Recent Developments of the Real-Time Capabilities of IceCube

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TAUP 2015
Neutrinos B

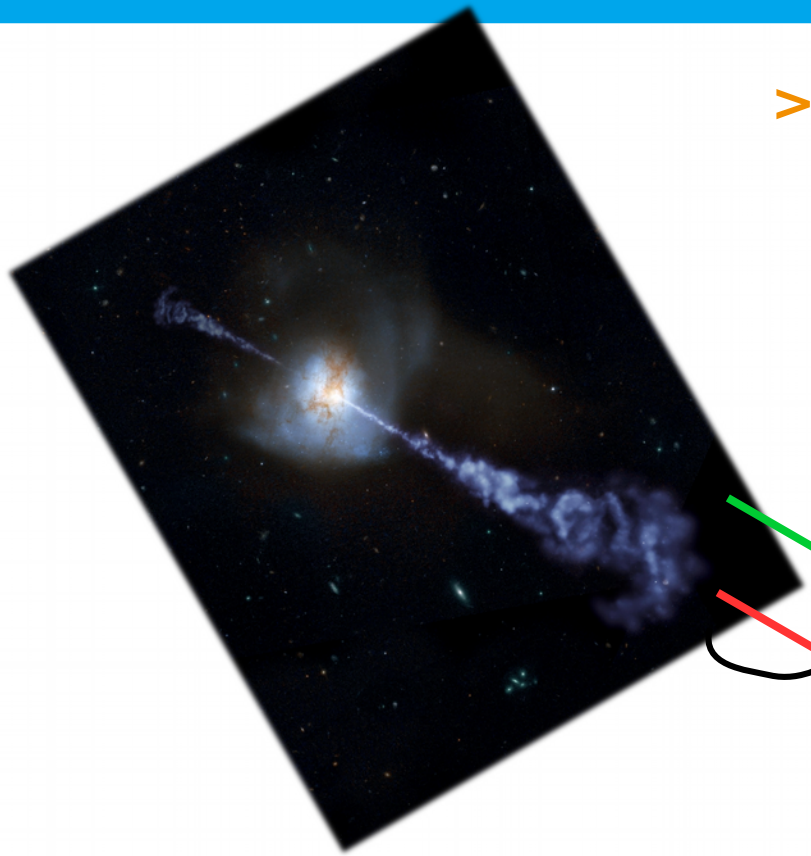
Torino, 2015/09/10

HELMHOLTZ
ASSOCIATION

ICECUBE

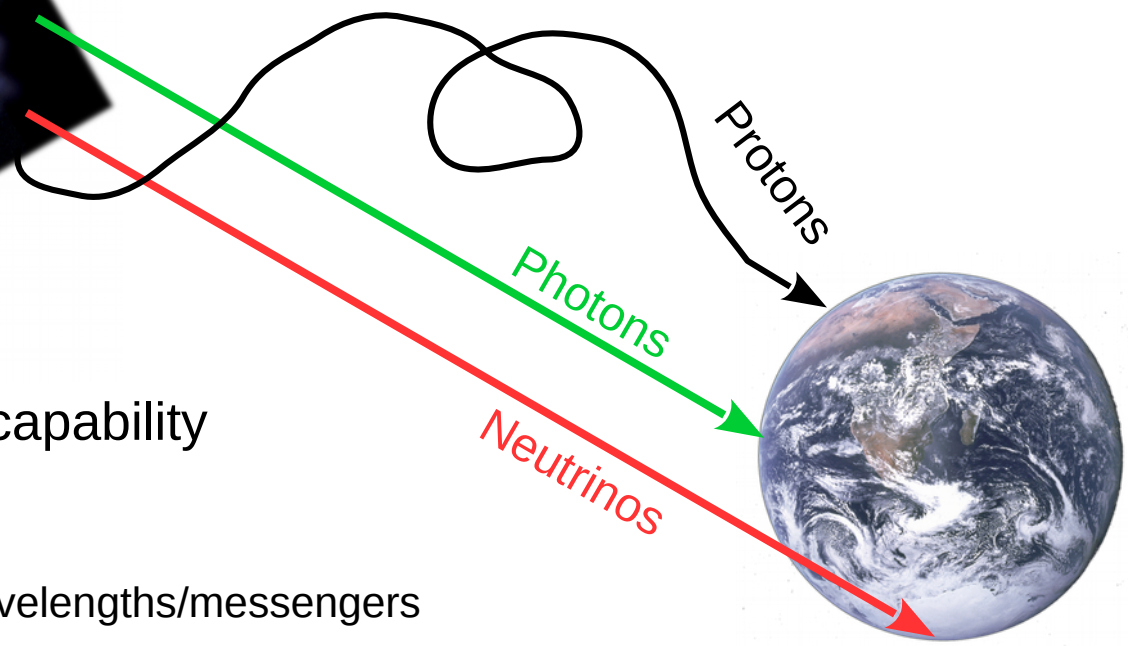
DESY

Multi-Messenger Observations



> Combination of different messengers:

- Increased sensitivity
- Obtain the complete picture



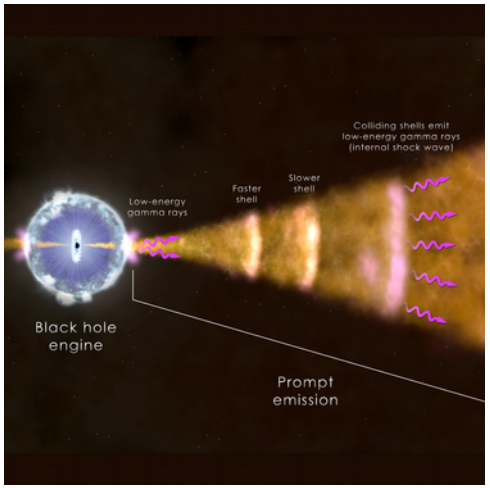
> IceCube: 4π 24/7 trigger capability

> Follow-Up Observatories:

