AMON Searches for Jointly-Emitting Neutrino + Gamma-Ray Transients

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AMON ν+γ Archival Analysis

Look for statistically significant coincidences between high-energy neutrinos and gamma-ray signals:

Public IceCube Data (IC40) → Fermi LAT Data → The code is ready. The analysis is done.

Public IceCube Data (IC40) → Swift Data → The code is almost ready, in optimizing phase.

Archival analysis helps us to validate our understanding of the component datasets and to explore different candidate statistical approaches to generating AMON alerts for the network's follow-up partners.

IC40 and Fermi LAT Data Properties I

Motivation:

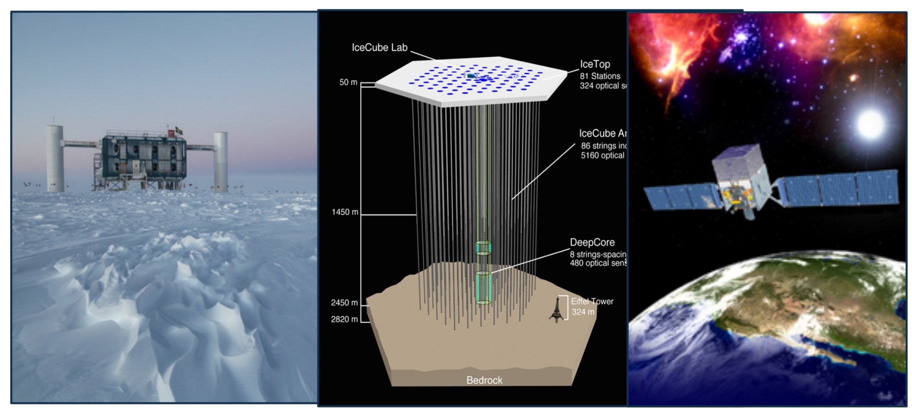
Started by
J. Fixelle and
M. Smith
(Penn State)

- The IceCube observatory have reported an excess of high-energy astrophysical neutrinos;
- Theoretical models predict detectable neutrino emission will be paired with a prompt electromagnetic signal.

	IC40	Fermi LAT
Signal	Cosmic ν	Cosmic γ
Background	Atmospheric ν, CRs	Galactic γ, CRs
Energy	$\geq$ 1 TeV	20 MeV - 100 GeV
PSF	Fisher: $\frac{1}{2\pi\sigma_\nu^2}\exp\left(-\frac{(\hat{x}_\nu-\hat{x})^2}{2\sigma_\nu^2}\right)$	King: $\frac{1}{2\pi\sigma_\gamma^2}\left(1-\frac{1}{\gamma}\right)\left[1+\frac{1}{2\gamma}.\frac{(\hat{x}_\gamma-\hat{x})^2}{\sigma_\gamma^2}\right]^{-\gamma}$

IC40 and Fermi LAT Data Properties II

- Temporal overlap ≈ 41.5 weeks
- Photon energy ≥ 200 MeV
- Photon and spacecraft zenith direction < 65°
- Public IceCube data: Northern hemisphere neutrinos only
- ≈ 4.1×10^6 photon events.
- ≈ 15,000 neutrino events.



Analysis Method

- Spatial coincidence: < 15°
- Temporal coincidence: ±50 s

Steps of the analysis:

- Null distribution
  - Scrambling the neutrino time and RA, keep Dec and E.
  - No scrambling for LAT data.
- Signal distribution
  - Matching a LAT photon event with IC40 neutrino events.
- Excess Detection:
  - Anderson-Darling Test
  - Signal Extraction

Null and Signal Distributions: Log-Likelihood Statistics

To conduct this analysis, an un-binned log-likelihood function is considered:

$$\lambda = 2\ln(P_{LAT}(\hat{x} \mid \hat{x}_\gamma)P_{IC}(\hat{x} \mid \hat{x}_\nu)) - 2\ln(B(\hat{x}_\gamma))$$

