Timeline

Cosmology

Timeline Cosmology

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

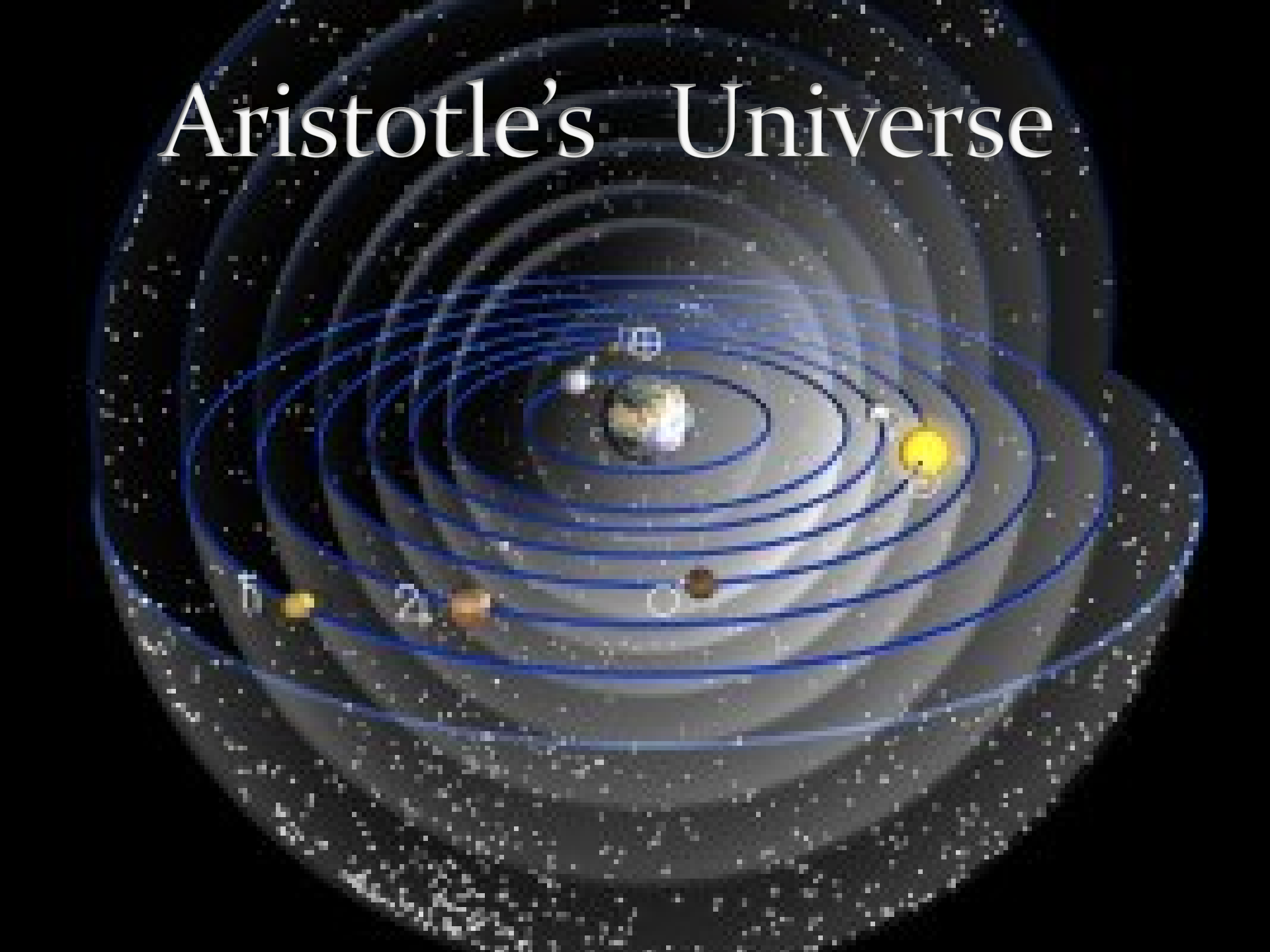
- **12th century BCE**
  Rigveda has some cosmological hymns, most notably the Nasadiya Sukta

- **6th 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

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

- **4th 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



- **3rd 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 2nd century BCE by Seleucus of Seleucia

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

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

- **2nd 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

- **5th-13th 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.

