Cosmology
WS 2022

Luca Amendola

Calendar, script, exercises, info:

http://www.thphys.uni-heidelberg.de/~amendola/teaching.html

Recording of the lectures

- Lectures will be recorded (not streamed in real-time)
- They will be available possibly within the next day
- If you don’t want your voice being recorded when asking questions, please ask them during the break or at the end
- In case of problems with the recording system, I’ll record a new lecture within a few days or use an older recorded lecture

Updated Covid rule

https://www.uni-heidelberg.de/en/newsroom/measures-of-the-university-for-protection-against-the-coronavirus

If it is not possible to maintain the minimum distance inside the buildings, **all degree-related lectures/classes, exams etc.** must respect the following procedure

•Students are urgently recommended to wear a medical mask or an FFP2 mask

•Wearing at least a surgical mask is mandatory for all other persons present, including teachers, if they cannot maintain the minimum distance inside the university buildings

Apart from degree-related activities, all those present in all areas of the university must wear at least a surgical mask if they cannot maintain the minimum distance inside the buildings.

Goals of this course

Understand the dynamics of our Universe across time and space: expansion, growth of perturbations

Learn the basics of the cosmic thermal history

Learn the basics of inflationary theory

Know the main observation tools at our disposal

Be able to read research articles and more advanced books, and to follow general seminars in this area

Course

Part I: the homogeneous Universe

General relativity, FLRW metric, Friedmann equations, radiation and matter era, thermal history, age of the Universe, cosmological constant, inflation

Part II: the inhomogeneous Universe

Linear perturbation theory, statistics of spatial distributions, inflationary perturbations, CMB, galaxy power spectrum, weak lensing

Part III: Galaxies and Clusters

Non-linear perturbations, masses of galaxies and clusters, diffused gas, dark matter

Texts:

- lecture notes (see course web page)
- S. Dodelson, Modern Cosmology
- L. Amendola & S. Tsujikawa, Dark Energy

for other texts, see lecture notes

Exercises

- http://www.thphys.uni-heidelberg.de/~amendola/teaching.html
- Tutorials begin next week; please register on the practice groups (link on webpage)
- Every Sunday or Monday, I'll post the exercise sheet on the course web page and on the practice group page
- The exercises have to be handed in by the subsequent Monday (or Tuesday if there is a holiday)
- You can work alone or in pairs
- You should send the pdf or a clearly readable picture of your solution to your tutor via email (or arrange with the tutor other ways to hand in the sheets, e.g. in person)
- exercises will be discussed in the tutorials (except for the first week)
- they will be (generously) graded
- You have to pass a minimum threshold (roughly half the points) to be admitted to the final exam
- even if you fail to submit one or two sheets, you can easily reach the required threshold if you work seriously on the other exercises
- you might earn extra points if you offer to solve some exercises during the tutorials
- some exercises require you to read the lecture notes beyond the lectures!

Cosmology

A course unlike the others...

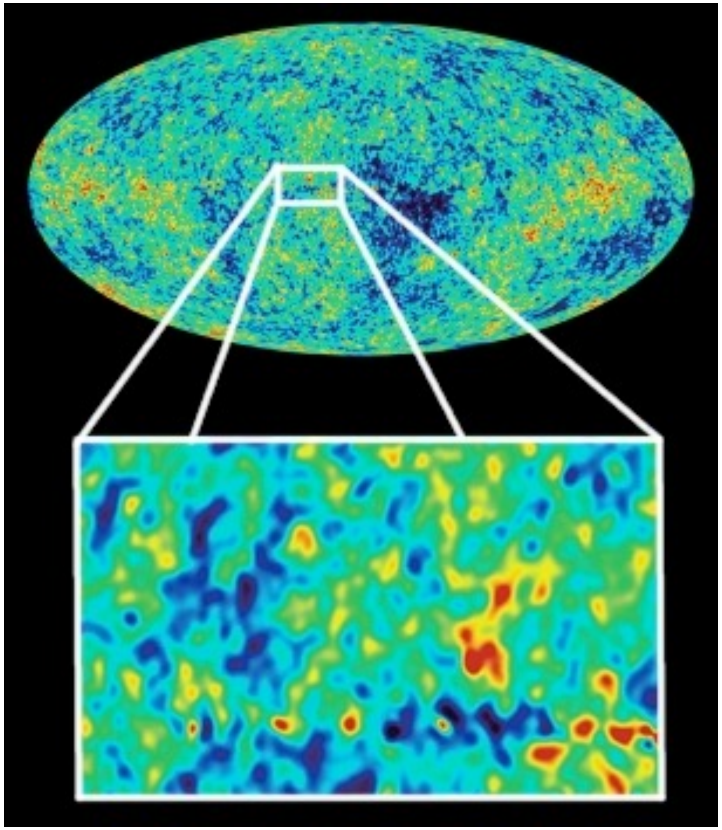
- Covering billions of years and of light-years
- Energies from eV to TeV, to billions of TeV
- From atom recombination to formation of galaxies
- Particles, Black holes, stars, gas clouds, galaxies, clusters...
- General relativity, electromagnetism, quantum fields, thermodynamics, astrophysics...
- Approximations, simplifications, hardly testable hypotheses
- Combine astronomical observations with accelerator experiments
- Mind-boggling concepts, even if mathematics is often very simple!
- A history that goes from Plato to Copernicus, Newton, Einstein, Hubble etc

Don't expect to come up with a deep understanding of everything!

Be ready to accept some results as they are, at least at the beginning!

What the Universe looks like

after the big bang...



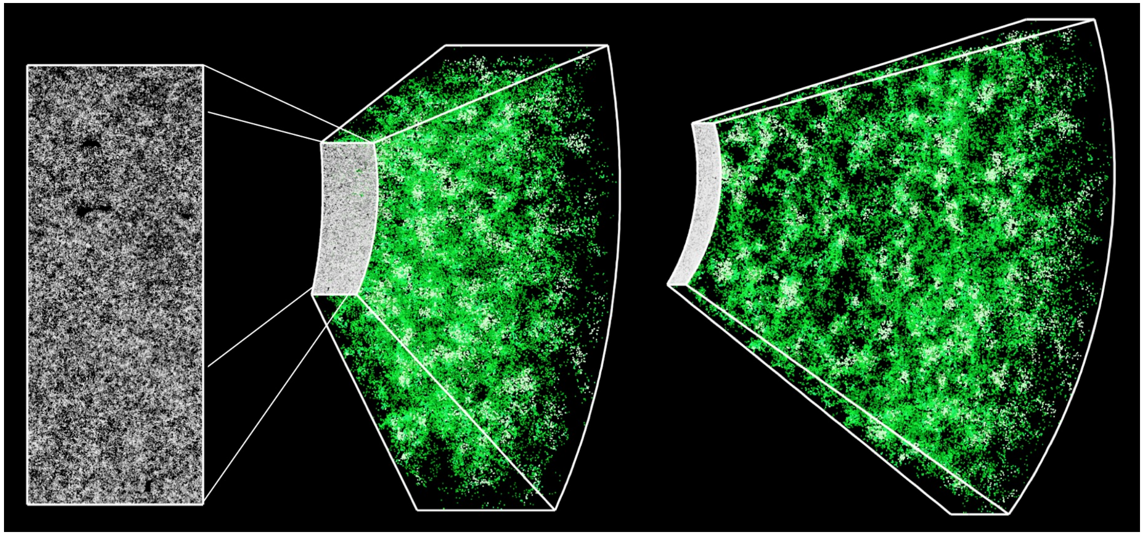
WMAP collaboration

The small primordial fluctuations on the sky (wavelength around 1 mm):

The Universe 400000 years after big bang

What the Universe looks like

...today



SDSS/BOSS survey
1.2 million galaxies

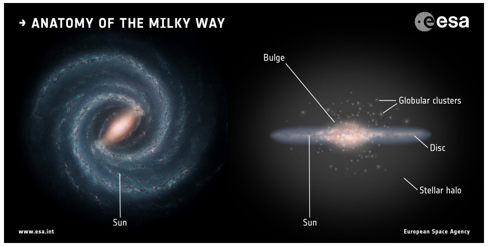
Jeremy Tinker and
the SDSS-III collaboration

7 billion light-years

Scales…

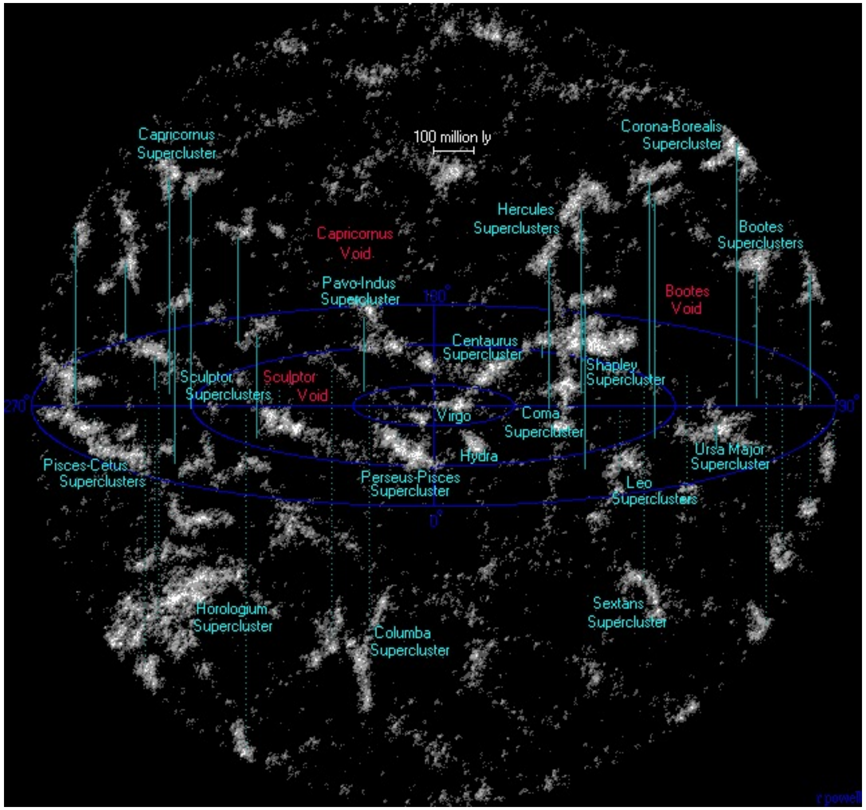
1 parsec= 3.26 light years

(Sun= 8 light-minutes)



