Observational Cosmology

Lecture I

C. Porciani

AIfA Bonn

Summer Semester 2012

Lecturers

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Lectures: Wednesday 11:15-12:45

Office Hours: by appointment

Course website: http://www.astro.uni-bonn.de/~kbasu/astro845.html

Exercise classes

Who wants credits for this course should attend the exercise classes and do homework (not much).

Also little projects are available.

Hands up who is interested

We need to decide when the classes will be held

First class will review FRW metric and basic cosmology

TA: Jennifer Pollack

jpollack@astro.uni-bonn.de

Textbooks

- There will be no official textbook for the course
- The class will focus on the most recent advancements in cosmology which are often not yet textbook material
- Some lecture notes and the slides will be made available in pdf format
- Recommended readings will be suggested from time to time

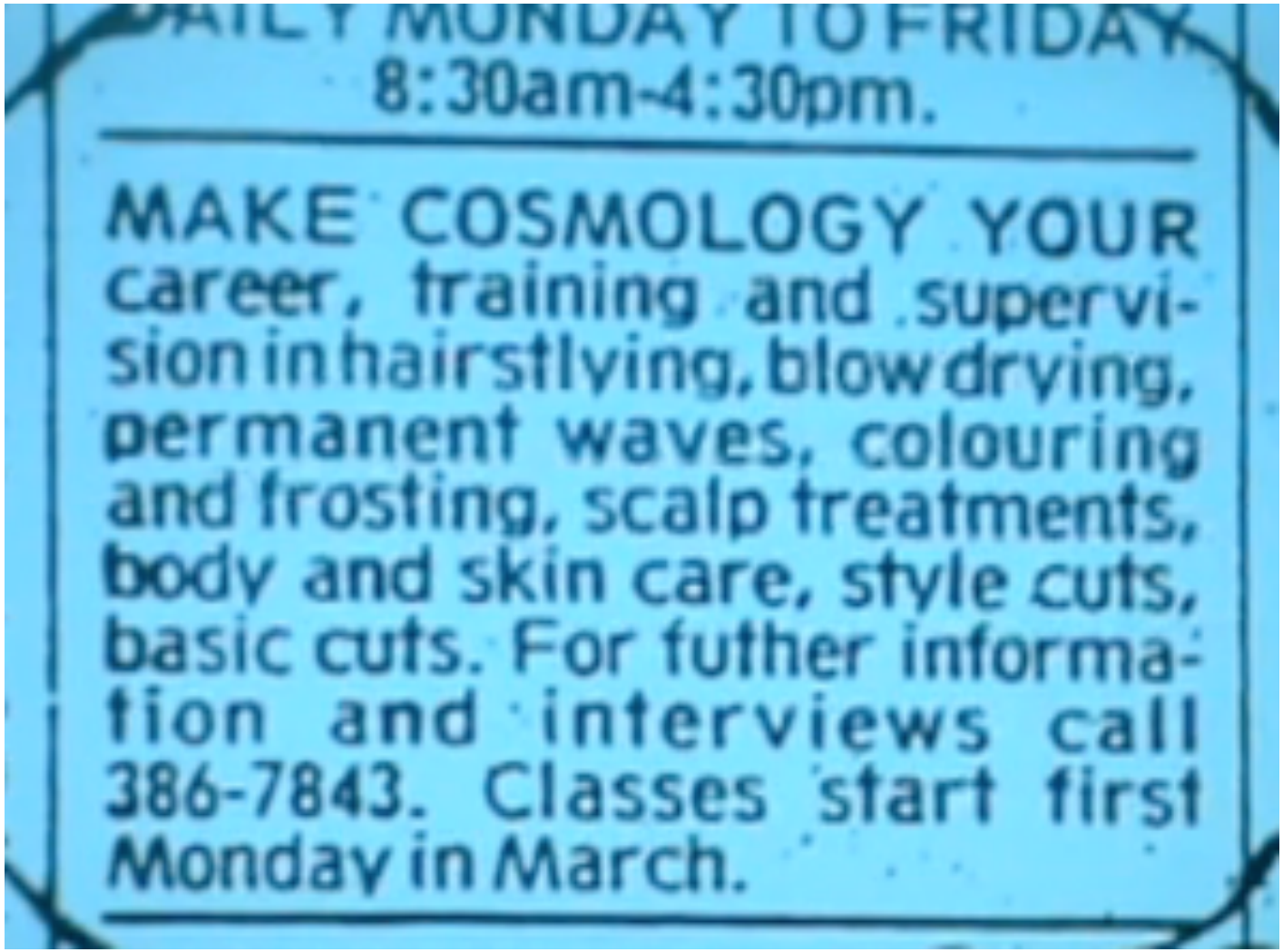
Feedback

- Feedback and interaction is greatly appreciated
- This is your class! Feel free to stop me any time if you are not understanding something
- There are no stupid questions, please, do not be scared to ask
- We will always start a class with questions regarding the previous one

Assessing the right level of the class

- Please write down your name, e-mail address, and semester (or Master, PhD, etc.)
- Hands up who took a basic cosmology class
- Hands up who is confident knowing the FRW metric
- Hands up who knows Friedmann equations and what is the critical density of the universe
- Hands up who knows what dark energy is

WHAT IS THIS COURSE ABOUT?

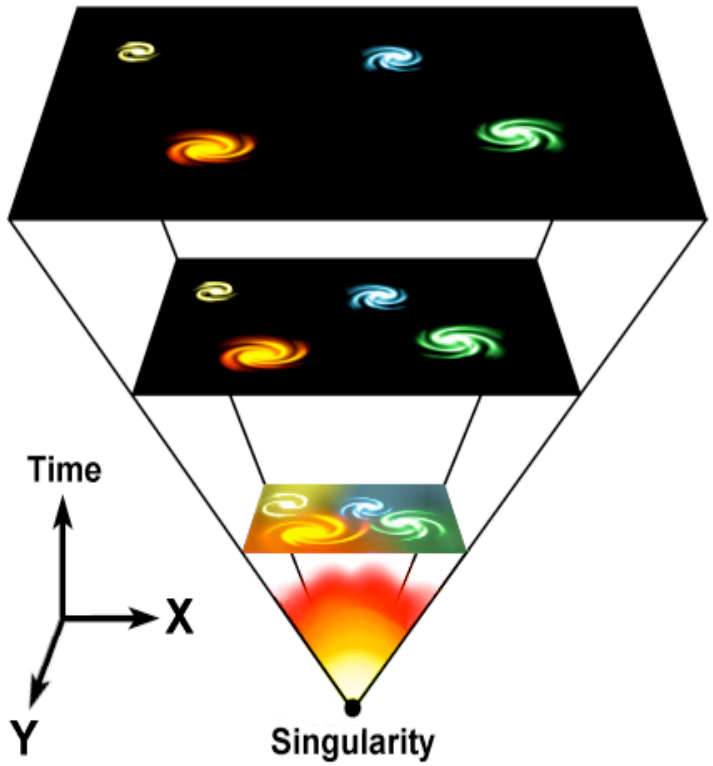


Cosmology + ET = Cosmetology

Cosmology

- Etymology:
  Κοσμος "the physical world" + λογια "discourse"

- The science of the origin, the structure, and the development of the universe as a whole



All science learning begins with questions

- What does the Universe look like?
- What is it made of?
- Is it finite or infinite?
- How old is it?
- How will it end?
- What does physics say about the Universe?
- What does the Universe say about physics?
- How did the structures we see form?
- When did they form?
- Where do we fit into this picture?

The atypical lecture of today

- What is this course about?

  It is mainly about the future of cosmology

"There is no future without tradition" (O. Marquard)

- The birth of modern cosmology

  The human mind and the Universe

  (historical - epistemological approach)

- Observational facts and definitions

The ancient universe

Laconian amphora,
6th century BC,
Vatican Museums, Rome

The only instrument available

Xinhua/ Xu Suhui Photo

The Nebra sky disk, Bronze Age, 1600 B.C. (??), Nebra, Germany

The birth of astronomy

- Early astronomy was about repeating phenomena and the measure of time (calendar, seasons)

- As far as we know, there was no explanatory attempt, the idea was to describe regularities. The study of sky phenomena was useful to sailors and for agriculture.

- Astronomy was always linked to astrology, myth and religion

- The first scientific revolution happened in the 8^{th} century B.C. when Babylonians started developing logically consistent, predictive models of the solar system based on some assumptions

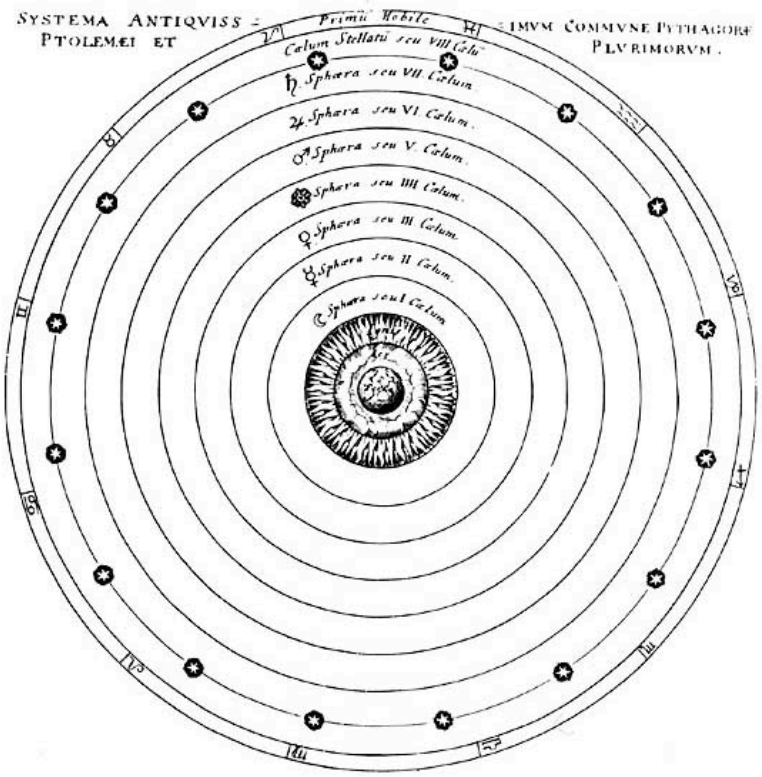
The Aristotelic universe

- Aristotle (384-322 BC), building upon the work of Eudoxus (409-356 BC), developed the classic model of antiquity

- The Universe is composed of 55 concentric spheres (grouped in 8 ``heavens'') made of aether (quintessence) with the Earth at the center

- The ``Primum Mobile'' imparts motion to the spheres

- Distinction between the supra-lunar and sub-lunar worlds

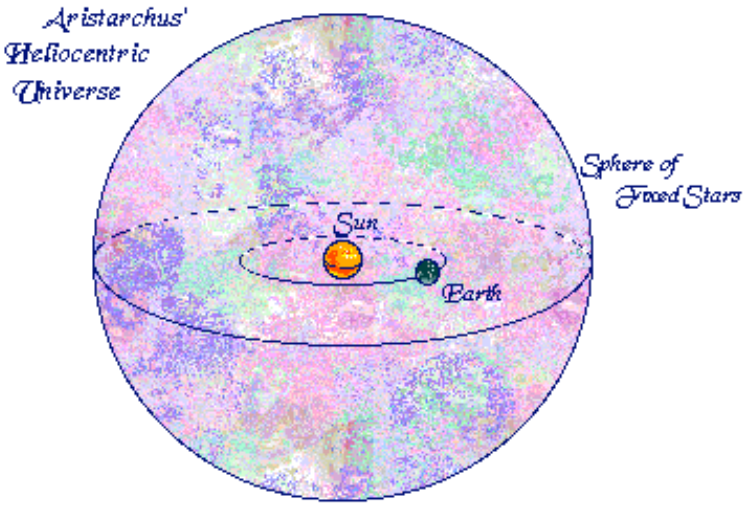


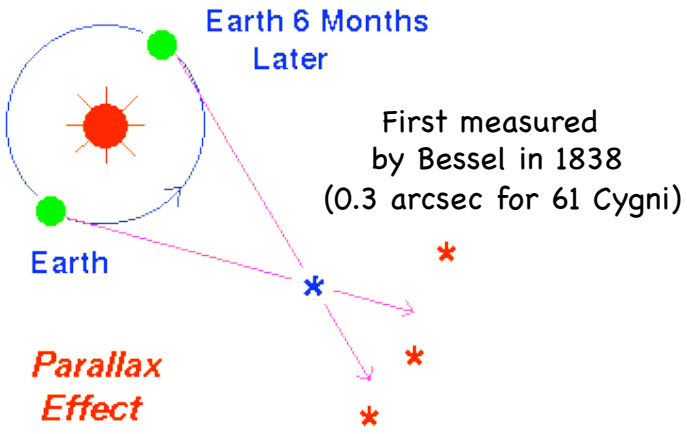
The first heliocentric system

- Aristarchus of Samos (310-230 BC) proposed the first heliocentric system for the Universe