- **8th 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.


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 ou Galaxy (Milky Way)

PHILOSOPHIÆ NATURALIS PRINCIPIA MATHEMATICA.

Autore *J S. NEWTONO* Trin. Coll. Cantab. Soc. Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

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S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

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Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Isaac Newton

(1642-1726)

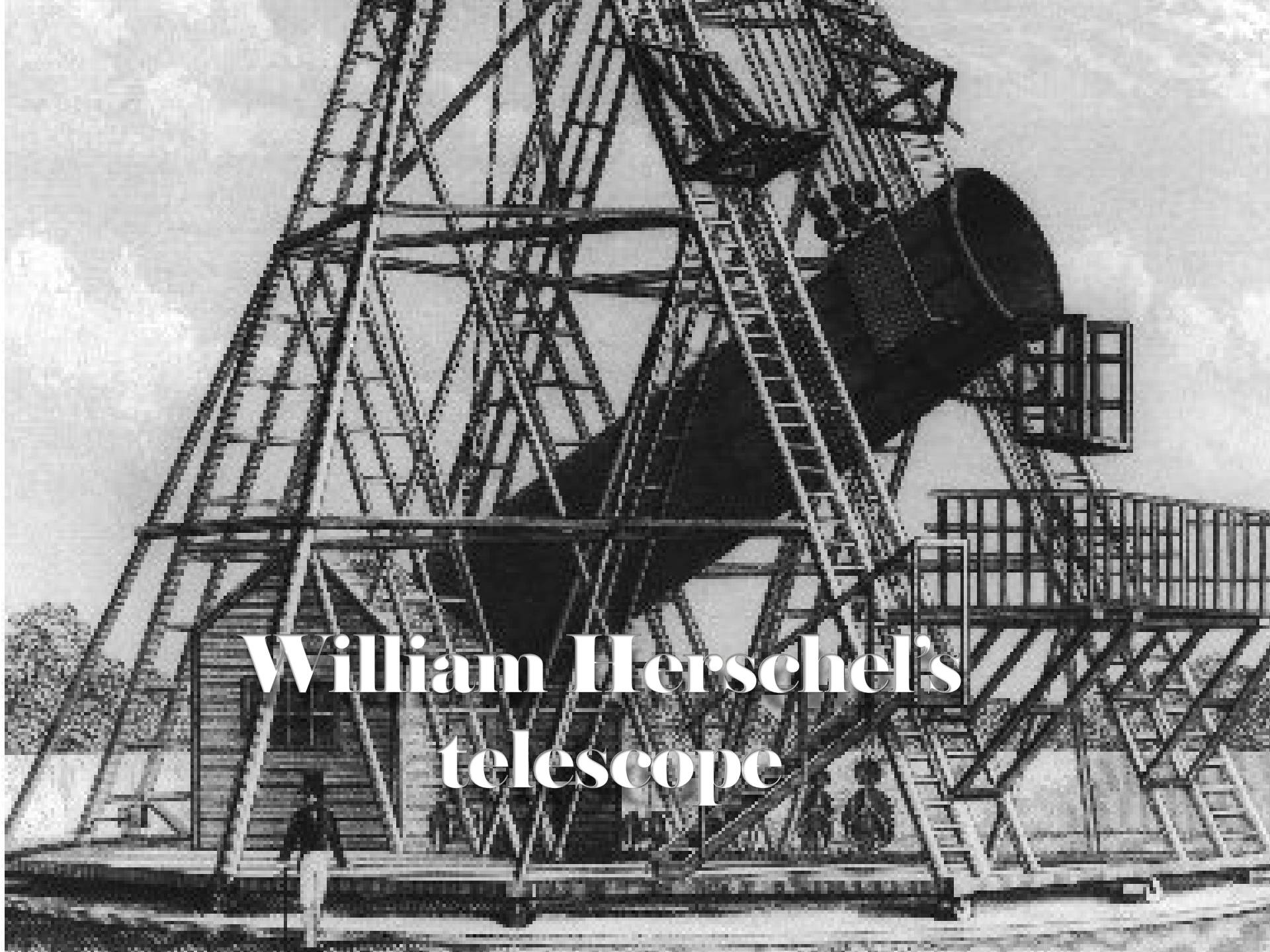
- **1826**
  Heinrich Wilhelm Olbers
  - Olber's paradox (why is the night sky dark ?)

