Introductory Particle Cosmology

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Lecture 1

Introduction

Mathematical Tools

Generic Vector Bases
Basis Change
Vectors in Curved Geometries
Tensors, Metric Tensor
(Riemann) Manifolds
Connection
Geodesics and Curvature

General Relativity

Equivalence Principle
Einstein Equations

Cosmology

Cosmological Principle
FLRW Metric
Friedmann Equations
Cosmic Distances
Cosmological Models

Observation

CMB
Structure Formation
Red-shift/Distance

Standard Model

Brief History
Particle Content
Gauge Principle, CPV, Strong CP
EW Symmetry Breaking
Beyond the SM

Particle Cosmology

Dark Matter (Models + Exp.)
Dark Energy (Models + Exp)
Inflationary Models
Gravitational Waves
Density Perturbations

Notes and Slides:
www.staff.uni-mainz.de/doria/partcosm.html

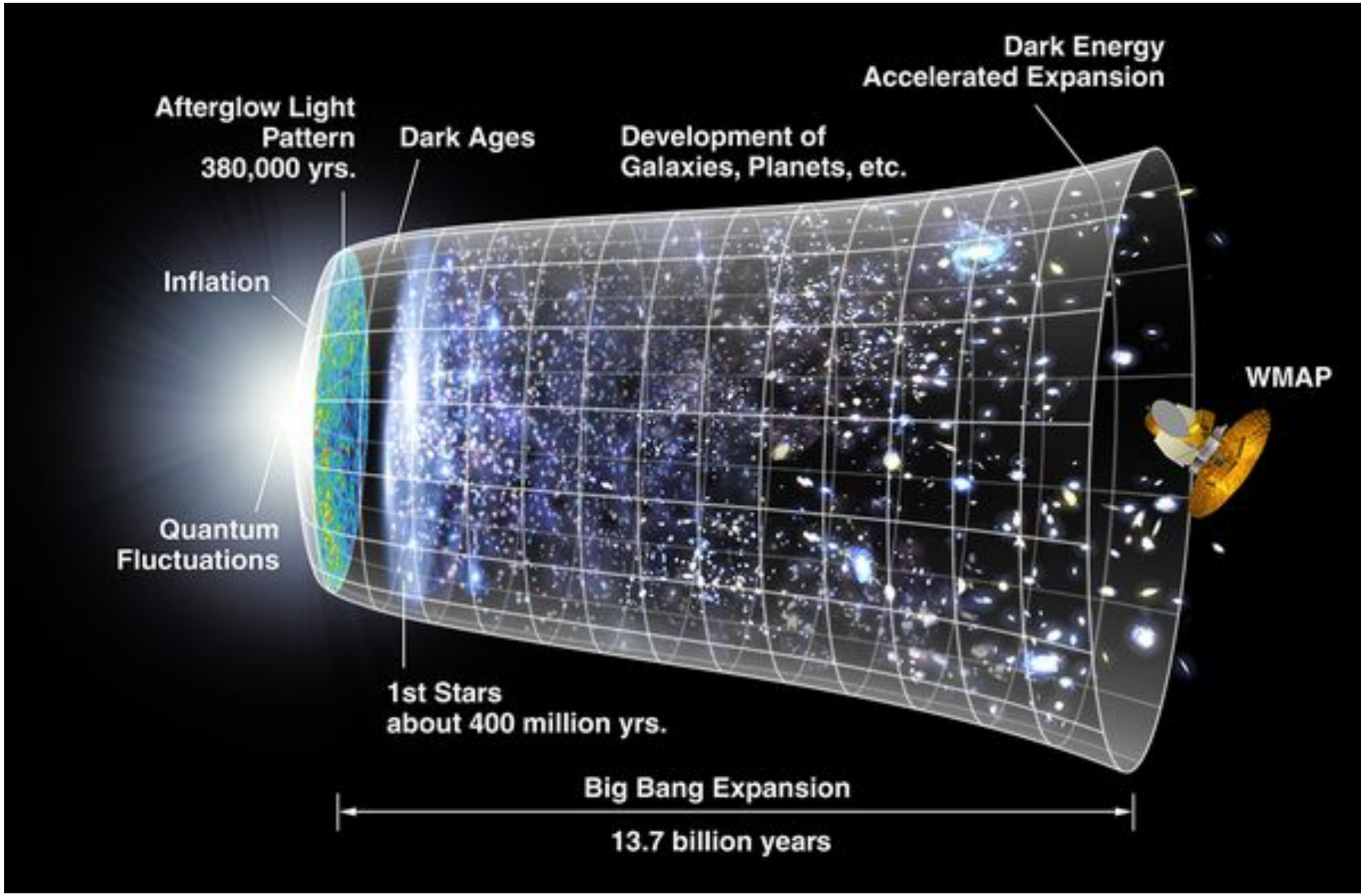
Plan

	Datum	Von	Bis	Raum
1	**Di, 17. Apr. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
2	**Do, 19. Apr. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
3	**Di, 24. Apr. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
4	**Do, 26. Apr. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
5	**Do, 3. Mai 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
6	**Di, 8. Mai 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
7	**Di, 15. Mai 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
8	**Do, 17. Mai 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
9	**Di, 22. Mai 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
10	**Do, 24. Mai 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
11	**Di, 29. Mai 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
12	**Di, 5. Jun. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
13	**Do, 7. Jun. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
14	**Di, 12. Jun. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
15	**Do, 14. Jun. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
16	**Di, 19. Jun. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
17	**Do, 21. Jun. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
18	**Di, 26. Jun. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
19	**Do, 28. Jun. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**
20	**Di, 3. Jul. 2018**	**10:00**	**12:00**	**05 119 Minkowski-Raum**
21	**Do, 5. Jul. 2018**	**08:00**	**10:00**	**05 119 Minkowski-Raum**

H.Minkowski
(1864-1909)

