



# Cosmology: How Did We Learn About The Universe

By Dr. Philip N. Eisner  
May 2015

Ptolemy made a universe, which lasted 1400 years.

Newton also made a universe, which has lasted 300 years.

Einstein has made a universe, and I can't tell you how long that will last.

George Bernard Shaw, 28 October 1930

# Aurora And Milky Way



Babylonian Astronomers Make  
Careful Observations For Calendars,  
Astrology, & Fearful Eclipses  
c. 1580 BCE

570 BCE to 300 BCE

Pythagoras, Plato,  
Euclid

Pure Mathematics  
Underlies The  
Universe's Structure,  
Not Gods

600 BCE to 200 CE

Anaximander, Heraclides,  
Aristarchus, Eratosthemes,  
Hipparchus, Ptolemy  
Careful, Sophisticated  
Observations Necessary To  
Understand The Universe

1500 to present

Copernicus, Newton,  
Einstein, Lemaitre,  
Weinberg, Hawking, Guth

1570 to present

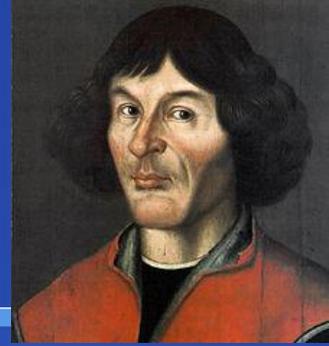
Galileo, Cassini, Brahe, Kepler,  
Herschel, Messier, Slipher,  
Hubble, Penzias & Wilson

# The Moon Passes Through The Earth's Shadow

Aristarchus →



# Copernicus (1473-1543)



- Reclusive Polish canon, who put the **Sun back at the center of the Universe** using mostly observational data from Ptolemy and later Arab astronomers.
  - His Sun-centered system improved predictive techniques for planetary positions, but epicycles and detents remained.
  - He printed a few copies of *Commentariolus* outlining his **new heliocentric model** in the early 1500's.
- His 1543 book, *De revolutionibus orbium coelestium*, is packed with data, formulas, tables, and diagrams that were only useful to skillful astronomers, yet it started **The Copernican Revolution**.



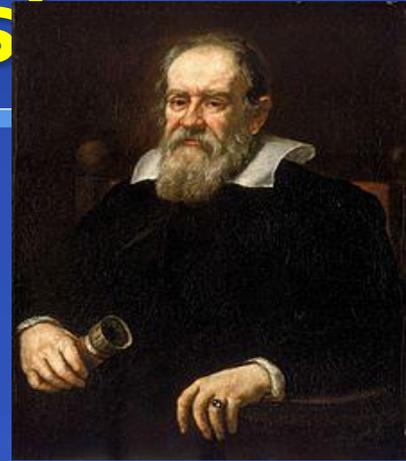
# Tycho Brahe & Johannes Kepler



- Brahe (1546-1601) developed a superbly instrumented observatory **before telescopes**.
- He discovered a bright new star, a **stella nova**, on 11/11/1572. He showed that the Great Comet of 1577 was >6 times further away than the Moon.
- Kepler (1571-1630), Brahe's disciple, and a superb observer, discovered that planets travel in **elliptical orbits (1609)** with the Sun located at one focus of the ellipse. [Kepler's 1<sup>st</sup> law of planetary motion]
- Kepler published ***Astronomia Nova*** in 1609.

# Galileo Galilei (1564-1642) - The First Truly Modern Scientist

- He developed the **experimental data** and the **mathematical equations** that describe the motion of falling objects on Earth.
- He emphasized **experimentation and mathematical description** of the results; although a pious Catholic, he believed he could lead the Church into a new era of natural philosophy.
- He read Copernicus's *De Revolutionibus* and agreed that **planets revolve around the Sun**; he insisted it was a fact of nature.



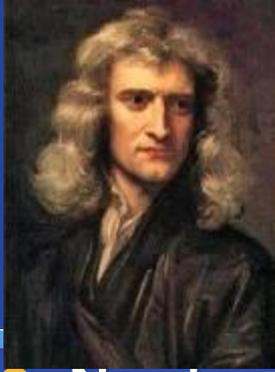
# Galileo's Two Great Publications

- First to point a **telescope** at the heavens. Discovered Venus has **phases like our Moon**, an important proof against the Ptolemaic system. Discovered Jupiter's moons and mountains on our Moon. The ***Starry Messenger*** (*Sidereus Nuncius* 1610) contains his telescopic observations.
- His 1638 masterpiece, ***Dialogues Concerning the Two New Sciences***, was published in Leyden.
- He developed the principle of **Galilean relativity**: no experiment inside a closed capsule can measure its **velocity**; only observable **relative** to other objects.

# Galileo's Refracting Telescope-1609



Galileo discovered stars **not visible with the naked eye**; he found that the Milky Way was comprised of **myriads of stars**.



# Newton (1643-1727), Gravity, And Absolute Space & Time

- Newton took Galileo's gravity equations for falling bodies on Earth and extended them to the whole Universe. He showed mathematically that an instantaneously acting  $1/R^2$  gravity force produces Kepler's elliptical orbits.
- Newton's published his masterpiece, *Philosophiæ naturalis principia mathematica*, in July 1687.
- Newton believed in **Absolute Space and Time**. Positions and movements are with respect to Absolute Space and behind our measurements is an Absolute Time that God perceives.
- He believed the **Universe is infinite** since God was infinite (and to keep all masses from **agglomerating into one mass at the center!**).
- Using relative luminosities, he measured the distance to stars. He invented the reflecting telescope, widely used to the present time.

