Dark 2002 and Beyond

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Abstract. Salient aspects of the meeting are summarized, including our knowledge of dark matter at different cosmological and astrophysical distance scales, ranging from large-scale structure to the cores of galaxies, and our speculations on particle candidates for dark matter, including neutrinos, neutralinos, axinos, gravitinos and cryptons. Comments are also made on prospects for detecting dark matter particles and on the dark energy problem.

The speakers at this conference have come from different backgrounds, from that of macrophysics - namely astrophysics and cosmology, and from that of microphysics - namely that of particle physics experiments and theory. We have come together to discuss a weighty subject namely the nature of most of the stuff in the Universe. In this brief summary, I shall not be able to do justice to all the interesting talks we have heard, and I apologize in advance to those whose work is unjustifiably underemphasized. Inevitably, my summary adopts personal points of view, that you may not share.

This talk is ordered according to a sequence of decreasing distance scales, from the overall size of the Universe at $\sim 10^{10}$ pc down to the Planck length of 10^{-33} cm $\sim 10^{-52}$ pc. Astrophysical scales that we meet along the way include the $\sim 10^{8}$ pc of clusters of galaxies, the $\sim 10^{5}$ pc of galactic haloes, the $\sim 10^{3}$ pc of the cusps of rotation curves, and the ~ 1 pc of the central region of the Milky Way. Among the distance scales of particle-physics experiments that we meet are the $\sim 10^{-6}$ pc traveled by solar neutrinos, the $\sim 10^{-10}$ pc travelled by atmospheric neutrinos, the $\sim 10^{-12}$ pc of long-baseline neutrino experiments, and the $\sim 10^{-13}$ pc size of the LHC accelerator. Typical particle sizes we meet include the Compton wavelength $\sim 10^{-22}$ pc of the neutrino, the Compton wavelength $\sim 10^{-36}$ pc of supersymmetric particles, and the characteristic wavelength $\sim 10^{-44}$ pc of the ultra-high-energy cosmic rays.

Somewhere along this trail, the puzzle of dark matter will surely be solved, even if we do not yet know where.

1 Dark Matter on Different Distance Scales

1.1 Cosmological Density Parameters

As we have heard at this meeting, there is abundant evidence for the dominance of dark matter and dark energy on the largest distance scales. The cosmological microwave background (CMB) radiation [1] tells us that the total energy density of the Universe, Ω_{tot}, is very close to the critical value marking the boundary between open and closed universes [2]. This information is provided, in particular, by the value of the multipole $\ell \sim 210$ at which the first acoustic peak appears in the CMB, as seen in Fig. 1. This tells us, in effect, the relative sizes of the Universe today and when the nuclei and free electrons in the primordial plasma combined to form neutral atoms. There are now indications for a second and even a third acoustic peak in the CMB at higher ℓ [1], but these are not yet securely established. However, the magnitudes of the fluctuations $\delta T/T$ at these larger values of ℓ already tell us that the overall baryon density $\Omega_b \ll 1$, agreeing to within ~ 50 % with the value estimated on the basis of Big Bang nucleosynthesis calculations. Other information about the large-scale geometry of the Universe for redshifts $z \lesssim 1$ is provided by data on high-z supernovae [3], which constrain a combination of the matter density Ω_m and the vacuum energy density Ω_Λ. Combining the CMB and high-z supernova data, one finds fairly accurate values for the cosmological density parameters [2]:

$$\begin{aligned} \Omega_{tot} &= 1.02 \pm 0.06 \ , \ \Omega_m h^2 = 0.13 \pm 0.05, \\ \Omega_\Lambda &= 0.5 \pm 0.2 \qquad , \ \Omega_b h^2 = 0.022 \pm 0.004, \end{aligned} \tag{1}$$

where h is the present-day Hubble expansion rate in units of 100 km/s/Mpc, consistent with the 'concordance model': $\Omega_{tot} \sim 1, \Omega_\Lambda/\Omega_m \sim 2 \to 3$ with Ω_b small, as seen in Fig. 2. These data may also be used to constrain neutrino degeneracy [5].

There are excellent prospects for significant progress in improving the CMB constraints using data from the MAP and Planck satellites [6]. One of the open issues concerns the amount of information likely to be obtained at large ℓ [7], particularly from polarization measurements [6]. These must contend with weak lensing effects that must be subtracted in order to extract useful cosmological information.

1.2 Large-Scale Structure

The standard paradigm is that large-scale structures in the Universe are formed by gravitational instabilities, building on the primordial density perturbations observed in the CMB [1], with baryons falling into the 'holes' that are amplified by cold dark matter. Galaxy formation is considered to be more complex than cluster formation, with nonlinear astrophysical processes coming into play. Calculating galaxy formation is therefore more challenging numerically, though it may be guided by semi-analytical models. The general belief is that clusters formed before galaxies, which were formed by mergers of smaller structures.

The observational data on clusters of galaxies support the 'concordance model' in several different ways. Data on X-rays from rich clusters can be used to estimate the ratio Ω_m/Ω_b [10], the results suggesting again that $\Omega_m \ll 1$.

[1] Which are commonly thought to arise from an early epoch of inflation [8,9].

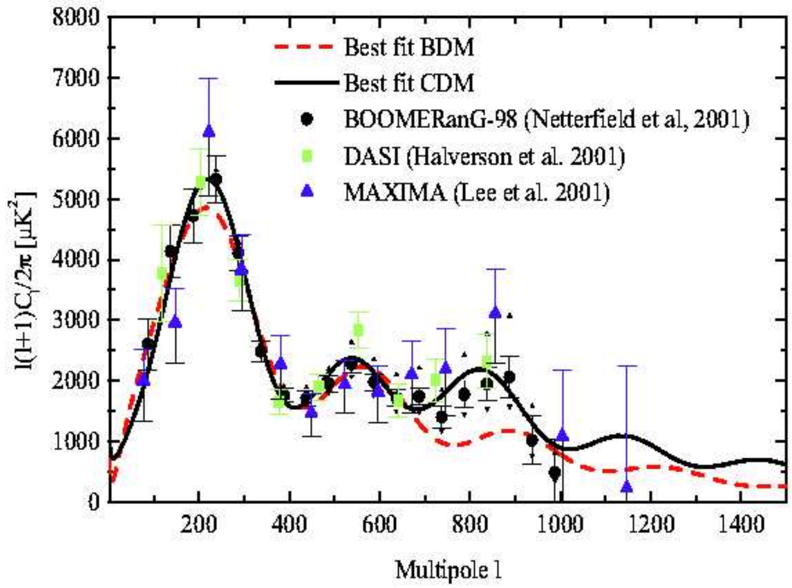

Fig. 1. Recent compilation of data on the cosmic microwave background (CMB), exhibiting clearly the first acoustic peak, whose location fixes Ω_{tot}, and the possible second and third peaks at larger ℓ [1].

The evolution of large-scale structure as a function of redshift also supports the concordance model, there being many more clusters at high z than would be expected in an Einstein-de-Sitter cosmology with $\Omega_m \sim \Omega_{tot} \sim 1$ [11]. Moreover, the shape of the two-point correlation function for galaxy clusters, as measured by the REFLEX collaboration, agrees with the concordance model, and is very similar in shape to that of the two-point correlation function for galaxies. The overall normalization of the cluster correlation function is considerably higher, as expected from the 'biasing' phenomenon, according to which rarer peaks are correlated more strongly than those of lower significance [11].

Several large new surveys of galaxy redshifts are underway, with some initial results from samples of $\sim 10^5$ galaxies now becoming available. Results from the first release of Sloane Digital Sky Survey (SDSS) data (29,000 redshifts) agree very well with those from the 2dF (200,000 redshifts) team and from the LCRS data (26,000 redshifts). Once again, the shape of the two-point correlation function agrees very well with the concordance model, and disagrees with the Einstein-de-Sitter model.

Just as the CMB is expected to display several acoustic peaks, so also the galaxy correlation function is expected to exhibit baryonic 'wiggles' on scales up to ~ 100 Mpc. There was recently a claim [12] to have observed an indication of them, but the amplitude was unexpectedly large, and a more recent reanalysis casts doubt on the 'wiggle' interpretation [13], as seen in Fig. 3.

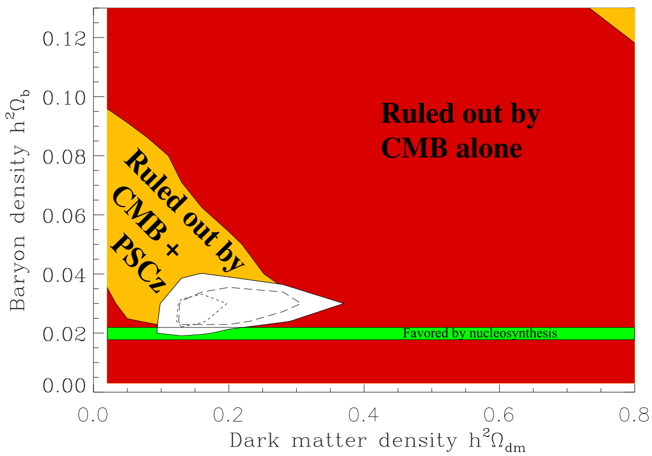

Fig. 2. The combination of cosmological data favours the 'concordance' model with $\Omega_{tot} \sim 1, \Omega_\Lambda/\Omega_m \sim 2 \to 3$ and Ω_b small, in agreement with cosmological nucleosynthesis [4].

