

**APS Neutrino Study:**  
**Report of the Neutrino Astrophysics and Cosmology**  
**Working Group**

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FIG. 1: Hubble Space Telescope image of the SN 1987A remnant in the Large Magellanic Cloud, a close companion of the Milky Way. Beyond the Sun and SN 1987A, cosmic neutrino sources remain undiscovered. An entire Universe awaits, and the prospects for present and next-generation experiments are excellent.

## INTRODUCTION

In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics “for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.” However, while astronomy has undergone a revolution in understanding by synthesizing data taken at many wavelengths, the universe has only barely been glimpsed in neutrinos, just the Sun and the nearby SN 1987A. An entire universe awaits, and since neutrinos can probe astrophysical objects at densities, energies, and distances that are otherwise inaccessible, the results are expected to be particularly exciting. Similarly, the revolution in quantitative cosmology has heightened the need for very precise tests that depend on the effects of neutrinos, and prominent among them is the search for the effects of neutrino mass, since neutrinos are a small but known component of the dark matter.

### Questions of the Neutrino Study:

The Neutrino Astrophysics and Cosmology Working Group put special emphasis on the following primary questions of the Neutrino Study; there are strong connections to the other questions as well.

- *What is the role of neutrinos in shaping the universe?*
- *Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the universe?*
- *What can neutrinos disclose about the deep interiors of astrophysical objects, and about the mysterious sources of very high energy cosmic rays?*

The impact of neutrino physics on astrophysics and cosmology is directly connected to many of the highest priority questions in those fields, a case made in more detail in the next twelve sections of this report, covering the following topics:

1. ORIGIN AND NATURE OF THE COSMIC RAYS
2. GZK NEUTRINO DETECTION AND NEW PHYSICS ABOVE A TEV
3. NEUTRINO PROBES OF HIGH ENERGY ASTROPHYSICAL SOURCES
4. DARK MATTER SEARCHES USING NEUTRINOS
5. NEUTRINOS AS A PROBE OF SUPERNOVAE
6. SUPERNOVA NEUTRINOS AS TESTS OF PARTICLE PHYSICS
7. DIFFUSE SUPERNOVA NEUTRINO BACKGROUND
8. MEASUREMENTS OF NEUTRINO-NUCLEUS CROSS SECTIONS
9. LEPTOGENESIS AND THE ORIGIN OF THE BARYON ASYMMETRY
10. PRECISION BIG BANG NUCLEOSYNTHESIS TESTS
11. PRECISION COSMIC MICROWAVE BACKGROUND TESTS
12. NEUTRINO MASS AND LARGE SCALE STRUCTURE

### Working Group Recommendations:

The recommendations of the Neutrino Astrophysics and Cosmology Working Group were developed in the context of these twelve topics, and are designed to provide strategies for answering the Questions of the Neutrino Study identified above. We provide recommendations that, for a modest investment, promise very important progress in neutrino physics, with fundamental impact in astrophysics, cosmology, particle physics, and nuclear physics. The recommendations focus broadly on programmatic themes that are required to maintain the vitality of neutrino astrophysics and cosmology while providing guidance on the long range goals of the field. We limited our recommendations to those experimental concepts and/or detectors that require new money from US funding agencies in the short term.

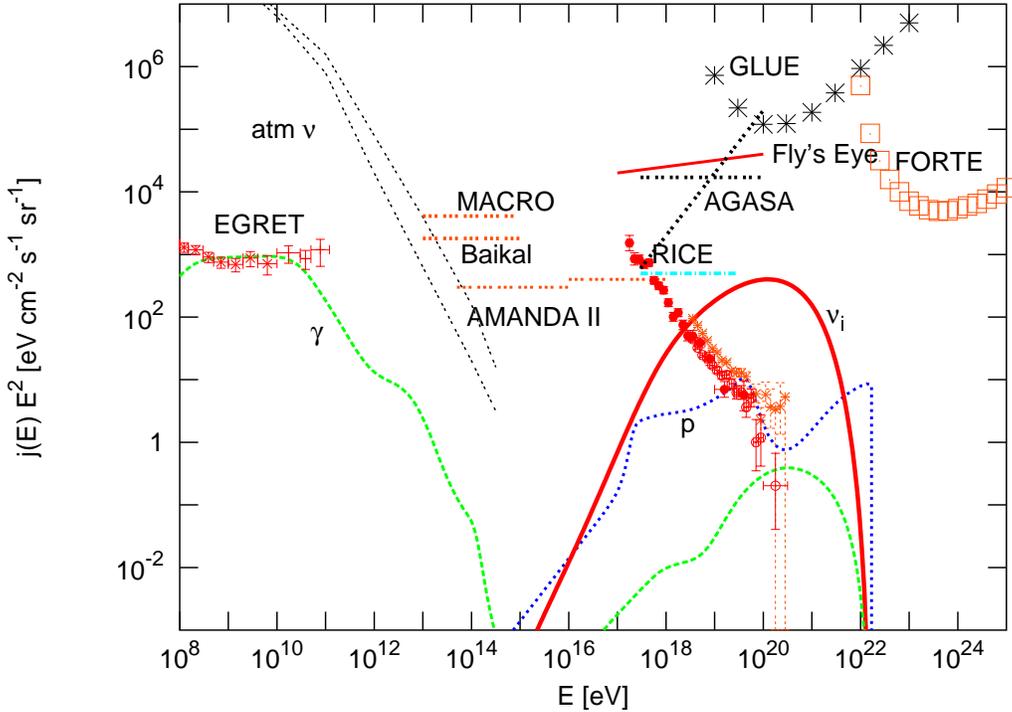


FIG. 2: Results are shown for the neutrino flux (solid red line) predicted by a model of D.V. Semikoz and G. Sigl (JCAP 0404:003 (2004) [hep-ph/0309328]), compared to existing limits (labeled by the experiments). This model is chosen to produce the largest neutrino flux compatible with both the cosmic ray (red data points, blue dotted lines) and gamma ray data (red data points, green dashed lines), yet it remains beyond the reach of current experiments. A new generation of experiments is needed to test these very important predictions, as well as to begin to survey the ultra-high energy universe for new sources.

- **We strongly recommend the development of experimental techniques that focus on the detection of astrophysical neutrinos, especially in the energy range above  $10^{15}$  eV.**

EeV ( $10^{18}$  eV) neutrinos are expected from the collision of ultra-high cosmic rays and microwave background photons. Current generation experiments must be followed by more ambitious efforts that target specific neutrino species or energy regimes. In particular, we focus our recommendation on the measurement of neutrino energies beyond  $10^{15}$  eV. At these extreme energies, a new view of sources in the distant, high-energy universe can be constructed; photons from the same sources would be absorbed, and cosmic rays would be deflected by magnetic fields. In addition, the detection of these neutrinos at Earth probes the energy frontier in the interaction energy, beyond the reach of accelerators, perhaps revealing the onset of new physics. Finally, the sources themselves may be exotic, arising from dark matter annihilation or decay. In order to open this unique window on testing the particle nature of the dark matter, astrophysical sources must be understood first.

The next generation detectors must improve on the basic optical Cherenkov, radio Cherenkov and air shower techniques currently employed by detectors in operation or under construction. We also encourage R&D for the development of novel neutrino detection techniques based on acoustic pulses or fluorescence flashes in order to assess backgrounds and signal efficiency.

We estimate that the appropriate cost is less than \$10 million to enhance radio-based technologies or develop new technologies for high energy neutrino detection. The technical goal of the next generation detector should be to increase the sensitivity by factor of 10, which may be adequate to measure the energy spectrum of the expected GZK (Greisen-Zatsepin-Kuzmin) neutrinos, produced by the interactions of ultra-high energy cosmic ray protons with the cosmic microwave background. The research and development phase for these experiments is likely to require 3-5 years.

- **We recommend support for new precision measurements of neutrino-nucleus cross sections in the energy range of a few tens of MeV.**

These cross sections, which are uncertain at the level of several times 10% from theory, are very important for understanding supernovae, specifically the neutrino opacities, nucleosynthesis, and detection. For example, in the event of a Milky Way supernova, Super-Kamiokande would observe  $\sim 10^3$  events from neutrino scattering on oxygen nuclei. Those cross sections, which have never been measured, are crucial for the interpretation of the data, and especially for the effects of neutrino mixing. These measurements would be of fundamental interest for constraining nuclear models, and measurements on a few different nuclei would reduce theoretical uncertainties for the cross sections on unmeasured nuclei. Low-energy neutrino-nucleus experiments would also provide important constraints on cross sections in the GeV range, important for future sensitive oscillation studies at accelerators, for example regarding visible de-excitations of the residual nucleus. The availability of an intense source of neutrinos, with energy spectra matching those from supernovae, combined with the strong current interest in neutrinos for supernova science, makes a compelling case for the development of a neutrino-nucleus scattering research facility. At present, the only realistic near-term possibility would be the stopped-muon source at the Spallation Neutrino Source. Ultimately, it may also be possible to create a low-energy beta-beam source, and this possibility, and its connection to a possible Rare Isotope Accelerator, should be monitored in the future. Ideally, this Neutrino Study will consider a comprehensive approach to the issue of measuring neutrino cross sections, both for their intrinsic and practical interest.

We estimate that measurements of neutrino cross-section recommended by this working group can be accomplished for less than \$10 million, with R&D requiring \$0.5 million for one year. Construction will require two additional years.

- **We recommend that adequate resources be provided to allow existing large-volume solar, reactor, proton decay, and high energy neutrino telescopes to observe neutrinos from the next supernova explosion and participate in a worldwide monitoring system. Furthermore, future large-volume detectors should consider the detection of supernova neutrinos an important science goal and plan accordingly.**

Core-collapse supernovae are prodigious sources of neutrinos with energies of a few tens of MeV. Though only about 20 neutrinos were observed from Supernova 1987A, those precious few events have led to literally thousands of published papers. The observation of neutrinos from another supernova is one of the most important goals of particle and nuclear astrophysics. With much larger detectors, and much higher statistics expected, the scientific payoff would be significantly greater. Since supernovae in the Milky Way are rare, at a rate of a few per century, it is vitally important that existing and future detectors, built for other purposes, be able to observe a neutrino burst with maximum livetime and detector efficiency; several detectors are needed, to maximize the certainty of detection, and for their complementary abilities. It is also extremely important to detect the diffuse supernova neutrino background, the fossil record of all of the supernovae in the universe. The limit from Super-Kamiokande is just above theoretical predictions that are normalized to the measured star formation rate as a function of redshift.

We anticipate that the investment to insure that large volume detectors maintain sensitivity to galactic supernovae, as well as the diffuse supernova neutrino background from all supernovae, will be less than \$10 million over the next 5 years. New large volume detectors expected for long-baseline, reactor, proton-decay, solar, and high energy neutrino detectors should consider new ideas to enhance the capabilities for the detection of supernova neutrinos. The cost is not possible to determine at this time.

### Working Group Endorsements:

In addition to our recommendations, we wish to express our strong and enthusiastic endorsement of four other science goals in neutrino physics.

- **We enthusiastically support continued investment in a vigorous and multi-faceted effort to precisely (but indirectly) measure the cosmological *neutrino* background through**

its effects on big-bang nucleosynthesis, the cosmic microwave background, and the large-scale structure of galaxies; in particular, weak gravitational lensing techniques offer a very realistic and exciting possibility of measuring neutrino masses down to the scale indicated by neutrino oscillations.

Big bang nucleosynthesis (BBN) and cosmic microwave background (CMB) observations are each sensitive to the number of neutrino flavors, and the present constraints are roughly  $N_{BBN} = 2 - 4$  and  $N_{CMB} = 1 - 6$ , respectively, in agreement with accelerator data. Next-generation observations of the primordial abundances of deuterium, helium and lithium will improve the precision of BBN, testing both the standard model of particle physics and the framework of standard cosmology. Though less sensitive now, the CMB constraint on the number of neutrino flavors is expected to markedly improve, to an uncertainty of well less than 1 equivalent neutrino. Note that extra particles, such as sterile neutrinos, could add about 1 additional flavor, so that these measurements are extremely important for testing whether the three-flavor oscillation picture is complete.

Neutrinos are the only known component of the non-baryonic dark matter. The present cosmological limit on neutrino mass, coupled with the measured mass-squared differences from solar and atmospheric neutrino data, is presently at the level of  $0.3 - 0.6$  eV, a few times more stringent than limits inferred from the tritium beta-decay experiments. Future cosmological tests of neutrino mass with galaxies and the cosmic microwave background have excellent prospects for reaching the mass scale of  $\sqrt{dm_{atm}^2} \sim 0.05$  eV, by which the discovery of at least one neutrino mass is guaranteed. Cosmological and astrophysical data provide a novel suite of tools to determine neutrino properties and simultaneously provide an independent cross-check for laboratory tritium beta decay and neutrinoless double beta experiments. If neutrino mass is discovered by cosmological observations, it will confirm our assumption that the relativistic particle background required by BBN and the CMB is indeed composed of neutrinos.

Leptogenesis models connect neutrinos to the unexplained matter dominance of the universe, and may also connect light neutrino masses to GUT-scale physics. A crucial observable for these models is the scale of the light neutrino masses.

- **We enthusiastically support theoretical and computational efforts that integrate the latest results in astronomy, astrophysics, cosmology, particle physics, and nuclear physics to constrain the properties of neutrinos and elucidate their role in the universe.**

Theory plays an especially important role in integrating and interpreting the progress in all the fields represented by this working group. To fully realize the benefits accrued from these ever-growing connections, it is essential to adequately fund the theoretical community.

It has become increasingly clear that important astrophysical phenomena, such as core collapse supernovae, in which neutrinos play a central role and which can be used to probe the properties of neutrinos under conditions not accessible in terrestrial experiment, are multiphysics phenomena that require large-scale, multidisciplinary collaboration and computation for their understanding. This presents a new paradigm for theoretical investigation, resembling more the longer-term, larger-scale investigations traditionally supported under experimental science programs than the single-investigator, or small-group-investigator, efforts traditionally support by theory programs. This new investigation paradigm presents, therefore, a new dimension to the process of setting priorities for future investigations in neutrino physics and astrophysics, and should be taken into account.

- **We enthusiastically support the scientific goals of the current program in galactic and extra-galactic neutrino astrophysics experiments, including Super-Kamiokande, AMANDA, and NT-200 deployed in Lake Baikal. Furthermore, we endorse the timely completion of projects under construction, such as IceCube, undersea programs in the Mediterranean, ANITA, and AUGER.**
- **Though solar neutrinos were not in our purview, we endorse the conclusion of the Solar/Atmospheric Working Group that it is important to precisely measure solar neutrinos, and strongly support the development of techniques which could also be used for direct dark matter detection.**

## Preface to the Twelve Working Group Topics:

Neutrino detection is a tough business. When first proposed as a fundamental constituent of matter back in the first half of the twentieth century, the brightest minds in experimental physics generally considered the neutrino impossible to observe. Wolfgang Pauli, who first postulated the neutrino, rued his creation, because he thought that he had invented a particle that could not be discovered. When Frederick Reines and Clyde Cowen proved Pauli wrong on this account, the detection of the neutrino was considered so significant and such an experimental tour-de-force that a Nobel Prize was awarded in 1995. Why go through such heroic efforts to detect and measure the properties of the neutrino? This report hopes to answer this question from the perspective of astrophysics and cosmology.

Yogi Berra once quipped, “You can see a lot just by looking”, and the neutrino presents us with a powerful tool to look deep into the heart of the most explosive objects in the cosmos and deep into the far reaches of the universe. The importance of the neutrino in astrophysics was quickly recognized. In 1938, Bethe and Critchfield outlined a series of nuclear reactions deep in the interior that provided the first realistic mechanism to power the sun. Unfortunately, it is not possible to use conventional optical telescopes to look into the center of the sun. However, detailed calculations by John Bahcall in the 1960’s led to the idea that the neutrino, a copious byproduct of the nuclear reactions, could be detected and used to directly verify the theory of solar energy. The experimental detection of solar neutrinos by Ray Davis and the subsequent development of solar neutrino astronomy by Masatoshi Koshiba resulted in yet another Nobel Prize in 2002. These pioneering efforts first uncovered an interesting conundrum: the detection rate of solar neutrinos was less than half of the expected rate in water detectors and only a third in the Chlorine detector of Ray Davis. Was this a problem with our understanding of the sun or was there some new fundamental physics about neutrinos that had not been uncovered by terrestrial experiments? We now know that these early experiments provided the first hint that neutrinos have non-zero mass and the morphing between the electron neutrino and other types was enhanced by the matter of the sun, an effect referred to the Mikheyev-Smirnov-Wolfenstein (MSW) effect in honor of its discoverers. The exciting history of the detection and impact of solar neutrinos is the subject of the report by the Solar and Atmospheric Neutrinos Working Group.

While the story of solar neutrinos provides the first example of the intimate connection between astrophysics and fundamental particle physics, the discussion in the subsequent sections of this report demonstrate that it is far from unique. Today, astrophysicists widely believe that neutrinos will play an important role in deciphering the energy sources that drive the most powerful objects in our galaxy and beyond, such as supernovae, black holes, Active Galactic Nuclei, and Gamma Ray Bursts. Astrophysicists hope that high energy neutrinos point back to the sources of cosmic rays, which are enormously energetic particles that rain down on earth. A few cosmic rays are observed to possess energies that are nearly a million times LARGER than produced by Fermilab or LHC at CERN. But how are they made and where do they come from? We do not know at present and the mystery is only deepening. Detection of neutrinos from astrophysical sources would provide insight on the longstanding question of the origin of highest energy cosmic rays. The pioneering AMANDA high energy neutrino telescope, located more than a mile beneath the snow surface at the South Pole, is designed to search for astrophysical sources of neutrinos at TeV energies. Both AMANDA, and its successor, IceCube, are beautiful examples of productive international collaboration. Several scientific panels have discussed the scientific potential of high energy neutrino astronomy, including the report by the NRC Astronomy and Astrophysics Survey Committee and the NRC report “Neutrinos and Beyond”. We should also point out that several (predominantly) European efforts to construct a neutrino telescope in the Mediterranean Sea are currently underway.

The rich potential of multi-messenger astronomy remains an enticing promise even though no extrasolar sources of neutrinos have been detected, except for the supernova that was observed in 1987. There is intriguing indirect evidence which suggests that existing experiments like AMANDA, or those now under construction, are tantalizingly close to the sensitivity required to detect astrophysical neutrinos. Collectively, current generation and approved detectors observe neutrino energies that span over 10 orders of magnitude.

