

**Timeline**

**Cosmology**

# Timeline Cosmology

- **2nd Millennium BCE**  
*Mesopotamian cosmology* has a flat, circular Earth enclosed in a cosmic Ocean

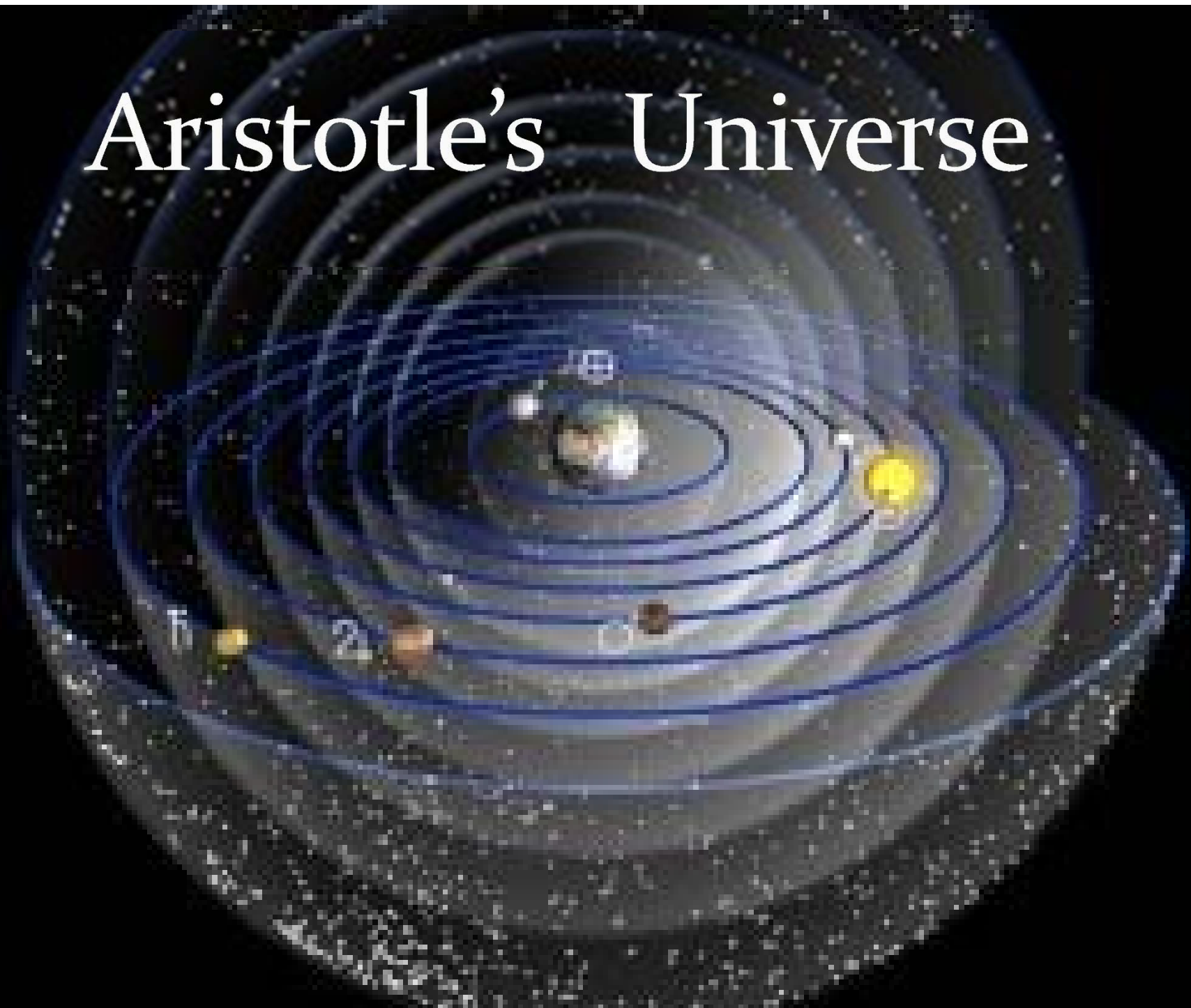
- **12<sup>th</sup> century BCE**  
*Rigveda* has some cosmological hymns, most notably the Nasadiya Sukta

- **6<sup>th</sup> century BCE**  
*Anaximander*, the first (true) cosmologist
  - pre-Socratic philosopher from Miletus, Ionia
  - Nature ruled by natural laws
  - Apeiron (boundless, infinite, indefinite), that out of which the universe originates