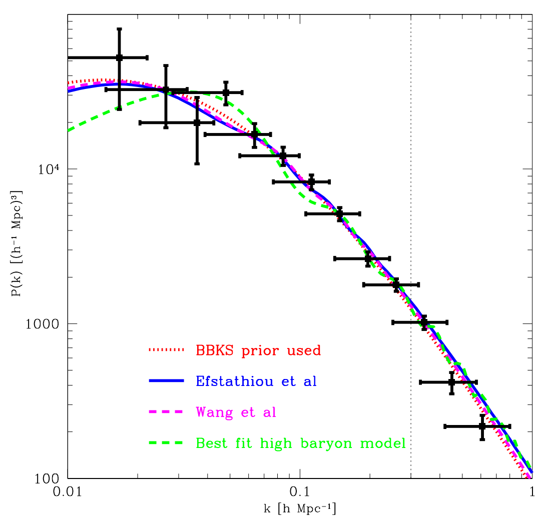

Fig. 3. A recent reanalysis [13] of the data of [12] does not reveal any baryonic 'wiggles'.

Models of structure formation are also constrained by data on quasars and Lyman α forests. The numbers of high-z quasars are problematic for hot- and warm-dark-matter models, but are consistent with the concordance model. The data on Lyman α forests are particularly interesting, because reduced nonlinearities render their interpretation less ambiguous than those of galaxies.

As repeatedly mentioned, all these data are consistent with the concordance model. Combining them with the CMB and high-z supernova data, one obtains the refined estimates:

$$\begin{aligned} \Omega_{tot} &= 0.99 \pm 0.03 \ , \ \Omega_m h^2 = 0.14 \pm 0.02, \\ \Omega_\Lambda &= 0.65 \pm 0.05 \ \ , \ \Omega_b h^2 = 0.021 \pm 0.003. \end{aligned} \tag{2}$$

However, there are some open issues in structure formation. One is that walls of galaxies are seen in the data that do not appear in simulations, although this is not seen as a serious problem. Another potential problem is provided by density profiles in groups and clusters of galaxies, but here recent simulations now indicate that energy ejection due to supernovae breaks self-similarity in a manner consistent with observation, within the concordance model. There have also been worries about the numbers of satellite galaxies, with many fewer being observed than are expected in the concordance model. However, there are reasons to think that small galaxies might not light up [14], since their conventional matter could be dispersed by the radiation from the first generation of stars.

1.3 Dynamics of Cusps

Another potential problem is whether cold dark matter predictions of cusps in the cores of galaxies are compatible with observations [10]. The cold dark matter density in a generic spheroidal galactic halo may be parameterized by

$$\rho(r) \ = \ \frac{r_0^\gamma}{r^\gamma (1 + (\frac{r}{r_0})^\alpha)^{\frac{(\beta-\gamma)}{\alpha}}}, \tag{3}$$

where r_0 is some scale factor. Early isothermal models of galactic haloes were nonsingular, with $\gamma = 0, \alpha = \beta = 2$. These were superseded by Navarro-Frenk-White profiles [15] with central singularities: $\gamma = 1, \alpha = 1, \beta = 3$, and more recently by even more singular profiles: $\gamma = 1.5, \alpha = 1.5, \beta = 3$ [16]. Observations do not support such singular cusps, and various attempts have been made to understand whether and how they might be weakened.

One suggestion has been that the annihilations of dark-matter particles in the cusps might generate particles and radiation pressure that would disperse the cusps. However, it seems questionable whether the annihilation rates found in plausible models are large enough, and the annihilations are so constrained by upper limits on synchrotron radiation that this mechanism seems unlikely to work [16].

Another suggestion made at this meeting, that seems more promising, is that black holes at the centers of galaxies [17] may disrupt the cusps via the gravitational slingshot effect acting on individual dark-matter particles [16], as seen in Fig. 4. This effect could be important during mergers, and simulations indicate that a further suppression of the core density would occur if there is a

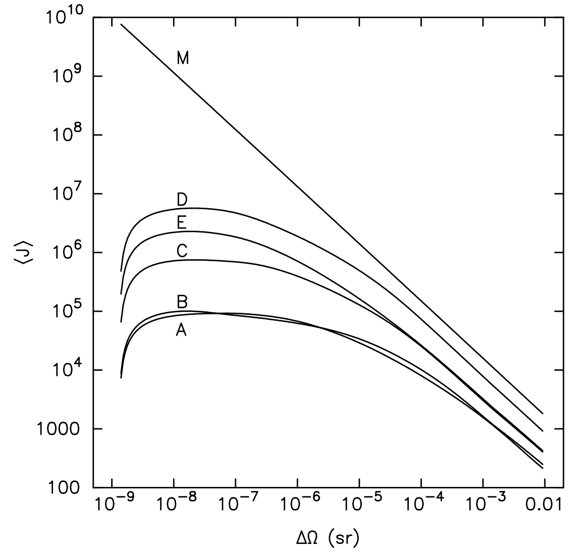

Fig. 4. The gravitational slingshot effect may suppress the density in a galactice core: the curves illustrate the reductions in the photon flux from relic annihilation, integrated over the indicated angular range, as found in different scenarios [16].

hierarchy of mergers. It does not seem at the moment that the apparent absence of cusps in generic galaxies is necessarily a big problem for cold dark matter.

A more specialized question concerns the center of the Milky Way. As discussed in more detail below, this is known to contain a central massive object weighing $\sim 3{\times}10^6$ solar masses, that is normally presumed to be a black hole [18]. Like any other galaxy, one would expect the history of our own to have included a number of mergers, that are likely to have suppressed the central density spike. For this reason, the density of cold dark matter at the center of the Milky Way, and hence the rate of their annihilations, has a considerable uncertainty that must be borne in mind when assessing dark-matter detection strategies, as discussed later.

1.4 Matter Content of the Milky Way

As we have been reminded at this meeting, one form of dark matter has been discovered, namely MACHOs [19]. It is still unclear what fraction of the microlensing events is due to MACHOs in our galactic halo, and what fractions are due to objects in either the Magellanic Clouds or our own (extended) galactic disc. If all the observed microlensing events originate from our galactic halo, as much as 8 % to 40 % of it could be composed of MACHOs. However, it now seems clear that MACHOs cannot constitute the bulk of the halo of the Milky Way [20].

A topic discussed at length at this meeting has been the composition of the central object in our galaxy, Sagittarius A*, that weighs $\sim 3 \times 10^6$ solar masses [18], as seen in Fig. 5. Although this is normally presumed to be a black hole, but this has not been established. We know from the observation of adjacent stellar orbits that the central mass must be concentrated within a small radius. Curvature has been observed in the orbits of some nearby stars, as seen in Fig. 6, and the rate of precession of these orbits promises to become a useful tool for measuring how much of the mass of Sagittarius A* is extended.

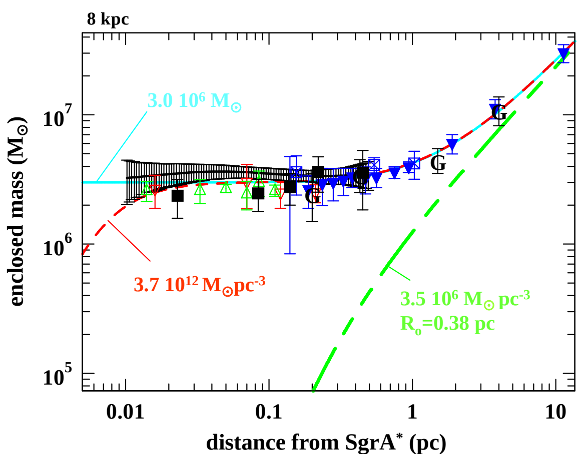

Fig. 5. The centre of the Milky Way contains a heavy object Sagittarius A*, with a mass $\sim 3 \times 10^6$ solar masses concentrated in a small radius [18].

A point in favour of the black hole interpretation of Sagittarius A* is that it has been observed to flare in X-rays, exhibiting large luminosity variations over very short time scales [21]. Matter falling into a black hole is expected to emit X-rays, and the rapid time variation indicates that the central engine of Sagittarius A* must be small. However, Sagittarius A* is not very bright, and it has been argued that this poses a so-called 'blackness problem' which motivates considering other models. However, as was discussed here [18], the blackness of Sagittarius A* is not necessarily a problem, since there are advective flow models that appear well able to reproduce its observed brightness [22].

