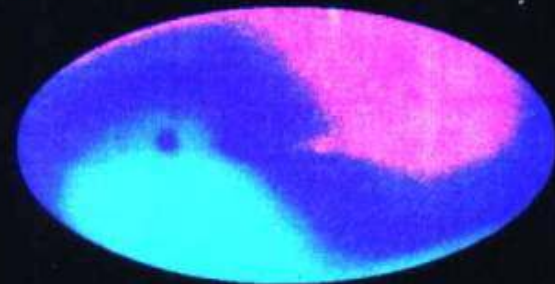
Sky map from DMR,
2.7 K +/- 0.003 K

Doppler Effect of Sun's
motion removed ($v/c = 0.001$)

Cosmic temperature/density
variations at 389,000 years, +/-
0.00003 K (part in 100,000)

PHYSICS TODAY

JUNE 1992



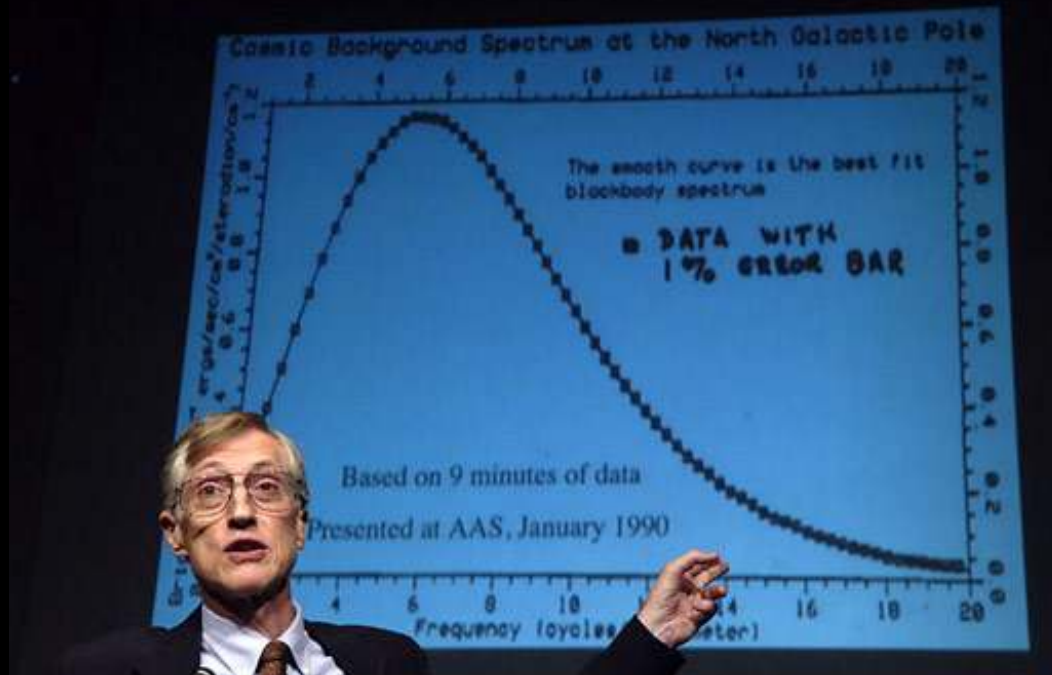


Nobel Prize Press Release

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2006 jointly to **John C. Mather**, NASA Goddard Space Flight Center, Greenbelt, MD, USA, and **George F. Smoot**, University of California, Berkeley, CA, USA *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*.



From Press Conference to Stockholm



July 2, 2008

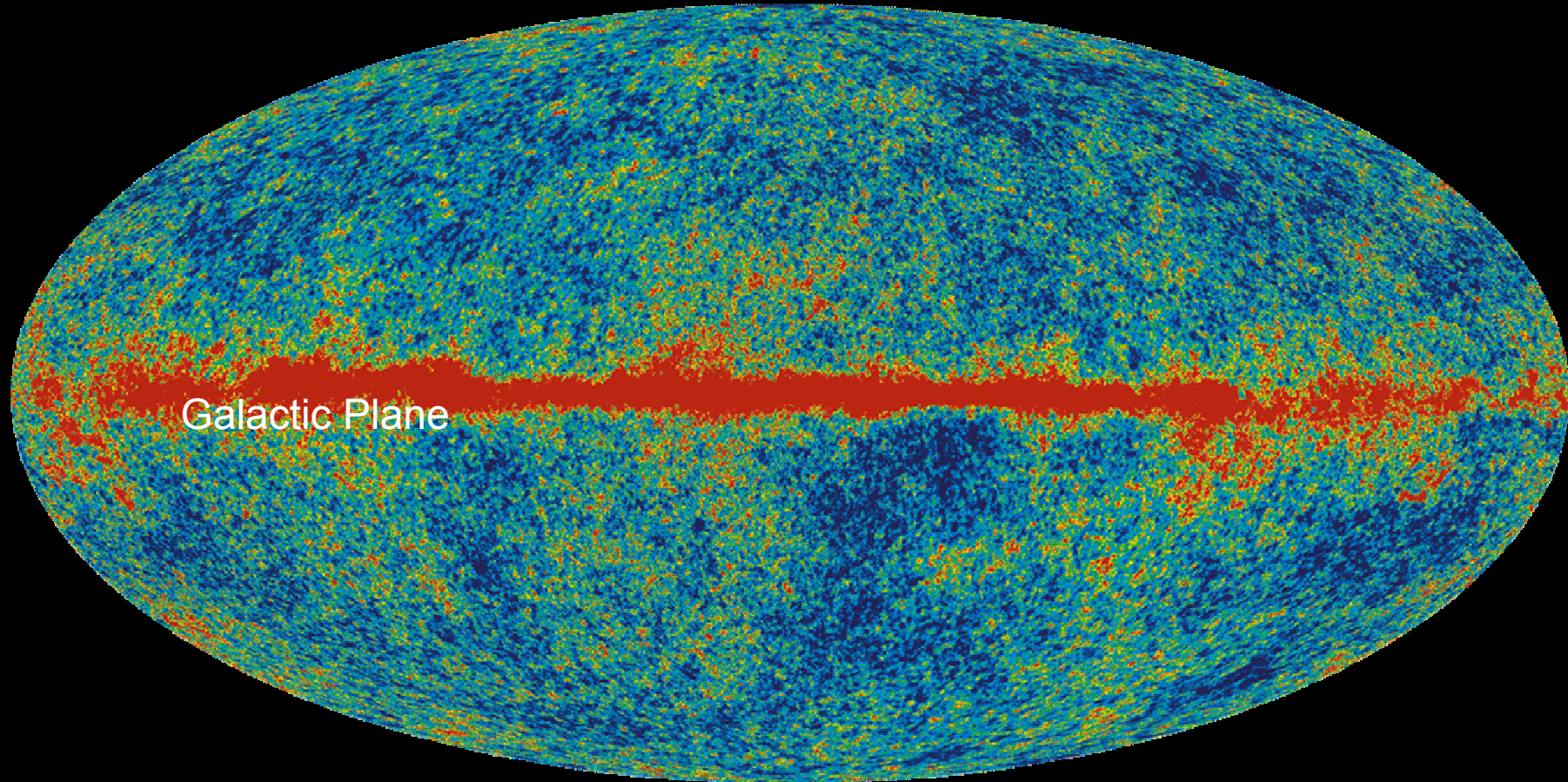
Mather Crete 2008



24



The Universe at age 380,000 years as seen by Wilkinson Microwave Anisotropy Probe (3 years of data)



