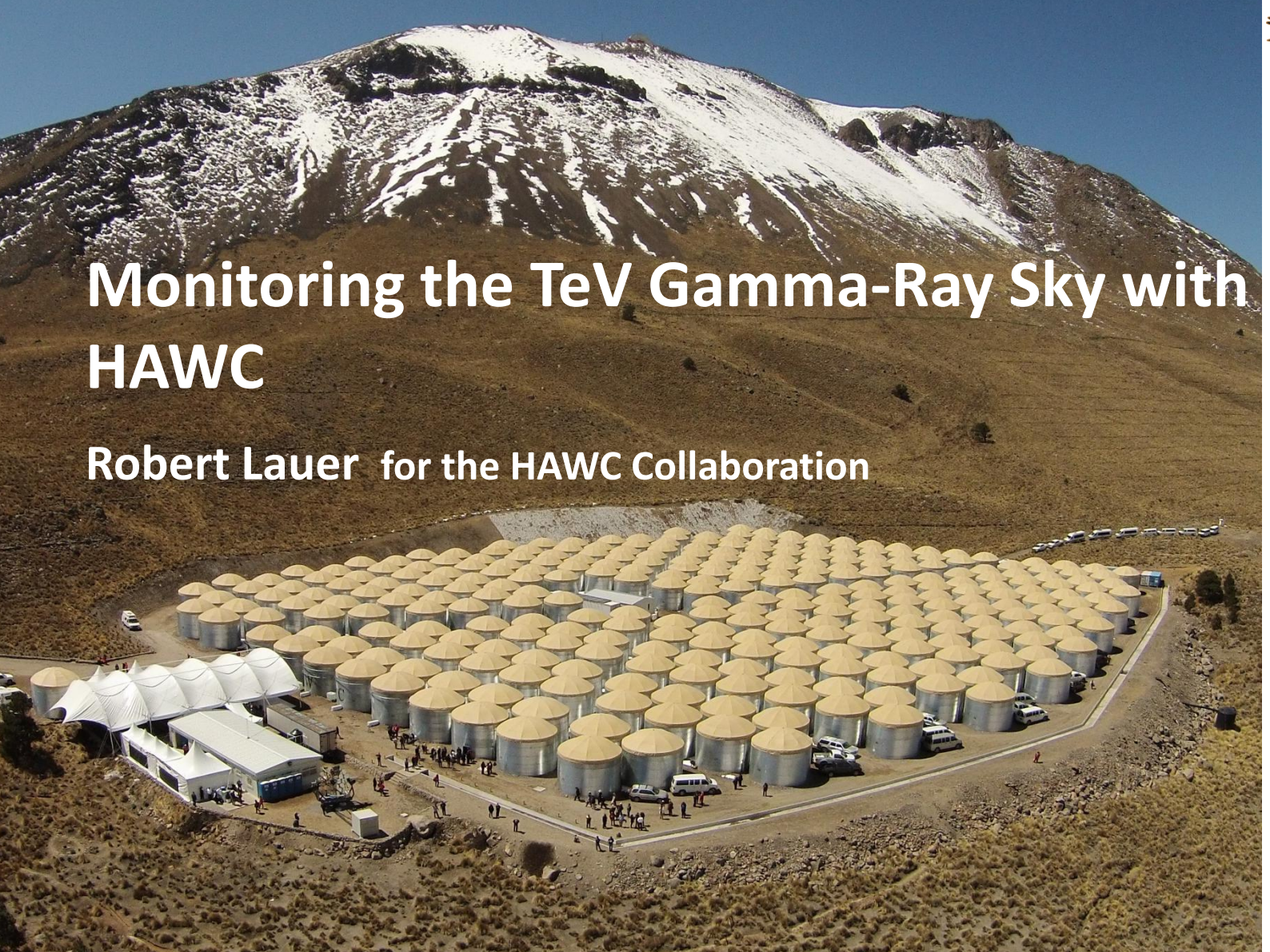


Monitoring the TeV Gamma-Ray Sky with HAWC

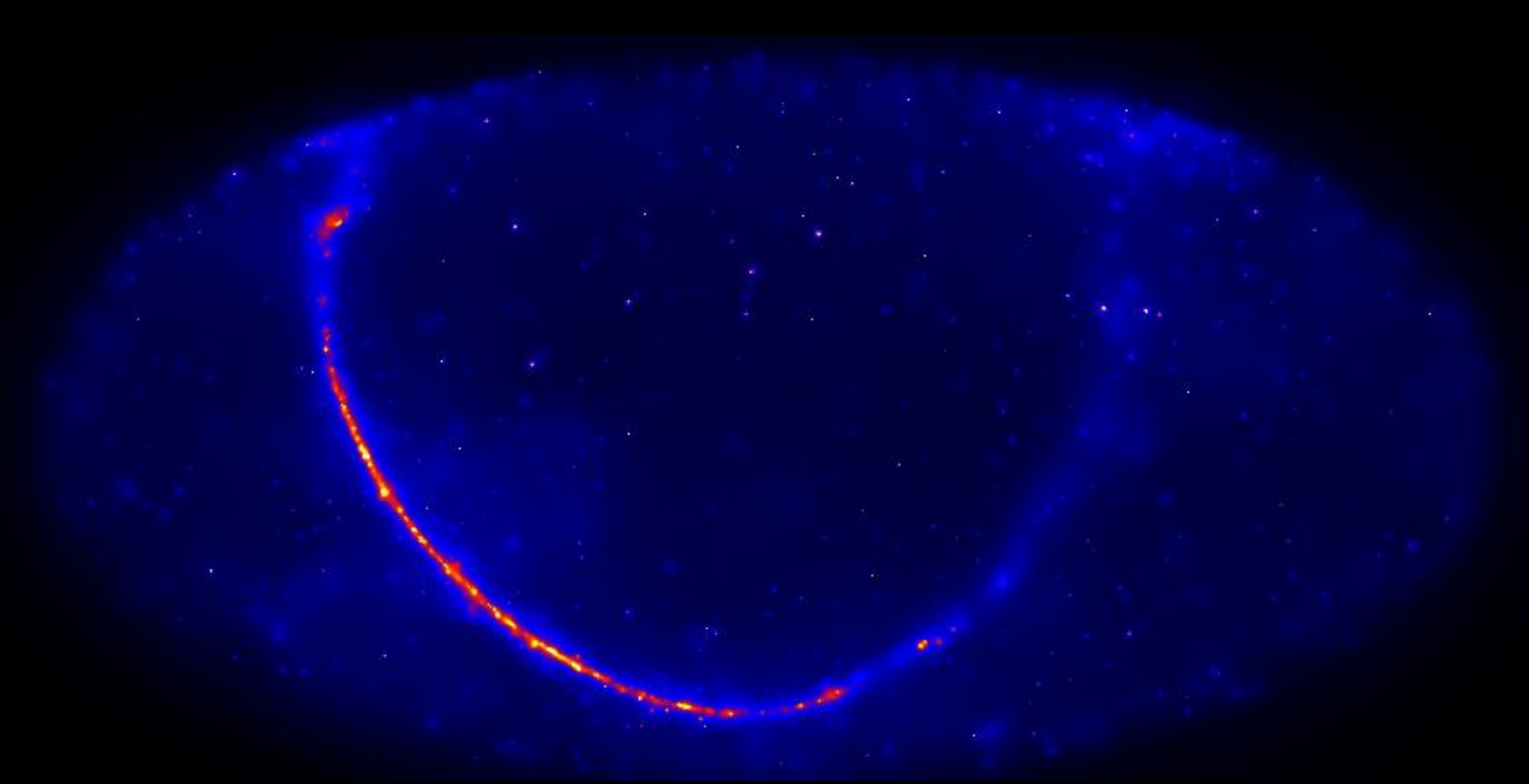
Robert Lauer for the HAWC Collaboration

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

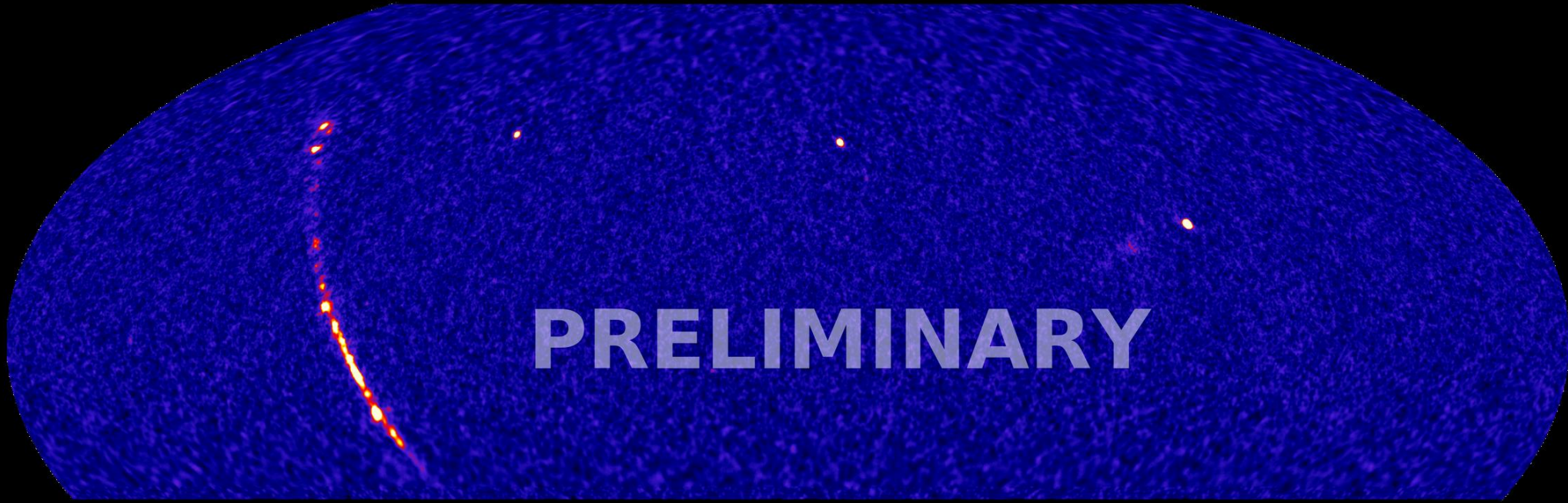
THE UNIVERSITY of NEW MEXICO

HAP Workshop:
Monitoring the Non-Thermal Universe

Cochem, Germany
December 7, 2016



Fermi-LAT, > 50 GeV

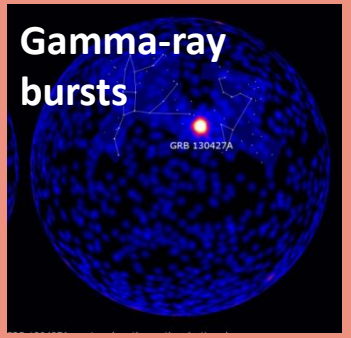


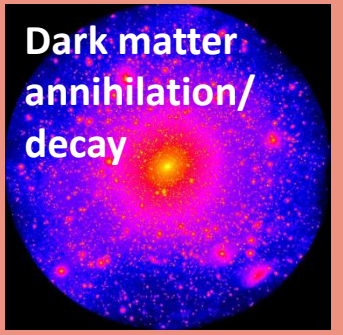
HAWC ≳ 1 TeV *

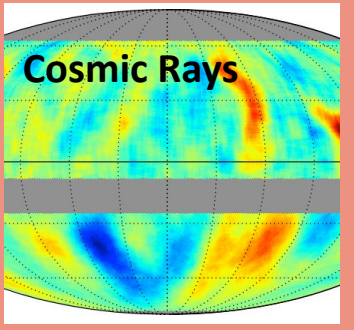
* depending on declination and spectrum

HAWC Science Goals

TeV Astrophysics



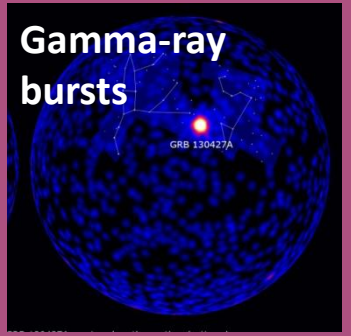


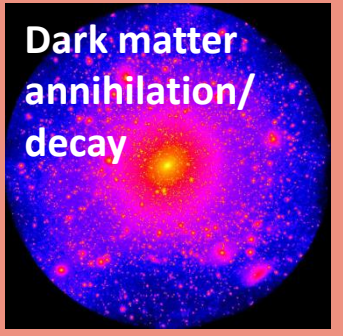


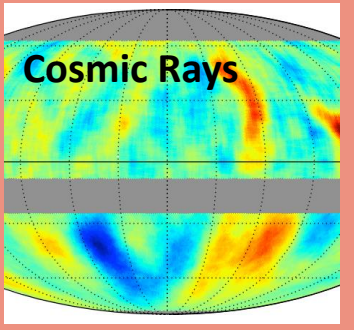
And more: **Solar Physics**
Exotic Particles
…

