HAWC Real-Time Searches

Tom Weisgarber

4th AMON Workshop

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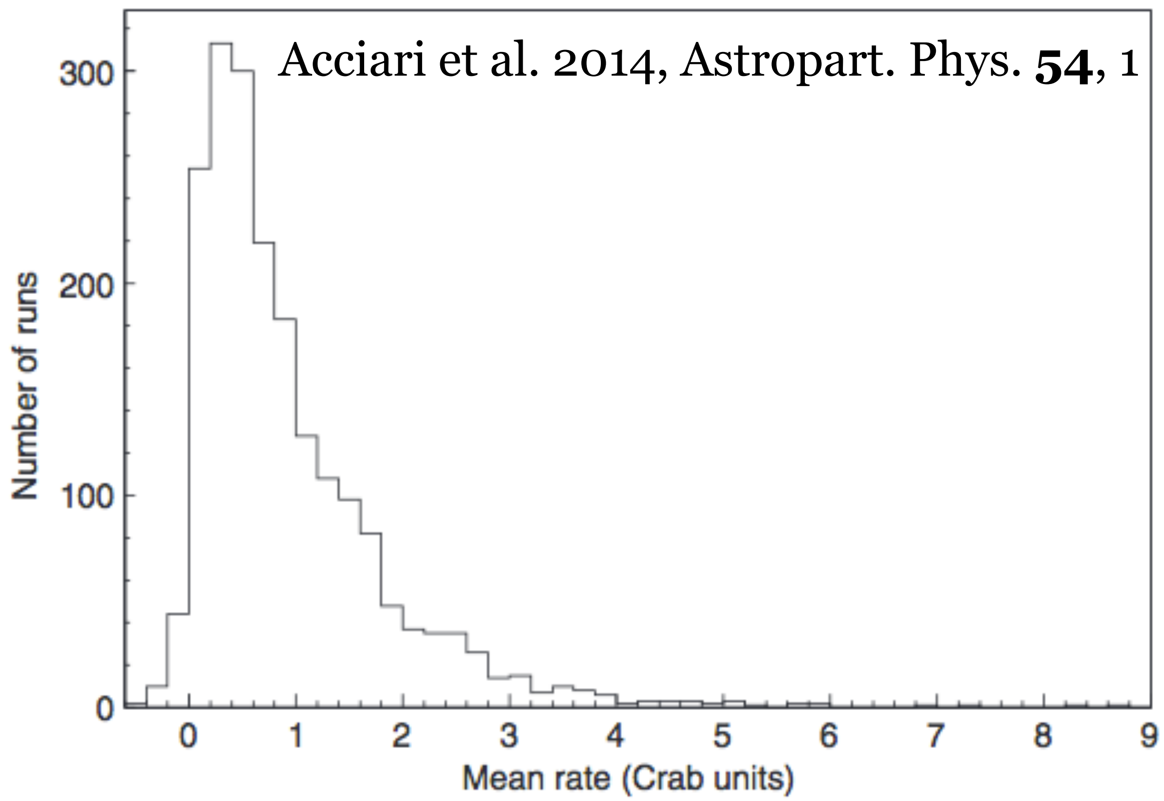
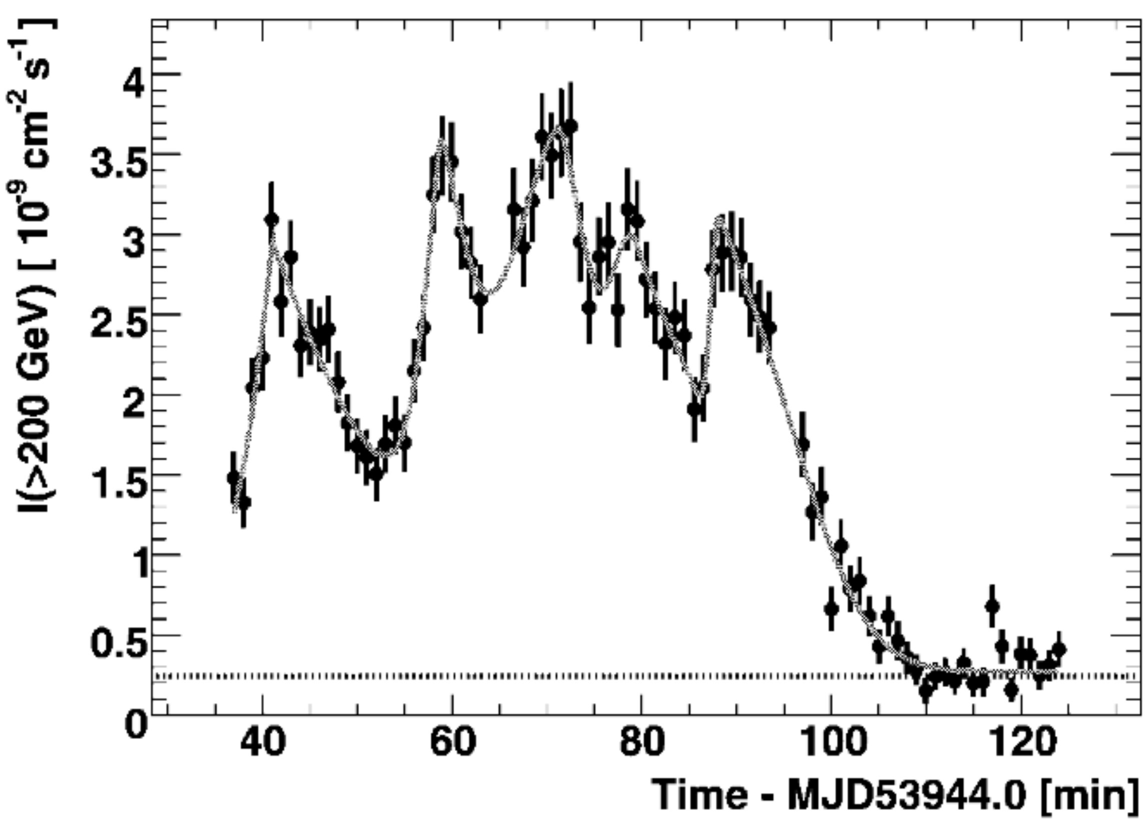
Flare search motivation

- Blazars are known to produce **extreme flares** that can exceed their quiescent emission by large factors
- Flares at the highest energies may not have lower energy counterparts or be caught by pointed instruments: **a TeV survey instrument** is needed

- Extreme flare of PKS 2155-304 in July 2006: how many similar flares have been missed?



