Seeking Multimessenger Transients:
Fermi LAT Photon + High-Energy Neutrino Coincidences from IceCube and ANTARES

Colin Turley and the
Astrophysical Multimessenger Observatory Network (AMON),
with assistance from the IceCube and ANTARES Collaborations

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Astrophysical Multimessenger Observatory Network

- **Multimessenger transients:** Photons, neutrinos, cosmic rays, gravitational waves (⩾2 of these)
- High-energy astrophysical neutrinos: One source known
- Generic + specific considerations for correlated neutrino and gamma-ray ($\nu+\gamma$) emission
- Time-sensitive coincidence analysis

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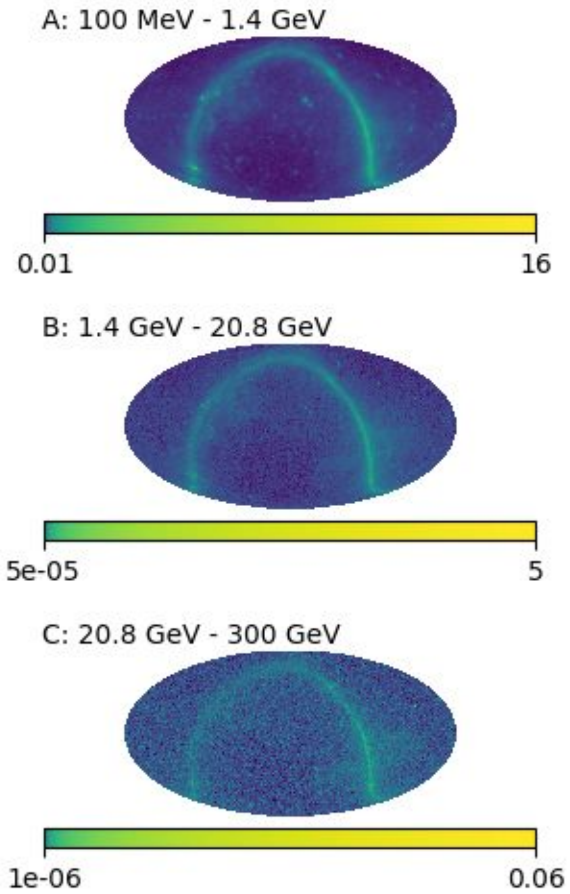
Coincident Analysis

- Coincidence Requirements:
  Temporal: $\Delta t = \pm 100$ s
  Spatial: $\Delta\theta < 5°$
- Arrival direction of particles is uncertain, given by Point Spread Function (PSF) $P_{\nu\gamma}(x)$
- Localize coincidence by max overlap of PSFs at location x
- Rank coincidence by log likelihood statistic for n_ν neutrinos and n_γ photons:

$$\lambda = 2\ln \frac{P_{\nu\gamma}(\vec{x})(n_\nu! n_\gamma!)}{B_\gamma(\vec{x})}$$

- Higher λ - more significant coincidence



Background maps, $B_\gamma(x)$, for the Fermi events in three energy bins

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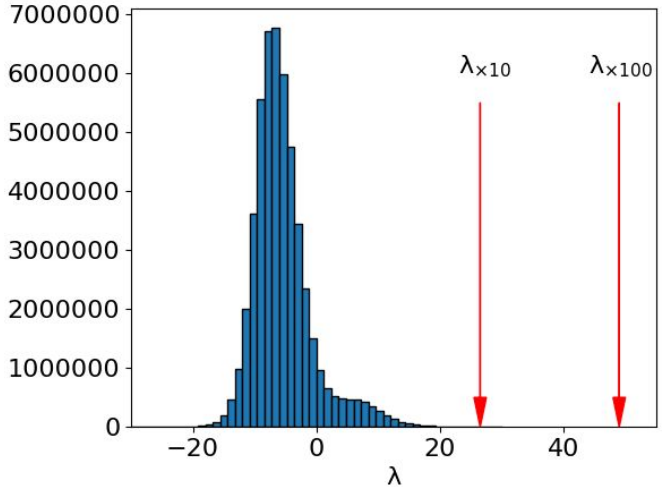
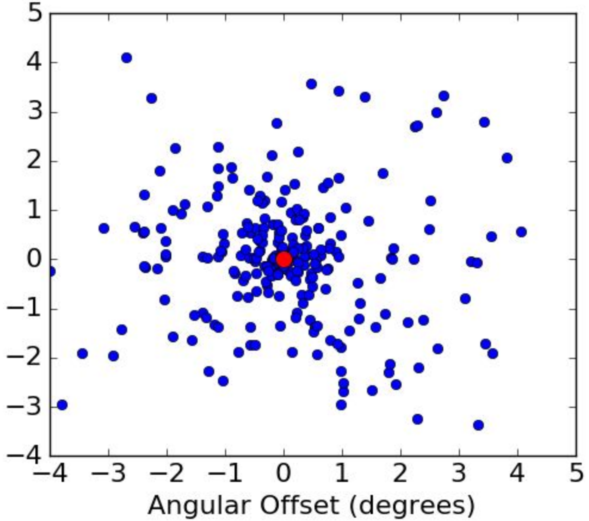
Archival Results: Singular Events