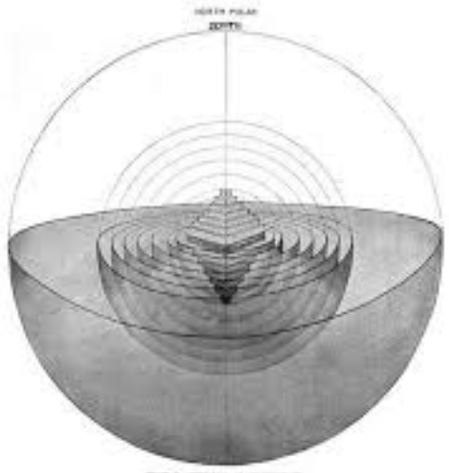
Physics Dept. Building, 5th Floor

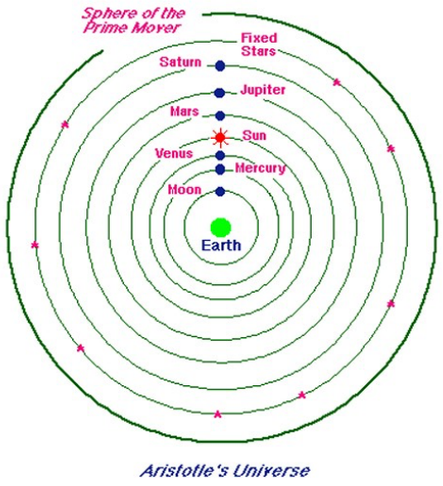
Cosmic History



(Ancient) History

<16th century BC, Mesopotamian:
Flat, circular Earth in the middle of an ocean

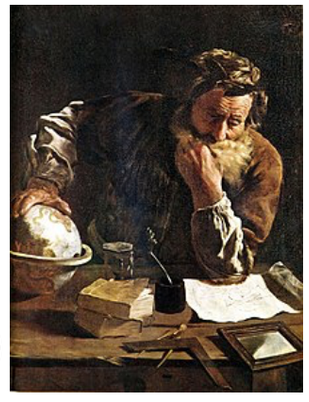




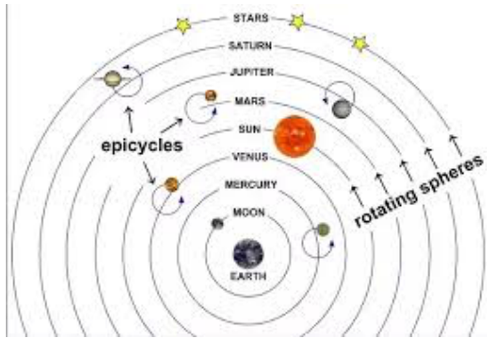
Aristotle's Universe

4th century BC, Aristotle:
Earth-centric, finite, immutable universe

3th century BC, Archimedes
"measured" the diameter of the Universe (2lyr !)

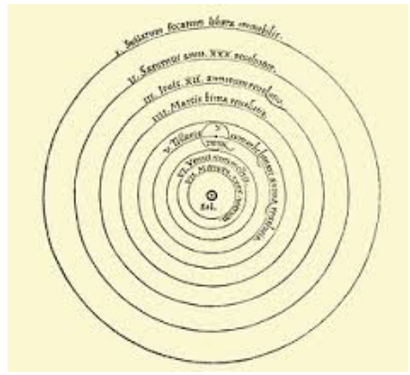