Galactic Plane



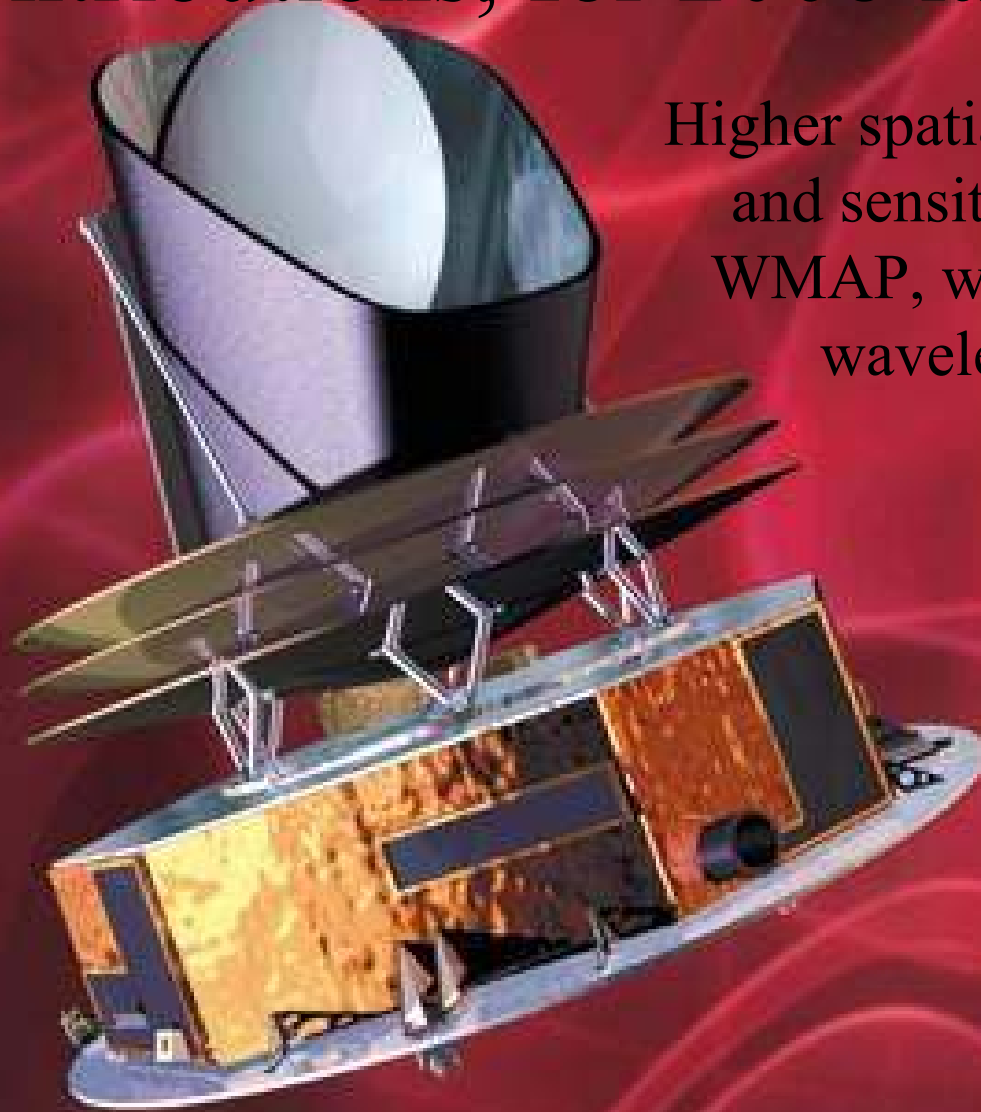
July 2, 2008

Mather Crete 2008

25

Planck Mission - ESA-led with NASA contributions, for 2008 launch

Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

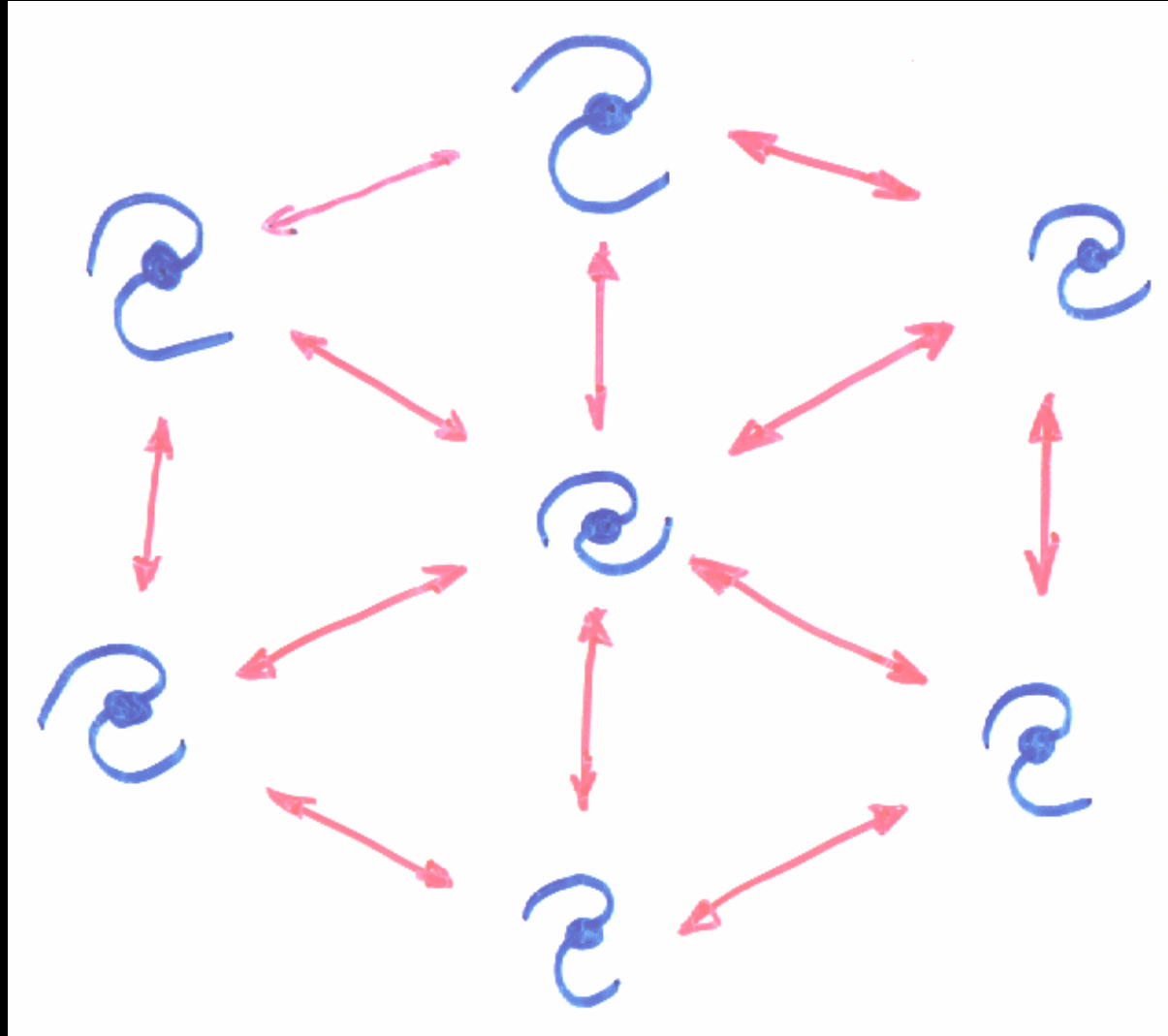


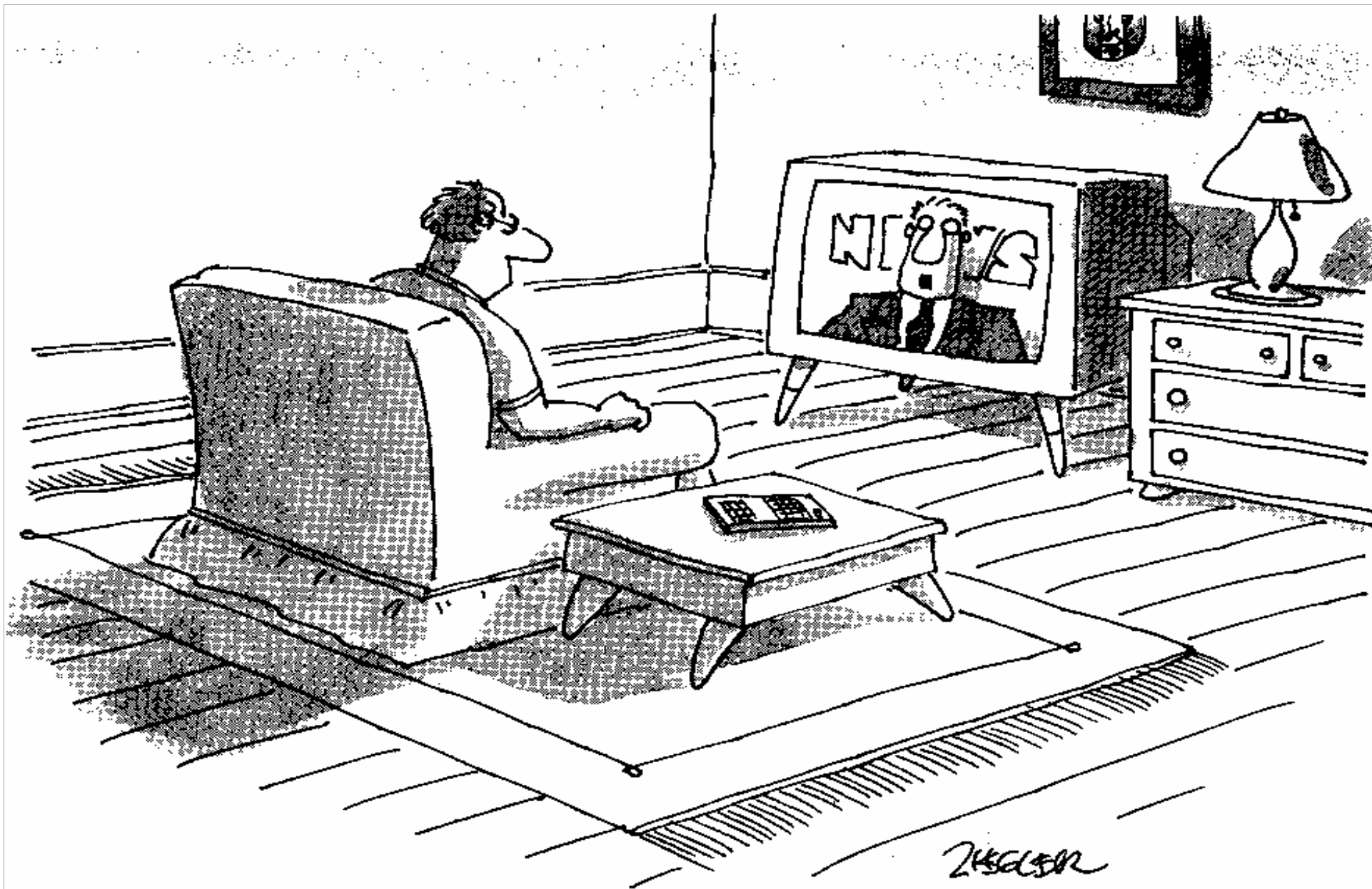


Galaxies attract each other, so the expansion should be slowing down -- Right??

To tell, we need to compare the velocity we measure on nearby galaxies to ones at very high redshift.

In other words, we need to extend Hubble's velocity vs distance plot to much greater distances.

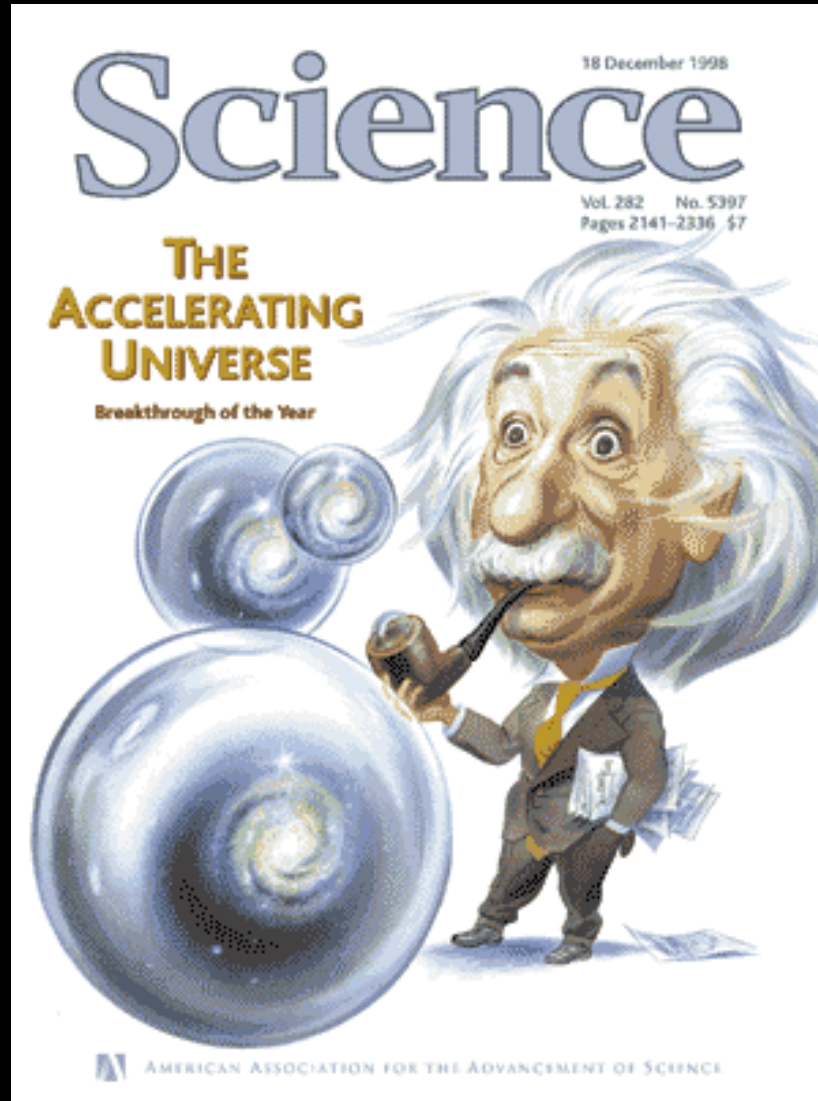




"Scientists confirmed today that everything we know about the structure of the universe is wronged-y-wrong-wrong."