- If the Earth was changing position with respect to the Sun, stellar parallax should have been observed

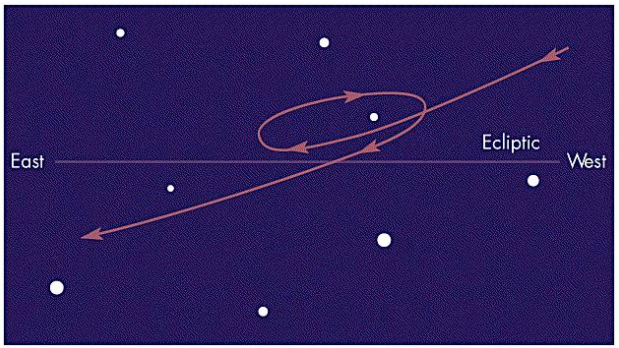
- No parallax was detected and the heliocentric model was quickly forgotten (importance of observations)

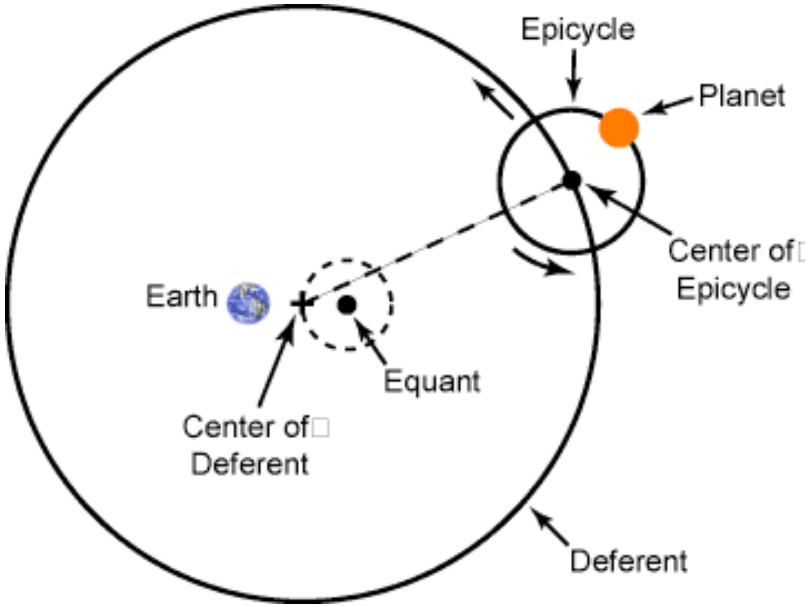




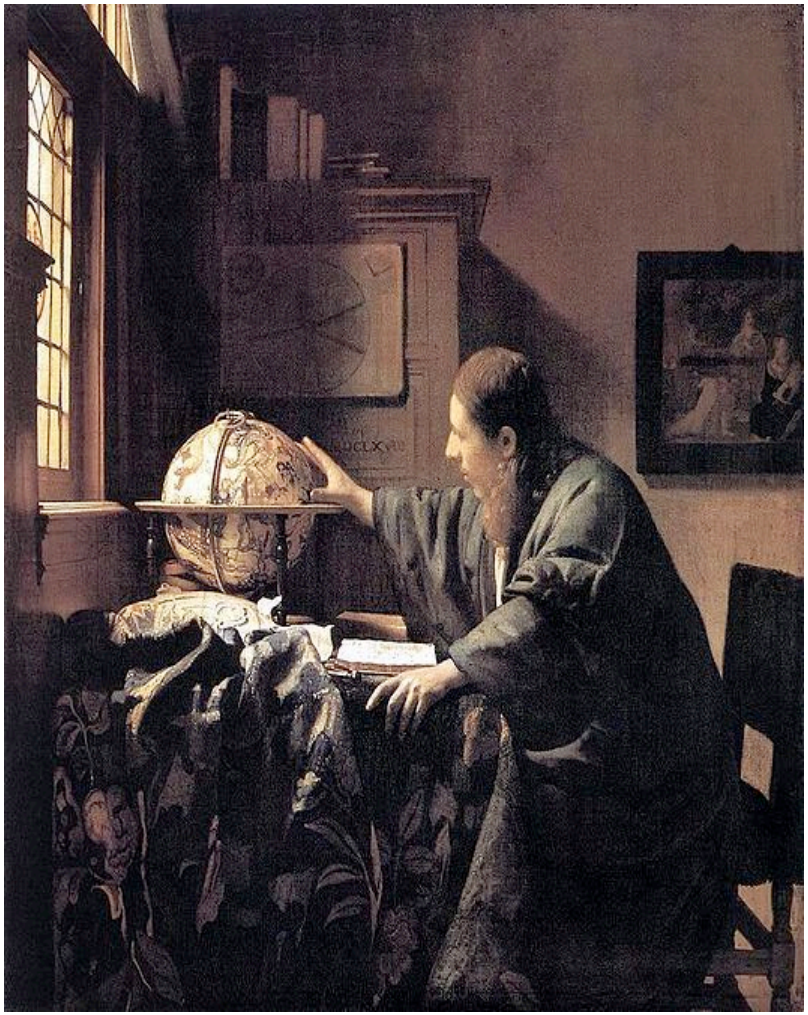
The Ptolemaic Universe

- The troubling observations of varying planetary brightness and retrograde motion could not be explained by Aristotle's model
- Hipparchus (190-120 BC) and Ptolemy (85-165 AD) "improved" it to accommodate them
- Ptolemy's conception of a geocentric, finite and ethernal Universe lasted for almost 2000 years!

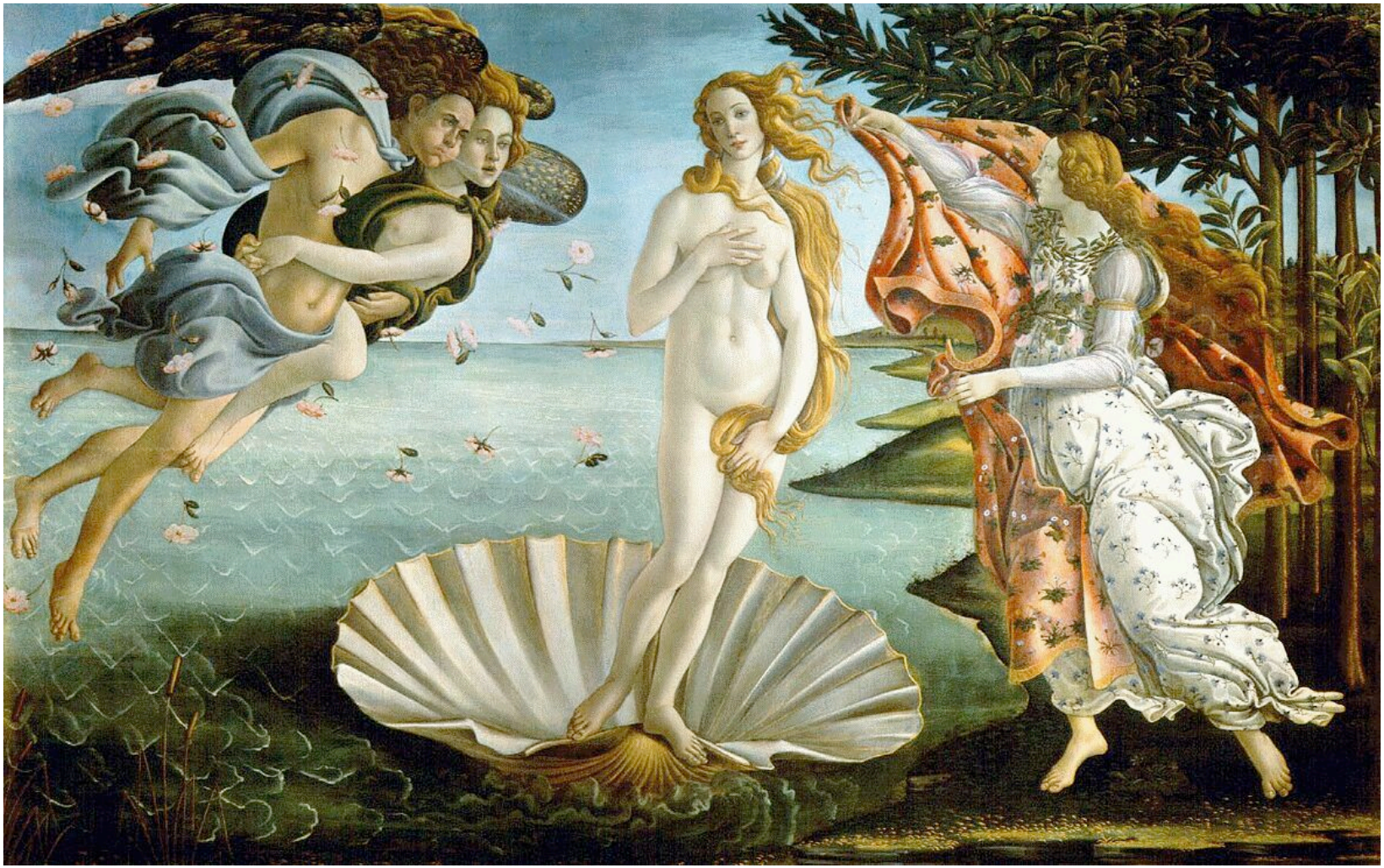




The classic universe



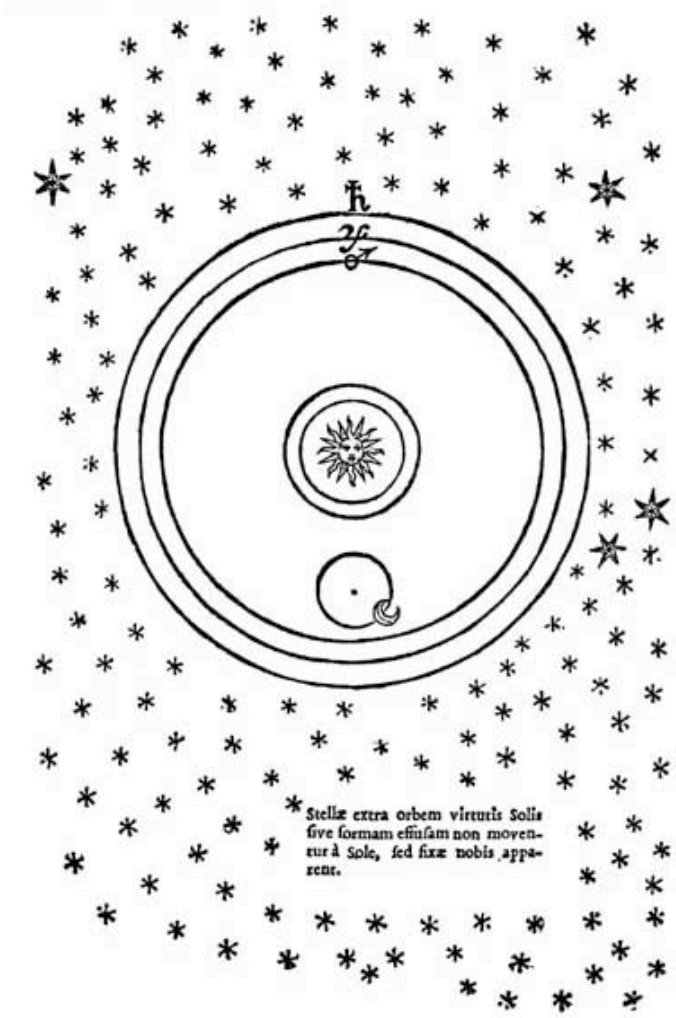
Johannes Vermeer, 1668 (Musée du Louvre, Paris)