2th century BC, Ptolemy:
Earth-Centred universe, Sun and planets revolving



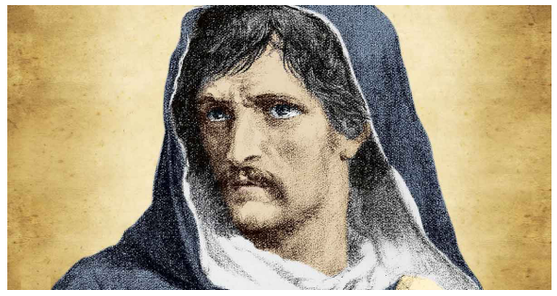
Non-European astronomers proposing Sun-centered theories

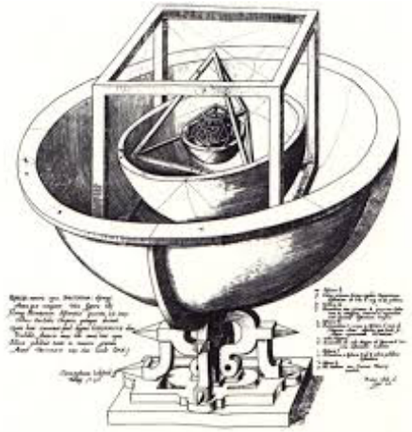
(non-BC) History



1540s: Copernicus
proposes the heliocentric theory

1584: Giordano Bruno
proposes a non-privileged position of the Sun in the cosmos.





1600s: Kepler
discovered his laws and elliptic motion.
He believed in a finite universe

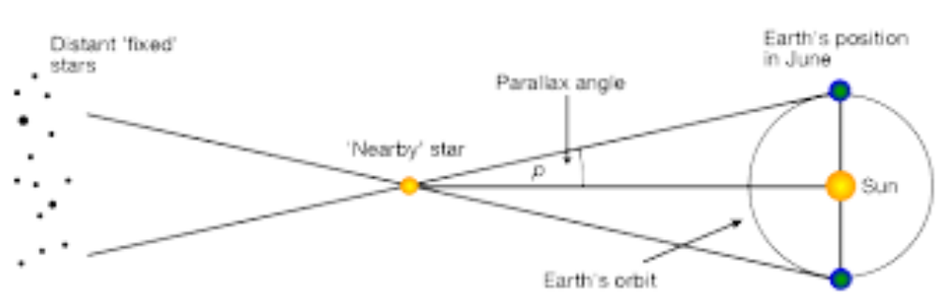
1680s: Isaac Newton:
Theory if Gravitation

