PROSPECTS IN ASTROPARTICLE PHYSICS

John ELLIS

*Theoretical Physics Division, CERN**CH-1211 Geneva 23**E-mail: John.Ellis@cern.ch*

The close links between particle physics - the study of the very small - and cosmology - the study of the very large - are reviewed. Many of the most fundamental problems in the macrophysical history of the Universe can only be solved with knowledge of the fundamental laws of microphysics. Conversely, some speculations about particle physics may be testable only in astrophysics. The density budget of the Universe, particle candidates for dark matter and the search for supersymmetry with both astrophysical and accelerator experiments are discussed in more detail.

1 Particles and Forces

At different scales in the Universe, we see many **structures** with different sizes, each made of *constituents* bound together by different fundamental forces. At the largest scale of 10^{23} cm, **clusters** are composed of *galaxies* held together by gravity. At a scale of 10^{21} cm, **galaxies** are made out of *solar systems*, again held together by gravity. With typical sizes of 10^{14} cm, **solar systems** comprise *stars and planets*, again held together by gravity, which together with the strong and weak nuclear interactions provides stars (and hence planets) with their energy. At scales $\sim 10^9$ cm, **planets**, jumping a few steps, are composed of *molecules*, held together by gravity and electromagnetism. In turn, at scales $\sim 10^{-6}$ cm, **molecules** are composed of *atoms*, held together by electromagnetism. At a scales $\sim 10^{-8}$ cm, **atoms** are in turn composed of *nuclei* and *electrons*, again held together by electromagnetism. Going down to a scale of 10^{-12} cm, **nuclei** are composed of *protons* and *neutrons*, called collectively *nucleons*, held together by the strong nuclear interactions and occasionally decaying via the weak nuclear interactions. With sizes of 10^{-13} cm, the **nucleons** are composed of *quarks* and gluons, confined together by the strong nuclear interactions.

It is apparent from this descent down the cosmological distance ladder that what one interprets as a *constituent* depends on the scale at which one analyzes a composite **structure**. At the moment, there are three *constituents* in the above list that are, as far as we can tell, fundamental at even the smallest distances $\sim 10^{-17}$ cm probed by experiments. Are these truly elementary, or are they in turn composed of even smaller *constituents*? Only time and experiments at smaller distances (higher energies) will be able to tell. For the

moment, our experimental knowledge of these 'elementary' particles, summarized in the Standard Model, already allows us to describe the Universe since it was about 10^{-10} s old. This and our speculations about the earlier history of the Universe are shown in Fig. 1.

Figure 1: The history of the Universe, showing the rôles of elementary particles. Note in particular the emission of the cosmic microwave background when the Universe was about 300,000 years old, Big-Bang nucleosynthesis when the Universe was about 100 seconds old, and the possible inflationary epoch when the Universe was less than 10^{-30} seconds old.

2 The Standard Model

According to this theory, which describes successfully all confirmed data from particle accelerators, there are four fundamental forces, those of gravity, electromagnetism, the strong and weak nuclear interactions. The first three of these are carried by massless intermediate bosonic particles, the graviton ^a, the photon - well-known since the work of Planck and Einstein, the gluon -

^aStrictly speaking, the existence of the graviton has not been confirmed by experiment, but it is confidently predicted to exist, as an inevitable consequence of any quantum theory of gravity.

discovered at DESY in Germany in 1979¹, and the intermediate boson $W^\pm$ and Z^0 - discovered at CERN in 1983².

The interactions of these carrier bosons with the fundamental matter particles have many similarities: One of the biggest puzzles of the Standard Model is why and how the $W^\pm$ and Z^0 particles are so massive - weighing as much as a medium-sized nucleus, whereas the other intermediate bosons are massless.

All of the known stuff in the Universe is fabricated out of a limited number of species of matter particles, six quarks weighing between a few MeV (the up and down quarks) and about 170 GeV (the top quark), the electron and its accompanying neutrino, and two heavier siblings of the electron, the muon and tau, both with their own partner neutrinos. Another of the big puzzles left open by the Standard Model is why Nature chose to have so many fundamental matter constituents, no more and no less. CERN's largest accelerator LEP has provided us with strong reasons to think there are no more matter species, since it has established that there are precisely three different neutrino species³, and hence, by extension, three electron-like particles and three pairs of quarks.