HAWC Science Goals

Extra-Galactic





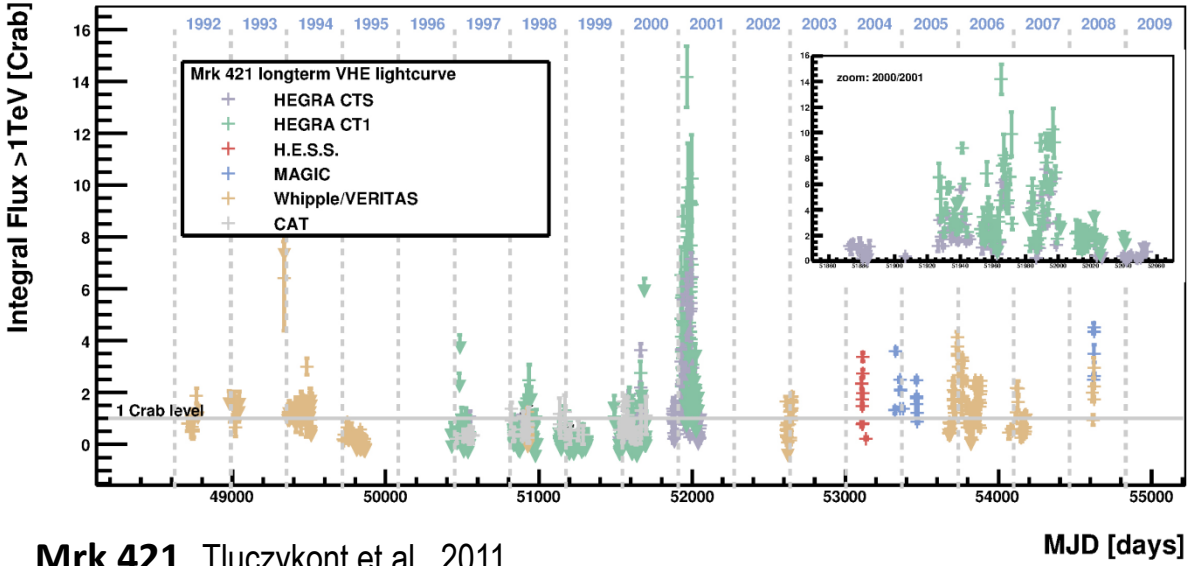


TeV Astrophysics

Need for wide FoV:
- Many source candidates
- Highly variable fluxes
- Correlation search with weakly localized neutrinos, grav. waves

- **Sources of ultra-high energy cosmic rays ?**
- **Absorption measurements of inter-galactic fields**
- **Fundamental photon physics:**
  axion-like particles, Lorentz invariance violation,...

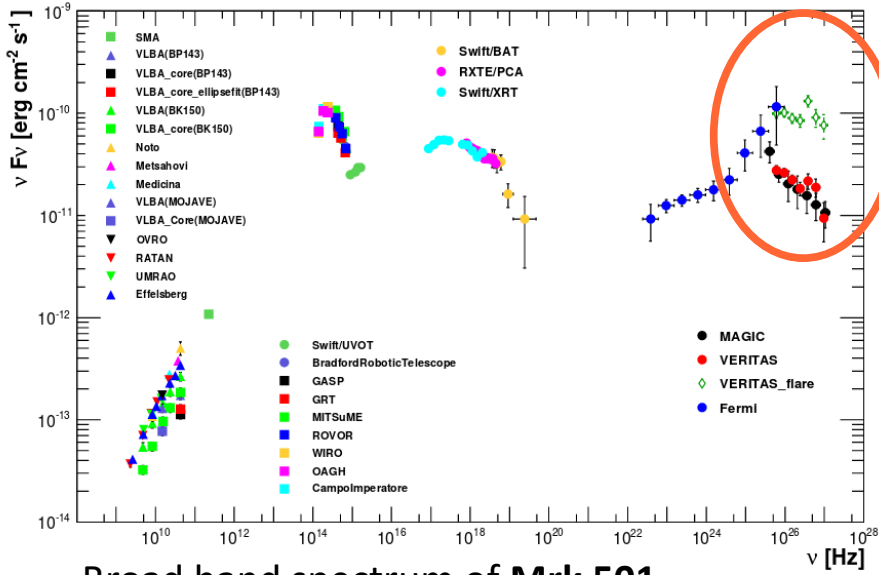
HAWC Science: TeV Blazars



Mrk 421, Tluczykont et al., 2011

- Variability on various time scales
- Order-of-magnitude changes in flux
- Changes in spectral shape

Extreme changes, unique TeV behavior?



Broad band spectrum of **Mrk 501**
Abdo et al., 2013

Most data from Air Cherenkov Telescopes, limited by:

- **small FoV** (typically only 1 source)
- **dark nights** requirement
- **often biased** towards flare follow-ups

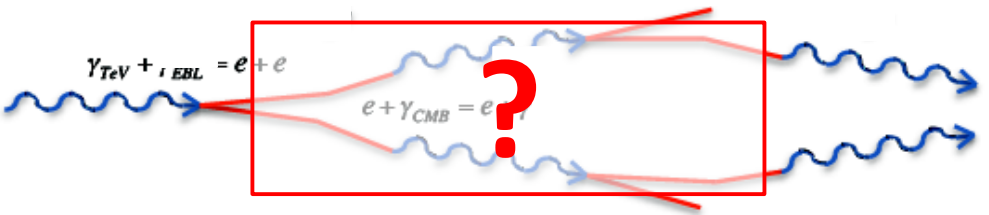
What are we missing between snapshots?

Physics from Active Galactic Nuclei (AGN) Monitoring

AGN studies with unbiased TeV data:

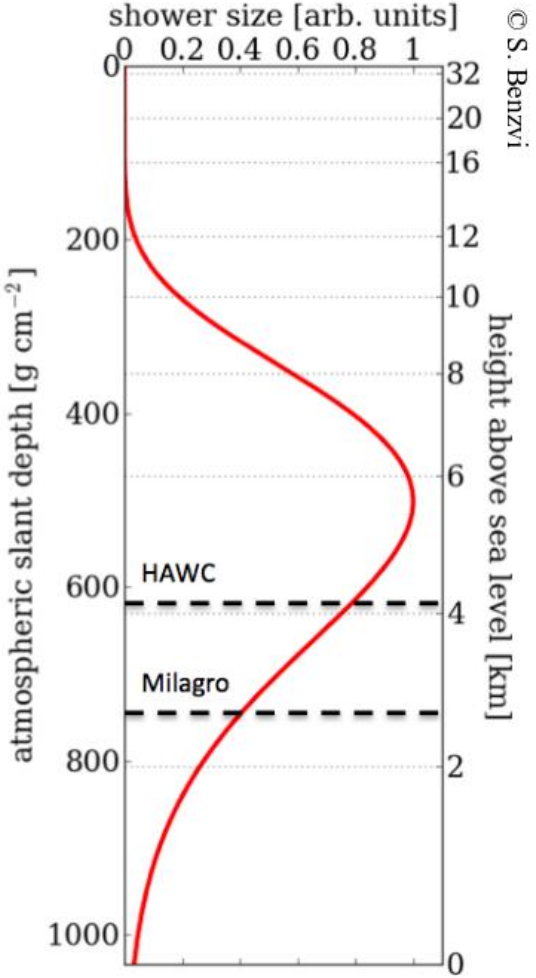
- **Flaring duty cycle** → acceleration mechanism
- **Orphan flare search** → leptonic vs. hadronic acceleration
- **Flare alerts** → trigger multi-wavelength follow-ups
- **Multi-messenger search** → neutrino and cosmic ray origin checks

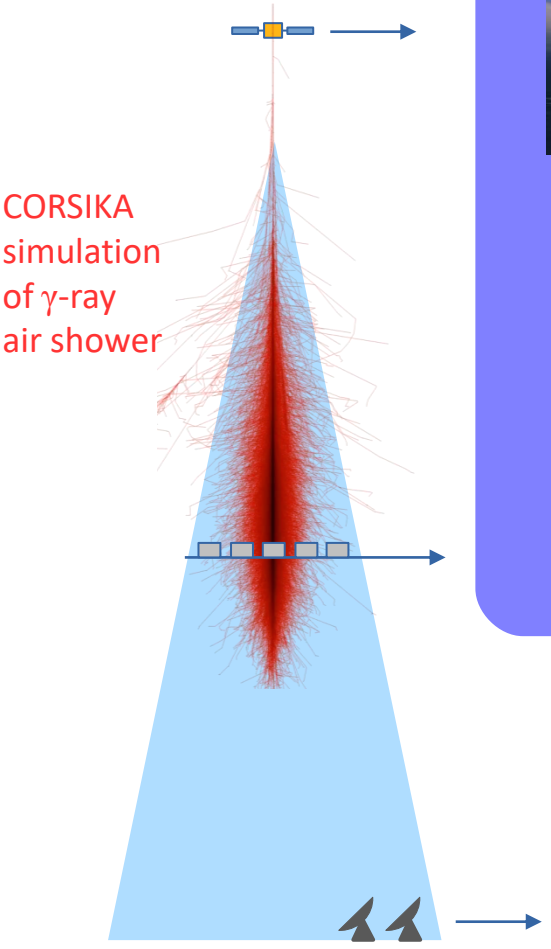
Cosmological features and fundamental physics illumi-nated by bright flare emission:



- **Extra-galactic Background Light** studies
- **Axion-like dark matter** searches
- **Inter-galactic magnetic field** measurement
- **Lorentz invariance violation and quantum gravity** tests

Gamma-Ray Detection





Direct γ-detection

Shower particle interception

Shower imaging

Wide Field of View, Continuous Operations

TeV Sensitivity

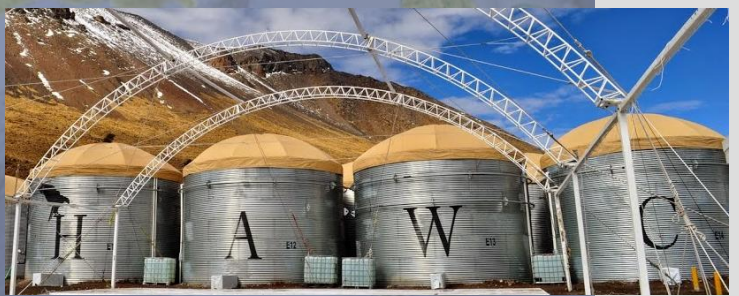
The HAWC Collaboration

From MILAGRO to HAWC

MILAGRO

- Jemez Mountains, NM
- **2350 m** above sea level
- operated from 2000 to 2008
-

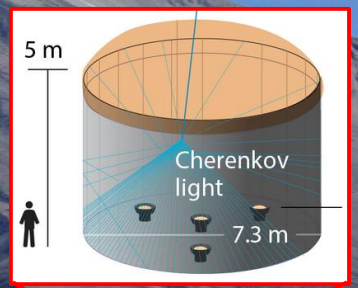
High
Altitude
Water
Cherenkov Observatory



The HAWC Observatory

- **22,000 m^2** air shower array
- **300 Water Cherenkov detectors** (WCD)
- **180,000 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.

