Observational Cosmology

Lecture I

C. Porciani
AIfA Bonn

Summer Semester 2014

Lecturers

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Lectures: Wednesday 13:15-15:00

Office Hours: by appointment

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

Exercise classes

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

>50% of the problem sets is expected
(the better you do the more "bonus" for the final grade)

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: Mikolaj Borzyszkowski mikolajb@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

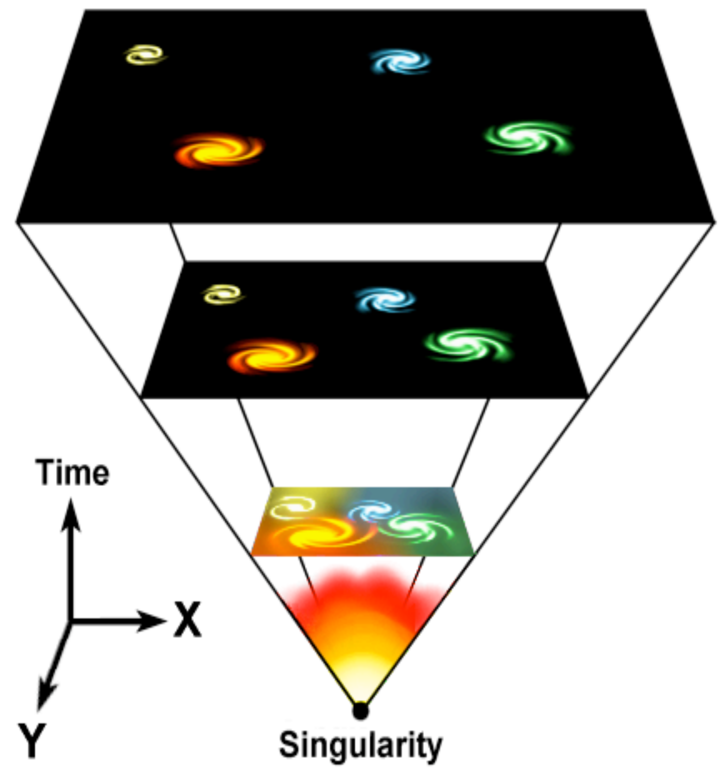
- Please write down your name, e-mail address, and semester (or Master, PhD, etc.)
- Hands up who took a basic cosmology class
- Hands up who is confident knowing the FRW metric
- Hands up who knows Friedmann equations and what is the critical density of the universe
- Hands up who knows what dark energy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

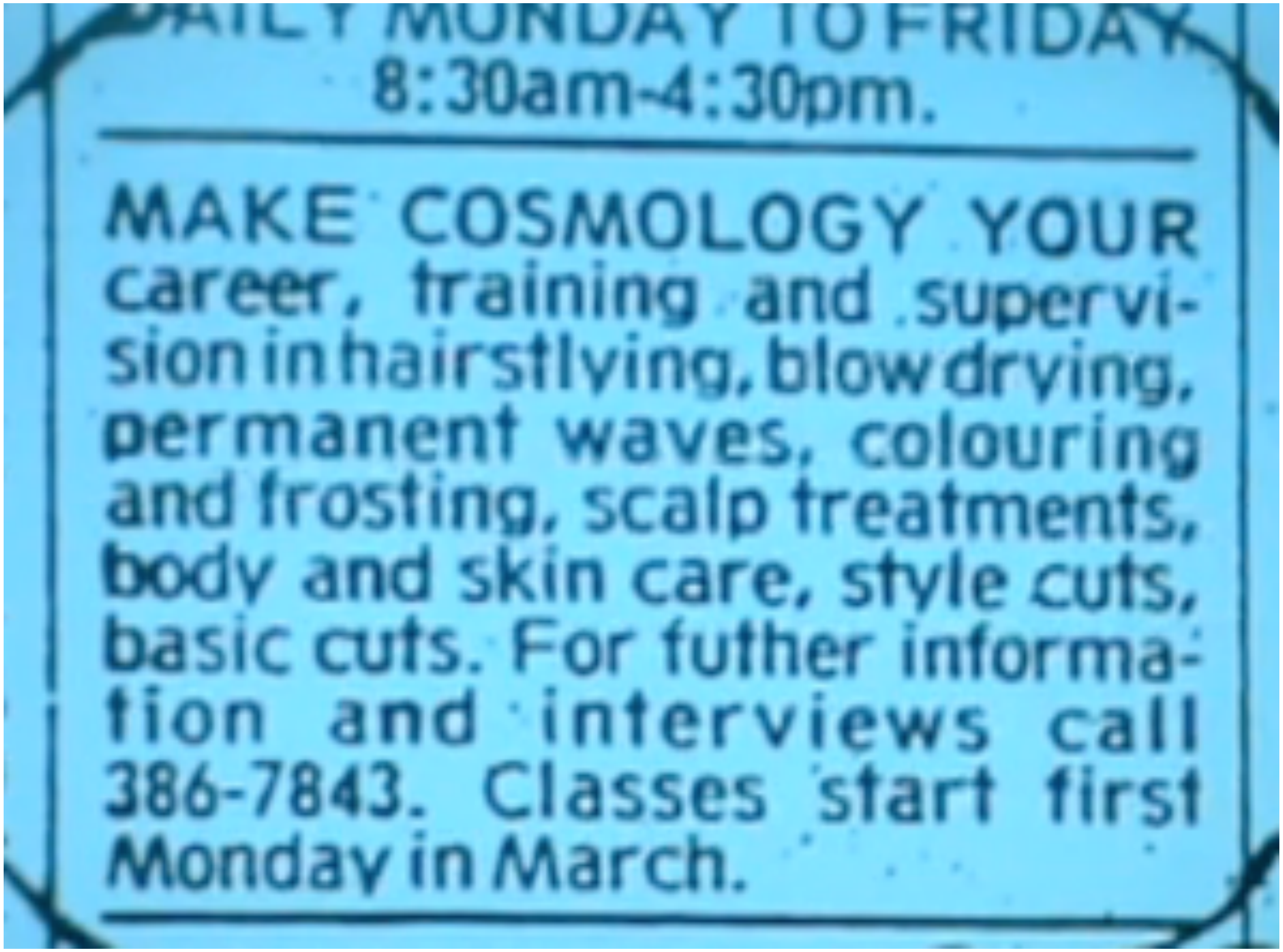
WHAT IS THIS COURSE ABOUT?

Cosmology

- Etymology:
  Κ ο σ μ ο σ "the physical world" + λ ο γ ι α "discourse"

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





DAILY MONDAY TO FRIDAY
8:30am-4:30pm.

MAKE COSMOLOGY YOUR career, training and supervision in hairstlying, blowdrying, permanent waves, colouring and frosting, scalp treatments, body and skin care, style cuts, basic cuts. For futher information and interviews call 386-7843. Classes start first Monday in March.

Cosmology + ET = Cosmetology
Still derives from κ ο σ μ ο σ intended as "order" (from the verb kosmein=to adorn)

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

"The future needs heritage" (Odo Marquard)
"There is no future without tradition" (Wang Shu)

- The birth of modern cosmology

  The human mind and the Universe
  (historical - epistemological approach)

- Observational facts and definitions

Zukunft braucht Herkunft

"... the new world cannot exist without the old skills. Humanity is lame without modernity, modernity without humanity is cold: modernity needs humanity, because the future needs our heritage."

Odo Marquard

Amateur Architectural Studio
(2012 Pritzker prize)

The ancient universe

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

The only instrument available

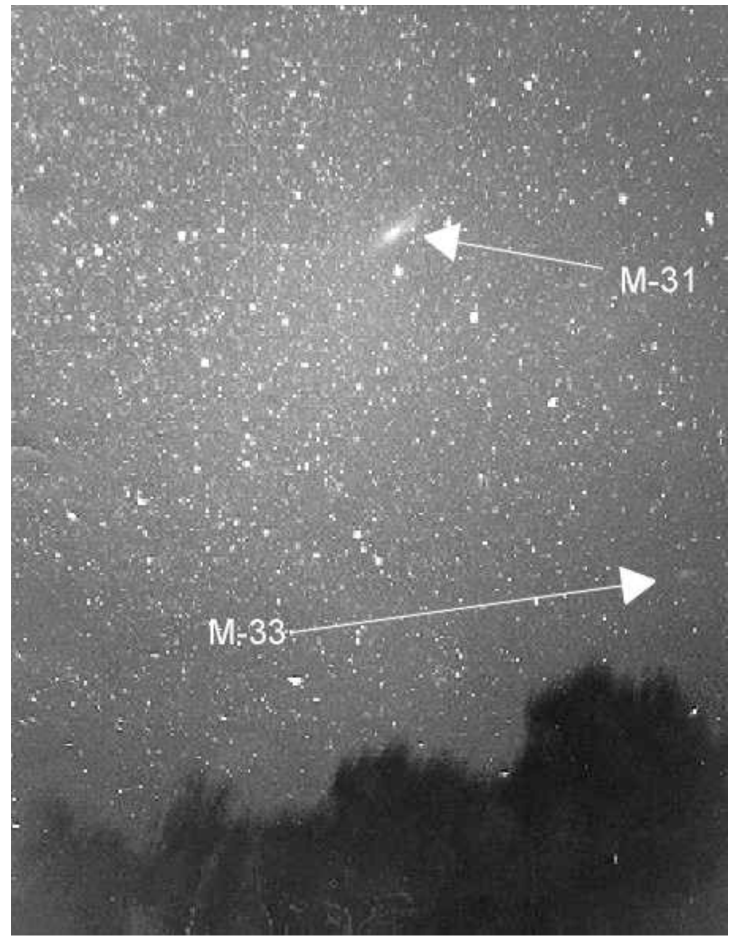
Xinhua/ Xu Suhui Photo

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

The modern version

The universe with naked eyes

Photo: Kerry-Ann Lecky Hepburn



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

The birth of astronomy

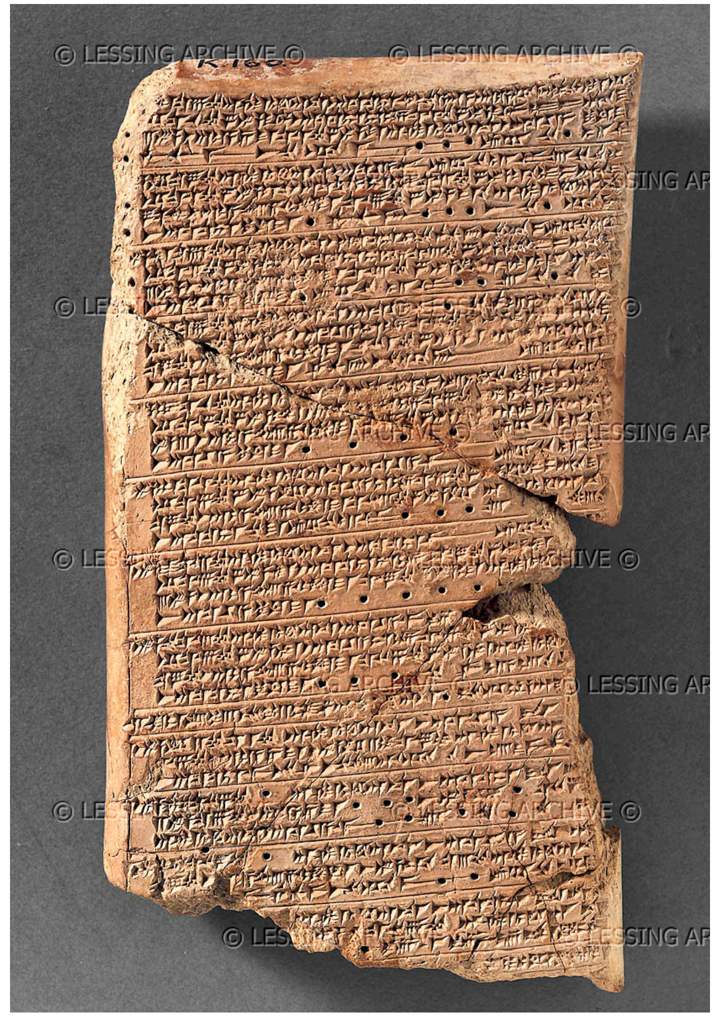
- Early astronomy was about repeating phenomena and the measure of time (calendar, seasons)
- As far as we know, there was no explanatory attempt, the idea was to describe regularities. The study of sky phenomena was useful to sailors and for agriculture (e.g. to predict the annual flooding of the Nile in ancient Egypt where a 365 days calendar was already in use during the 3° millennium BCE)
- 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. Only fragments have survived (mainly with ephemerides which were recorded already since several centuries in India).
- Subsequent developments in the Hellenistic, Indian and Islamic worlds and in the West (if not all science) are based upon Babylonian astronomy (Aaboe 1974)

An example

Neo-Assyrian cuneiform tablet from the library of Nineveh (now Northern Iraq).

This is a copy made in the 7th century BCE of an original list of observations of Venus made 1000 years before, during the reign of Ammissaduqa, king of Babylon (now central Iraq).

British Museum, London

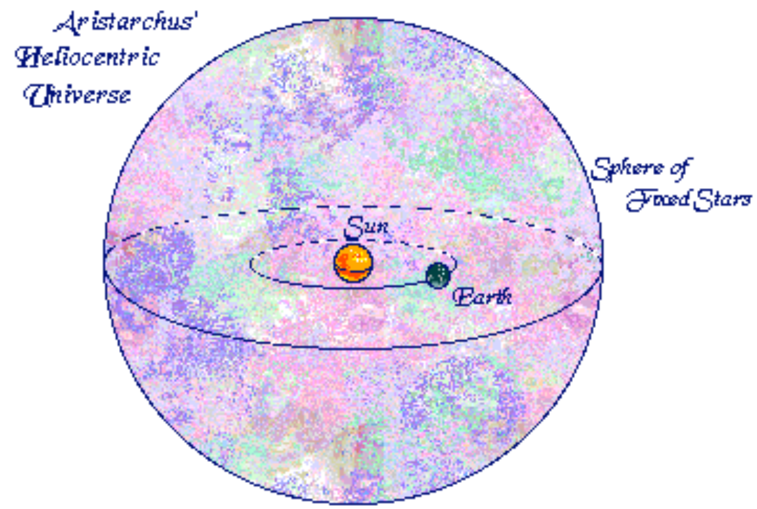


The Aristotelic universe

- 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 transparent aether (quintessence) with the planet Earth (made of Fire, Air, Water and Earth) at the center
- The ``Primum Mobile'' imparts motion to the spheres
- Distinction between the supra-lunar (perfect and unchanging) and sub-lunar worlds (filled with death, change and decay)

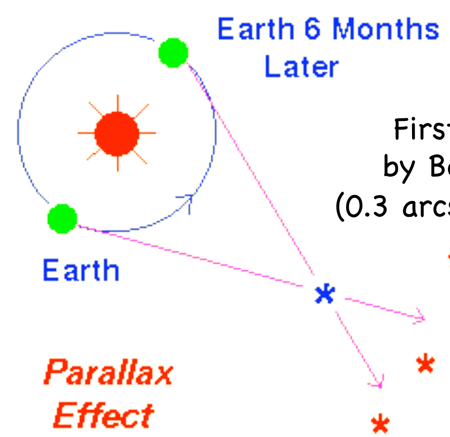
The first heliocentric system

- 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

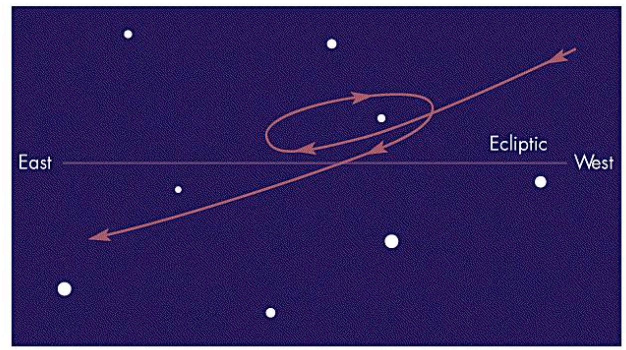
- No parallax was detected and the heliocentric model was quickly forgotten (importance of observations!)

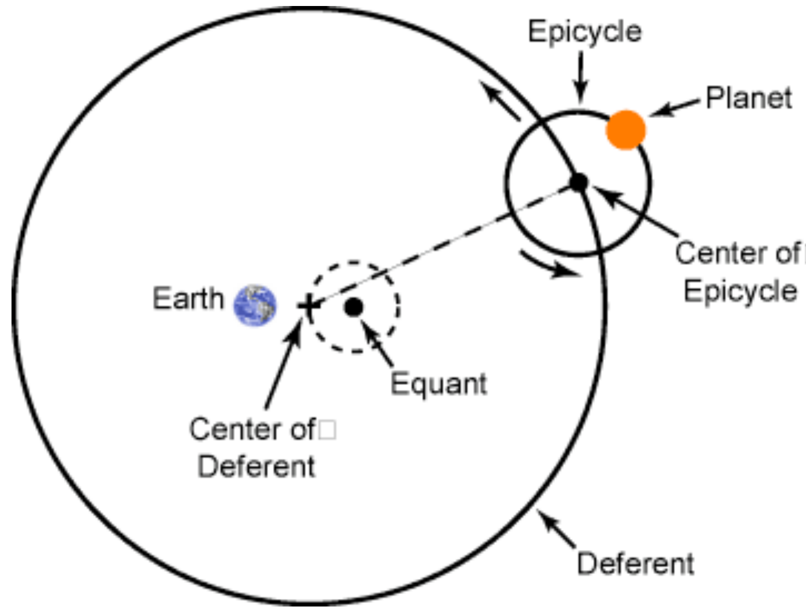


First measured by Bessel in 1838 (0.3 arcsec for 61 Cygni)

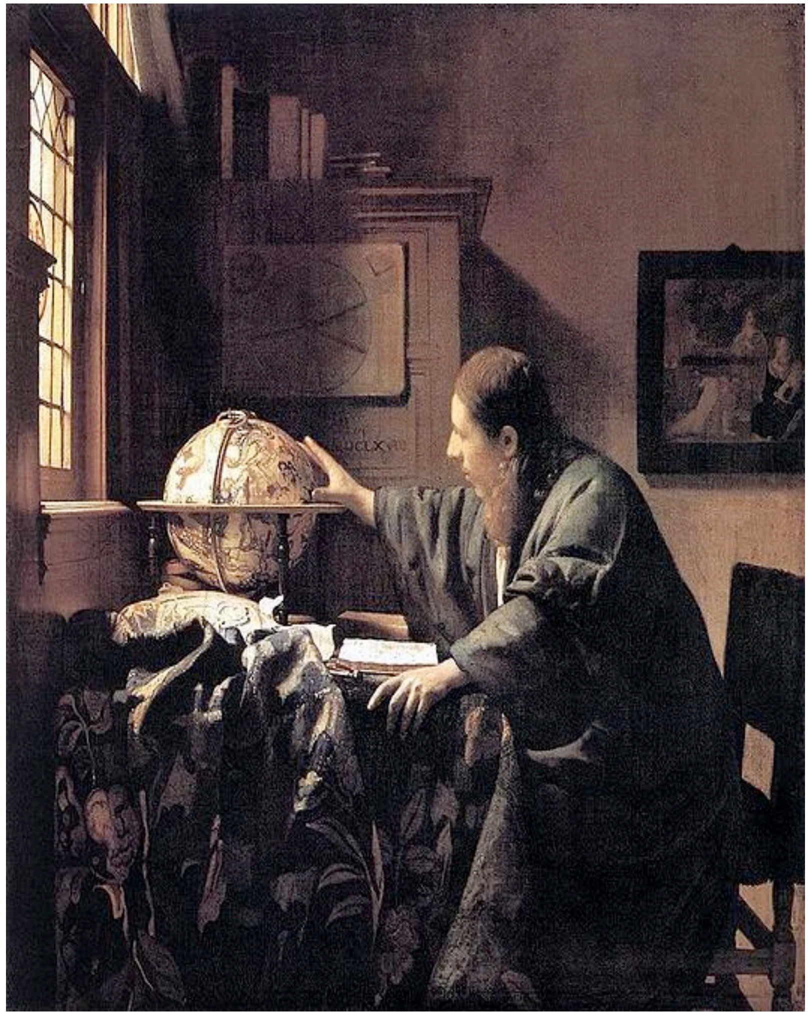
The Ptolemaic Universe

- 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, author of the Almagest, a treatise on astronomy) "improved" it to accommodate them
- Ptolemy's conception of a geocentric, finite and ethernal Universe lasted for almost 2000 years!

