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Probing Pseudo-Dirac Neutrinos with Astrophysical Sources at IceCube

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The recent observation of NGC 1068 by the IceCube Neutrino Observatory has opened a new window to neutrino physics with astrophysical baselines. In this contribution, we show the results of a new method to probe the nature of neutrino masses using these observations. In particular, our method enables searching for signatures of pseudo-Dirac neutrinos with mass-squared differences that reach down to $\delta m^2 \geq 1e-21\text{eV}^2$, improving the reach of terrestrial experiments by more than a billion. Finally, we discuss how the discovery of a constellation of neutrino sources can further increase the sensitivity and cover a wider range of δm^2 values.

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1. Introduction

Astrophysical objects are be the sources of the most extreme of all detectable neutrinos: the highest energy, the longest lived, and the furthest traveled. The recent observations by the IceCube collaboration of neutrinos from extra-galactic point sources [4, 18] and from our own Milky Way galaxy [5] indicate the beginning of a new generation of neutrino astronomy. New sources offer the opportunity to do new physics. Neutrinos from the active galactic nucleus NGC-1068 must have traveled megaparsecs to reach our detectors, distances many orders of magnitude greater than those traveled by any solar, atmospheric, reactor, or accelerator neutrino ever detected. A sample of neutrinos from such a source could thus be used to probe unexplored extra long baseline new physics.

One such very long baseline phenomena is a signature of the pseudo-Dirac model of neutrino masses. In this scenario, the Standard Model (SM) is extended by three singlet "sterile" neutrino fields, which after electroweak symmetry-breaking form Dirac mass terms with the active neutrino fields as well as very small Majorana mass terms. This system has two sets of mass eigenstates, whose masses are separated only by very small splittings, and which are each composed of a nearly fifty-fifty admixture of active and sterile neutrino flavor states. The result of the tiny splitting and nearly maximal mixing is very long baseline oscillations between active and sterile states. Because of the tiny mass splittings, these oscillations can be observed only at extremely large values of the ratio of the baseline L to the neutrino energy E.

In this work, we show that samples of neutrino from astrophysical sources can be used to search for pseudo-Dirac oscillation induced features in the observed energy spectrum. Such studies will be sensitive to never before explored regions of parameter space. Additionally, a combined analysis of neutrinos from multiple different source classes could probe overlapping regions of parameter space, reducing the impact of uncertainties in the production spectra.

2. Analysis

The recent northern-sky IceCube point-source analysis found three statistically significant sources, NGC 1068, PKS 1424+240, and TXS 0506+056, located at approximately 16 Mpc, 2.6 Gpc and 1.4 Gpc, respectively. The analysis used only track-like events, which have excellent (1^{deg}) angular resolution [2, 3]. For this study, we compute the event distribution over energy for each source by multiplying a flux hypothesis by the IceCube track effective area [2]. We assume the neutrino production mechanism at each source is charged pion decay, such that the flavor ratio at production is (1,2,0). As the IceCube result was found using a track sample, we count only muon-neutrinos and the roughly 17% of tau-neutrinos which interact to produce muons, and therefore tracks, in the IceCube detector volume. To account for the limited energy resolution of the detector, which severely impacts the ability to resolve shape features in the energy spectrum, we integrate against the energy resolution function $P(E_{\text{reco}}|E_{\text{true}})$. We model this function as a Gaussian in log-energy with width 30% [1].

To compute the signature of pseudo-Dirac oscillations, we multiply the source fluxes by the oscillatory survival probability,

$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3}|U_{\beta j}|^2|U_{\alpha j}|^2\left[1+\cos\left(\frac{\delta m_j^2 L_{\text{eff}}}{2E_\nu}\right)\right]. \tag{1}$$

This probability is averaged over the relatively high-frequency oscillations corresponding to the atmospheric and solar mass splittings. The propagation length-scale term L_{eff} is a function of the source redshift, and accounts for the phase picked up the neutrino fields as they travel in a universe expanding with Hubble parameter H.

$$\int \mathcal{H}(t)dt = \frac{U\mathcal{M}^2U^*}{E_\nu}\int\frac{dz}{H(z)(1+z)^2} \equiv \frac{U\mathcal{M}^2U^*}{E_\nu}L_{\text{eff}}. \tag{2}$$

We assume maximal active-sterile mixing in each mass state, and made the simplifying choice to consider only the subset of pseudo-Dirac scenarios in which the active-sterile mass-squared splittings for all three mass states are equal to the same value, δm^2. In this subset of scenarios, pseudo-Dirac oscillations affect all flavors equally, and do not modify flavor ratios at detection. We also assume the production region of each source is sufficiently small with respect to the distance to the detector that incoherent contributions of neutrinos produced at different locations can be neglected.

