Identifying Short, Extreme Blazar Flares with the HAWC Real-Time Flare Monitor

Thomas Weisgarber

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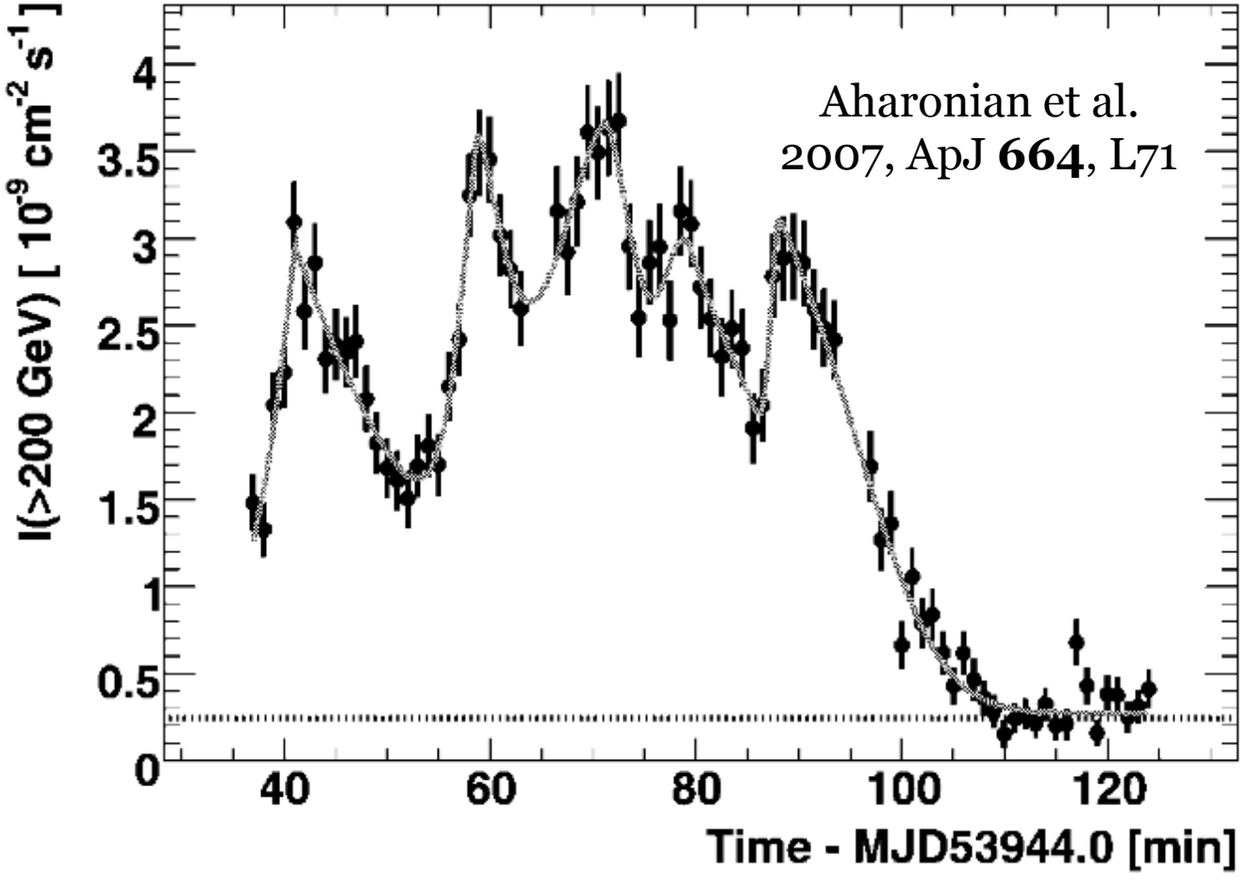
Motivation for short, extreme flares

- Short time scale flares give us a window into the dynamics of the blazar central engine
- Multiwavelength picture important for constraining flare models
- Increased event counts enable probes of intergalactic space, Lorentz invariance violation
- TeV flares not always predicted by X-ray or GeV flares



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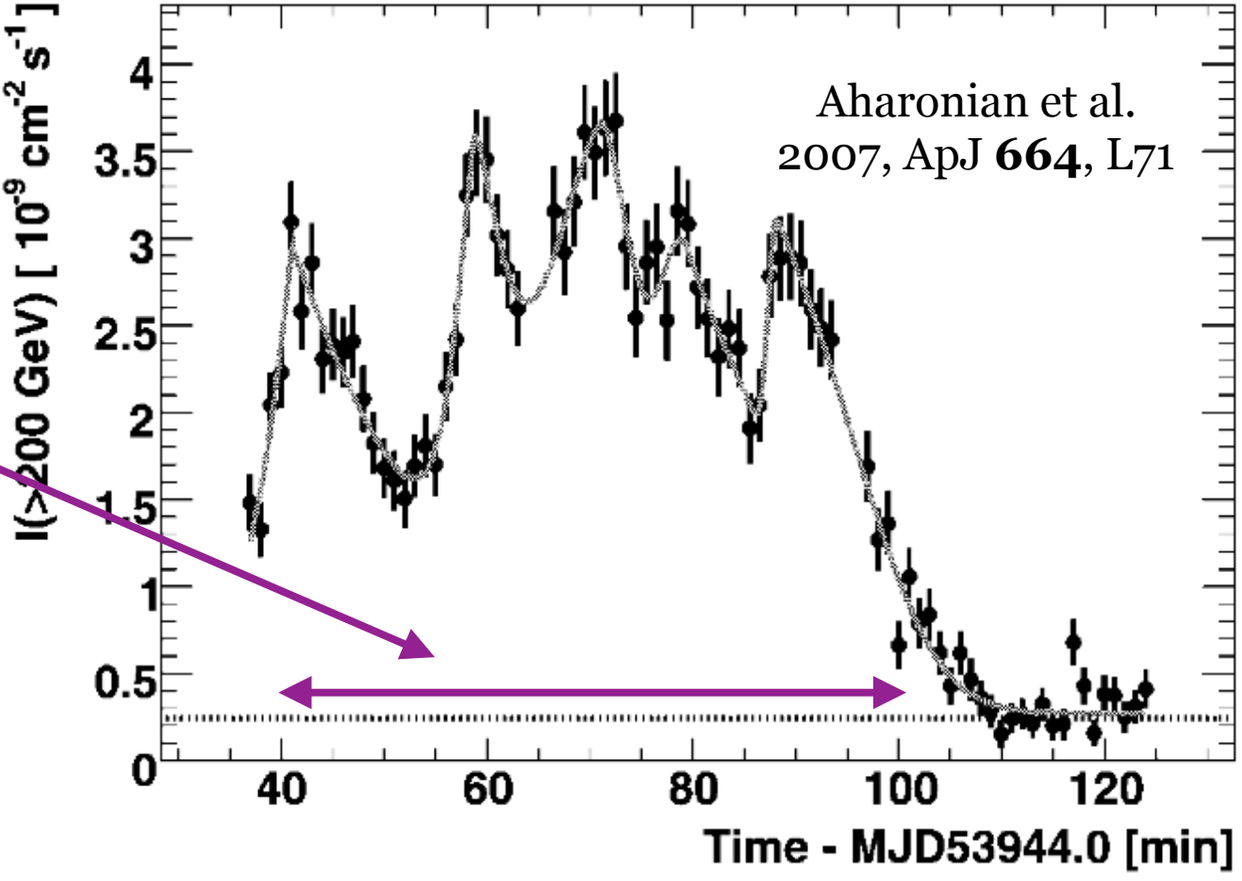
about
1 hour



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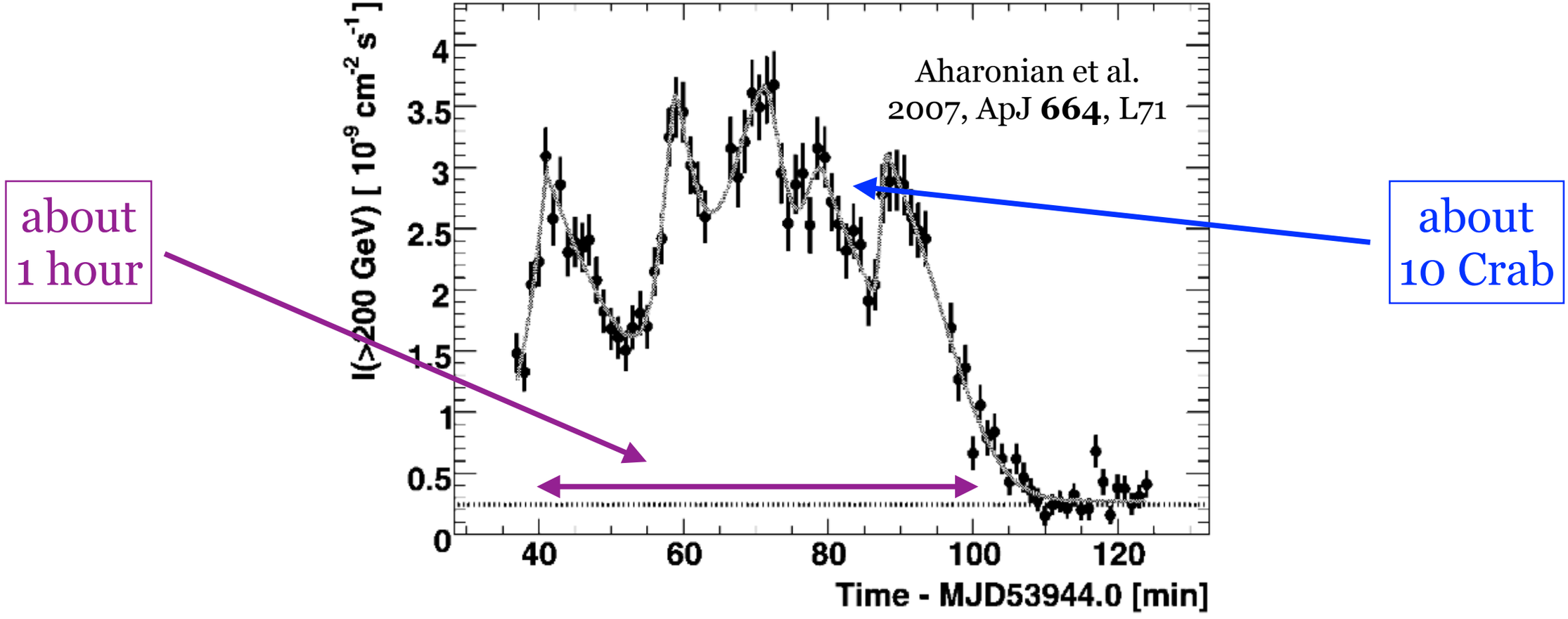
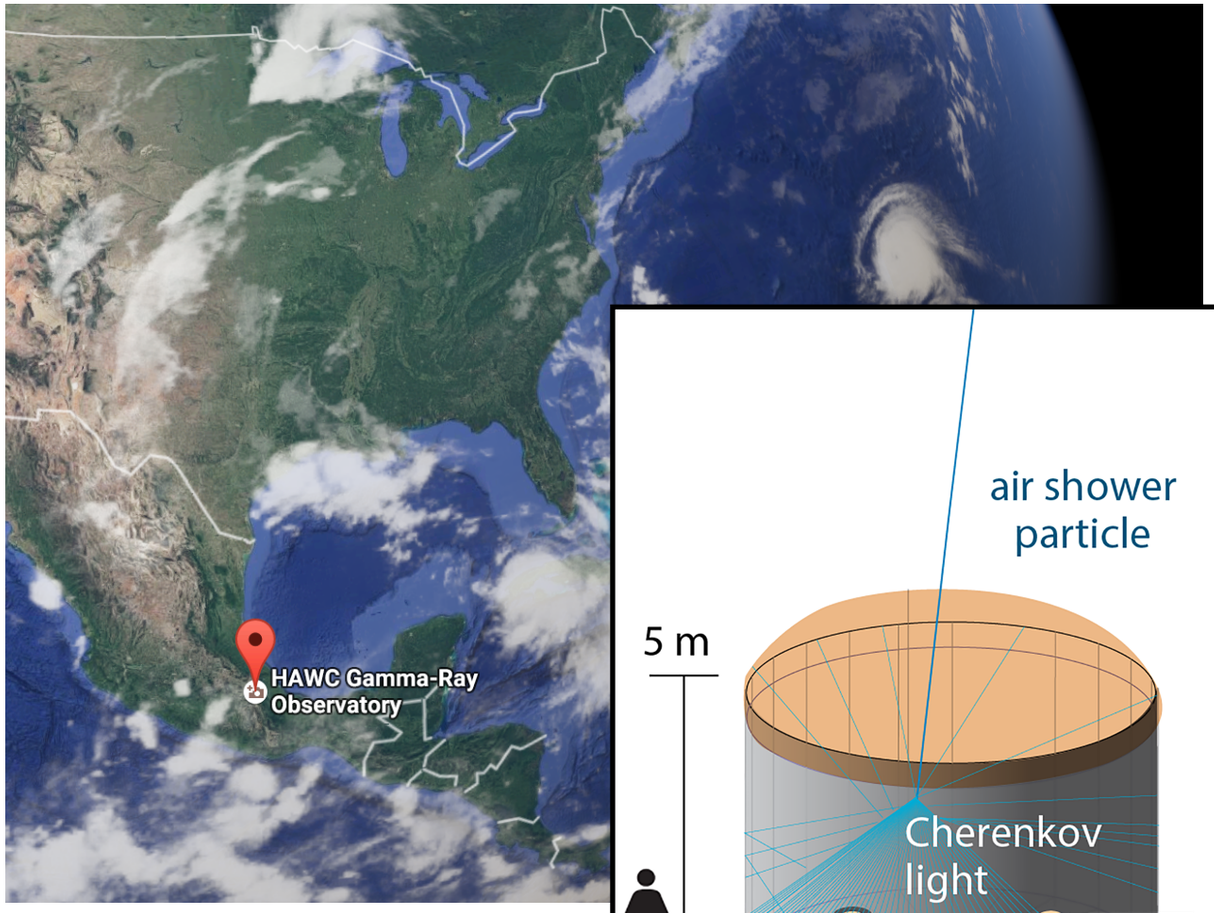
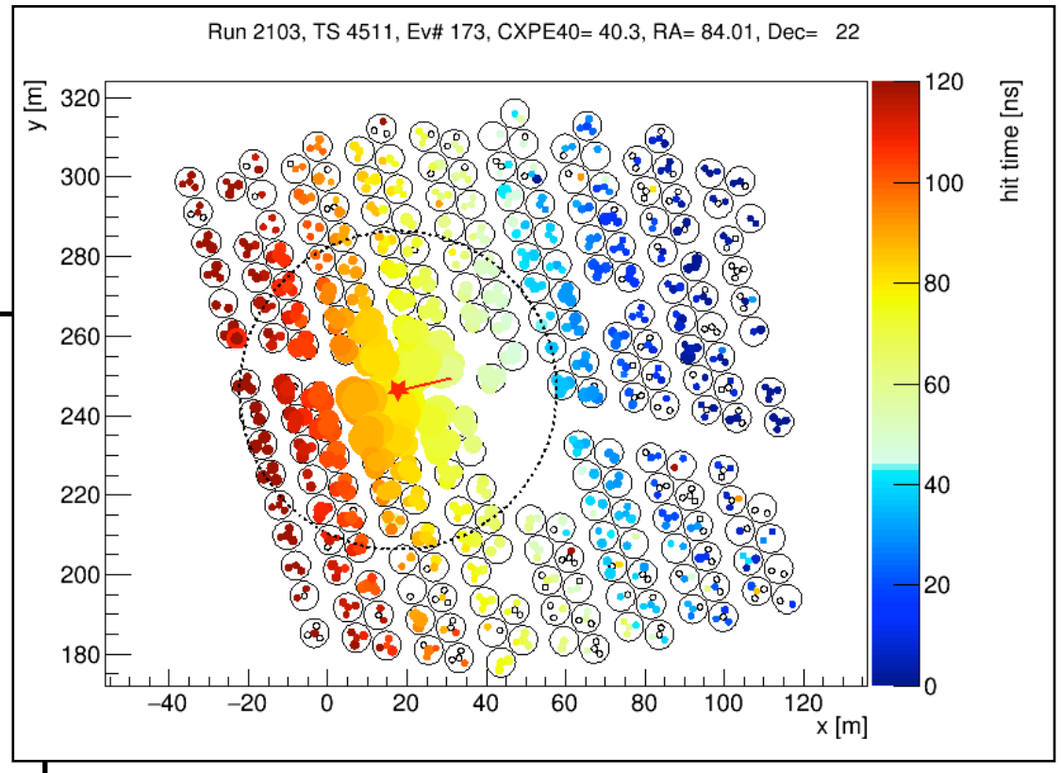


