CONNECTIONS BETWEEN BIG AND SMALL

John Ellis*
Theory Division
CERN, CH-1211 Geneva 23, Switzerland

ABSTRACT

Big-Bang cosmology and ideas for possible physics beyond the Standard Model of particle physics are introduced. The density budget of the Universe is audited, and the issues involved in calculating the baryon density from microphysics are mentioned, as is the role of cold dark matter in the formation of cosmological structures. Candidates for cold dark matter are introduced, with particular attention to the lightest supersymmetric particle and metastable superheavy relics. Prospects for detecting supersymmetric dark matter in non-accelerator experiments are assessed, and the possible role of decays in generating ultra-high-energy cosmic rays is discussed. More details of these and other astroparticle topics are presented during the rest of this Summer Institute.

1 Introduction

My task in this opening lecture is to set the stage for the subsequent lectures that develop in more detail the connections between particle physics and cosmology. To do so, I first recall the essential aspects of standard Big-Bang cosmology, emphasizing that the questions it raises about the early history of the Universe can only be answered by particle physics. The latter is described by its own Standard Model, which makes successful quantitative predictions for accelerator experiments, but leaves open many fundamental questions. These include the origin of particle masses, the proliferation of different types of elementary particles and the possible unification of all the particle interactions. In combination with accelerator experiments, astrophysics and cosmology may cast important light on the solutions of these problems. According to astrophysicists and cosmologists, most of the matter in the Universe has never been seen, and cannot consist of ordinary matter.[1] The formation of structures in the Universe would be helped by the presence of massive weakly-interacting cold dark matter particles.[2] Candidates for these include the lightest supersymmetric particle (LSP),[3] the axion[4] and metastable superheavy particles[5] whose decays might be responsible for ultra-high-energy cosmic rays beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff,[6] if they exist. These are just a few of the connections between the very big and the very small that are developed by other lecturers at this Summer Institute.

2 Big-Bang Cosmology

According to standard Big-Bang cosmology,[7] the entire visible Universe is expanding homogeneously and isotropically from a very dense and hot initial state. The first direct piece of evidence for this was the discovery by Hubble that distant objects in the Universe are receding from each other at velocities proportional to their distances from each other:

$$v \;=\; H \cdot d, \tag{1}$$

where v is the recession velocity, d is the distance and the Hubble constant $H \equiv h \cdot 100$ km/s/Mpc where $h \simeq 0.7$.[8] Observations of the Universe suggest that it is indeed very homogeneous and isotropic on large scales $\gtrsim 1000$ Mpc.[9]

The next piece of evidence for the Big Bang to be discovered was the cosmic microwave background (CMB) radiation.[10] Extrapolating the present Hubble expansion back in time, the CMB is thought to have been emitted when the Universe was about

3000 times smaller and hotter than it is today, with age $\sim 3 \times 10^5$ y. The CMB has a dipole deviation from isotropy at the 10^{-3} level, which is believed to be due to the Earth's motion relative to a Machian cosmological frame. Smaller-scale anisotropies have been discovered more recently by the COBE satellite and subsequent experiments, as seen in Fig. 1,[11] and may provide a window on the Universe when it was much younger still, as we shall see later.

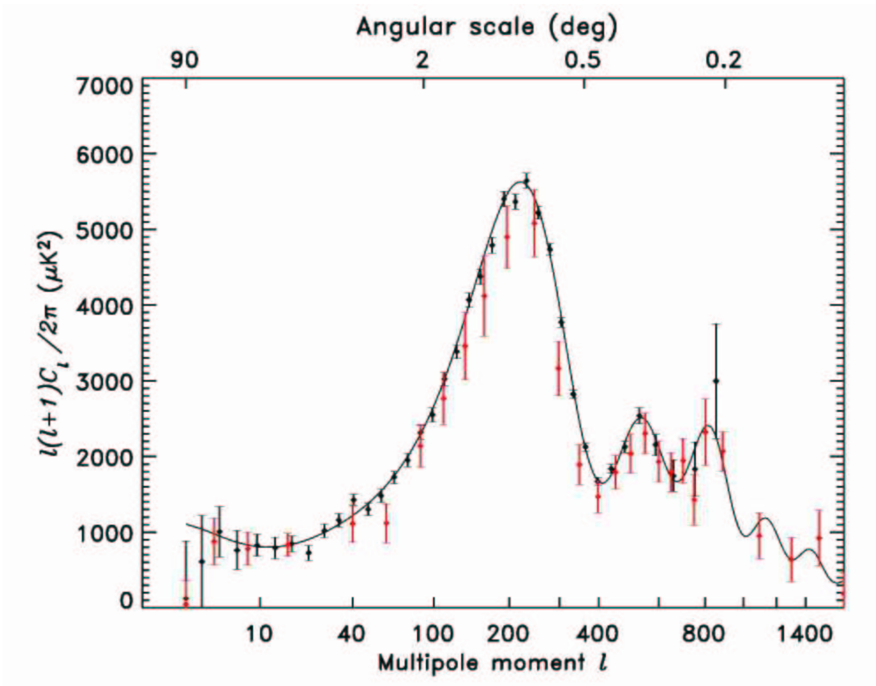

Fig. 1. A compilation of data on fluctuations in the cosmic microwave background radiation.[11] The darker (black) error bars are those from the WMAP satellite, the lighter (red) error bars are those of previous CMB experiments.

The third piece of evidence for the Big Bang was provided by the abundances of light elements seen in Fig. 2, which are thought to have been established when the Universe was about 10^8 times smaller and hotter than it is today,[12] with age ~ 1 to 10^2 s. This nuclear 'cooking' must have occurred when the temperature T of the Universe corresponded to characteristic particle energies ~ 1 MeV.

