PUBLIC UNDERSTANDING OF SCIENCE **(Abridged version, short text)**

Light in life and science

The role of light in nature and science is discussed using typical examples from biology, physics and cosmology.

by Georg Wolschin

The UNESCO Year of Light 2015 has created an incentive for many individuals and institutions to reconsider the role of light (Fig. 1) in general and more specifically, in science.

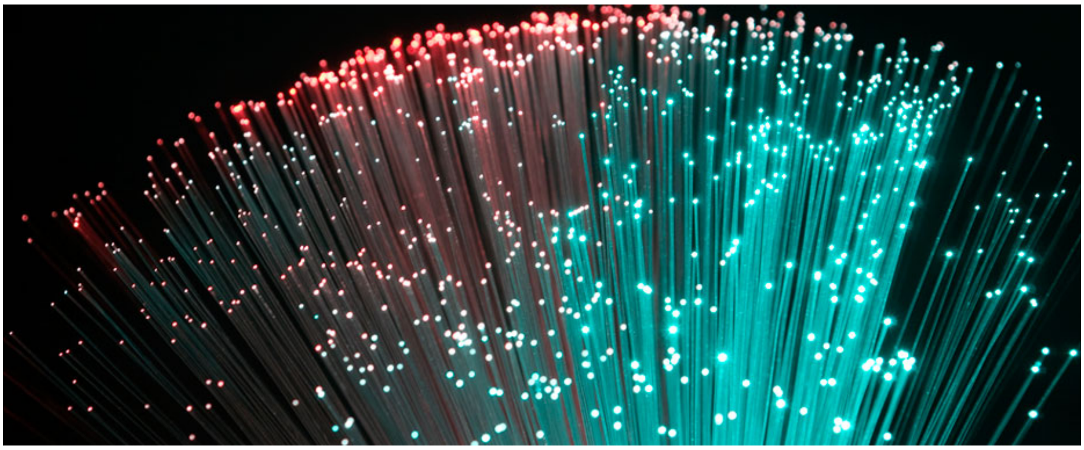


Fig. 1: Light is in the air. © International year of light 2015.

Light fascinates people (Fig. 2) and it beautifies nature, as is evident to everybody who has watched optical events such as polar light (Fig. 3).

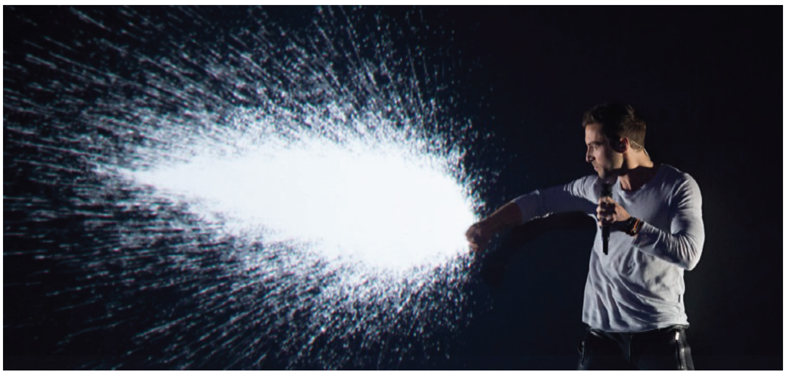


Fig.2: © Måns Zelmerlöw, Eurovision song contest 2015.

Fig. 3: Polar light. © International year of light 2015.

The aurora can not only be seen on the earth, but also from outer space where it is quite spectacular (Fig. 4)

Fig. 4: Aurora as seen from the space station. © NASA/ Scott Kelly.

In addition to the obvious role in nature, light also offers an important cultural dimension for humans, in particular in a religious or spiritual context (Fig. 5)

Fig. 5: Candlelight. © International year of light 2015.

Light has invaded and influenced all areas of science and technology (Fig.6) ...

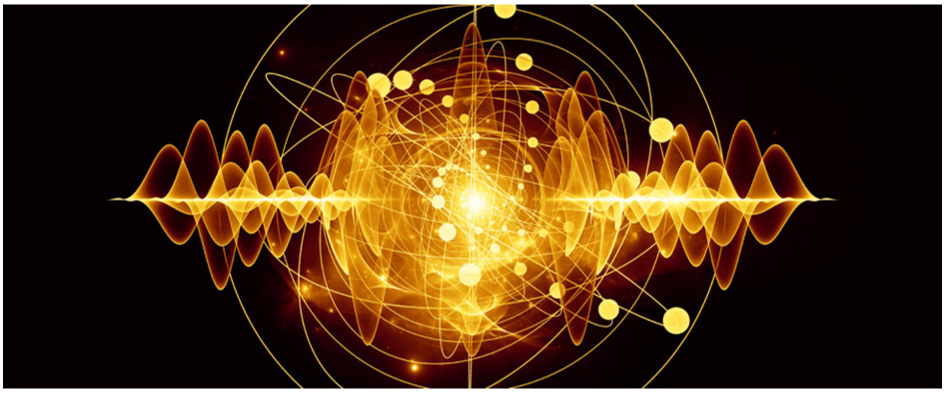


Fig. 6: Oscilloscope. © International year of light 2015.

... and in particular, biology. See this example of a female glowworm that attracts males with her light. Interestingly, the efficiency of energy conversion to light in her body is about 95 %, far above what technology can achieve today.

Fig. 7: Female glowworm. © Wikipedia.

On a more serious account, biological research based on light has made great progress in the past 15 years. This is particularly due to the successful works that extend light microscopy below the so-called Abbe limit. This law had been considered as insurmountable for many years. It relates the smallest distance d that an optical microscope can resolve to the wavelength λ of light according to $d = \lambda / (n \cdot \sin\alpha)$, with the angular aperture 2α and the index of refraction n of the medium (air or a fluid). Using fluorescence markers, it has turned out to be possible to undercut this limit and provide optical images of biological structures in unprecedented resolution (Fig. 8).

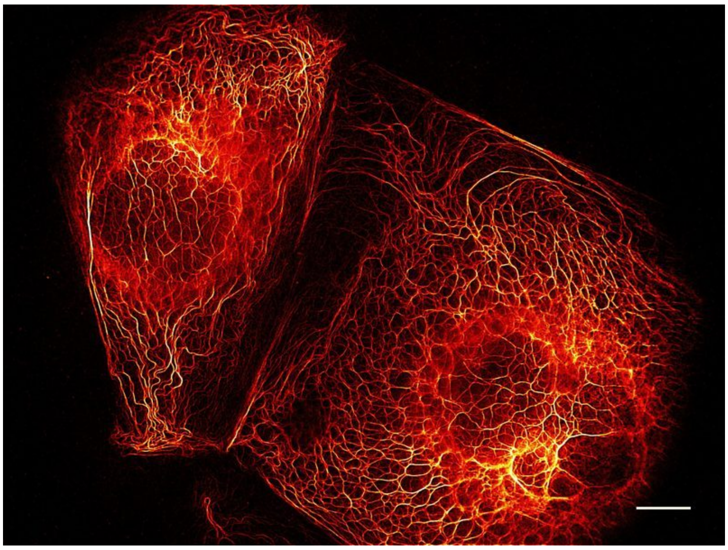


Fig. 8: RESOLFT (Reversible saturable optical fluorescence transitions) microscopy provides optical images of protein structures (here: Keratin) in living cells. Scale = 10 μm. © MPI für biophysikalische Chemie / Stefan W. Hell, Andriy Chmyrov.

