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PARTICLE COSMOLOGY COMES OF AGE

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The application of modern ideas in particle physics to astrophysical and cosmological settings is a continuation of a fruitful tradition in astrophysics which began with the application of atomic physics, and then nuclear physics. In the past decade particle cosmology and particle astrophysics have been recognized as 'legitimate activities' by both particle physicists and astrophysicists and astronomers. During this time there has been a high level of theoretical activity producing much speculation about the earliest history of the Universe, as well as important and interesting astrophysical and cosmological constraints to particle physics theories. This period of intense theoretical activity has produced a number of ideas most worthy of careful consideration and scrutiny, and even more importantly, amenable to experimental/observational test. Among the ideas which are likely to be tested in the next decade are: the cosmological bound to the number of neutrino flavors, inflation, relic WIMPs as the dark matter, and MSW neutrino oscillations as a solution to the solar neutrino problems.

1. INTRODUCTION

The past two decades have produced two remarkable standard models: the $SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge theory of the strong, weak, and electromagnetic interactions[1], and the hot Big Bang cosmology[2], and a theoretical understanding of some of the most interesting astrophysical objects in the Universe–pulsars, neutron stars, black holes, and QSOs. As many successful theoretical frameworks have in the past, these two standard models have provided sufficient theoretical illumination to show us their shortcomings and even to point to 'grander standard models'.

The standard model of particle theory patches together the known interactions (less gravity!) and the quarks and leptons in a theory with some 20 or so unspecified, but crucial parameters (fermion masses, CP violation, weak mixing angle, family mixing angles, etc.). Grand unified theories[3] go a step further, truly unifying the strong, weak, and electromagnetic interactions; unfortunately, the shining prediction of the simplest unified model, SU(5), a proton lifetime of a mere $10^{30 \text{ or so}}$ years, seems to have been falsified (drat!)[4]. Supersymmetry provides an attractive solution to the nagging problem of fundamental scalars in the theory (and the gauge hierarchy problem), and is and will continue to be tested at current and future accelerators. Superstring theories[5] have provided us with the first candidate for a 'Theory of Everything', unifying gravity with the other interactions in a finite theory.

Unfortunately, definitive superstring predictions have been few and far between (perhaps even non-existent).

The hot Big Bang model provides a reliable and tested accounting of the history of the Universe from $\sim 10^{-2}$ sec ($T \sim 10$ MeV) until today some 15 Gyr ($T = 2.75$ K) after the bang. The model accounts for the universal expansion (or Hubble flow of galaxies), the existence of the 2.75 K cosmic background radiation, the abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li, and a general framework for understanding the formation of structure in the Universe (galaxies, clusters of galaxies, superclusters, etc.). This standard model too has its shortcomings, begging explanations for: the origin of the baryon asymmetry of the Universe, the origin of the primeval inhomogeneities necessary to initiate structure formation, the composition of the dark matter, and the very special initial data required for a model Universe to evolve into one that resembles ours today. [Those initial data are: a smooth patch with size and curvature radius much, much larger than the horizon at the initial epoch.] The past decade of theoretical speculation about particle physics at very high energies ($\gg$ TeV) has produced some very interesting cosmological speculations regarding these cosmological puzzles. Baryogenesis, the scenario in which non-equilibrium B, C and CP violating interactions allow the Universe to develop a baryon asymmetry at very early times ($\sim 10^{-34}$ sec), provides a framework for understanding the baryon asymmetry of the Universe[6]. Relic weakly-interacting massive (and stable) particles (WIMPs) are ideal dark matter candidates[7]. Inflation[8] offers a very attractive scenario which can account for the smoothness, flatness, and origin of primeval inhomogeneities (in addition to circumventing the very troublesome cosmic overproduction of superheavy magnetic monopoles which results in the standard cosmology with the simplest grand unfied theories[9]). Cosmic strings provide another interesting early Universe model for the origin of the primeval inhomogeneities needed to initiate structure formation[10]. These line singularities which might be formed in a very early ($t \sim 10^{-38}$ sec) SSB phase transition (e.g., the breaking of a $U(1')$ symmetry), lead to a scale free distribution of loops, which subsequently act as seeds for structure formation.

A puzzle apparently involving both cosmology and particle physics is the present value of the cosmological constant (or equivalently, the absolute energy of our vacuum state). Based upon the total energy density of the Universe, we can infer that $\rho_{vac} \lesssim 10^{-46}$ GeV^4, whereas known symmetry principles would permit a value as large as $\rho_{vac} \sim m_{pl}^4 \simeq 10^{76}$ GeV^4 (supersymmetry might restrict ρ_{vac} to be $\lesssim M_W^4 \simeq 10^{10}$ GeV^4). An attractive and compelling idea to explain the present smallness of ρ_{vac} has thus far eluded even theoretical speculation.

An equally important aspect of the Inner Space/Outer Space connection is the use of the Universe (both 'early' and contemporary) as a heavenly laboratory to test theoretical predictions which are beyond the reach of terrestrial laboratories. Important astrophysical limits have been placed upon: the number of light ($\lesssim$ MeV) neutrino flavors[11]; the properties of unstable neutrinos[12]; the mass of the axion; the mass of the Higgs boson in the Weinberg-Salam-Glashow theory[13]; masses and coupling strengths of stable particles; the flux of relic monopoles[14]. These constraints take advantage of the large particle fluxes and energies available in the early Universe (up to 10^{109} cm^{-2} s^{-1} and 10^{19} GeV) and unique astrophysical environments that exist today: newly-born neutron stars ($\rho \sim 8 \times 10^{14}$ g cm^{-3} and $T \simeq 50$ MeV), red giant stars ($\rho \sim 100$ g cm^{-3} and $T \simeq 10^8$ K), large-scale coherent magnetic fields ($B \sim 3 \times 10^{-6}$ G and size $\simeq 10^{21}$ cm), etc.

Rather than try to review all of the exciting work at the particle physics-cosmology and astrophysics interface (in itself an impossible task), I will focus on the very attractive and worthy speculations that can and should be tested in the next decade, or so. [By so doing, I will necessarily pass over much exciting and important work on the topics of the quantum origin of the Universe, higher dimensional cosmology and compactification, and the very earliest history of the Universe.] Healthy science requires a dynamical balance between passionate theoretical speculation and cold, hard experimental fact. That balance has been tipped in the direction of theoretical speculation in the past decade and some balance needs to be, and moreover, can be restored. The theoretical ideas which I will focus on are: inflation, cosmological neutrino counting, relic WIMPs as the dark matter, and MSW neutrino oscillations as a solution to the solar neutrino problem. These ideas are all very worthy of serious consideration, and are amenable to experimental/observational tests in the next decade or so.

2. THE INFLATIONARY PARADIGM

Inflation has come a long way since the ill-fated model of Guth[8]. Stated in its most general terms, inflation involves the dynamical evolution of a weakly-coupled scalar field (probably a gauge singlet field) which is initially displaced from the minimum of its scalar potential[15]. [That minimum might be at $\phi = \sigma \neq 0$, as reminiscent of a SSB potential, or at $\phi = 0$, as favored by Linde[16], and called 'chaotic inflation'.] As the scalar field evolves to its minimum the enormous potential energy (associated with $V(\phi)$) drives an exponential expansion of the Universe, allowing an initially small smooth patch to be inflated to a size large enough to easily encompass all that we see today. Moreover, just as inflating a balloon increases its radius of curvature and makes its spatial geometry 'flatter', inflation makes the spatial geometry of the patch which inflates flat (setting Ω very nearly equal to 1).

