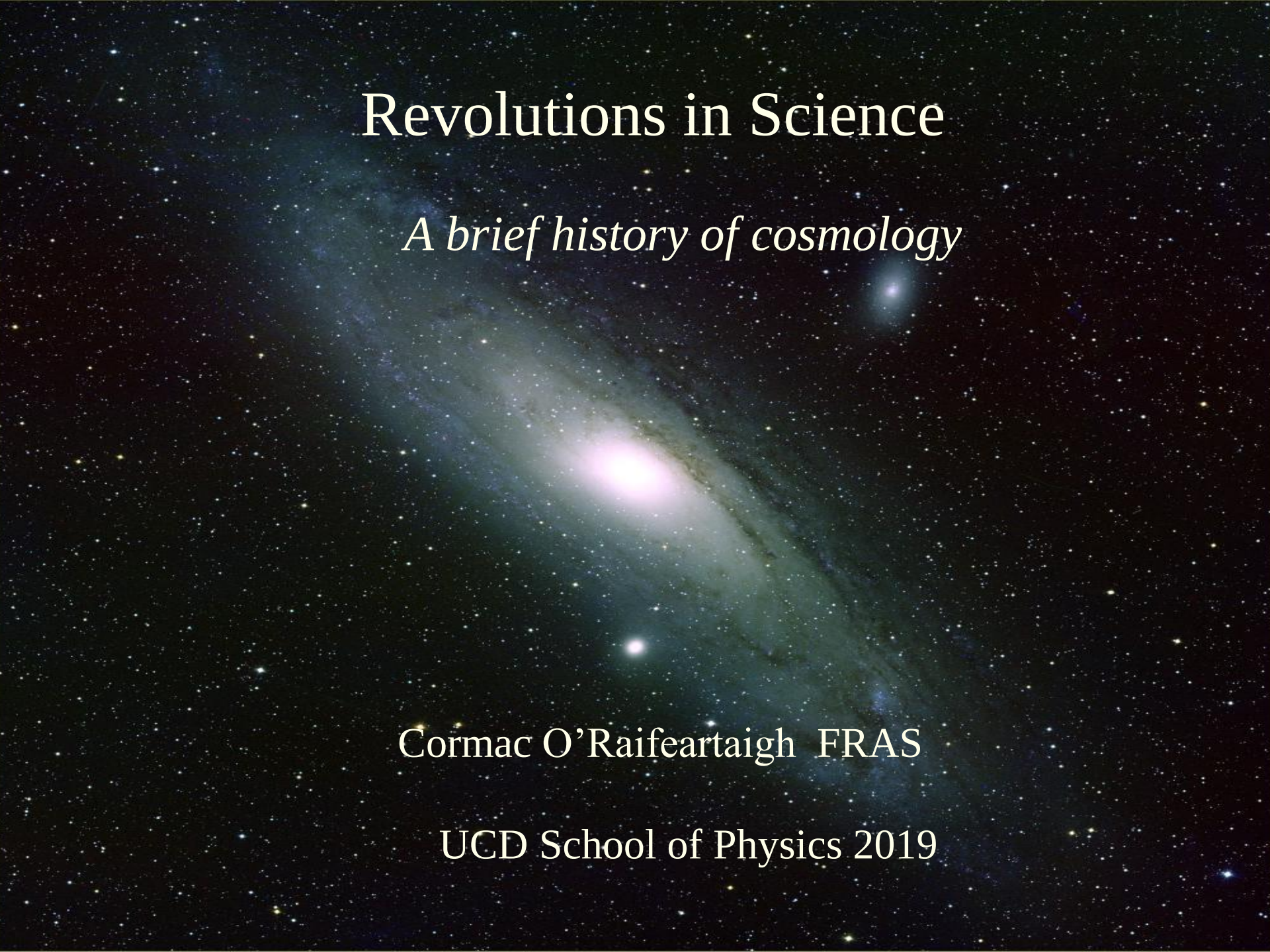


Revolutions in Science

A brief history of cosmology

Cormac O'Raifeartaigh FRAS

UCD School of Physics 2019

Cosmology: the study of the universe

- **Is the universe finite?**

  How big is it?

- **Is the universe eternal?**

  How old is it?

- **How did the universe begin?**

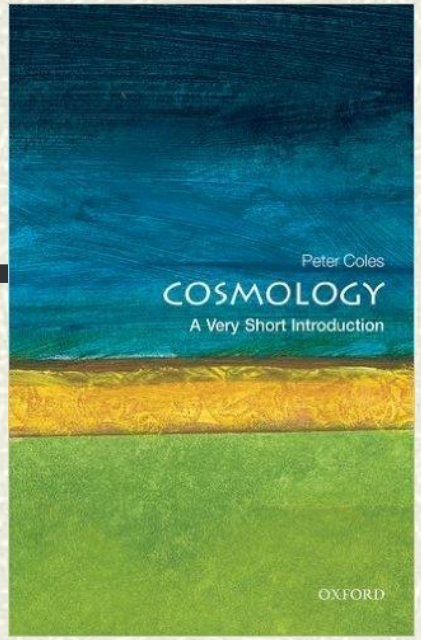
  How will it end?

- **What is the nature of time?**

  What is the nature of space?

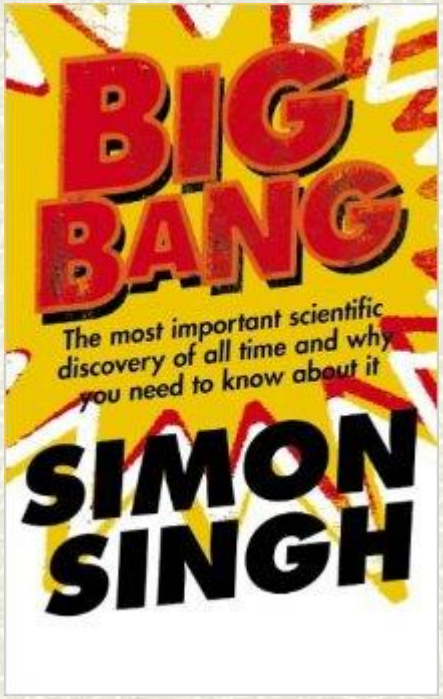
Science or philosophy?

Useful Texts



- **A Very Short Introduction to Cosmology**
  Peter Coles (OUP)

- **The Big Bang**
  Simon Singh



- **Cosmology**
  Edward Harrison (CUP)

- **The Cambridge Illustrated History of Astronomy**
  Michael Hoskin (CUP)

Webpage: Antimatter

Secure | https://coraifeartaigh.wordpress.com/science-universe-and-society-yr-1/

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Antimatter

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Lecture Notes

Science, Universe and Society (UCD, 2017)

- Revolutions-in-science

****

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Recent Entries

- A new year, a new semester
- End of the second semester
- Skiing in Zermatt with the Ski Club

Categories

- Astronomy
- CERN
- Cosmology (general)
- Cosmology 101
- Global warming
- History and philosophy of

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Earliest cosmology

I The age of magic

Every that happened due to spirits

- **The anthropomorphic universe**

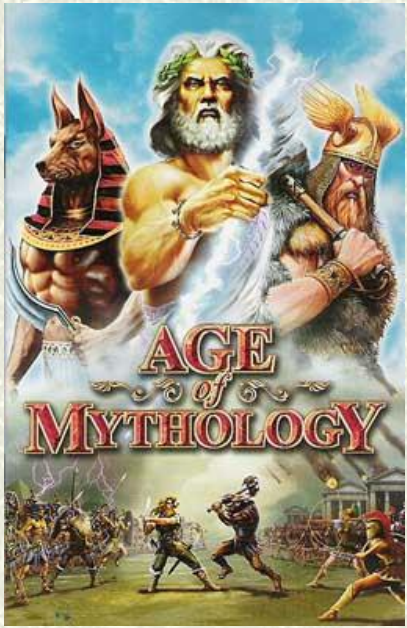
  Fashioned in the image of mankind

II The age of mythology

Creation myths

- **The anthropocentric universe**

  Spirits become remote Gods and Goddesses



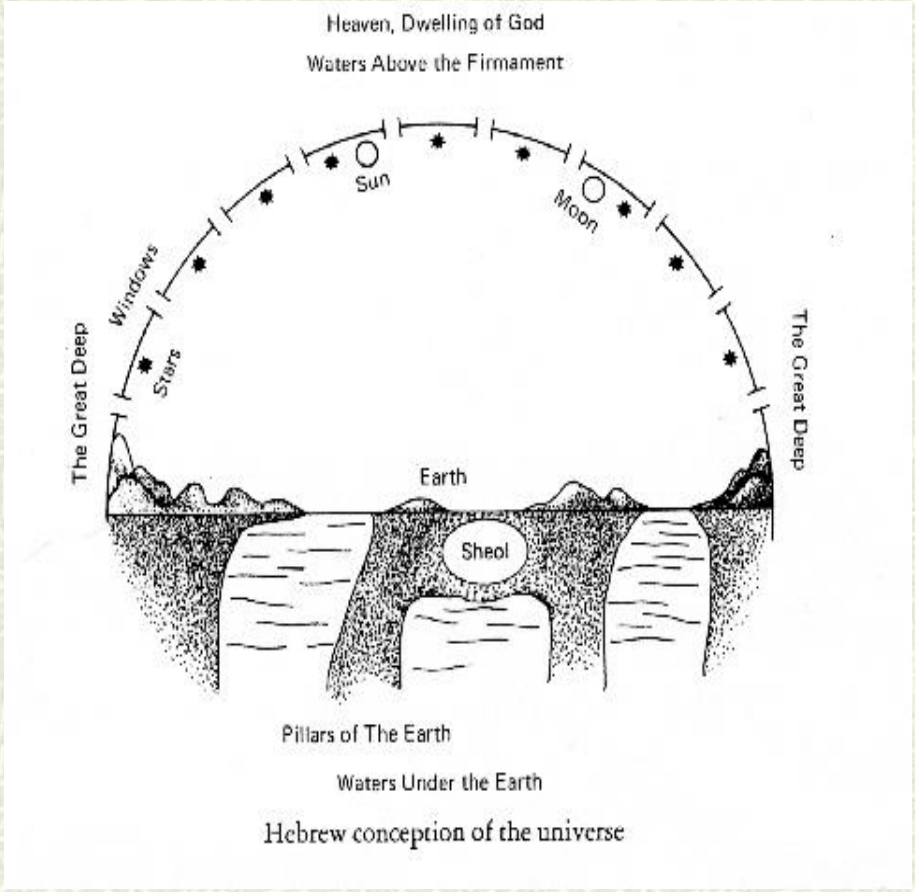
Sumerians, Assyrians, Babylonians, Minoans, Greek, Jews, Chinese, Norse, Celts, Mayans

Early mythology

Babylonians, Egyptians and Hebrews (6000 BC)

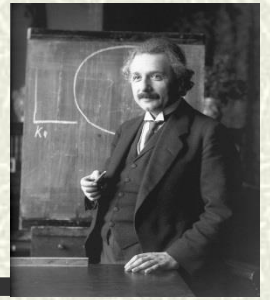
- Earth in the center of an oyster, covered by dome
- Water underneath and overhead, closed in on all sides
- Moderate dimensions
- Sun, moon and stars progress across dome
- Universe guided by deity, explained by myth

The Babylonian universe



The Hebrew universe

Earliest observations: astronomy



Chaldean priests (3800 BC)

- Timetables of the motion of the stars and the planets
- Stars stationary, planets move across a lane in the sky (zodiac)
- Length of the year
- Astronomy and astrology, calanders
- Predicted astronomical events

Observation without explanation

The Babylonians

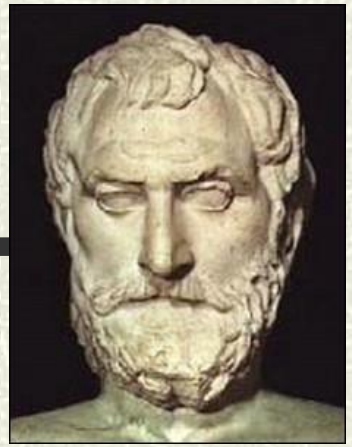
- **Observations of the stars**
  Nabonassar (747 BC)

- **Calendar**
  360 days = 1 year
  Lunar months: varied

- **Measuring time**
  The gnomon (sundial); 12 parts of the day
  1 hour = 60 minutes: 1 minute = 60 seconds

- **Observations of the planets**
- *The Zodiac*
- *Circle on which the planets moved*

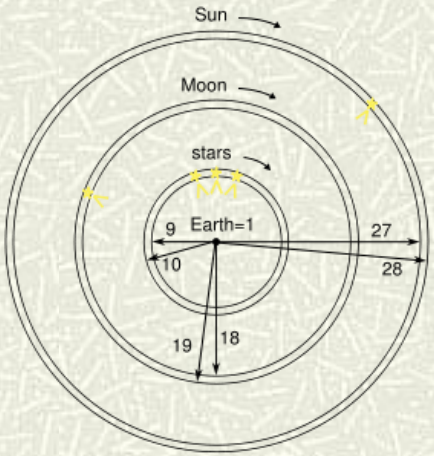
The cosmology of ancient Greece



Ionian philosophers (6th cent BC)

Natural causes: not concerned with deities

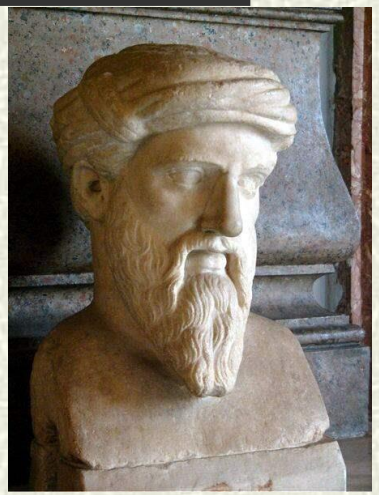
- ***Thales of Miletos*** (625-547 BC)
  What is the basic material of the Universe? Water
  Earth floats on water



- ***Anaximander of Miletos*** (610-545 BC)
  Raw material of universe: undefined apeiron
  Earth floats in universe infinite in time and space
  Mechanical model of the universe
  Estimated sizes and distances to sun and moon

- ***Anaximenes of Miletos*** (585-528 BC)
  Raw material: air. Earth floats on air
  Stars evolved from earth ; float on sphere above

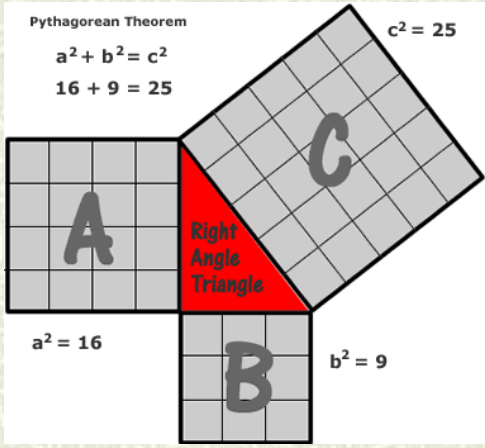
Pythagoras of Samos (570-495 BC)



- *Founder of science*
- *Mathematization of experience: numbers sacred and eternal*
- *Highest form of philosophy*
- *All things have form, all form defined by numbers*

- *Pitch of a note depends on the length of string that produces it*
- *Intervals in the scale produced by simple numeric ratios*

- *Reality could be reduced to number series and number ratios*



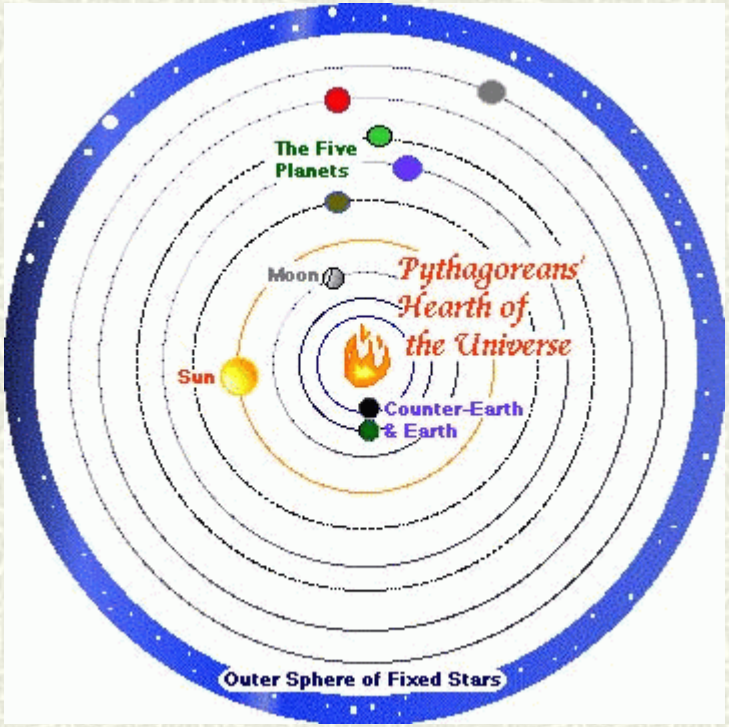
Theorem: ***Areas of the two smaller squares of the sides of right-angled triangle will equal the area of the larger square***

The Pythagoran universe

- **Earth is a sphere**
  Ships on horizon
  Lunar eclipses
  Shape of moon and sun

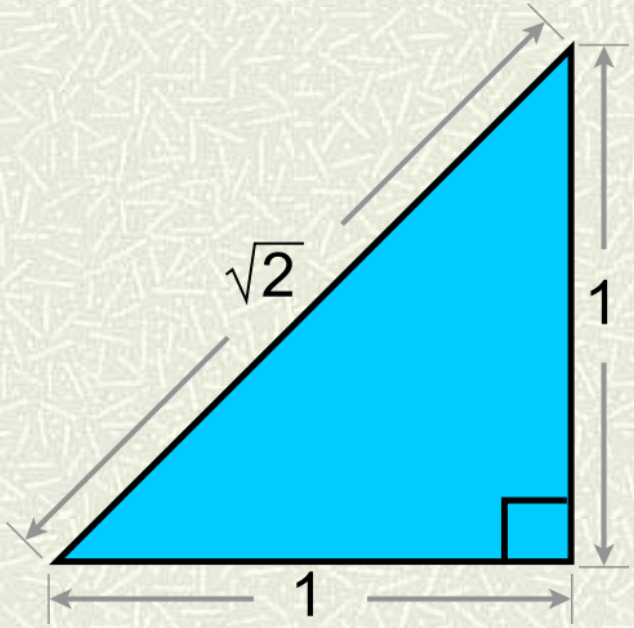
- **Orbits**
  Sun, moon and planets revolve around central fire
  Each planet hums on a different pitch
  Intervals between orbits governed by laws of harmony

- **Major influence**
  Plato
  Kepler



Downfall of the Pythagorans

- **Discovery of irrational numbers**
  The diagonal of a square
- **Arithmetic and geometry**
  Breakdown in point-to-point correspondence
- **Tried to keep secret**
- **Dissolution of brotherhood**
  Also due to egalitarian practices, socialist society



Pythagoras: founder of European culture, source of Platonism

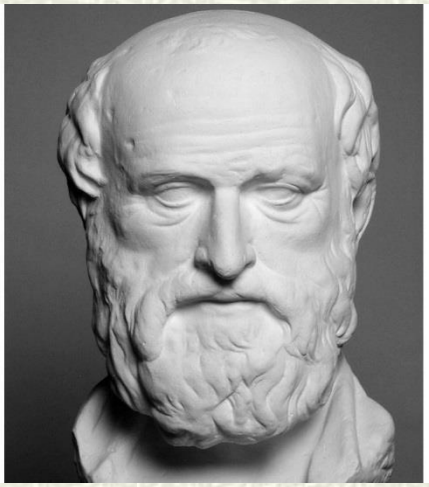
Legacy of Pythagoran School

- **Spherical earth**
  Attracts everything to its center

- **Aristarchus of Samos** (310 BC)
  "On the sizes and distances of the sun and moon"