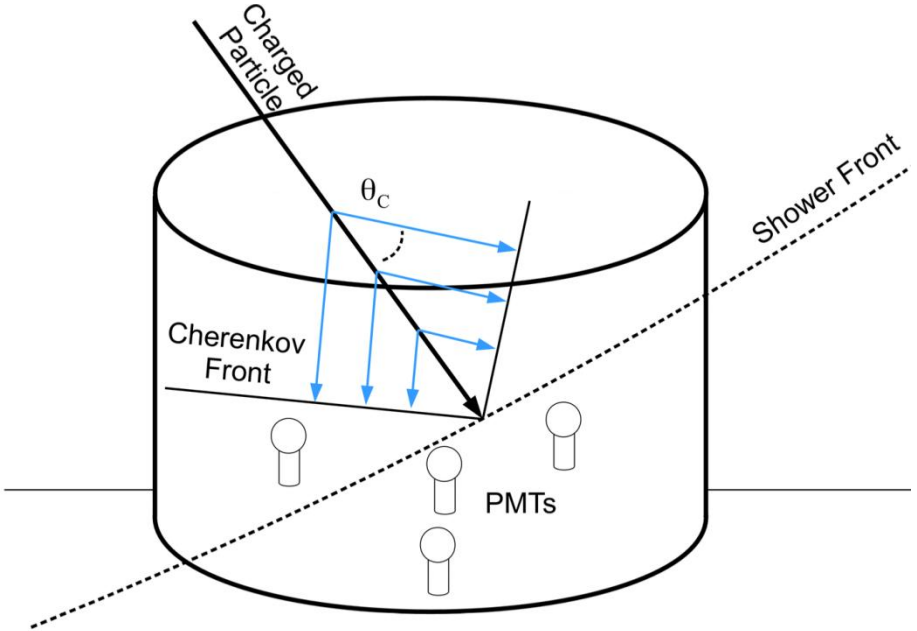


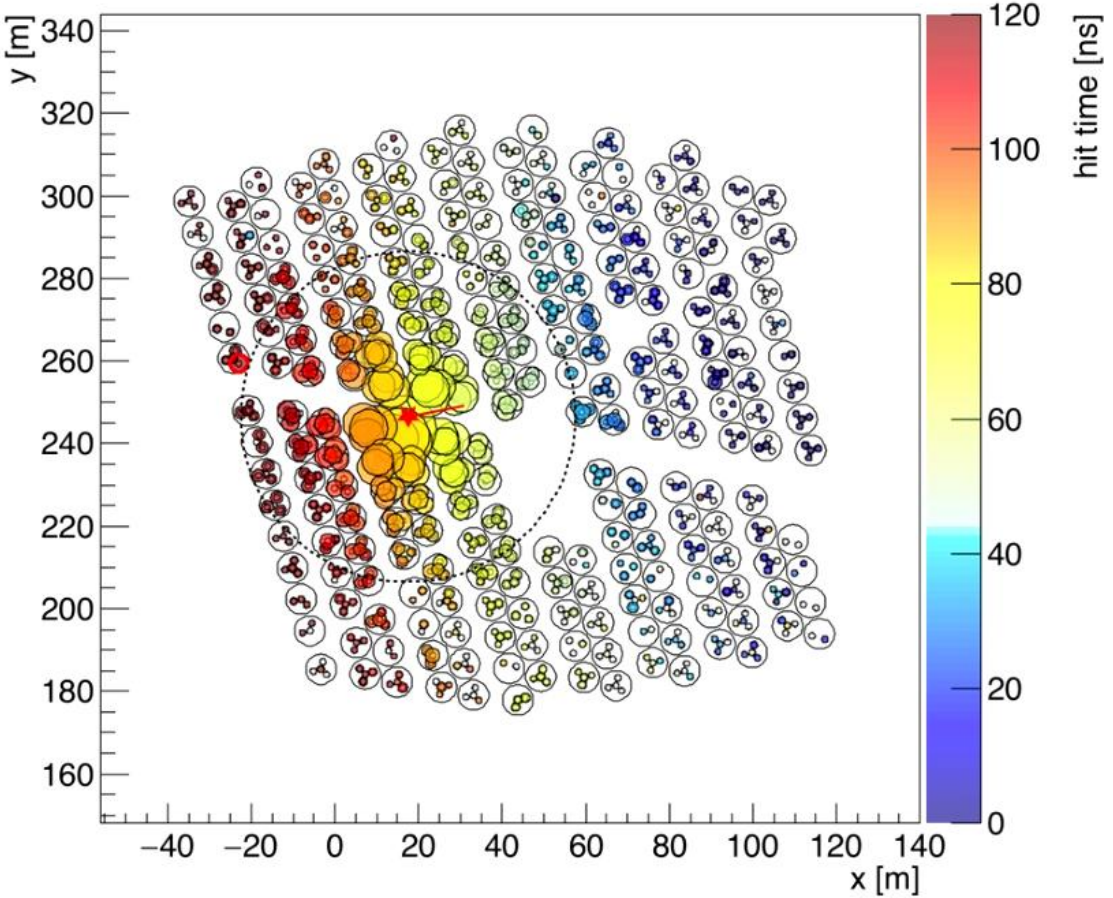
HAWC
4100 m a.s.l.

Large
Millimeter
Telescope
Alfonso Serrano

Tliltepetl
Sierra Negra
4582m a.s.l.

Air Shower Reconstruction

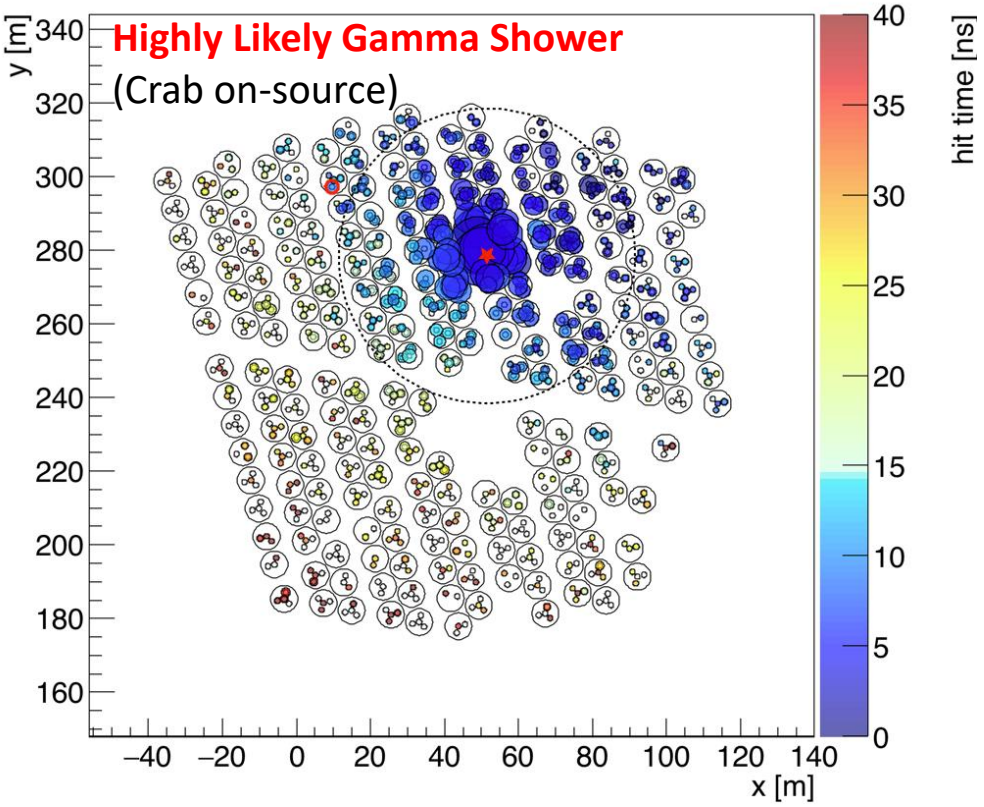


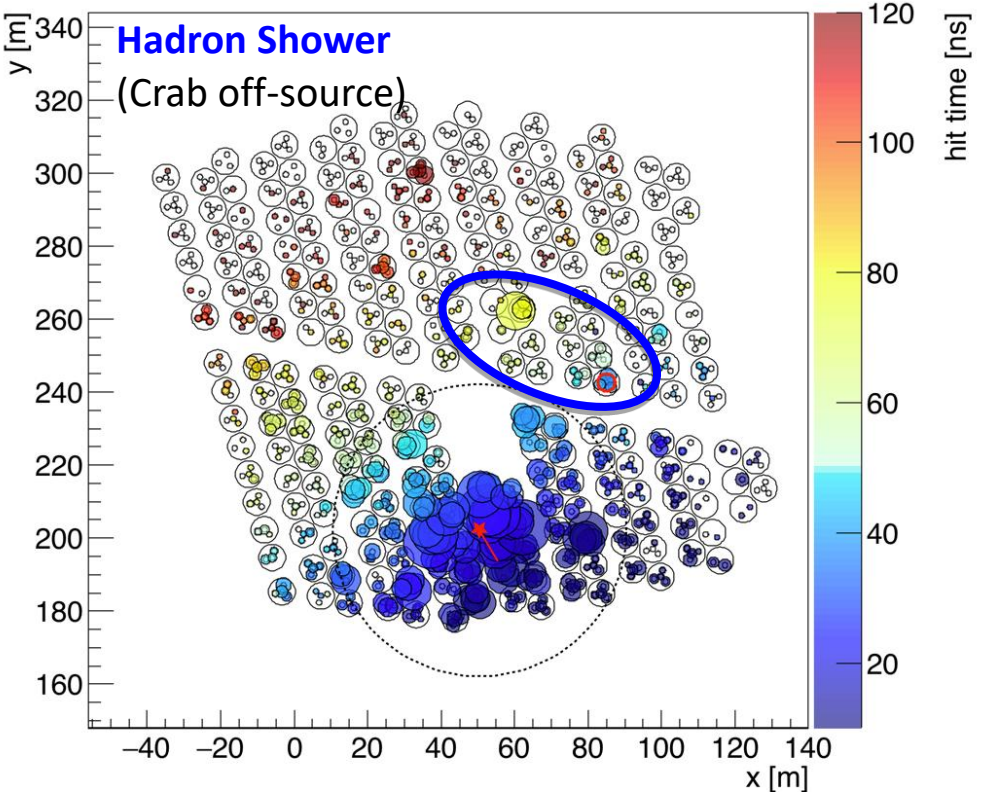


Air Shower Reconstruction:

1) **Detected Charge → Core Position**
   (>4 orders of magnitude dynamic range)
2) **Hit times → Shower plane**
   (< 1ns timing)

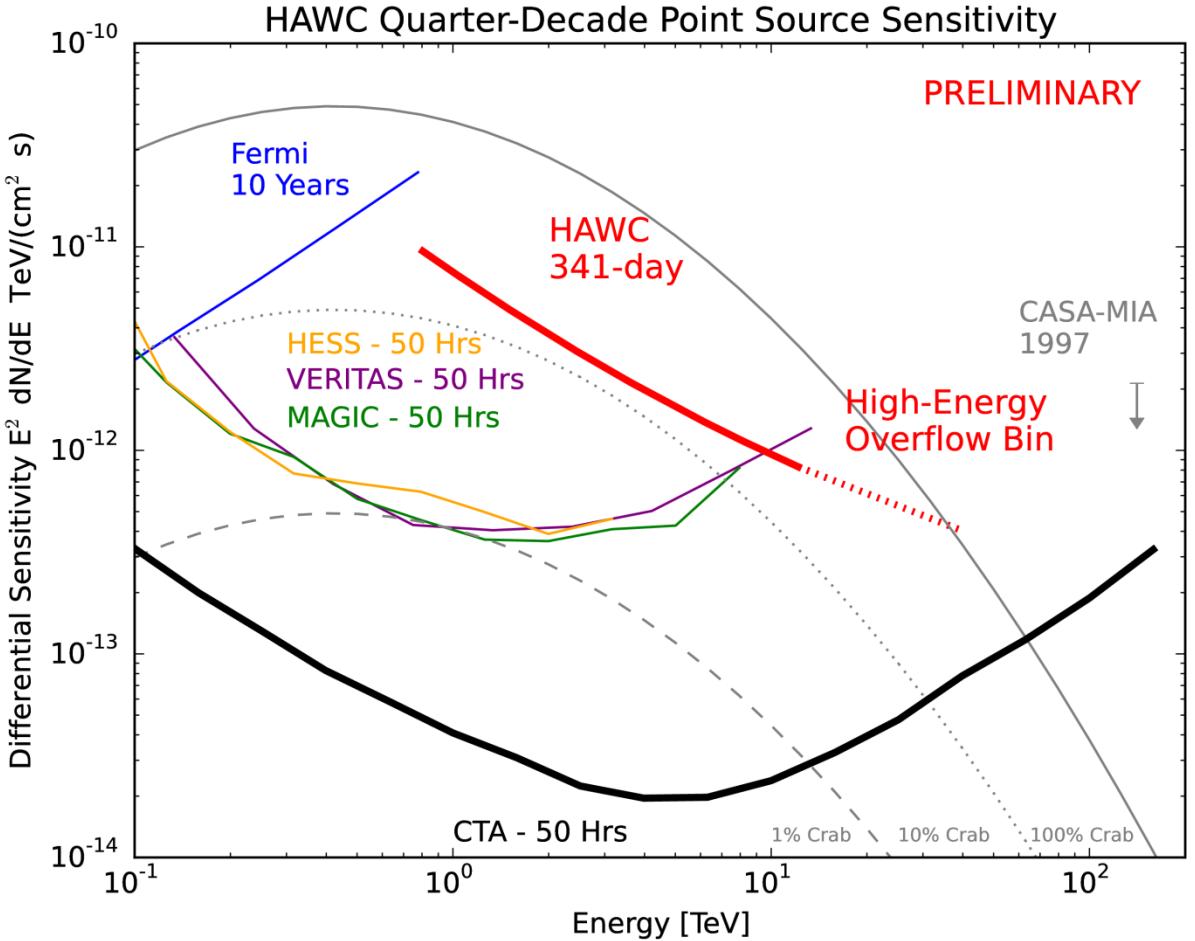
Discrimination of Gamma Rays

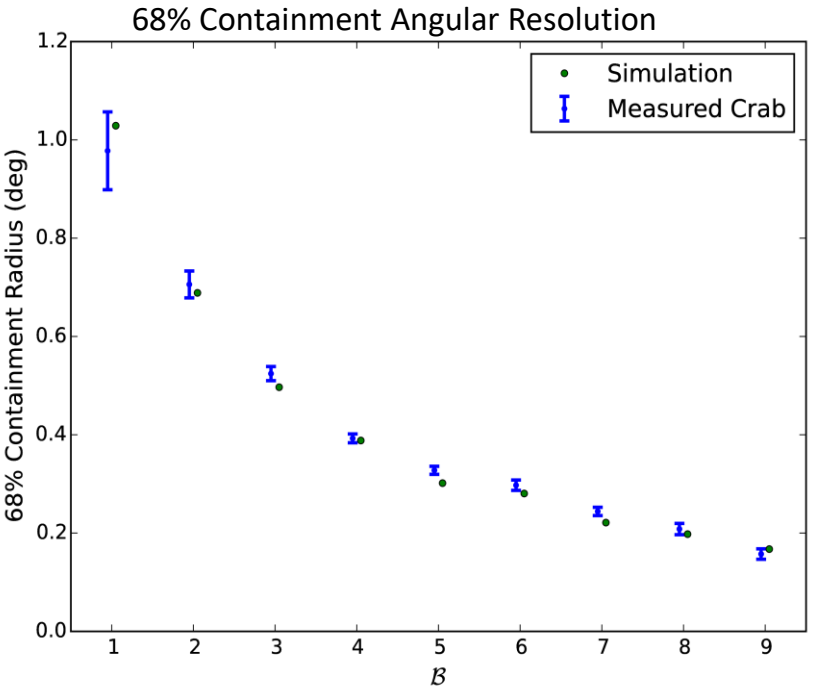




Reject **hadronic primaries** via **bright hits outside the core and uneven charge distribution**