Although the GZK mechanism provides a compelling theoretical prediction for extragalactic neutrinos, there may well be other important sources of extremely high energy neutrinos. For example, one idea discussed in the literature involves the decay of supermassive particles. This and other exotic ideas for neutrino production highlight the richness of the physics potential of astrophysical and cosmological probes. Furthermore, if any source can produce neutrino energies that extend up to  $\sim 10^{22}$  eV, then it

becomes possible to directly observe the cosmological neutrino background, a residue from the Big Bang, by detecting an absorption feature at the Z-boson resonance.

Arguably the most exciting developments in physics during the past decade evolved from the study of distant supernovae and the cosmic microwave background. From these studies, we now know that the universe contains a surprising mixture of ordinary matter, dark matter of unknown identity, and dark energy of unknown physics. We also know that the Universe contains far more matter than anti-matter, a situation that is not obvious from the interactions observed in earthbound accelerator experiments. If one assumes that the early universe was symmetric with respect to matter and anti-matter, then at one point, the preponderance of matter over anti-matter must be created dynamically. In 1967, Sakharov pointed out that one possible mechanism required the violation of the CP symmetry and baryon number. CP violation was indeed discovered by Cronin and Fitch, but searches for the violation of baryon number have all failed. In particular, the violation of baryon number is required for protons to decay into less massive particles, but the proton remains stubbornly stable. An alternative proposal is known as leptogenesis. Here it is assumed that early in the history of the universe, a preponderance of leptons (e.g., electrons and neutrinos) over anti-leptons was produced. It is then possible within the standard model to transfer the excess in leptons to an excess in all matter by non-perturbative effects that conserve the difference between the net baryon and lepton number,  $B - L$ . For this scenario to work there must be lepton number violation and CP violation specifically associated with leptons. The quest to measure the degree of CP violation in lepton interactions is a major physics goal of the neutrino community.

Big Bang cosmology predicts that neutrinos outnumber protons and nuclei by about a billion. Since we also know from recent studies of the atmospheric and solar neutrino fluxes that neutrinos have mass, the residual neutrinos from Big Bang constitute part of the dark matter of the Universe, the only dark matter constituent identified so far. Present limits on neutrino mass tell us that neutrinos are only a small part of the dark matter, but even relatively small masses can influence the structure and patterns of clustering of galaxies and fluctuations of the cosmic microwave background.

It is really no surprise that the electrically neutral and nearly massless neutrino provides an astonishing breadth of opportunities for astrophysicists and cosmologists. Neutrinos interact solely by the weak interaction, the only known stable particle with this property. Consequently, astrophysicists can detect neutrinos that begin their journey from any point in the Universe. Once produced, they can escape from the hot dense cores of Active Galactic Nuclei or exploding supernova, and then travel to earth unimpeded by anything else. They are not deflected by magnetic fields, so they travel in straight lines. The messages they carry are key to understanding the internal engines that drive these distant beacons. It is safe to say that a more complete understanding of all the fundamental physics properties of the neutrino provides the greatest chance to extract as much as possible from the neutrino messenger.

Neutrino properties such as neutrino mass, oscillation, and perhaps most importantly, unanticipated interaction mechanisms can be probed over a broad range of environmental conditions found throughout the cosmos. Experiments that utilize astrophysical neutrinos can survey large patches of parameter space, and help to provide insight on where to focus the next generation of terrestrial experiments. Neutrino mass impacts subtle details of fluctuations in the cosmic microwave background radiation, and neutrino oscillation implies that cosmic accelerators will illuminate the earth with beam containing all neutrino flavors. This report summarizes several, but by no means all, of the important ideas and experimental techniques that are poised to take advantage of the opportunities that nature provides. Moreover, we highlight the complementary role of neutrinos from astrophysical phenomena in leading to breakthroughs in the understanding of neutrino properties and the measurement of neutrino properties by accelerator and reactor experiments in the interpretation of astrophysical data.

The following twelve sections explore these rich topics in neutrino astrophysics and cosmology in more detail.

## ORIGIN AND NATURE OF THE COSMIC RAYS

The assumption that the Ultra High Energy Cosmic Rays (UHECR) are nuclei (presumably protons) accelerated in luminous extragalactic sources provides a natural connection between these particles and ultra high neutrinos. This was first realized by Berezhinsky&Zatsepin [1] soon after the introduction of the Greisen-Kuzmin-Zatsepin (GZK) effect [2]. The first realistic calculation of the generated neutrino flux was made by Stecker [3]. The problem has been revisited many times after the paper of Hill&Schramm [4] who used the non-detection of such neutrinos to limit the cosmological evolution of the sources of UHECR.

Cosmological neutrinos are produced in interactions of the UHECR with the ambient photon fields, mostly with the microwave background radiation. The GZK effect is the limit on the high energy extension of the cosmic ray spectrum in case their sources are isotropically and homogeneously distributed in the Universe. The physics of these photoproduction interactions is very well known. Although the energy of the interacting protons is very high, the center of mass energy is low, mostly at the photoproduction threshold. The interaction cross section is studied at accelerators and is very well known. Most of the interactions happen at the  $\Delta^+$  resonance where the cross section reaches  $500\mu\text{b}$ . The mean free path reaches a minimum of 3.4 Megaparsecs (Mpc) at energy of  $6\times 10^{20}$  eV. The average energy loss of  $10^{20}$  protons is about 20% per interaction and slowly increases with the proton (and center of mass) energy.

The fluxes of cosmological neutrinos are, however, very uncertain because of the lack of certainty in the astrophysical input. The main parameters that define the magnitude and the spectral shape of the cosmological neutrino fluxes are: the total UHECR source luminosity  $L_{CR}$ , the shape of the UHECR injection spectrum  $\alpha_{CR}$ , the maximum UHECR energy at acceleration  $E_{max}$  and the cosmological evolution of the UHECR sources. These are the same parameters that Waxman&Bahcall [5] used to set a limit on the neutrino fluxes generated in optically thin sources of UHECR. We will first use the parameters of this limit to compare the cosmological to source neutrinos.

Waxman&Bahcall use cosmic ray source luminosity  $L_{CR} = 4.5 \pm 1.5 \times 10^{44}$  erg/Mpc<sup>3</sup>/yr between  $10^{19}$  and  $10^{21}$  eV for power law with  $\alpha = 2$ . The assumption is that no cosmic rays are accelerated above  $10^{21}$  eV. The cosmological evolution of the source luminosity is assumed to be  $(1+z)^3$  to  $z = 1.9$  then flat to  $z=2.7$  with an exponential decay at larger redshifts. Fig. 3 shows the cosmological neutrino fluxes that correspond to these input parameters [6]. Cosmological model used is with  $\Omega_\Lambda = 0.7$  and  $\Omega_M = 0.3$  and  $H_0 = 75$  km/s/Mpc.

At energy about  $3\times 10^{18}$  eV the cosmological fluxes of  $\nu_\mu + \bar{\nu}_\mu$  are very close to the limit for source neutrinos. The reason is simple - in propagation from large distances protons lose almost all of their energy in interactions on MBR. An interesting feature is the flux of  $\bar{\nu}_e$  which peaks at energy about  $3\times 10^{15}$  eV. The origin of this flux is neutron decay, and a small  $\bar{\nu}_e$  flux is generated in neutron interactions on MBR.

The cosmological evolution of the sources (n=3) increases the fluxes by about a factor of five. The increase, however, is energy dependent. The highest energy neutrinos are generated at very small redshifts. The low energy neutrinos come from high redshifts because of two reasons: the threshold energy of protons for photoproduction interaction decreases, and the generated neutrinos are further redshifted to the current epoch. This flux would generate about 0.4 neutrino induced showers per year in the IceCube [7] neutrino detector and 0.9 events in the Auger[8] observatory (for target mass of  $30\text{ km}^3$  of water) assuming that at arrival at Earth the flavor ratio  $\nu_e : \nu_\mu : \nu_\tau$  is 1:1:1 because of neutrino oscillations. ANITA is expected to observe several events per year. It is difficult to estimate the rate in EUSO [9] because of its yet unknown energy threshold. These events come from the NC interactions of all neutrinos, CC interactions of  $\nu_e$ , the hadronic ( $y$ ) part of the CC interactions of muon and tau neutrinos and from  $\tau$  decay. The Glashow resonance does not produce high rate of events because of its narrow width. Ice Cube should also detect very energetic muons with a comparable rate which is difficult to predict in a simple way.

The expected flux of GZK neutrinos depends on several ingredients:

- *UHECR luminosity* The source luminosity derived by Waxman is, however, very uncertain. It is reasonable when the normalization is at  $10^{19}$  eV, but it would easily increase by a factor of three if the majority of the cosmic rays above  $3\times 10^{18}$  are also of extragalactic origin, On the other hand, if the local flux of UHECR is higher than the average in the Universe (since the matter density in the local Universe is somewhat higher than the average one) the luminosity could easily decrease by a factor of two.
- *Maximum injection energy* The calculation shown in Fig. 3 is done with  $\alpha=2$  power law spectrum extending to  $10^{22}$  eV with exponential cutoff at  $10^{21.5}$ . A decrease of the maximum acceleration

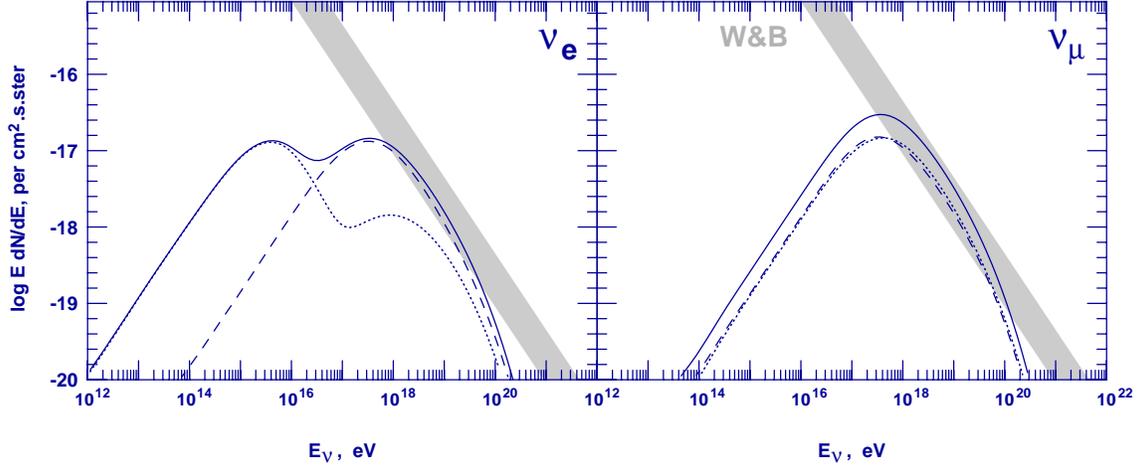


FIG. 3: The flux of cosmological neutrinos is compared to the Waxman&Bahcall limit for source  $\nu_\mu + \bar{\nu}_\mu$ , which is plotted as a shaded band. The upper edge of the band is for source luminosity evolution as  $(1+z)^3$  and the lower one is for no cosmological evolution.

energy by a factor of 10 would decrease significantly the cosmological neutrino flux as the number of interaction proton decreases.

- *Injection spectrum* Most of the analyses of the injection spectrum that generates the observed UHECR after propagation estimate an injection spectrum not flatter than a power law with  $\alpha = 2.5$ . The extreme case is developed by Berezhinsky et al [10] who derive an  $\alpha=2.7$  injection spectrum. The luminosity required for the explanation of the observed events in the  $10^{19} - 10^{20}$  range then becomes  $4.5 \times 10^{47}$  erg Mpc $^{-3}$ yr $^{-1}$ . A steeper spectrum would generate only a small event rate for the giant air shower arrays.
- *Cosmological evolution* Expressed in terms of  $(1+z)^n$  the cosmological evolution of different objects is observed to be between  $n=3$  and 4. A strong evolution with  $n = 4$  will not only increase the total flux of cosmological neutrinos, but will also move the maximum flux to somewhat lower neutrino energy, since the contribution at large redshift increases.
- *Other photon targets* Finally the MBR is not the only universal photon target. Especially interesting is the isotropic infrared and optical background (IRB). Its total density is significantly smaller than that of MBR. Recent models of IRB give 1.6 photons/cm $^3$ , a factor of 250 less than the MBR. On the other hand, protons of lower energy can interact on the IRB, and the smaller number density has to be weighted with the larger flux of interacting protons. The present Universe is optically thin to  $10^{19}$  eV and lower energy protons, but even at small redshift the proton interaction rate quickly increases. The probability of  $10^{18}$  eV proton interactions could also be increased if the UHECR sources are in regions of high magnetic field and infrared background density.

The estimated shower event rates above  $10^{15}$  eV per km $^3$ yr vary from 0.2 and 1.2 for the Waxman&Bahcall luminosity function. The lowest rate corresponds to local UHECR density exceeding the average in the Universe by a factor of two, flat power law injection spectrum ( $\alpha=2$ ), and  $(1+z)^n$  cosmological evolution. This rates corresponds to one half of the fluxes shown in Fig. 3. The higher rate is achieved by assuming that we see the average UHECR density, the injection spectrum is with  $\alpha=2.5$ , and the cosmological evolution is with  $n=4$ . It also includes interactions on the infrared background radiation. The corresponding event rates for shower energy above  $10^{19}$  eV, which are suitable for the Auger observatory vary between 0.44 and 0.66 for 30 km $^3$  of water target. Both event rates would increase by approximately the same coefficient if the UHECR luminosity were higher. The difference between the event rates reflects the shape of the UHECR injection spectrum and could be further affected by an increase or decrease of the maximum injection energy.

The possible detection of cosmological neutrinos should be analyzed together with the shape of the UHECR spectrum above the GZK cutoff at  $4 \times 10^{19}$  eV. Here the AUGER results are eagerly awaited. If it confirms with high experimental statistics the GZK feature, as claimed by the HiRes experiment [11], the flux of cosmological neutrinos would reveal the distribution of sources that generate UHECR in our cosmological neighborhood. If there is no observed cutoff (as claimed by the AGASA [12] experiment), the flux of cosmological neutrinos would be much smaller and possibly undetectable. This would be an argument in favor of the top-down exotic scenarios for the UHECR origin. Such scenarios inevitably predict specific UHE neutrino spectra.

In the most optimistic, although not unrealistic, case that UHECR sources are embedded in regions of high magnetic field and ambient photon density, the detection of even single UHE neutrino could help reveal the source direction.

## GZK NEUTRINO DETECTION AND NEW PHYSICS ABOVE A TeV

*The GZK cutoff:* Four decades ago, two completely unexpected and unrelated discoveries - ultra high energy (UHE) cosmic rays and the cosmic microwave background radiation (CMB) combined to open new windows on the Universe. Within several years of the CMB discovery, Greisen and, independently, Zatsepin and Kuzmin (GZK) pointed out that UHE cosmic ray protons interacting with the CMB above photo-pion production threshold would lose energy until they fell below threshold. They found that experiments should see an upper cutoff in the spectrum in the interval  $10^7$  TeV to  $10^8$  TeV, or  $\sqrt{s} \approx 150$  TeV to 450 TeV, if the sources lay beyond 50 Megaparsecs or so.

*The GZK neutrinos:* Past and ongoing cosmic ray experiments agree that there are tens of events above  $10^7$  TeV with fluxes of roughly one per square kilometer per century. Experiments disagree whether enough events sufficiently above  $10^8$  TeV have been seen to indicate violation of the cutoff [13]. The status of the GZK cutoff is an open question, which may be answered by the AUGER experiment within the next several years. Regardless of the resolution to the GZK cutoff question, the mere fact that the UHE cosmic rays exist has a crucial impact on the prospects for opening up UHE neutrino astrophysics at neutrino energies above  $10^5$  TeV. (This translates to 15 TeV in  $\sqrt{s}$  - the LHC with hadron+lepton! The highest laboratory energy charged current cross section measurement at  $\sqrt{s} = 320$  GeV from DESY corresponds to  $E_\nu = 50$  TeV.)

Accepting the GZK picture, one anticipates a “guaranteed” flux of UHE neutrinos, as presented in Stanev’s cosmological flux section in this working group’s report. Though the general arguments for the existence of the GZK flux are more than reasonable, the shape and normalization of the spectrum is not nailed down. Currently available models allow a wide range of spectra that are consistent with constraints from photon fluxes and from the cosmic ray data itself. Clearly the first goal is to establish the existence of a UHE neutrino flux and a number of first surveys have already established limits on fluxes from  $10^3$  TeV into and above the GZK region [14]. The good news is that *the second generation of existing detectors and new detectors in the design and development stage promise to cover most of the flux estimates.* The continuation of this expansion of the “cast a broad net” effort is completely justified in light of advances so far and future projections [15], as illustrated in Fig. 4. The challenge for the future is to find ways to fight the rapidly falling fluxes with increasing effective areas/volumes to reach observable levels as energy rises.

*UHE neutrino world:* The first detection of UHE neutrinos will be an electrifying event in its own right and profound in its implication for explorations of cosmologically distant sources and neutrino interactions. It is precisely because the interactions of neutrinos are weak at low  $\sqrt{s}$  that they can reveal information from their sources directly, arriving along the line of sight. For the same reason, they are prime candidates to reveal new physics at high  $\sqrt{s}$  when they collide with nucleon targets in detectors. The contrast between expected and unexpected physics is not buried under strong interactions

Post discovery possibilities include studies of the correlation of neutrino events with known high energy sources like quasars or gamma ray bursts. Pointing with error cones at the few degree level or better, typical of highest energy cosmic ray events, should be sufficient to find or reject correlation (or, more conservatively, find or reject absence of correlation - a less model dependent hypothesis). Comparing the neutrino event characteristics, energy spectrum and directions with the cosmic ray shower data should reveal much about the sources and about the identity, whether standard or not, of the cosmic rays. The proton hypothesis for the high end of the spectrum is consistent with current data, but a unique identification is needed.

The difficult job of disentangling neutrino physics from the neutrino fluxes in data analysis will begin in earnest after discovery, with design and deployment of enhanced second generation or third generation detectors. In the course of this evolution, the most effective, complementary techniques should emerge, along with a better understanding of backgrounds, and the elimination of models giving overly optimistic flux estimates. One expects that advances in neutrino physics will be accelerated by advances in cosmic ray physics in general. For example the constraints on the GZK flux possibilities will increase as the gamma and the hadronic cosmic ray data improve.