Figure 2: Measurements of particle production at CERN's LEP accelerator at energies corresponding to the mass of the Z^0 boson agree very accurately with the Standard Model³, after QED and other radiative corrections are included. In particular, the height and width of the Z^0 peak are very sensitive to the number of neutrino species, which is determined to be three.

As seen in Fig. 2, the Standard Model has been tested at the 0.1 % level by experiments at LEP and elsewhere, giving us confidence that we understand

physics at energies less than ~ 100 GeV, emboldening us to describe the history of the Universe back ever since typical particle energies fell below ~ 100 GeV, when the Universe was about 10^{-10} s old.

3 The Big Bang

According to this 'Standard Model' of cosmology, the Universe is undergoing some sort of (approximately) homogeneous and isotropic expansion. The first evidence for the Big Bang was the Hubble expansion of distant galaxies. According to elementary thermodynamics, a gas in adiabatic expansion gradually cools, according to

$$a \times T \sim \text{constant}, \quad (1)$$

where a and T are the size and temperature of the Universe, respectively. There are two very important pieces of evidence that this simple-minded Big Bang picture can be extrapolated back to when the Universe was much smaller and hotter than it is today.

Figure 3: The cosmic microwave background sky, as measured by the COBE satellite⁴. The radiation is isotropic to one part per mille, the level at which the dipole asymmetry due to the Earth's motion appears. This plot shows the fluctuations at the level of 10^{-5} that may be due to quantum effects in the early Universe during inflation.

The first piece of evidence is provided by the **cosmological microwave background radiation**, illustrated in maps from the COBE satellite in Fig. 3⁴,

which bathes us in ~ 400 photons/cm³ with an effective temperature of ~ 3 K. These are thought to reach us from an epoch when the Universe was about 3000 times hotter and smaller than it is now. Before then, the photons would have been interacting with electrons and nuclei in an electromagnetic plasma, but have been streaming freely since the Universe cooled below a few thousand K, and the electrons and nuclei combined to form stable neutral atoms.

Another piece of evidence is provided by the success of calculations of the amounts of light elements that would have been produced early in the Big Bang⁵, when the Universe was about 10^9 times smaller and hotter than it is today. This would have happened when the Universe was between 1 and 100 s old, when the temperature was between about 10^9 and 10^{10} K. According to the standard Big-Bang nucleosynthesis calculations, about 24 % by weight of ⁴He would have been produced then, and smaller amounts of Deuterium, ³He and Lithium. All these light elements have been seen in astrophysical observations, with abundances close to those calculated, assuming that the overall density of conventional nuclear matter in the Universe, ρ_B , is a few % of the critical density that would be required to reverse the expansion of the Universe, as seen in Fig.4⁵.

Figure 4: Comparison between measurements of the abundances of light elements and calculations based on Big-Bang nucleosynthesis, which are in good agreement if conventional matter constitutes a few % of the critical density that would be required to reverse the expansion of the Universe⁵.

These two pieces of evidence encourage us to take seriously Big-Bang cosmology, and try to probe it back at even earlier times. Assuming that the expansion of the Universe was dominated at early times by relativistic particles, one would expect

$$t \sim a^2 \sim \frac{1}{T^2}, \quad (2)$$

where t is the age of the Universe. Putting in the numbers, one estimates that the temperature would have been about 10^{10} K when the age $t \sim 1$ s, corresponding to typical particle energies $E \sim 1$ MeV, comparable to the mass of the electron. More generally, one may estimate that

$$t(\text{seconds}) \sim \frac{1}{T(\text{MeV})^2}. \quad (3)$$

For example, the temperature would have been about 10^{13} K, corresponding to ~ 1 GeV and the proton mass, when the age of the Universe was about one microsecond. It is clear that one needs to be able to understand particle physics in order to be able to calculate the history of the very early Universe.

