

Timeline

Cosmology

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with thanks to Bernard J.T. Jones

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

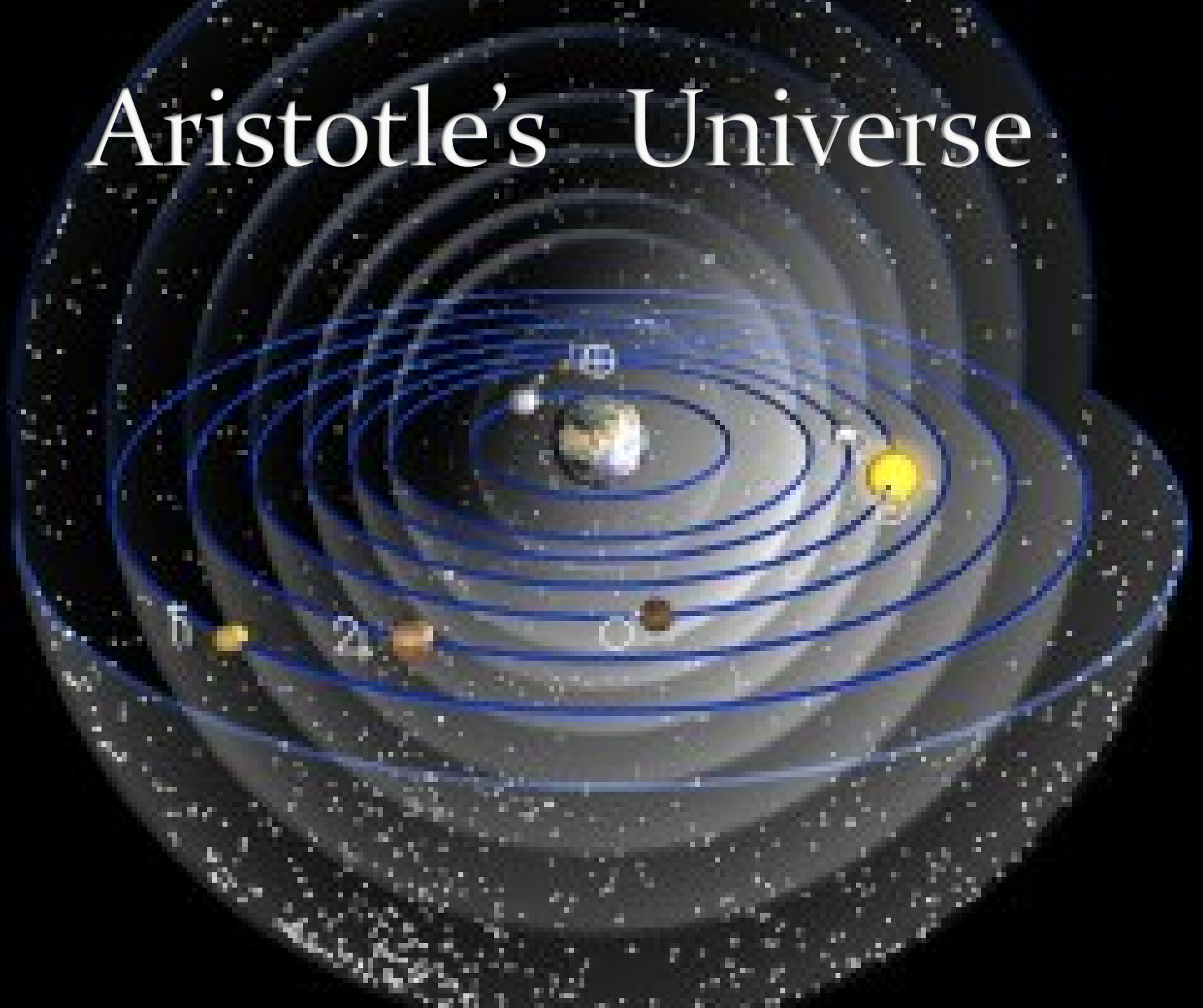
- Timaeus
- dialogue describing the creation of the Universe,
- demiurg created the world on the basis of geometric forms (Platonic solids)

- **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



Hellenistic Scientific Revolution

- 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 century CE

Martianus Capella (c. 410-420)

- *De nuptiis Philologiae et Mercurii* (aka "De septem disciplinis"), 5th century encyclopedia
- 8th book describes a geocentric universe, with the Sun orbiting Earth, and Venus and Mercury orbiting the Sun, (much like late 16th century Brahe model)

Medieval Hindu & Islamic World

5th-13th century CE

Aryabhata (India) and *Al-Sijzi* (Iran)

propose that the Earth rotates around its axis.

Nasir al-Din al-Tusi (1201–1274)

First empirical evidence for Earth's rotation by Nasir al-Din al-Tusi.

