# The depth of the heavens: Belief and knowledge during 2500 years

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We see the Sun, Moon, and stars in the heavens as if placed on the inside of a sphere. But even early man had ideas about the distances to these heavenly objects. The Greek philosopher Anaxagoras living in Athens 2500 years ago claimed that the Sun is a fiery rock larger than the whole Peloponnesian peninsula. This implies a distance to the Sun larger than 20,000 km. Anaxagoras, however, was accused of blasphemy and had to leave Athens for that reason. His contemporaries believed that the sun god Helios drove his fiery wagon with the Sun across the sky in the day and returned at night sleeping on his ship.

Do we perhaps see this empty golden ship of Helios on the 'Disc of Heavens' from Nebra? This gold plated bronze disc (Figure1) from 1600 B.C. would then be the first known image of cosmos in the history of mankind.

What is in the heavens? Men at all times have seen the Moon, Sun, planets, and stars. Christians in Antiquity and Middle Ages have believed that also God, angels, and saints live in the heavens. Astronomers today do of course find the Moon, Sun, planets, and stars in the heavens, but also star clusters, galaxies, dust, gas, white dwarfs, neutron stars, black holes, and quasars, and furthermore *invisible dark matter* whose true physical nature is a great mystery of astronomy today, since it is not made of atoms or the like.

But we shall be mostly concerned with the belief of mankind over times about the size of the universe with respect to distances to the Moon, Sun, planets, and stars. The recent 100 years with galaxies and the Big Bang shall however be mentioned at last.

## The universe of Dante Alighieri

From the present we shall first jump back in time 700 years to Dante's famous Divine Comedy, before returning to the ancient Greeks. A few years ago I began to reread the classics. I said to myself: "it is time since your are in your sixties, read now while still clear in your head". Dante wanders through Hell, Purgatory, and Paradise, and it struck me how often he mentions astronomical subjects. He was well acquainted with the knowledge of his time which he had studied at the universities in Florence and Bologna. It was obviously important for him to include these astronomical or physical aspects—in a poetical cloth, but still clear enough if you read the commentaries.

At the bottom of Hell stands the giant Lucifer with his genitals at the centre of the Earth. This is seen on a drawing (Figure 2) by Sandro Botticelli (1444-1510). Dante must pass Lucifer to enter the channel that leads through the Earth to the mountain of Purgatory on the other side of the Earth. Dante has to ride on the back of his guide, the roman poet Vergil, who courageously clutches to the thick fur of Lucifer and crawls downwards. When he reaches the rounding of the hip near the Earth's centre he must turn around and continue with the head in the other direction. We meet now the physics of Aristotle (384-322 B.C.), saying that bodies seek their 'natural place', which means here the centre of Earth. For Aristotle the attraction of a body towards the centre of Earth was constant, while Newton 400 years later predicts zero gravity at the centre.

When standing on the Purgatory Mountain watching the rising Sun, Dante notices that the Sun will pass over his *left* shoulder. Vergil readily explains that this follows from standing on the southern hemisphere.

I could continue with examples from Dante. His descriptions are so clear that it is possible to draw the picture that Dante and the Middle Ages saw, the universe with the Earth at its centre, surrounded by the spheres of Fire, Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, the fixed stars, the crystal sphere, and uppermost Empyreum with the saints, the angels, and God. This naïve and very popular view of the cosmos in the Middle Ages with the Earth and God at the extremes was not shared by theologians who meant that God is omnipresent at all times.

Dante's picture of the universe with the Earth and God at the extremes is suitable for our table where we give the distances in the visible universe, firstly as given by Ptolemy, secondly the true distances as they have become known during times. Dante has undoubtedly known the distances given by the famous Greek astronomer Ptolemy about AD 150 since his distances were accepted and well known in the whole educated world, the Christian as the Muslim.

**▸ Table: Historical and Contemporary Distances**

The visible universe is a million billion times larger than Tycho Brahe believed.