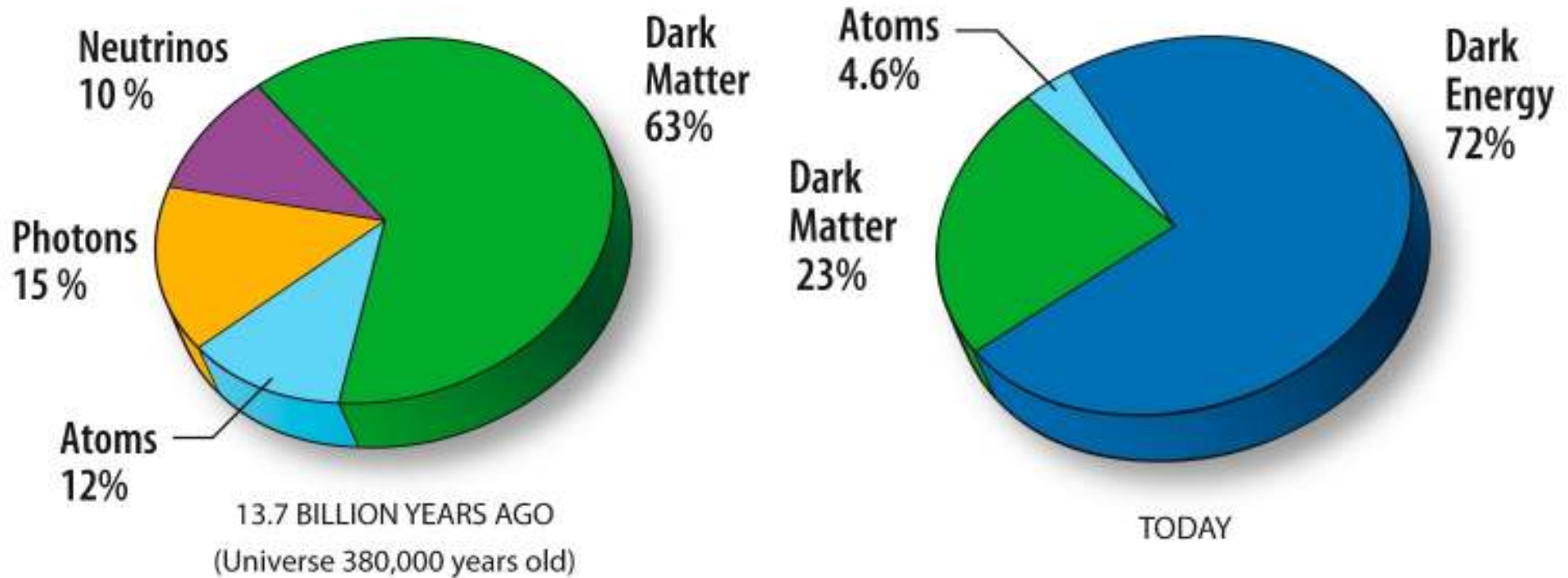


Dark Energy!





Changing Mix of Mysteries

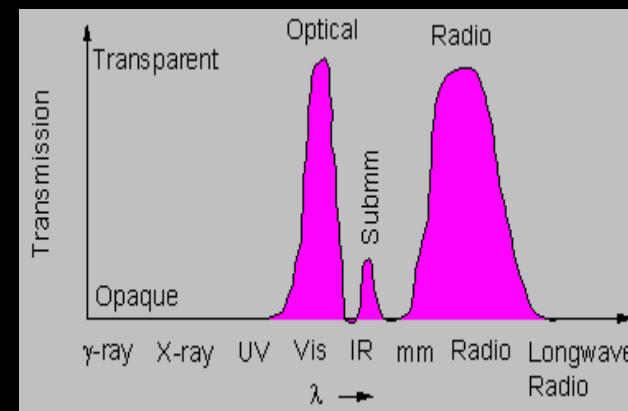
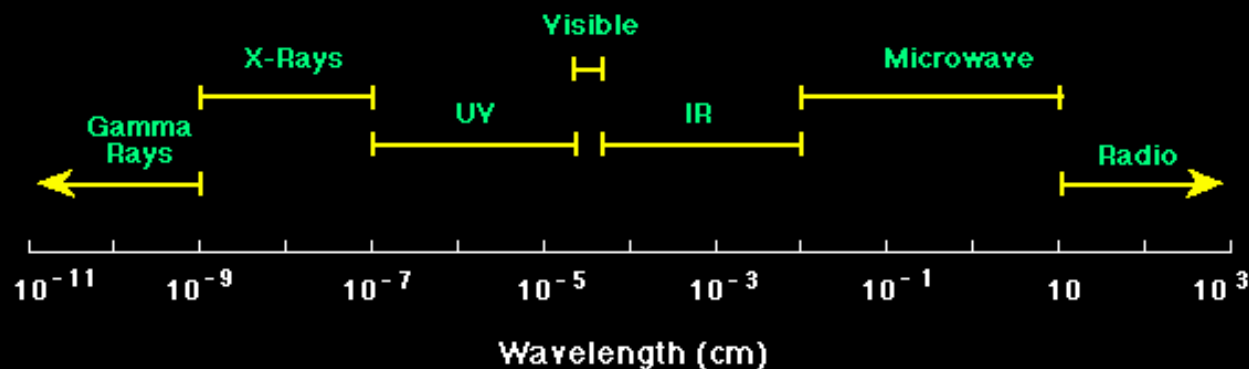


- Photon and neutrino fractions diminish
- Dark Energy fraction grows with time

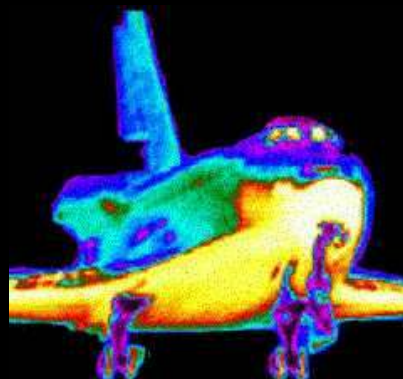


Light comes in more colors than our eyes can see

Light from the first galaxies is **redshifted** from the visible into the infrared.



Infrared is heat radiation
Our eyes can't see it, but our skin can feel it





James Webb Space Telescope (JWST)

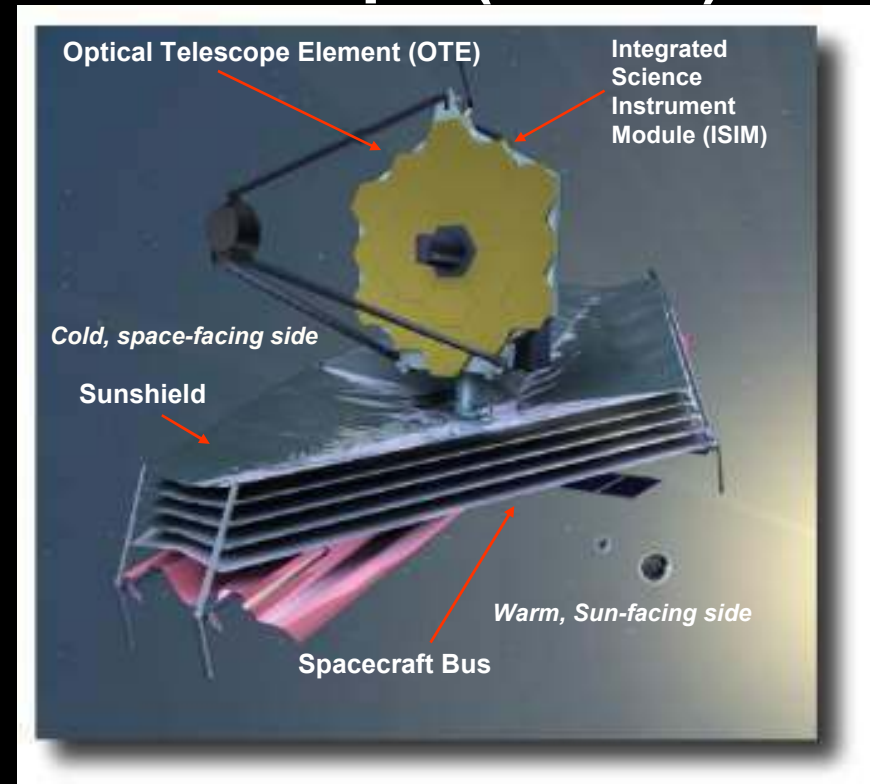
Organization

- 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 Spectrograph (NIRSpec) – ESA
 - Mid-Infrared Instrument (MIRI) – JPL/ESA
 - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute

Description

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

www.JWST.nasa.gov



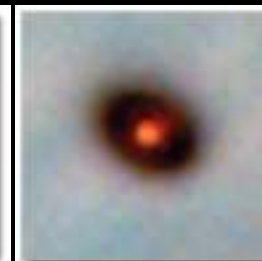
JWST Science Themes



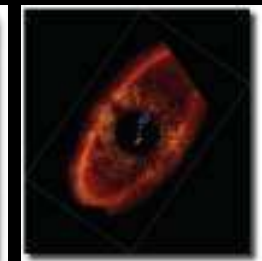
End of the dark ages: First light and reionization



