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Summary of the Texas/Pascos '92 Symposium*

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ABSTRACT

I summarize some of the principal topics discussed at this joint symposium, emphasizing particularly results and theoretical speculations which have some bearing on the issue of the dark matter in the universe.

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INTRODUCTION

The task of summarizing as broad and far ranging a conference as the 1992 Texas/Pascos combined symposium (even in a duet with Martin Rees!) is essentially impossible. As a result, I was forced to make a sharp selection among the topics which I wanted to discuss. Fortunately, because many of the theoretical speakers on particle physics at the joint symposium took great pains to make their talks general enough, I felt that I could forego summarizing their excellent overviews of the field. Thus I could concentrate more on the experimental, observational and phenomenological aspects of the symposium, where particle physics is likely to have an impact on astrophysics and cosmology and vice versa.

The principal impression that I derived from the beautiful results, so much discussed at the symposium, on the fluctuations in the cosmic microwave background[1] and on the large scale structure of the universe[2] is that the prediction of inflation

$$\Omega = 1$$

begins to make observational sense. Because one knows from primordial nucleosynthesis[3] that the fraction of Ω in baryons, Ω_B, is less than 10%, it is clear that a compelling task for particle physicists is to find candidates for the remaining 90% of Ω. Furthermore, the power spectrum of the density fluctuations suggests keeping an open mind about what is the nature of this, so called, dark matter[4]. At the moment it seems sensible to discuss both cold and hot dark matter candidates particularly because, as shown in FIGURE 1, mixed hot and cold dark matter scenarios seem to give quite a nice fit to the power spectrum.

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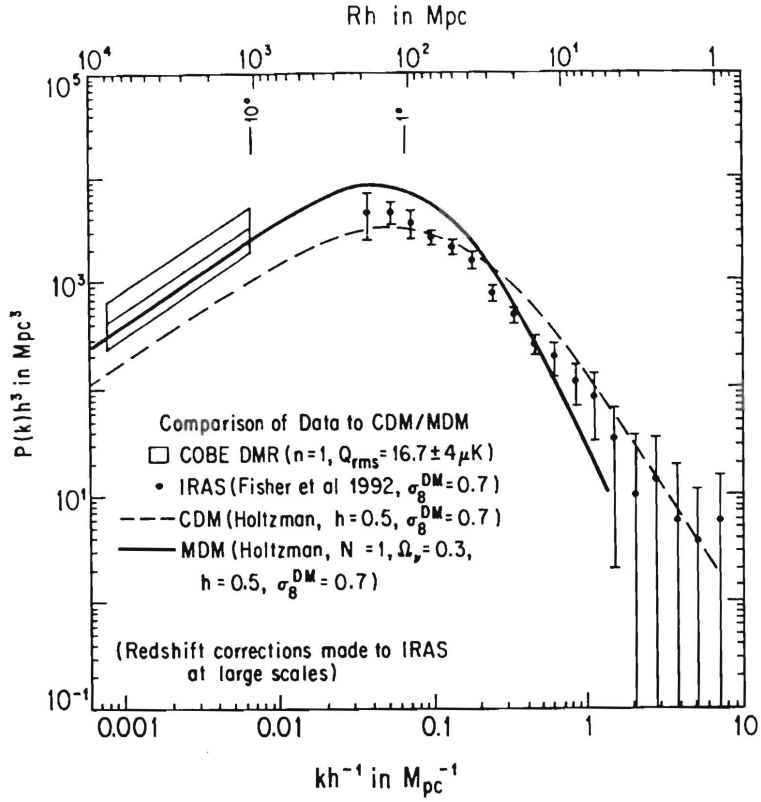

FIGURE 1. Power spectrum of density fluctuations, adapted from[2]. The mixed hot and cold dark matter fit is from[5].

In my summary, thus, I will focus principally on four topics discussed in Texas/Pascos '92 which impact on the dark matter issue. They are:

i.) The consistency of the standard model of particle physics.
ii.) The properties of neutrinos.
iii.) The nature of the $SU(2) \times U(1)$ breakdown.
iv.) The origin of CP violation

THE CONSISTENCY OF THE STANDARD MODEL

All experimental data at the present moment is in beautiful accord with the $SU(3) \times SU(2) \times U(1)$ model of the strong and electroweak interactions. As David Gross[6] said in his talk at the symposium, the standard model affords a solid pedestal for extrapolation. A nice pictorial representation of how well the $SU(2) \times U(1)$ theory agrees with experiment, for a top quark of mass around 150 GeV, is shown in FIGURE 2, which is taken from the talk of Paul Langacker[7]. This is indeed a "solid pedestal", for there is no question that the top quark exists, as there is very good evidence that the b quark is part of a weak isospin doublet[7]. Careful comparison of the precise data from LEP[8], along with data on deep inelastic neutrino scattering and on the W mass[9], with the predictions of the standard model, including radiative corrections, gives the 95% C.L. bound[7] for the top mass