ESO

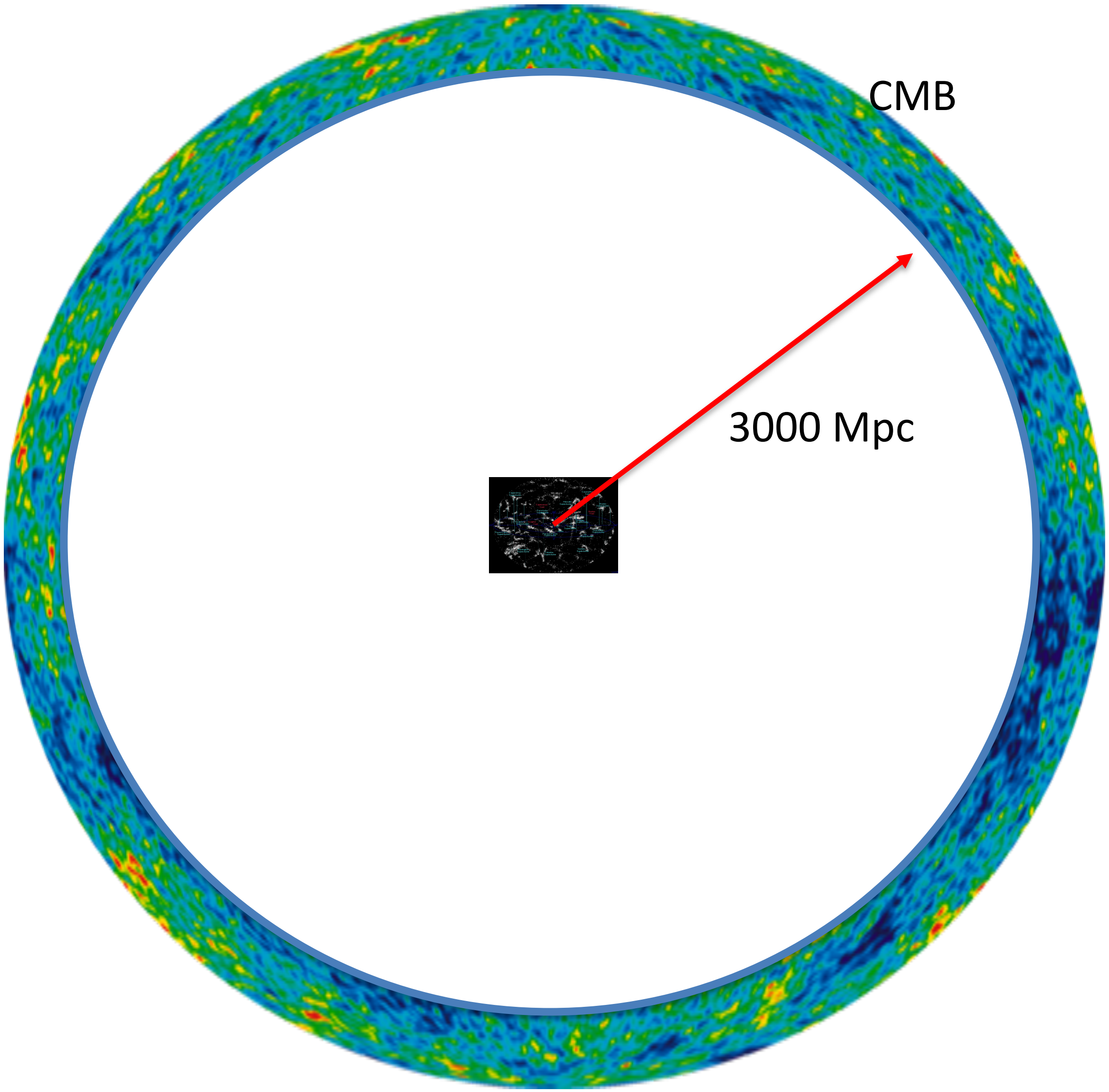
Up to 10s kpc



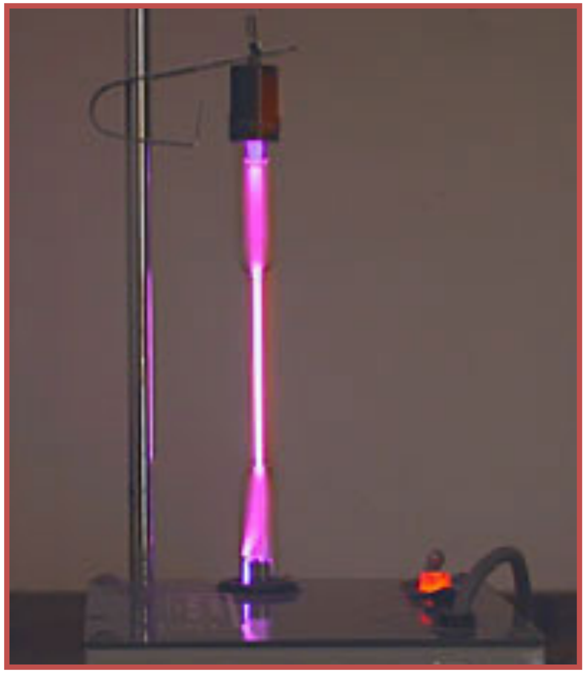
R. Powell, Wikipedia

Up to ~100 Mpc

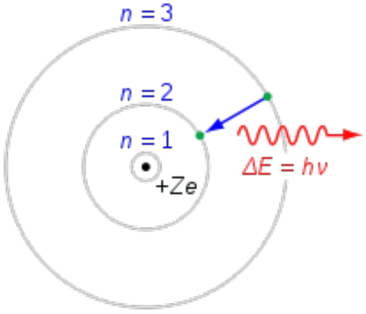
Scales…



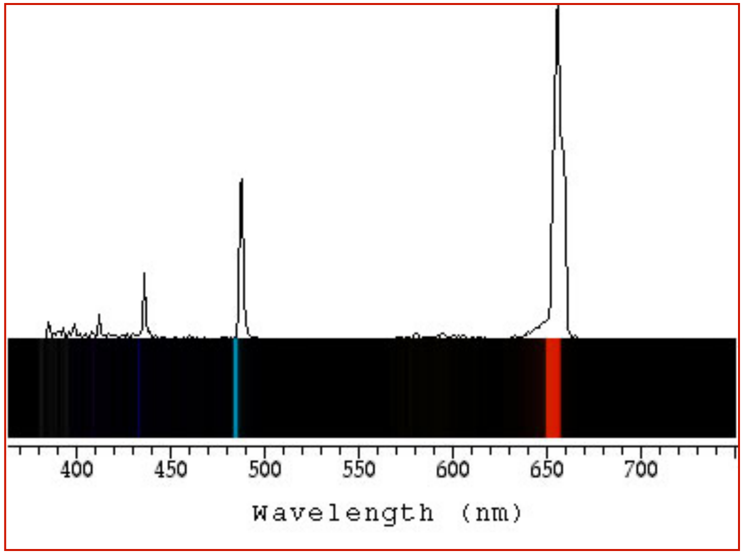
Evidence for an expanding universe



Hydrogen lamp



The spectrum of hydrogen gas is a unique fingerprint of that element

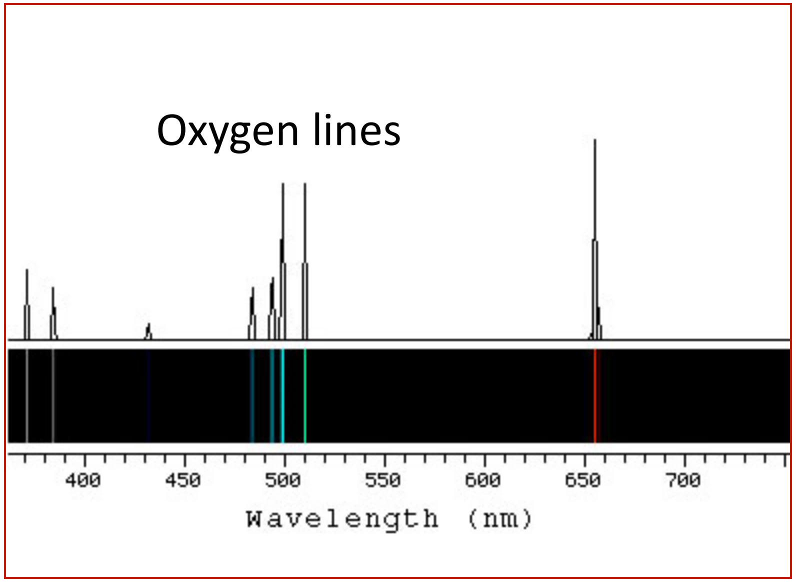


H-alpha line
656 nm

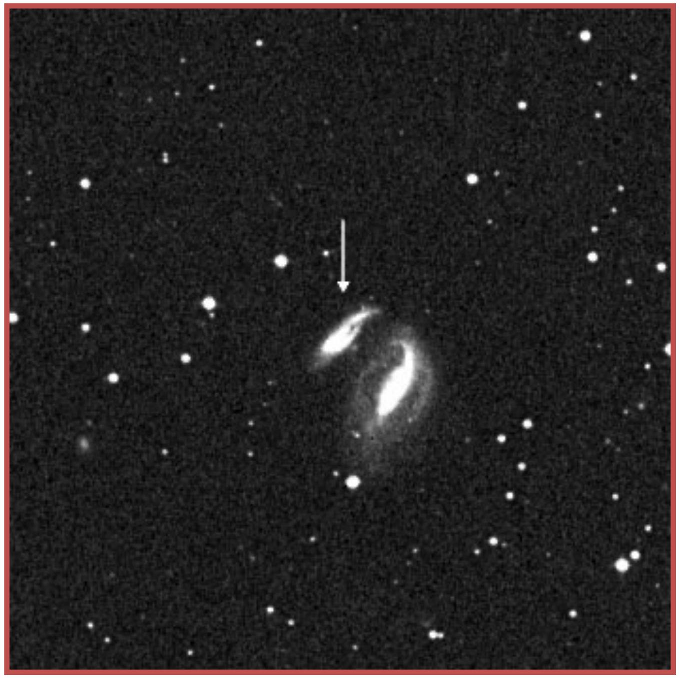
Evidence for an expanding universe

Orion Nebula

When we see a repeat of the pattern we saw in the lab, we know hydrogen is present