HAWC sensitivity

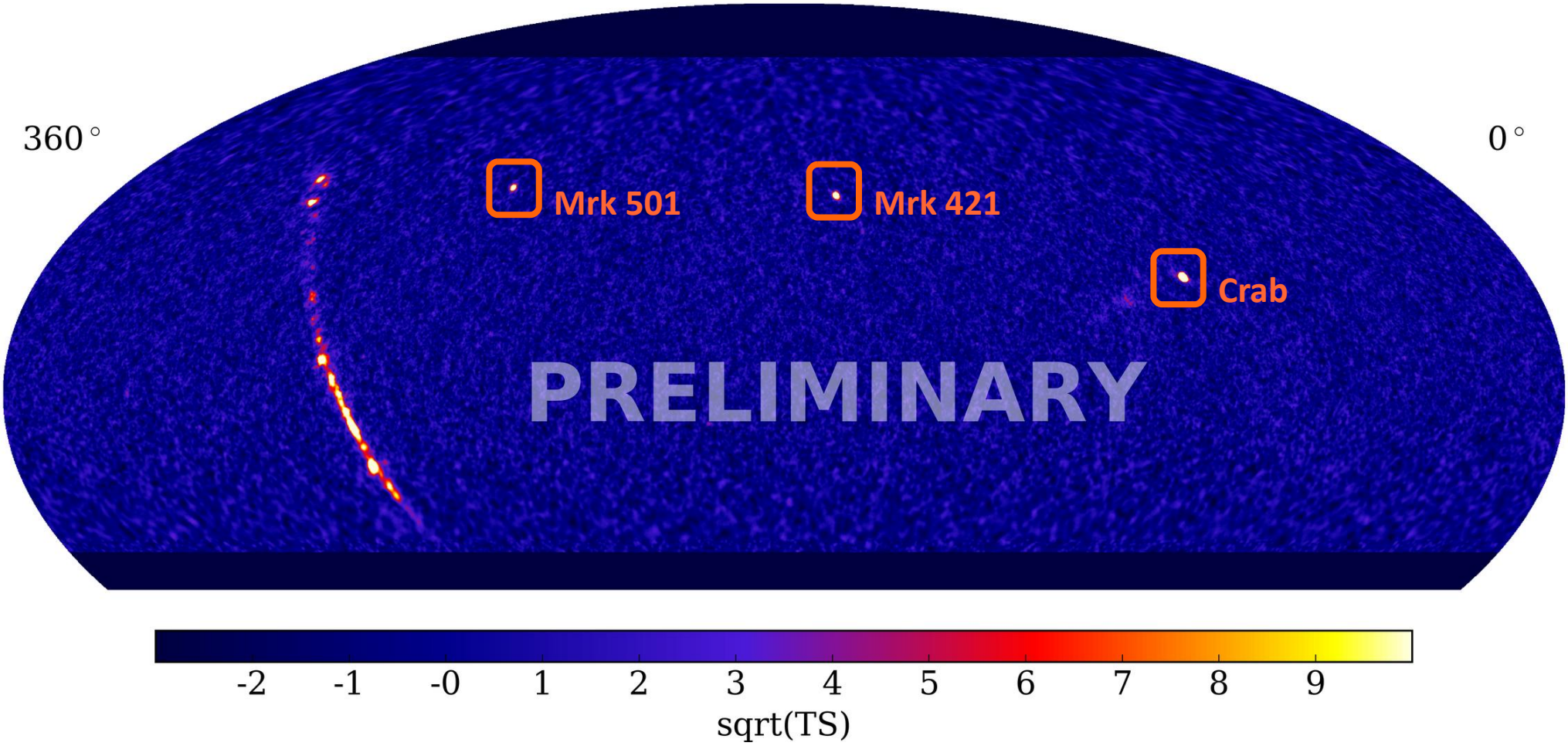




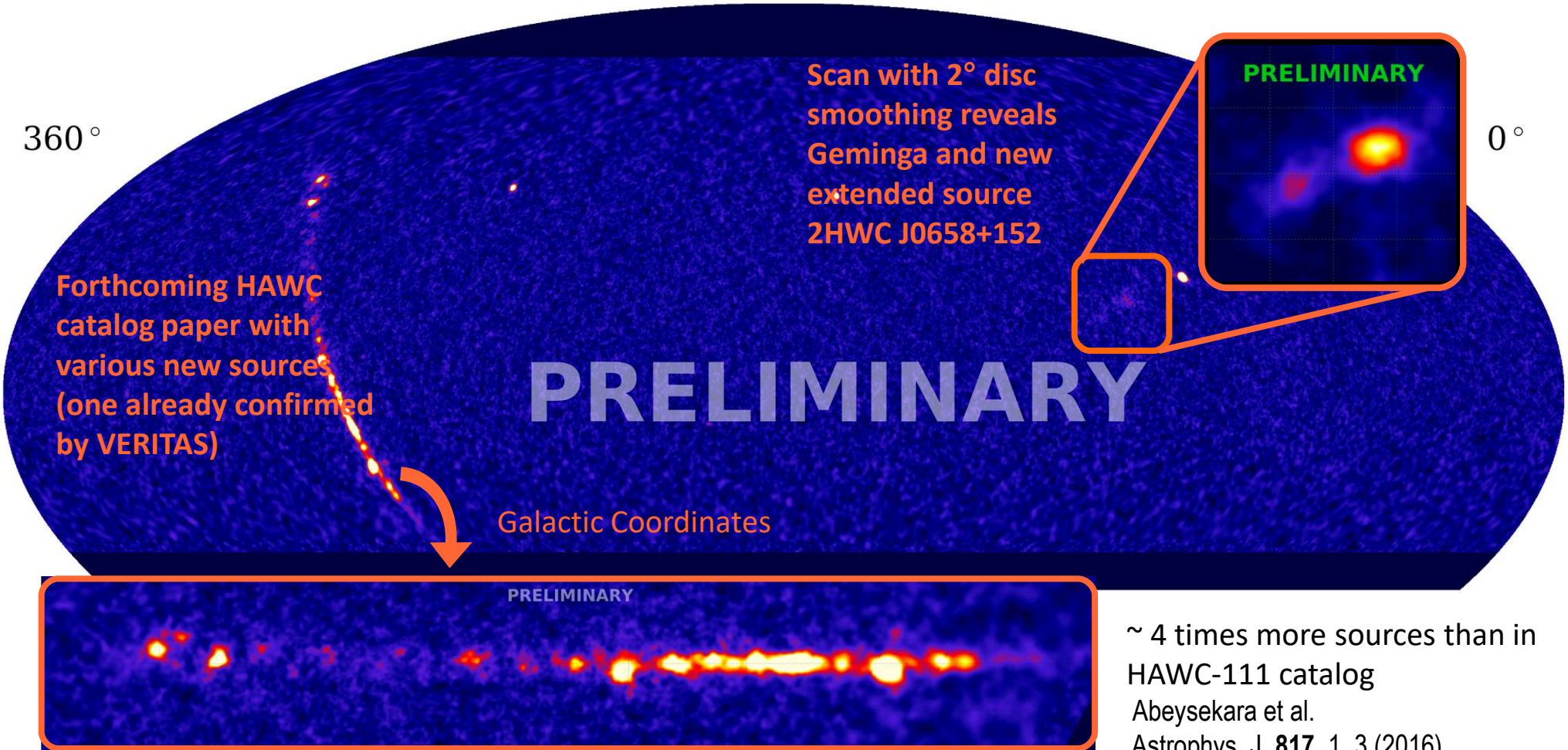
HAWC Sensitivity to point sources:

Abeysekara et al.
Astropart. Phys., 50-52 (2013)

HAWC – First 17 months of data from completed HAWC



HAWC – First 17 months of data from completed HAWC



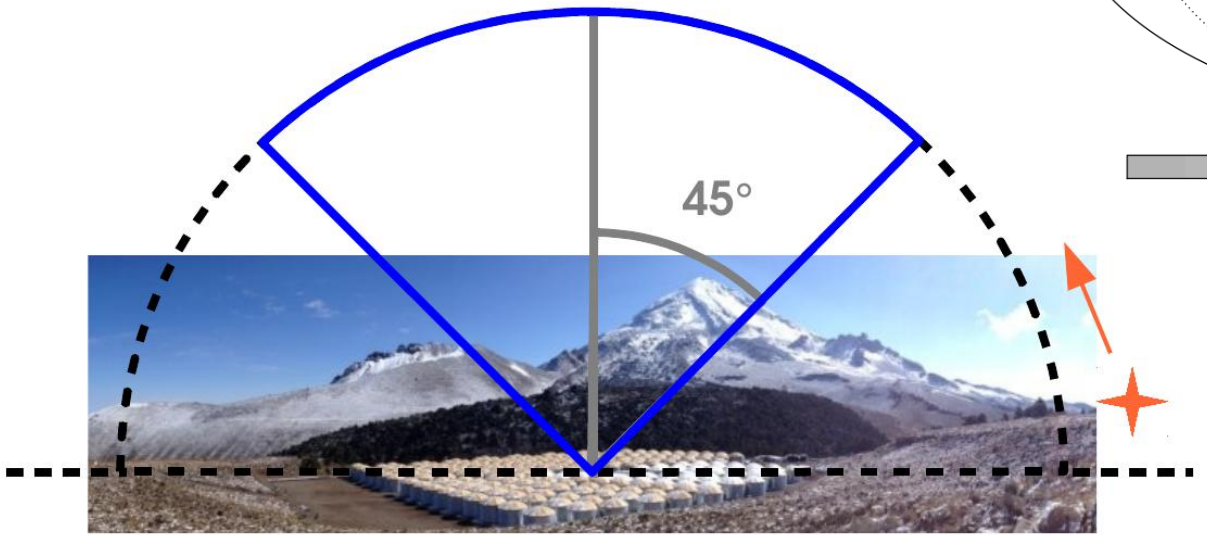
~ 4 times more sources than in HAWC-111 catalog