(non-BC) History

1755: I. Kant
argues that nebulae are really separate galaxies

1826: Olber's Paradox

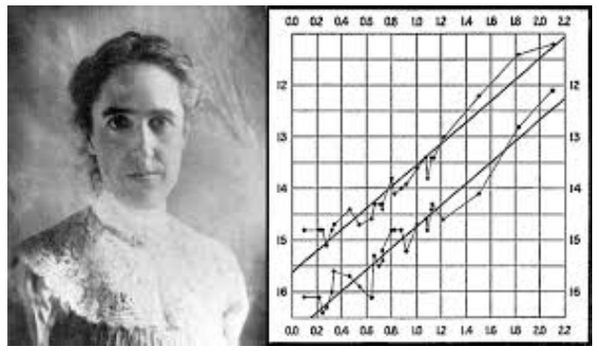
1837: Bessel
successfully measures the first parallax



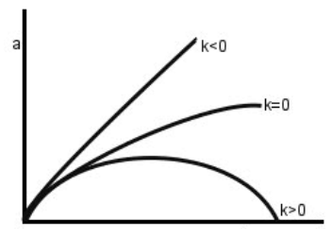
1915: A. Einstein
publishes the General Relativity Theory

(after GR) History

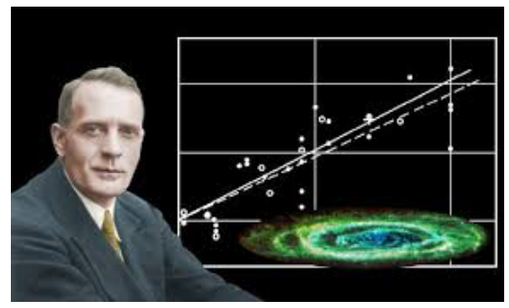
1912: Henrietta Leavitt discovers the Cepheid variable stars



1922: Friedmann finds expanding solutions of GR



1923: E. Hubble measures an apparent expansion of the universe



1933: E. Milne states the Cosmological Principle

1948: G. Gamow predicts the CMB

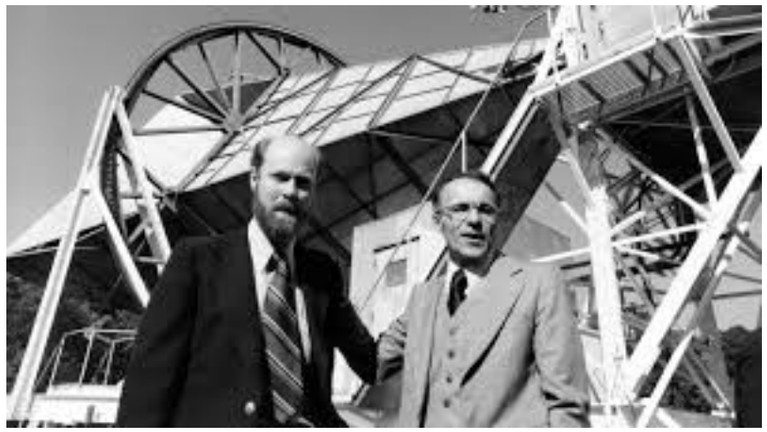
The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

(after GR) History

1950: F. Hoyle coins the word “Big-Bang”

