Chapter 3

Astrophysical Aspects of Neutrinos

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Neutrino astronomy is on the verge of discovering new sources, and this will lead to important advances in astrophysics, cosmology, particle physics, and nuclear physics. This paper is meant for non-experts, so that they might understand the basic issues in this field.

3.1. General Introduction

It has long been appreciated that neutrino astronomy would have unique advantages. The principal one, due to the weak interactions of neutrinos, is that they would be able to penetrate even great column densities of matter. This could be in dense sources themselves, like stars, supernovae, or active galactic nuclei. It could also be across the universe itself. Of course, the small interaction cross section is also the curse of neutrino astronomy, and to date, only two extraterrestrial sources have been observed: the Sun, and Supernova 1987A. That's it.

However, a new generation of detectors is coming online, and their capabilities are significantly better than anything built before. Additionally, a great deal of theoretical effort, taking advantage of the very rapid increases in the quality and quantity of astrophysical data, has refined estimates of predicted fluxes. The basic message is that the detector capabilities appear to have nearly met the theoretical predictions, and that the next decade should see several exciting first discoveries.

For these two talks, I was asked to introduce the topics of supernova neutrinos and high-energy neutrinos. See the other talks in this volume for more about these and related topics. To increase the probability of this paper being read, I have condensed the material covered in my computer presentation, focusing on the basic framework instead of the details. In the actual lectures, I made extensive use of the blackboard, and of interaction with the students through questions from them (and to them). It isn't possible to represent that here. I thank the students for their active participation, and hope that they've all solved the suggested problems!

3.2. PART ONE: Supernova Neutrinos

3.2.1. *Preamble*

Over the centuries, supernovae, which appear as bright stars and then disappear within a few months, have amazed and confused us. We're still amazed, and as Fermi said, we're still confused, just on a higher level. The historical observations of supernovae were of rare objects in our own Milky Way Galaxy (here and elsewhere, "Galaxy" is used for the Milky Way, and "galaxy" for the generic case). Now that we know their distances, we know that supernovae are extremely luminous in the optical, in fact comparable to the starlight from the whole host galaxy. But that's not the half of it, literally. If you had neutrino-detecting eyes, you'd see the neutrino burst from a single core-collapse supernova outshine the steady-state neutrino emission from all the stars in a galaxy (the analog of solar neutrinos) by a factor more like 10^{15} (that's a lot!). This is what enabled the detection of about 20 neutrinos from Supernova (SN) 1987A, despite its great distance.

A good general rule in decoding physical processes is "Follow the energy," much like "Follow the money" for understanding certain human endeavors. For core-collapse supernovae, this means the neutrinos, while for thermonuclear supernovae, this means the gamma rays. These are the direct messengers that reveal the details of the explosions. In the following, I'll discuss this in more detail, mostly focusing on the "observational" perspective, since it's easy to be convinced that observing these direct messengers is important, while hard to think of how to actually do it. As I will emphasize, this is much more than just astronomy for its own sake: these data play a crucial role in testing the properties of neutrinos, and more generally, in probing light degrees of freedom beyond the Standard Model.

3.2.2. *Introduction*

Stars form from the collapse and fragmentation of gas clouds, and empirically, the stellar Initial Mass Function is something like $dn/dm \sim m^{-2.35}$, where $m = M_{\rm star}/M_{\rm sun}$, as first pointed out by Salpeter in 1955, and refined by many authors since. You'll notice that this distribution is not renormalizable, but don't start worrying about dimensional regularization – a simple cutoff near $m = 0.1$ is enough for our purposes. What is the fate of these stars? There are two interesting broad categories. The "types" are observational distinctions, based on spectral lines, but the divisions below are based on the physical mechanisms.

- **Thermonuclear (Type Ia) supernovae**
These have progenitors with $m \sim 3$–8, and live for $\sim$ Gyr. The interesting case is when the progenitor has ended its nuclear fusion processes at the stage of being a carbon/oxygen white dwarf, while it has a binary companion that donates mass through accretion. Once the mass of the progenitor grows above the Chandrasekhar mass of $m = 1.4$, this carbon and oxygen will explosively burn all the way up to elements near iron, generating a tremendous amount of energy. The most important isotope produced is ^{56}Ni, which decays to ^{56}Co with $\tau = 9$ days, which then decays to stable ^{56}Fe with $\tau = 110$ days. These decays produce MeV gamma rays and positrons that power the optical light curve. Indeed, a plot of luminosity versus time directly shows the two exponential components.
- **Core-collapse (Type II/Ib/Ic) supernovae**
These have progenitors with $m \sim 8$–40, and live for less than ~ 0.1 Gyr. Importantly, the dynamics depend only on single stars, and not whether they happen to be in binaries or not. As you know, the source of stellar energy is nuclear fusion reactions, which burn light elements into progressively heavier ones, until elements near iron are reached, and the reactions stop being exothermic. Until that point, as each nuclear fuel is exhausted, the star contracts until the core is hot and dense enough to ignite the next one (remember, these reactions are suppressed by the Coulomb barrier). The cutoff of $m \sim 8$ denotes the requirement of being able to burn all the way up to iron. So what happens at that point? Once there is a $m \sim 1.4$ iron core, it is no longer generating nuclear energy, but it could support itself by electron degeneracy pressure, except for the fact that the massive envelope of the star is weighing down on it. As discussed below, this leads to the collapse of the core and the formation of a hot and dense proto-neutron star, which cools primarily by neutrino emission over a timescale of seconds.

