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IceCube search for neutrinos from novae

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Despite being one of the longest known classes of astrophysical transients, novae continue to present modern surprises. The *Fermi*-LAT discovered that many if not all novae are GeV gamma ray sources, even though theoretical models had not even considered them as a possible source class. More recently, MAGIC and H.E.S.S. detected TeV gamma rays from a nova. Moreover, there is strong evidence that the gamma rays are produced hadronically, and that the long-studied optical emission by novae is also shock-powered. If this is true, novae should emit a neutrino signal correlated with their gamma-ray and optical signals. We present the first search for neutrinos from novae. Because the neutrino energy spectrum is expected to match the gamma-ray spectrum, we use an IceCube DeepCore event selection focused on GeV-TeV neutrinos. We present results from two searches, one for neutrinos correlated with gamma-ray emission and one for neutrinos correlated with optical emission. The event selection presented here is promising for additional astrophysical transients including gamma-ray bursts and gravitational wave sources.

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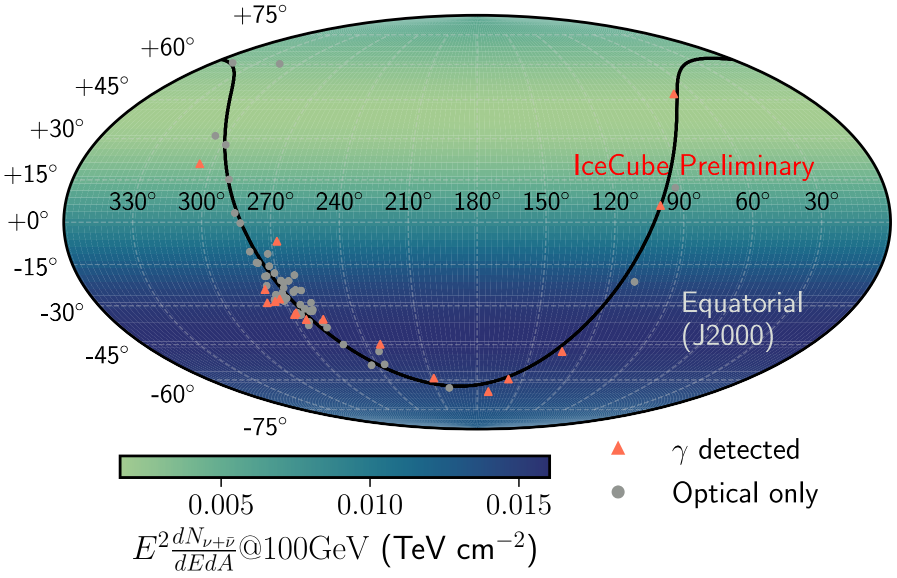

Figure 1: Locations of novae considered in this analysis. Gamma-ray detected novae are shown in orange, including nova RS Oph, while those only detected at other wavelengths are shown in gray. These novae are shown on top of the sensitivity of the IceCube analysis to a single nova with a time window of one day.

1. Introduction

Novae, one of the longest known, historical classes of astrophysical transients, continue to surprise us. In addition to the GeV gamma rays discovered by Fermi LAT, MAGIC and H.E.S.S. have recently discovered nova emission approaching the TeV scale. Those novae that are brightest in the optical band have been detected in gamma rays, indicating that many or potentially all novae emit gamma rays and that those that have not been detected are simply below instrument detection thresholds. Furthermore, strong correlation between the optical and gamma-ray light curves indicates that shock acceleration powers not only the gamma-ray emission, but also the optical emission and therefore the total bolometric power of novae. If the gamma-ray emission mechanism is hadronic rather than leptonic, neutrinos are expected to accompany the gamma-ray signal. Novae could even be brighter in neutrinos than in gamma rays if the gamma rays are partially absorbed within the source. We present the first search for neutrinos from novae, using the IceCube Neutrino Observatory. We use a new event selection, GRECO Astronomy [1, Appendix B], which uses IceCube-DeepCore, the densely instrumented inner subarray of IceCube.

1.1 Nova Sample

The catalog of novae used in this search is described in full in [1, Appendix A]. At the time of that study, we only had processed GRECO Astronomy data spanning April 2012 to May 2020. With the addition of two more years of processed data (up to October 2022), it is now possible to include nova RS Ophiuchi in the list of neutrino source candiates. All of these novae, including RS Oph, are shown in Figure 1.