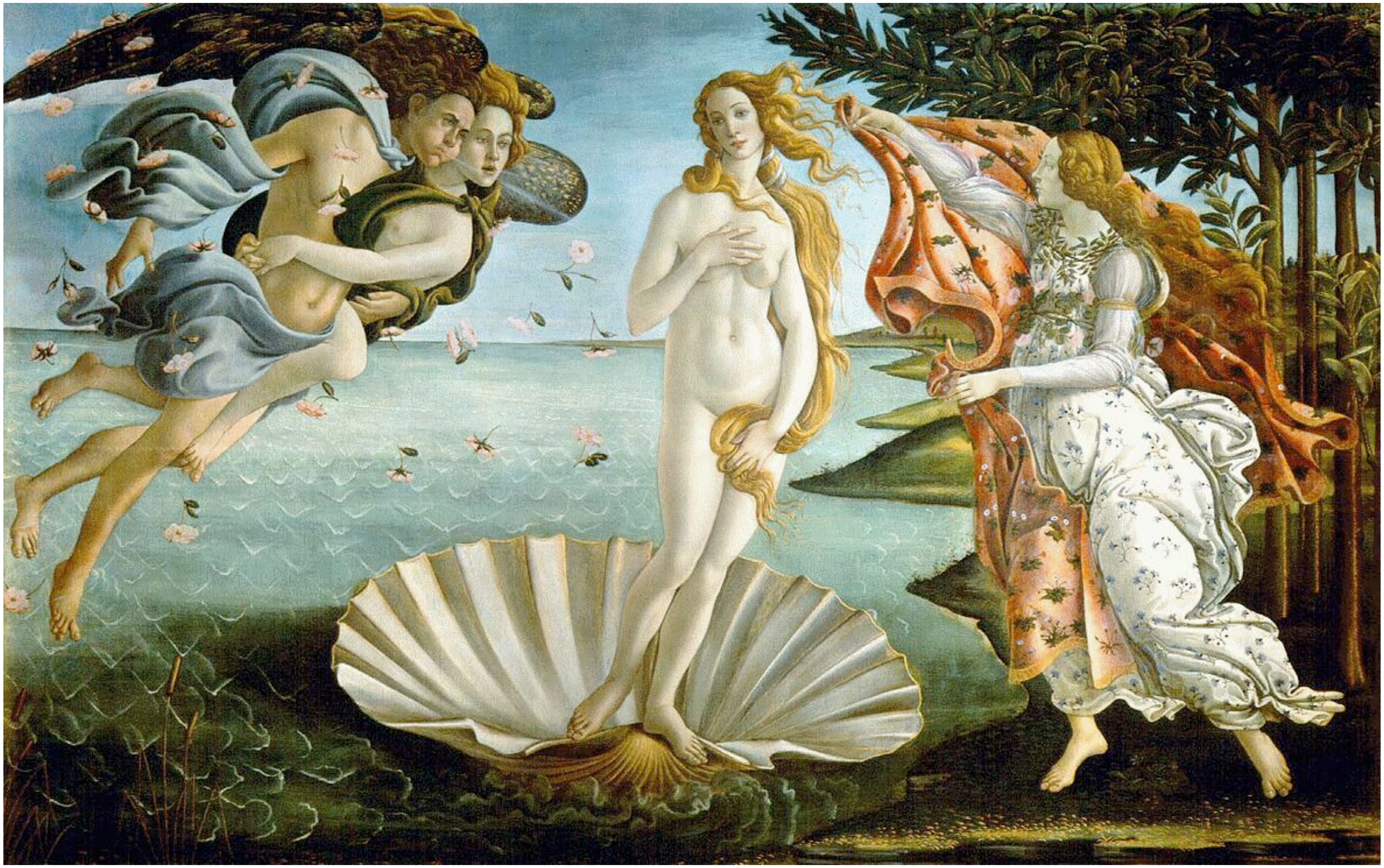




The classic universe



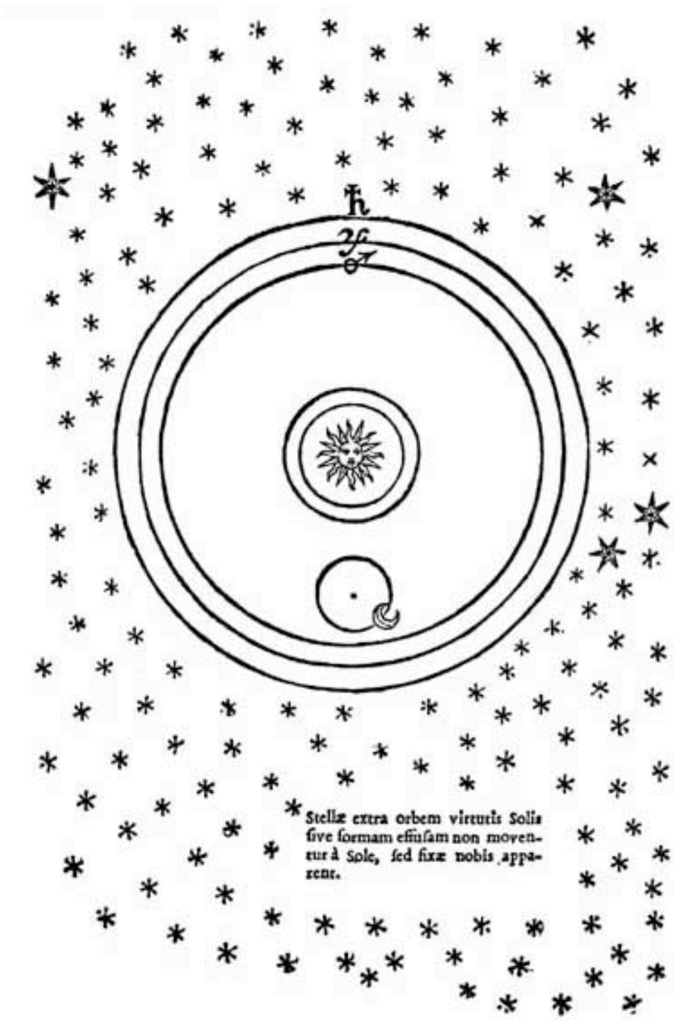
Johannes Vermeer, 1668 (Musée du Louvre, Paris)

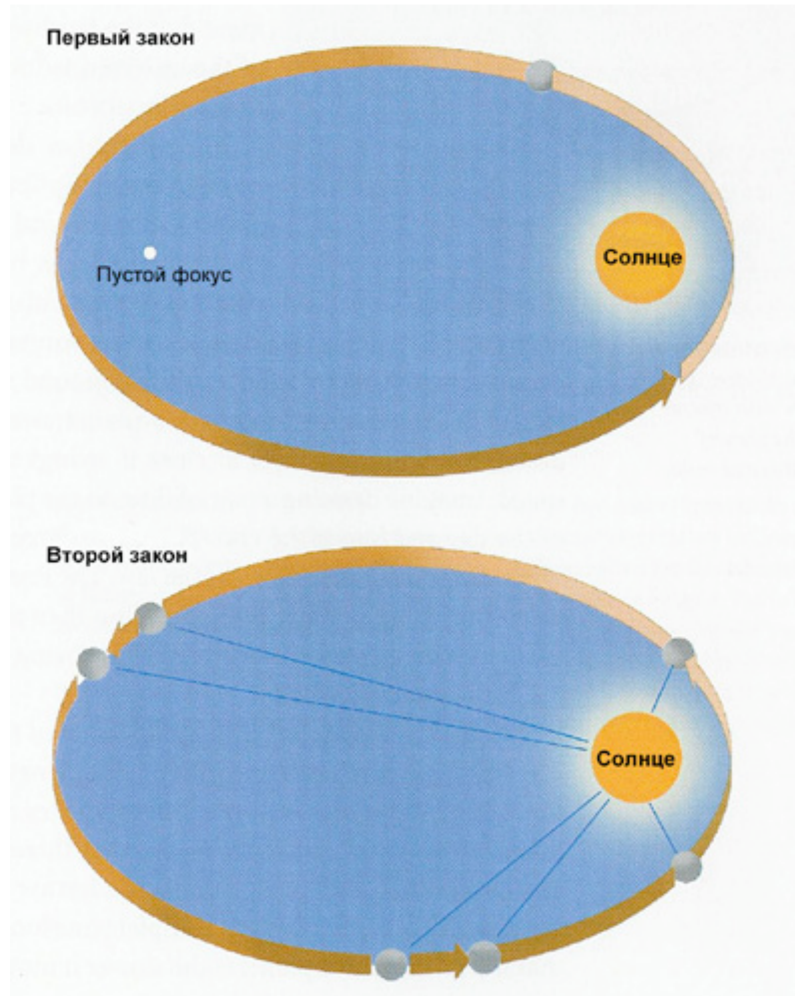


Sandro Botticelli, 1483-1485 (Galleria degli Uffizi, Firenze)

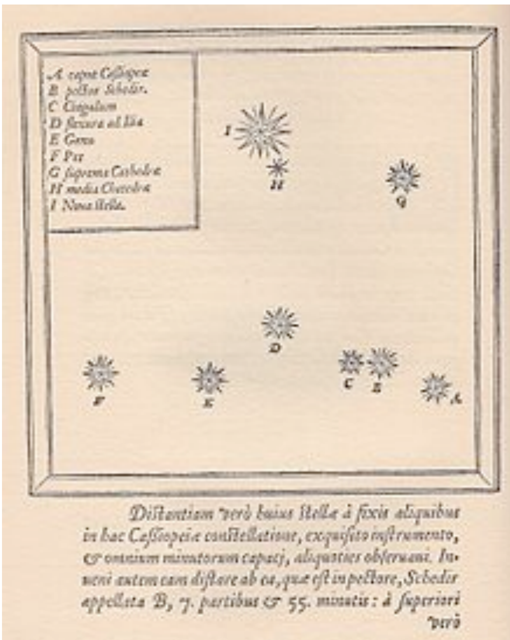
Copernicus, Tycho Brahe & Kepler

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



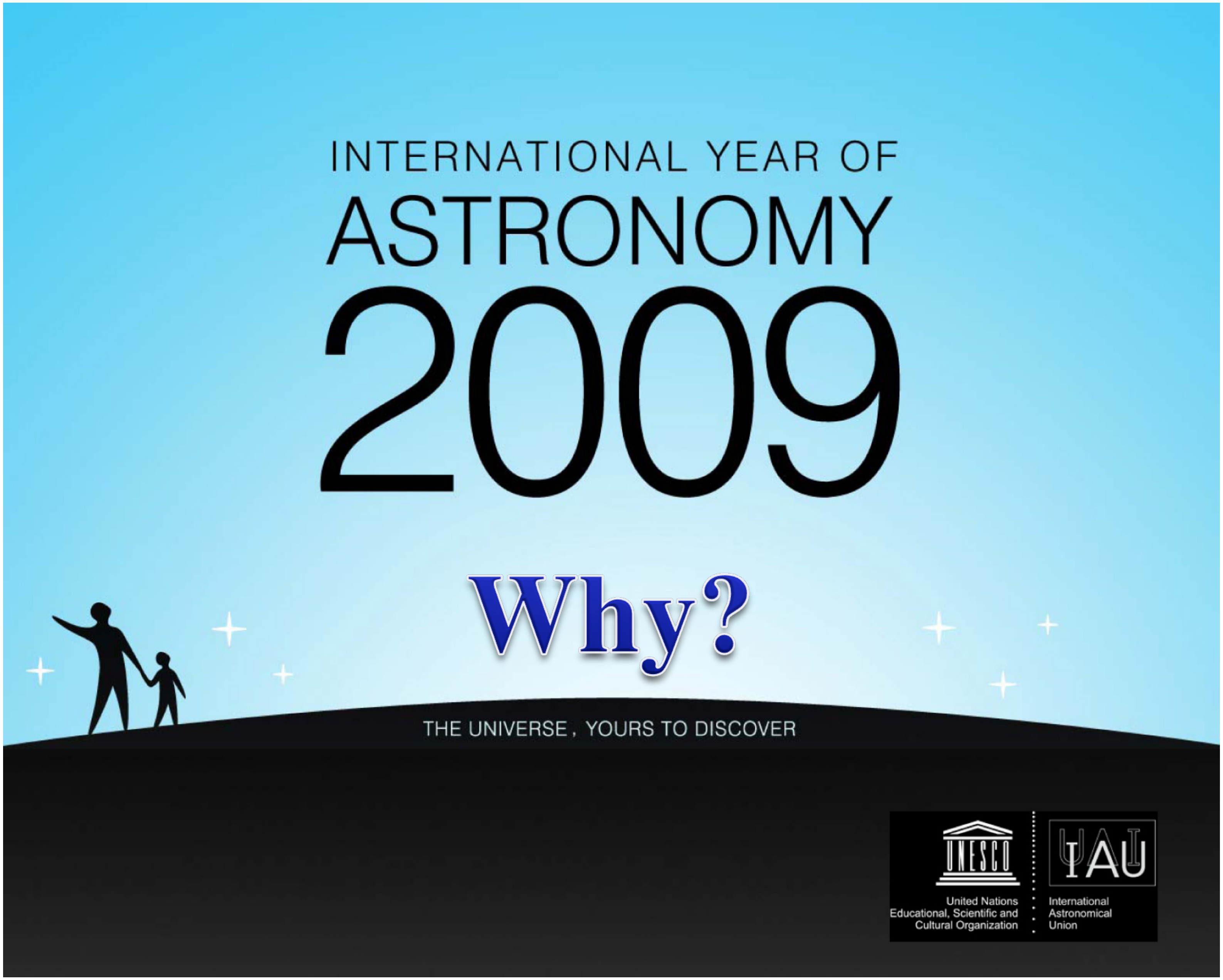


The celestial realm is mutable



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 (De nova stella, 1573)

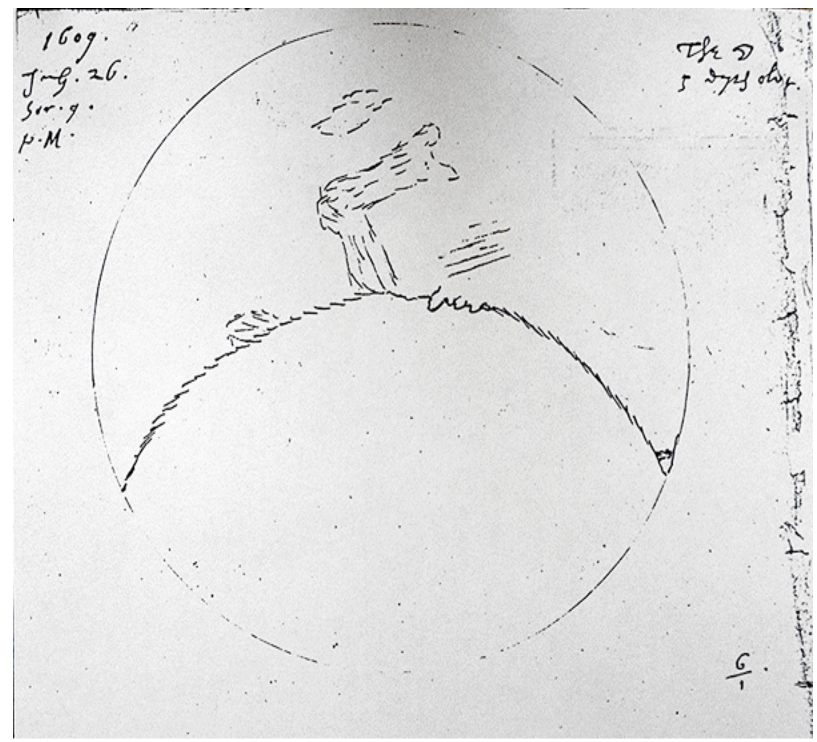

INTERNATIONAL YEAR OF
ASTRONOMY
2009
Why?
THE UNIVERSE, YOURS TO DISCOVER
UNESCO
United Nations
Educational, Scientific and
Cultural Organization
IAU
International
Astronomical
Union