1965: A. Penzias and R. Wilson discover the CMB



1967: A. Sakharov states the requirements for baryogengesis

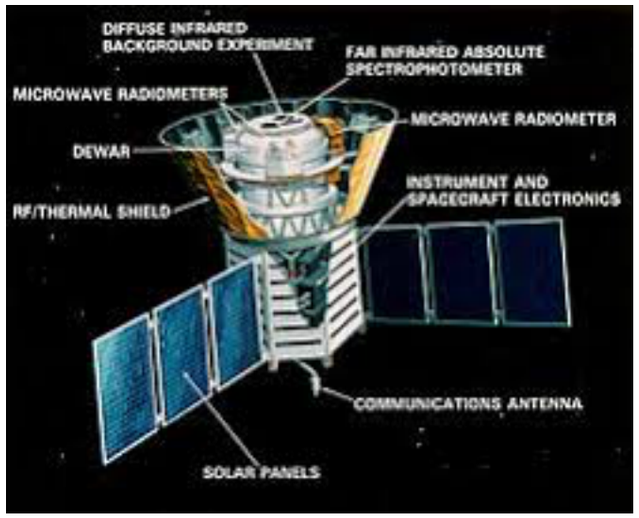
1970: V. Rubin and K. Ford
present precise data on galaxy rotational curves

(Modern) History

1980: A. Guth presents the idea of cosmic inflation

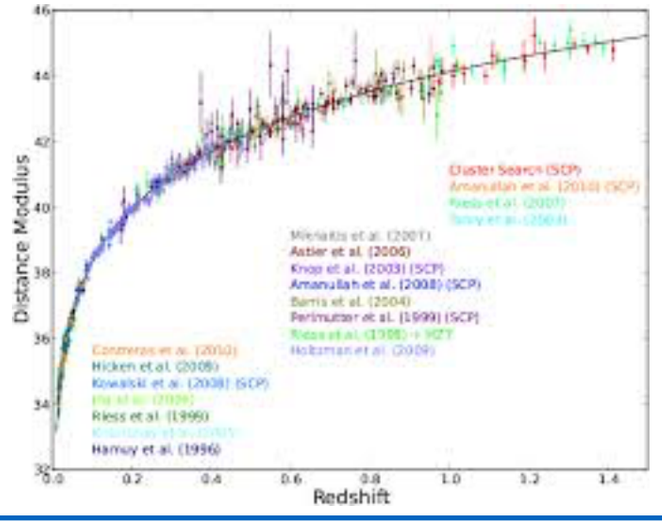
1982: J.Peebles and others propose CDM

1990s: COBE Mission
and the first measurement of CMB anisotropy



1996: Hubble Space Telescope deep-field pictures

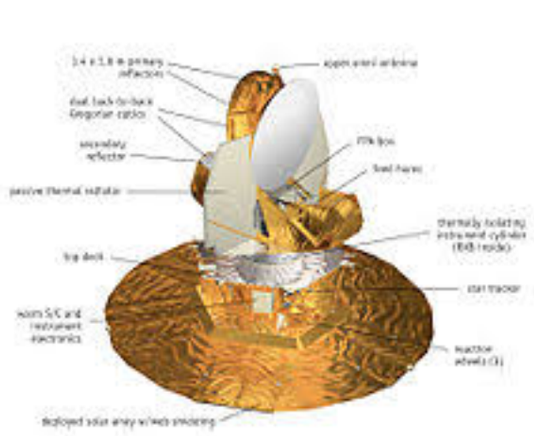
1998: Supernova Cosmology Project and High-Z Supernova Search



(Modern) History

1999: More **COBE** data and **BOOMERanG** experiment

2003-2011: WMAP, Planck and LambdaCDM



2014: BICEP2 and (the not confirmed) B-modes

2016: First Measurement on Earth of Gravitational Waves

Successes and Issues

Successes of the Standard Model of Cosmology

- Explains the dark sky (Olber's Paradox)
- Expansion of the Universe
- Approximately correct age of the Universe vs oldest stars
- Existence of the Cosmic Microwave Background (CMB)
- Primordial nuclear abundances

Issues:

- Baryon asymmetry
- Flatness
- Homogeneity
- Origin of the primordial fluctuations
- …

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Inflation as possible solution

