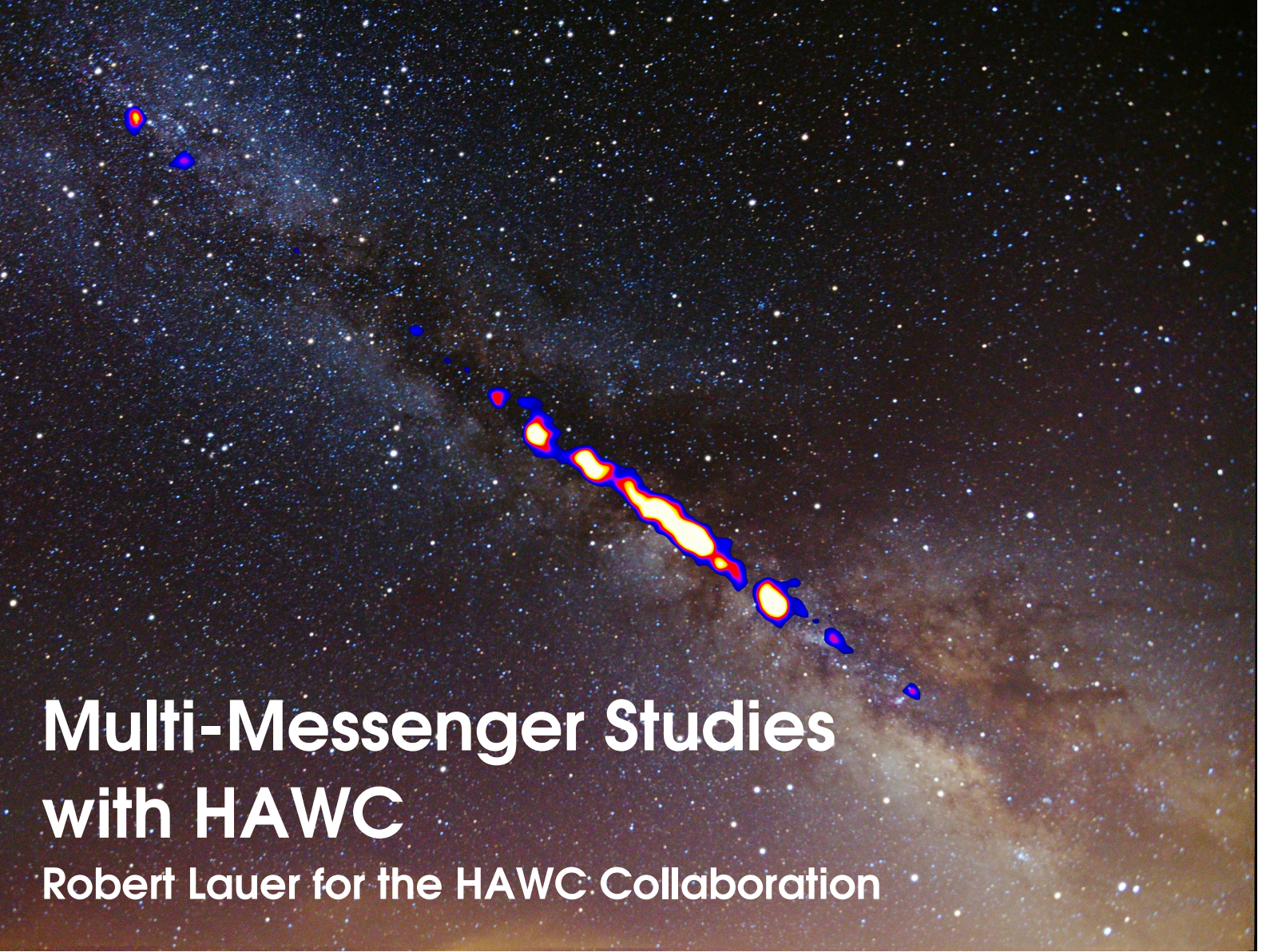


Multi-Messenger Studies with HAWC

Robert Lauer for the HAWC Collaboration

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

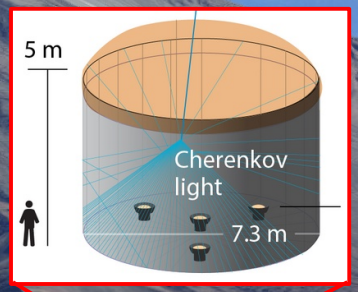
THE UNIVERSITY of NEW MEXICO

AMON Workshop
Cochem, Germany
Dec 10, 2016

The HAWC Observatory

- **22,000 m^2** air shower array
- **300 Water Cherenkov detectors** (WCD)
- **200,000 liters** of purified water **per WCD**
- **4 PMTs per WCD** (3x 8" from Milagro + 1x 10"high QE)
- **Completed March 2015**

Citlaltepetl
Pico de Orizaba
5610m a.s.l.

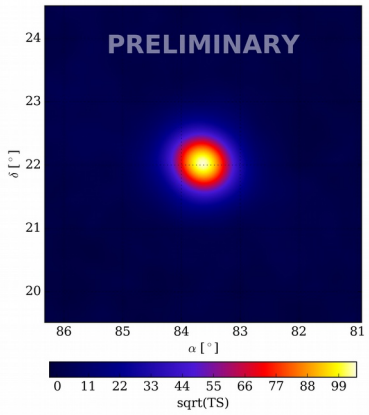


HAWC
4100 m a.s.l.

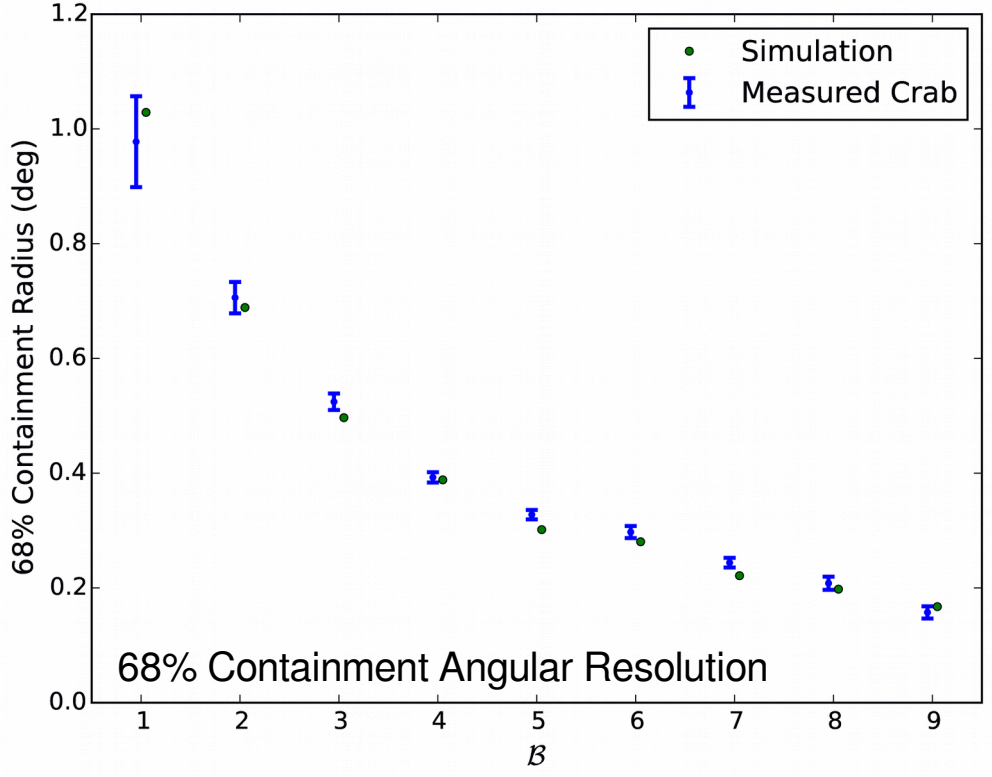
Large Millimeter Telescope
Alfonso Serrano

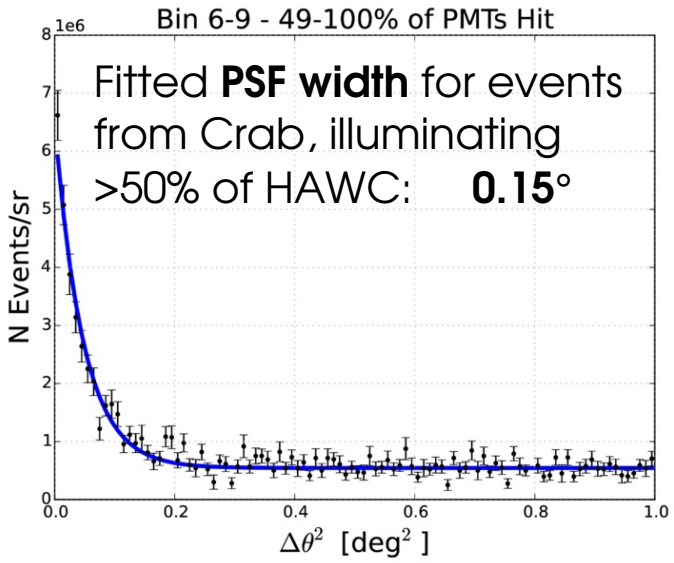
Tliltepetl
Sierra Negra
4582m a.s.l.