- ***Eratosthenes***
  Measured circumference of earth from summer solstice
  Deduced relative size of moon (from lunar eclipse)
  Deduced distance of moon from earth (from geometry)

  Deduced sun-earth/moon-earth distance (from half-moon)
  Deduced sun-earth distance
  Deduced relative size of sun (from solar eclipse)

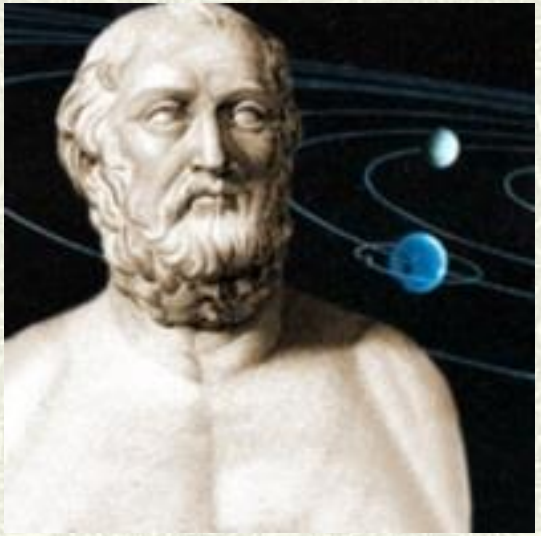


Eratosthenes 276 –195 BC

$$r_S / d_S = r_M / d_M$$

Philolaus and Aristarchus

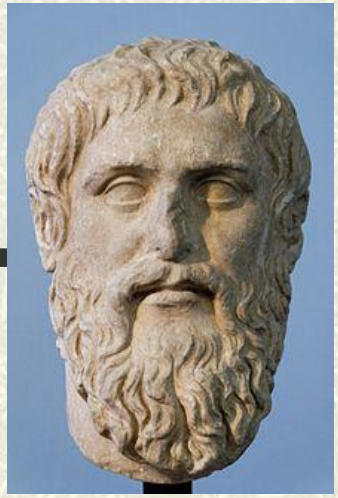
- *Earth sphere has motion: rotates about its own axis*
- *Daily revolution of the sky caused by earth's own motion*
- *Separated day and night, annual motion of the planets*
- *Earth orbits sun*
- *First suggestion of heliocentric system*



Aristarchus 310-230 BC

Quoted by **Archimedes**: yet heliocentric system was discarded

Plato and Aristotle



- Heroic age followed by decline

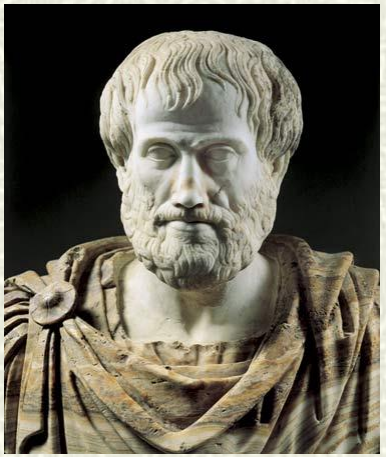
  Should have been Aristarchus - Copernicus - Galileo

- **Plato**: certainty in mathematics, not naturalism

  Shape of the world must be a perfect sphere

  All motion perfect circles at uniform speed

Plato 424 – 348 BC



- Science dominated by **Aristotle** (logic and empiricism)

  God spins the world from outside it, not from center

  Earth and moon space subject to change: nowhere else

  All celestial bodies orbit earth in perfect circles

<u>Spherical universe rotates about spherical earth</u>

Aristotle 384 – 322 BC

The dogma of Plato and Aristotle

- Planetary motion must be shown to be result of circular motions
  Aristotle: used 54 spheres to account for motion of the planets

- **Ptolemy** (AD 150) : ultimate earth-centered model
  Complicated epicycle system for circular motion of celestial objects
  Ferris Wheel universe

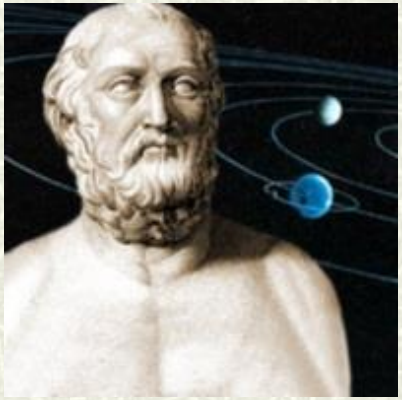
- **Tradition**
  Enshrined in 'He Magele Syntaxis' (later 'The Almagest')
  Kept alive by Islamic scholars during the middle ages
  Re-introduced to Europe in 1175 - 1600

- **<u>Dogma dismissed reality: 3 fundamental conceits</u>**

Dualism of celestial and terrestrial motion
Immobility of earth
All heavenly motion perfectly circular

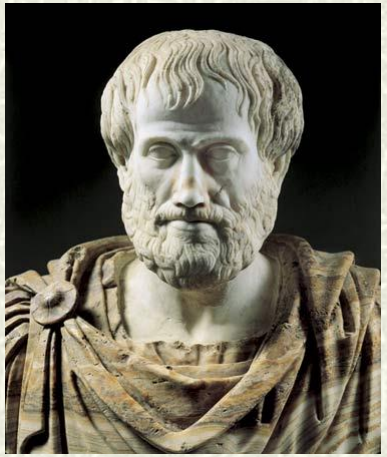
Why was Aristarchus universe discarded?

- Objects fall towards earth
- No wind blowing against us
- No obvious motion of stars
  (*stars too far away to observe stellar parallax*)
- Heliocentric model rejected
  Geocentic model retained
- One snag: motion of planets
  Anomaly in paradigm

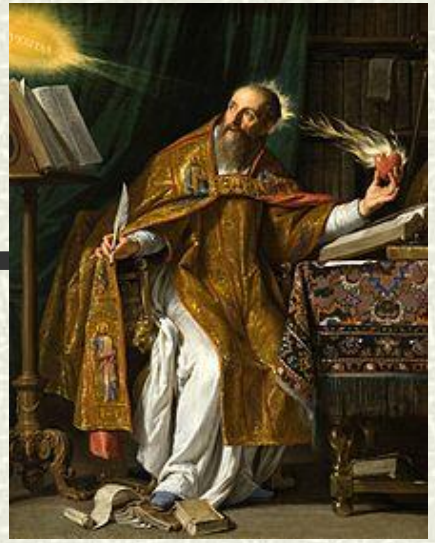


Aristarchus 310-230 BC

Aristotle 384 – 322 BC



Towards the Middle Ages



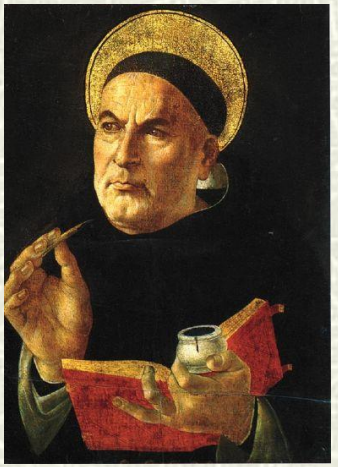
St. Augustine (354-430)

Platonism adopted by Christianity (**St Augustine** etc)

*Ignored early Greeks, adopted only **Plato's** philosophy: neoplatonism*
11cent AD: same view as 5th cent BC

Medieval philosophy
Aristotle's 55 spheres, Ptolemy's 40 epicyles
Replaced by10 revolving spheres: disregarded stellar observation
1000 AD: Portolano charts for navigation

12-16th century: Aristotlean philosophy adopted
Muslims: carried fragments of Euclid , Archimedes and Aristotle to Europe
Improved Calendric astronomy and planetary tables
Important Indian numerals (including zero) and algebra
*Christianity and Aristotelianism (**Thomas Aquinas**)*



St. Aquinas (1225-1274)

Aquinas: first proof of God (based on Aristotelian physics)
Unmoved mover = God

Summary

By 1500 AD, Europe ‘knew’ less than Archimedes in 200 BC

1. Splitting of Universe into 2 spheres
2. Geocentric dogma
3. Uniform motion in perfect circles dogma
4. Divorce of mathematics from science
5. Divorce of experiment from science

These 5 handicaps were to be overcome by
Copernicus, Kepler and Galileo

The Renaissance

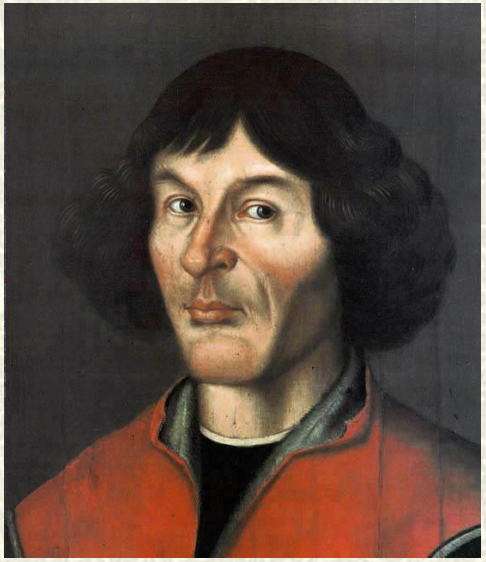
- **Universities: Revival of learning**
  Bologna, Paris, Oxford and Cambridge
- **Roger Bacon, William of Ockham and Albert the Great**
  Study of nature: empiricism
- **Ockham's razor**
  Opposed Aquinas
  "All other things equal, simpler explanation more likely"
- **Nicole d'Oresme**
  Geocentric universe not proven
- **Nicholas of Cusa**
- *Earth not hub of universe*
- **Nicolas Copernicus**

Roger Bacon (1220-1292)

William of Ockham (1280-1349)

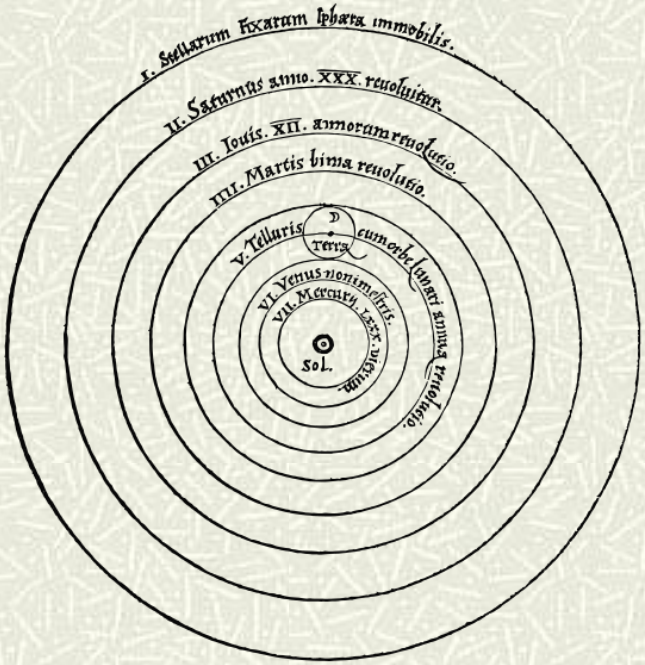
Nicolas Copernicus (1473-1543)

- Born in Poland (Prussia) in 1743
- Studied at the Universities of Krakow, Bologna and Padua
- Trained as Catholic canon
- Polyglot, polymath
- Simple instruments for observing the sky
- Used observations of the Chaldeans and the Greeks
- Improved astronomical tables
- Published *Commentariolus* (1514)



Nicolas Copernicus
(1473-1543)

Nicolas Copernicus

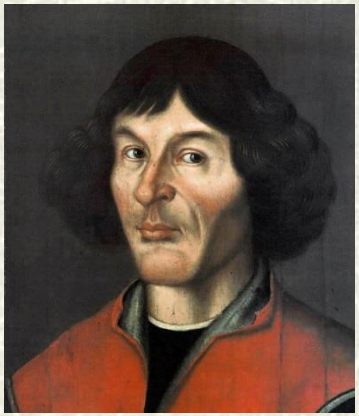


Commentariolus (1514) : 7 axioms

1. Heavenly bodies do not share a common center
2. Earth is not the centre of the universe
3. Centre of the universe is near the sun
4. Earth's distance to sun negligible compared to distance to stars
5. Daily motion of stars is due to rotation of the earth
6. Earth, planets revolve around sun
7. Retrograde motion of the planets is due to motion of earth

Distributed to friends, academics: became well-known

Earth cannot be stationary, Ptolemy system inconsistent
Heliocentric model (aware of early Greeks)



Nicolas Copernicus
(1473-1543)

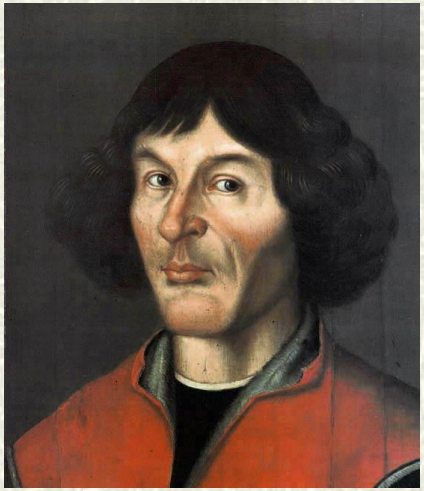
Nicolas Copernicus

Book of the Revolutions of the Heavenly Spheres (1543)

- Published with aid of Georg von Lauchen (Rheticus)
- Technical version of Commentariolus
- Ahead of its time (earth just a planet like others)

Problems

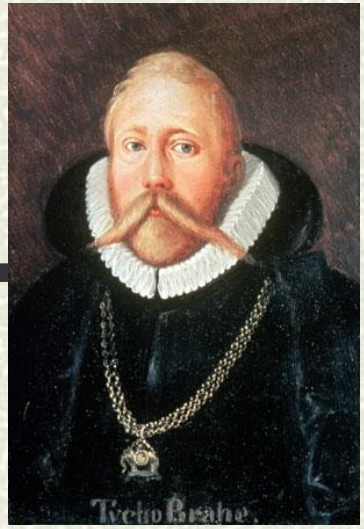
- Copernican system quite complicated (48 epicycles)
- Less accurate predictions of planetary motion
- Universe de-centralized: no natural center of directions
- Undermined by preface (Osiander)



Nicolas Copernicus
(1473-1543)

Not adopted for many years: unnecessary, opposed by Church

2. Tycho de Brahe



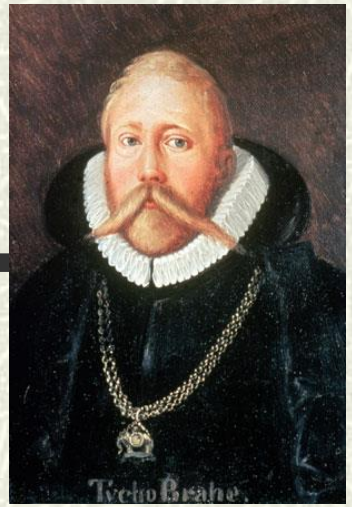
Tycho de Brahe
1546-1601

Danish nobleman
Observational astronomy to new level
Own observatory on island of Hven
Expensive instruments: precise and continuous data

Observed distant nova (SN1572)
Observed distant comet (1577)
Heavens not immutable
Sympathetic to Copernican ideas
'Mixed' model of universe (1588)

Migrated to Prague (imperial mathematician)
Employed ***Kepler*** to study Mars
Gave data sparingly to Kepler
Died from drink (1600)

The Tychonian model



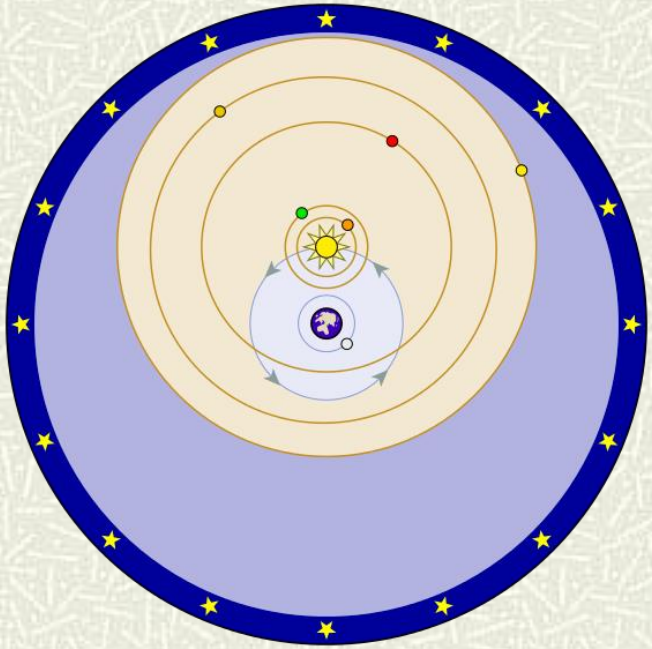
Tycho de Brahe
1546-1601

Observational astronomy to new level (own observatory)
Observations showed heavens not immutable

Sympathetic to Copernican ideas
Critical of Copernicus's observations

Convinced of immobility of earth
Lack of stellar parallax v. sizes of stars
Aristotlean physics, religion

'Mixed' model of universe (1588)
Planets orbit sun
Sun and moon orbit earth



Geo-heliocentric model

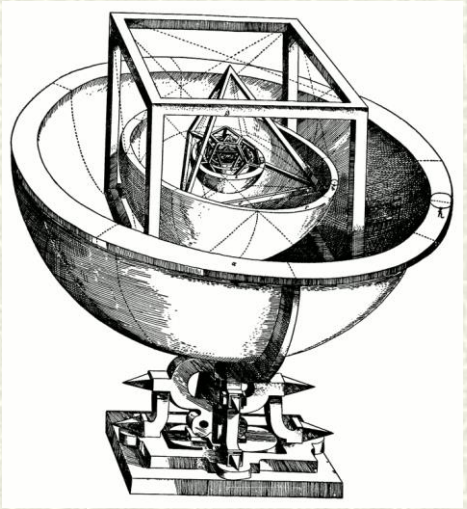
Johannes Kepler

Johannes Kepler
1571-1630

Born in Germany: not high-born
Mathematical prodigy
Attended University of Tubingen
Trained as Lutheran cleric
Became teacher of mathematics and astronomy in Graz

Defended **Copernicus** while still a young priest
Mysterium Cosmographicum (1596)
Reconciled Copernican model with scripture
First public commitment by astronomer to Copernican system
Platonic solid model of the cosmos

Hired by Tycho de Brahe (1600)
Given Mars project, but limited data
Not convinced by Tychonian model
Tycho dies after a few months



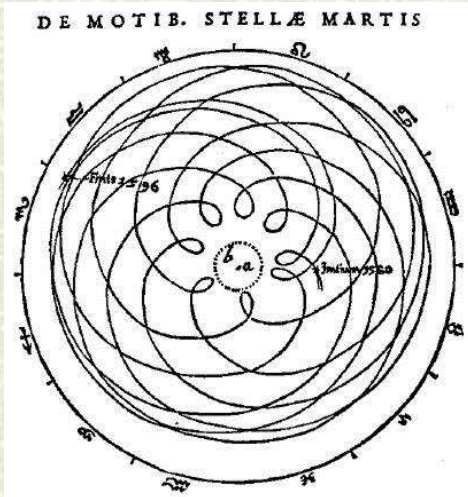
Platonic solids

Johannes Kepler

1571-1630

Death of Tycho de Brahe
Kepler becomes Imperial Mathematicus (1601)
Access to all of Tycho's data
Solves problem of the orbit of Mars (8 years)

