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REVIEW OF DARK MATTER*

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ABSTRACT

There is increasing evidence that baryons constitute $< 10\%$ of the mass of the universe. It is likely that the non-luminous matter, which must be particles outside the Standard Model of particle physics, is made up of $\sim 70\%$ cold dark matter and $\sim 30\%$ hot dark matter. If the solar ν_e and atmospheric ν_μ deficits are manifestations of neutrino mass, then there is a unique pattern of neutrino masses to accommodate the hot dark matter, pointing to needed terrestrial experiments. The cold component can be searched for directly, and already the exclusion of Dirac candidates extends over 12 orders of magnitude in particle mass and 20 orders of magnitude in cross section. This search must now get to cross sections less than one-tenth that of the weak interaction for Dirac masses > 20 GeV and utilize detector nuclei with spin for Majorana masses $\gtrsim 10$ GeV. A program to achieve these goals is being implemented with a cryogenic detector.

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1. EVIDENCE FOR DARK MATTER

Observational information increasingly points to the density of the universe's being far greater than the mass one can detect by other than gravitational means. Some of that non-luminous mass is in familiar baryonic form, but much more of it must be particles which are not in the Standard Model of particle physics. Thus the search for this dark matter is of great importance to particle physics, astrophysics, and cosmology.

The success of nucleosynthesis theory in predicting the abundance in the universe of ^{4}He, ^{3}H, ^{2}H, and ^{7}Li, as well as three flavors of neutrinos, gives confidence that the ratio of the mass density to the density required to just close the universe is $\Omega = 0.05 \pm .03$.[1] Observed baryons give only $\Omega \approx 0.007$, so there must be some unseen baryonic matter. This is most likely in the form of Jupiters (stars too small to have initiated nuclear burning), very small black holes ($< 10^{-6}$ solar masses) or neutral hydrogen.

The need for non-baryonic mass increases with increasing scale. The tangential velocity, v, of a mass, m, in a galaxy remains constant out to a radius, r, about an order of magnitude beyond the luminous mass, M, whereas from $GmM/r^2 = mv^2/r$, $v \propto r^{-1/2}$ would be expected. Unobserved mass increasing linearly with r must exist, giving $\Omega = 0.05$–0.10, but the fall-off in v is seldom observed. On the scale of galactic clusters, need for $\Omega = 0.1$–0.3 is required both by the motion of galaxies with respect to the center of luminous mass of the cluster and by gravitational lensing by the cluster of a distant light source. Very large scale velocity fields from the flow of galaxies and galactic clusters require $\Omega > 0.3$ at the 4–6 standard deviation level,[2] and these data favor $\Omega = 1$. The flat universe of $\Omega = 1$ is very likely because it is the only time-stable value for a zero cosmological constant. Unless there is severe fine tuning in the early universe, the present density should have been driven far out of the present range, toward 0 or ∞, unless $\Omega = 1$. Inflation theory, which provides an explanation for several otherwise inexplicable puzzles, also requires $\Omega = 1$.

2. APPARENT NEED FOR MIXED DARK MATTER

An explanation is required for the need for larger Ω the bigger the scale. Another dark matter conundrum to be understood is how it affects the formation of structure in the universe. Both of these issues can be explained in a model[3] which, in addition to the required small amount of baryonic dark matter, has a mixture of hot and cold dark matter. Relativistic hot dark matter tends to wash out density fluctuations, while slowly moving cold dark matter would enhance initial fluctuations to seed the concentration of baryons.

Data on the extent of structure in the universe is now available on a wide range of distance scales. Evidence from the COBE results on the anisotropy of the cosmic microwave background radiation, galaxy-galaxy angular correlations, large-scale velocity fields, and correlations of galactic clusters can all be fit[4]if the universe contains 70% cold dark matter and 30% hot dark matter contributed by $\sim$ 7 eV in neutrino mass. Such a model provides a consistent explanation not only of the shape of the density fluctuation spectrum, but also the observed estimates of the absolute density on small and large scales. While the fits have been made with a single neutrino, dividing the mass among more than one neutrino would work even better.[5]

3. BARYONIC DARK MATTER

It is barely possible that there could be enough baryonic dark matter to account for all the dark matter in our galaxy. In that case we would have to rely on accelerator experiments and theoretical input to determine the nature of non-baryonic dark matter. While solely baryonic dark matter is unlikely in view of the probable need for cold dark matter for galaxy formation, it is certainly important to ascertain the nature of the baryonic dark matter.