As alternatives to the black hole hypothesis, balls of condensed bosons or fermions [23,24,25,26] have been proposed as alternative models for Sagittarius A*. The latter model postulates a neutral, weakly-interacting fermion weighing

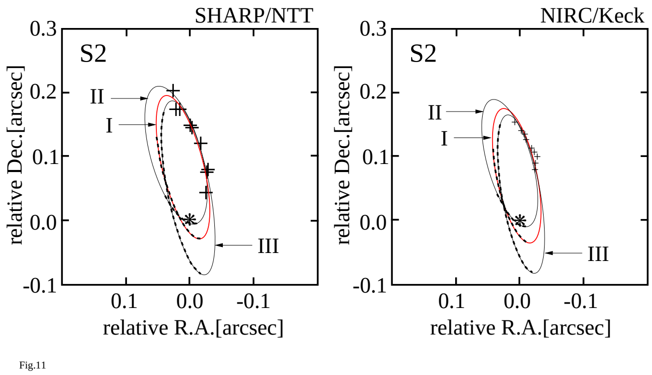

Fig. 6. Orbit of the star S2 near the heavy object Sagittarius A* at the centre of the Milky Way, exhibiting clearly the curvature due to its gravitational attraction [18].

about 15 KeV, and we have seen here detailed simulations of the evolution with time of a ball made out of such fermions [23], as seen in Fig. 7. This could not be a conventional neutrino, because the oscillation experiments tell us that they are degenerate to within 10^{-2} eV^2, and Tritium β-decay experiments tell us that the ν_e mass is less than about 2.5 eV. Moreover, astrophysical and cosmological data suggest a similar upper limit on all the neutrino species. We also heard how such a fermion might also constitute the halo of the Milky Way [25].

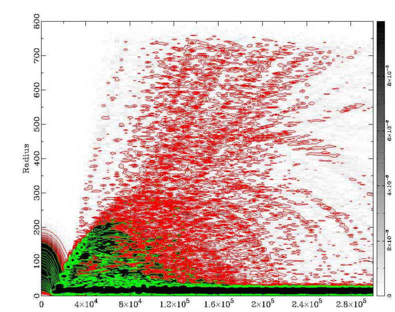

Fig. 7. Illustration of the formation of a fermion ball [23], showing the initial infall and the subsequent bouncing of material, some of which escapes while most falls back.

A potential 'smoking gun' for the black-hole interpretation of Sagittarius A* is a Fe emission line at about 8.6 KeV, that is expected to be smeared by the gravitational redshift near the horizon. An effect consistent with this expectation has been reported. On the other hand, radiative decay of a fermion weighing 15 to 17 KeV could also produce photons in the same energy range!

In my view, there is no reason to abandon the conservative black-hole paradigm for Sagittarius A*, and Occam's razor prompts me to favour it. On the other hand, such a paradigm must be challenged constantly, and it is good to have a rival model that we can use to benchmark the success of the black-hole paradigm.

2 Particle Candidates for Dark Matter

Now that the astrophysicists have convinced us of the necessity of dark matter, what candidates have we particle physicists to offer? *Neutrinos* are the prime candidates for hot dark matter, whereas there are numerous candidates for cold dark matter, including *axions*, supersymmetric particles such as the lightest *neutralino*, the *axino* and the *gravitino*, and possible superheavy metastable relics such as *cryptons*. Axions were not much discussed here, so I concentrate on neutrinos, supersymmetric particles and superheavy relics.

2.1 Neutrinos

As we were reminded at this meeting, alternative interpretations of the solar and atmospheric neutrino data are not excluded, but oscillations between different neutrino mass eigenstates are very much the favoured interpretations [27].

In the case of atmospheric neutrinos, the favoured oscillation pattern is $\nu_\mu \to \nu_\tau$. There is no evidence for oscillations involving the ν_e, there being no anomaly in the atmospheric ν_e data, and we also have a stronger upper limit on $\nu_e \to \nu_\mu$ oscillations from the Chooz data. Also, $\nu_\mu \to \nu_{sterile}$ oscillations are disfavoured by the zenith-angle distributions. The central value of the mass-squared difference $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2, and the mixing angle is large: $\sin^2 2\theta > 0.8$ [28].

In the case of solar neutrinos, $\nu_e \to \nu_\mu$ and/or ν_τ oscillations are preferred, though some admixture of $\nu_e \to \nu_{sterile}$ cannot be excluded. After SNO [29], the data increasingly favour the large-mixing-angle (LMA) solution, with 10^{-5} eV^2 $<$ $\Delta m^2 < 10^{-4}$ eV^2, though large mixing with a somewhat smaller value of Δm^2 (the LOW solution) is also possible [30], as seen in Fig. 8.

We heard at this meeting of a possible indication for neutrinoless double-β decay, corresponding to 0.11 eV $< < m >_{\beta\beta} <$ 0.56 eV [31] [2]. The claimed significance is not high, around 2 σ, whereas 4 or 5 σ would be needed to claim a discovery. The claimed indication rests on the interpretation of one possible bump in the energy spectrum, with some other bumps being interpreted as other radioactive decays, and the rest resisting interpretation. However, the analysis has been criticized [33], in particular because the strengths of the other claimed radioactive decays appear to be too high. The Heidelberg-Moscow experiment has now reached the limit of its sensitivity, so we must wait to see what other experiments find. In a conventional hierarchical scenario for neutrino masses, one could expect to see a signal at the level $< m >_{\beta\beta} \sim 0.01$ eV, for which a future large-scale experiment such as the GENIUS proposal will be needed.

[2] The possible interpretation in the context of oscillation experiments was also discussed here [32].

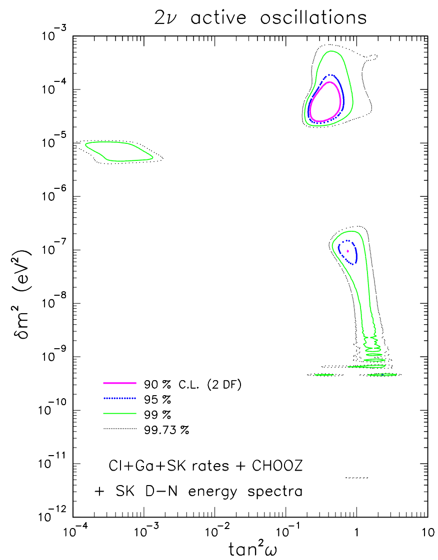

Fig. 8. Regions of 2-neutrino oscillation parameters allowed [30] by the available solar neutrino data, including those from SNO [29].

Tritium β-decay experiments are largely complementary to neutrinoless double-β decay experiments [34], since they measure a different observable:

$$< m >_\beta \equiv \Sigma_i |U_{ei}|^2 m_i \text{ vs } < m >_{\beta\beta} \equiv |\Sigma_I U_{ei}^2 e^{i\phi_i} m_i|. \tag{4}$$

As we heard at this meeting, the previous problems of these experiments, namely the tendency to prefer negative values of $< m >_\beta^2$ and the appearance of a 'bump' near the end of the spectrum, have now been resolved. The former has been traced to a roughening transition in the frozen Tritium surface layer, and the latter to plasma effects related to particles trapped in the spectrometer. The limits accessible with the present experiments have now been almost saturated. Each experiment reports an upper limit $\sim$ 2.2 eV, but a more conservative interpretation would be

$$< m >_\beta < 2.5 \text{ eV}. \tag{5}$$

As we also heard at this meeting, there are ambitious ideas for a next-generation experiment called KATRIN [35], which is proposed to be 70 m long and 8 m in diameter, and able to reach a limit of 0.35 eV. This is certainly a worthwhile objective, but the question still remains: how to reach the atmospheric neutrino mass scale ~ 0.05 eV.

Combining the upper limit (5) from Tritium β decay with the upper limit $< m >_{\beta\beta} < 0.56$ eV from $\beta\beta_{0\nu}$ decay, and recalling the lower limits: $\Delta m^2 >$

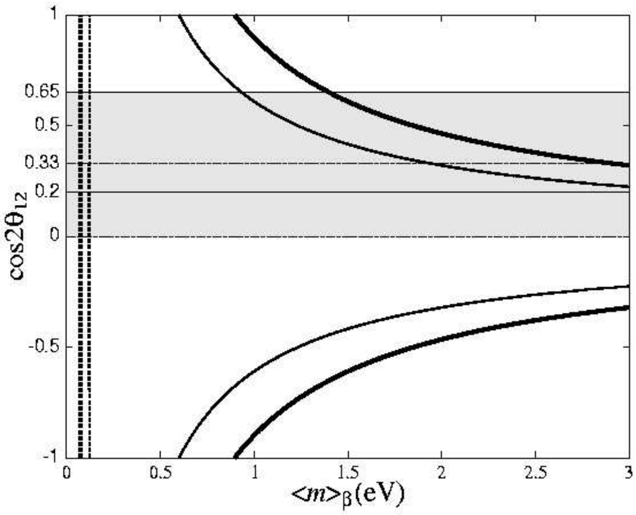

Fig. 9. The constraint on the neutrino mixing angle θ_{12} and the Tritium β-decay observable $< m >_\beta$ that would be imposed if 0.11 eV $< < m >_{\beta\beta} <$ 0.56 eV (thin lines) or 0.05 eV $< < m >_{\beta\beta} <$ 0.84 eV (thick lines) [32]. The ranges of θ_{12} favoured by the LMA (LOW) solutions are shaded between thin solid (dashed) lines.

