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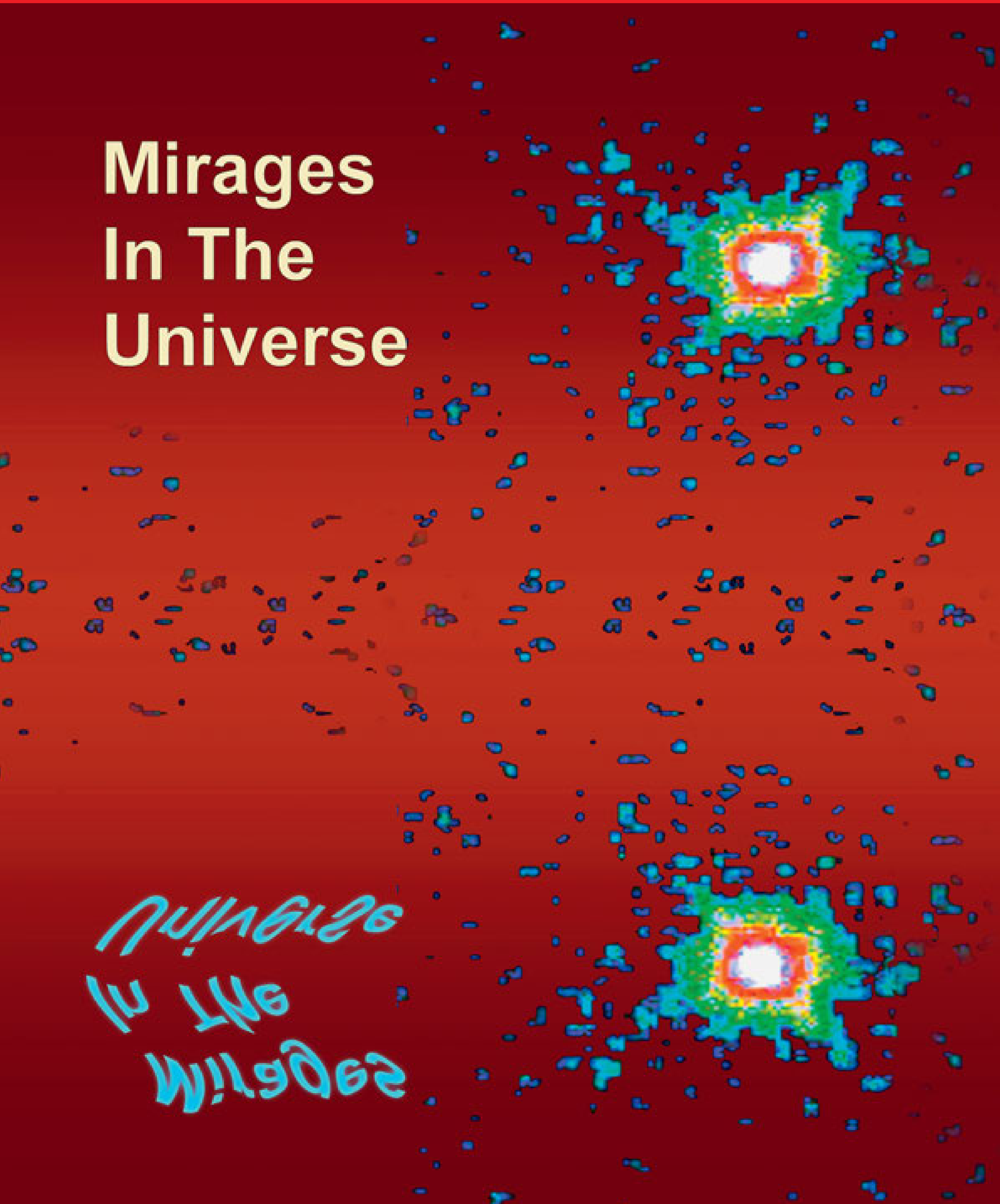
Mirages In The Universe



Editorial

When it comes to astrophysics, one can't go past Albert Einstein. His overwhelming intellectual authority endowed science with a series of landmarks, of which the General Theory of Relativity perhaps stands out most. Upon publishing the Special Theory of Relativity in 1905 he embarked on an eight-year search for a relativistic theory of gravity. After numerous detours and false starts, his work culminated in the presentation to the Prussian Academy of Science in November 1915 of what are now known as the Einstein field equations. These equations specify how the geometry of space and time is ruled by matter and gravity, and form the core of his General Theory of Relativity.

Even though the theory is clearly superior to Newtonian gravity, General Relativity remained something of a curiosity among physical theories for several decades. This didn't change even when the deflection of starlight by the Sun, as predicted by General Relativity, was observed by Sir Arthur Stanley Eddington on an expedition during the total solar eclipse of 29 May 1919: Einstein became instantly famous, while his theory remained a Sleeping Beauty.

This did change, however, in the 1960's and 1970's when ever more precise solar system tests confirmed its predictive power. One of the theory's most popular forecasts refers to gravitational lensing, the effect observed by Eddington in 1919. Even though gravitational lenses tend to create mirages that blur reality, they have evolved in the hands of astrophysicists into a powerful tool to detect the presence and distribution of dark matter or to estimate the age of the Universe, just to name two notable examples.

All those exciting topics made up the milestones of the talk on Mirages in the Universe by Professor Georges Meylan, Director of the Laboratory of Astrophysics, École Polytechnique Fédérale de Lausanne for the Pro ISSI audience on 22 March 2012. It is with great pleasure that we publish herewith an issue of Spatium entirely devoted to one of astronomy's most intriguing aspects, the mirages in the Universe.

Hansjörg Schlaepfer
Brissago, November 2013

Impressum

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Mirages in the Universe[1]

by Prof. Georges Meylan, Laboratory of Astrophysics, École Polytechnique Fédérale de Lausanne (EPFL)

Introduction

Mirages in the Universe? Well, we have heard about mirages on Earth, such as the Fata Morgana, the flickering apparitions in the hot desert. But mirages in the Universe? Do such elusory features exist in space too, and if this is the case, how do they form, and further: are they more than just an exotic oddity amusing astrophysicists?

Fig. 1 (left): The Moon setting in Casco Bay in Maine. The Moon's shape is disturbed near the horizon as a consequence of refraction effects by the Earth's atmosphere. The image of a second Moon rises slowly towards the first, both eventually merging during setting. (Credit: John Stetson).