The most likely baryonic candidates are objects which can be between 10^{-7} and 10^{-1} solar masses. If lighter than the lower limit, they would have evaporated away in a galactic

time scale, and if heavier than the upper limit, they would have become visible by nuclear ignition. These MAssive Compact Halo Objects, or MACHOS, are being looked for by gravitational microlensing, a search for the brightening of one of $\sim 10^7$ stars in the Magellanic Cloud as a MACHO passes across the line of sight to that star. This brightening has a characteristic time dependence and would be achromatic. So far the three groups[6] doing this work have demonstrated feasibility, in that the photographic plates and CCD cameras have discovered many variable stars, but with no MACHO candidates yet, the background problems seem well in hand. The present results are still well below the level of the few events per year expected if all the galactic dark matter were baryonic.

4. HOT DARK MATTER

The light, but not massless (as it is in the Standard Model) neutrino has long been a candidate for dark matter, since there are $\sim 10^2/\mathrm{cm}^3$ of each family everywhere, and a mass of ~ 25 eV would give $\Omega = 1$. The problem of galaxy formation has to be solved by introducing topological seeds, such as cosmic strings, and there is also the difficulty that dwarf galaxies cannot hold enough such light neutrinos to provide their needed dark matter. A better use for neutrinos, mentioned above, is as a minority component of dark matter.

Since the direct detection of relic neutrinos appears to be impossible, their existence will have to be deduced from neutrino oscillation information. Conventional wisdom has the ν_τ playing this role, but if all current hints of neutrino mass are correct, that scheme is wrong, and there is a more likely scenario.[7] There are at present three indications of neutrino mass: (1) the deficit of solar ν_e's, (2) the depletion of atmospheric ν_μ's relative to ν_e's, and (3) the apparent need for some hot dark matter. If all of these are indeed due to neutrino mass, there are only three logical possibilities for the pattern of neutrino masses and mixings: (A) ν_e, ν_μ, and ν_τ are all about 2.3 eV in mass, (B) ν_e, ν_μ, and ν_τ are all very

light, and one or more sterile neutrinos, ν_s, provide the dark matter, or (C) ν_e and ν_s are very light and ν_μ and ν_τ are about 3.5 eV each. Case (A) is probably ruled out by the non-observation of neutrinoless double beta decay. Case (B) is also probably ruled out because the ν_s decoupled so early in the expansion of the universe that their numbers depleted, making their required mass $\gg$ 7 eV, which in turn makes them too slow to perform the function of the hot dark matter. That leaves only case (C), which explains the ν_e solar deficit via $\nu_e \to \nu_s$, with about the same Δm^2 and mixing angle as for $\nu_e \to \nu_\mu$. There is also no difficulty with too many neutrinos at the time of nucleosynthesis, since a ν_s that light (and with the mixing angles of either the non-adiabatic MSW or vacuum oscillation cases) was not then in equilibrium. Case (C) explains the atmospheric ν_μ depletion via $\nu_\mu \to \nu_\tau$, with these nearly degenerate heavier neutrinos also providing an even better fit to the structure information than a single 7 eV neutrino.[5)]

The question of ν_e to ν_s or ν_μ should be settled by the neutral current detection at SNO or BOREXINO. A check on the $\nu_\mu \to \nu_\tau$ of the atmospheric ν_μ depletion could be provided by long baseline neutrino oscillation experiments planned at Brookhaven and Fermilab. The essential feature of a $\Delta m^2 \sim 10$ eV^2 mass difference between the ν_e–ν_s and ν_μ–ν_τ sectors can be tested best by a $\nu_\mu \to \nu_e$ oscillation experiment, although the less sensitive and more difficult $\nu_e \to \nu_\tau$ experiment should also be done, because these mixings are model dependent. The LSND experiment at Los Alamos as early as 1994 could achieve a limit on $\sin^2 2\theta_{e\mu} \sim 3 \times 10^{-4}$ at this Δm^2, if current funding problems do not interfere.