8th century CE

Puranic Hindu cosmology,

the Universe goes through repeated cycles of creation, destruction and rebirth, with each cycle lasting 4.32 billion years.

8th century CE

Imam Muhammed al-Baqir (676-733)

medieval Islamic scholars endorse idea of pluralistic universe

"Maybe you see that God created only this single world and that God did not create humans besides you.

Well, I swear by God that God created thousands and thousands of worlds and thousands and thousands of humankind."

13th century CE

Fakhr ad-Din ar-Razi (1149–1209),

Matalib al-Aliya

criticizes geocentric model and within the universe and explores the notion of the existence of a plural worlds in the context of his commentary on the Quranic verse, "All praise belongs to God, Lord of the Worlds". He raises the question of whether the term "worlds" in this verse refers to

"multiple worlds within this single universe or cosmos, or to many other universes or a multiverse beyond this known universe."

European Middle Ages

10th century CE, Carolingian times

unknown Irish monk, ~ 950-960 CE

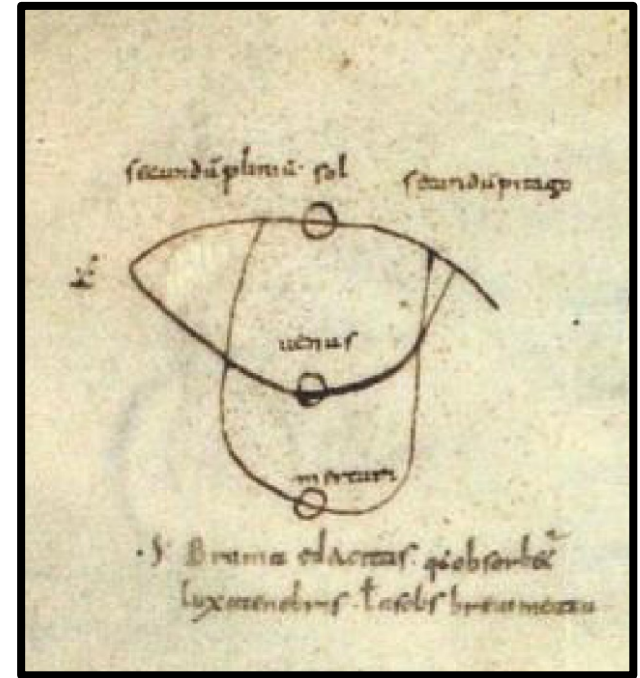
- awareness of alternatives to geocentric universe:
sketch Venus & Mercury orbit around Sun (!!!!),
in copy of Martianus Capella "De septem disciplinis"

1230

Johannes de Sacrobosco, 1195-1230

Tractatus de Sphaera/De sphaera mundi (1230)

- Earth as a sphere



13th century CE

Robert Grosseteste (1175-1253), Anglo-Norman

De Luce (On Light) (1225)

- first work stating that a single set of physical laws account for different structures of heavens and Earth
- nine-sphere universe, formed in series of "phase" transitions
- an initial explosion (!!!!) of a primordial sort of light, expands the Universe into an enormous sphere, thinning matter as it goes. Sounds like **Big Bang**

15th century CE

Nicolas de Cusa, 1401-1464

De Docta Ignorantia (1440)

- first European work stating that other stars would be other worlds:

“Life, as it exists on Earth in the form of men, animals and plants, is to be found, let us suppose in a high form in the solar and stellar regions. Rather than think that so many stars and parts of the heavens are uninhabited and that this earth of ours alone is peopled we will suppose that in every region there are inhabitants, differing in nature by rank and all owing their origin to God ...”,

- work explicitly states a “Cosmological Principle”

“The universe has no circumference, for if it had a center and a circumference there would be some and some thing beyond the world, suppositions which are wholly lacking in truth. Since, therefore, it is impossible that the universe should be enclosed within a corporeal center and corporeal boundary, it is not within our power to understand the universe, whose center and circumference are God. ”

1584

Giordano Bruno, 1548-1600

De l'Infinito, Universo e Mondi (1584)

”Innumerable celestial bodies, stars, globes, suns and earths may be sensibly perceived therein by us and an infinite number of them may be inferred by our own reason.”



Nikolaus Copernicus
(1473-1543)

The Scientific Revolution

- 1543

Nicolaus Copernicus

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

- 1576

Thomas Digges (1546-1595)

A Prognostication everlasting (1576)

First expose – in appendix - of Copernican heliocentric model of the Universe in English language.

Digges states – going further than Copernicus - that the Universe is infinite, and contains infinitely many stars.

“Digges’ original contribution to cosmology consisted of dismantling the starry sphere throughout endless space

... Digges pioneered ... the idea of an unlimited sphere filled with the mingling rays of countless stars.” (E. Harrison)

- 1572

Tycho Brahe

Tycho’s supernova

Ultimate evidence and challenge against the Aristotelian view of a serene unchanging Universe.