Angular distributions of events can go far to resolve the interactions from the fluxes. This demands a significant number of events with reasonable angular resolution, since binning in angle near the horizon will be required for the events in the GZK range. At energies in the  $10^3$  TeV to  $10^4$  TeV range, fluxes from the low end [17] to the high end [18] of currently available estimates, would allow a  $KM^3$  detector or ANITA to discriminate the standard model cross sections from those resulting from a rapid rise starting at the 1- 2 TeV scale. An attractive theoretical proposal with this feature is low scale gravity

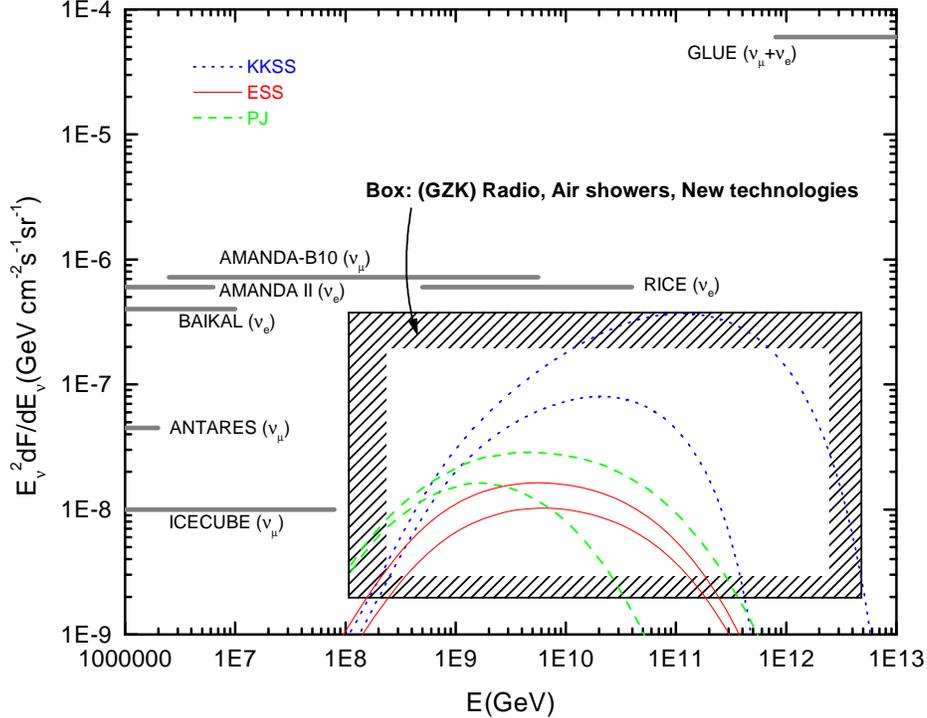


FIG. 4: GZK  $\nu_e$  flux models from Protheroe and Johnson, Kalashev et al. and Engel, Seckel, and Stanev [16], covering a wide range of values, are shown with current limits (AMANDA, RICE, Baikal, and GLUE) and projected flux sensitivities (ANTARES and ICECUBE) and corresponding energy ranges. We chose references that present limits for  $E^{-2}$  effective fluxes over a given energy range. It should be kept in mind that these rough sensitivity projections depend on uncertain assumptions and varying conventions.

[19], recognized as potentially significant for UHE neutrino astrophysics [20]. It was further realized that production of micro black holes should set in when  $\sqrt{s}$  exceeds the extra-dimensional gravity scale, potentially increasing the  $\nu - N$  cross section by a large factor [21].

GZK neutrino fluxes do not extend down to the  $10^3$  TeV to  $10^4$  TeV regime, the top of the range where there is still roughly 30 degrees below the horizon where useful numbers of neutrinos may be detectable. In the GZK regime, rather good angular resolution combined with much larger effective detector volumes would be needed to do the job, which may be achievable with the air shower observatories or large volume surveys in ice, salt or water in combination with established techniques extended upward from lower energy to provide calibration. With downward event rates alone, establishing the spectrum and using general shape features expected of cosmogenic neutrino fluxes, cross sections that rise radically faster than the standard model cross sections might be distinguished. This question is especially interesting for low scale gravity with 5 or 6 large extra dimensions, which are relatively unconstrained by other astrophysical and accelerator data. Several groups have pursued this question and find that current detection limits set constraints on a range of scenarios for neutrino fluxes and black hole physics [22].

*Other new physics connections:* The new physics emphasis above has been on the GZK flux and the new physics of neutrinos that may be discovered by their interactions. Entirely different questions can also be addressed. Bounds on TeV-scale WIMPS annihilating in the center of the Earth have been set by searching for non-atmospheric, upcoming neutrinos at AMANDA [23]. The extension of this “TeV - physics” search is an important tie-in with dark matter physics for the extended programs in the  $E_\nu =$

1-100 TeV range. Detectors can also be “multi-taskers”, looking for monopoles, which have distinctive signatures in certain detectors, or post GZK neutrinos that may originate in a “top down” picture like topological defects with masses of order,  $10^{14}$  GeV, and “hidden” from hadrons and photons. Extreme demands on detectors would be required to do physics with sources at these energies; proposals include search for direct evidence of the cosmic neutrino background, determination of the absolute value of neutrino masses [24], and distinguishing between Majorana and “pseudo-Dirac” neutrinos at the  $10^{-18}$  eV level [25]! Among other fundamental questions that may be accessible with UHE neutrino experiments is the limit to which Lorentz symmetry violation can be pushed [26].

This is the high energy neutrino frontier field. The experimental efforts are already numerous and varied. Continued support for development and deployment of current techniques and research must be continued if the breakthrough to first observations is to be made. Serious investment in exploratory methods like acoustic, radio, and offshoots will be needed to achieve future data sets big enough to do detailed science.

## NEUTRINO PROBES OF HIGH ENERGY ASTROPHYSICAL SOURCES

Active galactic nuclei (AGN), gamma-ray bursts (GRB), and related objects such as supernovae (SN), black holes (BH) and neutron stars (NS) are among the most energetic sources in the Universe, involving energy densities and gravitational fields far surpassing anything achievable in the laboratory. Yet the phenomenology and theoretical understanding of these high-energy sources has been severely limited by the fact that our information about them has been obtained almost exclusively through the electromagnetic channel. This extends in some cases up to tens of GeV, and in rare cases to TeV energies [32]. However, these sources are thought to be also copious emitters of gravitational waves, as well as of cosmic rays and neutrinos, whose energy fluxes may rival that in the electromagnetic channel. Furthermore, in the latter two cases the particle energies may reach [35, 38] up to  $\sim 10^{20}$  eV (the GZK range), which exceeds by up to eight orders of magnitude that of the most energetic photons detectable. The amount of information available in these new channels is of a completely different nature than that so far available.

Besides providing tests of fundamental physics extending up to the so far unexplored PeV center-of-momentum energy range, ultra-high energy neutrino measurements could yield crucial insights into the origin and propagation of cosmic rays, and would provide a unique probe into the nature of these high energy astrophysical sources. They would directly probe both the hadronic content of the jets inferred in AGN and GRB, and the cosmic ray acceleration process thought to give rise to the diffuse cosmic ray background, the atmospheric neutrino background, and a portion of the MeV to multi-GeV gamma-ray background. Neutrinos in the TeV-EeV range would mainly arise from photomeson interactions between protons and intra-source photons, created either from synchrotron and inverse Compton processes or from hadronic decay cascades followed by the same processes. In the former case, the photons are linked to electrons or positrons thought to be accelerated in shocks, or possibly magnetic reconnection sheets. The same accelerators would unavoidably also accelerate protons, if these are present in the same regions. In addition,  $\lesssim$  GeV neutrinos may also be produced in GRB by proton inelastic collisions with thermal nucleons [29]. Proton acceleration definitely occurs in some sources, as evidenced by the detected cosmic rays. Thus, the efficiency of neutrino generation in GRB [39] and AGN [34], two of the most widely suspected bottom-up astrophysical sources of cosmic rays, would give direct diagnostics for several of the key parameters relevant for the CR astrophysical acceleration hypothesis, as well as providing crucial information on the physical conditions in these sources. Among such parameters are the baryon load of the (electromagnetically detected) jets, the injection rate and efficiency of proton acceleration in such jets, and the losses incurred (e.g. the density of target photons or nucleons, which translates into constraints on the magnetic field strength, typical shock region dimension and jet bulk Lorentz factor).

The neutrinos, unlike the cosmic rays, point back at their source of origin; and unlike the photons, they will not be absorbed or obscured by intervening material. Aside from the difficulty of detecting them, they constitute an ideal tomography probe of the most dense and energetic regions of high energy sources. In the TeV energy range, the expected angular resolution of cubic kilometer ice or water Cherenkov detectors is  $\theta \sim 0.5 - 1$  degree [28], which is well below the confusion limit. For burst-like sources, such as the 10-100 second duration GRB or the hour-day gamma-ray flares in blazars, one expects both the angular and temporal signature to help drive the background down.

One of the major questions in both AGN and GRB models is the composition of the jets: are they purely MHD jets, dominated by magnetic stresses and with an inertia provided mainly by  $e^\pm$ , or are they  $e, p$  jets, where the inertia is mainly provided by baryons entrained in the jet? The astrophysical evidence is mixed. For AGN, on the one hand the jet ram pressure inferred from the dynamics of the advance of the jet head into the intergalactic medium suggests they are baryon loaded, while on the other hand, radio measurements of the Faraday depolarization of the jet radio emission has suggested in some cases that the jets have comparable numbers of electrons and positrons. Some degree of baryon entrainment is unavoidable, even if a jet is initially purely MHD, from exchange instabilities occurring at the interface between the jet and the galactic surroundings, so that the question is really what is the degree of baryon loading. For GRB, much recent excitement has been generated by the claim of the detection of a high degree of gamma-ray linear polarization in the MeV range [30]. While debated, this observation could be suggestive of an MHD jet. On the other, baryonic jet models have proved much more useful in interpreting photon observations over a wide range of frequencies.

The dichotomy between leptonic (MHD) and hadronic jets has parallel implications for the electromagnetic radiation of these objects, in particular for the TeV gamma-ray emission from very nearby blazars such as Mrk 421 and Mrk 501, which are at small enough redshifts to avoid excessive photopair attenuation by the diffuse infrared background. The usual leptonic jet interpretation of this radiation in

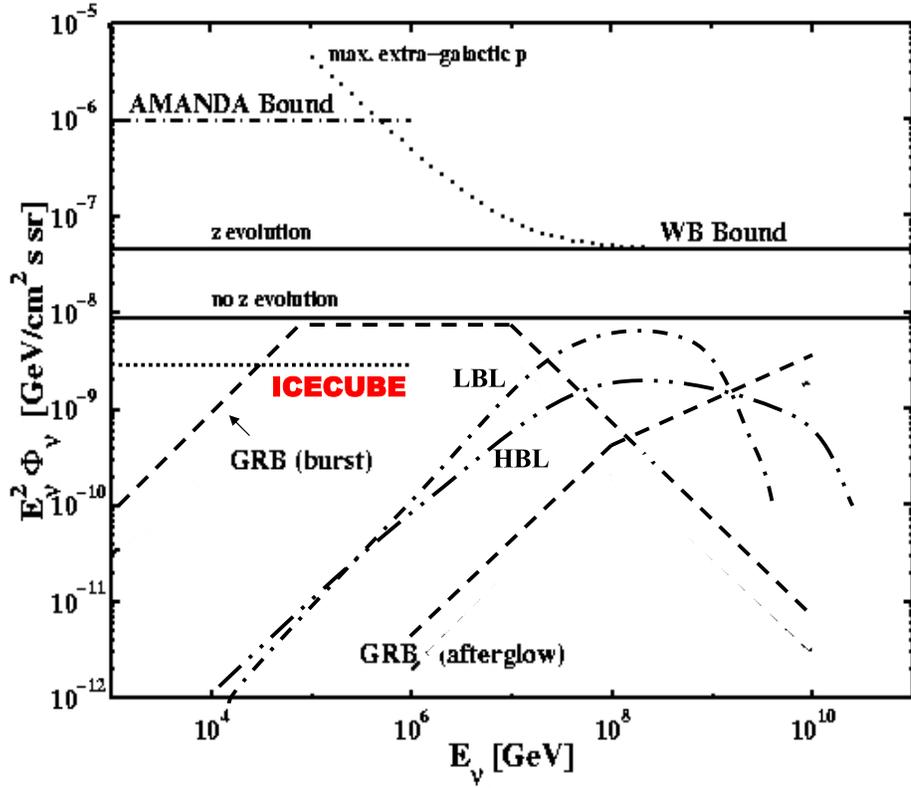


FIG. 5: The diffuse muon neutrino flux from proton acceleration and  $p, \gamma$  interactions in a) GRB (burst) internal shocks and GRB afterglows, following [37], using current evolution and beaming constraints, without inclusion of a buried jet population; and b) BL Lac galaxies including low peak blazars (LBL) and high peak blazars (HBL), using the proton synchrotron blazar model [34]. Also shown is the WB limit [41], and the atmospheric neutrino background.

terms of inverse Compton up-scattering of the synchrotron X-ray photons [31] is certainly viable, and is viewed as a conservative extension of the sub-MeV phenomenology of well-studied high energy astrophysical sources. The alternative hadronic jet interpretation relies on protons accelerated to energies  $\gtrsim 10^5$  GeV leading to electromagnetic cascades and  $e^\pm, \mu^+$  synchrotron and IC. This is also viable, although it requires denser photon target densities, and much higher magnetic fields than leptonic models, hence higher total energies [27]. On the other hand, it could be viewed as conservative too, in the sense that it is hard to see how protons could avoid being accelerated, if present, and they would suffer much weaker losses during the acceleration process. At the simplest level, the test for both GRB and AGN is the prediction from purely MHD jets that they would produce no photomeson neutrinos, while the baryon-loaded  $e, p$  (neutral) jets would produce  $\sim 10 - 100$  TeV neutrino emission, as a consequence of the  $p, \gamma$  interactions in the jets. These neutrinos are the least model dependent prediction, which arise typically, from 0.1-1 PeV protons interacting with X-rays in the jet comoving frame, whose bulk Lorentz factor are of order 10(100) for AGN (GRB). More model-dependent predictions in GRB include EeV neutrinos from interaction of GZK energy protons interacting with optical/UV photons arising in the reverse external shock [40], and TeV neutrinos from proton interactions with thermal X-rays in pre-GRB buried jets [33] making their way out through their massive stellar progenitor's envelope.

Some of the early AGN neutrino flux predictions have, in fact, already been indirectly constrained by the fact that they exceeded the so-called Waxman-Bahcall [40] limit provided by the connection between ultra-high energy cosmic rays and neutrinos. The predictions for less extreme AGN parameters, as well as

the corresponding predictions for GRB, lie below this limit. The current sensitivity limit of AMANDA is just beginning to reach the level where it is comparable to the observed gamma-ray flux from a specific AGN. Neutrino flux predictions involve assumptions about the proton to lepton ratio in the jets, as well as about the relative efficiency of injection of these particles into the acceleration process. The latter is usually assumed to be some form of Fermi acceleration, although in MHD models magnetic dissipation could lead to acceleration by the EMF of the transient electric fields. Explanations for the recent claim of a high gamma-ray polarization in a GRB have been attempted both in the context of MHD and baryonic jets, and a clear non-detection of 100 TeV neutrinos in GRB would lend some support to the former.

Observations of 10-100 TeV neutrinos in AGNs and GRBs, associated with GeV-TeV gamma-ray flares (e.g. observed with Whipple, Veritas, MILAGRO, HESS, GLAST, etc. [32]) would provide convincing evidence for both a significant baryon content in the jets, and for efficient injection and acceleration of protons. This could rule out predominantly MHD jets, which in the case of GRB would put severe constraints on the magnetar scenario, where the central engine is assumed to be a strongly magnetized neutron star. It could also constrain, both in GRB and AGN, the Blandford-Znajek mechanism for powering the jet by magnetic fields which couple to a fast-rotating central black hole. A detection or non-detection would also constrain the location of the shocks, the photon energy density, the mechanism of production of the photons, and the efficiency for turbulent magnetic field amplification in the shocks. The observation of EeV neutrinos, implying GZK protons from GRB or AGN would require measuring extremely low fluxes, possible only with experiments on the scale of EUSO/OWL. However the event rates of TeV neutrinos from buried pre-GRB jets is higher than that of 100 TeV neutrinos coincident with the MeV gamma-rays, and would be observable with ICECUBE or ANTARES from individual bursts a few times per decade. Micro-quasars, which are believed to be stellar-mass black hole accreting sources producing sem-relativistic jets, are less luminous but much closer in distance than GRB, and may also be detectable individually in the TeV range.

Such astrophysical studies are necessary to provide a base-line or boundary, beyond which new physics may be considered compelling. Such measurements will allow to make novel tests of possible non-standard neutrino properties. For instance, neutrino decay would change the flavor ratios from the expected  $\nu_e:\nu_\mu:\nu_\tau=1:1:1$ ; increases in the  $\nu, N$  interaction at energies  $\gtrsim 10^{18}$  eV due to black hole formation due to extra dimensions, or tachyonic effects, would give substantially greater fluxes than the modest ones predicted by standard model astrophysics, etc.

## DARK MATTER SEARCHES USING NEUTRINOS

In recent years there has been tremendous progress in our understanding of the universe on the largest scales. For the first time, cosmological measurements have provided a complete census of the universe. In units of the critical density, the energy densities of baryons, non-baryonic dark matter, and dark energy are [42, 43]

$$\Omega_B = 0.044 \pm 0.004 \tag{1}$$

$$\Omega_{\text{DM}} = 0.23 \pm 0.04 \tag{2}$$

$$\Omega_\Lambda = 0.73 \pm 0.04 . \tag{3}$$

At the same time, the microscopic identities of dark matter and dark energy are at present unknown and are among the most important open questions in science today. New particles are required, and a fundamental understanding of the dark universe therefore draws on complementary approaches from both cosmology/astrophysics and particle/nuclear physics.

Neutrinos play a unique and promising role in resolving these mysteries. This is especially true in the case of dark matter, where the importance of neutrinos may be understood from simple and general considerations. The stability of individual dark matter particles is typically guaranteed by a conserved parity. These conservation laws, however, allow pairs of dark matter particles to annihilate into ordinary particles, providing a signal for dark matter detection. Such signals are, of course, greatly enhanced when the dark matter particle density and annihilation rate are large, as they are expected to be at the center of astrophysical bodies. Unfortunately, when dark matter particles annihilate in these regions, most of their annihilation products are immediately absorbed. Neutrinos, however, are not. High energy neutrinos from the cores of the Sun [44–50] and Earth [44, 51–53] are therefore promising signals for dark matter detection.