- **5<sup>th</sup> century BCE**  
*Plato*
  - Timaeus
  - dialogue describing the creation of the Universe,
  - demiurg created the world on the basis of geometric forms (Platonic solids)

- **4<sup>th</sup> century BCE**  
*Aristotle*
  - proposes an Earth-centered universe in which the Earth is stationary and the cosmos, is finite in extent but infinite in time

# Aristotle's Universe



- **3<sup>rd</sup> century BCE**  
*Aristarchus of Samos*
  - proposes a heliocentric (sun-centered) Universe, based on his conclusion/determination that the Sun is much larger than Earth
  - further support in 2<sup>nd</sup> century BCE by Seleucus of Seleucia

- **3<sup>rd</sup> century BCE**  
*Archimedes*
  - book *The Sand Reckoner*: diameter of cosmos ~ 2 lightyears
  - heliocentric Universe not possible

- **3<sup>rd</sup> century BCE**  
*Apollonius of Perga*
  - epicycle theory for lunar and planetary motions

- **2<sup>nd</sup> century CE**  
*Ptolemaeus*
  - *Almagest/Syntaxis*: culmination of ancient Graeco-Roman astronomy
  - Earth-centered Universe, with Sun, Moon and planets revolving on epicyclic orbits around Earth

- **5<sup>th</sup>-13<sup>th</sup> century CE**  
*Aryabhata* (India) and *Al-Sijzi* (Iran) propose that the Earth rotates around its axis.  
First empirical evidence for Earth's rotation by Nasir al-Din al-Tusi.
- **8<sup>th</sup> century CE**  
Puranic Hindu cosmology, in which the Universe goes through repeated cycles of creation, destruction and rebirth, with each cycle lasting 4.32 billion years.

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**Nikolaus Copernicus**  
(1473-1543)

- **1543**

***Nicolaus Copernicus***

- publishes heliocentric universe in *De Revolutionibus Orbium Coelestium*
- implicit introduction Copernican principle: Earth/Sun is not special

- **1609-1632**

***Galileo Galilei***

- by means of (telescopic) observations, proves the validity of the heliocentric Universe.

- **1609/1619**

***Johannes Kepler***

- the 3 Kepler laws, describing the elliptical orbits of the planets around the Sun

- **1687**

***Isaac Newton***

- discovers Gravitational Force as agent behind cosmic motions
- publishes his *Principia* (*Philosophiae Naturalis Principia Mathematica*), which establishes the natural laws of motion and gravity (the latter only to be replaced by Einstein's theory of GR)

- **1755**

***Immanuel Kant***

- asserts that nebulae are really galaxies separate from and outside from the Milky Way,
- calling these Island Universes

- **1785**

***William Herschel***

- proposes theory that our Sun is at or near the center of our Galaxy (Milky Way)

PHILOSOPHIÆ  
NATURALIS  
PRINCIPIA  
MATHEMATICA.

Autore <sup>nao</sup> J. S. NEWTON <sup>Equite literato,</sup> Trin. Coll. Cantab. Soc. Mathematicos  
Professore <sup>et Societatis Regiæ Sodali.</sup> Lucasiano, & Societatis Regiæ Sodali.

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Julii 5. 1686.

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plures Bibliopolas. Anno MDCLXXXVII.

Isaac Newton

(1642-1726)

- **1826**

***Heinrich Wilhelm Olbers***

- Olber's paradox (why is the night sky dark ?)

- **1837**

***Friedrich Bessel, Thomas Henderson, Otto Struve***

- measurement parallax of a few nearby stars: the first measurement of any distances outside the Solar System.

- establishes the vast distances between the stars

- **1848**

***Edgar Allan Poe***

- first correct solution to Olber's paradox in *Eureka: A Prose Poem*, an essay that also suggests the expansion of the universe