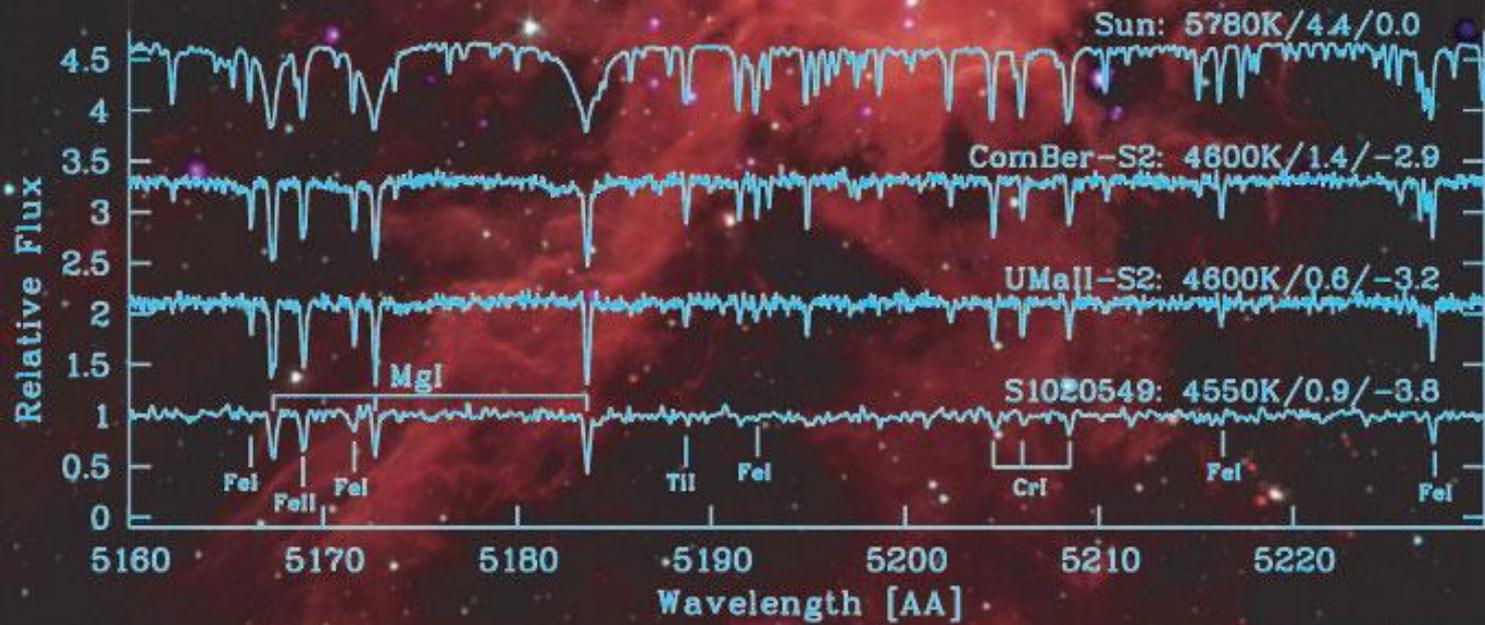


# The Observed Universe's Status In 1900



- The Universe was Newtonian and only 1000 light-years in radius. Friedrich Bessel, in 1838, measured the **distance (4-25 light years) to a few stars by parallax.**
- William Huggins' (1824-1910) spectroscopy showed that stars were made from the **same elements we observe on Earth.**
- Charles Messier, on a roof in Paris, found **110 non-star objects.**
- Discovered **Uranus and Neptune**, but telescopic observations were limited by the size of light-gathering optics, poor detector sensitivity, and increasing air and light pollution.
- **Mercury's orbit did not obey Newton's laws (Urbain Le Verrier, 1859).** Physicists could not find a medium (aether) for light waves; **light did not obey Galilean relativity.**

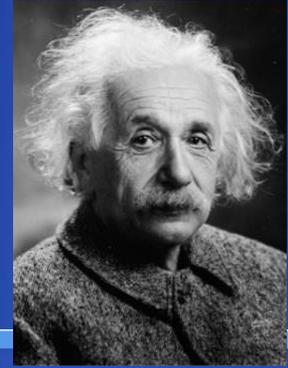
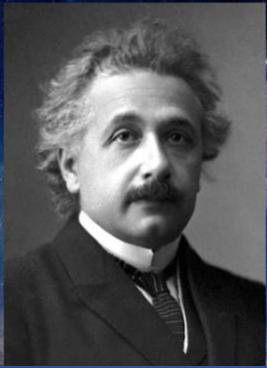
# Spectroscopy Of Stars





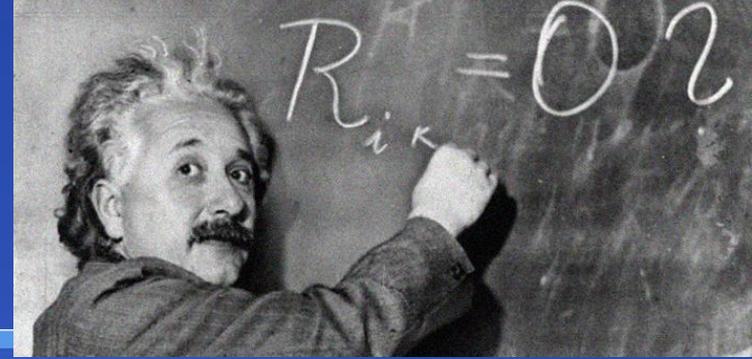
Planets & Earth's  
Moon

# Einstein's Theory of General Relativity (1915)



- Replaces Newton's theories of gravity and cosmology.
  - Eliminates action at a distance.
  - Agrees with all observations from 1915 to present.
  - Key Ideas: The Equivalence Principle and local physics is the same regardless of motion, even accelerating motion.
- Uses a **non-Euclidean** (Riemannian), 4-dimensional space-time geometry with non-linear field equations and 4-dimensional tensors to describe the Universe.
  - Mass and energy distributions **determine the space-time geometry.**
  - Objects move on **geodesics** through the curved space-time.

# General Relativity Equation



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G/c^4) T_{\mu\nu}$$

$\Lambda$  is the famous cosmological constant.

On the left are the space-time curvatures and Riemann curvature tensor; on the right is the tensor which contains the space-time energy and momentum densities. **I.e., the curvature of space-time equals the distribution of matter plus energy.**

The subscripts,  $\mu$  and  $\nu$ , represent sums over the 4 space-time dimensions. The equation above expands to 16 non-linear differential equations.

# 4 Key Tests of General Relativity

- Mercury's **orbital precession**. (Urbain Le Verrier, 1858, & Einstein's calculation, 1916)
- **Bending of light** by masses such as Sun and stars. (Arthur Eddington, 1919)
- **Gravitational time dilation and gravitational red shift**. (Pound & Rebka, 1959 & GPS)
- **Orbital decay** due to emission of gravitational waves. (Hulse & Taylor, 1974)

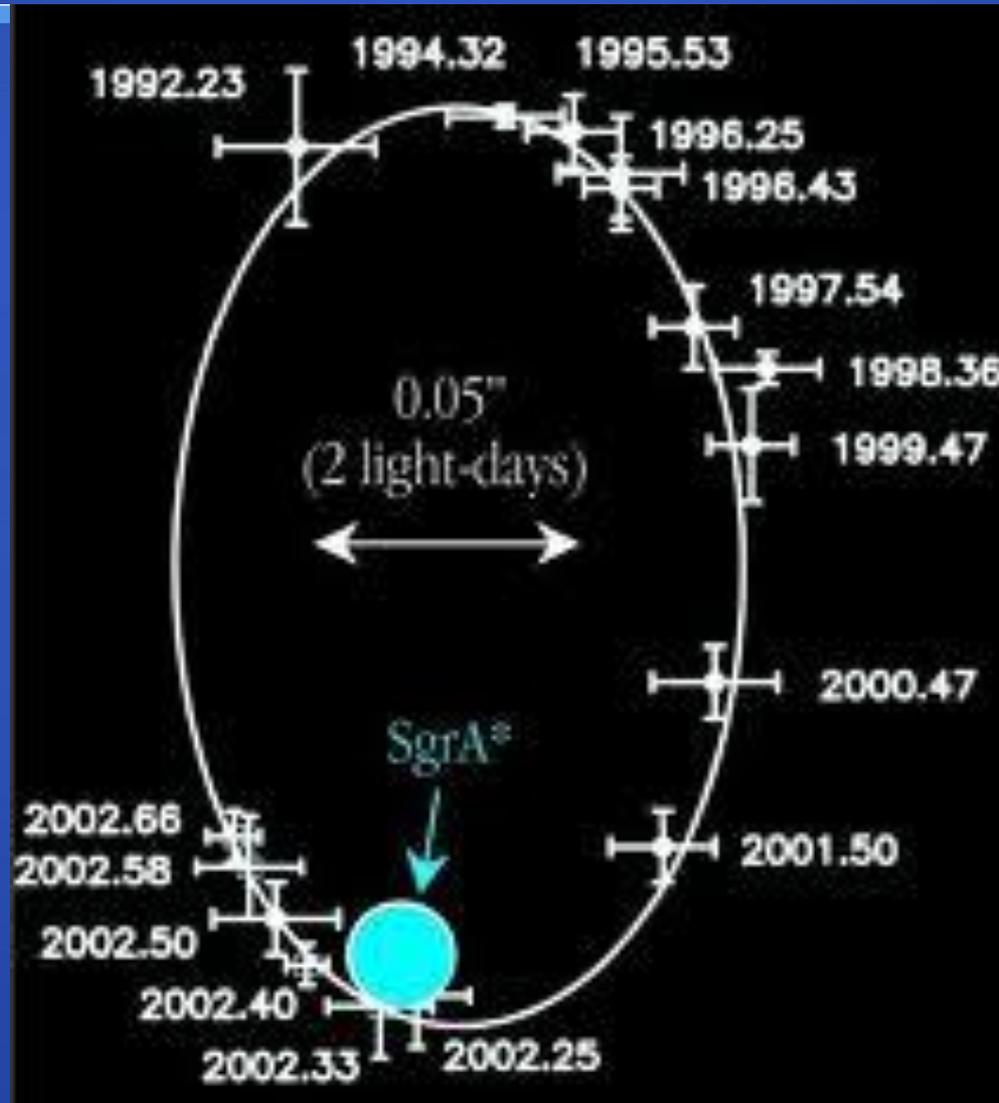
# Early Black Hole Calculations

- In 1915, the German astronomer Karl Schwarzschild solved Einstein's equations for the space-time around a single spherical mass. By varying its radius and matter density, he discovered the "Black Hole."
- Subrahmanyan Chandrasekhar showed in 1935 that relativistic quantum mechanics predicted that certain white-dwarf stars could become Black Holes.
- Robert Oppenheimer with his student Hartland Snyder calculated Black Hole's existence in 1939 while studying the life endpoint of neutron stars.