The assembly of galaxies



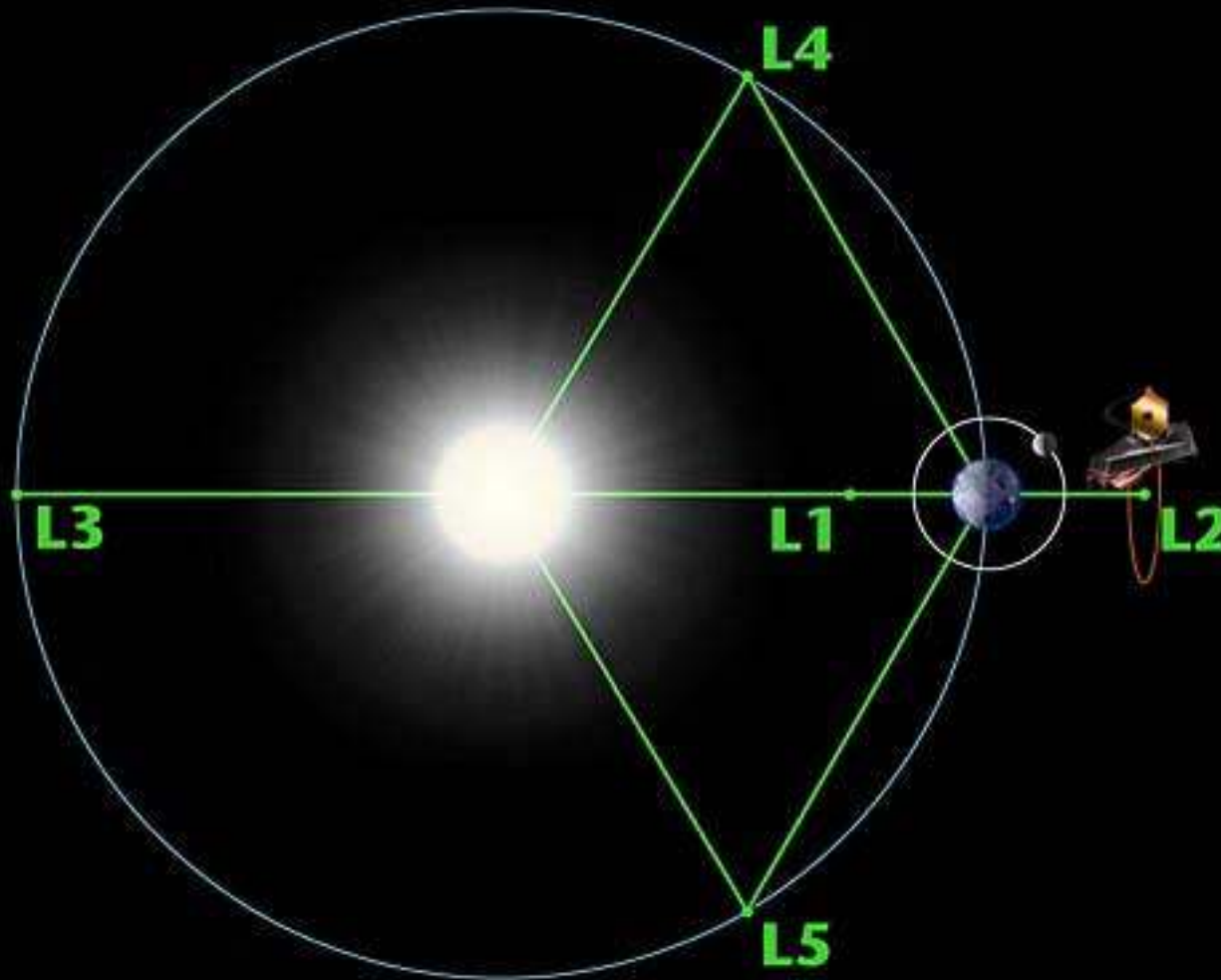
Birth of stars and proto-planetary systems



Planetary systems and the origin of life



JWST Orbits the Sun-Earth Lagrange Point L2





Full scale model at GSFC



JWST Deployment video

July 2, 2008

Mather Crete 2008

35

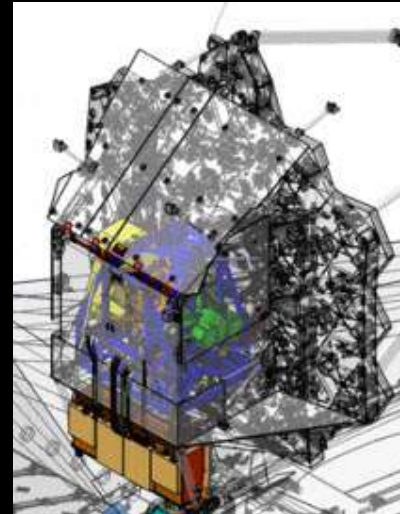


JWST Technology

Mirror Phasing Algorithms



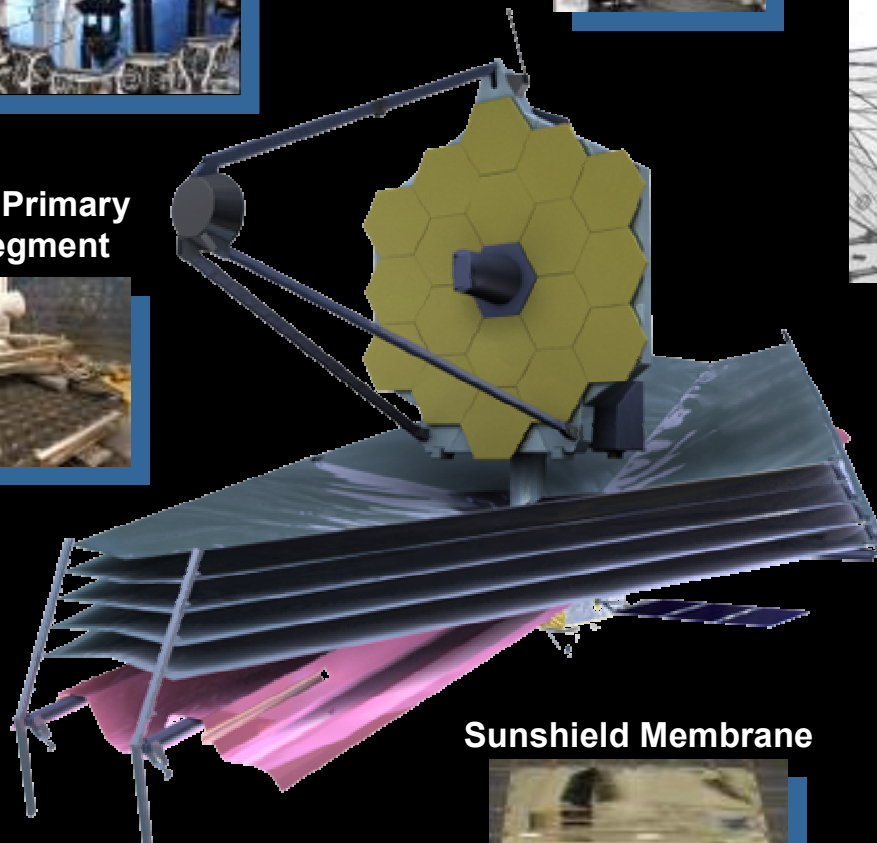
Backplane



Near-Infrared Detector



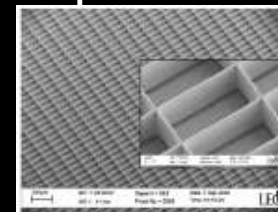
Beryllium Primary Mirror Segment



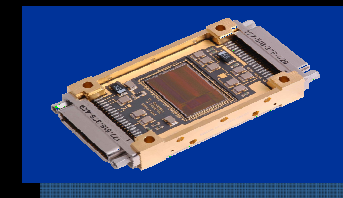
Mid-Infrared Detector



μ Shutters



Cryogenic ASICs



Cryocooler



Sunshield Membrane



July 2, 2008

2008

36



Testbed Telescope



July 2, 2008

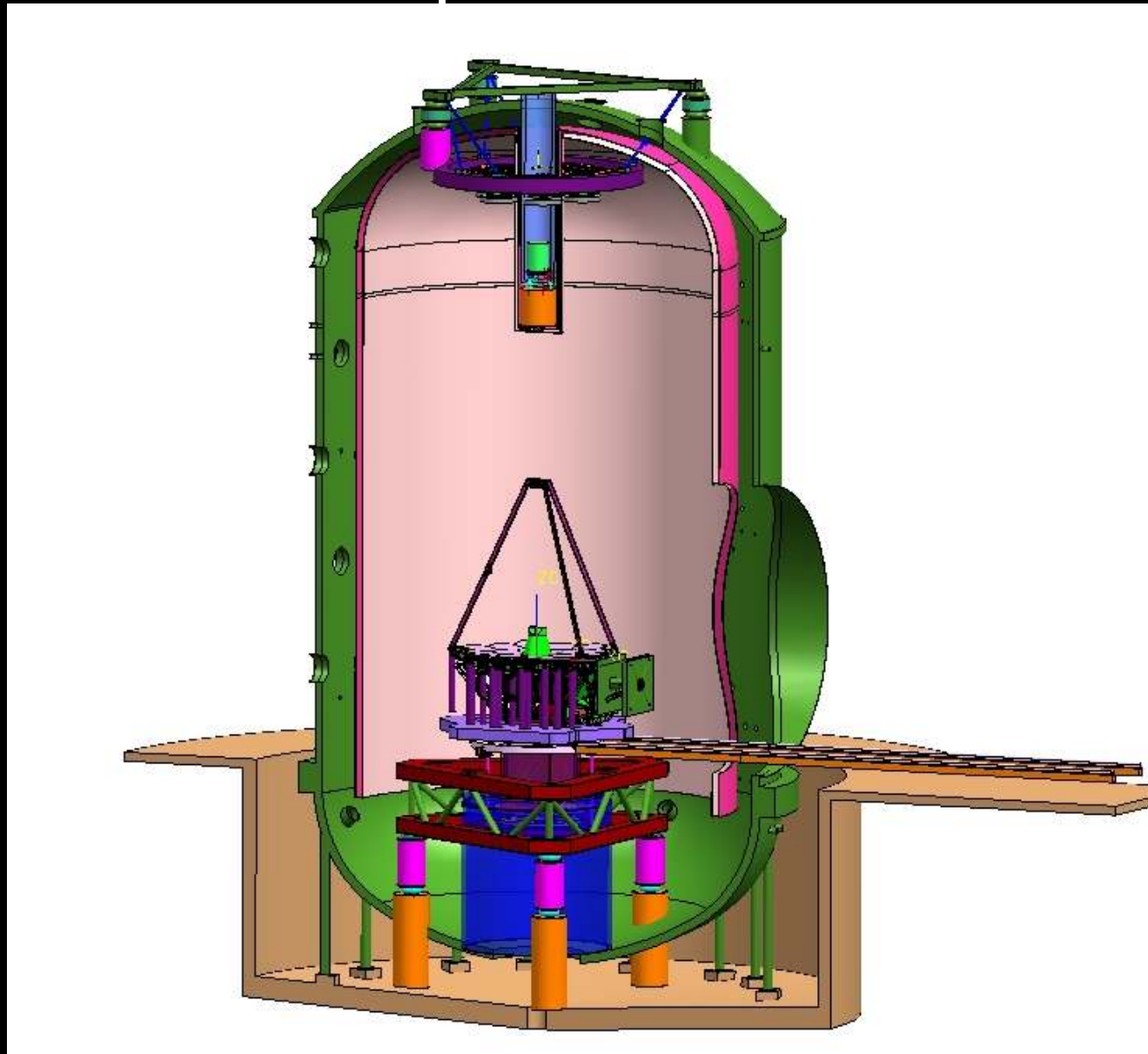


- 1/6 scale model with all the same adjustments
- Proves that all the adjustment procedures work as expected