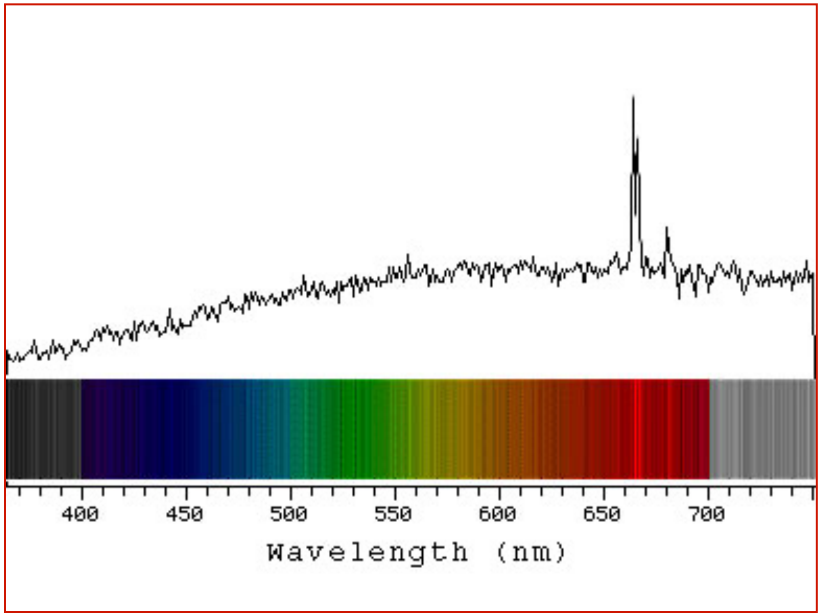


Evidence for an expanding universe



Galaxy UGC 12915

We see the same repeating pattern of lines in a galaxy, but displaced to the red

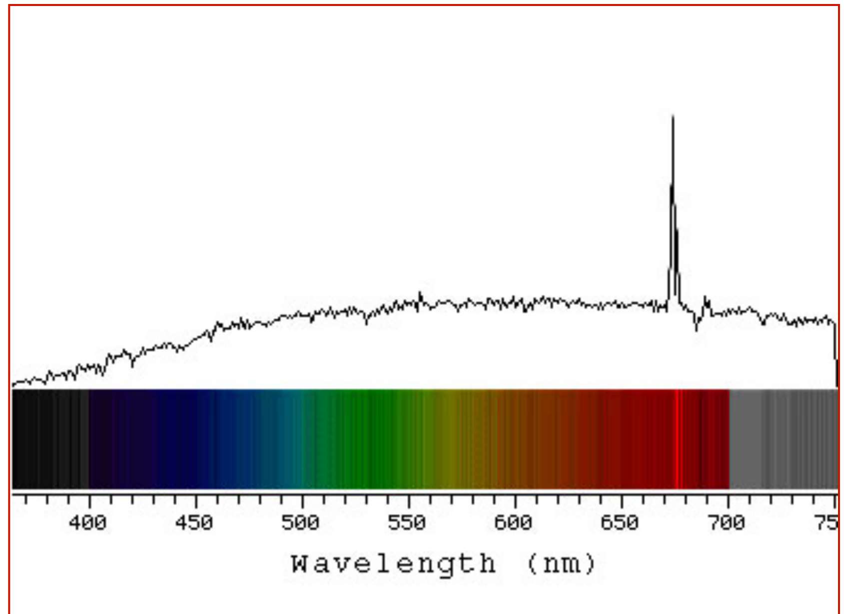


Data courtesy Emilio Falco, CfA

Evidence for an expanding universe

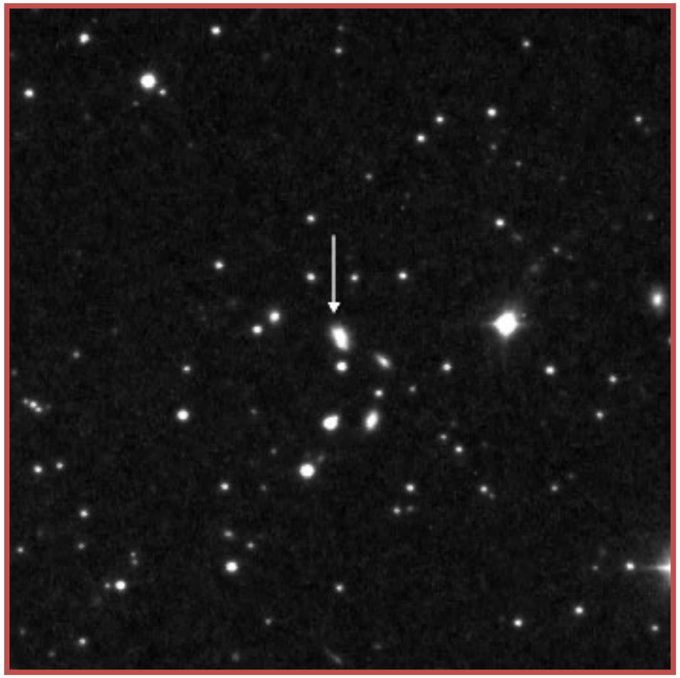
Galaxy UGC 12508

The further the galaxy,
the more the shift to the red



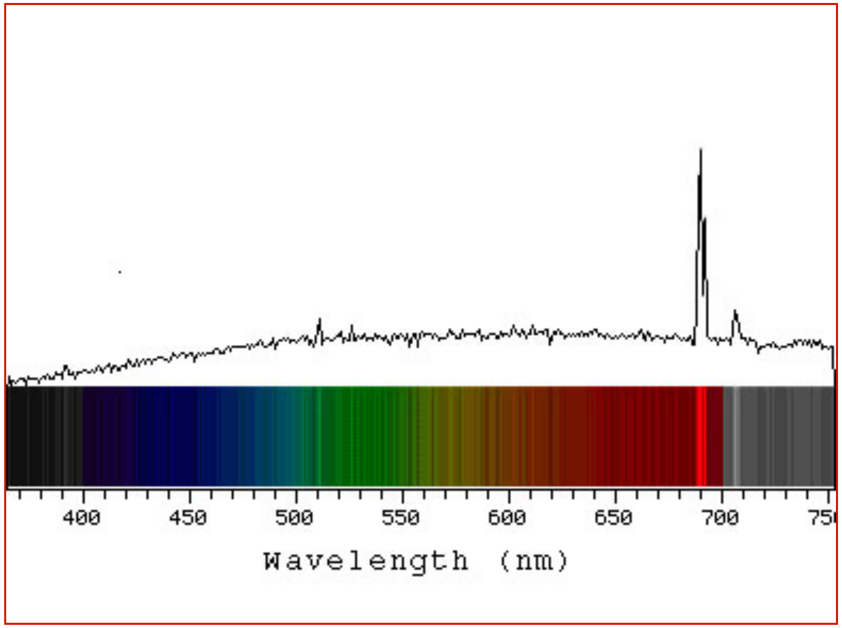
Data courtesy Emilio Falco, CfA

Evidence for an expanding universe



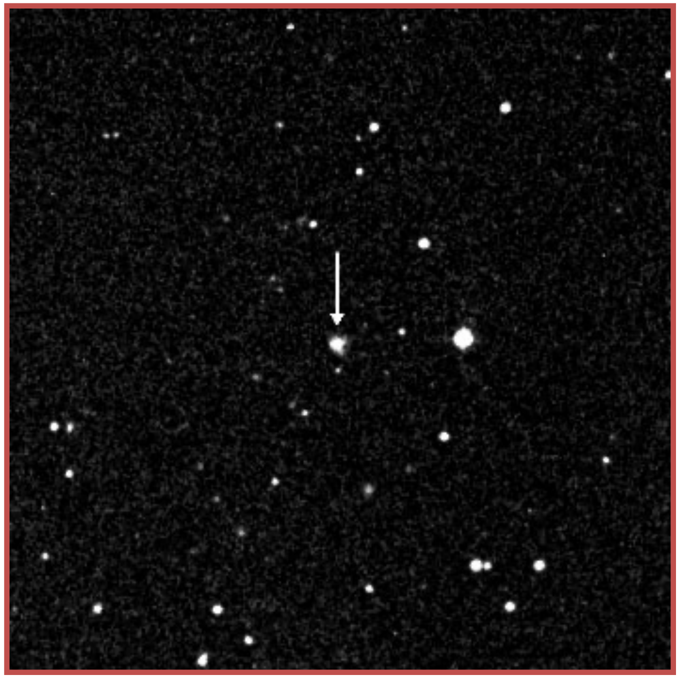
Galaxy KUG 1750

The greater the red shift,
the faster the galaxy is receding



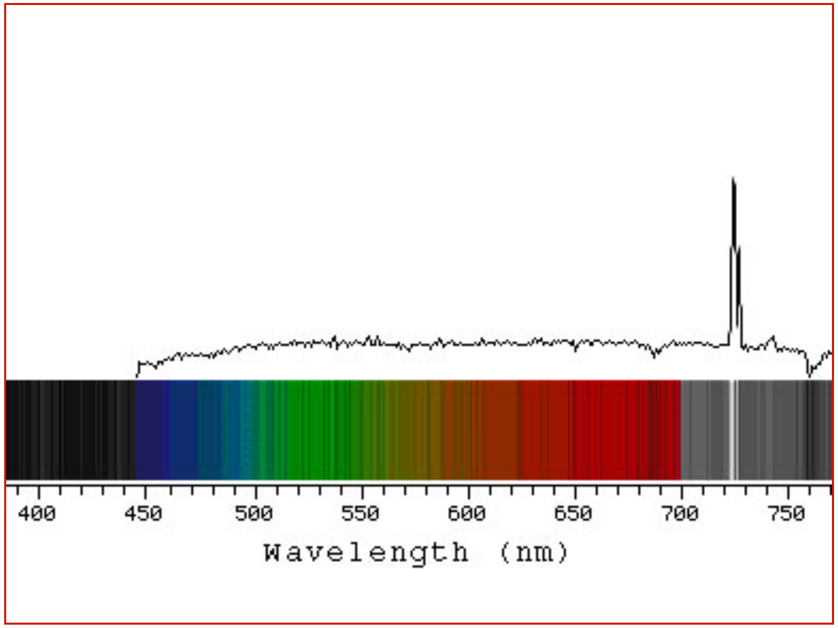
Data courtesy Emilio Falco, CfA

Evidence for an expanding universe



Galaxy KUG 1217

The red shift is caused
by the expansion of space.