Galileo Galilei (1564-1642)

a troublemaker

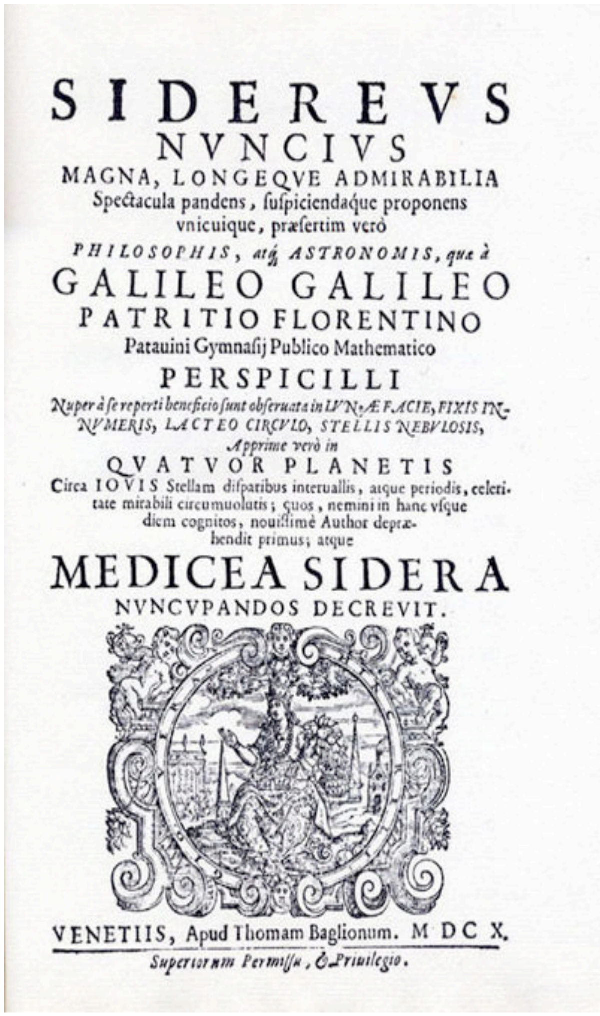
Galileo made a splash

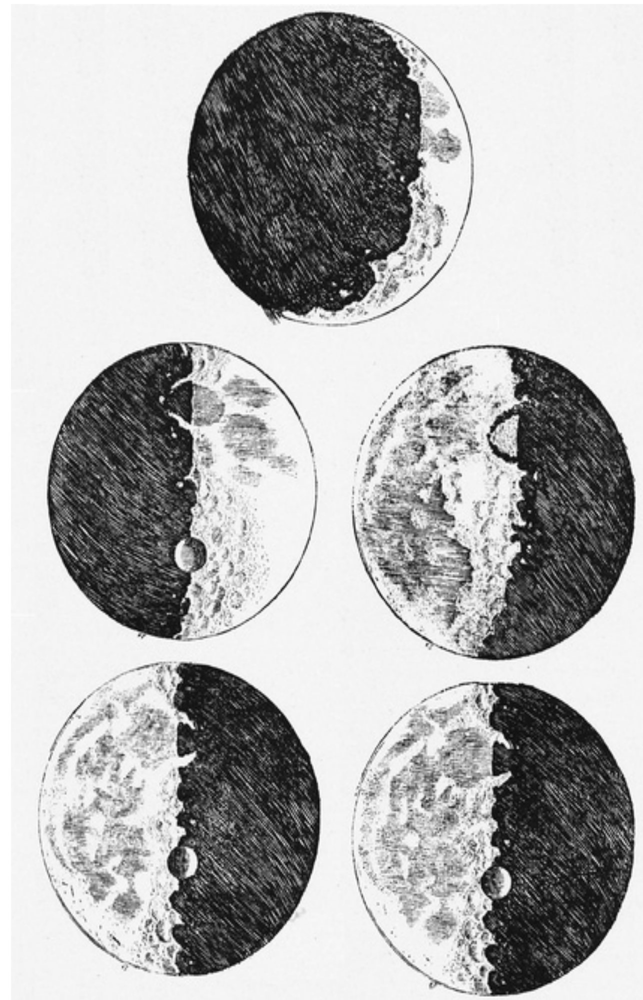
Hans Lippershey (1570-1619)
Jacob Metius (1571-1624/31)
Zacharias Janssen (1585?-1632?)



Thomas Harriot (1560-1621)

Sidereus Nuncius

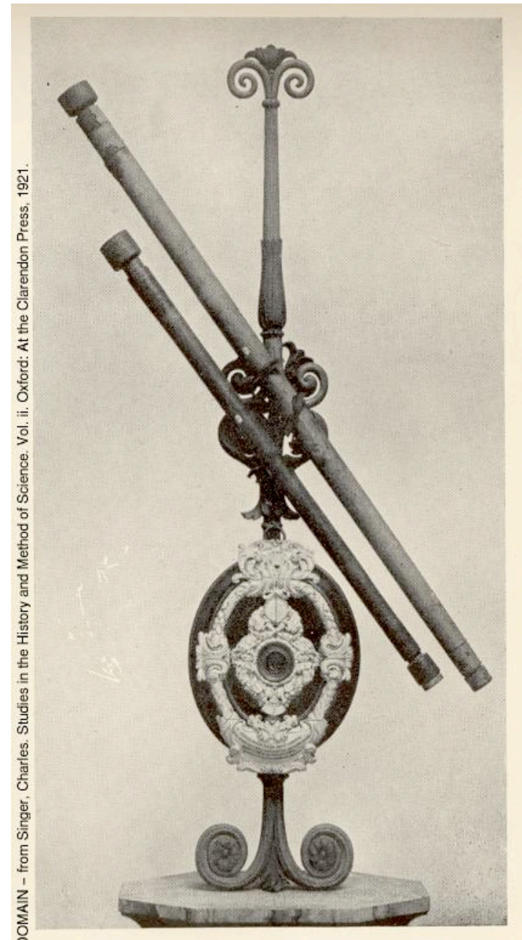

SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.



Galileo Galilei

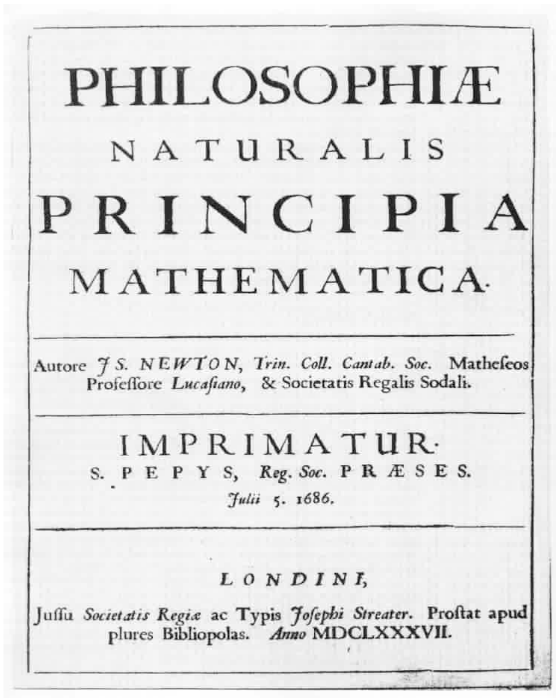
The Ptolemaic model is definitively disproved:

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



Galileo's Telescopes
The cracked lens is mounted in centre

Isaac Newton (1642-1727)



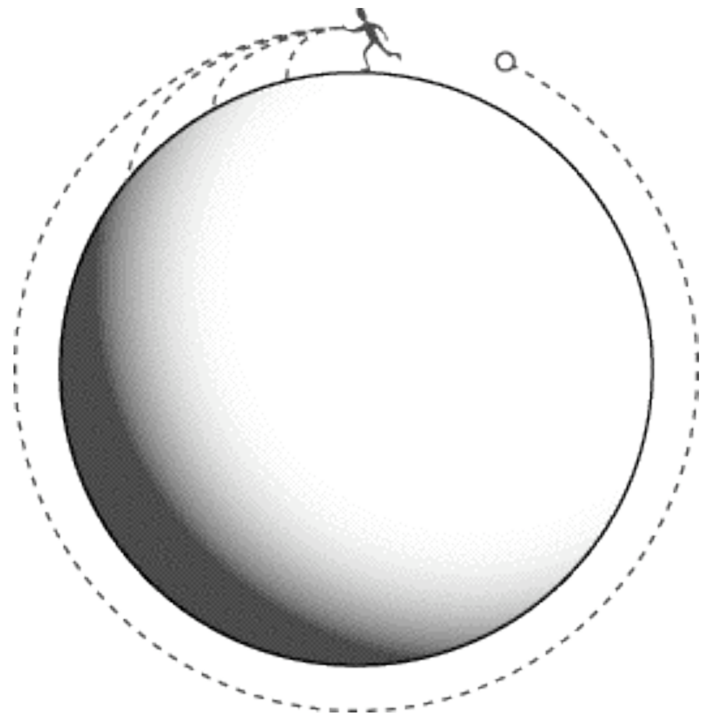
PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

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.



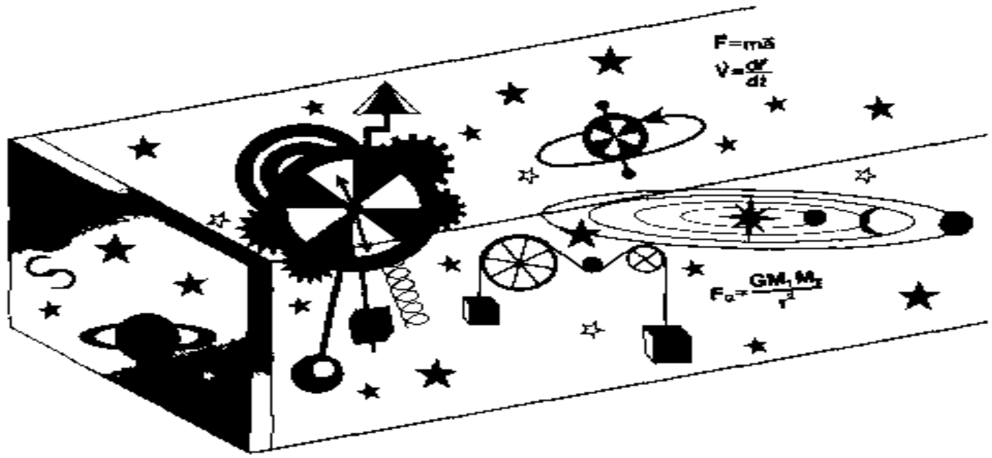
Authentic revolution:

New Mechanics + Law of Universal Gravitation

Perfect agreement with observational data

Celestial mechanics is a solved problem!

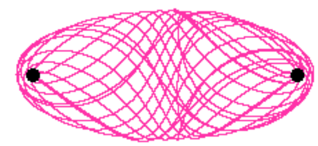
The clockwork Universe



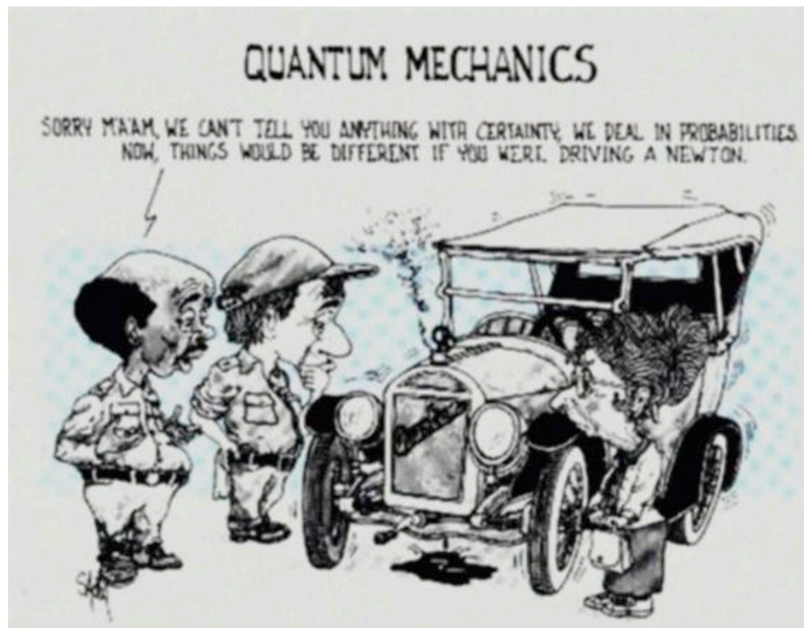
- Newton's Cosmology admits the existence of absolute time and absolute space (they exist also where there is no matter and they will always do)
- The Universe of Newtonian physics is perfectly deterministic
- In principle, we can predict the entire future of the Universe from a knowledge of the initial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

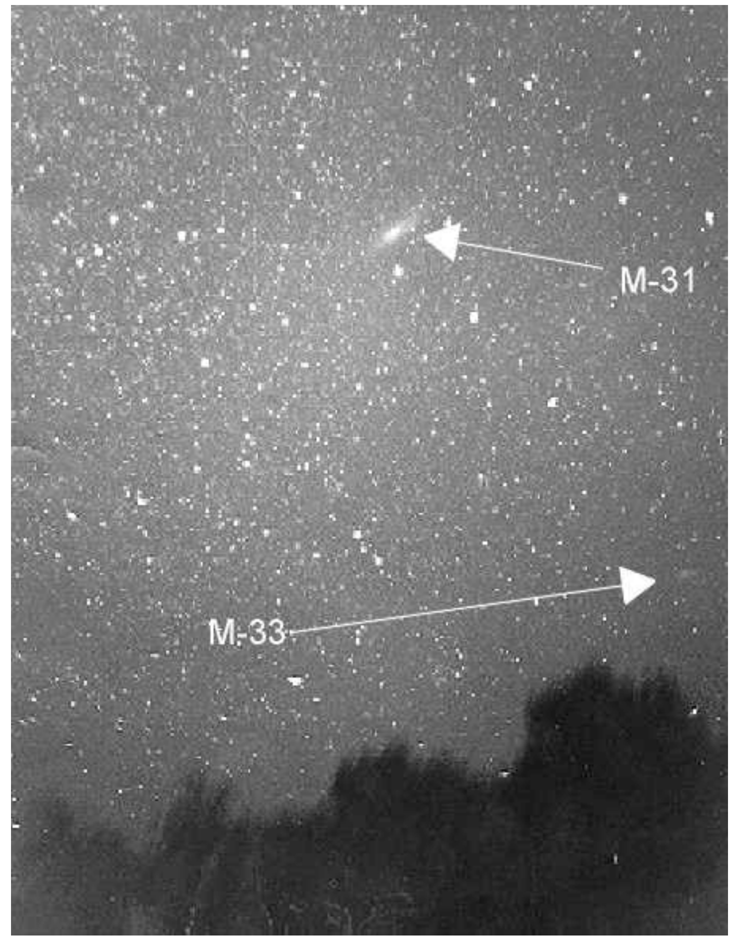


The modern universe

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

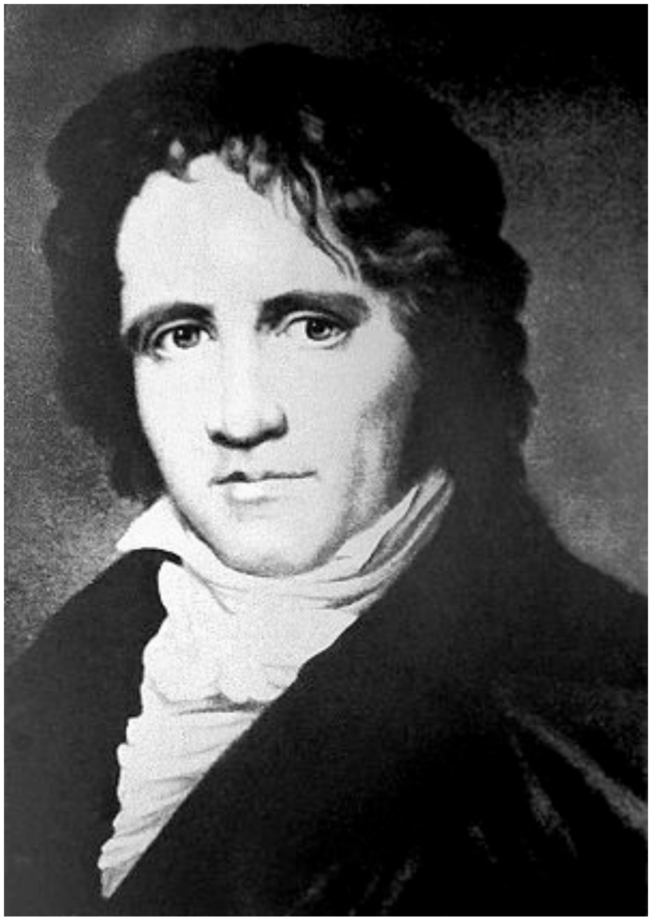
The universe with naked eyes

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”

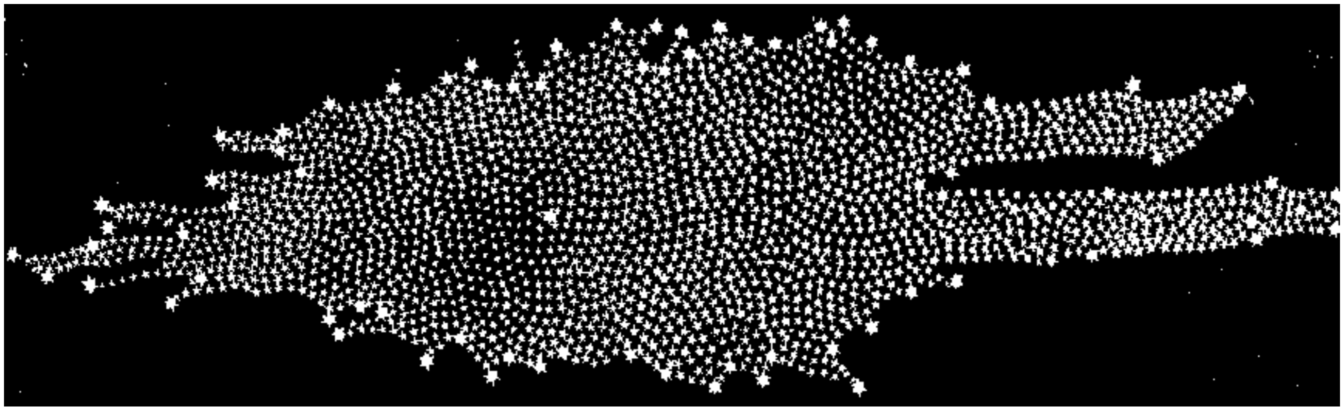
Galileo resolved the Milky Way (MW) into faint stars