Particle Cosmology

10^{34} K — 10^{30} eV

10^{24} K — 10^{20} eV

10^{14} K — 10^{10} eV

10^{4} K — 10^{0} eV

10^{-6} K — 10^{-10} eV

10^{-16} K — 10^{-20} eV

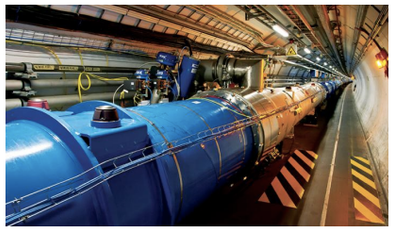
10^{-26} K — 10^{-30} eV

10^{-36} K — 10^{-40} eV

$$E_{\mathrm{P}} = \sqrt{\frac{\hbar c^5}{G}},$$

Planck Scale

LHC Collisions



10^{-37} m

10^{-27} m

10^{-17} m

10^{-7} m

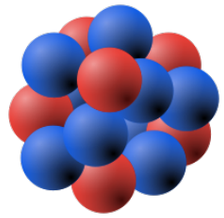
10^{3} m

10^{13} m

10^{23} m

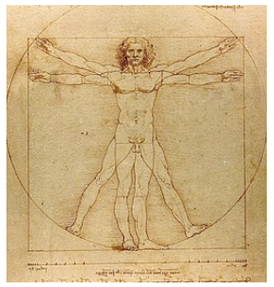
10^{33} m

Nuclei

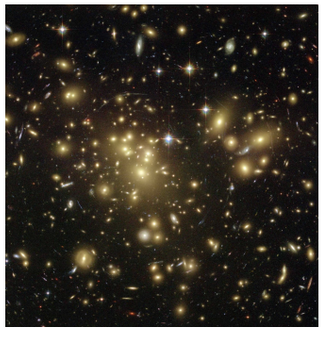


Atoms

Our Size



Galaxy Clusters



Size of the Universe

Particle Cosmology

10^{34} K — 10^{30} eV

10^{24} K — 10^{20} eV

10^{14} K — 10^{10} eV

10^{4} K — 10^{0} eV

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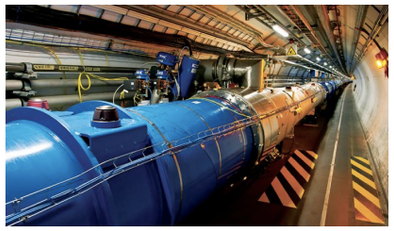
Planck Scale

