Einstein's Blunder

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The Planet's Smartest Man

Albert Einstein (Figure 1, left) is considered one of the greatest scientists who ever lived. He has entered the collective imagination as the epitome of genius - a very selected club of individuals, including only a handful of others, who are almost universally recognized as having changed our view of the world.

This is the fascinating story of what happened that one time when Einstein's genius got it wrong.

In the early morning of Dec 31st, 1930, Albert Einstein and his wife Elsa arrived in San Diego, California, for a much-awaited 2-months long visit to the California Institute of Technology in Pasadena, and the Mount Wilson Observatory, at the time the prime observatory in the world. The Einsteins had left Berlin from the Bahnhof Zoo train station on the evening of Nov 30th, then sailed from Antwerp on Dec 3rd. aboard the steamer S.S. Belgenland, where they occupied three luxurious staterooms permanently filled with fresh flowers, courtesy of their American hosts. Einstein didn't appreciate the attention though, as he found the accommodation "excessive and pretentious". They reached California after a stop in New York, where photographers and journalists "lunged out at him like hungry wolves", as befitted a scientific personality who achieved rockstar status before there even were rockstars. When Einstein arrived in Pasadena, the hype around his visit had reached such an intensity that he was besieged by the press, photographers, autographs seekers and crackpots of every description. Crowds of small boys gathered wherever he went. Shopkeepers stocked special merchandise, worthy of "the planet's smartest man".

Figure 1: Albert Einstein (left, pictured in Vienna in 1921) and Edwin Hubble (right, pictured in 1931). Images in the public domain.

The predictions of Einstein's theory of General Relativity, which he published in 1915, had been spectacularly confirmed by observations of the apparent position of stars around the sun during a total solar eclipse in 1919. On that occasion, newspapers around the world hailed the discovery in almost mystical terms. *The New York Times* blared: "Lights all askew in the heavens. Men of science more or less agog over results of eclipse observations"[1]. The special cable reporting from the Royal Astronomical Society meeting in London, where astronomer Arthur Eddington had presented the results of the eclipse expedition he had led, quotes the Royal Society president and Nobel prize winner J.J. Thompson as saying that since "[the difference between Newton's and Einstein's theory of gravity] can only be expressed in strictly scientific terms, it is useless to endeavor to detail them for the man in the street". The solar astronomer William James Lockyer, son of Sir Norman Lockyer, the discoverer of helium, was more reassuring if perhaps involuntarily self-aggrandizing: "The discoveries, while very important, did not, however, affect anything on this earth. They do not personally concern ordinary human beings; only astronomers are affected"[2].

The Mysterious Redshifts

Perhaps no astronomer was keener to meet the great theoretical physicist than Edwin Hubble (Figure 1, right). Hubble had made himself a name as one of the greatest extra-galactic astronomers of the time, aided in this by his having access to the largest telescope in the world (the 100-inch Hooker telescope at Mount Wilson) and being helped by an exceptionally skilled assistant, Milton Humason, who rose from being a janitor in the observatory to become Hubble's indispensable right hand at the telescope.

In 1923, Hubble had settled once and for all the question of whether the Andromeda galaxy was part of our own galaxy, the Milky Way, or a galaxy in itself, a discovery I discuss in greater detail in my Gresham lecture "Understanding the Universe with AI" (Nov 23rd, 2020). By 1929, Hubble, with the help of Humason, had amassed measurements of the distance of several dozen galaxies, together with observations of their spectra. A spectrum is the breaking up of light from a source into its constituent parts -- much like the white light from the Sun is divided into a rainbow when it passes through a prism (or a droplet of water in the atmosphere, creating the beautifully coloured arches in the sky). The same technique was used by Hubble and Humason to break up the light from distant galaxies and record the results on photographic plates. The light from a galaxy is a complex mixture of all the light emitted by their constituent stars and loose hydrogen gas, which is also absorbed and re-emitted by dust grains in the space between stars. The spectrum contains "fingerprint signatures" of the elements that make up the stars and the gas, in the form of strong emission (or absorption) at certain specific wavelengths (i.e., colours of light).