Not only in biology, but also in other research fields such as geology and astrophysics light has an important role, as is immediately obvious when watching the impact of a meteorite hitting the earth (Fig. 9)

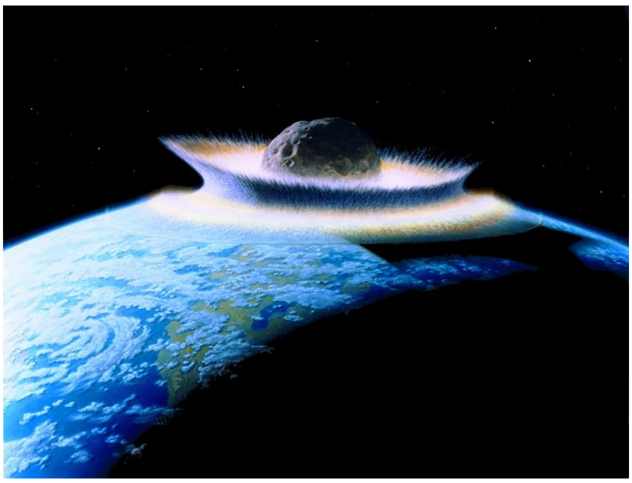


Fig. 9: Asteroid hits the earth, with spectacular optical emissions (artist's view, © Don Davis).

Whereas asteroid impacts on earth are difficult to predict and even more so, to prevent, man-made disasters such as the atomic bomb explosions above Hiroshima and Nagasaki – which were also accompanied by intense optical emissions – will hopefully not occur any more in the future.

Fig. 10: Fission bomb mushroom clouds above Hiroshima (uranium) and Nagasaki (plutonium). The two bombings, which killed at least 129,000 people, remain the only use of nuclear weapons for warfare in history. © New York Times.

Electromagnetic waves are usually not restricted to the optical part of the spectrum. Visible light spans only a small fraction of the electromagnetic spectrum; the significant rest (Fig. 11) is important in daily life as well as in many research fields.

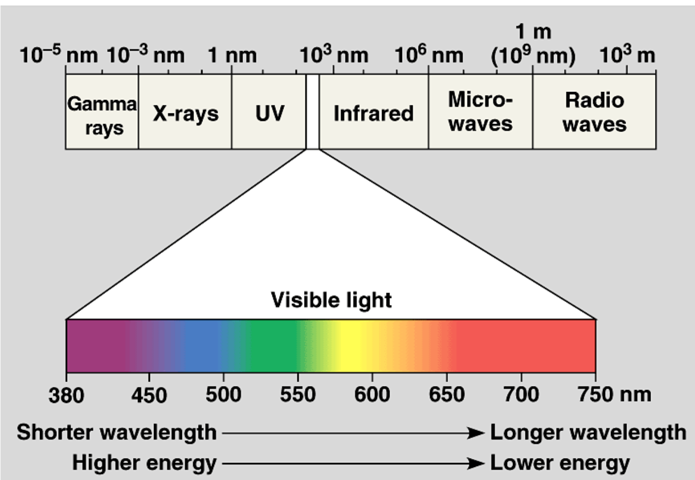


Fig. 11: Visible light spans only a small fraction of the electromagnetic spectrum. © Wikipedia.

Astronomy for example started with optical investigations of the sky, first with the bare eye, later – in the 17th century by researchers such als Galileo Galilei (Fig. 12) with optical telescopes.

Fig. 12: Galileo Galilei (1564 – 1642). The Galileo Project is a source of information on the work and life of Galileo. © Wikipedia.

Nowadays optical telescopes have mirror diameters of 8 meters and more. Fig. 13 shows the European Extremely Large Telescope (E-ELT) design with a main mirror diameter of 39 meter. It will be built in the Atacama desert in Chile, first light is planned for 2024. Atmospheric turbulences will be corrected using adaptive optics. Spectrography will not only be possible in the optical, but also in the infrared region of the spectrum.

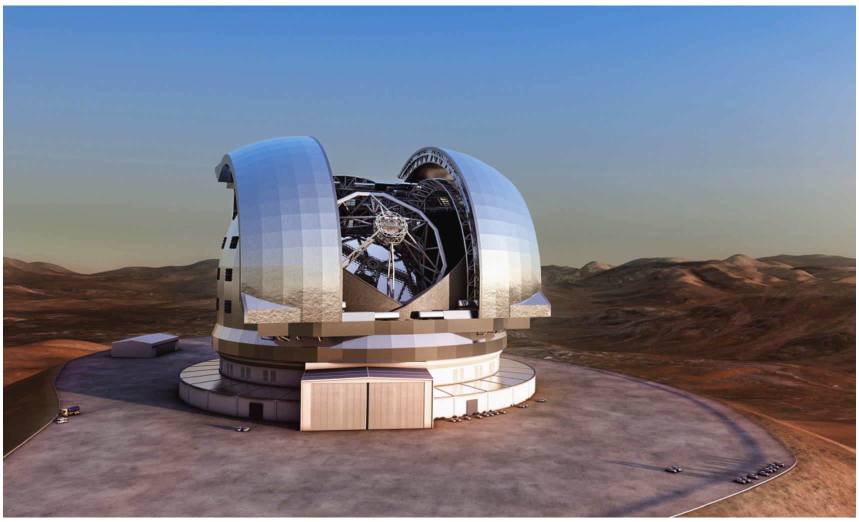


Fig. 13: Extremely Large Telescope, design study. © ESO.

The sun and stars emit ultraviolet, visible and infrared light. The spectrum of a star is close to a blackbody spectrum, it is in thermal equilibrium (Fig. 14). However, many processes in astrophysics deviate strongly from thermal equilibrium – such as jets in galaxies.

