PARTICLE ASTROPHYSICS AFTER COBE
BLOIS92 SUMMARY TALK

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Abstract

The IV Rencontres de Blois, on Particle Astrophysics, held at the Château de Blois, June 15-20, 1992, was a meeting well-timed for a reconsideration of the issues in particle astrophysics in the light of the COBE discovery of the cosmic microwave background (CMB) fluctuations. This is a summary of what I thought were the most interesting things discussed at Blois: (1) The near-success of Cold Dark Matter (CDM) in predicting the COBE fluctuation amplitude, which favors the hypothesis that structure formed in the universe through gravitational collapse. (2) The indications that \( \Omega \approx 1 \) and that the power spectrum has a little more power on supercluster and larger scales than CDM. These are suggested by the IRAS and CfA redshift surveys and POTENT galaxy peculiar velocity analysis, and also by the COBE data. (3) The consequent demise of CDM and the rise of hybrid schemes such as Cold+Hot Dark Matter (C+HDM). (4) The possible implications for neutrino masses and mixings, and for cosmology, of the recent results on solar neutrinos. (5) The first discovery of TeV \( \gamma \) rays from an extragalactic source, which was announced at Blois.

I also summarize here a number of the exciting ongoing and planned experiments and observations discussed at Blois: CERN experiments on \( \nu_\mu \nu_\tau \) oscillations, which may be sufficiently sensitive to detect the \( \nu_\tau \) if its mass lies in the cosmologically interesting mass range 1-10^2 eV; dark matter searches, including the French
and Berkeley-Livermore-Mt. Stromlo MACHO search and the searches for WIMPs and axions; and the construction of ambitious laser interferometer gravity wave detectors such as LIGO in the U.S. and VIRGO in France and Italy. The commitment of funds for VIRGO was announced at Blois by the French Minister of Research and Space, Hubert Curien.
I. Introduction

The goal of Particle Astrophysics is to construct a fundamental theory of the material universe—i.e., to explain elegantly and economically observations from the smallest physical scale to the entire cosmological horizon. Of course, science can never tell us which theories are “true”; at best it can only tell us which are false. Paradoxically, the theories that most closely approach truth are those whose limits are known, like Newtonian Mechanics. We know where Newtonian Mechanics is valid because we know precisely where and how it fails, since it is enveloped on all sides by more accurate theories: Quantum Mechanics for small sizes, Special Relativity for high speeds, General Relativity for large size or large gravitational potential $\phi \sim m/r$.\[^{[1]}\] It has even been possible to combine some of these theories, as in QED. But we do not know where or how these theories in turn fail. So our goal is to construct enveloping theories for them.

In particular, in particle physics our goal is to construct an enveloping theory for the 3-2-1 “Standard Model,” based on the $\text{SU}(3)_c \times [\text{SU}(2) \times \text{U}(1)]_{\text{ew}}$ gauge group for three generations of quarks and leptons, with all three neutrinos massless. A century ago, there were only a few “clouds on the horizon” portending the storms that destroyed classical physics. Perhaps the main cloud now on the horizon of the particle physics Standard Model is the hint of neutrino mass from the solar neutrino data, which I will summarise in §IV.

In cosmology, we do not yet even have a fundamental theory. Cosmology today is like physics before Newtonian Mechanics or geology before Plate Tectonics. We only have bits and pieces of the story. Perhaps standard Big Bang Nucleosynthesis is such a piece. Almost certainly General Relativity is. Cold Dark Matter (CDM) was an educated guess regarding such a fundamental theory. But, like the original SU(5) Grand Unified Theory in particle physics, CDM was apparently too simple to be true, as I will summarize in §II-III. In constructing a fundamental theory of cosmology, it now appears that the data requires a hybrid theory containing elements of at least two simpler theories, such as Cold + Hot Dark Matter (C+HDM; see §III). The resulting theory may thus be a little like the 3-2-1 standard model of particle physics, which is of course also a hybrid theory. Another possibly useful analogy is elliptical planetary orbits. For millennia, until Kepler and Newton, astronomical prejudice favored circles; now we know that only an unusual accident of planetary formation would give truly circular orbits (i.e., very small ellipticity).

II. Cold Dark Matter

In saying that the data do not favor the original CDM theory, I do not mean to imply that there is any evidence against all or most of the dark matter being of the “cold” variety, such as weakly interacting massive particles (WIMPs) or axions. I propose to use capital letters CDM (Cold Dark Matter) to refer to the “standard
CDM” theory based not only on the assumption that the dark matter is cold, but also on the assumptions that structure in the universe grew gravitationally from Gaussian adiabatic fluctuations with a Zel’dovich spectrum in a universe of critical density (Ω = 1). These latter assumptions are of course just what the simplest versions of inflation imply.\(^2\)

With CDM, the primordial Zel’dovich \(|\delta_k|^2 \propto k^n\) spectrum with \(n = 1\) is preserved on large scales but tilted toward \(n \approx -3\) on short scales because matter fluctuations that enter the horizon in the radiation-dominated universe grow only logarithmically.\(^3\) The division between these regimes occurs at the transition between radiation and matter domination, which corresponds to a length scale of about 13 \((\Omega_0 h^2)^{-1}\) Mpc, or a mass scale of about \(3.2 \times 10^{14} (\Omega_0 h^2)^{-2} M_\odot\). This is where the CDM fluctuation spectrum has a “knee;” for lengths or masses larger than this, the amplitude of the fluctuations starts to fall off rapidly, approaching the primordial Zel’dovich spectrum on large length scales.