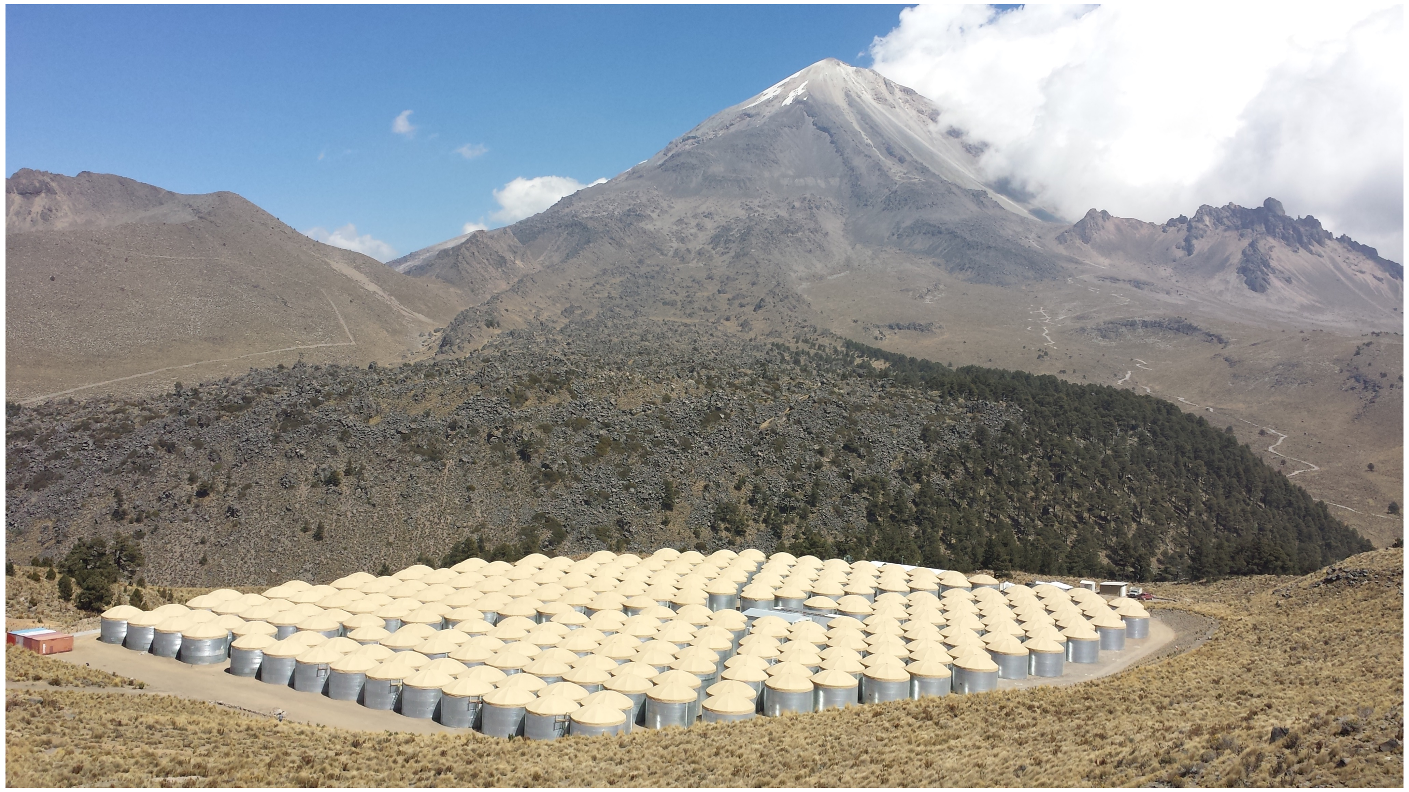


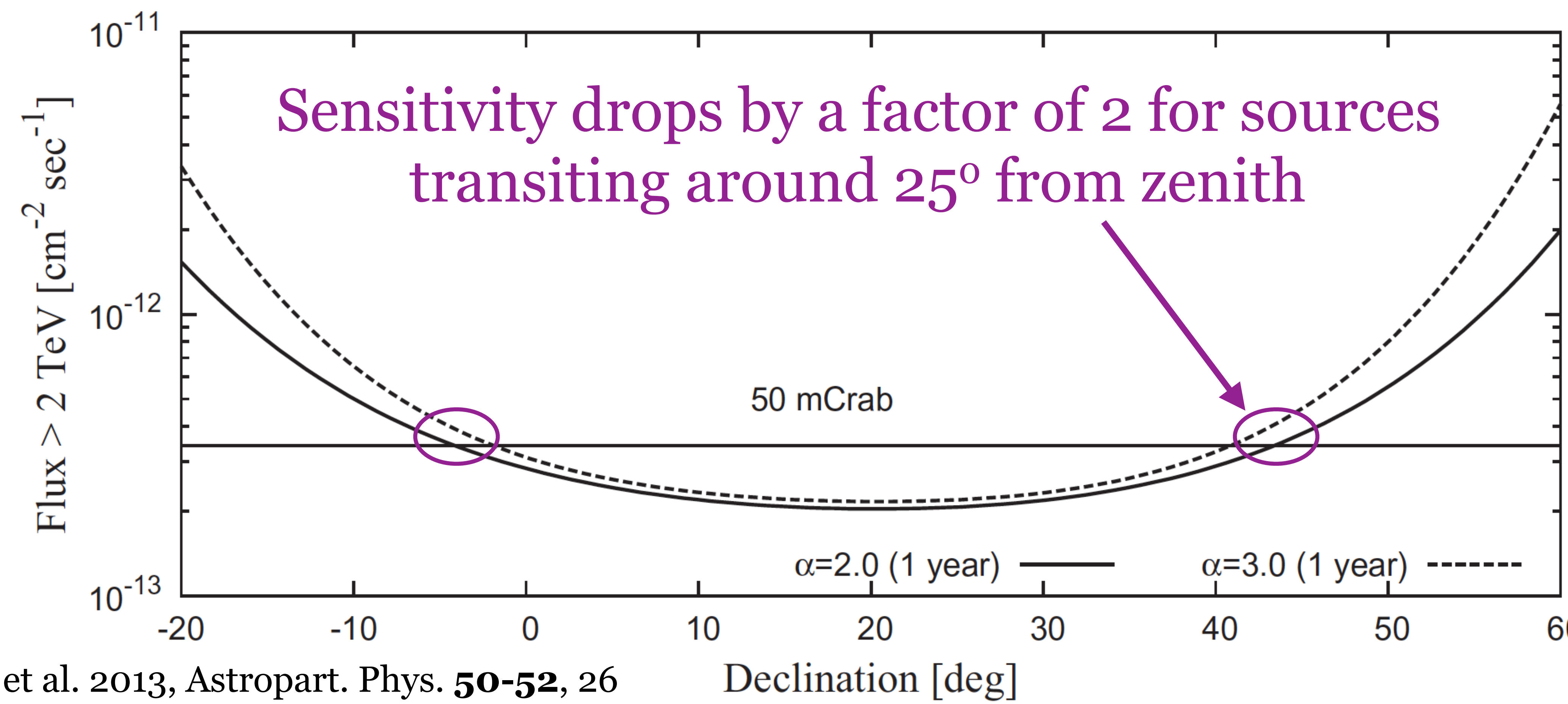
- History of Mrk 421 reveals several strong flares: is this rate biased by the observing strategy?

