SUPERNOVA REMNANT

NEUTRINOS

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Crocker, Melia & Volkas, ApJS, 130:339 (2000)

Crocker, Melia & Volkas, astro-ph/0106090

Two take-home messages

1. Sgr A East, an unusual SNR located at the Galactic Centre, will be a very important source for Neutrino Telescopy. Sufficient events will accrue from Sgr A East neutrinos that we will be able to test new and interesting particle physics.

2. Ultra-long-baseling neutrino oscillations may be uncovered in astrophysical neutrino signals through the detection of spectral distortions.

1. Plan

1. SNRs as power law sources of cosmic rays, γ-rays, and high energy neutrinos.
2. Neutrinos from 3 SNRs, including Sgr A East.
3. Searching for oscillations in SNR neutrino signals. Why on earth might we expect ultra-long-baseling neutrino oscillations?
4. Results: regions of parameter space that might be probed with neutrinos from Sgr A East.

2. SNRs and cosmic rays

Strong shocks associated with shell-type SNRs are the most likely sites for the diffusive shock acceleration of cosmic rays up to the 'knee' at around 5×10^{15} eV.

One piece of evidence for this: shock acceleration models produce a particle spectrum that goes as $E^{-2.0}$. This agrees with that determined for cosmic rays at source (after correcting for propagation effects).

If SNRs are responsible for hadronic acceleration to these energies, then we would expect a concomitant neutrino flux from these objects from interactions of these hadrons (in particular, protons) with ambient nucleons.

3. SNR gamma ray and neutrino signals

Interactions between shock-accelerated protons and ambient nucleons produces pions and other mesons.

π^0's decay to produce γ's whereas decay chain of $\pi^\pm$ leads to ν_μ and ν_e production (not distinguishing neutrino from anti-neutrino: neutrino telescopes can't, in general, do this).

Overall, we expect approximately one ν for every γ and flavour ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : \sim 0$ (for energies in question) – *at the source*.

Above around 10 GeV, the pion distribution settles into the asymptotic form suggested by Feynman scaling so that pions and their decay γ's and ν's reflect the distribution of the underlying parent protons.

All this means that **the high energy** ($>$10 GeV) **gamma ray signal from a particular SNR provides us with a handle on its expected neutrino flux**.

4. Summary of expectations for SNR neutrinos:

1. Neutrino spectrum will be governed by a power law with spectral index close to 2.0.

2. The neutrino flux from a SNR found by a neutrino telescope would therefore be expected to produce a straight line on a plot of $log(\text{flux } \nu)$ vs. $log(E_\nu)$.

3. Precise value of ν spectral index and normalization of power law describing the ν flux can be supplied by super-10 GeV γ-ray signal from object.

4. *Some* SNRs must accelerate ν's to at least $\sim \frac{1}{10}^{*} \times E_{knee} \sim 5 \times 10^{14}$ eV.

*The **maximum energy** attained by a SNR's neutrinos is around $\frac{1}{10}$ of that obtained by shock accelerated p's.

Maximum SNR **p** energy is determined by a number of factors like the age of the remnant, total energy released in the initial explosion, magnetic field strength, ambient material density, etc.

5. Candidate SNRs for high energy neutrino generation

Somewhat disappointingly (and mysteriously ⇒ whence come the cosmic rays?) searches for TeV γ-ray emission from SNRs with ground-based arrays have been negative in the main.

Some notable exceptions, however, include:

1. SN 1006
2. RXJ1713.7-3946
3. Sgr A East

- 1. and 2. detected by the CANGAROO ground array at TeV energies.
- 1. and 2. located out of the galactic plane in regions of low ISM density at distances $\mathcal{O}(kpc)$.
- Whether the γ-rays detected from them are hadronic or leptonic in origin, they present evidence for shock acceleration of protons to high energies (at least 100 TeV) given that more significant loss processes act on electrons than protons in SNR environments.
- 1. and 2. should each generate $\boldsymbol{\mathcal{O}(5)}$ **muon neutrino events per year** in a Mediterranean, km^2 neutrino telescope above signal = background (around TeV) ⇒ enough statistics to do some interesting astrophysics but not sufficient for particle physics.