Standard CDM\(^4\) with biased galaxy formation\(^5\) gives an excellent account of structure formation from galaxy to cluster scales. But as Juskiewicz summarizes in these proceedings, all the available evidence on large scale structure—from the galaxy streaming velocities, APM\(^6\) and COSMOS\(^7\) measurements of the galaxy angular correlation function \(w_g(\theta)\), IRAS and CfA redshift surveys (see also de Lapparent, these proceedings), radio galaxy and rich clusters data,\(^8\) and now COBE—is pretty consistent. And this evidence suggests that a little more power is required on length scales of \(\sim 10^2\) Mpc and beyond than that in the CDM fluctuation spectrum—at least, if the visible matter is related to the underlying mass distribution in a simple way.\(^9\) CDM could perhaps be consistent with the data if galaxy formation, like the weather, is such a complicated process that it can only be described by a rather arbitrary biasing prescription.\(^10\) But as an originator of CDM, I have always felt that one of its most attractive features is its highly predictive character. So I consider such CDM models to be non-standard, and not obviously more attractive than other CDM variants such as \(\Omega = 0\) CDM or C+HDM, for example.

To keep the situation in perspective, it is important to note that CDM does not fail by very much. COBE sees \(10^\circ\) fluctuations with rms amplitude over the whole sky of \(\Delta T/T \approx 10^{-5}\). The amplitude predicted by standard CDM is \(10^{-5}/b\), where the biasing factor \(b\) is as usual the inverse of the rms mass fluctuation in a sphere of radius 8 \(h^{-1}\) Mpc.\(^11\) Thus with \(b = 1\), CDM agrees with COBE, and also incidentally with much of the large scale data. However, almost all nonlinear CDM calculations agree that \(b \approx 1\) CDM predicts galaxy velocities on small scales that are too high, while \(b \approx 2.5\) does much better in this regard. Thus the problem with CDM is only about a factor of two or three. But the COBE and large scale galaxy
distribution data are now so good that this sort of fudge is unacceptable! However, this near-agreement certainly does suggest that some—perhaps most—of the basic assumptions of CDM may be right. In particular, it suggests that structure grew in the universe by gravitational collapse rather than, for example, because of energy input from giant explosions: Matter fell, it wasn’t pushed!

III. Hybrid Models for Large Scale Structure

Perhaps the simplest variant of CDM that remains viable has $\Omega \approx 0.2$ with $h \approx 1$ and a cosmological constant $\lambda \equiv \Lambda/3H_0^2 = 1 - \Omega$ for consistency with inflation and with CMB constraints. This model has more large scale power than standard CDM mainly because matter domination occurs later with $\Omega$ lower, so the “knee” in the power spectrum is moved to larger scales. This model is claimed to be consistent with the galaxy angular correlation function $w_\theta(\theta),$\textsuperscript{12} with the observed rich cluster correlation function $\xi_c(r),$\textsuperscript{13} and mass function,\textsuperscript{14} and with power spectra from clusters,\textsuperscript{15} the CfA slices (de Lapparent, these proceedings), and the Southern Sky redshift survey.\textsuperscript{16} There is a possible problem in this model simultaneously fitting the large-scale peculiar velocities, which require small linear bias $b < 1$, and COBE, which requires larger $b.$\textsuperscript{17}

There are, moreover, several indications that $\Omega \approx 1$, for example CMB dipole vs. QDOT/IRAS data, comparison of IRAS density and galaxy peculiar velocity data, reconstructing Gaussian initial conditions from the POTENT analysis of galaxy peculiar velocity data, and void outflow (see the talks by Dekel and Yahil in these proceedings). While this evidence that $\Omega = 1$ is still not compelling, and the arguments for a large Hubble parameter\textsuperscript{18} and an old universe do point toward smaller $\Omega$, I personally am persuaded that it is likely that $\Omega = 1$.

The question arises whether any $\Omega = 1$ model with a physically motivated smooth spectrum of adiabatic Gaussian fluctuations can account for all the data now available, including the COBE CMB fluctuations (corresponding to scales of 3000–300 h$^{-1}$ Mpc), large scale structure data (300–10 h$^{-1}$ Mpc scales: galaxy angular correlations $w_\theta(\theta)$, the cluster correlation function $\xi_c(r)$, and galaxy streaming velocities, etc.), and smaller scale structure data (10 h$^{-1}$ Mpc–10 h$^{-1}$ kpc: galaxy formation, correlations, and velocities)?

One variant of standard CDM that has received much attention recently\textsuperscript{19} keeps all the usual assumptions except the Zel’dovich primordial spectrum $|\delta_k|^2 \propto k^n$ with $n = 1$, substituting instead “tilted” spectra with $n \approx 0.5 - 0.7$ that arise from more or less complicated inflationary models. Such models have the virtue of being very well specified, with $n$ being the only additional parameter beyond those of standard CDM. However, the latest and most detailed studies\textsuperscript{20} conclude that “tilted” CDM is marginal at best. For example, for $n < 0.6$, sufficiently small
to account for the observed large scale structure, there is probably too little early galaxy formation. Of course, it is possible to get much more general non-Zel’dovich primordial fluctuation spectra from inflation\textsuperscript{[21]} but these “designer spectra” are neither well motivated nor well specified.

I will use the phrase Cold + Hot Dark Matter (C+HDM) to refer to a model with $\Omega = 1$ having roughly half as much hot (light neutrino) dark matter as cold dark matter. These proportions of hot and cold dark matter are required to fit the large-scale structure data (as I discuss further in my contributed paper in these proceedings). C+HDM is physically at least as well motivated as tilted CDM or any other variant of CDM that we know. Moreover it is well specified and has only one additional parameter beyond those of standard CDM: the neutrino mass $m(\nu_\tau)$, or equivalently

$$
\Omega_\nu = \left[ \frac{m(\nu_\tau)}{23 \text{ eV}} \right] h_{50}^{-2},
$$

where $h_{50}(= 2h)$ is the Hubble parameter $H_0$ in units of 50 km s$^{-1}$ Mpc$^{-1}$\textsuperscript{[22]} The required value of $m(\nu_\tau)$, about 7 eV for $h_{50} \approx 1$, is consistent with the value implied by the currently available solar neutrino data plus the old “seesaw” models of neutrino masses, as I will discuss in §IV below. The neutrinos provide an unclustered dark matter component on small scales, which could help explain why dynamical estimates give $\Omega < 1$ on small scales. The out-of-equilibrium relativistic Fermi-Dirac statistics of the neutrinos\textsuperscript{[23]} enhances this effect.