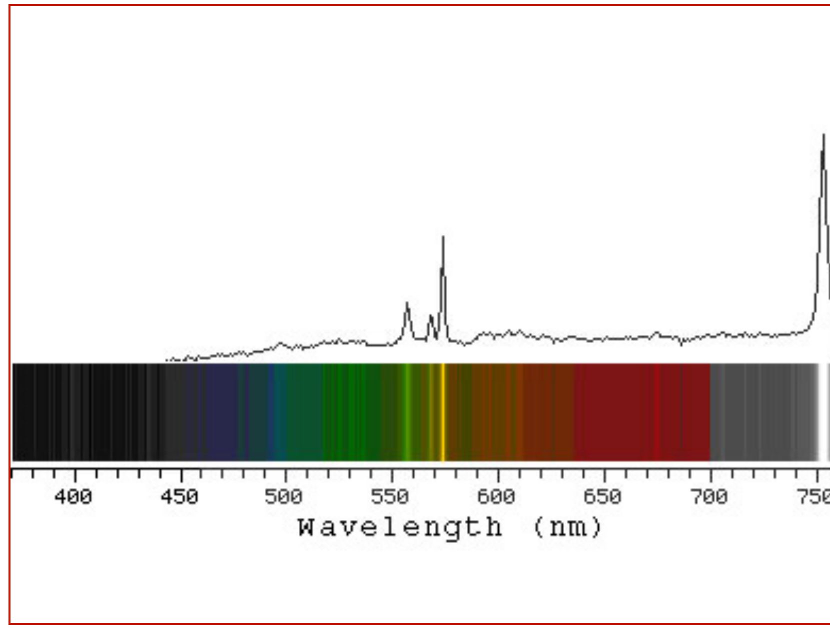


Data courtesy Emilio Falco, CfA

Evidence for an expanding universe

Galaxy IRAS F09159

The red shift is evidence for an expanding universe



Data courtesy Emilio Falco, CfA

redshift $$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

Goals of Cosmology

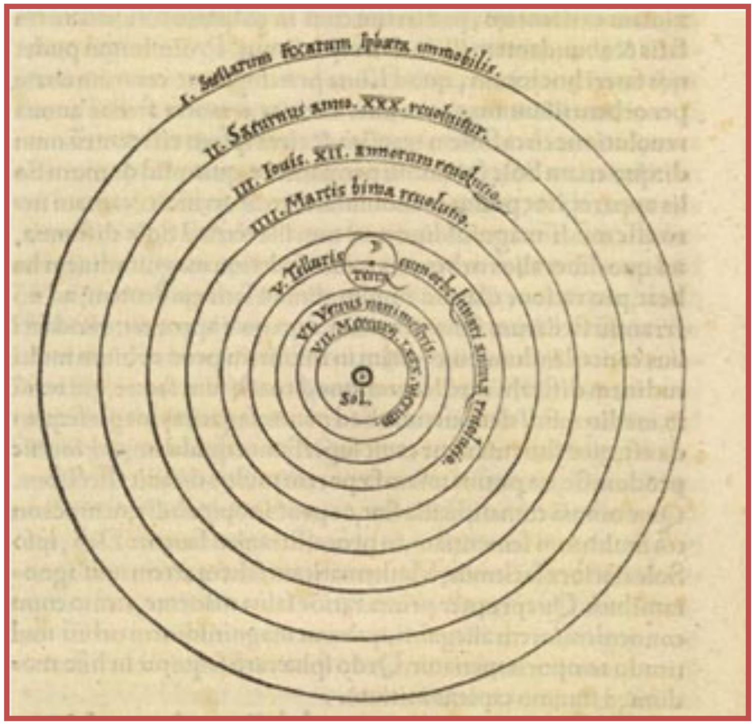
- Reconstruct the history of the Universe
- Understand the formation of nuclei and atoms
- Understand the formation of large-scale structure
- Find out what is the stuff that composes the Universe
- Grasp the nature of dark matter and dark energy
- Find whether the laws of nature are the same everywhere
- Explore very early epochs, very high energy: new physics?

A short history of Cosmology

Fourth-fifth century b.C.

Plato: the Universe has a beginning and an end
Aristotle: the Universe has no beginning and no end
Both: cosmic matter is made out of a “quintessence”

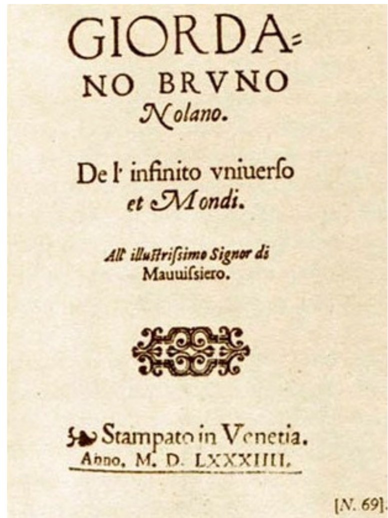
The Copernican revolution



Copernicus (1541):

The Earth moves! The Sun lies at the center!

An infinite Universe?



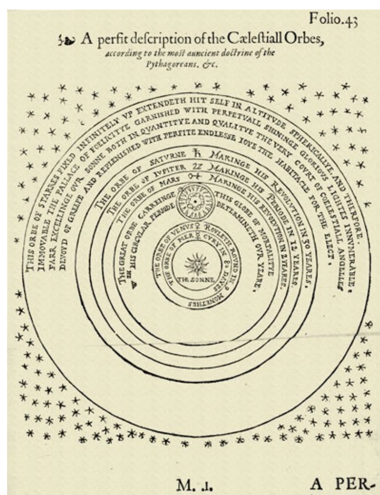
GIORDA-
NO BRVNO
Nolano.

De l' infinito vniuerſo
et Mondi.

All' illuſtriſsimo Signor di
Mauuiſsiero.

Stampato in Venetia.
Anno. M. D. LXXXIIII.

[N. 69]



16th century

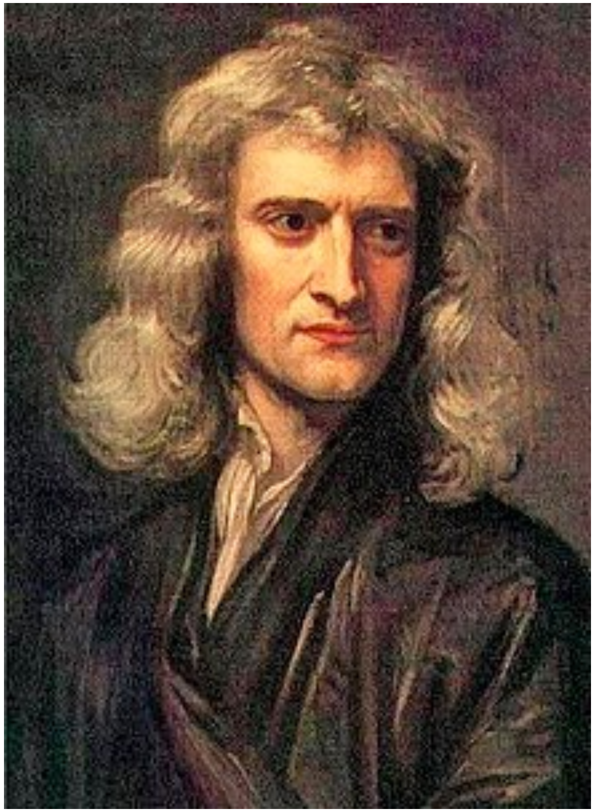
Giordano Bruno: the Universe and the “worlds” it contains are infinite (1584)

Thomas Digges: the first representation of an infinite Universe (1576)

Universal gravity

Newton: Universal gravitational law (1687)

