Dark Matter and Dark Energy: Summary and Future Directions

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This paper reviews the progress reported at this Royal Society Discussion Meeting and advertizes some possible future directions in our drive to understand dark matter and dark energy. Additionally, a first attempt is made to place in context the exciting new results from the WMAP satellite, which were published shortly after this Meeting. In the first part of this review, pieces of observational evidence shown here that bear on the amounts of dark matter and dark energy are reviewed. Subsequently, particle candidates for dark matter are mentioned, and detection strategies are discussed. Finally, ideas are presented for calculating the amounts of dark matter and dark energy, and possibly relating them to laboratory data.

Keywords: cosmology, particle physics, dark matter, dark energy

1. The Density Budget of the Universe

It is convenient to express the mean densities ρ_i of various quantities in the Universe in terms of their fractions relative to the critical density: $\Omega_i \equiv \rho_i/\rho_{crit}$. The theory of cosmological inflation strongly suggests that the the total density should be very close to the critical one: $\Omega_{tot} \simeq 1$, and this is supported by the available data on the cosmic microwave background radiation (CMB) (Bond 2003). The fluctuations observed in the CMB at a level $\sim 10^{-5}$ in amplitude exhibit a peak at a partial wave $\ell \sim 200$, as would be produced by acoustic oscillations in a flat Universe with $\Omega_{tot} \simeq 1$. At lower partial waves, $\ell \ll 200$, the CMB fluctuations are believed to be dominated by the Sachs-Wolfe effect due to the gravitational potential, and more acoustic oscillations are expected at larger $\ell > 200$, whose relative heights depend on the baryon density Ω_b. At even larger $\ell \gtrsim 1000$, these oscillations should be progressively damped away.

Fig. 1 compares measurements of CMB fluctuations made before WMAP (Bond 2003) with the WMAP data themselves (Bennett *et al.* 2003; Hinshaw *et al.* 2003), that were released shortly after this Meeting. The position of the first acoustic peak indeed corresponds to a flat Universe with $\Omega_{tot} \simeq 1$: in particular, now WMAP finds $\Omega_{tot} = 1.02 \pm 0.02$ (Spergel *et al.* 2003), and two more acoustic peaks are established with high significance, providing a new determination of $\Omega_b h^2 = 0.0224 \pm 0.0009$, where $h \sim 0.7$ is the present Hubble expansion rate H, measured in units of 100km/s/Mpc. The likelihood functions for various cosmological parameters are shown in Fig. 2. Remarkably, there is excellent consistency between the estimate of the present-day Hubble constant $H \sim 72$km/s/Mpc from WMAP (Spergel *et*
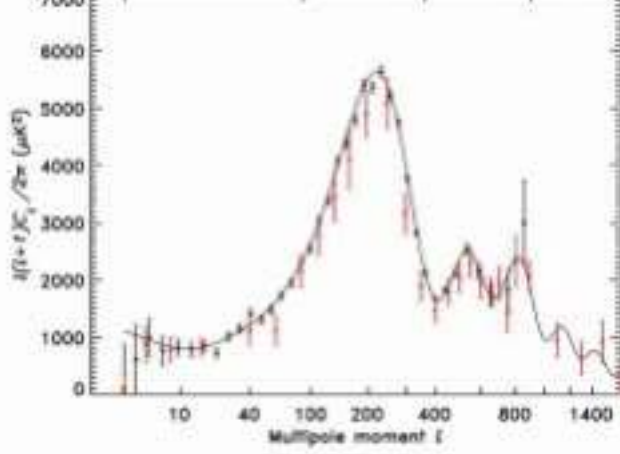
Figure 1. *Spectrum of fluctuations in the cosmic microwave background measured by WMAP (darker points with smaller error bars), compared with previous measurements (lighter points with larger error bars, extending to greater ℓ) (Hinshaw et al. 2003).*

al. 2003) with that inferred from the local distance ladder based, e.g., on Cepheid variables.
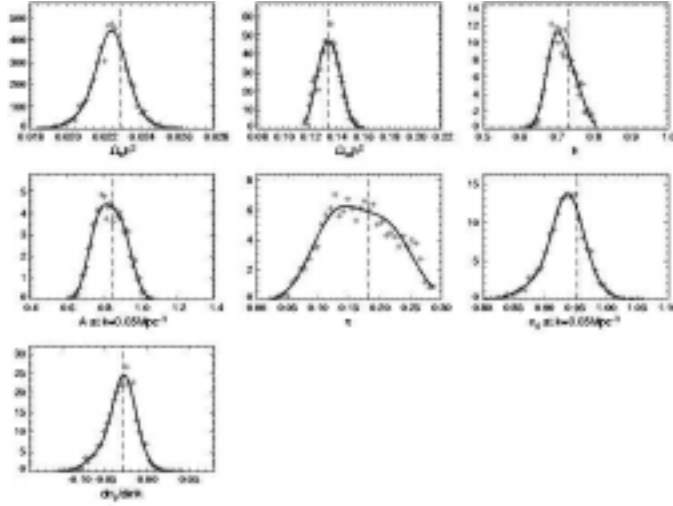

Figure 2. *The likelihood functions for various cosmological parameters obtained from the WMAP data analysis (Spergel et al. 2003). The panels show the baryon density $\Omega_b h^2$, the matter density $\Omega_m h^2$, the Hubble expansion rate h, the strength A, the optical depth τ, the spectral index n_s and its rate of change $dn_s/\ln k$, respectively.*

As seen in Fig 3, the combination of CMB data with those on high-redshift Type-Ia supernovae (Perlmutter 2003; Perlmutter & Schmidt 2003) and on large-scale structure (Peacock 2003*a*, *b*) favour strongly a flat Universe with about 30 % of (mainly dark) matter and 70 % of vacuum (dark) energy. Type-Ia supernovae probe the geometry of the Universe at redshifts $z \lesssim 1$. They disagree with a flat
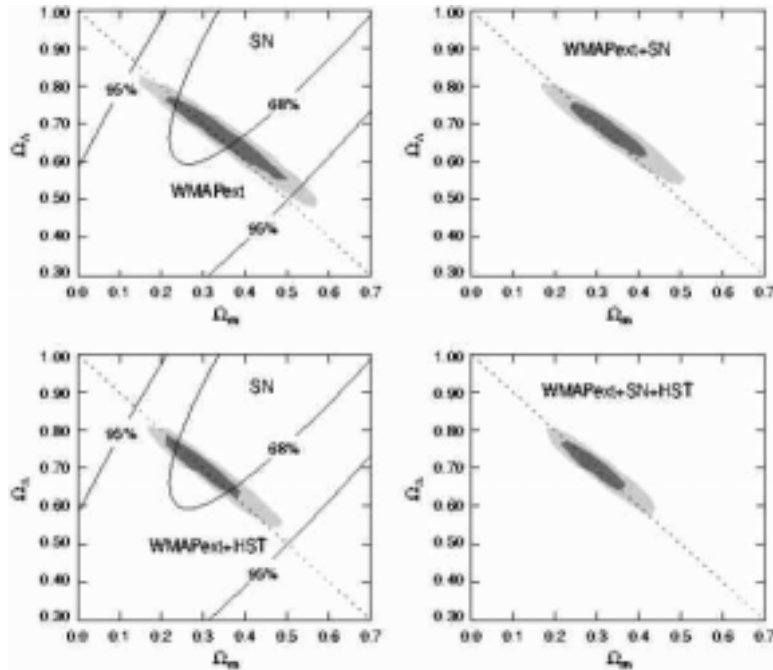
Figure 3. *The density of matter Ω_m and dark energy Ω_Λ inferred from WMAP and other CMB data (WMAPext), and from combining them with supernova and Hubble Space Telescope data (Spergel et al. 2003).*