The main objection to C+HDM in principle is the apparent unlikelihood of having two different dark matter components each making comparable contributions to the mass density. Although one of the earliest C+HDM papers\textsuperscript{[24]} proposed a particle physics model to account for this, I am unaware of any such model that is attractive. However, the entire particle physics Standard Model begs for further explanation, so it should not disturb us to contemplate one more feature that, if valid, would call for a more fundamental justification.

Basic properties of mixed dark matter models were worked out some time ago;\textsuperscript{[25]} and the fact that C+HDM with $\Omega_{cdm} \approx 0.6$ and $\Omega_\nu \approx 0.3$ is a promising model for large scale structure was established by several previous linear calculations.\textsuperscript{[26]} The C+HDM power spectrum\textsuperscript{[27]} fits the data better than any other model yet proposed.\textsuperscript{[28]} A simplified nonlinear calculation in a 14 Mpc box has been done with the initial neutrino fluctuations set equal to zero.\textsuperscript{[29]} My colleagues and I have just done the first detailed nonlinear calculations for C+HDM, with proper initial conditions, sufficiently many hot particles to sample velocity space adequately, and a careful analysis of dark matter and galaxy correlations and velocities with comparisons to the available data.\textsuperscript{[30]} We find that C+HDM normalized with linear bias factor $b = 1.5$ is consistent both with the COBE data and with
the observed galaxy correlations. The number density of galaxy-mass halos is only a little smaller than for CDM at zero redshift but increasingly smaller at redshift \( z > 2 \), but the numbers of cluster-mass halos are slightly larger. We also find that on galaxy scales the neutrino velocities and flatter power spectrum in C+HDM result in galaxy pairwise velocities that are in good agreement with the data, and about 30\% smaller than in CDM with the same biasing factor. On scales of several tens of Mpc, the C+HDM streaming velocities are considerably larger than CDM. As a result, the “cosmic Mach number”\(^{[31]}\) in C+HDM is about a factor of two larger than in CDM, and probably in better agreement with observations.

Thus C+HDM looks promising as a model of structure formation. The presence of a hot component requires the introduction of a single additional parameter beyond standard CDM — \( m(\nu_\tau) \) or equivalently \( \Omega_\nu \) — and allows this model to fit essentially all the available cosmological data remarkably well—except the latest upper limit on \( \sim 1^\circ \) CMB fluctuations from the Santa Barbara South Pole experiment.\(^{[32]}\) It has been claimed that no Gaussian model can simultaneously account for these data and the high values of the large scale galaxy streaming velocities suggested by the latest data.\(^{[33]}\) However, only one channel of the South Pole data were analyzed, with the signal in the other three channels is interpreted as being galactic in origin.\(^{[32]}\) It will be interesting to see whether independent data sets show \( \sim 1^\circ \) CMB fluctuations at the level predicted by C+HDM.

Of the non-Gaussian models that have been proposed,\(^{[34]}\) the idea of structure formation by wakes of long cosmic strings is now perhaps the most interesting one. Cosmic strings and cosmic texture are both generic, in the sense that particle physics Lagrangians with suitable sets of scalar fields will automatically generate such topological structures in the early universe. The texture model now appears to be ruled out by the COBE data.\(^{[35]}\) And the version of cosmic strings that was most thoroughly investigated, in which structure is seeded by small loops of cosmic string, has now been ruled out since high resolution simulations show that these loops do not survive long enough: they are quickly cut up by string crossing and reconnection.

The \( \Omega = 1 \) long-string-wake Strings + Hot Dark Matter model is well motivated and well specified—in fact, it has only one parameter, the mass per unit length on the string. The dark matter in this scheme is presumably hot dark matter: a \( \tau \) neutrino with mass \( m(\nu_\tau) \) given by Eq. (1). This (like the \( m(\nu_\tau) \) needed for C+HDM) is in the range suggested by the MSW explanation of the solar neutrino data plus simple seesaw neutrino mass models. With long string wakes providing the seeds for structure formation, using hot rather than cold dark matter gives this model relatively more large scale power and is expected to suppress the formation of dense cores of dark matter in galaxies. Preliminary investigation of this scenario
suggests that it might be consistent with COBE and the large scale structure data (Bouchet, these proceedings). More detailed calculations will be required to see whether this is really true, and also whether the galaxies formed in this model have the right properties and distribution.

My sketched Figure summarizes this discussion. The three most popular models for large scale structure of the early-to-mid-1980s—HDM, CDM, and Cosmic String Loops—are now all dead and buried (at least in their simplest incarnations). Let them rest in peace! But from their graves the three leading present models are growing: CDM in an $\Omega \approx 0.2$ universe with a cosmological constant, $\Omega = 1$ C+HDM, and $\Omega = 1$ String Wakes (with hot dark matter). The former two are Gaussian models consistent with cosmic inflation, the latter is a non-Gaussian model that may be consistent with inflation. If measurements of the cosmological parameters turn out to give low $\Omega$ and high $H_0 = 80 - 100$ km s$^{-1}$ Mpc$^{-1}$, then the first of these models is favored. If the indications from galaxy peculiar velocities and other data that $\Omega \approx 1$ are valid, then the latter two models are favored. Of course, many other models have been proposed, and many more are possible. We have been surprised before by the data and are likely to be surprised again!