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

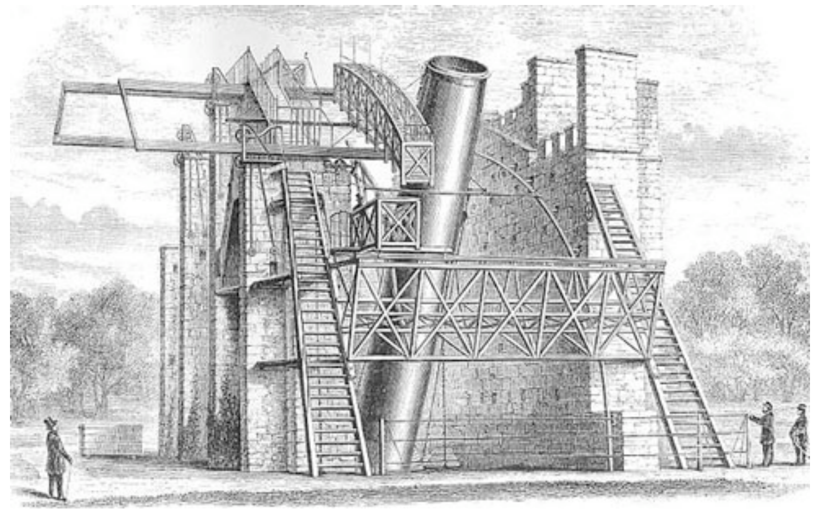
The Milky Way



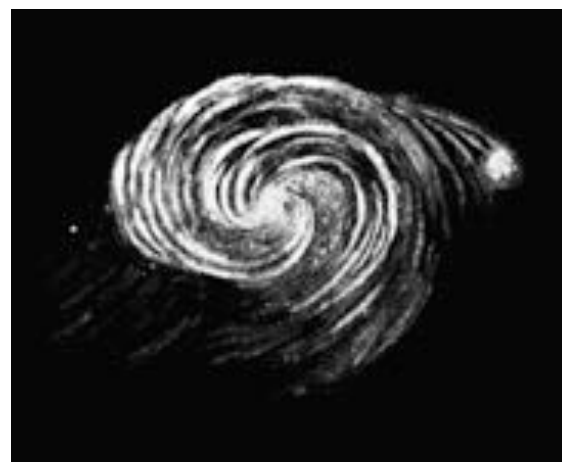
A sketch by Herschel based on star counts (1785)

- 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

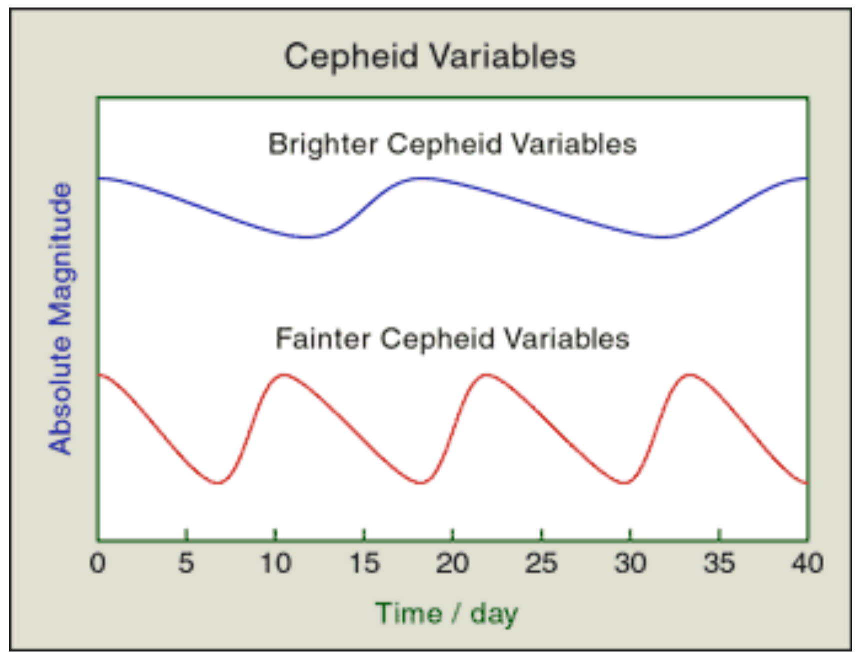
Heber D. Curtis (but Sun in the centre)

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"

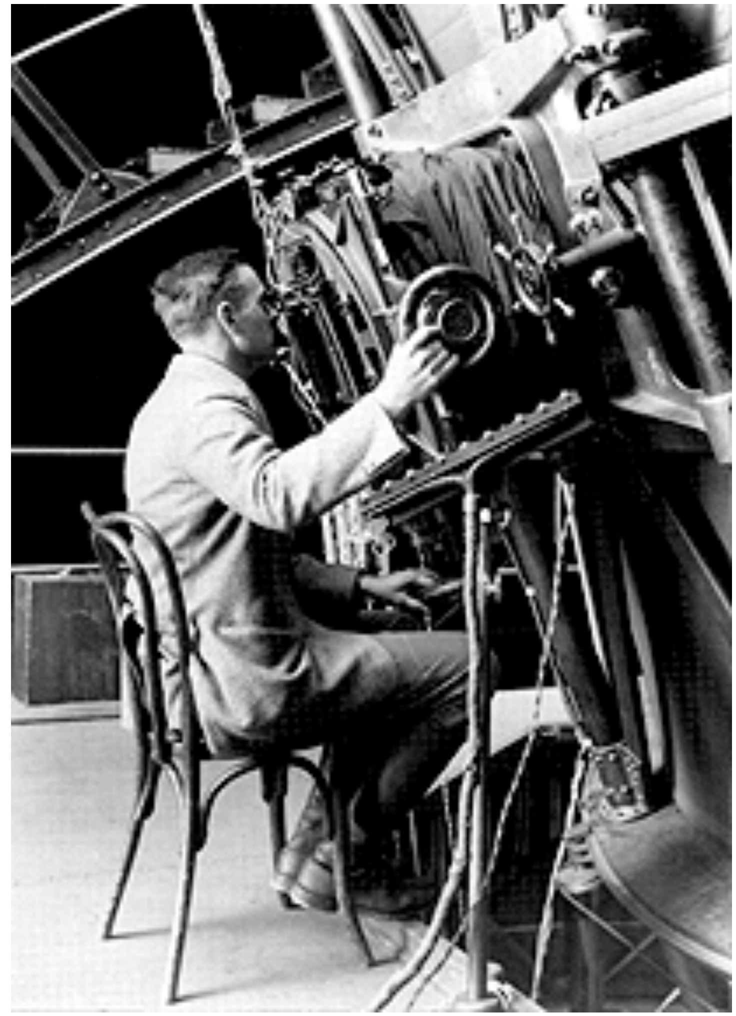


In 1924 the Universe grows bigger

- 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

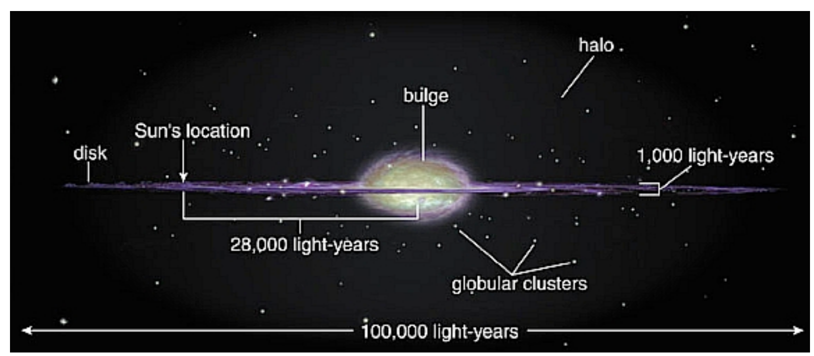
- This clearly made M31 a "galaxy" on its own right



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

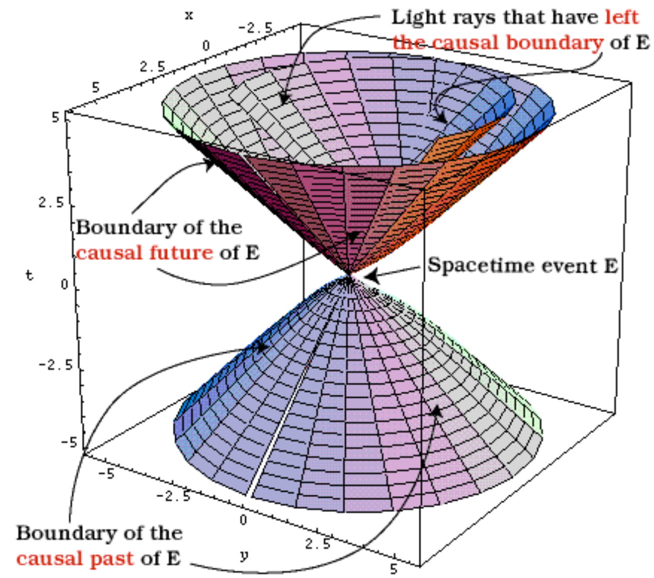
M33
The Triangulum Galaxy
3 million light years away

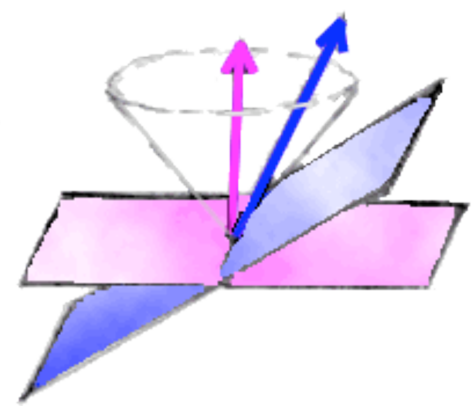
What about progress in the theoretical description of the universe?

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)



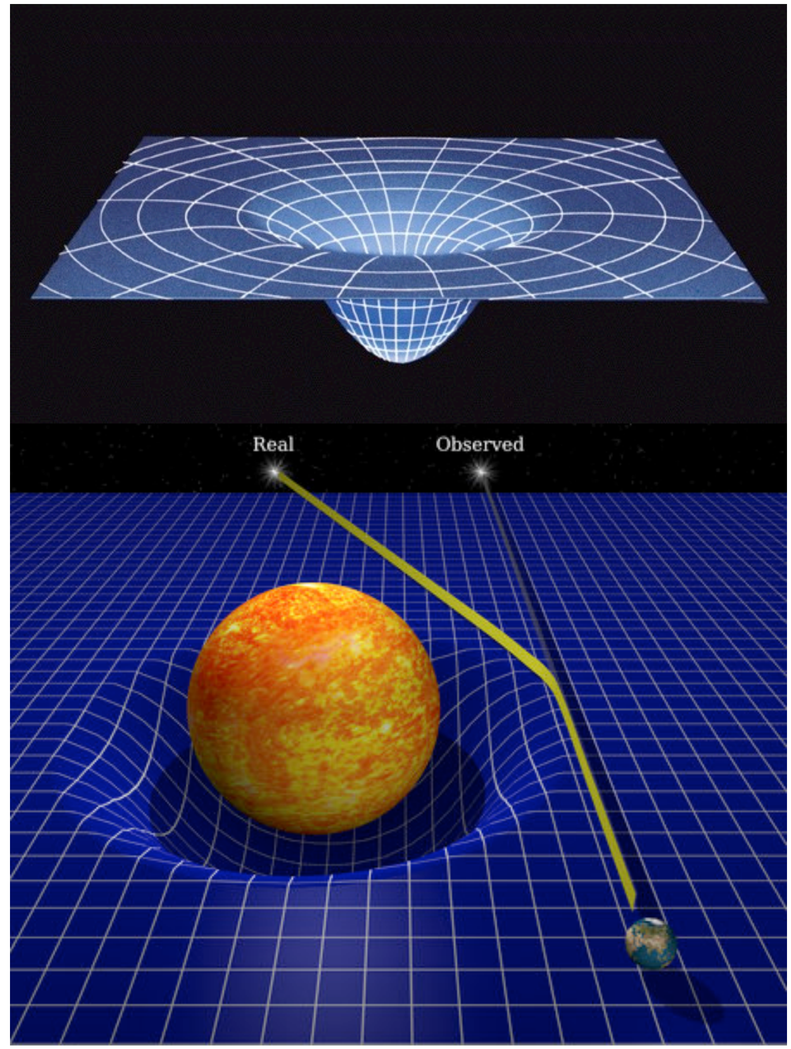


Telescopes are time machines

- 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!

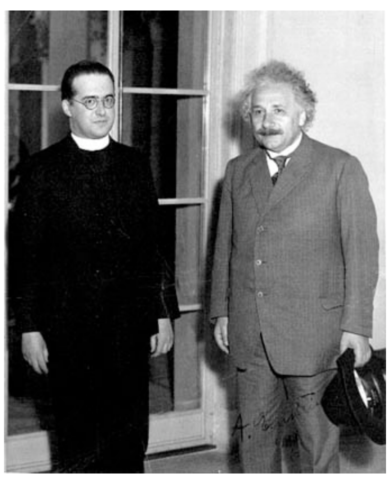
The Relativistic Universe

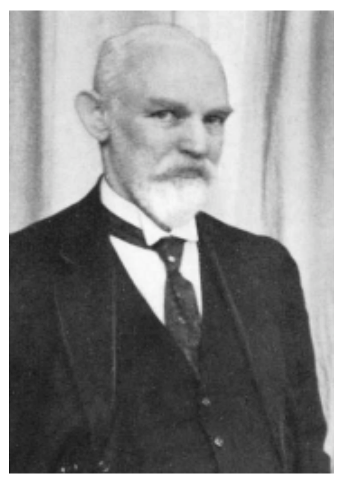
- In 1916 Einstein publishes the General Theory of Relativity and in 1917, Willem De Sitter (1872-1934) uses it to describe an expanding Universe
- General Relativity explains gravity as the curvature of space-time
- Energy tells space-time how to curve, space-time tells matter how to move
- No action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

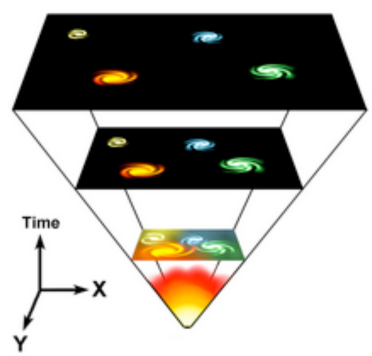


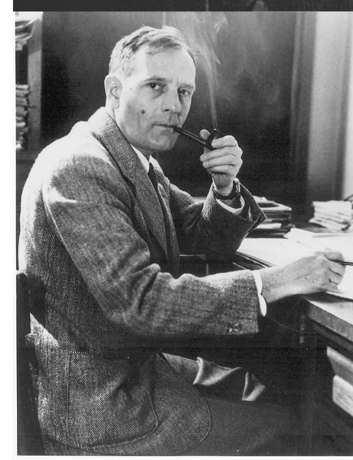
Cosmic expansion: the main contributors

The observational evidence for cosmic expansion is the first pillar on which our standard model of cosmology is based.

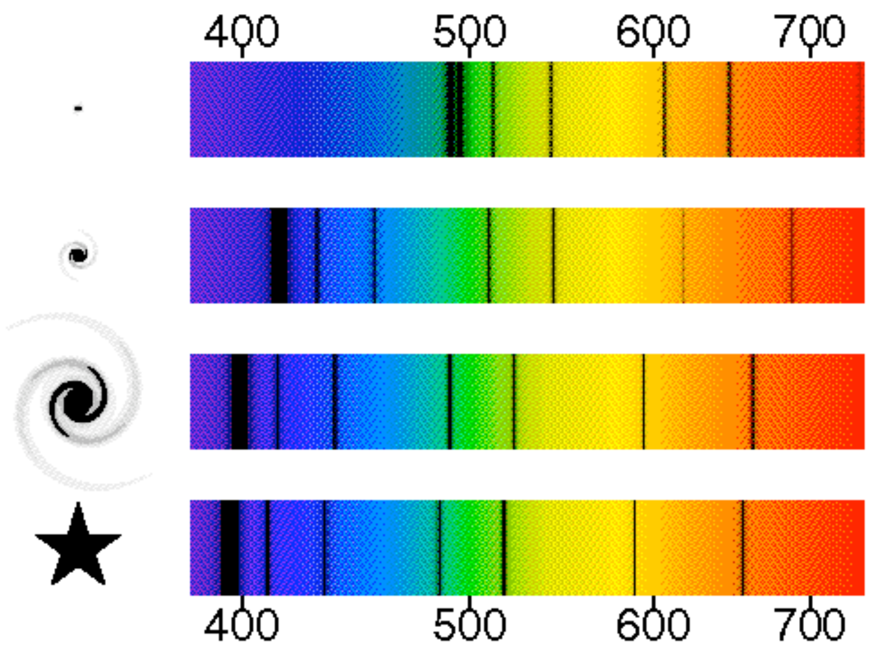








Most galaxies have redshifted spectra

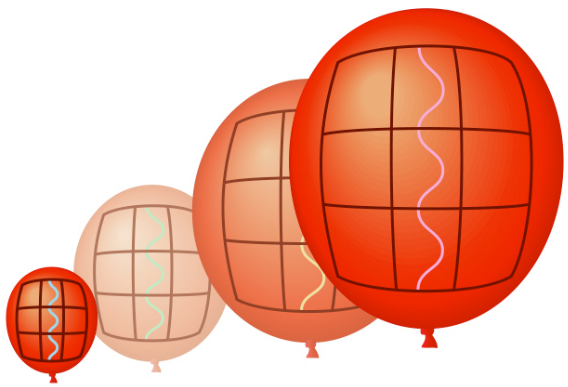


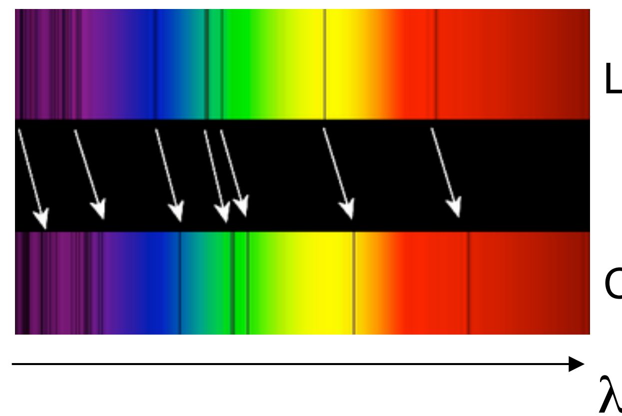
Vesto Slipher
1912

The quest for the expansion

- 1912: Vesto Slipher discovers that most spiral nebulae have a redshifted spectrum
- 1917: Scientists start using GR to describe the whole universe. Albert Einstein favours a static (but unstable) model where Λ balances gravitational attraction
- 1917: Willem de Sitter finds that GR admits a cosmological metric redshift in an empty universe
- 1922: Alex Friedmann finds that an expanding universe is a solution to GR field equations
- 1924: Edwin Hubble shows that most nebulae are stellar systems like the Milky Way
- 1927: Georges Lemaître independently derives the expanding solution found by Friedmann and is told by Einstein "Vos calculs sont corrects, mais votre physique est abominable"
- 1929-1931: Hubble and Humason find striking evidence for the expansion of the universe by measuring a linear relation between the redshift and the distance of nearby galaxies