$\Omega_{tot} = 1$ Universe that has no vacuum energy, and also with an open $\Omega_m \simeq 0.3$ Universe (Perlmutter 2003; Perlmutter & Schmidt 2003). They appear to be adequate standard candles, and two observed supernovae with $z > 1$ argue strongly against dust or evolution effects that would be sufficient to cloud their geometrical interpretation. The supernovae indicate that the expansion of the Universe is currently accelerating, though it had been decelerating when z was > 1. There are good prospects for improving substantially the accuracy of the supernova data, by a combination of continued ground-based and subsequent space observations using the SNAP satellite project (Perlmutter 2003; Perlmutter & Schmidt 2003).

It is impressive that the baryon density inferred from WMAP data (Spergel *et al.* 2003) is in good agreement with the value calculated previously on the basis of Big-Bang nucleosynthesis (BBN), which depends on completely different (nuclear) physics. Fig. 4 compares the abundances of light elements calculated using the WMAP value of $\Omega_b h^2$ with those inferred from astrophysical data (Cyburt *et al.* 2003). Depending on the astrophysical assumptions that are made in extracting the light-element abundances from astrophysical data, there is respectable overlap.

As we heard at this Meeting, several pillars of inflation theory have now been verified by WMAP and other CMB data (Bond 2003): the Sachs-Wolfe effect due to fluctuations in the large-scale gravitational potential were first seen by the COBE satellite, the first acoustic peak was seen in the CMB spectrum at $\ell \sim 210$ and this has been followed by two more peaks and the intervening dips, the damping tail of
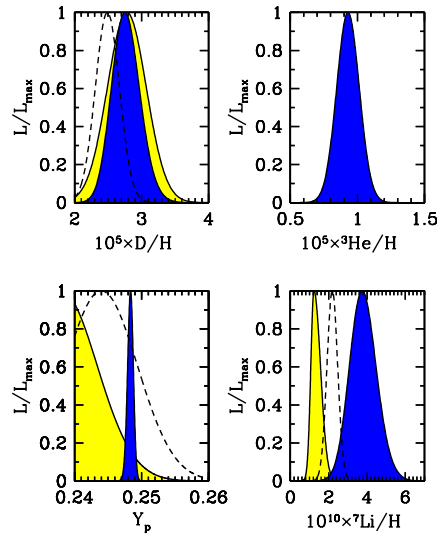
Figure 4. *The likelihood functions for the primordial abundances of light elements inferred from astrophysical observations (lighter, yellow shaded regions) compared with those calculated using the CMB value of $\Omega_b h^2$ (darker, blue shaded regions). The dashed curves are likelihood functions obtained under different astrophysical assumptions (Cyburt et al. 2003).*

the fluctuation spectrum expected at $\ell \gtrsim 1000$ has been seen, polarization has been observed, and the primary anisotropies are predominantly Gaussian. WMAP has, additionally, measured the thickness of the last scattering surface and observed the reionization of the Universe when $z \sim 20$ by the first generation of stars (Kogut *et al.* 2003). Remaining to be established are secondary anisotropies, due, e.g., to the Sunyaev-Zeldovich effect, weak lensing and inhomogeneous reionization, and tensor perturbations induced by gravity waves.

As we also heard at this meeting, the values of Ω_{CDM} inferred from X-ray studies of gas in rich clusters using the Chandra satellite (Rees 2003), which indicate $\Omega_{CDM} = 0.325 \pm 0.34$, gravitational lensing (Schneider 2003) and data on large-scale structure, e.g., from the 2dF galaxy redshift survey (Peacock 2003*a*, *b*), are very consistent with that inferred by combining CMB and supernova data. The WMAP data confirm this concordance with higher precision: $\Omega_{CDM} h^2 = 0.111 \pm 0.009$ (Spergel *et al.* 2003).

The 2dF galaxy survey has examined two wedges through the Universe. Significant structures are seen at low redshifts, which die away at larger redshifts where the Universe becomes more homogeneous and isotropic. The perturbation power spectrum at these large scales matches nicely with that seen in the CMB data, whilst the structures seen at small scales would *not* be present in a baryon-dominated Universe, or one with a significant fraction of hot dark matter. Indeed,

the 2dF data were used to infer an upper limit on the sum of the neutrino masses of 1.8 eV (Elgaroy *et al.* 2002), which has recently been improved using WMAP data (Spergel *et al.* 2003) to

$$\Sigma_{\nu_i} m_{\nu_i} < 0.7 \text{ eV}, \tag{1.1}$$

as seen in Fig. 5. This impressive upper limit is substantially better than even the most stringent direct laboratory upper limit on an individual neutrino mass, as discussed in the next Section. Thw WMAP data also provide (Crotty *et al.* 2003) a new limit on the effective number of light neutrino species, beyond the three within the Standard Model:

$$-1.5 \ < \ \Delta N_\nu^{eff} \ < \ 4.2. \tag{1.2}$$

This limit is not as stringent as that from LEP, but applies to additional light degrees of freedom that might not be produced in Z decay.
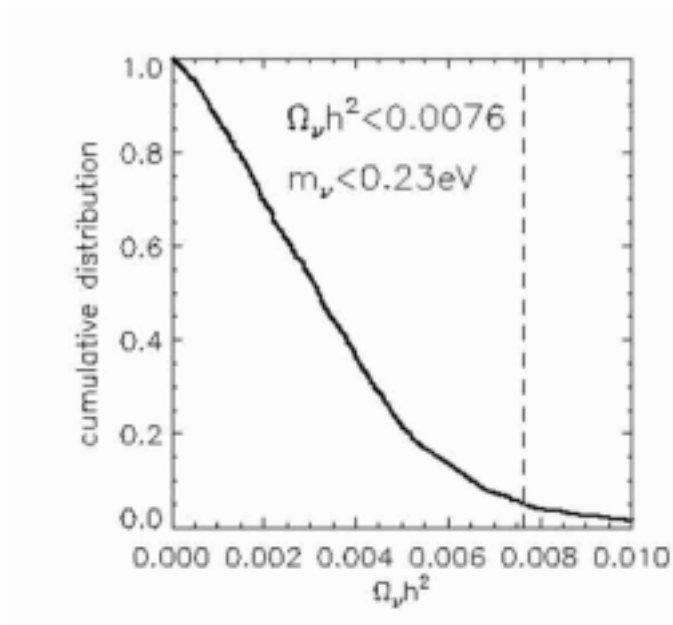