$$m_t < 193\ GeV \quad .$$

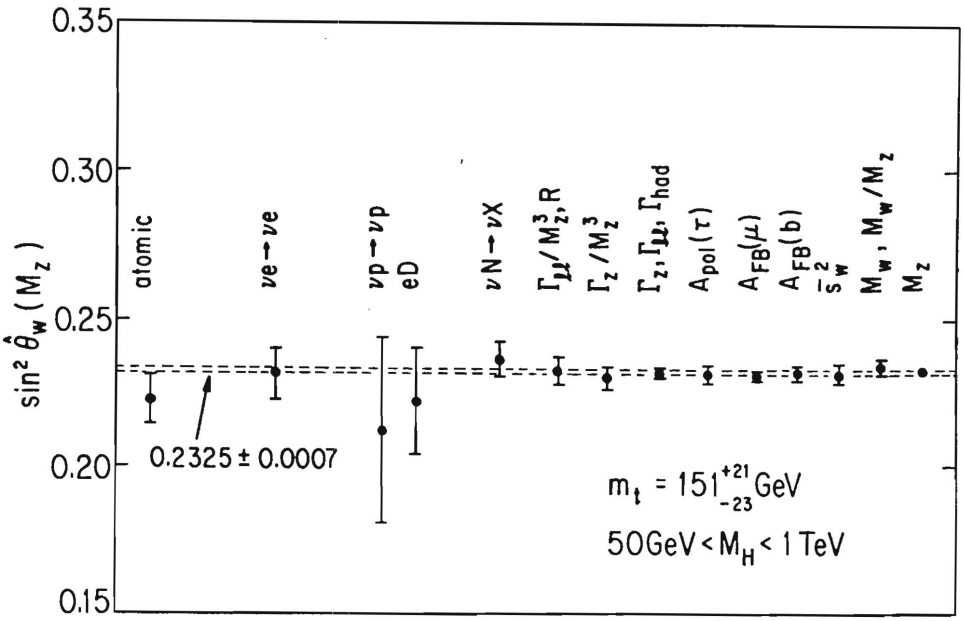

FIGURE 2. Values of the electroweak mixing parameters $\sin^2\hat{\theta}_w(M_z)$ obtained by different experiments, spanning a q^2-range of 10 orders of magnitude. Adapted from[7].

For a Higgs mass $M_H = 300\ GeV$, the best fit value is

$$m_t = 150\ {}^{+17}_{-23}\ {}^{+15}_{-17}\ GeV\ ,$$

where the second error arises from letting the Higgs mass range from 50 GeV to 1 TeV.

Even though the top quark mass is well constrained by these studies, for checking the standard model it is important that the top quark be discovered with a mass in the predicted range! As John Peoples[9] emphasized in his talk, the Tevatron collider at Fermilab is uniquely placed to discover top. Nevertheless, searching for top is hard because the cross section for producing $t\bar{t}$ pairs at the Tevatron, shown in FIGURE 3, is small. Furthermore, the detectable signal in the cleanest channel, consisting of an electron, a muon, plus jets and missing energy, coming from the leptonic decay of the W bosons produced in top decay ($t\bar{t} \to W^+W^-b\bar{b} \to e^+ + \mu^-$ + jets + missing energy) is only about 5% of this rate. Although a couple of tantalyzing events exist, it will be some time before a definite signal can be established. TABLE 1, adopted from Peoples[9], gives the expected luminosity that the Tevatron should deliver, per detector, for different time periods and the top quark mass reach in each case.

TABLE 1: Searching for Top at the Tevatron Collider

Period	Expected integrated luminosity	Top mass reach
92/93	20 pb^{-1}	$m_t \leq 120\ GeV$
93/94	60 pb^{-1}	$m_t \leq 160\ GeV$
Main Injector	500 pb^{-1}	$m_t \leq 220\ GeV$

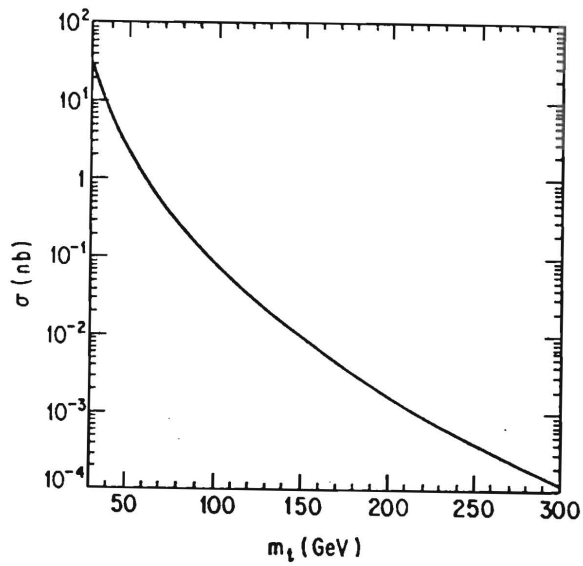

FIGURE 3. Expected cross section for top production at the Tevatron, as a function of top mass, from[10].

Although the discovery of top is not directly connected with the question of dark matter, one will only be totally sure about the full consistency of the standard model when top is found. Furthermore, the search for top at the Tevatron goes hand in hand with the search for new phenomena at the highest energies available today. As I shall comment below, such searches if successful might be of fundamental importance to the dark matter issue.

NEUTRINO PROPERTIES

LEP provides a strong bound on the number of neutrino families[8]

$$N_\nu = 3.04 \pm 0.04 \quad .$$

This number is in agreement with the bound obtained from the amount of primordial helium[3], but it has broader implications. In particular, the LEP

bound excludes much heavier neutrino masses ($m_\nu \leq M_Z/2$), essentially ruling out very heavy neutrinos as possible dark matter candidates.

In the standard model, right handed neutrinos (ν_R) play a special role since they are $SU(2) \times U(1)$ singlets. If these excitations are not introduced in the model, then in the absence of physics beyond the standard model, neutrinos are massless. On the other hand, if right handed neutrinos are present, then one can have an $SU(2) \times U(1)$ invariant Majorana mass for ν_R and, after symmetry breakdown, a Dirac mass m_D connecting ν_R with ν_L. If the ν_R Majorana mass M is large, then the physical mass for the neutrinos which participate in the weak interactions can be quite small, being of order

$$m_\nu \simeq \frac{m_D^2}{M} \quad .$$

This is the celebrated see-saw mechanism[11].