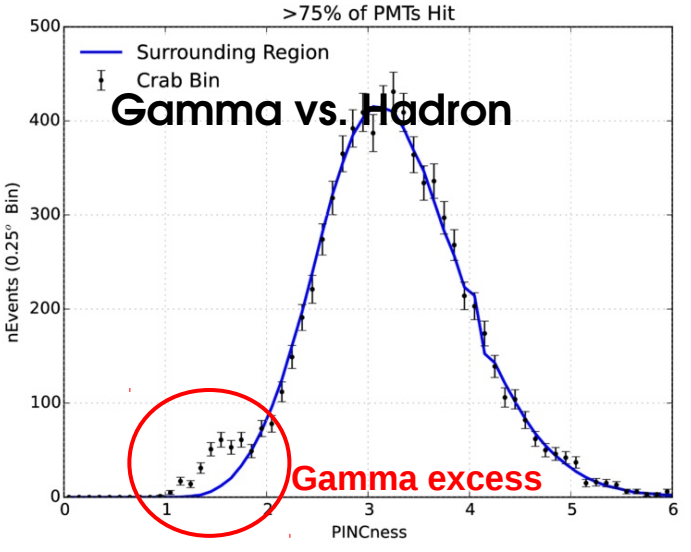
Crab Nebula Performance



Crab Pulsar Wind Nebula:
>100σ detection in 508 transits



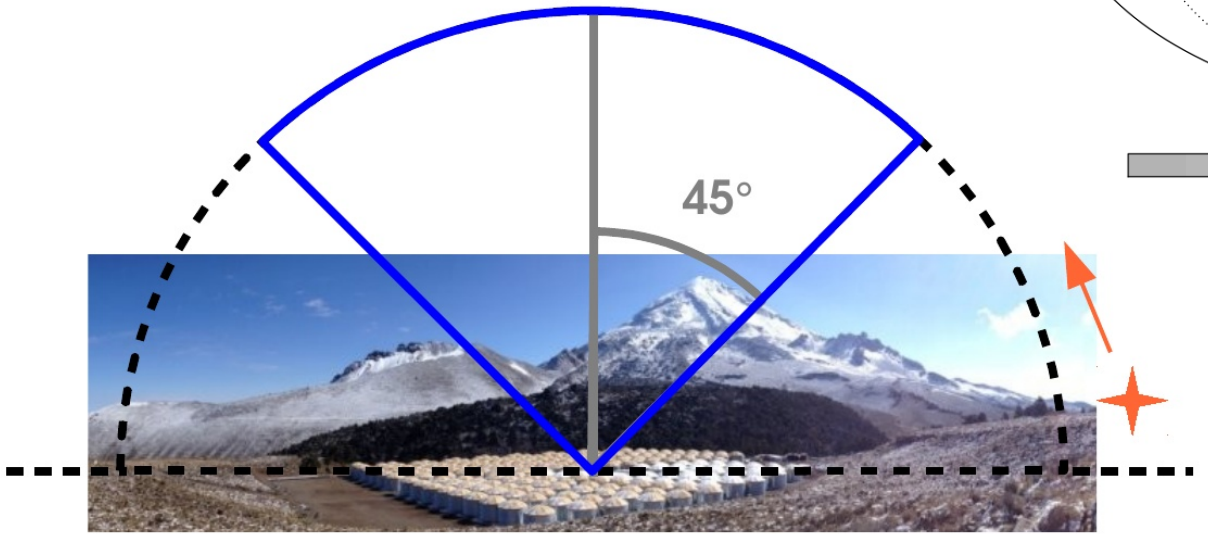


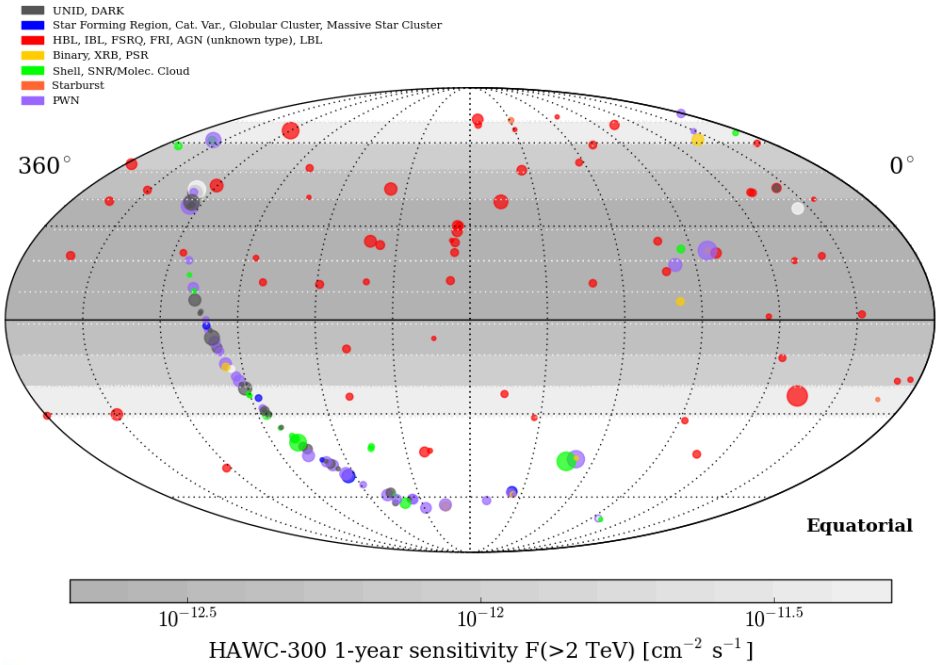


HAWC Field of View

2 sr instantaneous FoV:
Monitoring 2/3 of the sky each day

Maximum transit time: ~6 hours
for sources with peak elevation near zenith
(e.g. the Crab)



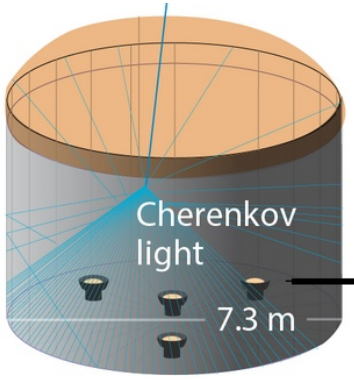


Red: **TeV-emitting AGNs** (TeVCat)

HAWC is continuously monitoring the sky between declinations -25 and +65

Average Crab significance: 5σ
(culminates 3° from zenith)

Online: Automated Monitoring

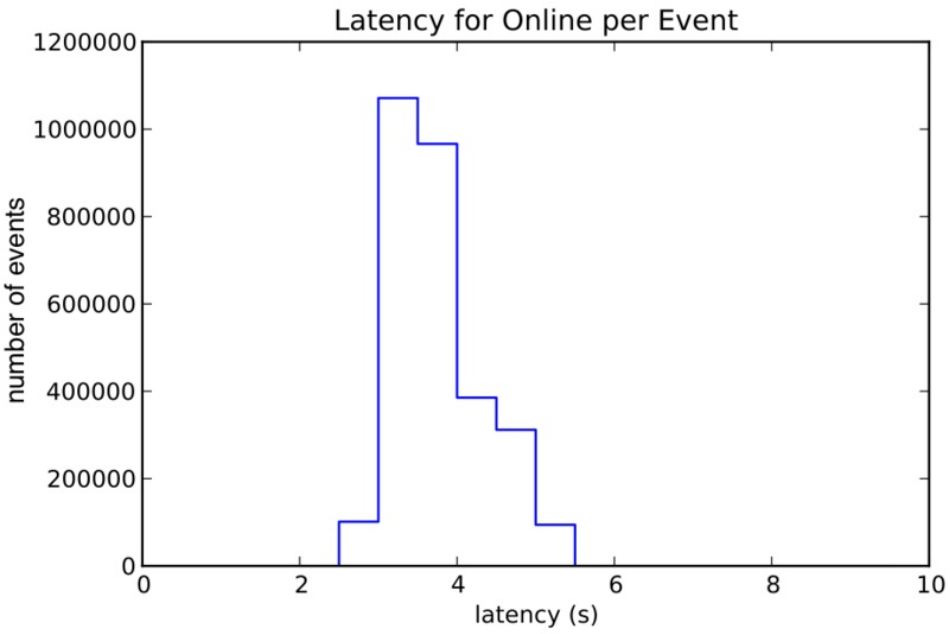


Data Acquisition:
Time-to-Digital
Converter

Trigger Software

Reconstruction Clients

Disk
for transport
off-site



Daily Light Curve Monitor

All-sky GRB search

Triggered GRB follow-ups

Targeted short flare monitor

All-sky long-flare monitor

Coming soon

HAWC Transient Operation Modes

HAWC-Triggered Alerts

- **Automated analysis program** running online
- Different searches optimized e.g. for GRBs and AGN flares
- Internal email alerts when thresholds are passed
- **Fast review and GCN/ATEL templates** for expected alerts

External Triggers with HAWC Follow-Up

- **Multi-wavelength and Multi-Messenger Triggers received** via:
  - private MoU contacts
  - public GCNs, ATELs
- Follow-up on **various time scales**, depending on type of alert
- Both automated and manual follow-ups

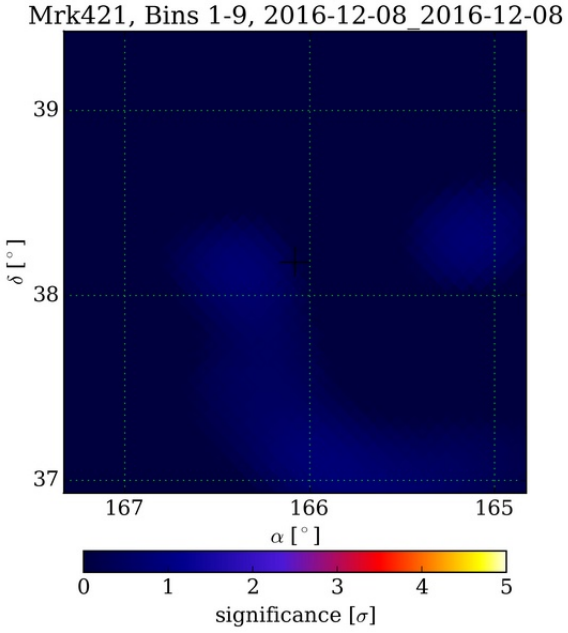
HAWC-Triggered Alerts

Online Light Curve Monitoring: Thresholds

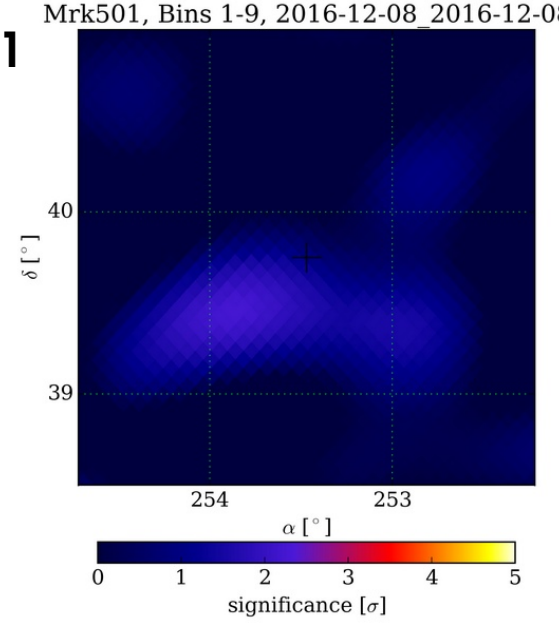
Lauer et al.
Proc. Of Gamma2016,
arXiv 1610.05172

Currently, Mrk 421 and 501 are the only extra-galactic HAWC detections

Mrk 421



Mrk 501



Available minutes after completed (6 hour) transit

Current threshold for flare alerts of the Markarians:

~3 Crab Units*, based on IACT community consensus → **6^{-11} photons cm^{-2} s^{-1} above 1 TeV**

