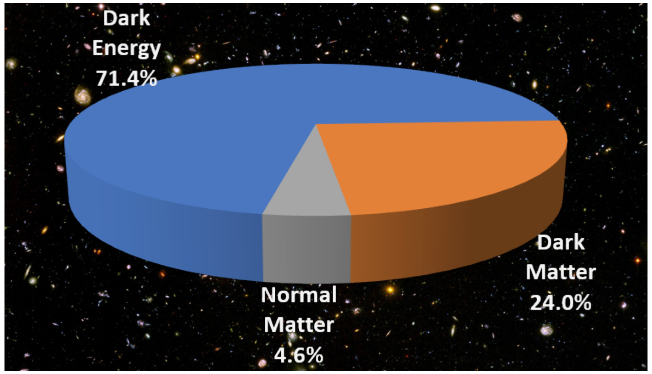
ing the collision of Dark Matter with atoms in ultra-sensitive detectors such as XENONnT, or by their production in the LHC. We investigate in detail the interplay between theoretical motivations of the candidates in models beyond the Standard Model, their constraints from different experimental detection methods, and the mechanism to produce them in the early Universe in the appropriate amount.

The Mystery of Dark Energy

The Dark Energy contributes the largest part (about 71.4%) of the Universe, and is one of the biggest unresolved puzzles of physics. While all normal forms of matter are slowing down the expansion of the Universe, the Dark Energy induces the observed accelerated expansion. In standard cosmology, the Dark Energy corresponds to a cosmological constant, and already there emerges the question why its value is such special. With respect to quantum mechanics, it is even more mysterious since the expected zero-point energy should be by many orders of magnitude larger than the observed one. So far, the origin of this mysterious phenomenon is largely unravelled, but several interesting attempts to explain it exist, in which the Dark Energy is connected with special scalar fields and their dynamics.



Energy composition of the Universe according to the new results of the WMAP satellite. In the background galaxies of the Hubble ultra deep field. (Image: the Hubble Heritage)

Title picture: Methods to detect Dark Matter: directly by collision with matter in detectors, indirectly by astrophysical observation of its decay and annihilation processes, or production at accelerators. Background: millennium simulation (MPI for Astrophysics).

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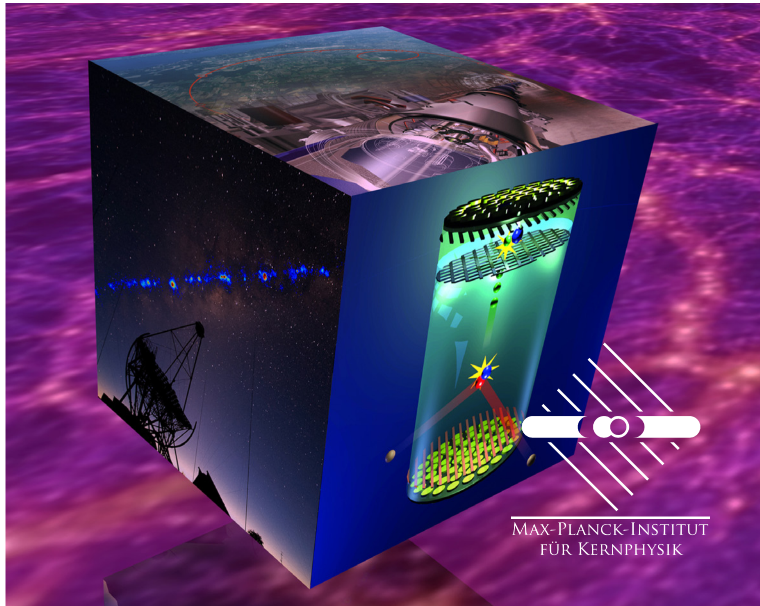
The Max-Planck-Institut für Kernphysik (MPIK) is one of 86 institutes and research establishments of the Max-Planck-Gesellschaft. The MPIK does basic experimental and theoretical research in the fields of Astroparticle Physics and Quantum Dynamics.

Theoretical Astroparticle Physics and Cosmology



Theoretical
Astroparticle Physics and Cosmology

Bridging Particle Physics and Astrophysics

Modern theoretical physics demonstrates that the behaviour of the elementary particles on the tiniest scales and the evolution of the Universe at the largest scales are inseparably connected with each other. These fascinating connections are the research topic of astroparticle physics and cosmology. On the one hand, detailed knowledge of particle physics processes is necessary to understand the development of the early Universe. On the other hand, astrophysical and cosmological observations allow interesting conclusions to be drawn about the properties of the elementary particles.