- **1860**

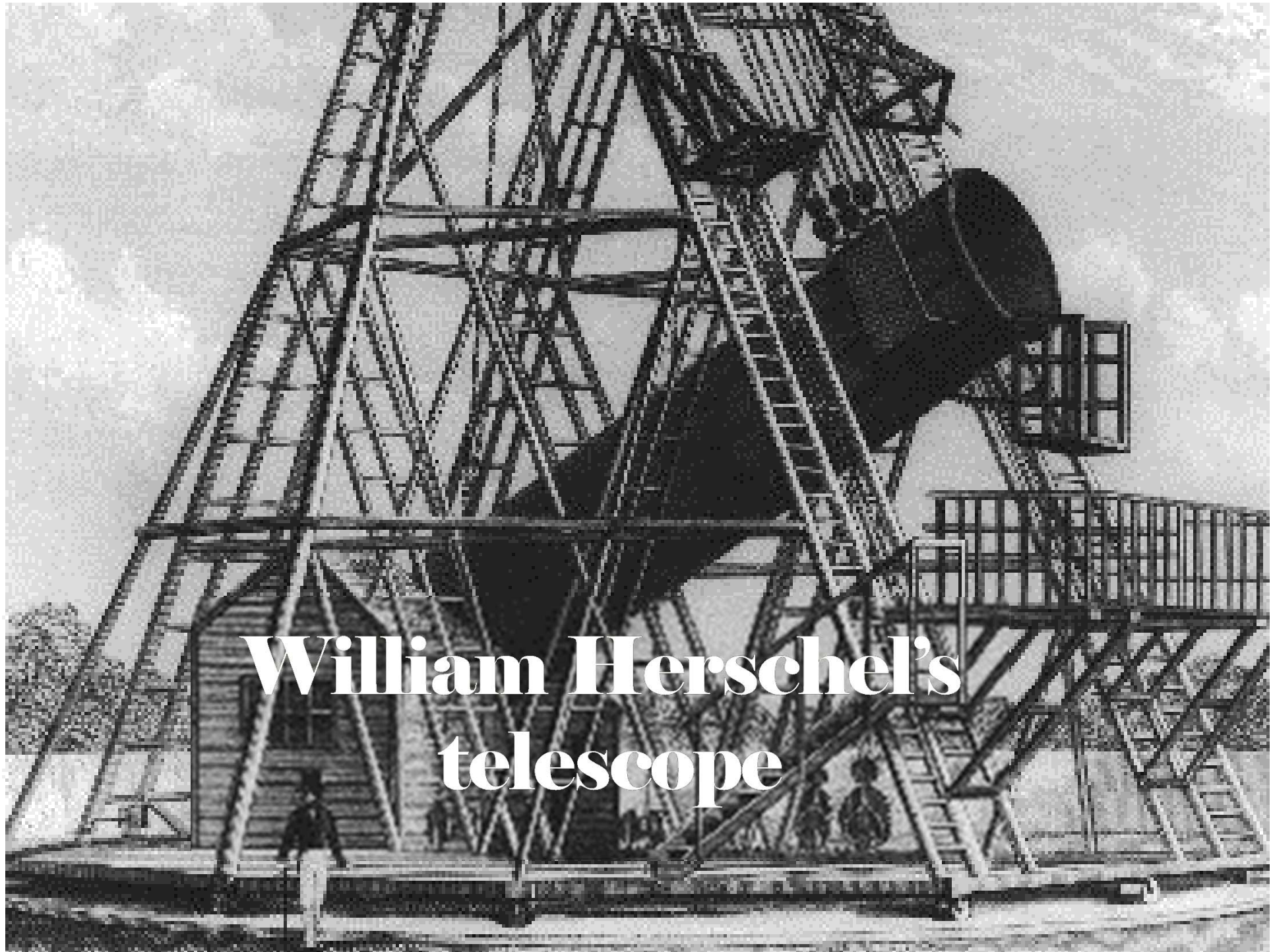
***William Huggins***

- develops astronomical spectroscopy :

Orion nebula is mostly made of gas, the Andromeda nebula dominated by stars

-





**William Herschel's  
telescope**

- **1905**  
**Albert Einstein**
  - Special Theory of Relativity
  - space and time are not separate continua, instead they define a 4-dim. spacetime continuum

- **1915**  
**Albert Einstein**
  - General Theory of Relativity:  
*Einstein field equations*
  - represents an entirely new theory of gravity, in which gravity is the result of the local curvature of space, hence replacing the action-at-a-distance theory of Newton.
  - spacetime becomes a flexible dynamic medium, warped by energy density

- **1917**  
**Willem de Sitter**
  - first general relativistic cosmology, de Sitter Universe
  - empty expanding Universe with cosmological constant

- **1912**  
**Henrietta Leavitt**
  - Cepheid variable stars period-luminosity relation
  - crucial step in measuring distances to other galaxies

- **1920-1921**  
**Harlow Shapley & Heber Curtis**
  - Shapley – Curtis debate or “Great Debate”, National Academy of Science
  - debate on the distances to spiral nebulae:  
are they individual galaxies like the Milky Way or are they part of the Milky Way

- **1923**  
**Edwin Hubble**
  - measures distance to few nearby spiral nebulae (Andromeda Galaxy, Triangulum galaxy, NGC 6822)
  - distances place them far outside our Milky Way
  - demonstrates that the spiral nebulae are galaxies outside our own Galaxy, the Milky Way
  - In other words, the Galaxy loses its central unique position and the Universe turns out to be much, much larger

A black and white, close-up portrait of Albert Einstein. He is looking directly at the camera with a slight, thoughtful expression. His hair is wild and unkempt, and he has a prominent mustache. He is wearing a dark suit jacket over a light-colored shirt and a dark tie. The background is dark and out of focus.