In both cases, a tremendous amount of energy is released in a time that is very short compared to the lifetimes of stars, the resulting optical displays are crudely similar, and shell remnants are left behind. For thermonuclear supernovae, the source of the energy is nuclear fusion reactions, primarily revealed by the gamma rays from nuclear decays. The neutrino emission is subdominant, and no compact remnant is left behind. For core-collapse supernovae (often referred to as type-II supernovae, even when this is inclusive of types Ib and Ic as well), the source of the energy is gravitational, and is primarily revealed by the neutrinos emitted from the newly-formed neutron star (which may ultimately become a black hole). There is also gamma-ray emission, but it is subdominant compared to the neutrinos. Finally, one interesting fact is that for both categories of supernova, the explosion energy is about 10^{51} erg, known as 1 "f.o.e." (fifty-one erg) or 1 "Bethe." Note that this is about $10^{-3} Mc^2$ for 1 solar mass of material.

The neutrino and gamma-ray emissions from supernovae could in principle be detected from individual objects, or as diffuse glows from all past supernovae. Although low-mass stars are much more common than high-mass stars, type Ia supernovae are more rare than core-collapse supernovae by a factor of several, due to the requirement of being in a suitable binary. Before we get into details, here's where things stand on observations of the direct messengers.

- **Gamma rays from thermonuclear supernovae**
  These have never been robustly detected from individual objects, though in a few cases the COMPTEL instrument set interesting limits. While a diffuse background of gamma rays is seen in the MeV range (and beyond), it is now thought that supernovae do not contribute significantly, making it more of a mystery what does.

- **Neutrinos from core-collapse supernovae**
  These have been seen just once, from SN 1987A, but only with about 20 events. No diffuse background of neutrinos has been seen yet, placing interestingly tight limits on the contribution from supernovae.

For particle physicists, the primary interest is on two points. If neutrinos have unexpected properties, or if there are new light particles that effectively carry away energy, then the neutrino emission per supernova could be altered. If there are processes in the universe that produce MeV gamma rays, directly or after redshifting, e.g., dark matter decay, then these may explain the observed gamma-ray background.

Now let's turn to the basics of the neutrino emission from core-collapse supernovae. The gravitational binding energy release can be simply estimated. The gravitational self-energy of a constant-density sphere is $(3/5)G_N M^2/R$, and so

$$\Delta E \simeq \frac{3}{5}\frac{G_N M_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{G_N M_{NS}^2}{R_{core}} \simeq 3 \times 10^{53}\ \mathrm{erg} \simeq 2 \times 10^{59}\ \mathrm{MeV}\,,$$

using the observed facts that neutron stars have masses of about $m = 1.4$ and radii of about 10 km. Note that the second term in the difference is negligible. This is a tremendous amount of energy, trapped inside a very dense object, and so no particles can escape and carry away energy except neutrinos. In fact, even the neutrinos must diffuse out, as the density is high enough to counteract the smallness of their interaction cross sections.

The core collapses until it reaches near-nuclear densities, at which point it cannot proceed further, and hitting this wall creates an outgoing shock. If successful, the shock will propagate though the envelope of the star, lifting it off and creating the optical supernova. If not, it will stall, and then the inflow of further material will lead to black hole formation and no optical supernova.

The neutrinos are emitted from the core, within seconds of the collapse, and carry nearly the full binding energy release noted above. It takes perhaps hours or days for the shock to break through the envelope and begin the optical supernova, which is then bright for months. Importantly, the neutrinos are received *before* the light. It's not that they are tachyons, but rather just that they were emitted first. The kinetic energy of the supernova ejecta is only $\sim 1\%$ of the total energy, and the energy in the optical emission is even less. The neutrinos are the most interesting, since they carry most of the energy, are emitted in the shortest and earliest time, and come from the densest regions. Other than gravitational waves, which have yet to be observed, only neutrinos can reveal the inner dynamics of the core collapse process.

As noted, the neutrinos diffuse through the proto-neutron star, meaning that they leave on a longer timescale and with lower energies than they would if it were less dense. It is typically assumed that the neutrino emission per flavor (all six, counting neutrinos and antineutrinos) is comparable. That is, each takes about 1/6 of the binding energy, and has thermal spectral with average energies of 10–20 MeV. There is a vast literature about the differences between flavors, and using this to test neutrino mixing, but

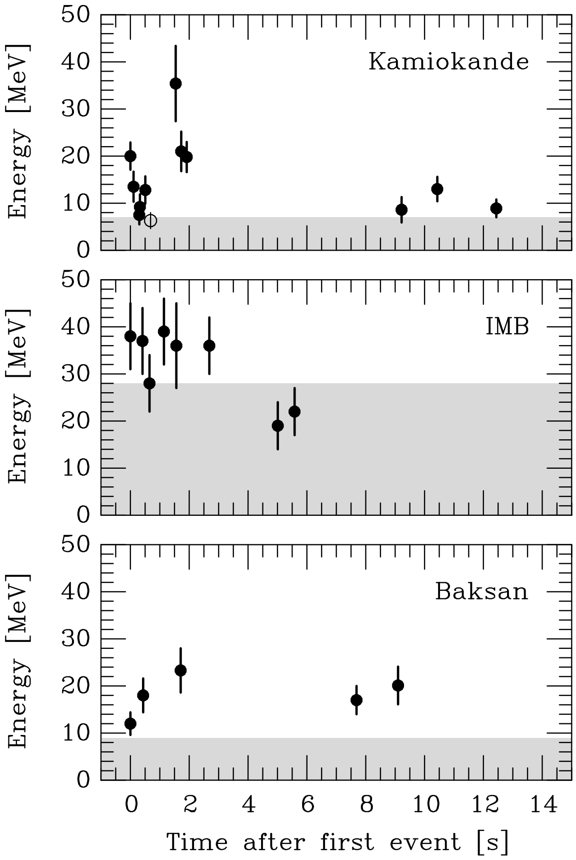

Fig. 3.1. Scatterplots of the neutrino events associated with SN1987A, as seen in the Kamiokande [2], IMB [3], and Baksan [4] detectors. The shaded regions indicate the nominal detector energy thresholds. Figure taken from Ref. [5].

this is beyond our scope.