	Scrambled Results			Unscrambled	
	$\langle n_{\nu\text{-}\gamma} \rangle$	$\lambda_{\times 10}$	$\lambda_{\times 100}$	$n_{\nu\text{-}\gamma}$	λ_{max}
IC40	1090 ± 30	23.9	27.2	1128	20.3
IC59-N	4970 ± 65	26.5	49.0	5046	17.8
IC59-S	7072 ± 76	26.8	31.5	7080	24.4

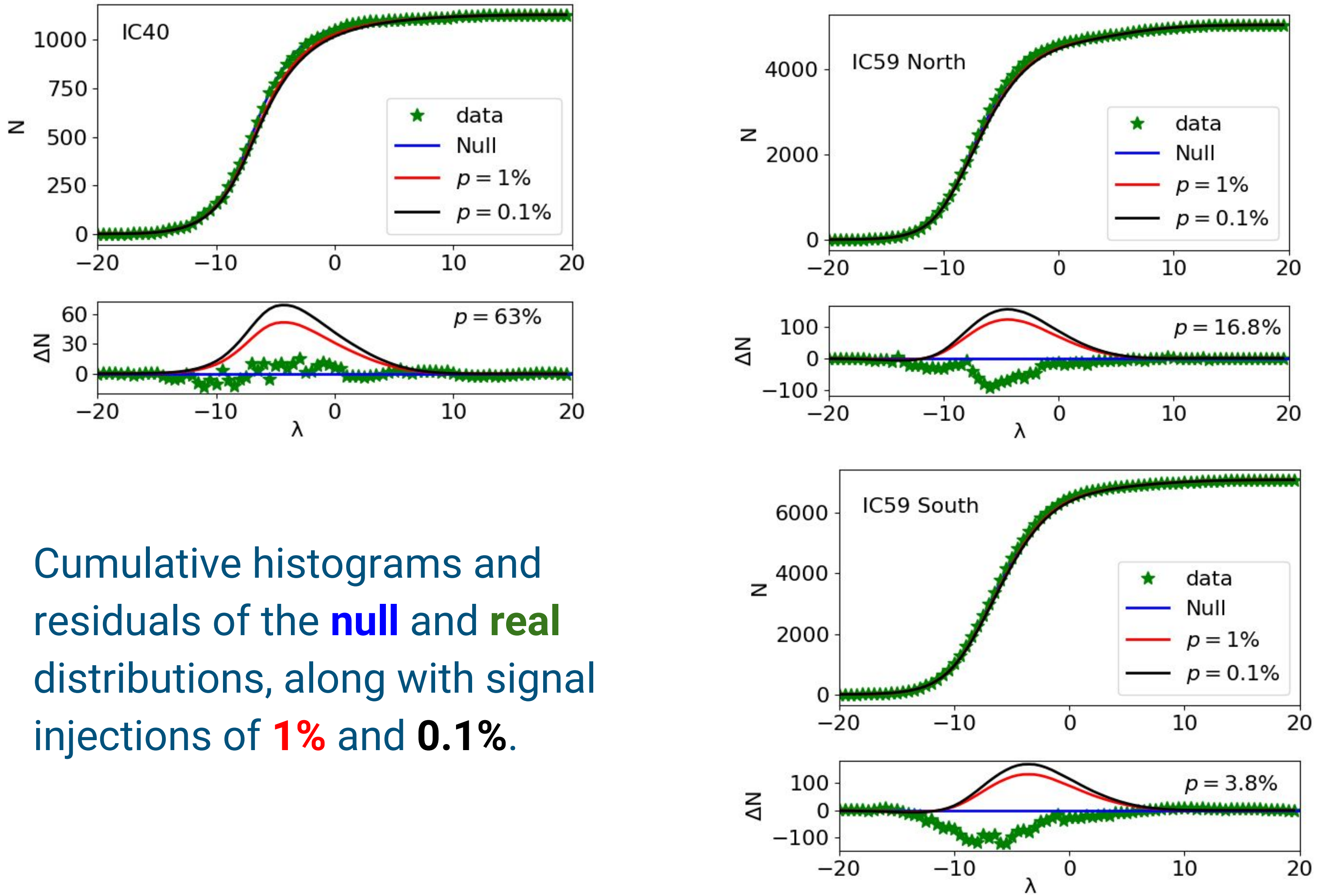


Top: Histogram of scrambled IC59 northern events, including thresholds with false alarm rates of 1 per decade and 1 per century

Bottom: Simulated forced coincidence between a neutrino and GRB 090902B yielding a 218-photon coincidence and a λ value of 2560.2