**Albert Einstein**

**(1879-1955)**

- **1922**  
**Vesto Slipher**  
- finds that spiral nebulae are systematically redshifted, ie. moving away from us
- **1922**  
**Alexander Friedmann**  
- Friedmann solution to the Einstein field equations, now known as *Friedmann-Robertson-Walker-Lemaitre equations*  
- solutions for a perfectly uniform space  
- imply expansion of the space
- **1927**  
**Georges Lemaitre**  
- solutions for Einstein field equations, for a perfectly uniform space, confirming Friedmann  
- discusses the implications, that of an expanding Universe and the creation of the Universe  
- predicts distance-redshift relation (later known as Hubble relation)  
- may indeed have discovered the expansion of the Universe from existing data (ongoing discussion)

- **1929**  
**Edwin Hubble**  
- discovery linear redshift-distance relation (the Hubble relation)  
- ie. the discovery of the EXPANDING UNIVERSE

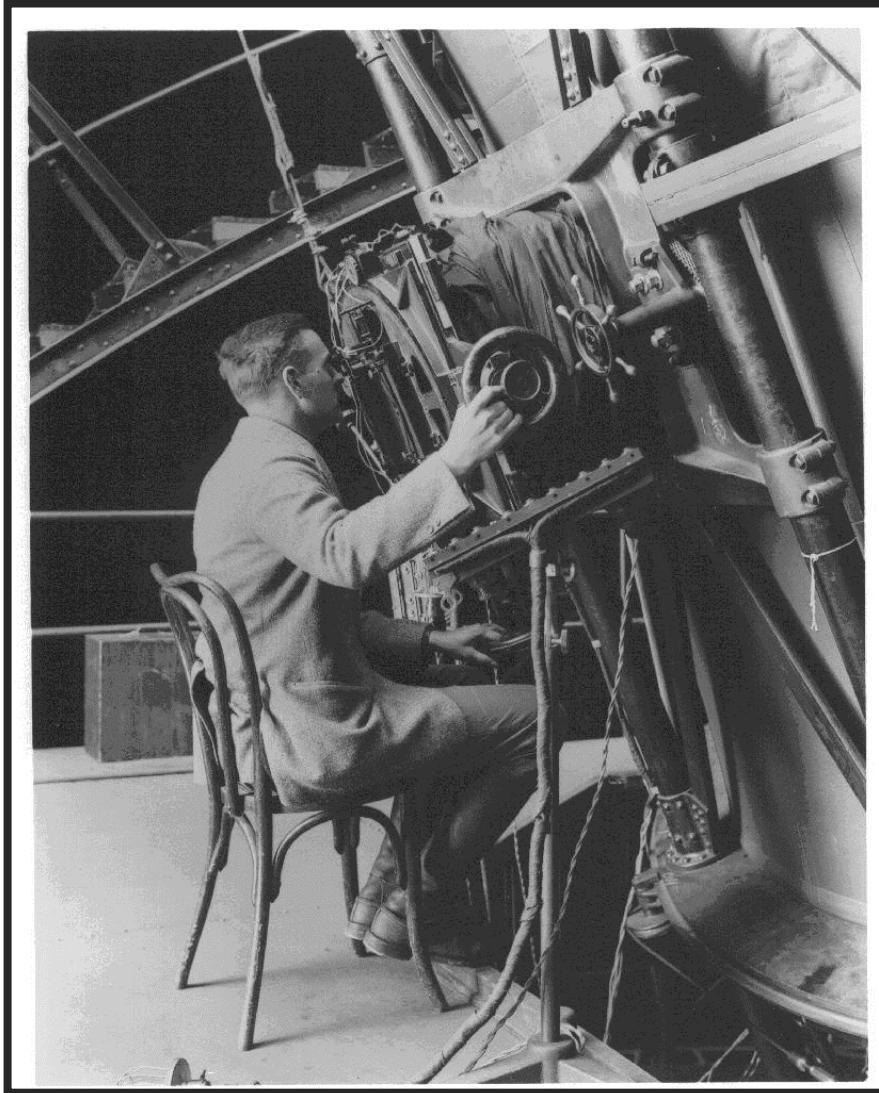
- **1933**  
**Edward Milne**  
- formulation of the *Cosmological Principle*  
- Universe is *Isotropic* and *Homogeneous* (on scales larger than 100 million lightyears)
- **1933**  
**Fritz Zwicky**  
- discovery of existence of dark matter, from galaxy velocities in Coma cluster of galaxies
- **1934**  
**Georges Lemaitre**  
- Cosmological constant (free factor in Einstein field equations):  
interpretation in terms of vacuum energy with an unusual perfect equation of state



