Dark matter dominates the contents of the universe. The Milky Way is full of dark matter. Is dark matter an as yet undiscovered particle? The search for dark matter focuses on deep underground and large telescopes on the earth and in space. The most massive objects in the universe are giant clusters of galaxies that are dominated by dark matter. Clusters and massive galaxies are dark matter telescopes and amplify background galaxy images by gravitational lensing. The distortions of the images of distant galaxies by lensing yields a map of the dark matter distribution throughout the universe.

The dark matter saga began with Fritz Zwicky in 1933. He realised that the Coma cluster of galaxies would fly apart were it not held together by unseen matter. He estimated that there had to be ten times more dark matter than visible matter. The only data available at that time were the measurements of the relative velocities of the cluster galaxies. We now have measurements of cluster masses from more refined and accurate techniques, but Zwicky's original estimate is largely confirmed. With the advent of gravitational lensing studies, dark matter maps of galaxy clusters are now routinely produced, especially by using the high resolution of the Hubble Space Telescope.

Some two decades later, observations of nearby spiral galaxies began to show evidence for dark matter. The best case was made for the Andromeda galaxy, a neighbour of the Milky Way galaxy. Vera Rubin used optical data to study nebulae surrounding massive stars in Andromeda. These are very bright and could be studied throughout the luminous part of the galaxy and even beyond.

She was able to measure the radial components of the velocities of these ionized hydrogen clouds, and could trace the rotation of the parent galaxy. There was strong evidence that the rotation curve did not decrease with distance from the centre of the galaxy. Her result was soon confirmed by radio astronomer Morton Roberts, who performed similar measurements for atomic hydrogen clouds. These extended to much larger distances. There was now little doubt: most of the mass of the galaxy was dark, otherwise the cloud velocities would decrease with increasing distance from the luminous mass of the galaxy. Over the next decade similar evidence was found for many other nearby galaxies.

The global perspective on dark matter

Astronomically, the existence of dark matter has now been inferred from its gravitational effects on all scales, from the velocities of stars and gas clouds around the centers of galaxies, through the motions of galaxies in clusters, and all the way to the formation of cosmic structure, and the evolution of the universe as a whole.

Results on the anisotropies in the cosmic microwave background radiation (from the Planck and WMAP satellites) suggest that about a quarter of the cosmic energy budget is in the form of dark matter. Since ordinary (baryonic) matter only amounts to less than 5% of the universe's mass-energy, this means that most of the universe's mass (about 85%) is dark. Dark matter is supposed to provide the scaffolding on which the large-scale structure of the universe coalesces.

According to the leading mainstream view on the nature of dark matter, it is nonbaryonic (not composed of standard model particles such as protons or neutrons), and it is supposed to consist of weakly interacting massive particles (WIMPs). These are particles that interact among themselves and with ordinary matter only via the weak nuclear force and gravitationally (but not electromagnetically or via the strong nuclear force).

The WIMPs were omnipresent very early in the universe. Just like the dominant radiation and the traces of ordinary matter, they were relativistic, moving in random directions at the speed of light. As the universe expanded, the matter cooled and eventually the WIMPs became non-relativistic, that is their typical velocities were less than the speed of light. Since space effectively expands at the speed of light, the WIMP particles tend to fall behind. There is a maximum distance they can travel. We call this the “free-streaming length” of these particles—the distance the particles could have moved in the early universe, before the cosmic expansion caught up with them.

Requirements arising from cosmic structure formation place significant constraints on the free streaming length. Smaller structures cannot survive. Reproducing the observed large-scale-structure requires the dark matter particles to be “cold.” The free-streaming length has to be considerably smaller than the dimensions of a protogalaxy. The key question that arises is: what might these cold WIMPs be?

At least until recently, most physicists would have guessed that WIMPs are the lightest of the so-called supersymmetric (SUSY) particles. These are subatomic particles predicted to exist in the context of an all-embracing symmetry, according to which every fundamental particle we know, such as the electron, photon, or quark, has a yet-undiscovered massive partner. SUSY is a symmetry that most physicists are convinced was valid at sufficiently high energies in the very early universe. Almost all of the partner particles decayed or
annihilated with each other, but the lightest was stable and survived.