6. Sgr A East

An unusual source of unusual importance

- located at Galactic Centre ($\sim$ 8 kpc distant)
- remnant of a supernova-like event of extreme energetics ($\sim 40 \times$ energy released in a conventional supernova); the outcome of a too-close approach by a star to the central galactic black hole?
- broad-band photonic spectrum extremely well-characterised, in particular, its γ-ray signal has been measured by EGRET on the Compton G.R.O. (GeV energies) and (tentatively) by the Whipple ground array (TeV energies).
- should produce **$\mathcal{O}(50)$ muon neutrino events per year** in a Mediterranean, km^2 neutrino telescope above signal=background (around few 100 GeV).
- may even produce $\mathcal{O}(30)$ muon neutrino events per year in a km^2 neutrino telescope at the South Pole above the atmospheric *muon* background.

7. What particle physics can we extract from a SNR neutrino beam?

ANS: We can perform ultra-high energy and ultra-long baseline neutrino oscillation experiments, viz.

1. confirm existing atmospheric (and perhaps solar) oscillation schemes over vastly different energy and distance regimes. (One simple test: look for ν_τ's from a SNR at energies below where production at source is expected.)

2. probe **tiny** δm^2's, not able to be investigated with terrestrial or Solar System-scale experiments.
   Range of δm^2's we can investigate are defined by:

$$E_{(Sig=Bkgd)} < E_{crit} < E_{max}$$

$$\text{where} \quad L_{osc}(E_{crit}, \delta m^2) \quad \equiv \quad L_{SNR}.$$

Given

$$L_{osc} \qquad \sim \qquad \frac{E/PeV}{\delta m^2/10^{-10} eV^2}\ \text{kpc}$$

ranges of δm^2 probed (in principle) by SNR ν's are:

$$10^{-10} \rightarrow 10^{-14}\ \text{eV}^2 \text{ for } 1 \text{ kpc}$$

$$10^{-11} \rightarrow 10^{-15}\ \text{eV}^2 \text{ for } 10 \text{ kpc}$$

8. Finding oscillations in SNR neutrino signals

Generically, three types of evidence:

1. Determine that the neutrino flavour ratios at point of generation are different to those found at point of detection.
2. Observe a discrepancy between detected and expected flux of a particular neutrino species.
3. Find a *spectral anomaly*, i.e., a distortion of a particular neutrino flavour's energy distribution away from its
   (a) expected shape
   (b) expected slope.

For a SNR ν signal,

a. ⇒ deviation away from pure power-law scaling of neutrino flux with energy (i.e., non-linearity on the $log(\text{flux } \nu)$ vs. $log(E_\nu)$ plot).

b. ⇒ difference between the index of the neutrino spectrum and that of the super-10 GeV photon spectrum.

9. Spectral Distortion as an Oscillation Diagnostic

Advantages of this method over other two include that it

1. only requires observation of a single neutrino species: ν_μ's for SNRs in practice.
2. can give a range for the δm^2 governing the oscillations, not just a lower bound.
3. doesn't demand that we have an **un**-realistically well-constrained expectation (from the super-10 GeV γ-ray signal) for the normalization of the neutrino flux power law: we only need sufficient statistics to find a distorted *shape* or *slope*.

So, what do you hope to see in a SNR ν signal distorted by tiny δm^2's? Three regimes

1. $E_\nu \ll E_{crit}$ ($\Rightarrow$ **averaged oscillations**) $\Rightarrow$ ν spectrum = power law, $\propto E^{-\alpha}$, with α the same as that of the super-10 GeV γ-rays, but with only some fraction ($\geq 1/2$) of the neutrino flux *expected* on the basis of this photon signal.
2. $E_\nu \sim E_{crit}$ ($\Rightarrow$ **oscillatory regime**), here there will be deviation from linearity on the log(flux ν)-$log(E_\nu)$ plot.
3. $E_\nu \gg E_{crit}$ ($\Rightarrow$ **no oscillations** over ν propagation) $\Rightarrow$ return to power law $\propto E^{-\alpha}$ *and* the flux of neutrinos should be what we expect given the photon signal.

10. Theoretical Motivations

But,but,but...