The SN 1987A data are shown in Fig. 3.1. These are consistent with mostly being signal events due to inverse beta decay on free protons, $\bar{\nu}_e + p \to e^+ + n$. This reaction channel is special due to its large cross section, and the fact that the outgoing positron carries nearly the full antineutrino energy. The other flavors are much harder to detect. The first thing to notice is that the duration of the burst was about 10 seconds. The second is that the typical energies were low tens of MeV. (This is complicated somewhat by the nontrivial response function of the detectors, especially

IMB, which was only effective at the highest energies.) At zeroth order, the Kamiokande and IMB data are consistent with each other and theoretical expectations. The Baksan data are quite puzzling, as this detector was about ten times smaller than Kamiokande, and thus they should have seen ~ 1 event; probably detector backgrounds were present.

The most important message is that these data are consistent with the picture of slow diffusion out of a very hot and dense object, i.e., with the birth of a neutron star, as is suggested also by the total energetics, assuming a comparable neutrino emission per flavor. You can easily estimate the number of detected events yourself, using the total energy noted above, the inverse beta cross section, and the distance of 50 kpc. (Interestingly, there is still no good astronomical evidence for such a compact object in the SN 1987A remnant.) This kind of basic confirmation of the explosion mechanism is what can do with such a small number of neutrino events.

How can we gather more supernova neutrinos? There are three possibilities. First, **Milky Way** objects, with $D \simeq 10$ kpc. Taking into account the fact that we have much larger detectors now, and assuming a typical distance in the Milky Way, we expect about 10^4 detected events in Super-Kamiokande. Unfortunately, the frequency is probably only 2 or 3 times per century, but we might get lucky. It will be very obvious if it happens. Second, **Nearby** objects with $D \sim 10$ Mpc or less. For these, one would need a much larger detector, at the 1 Mton scale, and the number of detected events per supenova is ~ 1. On the other hand, the frequency is about once per year. To reduce backgrounds, this would require a coincident detection of say two or more neutrinos, or one neutrino and the optical signal. Third, **Distant** objects from redshifts $z \sim 1$–2 or less. As a crude guide to how this works, imagine a supernova at a distance such that the expected number of detected events in Super-Kamiokande is 10^{-6}. Almost all of the time, nothing happens, but for one supernova in a million, one neutrino will be detected. This seems crazy until you realize that the supernova rate of the universe is a few per second. Putting this together more carefully leads to an expectation of several detected supernova events per year in Super-Kamiokande (these will be uncorrelated with the optical supernovae, due to the nearly isotropic nature of the detection cross section). A strong rejection of detector backgrounds is required to make this work.

Of these three detection modes, I'll focus on the last, as it is the least familiar.

3.2.3. *Supernovae in the Milky Way*

At present, the flagship supernova neutrino detector is Super-Kamiokande, which is located in a deep mine in Japan. It is the largest detector with the ability to separate individual supernova neutrino events from detector backgrounds. Its huge fiducial volume contains 22.5 kton of ultrapure water. Relativistic charged particles in a material emit optical Čerenkov radiation, which is detected by photomultiplier tubes around the periphery.

With $\sim 10^4$ events detected for a Milky Way supernova, the Super-Kamiokande data could be used to map out the details of the neutrino spectrum and luminosity profile. Additionally, other neutrino detection reactions, for which the yields are at the 1–10% level in comparison to inverse beta decay, would become important, revealing more about the flavors besides $\bar{\nu}_e$. The aspects of detecting a Milky Way supernova are very interesting, and have been extensively discussed elsewhere.

3.2.4. *Supernovae in Nearby Galaxies*

If Super-Kamiokande can detect 10^4 events at a supernova distance of 10 kpc, then it can expect to detect 1 event for a supernova distance of 1 Mpc, somewhat larger than the distance to the M31 (Andromeda) and M33 (Triangulum) galaxies. Unfortunately, a single event isn't exciting by itself, and anyway, these galaxies appear to have even lower supernova rates than the Milky Way. Still, it makes one wonder about greater distances. The number of galaxies in each new radial shell in distance increases like D^2, while the flux of each falls like $1/D^2$. As mentioned, one can beat even small Poisson expectations with enough tries, so this is intriguing.

An estimate based on the known nearby galaxies shows that the supernova rate with 10 Mpc should be about one per year, and this is shown in Fig. 3.2. In fact, the observed rates in the past few years have been even higher. A detailed calculation shows that a larger detector than Super-Kamiokande, something more on the 1 Mton scale, could detect about one supernova neutrino per year. (Such detectors are being considered for proton decay studies and as targets for long-baseline neutrino beams.) That seems like a small rate, but bear in mind that in the twenty years since SN 1987A, exactly zero supernova neutrinos have been (identifiably) detected. To reduce backgrounds, these nearby supernovae would need a coincidence of at least two neutrinos or one neutrino and the optical signal. Perhaps most importantly, the detection of even a single neutrino would fix the start time of the collapse to about ten seconds, compared to the precision