IV. Solar Neutrinos, Neutrino Masses, and Hot Dark Matter

The GALLEX intermediate-energy solar neutrino flux of $83 \pm 19 \pm 8$ SNU (d’Angelo, these proceedings) is only a little less than expected in the Standard Solar Model (SSM); and the entire SAGE dataset (Gavrin, these proceedings) is not in disagreement with this. However, the high-energy solar neutrino data from Kamiokande-III and Homestake (Totsuko, Lande, these proceedings) are not compatible with the SSM (Bahcall, Turck-Chièze, these proceedings). The MSW neutrino-oscillation idea now seems very attractive—and certainly less ad hoc than other proposed solutions to the solar neutrino puzzle. It is interesting that it may also help explain why supernovae explode (see Raffelt, these proceedings).

The MSW scheme requires that both the electron neutrino $\nu_e$ and at least one other neutrino—say, the muon neutrino $\nu_\mu$—have a nonvanishing mass, with $m(\nu_\mu) > m(\nu_e)$. Then the electron neutrinos emitted in the center of the sun get an effective mass $m_{\text{eff}}(\nu_e)$ because of the high electron density there. MSW also requires that $m(\nu_\mu) < m_{\text{eff}}(\nu_e)$, and that there be a nonvanishing mixing between $\nu_\mu$ and $\nu_e$, analogous to the Cabibbo mixing between the first two quark generations. Then as the $\nu_e$’s stream out of the center of the sun, $m_{\text{eff}}(\nu_e)$ decreases and eventually crosses $m(\nu_\mu)$. As usual in quantum-mechanical level crossing, the probability of conversion of $\nu_e$ into $\nu_\mu$ will depend on the $\nu_e$ energy and on the neutrino mixing and Masses—actually on $m(\nu_\mu)^2 - m(\nu_e)^2$. If we assume that
\(m(\nu_{\mu}) \gg m(\nu_e)\), then the combined solar neutrino data imply that

\[m(\nu_{\mu}) \approx (2 - 3) \times 10^{-3} \text{eV},\]  

(2)

with the \(\nu_e\nu_\mu\) mixing angle \(\theta_{e\mu}\) confined to two small regions, either large or small (nonadiabatic) mixing (\(\sin 2\theta_{e\mu} \approx 0.8\) or 0.1).

A muon neutrino mass in this range was expected in the context of the “seesaw” mechanism for generating neutrino masses,\(^{[38]}\) in which the light left-handed neutrinos mix with heavy (mass \(M\)) right-handed Majorana neutrinos. The resulting neutrino masses are related to the squares of the masses of the upper component quarks of the same generations: \(m(\nu_{e,\mu,\tau}) \approx m_{u,c,t}^2/M\);\(^{[39]}\) so

\[m(\nu_\tau) = \eta(m_t/m_c)^2m(\nu_\mu),\]  

(3)

where \(\eta \sim 0.3\) is a model-dependent factor including the effects of the running of coupling constants. With \(m(\nu_\mu)\) of Eq. (2) from the solar neutrino data, and a top quark mass \(\sim 10^2\) times that of the charmed quark, this leads to \(m(\nu_\tau) \sim 10\) eV, and correspondingly to a cosmological density of \(\tau\) neutrinos again given by Eq. (1). Even if the seesaw idea is right, however, it remains an assumption of simplicity that the heavy right-handed neutrinos in all three generations have essentially the same mass \(M\); if this is not true, then the mass estimate for \(m(\nu_\tau)\) above is invalid.

Most exciting, the Chorus and Nomad \(\nu_\mu\nu_\tau\) oscillation experiments now underway at CERN should see a signal within about two years if these neutrino mass and mixing models are right (Vanucci, these proceedings and §V below).

To summarize: the very plausible MSW explanation of the solar neutrino data requires neutrino mass, and thereby goes beyond the Standard Model of particle physics. And the combination of that, together with the admittedly rather speculative seesaw model of neutrino masses with a single intermediate mass scale \(M\), leads to the prediction that light \(\tau\) neutrinos—hot dark matter—may be all or at least a considerable fraction of the dark matter.

V. Dark Matter Detection

A. Light neutrinos—new neutrino oscillation experiments

These speculations about neutrino masses can be tested by experiments now underway at CERN, and also by using the next generation of solar neutrino detectors, including Super-Kamiokande and Sudbury Neutrino Observatory, to clarify the energy-dependence and generational composition of the solar neutrinos reaching the earth. By measuring the energy spectrum of high energy solar neutrinos
using both charged and neutral current interactions, these experiments can help determine whether the MSW model can explain the data, and if so for which values of muon neutrino mass and $\nu_e\nu_\mu$ mixing angle (Totsuka, Bahcall, these proceedings).

Because they are less well known than the solar neutrino experiments, I will describe here in a little more detail the new $\nu_\mu\nu_\tau$ oscillation experiments now being built at CERN (Vanucci, these proceedings). In the Chorus experiment (CERN-WA-095, approved September 1991), a beam of muon neutrinos produced by the proton beam of the CERN-SPS accelerator is directed at a target consisting of nearly a ton of nuclear emulsion stacks. If $m(\nu_\tau)$ lies in the cosmologically interesting range from a few eV to $\sim 10^2$ eV and the $\nu_\mu\nu_\tau$ mixing angle $\theta$ satisfies $\sin^2 2\theta \gtrsim 3 \times 10^{-4}$, then a substantial number of $\nu_\mu$ will oscillate to $\nu_\tau$ on their way to the detector. The emulsion stack will then capture the $\sim 1$ mm tracks of the relativistic $\tau$ leptons produced by $\nu_\tau + \text{nucleon} \rightarrow \tau^- + X$, thereby providing the first direct evidence for the $\tau$ lepton as well as a measurement of its mass and of $\theta$. The hard part is finding the tracks! They are to be located by a combination of techniques, including scintillating fiber trackers, a layer of emulsion that is changed biweekly, and a calorimeter that tags the $\tau^-$ decay by its transverse momentum imbalance. The complementary Nomad experiment (CERN-WA-096, also approved September 1991) looks for $\tau$ production from the $\nu_\mu$ beam in a 3 ton drift chamber target by a magnetic detector based on the old CERN UA1 magnet. It searches for the various decay modes of the $\tau$ using kinematical criteria, and has roughly the same sensitivity as Chorus.

