Present and Future Underground Experiments*

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Abstract

We review key present and future underground experiments in the following areas: nucleon decay, with emphasis on the search for $p \to K^+ \bar{\nu}_\mu$, search for low energy cosmological neutrino sources, search for cold dark matter particles, with emphasis on LSP in supersymmetry, and the search for massive neutrinos using accelerator neutrino beams and future detection of supernova neutrinos. In this report we emphasize the ICARUS detector for the Gran Sasso Laboratory and long baseline neutrino beams from CERN to this laboratory.

1. The Nature of Underground Experiments and Laboratories

The earliest underground experiments were probably to observe the flux of cosmic ray muons that had penetrated through the overburden and thus determine the flux above some energy threshold. Now we go underground to get away from the cosmic ray muons and radioactivity as much as possible. Other early underground experiments detected the ^{8}B Solar neutrinos and the atmospheric neutrinos and search for double β decay[1]. In the mid 1970's the nature of these experiments changed with the motivation to search for proton decay to $10^{30} - 10^{31}$ years[2]. This required high mass sophisticated detectors to be placed under the maximal shielding[3,4,5,6,7]. Another major change was the development of a *real* laboratory (i.e., providing the comfort of an accelerator laboratory) like the INFN Gran Sasso Laboratory and others around the world. Table 1 lists some of the types of experiments currently being constructed or carried out at these laboratories. Fig. 1 shows a schematic of an underground experiment with the attendant backgrounds. Fig. 2 shows the μ flux at the various sites

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Table 1: Underground Experiments

	Physics Goal	Types of Detectors	Experiments (some examples)
a)	Solar Neutrinos	H_2O, Gallium $^{37}C\ell$, D_2O ^{42}Ar	Homestake Kamiokande Sudbury Gran Sasso Russia
b)	Proton Decay	H_2O, Fe Plates ^{42}Ar	Kamioka Soudan Gran Sasso
c)	WIMP – LSP Search (CDM)	Ge, GaAs Xe, NaI	Boutry, UK Stanford Gran Sasso Mt. Blanc
d)	Cosmological Neutrinos	^{42}Ar, H_2O	Gran Sasso Kamioka
e)	Long Baseline Accelerator Neutrino Beam	^{42}Ar, Scintillation	Gran Sasso BNL LANL FNAL
f)	Monopole Search	Various	Gran Sasso

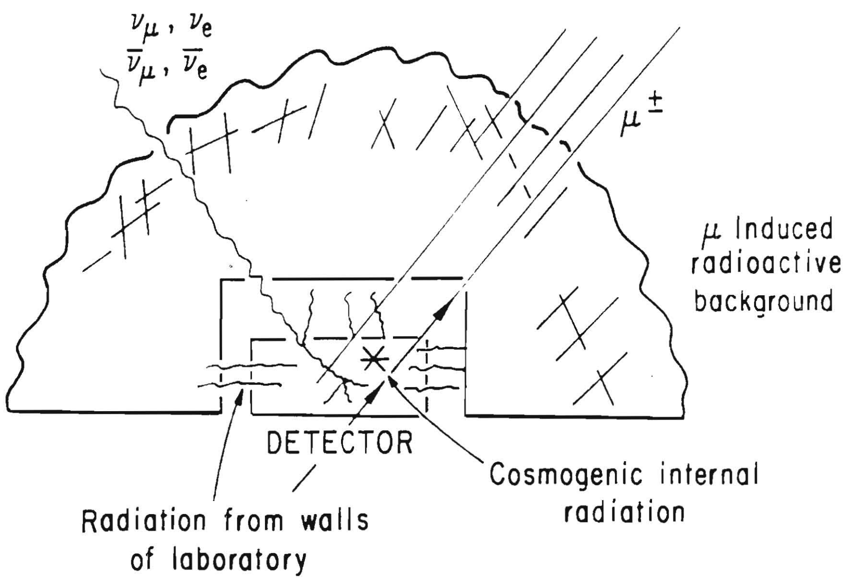
in the world where underground experiments are or were being carried out. Table 1 lists some of the types of underground experiments and some of the locations where the various experiments are underway.

2. Present Nucleon Decay Search with Emphasis on $p \to K^+ \bar{\nu}_\mu$

Of all the unsolved problems in science one of th ..most intriguing is the *stability* of the proton. There is no well-established physical principle that maintains this stability[2]. An equally profound mystery is the apparent excess of matter over antimatter in the universe. There may be a connection between proton disintegration and the matter – antimatter asymmetry in that in the early universe protons were formed more abundantly than antiprotons in a reverse "proton decay" type of process. Thus,

BACKGROUNDS FOR UNDERGROUND EXPERIMENTS

- THE REAL ISSUE -



$\mu^\pm$ - Reduce flux by deep laboratory site

γ, β, n from walls - low radioactive enclosure

ν_μ, ν_e $\cdots$ Interactions in detector $\rightleftharpoons$ detector resolution and pattern discrimination

γ, β from inside detector - choose low radioactivity materials

Figure 1: Backgrounds for underground experiments.

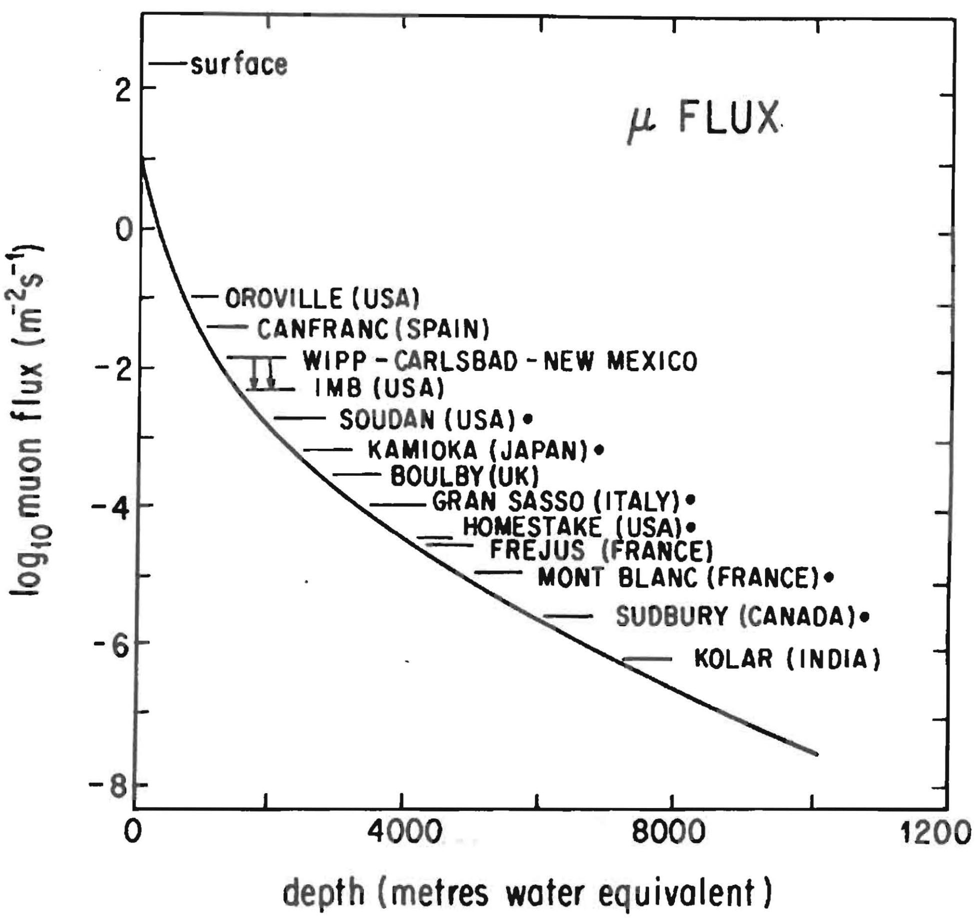


Figure 2: μ flux at various sites in the world.

the observation of proton instability would have profound implications concerning the nature of the universe.