- Why expect oscillations governed by such tiny δm^2's?
- Why expect that such ultra long wavelength oscillations, even if they do occur, are large enough in amplitude to be seen?
- The new oscillation scale also demands one or more new neutrino mass eigenstates. The theory will then contain additional weak eigenstates which are obliged to be sterile neutrinos but what theoretical motivation do we have for sterile neutrinos?

Two well-motivated theoretical scenarios that naturally incorporate all these elements:

1. the **Exact Parity** or **Mirror Matter Model**
2. generically, active↔sterile **Pseudo-Dirac Scenarios**

In both these, we get (effectively) maximal mixing between every active neutrino species and its sterile partner.

11. Some Options

∃ some freedom in accommodating existing neutrino anomalies. Assuming that the atmospheric anomaly is explained by maximal mixing between ν_μ and ν_τ, then explain the solar neutrino anomaly with

1. mixing between ν_e and its sterile partner ν_e'; the SNO results cast doubt on the phenomenological viability of this option which we label six neutrino mixing.
2. mixing between ν_e and the already maximally-mixed $\nu_\mu \leftrightarrow \nu_\tau$ subsystem ($\Rightarrow$ bi-maximal mixing in the active sector), but also postulate hierarchy of active↔sterile mass splittings s.t. largest splitting affects ν_μ oscillation phenomenology over galactic length scales, whereas the other splittings are too small to be evidenced.

   Phenomenologically, this class of cases simply involves mixing between 3 active and 1 sterile neutrino, we label this class four neutrino mixing.

12. Phenomenological Implications

$\sim$ summed up by the different scenarios' effect on $F_{\nu_\mu}(E_{\nu_\mu})$, the energy-dependent fraction of the total, initial neutrino flux that arrives at earth with flavour ν_μ. Remembering that we don't expect significant ν_τ generation at source, can write this as:

$$\begin{aligned} F_{\nu_\mu} &= 1/3 \times P(\nu_e \to \nu_\mu) \; + \; 2/3 \times P(\nu_\mu \to \nu_\mu) \\ &\equiv \rho - \sigma \sin^2 \left(\frac{\pi L_{SNR}}{L_{osc}} \right) \end{aligned}$$

where L_{osc} is the (ultra long wavelength) oscillation length and L_{SNR} is the distance to the SNR.

- $\rho = 1/3$ for all scenarios investigated
- $\sigma = 1/3$ for the six neutrino mixing scheme
- $\sigma = 1/6$ or $\sigma = 1/12$ for the four neutrino mixing schemes

13. Results for Sgr A East

- Can't detect spectral distortion with great statistical certainty from Sgr A East ν event rates (i.e., shape) alone.
- *Can* detect oscillations in Sgr A East neutrino signal if fitted power required to have same spectral index as the super-10 GeV γ-rays and the oscillations produced by six neutrino mixing scheme with δm^2 in the approximate range 10^{-13} to 10^{-15} eV^2 (i.e., from slope).

δm (eV)	χ^2	$\frac{\chi^2}{d.o.f.}$
10^{-11}	~ 0	~ 0
10^{-12}	3.2	1.1
10^{-13}	16.1	5.4
10^{-14}	19.3	6.4
10^{-15}	12.0	4.0
10^{-16}	~ 0	~ 0
no osc	~ 0	~ 0

Table 1: χ^2 and $\frac{\chi^2}{d.o.f.}$ values for the fitting of a power law with variable normalization (but with spectral index fixed to 2.1, the value supplied by the super-10 GeV γ-rays) to modelled differential fluxes of Sgr A East ν's for different values of δm^2 and the six neutrino mixing scenario (ten years' data).

The other mixing scenarios require longer observation periods to discover/exclude oscillations with same certainty.

14. Conclusion

1. Sgr A East will be a very important source for Neutrino Telescopy.

2. Ultra-long-baseling neutrino oscillations may be uncovered in astrophysical neutrino signals through the detection of spectral distortions.

3. With the Sgr A East neutrino beam and using the spectral distortion method, experimentalists will be able to confirm or exclude the existence of ultra-long baseline oscillations governed by a δm^2 in the range 10^{-13} to 10^{-15} eV^2. Ten years' data will uncover oscillations operating under the six-neutrino scheme. The four-neutrino schemes will require longer observing periods to achieve the same statistical certainty.