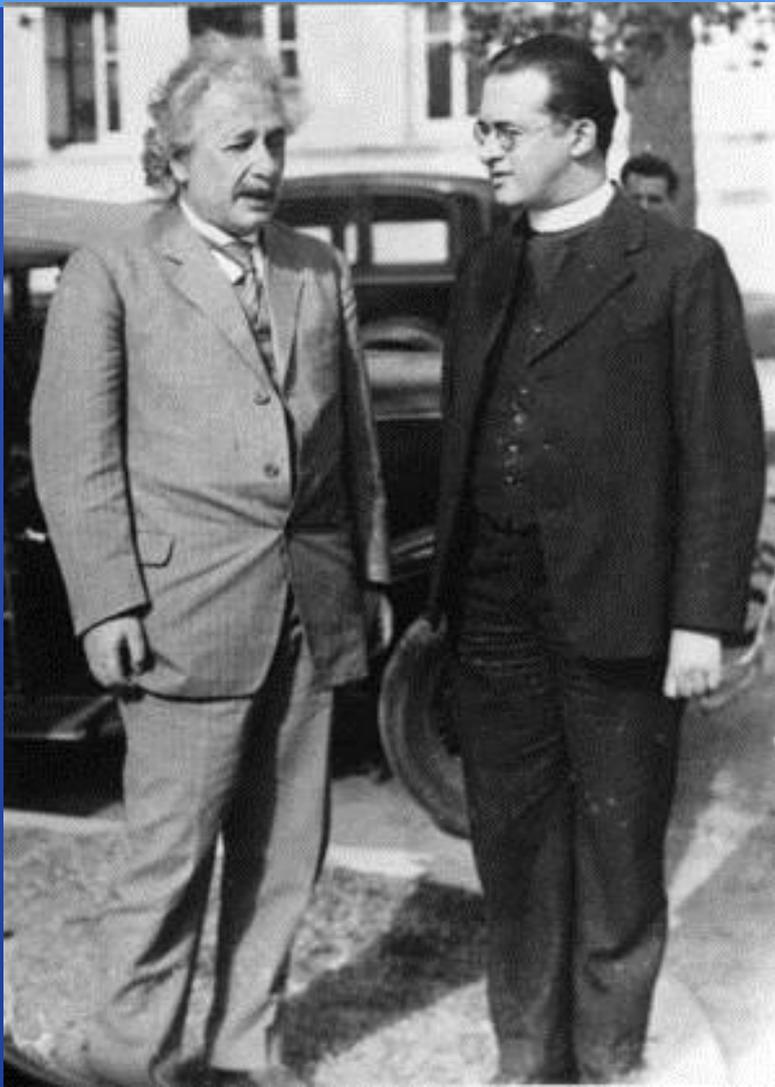
# A Black Hole Over The Smithsonian Institute Castle



# Star Orbiting A Black Hole At Center Of Milky Way Galaxy



# Lemaitre's Expanding Universe Solution To Einstein's Equations



- George Lemaitre (1894-1966), an MIT graduate student and RC Belgian priest, developed an **expanding universe solution** to Einstein's General Relativity equations in 1927.
- Friedman and the Dutch astronomer de Sitter had earlier derived similar solutions, **but were largely ignored.**
- Lemaitre was the first to derive **Hubble's Law**,  $v=Hd$ , and estimate Hubble's constant,  $H$ .
- Lemaitre proposed the hypothesis of the primeval atom or "Cosmic Egg", **later called the "Big Bang."**



# The Big Bang Theory



- Vesto Slipher discovered, with the Lowell Observatory's 24" reflecting telescope, **strong red shifts in about a dozen galaxies**; he reported his findings in 1914 (Edwin Hubble was in the audience).
- Hubble in 1929 combined his measurements of **galactic distances** with Slipher's **red shift measurements** to show that the Universe is **expanding and had a beginning (by extrapolating back in time)**.
  - **Henrietta Leavitt's** vital discovery of Cepheid variable stars in 1912 gave Hubble a distance scale.
- **The Big Bang Theory is the leading explanation about how the universe developed.** It hypothesizes that the Universe started with a singularity, then expanded over the next 13.8 billion years to the cosmos we observe today.

# Alpher, Bethe, and Gamow

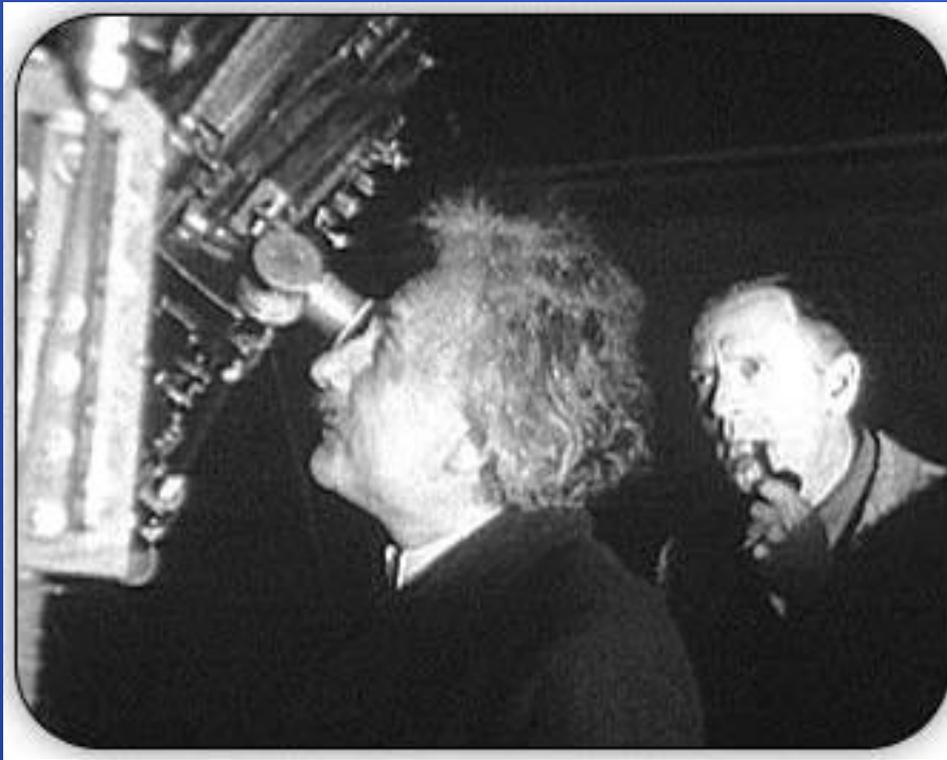
## 1948 "Big Bang" Publication



- Describes the production of H, He, and Li between 30 and 300 seconds after the beginning of **Lemaitre's "Big Bang"**.
- They argued that the Big Bang would create H, He, and heavier elements through nuclear-synthesis in the **correct proportions** to explain their abundance in the early universe.
- In 1939, Hans Bethe published a paper (won a **Nobel Prize**) on how stars' energy comes from a nuclear fusion process.



# Einstein & Hubble At Mt. Wilson's 100" Telescope, 01/29/1931



- Einstein came to U.S. in 1930 to meet Edwin Hubble and see his data on red shifts of galactic light.
- His data showed that the universe was expanding in accordance with Einstein's General Relativity equations.



