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DARK MATTERS UNDER LAND AND SEA

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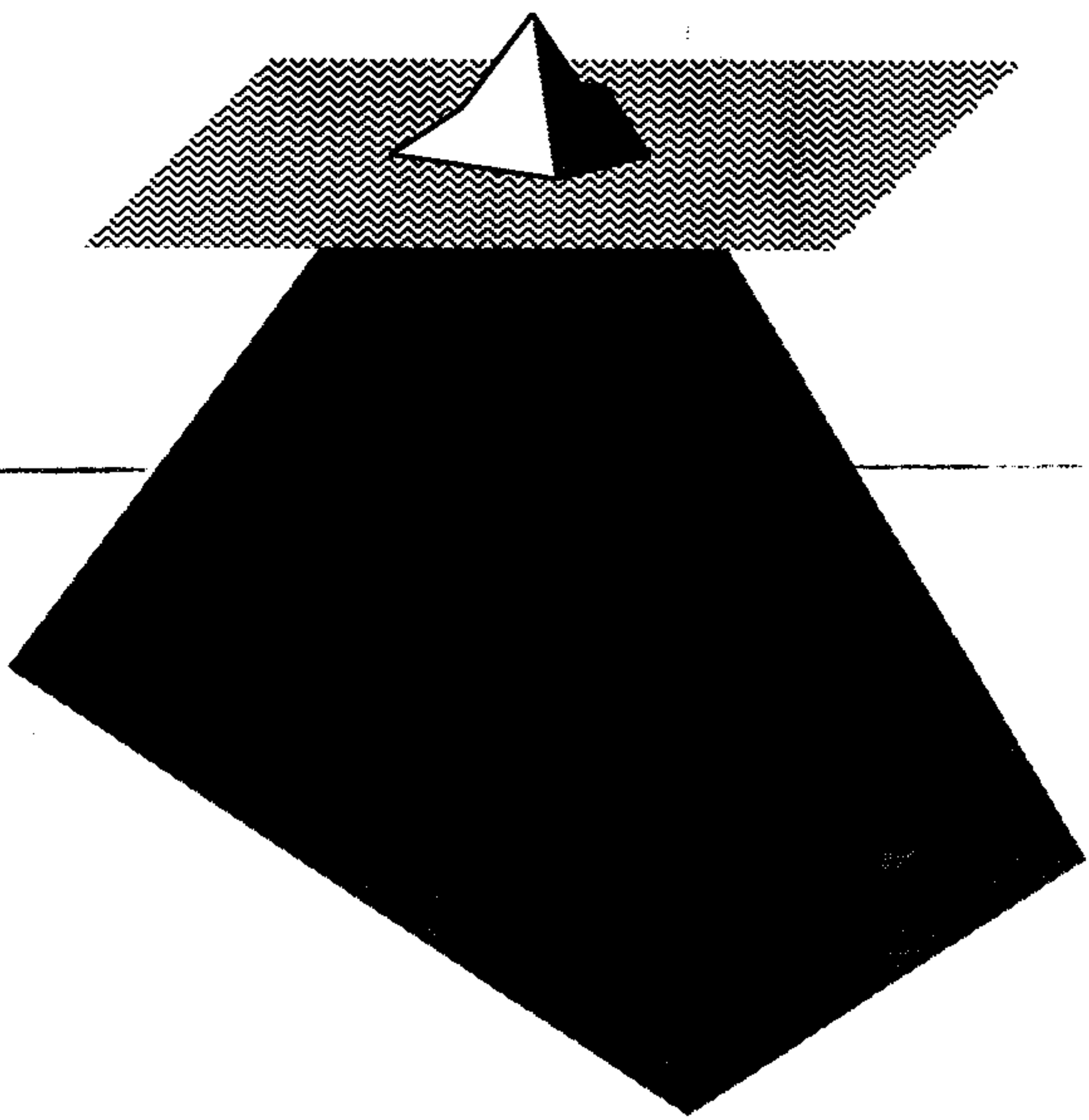

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Abstract

Among the various candidates for the dark matter of the universe are particles which are far more massive than atoms but of atomic dimensions. Such particles would penetrate to great depths in the earth and yet possibly be detectable by the light emitted in their collisions with matter. Existing or planned underground instruments should be sensitive to this type of dark matter in the mass range $10^{-10} < \mathcal{M} < 0.1$ g, if it comprises the bulk of the mass of the galaxy. A comparably sensitive technique appears to be underwater where a few large photomultiplier tubes could see the light emitted by the particles hundreds of meters away.