One of the landmarks during the early history of the Universe would have been the confinement of the quarks into nucleons and mesons, which is believed to have occurred when the Universe was between 10^{-6} and 10^{-5} s old. Looking further back, the temperature of the Universe would have been the equivalent of 100 GeV, comparable to the mass of the intermediate W and Z bosons, when the Universe was about 10^{-10} s old. The physics needed to describe the Universe from this age onwards is presumably provided by the Standard Model, that has been so well studied in accelerator experiments. Future experiments with the LHC accelerator⁶ will probe particle energies and masses up to about 10^3 GeV or 1 TeV, exploring the history of the Universe back to when it was about 10^{-12} s old. The history of the Universe before this epoch may lie beyond the direct reach of experiments with particle accelerators.

4 The Big Problems in Cosmology

Here are a few of the major problems in cosmology that may find solutions in particle physics.

4.1 *The Origin of the Matter in the Universe*

As we have just seen, the success of Big-Bang nucleosynthesis calculations indicates that the amount of conventional matter in the Universe is a few % of the critical amount required to reverse its expansion. By way of comparison,

the number of photons in the Universe, mainly in the cosmological microwave background radiation, is many orders of magnitude larger:

$$\frac{n_B}{n_\gamma} \sim \text{few} \times 10^{-10}. \quad (4)$$

So one question that arises immediately is why there are a few matter particles, and not many more, or perhaps none at all? This puzzle is deepened by the fact that relativistic quantum theory requires every particle to possess a corresponding antiparticle, with equal mass and opposite internal properties. Indeed, the first observed antiparticle, that of the electron, was discovered in the cosmic rays. By now, many more types of antiparticle have been produced in accelerators, experiments are routinely made with beams of antiparticles, and antiatoms have been manufactured⁷. This poses a second set of questions: are there any large concentrations of antiparticles in the Universe, and, if not, why not?

A small number of antiprotons have been found in the cosmic rays, but the observed rate is compatible with the hypothesis of secondary production in the collisions of primary matter cosmic rays⁸. A ‘smoking gun’ for primary antimatter in the cosmic rays would be the observation of antinuclei, which are very difficult to produce in the collisions of matter particles. None have yet been seen. For example, the AMS experiment - see Fig. 5 - first flown on the space shuttle found no anti-⁴He nuclei in an exposure that detected 2.86×10^6 normal ⁴He nuclei, as seen in Fig. 6⁹. Thus it seems unlikely that there are any large astrophysical concentrations of antimatter near the Earth. Indeed, if there were any in our local cluster of galaxies, we would have seen γ -ray emission from the boundary between the antimatter and matter regions. Even more distant concentrations of antimatter could have affected the cosmic microwave background radiation¹⁰. Moreover, no satisfactory mechanism has ever been found for separating matter and antimatter on an astrophysical scale. Therefore, the belief is that there are no large amounts of antimatter within the observable Universe.

Particle physics can explain this apparent dominance of the Universe by matter. The idea starts from the observation that, if there were a small excess of matter particles (quarks) in the early Universe over the number of antiquarks, essentially all the antiquarks would subsequently have been annihilated by quarks, leaving behind the small excess density of quarks, which would constitute the matter we see around us in the Universe today. This annihilation of the antiquarks would have taken place around the time when quarks were confined into nucleons in the early Universe, when it was between 10^{-6} and 10^{-5} s old.

Figure 5: The AMS space experiment⁹, which was first launched on the space shuttle, and will be returned to spend a longer time on the International Space Station.

Figure 6: Observations of ${}^4\text{He}$ nuclei by the AMS experiment during its first flight: no anti- ${}^4\text{He}$ nuclei were seen⁹.

The next problem is to generate this small matter excess. The three necessary conditions were set down in 1967 by the Russian physicist Sakharov¹¹, who is shown in Fig. 7. (1): There should be differences between the interactions of matter and antimatter particles - which have indeed been observed in many different laboratory experiments. (2): There should exist interactions capable of changing the total quark number - these are predicted in the Standard Model and many of its extensions, though none has yet been observed. (3): There should be an arrow of time - this is provided automatically by the expansion of the Universe, which may lead to first-order phase transitions, for example at the quark confinement transition, or earlier at the epoch $\sim 10^{-10}$ s when particles acquired their masses, or even earlier still.