Fig. 2 (right): The image of the setting Sun is perturbed in a similar way. This image displays even the elusive green flash at the top of the solar disk. (Credit: Karina Hamalainen)

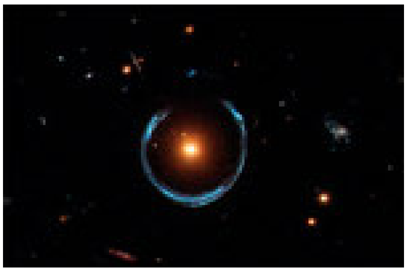
The answer is yes, of course, and the present issue of *Spatium* aims at providing our readers with an insight into this fascinating field of astronomy. In the framework of his General Relativity Theory in the mid-1910's Albert Einstein[2] postulated the existence of mirages long before they were actually observed. Today, scientists do not only enjoy their beauty but also have learned to exploit their scientific potential as a powerful tool to observe the Universe. First, let us contemplate some mirages we are all familiar with.

On Earth, mirages may appear when light is bent by layers of air with different temperatures over land or over the sea. Light propagates in air with a speed that depends on the air density and hence its temperature. Warm air immediately above the ocean or the terrain may cause the Sun or Moon's rays to be mirrored upwards producing the inverted image of a second Sun or Moon eventually merging with the first during setting. This may lead to the fancy *Etruscan Vase* moonset as shown in **Fig. 1** and the colourful sunset of **Fig. 2.**

In the Universe, other effects give rise to mirages. Here, it is the curvature of space-time, a phenomenon described first by Albert Einstein, that distorts our vision. This may take such fascinating forms as the famous Einstein ring of which an example is shown in **Fig. 3.** The amazing blue ring is not a real physical entity in space, but rather the image of one single object behind the yellow galaxy in the foreground. Its enormous mass causes the light rays from the blue background object to be bent in such a way as to form a regular, nearly perfect ring around the galaxy.

We conclude that mirages exist in the Universe and that they are induced by the presence of huge aggregations of mass. What makes them most valuable for scientists is the fact that not only the mass of visible matter, but also that of invisible dark matter gives rise to mirages. Hence, mirages help open the window towards the dark Universe.

Fig. 3: The Horseshoe Einstein ring. The gravity of the luminous yellow galaxy in the foreground has distorted the light coming from a much more distant blue galaxy. In this case, the alignment is so precise that the background galaxy is imaged as a nearly perfect ring or a horseshoe. As such lensing effects were predicted by Albert Einstein, rings like this are now known as Einstein Rings. (Credit: NASA/ESA)



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[1] The present issue of *Spatium* reports on the lecture given by Prof. Meylan for the Pro ISSI Association on 22 March 2012. The notes were taken by Dr. Hansjörg Schlaepfer.

[2] Albert Einstein, 1879, Ulm – 1955, Princeton, New Jersey, Swiss-US physicist, Nobel prize laureate in physics, 1922.

The Mechanism of Mirages

Let us now come to the facts that help us to understand the physical processes that create mirages in the Universe and to appreciate their value for astrophysicists. To this end, we begin with enumerating the forms and types of matter in the Universe.

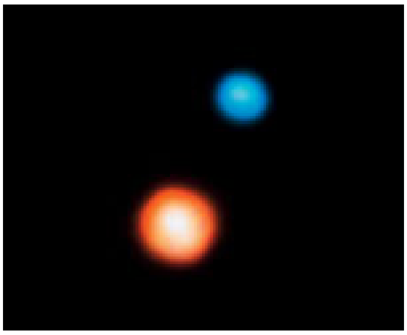


Fig. 4: Beta Albireo. The two bright stars of Albireo in the Constellation of the Swan (Cygnus) are some 380 light-years away. It is the fifth brightest star system in the sky and easily visible to the unaided eye. They circle around each other in about 75,000 years. (Credit: Giuseppe Donatiello)

Matter in Space

From our everyday experience, we know what astrophysicists call (ordinary) baryonic matter. It constitutes the visible performers of the theatre of the Universe. Those are the stars with their planets, clusters of stars, galaxies with a lot of gas and dust and entire clusters of galaxies. A good example of a star is of course our Sun, but also Beta Albireo in the constellation of Cygnus, see **Fig. 4.** It is actually a double star where the two partners have different temperatures and hence different colours in the visible.

Stars come also in entire families as in the case of the cluster of stars of the Pleiades that contain a few thousand stars, **Fig. 5.** As this is a young cluster of stars, there is still much remaining gas in between.

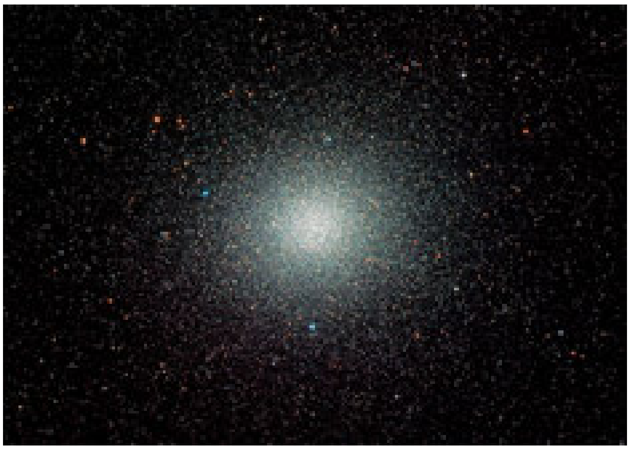
Other stars come in entire globular clusters that contain not a few thousand but rather a few million stars, such as Omega Centauri, **Fig. 6.**

Much visible matter in the Universe is also contained in dust and gas in large picturesque structures, such as for instance the Orion nebula, **Fig. 7** on the opposite page.

Fig. 7: The Great Orion Nebula is an immense, nearby star-birth region, located in the same spiral arm of our Galaxy as the Sun. The various colours highlight the emission of different gases. The nebula contains many stellar nurseries where gas and dust are currently forming hot young stars[3]. (Credit: NASA/ESA)

Fig. 5: The Pleiades can be seen with the naked eye in the Orion Constellation. It is one of the brightest clusters in the sky counting over 3,000 stars. Huge clouds of dust and gas surround the stars constituting the raw material that eventually will build up new stars. (Credit: NASA/ESA)

Fig. 6: Omega Centauri: the globular star cluster NGC 5139 is over 10 billion years old. It holds nearly than ten million stars in a sphere some 150 light-years in diameter. (Credit: ESA/NASA)



[3] See *Spatium* no. 6: From Dust to Planets by Willy Benz, October 2000.