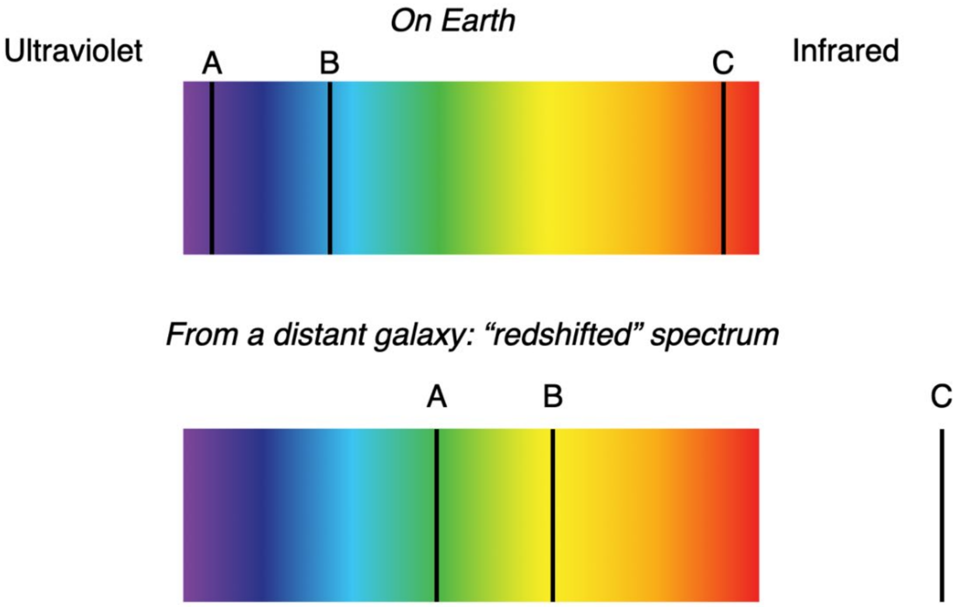

Figure 2: The "atomic fingerprint" of hydrogen (black lines) in the visibile spectrum is shifted towards the red in distant galaxies, more so the farther the galaxy is from us. This phenomenon, akin but different from a Doppler shift, is called "redshift".

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[1] The New York Times, Nov 10th, 1919

[2] *Ibid.*

This is ultimately a consequence of quantum mechanics, which dictates that electrons can only orbit the nucleus of atoms at certain discrete energy levels. The energy emitted or absorbed when the electrons jump between energy levels is translated into the specific wavelengths of light that are the fingerprint signature of each element, something that had been known since 1915 thanks to the work of Vesto Melvin Slipher. Hubble observed that the more distant the galaxy was, the further towards the red end of the spectrum the fingerprint signatures of its constituent atoms was shifted (Figure 2). This "redshift" of light was puzzling: Hubble interpreted it as a manifestation of the recession velocity of the galaxy, meaning that the light was redshifted because the galaxy was moving away from us. A similar shift, called "Doppler shift", is familiar to us from everyday experience with sound: the pitch of a police siren moving away is shifted towards the bass (corresponding to red for light), while it is shifted to a higher tone if the police car is approaching (corresponding to blue for light). Not only did nearly all of the galaxies observed by Hubble have their spectrum displaced towards the red; there was a trend in the amount of redshift, and hence recession velocity, with distance. Hubble drew a line connecting distance to redshift: more distant galaxies were moving away from us at a faster rate. The constant of proportionality between the two is today called the Hubble-Lemaître constant. Its inverse gives an estimate of the time elapsed since the Big Bang, for the faster the universe is expanding today, the younger its age[3].

Hubble was keen to share with Einstein his results about the redshift of galaxies, for these appeared to disprove Einstein's model of a static, unchanging universe. Indeed, unbeknown to Hubble, his mysterious redshifts were in perfect accord with a theoretical description of the universe put forward in 1927 by the Belgian priest Georges Lemaître. Lemaître had found a solution to Einstein's equations of General Relativity that described a cosmos whose size expanded over time - a dynamical universe in stark contrast with Einstein's preferred solution of a static universe, unchanging with time. Already in 1927, Lemaître had predicted the relationship between distance and redshift measured observationally by Hubble in 1929. His discovery went however unnoticed, as he published it in an obscure Belgian scientific journal. When Lemaître personally handed Einstein a copy of his work at the 1927 Solvay congress, the German physicist said that the Belgian priest's model was, from a physical point of view, "abominable".

To understand the significance of this, we must take a step back and discuss the fundamental concept at the heart of Einstein's equations of General Relativity.