0.003 eV^2 from atmospheric neutrinos, 10^{-4} eV^2 for the LMA solar solution, one can infer the following allowed range for the total relic neutrino density:

$$0.001 < \Sigma_\nu \Omega_\nu < 0.18. \tag{6}$$

Though not conclusive, this is certainly consistent with the lack of enthusiasm for hot dark matter indicated by studies of large-scale structure. The CMB is relatively insensitive to Ω_ν, whereas large-scale structure is very sensitive to Ω_ν [4].

We can look forward to significant advances in neutrino physics in the coming years that will check the emergent picture outlined above. The SNO experiment will soon provide important new data on the ratio of neutral- and charged-current events [29]. Also starting to take data is the KamLAND experiment [36], which should provide a conclusive test of the LMA interpretation of the solar neutrino data. Shortly, we can also expect important data from BOREXINO [37], that will also help pin down the interpretation of solar neutrinos.

Long-baseline neutrino experiments [38] are now swinging into action to probe the interpretation of atmospheric neutrinos, led by K2K [39]. The Super-KAMIOKANDE detector is currently being reconfigured after its accident, so as to enable data-taking for the K2K experiment to restart. Meanwhile, the NUMI beam and the MINOS detector are being prepared in the United States [40], in parallel with the CNGS beam and the OPERA detector in Europe [41]. The MINOS experiment is aimed at measurements of the oscillation pattern, neutral- and charged-current rates, and the search for ν_e appearance in a ν_μ beam, whilst the OPERA detector is aimed at detecting τ production in a ν_μ beam due to $\nu_\mu \to \nu_\tau$ oscillations. In the longer term, the JHF is under construction [42], and will provide the opportunity to generate a more intense neutrino beam that could be directed towards the SuperKAMIOKANDE detector or its projected megaton-class successor, HyperKAMIOKANDE. The latter would provide a first opportunity to search for CP neutrino oscillations.

The search for CP violation could be made much more precise if more intense, pure ν_e and/or ν_μ were available. A relatively new idea to realize this objective is to store radioactive ions whose decays would yield pure ν_e and $\bar{\nu}_e$ beams [43]. A longer-standing concept is that of a neutrino factory based on the decays of muons in a storage ring [44]. Since this produces simultaneously ν_μ and $\bar{\nu}_e$ beams, both with well-understood spectra, a neutrino factory is the ultimate weaqpon for neutrino-oscillation studies. Among the objectives of this programme would be the ultimate searches for θ_{13} and CP violation [45], and determining the sign of the neutrino mass hierarchy.

In addition to neutrino-oscillation studies, a neutrino factory would also offer interesting prospects for high-statistics studies of neutrino interactions with a short-baseline beam [46]. The intense proton source would provide other particle physics opportunities, for example using stopped or slow muons [47], as well as opportunities in other areas of physics [48]. Many accelerator laboratories around the world, including Europe, Japan and the United States, have initiated studies of neutrino factories. However, in each region it seems that the first choice for a major new accelerator facility is a linear e^+e^- collider. Thus there is a danger that the neutrino factory will be ‘always the bridesmaid, never the bride’. The priority accorded a linear e^+e^- collider is understandable, but a balanced accelerator programme for the world should surely also include a neutrino factory somewhere. Both machines could cast important light on the dark matter problem, in different ways.

2.2 Supersymmetric Dark Matter

Assuming that $R \equiv (-1)^{B+L+2S}$ is conserved, the lightest supersymmetric particle (LSP) is stable, and may be an ideal candidate for cold dark matter, provided it is neutral and has no strong interactions. The possibility most often studied [49] is that the LSP is the lightest *neutralino* χ, a mixture of the supersymmetric partners of the photon, Z^0 boson and neutral Higgs bosons. Another option mentioned here is that the LSP is the *axino* $\tilde{a}$, the supersymmetric partner of the hypothetical axion. Finally, there is the *gravitino* $\widetilde{G}$, which is generally unwelcome, since detecting it would be very difficult. The gravitino option was not discussed here, so I do not discuss it either. Instead, I focus mainly on the lightest neutralino χ, mentioning more briefly the axino option.

Neutralino Dark Matter In some sense, the neutralino is the most ‘natural’ candidate in the minimal supersymmetric extension of the Standard Model (MSSM), since one normally expects it to be lighter than the the gravitino in models based on supergravity, and a relic density in the range of interest to astrophysicists and cosmologists: $0.1 < \Omega_\chi h^2 < 0.3$ is 'generic'. As several speakers have shown here, neutralino dark matter is compatible with all the available accelerator constraints, including searches for supersymmetric particles at LEP [50], HERA [51] and the Tevatron collider, as well as the indirect constraints imposed by measurements of $b \to s\gamma$ and $g_\mu - 2$ [52,53,54,55,56]. In the most constrained versions of the MSSM, in which scalar and fermionic sparticle masses are each universal at some input grand-unification scale, as in simple supergravity (SUGRA) models, the lightest neutralino probably weighs more than about 100 GeV [57]. Figs. 10 and 11 show examples of the allowed parameter space in the constrained MSSM, illustrating the range allowed by the $g_\mu - 2$ constraint at the 1.5-σ level, and the potential power of the search for $B_s \to \mu^+\mu^-$ at the Tevatron collider, respectively.

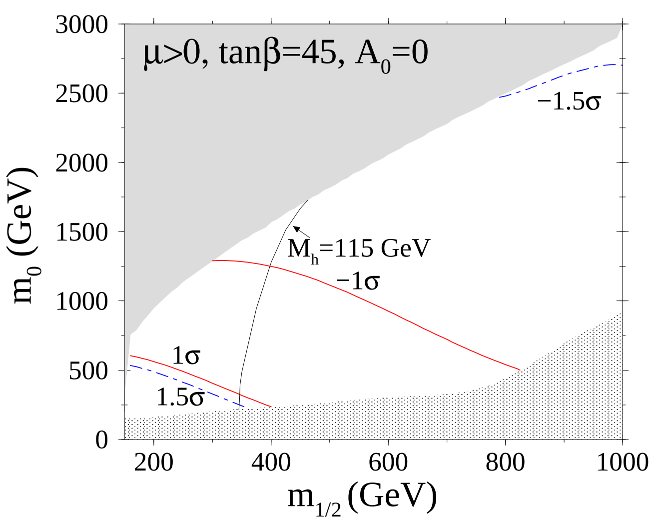

Fig. 10. Compilation of limits on the constrained MSSM for $\mu > 0, \tan\beta = 45, A_0 = 0$, showing in particular the region favoured by $g_\mu - 2$ [54] at the $\pm 1, 1.5$-σ levels. Electroweak symmetry breaking is not posible in the shaded region at the top, and the lightest supersymmetric particle would be the lighter $\tilde{\tau}$ in the hatched region at the bottom.

The allowed parameter space may be explored theoretically either by parameter scans, or by focusing on specific benchmark scenarios intended to illustrate the range of possibilities left open by the experimental constraints [58]. These indicate that dark matter searches can expect strong competition from future accelerators, notably the LHC. This will be able to explore much of the domain of parameters allowed by the relic density constraint and current experimental constraints. Moreover, as has been revealed by specific benchmark studies illus-

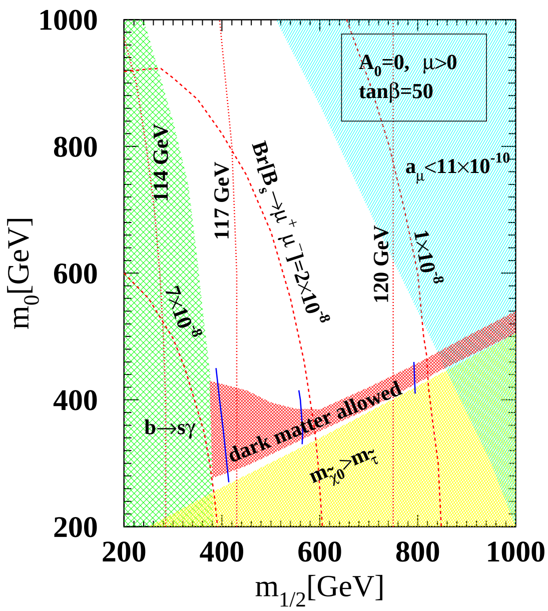

Fig. 11. Compilation of limits on the constrained MSSM for $\mu > 0, \tan\beta = 55, A_0 = 0$, showing in particular the region accessible to the search for $B_s \to \mu^+\mu^-$ at the Tevatron collider [55]. Regions on the left and right are disfavoured by $b \to s\gamma$ and $g_\mu - 2$, respectively. In the hatched region at the bottom, the lightest supersymmetric particle would be the lighter $\tilde{\tau}$. The allowed region for supersymmetric dark matter is shaded.

trtaed in Fig. 12, in much of the accessible parameter space the LHC may be able to discover several different types of supersymmetric particles, and measure the CMSSM parameters quite accurately. However, as also shown in Fig. 12, there are some benchmark scenarios where the LHC does little more than discover the lightest MSSM Higgs boson. Experiments searching for dark matter have an almost clear field until 2007, but will then get some serious competition: caveat the LHC!