5. COLD DARK MATTER

There are a very large number of cold dark matter candidates, of which only a few are motivated by needs other than to be dark matter. One is the axion, which would result from a possible solution to the strong CP problem. Despite requiring a mass $\sim 10^{-5}$ eV to give $\Omega = 1$, axions are a cold dark matter candidate. The lack of evidence for energy

transport by axions in stellar cooling and from SN1987A limits axion mass to $\lesssim 10^{-3}$ eV. Two experiments[8)] have been developed to detect axions by looking for the conversion of axions to photons in a magnetic field, but lack a factor of $\sim 10^2$ in sensitivity for doing so. A new experiment[9)] is currently being constructed with a much higher field superconducting magnet which could have the required sensitivity.

There used to be also considerable motivation for a heavy fourth-generation neutrino as dark matter. The SLC/LEP limitation to three generations of weak isodoublet neutrinos of mass $\lesssim$ 45 GeV eliminated a fourth Majorana neutrino, since to be dark matter its mass would have to be $\sim$ 5–8 GeV, which is determined by its annihilation rate when such neutrinos could have been in thermal equilibrium in the early universe. Such a Majorana neutrino may have been ruled out previously by indirect dark matter searches performed at the proton decay detectors, Fréjus, Kamioka, and IMB. The Majorana particles could be captured by the sun or earth, annihilate in pairs, and produce energetic neutrinos from the cascade decays of heavy flavor annihilation products. The energetic neutrinos then need to be detected above the background of atmospheric neutrinos. Space limitations prevent discussing the observations or the controversy about the interpretation of the complex chain of events involved.

In contrast to the Majorana case, a Dirac neutrino could have had a wide mass range, since an initial particle-antiparticle asymmetry would allow the annihilation rate to be adjusted suitably. The SLC/LEP result conclusively ruled out the 4–10 GeV Dirac mass range. Masses larger then 10 GeV had already been eliminated by underground Ge semiconductor detectors sensitive to nuclear recoils struck by such a particle. Three experiments[10,11] have searched for dark matter. Results presented here are from the UCSB/LBL/UCB data, although the others are similar. The exclusion plot of Fig. 1 assumes a conservative dark matter galactic halo density of 0.3 GeV/cm^3 $= 5 \times 10^{-25}$ g/cm^3 and a Maxwellian dark matter velocity distribution of $v_{rms} \approx 300$ km/s. Each particle

mass is assumed in turn to be the source of dark matter, and the results are for the case of spin-independent interactions, for which there is nuclear coherence. Particles having the normal weak interaction would lie along the line in Fig. 1 labelled "Dirac ν," and are excluded between 10 GeV and $\sim$ 3 TeV. Since $\sim$ 30 eV–4 GeV would give $\Omega > 1$, all isodoublet Dirac neutrinos $\gtrsim$ 30 eV are eliminated as dark matter, if the upper mass limit is really[12] $\sim$ 1 TeV. Also ruled out as dark matter are the lightest technibaryon and any particle above and to the right of the solid line.

A region shown in Fig. 1 refers to a class of Weakly Interacting Massive Particles (WIMPs) called Cosmions, which could be dark matter and also solve the solar ν problem. The Cosmion could be captured in the sun and fall toward the center, where its motion to larger radii would cool the solar core by the $\sim$ 10% needed to reduce the flux of ^{8}B solar neutrinos.[13] The Cosmions were essentially excluded[14] using Si detectors in the UCSB/LBL/UCB apparatus, since these are more sensitive to lower masses than is Ge.

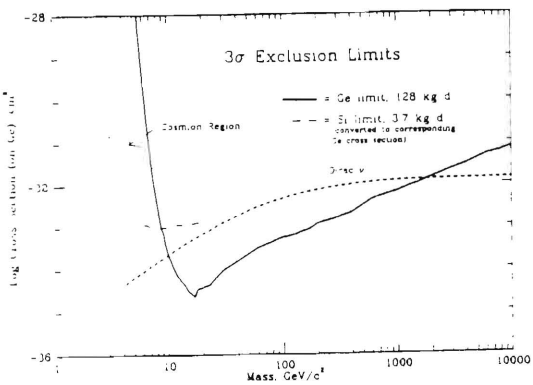

Fig. 1. **Exclusion plot for the mass and elastic cross section on Ge for dark matter particles. The weak interaction cross section is indicated by "Dirac ν."**

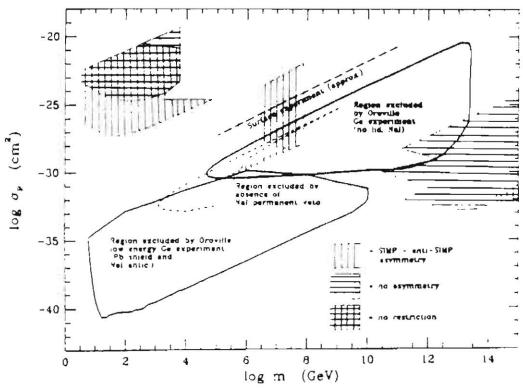

Fig. 2. Exclusion plots for the mass and cross section on protons for dark matter particles, showing also the regions Ref. 15 found were not excluded by other information.