# Recent Discoveries About Our Universe

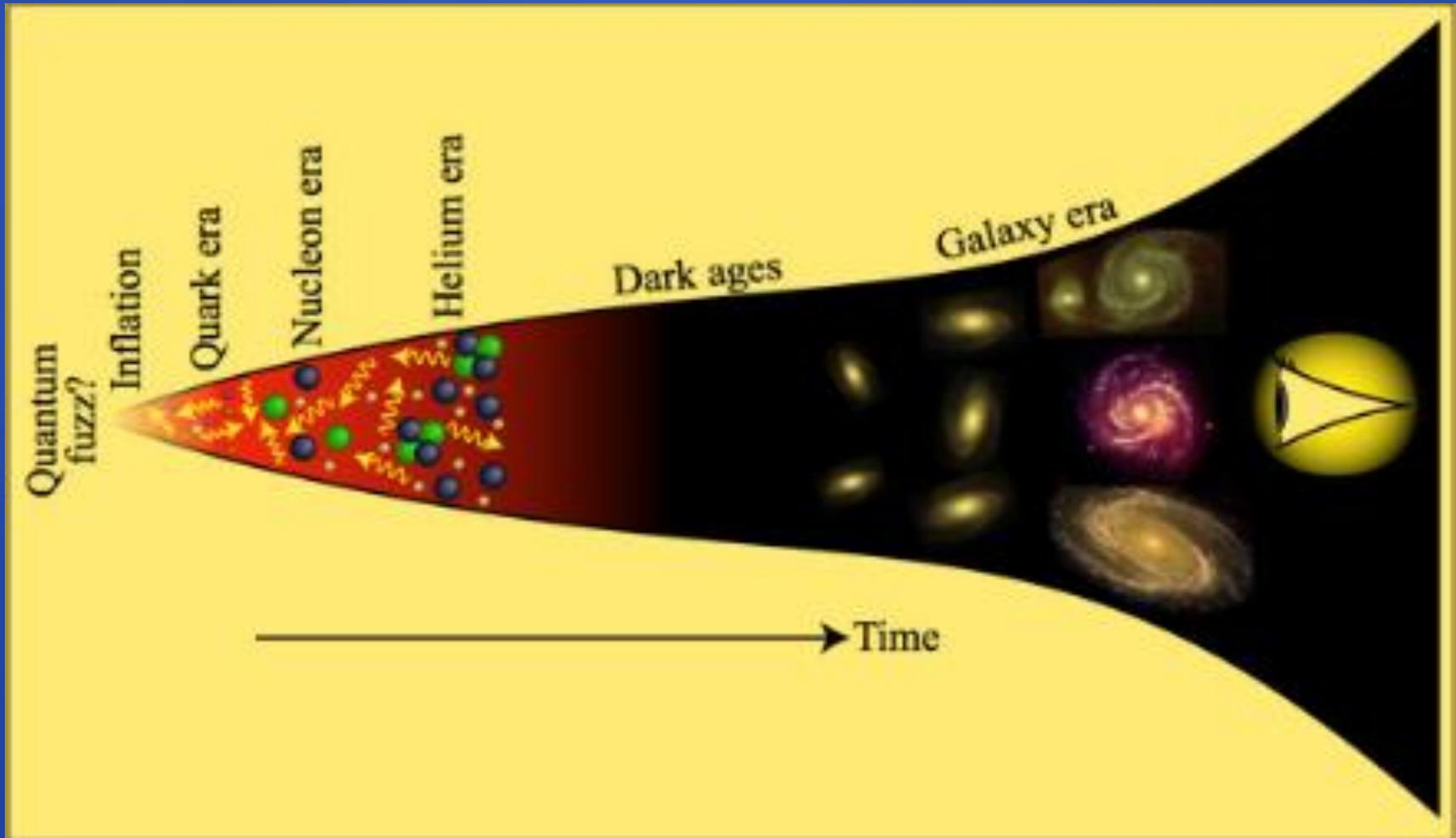


- It is expanding faster and faster.
  - A new kind of energy is causing this expansion acceleration.
- 95.1% of mass & energy is unknown dark matter & energy!
  - 4.9% atomic matter; 26.6% dark matter; 68.5% dark energy.
- Penzias and Wilson discover IR from the early hot Universe in 1965 (greatly cooled by expansion). Its recent analysis confirms the early history of the expanding Universe. In 1992, George Smoot and John Mather observed fluctuations in the IR mapping with the COBE satellite.
- Alan Guth, from 1979-1983, developed a theory of the Universe's emergence from the vacuum with a huge volume and mass inflation in a very brief flash of time.

# The Accelerated Expansion Of The Universe

- By 2000, 2 teams of astronomers had measured redshifts of many very **distant supernovas** and concluded **the Universe's expansion is accelerating**.
- For their discovery the leaders of the two teams, Saul Perlmutter, Brian Schmidt, and Adam Riess, were awarded the **Nobel Prize in 2011**.
- This means that Einstein's General Relativity equations need a **Cosmological Constant** which would produce a large force expanding space.
  - The new model universe consists of atoms, cold dark matter, and a cosmological constant.

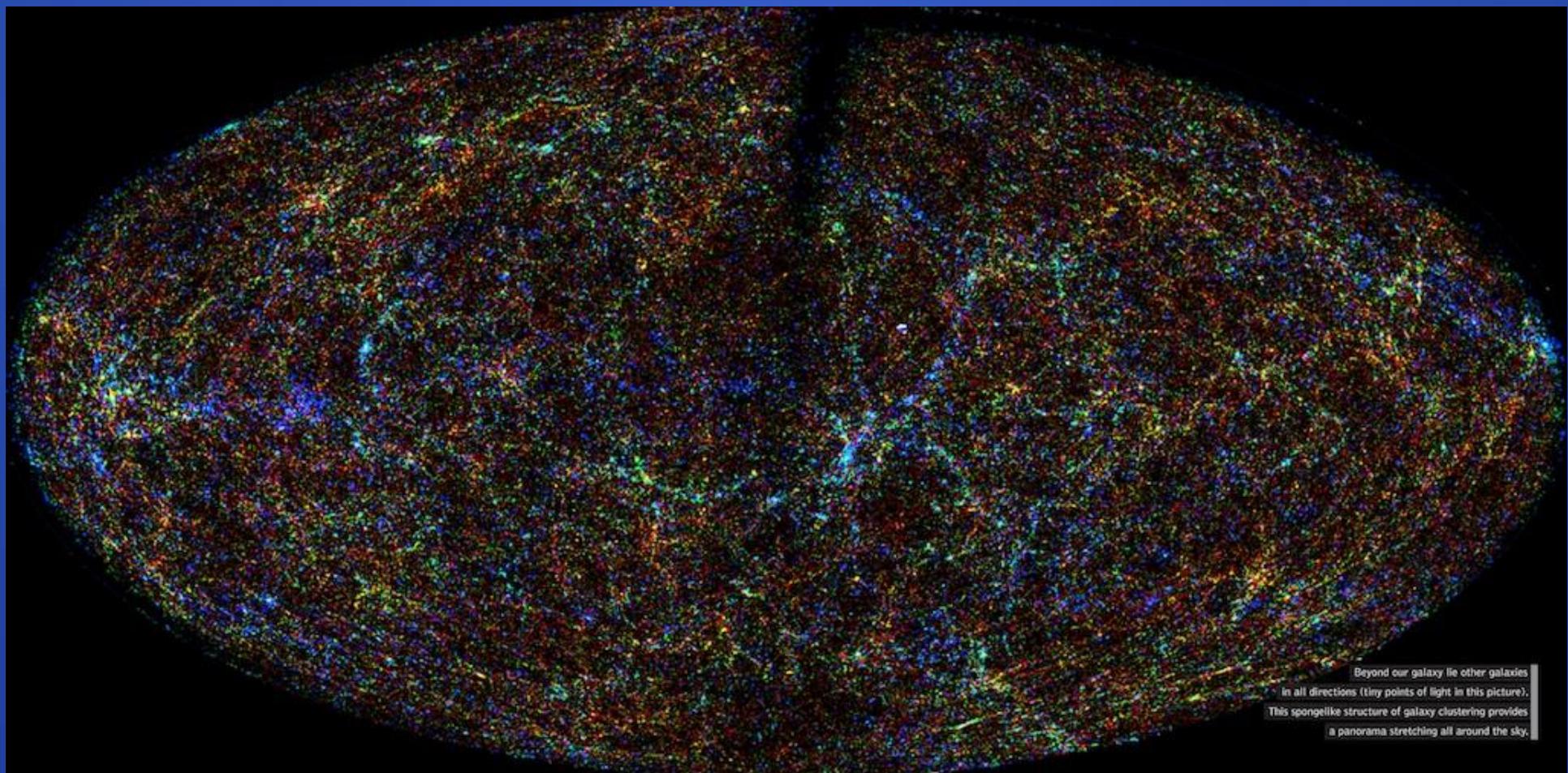
# The Development Of Our 13.8-Billion-Year-Old Universe