- 1609-1632

Galileo Galilei

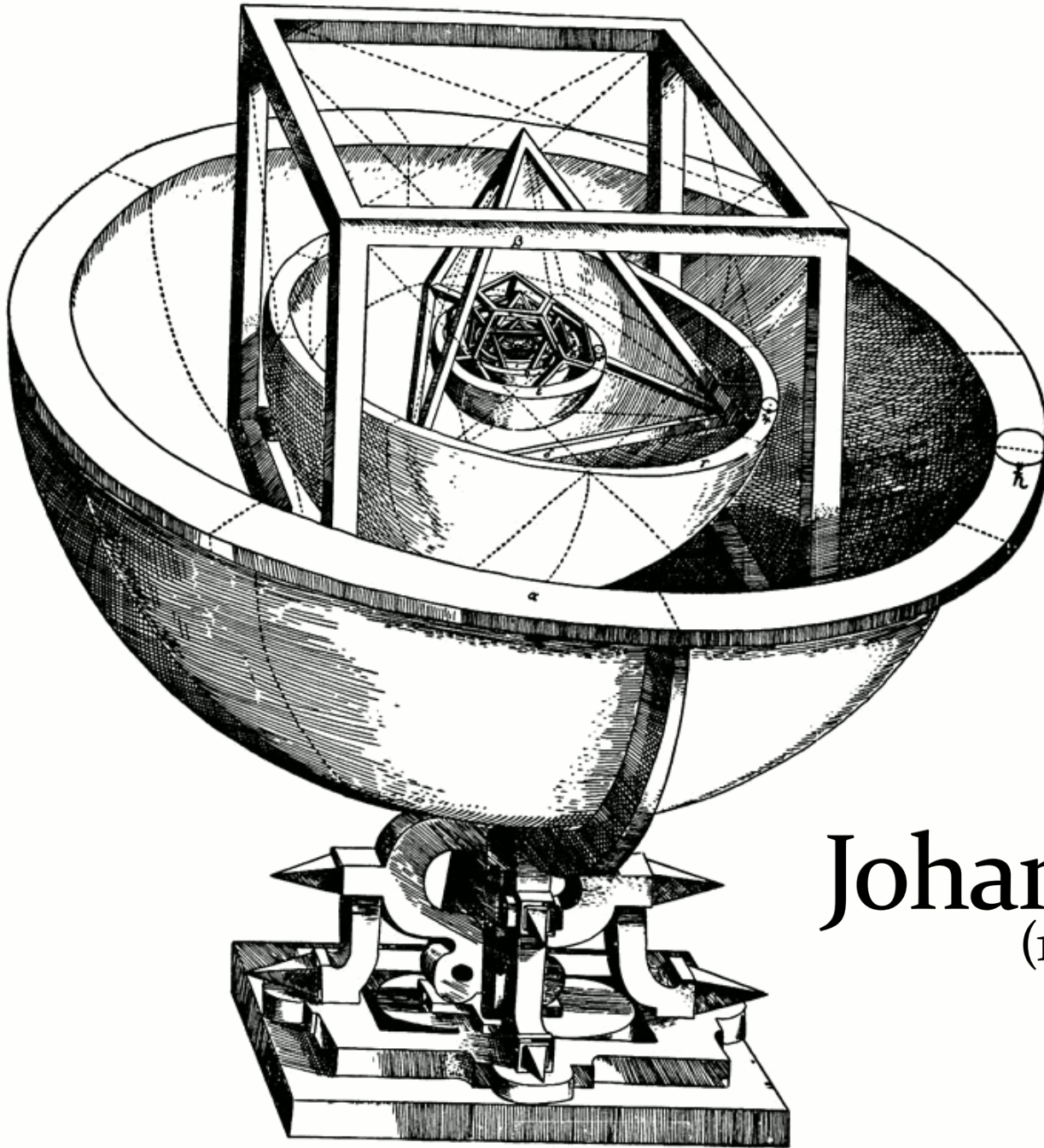
by means of (telescopic) observations, proves the validity of the heliocentric Universe.

- 1610 , **Siderius Nuncius**

first published work on observations made by telescope

- 1632, **Dialogue Concerning the Two Chief World Systems**

Debate between Salviati, exposing the Copernican heliocentric Universe and Simplicio, defending the old traditional Ptolemaic geocentric model.



Johannes Kepler
(1571-1630)

The Scientific Revolution:

Mechanization of the Universe

- **1609/1619**

Johannes Kepler

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

- **1687**

Isaac Newton

Philosophiae Naturalis Principia Mathematica

- 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)

PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

^{auto} Autore ^{Equite literato,} J. S. NEWTON ^{Trin. Coll. Cantab. Soc. Matheseos}
^{Professore} ^{Lucasiano,} & Societatis Regiæ Sodali.
^{et Societatis Regiæ Societatis præside.}

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

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

Isaac Newton

(1642-1726)

- **1576**

Thomas Digges

Following his statement of an infinite universe, filled with an infinite number of stars, Digges is the first to identify the “*dark night sky paradox*”.