1. Introduction

Surely one of the great outstanding questions in science is the nature of the **dark matter** which is believed to comprise 90-99% of the universe.[1] Among the many possibilities which have been considered are particles which are massive by atomic standards. These include *monopoles,* [2] *quark nuggets,* [3] *maximons* [4] among others. Stable particles not composed of the same constituents as normal matter might exist at or above the various unification or compactification scales: $\mathcal{M} > 10^{14}$ GeV/$c^2 \approx 10^{-10}$ g. They are far too massive to be produced in accelerators, but may be left over from the early universe if they possess a conserved quantum number which prevented their decay. Being already non-relativistic when the universe was very hot and small, their density fluctuations could have formed the seeds around which structures at the smallest astronomical scales formed and they could still exist as dark clouds within and around galaxies. If they constitute the major portion of the mass of our galaxy, then their flux can be estimated. Although great in number throughout the universe, this flux would still be low enough for them to have remained undetected up to this time. If at rest with respect to the Milky Way, they would be moving relative to the earth at the speed of the solar system through the galaxy, about 250 km/s.

There is a great variety of experiments looking for dark matter in every mass range. Here we consider the possibilities for those candidates which lend themselves to detection deep underground or undersea. De Rujula and Glashow[5] have studied the detection of quark nuggets, or *nuclearites*, in which the presence of strange quarks makes possible a high mass stable state. Applications to the Gran Sasso underground project MACRO[6] are discussed by Longo[7] and Giacomelli *et al.*.[8] It is proposed here that much of what these authors say applies to a wider class of very heavy dark matter candidates relevant to deep detectors; for example, heavy monopoles which capture nuclei or **any** generic heavy particle which has the density of nuclear matter or the ability to attach itself to nuclei or atoms. Further, it is found that **underwater** instruments such as the Deep Undersea Muon and Neutrino Detector, DUMAND,[9] are particularly attractive way to search for dark matter.

The candidates for the particles of dark matter, in the phenomenological class being considered here, have a number of general characteristics which are easy to predict, and which allow reasonable guesses to be made as to their detectability. They are very massive, with the density of nuclear matter, but can have at least atomic dimensions. They would probably appear electrically neutral, being surrounded by an electron cloud if fundamentally positively charged and probably not negatively charged. Although neutral, they could still lose large amounts of energy by atomic collisions, typically many GeV's per cm in some cases, which makes them quite detectable. This energy loss, though stupendous by normal elementary particle standards, can still be a small fraction of the particle's kinetic energy; thus the heavier dark particles are highly penetrating, able to reach depths in the earth or sea where they might be more readily distinguished from conventional cosmic ray backgrounds.

2. The Basic Equations

The flux of dark particles of mass $\mathcal{M}$ can be calculated from $F = \rho_d v/\mathcal{M}$ where ρ_d is their mass density and v is the speed at which the earth moves through the dark cloud. An upper limit can be estimated, applying to the case in which they constitute all the dark mass of the galaxy, $\rho_d = 10^{-24}$ gcm^{-3} and v = 250 km/s:

$$F < 7.8/\mathcal{M} \ \ \mathrm{km}^{-2}\mathrm{yr}^{-1}(2\pi \ \mathrm{sr})^{-1} \tag{1}$$

where $\mathcal{M}$ is in gms. This is shown in Fig. 1. The acceptance of the underground experiment MACRO to an isotropic flux is 1200 m^{2}sr.[6] Assuming that 10 events per year passing through the instrument would be a detectable signal and 100% detection efficiency, MACRO is capable of searching for candidates with masses up to about 0.1 g, as shown.[7,8] Other underground experiments with smaller acceptances can be scaled accordingly. Also shown is the experimental limit set by the search for magnetic monopoles in samples of ancient mica.[10]