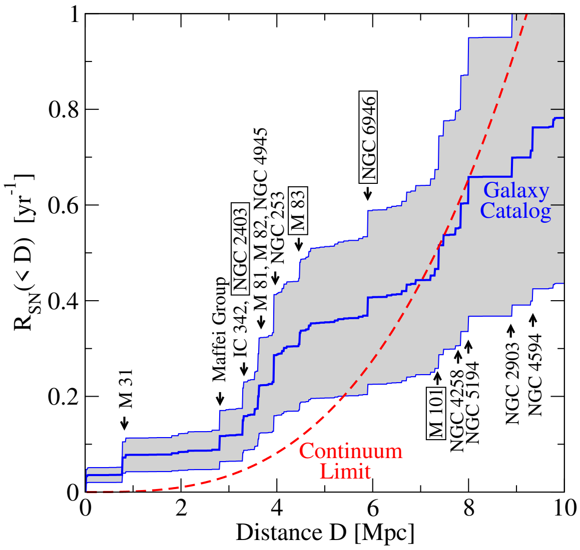

Fig. 3.2. The predicted cumulative supernova rate for nearby galaxies is shown by the blue line, and its uncertainty by the grey band (together denoted as "Galaxy Catalog"). The redshift $z = 0$ limit of the cosmic supernova rate is also shown ("Continuum Limit"). The observed local supernova rate in recent years has been higher than either prediction. Figure taken from Ref. [6].

of about one day that might be determined from the optical signal. This would be very useful for refining the window in which to look for a faint gravitational wave signal.

Related to this is an effort called NO SWEAT (Neutrino-Oriented Supernova Whole-Earth Telescope), led by Avishay Gal-Yam, to use a network of telescopes worldwide to find all supernovae in nearby galaxies.

3.2.5. *DSNB: First Good Limit*

The star formation rate was larger in the past, and in particular, was about 10 times larger at redshift $z \simeq 1$ than it is today. Since the lifetimes of massive stars are short, the core-collapse supernova rate should closely follow the evolution of the star formation rate, up to a constant factor. This gives more weight to distant supernovae than if the rate were constant. On the other hand, for supernova beyond $z \sim 1$, the neutrinos are so redshifted that their detection probabilities are too low (at lower energy, the detection cross section goes down while the detector background rates increase).

Integrating the neutrino emission per supernova with the evolving su-

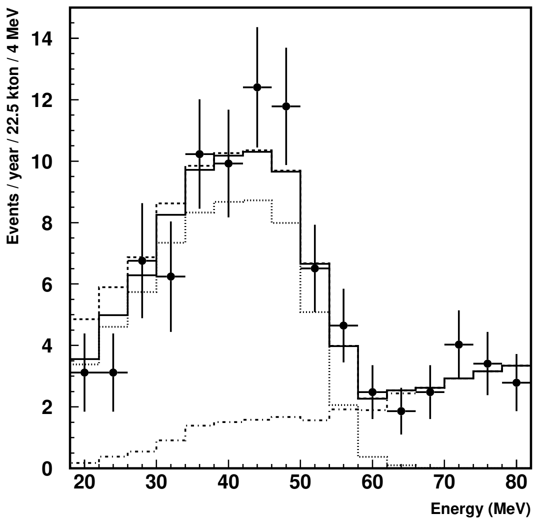

Fig. 3.3. The event spectrum measured in Super-Kamiokande is denoted by the points with error bars. The solid line indicates the expected total detector background rate (the dotted component is due to muon neutrinos, and the dot-dashed component is due to electron neutrinos). The dashed line above the solid line indicates how large of an excess due to DSNB events could be present, given the statistical uncertainties. Figure taken from Ref. [7].

pernova rate, and taking into account the cosmological factors, the accumulated spectrum of all past supernovae can be calculated. This is known as the Diffuse Supernova Neutrino Background (DSNB), or sometimes as relic supernova neutrinos (which is a confusing and deprecated term, i.e., these have nothing to do with the 2 K relic background of neutrinos that decoupled just before big-bang nucleosynthesis).

In 2000, a paper by Kaplinghat, Steigman, and Walker calculated the largest plausible DSNB flux, and found it to be 2.2 cm^{-2} s^{-1} for electron antineutrinos above 19.3 MeV. This was about 100 times smaller than the existing limit from Kamiokande, so the prospects for detection didn't look great. Other calculations with reasonable inputs (by modern standards) gave results that were a few to several times smaller.

In 2003, the Super-Kamiokande collaboration published a limit that was 1.2 in the above units. This was a milestone, because it showed for the first time that there was hope of reaching the range in which a detection might be

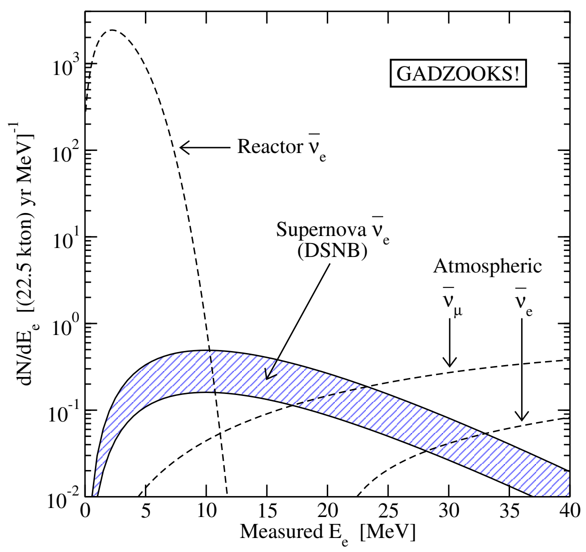

Fig. 3.4. The DSNB signal and detector backgrounds expected in Super-Kamiokande if gadolinium is added. Figure taken from Ref. [8].

made. Still, as shown in Fig. 3.3, there are large detector backgrounds that make it difficult to identify the DSNB signal. Note that for a background-limited search, like this one, to improve the signal sensitivity by a factor of 3 takes a factor 9 more statistics. Since this figure was based on 4 years of data, this would take a long time to collect (comparable to the wait for a Galactic supernova!).