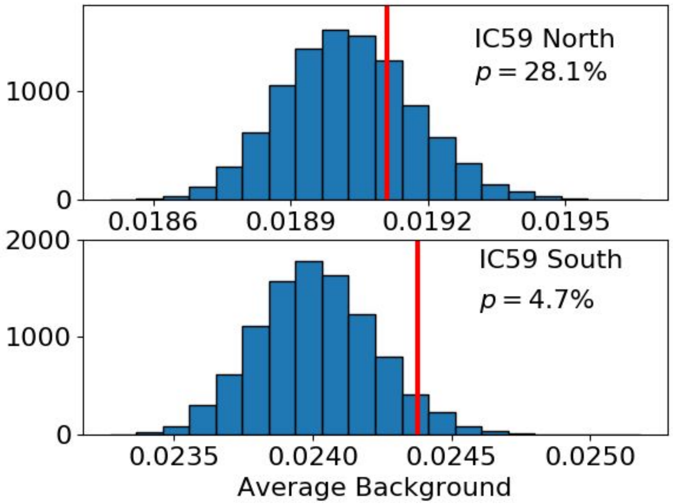
Archival Results: Subthreshold



Cumulative histograms and residuals of the **null** and **real** distributions, along with signal injections of **1%** and **0.1%**.

Possible ν+γ Correlation

- ***Possible*** cause of low-λ excess: Correlation between neutrino and photon positions (in steady state)
- ***Tested*** via mean photon background at each neutrino position
- ***Tentative support*** from IC59 data
- No statistical excess in IC40 data