Protons are extremely stable. So far, the lifetime for disintegration by any possible mechanism into any possible final state has been shown to be greater than 10^{27} yr. Thus, protons are the longest-lived particles that we know of. The corresponding limit for the disintegration of the electron is 10^{22} yr. Could protons be completely stable? This seems unlikely since such a stability would imply a rigorously conserved "quantum number." One such quantum number is electric charge, and electrons are expected to be entirely stable because there is no way for the electron to disintegrate and conserve the electric charge and energy at the same time. In the case of the proton there are many possible ways for it to decay while conserving electric charge and energy.

The theory of nucleon decay can be distinguished by the mechanism by which the baryon number of the nucleon is reduced to zero in the final state products. Two general possibilities have been proposed, which we can indicate schematically:

1. Nucleon $\rightarrow$ 3 quarks $\rightarrow$ antilepton + antiquark + quark

2. Nucleon $\rightarrow$ 3 quarks $\rightarrow$ leptons + antileptons + quarks + antiquarks

A classic example of decay type (1) is $p \rightarrow u + u + d \rightarrow e^+ + \bar{d} + d \rightarrow e^+ +$ neutral meson (π^0). An example of type (2) decay is $n \rightarrow u + u + d \rightarrow \mu + \mu + \nu^- + \bar{u} + d \rightarrow \nu + \nu + \mu^- + \pi^+$. In this case the individual quarks have decayed and the quark-antiquarks have been produced in the final interactions of the system. In this final state about one-half of the nucleon energy goes into neutrinos. Decay of types (1) and (2) follows from a large variety of theoretical models of grand unification of forces.

The two basic kinds of theories for proton decay are related to the mechanism by which the baryonic charge is converted to leptonic charge. A third type of proton decay is expected in the theory that combines grand unification and supersymmetry. This is sometimes called a SUSY-GUTS theory. The dominant decay mode is expected to[8]

$$p \rightarrow K^+ + \bar{\nu} \tag{1}$$

Since there is a theoretical prediction for supersymmetry it will be important to search for this decay mode in future experiments.

Table 2 lists some of the various proton decay experiments that have been carried out or are in progress now and the accumulated sensitivity in the units of kiloton-yrs. Note that there are more than 0.10 Kiloton-yrs of accumulated sensitivity; any new proton decay experiment must contend with this fact.

The current generation of detectors has nearly exhausted the lifetime range up to $\sim 10^{32}$ years. The scaling rules for the proton decay search are[9]

$$\tau_p \propto N_p \text{ [protons in detector]} \qquad S/N >> 1 \tag{2}$$

$$\tau_p \propto \sqrt{N_p} \qquad S/N \lesssim 1 \tag{3}$$

Table 2: Nucleon Decay Experiments

Experiment	Type	Status	Available Analysis Sensitivity (Kt.y.)
Kolar	Track Calorimetry	Closed (?)	0.8
IMB	Water Cherenkov	Stopped	3.8 to 7.2
Nusex	Track Calorimetry	Stopped	0.36
HPW	Water Cherenkov	Stopped (1985)	0.14
Kamioka	Water Cherenkov	Running	3.76
Frejus	Track Calorimetry	Stopped (1988)	1.5 to 2
Soudan 2	Track Calorimetry completed to 1Kt at the end of 1992	Running with 0.7Kt, on nucleon decay	No published results

Table 3: Current Situation in Search for $p \to K^+ \bar{\nu}$

Mode	Candidates	GB*	Group
$K_{\mu 2}$	11	8.6	KAM I/II 4.92Kt.y.
$K_{\mu 2}$	6	4.7	IMB (90) 3.76Kt.y.
$K_{\mu 2}$, $K_{\pi 2}$	1	1.8	Frejus 1.3Kt.y.
	18	15.1	9.98Kt.y.
$K_{\pi 2}^{**}$	3		IMB

*Region of $K_{\mu 2}$ in (μ/e) / $(\mu/e)_{\text{cal}} < 1$
** $\tau / B \geq 6 \times 10^{31}$y 90% C.L.

where S is the signal for proton decay and N is the background. In the latter case, (?), a background subtraction is required and this reduces the statistical power of the detector.

In order to explore the $\tau_p \sim 10^{32} - 10^{34}$ yrs region, we choose between two options:

1. construct very large detectors (M$\sim 10^5$ Tons) that will have $S / N \lesssim 1$ or
2. construct detectors with M$\sim 10^4$ Tons with $S / N >> 1$.

In Table 3 we list the current number of candidates for the decay $p \to K^+ \nu^-$. Note that ~ 21 candidates have been reported. While these could be completely explained by background there could be, in our opinion, a signal that would be equivalent to $\tau / B \sim 10^{31} - 10^{32}$ yrs for this mode. Clearly, new experiments are required to resolve this issue.

3. Future Detectors for Nucleon Decay Search – ICARUS

Two new detectors are being constructed to continue the search for proton decay

1. Super Kamiokande[11]

Table 4: Parameters of the Super Kamiokande Detector

Size	39 m (ϕ) $\times$41 m (h)
Total mass	50,000 t
Fiducial mass	25,000 t (depending on specific physics item)
Number of PMT's	11,200
Veto PMT's	700
Coverage	40%
Energy resolution	2.6% / $\sqrt{E}$ high energy electrons (E in GeV) 14% / $\sqrt{E/10\,\mathrm{MeV}}$ for electrons with $E < 50\,\mathrm{MeV}$
Position resolution	50 cm 10 MeV electrons 10 cm $p \rightarrow e\pi^0$ events
Angular resolution	27° 10 MeV electrons 1° through going muons

Table 5: The ICARUS cryostat parameters

	Internal vessel	External vessel
Shape	horizontal cylinder with domed ends	horizontal cylinder with flat ends
Diameter	16.0 m net	18.2 external
Length	20.0 m net	24.8 m external
Volume	4,180 m^3 net, total	–
Filling ratio	0.90 to 0.95	–
Design pressure	0.2 + hydro.	0.1 MPa external
Design temperature	85° K	20° C
Material	AISI 304 L	9% Ni steel
Hull structure	double, compart.	single, reinforced rings
Ends structure	double, compart.	sandwich, part. open
Body weight	$\sim$ 750 t Total	$\sim$ 500 t Total

2. ICARUS[12]

The parameters of Super Kamiokande are listed in Table 4 and the detector is shown in Fig. 3[11]. This will indeed be a very impressive detector but will largely work in the $\sqrt{N}$ region for $p \to K^+\bar{\nu}$, in our opinion.

The ICARUS detector is based on a new detector concept of electron drift in ultra pure liquid argon. The principle is shown in Fig. 4. In Table 5 and Fig. 4 we show the expected first model of ICARUS for Hall C of the Gran Sasso[13]. An extensive and very successful R & D program for the ICARUS detector has been carried out and is discussed in Ref. 12. We now turn to some event simulation for the proton decay signature in ICARUS.

Fig. 5 shows a simulated $p \to K^+\bar{\nu}$ decay. Note the bubble chamber-like quality of these events. We estimate that a single event of this type could prove the existence of proton decay[9,13]! Fig. 6 shows some other decay mode simulation[9,13].