Are these experiments sensitive enough? Yes, if the $\nu_\mu\nu_\tau$ mixing angle $\theta$ is comparable to the corresponding quark mixing angle $\theta_{23} \approx 0.04\pm0.01$, which would imply $\sin^2 2\theta \gtrsim \text{few} \times 10^{-3}$. Several particle physics models of neutrino masses and mixings also suggest that Chorus and Nomad may be sensitive enough. But even if $\theta$ is too small for $\tau$s from $\nu_\mu\nu_\tau$ oscillations to be seen in these CERN experiments, all is not lost: an emulsion experiment similar to Chorus has been proposed at Fermilab that will be an order of magnitude more sensitive after the injector upgrade has been completed. Thus it seems quite likely that if $m(\nu_\tau)$ is in the range required for Cold + Hot Dark Matter or Strings + Hot Dark Matter models, this will soon be confirmed by accelerator experiments.

B. WIMPs and Axions

The cold dark matter particle candidates that are well-motivated (in the sense that they have been proposed for good particle-physics reasons independent of their possible cosmological properties) are axions, still the best solution to the strong-CP problem, and weakly interacting massive particles (WIMPs), in particular the lightest supersymmetric partner particle (LSP). Both are detectable in the laboratory (Sadoulet, these proceedings).
WIMPs that form the halo of our galaxy have an rms speed of about $v = 300 \text{ km s}^{-1} = 10^{-3} c$ (a little higher than the 220 km s$^{-1}$ orbital speed of the sun in the galactic disk, since the velocity of halo matter should be essentially isotropic). Thus a WIMP of mass $m$ has kinetic energy $\frac{1}{2}mv^2 = \frac{1}{2}(mc^2/\text{Gev}) \text{ keV}$, which can be transferred as recoil energy to a nucleus in a target in the laboratory. The probability of such interactions is of course determined by the collision cross section; non-detection of such events by ionization detectors has already excluded large-cross-section WIMPs such as massive Dirac neutrinos for a large range of masses. A typical event rate for allowed LSP WIMP dark matter particles is of the order of an event per kg of target material per day, so the problems are to have a large enough target to get a decent event rate, and then to distinguish these dark matter events from various backgrounds. The group associated with the Center for Particle Astrophysics at Berkeley has demonstrated the efficacy of background rejection by simultaneous detection of ionization and phonons from the nuclear recoil in a germanium detector at a few millidegrees K. (Nuclear recoil produces a weaker ionization but a stronger phonon signal, while the energy distribution is just the opposite for the main background, electron recoil from Compton scattering.) Other groups are pursuing other approaches. It is clear that detection of WIMP dark matter will be hard, but it does appear to be technologically feasible. In a few years, experiments will either have discovered the dark matter WIMP or ruled out a significant part of the possible parameter space.

Axion searches attempt to detect the conversion of axions, expected to have rest mass about $10^{-5} \text{ eV}$, into photons of the same energy in a strong magnetic field. (Despite their low mass, axions are cold rather than hot dark matter since they form as a non-thermal vacuum condensate.) Such searches have been conducted both at Brookhaven National Laboratory and at the University of Florida, but their sensitivity was about two orders of magnitude too low to detect the predicted axion density. The detection probability goes as the volume times the square of the magnetic field, so it is hoped that the availability of a large powerful magnet at Livermore National Laboratory will permit a search with sufficient sensitivity to detect axion dark matter or rule out essentially the entire expected mass range.

C. Searching for MACHOs by microlensing

It is possible that at least a fraction of the dark matter in galaxy halos consists of some sort of astrophysical objects. One possibility is that most of the ordinary matter in the Universe may have been processed through a first generation of “Population III” stars. Dark remnants of these objects have been termed “Massive Astrophysical Compact Halo Objects” (MACHOs) by Kim Griest.

What form might the MACHOs take? A variety of constraints suggests that they might either be black hole remnants of a population of “Very Massive Objects”
(VMOs) larger than 100 $M_\odot$ that collapse entirely without ejecta during their oxygen burning stage, or else objects that are too small to burn hydrogen at all (brown dwarfs or jupiters). It is also possible that they are primordial black holes.