Cosmological redshift

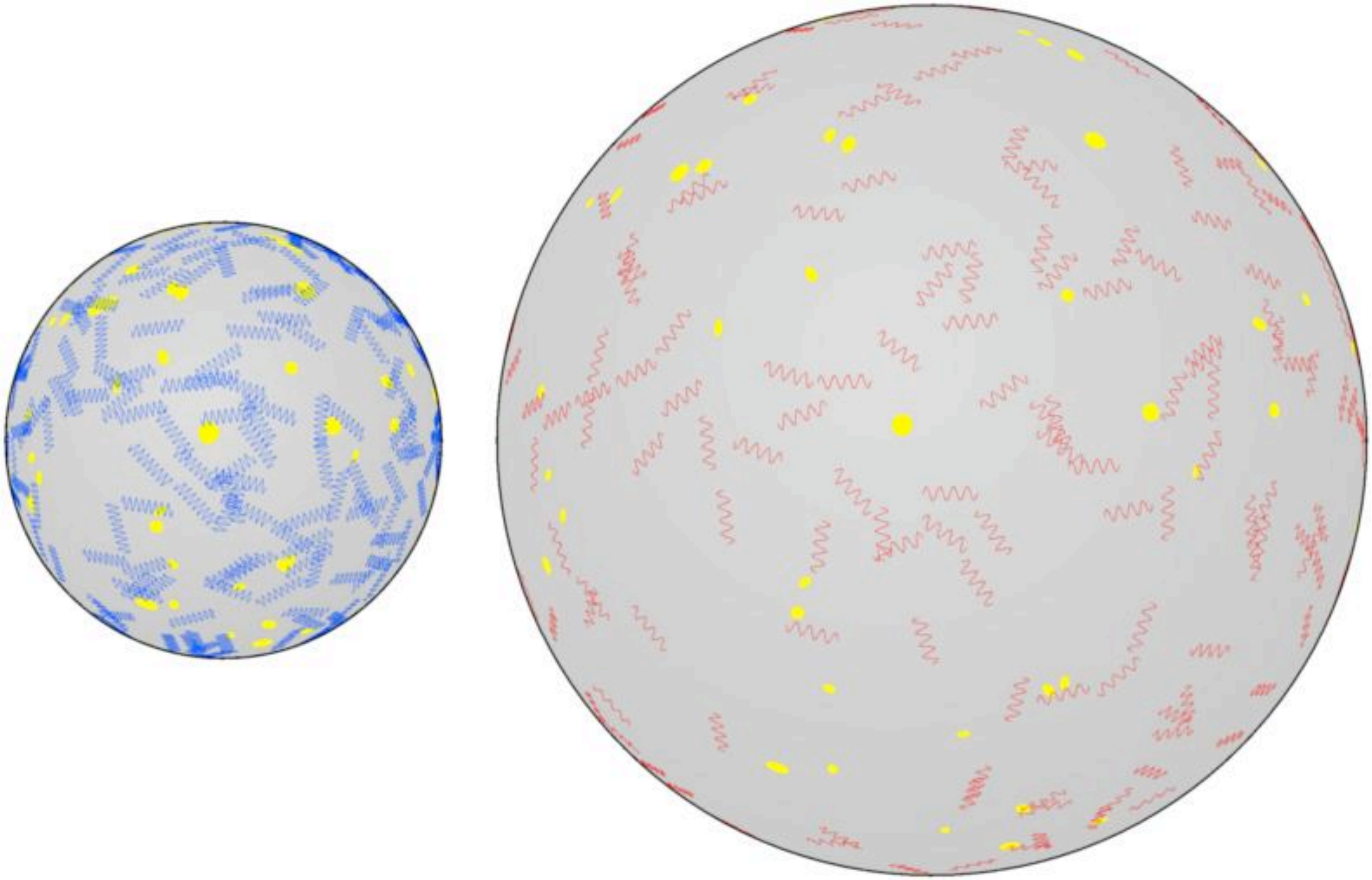




- Cosmological redshift: the wavelength of EM signals is stretched by the cosmic expansion.

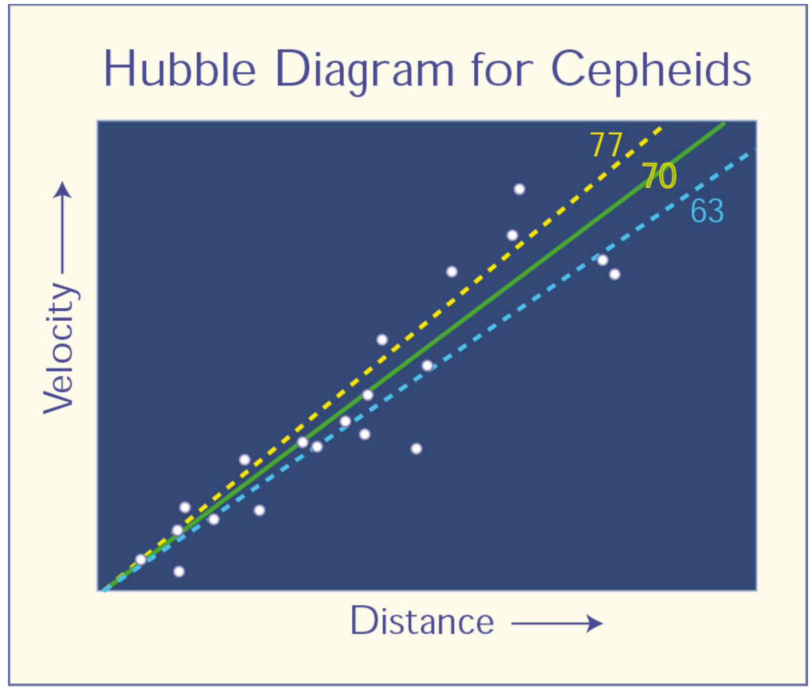
- Spectra are shifted in frequency towards the red by a factor
  1+z = (present-day size of the universe)/(size at photon emission)=$a(t_0)/a(t_{em})$

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



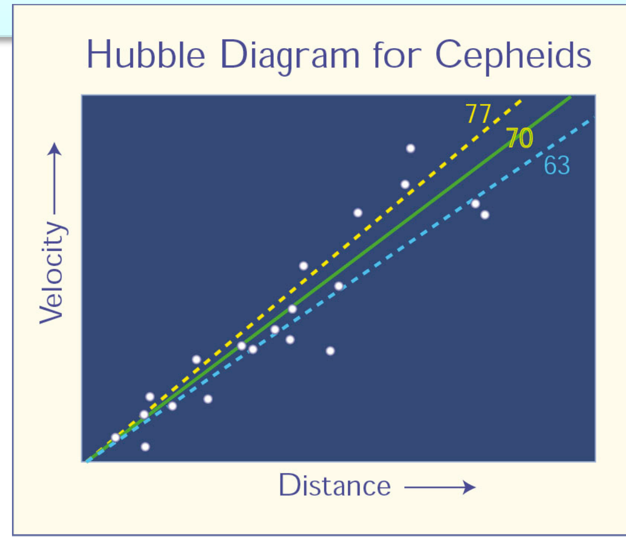
The Hubble diagram

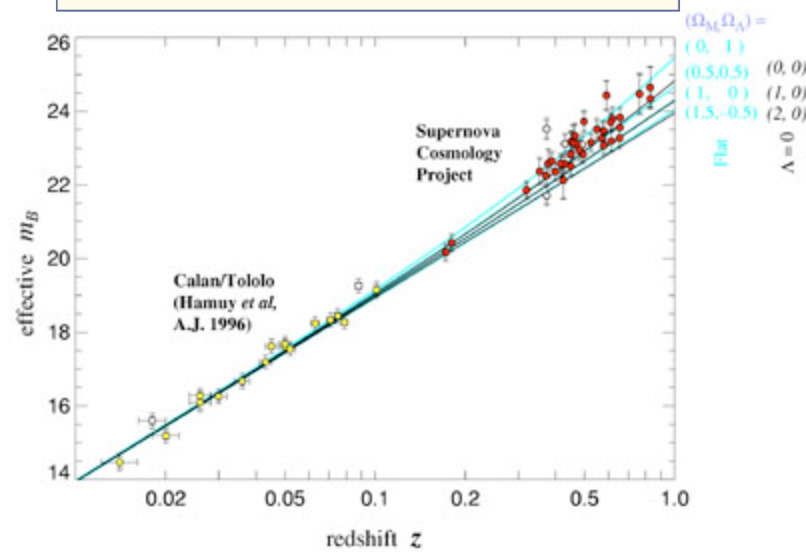
- Taylor expansion of the lumin. distance-redshift relation: $H_0\, d_L/c = z + (1-q_0)z^2/2 + \ldots$
- This is the observational version of the Hubble's law
- It is very difficult to measure distances on cosmological scales
- Need for standard or standardizable candles
- The best we have today are Cepheid stars (PL or PLC relation) and Supernovae Ia (peak brightness - decay time relation)



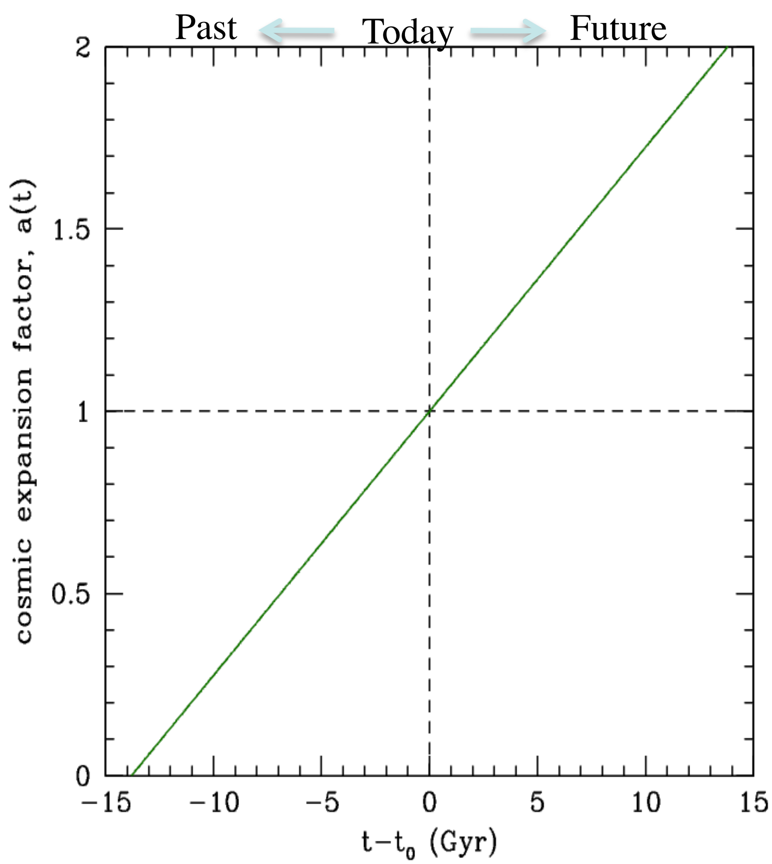
Current estimates

- Improvement: Hipparcos accurate determination of the parallax of local Cepheids
- HST key project (based on Cepheids)
  $H_0 = 72 \pm 8$ km/s/Mpc
  (Freedman et al. 2001)
- Hubble diagram with SNa Ia
  $H_0 = 73 \pm 7$ km/s/Mpc
  (Riess et al. 2005)
- Other estimates from different datasets lie in the same ballpark
- This sets the size and age of the observable universe





The cosmic expansion history

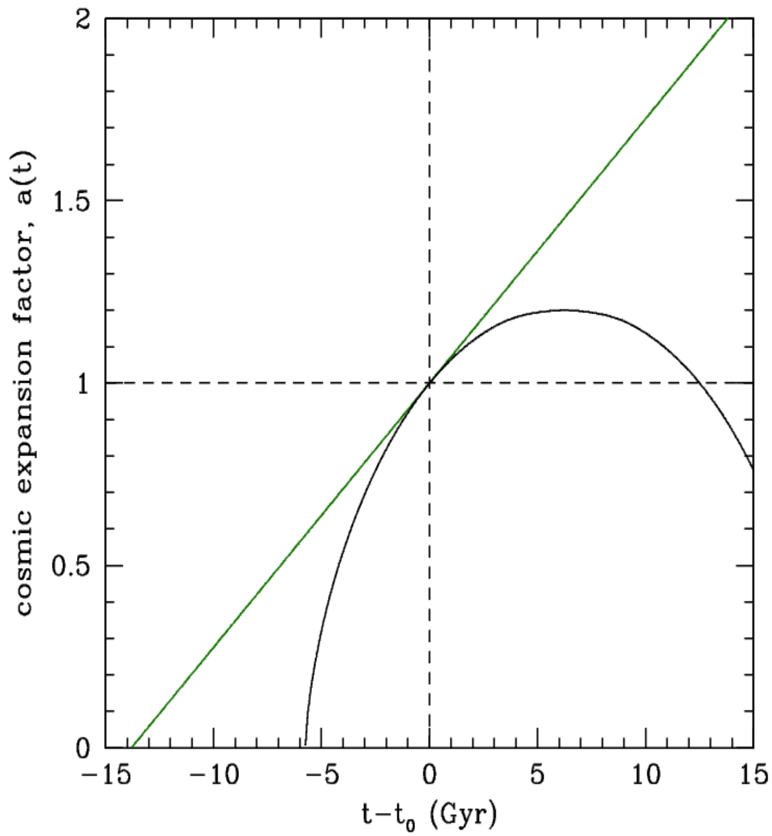


Friedmann equations state that, given the current expansion rate, the past and future expansion history depend on what the universe is made of.

Let us consider a few examples:

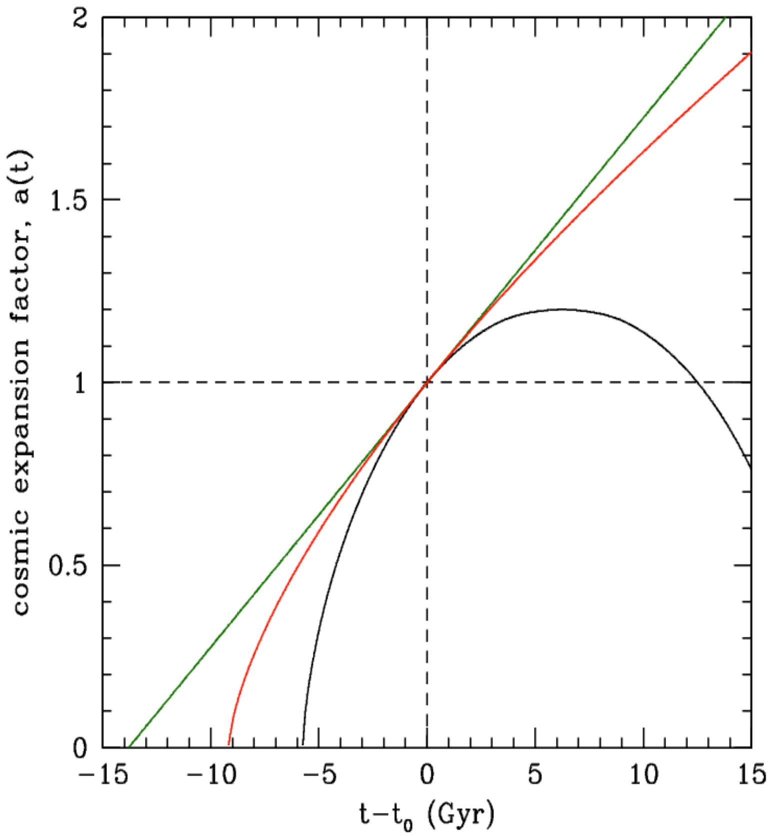
- Empty universe. The universe has always expanded at the current rate (no slowdown or acceleration): $a(t)=H_0\,(t-t_0)$
- H_0= 100 h km/s/Mps, h=0.71 ± 0.02

The cosmic expansion history



- The universe has always expanded at the current rate
- The universe contains a lot of matter (Ω_m= 6) and collapses in the future

The cosmic expansion history



- The universe has always expanded at the current rate
- The universe contains a lot of matter (Ω_m= 6)
- The universe contains less matter (Ω_m= 1) and asymptotically stops expanding in the infinite future. We use this value of the matter density as a reference and call it "critical density".

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G}, \qquad \Omega_{\rm m} = \frac{\rho_{\rm m}}{\rho_{\rm crit}}$$

Friedmann equations show that k=sign(Ω_{tot}−1) with Ω_{tot}= Ω_m+ Ω_r+ Ω_Λ

Singularity in the past?

In all models we have considered so far, the scale factor of the universe vanishes somewhen in the past.

This "singularity" (conventionally dubbed the "big bang") is an artifact due to the fact that we extrapolated Einstein's equations to a regime in which they are not valid.

GR is a classical theory of gravity and cannot describe arbitrarily high densities at which we expect quantum effects to be important.

Therefore, we should trust the results of the model only up to a fraction of a second before the singularity. A theory of quantum gravity should be used to describe the very early phases. Regrettably this theory is not yet available.