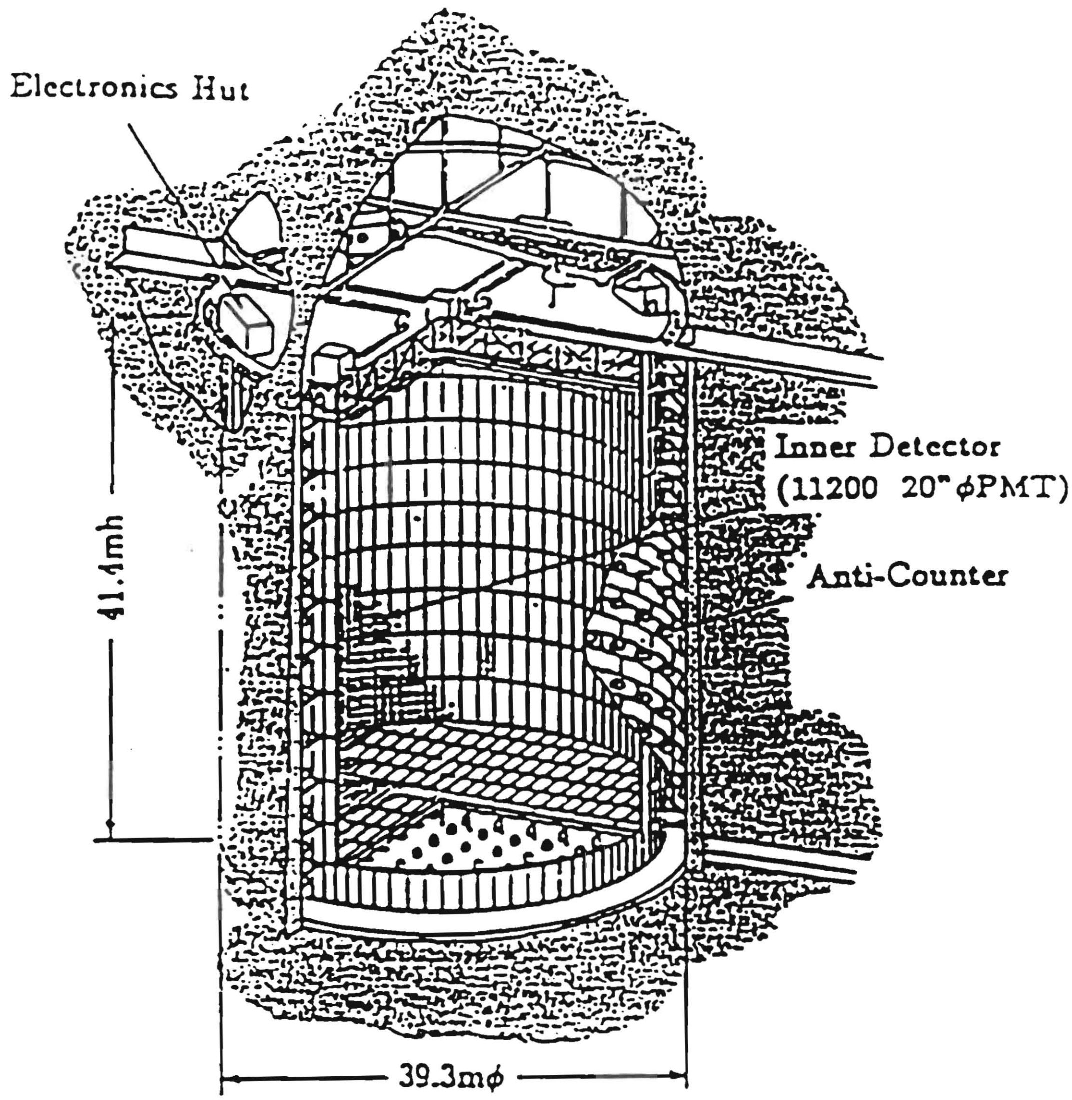
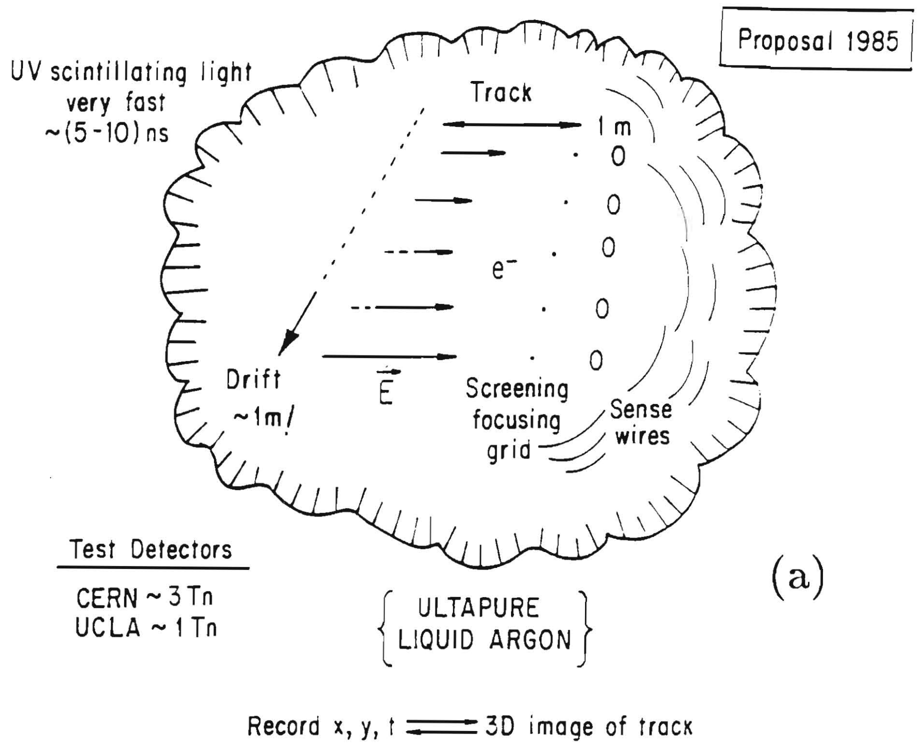
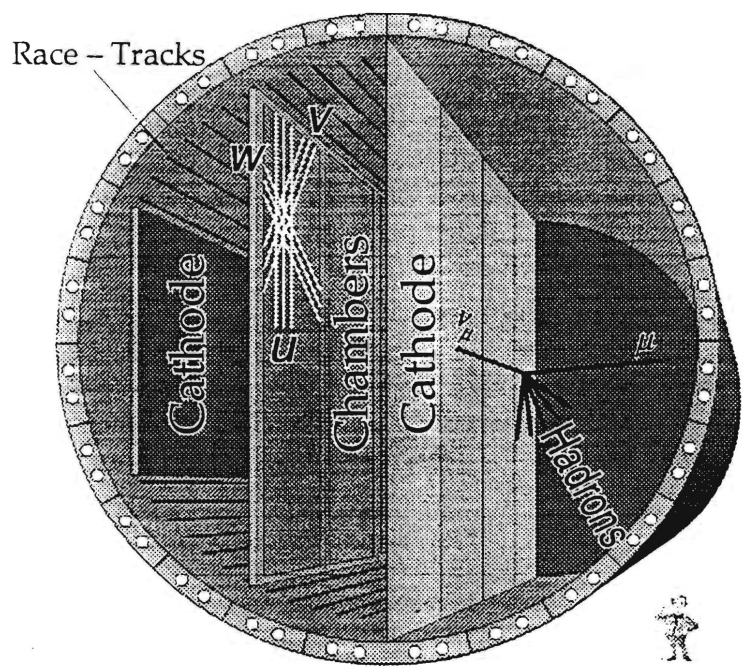


Figure 3: The superkamiokande detector.



(a)



(b)

Figure 4: ICARUS concept: (a) an electron drift image chamber, (b) an artist view of one ICARUS module for Gran Sasso.

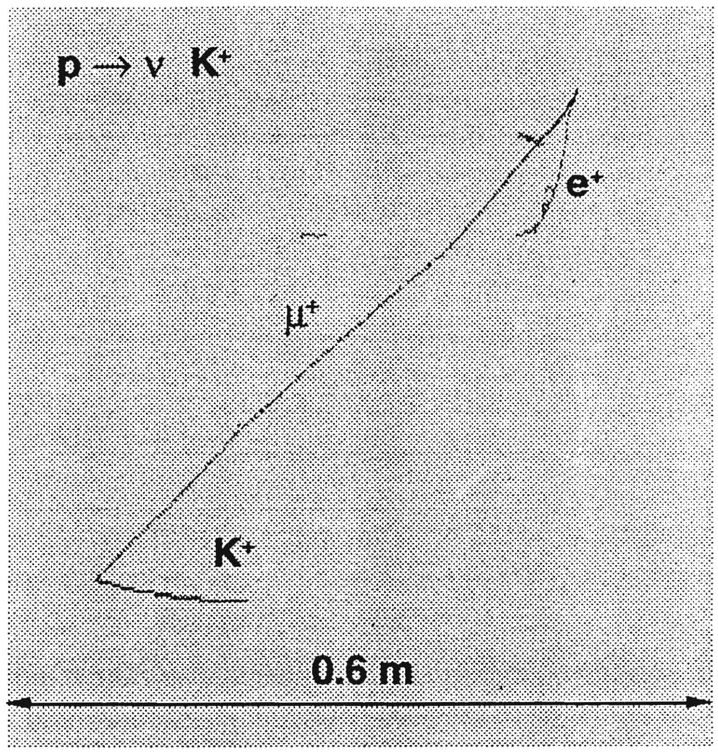


Figure 5: Simulated proton decay in the Supersymmetrically preferred channel $p \longrightarrow \nu K^+$ as it will be observed in ICARUS.