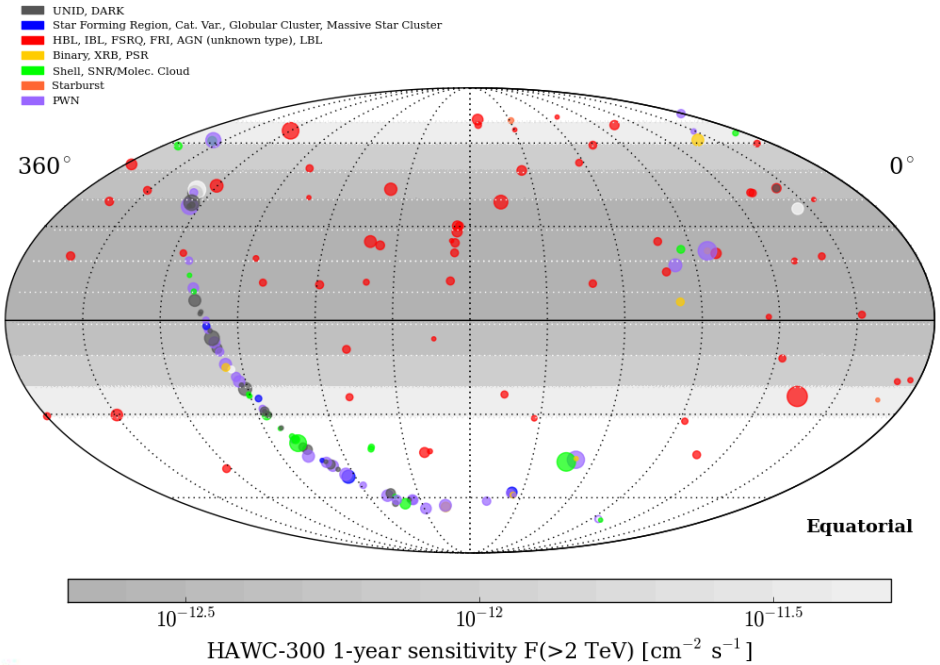
Abeysekara et al.
Astrophys. J. **817**, 1, 3 (2016)

HAWC Field of View

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

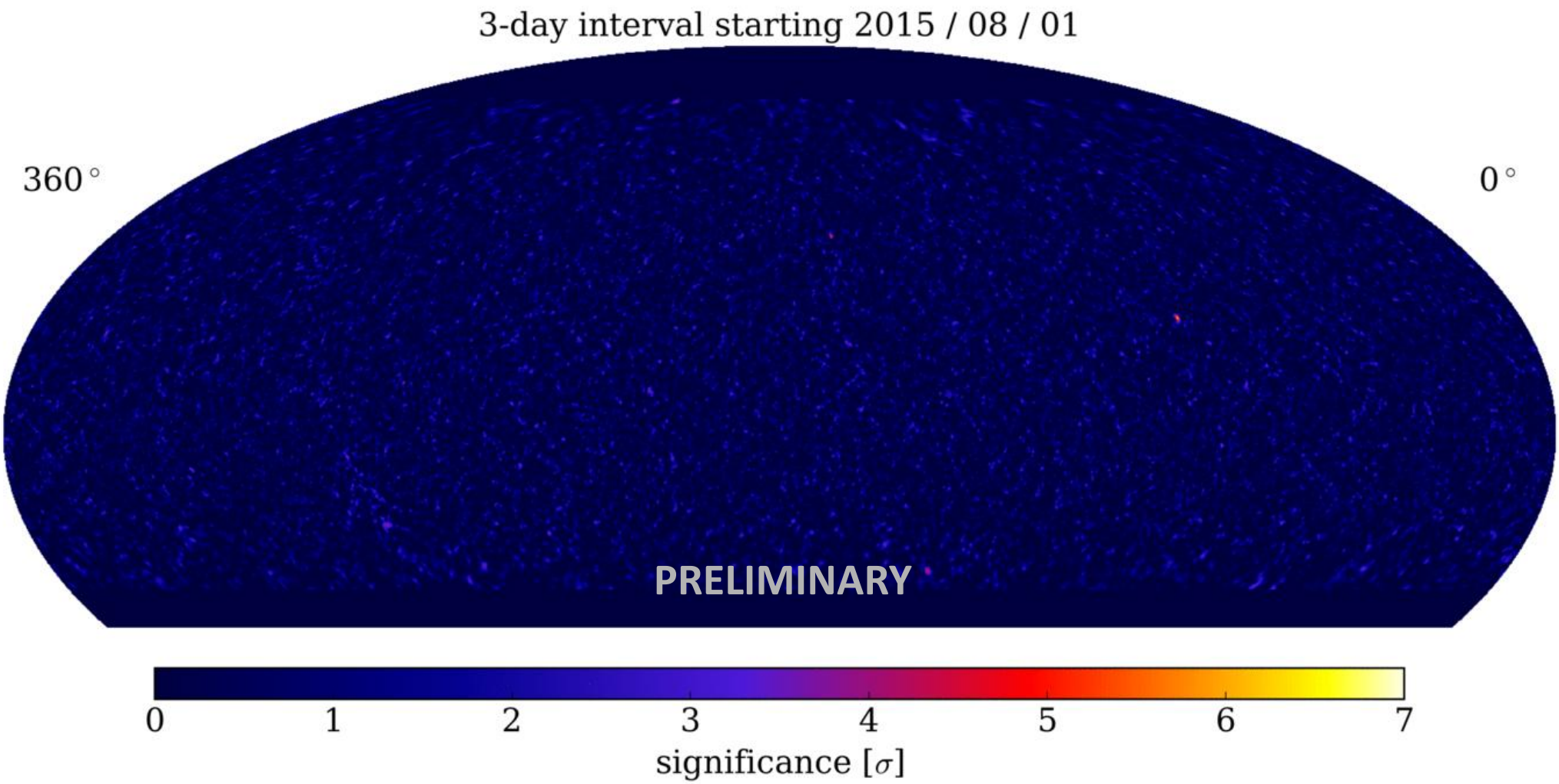
Maximum transit time: ~6 hours
for sources with peak elevation near zenith
(e.g. the Crab)





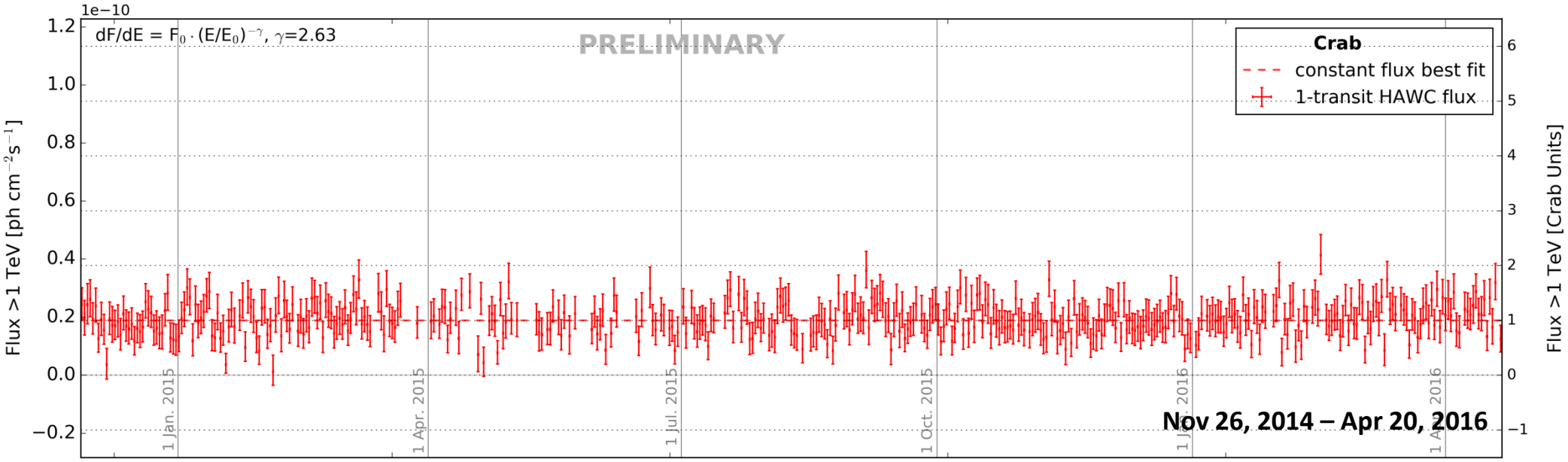
Red: **TeV-emitting AGNs** (TeVCat)

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


3-day interval starting 2015 / 08 / 01
360°
0°
PRELIMINARY
0
1
2
3
4
5
6
7
significance [σ]

Crab Nebula: Daily Flux Light Curve

Lauer et al. (Gamma2016)
arXiv 1610.05685



Data from 472 transits: **~2700 hours**

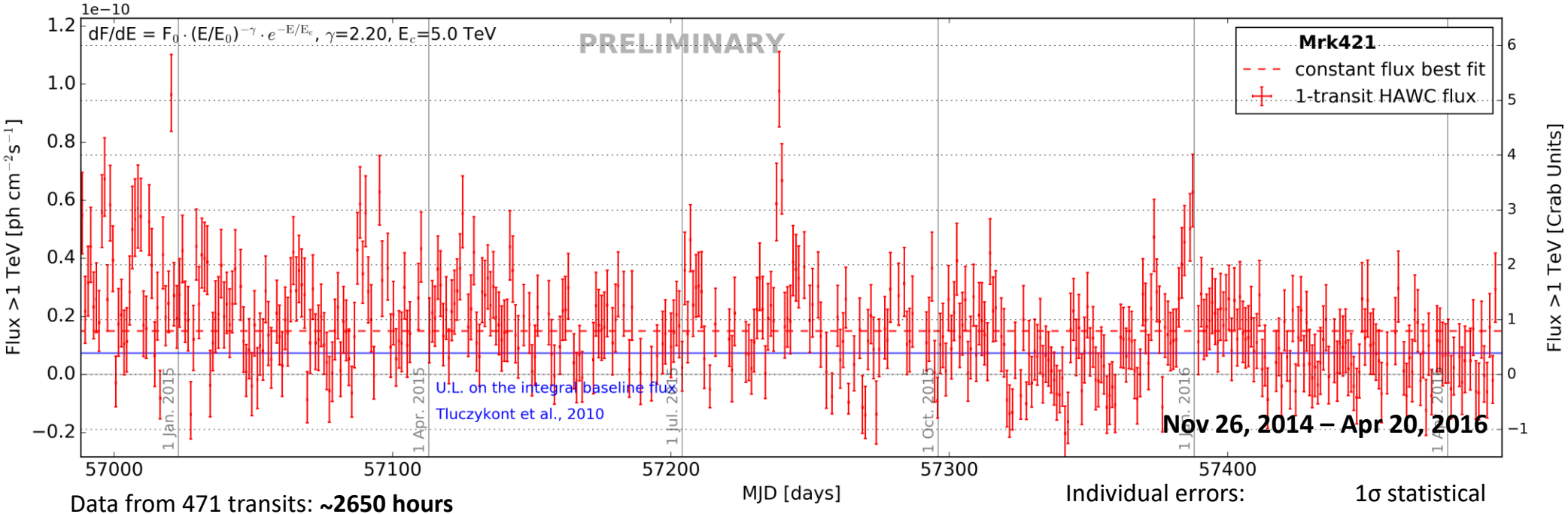
Individual errors: 1σ statistical

A likelihood test shows that the **data is consistent with a constant flux (p-value 0.29).**

No increased TeV activity detected during latest MeV flare reported by Fermi for 12 days in December 2015 / January 2016 (Buehler et al., ATEL 8519)

Markarian 421: Daily Flux Light Curve

Lauer et al. (Gamma2016)
arXiv 1610.05685



Data from 471 transits: **~2650 hours**

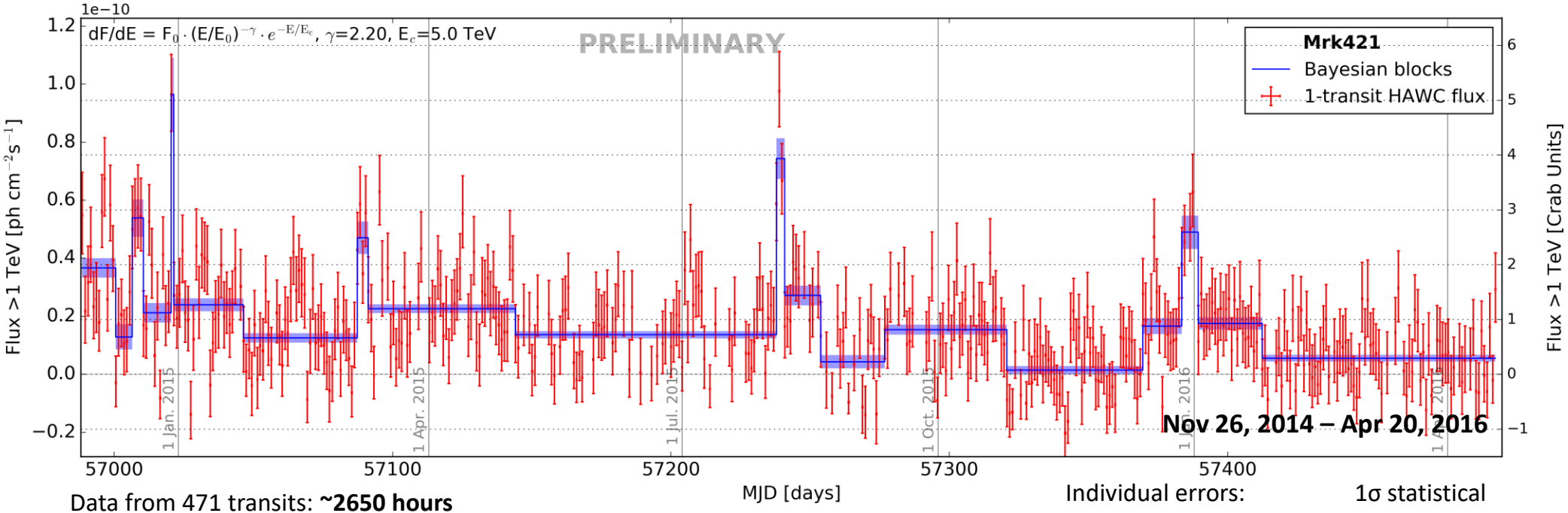
Individual errors: 1σ statistical

Likelihood variability: **Inconsistent with constant flux, p-value $<10^{-10}$**

per-transit flux changes by **up to factor 4 within 1 sidereal day**

Markarian 421: Daily Flux Light Curve

Lauer et al. (Gamma2016)
arXiv 1610.05685



Data from 471 transits: **~2650 hours**

Individual errors: 1σ statistical

Bayesian Blocks:
Scargle et al. (2013)