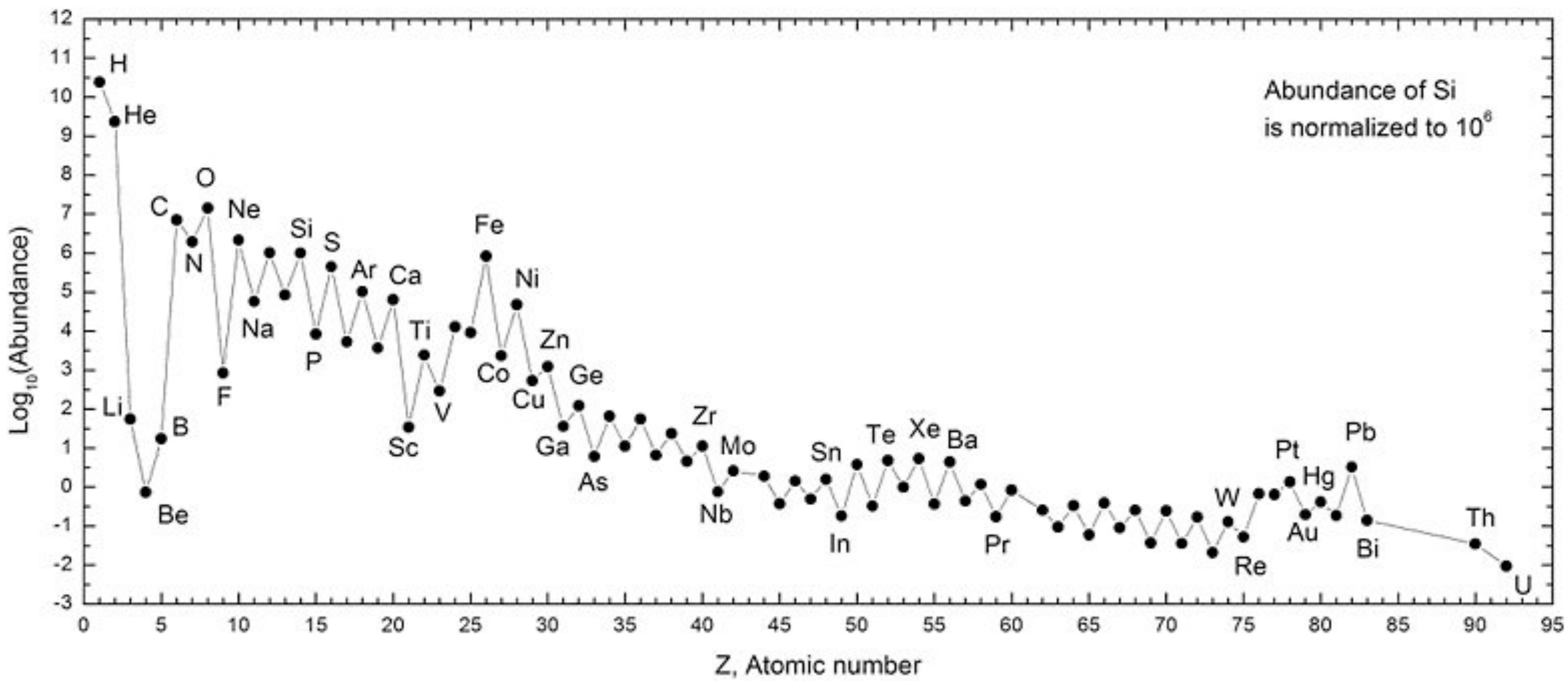
Inflationary models give a speculative explanation of the origin of cosmic expansion without requiring a "bang".

Note that the "big bang" is not an explosion happening at a particular place in space, rather it is the origin of space-time and happens everywhere

Cosmic abundances

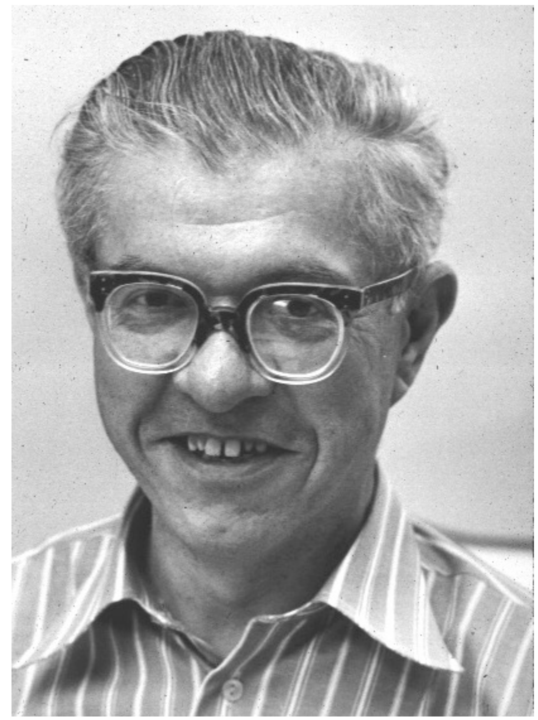
1925 Cecilia Payne: The abundances of chemical elements in stars are remarkably uniform. The Sun and other stars are composed almost entirely of hydrogen and helium.

"almost certainly not real" (Henry Norris Russell)



Solar system abundances

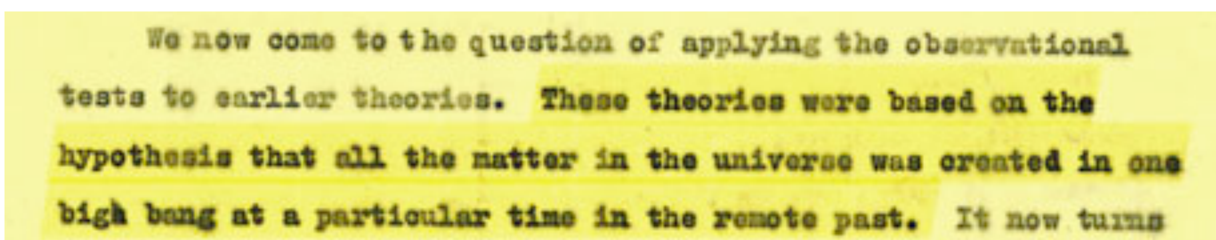
A hot and dense start?



The universe started in a very hot and dense phase. ALL chemical elements are built via neutron capture and beta decay everywhere at very early times when T≈10^9 K (Alpher, Bethe & Gamow 1948).

The universe looks always the same under the combined action of cosmic expansion and matter creation. The chemical elements are "cooked" by nuclear reactions in stars (Hoyle, Gold & Bondi 1948).

The christening of the big bang



We now come to the question of applying the observational tests to earlier theories. These theories were based on the hypothesis that all the matter in the universe was created in one bigh bang at a particular time in the remote past. It now turns

(Fred Hoyle, 1949)

Consequences of a dense start

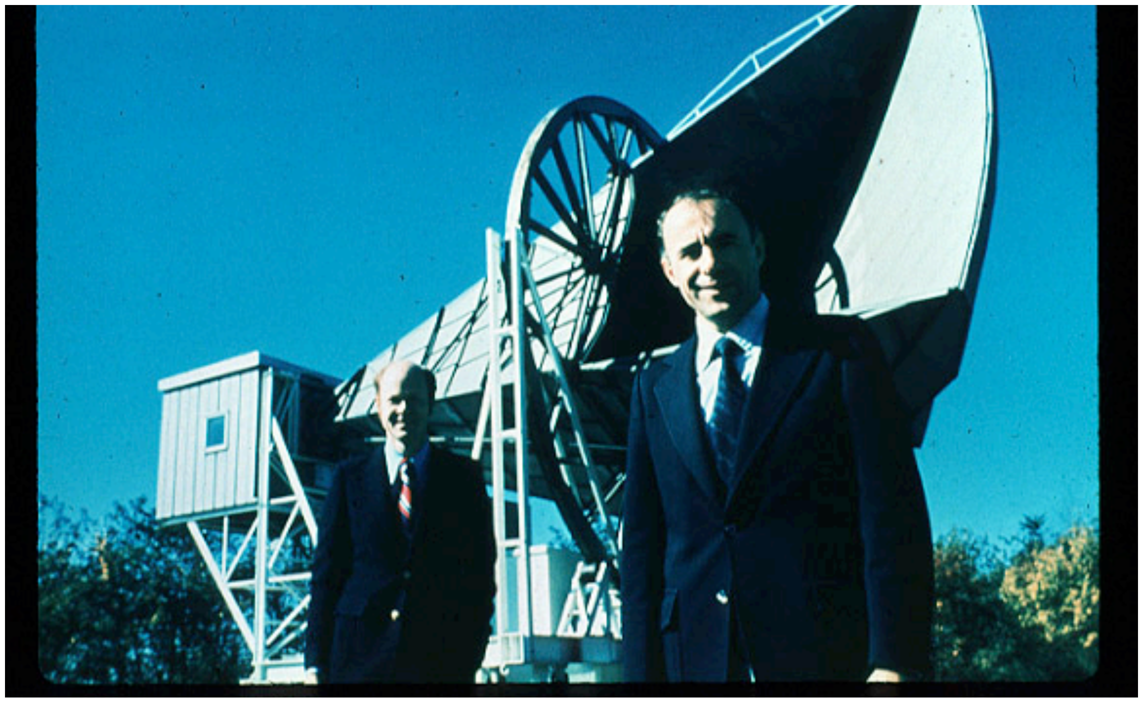
1949: Alpher & Herman predict that the dense early phases of the universe should leave an imprint in the form of isotropic background radiation in the microwave regime. This is composed of the redshifted photons released in the early universe when they could not interact anymore with matter (below T≈3000 K hydrogen becomes neutral). This background should have a blackbody spectrum (as radiation was in thermal equilibrium with matter through frequent interactions before being released)

1950s: Gamow, Alpher & Herman compute that the characteristic temperature of this radiation should be around 5 K

1964: Doroshkevich & Novikov show that the relic radiation should be observable with the available facilities

The cosmic microwave background

The Nobel Prize in Physics 1978
Pyotr Kapitsa, Arno Penzias, Robert Woodrow Wilson



The discovery of the cosmic microwave background at T=3K by Penzias and Wilson in 1964 is the second pillar on which the standard model of cosmology is based. This provides evidence that the universe evolved from a very dense and hot past

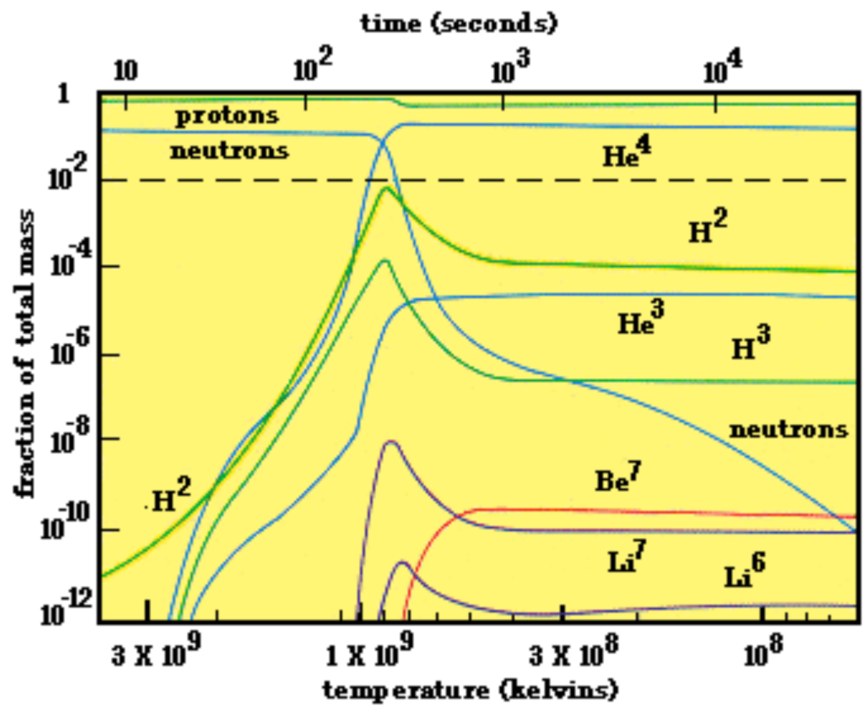
Big-bang nucleosynthesis

The current tenant is that primordial nucleosynthesis (BBN) took place at a cosmic age between 1 and 1000 s (i.e. until densities and temperatures were too low for nuclear reactions)

BBN produced nearly 24% in mass of Helium 4 along with trace amounts of Deuterium, Helium 3, Lythium and Berillium

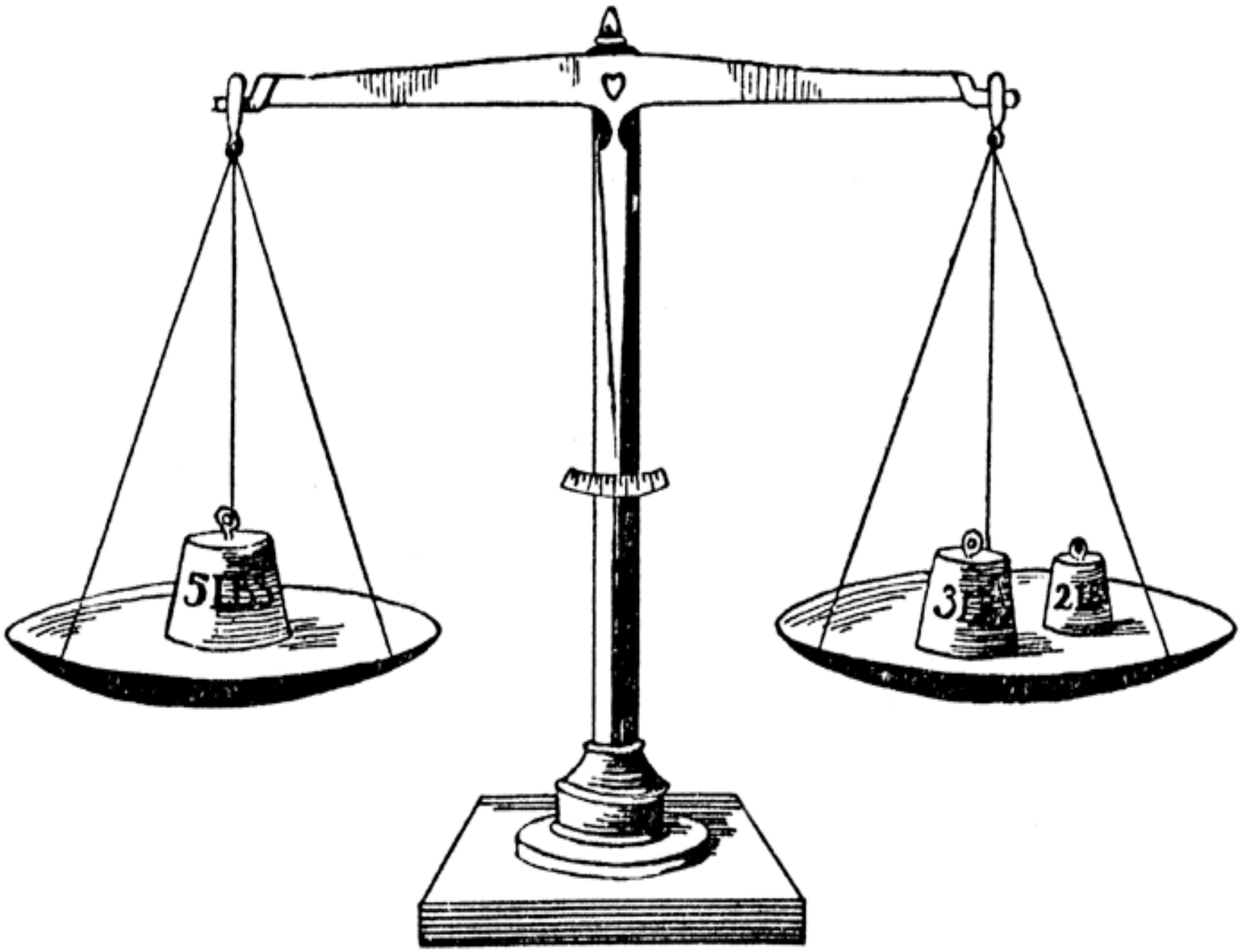
We now firmly believe that all heavier elements have been (and still are) synthesized in stars

So both Gamow and Hoyle were partially right and partially wrong

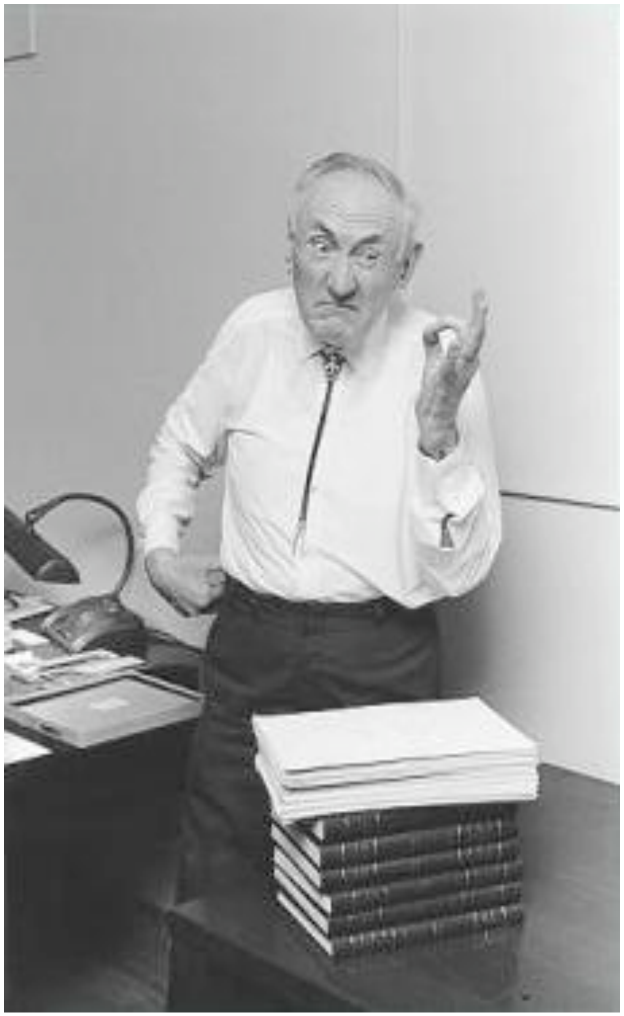


The successful comparison of the BBN predictions with observational data on the abundance of light elements is the third pillar on which our standard cosmological model is based.

How do you weigh galaxies?



Weighing galaxies with gravity



1933: first evidence for dark matter

Die Rotverschiebung von extragalaktischen Nebeln

von **F. Zwicky.**

(16. II. 33.)