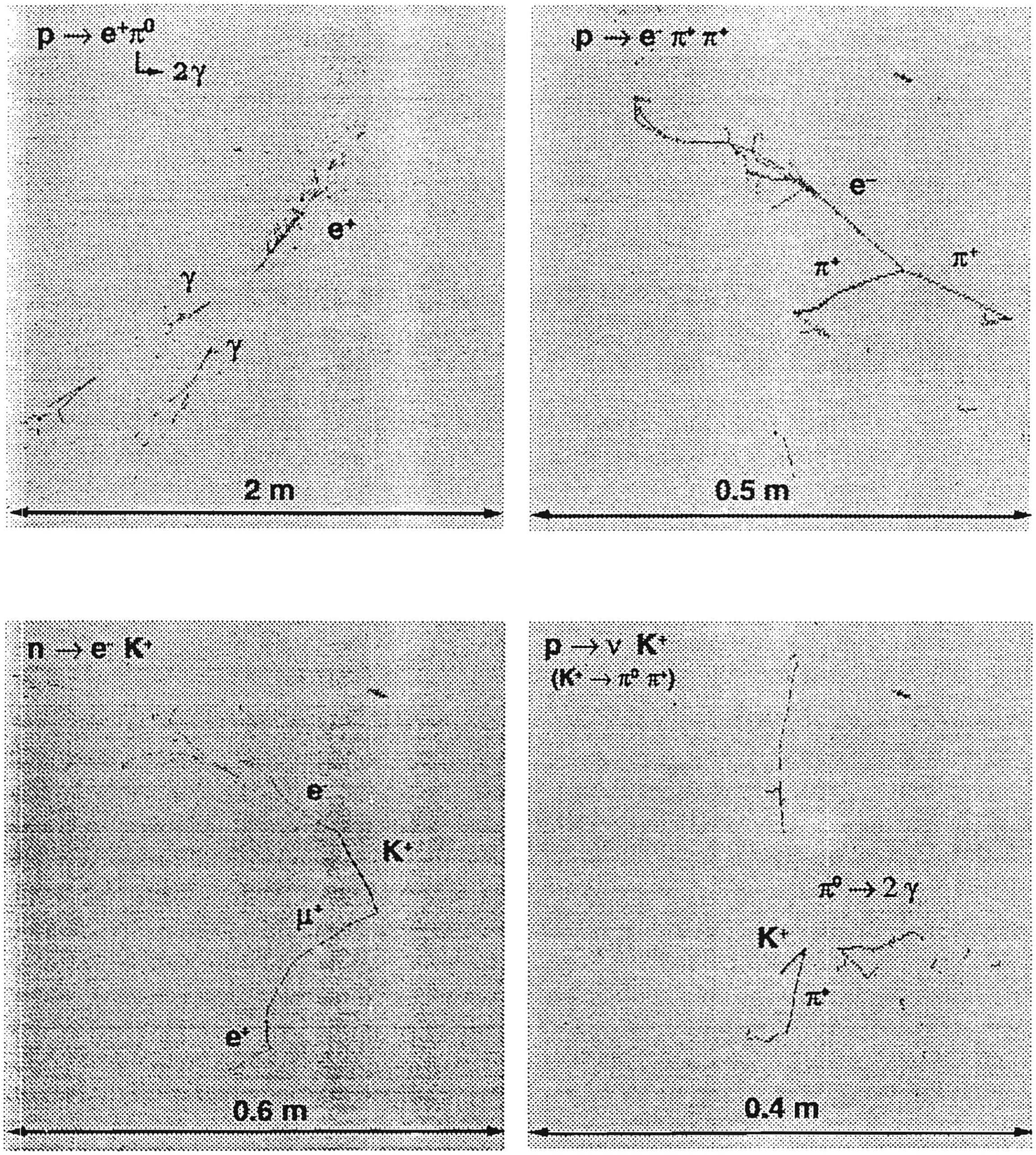


Figure 6: Simulation of various nucleon decays in liquid argon which illustrates the signature of electrons, pions, kaons, protons, etc., in ICARUS. The dimensions are indicated for each figure.

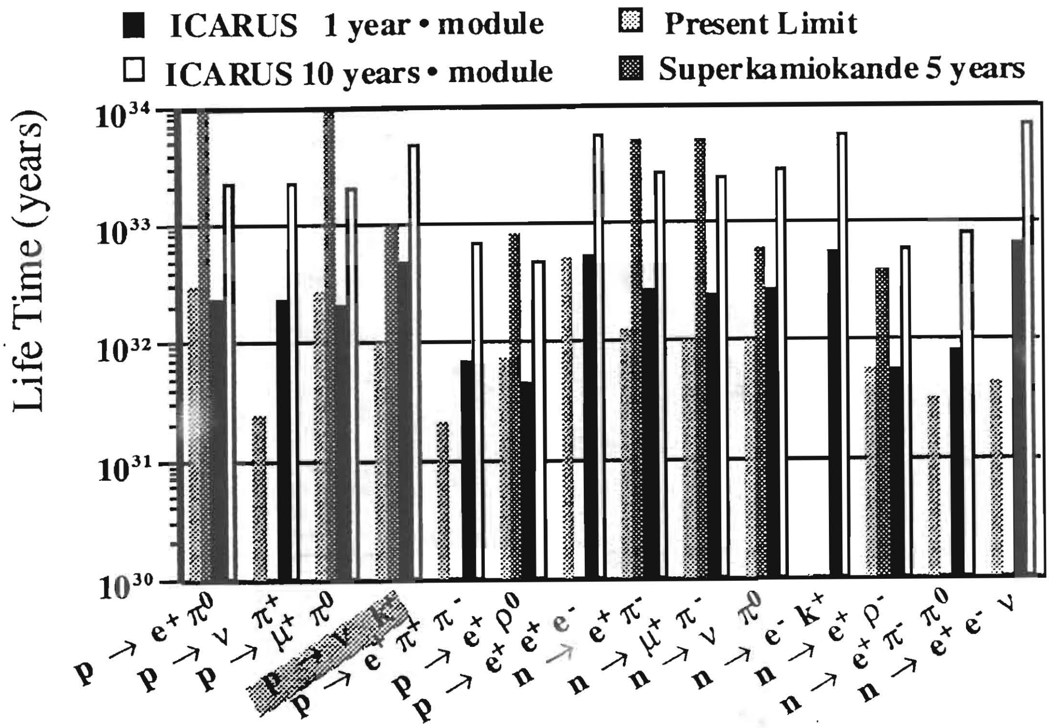


Figure 7: ICARUS proton decay sensitivity compared with present limits and with Super Kamiokande.

In Fig. 7 we compare the sensitivity of ICARUS and Super Kamiokande to the various proton decay channels[13]. Of course, the real motivation for searching for proton decay is to test the GUT concept. With the new electroweak data from LEP we believe SUSY - SU(5) GUT's is a viable theory, as shown in Fig. 8[13].

4. Cosmological Neutrino Detection in Window of Opportunity at Low Energy[14]

ICARUS and Super Kamiokande could also make another important discovery: the existence of Relic 10 − 40 MeV Neutrinos or Antineutrinos that could come from the early universe or from the integrated Supernova in our Galaxy. Fig. 9 shows this window of opportunity for such a discovery.

The detection of diffuse microwave background photons provided a revolution in Astrophysics and Cosmology. The detection of a primordial neutrino background would likely be as important. Unfortunately, this detection is going to be extremely difficult. On the other hand, so little is known about the low energy neutrino that the flux could possibly be much larger than is presently expected. This would be a major discovery.