3.2.6. *DSNB: Detection with Gadolinium*

In order to make progress, it is necessary to find a way to eliminate or at least severely reduce the detector background. Mark Vagins (a member of the Super-Kamiokande collaboration) and I decided to put our heads together to find a way to isolate the DSNB signal. This resulted in a 2004 article in Physical Review Letters, though we were forced to remove the code name of the project, "GADZOOKS!," from the title and text (but see the arXiv version). Recall that the detection reaction is $\bar{\nu}_e + p \to e^+ + n$, and that at present, only the positron is detected. We realized that the key was to detect the neutron in time and space coincidence with the positron. This is an old idea, and was used by Reines and Cowan in the first detection of neutrinos (antineutrinos from a nuclear reactor).

Saying that we had to detect the neutron was the easy part. It was more challenging to find a way to do this in a water-based detector, where normally the neutrons capture on free protons. That produces a 2.2 MeV gamma ray that Compton scatters electrons, but they are too low in energy to be detectable. We pointed out that the required neutron tagging might be possible by using a 0.2% admixture of dissolved gadolinium trichloride ($GdCl_3$). Gadolinium has a huge neutron capture cross section, and produces an 8 MeV gamma-ray cascade that reconstructs as an equivalent single electron of about 5 MeV, which is readily detectable.

The really hard part was in establishing that this technique might be possible in practice, which involved raising and answering many difficult technical questions. (Among them, finding a suitable water-soluble compound of gadolinium.) Somewhat to our surprise, we found no obvious obstacles. Mark Vagins has been leading a detailed research and development effort, and so far, the prospects look very good.

In Fig. 3.4, the spectra expected in Super-Kamiokande if gadolinium is added are shown. The atmospheric neutrino backgrounds mentioned above are reduced by a factor of about 5. Additionally, backgrounds at lower energies are severely reduced, allowing the use of a much lower threshold energy. At moderate energies, it should be possible to cleanly identify DSNB signal events.

3.2.7. *DSNB: Astrophysical Impact*

Now let's return to the predicted DSNB spectrum. If either the assumed star formation rate or the neutrino emission per supernova were too large, then the predicted DSNB flux would already be ruled out the the Super-Kamiokande data.

Even since the time of the Super-Kamiokande limit, the astrophysical data have improved substantially. Andrew Hopkins and I synthesized a wide variety of data to constrain the star formation and supernova rate histories. An example fit is shown in Fig. 3.5. The uncertainty band is much more narrow now than it was just a few years ago. The normalization of the cosmic star formation rate depends on dust corrections. If the true star formation rate were even somewhat larger than determined here, then the DSNB neutrino flux would be too large relative to the Super-Kamiokande limit. The only way out would be to require a substantially lower neutrino emission per supernova.

The corresponding calculated supernova rates are in good agreement

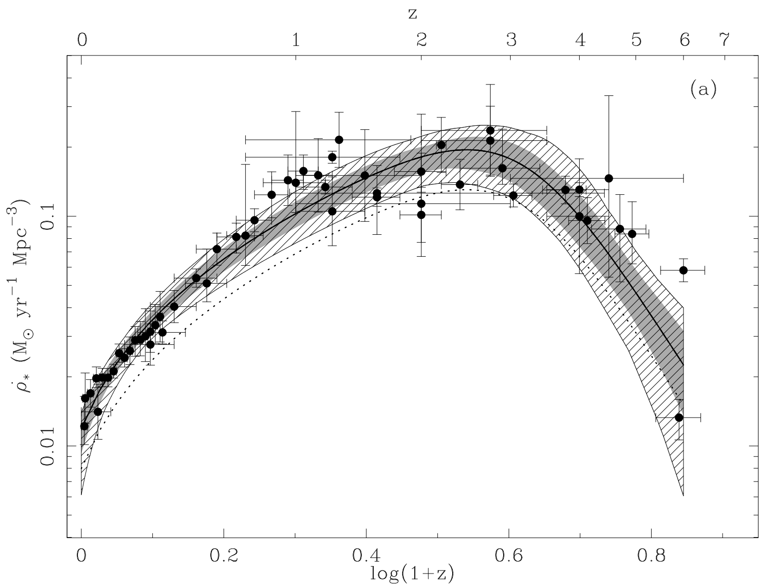

Fig. 3.5. The star formation rate history, with selected data shown by points and the fit and uncertainty shown by the bands. Figure taken from Ref. [9].

with data. As an interesting aside, it was shown that the diffuse gamma-ray background from type Ia supernovae is too small to account for the observed data in the MeV range. That is particularly significant because many limits on exotic particle physics depend on just this energy range.

3.2.8. *Back to the Scene of the Crime: SN 1987A*

If we now know the star formation history, then the only remaining unknown is the neutrino emission per supernova. Hasan Yüksel, Shin'ichiro Ando, and I considered how well the Super-Kamiokande data already restrict the neutrino emission per supernova. The emission models are usually parametrized in terms of the time-integrated luminosity (or portion of the binding energy release) and the average energy per neutrino (related to the temperature of the spectrum). I mentioned above that the Kamiokande and IMB data on the emission from SN 1987A were mostly consistent. In fact, when fitted with thermal spectra, there are some discrepancies.