- **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

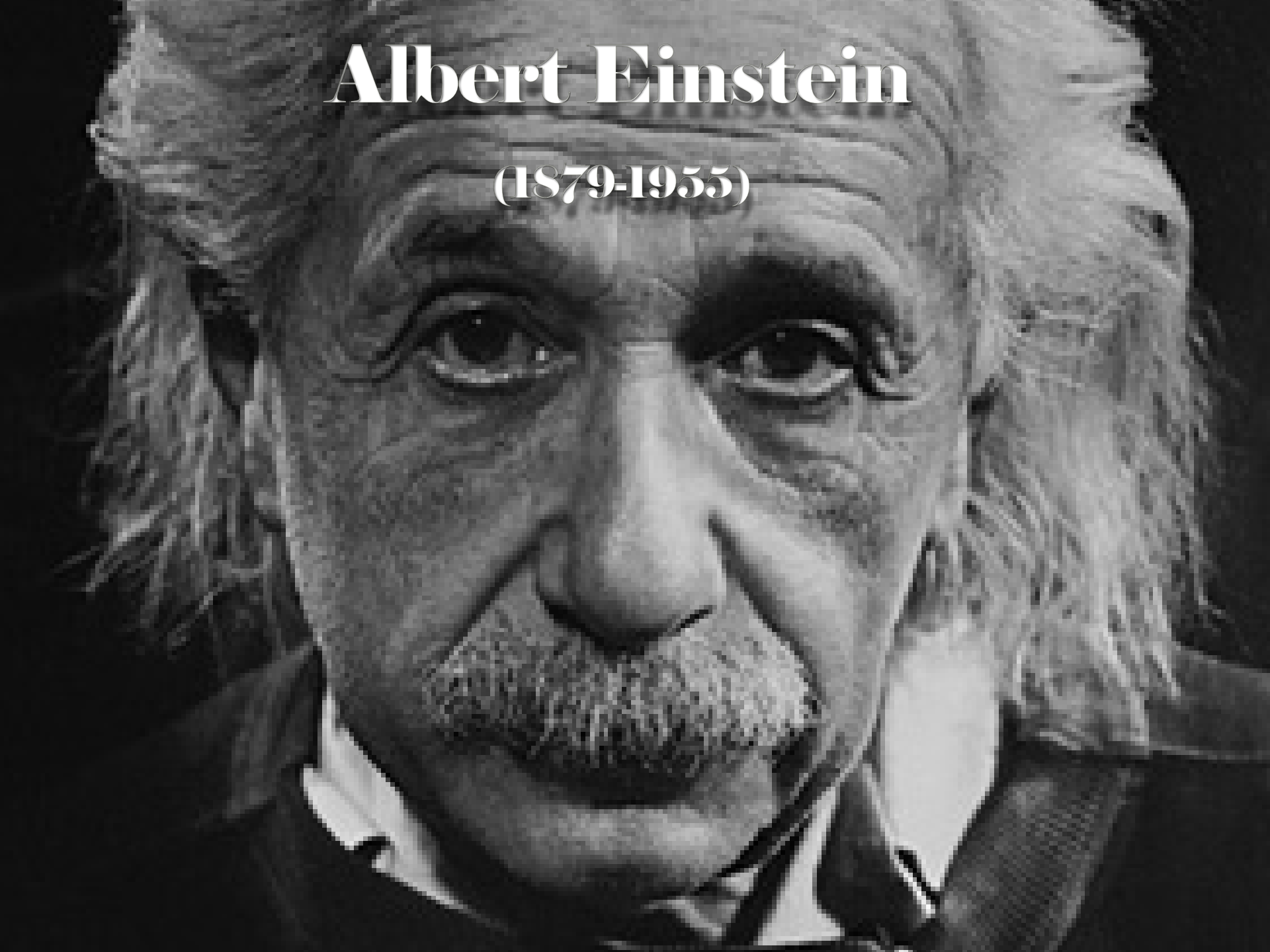
- **1915**
  Albert Einstein
  - General Theory of Relativity:
    Einstein field equations
  - represents an entirely new theory of gravity, in which gravity is the result of the local curvature of space, hence replacing the action-at-a-distance theory of Newton.
  - spacetime becomes a flexible dynamic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