How are the dark particles detected? Following De Rujula and Glashow,[5] the particle plows through the medium like a tiny meteorite, losing energy by atomic collisions so that

$$dE/dx = - A\rho v^2 \tag{2}$$

where v is the speed of the particle, A is its effective cross-sectional area, and ρ is the density of the medium. They assume a density of the strange-quark matter of the nuclearite of $\rho_N = 3.6\mathrm{x}10^{14}$ gcm^{-3}, somewhat larger than normal nuclear matter, so that, for $\mathcal{M} > 1.5\mathrm{x}10^{-9}$ g,

$$A = \pi(3\mathcal{M}/4\pi\rho_N)2/3 \tag{3a}$$

For $\mathcal{M} < 1.5\mathrm{x}10^{-9}$ g, (3a) gives an area smaller than an atom; so in this case they take

$$A = \pi x 10^{-16} \text{ cm}^2 \tag{3b}$$

Although proposed originally for quark nuggets, these assumptions appear to be general enough to apply, at least crudely, to any of the heavy dark matter candidates, such as monopoles, which can surround themselves with an atomic-like electron cloud. They would not apply in the case of particles with purely gravitational interactions unless these particles have accreted nucleons over the ages.

The velocity of a dark particle when it reaches a depth D in the earth or sea is

$$v(D) = v_o \exp(-A\rho D/\mathcal{M}) \tag{4}$$

where v_o is the initial velocity. The range is

$$\begin{aligned} R &= 2.2x10^5 \,[\mathcal{M}/1 \text{ ng}] \text{ m.w.e.} && \mathcal{M} < 1.5 \text{ ng} \\ &= 3.0x10^5 \,[\mathcal{M}/1 \text{ ng}]^{1/3} \text{ m.w.e} && \mathcal{M} > 1.5 \text{ ng} \end{aligned} \tag{5}$$

Equation (5) imples that $\mathcal{M} > 2x10^{-11}$ g is accessible to instruments at depths of 4000 m.w.e. or less.

Some of the energy loss is likely to appear as visible light. De Rujula and Glashow[5] estimate the luminous efficiency η by assuming that the light is emitted as black-body radiation from an expanding cylindrical thermal shock wave, again a very general assumption which could apply to other candidates besides quark nuggets. For highly transparent water they get $\eta = 2x10^{-5}$. I have repeated their calculation for the visible spectral transmission band 350-650 nm and for a narrow band of 400-500 nm which corresponds approximately to seawater.[11] The results are shown in Fig. 2. We see that η depends on $\mathcal{M}$ for lower masses, and is generally smaller than they estimate; for the narrow seawater band, η ranges from a peak at $\mathcal{M} = 5x10^{-11}$ g of $8x10^{-6}$ to about $2x10^{-6}$ for $\mathcal{M} > 3x10^{-9}$ g.

Finally, if E_γ is the average photon energy, then the number of photons emitted per unit path length is

$$dn/dx = -(\eta / E_\gamma)\, dE/dx \qquad (6)$$

where dE/dx is given by (2).

A Numerical Example

As a specific example to give a feel for the numbers, let us consider a particle with $\mathcal{M} = 10^{16}$ GeV/c^2 = 2×10^{-8} g. Assume it passes through seawater. From (3a) the cross sectional area of the particle is is 1.6×10^{-13} cm^2. From (2), dE/dx = -580 GeV/cm and, from (4) and (5), such a particle would reach a depth of 4000 m.w.e. with a speed of 240 km/s. From (6) we get dn/dx = 4×10^5 photons/cm in seawater, where we take $\eta = 2\times10^{-6}$ and E_γ = 2.8 eV. Over a 100 m path length, three times the light attenuation length of seawater in the deep ocean, this is a grand total of 4×10^9 photons for one dark particle track. The signal will appear in a long pulse 100/v $\approx$ 300 μs in duration. Although there will be background counts from the radiactivity of seawater and possibly bioluminescence in this time interval, it should be possible to detect such an event occurring ~100 m from a photomultiplier tube (PMT). Thus the effective area for an undersea detector can be very large: of the order of 10^4 m^2, far larger than the physical dimensions of the instrument itself, making deep ocean detection a promising way to search for very heavy dark matter. Let us try to put this more precisely.

Capability of Undersea Instruments

The acceptance of an **underground** detector such as MACRO to isotropic through-going tracks is easy to estimate: it is simply π times the surface area. The energy loss of the generic dark particles considered here is so large that their detection efficiency in scintillators should be essentially 100%. An **undersea** instrument such as DUMAND, on the other hand, utilizes the ocean as the basic detection medium and its acceptance is less obvious. Preliminary Monte Carlo studies have been performed to determine the effective detection area of an array of seven photomultiplier (PMT) tubes arranged 5 m apart on a vertical string and deployed on the ocean bottom. This configuration was chosen to coincide with the already-exisiting DUMAND Stage I instrument, the ***Short Prototype String (SPS)***, which was designed to be deployed from a ship but which could be deployed on the ocean floor and attached to shore with an electro-optic cable.