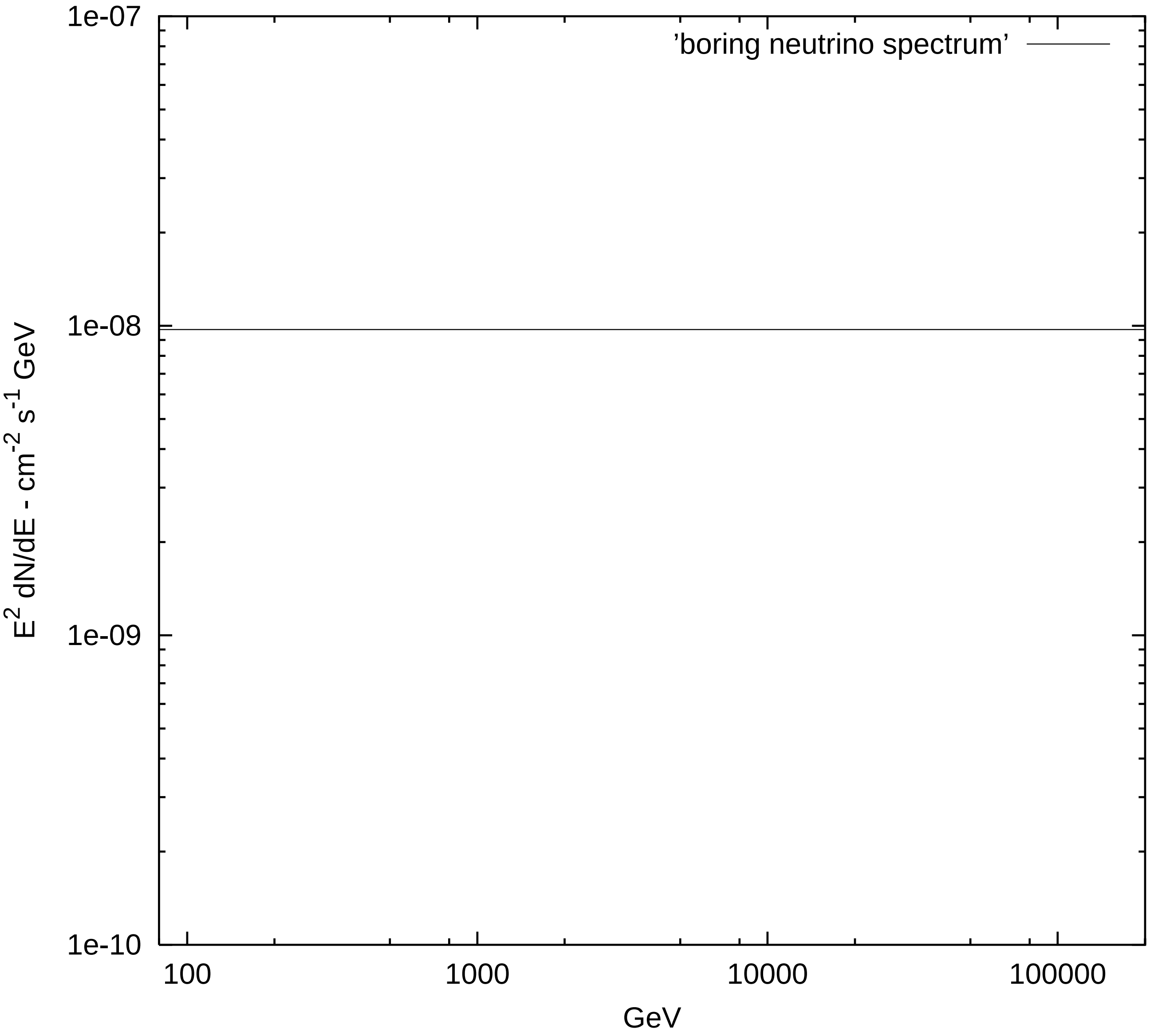

Fig. 1.— The sort of uninteresting neutrino spectrum expected in the absence of oscillations. Note that, because the y-axis is weighted by E^2 and the spectrum goes as $E^{-2.0}$, the graph has zero gradient.