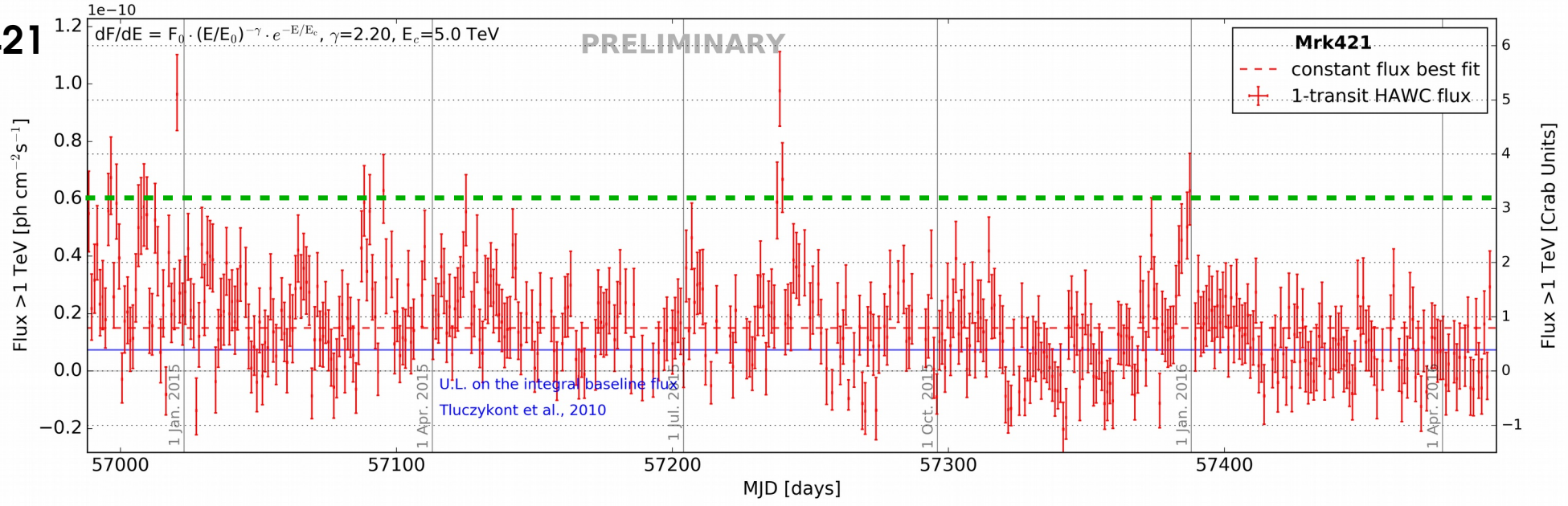
*** depends on threshold and assumed spectrum**

Online Light Curve Monitoring: Thresholds

Currently, Mrk 421 and 501 are the only extra-galactic HAWC detections

Lauer et al.
Proc. Of Gamma2016,
arXiv 1610.05172

Mrk 421



Current threshold for flare alerts of the Markarians:

~3 Crab Units, based on IACT community consensus → **6^{-11} photons cm^{-2} s^{-1} above 1 TeV**

Given the HAWC 1-transit statistical uncertainties: Mrk 421 → ~5σ
Mrk 501 → **~9σ**

Large potential for "sub-threshold" alerts, if desired!

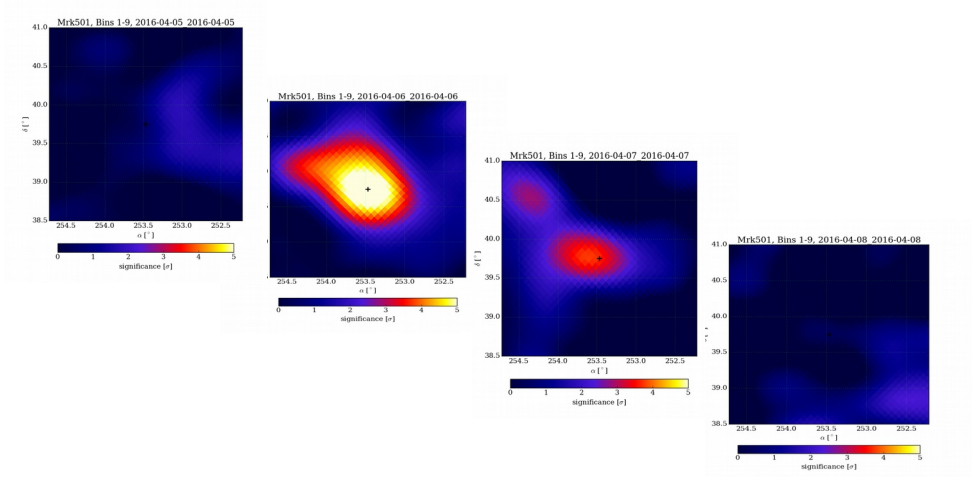
Online Light Curve Monitoring: Two Flare Alerts in 2016

First HAWC flare trigger

HAWC detection of increased TeV flux state for Markarian 501

ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar



First joint HAWC flare announcement

Enhanced and increasing activity in gamma rays and X-rays from the HBL Mrk421

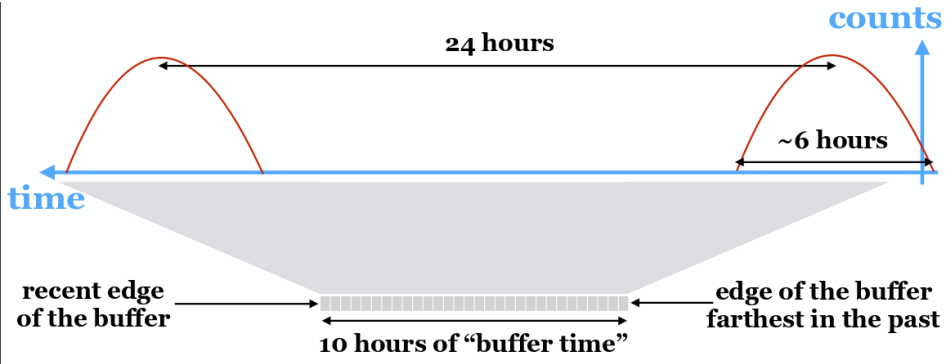
ATel #9137; *A. Biland (ETH Zurich) and D. Dorner (University of Wuerzburg, FAU Erlangen) for the FACT Collaboration, R. Lauer (University of New Mexico) and J. Wood (University of Maryland) for the HAWC Collaobration, B. Kapanadze (Abastumani Astrophysical Observatory, Ilia State University), A. Kreikenbohm (University of Wuerzburg)*
on 10 Jun 2016; 19:00 UT
Credential Certification: Daniela Dorner (dorner@astro.uni-wuerzburg.de)

Subjects: X-ray, Gamma Ray, TeV, VHE, AGN, Blazar

FACT and HAWC with daily TeV coverage and complementary observation windows.

HAWC, FACT and SWIFT all show **rising fluxes with highest values on June 9, 2016** (~ 3 x Crab flux).

Online Flare Monitor: Fast Detection of Extreme Flares

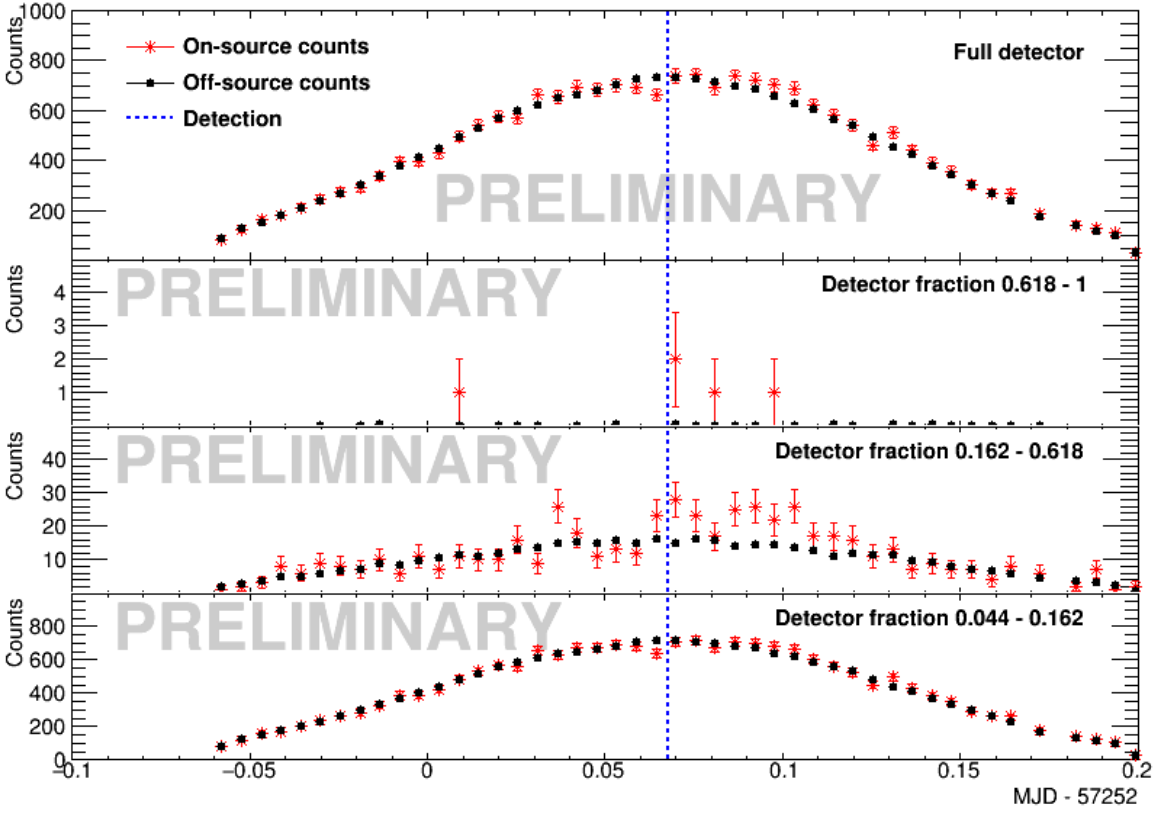


Real-time rate monitor for known blazar directions, identifying flares from excess rates via Bayesian Blocks algorithm.

Fast Flare Monitor is now running online!
After test period, alerts of large flares will automatically be sent immediately after detection.