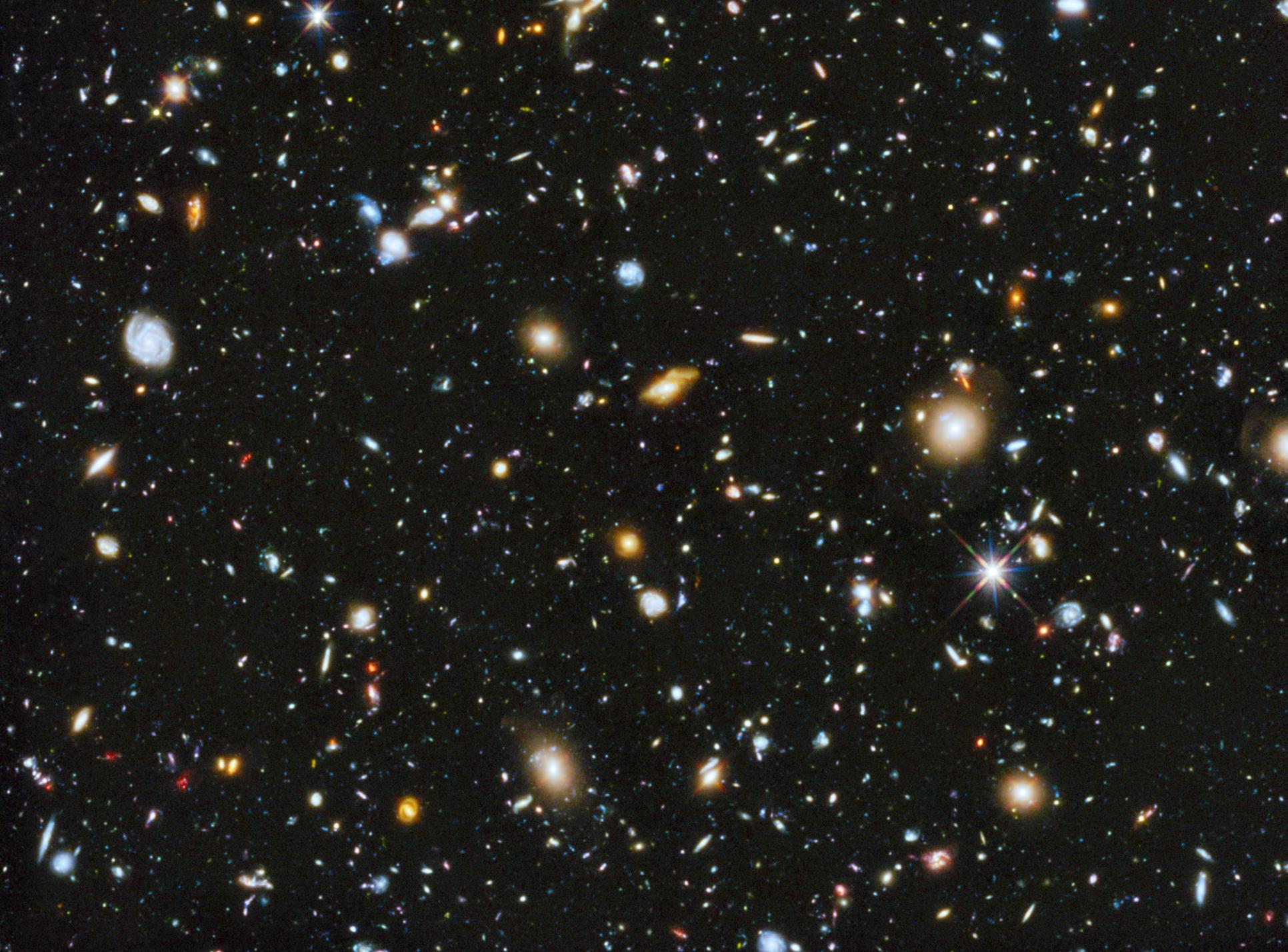
# Some Aspects Of Our Universe We Are Sure Of.

- Hydrogen, Helium, and most of the Lithium in the Universe were **made by nuclear fusion in the Big Bang in a few minutes**. The rest of the elements were made later in successive generations of stars. **We are made of star stuff!**
- Universe looks the **same in every direction** (on large scales) and contains **> 100 billion galaxies** with each galaxy **having at least 100 billion stars**.
- The Universe's radius is now about **50-billion light-years**.
- Most stars in our galaxy have a **system of planets**. **We have observed Earth-like planets** in many of them.

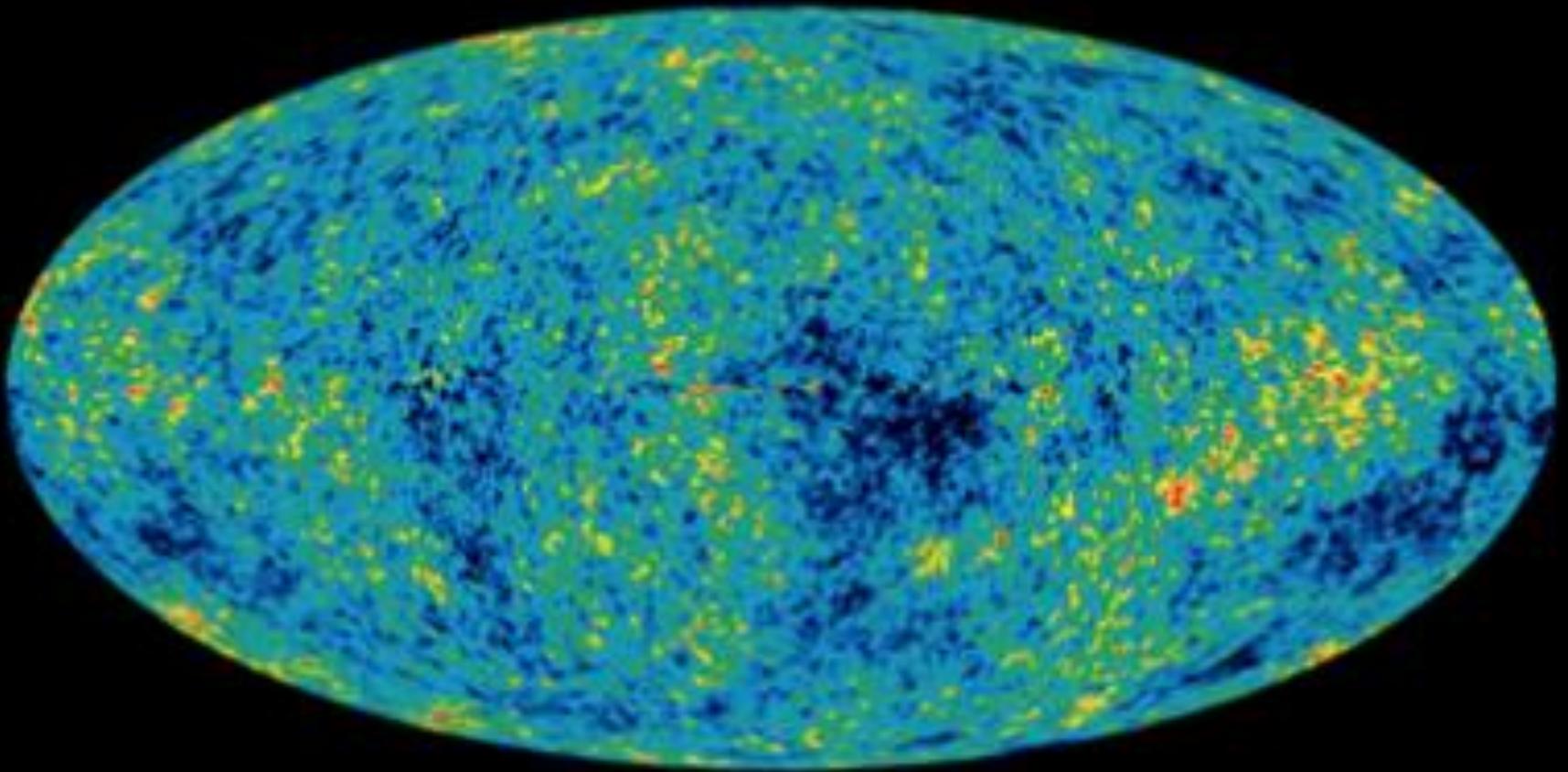
# A Sponge-Like Structure Of Galaxy Clustering In Our Universe