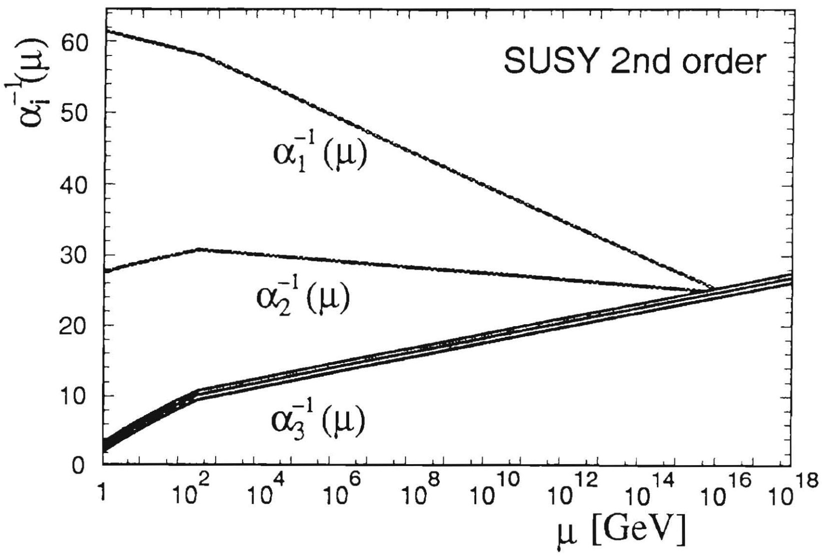


Figure 8: Extrapolation of the weak, electromagnetic and strong coupling constants in the framework of the Minimal SUSY model.

There are many possible sources of diffuse neutrinos. For example, from processes like Wimp annihilation in the early universe to exploring black holes. The low energy gamma flux is attenuated by electro-magnetic processes in the universe; the neutrino flux is not. Thus, the ν-flux could be much larger than the observed γ-flux.

5. Search for WIMPS – LSP / CDM – Novel Detectors

The search for WIMPS and the LSP for Supersymmetric theories is of enormous importance[15]. We shall not attempt to survey this important field but discuss the possible use of the ICARUS technology and liquid Xenon. First, we describe an "ideal" WIMP detector in Table 6. Such a detector would need a space resolution of $\sim$ 10 nanometers, which is not presently possible. Thus, other techniques must be employed until we can develop an ideal detector.

We discuss here the use of a liquid Xenon detector[16]. The kinematics of WIMP detection are given in Table 7. J. Park at UCLA, has calculated the average recoil energy and the conversion to scintillation light in liquid Xenon, as shown in Fig. 10a and b[17]. Note that the mean recoil energy of a 200 GeV WIMP is 50 KeV in Xenon. Most likely a Xenon detector will be most sensitive to massive WIMPS with mass $<$ 100 GeV. In Table 8 we list the signature and background disconnection for liquid Xenon and in Fig. 11 some experimental tests carried out by the ICARUS group. Recently a UCLA-RAL group has proposed a variant of such a detector as shown in Fig. 12. Fig. 13 shows the possible reach of this detector[19].

One of the major advantages of such a detector is the possibility to scale it to the ton mass scale. This could be very important if the amount of nonbaryonic dark

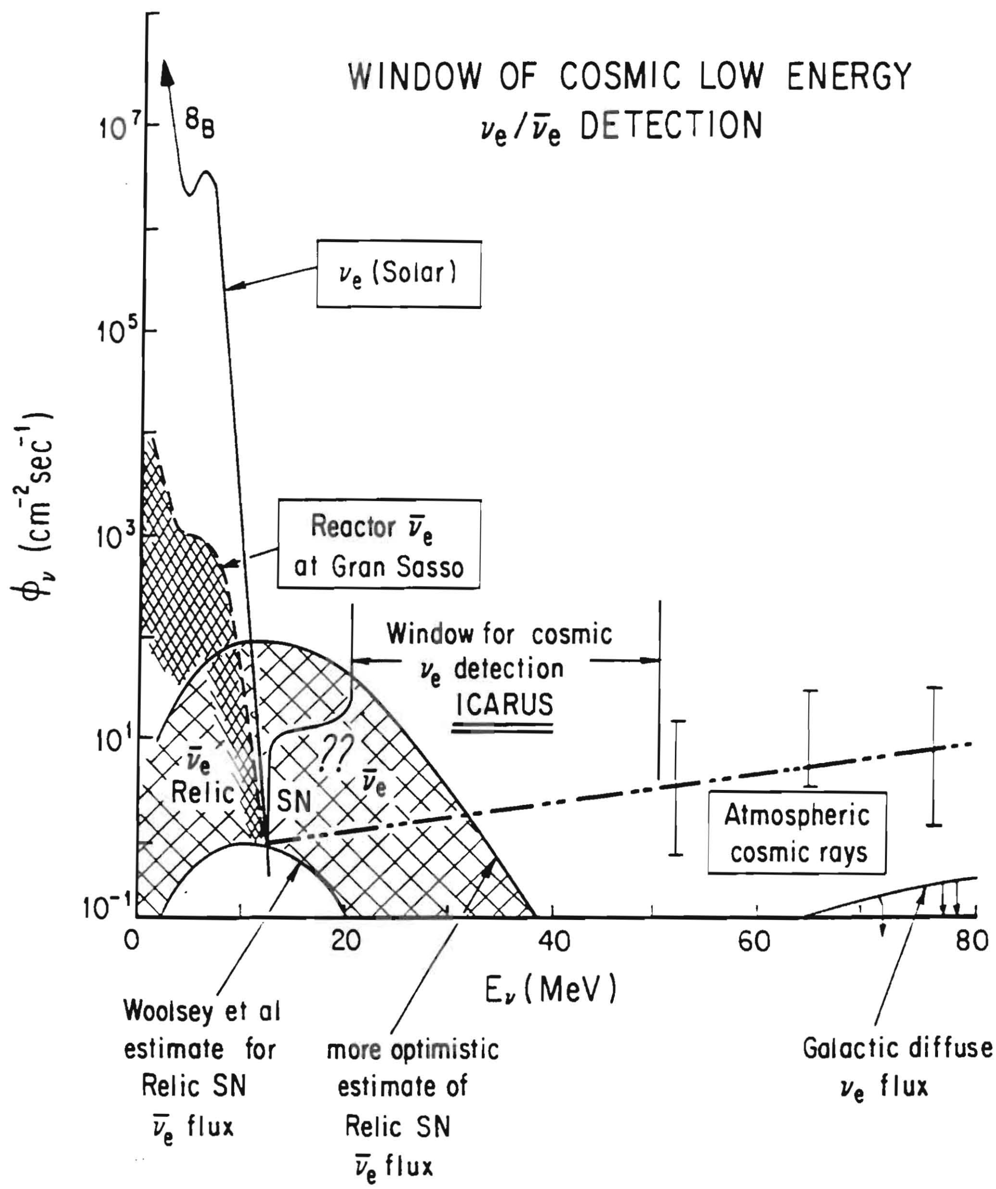


Figure 9: Window of cosmic low energy ν_e / $\bar{\nu}_e$ detection[14].