If the MACHOs are VMO remnants, they would have two important observational signatures: a background of gravitational radiation generated by the black hole collapses and a background of electromagnetic radiation generated by the VMOs’ nuclear-burning phase. The gravitational radiation may be detectable when laser interferometers go on the air in the mid-1990s (see §VII below), but this depends on the very uncertain efficiency with which collapsing VMOs produce gravitational waves. The electromagnetic radiation background might peak at 10 microns, where it would be hidden by zodiacal light; or it could have been reprocessed by dust scattering, in which case it would produce near-infrared spectral distortions that the DIRBE instrument on COBE could observe, anticorrelated in angle with submillimeter CMB fluctuations.[41]

The most interesting observational consequence of jupiters would be their gravitational microlensing effects. Lensing occurs because light is bent in a gravitational field. There are two distinct effects. “Macrolensing” occurs when the light from a distant object like a quasar is bent by the gravity of an intervening galaxy or cluster to produce multiple images. “Microlensing” occurs at similar cosmological distances when an individual halo object traverses one of the macrolensed images, thereby causing its brightness to vary relative to the other images. This is only detectable at cosmological distances for halo objects in the mass range below 0.1 $M_\odot$ because the timescale of the fluctuation increases as the square root of the deflector mass and exceeds an astronomer’s lifetime above 0.1 $M_\odot$. One can therefore use this effect to look for jupiters but not VMO remnants. In fact, there is already one claimed case of microlensing of a quasar,[42] with the deflector mass in the range 0.001 - 0.1 $M_\odot$. However, in this case the optical depth for microlensing was probably greater than unity along the light path through the center of the lensing galaxy, which makes the deduction of the deflector mass uncertain. Also, near a galaxy center the most likely deflectors are ordinary matter rather than MACHOs.

The most promising approach appears to be to seek microlensing by MACHOs in our own Galactic halo by looking for intensity variations of stars in the Large Magellanic Cloud (LMC).[43] In this case the timescale of the variation is shorter, about a week for a lensing object of 0.1 $M_\odot$. It again varies as the square root of the microlensing mass, so that it would be practical to look for black hole remnants from VMOs as well as jupiters. However, the probability of a particular star being microlensed is only $\sim 10^{-6}$, so one therefore has to look repeatedly at many stars.

Two groups have initiated searches for local microlensing. A group of French
astronomers and particle physicists, represented at Blois by Ansari, has analysed
Schmidt telescope plates of the LMC, several hundred of which are presently avail-
able, half taken since supernova 1987A. Both they and the Berkeley-Livermore-Mt.
Stromlo (Australia) collaboration are also repeatedly imaging the LMC with CCD
cameras on dedicated telescopes in the Southern Hemisphere. Since microlensing
events with light amplification factor $A$ are distributed uniformly in $A^{-1}$ (which is
proportional to the distance of closest approach of the lensing object to the line of
sight to the lensed star), the large-$A$ events that will provide the most convincing
signal should not be that uncommon. But large-$A$ events have short duration,
and the requirement of frequent sampling favors the CCD approach over plates
in searching for jupiters. The fact that the increase in a star’s brightness due to
microlensing is independent of wavelength should help to distinguish lensing events
from intrinsic stellar variations, in which the color usually changes with brightness.

VI. Getting Close to the Monsters

By “monsters” I mean the compact objects such as black holes that presum-
ably power the astrophysical sources of many of the highest energy particles. Of
course, the only particles whose sources we can trace are those that travel in
straight lines—photons or neutrinos, or perhaps the very highest energy charged
particles. The directions of charged particles of lower energy are randomized by
the magnetic fields in our galaxy. Since several detectors have now seen high en-
ergy photons from the Crab pulsar, including observations of TeV photons by the
Whipple Čerenkov telescope (Weekes, these proceedings), subsequently confirmed
by two French experiments, we know that neutron stars can produce TeV particles.
(Čerenkov telescopes observe the Čerenkov radiation produced in the atmosphere
by the particle showers initiated by energetic cosmic rays.)

EGRET, which has the highest energy sensitivity of the four photon detectors
on the Compton Gamma Ray Observatory, has detected GeV photons from the
directions of several extragalactic sources (Strong, these proceedings), including the
quasars 3C373 and 3C279. All these sources are Active Galactic Nuclei (AGNs)
of the “blazar” variety, thought to be cases where the axis of powerful beamed
radiation is oriented almost directly along our line of sight.$^{[44]}$

One of the most exciting announcements at Blois92 was the first detection
of TeV extragalactic $\gamma$ rays, again by the Whipple Čerenkov telescope (Lamb,
these proceedings)$^{[45]}$. The flux detected above 0.5 TeV was 0.3 that of the Crab
Nebula. What was perhaps most notable about this discovery was the fact that the
source was not 3C279 but rather the galaxy Mkn 421, the nearest of the EGRET
extragalactic sources, at a distance of about 90 $h^{-1}$ Mpc ($z = 0.031$). When it
was flaring last spring, 3C279 was brighter than Mkn 421 at the GeV energies to
which EGRET is sensitive, even though 3C279, at a redshift $z = 0.538$, is much
farther away. But the Whipple telescope could not detect 3C279. An appealing explanation is that the TeV photons from the more distant sources were absorbed by $\gamma + \gamma \rightarrow e^+ + e^-$ scattering on redshifted starlight. For typical estimates of the density of such starlight, the universe will be optically thick to TeV photons for redshift $z \gtrsim 0.2$ (Stecker, these proceedings).

A TeV photon scattering on an eV starlight photon has a center-of-mass energy of order an MeV, just enough to produce a $e^+e^-$ pair. The $e^+e^-$ pair production cross section is largest just above threshold, so the absorption should be greatest for TeV energies. This explanation of the nonobservation of the more distant sources of GeV photons can be confirmed by observing high-energy photon sources at intermediate distances and at higher energies, using Čerenkov telescopes and/or extensive air shower arrays (Ong, these proceedings). If it turns out to be right, it opens a new sort of astronomy, since this indirect observation of the density of redshifted starlight can probe the era of galaxy formation. (I know of no other way to measure the density of eV photons in the universe. We can’t do it nearby, since the Milky Way is itself a copious source of near-infrared photons.)

Yet another new sort of astronomy is suggested by these observations. It is plausible that all EGRET AGNs are powerful sources of high energy neutrinos as well as photons. The new large neutrino telescopes such as DUMAND (in the sea near Hawaii) and AMANDA (in the ice at the South Pole) should be able to detect TeV neutrinos from the same sources. The fluxes, energy spectra, and time behavior of these high energy neutral particle signals should tell us much about the physics in the exotic regions close to the monsters (Stecker, these proceedings).