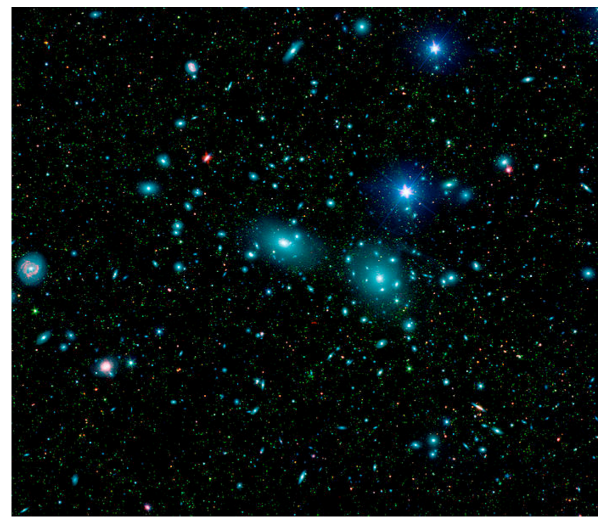
Helvetica Physica Acta, 1933, 6, 110

Virial theorem

$$2\left\langle E_{kin}\right\rangle = -\left\langle E_{pot}\right\rangle$$

$$M\left\langle v^2\right\rangle \approx \frac{GM^2}{R}$$

$$M \approx \frac{R\left\langle v^2\right\rangle}{G}$$



The characteristic speed of galaxies in the Coma cluster suggests that the cluster contains 160 times more mass that we can deduce from the stellar light (nowadays we believe the discrepancy is a factor of 30)

Christening of dark matter

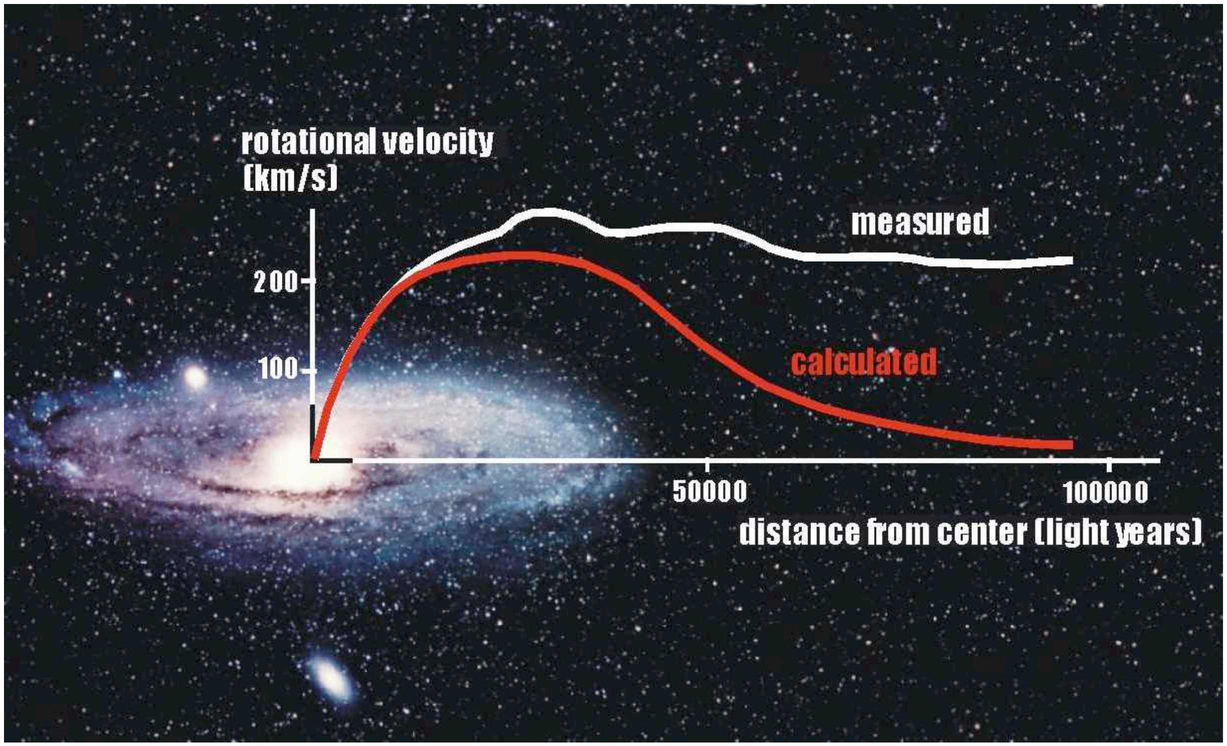
Fritz Zwicky (1933)

was einer Geschwindigkeit von nur 10 m/sek entspricht. Um also auf diese Weise zu einer Erklärung für die grossen Streugeschwindigkeiten zu kommen, müsste man noch eine sehr viel grössere Dichte dunkler Materie zulassen als unter 1. oder 2.

Fritz Zwicky (1937)

2. We must know how much dark matter is incorporated in nebulae in the form of cool and cold stars, macroscopic and microscopic solid bodies, and gases.

Early evidence confirmed: rotation curves of spiral galaxies



Credit: Queens University

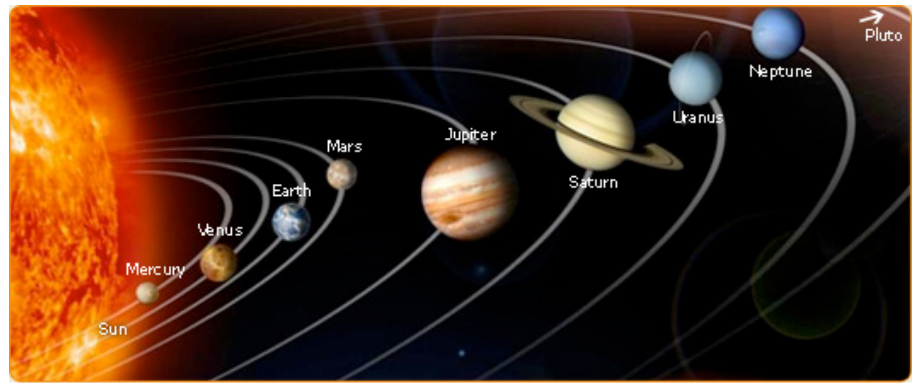
Stars and ionized gas (optical Hα line): Rubin & Ford (1970), Rubin, Thonnard & Ford (1978), Rubin, Ford & Thonnard (1980)

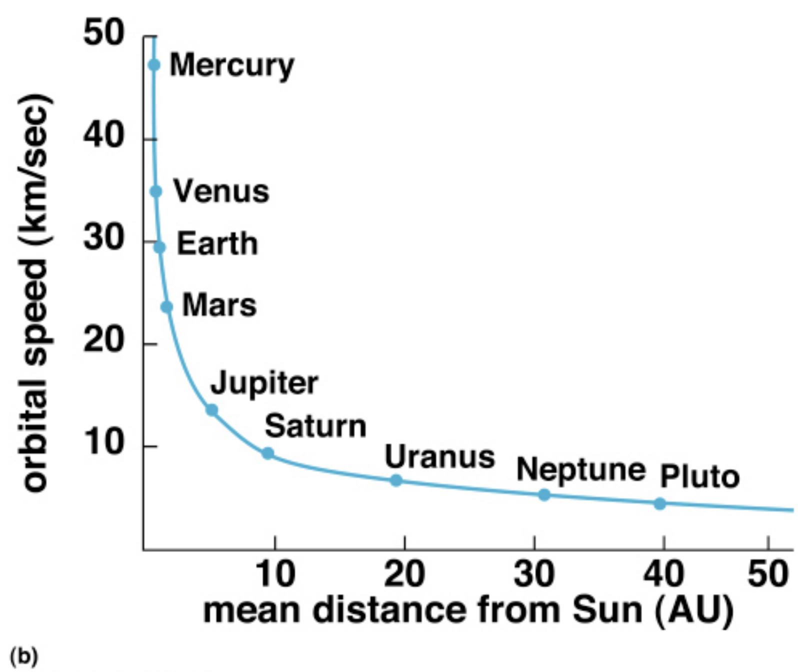
Neutral hydrogen (radio, 21-cm line): Freeman (1970), Bosma (1981)

Keplerian motion

Courtesy: Benediktenkloster Krems

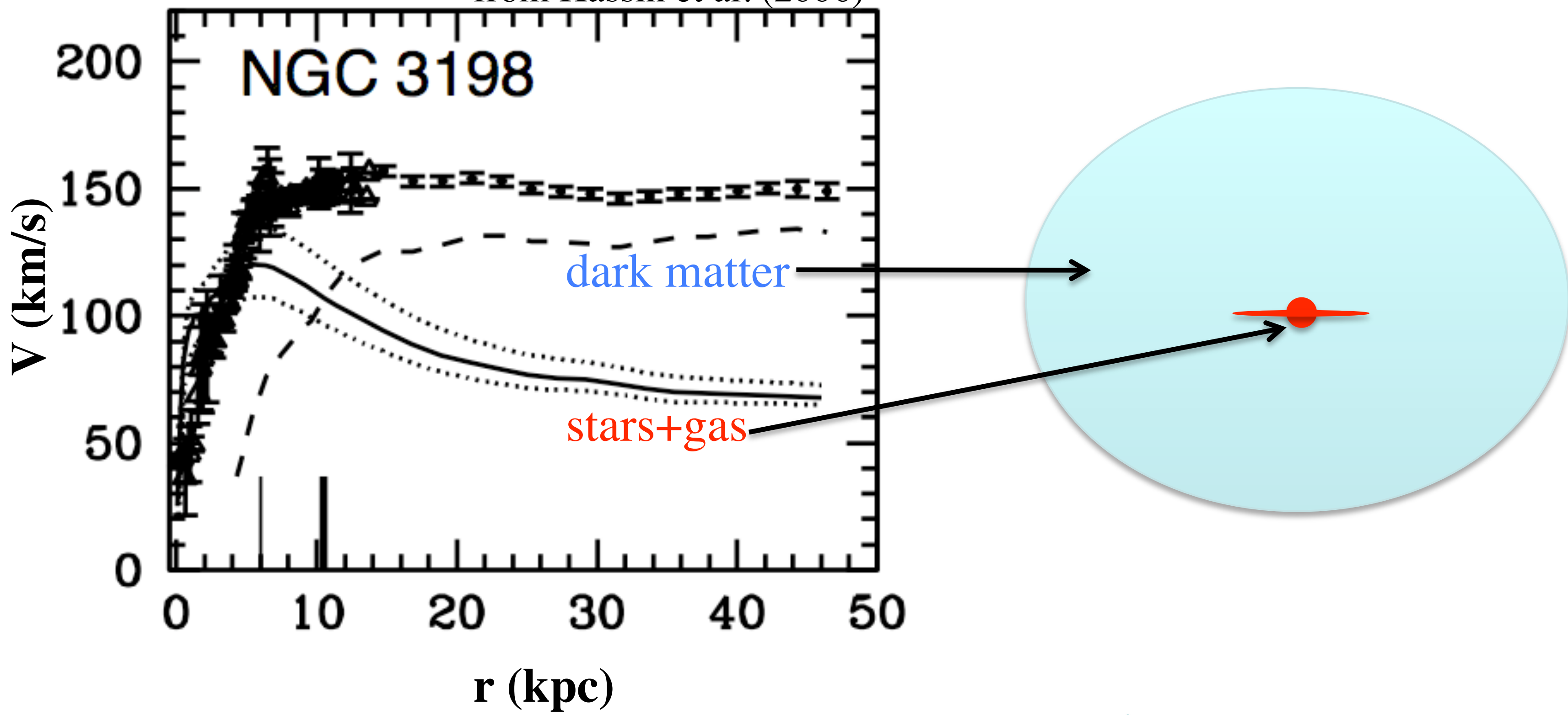
$$v^2 = \frac{GM_{int}}{r}$$



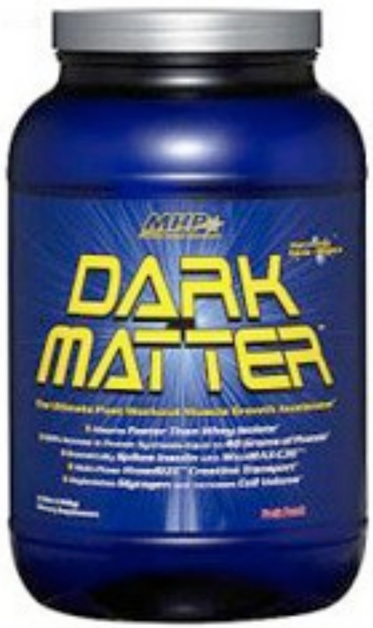


Dark-matter halos

from Kassin et al. (2006)



What is the dark matter made of?



Supplement Facts
Serving Size: 2 Scoops (60.8 g)
Servings Per Container: Approximately 20

	Amount Per Serving	% Daily Value
Calories	240	
Calories From Fat	0 g	
Total Fat	0 g	0% †
Saturated Fat	0 g	0% †
Trans Fat	0 g	‡
Cholesterol	0 g	0% †
Sodium	0 mg	0% †
Total Carbohydrate	48 g	16% †
Sugars	10 g	‡
Dietary Fiber	0 g	0% †
Protein	12 g	24% †
DARK MATTER™ Proprietary Blend (Patent Pending) **The Ultimate Post-Workout Muscle Growth Accelerator™:**	**60 g**	‡

WaxiMAX™-C3G: Low Viscosity High Molecular Weight Osmotic Waxy Maize Starch with Molecular Dispersion Technology
Waxy Maize, Maltoplex-18™ Glucose Polymer, Dextrose, C3G anthocyanidins

HydroSIZE™: Multi-Phase Creatine Transport and Cell Volumizing Matrix
InstaPeak™ (Instant Acting Peak Plasma Concentration Creatine Pyruvate), IntraPhase™ (Glucose Bound Creatine Gluconate), MicroTein™ (Microencapsulated Sustained Release Creatine Monohydrate), Glycerol Monostearate

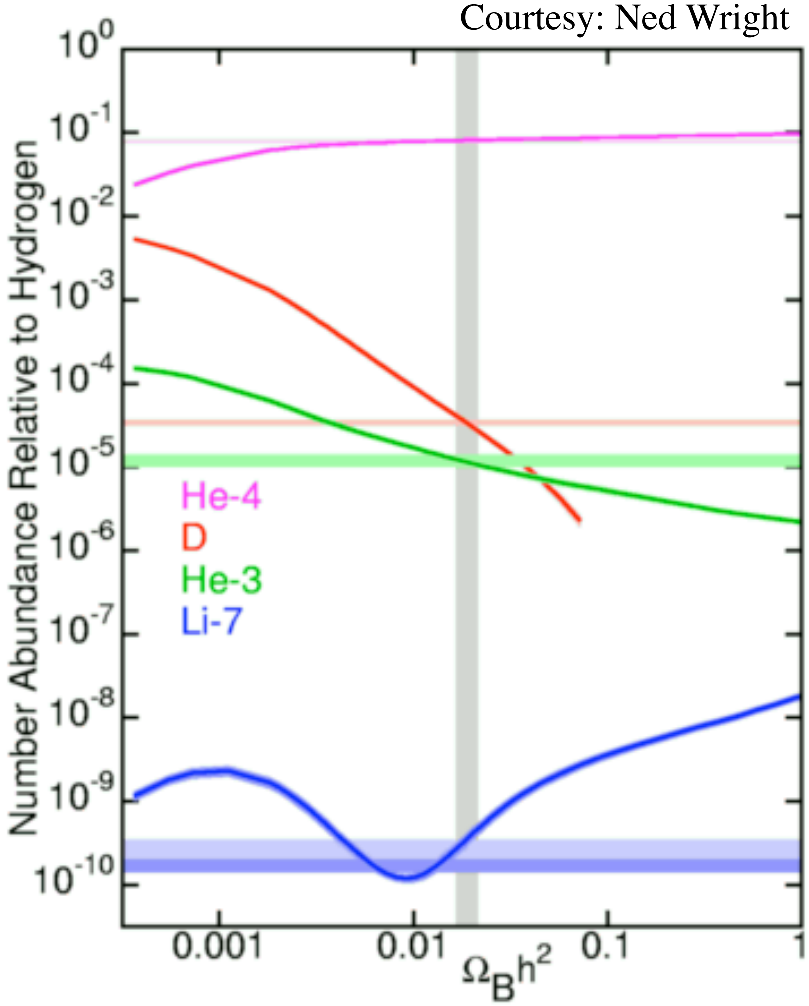
ProSYNTHAGEN™: Protein Synthesis Accelerator (Dual Portal Anabolic Amino Acid Infusion)
Free Form Infusion (L-Leucine, L-Lysine, L-Phenylalanine, L-Threonine, L-Valine, L-Histidine, L-Isoleucine, L-Methione), ***Leucrose™*** *Peptide Infusion* (Leucine-Alanine Di-Peptide)

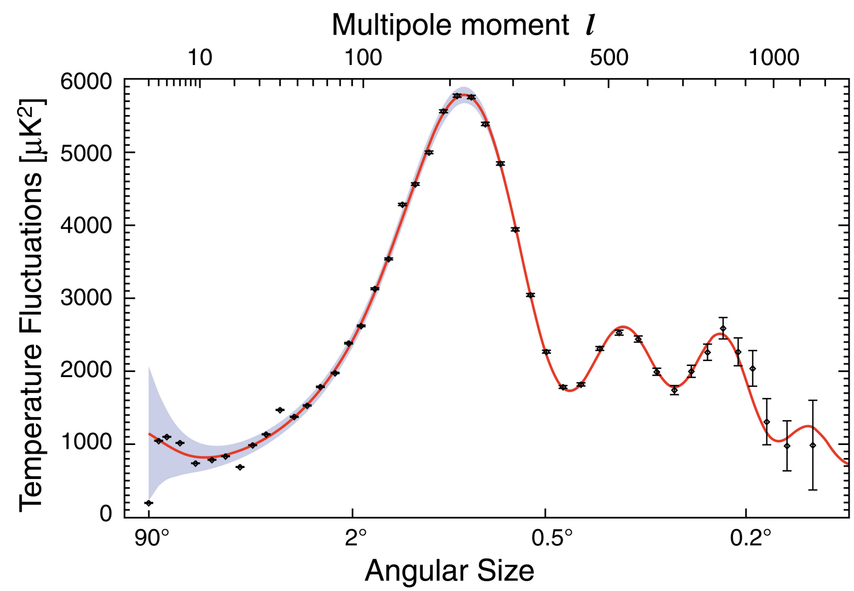
‡ Daily Value not established. † Percent Daily Values are based on a 2,000 calorie diet.