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 discusssion)

- **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 □-□-□ paper
  - describes how the Big bang would by means of nuclear synthesis in the early universe create hydrogen, helium and heavier elements

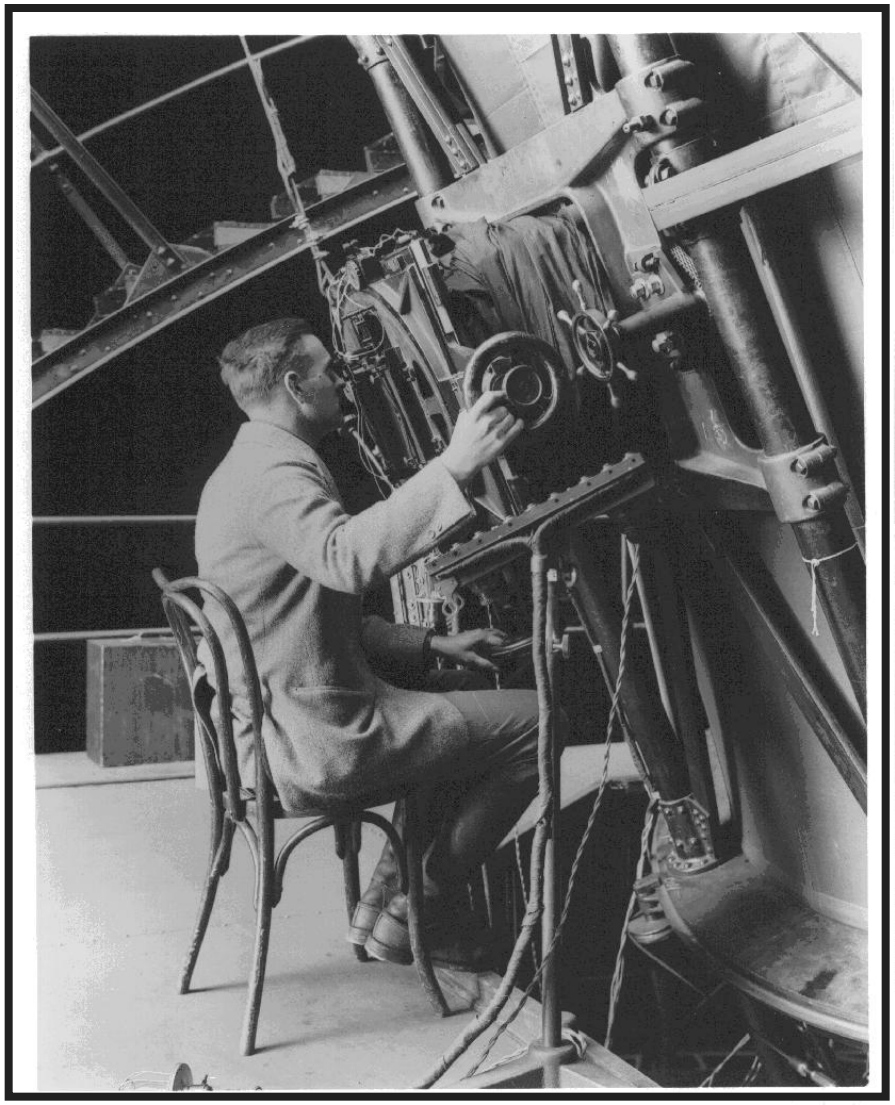
- **1948**
  Ralph Alpher & Robert Herman
  - as a consequence of their studies of nucleosynthesis in the early expanding Big Bang universe, theoretical prediction of the existence of a residual, homogeneous, isotropic blackbody radiation
  - they estimate "the temperature in the universe" at 5 K.
  - 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