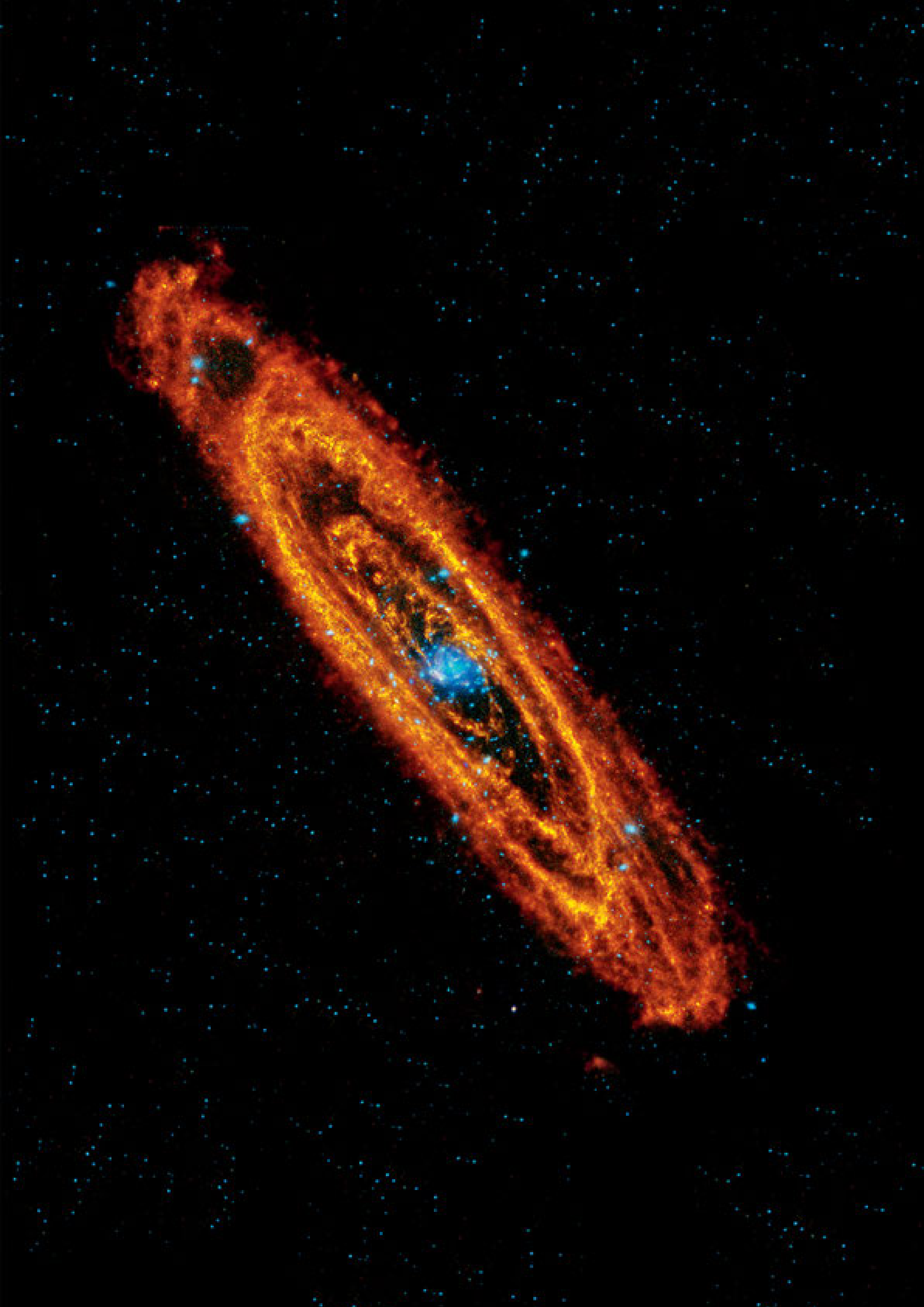
Then, we have galaxies of all types: mixed forms like the stunning Sombrero M104 **(Fig. 8)** or beautiful spiral galaxies, like Andromeda (**Fig. 9**, at right).

Now, all these wonderful celestial objects are made of visible baryonic matter, the same as you and me. Yet, careful analysis of the dynamics of galaxies provides the puzzling result that the visible matter contained in the galaxy cannot generate enough gravitational pull to counteract the centrifugal force acting on the stars that circle around the galactic centre. It was the Swiss astrophysicist Fritz Zwicky[4] who in the late 1940's became aware of this problem and was among the first to stipulate the existence of dark matter[5], a strange form of matter that cannot be seen yet produces gravitational attraction like ordinary matter, enough to keep the stars in the galaxies on their regular orbit. We have, thus, two components in the Universe that generate gravity fields and hence possibly give rise to mirages: visible baryonic matter and dark matter. Yet, to understand the mechanism fully, we have to look at the behaviour of space in the vicinity of very massive aggregations of matter, where gravity fields reach extremely high strengths.

Fig. 9: Andromeda: Our nearest large galactic neighbour. Two ESA observatories have combined forces to show the Andromeda Galaxy in a new light. The Herschel spacecraft's telescope sees rings of star formations in this, the most detailed image of the Andromeda Galaxy ever taken at infrared wavelengths shown here in redish/yellow hues. The XMM-Newton's telescope shows dying stars shining x-rays into space in bluish tones. (Credit: ESA)

Fig. 8: The M104 Galaxy (Sombrero) is named for its hat-like resemblance. It features a prominent dust lane and a bright halo of stars and globular clusters. Billions of stars cause the diffuse glow of the extended central bulge. M104's spectacular dust rings harbour many younger and brighter stars. The very centre of the Sombrero glows across the entire electromagnetic spectrum and is thought to house a large black hole[6]. (Credit: NASA/ESA)

4 Fritz Zwicky, 1898, Warna, Bulgaria – 1974, Pasadena, USA, Swiss astronomer and physicist.
5 See *Spatium* no. 7: In Search of the Dark Matter in the Universe by Klaus Pretzl, May 2007.
6 See *Spatium* no. 28: How Black Are Black Holes? by Marizio Falanga, December 2011.