The HAWC observatory

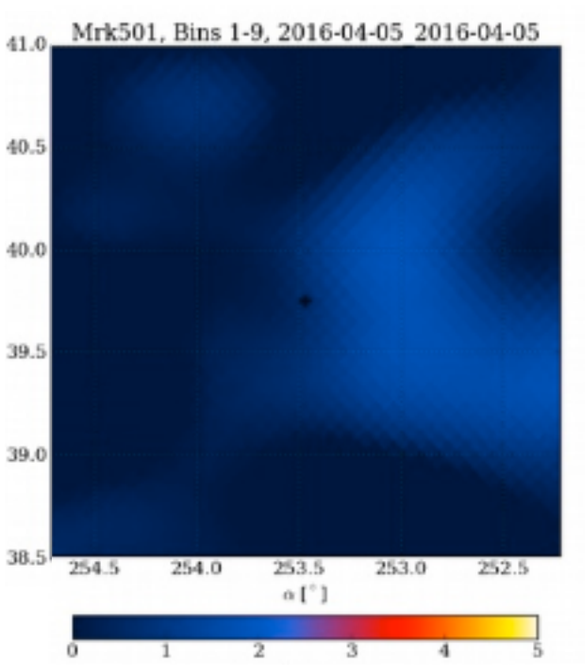
- High Altitude Water Cherenkov
- 4,100 m above sea level at 19° N latitude in the state of Puebla, Mexico
- 300 optically isolated water Cherenkov detectors
- Wide-field (~2 sr) detector for TeV-scale gamma rays and cosmic rays: complementarity with pointed instruments
- Reconstruct particle properties based on deposition of charge at ground level from secondary air showers

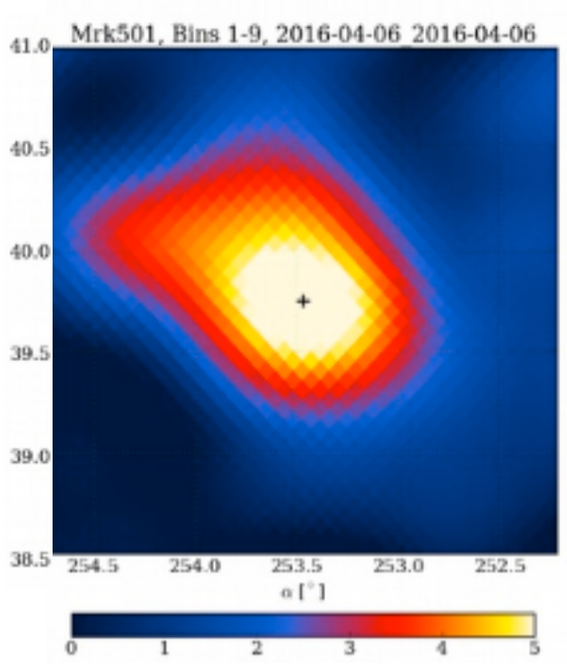


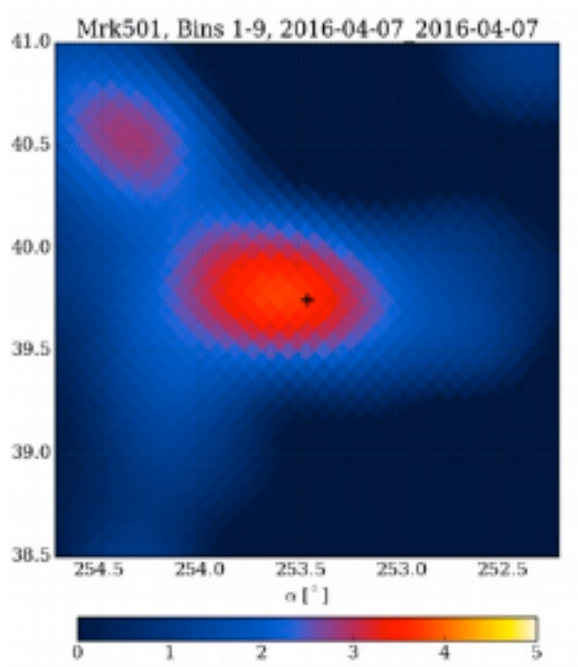


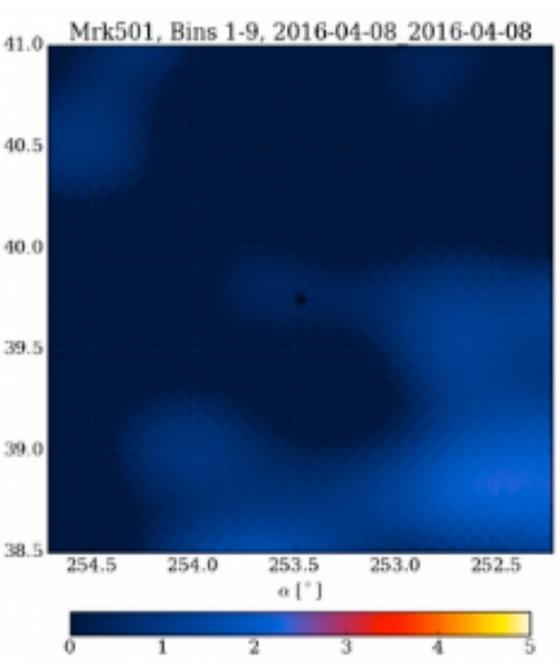
HAWC transient searches

- Daily flare monitor
  - Observes entire sky with an integration time of 1 source transit (about 6 hours)
  - Public alerts from the Mrk 421 and Mrk 501, all-sky effort still in progress
  - Example alert ATEL #8922
  - Integration times of 1/2 source transit currently running, will become available
- All-sky GRB monitor
  - Dedicated low-energy search (talk to Josh Wood for details)