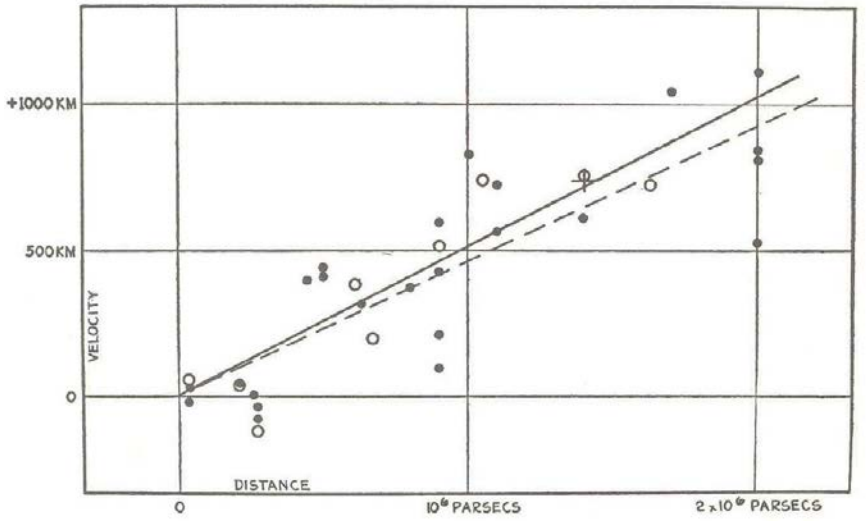
- **1957**
  Margaret Burbidge, Geoffrey Burbidge, William Fowler & Fred Hoyle
  - landmark B^2FH paper
  - Synthesis of the Elements in Stars
  - describes how all elements, heaver than lithium, are synthesize by nuclear processes in the cores of stars
  - We are stardust !