The exclusion region does not end at the boundaries of Fig. 1, as seen in Fig. 2. Note that the cross section of Fig. 1 is on Ge, while that of Fig. 2 is for protons. Interest in Strongly Interacting Massive Particles (SIMPs) as dark matter prompted Starkman

et al.[15] to find regions of mass-cross section space viable for dark matter candidates. The most likely remaining region was the mass range $10^6 - 10^8$ GeV with a cross section on protons of $10^{-28} - 10^{-22}$ cm^2 and a narrow "finger" reaching down to 10^5 GeV and 10^{-30} cm^2. To search this region the Pb shielding and NaI veto above the Ge detectors in the UCSB/LBL/UCB apparatus were removed, giving the "no-lid, NaI" exclusion region shown. To extend the upper boundary, some data were taken with a Ge detector at the surface, giving the dashed line. Another exclusion region is dashed in and labeled "absence of a NaI permanent veto", since in this region there would always be a SIMP in the NaI within the electronics dead time. This region extends into the exclusion area of Fig. 1, which is shown completely here.

With so much of the SIMP mass–cross section space eliminated, it is improbable that any particle with stronger than the standard weak interaction can be the main component of dark matter. There is also a limit[12,16] that any stable elementary particle which was once in thermal equilibrium in the early universe has to have a mass less than $\sim 10^3$ TeV.

6. FUTURE DIRECT DETECTION OF DARK MATTER

The need is now to go to cross sections well below weak for Dirac particles and especially to achieve sensitivity to Majorana particles with their spin-dependent interactions, particularly the lightest supersymmetric particle (LSP). The LSP is a well motivated dark matter candidate, since it was invented for a purpose other than to be dark matter, and an $\Omega = 1$ density is achieved quite naturally for a range of LSP parameters. If R-parity ($+1$ for particles, -1 for their supersymmetric partners) is conserved, the LSP is stable, but in any case it is likely to be long lived. The LSP is generally considered to be a neutralino, some mass state which is a mixture of the interaction states of the superpartners of the hypercharge gauge boson, the neutral SU(2) gauge boson, and the neutral components of Higgs doublets. The nature of that mixture determines how readily the particle can be detected,

but already accelerator and nonaccelerator experiments have considerably restricted the parameter space. The large number of free supersymmetric parameters are reduced in the Minimal Supersymmetric Standard Model (MSSM), particularly when grand unification (GU) is assumed, typified by the association with SU(5). Under these conditions LEP and CDF results restrict the neutralino to be more massive than $\sim$ 20 GeV. If one relaxes the assumption of GU,[17] neutralino masses giving $\Omega = 1$ can be $\sim$ 10 GeV, and outside the MSSM there are not well-defined limits on neutralino mass. However, the accelerator results and the requirement of $\Omega = 1$ still restricts the parameters considerably. In general it is likely that if the neutralino is dark matter, its mass is between 20 and 150 GeV.[18]

With the limitations from LEP and those shown in Fig. 1, for Dirac particles also masses > 20 GeV are of interest. Reduction of backgrounds to get to smaller cross sections for both the Dirac and Majorana particles is essential. In the latter case it is also necessary to have a nucleus with spin. Since the semiconductor experiments have involved extensive efforts to reduce backgrounds, significant further reductions require a new technique.

7. A CRYOGENIC EXPERIMENT

As backgrounds are due mainly to electrons (from β decays, Compton scattering, or photoelectrons), which ionize efficiently at low energies, whereas the nuclear recoil signal produces mainly phonons, a simultaneous measurement of phonons and ionization energies would provide an excellent discriminant. A semiconductor detector requires an electric field of $\sim 10^3$ V/cm to remove free charge carriers and fully deplete the crystal, but such a field moving the ionization charge creates phonons which swamp the original phonon component of the particle interaction. However, the phonon signal can be detected using very low temperatures ($\sim 0.03°$ K), since the impurity charges are then frozen out from the bands, and only about 0.5 V/cm is needed to collect ionization electrons and holes. The low temperature also provides a measurable temperature rise resulting from the particle

interaction, as the heat capacity of the detector is proportional to the cube of the absolute temperature.