Back when the Universe was $\sim 10^{-6}$ to $\sim 10^{-5}$ s old, it is thought to have made a transition from a plasma of quarks and gluons to hadrons at a temperature $T \sim 100$ MeV.[13] Previous to that, the electroweak transition when Standard Model particles acquired their masses is thought have occurred when the Universe was $\sim 10^{-12}$ to $\sim 10^{-10}$ s old, and the temperature $T \sim 100$ GeV.[14]

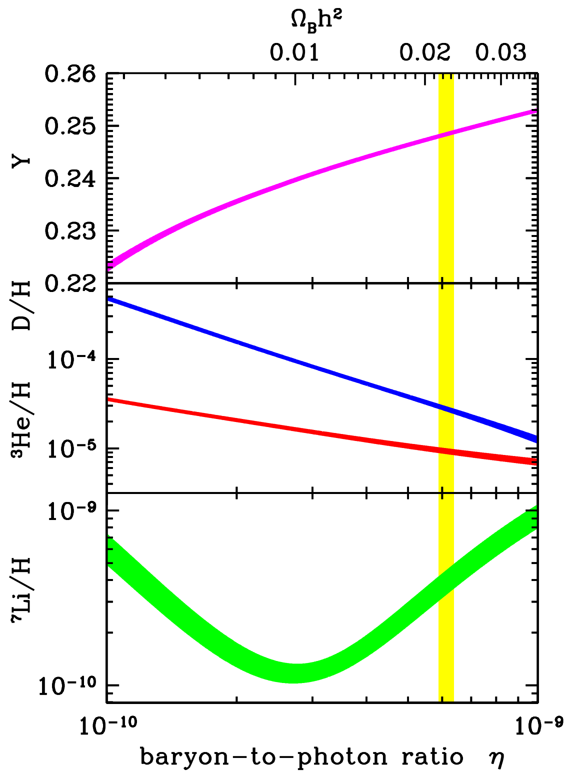

Fig. 2. There is good concordance between the observed abundances of light elements and calculations of Big-Bang nucleosynthesis.[12]

During the expansion of the Universe, it acts as a 'cosmic decelerator', whose effective temperature T falls as it expands[7]:

$$T \sim \frac{1}{a}, \tag{2}$$

where a is the scale factor measuring the size of the Universe. During the early history of the Universe when most particle masses were negligible, the rate of expansion was such that the age

$$t \sim a^2 \sim \frac{1}{T^2}. \tag{3}$$

Inserting the units, one finds that the temperature of the Universe would have been about 10^{10} K when it was about a second old. Such high temperatures correspond to high energies for the thermalized particles: 10^{10} K ~ 1 MeV (cf the electron mass $\sim 1/2$ MeV), 10^{13} K ~ 1 GeV (cf the proton mass ~ 1 GeV). In general, the time-temperature relation is such that

$$t(\mathrm{sec}) \sim \frac{1}{T(\mathrm{MeV})^2}. \tag{4}$$

Thus, it is clear that the very early history of the Universe must have been dominated by elementary particles, and only their physics can explain how the Universe got to be the way it is today.

3 Particle Physics beyond the Standard Model

As you can see in Fig. 3, data from the LEP accelerator are, unfortunately, in excellent agreement with the Standard Model. Indeed, no accelerator data provide evidence for physics beyond the Standard Model. Nevertheless, particle physicists are convinced that there must be accessible physics beyond the Standard Model, because it leaves many fundamental questions unanswered. We seek the *Origin of Particle Masses* and the reason why they are so much smaller than the Planck mass $m_P \sim 10^{19}$ GeV. Are the masses due to a Higgs boson, and is it accompanied by supersymmetric particles? We seek a *Theory of Flavour*, because the Standard Model has six random-seeming quark masses, three disparate charged-lepton masses, three weak mixing angles and the CP-violating Kobayashi-Maskawa phase. Moreover, we seek a *Grand Unified Theory*, because the Standard Model has three independent gauge couplings and (potentially) a CP-violating phase in QCD. Altogether, the Standard Model has a total of 19 parameters, without even addressing the more fundamental questions of the origins of the particle quantum numbers. Beyond all these beyonds, other theorists seek a *Theory of Everything* that includes gravity, reconciles it with quantum mechanics, explains the origin of space-time and why we live in four dimensions (if we do so).

Non-accelerator neutrino experiments[16,17] now provide us with the first direct evidence for physics beyond the Standard Model, convincing us that neutrinos oscillate and have different non-zero masses. To describe these, we need three neutrino mass parameters, three neutrino mixing angles and three CP-violating phases in the neutrino sector. Moreover, we should not forget about gravity, with at least two parameters to understand: Newton's constant $G_N \equiv m_P^{-2} \sim (10^{19}\ \mathrm{GeV})^{-2}$ and the cosmological 'constant', which recent data suggest is non-zero,[1] and may not even be constant. Talking of cosmology, we would need at least one extra parameter to produce an inflationary potential, and at least one other to generate the baryon asymmetry, which cannot be explained within the Standard Model.