Figure 7: The Russian physicist Andrei Dimitrievich Sakharov, who showed how the matter-antimatter asymmetry of the Universe could be explained in terms of particle physics¹¹.

Two favoured scenarios are that the matter-antimatter asymmetry arose at this mass transition¹², or in the decays of ultra-heavy neutrinos¹³. In either case, it might be possible to relate the observed density of matter in the Universe to matter-antimatter differences in the laboratory. These might be, respectively, in the properties of Higgs bosons¹⁴, or in neutrino oscillations and muon and tau decays¹⁵. Using such laboratory measurements to calculate the

amount of matter in the Universe would certainly be a wonderful breakthrough for astroparticle physics.

4.2 The Size and Age of the Universe

Why is the Universe so large and so old, and why is Euclidean geometry a good approximation? These questions are so fundamental, that one tends not even to ask them, taking them rather as givens. To formulate the questions, one must consider the Friedman equation that describes the expansion of a homogeneous and isotropic Universe:

$$\left(\frac{\dot{a}}{a}\right)^2 = \rho G_N - \frac{k}{a^2}, \quad (5)$$

where $G_N \equiv 1/m_P^2$, where m_P is the Planck mass: $m_P \sim 10^{19}$ GeV, ρ is the energy density and $k = -1, 0$ or 1 is the overall curvature of the Universe. The critical density corresponds to $k = 0$, and cosmological data suggest that the overall density of the Universe is within some small factor of this value. The only dimensionful parameter in (5) is $m_P \sim 10^{19}$ GeV, so ‘typical’ solutions of the equation would have a characteristic size comparable to the Planck length $\ell_P \sim 10^{-33}$ cm and a characteristic time-scale $\sim t_P \sim 10^{-43}$ s. Clearly, we do not live in such a ‘typical’ solution, and our Universe must be ‘special’ in some sense. This ‘specialness’ may be due to cosmological inflation¹⁶.

The theory of cosmological inflation postulates that the Universe underwent a period of exponential expansion at some very early time in its history. Clearly, this would help explain how the Universe was able to grow so large. Also, during this period of exponential expansion, the last term in (5) would be correspondingly suppressed, implying that the energy density would become very close to the critical density, for which this last term should vanish. In this case, the Universe would have no detectable curvature, and Euclidean geometry would rule¹⁶.

Cosmological inflation could also help explain the homogeneity and isotropy of the Universe, that are taken as assumptions in conventional Friedman cosmology. Tracing backwards the history of parts of the Universe that are currently very separated, we see that they would have been very close before the inflationary period. It is then no longer surprising that these different parts of the Universe should now look very similar. On the other hand, in conventional Big Bang cosmology, distant parts of the Universe would have had no chance to ‘compare notes’ and arrange to coordinate their behaviours, and the large-scale homogeneity and isotropy of the Universe would be mysterious¹⁶.

Any mechanism for driving this inflationary expansion must be phrased in terms of particle physics. What is required is an (almost) constant energy

density in the Universe. This could be provided, for example, by the energy of some scalar field, analogous to the Higgs field thought to be responsible for giving masses to elementary particles. Personally, I expect this simple idea to be replaced by some more fundamental idea in string theory¹⁷, but here we use the scalar-field paradigm to guide our thinking.

One of the major successes of inflationary cosmology is that it not only explains the homogeneity and isotropy of the Universe, but also enables one to calculate the small deviations to be expected¹⁶. These arise from quantum fluctuations during the period of exponential expansion, and are related to the magnitude of the vacuum energy during inflation. Thus, they may be linked to the energy scale of the scalar field assumed to drive inflation.

COBE⁴ and other experiments¹⁸ have observed fluctuations in the cosmic microwave background radiation, corresponding to variations in the energy density

$$\delta\rho/\rho \sim 10^{-5} \sim \left(\frac{E}{m_P}\right)^2, \quad (6)$$

as shown in Fig. 8. Interpreted within the inflationary framework described above, these fluctuations suggest that the energy scale E of the conjectured scalar field must be far beyond the scale of the weak interactions, probably in the range 10^{12} to 10^{16} GeV. You may ask, if the inflationary energy scale is so large, how can we subject the theory to experimental test? Direct experimental tests in the laboratory may be long time away, but inflation may be linked to some Grand Unified Theory, which may be tested indirectly by searching for proton decay and/or neutrino masses. More directly, plenty of cross-checks of inflationary models are possible, by looking at the spectrum of scalar and tensor perturbations in the cosmic microwave background radiation at different angular scales.

