Seeing >100 TeV Gamma Rays with Extensive Air Shower (EAS) Arrays

Kirsten Tollefson
Michigan State University
July 31, 2019

High Altitude Water Cherenkov (HAWC)
Indirect Gamma-Ray Detector Techniques

Extensive Air Shower (EAS) Array

R. Mukherjee - Review talk on July 27

K. Tollefson, MSU

ICRC, July 2019
Comparison of Detector Techniques

Wide Field of View, Continuous Operations

Space Based

Fermi
AGILE
EGRET

30 MeV – 300 GeV

TeV Sensitivity

Extensive Air Shower (EAS) Arrays

HAWC
ARGO
Milagro
Tibet ASγ
LHAASO

500 GeV – 100 TeV

Imaging Atmospheric Cherenkov Telescopes (IACTs)

VERITAS
HESS
MAGIC
CTA

50 GeV – 20 TeV

ICRC, July 2019
Gold Alert – 50% purity threshold for astrophysical neutrino

Flat-Spectrum Radio Quasar (FSRQ) PKS 1502+106 is located within 50% uncertainty region of event with an offset of 0.31°

HAWC is following up!
EAS v. IACT

Simulation (CORSIKA)

<table>
<thead>
<tr>
<th></th>
<th>EAS Array</th>
<th>IACT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View (FOV)</td>
<td>~90° (~2 sr)</td>
<td>~5° (~4 msr)</td>
</tr>
<tr>
<td>Duty Factor</td>
<td>~100%</td>
<td>~10%</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>1° - 0.2°</td>
<td>0.1° - 0.06°</td>
</tr>
<tr>
<td>Energy Range</td>
<td>500 GeV - 100 TeV</td>
<td>50 GeV – 50 TeV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>50% - 30%</td>
<td>20% - 8%</td>
</tr>
</tbody>
</table>

EAS – Altitude Matters
Higher = Lower Energy
EAS Detectors

K. Kawata – Tibet AS Highlights talk on July 30

Altitude (Meters)

4300 m

4100 m

2600 m

Milagro

ARGO-YBJ

YangBaJing, Tibet

HAWC

Puebla, Mexico

New Mexico, USA

Time (Year)

1990s

2015

2019

K. Tollefson, MSU

ICRC, July 2019
HAWC Sky Map with 1128 days (~50 sources)

Mrk 501
20 $\sigma$

Mrk 421
50 $\sigma$

Crab Nebula
150 $\sigma$

Geminga

Galactic Center

2HWC catalog ApJ 2017 was 507 days and contained 39 sources of which 10 were new
HAWC Sky Map with 1346 Days

BRAND NEW

New reconstruction improvements coming soon
Crab Nebula Spectrum

New energy estimators (NN and GP) vs. \texttt{fhit} give better energy resolution

Accepted by ApJ on July 3, 2019

HAWC and Tibet Crab Spectrum

Tibet III + Muon Detectors increase energy range

K. Kawata, PoS(ICRC2019)712
X. Chen, PoS(ICRC2019)647

Energy (TeV)

$E^2 \frac{dN}{dE}$ (TeV cm$^{-2}$ s$^{-1}$)

July 29, 2019
Tibet paper
PRL 123, 051101

K. Tollefson, MSU
ICRC, July 2019
IACTs Getting to Higher Energies

IACTs can observe at very high zenith angles to get to higher energies

PoS(ICRC2019)759
Altitude and Size of EAS Detectors

<table>
<thead>
<tr>
<th>Altitude (Meters)</th>
<th>Time (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4400 m</td>
<td>2019</td>
</tr>
<tr>
<td>4300 m</td>
<td>2015</td>
</tr>
<tr>
<td>4100 m</td>
<td>1990s</td>
</tr>
<tr>
<td>2600 m</td>
<td></td>
</tr>
</tbody>
</table>

All in the Northern Hemisphere

Large High Altitude Air Shower Observatory
Hybrid Detection of EASs by LHAASO

CATCHING RAYS
China’s new observatory will intercept ultra-high-energy γ-ray particles and cosmic rays.

Courtesy: Nature

12 wide-field-of-view air Cherenkov telescopes
5,195 scintillator detectors
80,000-m² surface-water Cherenkov detector
1,171 underground water Cherenkov tanks

~25,000 m

4,400 m
LHAASO WCDA #1 Sky Map

- First water pool (WCDA #1) taking data since April 2019
- ½ LHAASO ready for operation by end of 2019
- Construction complete 2020

- Data up to 2019-06-30
- Live time: 57 days
- Crab: 27σ
- 5 sources > 5 σ

M. Chen, PoS(ICRC2019)217

preliminary
Highest Energy Source Catalog

See 8 extended sources in Inner Galactic Plane $>56$ TeV, of which 3 seen $>100$ TeV.