Aharonian et al. 2007, ApJ **664**, L71

HAWC

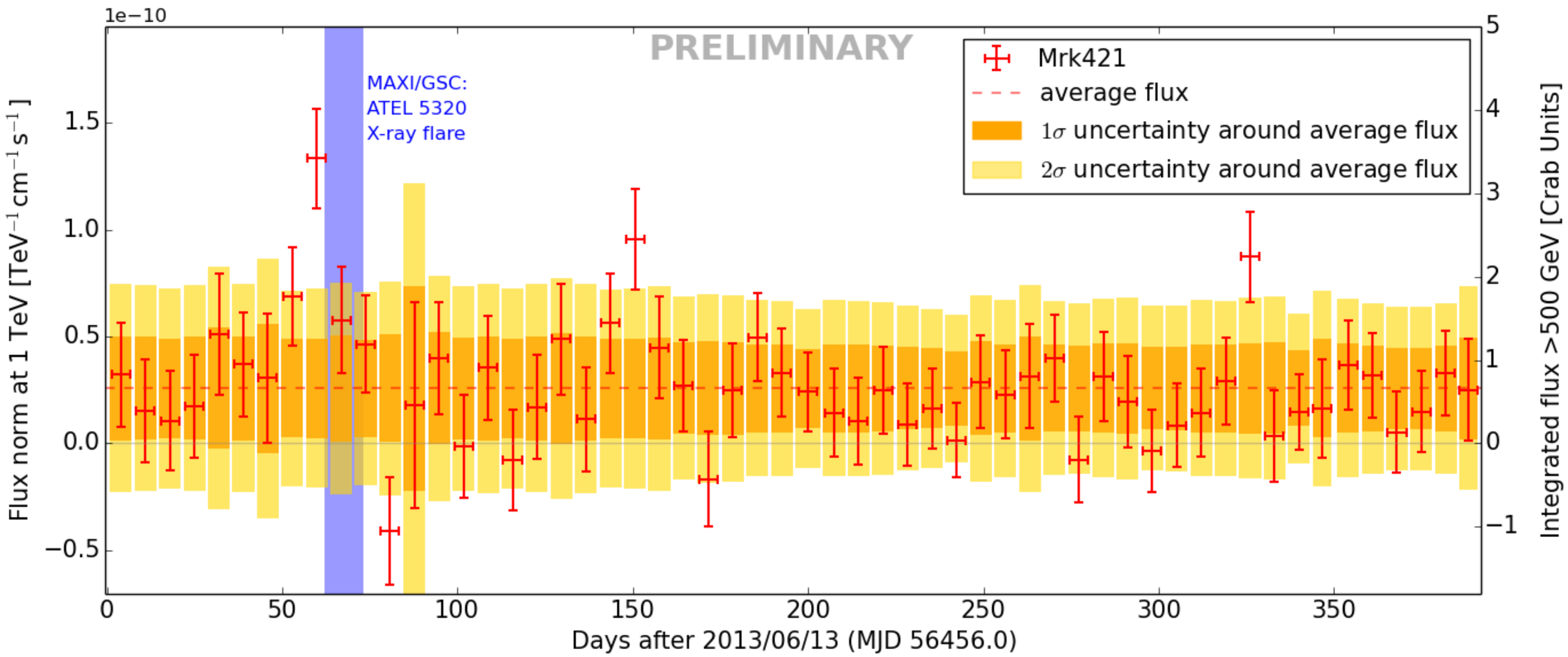
- High Altitude Water Cherenkov Observatory recently completed
- Provides **TeV survey capabilities** for a large fraction of the sky
  - Best sensitivity to sources between -6° and +44° in declination

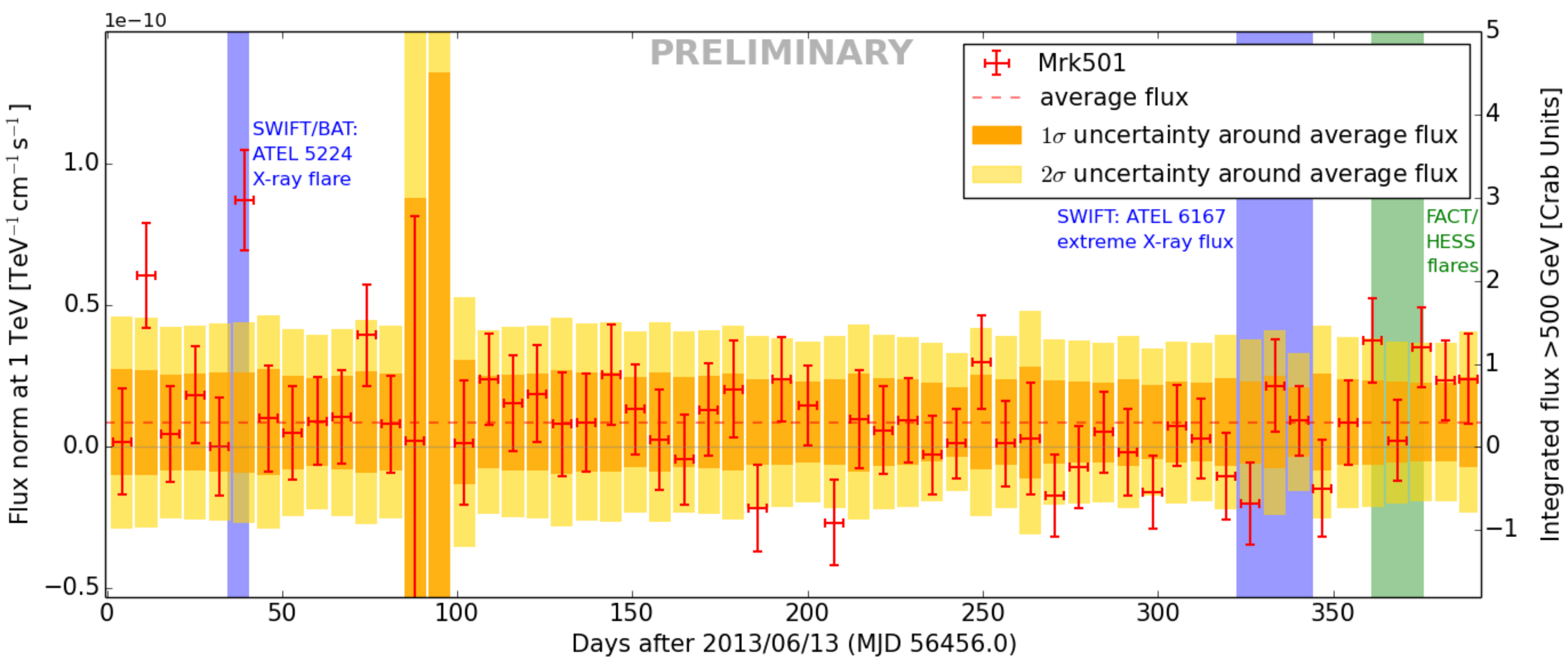




Abeysekara et al. 2013, Astropart. Phys. **50-52**, 26

HAWC flaring sources





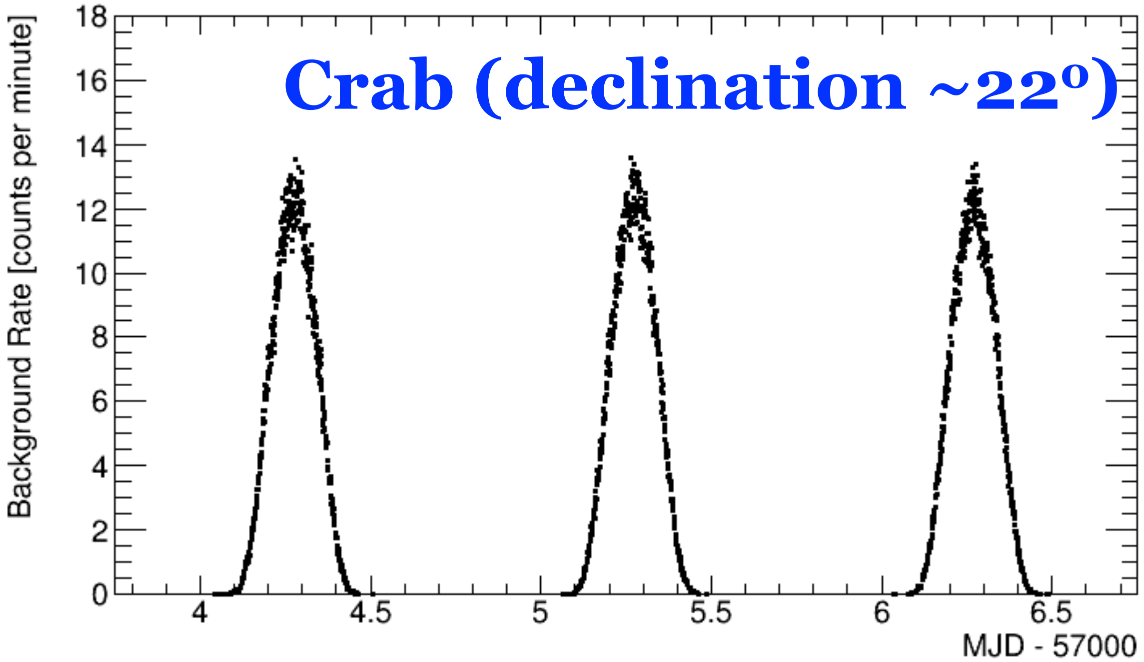
- Evidence for flaring activity in the Mrk 421 and Mrk 501 exists in early HAWC data
- An online monitor with the capability to identify highly significant flares **automatically, rapidly,** and with **high confidence** is needed