The directions of the highest energy cosmic rays, those with $E \gtrsim 4 \times 10^{19}$ eV, are not isotropic; the favored direction is in the general direction of the Virgo cluster, the nearest large concentration of galaxies (Cesarsky, Cronin, these proceedings), although it is not entirely clear that this is statistically significant when observational biases are taken into account. Determining the direction of the highest energy cosmic rays could clarify both their composition and sources. Remarkably, it appears to be possible to build a detector for such cosmic rays with the huge collection area of $\sim 5000$ km$^2$ for as little as $\$50$ million (Cronin, these proceedings). Depending on the flux extrapolation, such a detector could collect $\sim 5000$ events per year with $E > 10^{19}$ eV (five times the total seen so far) and $\sim 5$ per year with $E > 10^{20}$ eV.

Although $\gamma$ ray bursts have long been known (they were first discovered in the 1960s by satellites designed to detect nuclear explosions on or near the earth), the accumulating statistics from the BATSE detector on the Compton GRO satellite have shown that their distribution is remarkably isotropic. This makes it unlikely that their sources are galactic (unless they are close to the solar system) or even
in nearby galaxies, since the stars in our galaxy and the nearby galaxies are both quite anisotropically distributed. If the bursts arise at cosmological distances, an interesting possibility is that they come from coalescing binary neutron stars (see Glashow, these proceedings). We know from binary pulsar observations that such systems exist. Of the 20 binary pulsars in our galaxy for which accurate Kepler parameters have so far been determined, five are binaries in which both members are neutron stars (Taylor, these proceedings). Reasonable estimates suggest that there should be plenty of such systems out to the horizon to account for the several hundred γ ray bursts observed per year. A challenge for all models of γ ray bursts is to understand why so much of the energy emerges as γ rays. The time dependence of the bursts is also quite interesting, with several categories of bursts having features from milliseconds to several seconds.

The news about binary pulsar observations is that they have recently allowed a test of strong-field gravity (Taylor, these proceedings). Neutron stars have a surface gravitational potential $GM/c^2R \approx 0.2, 10^5$ times larger than that at the surface of the sun. Some time ago, binary pulsar data was used to confirm that binary pulsars emit gravitational radiation at the expected rate; this test is now at the 0.5% level. The latest work\cite{46} has measured velocity-dependent and nonlinear gravitational phenomena independently of the effects of gravitational radiation. General relativity passes this new test perfectly. The current upgrade of the Arecibo telescope will permit still more sensitive tests.

One of the most important announcements at Blois92 was the commitment of funds from the French government for the French-Italian VIRGO interferometric gravity wave observatory. U.S. government funding for the LIGO detector has also been made available. These detectors should begin to have sufficient sensitivity to see gravity waves, although this may have to wait until advanced detectors replace the first generation devices currently planned for these observatories (Thorne, these proceedings). Several of the phenomena I discussed above are possible sources for such gravity waves, including VMO collapse and the “last three minutes” of coalescing binary neutron stars.

VII. Conclusion

This is certainly a golden age for cosmology and particle astrophysics! We are blessed with wonderful astronomical instruments and accelerator experiments that each year open new windows through which we see things that clarify the initial conditions, the composition, and the evolution of the universe. The fact that the $\nu_e\nu_\mu$ oscillation experiments now starting at CERN may confirm the prediction of Cold+Hot Dark Matter that $m(\nu_\tau) \sim 7h_{50}^2$ eV, or perhaps that of Strings+HDM that $m(\nu_\tau) \sim 23h_{50}^2$ eV, is a perfect illustration of the interconnections growing between cosmology and particle physics.
I have read in the newspapers that some in France are unhappy with the rather bloody words of the Marseilleise. I will conclude this written version as I concluded my summary talk at Blois, with some new words to the same stirring melody:

"Bloiseilleise"

Cosmologists and astrophysicists,  
The day of glory will soon arrive!  
While we outline the tasks still before us,  
We have fed well but ignored our wives  
We have fed well but ignored our wives.  
They may think we have no sensitivity...  
But in detection of dark matter, yes we do!  
We’ll find out what the universe is made of,  
And eliminate those factors of two.  
To your pencils, colleagues at Blois!  
Frame a theory elegant and clear!  
March on / March on  
We’ll diet when we’re gone,  
And give our thanks to Tran!

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Caption for Cartoon Figure—Standard CDM with constant linear bias $b$ is inconsistent with the data, as is standard HDM. The idea that loops of cosmic string seed structure formation has been killed by high-resolution simulations showing that the loops do not survive long enough. But from the graves of these models potentially successful models are growing: CDM with $\Omega \approx 0.2$ and a cosmological constant, and $\Omega = 1$ Cold+Hot Dark Matter and Strings + Hot Dark Matter.
REFERENCES