**the Hot Big Bang**

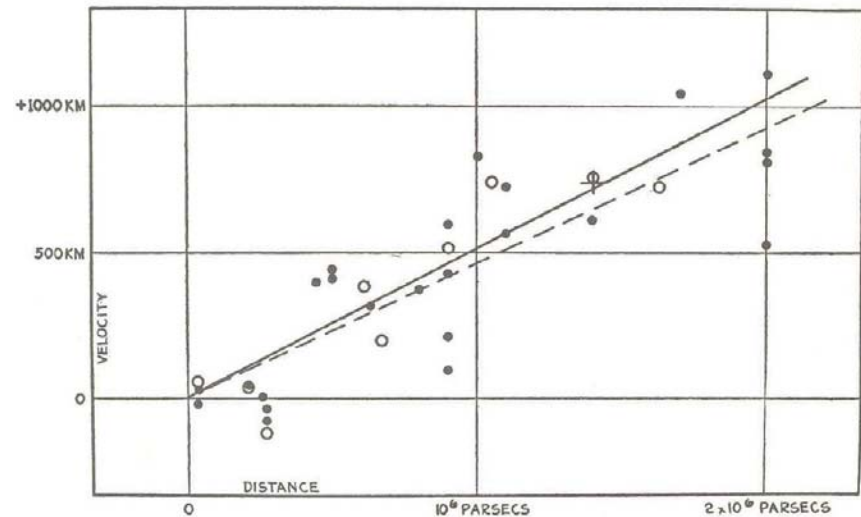
- **1946**  
***Evgeni M. Lifschitz***  
- formulation, in a relativistic context, of gravitational instability in an expanding universe, the prevailing theory for the formation of structure in the Universe
- **1946**  
***George Gamow***  
- *Hot Big Bang*  
- predicts the existence of a cosmic radiation field with a temperature of 50 K (is 2.725K), presuming all chemical elements were formed in the hot Big Bang.
- **1948**  
***Ralph Alpher, Hans Bethe, George Gamow***  
- the  $\alpha$ - $\beta$ - $\gamma$  paper  
- describes how the Big bang would by means of nuclear synthesis in the early universe create hydrogen, helium and heavier elements
- **1948**  
***Ralph Alpher & Robert Herman***  
- as a consequence of their studies of nucleosynthesis in the early expanding Big Bang universe, theoretical prediction of the existence of a residual, homogeneous, isotropic blackbody radiation  
- they estimate "the temperature in the universe" at 5 K.  
- in 1965 discovered as the Cosmic Microwave Background Radiation
- **1948**  
***Hermann Bondi, Thomas Gold, Fred Hoyle***  
- proposal *Steady State Cosmology*, based on the perfect cosmological principle
- **1950**  
***Fred Hoyle***  
- coins the term *Big Bang*, meant in a derisive way
- **1957**  
***Margaret Burbidge, Geoffrey Burbidge, William Fowler & Fred Hoyle***  
- landmark B<sup>2</sup>FH paper  
- Synthesis of the Elements in Stars  
- describes how all elements, heavier than lithium, are synthesized by nuclear processes in the cores of stars  
- We are stardust !

# Expanding Universe



*Edwin Hubble*

*(1889-1953)*



$$v = H r$$

**Hubble Expansion**

- **1963**  
**Maarten Schmidt**  
- discovery of the first quasar, active nuclei of galaxies visible out to very high redshifts in the Universe

- **1965**  
**Arno Penzias & Robert Wilson**  
- Discovery of the 2.7K *Microwave Background Radiation* (CMB)  
- ultimate proof of the Hot Big Bang  
- Nobelprize Physics in 1978