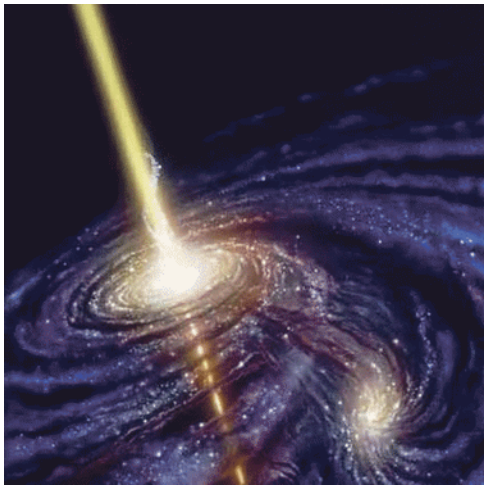
- Sensitive to different wavelengths/messengers
- Limited field of view, weather-dependent

Transient and Variable Sources

> Temporal evolution of astrophysical objects



GRB: 10 – 100 s



AGN flare: ~ 10 d

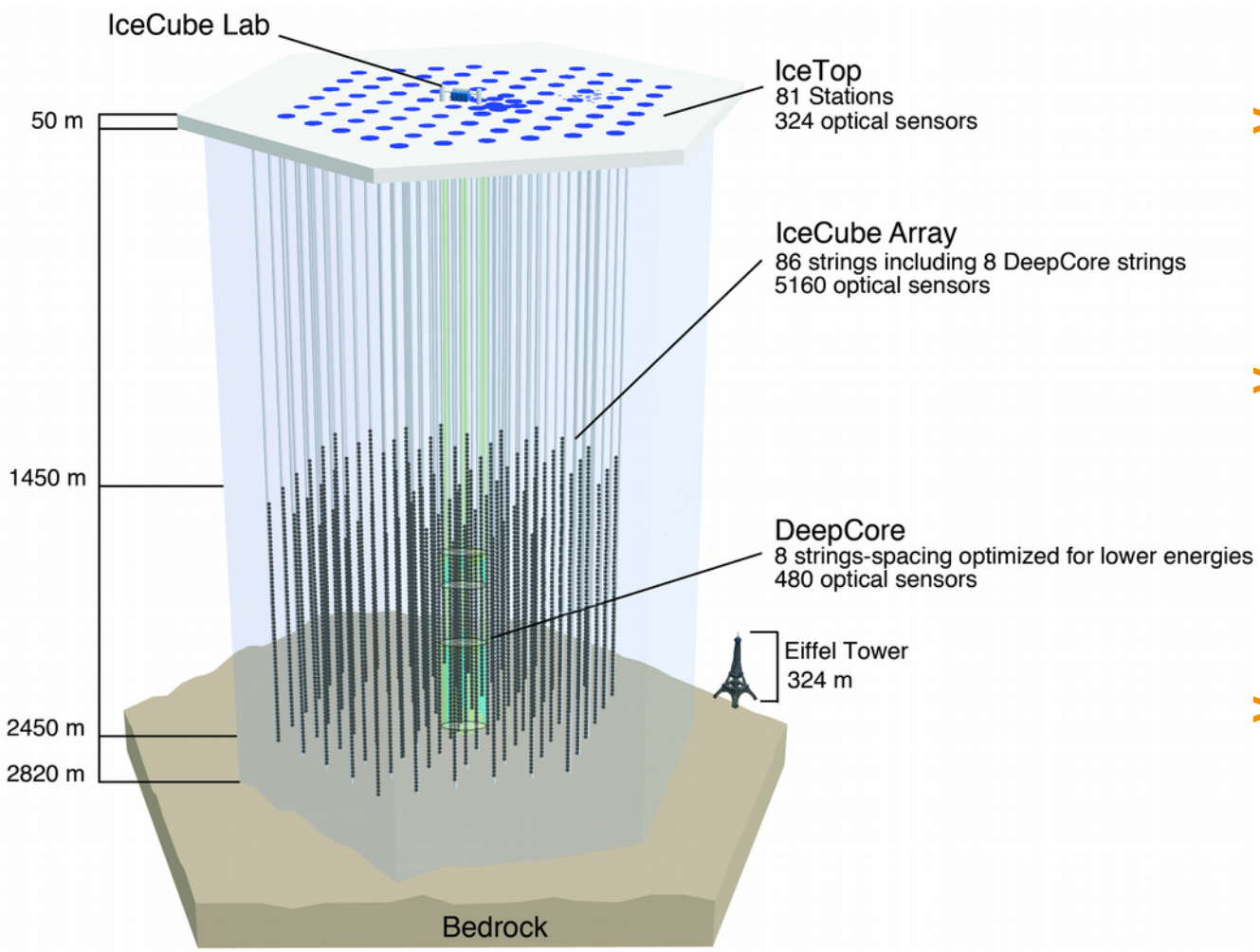
SN: ~ 100 d

> Wide variety of timescales for evolution

> Detectable in time-dependent analyses

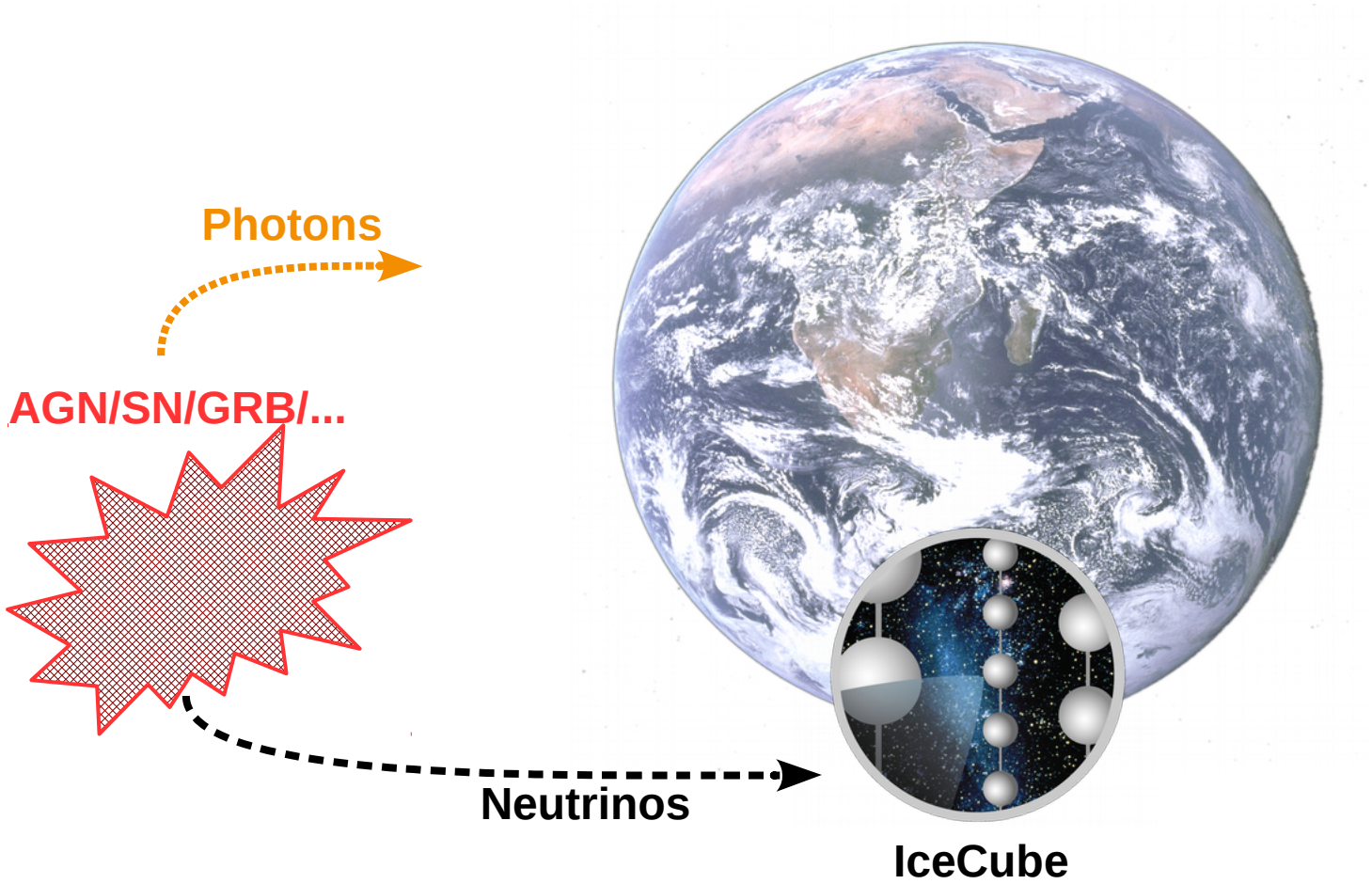
> Improved sensitivity from multi-wavelength observations