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

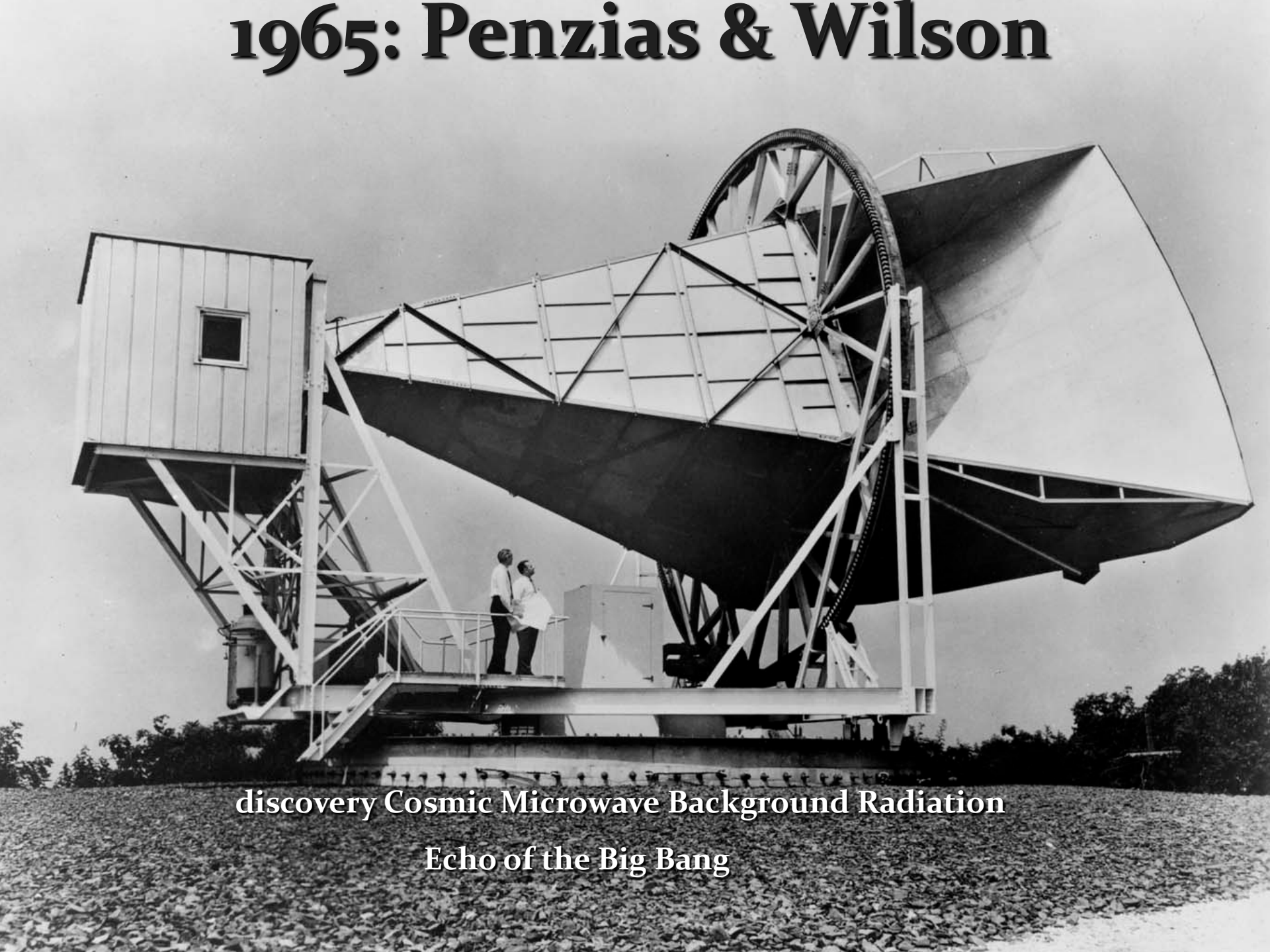
- **1965**
  Arno Penzias & Robert Wilson
  - Discovery of the 2.7K *Microwave Background Radiation* (CMB)
  - ultimate proof of the Hot Big Bang
  - Nobelprize Physics in 1978