LHC Collisions



10^{-37} m

10^{-27} m

10^{-17} m

10^{-7} m

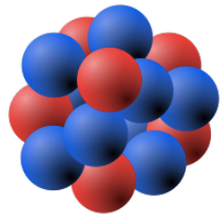
10^{3} m

10^{13} m

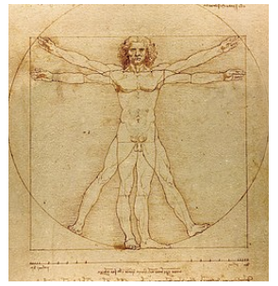
10^{23} m

10^{33} m

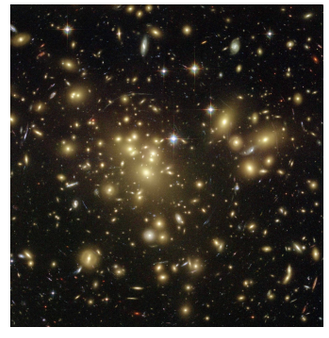
Nuclei
Atoms



Our Size



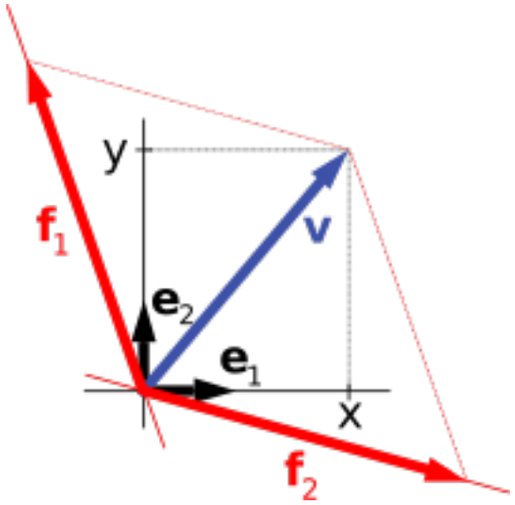
Galaxy Clusters

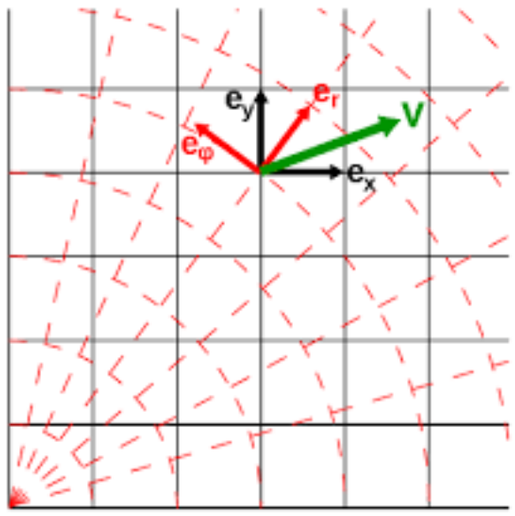


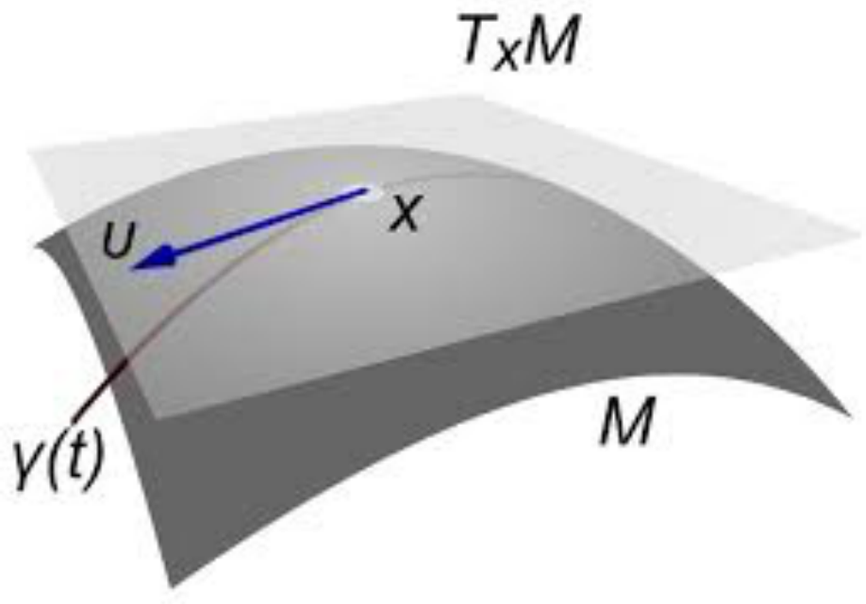
Size of the Universe

Part 1: Mathematical Tools

Vector Spaces
(Ortho-normal) bases
Change of Basis
Non-orthonormal bases
Covariant and contravariant vectors
Tensors
Curved Spaces
Vectors on curved spaces
Covariant Differentiation
Geodetics
Curvature







...but first some Physics

Natural Units $c = \hbar = \epsilon_\circ = k_B = 1$

$c =$ speed of light $= 2.9979 \times 10^8$ m/s

$\hbar =$ reduced Planck constant $= 1.0546 \times 10^{-34}$ J s

$\epsilon_\circ =$ electric constant $= 8.8542 \times 10^{-12}$ A^2 s^4 kg^{-1} m^{-3}

$k_B =$ Boltzmann constant $= 1.3806 \times 10^{-23}$ J K^{-1}

Consequences of this choice:

$$1s = 2.9979 \times 10^8 m$$

$$1s^{-1} = 1.0546^{-34} J$$

Let's try to measure everything with Energy!