The IceCube Neutrino Observatory

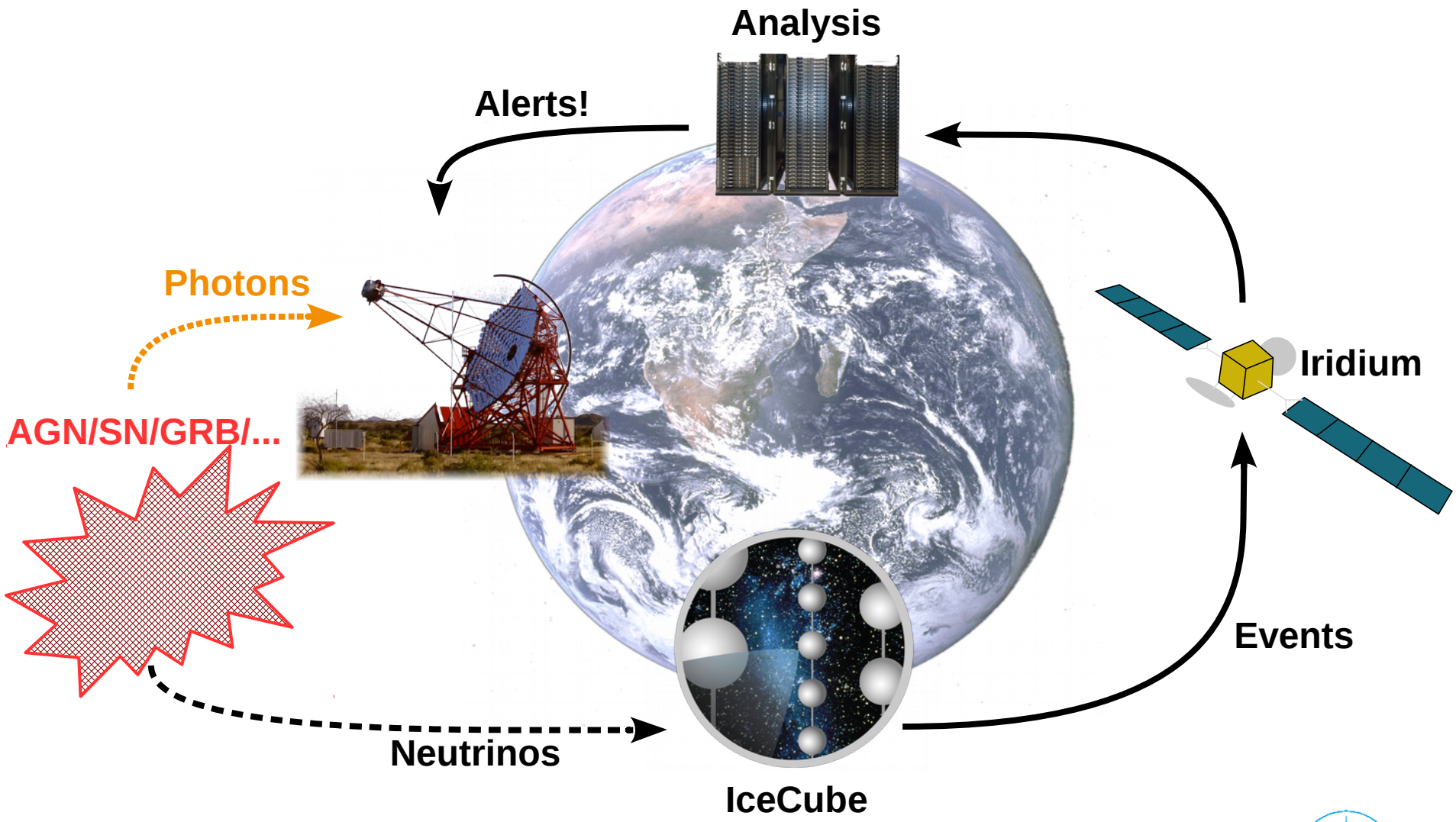


- 1km³ detector for Cherenkov light
- In this talk: μ-tracks from CC ν_μ-int.
- Angular resolution of ≤ 1 deg

The Follow-Up Procedure



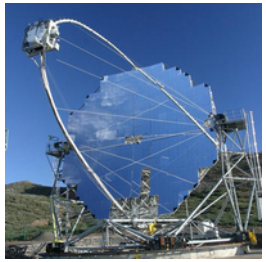
The Follow-Up Procedure

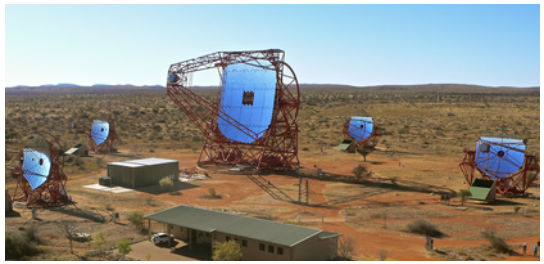


(Current) Follow-Up Observatories

> Gamma rays

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



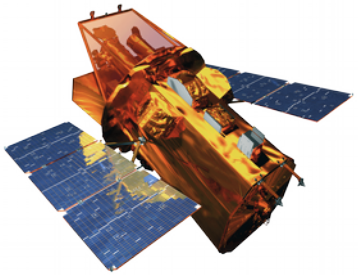


> Optical

- 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!**

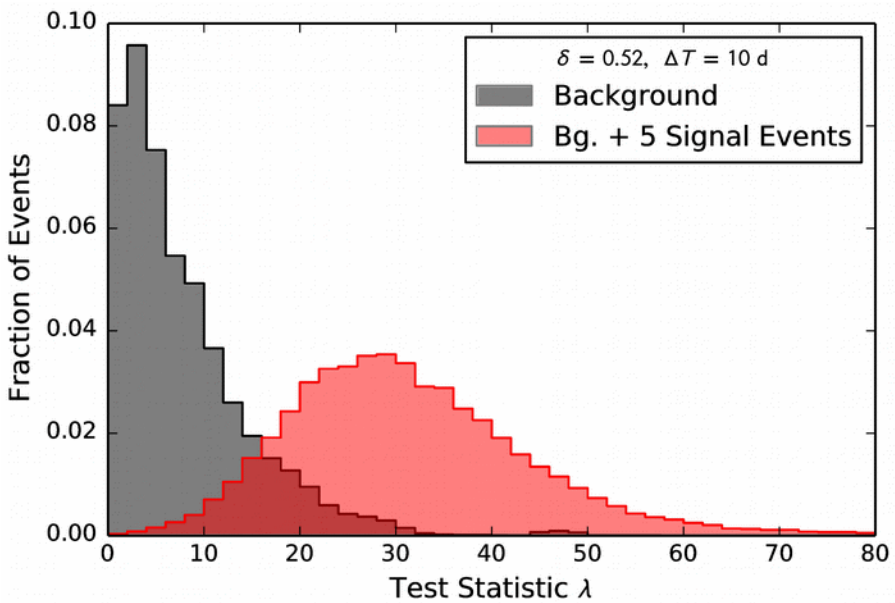