Irrespective of these theoretical speculations, however, there is no direct evidence for any non vanishing neutrino mass. Bowles[12] reported that the most accurate bound on the electron neutrino mass, coming from Tritium beta decay is now, at 95% C.L.,

$$m_{\nu_e} < 7.2 \; eV \quad .$$

If one assumes that the electron neutrino is a Majorana particle, then the above bound can be strengthened to less than about an eV, from the non observation of neutrinoless double beta decay . Still on the subject of neutrino masses, 1992 also saw the demise of the 17 KeV neutrino, thanks particularly to a beautiful controlled negative experiment by Mortara et al[13]. This is a pity, for the presence of such a massive neutrino would have provided fantastic challenges for astrophysics, particle physics and cosmology![14]

Indirect evidence for neutrino masses can be adduced, however, from positive signals of neutrino oscillations. Bowles[12] in his report to the symposium emphasized that there remains a persistent discrepancy in the ratio of the ν_μ to ν_e atmospheric flux seen by the large water Cerenkov detectors, which is significantly different from unity. This effect can be interpreted as being due to ν_μ to ν_τ oscillations. The data from the various experiments is summarized in TABLE 2 and the allowed region in a $\Delta m^2 - \sin^2 2\theta$ plot is shown in FIGURE 4, taken from[12]. One sees from FIGURE 4 that the mixing angle required is quite large: $V_{\nu_\mu \nu_\tau} = \sin\theta \simeq 0.4$. Such large mixing angles are not favored in the theoretical models presented by Lawrence Hall[15] - where typically $V_{\nu_\mu \nu_\tau}$ ranged from 0.03 to 0.08. They are also an order of magnitude larger than the analogous quark mixing angle $V_{cb} \simeq 0.04$[16]. Lastly, the region of masses allowed in FIGURE 4, barring incredible cancellations, leads to a value for m_{ν_τ} (or m_{ν_μ}) which is not cosmologically interesting for the dark problem, since $m_{\nu_\tau} < eV$.

TABLE 2: Ratio of ν_μ/ν_e atmospheric flux seen in different experiments

Experiment	ν_μ/ν_e flux
Kamiokande	$0.60\ ^{+0.07}_{-0.06} \pm 0.05$
IMB-3	$0.54 \pm 0.05 \pm 0.12$
Frejus	$0.87 \pm 0.16 \pm 0.08$
Nusex	$0.99\ ^{+0.35}_{-0.25}$
IMB-3 Throughgoing	$1.01 \pm 0.03 \pm 0.11$

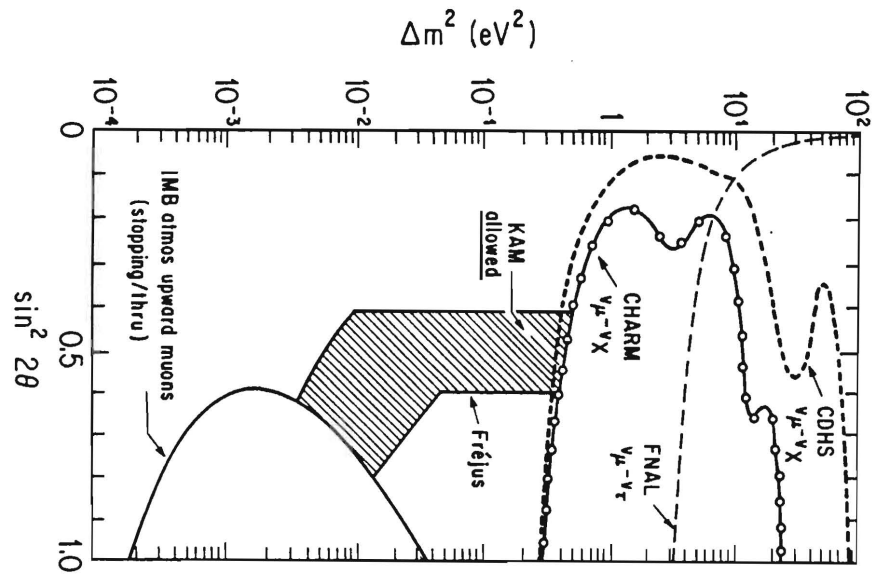

FIGURE 4. Allowed an excluded regions for ν_μ oscillations, from[12].

Potentially much more interesting for the issue of neutrino masses, and the idea that some neutrino species is part of the dark matter, are the solar neutrino results. These results were discussed here by Totsuka[17], Spiro[18] and Bahcall[19]. These speakers emphasized, and I agree with them, that if one takes **all data at face value** there is a strong hint of new neutrino physics. The data, along with the prediction for the standard solar model, according to the calculation of Bahcall and Pinsennault[20] and of Turk-Chiese et al[21], is summarized in TABLE 3. To appreciate this table, it is important to understand the region of sensitivity of each experiment, both in terms

TABLE 3: Solar neutrino data and theoretical expectations

Experiemnt	Result	Theoretical Predictions
Homestake ^{37}Cl	2.28 ± 0.23 SSM	7.9±0.9 [Ref.20] 6.4±1.4 [Ref.21]
Kamiokande $E_\nu > 7.5\ MeV$	$[0.49 \pm 0.05 \pm 0.06]$ SSM	*SSM* prediction used is that of [Ref.20]
SAGE ^{71}Ga	$(58^{+17}_{-24} \pm 14)$ SNU	132^{+20}_{-17} [Ref.20]
Gallex ^{71}Ga	$(83 \pm 17 \pm 8)$ SNU	125 ± 5 [Ref.21]