As the scalar field ϕ reaches its minimum, it oscillates about the minimum. The enormous initial vacuum energy then exists in the form of coherent ϕ oscillations, equivalently a condensate of zero momentum ϕ particles. Eventually, these ϕ particles decay into light fields (through the coupling of the ϕ to other fields in the theory), thereby converting the vacuum energy into relativistic particles and reheating the Universe. The usual radiation-dominated (and eventually matter-dominated) phases of the standard cosmology follow (including baryogenesis since any pre-inflationary baryon asymmetry will be exponentially diluted during inflation).

During the exponential expansion (called a de Sitter phase), de Sitter space produced quantum fluctuations in the scalar field and in the metric result in a definite spectrum of both adiabatic density perturbations[17] and gravitational waves[18]. The spectrum of the adiabatic density perturbations is the constant-curvature spectrum first discussed by Harrison and Zel'dovich[19], with amplitude that depends upon the scalar potential (typically proportional to the dimensionless, quartic self-coupling of the ϕ field to the 1/2 power).

The process of inflation frees the present state of the Universe (in regions exponentially larger than our present observable Universe, $d \sim 10^{28}$ cm) from extreme dependence upon the initial state of the Universe. That all initial geometries will undergo inflation, producing large, flat and smooth regions has been by no means 'proven'. In fact, very highly-curved models will indeed recollapse before they can inflate. However, the situation is far better than in 1973 when Collins and Hawking[20] showed that the set of initial data which evolved to a Universe qualitatively similar to ours is of measure zero. In inflationary models, it has been shown that all initially homogeneous (but anisotropic) spacetimes inflate[21], and that many inhomogeneous models do also[22].

The inflationary scenario is extremely attractive (to say the least!), but it is not without its shortcomings–none, however, appear to be fatal yet. First, it requires a very weakly-coupled scalar field so that the adiabatic density perturbations are of an acceptable magnitude ($\delta\rho/\rho \lesssim 10^{-4} - 10^{-5}$). So weakly-coupled, that ϕ probably must be a gauge singlet and probably was never in thermal equilibrium. That of course also means that the microphysics which leads to it being displaced from the minimum of its potential is at present unspecified: the initial value of ϕ must be taken as an 'initial condition'. Moreover, how ϕ fits into the grand scheme of things is still a mystery. Inflationary models exist where ϕ is: (i) a 'random' scalar field (chaotic inflation); (ii) leads to supersymmetry breaking; (iii) induces GUT symmetry breaking; (iv) is identified with the radius of the extra dimensions (in higher dimensional theories); (v) is identified with the Ricci scalar (in higher derivative theories of gravity); (vi) induces Newton's constant (in induced gravity theories). Since inflation involves physics at energy scales $\gtrsim 10^{12}$ GeV or so the lack of a definite, compelling model should be viewed in the light of the fact that we are still far from having even a viable candidate particle physics theory at such energy scales.

Inflation is very definitely a theoretical speculation worthy of experimental/ observational scrutiny. I am most excited about the fact that important and significant tests of inflation can and will be made in the next decade or so. Let me begin by reviewing the inescapable predictions of inflation. They are:

- $\Omega = 1 \pm 10^{-\mathrm{BIG}\#}$ (where $\Omega = \rho_{TOT}/\rho_{crit}$, ρ_{TOT} = total energy density including matter, radiation, and vacuum energy)
- adiabatic density perturbations with the Harrison-Zel'dovich spectrum
- spectrum of gravitational waves with wavelengths $\lambda \simeq 1$ km up to 10^{28} cm (present

horizon), and no $\sim$ 1 K thermal spectrum of relic gravitational waves. [In the standard cosmology there should be the gravitational wave analog of the 2.75 K photon background with a temperature of order 1 K, a relic from the Planck epoch. In inflationary scenarios, these primeval gravitons like any other pre-inflationary relic are exponentially diluted during inflation.]

I refer to these as inescapable predictions as many 'options' have been added to the inflationary scenario. In more baroque (or even roccoco) inflationary scenarios one can also produce: isocurvature axion perturbations[23], non-scale invariant adiabatic fluctuations[24], primeval magnetic fields[25], large bubbles[26]. In testing the inflationary paradigm I will restrict my attention to the three essential predictions mentioned above.

First, consider the prediction that $\Omega \simeq 1$. For more than three decades astronomers have attempted to determine the curvature of space by measuring the deceleration parameter

$$q_0 \equiv -(\ddot{R}/R)/H^2 = \Omega(1 + 3p/\rho)/2$$

by recourse to the Hubble diagram (redshift-luminosity relation) without great success, largely due to the lack of 'standard candles' at high redshift and worries about the effects of galactic evolution. [Here p and ρ are the present pressure and energy density of the cosmic fluid, R is the cosmic scale factor, and H is the Hubble constant. In the canonical matter-dominated Universe $p \ll \rho$ and $q_0 = \Omega/2 = 1/2$.]

Recently, Loh and Spillar[27] have used a different technique, one with great 'cosmological leverage', to attempt to determine the curvature of space. By counting galaxies (per solid angle per redshift interval) they infer the dependence of the volume element of the Universe upon distance (actually redshift), and thereby measure the curvature of space. Before stating their result, I should caution the reader about their assumptions and possible deficiencies in their approach.

In order to measure sufficient numbers ($\sim$ few 1000) of redshifts they must use a multi-filter technique to determine the redshifts of their sample of galaxies, rather than directly measuring the spectra of the galaxies. This is far from being a fool-proof and completely tested technique. To convert a galactic number density to a physical volume, they must make assumptions about the constancy of the number density of galaxies and the distribution of galaxy luminosities. While they test both assumptions with their data set, their assumptions and redshift determination technique are controversial and have not yet been completely established, or whole-heartedly accepted by most members of the astronomical community.

After such caveats it would be most prudent to merely praise the potential of the technique and not report their result. But since they got the 'correct answer' (at least according to a die-hard inflationist) I will report their result:

$$\Omega = 0.9^{+0.7}_{-0.5} \quad (95\%\,\mathrm{cl})$$

This technique is a very powerful one indeed and will be used by others in the near future. Moreover, with the advent of more sophisticated means of measuring large numbers of redshifts (other similar multi-band techniques, simultaneous measurement of many galaxy redshifts using fiberoptics and templates, etc.) there is likely to be progress in determining q_0 by galaxy counts, the Hubble diagram, or perhaps using another technique (angular size-redshift relation) in the next decade. Remember, the falsification of inflation only requires a reliable determination of Ω which is appreciably less than unity (say, 0.8 or even 0.9).

There are other tests of the prediction $\Omega = 1$. Assuming that the Universe is presently matter-dominated, the product of the present Hubble parameter H_0 and the age of the Universe t_0 must be 2/3. The Hubble parameter is not known with great precision; our present knowledge only constrains it to the range: 40-100 km s^{-1} Mpc^{-1}. Likewise, other independent measures of the age of the Universe (dating of the radioactive elements and the oldest stars) are not yet definitive, and at best put the age in the range 12-20 Gyr[28]. Together these determinations constrain H_0t_0 to the interval: 0.49-2.0—not a very interesting test. However, suppose that future observations would determine H_0 to be ≥ 55 km s^{-1} Mpc^{-1}. Then with the same interval of possible ages for the Universe, H_0t_0 is constrained to be ≥ 0.67. The age of the Universe has been a powerful test of cosmological models and observations in the past, and could again prove to be in the future. [In passing, I note that if vacuum energy makes a substantial contribution to ρ_{TOT} today, H_0t_0 can be much greater than 2/3. For a Universe with vacuum energy ($= \Omega_{vac}$) and non-relativistic matter ($= \Omega_{NR}$),

$$H_0t_0 = \frac{2}{3}\ln[(1+\Omega_{vac}^{1/2})/\Omega_{NR}^{1/2}]/\Omega_{vac}^{1/2}$$

which for $\Omega_{vac} = 0.8, 0.9$ gives $H_0t_0 = 1.1, 1.3$ (see Ref. 29)].