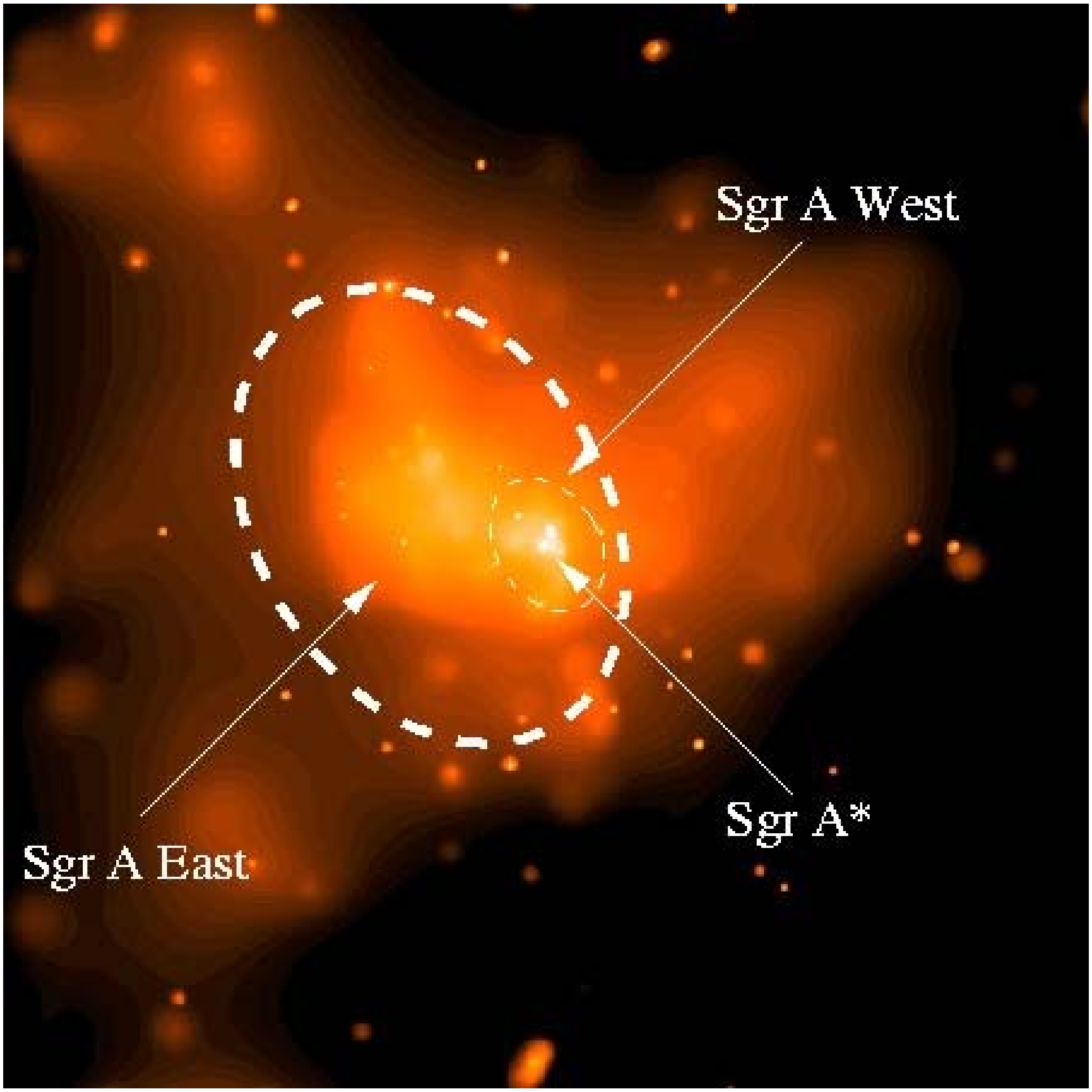

Fig. 2.— Chandra X-ray image of the supernova remnant Sgr A East, the area, known as Sgr A West, where spiral-shaped streams of gas are falling on to the central galactic black hole Sgr A* and the blak hole accretion disk itself. Credit: NASA/G.Garmire (PSU)/F.Baganoff (MIT)