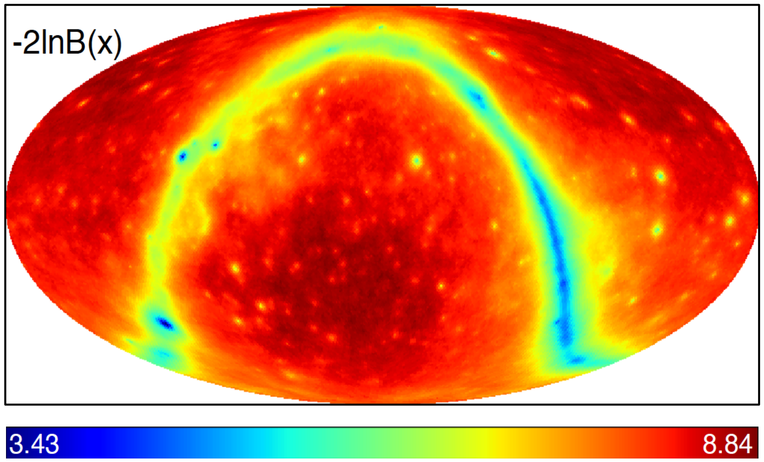
$\hat{x}_\nu, \hat{x}_\gamma$: are neutrino and photon event positions.

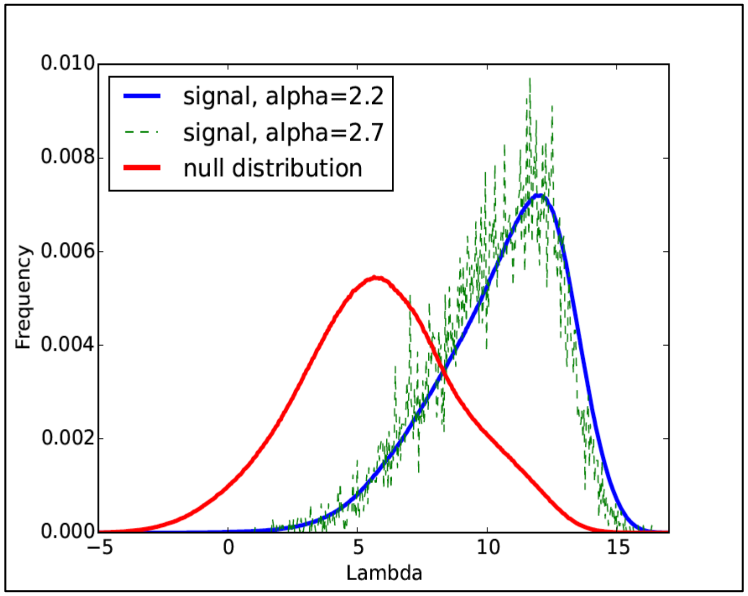
$\hat{x}$: is conjectured source position.

$B(\hat{x}_\gamma)$: is the background rejection term; biases against regions of high photon count/ low exposure.

$$B(\hat{x}) = \int \Phi(\hat{x}, E)A(\hat{x}, E)dE \frac{\int \left(\frac{dN}{dE}\right)_{test} dE}{\int \left(\frac{dN}{dE}\right)_{test} A(\hat{x}, E)dE} \propto \frac{\text{event rate}(\hat{x})}{\text{exposure}(\hat{x})}$$

To test the analysis's effectiveness:
a series of 10,000 scrambled data tests and
a series of 10,000 signal tests were performed.