One can also attempt to determine Ω by determining the mass density of the Universe. I will leave this issue until my discussion of dark matter, except to say that inflation necessarily requires a non-baryonic dominated Universe. That is because the predictions of primordial synthesis are only concordant with the observations for $\Omega_B \leq 0.15$.

Next the scale-invariant spectrum of adiabatic density perturbations. The amplitude of these perturbations is very model dependent, and for the present will have to be set by other considerations; in particular, by the anisotropy of the microwave background radiation and structure formation. Roughly speaking, in order to initiate structure formation that will evolve to what we observe by the present epoch, an amplitude of 10^{-5} (give or take a factor of 3) is required. In passing I mention that achieving inflation-produced adiabatic fluctuations of this amplitude has posed the most difficult requirement for inflationary models and is the requirement that necessitates ϕ being a very weakly-coupled scalar field.

Adiabatic density perturbations correspond to fluctuations in the 'Newtonian gravitational potential' (as phrased in Newtonian language), and as such result in fluctuations in the redshift that a photon suffers since 'last scattering' (at the decoupling epoch, $t \simeq$ few 100,000 yrs and redshift ~ 1200), and thereby fluctuations in the microwave temperature. On large angular scales ($\gg 1°$), corresponding to superhorizon sized separations at last scattering, these are the dominant source of temperature fluctuations, *and* because these angular scales correspond to superhorizon-sized separations, fluctuations on these scales cannot be affected by microphysical processes. As such, large angular scale anisotropy in the microwave temperature provides an untampered record of the perturbation spectrum. Fluctuations on these scales are directly related to the density perturbations: $(\delta T/T) \simeq \frac{1}{2}(\delta\rho/\rho)$ (the Sachs-Wolfe effect[30]). An escapable prediction then, is $\delta T/T \gtrsim$ few $\times 10^{-6}$. Current upper limits to the anisotropy on large scales are of the order few $\times 10^{-5}$. With the technical advances (particularly cryogenic bolometric detectors) on the horizon, the inescapable inflationary prediction of $\delta T/T \gtrsim$ few $\times 10^{-6}$ seems very likely to be tested soon. For a recent review of the experimental situation, see Ref. 31.

[Fluctuations in the microwave temperature of a similar, or even larger amplitude also result on smaller scales. However, their amplitude and angular dependence are affected by microphysics and are therefore dependent on the details of structure formation. They too are very important (and may even be detected first), but have a less clear interpretation. For a discussion of the theoretical predictions for microwave fluctuations, see Refs. 32.]

Finally, the third inescapable prediction of inflation: a spectrum of gravitational waves with wavelengths from ~ 1 km to 10^{28} cm, and the absense of the ~ 1 K thermal spectrum of gravitational waves. For wavelengths λ_{GW} from 1 km $(10^{14}\ \mathrm{GeV/M})^{2/3}$ $(10^{10}\ \mathrm{GeV}/T_{RH})^{1/3}$ to 300 km $(10^{10}\ \mathrm{GeV}/T_{RH})$, the energy density per octave rises as λ_{GW}^2 (to $2\times 10^{-4}(H_I/m_{pl})^2\rho_{crit}$); from 300 km $(10^{10}\ \mathrm{GeV}/T_{RH})$ to $\sim 12h^{-2}$ Mpc the energy density per octave is constant; and from $\sim 12h^{-2}$ Mpc to $10^{28}h^{-1}$ cm it rises as λ_{GW}^2 (to a value of $(H_I/m_{pl})^2$). Here M^4 is the vacuum energy density during inflation, T_{RH} is the reheat temperature after inflation, and H_I is the value of the Hubble constant during inflation, which must be less than $\sim 10^{-4}\ m_{pl}$ (otherwise the gravitational waves with $\lambda_{GW} \sim 10^{28}h^{-1}$ cm would lead to a quadrupole microwave anisotropy greater than that observed). The thermal spectrum of gravitational waves, which is predicted to be absent, would have had its peak at $\sim$ few mm and would contribute $\sim 10^{-8}\rho_{crit}$. The spectrum of gravitational waves too provides an unspoiled record of inflation, and could even provide information about the details of inflation (M, $H_I \sim M^2/m_{pl}$, and T_{RH}). At this point it is fair to say that heroic efforts would be required to test these predictions.

As I stated earlier, the standard cosmology provides a general picture of how structure formation must have proceeded[33]: small primeval inhomogeneities begin to grow via the Jeans instability when the Universe becomes matter-dominated ($t \sim 1000$ yrs), eventually resulting in the plethora of structures we observe today—galaxies, clusters of galaxies, superclusters, voids, etc. In the past, progress toward constructing a more detailed picture of structure formation has been hampered by the lack of specific initial data for the structure formation problem: namely, the quantity and composition of matter, and the amplitude, type, and spectrum of density perturbations. Inflation provides highly specific initial data, making detailed numerical simulation of structure formation possible. In turn, these detailed simulations provide yet another means of testing the inflationary paradigm. I will return to structure formation shortly.

3. DARK MATTER: THE RELIC WIMP HYPOTHESIS

One of the most fundamental questions one can ask about the Universe is, how much stuff is there in it? The energy (or mass) density of the Universe is usually measured relative to the critical density, $\rho_i = \Omega_i \rho_{crit}$, where $\rho_{crit} = 1.88h^2 \times 10^{-29}\mathrm{gcm}^{-3} \simeq 1.05h^2 \times 10^4 \mathrm{eVcm}^{-3}$. About the only contribution we know very precisely is that of the photons in the micorowave background radiation: $\Omega_{photon}h^2 = 3 \times 10^{-5}(T/2.7K)^4$. Luminous matter (stars made of baryons, hot x-ray emitting gas, etc.) is easy to keep track of too, and contributes: $\Omega_{lum} \simeq 0.01$. Primordial nucleosynthesis provides a powerful (but indirect) means of determining the contribution of the baryonic matter; consistency between the predicted abundances of D, ^{3}He, ^{4}He, and ^{7}Li and their observed abundances implies[34]: $0.014 \lesssim \Omega_B h^2 \lesssim 0.035$, or $0.014 \lesssim \Omega_B \lesssim 0.15$. This already suggests that some of the baryonic material is dark, and of course there are many guises for dark baryons to assume—white dwarfs, neutron stars, black holes, jupiters, etc. Before going on I would be remiss not to at least mention the two nonstandard scenarios for primordial nucleosynthesis recently suggested and which might allow the nucleosynthesis bound to be circumvented: (i) the effects of inhomogeneities in the baryon number density due to a strongly first order deconfinement phase transition[35], and (ii) the effects of a particle which decays after nucleosynthesis and initiates a chain of nuclear reactions which readjusts the light element abundances[36]. My own opinion and bias is that neither will actually prove viable—both seem to have difficulties accounting for the observed ^{7}Li abundance; however, both are very intriguing possibilities.

The strongest evidence for massive amounts of dark matter in the Universe comes from dynamical determinations of the masses of spiral galaxies (through measurements of their rotation curves) and groups of galaxies (through virial mass determinations). Both indicate that the dynamical mass which clusters with galaxies (and on scales $\lesssim$ 30 Mpc) contributes: $\Omega_{\lesssim 30Mpc} \simeq 0.2 \pm 0.1$, where '$\pm 0.1$' is not meant to be a formal error estimate, but rather an indication of the spread of the mass determinations by different means. [There is also a great body of other dynamical evidence for the predominance of dark matter, and $\Omega_{\lesssim 30Mpc} \simeq 0.2 \pm 0.1$; for a very complete review I suggest Ref. 37.] The rotation curve measurements of spiral galaxies like our own indicate that this dark matter, so-called because its gravitational effects are felt but no light is detected, exists in an extended spherical halo (although the evidence for the sphericity is at best weak) with density profile $\rho_{halo}(r) \sim (r^2 + a^2)^{-1}$ ($a =$ 'core radius' $\sim$ 10 kpc). Without question dark matter is the dominant component to the mass density of the Universe—by a factor of at least 10.

