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Behind the Scenes of the Universe

FROM THE HIGGS TO DARK MATTER

GIANFRANCO BERTONE

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To Nadia. And to our son Francesco,
the most sweet distraction an author can hope for.

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Preface

An extraordinary discovery has recently shaken the foundations of cosmology and particle physics, sparking a scientific revolution that has profoundly modified our understanding of the universe we live in, and that is still far from over.

Pioneering astronomers in the 1920s and 1930s had already noticed suspicious anomalies in the motion of celestial bodies in distant galaxies and clusters of galaxies, but it wasn't until the late 20th century that the scientific community was confronted with an astonishing conclusion: the universe is filled with an unknown, elusive substance that is *fundamentally different* from anything we have ever seen with our telescopes or measured in our laboratories.

It is called *dark matter*, and it constitutes one of the most pressing challenges of modern science. Its existence is much more than an academic curiosity, as dark matter provides the invisible scaffolding that keeps together all astrophysical structures in the universe. Take it away from a galaxy like our own Milky Way, and all its stars and planets would fly away like bullets in intergalactic space!

In the last 30 years we have learnt a lot about the properties of this mysterious substance. For instance, we have measured its abundance in the universe with exquisite accuracy, and we now know that it is far more abundant than the matter we are familiar with. We do not yet know what its nature is, but we can confidently say that *it must be made of new, as yet undiscovered particles*, unless we are being completely misled by a wide array of astrophysical and cosmological observations.

The consequences of this discovery are astonishing. The extraordinary show offered by the cosmos—the dance of planets around stars, the delicate appearance of distant nebulae, the violent clash of giant galaxies, and ultimately the very mystery of our own existence—takes place on a colossal, invisible stage made of ever-growing halos of invisible matter. And we, as human beings, are made of a relatively rare form of matter in the universe: we are *special*, in a way we had never suspected.

A worldwide race is under way to identify dark matter, with experimental facilities that include CERN's particle accelerator and a variety of astroparticle experiments located underground and in orbit around the Earth.

In this book, aimed at general readers with an interest in science, I describe the strategies proposed by physicists to go *behind the scenes* of the universe, in order to identify the nature of dark matter. I will argue that we are about to witness a pivotal paradigm shift in physics. Thirty years have passed since the current leading theories were proposed to solve the dark matter problem, and at least two generations of physicists have worked out detailed predictions for a wide array of experimental searches and built ever-larger and more sensitive experiments to find dark matter particles.

The time has now come either to rule out these theories, and move on to new ideas, or to discover dark matter and pave the way to a new era of cosmology and particle physics.

Gianfranco Bertone

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A dark mystery

On December 12, 2010, high-ranking members of the State Council of China met with representatives of Tsinghua University, Beijing, in the mountainous province of Sichuan, to inaugurate the world's deepest underground laboratory for astroparticle physics: a 1400-cubic-meter hall excavated deep in the heart of Jinping Mountain, two and a half kilometers below the surface.

Thirteen thousand kilometers south, almost simultaneously, a team of scientists were pumping hot water into the ice of the Antarctic plateau to drill the last of a series of 80 holes, 2500 meters deep and 60 centimeters wide, and to deploy in that hole the last string of detectors for the IceCube telescope, marking the end of its construction phase, which had started seven years earlier, and the beginning of the experiment itself.

In an even more unlikely location, on May 19, 2011, a team of astronauts aboard NASA's Space Shuttle *Endeavour* removed the six-ton detector AMS-02 from the Shuttle bay and handed it over to the astronauts of the International Space Station, in a spectacular delivery between robotic arms 350 kilometers *above* the ground.[1]

These are but the latest additions to an ever-growing list of impressive scientific facilities for astroparticle physics, a booming field of scientific research at the interface between astrophysics and particle physics: gamma-ray and antimatter satellites, orbiting

[1] Spectacular footage of the delivery can be found on YouTube at <http://www.youtube.com/watch?v=RqksBepilVs>.

freely around the Earth or attached to the International Space Station; neutrino telescopes, buried in the ice of the South Pole or anchored at the bottom of the Mediterranean Sea; and particle accelerators, smashing elementary particles at extremely high energies.

Scientists hope that by combining data from all these experiments they will be able to shed light on one of the biggest open problems of modern science, a mystery that challenges our understanding of the universe and of our place in it: *dark matter*. The roots of this mystery run deep in time, but only very recently has the dark matter problem manifested itself in all its inexorable, fierce difficulty, shaking the foundations of cosmology and particle physics.