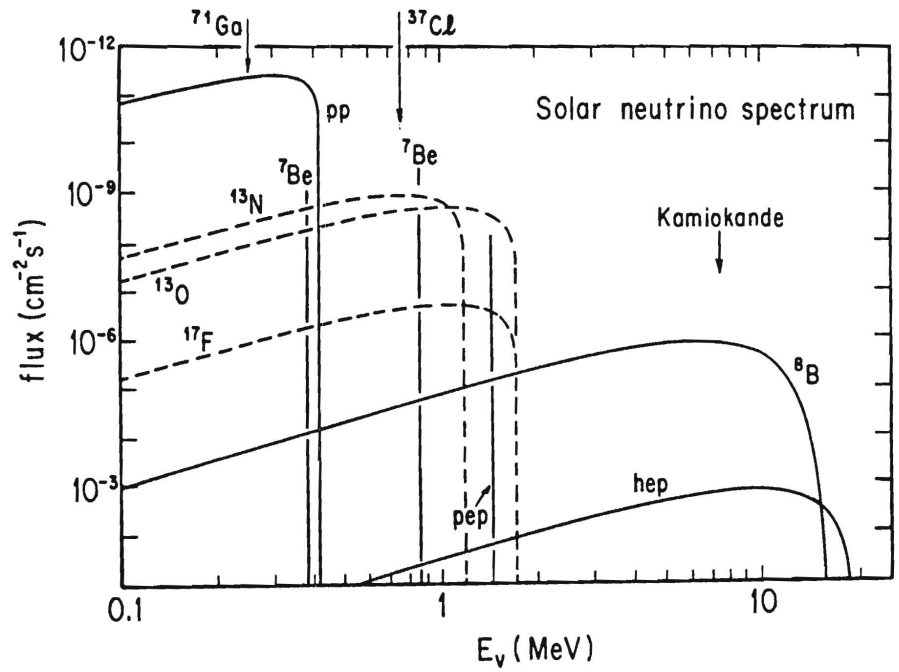

FIGURE 5. Neutrino flux arising from the various solar reactions, adopted from[22]. Also shown in the figure are the threshold of the different solar neutrino experiments.

of the threshold of the reaction involved and of the solar reaction which is accessible. This is sketched as a function of the neutrino flux in FIGURE 5, adapted from[22].

To obtain agreement with all the data summarized in TABLE 3, one requires that there should be some new neutrino physics[19]. This new physics should be able to:

i.) reduce the ^8B flux by about 50%

ii.) essentially kill altogether the flux of neutrinos from the 860 KeV ^7Be line

iii.) preserve the pp neutrino flux.

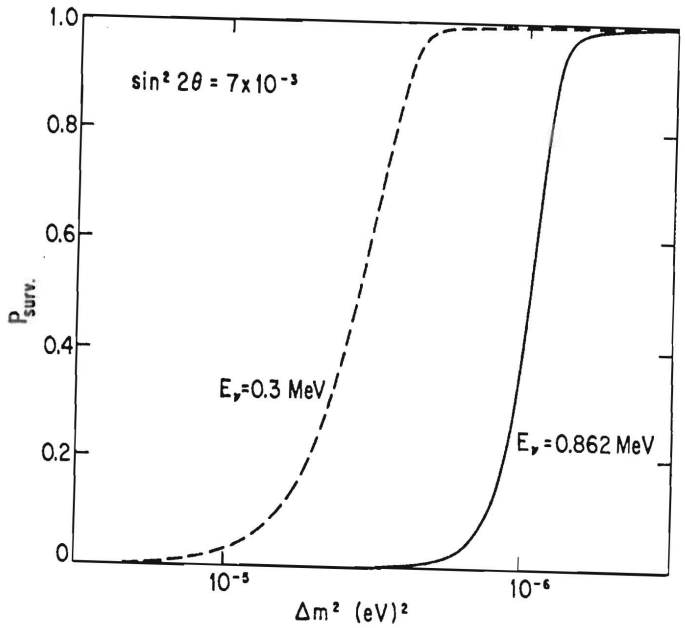

FIGURE 6. Survival probability of neutrinos of different energies as a function of Δm^2, for fixed $\sin\theta$, from[24].

very little information on what actually causes the breakdown of $SU(2)\times U(1)$ to $U(1)_{em}$. The simplest possibility is that this breakdown is caused by a complex scalar doublet of elementary scalar fields Φ which acquire a non trivial vacuum expectation value, $< \Phi > \simeq 175\ GeV$. This symmetry breaking mechanism has a tell tale debris, the presence in the spectrum of the theory of a single neutral particle: the Higgs boson H. Although the Higgs mass is proportional to the vacuum expectation value $< \Phi >$, the constant of proportionality (which is related to the self coupling λ of the doublet field Φ) is unknown:

$$M_H = 2\lambda^{1/2} < \Phi > \quad .$$

Nevertheless, data from LEP already provides a rather important bound on M_H (and λ)[8]

$$M_H > 60\ GeV \qquad (\lambda > 0.03)$$

Although a single doublet scalar field Φ, with appropriate self interactions, can cause the desired breakdown, there is considerable theoretical unhappiness about this scenario. This issue, and some of its remedies, was discussed in some detail in this symposium by John Ellis[26], Frank Wilczek[27] and Fabio Zwirner[28]. Basically, in any theory which has some high energy cutoff, it is not natural to have a very light scalar field. In such theories, one would expect to have $M_H \sim \Lambda_{cutoff}$, rather than have $M_H \sim < \Phi >$. Because one expects the Planck mass, M_P, to provide a natural cutoff to any particle

of hints (are they red-herrings?) in present day data that supersymmetry may be the way of nature. This inferential evidence is the following:

i) Precision electroweak tests favor (slightly) a light Higgs boson. This is quite consistent with supersymmetric theories where one expects $\lambda \sim 0\,(e^2)$. Furthermore, as discussed by Zwirner[28], a model independent fit of all electroweak data, in terms of two parameters (ϵ_1 and ϵ_3) related to the gauge boson vacuum polarization tensors, clearly disfavors certain classes of dynamical symmetry breaking models. This is illustrated in FIGURE 8.