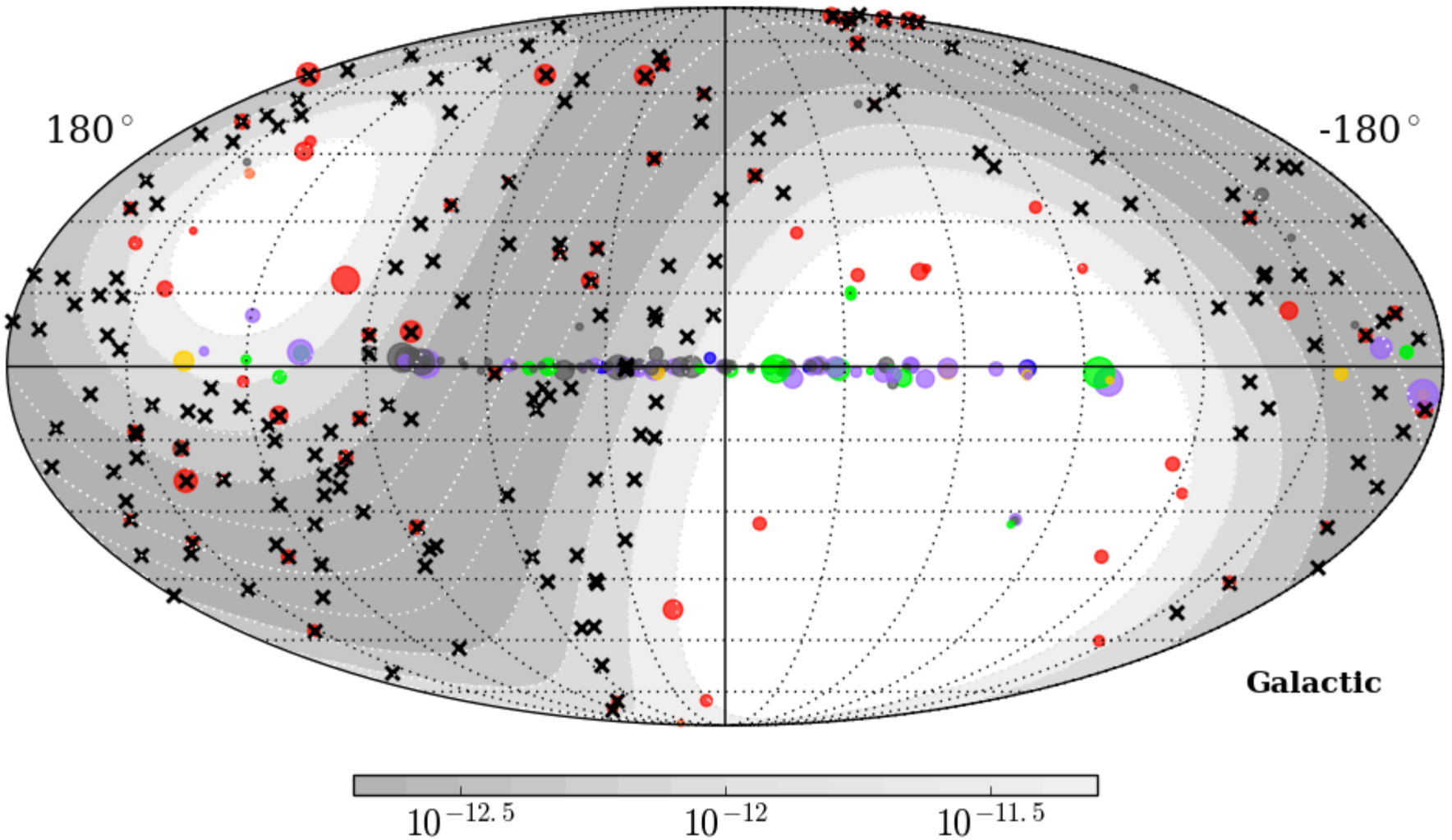






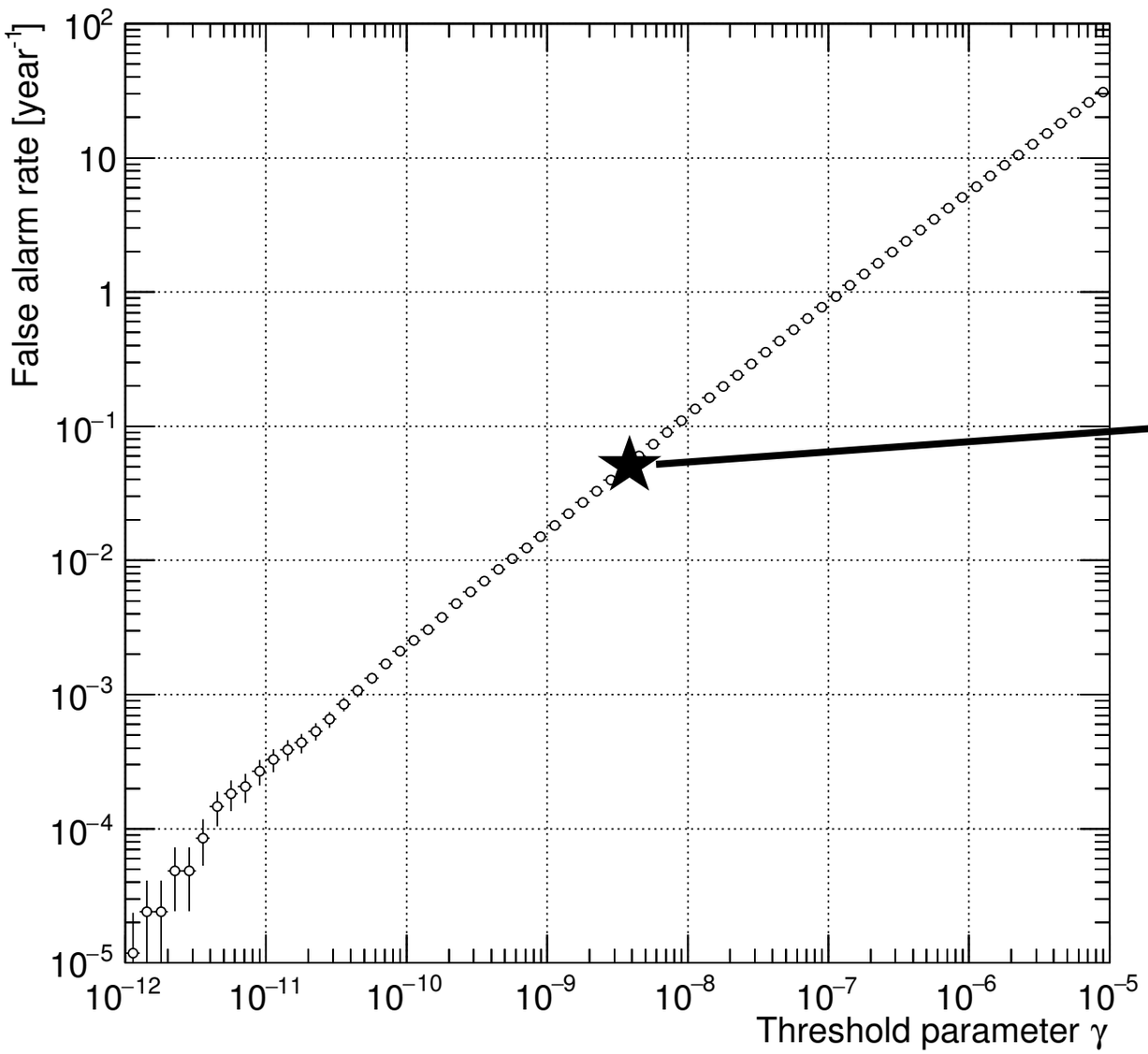
HAWC transient searches

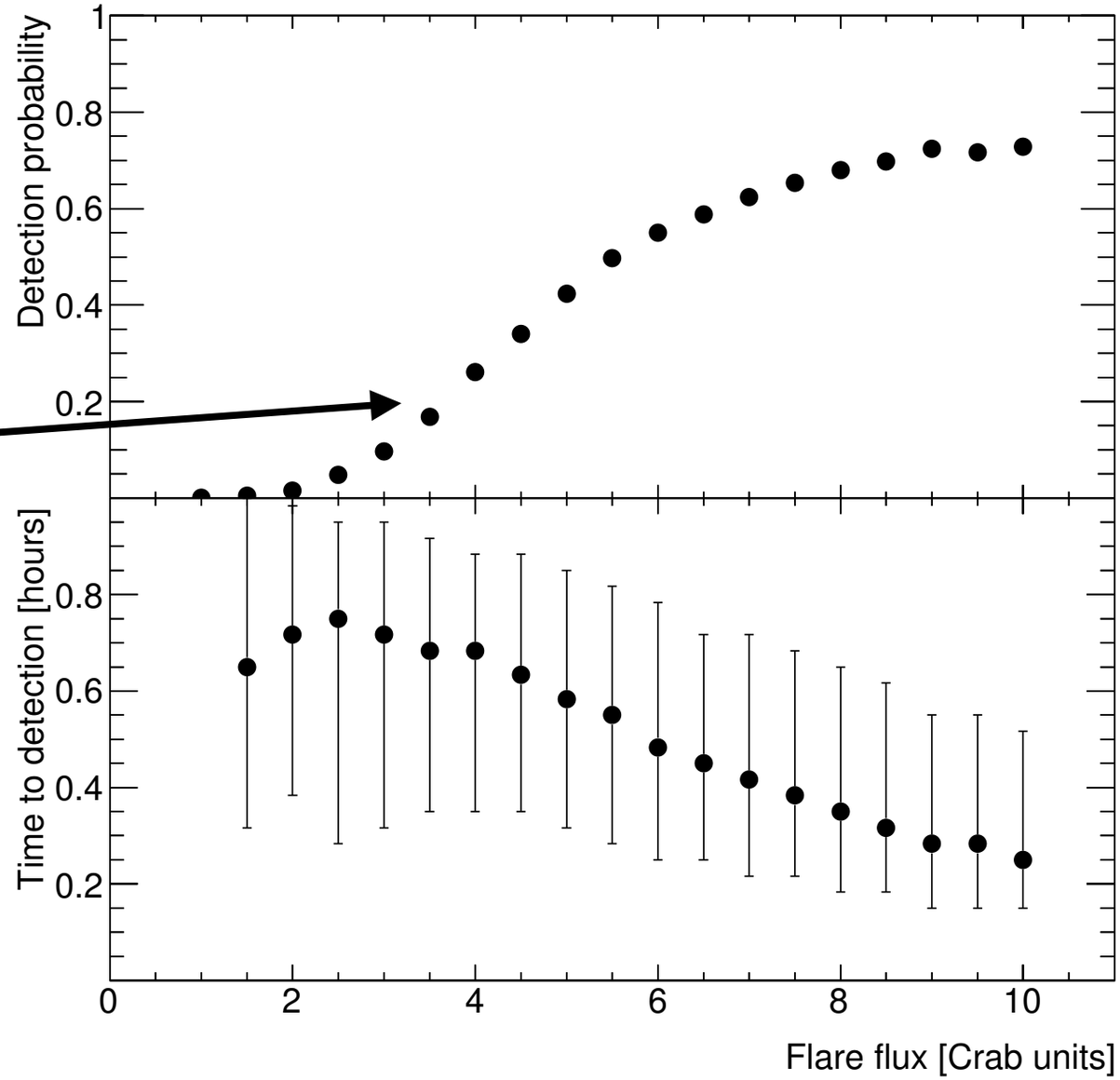
- Real-time flare monitor
  - Searches for ~1 hour time scale variability with a resolution of 2 minutes
  - Monitors a dedicated list of 187 sources: extragalactic TeVCat and 2FHL within HAWC sky coverage
  - Alerts sent under MoU, with general public alerts under development
  - Automatic alerts



Flare monitor sensitivity

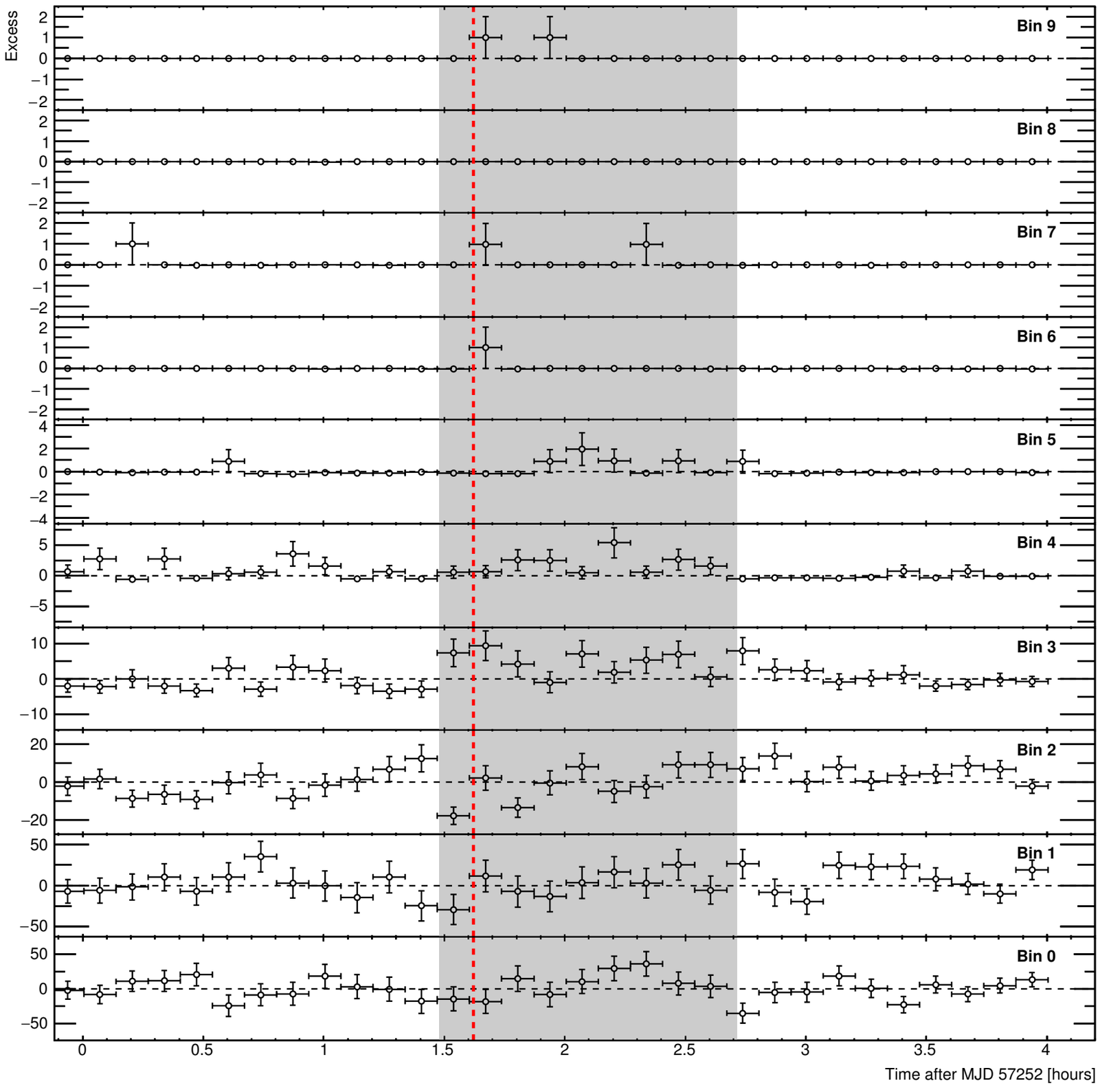
- Real-time flare monitor performs a likelihood ratio test on each monitored source:
  - H_0: the data for the previous 10 hours is modeled by steady or no flux
  - H_1: the data for the previous 10 hours has an increase in flux at one point
  - Test whether $\Delta \ln L > -\ln \gamma$, with γ a threshold parameter input
- Sensitivity for 1-hour flares at around 4 or 5 Crab units





Detection probability defined in Abeysekara et al. 2017, ApJ **843**, 116

Detection of Mrk 501 flare in offline data

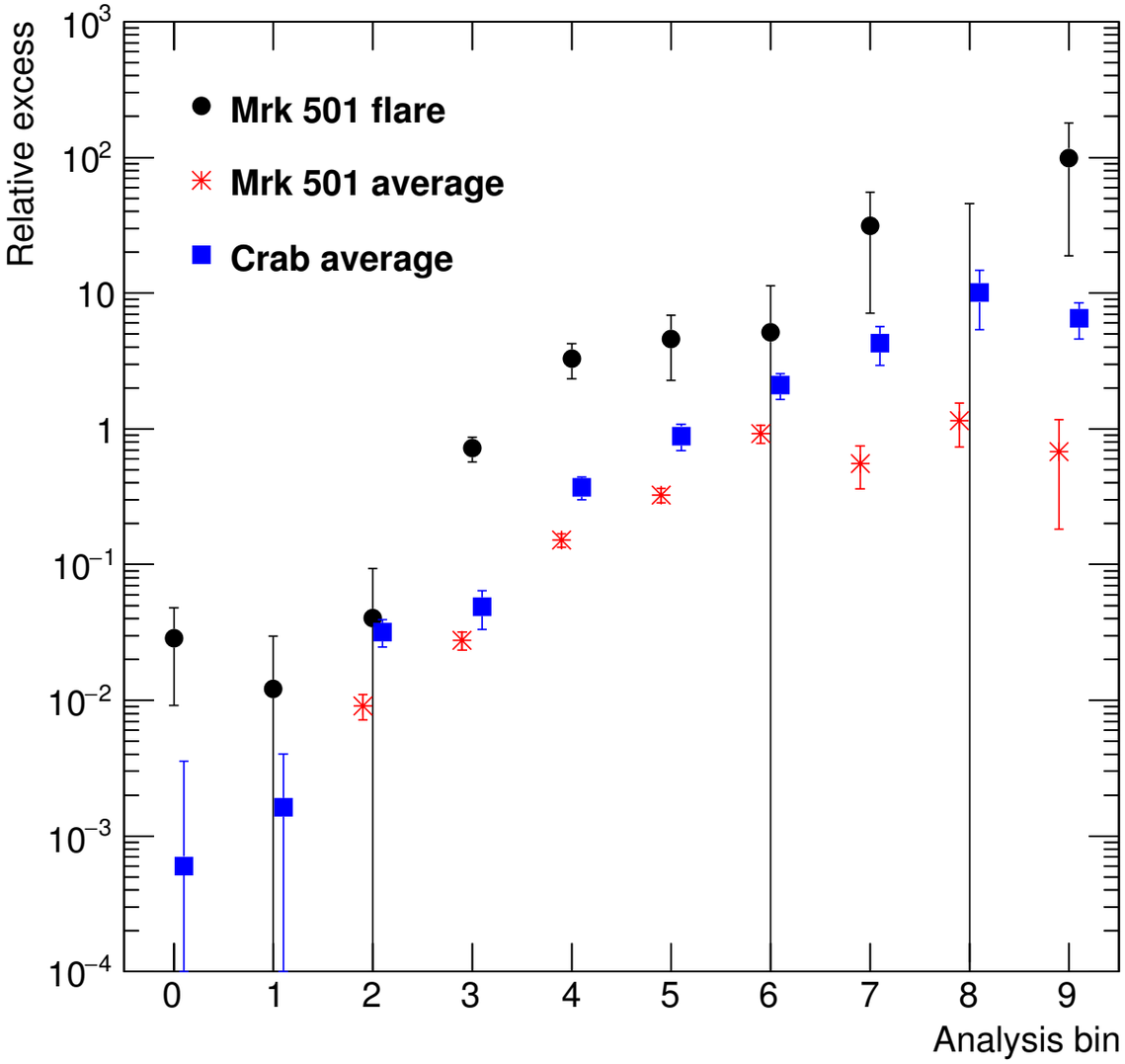


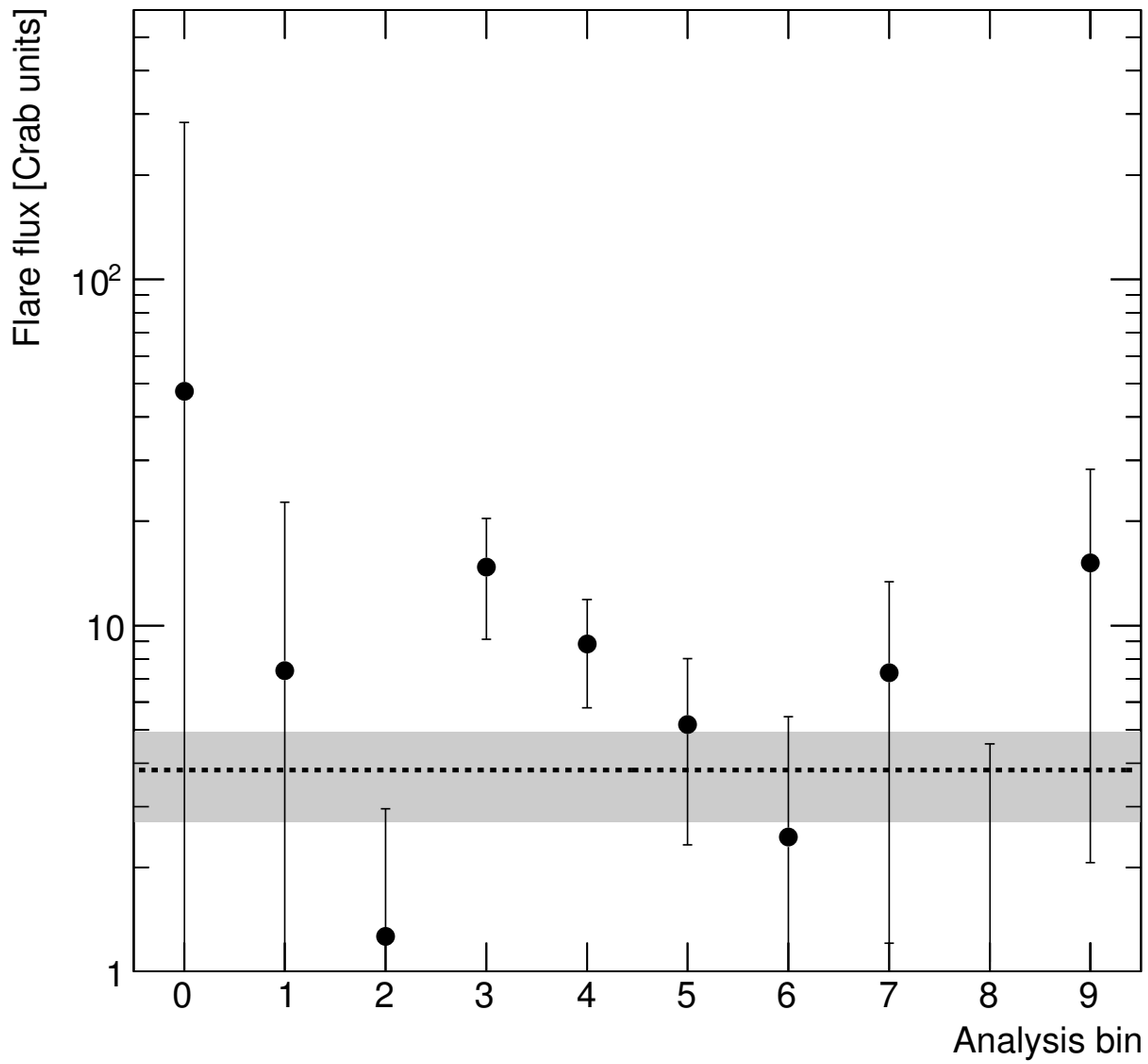
- Search run over 18 months of HAWC data, from 26 Nov 2014 to 1 June 2016
- HAWC analysis bins are energy proxy bins that correspond to fraction of PMTs participating in an event
- Most significant flare from Mrk 501 on 18 August 2015, lasting ~74 minutes
- Equivalent false alarm rate of 0.007 events per year