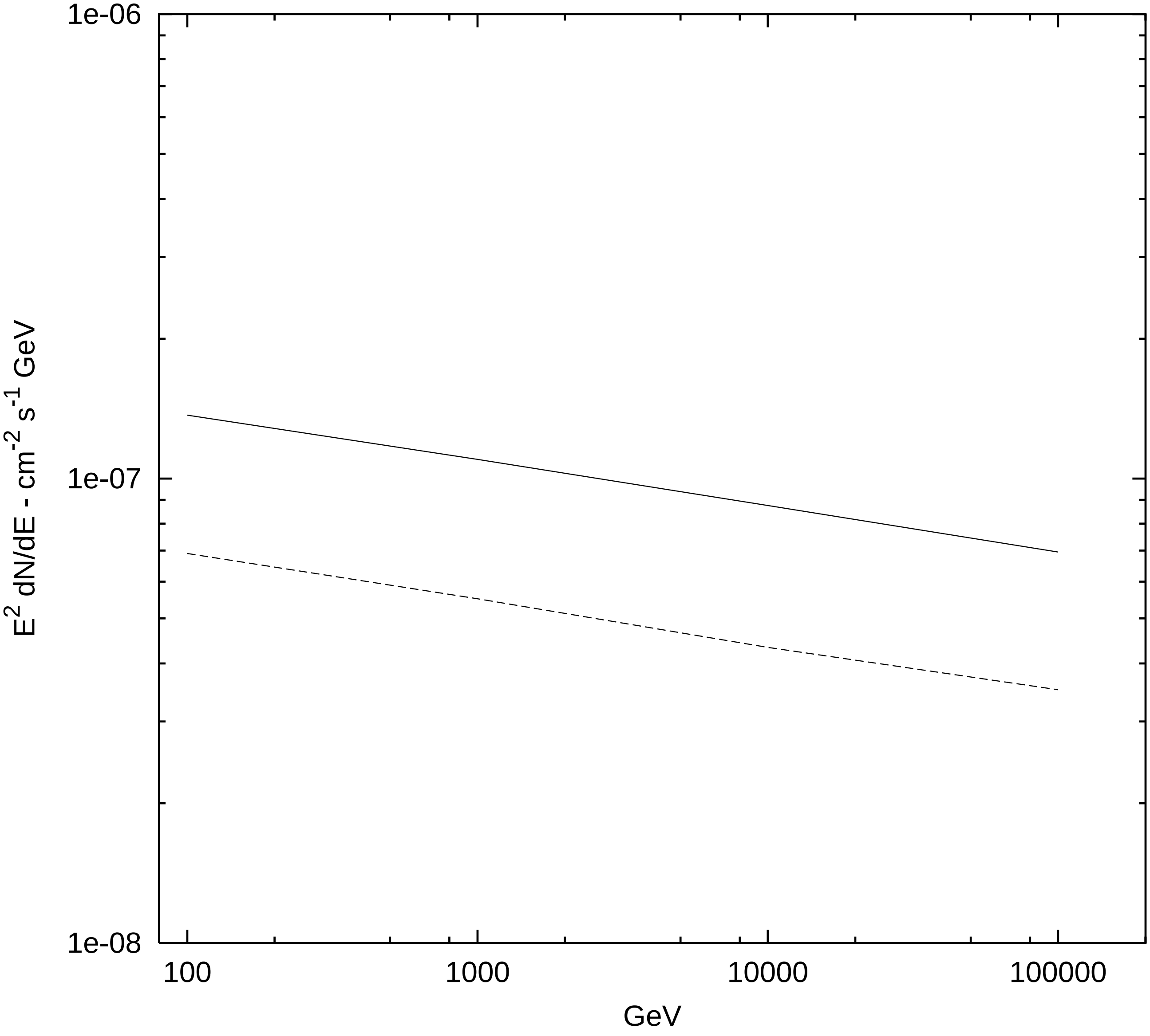

Fig. 3.— Example neutrino spectra for three cases: (i)δm^2 **too small** $\Rightarrow E_{crit} < E_{(Sig=Bkgnd)} \Rightarrow$ **no oscillations** over neutrino propagation. (ii)δm^2 **too big** $\Rightarrow E_{crit} > E_{max} \Rightarrow$ **averaged oscillations** over entire spectrum. (iii)δm^2 in right range $\Rightarrow E_{(Sig=BckGnd)} < E_{crit} < E_{max} \Rightarrow$ for increasing energy over neutrino spectrum, go from **averaged oscillations** → distortion-inducing **oscillatory regime** → **no oscillations**.