The Curvature of Space-Time

It was Albert Einstein who, in his General Relativity Theory recognized that very massive objects, such as the Sun or entire galaxies, tend to curve the space time geometry. This means that the path of light does not follow a straight line from its origin down to the observer but rather is bent by the gravity of such aggregations of mass. **Fig. 10** depicts this effect schematically reduced to two dimensions: the light rays from the background object A are bent by the Sun's gravity field at the centre. The observer at point B will see the background object twice at different places, of which neither one is correct: those are the mirages in the Universe. We have, hence, to conclude that it is the curvature of space-time that generates the mirages in the Universe.

Testing Einstein's General Relativity Theory

Upon publication in 1915, the General Relativity Theory did not readily find approval by the scientific community. For example, in 1922 the Nobel prize committee preferred to assign Einstein the award for other findings[7]. Yet it stirred up enough interest for scientists to conceive elaborate tests to check the theoretical predictions. The first occasion came on 29 May 1919 when a complete solar eclipse was forecast that could be seen in parts of the world. During an eclipse, the Moon's disk covers the disk of the Sun thereby blocking its overwhelming luminosity. This allows scientists to observe the fainter stars in the background of the Sun. Now, according to classical Newtonian physics, the light rays from stars in the background pass by the Sun and are slightly deferred. According to Einstein, however, the solar mass causes enough gravity to curve the space-time in the Sun's vicinity and hence to bend the light rays from the stars behind the Sun, this with an intensity twice as large as in the case of the Newtonian dynamics.

It was the British scientist, Sir Arthur Eddington[8] who was commissioned to undertake an expedition to the Principe Island in the African Gulf of Guinea, where the eclipse would be complete. Com-

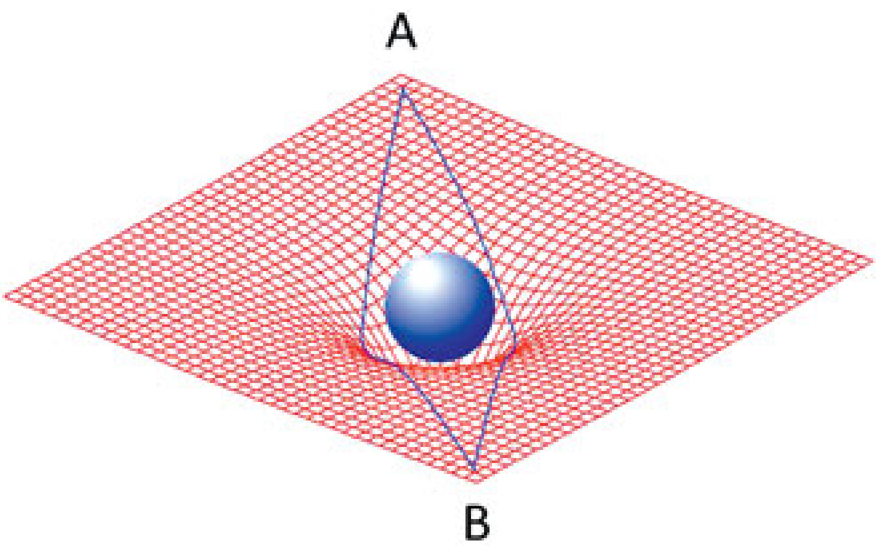


Fig. 10: Following Einstein's General Relativity, space-time is curved by massive objects such as the Sun. This graph shows the effect reduced to two dimensions: an observer at B will observe the background object not at its true place A, but rather at two distinct, apparent places.

[7] Albert Einstein was named Nobel prize laureate in 1922 honouring his theory on the photoelectric effect published 17 years earlier.

[8] Sir Arthur Stanley Eddington, 1882, Kendal, Great Britain – 1944, Cambridge, British astrophysicist.

paring the image of the stars behind the Sun during eclipse with their image taken when the Sun was elsewhere would reveal the effect of light bending as stipulated by Einstein. The sensation in the world's science community – and not only – was complete when Eddington confirmed Einstein's predictions. That was the very first experimental validation of the General Theory of Relativity after the solution of the precession of Mercury's perihelion. The shift of the light rays near its limb is equal to 1.75 seconds of arc, which is small but was already measurable at that time. One arcsec compares with a Swiss franc at a distance of 4.7 km.

So, we conclude that Eddington was the first to witness mirages in the Universe and that the Sun was the first gravitational lens ever observed.

From Glass Lenses to Gravitational Lenses

The effect of a gravitational lens as sketched in **Fig. 11** strongly resembles the bundling of light rays by an ordinary lens. In both cases shown in **Fig. 11** incoming light rays are deviated from their original path. In the case of the lens, the difference of the refraction index between the lens material and that of air gives rise to the deflection. In space, aggregations of mass curve space-time which in turn leads to the deviation of the light rays in a very similar way. This is why the effect is called gravitational lensing, a term first introduced by Albert Einstein. Any massive aggregation of mass, be it a star like the Sun, or a spiral galaxy, or any other large object, will act as a gravitational lens. However, in contrast to glass optics that may be of excellent quality, gravitational lenses possess more than just one focal point in general and will hence produce blurred images. This makes their interpretation a little more complicated than those of an optical lens.

Now, scientists are inventive: instead of coming to terms with those limitations, they try to exploit their scientific potential. The Laboratory of Astrophysics at the EPFL[9] has put gravitational lensing into the focus of one of its research fields. Despite their poor imaging properties, gravitational lenses are scientifically attractive: as outlined above, it is not only the visible baryonic matter that may give rise to gravitational lensing but dark matter as well. This allows scientists to observe parts of the invisible Universe. Even more: while ordinary visible matter accounts for a mere 5% of the matter in the Universe, dark matter amounts to some 27%, consequently gravitational lensing provides the key to fundamentally new observations from which we can draw important cosmological conclusions that cannot be made based on observing visible matter alone. Though, before entering this aspect, we will address some historical aspects of gravitational lensing.