(The unit 1 light-year = 1.49 billion Earth radii) Ptolemy is far from being the first to give distances to planets and stars, but his distances gained the status of highest authority during the following 1500 years. He had his values for the Earth radius and distances to Moon and Sun from astronomers working between the years 300 and 100 B.C. Their value for the Sun was 20 times too small, and not even Tycho Brahe knew better. After his time doubts arose, first for Johannes Kepler in 1617. But it took 150 years before the distance to the Sun was safely known from new observations, namely from Venus transits of the solar disc.

| Distance to | Ptolemy (~AD 150) Dante and Tycho Brahe | True distance |
|---|---|---|
| Centre of Earth | 1 Earth radius = ~ 6000 km | 1 Earth radius = 6370 km |
| Moon | 33 – 64 Earth radii | 60 Earth radii |
| Sun | 1210 Earth radii | 25 000 Earth radii since 1770 |
| Stars | 20 000 Earth radii = 0.000 014 light-years | Over 10 light-years since 1838 |
| Most distant stars in the Milky Way | — | 30 000 light-years in year 1900 |
| Most distant galaxies observable by 1960 | — | 2 billion light-years in year 1960 |
| Extreme of the visible universe | Stars: 20 000 Earth radii = 0.000 014 light-years | 13.7 billion light-years in year 2003 |
| God and the angels | — | — |



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## Speculative ideas

Greek thinking about the system of nature flourished in the regions along the eastern Mediterranean from Archimedes in Syracuse on Sicily to Erathostenes and Ptolemy in Alexandria, and it was active in a very long period of time from about year 600 B.C. to year AD 200 Of course only a narrow part of the societies had time and interest for such matters, but their thoughts were transmitted over times by Romans and Arabs into the Middle Ages.

The Greek philosophers were seeking explanations by *laws of nature* while others in the societies belived in the intervention of events by the sometimes very human gods. This neglect of the gods did usually not lead to political prosecution because of the democratic structure of Greek societies.

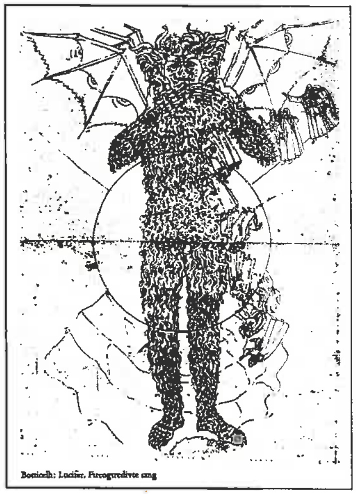
In other societies of the time where the rulers either called themselves gods or claimed to be in close family with gods, such thoughts would be considered as an attack on the social order, resulting in danger of life for those speaking of rational explanations. When Anaxagoras in Athens was blamed for blasphemy it is considered by present-day historians as a result of the political struggle after Perikles who was a close friend of Anaxagoras.

The Greek thinkers wanted to understand the whole universe through rational explanations. About 400 B.C. they formed the opinion that everything consists of four elements: *fire, air, water, and earth* which are themselves not composed of smaller elements. This opinion was the basis for all science until Boyle and Lavoisier about 1700, and we still meet it in TV and popular journals. The Chinese tradition has five elements, the same four as in Europe plus *wood* as a fifth element.

Probably many readers will agree that this opinion is scientifically wrong. It is a speculative idea, not based on thorough physical-chemical observations. *Speculative ideas* shall not mean pure guesswork but, at best, a thinking originating in the deepest imagination the philosopher has about the principles of nature, but which has only a loose connection to experience. We should not merely shake our heads about the old thinkers. We must realize that truth is very difficult to find, so we still live with many erroneous concepts. But in mathematics and science it is possible to gain such a degree of certainty through thinking and experience that very little reason for doubt is left.

We meet speculative ideas with most of the ancient thinkers, which is not said to belittle the historical role of, for instance, Plato and Aristotle, but here Archimedes (~287-212 B.C.) occupies a unique position as the one whose methods and results have eternal validity, for instance the rules of equilibrium and of buoyancy in water, which were derived through experience and mathematical theory. Archimedes deserves to be called the *father of modern science.*

▲ **Fig. 1:** The Disc of Heavens from Nebra in Germany—This archeological and cultural sensation became known in 2002 and is dated to 1600 B.C., the early bronze age. Anybody can see it has an astronomical subject: Sun, Moon and stars. It is the oldest image of the cosmos.



▲ **Fig. 2:** Lucifer at the centre of Earth in a drawing by Sandro Botticelli about 1500—Vergil with Dante on his back is crawling down and turns upside down, when he reaches the centre.

All the speculative ideas spring from the irresistible human desire to seek and also to provide an explanation for everything seen and experienced, for instance for the true nature of the Sun and the cycle of day and night, for the creation of the world and man, for life after death, and for the inner motives of politicians. Man adopts these explanations partly through own reasoning, partly by believing in (ancient) authorities or charismatic leaders. Critical sense and hard work can however gradually lead to explanations (theoretical descriptions a physicist would say) which are self-consistent and which agree with the most important observations.