Figure 5. *The likelihood function for the total neutrino density $\Omega_\nu h^2$ derived by WMAP (Spergel et al. 2003). The upper limit $m_\nu < 0.23$ eV applies if there are three degenerate neutrinos.*

2. What is it?

As discussed here by Kolb (2003), particle candidates for dark matter range from the axion with a mass $\gtrsim 10^{-15}$ GeV (van Bibber 2003) to cryptons with masses $\lesssim 10^{+15}$ GeV (Ellis *et al.* 1990; Benakli *et al.* 1999), via neutrinos with masses $\lesssim 10^{-10}$ GeV, the gravitino and the lightest supersymmetric particle with a mass

$\gtrsim 10^2$ GeV (Ellis *et al.* 1984; Goldberg 1983). In recent years, there has been considerable experimental progress in understanding neutrino masses, so I start with them, even though cosmology now disfavours the hot dark matter they would provide (Spergel *et al.* 2003). All the others are candidates for cold dark matter, except for the gravitino, which might constitute warm dark matter, another possibility now disfavoured by the WMAP evidence for reionization when $z \sim 20$ (Kogut *et al.* 2003).

(*a*) *Neutrinos*

Particle theorists expect particles to have masses that vanish exactly only if they are protected by some unbroken gauge symmetry, much as the photon is massless because of the U(1) gauge symmetry of electromagnetism, that is associated with the conservation of electric charge. There is no corresponding exact gauge symmetry to protect lepton number, so we expect it to be violated and neutrinos to acquire masses. This is indeed the accepted interpretation of the observed oscillations between different types of neutrinos, which are made possible by mixing into non-degenerate mass eigenstates (Wark 2003); Pakvasa & Valle 2003).

Neutrino masses could arise even within the Standard Model of particle physics, without adding any new particles, at the expense of introducing a interaction between two neutrino fields and two Higgs fields (Barbieri *et al.* 1980):

$$1M\nu H \cdot \nu H \; \to \; m_\nu = \langle 0|H0\rangle^2 M. \tag{2.1}$$

However, such an interaction would be non-renormalizable, and therefore is not thought to be fundamental. The (presumably large) mass scale M appearing the denominator of (2.1) is generally thought to originate from the exchange of some massive fermionic particle that mixes with the light neutrino (Gell-Mann *et al.* 1979; Yanagida 1979; Mohapatra & Senjanovic 1980):

$$(\nu_L, N) \begin{pmatrix} 0 & M_D \\ M_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}, \tag{2.2}$$

Diagonalization of this matrix naturally yields small neutrino masses, since we expect that the Dirac mass term m_D is of the same order as quark and lepton masses, and $M \gg m_W$.

We have the following direct experimental upper limits on neutrino masses. From measurements of the end-point in Tritium β decay, we know that (Weinheimer *et al.* 1999; Lobashov *et al.* 1999):

$$m_{\nu_e} \; \lesssim \; 2.5 \text{ eV}, \tag{2.3}$$

and there are prospects to improve this limit down to about 0.5 eV with the proposed KATRIN experiment (Osipowicz *et al.* 2001). From measurements of $\pi \to \mu\nu$ decay, we know that (Hagiwara *et al.* 2002):

$$m_{\nu_\mu} \; < \; 190 \text{ KeV}, \tag{2.4}$$

and there are prospects to improve this limit by a factor ~ 20. From measurements of $\tau \to n\pi\nu$ decay, we know that (Hagiwara *et al.* 2002):

$$m_{\nu_\tau} \; < \; 18.2 \text{ MeV}, \tag{2.5}$$

and there are prospects to improve this limit to ~ 5 MeV.

However, the most stringent laboratory limit on neutrino masses may come from searches for neutrinoless double-β decay, which constrain the sum of the neutrinos' Majorana masses weighted by their couplings to electrons (Klapdor-Kleingrothaus *et al.* 2001):

$$\langle m_\nu \rangle_e \equiv |\Sigma_{\nu_i} m_{\nu_i} U_{ei}^2| \lesssim 0.35 \text{ eV} \tag{2.6}$$

and there are prospects to improve this limit to ~ 0.01 eV in a future round of experiments. The impact of the limit (2.6) in relation to the cosmological upper limit (1.1) is discussed below, after we have gathered further experimental input from neutrino-oscillation experiments.

The neutrino mass matrix (2.2) should be regarded also as a matrix in flavour space. When it is diagonalized, the neutrino mass eigenstates will not, in general, coincide with the flavour eigenstates that partner the mass eigenstates of the charged leptons. The mixing matrix between them (Maki *et al.* 1962) may be written in the form

$$V \;=\; \left(\begin{array}{ccc} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{array} \right) \left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{array} \right) \left(\begin{array}{ccc} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13}e^{-i\delta} \end{array} \right). \tag{2.7}$$

where the symbols c, s_{ij} denote the standard trigonometric functions of the three real 'Euler' mixing angles $\theta_{12,23,31}$, and δ is a CP-violating phase that can in principle also be observed in neutrino-oscillation experiments (De Rújula *et al.* 1999). Additionally, there are two CP-violating phases $\phi_{1,2}$ that appear in the double-β observable (2.6), but do not affect neutrino oscillations.

The pioneering Super-Kamiokande and other experiments have shown that atmospheric neutrinos oscillate, with the following difference in squared masses and mixing angle (Fukuda *et al.* 1998):

$$\delta m^2 \;\simeq\; 2.4 \times 10^{-3} \text{ eV}^2, \; \sin^2 2\theta_{23} \simeq 1.0, \tag{2.8}$$

which is very consistent with the K2K reactor neutrino experiment (Ahn *et al.* 2002), as seen in the left panel of Fig. 6. A flurry of recent solar neutrino experiments, most notably SNO (Ahmad *et al.* 2002*a*, *b*), have established beyond any doubt that they also oscillate, with

$$\delta m^2 \;\simeq\; 6 \times 10^{-5} \text{ eV}^2, \; \tan^2 \theta_{31} \simeq 0.5. \tag{2.9}$$

Most recently, the KamLAND experiment has reported a deficit of electron antineutrinos from nuclear power reactors, leading to a very similar set of preferred parameters, as seen in the right panel of Fig. 6 (Eguchi *et al.* 2003).