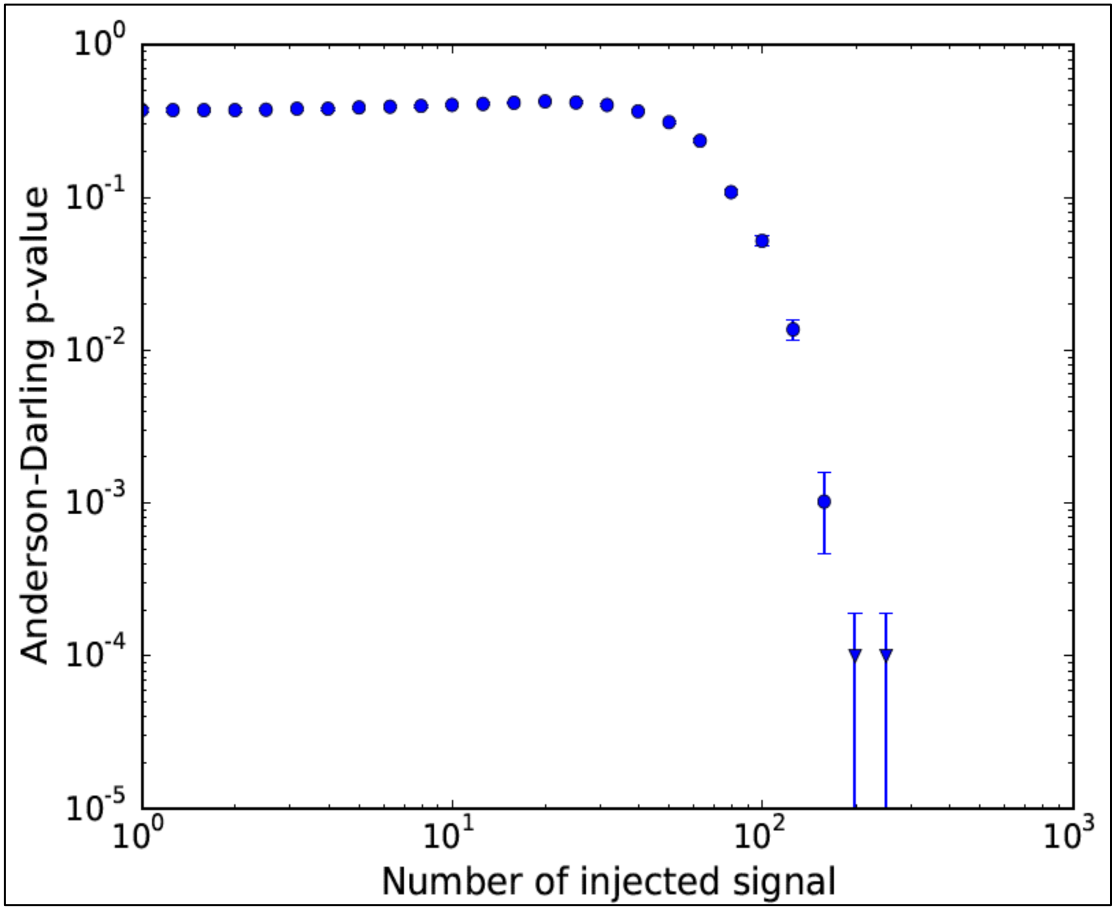


Excess Detection: Anderson-Darling Test

Once we have the signal and background sorted out, we must choose an approach to determine a statistical excess.

$$\omega^2 = \int [F_n(x) - F(x)]^2 \cdot [F(x)\,(1 - F(x))]^{-1}\, dF(x)$$

- For this test statistics, a p-value must be obtained.
- Create a set of randomized null distributions (10,000 trials) and compute their respective values of ω^2.
- To obtain an estimate for the analysis effectiveness, we injected false signal photons randomly chosen from a single signal run with spectral index 2.2.