The effect of pseudo-Dirac oscillations is to cause a disappearance 'dip' feature in the observed energy spectrum, as visible in 1. This dip is smeared by the detector energy resolution. Additionally visible in the figure is a factor of two reduction in the observed event counts of the pseudo-Dirac hypothesis. This reduction is caused by un-resolvable high-frequency active-sterile oscillations, which average. As the neutrino flux normalization for each source is entirely unknown, this effect cannot be distinguished statistically.

3. Results

To compute our sensitivity to the pseudo-Dirac mass-squared splitting parameter space, we do a likelihood ratio test, and model the likelihood of the null and alternative hypotheses as the products of Poisson distributions in each energy bin. We generate pseudo-data using the most-likely power law source spectra from the IceCube results. In this initial study, we neglect the background event distribution, which would further mask the oscillation effect. A more conservative result could be achieved by using an effective likelihood with modeling uncertainty on the number of signal events [7].

Because sensitivity to pseudo-Dirac parameters comes from features in the observed energy distribution, it is important to account for the generally unknown shape of the source spectra. We marginalize the likelihood ratio over multiple flux hypotheses: a power-law, a power-law with an exponential cut-off, and a log-parabola $\phi(E) = \phi_0 \cdot (E/E_0)^{-(\alpha+\beta\log_{10}(E/E_0))}$. The exponential cutoff model can describe sources with a spectral cut-off, while the log-parabola model mimics a bump-like spectrum like that of many models found in recent literature[12]. We treat the normalization and other parameters of these hypotheses as nuisance parameters without any priors.

We compute sensitivities for both current statistics, using the three significant sources reported by the IceCube collaboration, and with the eight-fold increase in statistics of IceCube Gen-2, using

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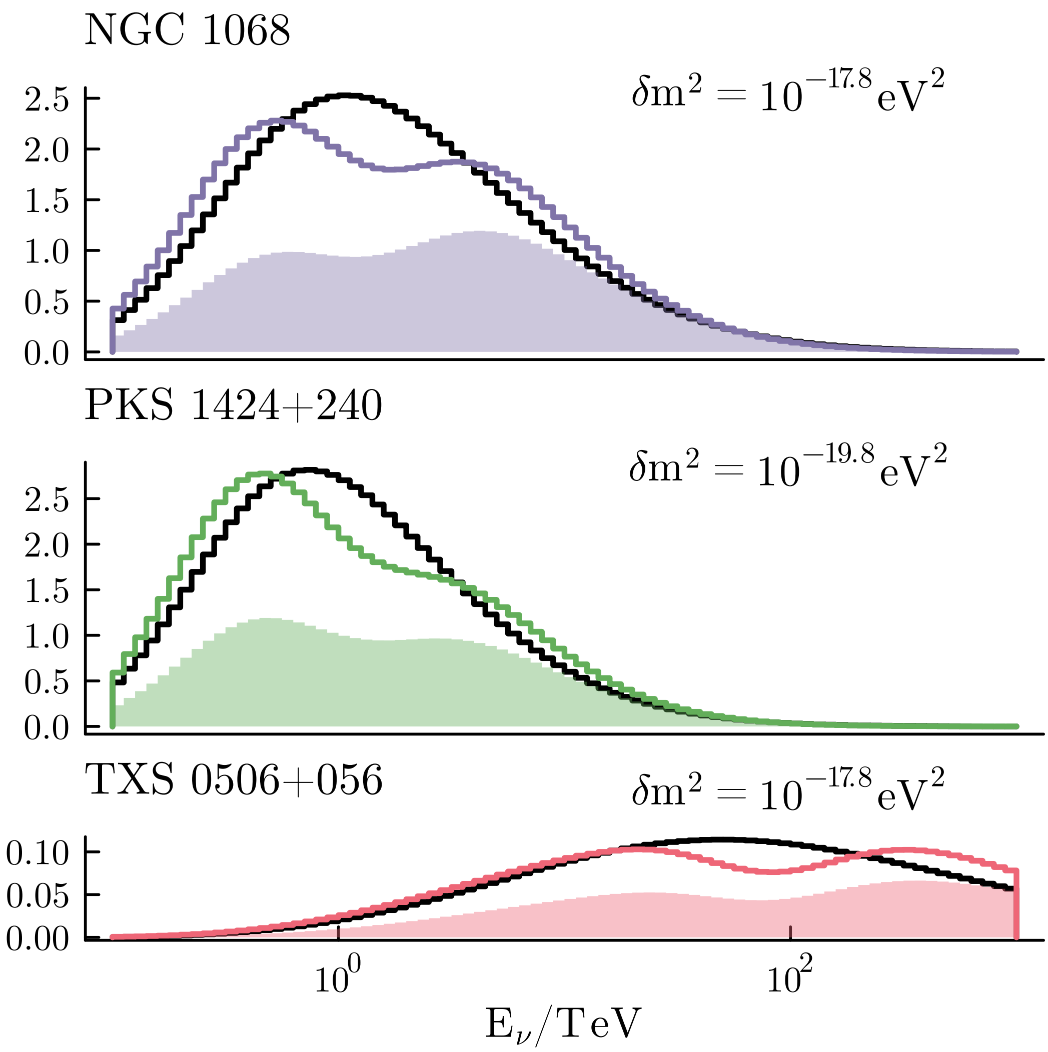