- **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*

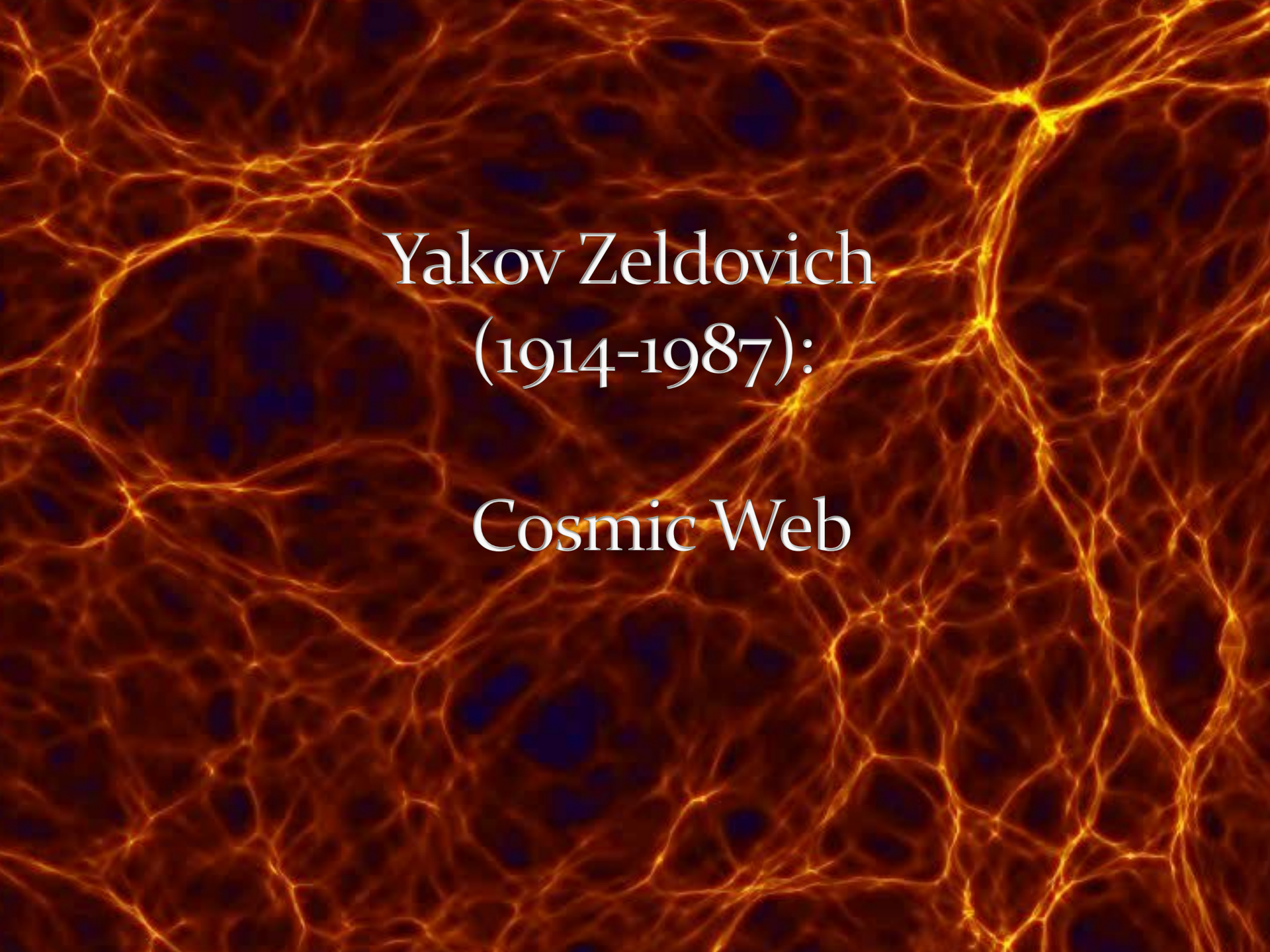
- **1980**
  Alan Guth, Alexei Starobinsky
  - *Inflationary Big Bang universe*
  - possible solution to the socalled horizon and flatness problems of standard Big Bang models
  - has become a key element of the standard Big Bang model

- **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/indictions 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**