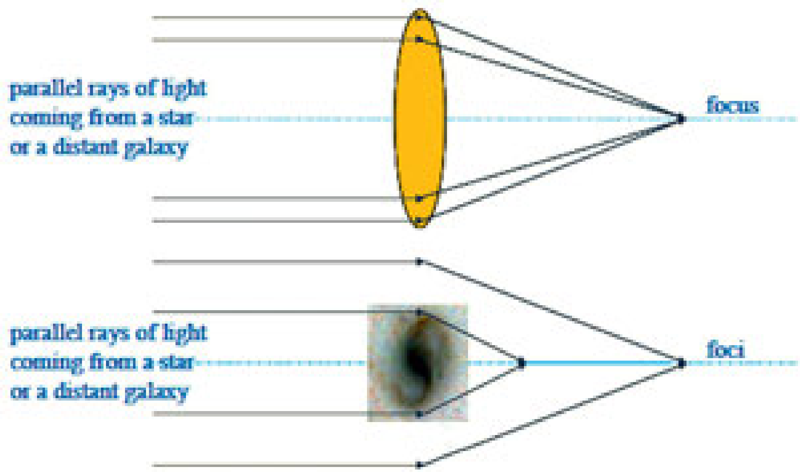


Fig. 11: From glass lenses to gravitational lenses. In a glass lens, parallel rays of light from a distant object are bundled and brought to a focus. In a gravitational lens, a massive aggregation of mass, such as a spiral galaxy, causes the curvature of space-time which in turn leads to the focusing of the incoming light from a distant object.

[9] École Polytechnique Fédérale de Lausanne.

The History of Gravitational Lensing

After successfully observing the Sun's gravitational lensing effect, the question arose whether other such examples might exist in the Universe. The answer is yes, of course; and they were soon investigated by Orest Khvolson[10] in 1924 and Einstein 1936. Einstein was considering the lensing effect between two stars in perfect alignment with the observer which ideally would lead to the so-called Einstein ring **(Fig. 3).** In this arrangement, the background object appears as a ring around the foreground star provided that the mass distribution of the lensing object is fully symmetric around the optical axis. Yet, he concluded that there is no hope of observing this phenomenon, as the angle covered by the ring would be of the order of some milli-arcseconds which was far beyond the technological capabilities at that time. Consequently, he argued that the probability of finding such a perfect alignment was practically equal to zero.

In 1937 while working at the Californian Institute of Technology, Fritz Zwicky found that the effect involving two galaxies should be much stronger and more frequent than the alignment of two stars. This brought him to the conclusion, that the case of a star lensing another star offers an ideal but useless test of General Relativity, but he thought it highly probable that the effect would be observed involving two galaxies. He was perfectly right. Yet, partly as a consequence of World War II, science needed another 60 years to find the second example of a gravitational lens.

In the meantime, technology had made major progress: Charge Coupled Devices (CCDs)[11] came up that replaced the photographic plates for astronomical observations. Furthermore, in the early 60's, quasars[12] were discovered, that are very bright nuclei of very distant galaxies. With these assets at hand, the probability became high that further gravitational lenses could be observed. In fact, this happened in 1979 when the first extragalactic gravitational lens at cosmological distances was found[13] – by chance. Walsh, Carswell and Weymann were observing two quasars that looked suspiciously similar. Known as QSO 0957+561 A and B, and separated by only 5.7 arc seconds in the sky, the two objects had nearly identical magnitudes, redshifts[14] and spectra. "*Difficulties arise in describing them as two distinct objects,*" the researchers argued. "*Gravitational lensing offered a more likely explanation: light from a single source, after travelling along distinct, bending paths through the gravitational field of some large intervening object, was arriving at the Earth from two slightly different directions.*

Fig. 12 shows the underlying idea: the observer at left looks at the quasar QSO at right. A galaxy in between acts as a lens constructing two images of the quasar. The spectra of both images are identical, which proves that the two images originate from the same object. Initially, part of the scientific community was sceptical about this revolutionary interpretation, today, however, we know, that QSO

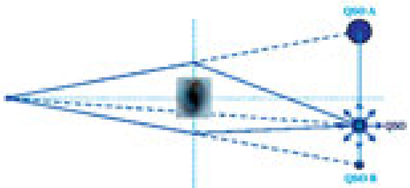


Fig. 12: A galaxy in the centre acts as a gravitational lens producing two images of the quasar QSO 0957+561 in the distant background. Note that the different paths of the two images have different lengths in general giving rise to different time lapses between emission at the quasar and arrival at the observer.

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10 Orest Danilovich Khvolson, 1852, Saint Petersburg – 1934, Leningrad, Russian physicist.

11 Charge-Coupled Devices are light sensitive electronic sensors that are used to generate electronic images. The first such devices were built in 1970.

12 The name quasar stems from the compound "quasi-stellar radio source".

13 Walsh, Carswell and Weymann in *Nature* 279, 381–384 (1979).

14 When a light emitting body recedes fast enough, an observer will see its light shifted towards the red as a consequence of an effect similar to the Doppler effect. This is called redshift. The redshift is a measure for the speed at which a body apparently moves away from the observer.

0957+561 A and B constitute a most valuable confirmation of Einstein's General Relativity Theory.

Since 1979, when this second observation of a gravitational lens was made, scientists have accumulated a few hundred of such observations. One of the most famous examples is the Einstein Cross shown in **Fig. 13**, where the nucleus of a spiral galaxy at a distance of 8 billion light years is imaged four times by a massive lensing galaxy located 400 million light years away in the foreground. As all four images have exactly the same spectra, the hypothesis that they are four different objects is completely ruled out. It is therefore a beautiful effect of gravitational lensing.

We have shown two different cases of an alignment of the observer, the lens and the source. If the distribution of matter of the lensing galaxy is symmetric along the optical axis, the image will take the form of an Einstein ring around the lensing galaxy. If, however, there is a slight asymmetry, then the result will be an Einstein Cross.

Another beautiful example of a gravitational lens is the cluster of galaxies called Abell 1689. The bright galaxies of this cluster are massive and hence their sum – the cluster – constitutes a powerful gravitational lens. In **Fig. 14** (on the next page) the galaxies appear yellow, while the blue galaxies are the images of background galaxies. If one looks very carefully at this image one finds several thousand such images with a great variety of shapes. One is even creating parts of an Einstein ring. Abell 1689 is of utmost scientific value as one can measure all the images to reconstruct the distribution of matter causing the observed images. Yet, the theoretic modelling process turns out to be quite demanding: it can be compared with the problem of identifying the speed and the mass of a car after an accident by looking at the damaged car and analysing the damage caused by another car. Careful analyses of Abell 1689 have provided a clear understanding of what is happening out there. In addition, it is one of the best examples to prove the presence of dark matter: without injecting dark matter in the theoretical model one cannot reproduce the effects of gravitational lensing as we can observe them.