Figure 1: Calculated event distributions for the three most significant sources under the SM (black) and the pseudo-Dirac (filled color) hypotheses. When we maximize the likelihood that the pseudo-Dirac hypothesis can describe SM-like data, by allowing the flux parameters to vary, (color) the difference between the two distributions is reduced.

a larger catalogue of all sources for which the IceCube point source analysis found at least 1.1σ local significance. The properties of all sources considered are listed in 1. Uncertainties in the redshifts, and thus in the effective distances, shift the associated sensitivity regions, but don't reduce their magnitude.

The sensitivity resulting in both cases are plotted in 2. The dashed black curve in each plot indicates the total sensitivity after marginalizing over all three flux hypotheses, while the solid shaded regions consider only power-law flux hypotheses. The regions of parameter space that could be explored by the extra-galactic point sources in this study are mostly unexplored thus far.

Mass-squared splittings at order $10^{-19.5}\mathrm{eV}^{-2}$ were previously probed using events from Supernova 1987A [9].

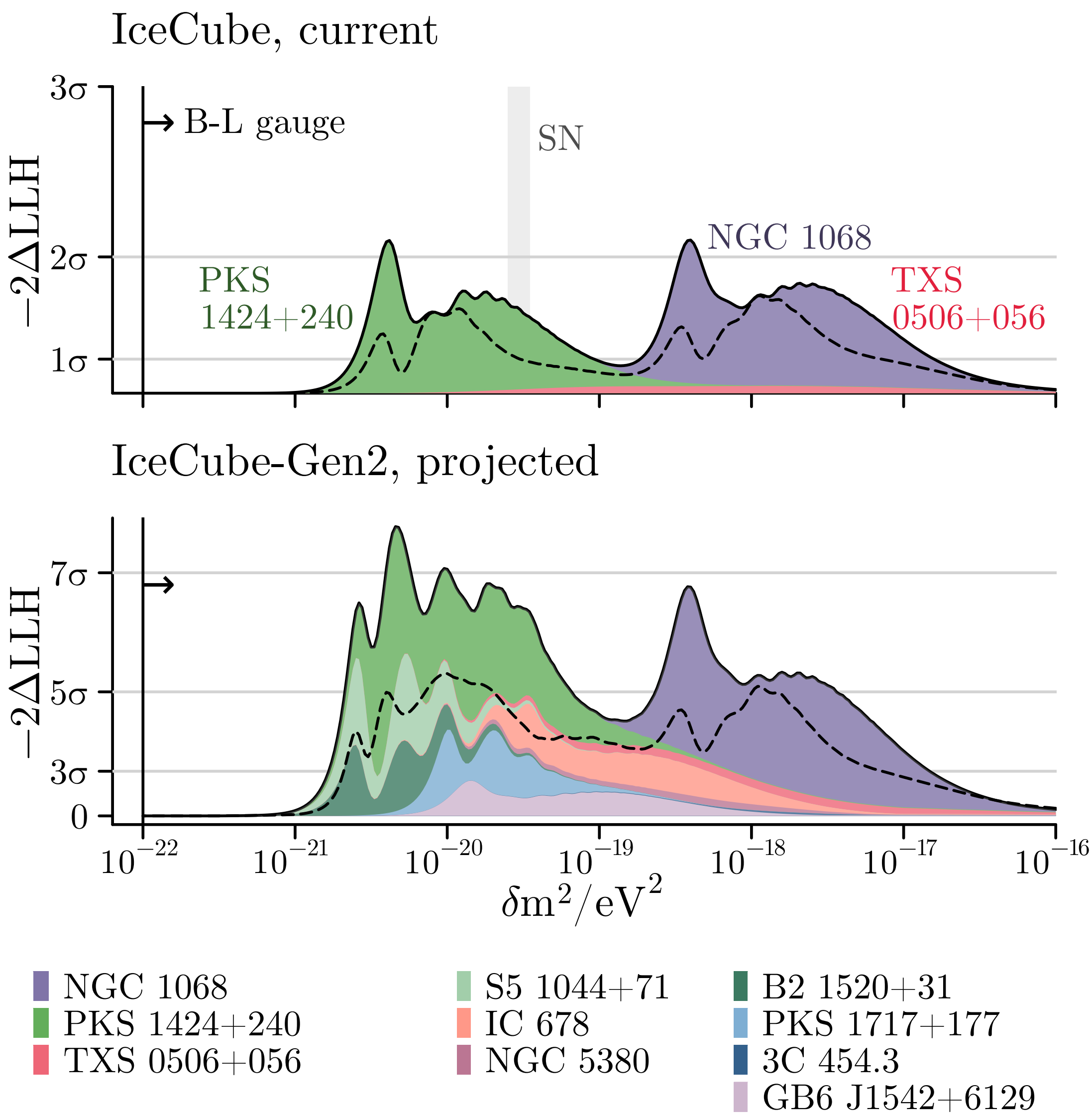

Figure 2: *Top:* Total sensitivity assuming a power-law flux model (black), computed by stacking that of each of the three currently significant sources (plotted separately in color). The dashed black curve indicates the sensitivity obtained after marginalizing over different source hypotheses. The grey-shaded region indicates the 3σ region excluded by SN 1987 A. *Bottom:* Projected sensitivity of IceCube Gen2, using ten astrophysical sources and assuming 8x statistics.