In the Monte Carlo (MC) calculation, tracks of dark particles are generated randomly within a cylinder of radius ρ centered at the center of the string and oriented at an angle θ with the string, where $\cos\theta$ is random between zero and one to correspond to detection over 2π solid angle. From above, the photoelectron current in a given PMT at a time t is:

$$i(t) = -v\epsilon A_{PMT}\ (\eta/E_\gamma)\ dE/dx\ e^{-r(t)/L}\ /4\pi r(t)^2 \qquad (7)$$

where $\epsilon = 0.2$ is the PMT quantum efficiency, $A_{PMT} =$ 1300 cm^2 is the PMT effective area, $\eta = 2\times10^{-6}$ (typically) is the light conversion efficiency, and L = 30 m is the light attenuation length for seawater. If y is the perpendicular distance from a given PMT to the track, then at a time t the particle is at a distance $r(t) = [(vt)^2 + y^2]^{1/2}$, where the the peak current is at t = 0 (see Fig. 3).

From equation (7) the light curve can be written:

$$i(t) = i(0)\ \exp\{1 - [1 + (vt/y)^2]^{1/2}\}/\ [1 + (vt/y)^2] \qquad (8)$$

From geometry it also can be shown that the time interval between peak arrival times at two PMT's at vertical positions z and z + Δz is given by:

$$c\Delta t = \Delta z\ \cos\theta/\beta\ + n[b^2+(z+\Delta z)^2\sin^2\theta]^{1/2} - n[b^2+z^2\sin^2\theta]^{1/2} \qquad (9)$$

where $n = 1.35$ is the index of refraction and b is the impact parameter or distance of closest approach to the vertical line defined by the string (see Fig. 3). Except for tracks within 1^{o} of the horizontal, (9) is essentially given by the first term. For the two ends of the string, $\Delta z = 30$ m and $\Delta t = 122\cos\theta$ μs for $v = 250$ km/s. The FWHM of the light curve depends on both the track distance y and dark particle mass $\mathcal{M}$, ranging from as low as a few μs to over 1000 μs; the average FWHM is 180 μs for $\mathcal{M} = 10^{-9}$ g and 500 μs for $\mathcal{M} = 1$ g.

The following trigger has been used: Hits are required in at least three PMT's in which the peak signal current exceeds 1 photoelectron per μs. This is significantly greater than the background expected from K^{40} in the ocean: 100 KHz = 0.1 photoelectron per μs. To distinguish the dark particle signal from bioluminescent flashes, the peaks of the light curves in two PMT's must be separated by more than 10 μs, signalling the fact that we have detected a particle moving slower than light but faster than fish.

If F is the fraction of events which pass this trigger cut and the radius ρ of the cylinder in which event are generated is large enough so that negligible events can be detected beyond that range, the effective detector area is then given by

$$A_{eff} = F\,\pi\rho^2 \equiv \pi R_{eff}^{\,2} \qquad (10)$$

where we define R_{eff} as the *effective radius* of the detector. In Fig. 4 this effective radius is shown as a function of dark particle mass. A value $\rho = 500$ m was used for the MC cylinder, with 10,000 MC events for each $\mathcal{M}$. The true effective radius will also be somewhat lower owing to the screening of the ocean bottom, which has not been estimated.

The detectable flux of dark particles can be computed from the effective area A_{eff} as the value which will give 10 events per year. This is shown in Fig. 1 as a function of $\mathcal{M}$ for the seven PMT configuration. We see that undersea detectors can search for dark matter in the range $10^{-10} < \mathcal{M} < 1$ g with a sensitivity compared to the largest underground instruments, which is about an order of magnitude worse at the lower mass but two orders of magnitude better at the higher masses, thus extending the upper mass limit for the seach from 0.1 to 1 g.