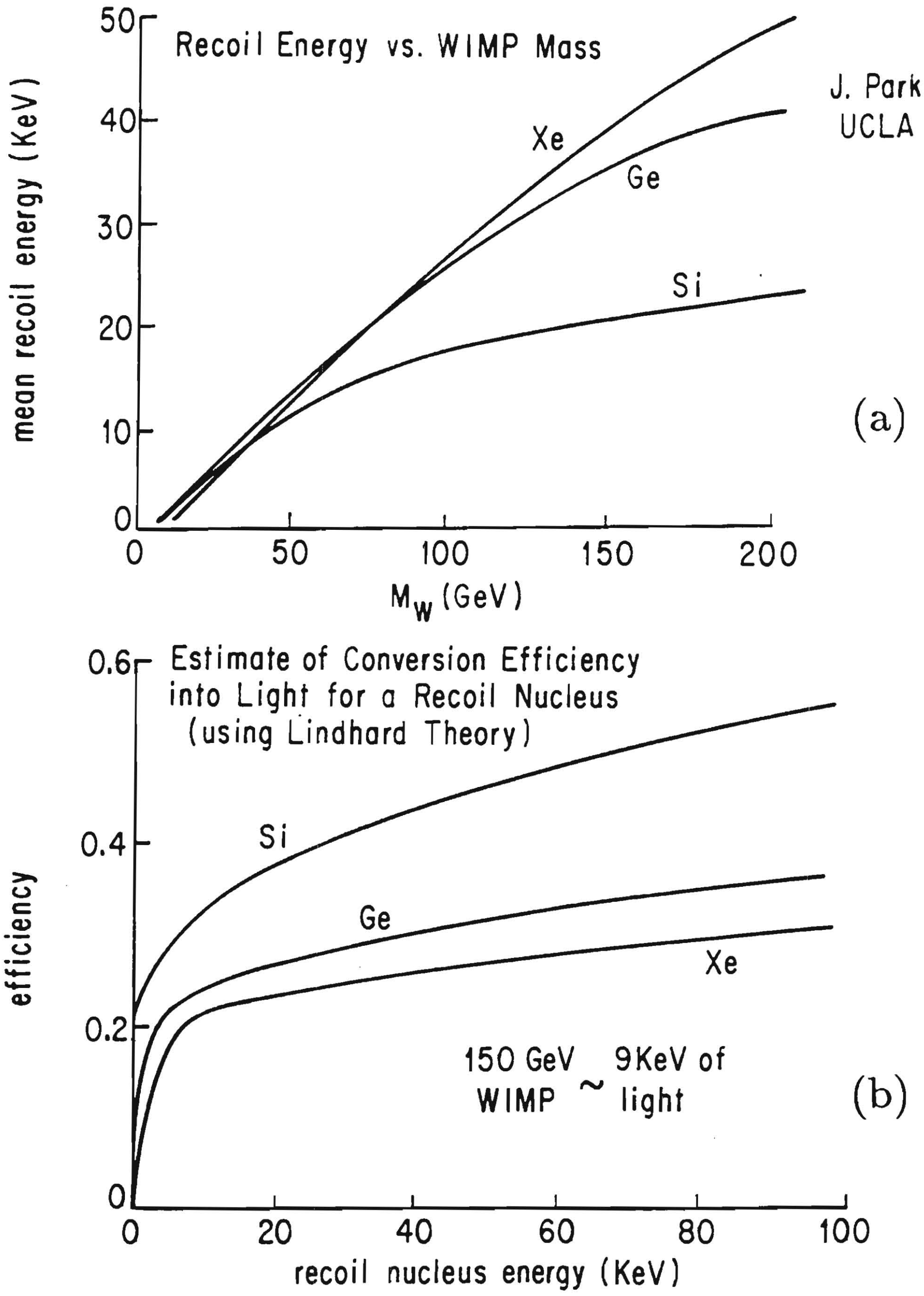


Figure 10: Average recoil energy and the conversion to scintillation light.

Table 6: The Ideal WIMP Detector

	TARGET A Nucleus	
	$\langle v_W \rangle = 300\text{Km/sec}$	$M_W > 20\text{GeV}$ $< 1\text{TeV}$
	$A \rightarrow$ Range Range ~ 10nm (10^{-6}cm)	$E_A \sim f(M_W) \sim 10\text{KeV}$ $\rightarrow 50\text{KeV}$
i)	A – Correct Spin for Maximal $\tau \left[\sim \frac{10^{-37}\text{cm}^2}{\beta}\right]$	
ii)	Measure Unique Properties	E_A – Calorimeter Range
iii)	Detector Size [10 – 1000]Kg	[Rate $(1 - 10^{-2})\text{Kg}^{-1}\text{Day}$] For all Halo DM = WIMP $\rightarrow$ Reduced By ?
iv)	Very Low Background	MACHO Observation

Table 7: Direct detection by nuclear recoil of Dark Matter candidates.

WIMP's: massive neutrinos
light supersymmetric particles,
. . . . . .

Event rate for elastic scattering of DM on nuclei

$$R = 4.3 \frac{X_N}{m_N m_\delta} \sigma_{\delta N 38}\, \rho_{0.3} < V_{300} > \text{Kg}^{-1}\,\text{day}^{-1}$$

Energy of the recoil nucleus

$$\Delta E = \frac{m_N m_\delta^2}{(m_N + m_N)^2} V^2 (1 - \cos(\theta))$$

$$\Delta E \sim 2 \frac{m_N m_\delta^2}{(m_N + m_\delta)^2} \text{KeV}$$

Table 8: Signature and Background in Liquid Xenon

Recoil Nuclei
Heavily ionizing particle
High recombination, hence:
mainly scintillation light produced

Radioactivity
Minimum ionizing particle
Low recombination, hence:
Both charge and light produced

In Liquid Xenon
Both charge and light are visible
This provides an efficient way for
signal to background rejection.

Moreover in Xenon no long-lived
natural isotopes are present:
Xe^{127} has the longest decay time
($\sim$ 36 days)

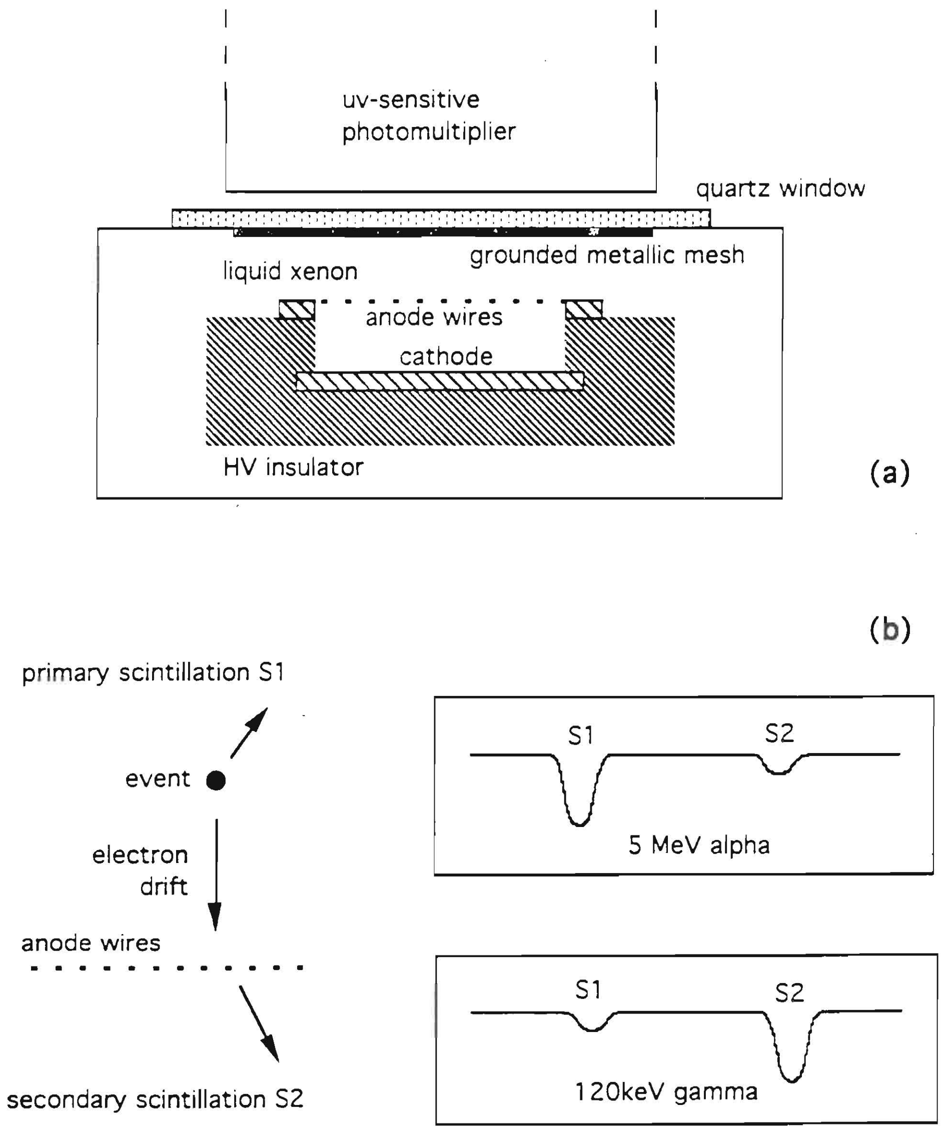


Figure 11: (a) Geometry of liquid xenon test chamber, (b) observed primary and secondary scintillation signals showing $S1\,/\,S2 >> 1$ for alpha events and $S1\,/\,S2 << 1$ for gamma events.