Other Ingredients: Black rice extract, citric acid, malic acid, silica, natural and artificial flavors, Red 40, acesulfame potassium, sucralose and Blue 1.

Contains corn.

Big-bang nucleosynthesis and CMB anisotropies

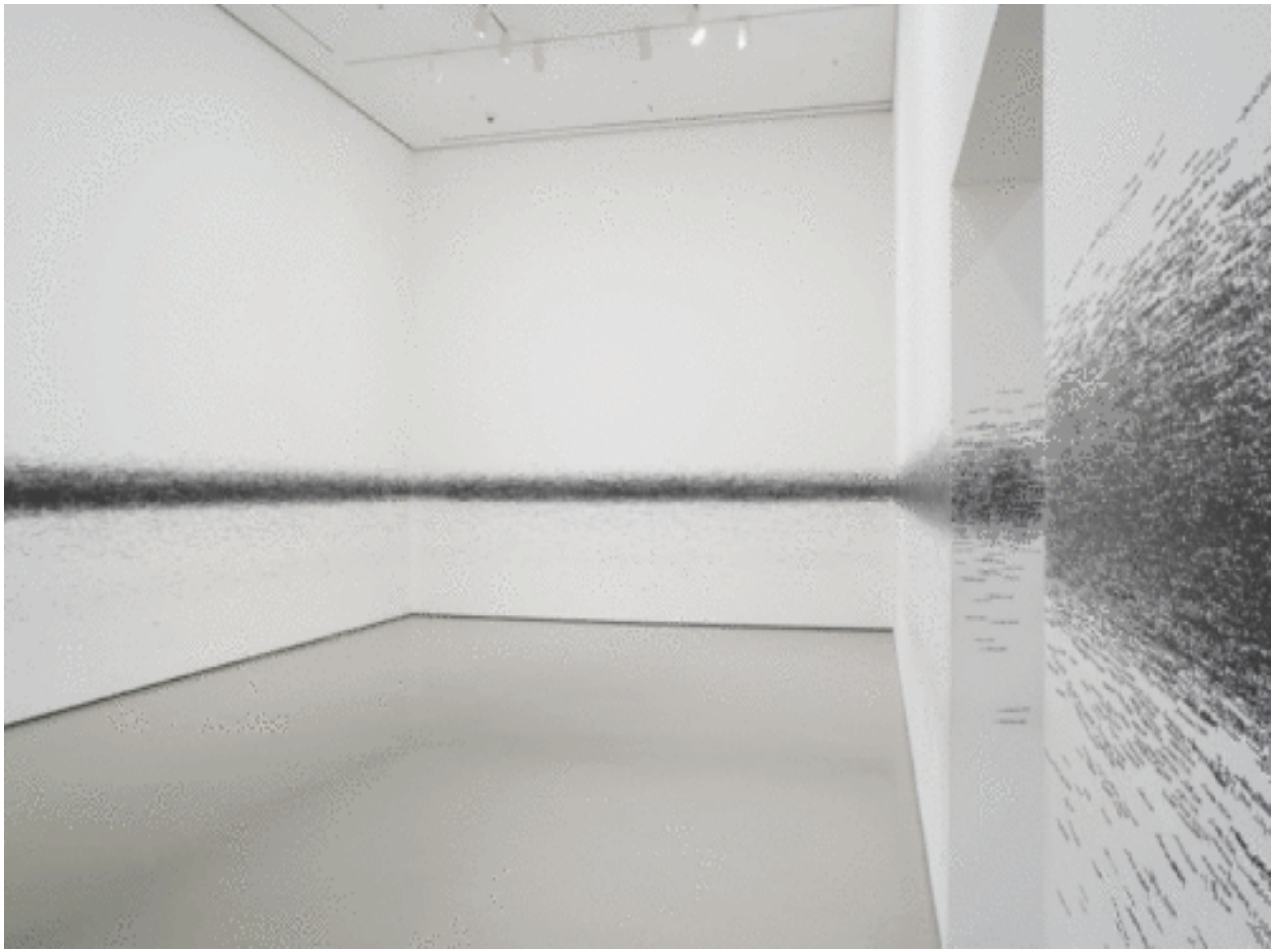




$\Omega_b h^2 = 0.0214 \pm 0.002$ (BBN)
$\Omega_b h^2 = 0.02258 \pm 0.00057$ (CMB)

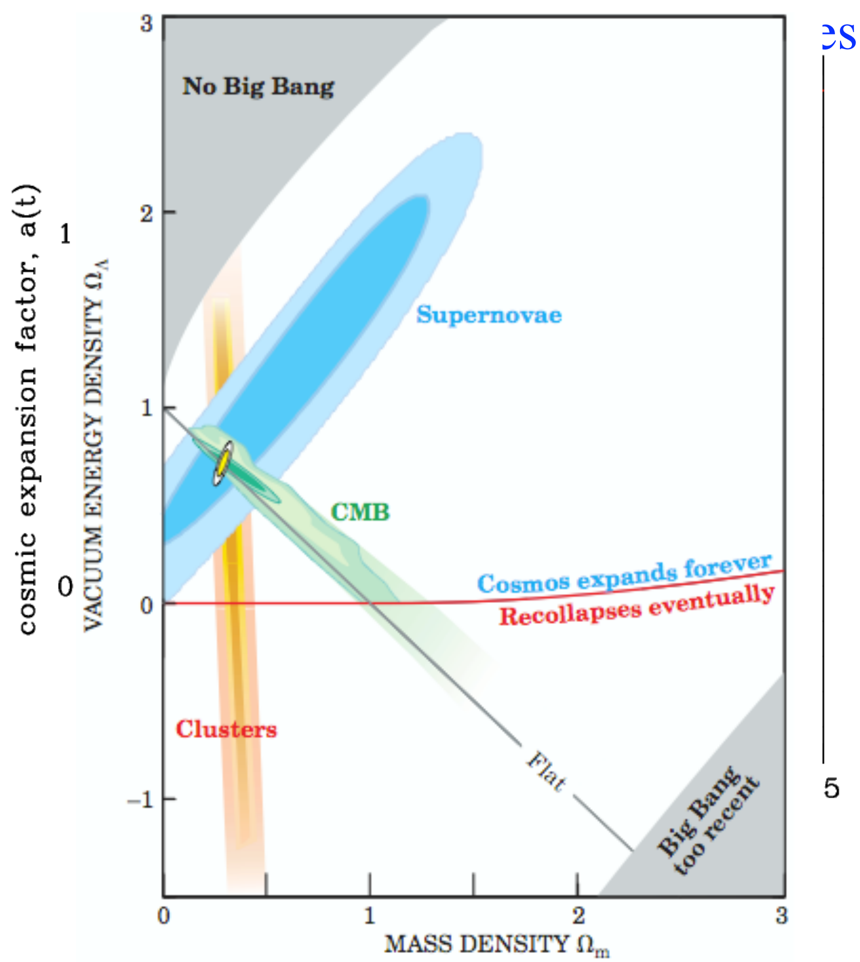
The dark matter cannot be formed by the same stuff we are made of!!!

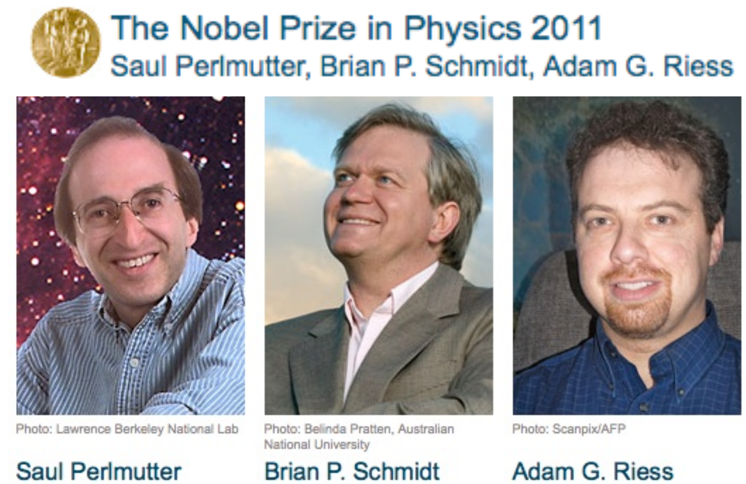
The contemporary universe

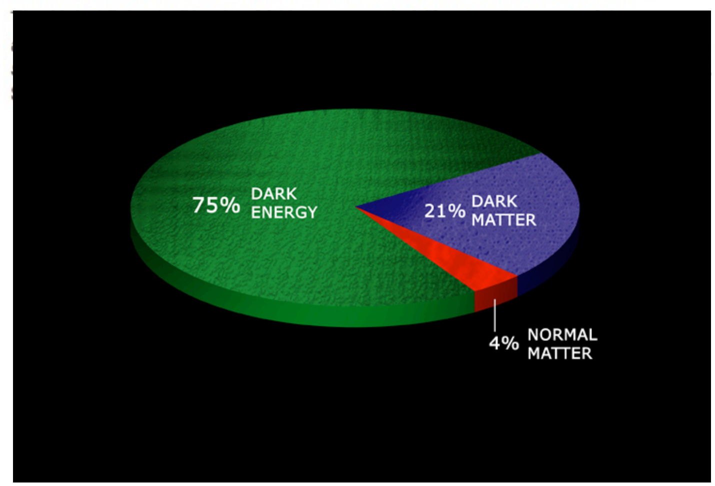


Roman Ondak, 2007 (The Museum of Modern Art, New York)

The accelerating universe

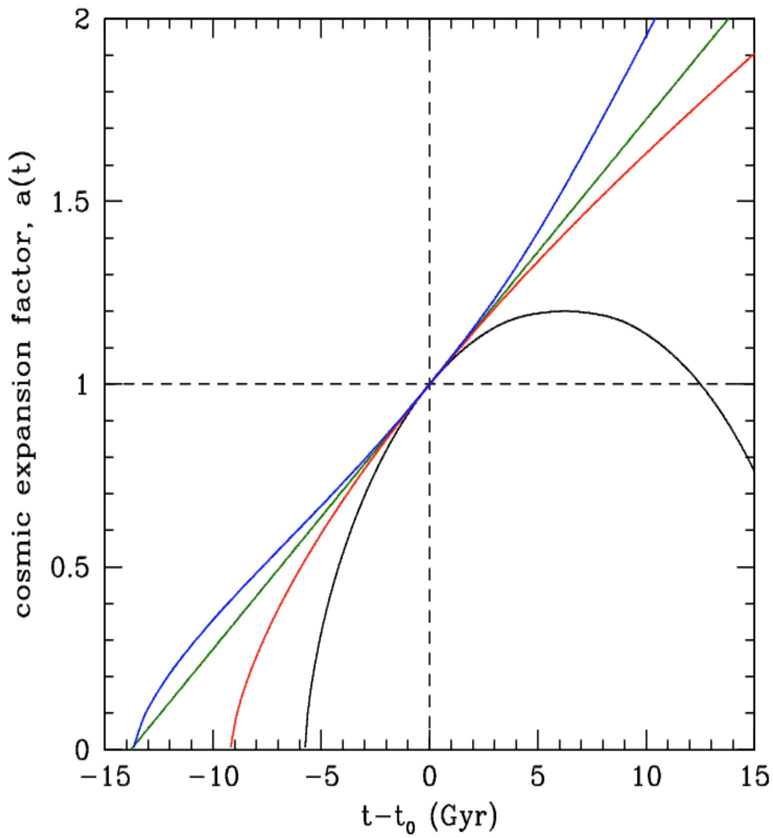






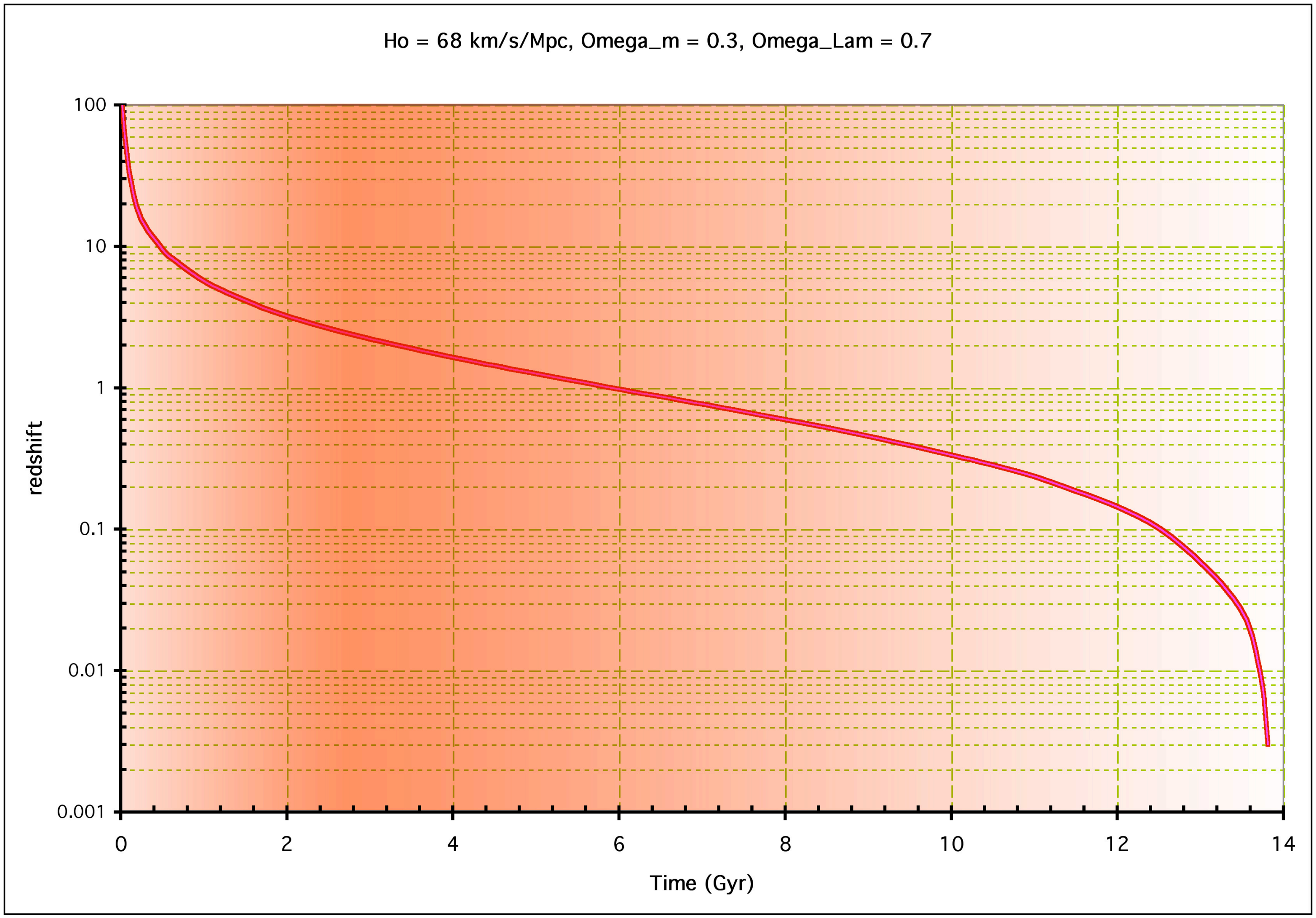
$\Omega_{tot} \approx 1$

The cosmic expansion history

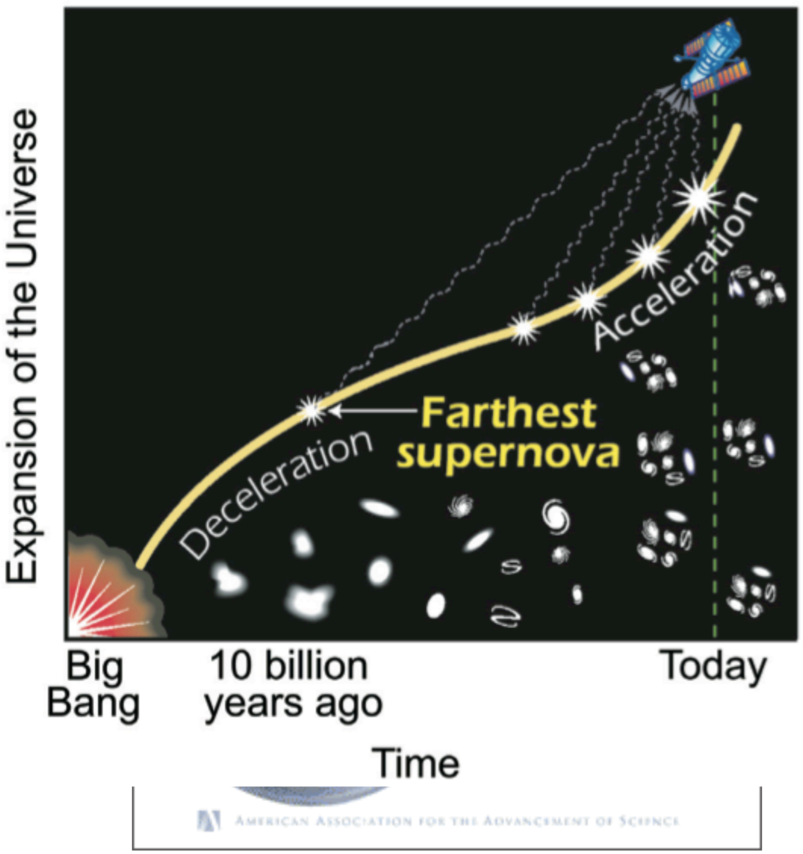


- The universe has always expanded at the current rate
- The universe contains a lot of matter (Ω_m= 6)
- The universe contains less matter (Ω_m= 1)
- The universe contains a mix of matter and "dark energy" (Ω_m= 0.27, Ω_Λ= 0.73)

Redshift vs time



Dark energy, a primer



- Acceleration of cosmic expansion discovered in 1998 from observation of the distance-redshift relation of supernovae Ia

- Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

then implies $p < -\rho c^2 / 3$ (i.e. a strongly negative pressure or tension)

- The (hypothetical) dominant negative pressure component has been dubbed "dark energy" (name coined by M. Turner)