1.2 Analysis techniques

The analysis uses an unbinned maximum likelihood technique described in [1]. We assume neutrino emission with a power-law spectrum $dN_{\nu+\bar{\nu}}/dE \propto E^{-\gamma}$, with γ the spectral index. We maximize the likelihood and define our test statistic (TS) as the log-likelihood ratio between the best-fit signal and the background hypothesis

$$\mathrm{TS} = -2\ln\left[\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(n_s = 0)}\right], \tag{1}$$

with $\hat{n}_s$ the best-fit number of signal events and $\hat{\gamma}$ the spectral index of a given source. In the case where $\hat{n}_s = 0$, our observed TS = 0, which represents an underfluctuation with respect to the expected number of background events in the short time window considered.

2. Individual gamma-ray correlation analysis

We search for neutrino emission coincident with each of the gamma-ray detected novae, as described in [1]. For each nova, we define our on-time window to be the detection time of the nova by *Fermi*-LAT. The time windows are chosen to match those given by [2] for most novae, with a few exceptions. Two novae, V745 Sco and V1535 Sco, were identified as candidate gamma-ray sources because they did not reach a detection at the 3σ level in [3], so we use the detection times reported in that paper. Two other novae, V3890 Sgr and V1707 Sco, had more recent outbursts reported by *Fermi*-LAT in real-time via the Astronomer's Telegram (ATel), so we use their detection times as reported in their ATels (ATel 13114 and ATel 13116, respectively). The time window for each nova is given in Table 1.

We do not detect any significant neutrino emission from any of the novae, so we set 90% confidence level (CL) upper limits. All of these limits are plotted in Fig. 2.

2.1 Search for neutrinos from RS Ophiuchi

For the analysis searching for neutrino emission from nova RS Oph, we use two additional processed years of GRECO Astronomy data, including data up to October 2022. We use the same analysis as that of the other 16 gamma-ray detected novae. To chose the time window considered for RS Oph, we again use the detection time window by *Fermi*-LAT given in [5], with a total duration of 30 days. This also covers the TeV detections of RS Ophiuchi reported by H.E.S.S. [6] and MAGIC [5].

No significant neutrino emission is found from nova RS Oph. We compare the observed test statistic (TS) to a distribution of 10,000 pseudo-experiments, generated from scrambling our data in right ascension. The observed test statistic, compared to the background TS distribution for this source can be seen in Fig 3. We then place 90% CL upper limits using the one-sided Neyman-Pearson construction. The upper limit assuming a spectrum $dN_{\nu+\bar{\nu}}/dE \propto E^{-2}$ is plotted in Fig. 4, compared to the upper limit for high-energy neutrino emission computed in real-time using the Fast Response Analysis [7], which uses the Gamma-ray follow-up (GFU, [8]) data sample, with results reported in ATel 14851. These are compared to a joint fit for gamma-ray observations from *Fermi*-LAT and MAGIC and neutrino expectations calculated in [5].