## Greek theory and observations

The Greeks introduced *theory* in astronomy in order to predict positions of the planets and eclipses of Sun and Moon. They proposed many possible systems of the universe until Ptolemy's authority overshadowed everything else. Anaximenes of Milet says about 600 B.C. that Earth is a cylinder, three times broader than high, and that it is surrounded by three concentric rings carrying Moon, Sun, and the fixed stars. These rings have diameters of respectively nine, eighteen, and twentyseven times the Earth's diameter. At the same time Pythagoras realizes that the Earth is spherical, partly for the mathematical and speculative reason that he considered the sphere to be the ideal form of a body, partly because he saw the circular shadow of Earth cast on the Moon at lunar eclipse. Philolaus says about 400 B.C. that Earth circles the Sun in the time of one day and night. About the year 350 B.C. Aristotle places the Earth at centre, and it is surrounded by concentric spheres of water, air, and fire, followed by spheres for the heavenly bodies. This system was to become the basis for cosmology and physics for most of the next two thousand years.

A very interesting idea was proposed by Aristarch about 280 B.C., that Earth circles the Sun in one year while it rotates about its own axis in the time of one day and night. But the idea did not get wide acceptance at that time. It took 1800 years before Nicolaus Copernicus (1473-1543) made the same proposal thus moving the centre of the universe from the Earth to the Sun.

The size of the Earth was correctly determined by the ancient Greeks. It was noticed that the Sun stood higher in the sky at noon at a given time of the year when seen from a southern latitude than from a more northern. From the difference in altitude measured in degrees and the distances between the two places on Earth it was easy for Erathostenes about 250 B.C. to compute the circumference of the Earth when he rightly assumed that the Sun was very very far away.

Also the Moon's distance was determined. Hipparchus, *the father of astronomy*, did it about 120 B.C. by means of a solar eclipse that had taken place on 14 March 189 B.C. He knew from reports

▶ Fig. 3: God as the architect, illustration from a Middle Age bible—God has created the universe after geometric and harmonic principles. To seek these principles was therefore to seek and worship God, meant for instance Kepler.

of the event that the Sun covered the whole Moon as seen from Hellespont, but only four fifths of the Sun was covered in Alexandria. He correctly assumed that the Sun was much further away than the Moon and could then easily compute the distance to the Moon.

The angular shift of the Moon with respect to the Sun between observations from two places on the Earth was thus used to measure the distance to the Moon. A similar method of angular shift is applied in our modern times to measure the distances to stars. The angle between a nearby star and one far away changes with time. Considering two observations half a year apart the angle has changed the most, because the Earth after half a year has moved to the other side of the Sun, that means it is shifted by 300 million km. This measurement is complicated by the individual straight motion of the two stars through space. Therefore the separation of the *proper motion* of a star from its distance requires several years of observations.

## Music of the spheres

The sequence of the planets and the dimensions of the cosmos were not agreed upon in Antiquity. We find the sequence: Earth, Moon, Sun, planets, and: Earth, Moon, Venus, Mercury, Sun, and: Earth, Moon, Sun, Venus, Mercury. Agreement was only reached with the advent of Copernicus who placed the Sun at the centre: Sun, Mercury, Venus, Earth while the Moon was still closest to the Earth.

Music theory was used to find the size of planetary orbits since the natural intervals of tones were considered fundamental for the system of nature. The *harmony of spheres* was an important concept all the time from Pythagoras to Kepler's *Mysterium Cosmographicum* in 1596. Nowadays we can see that it is completely wrong, without a real connection to the laws of nature in astronomy, and the results obtained by the various ancient scientist were in fact very different.

Music theory as a tool in astronomy became completely meaningless and superfluous with the laws of nature presented in Newton's famous work *Principia Mathematica Philosophiae Naturalis* from 1687, a book on a new physics that came to revolutionize the world.

Newton describes the laws of nature mathematically by means of concepts as velocity, acceleration, force, mass, absolute time, absolute space, and gravity, concepts previously unknown or without a precise meaning.

Newton created his laws on the basis of the laws of planetary motion which Kepler had found on the basis of Tycho Brahe's measurements. But Newton's laws are valid everywhere in the whole world, in the entire universe. They have since been applied to describe all phenomena in nature, the motion of planets, and the structure of atoms. They are applied throughout modern techniques: for construction of bridges, telescopes, motors, rockets etc.