A Mischievous Stunt

General Relativity is built around a simple principle with far-reaching consequences: that acceleration due to gravity is indistinguishable from acceleration due to motion through space. If you are in a spaceship with no windows and measure a downward acceleration of 9.81 m/s^2 , there is no local experiment you can perform inside the spaceship that will tell you whether the spaceship is stationary on the surface of the Earth (and the acceleration is therefore due to the presence of the Earth's mass) or whether it is actually accelerating upwards in empty space at the same rate. This is called "the equivalence principle", which Einstein formulated already in 1911 and then used as a guide in his development of General Relativity, which he unveiled in 1915.

General Relativity is a geometric theory of gravitation: at its heart, it says that what we experience as "the force" of gravity is in reality a consequence of the shape of space, which is bent by the presence of mass. Einstein's equations of General Relativity link together the shape of spacetime with the distribution of mass and energy in space: despite Thompson's misgivings about explaining General Relativity to "the man in the street", theoretical physicist and creator of the concept of wormhole John Wheeler neatly summarized it in simple terms: “Space-time tells matter how to move; matter tells space-time how to curve”.

When Einstein attempted to apply his equations to the whole universe, he quickly realized that the presence of mass in the form of galaxies would lead to the universe collapsing onto itself. Einstein's conception of the universe at the time was that of a finite, never-changing sphere containing a homogeneous distribution of matter, at least on sufficiently large scales (in his 1917 paper, he off-handedly dispatched comparison with observations by stating: "whether, from the standpoint of present astronomical knowledge, [my view of the universe] is tenable, will not here be discussed"[4]). He therefore saw it necessary to modify his earlier

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[3] This is no longer true if the expansion of the universe is accelerating, as will be discussed shortly.

[4] Albert Einstein, ‘‘Cosmological Considerations in the General Theory of Relativity,’’ CPAE, vol. 6, doc. 43, https://einsteinpapers.press.princeton.edu/vol6-trans/433 p. 432

equations by introducing a new piece, a new universal constant which he denoted with the Greek letter lambda (Einstein used lower-case lambda; today's usage adopts the upper-case letter, Λ, instead). The presence of lambda described a repulsive force that filled the whole space, which counteracted the attractive force of gravity exactly if Lambda was chosen appropriately to match the mean density of the matter filling the cosmos. Einstein fully realized that his new constant complicated the simple beauty of his theory without there being any observational support for its existence. In March 1917 he wrote to the mathematician Felix Klein: "The new version of the theory means, formally, a complication of the foundations and will probably be looked upon by almost all our colleagues as an interesting, though mischievous and superfluous stunt, particularly since it is unlikely that empirical support will be obtainable in the foreseeable future"[5].

Einstein's conviction of the immutability of the universe was strong enough to force his hand and change his theory to match. When the Russian mathematician Alexander Friedmann first and Georges Lemaître later came up with alternative solutions that did not require the Lambda term but described an evolving universe, Einstein staunchly opposed them. But by 1930, Einstein's conviction began to wobble: the English astrophysicist Arthur Eddington, who had played a major role in publicizing Einstein's theory to the English-speaking world and in proving him right with the 1919 solar eclipse expedition, convinced him that his static universe solution was unstable, generously acknowledging that Georges Lemaître had reached this conclusion first when he learnt of the Abbé's work. Eddington also apprised Einstein of the latest observational developments, including Hubble's observations.

By the time he reached Pasadena, Einstein was ready to pivot.

The Man Who Proved Einstein Wrong

During his visit to Pasadena, Einstein took part in several meetings with theoretical physicists at Caltech, led by the General Relativity expert Richard Tolman, and the astronomers of Mount Wilson - where Hubble, who was nicknamed "the Major", with his imposing figure and impeccably dressed, was keen to be pictured next to the German genius whenever a group photograph was taken, towering over him with his six feet two inches athletic stature. The national press ran a blow-by-blow account of every utterance of Einstein's, who, it was reported, had come to California to seek the help of "the scientists at Mount Wilson Observatory and the California Institute of Technology to solve the major problem of his mind, whether gravitation, light, electricity and electromagnetism are not different forms of the same thing".[6]