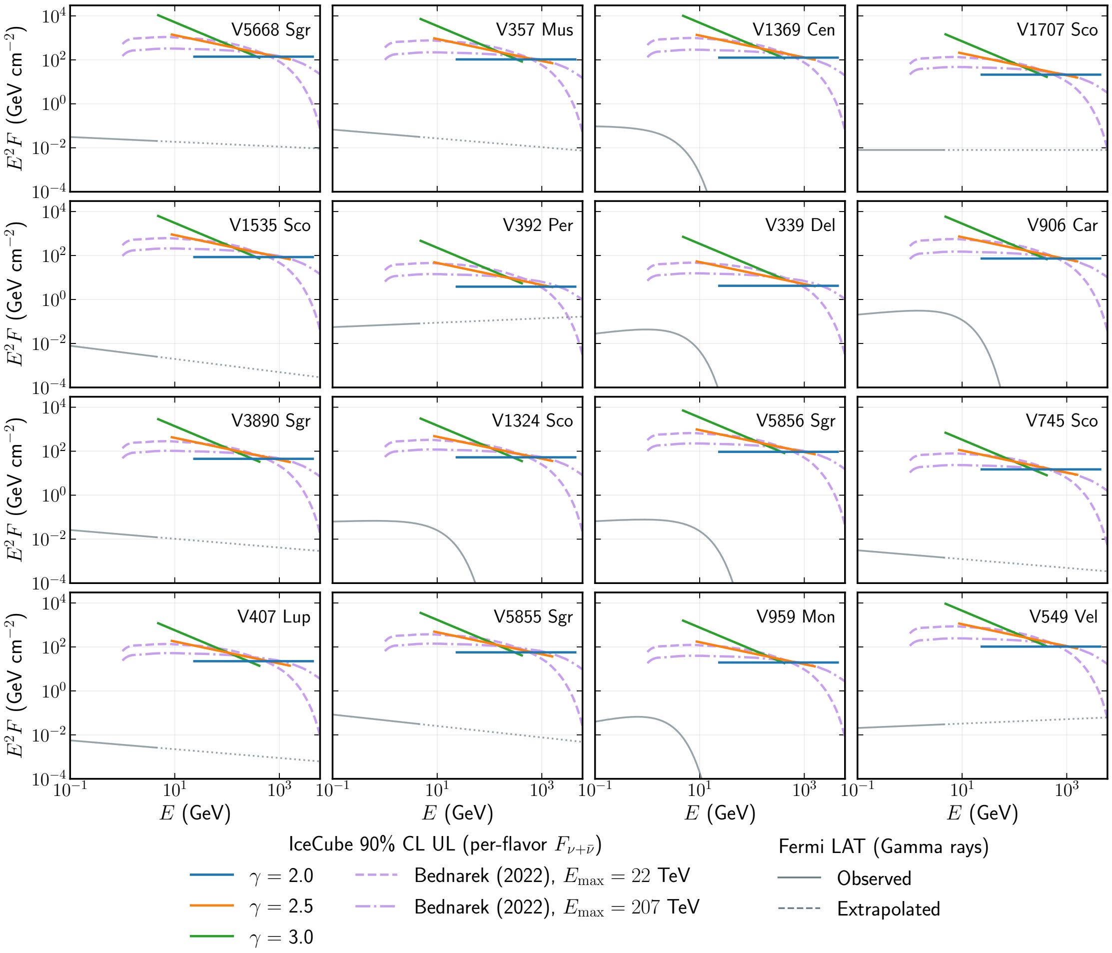

Figure 2: Upper limits on neutrino emission from all of the novae analyzed in the gamma-ray correlation analysis (adapted from [1]). Upper limits on power laws span the central 90% energy ranges of the GRECO Astronomy data set for the given spectral index, and are rescaled by the systematic uncertainties to provide conservative upper limits, as discussed in [1, Section 4.3]. In addition to constraining power-laws, we also inject the spectral shapes from models in [4], and our upper limits on those spectra are shown in pink. We compare these fluxes to the *Fermi*-LAT measured gamma-ray fluxes (gray). For those gamma-ray detected novae which did not show evidence for a cutoff in the gamma-ray spectra, we show the lines as dotted past the global cutoff energy found in [3].

We set upper limits for a power-law spectrum with 3 different spectral indices, as well as a physical model for neutrino emission in novae [4], shown in Fig. 5. We also show a joint fit to the gamma-ray observations from *Fermi*-LAT and H.E.S.S. at the peak of the gamma-ray emission (August 9th, 2021), and observations five days later (August 13th, 2021). An updated table of results, including analysis results for nova RS Oph, is provided in Table 1.

3. Stacking analysis

In addition to searching individual novae for neutrino emission, we performed two stacking analyses. One stacked 16 gamma-ray detected novae, excluding RS Oph, because the analysis was

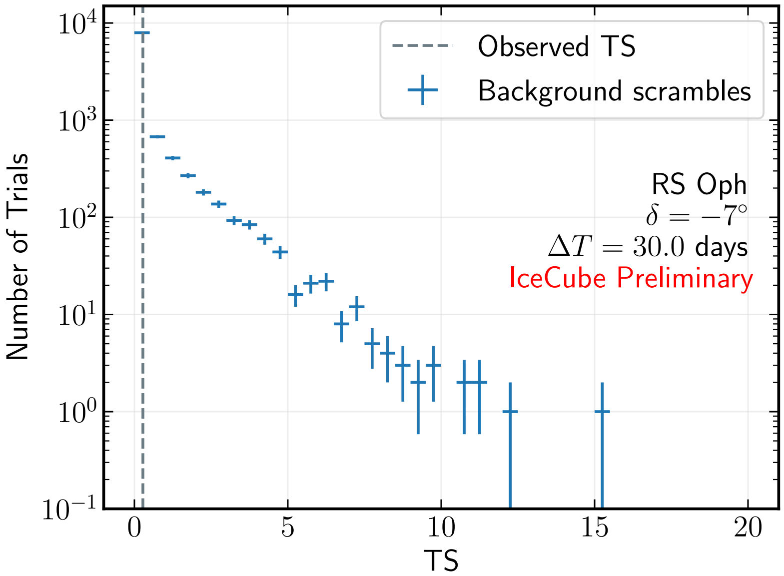

Figure 3: Background test statistic distribution for an analysis of GRECO data using a 30 day time window at the location of nova RS Oph, with the unblinded TS for nova RS Oph shown in the grey dashed line.