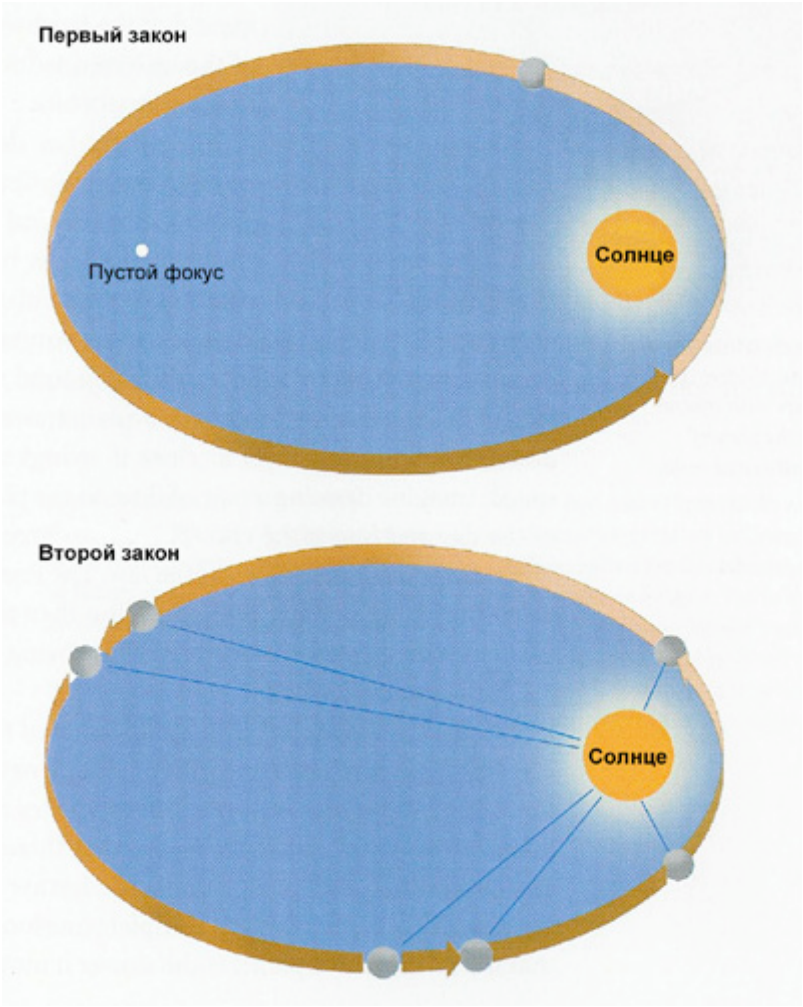


Sandro Botticelli, 1483-1485 (Galleria degli Uffizi, Firenze)

Copernicus, Tycho Brahe & Kepler

(1470-1543) (1546-1601) (1571-1630)

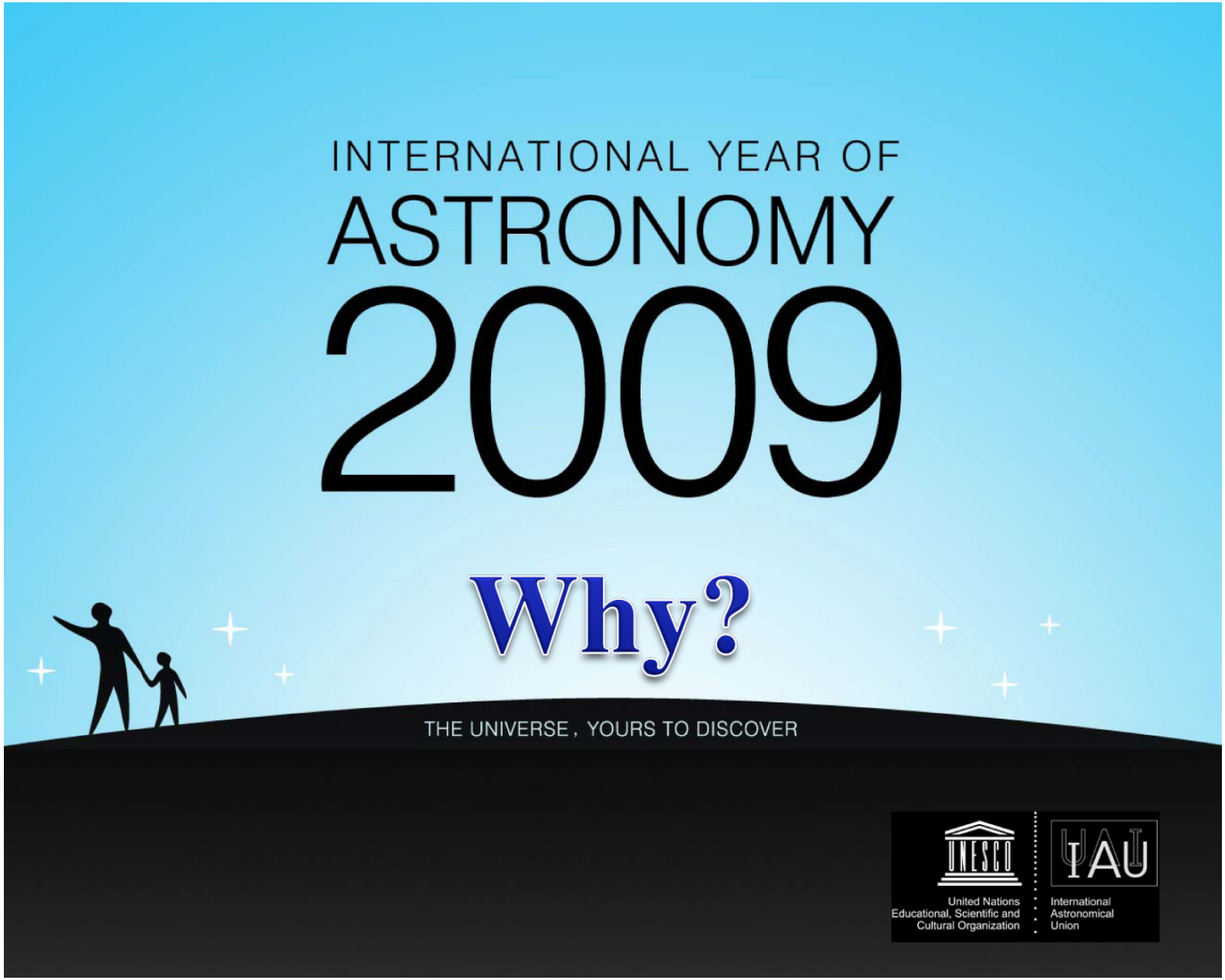




The celestial realm is mutable

Amazed, and as if astonished and stupefied, I stood still, gazing for a certain length of time with my eyes fixed intently upon it and noticing that same star placed close to the stars which antiquity attributed to Cassiopeia. When I had satisfied myself that no star of that kind had ever shone forth before, I was led into such perplexity by the unbelievability of the thing that I began to doubt the faith of my own eyes.

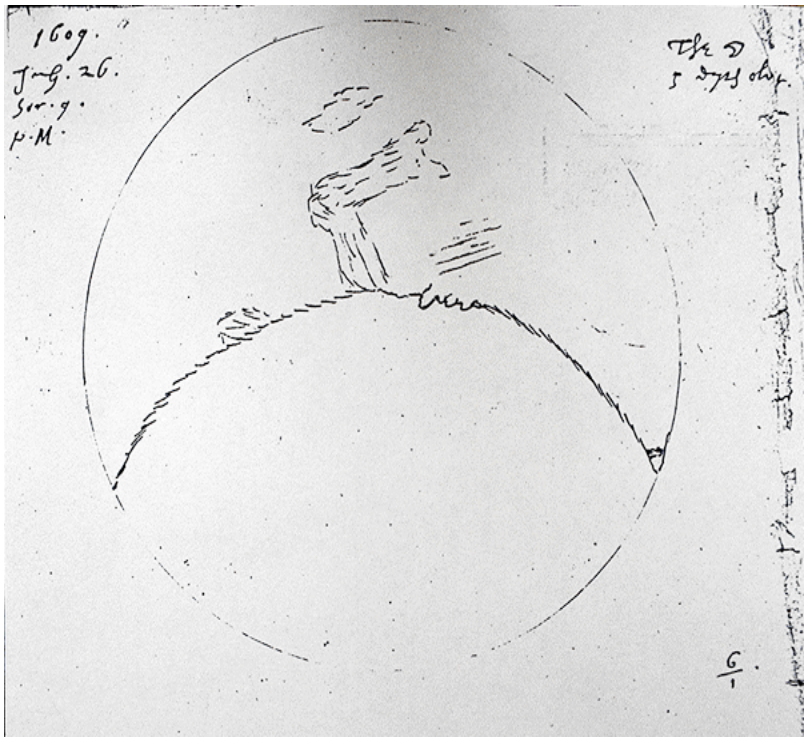
Tycho Brahe


INTERNATIONAL YEAR OF
ASTRONOMY
2009
Why?
THE UNIVERSE, YOURS TO DISCOVER
United Nations
Educational, Scientific and
Cultural Organization
International
Astronomical
Union

Galileo Galilei (1564-1642)
a troublemaker

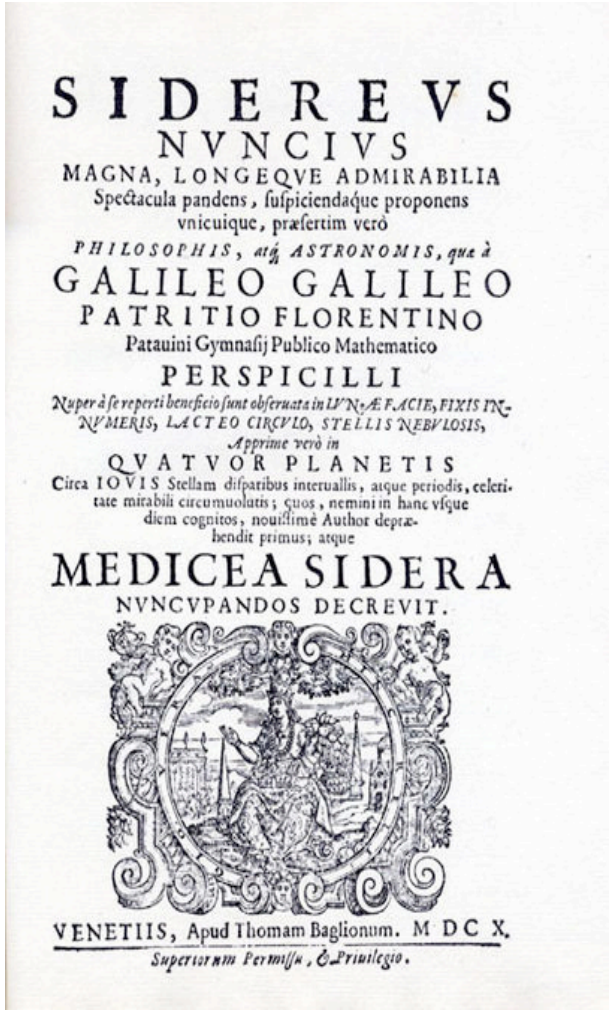
Galileo made a splash

Hans Lippershey (1570-1619)