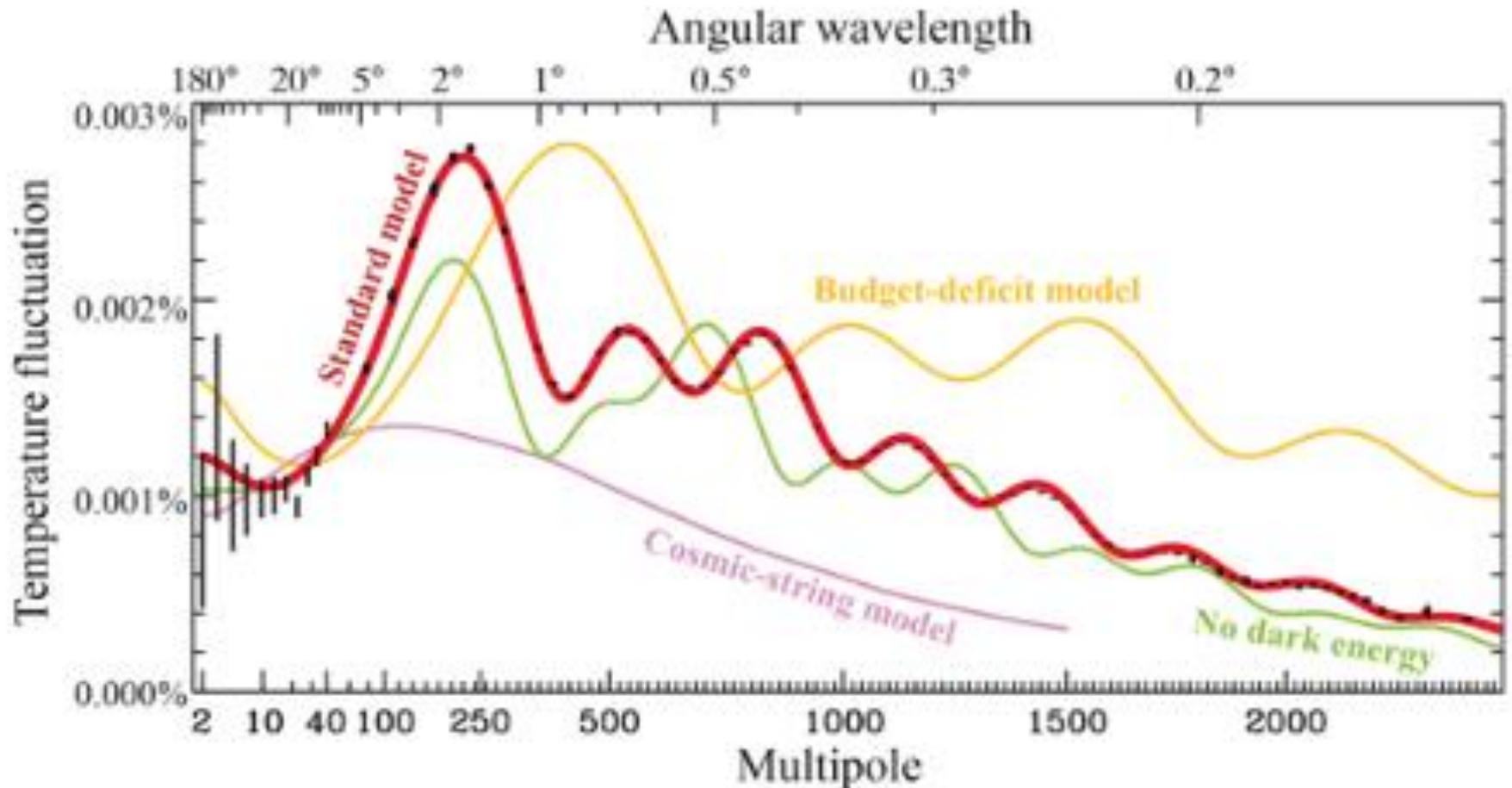
Beyond our galaxy lie other galaxies  
in all directions (tiny points of light in this picture).  
This spongelike structure of galaxy clustering provides  
a panorama stretching all around the sky.



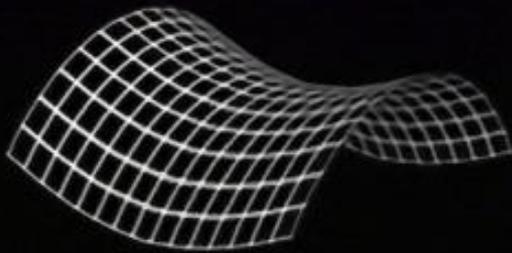
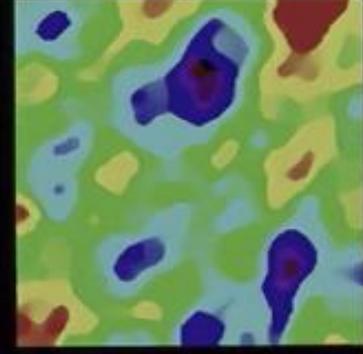
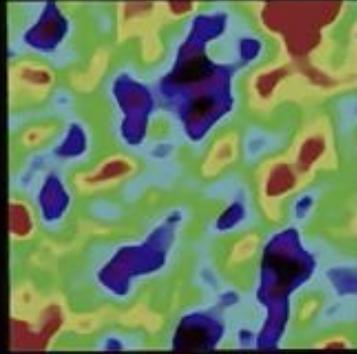
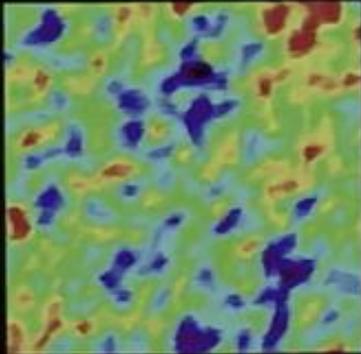
# Cosmic Microwave Background: Color Indicates Different T's



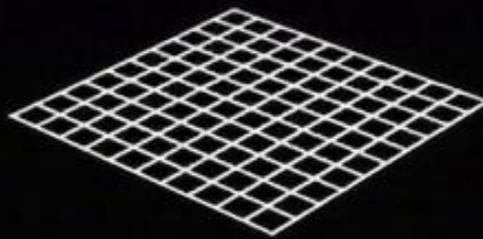
# Spectrum of Temperature Fluctuations Of Cosmic Microwaves