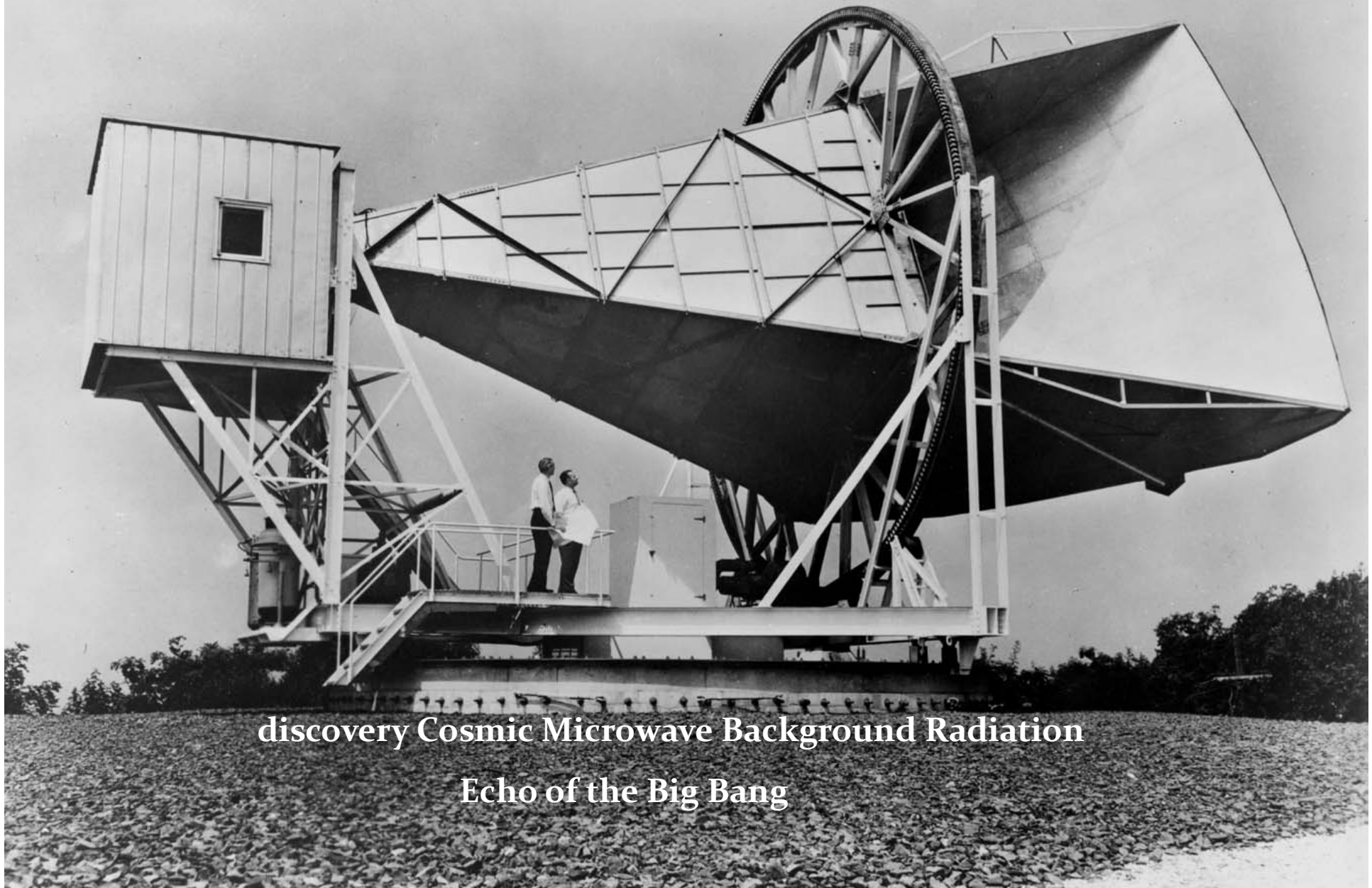
- **1965**  
**Robert Dicke, Jim Peebles, Peter Roll & David Wilkinson**  
- interpretation of the CMB as the relic radiation from the Big Bang

- **1966**  
**Jim Peebles**  
- predicts the correct helium abundance, produced as a result of early Universe Big Bang nucleosynthesis

- **1966**  
**Stephen Hawking & George Ellis**  
- *Singularity Theorem*  
- they show that any plausible general relativistic cosmology is singular