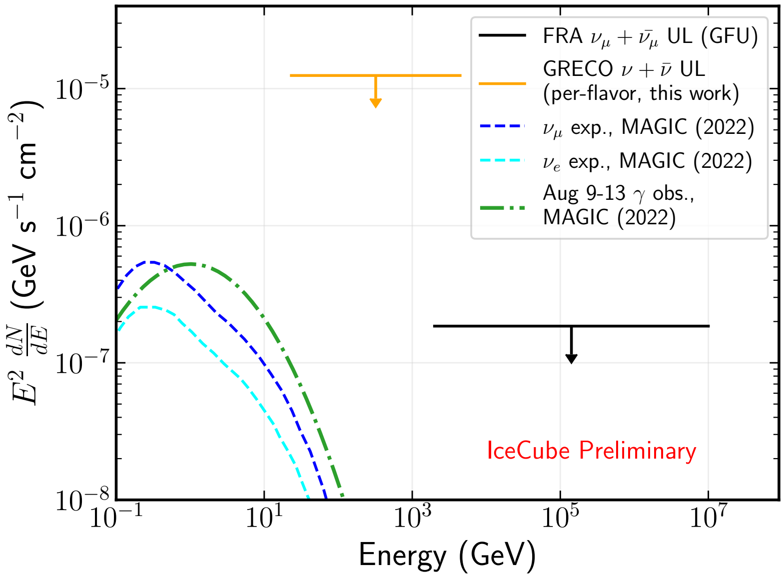

Figure 4: Upper limits for GRECO and Fast Response (ATel 14851), which uses the GFU sample for nova RS Oph. In addition, the Log-Parabola fit to the MAGIC and Fermi-LAT observations from the outburst (Aug 9-13) is plotted in the green dash-dotted curve [5, Suppl. Table 3]. Also shown are neutrino expectations calculated by [5, Suppl. Fig. 1] assuming p-p interactions.

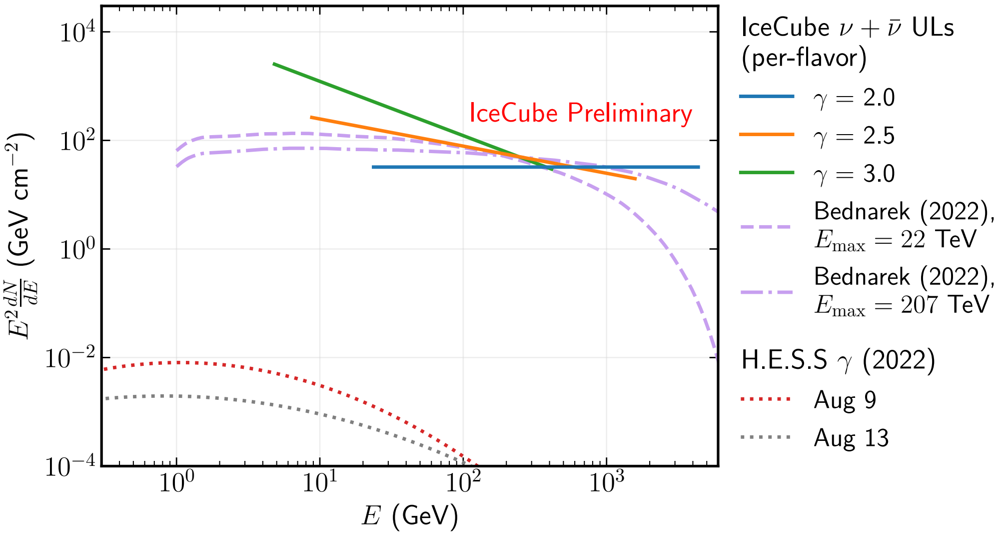

Figure 5: Upper limits on neutrino emission from RS Ophiuchi. Upper limits on power laws span the central 90% energy ranges of the GRECO Astronomy data set for the given spectral index, and account for systematic uncertainties as discussed in [1, Sec. 4.3]. In addition to constraining power-laws, we also inject the spectral shapes from models in [4], and our upper limits on those spectra are shown in pink. Joint fits to the H.E.S.S. and *Fermi*-LAT observations of RS Ophiuchi for August 9th and August 13th are shown as dotted curves [6, Fig.3].