Using the range of θ_{12} allowed by the solar and KamLAND data, one can establish a correlation between the relic neutrino density $\Omega_\nu h^2$ and the neutrinoless double-β decay observable $\langle m_\nu \rangle_e$, as seen in Fig. 7 (Minakata & Sugiyama 2002). Pre-WMAP, the experimental limit on $\langle m_\nu \rangle_e$ could be used to set the bound (Minakata & Sugiyama 2002)

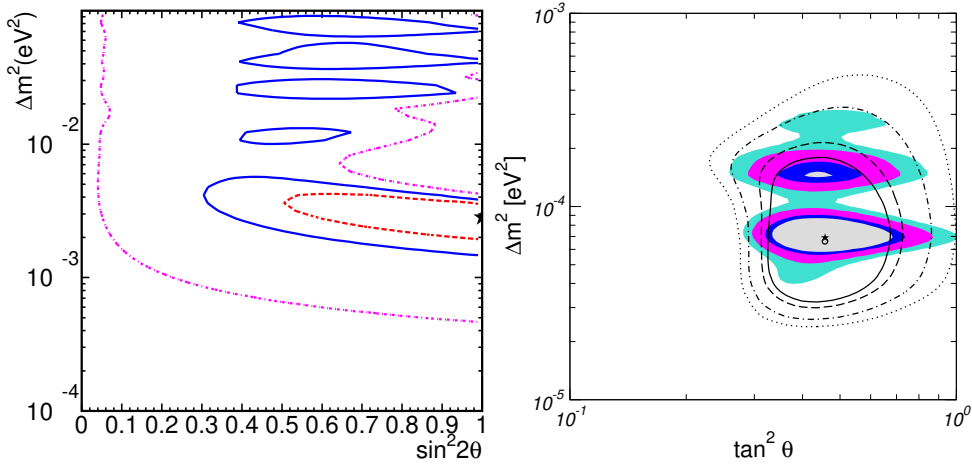$$10^{-3} \;\lesssim\; \Omega_\nu h^2 \;\lesssim\; 10^{-1}. \tag{2.10}$$

Figure 6. *Left panel: The region of neutrino oscillation parameters* $(\sin^2 2\theta, \Delta m^2)$ *inferred from the K2K reactor experiment (Ahn et al. 2002) includes the central values favoured by the Super-Kamiokande atmospheric-neutrino experiment, indicated by the star (Fukuda et al. 1998). Right panel: The region of neutrino oscillation parameters* $(\tan^2 \theta, \Delta m^2)$ *inferred from solar-neutrino experiments is very consistent with derived from the KamLAND reactor neutrino experiment (Eguchi et al. 2003). The shaded regions show the combined probability distribution (Pakvasa & Valle, 2003).*

Alternatively, now that WMAP has set a tighter upper bound $\Omega_\nu h^2 < 0.0076$ (1.1), one can use this correlation to set an upper bound:

$$< m_\nu >_e \lesssim 0.1 \text{ eV}, \qquad (2.11)$$

which is difficult to reconcile with the signal reported in (Klapdor-Kleingrothaus *et al.* 2002).

The 'Holy Grail' of neutrino physics is CP violation in neutrino oscillations, which would manifest itself as a difference between the oscillation probabilities for neutrinos and antineutrinos (De Rújula *et al.* 1999):

$$P\left(\nu_e \rightarrow \nu_\mu\right) - P\left(\bar{\nu}_e \rightarrow \bar{\nu}_\mu\right) \quad = 16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \qquad (2.12)$$
$$\sin\left(\Delta m_{12}^2 4EL\right) \sin\left(\Delta m_{13}^2 4EL\right) \sin\left(\Delta m_{23}^2 4EL\right),$$

For this to be observable, Δm_{12} and θ_{12} have to be large, as SNO and KamLAND have shown to be the case, and also θ_{13} has to be large enough - which remains to be seen.

In fact, even the minimal seesaw model contains many additional parameters that are not observable in neutrino oscillations (Casas & Ibarra 2001). In addition to the three masses of the charged leptons, there are three light-neutrino masses, three light-neutrino mixing angles and three CP-violating phases in the light-neutrino sector: the oscillation phase δ and the two Majorana phases that are relevant to neutrinoless double-β decay experiments. As well, there are three heavy singlet-neutrino masses, three more mixing angles and three more CP-violating phases that become observable in the heavy-neutrino sector, making a total of 18 parameters.
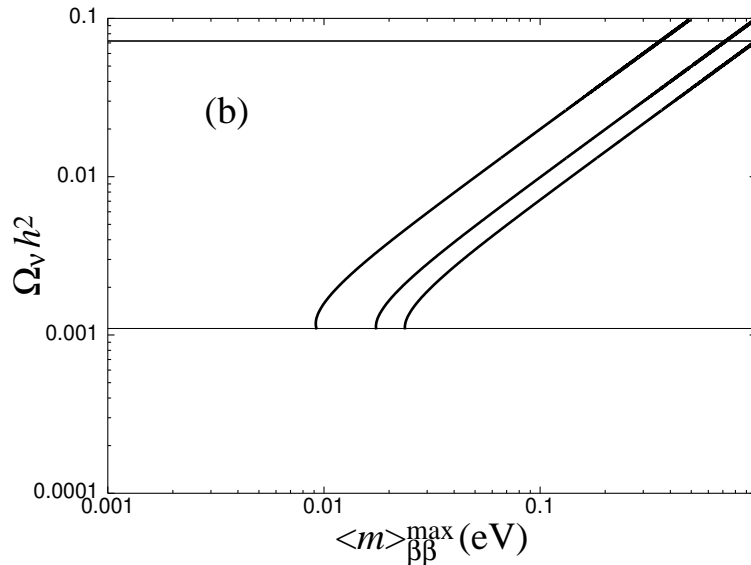
Figure 7. *Correlation between $\Omega_\nu h^2$ and $\langle m_\nu \rangle_e$. The different diagonal lines correspond to uncertainties in the measurements by KamLAND and other experiments (Minakata & Sugiyama 2002).*

Out of all these parameters, so far just four light-neutrino parameters are known, two differences in masses squared and two real mixing angles.

As discussed later, it is often thought that there may be a connection between CP violation in the neutrino sector and the baryon density in the Universe, via leptogenesis. Unfortunately, this connection is somewhat indirect, since the three CP-violating phases measurable in the light-neutrino sector to not contribute to leptogenesis, which is controlled by the other phases that are not observable directly at low energies (Ellis & Raidal 2002). However, if the seesaw model is combined with supersymmetry, these extra phases contribute to the renormalization of soft superymmetry-breaking parameters at low energies, and hence may have indirect observable effects (Ellis *et al.* 2002*a*, *b*).