Remarkably, we can calculate how many survived. The relic fraction depends mostly just on how much dark matter there is. Identifying dark matter particles with the lightest survivor from SUSY naturally gives the particle mass range, typically hundreds of proton masses, and the interaction strength, invariably weak. But if it interacted too weakly, there would be too many survivors, if too strongly, too few. Like Goldilocks, the properties must be just right...if the dark matter particle is the lightest stable SUSY relic.

It is this coincidence that has motivated a plethora of ever more sensitive direct detection experiments. Following the well-established tradition of the scientific method, once well-founded theoretical predictions exist, experiments are designed to test these predictions. Here, however, physicists were in for a surprise: Numerous searches failed to detect WIMPs.

**Direct detection**

In spite of the seemingly compelling observational and theoretical basis for the existence of dark matter—matter that neither emits nor absorbs electromagnetic radiation—all attempts so far have failed to convincingly detect its particle constituents. Hitherto all searches have failed.

Millions of WIMPS pass through our detectors every second. Despite the very weak interactions, direct detection of WIMPS is feasible by elastic scattering on some target material. One disappointment in a long string of negative results was the announcement in 2014 by the most sensitive detector to date—the Large Underground Xenon (LUX) experiment in a deep mine in South Dakota—that the analysis of data accumulated over many months showed no sign of any dark matter signal. A number of other deep underground experiments confirm this result.

Similarly, axions (another type of potential dark matter candidate) remain elusive despite a number of ongoing experiments. Axions are low mass weakly interacting particles, perhaps only a billionth the mass of a proton, but interact electromagnetically in strong magnetic field cavities. A variety of experiments aiming at the detection of axion dark matter particles have been operating since the 1980s, without success.

However one existing experimental approach in direct detection has produced intriguing results, and this deserves a closer look. The DAMA/LIBRA particle detector installed at the Gran Sasso Laboratory, installed in a tunnel below a mountain in northern Italy, uses as scintillators highly radio-pure thallium-doped sodium iodide crystals to seek annual modulation of the WIMP signal. This experiment has been collecting data for over 13 years.

The idea behind the DAMA experiment is simple. Our Galaxy is supposed to be surrounded by a dark matter halo. As the Earth is revolving around the Sun, and the Sun around the centre of our Galaxy, during half of the year the velocities of the Earth and the Sun combine, while during the other half they are in opposite directions. This effect produces an annual modulation in the rate at which halo dark matter particles hit the detector, with a peak expected in June and a minimum in December. The DAMA results indeed show a modulation, with a very high statistical significance.

Unfortunately, several other direct detection experiments (with null results) have excluded most of the parameter space (in terms of the mass of the putative dark matter particles and their cross-section for interaction) implied by the DAMA results. Given the many uncertainties, the results from DAMA are not conclusive enough to constitute a discovery of dark matter.

There is no denying that DAMA detects a modulation, but since many phenomena that might lead to deep underground signals, due for example to natural radioactivity in the rock, repeat seasonally with a period of one year, it is not clear what the detection means. However several experiments are under way that is designed to replicate the DAMA experiment with the same type of detector at a different location (with a higher sensitivity). One will be at the South Pole, where the modulation signal, if real, should be 180 degrees out of phase with that in the northern hemisphere.

**What's next in direct detection?**

The first thing that clearly must happen is for the existing and planned experiments to run their course and for their results to be carefully evaluated. New experiments are planned to go from the ton scale, the current detector mass, up to a hundred tons, making the experiment 100 times more sensitive.

Experience with the discovery of the Higgs boson has shown that success can come even after more than four decades of trials. The majority of the current experiments use either cryogenic detectors (that detect the heat released when a particle hits an atom in a crystal), or noble liquid (xenon or argon) detectors (that monitor the scintillation produced in collisions).

But it may be that detectors simply are not large enough. The WIMP miracle is the simple argument that tells us the expected interaction strength of dark matter particles if they are at the expected abundance. So it also tells us how low we have to go in sensitivity to detect the elusive WIMPs. The answer is about two more factors of 10
in detector mass. At this point, neutrinos from the earth’s atmosphere give an impenetrable background: we can never do better, it seems.