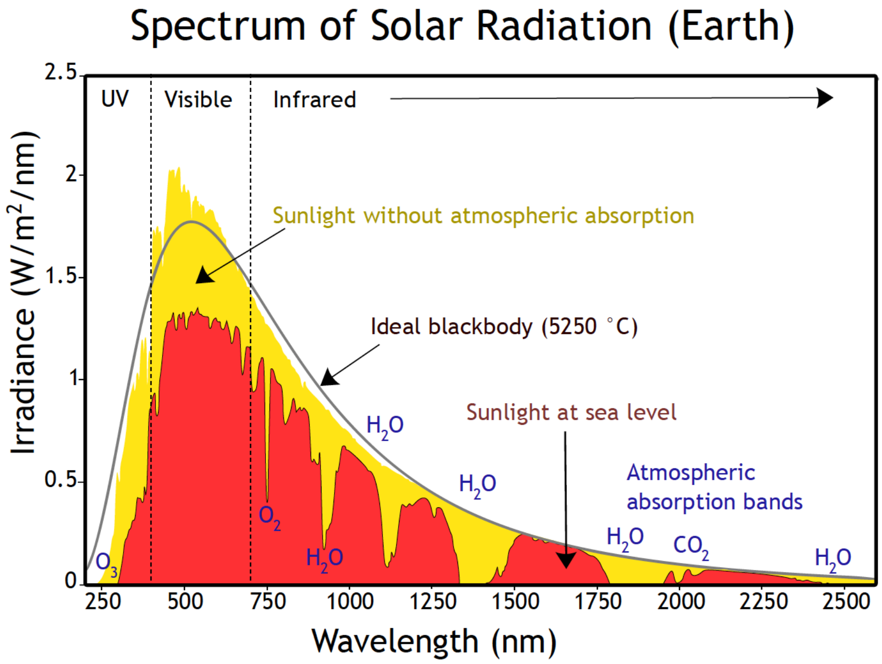


Fig. 14: Spectrum of the solar radiation. © Wikipedia.

The light that stars emit is partially absorbed by the stellar atmospheres. The detection of characteristic Fraunhofer absorption lines (Fig. 15) allows to identify the corresponding elements

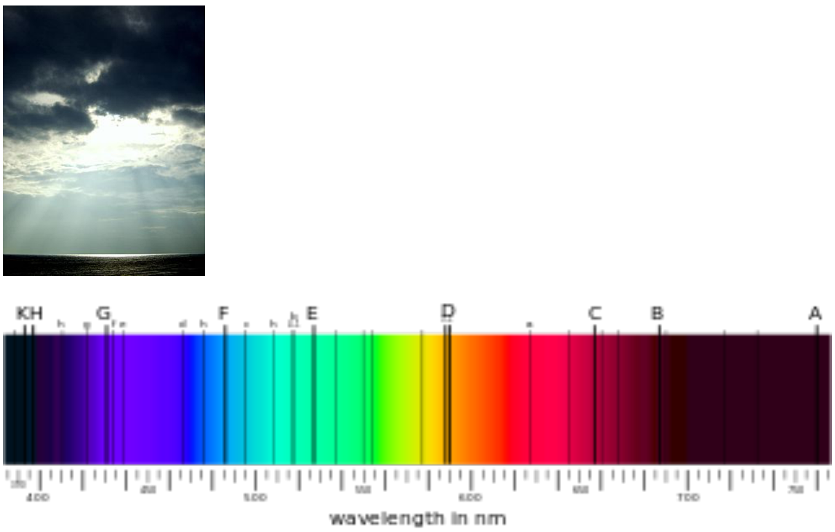


Fig. 15: Fraunhofer absorption lines in the solar spectrum. © Wikipedia.

There was also light in the beginning of the universe (Fig. 16). Matter and antimatter was then created from energy, $E = \sqrt{(p^2 + m^2)}$, and the universe became opaque, it expanded and cooled..

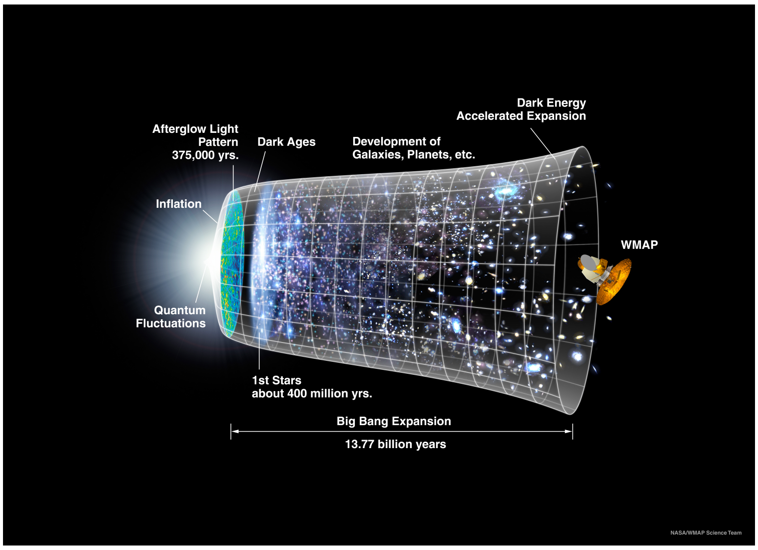


Fig. 16: Evolution of the universe. © WMAP Collaboration.

..until 380 000 years after the big bang electrons and protons formed hydrogen atoms, and the universe became transparent: We can now look back to this dawn of time (Fig. 18).

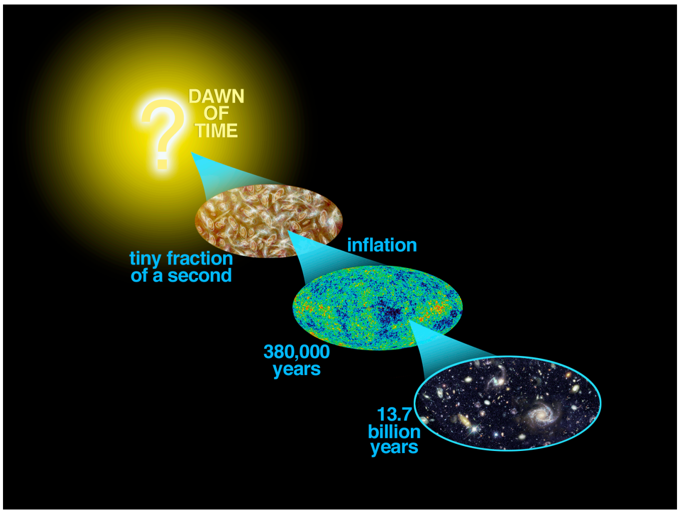


Fig. 17: Inflationary phase in the evolution of the universe.
© WMAP Collaboration.

The redshift of spectral lines (their shift towards longer wavelengths) that was discovered by Vesto Slipher (Fig. 18) is evidence for the expansion of the universe as time progresses. Edwin Hubble discovered a linear relation between the expansion velocity and the distance: the farther away a galaxy is, the faster it recedes from all other galaxies.

Fig. 18: Vesto Slipher and Edwin Hubble. © Wikipedia.

One can measure the full spectrum of the cosmic microwave background radiation (CMB) that had been discovered by Penzias and Wilson in 1964/65 at a single frequency (4.1 Gigahertz). It turns out to be the best blackbody spectrum occuring in nature – much more precise than the solar spectrum discussed before. The measurement (Fig. 19) was performed with various instruments - earth-bound telescopes as well as spectrometers on balloons and satellites, notably with the COBE (Cosmic background explorer) satellite in the time period 1989 to 1993. Today's temperature is 2.726 Kelvin, down from an initial temperature of about 3000 Kelvin at the time of recombination due to the cosmic expansion.