This is not just an academic study, since these perturbations are thought to be the origins of the large-scale structures in the Universe, such as galaxies and their clusters. For this idea to work, the presence of dark matter is essential, to accelerate the growth of the inflationary perturbations. As we now discuss, there are plenty of other reasons to think that the Universe contains a large fraction of unseen dark matter, which may be composed of elementary particles.

5 The Density Budget of the Universe

We have seen earlier that inflation predicts that the overall energy density of the Universe should be close to the critical density. Observations of the cosmic microwave background radiation, in particular the scale at which their

Figure 8: The spectrum of fluctuations in the cosmic microwave background radiation observed by COBE⁴ and successor experiments¹⁸ on different angular scales. Fits to these and other cosmological data indicate that the overall density of the Universe is very close to the critical density, that about 30 % of this density is provided by matter, and that only a few % of the total density can be composed of conventional matter, in agreement with Big-Bang nucleosynthesis calculations.

perturbations are largest, indicate that the overall energy density is indeed within about 10% of the critical value. On the other hand, as we also saw earlier, the success of Big Bang nucleosynthesis calculations suggests that the density of conventional matter is only a few % of the critical density. Observations of large-scale structures are consistent with this range, but suggest that this must be embedded in a much larger density of unseen dark matter, with perhaps 30% of the critical value¹⁹. This possibility is supported by observations of distant supernovae, in conjunction with the measurements of the cosmic microwave radiation, as seen in Fig. 9²⁰.

Within this consistent emerging picture, about 2/3 of the critical density would consist of energy in the vacuum, not associated with physical particles. If it were time-independent, it would be the cosmological constant, about which theorists have speculated ever since Einstein noticed that it was permitted by the equations of General Relativity. Calculating the value of the cosmological constant would only be possible in a complete quantum theory of gravity, such as string theory. Most attempts to calculate it have been oriented towards

proving that the cosmological constant vanishes, which would probably require some very powerful symmetry that has never been identified. Observations suggest that it might be more fruitful to try to calculate some non-zero value with the aid of some approximate symmetry. Alternatively, it may be that the vacuum energy is time-dependent, as in models of ‘quintessence’[?]. In this case, some ultra-light scalar particle might exist, and have some detectable signature.

Figure 9: Observations of high-redshift supernovae²⁰ impose constraints on the density of matter and energy in the Universe. Taken together with data on the cosmic microwave background radiation^{4,18}, which suggest that the total density is close to the critical density, they suggest that matter constitutes about 30 % of the total, with the remainder being vacuum energy.

6 Particle Candidates for Dark Matter

Dark matter may conveniently be divided into two general categories: *cold* dark matter, which was non-relativistic at the epoch when matter and radiation decoupled in the early Universe, releasing the microwave background radiation, and *hot* dark matter, which was relativistic at that epoch. Cold dark matter

is favoured by theorists of structure formation, since it enables structures of all sizes to grow through gravitational instabilities. Hot dark matter would escape from smaller structures, causing them to grow more slowly and appear later than is suggested by observations.

Figure 10: A compilation of the available data on neutrino oscillations²¹, including the unconfirmed data from the LSND experiment²⁴, and the confirmed data on atmospheric²² and solar neutrino oscillations²³.

This is unfortunate, as neutrinos are perfect candidates for hot dark matter, as the observations of solar and atmospheric neutrino oscillations strongly suggest that they have small but non-zero masses, as illustrated in Fig. 10²¹. The ‘smoking gun’ for atmospheric neutrino oscillations was the observation of distorted zenith-angle distributions by the Super-Kamiokande Collaboration²². That for solar neutrino oscillations has been the recent observation by the SNO Collaboration that the rates for elastic neutrino-electron scattering and charged-current scattering do not tally unless some of the electron neutrinos produced by the Sun have oscillated into muon and/or tau neutrinos²³.

Perhaps happily for the theorists of astrophysical structure formation, the oscillation data do not require neutrino masses large enough to influence strongly structure formation.