Mars orbits sun in elliptical path
All planets move in elliptical paths: no epicycles
First accurate heliocentric model of universe
"Astronomia Nova " (1609)



Simple, elegant model
Natural laws: precise, verifiable statements based on data
Material bodies acted upon by forces
Accurate predictions

Ignored by Germans and Italians (incl. **Galileo?**)
Accepted by British (Thomas Harriot, Jeremiah Horrocks)

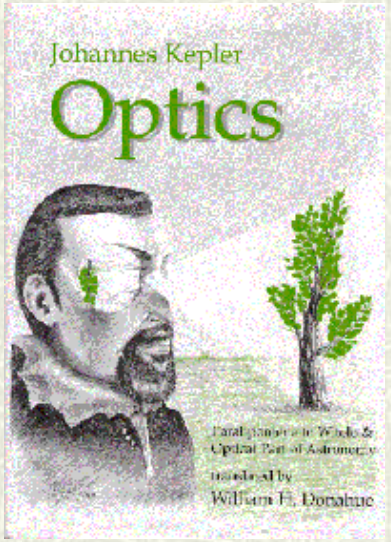
Kepler's universe

Johannes Kepler
1571-1630

Kepler's planetary laws

1. Planets move in elliptical orbits (not circles)
2. Planets continuously vary their speed (not uniform)
3. Sun is at focus of ellipse (not center of circle)

Kepler's other work: founded instrumental optics



Optics (1604)
Study of refraction by lenses
Light intensity α $1/r^2$
Principle of sight, spectacles
Camera obscura

Galileo Galilei

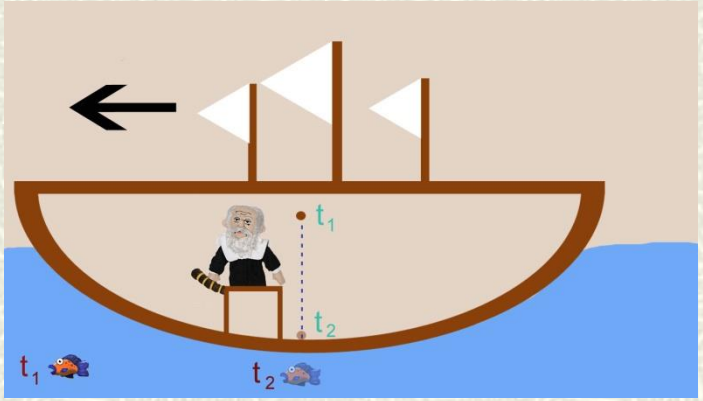
Galileo Galilei
1564-1642

Studied pendulum as student
(period depends only on length)
Invented pendulum timing device

Appointed lecturer in mathematics at the University of Pisa (1589)
Chair of Mathematics at the University of Padua (1592)

Studied mechanics in detail
Laid foundations of dynamics
Laws of motion of falling bodies
Optics: lenses, mirrors and camera obscura

Relativity of motion
Ball drops independent of ship's motion
Could earth be moving?



Relativity of motion

Galileo's astronomy

Galileo Galilei
1564-1642

Improved Dutch model of telescope (mag x 30)

Discovered Lunar surface not smooth (contradicts Ptolemy)

Discovered moons of Jupiter : earth not center of all things

Discovered phases of Venus (as predicted by Copernicus)

Discovered innumerable stars in Milky Way

Discovered sunspots: sun subject to decay etc

Defended Copernican system *Sidereus Nuncius 1610*

Measurements confirmed by Jesuits

The Galileo Affair (I)

University Aristotelians opposed Galileo

Letter to Castelli/ Grand Duchess Christina

Defended Copernican system, suggested scriptures not literal

Church Charges brought against Galileo in 1615, dropped

Church demanded proof of Copernican system

Galileo refused (couldn't prove): ignored Kepler's findings

Galileo censured by decree (1616): Copernican model outlawed

Galileo Galilei
1564-1642

The Galileo Affair (II)

Dialogue of the two world systems

1623: New pope friendly towards Galileo

1632: *"Dialogue on the Great World Systems"*

Propounds Copernican system: pope cast as Simplicio

Pope displeased, felt deceived

1633: Galileo interrogated by Inquisition
Found guilty of defying 1616 decree
Sentence: House arrest for life: *Dialogue* prohibited

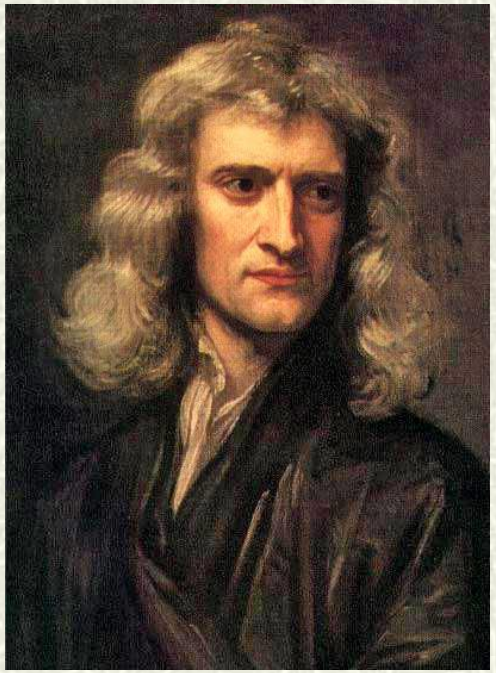
After trial
Magnum Opus – dynamics
Dialogue Concerning Two New Sciences (1636)

Isaac Newton

Born in Lincolnshire 1642
Promising student
Studied mathematics at Cambridge (TC)
Studies interrupted by Great Plague of 1666
Significant work at home in calculus, optics, gravitation

Gravitation theory synthesized what went before
1. Kepler's laws (planetary motion)
2. Galileo's laws (motion of bodies on earth)

What is nature of the force that drives the planets?
What will a body do if left alone?



Isaac Newton
1642 – 1727

Key step: ***Identified Keplerian orbit of moon with Galilean orbit of projectile***

Isaac Newton (1642 – 1727)

Newton's Principia (1687):

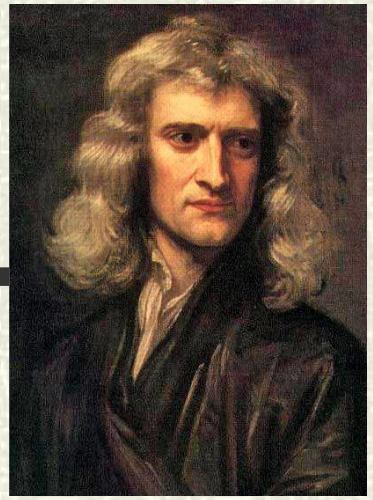
Law 1 *Every body continues in its state of rest, or uniform motion in a straight line, unless compelled to change by forces acting on it*

Law 2: *The change in motion is proportional to the force impressed, and in the direction of the force*

Law 3: *To every action there is always an equal and opposite reaction: the mutual actions of two bodies upon each other are always equal, and directed to contrary parts*

Laws 6 and 7: *Universal Law of Gravitation* $F_G = Gm_1m_2/r^2$

Isaac Newton



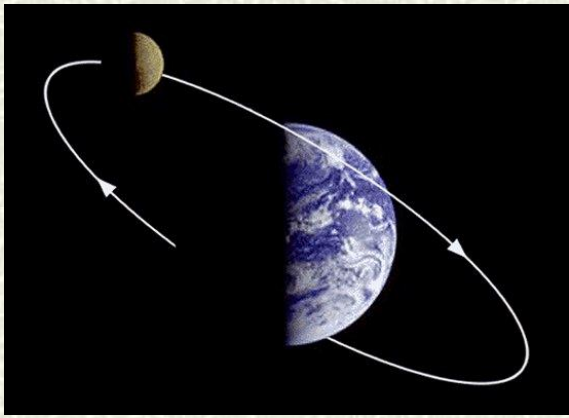
Isaac Newton
1642 – 1727

Universal law of gravity (1666)
Force of attraction proportional to the masses,
Inversely proportional to square of separation

$$F_G = GMm/r^2$$

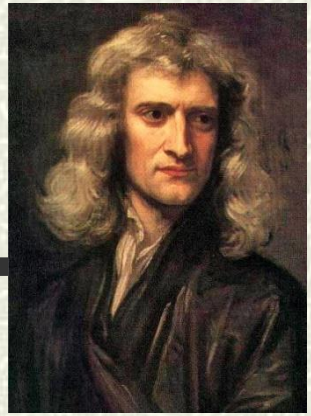
Dropped for 20 years
Developed mechanics and calculus

Goaded back to problem by Halley
Computes force of earth's attraction for the moon (1686)
Explains observed motion: repeated for sun
Showed orbit produced by law was Kepler ellipse
Kepler's laws arise as consequence



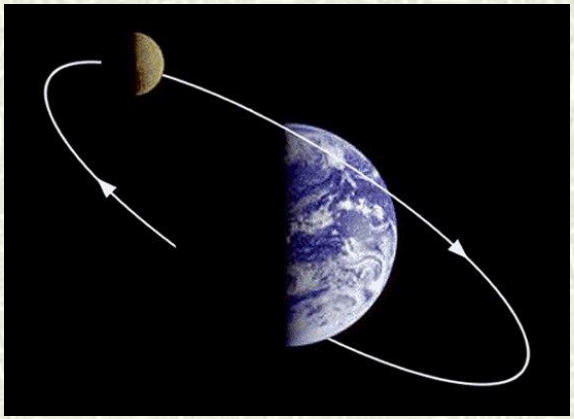
Moon = falling body

Newton's law of gravity



$F_G = GMm/r^2$ G = constant (6.6×10^{-11})

Unites terrestrial and celestial gravity
Force on apple = force on planets

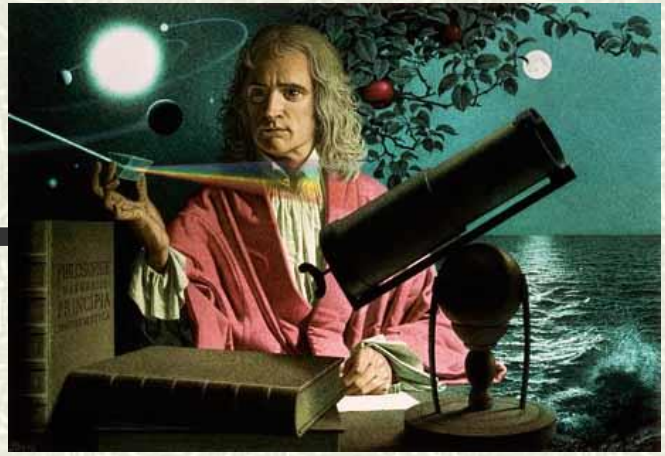


F_G v. weak force (G extremely small)
F_G *only seen when one mass is a planet*
F_G always attractive
M,m = inertial mass (see N2)

How does F_G act instantaneously across huge distances?

$$F = \frac{Gm_1m_2}{r^2}$$

The Newtonian universe

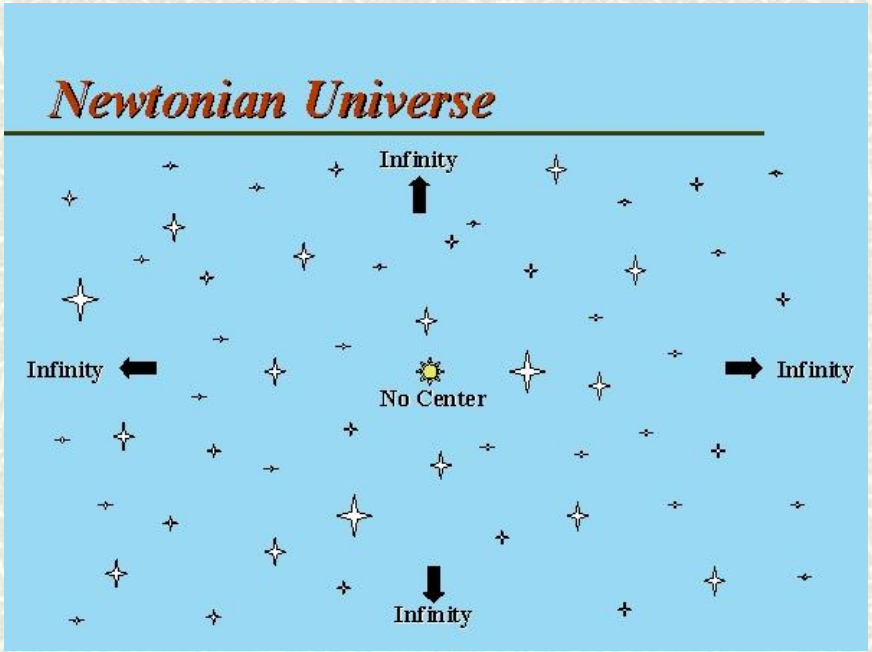


1. Force of gravity –
Attractive, weak, infinite range

2. Eternal universe (infinite in time)
No beginning, no end

3. Bentley's paradox
Why doesn't gravity crush universe?
Finite mass in infinite space (Newton)

4. Olbers' paradox
Why is the sky dark at night?



Clockwork universe: space and time a fixed stage

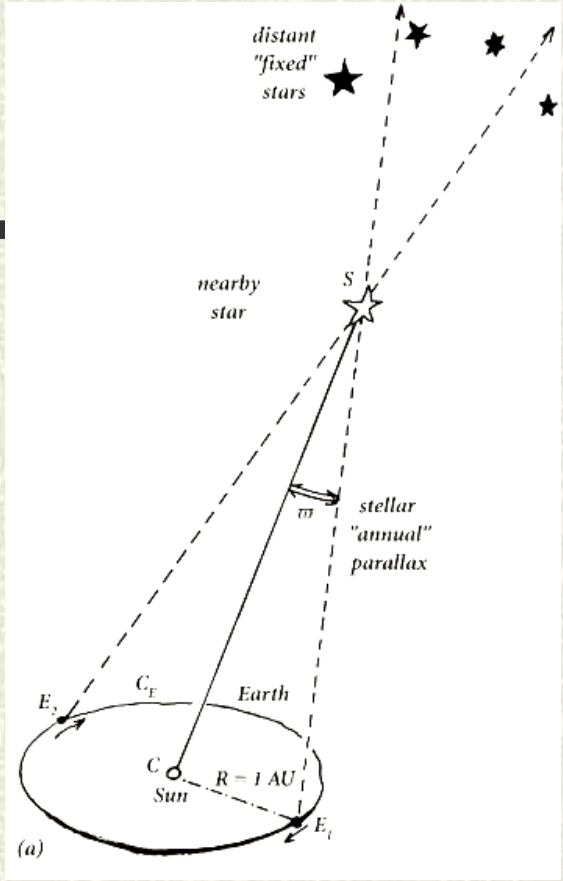
Astronomy in the 19th century

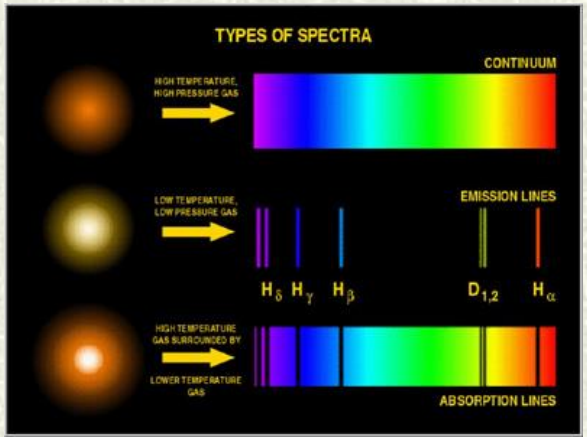
1. Improved telescopes
Distances to stars

2. Stellar parallax
Bessel 1838

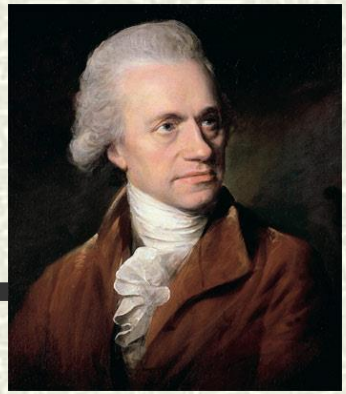
3. Photography
Improved images

4. Spectroscopy
Analysis of starlight
Spectral lines of known elements
Stars made of familiar elements





The starry nebulae



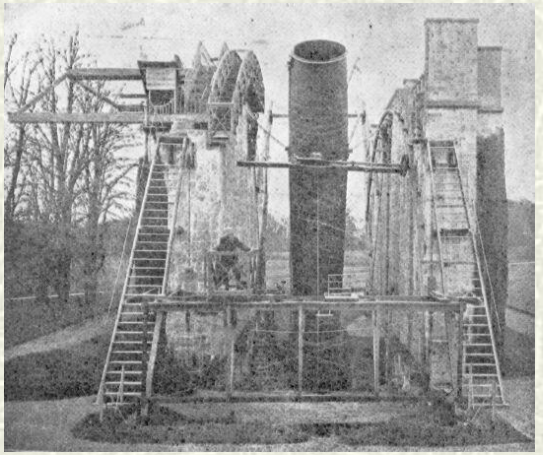
William Herschel 1738-1822

Extremely distant, cloud-like formations

Island universes? Kant, Laplace

Study of the nebulae using large telescopes

Herschel: 36-inch reflecting telescope



Some nebulae have spiral structure

Earl of Rosse (1845):72-inch telescope, Birr castle

Stars within spirals

Earl of Rosse: *Birr castle*

Distance to the nebulae?

Too distant for parallax method

William Parsons 1738-1822

The motion of the nebulae

V.M. Slipher
1875-1969

Vesto Slipher

Use of spectrograph to study nebulae
Lens speed of camera: Exposure time

First study of the nebulae (Lowell Observatory)

Light significantly blue-shifted (1912)
Dopper shift due to radial motion?
Approaching at 300 km/s

Redshift of the spiral nebulae

45 Doppler shifts (1917): all red-shifted except 4
Radial velocity outward? Large velocities: 300 to 1100 km/s

Conclusion

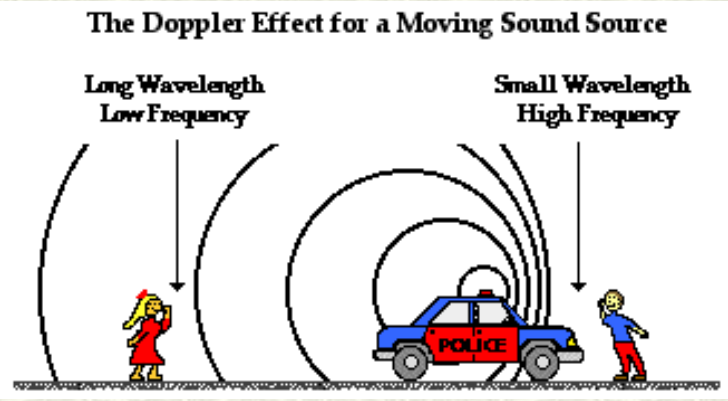
Distant nebulae moving away: most distant moving fastest

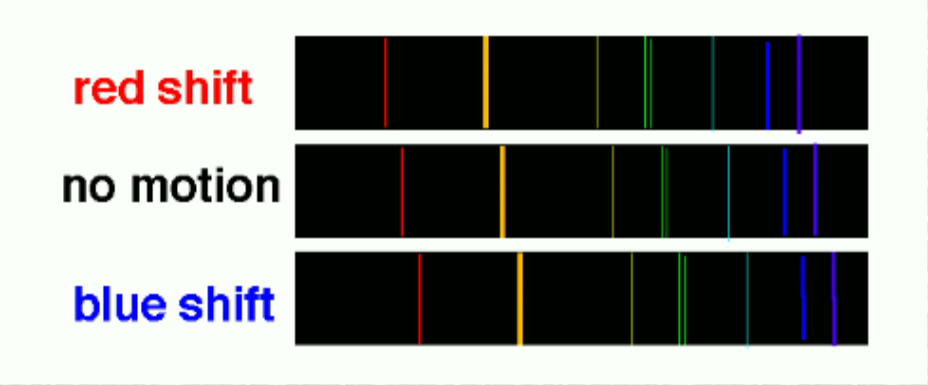
The Doppler effect

*Perceived **frequency*** of light and sound depends on relative motion of observers

Measure motion of object by measuring shift in frequency of light emitted

Christian Doppler
1803-1853





The great debate

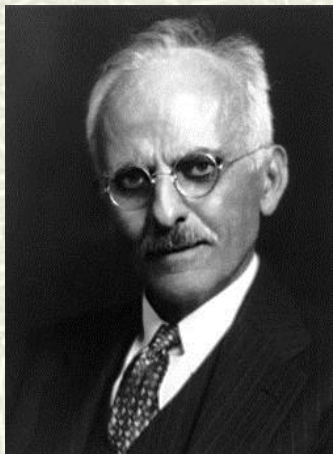
Henrietta Leavitt
1868-1921

A new measurement of distance (Leavitt)
Pulsating stars: Cepheid variables (1912)
Intrinsic luminosity related to period of pulsation
Measure distance by measuring period of luminosity

Harlow Shapley
1885-1972

Size of Milky Way (Shapley)
Use Leavitt's law to measure Milky Way (0.5 M LY)
V bright nova in Andromeda: within Milky Way?