- **1610**

Johannes Kepler

Letter to Galilei (1610)

Puzzled by the night’s darkness: in 1610 he wrote in a letter to Galileo that in an infinite universe filled with stars, “the whole celestial vault would be as luminous as the Sun.” Kepler’s proposed solution to the paradox is that the universe has to be finite(this fell in line with Kepler’s religious beliefs that the entire universe was “for man’s sake.”)

- **1686**

Bernard le Bovier de Fontenelle (1657-1757)

Entretiens sur la pluralité des mondes/Conversations on the Plurality of the Worlds (1686)

Book describes new Copernican cosmology, and speculates on the plurality of worlds.

In a series of conversations between a philosopher and a marquise, who walk in the latter's garden at night and gaze at stars, the philosopher explains the heliocentric model and also muses on the possibility of extraterrestrial life.

- **1755**

Immanuel Kant

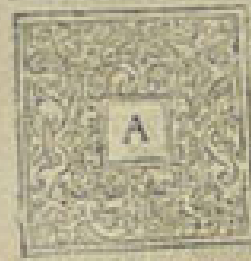
- asserts that nebulae are really galaxies separate from and outside from the Milky Way,
- calling these Island Universes



Thomas Digges

(1546-1595)

A PERFIT DESCRIPTION
 on of the Cœlestiall Orbes, according
 to the most ancient doctrine of the Pythagoreans:
 lately revived by Copernicus, and by Geometri-
 call Demonstrations: p-
 proued.



Though in this most excellent and difficult part of Philosophy in all times have been sundrie opinions touching the situation and moving of the bodies celestiall, yet in certaine principles, all Philosophers of any account of all ages have agreed and consented. First that the Orbe of the fixed stars is of all other the most high, the farthest of hand, and comprehends the other Spheres of wandering Starres. And of these Straying bodies called Planets, the old Philosophers thought it a good ground in reason, that the nearest to the Centre should swiftest move, because the circle was least and thereby the sooner overspased, and the farther distant, the more slow. Wherefore as the Moone being swiftest in course, is found also by measure highest, so have all agreed that the Orbe of the fixed stars in moving the slowest of all the Planets, is also the highest: the first, and then 2 and 3 there hath been great controversy, because they stray not every way from the Summit, as the rest do. And therefore some have placed them about the Summit, as Plato in his Timæo: others beneath, as Ptoleme, and the greater part of them that followed him. Alpetragius was of opinion that 2 and 3 were about the Summit, and sundrie treatens have beene written in defence of their opinions. They that follow Ptoleme (supposing that all starres should have obscure and warme bodies shining with borrowed light like the Moone) have alleaged that if these Planets were lower then the Summit then should they sometime observe some part of the bodie of the Summit, and also shine, not with a light circular, but segmentall:

According to the most ancient doctrine of the Pythagoreans, &c.

19th Century

- 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**

20th Century – Relativistic Cosmology

- 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

- 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

- 1933

Edward Milne

- formulation of the *Cosmological Principle*
- Universe is *Isotropic* and *Homogeneous* (on scales larger than 100 million lightyears)

A black and white, high-contrast portrait of Albert Einstein. He is shown from the chest up, wearing a dark suit jacket, a white collared shirt, and a dark tie. His hair is wild and unkempt, and he has a prominent mustache. The background is dark and indistinct.

Albert Einstein

(1879-1955)

20th Century – the Universe Expanding

- **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

- **1922**
Vesto Slipher
 - finds that spiral nebulae are systematically redshifted, ie. moving away from us

- **1923/1925**
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, overnight the Galaxy loses its central unique position and the Universe turns out to be much, much larger than previously presumed

20th Century – the Universe Expanding

- 1927

Georges Lemaitre

Annales de la Société Scientifique de Bruxelles,

“Univers homogène de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extragalactiques”

("A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae")

- predicts distance-redshift relation (later known as Hubble relation, since Oct. 2018 **“Hubble-Lemaitre relation”**)
- discovered the EXPANSION OF THE UNIVERSE from existing data (formally recognized by IAU in Oct. 2018)

- 1929

Edwin Hubble

PNAS, "A relation between distance and radial velocity among extra-galactic nebulae"

- discovery linear redshift-distance relation (the Hubble relation, since Oct. 2018 **“Hubble-Lemaitre relation”**)
- ie. the discovery of the EXPANDING UNIVERSE

-

1930s - early Big Bang theory & discovery Dark Matter

- **1931**

Georges Lemaitre

proposes Big Bang theory:

the universe expanded from an initial point, called the "Primeval Atom"