Key pieces of information about neutrino oscillations will be provided by the upcoming generation of experiments using neutrino beams from accelerators. Already, early results from the K2K experiment seem to confirm the oscillation interpretation of the atmospheric experiments²⁵. The KamLAND experiment will soon be probing the interpretation of solar neutrino experiments using neutrinos produced by nuclear power reactors. Somewhat later, the NuMI/MINOS and CNGS/OPERA projects should answer definitively the question how atmospheric neutrinos oscillate, into tau and/or electron neutrinos. This is a very nice example of the interdependence of accelerator and non-accelerator experiments.

The neutrino saga leaves in need of cold dark matter. Let me just mention three particle candidates for it. One is the *axion*, a light boson postulated to explain why the strong interactions are very symmetric between matter and antimatter²⁶. Axions would be present in the Universe as coherent waves that would be non-relativistic, despite the small axion mass. The axion is certainly a plausible dark matter candidate, although there is no particularly good reason why it should have a relic density of relevance to cosmology.

At the other end of the candidates' mass spectrum, there are ultra-heavy (meta-)stable particles that emerge naturally in some string models²⁷. If they decay with a suitable lifetime, they might generate the ultra-high-energy cosmic rays that are difficult to explain in terms of conventional astrophysical sources. One of the most interesting recent developments has been the realization that ultra-heavy relic particles might naturally have been produced with a density of cosmological interest, around the epoch of inflation²⁸.

Finally, I should like to mention the *lightest supersymmetric particle* (LSP), which is expected to be stable in generic supersymmetric models²⁹. In many of these models, the LSP is some combination of the supersymmetric partners of the photon, Z boson and neutral Higgs bosons, called the lightest neutralino. Encouragingly, one finds that the relic density of neutralinos naturally falls within the range of interest for cosmology. For this reason, as well as theoretical prejudice, the LSP is my favourite particle candidate for cold dark matter. In the rest of this talk, I concentrate on this possibility.

7 Experimental Constraints on Supersymmetric Dark Matter

Many accelerator experiments have been searching unsuccessfully for evidence of supersymmetry. Two indirect hints have been found. One is the consistency

of LEP measurements of the strengths of the different fundamental interactions with the prediction of a Grand Unified Theory, *if* supersymmetry appears at the TeV scale³⁰, as desired if it is to stabilize the scale of the weak interactions. Another hint may be provided by the preference of high-precision data from LEP and elsewhere for a relatively light Higgs boson³, as predicted by supersymmetric models³¹.

However, there have been no positive results from direct searches at LEP and elsewhere for supersymmetric particles. For example, LEP has established lower limits of about 100 GeV on the masses of the selectron - the supersymmetric partner of the electron, as seen in Fig. 11 and the chargino - a charged counterpart of the neutralino³². LEP also established a lower limit of 114 GeV on the mass of the Higgs boson as seen in Fig. 12³³, which in turn imposes important indirect constraints on supersymmetric particle masses³⁴. Towards the end of its life, LEP provided some hints of a Higgs boson weighing about 115 GeV³³, but these could not be confirmed before LEP had to be closed down to make way for the LHC, the next accelerator in the LEP tunnel.

Figure 11: Combined data from the LEP experiments exclude a selectron (supersymmetric partner of the electron) weighing less than about 100 GeV³².

Fig. 13 displays some examples of the interplay between these various constraints, together with the domain of supersymmetric parameter space where the neutralino relic density lies within the range favoured by cosmology³⁵. Also shown are the indirect constraints coming from the agreement of measurements

Figure 12: Direct searches by the LEP experiments exclude a Standard Model Higgs boson weighing less than about 114 GeV³³, but indirect indications favour one weighing less than about 200 GeV³.

Figure 13: Combination of experimental constraints on input supersymmetric particle masses including limits on selectrons and charginos (dot-dashed blue and dashed black lines), $b \rightarrow s\gamma$ (dark, green shading), the Higgs mass (dash-dotted red line), cosmology (very dark red region excluded, pale turquoise region favoured) and $g_\mu - 2$ (shaded pink region allowed at 2σ ³⁵).

of $b \rightarrow s\gamma$ decay with the Standard Model, and from the recent BNL measurement of $g_\mu - 2$, the anomalous magnetic moment of the muon³⁶. In the latter case, it seemed originally that there might be a significant discrepancy with the Standard Model, but a recent re-evaluation of the light-by-light scattering has reduced this discrepancy³⁷.