The understanding of the universe had proceeded rather linearly from the beginning of the 20th century, when Hubble had discovered the expansion of the universe. But when, in the 1970s, scientists tried to put together the many pieces of the cosmic puzzle (like the abundance of light chemical elements in the universe, the motion of stars in galaxies, and the velocity dispersion of galaxies in clusters) and to come up with a consistent cosmological model, these pieces just didn't seem to fit. To complete the puzzle, the existence of a new form of matter, *dark* matter, had to be postulated.

In an article that appeared on October 1, 1974, in the prestigious *Astrophysical Journal*, renowned Princeton cosmologists described the paradigm shift that was taking place with these shocking words:[2]

> There are reasons, increasing in number and quality, to believe that the masses of ordinary galaxies may have been underestimated by a factor 10 or more.

A factor of ten! All of a sudden, the familiar galaxies that had been observed and studied for decades, the *ordinary* systems of stars and gas whose structure was believed to be well understood,

[2] J. P. Ostriker, P. J. E. Peebles, and A. Yahil, "The size and mass of galaxies, and the mass of the universe", *Astrophysical Journal* 193 (1974) L1–L4.

had become uncomfortably big, too massive, and, overall, frankly bizarre. Nobody knew anymore what they, or at that point anything else in the universe, were actually made of. The standard picture of a galaxy, thought to be a simple disk of stars rotating along with their planets around a common center, and immersed in a sea of dilute gas, had suddenly become inaccurate and misleading. Gas and stars were just a small part of a much larger, more massive, *halo* of invisible matter.

The implications of this paradigm shift are staggering, and so deep that we have just started exploring them. The most important, perhaps, is that the existence of stars, black holes, supernovae, planets, and the Earth itself, in short, everything we know, is possible thanks to a sort of "cosmic scaffolding" made up of dark matter. Take dark matter away from a galaxy, and its stars and planets would break loose like bullets in the intergalactic space. This also means that we, as human beings, are not made of the same stuff that most the universe is composed of: we are *special*, in a way we had never suspected.

In modern cosmology, dark matter provides, in a way, the "stage" for the "cosmic show", a stage that was assembled when the universe was young, way before the time when stars started to shine and planets started to form, and this stage is still evolving. It is, in short, *the supporting structure of the universe*. It solves in a single stroke many problems in astrophysics and cosmology, and it provides a self-consistent framework for the structure and evolution of the universe.

Physicists, however, are hard to convince. Above all, we are reluctant to introduce new concepts, let alone new forms of matter, without hard, incontrovertible evidence. As much as astrophysical observations point to the existence of this unknown component of the universe, we simply cannot accept it until we can measure its properties and study it in our laboratories. As Robert Pirsig put it in his *Zen and the Art of Motorcycle Maintenance*,

> The real purpose of scientific method is to make sure Nature hasn't misled you into thinking you know something you don't actually know.

From modifications of gravity to new particles, and from faint stars to mirror worlds, the list of solutions proposed to the dark matter puzzle is very, *very* long, and new ideas continue to be proposed today.

As a result, to the untrained eye, modern physics journals sometimes evoke those ancient manuscripts, such as medieval bestiaries or Egyptian papyri, in which real animals seamlessly mingled with bizarre monsters and other imaginary beings. In fact, they teem with a wide array of exotic particles with bizarre names and even more bizarre properties, mingling with the already rich and heterogeneous zoo of known particles and fields.

Physicists, in a sense, are like ancient geographers, who drew monsters and other imaginary beings beyond the frontiers of the known lands. In order to explain dark matter, they have imagined new particles populating the "terra incognita" of particle physics. To detect these dark matter candidates or to rule them out is one of the greatest scientific challenges of the 21st century.

Perhaps they will turn out to exist only in the imaginative minds of particle physicists, as happened for the mythological monsters of ancient civilizations. But just as some of those ancient monsters actually turned out to be distorted perceptions of real animals, the hope is that through carefully designed experiments we will finally be able to detect dark matter particles and to shed light on some of the darkest mysteries of the modern science.

This book is about the quest for dark matter: the reasons that push scientists to believe that it exists, the theories that have been put forward to explain it, and the worldwide race currently in progress to identify it.