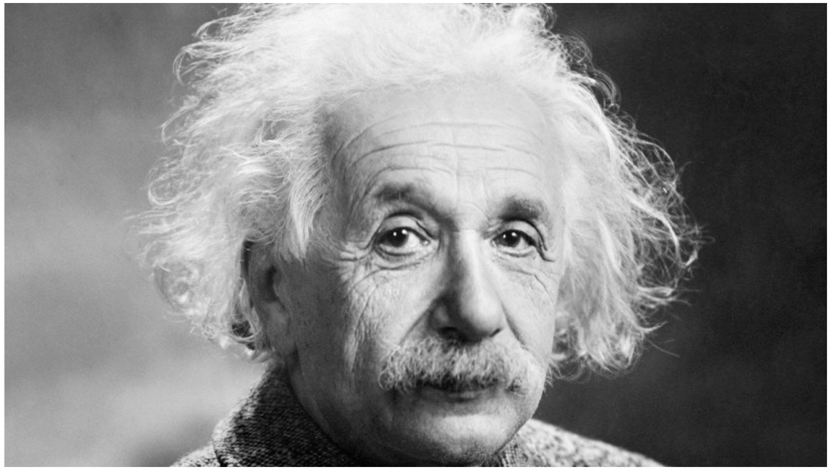
Problem of stability under gravity



Universal gravity

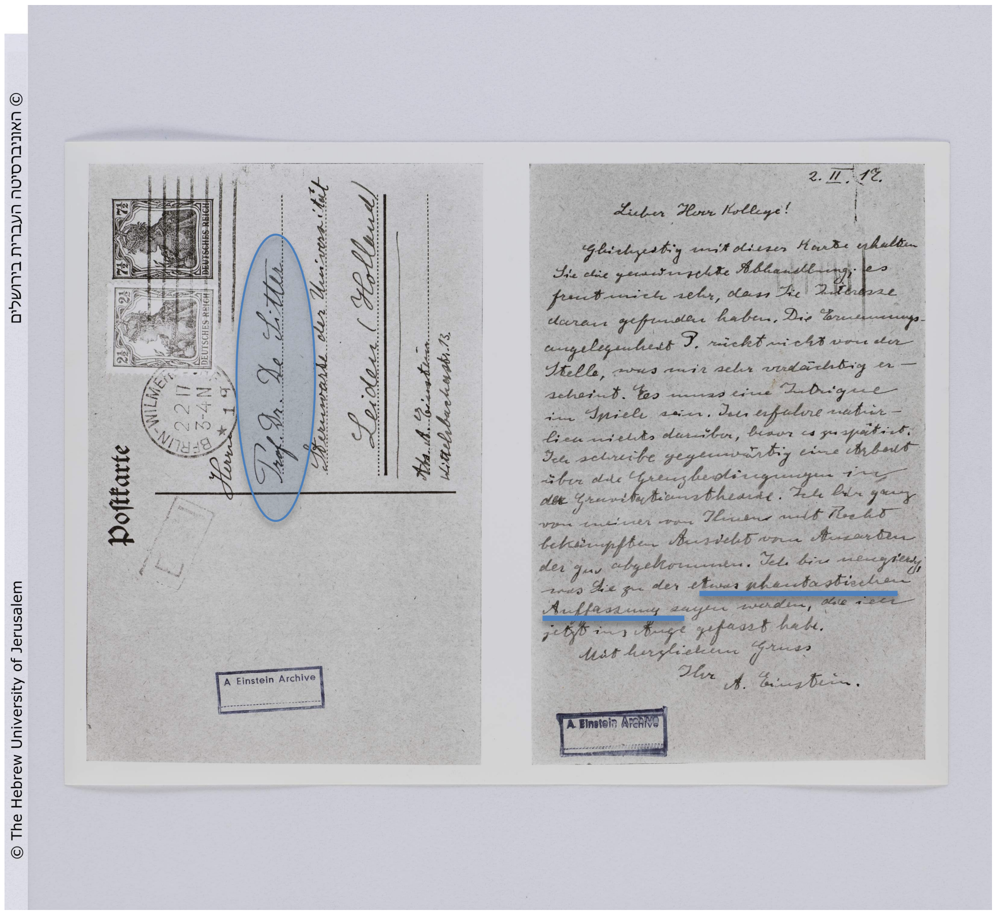
Einstein: Universal gravitational law (1915)

Problem of stability under gravity



$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \kappa T_{\mu\nu}$$

A somewhat crazy idea...


Postkarte

Herrn Prof. Dr. de Sitter
Sternwarte der Universität
Leiden (Holland)

Abs. A. Einstein
Wittelsbacherstr. 13

A Einstein Archive

2. II. 17.

Lieber Herr Kollege!

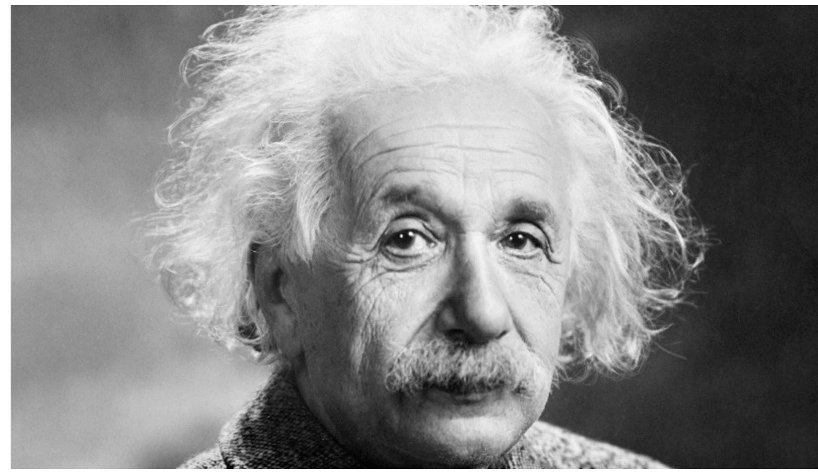
Gleichzeitig mit dieser Karte erhalten Sie die gewünschte Abhandlung; es freut mich sehr, dass Sie Interesse daran gefunden haben. Die Ernennungsangelegenheit P. rückt nicht von der Stelle, was mir sehr verdächtig erscheint. Es muss eine Intrigue im Spiele sein. Ich erfahre natürlich nichts darüber, bevor es zu spät ist. Ich schreibe gegenwärtig eine Arbeit über die Grenzbedingungen in der Gravitationstheorie. Ich bin ganz von meiner von Ihnen mit Recht bekämpften Ansicht vom Ausarten der $g_{\mu\nu}$ abgekommen. Ich bin neugierig, was Sie zu der etwas phantastischen Auffassung sagen werden, die ich jetzt ins Auge gefasst habe.

Mit herzlichem Gruss
Ihr A. Einstein.

A. Einstein Archive

Einstein to de Sitter 02.02.1917

Universal gravity reloaded



Einstein: General Relativity (1915)

Problem of stability under gravity!

The GR equations are unstable (gravity is attractive): in 1917, Einstein introduces the cosmological constant

and formulates the Cosmological Principle: the Universe is approximately homogeneous and isotropic

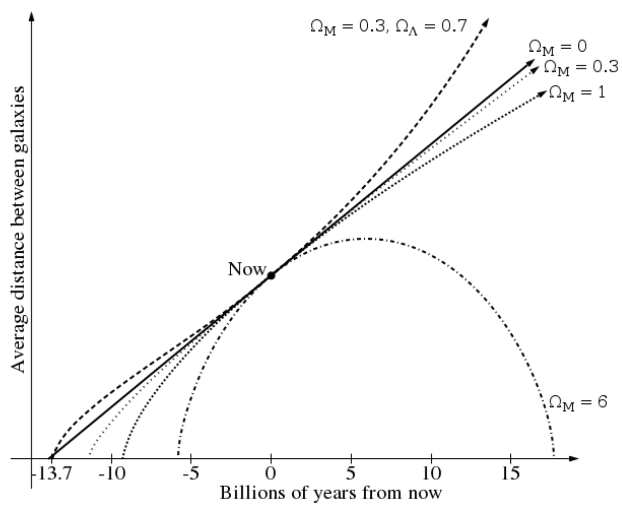
However, the system of equations (14) allows a readily suggested extension which is compatible with the relativity postulate, and is perfectly analogous to the extension of Poisson's equation given by equation (2). For on the left-hand side of field equation (13) we may add the fundamental tensor $g_{\mu\nu}$, multiplied by a universal constant, $-\lambda$, at present unknown, without destroying the general covariance. In place of field equation (13) we write

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T) \quad . \quad . \quad (13a)$$

This field equation, with λ sufficiently small, is in any case also compatible with the facts of experience derived from the solar system. It also satisfies laws of conservation of momentum and energy, because we arrive at (13a) in place of (13) by introducing into Hamilton's principle, instead of the scalar of Riemann's tensor, this scalar increased by a

A dynamical Universe

Alexander Friedmann: solving the cosmological equations (1921)

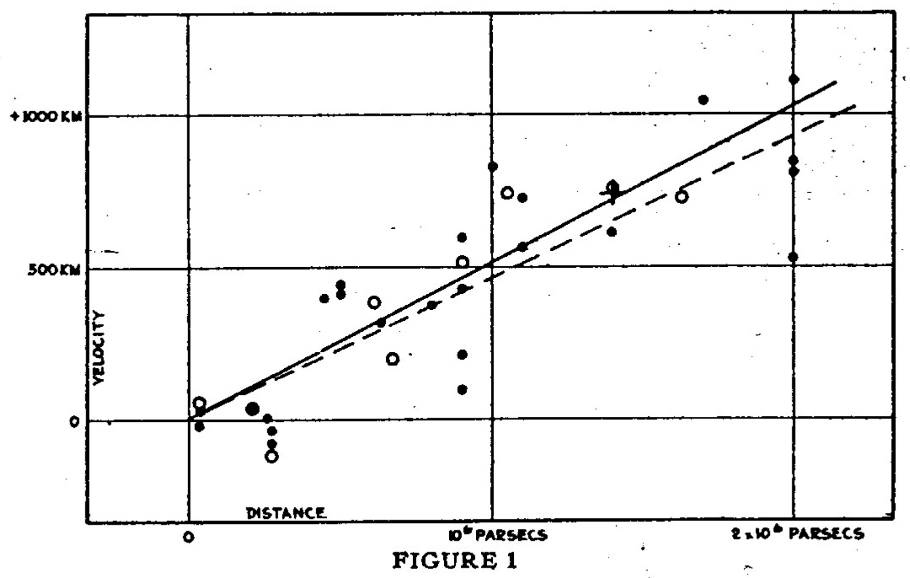


The expanding Universe

Edwin Hubble (1929): Hubble-Lemaitre Law
(also discovered by Lemaitre in 1927)

$$v = H_0 r$$

velocity

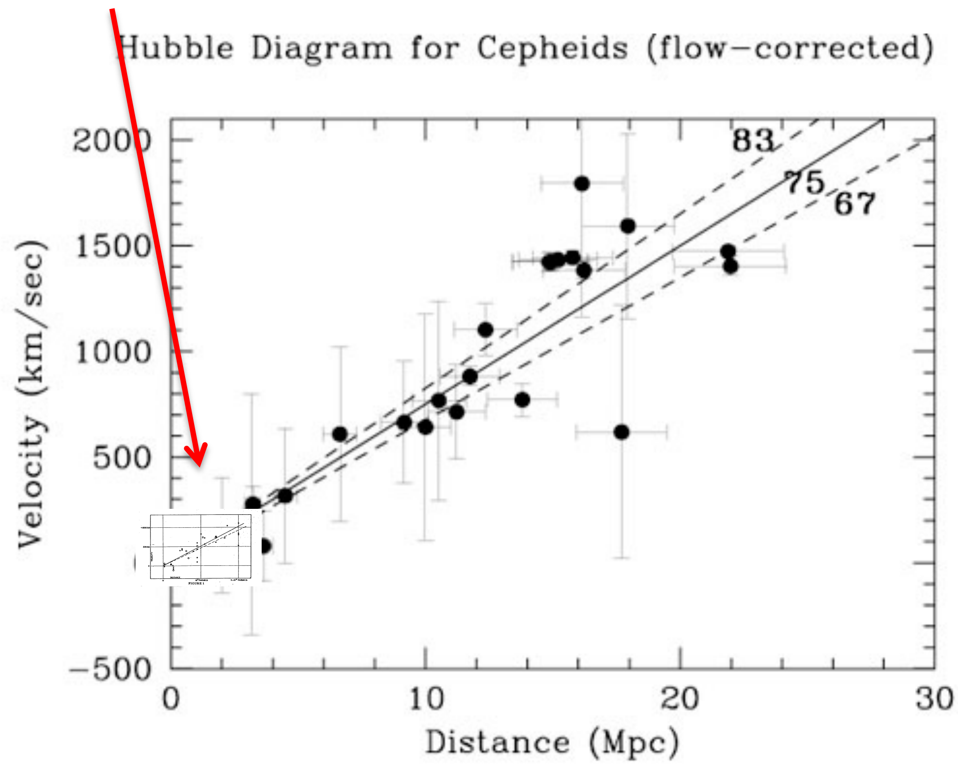


distance

The expanding Universe

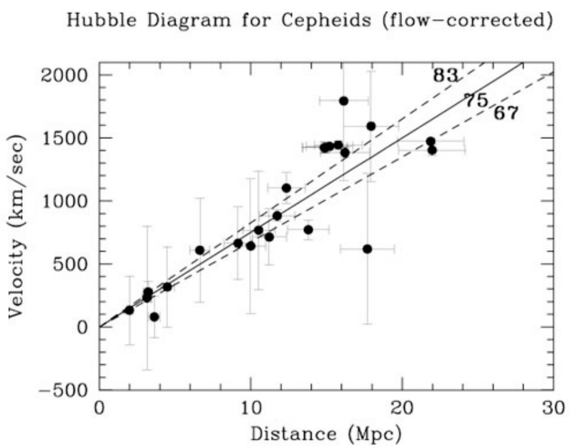
Edwin Hubble (1929): Hubble-Lemaitre Law
(also discovered by Lemaitre in 1927)