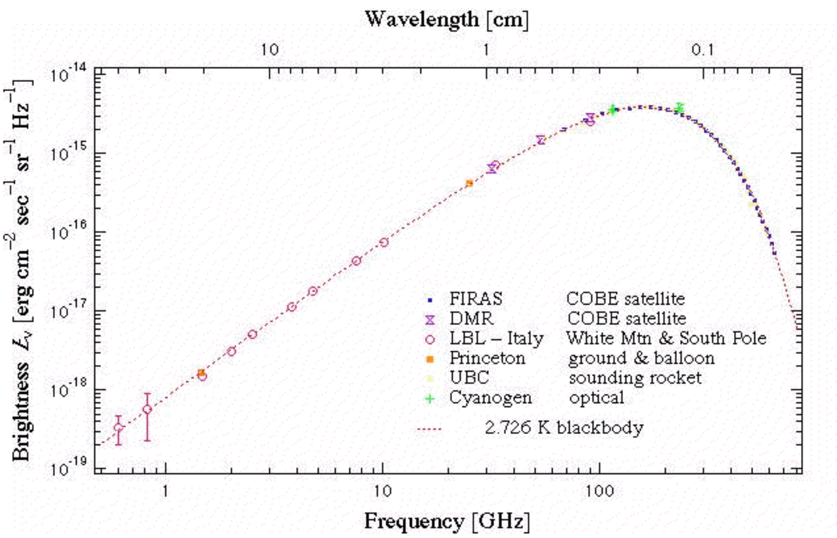


Fig. 19: Blackbody spectrum of the cosmic microwave background radiation. © Cobe Collaboration.

In addition to the excellent measurement of the mean value, the CMB was found to have an intrinsic "anisotropy" at a level of a part in 100,000 (Fig. 20). These tiny variations in the intensity of the CMB over the sky correspond to fluctuations of the temperature around the mean value. They show how matter and energy was distributed at a time when protons and electrons recombined to form hydrogen, about 380,000 years after the big bang. Later these early structures developed into galaxies, galaxy clusters, and the large scale structures that we see in the universe today.

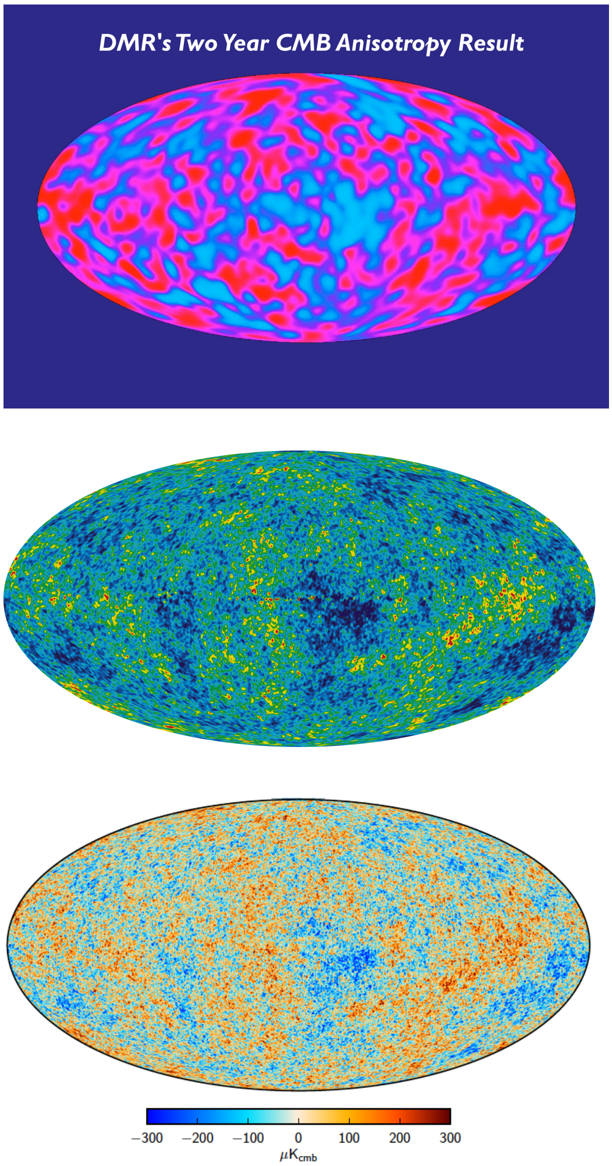


Fig. 20: Temperature fluctuations of the cosmic microwave background radiation as measured by the COBE, WMAP and Planck Collaborations (top to bottom).

Theoretical models for the expansion of the universe are mostly based on the theory of general relativity, which has superseded the old Newtonian idea of gravity as an interaction that is instantaneous over large distances. Albert Einstein (Fig. 21) formulated the field equations of general relativity in 1915 based on the concept that gravity is related to the properties of space and time. In particular, the curvature of spacetime is related to the energy and momentum of the matter and radiation. The latter is expressed through an energy-momentum tensor occurring on the right-hand side of the field equations, whereas the curvature tensor is appearing on the left-hand side, together with the metric tensor .

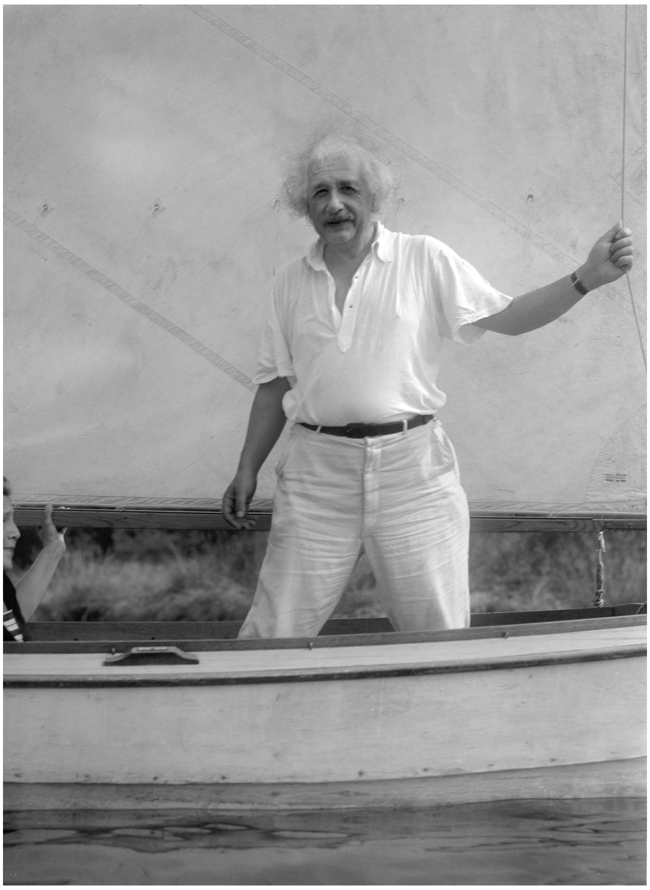


Fig. 21: Albert Einstein sailing.
© The Lotte Jacobi Collection, University of New Hampshire.