## Middle Ages

We must not forget the contribution from the Middle Ages. Christian thinkers were much concerned with the concepts of *time, eternity, and space* because the Christian God is eternal and omnipresent. They created a philosophical language in which they could speak about these matters in a way that made sense. During

Antiquity and Middle Ages the Christian teachers (missionaries and priests) fought astrology and old superstition, which however still have a firm grip in many people of our time. But superstition is quite alien to the Christian belief in an ordered world, a world and a universe ordered in harmony by the eternal God, a God who does not interfere in everyday matters. God as architect of the universe appears, for instance on a illustration in a bible from the Middle Ages. A belief in miracles hardly complies with this concept of God.

In the Christian Europe a broader part of society gradually got a theoretical education than in ancient Greece. It was a rather widely shared opinion in the 16th century that it is permitted to seek the laws of nature for the sole purpose of discovering these laws. Previously, such studies always had to be accompanied by and to end with a praise of the Almighty God. Tycho Brahe and Galilei enjoyed this freedom of research for a while, but they both came to suffer when conservative theologists gained strength again.

## The light from the Big Bang

The attentive reader will have noticed that astronomers have often changed opinion about distances, sometimes slowly, sometimes very quickly. They held to the Ptolemaic distances even up to Tycho Brahe. But the visible universe is now one million billion times larger than that of Tycho Brahe, and it has "grown" most quickly during the recent 100 years, by nearly a factor one million according to the table. The reader must ask: *Do we know anything certain at all? Can it continue to grow like this?*

The answers are respectively YES and NO.

Instruments and methods of measurement are fundamental for our knowledge of the universe. But it would require too much space here to describe these matters and the methods to interprete the observations. I must try to gain the reader's confidence through historical information.

I venture to claim that *we know something for certain*, for instance the size of the Earth and the distance to the Moon were nearly right before 100 B.C. The *distance to the Sun* could only be accurately measured after the invention of the telescope and its use in astronomical observations by Galilei in 1610. But astronomers still had to wait for a very seldom event, a passage of Venus across the solar disc, and to send expeditions to exotic places of Earth to get the observations that could provide the much wanted distance to the Sun. That happened for the first time in 1761, and the method worked to satisfaction. In our times some distances in our solar system have been measured directly by reflection of radar signals from Earth to for instance the Moon and Venus.

Progress in measuring the *distance to stars* had to wait for the industrial revolution. One of the preconditions of this revolution was to know the laws of nature as described by Newton in 1687. Since Copernicus in 1543 wrote that the Sun is the centre of Earth's orbit, astronomers had tried to measure the distance to stars through the annual shift of position. But they could only succeed after development of good telescopes, and, not the least, a good mathematical method to treat observations and their errors. The mathematical method of 'least squares' was described by Gauss in 1802. The measurement and the data analysis were mastered by

Bessel for the star No.61 in the constellation of Swan. His careful analysis and its publication in 1838 convinced other astronomers about the reality of the result, contrary to numerous other published 'stellar distances' since Copernicus. The distance of 11.2 light years is a million times larger than Ptolemy's distance to the stars.

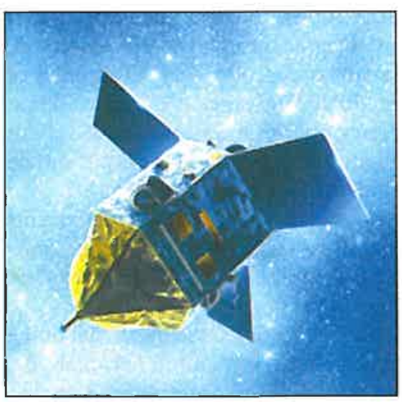
The measurement of distances by the annual angular shift has now been possible for stars (see Figure 4) that are within a distance from the Sun of a few per cent of the extent of our Galaxy.

The distance of stars very far away, for instance in other galaxies, can be derived from their observed brightness. The brightness of a star decreases by the square of the distance. This means that a star which is two times further away than a nearby star of the same type is fainter by a factor four. The type of a star can be measured by a study of its spectrum where the colour components of the light are recorded with sufficient detail.

Large telescopes were required to observe the spectra of stars. The interpretation of stellar spectra required a *theory of heat* and an *atomic theory* which were developed in the 19$^{th}$ and 20$^{th}$ centuries. That was possible on the basis of Newton's laws, and later other deep laws were discovered, *quantum theory* and *theory of relativity*.