Discussion

As mentioned, the seven PMT array was chosen to coincide with the already-existing DUMAND Stage I instrument, the SPS, which is currently being tested suspended from a ship. To be used for the purpose of dark matter detection, this instrument would have to be deployed on the ocean bottom for a period of several months or more. A larger instrument with of the order of 100 PMT's is currently under study, primarily as a very high energy neutrino telescope.[12] Such an array would only be about 20-30% more sensitive than the SPS since extra PMT's and greater array size add only marginally to the already-large effective area, mainly improving signal discrimination.

We must ask whether the mica experiment[10] has already ruled out its existence in the region of interest to deep underground or undersea detectors. As seen from Fig. 1, mica seems to set a very strong limit, except for the small window $10^{-10} < \mathcal{M} < 10^{-9}$ g. This limit was estimated specifically for monopoles, but it may also be applicable to the dark matter candidates considered here. The mica limit is based on the assumption that the monopoles attach to nuclei which elastically scatter as they pass through the mica, leaving a trail of lattice defects. Even if one interprets the mica results as applying to a wider class of candidates than monopoles, it can be argued that a relatively inexpensive ocean-bottom experiment is worth doing since it, at the very least, would be able to confirm that a large class of dark matter candidates over a mass range of 11 orders of magnitude can be ruled out as the primary component of dark matter in the galaxy.

Conclusions

There are reasons to speculate that the dark matter which comprises 90-99% of the universe could be composed of non-nucleonic particles with masses much greater than atoms. The maximum flux of these particles can be estimated from their expected density and the velocity of the solar system in the galaxy. Above a mass of 2×10^{-11}g they would penetrate 4000 m.w.e. of rock or water. Even if neutral, they may ionize matter by collisions giving off energies of the order of GeV per cm. Large underground experiments such as MACRO will be able to search for these particles in the mass range 10^{-10} to 0.1 g. Comparable sensitivity out to 1 g is achieved by an array of a small number of photomultiplier tubes in the deep ocean, for example, the already existing DUMAND Short Prototype String. Neither of these techniques can set limits comparable to those for monopoles from studies of ancient mica. Nevertheless these experiments can help rule out a large class of candidates as the major component of dark matter in the galaxy: those with mass in the range 10^{-11} to 1 g and effective cross sectional area no smaller than that of atoms.

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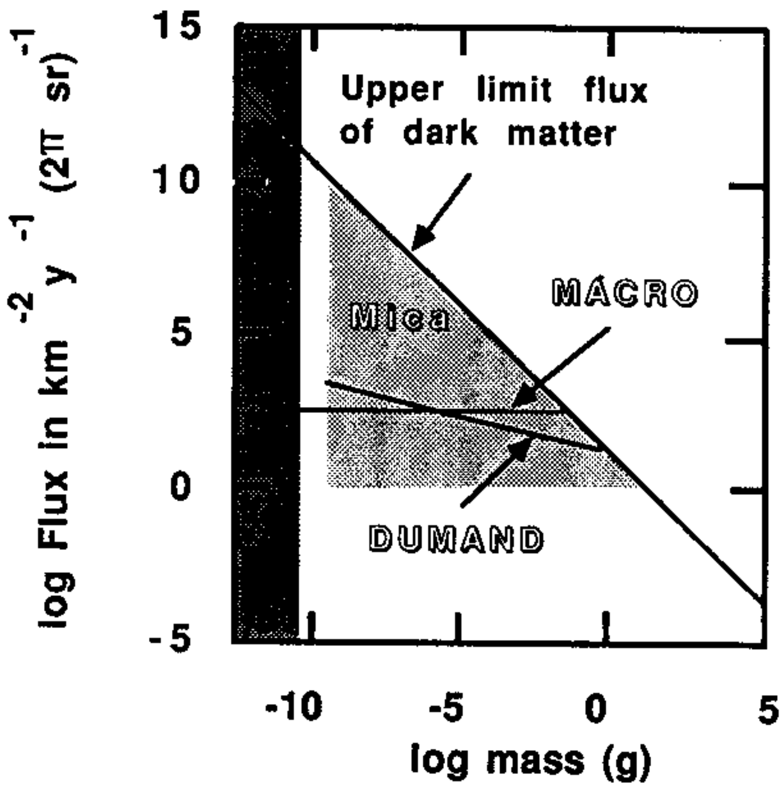

Fig. 1. Flux of dark matter as a function of the particle mass and the limits set or possible in the Mica, MACRO and DUMAND experiments. The dark band on the left is inacccessible to deep detectors.