[On a more local note, Bahcall[38] has emphasized the *possible* (my use of the word possible!) existence of dark matter within the disk of our galaxy. Dynamical determinations of the local mass density (based upon the motions of stars) and a direct inventory of the mass density (including stars, gas, dust, white dwarfs, etc.) disagree by a factor of about two. An optimist might say that such agreement is remarkable; a skeptic might say that this is evidence for dark matter with $\Omega_{Bahcall} \simeq 0.01$ right in our own neighborhood. The local halo density fails by more than a factor of 10 to account for this local dark matter.]

What is one to conclude from my very brief summary of dynamical determinations of Ω?

• There is no question that the dark component dominates the present mass density of the Universe (by a factor of at least 10), contributing, $\Omega_{\lesssim 30Mpc} \simeq 0.2 \pm 0.1$, as determined by measurements of the mass which clusters with bright galaxies on scales $\lesssim 30$ Mpc.

• Primordial nucleosynthesis strongly suggests that some of the dark matter is baryonic—no surprise here, and unless one can preclude $\Omega_{\lesssim 30Mpc} \lesssim 0.15$, *all* of the dark matter known to exist *could* be baryonic—but how boring!

• I have been very careful to label the dynamically-determined dark component by the subscript '$\lesssim 30Mpc$'; I did so for a very important reason. The dynamical measurements are only sensitive to matter which clusters with bright galaxies (i.e., is found where bright galaxies are), and the dynamical determinations have only probed structures as large as 30 Mpc (in actuality, probably no larger than 10 Mpc). Any dark matter which is distributed smoothly on these scales, or not associated with bright galaxies would not have been detected. This of course is in contrast to the measurements of the curvature of space (through q_o), which are sensitive to the average density of the Universe. *If inflation is correct, and if astronomers have not misled with regard to* $\Omega_{\lesssim 30Mpc}$, then there must be an unclustered component to the dark matter, and this unclustered component must contribute $\Omega_{Smooth} \simeq 0.8 \mp 0.1$. This is a very important consideration which I will return to again. In any case, if inflation is correct (or if $\Omega_{TOT} \gtrsim 0.15$), then the dark matter must be nonbaryonic (remembering the small loophole involving nonstandard pictures of primordial nucleosynthesis).

Needless to say early Universe cosmology provides the ideal candidate for the dark matter in the Universe: stable relics from the earliest moments of the Universe, or generically WIMPs (Weakly-Interacting Massive Particles). A particle species which is weakly-interacting, but was once in thermal equilibrium, will have a relic abundance today, because at some point in the history of the Universe its annihilation rate can no longer keep pace with the expansion rate of the Universe (which sets the rate of change of the temperature of the Universe). At this time its interactions 'freeze out' and its abundance 'freezes in' (for details see Ref. 39). If 'freeze out' occurs when the temperature is greater than the mass of the particle (as in the case of a light ($\lesssim$ MeV) neutrino species), then its relic abundance is comparable to that of the microwave photons ($n_\gamma \simeq 400\mathrm{cm}^{-3}$); for a light neutrino species, $n_{\bar{\nu}\nu} = \frac{4}{11} n_\gamma \simeq 109\mathrm{cm}^{-3}$. In the other extreme, if 'freeze out' occurs when the temperature of the Universe is much less than the mass of the species, its relic abundance relative to the photons is proportional to $(\langle(\sigma v)_{ann}\rangle m_{WIMP})^{-1}$. Examples of possible thermal relics which could contribute significantly to the present density of the Universe are: light neutrinos[40], heavy neutrinos[41], photinos, sneutrinos, higgsinos[42], ...

In addition to thermal relics, nonthermal relics can be produced during the earliest history of the Universe. Most nonthermal relics are produced in a phase transition; examples include: superheavy magnetic monopoles[9], axions[43], soliton stars[44], cosmic strings[10], ... None of these relics would have ever been in thermal equilibrium.

[In passing I mention that if indeed the dark matter is relic WIMPs, then cosmologists have yet another dimensionless number to explain: $r = \Omega_{WIMP}/\Omega_B \simeq 10$. Why should r be of order unity, and not say 10^{-26}, or 10^{26}? If the WIMP is a heavy neutrino, sneutrino, photino, etc., then this may trace to the smallness of the weak scale relative to the Planck scale, or to the cosmic WIMP asymmetry being comparable to the baryon asymmetry. If the WIMP is an axion, it could trace to the closeness of the axion scale to the Planck scale.[44a]]

In sum, early cosmology provides the cosmologists with a more than ample list of candidates for the dark matter, and many with very good theoretical motivation. The Universe is indeed predominantly dark matter, of unknown composition. Moreover, if inflation is correct, then the dark matter is necessarily exotic. Like the inflationary paradigm, the relic WIMP hypothesis is very well-motivated and worthy of careful consideration and experimental scrutiny.

The relic WIMP hypothesis is being and will continue to be tested in a variety of very clever experiments. Some of these efforts are *direct*, in that they involve actually directly detecting the cosmic reservoir of relic particles. Others are *indirect*, in that they involve creating the hypothetical WIMP in the laboratory and/or determining its properties: once the particle species is known to exist and its properties (mass, annihilation cross section) are determined, theoretical cosmology can be used to infer its role as the dark matter. The simplest example of this process of inferrence is the light neutrino: cosmologists are very confident that they know the relic abundance of neutrinos, and so a definitive determination of the electron neutrino mass in the 20-30 eV range would establish electron neutrinos as the dark matter.

A variety of direct tests of the relic WIMP hypothesis are underway or will be underway in the coming years. They include:

• Axion detectors—wherein the anomalous coupling of the axion to 2 photons is exploited. Axions are coaxed to photoconvert in an inhomogeneous magnetic field, and subsequently excite a microwave cavity. The first prototype experiments has already set bounds to the local density of relic axions of mass $\sim 10^{-5}$ eV (Ref. 45).

• Bolometric detectors—wherein relic WIMPs with scattering cross sections comparable to the weak interaction elastically scatter and deposit keV energies which are then detected by low-background, cryogenic detectors. Already, interesting null results have been obtained by two double β-decay experiments[46] (which were not even designed for this purpose). A great deal of effort is now going in to the development of cryogenic detectors for the purpose of detecting relic WIMPs[47].

• Monopole detectors—although superheavy magnetic monopoles have to be considered a longshot to be the dark matter, given both the theoretical uncertainty about their relic abundance (estimates ranging from so many that the Universe would only be 30,000 yrs old today to less than one in the whole of the observable Universe!) and the very stringent astrophysical limits that exist on their relic abundance, at least one very large ionization detector is being built, the MACROS detector in the Gran Sasso Laboratory. This football-field sized detector will reach a sensitivity of ~ 0.1 Parker or $\simeq 10^{-16}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{sec}^{-1}$. Other large monopole detectors (including induction detectors) are being planned.

• WIMP Scatology—a variety of semi-direct schemes have been suggested wherein the annihilation products of the WIMP's within are galaxy are detected. For example, WIMP annihilations within the halo of our galaxy can produce antiprotons[48] and γ-rays which can be detected. Of particular interest is the possibility that the WIMP annihilations produce quarkonium and a series of monoenergetic γ-ray lines (WIMP + antiWIMP $\rightarrow Q\bar{Q} + \gamma$)[49]. The energies of the lines and the spatial variation of the γ-ray flux would allow an accurate determination of the WIMP mass and of the halo density distribution[50].