Abeysekara et al. 2017, ApJ **843**, 116

Detection of Mrk 501 flare in offline data

- Detected flare consistent with sensitivity of flare monitor
- Flare was also detected in standard single-transit offline analysis
  - Further spectral and light curve details presented by D. Dorner and R. Lauer in "Joint blazar analysis with FACT and HAWC" (ICRC 2017)





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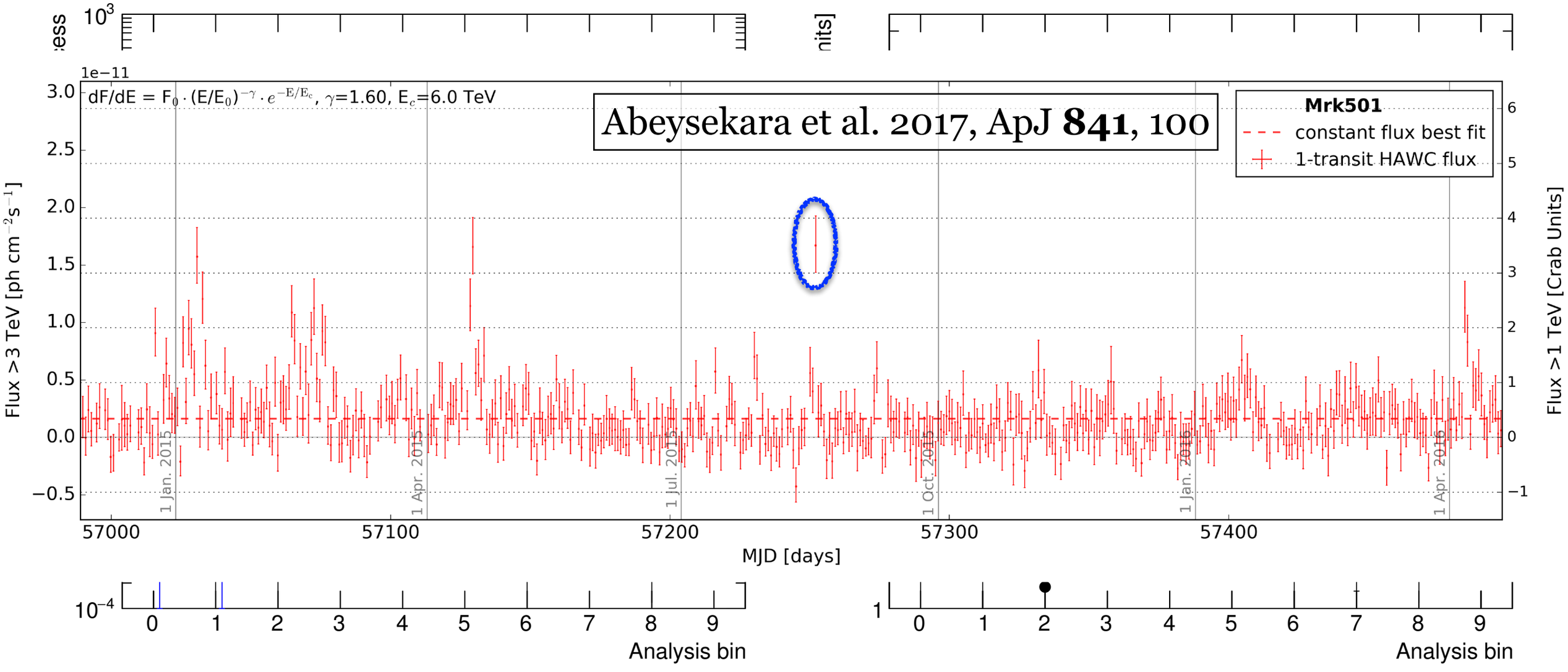
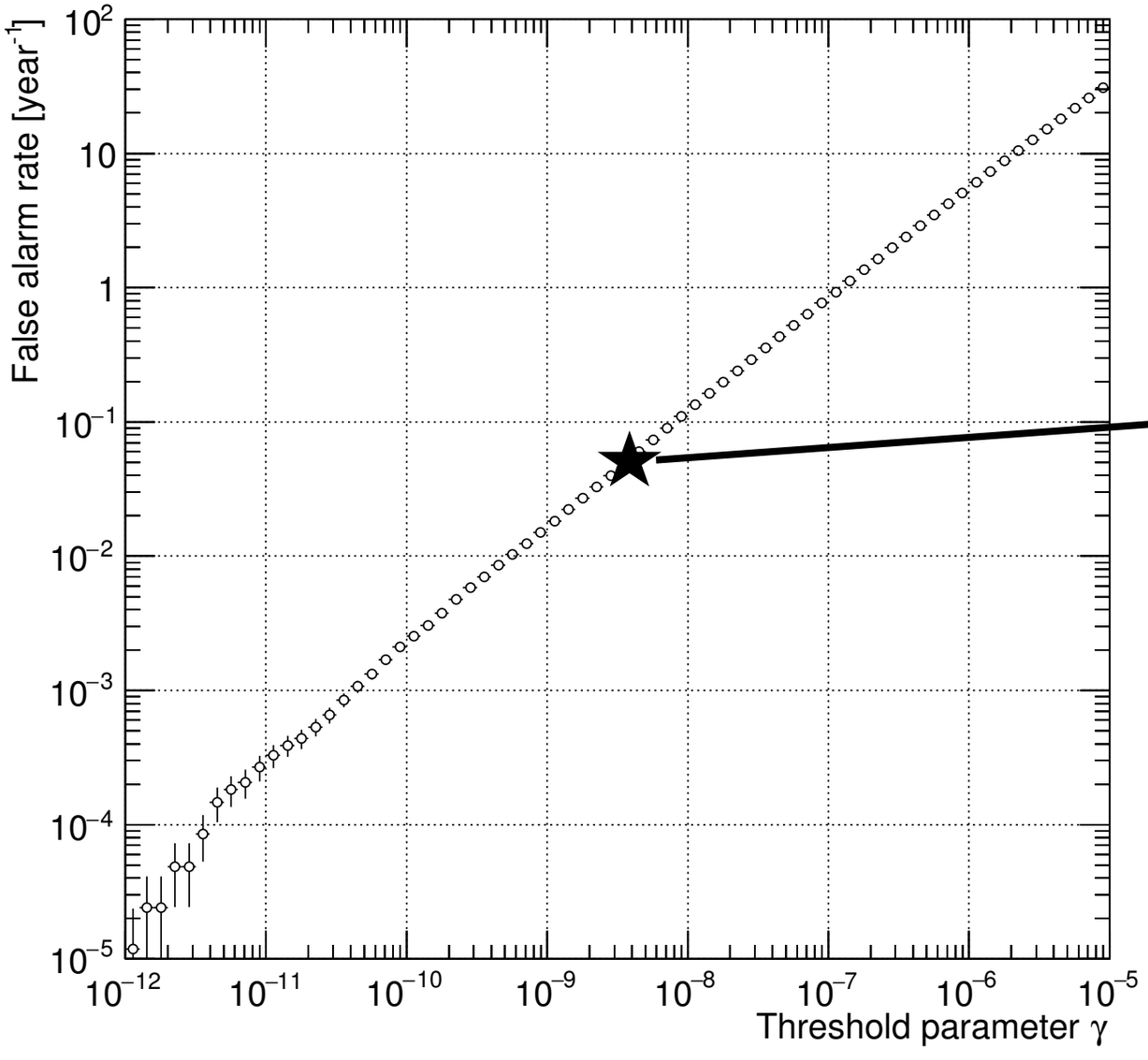
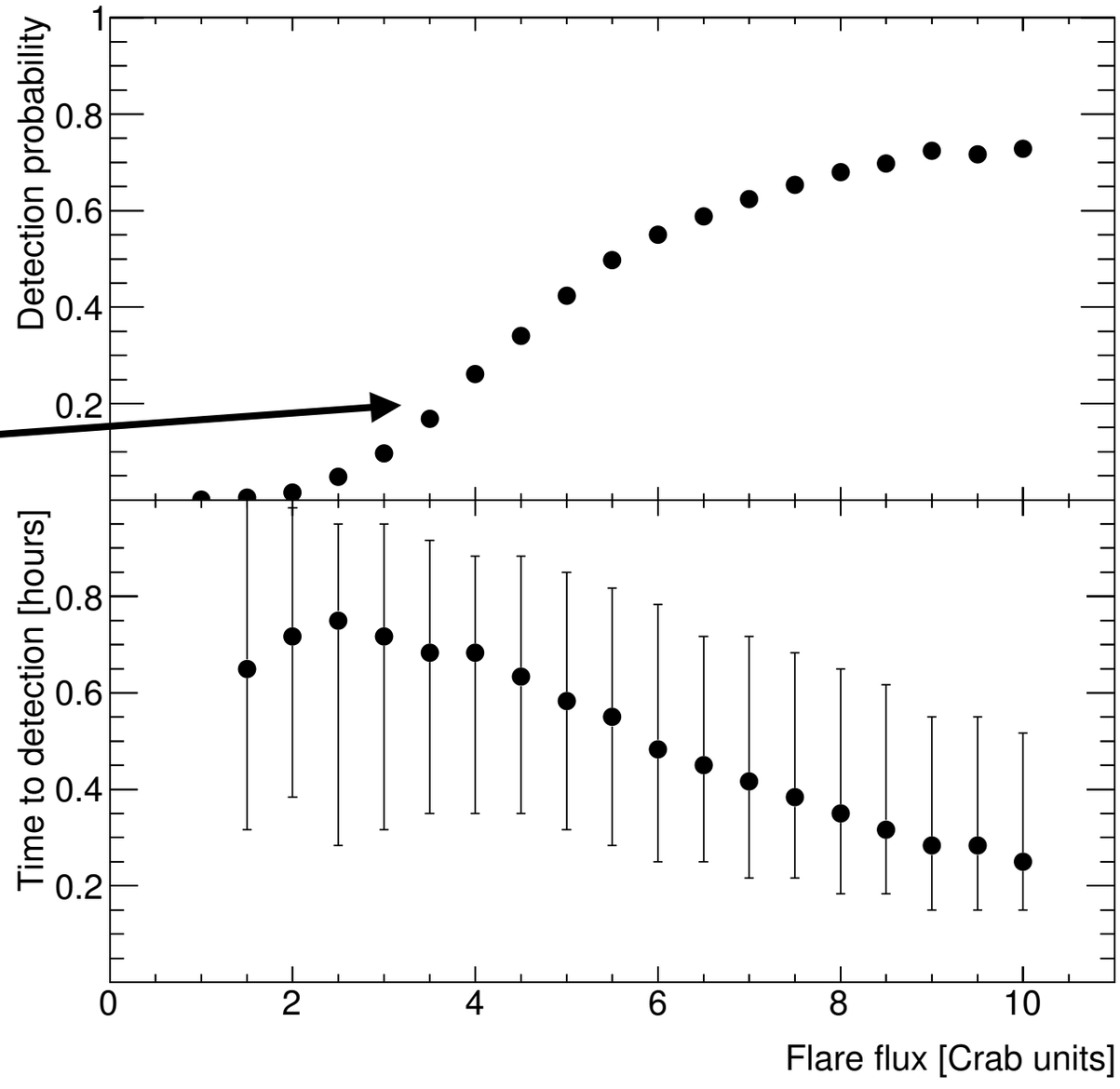


Extending to sub-threshold flares

- For a higher false alarm rate, we may detect transient activity statistically
- Increased probability in the region below the real-time flare monitor usual threshold yields sensitivity to weaker flares, but not on a flare-by-flare basis