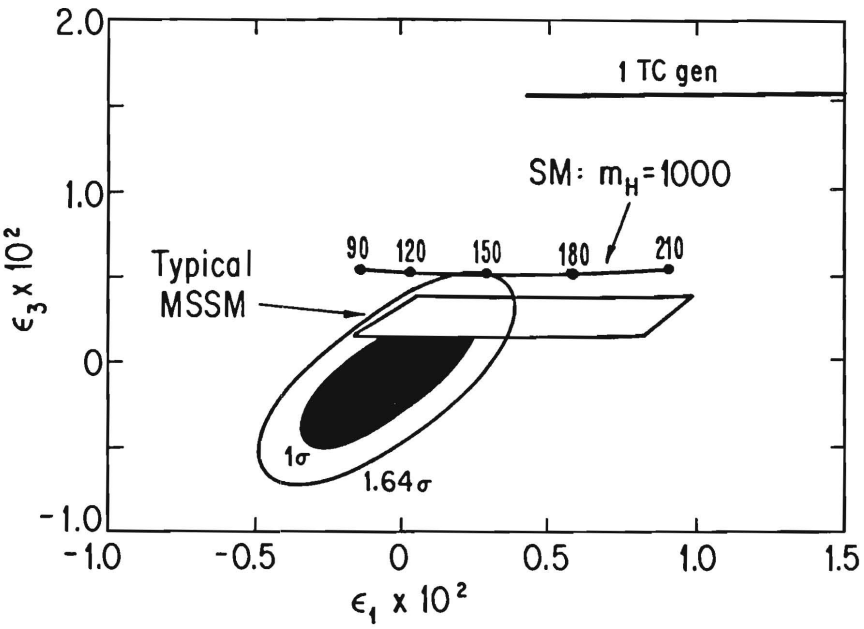

FIGURE 8. Allowed regions in the $\epsilon_1 - \epsilon_3$ plane from a fit of all electroweak data by[30]. Also shown in the figure are the expectations of the minimal supersymmetric standard model and an estimate[31] of what is expected in a simple one technigeneration dynamical symmetry breaking model. From,[28].

ii) If one extrapolates by means of the renormalization group the $SU(3)$, $SU(2)$ and $U(1)$ coupling constants measured at a scale $q^2 \simeq M_Z^2$ to high energy, one finds that these coupling constants tend toward each other. If only ordinary matter is included, these couplings do not quite unify. However, remarkably, if one includes supersymmetric partners to all the known excitations, assuming their masses lie below $1 - 10\ TeV$, one finds that all these coupling constants meet at $M_X \simeq 10^{16}\ GeV$! These two coupling constant evolutions are shown in FIGURE 9.

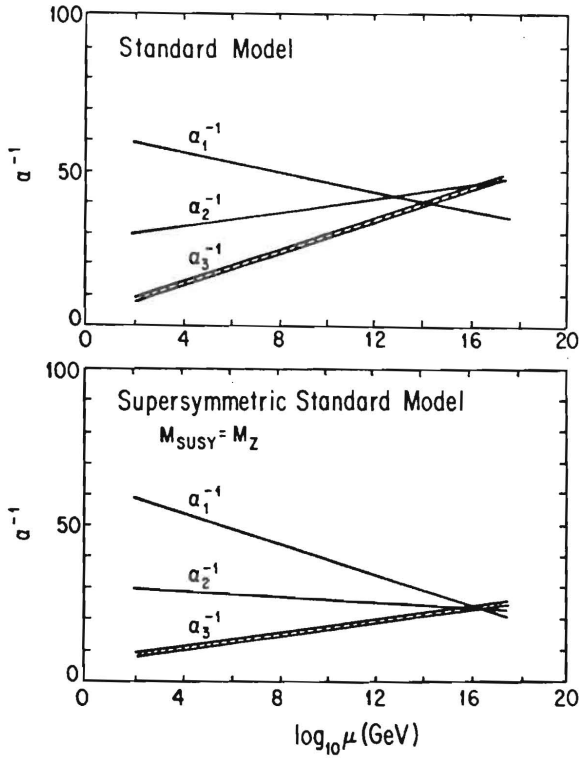

FIGURE 9. Evolution of the $SU(3), SU(2)$ and $U(1)$ coupling constants according to the renormalization group, excluding and including "low mass" supersymmetric matter. From[7].

In view of the above interesting observations, even in the absence of the discovery of any super partners, one must take the possibility of supersymmetry very seriously. As is well known, supersymmetry pairs particles of half-integer spin with particles of integer spin. Thus, the spin 1 gauge bosons have as partners spin 1/2 gauginos; the spin 1/2 quarks and leptons have spin 0 squarks and sleptons as partners; and the spin 0 Higgs boson has as partner a spin 1/2 Higgsino. Actually, to implement supersymmetry in the standard model it is necessary to introduce two complex doublets, Φ_1, and Φ_2, rather than just one[32]. As a result, the physical spectrum of the minimal supersymmetric extension of the standard model (MSSM) contains five spin 0 Higgs bosons, two charged and three neutral, along with their spin 1/2 super partners.

Because no super partners have yet been detected, it is clear that supersymmetry is broken in nature. However, the precise mechanism which induces a splitting between particle masses (m) and sparticle masses ($\tilde{m}$) is not well understood. Because of this, the sparticle spectrum is quite model dependent. Unfortunately, as Zwirner has emphasized in this meeting[28], this model dependence makes the mass limits on sparticles one derives from experiment also subject to various uncertainties. For instance, if cascade decays are excluded, one can use the high energy data from the Tevatron to set

rather strong bounds on squark and gluino masses ($m_{\tilde{g}} \geq 141\ GeV$; $m_{\tilde{q}} \geq 126\ GeV$). However, these bounds can be substantially eroded - and even avoided - if different supersymmetric cascade chains are included[33].