The neutrino flux from dark matter annihilation is determined by a number of factors. First and foremost, it depends on the dark matter number density at the source, which is governed by the competing processes of capture and annihilation. A dark matter particle  $\chi$  is captured when an interaction  $\chi N \rightarrow \chi N$  reduces its velocity to below the escape velocity. Once this happens, subsequent interactions typically allow the dark matter to settle to the core. At the same time, dark matter particles annihilate in the core through the processes  $\chi\chi \rightarrow f\bar{f}, WW, ZZ$ , reducing the number of  $\chi$  particles.

If  $C$  is the capture rate and  $A$  is the total annihilation cross section times relative velocity per volume, the number  $N$  of dark matter particles at the source satisfies  $\dot{N} = C - AN^2$ . The present annihilation rate is therefore

$$\Gamma_A = \frac{1}{2}AN^2 = \frac{1}{2}C \tanh^2(\sqrt{CA}t) , \tag{4}$$

where  $t$  is the collection time. For signals from the Sun or Earth,  $t \approx 4.5$  Gyr, the age of the solar system. For large enough  $t$ , the annihilation rate approaches its maximal value  $\Gamma_A = \frac{1}{2}C$  and is a function of the capture rate alone. More generally, however, the neutrino flux depends on both  $C$  and  $A$ , in contrast to direct detection rates, which depend only on scattering cross sections, and other indirect detection rates, which depend only on the annihilation cross sections.

Neutrinos produced in the annihilation processes  $\chi\chi \rightarrow f\bar{f}, WW, ZZ$  propagate to the Earth's surface, where they may be detected through their charged-current interactions. The most promising signal is from upward-going muon neutrinos that convert to muons in the surrounding rock, water, or ice, producing through-going muons in detectors. The detection rate for such neutrinos is greatly enhanced for high energy neutrinos, as both the charged-current cross section and the muon range are proportional to  $E_\nu$ .

The resulting muon fluxes are sensitive to many effects and are subject to astrophysical uncertainties. For standard halo dark matter populations, the signal is fairly well-determined, as it depends primarily on the local dark matter density, and so is insensitive to details of halo models. Additional dark matter populations may, however, significantly enhance predictions for muon fluxes. (See, for example, Refs. [54, 55].) Muon signals are also sensitive to the details of capture rates [56] and effects in propagating the neutrinos from the core to the surface [44, 57–59].

The neutrino signal for dark matter detection has been analyzed for a variety of dark matter possibilities. Among the most compelling candidates are WIMPs, weakly-interacting massive particles. Such particles have masses given by the weak scale  $M_W \sim \mathcal{O}(100)$  GeV, and interact with ordinary matter

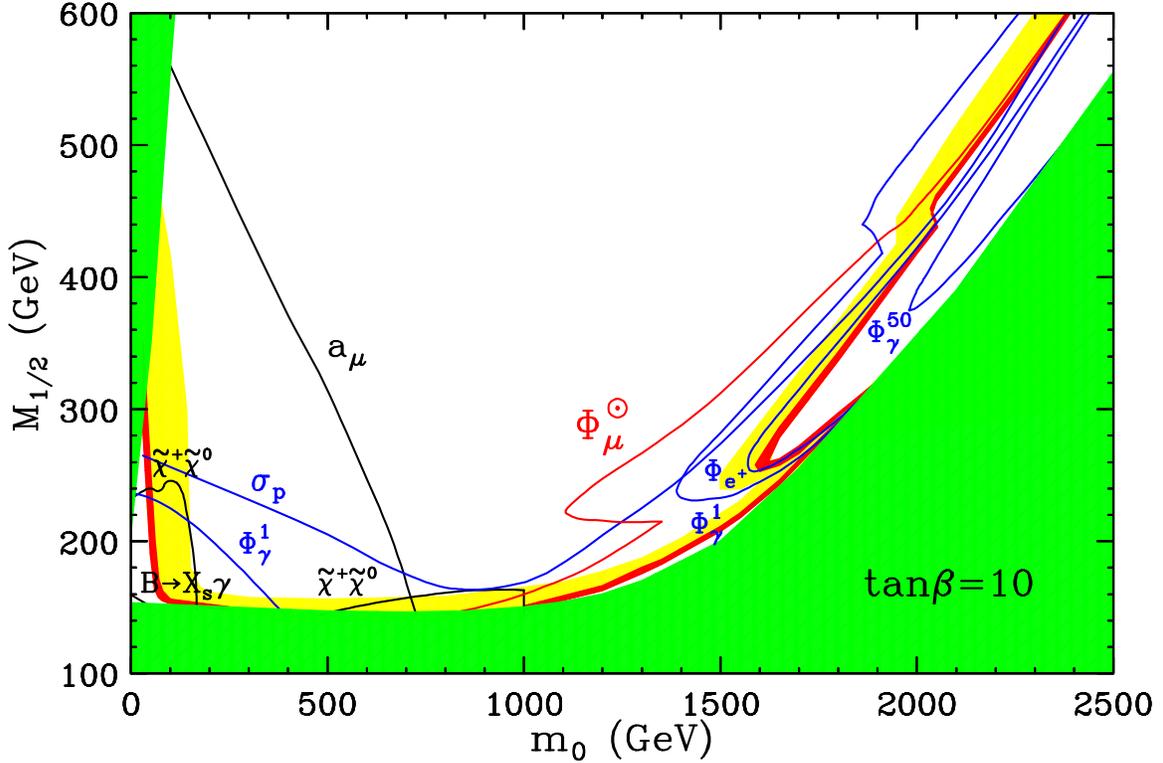


FIG. 6: Estimated reaches of neutrino telescope searches for neutralino dark matter ( $\Phi_\mu^\odot$ , red), other dark matter searches (blue), and various high-energy collider and low-energy precision searches (black) in minimal supergravity parameter space. The remaining minimal supergravity parameters are fixed to  $\tan\beta = 10$ ,  $A_0 = 0$ , and  $\mu > 0$ . The green shaded regions are excluded by chargino mass bounds and the requirement that the dark matter particle be neutral. The regions probed extend the labeled contours toward the forbidden, green regions. In the red and yellow shaded regions, the neutralino thermal relic density satisfies post-WMAP ( $0.094 < \Omega_{\text{DM}} h^2 < 0.129$ ) and pre-WMAP ( $0.1 < \Omega_{\text{DM}} h^2 < 0.3$ ) bounds, respectively. Updated from Ref. [60].

with cross sections  $\sigma \sim M_W^{-4}$ . WIMPs are motivated not only by the dark matter problem, but also independently by attempts to understand the electroweak scale and electroweak symmetry breaking. Even more tantalizing, the thermal relic density of dark matter particles emerging from the hot Big Bang may be calculated given their mass and interaction cross sections. For the typical WIMP parameters given above, the relic density is naturally in a range consistent with the observed value of Eq. (2).

The prototypical WIMPs, and by far the most studied, are neutralinos in supersymmetry. Neutralinos are Majorana fermions that are, in general, mixtures of the fermionic superpartners of the U(1) hypercharge gauge boson, the neutral SU(2) gauge boson, and the Higgs scalars. Their Majorana-ness has an immediate implication for the neutrino signal. For a pair of Majorana fermions, the initial state has spin 0, and so the most promising possible signal,  $\chi\chi \rightarrow \nu\bar{\nu}$ , is effectively absent, since it is helicity- or  $P$ -wave-suppressed. As a result, for neutralino dark matter, the highest neutrino energies are typically  $E_\nu \sim \frac{1}{2}m_\chi$  from  $\chi\chi \rightarrow WW, ZZ$  to  $\frac{1}{3}m_\chi$  from  $\chi\chi \rightarrow \tau\bar{\tau}$ .

Given a particular supersymmetric model framework, the reach of neutrino telescopes for discovering neutralino dark matter may be determined. The results for minimal supergravity are given in Fig. 6. Minimal supergravity is a simple framework that encapsulates many appealing features of supersymmetry. It assumes that the supersymmetric scalars and gauginos have unified masses  $m_0$  and  $M_{1/2}$  at the scale of force unification. The reach of neutrino telescopes in the  $(m_0, M_{1/2})$  plane is shown in Fig. 6. The region probed by neutrinos from the Sun is indicated by the  $\Phi_\mu^\odot$  contour, where a sensitivity to muon fluxes above  $100 \text{ km}^{-2} \text{ yr}^{-1}$  is assumed. Such sensitivities may be reached in the near future by experiments such as AMANDA and ANTARES. These and other neutrino telescopes, along with their more salient characteristics and flux limits (where available), are listed in Table I.

Figure 6 illustrates many key points. First, the reach of neutrino telescopes is significant. In Fig. 6

TABLE I: Current and planned neutrino experiments. We list also each experiment's start date, physical dimensions (or approximate effective area), muon threshold energy  $E_\mu^{\text{thr}}$  in GeV, and 90% CL flux limits for the Earth  $\Phi_\mu^\oplus$  and Sun  $\Phi_\mu^\odot$  in  $\text{km}^{-2} \text{yr}^{-1}$  for half-cone angle  $\theta \approx 15^\circ$  when available. From Ref. [60].

Experiment	Type	Date	Dimensions	$E_\mu^{\text{thr}}$	$\Phi_\mu^\oplus$	$\Phi_\mu^\odot$
Baksan	Ground	1978	$17 \times 17 \times 11 \text{ m}^3$	1	$6.6 \times 10^3$	$7.6 \times 10^3$
Kamiokande	Ground	1983	$\sim 150 \text{ m}^2$	3	$10 \times 10^3$	$17 \times 10^3$
MACRO	Ground	1989	$12 \times 77 \times 9 \text{ m}^3$	2	$3.2 \times 10^3$	$6.5 \times 10^3$
Super-Kamiokande	Ground	1996	$\sim 1200 \text{ m}^2$	1.6	$1.9 \times 10^3$	$5.0 \times 10^3$
Baikal NT-96	Water	1996	$\sim 1000 \text{ m}^2$	10	$15 \times 10^3$	
AMANDA B-10	Under-ice	1997	$\sim 1000 \text{ m}^2$ <sup>†</sup>	$\sim 25$	$44 \times 10^3$ <sup>†</sup>	
Baikal NT-200	Water	1998	$\sim 2000 \text{ m}^2$	$\sim 10$		
AMANDA II	Ice	2000	$\sim 3 \times 10^4 \text{ m}^2$	$\sim 50$		
NESTOR <sup>§</sup>	Water		$\sim 10^4 \text{ m}^2$ <sup>‡</sup>	few		
ANTARES	Water		$\sim 2 \times 10^4 \text{ m}^2$ <sup>‡</sup>	$\sim 5$ – $10$		
IceCube	Ice		$\sim 10^6 \text{ m}^2$			

<sup>†</sup> Hard spectrum,  $m_\chi = 100 \text{ GeV}$ . <sup>§</sup> One tower. <sup>‡</sup>  $E_\mu \sim 100 \text{ GeV}$ .

the red shaded region indicates the region of parameter space in which the neutralino thermal relic density is in the range favored by WMAP. Although current bounds do not restrict the parameter space substantially, the neutrino signal is observable in the near future for all of the red region with  $m_0 \gtrsim \text{TeV}$ . Second, the neutrino signal, along with other indirect dark matter signals, is complementary to other signals of supersymmetry. The reaches of many other supersymmetry searches are also shown in Fig. 6. We find that traditional particle physics signals, such as the trilepton signal from  $\chi^\pm \chi^0$  production at the Tevatron or deviations in  $B \rightarrow X_s \gamma$  and the muon's anomalous magnetic moment  $a_\mu$ , are effective for  $m_0 \lesssim \text{TeV}$ , but are ineffective for large  $m_0$ . Neutrino telescopes therefore provide a complementary method for searches for new physics.

Muon energy thresholds, listed in Table I, have not been included in Fig. 6. Since the muon detection rate is dominated by high energy muons as noted above, the threshold energy is typically not important, especially in the regions where a detectable signal is expected. This is not the case for all detectors, however. For example, since muons lose 0.26 GeV per meter in water and ice, neutrino telescopes requiring track lengths of  $\sim 100 \text{ m}$  will have thresholds of order  $\sim 25 \text{ GeV}$ . The dependence on threshold energy has been studied in Refs. [61, 62], where it was found that for threshold energies of  $E_\mu^{\text{thr}} \sim \frac{1}{4} m_\chi$  to  $\frac{1}{6} m_\chi$ , the loss of signal is substantial. Low threshold energies in neutrino telescopes are clearly very important for dark matter detection.

Several other studies of neutrino telescope dark matter searches have been conducted in this and more general supersymmetric frameworks [63], and also in completely different scenarios. A particularly interesting example is the case of theories with extra spatial dimensions. In so-called universal extra dimension scenarios [64], in which all fields of the standard model propagate in all extra dimensions, the lightest Kaluza-Klein particle may be the dark matter. The requirement that the low energy degrees of freedom include only those of the standard model typically imposes a Kaluza-Klein parity, which makes the lightest Kaluza-Klein particle stable, and for  $\text{TeV}^{-1}$  size extra dimensions, the lightest Kaluza-Klein particle is a WIMP with naturally the correct thermal relic density [65].

If  $B^1$ , the lightest Kaluza-Klein partner of the hypercharge gauge boson, is the dark matter, the dark matter is a massive spin 1 particle. Angular momentum constraints, which eliminated the most promising models in the neutralino case, then do not imply helicity suppression for annihilation to fermion pairs. The annihilation  $\chi\chi \rightarrow \nu\bar{\nu}$  is therefore unsuppressed, and provides, in fact, the dominant source of neutrinos, with  $E_\nu = m_\chi$ . Studies of the neutrino signal for Kaluza-Klein dark matter [66–68] have found reaches up to  $m_{B^1} = 600 \text{ GeV}$  for AMANDA and ANTARES, and up to  $m_{B^1} = 1.4 \text{ TeV}$  for IceCube, competitive with other methods for discovering dark matter in these scenarios.

## NEUTRINOS AS A PROBE OF SUPERNOVAE

The deaths of massive stars through spectacular stellar explosions known as core collapse supernovae are the single most important source of elements in the Universe. They are the dominant source of elements between oxygen and iron and are believed to be responsible for producing half the elements heavier than iron. Many of these elements were necessary for the evolution of life. Moreover, gamma-ray and x-ray observations of gamma-ray bursts have now illuminated an association between these bursts and core collapse supernovae, and in the last five years a number of hyper-energetic core collapse supernovae have been observed, reaffirming their status as the most energetic events in the Universe. And we now stand at a threshold. Galactic core collapse supernovae are among the sources expected to generate gravitational waves that can be detected by observatories around the world. A detection would mark the birth of an entirely new subfield of astronomy and would be the first direct evidence of the physical and dynamic nature of spacetime.

In addition to their place in the cosmic hierarchy, the extremes of density, temperature, and composition encountered in core collapse supernovae provide an opportunity to explore fundamental nuclear and particle physics that would otherwise be inaccessible in terrestrial experiments. Supernovae serve as cosmic laboratories, and supernova models are the bridge between observations (bringing us information about these explosions) and the fundamental physics we seek. In the event of a Galactic core collapse supernova, the joint detection of the neutrinos and gravitational waves would provide a wealth of information that will both help us develop and validate supernova models and, given sufficiently sophisticated models, allow us to extract significant information about the high-density, neutron-rich environment in the collapsing stellar core and proto-neutron star.

The connections between supernova observations, supernova models, and fundamental physics is brought full circle when we consider the role of terrestrial nuclear physics experiments. For example, measurements of neutrino-nucleus cross sections validate the nuclear structure models that underpin the calculations of stellar core neutrino-nucleus weak interactions. These define the dynamics of stellar core collapse and set the stage for the supernova dynamics that occurs after stellar core bounce [77]. Terrestrial experiments will enable more sophisticated supernova models, which in turn will allow, when detailed neutrino observations become available, a more accurate discrimination of nuclear models for the high-density, neutron-rich stellar core regions.

Core collapse supernovae result from the gravitational collapse of the iron core of a massive star (more than ten times the mass of the Sun). The inner iron core undergoes a transition to nuclear matter and rebounds at supernuclear densities to launch a shock wave into the outer iron core. This shock wave dissociates the outer iron core nuclei to form a hot mantle of neutrons and protons outside of the unshocked inner, nuclear matter core. The shock wave must ultimately propagate out of the iron core and through the successive stellar layers of increasingly lighter elements to produce the supernova.

Much work remains to be done to elucidate the core collapse supernova mechanism. These are neutrino-driven events involving the turbulent fluid flow in the exploding stellar core, stellar core rotation and magnetic fields, and strong (general relativistic) as opposed to weak (Newtonian) gravitational fields. Meeting the scientific challenge will ultimately require three-dimensional general relativistic radiation magnetohydrodynamics simulations with three-dimensional, multi-neutrino-energy, multi-neutrino-angle neutrino transport. This state of the art macrophysics must be matched by state of the art microphysics that will describe the stellar core sub- and super-nuclear density nuclear physics and the neutrino-stellar core weak interaction physics. The cooperation of nuclear physicists, particle physicists, and astrophysicists has already proven to be a very effective way to address this Grand Challenge problem (e.g., see the DOE SciDAC-funded TeraScale Supernova Initiative: [www.tsi-scidac.org](http://www.tsi-scidac.org)), and a sustained large-scale, multi-physics effort will be needed to systematically arrive at its solution. Current supercomputers are enabling the first detailed two-dimensional simulations. A ten-fold increase in capability would provide, for the first time, the opportunity to simulate supernovae realistically, in three dimensions. This increase in computing power is expected within the next five years. Given the challenge of modeling such nonlinear multi-physics systems, and the opportunity afforded by Tera- and Peta-Scale computing platforms, input from experiment and/or observation is both essential and timely.

The neutrino and gravitational wave emissions from core collapse supernovae provide direct information about the dynamics at the center of the exploding star and, therefore, about the explosion mechanism itself. Instabilities in the proto-neutron star, such as convection or doubly-diffusive instabilities (e.g., lepto-entropy fingers, neutron fingers), and rotation will have a direct impact on the emergent neutrino fluxes and, therefore, the explosion mechanism and supernova byproducts. Thus, a detailed three-flavor

neutrino pulse detection by SK, SNO, ICARUS, KamLAND, and LVD, among others, would provide a template against which models of the turbulent and rotating stellar core dynamics could be developed and validated.