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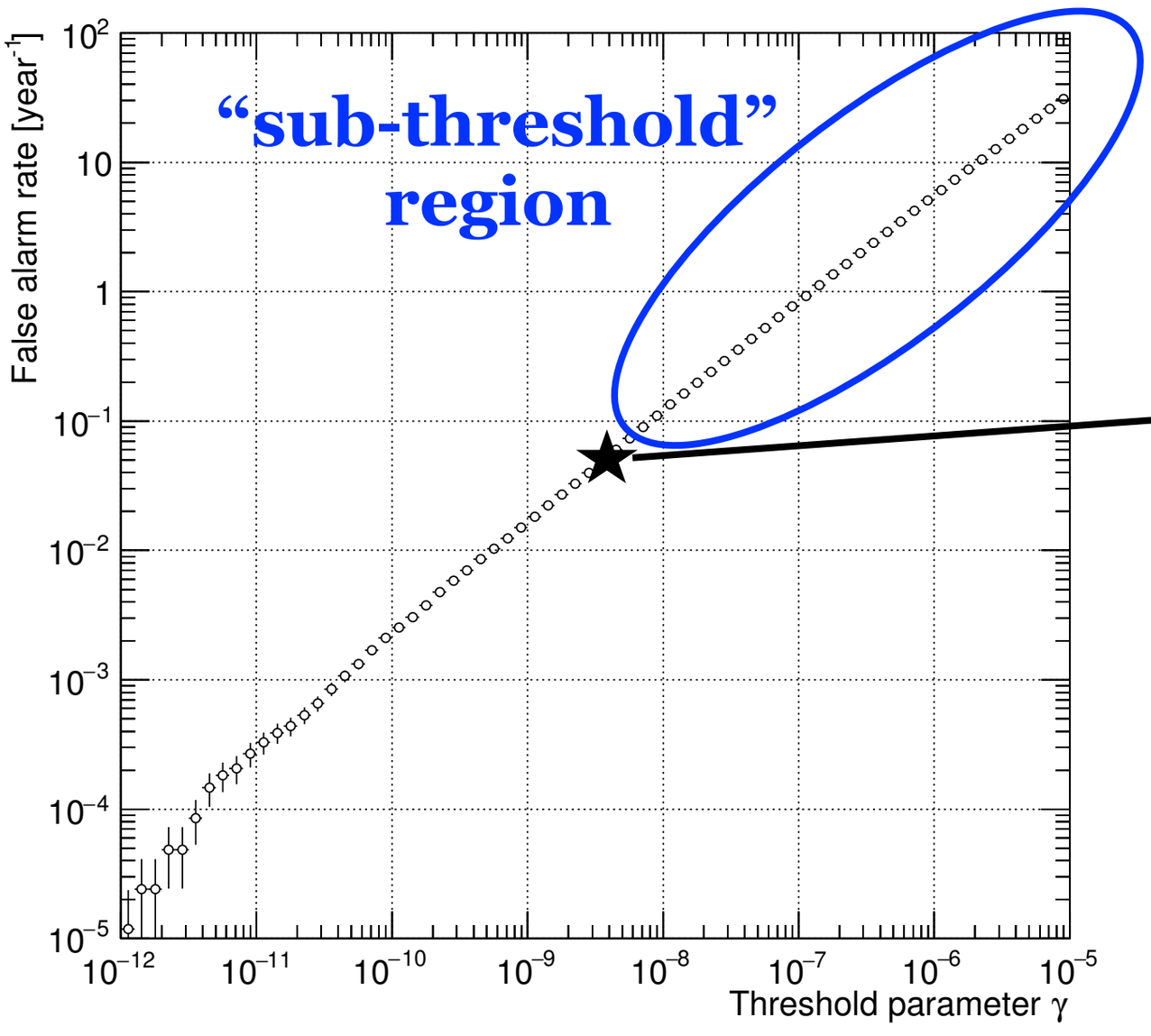
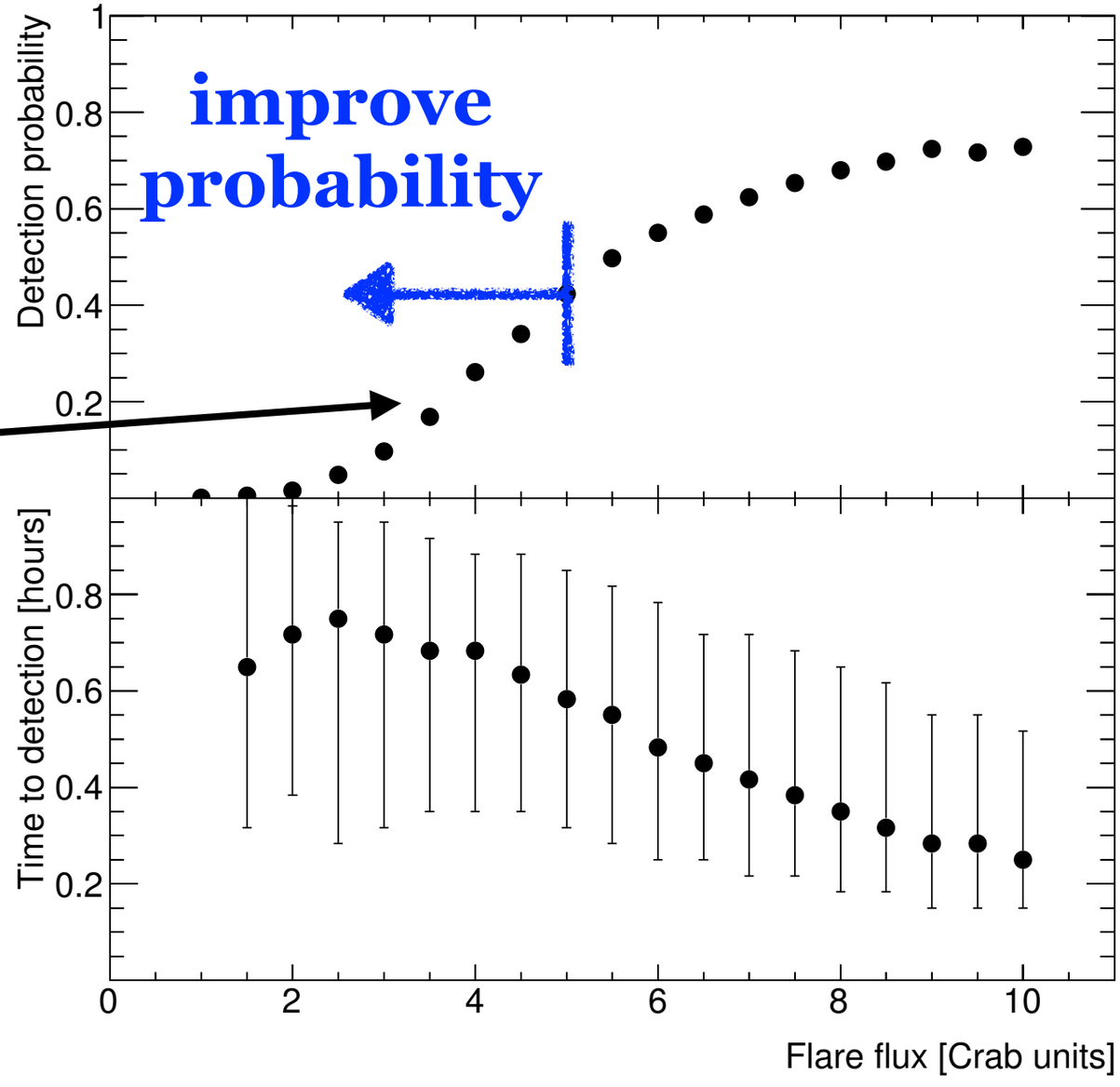
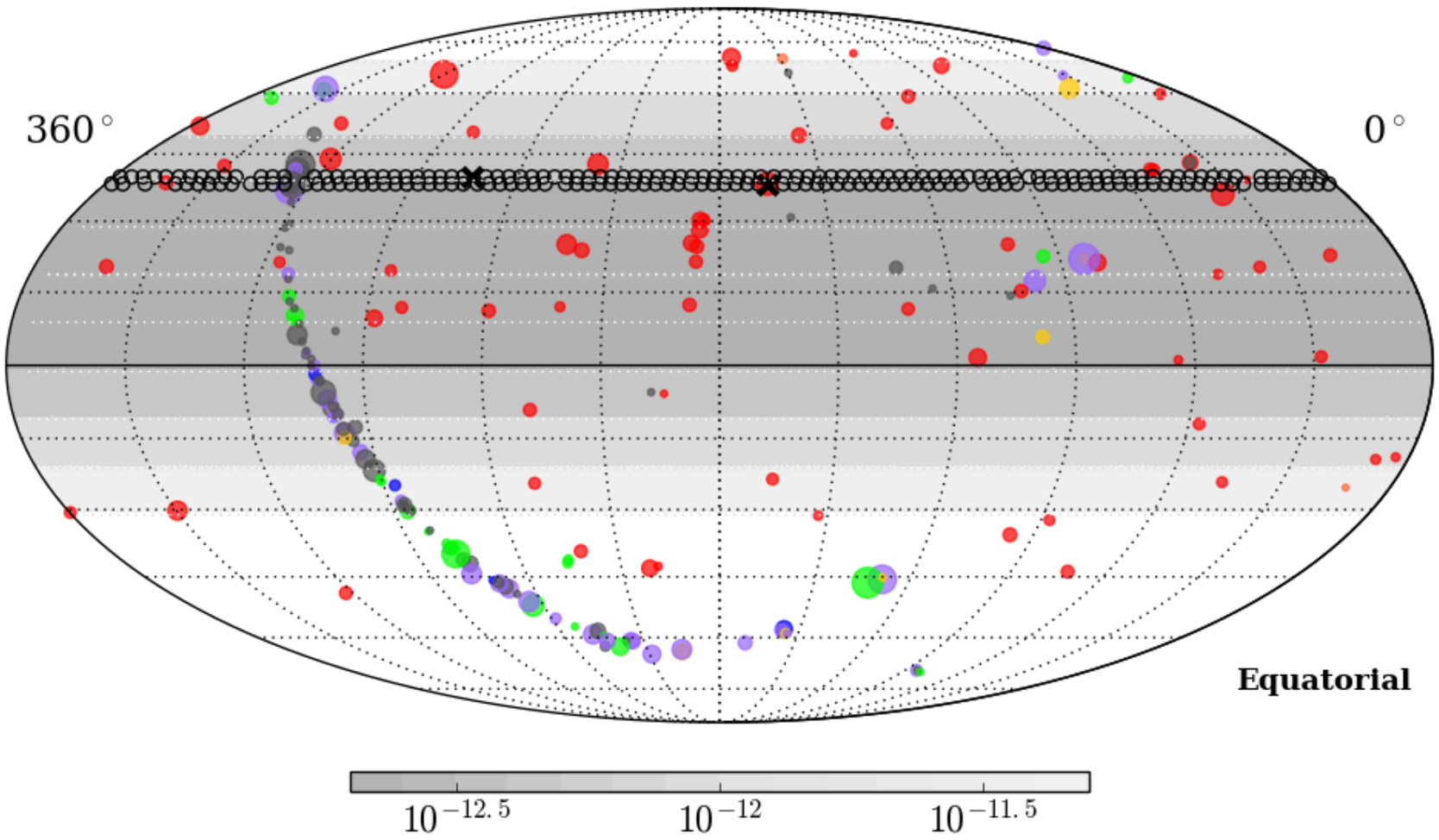
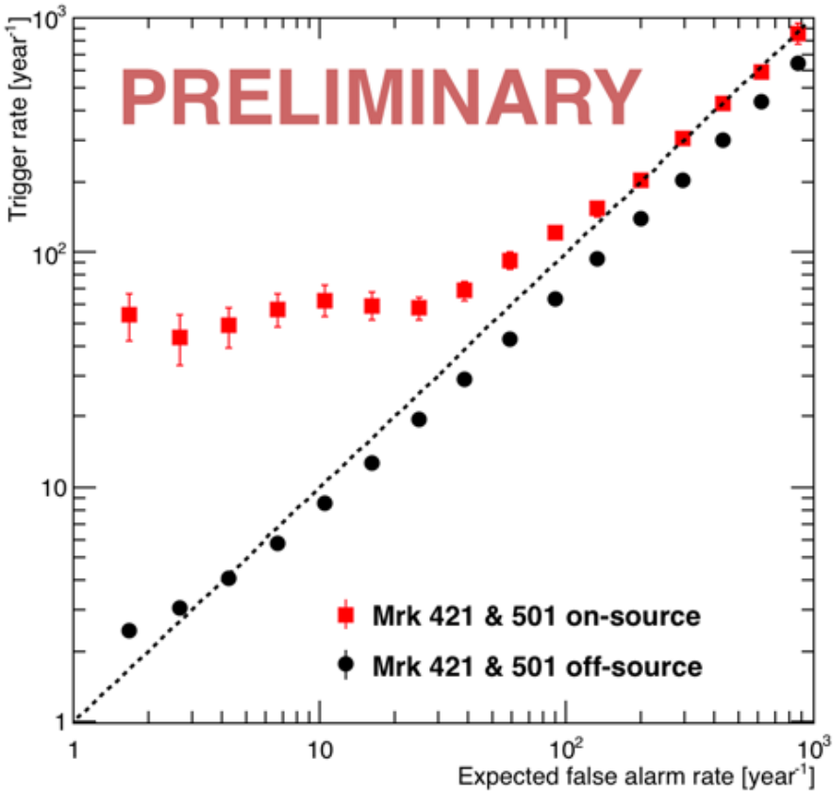




Sub-threshold Markarian flares

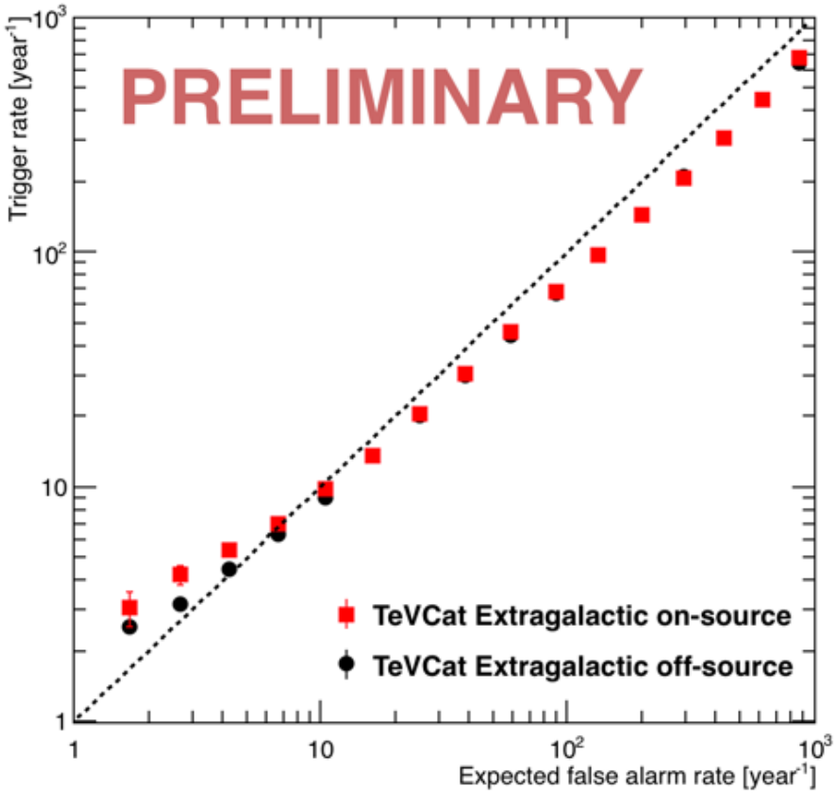
- Markarian 421 and 501
- 2 targets, 100 off-source regions per target