Neutralino Relic Density Calculations These often assume universal input scalar masses, termed here the CMSSM, as found in minimal supergravity (mSUGRA) models. In the CMSSM, there is a 'bulk' region of relatively low values of $m_{1/2}, m_0$ where the relic density falls with in the range $0.1 < \Omega_\chi h^2 < 0.3$ favoured by astrophysics and cosmology. Stretching out from the bulk region to larger $m_{1/2}$ and/or m_0 are filaments of parameter space where special circumstances suppress the relic density, in some of which the LSP mass m_χ may be significantly heavier. These filaments may appear because of coannihilation [59] - in which the relic LSP density is suppressed by mutual annihilations with other sparticles that happen to be only slightly heavier, rapid annihilation through direct-channel boson resonances - in particular the heavier neutral MSSM Higgs bosons A, H, and in the 'focus-point' region [60] near the boundary where calculations of electroweak symmetry breaking fail.

The relic density in the bulk region is relatively insensitive to the exact values of the input CMSSM parameters, and to differences in the (inevitable) approximations made in the calculations [61]. However, relic-density calculations in the filament regions are much more sensitive to these input values and approximations, and hence more likely to differ from one paper to another, as we have seen at this meeting. Several different codes for calculating the relic density are now available, and the most recent ones generally agree quite well, once the differences in inputs and approximations are straightened out.

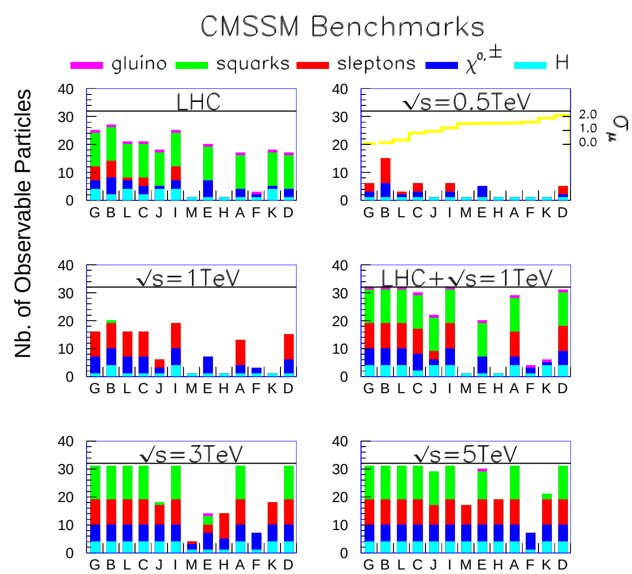

Fig. 12. Summary of the prospective sensitivities of the LHC and lepton colliders with different $\sqrt{s}$ energies to CMSSM particle production in the proposed benchmark scenarios [58], which are ordered by their distance from the central value of $g_\mu - 2$, as indicated by the pale (yellow) line in the second panel. We see clearly the complementarity between a lepton ollider and the LHC in the TeV range of energies [58], with the former excelling for non-strongly-interacting particles, and the LHC for strongly-interacting sparticles.

Strategies to Search for Neutralinos The most direct signal for supersymmetric dark matter would be *scattering on nuclei* [62], a topic discussed by many speakers at this meeting. The observation of an annual modulation effect in the DAMA detector was reported here [63], but the source of the modulation has not yet been pinned down. Detectors using other techniques have not yet been able to confirm the DAMA results [64], but neither have they yet been ruled out. Most calculations now agree that it is very difficult to reproduce in the constrained MSSM the elastic scattering cross section that would be required by DAMA [52,56,65], as seen for example in Fig. 13.

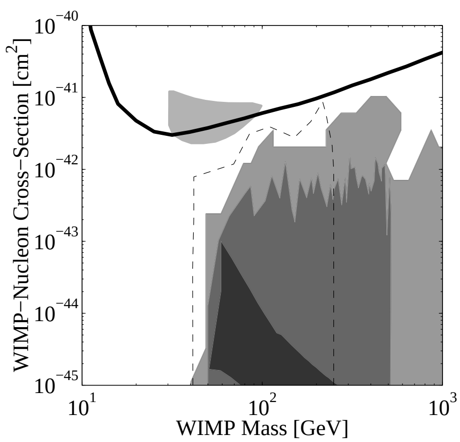

Fig. 13. The elastic scattering cross section possible in the constrained MSSM [52,56,65] lies considerably below the range suggested by DAMA [63], which is not yet excluded by CDMS [64].

A less direct strategy is to look for the products on LSP *annihilations inside the Sun or Earth*. These would produce neutrinos with relatively high energies, whose interactions in rock would yield muons that could be detected in a detector deep underground, underwater [66] or in ice [67]. The prospects for detecting these muons are quite model-dependent, but it seems that annihilations inside the Sun might be more promising, at least in the benchmark scenarios [68] shown in the upper panel of Fig. 14.

Other suggestions have been to look for positrons or antiprotons produced by LSP *annihilations in the halo of the Milky Way*. Quite a large number of cosmic-ray antiprotons have now been observed, but their flux and modulation with the solar cycle are consistent with secondary production by primary matter cosmic rays. As shown here by the AMS collaboration [69], low-energy positrons in near space are also mainly produced by the collisions of cosmic rays, in the Earth's atmosphere, though there are still some hints of a possible anomaly at higher energies. However, it does not seem possible to reproduce this hint in the CMSSM [68].

Another suggestion has been to look for γ-ray production by *annihilations in the core of the Milky Way*, where the relic density may be enhanced. However, as

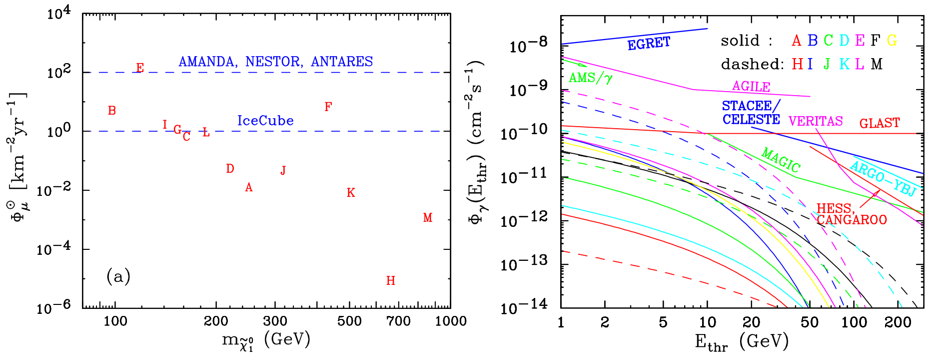

Fig. 14. Fluxes (upper) of muons from the core of the Sun that could be detected in a detector deep underground, underwater or in ice, and (lower) of photons from the core of the Milky Way, as calculated [68] in the proposed benchmark scenarios. The calculations are compared with the estimated sensitivities of the experiments shown.

discussed earlier, there are considerable uncertainties in this possible enhancement. Depending on its magnitude, some benchmark scenarios might offer hopes for detection in this way [68,70], as shown in the lower panel of Fig. 14.

The general conclusion from these benchmark studies in the CMSSM is: think big! Detectors much larger than the present generation would be required to have a good chance of detecting elastic scattering, and km^3 detectors are probably needed to see annihilations in the Sun or Earth.

Comments on Neutralino Scattering One of the most important contributions to spin-independent elastic scattering is that due to Higgs exchange, and one of the reasons why current predictions for the cross section are less optimistic than a few years ago is the dramatic improvement in the lower limit on the Higgs mass from LEP. The lower limit of 114.1 GeV in the Standard Model [71] also applies to the CMSSM in regions of interest for dark matter, and in the more general MSSM when $\tan\beta \lesssim 8$ [72].

The proton and neutron structure effects on both the spin-dependent and -independent elastic scattering cross sections are relatively well under control. Despite residual uncertainties in some relevant hadronic matrix elements, other uncertainties are probably considerably larger.