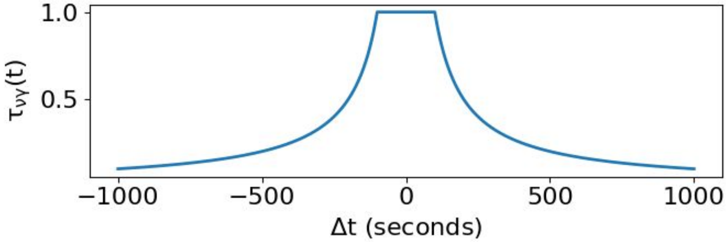


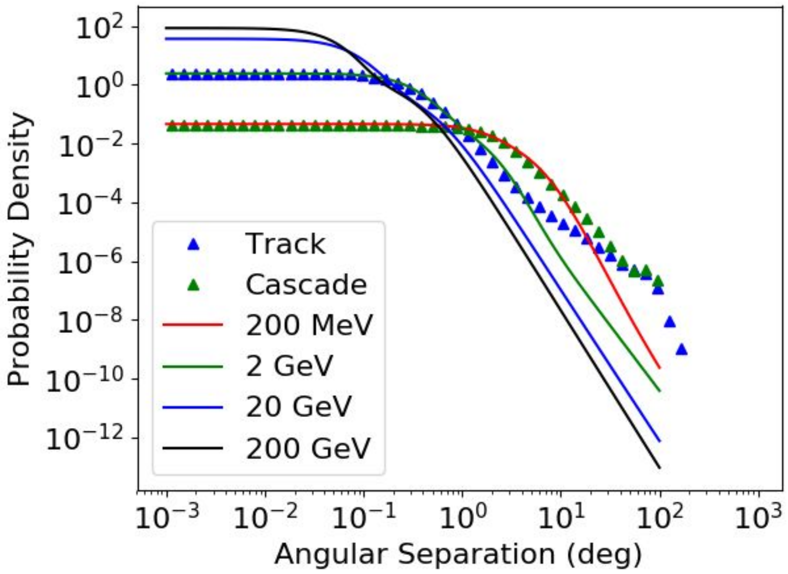
Histograms of the average photon background at the location of each neutrino for 10,000 scrambled datasets. Background for the unscrambled distribution is shown in red.

ANTARES Archival Analysis

- 6774 tracks and 162 cascades coincident with LAT data
- Slight changes to coincidence requirements for this search:
  - Temporal: $\Delta t = \pm 1000$ s
  - Spatial: $\Delta\theta < 5°$ (tracks)
  - Spatial: $\Delta\theta < 10°$ (cascades)
- Modify log likelihood to account for temporal separation and neutrino cosmic p-value

$$\lambda = 2\ln\frac{P_{\nu\gamma}(\vec{x})(n_\nu! n_\gamma!)(\tau_{\nu\gamma})}{B_\gamma(\vec{x})} + \ln\frac{p}{1-p}$$



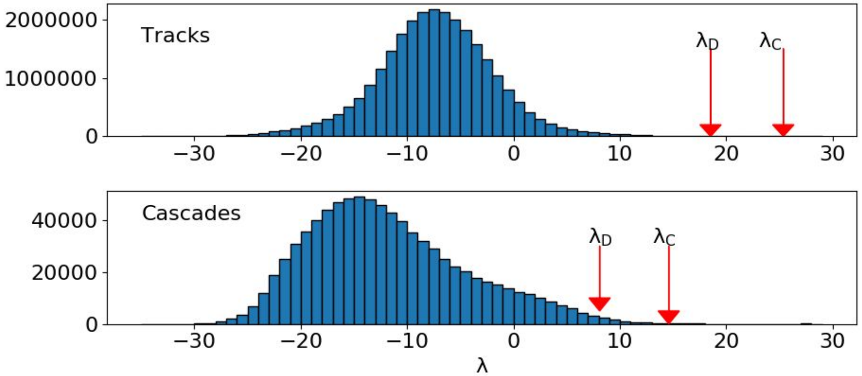


Top: PSFs for ANTARES track and cascade events, along with PSFs for Fermi photons of various energies, front type conversion, and an inclination angle of less than 40 degrees