The visit came to its climax on Feb. 4th, 1931, when Einstein gave a scientific seminar, in German, in the library of Mount Wilson observatory. At the end of an hour and a half of highly technical discussions of his General Relativity equations, when he was asked to explain the relationship between his equations and cosmology, he declared with a smile that "regardless of what field equations are used, space never can by anything similar to the old symmetrical space theory"[7]. An Associated Press reporter, Walter B. Clausen, wrote that "gasps of astonishment swept through the library of Mount Wilson observatory today, when [Einstein] with a few simple words made the revelation". The report then goes on to attribute the merit for changing the mind of the Berlin professor to "two great California scientists, the astronomer Dr Edwin P. Hubble of Mount Wilson Observatory and physicist Dr Richard Tolman of Caltech". The day after, the story made the front page of the New York Times and many other national and local newspaper. *The Springfield Daily News*, the local paper of Hubble's hometown in Missouri, ran a headline that read: "Youth who left Ozark Mountains to Study Stars Causes Einstein to Change His Mind"[8]. Hubble was catapulted to international fame as the man who proved Einstein wrong.

There are however reasons to believe that the story didn't quite go this way. It is true that Einstein abandoned his old, static model of the universe during his visit to Pasadena. A week later he emphatically told reporters that "The redshift of distant nebulae has smashed my old construction like a hammer blow," and he even

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[5] Albert Einstein, letter to Felix Klein March 26, 1917, CPAE, vol. 8, doc. 319, http://einsteinpapers.press.princeton.edu/vol8-trans/339.

[6] The New York Times, Jan 3rd, 1931 (front page)

[7] The New York Times, Feb 5th, 1931.

[8] Quoted in Gale E. Christianson, *Edwin Hubble. Mariner of the Nebulae,* Farrar, Straus and Giroux (New York: 1995), p. 210.

"[swung] down his hand to illustrate".[9] However, for a man whose work supposedly made such a forceful impression on Einstein, Hubble is given very short shrift in the Berlin professor's personal diary: not only is Edwin Hubble never mentioned by name in Einstein's diary during his visit to California. He is not even name checked in the farewell address Einstein gave to the Pasadena community before taking his leave on March 1st, 1931. Whether or not Hubble was the instigator of Einstein's conversion to a dynamic universe, one that could do without his troublesome Lambda term, we will never know. Perhaps Einstein had already been convinced by the many theoretical criticisms of his static universe model voiced by Eddington, Friedmann, Lemaître and de Sitter (a Dutch mathematician and astronomer who had proposed a model of dynamic universe entirely devoid of matter). Perhaps, for Einstein the mystery of the observed redshifts was merely the last nail in the Lambda coffin, not the clinching argument the press made it out to be. It appears however that Einstein, the gifted theoretician, did admire Hubble's painstakingly difficult observational work. Upon returning to Pasadena in Nov 1931 (this time never to go back to Hitler's Germany), one afternoon Einstein broke the silence to tell Hubble's wife, Grace: "Your husband's work is beautiful -- and -- he has a beautiful spirit".[10]

Einstein's Greatest Blunder

Upon his return to Europe after his first visit to Pasadena, Einstein wrote a paper in which he made it plain that his old, static universe was no longer tenable. Lambda was dead -- at least for the man who invented it in the first place. Others felt differently: without a cosmological constant, the estimated age of the universe was smaller than the age of the Solar System, an obviously problematic discrepancy that Einstein attributed to the idealized nature of assuming a universe uniformly filled with matter -- so very unlikely our own, where millions of light years of emptiness separate galaxies containing hundreds of billions of stars (whether or not the intergalactic void is truly empty is a question we shall return to). In 1956, a year after Einstein's death, Russian emigré physicist George Gamov claimed that Einstein described the cosmological constant to him as "the biggest blunder he made in his entire life". This remark grew to become legendary, and to this date there is no certainty whether Einstein truly ever put it in these terms. No statement of this kind has ever been found among his numerous papers (although not all of them have been fully scrutinized), and Gamov's reputation as a man prone to pranks and the occasional hoax (as well as being a heavy drinker) didn't help in establishing the truthfulness of his report. On the other hand, two other physicists, Archibald Wheeler and Ralph Alpher, also claimed to have witnessed Einstein making the remark. Whether he actually described Lambda as his greatest blunder or not, there is no doubt that Einstein never regretted jettisoning it from his equations. In a 1947 letter to Lemaître he explained that he considered the cosmological constant "ugly":

‘‘Since I have introduced this term, I always had a bad conscience [...] I found it very ugly indeed that the field law of gravitation should be composed of two logically independent terms which are connected by addition. About the justification of such feelings concerning logical simplicity, it is difficult to argue. I cannot help but feel it strongly and I am unable to believe that such an ugly thing should be realised in nature.’’[11]