Last year, the initial interpretation of the BNL experiment [73] on $g_\mu - 2$ gave considerable hope to searches for elastic scattering, as it appeared to exclude large values of $m_{1/2}$ and m_0 [74]. However, with the recent correction of the sign of the hadronic light-by-light scattering contribution [75], the previous 'discrepancy' with the Standard Model prediction for $g_\mu - 2$ has been greatly reduced, large values of $m_{1/2}$ and m_0 are again allowed [54,53], and the elastic scattering rate may be very small, as exemplified by the benchmark studies [68]. However, it remains true that the rate could be quite large if $g_\mu - 2$ eventually settles down close to its present central value, and if there are no further Standard Model surprises in store.

As was discussed here, annual modulation is a potentially powerful tool for convincing skeptics that a detector signal is indeed due to the scattering of dark matter, particularly when combined with directional information [76]. The DAMA experiment is currently under pressure from a number of other experiments [64,77,78,79,80,81,82,83]. In view of the possible ambiguities in the interpretation of any experimental signal, it is desirable to explore as many different techniques as possible, and it was encouraging to hear here that studies using Sodium Iodide, Germanium, Xenon, Calcium Fluoride, Lithium Fluoride and Aluminium as target materials are underway. It was also encouraging to hear that Pulse Shape Discrimination, Time Projection Chambers, Silicon Drift Detectors, and phonon-based detection strategies are being explored. It would be particularly impressive to find a confirmatory signal for spin-dependent scattering, and I recall that Fluorine is the most promising material for this purpose [84].

Axino Dark Matter As discussed here [85], the axino $\tilde{a}$ is quite a 'natural possibility in an extension of the MSSM that includes an axion in order to explain why the strong interactions conserve CP. The decay constant F_a that reflects the scale of axion dynamics should be $\lesssim 10^{11}$ GeV, so as to avoid having too much axionic cold dark matter. As in the MSSM, a plausible mass scale for the lightest neutralino is $m_\chi \sim 100$ GeV. Assuming these values for F_a and m_χ, Fig. 15 displays the allowed range of the model parameter space in the $m_{\tilde{a}}, T_R$ plane, where T_R is the reheating temperature after inflation. As seen in Fig. 15, one must require $T_R \lesssim 10$ TeV and $m_{\tilde{a}} \gtrsim 10$ MeV. The latter is not a problem, since models typically yield $m_{\tilde{a}} \sim 10$ GeV, but in that case $T_R \lesssim 100$ GeV would be needed, implying a somewhat unconventional cosmology.

Gravitino Dark Matter? The thermal production of gravitinos following inflation has long been regarded as a potential problem for cosmology. To avoid this, it is generally considered that the reheating temperature cannot be too high: $T_R \lesssim 10^9$ GeV. In recent years, the possibility of overproducing gravitinos during inflation has also been raised [86]. As we heard here, inflatinos are certainly produced copiously, but these are not thought to convert into relic gravitinos [87].

Since gravitinos have only gravitational-strength interactions, gravitino dark matter would be unobservable, and hence a nightmare for detection experiments. In most supergravity scenarios, the gravitino weighs more than the lightest neutralino, and is unstable. However, the possibility has been raised of a light gravitino weighing ~ 1 KeV, which would be a potential candidate for warm dark matter. However, this possibility does not seem to be required, or even favoured, by cosmology, so is not pursued here.

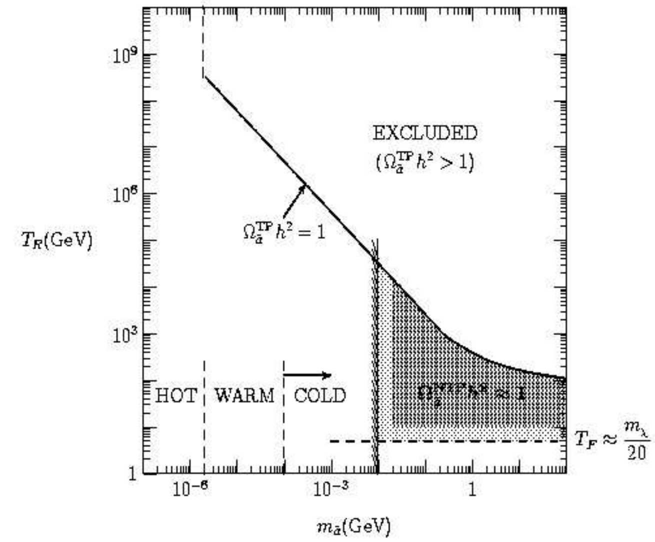

Fig. 15. Compilation of constraints on axino dark matter [85], as functions of the reheating temperature T_R and the axino mass $m_{\tilde{a}}$.

2.3 Metastable Superheavy Relics?

As was discussed by several speakers at this meeting, there may well exist ultra-high-energy cosmic rays (UHECR) beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff, that is expected due to interactions with the CMB [88]. The experimental situation is not yet clear, since there are issues of energy calibration and flux normalization between the two experiments with the highest statistics, AGASA and Hi-Res. Experiments at CERN might be able to help by updating studies of fluoresecence due to particles passing through Nitrogen, and by validating models of high-energy particle interactions at the LHC.

Assuming that UHECR beyond the GZK cutoff do exist, there are two main scenarios for their origins: bottom-up mechanisms involving discrete sources within the GZK range, and top-down mechanisms that invoke the decays of ultra-massive particles or topological defects [89].

Bottom-up mechanisms are clearly more conservative (and hence more plausible?). They suggest that the observed UHECR should cluster and perhaps align with sources observable by other means, such as active galactic nuclei or gamma-ray bursters, unless intergalactic magnetic fields are strong enough to spread them out. There have indeed been reports of clustering and possible alignment, but these have yet to attain consensus.

It has been realized that the gravitational production of superheavy unstable relics, *cryptons*, is likely to be efficient enough to provide an interesting relic density. Moreover, the hidden sectors of string models generically contain such particles, which naturally have long lifetimes, thanks to selection rules and because interactions between the hidden and observable sectors are usually of very high order and very weak. As we heard at this meeting [90], the crypton decay spectrum may fit well the apparent excess of UHECR beyond the GZK cutoff. However, models tend to predict a large γ/proton ratio, whereas the observed UHECR have been consistent with protons and could not all be photons. In any crypton model, most of the UHECR would originate from decays within the halo of the Milky Way. This means that their arrival directions should exhibit a galactic anisotropy, and could also cluster if much of the halo consists of clumped cold dark matter.

A third scenario discussed at this meeting is the Z-burst model, according to which the UHECR observed originate from collision between primary UHE neutrinos that strike relic dark matter neutrinos to produce Z^0 bosons that subsequently decay. This scenario requires relic neutrinos that are somewhat heavier than one might expect on the basis of atmospheric and solar oscillation experiments, but the hypothesis cannot be excluded at present, as seen for example in Fig. 16 [90].

As we heard at this meeting, a series of ambitious experiments on UHECR are now being prepared or planned. The Auger experiment currently being constructed in Argentina will combine fluorescence and calorimetric techniques, and have a much larger surface area than previous experiments [91]. EUSO [92] and OWL-Airwatch are proposals for space experiments to look down at fluorescence in the atmosphere over much larger areas still. The physics issues concerning UHECR are on their way to being resolved.

2.4 Alternative Particle Models for Dark Matter

If all the above, more conventional, particle candidates for dark matter fall by the wayside, theorists have more exotic candidates in their back pockets [93,94,95]. For example, there could be interacting massive fermions that resemble warm dark matter, should that be required. Alternatively, there could be interacting scalar dark matter. One of these possibilities might become interesting if the cold dark matter paradigm fails.

3 Dark Energy

As we were reminded repeatedly at this meeting, the cosmological concordance model seems to require some form of dark energy in ‘empty’ space, which should make the dominant contribution to the overall energy density of the Universe:

$$\Omega_\Lambda \quad = \quad 0.65 \pm 0.05. \tag{7}$$

Attempts to measure its equation of state suggest that it is almost constant:

$$\omega_Q \quad < \quad 0.7, \tag{8}$$

ruling out some attractive tracking quintessence models [96].

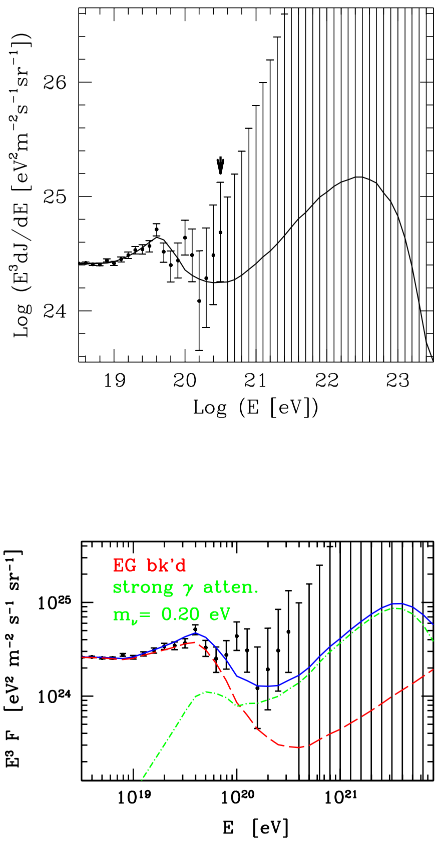

Fig. 16. Illustrations of fits to the UHECR data in the crypton decay (upper) and Z-burst (lower) models [90].