The Center for Particle Astrophysics group demonstrated[19] this technique using a 60 g. crystal of Ge and neutron-transmutation-doped thermistors. Figure 3 shows the ionization and phonon response to X-rays from ^{241}Am, while Fig. 4 displays a measurement with that X-ray source and a ^{252}Cf neutron source. With the current resolutions (FWHM of 1.7 keV for ionization and 1.9 keV for phonons at 60 keV), an additional background rejection of $> 10^2$ is calculated, and it is likely that those numbers will improve.

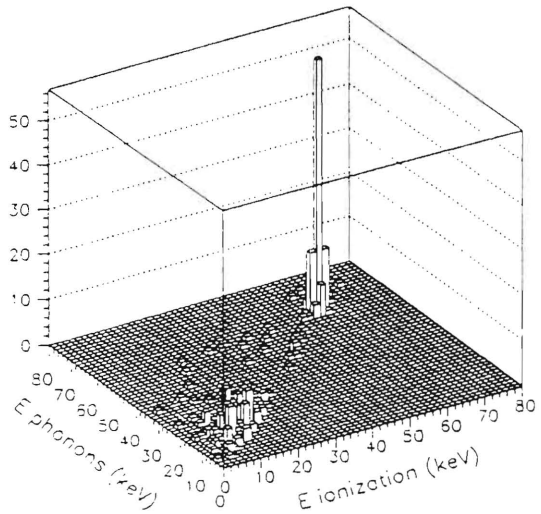

Fig. 3. Signals from 14, 18, and 60-keV X-rays (from ^{241}Am) in a 60 g. Ge crystal operated at 0.03° K, for which both the ionization and heat (phonons) have been measured.

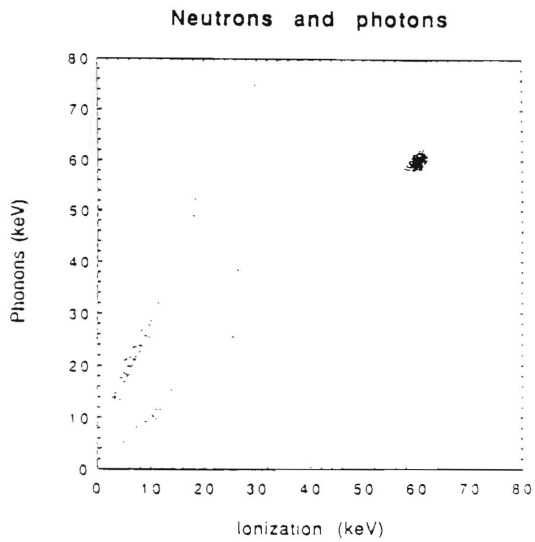

Fig. 4. Response of the 60 g. Ge crystal to a ^{252}Cf neutron source, shielded by 11" of Pb, and X-rays from ^{241}Am. Resolution of the two populations begins at $\sim$ 3 keV of ionization.

This technique will be applied in an experiment presently being implemented at a shallow (20 m.w.e.) site on the Stanford campus by the UCSB/LBL/UCB/Stanford/INR Baksan group. Since the technique is new and dilution refrigerators require attention, a location was chosen on the basis of ready access. The Oroville site[12] at 600 m.w.e. was by far the shallowest heretofore used for a dark matter search. Cosmic ray muons are a problem in that they produce neutrons which can give nuclear recoils. A highly

efficient muon veto counter must be constructed and provide a deadtime after the passage of the muon until the neutron is at least of too low an energy to give a measureable recoil. The neutrons, produced mainly in the Pb shield needed to reduce external radioactivity, are moderated by polyethylene. According to calculations, the main remaining source of neutrons are the Cu fixtures needed to contain the detectors at low temperature. The shielding can be quite complete because the dilution refrigerator has been constructed with an unusual side exit so that cooling can be achieved in a separate cold box.

