Recent Developments of the Real-Time Capabilities of IceCube

Thomas Kintscher for the IceCube Collaboration

TAUP 2015
Neutrinos B

Torino, 2015/09/10
Multi-Messenger Observations

> Combination of different messengers:
  - Increased sensitivity
  - Obtain the complete picture

> IceCube: $4\pi$ 24/7 trigger capability

> Follow-Up Observatories:
  - Sensitive to different wavelengths/messengers
  - Limited field of view, weather-dependent
Transient and Variable Sources

> Temporal evolution of astrophysical objects

GRB: 10 – 100 s

AGN flare: ~ 10 d

SN: ~ 100 d

> Wide variety of timescales for evolution

> Detectable in time-dependent analyses

> Improved sensitivity from multi-wavelength observations
The IceCube Neutrino Observatory

- 1km³ detector for Cherenkov light
- In this talk: μ-tracks from CC $\nu_\mu$-int.
- Angular resolution of $\leq 1$ deg
The Follow-Up Procedure

AGN/SN/GRB/... → Photons → Neutrinos → IceCube
(Current) Follow-Up Observatories

> **Gamma rays**

- **MAGIC** (1 alert / year)
- **VERITAS** (3 alerts / year)
- **HESS** (t.b.d.)
- Energy ranges: ~ 50 GeV – 50 TeV
- FoV: ~ 3.5 deg.

> **Optical**

- **PTF** (9 alerts / year)
  > FoV: 7.3 sq. deg.
- **ZTF** (under construction)
  > FoV: 47 deg.

> **X-rays: SWIFT-XRT** (7 alerts / year)

- FoV: 0.4 deg. (→ 1.1 deg.)
- Energy: 0.2 – 10 keV
Follow-Up System in IceCube

> Real-time event selection at the South Pole
  - Fast event reconstruction and filtering
  - Pick well-reconstructed tracks

> Likelihood analysis in the North
  - Optical/X-Ray: short timescale (fixed to 100 s), all-sky
  - Gamma-Ray: variable clustering of events (up to 21 d), source list
  - Significance calculation → Alert generation

> Forwarding to follow-up observatories
  - Test of source visibility
  - Contacted by automated emails
  - AMON stream: sub-threshold events for correlation analyses

> Total latency: a few minutes!
Status: Follow-Up with Gamma-Ray Observation

Marginalized likelihood:

\[ \mathcal{L}(x_i, t_i, E_i|n_{\text{sig}}, \gamma) = \prod_{i=0}^{N} \left( \frac{n_{\text{sig}}}{N} S_i + \left(1 - \frac{n_{\text{sig}}}{N}\right) B_i \right) \]

\( S_i/B_i \): PDFs containing spatial, energy and timing information

Test statistic:

\[ \lambda = -2 \ln \left( \frac{U(T^\text{sig}_s, T_e)}{U(T_s, T_e)} \frac{\mathcal{L}(n_{\text{sig}} = 0)}{\mathcal{L}(\gamma, n_{\text{sig}})} \right) \]

Significance threshold determined by allocated observation time:

- VERITAS: \(-\log_{10}(p) = 3.663 (3.5\sigma)\)
- 40% observation probability (weather, etc.)
- \(~ 3\) alerts / year
Status: Alerts from Gamma-Ray Follow-Up

- Running stable since March 2012
- Number of physics alerts sent so far: 14

- Latest alert: 2015/07/05
  - $N_{\text{observed}}$: 4
  - Duration: 1.2 d
  - $-\log_{10}(\text{pre-trial p-value})$: 4.086

- Alert forwarded to VERITAS
- No observation due to scheduled maintenance...
> Running stable since March 2012
> Number of physics alerts sent so far: 14

> Most significant: 2012/11/09
  - $N_{\text{observed}}$: 6
  - Duration: 4.169 d
  - $-\log_{10}(\text{pre-trial p-value})$: 4.637

> Alert forwarded to VERITAS

> No significant evidence for gamma-ray emission seen
Status: Follow-Up with Optical/X-ray Observations

> Tracks from the northern sky

> Closely clustered events on very short timescales

  - Angular distance: < 3.5°
  - Temporal distance: < 100 s

> Test quantity: \[ \lambda = -2 \log \mathcal{L} \]

\[
= \frac{\Delta \psi^2}{\sigma_q^2} + 2 \log (2\pi \sigma_q^2) - 2 \log \left(1 - \exp \left(-\frac{\theta_A^2}{2\sigma_w^2}\right)\right) + 2 \log \left(\frac{\Delta T}{100 \text{s}}\right)
\]