Weisgarber et al.
Proc. Of Gamma2016,
arXiv 1610.05685

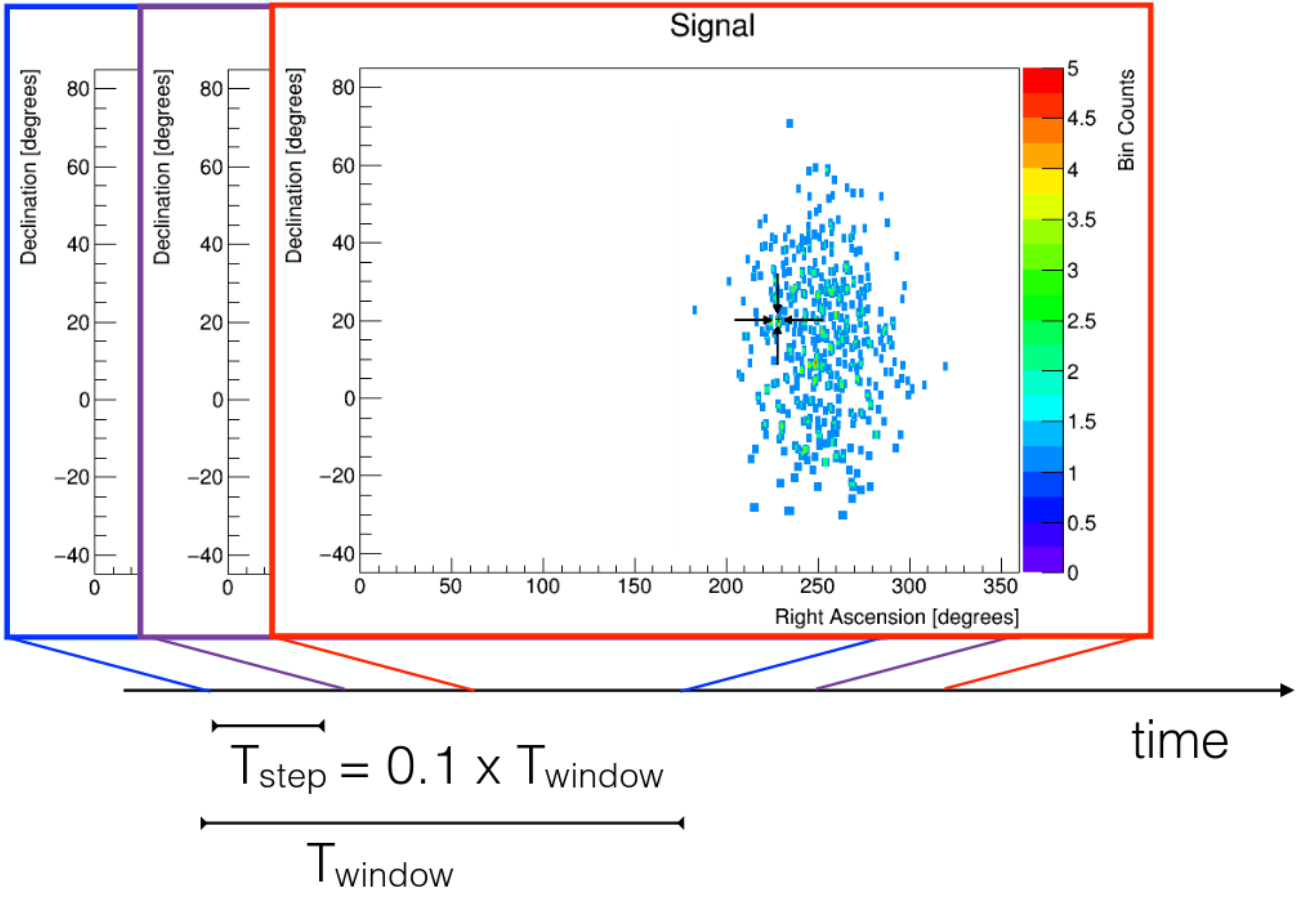
Test on offline data:
Markarian 501 in HAWC data from August 18, 2015



Untriggered GRB Search

- **Search all of HAWC sky:**
  0-50° in zenith
- Three sliding time windows:
  0.2, 1, and 10 seconds
- **2.1° x 2.1°** spatial bin
- GRB-optimized:
  single energy-proxy bin

So far no detection



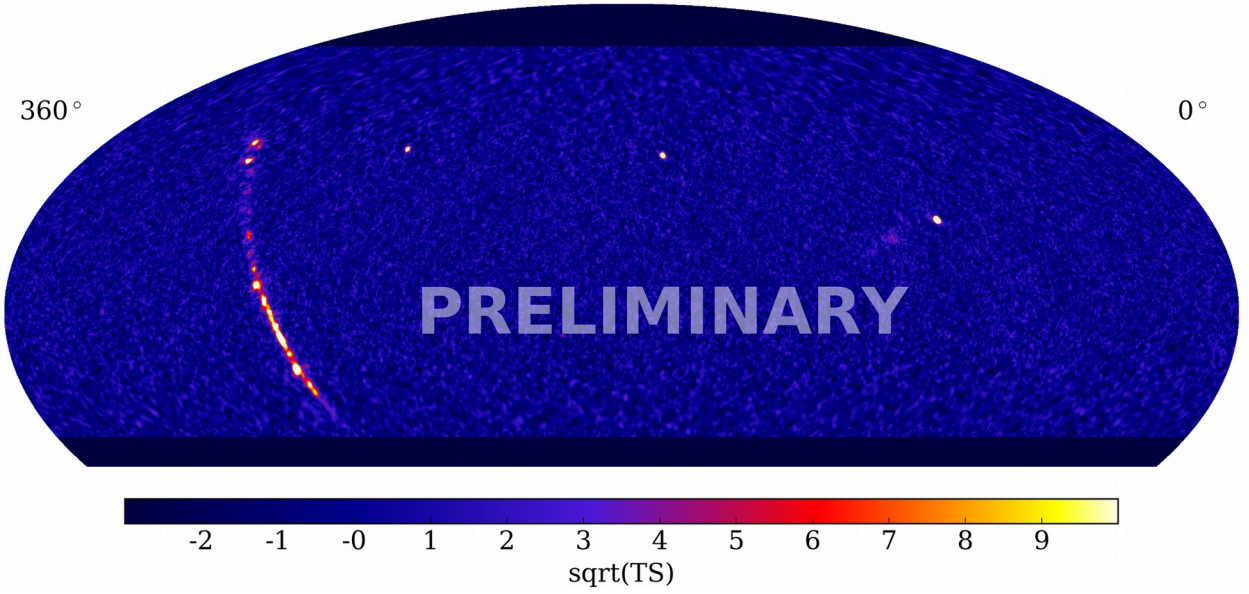
Wood et al.
Proc. Of ICRC 2015,
arXiv 1508.04120

External Alert Follow-Up

Offline Follow-Up: Time Integrated and Day-Scale Searches

1) For potentially steady or repeating sources:

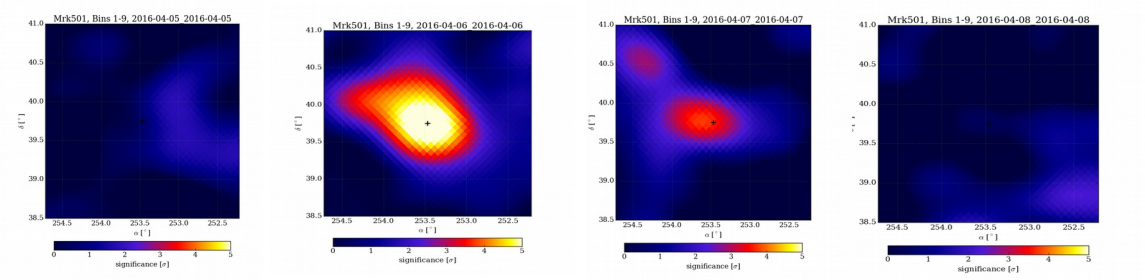
   Use **all past integrated data** and provide total significance and **average flux (limits)**



2) For potentially variable sources:

   Time-resolved scan, for example GRB-like (seconds) or Blazar-like (one to a few transits)

   We regularly follow up e.g. on Fermi-LAT flare advocate alerts (under MoU)



Gamma-Ray Burst Follow-Up

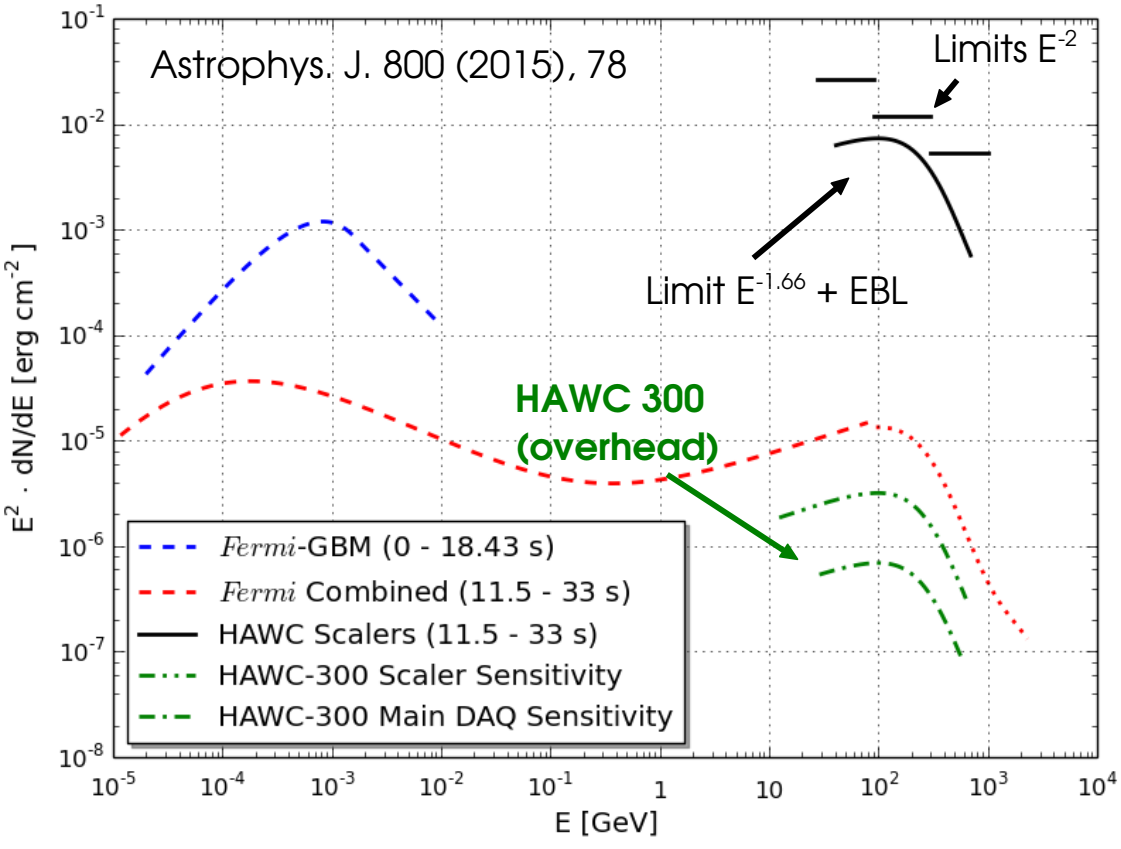
Expecting clear signal from known high energy burst type:
- Abeysekara et al., 2014 **ApJ** 800, 70
- Gilmore & Taboada, **NIM** A 2013

Online Algorithms:

Triggered GRB Follow-Up:
Automated check of GRB alerts (Swift and GBM).

So far no detection in HAWC

Forthcoming publication on limits for bursts with HAWC coverage over the last 2 years.