Mather Crete 2008

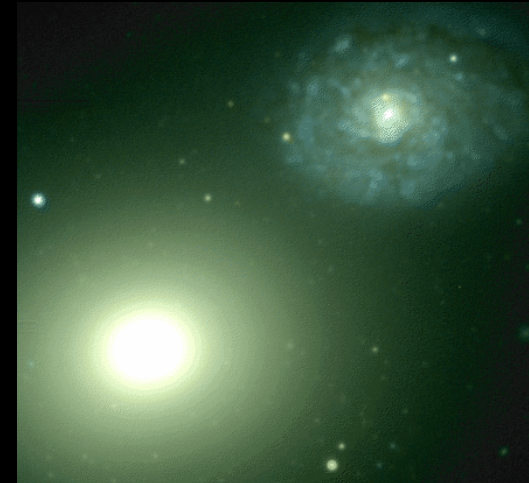
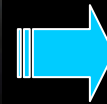
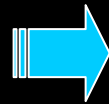


JWST cold optical test in Houston





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
- Observations:
 - NIRCам imaging
 - Spectra of 1000s of galaxies

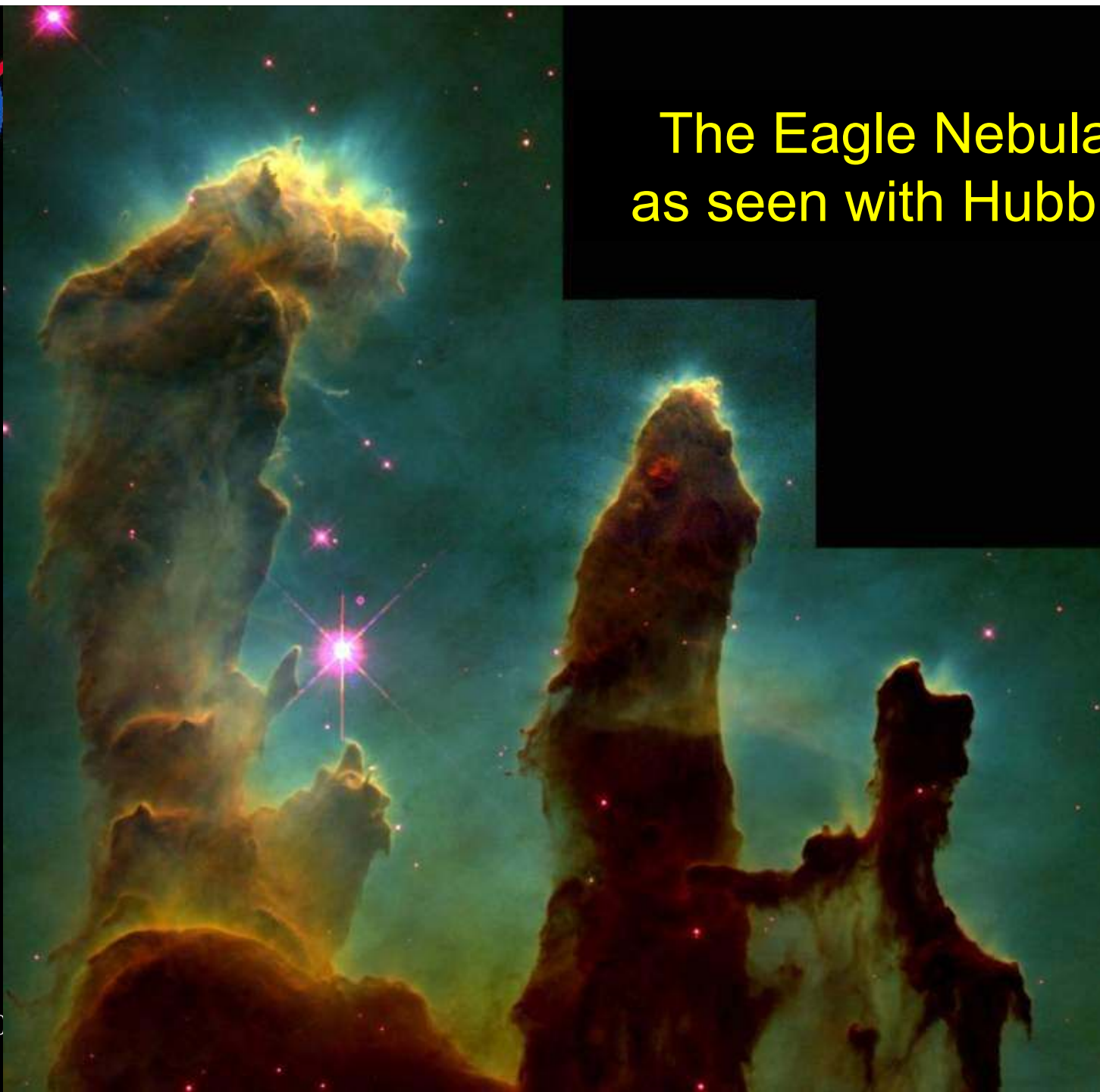


End of the dark ages: first light?

S. Beckwith and
HUDF team , 2004

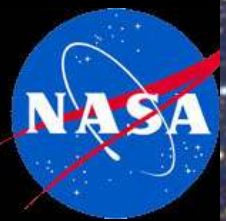


The Eagle Nebula as seen with Hubble



July 2, 20

41



The Eagle Nebula as seen in the infrared



M. J. McCaughrean
and M. Andersen, 1994



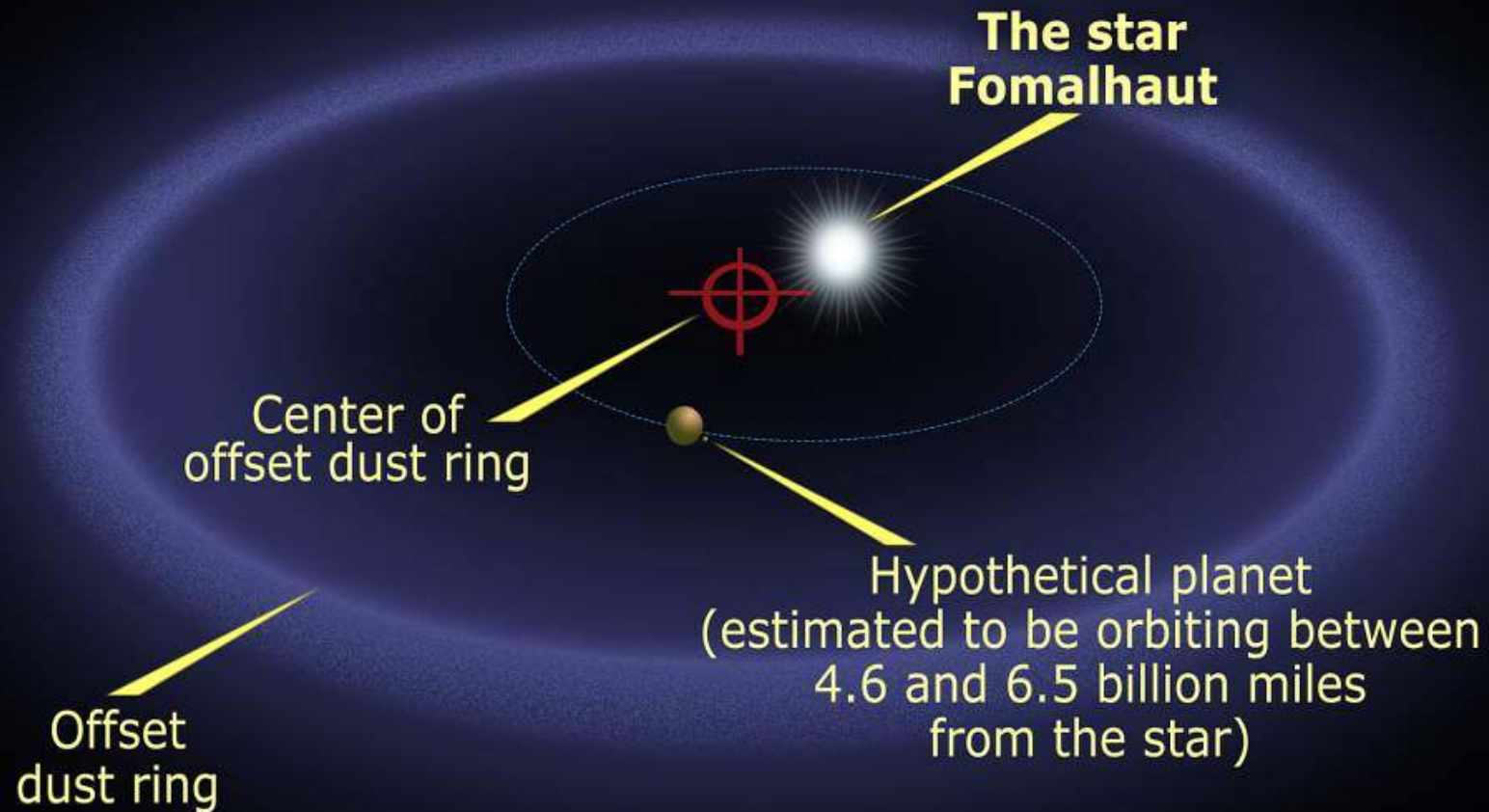
Stars in dust disks in Orion



C. R. Odell et al. 1994



Planetary systems and the origins of life



Kalas, Graham and Clampin 2005



Primary

Secondary

- Planet blocks light from star
- Visible/NIR light (Hubble/JWST)
- Radius of planet/star
- Absorption spectroscopy of planet's atmosphere
- JWST: Look for moons, constituents of atmosphere, Earth-like planets with water