Lemaître himself also described his theory as "the Cosmic Egg exploding at the moment of the creation"

- **1950**

Fred Hoyle

- coins the term *Big Bang*, meant in a derisive way

- **1932**

Jan Oort

- first indication for the existence of dark matter,

- from measurements of the motions of stars in the Milky Way, implying the mass of the Galactic plane must be more than the mass of the stars that can be seen

- **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

A cosmic scene featuring a bright, glowing central light source, possibly a star or a galaxy core, surrounded by a vast field of stars and a network of faint, intersecting lines that suggest a complex structure or a field of forces. The overall color palette is dominated by deep blues and purples, with the central light source emitting a bright white and yellow glow.

the Hot Big Bang

1940s & 1950s - the Big Bang theory

- 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 α - β - γ 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

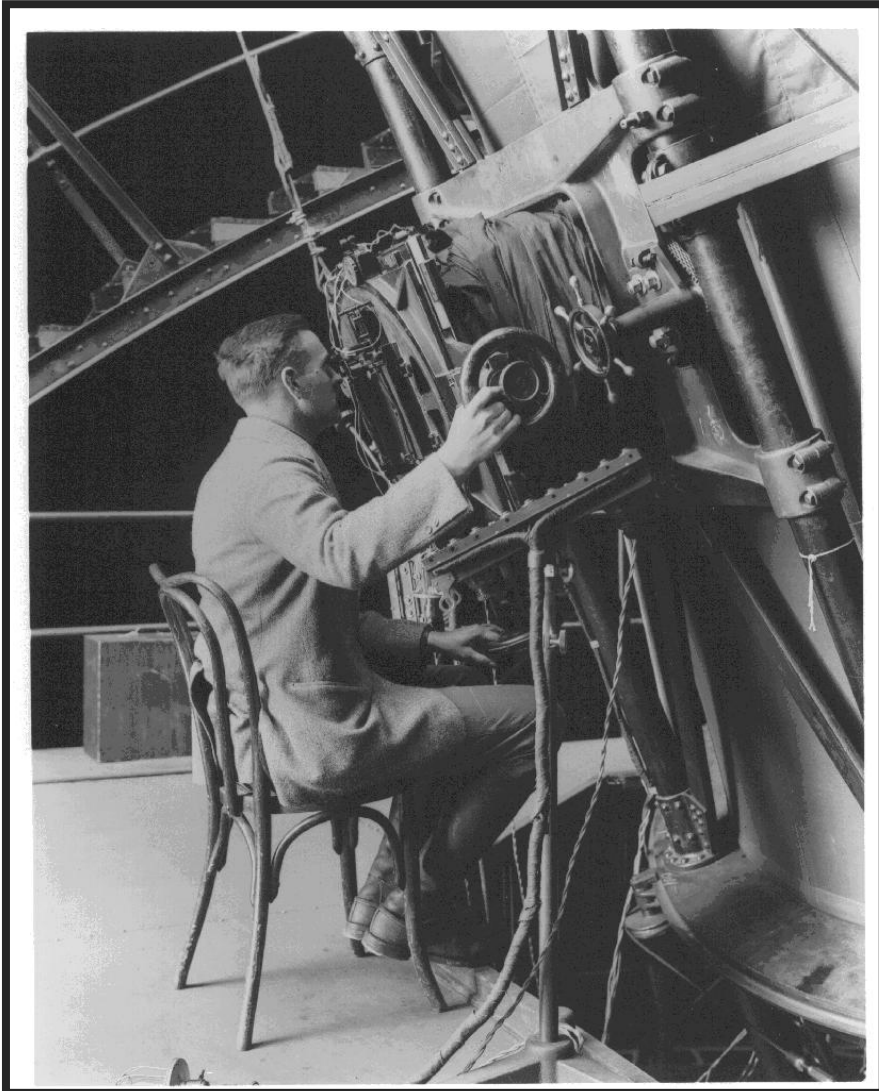
- proposal *Steady State Cosmology*, based on the perfect cosmological principle