A View Back to the Beginning of the Universe

The stars, planets, and galaxies that comprise our Universe today originally emerged from a hot, largely homogeneous plasma of elementary particles. During the course of the expansion of the Universe, the plasma cooled down and passed through a number of so-called "phase transitions". After about 300 000 years since the Big Bang, the first atoms came into existence when atomic nuclei and electrons combined. In an even earlier phase, a few seconds after the Big Bang, even atomic nuclei could not yet exist. Instead their constituents – protons and neutrons – were present as free, unbound particles. But these were formed only about a millionth of a second after the Big Bang from still more fundamental constituents, the quarks.

Up-to-date model calculations are able to trace the evolution of the Universe back to a billionth of a second after the Big Bang in a reliable manner, but there are numerous attempts to advance still further – towards epochs lying less than 10^{-43} seconds after the Big Bang.

A completely new window into the earliest epochs and in the farthest events of the Universe has been opened by the discovery of gravitational waves. By observing them, a large number of cosmological and particle physics models can now be tested.

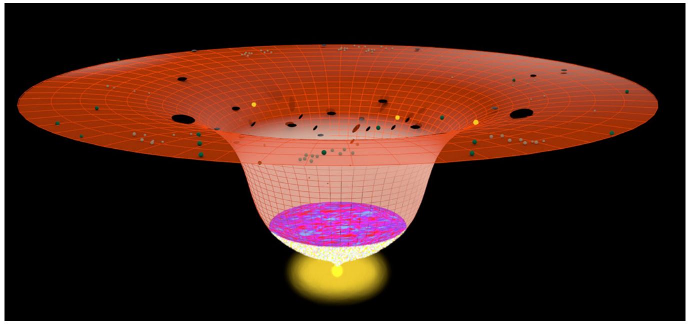


Illustration of the accelerated expansion of the Universe. The cosmic microwave background (pink/blue) indicates the end of the inflationary expansion just after the Big Bang.

Neutrinos in Astrophysics and Cosmology

Due to their unique properties, neutrinos offer insight into otherwise not accessible regions. For example, they are produced in large amounts in certain stellar explosions and thereby influence both the course of this "supernova" and their mutual interconversion. Observing these neutrinos may provide valuable hints on yet unknown neutrino properties.

Since neutrinos are present in large amounts in the Universe, they may have consequences for the development of the cosmos despite their tiny mass. This affects the production of the elements of the periodic table in the early Universe, or the distribution of galaxies as it is observable today.

Additional "sterile" neutrinos which interact even weaker with other particles and are contained in many theories beyond the Standard Model, take even more fundamental impact. They would have been produced in the Big Bang in large number; however, they are unstable and thus decay immediately. This implies the possibility that more matter than antimatter is generated. This mechanism is called "leptogenesis"; thereby one of the biggest puzzles of physics would be resolved, namely why there has been a small excess of matter. Interestingly, these sterile neutrinos may explain the smallness of the observed neutrino masses.

Besides leptogenesis, there are other possibilities to generate a matter-antimatter asymmetry. The explanations range from theories of the grand unification at extremely high energies to the existence of new particles that might be accessible at particle accelerators.

Dark Matter

We know from astrophysical and cosmological observations that only about 4.6% of the Universe consists of the known elementary particles. The remainder consists of Dark Matter (approximately 24%) and Dark Energy (about 71.4%). Dark Matter most probably consists of yet unknown types of elementary particles. The development of particle physics models that provide an explanation for the existence of Dark Matter and allow the calculation of its properties represents a big challenge for theoretical particle physics.

Presently, a number of different models are investigated. For example, it could be that the lightest of the abovementioned sterile neutrinos may constitute Dark Matter, provided its mass amounts to a certain order of magnitude. Further, so-called "Weakly Interacting Massive Particles" (WIMPs), which are hypothesized in many extensions of the Standard Model of particle physics, are promising candidates. Further candidates are axions, light elementary particles, that are contained in theories able to solve a certain problem of strong interactions.

All the candidates differ by their production mechanism in the early Universe, and also by their possible detection principle. For example, this may be accomplished by observ-

Theoretical proposals to explain Dark Matter: (clockwise) weak interaction, neutrinos, light bosons, other particles gravitation, and macroscopic objects.