Nebulae outside Milky Way? (Curtis)
Emission lines Doppler-shifted : Vesto Slipher
Motion too great to be confined to Milky Way



Heber Curtis
1872-1942

Measurement of distance to nebulae (Hubble)
Well outside Milky Way

Hubble's answer (1925)

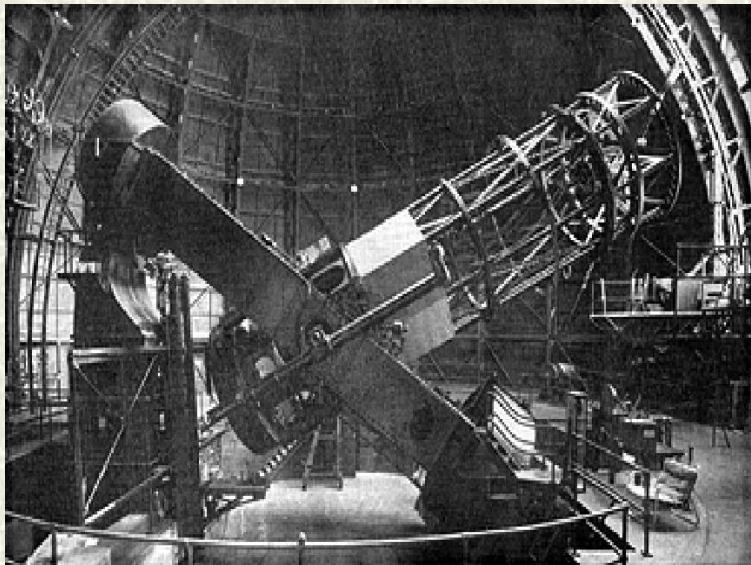
- Edwin Hubble (1921)
- Ambitious astronomer

- Hooker telescope (Mt Wilson, 1917)
- 100-inch reflector

- Resolved Cepheid stars in nebulae
- Known luminosity and distance
- Far beyond Milky Way! (1925)

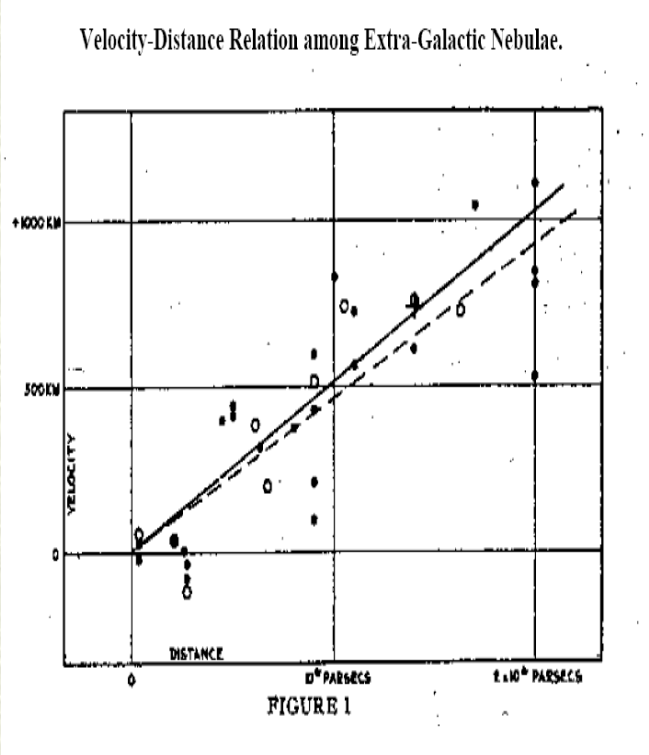
Nebulae are distinct galaxies

Edwin Hubble (1889-1953)



Hubble's Law (1929)

- What do the velocities of the galaxies mean?
- Is there a relation between distance and velocity ?
- Combine 24 distances with Slipher redshifts
- Approx linear relation: **Hubble's law**



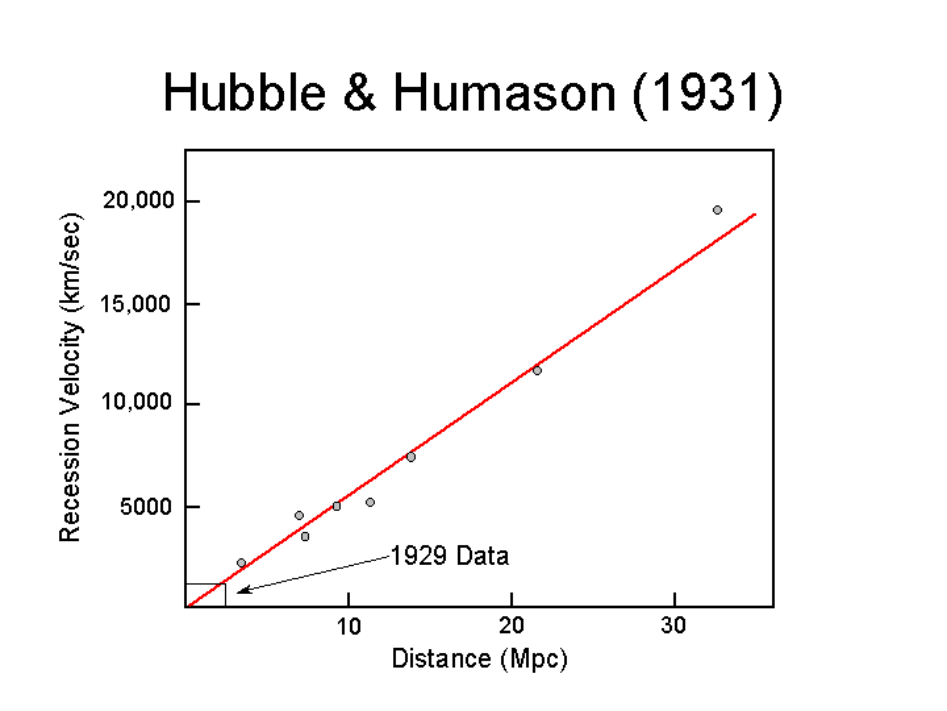
Furthest galaxies receding fastest

Slipher not acknowledged

H = 585 km/s/Mpc

Justification (1931)

- Distances for 40 galaxies
- Redshifts for 40 galaxies
- Reduced scatter – linear relation
- Justification



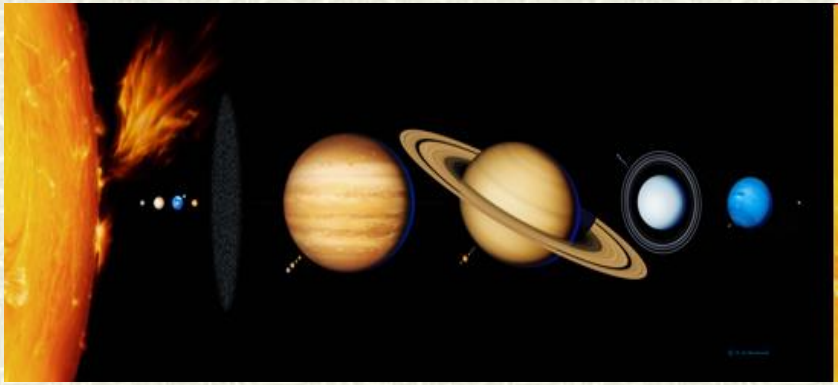
Explanation?

The expanding universe

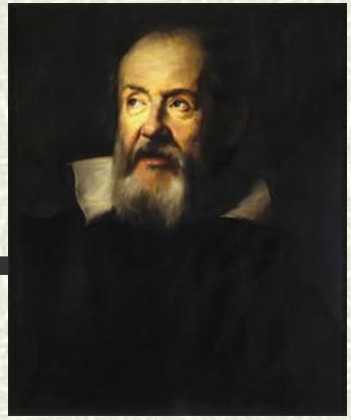
- What do the redshifts represent?
- Recession velocities for distant galaxies?
- If so, why?
- Newtonian gravity pulls in $F = GMm/r^2$
- What is pushing out?

Isaac Newton

Space, time fixed

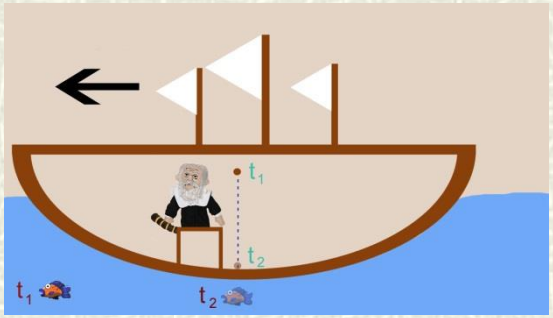


Relativity



Galileo Galilei (1564-1642)

- **The principle of relativity**
  - *Laws of mechanics identical for observers in uniform motion*
  - *Non-accelerated motion*



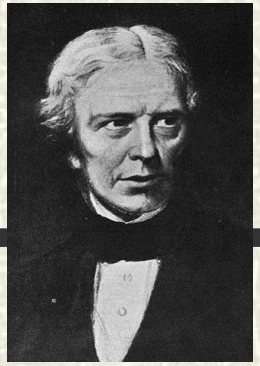
- **Galileo**
  - *Motion of ball in cabin of sailing ship*
  - *Impossible to deduce motion of ship*

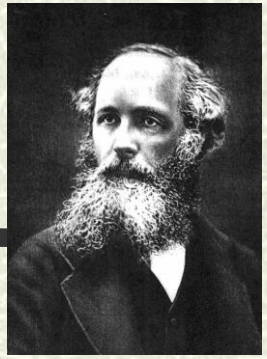
- **Application**
  - *Elizabeth I and the Irish Chieftains*

Elizabeth I (1558-1603)

- **Everyday experience**
  - *Cup of tea on train*
  - *Life on earth*

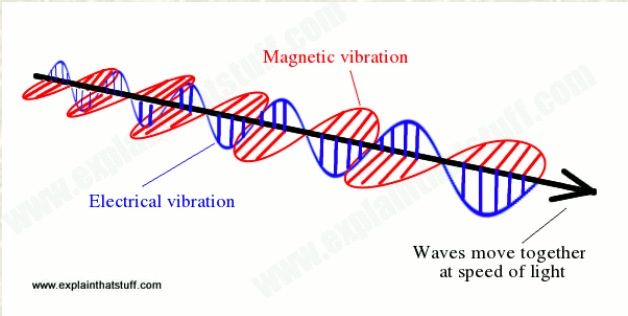
Relativity in the 19th century





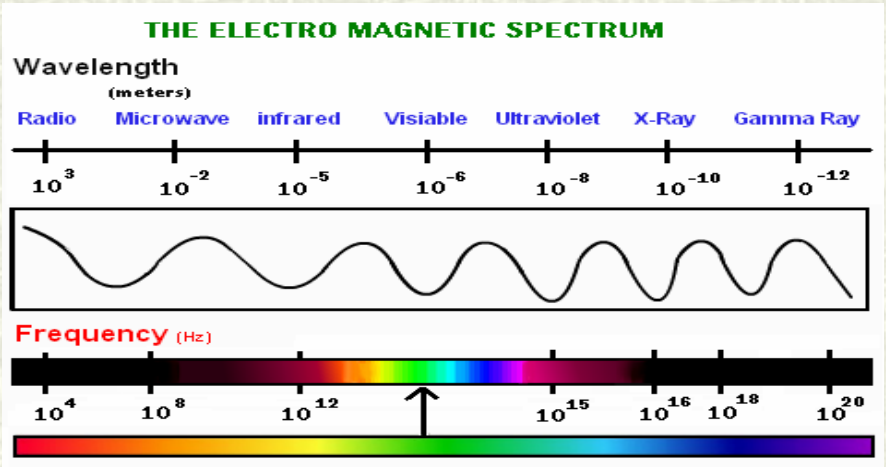
Michael Faraday JC Maxwell

- **Electromagnetism**
  Electricity and magnetism = electromagnetism
  Speed of electromagnetic wave = speed of light



- **Light = an electromagnetic wave**
  Travelling wave
  Changing electric and magnetic fields

- **The electromagnetic spectrum**
  From radio waves to X-rays

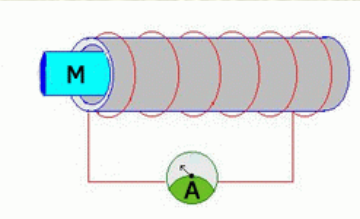


- **<u>Speed of light absolute?</u>**
  Fixed for all observers?
  Michelson-Morley experiment

Einstein's special theory of relativity

- **Two new principles (1905)**
  - *Laws of physics the same for observers in uniform motion*
  - *Speed of light the same for observers in uniform motion*

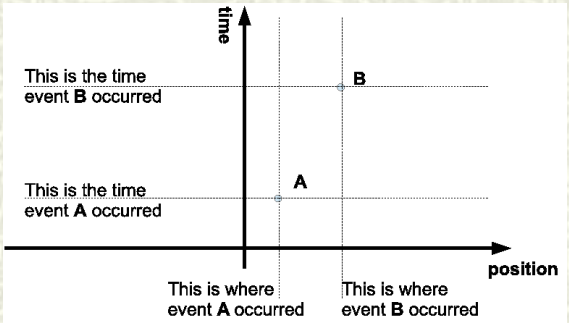
- **Implications**
  - *Distance and time not absolute* $v = s/t$
  - *Experienced differently by bodies in motion*



- **Predictions for high-speed bodies**
  - *Length contraction; time dilation*
  - *Mass increase; equivalence of mass and energy* $E = mc^2$

$$ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$$

- **Space + time = spacetime**
  - *Space-time invariant (Minkowski)*

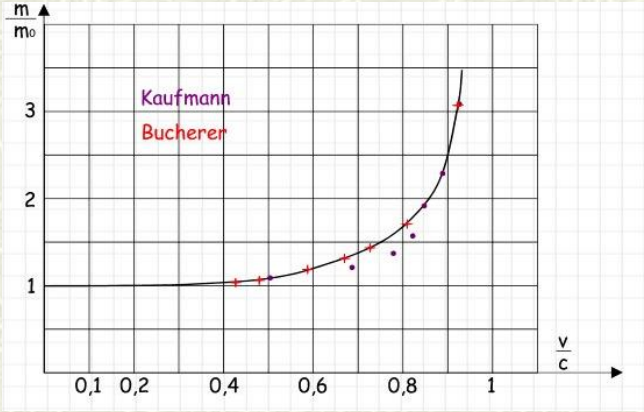


Evidence for special relativity

- **Mass increase**

  The experiments of Kaufmann and Bucherer

$$m' = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

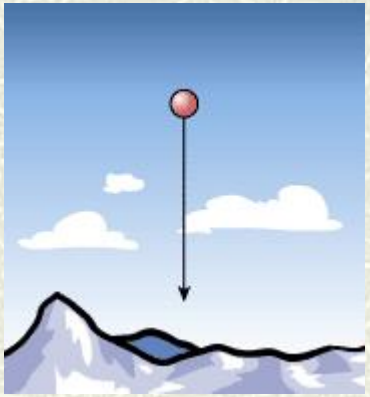


- **Time dilation**

  The long-lived muon

  2 μs → 22 μs

$$t' = \frac{t_0}{\sqrt{1 - v^2/c^2}}$$



- **Invariance of the speed of light**

  Always measured as c

- **Particle experiments at the LHC**

  Maximum velocity = c

  Mass increase

  Particle creation

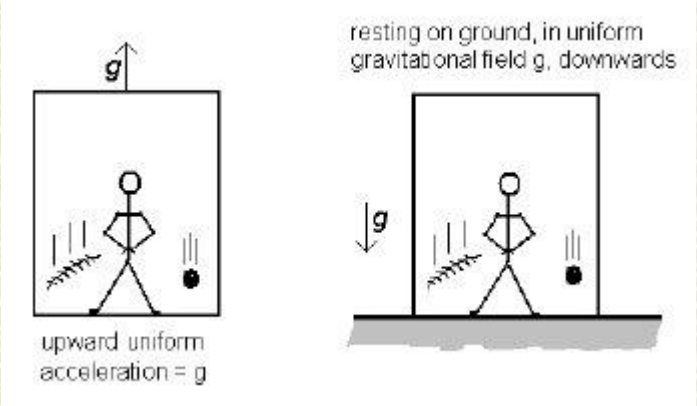
$$E = mc^2$$

The general theory of relativity (1916)

- **Extending the special theory (1907-)**

  Relativity and accelerated motion?

  Relativity and gravity?