Both the earth and the sun will capture WIMPs incident upon them, and WIMPs within these objects will occasionally annihilate, producing energetic neutrinos ($E_\nu \simeq 100's$ MeV-*few* GeV).[51] These neutrinos can be detected in large underground detectors, such as KII, IMB, Frejus, and others. Interesting limits have already been obtained, probably excluding heavy neutrinos more massive than 5 GeV and sneutrinos more mass than 3-5 GeV, and starting to exclude photino masses of 5-15 GeV (Refs. 52,53). [If the relic WIMPs carry a conserved quantum number and their abundance is predominatly WIMPs or antiWIMPs, then there will be no WIMP annihilations, and this means of detection is rendered impotent.]

As viewed by a cosmologist, the indirect search methods include:

• Neutrino oscillation experiments

• Neutrino mass experiments

• Neutrinoless double β-decay experiments

• Accelerator particle searches (for photinos, sneutrinos, selectrons, and whatever else!)

• Study of structure formation—structure formation scenarios based on the WIMP hypothesis may shed some very indirect light on the dark matter problem, precluding one candidate, or favoring another.

To summarize, without a doubt we live in a Universe whose primary component of mass density is dark and presently unidentified. The nature of the dark matter is most clearly one of the burning questions facing cosmology today. There are strong indications that the dark matter is non-baryonic, and the WIMP hypothesis is a very attractive one. I am most excited by the fact that it is a testable hypothesis , and one which is attracting the efforts of some of the most talented experimentalists.

4. STRUCTURE FORMATION

As I emphasized earlier, structure formation can be viewed as an initial data problem, the initial data being the quantity and composition of the dark matter, and the nature of the primeval fluctuations. With regard to both, inflation makes very definite predictions: $\Omega_{TOT} \simeq 1.0$, which together with the primordial nucleosynthesis constraint implies: $\Omega_B \simeq 0.1$ and $\Omega_{WIMP} \simeq 0.9$; and the Harrison-Zel'dovich spectrum of primeval adiabatic density perturbations. Inflation does not make a definite prediction about the amplitude of the perturbations; at present that has to be determined by other considerations, e.g., normalization to the degree of inhomogeneity seen today (either in the clustering of galaxies or the anisotropy of the microwave background).

These inflation motivated initial data lead to two very definite stories of structure formation: hot and cold dark matter—or neutrinos and anything else. The WIMPs themselves can modify the primeval fluctuation spectrum by streaming out of overdense regions and into underdense regions before the Universe becomes matter-dominated and gravity begins to affect the perturbations and spurs their growth[54]. At the time of matter-radiation density equality, neutrinos are semi-relativistic, while all the other dark matter candidates being much heavier are very non-relativistic. [Axions are an exception to this generality; because they are born in a coherent zero-momentum state, they are always non-relativistic.] For this reason, neutrinos lead to the damping of perturbations on relatively large scales, up to $\simeq 13h^{-2}$ Mpc (for reference, 1 Mpc is the perturbation scale for a galaxy). For the other candidates damping is not important because of their low velocities are so low that they cannot 'free stream' very far.

The large damping scale has a profound effect on how structure formation proceeds in the hot dark matter scenario (HDM). The first structures that form are necessarily large (supercluster size), and then must fragment into smaller objects like galaxies, through complicated gas hydrodynamical processes. Structure is said to form 'top-down'. The existence of a scale—the damping scale due to neutrino streaming, leaves a noticeable imprint on the structure today—cell-like voids of size $\sim 13h^{-2}$ Mpc.

The successes of the HDM scenario all seem to involve the existence of this scale. The large-scale (> 10 Mpc) structure which results *qualitatively* resembles what is seen today (a point to which I will return). Since neutrinos are weakly-interacting they do not (for the most part) find their way into galaxies, and stay smoothly distributed, and thereby nicely account for the unclustered dark matter ($\Omega_{Smooth} \simeq 0.8 \pm 0.1$). The shortcomings also trace to the large-damping scale. In order that the Universe is not much more clumped than it is observed to be today, the epoch of 'pancaking' (Zel'dovich called the first large structures that form 'pancakes' or 'blini') must have occurred quite recently—so recently that galaxies would not have formed until redshifts of order unity or less. This is in direct conflict with the QSO's seen at redshifts as large as 4.5 and galaxies at redshifts as large as 3. On small angular scales ($\ll 1°$), the microwave temperature fluctuations predicted are very close to the observational upper limits[32]. A factor of 3 (or even smaller) increase in sensitivity would either falsify, or lend credence to the HDM scenario.

The present status of HDM is down, but not yet completely out[55]. The loophole being gas hydrodynamics: it is straightforward to simulate the evolution of the neutrinos, for them only gravity is important, but simulating the evolution of the baryons and formation of galaxies is much more difficult, as it involves gas hydrodynamics in a crucial way.

In the cold dark matter scenario (CDM) structure forms from the 'bottom-up': small objects (galaxy sized or smaller) form first and then cluster together to form larger objects (clusters, superclusters, etc.). CDM has been remarkably successful at explaining the observed properties of galaxies[56,57]: their masses, mass densities, rotation curves, and their number density; the galaxy-galaxy correlation function, and galaxy pairwise velocities. It has been less successful in accounting for the large-scale structure of the Universe—which we are just beginning to map out (a point to which I will return). And then there is the Ω-problem: accounting for the necessary unclustered dark matter. Unlike the HDM story, where neutrinos would not be expected to cluster on scales $\lesssim$ 30 Mpc or so, nothing should prevent CDM WIMPs from settling into the halos of galaxies, and clusters of galaxies—just where they are apparently not seen!

A very clever solution to this puzzle is known as biasing[58]. The idea goes like this: suppose that the actual lighting up of a galaxy is not 100% efficient and that only 1 in 4 galactic-sized objects (all composed of the same mix of baryons and WIMPs) is bright enough to be seen today. [As an aside I mention that being bright enough to be seen is no mean feat! The surface brightness of a typical spiral galaxy is only about one order-of-magnitude greater than that of the night sky; put another way, were spiral galaxies three times as large (in linear dimension), they would fade into the night sky.] In the biasing scenario unlit galaxies provide $\Omega_{Smooth} \simeq 0.8 \pm 0.1$. But why would they be less clustered? That's where the clever part comes in! The inflation-produced fluctuations are gaussian distributed: that is, there is not a unique perturbation amplitude, but a distribution of perturbation amplitudes on the galactic scale. The 'high peaks' (large amplitude, say 3σ fluctuations) are necessarily more clustered and collapse to form galaxies earlier. The more common 1σ peaks collapse later and are less clustered, i.e., *more smoothly* distributed. [That the high peaks are more correlated is a non-linear aspect of the statistics of the fluctuation spectrum: it is exponentially less likely to have an isolated high peak, than to have several moderate-sized peaks which are sitting on the crest of a longer wavelength fluctuation.] The final key to biasing is the physical mechanism to explain why the 1σ peaks do not light up to become bright galaxies. A number of plausible mechanisms have been suggested[59]; as of yet no one mechanism has proven to be compelling. For example, since the 1σ peaks form galaxies later, the central densities of these galaxies will be lower (corresponding to shallower potential wells), making them more vulnerable to the loss of the gas which is needed to continually form stars; to wit, it has been suggested that the first generation of massive stars might sweep out most of the gas when they explode as supernovae. Some have called biasing *ad hoc*; while it is clear that some kind of biasing is necessary in order for CDM to explain the Ω-problem, it also seems equally clear that galaxy formation must involve nitty-gritty astrophysics in addition to gravity. Like it or not all scenarios of structure formation will have to address the astrophysical aspects of galaxy formation: that is, biasing in one form or another is likely to be a fact of galaxy formation.

Finally, the small scale ($\ll 1^{\circ}$) microwave anisotropies predicted in the CDM are still a factor of 3-10 below the present upper limits ($\delta T/T \lesssim 3\times 10^{-5}$)[32].