(*b*) *Problems with Cold Dark Matter?*

A recurring question is whether the cold dark matter paradigm for structure formation is compatible with all the observational data (Navarro 2003; Abadi *et al.* 2002). One of the issues is the mass profile at the core of a galactic halo. As we heard at this meeting, density profiles clearly differ from naive power laws, and are much shallower than simple isothermal models. However, the haloes of $\gamma < 2.5$ seem to be in reasonable agreement with CDM sumulations, though there are still problems with $\gamma > 2.5$ galaxies. The theoretical predictions are not yet conclusive, though, with questions such as triaxiality, departures from equilibrium and time dependence remaining to be resolved. Another issue is halo substructure and the abundance of Milky Way satellites. However, the latest news is that there is apparently better
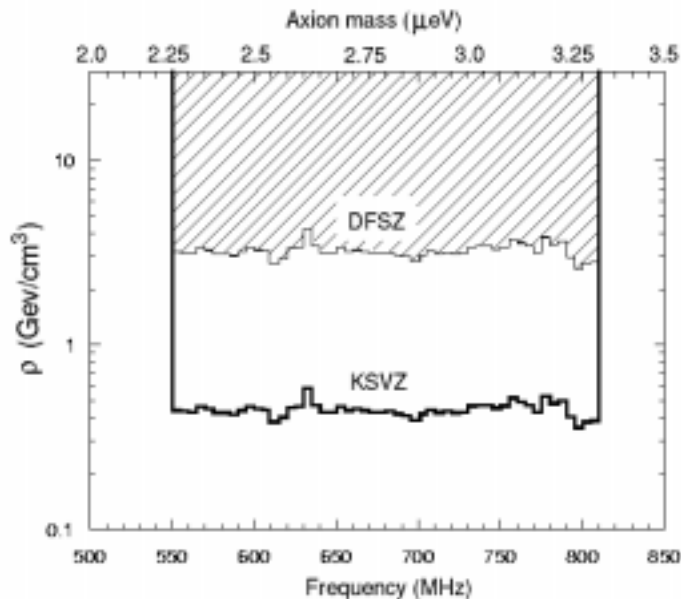
Figure 8. *Exclusion domains for the halo density of different types of axion, as functions of the frequency corresponding to the possible axion mass, as obtained from microwave cavity experiments (van Bibber 2003; Asztalos et al. 2001).*

agreement between the number of Milky Way satellites and the number of massive halo substructures predicted in CDM simulations. It has been argued that a Milky Way-like stellar disk would be thickened if there were substructures in the halo, but recent simulations do not display any significant such effect (Navarro 2003; Abadi *et al.* 2002).

Thus, the latest advice from the simulators seems to be that there is no show-stopper for the CDM paradigm, so let us examine some of the candidates for the CDM.

(c) Axions

As we heard here from van Bibber (van Bibber 2003), axions were invented in order to conserve CP in the strong interactions: in the picturesque analogy of Sikivie (Sikivie 1996), to explain why the strong-interaction pool table is apparently horizontal. Axion-like particles may be characterized by a two-dimensional parameter space, consisting of the axion mass m_a and its coupling to pairs of photons, $g_{a\gamma}$. Many areas of this parameter space are excluded by laser experiments, telescopes, searches for solar axions currently being extended by the CAST experiment at CERN (Irastorza *et al.* 2002), astrophysical constraints (Hagiwara *et al.* 2002) and searches for halo axions using microwave cavities (Asztalos *et al.* 2001), as seen in Fig. 8. These and searches using Rydberg atoms (Yamamoto *et al.* 2001) have the best chances of excluding ragions of parameter space where the axion might constitute cold dark matter.

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(*d*) *Supersymmetric Dark Matter*

The appearance of supersymmetry at the TeV scale was originally motivated by the hierarchy problem (Maiani 1979; 't Hooft 1979; Witten 1981) - why is $m_W \ll m_P \sim 10^{19}$ GeV, the only candidate we have for a fundamental mass scale in physics, or alternatively why is the Coulomb potential in an atom so much larger than the Newton potential? The former is $\propto e^2 = \mathcal{O}(1)$, whereas the latter is $\propto G_N m^2 \sim m^2/m_P^2$, where m is a typical particle mass scale. It is not sufficient simply to set particle masses such as $m_W \ll m_P$, since quantum corrections will increase them again. Many one-loop quantum corrections each yield

$$\delta m_W^2 \simeq \mathcal{O}(\alpha\pi)\,\Lambda^2, \tag{2.13}$$

where Λ is an effective cut-off, representing the scale at which the Standard Model ceases to be valid, and new physics appears. If $\Lambda \simeq m_P$ or the GUT scale $\sim 10^{16}$ GeV, the 'small' correction (2.13) will be much larger than the physical value of m_W^2. It would require 'unnatural' fine-tuning to choose the bare value of m_W^2 to be almost equal and opposite to the 'small' correction (2.13), so that their combination happens to have the right magnitude. Alternatively, supersymmetry introduces an effective cut-off Λ by postulating equal numbers of bosons and fermions with identical couplings, in which case the corrections (2.13) cancel among themselves, leaving

$$\delta m_W^2 \simeq \mathcal{O}(\alpha\pi)\,(m_B^2 - m_F^2), \tag{2.14}$$

which is $\lesssim m_W^2$ if

$$|m_B^2 - m_F^2| \lesssim \mathcal{O}(1)\ \text{TeV}^2, \tag{2.15}$$

i.e., if supersymmetry appears at relatively low energy.

This naturalness argument for low-energy supersymmetry is supported by several pieces of indirect empirical evidence. *One* is that the strengths of the different gauge interactions measured at low energies, particularly at the LEP accelerator, are consistent with unification at high energies *if* there are low-mass supersymmetric particles (Ellis *et al.* 1991*b*; Amaldi *et al.* 1991; Langacker & Luo 1991; Giunti *et al.* 1991). *A second* is that LEP and other precision low-energy data are fitted well by the Standard Model *if* there is a relatively light Higgs boson with mass < 200 GeV, very consistent with the range $m_h \lesssim 130$ GeV predicted by supersymmetry (Okada *et al.* 1991; Ellis *et al.* 1991*a*; Haber & Hempfling 1991). *A third* is that the minimal supersymmetric extension of the Standard Model (MSSM) contains a good candidate χ for cold dark matter, which has a suitable relic density if the supersymmetric mass scale $\lesssim 1$ TeV (Ellis *et al.* 1984; Goldberg 1983). *A fourth* may be provided by the anomalous magnetic moment of the muon, $g_\mu - 2$ (Brown *et al.* 2001; Bennett *et al.* 2002), *if* its experimental value deviates significantly from the Standard Model prediction.