July 2, 2008

- Star blocks light from planet
- Mid-Infrared light (Spitzer/JWST)
- Direct detection of photons from planet
- Temperature of planet
- Emission from surface
- JWST: Atmospheric characteristics, constituents of atmosphere, map planets

Mather Crete 2008

45

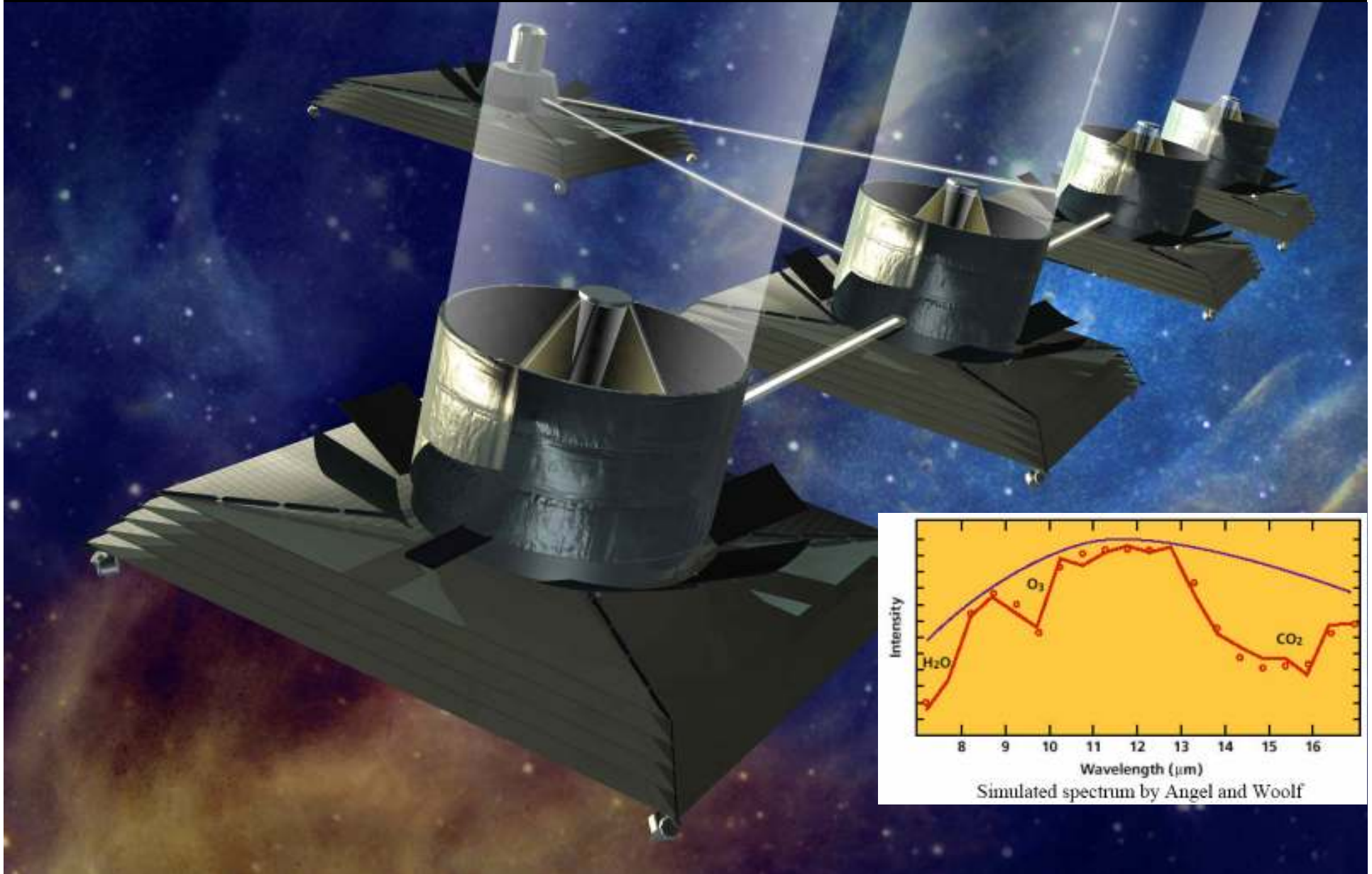


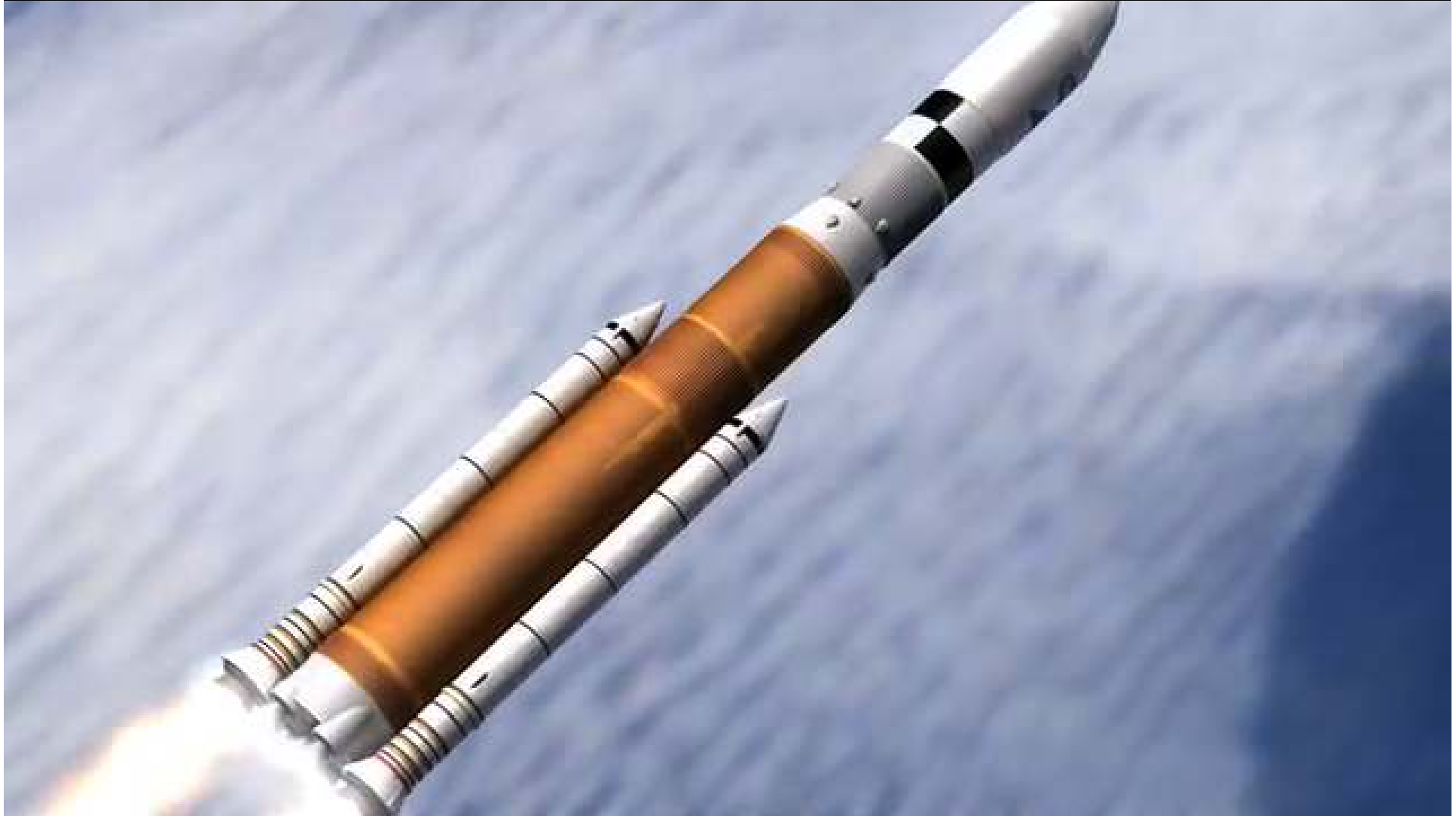
Europa

Europa has an ocean and ice sheets



Terrestrial Planet Finder Concept - Interferometer





July 2, 2008

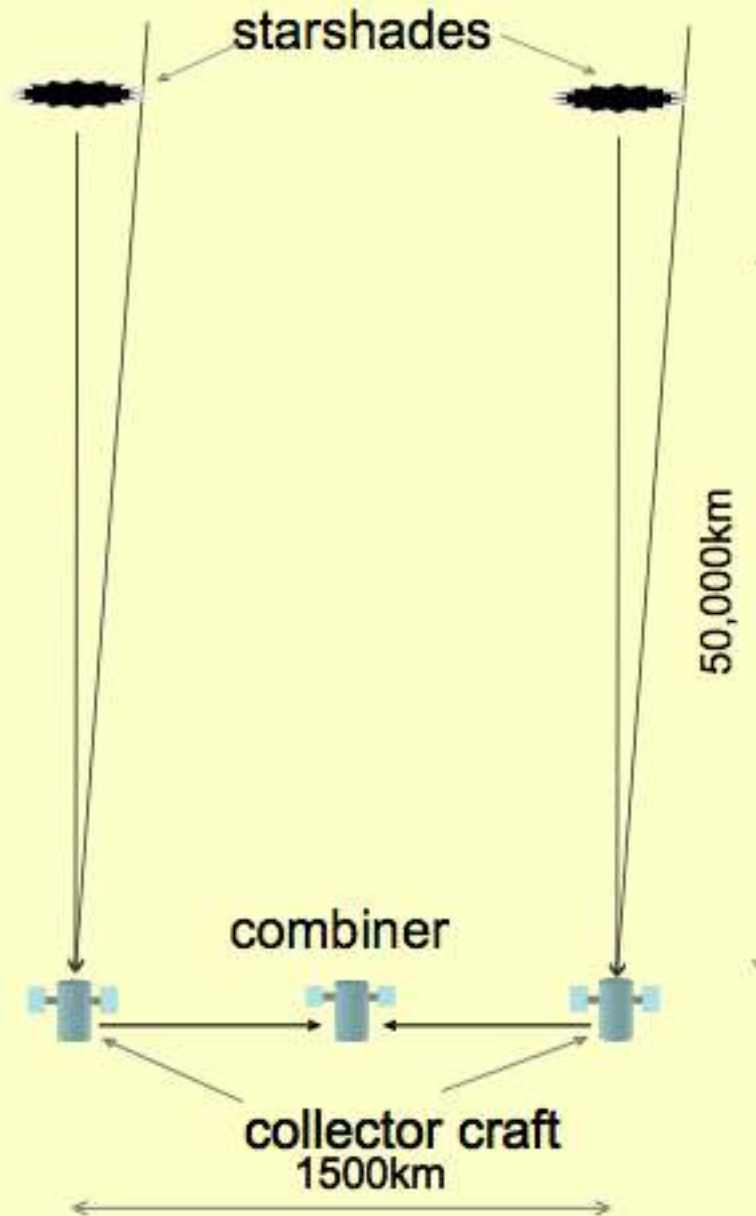
Mather Crete 2008

48

NWI Concept

New Worlds
Imager

Webster Cash
concept, University
of Colorado



What happened before the Big Bang?