4. Conclusion

Our results are primarily limited by statistics and poor energy resolution, as well as uncertainties in source spectra. Detector upgrades should reduce the importance of the first and the latter. Larger detectors will accumulate more statistics, and thus become sensitive to a wider variety of sources;

Source	Source Type	$-\log_{10} p_{\text{local}}$	$\hat{n}_s$	$\hat{\gamma}$	z	z Ref.
NGC 1068	SBG/AGN	7.0	79	3.2	0.0038 ± 0.00001	[11]
PKS 1424+240	BLL	4.0	77	3.5	0.6047 ± 0.1	[15]
TXS 0506+056	BLL/FSRQ	3.6	5	2.0	0.3365 ± 0.001	[14]
S5 1044+71	FSRQ	1.3	45	4.3	1.1500	[16]
IC 678	GAL	0.9	22	3.1	0.04799 ± 0.00002	[6]
NGC 5380	GAL	0.9	4	2.4	0.010584 ± 0.000077	[8]
B2 1520+31	FSRQ	1.0	35	4.3	1.48875 ± 0.00025	[6]
PKS 1717+177	BLL	1.0	34	4.3	0.137	[17]
3C 454.3	FSRQ	1.2	1	1.5	0.859	[13]
GB6 J1542+6129	BLL	1.9	16	4.3	0.117	[10]

Table 1: The ten astrophysical sources considered in this work. The first three are the most significant. The maximum likelihood values $-\log_{10} p_{\text{local}}, \hat{n}_s, \hat{\gamma}$ are copied from Ref. [4]. The redshifts are obtained from different sources, as listed in the last column.

in turn, analyses considering more source classes will be more robust to flux uncertainties, which are presumably uncorrelated between different source classes. IceCube Gen-2 should therefore be well-positioned to search for evidence of pseudo-Dirac neutrinos.

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