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

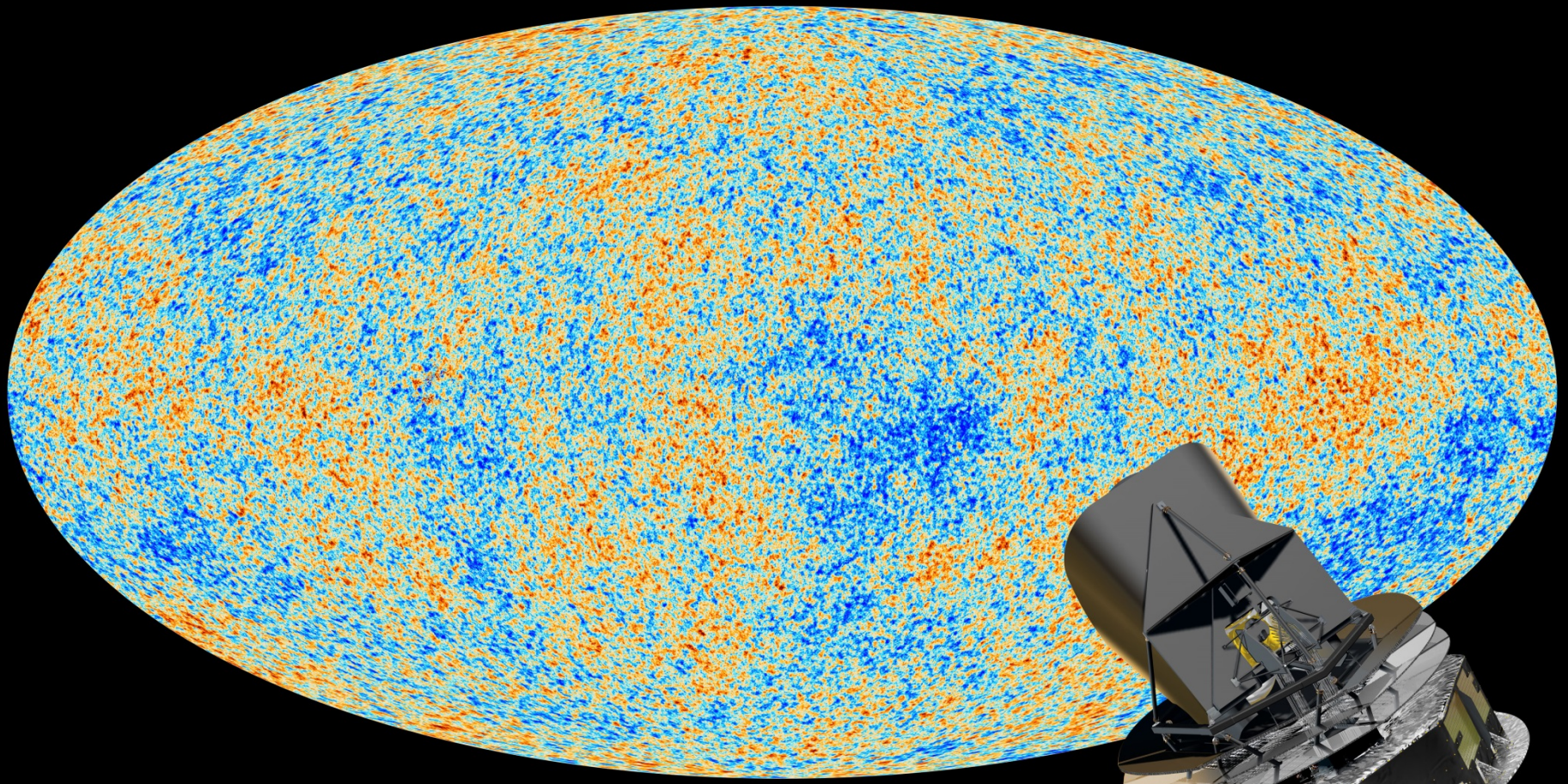
- **1997-2002**
  2dFGRS galaxy redshift survey
  - first large scale systematic survey of the spatial galaxy distribution
  - conducted with the 3.9m Anglo-Australian Telescope
  - mapped the positions of 232,155 galaxies in 2 narrow slices out to a redshift of 0.2
  - structure mapped is that of a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

Precision Cosmology

- Universe 380.000 yrs after Big Bang
- 13.8 Gyrs ago (13.798 ± 0.037 Gyrs)
- Temperature T = 2.72548 ± 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
  - proviedes 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 realiyt 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