So, we come to the conclusion, that the Sun is not the only case of a gravitational lens, but rather that the Universe is full of such lenses. In every direction one looks out into space, there is matter at different distances distorting our vision of the background. The cartoon in **Fig. 15** brings it to the point: While at first it seems a bit exaggerated (which is the right of a good cartoon), it is an astronomer's daily reality. The whole sky as we can see it, is completely perturbed by

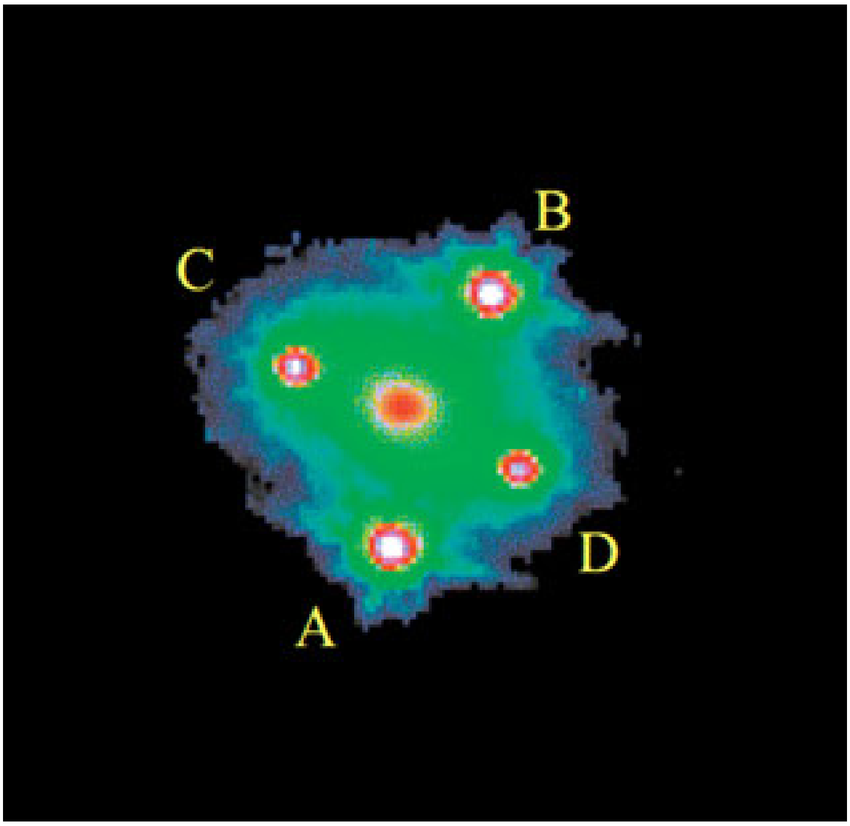
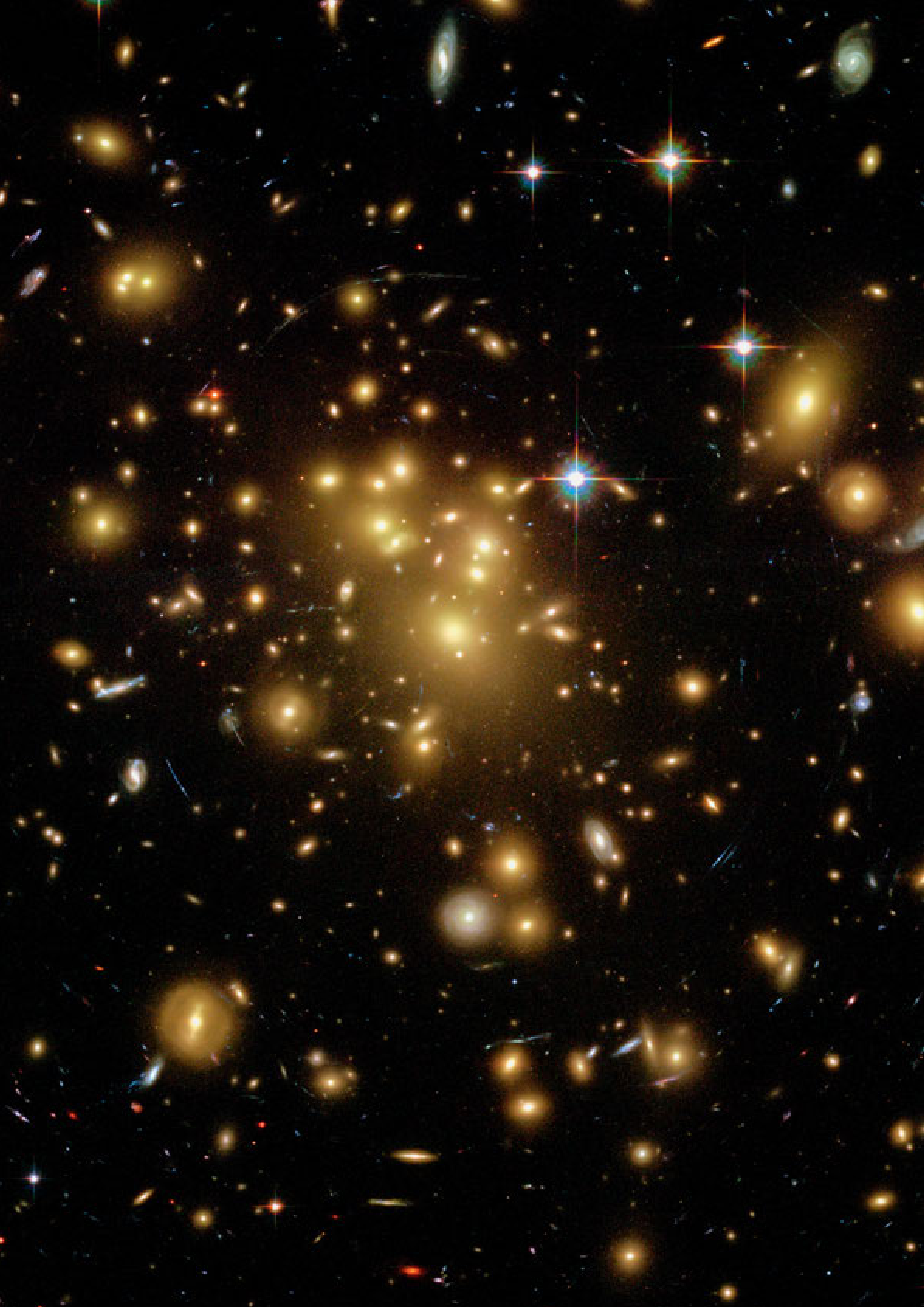


Fig. 13: The Einstein Cross QSO 2237+0305. A galaxy in the foreground creates four different images A, B, C and D of the same distant quasar in the background. (Credit: NASA/ESA)



gravitational lensing. Gravitational lenses have become an interesting tool as we are going to show below.