In Fig. 3.6, I show that the DSNB data are probing neutrino emission parameters only slightly larger than those deduced from the SN 1987A data. With reduced detector backgrounds, the DSNB spectrum would be a new

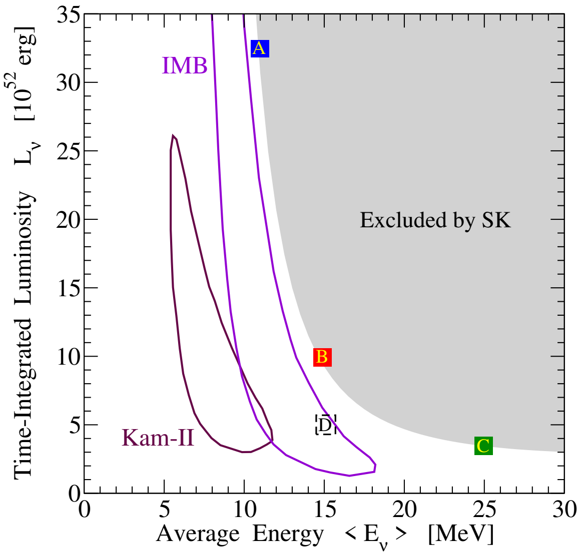

Fig. 3.6. The contours labeled Kam-II and IMB are the allowed regions from the SN 1987A data, assuming a thermal spectrum [10]. The shaded region is what is already excluded by the non-observation of a DSNB signal in Super-Kamiokande. Figure taken from Ref. [11].

way to measure the neutrino emission per supernova.

3.2.9. *Conclusions*

Why is understanding supernovae interesting and important? For particle physics, it is to test the properties of neutrinos, and to search for new low-mass particles that cool the proto-neutron star. For nuclear physics, it is to constrain the neutron star equation of state and to shed light on the formation of the elements. For astrophysics, it is to understand the stellar life and death cycles and to understand the supernova mechanisms. For cosmology, it is to better understand the details of whether type Ia supernovae are standard candles, and to probe the origins of the gamma-ray and neutrino backgrounds. With more data, we can't lose.

3.3. PART TWO: High-Energy Neutrinos

3.3.1. *Introduction*

Now that we've covered the specific example of supernova neutrinos, let's step back and comment on the general status and outlook in neutrino astrophysics.

Unique among the Standard Model fermions, neutrinos are neutral, and more generally, have only weak interactions. This makes them potentially sensitive to even very feeble postulated new interactions. While the discovery of neutrino mass and mixing was "new physics" beyond the minimal Standard Model, the discovery of any new interactions would be a much more radical step, as it would require new particles as well.

This is one reason that we're interested in neutrinos. The other, already discussed, is that they will be especially powerful probes of astrophysical objects, once these neutrinos are detected. Already with the neutrinos from the Sun and SN 1987A, the scientific return was very rich: not only confirmation of the physics of their interiors, but also a crucial piece in the discovery of neutrino mass and mixing. Ray Davis and Masatoshi Koshiba shared in the 2002 Nobel Prize for this work, and their citation reads, "...for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos...."

The general achievements in neutrino physics in just the recent past might be summarized as follows. The **cosmological** results are the consistency of big-bang nucleosynthesis yields with three flavors of neutrinos, and the exclusion of neutrinos as the (hot) dark matter. In both cases, these facts have been established independently in the laboratory as well. The **astrophysical** results are the discovery of neutrinos from SN 1987A and the solution of the solar neutrino problem. The **fundamental** results are the discovery of neutrino mass and mixing, and the clear exclusion of a huge range of formerly allowed models of exotic neutrino properties.

One of the lessons from this list is that we need data from new sources to make new discoveries, and that those discoveries may have a broader impact than initially thought. Astrophysical sources reach extremes of density, distance, and energy, and this will allow unprecedented tests of neutrino properties, for example.

We can identify three frontiers where new sources will likely be discovered soon. By the rough energy scale of the neutrinos, we might call these the MeV (10^{-6} TeV) scale, the TeV scale, and the EeV (10^{6} TeV) scale.

At the MeV scale, the focus is on the **Visible Universe**, i.e., stars and supernovae, and Super-Kamiokande is the main detector. At the TeV scale, the focus is on the **Nonthermal Universe**, i.e., jets powered by black holes, and the primary detector is AMANDA, which is being succeeded by IceCube. At the EeV scale, the focus is on the **Extreme Universe**, i.e., at the energy frontier of the highest-energy cosmic rays, and one of the key detectors is ANITA.

Why do we think that high-energy neutrinos even exist? First, because cosmic rays (probably mostly protons) are observed at energies as high as 10^{20} eV, and they are increasingly abundant down to at least the GeV range. Something is accelerating these cosmic rays, and it is very likely that these sources also produce neutrinos. Second, because extragalactic gamma-ray sources have been observed with energies up to about 10 TeV (and galactic sources up to about 100 TeV). Again, something is producing these particles, and in large fluxes, and it is likely that neutrinos are also produced.

So then why do we need neutrinos? The problem with cosmic rays is that they are easily deflected by magnetic fields, and so only their isotropic flux has been observed, making the identification of their sources very difficult. The problem with photons is that they are easily attenuated: a TeV gamma ray colliding with an eV starlight photon is able to produce an electron-positron pair. Thus at high energies, only nearby objects can be seen.

High-energy neutrinos can be made through either proton-proton or proton-photon collisions, depending on energies. In either case, pions are readily produced, and typically comparable numbers of neutral and charged pions are made. Neutral pions decay as $\pi^0 \to \gamma+\gamma$, and charged pions decay as $\pi^+ \to \mu^+ + \nu_\mu$, followed by $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ (with obvious changes for the charge conjugate). This is the **hadronic** mechanism for producing gamma rays and neutrinos. There is also a **leptonic** mechanism, based on the inverse Compton scattering reaction $e^- + \gamma \to \gamma + e^-$, where fast electrons collide with low-energy photons and promote them to high-energy gamma rays. Note that the leptonic process produces no neutrinos. It is a major mystery whether the observed high energy gamma-ray sources are powered by the hadronic or leptonic mechanism. This is a key to uncovering the sources of the cosmic rays.