The neutrino emission from a core collapse supernova occurs in three major stages: (1) The emission of electron neutrinos during stellar core collapse and an electron neutrino burst  $\sim 10^{53}$  erg/s only milliseconds after stellar core bounce, as the supernova shock wave passes through the electron neutrinosphere, at which point the trapped electron neutrinos behind the shock generated by rapid electron capture on the shock-liberated protons are free to escape. (2) A longer-term Kelvin-Helmholtz cooling phase of the proto-neutron star, which occurs over a period  $\sim 10$  s during which time the supernova is launched and the proto-neutron star cools to form a neutron star or a black hole. This phase is characterized by the emission of neutrinos of all three flavors, and their antineutrinos, from the hot, proto-neutron star mantle and the liberation in the form of these neutrinos of the  $\sim 10^{53}$  erg of gravitational binding energy of a neutron star. The neutrinos are emitted at the staggering rate  $\sim 10^{52-53}$  erg s $^{-1}$  with RMS energies between 10 and 25 MeV. (3) A long-term ( $\sim 10$ -100 s) neutron star cooling phase.

The electron neutrino burst is a probe of the physics of stellar core collapse, bounce, and initial shock formation and propagation [85]. It would be observable in the event of a Galactic supernova. Electron capture on nuclei during stellar core collapse determines the size of the inner iron core and thus the initial location and energy of the supernova shock wave at core bounce, which then sets the stage for everything that follows. In turn, electron capture on the nuclei in the stellar core during collapse depends on their detailed nuclear structure. An electron-neutrino burst detection has never been achieved. Such a detection would shed light on both stellar core collapse and nuclear structure physics.

Regarding the second neutrino emission phase, current supernova models indicate that a combination of fluid instabilities below the supernova shock wave and rotation of the stellar core will affect the luminosities and mean energies of the neutrinos emanating from the hot mantle during this phase [74, 76]. To complicate matters further, in the case of a rotating core the observed neutrino luminosities along the rotation axis and along the equator could differ by as much as a factor of three [78].

Current models also indicate that the stellar core collapse and bounce dynamics, which is tied to the rotation of the core, and the different fluid instabilities that may develop below the shock will have distinct gravitational wave signatures that, in the event of a Galactic supernova, may be detectable by both LIGO I and LIGO II [81]. The gross stellar core collapse and bounce and the different fluid instabilities will yield gravitational wave signatures at different frequencies in the 10-3000 Hz range, and with different amplitudes. Thus, core collapse supernovae provide an opportunity for a joint detection of both neutrinos and gravitational waves, with one leveraging the other; each would provide a complementary diagnostic for supernova models.

But all of the models mentioned above are far from complete. In reality, the impact of a detailed neutrino (and gravitational wave) detection would be felt at an even more fundamental level. Currently, there are no core collapse supernova models that both implement realistic neutrino transport and explode, whether the models are one-dimensional (spherically symmetric) [79, 83, 85] or two-dimensional (axisymmetric) [74, 80] (there are as yet no three-dimensional models with sufficiently realistic neutrino transport). Moreover, there are no sufficiently complex models that include all of the known potentially relevant physics and none at all that include magnetic fields and are sufficiently realistic in other respects that can reliably explore the possible role magnetic fields may play in supernova dynamics [69]. Thus, a detailed neutrino light curve would illuminate much about the nature of stellar core collapse and bounce, the postbounce evolution, and the physics responsible for the generation of the supernova.

Detailed neutrino signatures will supply volumes of information not only about the macroscopic physics of the stellar core during explosion but about its microscopic physics. In particular, emergent neutrino fluxes will depend on the energetics of shock formation and the proto-neutron star evolution, both of which depend on the high-density equation of state at and after bounce. For example, the development of fluid instabilities in the proto-neutron star depend on this equation of state [71]. In turn, these affect the neutrino fluxes, with vigorous instabilities potentially associated with significant boosts in luminosity. At late times, during phase three of the neutrino signature from core collapse supernovae, compositional changes (e.g., the existence of quarks) can have catastrophic consequences, leading to metastability of the newly formed neutron star and the dynamic collapse to a black hole, with a corresponding sharp cutoff in the neutrino luminosities. Such events are potentially detectable for a Galactic supernova, especially if detector sizes are significantly increased and/or new detector technologies are implemented [72, 73].

It is exciting to think about the scientific revolution that would occur in the event of a Galactic supernova, but at the same time one's excitement is always tempered by the fact that, on average, a

Galactic core collapse supernova is expected only twice per century (although the birth rate of pulsars, which are born in core collapse supernovae, has recently been estimated to be at the significantly higher rate of four per century [75]). On the other hand, if such supernovae were visible in neutrinos out to the Virgo cluster, the core collapse supernova rate would rise dramatically to a few per year. Thus, both larger-scale experiments and new neutrino detection technologies, which would make this possible, should seriously be explored. The scientific payoff would be substantial.

Finally, it is now an experimental fact that neutrinos have mass. The implications are far-reaching and include implications for core collapse supernova dynamics and phenomenology. First, neutrino mixing deep within the stellar core could have a dramatic impact on the emergent neutrino fluxes from the proto-neutron star and thereby affect the explosion mechanism and observables [84]. Second, neutrino mixing also leads to characteristic signatures in supernova neutrino detection. Consequently, knowledge and deconvolution of this mixing would be required in order to use the detected fluxes to validate supernova models and extract information relating to the high-density nuclear physics. Thus, developments in supernova theory and our ultimate understanding of these great cosmic events is not independent of exciting developments that have and will take place in other areas of astrophysics and particle physics.

## SUPERNOVA NEUTRINOS AS TESTS OF PARTICLE PHYSICS

Core collapse supernovae are widely touted as laboratories for fundamental neutrino, nuclear, and particle physics. In fact, there are aspects of this assertion which are true and aspects which are false. The truth is that much of the physics and phenomenology of supernova core collapse and explosion *is* sensitive to fundamental issues in the weak interaction, especially as regards neutrinos. However, it is frequently also true that we do not yet understand the core collapse supernova phenomenon at a level sufficient to turn this sensitivity to input physics into hard constraints on fundamental particle physics.

Aiding and abetting our ignorance of the details of core collapse supernovae is the sad state of supernova neutrino astronomy: our only record of the neutrino signal from collapse is the handful of events from SN 1987a. There is, on the other hand, every reason to think that progress will be made and that a better understanding of core collapse physics, perhaps coupled with a neutrino signature in modern detectors from a Galactic collapse event, will allow us to exploit the tremendous and tantalizing sensitivity of collapse/explosion physics to neutrino properties, flavor mixing, as well as new physics. It is even conceivable that new fundamental neutrino physics could be a key to understanding, for example, why (some?) collapse events lead to explosions and perhaps how heavy elements are formed.

Why are core collapse supernovae so sensitive to input weak interaction and neutrino physics and yet so difficult to understand? We can give a succinct answer to this: (1) nearly all of the energy available in this problem resides in seas of neutrinos in the core; (2) the energy of the supernova explosion is tiny, comprising only some 1% of the energy in these neutrino seas. The essence of the supernova problem is to figure out how  $\sim 1\%$  of the energy resident in the neutrino seas in the core is transported out and deposited behind or near a nascent shock. The transport problem depends, in turn, on uncertain aspects of the high density nuclear equation of state, weak interactions at high density, and perhaps multi-dimensional issues in radiation hydrodynamics coupled with neutrino flavor evolution physics. Magnetic fields and MHD may play a role as well. And in all of this great accuracy is necessary because, for example, the explosion energy is such a small fraction of the total energy.

With this discouraging assessment particle physicists may be heading for the exits. Not so fast. The possibilities are seductive, however, as this whole collapse/explosion process can be exquisitely sensitive to lepton number violation. The collapse/explosion environment affords a unique sensitivity to neutrino interactions and properties that are matched nowhere else in the universe save, possibly, for the Big Bang.

When the Chandrasekhar mass iron core collapses to a distended neutron star in  $\sim 1$  s some  $10^{52}$  ergs of gravitational binding energy are released promptly, roughly 99% of this as neutrinos of all flavors. This complements the sea of mainly  $\nu_e$  neutrinos produced by electron capture during the collapse or Infall Epoch. The collapse is halted at or above nuclear density and a shock wave is generated. This shock moves out to hundreds of kilometers from the core on a timescale of order a hundred milliseconds and stalls. Meanwhile, and subsequently, the neutron star core contracts quasi-statically, eventually releasing some  $10^{53}$  ergs as neutrinos. The energy in the neutrino seas at this point is  $\sim 10\%$  of the rest mass of the neutron star!

All aspects of this process are sensitive to neutrino flavor evolution. If  $\nu_e$ 's are converted to another type of neutrino, either active or sterile, then electron capture will be unblocked, the electron fraction will be reduced (rendering the collapsing stellar core more neutron-rich), and the subsequent bounce shock will be weaker and the thermodynamic structure of the core will be altered, in broad brush increasing the entropy for active-active transformation and likely decreasing it for active-sterile conversion. The weaker shock energy will translate into a smaller radius of stall-out and, perhaps, a reduced re-heating rate from neutrino energy deposition. If we understood where the explosion came from we might be able to use these considerations to put rather stringent constraints on a number of lepton number violating interactions/processes in the Infall Epoch.

Clearly, a better understanding of the shock re-heating process would be beneficial. We could someday get this from a detailed neutrino signal. Likewise, it is conceivable that nucleosynthesis, especially of the heavy r-process elements, could give us important clues about what is going on after core bounce. Many neutrino processes which involve lepton number violation can be important in this post-bounce regime.

Active-sterile neutrino flavor conversion has been invoked over a wide range of sterile neutrino masses and mixings to, among other things, explain pulsar kicks and enhanced shock re-heating, and to give a robust scenario for successful r-process nucleosynthesis in slow neutrino-driven winds. The neutrino process (neutrino-nucleus spallation) may also be sensitive to this process if active neutrino energies are increased.

Obviously, the active neutrino signal from the supernova can also be affected by both active-active and

active-sterile neutrino flavor conversion. The role of the density jump associated with the shock can be important. In fact, it may afford insight into the neutrino mass and mixing spectrum, shedding light on, for example,  $\theta_{13}$ . Alternatively, if these neutrino mixing properties are known independently from laboratory experiments, then the neutrino signal could let us probe shock propagation during and after the re-heating event.

In all of these regimes, new neutrino interactions, such as those from extensions of the Standard Model can have important effects. Our model for collapse and explosion could be changed by new interactions, though perhaps not yet to a large enough extent for legitimate constraint. The history of the supernova problem makes this abundantly clear. For example, the discovery of neutral currents completely altered our view of stellar collapse.

Finally, suppose we restrict our attention to the known active neutrinos. The recent experimental revolution in neutrino physics has arguably given us all the neutrino mass-squared differences (though not the absolute masses) and all of the vacuum mixing properties save for  $\theta_{13}$  and the CP-violating phase. The unfortunate truth is that we are not yet able to take this hard-won data and calculate the consequences for neutrino flavor evolution either inside or above the neutron star! This is because the neutrino flavor evolution problem in the supernova environment, unlike the sun, is fiercely non-linear and in a unique way. The potential which governs neutrino flavor transformation is dominated by neutrino-neutrino forward scattering. In turn, this process depends on the flavor states of the neutrinos.

If we consider the coherent evolution/propagation of neutrinos above the neutron star, then a given neutrino world line will intersect the world lines of other neutrinos and, possibly, lead to a forward scattering events. Essentially all such trajectories have flavor evolution histories which are coupled to one another through quantum entanglement engendered by forward scattering. This is a unique kind of transport problem.

Of course, if the emergent fluxes and energy spectra of the various flavors of neutrinos at the neutron star surface are identical, then swapping neutrino flavors will have no effect on any aspect of supernova physics. In fact, current simulations and neutrino transport calculations seem to suggest that this is the case at early times post-bounce. Whether or not this remains true over the some 20 s of neutron star contraction where neutrino fluxes are appreciable remains to be determined. Changes in the core, especially to the equation of state and to the net lepton number residing in the core, likely will lead to energy spectrum and flux differences between the neutrino flavors.

In any case, progress on understanding the core collapse supernova phenomenon may well depend on what we know about and our ability to model how the weakly interacting sector evolves. The daunting nature of the supernova problem should not discourage us from striving for better insight.

## DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

There is a diffuse supernova neutrino background (SNB) coming from all core collapse supernova (predominantly “Type II”) and it is within reach of current water Cerenkov detectors (*e.g.*, Super-K). Best estimates[86] for the expected SNB predict an event rate that is just consistent with Super-K’s upper limit[87] (see Fig. 7). The detection of this background provides, at a minimum, the first detection of cosmological neutrinos (*i.e.*, outside our Local Group) and an independent measurement of the star formation rate (SFR) out to a redshift of  $z \sim 1$ [88]. For example, the current Super-K upper-limit to the SNB above 19 MeV ( $1.2\bar{\nu}_e\text{cm}^{-2}\text{sec}^{-1}$ ) already admits constraints on the SFR out to  $z \sim 1$  that are competitive with optical surveys like the Sloan Digital Sky Survey (SDSS)[86]. Lower threshold, larger detectors than Super-K (*e.g.*, a doped Super-K like GADZOOKS[89], KamLAND[90], HyperK[91], or UNO[92]) have further reach in redshift and thus can provide information regarding supernovae and star formation in the high-redshift Universe, an epoch where photon observations are complicated by intervening material.

The event rate for  $\bar{\nu}_e + p \rightarrow n + e^+$  associated with the diffuse SNB depends on the  $\bar{\nu}$  energy spectrum produced by each core collapse supernova (now set by models, but possibly to be pinned down by direct observations of Galactic supernovae), an assumed mixing of the  $\bar{\nu}$ , either in-flight or within the

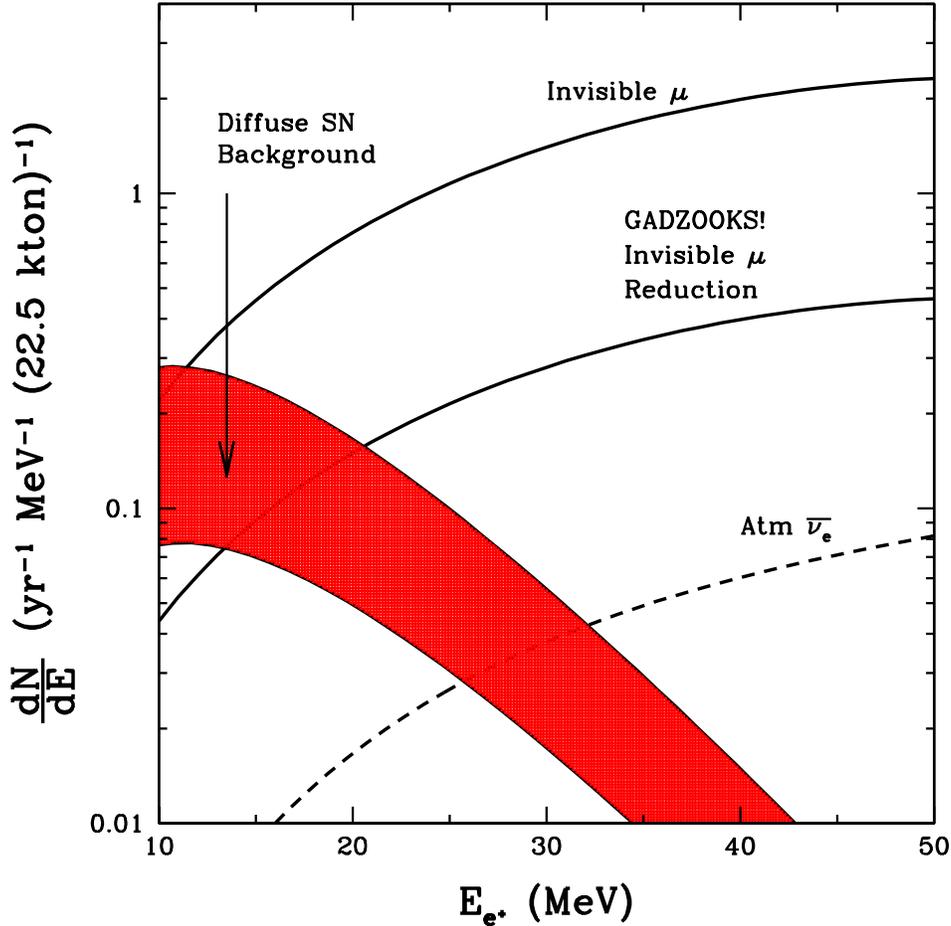


FIG. 7: The diffuse supernova neutrino background (shaded) and competing backgrounds at Super-K and GADZOOKS (a Gd-doped Super-K). The diffuse SNB is calculated using proxies for the supernova rate as a function of redshift. Best estimates for this rate are just consistent with the Super-K upper limit on the SNB and correspond to the top of the shaded curve. The lower border of the SNB corresponds to the minimum background consistent with estimates of the supernova rate.

supernova (constrained by solar, atmospheric, and variable-baseline neutrino oscillation experiments), and the supernova redshift distribution. For Super-K, operating at a threshold of 19 MeV, the neutrino temperatures in the supernova limit the accessible range to  $0 \lesssim z \lesssim 1$ . In this range there are several proxies to the SN rate: the UV and  $H\alpha$  luminosity densities, the metal enrichment rate, and the cosmic optical spectrum as measured by the SDSS. Combining these different methods results in a best-estimate to the SN rate which yields a diffuse SNB that is tantalizingly close to the Super-K upper bound. Fig. 7 shows the allowed range of the diffuse SNB signal based on the above-mentioned optical proxies as limited by the Super-K upper limit (star formation rates, acceptable on the basis of optical surveys, which would produce a diffuse SNB detectable by Super-K, have been eliminated). Also shown are the relevant backgrounds for Super-K and, for comparison, GADZOOKS. The lower boundary represents the minimum diffuse SNB consistent with SDSS observations (similar to other estimates ([88],[93]) and representative of the dependence of the SNB on proxies of the SFR).