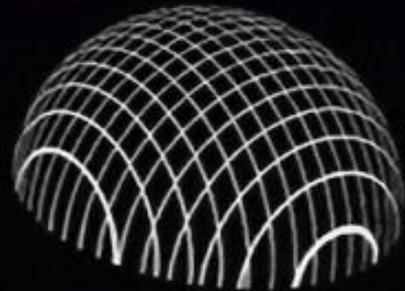
# GEOMETRY OF THE UNIVERSE



**OPEN**



**FLAT**



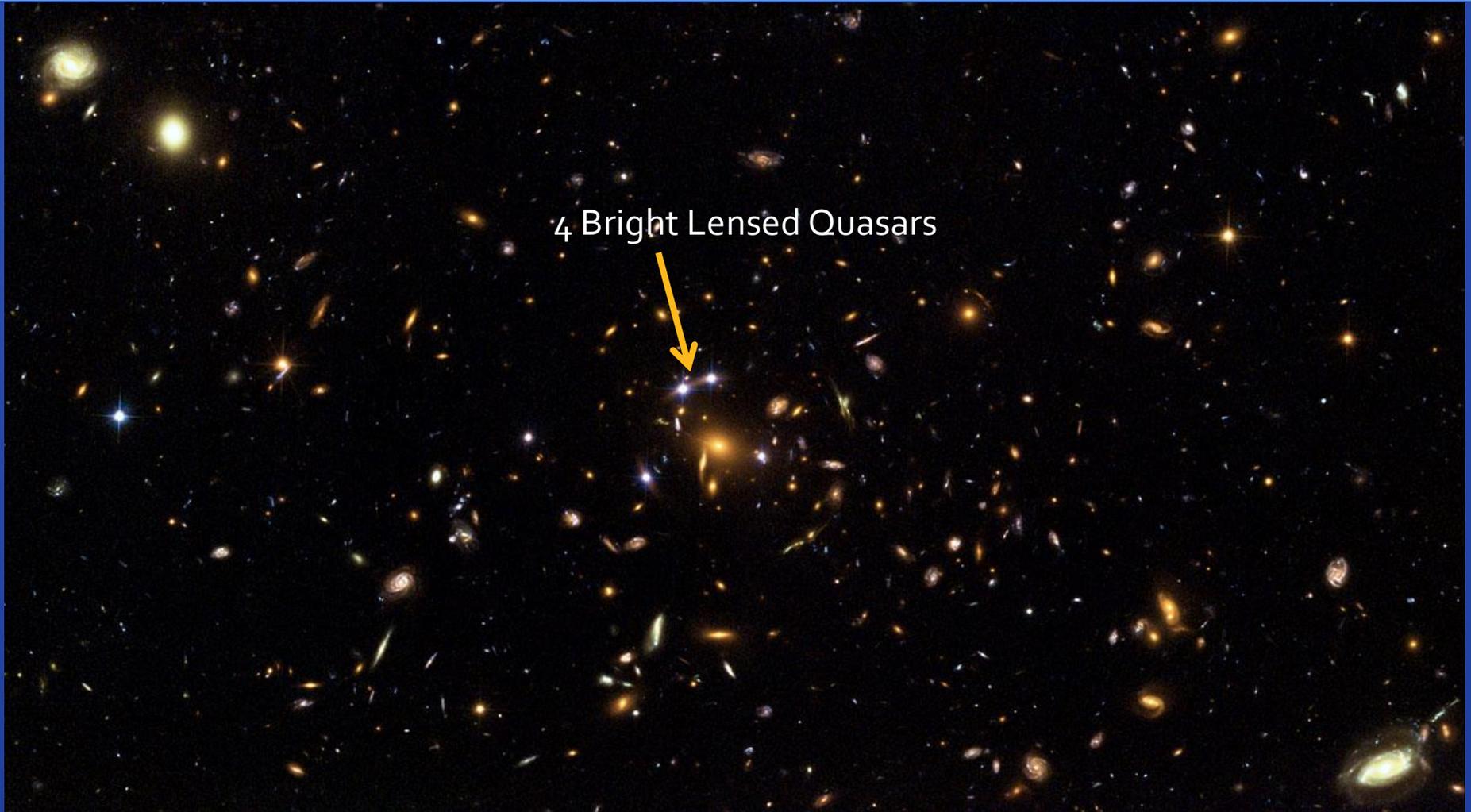
**CLOSED**

# Quasi Stellar Radio Sources

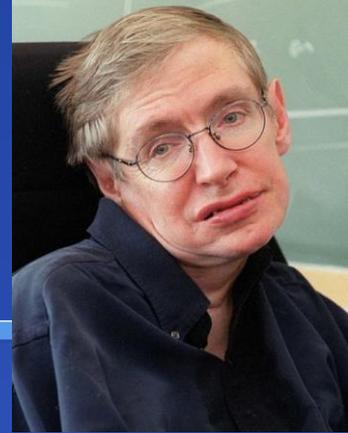
## “Quasars” and “Pulsars”

- First found by Martin Ryle in 1951; by 1963, after radio detector improvements, he and Robert Lovell had a large catalogue (3C) of bright radio sources.
- In 1963, Maarten Schmidt with the Hale telescope found very bright star-like objects that **coincided** with Ryle and Lovell’s quasars, but **they had huge redshifts and were billions of light years away!** 3C273 and 3C48 were producing as much **visible light as one hundred galaxies put together!**
- Closer and smaller pulsating radio sources (Pulsars) were discovered by Jocelyn Bell, et al, in 1968.