Current plans are to take data with three 0.5 kg detectors, one of normal Ge, one enriched in ^{73}Ge (spin 9/2), and one enriched in ^{76}Ge (spin 0). This will provide appropriate cross checks and allow the simultaneous search for Dirac and Majorana dark matter. If we can achieve electron background levels comparable to those we now have in the semiconductor experiment at Oroville, this should begin the exploration of the region in which the lightest supersymmetric particle could exist, as shown in Fig. 5.

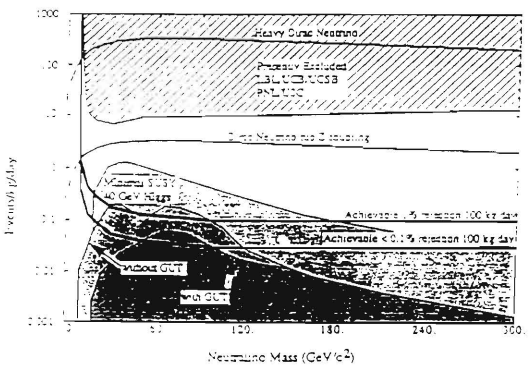

Fig. 5. Exclusion plot of event rate vs. particle mass showing the already excluded region of Fig. 1 and the neutralino region with various theoretical assumptions. The lines show limits to be achieved after 100 kg days using a ^{73}Ge crystal and having 1% and 0.1% additional rejection from simultaneous ionization and phonon measurements.

8. CONCLUSIONS

If dark matter is indeed 70% cold and 30% hot, the nature of the latter will have to be determined by terrestrial experiments, guidance for which comes from present indications for neutrino mass. These suggest a unique pattern for neutrino masses. The cold component is amenable to direct search, and already by this means Dirac candidates covering

12 orders of magnitude in mass and 20 orders of magnitude in cross section have been eliminated. Some Majorana particles have also been ruled out. Further progress can come from new techniques, including the simultaneous measurement of phonons and ionization, now being implemented.

REFERENCES

1. T.P. Walker et al., *Ap. J.* **376**, 51 (1991) and OSU-TA-1/93 (1993).
2. A. Nusser and A. Dekel, *Ap. J.* **405**, 437 (1993).
3. Q. Shafi and F.W. Stecker, *Phys. Rev. Lett.* **53**, 1292 (1984).
4. E.L. Wright et al., *Ap. J.* **396**, L13 (1992); M. Davis, F.J. Summers and D. Schlegel, *Nature* **359**, 393 (1992); A.N. Taylor and M. Rowan-Robinson, *Nature* **359**, 396 (1992); R.K. Schaefer and Q. Shafi, BA-92-28 (1992); J.A. Holtzman and J.R. Primack, *Ap. J.* **405**, 428 (1993).
5. M. Davis and J. Primack, private communications.
6. Center for Particle Astrophysics, Lawrence Livermore, Mt. Stromlo; Princeton, Carnegie Obs., Warsaw Univ.; IAP, Obs. de Paris, Marseille, Saclay, Orsay.
7. D.O. Caldwell and R.N. Mohapatra UCSB-HEP-93-03 (1993, submitted to Phys. Rev. Lett.); references to the original literature can be found therein.
8. W. Wuensch *et al.*, *Phys. Rev. D* **40**, 3153 (1989); C. Hagmann *et al.*, *Phys. Rev. D* **42**, 1297 (1990).
9. LLNL, Florida, INR, UCB, Chicago, SLAC Collaboration.
10. S.P. Ahlen et al., *Phys. Lett.* , B195, 603 (1987); F. Boehm et al., *Phys. Lett.* **B255**, 143 (1991).
11. D.O. Caldwell et al., *Phys. Rev. Lett.* **61**, 510 (1988).
12. K. Griest and M. Kamionkowski, *Phys. Rev. Lett.* **64**, 615 (1990).
13. R.L. Gilliland et al., *Ap. J.* **306**, 703 (1986) and earlier references therein.
14. D.O. Caldwell et al., *Phys. Rev. Lett.* **65**, 1305 (1990).
15. G.D. Starkman et al., *Phys. Rev. D* **41**, 3594 (1990).
16. A.-C. Davis and R.H. Brandenberger, *Phys. Lett.* **B284**, 81 (1992).
17. K. Griest and L. Roszkowski, *Phys. Rev. D* **46**, 3309 (1992).
18. L. Roszkowski, *Phys. Lett.* **B262**, 59 (1991).
19. T. Shutt *et al.*, *Phys. Rev. Lett.* **69**, 3425, 3531 (1992).