1. C.W. Misner 1977, in *Cosmology, History, and Theology* W. Yourgrau & A.D. Breck, eds. (Plenum Press), p. 75.
2. Recent reviews are A. Linde 1990, *Particle Physics and Inflationary Cosmology* (Harwood); K. Olive 1990, Phys. Rep. 190, 307.
3. J.R. Primack & G.R. Blumenthal 1984, in *Clusters and Groups of Galaxies* F. Mardirossian, G. Giuricin & M. Mezzetti, eds. (D. Reidel, Dordrecht) p. 435; reprinted in *Particle Physics and Cosmology: Dark Matter*, M. Srednicki, ed. (North-Holland, 1990), p. 90.
4. G.R. Blumenthal, S. Faber, J.R. Primack, & M. Rees 1984, Nature 311, 517.
5. M. Davis, G. Efstathiou, C. Frenk & S.D.M. White 1985, Ap. J. 292, 371.
6. S.J. Maddox et al. 1990, M.N.R.A.S. 242, 43P.
7. C.A. Collins, R.C. Nichol & S.L Lumsden 1992, M.N.R.A.S. 254, 295.
8. J.A. Peacock & M.J. West 1992, MN.R.A.S., in press; S. Olivier, J.R. Primack, G. Blumenthal & A. Dekel 1993, Ap. J., in press.
9. For a recent review, see M. Davis, G. Efstathiou, C.S. Frenk, and S.D.M. White 1992, Nature 356, 489.
10. E.g., A. Babul & S.D.M. White 1991, M.N.R.A.S. 253, 31P.
11. In a sphere of this radius, the rms fluctuation in the number of optically bright galaxies is unity. As usual, we use the reduced Hubble parameter $h \equiv H_0/[100 \text{ km s}^{-1} \text{ Mpc}^{-1}]$.
12. G. Efstathiou, W.J. Sutherland & S.J. Maddox 1990, Nature 348, 705.
13. See also J.R. Primack in these proceedings, and J. Holtzman & J.R. Primack 1993, Ap. J., in press.
14. P. Lilje 1992, Ap. J. Lett. 386, L33; N. Bahcall & R. Cen 1992, Ap. J., in press.
15. R. Scaramella 1992, Ap. J. Lett. 390, L57.
16. C. Park, J.R. Gott & L.N. da Costa 1992, Ap.J. Lett. 392, L51.
17. G. Efstathiou, J.R. Bond & S.D.M. White 1992, M.N.R.A.S. 258, 1P.
18. J.P. Huchra 1992, Science 256, 321; S. van den Bergh 1992, Science 258, 421.
19. E.g., R. Cen, N.Y. Gnedin, L.A. Kofman & J.P Ostriker 1992, Ap. J. Lett., in press.
20. F.C. Adams et al. 1992, Fermilab preprint; A.R. Liddle & D.H. Lyth 1992, Sussex preprint.
21. For a review, see e.g. J.R. Primack 1991, in Proc. IUPAP Conf. Primordial Nucleosynthesis and Evolution of Early Universe, K. Sato, ed. (Kluwer), p. 193.

22. With $\Omega = 1$, the age of the universe $t_0 = 13.04 h^{-1}_{50} \text{Gy}$, so avoiding conflict with Globular Cluster and other age estimates requires $h_{50} < 1$.

23. Once the neutrinos decouple, their momenta just redshift; see e.g., Weinberg 1972, Gravitation and Cosmology (Wiley), p. 535.

24. K. Shafi & F. Stecker 1984, Phys. Rev. Lett. 53, 1292.

25. L.Z. Fang, S.X. Li & S.P. Xiang 1984, Astr. Astrophys. 140, 77; R. Valdarnini & S. Bonometto 1985, Astr. Astrophys. 146, 235; S. Achilli, F. Occhionero & R. Scaramella 1985, Ap. J. 299, 577.

26. See my contributed talk in these proceedings.

27. J. Holtzman 1989, Ap. J. Supp. 71, 1.

28. A.N. Taylor & M. Rowan-Robinson 1992, Nature 359, 396.

29. M. Davis, F.J. Summers & D. Schlegel 1992, Nature 359, 393.

30. A. Klypin, J. Holtzman, J.R. Primack & E. Regős 1992, UCSC preprint.

31. J.P. Ostriker and Y. Suto 1990, Ap. J. 348, 378; Y. Suto, R. Cen, and J.P. Ostriker 1992, Ap. J. 395, 1.

32. T. Gaier et al. 1992, Ap. J. Lett. 398, L1.

33. K.M. Gorski, 1992, Ap. J. Lett. 398, L5.

34. See e.g. L. Kofman et al. 1991, in Proceedings, Workshop on Large Scale Structure and Peculiar Motions in the Universe, D.W. Latham and L.N. da Costa, eds. (Astronomical Society of the Pacific), p. 251; D.S. Salopek 1992, Phys. Rev. D45, 1139.

35. D. Spergel, personal communication.

36. H. Hodges and J.R. Primack 1991, Phys. Rev. D43, 3155.

37. G.M. Fuller et al. 1992, Ap. J. 389, 517.

38. T. Yanagida 1978, Prog. Theor. Phys. B135, 66; M. Gell-Mann, P. Raymond & R Slansky 1979, in Supergravity ed. P. van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam), p. 315.

39. For more detailed models, see e.g. S.A. Bludman, D.C. Kennedy, and P.G. Langacker 1992, Phys. Rev. D45, 1810; J. Ellis, J.L. Lopez & D.V Nanopoulos, 1992, Preprint CERN-TH.6569/92; and S. Dimopoulos, L. Hall & S. Raby 1992, preprint LBL-32484.
40. J.R. Primack, D. Seckel & B. Sadoulet 1988, Ann. Rev. Nucl. Part. Sci. 38, 751; P.F. Smith and J.D. Lewin 1990, Phys. Rep. 187, 203.

41. B.J. Carr & J.R. Primack 1990, Nature, 345, 478; J.R. Bond, B.J. Carr & C.J. Hogan 1991, Ap. J. 367, 420.

42. M.J. Irwin et al. 1989, Astr. J. 98, 1989.

43. B. Paczynski 1986, Ap. J. 304, 1; K. Griest 1991, Ap. J. 366, 412; K. Griest et al. 1991, Ap. j. Lett. 372, L79.

44. C.D. Dermer & R. Schlickeriser 1992, Science 257, 1642.

45. M. Punch et al. 1992, Nature 358, 477.

46. J.H. Taylor et al. 1992, Nature 355, 132.