# Gravitational Lensing Of Quasars



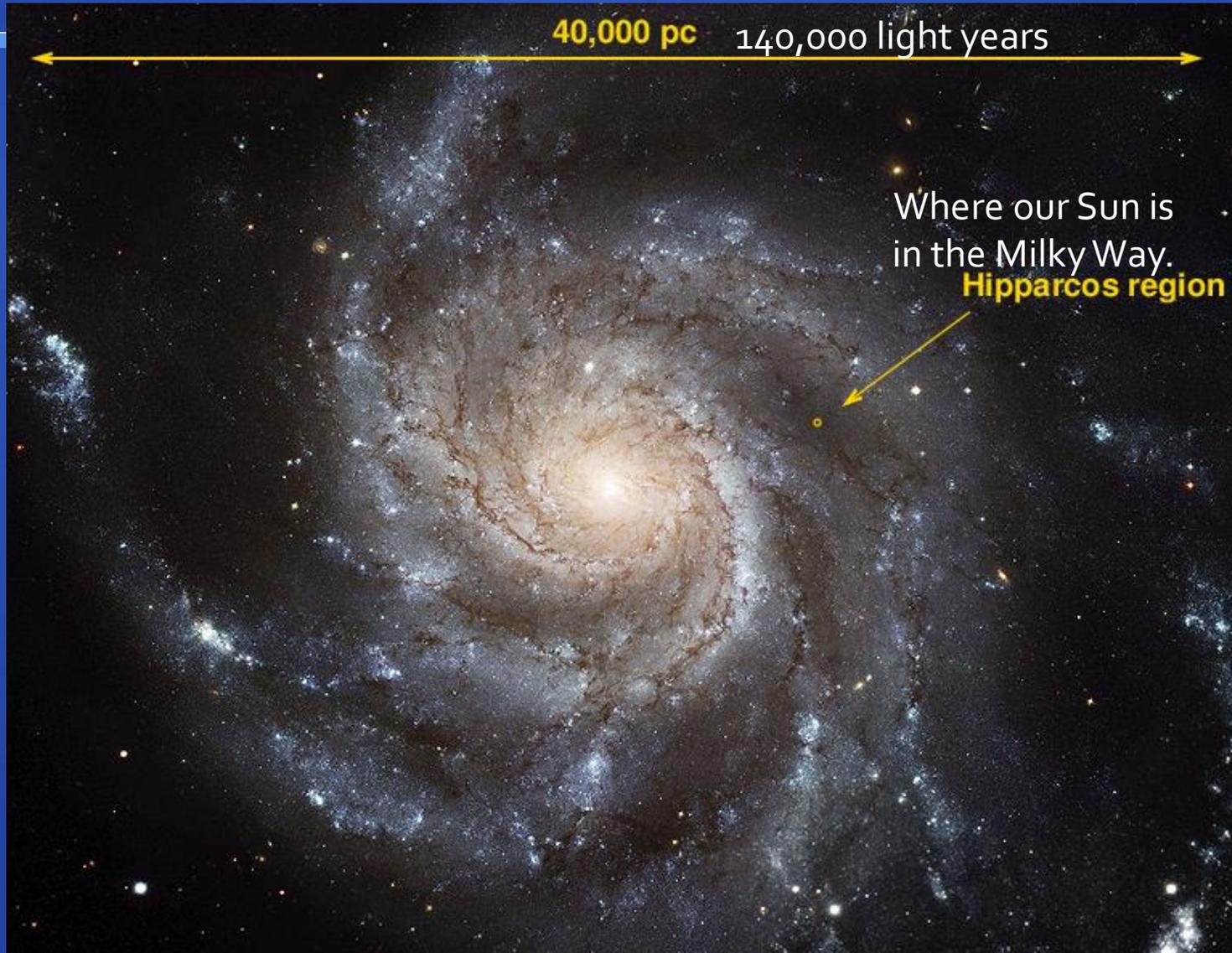
# The Black Hole Controversy



- Despite the many calculations leading to Black Holes since 1917, astronomers and most physicists, including Einstein, did not believe Black Holes (or gravitational singularities) actually existed in our universe even as late as 1963.
- In the early 1970's new calculations showed that Black Holes were simple objects having 3 characteristics only: mass, spin, and charge. Kip Torne, Stephen Hawking, and Yakov Zel'dovich were the leaders.
- In 1974, Stephen Hawking showed that Black Holes had entropy and radiated heat, known as Hawking radiation. The Fermi space telescope will look for this radiation.

# Spiral Galaxy Similar To Our Galaxy

## Messier 101



# Bibliography

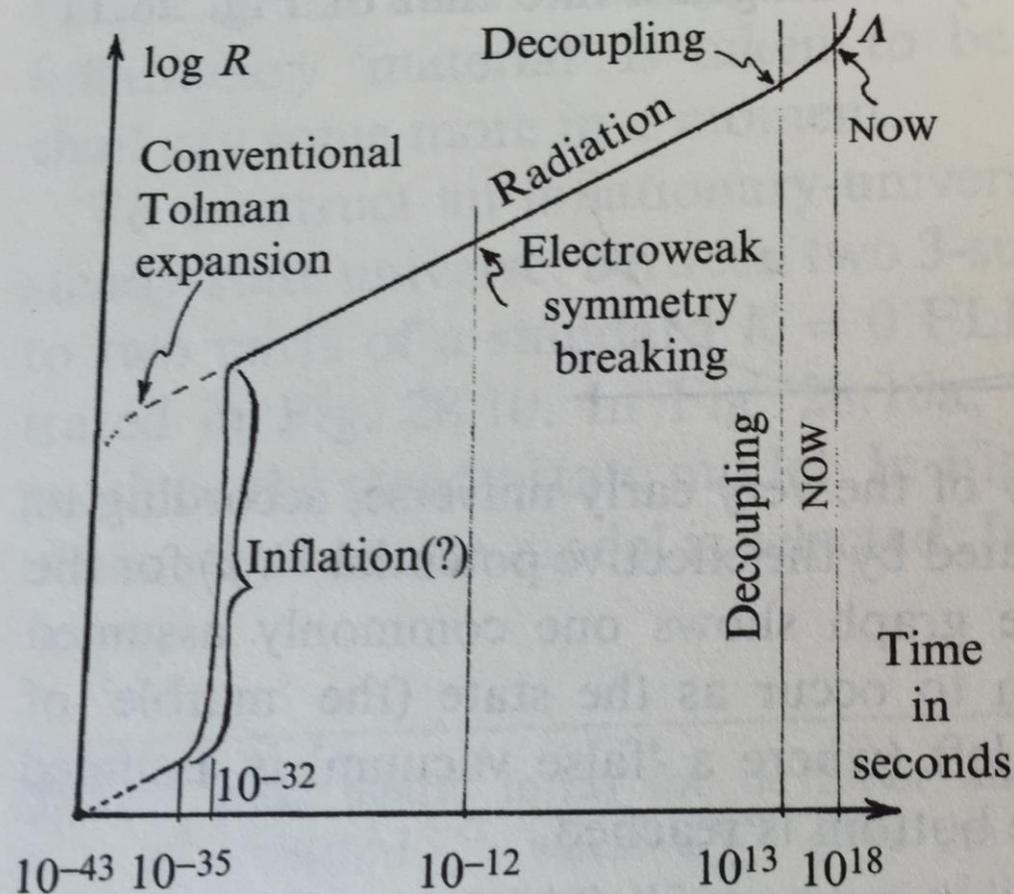
- *The Meaning of Relativity*, by Albert Einstein (5<sup>th</sup> Edition 1955)
- *Introduction To The Theory Of Relativity*, by Peter Bergmann (1942)
- *Cosmology*, by H. Bondi (2<sup>nd</sup> Edition 1961)
- *Albert Einstein And The Cosmic World Order*, by Cornelius Lanczos (1962)
- *Astronomy and Cosmology-A Modern Course*, by Fred Hoyle (1975)
- *God And The Astronomers*, by Robert Jastrow (1978)
- *The Copernican Revolution-Planetary Astronomy In The Development Of Western Thought*, by Thomas S. Kuhn (1985)
- *A More Perfect Heaven: How Copernicus Revolutionized The Cosmos*, by Dava Sobel (2011)
- *The Cosmic Landscape*, by Leonard Susskind (2006)
- *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins*, by Alan Guth (1997)
- *The Dancing Universe-From Creation Myths To The Big Bang*, by Marcelo Gleiser (1997)
- *Hubble Space Telescope-New Views of the Universe*, by Mark Voit (2000)
- *The Road To Reality- A Complete Guide To The Laws Of The Universe*, by Roger Penrose (2004)
- *The Fabric Of The Cosmos: Space, Time, And The Texture Of Reality*, by Brian Greene (2004)
- *A Brief History Of The Universe From Ancient Babylon To The Big Bang*, by J.P. McEvoy (2010)
- *The Accidental Universe-The World You Thought You Knew*, by Alan Lightman (2013)
- *Our Mathematical Universe-My Quest for the Ultimate Nature of Reality*, by Max Tegmark (2014)
- *The Cave and the Light: Plato Versus Aristotle, And The Struggle For The Soul Of Western Civilization*, by Arthur Herman (2014)
- *The Perfect Theory*, by Pedro Ferreira (2014)

# 4 More Tests Of General Relativity

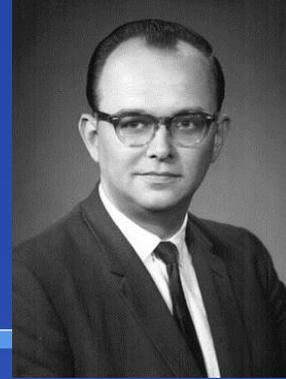
- **Direct measurement of gravity waves.** LIGO (Laser-Interferometer Gravitational-wave Observatory) and LISA (Laser Interferometer Space Antenna).
- **Dragging of inertial frames by a rotating body.** Gravity Probe B. This is a very small effect for the Earth.
- **Event Horizon Telescope** will look at the surface of the Black Hole at the center of our galaxy. Its resolution will be  $10^{-9}$  of an angular degree!
- SKA (**Square Kilometer Array**) radio telescope has 50 times Hubble's resolution and will help determine the large-scale structure of the Universe and observe the first stars and galaxies.

# History Of Universe

## Log-Log Plot Of Radius vs Time



# Speculative New Ideas-The Multiverse



- The latest inflation ideas predict that there is a **continuous production of inflationary universes out of the vacuum**; therefore, there are probably at any time a large number of non-interacting “universes”.
- An **interpretation** of Quantum Mechanics due to Hugh Everett III (1930 –1982) postulates that quantum processes give rise to alternate universes; i.e., all possible results of a quantum process **actually occur because a new universe appears for each outcome**.
  - This implies an incomprehensibly large number of universes!
  - This idea is now quite widely accepted by physicists!

# Eternal Inflation And Multi-Universes