$$v = H_0 r$$



NASA Hubble ST

H_0 as space and time scale



$$v = H_0 r$$

$$H_0 = 70 \frac{km}{\sec \bullet Mpc} = 100h \frac{km}{\sec \bullet Mpc}$$

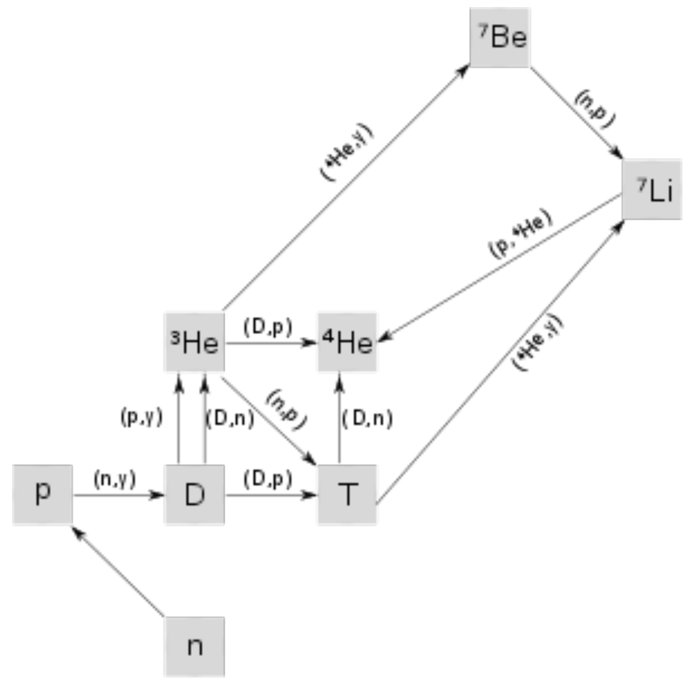
$$\frac{c}{H_0} = 3000 \,\text{Mpc} / h$$

$$\frac{1}{H_0} = 10 \,\text{Gyr} / h$$

Hot big bang:
Cosmology becomes a science

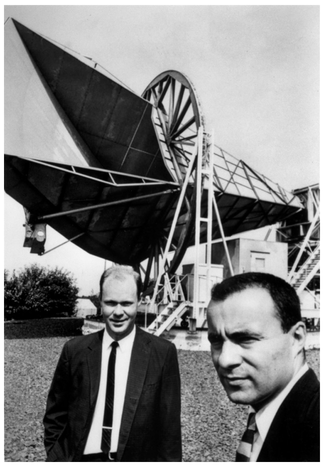
Hot big bang

George Gamow (50s): physical consequences of a hot phase: formation of light nuclei, cosmic relic radiation around 5K



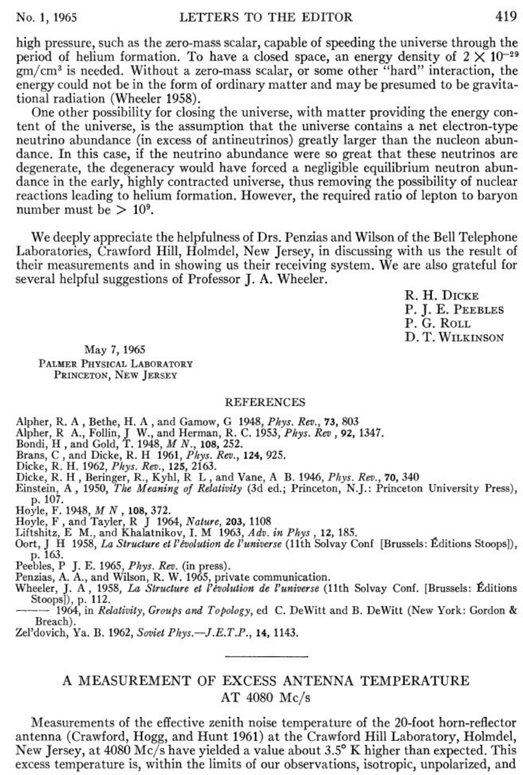
Cosmic Microwave background

Arno Penzias and Robert Wilson (1965): excess temperature at 3K uniform in the sky



Explanation
(Dicke et al.)

Discovery
(Penzias and Wilson)



No. 1, 1965 LETTERS TO THE EDITOR 419

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.
Bondi, H , and Gold, T. 1948, *M N.*, **108**, 252.
Brans, C , and Dicke, R. H 1961, *Phys. Rev.*, **124**, 925.
Dicke, R. H. 1962, *Phys. Rev.*, **125**, 2163.
Dicke, R. H , Beringer, R., Kyhl, R L , and Vane, A B. 1946, *Phys. Rev.*, **70**, 340
Einstein, A , 1950, *The Meaning of Relativity* (3d ed.; Princeton, N.J.: Princeton University Press), p. 107.
Hoyle, F. 1948, *M N* , **108**, 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203**, 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12**, 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

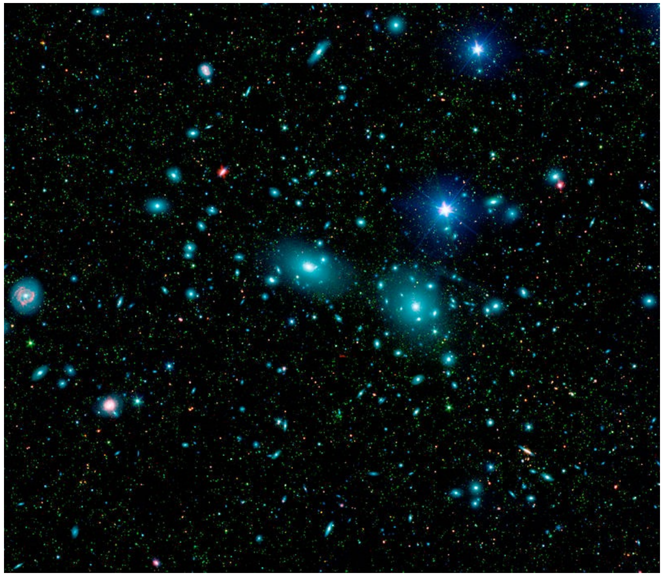
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

Hot topics in Cosmology

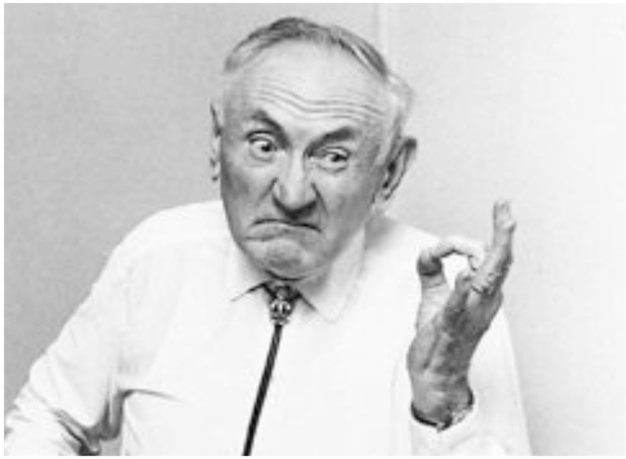
- Dark matter
- Inflation
- Cosmic Microwave Background
- Dark energy

Dark matter?

Fritz Zwicky (30s): mismatch between light and mass in Coma cluster



NASA / JPL-Caltech / L. Jenkins (GSFC)



Dark matter!

Vera Rubin and Kent Ford (1970): rotational curves of galaxies in excess of expected from visible light

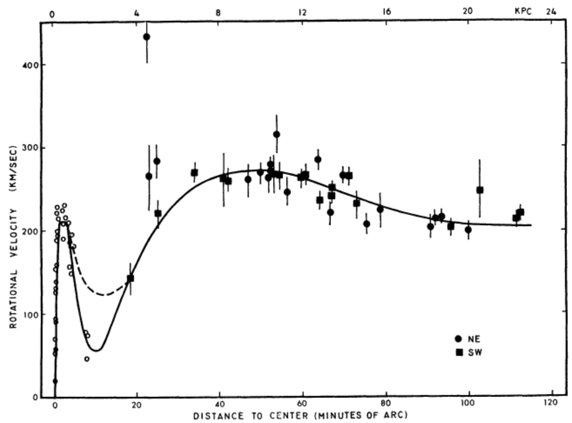
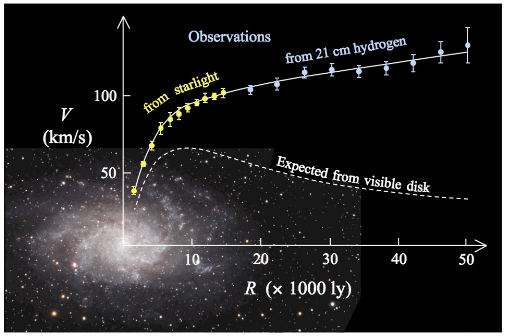
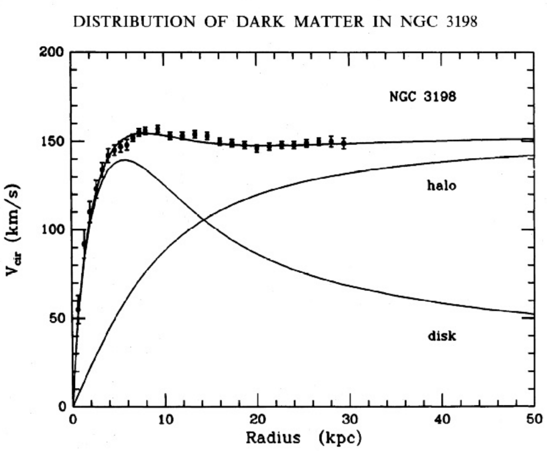