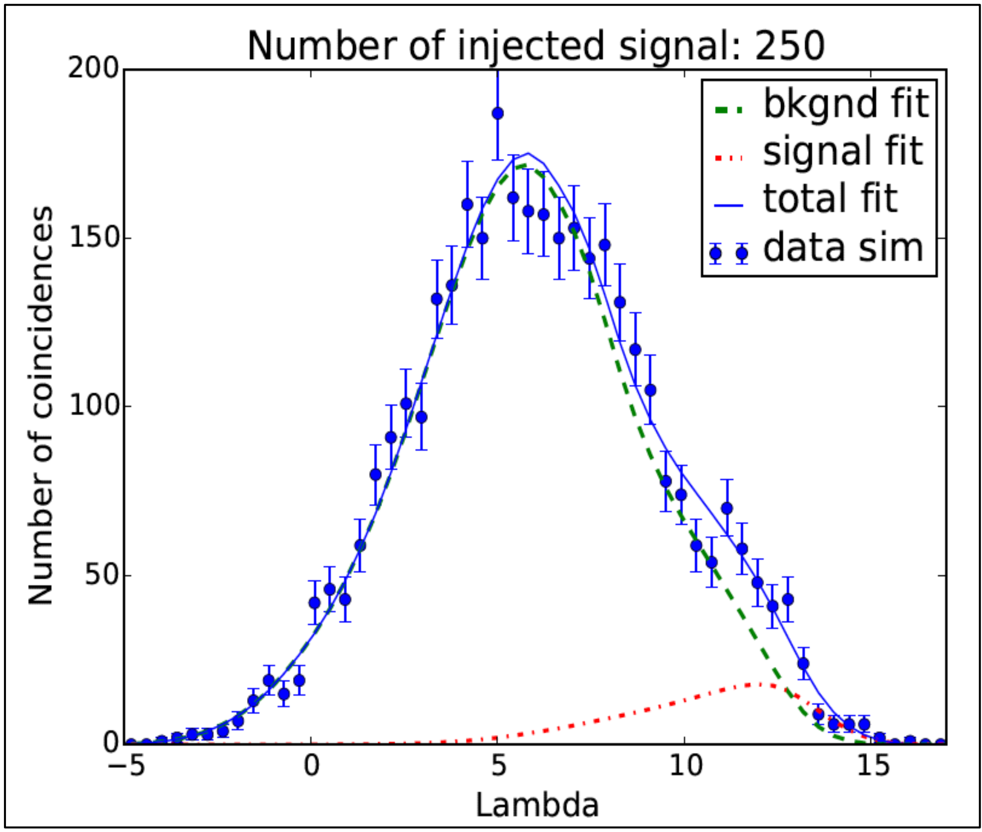


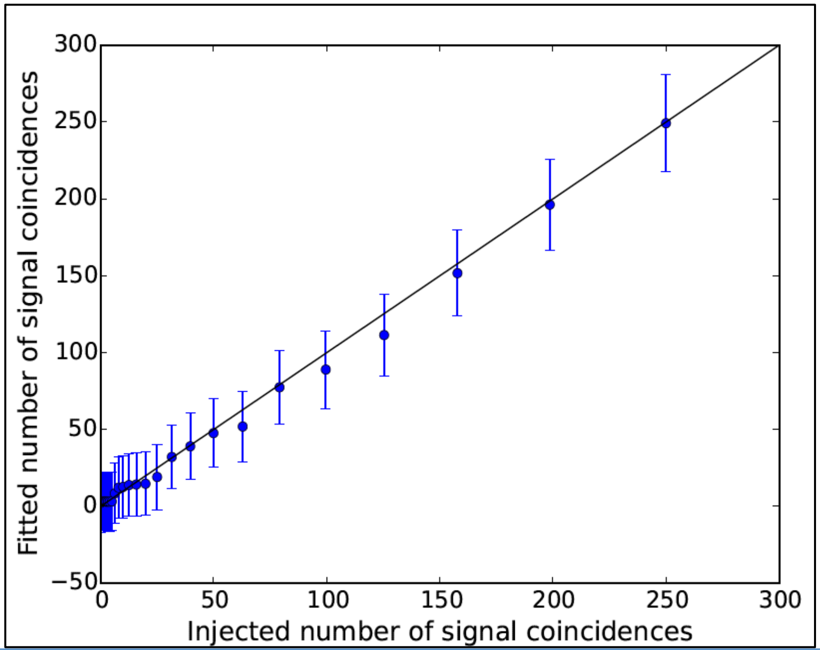
Excess Detection: Signal Extraction

Binned log-likelihood analysis given by:

$$-2\ln\mathcal{L} = 2(s+b) - \sum_{k=1}^{N_{bins}} 2\ln\left(s\mathcal{S}_k + b\mathcal{B}_k\right)$$

s: number of signal events
b: number of background events
S_k: binned high statistics signal distribution
B_k: binned high statistics background distribution
Null hypothesis: s=0, b=N_{coinc}