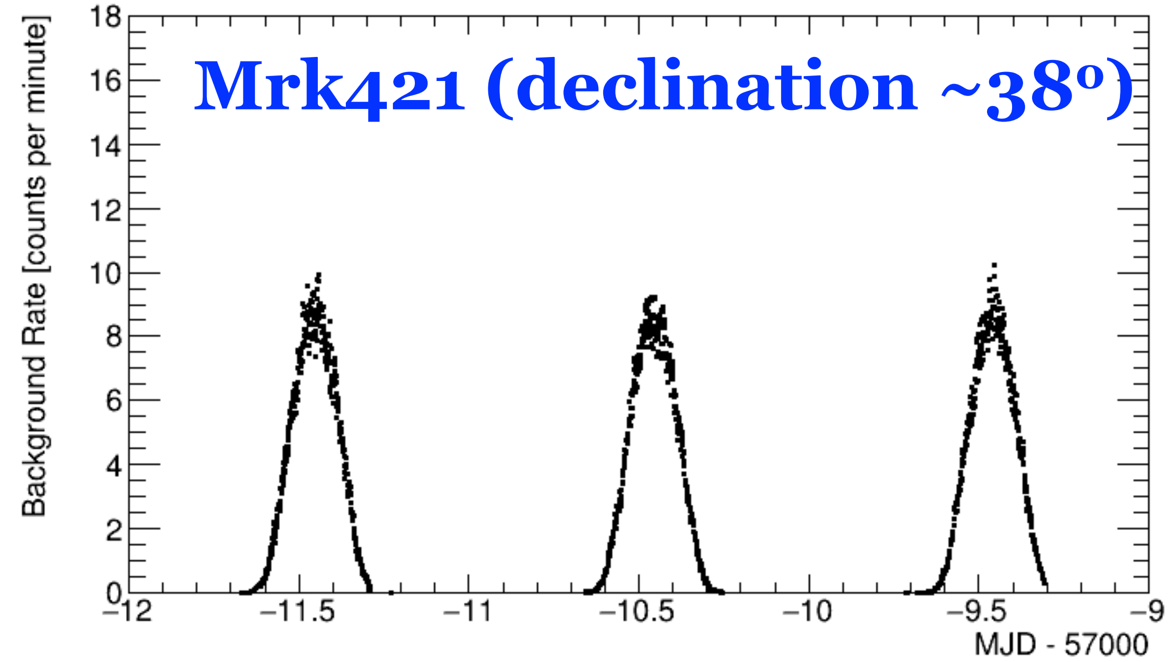
The HAWC Flare Monitor

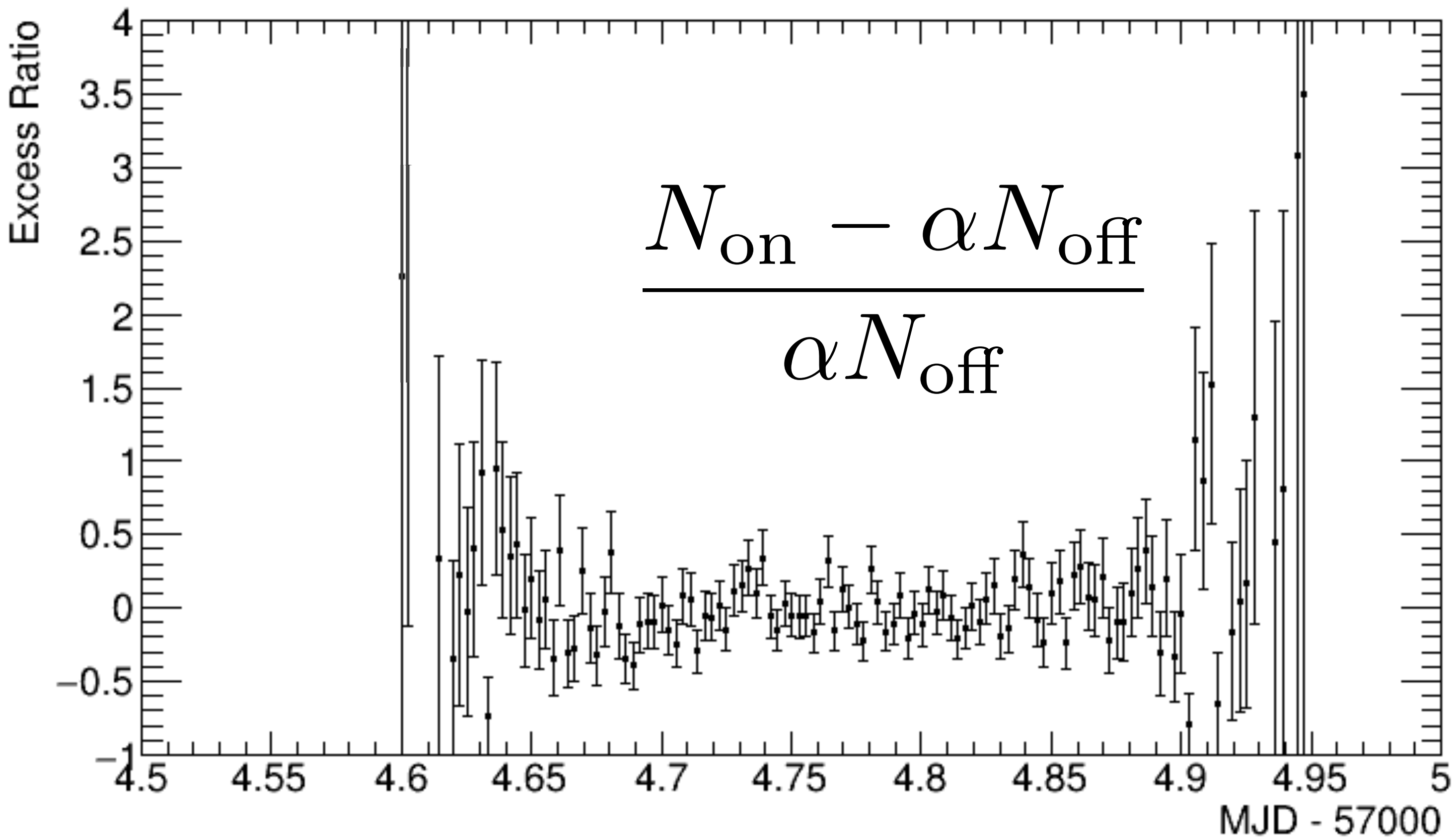
- Primary goal is to issue real-time alerts as soon as a flare is detected from a **selection** of gamma-ray source candidates
  - Sources in the selection are divided into classes based on the probability of gamma-ray flares occurring
  - We plan to consider an all-sky approach after monitor comes online
- Data analysis occurs **at the HAWC site**
  - No delay in waiting for data to arrive at data centers
  - Fully compatible with optimized offline analysis
- Searches for **flares only**
  - Sensitivity unaffected by the presence of quiescent emission
- HAWC is a young instrument; many plots here are subject to change