The Die-hard Lambda

In the four decades after Einstein's death, his rejected brainchild underwent alternating fortunes, all the while stubbornly refusing to be written off. The working hypothesis for the makeup of the universe became the so-called Einstein-de Sitter model, in which the universe contains only matter and no cosmological constant, and the average density of matter is such to make the geometry of space flat (see my Gresham lecture "Weighing the Universe", Nov 4th, 2019). In the Einstein-de Sitter model, the geometry of space is Euclidean (i.e., parallel lines meet at infinity), and the universe's expansion slows down under the influence of the gravity "generated" (in a Newtonian sense) by the mass it contains. It is a beautifully simple universe, where both spatial curvature and the cosmological constant are slashed away with a fell swoop of Occam's razor, the principle that simpler theories ought to be preferred over more complicated ones if they are sufficiently able to explain the data at hand. At the dawn of observational cosmology, data were preciously scarce, and the Einstein-de Sitter model seemed at first an adequate description of the Universe. By the early 60s, through

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[9] The New York Times, Feb 12th, 1931.

[10] Gale E. Christianson, *op. cit.,* p. 211.

[11] Einstein, A., letter to Georges Lemaˆıtre, September 26, 1947, Albert Einstein Archive Online, item 15-85, http://alberteinstein.info/vufind1/Record/EAR000031167

the work of astronomers Walter Baade and Allan Sandage and others, the rate of expansion of the universe, which Hubble had over-estimated to 500 km/s/Mpc, was revised very substantially downwards, to about 75 km/s/Mpc. This increased the age of the universe from Hubble's 2 bn years (younger than the age of the Earth, approximately 5 bn years) to a more substantial 13 bn years.

But the Einstein-de Sitter model soon ran into troubles: observers consistently failed to find evidence for the necessary amount of matter to make the universe flat as predicted by the model, a situation that didn't improve even after the introduction of dark matter (see my Gresham lecture "Mysteries of the dark cosmos", Apr 27th, 2020). Over and over again, observations indicated that the total density of matter was around 30% of what was required to make the universe flat as in the Einstein-de Sitter model; of this matter, only a sixth or so was in the form of normal atoms; the rest being made up of a new kind of particles dubbed "dark matter".

The situation became even more puzzling in the 80s and early 90s, when a new theoretical idea, combined with the first observations of imperfections in the leftover light from the Big Bang pushed some theorists to turn in desperation towards Lambda once again. The theory of inflation was introduced to explain the otherwise incomprehensible observation that the leftover light from the Big Bang, the cosmic microwave background, has the same average temperature everywhere in the sky - a uniform 2.72 K that had no reason to be, given that patches in the sky separated by more than twice the diameter of the full Moon would never have been in contact in the Einstein-de Sitter model. What was responsible then for the fact that they had exactly the same temperature? Inflation was the *deus ex machina* that came to the rescue by positing a burst of exponential, accelerated expansion at the very beginning of the universe, which in a very short amount of time enlarged a small patch of space by over 40 orders of magnitude, thus taking a small region that was initially all at the same temperature and stretching it so much that, under ordinary, non-accelerated expansion, it would appear as to never have been in contact.

The inflationary model made the forceful prediction that the universe today ought to be spatially flat, exactly like in the Einstein-de Sitter model, since any initial curvature of space would have been "ironed out" by the exponential expansion early on. While inflation seemed to support the idea of an Einstein-de Sitter universe, in 1992 the first detection of fluctuations in the otherwise uniform temperature of the leftover light from the Big Bang spelt disaster: the amount of fluctuations was as expected in a universe filled with a combination of normal matter and dark matter, but only if the present rate of the expansion of the universe was smaller than 50 km/s/Mpc, in stark contradiction with Hubble Space Telescope measurements that put it at 80 km/s/Mpc. The alternative was a flat universe, as supported by inflation, but where the total matter and energy of the cosmos was supplied by a combination of normal matter, dark matter and a substantial cosmological constant, perhaps as much as 70% of the total.

Einstein's "superfluous stunt" was back on the table.