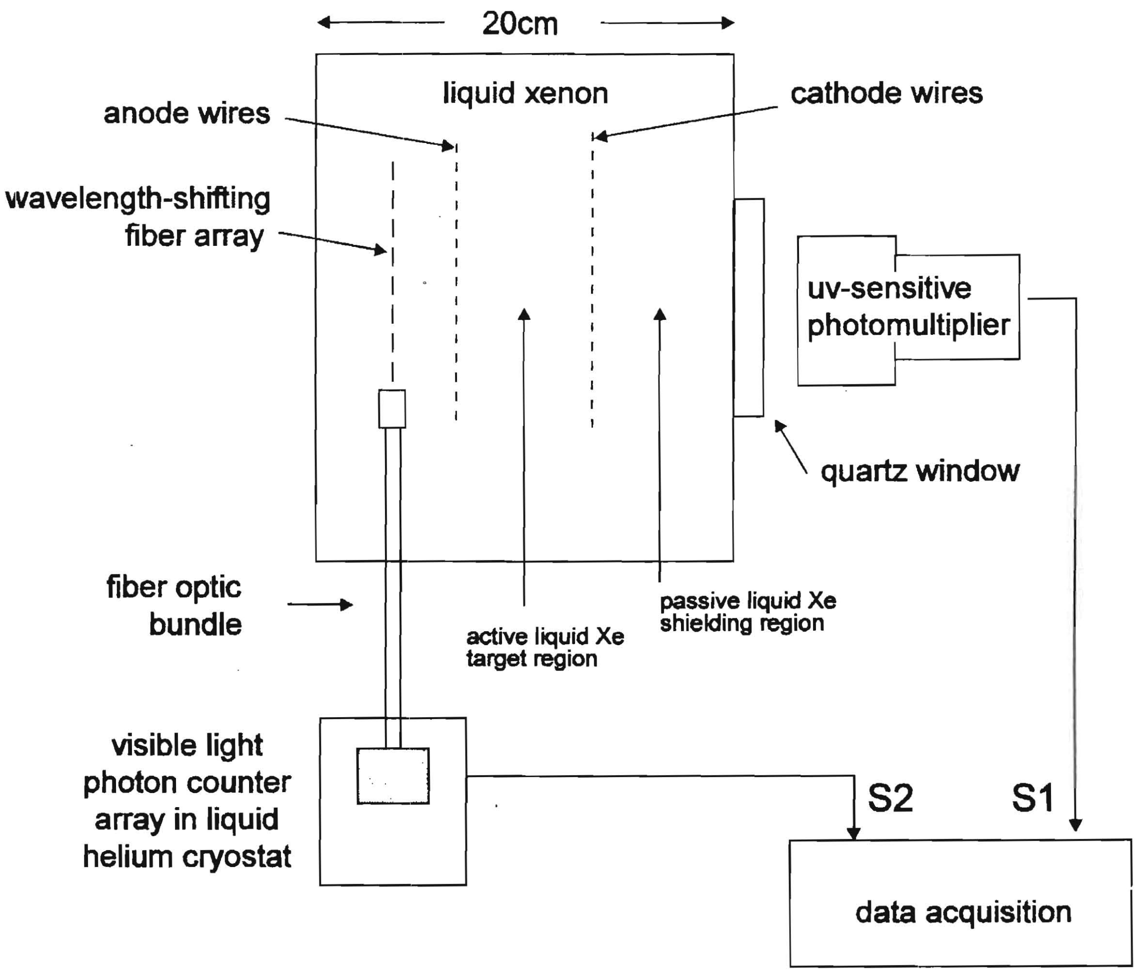


Figure 12: Schematic design of proposed prototype liquid xenon detector.

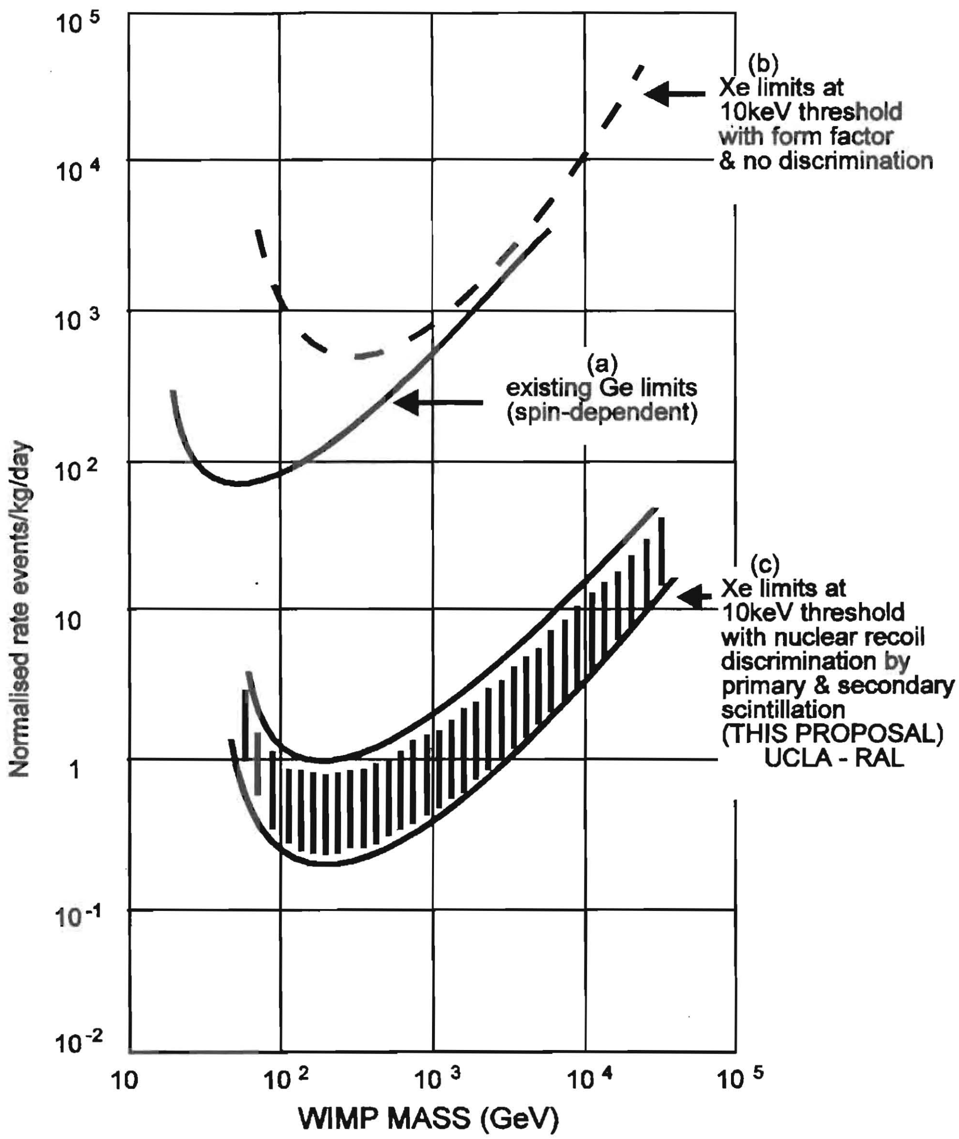


Figure 13: Typical dark matter limits from (a) existing underground Ge detectors, (b) liquid xenon detector without discrimination, and (c) proposed liquid xenon detector.

matter is uncertain due to the recent observations of MACHOS[19].

6. Search for Neutrino Mass Using Neutrino Oscillations

Another variant of dark matter – Hot Dark matter – could be due to massive neutrinos. At present there are only two ways to uniquely detect a neutrino mass

1. neutrino oscillations [$\nu_x \rightarrow \nu_y$]

2. time of flight of neutrinos from galactic or extra galactic supernova events

We will briefly summarize the situation in neutrino oscillation here; the use of galactic supernova can be found in Ref. 20.