Left: Temporal weighting function $\tau_{\nu\gamma}$

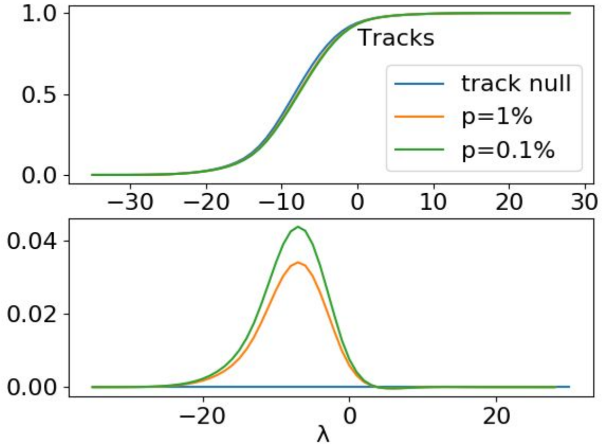
Scrambled Results

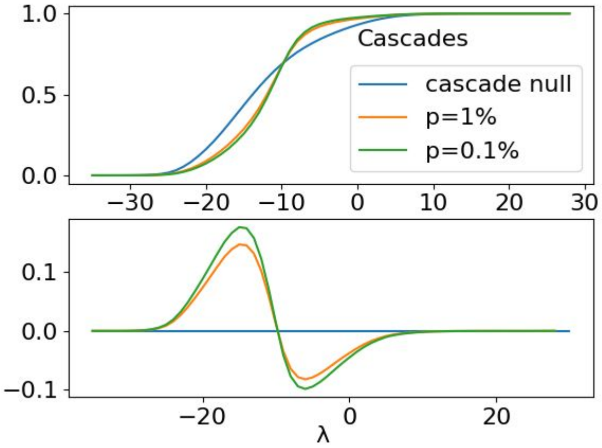
	Scrambled Results			Unscrambled	
	$\langle n_{\nu\text{-}\gamma} \rangle$	λ_D	λ_C	$n_{\nu\text{-}\gamma}$	λ_{max}
Tracks	2715 ± 36	18.5	25.4	tbd	tbd
Cascades	83.6 ± 5.8	8.1	14.6	tbd	tbd



Up: Histograms of the null distribution for the tracks and cascades. Red arrows mark the 1/decade and 1/century thresholds

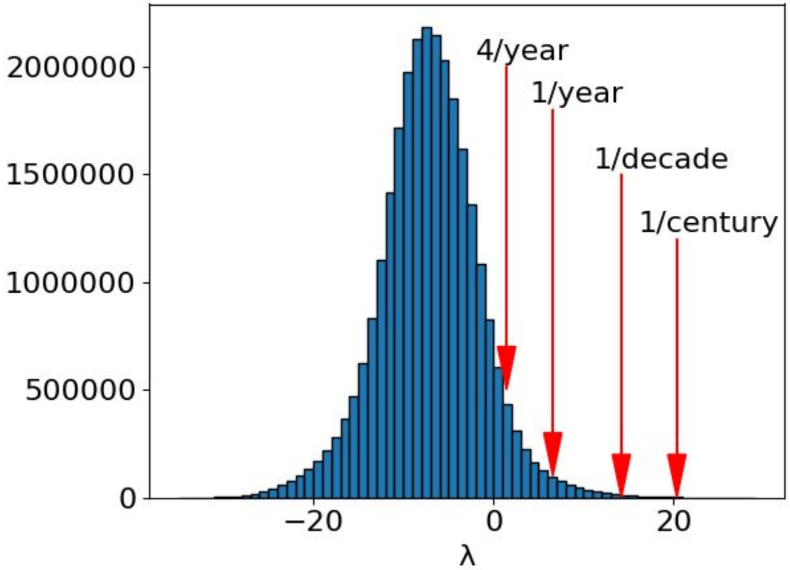
Left: Cumulative histograms and residual plots for the null distribution and signal injections yielding p-values of 1% and 0.1%





Real Time Alerts

- ANTARES neutrino events ingested in real-time by AMON
- *Fermi* events downloaded as they appear
- Average photon "delay" of 5.4 hours
- Calculate lambda for every coincidence
- GCN notices for events exceeding threshold for 4 $year^{-1}$ FAR
- Currently in test mode
- Waiting on GCN stream activation and collaboration approval



Histogram of the lambda distribution to calibrate alert thresholds.

Conclusions

- Developed a time-sensitive **ν+γ** coincidence analysis for IceCube, ANTARES, and *Fermi* LAT data
- Demonstrated sensitivity to **rare high-multiplicity events**, such as a LAT gamma-ray burst + singlet neutrino
- Demonstrated sensitivity to **subthreshold populations**
- **IceCube archival** result: Possible (p=4.7%) correlation between **ν+γ** positions in steady state (Galactic plane?) – to be explored with full IceCube dataset
- **ANTARES archival** analysis: Awaiting permission to unscramble ANTARES data
- **Real-time ν+γ analyses**: Running on AMON servers, tested with GCN, awaiting collaboration approvals