We heard at this meeting of some interesting new ideas. For example, the existence of large extra dimensions would offer new approaches [97], such as obtaining Λ from self-tuning in five dimensions, or radion quintessence in six dimensions. Other ideas proposed here included a Chaplygin gas [98] and a repulsive force in massive QED: 'spintessence' [99]. Certainly new ideas are desperately needed.

However, in my view, it makes no sense to discuss dark energy outside the framework of a complete quantum theory of gravity. Indeed, explaining the presence and magnitude of dark energy is surely the greatest challenge for a candidate quantum theory of gravity such as string theory. The Holy Grail of such a theory should be to calculate the amount of dark energy from first principles.

4 Final Remarks

The quest for dark matter is entering an exciting phase. Astrophysicists and cosmologists keep on telling us particle physicists that a large amount of dark matter is certainly required, and that it is probably mainly cold. There are still some nagging worries about this paradigm, related to galactic cores and the absence of observable small satellite galaxies, but these seem resolvable [100] and there is no serious rival to the cold dark matter paradigm [94]. However, astrophysicists cannot tell us what this dark matter is composed of: that is the task of we particle physicists.

We certainly have plenty of candidates, ranging from axions through supersymmetric particles to cryptons. Which if any of these is correct can only be decided by particle experiments, either with accelerators or using astrophysical sources. The greatest accelerator hopes lie with the LHC, but non-accelerator experiments have an almost free rein until it starts taking data in 2007, and some candidates such as axions and cryptons lie beyond the reach of accelerators.

Dark energy is even more of a challenge than dark matter. Particle physicists did not expect it, and do not have many convincing ideas for its origin. A deeper understanding of quantum gravity is surely necessary.

Given this state of ferment, there is plenty to keep us all busy until the next Dark 200N meeting!

References

1. A. T. Lee *et al.*, Astrophys. J. **561**, L1 (2001) [arXiv:astro-ph/0104459]; N. W. Halverson *et al.* [DASI Collaboration], arXiv:astro-ph/0104489; C. B. Netterfield *et al.* [Boomerang Collaboration], arXiv:astro-ph/0104460; J. R. Bond *et al.* [MaxiBoom Collaboration], arXiv:astro-ph/0011378; P. de Bernardis *et al.*, arXiv:astro-ph/0105296.
2. See, for example, A. Melchiorri and J. Silk, arXiv:astro-ph/0203200; A. Melchiorri, arXiv:astro-ph/0204017 and talk at this meeting.
3. A. G. Riess *et al.* [Supernova Search Team Collaboration], Astron. J. **116**, 1009 (1998) [arXiv:astro-ph/9805201]; S. Perlmutter *et al.* [Supernova Cosmology Project Collaboration], Astrophys. J. **517**, 565 (1999) [arXiv:astro-ph/9812133].
4. M. Tegmark, M. Zaldarriaga and A. J. Hamilton, Phys. Rev. D **63**, 043007 (2001) [arXiv:astro-ph/0008167]; and A. J. Hamilton, talk at this meeting.
5. M. Orito, T. Kajino, G. J. Mathews and Y. Wang, arXiv:astro-ph/0203352; and T. Kajino, talk at this meeting.
6. A. Cooray, arXiv:astro-ph/0203048; and talk at this meeting.
7. N. Aghanim, P. G. Castro, A. Melchiorri and J. Silk, arXiv:astro-ph/0203112.
8. D. H. Lyth and A. Riotto, Phys. Rept. **314**, 1 (1999) [arXiv:hep-ph/9807278].
9. R. Hofmann and M. T. Keil, arXiv:hep-ph/0111076; and R. Hofmann, talk at this meeting.
10. N. Menci, talk at this meeting.
11. S. Borgani and L. Guzzo, arXiv:astro-ph/0012439; and L. Guzzo, talk at this meeting.
12. W. J. Percival *et al.*, arXiv:astro-ph/0105252.

13. M. Tegmark, A. J. S. Hamilton and Y.-z. Xu astro-ph/0111575; and A. J. S. Hamilton, talk at this meeting.
14. F. Governato, S. Ghigna and B. Moore, arXiv:astro-ph/0105443.
15. J. F. Navarro, C. S. Frenk and S. D. White, Astrophys. J. **462**, 563 (1996) [arXiv:astro-ph/9508025].
16. D. Merritt, M. Milosavljevic, L. Verde and R. Jimenez, arXiv:astro-ph/0201376; and D. Merritt, talk at this meeting.
17. G. Madejski, talk at this meeting.
18. R. Genzel, C. Pichon, A. Eckart, O. E. Gerhard and T. Ott, arXiv:astro-ph/0001428; A. Eckart, R. Genzel, T. Ott and R. Schoedel astro-ph/0201031; and A. Eckart, talk at this meeting.
19. K. Griest, talk at this meeting.
20. A. J. Drake, talk at this meeting.
21. F. K. Baganoff *et al.*, Nature, **413**, 45 (2001); and F. K. Baganoff, talk at this meeting.
22. E. Quataert, R. Narayan and M. Reid, arXiv:astro-ph/9903412.
23. N. Bilic, R. J. Lindebaum, G. B. Tupper and R. D. Viollier, Phys. Lett. B **515**, 105 (2001) [arXiv:astro-ph/0106209]; and R. J. Lindebaum, talk at this meeting.
24. P. H. Chavanis, astro-ph/0108378, and talk at this meeting.
25. N. Bilic, G. B. Tupper and R. D. Viollier, arXiv:astro-ph/0111366; and talk at this meeting.
26. N. Bilic, F. Munyaneza, G. B. Tupper and R. D. Viollier, arXiv:astro-ph/0111536; and R. D. Viollier, talk at this meeting.
27. J. W. Valle, talk at this meeting.
28. Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562 (1998) [arXiv:hep-ex/9807003].
29. Q. R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. **87**, 071301 (2001) [arXiv:nucl-ex/0106015]; A. Hime, talk at this meeting.
30. G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, arXiv:hep-ph/0201290.
31. H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney and I. V. Krivosheina, Mod. Phys. Lett. A **16**, 2409 (2002) [arXiv:hep-ph/0201231]; and H. V. Klapdor-Kleingrothaus, talk at this meeting.
32. H. Minakata and H. Sugiyama, arXiv:hep-ph/0202003; and H. Minakata, talk at this meeting.
33. F. Feruglio, A. Strumia and F. Vissani, arXiv:hep-ph/0201291; C. E. Aalseth *et al.*, arXiv:hep-ex/0202018.
34. E. W. Otten, talk at this meeting.
35. A. Osipowicz *et al.* [KATRIN Collaboration], arXiv:hep-ex/0109033; and M. Steidl, talk at this meeting.
36. A. Piepke [KamLAND Collaboration], Nucl. Phys. Proc. Suppl. **91**, 99 (2001).
37. G. Ranucci *et al.* [BOREXINO Collaboration], Nucl. Phys. Proc. Suppl. **91**, 58 (2001).
38. K. Zuber, talk at this meeting.
39. S. H. Ahn *et al.* [K2K Collaboration], Phys. Lett. B **511**, 178 (2001) [arXiv:hep-ex/0103001].
40. E. Ables *et al.* [MINOS Collaboration], FERMILAB-PROPOSAL-P-875.
41. M. Guler *et al.* [OPERA Collaboration], CERN-SPSC-2000-028.
42. See, for example, M. Aoki, hep-ph/0204008.
43. P. Zucchelli, arXiv:hep-ex/0107006.