Three are types of neutrino oscillation experiments can be imagined:

1. short baseline accelerator neutrinos

2. long baseline accelerator neutrinos

3. natural neutrinos from.. he Sun or a supernova or the Cosmic Radiation

Since there are three neutrinos known the search for neutrino oscillations can use both positive data, i.e. an observation of $\nu_x \rightarrow \nu_y$, or negative data, i.e. a limit on $\nu_x \rightarrow \nu_y$. Therefore, all the (3) types of experiments may be necessary to actually determine which neutrinos are actually oscillating to which and the mixing angles and masses parameters. A generalized sensitivity range of the ICARUS[13] and CHORUS/NOMAD[21] as well as solar neutrino experiments is shown in Fig. 13. The most promising long baseline experiments are using a neutrino beam from CERN to the ICARUS detector at the Gran Sasso[13]. Fig. 14 show the layout of the neutrino beam which would be accomplished using the LHC transfer tunnel[13].

As part of the work for the LHC project at CERN injection transfer lines are being designed to bring the fast extracted beams from the SPS to the new collider. The primary proton beam for a ν production target to feed Gran Sasso with only minor modifications can be derived from the one, TI48, which links SPS / LSS4 to LHC / P8.

7. Summary and Acknowledgements

In this review article we have stressed underground or non accelerator particle physics experiments that are of cosmological significance and also require new detector technology. In order of my own believe for importance, I would order the physics experiments the following way:

1. Proton Decay – $p \rightarrow K^+\bar{\nu}$ – Baryon Asymmetry of the Universe

2. WIMP Detection – Cold Dark Matter

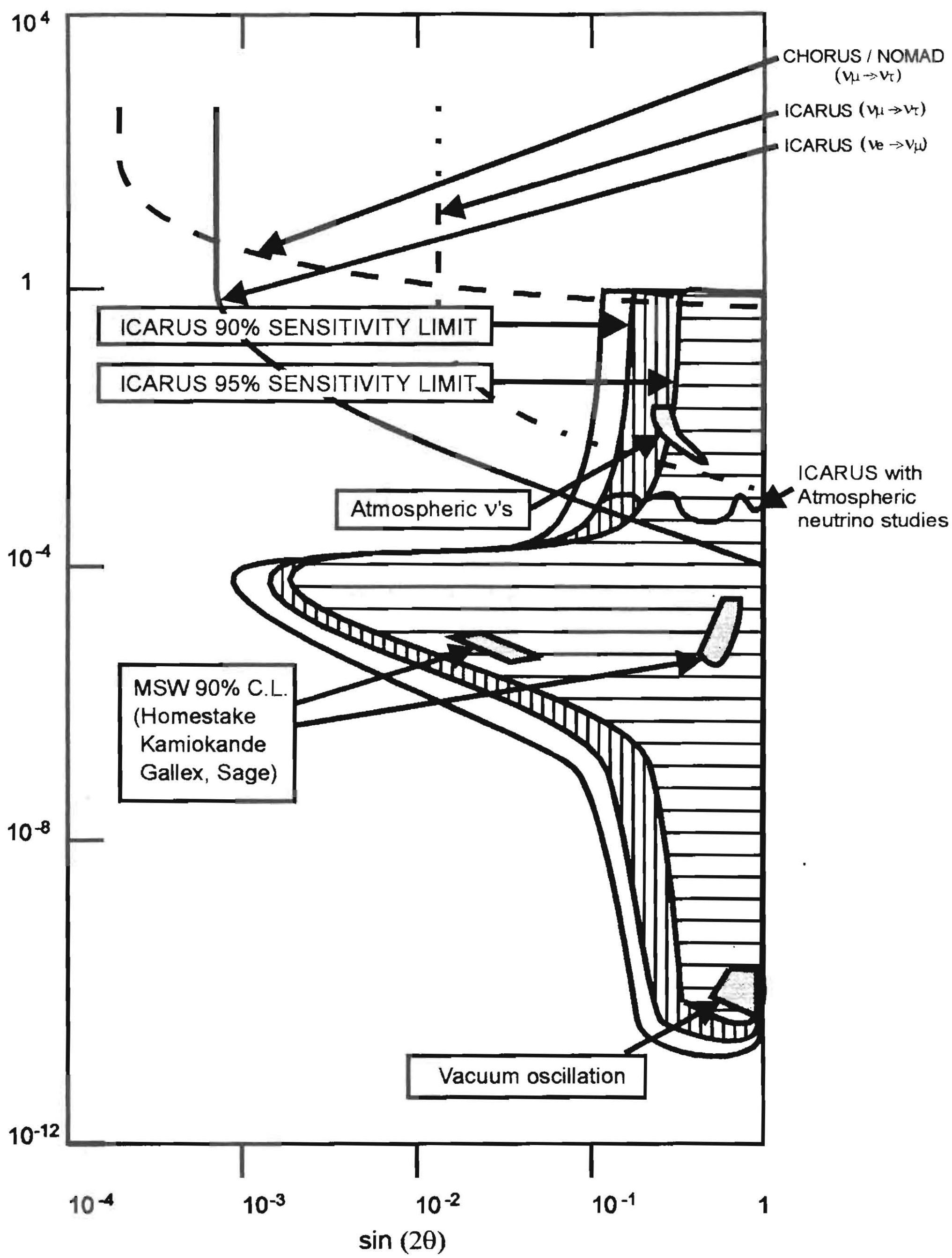


Figure 14: Most of phase space Δm^2, $sm^2 < \theta$ covered by CHORUS/NOMAD, ICARUS and solar neutrino experiments (MSW).

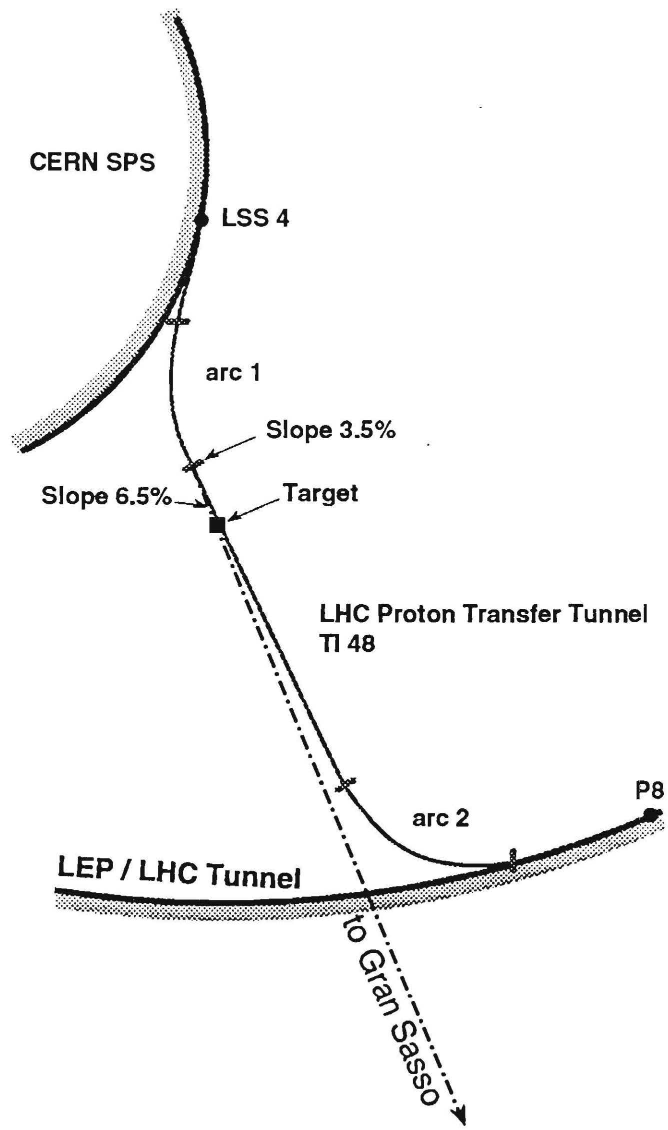


Figure 15: Geometric characteristics of the CERN neutrino beam to Gran Sasso.

3. Short Baseline Neutrino Oscillation – Hot Dark Matter
4. Cosmological Neutrinos (20 - 40 MeV) – New Sources of Neutrinos from the Early Universe
5. Long Baseline Neutrino Oscillations – New Particle Physics Implications
6. Solar Neutrinos – Oscillations or Solar Model

I wish to thank members of the ICARUS group for a long collaboration. I also want to thank members of the UCLA-RAL-Imperial College collaboration.

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