Physicists are already planning for a scaled-up version of LUX. The proposed LUX ZEPLIN is supposed to use seven metric tons of liquid xenon, compared to the 350 kilograms at LUX. The next step, under design, is a 100 ton-scale detector, and that will be the ultimate limit for any future effort in direct detection.

**Particle colliders**

A second type of search for dark matter particles involves smashing protons together at unprecedentedly high energies.

One could thereby hope to produce dark matter particles directly. The Large Hadron Collider (LHC) in Geneva does precisely this. No experimental evidence for the existence of the theoretically predicted *supersymmetric* particles—subatomic partners to the known elementary particles—has been seen so far.

The LHC is expected to resume operation in 2016 at close to its design energy of 14 Tev (twice the energy at which it operated for the first three years). Some physicists hope that doubling the energy would finally reveal signatures of departure from the “standard model”—the theoretical framework for how subatomic particles should act—and provide a glimpse of supersymmetric particles.

Just before it closed down for the winter in late 2015, a time when the electricity needs of Geneva make running the LHC unacceptably expensive, there were hints of a new signal at an energy of 750 GeV. This consisted of a pair of photons, an unexpected result, that some have suggested might be due to new physics associated with the decay of a TeV mass dark matter particle created in high energy proton collisions in the collider beam. However the detection was not of high significance. All attention will focus on the new run of the LHC beginning in Spring 2016 which will either confirm the signal, and thereby excite the dark matter community, or demonstrate that it was simply a statistical fluke.

Will this be a high enough energy? The measurement of a Higgs particle lighter than was expected along with the failure so far to detect any hints of SUSY tells us that we may need to push towards even higher energies.

Given that SUSY at such a high energy scale becomes increasingly unnatural as the SUSY scale moves away from the Higgs mass, many particle physicists believe that a future 100 Tev collider merits serious consideration as the ultimate step in exploring the high energy physics frontier.

Beyond 100 Tev, the odds become increasingly unlikely that one could retain SUSY. We would have reached a threshold. For dark matter searches, this is exciting news. Direct detection experiments do have sensitivity up to this mass range. Fundamental arguments motivated by the early hot phase of the Big Bang tell us that the maximum mass of the dark matter particle, if it once was abundant in the very early universe, is around 50 or 100 Tev. Hence a future 100 Tev collider could definitively explore the dark matter implications motivated both by particle physics via SUSY and of cosmology via the predicted relic abundance of WIMPs from the Big Bang.

**Indirect detection**

Indirect detection of dark matter has hitherto been equally inconclusive. A unique collaboration by NASA with the US Department of Energy resulted in construction of the Alpha Magnetic Spectrometer (AMS-02) on board the International Space Station. This experiment recently reported the observation of more than 400,000 positrons (antiparticles of electrons) with a positron to electron excess that was consistent with the positrons originating from dark matter particles colliding and annihilating one another. These results appeared to strengthen an earlier 2008 report from another space-based experiment, an Italian-Russian satellite called the Payload for Antimatter/Matter Exploration and Light-nuclei Astrophysics (PAMELA).

However, the sources of these positrons could plausibly be pulsars (rapidly rotating neutron stars), rather than dark matter. There are a number of nearby nebulae believed to be powered by relativistic electron-positron winds from pulsars. The nearest of these is Geminga, about three hundred light years away. These nebulae leak electron-positron pairs, which diffuse throughout the interstellar medium. The numbers are uncertain, but an astrophysical source of positrons could certainly account for the observed increase in positron fraction at high energies. Future observations by AMS-02 are expected to distinguish between these alternative hypotheses. If the positron fraction continues to rise with energy, and then abruptly declines, this would be a smoking gun signal for dark matter. The answer should be forthcoming within the next two years.

Another source of excitement that recently ebbed and faded was the putative detection of a gamma ray excess from the Galactic Center by the Fermi satellite gamma ray telescope in the form of a 130 GeV line. Analysis of data on diffuse gamma ray emission from the Fermi gamma ray space telescope revealed a possible line feature that was strongest towards the center of our galaxy, where the concentration of dark matter is highest. Only dark matter annihilations or decays would be capable of producing such a spectral feature. Unfortunately continuing observations reveal a similar but smaller excess from the Earth’s limb, demonstrating that at least part of the signal must be instrumental in origin. Moreover as more data has been taken, the significance of any signal has not increased.
However one intriguing result from the Fermi satellite has stood the test of time, over the past several years. It provides the strongest evidence to date for dark matter. The Fermi telescope observes gamma rays from 100 MeV to several hundred GeV. It has discovered hundreds of discrete sources, including millisecond pulsars and distant active galactic nuclei, as well as extended sources such as supernova remnants.