HAWC survey capabilities

- HAWC sensitivity and duty cycle depend on source declination
- Must be accounted for when searching for changes







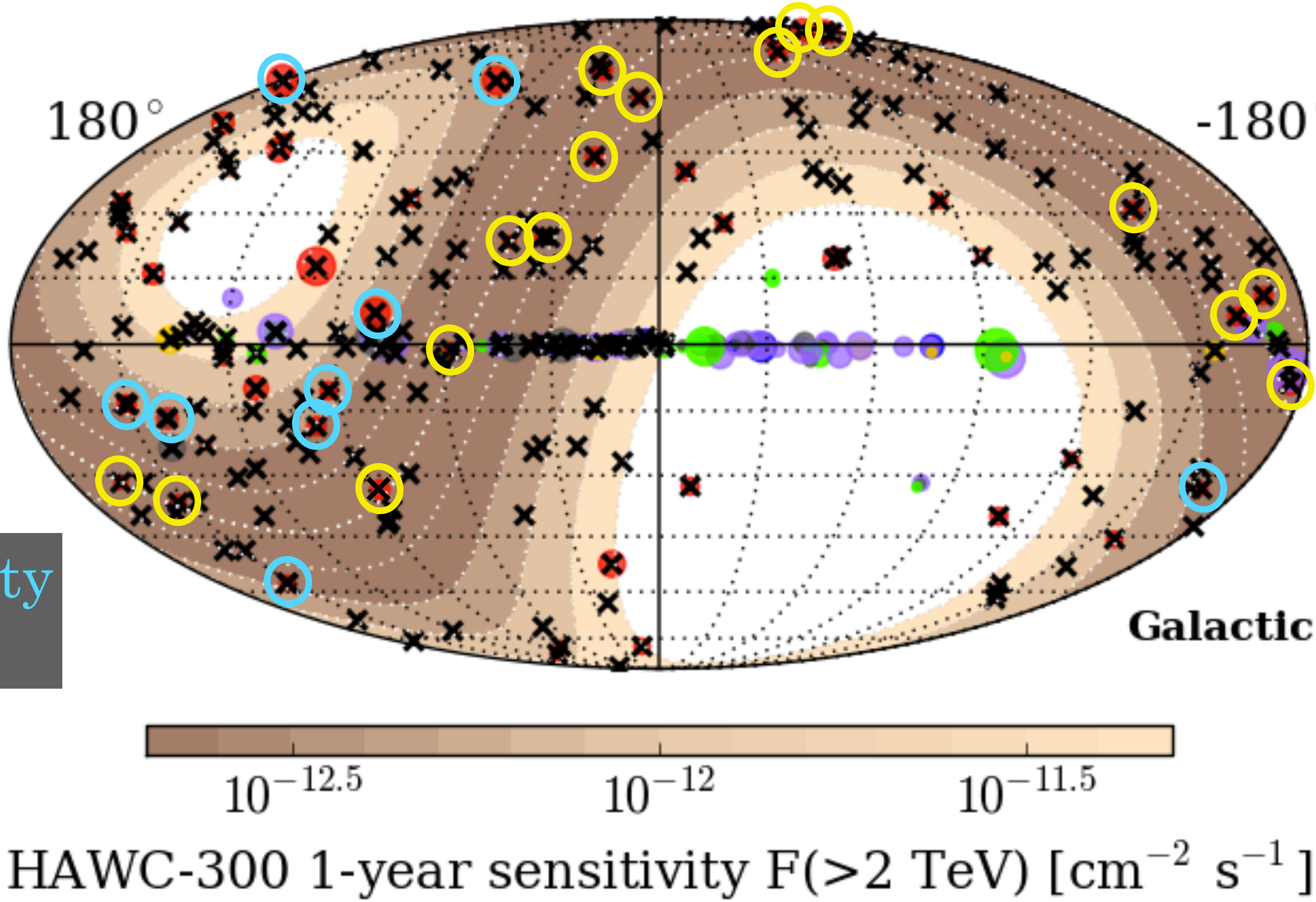
- Scaling signal by the measured strength of the background eliminates effects due to the source transit

HAWC survey capabilities

- Source selection taken from TeVCat and 2FHL nearby (z < 1) blazars
- Currently refining source selection (Galactic sources will be excluded in first pass)

~25% duty cycle

~20% duty cycle



Flare monitor implementation

- Flare monitor employs a method inspired by the **Bayesian block** algorithm (Scargle et al. 2013, ApJ **764**, 167)
  - Data are partitioned into **blocks** consistent with a **constant rate** based on a **fitness function** (usually the log likelihood)
  - **Change points** occur at the edges of the blocks and are taken to be flares
  - The algorithm runs over a **sliding buffer** of 600 minutes with 2 minute resolution (subject to change)
- The false positive rate is controlled by a **prior parameter** $\boldsymbol{\gamma}$ ($0 < \gamma < 1$) which penalizes representations with large numbers of blocks
  - The normalized prior probability for n blocks when there are N observations is:

$$P(n) = \frac{1-\gamma}{1-\gamma^{N+1}}\gamma^n$$

  - Since the false positive rate must be low, γ must be very small, and the full algorithm is unnecessary: we therefore test only the presence of a **single** change point

Flare monitor implementation

- A typical HAWC observation yields a number of on-source counts n_i and a number of off-source counts, m_i
- The likelihood of the data given a Poisson model for the counts is then

$$L(n_i, m_i|\lambda_i, \mu_i) = \left(\frac{\lambda_i^{n_i} e^{-\lambda_i}}{\Gamma(n_i+1)}\right)\left(\frac{\mu_i^{m_i} e^{-\mu_i}}{\Gamma(m_i+1)}\right)$$

- To account for the source transit, we re-cast the likelihood in terms of the signal to background ratio q_i:

$$(\lambda_i, \mu_i) \to \left(q_i = \frac{\lambda_i}{\alpha\mu_i}, \mu_i\right)$$