IceCube Neutrino Follow-Up

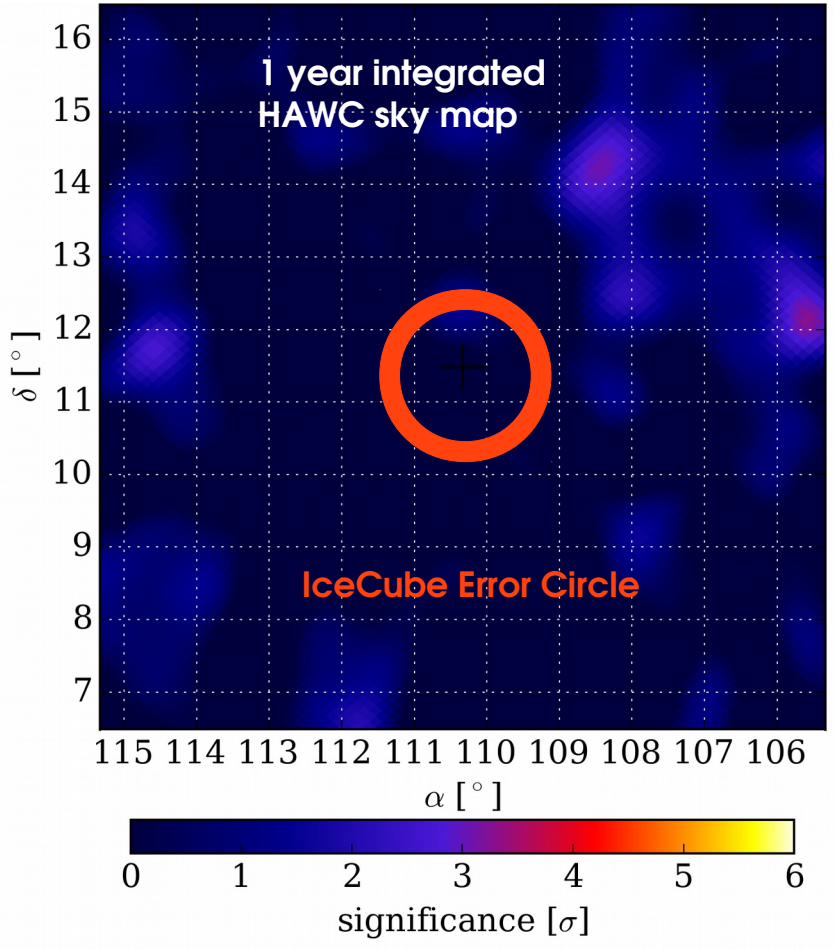
IceCube ATEL #7856:

- Highest energy Muon Neutrino with **E > 2.6 PeV,** June 11, 2014
- If neutrinos from $\pi^{+/-}$-decay, we **expect γ–rays from π^0-decay**

HAWC (1/3 completed), ATel: #7868

- 1 year integrated map (steady source)
- Short time searches ±1, ±2 and ±5 days

→ **Results consistent with only background**



IceCube Neutrino Follow-Up

IceCube ATEL #7856:

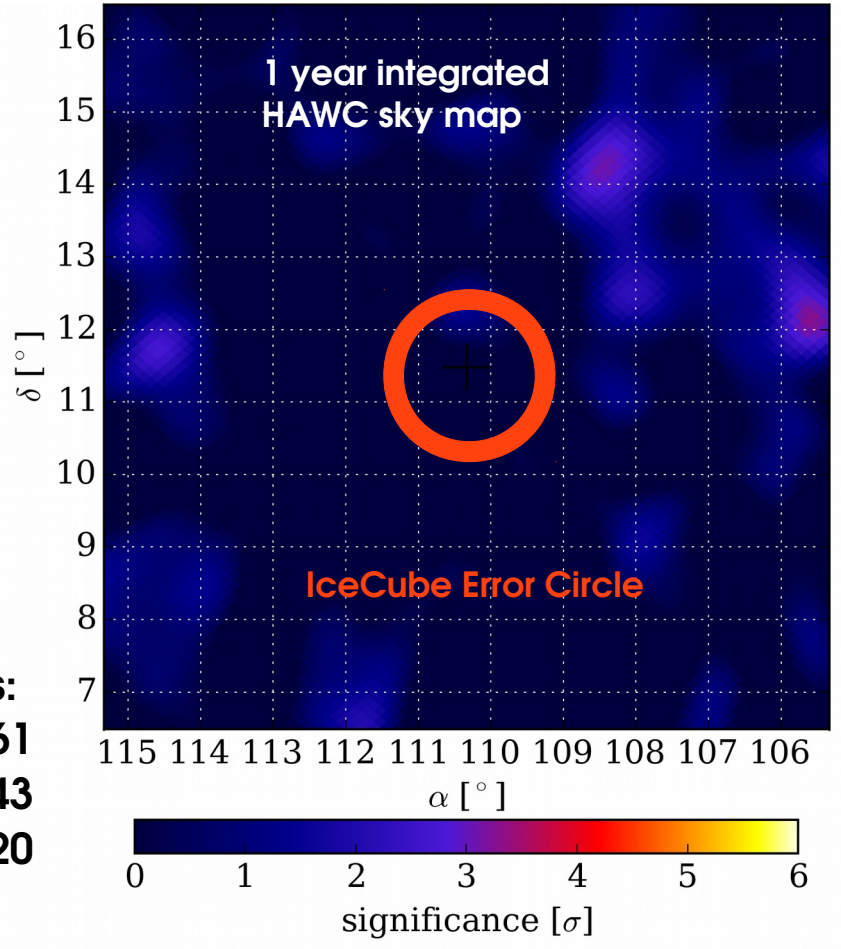
- **Highest energy Muon Neutrino** with **E > 2.6 PeV**, June 11, 2014
- If neutrinos from $\pi^{+/-}$-decay we **expect γ–rays from π^0-decay**

HAWC (143 completed) ATel: #7868

- 1 year integrated map (steady source)
- Short time searches ±1, ±2 and ±5 days

→ **Results consistent with only background**

Now routine operation for new alerts

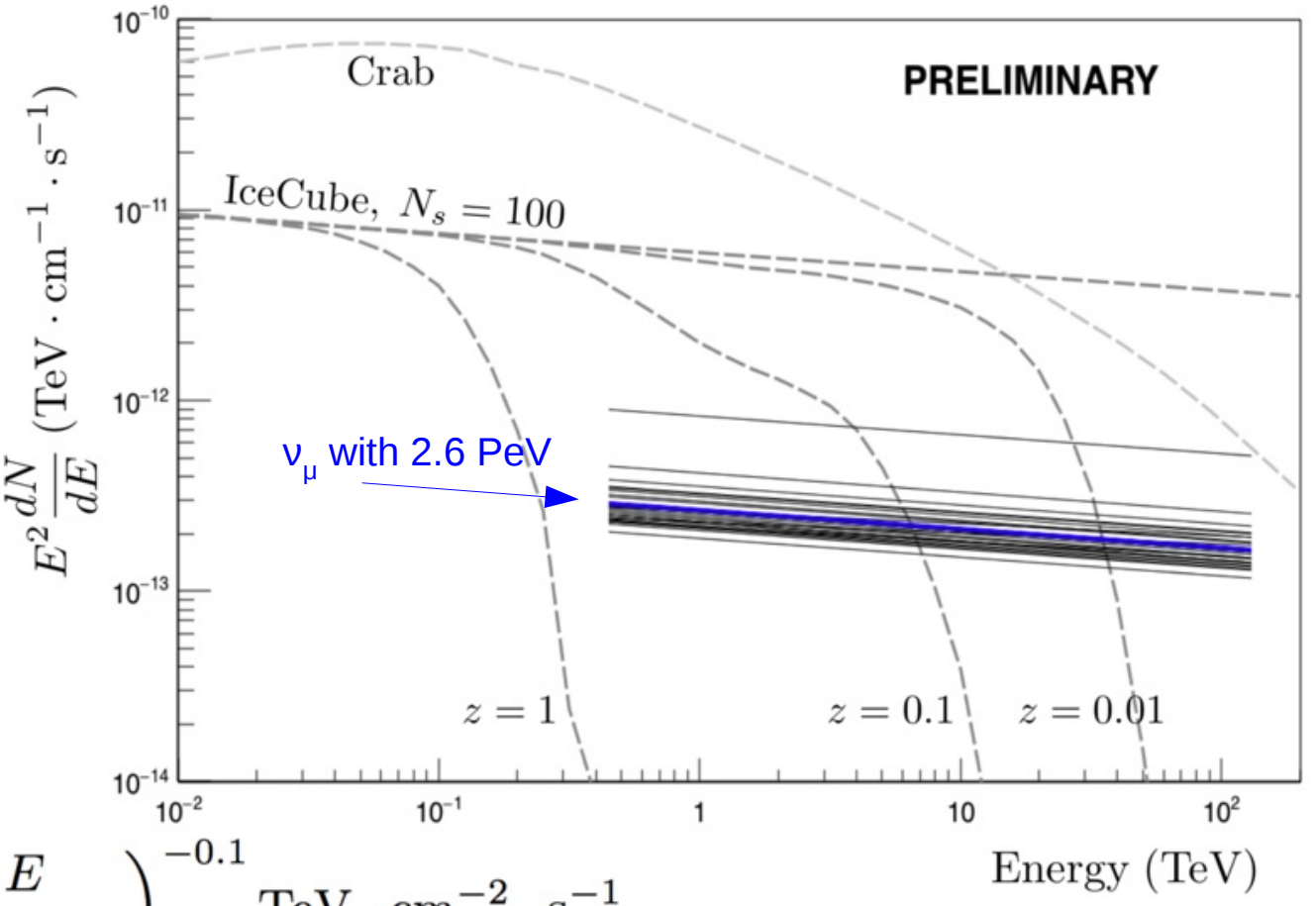


Most recent HAWC follow-ups on similar IceCube events:

- IceCube 20160427: HAWC non-detection **GCN 19361**
- IceCube 20160731: HAWC non-detection **GCN 19743**
- IceCube 20161103: HAWC non-detection **GCN 20120**

IceCube Follow-Up

IceCube **locations of 28 highest energy neutrino tracks** in 6 years of data, see Aartsen aet al., 2016, arXiv:1607.08006



HAWC time-integrated limits compared to expected fluxes assuming IceCube **neutrino flux is steady and originating from N_s point sources:**