In addition however, Fermi has reported a diffuse glow of gamma rays extending up to around 20 degrees from the centre of our galaxy. This is just where the dark matter in our galaxy is most concentrated. There are other contributions to diffuse gamma rays, most notably from the interaction of high energy cosmic rays with dense interstellar gas clouds.

Once all known gamma ray emission is subtracted from the observed flux, a diffuse excess of gamma rays remains. Curiously, it is distributed spherically symmetrically about the Galactic centre, just like the dark matter. Its intensity rises towards the center just as expected if the dark matter produces gamma rays by annihilations between dark matter particles. Both radial dependence and the intensity fit the simplest WIMP model. And the spectrum of the excess gamma rays resembles exactly what is expected from a 30 GeV WIMP.

It almost seems too good to be true. Unfortunately there is a rival theory, that of thousands of weak gamma ray sources in the central region, collectively contributing to the diffuse flux. These sources are most naturally millisecond pulsars. Study of the fluctuations in the diffuse gamma ray emission favours many sources over a truly diffuse flux, even though one cannot detect the individual sources. However the dark matter could also be highly clumpy, which would make it harder to disentangle the rival models.

A new player in the dark matter field at TeV gamma ray energies is the HESS Gamma ray telescope, a Cerenkov array in Namibia, which has begun observing the inner galaxy in the 100 GeV to 10 TeV energy range. Remarkably HESS reports a diffuse spherical glow at TeV energies emanating over the central 20 degrees of our galaxy. This too is completely unexpected.

Perhaps this is telling us that the gamma rays at Fermi and HESS energies come from novel sources of cosmic ray acceleration in the inner galaxy. Or more optimistically for dark matter, the gamma ray signals might incorporate a blend from millisecond pulsars and dark matter annihilations, both capable of injecting highly energetic electrons that scatter off the diffuse light and heat up the infrared and optical photons to gamma ray energies. Only improved observations will help disentangle the situation. A new array of gamma ray telescopes, called the Cerenkov Telescope Array, will be constructed in the next few years to probe our galaxy at unprecedented angular resolution to help decode the mysteries of the gamma ray sky.

The ambiguity and uncertainty associated with these results serve to demonstrate how murky the searches for dark matter have become. After decades in which experiments periodically reported to have spotted a potential sign of dark matter, only for those results to be later dismissed, physicists have justifiably learned to be extremely skeptical of any claimed detection.

New directions

We certainly should be preparing to seek broader categories of dark matter particles, or even unparticles, as dubbed by one theorist. These particles might for example not undergo annihilations but could have an enhanced scattering signal. If in addition they had light masses, below say ten proton masses, one would find that the Sun could be as powerful a collector and detector as any terrestrial experiment. Such particles would slightly modify the temperature profile of the sun and thereby affect the granular noise that is studied on the surface of the sun. These are eddies that rise, fall and swirl in the chromosphere. One measures the velocities of fluid elements by Doppler spectroscopy.

This has led to the science of helioseismology, which enables one to study long wavelength disturbance that propagate inside the sun. No evidence for dark matter in the sun has yet been found, although the helioseismological signals are very difficult to reconcile with our model of the sun. We can actually measure the temperature at the centre of the sun from the neutrino flux produced at MeV energies, and this is a key ingredient for our standard model of the sun.

If dark matter particles collect in the sun, they annihilate in the core of the sun, and neutrinos at GeV energies escape from the sun. These neutrinos traverse the earth where they produce muons which in turn can be intercepted in underground detectors by looking for faint flashes of light. There are experiments such as SuperKamiokande in Japan that monitor the sun for such neutrinos, and so far have not found any candidate events.

Very massive particles cannot easily be seen by any direct or even indirect experiments because their flux is so low. But with some ingenuity one can imagine that cold objects such as old neutron stars or white dwarfs might potentially provide novel signals. Of course, theorists are incredibly ingenious and will no doubt continue to provide new ideas for experimentalists in the increasingly desperate search for dark matter.