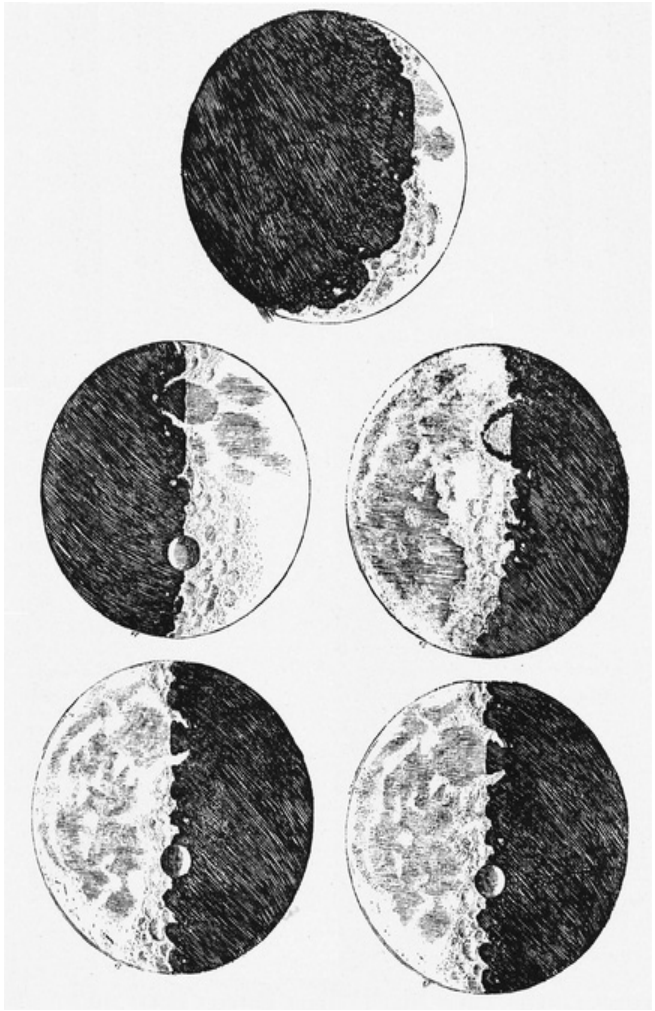
Thomas Harriot (1560-1621)

Sidereus Nuncius



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolatis; quos, nemini in hanc vsque diem cognitos, nouissimè Author deprehendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

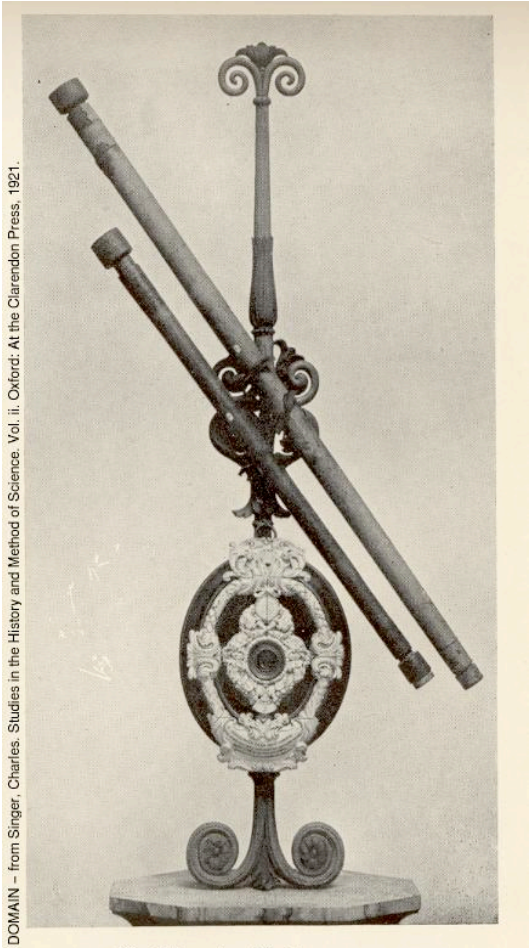
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.



Galileo Galilei

The Ptolemaic model is definitively disproved:

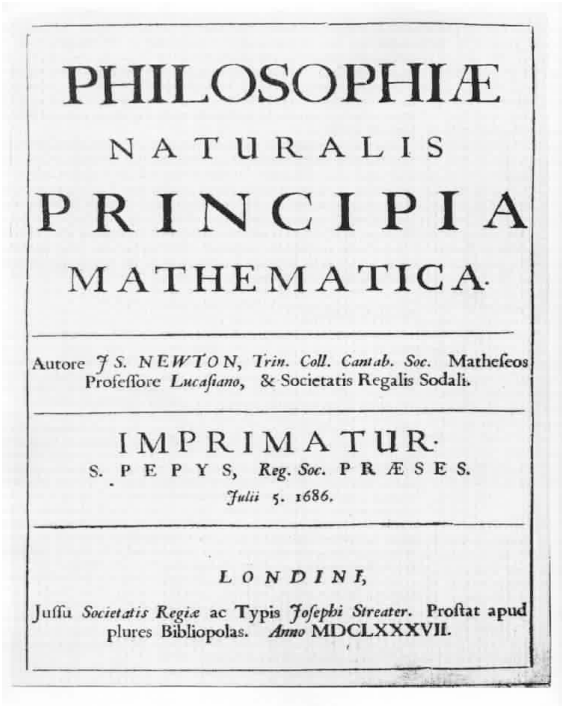
- The Moon is as rocky as the Earth
- The Sun has spots and rotates
- Jupiter has moons
- Venus has phases
- There are stars which are not visible without a telescope



PUBLIC DOMAIN – from Singer, Charles. Studies in the History and Method of Science. Vol. ii. Oxford: At the Clarendon Press. 1921.

Galileo's Telescopes
The cracked lens is mounted in centre

Isaac Newton (1642-1727)

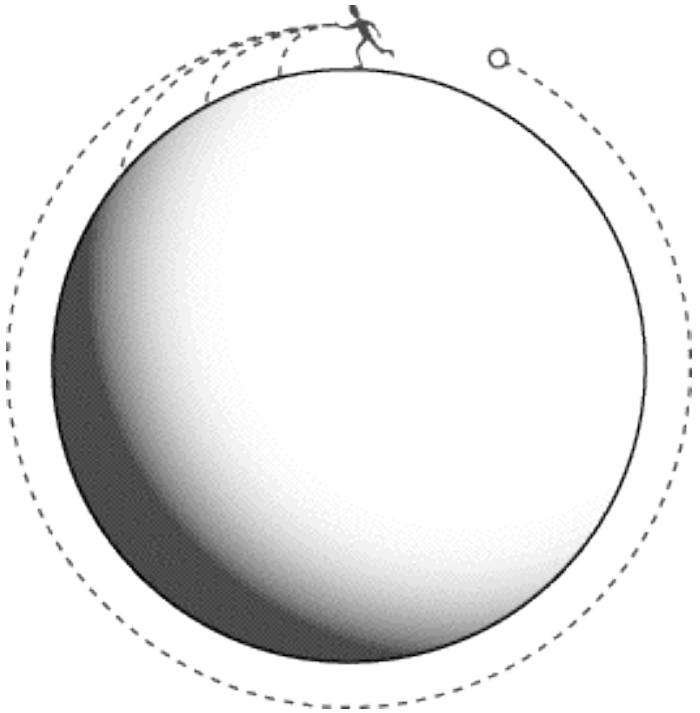


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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

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

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



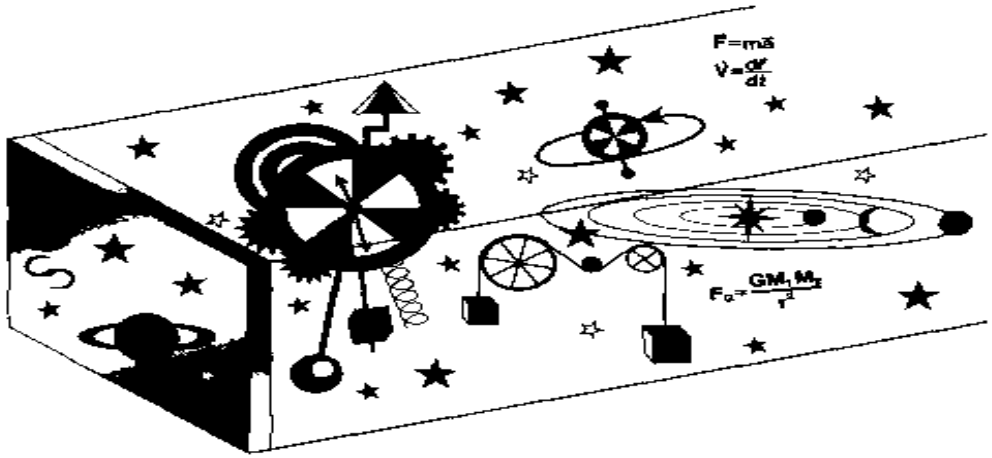
Authentic revolution:

New Mechanics + Law of Universal Gravitation

Perfect agreement with observational data

Celestial mechanics is a solved problem!

The clockwork Universe

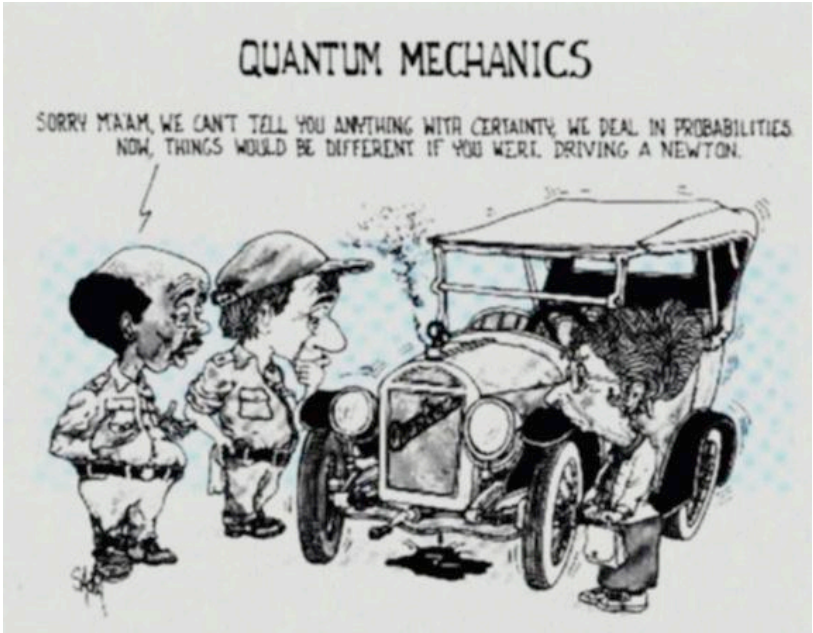


- Newton's Cosmology admits the existence of absolute time and absolute space (they exist also where there is no matter and they will always do)
- The Universe of Newtonian physics is perfectly deterministic
- In principle, we can predict the entire future of the Universe from a knowledge of the initial positions and velocities

Beyond clockwork: the 20th century

- Gravitating systems of more than 2 bodies are chaotic (small differences in the initial conditions lead to divergence of the solutions)

- Quantum Mechanics has a probabilistic nature which stems from the act of measurement

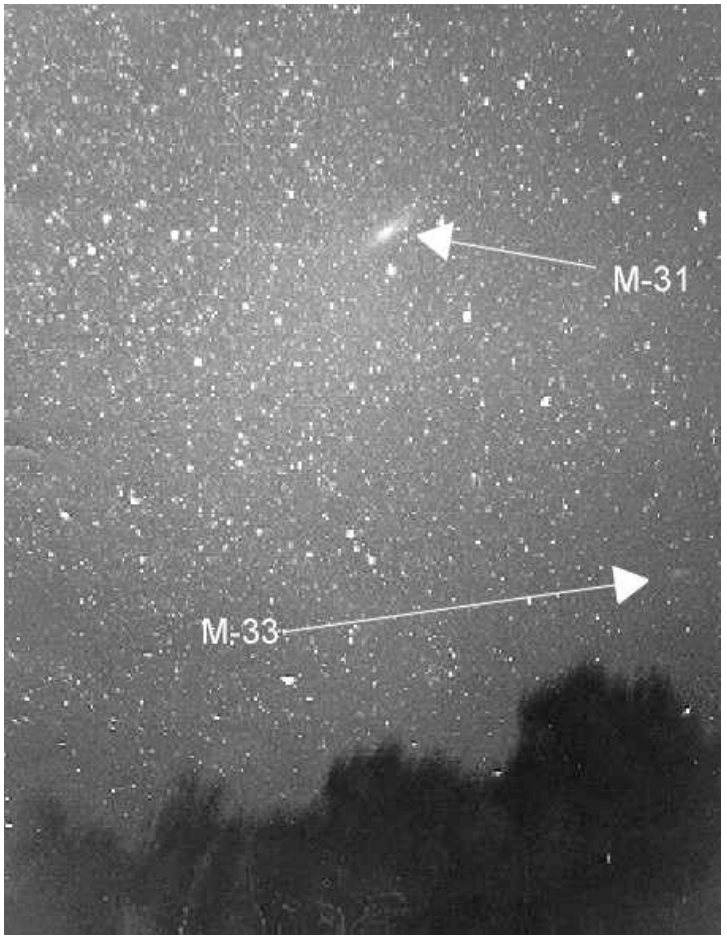


The modern universe

Vincent Van Gogh, 1889 (The Museum of Modern Art, New York)