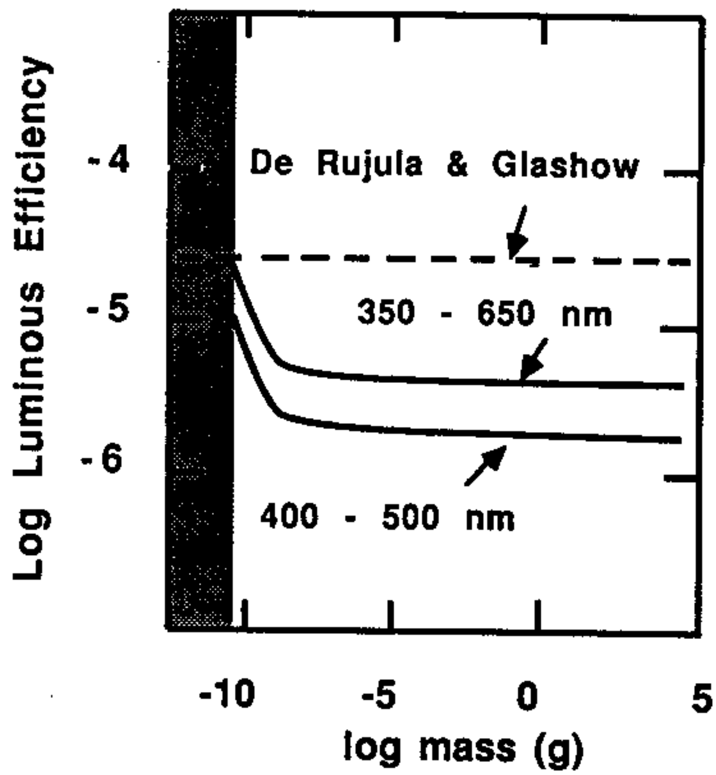

Fig. 2. The luminous efficiency as a function of dark particle mass, for two spectral bands. The 400 - 500 nm band was used in this report. The calculation of De Rujula and Glashow gives 2×10^{-5} independent of mass, for highly transparent water.