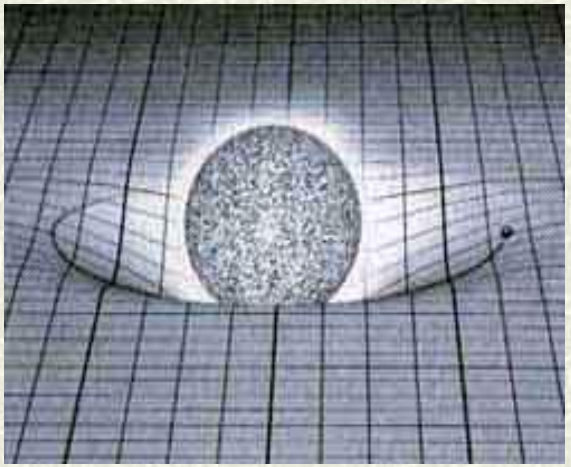
- **The principle of equivalence**

  Equivalence of gravity and acceleration

- **Mach's principle**

  Inertial mass defined relative to matter

  Space and time defined by matter



- **A long road (1907-1915)**

  Curvilinear geometry, tensor algebra

  Gravity = curvature of space-time

The field equations of GR (1915)

$$G_{\mu\nu} = - \kappa T_{\mu\nu}$$

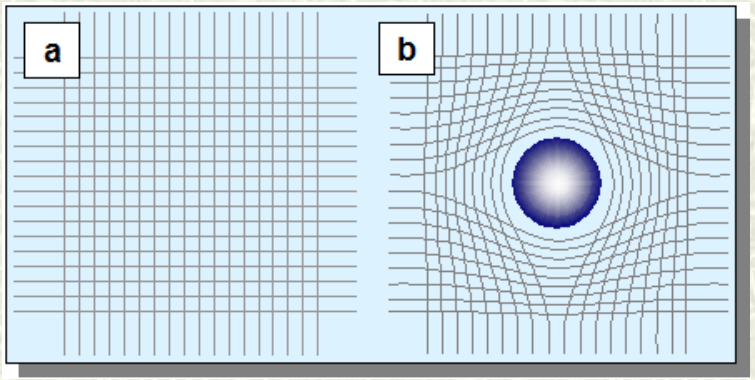
10 non-linear differential equations that relate the geometry of spacetime to the density and flow of energy and momentum

SR $ds^2 = dx^2 + dy^2 + dz^2 - c^2dt^2$

GR $ds^2 = g_{\mu\nu}dx^\mu dx^\nu$

$$ds^2 = \sum_{\mu,\nu=1}^{4} n_{\mu\nu}dx^\mu dx^\nu$$

$$n_{\mu\nu} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

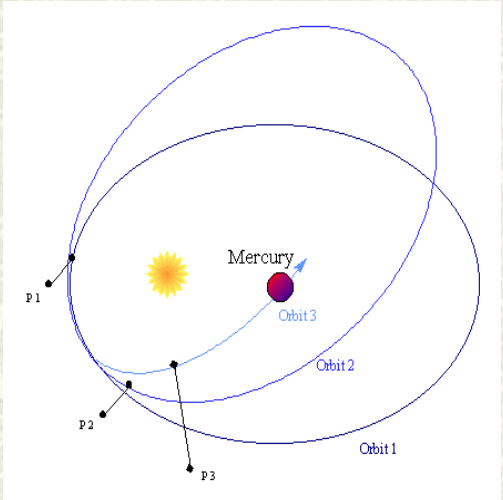


$$ds^2 = \sum_{\mu,\nu=1}^{4} g_{\mu\nu}dx^\mu dx^\nu$$

$g_{\mu\nu}$ *: variables*

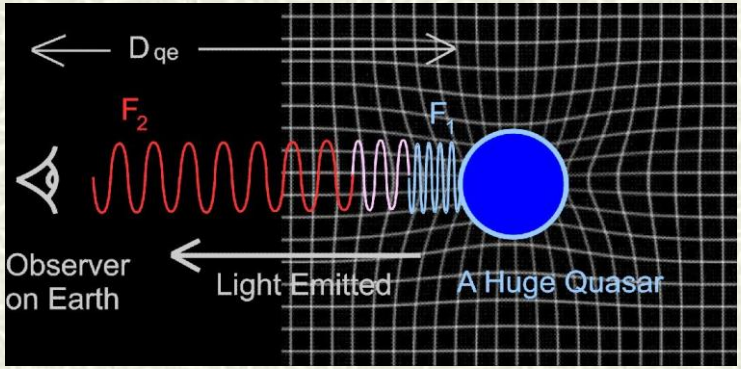
Three astronomical tests (Einstein, 1916)

- **Different in principle from Newton's gravity**
  Small deviations in practice (weak scale)

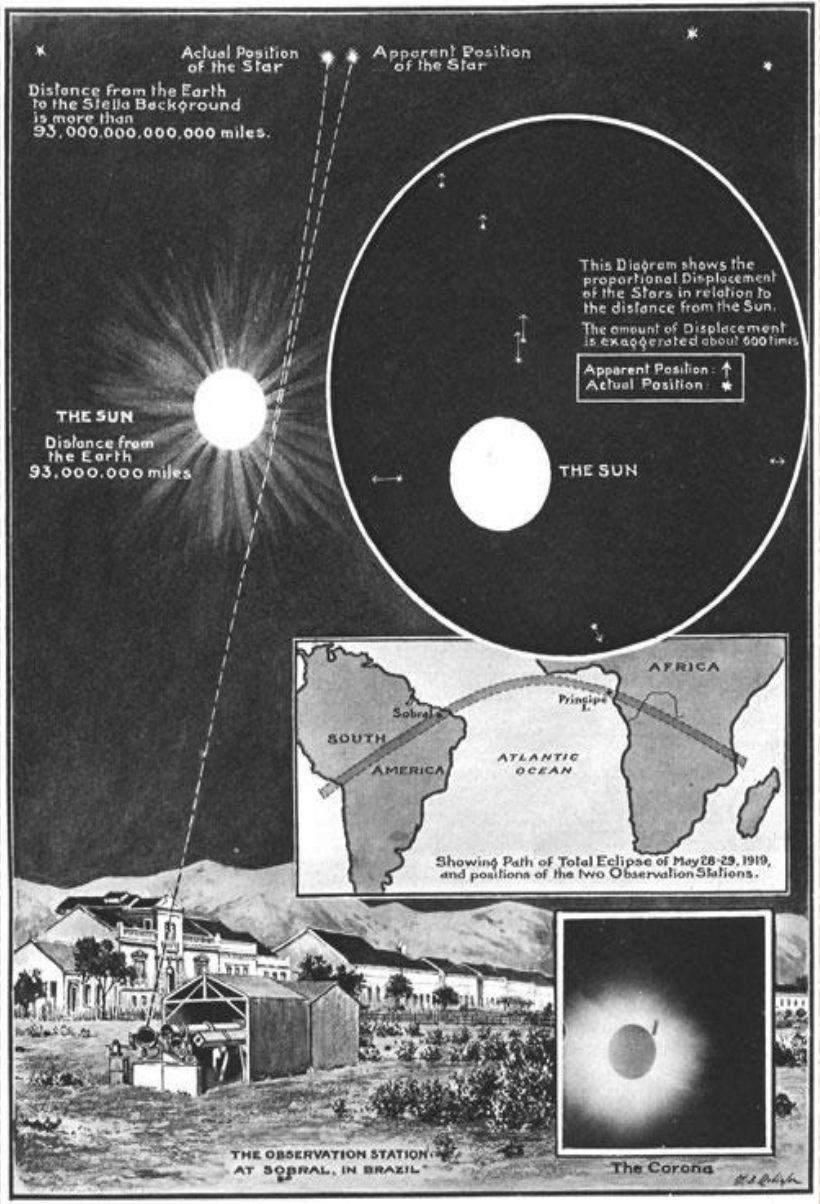


- **The perihelion of Mercury**
  Well-known anomaly in Mercury's orbit (43" per century)
  Postdicted by GR (1916)

- **The bending of starlight by the sun** (1.7")
  Eclipse expeditions of Eddington and Dyson (1919)
  Successful measurement (large error margin)



- **Gravitational redshift**
  Time dilation in strong gravitational field
  Light from a massive star redshifted?



Eclipse Results (1919)

Sobral: 1.98" +/- 0.16
Principe: 1.7" +/- 0.4

Einstein famous (1919)

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Asymmetric controversy (Collins and Pinch 1970s)
Claim of bias; rebutted by astronomers (RAS)

Einstein's universe

- **Einstein: apply GR to the Universe (1917)**

  Ultimate test for new theory of gravitation

- **Assumptions**

  Static universe (small velocities of the stars)

  Mach's principle (metric tensor to vanish at infinity)

  Isotropy and homogeneity (simplicity)

- **Boundary problem**

  Assume cosmos of closed curvature

  But…no consistent solution

- **New term in field equations!**

  Cosmic constant - anti-gravity term

  Radius and density defined by λ

Doc. 43

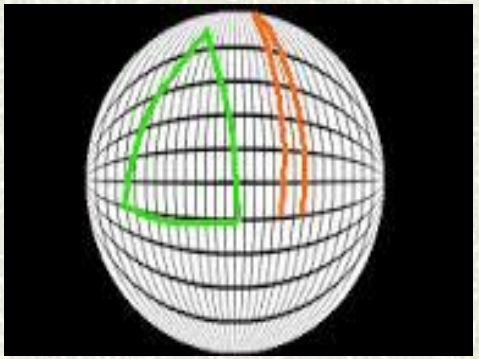
Cosmological Considerations in the General Theory of Relativity

This translation by W. Perrett and G. B. Jeffery is reprinted from H. A. Lorentz et al., *The Principle of Relativity* (Dover, 1952), pp. 175–188.

IT is well known that Poisson's equation

$$\nabla^2\phi = 4\pi K\rho \quad . \quad . \quad . \quad . \quad (1)$$

in combination with the equations of motion of a material point is not as yet a perfect substitute for Newton's theory of action at a distance. There is still to be taken into account the condition that at spatial infinity the potential ϕ tends



$$G_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}$$

Friedman's universe

Alexander Friedman (1888 -1925)

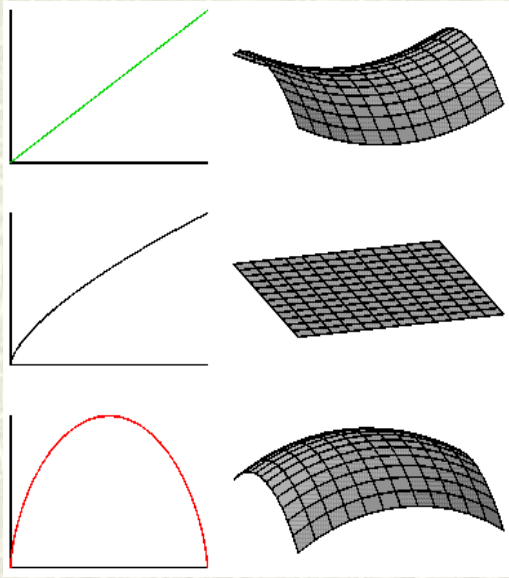
- **Allow time-varying solutions (1922)**
  - *Assume homogeneity, isotropy, positive curvature*
  - *Two independent differential equations from GFE*

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

$$\frac{3R'^2}{R^2} + \frac{3c^2}{R^2} - \lambda = \kappa c^2 \rho,$$

$$\frac{R'^2}{R^2} + \frac{2RR''}{R^2} + \frac{c^2}{R^2} - \lambda = 0.$$

- **Evolving universes**
  - *Density of matter varies over time*
- **Negative spatial curvature (1924)**
  - *Cosmic evolution, geometry depends on matter*
- **Overlooked by community**
  - *Considered 'suspicious' by Einstein*
  - *Mathematical correction, later retracted*
  - *"~~To this a physical reality can hardly be ascribed~~"*



Lemaître's universe (1927)

Fr Georges Lemaître

- **Expanding model of the cosmos from GR**
  Similar but not identical to Friedman 1922

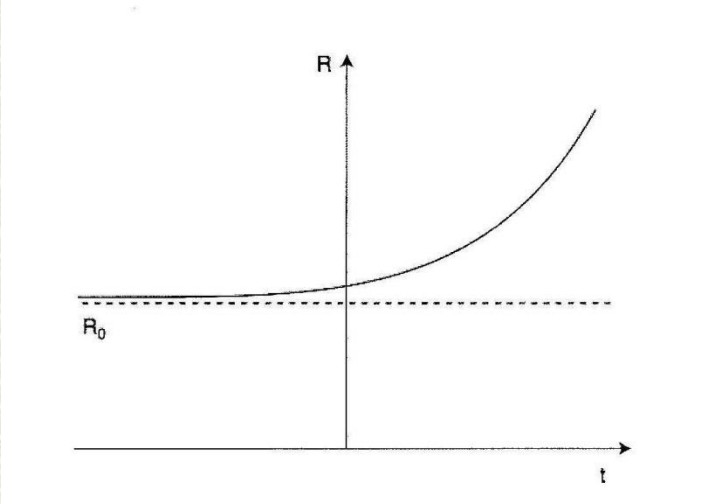
$$3\frac{R'^2}{R^2}+\frac{3}{R^2}=\lambda+\kappa\rho$$

- **Redshifts of galaxies = expansion of space?**
  Redshifts from Slipher, distances from Hubble

$$2\frac{R''}{R}+\frac{R'^2}{R^2}+\frac{1}{R^2}=\lambda-\kappa p$$

- **Ignored by community**
  Belgian journal (in French)
  Rejected by Einstein: "Vôtre physique est abominable"

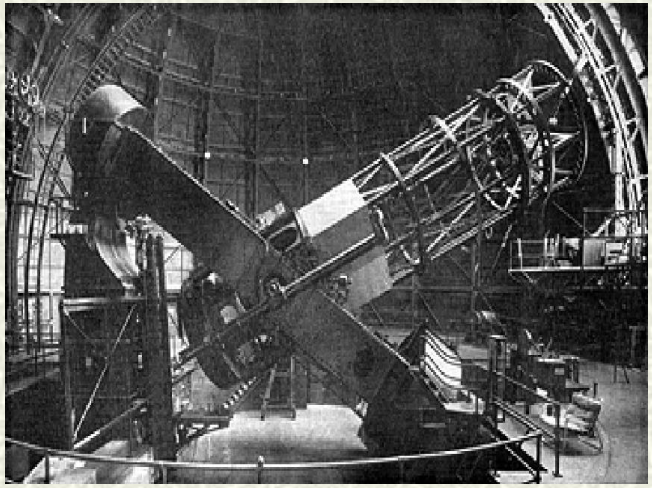
- **Lemaître's recollection (1958)**
  "Einstein not up-to-date with astronomy"

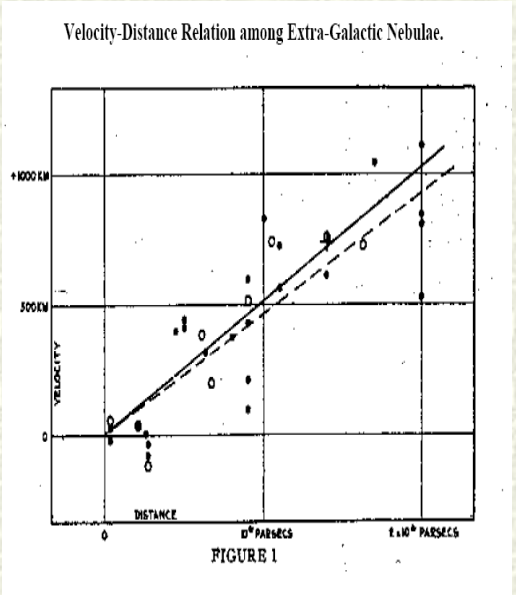


The watershed: Hubble's law (1929)

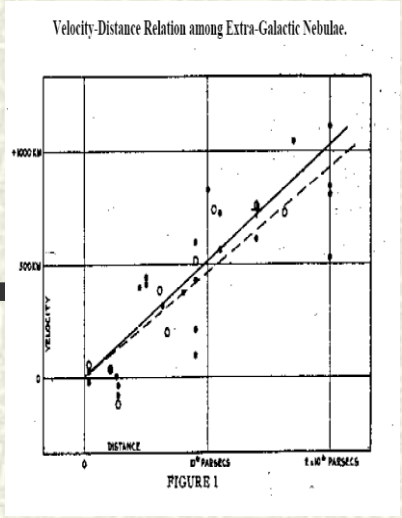
- **The redshifts of the spiral nebulae**
  Doppler shifts? (Slipher 1915, 1917)
- **The distances to the nebulae**
  Far beyond Milky Way (Hubble 1925)
- **A redshift/distance relation**
  Linear relation (Hubble, 1929)
  $H = 500\ kms^{-1}\ Mpc^{-1}$
- **Landmark result in astronomy**
  Furthest galaxies receding the fastest

Link to relativity

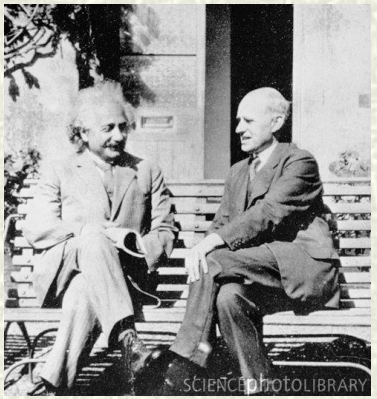




The expanding universe (1930)



- **RAS meeting (May 1930)**
  If redshifts are velocities, and if effect is non-local
  Hubble's law = expansion of space? (Edd., de Sitter)



- **Dynamic model required**
  Static model unstable

- **Lemaître model adopted**
  1927 expanding model republished in English (1931)
  Observational section omitted (rightly)

- **Lemaître-Friedman cosmology accepted**
  Time-varying radius, decreasing density of matter

Who discovered the expanding universe?

- Einstein *Basic framework for theory*
- Friedman *Expanding universe (theoretical)*
- Hubble, Slipher *Recession of the galaxies (obs)*
- Lemaitre *Observation + theory*

'Hubble graph' should be Hubble-Slipher graph

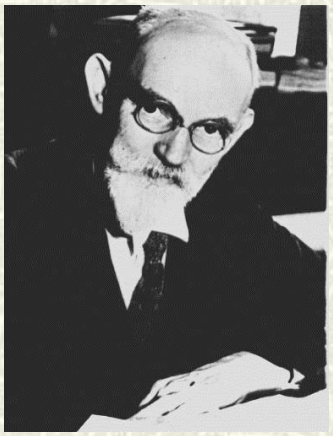
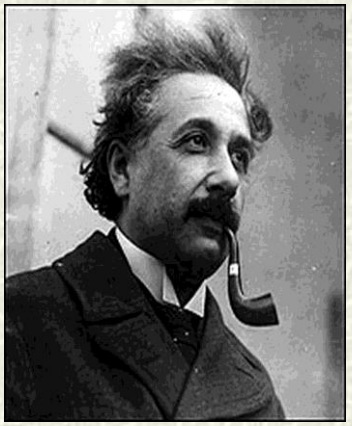
'Hubble expansion should be Hubble-Lemaitre expansion

Astronomers sceptical (Hubble)

Models of the expanding universe (1930 -)

- **Tolman (1930, 31)**
  Expansion caused by annihilation of matter ?
- **Eddington (1930, 31)**
  On the instability of the Einstein universe
  Expansion caused by condensation?
- **de Sitter (1930, 31)**
  Variety of expanding models
- **Heckmann (1931,32)**
  Spatial curvature (not translated)
- **Einstein (1931, 32)**
  Friedman-Einstein model $\lambda = 0,\ k = 1$
  Einstein-de Sitter model $\lambda = 0, k = 0$



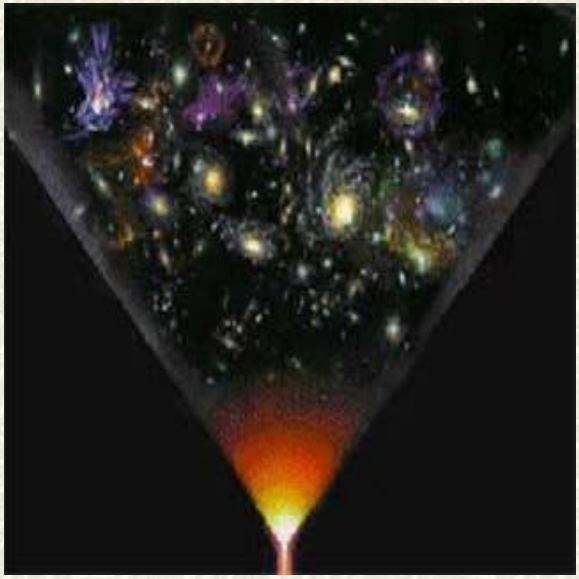



If redshifts represent expansion…
If effect is global…

A strange prediction: the big bang

Fr Georges Lemaître

- **Lemaître 1931**: expanding *U* smaller in the past
- Extrapolate to very early epochs
- Extremely dense, extremely hot
- Expanding and cooling ever since
- ‘Fireworks beginning’ at $R = 0$?