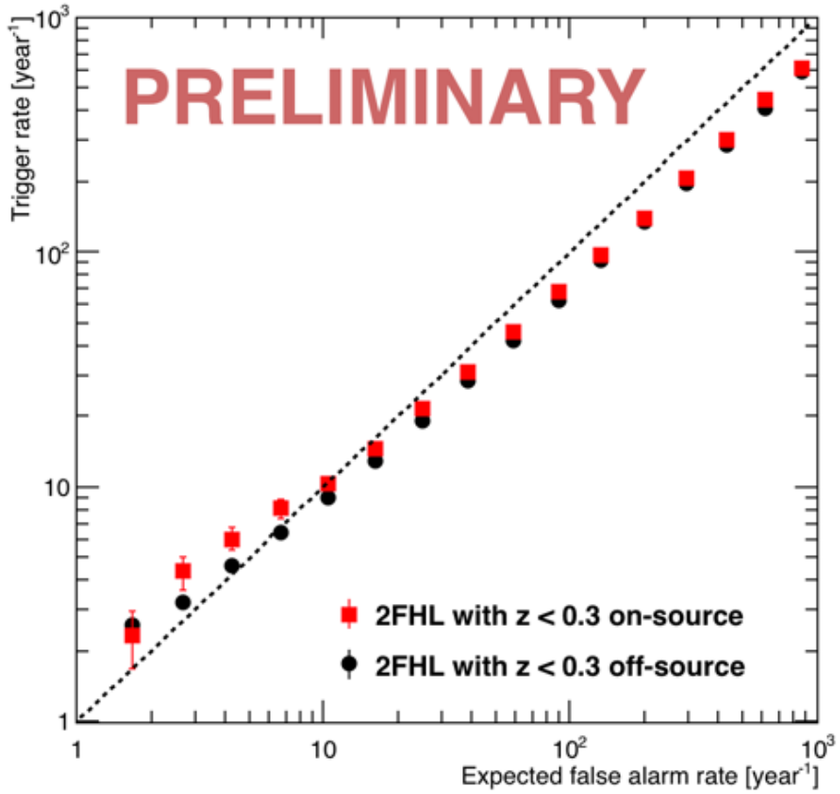


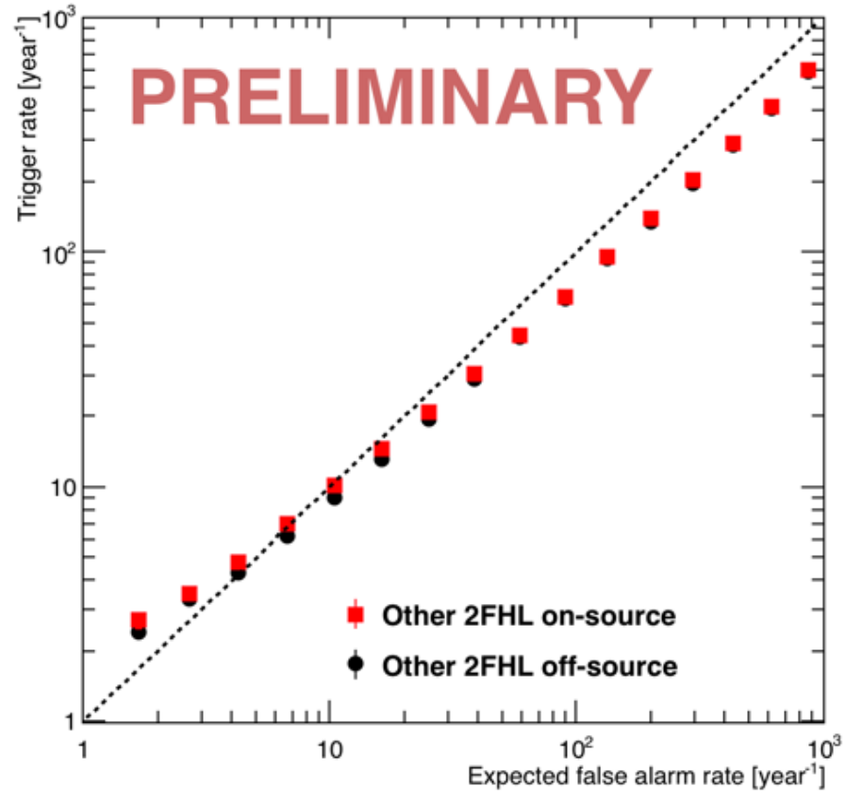


Sub-threshold flares

- No significant detections in other flare monitor targets
- Further analysis will search for above-threshold and sub-threshold flares in individual targets





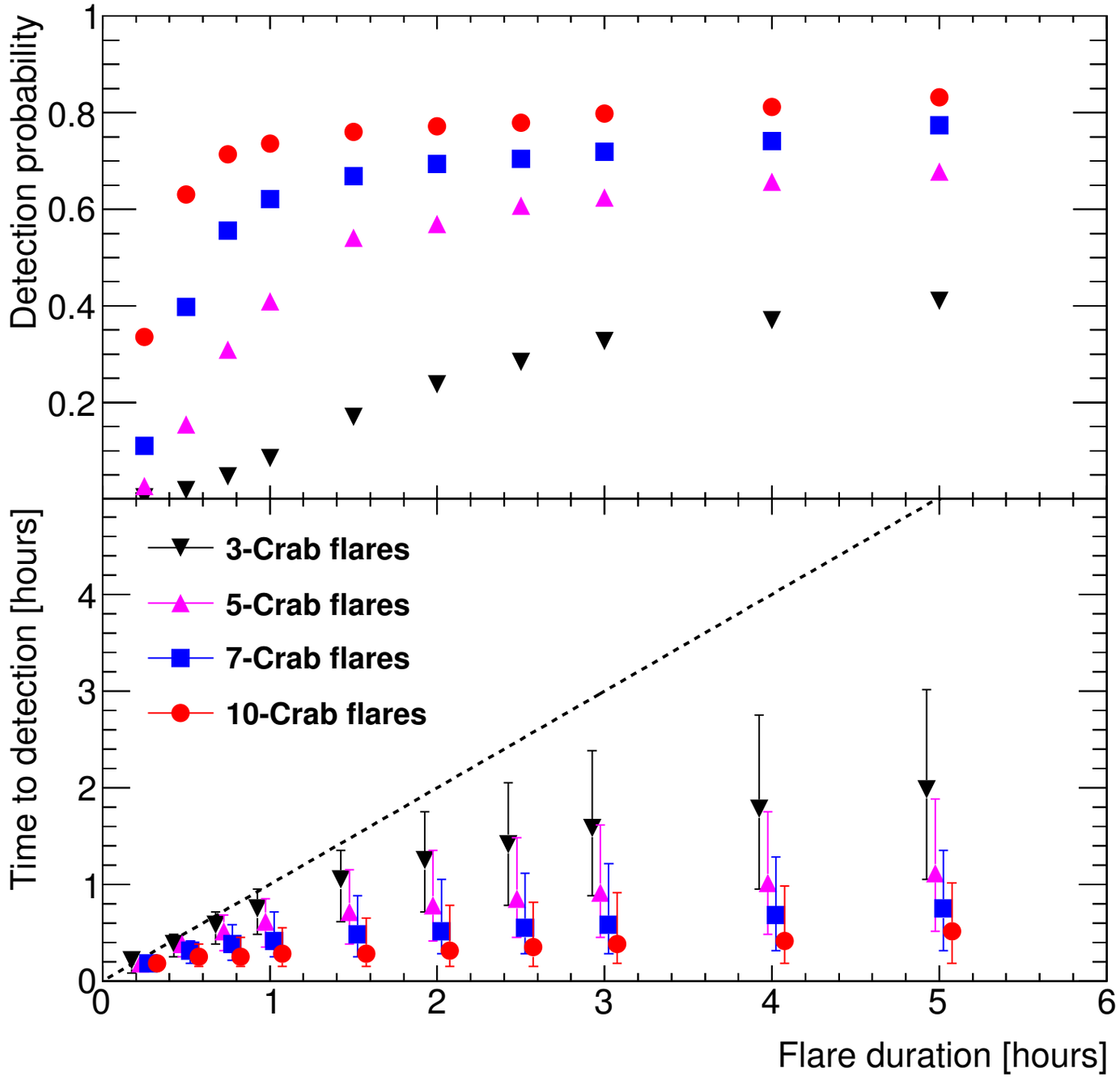


Moving forward

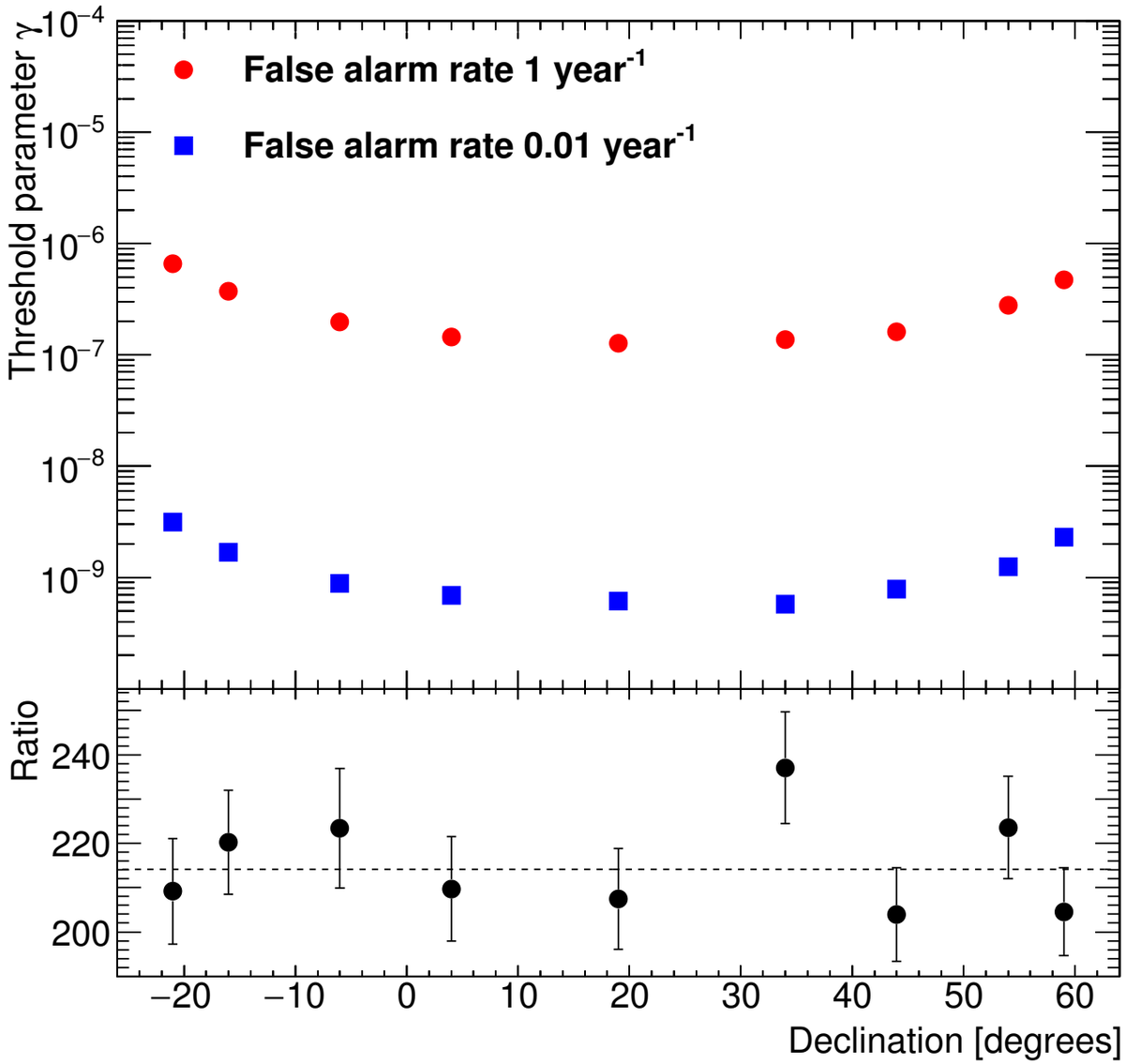
- HAWC flare monitor continues to operate in triggered mode, sending MoU alerts and soon to the general community
- Clear detection of both sub-threshold and above-threshold activity in the nearby TeV sources Mrk 421 and Mrk 501
- Initial search for sub-threshold activity in other likely targets so far shows no conclusive detection
- Above-threshold search and more detailed sub-threshold searches currently in progress