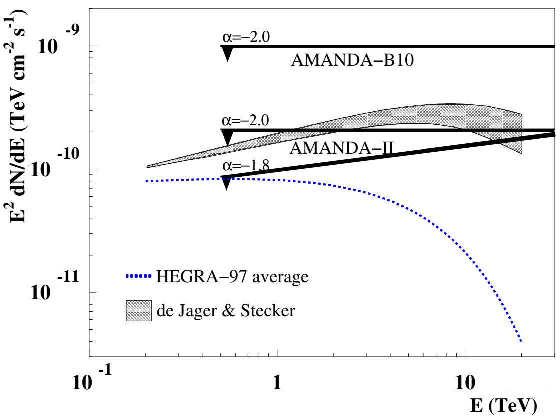

Fig. 3.7. The dotted line is based on gamma-ray observations of the nearby AGN Markarian 501 by the HEGRA experiment, and the shaded band is a calculation that removes the assumed affects of attenuation en route. The labeled solid lines indicate AMANDA limits on the neutrino flux. This object flares, and the gamma ray and neutrino data are not contemporaneous. Figure taken from Ref. [12].

3.3.2. *Sources and Detection at ~ 1 TeV*

At the simplest level, hadronic sources produce nearly equal fluxes of gamma rays and neutrinos (the corrections due to multiplicities, decay energies, and neutrino mixing can be easily taken into account). Therefore, the observed gamma-ray spectrum of an object like an AGN is a strong predictor of the neutrino spectrum, if the source is hadronic (if it is leptonic, then the neutrino flux will be zero). Any attenuation of the gamma-ray spectrum en route would mean that the neutrino flux would be even larger. An example is illustrated in Fig. 3.7, where it is shown that the neutrino detectors are now approaching the required level of flux sensitivity.

For hadronic sources, the initial neutrino flavor ratios (adding neutrinos and antineutrinos) are $\phi_e : \phi_\mu : \phi_\tau = 1 : 2 : 0$, following simply from the pion and muon decay chains. After vacuum neutrino mixing en route, these will become $\phi_e : \phi_\mu : \phi_\tau = 1 : 1 : 1$.

Of all flavors, the muon neutrinos are the easiest to detect and identify. Through charged-current deep inelastic scattering reactions, these produce muons that carry most of the neutrino energy, and which have only a very small deflection from the neutrino direction. Muons and other charged particles produce optical Čerenkov radiation in the detector, which is registered by photomultiplier tubes throughout the volume. Muons produce

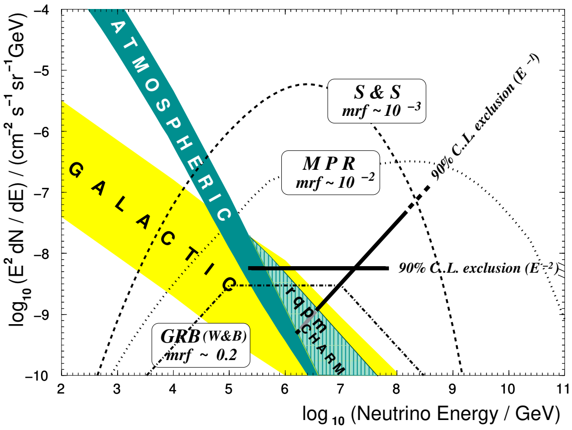

Fig. 3.8. The sensitivity of IceCube is marked with heavy solid lines, as labeled. The broken lines indicate various astrophysical diffuse flux models. The shaded regions indicate the atmospheric neutrino, prompt/charm component thereof, and Galactic neutrino backgrounds. Figure taken from Ref. [13].

spectacular long tracks that can range through the kilometer of the detector and beyond. The detection of electron and tau neutrinos is interesting and important too, but beyond our scope here.

To screen out enormous backgrounds from downgoing atmospheric muons, these detectors only look for upgoing events. Since muons cannot pass through Earth, these muons must have been created just below the detector by upgoing neutrinos. Even after this, there are backgrounds due to atmospheric neutrinos, themselves produced on the other side of Earth, and thus hardly extraterrestrial.

An astrophysical point source can be identified as an excess in a given direction, whereas the atmospheric neutrino background is smoothly varying. Transient point sources are even easier to recognize. On the other hand, diffuse astrophysical neutrino fluxes are quite hard to separate from the atmospheric neutrino background. The principal technique is that the former are believed to have spectra close to E^{-2}, while the latter is closer to E^{-3}, and steeper at higher energies. Thus at high energies the astrophysical diffuse fluxes should emerge as dominant. Once cannot go too high in energy – the event rates get too low, and Earth becomes opaque to neutrinos at around 100 TeV. An example of the diffuse flux sensitivity of IceCube is shown in Fig. 3.8.

3.3.3. *Testing Neutrino Properties*

As an example of a novel neutrino property that could be tested once astrophysical sources are observed, consider neutrino decay. Why should neutrinos decay? Other than the fact that there is no interaction that can cause fast neutrino decay, why shouldn't they decay? The other massive fermions all decay into the lowest-mass generation in their family. (Neutrinos can too, via the weak interaction, but it is exceedingly slow.) We'll consider simply neutrino disappearance, i.e., that the other particle in the decay of one neutrino mass eigenstate to another is too weakly interacting to be detected. It is quite hard to test for the effects of such decays.

Decay will deplete the original flux as

$$\exp\left(-t/\tau_{lab}\right) = \exp\left(-\frac{L}{E} \times \frac{m}{\tau}\right) ,$$

where L is distance, E the energy, m the mass, and τ the proper lifetime. For the Sun, the τ/m scale that can be probed is up to about 10^{-4} s/eV. On the other hand, for distant astrophysical sources of TeV neutrinos, L/E may be such that τ/m up to about 10^{+4} s/eV is relevant!