Because the expected Super-K signal is small, alternative means of detecting the diffuse SNB should be considered. Bigger is better because it allows a more accurate determination of the signal and therefore more accurate measurements of the high redshift Universe will result. A detector which lowers the detection threshold will automatically increase the redshift sensitivity. As an example, even in the relatively small KamLAND detector one has the hope of using the difference between the Super-K signal and the KamLAND signal (appropriately normalized) to probe SFRs beyond  $z \sim 1$ . Roughly 5% of Super-K's event rate comes from  $z \gtrsim 1$  while roughly 30% of a KamLAND detection would be from supernova at  $z \gtrsim 1$ . Clearly the smallness of KamLAND will limit the quality of this comparison and it would be more desirable to have a low-threshold detector of equal or greater than Super-K size.

## MEASUREMENTS OF NEUTRINO-NUCLEUS CROSS SECTIONS

Core collapse supernovae are among the most energetic explosions in our universe, releasing  $10^{46}$  Joules of energy, 98% in the form of neutrinos of all flavors which emanate at a staggering rate of  $10^{57}$  neutrinos per second. The energy emitted as visible light, which is only one ten-thousandth the energy emitted in neutrinos, is enough to make these explosions as bright as an entire galaxy. These explosions almost entirely disrupt stars more massive than 8-10 solar masses, producing and disseminating into the interstellar medium many of the elements heavier than hydrogen and helium. Supernovae are a key link in our chain of origins from the big bang to the formation of life on earth and serve as laboratories for physics beyond the standard model and for matter at extremes of density, temperature, and neutron fraction that cannot be produced in terrestrial laboratories.

As the name suggests, core collapse supernovae result from the collapse of the core of a massive star at the end of its life. The collapse proceeds to supernuclear densities, at which point the core becomes incompressible, rebounds, and launches a shock wave into the star that is ultimately responsible for the explosion. The shock wave stalls, however, due to several enervating processes [94], and the shock is believed to be revived at least in part by the intense flux of neutrinos which emanates from the proto-neutron star at the center of the explosion [95, 96]. Reactions between this neutrino flux and the in-falling stellar layers also play a role in the production of many elements heavier than iron.

Precision neutrino-nucleus cross section measurements are crucial to improving our understanding of supernovae. Their importance arises in three related areas: (1) supernova dynamics, (2) supernova nucleosynthesis, and (3) terrestrial supernova neutrino detection.

### (1) Supernova Dynamics

Despite the observational fact that stars do explode, core-collapse supernova models have historically had difficulty repeating this feat. One likely culprit is incomplete knowledge of important micro-physics, in particular, the vitally important contributions of weak interactions (electron capture and neutrino induced reactions) [97, 98].

Recent studies have demonstrated unequivocally that electron capture on nuclei plays a major role in dictating the dynamics of stellar core collapse, which sets the stage for all of the supernova dynamics that occur after stellar core bounce and the formation of the supernova shock wave. Past supernova models used naive electron capture rates based on a simple independent-particle shell model for the nuclei in the stellar core [99]. Recent supernova calculations use a model which better captures the realistic shell structure of the nuclei found in the core and the collective excitations of nucleons in such nuclei during weak interactions such as electron capture [100]. Comparisons between these two studies demonstrate that the more realistic electron capture rates lead to quantitative and qualitative changes in the stellar core profiles in density, temperature, and composition after stellar core bounce, thereby affecting the strength and the launch radius of the supernova shock wave. These differences have ramifications for both supernova dynamics and supernova element synthesis.

It is impossible to directly measure weak-interaction electron capture cross sections at these energies due to the distorting influence of atomic electrons. Some information relevant to electron capture rates has been obtained from  $(p, n)$  transfer reactions. But these reactions yield unambiguous information only for the Gamow-Teller part of the weak operator responsible for electron capture. In addition, at excitation energies above the Gamow-Teller peak the contributions from non-zero angular momentum components are difficult, if not impossible to isolate. Furthermore, even Gamow-Teller peak measurements are sparse for  $A > 65$ . Measuring cross sections for electron-neutrino capture on nuclei is equivalent to measuring cross sections for electron capture on that same nucleus since they are inverse processes, and it is the only way to make these measurements. Also, comparisons between  $(p, n)$  transfer reaction data and electron-neutrino capture data for energies above the Gamow-Teller peak will help to deconvolute the non-zero angular momentum contributions. Thus experiments to measure neutrino capture rates are complementary to  $(p, n)$  measurements at RIA. This has implications for any application that requires accurate nuclear structure theory input.

It would, of course, be impossible to experimentally measure cross sections for all the thousands of weak interaction rates needed in realistic simulations of supernovae and supernova nucleosynthesis. Nonetheless, a finite, but strategically chosen set of measurements will validate the fundamental nuclear structure models at the foundation of the thousands of rate computations that are input to the supernova models.

### (2) Supernova Nucleosynthesis

Nucleosynthesis in core collapse supernovae falls into three basic categories: (i) explosive nucleosynthesis that occurs as the shock wave passes through the stellar layers and causes nuclear fusion through compression and heating of the material, (ii) neutrino nucleosynthesis in the ejected layers that occurs as these layers are exposed to the intense neutrino flux emerging from the proto-neutron star, which is responsible for generating the explosion to begin with, and (iii)  $r$ -process nucleosynthesis that occurs in a neutrino-driven wind emanating from the proto-neutron star after the explosion is initiated. In all cases, the final elemental abundances produced and ejected are affected through nuclear transmutations by the neutrino-nucleus interactions that occur [101–104]. Precision neutrino-nucleus cross section measurements are therefore necessary for a quantitative understanding. In a supernova many of the reactions take place on nuclei that unstable and/or are in excited states. Cross sections for such reactions are obviously not feasible, so the role of neutrino cross section measurements will be to constrain nuclear structure theory on a strategically chosen set of nuclei that are similar enough to the nuclei of interest that reasonable extrapolations can be made.

### (3) Supernova Neutrino Detection

An incredible wealth of information was derived from the handful of neutrinos emanating from supernova SN1987a that were measured in terrestrial detectors. The time and energy distributions of neutrinos emanating from a supernova (the “light curve” provide the only way to experimentally explore supernova dynamics at the earliest and deepest stages of the explosion – the only way to take a “picture” of the birth of a neutron star, and possibly a black hole. The ability to detect, understand, and ultimately use the detailed neutrino light curve from a future core collapse supernova in our galaxy is integral to a) developing better supernova models and b) using precision supernova models together with detailed astronomical observations in order to cull fundamental nuclear physics that would otherwise be inaccessible in terrestrial experiments. In turn, this will require accurate knowledge of the response function (cross sections and byproducts of neutrino interactions in the detector material) of a terrestrial neutrino detector to the incoming supernova neutrino flux. From deuterium to lead, a number of nuclei have been proposed and, in some cases, used as supernova detector materials [105–108]. In all cases, accurate cross sections for neutrino-nucleus interactions in the relevant energy range are essential.

At this moment there is a unique opportunity to carry out a long term program of neutrino cross section measurements on a range of appropriate nuclear targets due to the construction of the Spallation Neutron Source (SNS) at Oak Ridge National Lab. The SNS generates a short (380 ns FWHM), very intense ( $10^{14}$  protons/pulse) 60 Hz, 1 GeV proton beam which stops in a mercury target, producing pulsed neutron beams that will be primarily used for solid-state physics measurements. As a by-product, very intense neutrino pulses will be produced through the decay-at-rest (DAR) of pions and muons. This combination of the DAR neutrino spectra, intensity and time structure makes the SNS uniquely suited to make an extensive set of precision neutrino-nucleus cross section measurements:

*Energy spectrum:* The neutrino spectrum has strong overlap with the neutrino spectra present inside a supernova, as shown in Fig. 8. Furthermore, the spectrum is well-defined by the kinematics of the pion and muon decays, making interpretation of the data much easier.

*Intensity:* The SNS will produce  $10^{15}$  neutrinos/sec from pion and muon decays. With this flux, a 10 ton fiducial detector situated 20 meters from the mercury production target would be expected to measure several thousand neutrino interactions per year.

*Time structure:* The pulsed nature of the beam allows the detector to be shut off except for a few microseconds after each pulse, effectively blocking out most cosmic-ray interactions (a background reduction equivalent to locating the detector underground with a 2.3 km water-equivalent overburden).

A suitable location at the SNS (sufficient load-capacity, not interfering with neutron-scattering instruments, with a volume sufficient to hold a passive-shielding bunker and an active veto system plus two 10 ton fiducial detectors) has been identified. Detector concepts have been developed which allow measurement of both solid and liquid targets. In both cases the detectors can be reused with different target elements, thus minimizing the costs of a multi-target program. Simulations of these detectors indicate that there is sufficient angular and energy resolution of the outgoing electron to allow the double differential charged current measurements, which is important for using these measurements to benchmark nuclear structure theory. Neutral current measurements are relatively difficult because their signal in the detector is more subtle. However, such measurements may be possible (given appropriate detector development, and shielding design) during an SNS proton pulse. During this time the intensity of muon neutrinos, which result from pion decay, is orders of magnitude higher than the intensity of other neutrino flavors due to the shorter pion lifetime. Muon neutrinos also have the benefit of being mono-energetic since they are a two-body decay product. Neutrino-nucleus interactions are the only way

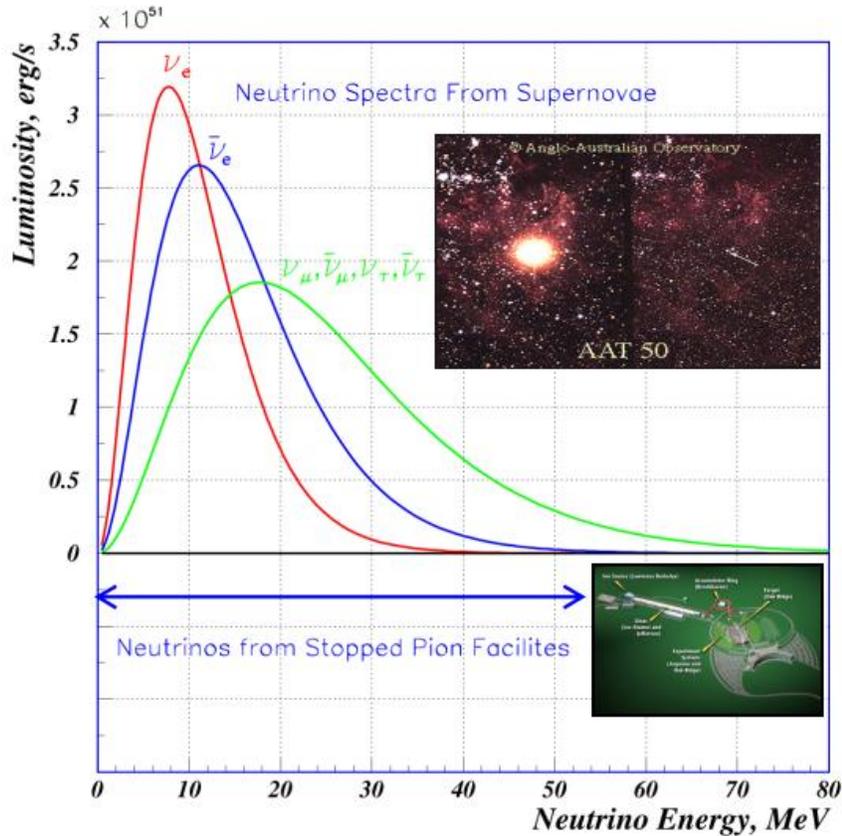


FIG. 8: The neutrinos produced by stopped-pion facilities are in just the right energy range to measure the neutrino-nucleus cross sections required for understanding supernova neutrino emission.

to get information on neutral current nuclear excitations.

In addition to the two general-purpose detectors it would also be possible to install elements of supernova neutrino detectors in the shielded bunker and *directly* calibrate them with a known flux of neutrinos (flavor and energy) having an energy spectrum overlapping that of supernova neutrinos.

A broad range of precision neutrino nucleus interaction measurements are key to understanding supernovae – both nucleosynthesis and the explosion mechanism – and are therefore key to understanding our star dust origins. Such measurements also provide input to nuclear structure theory that is unique and complementary to that which will be obtained at RIA. Constructing the ideal neutrino source with which to make such measurements would require an enormous investment. However, this ideal source – the Spallation Neutron Source – is already under construction for completely different purposes. The neutrinos which are produced are a serendipitous by-product, providing us with a unique opportunity to make these important measurements.

## LEPTOGENESIS AND THE ORIGIN OF THE BARYON ASYMMETRY

One of the most striking impact of neutrino physics on cosmology is a possible explanation to the baryon asymmetry of the universe, called “leptogenesis.” This is a surprising connection, as the *baryon* asymmetry as we see from our own existence and in the Big Bang Nucleosynthesis is in *quarks*, not in neutrinos.

The crucial ingredient in the connection between neutrino physics and baryon asymmetry is the electroweak anomaly, an effect in the *Standard Model*. As first pointed out by 't Hooft [109], the baryon number  $B$  is conserved classically in the Standard Model, but not quantum mechanically. Similarly, the lepton number  $L$  is not conserved either, while  $B - L$  is. The anomaly is a tunneling effect at the zero temperature and hence highly suppressed by a WKB-like factor (“instanton”)  $e^{-2\pi/\alpha_w} \approx 10^{-1517}$ . However, at high temperatures too hot for the Higgs Bose-Einstein condensate, it is not a tunneling because classical transitions are allowed by the thermal fluctuation of electroweak gauge fields in the plasma [110]. Then the rate of anomaly-induced  $B$ - and  $L$ -violating process is suppressed only by  $10\alpha_W^5 \approx 10^{-6}$  [111]. In fact,  $B$ - and  $L$ -violation is in equilibrium for the range of temperatures approximately for  $10^2$ – $10^{11}$  GeV. This anomaly effect can be understood schematically in Fig. 9.

If, due to some reason, there is net asymmetry in  $B - L$ , the chemical equilibrium in gauge and Yukawa interactions as well as the anomaly effects is obtained at [112]

$$B \simeq 0.35(B - L), \quad L \simeq -0.65(B - L). \quad (5)$$

The important question is then how an asymmetry in  $B - L$  had been created. It obviously requires violation of  $B - L$ . The most popular mechanism for it is the seesaw mechanism [113]. It postulates heavy right-handed neutrinos  $N$  with no gauge interactions (they may well have gauge interactions at yet higher energy scales, such as in  $SO(10)$  grand unified theories) but with Yukawa interactions

$$\mathcal{L} = - \left( \frac{M_\alpha}{2} N_\alpha N_\alpha + h_{\alpha i} N_\alpha L_i H + c.c. \right). \quad (6)$$

One can always choose the basis for  $N_\alpha$  such that their masses are diagonal and real positive  $M_\alpha > 0$ , while the Yukawa couplings  $h_{\alpha i}$  are in general three-by-three complex matrix with 18 independent parameters. Using the rephasing of charged lepton fields, the physical parameters in  $h_{\alpha i}$  are reduced to 15. On the other hand, CP is conserved only if there is a basis where all entries of  $h_{\alpha i}$  are real, and hence with only 9 parameters. Therefore there are  $15 - 9 = 6$  CP-violating phases in general. Only one of them can appear in neutrino oscillation, two in Majorana phases, and three others appear only in processes that involve the right-handed neutrinos directly.

In early universe,  $N_\alpha$  were present in the thermal bath, and decayed eventually. If  $\sum_i |h_{\alpha i}|^2 \lesssim M_\alpha / (10^{16} \text{ GeV})$ , they have too small decay and inverse decay rates to stay in thermal equilibrium. They “hang around” for a while before they decay at a temperature much below their masses. On the other hand, the decay may be CP violating. At the tree-level,  $N_\alpha$  decays equally into  $LH$  and its CP conjugate. At the one-loop level, however, the interference between the tree-level amplitude and the absorptive part in the one-loop level amplitude (Fig. 10) results in a direct CP asymmetry [114]

$$\epsilon_1 \equiv BR(N_1 \rightarrow LH) - BR(N_1 \rightarrow \overline{(LH)}) \simeq \frac{1}{2\pi} \frac{\sum_{i,j} \Im(h_{1i} h_{1j} h_{3i}^* h_{3j}^*)}{\sum_i |h_{1i}|^2} \frac{M_1}{M_3}. \quad (7)$$

Here, we assumed that the relevant decay is that of  $N_1$ , ignored loops in  $N_2$ , and assumed a hierarchical spectrum  $M_3 \gg M_1$ . One can show that this quantity cannot exceed [115]

$$|\epsilon_1| \leq \frac{3}{16\pi} \frac{M_1}{v^2} \sqrt{\Delta m_{23}^2} \simeq 10^{-6} \left( \frac{M_1}{10^{10} \text{ GeV}} \right) \left( \frac{m_3}{0.05 \text{ eV}} \right). \quad (8)$$

To produce a sufficient baryon asymmetry, one finds a lower limit on the right-handed neutrino mass of  $4 \times 10^8 \text{ GeV}$ , and correspondingly an upper limit on the neutrino mass  $m_i < 0.12 \text{ eV}$  [116]. These bounds, however, can be evaded if there is an extreme mass degeneracy among right-handed neutrinos within their widths because the indirect CP violation in their mixing can enhance the resulting asymmetry.

Because right-handed neutrinos are required to be heavy, the reheating temperature after the inflation must be high,  $T_{RH} > 3 \times 10^9 \text{ GeV}$  [116]. This high temperature is in conflict with the gravitino problem

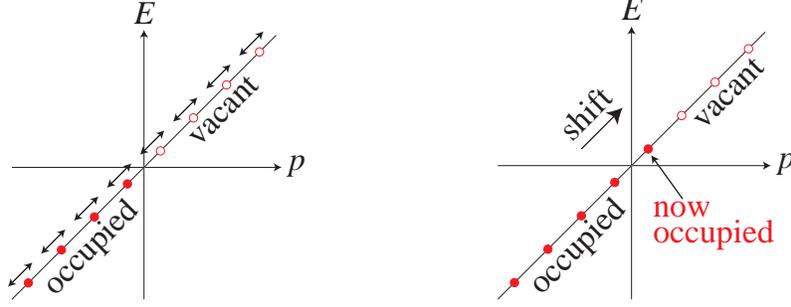


FIG. 9: Schematic explanation of the electroweak anomaly effect. (1) Negative energy states of the Dirac equation are occupied while positive energy states are left vacant. Thermal fluctuations of the  $W$  field move the energy levels up and down. (2) Once in a while, the fluctuation grows so big that all energy levels are shifted by one unit. Then a particle is found occupying a positive energy state. The same process occurs for all particles coupled to the  $W$ -boson, and hence left-handed leptons and left-handed quarks of all three colors change their numbers by the same amount; hence  $\Delta L = \Delta B$ .