This brings me to the topic of large-scale structure, by which I mean structures larger than galaxies. While the properties of galaxies are relatively well understood (masses, luminosities, rotation curves, galaxy-galaxy correlation function, etc.) the large scale structure of the Universe is not. To oversimplify somewhat, our lack of understanding traces to the absence of a good 3-dimensional map of the Universe. While the sky positions of more than 2 million galaxies are known, only about 30,000 galaxy redshifts have been determined. That situation is improving and is likely to significantly improve in the next decade, particularly as larger redshift surveys are completed.

The large-scale structure of the Universe holds great promise to discriminate between scenarios of structure formation, and thereby test both the WIMP hypothesis and the inflationary paradigm. The present observational data give us a preliminary view of large-scale structure which is both fascinating and puzzling. If all the observations are correct, none of the present scenarios are viable! Those observations include:

• The frothy distribution of bright galaxies seen by de Lapparent et al.[60] in their slices of the Universe survey: galaxies clumped around empty regions of size $\sim (10-20)h^{-1}$ Mpc.

• Large-scale streaming velocities. Several groups have reported galaxy streaming motions of the order 600 km s^{-1} coherent over a region of $50h^{-1}$ Mpc[61]. Streaming velocity here means velocity relative to the Hubble flow. Such motions are expected as they are produced by the inhomogeneous distribution of matter. Of course, one expects that on larger scales these velocities should become smaller as the Universe is believed to be smoother (as evidenced by the isotropy of the microwave background radiation). The peculiar field provides a direct probe of the inhomogeneity of the Universe with galaxies in effect being used as test particles (rather than tracers of the mass itself). However, peculiar velocities are difficult to measure (as they require accurate distance measurements—the Hubble velocity, determined by the galaxy's distance, must be subtracted from the measured recessional velocity). The observations and their interpretation are far from being settled.

• The cluster-cluster correlation function, which is about 30 times larger than the galaxy-galaxy correlation function. The galaxy-galaxy correlation function is well established, and in the simplest models of structure where light faithfully traces the mass and the density perturbations are gaussian, the two should be equivalent. The present observation[62], that clusters are more correlated than galaxies, is puzzling and was the original motivation for the biasing idea. However, the observational data must be considered in the light of the absence of a reliable and objective catalogue of clusters. The supercluster-supercluster correlation function has also been measured[62] (and it too is large)—however, the statistics and the sample are even poorer than that of the clusters.

• The existence of very large structures, 'super superclusters' of size approaching 10% of the horizon have been reported[63]. Even in the slice of the Universe survey, the voids seen are comparable to the size of the survey itself. That even raises the question, is the Universe smooth on large scales? The isotropy of the microwave background radiation provides very strong evidence that it must be. Could it be that the bright galaxies are very inhomogeneously distributed, as in the biasing picture, and are misleading us about the mass distribution? Many answers should be forthcoming in the next decade, providing us both a clearer picture of the Universe on the largest scales and crucial tests of the predictions of early Universe cosmology.

Before I go I should at least mention alternatives to the two conventional pictures, hot and cold matter with inflation-produced adiabatic density inhomogeneities. With regard to the Ω problem, it has been suggested that the smooth component of mass density is relativistic particles produced by the recent decay of unstable WIMPs[64], or even a relic cosmological term[65]. Another very interesting and very different possibility is that of cosmic strings[10]. These 1-dimensional topological objects are necessarily produced in a SSB phase transition, and if they are to be of cosmological interest, the transition temperature must be very high, of order 10^{16} GeV (or a coupling constant must be very small). For this reason they seem on the face of it incompatible with inflation, as the reheat temperatures in inflationary models are typically very much lower ($\lesssim 10^{10}$ GeV), and any string produced before inflation is exponentially diluted. Be that as it may, cosmic strings provide a very intriguing and possibly promising alternative which has received a great deal of attention. The further twist, that cosmic strings may be superconducting[66], makes an interesting scenario mind-boggling[67], with strings carrying currents as large as 10^{20} A and releasing energies of 10^{60} ergs which trigger explosive galaxy formation. String scenarios too may require exotic dark matter, and are also amenable to numerous observational tests.

5. THE UNIVERSE AS A HEAVENLY LABORATORY

The early Universe and various contemporary astrophysical sites have proven to be invaluable laboratories for studying elementary particle physics in regimes beyond the reach of earthly laboratories. I dare say that every particle physicist is by now familiar with the bounds provided by primordial nucleosynthesis on the existence of additional light ($\lesssim$ MeV) particle species, most especially the bound on the number of light neutrino species due to Schramm, Steigman and their collaborators[11]: $N_\nu \leq 4$. Laboratory experiment is rapidly closing in on this bound (experiments at $e^\pm$ accelerators ($e^+e^- \to \gamma +$ missing energy), and at p$\bar{\text{p}}$ colliders (using the widths of both the $W^\pm$ and Z°)), and soon the direct, high statistics measurement of the width of the Z° at SLC and LEP. When confirmed (I am a cosmic optimist!), this will be a feather-in-the-cap of cosmologists and a further crucial test of primordial nucleosynthesis. If there should indeed be a fourth light neutrino species, primordial nucleosynthesis would all but preclude any additional light particle species.

Almost equally well-known is the fact that the present mass density of the Universe (to be more precise, the age of the Universe) can be used to restrict the properties (mass and annihilation cross section) of stable particles. As mentioned previously any stable particle species which was once in thermal equilibrium will have a relic abundance determined by the strength of its interactions.[39] This line of reasoning has been applied to light neutrinos[40] ($m_\nu \lesssim 100$ eV); to 'heavy' neutrinos[41] ($m_\nu \gtrsim 3$ GeV); to other 'heavy' particles with annihilation cross sections of roughly weak strength[42]—photinos, sneutrinos, higgsinos, etc ($m \gtrsim O$ (10 GeV)); and to objects which are produced in phase transitions, e.g., superheavy magnetic monopoles, axions, domain walls, cosmic strings,...

The axion above all has illustrated the versatility of astrophysical and cosmological constraints. Relic low mass axions ($\lesssim 10^{-2}$ eV) are mainly produced coherently[43], and $\Omega_a \simeq (m_a/10^{-5}\ \mathrm{eV})^{-1.18}$. Except in inflationary models (where Ω_a depends upon the initial misalignment angle of the axion field squared[68]), $m_a \lesssim 10^{-6}$ eV is precluded. Relic high mass axions ($\gtrsim 10^{-2}$ eV) are mainly produced thermally[69], and contribute: $\Omega_a \simeq 10^{-2}$ (m_a/eV). The decays of eV-mass relic axions ($a \to 2\gamma$) should produce photon line radiation which can be detected[69,70]! The absence of strong, narrow lines preclude an axion mass $\gtrsim 5$ eV (Ref. 69), and relic axions of mass 2-5 eV produce line radiation which is potentially detectable[69].

Being light, weakly-interacting particles, axions are produced in large numbers in the cores of stars of all types (our Sun, red giants, white dwarfs, neutron stars, supernovae) and stream right out, thereby acting as a potentially efficient coolant. Their effect upon stellar evolution has been used to exclude the possibility of axion masses[71] $\gtrsim 10^{-2}$ eV (DFS axion[72]) or 3-40 eV (hadronic axion[73]), leaving an axion window:

$$10^{-6}\ \mathrm{eV} - 10^{-2}\ \mathrm{eV} \qquad \text{(DFS)}$$

$$10^{-6}\ \mathrm{eV} - (3-40)\ \mathrm{eV} \qquad \text{(hadronic)}$$

(remembering that in inflationary models $m_a \lesssim 10^{-6}$ eV cannot definitely be excluded). [Very recently, several groups of authors have used axion emission from SN 1987a to slightly further narrow the window, excluding axion masses in the range: $3 - 10^{-3}$ eV (Ref. 74).]