When considering the experimental, cosmological and theoretical constraints on the MSSM, it is common to assume that all the unseen spin-0 supersymmetric particles have some universal mass m_0 at some GUT input scale, and similarly for the unseen fermion masses $m_{1/2}$. These two parameters of this constrained MSSM (CMSSM) are restricted by the absences of supersymmetric particles at

LEP: $m_{\chi^{\pm}} \gtrsim 103$ GeV, $m_{\tilde{e}} \gtrsim 99$ GeV, and at the Fermilab Tevatron collider. They are also restricted indirectly by the absence of a Higgs boson at LEP: $m_h > 114.4$ GeV, and by the fact that $b \to s\gamma$ decay is consistent with the Standard Model, and potentially by the BNL measurement of $g_\mu - 2$, as seen in Fig. 9 (Ellis *et al.* 2003a; Lahanas & Naopoulos 2003).
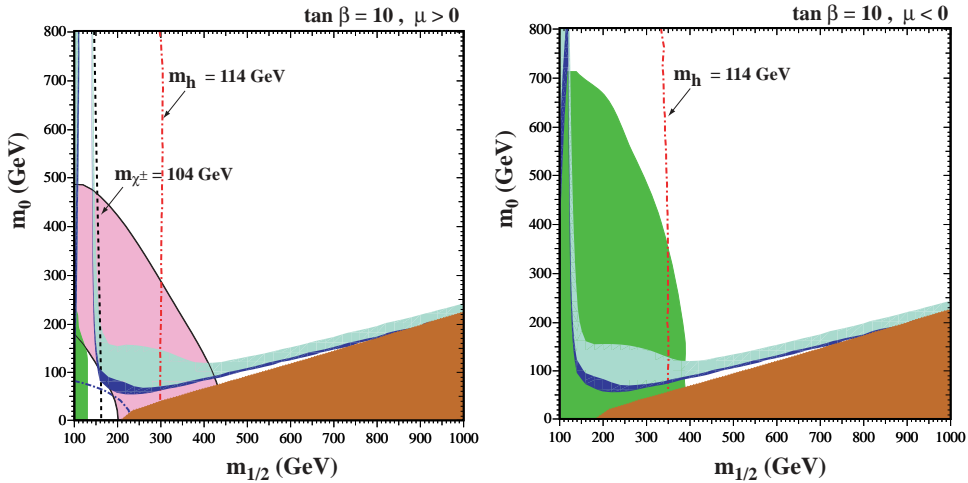

Figure 9. *The $(m_{1/2}, m_0)$ planes for (left panel) $\tan\beta = 10, \mu > 0$, and (right panel) $\tan\beta = 10, \mu < 0$. In each panel, the region allowed by the older cosmological constraint $0.1 \le \Omega_\chi h^2 \le 0.3$ has light shading, and the region allowed by the newer WMAP cosmological constraint $0.094 \le \Omega_\chi h^2 \le 0.129$ has very dark shading. The region with dark (red) shading is disallowed because there the lightest supersymmetric particle would be charged. The regions excluded by $b \to s\gamma$ have medium (green) shading, and those in panels (a,d) that are favoured by $g_\mu - 2$ at the 2-σ level have medium (pink) shading. LEP constraints on the Higgs and supersymmetric particle masses are also shown (Ellis et al. 2003a).*

As shown there, the CMSSM parameter space is also restricted by cosmological bounds on the amount of cold dark matter, $\Omega_{CDM} h^2$. Since $\rho_\chi = m_\chi n_\chi$, and the relic number density $n_\chi \propto 1/\sigma_{ann}(\chi\chi \to ...)$ where $\sigma_{ann}(\chi\chi \to ...) \propto 1/m^2$, the relic density generically increases with increasing sparticle masses. For some time, the conservative upper limit on $\Omega_{CDM} h^2$ has been < 0.3 (Lahanas *et al.* 2000, 2001a, 2001b; Barger & Kao 2001; Arnowitt & Dutta 2002), but the recent WMAP data allow this to be reduced to < 0.129 at the 2-σ level. As seen in Fig. 9, this improved upper limit significantly improves the cosmological upper limit on the sparticle mass scale (Ellis *et al.* 2003a, Lahanas & Nanopoulos 2003). If there are other important components of the cold dark matter, the CMSSM parameters could lie below the dark (blue) strips in Fig. 9.

In order to facilitate discussion of the physics reaches of different accelerators and strategies for detecting dark matter, it is convenient to focus on a limited number of benchmark scenarios that illustrate the various different supersymmetric possibilities (Battaglia *et al.* 2001). In many of these scenarios, supersymmetry would be very easy to observe at the LHC, and many different types of super-

symmetric particle might be discovered. However, searches for astrophysical dark matter may be competitive for some scenarios (Ellis *et al.* 2001).

One strategy is to look for relic annihilations out in the galactic halo, which might produce detectable antiprotons or positrons in the cosmic rays (Silk & Srednicki 1984). As discussed here by Carr (2003), both the PAMELA (Pearce *et al.* 2002) and AMS (Aguilar *et al.* 2002) space experiments will be looking for these signals, though the rates are not very promising in the benchmark scenarios we studied (Ellis *et al.* 2001). Alternatively, one might look for annihilations in the core of our galaxy, which might produce detectable gamma rays. As seen in the left panel of Fig. 10, this may be possible in certain benchmark scenarios (Ellis *et al.* 2001), although the rate is rather uncertain because of the unknown enhancement of relic particles in our galactic core. A third strategy is to look for annihilations inside the Sun or Earth (Silk *et al.* 1985), where the local density of relic particles is enhanced in a calculable way by scattering off matter, which causes them to lose energy and become gravitationally bound. The signature would then be energetic neutrinos that might produce detectable muons. As also discussed here by Carr (2003), several underwater and ice experiments are underway or planned to look for this signature, and this strategy looks promising for several benchmark scenarios, as seen in the right panel of Fig. 10 †.
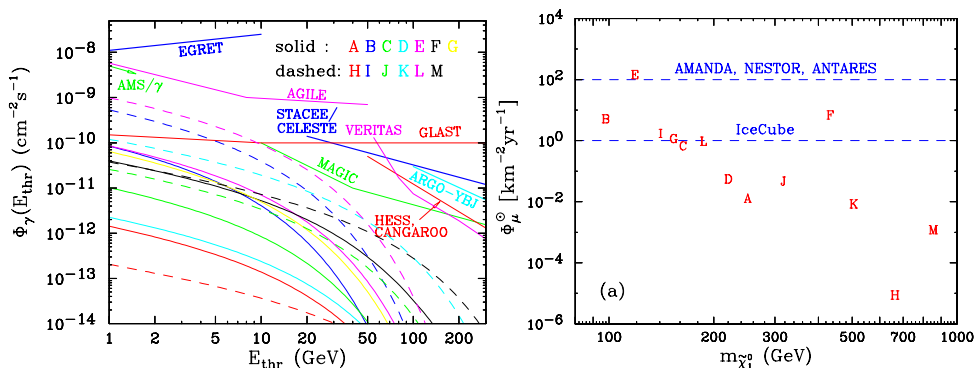

Figure 10. *Left panel: Spectra of photons from the annihilations of dark matter particles in the core of our galaxy, in different benchmark supersymmetric models (Ellis et al. 2001). Right panel: Signals for muons produced by energetic neutrinos originating from annihilations of dark matter particles in the core of the Sun, in the same benchmark supersymmetric models (Ellis et al. 2001).*