Status: Follow-Up with Gamma-Ray Observation

> Marginalized likelihood: $\mathcal{L}(x_i, t_i, E_i | n_{sig}, \gamma) = \prod_{i=0}^{N} \left(\frac{n_{sig}}{N} S_i + \left(1 - \frac{n_{sig}}{N}\right) B_i \right)$

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

> Test statistic:

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



> Significance threshold determined by allocated observation time:

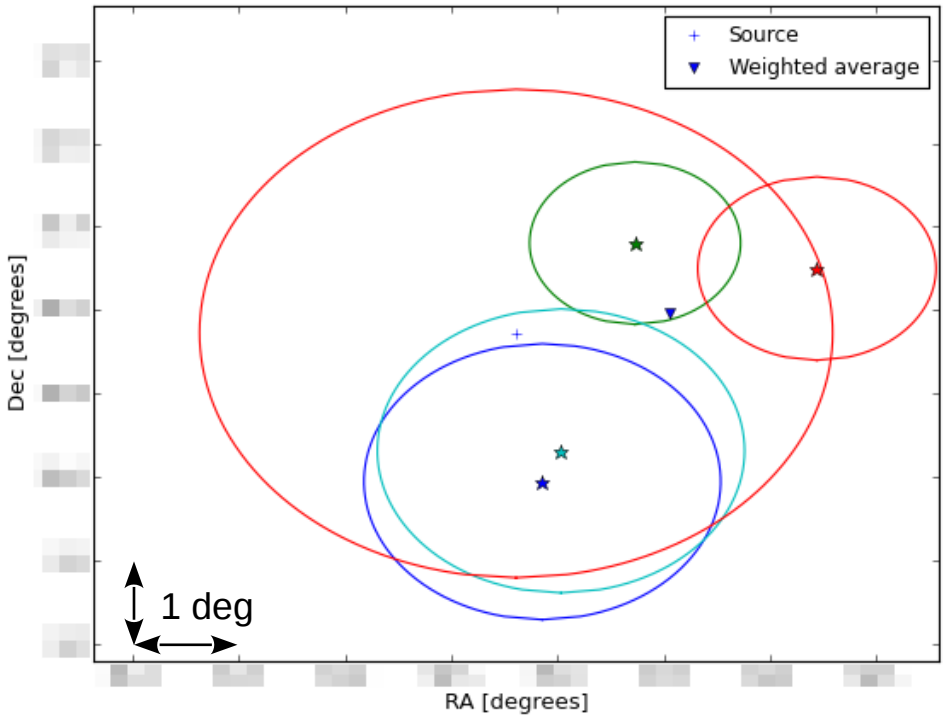
- VERITAS: -log10(p) = 3.663 (3.5σ)
- 40% observation probability (weather, etc.)
- ~ 3 alerts / year