Through radio techniques and observations from outside the Earth's atmosphere it has been possible during the recent fifty years to study electromagnetic radiation in all wavelengths, not only in the narrow band around the visually visible light which was the basis for all previous astronomy. By 1960 the Palomar 5 meter telescope could record faint galaxies as far away as 2 billion light-years, and nowadays from the Hubble Space Telescope distant galaxies have been observed where the light has been on its way for nearly 13 billion years, almost since the universe began with the Big Bang.

We have observed the radiation emitted when the universe was only 380,000 years old when the temperature of the Big Bang 'fire ball' had fallen below 3000 degrees. At this temperature the gas in the universe becomes transparent so that the radiation can travel unhindered, not being absorbed again as when the gas is hotter. This radiation was discovered by Penzias and Wilson in 1964 as microwaves coming from all over the sky. This *cosmic background radiation* has much longer wavelengths now than when its was emitted because of the expansion of the universe during the time since the radiation started its journey 13.7 billion years ago. This age of the universe has been measured with a precision of 1 per cent by a recent satellite, WMAP.



The long wavelengths of the radiation correspond to a radiation temperature of only 2.726 degrees above the absolute zero point of −273.15 degrees Celsius. The temperature of the radiation is very constant over the whole sky, varying by only 40 millionths of a degree. The mathematical analysis of the accurately measured variations has given crucial information about the early development of the universe.

▲ Fig. 4: HIPPARCOS, the first astrometric satellite, measured accurate distances of stars. It was launched by the European Space Agency in 1989. In 3 years Hipparcos obtained distances for 120,000 stars up to 1000 light-years away. It provided 2.5 million stars for the Tycho-2 Catalogue including positions, proper motions, and colour measurements.

### The invisible universe

The light or any radiation we observe from an object in the universe can only have been on its way since the Big Bang 13.7 billion years ago. This very long, but finite time defines *our cosmic horizon* which is a sphere centred on the observer. The distance to objects in the visible universe, that is the universe inside our cosmic horizon, has been our main subject. It must, however, be stressed that the whole universe is much larger, perhaps even infinite in size; but according to observations with the WMAP satellite the universe is probably finite. In any case the whole universe has no centre, it looks approximately the same in its large-scale features for any observer. This is called the *cosmological principle* which is basis for all modern cosmology and which is also in accordance with accurate observations for instance by WMAP.

Some words about time, space, and distances are required. We see a distant galaxy as it looked when light left it several billion years ago which is called the *look-back time* of the galaxy. We define the *look-back distance* to the galaxy as the look-back time multiplied with the speed of light 300,000 km per second.

We may observe the angular size and the brightness of a galaxy at some distance. If the same kind of galaxy is observed at a twice larger distance we expect it to look twice smaller and four times fainter. These laws are accurately valid up to distances of several hundred million light-years, but not for many billion light-years. For such galaxies *other kinds of distances* than the look-back distance are required to describe our observations with the same laws.

Space and time are described as a four-dimensional space-time in the general theory of relativity presented by Einstein in 1915, and this theory has ever since been the preferred mathematical basis for studies of the universe. It describes a universe which has no centre, and it provides new kinds of distances in an expanding universe by which the angular size and brightness of a galaxy can be treated consistently, even at the largest distances.

The theory of relativity does not actually predict that the universe expands, but it allows an expansion or a contraction. The actual expansion was discovered by Edwin Hubble in 1929 when he found that the lines in spectra of distant galaxies were shifted towards red indicating a velocity away from us, with larger velocities for larger distances. Since the velocity is proportional to the distance, an observer at any position in the universe will see similar expansion velocities, in accordance with the cosmological principle.

Modern observations and theory have reached the most distant parts of the visible universe with great succes in obtaining a consistent picture through mathematical descriptions. One of the most astounding results is that the mass of all visible matter (that is atomic matter as stars, dust, and gas) is too small to explain the observed velocities in galaxies and clusters of galaxies. The total gravity required by the observed velocities is ascribed to the visible atomic matter plus some kind of *dark matter* which has been a riddle in astronomy for seventy years. It appears now that there is ten times as much dark matter as atomic matter. In fact the formation of galaxies and galaxy clusters is totally dominated by the gravity of the dark matter, while the atomic matter merely shows us the motion of the dark matter.

A more recently discovered riddle of similar magnitude is based on observation of very distant objects in the universe. It appears that the expansion of the universe is faster now than it was

features

in the past. This effect is ascribed to *dark energy* which accelerates the expansion.