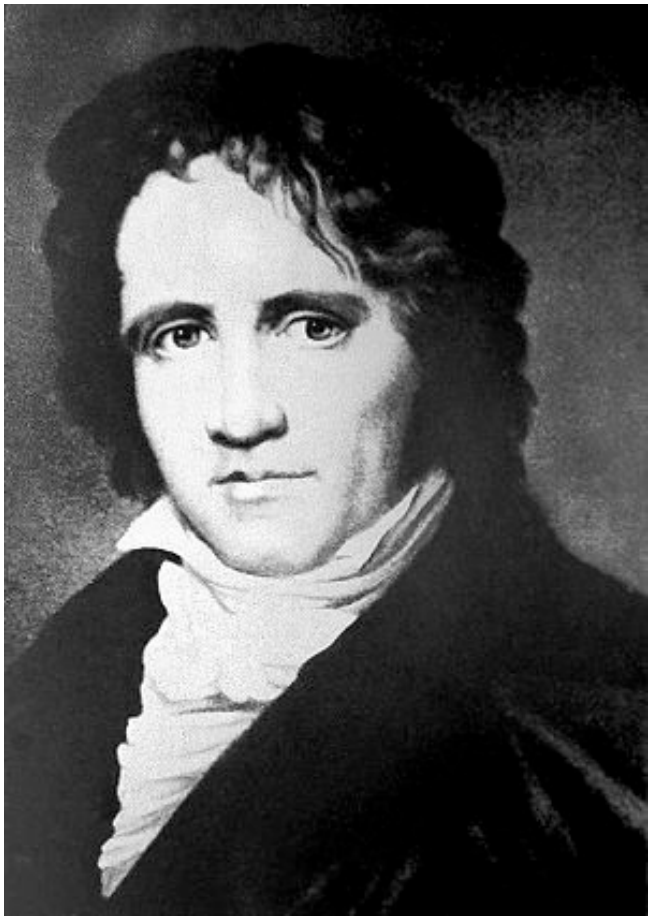
The universe with naked eyes

Photo: Kerry-Ann Lecky Hepburn



Tintoretto, 1575-1580 (The National Gallery, London)

Measuring the size and the ingredients of the universe



F. W. Bessel (1784-1846)

J. von Fraunhofer (1787-1826)

The "Realm of the Nebulae"

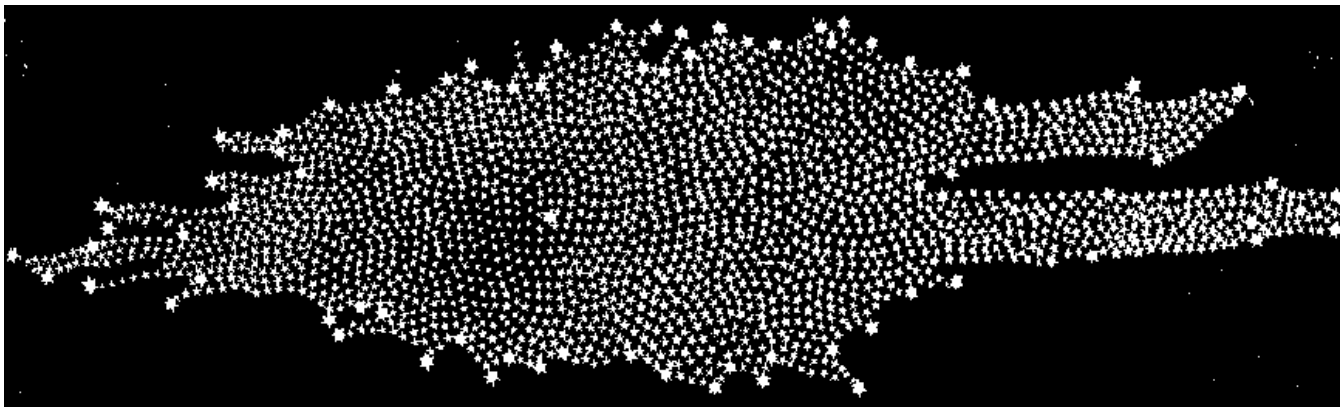
Galileo resolved the Milky Way (MW) into faint stars

Kant (1724-1804) proposed that the MW was a disk of stars and that there could be similar "island universes" distributed throughout space

Messier (1730-1817) and Herschel (1738-1822) found many "nebulae" (fuzzy, diffuse looking objects which appeared at fixed positions on the sky)

Parsons (1800-1867) observed that some nebulae had a spiral structure

The Milky Way



A sketch by Herschel based on star counts (1785)

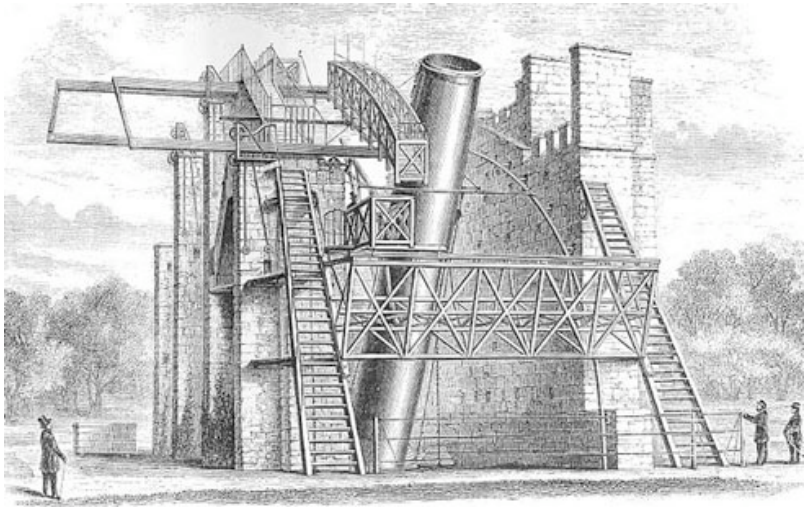
- Based on stellar counts, Kapteyn (1851-1922) developed a lens-shaped model of the MW. This was 30,000 ly across, 6,000 ly thick and the solar system was very near to the centre
- From the distribution of globular clusters, in 1918, Shapley inferred that the diameter of the WM was 300,000 ly and the center was located in the constellation of Sagittarius some 19,000 ly away from the Sun
- Studying the motion of stars in the vicinity of the Sun, Oort measured a size in line with Kapteyn and the position of the centre in line with Shapley
- The discovery of interstellar absorption of starlight (Trumpler, 1930s) reconciled the different measurements (diam=100,000 ly, thick=1,000 ly, d_{GC}=26,400 ly)

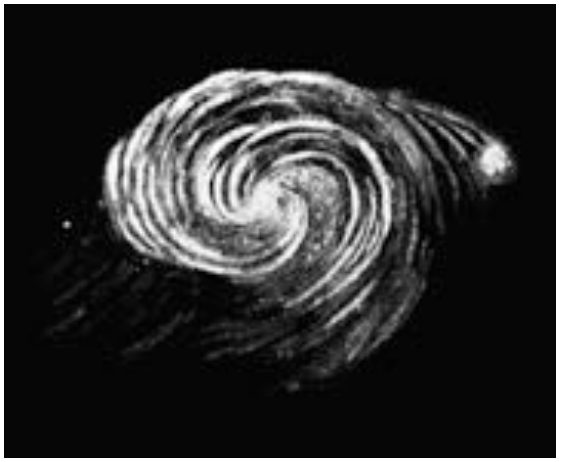
The realm of the nebulae

- Charles Messier (1730-1817)

- Wilhelm Herschel (1738-1822)

- In 1845 William Parsons (Earl of Rosse) discovered the "spiral nebulae" using its "Leviathan of Parsonstown" (1.83 m)





The "Realm of the Nebulae"

Helium was identified by emission lines in the Sun spectrum in 1868 (by Janssen & Lockyer) and later found on Earth 1895.

In 1864 the English astronomer Williams Huggins postulated the existence of a new element (dubbed "nebulium") to explain the strong green emission lines found in what is nowadays known as Cat's Eye nebula.

In 1927 Ira Sprague Bowen showed that these emission lines were due to (electric-dipole) forbidden transitions of doubly ionized oxygen.

The origin of the nebulae

Island universe hypothesis

- The spiral nebulae are other Milky Ways made of stars
- Very distant and external to our Galaxy
- Kant (1775), Alexander von Humboldt (1845)

Nebular hypothesis

- The spiral nebulae are swirling gas clouds
- Nearby and internal to our Milky Way
- Might be forming solar systems
- Laplace (1796)

26 April 1920: the great debate

Heber D. Curtis (but Sun in the centre)

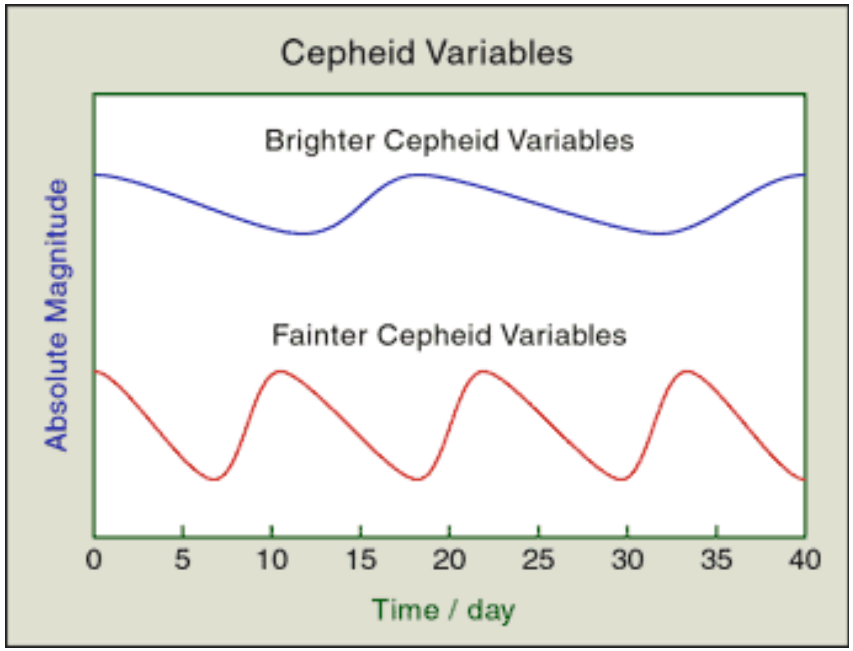
Harlow Shapley (but Sun off centre)

Harvard Observatory Director Pickering:

"A great observatory should be carefully organized and administered as a railroad…
A great savings may be effectuated by employing unskilled and therefore inexpensive labor, of course under careful supervision."