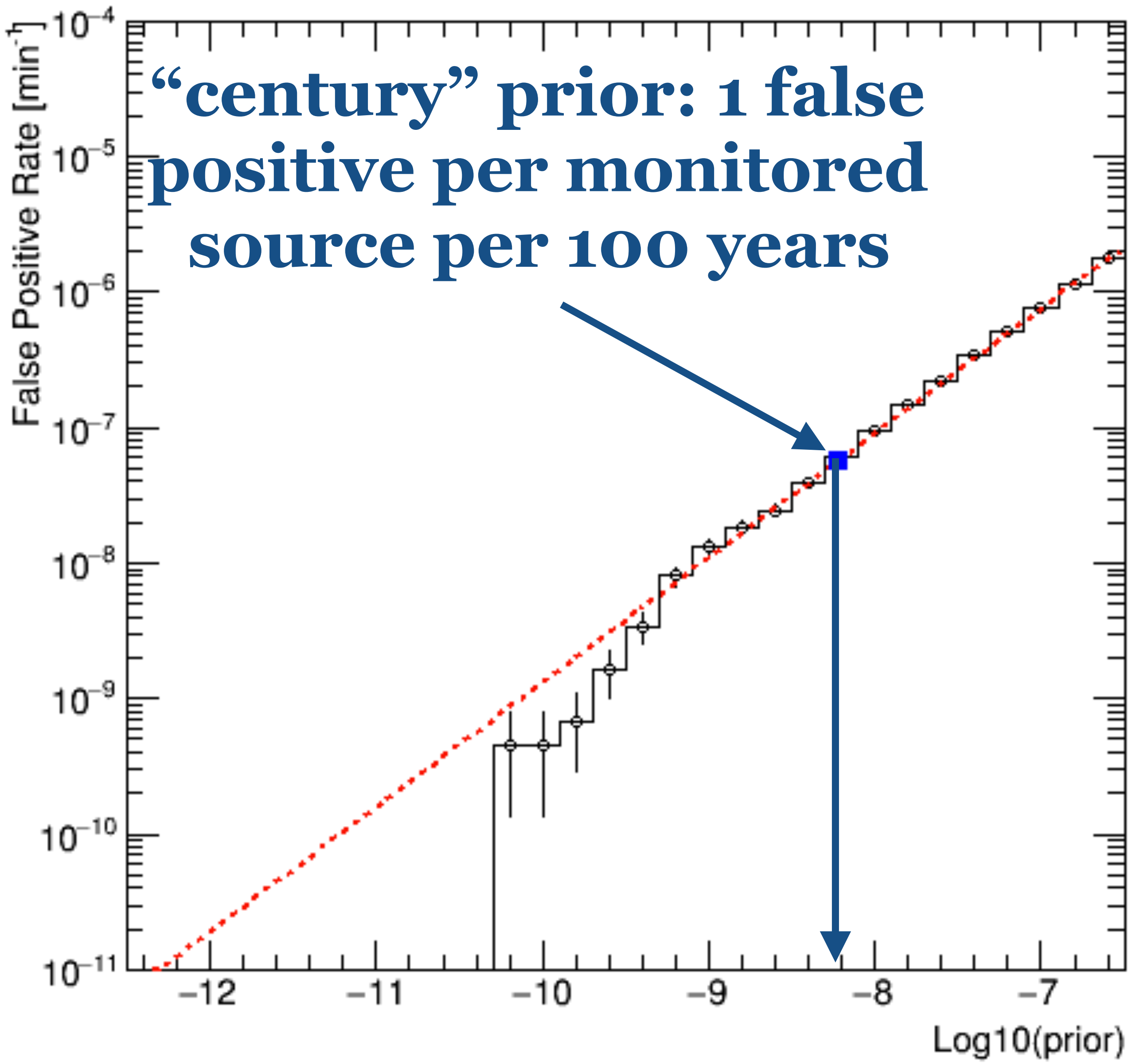
- And write the fitness for a block B_k of d observations to be constant as:

$$f(B_k) = \sum_{i=1}^{d} \ln L_i^{\max}(q_i = q, \mu_i)$$

- Source transit dependence is eliminated, **provided that the gamma-ray and cosmic-ray zenith angle responses are the same**

Flare monitor implementation

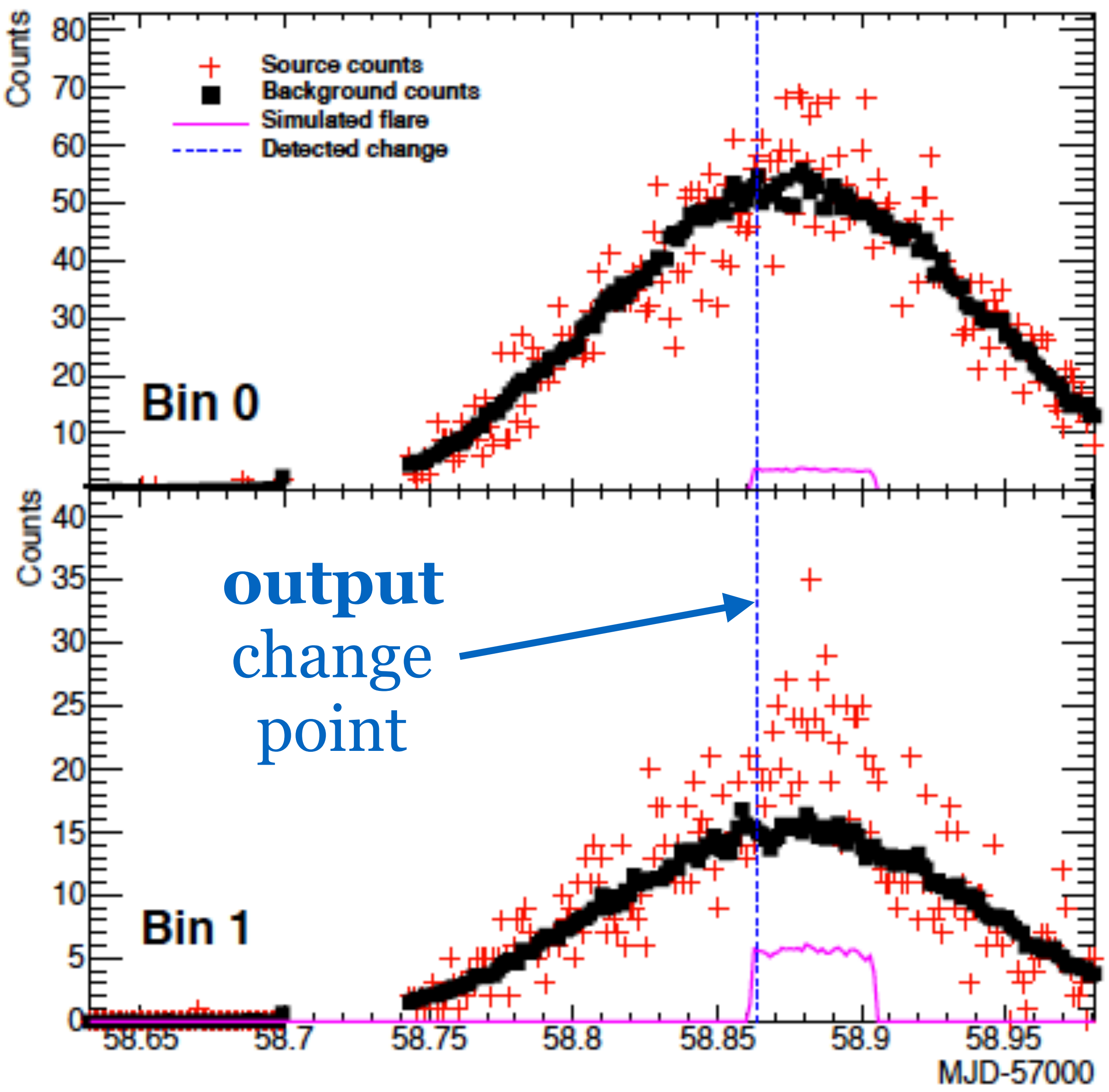
- Multiple analysis bins are easily accommodated: simply add the fitness contribution for each bin
- We restrict contributions to the fitness to points where the signal to background ratio **increases**