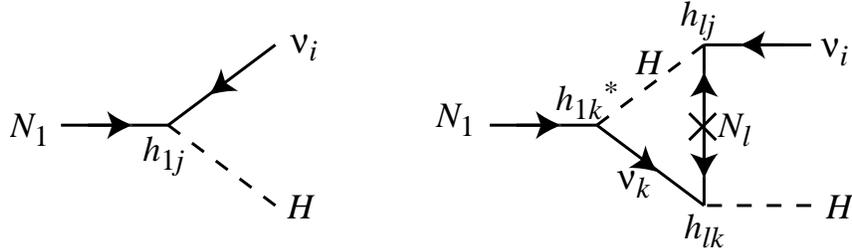


FIG. 10: The interference between the tree-level and the one-loop amplitudes causes the decay asymmetry.

if there is supersymmetry. For  $m_{3/2} \simeq 100$  GeV–1 TeV, and for purely photonic decay  $\tilde{G} \rightarrow \tilde{\chi}\gamma$ , the reheating temperature must be below  $10^6$ – $10^9$  GeV [117]. For hadronic decay, the bound may be even tighter [118]. There are several ways out of this conflict. One is to assume very heavy gravitino  $m_{3/2} \gtrsim 50$  TeV as in anomaly-mediated supersymmetry breaking [120, 121]; then the gravitinos decay before the Big-Bang Nucleosynthesis and are harmless. The reheating temperature can be as high as  $10^{11}$  GeV in this case [117], sufficient for thermal leptogenesis. Another possibility is to assume non-thermal production of right-handed neutrinos. They may be produced directly by inflaton decay [122], or their scalar partners may be the source of the energy density [123]. Right-handed sneutrino may even be the inflaton itself [124]. Then the reheating temperature can be as low as  $10^6$  GeV to suppress gravitino production, while a sufficient baryon asymmetry can be obtained [125].

Finally, it is important to note that the Majorana-ness of neutrinos is not mandatory for leptogenesis [126, 127]. If neutrinos are Dirac, there is no lepton number violation. On the other hand, the right-handed neutrinos are light (degenerate with left-handed ones by definition) and have only Yukawa interaction as small as  $10^{-13}$ . Therefore, even if there is no overall lepton asymmetry, it is possible to “store” asymmetry in right-handed neutrinos while the asymmetry in the other leptons is shared with quarks via the anomaly.

Can we prove leptogenesis experimentally? Clearly we need CP violation in the neutrino sector for leptogenesis. Unfortunately, the CP violation we can probe in neutrino oscillation may not be the CP violation needed in leptogenesis. In some less general models of neutrino mass, they are correlated (*e.g.*, the model with only two  $N$  [128]). Nonetheless the observation of CP violation and neutrinoless double beta decay would provide strong circumstantial evidence for leptogenesis. Further model-dependent but supporting evidence may be found in lepton-flavor violation if right-handed neutrino interactions leave imprint in mass matrices of sleptons in supersymmetric models (see, *e.g.*, [119, 130, 131]). Even though we may not be able to convict leptogenesis in a criminal trial, we may still find it guilty in a civil case.

## PRECISION BIG BANG NUCLEOSYNTHESIS TESTS

Big bang nucleosynthesis is the cosmological theory of the origin of the light element isotopes D,  $^3\text{He}$ ,  $^4\text{He}$ , and  $^7\text{Li}$  [132]. The success of the theory when compared to the observational determinations of the light elements allows one to place strong constraints on the physics of the early Universe at a time scale of 1-100 seconds after the big bang.  $^4\text{He}$  is a sensitive probe of deviations from the standard model and its abundance is determined primarily by the neutron to proton ratio when nucleosynthesis begins at a temperature of  $\sim 100$  keV (to a good approximation all neutrons are then bound to form  $^4\text{He}$ ).

The ratio  $n/p$  is determined by the competition between the weak interaction rates which interconvert neutrons and protons,

$$p + e^- \leftrightarrow n + \nu_e, \quad n + e^+ \leftrightarrow p + \bar{\nu}_e, \quad n \leftrightarrow p + e^- + \bar{\nu}_e \quad (9)$$

and the expansion rate, and is largely given by the Boltzmann factor

$$n/p \sim e^{-(m_n - m_p)/T_f} \quad (10)$$

where  $m_n - m_p$  is the neutron to proton mass difference. The weak interactions freeze out at a temperature of roughly 1 MeV when the weak interaction rate,  $\Gamma_{\text{wk}} \sim G_F^2 T^5$  is comparable to the Hubble expansion

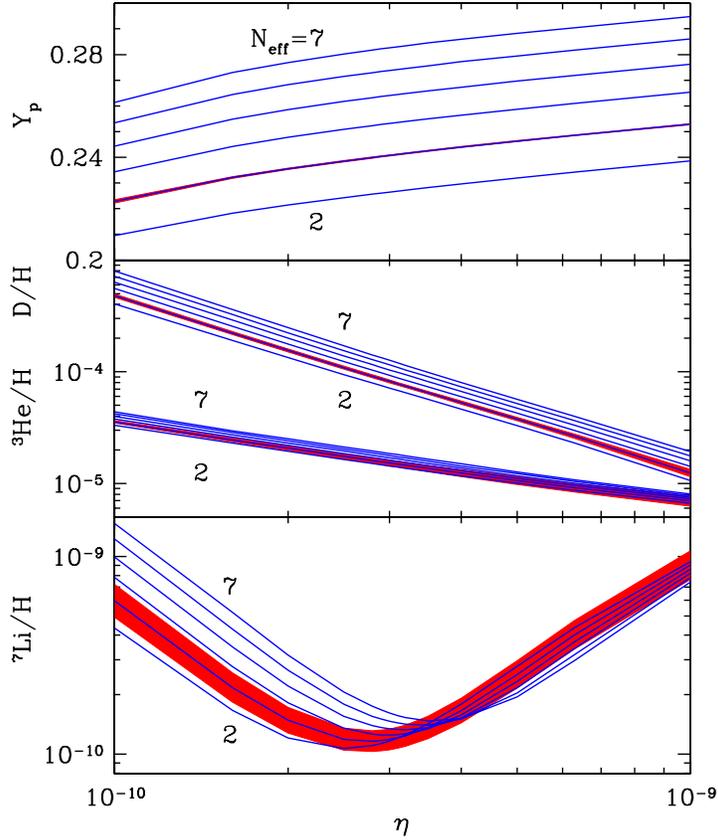


FIG. 11: The light element abundances as a function of the baryon-to-photon ratio for different values of  $N_\nu$  [133].

rate,  $H(T) \sim \sqrt{G_N N} T^2$ , where  $N = g_\gamma + \frac{7}{8}g_e + \frac{7}{8}g_\nu N_\nu = \frac{11}{2} + \frac{7}{4}N_\nu$  for  $g_\gamma = g_\nu = 2$  and  $g_e = 4$  and  $N_\nu$  is the number of neutrino flavors. Freeze-out is then determined by

$$G_F^2 T_f^5 \sim \sqrt{G_N N} T_f^2 \quad (11)$$

The freeze-out condition implies the scaling  $T_f^3 \sim \sqrt{N}$ . From Eqs. (10) and (11), it is then clear that changes in  $N$ , caused for example by a change in the number of light neutrinos  $N_\nu$ , would directly influence  $n/p$ , and hence the  ${}^4\text{He}$  abundance, which is given by  $Y_p = 2(n/p)/[1 + (n/p)]$ . The dependence of the light element abundances on  $N_\nu$  is shown in Figure 11 [133], where plotted is the mass fraction of  ${}^4\text{He}$ ,  $Y$ , and the abundances by number of the D,  ${}^3\text{He}$ , and  ${}^7\text{Li}$  as a function of the baryon-to-photon ratio,  $\eta$ , for values of  $N_\nu = 2 - 7$ . As one can see, an upper limit to  $Y$ , combined with a lower limit to  $\eta$  will yield an upper limit to  $N_\nu$  [134]. It should be noted that although the number of light neutrino flavors has been fixed by experiments at LEP and SLAC, the BBN bound is not solely restricted to neutrinos, but rather any relativistic particle species present in the early Universe at the time of BBN. In this sense,  $N_\nu > 3$  is simply a surrogate for any new particle species.

Assuming no new physics at low energies, the value of  $\eta$  is the sole input parameter to BBN calculations. Historically, it has been fixed by the comparison between BBN predictions and the observational determinations of the isotopic abundances. However, the high precision results from WMAP [135], have determined the primordial spectrum of density fluctuations down to small angular scales with excellent agreement with galaxy and cluster surveys and these results have led to a determination of the baryon

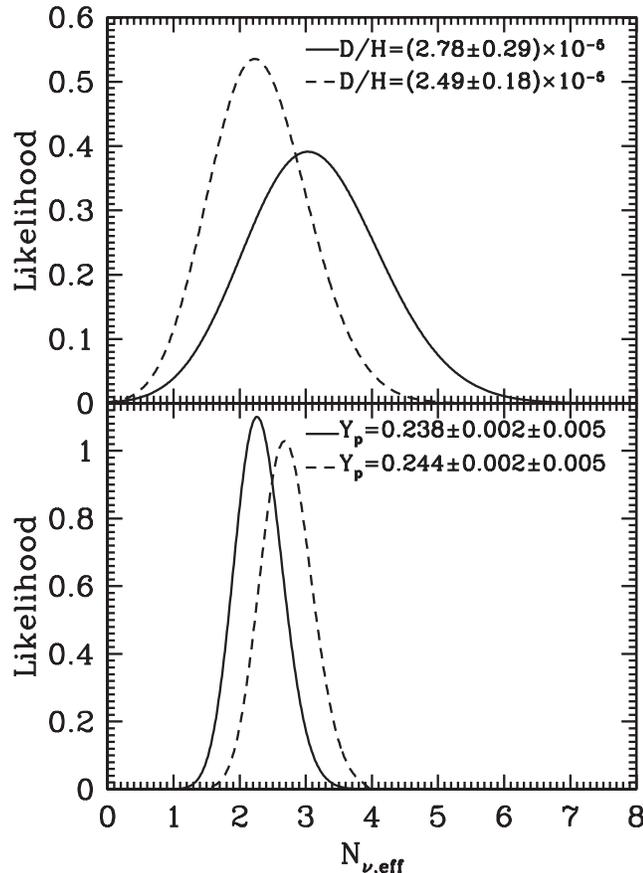


FIG. 12: Likelihoods for  $N_{\nu,\text{eff}}$  as predicted by the WMAP  $\eta$  and light element observations: (a) deuterium (b) helium.

density of unprecedented accuracy. The WMAP result of  $\Omega_B h^2 = 0.0224 \pm 0.0009$  is equivalent to  $\eta_{10} = 6.14 \pm 0.25$ , where  $\eta_{10} = 10^{10} \eta$ . This result is the WMAP best fit assuming a varying spectral index and is sensitive mostly to WMAP alone (primarily the first and second acoustic peaks) but does include CBI [136] and ACBAR [137] data on smaller angular scales, and Lyman  $\alpha$  forest data (and 2dF redshift survey data [138]) on large angular scales.

With the value of  $\eta$  fixed, one can use He abundance measurements to set limits on new physics [140]. At the WMAP value of  $\eta$ , the  ${}^4\text{He}$  abundance is predicted to be  $Y_P = 0.2484_{-0.0005}^{+0.0004}$  [139] and is somewhat high compared with observationally determined values of  $Y_P = 0.238 \pm 0.002 \pm 0.005$  [141] or  $Y_P = 0.242 \pm 0.002 \pm 0.005$  [142]. This discrepancy likely is due to systematic errors (possibly due to underlying He absorption [143]). Indeed a preliminary analysis with these effects included shows much better agreement [144]. Until this situation is better understood, caution is in order.

The  $N_{\nu,\text{eff}}$  likelihood calculated [133, 139, 145] using observed  ${}^4\text{He}$  abundances appears in Fig. 12b. As pointed out above, all available  ${}^4\text{He}$  abundance observations fall short of the CMB-BBN predicted value. This shortfall manifests itself in Fig. 12b by driving  $N_{\nu,\text{eff}}$  down below 3 for both observed  ${}^4\text{He}$  abundances, to  $N_{\nu,\text{eff}} \approx 2.5$ . The width of these distributions is quite narrow,  $\Delta N_{\nu,\text{eff}} \approx 0.4$ , due to the strong sensitivity of  ${}^4\text{He}$  to  $N_{\nu,\text{eff}}$ . Indeed, the width of the likelihood is dominated by the large systematic uncertainties in the  ${}^4\text{He}$  observations. In order for this constraint to be considered robust, we must understand the hidden systematics in the  ${}^4\text{He}$  observations. Assuming a prior of  $N_{\nu,\text{eff}} \geq 3.0$  the corresponding 95% CL upper limits are:  $N_{\nu,\text{eff}} < 3.4$  for  $Y_P = 0.238$ ;  $N_{\nu,\text{eff}} < 3.6$  for  $Y_P = 0.244$ . When underlying absorption is included, the upper limit on  $N_{\nu,\text{eff}}$ , may be significantly increased.

On the other hand, deuterium may not appear to suffer from large systematics. It is, however, limited by the low number statistics due to the difficulty of finding high-redshift systems well-suited for accurate D/H determinations. Given that D predictions from WMAP agree quite well with observations, we can now use D to place an interesting limit on  $N_{\nu,\text{eff}}$  [139]. D is not as sensitive to  $N_{\nu,\text{eff}}$  as  ${}^4\text{He}$  is, but none-the-less it does have a significant dependence. The relative error in the observed abundance of D/H ranges from 7-10%, depending on what systems are chosen for averaging. If the five most reliable systems are chosen, the peak of the  $N_{\nu,\text{eff}}$  likelihood distribution lies at  $N_{\nu,\text{eff}} \approx 3.0$ , with a width of  $\Delta N_{\nu,\text{eff}} \approx 1.0$  as seen in Fig. 12a. However, if we limit our sample to the two D systems that have had multiple absorption features observed, then the peak shifts to  $N_{\nu,\text{eff}} \approx 2.2$ , with a width of  $\Delta N_{\nu,\text{eff}} \approx 0.7$ . Given the low number of observations, it is difficult to qualify these results. The differences could be statistical in nature, or could be hinting at some underlying systematic affecting these systems. Adopting the five system D average,  $\text{D}/\text{H} = (2.78 \pm 0.29) \times 10^{-5}$ , the upper limit on  $N_{\nu,\text{eff}}$  is  $N_{\nu,\text{eff}} < 5.2$ , assuming the prior  $N_{\nu,\text{eff}} \geq 3$ .

## PRECISION COSMIC MICROWAVE BACKGROUND TESTS

The WMAP experiment showed that the standard cosmological model is a good phenomenological description of the observed universe [146]. In combination with other observations (supernova Ia and large scale structure), the consistent picture that emerges has matter contributing about 30% and dark energy about 70% to the energy density of the universe. Most of the matter is dark; baryons contribute about 4% while neutrinos contribute less than 2% to the total energy density of the universe. Given that the basic phenomenological structure is in place, one can look forward to the future with some confidence. The CMB has much more to offer if smaller scales and smaller features can be probed. This will require high angular resolution, high sensitivity experiments.

There are three questions of relevance for neutrino physics that CMB (and in general cosmology) could help answer. How many? What are their masses? How do they get massive? The issue of “how many” is related to the number of light degrees of freedom which is sensitive to the presence of sterile neutrinos. It should be noted that if the apparent LSND excess of  $\bar{\nu}_e$  is not due to systematic errors then a sterile (fourth) neutrino is required. It is possible for the abundance of this sterile neutrino to be cosmologically relevant. Also, depending on the mass hierarchy, the required (LSND) mass-squared difference could affect the overall mass scale. The MiniBooNE experiment currently underway at Fermilab will soon test the LSND neutrino oscillation hypothesis.

The fact that the CMB could have imprints of the mass generation mechanism might seem surprising, but a couple of examples should clarify this connection. Certain neutrino mass terms permit the possibility of a heavy neutrino decaying into a lighter one and a scalar particle (called Majoron). Long lifetime decays of this kind can be constrained using the CMB [147]. A more interesting example is that of neutrino mass generation through spontaneous breaking of approximate lepton flavor symmetries at or below the weak scale [148]. The presence of light Pseudo-Goldstone bosons changes the CMB anisotropy through the introduction of new degrees of freedom and new scattering channels for the neutrino [148].

The current large scale structure surveys (2dFGRS, SDSS) and WMAP together already provide powerful constraints on neutrino mass. We know that the sum of the active neutrino masses is less than about 1 eV [149]. The sum of the active neutrino masses,  $m_\nu$ , is related to their energy density  $\rho_\nu$  as  $m_\nu \approx \rho_\nu / (\text{meV})^4$ . At the lower end, atmospheric neutrino oscillations constrain the mass of at least one active neutrino to be larger than about 0.05 eV. It is indeed wonderful that this window from 0.05 eV to 1 eV can be probed with both laboratory experiments and cosmological observations.

Another parameter relevant for neutrino physics that future CMB experiments can measure well is the number of light degrees of freedom  $N_\nu$ , traditionally labeled “number of neutrinos”. It measures the energy density of relativistic particles in units of the energy density of one active neutrino species. Significant improvement in the measurement of both  $m_\nu$  and  $N_\nu$  (using CMB) will require future precision measurement of the CMB anisotropy from few to 20 arcminute angular scales.

Changing  $N_\nu$  affects the CMB anisotropy imprinted on the last scattering surface (called the primary CMB). There are two predominant effects. First, changing  $N_\nu$  changes the expansion rate of the universe. At last scattering, this leads to a change in the sound horizon and damping length (of the photon-baryon fluid). The change in the sound horizon shifts the position of the peaks and troughs in the anisotropy spectrum while the change in the damping length (relative to the sound horizon) changes its amplitude. The second effect operates around the location of the first peak and on angular scales larger than that. The presence (or lack) of radiation has an effect on the CMB even after last scattering. The reason is that in the presence of radiation (in fact anything other than pressureless matter) the gravitational potential changes with time (decays). The photons traversing these potential wells pick up a net red-shift or blue-shift which enhances the amplitude of the anisotropy spectrum.