Rejected by community (1930-60)

Simplified models

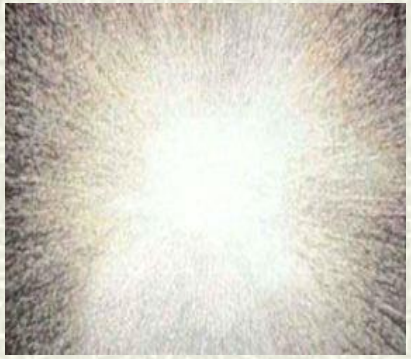
Timescale problem

Later called ***‘The big bang’***

A second line of evidence

- **Gamow and nuclear physics (1940s)**
  Student of Friedman
- **How were the chemical elements formed?**
  Problems with stellar nucleosynthesis
- **Elements formed in the infant hot universe?**
  Theory predicts U = 75% Hydrogen, 25% Helium
- **Agreement with observation**
  Victory for big bang model

Georges Gamow



Heavier atoms formed in stars

Bonus: cosmic background radiation

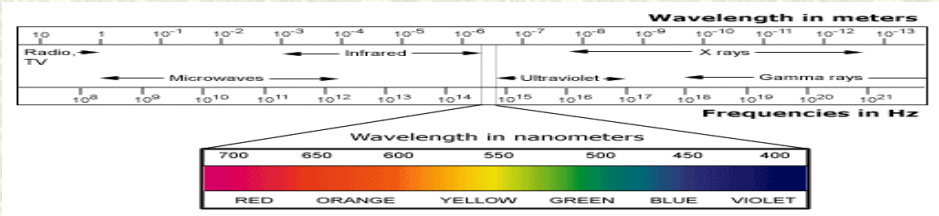
- Infant universe very hot
- Dominated by radiation
- Radiation still observable today?

  Low temp, microwave frequency
- A fossil from the early universe!

  Released when atoms formed (300,000 yr)

Alpher, Gamow and Herman

No-one looked



The steady-state universe (1948)

- **Expanding but unchanging universe**

  Hoyle, Bondi and Gold (1948)

  Disliked extrapolation to early epochs

  Perfect cosmological principle?

Bondi, Gold and Hoyle

- **Requires continuous creation of matter**

  Very little matter required

  No beginning, no age paradox

Hoyle and Narlikar (1962)

- **Replace λ with creation term** (Hoyle)

$$G_{\mu\nu} + C_{\mu\nu} = - k T_{\mu\nu}$$

- **Improved version (1962)**

$$G_{\mu\nu} + \lambda g_{\mu\nu} = k T (C_{\mu} + C_{\nu})$$

Steady-state vs big bang (1950-70)

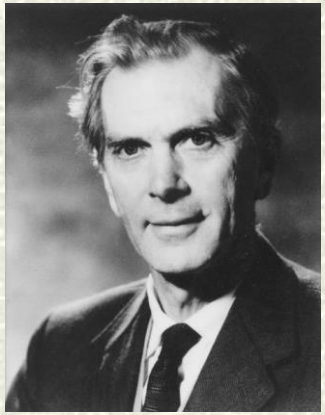
- **Optical astronomy (1950s)**
  Revised distances to the nebulae (Baade, Sandage)
  New timescale of expansion

- **Radio-astronomy (1960s)**
  Galaxy distributions at different epochs
  Cambridge 3C Survey (Ryle)

- **Nucleosynthesis of light elements**
  Gamow et al. 1948

- **Cosmic microwave background (1965)**
  Low temperature, low frequency
  Remnant of young, hot universe

Allen Sandage

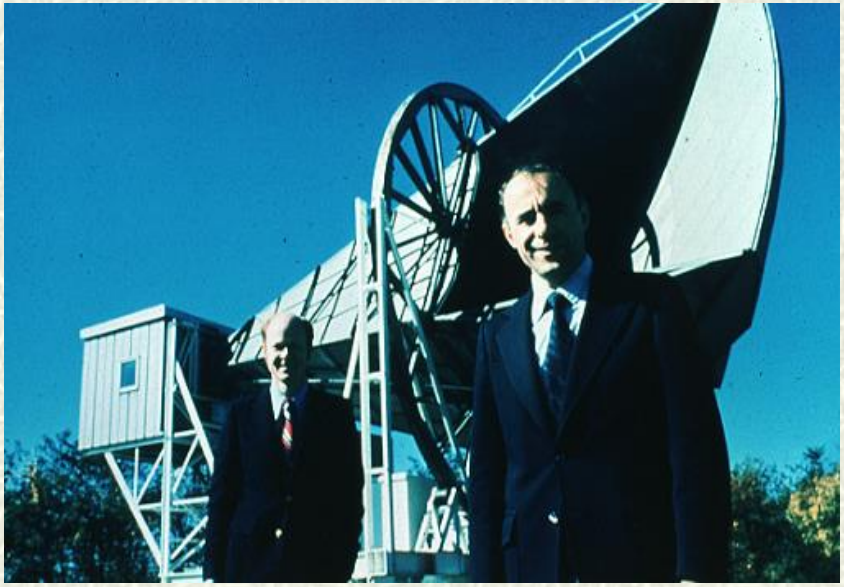


Martin Ryle

Cosmic background radiation (exp)

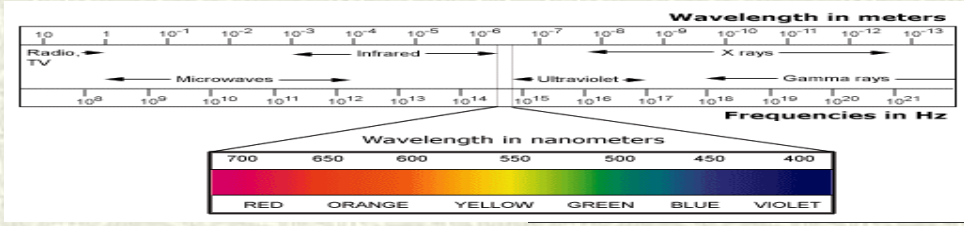
CMB discovered accidentally

- Universal signal (1965)
- Low frequency (microwave)
- Low temperature (3K)



Penzias and Wilson (1965)

Echo of Big Bang!



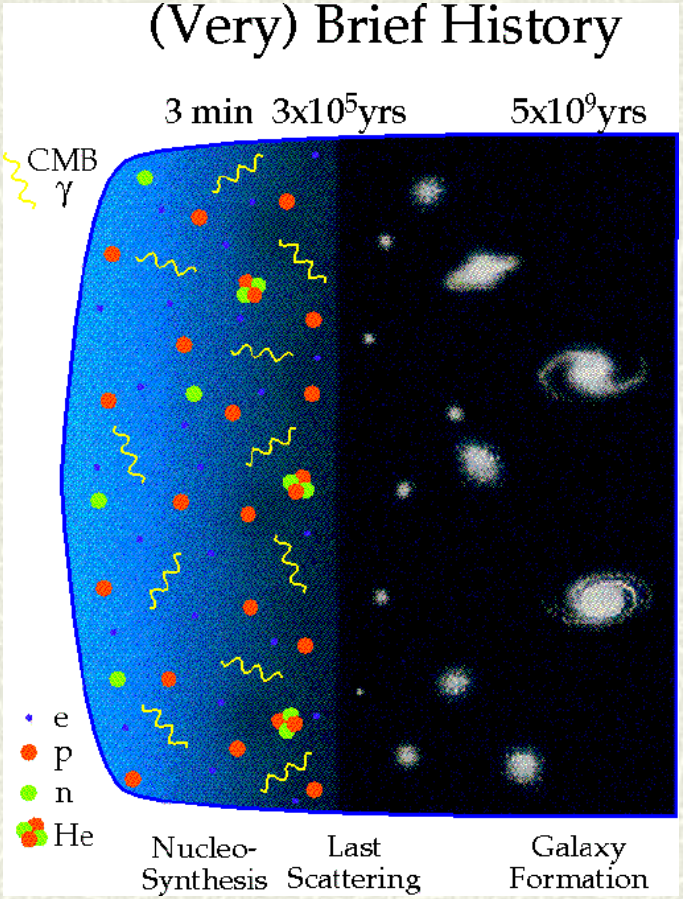
The big bang – evidence

1. The expansion of the *U*

2. The abundance of ***H*** and ***He***

3. The distribution of the galaxies

4. The cosmic microwave background



How did it start?

Cosmology in the 1970s, 1980s

- **Astronomical search for cosmic parameters**
  Density of matter, rate of expansion

- **The search for two numbers**
  H_0, Ω_M
  q_0

$$q_0 = \frac{\Omega_M}{2}$$

Allan Sandage

- **Hypothesis of dark matter**
  Dynamics of galaxy rotation
  Some matter seen only by its gravitational effect

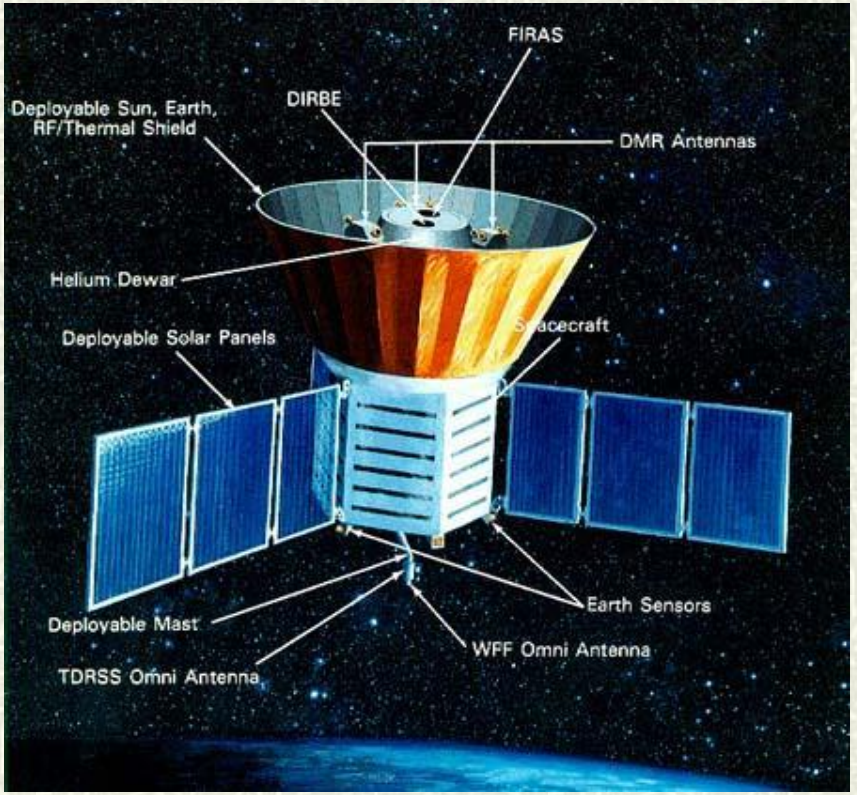
- **Problems**
  Density of matter too small to close universe
  But no evidence of spatial curvature!

Vera Rubin

Modern measurements of the CMB

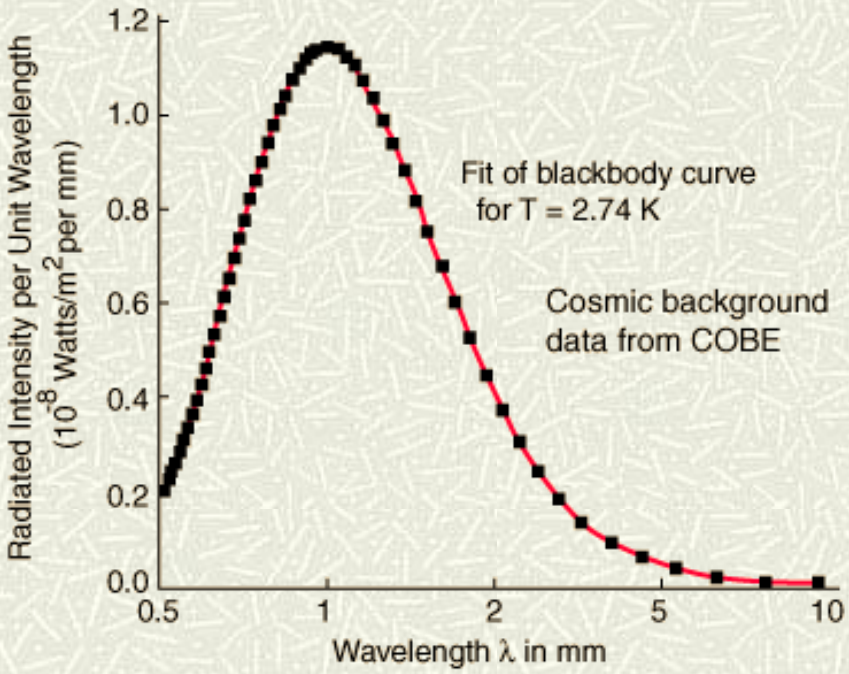
- Details of background radiation
- Full spectrum
- Comparison with theory
- Perturbations?

- ***Ground telescopes***
- ***Balloon experiments***
- ***Satellite experiments***



COBE satellite (1992)

Cosmic background radiation



COBE (1992)

Nobel Prize 2006

- **Expected temperature**
- **Expected frequency**
- **Perfect blackbody spectrum**

- *radiation too uniform?*
- *perturbations < 1 in* 10^5 ?
- *galaxy formation?*

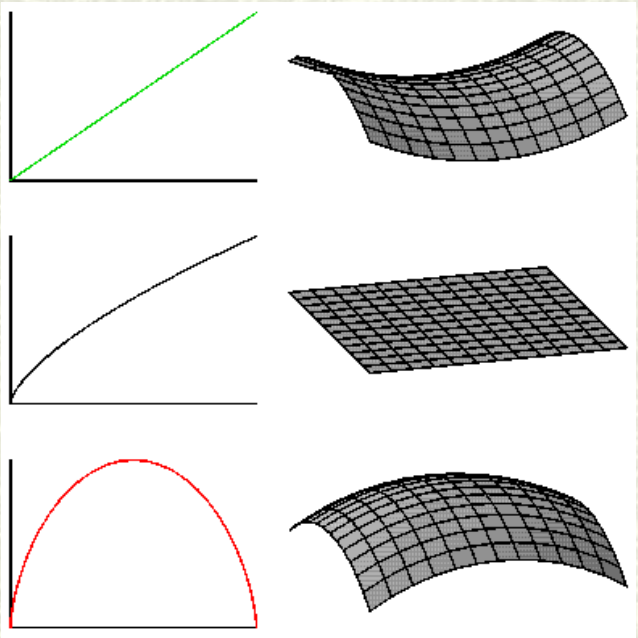
Problems

Robert Dicke

Background radiation raised new questions

- Horizon problem *why so uniform?*
- Galaxy problem *how did galaxies form?*
- Flatness problem *fine balance?*

Conflict between theory and experiment
Astrophysics: $\Omega = 0.3$



Dark Matter

- First suggested in 1930s
- Stellar motion

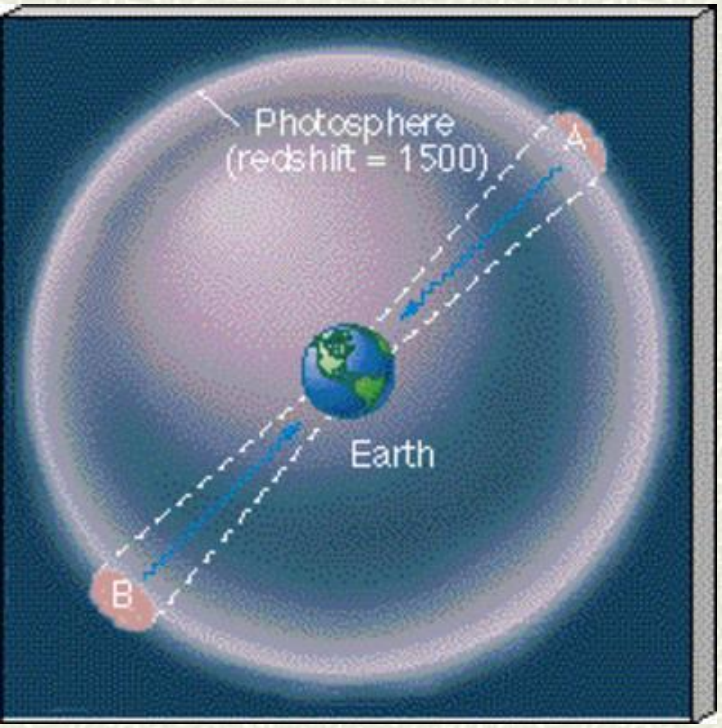
normal gravitational effect but cannot be seen directly

- Explains motion of stars
- Explains motion of galaxies
- Explains gravitational lensing

Matter = OM (20%) + DM (80%)

$\Omega = 0.3$?

The horizon problem



•Two distant regions of microwave background have similar temps

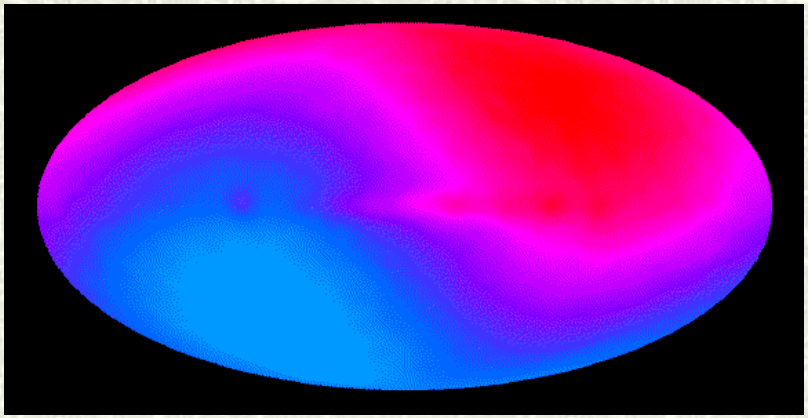
Why?

Too far apart to be causally connected

- Finite speed of light
- Finite age of cosmos

Something wrong with lookback

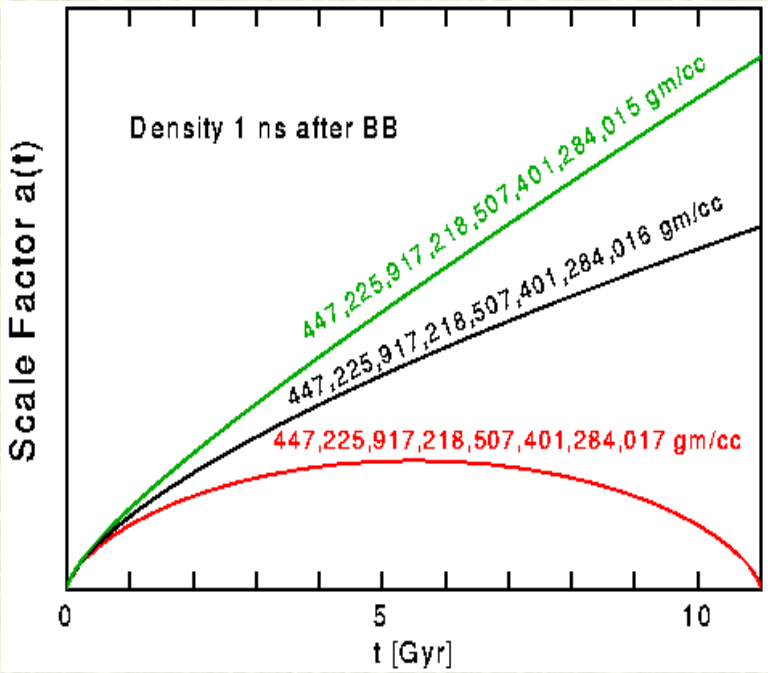
Galaxy formation problem



- Microwave background smooth on large scale
- No deviations from homogeneity obvious

  (1 in 10,000)
- How did slight perturbations become galaxies?