- 1957

Margaret Burbidge, Geoffrey Burbidge, William Fowler & Fred Hoyle

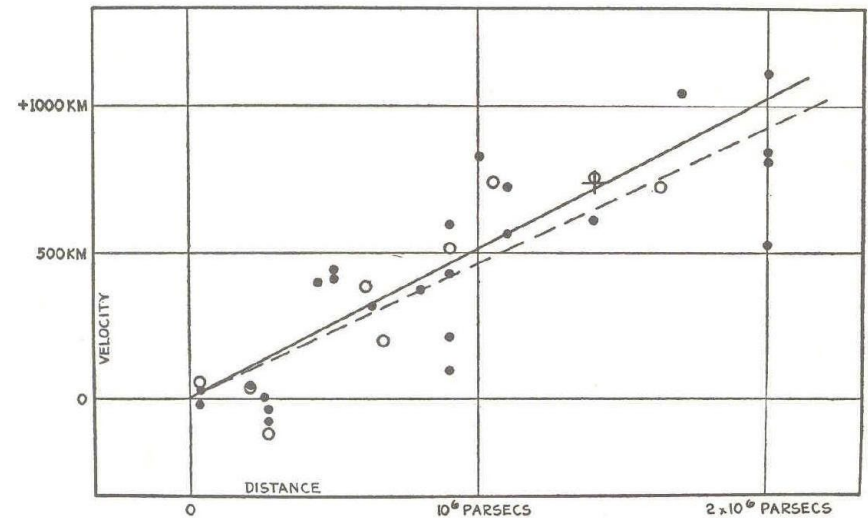
- landmark B²FH paper
- Synthesis of the Elements in Stars
- describes how all elements, heavier than lithium, are synthesized by nuclear processes in the cores of stars
- We are stardust !

Expanding Universe



Edwin Hubble

(1889-1953)



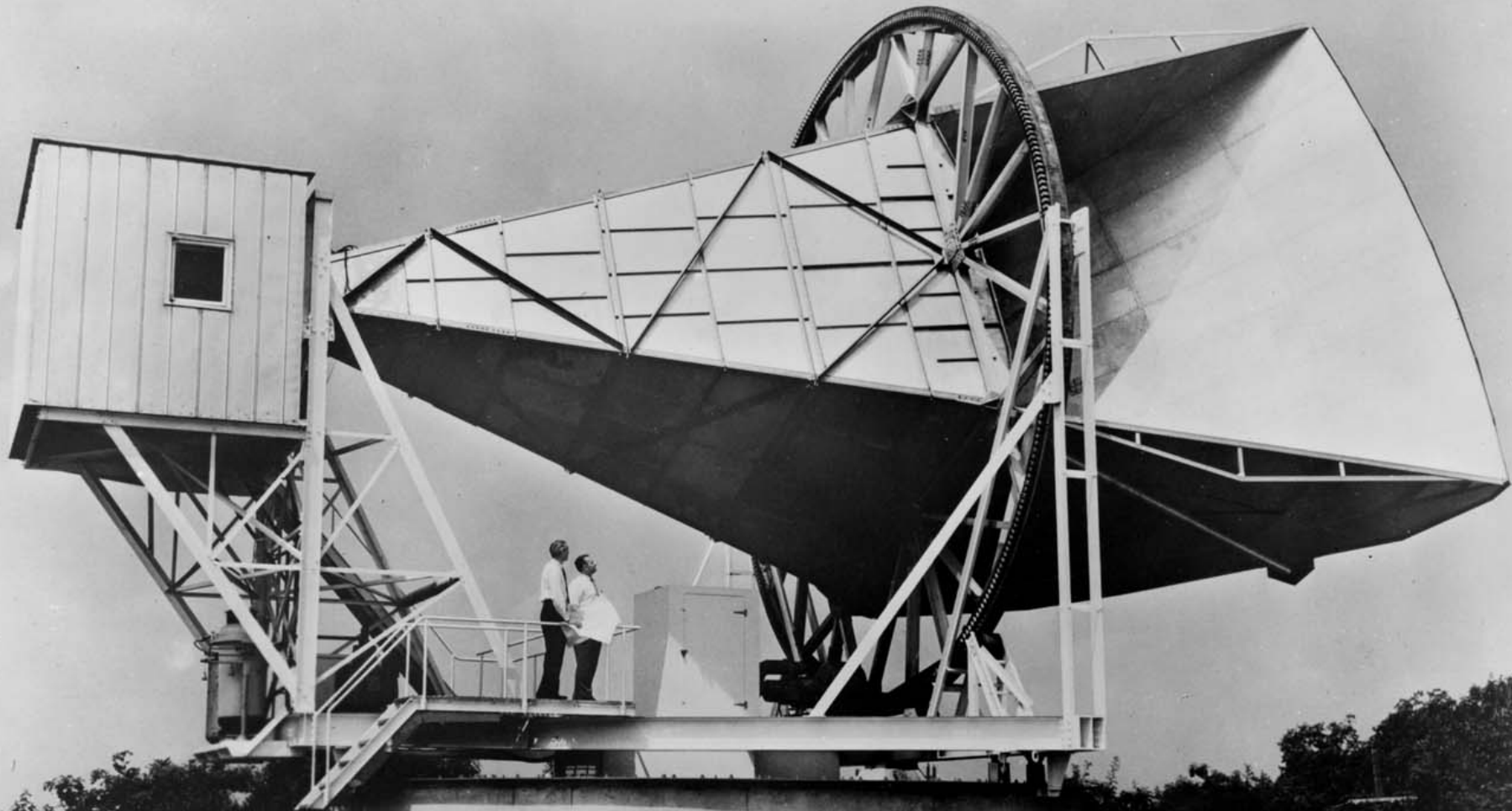
$$v = H r$$

Hubble Expansion

1960s – Big Bang & Physical Cosmology

- **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
- **1978**
Albert Bosma
PhD thesis, Univ. Groningen (1978)
clenching evidence of dark matter through the 21cm flat rotation curves of disk galaxies
- **1980**
Vera Rubin
- Dark Matter confirmed as making up 5-10 times more than ordinary matter, through the flat rotation curves of spiral galaxies