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
  - $N_{observed}$: 4
  - Duration: 1.2 d
  - $-\log_{10}$(pre-trial p-value): 4.086

- Alert forwarded to VERITAS
- No observation due to scheduled maintenance...

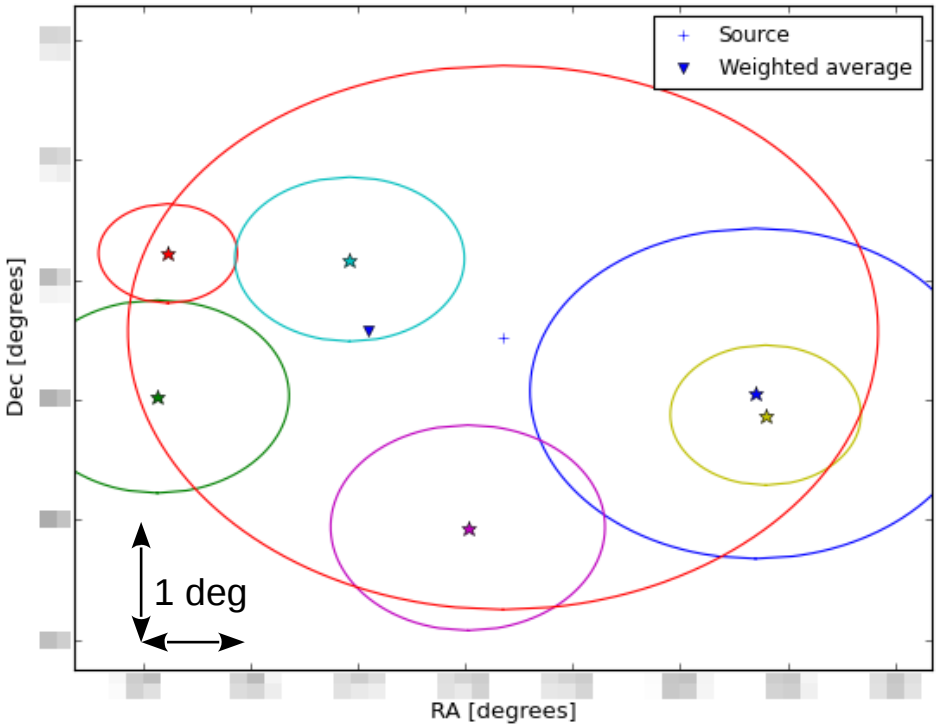


Status: Alerts from Gamma-Ray Follow-Up

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

- Most significant: 2012/11/09
  - $N_{observed}$: 6
  - Duration: 4.169 d
  - $-\log_{10}$(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: $\lambda = -2 \log \mathcal{L}$

$$= \frac{\Delta\Psi^2}{\sigma_q^2} + 2\log(2\pi\sigma_q^2) - 2\log\left(1 - \exp\left(-\frac{\theta_A^2}{2\sigma_w^2}\right)\right) + 2\log\left(\frac{\Delta T}{100\,\mathrm{s}}\right)$$

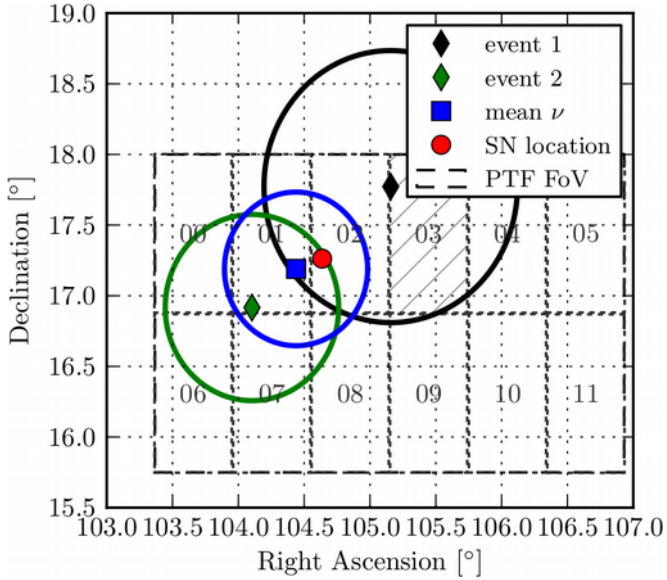
- angular separation, reconstruction quality, events in telescope's FoV, small time intervals

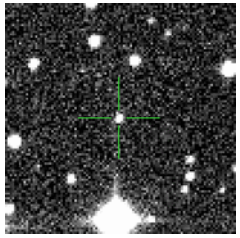
> Forwarding to

- 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

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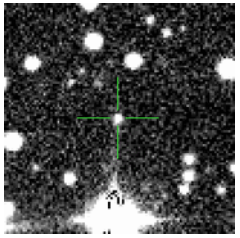
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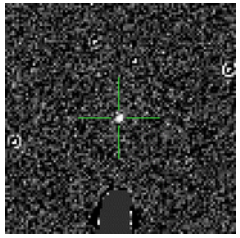
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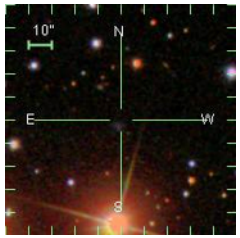