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References

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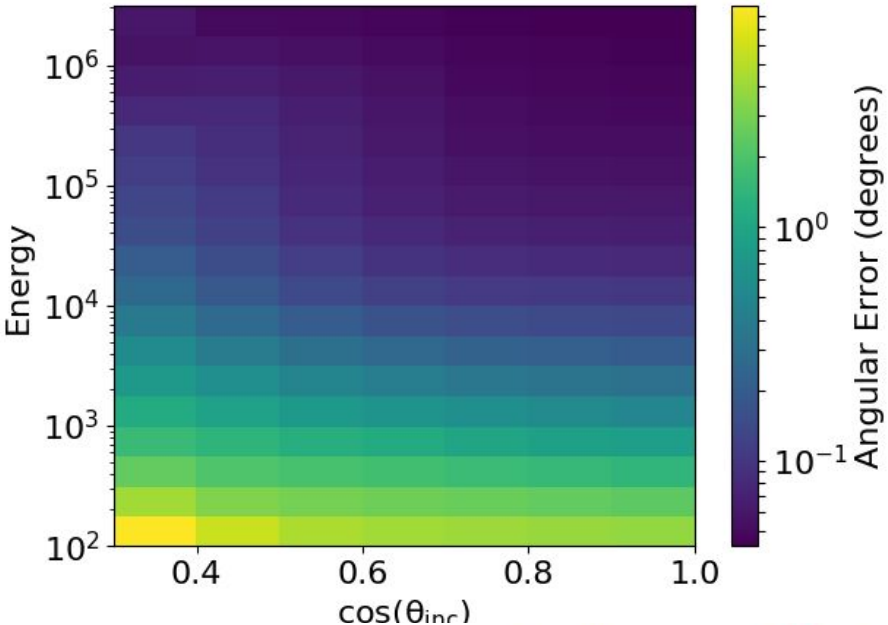
Backup Slides

Extra: Fermi Angular Error



$$K(x,\sigma,\gamma) = \frac{1}{2\pi\sigma^2}\left(1-\frac{1}{\gamma}\right)\cdot\left[1+\frac{1}{2\gamma}\cdot\frac{x^2}{\sigma^2}\right]^{-\gamma}$$

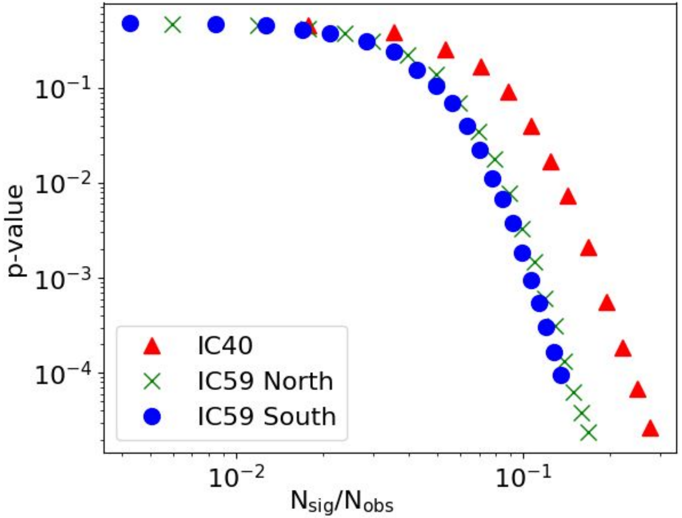
$$P(x;\vec{\alpha}_P) = f_{\mathrm{core}}K(x,\sigma_{\mathrm{core}},\gamma_{\mathrm{core}}) + (1-f_{\mathrm{core}})K(x,\sigma_{\mathrm{tail}},\gamma_{\mathrm{tail}})$$

Signal Injection

- Create signal events by:

1. Center photon and neutrino PSFs, and place all particles weighted by their PSFs
2. Put coincidence at random sky location
3. Calculate lambda value

- Inject signal events into the null distribution
- Use Anderson-Darling k-sample test to look for statistical excess of signal events