designed prior to its 2021 outburst, to test the hypothesis that neutrino emission is proportional to the gamma-ray flux. The other stacked N optically-detected novae, to test the hypothesis that neutrino emission is proportional to the optical flux. While gamma-ray and neutrino emission are tightly coupled at production in hadronic models, there may be substantial absorption of the gamma-ray signal, in which case the optical flux is expected to better trace the neutrino emission. Under the particular proportionality models tested by these stacking analyses, they achieve sensitivity superior to the single-nova analyses presented in Section 2. Results from the stacking analyses are shown in Fig. 6. No significant signal is found in either analysis, and we therefore place upper limits on the total number of signal neutrinos summed over all novae as a function of the power law index, for each of the two stacking hypotheses.

4. Discussion/Conclusion

We have presented several searches for neutrinos from novae using a new IceCube DeepCore event selection named GRECO Astronomy. In [1], we described searches for neutrinos from 16 individual gamma-ray-detected novae. That analysis was developed before the 2021 outburst of RS Oph, which was detected by MAGIC and H.E.S.S. In addition to the real-time search for TeV-PeV neutrinos from that outburst reported in [9], we have now added an archival search for GeV-TeV neutrinos from RS Oph using GRECO Astronomy. In addition to the search for neutrinos from individual novae, we performed two stacking searches, one based on gamma-ray fluxes and one based on optical fluxes. There is no evidence for neutrino emission from novae in any of the analyses, and the upper limits we present are an order of magnitude above the measured gamma-ray

Name	α	δ	MJD_start	MJD_stop	ΔT (days)	TS	$\hat{n}_s$	$\hat{\gamma}$	pre-trial p-value	$E^2 F_{\nu+\bar{\nu}}$ @ 1 TeV (GeV cm^{-2})
V1324 Sco	267.7°	-32.6°	56093.0	56110.0	17.0	0.00	0.0	–	1.000	52.9
V959 Mon	99.9°	+5.9°	56097.0	56119.0	22.0	1.14	14.8	2.75	0.197	19.5
V339 Del	305.9°	+20.8°	56520.0	56547.0	27.0	0.00	0.0	–	1.000	4.21
V1369 Cen	208.7°	-59.2°	56634.0	56672.0	38.0	0.01	3.8	4.00	0.070	125.9
V745 Sco	268.8°	-33.2°	56694.0	56695.0	1.0	0.00	0.0	–	1.000	14.9
V1535 Sco	255.9°	-35.1°	57064.0	57071.0	7.0	6.95	59.9	3.02	0.002	85.2
V5668 Sgr	279.2°	-28.9°	57105.0	57158.0	53.0	1.30	62.0	3.16	0.112	139.2
V407 Lup	232.3°	-44.8°	57657.0	57660.0	3.0	0.00	0.0	–	1.000	22.4
V5855 Sgr	272.6°	-27.5°	57686.0	57712.0	26.0	0.00	0.0	–	1.000	56.6
V5856 Sgr	275.2°	-28.4°	57700.0	57715.0	15.0	5.13	40.3	2.81	0.015	94.0
V549 Vel	132.6°	-47.8°	58037.0	58070.0	33.0	0.22	22.4	4.00	0.062	103.2
V357 Mus	171.6°	-65.5°	58129.0	58156.0	27.0	0.01	5.0	4.00	0.115	104.6
V906 Car	159.1°	-59.6°	58216.0	58239.0	23.0	0.00	0.0	–	1.000	73.0
V392 Per	70.8°	+47.4°	58238.0	58246.0	8.0	0.88	15.4	3.64	0.373	3.84
V3890 Sgr	277.7°	-24.0°	58718.0	58739.0	21.0	0.00	0.0	–	1.000	45.1
V1707 Sco	264.3°	-35.2°	58740.0	58744.0	4.0	0.00	0.0	–	1.000	21.2
RS Oph	267.6°	-6.7°	59434.8	59464.8	30.0	0.28	3.8	2.4	0.255	32.2

Table 1: Results from the gamma-ray correlation analysis. MJD_start and MJD_stop represent the beginning and end of when a nova was detected by *Fermi*-LAT, respectively. This is the same time window used for the neutrino search. The observed test statistic (TS), best-fit number of signal events ($\hat{n}_s$) and best-fit spectral index ($\hat{\gamma}$) for the neutrino search from each nova are given here (Note that $\hat{\gamma}$ is undefinded in the case of $\hat{n}_s = 0$). The p-values shown are before accounting for the factor accrued from performing multiple searches. The final column gives the time-integrated flux upper limit for each nova, assuming a power-law spectrum with a spectral index of 2.0 ($dN_{\nu+\bar{\nu}}/dE \propto E^{-2}$) and including the systematic uncertainty as discussed in [1, Section 4.3].

fluxes and corresponding neutrino predictions. Nevertheless, these upper limits can already reject scenarios in which a large fraction of the gamma-ray emission is absorbed within the source.