SDSS

Status: No triplet from Optical/X-ray Follow-Up

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

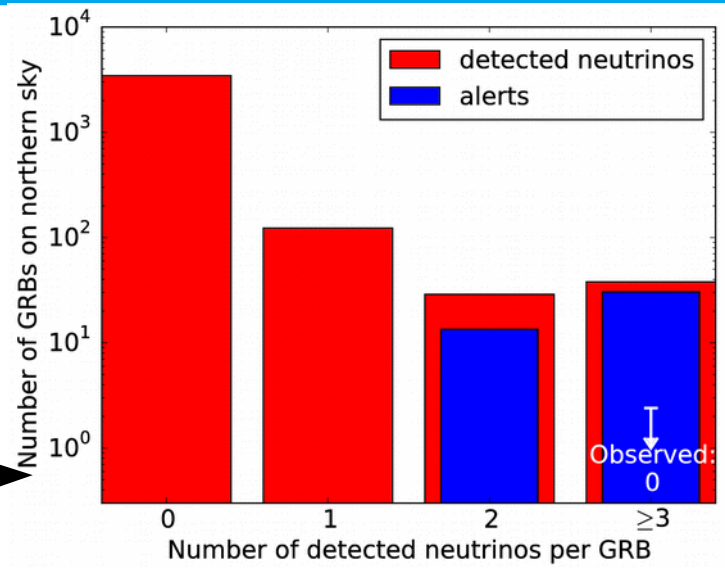
> Assume: Diffuse ν-flux from GRBs
→ Number of triplets?

- SWIFT: ~1500 GRBs/year/hemisphere

> 4500 GRBs emitting diffuse flux

> 10s of GRBs generating triplets

> … but none observed!



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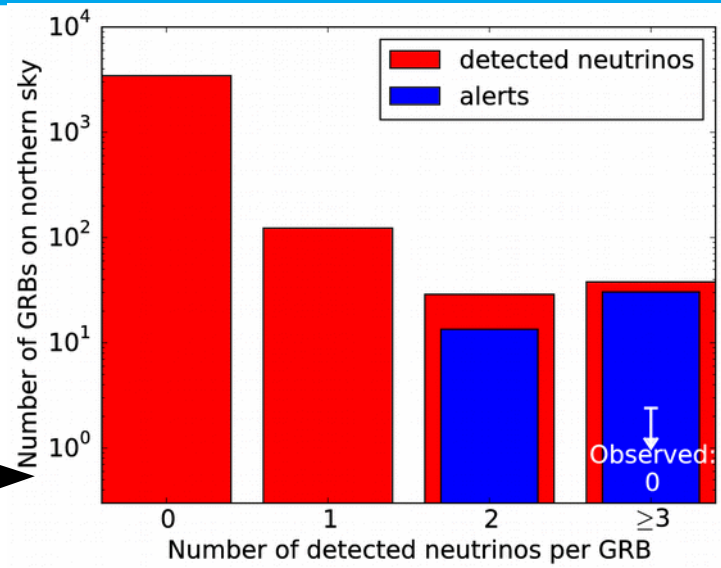
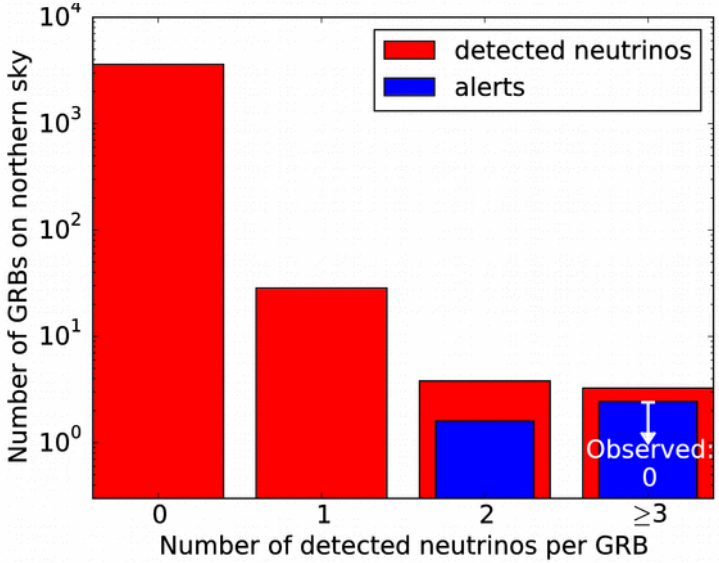


> brightest GRB: < 3 neutrinos!

> **Scaled contribution from GRBs yields limit on astrophysical ν-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

	Time (UTC)	$-\log_{10}$(pre-trial p-value)	N_{obs}	Duration (days)	Follow-up	Experiment observed
1	2012-04-14 23:47:44	3.47	6	7.617	No	**-**
2	2012-08-20 09:53:00	3.75	6	6.344	No	**-**
3	2012-09-13 01:52:06	4.06	2	0.001	**Yes (MAGIC)**	**No**
4	2012-11-09 07:28:28	4.64	6	4.169	**Yes (VERITAS)**	**Yes**
5	2013-04-29 06:36:05	4.07	8	15.801	No	-
6	2013-09-14 21:10:21	3.75 (4.01)	8 (10)	13.843 (20.73)	**Yes (MAGIC)**	**No**
7	2014-02-19 23:18:47	4.07 (4.59)	8 (10)	12.844 (19.667)	**Yes (VERITAS)**	**Yes**
8	2014-03-09 10:28:01	3.40	9	20.944	**Yes (MAGIC)**	**No**
9	2014-06-22 02:42:34	4.34	3	0.118	No	-
10	2014-09-24 13:47:29	3.20	2	0.007	No	-
11	**2014-10-05** 15:05:03	4.05	9	18.631	**Yes (VERITAS)**	**Yes**
12	**2014-11-16** 17:00:19	3.64 (5.04)	3 (4)	0.301 (0.576)	**Yes (VERITAS)**	**No**
13	**2015-04-27** 04:55:58	3.971	8	16.395	No	**-**

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

South Pole

- Visibility/Significance
- Follow-Up Observatory

- LLH Analysis
- Alert Generation

For each: OFU/ GFU

- Follow-Up Observatory

North

> Recent SPTS testing successful!