What's at the center of a black hole?

How did we get here?

Are we alone?

What is our cosmic destiny?

What are space and time?

... Big Questions, open now!



The End

And the beginning!



Goddard Summer Programs

- <http://university.gsfc.nasa.gov/>
- Undergraduate applications
 - Open Nov. 15, 2007
 - Close Jan. 14, 2008

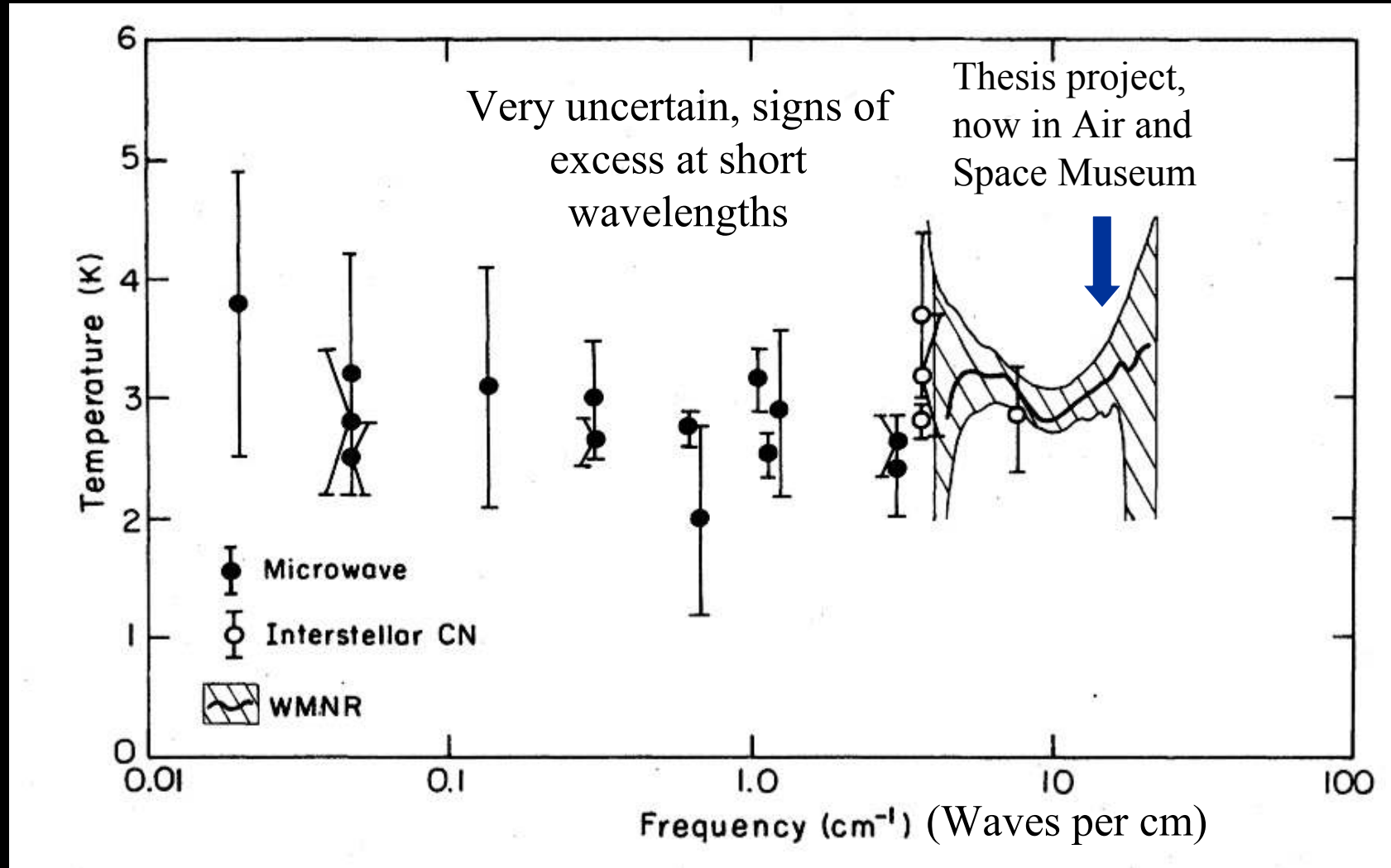


Physics in 1970

- 1965, Cosmic Microwave Background discovery announced - Penzias & Wilson (Nobel 1978); Dicke, Peebles, Roll, & Wilkinson theory paper
- CMB spectrum appears wrong: 50x too much energy at short wavelengths, possible spectrum line in it
- Richards, Townes, Werner, Mather, and Woody start CMB projects
- Lockin amplifier used vacuum tubes
- Fast Fourier transform just invented, no pocket calculators yet
- PDP-11 advanced lab computer programmed by paper tape
- IR detectors made with wire saw, CP-4 etch, indium solder, and tiny wires, with tweezers



Measured Background Radiation, 1975, from thesis project, completed by Woody





How the Universe (might have) made Galaxies



COBE (Cosmic Background Explorer) Pre-History

- 1974, NASA Announcement of Opportunity for Explorer satellites: ~ 150 proposals, including:
 - 2 IRAS (Infrared Astronomical Satellite) proposals
 - JPL anisotropy proposal (Gulkin, Janssen...)
 - Berkeley anisotropy proposal (Alvarez, Smoot...)
 - NASA Goddard/MIT/Princeton COBE proposal (Hauser, Mather, Muehlner, Silverberg, Thaddeus, Weiss, Wilkinson)



Confirming the Big Bang Theory



© Eli Dwek

I wish He wouldn't keep that
darn thermostat at 3 K!



How do planets form?

- Giant planets could be signpost of process that creates Earth-like planets
- Solar System primordial disk is now in small planets, moons, asteroids and comets
- Observations:
 - Coronagraphy of exosolar planets
 - Transits
 - Compare spectra of comets and circumstellar disks



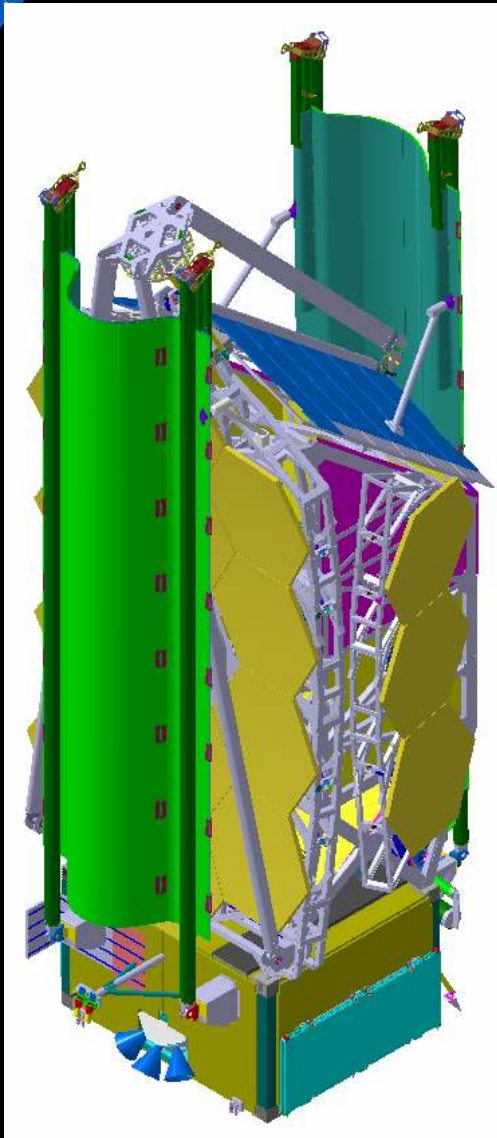
Planetary Transits

- Transit:
 - When a planet goes between its star and our line of sight.
- We can learn:
 - Planet size & mass → composition!
 - Constituents of the atmosphere.
 - Temperature of the planet.