Cosmological arguments have even been used to constrain the mass of the Weinberg-Salam-Glashow higgs[13]. In standard models with a single doublet of Higgs (and no quarks with mass nearly degenerate with the $W^\pm$), the neutral Higgs mass must be greater than$\sim$ 10.6 GeV (the Coleman-Weinberg higgs mass), otherwise the Universe would get hung up in the symmetric vacuum state ($\phi = 0$) during the electroweak SSB phase transition.

SN 1987a (discussed in greater detail in Schramm's contribution to these proceedings), in addition to confirming astrophysicists' basic model of a type II supernova, has proven to be an interesting heavenly-laboratory. The detection of $\bar{\nu}_e$'s by the KII and IMB detectors[75] has:

(i) led to a ν_e mass limit of order 20 eV (comparable to the existing laboratory limits)[76];

(ii) placed a limit to the number of light neutrino species: $N_\nu \lesssim O(6)$;

(iii) constrained the unknown interactions of neutrinos with themselves and other particles: $\langle\sigma v\rangle \lesssim 3 \times 10^{-26}$ cm^2 (Ref. 77);

(iv) placed a limit to lifetime of the ν_e[75]: $\tau \gtrsim 5 \times 10^5$ sec (m_ν/eV);

(v) excluded a range of axion masses: $m_a \simeq 10^{-3}$ eV $-$ 3 eV (Refs. 74);

(vi) set a limit to the magnetic moment of the electron neutrino: $\mu_{\nu_e} \lesssim 10^{-12}\mu_B$ (Ref. 78).

(vii) the absence of high energy γ rays provides a very stringent limit to the lifetime and radiative branching ratio (B_γ) of any neutrino species: $\tau \gtrsim 3.4 \times 10^{15}/(m_\nu/\text{eV})$ sec (Ref. 79).

I hope that these few examples have served to illustrate the utility of astrophysical and cosmological constraints to particle physics theories. Because much of the theoretical speculation in recent years has been about physics at energy scales far beyond the reach of terrestrial laboratories, heavenly laboratories have proven invaluable. And finally, the most well-known prediction, $N_\nu \leq 4$, will soon be tested directly.

6. FUNDAMENTAL PHYSICS SOLUTIONS TO THE SOLAR NEUTRINO PROBLEM

For a number of years now there has been a discrepancy of about a factor of three between the predicted rate in Davis' ^{37}Cl experiment solar neutrino experiment ($\simeq$ 8 SNU) and Davis' measured rate ($\simeq 2.1 \pm 0.3$ SNU) (see e.g., Ref. 80). [Before going on I should pause to say that the detection of the ^{8}B solar neutrinos by Davis[81] must rank as one of the most significant and outstanding experimental efforts in this century.] I hasten to remind the reader that the ^{37}Cl experiment is only sensitive to the very energetic ^{8}B ν_e's produced in a reaction chain that accounts for only $\sim 0.02\%$ the energy released by nuclear reactions in the sun; and that the flux of ^{8}B neutrinos is proportiional to the central temperature to a very high power (somewhere between 12 and 22 depending upon which other quantities are held fixed). Bahcall and his collaborators[80] have provided invaluable theoretical support in the solar neutrino effort, most noticeably their predictions for the conversion rate ($^{37}\text{Cl} \rightarrow {}^{37}\text{Ar}$) in Davis' experiment. In addition to his predicted SNU rate, Bahcall[80] also attempts to assign an effective 3σ theoretical uncertainty in the prediction (or as he now terms it, total theoretical range); at present $\sim$ 2.6 SNU. Based upon this 'theoretical 3σ uncertainty' there does indeed appear to be a very significant descrepancy.

To this astrophysicist one of the most important papers submitted at this meeting is the KII collaboration's paper setting an upper limit to the ^{8}B neutrino flux from the sun, $\leq$ 4 SNU (90% cl). Their impressive result, made possible by their heroic efforts to eliminate/control their low energy backgrounds, so that they could detect ^{8}B solar neutrinos of energy as low as 5 MeV (through ν_e-$e^- \to \nu_e$-e^- scattering), is consistent with Davis' low standing radio-chemical result.

How serious is the solar neutrino problem? Being a person who looks at a half-empty beer mug and sees it as being half-full, I am very impressed that ^{8}B neutrinos were indeed detected and that the observed rate indicates a discrepancy in the calculated central temperature of the sun and the experimentally inferred temperature of less than 10%. [Because of the strong temperature dependence of the ^{8}B neutrino flux, measuring this flux has often been likened to taking the solar temperature.] Because I find it difficult to imagine placing a standard deviation on a theoretical framework (in this case the standard solar model), the apparent temperature discrepancy of $\lesssim 10\%$ impresses me more than a '7σ' deviation between experiment (2.1 SNU) and theory (8 SNU). In my heart of hearts, I believe that the solution to the solar neutrino problem probably involves nitty-gritty astrophysics—convection, rotation, magnetic effects, mixing,... However, there is a *prima facie* discrepancy between excellent experiment and equally excellent theory, and the alternative particle physics explanations are so intriguing they deserve very serious consideration. If one of the below mentioned explanations should prove correct, we would learn something very important about fundamental physics at a scale inaccessible to laboratory experiment at present. I list the possible 'fundamental physics' solutions in my own (biased) order of preference.

(1)Neutrino oscillations—thanks to the work of Mikheyev, Smirnov, and Wolfenstein[83], we know that there are three qualitatively different solutions involving neutrino oscillations: (i) 'vacuum oscillations' with large mixing: $\sin^2 2\theta \sim O(1)$ and $\Delta m_\nu^2 \simeq 10^{-4}\ \mathrm{eV}^2 - 10^{-8}\ \mathrm{eV}^2$; (ii) adiabatic matter oscillations (the 'Bethe solution')[84]: $\Delta m_\nu^2 \simeq 10^{-4}\ \mathrm{eV}^2$ and $\sin^2 2\theta \gtrsim 3\times 10^{-4}$; (iii) non-adiabatic matter oscillations[85]: $\sin^2 2\theta \Delta m_\nu^2 \simeq 3\times 10^{-8}\ \mathrm{eV}^2$ (here $\Delta m_\nu^2 = m_{\nu_i}^2 - m_{\nu_e}^2$).

The three different solutions are characterized by very different predicted rates for the Gallium experiment (which is sensitive to the pp low energy neutrinos): (i) similarly low rate in the Gallium experiment; (ii) essentially standard rate in the Gallium experiment; (iii) greater discrepancy in the Gallium experiment. Solutions (ii) and (iii) are particularly attractive, as they do not require large neutrino mixing angles. For a detailed calculation of the rates for the ^{37}Cl and Gallium experiments with MSW neutrino oscillations see Ref. 86.

(2)Relic WIMPs as a core coolant—Faulkner et al.[87] pointed out that particles of mass $\sim (3-10)$ GeV and elastic scattering cross section $\sim 4\times 10^{-36}\mathrm{cm}^2$ (roughly a weak interaction cross section) would act as an ideal 'coolant' in the sun's core, by virtue of having a mean free path comparable to the size of the core. With an abundance of order $\sim 10^{-12}$ per baryon they would transport enough additional heat away from the core to lower the core temperature the required $\sim$10%. This idea was rediscovered by Press and Spergel[88] who suggested in addition that the WIMPs in the sun might be the very same WIMPs which account for the dark matter in the Universe, and that their abundance in the sun could be explained by the sun's capture of relic WIMPs. As it turns out the simplest version of this idea is rendered inviable by WIMP annihilations within the sun[89] (which severely reduces their abundance). This problem is not easily solved as the scattering and annihilation cross sections are of a similar size. Several 'less simple' ideas have been suggested to suppress annihilation while keeping the scattering cross section sufficiently large[90]. They basically involve giving the WIMP a conserved quantum number, and letting its relic abundance be determined by the cosmic asymmetry between WIMPs and anti WIMPs (as the relic abundance of baryons is determined; presumably the WIMP-antiWIMP asymmetry arises in a manner similar to the baryon asymmetry). This of course, obviates the need to worry about WIMP-antiWIMP annihilations. Raby and West[90] have constructed a model wherein the WIMP is a stable 4th generation neutrino whose mass is nearly degenerate with its charged lepton partner, and whose scattering cross section is enhanced by its strong coupling to the Higgs sector (a mass nearly degenerate with its charged partner is needed to evade laboratory bounds on the mass of a 4th generation lepton pair).