1965: Penzias & Wilson



discovery Cosmic Microwave Background Radiation

Echo of the Big Bang

1980s – Cosmic Structure & the Cosmic Web

- **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 and nodes against a dark blue background. The filaments form a web-like structure, with some thicker 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

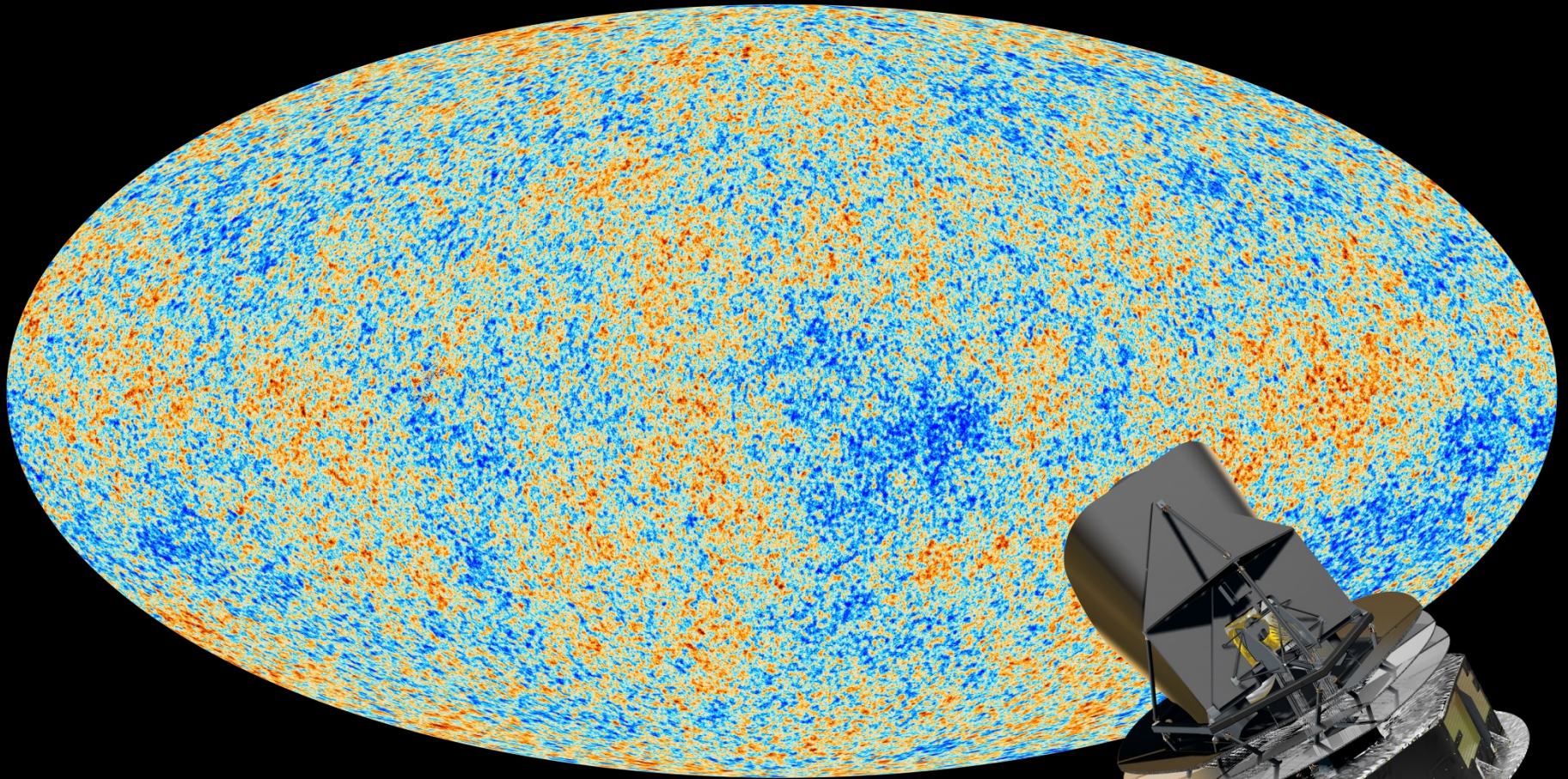
- **1997-2002**
2dFGRS galaxy redshift survey
 - first large scale systematic survey of the spatial galaxy distribution
 - conducted with the 3.9m Anglo-Australian Telescope
 - mapped the positions of 232,155 galaxies in 2 narrow slices out to a redshift of 0.2
 - structure mapped is that of a Cosmic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