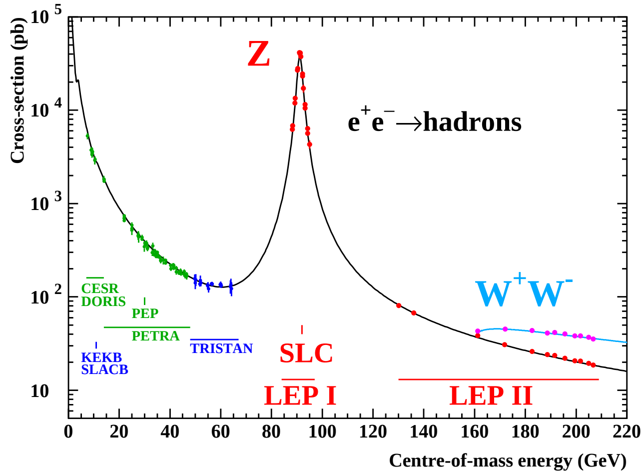

Fig. 3. Data from LEP and other e^+e^- experiments agree perfectly with the predictions of the Standard Model.[15]

At what energy scale might new physics beyond the Standard Model appear, between the energies $\lesssim 100$ GeV already explored and the Planck energy $\simeq 10^{19}$ GeV? The Problem of Mass must presumably be solved by new physics at some energy $\lesssim 1$ TeV, whether it be just a Higgs boson or some richer physics such as supersymmetry.[18] Simple ideas of Grand Unification suggest new physics at a scale $\simeq 10^{16}$ GeV.[19] On the other hand, we have no good idea what energy scale might be associated with the solution to the Problem of Flavour, or where extra dimensions might appear. If there is a significant discrepancy between the BNL measurement of the muon anomalous magnetic moment[20] and the Standard Model, which is not yet established, this could only removed by new physics at a scale $\lesssim 1$ TeV. There are two circumstantial pieces of evidence in favour of Grand Unification, namely the existence of neutrino masses - which might have been generated at some mass scale between $\simeq 10^{10}$ GeV and $\simeq 10^{15}$ GeV - and the weak neutral-current mixing angle $\sin^2\theta_W$. The value of the latter could be explained by Grand Unification at a scale $\simeq 10^{16}$ GeV combined with supersymmetry at a scale $\simeq 10^3$ GeV.[19]

The LHC will be able to discover 'any' new physics at a scale $\lesssim 10^3$ GeV, but many of the other ideas mentioned above may not be directly testable at accelerators for the foreseeable future. Astrophysics and cosmology may provide the only laboratories for testing some of these ideas. For example, the cosmic microwave background (CMB) and inflation may be providing a direct window on physics at the GUT scale, and ultra-high-energy cosmic rays (UHECRs) might be due to the decays of metastable superheavy particle weighing $\sim 10^{13}$ GeV or so.[21] On the other hand, many particle candidates for dark matter weigh $\lesssim 1$ TeV and could be detected at the LHC. It seems that accelerators, astrophysics and cosmology are condemned to symbiosis.

4 Density Budget of the Universe

What does the Universe contain? Let us enumerate its composition in terms of the density budget of the Universe, measured relative to the critical density: $\Omega_i \equiv \rho_i/\rho_{crit}$.

Inflation[22] suggests that the *total density* of the Universe is very close to the critical value: $\Omega_{tot} \simeq 1 \pm O(10^{-4})$, and this estimate is supported by CMB data.[10] I remind you that inflation explains why the Universe is so large: the scale size $a \gg \ell_P \sim 10^{-33}$ cm, why the Universe is so old: its age $t \gg t_P \sim 10^{-43}$ s, why its geometry is so nearly flat with a Euclidean geometry, and why the Universe is so homogeneous on large scales.

It achieves these feats by postulating an epoch of (near-) exponential expansion during the very early Universe, making the Universe very large and giving it a long time to recollapse (if it ever will). Even the most distant parts of the observable Universe would have been very close to each other prior to this inflationary epoch, and so could have synchronized their behaviours. This inflationary expansion would have blown the Universe up like an inflated ballon, which seems almost flat to an ant living on its surface. During the inflationary expansion, quantum fluctuations in the inflaton field would have generated small density perturbations (cf. the observations in Fig. 1) capable of growing into the structures seen in the Universe today,[23] as discussed later.

Big-Bang Nucleosynthesis suggests that the *baryon density* $\Omega_b \simeq 0.04$,[12] an estimate that has been supported by analyses of the relative sizes of small fluctuations in the CMB at different scales.[10]

The baryons are insufficient to explain the *total matter density* $\Omega_m \simeq 0.3$, as estimated independently by analyses of clusters of galaxies and, more recently, by combining the observations of high-redshift supernovae with those of the CMB. The supernovae constrain the density budget of the Universe in a way that is almost orthogonal to the CMB constraint, and is very consistent with the prior indications from galaxy clusters.[1]

Observations of the structures that have formed at different scales in the Universe suggest that most of the missing dark matter is in the form of non-relativistic *cold dark matter*, as discussed in the next session.

The theory of structure formation suggests that very little of the dark matter is in the form of *hot dark matter* particles that were relativistic when structures started to form:

$\Omega_{hot}h^2 < 0.0076$.[11] Applying this constraint to neutrinos, for which

$$\Omega_\nu h^2 \simeq \frac{\Sigma_i m_{\nu_i}}{93\text{eV}}, \quad (5)$$

this constraint tells us that $\Sigma_i m_{\nu_i} < 0.7$ eV, a limit that is highly competitive with direct limits.[24]

If $\Omega_{tot} \simeq 1$ and the matter density $\Omega_m \sim 0.3$, how do we balance the density budget of the Universe? There must be *vacuum energy* Λ with $\Omega_\Lambda \sim 0.7$. All the available cosmological data are consistent with Λ having been constant at redshifts $z \lesssim 1$, as per Einstein's original suggestion of a cosmological constant. However, we cannot yet exclude some slowly varying source of vacuum energy, 'quintessence' with an equation of state parametrized by $w \equiv p/\rho \lesssim -0.8$.[25] Measurable vacuum energy would provide a second general-relativity observable to explain, in addition to the Planck mass scale m_P. This would provide a tremendous opportunity for any theory of everything including quantum gravity, such as string theory. The ultimate challenge for theoretical physics may be to calculate Λ.