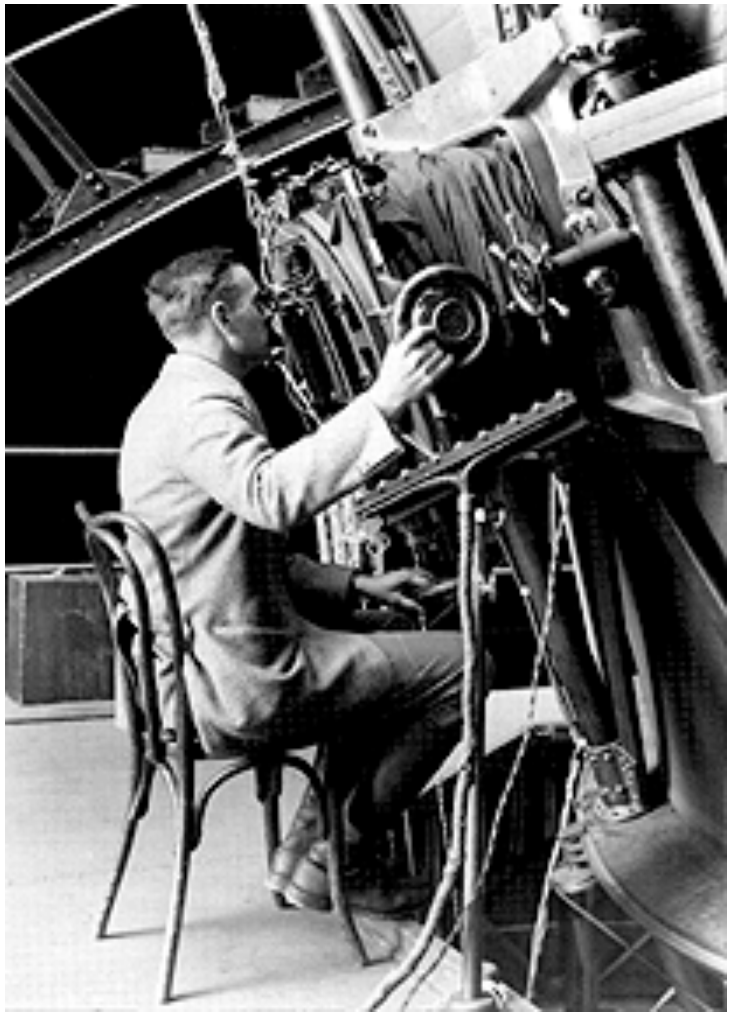
Henrietta Swann Leavitt (1868-1921)

- "It is worthy of notice that brighter variables have longer periods"



In 1924 the Universe grows bigger

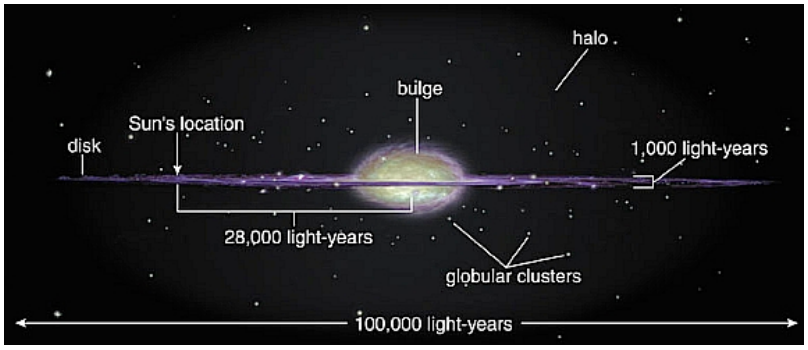
- In 1924, Edwin Hubble (1889-1953) detected some cepheid variable stars in the M31 nebula
- Using the period-luminosity relation determined by H. Leavitt (1868-1921) he found a distance to M31 of nearly a million light-years, a factor of 10 larger than the size of the Milky Way
- This clearly made M31 a "galaxy" on its own right



Our home

Our galaxy itself contains a hundred billion stars;
it's a hundred thousand light years side to side.
It bulges in the middle - sixteen thousand light years thick -,
but out by us it's just three thousand light years wide.
With thirty thousand light years from galactic centrepoint
we go round every two hundred million years -
and our galaxy is only one of millions, of billions,
in this amazing and expanding universe!

Eric Idle, The Galaxy Song ("The Meaning of Life")



Our neighbours

M31
The Andromeda Galaxy
2.56 million light years away

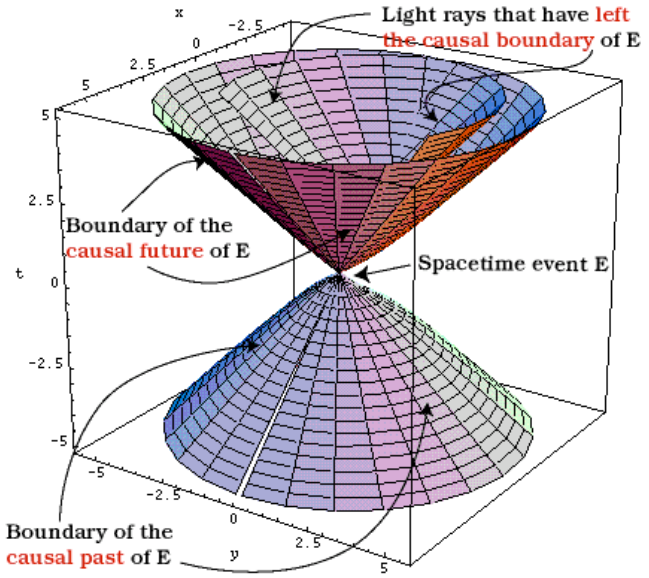
M33
The Triangulum Galaxy
3 million light years away

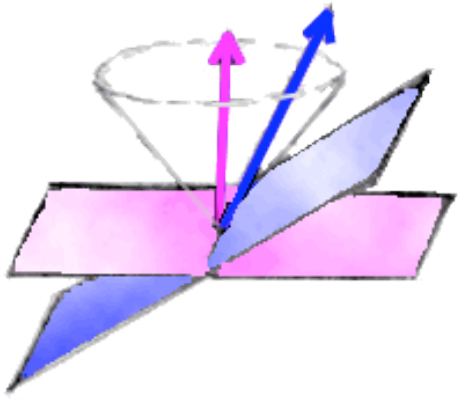
What about progress in the theoretical description of the universe?

The birth of space-time

In 1905, Einstein (1879-1955) publishes his theory of special relativity (building upon the work of Lorentz). This is based on two postulates:

- The laws of physics take the same form in all inertial frames (regardless of their velocity)
- The speed of light c is a universal constant, the same in any inertial frame
- The theory leads to the relativity of simultaneity and then to the concept of space-time (introduced by Minkowski)
- A metric tensor tells how to compute the distance between any two points (events)





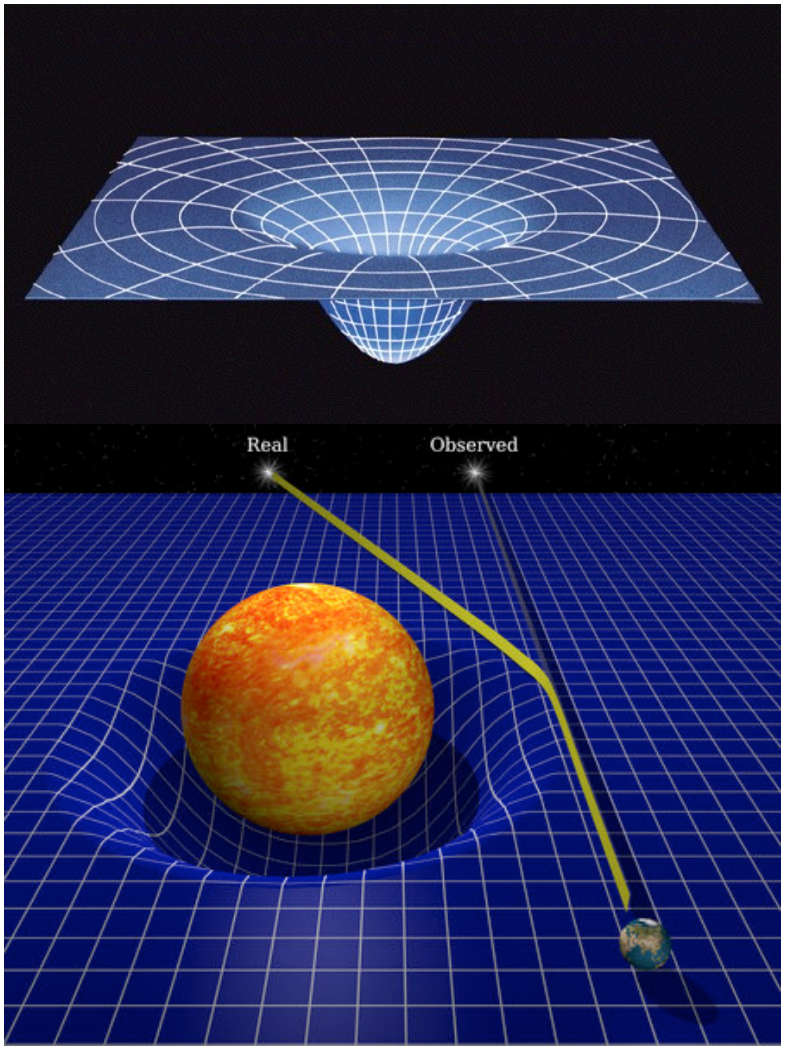
Telescopes are time machines

- Looking out in space is looking back in time due to the finite speed of light

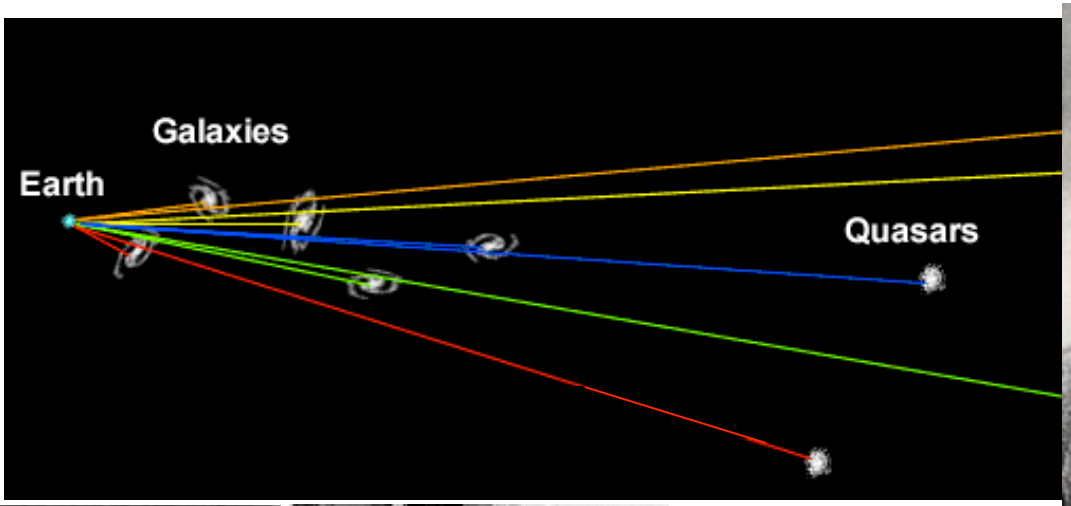
- Imagine you get a postcard from some friends. You know how they were then not how they are now!