The field equations of general relativity can then be expressed as

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

with G the gravitational constant, c the velocity of light, $R_{\mu\nu}$ the Ricci-Tensor, R the curvature scalar, $g_{\mu\nu}$ the metric tensor, $T_{\mu\nu}$ the energy-momentum tensor and **Λ the cosmological constant** (corresponding to a constant density of dark energy).

The value $\Lambda = 0$ results already in Friedman's solutions for an expanding space; for $\Lambda > 0$ the expansion is accelerated. Calculating Λ from the vacuum energy $\Lambda c^2/(8\pi G)$ gives, however, a wrong order of magnitude.

- For a spatially homogeneous und isotropic universe the »metric« (squared distance between two space-time points) can be written as

$$ds^2 = a(t)ds_3^2 - dt^2$$

- The time evolution of the »scale factor« a(t) is determined from the field equations through the energy-momentum tensor. Alexander Friedman (Fig. 22) has 1922 derived the equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

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

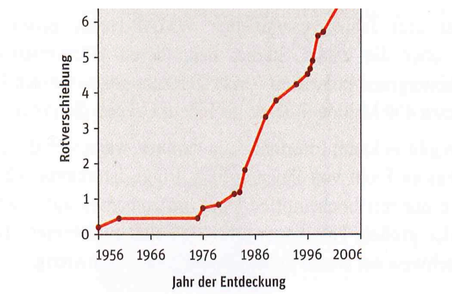
The Hubble parameter H (t) determines the expansion rate as in Hubble's law, $d = H \cdot v$; ρ is the density and p the pressure. Friedman's solutions of these equations describe the expanding universe.

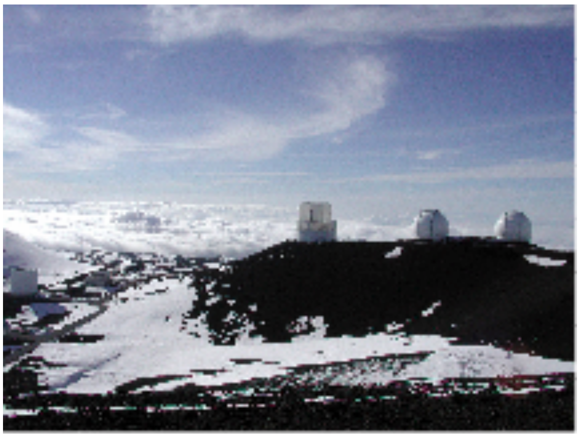
Fig. 22: Alexander Friedman.

Observational evidence that the expansion of the universe is not uniform, but accelerating in recent epochs has been inferred since 1998 from data on supernovae type Ia which – due to their homogeneous intrinsic properties – serve as standard candles to determine cosmological distances (Fig. 23).

Fig. 23: Spiral galaxy NGC 4526 with supernova Ia SN 1994 D. The distance of the galaxy is 55 Mio lightyears, the redshift $z = 2.01 \cdot 10^{-6}$.

A precise measure of the distance of a galaxy is given by the redshift z of its spectral lines. In the past decades galaxies with ever increasing redshift were discovered (Fig. 24). For example, in the spectrum of the galaxy IOK-1 with a redshift of $z = 6.96$ (measured with the Subaru-teleskope, Hawaii) the Lyman-alpha emission line is visible at $\lambda = 968.2$ nanometer. The laboratory wave length of this line is, however, only $\lambda_0 = 121.6$ nanometer; the redshift z is then calculated from $\lambda = (1 + z)\,\lambda_0$





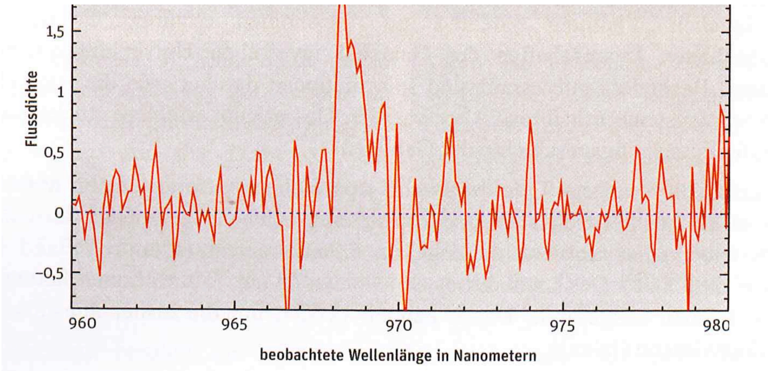


Fig. 24: Redshift of distant galaxies. Top: Redshift *z* vs. year of discovery. Middle: 8.2 m Subaru-telescope on Mauna Kea in Hawaii where many high-redshift galaxies have been discovered. Bottom: Lyman-alpha emission line in a galaxy with redshift $z = 6.96$.

In the observations of supernovae Ia (exploding white dwarfs which have exceeded their stability limit) that are being used to detect an accelerated expansion of the universe, however, the relevant redshift range is below $z \approx 2$, corresponding to the late universe (Fig. 25): An acceleration for $z \leq 1$ (corresponding to ≤ 5.9 billion years; the age of the universe is 13.8 billion years), turns into a deceleration for larger redshifts.

Whereas the spectral lines are used to determine the redshift of the supernovae, their peak brightness is converted into a so-called luminosity distance. For small redshifts $z < 0.1$, this gives an almost linear distance-redshift relation due to Hubble's law.

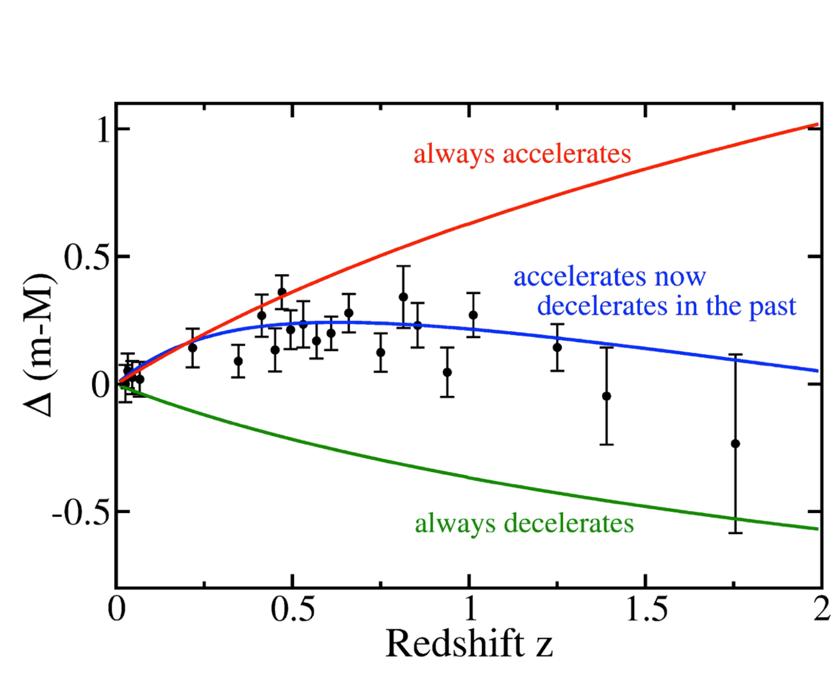


Fig. 25: Accelerated expansion of space and supernova Ia data: Apparent brightness (as a measure of distance) vs. redshift. © M. Turner, D. Huterer.