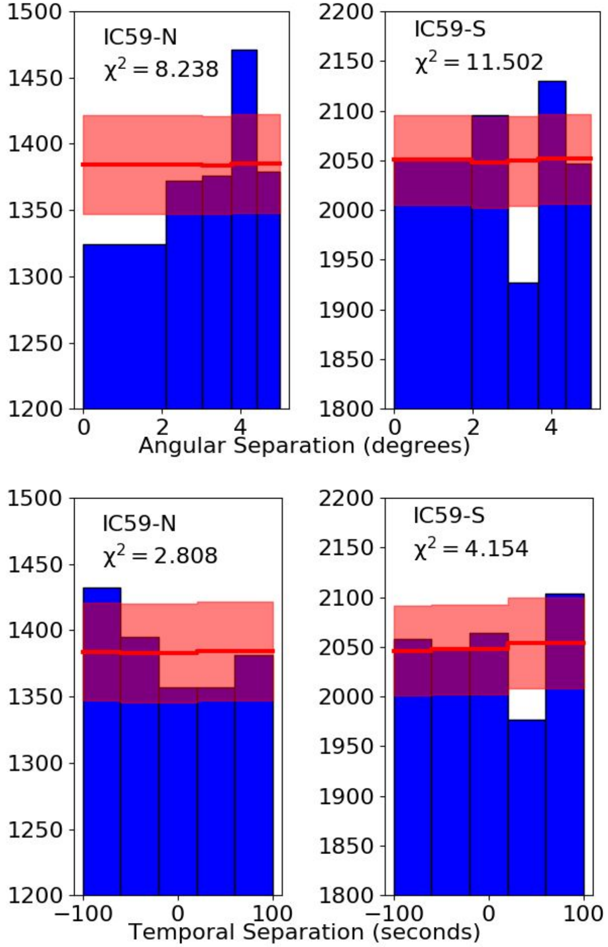


Anderson-Darling p-value as a function of fraction of signals injected for IceCube public data

	1% P-value	0.1% P-value
IC40	150 events	210 events
IC59-N	440 events	570 events
IC59-S	565 events	740 events

Signal Vetting

- Possible causes of low-λ excess:
  - Signal with a soft power law
  - Systematic error in PSFs
- Test by checking for systematic trends in angular and temporal separation
- No significant trends observed



Top: Histograms of the ν-γ angular separation for the IC59 northern (left) and southern (right) data. Bins are sized to make the null distribution flat.

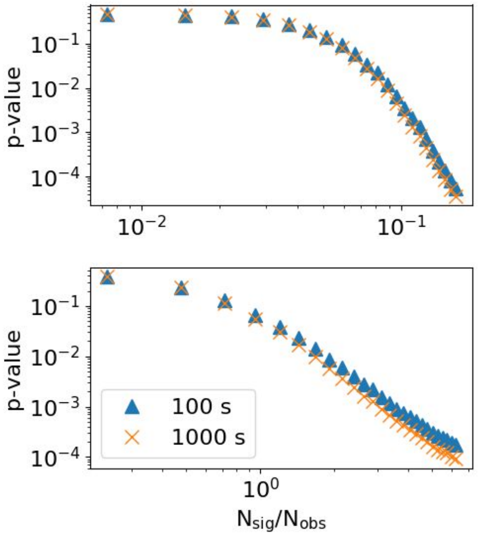
Bottom: Histograms of the ν-γ temporal separation for the IC59 northern (left) and southern (right) data. Bins are each 40 second wide.

ANTARES Signal Injection

- Create signal events by:

1. Center photon and neutrino PSFs, and place all particles weighted by their PSFs
2. Put coincidence at random sky location, weighted by ANTARES field of view
3. Add background photons based on sky location and Fermi background map
4. Calculate lambda value

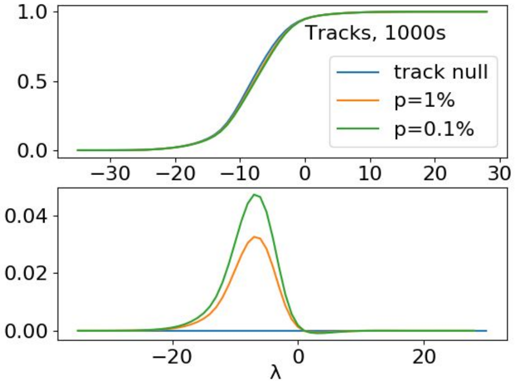
- Inject signal events into the null distribution
- Use Anderson-Darling k-sample test to look for statistical excess of signal events