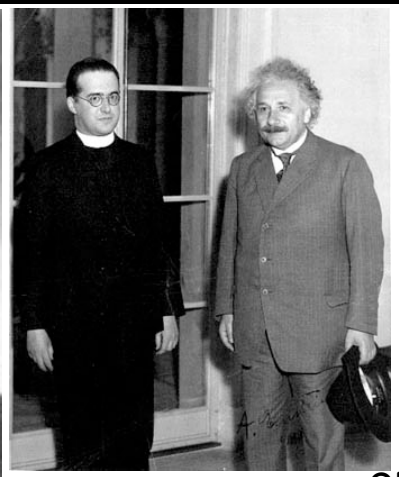
The Relativistic Universe

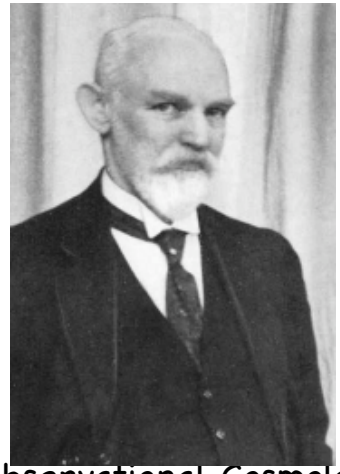
- In 1916 Einstein publishes the General Theory of Relativity and in 1917, Willem De Sitter (1872-1934) uses it to describe an expanding Universe
- General Relativity explains gravity as the curvature of space-time
- Energy tells space-time how to curve, space-time tells matter how to move
- No action at a distance, just GEOMETRY

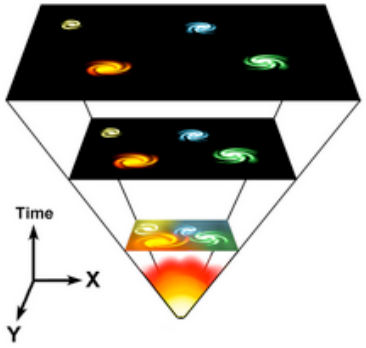


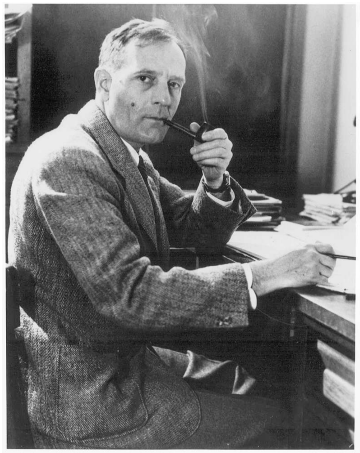
An observational surprise: cosmic expansion



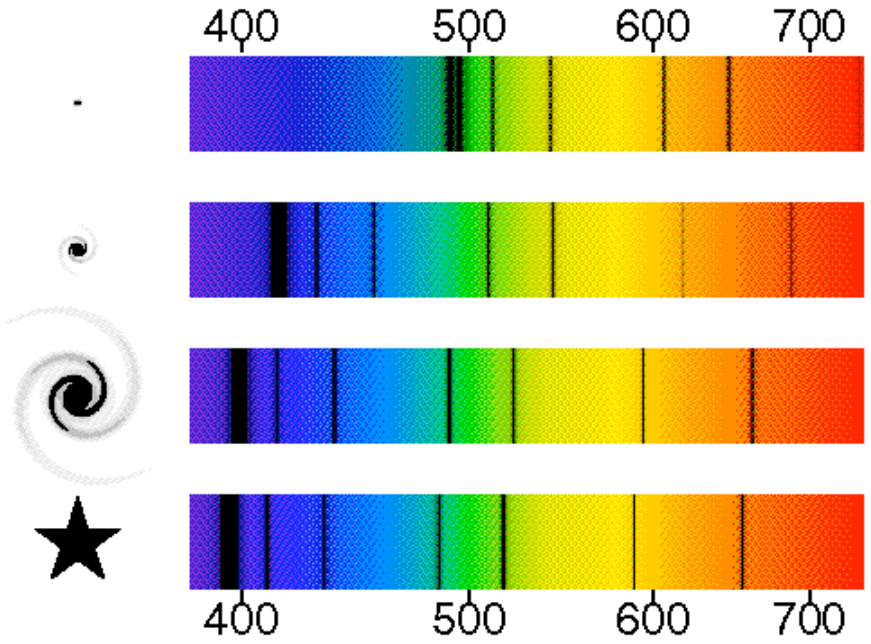








Most galaxies have redshifted spectra



Vesto Slipher
1912

The quest for the expansion

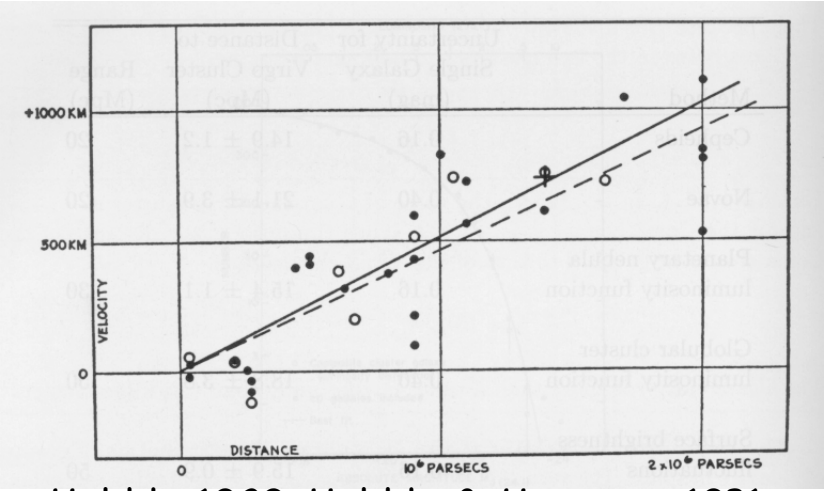
- 1912: Vesto Slipher discovers that most spiral nebulae have a redshifted spectrum
- From 1917, people starts using GR to describe the Universe. Einstein favours a static (but unstable) model
- 1917: Willem de Sitter finds that GR admits a cosmological metrical redshift in an empty universe
- 1922: Alex Friedmann finds that an expanding universe is a solution to GR field equations
- 1927: Georges Lemaitre independently derives the expanding solution and is told by Einstein "Vos calculs sont corrects, mais votre physique est abominable"

The quest for the expansion

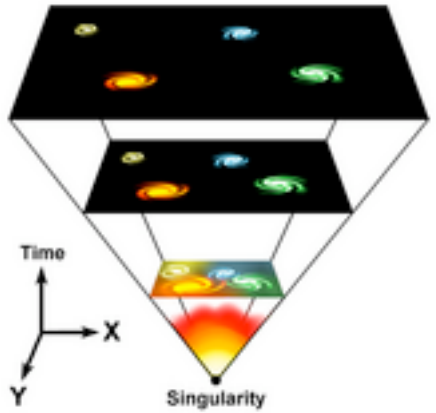
- 1929: Edwin Hubble (with Milton Humason) finds that there is a linear correlation between redshift and distance suggesting the reality of cosmic expansion

- This is one of the pillars of modern cosmology!

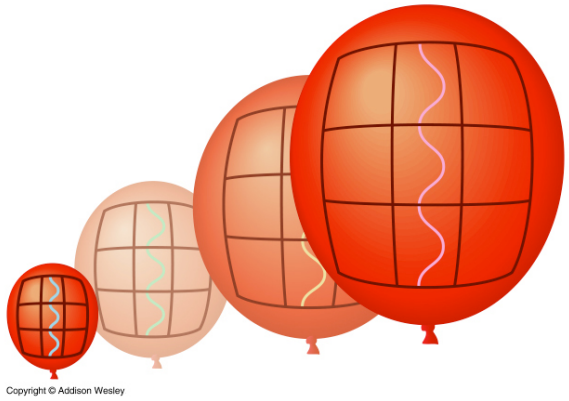
- 1935: Robertson & Walker show that the FLRW solution is the only one that can describe a homogenous and isotropic universe