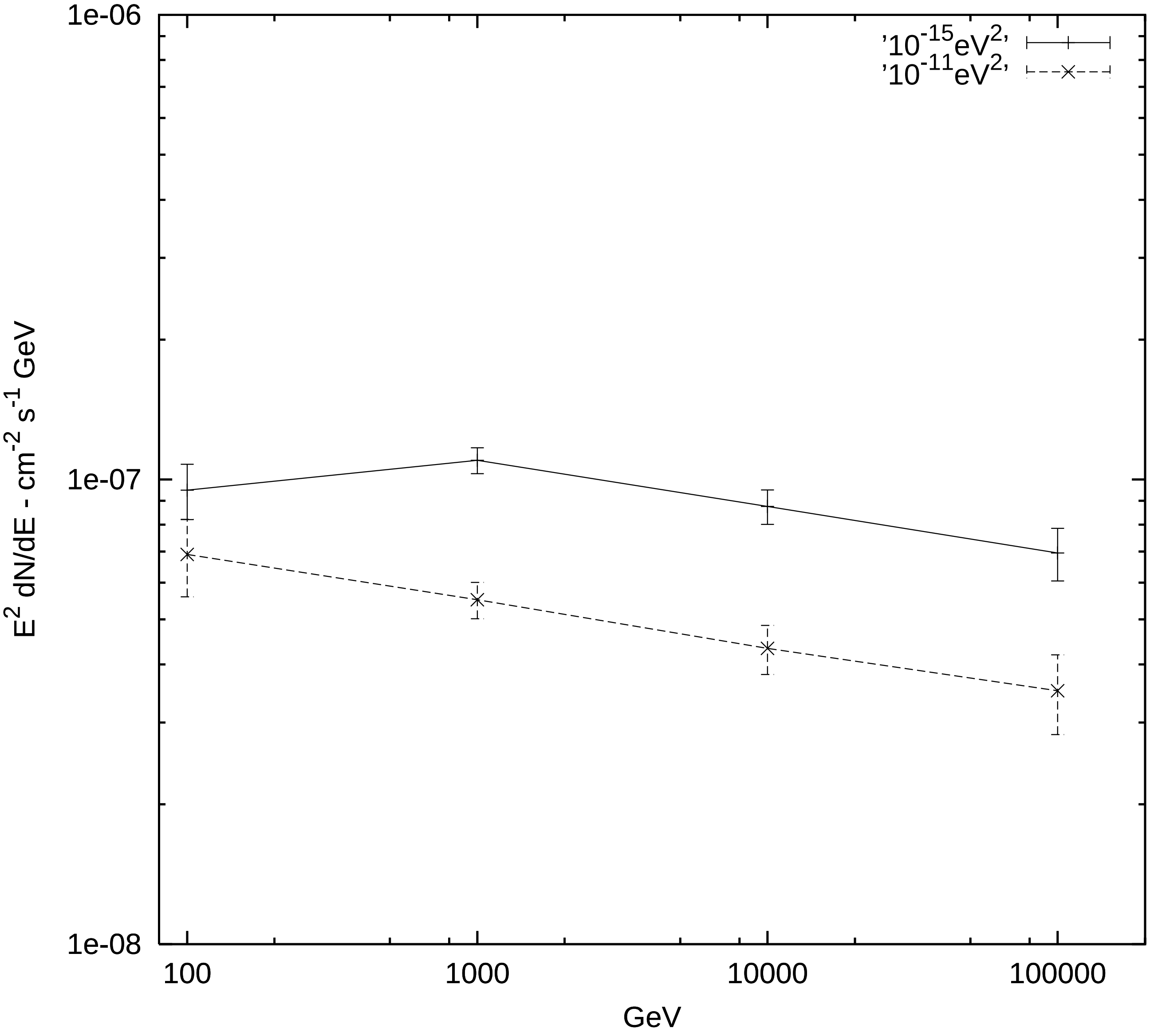

Fig. 4.— E^2-weighted differential flux from the Sgr A East ν source with (i)$\delta m^2 = 10^{-15}$ eV^2 and (ii)averaged oscillations assuming the six neutrino mixing scheme as reconstructed from ten years' simulated data. The vertical error bars show the relative statistical error.