For this type of solution, the ^{37}Cl rate is suppressed, but the Gallium rate is unaffected. In addition, in such a model the central density of the sun is necessarily higher than in the standard solar model: this is because the central temperature is lower and the same central pressure ($p \propto \rho T$) is required to support the star. Solar seismology may in the future be able to discriminate between such a model and the standard solar model by providing information about the central density of the sun (see Ref. 80).

(3) Neutrino magnetic moment—Cisneros[91] and Voloshin, et al.[92] have pointed out that a neutrino moment of order $\mu_{\nu_e} \simeq (0.3 - 1.0) \times 10^{-10}\mu_B$ ($\mu_B = e/2m_e$) would permit a solution wherein the left handed ν_e's produced in the sun are rotated to the sterile right-handed state by the sun's magnetic field. Such a large neutrino magnetic moment is difficult to arrange in the standard model; and SN 1987a may already preclude such a large magnetic moment for the electron neutrino[78].

While if I had to bet on solutions to the solar neutrino problem I would put at least half of my money on a solution involving nitty-gritty astrophysics, the three particle physics solutions mentioned above are quite interesting and even more importantly testable! Further results from the KII collaboration, the Gallium experiment, the proposed Sudbury Neutrino Observatory[93], clever new ideas like the liquid ^{4}He detector proposed by Lanou et al.[94], and solar seismology should put these scenarios to the test of experiment, and soon!

7. EPILOGUE

The interface of cosmology, astrophysics, and particle physics has proven to be a very exciting, active, and important area of research in the past decade. Research in this area has brought together a very diverse cast of characters—astrophysicists, astronomers, cosmologists, particle theorists, particle experimentalists, low temperature physicists, cosmic-ray physicists, nuclear physicists, ... The discipline has been dominated by theoretical speculation during this decade. Continued progress and the maturation of the discipline will require experimental and observational grounding, and soon! I am very confident that that will occur over the next years, and boldly proclaim that particle cosmology has come of age. I hope that at a Lepton-Photon Meeting in the not too distant future some of the experimental and observational tests I have disucssed will come to pass and with exciting results to report!

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10. QUESTIONS

R. E. Marshak, Virginia

You have correctly pointed out the great sensitivity of the ^{8}B-generated neutrinos to the central temperature of the sun (approximately the 13th power). For the present solar neutrino problem to exist, this requires an accuracy of just a few percent in Bahcall's calculation. Having been the first to show—almost a half century ago—that Eddington's value of twenty million degrees for the central temperature should be reduced to about fifteen million (when better account is taken of the chemical composition, the opacity, convection, etc.), I simply ask a full-fledged astronomer—which I am not—whether the central solar temperature is now known to better than one million degrees?

Answer

Well if everyone in the audience promises not to get back to John Bahcall, I will remind you that I listed as my number one solution to the solar netrino problem nitty-gritty astrophysics. I think that John has done an exceedingly careful calculation. Perhaps though, he is taking his calculation a bit too seriously. I do not understand how one can put a standard deviation on a theoretical model, and as you point out the model involves various assumptions—for example that the chemical composition of the sun is uniform. Moreover, it relies upon a rather pedestrian treatment of convection and it ignores rotation. I think that it is an exceedingly good model and "prima facie" evidence that there is indeed a problem. In the end if I had to bet 1 DM, I would bet 50 pf that it has to do with astrophysics and 50 pf that it involves fundamental physics. And of course I think fundamental physics solutions are so interesting that they should be pursued.

B.F.L. Ward, Tennessee

In your list of passionate speculations which may be tested experimentally soon, you list $N_\nu \leq 4$. I had always thought that this was a relatively firm result of the standard cosmological model. Why do you call it a "passionate speculation"?

Answer

It must be my Italian blood...Seriously, I mean this too is a theoretical prediction of the standard cosmology. Perhaps speculation is too strong a word, but it is a very significant test of Big Bang nucleosynthesis, which is our earliest test of the standard cosmology as we work our way back to the Planck time. The light elements are the oldest relics we have, and the Big Bang cosmology has gone out on a limb and says look, all these elemental abundances agree, but only if $N_\nu \leq 4$. If you guys come back and show us that there are six light neutrino families then I suspect I won't get invited to a meeting like this soon. On the other hand if you show that there are indeed less that or equal to four light neutrino flavors, that would be a striking confirmation of this prediction.

T. Degrand, Colorado

One conclusion which I get from your talk is that all of the problems which you discussed are solved by particles which have never been seen and in fact none of the particles which we already have discovered are any good for solving any cosmological problems!

Answer

Hopefully that will be rectified...and soon! I do think some of the speculations are amenable to test in the near future; admittedly, inflation is not likely to be directly confirmed by experiments done in earthly laboratories in the near future, but there are aspects of it that can be tested. For example, that dark matter dominates the mass density and that the dark matter is relic particles can and is being tested. Perhaps I did not devote enough time to that part of my talk. I think that the experiments that attempting to detect the sea of WIMP's that we are swimming in are extremely exciting and important. Let me again mention one experiment, the Fermilab-Brookhaven-Rochester collaboration looking for relic axions, whose coupling strength is $\sim 1/10^{12}$ GeV. They already have some interesting preliminary results[45], and are coming close to testing the axion as a dark matter candidate. It could be that two years from now they will be giving one of the most important talks of this meeting reporting that they have detected relic axions; or it could be the photinos will be discovered in a cryogenic detector. While you are right, some of the predictions are still beyond reach, some of them are coming within our grasp and will test these early Universe speculations in a very important and dramatic way.

R.G.H. Robertson, Los Alamos National Laboratory

I take it that you are not impressed by models recently proposed where an inhomogeneous baryon number density allows one to get $\Omega_B = 1$. I am speaking, for example, of the work of G. Mathews et. al. at Livermore.

Answer

In the last couple of years, a number of people have been considered whether or not the quark-hadron transition could have important implications for primordial nucleosynthesis. In particular, several groups have been studying the idea that quark-hadron transition could lead to local inhomogeneities in the baryon to photon ratio and that primordial nucleosynthesis could be quite a bit more complicated than we thought. Until a few months ago many authors, including the ones you have mentioned, were making claims that when you took these inhomogeneities into account it could be possible to have $\Omega_B = 1$. If true, this would be exceedingly interesting. However, I think that there is beginning to be a consensus now that this is unlikely for several reasons. First of all, in order for this scenario to work, the deconfinement transition temperature would have to be around 100 MeV, while the lattice calculations are giving a temperature more like 125-200 MeV or greater. Second, the deconfinement transition would have to be strongly-first order and the indications are that it is perhaps first order but probably not strongly first order. And thirdly, let us suppose there is a strongly first-order deconfinement transition at 100 MeV, two very big suppositions. Then we have to ask can we have $\Omega_B = 1$ and still have concordance between theory and observation. I think that the answer to this is a resounding NO, the problem being ^{7}Li. In such models, to have $\Omega_B = 1$, one overproduces ^{7}Li by something like a factor of 1000.