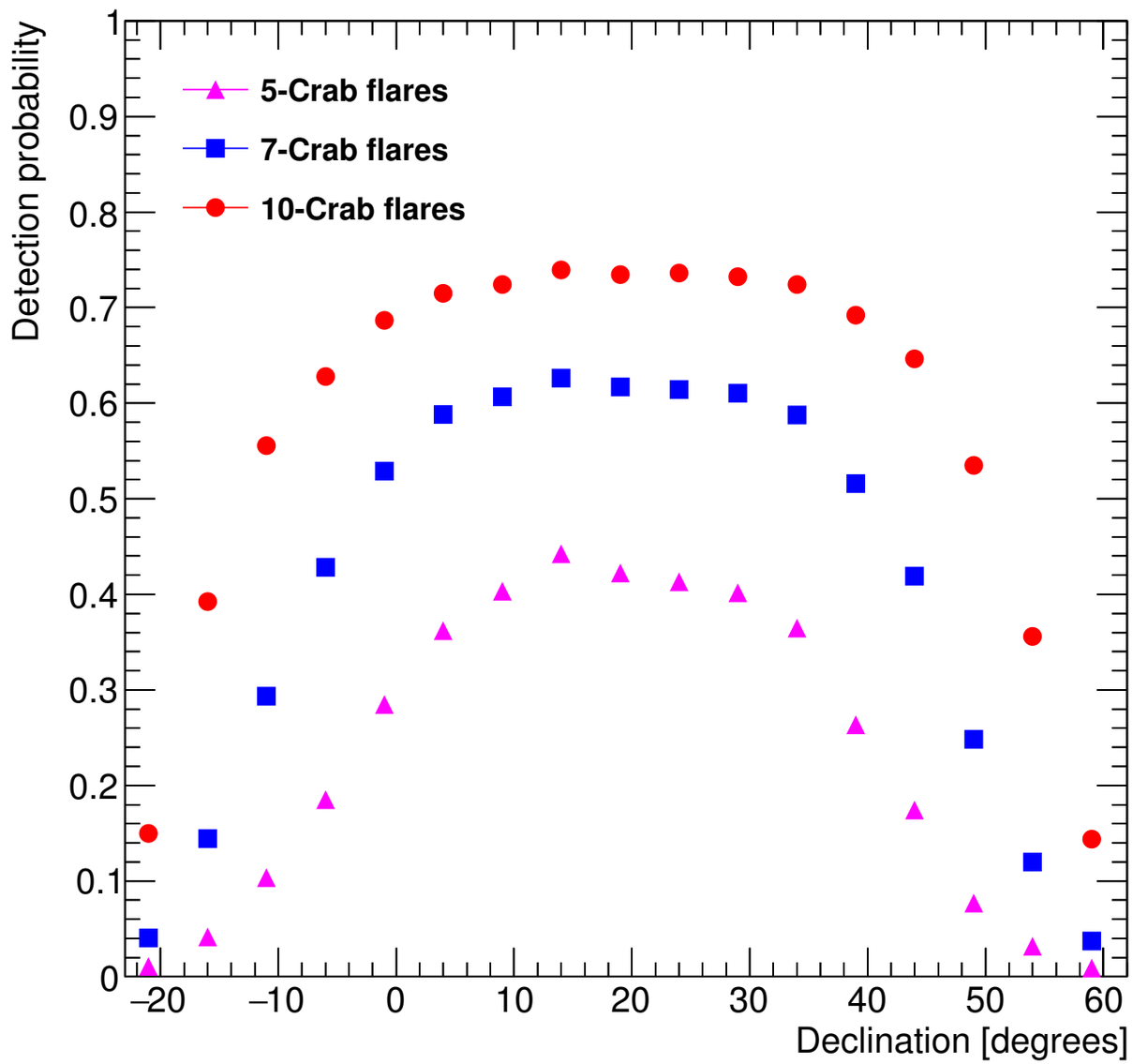
Supporting Material

Duration dependence

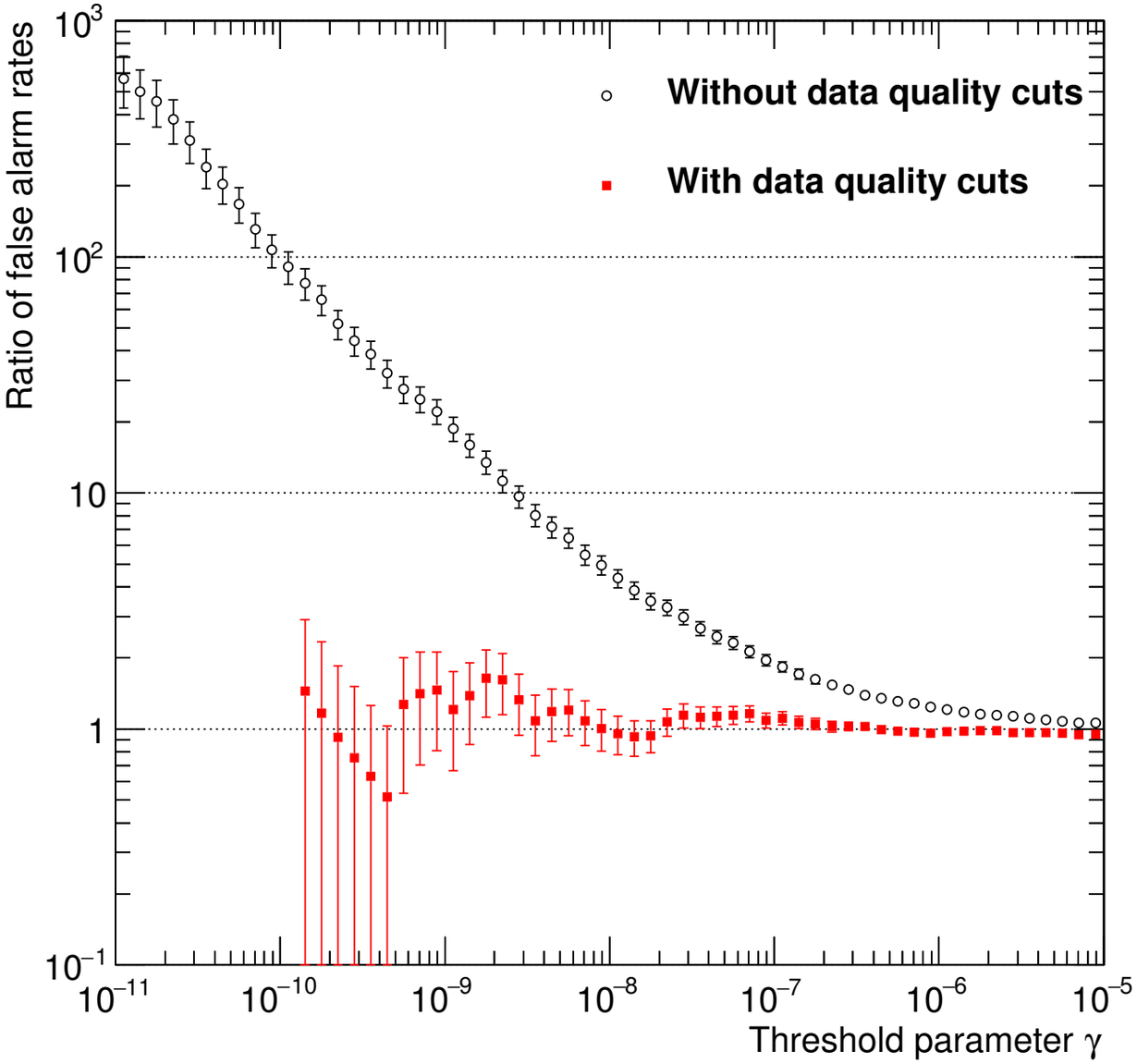


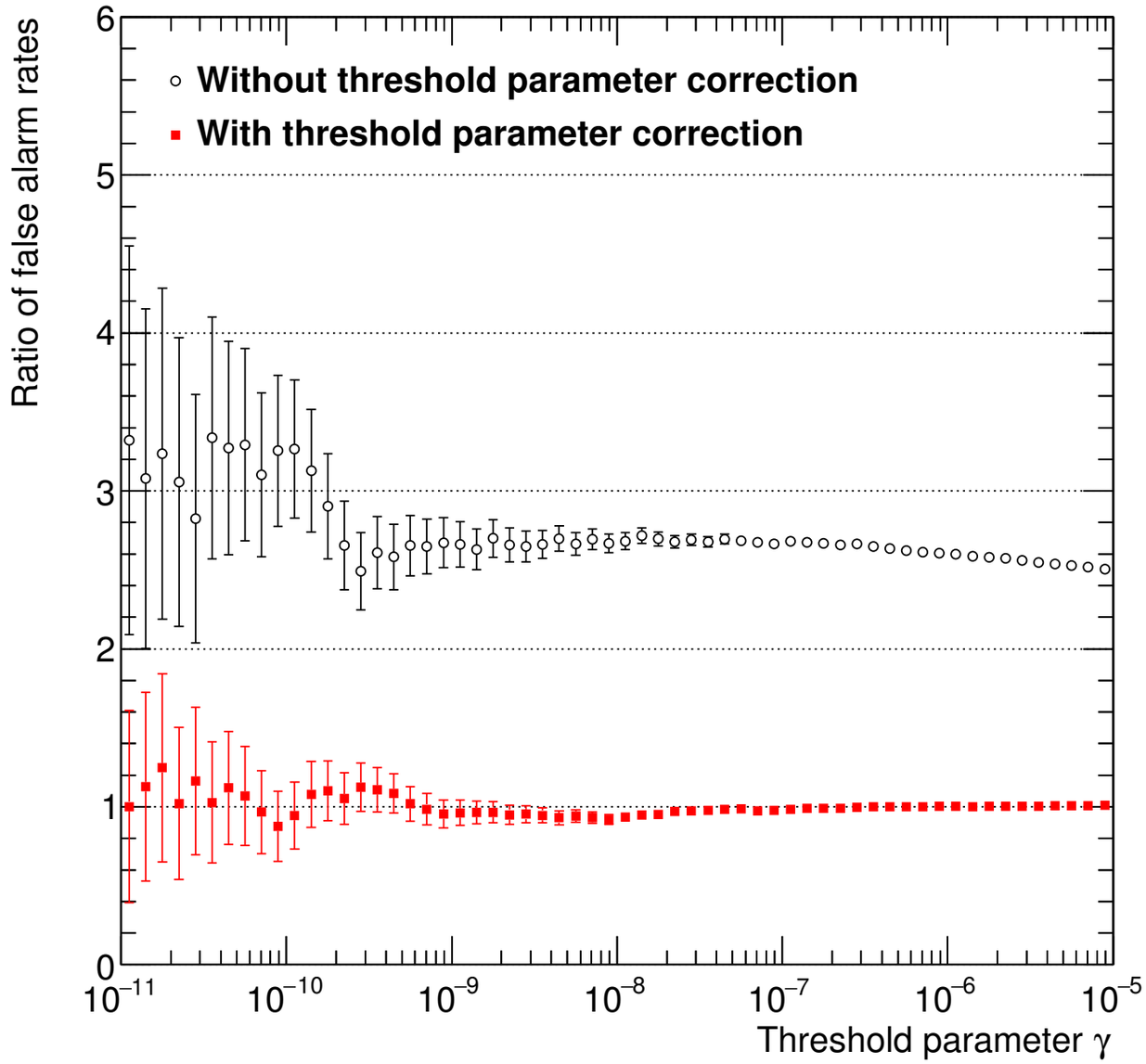
Declination dependence





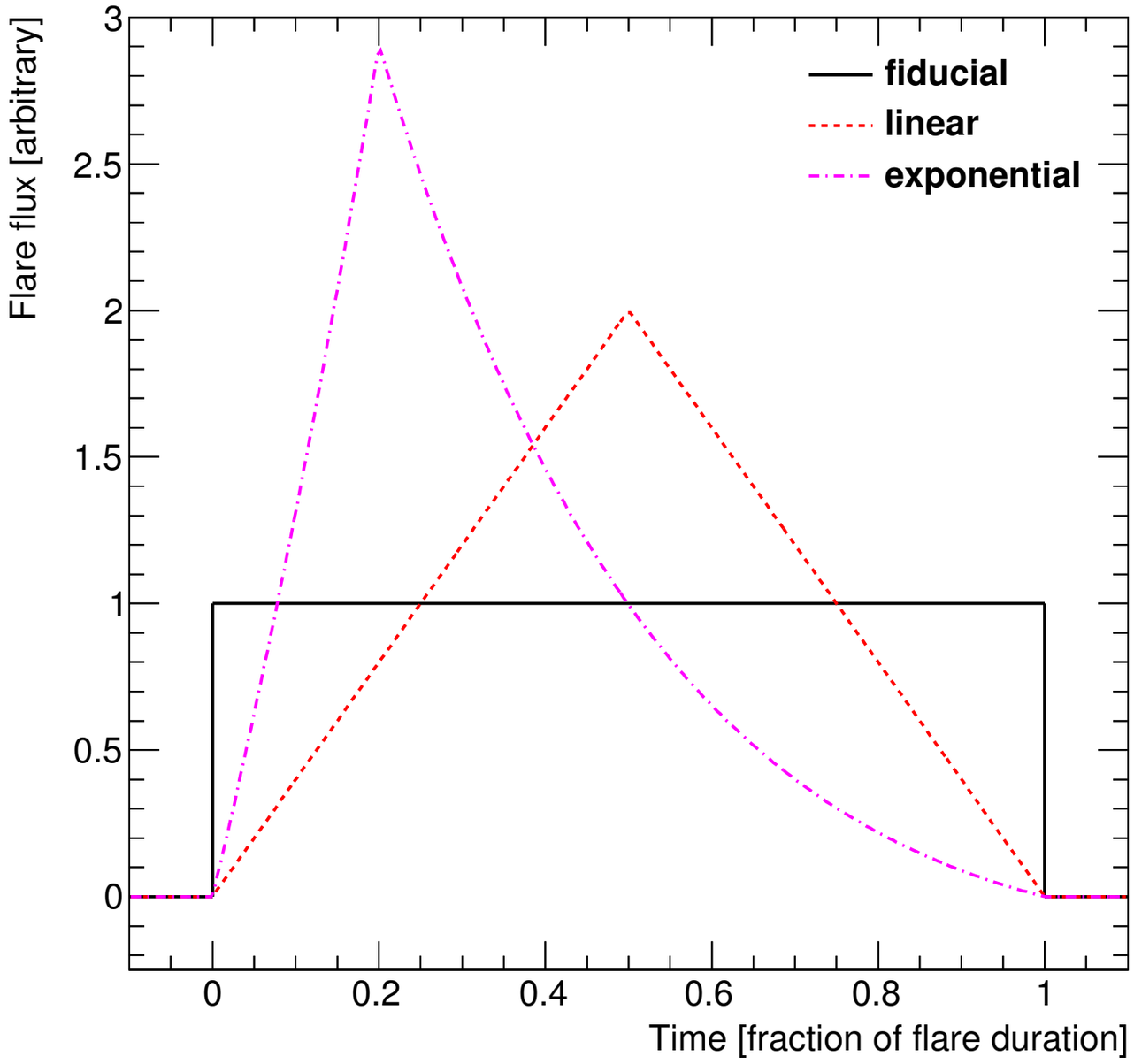
Various corrections



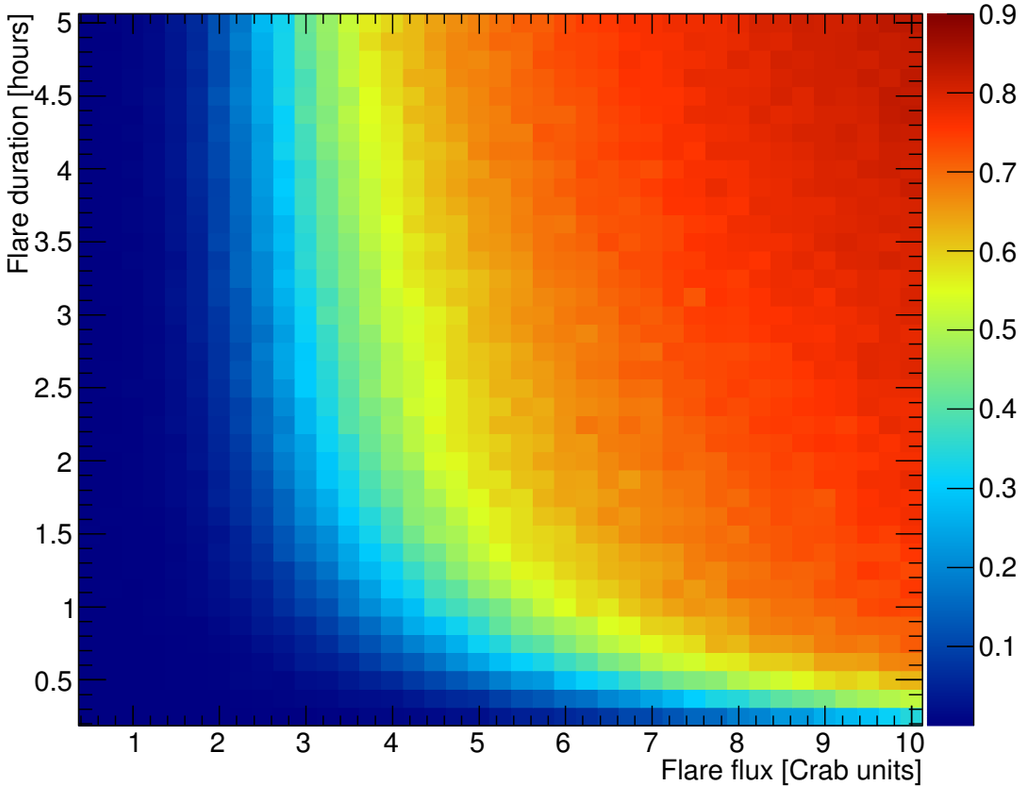


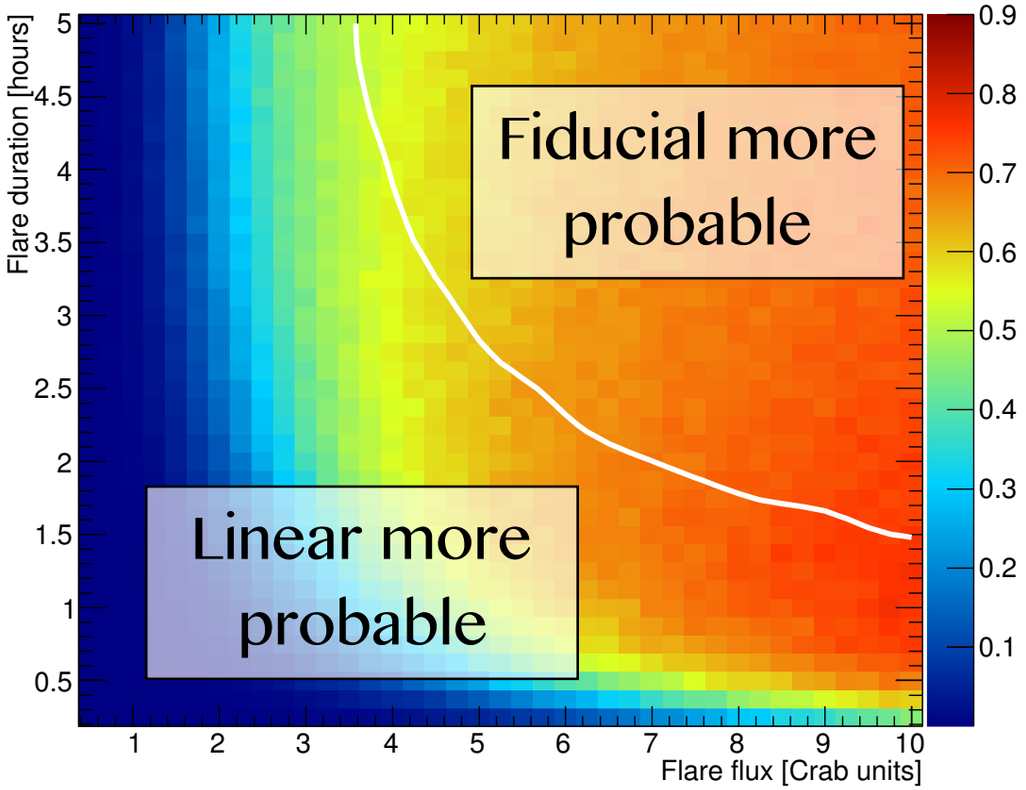
Flare monitor sensitivity

- Linear and exponential flare shapes alter the detection probability compared to the fiducial square wave shape



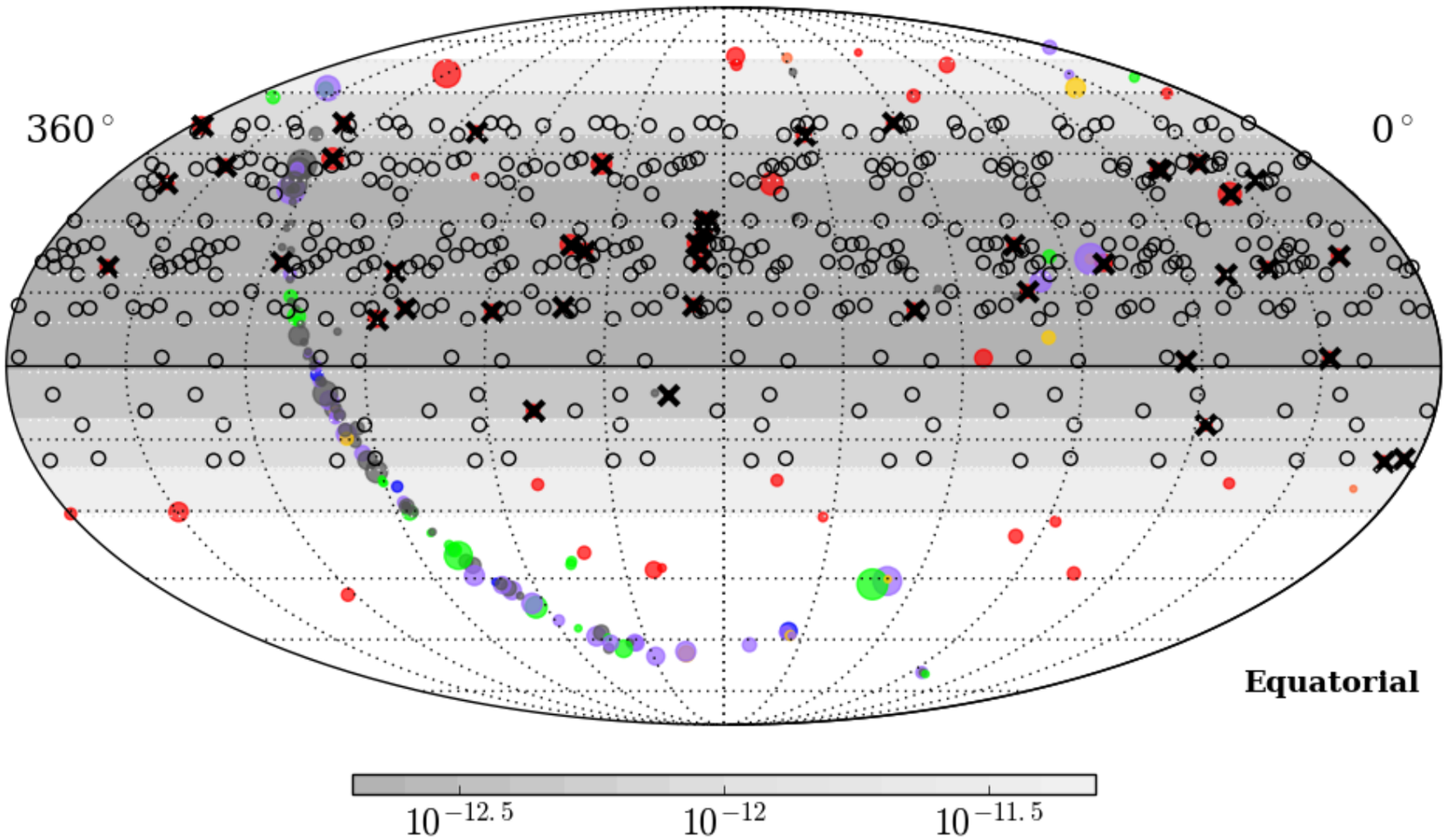
Detection Probability



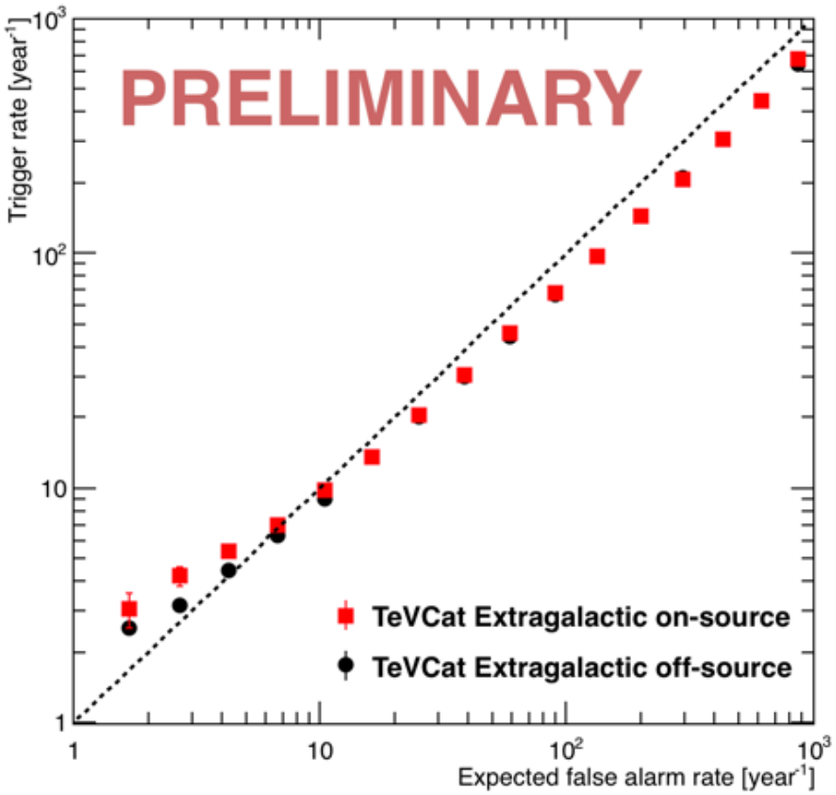