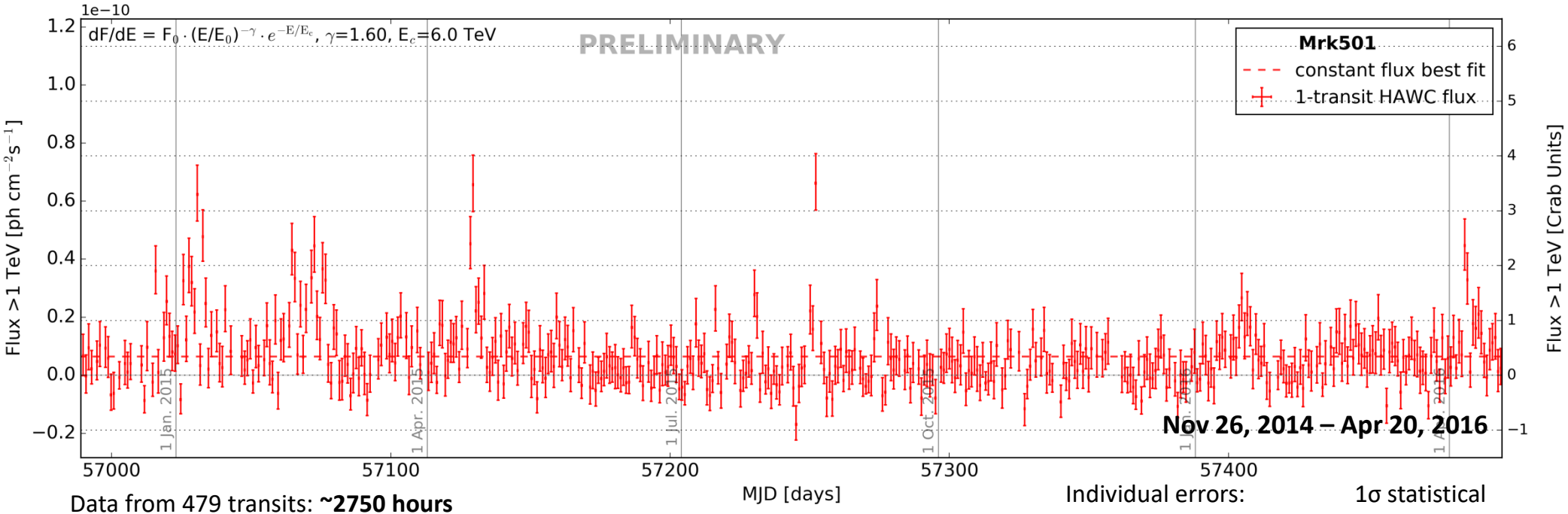
19 distinct flux states (5% false positive probability)
→ wide spread, **no dominating low flux state**

TeV Duty Cycle:

Exceeding archival baseline upper limit (Tluczykont et al., 2013) by 3σ for **~70%** of time

Markarian 501: Daily Flux Light Curve

Lauer et al. (Gamma2016)
arXiv 1610.05685



Data from 479 transits: **~2750 hours**

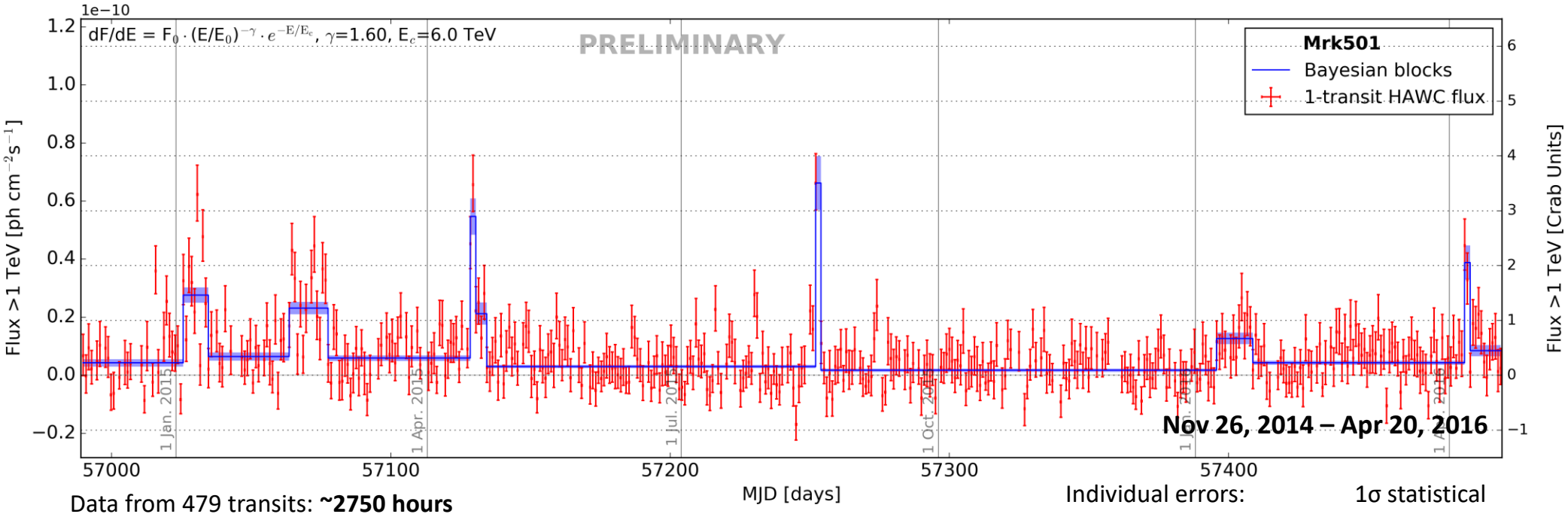
Individual errors: 1σ statistical

Likelihood variability: **Inconsistent with constant flux, p-value <10^{-10}**

per-transit flux changes by **up to factor 8 within 1 sidereal day**

Markarian 501: Daily Flux Light Curve

Lauer et al. (Gamma2016)
arXiv 1610.05685



Data from 479 transits: **~2750 hours**

Individual errors: 1σ statistical

Likelihood variability: **Inconsistent with constant flux, p-value $<10^{-10}$**

per-transit flux changes by **up to factor 8 within 1 sidereal day**

Bayesian Blocks:
Scargle et al. (2013)

14 distinct flux states (5% false positive probability)

→ dominating low flux state of ~0.2 x Crab flux > 1 TeV

Multi-Wavelength Analysis

keV MeV GeV TeV

Swift
NuStar
MAXI

Fermi
AGILE
INTEGRAL

VERITAS
HESS
MAGIC
FACT

HAWC

See the poster!

Towards **truely joint analysis: 3ML software framework:**

- Used already in e.g. Fermi, HAWC
- further development in progress

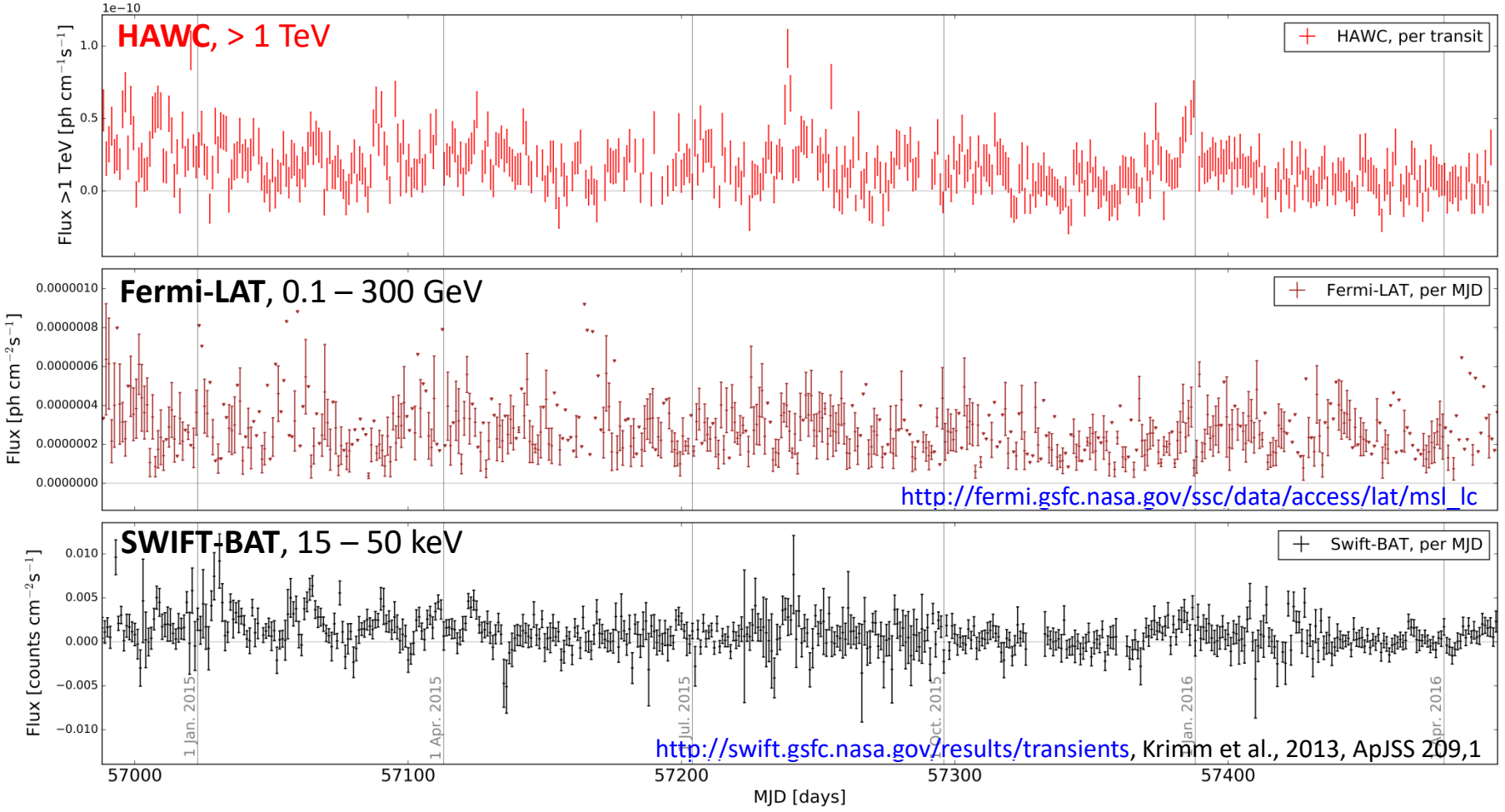
3ML
The Multi-Mission Maximum Likelihood framework