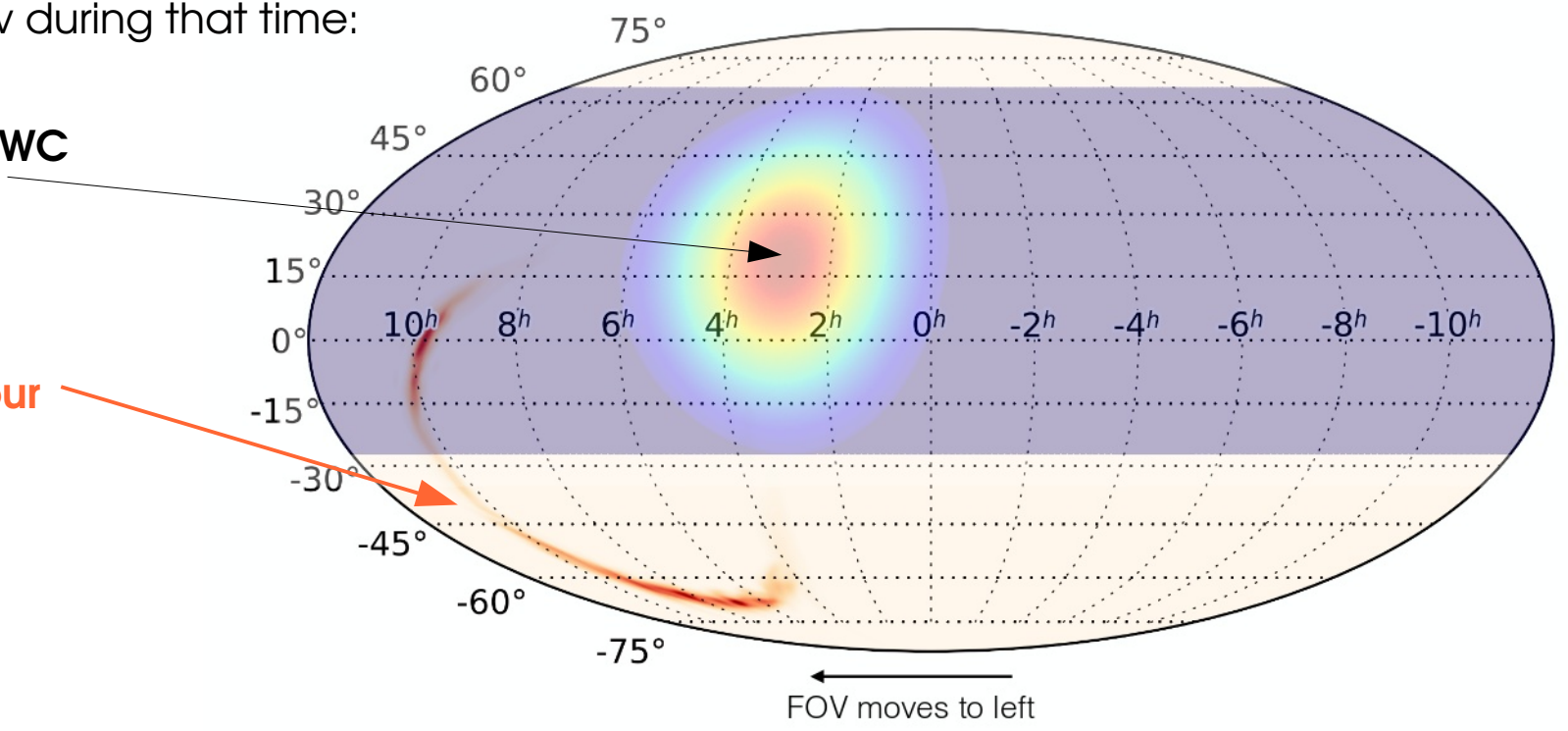
$$E^2 \frac{dN_\nu}{dE} = \frac{4\pi}{N_s} \times 3 \times 10^{-11} \left(\frac{E}{100\ \mathrm{TeV}} \right)^{-0.1} \mathrm{TeV} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$$

(N_S >70 suggested by IceCube data, PRL 2014)

Follow-up on first Gravitational Wave Alert

LIGO: GW150914, 2015-09-14 09:50:45 UTC, **first gravitational wave detection**

HAWC field of view during that time:

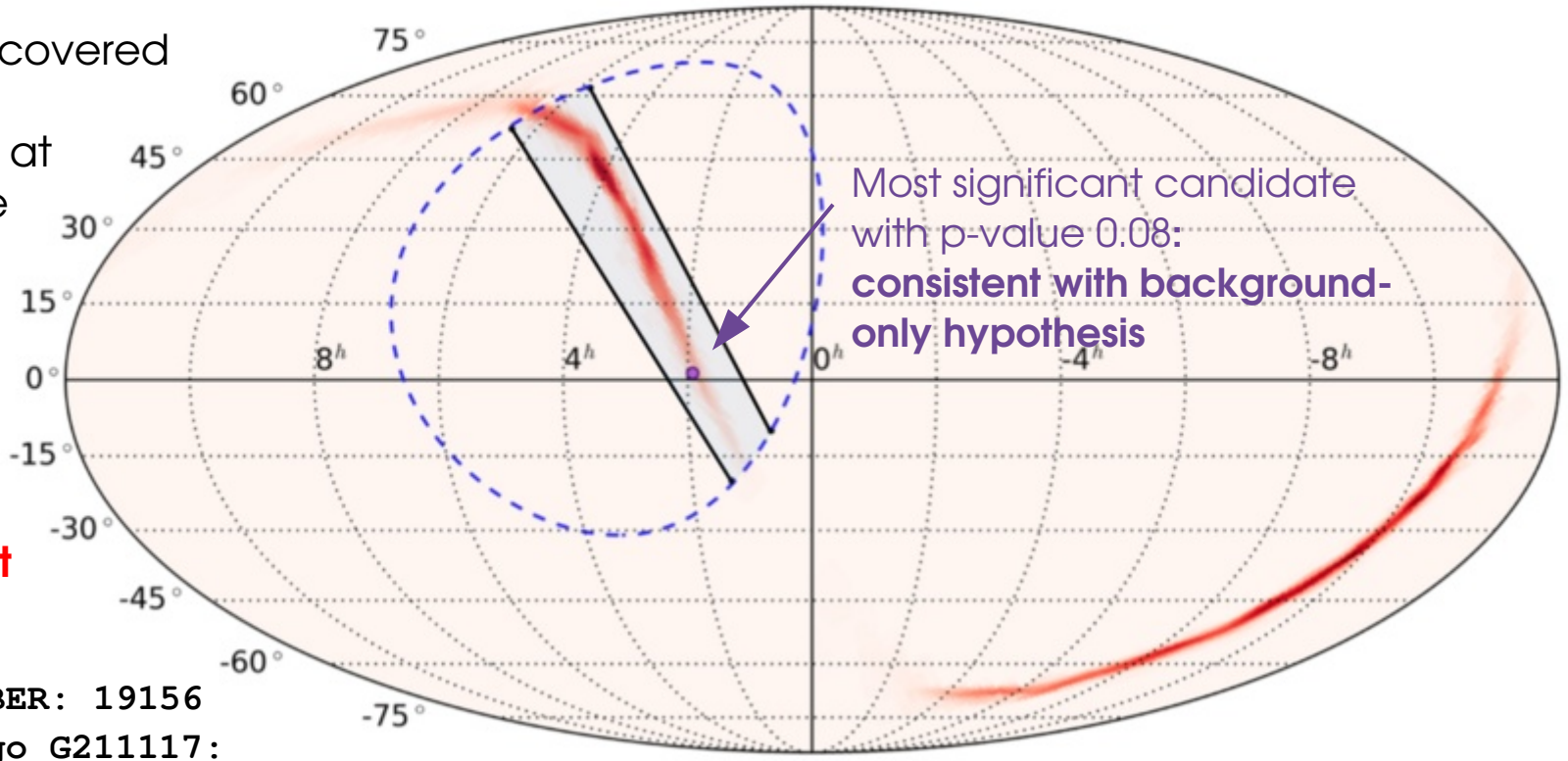


No simultaneous coverage with HAWC

Follow-up on 2nd Gravitational Wave Alert

LIGO: GW151226, 2015-12-26 03:38:53 UTC

HAWC field of view covered a large part of the localization contour at time of coincidence

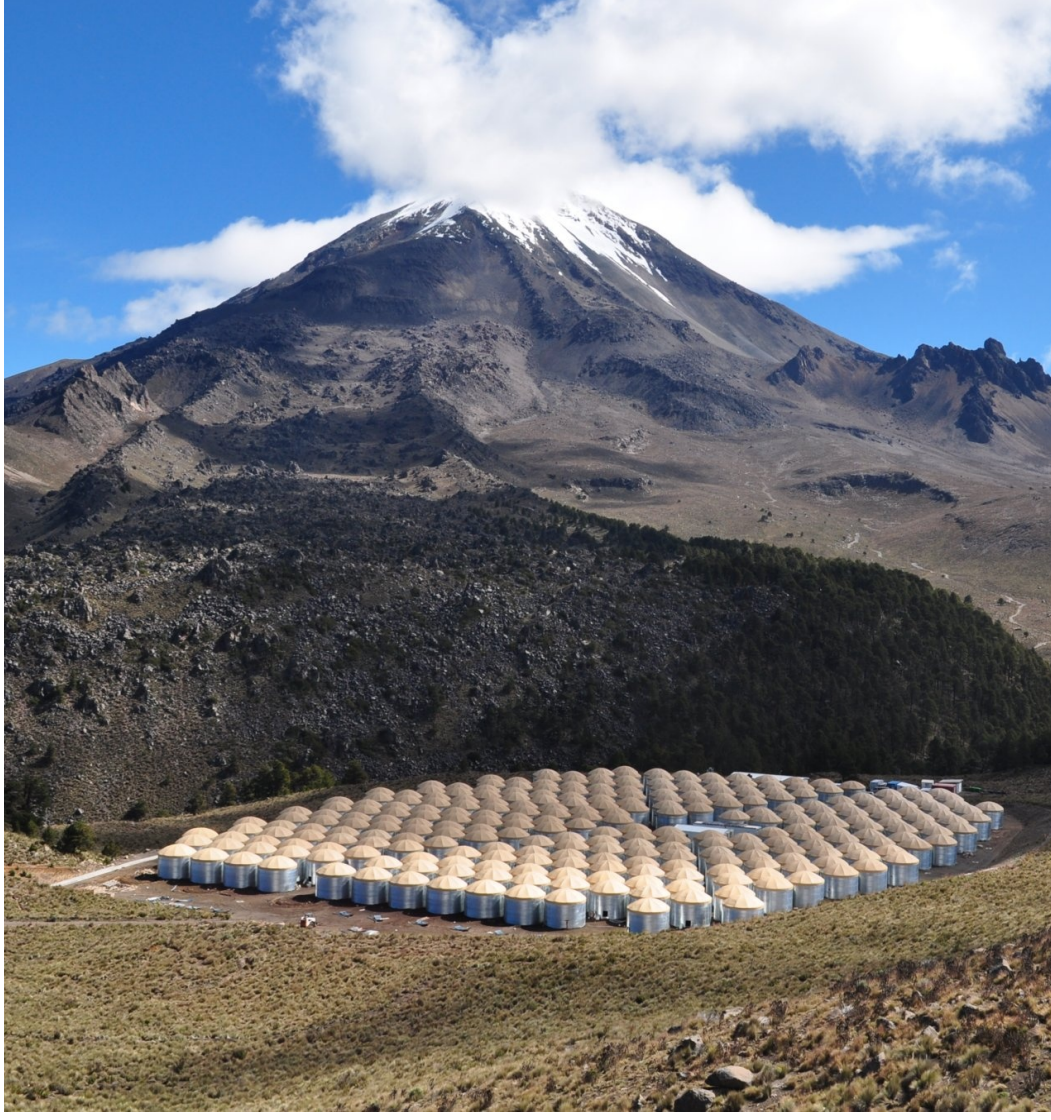


A GRB-optimized Search within ±10 s shows no significant excesses, see:

```
GCN CIRCULAR, NUMBER: 19156
SUBJECT: LIGO/Virgo G211117:
HAWC follow-up of northern sky
```