5 Cosmological Baryogenesis

We have seen that Big-Bang Nucleosynthesis[12] and the CMB[10] independently imply that baryons make up only a few % of the density of the Universe. Numerically, this corresponds to a baryon-to-photon ratio $n_b/n_\gamma \sim 10^{-9}$–$10^{-10}$, raising several questions. Why is there so little baryonic matter? Why is there any at all? Why is there apparently no antimatter?

Astronauts did not disappear in a burst of radiation when they landed on the Moon, and neither have space probes landing on Mars or an asteroid. The small abundance of antiprotons in the cosmic rays is consistent with their production by primary matter cosmic rays,[26] and no antinuclei have been seen.[27] If there were any large concentration of antimatter in our local cluster of galaxies, we would have detected radiation from matter-antimatter annihilations at its boundary. The CMB would have been distorted by similar radiation from any matter-antimatter boundary within the observable Universe.[28] So it seems that there must be a real cosmological asymmetry between matter and antimatter.

This could be explained if, going back to when the Universe was less than 10^{-6} s old, it contained about one extra quark for every 10^9 quark-antiquark pairs in the primordial soup. As the Universe expanded, most of the quarks would have annihilated with those antiquarks to produce radiation, and the few quarks left over would have survived to combine into the baryons seen today. Where did this small quark-antiquark asymmetry originate? Did the Big Bang start off with it, or did the laws of Nature generate it during the subsequent expansion?

The conditions for such cosmological baryogenesis were established by Sakharov in 1967.[29] There has to be a difference between the interactions of matter and antimatter particles, in the form of charge-conjugation (C) violation, which was discovered in the weak interactions in 1957, and CP violation, which was discovered in kaon decays in 1964. There must also have been a departure from thermal equilibrium, which would have been possible during a phase transition, perhaps the electroweak phase transition when $t \sim 10^{-10}$ s or a GUT phase transition when $t \sim 10^{-36}$ s, or at the end of inflation. Finally, there must have been a violation of baryon number, which would have happened through nonperturbative weak interactions at high temperatures[30] and is thought to be a generic feature of GUTs.

Various specific mechanisms for Big-Bang baryogenesis have been proposed, ranging from the out-of-equilibrium decays of GUT bosons[31] or heavy neutrinos[32] to processes around the epoch of the electroweak phase transition. The CP violation in the Standard Model seems inadequate to generate the required baryon asymmetry, but this might be possible if it is extended to include supersymmetry.[33]

6 Formation of Structures

How have these hard-won baryons organized themselves into the structures - clusters, galaxies, stars, planets and us - that we see in the Universe today? As already mentioned, the prime candidates for the seeds of these structures are quantum fluctuations in the inflaton field, which would have caused different parts of the Universe to expand differently and generated a *Gaussian random field* of density perturbations.[23] If the inflaton energy was roughly constant during inflation, these perturbations would be *almost scale-invariant*, as postulated by astrophysicists. The CMB data shown in Fig. 1 are consistent with both these properties. Accepting this scenario, the magnitude of the primordial perturbations would be related to the field energy density μ^4 during inflation:

$$\left(\frac{\delta T}{T}\right) \propto \left(\frac{\delta \rho}{\rho}\right) \propto \mu^2 G_N. \tag{6}$$

Inserting the magnitude of $\delta\rho/\rho \sim 10^{-5}$ observed by the COBE and subsequent experiments,[10] one estimates

$$\mu \simeq 10^{16} \text{ GeV}, \tag{7}$$

comparable with the GUT scale.[19]

These primordial perturbations would have produced embryonic potential wells into which the non-relativistic cold dark matter particles would have fallen, while relativistic hot dark matter particles would have escaped. In this way, cold matter particles would have amplified the amplitudes of the primordial density perturbations, while the baryons were still coupled to the relativistic radiation. Then, when the baryonic matter and radiation 're-' combined to form atoms, they would have fallen into the deeper potential wells prepared by the cold dark matter. This theory of structure formation fits remarkably well the data on all scales from over 10^3 Mpc down to ~ 1 Mpc.[10,9]

7 Candidates for Dark Matter

It is this agreement that provides the most stringent upper limit on the possible hot dark matter such as neutrinos. As discussed earlier, most of the dark matter is thought to be non-relativistic cold dark matter. There are almost as many candidates for this as in the 2003 Californian gubernatorial election but, as in that case, some of the candidates are more favoured than others.

Lightest Supersymmetric Particle: The existence of supersymmetry at relatively low energies $\lesssim 1$ TeV is motivated by the hierarchy problem, namely why is the electroweak scale $m_W \ll m_P \sim 10^{19}$ GeV, the only candidate we have for a primary mass scale in physics.[34] Alternatively, one may rephrase this question as why the Fermi constant $G_F \gg G_N$, the Newton constant, or as why the Coulomb potential $V_{Coulomb} \gg V_{Newton}$ in an atom. This can be traced to the fact that $Ze^2 = O(1) \gg m^2/m_P^2$, which is in turn due to the fact that the masses of particles in atoms $m \lesssim m_W \ll m_P$.