Most supersymmetric extensions of the standard model preserve a discrete symmetry, called R parity, which can be taken as $R = -1$ for sparticles and $R = +1$ for particles. This symmetry guarantees that the lightest supersymmetric particle (the LSP) is stable. If the LSP is neutral, it is an ideal candidate for cold dark matter. In the MSSM one has four spin 1/2 such neutralinos, the partners of the photon ($\tilde{\gamma}$) and the $Z^0(\tilde{Z})$ and the two Higgsinos ($\tilde{\Phi}_1, \tilde{\Phi}_2$). The LSP is generally assumed to be a linear combination of these states.

$$\tilde{\delta} = a_\gamma \tilde{\gamma} + a_Z \tilde{Z} + a_1 \tilde{\Phi}_1 + a_2 \tilde{\Phi}_2$$

with the a_i being model dependent coefficients. As Greist discussed in the symposium[34], neutralino annihilation into ordinary quarks and leptons (see FIGURE 10) is a weak process, both because of the weak neutralino-fermion sfermion coupling and because the sfermion exchanged is supposed to be quite heavy. It is this feature that allows neutralinos, to be creditable candidates for cold dark matter (CDM).

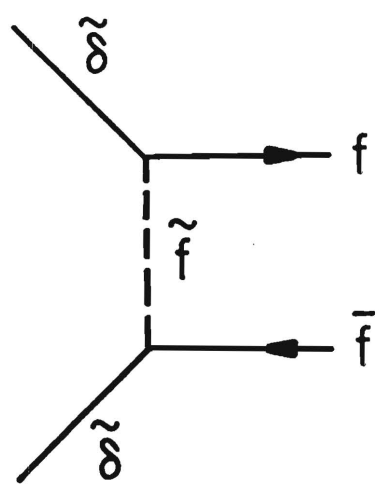

FIGURE 10. Neutralino annihilation into fermion-antifermion pairs, through sfermion exchange.

Even though one does not know the mass of the LSP, the detection of neutralinos can be well estimated. This is because the neutralino interaction of FIGURE 10, which make it a potential dark matter candidate, are also

the same interactions which are crucial for their experimental detection. As FIGURE 11, taken from Greist's talk[34], shows dark matter experiments now being mounted will begin to probe an interesting range in the parameter space of supersymmetric theories. Indeed, if one is optimistic, one may even imagine, that these dark matter searches may be the way in which supersymmetry (very indirectly) will be discovered!

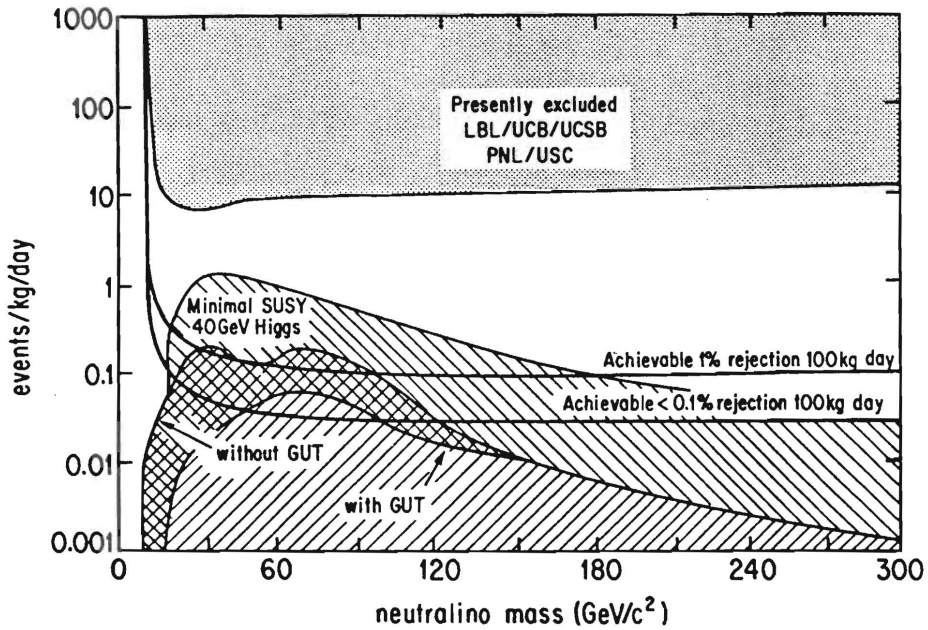

FIGURE 11. Event rate expected for neutralino dark matter, under certain model assumptions, along with present limits and future expectations of cold dark matter searches, from[34].

The precise nature of the electroweak phase transition, besides being of theoretical interest, has, however, a much more direct import related to the issue of baryogenesis. This was discussed in the symposium by Andy Cohen[35]. What is firmly established is that in the standard electroweak theory the rate for $(B + L)$ - violation is much faster than the universe's expansion rate, H, for a large range of temperatures at or above those of the electroweak phase transition. As a result of this, so called, KRS mechanism[36] any preexisting $(B+L)$-asymmetry in the universe is erased. This leaves two options to explain the baryon asymmetry which is observed in the universe now. Either this asymmetry originates from some primordial $(B - L)$ asymmetry, or the present day baryon asymmetry is generated at the electroweak phase transition. The first option has no direct connection with the nature of the electroweak phase transition, but it may have some bearing on neutrino physics[37]. However, the exciting possibility of baryogenesis at the electroweak scale is crucially dependent on the nature of the electroweak phase transition.

As Cohen[35] explained in his talk, to generate the baryon asymmetry at the electroweak phase transition one needs two principal conditions to occur:

i) The electroweak phase transition must be sufficiently strongly first order, so that the vacuum expectation value of the Higgs field is greater than, or of order of T^* :

$$< \Phi\ (T^*)\ > \geq\ T^*$$

Only if this inequality holds, will the sphaleron mass $M_{sp} \sim < \Phi(T^*) >$, which governs the (B + L) violating rate, be sufficiently big so that

$$\Gamma_{B+L\ \text{viol.}}\ (T^*)\ \sim\ e^{-\frac{M_{sp}(T^*)}{T^*}}\ << H$$

ii) There must be efficient kinetics (and sufficient CP violation) in the bubble nucleation at the first order phase transition to produce a large enough baryon asymmetry.