The flatness problem



At t = 1 s, Ω = 1 to within 1:10^{15})

Slightest deviation from flatness

→

runaway expansion or crunch

Not observed

Why so finely balanced initially?

Ω = 1?

Astrophysics: ***Ω= 0.3 ?***

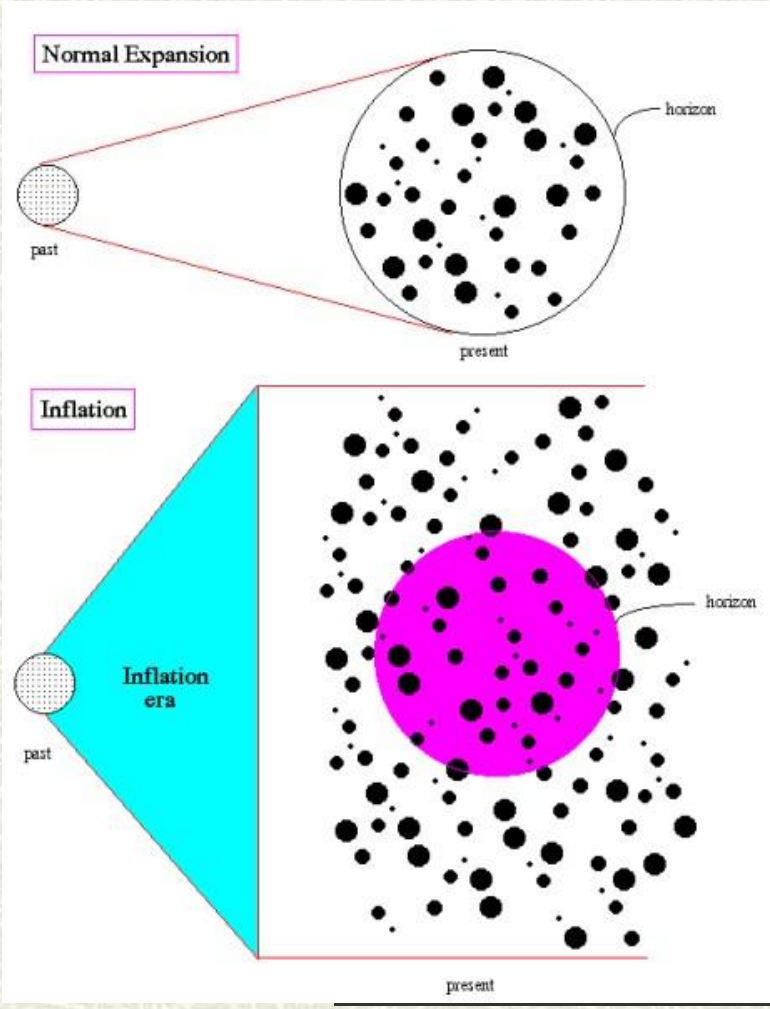
The Theory of Inflation (1981)

- Initial **exponential expansion**
- Driven by *phase transition*

Repulsive force

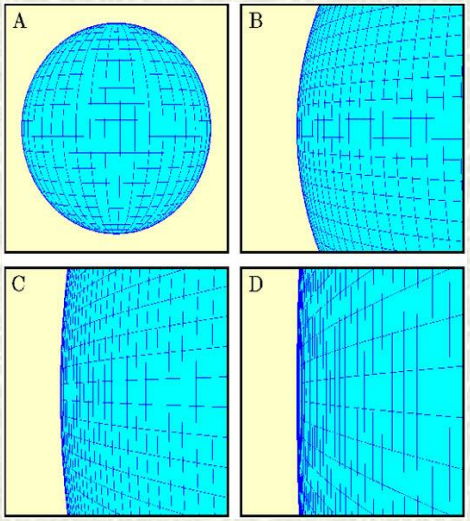
- Expansion of 10^{35} in 10^{-32} s
- Smooths out inhomogeneities
- Smooths out curvature

'No hair' universe

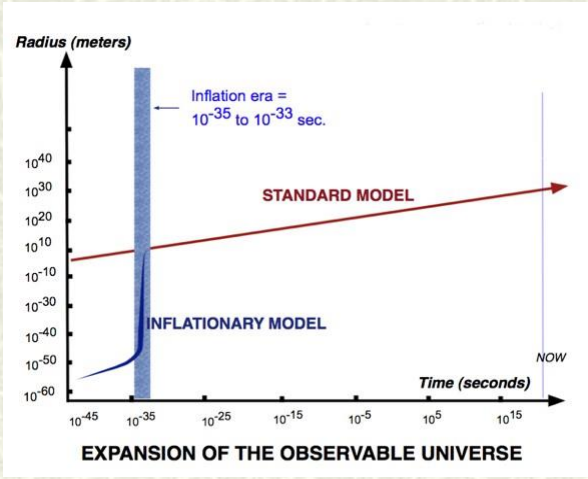


The inflationary universe

- Solves horizon problem
  Early U incredibly small
- Solves flatness problem
  Geometry driven towards flatness
- Mechanism for galaxy formation
  Quantum fluctuations inflated



$\Omega = 1$?



Conflict between theorists and experimentalists

Problems with standard model (1980-1998)

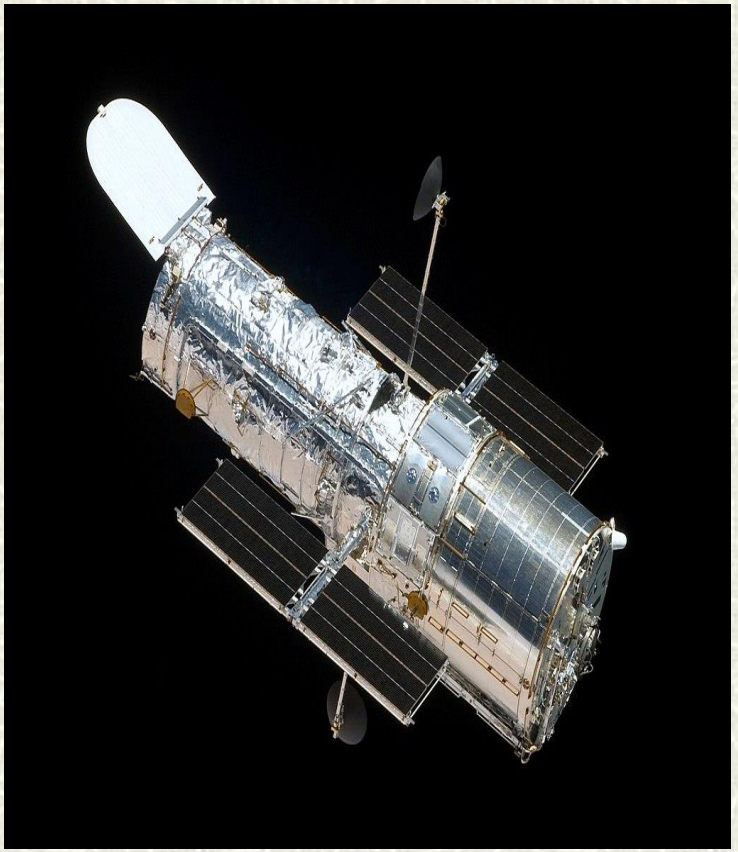
- Einstein-de Sitter: $\lambda = 0, k = 0$
- Flatness prediction (Dicke, inflation)

  $k = 0$
- But: $\Omega_M = 0.3$
- But: new timescale problem from HST

  $H = 87\ kms^{-1}\ Mpc^{-1} : t = 11.2 \times 10^9\ yr$

  too young

Is model wrong? Is $\lambda \neq 0$?



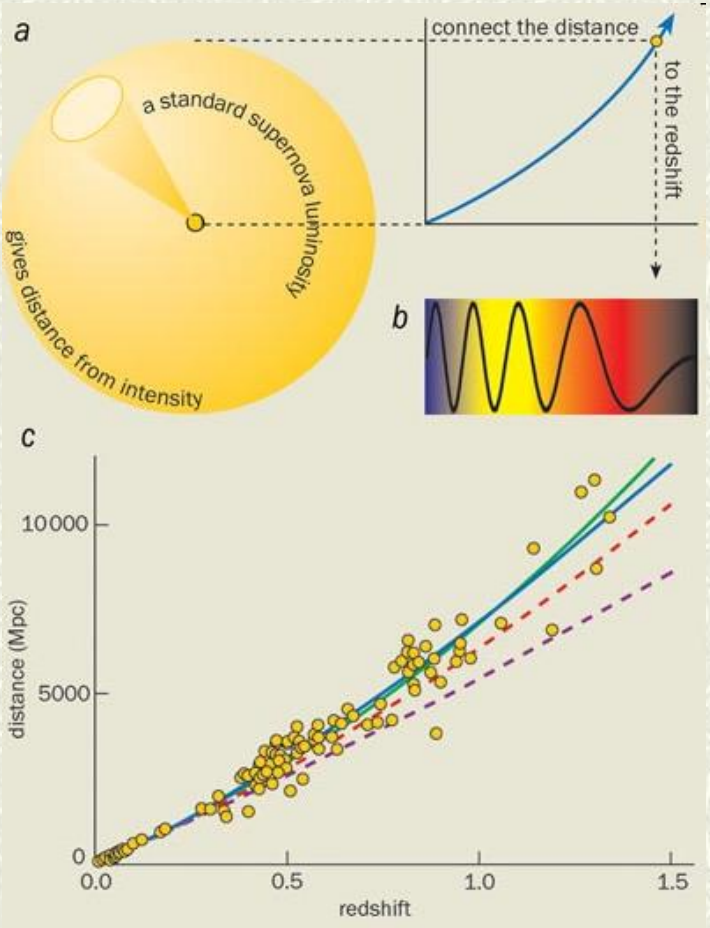
Hubble Space Telescope
1990

The accelerating universe (1998)

- Supernovae as standard candles (1998)
- Furthest galaxies too far away
- Expansion accelerating
- Implies repulsive energy

  Dark Energy ($\lambda \neq 0$)

- Possible support for inflation ($\Omega = 1$?)

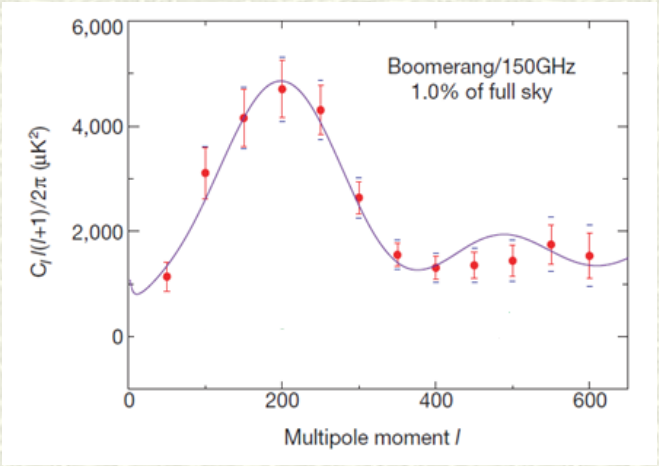


The flat universe (2000)

- Balloon measurements of CMB
- The BOOMERANG experiment
- The MAXIMA experiment
- Geometry is flat ($\Omega = 1$)

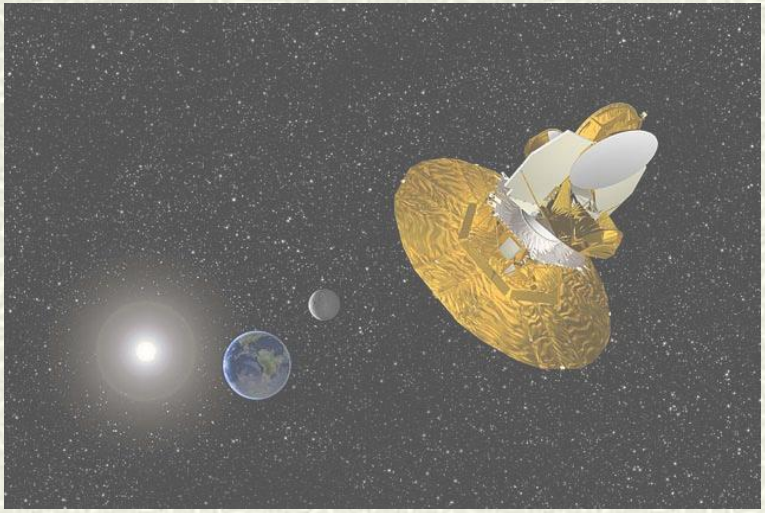
  Implies dark energy component

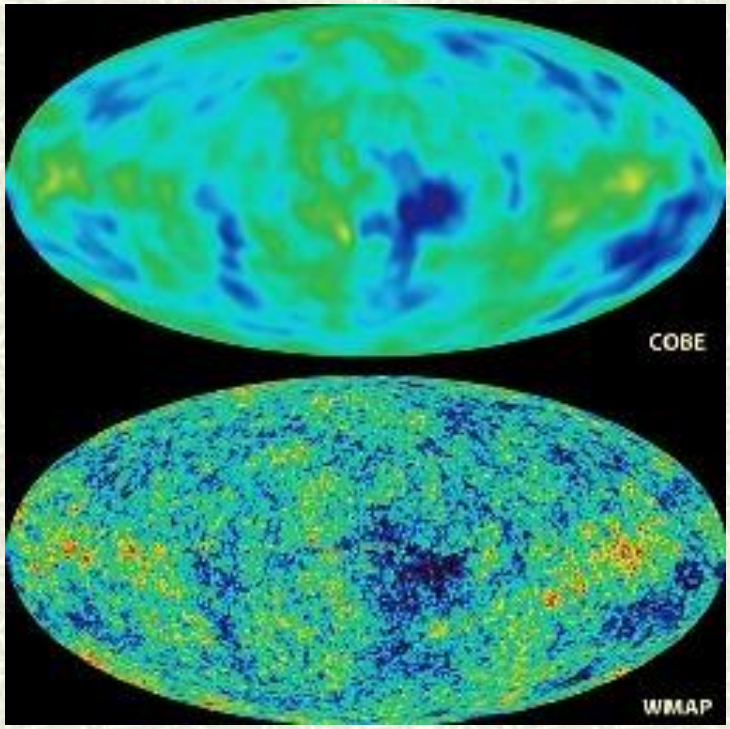
  $\Omega_M + \Omega_\lambda = 1 \quad (\Omega_\lambda = 0.7)$
- Support for inflation



WMAP Satellite (2002)

- Details of *CMB* spectrum
- Details of galaxy formation
- Details of flatness of *U*
- Details of dark energy





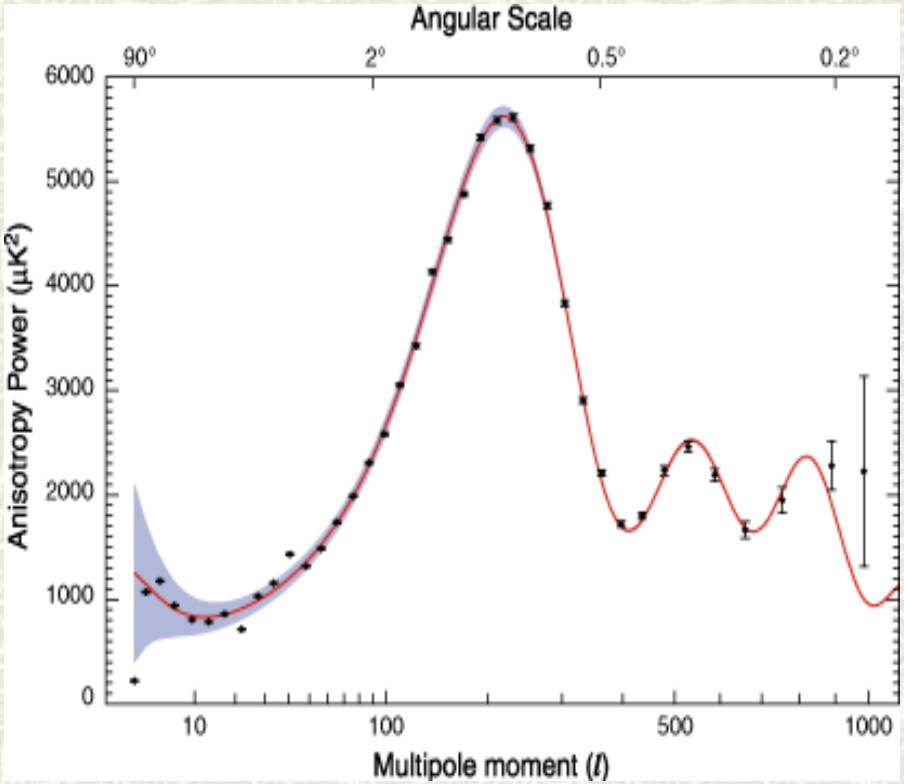
Cosmic microwave background

WMAP measurements of CMB (2005)

- Spectrum of *T* variations
- Geometry is flat (to 1%)
- Dark energy 74%

Strong support for dark energy

Strong support for inflation

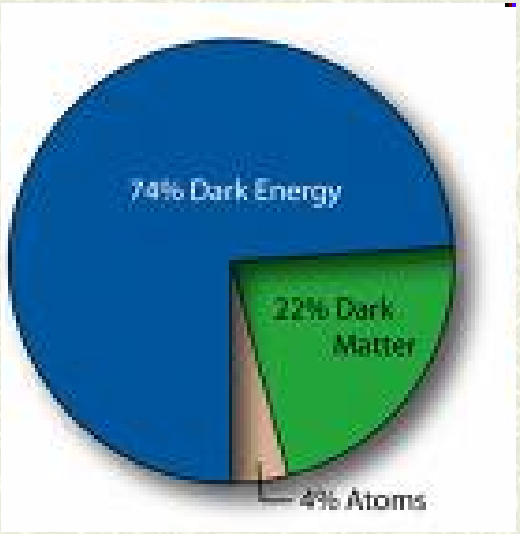


Fit to theory

Modern big bang model: *Λ-CDM*

A flat, accelerating universe containing matter, dark matter and dark energy

1. Ordinary matter: 4% (astrophysics)
2. Dark matter: 22% (astrophysics)
3. Dark energy : 74% (supernova, CMB)



ΛCDM

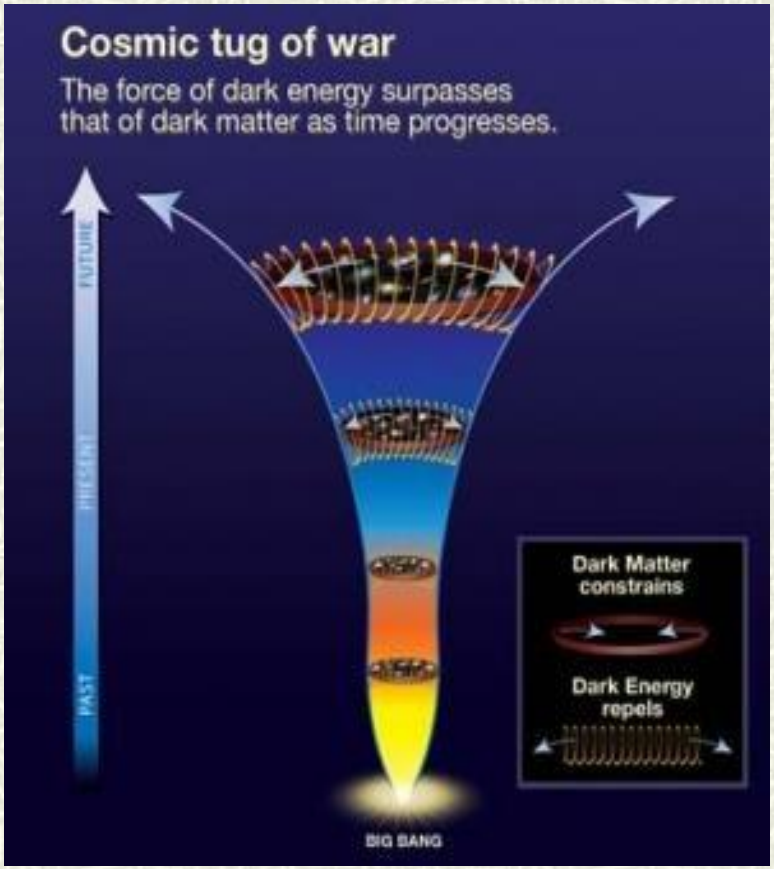
Ω = 1

Cause of acceleration: dark energy

- Predicted by relativity
- Cosmological constant
- Natural tendency of space to expand

- Energy of vacuum?
- Why so small?
- Why of similar density to matter?