Fig.14 at left: Abell 1689, one of the most massive objects in the Universe, is also one of the most effective gravitational lenses. (Credit: NASA/ESA)

Fig. 15: An astronomer's nightmare. (Credit: Sidney Harris)

Applications of Gravitational Lensing

Let us now look at two examples of studies undertaken in the Laboratory of Astrophysics at EPFL to exploit the effect of gravitational lensing for astrophysical purposes. The first is the determination of the Hubble constant[15], which is a measure of the expansion rate of the Universe and its age.

In the early 1960's, the Norwegian astrophysicist Sjur Refsdal[16] established that any change in the intrinsic luminosity of any distant background might be exploited to that end. Refsdal was thinking of the observation of Supernovae since quasars had not yet been discovered at that time. If a quasar can be observed behind a lensing object, then its light will reach us on different paths with different lengths, as outlined in **Fig. 12.** Therefore, there will be a time delay between the light reaching us on the different paths. This time delay has two constituents: The geometric term t_{geom} represents the delay induced by the longer light path as compared to the shorter one. The gravitational term t_{grav} represents the delay due to the relativistic time dilation induced by the gravitational field of the lensing object. This arrangement permits us to determine the absolute distance between the observer and the quasar in the background. Yet, this is not all: the quasar spectrum will be characterized by a redshift caused by its recession speed relative to the observer. Therefore, one can, in addition to the quasar's absolute distance, also measure its escape velocity. This in turn allows us to estimate the rate of expansion of the Universe. Extrapolating back in time gives a value for the age of the Universe (13.7 billion years[17]).

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15 The Hubble constant H_0 is named after the US-American astronomer Edwin Hubble. It constitutes one of the most fundamental parameters in cosmology describing the present rate of expansion of the Universe. Since its discovery and first measurement by Georges Lemaître in 1927 the value has continuously been changing as a consequence of the ever improving observational means.
The reciprocal value $1/H_0$ is called Hubble time referring to the age of the Universe in the case of a void Universe. Normal (baryonic) matter, dark matter and dark energy may, according to their intrinsic nature and importance, accelerate or decelerate the expansion.

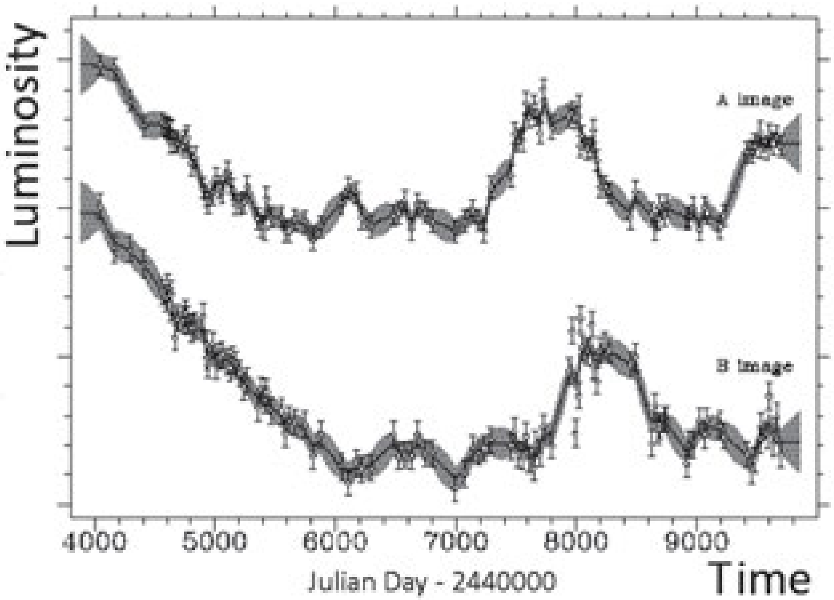
16 Sjur Refsdal, 1935, Oslo – 2009, Oslo, Norwegian astrophysicist.

17 See *Spatium* no. 1: Die Entstehung des Universums by Johannes Geiss, April 1998.

The first quasar enjoying this procedure was the well-known QSO 0957+561. **Fig. 16** shows the luminosity curves of the quasar's two images as a function of time. After a relatively flat part, a huge increase can be seen followed by a decrease of similar extent. The lower line shows the luminosity of image B, with very similar features to image A, but with a time delay of about 470 days. After careful analyses of this quasar's data – and no less complex modellization – scientists reached a value of H_0 of 67 km s^{-1} $Mpsc^{-1}$ for the Hubble constant.

Initiated and led by EPFL, the international Cosmograil[18] programme is aimed at providing updated values for the age of the Universe. In this context, we are currently observing about 30 such time delays from very different places such as Chile, La Palma, Uzbekistan and Bangalore. For determining the quasars redshift we use amongst others the Very Large Telescope[19], the Keck Observatory[20], and for the clearest images of course the NASA/ESA Hubble Space telescope to identify the images exact positions. So, we have colleagues in all these spots that benefit from the clear sky there and our common research programme.

Fig. 16: Luminosity over time of the two images of quasar QSO 0957+561.
Separated by a time delay of 470 days they are nearly identical. This time delay together with the quasar redshift allows for estimating the rate of expansion of the Universe and consequently its age. (Credit: Haarsma et al., 1997, ApJ, 479, 102)



It is worth mentioning that such observations are very demanding and some may even turn out to be completely useless. **Fig. 17** for instance shows a quasar with two images. Yet, their luminosity curves do not reveal any similarity from which to determine a trustworthy time delay. The interpretation of this result is that unseen stars passing by the lensing galaxy cause disturbing micro-lensing effects that completely destroy any information regarding the time delay. After years of intense observation, we had to discard all the data of a few quasars. Yet, it told us also that we have to be very careful while interpreting our observations and insist on the required long observation time to exclude potential mystifications. It is only after observing over a few seasons of the quasar, that such detrimental effects can be identified safely.