Unbiased and Regular Monitoring

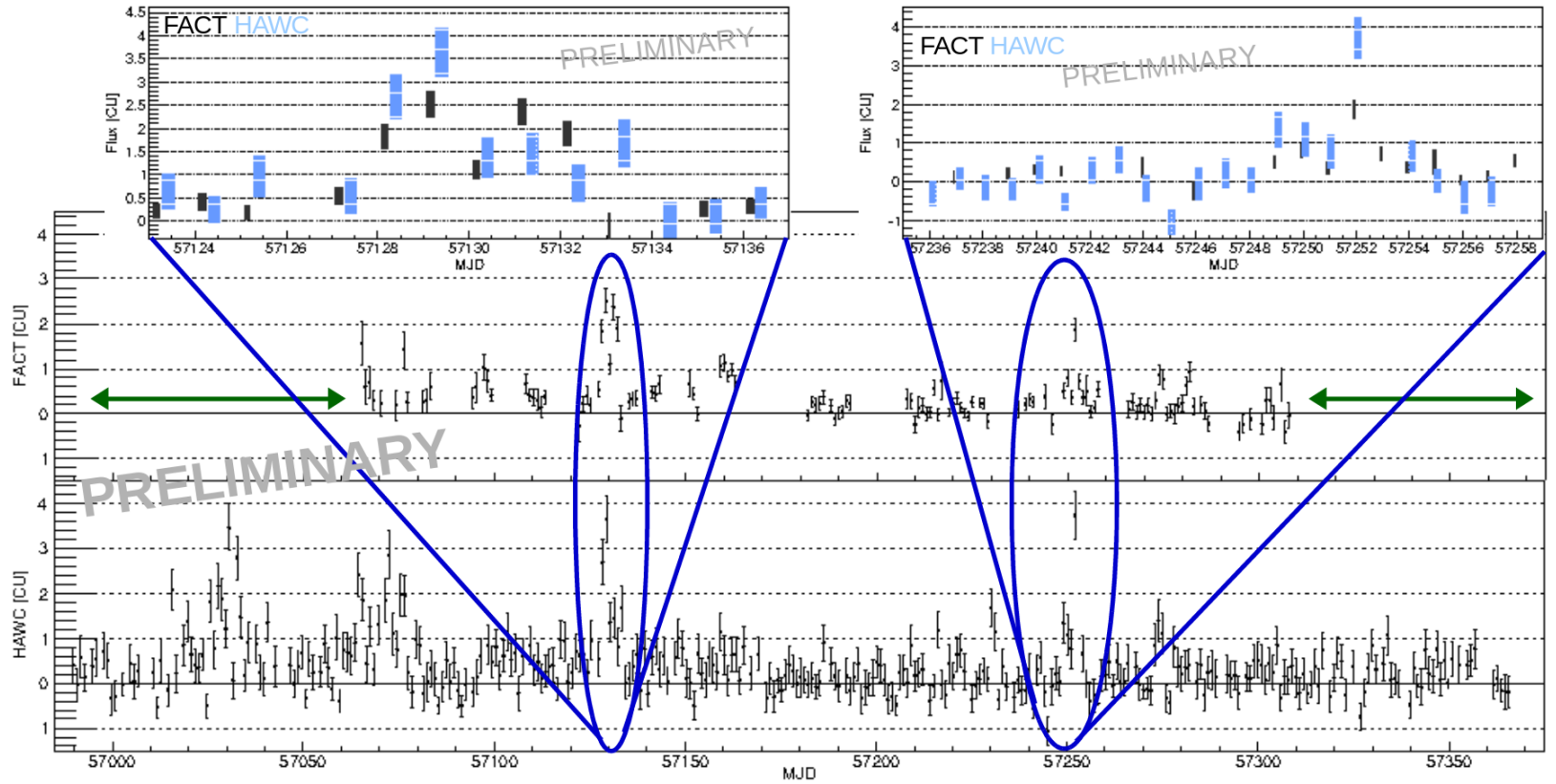
Mrk 421

HAWC joins monitoring instruments that provide **regular daily fluxes.**

Unbiased, continuous correlation studies



First Joint Light Curve Study between FACT and HAWC



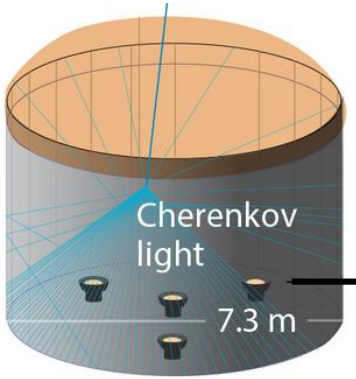
Mrk 501
daily light curve

Dorner, Lauer, et al.,
Proc. of Gamma 2016
arXiv:1610.06627

Comparison of daily fluxes between FACT and HAWC:

- **Expand continuous observation from ~6 to 12 hours** to study intra-night variability
- Study spectral changes over **extended energy range** (~750 GeV vs. 1-2 TeV threshold)

Online Monitoring

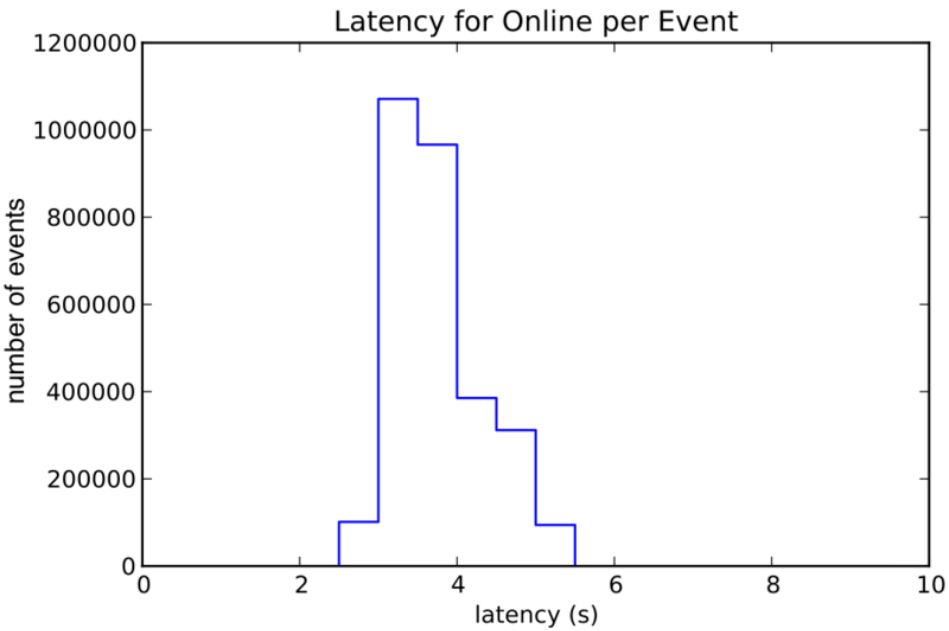


Data Acquisition:
Time-to-Digital
Converter

Trigger Software

Reconstruction Clients

Disk
for transport
off-site



Daily Light Curves

All-sky GRB search

Triggered GRB follow-ups

Targeted short flare monitor

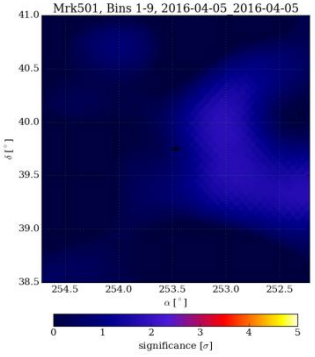
All-sky long-flare monitor

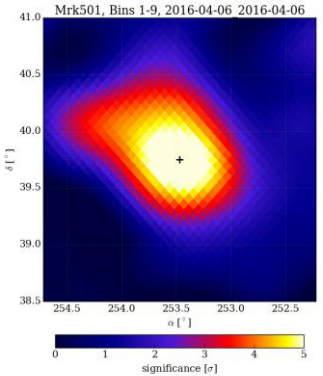
Coming soon

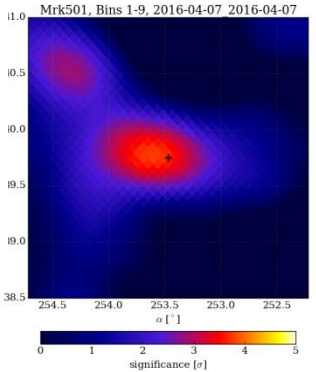
First HAWC-Triggered Transient Alert

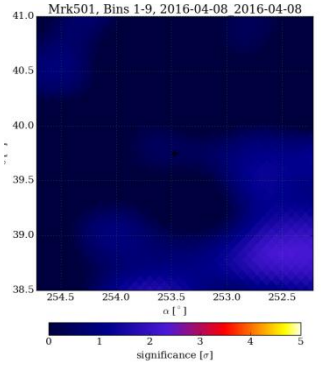
HAWC detection of increased TeV flux state for Markarian 501

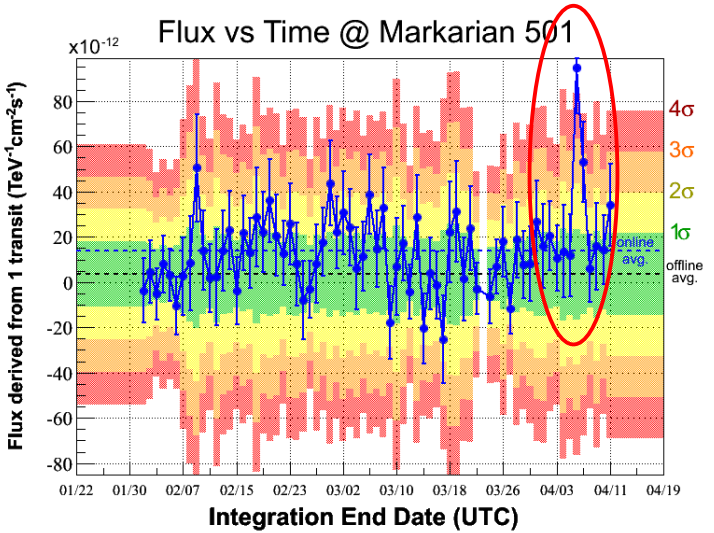
ATel #8922; *Andrés Sandoval (IF-UNAM), Robert Lauer (UNM), Joshua Wood (UMD) on behalf of the HAWC collaboration*
on 7 Apr 2016; 23:38 UT
Credential Certification: C. Michelle Hui (c.m.hui@nasa.gov)











First Joint Flare Announcement: Markarian 421

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

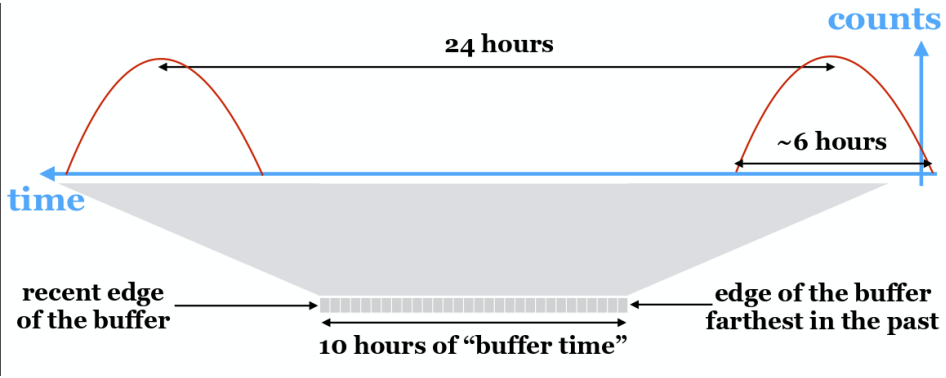
FACT, HAWC and Swift-XRT report an enhanced flux from the high-energy peaked BL Lac type object Mrk 421 both in gamma rays above 750 GeV and in the 0.3-10 keV band in X-rays respectively.

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).

SWIFT observations at 0.3-10 keV:
"Note that higher or comparable X-ray fluxes were observed only four times so far."

Flare Monitor: Fast Detection of Extreme Flares

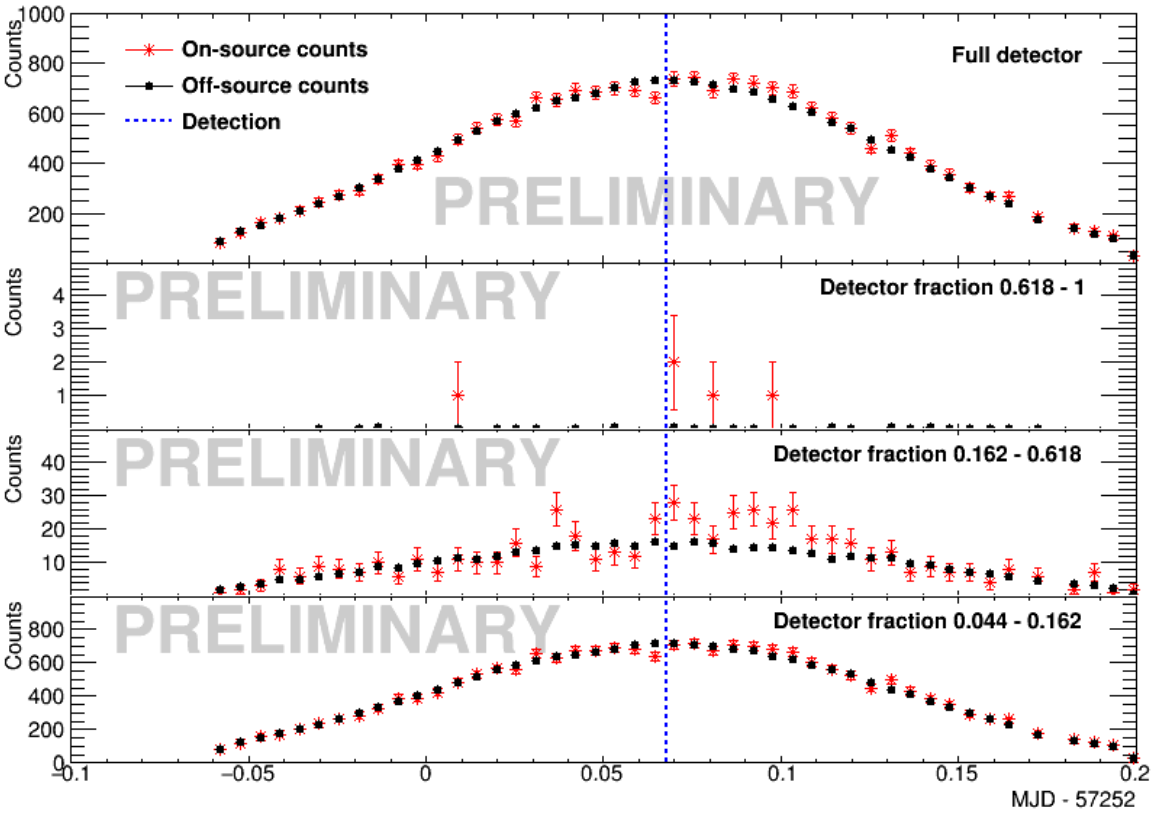


Real-time rate monitor for known blazar directions, identifying flares based on Bayesian Blocks algorithm.