How can we tell if decay has occurred, if the neutrino fluxes are uncertain? As mentioned, the flavor ratios after vacuum oscillations are expected to be $\phi_e : \phi_\mu : \phi_\tau = 1 : 1 : 1$. However, it is among the mass eigenstates, not the flavor eigenstates, where decays take place. Suppose that the heaviest two mass eigenstates have decayed, leaving only the lightest mass eigenstate. What is its flavor composition? In the normal hierarchy, it has flavor ratios $\phi_e : \phi_\mu : \phi_\tau \sim 5 : 1 : 1$, whereas in the inverted hierarchy, they are $\sim 0 : 1 : 1$. In either case, they are quite distinct from the no-decay case, and the flavor identification capabilities of IceCube should be able to distinguish these possibilities.

3.3.4. *Sources and Detection at* $\sim 10^6$ *TeV*

Cosmic rays have been observed at energies above 10^{20} eV, and there are no good answers as to what astrophysical accelerators may have produced them. However, this becomes even more puzzling when it is noted that the universe should be opaque to protons above about 3×10^{19} eV traveling over more than 100 Mpc. There are no obvious sources within that distance.

The process by which protons are attenuated is $p + \gamma \to p + \pi^0, n + \pi^+$, where both final states are possible, and the target photon is from the cosmic microwave background. As with the hadronic processes discussed

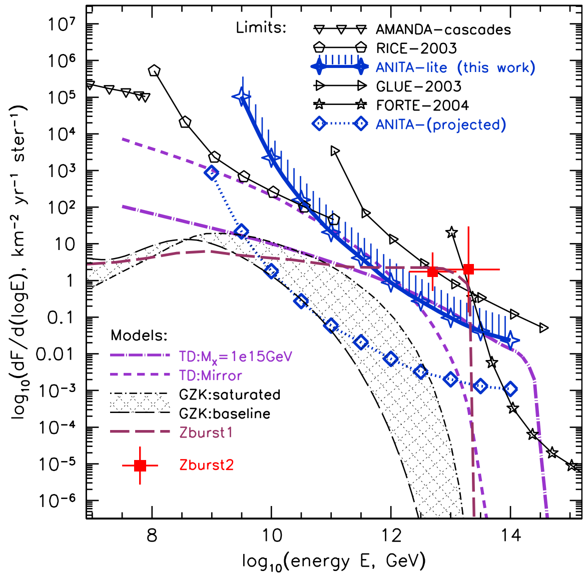

Fig. 3.9. Real and projected neutrino flux sensitivities of various experiments (lines with points), along with various models (as labeled). Figure taken from Ref. [14].

above, the neutral pion decays produce gamma rays and the charged pion decays produce neutrinos. The gamma rays are themselves attenuated, but the neutrino flux builds up when integrating over sources everywhere in the universe. Since the attenuation process for the protons is called the GZK process (Greisen-Zatsepin-Kuzmin), these are called GZK neutrinos. Typical energies are in the EeV range, and an isotropic diffuse flux is expected.

New experiments are being deployed to search for the GZK neutrino flux, as shown in Fig. 3.9. Unlike IceCube, which is based on optical Čerenkov radiation, ANITA and other experiments are based on radio Čerenkov radiation that is emitted coherently from the whole shower initiated by a neutrino in the ice or other transparent medium. ANITA is using the Antarctic ice cap as the detector, and is observing it with radio antennas mounted on a balloon. So far, detector backgrounds appear to be negligible, meaning that it should be straightforward to improve the signal sensitivity with more exposure.

In Fig. 3.10, I show the results of a very recent calculation of the expected GZK neutrino fluxes.

Interestingly, when adjusted for the neutrino-quark center of mass en-

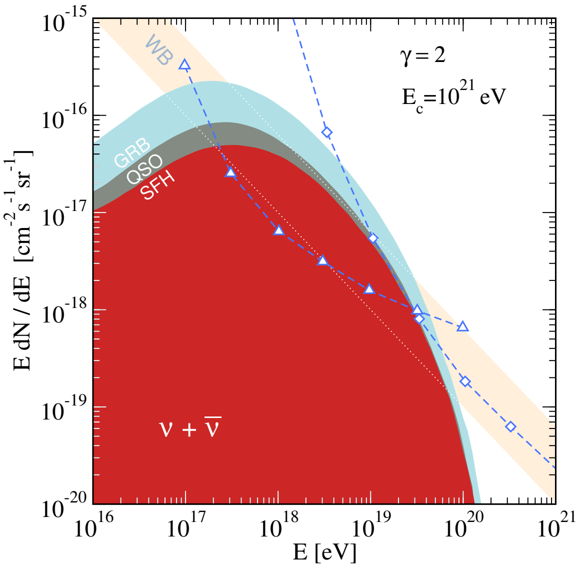

Fig. 3.10. Predicted GZK neutrino fluxes, assuming that ultrahigh energy cosmic rays are produced in gamma-ray bursts, and according to how the latter rate evolves with redshift (i.e., following the star formation rate alone, or rising like that of the quasars, or depending on both the star formation rate and the evolving local metallicity. The "WB" band is the Waxman-Bahcall bound. The curves with points are projected sensitivities for ANITA (upper) and ARIANNA (lower). Figure taken from Ref. [15].

ergy, the detection reactions are probing above the TeV scale, opening the prospect of sensitivity to new physics in the detection alone.

3.3.5. *Conclusions*

So far, zero high-energy astrophysical neutrinos have been detected. However, the near-term prospects are very good, and are strongly motivated by measured data on high-energy protons and photons. Still, this will not be easy, and large detectors with strong background rejection will be needed. If successful, these experiments will make important astrophysical discoveries, e.g., whether gamma-ray sources are based on the hadronic or leptonic mechanisms, the origins of cosmic rays at all energies, etc. We might even learn something new about neutrinos in the process!

Acknowledgments

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References

[1] **Disclaimer:** I have been very light on referencing, in fact only noting the sources of the figures shown, to make the paper more readable.
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