A second area where the Laboratory of Astrophysics at EPFL is active relates to the forthcoming ESA Euclid mission scheduled for launch in 2020. It aims to measure the geometry of the Universe. It is now assumed that ordinary visible matter makes up only about 5% of the Universe, and that a further

[18] COSMOGRAIL is an acronym for COSmological MOnitoring of GRAvitational Lenses: It involves eight teams grouped in five nodes depending on their respective country, namely Switzerland, Belgium, England, Uzbekistan and India.

[19] The Very Large Telescope (VLT) is a set of four telescopes operated by the European Southern Observatory (ESO) of which Switzerland is one of the founding members. It is based on Cerro Paranal in the Atacama Desert of Northern Chile. Each telescopes has a primary mirror 8.2 m across.

[20] The US-American W. M. Keck Observatory is placed on top of Hawaii Mauna Kea volcano 4,145 m above sea level. The two telescopes' primary mirrors are 10 meters in diameter.

27% is dark matter. The rest is thought to be dark energy. This strange component had to be introduced in cosmological models some 15 years ago when, in contrast to what one would expect, it was found that the rate of expansion of the Universe is accelerating. Dark energy is assumed to be repulsive and hence may be the cause for the accelerated expansion.
This leads to the uncomfortable fact that the mass-energy budget of the Universe is dominated by dark energy and dark matter of which science has no sound observational explanation up to now. As these constituents account for 96% of the energy and matter in the Universe this is very unsatisfying. Even worse: the existence and the energy scale of dark energy, which accounts for the majority (68%) of the energy in the Universe, cannot be explained with current knowledge of fundamental physics. This opens a wide field of activity for future generations of space scientists…
Euclid is to map the geometry of the dark Universe. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures. It achieves this by measuring shapes and redshifts of about 1.5 billion galaxies and clusters of galaxies out to redshifts of about 2, which is equivalent to a look-back time of 10 billion years. It will therefore cover the entire period over which dark energy is thought to have played a significant role in accelerating the expansion. Together with national and international partners, the Laboratory of Astrophysics, EPFL, is engaged in contributing to the Euclid mission. With more than 1,000 scientists now involved from across Europe and other parts of the world, the Euclid Consortium is the biggest astronomy collaboration ever created and is already bigger than those existing for any other ESA mission.

Conclusion

The phenomenon of gravitational lensing provides fascinating cosmic mirages. Yet, much more important, it provides a set of powerful tools for studying the Universe. It allows for cosmological measurements of fundamental parameters related to dark matter and dark energy essential for furthering our understanding. Together with our partners in Switzerland and abroad we are strongly committed to providing major contributions to this fascinating field of science.

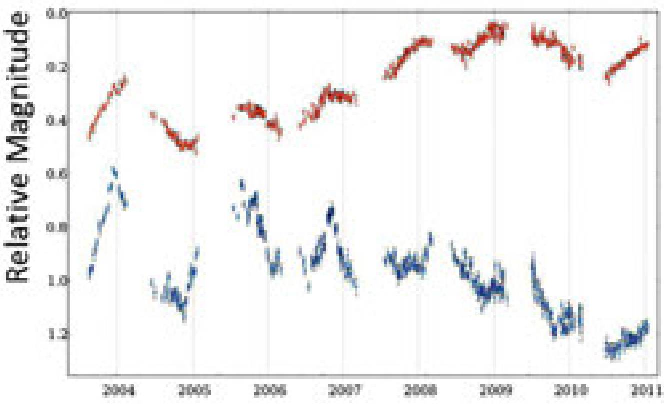


Fig. 17: The luminosity evolution of the quasar's J0158-4325 two images shows the effect of micro-lensing from unknown masses passing by in the foreground. Such data cannot be used for determining the time delay, yet (fortunately) for other applications. (Credit: EPFL-Cosmograil, in collaboration with C.S. Kochanek, C. Morgan, L. Hainline (OSU & USNA)

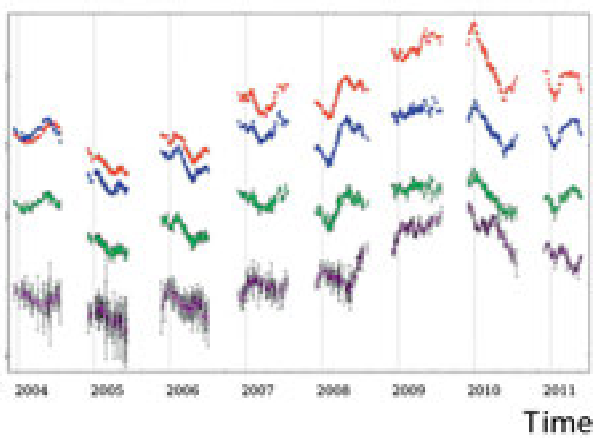


Fig. 18. The luminosity evolution of the four images of the quasar RXS J1131-1231. The high-quality photometry over a period of 8 years combined with few fluctuations due to micro-lensing make this quasar an ideal case for time delay measurement and Hubble constant determination. In the framework of our EPFL-Cosmograil collaboration, we have more than 20 quasars with such exquisite light curves. (Credit: Tewes et al. 2013 A&A 556 22)

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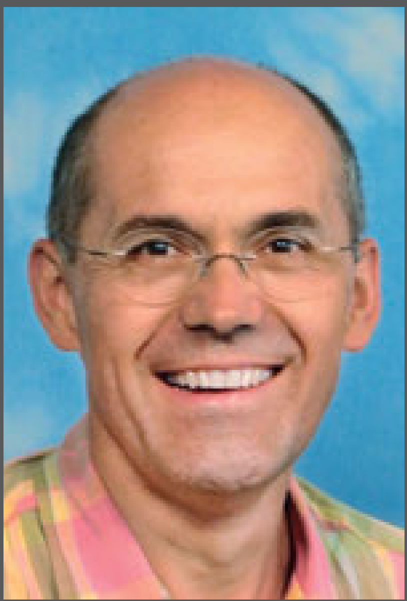

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Professor Meylan serves in many scientific organizations and committees, not least ISSI's science committee.