This means: $[time] = [length] = [Energy]^{-1}$

What about velocity, momentum, mass,...?

Conversions

Conversion form SI

SI units are combinations of mass/length/time units.
We would like to convert everything in energy, eventually setting hbar=c=1

$$kg^{\alpha} m^{\beta} s^{\gamma} = E^{a} \hbar^{b} c^{c}$$

Converting E, hbar, c in SI units and comparing the exponents, we obtain

$$kg^{\alpha} m^{\beta} s^{\gamma} = E^{\alpha-\beta-\gamma} \hbar^{\beta+\gamma} c^{\beta-2\alpha}$$

Common choice for [E] is GeV (1.6022×10^{-10} J)

Conversions

Variable	SI Unit	Natural Unit	Factor	Natural unit → SI unit
mass	kg	E	c^{-2}	$1\ \mathrm{GeV} \rightarrow 1.7827 \times 10^{-27}\ \mathrm{kg}$
length	m	E^{-1}	$\hbar c$	$1\ \mathrm{GeV}^{-1} \rightarrow 1.9733 \times 10^{-16}\ \mathrm{m}$
time	s	E^{-1}	$\hbar$	$1\ \mathrm{GeV}^{-1} \rightarrow 6.5823 \times 10^{-25}\ \mathrm{s}$
energy	$\mathrm{kg\ m^2\ s^{-2}}$	E	1	$1\ \mathrm{GeV} \rightarrow 1.6022 \times 10^{-10}\ \mathrm{J}$
momentum	$\mathrm{kg\ m\ s^{-1}}$	E	c^{-1}	$1\ \mathrm{GeV} \rightarrow 5.3444 \times 10^{-19}\ \mathrm{kg\ m\ s^{-1}}$
velocity	$\mathrm{m\ s^{-1}}$	dimensionless	c	$1 \rightarrow 2.9979 \times 10^{8}\ \mathrm{m\ s^{-1}}$
angular momentum	$\mathrm{kg\ m^2\ s^{-1}}$	dimensionless	$\hbar$	$1 \rightarrow 1.0546 \times 10^{-34}\ \mathrm{J\ s}$
area	$\mathrm{m^2}$	E^{-2}	$(\hbar c)^2$	$1\ \mathrm{GeV}^{-2} \rightarrow 3.8938 \times 10^{-32}\ \mathrm{m^2}$
force	$\mathrm{kg\ m\ s^{-2}}$	E^2	$(\hbar c)^{-1}$	$1\ \mathrm{GeV}^2 \rightarrow 8.1194 \times 10^{5}\ \mathrm{N}$
energy density	$\mathrm{kg\ m^{-1}\ s^{-2}}$	E^4	$(\hbar c)^{-3}$	$1\ \mathrm{GeV}^4 \rightarrow 2.0852 \times 10^{37}\ \mathrm{J\ m^{-3}}$
charge	$\mathrm{C = A \cdot s}$	dimensionless	1	$1 \rightarrow 5.2909 \times 10^{-19}\ \mathrm{C}$

Note: Geometrized unit system: G=c=1 (everything in length units, conv.factor= $G^{-\alpha} c^{2\alpha-\gamma}$)
Planck Units (G=c=habar=1: everything in units of Planck scales, see next slide)

Planck Scale

The fundamental constants of Nature set a natural scale for the measurement units:

Planck length: $l_P = \sqrt{\frac{\hbar G}{c^3}} \qquad \sim 1.6 \times 10^{-35} m$

Planck Mass: $m_P = \sqrt{\frac{\hbar c}{G}} \qquad \sim 2.1 \times 10^{-8} kg$

Planck Time: $t_P = \sqrt{\frac{\hbar G}{c^5}} \qquad \sim 5.4 \times 10^{-44} s$

Planck Energy: $E_P = \sqrt{\frac{\hbar c^5}{G}} \qquad \sim 1.96 \times 10^9 J \sim 1.22 \times 10^{19} GeV$

..etc...