At present, it is far from obvious whether one can achieve both of these conditions in reasonable models. What is clear, however, is that the standard model with only one Higgs doublet does not appear to possess a strong enough first order phase transition. Indeed, for $M_H\ >\ 60\ GeV$ - as LEP informs us[8] - calculations show[35] that $<\ \phi(T^*)\ >$ is near to $1/2\ T^*$, rather than T^*. Thus any baryon asymmetry generated at the electroweak scale gets again rapidly erased after the phase transition. It follows, therefore, that also from the point of view of electroweak baryogenesis, extension of the standard model involving more doublets - as in supersymmetric theories - are rather desirable.

ORIGIN OF CP VIOLATION

The observation of CP violation in the Kaon system, as well as the existence of a matter-antimatter asymmetry in the universe (which is more inferentially connected with CP violation), can be accounted theoretically in one of two ways:

i) Either the Lagrangian of the theory is invariant under CP transformations, but the vacuum state is not so invariant.
ii) Or, the Lagrangian itself is not invariant under these transformations.

Although the first option is interesting, spontaneous CP breaking is disfavored because of potential cosmological problems. If spontaneous CP breaking occurs at low enough scales - below that of inflation - it will produce CP domains in the universe which, today, have energy density in their walls

much exceeding the universe's closure density[38]. For this reason, the second option above appears more sensible and, as Helen Quinn[39] discussed here, it has a variety of consequences.

In the standard model, with three generations of quarks and leptons, explicit CP violation arises only through the complex Yukawa couplings of the fermions with the Higgs doublet Φ. In the quark sector all CP violating effects are proportional to a single phase δ, which enters in the Cabibbo Kobayashi Maskawa mixing matrix V_{CKM}. Although CP violating effects in the Kaon system, typified by the parameter $\epsilon \sim 0(10^{-3})$, are small, in the standard model this does not necessarily imply that the phase δ is also small. Indeed, ϵ is naturally small in the standard model because it is proportional to the product of small mixing angles in the mixing matrix V_{CKM}. Nevertheless, as Martinelli[40] emphasized in the symposium, an important test that CP violation in the Kaon system indeed comes about through CKM mixing is to measure a non vanishing value for ϵ'/ϵ, since ϵ' is directly connected to CP violation due to quark mixing ($\Delta s = 1$ CP violation). Unfortunately, present data on ϵ'/ϵ is not definitive and the theoretical predictions[40] for this ratio, particularly for large top masses, are very small. Nevertheless, experiments presently being planned at Fermilab and CERN should clarify this matter in a few years time.

Although these experiments should tell us whether the CKM phase δ is non vanishing, more detailed tests of the standard model predictions will have to await experiments in the B system. In B decays, as Quinn[39] discussed, one can measure CP asymmetries that are directly proportional to the phases of CKM matrix elements. These asymmetries should be large, since they are not suppressed by additional intrafamily mixing angles. Furthermore, experiments in the B system are also likely to probe whether there are additional sources of CP violation. Indeed, any extensions of the standard model, in general, will introduce further CP violating phases, leading to different results than those expected in the standard model.

Perhaps the most sensitive probe for these additional CP violating phases is the neutron electric dipole moment. In the standard model, one expects $d_n \leq 10^{-30}$ ecm, while values of d_n of $0(10^{-26} - 10^{27}$ ecm) arise quite naturally in most simple extensions of the standard model[41]. These latter values are quite interesting since they are near the present experimental bound on this quantity. The CP violation provided by the standard model also does not appear likely to be at the origin of the universe matter-antimatter asymmetry. Baryogenesis at the GUT scale, in general, involves further phases, besides the CKM phase δ[42] and, as I indicated earlier, also baryogenesis at the electroweak scale appears to require extensions of the standard model.

Even within the standard model, one cannot avoid worrying about the strong CP probem[43]. Because of the nontrivial nature of the vacuum state of

the standard model, the Langrangian that describes strong and electroweak interaction acquires an additional term, involving the product of electric and magnetic color fields, which is purely CP odd:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\bar{\theta} g_3^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

The parameter $\bar{\theta}$ above is a combination of a vacuum angle θ, characterizing the QCD vacuum, and a phase associated with the quark mass matrix

$$\bar{\theta} = \theta + ArgdetM$$

The presence of the above extra interaction induces an enormous dipole moment for the neutron, for $\bar{\theta}$ angles of 0(1). To agree with the present bound on d_n, one must require that the parameter $\bar{\theta}$, which is a sum of QCD and electroweak contributions, be extremely small

$$\bar{\theta} < 10^{-9} - 10^{-10} \quad .$$

Why this should be so is the strong CP problem[43].

To my mind (but I may be prejudiced!), the only natural solution to this conundrum comes about if one imposes an extra global symmetry on the theory[44] - a chiral $U(1)$ symmetry: $U(1)_{PQ}$. This symmetry replaces the parameter $\bar{\theta}$ by a dynamical field $a(x)$, the axion field[45] :

$$\bar{\theta} \rightarrow \frac{a(x)}{f}$$

The scale f entering above is the scale at which the chiral global symmetry $U(1)_{PQ}$ breaks down.

Although the $U(1)_{PQ}$ symmetry and its concomitant axion arose in attempts to solve a low energy problem, this symmetry and axions may have deeper and more significant roles. Indeed, as Gross[6] discussed in this symposium, in superstring models of quantum gravity axions very naturally appear as supersymmetric partners of dilatons. Furthermore, axions can play a cosmological role. As the universe cools past temperatures $T \sim f$ towards temperatures of the order of GeVs, the axion field oscillates towards its low energy value, where $\bar{\theta} = 0$. The energy density in these oscillations, for f sufficiently large, $f \sim 10^{12}\ GeV$, can serve to close the universe[46]. Because these are zero momentum oscillations, axions are natural candidates for cold dark matter.