# 1965: Penzias & Wilson



**discovery Cosmic Microwave Background Radiation**

**Echo of the Big Bang**

- **1970**  
**Yakov Zeldovich**  
 - *Zeldovich formalism*  
 - *theory of anisotropic gravitational collapse for the formation of structure in the Universe*
- **1980**  
**Alan Guth, Alexei Starobinsky**  
 - *Inflationary Big Bang universe*  
 - possible solution to the so-called horizon and flatness problems of standard Big Bang models  
 - has become a key element of the standard Big Bang model
- **1982-1984**  
**Jim Peebles, Dick Bond, George Blumenthal**  
 - universe dominated by Cold Dark Matter
  - **1983-1987**  
**Klypin & Shandarin 1983**  
**Davis, Efstathiou, Frenk & White 1985-1987**  
 - the first large computer simulations of cosmic structure formation  
 - DEFW show that cold dark matter based simulations produce a reasonable match to observations
  - **1986**  
**de Lapparent, Geller & Huchra**  
 discovery of the **Cosmic Web** by the **CfA2 survey** "Slice of the Universe"  
 - final confirmation of earlier suggestions/indications of a weblike/cellular structure in the Universe  
 - by **Einasto et al. (1980)** while  
 - later the reality of the Cosmic Web got confirmed in an unambiguous fashion  
 by the maps of the 2dFGRS redshift survey (1997-2002)
  - **1990**  
**George Efstathiou, Steve Maddox & Will Sutherland**  
 - **APM survey**: computer processed measurement of the galaxy distribution on the southern sky  
 - first direct detection and claim of the impact of a **Cosmological Constant**

A visualization of the Cosmic Web, showing a complex network of glowing orange and yellow filaments against a dark blue background. The filaments form a dense, interconnected web of lines, with some brighter nodes where multiple filaments intersect.

Yakov Zeldovich  
(1914-1987):

Cosmic Web

- **1990**  
**COBE** CMB satellite, **John Mather**
  - precise measurement of the blackbody spectrum of the Cosmic Microwave Background
  - confirmation of blackbody nature of CMB, to a precision of 1 in  $10^5$ , the strongest and ultimate evidence for the reality of the Hot Big Bang
  - $T=2.725$  K
  - Nobelprize physics 2006

- **1990**  
**COBE** CMB satellite, **George Smoot**
  - discovery of tiny anisotropies in the CMB,
  - the seeds of structure formation in the Universe
  - confirmation of the gravitational instability theory for structure formation in the Universe
  - provides the baby picture of structure of the Universe “only” 379,000 years after the Big Bang
  - Nobelprize physics 2006

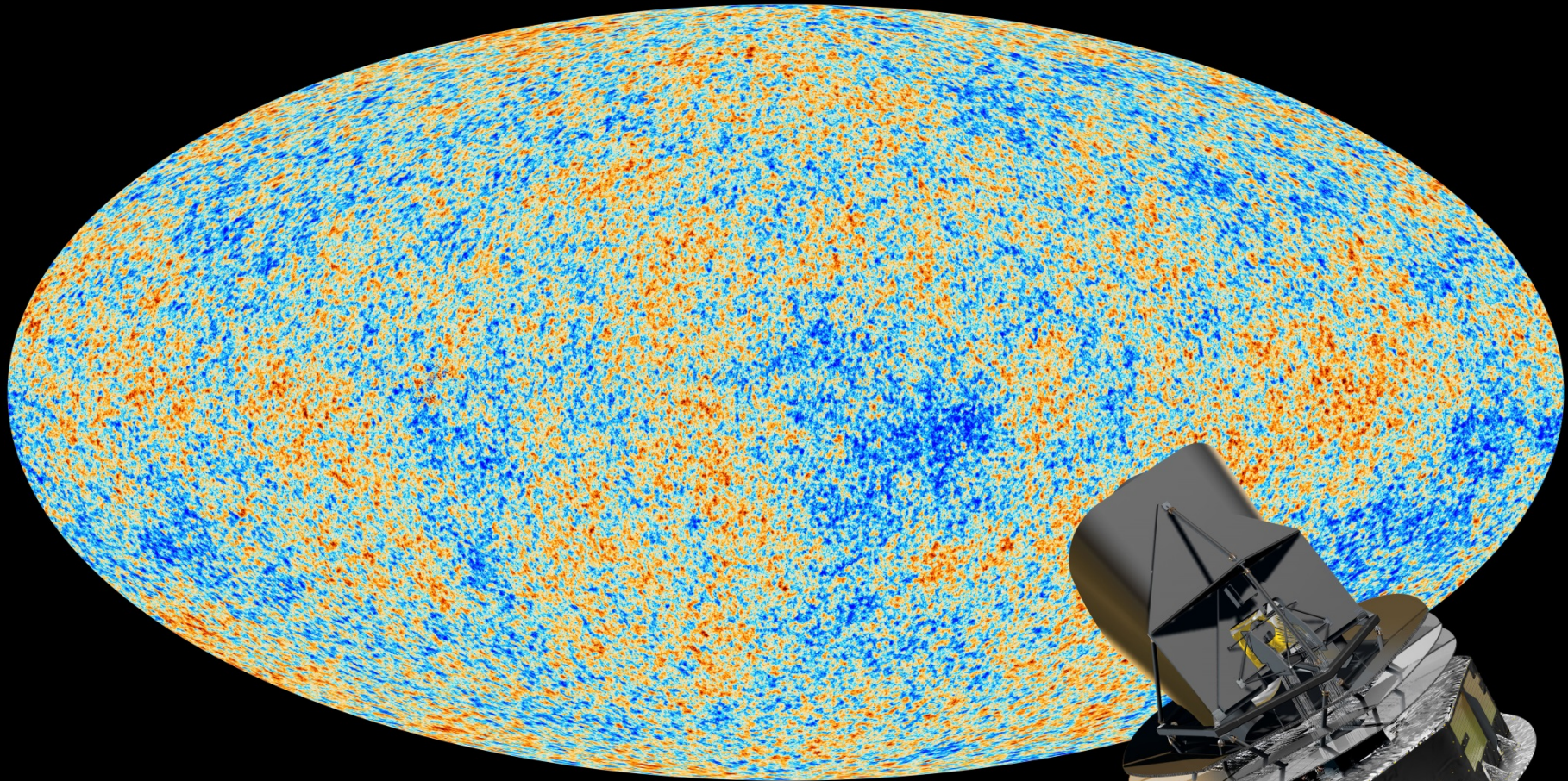
- **1997-2002**  
**2dFGRS galaxy redshift survey**
  - first large scale systematic survey of the spatial galaxy distribution
  - conducted with the 3.9m Anglo-Australian Telescope
  - mapped the positions of 232,155 galaxies in 2 narrow slices out to a redshift of 0.2
  - structure mapped is that of a Cosmic Web