- **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 Λ CDM cosmology

Precision Cosmology

- Universe 380.000 yrs after Big Bang
- 13.8 Gyrs ago (13.798 \pm 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

21st Century - 3rd Millennium: Precision Cosmology

- **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

- **2013-2018**

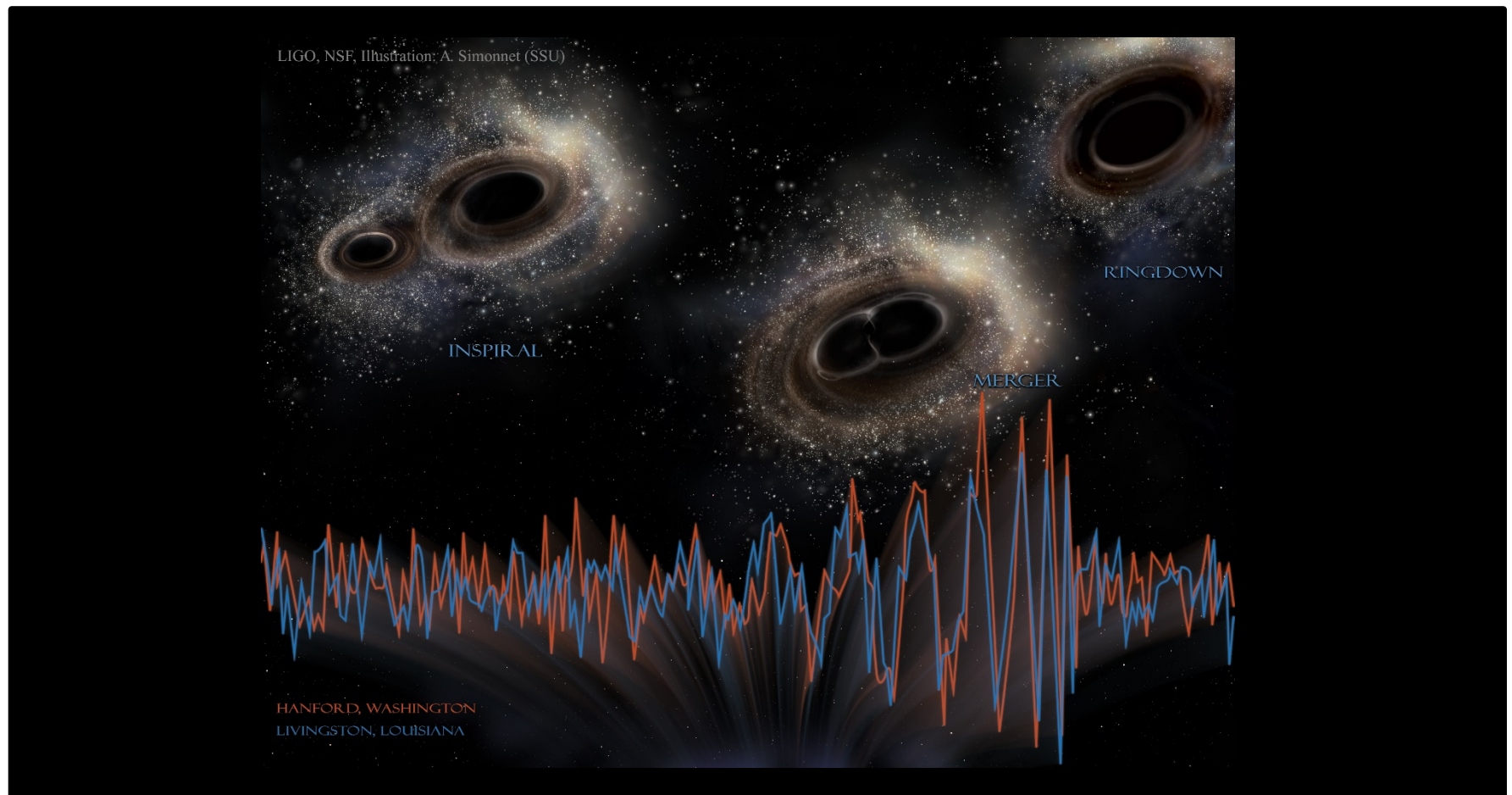
Planck CMB satellite

- 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

2015-2017

LIGO discovery of gravitational waves

- Largest and most ambitious project ever funded by (US) NSF
- Confirmation of General Theory of Relativity, to amazingly high precision
- 6th discovered event: aug. 2017, collision 2 neutron stars: velocity of gravity = velocity light
- Nobelprize physics 2017: Weiss, Thorne, Barish
- entirely new window on the Universe





Inflationary Universe