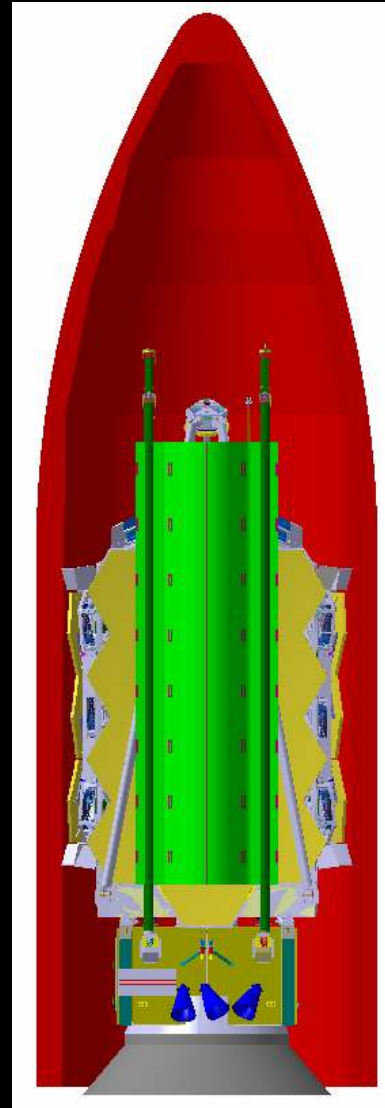
STEREO view of the Moon transiting the Sun



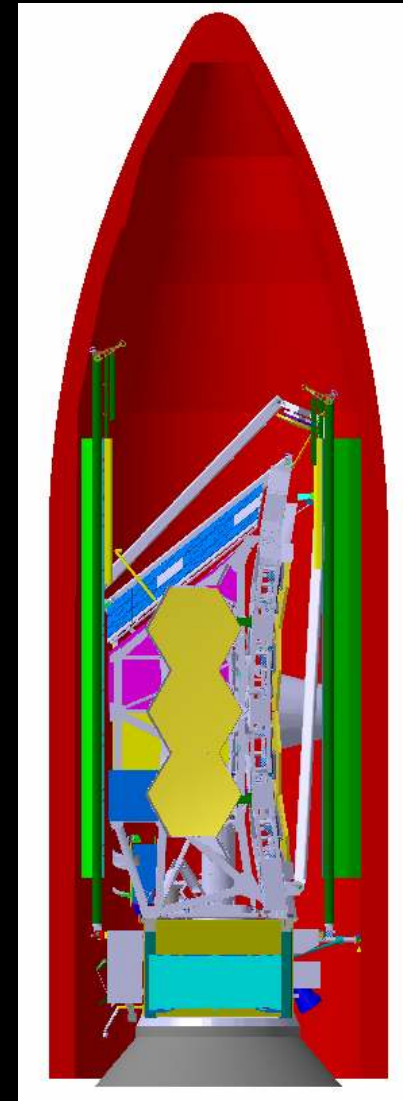
JWST folds up inside ESA-provided Ariane 5



July 2, 2008



Mather Crete 2008

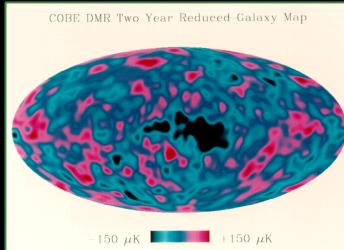


60



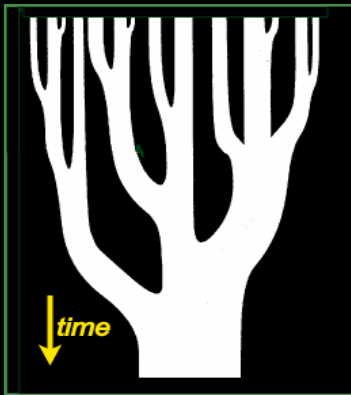
Breve historial del Universo

Big Bang
seen by
COBE &
WMAP



?

Galaxy
assembly



?

Galaxies,
stars,
planets,
life

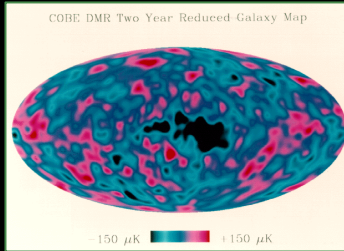


- Tremendo follon espacial - expansion exponencial, fluctuaciones primordiales, materia/antimateria, materia oscura, energia oscura, hace 13.7 +/- 0.2 mil millones de años.
- Aniquilacion de antiparticulas, 1 parte en mil millon de materia remanente
- Formacion de nucleos de helio, 3 minutos, redshift $z = 10^9$
 - $[1+z = \text{tamaño del universo ahora/tamaño entonces}]$
- Formacion del gas neutro “recombinacion”, 389,000 años, $z=1089$
- Poblacion III estrellas supermasivas, super-supernovas, y agujeros negros, $z = 17$, (edad 200 Maños)
- Formacion de galaxias en trozos pequeños, formacion estelar, coagulacion y acumulacion de trozos de galaxias, hasta $z \sim 1$
- Tierra y Sol se formaron, hace 4.5 mil millones de años
- Mamiferos dominan, hace ~ 55 millones de años
- Seres humanos, leones, tigres, y mamuts, hace 1-2 millones de años
- Telescopios, Galileo, 1609: ~ 400 años
- Teoria de relatividad especial, 100 años
- Fundacion de la NASA, 1 Oct. 1958
- Indicios de vida en otros planetas...?
- Futuro: nos freimos (mil millones de años), Nebulosa de Andromeda chocara con la Via Lactea (5 mil millones), Sol se apaga (7.6 mil millones), universo sigue en expansion cada vez mas rapida, las luces del universo se apagan



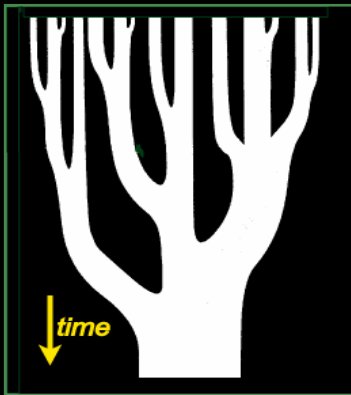
Breve historial del Universo

Big Bang
seen by
COBE &
WMAP



?

Galaxy
assembly



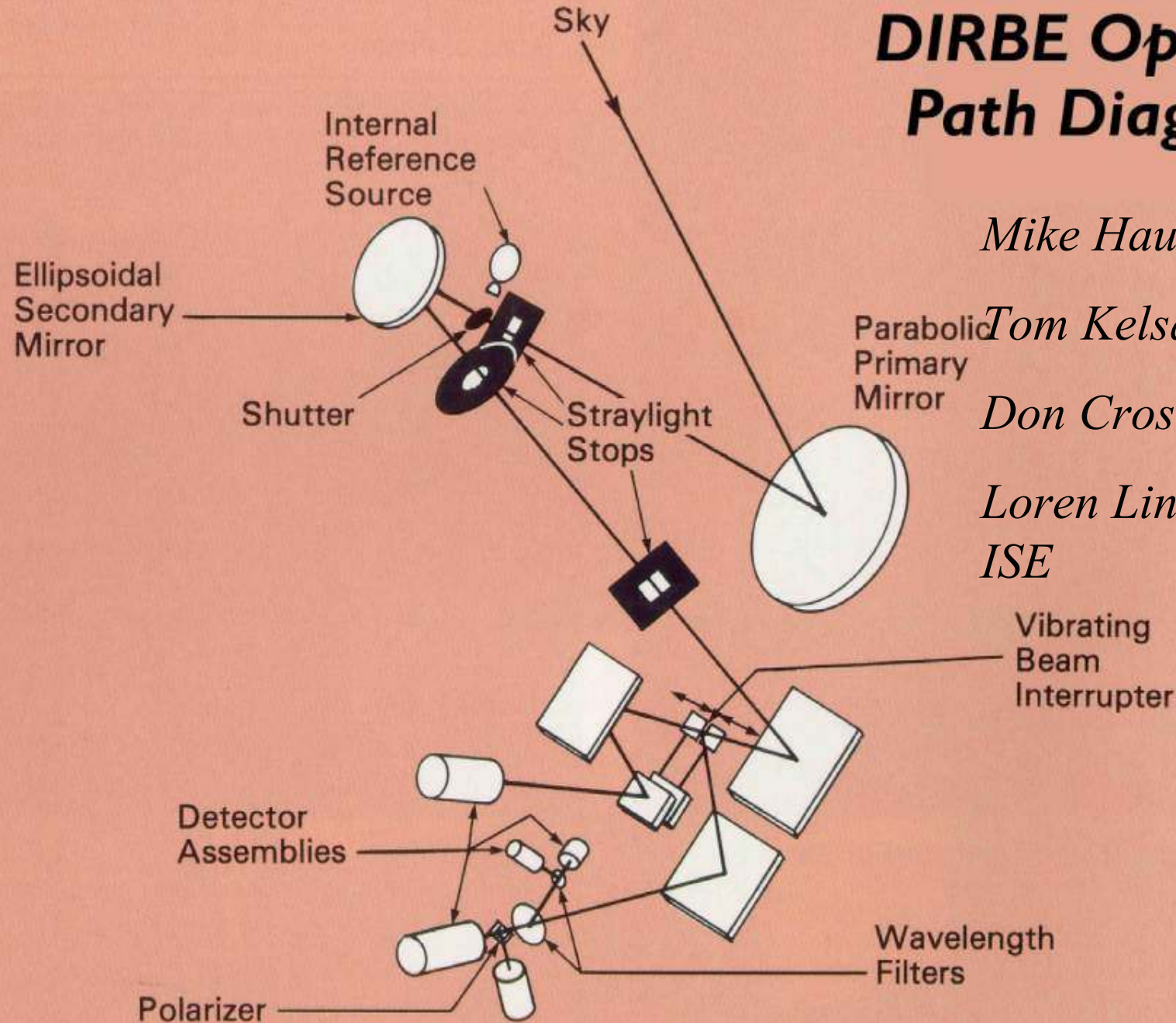
?

Galaxies,
stars,
planets,
life



- Tremendo follon espacial - expansion exponencial, fluctuaciones primordiales, materia/antimateria, materia oscura, energia oscura, hace 13.7 +/- 0.2 mil millones de años.
- Aniquilacion de antiparticulas, 1 parte en mil millon de materia remanente
- Formacion de nucleos de helio, 3 minutos, redshift $z = 10^9$
 - $[1+z = \text{tamaño del universo ahora/tamaño entonces}]$
- Formacion del gas neutro “rcombinacion”, 389,000 años, $z=1089$
- Poblacion III estrellas supermasivas, super-supernovas, y agujeros negros, $z = 17$, (edad 200 Maños)
- Formacion de galaxias en trozos pequeños, formacion estelar, coagulacion y acumulacion de trozos de galaxias, hasta $z \sim 1$
- Tierra y Sol se formaron, hace 4.5 mil millones de años
- Mamiferos dominan, hace ~ 55 millones de años
- Seres humanos, leones, tigres, y mamuts, hace 1-2 millones de años
- Telescopios, Galileo, 1609: ~ 400 años
- Teoria de relatividad especial, 1905, ~100 años
- Fundacion de la NASA, 1 Oct. 1958
- Indicios de vida en otros planetas...?
- Futuro: nos freimos (mil millones de años), Nebulosa de Andromeda chocara con la Via Lactea (5 mil millones), Sol se apaga (7.6 mil millones), universo sigue en expansion cada vez mas rapida, las luces del universo se apagan

DIRBE Optical Path Diagram



Mike Hauser, PI

Tom Kelsall, DPI

Don Crosby, IE

Loren Linstrom, ISE