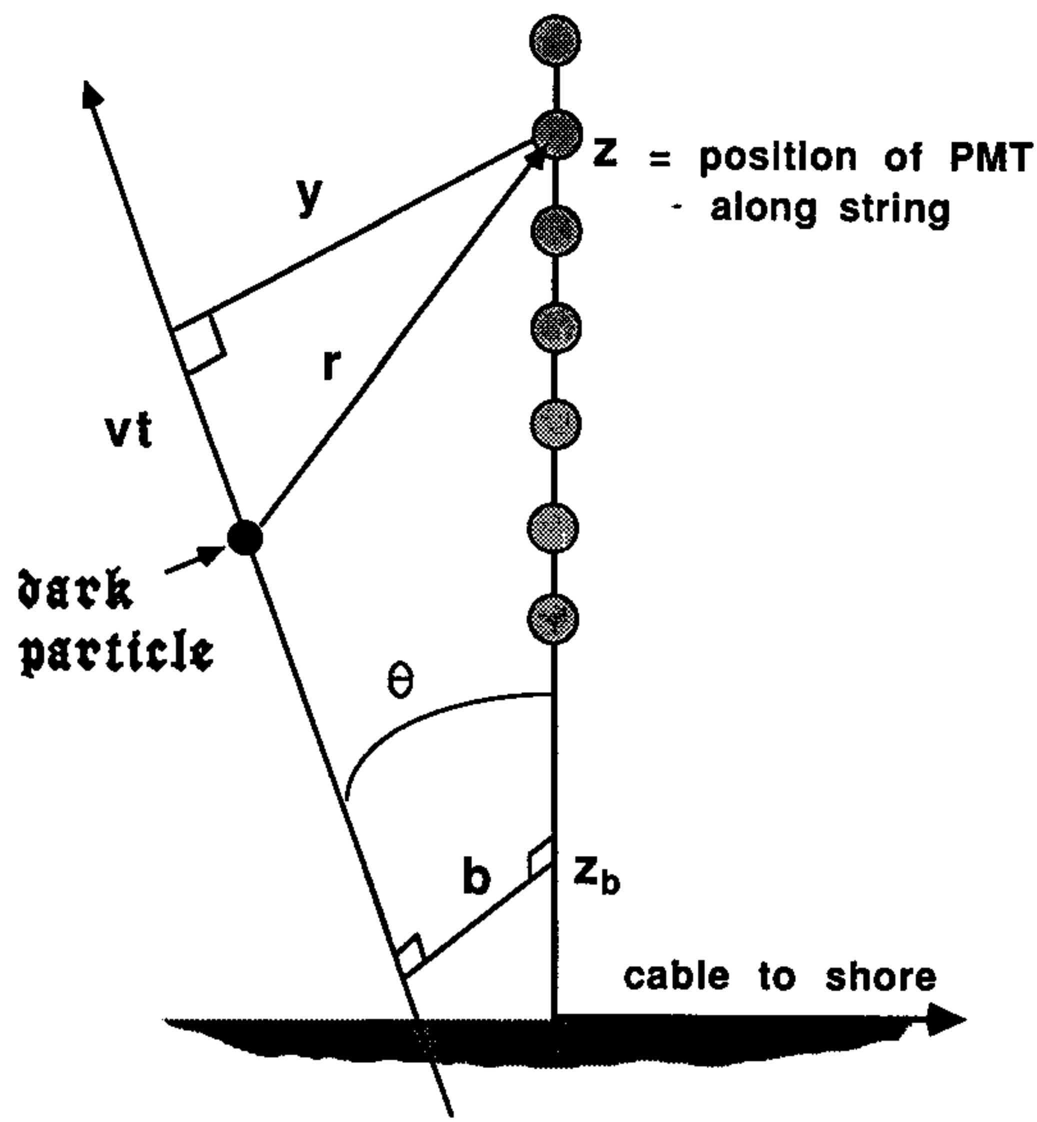

Fig. 3. The seven PMT Short Prototype String is shown deployed on the ocean bottom. A dark particle of speed v emits isotropic light which peaks, for a given PMT, when r = y at t = 0.

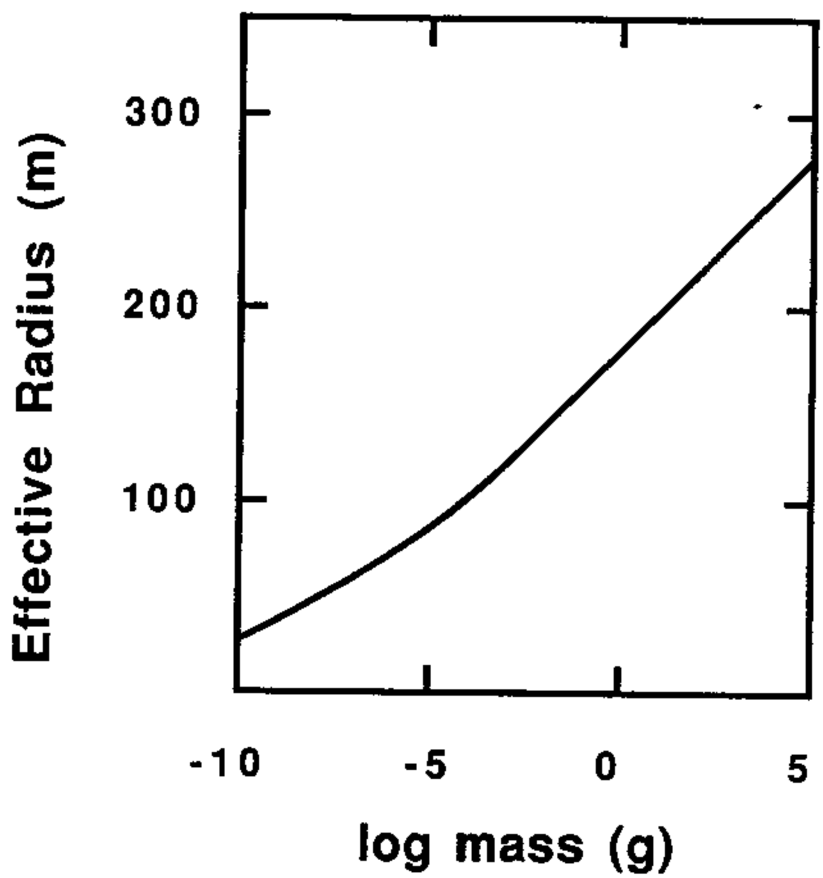

Fig. 4. Effective detector radius of the bottom-moored PMT string as a function of dark particle mass, for the trigger described in the text.