The most satisfactory way to look for supersymmetric relic particles is directly via their scattering on nuclei in a low-background laboratory experiment Goodman & Witten 1985). There are two types of scattering matrix elements, spin-independent - which are normally dominant for heavier nuclei, and spin-dependent - which could be interesting for lighter elements such as fluorine. The best experimental sensitivities so far are for spin-independent scattering, and one experiment has claimed a positive signal (Bernabei *et al.* 1998). However, this has not been

† It will be interesting to have such neutrino telescopes in different hemispheres, which will be able to scan different regions of the sky for astrophysical high-energy neutrino sources.

confirmed by a number of other experiments, as discussed here by Kraus (2003) and Smith (2003). In the benchmark scenarios the rates are considerably below the present experimental sensitivities, but there are prospects for improving the sensitivity into the interesting range, as also discussed by Kraus (2003) and Smith (2003), as seen in Fig. 11.
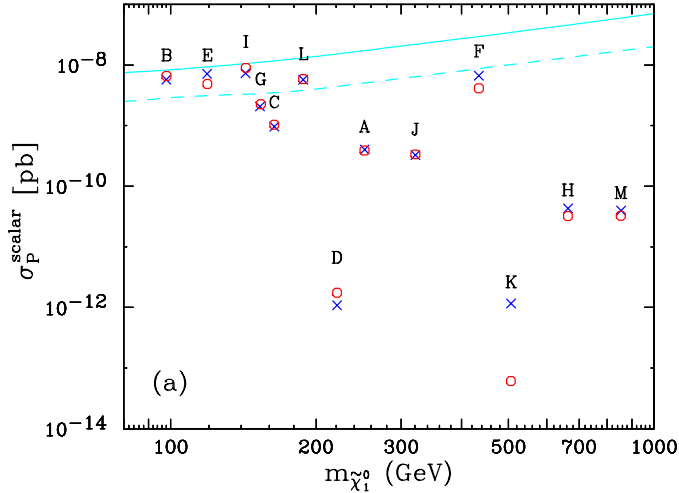

Figure 11. *Rates calculated for the spin-independent elastic scattering of dark matter particles off protons in the same benchmark supersymmetric models (Ellis et al. 2001) as in Fig. 10.*

Overall, the searches for astrophysical supersymmetric dark matter have discovery prospects (Ellis *et al.* 2001) that are comparable with those of the LHC (Battaglia *et al.* 2001).

(*e*) *Superheavy Dark Matter*

As discussed here by Kolb (2003), it has recently been realized that interesting amounts of superheavy particles with masses $\sim 10^{14\pm5}$ GeV might have been produced non-thermally in the very early Universe, either via pre- and reheating following inflation, or during bubble collisions, or by gravitational effects in the expanding Universe. If any of these superheavy particles were metastable they might be able, as seen in Fig. 12, to explain the ultra-high-energy cosmic rays that seem (Takeda *et al.* 2002; Abu-Zayyad *et al.* 2002) to appear beyond the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen 1966; Zatsepin & Kuzmin 1966). Such models have to face some challenges, notably from upper limits on the fractions of gamma rays at ultra-high energies, but might exhibit distinctive signatures such as a galactic anisotropy (Sarkar 2002). Examples of such superheavy particles are the cryptons found in some models derived from string theory, which naturally have masses $\sim 10^{12\pm2}$ GeV and are metastable (like protons), decaying via higher-order multiparticle interactions (Ellis *et al.* 1990; Benakli *et al.* 1999). The Pierre Auger experiment (Cronin *et al.* 2002) will be able to tell us whether ultra-high-energy

cosmic rays really exist beyond the GZK cutoff, and, if so, whether they are due to some such exotic top-down mechanism, or whether they have some bottom-up astrophysical origin. Following Auger, there are ideas for space experiments such as EUSO (Petrolini *et al.* 2002) that could have even better sensitivities to ultra-high-energy cosmic rays.
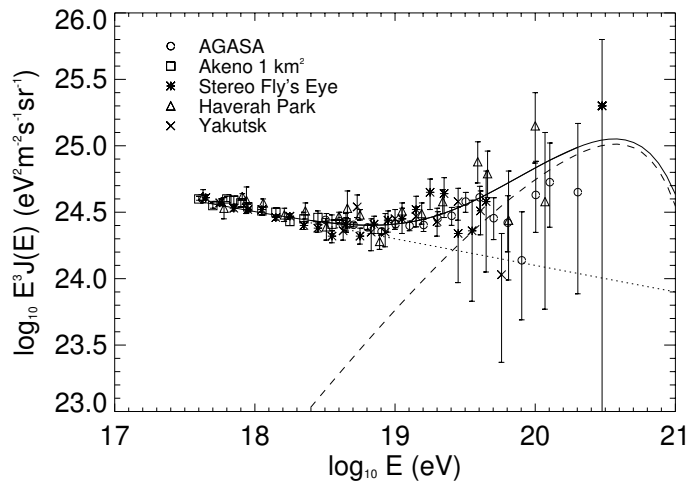

Figure 12. *Calculation of the spectrum of ultra-high-energy cosmic rays that might be produced by the decays (Sarkar 2002) of metastable superheavy particles.*

3. Calculate it!

Now that we have a good idea of the matter and energy content of the Universe, and some prospects for detecting it, the next task is to calculate it from first principles on the basis of microphysics and laboratory data.

• Ω_b: As Sakharov taught us (Sakharov 1967), baryogenesis requires the violation of charge conjugation C and its combination CP with parity, interactions that violate baryon number B, and a departure from thermal equilibrium. The first two have been observed for quarks, and are expected within the Standard Model. B violation is also expected in the Standard Model, at the non-perturbative level. One might therefore wonder whether the observed cosmological baryon asymmetry could have been generated by the Standard Model alone, but the answer seems to be no (Gavela *et al.* 1994). However, it might be possible in the MSSM, if it contains additional sources of CP violation beyond the Standard Model (Carena *et al.* 2003). An attractive alternative is leptogenesis (Fukugita & Yanagida 1986), according to which first the decays of heavy singlet neutrinos create a CP-violating asymmetry $\Delta L \neq 0$, and then this is partially converted into a baryon asymmetry by non-perturbative weak interactions.

At the one-loop level, the asymmetry in the decays of one heavy singlet neutrino

N_i due to exchanges of another one, N_j, is

$$\epsilon_{ij} = 18\pi 1(Y_\nu Y_\nu^\dagger)_{ii} \text{Im}\left((Y_\nu Y_\nu^\dagger)_{ij}\right)^2 f\left(M_j M_i\right), \qquad (3.1)$$

where Y_ν is a matrix of Yukawa couplings between heavy singlet and light doublet neutrinos. The expression (3.1) involves a sum over the light leptons, and hence is independent of the CP-violating MNS phase δ and the Majorana phases $\phi_{1,2}$. Instead, it is controlled by extra phase parameters that are not directly accessible to low-energy experiments.