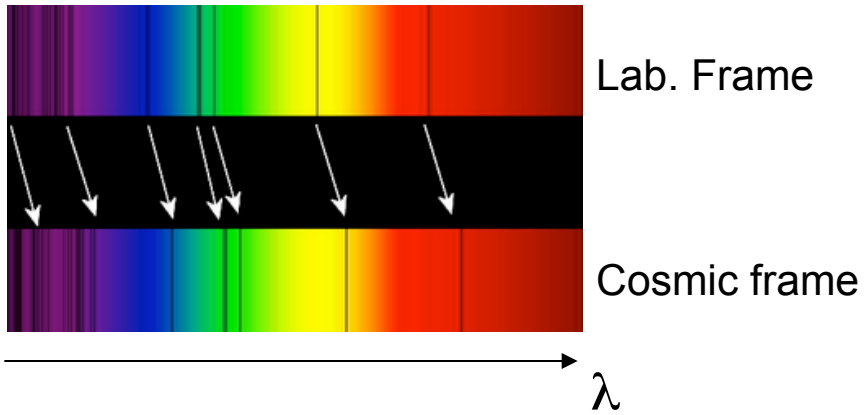


Hubble 1929, Hubble & Humason 1931



Cosmological redshift

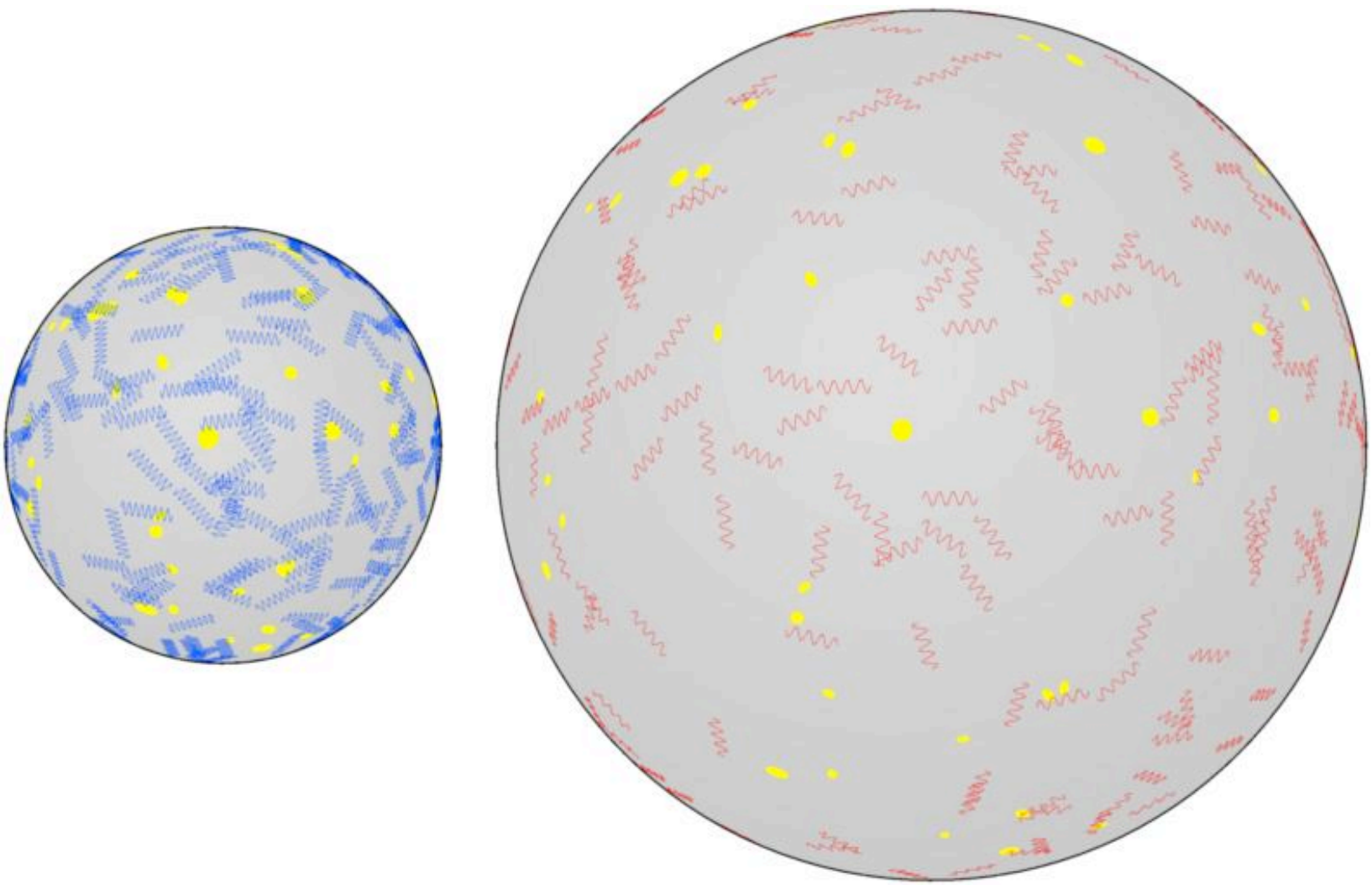




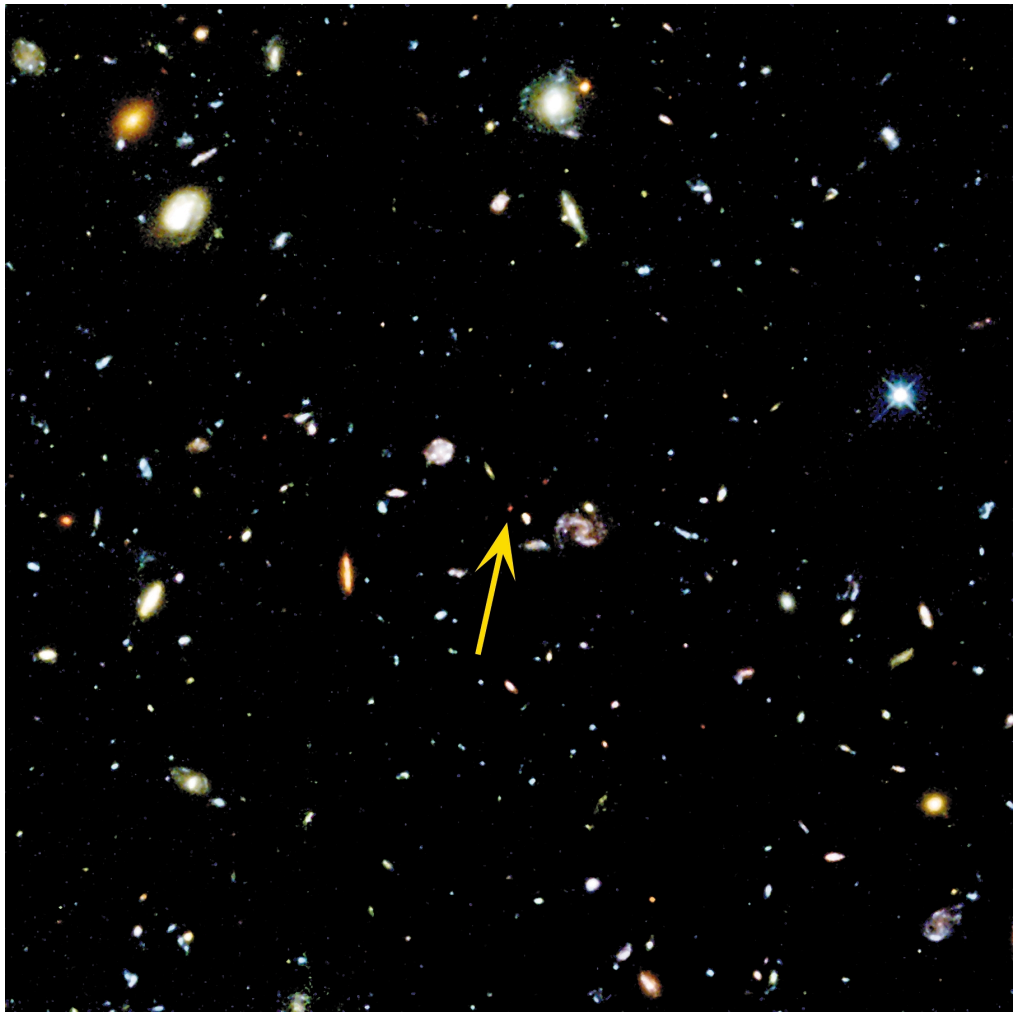
- Cosmological redshift: the wavelength of EM signals is stretched by the cosmic expansion.

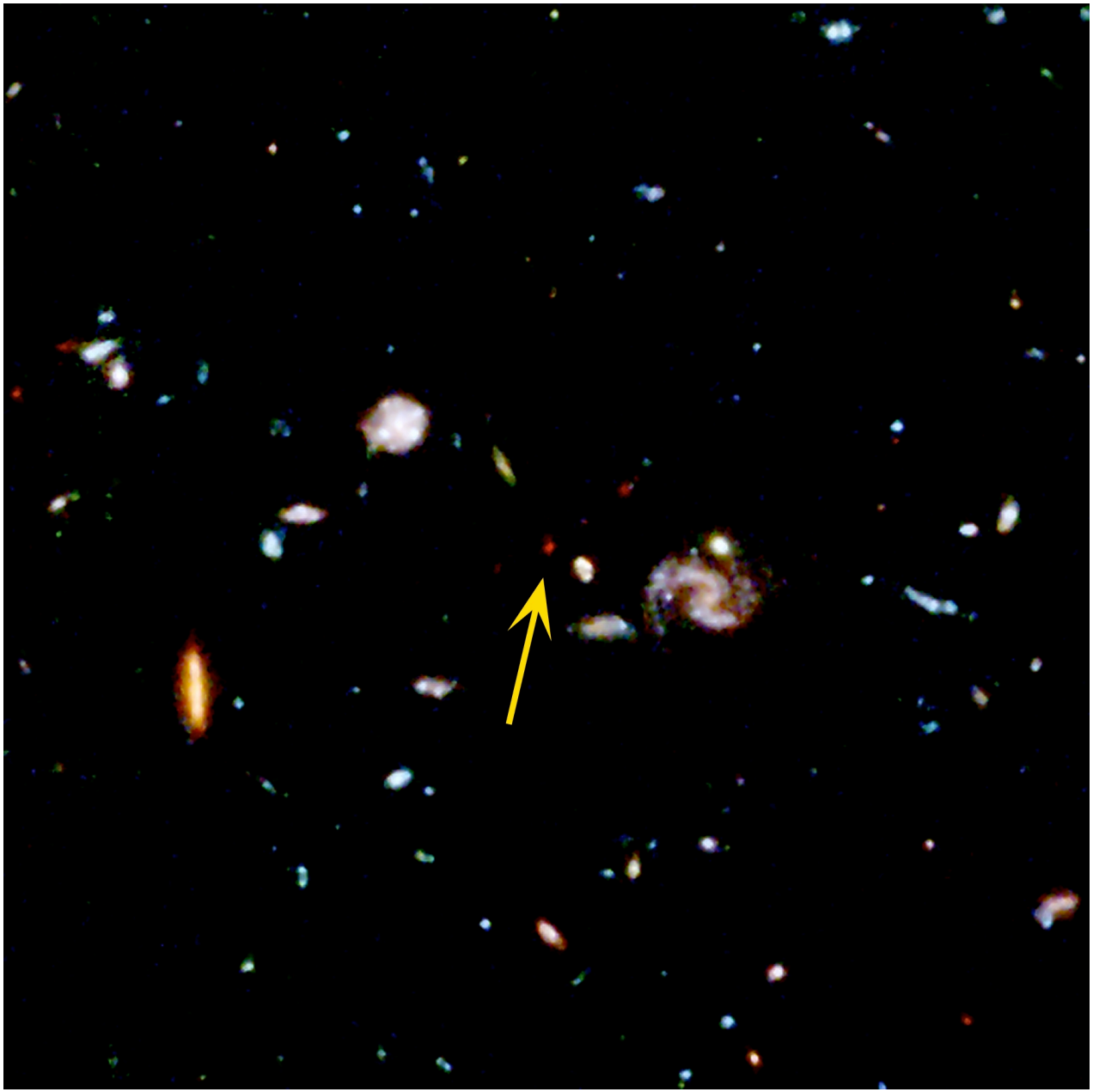
- Spectra are shifted in frequency towards the red by a factor
  1+z = (present-day size of the universe)/(size at photon emission)=$a(t_0)/a(t_{em})$

$$1 + z = \lambda_{obs} / \lambda_{em}$$

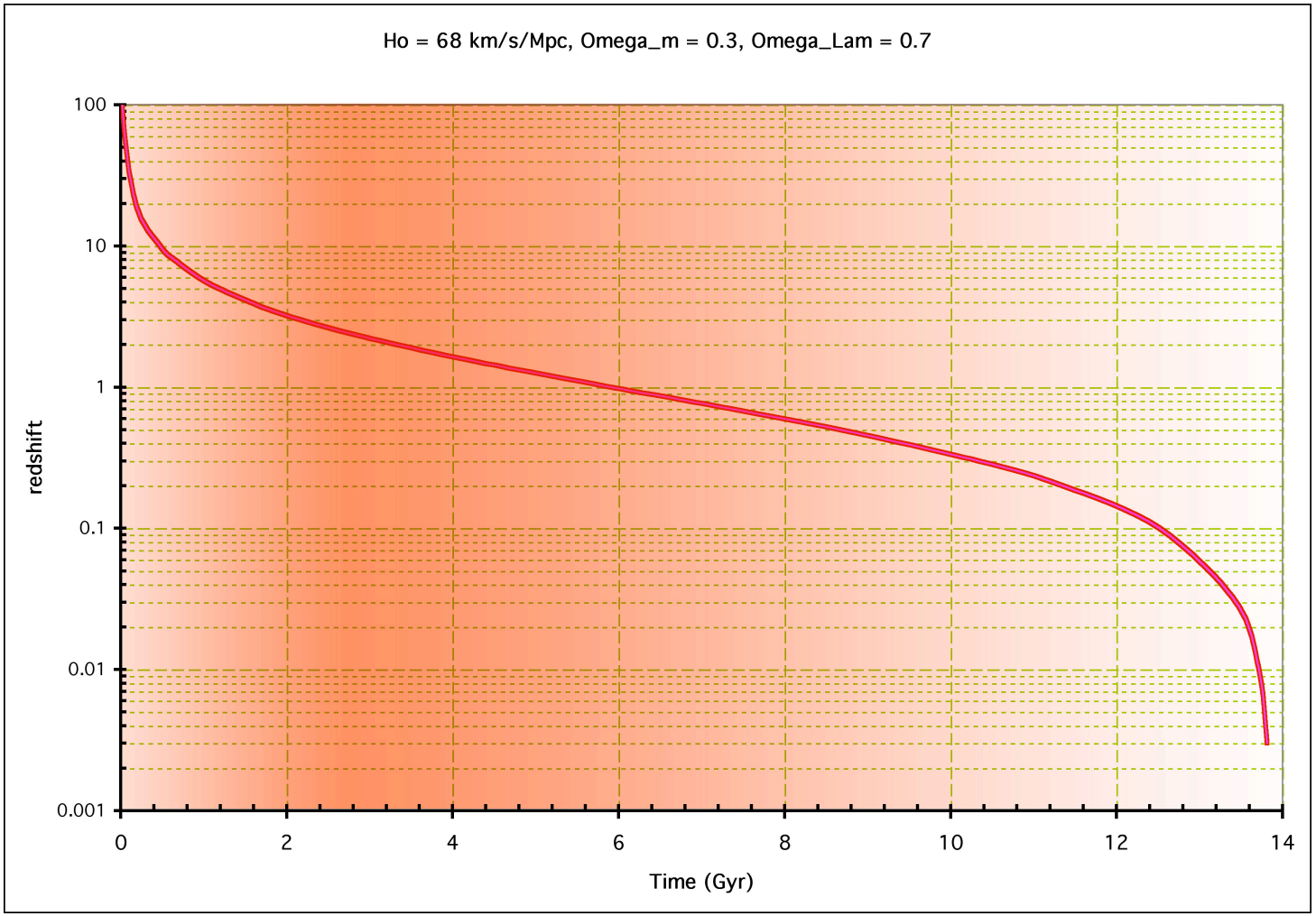


A galaxy at redshift 6





Redshift vs time



The universe is a huge, old and nearly empty place!

It is covenient to use specially suited units to describe its properties

Local universe

- Mass: solar mass, 1 $M_\odot = 1.989 \times 10^{30}$ kg
- Length: parsec, 1 pc $= 3.0856 \times 10^{16}$ m
- Luminosity (work): solar luminosity, 1 $L_\odot = 3.90 \times 10^{26}$ W

Distant universe

- Expansion rate: Hubble parameter, $H_o = 100\ h$ km/s/Mpc
- Time: Hubble time, $1/H_o = 9.778 \times 10^9\ h^{-1}$ yr
- Length: Hubble radius, $c/H_o = 2997.9\ h^{-1}$ Mpc
- Density: $\rho = 2.7755 \times 10^{11}\ \Omega h^2\ M_\odot\ \mathrm{Mpc}^{-3} =$
  $= 1.8791 \times 10^{-26}\ \Omega h^2$ kg m^{-3} $\approx 11\ \Omega h^2$ protons m^{-3}