In Search of a New Beacon

The Lambda revival of the early 90s brought to the fore a very different kind of cosmological model than Einstein's original static universe. While in Einstein's proposal Lambda was carefully picked to exactly counterbalance the gravity due to matter and so create a static, if unstable, universe, in the new model Lambda was the predominant player in the contemporary universe. Theorists moved the Lambda term from the left-hand-side of Einstein's equations, describing the curvature of spacetime, to the right-hand-side, where the matter and energy content of the cosmos reside. This led to a different physical interpretation: Lambda became a new form of energy, filling uniformly the whole of space, and with the uncanny property of possessing negative pressure. The notion of dark energy was born, a reinterpretation of Einstein's Lambda term. Dark energy, differently from dark matter and its gravitational attraction, has a repulsive effect on the expansion of the universe, which leads to an accelerated expansion, much in the same way as inflation in the very early universe. The effect of dark energy only comes into play relatively late in the life story of the universe, around 6 bn years ago. This model is today called "Lambda-CDM concordance model", where Lambda stands for the cosmological constant/dark energy, CDM for "cold dark matter", and "concordance" expresses the fact that it is in good accord with most cosmological observations. In the Lambda-CDM model, once the universe emerges out of the accelerated expansion powered by inflation right after the Big Bang, its expansion speed slows down: for the first 50,000 years, the slowing down is caused by radiation (made of light and neutrinos), and for the next 7 bn years by matter, both dark and visible. At that point in time, 6 bn years ago, dark energy becomes important, and the expansion picks up speed once again -- presumably continuing accelerating into the future, for all of eternity.

This model of the universe was hotly debated in the early 90s, as it seemed too ugly from a theoretical point of view, requiring as it did not one, but two dark, unknown entities, dark matter and dark energy, which together were allegedly responsible for 95% of the contents of the universe. Many cosmologists hanged on to the conceptually simpler Einstein-de Sitter model, hoping that the missing matter would somehow turn up in the observations. Two teams of astronomers, one led by Adam Riess at Johns Hopkins University and Brian Schmidt at Australian National University and the other by Saul Perlmutter at the University of California, Berkeley, independently and almost simultaneously set out to measure the deceleration of the universe. They hoped that by determining precisely by how much the universe's expansion is slowing down today, they could settle once and for all how much matter it contains. But, as Saul Perlmutter would later say when collecting his half of the Nobel Prize for physics in 2011: "Well, you can’t trust the theorists, they have been telling us all sorts of things that turned out to be wrong once we actually did the measurement.”[12]

The astronomers turned to a new tool to try and determine the expansion history of the universe, in an attempt to peer much further into space than Hubble ever could. Their key challenge was to measure the relationship between the redshift of galaxies and their distance from us, much like Hubble had done but too much bigger distances, up to 8 billion light years away compared with Hubble's meager 6 million light years. Mere galaxies weren't up to this task: what was needed was a much more powerful light beacon, one that could be seen from billions of light years away and whose power output was known. By measuring the amount of light from the beacon reaching the Earth, the astronomers could estimate its distance, as the light flux is reduced in proportion to the amount of expansion the universe underwent between the moment when the light was emitted and today. It was extremely important to choose beacons that were both bright and reliably uniform in the amount of light they emitted. If different beacons produced different number of lights, the measured flux at the location of the Earth would be a reflection not just of their distance from us, but also of their intrinsic variability, which would invalidate the distance measurement.

The two teams known as SPC (led by Perlmutter) and HZT (led by Schmidt and Riess, then a postdoctoral researcher) chose as beacons a type of stellar explosion called "supernova type Ia" (Figure 3). A supernova type Ia occurs when a type of old, compact and very dense star called a white dwarf gains mass from a companion star. White dwarfs pack the mass of the Sun into a cold star the size of the Earth, with the result that one spoonful of white dwarf matter weighs about a ton. If a white dwarf is in a binary orbit with another star, be it a regular star or another white dwarf, it can gain additional mass by sucking in gravitationally the gas from the companion, regular star, or by merging with the second white dwarf. The resulting additional pressure onto the core of the white dwarf sets off a thermonuclear chain reaction that in a fraction of a second completely destroys the star, emitting an enormous amount of energy, typically 10 billion times the yearly power output of the Sun. The bright phase of the supernova lasts for about 3 weeks, after which it fades away and becomes undetectable a year after the explosion. The famous "new star", which appeared in Cassiopeia and which for a week in November 1572 shone more brightly than Venus, was a supernova type Ia exploding in our own galaxy, the Milky Way. It is now called "Tycho's supernova" as it was observed and described in great detail by the greatest naked-eye astronomer of all times, Tycho Brahe.