This analysis uses a new event selection, GRECO Astronomy, which is well suited for astrophysical transients and has already been used for other source classes including gravitational wave sources and gamma-ray bursts. The IceCube Upgrade is a fully funded project now underway to install an additional seven strings within DeepCore, with even denser instrumentation than DeepCore both horizontally and vertically. It will directly improve the performance of IceCube in the GeV-TeV band. In particular, event direction reconstruction will improve over that demonstrated with GRECO Astronomy, lowering the effective background rate in analyses of astrophysical sources. In addition to the neutrino paticle physics for which it was designed, the IceCube Upgrade will enable IceCube to continue to advance neutrino astronomy in the GeV-TeV band, where gamma-ray telescopes have demonstrated the sky to be full of a variety of surprising sources including novae.

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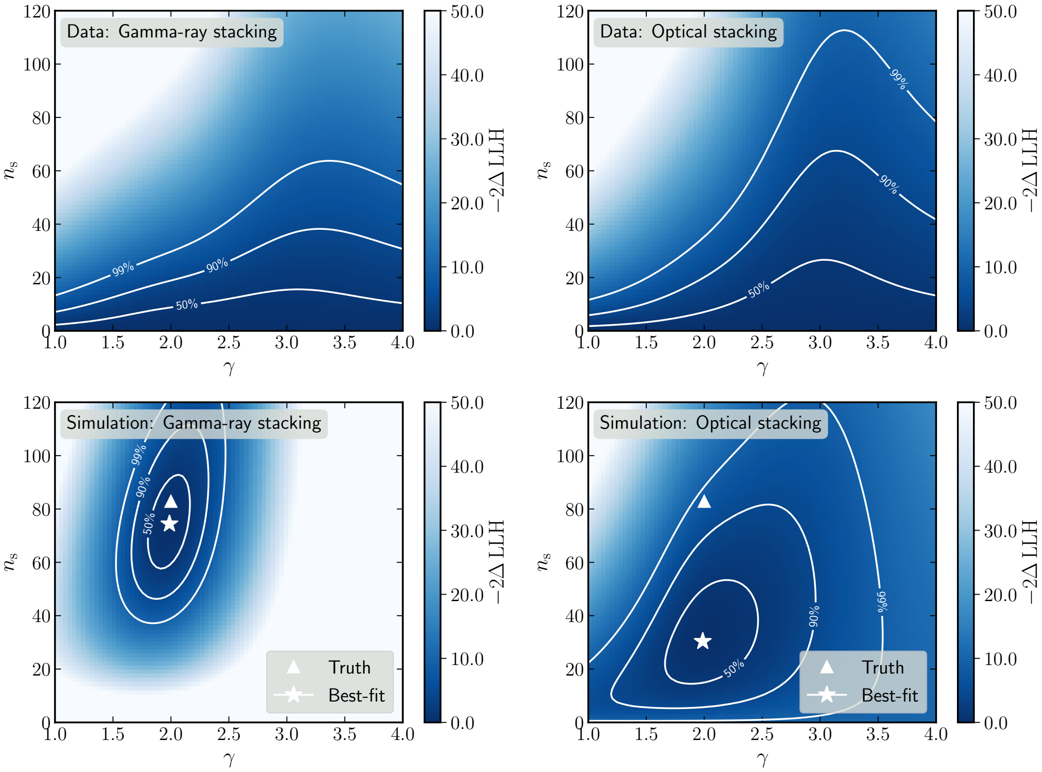

Figure 6: Likelihood contours in (n_s, γ) for the gamma-ray stacking analysis (left) and for the optical stacking analysis (right), reproduced from [1]. Here, n_s refers to the total number of signal events for the entire stacked sample. The top row shows our observed data and the bottom row shows a sample pseudo-experiment with injected signal. Contours denote 50%, 90%, and 99% containment assuming Wilk's theorem with two degrees of freedom. For our observed data (top), $\hat{\gamma}$ is undefined when $\hat{n}_s = 0$, so we do not include a best-fit point on these panels.

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