K. Tollefson, MSU

ICRC, July 2019
Spectra of 100 TeV Sources

Spectra of sources emitting above 100 TeV

PRELIMINARY

\[ E^2 \frac{dN}{dE} \text{ (TeV cm}^{-2} \text{ s}^{-1}) \]

- eHWC J1825-134 overlaps with both HESS J1825-134 and HESS J1826-130
- MGRO J1908+06
- eHWC J1907+063
- Cygnus region
  - B. Hona, PoS(ICRC2019)699
- eHWC J2019+368
- Cygnus region
  - F. Salesa Greus, PoS(ICRC2019)781

- eHWC J1825-134 overlaps with both HESS J1825-134 and HESS J1826-130

1 TeV

Energy (TeV)

100 TeV
Evidence for $>100$ TeV Photons with HAWC

- Find cut-off energy ($E_c$) above which spectrum is inconsistent with background + mis-reconstructed events
- Likelihood fit of chosen spectrum model compared to spectrum with hard cut-off at $E_c$
  - Galactic sources modeled by power law with exponential cut-off
  - Crab modeled by a power law

\[
\Phi_{\text{obs}} = \Phi_{\text{emit}}(E) \Theta(E_{\text{cut}} - E)
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>$E_c$ (95%) TeV</th>
<th>$E_c$ (3σ) TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2HWC J1825-134</td>
<td>253</td>
<td>168</td>
</tr>
<tr>
<td>2HWC J1908+063</td>
<td>213</td>
<td>156</td>
</tr>
<tr>
<td>Crab (HAWC)</td>
<td>152</td>
<td>96</td>
</tr>
<tr>
<td>2HWC J2031+415</td>
<td>144</td>
<td>78</td>
</tr>
<tr>
<td>2HWC J2019+367</td>
<td>121</td>
<td>86</td>
</tr>
<tr>
<td>J1839-057</td>
<td>79</td>
<td>66</td>
</tr>
<tr>
<td>2HWC J1844-032</td>
<td>77</td>
<td>63</td>
</tr>
<tr>
<td>Crab (HEGRA)</td>
<td>56 (2.7σ)</td>
<td></td>
</tr>
</tbody>
</table>
Lorentz Invariance Violation (LIV)

LIV can modify dispersion relation:

$$E_a^2 - p_a^2 = m_a^2 \pm |\alpha_{a,n}| A_a^{n+2}$$

where:

- $A = \{E, p\}$
- $|\alpha_n| = |\epsilon_0^{(n)}| / M^n = 1/(E_{LIV}^{(n)})^n$

Leading order of correction

H. Martinez-Huerta and A. Perez-Lorenzana

Energy scale of new physics

$n = 0, 1, 2, \ldots$

LIV parameter

LIV coefficients
Highest Energy Photons set LIV Limits

Superluminal phenomena, such as photon decay, possible:

\[ \alpha \gamma, n < E_{\gamma}^{-n} \left[ \frac{4m_e^2}{E_{\gamma}^2 - 4m_e^2} \right] \]

\[ E_{LIV}^{(n)} > E_{\gamma} \left[ \frac{E_{\gamma}^2 - 4m_e^2}{4m_e^2} \right]^{1/n} \]

- Creates a cut-off in energy spectra
- Existence of HAWC high-energy photons limit \( E_{LIV} > 10^{31} \text{ eV} \)
- Most constraining limit on \( n=1 \) of \( E_{LIV} \)

See Martinez-Huerta’s talk GAI11c at 17:00 TODAY in Shannon Hall

H. Martinez-Huerta, PoS(ICRC2019)328
- **High energy** gamma rays are only produced by *non-thermal* processes.
  - Inverse Compton Scattering (for electrons) – **Leptonic** Model
  - Neutral pion decay (for protons) – **Hadronic** Model

\[ p + p \rightarrow p + p + \pi^0 \]
\[ \pi^0 \rightarrow \gamma + \gamma \]

K. Tollefson, MSU ICRC, July 2019
An Example of Particle Acceleration Models for Tycho

Photon Energy Spectrum for Tycho SNR

Leptonic Model

Hadronic Model

Cutoff energies are higher in hadronic models as the electrons in leptonic models suffer from synchrotron losses
First direct proof of particle acceleration to $E > 100$ TeV in jets

- Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
- Cooling time of such high energy electrons requires acceleration in the jet lobes far from central black hole

HAWC significance with the overlay of x-ray contours. The HAWC detection is correlated with the jet lobes and not the black hole.
SS 433 Multiwavelength Spectrum

High energy electrons accelerated in low B field from slow jets are difficult to explain

- Hadronic model requires too much energy
- PeV electron model in 16 mGauss field fits data

Photon Spectrum for Eastern emission region
Future Sensitivity to Acceleration Models for Tycho

Photon Energy Spectrum for Tycho SNR

Tycho is not in HAWC’s FOV

Slide courtesy of LHAASO
Geminga, an old pulsar

Science 358:911-914 (2017)