- angular separation, reconstruction quality, events in telescope's FoV, small time intervals

> Forwarding to

  - PTF: 9 alerts / year
  - SWIFT: 7 alerts / year
Status: Alerts from Optical/X-ray Follow-Up

> 2012/03/30: Most significant OFU alert to PTF
  - Two neutrinos within 1.7 s

> Detection of core-collapse supernova PTF12csy within 0.14 deg
  - Distance: 300 Mpc
  - Age: > 169 days

> p-Value: 0.014 (2.6σ)

> Chance detection, neutrinos likely unrelated to SN

> [arXiv:1506.03115], accepted by ApJ

[Diagram showing celestial coordinates and event locations]
> After 3 years: no triplet observed!

> Assume: Diffuse $\nu$-flux from GRBs
  → Number of triplets?
  - SWIFT: ~1500 GRBs/year/hemisphere

> 4500 GRBs emitting diffuse flux

> 10s of GRBs generating triplets

> … but none observed!
Status: No triplet from Optical/X-ray Follow-Up

> After 3 years: **no triplet observed!**

> Assume: Diffuse $\nu$-flux from GRBs → Number of triplets?
  - SWIFT: $\sim$1500 GRBs/year/hemisphere

> 4500 GRBs emitting diffuse flux

> 10s of GRBs generating triplets

> ... but none observed!

> brightest GRB: < 3 neutrinos!

> **Scaled contribution from GRBs yields limit on astrophysical $\nu$-flux!**

(Paper in preparation by Nora Linn Strotjohann et al.)
Summary and Outlook

✔ Mature selection of high-quality tracks in real-time
✔ Several running analyses: gamma-ray, optical, x-ray
✔ Physics results:
  ✔ Chance observation of supernova
  ✔ Limits on transients
✔ Physics analysis and alert distribution within 5 minutes!

> Improved event selection
  ▪ More precise angular error estimator, latest reconstructions → better sensitivity...

> Generic analysis: unbiased all-sky, arbitrary timescales
Thank you for your attention!
Backup
Status: Recent Alerts from GFU

> Running stable since March 2012
> Number of physics alerts sent so far: 14

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>-log(_10) (pre-trial p-value)</th>
<th>(N_{\text{obs}})</th>
<th>Duration (days)</th>
<th>Follow-up</th>
<th>Experiment observed</th>
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<tbody>
<tr>
<td>1 2012-04-14 23:47:44</td>
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Updates for IC86-5: Single Event Stream

> Previous Design:

- Trigger
- Level 1 (μ tracks)
- Level 2 (hq selection)
- Straight Cuts
- Binned Analysis
- Alert Generation

For each:

OFU/GFU

> New Design:

- Trigger
- Level 1 (μ tracks)
- Level 2 (hq selection)
- BDT Selection

For each:

OFU/GFU

Visible/Significance

Follow-Up Observatory

> Recent SPTS testing successful!
Updates for IC86-5: GFU BDT Selection

> Old: straight cuts, upgoing only

> New: BDT event selection using PyBDT

- **Upgoing BDT**
  - Trained with spectrum of -2.7
  - Training Variables:
    - Bayesian LLH Ratio
    - \(\langle \text{MPE Fit, Line Fit} \rangle\)
    - Length of direct hits (Time Window C)
    - Number of direct hits (Time Window C)
    - Speed from Line Fit
    - MPE Fit Zenith
    - Log10(MuE)
    - Scaled MPE llh: \(-\log L / (N_{\text{dom}} - 3.5)\)
    - Max(cos(SplitFit Zenith) – cos(MPE Zenith))
    - Cos(Min(SplitFit Zenith)) – cos(MPE Zenith) – 0.5
    - Separation
    - Empty distance / Length of direct hits (C)
    - Smoothness (S_{all})
    - Log10(Q_{tot})
    - Distance to `Center of Gravity'

- **Downgoing BDT**
  - Combination of spectral weights -1, -2 and -3
  - Same training variables
  - No Bayesian LLH Ratio
Updates for IC86-5: GFU BDT Selection