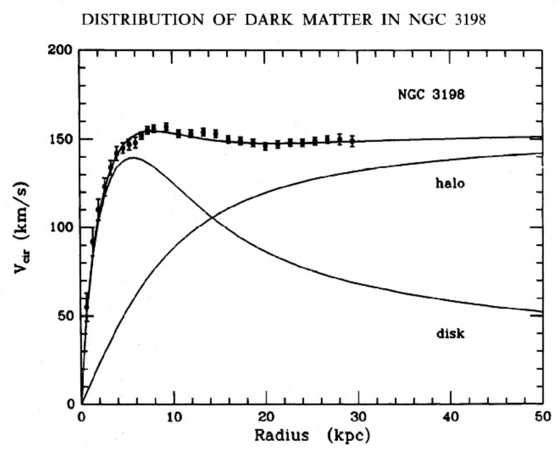
FIG. 9.—Rotational velocities for OB associations in M31, as a function of distance from the center. *Solid curve*, adopted rotation curve based on the velocities shown in Fig. 4. For $R \leq 12'$, curve is fifth-order polynomial; for $R > 12'$, curve is fourth-order polynomial required to remain approximately flat near $R = 120'$. Dashed curve near $R = 10'$ is a second rotation curve with higher inner minimum.

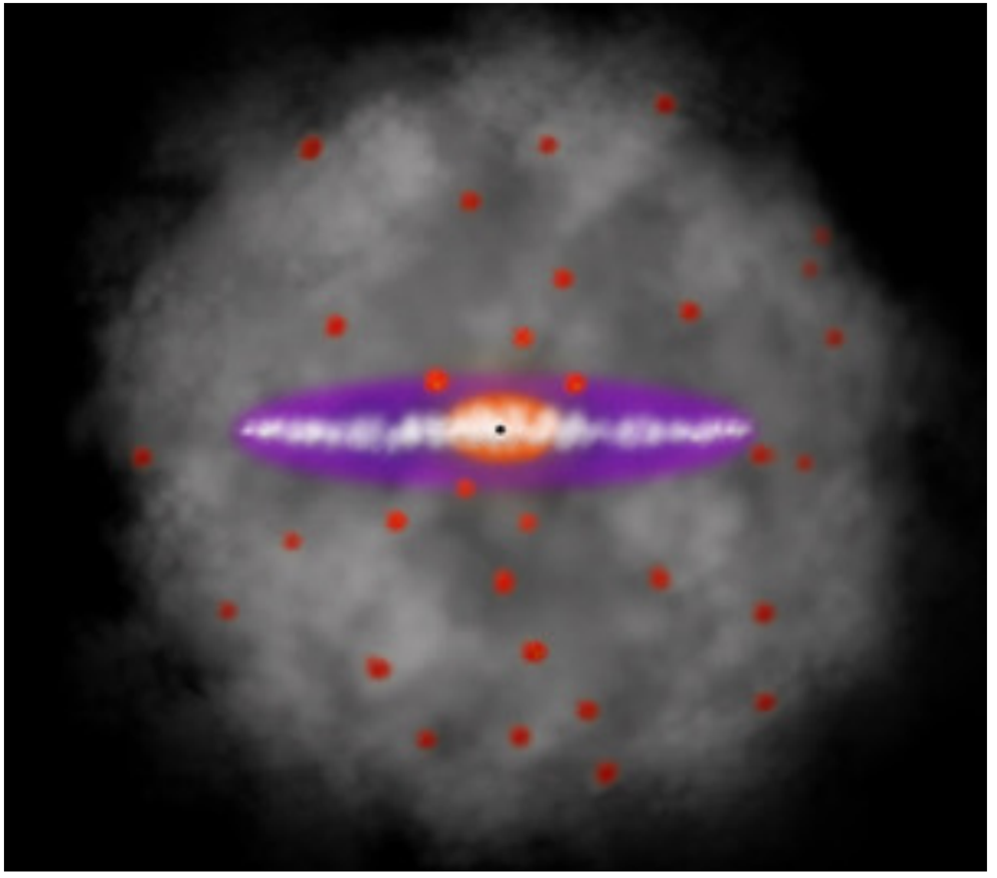
Andromeda galaxy





Dark matter!

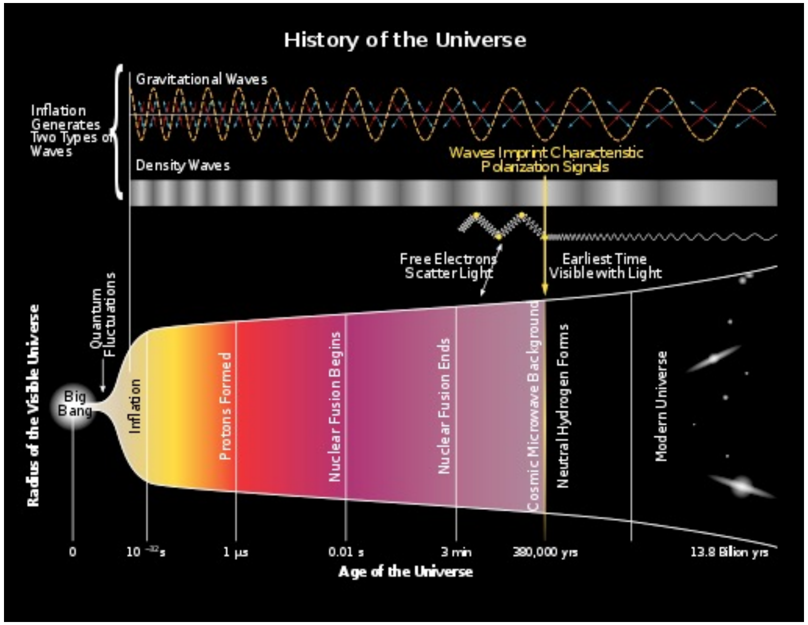




NASA/CXC/M.Weiss

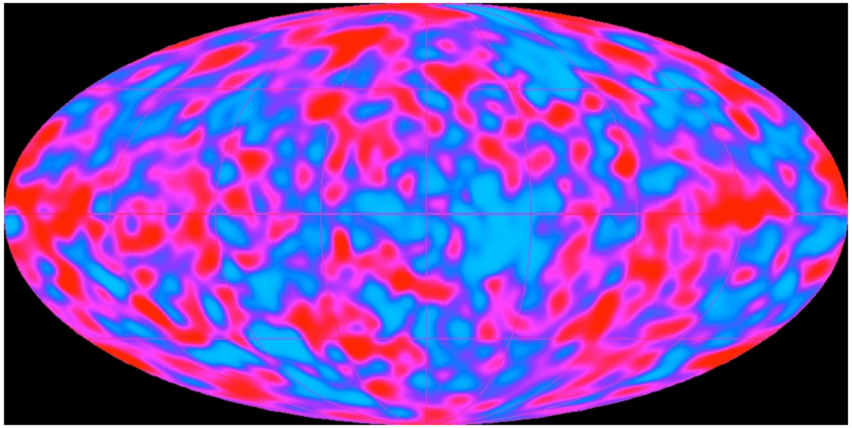
Inflation

Alan Guth (1981): after pioneering work by A. Starobinsky and others,
Guth proposes the inflationary model to explain the puzzles of standard cosmology

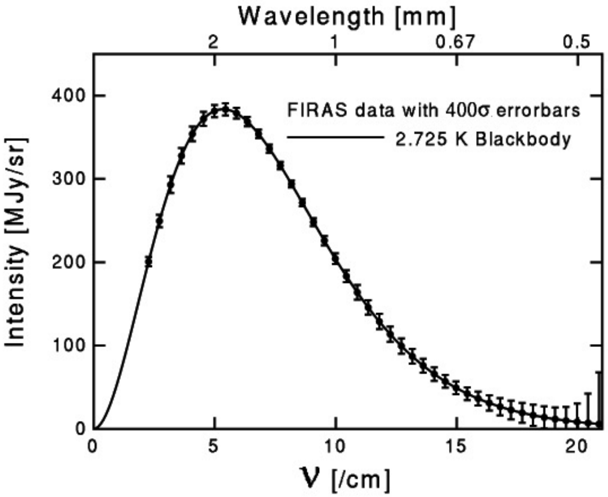


CMB fluctuations

COBE satellite (1992): the black-body 2.7K fluctuations on the CMB sky are finally detected, in agreement with expectations from the standard model with inflation



COBE map (NASA)

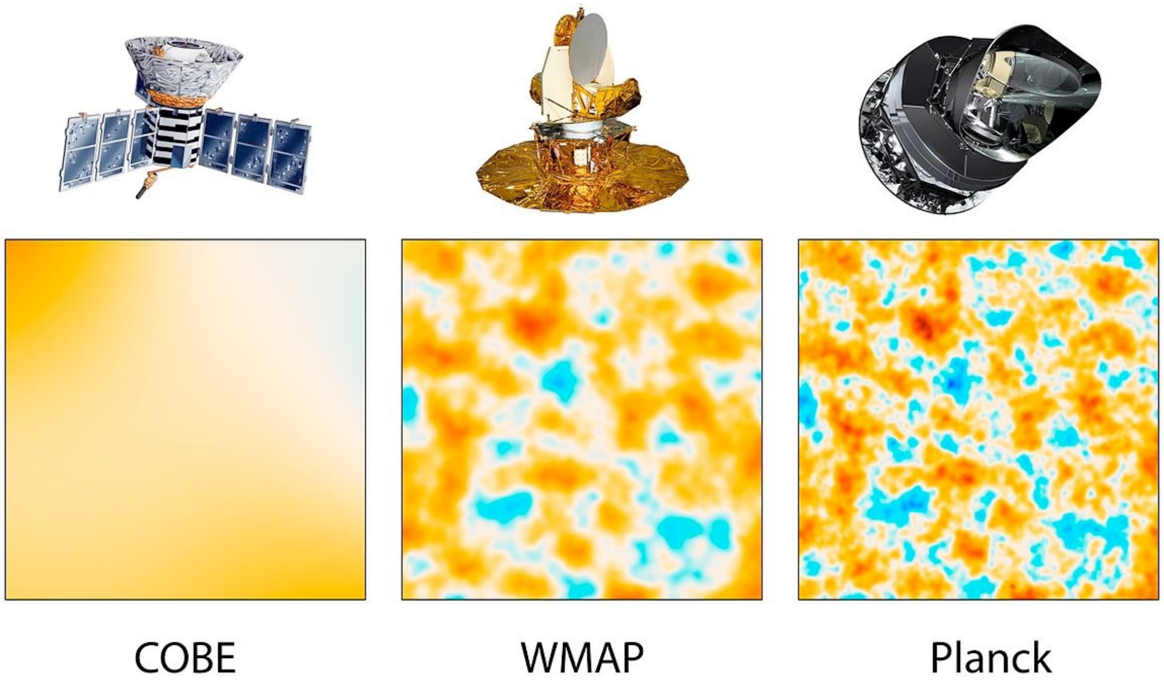


COBE FIRAS spectrum (NASA)