• Use angular extent of TeV nebula to measure the diffusion coefficient
• HAWC’s measured diffusion coefficient around Geminga is much lower than values derived from CR secondaries
• See G. Giacinti’s Review talk on July 30 for review of CR transport models
Using HAWC’s new Energy Estimators observe Geminga from 5 - 56 TeV and make energy dependent measurement of diffusion coefficient

H. Zhou, PoS(ICRC2019)832
Dark Matter Sources in HAWC’s FOV

Newly discovered sources (e.g. dwarf galaxies) can easily be added to searches.
Dark Matter Limits for Various Sources

HAWC will extend to higher masses with new energy estimators

WIMP Annihilation

WIMP Decay

Several talks in Dark Matter Session at 16:30 TODAY Festival Room

S. Hernabdez Cadena, PoS(ICRC2019)520
J. Lundeen, PoS(ICRC2019)528
J. Lundeen, PoS(ICRC2019)529

T. Yapici, PoS(ICRC2019)551
L. Oakes, PoS(ICRC2019)012
Evaporating Primordial Black Holes (PBHs)

PBH Burst Rate Density Upper Limits

PBHs with an initial mass of $\sim 5 \times 10^{14}$ g would be expiring now emitting a burst of gamma rays.

See K. Engel’s talk TODAY at 17:00 in Festival Room

K. Engel, PoS(ICRC2019)516
Outriggers Added to HAWC

350 Outriggers taking data since August 2018
Will improve energy resolution > 10 TeV

D. Huang, PoS(ICRC2019)700,
V. Joshi, PoS(ICRC2019)707,
V. Marandon, PoS(ICRC2019)736

K. Tollefson, MSU
Southern Wide FOV Gamma-ray Observatory (SWGO)

Altitude (Meters)

- >4500 m
- 4400 m
- 4300 m
- 4100 m
- 2600 m

Time (Year)

- 1990s
- 2015
- 2019

LHAASO

July 10, 2019

Large High Altitude Air Shower Observatory

All in the Northern Hemisphere

Tibet ASy

ARGO-YBJ

HAWC

Milagro

K. Tollefson, MSU ICRC, July 2019
Field of View Comparison for a Northern and a Southern EAS

Image Credit: NASA

THE FERMI BUBBLES

Image Credit: HAWC Collab. (Preliminary)

HAWC

SWGO

Invisible to HAWC

Invisible to HAWC & SWGO

THE GALACTIC CENTRE

Image Credit: SABAC

K. Tollefson, MSU

ICRC, July 2019
Southern Wide FOV Gamma-ray Observatory (SWGO)

• Formed new collaboration on July 1, 2019 to pursue R&D for SWGO
• Based on water Cherenkov technique
• Looking at 5 South American sites all >4.5 km up to 5km
• See www.SWGO.org for more info.

Join Us!

H. Schoorlemmer, PoS(ICRC2019)785
The Future of EAS Arrays is Bright

• Current EAS arrays are continuously surveying the northern hemisphere sky with their wide FOVs and are complementary to IACTs

• HAWC and Tibet ASγ+MD observe photons with Energies >100 TeV from astrophysical sources!

• LHAASO will be the largest and highest EAS detector when it is fully operational by 2021

• EAS detectors will help illuminate how astrophysical sources accelerate particles to the most extreme energies and constrain fundamental particle physics

• A new collaboration SWGO has been formed to propose an EAS array for the southern hemisphere – Join us!
THANK YOU
Daily Monitoring of Mrk421, Mrk501, Crab
HAWC sends alerts such as Astronomer’s Telegram (ATeL) to immediately alert community of activity.

HAWC monitors all gamma-ray sources visible to it every day.

April 5, 2016  
April 6, 2016  
April 7, 2016  
April 8, 2016
What’s Next: Improving HAWC’s low E response

Smaller showers overlap in time. New multiplane angle fitter improves HAWC sensitivity at lowest energies. Tests on Crab confirm. Pass 5 reconstruction of past data will occur soon.
LHAASO - A Large area EAS array
covering 1.3 km²

- 5195 EDs
  - 1 m² each
  - 15 m spacing

- 1171 MDs
  - 36 m² each
  - 30 m spacing

- 3120 WCDs
  - 25 m² each

- 18 WFCTs
LHAASO 1 Year sensitivity

Slide courtesy of LHAASO

K. Tollefson, MSU
ICRC, July 2019
HAWC’s Sensitivity with Outriggers

This sensitivity does not include improvements in HAWC reconstruction and analysis algorithms that will be implemented soon in new reconstruction pass.
Future Detector Sensitivities

![Graph showing differential point source sensitivity with data points for SWGO, HAWC, HESS, and CTA-South.

- SWGO: 1 year
- HAWC: 507 days
- HESS: 50 hours
- CTA-South: 50 hours

Logarithmic scale for $E^2 \times \text{Flux Sens. [ergs cm}^{-2} \text{s}^{-1}]$ against $\log_{10}(E_R / \text{GeV})$.}
Dark Matter Limits with SWGO