Search for other sub-threshold flares

- Extragalactic non-Markarian TeVCat sources, within HAWC sky coverage
- 44 targets, 10 off-source regions per target

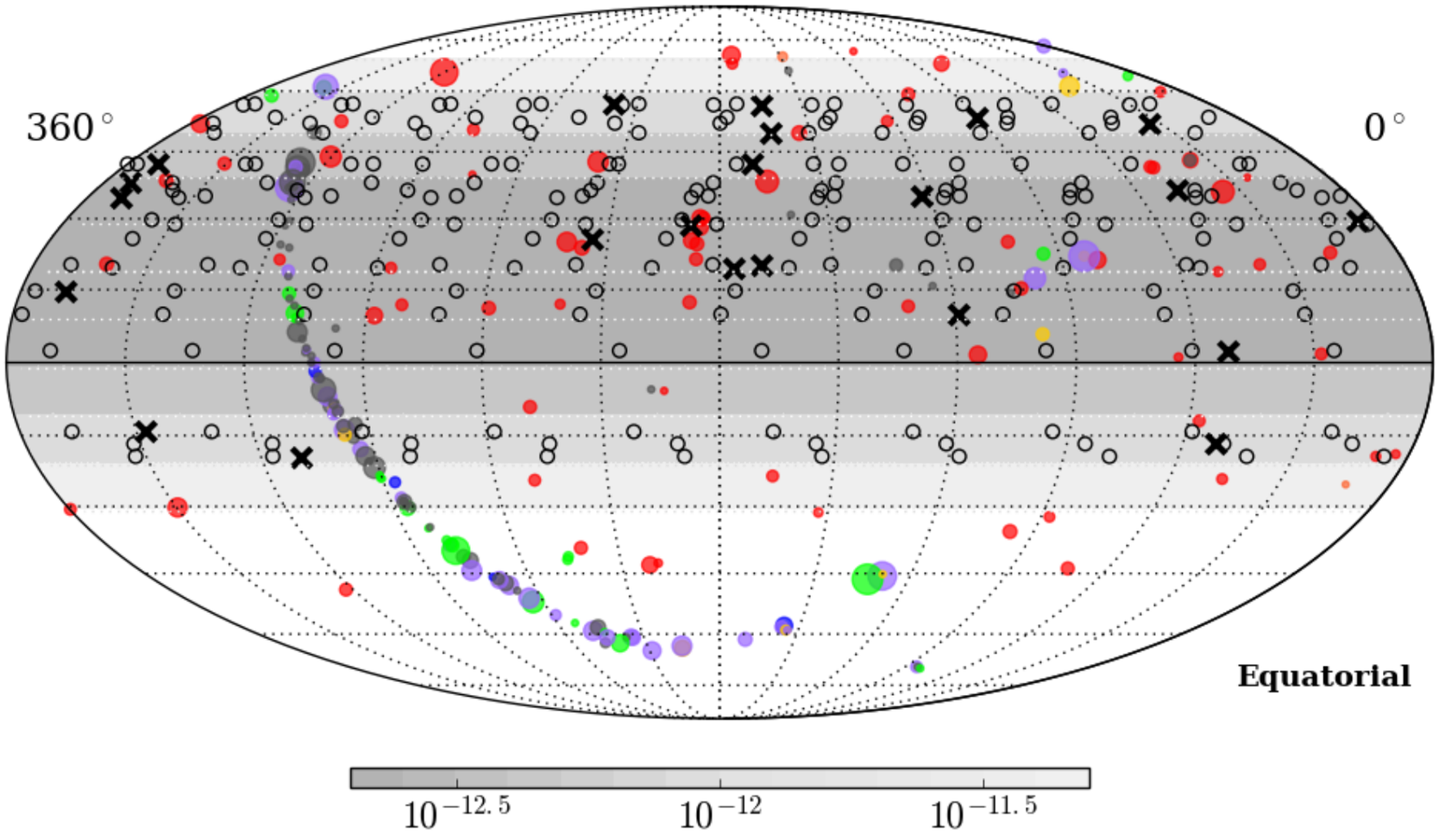


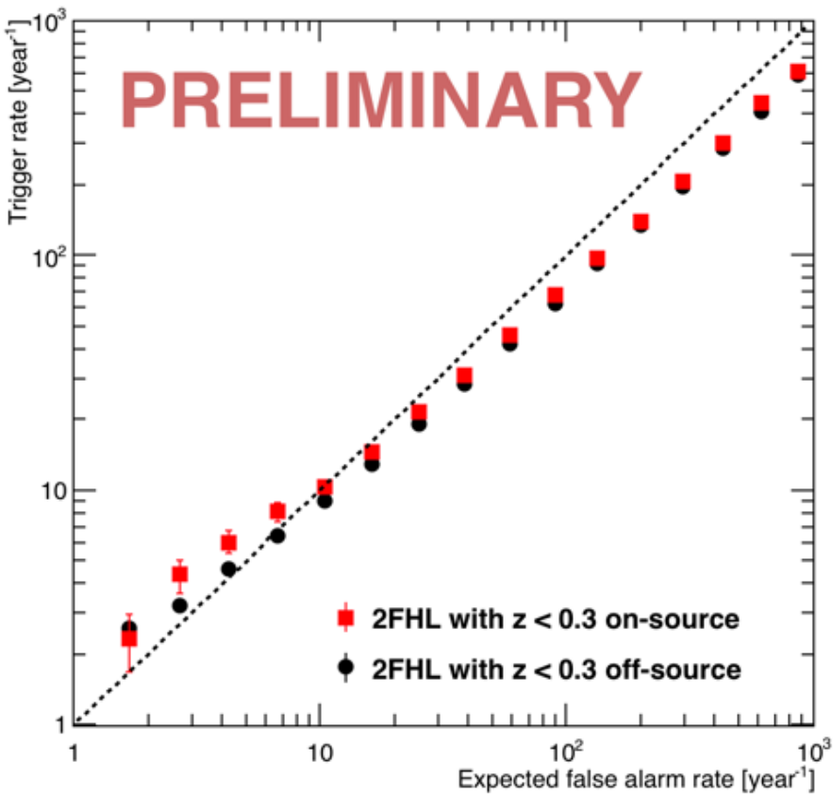
HAWC-300 1-year sensitivity F(>2 TeV) [cm^{-2} s^{-1}]



Search for other sub-threshold flares

- 2FHL non-TeVCat sources with known z < 0.3, within HAWC sky coverage
- 22 targets, 10 off-source regions per target





Search for other sub-threshold flares

- Other 2FHL non-TeVCat sources within HAWC sky coverage
- 119 targets, 4 off-source regions per target