Dark matter and dark energy are just convenient names used by astronomers when speaking of the large velocities seen in the motion of visible matter in the universe. It is the great challenge for present astronomy and physics to understand the *true physical nature* of dark matter and dark energy.

Finally some conclusions. The entire universe has *probably a finite volume*, being slightly curved through the presence of visible and dark matter, and of dark energy. The universe will *probably expand forever* and will do so *faster and faster* because of the presence of dark energy.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Erik Høg, Copenhagen University Observatory, has been involved in the European efforts in space astrometry since the earliest studies in the 1970s. In 1999 he received "The Director of Science Medal, *for outstanding contribution to the science programme*" of the European Space Agency



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# Particle physics from the Earth and from the sky

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Recent results in particle physics offer a good balance between the news "coming from the Earth", namely results from the various colliders, and news "coming from the sky", concerning solar and atmospheric neutrinos, astroparticle programmes, searches for dark matter, cosmic microwave background (CMB), cosmology, etc.

In the light of this information, gathered in particular from the 2003 Summer Conferences (EPS in Aachen, Lepton-Photon in Fermilab), an account of the status of our field is given. It will appear in two parts, corresponding approximatively to the division between the Earth and the sky. The first one covers the Electroweak Theory, ideas beyond the Standard Model, Quantum Chromodynamics (QCD), Beauty and heavy ion physics.

### Electroweak Theory

The Electroweak Theory (EWT), together with Quantum Chromodynamics (QCD), modern version of the strong interaction, builds the Standard Model (SM) of Particle Physics [1]. The EWT is a fully computable theory. All EW measurable quantities, called "observables", as for instance the properties of the various $Z^0$ decay modes, can be predicted with great accuracy and compared to measurements. Each of them allows in particular to determine the Weak Mixing Angle, i.e. the parameter of the 2×2 unitary matrix which transforms the two abstract neutral bosons of the EWT into the two neutral physical states, photon and $Z^0$. The internal consistency of the EWT implies that all values of the Weak Mixing Angle obtained should coincide. In terms of the standard Big Bang model, the breaking of the EW symmetry, namely the time at which known elementary particles got their mass, presumably through the Higgs mechanism*, occured at about $10^{-11}$s after the Big Bang.

The $e^+e^-$ high-energy colliders LEP at CERN and SLC (SLAC Linear Collider) have delivered their quasi-final results. Their contribution to the validation of the EWT has been invaluable. However, besides celebrating this great success, it is worth considering the few areas of obscurity left and discussing how one can hope to improve the precision measurements in the future.

It is amusing to remember what was expected from LEP, for instance at the time of the meeting held in Aachen, in the same place as the 2003 EPS Conference, in 1986. In nearly all domains the quality and accuracy of the final results of $Z^0$ and $W^\pm$ physics* have been much better than foreseen, in particular due to the progress made during the last decade on detectors (microvertex devices allowing a clean tag of beauty particles, by revealing their long lifetime (flight path) of about 1 picosecond (few mm), luminometers providing a very accurate absolute normalization of the various processes, etc), on methods (such as how to determine the number of neutrinos from the $Z^0$ properties, ...) and on the mastering of theoretical calculations.

Figure 1 and its legend recall what is the scenery of $e^+e^-$ collisions. Sitting on the huge $Z^0$ resonance, LEP recorded about 18 millions $Z^0$ events and SLC about half a million only, but with the strong bonus of a large polarization of the incident electrons and better conditions for beauty tagging. From this large amount of data, many observables were measured, often with an accuracy of one per mil or better. Later, LEP200 measured $e^+e^-$ interactions at higher center-of-mass energies, up to 206 GeV: it recorded about 40K W pair events and set quite strong lower mass limits on the Higgs boson and Supersymmetric Particles.

If one summarizes the whole set of available EW measurements (LEP/SLC and others) by performing a global fit [2], one finds that the SM accounts for the data in a satisfactory but nevertheless imperfect way: the probability of the fit is only 4.5%.

The measurement lying furthest from the average is that of the weak mixing angle by the NuTeV experiment in Fermilab [3], which scatters neutrinos and antineutrinos on target nuclei. Before invoking new physics, the possible "standard" causes of such a disagreement were carefully investigated: unexpected features of the quark distribution inside nucleons are the most likely culprits. If this measurement is excluded from the fit, the probability becomes 27.5%, a reassuring number.

The other noticeable disagreement concerns the two most precise electroweak measurements, namely the spin asymmetry $A_{LR}$ at SLC, i.e. the relative change of rate of $Z^0$ production in $e^+e^-$ collisions