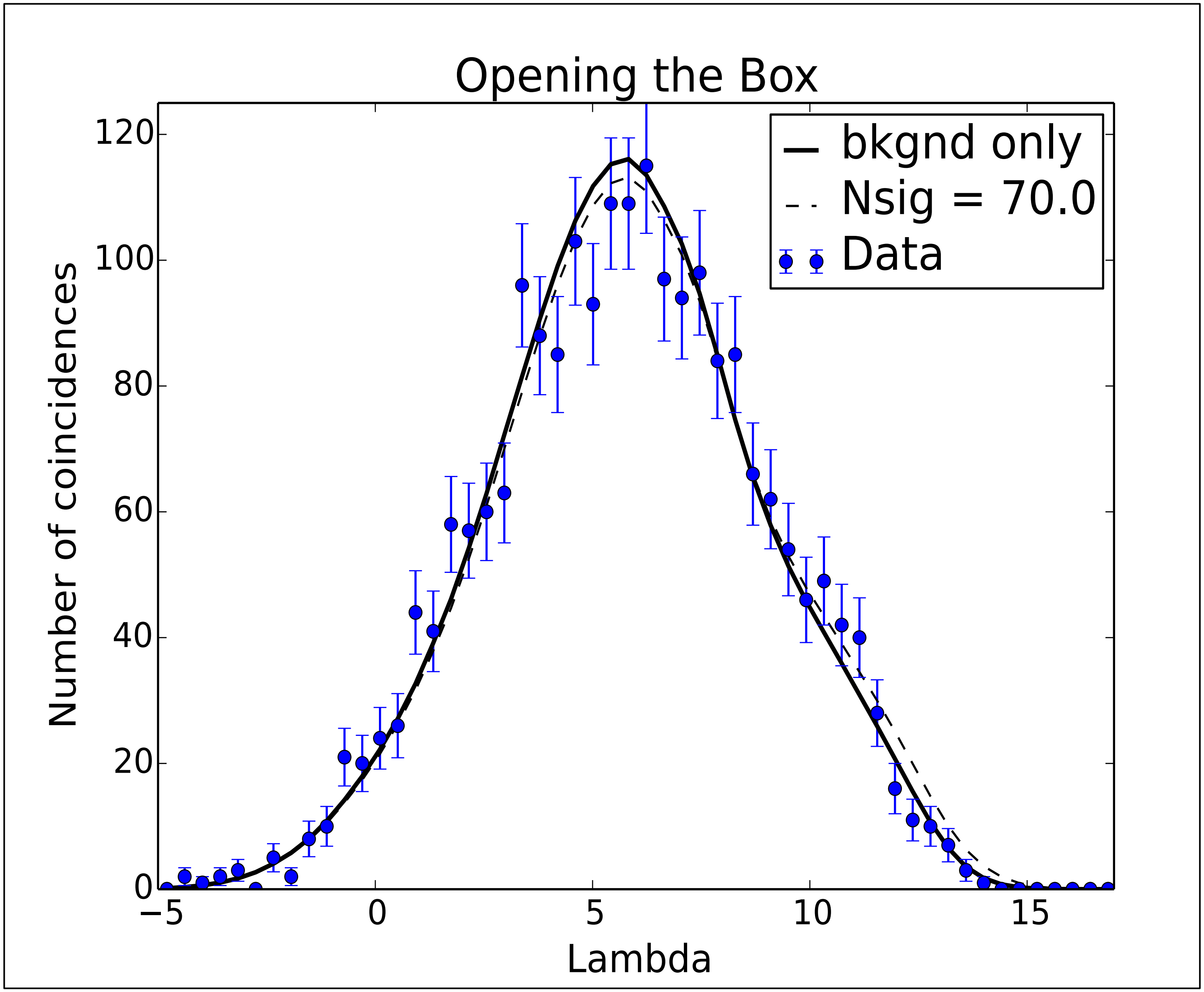
Injected coincidences using an $E_\gamma^{-2.2}$ test spectrum, with successful extraction. Showing retrieved signal number from the fit method as a function of injected signal.

Results with the Unblinded Data

Unblinded histogram in comparison with the background model and a theoretical model with Nsig=70.

After unblinding the data: 2138 coincidences were found within the cuts of $\psi \leq 15^{\circ}$ and $|\Delta t| \leq 50$ s.

The AD test on this data yields about 70 $\nu + \gamma$ coincidences. The P-value for this observation is 4%.



Summary

- IceCube + Fermi code is ready for archival analysis
- IceCube + Swift code is almost ready
- The statistical method for archival analysis of neutrino + photon is developed
- IC40 + Fermi results show that we are sensitive to about 70 signal with p-value of 4%.

Thanks for your attention