Summary & Outlook

- **HAWC is monitoring 2/3 of the sky, every day**, various automated searches
- **First HAWC-Triggered Blazar Flare alerts** have been sent in 2016, *expect more!*
- HAWC is **routinely following up on Multi-Wavelength/Messenger alerts**
- **Gamma-ray limits for track-like neutrino alerts** in both past and online data are providing constraints on source scenarios
- Expecting more **gravitational wave follow-ups**
- HAWC has **light curve data on locations in all its field of view**, many more studies possible



Back Up

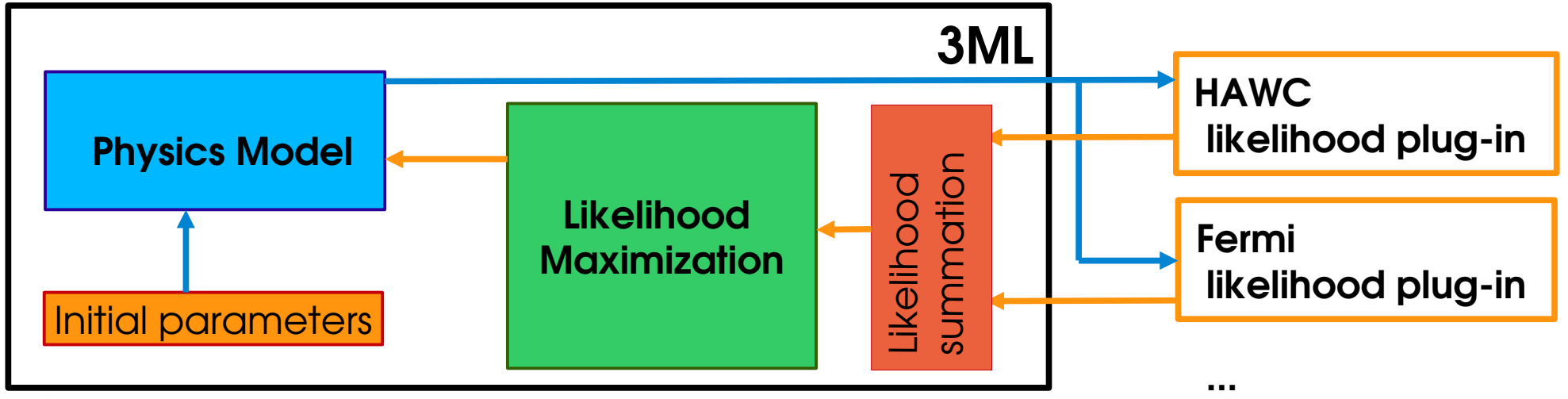
Joint analysis framework: 3ML

Likelihood and Bayesian Analysis:

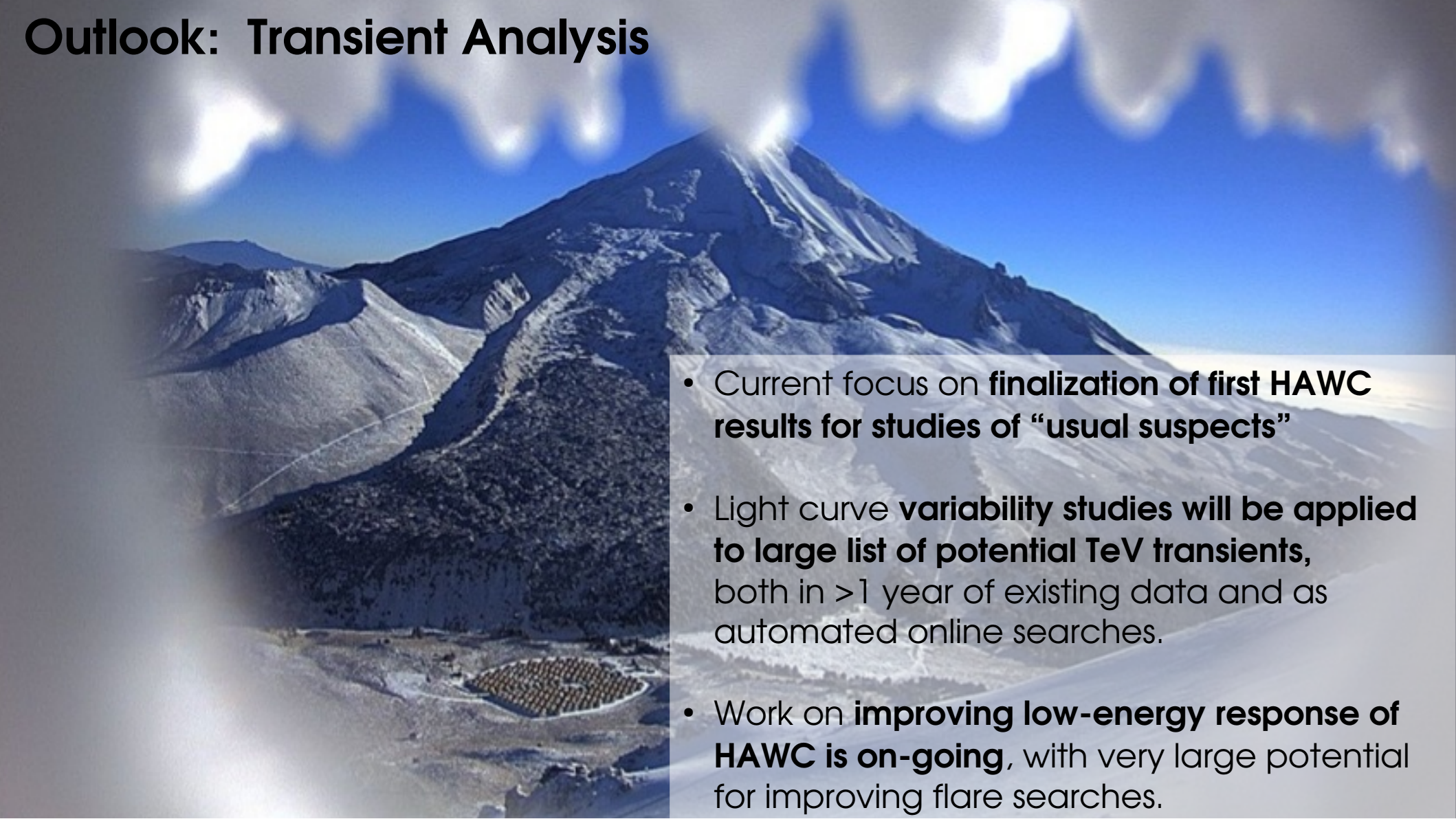
- User-friendly Python framework
- **Detection, Spectra, Light Curves,...**
- **Used already e.g. for HAWC, Fermi data**
- Joint HAWC + Fermi (+ VERITAS) studies in progress
- Plug-ins for X-ray data (SHERPA) available, other under development
- **Potential for multi-messenger model analyis**

3ML
The Multi-Mission Maximum Likelihood framework

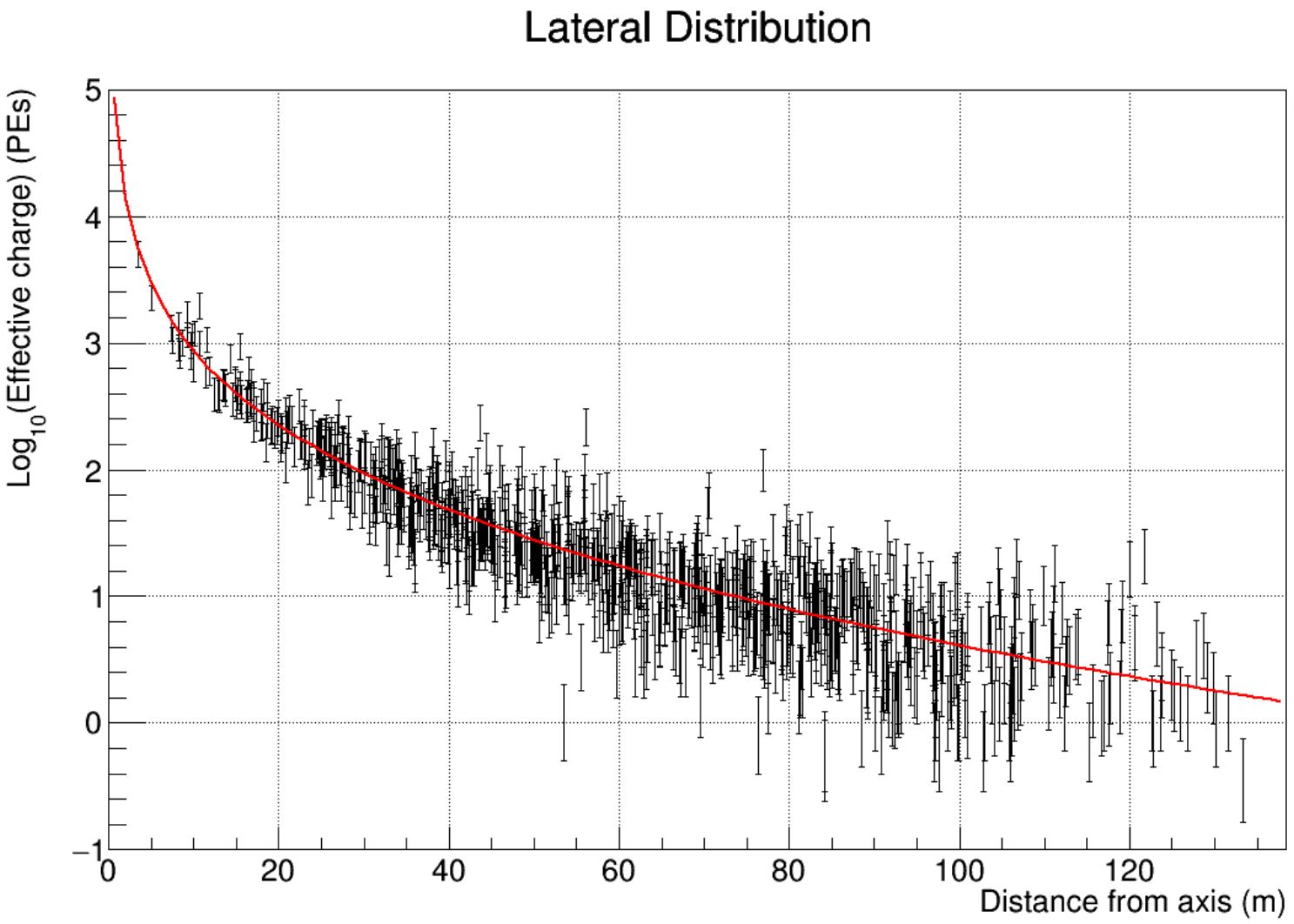
Led by Giacomo Vianello, Stanford
3ML on the web:
`threeml.stanford.edu`