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[12] Transcript from an interview with the 2011 Physics Laureates (accessed: Nov 8th, 2021), https://www.nobelprize.org/prizes/physics/2011/perlmutter/161848-2011-physics-laureates-interview/

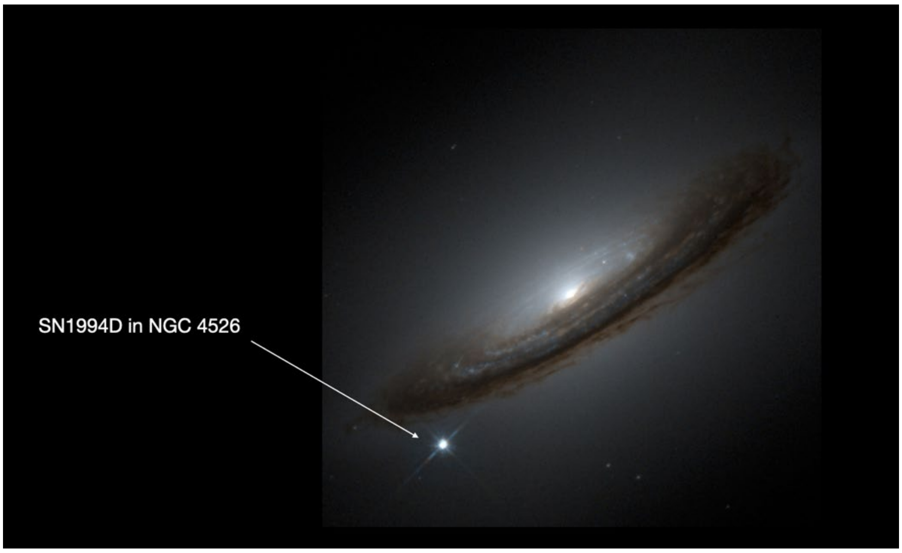

Figure 3: a supernova type Ia (indicated by the arrow) exploding in a nearby galaxy. Image: Treffers et al (1994).

Supernova type Ia, bright as they are, are however not all exactly the same: the amount of light they emit in the explosion depends on the details of how they gain mass, and how the thermonuclear reaction unfolds. Furthermore, their light is dimmed and reddened by interstellar dust it encounters on its way to us. The SCP and HZT teams went to great lengths to correct for all of these important effects, and once their independent analyses of 42 and 10 new, very distant supernovae, respectively, were concluded, the result was astounding: the universe was not decelerating as in the Einstein-de Sitter model, but it was clearly accelerating in its expansion, as predicted by the Lambda-CDM model with 70% of dark energy. Brian Schmidt, who shared a quarter of the Nobel Prize for the discovery, expressed the sense of surprise and self-doubt that overcame both teams: "What we were trying to prove was, was the universe slowing down a little or was it slowing down a lot? [...] So [when the result came about], I just said 'Ahh, alright where did we mess up?'".

But they hadn't messed up. The fact that two independent teams arrived at the same conclusion using different data and different analysis methods was seen as a powerful indication that the result was correct, unexpected as it was. Despite numerous challenges, both from the observational and data analysis perspective and from the theoretical point of view, their result of an accelerating, Lambda-dominated universe stands. Their original supernova collection has been increased to well over a thousand supernovae type Ia, and we will soon be able to observe tens of thousands of supernova explosions per year. The universe appears to be accelerating in its expansion, powered by the mysterious "mischievous stunt" of Einstein's that turned out not to be superfluous after all.

The Nature of Lambda

Einstein's blunder has turned out to be a prescient idea, put forward for the wrong reason ahead of its time. Dark energy is today one of the greatest mysteries of physics: some physicists believe it is just the tip of the iceberg of a much deeper revolution awaiting to be uncovered. For it has become clear since Einstein's time that if dark energy is just another constant of nature (like Newton's constant, setting the strength of gravity, or the charge of the electron, setting the strength of electromagnetism), then the smallness of its observed value cries out for an explanation. While dark energy makes up 70% of the contents of the universe today, from a particle physics perspective its energy is ridiculously small. It accounts for 70% of the total only in virtue of another peculiar and uncanny property: as the universe expands and its volume grows, the density of matter decreases in inverse proportion to the volume, while the density of dark energy remains constant. This could be a reflection of dark energy being a property of empty space itself, what physicists call "the vacuum". The vacuum of particle physics is nothing like the boring emptiness one would naively imagine. On the contrary, according to quantum mechanics it teems with a soup of virtual particles, emitted and reabsorbed all to quickly for them to leave any observable trace... except perhaps for a ghostly "zero-point energy", the energy of the vacuum itself. This is usually unobservable, but in cosmology it may manifest itself precisely as dark energy.