You might think it be sufficient to set $m_W \ll m_P$ by hand and forget about the hierarchy problem. However, this is insufficient because Standard Model loop corrections to the Higgs and/or W mass are quadratically divergent:

$$\delta m_{H,W}^2 \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2, \tag{8}$$

which is $\gg m_W^2$ if the cutoff Λ where the Standard Model breaks down and new physics appears $\sim m_{GUT}$ or m_P. These loop corrections can be controlled by postulating supersymmetry,[18] which predicts that bosons and fermions appear in pairs with equal couplings. Since the divergences in boson loops are positive and those in fermion loops are negative, (8) is replaced by

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)\left(m_B^2 - m_F^2\right), \tag{9}$$

which is $\lesssim m_W^2$ if

$$|m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2. \tag{10}$$

Thus, the loop corrections to the electroweak scale may be made naturally small by postulating small differences between supersymmetric partner particles.

It is a generic feature of many supersymmetric models that the lightest supersymmetric particle (LSP) is stable, as a result of a particular combination of baryon and lepton number being conserved. This ensures that heavier sparticles can only decay into lighter ones, and the LSP is stable because it has no allowed decay modes. Furthermore, generically the LSP is electrically neutral and has only weak interactions, making it an ideal weakly-interacting massive particle (WIMP).[3] Moreover, there are generic regions of the supersymmetric space where the relic LSP density falls within the range preferred by the cosmological data, as seen in Fig. 4.[35]

The LSP has many rivals to be the cold dark matter, including axions and the 'Schwarzenegger' candidate, an ultraheavy metastable particle.[37] The next two sections discuss how these candidates might be elected by experiment.

8 Searches for Dark Matter LSPs

Annihilations in the galactic halo: These would produce some antiprotons, positrons and photons that might be detectable among the cosmic rays.[38] As already discussed, the observed antiprotons appear completely consistent with production by primary matter cosmic rays.[26] The prospects for detecting LSP annihilation positrons do not look bright either, at least in a set of proposed supersymmetric benchmark scenarios.[36] The prospects for detecting LSP annihilation photons may be brighter, if the LSP density is enhanced in the core of the galaxy. As seen in Fig. 5,[36] GLAST might be the best-placed to detect these.

Annihilations in the Sun or Earth: As LSPs fly though the galaxy, some of them pass through the Solar System on hyperbolic trajectories. If they pass through the Sun or Earth, they may scatter, and the deposit of recoil energy may convert their trajectories into

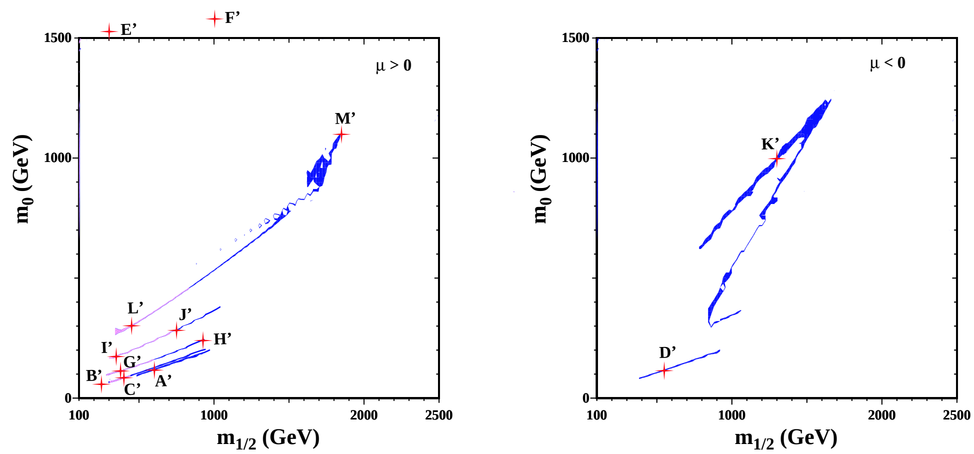

Fig. 4. Strips in the parameter space of the minimal supersymmetric extension of the Standard Model, assuming universal GUT-scale masses $(m_{1/2}, m_0)$ for the new supersymmetric fermions and bosons, respectively, that are consistent with accelerator and cosmological data.[35] The different strips correspond to different values of the ratio $\tan\beta$ of Higgs vev's, and the two panels to different signs of the Higgs mixing parameter μ. The crosses mark specific benchmark scenarios explored later.[36]

elliptical orbits with perihelions (perigees) below the surface of the Sun (Earth). They would then scatter repeatedly, losing more energy each time, until they eventually settle into a cloud in the core. There they would annihilate, and any high-energy neutrino they produce might be detectable in underground experiments,[39] either by interactions inside the detector or via collisions in nearby material that produce muons passing through the detector. As seen in Fig. 6,[36] annihilations inside the Sun would be detectable in several supersymmetric scenarios, whereas the prospects for detecting terrestrial annihilations do not look so good.

Direct detection of dark matter scattering: In many scenarios, it is also possible to detect directly the scattering of LSPs on nuclei in a low-background underground laboratory,[40] via the few KeV of recoil energy deposited. This scattering is expected to have both spin-dependent and spin-independent components, with the latter seeming more promising for the relatively heavy LSPs favoured by the absence of sparticles in collider experiments to date. As seen in Fig. 7,[36] dark matter may be detectable directly in this way in a number of supersymmetric scenarios, at least in some projected experiments.