We see that all the constraints are mutually compatible, with quite a range of different phenomenological possibilities allowed, including a ‘bulk’ region with relatively small sparticle masses, coannihilation ‘tails’ extending to larger $m_{1/2}$, a ‘focus-point’ region at larger m_0 , and possible rapid-annihilation ‘funnels’ at intermediate values of $m_{1/2}/m_0$. We have recently proposed³⁸ a set of benchmark supersymmetric scenarios shown in Fig. 14 that illustrate these various possibilities, which are intended to help concentrate the studies of future experiments with and without accelerators. Fig. 15 illustrates the numbers of different particles that may be detectable at some future accelerators³⁸.

Figure 14: Illustration of the proposed benchmark points in the $(m_{1/2}, m_0)$ plane: points A, B, C, D, G, I and L are in the ‘bulk’ region, points H and J in a coannihilation ‘tail’, points E and F in the ‘focus-point’ region, and points K and M along rapid-annihilation ‘funnels’.

8 Searches for Supersymmetric Dark Matter

Several strategies to search for supersymmetric dark matter have been proposed, and I review them here with particular reference to the benchmark scenarios introduced above³⁹. One strategy is to look for the products of the annihilations of dark matter particles in the galactic halo. These might produce observable antiprotons, positrons or photons. Several experiments have observed cosmic-ray antiprotons, but at rates quite compatible with production by primary matter cosmic rays⁸, and the prospects for discovering dark matter

Figure 15: Summary of the prospective sensitivities of the LHC and linear colliders at different $\sqrt{s}$ energies to CMSSM particle production in the proposed benchmark scenarios G, B, ..., which are ordered by their distance from the central value of $g_\mu - 2$, as indicated by the pale (yellow) line in the second panel. We see clearly the complementarity between an e^+e^- collider and the LHC⁶ in the TeV range of energies³⁸, with the former excelling for non-strongly-interacting particles, and the LHC for strongly-interacting sparticles and their cascade decays.

this way do not appear very promising. Positrons have also been observed by several experiments, and there has been a suggestion of anomalous production at energies around 10 GeV⁴⁰. The first flight of the AMS experiment on the space shuttle observed a surprisingly high ratio of positrons to electrons, but was able to show that they were produced by cosmic-ray collisions in the atmosphere. We recently evaluated the fluxes of positrons to be expected in the benchmark scenarios, which are not very encouraging³⁹. Better prospects may be offered by photons from relic annihilations in the galactic centre, as seen in Fig. 16. These are expected to be enhanced because of an enhancement of the relic density in the core of the galaxy, but the amount of this enhancement is rather uncertain. As we see in Fig. 16, the best prospects may be offered by benchmark scenarios L, I, and K. Another interesting possibility is to look for energetic neutrinos produced by relic annihilations inside the Sun or Earth,

The most satisfying way to detect supersymmetric dark matter particles would be directly, via their elastic scattering on nuclei in the laboratory. As seen in Fig. 18, there seem to be good prospects, particularly in benchmark scenarios B, I, E, L, G and F³⁹.

Figure 18: Rates for direct detection of the benchmark scenarios by spin-independent scattering on protons³⁹, compared with the sensitivities of different experiments.

9 Conclusions

As we have seen in this talk, there is a close and symbiotic relationship between particle physics and cosmology. Astrophysics and cosmology may cast light on many fundamental questions in particle physics that are impossible or difficult to study with particle accelerators, such as neutrino masses and the existence of supersymmetric particles. Conversely, many of the deepest problems in cosmology, such as the early history of the Universe, its size and age, the origins of its structures and of the matter it contains, as well as the nature of dark matter, may only be tackled using particle physics. In a very real sense, particle accelerators are not only microscopes, peering into physics on the very smallest distance scales, but also telescopes, exploring the Universe on the very largest scales and back to the very earliest times.

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