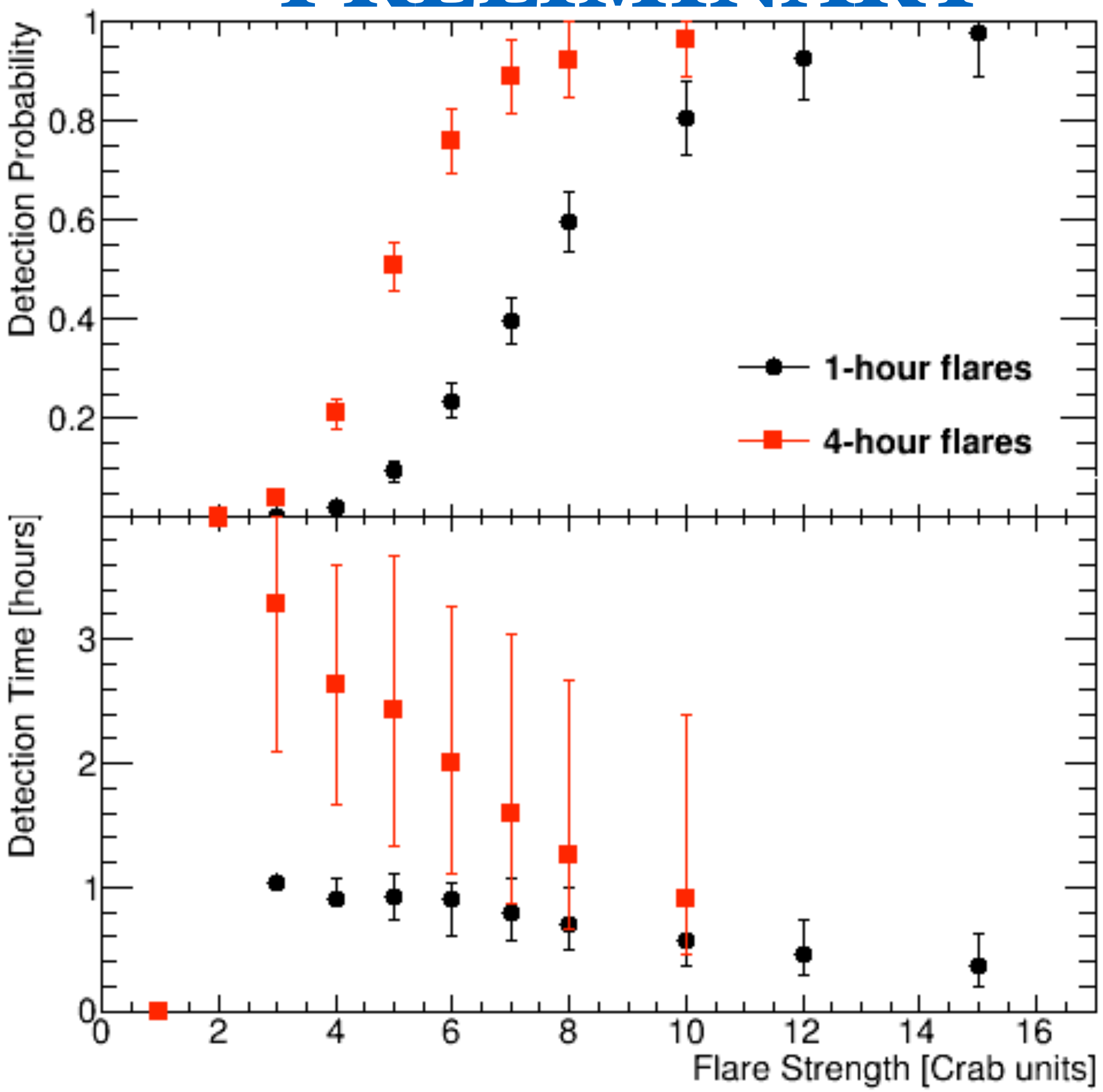
- When the number of monitored sources is large, the false positive rate must be set very low
- Derive false positive rate from **data** by taking the background counts as the true Poisson mean and **sampling** both on-source and off-source counts based on it
- This procedure enables us to simulate centuries of data

Flare monitor sensitivity

- Sensitivity for a given false positive rate is determined by simulation: inject flares **scaled to Crab Nebula excess**
- Excess ratio can depend on the analysis bin (2 shown for clarity)
- Rapid detection is important for **follow-up observations**



PRELIMINARY



Example alert email

attached plots (shown later)

Thomas Weisgarber -- UW Madison <tweisgarber@sequo   4:32 pm (9 days ago)

to ianwisher, westerhoff, weisgarber, me

Found change point:
Equivalent false positive rate: 0.0413869 events per year
Estimated significance for 1-day observation: 5.45909
Estimated significance for 1-month observation: 4.14238
Estimated significance for 1-year observation: 2.88448
Estimated significance for 1-decade observation: 1.15556
Source Identifier: FGLJ0534_5PP2201GHOSTPP210_PSRJ0534PP2200GHOSTPP210
Source Association: PSR J0534+2200 GHOST+210
Source RA (J2000): 293.628 deg.
Source Dec (J2000): 22.0191 deg.
Source Redshift: 0
Change point time: MJD 56987.98095454146
Change point age at first detection: 94.3657 min.
Change point present age: 94.3657 min.
Bayesian Block prior value: 0.002
Bayesian Block prior log: -6.21461
Bayesian Block total fitness: 7.14741
-> bin 0 contribution: 6.758
-> bin 1 contribution: 0
-> bin 2 contribution: 0.389412
Change point position in buffer: 5

estimates of significance (not accurate for this example)