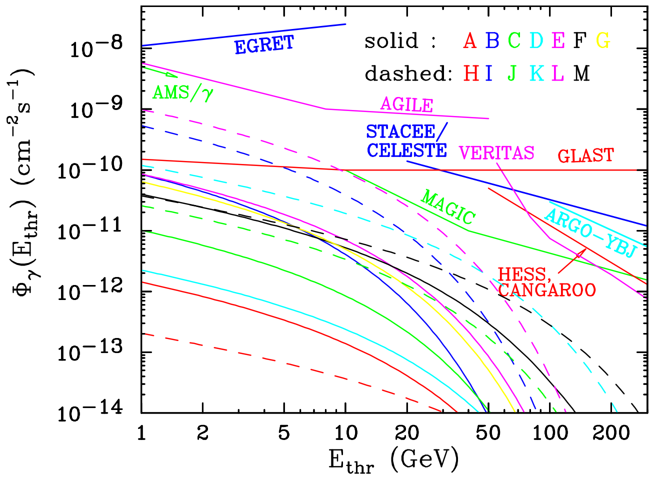

Fig. 5. Observations of γ rays from the galactic centre by GLAST and ground-based experiments may be able to test certain supersymmetric benchmark scenarios.[36]

9 New Physics in Ultra-High-Energy Cosmic Rays?

Now for the 'Arnold' candidate.[37] The spectrum of cosmic rays falls almost featurelessly $\sim E^{-\sim 3}$ until $E \sim$ few $\times 10^{19}$ GeV. At energies $E \gtrsim 10^{20}$ GeV, protons or nuclei coming from more than ~ 50 Mpc away would have scattered on CMB photons before reaching us, producing pions and losing energy — the GZK cutoff.[6]

The AGASA experiment[41] has reported seeing ultra-high-energy cosmic rays (UHECRs) beyond the GZK cutoff, but the HiRes experiment[42] does not. The Auger experiment[43] now under construction in Argentina should be able to tell us definitively whether such UHECRs exist. What might be their origins?

The most plausible is some 'bottom-up' mechanism of acceleration by astrophysical sources. The upper limit on the energy attainable with such a cosmic accelerator is

$$E \sim 10^{18} Z \left(\frac{R}{\mathrm{Kpc}}\right)\left(\frac{B}{\mu G}\right) \mathrm{eV}, \tag{11}$$

where Z is the atomic number of the accelerated nucleus, R is the size of the cosmic accelerator and B its magnetic field. Fig. 8 shows some of the possible astrophysical sources of UHECRs, including neutron stars, active galactic nuclei (AGNs), radio-galaxy lobes and galactic clusters with gamma-ray bursters (GRBs) being other possible sources. In any scenario based on such discrete sources, one might expect clustering of arrival directions and correlations with astrophysical objects, as has sometimes been claimed.[44]

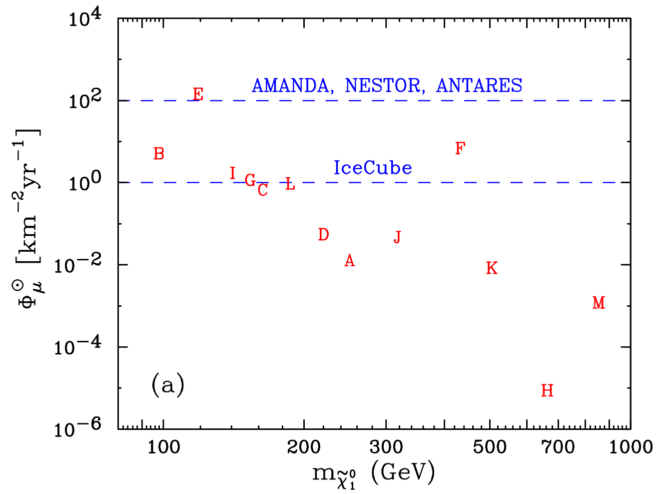

Fig. 6. Searches in IceCube and other km^2 detectors for energetic muons originating from the interactions of high-energy neutrinos produced by the annihilations of supersymmetric relic particles captured inside the Sun may probe some supersymmetric benchmark scenarios.[36]

Alternatively, one might postulate some 'top-down' model based on the decays or interactions of massive GUT-scale particles.[5] Such superheavy candidates include topological defects and metastable relic particles, such as the cryptons expected as relics of the hidden sector in string models.[21] The energy spectrum of their decays can fit the AGASA spectrum of UHECRs,[45] as seen in Fig. 9, but their composition is potentially an issue. In such models, most of the UHECRs would arise from decays within the halo of our own galaxy, and their arrival directions should be anisotropic. There could be some clustering if a large fraction of the cold dark matter in our galactic halo is clumped.

10 The End of the Beginning

Copernicus taught us that we do not live at the centre of the Universe. Modern astrophysicists teach us that we are not made of the same stuff as most of the matter in the Universe, and modern cosmologists teach us that matter is not even the dominant form of energy in the Universe. The challenge for coming observations is to prove these assertions and determine the nature of the missing matter and energy. The rest of this summer institute will provide you with some of the tools you will need for this task.

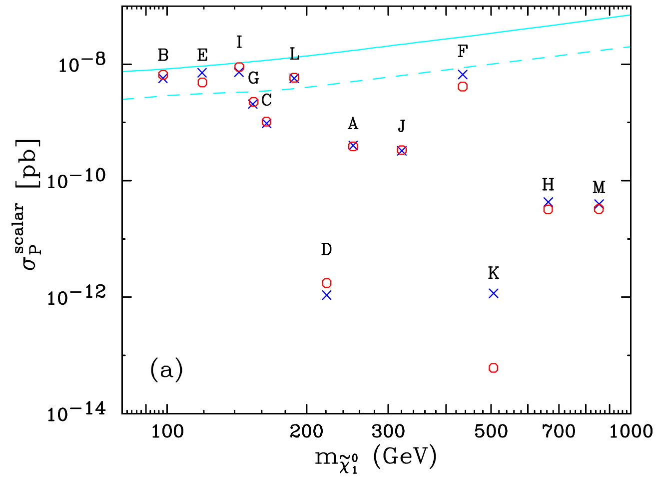

Fig. 7. Direct searches for the scattering of superysmmetric relic particles in underground detectors may probe some supersymmetric benchmark scenarios,[36] compared with the possible sensitivities of future experiments.