It is curious that the scale f which could make axions cosmologically significant is of the same order of magnitude as the see saw scale M which could make ν_τ cosmologically significant. Although one can construct models

where these two scales are clearly related[47], perhaps what is most important at this stage is that there are reasonable prospects that, if axions are the CDM, they can be detected on earth. All axion couplings scale as $1/f$, and thus are extremely weak. Furthermore, since $m_a \sim 1/f$ cosmologically significant axions have very small masses, in the $10^{-5} eV$ range. Nevertheless, the axion coupling to two photons can be used macroscopically for their detection. As Sikivie[48] first pointed out, in a strong enough magnetic field volume, the coupling of an axion to an $\vec{E}$ and $\vec{B}$ field shown in FIGURE 12 can induce detectable resonant oscillations in a cavity.

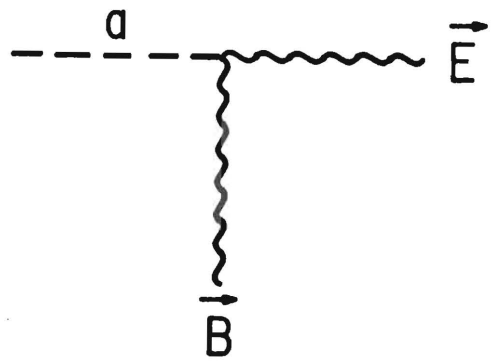

FIGURE 12. Axion-photon-photon coupling used for its detection.

Griest discussed[34] in this symposium, axion searches. As shown in FIGURE 13 present searches for cosmologically significant axions are about a factor of 100 to 1000 below the required sensitivity. However, as also shown in this figure, a proposed experiment at Livermore using a large volume, high field, magnet will get towards striking distance, at least for the so called KSVZ axions.

CONCLUDING REMARKS

Let me conclude by emphasizing two points. First, as was clearly point out a number of times during Pascos/Texas 92, particle physics has at least three plausible dark matter candidates:

i) A ν_τ, with mass in the 10 eV range.
ii) A neutralino which is the LSP, with mass in the 100 GeV range.
iii) An invisible axion, with mass in the $10^{-5} eV$ range.

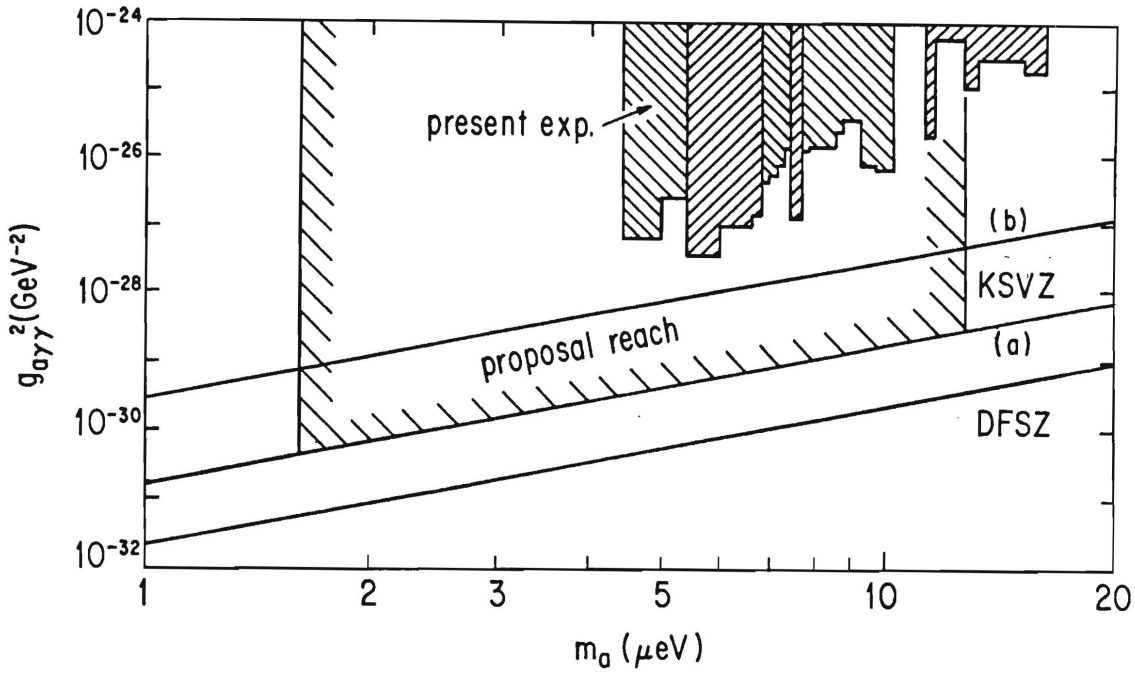

FIGURE 13. Present limits on axions, and expected reach of the Livermore experiment[34].

What is perhaps most amazing is that, despite the weak interactions and elusive character of these dark matter candidates, there are realistic prospects for their detection within the next 5-10 years! For the tau neutrino this should come from particle physic experiments, for the axion from astroparticle physics experiments and the race is on between particle and astroparticle experiments for the detection of signals from supersymmetry! This circumstance, more than anything else, reemphasizes how interconnected physics and astronomy have become.

The second, and last, comment I want to make concerns the possible proliferation of dark matter candidates. I believe there is nothing wrong with this. Indeed, in the context of inflation, it is perfectly sensible to have various kinds of dark matter. Inflation provides the constraint that $\Omega = 1$, while particle physics provides a set of parameters typifying various interactions and physical scales, like $M, \tilde{m}$ and f. A priori, of course, given a set of particle physics parameters, a given inflationary universe will evolve with different amounts of matter making up the total energy density of the universe at any given time. It might well be that for some universes a given species dominates at a given time. However, for the universe we live in, it is perfectly consistent to imagine that

$$\Omega = \sum_i \Omega_i = 1 \quad ,$$

with various Ω_i being significant today.

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