- Not well understood
- Fate of universe?



New results: Planck Satellite (ESA, 2013)

1. Improved sensitivity

$$\Delta T/T \approx 1x10^{-6}$$

2. Full spectrum of *T* anisotropy

New acoustic peaks :scale invariance?

Accurate values for Ω_Λ , Ω_M

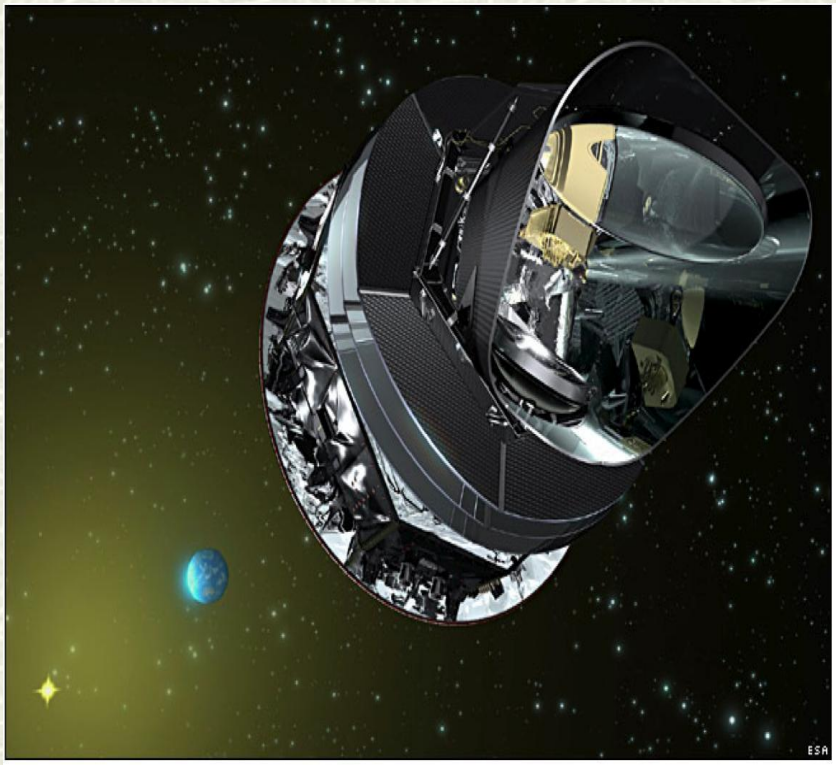
3. Gravitational lensing

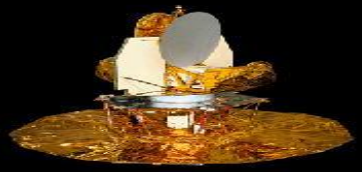
Remove degeneracies

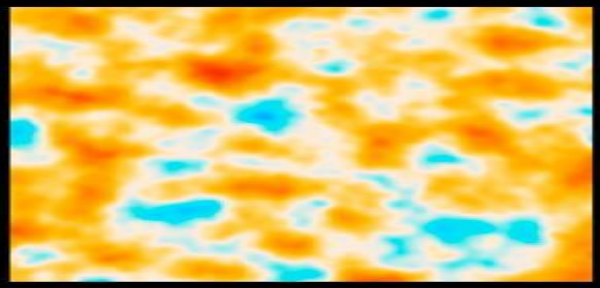
4. Polarization measurements

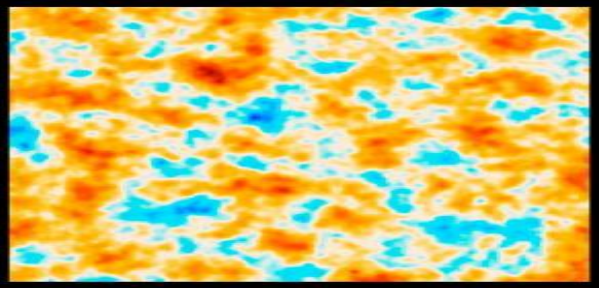
E-modes: fluctuations

B-modes: gravity waves?





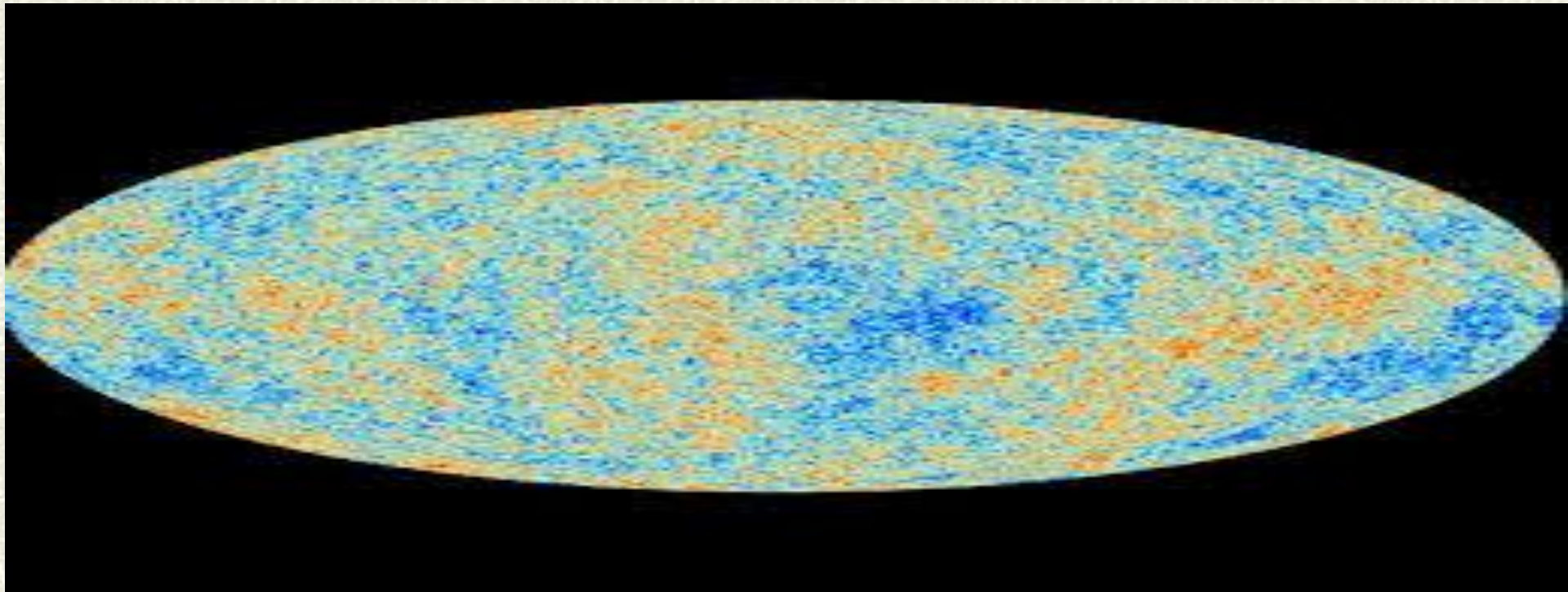




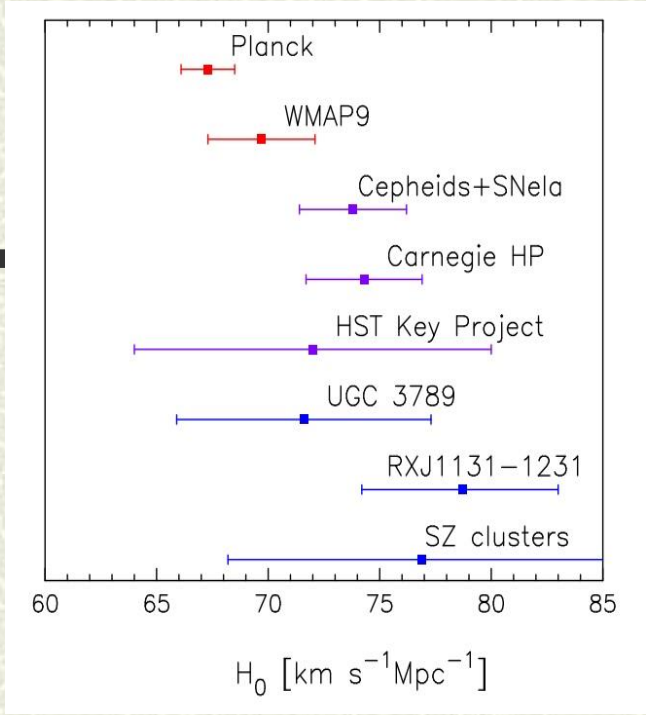
COBE

WMAP

Planck



Planck results (2013)



1. New Hubble constant

67.3 +- 1.2 km/s/MPC

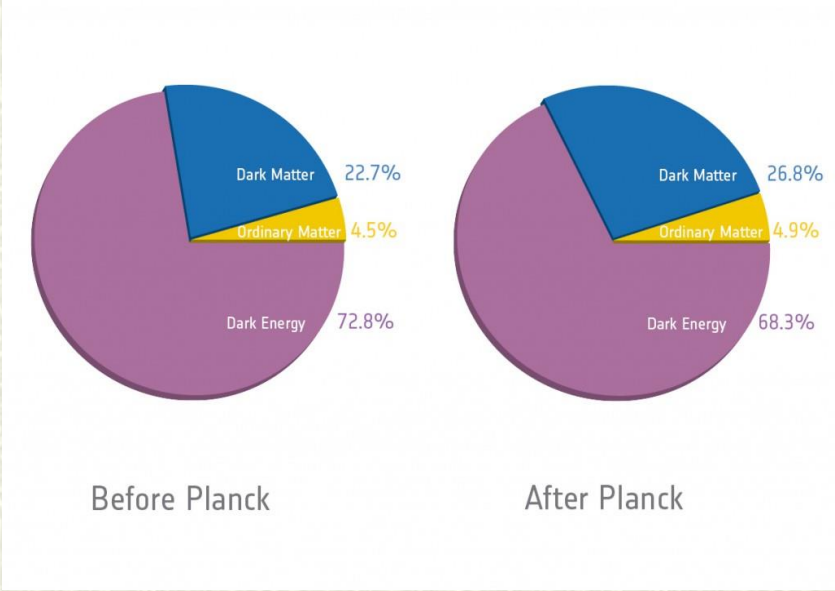
Age = 13.8 billion yr

2. Curvature ; flat

$\Omega_k = -0.0005 +- .07$

3. New mass/energy parameters

$\Omega_\Lambda = 68,\ \Omega_{DM} = 27, \Omega_{OM} = 4.9\ \%$



The big bang - problems

- Nature of dark energy?

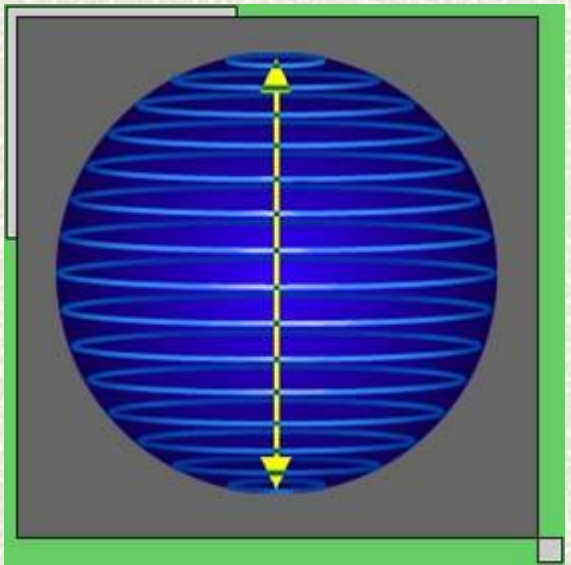
  Role in BB?

- Which model of inflation?

  The multiverse?

- The singularity problem

  What banged?
  What does time zero mean?
  No-boundary universe



The singularity: a cyclic universe?

- Breakdown at time zero
- No model of bang itself

- Multiple bangs?
- Colliding branes
- Prediction of string theory

- Cyclic universe
- Eternal universe

Cyclic universe

Tests? Non-Gaussianities in CMB

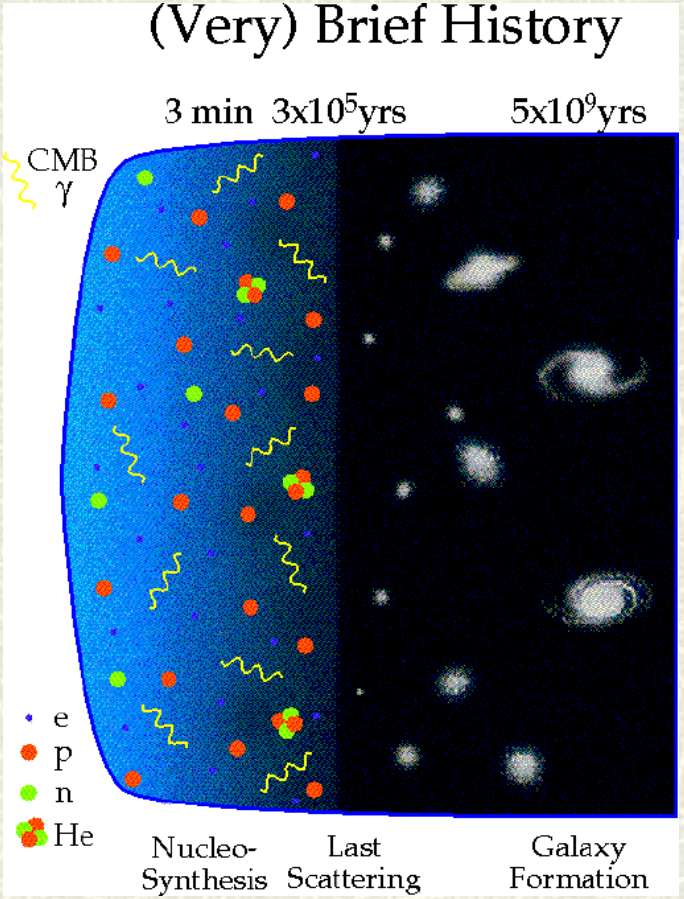
The big bang – evidence

1. The expansion of the *U*

2. The abundance of ***H*** and ***He***

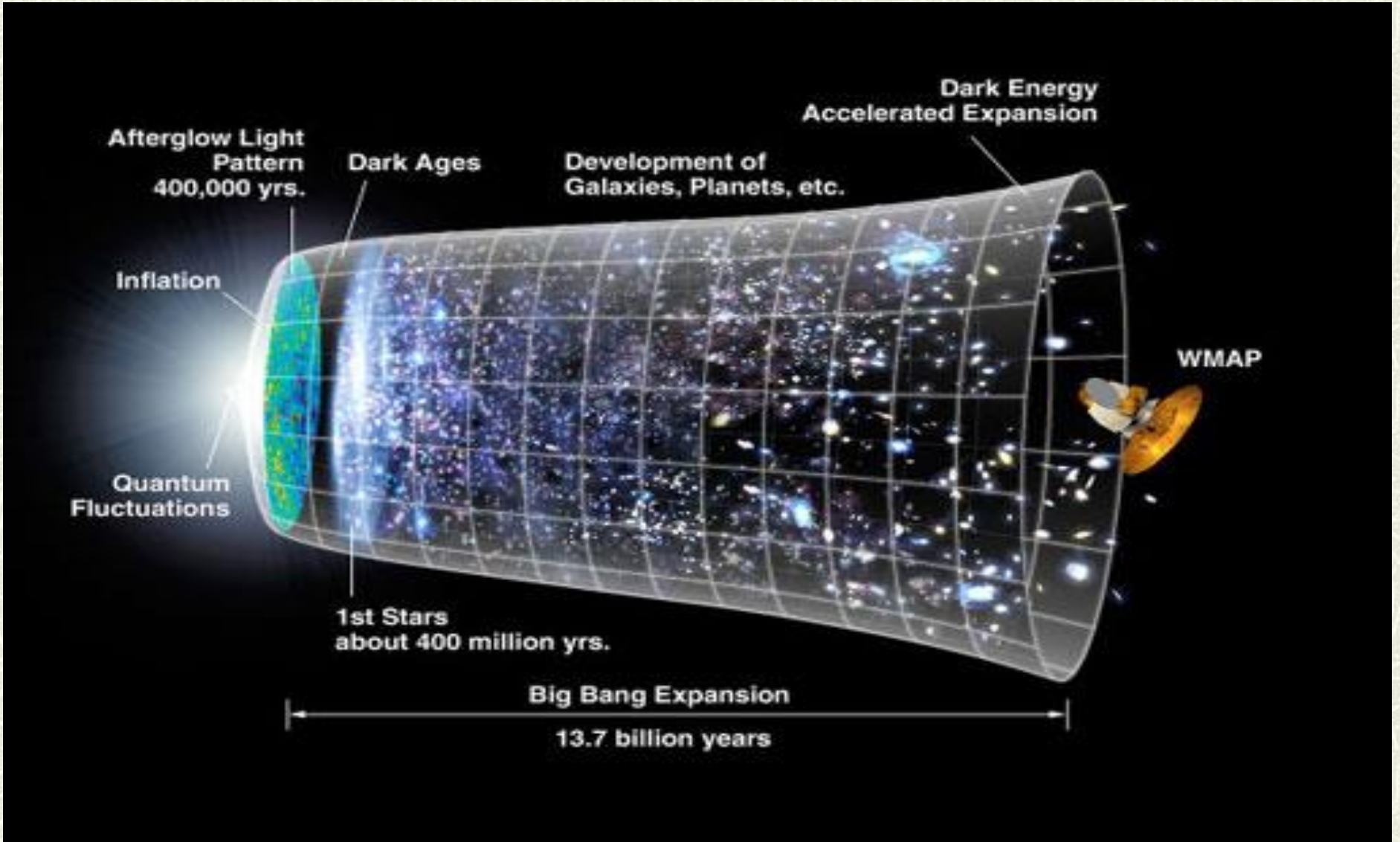
3. The distribution of the galaxies

4. The cosmic microwave background



How did it start?

The big bang model



Today's cosmological puzzles

- **Characteristics of background radiation**
  Isotropy, homogeneity, flatness (1970-80)

- **The theory of inflation (1981)**
  Exponential expansion within first second?
  Explanation for homogeneity, flatness, galaxy formation
  Which model of inflation? Bubble inflation?

- **Dark energy (1998)**
  Observation of accelerated expansion
  The return of the cosmological constant
  U mainly composed of dark energy

$$G_{\mu\nu} + \lambda g_{\mu\nu} = -\kappa T_{\mu\nu}$$

Nature of DE unknown