44. B. Autin, A. Blondel and J. R. Ellis, *Prospective study of muon storage rings at CERN*, CERN Yellow report CERN-99-02; C. Albright *et al.*, arXiv:hep-ex/0008064.
45. A. Bueno, M. Campanelli, S. Navas-Concha and A. Rubbia, arXiv:hep-ph/0112297; and references therein.
46. M. L. Mangano *et al.*, arXiv:hep-ph/0105155.
47. J. Aysto *et al.*, arXiv:hep-ph/0109217.
48. A. Belyaev *et al.* [Kaon Physics Working Group Collaboration], arXiv:hep-ph/0107046.
49. J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B **238**, 453 (1984).
50. LEP2 SUSY Working Group, `http://lepsusy.web.cern.ch/lepsusy/www/members.html`; S. Rosier-Lees, talk at this meeting.
51. H. Meyer, talk at this meeting.
52. A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, Phys. Lett. B **518**, 94 (2001) [arXiv:hep-ph/0107151]; A. B. Lahanas, D. V. Nanopoulos and V. C. Spanos, arXiv:hep-ph/0112134; V. C. Spanos, talk at this meeting.
53. J. R. Ellis, K. A. Olive and Y. Santoso, arXiv:hep-ph/0202110; J. R. Ellis, talk at this meeting.
54. U. Chattopadhyay, A. Corsetti and P. Nath, arXiv:hep-ph/0201001; U. Chattopadhyay, A. Corsetti and P. Nath, arXiv:hep-ph/0202275; P. Nath, talk at this meeting.
55. R. Arnowitt, B. Dutta, T. Kamon and M. Tanaka, arXiv:hep-ph/0203069; and R. Arnowitt, talk at this meeting.
56. L. Roszkowski, R. Ruiz de Austri and T. Nihei, JHEP **0108**, 024 (2001) [arXiv:hep-ph/0106334]; L. Roszkowski, talk at this meeting.
57. J. R. Ellis, T. Falk, G. Ganis, K. A. Olive and M. Srednicki, Phys. Lett. B **510**, 236 (2001) [arXiv:hep-ph/0102098].
58. M. Battaglia *et al.*, Eur. Phys. J. C **22**, 535 (2001) [arXiv:hep-ph/0106204].
59. J. R. Ellis, T. Falk, K. A. Olive and M. Srednicki, Astropart. Phys. **13**, 181 (2000) [Erratum-ibid. **15**, 413 (2000)] [arXiv:hep-ph/9905481].
60. J. L. Feng, K. T. Matchev and F. Wilczek, Phys. Lett. B **482**, 388 (2000) [arXiv:hep-ph/0004043].
61. J. R. Ellis and K. A. Olive, Phys. Lett. B **514**, 114 (2001) [arXiv:hep-ph/0105004].
62. M. W. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985).
63. P. Belli *et al.*, [DAMA Collaboration] arXiv:hep-ph/0112018; P. Belli *et al.*, arXiv:hep-ph/0203242; P. Belli, talk at this meeting.
64. D. Abrams *et al.*, [CDMS Collaboration] arXiv:astro-ph/0203500.
65. J. R. Ellis, A. Ferstl and K. A. Olive, arXiv:hep-ph/0111064.
66. E. Aslanides *et al.* [ANTARES Collaboration], arXiv:astro-ph/9907432; L. Thompson, talk at this meeting.
67. E. Andres *et al.* [AMANDA Collaboration], Nature **410**, 441 (2001); J. Ahrens *et al.* [AMANDA Collaboration], arXiv:astro-ph/0202370; W. Rhode, talk at this meeting.
68. J. R. Ellis, J. L. Feng, A. Ferstl, K. T. Matchev and K. A. Olive, arXiv:astro-ph/0110225.
69. J. Alcaraz *et al.* [AMS Collaboration], Phys. Lett. B **484**, 10 (2000) [Erratum-ibid. B **495**, 440 (2000)]; W. Wallraff, talk at this meeting.
70. For a recent optimistic analysis, see: G. Bertone *et al.*, arXiv:astro-ph/0203488.
71. LEP Higgs Working Group for Higgs boson searches, arXiv:hep-ex/0107029.

72. LEP Higgs Working Group for Higgs boson searches, arXiv:hep-ex/0107030.
73. H. N. Brown *et al.* [Muon g-2 Collaboration], Phys. Rev. Lett. **86**, 2227 (2001) [arXiv:hep-ex/0102017].
74. L. L. Everett, G. L. Kane, S. Rigolin and L. Wang, Phys. Rev. Lett. **86**, 3484 (2001) [arXiv:hep-ph/0102145]; J. L. Feng and K. T. Matchev, Phys. Rev. Lett. **86**, 3480 (2001) [arXiv:hep-ph/0102146]; E. A. Baltz and P. Gondolo, Phys. Rev. Lett. **86**, 5004 (2001) [arXiv:hep-ph/0102147]; U. Chattopadhyay and P. Nath, Phys. Rev. Lett. **86**, 5854 (2001) [arXiv:hep-ph/0102157]; S. Komine, T. Moroi and M. Yamaguchi, Phys. Lett. B **506**, 93 (2001) [arXiv:hep-ph/0102204]; J. Ellis, D. V. Nanopoulos and K. A. Olive, Phys. Lett. B **508** (2001) 65 [arXiv:hep-ph/0102331]; R. Arnowitt, B. Dutta, B. Hu and Y. Santoso, Phys. Lett. B **505** (2001) 177 [arXiv:hep-ph/0102344] S. P. Martin and J. D. Wells, Phys. Rev. D **64**, 035003 (2001) [arXiv:hep-ph/0103067]; H. Baer, C. Balazs, J. Ferrandis and X. Tata, Phys. Rev. D **64**, 035004 (2001) [arXiv:hep-ph/0103280].
75. M. Knecht and A. Nyffeler, arXiv:hep-ph/0111058; M. Knecht, A. Nyffeler, M. Perrottet and E. De Rafael, Phys. Rev. Lett. **88**, 071802 (2002) [arXiv:hep-ph/0111059]; M. Hayakawa and T. Kinoshita, arXiv:hep-ph/0112102; J. Bijnens, E. Pallante and J. Prades, Nucl. Phys. B **626**, 410 (2002) [arXiv:hep-ph/0112255]; M. Ramsey-Musolf and M. B. Wise, arXiv:hep-ph/0201297.
76. J. D. Vergados, Part. Nucl. Lett. **106**, 74 (2001) [arXiv:hep-ph/0010151]; and talk at this meeting.
77. D. B. Cline, arXiv:astro-ph/0111098; and talk at this meeting.
78. A. Benoit *et al.* [EDELWEISS Collaboration], Phys. Lett. B **513**, 15 (2001) [arXiv:astro-ph/0106094]; and A. Juillard, talk at this meeting.
79. I. Liubarsky *et al.*, Nucl. Phys. Proc. Suppl. **87**, 64 (2000); N. J. T. Smith, talk at this meeting.
80. F. Giuliani, talk at this meeting.
81. J. Jochum *et al.* [CRESST Collaboration], Phys. Atom. Nucl. **63**, 1242 (2000) [Yad. Fiz. **63N7**, 1315 (2000)] [arXiv:hep-ex/0005003]; W. Seidl, talk at this meeting.
82. R. Luscher *et al.*, Nucl. Phys. Proc. Suppl. **95**, 233 (2001); and J. Dawson, talk at this meeting.
83. H. V. Klapdor-Kleingrothaus, B. Majorovits, L. Baudis, A. Dietz, G. Heusser, I. Krivosheina and H. Strecker, arXiv:hep-ph/0103082; and I. Krivosheina, talk at this meeting.
84. J. R. Ellis and R. A. Flores, Nucl. Phys. B **400**, 25 (1993).
85. L. Covi, H. B. Kim, J. E. Kim and L. Roszkowski, JHEP **0105**, 033 (2001) [arXiv:hep-ph/0101009]; and J. E. Kim, talk at this meeting.
86. R. Kallosh, L. Kofman, A. D. Linde and A. Van Proeyen, Phys. Rev. D **61**, 103503 (2000) [arXiv:hep-th/9907124].
87. H. P. Nilles, K. A. Olive and M. Peloso, Phys. Lett. B **522**, 304 (2001) [arXiv:hep-ph/0107212]; H. P. Nilles, talk at this meeting.
88. T. J. Weiler, Nucl. Phys. Proc. Suppl. **91**, 462 (2001); and talk at this meeting.
89. V. Berezinsky and M. Kachelriess, Phys. Rev. D **63**, 034007 (2001) [arXiv:hep-ph/0009053]; V. Berezinsky, A. Z. Gazizov and S. I. Grigorieva, arXiv:hep-ph/0107306; V. Berezinsky, talk at this meeting.
90. Z. Fodor, S. D. Katz and A. Ringwald, arXiv:hep-ph/0203198; Z. Fodor, arXiv:hep-ph/0112298; Z. Fodor, talk at this meeting.
91. D. Zavrtanik [AUGER Collaboration], Nucl. Phys. Proc. Suppl. **85** (2000) 324.
92. O. Catalano, Nuovo Cim. **24C**, 445 (2001).
93. J. E. Lidsey, T. Matos and L. A. Urena-Lopez, arXiv:astro-ph/0111292; T. Matos, talk at this meeting.

94. P. Fayet, talk at this meeting.
95. C. Boehm, A. Riazuelo, S. H. Hansen and R. Schaeffer, arXiv:astro-ph/0112522; C. Boehm, talk at this meeting.
96. S. A. Bludman and M. Roos, Phys. Rev. D **65**, 043503 (2002) [arXiv:astro-ph/0109551]; S. A. Bludman, talk at this meeting.
97. A. Albrecht, C. P. Burgess, F. Ravndal and C. Skordis, arXiv:astro-ph/0107573; C. P. Burgess, talk at this meeting.
98. N. Bilic, G. B. Tupper and R. D. Viollier, arXiv:astro-ph/0111325; G. B. Tupper, talk at this meeting.
99. M. M. Brisudova, W. H. Kinney and R. Woodard, arXiv:hep-ph/0110174; W. H. Kinney, talk at this meeting.
100. C. Cress, talk at this meeting.