The trouble with this explanation is that the quantum mechanical calculation of this zero-point energy fails spectacularly. We know that at some point our quantum mechanical theory of the infinitesimally small breaks down: as we look at particles with higher and higher energies, we reach a point beyond which the Standard Model of particle physics loses its validity, as it is unable to incorporate gravity. Depending on what one assumes about the maximum range of validity of the Standard Model, the prediction from quantum mechanics for the zero-point energy of the vacuum differs. Even if we imagine that our current theories of the quantum world cease to work just above the energy range currently explored by particle physics colliders (where they work perfectly), the predicted zero-point energy is 40 orders of magnitude larger than what would be required to explain dark energy as vacuum energy. If dark energy is indeed a manifestation of the energy of the vacuum, nobody has been able to show why it should be so small.

Except perhaps by turning the problem on its head.

Nobel laureate Steven Weinberg, who played a major role in establishing both the model of fundamental interactions and the concordance model of cosmology, frustrated with the fruitless attempts to explain the smallness of Lambda, speculated in 1987 that "Perhaps Lambda must be small enough to allow the Universe to evolve to its present nearly empty and flat state, because otherwise there would be no scientists to worry about it". If we are to exist, Weinberg went on, the cosmological constant cannot be too large (as predicted by quantum mechanics), or its repulsive effect early on in the expansion of the universe would prevent the formation of galaxies and stars, and hence the evolution of biological beings such as ourselves able to measure it. Once galaxies have formed, the cosmological constant can continue to expand them away from each other without further influencing the processes leading to sentient life: the production of heavy elements in stars, the formation of planetary systems, the synthesis of organic molecules, the assembly of primitive lifeforms and the relentless trial and error of evolution; they can all safely proceed in the cocoon of the gravitational potential of a galaxy such as the Milky Way, oblivious to the constantly increasing redshifts of other galaxies, millions or billions of light years away.

Weinberg's original study predated the discovery of dark energy by over a decade, and he concluded then that this kind of argument failed to explain the smallness of Lambda. Indeed, Weinberg's requirement that Lambda be sufficiently small for galaxies to form before the universe begins accelerating leaves the possibility open that Lambda could be hundreds of times larger than it is in our universe -- something that was observationally ruled out already at the time of Weinberg's paper. However, the core idea that the existence of complex biological forms such as ourselves might say something about the likely value of Lambda in our universe, the so-called "anthropic cosmological principle", has been investigated in much further detail. The central requirement is that there exists not just one universe, but a multitude of universes, all with different values of Lambda (and, possibly, of other laws of nature as well). Across such an unimaginably vast multiverse, life would sprout and flourish only in the minority of universes where Lambda is sufficiently small for galaxies to exist in the first place -- ours among them. The question then becomes what creates this plethora of universes? One elegant possibility is to hark back to inflation: maybe our universe is only one patch of a collection of universes, all being inflated in different ways and each with its own physical properties, among them Lambda. Such a scenario is not directly testable, for we have no access to these other corners of the multiverse, but as we learn more about the properties of inflation, we may be able to better understand whether it is an actual possibility.

In 1917, at a time when the Milky Way was thought to be the only galaxy in the universe, Einstein wrote to de Sitter, with remarkable far-sightedness: "One day, our actual knowledge of the composition of the fixed-star sky, the apparent motions of fixed stars, and the position of spectral lines as a function of distance, will probably have come far enough for us to be able to decide empirically the question of whether or not Lambda vanishes"[13]. Not even Einstein could however have predicted that the discovery of a non-vanishing Lambda would push his successors to multiply universes *ad infinitum*, in the desperate hope of finally explaining the origin of his "mischievous stunt".

I am sure that Einstein would have reveled in the grand vistas on the nature of the universe that were revealed to us by his greatest blunder.

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[13] Einstein, A., letter to Willem de Sitter April 14, 1917, CPAE, vol. 8, doc. 325. https://einsteinpapers.press.princeton.edu/vol8-trans/343 (accessed Nov 8th, 2021).

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