source info

time and age of detected flare

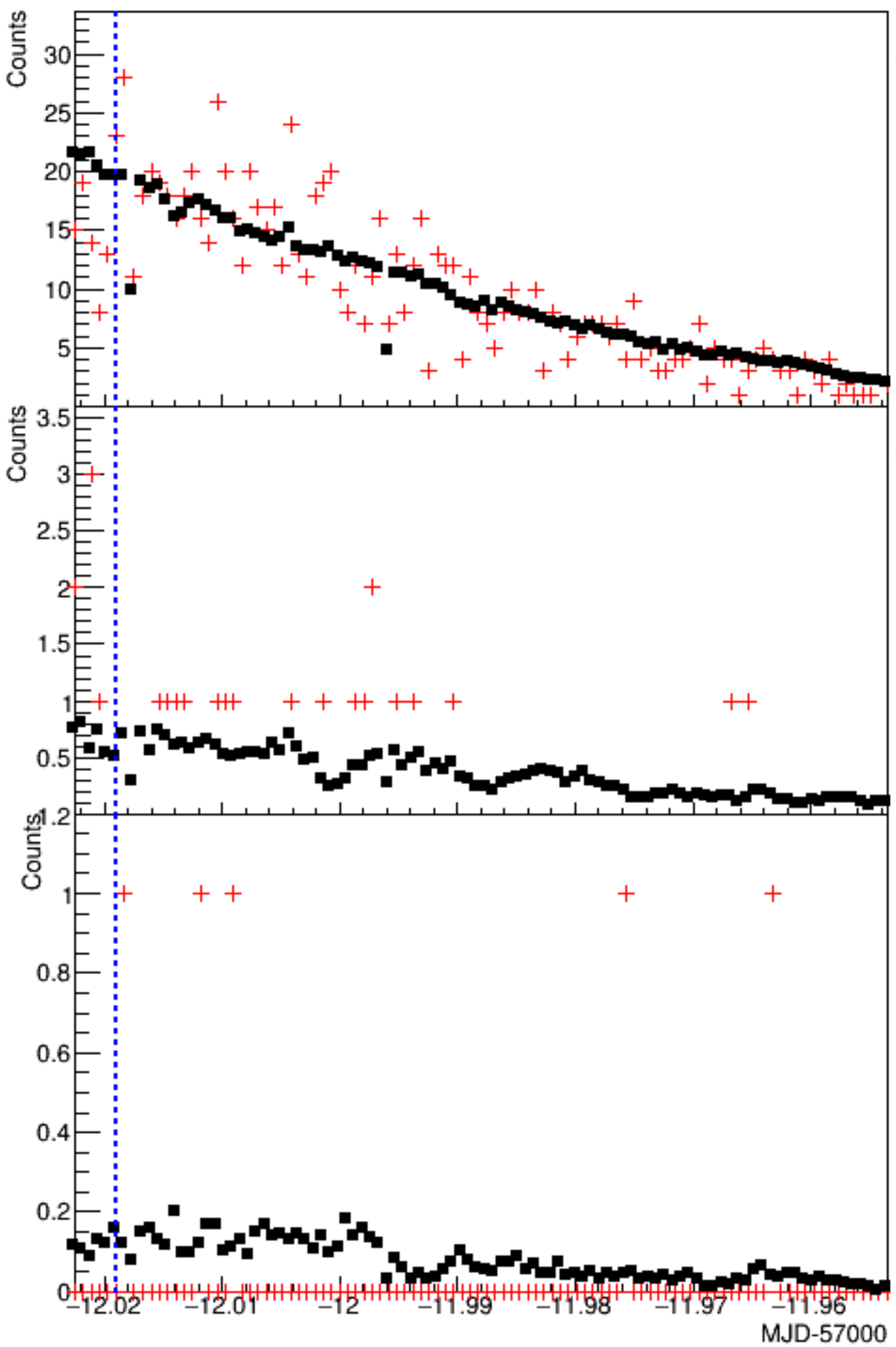
Example alert email

detailed contributions to fitness from analysis bins (will likely be replaced by energy bins in the future)

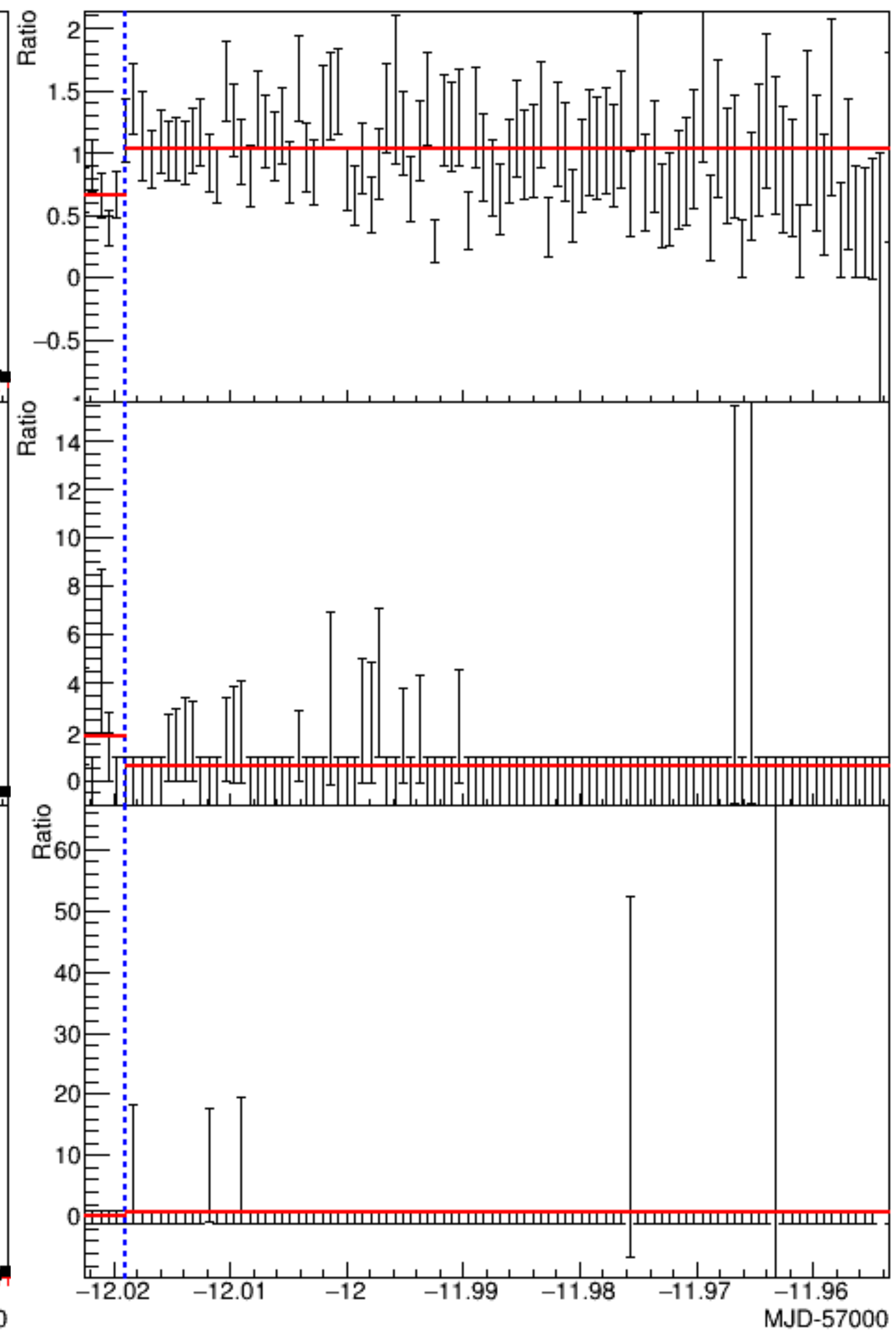
Source Dec (J2000): 22.0191 deg.
Source Redshift: 0
Change point time: MJD 56987.98095454146
Change point age at first detection: 94.3657 min.
Change point present age: 94.3657 min.
Bayesian Block prior value: 0.002
Bayesian Block prior log: -6.21461
Bayesian Block total fitness: 7.14741
-> bin 0 contribution: 6.758
-> bin 1 contribution: 0
-> bin 2 contribution: 0.389412
Change point position in buffer: 5
Number of change points in buffer: 1
Change point 0 at 5
Binwise ratios before and after change point 0:
Bin 0: 0.664836 to 1.03409
Bin 1: 1.78658 to 0.577703
Bin 2: 0 to 0.750151
Binwise estimated (Non,Noff,alpha,sigma) before and after change point 0:
Bin 0: (69,1837.57,0.0564796,-3.55096) to (890,15238.4,0.0564796,0.967379)
Bin 1: (6,88.0916,0.0381237,1.2668) to (18,817.283,0.0381237,-2.52143)
Bin 2: (0,19.3189,0.0282398,-1.0373) to (5,236.026,0.0282398,-0.666625)

Example alert email

On & off counts



Signal to background ratio



- Plots attached to alert email to improve confidence that alert is real
- If (after more data comes in) a reported alert **increases** in significance, an alert **update** is sent

Flare monitor for AMON

- Until now, we have been building the flare monitor with **follow-up** observations in mind (especially from IACTs and other pointed instruments that need to prioritize their targets)
- For **correlating alerts** between different experiments, a much higher false positive rate can be tolerated
- Straightforward adjustments to the HAWC flare monitor code would allow sub-threshold alerts to be sent
- False positive rate can be handled on an event-by-event basis
- Especially for these sub-threshold alerts, and even for the primary alerts, it would be good to have a more reliable method than email (would like to begin incorporating alerts in AMON framework very soon)
- Suggest 2 streams: basically high and low threshold

Summary

- HAWC flare monitor enables **rapid** and **automatic** detection of flares from a selection of TeV gamma-ray sources and probable candidates
- Although the flare monitor is focused on detecting flares with a very low false positive rate, increasing the false positive tolerance is easy
- Both above-threshold and sub-threshold alerts from the HAWC flare monitor fit well into the AMON structure
- Substantial improvements to the sensitivity based on improvements in the HAWC analysis code are **imminent**
- HAWC flare monitor will be deployed soon