References

[1] N. A. Bahcall, J. P. Ostriker, S. Perlmutter and P. J. Steinhardt, Science **284**, 1481 (1999) [arXiv:astro-ph/9906463].

[2] See, for example: F. R. Pearce *et al.*, *Simulations of galaxy formation in a cosmological volume*, arXiv:astro-ph/0010587.

[3] J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, *Nucl. Phys.* B **238**, 453 (1984); see also H. Goldberg, *Phys. Rev. Lett.* **50**, 1419 (1983).

[4] For a review and references, see: I. G. Irastorza *et al.*, Nucl. Phys. Proc. Suppl. **114**, 75 (2003).

[5] V. Berezinsky, M. Kachelriess and A. Vilenkin, *Phys. Rev. Lett.* **79**, 4302 (1997) [arXiv:astro-ph/9708217].

[6] K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, *Pisma Zh. Eksp. Teor. Fiz.* **4**, 114 (1966).

[7] E. W. Kolb and M. S. Turner, *The Early Universe* (Addison-Wesley, Redwood City, USA, 1990).

[8] W. L. Freedman *et al.*, Astrophys. J. **553**, 47 (2001) [arXiv:astro-ph/0012376].

[9] O. Elgaroy *et al.*, *Phys. Rev. Lett.* **89**, 061301 (2002) [arXiv:astro-ph/0204152].

[10] C. L. Bennett *et al.*, Astrophys. J. **464**, L1 (1996) [arXiv:astro-ph/9601067].

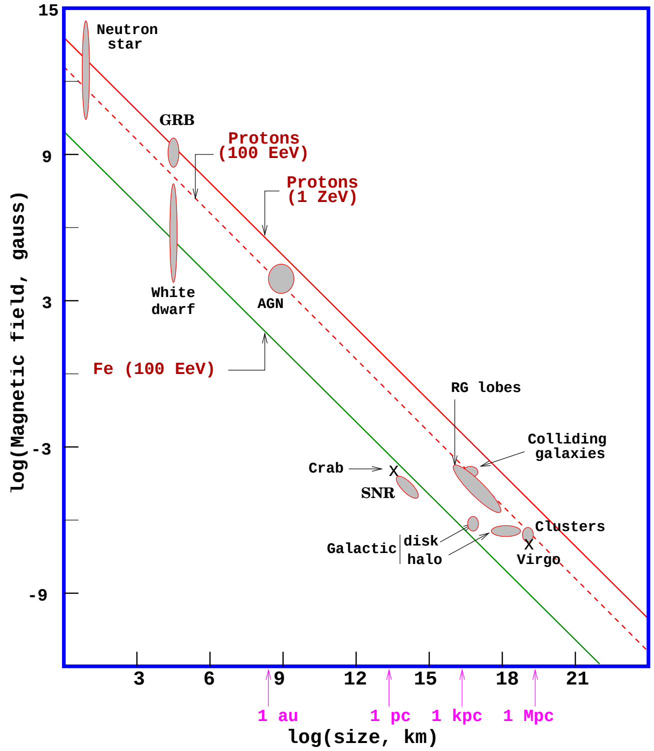

Fig. 8. Schematic plot of the sizes and magnetic field strengths of possible astrophysical sources of UHECRs.

[11] D. N. Spergel *et al.*, Astrophys. J. Suppl. **148**, 175 (2003) [arXiv:astro-ph/0302209].

[12] For a recent review, see: K. A. Olive, arXiv:astro-ph/0202486.

[13] For a review, see: H. Satz, Nucl. Phys. A **715**, 3 (2003) [arXiv:hep-ph/0209181].

[14] See, for example: K. Kajantie, M. Laine, K. Rummukainen and M. E. Shaposhnikov, Nucl. Phys. B **493**, 413 (1997) [arXiv:hep-lat/9612006].

[15] For a recent review, see: M. W. Grunewald, Nucl. Phys. Proc. Suppl. **117**, 280 (2003) [arXiv:hep-ex/0210003].

[16] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], *Phys. Rev. Lett.* **81**, 1562 (1998) [arXiv:hep-ex/9807003].

[17] Q. R. Ahmad *et al.* [SNO Collaboration], *Phys. Rev. Lett.* **89**, 011301 (2002) [arXiv:nucl-ex/0204008]; *Phys. Rev. Lett.* **89**, 011302 (2002) [arXiv:nucl-ex/0204009]; S. N. Ahmed *et al.* [SNO Collaboration], arXiv:nucl-ex/0309004.

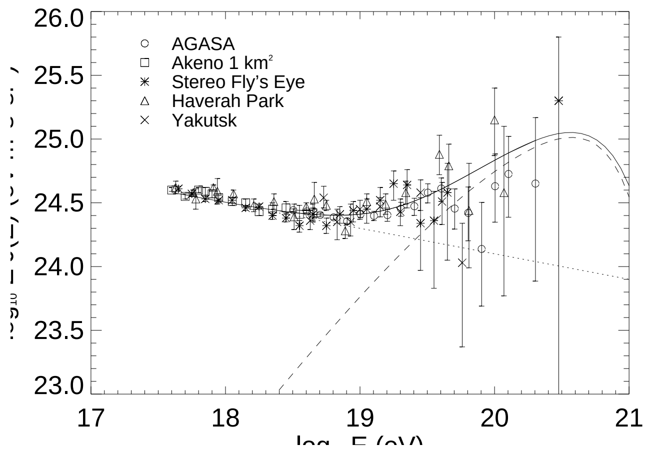

Fig. 9. A fit to the UHECR spectrum including an extrapolation of the lower-energy spectrum (dotted line) and the decays of superheavy particles (dashed line).[45]

[18] For an early review, see: P. Fayet and S. Ferrara, Phys. Rept. **32** (1977) 249; see also: H. P. Nilles, Phys. Rept. **110** (1984) 1; H. E. Haber and G. L. Kane, Phys. Rept. **117** (1985) 75.