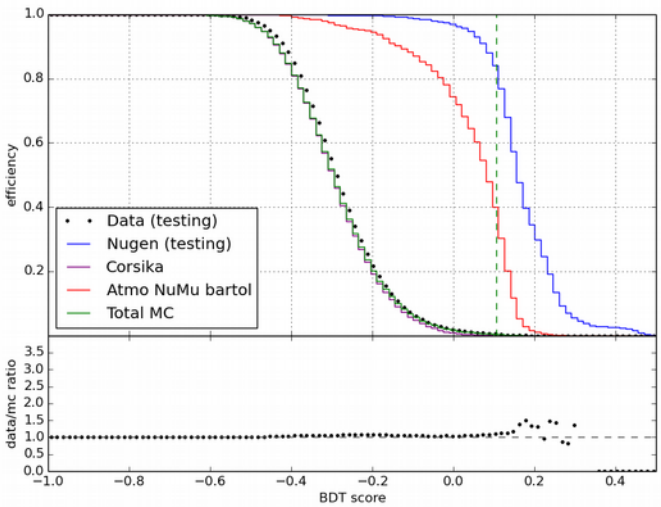
Updates for IC86-5: GFU BDT Selection

- Old: straight cuts, upgoing only
- New: BDT event selection using PyBDT
  - Upgoing BDT
    - Trained with spectrum of -2.7
    - Training Variables:
      - Bayesian LLH Ratio
      - ∢(MPE Fit, Line Fit)
      - 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_{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

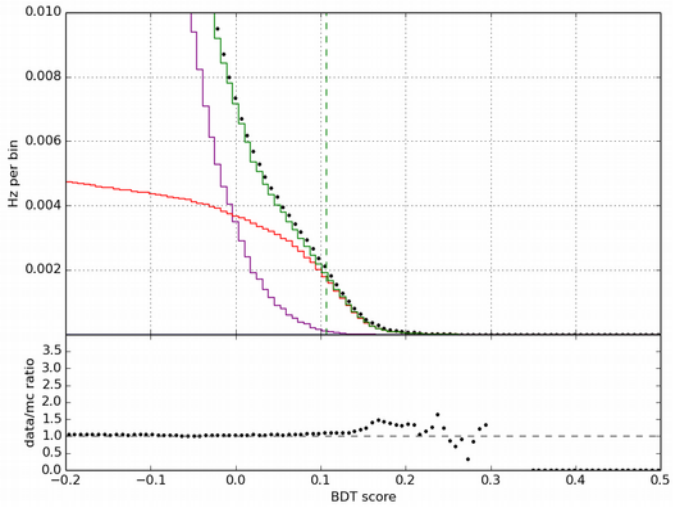
Updates for IC86-5: GFU BDT Selection

> Upgoing BDT:

- Efficiency:



Rate:



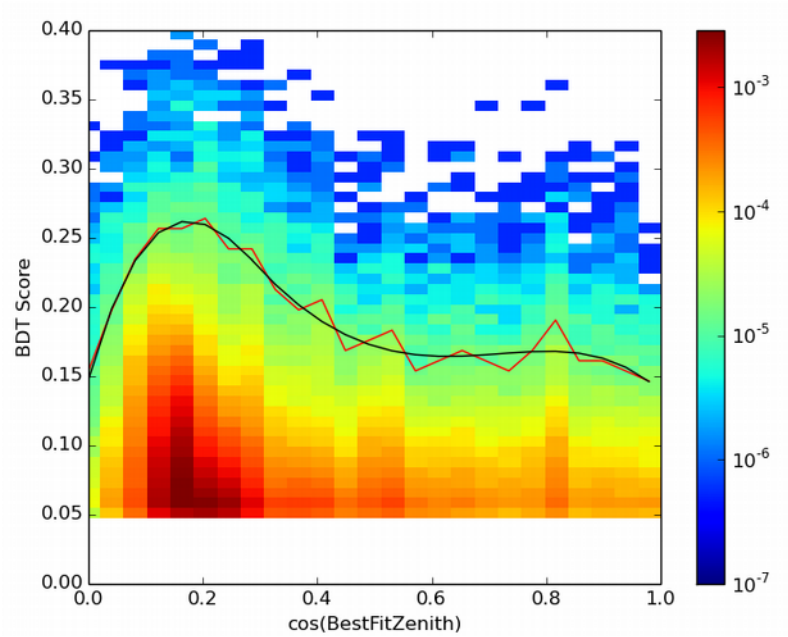
> Compared to straight cuts:

Method	Data rate	Atm. Nu Rate	E-2 efficiency
Straight Cuts	2.0 mHz	1.9 mHz	69 %
BDT Cut	1.9 mHz	1.7 mHz	81 % (+12%)

Updates for IC86-5: GFU BDT Selection

> Downgoing 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:

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

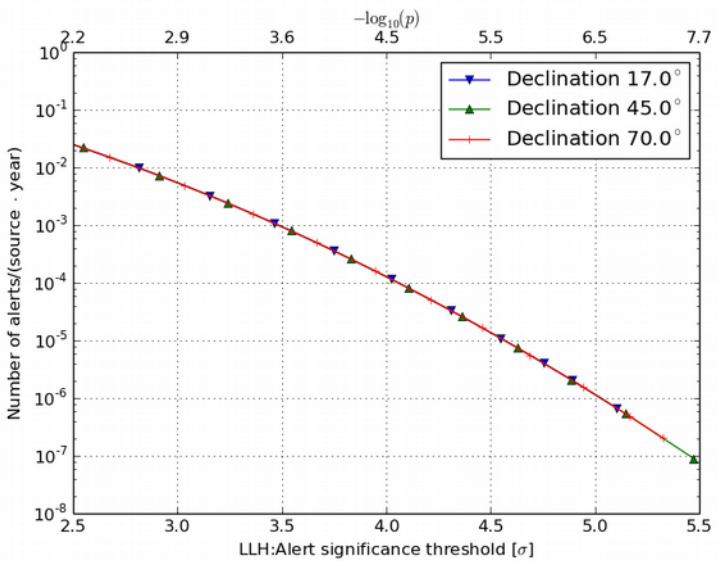
$$S_i = \mathcal{E}(E_i|\gamma) \times \frac{1}{2\pi\sigma^2} \exp - \frac{|\vec{x}_i - \vec{r}|^2}{2\sigma_i^2} \times \frac{1}{U(T_e, T_s)} \qquad B_i = \frac{1}{\Omega} \times \mathcal{E}(E_i|\nu_\mu^{\mathrm{atm}}) \times \frac{1}{U(T_e, T_s)}$$

> Test statistic:

$$\lambda = -2 \ln \left(\frac{U(T_s^{\mathrm{sig}}, T_e)}{U(T_s, T_e)} \frac{\mathcal{L}(\gamma = 0)}{\mathcal{L}(\gamma, n_{\mathrm{sig}})} \right)$$

> Significance threshold determined by observation time:

- VERITAS: -log10(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:

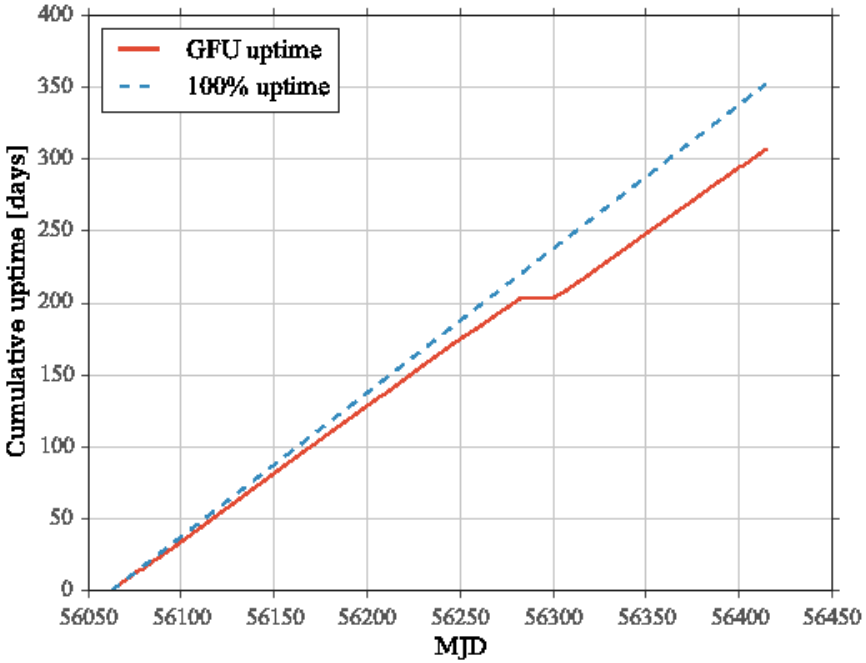
$$S_i = \alpha x_i + (1-\alpha) S_{i-1} \qquad \alpha = 0.01$$

$$\sigma_i = \sqrt{\langle x^2 \rangle - S_i S_i}$$

- **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!

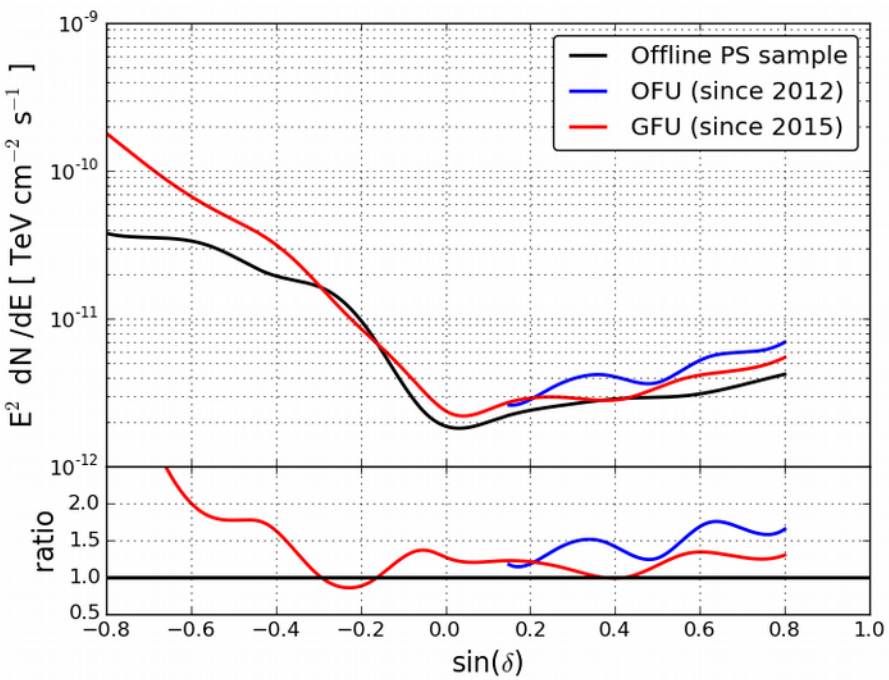
- Also a generalised likelihood?

> 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