I will argue that we are about to witness a revolution in this field of research in the next five to ten years, for either we will find dark matter particles, therefore opening up an entirely new branch of science, or we will inevitably witness the decline of the leading theories, forcing us to revisit our description of the universe.

A peek behind the scenes

If you look at the sky on a dark night, you will see the Milky Way as a glowing band of light across the firmament. The realization that what James Joyce called

> infinite lattiginous scintillating uncondensed milky way

is just the disk of stars and gas of the disk galaxy we live in, *as seen from the inside*, is for many a source of awe and inspiration, and for some a source of shivers of excitement down the spine. It gives the whole sky a sense of perspective, providing depth to the otherwise two-dimensional vault of the heavens.

Looking towards the constellation Sagittarius, you'll be looking at the Galactic center, which is at the same time the center of the disk of stars and gas of our galaxy, which constitutes essentially everything you can see in the sky with the naked eye, and the center of a spheroid of dark matter, the halo, about ten times larger, and ten times more massive than the disk.

The density of this halo is relatively high. For every square centimeter of the page you are reading, there are about 30 thousand dark matter particles passing through that surface every second, at a speed of about 100 kilometers per second.[3] The reason why we don't perceive these particles, even if we are constantly bombarded by them, is that they interact very weakly with ordinary matter, which is also the reason why dark matter is so difficult to measure.

The Milky Way contains many *substructures*, smaller concentrations of dark matter with small proportions of stars and gas, some of which are even visible to the naked eye, like the Magellanic Clouds. But the biggest concentration of dark matter

[3] The actual constraint derived from observation is on the mass density of dark matter, which is about 0.3 GeV cm^{-3}. To derive the number of particles through the surface, I have assumed that the mass of a dark matter particle is approximately 100 GeV, that is, about a hundred times the mass of a proton.

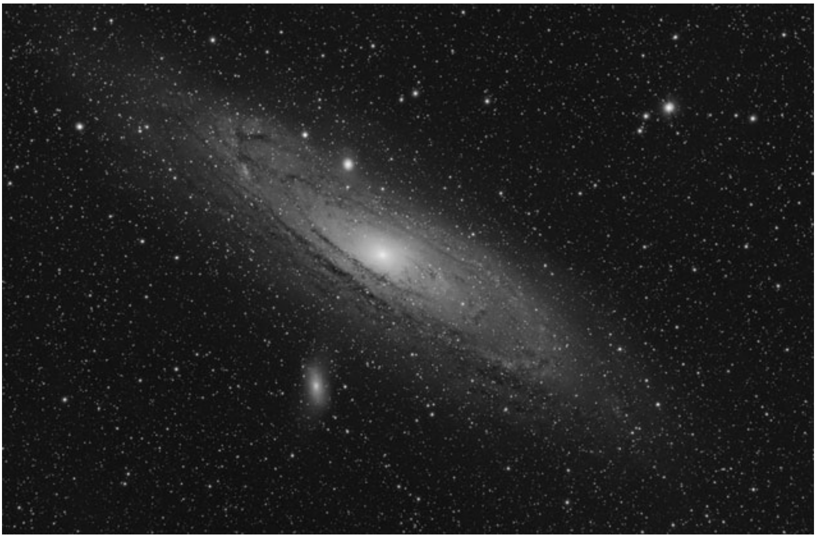

Figure 1.1: The Andromeda Galaxy, our sister galaxy.

beyond the Milky Way is our sister galaxy, the Andromeda Galaxy (Figure 1.1).

We can see it even with the naked eye as a blurred star, in the group of constellations that are named after the Perseus myth. But a telescope image reveals it as a beautiful spiral of stars and gas, similar in size and shape to our own Milky Way. It is the most distant object we can see with the naked eye, and the only extragalactic object that can be observed from the northern hemisphere.

With a telescope image, we can do more than admire its beauty. Since Newton, in fact, we have known how to calculate the velocity of an object gravitationally bound to a given mass: the faster the celestial object, the larger the mass. We can calculate, for instance, the speed of the Earth and of all the other planets as they orbit around the Sun, given the size of their orbits. But if we apply this technique to calculate the velocity of the stars in the Andromeda Galaxy, it fails.

This had actually already been observed by Horace W. Babcock in 1939: the Andromeda Galaxy rotates very fast at large radii, *as*