[19] J. Ellis, S. Kelley and D. V. Nanopoulos, *Phys. Lett.* B **260**, 131 (1991); U. Amaldi, W. de Boer and H. Furstenau, *Phys. Lett.* B **260**, 447 (1991); P. Langacker and M. x. Luo, *Phys. Rev.* D **44**, 817 (1991); C. Giunti, C. W. Kim and U. W. Lee, *Mod. Phys. Lett.* A **6**, 1745 (1991).

[20] G. W. Bennett *et al.* [Muon g-2 Collaboration], *Phys. Rev. Lett.* **89**, 101804 (2002) [Erratum-ibid. **89**, 1219903 (2002)] [arXiv:hep-ex/0208001].

[21] J. R. Ellis, J. L. Lopez and D. V. Nanopoulos, *Phys. Lett.* B **247**, 257 (1990); K. Benakli, J. R. Ellis and D. V. Nanopoulos, *Phys. Rev.* D **59**, 047301 (1999) [arXiv:hep-ph/9803333].

[22] For a review, see: D. H. Lyth and A. Riotto, *Phys. Rept.* **314**, 1 (1999) [arXiv:hep-ph/9807278].

[23] See, for example: J. M. Bardeen, P. J. Steinhardt and M. S. Turner, *Phys. Rev.* D **28**, 679 (1983).

[24] K. Hagiwara *et al.* [Particle Data Group Collaboration], Phys. Rev. D **66**, 010001 (2002).

[25] L. M. Wang, R. R. Caldwell, J. P. Ostriker and P. J. Steinhardt, Astrophys. J. **530**, 17 (2000) [arXiv:astro-ph/9901388].

[26] T. Maeno *et al.* [BESS Collaboration], Astropart. Phys. **16**, 121 (2001) [arXiv:astro-ph/0010381].

[27] M. Aguilar *et al.* [AMS Collaboration], Phys. Rept. **366**, 331 (2002) [Erratum-ibid. **380**, 97 (2003)].

[28] A. G. Cohen, A. De Rujula and S. L. Glashow, Astrophys. J. **495**, 539 (1998) [arXiv:astro-ph/9707087].

[29] A. D. Sakharov, *Pisma Zh. Eksp. Teor. Fiz.* **5**, 32 (1967)

[30] G. 't Hooft, Phys. Rev. D **14**, 3432 (1976) [Erratum-ibid. D **18**, 2199 (1978)].

[31] M. Yoshimura, Phys. Rev. Lett. **41**, 281 (1978) [Erratum-ibid. **42**, 746 (1979)].

[32] M. Fukugita and T. Yanagida, *Phys. Lett.* B **174**, 45 (1986).

[33] See, for example: M. Carena, M. Quiros, M. Seco and C. E. Wagner, Nucl. Phys. B **650**, 24 (2003) [arXiv:hep-ph/0208043].

[34] L. Maiani, *Proceedings of the 1979 Gif-sur-Yvette Summer School On Particle Physics*, 1; G. 't Hooft, in *Recent Developments in Gauge Theories, Proceedings of the Nato Advanced Study Institute, Cargese, 1979*, eds. G. 't Hooft *et al.*, (Plenum Press, NY, 1980); E. Witten, *Phys. Lett.* B **105**, 267 (1981).

[35] M. Battaglia *et al.*, *Eur. Phys. J.* C **22**, 535 (2001) [arXiv:hep-ph/0106204], as updated in M. Battaglia, A. De Roeck, J. R. Ellis, F. Gianotti, K. A. Olive and L. Pape, arXiv:hep-ph/0306219.

[36] J. Ellis, J. L. Feng, A. Ferstl, K. T. Matchev and K. A. Olive, arXiv:astro-ph/0110225.

[37] D. J. Chung, P. Crotty, E. W. Kolb and A. Riotto, Phys. Rev. D **64**, 043503 (2001) [arXiv:hep-ph/0104100].

[38] J. Silk and M. Srednicki, *Phys. Rev. Lett.* **53**, 624 (1984).

[39] J. Silk, K. A. Olive and M. Srednicki, *Phys. Rev. Lett.* **55**, 257 (1985).

[40] M. W. Goodman and E. Witten, *Phys. Rev.* D **31**, 3059 (1985).

[41] M. Takeda *et al.*, arXiv:astro-ph/0209422.

[42] T. Abu-Zayyad *et al.* [High Resolution Fly's Eye Collaboration], arXiv:astro-ph/0208243 and arXiv:astro-ph/0208301.

[43] A. Letessier-Selvon, arXiv:astro-ph/0208526; J. Cronin *et al.*, `http://www.auger.org/`.

[44] P. G. Tinyakov and I. I. Tkachev, *Pisma Zh. Eksp. Teor. Fiz.* **74**, 3 (2001) [arXiv:astro-ph/0102101].

[45] See, for example, S. Sarkar and R. Toldra, Nucl. Phys. B **621**, 495 (2002) [arXiv:hep-ph/0108098].