CMB fluctuations

COBE, WMAP, Planck: 25 yrs of CMB research in space

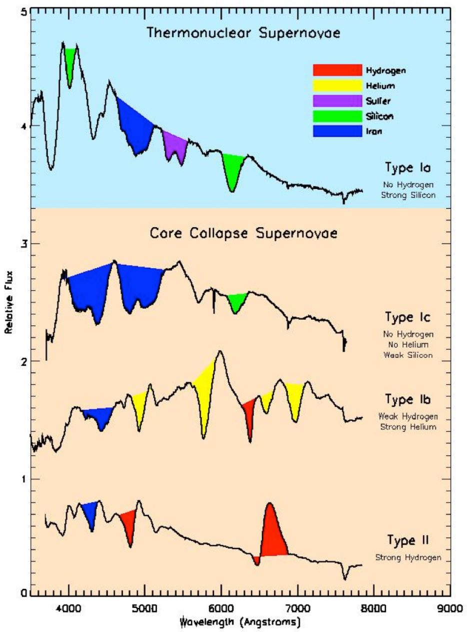
10 sq. deg.



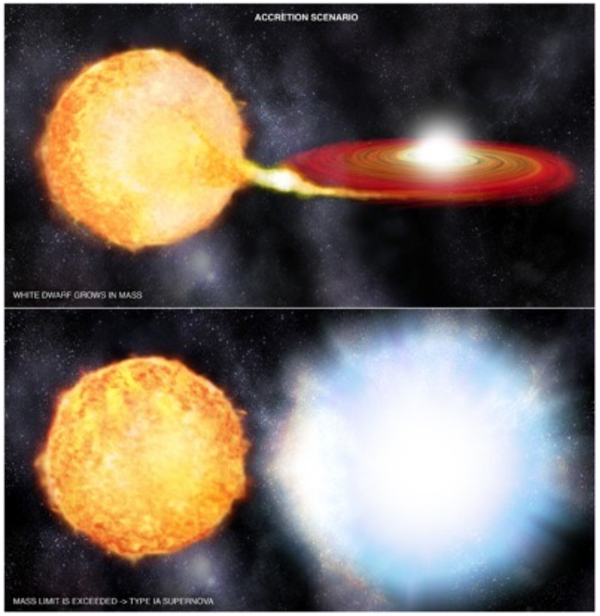
NASA/JPL-Caltech/ESA

Cosmic Acceleration

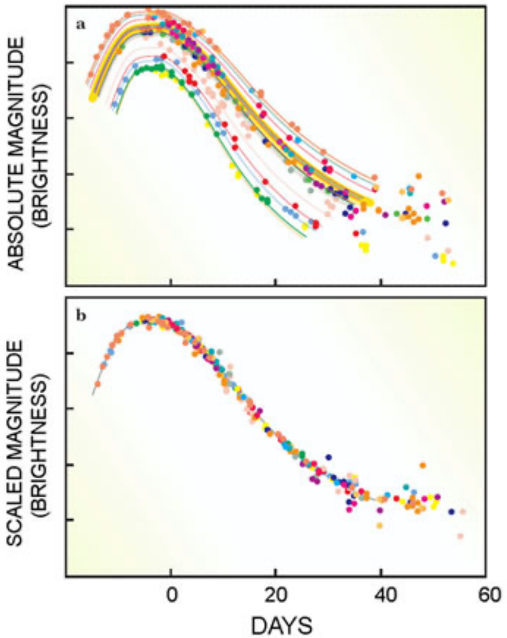
90s: supernovae Ia are standard candles



(from supernova.lbl.gov).



NASA/CXC/M Weiss



(Hamuy et al. 1996).

Supernovae

Credit: B. Dilday and the Sloan Digital Sky Survey.

Cosmic Acceleration

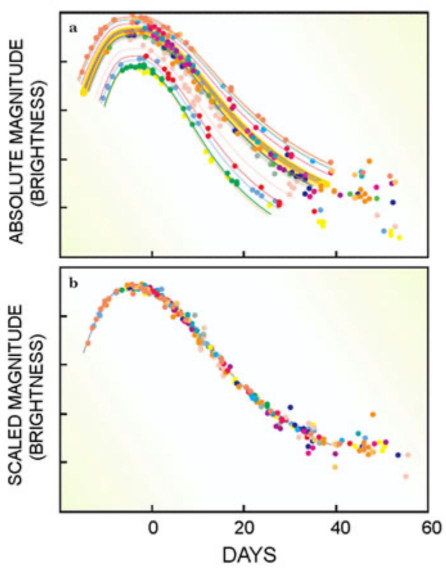
90s: supernovae Ia are standard candles

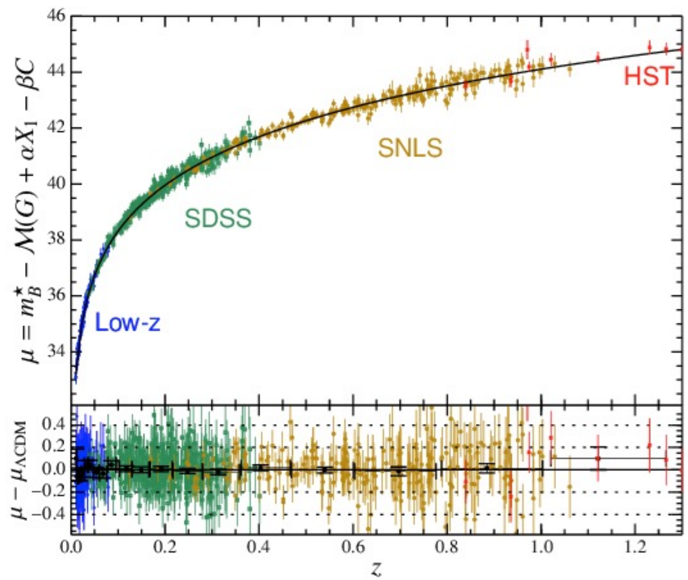
$$flux = \frac{\text{luminosity}}{4\pi \text{distance}^2}$$

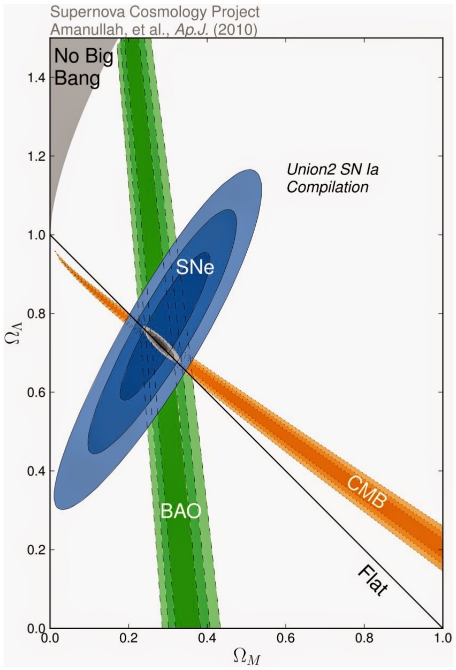
$$\frac{\text{velocity}}{\text{distance}} = \text{Hubble-constant}$$

Cosmic Acceleration

1998: discovery of the cosmic acceleration by Perlmutter, Schmidt, Riess







Course

Part I: the homogeneous Universe

General relativity, FLRW metric, Friedmann equations, radiation and matter era, thermal history, age of the Universe, cosmological constant, inflation

Part II: the inhomogeneous Universe

Linear perturbation theory, statistics of spatial distributions, inflationary perturbations, CMB, galaxy power spectrum, weak lensing

Part III: Galaxies and Clusters

Non-linear perturbations, masses of galaxies and clusters, diffused gas, dark matter

Texts:
- lecture notes (see course web page)
- S. Dodelson, Modern Cosmology
- L. Amendola & S. Tsujikawa, Dark Energy

for other texts, see lecture notes

Exercises

- Tutorial begin next week
- Every Monday, I'll post the exercise sheet on the course web page http://www.thphys.uni-heidelberg.de/~amendola/teaching.html
- The exercises have to be handed in by the subsequent Monday (or Tuesday is there is a holiday)
- You can work alone or in pairs
- You should send the pdf or a clearly readable picture of your solution to your tutor via email (or arrange with the tutor other ways to hand in the sheets, e.g. in person)
- exercises will be discussed in the tutorials (except for the first week)
- they will be (generously) graded
- You have to pass a minimum threshold (roughly half the points) to be admitted to the final exam
- even if you fail to submit one or two sheets, you can easily reach the required threshold if you work seriously on the other exercises
- you might earn extra points if you offer to solve some exercises during the tutorials
- some exercises require you to read the lecture notes beyond the lectures!

Random tips

- Read the lecture notes before the lectures
- read also at least one book of introduction to cosmology, e.g. one of those suggested on the course web page
- ask questions to yourself, to your colleagues, to the tutors and of course to me
- the lecture notes are quite complete; there is no need to take too many notes in class
- GR is not a requirement but we will use it at various points in the course and some important concepts will be introduced; if did not have any GR so far, you should read the basics, e.g. on my GR lecture notes or on a book (eg B. Schutz, A First Course in GR)