But since the expansion of the universe changes with time, the actual distance-redshift relation deviates from linearity, and by comparing with corresponding solutions of the Friedman's equations one can determine whether the expansion is accelerating, or decelerating in a certain redshift range (Fig. 26).

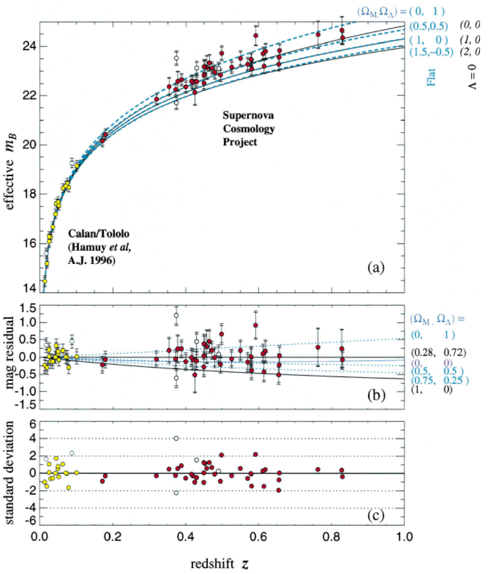


Fig. 26: Accelerated expansion of the universe as inferred from supernova Ia data assembled by the Supernova Cosmology project. Corresponding results exist from the High-*z* Supernova Search. © S. Perlmutter et al..

Whereas the supernovae Ia results for accelerated expansion of the universe by itself have a statistical significance of slightly more than 3 standard deviations and hence, would not suffice for a proof, there are additional observations to support the conjecture: baryonic acoustic oscillations (BAO), galaxy cluster counts and the fluctuations of the cosmic microwave background. Taken together, these provide convincing evidence for accelerated expansion of the late-time universe, Fig. 27.

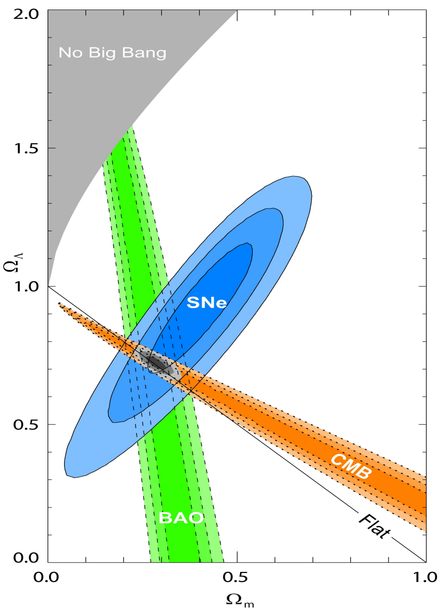


Fig. 27: Indicators for an accelerated expansion of the universe.

Ω_m is the matter density, Ω_Λ the density associated with the cosmological constant that accounts for the accelerated expansion. © M. Turner et al.

Baryonic acoustic oscillations arise from anisotropies of matter density where galaxies started to form. By observing the distances at which galaxies at different redshifts tend to cluster, it is possible to determine a standard angular diameter distance and use that to compare to the distances predicted by different cosmological models. Peaks in the correlation function are then used to confirm that the expansion of the universe is accelerating.

The mass functions of galaxy clusters (which describe the number density of the clusters above a threshold mass) provides additional evidence for the presence of dark energy that drives the accelerated expansion.

Quite convincing results for accelerated expansion arise from the detailed investigation of the fluctuations of the cosmic microwave background radiation. Fig. 28 (top) shows raw data with foreground emissions from dust that absorbs optical starlight and re-emits it in the microwave part of the spectrum. These measurements were made at 9 frequencies (30-857 GHz). Microwave point sources are also indicated. Since the dust signal depends on frequency, it is possible to reduce the data such that only the cosmological signal remains (bottom), creating the well-known temperature fluctuation map, here the data from the Planck collaboration (2013/15)

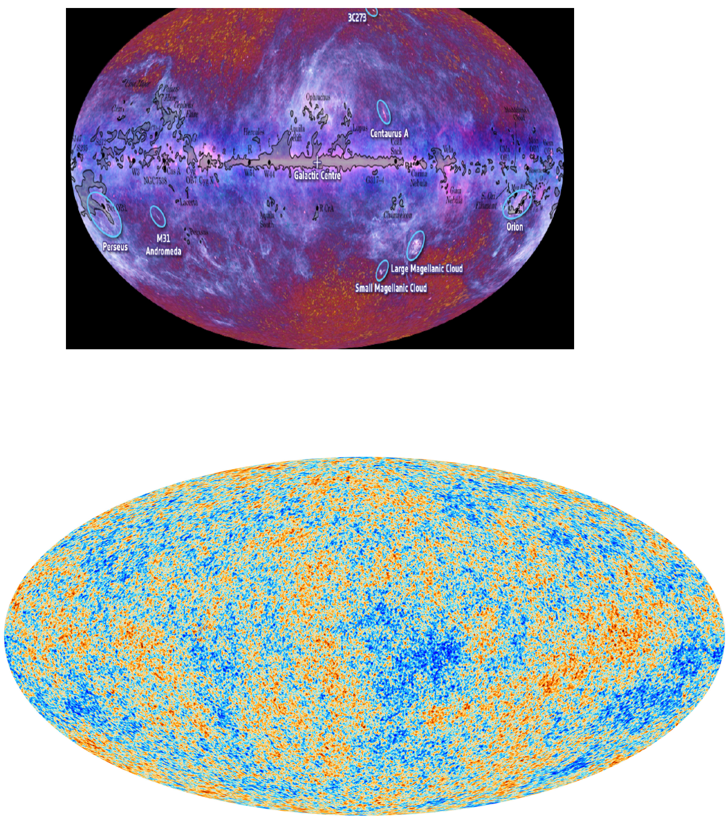


Fig. 28: Temperature fluctuations of the CMB: Planck results.