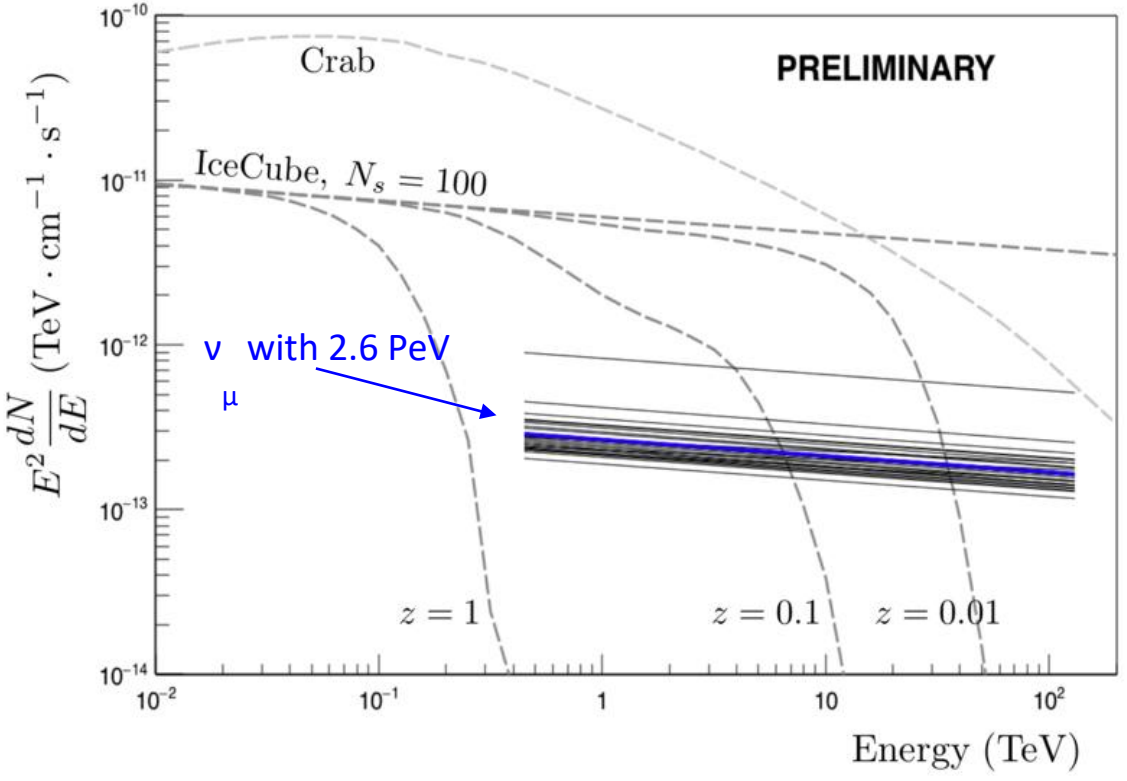
Flare monitor is now running online!
After test phase, flare alerts will be sent immediately following a detection.

Weisgarber et al. (Gamma2016)
arXiv 1610.05685

Test on offline data:
Identification of ~few hour flare flare for **Mrk 501** in HAWC data from August 18, 2015:



Multi-Messenger Follow-Up



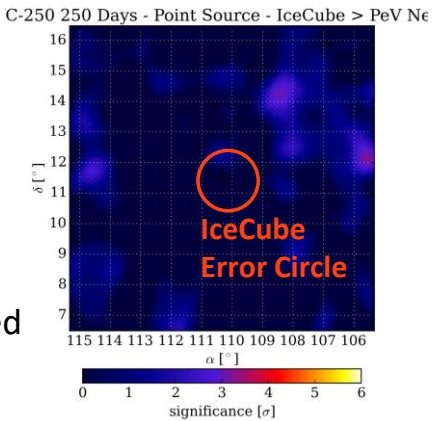
HAWC time-integrated limits for **locations of 28 highest energy neutrino tracks** in 6 years of **IceCube** data

HAWC can probe gamma-ray emission for:

- **steady source assumption**
  unique TeV coverage of long time scales
- **flare hypothesis (e.g. AGN)**
  search strategy involves checking individual closest transits and few days integration

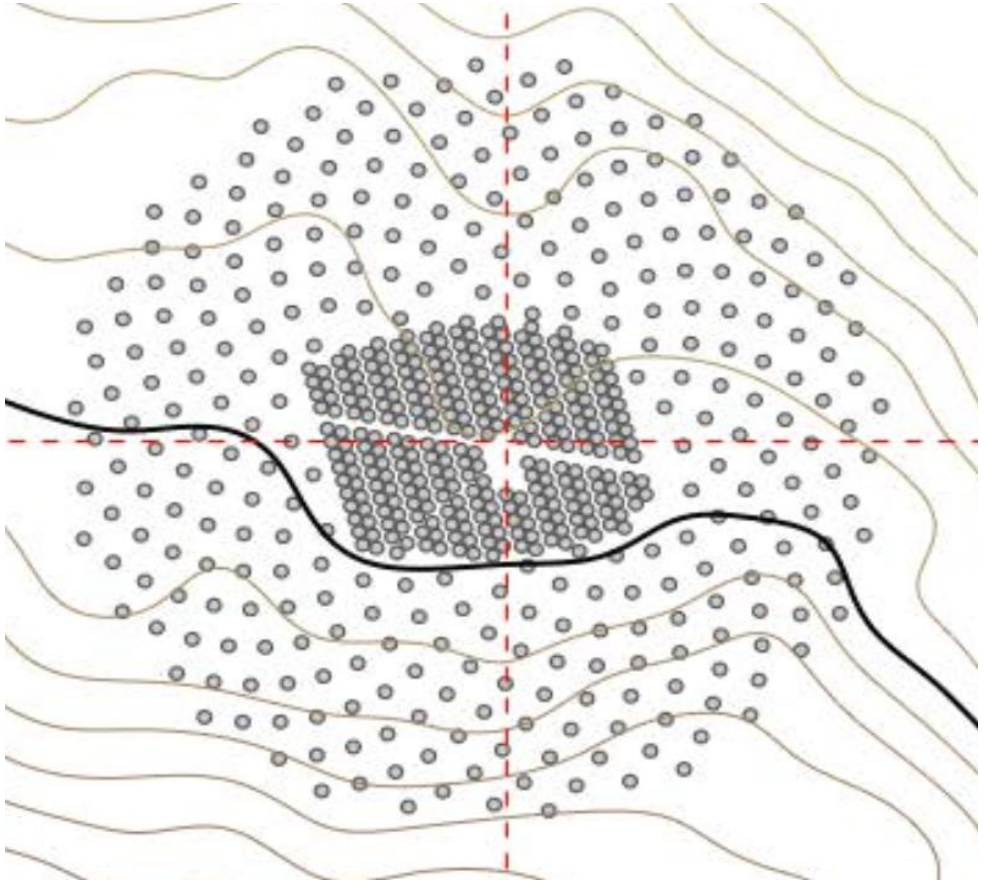
See e.g. 2.6 PeV neutrino follow-up:

Taboada et al., ATel: #7868



1 year integrated HAWC data

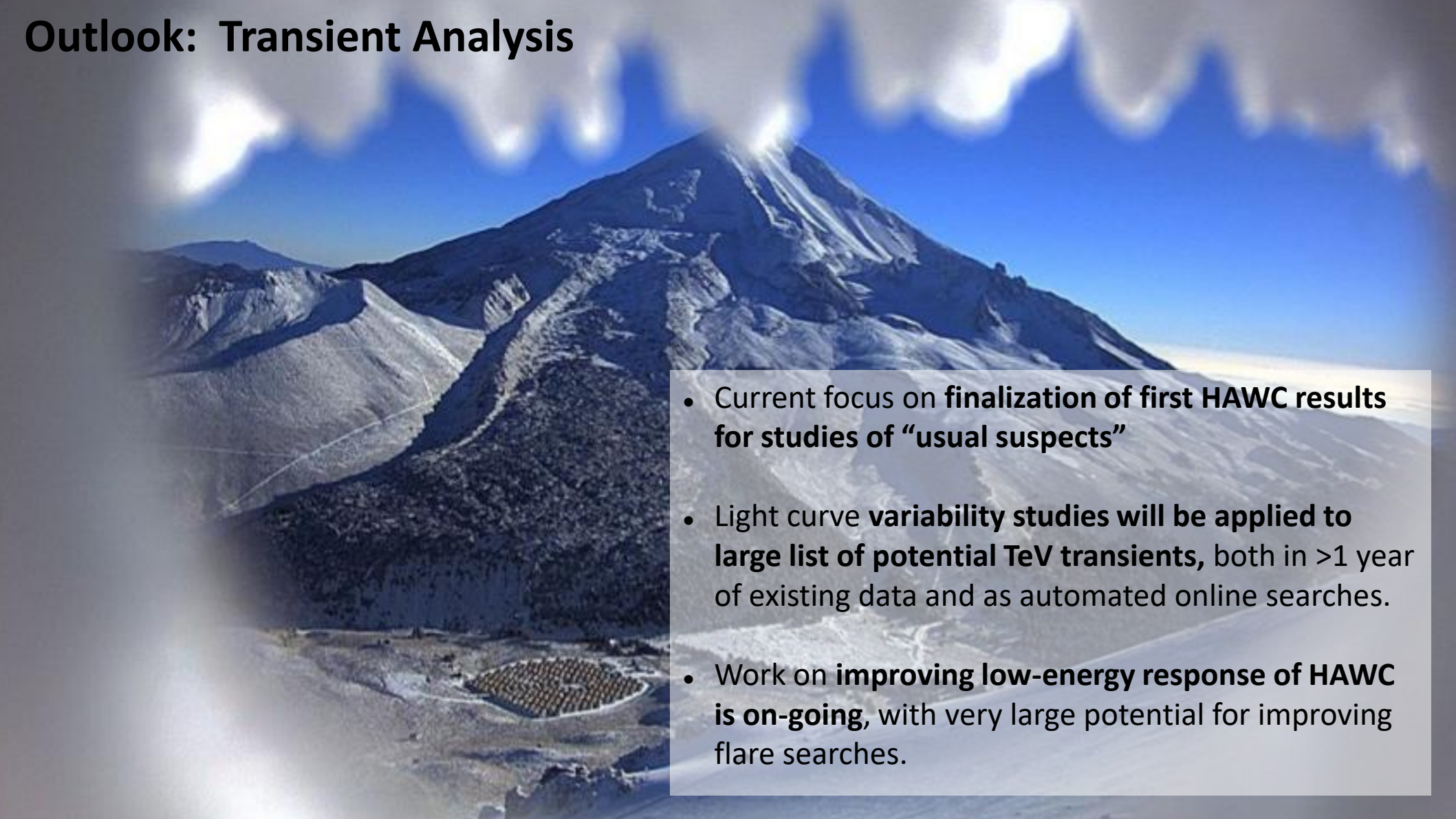
Outlook: Outrigger Extension



- 2500 liter WCDs: 1/80th size of HAWC WCDs
- Funded by LANL / Mexico / MPI-K Heidelberg
- Better **core position for largest showers**
- Increase effective area **above 10 TeV by 3-4x**

→ **Enhanced sensitivity for highest energies**

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.

Summary

- **HAWC is monitoring 2/3 of the sky, every day:**
  Immediate online processing:
  Be ready for more HAWC flare alerts!

- **Evenly sampled daily light curves:**
  unprecedented TeV data for detailed time series and correlation studies

- **Multi-wavelength and multi-messenger correlation studies**:
  Many opportunities for broad band studies of variability on various time scales