The worst scenarios are twofold. Firstly, there may be no single solution to the identity of dark matter particles. Secondly the dark matter particles may be almost completely elusive and interact only gravitationally, such as the gravitino, the SUSY counterpart of the graviton, the carrier of gravitational waves.
Our choices are not simple. There are simply too many astrophysical and cosmological detections for the dark matter problem to disappear. We at least are convinced that dark matter is here to stay. Elucidating its nature in the next decade will provide a fascinating challenge.

**Alternative scenarios?**

Perhaps we do not understand gravity. Einstein's theory, despite the overwhelming evidence for it most recently manifested by the LIGO discovery of gravitational waves, may simply be wrong in the low density outer parts of galaxies where dark matter seems to be dominant.

In addition to the obvious route—continuing the experimental searches—more attention should be given to identifying specific experimental/observational tests that can definitively rule out certain classes of alternative theories. If, however, dark matter is still not discovered in the next decade, and if some alternative theories are still standing, then these should be taken much more seriously than they are today.

The null results from LUX, the LHC, and other dark matter experiments are rapidly squeezing the regions of parameter space available to hide the dark matter particles. Consequently, some theorists have started to wonder whether dark matter truly exists. In fact, one alternative to dark matter, known as "Modified Newtonian Dynamics" (MOND), was proposed already as early as 1983. Physicist Moti Milgrom suggested this as a phenomenological framework, in which rather than invoking dark matter to explain velocities around galactic centers, he modified Newton's law of gravity. The idea is that Newton's force law must be tweaked at very low accelerations, such as the ones encountered at the very outskirts of galaxies. Remarkably, it was soon found that MOND accounts for the rotation curves of hundreds of nearby galaxies, without any need for dark matter, simply by choosing one parameter that represents the scale at which MOND-like gravity replaces that of Newton. However modern data shows that rotation curves, especially of dark matter–dominated dwarf galaxies, are often complex and require a more complicated model.

While the idea of alternatives to Einstein's gravity have gained very few supporters (and have proven very difficult to formulate as a complete theory), this approach also proven extremely hard to definitively reject. For instance, such theories often encounter difficulties in explaining galaxy dynamics on the scale of clusters of galaxies, but adding a component of baryonic non-luminous matter (about equal in quantity to the amount of luminous matter) would resolve the perceived discrepancies. Neutrinos of electron volt mass could plausibly provide such a component. The "Bullet Cluster" was hailed for a while as an ultimate refutation of MOND. In that cluster, observations seem to show a clear separation between the baryonic hot gas and the weakly interacting dark matter. However, later analyses again revealed that alternative gravity models, aided by some baryonic non-luminous component, could also fit the observations.

The advocates of modified gravity have not abandoned their pursuit of an alternative to Newtonian gravity. A crucial ingredient of Galilean mechanics and indeed Newton's laws of motion is the dependence on the observer's reference frame. Einstein considered that a universal theory of gravity should not be observer-dependent, and this motivated him to successfully develop the theory of relativity, in which there is no preferred frame. There are indeed observer-independent theories of modified gravity, but all suffer from faults. There are strong constraints from solar system measurements that leave little scope for natural choices of parameters.

On the largest scales, it is difficult to understand the strength of temperature fluctuations in the cosmic microwave background that are so elegantly explained in the simplest Big Bang model unless the universe is accelerating. More precisely, it is the combination of cosmological constraints, cosmic microwave background fluctuations, baryon acoustic oscillations in the large-scale distribution of galaxies, and supernova distance measurements that argue strongly for the cosmological constant as a solution for the observed acceleration. This is very surprising because the value observed for the acceleration is so much smaller than any "natural" value expected from the theory of the Big Bang. Some theorists are invoking modified gravity to address this equally grave astrophysics problem, that of the origin of the cosmological constant.

Perhaps the two great problems of modern cosmology, the nature of dark matter and the origin of the cosmological constant, are connected, but until now no theorist has found a shred of evidence for any compelling theory that provides such a unification. Modified gravity theories rapidly become complex and ugly, if they work at all. Dark matter seems here to stay. But the path forward remains to be clarified.