- **1998**  
**Supernova Cosmology Project, High-Z Supernova Search Team,**  
lead by **Saul Perlmutter, Adam Riess & Brian Schmidt**
  - *discovery of the acceleration of cosmic expansion*
  - provides first direct evidence for the existence of a non-zero cosmological constant
  - Nobelprize Physics 2012

- **2000-**  
**Sloan Digital Sky Survey (SDSS)**
  - multi-filter imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico
  - systematic mapping of the spatial galaxy distribution in major regions of the nearby Universe
  - as yet around 2,000,000 galaxies
  - clustering consistent with the cold dark matter theory of cosmic structure formation, including Cosmological Constant, the so-called  $\Lambda$ CDM cosmology

# Precision Cosmology

- Universe 380.000 yrs after Big Bang
- 13.8 Gyrs ago (13.798±0.037 Gyrs)
- Temperature  $T = 2.72548 \pm 0.00057$  K
- temperature/density fluctuations ( $\Delta T/T < 10^{-5}$ )



**Planck satellite map  
of the primordial Universe**

- **2000**  
**Witman et al., Bacon et al., Kaiser et al., van Waerbeke et al.** (4 independent groups)  
discovery/detection **Cosmic Shear**
  - gravitational lensing by cosmic mass distribution
  - induced by the dominant dark matter component in the cosmic mass distribution
  - provides a new and competitive probe of cosmological parameters

- **2003**  
**WMAP** CMB satellite
  - Wilkinson Microwave Anisotropy Probe,
  - US satellite mission measuring the CMB to subhorizon scales
  - mapping of cosmic acoustic waves and measurement angular fluctuation spectrum
  - opening era of *Precision Cosmology*
  - establishes accurate age determination of the Universe: 13.7 Gyr
  - establishes that the Universe has zero curvature (flat Universe)
  - established reality of Cosmological Constant/Dark Energy

- **2005**  
**Cole et al. , Eisenstein et al.**  
discovery **Baryonic Acoustic Oscillations**
  - from the maps of galaxy distribution from the 2dFGRS and SDSS galaxy redshift surveys, the first detection of the remnant acoustic oscillations: remnant of the primordial sound waves
  - new probe that confirms reality of Dark Energy/Cosmological Constant

- **2013-2015**  
**Planck CMB satellite**
  - European satellite mission measuring the CMB to unprecedented detail and accuracy
  - maps the polarization of the cosmic microwave background
  - detects the gravitational lensing of the CMB
  - establishes the age of the Universe to 13.8 Gyr



# Inflationary Universe