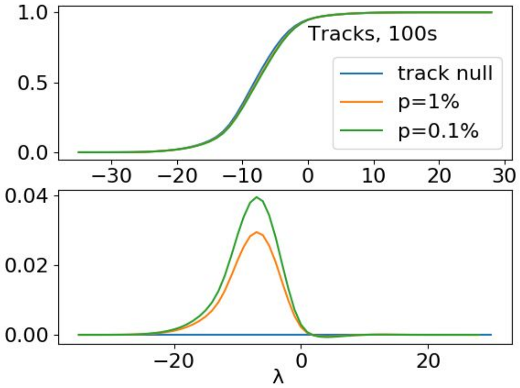


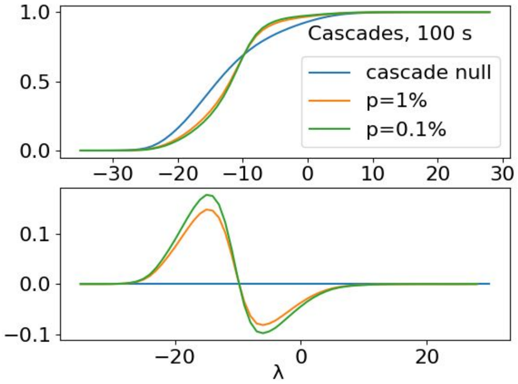
Anderson-Darling p-value as a function of fraction of signals injected for IceCube public data

	1% P-value	0.1% P-value
Tracks, 100 s	210 events	275 events
Tracks, 1000 s	200 events	270 events
Cascades, 100 s	150 events	280 events
Cascades, 1000 s	140 events	250 events

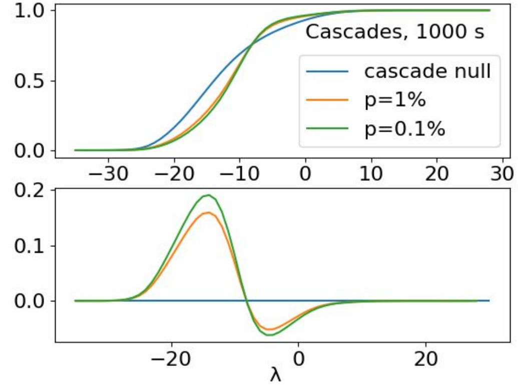
Scrambled Results



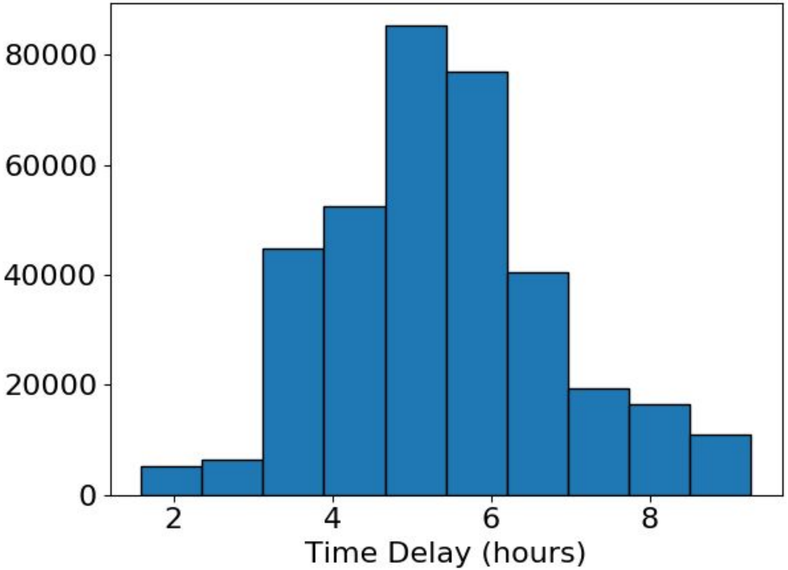




Cumulative histograms and residuals of the null distributions, along with signal injections yielding test statistics of 1% and 0.1%. Unscrambled results waiting on collaboration approval.



Photon delay



Histogram of the time difference between photon detection and download to the AMON machines. Average delay is 5.4 hours.