   This leptogenesis scenario produces effortlessly a baryon-to-photon ratio Y_B of the right order of magnitude. However, as seen in Fig. 13, the CP-violating decay asymmetry (3.1) is explicitly independent of δ (Ellis & Raidal 2002). On the other hand, other observables such as the charged-lepton-flavour-violating decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ may cast some indirect light on the mechanism of leptogenesis (Ellis *et al.* 2002*a*, *b*). Predictions for these decays may be refined if one makes extra hypotheses.
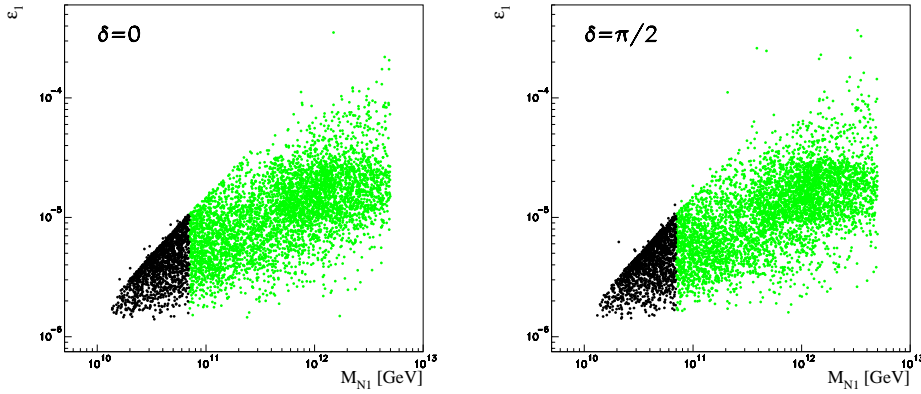

Figure 13. *Comparison of the CP-violating asymmetries in the decays of heavy singlet neutrinos giving rise to the cosmological baryon asymmetry via leptogenesis (left panel) without and (right panel) with maximal CP violation in neutrino oscillations (Ellis & Raidal 2002). They are indistinguishable.*

   One possibility is that the inflaton might be a heavy singlet sneutrino (Murayama *et al.* 1993, 1994). This would require a mass $\simeq 2 \times 10^{13}$ GeV, which is well within the range favoured by seesaw models. The sneutrino inflaton model predicts (Ellis *et al.* 2003*b*) values of the spectral index of scalar perturbations, the fraction of tensor perturbations and other CMB observables that are consistent with the WMAP data (Peiris *et al.* 2003) . Moreover, this model predicts a branching ratio for $\mu \to e\gamma$ within a couple of orders of magnitude of the present experimental upper limit.

   • Ω_{CDM}: The relic density of supersymmetric dark matter is calculable in terms of supersymmetric particle masses and Standard Model parameters. The sensitivity

to these parameters is quite small in generic regions, but may be larger in some exceptional regions corresponding to 'tails' of the MSSM parameter space (Ellis & Olive 2001). At least away from these regions, data from the LHC on supersymmetric parameters should enable the cold dark matter density to be calculated quite reliably.

• Ω_Λ: The biggest challenge may be the cosmological vacuum energy. For a long time, theorists tried to find reasons why the cosmological constant should vanish, but no convincing symmetry to guarantee this was ever found. Now cosmologists tell us that the vacuum energy actually does not vanish. Perhaps theorists' previous failure should be reinterpreted as a success? If the vacuum energy is indeed a constant, the hope is that it could be calculated from first principles in string or M theory. Alternatively, as argued here by Steinhardt 2003, perhaps the vacuum energy is presently relaxing towards zero, as in quintessence models (Maor *et al.* 2002). Such models are getting to be quite strongly constrained by the cosmological data, in particular those from high-redshift supernovae and WMAP (Spergel *et al.* 2003) as seen in Fig. 14, and it seems that the quintessence equation of state must be quite similar to that of a true cosmological constant (Spergel *et al.* 2003). Either way, the vacuum energy is a fascinating discovery that provides an exciting new opportunity for theoretical physics.
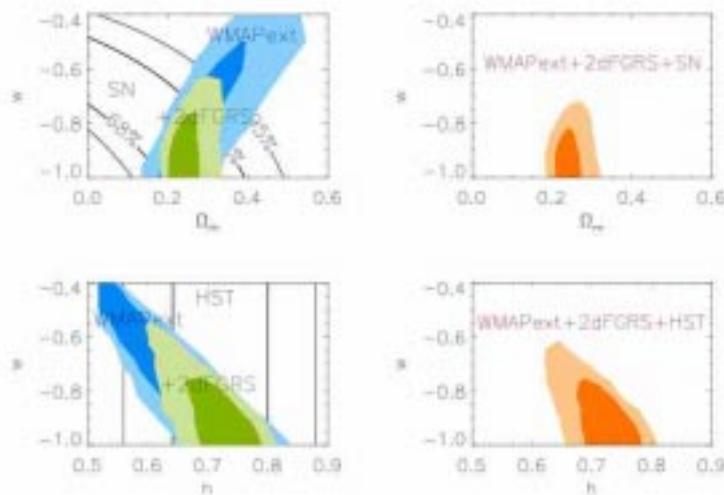

Figure 14. *Constraints on the equation of state of the dark energy from WMAP and other CMB data (WMAPext) combined with data on high-redshift supernovae, from the 2dF galaxy redshift survey and from the Hubble Space Telescope (Spergel et al. 2003).*

4. Test it!

Laboratory experiments have explored the energy range up to about 100 GeV, and quantum gravity must become important around the Planck energy $\sim 10^{19}$ GeV: where will new physics appear in this vast energy range? There are reasons to

think that *the origin of particle masses* will be found at some energy $\lesssim 10^3$ GeV. If they are indeed due to some elementary scalar Higgs field, this will provide a prototype for the inflaton. If the Higgs is accompanied by supersymmetry, this may provide the cold dark matter that fills the Universe. Some circumstantial evidence for supersymmetry may be provided by the anomalous magnetic moment of the muon and by measurements of the electroweak mixing angle θ_W, in the framework of *grand unified theories*. These would operate at energy scales $\sim 10^{16}$ GeV, far beyond the direct reach of accelerators. The first hints in favour of such theories have already been provided by experiments on astrophysical (solar and atmospheric) neutrinos, and cosmology may provide the best probes of grand unified theories, e.g., via inflation and/or super-heavy relic particles, which might be responsible for the ultra-high-energy cosmic rays. Cosmology may also be providing our first information about *quantum gravity*, in the form of the vacuum energy.

The LHC will extend the direct exploration of the energy frontier up to $\sim 10^3$ GeV. However, as these examples indicate, the unparallelled energies attained in the early Universe and in some astrophysical sources may provide the most direct tests of many ideas for physics beyond the Standard Model. The continuing dialogue between the two may tell us the origins of dark matter and dark energy.

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