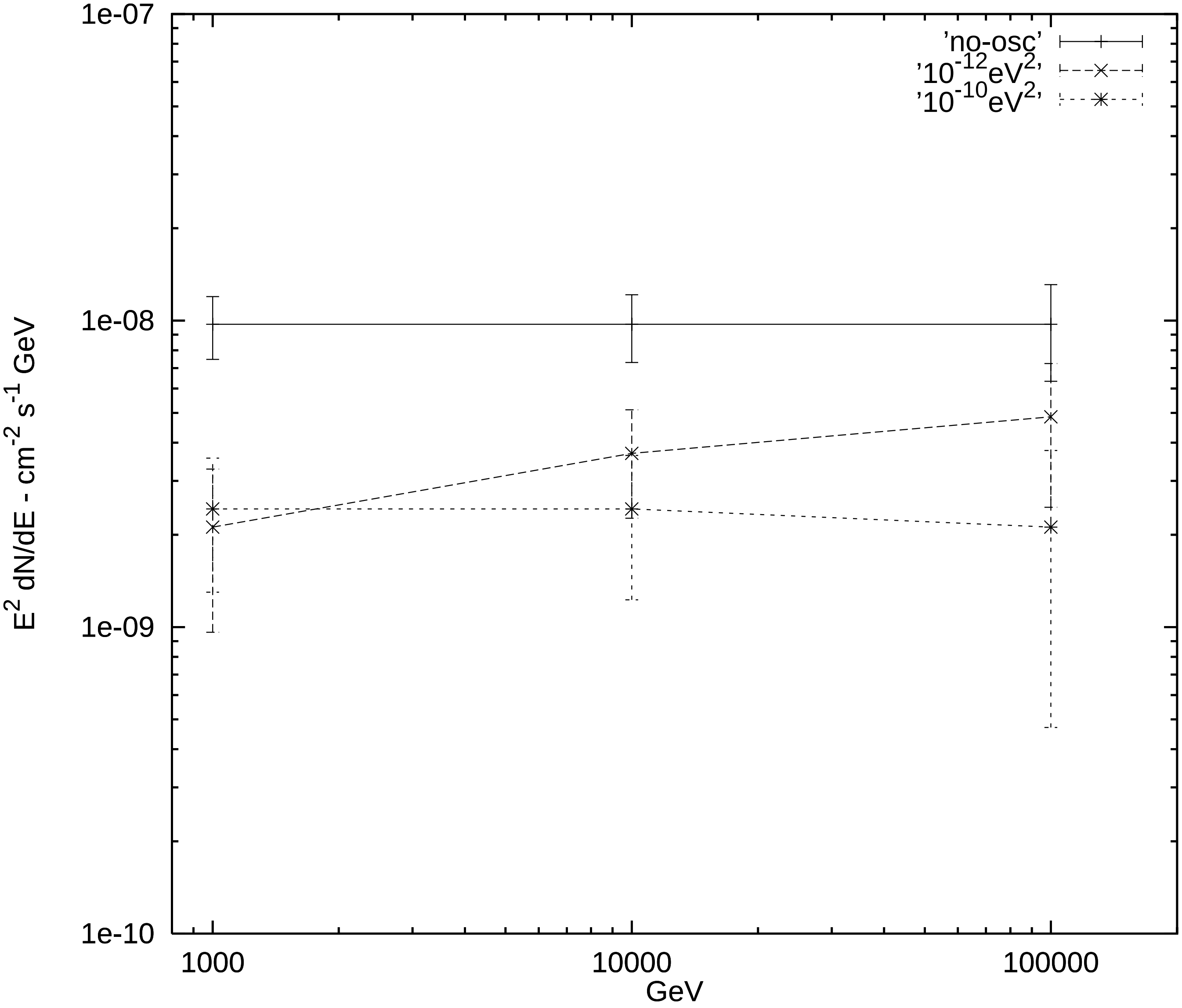

Fig. 5.— Energy^2-weighted differential flux from the SN 1006 ν source with a number of different oscillation scenarios.