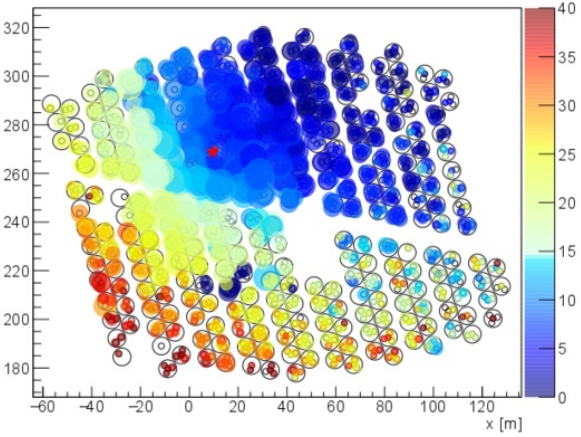


Outlook: Transient Analysis



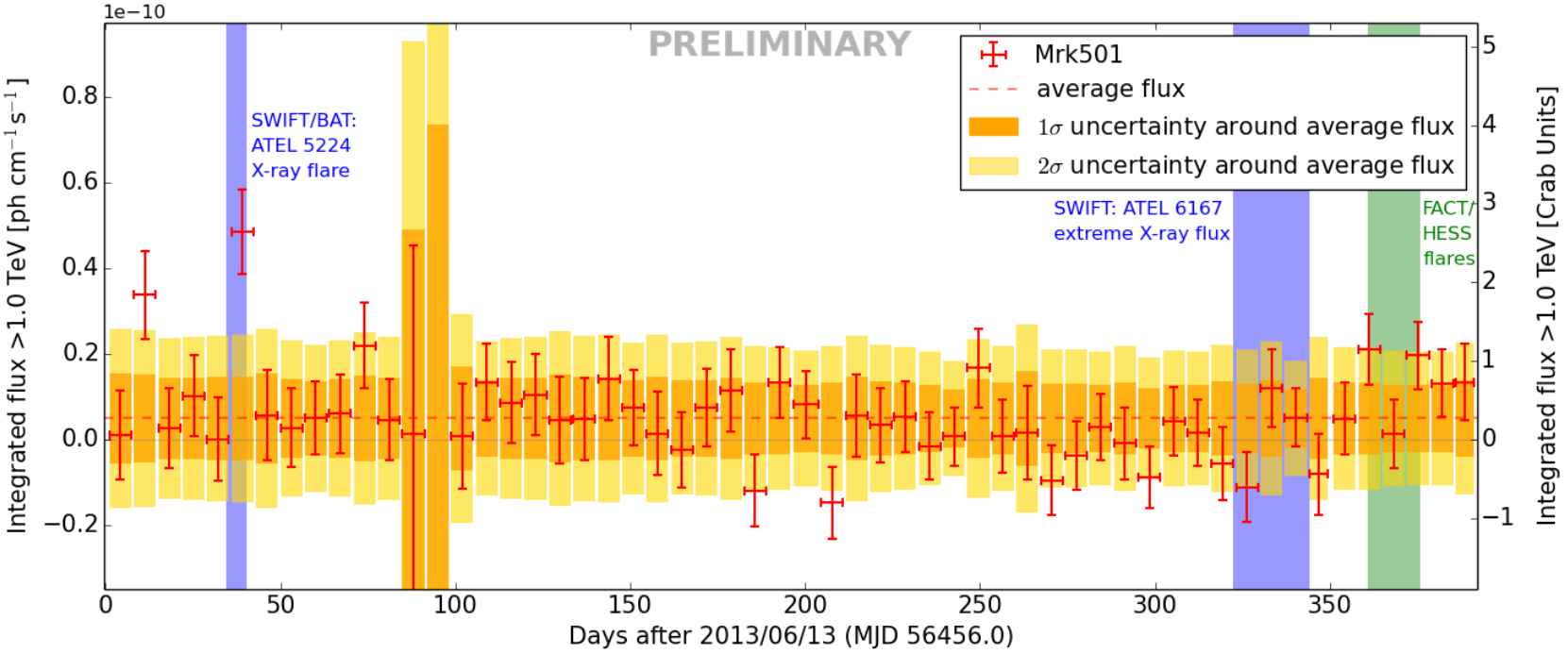
- Current focus on **finalization of first HAWC results for studies of "usual suspects"**
- Light curve **variability studies will be applied to large list of potential TeV transients,** both in >1 year of existing data and as automated online searches.
- Work on **improving low-energy response of HAWC is on-going**, with very large potential for improving flare searches.





Example event from the Crab
(Bin 9, high probability of being gamma ray)
Preliminary energy estimate: ~60 TeV

Mrk 501 flux light curve



HAWC-111 data from **June 13, 2013 to July 9, 2014**, binned in 7-day intervals.

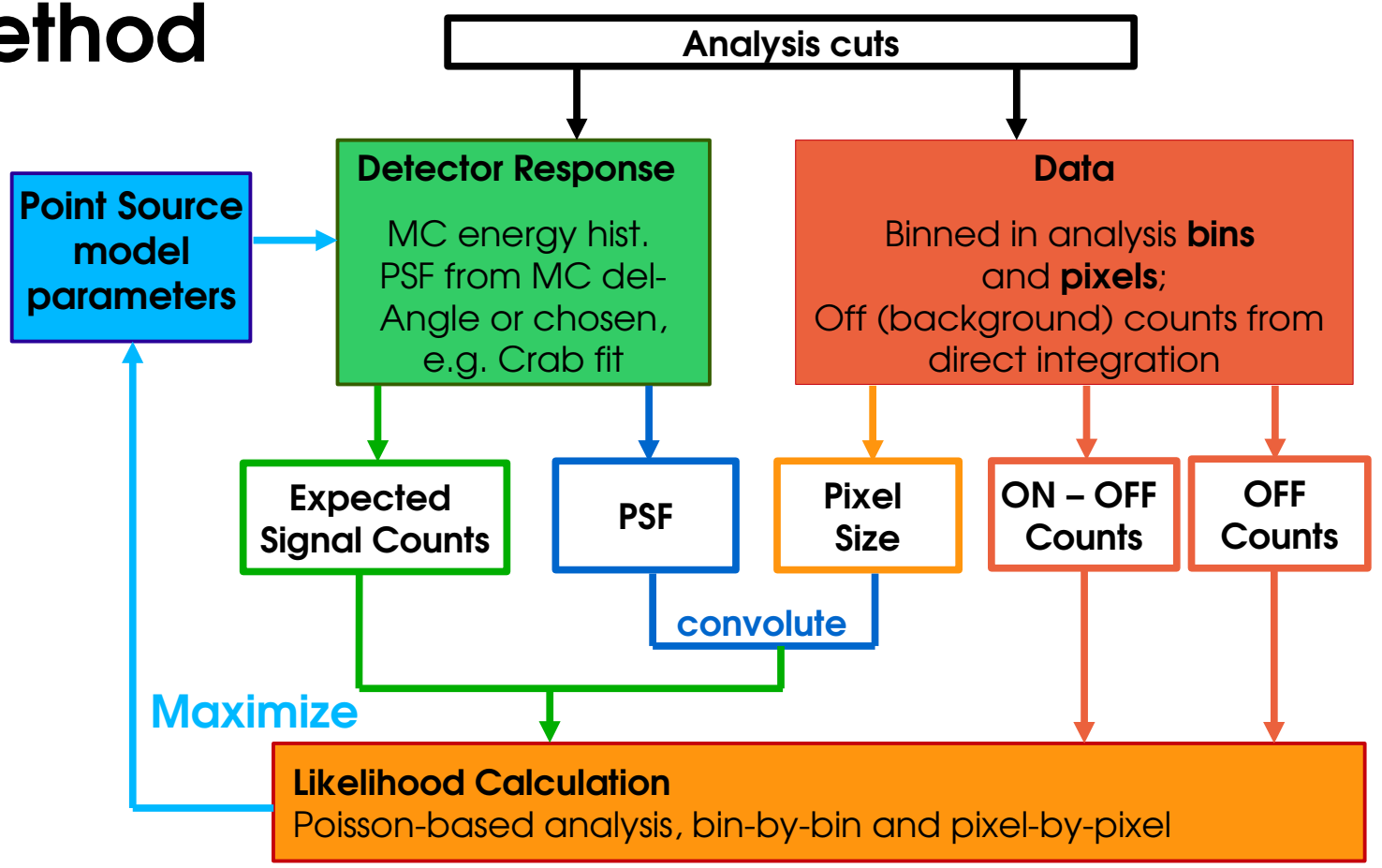
Highest flux coincides with onset of X-ray flare (SWIFT/BAT, 15-50 keV, ATEL 5320).
HAWC-only probability of this excess assuming a steady flux: 1.9×10^{-4} .
No significant features in HAWC fluxes during later X-ray flare, nor during June 2014 TeV flares (FACT, H.E.S.S., ATEL 6268, flare durations < 1 day)

Likelihood Method

Poisson statistics facilitate analysis for small signal counts in i**ntervals of ≥1 source transit**

See also framework description:

A high-level analysis framework for HAWC
P. Younk, R.L., et al.
ICRC 2015, #238



$$\mathcal{L}_S\left(\{F_0, s, c\}|\vec{N}\right) = \prod_b \prod_p P(N_{b,p}, S_{b,p} + B_{b,p})$$

Poisson probability

HAWC data

reconstructed events

XCDF (binary, user-defined precision)

cuts and binning

e.g. fraction of PMTs with signals (nHit), γ/hadron separator, ...

Energy estimator under development

Event size used as energy proxy:
number of PMTs with signals (nHit)
→ currently 10 analysis bins

Direct Integration
calculate background expectation for each bin

... O(10) maps (per time interval)

Healpix maps:
- **data event count**
- **background expectation**

each map stored as fits.gz