A Fourier decomposition of this map results in the so-called power spectrum of the temperature fluctuations for multipoles l (corresponding to angular distances $\theta = 180°/l$) shown in Fig. 29

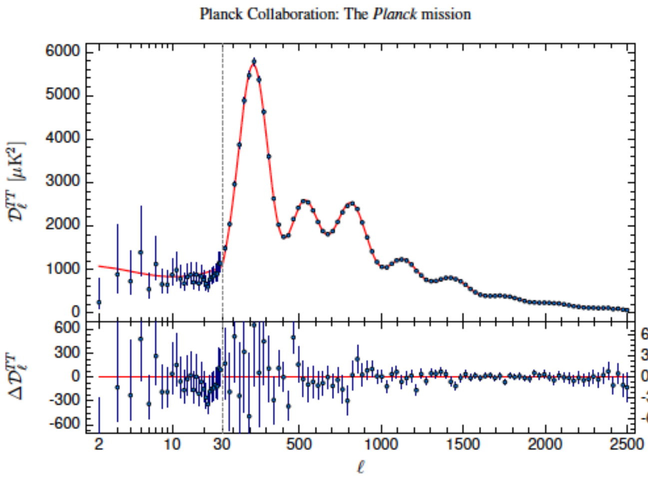


Fig. 29: Spectrum of the CMB fluctuations. © Planck Collaboration, 2015.

The data are compared with a six-parameter ΛCold Dark Matter (ΛCDM) model which serves to determine the relevant cosmological parameters. Using data from other experiments such as the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT), it is meanwhile possible to determine the power spectrum up to multipoles $l \approx 3000$ (Fig. 30)

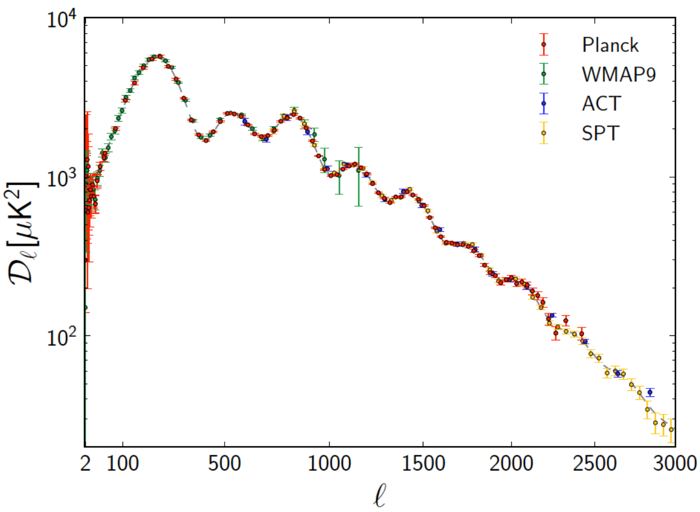


Fig. 30: Spectrum of the CMB fluctuations at large multipoles.
© WMAP/Planck /SPT/ACT Collaborations.

As a result, one can infer that

- the geometry of space is flat;
- the age of the universe is 13.799 billion years; the Hubble constant is H_0 = (67.8±0.038) km/(s·Mpc);
- Today's percentage of dark matter: 26.2 % of the energy density, dark energy 69.2 %, atoms (baryonic matter) 4.6 %.

(These are the 2015 Planck values. The 2013 results were sligthly different, as displayed in Fig. 31).

As compared to the values calculated for the time of recombination 380,000 years after the big bang, today's fraction of dark and baryonic matter has decreased, the fraction of dark energy has increased, Fig. 31

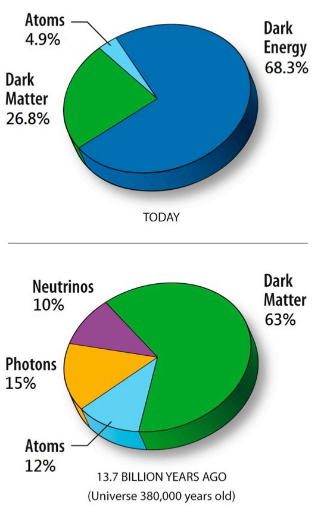


Fig. 31: Dark matter and dark energy contributions to the energy density of the universe today (top) and at recombination (bottom) in the ΛCDM model. © Planck Collaboration.

Neutrinos and photons represent today a tiny fraction of the energy density; at decoupling of radiation and energy, they accounted for up 25 %.

Interestingly, the fluctuations are not distributed evenly across the sky. In particular, a cold spot appears in the southern hemisphere (Fig. 32)

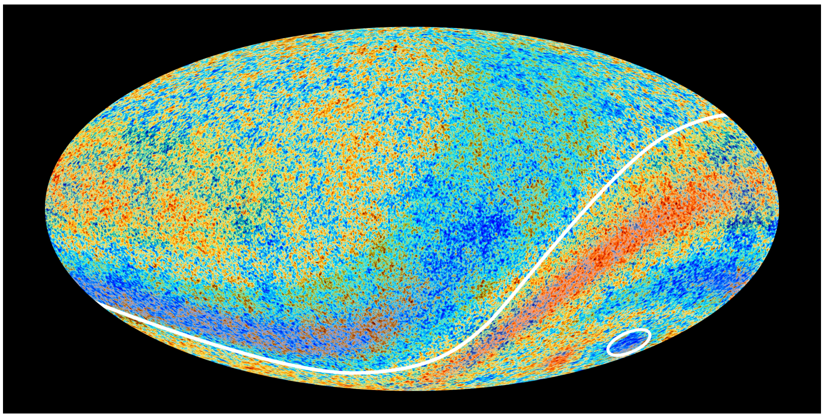


Fig. 32: Anisotropies of the CMB fluctuations. © Planck Collaboration.

In the context of the big-bang model such anisotropies in the temperature-fluctuation distribution should be traced back to the early inflationary phase, which apparently was not isotropic and would therefore be difficult to model based on a single inflationary field.

The large fraction of dark matter in the energy density – about five times the contribution of baryonic matter – is corroborated by many other astrophysical and cosmological results. Hence the indirect evidence for dark matter in the universe is probably better than that for dark energy. Particularly convincing are the results from colliding galaxy clusters such as the ‚bullet cluster',

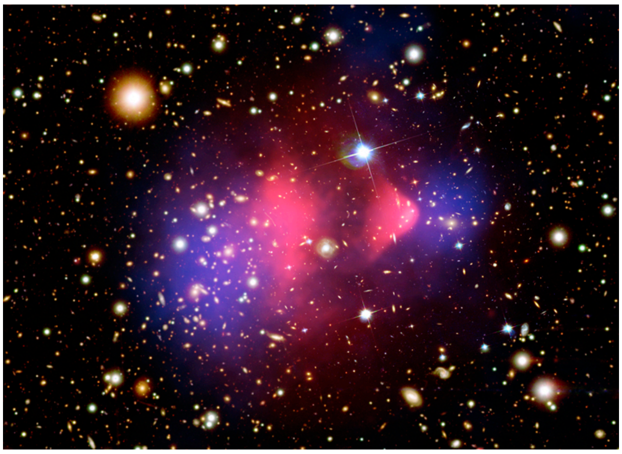


Fig. 33: This composit from optical and X-ray photographs shows the »Bullet Cluster«. Red: hot gas (Chandra/X-rays), yellow/white: galaxies (Magellan, HST), blue: Simulation of dark matter through the gravitational lens effect. © NASA.