A change in  $m_\nu$  gives rise to all of the above effects (though the changes are not degenerate with that of  $N_\nu$ ). However, a massive neutrino has an additional effect. On small scales, the presence of a massive neutrino damps the growth of structure (gravitational potential or equivalently the matter density perturbations). This is simply due to the larger thermal speed of the neutrino (as compared to that of dark matter). On large enough scales, the neutrino behaves like dark matter while on small scales, it moves freely in and out of dark matter potential wells. This effect can be used to put constraints on the neutrino mass using the observed galaxy power spectrum combined with CMB observations [150]. Eisenstein et al. [151] found that just the primary CMB spectrum from the Planck satellite can measure neutrino mass with an error of 0.26 eV. This sensitivity limit is related to the temperature of the photons at last scattering, 0.3 eV. No significant improvement is expected from combining Planck and the SDSS galaxy power spectrum [151, 152].

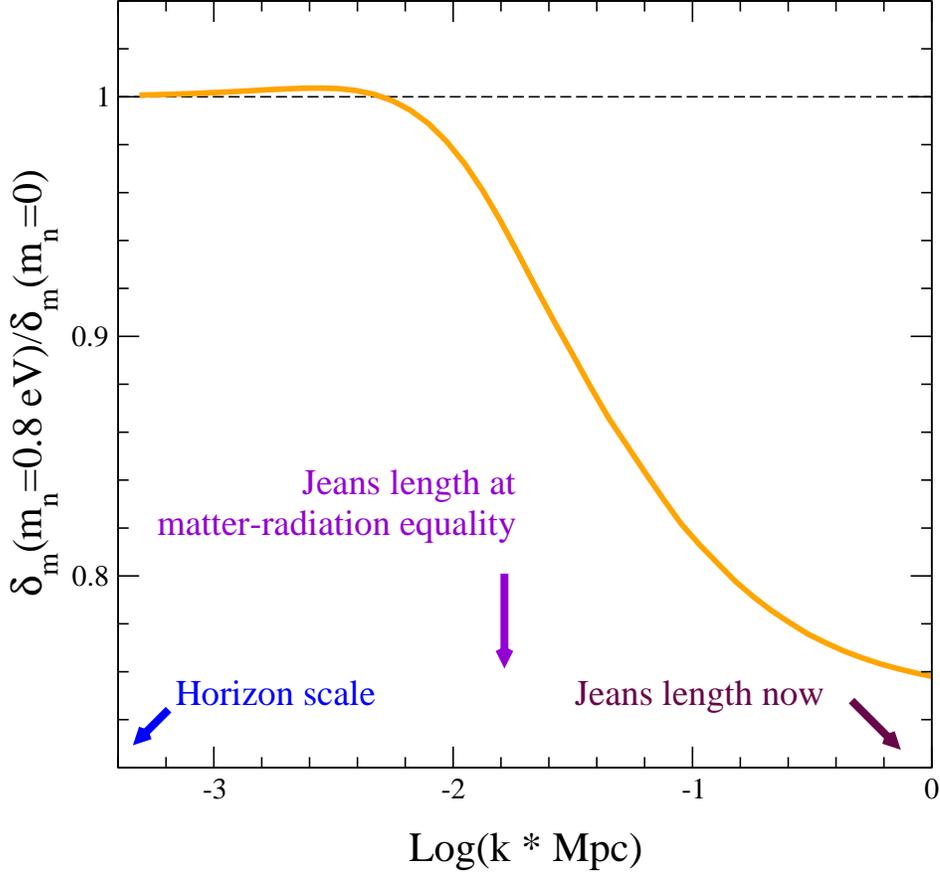


FIG. 13: The change in the matter density perturbation spectrum (as a function of inverse scale  $k$ ) when one neutrino is given a mass of 0.8 eV.

The alteration of the gravitational potential at late times changes the gravitational lensing of CMB photons as they traverse these potentials [153, 154]. Lensing results in the deflection of the CMB photons. These deflections are small, on average of the order of arcminutes. However, since the structure giving rise to these deflections is correlated on large scales, the lensing deflections are correlated over large angular scales. Including the gravitational lensing effect, the Planck error forecast improves to about 0.15 eV [155]. More ambitious CMB experiments could reduce this error to  $\sim 0.05$  eV [155]. Tomographic observations of the galaxy shear due to gravitational lensing can achieve similar sensitivity in  $m_\nu$  [156]. The physics in both cases is the same: gravitational lensing. However the observations and the associated systematics are very different. Complementary techniques are valuable since these measurements will be very challenging.

The effect of lensing on the CMB is simple to write down. For example, the *lensed* temperature  $T_U$  in a particular direction  $\vec{\theta}$  is related to the *unlensed* temperature  $T_L$  by the relation  $T_L(\vec{\theta}) = T_U(\vec{\theta} + \vec{d})$ . The lensing deflection field  $\vec{d}$  is related to the underlying density perturbations (gravitational potential wells). Thus a measurement of the statistical properties of this deflection field can in principle be translated into a measurement of the underlying density perturbations.

Lensing has three main effects on the CMB anisotropy spectrum. First, lensing introduces non-gaussianity (of a specific kind) into the otherwise gaussian CMB sky maps. This can be used to estimate the deflection field from CMB sky maps [157]. Second, lensing generates a specific pattern of polarization called B mode polarization (where B is used in the sense of “gradient-free”), the contribution from which is otherwise expected to be small [158]. If we are to use lensing to measure neutrino mass, this effect will play a vital role. Third, lensing due to its intrinsic non-gaussian nature shifts power from one scale to another. The net effect for the CMB anisotropy spectrum is that lensing becomes an important source of power on small scales because the primary (unlensed) CMB has an exponential drop in power on small scales.

The signature of a (say) 0.1 eV neutrino in the primary (unlensed) CMB anisotropy spectra is small. Such small masses are only detectable through their effect on lensing, which comes through their influence on the gravitational potential. The net suppression of the power spectrum is scale dependent and the relevant length scale is the Jeans length for neutrinos [152, 159, 160] which decreases with time as the neutrino thermal speed decreases. This suppression of growth is ameliorated on scales larger than the Jeans length at matter–radiation equality, where the neutrinos can cluster. Neutrinos never cluster on scales smaller than the Jeans length today. The net result is no effect on large scales and a suppression of power on small scales. This explains the scale dependence of density perturbations in the presence of a massive neutrino as plotted in Figure 13.

Future experiments like Planck will be able to statistically detect the lensing effect and thus measure or put upper limits on the neutrino mass. The expected  $1\text{-}\sigma$  error on  $m_\nu$  from Planck is 0.15 eV while that on  $N_\nu$  is 0.2. Planck maps combined with that from a ground-based but more sensitive experiment like the South Pole Telescope could do even better. Assuming the South Pole Telescope will run with polarized detectors, one could get up to 30% improvement in the expected errors.

Looking beyond Planck, it is conceivable that there will be another full sky mission. The primary aim of such an experiment will be to measure the primordial (inflationary) B mode signal which is expected to be present on large scales [161, 162]. The sensitivity and angular resolution required to measure the primordial B mode signal [163, 164] will allow one to achieve a lot more. If the foregrounds can be tamed, then one could hope to achieve a  $1\text{-}\sigma$  error of 0.05 eV on  $m_\nu$  and 0.1 on  $N_\nu$ . This would be spectacular.

## NEUTRINO MASS AND LARGE SCALE STRUCTURE

Structure in the universe forms differently if neutrinos have non-zero mass. In a universe without massive neutrinos, all matter (all massive particles) participates in the gravitational collapse that begins when the universe is about one hundred thousand years old. If neutrinos have mass, they constitute some of the matter today, but they were very hot early on, so they did not participate in collapse until they cooled sufficiently. Therefore, matter in a universe with massive neutrinos is more clustered than matter in a universe with massless neutrinos. It is this simple principle, well-known for over twenty years [165], that leads to the most stringent cosmological constraint on neutrino masses.

This constraint is based on the textbook calculation[166] that there are 112 neutrinos  $\text{cm}^{-3}$  for each generation. From this predicted number density, which follows directly from the thermodynamics of the universe at temperatures of order one MeV, we infer that the energy density of massive neutrinos compared to the critical density is

$$\Omega_\nu = 0.02 \left( \frac{\sum m_\nu}{1\text{eV}} \right) \left( \frac{72 \text{ km sec}^{-1} \text{Mpc}^{-1}}{H_0} \right)^2 \equiv 0.02 \left( \frac{\sum m_\nu}{1\text{eV}} \right) \left( \frac{0.72}{h} \right)^2 \quad (12)$$

where the sum is over the three generations and  $H_0$  is the Hubble constant, known to better than 10%. The statistical mechanics of the early universe also dictates that cosmic neutrinos have the thermal distribution of a massless gas (occupation number  $[e^{p/T_\nu} + 1]^{-1}$ ) with temperature  $T_\nu = (4/11)^{1/3} T_{\text{cmb}}$ . A massive neutrino therefore has a thermal velocity of order  $T_\nu/m_\nu \sim 2 \times 10^{-4}(1+z)(1\text{eV}/m_\nu)$  where  $z$  is the cosmic redshift. These thermal velocities enable neutrinos to freestream out of perturbation regions smaller than  $\lambda_{\text{fs}} \simeq 1\text{Mpc}(1\text{eV}/m_\nu)(1+z)^{1/2}$ . On length scales smaller than one Mpc, less matter is available to form potential wells, so perturbations have been suppressed for all times by the inability of neutrinos to cluster. There is thus a constant suppression in the power spectrum (which measures the clumpiness of the universe) on scales  $k \gtrsim 1\text{Mpc}^{-1}$ , as shown in Fig. 13. On slightly larger scales, neutrinos can participate in gravitational collapse when the freestreaming scale becomes smaller than the scale in question, so the suppression is not as severe. As Fig 13 illustrates, there is thus a monotonic decrease in the clustering strength as one moves from the largest scale affected (the horizon when perturbations begin to grow at matter domination) to the freestreaming scale today. This monotonic suppression from  $k \sim 10^{-2}\text{Mpc}^{-1}$  to  $k \sim 1\text{Mpc}^{-1}$  is a unique signature of massive neutrinos. The amplitude of the suppression depends only on the ratio of the massive neutrino density to the total matter density,  $f_\nu \equiv \Omega_\nu/\Omega_m$ .

The power spectrum is the simplest statistic characterizing the mass distribution in the universe. Therefore, the suppression in clustering due to massive neutrinos is most likely to be observed in the power spectrum, depicted for several values of neutrino mass in Fig. 14. The traditional way of measuring this two-point function is by analyzing galaxy surveys. Indeed, the most stringent cosmological constraints on neutrino mass currently come from two galaxy surveys, the Two Degree Field [167] and the Sloan Digital Sky Survey [168]. A cursory glance at the data in Fig. 14 shows that neutrino masses (actually the constraint is on the sum of all neutrino masses) greater than several eV are strongly disfavored by the data. There are two complications to this ‘‘chi-by-eye’’ appraisal though. The first is the concept of *bias*: the galaxy distribution does not necessarily accurately trace the mass distribution. Bias is thought to be most complicated on scales  $k \gtrsim 0.2h\text{Mpc}^{-1}$  so only data on larger scales is typically used to obtain neutrino constraints. Even with this cut, there is still no commonly accepted way to treat bias. The considerable scatter in the upper limits on neutrino mass from galaxy surveys [169] derives mostly from differences in the treatment of bias. The second complication is that changing other cosmological parameters can produce similar effects on the power spectrum. These *degeneracies* afflict all measures of the power spectrum and will be addressed below.

The power spectrum can also be inferred from the Lyman alpha forest [170]. Spectra of distant quasars show absorption at wavelengths corresponding to the Lyman alpha transition. An absorption line at wavelength  $\lambda$  corresponds to a region of neutral hydrogen at redshift  $1+z = \lambda/1215\text{\AA}$ . The clustering of the lines in the spectra therefore encodes information about the clustering of the neutral hydrogen and by extension the entire matter distribution. Again the way to think about the translation between the observations (flux power spectrum) and the Holy Grail (matter power spectrum) is that the flux is a biased tracer of the matter. The bias of the galaxy distribution is thought to be relatively simple on large scales, but it is difficult to simulate. The distribution traced by the forest on the other hand can be simulated quite accurately. Whereas galaxy formation simulators need to include information about

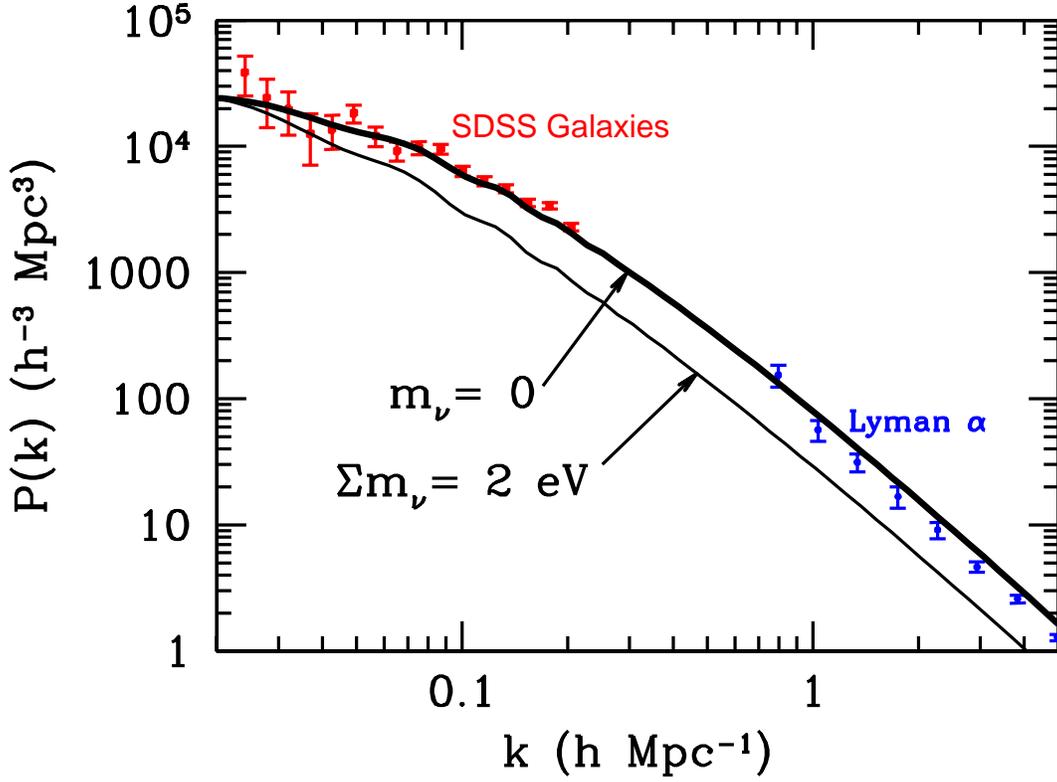


FIG. 14: The power spectrum of the matter distribution. A non-zero neutrino mass suppresses power on small scales (large  $k$ ). Data are from the Sloan Digital Sky Survey galaxies [168] and the Lyman alpha forest [170]. There is significant normalization uncertainty in both data sets and in the theory curves.

supernovae, feedback, gas physics, metallicities, and more, the Lyman alpha forest can be simulated with minor modifications of dark matter codes [171]. Further, the structures probed by the Lyman alpha forest are at much higher redshift (typically 3 – 4) so the clustering is less developed, more pristine. Quantitatively, this translates into the statement that wavenumbers as large as  $k \sim 1 h^{-1} \text{ Mpc}^{-1}$  can be compared confidently with theory, but this is a newer field of study than galaxy power spectra and therefore less developed. The systematics which contaminate the measurements therefore have not yet been fully explored and accounted for. The data in Fig. 14 probably have optimistic error bars, especially the overall normalization [172]. If indeed the normalization cannot be pinned down, then data on scales smaller than  $1 h \text{ Mpc}^{-1}$  is useless as a neutrino probe (recall that the difference in the spectrum induced by massive neutrinos asymptotes to a constant on these small scales). Nonetheless, the future in this field appears bright: the aforementioned galaxy surveys also will take hundreds of thousands of quasar spectra, so there is hope that the Lyman alpha forest will produce a robust measurement of the matter power spectrum at  $k \lesssim 1 h \text{ Mpc}^{-1}$  [173].

Both of the above power spectrum probes have already contributed useful constraints on neutrino mass. However, there is a third probe, less developed than the other two, that is potentially even more powerful and could reach masses as low as  $\sqrt{\delta m_{\text{atm}}}$ : weak gravitational lensing [174]. Note that at least one neutrino must have a mass of at least  $\sqrt{\delta m_{\text{atm}}}$ . Light from distant galaxies is deflected as it passes through the fluctuating gravitational potentials along the line of sight. By carefully studying these deflections, we can glean information about the underlying mass distribution. The most promising approach is to measure the ellipticities of many background galaxies. On average the projected 2D shapes of the galaxies will of course be circular. Deviations in the form of non-zero ellipticities carry information about the lensing field. These deviations are small, typically less than a percent, and require painstaking observations with careful attention to systematic problems. The observational status of weak lensing is comparable to the CMB anisotropy field a decade ago; i.e., it is in its infancy, just several few years past the initial detections [175]. Still, the community is so excited about weak lensing because *it measures*

*mass directly.* Instead of using galaxies or absorption lines as mass tracers, the observables are related to the mass distribution via the simplest tenets of general relativity. In other words, there is no bias. Current surveys do not yet have the sky coverage to constrain neutrino mass, but future looks very promising. There are many ongoing or planned wide-field weak lensing surveys [178], and they seem poised to push the neutrino mass limit down by more than an order of magnitude, close to  $\sqrt{\delta m_{\text{atm}}}$ .

Changes in other cosmological parameters affect the power spectrum in ways similar to massive neutrinos. Reducing the total matter density, for example, suppresses the power spectrum on scales of order  $k \sim 0.1h \text{ Mpc}^{-1}$ , so supplemental data (typically from the CMB) are needed to arrive at robust constraints. These degeneracies are often seen as *bad* and as contaminating the cosmological mass limits. There are two reasons this view should be abandoned, one technical and the other philosophical. First, it is quite straightforward to marginalize (integrate) over variations in other parameters; current constraints allow for as many as ten other parameters. We are fortunate that the CMB in particular constrains many of the parameters to which the matter power spectrum is insensitive. On a deeper level though, parameter degeneracies connect areas of physics once thought to be unrelated. As one example, consider the fact that future weak lensing surveys will be sensitive to the evolution of the power spectrum at different cosmic epochs. Neutrino masses will affect this evolution, but so will dark energy [176, 177]. So for example the spectacular laboratory constraints on neutrino masses anticipated over the coming decade will break cosmic degeneracies and enable us to learn about dark energy! The fields of elementary particle physics and astrophysics are therefore entwined as never before.

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