> Upgoing BDT:

- Efficiency:

- Rate:

> Compared to straight cuts:

<table>
<thead>
<tr>
<th>Method</th>
<th>Data rate</th>
<th>Atm. Nu Rate</th>
<th>E-2 efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Cuts</td>
<td>2.0 mHz</td>
<td>1.9 mHz</td>
<td>69 %</td>
</tr>
<tr>
<td>BDT Cut</td>
<td>1.9 mHz</td>
<td>1.7 mHz</td>
<td>81 % (+12%)</td>
</tr>
</tbody>
</table>
Updates for IC86-5: GFU BDT Selection

> Dowgoing BDT:
  - Rate: ~0.1 mHz in each bin
  - Piecewise polynomial fit
  - Zenith-dependent BDT Cut

> Total rate: ~7 mHz
  - Upgoing: 2 mHz
  - Downgoing: 5 mHz
  - ~110 kB/day via Prio-1
Updates for IC86-5: GFU Likelihood Analysis

> **Unbinned likelihood:**

\[
\mathcal{L}(x_i, t_i, E_i | n_{\text{sig}}, \gamma) = \prod_{i=0}^{N} \left( \frac{n_{\text{sig}}}{N} S_i + \left( 1 - \frac{n_{\text{sig}}}{N} \right) B_i \right)
\]

\[
S_i = \mathcal{E}(E_i | \gamma) \times \frac{1}{2\pi\sigma^2} \exp \left( -\frac{|\vec{x}_i - \vec{r}|^2}{2\sigma_i^2} \right) \times \frac{1}{U(T_e, T_s)}
\]

\[
B_i = \frac{1}{\Omega} \times \mathcal{E}(E_i | \nu_{\mu}^{\text{atm}}) \times \frac{1}{U(T_e, T_s)}
\]

> **Test statistic:**

\[
\lambda = -2 \ln \left( \frac{U(T^\text{sig}_s, T_e) \mathcal{L}(\gamma = 0)}{U(T_s, T_e) \mathcal{L}(\gamma, n_{\text{sig}})} \right)
\]

> **Significance threshold determined by observation time:**

- **VERITAS:** $-\log_{10}(p) = 3.663$ (3.5σ)
- 40% observation probability (weather, etc.)
- ~ 1 event / year
Updates for IC86-5: Real-time Monitoring

> 'Good Run List' not available online

> Need to assess detector stability and event quality in real-time
  
  ▪ Clustering of events recorded during stable running conditions
  ▪ Detector live time influences likelihood

> Current GFU stability criteria:
  
  ▪ In-Ice Simple Multiplicity Trigger
  ▪ Muon Filter rate
  ▪ Online Level 2 Filter rate

> Sliding window averages: \[ S_i = \alpha x_i + (1 - \alpha)S_{i-1} \quad \alpha = 0.01 \]
  \[ \sigma_i = \sqrt{\langle x^2 \rangle - S_iS_i} \]

> Stability score: \[ \xi_i = \sum_j \frac{|x_i^j - S_{i-1}^j|}{\sigma_{i-1}^j} \]
Updates for IC86-5: Real-time Monitoring

- Very good agreement with Good Run List
- Conservative live time estimate
- Previously: Queried from I3RateDb @ Pole

- New setup: Needs input from I3RateDb @ Madison
  - Until now: Rates transferred with Prio-2 via I3Live

> Desirable: Transfer trigger rates with Prio-1
Future Plans for GFU/OFU/XFU

> Similar event selections for OFU and GFU
  → Merge!
    - Also a generalised likelihood?

> Meanwhile: Better reconstructions available in Online Level 2
  → Make use of them!
    - (fast) SplineMPE
    - Paraboloid for upgoing events
    - Further improvements possible?

> Sensitivity study:
    - Plot using current selection
    - Goal: Come close to offline PS sensitivity!
Summary

> Previously:
  - GFU/OFU/XFU run reliably for years
  - Established feasibility of online follow-up

> What we did recently:
  - Introduced Online Single Event Stream
  - OFU/GFU BDT Selection @ Pole (now)
  - Southern sky included!
  - Likelihood analysis @ Madison (very soon)

> What we need:
  - Real-time stability monitoring

> What happens next:
  - Alert forwarding to HESS
  - Common event selection, improved sensitivity