Whereas the dark matter (Fig. 33,blue) as inferred from gravitational-lensing data is only weakly interacting when the clusters collide, the hot gas (red) interacts electromagnetically and is therefore slowed down. Models that use a modification of gravity rather than dark matter contributions can not easily reproduce this result. Still no convincing direct dark-matter detection has been reported so far, and also accelerator–based experiments at the Large Hadron Collider have not yet succeeded to find dark matter.

Attempts to find evidence for the early inflationary phase of the universe have also been made. A promising tool are primordial gravitational waves that should be generated during this phase. Whereas their frequency is too low and their expected amplitude is not strong enough to be detectable with terrestial interferometers such as LIGO, they should induce a characteristic polarization pattern on the cosmic microwave background radiation.

Several collaborations have been trying to detect such a so-called B-mode pattern in the CMB polarization. In 2014 a group from the Harvard-Smithsonian Observatory working at the South Pole (Fig. 34) claimed to have discovered this polarization pattern

Fig. 34: South Pole Telescope (SPT, left) und BICEP2 instrument (right). © Harvard University.

It was a very careful and well-conceived experiment, and the B-mode pattern that they found was convincing (Fig. 35).

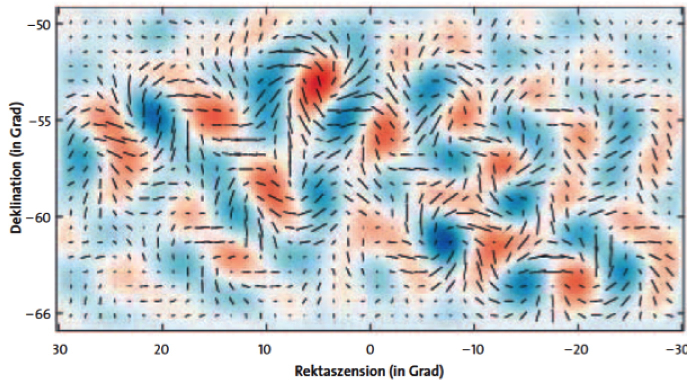


Fig. 35: B-mode polarization pattern found by BICEP2. © Phys. Rev. Lett. 112, 241101 (2014).

However, the same pattern is also produced by interstellar dust in the foreground that absorbs starlight: When the light is re-emitted in the microwave part of the spectrum, it shows B-mode polarization. In a joint paper with the Planck collaboration (Phys. Rev. Lett. 114,101301 (2015)) the initial claim was retracted:
'...We find strong evidence for dust and no statistically significant evidence for tensor modes.'

Hence the search for signals from the inflationary phase of the cosmic evolution remains as a topic for the future.

Not only in cosmology, but also in particle physics the role of electromagnetic radiation and the investigation of its properties such as polarization is a very important topic. Here only two examples from the Large Hadron Collider (Fig. 36) at CERN in Geneva are given

Fig. 36: The Large Hadron Collider LHC at CERN/ Geneva. © CERN.

In this advanced apparatus hydrogen nuclei (protons) are accelerated to very high energies – currently up to a center-of mass energy of 13 trillion electronvolt (13 TeV, Teraelectronvolt). Moreover, lead nuclei which contain 208 nucleons, 126 neutrons and 82 protons, can also be accelerated. When these heavy ions collide at a center-of mass-energy of several TeV, a short-lived high-temperature medium is formed, a so-called quark-gluon plasma.

In this new state of matter quarks and gluons are deconfined for a short period of about 10^{-23} seconds, and it is a most interesting challenge to find indirect evidence for this phase. Here photons are extremely useful since – different from strongly interacting particles such as pions – they can transport information from the quark-gluon phase directly to the detector. Indeed the currently available data show evidence for such direct photons, which would allow to estimate the value of the average temperature of the quark-gluon plasma. One finds a value in the range of 300 Million electronvolt (in energy units), Fig. 37.

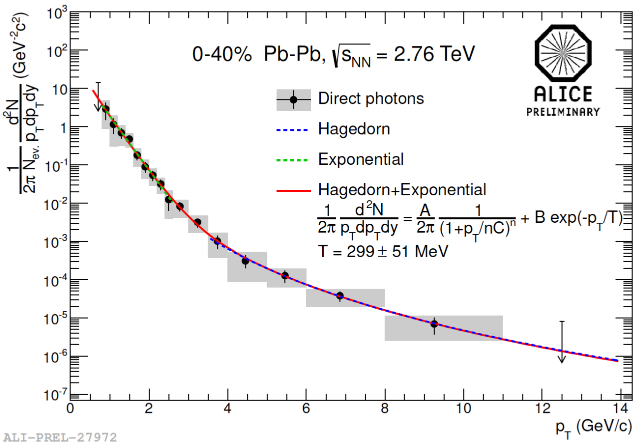


Fig. 37: Direct photons from Pb-Pb collisions at the Large Hadron Collider.
© ALICE Collaboration/ CERN.

In proton-proton collisions photons are also very relevant. This is evidenced, in particular, by the two-photon decay of the Higgs Boson – which was indeed one of the discovery channels for this particle. This scalar boson is a most important cornerstone of the standard model of particle physics that is required to explain the generation of mas. The two-photon discovery channel is shown in Fig. 38

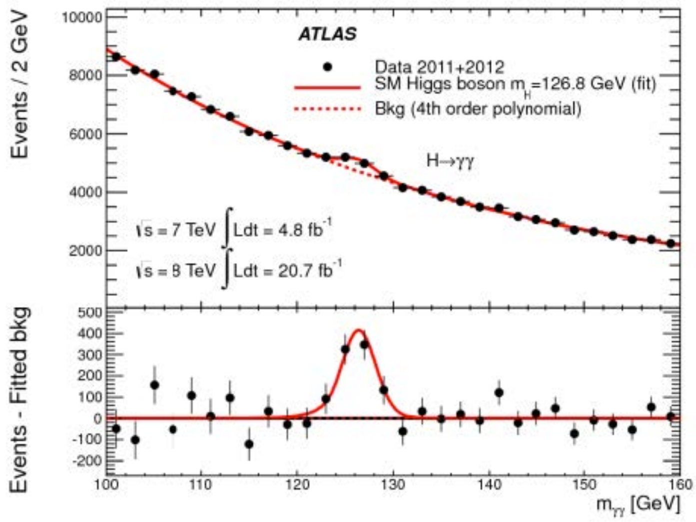


Fig. 38: Decay of the Higgs boson to two gamma rays as detected by ATLAS.
© ATLAS Collaboration/ CERN.

Two of the scientists who had developed the corresponding theory in the 1960s talked to each other in Fig. 39 before they received the Stockholm medal one year later

Fig. 39: François Englert and Peter Higgs on July 4, 2012 when the discovery of the Higgs Boson was announced in Geneva. © CERN.

Light is, however, not only important in biology, cosmology, and particle physics, but also to produce fireworks such as the one in Fig. 40

Fig. 40: Castle illumination in Heidelberg, Neckar

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