TeV Anisotropy with the HAWC Detector and Cosmic Ray Propagation Simulations

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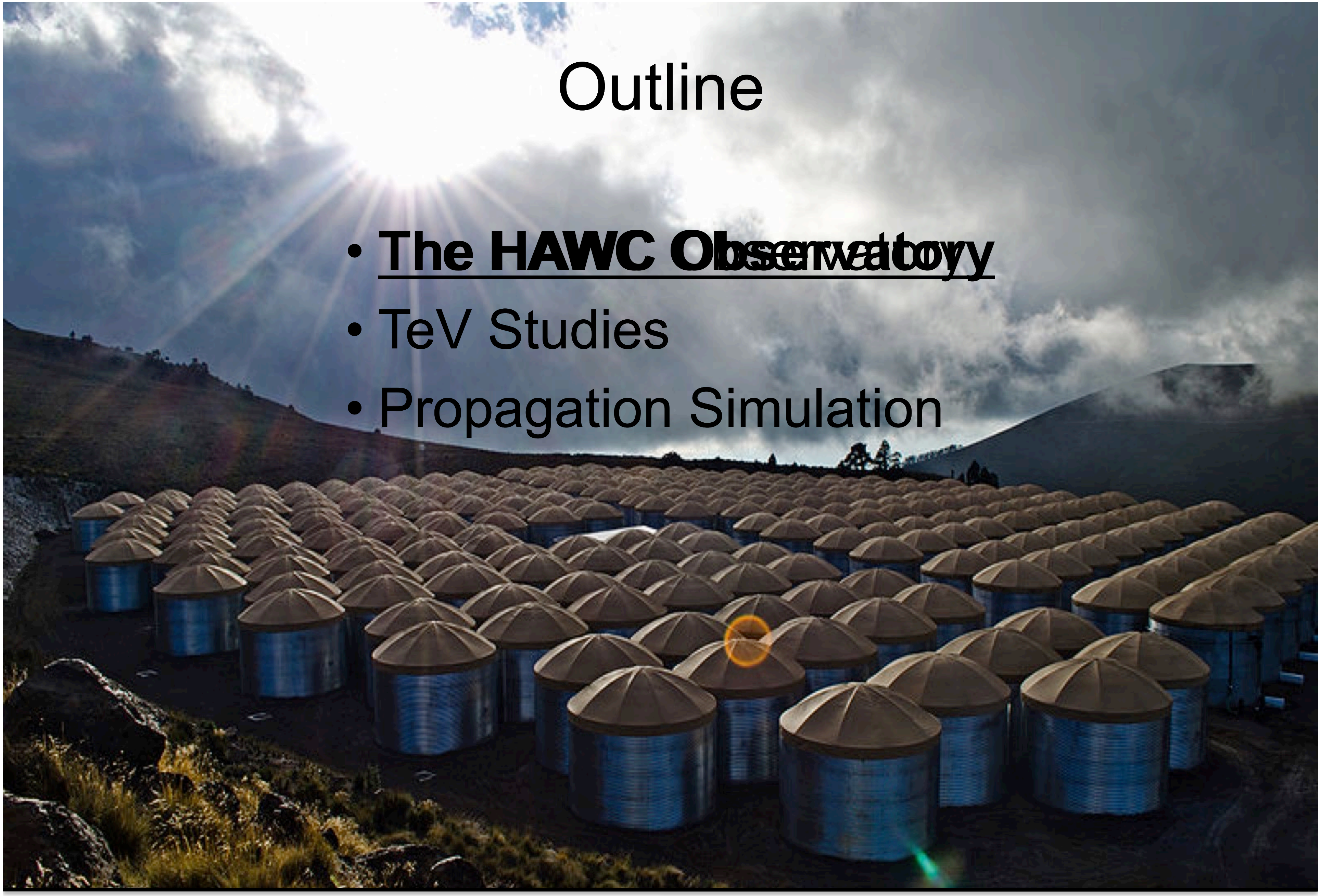
10 October, 2017

Outline

- **The HAWC Observatory**
- TeV Studies
- Propagation Simulation



The HAWC Observatory

97.3°W, 19.0°N

- Air-shower array near Puebla, Mexico
- 2nd gen. wide FOV (~2sr) cosmic-ray & γ-ray observatory
- Builds on the success of the Milagro experiment

High Altitude Water Cherenkov

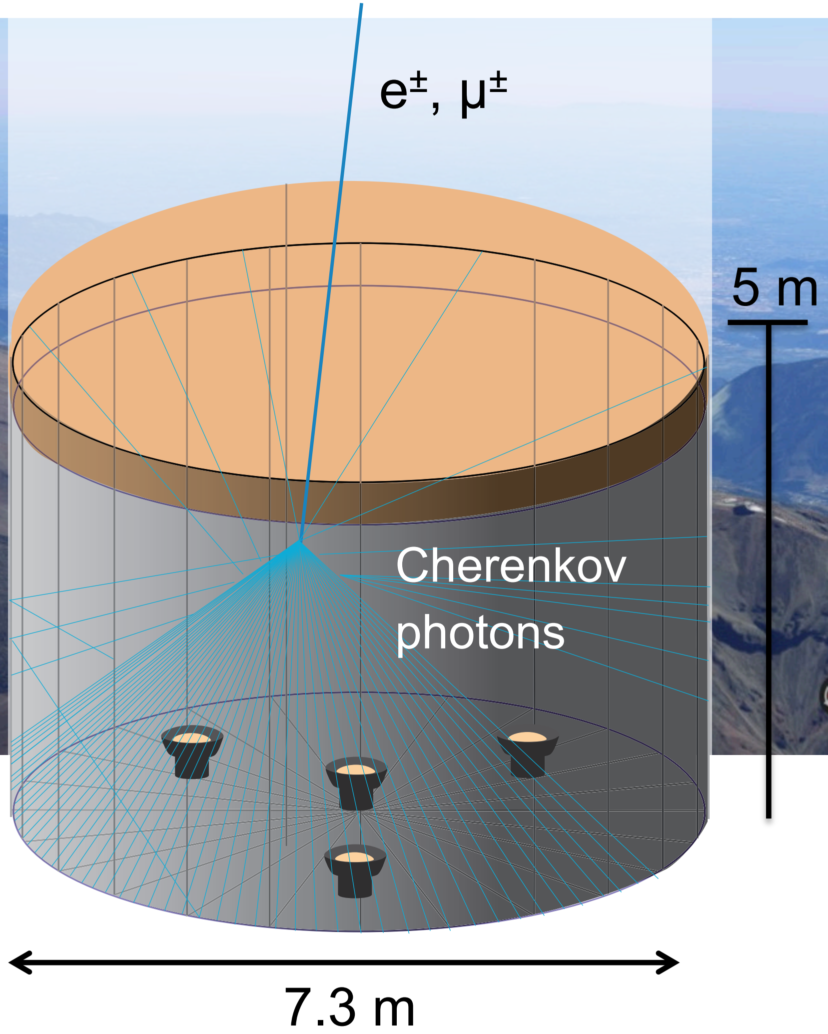
- On plateau between Pico de Orizaba and Sierra Negra
- 4,100 m a.s.l. (13,500 ft)

High Altitude Water Cherenkov

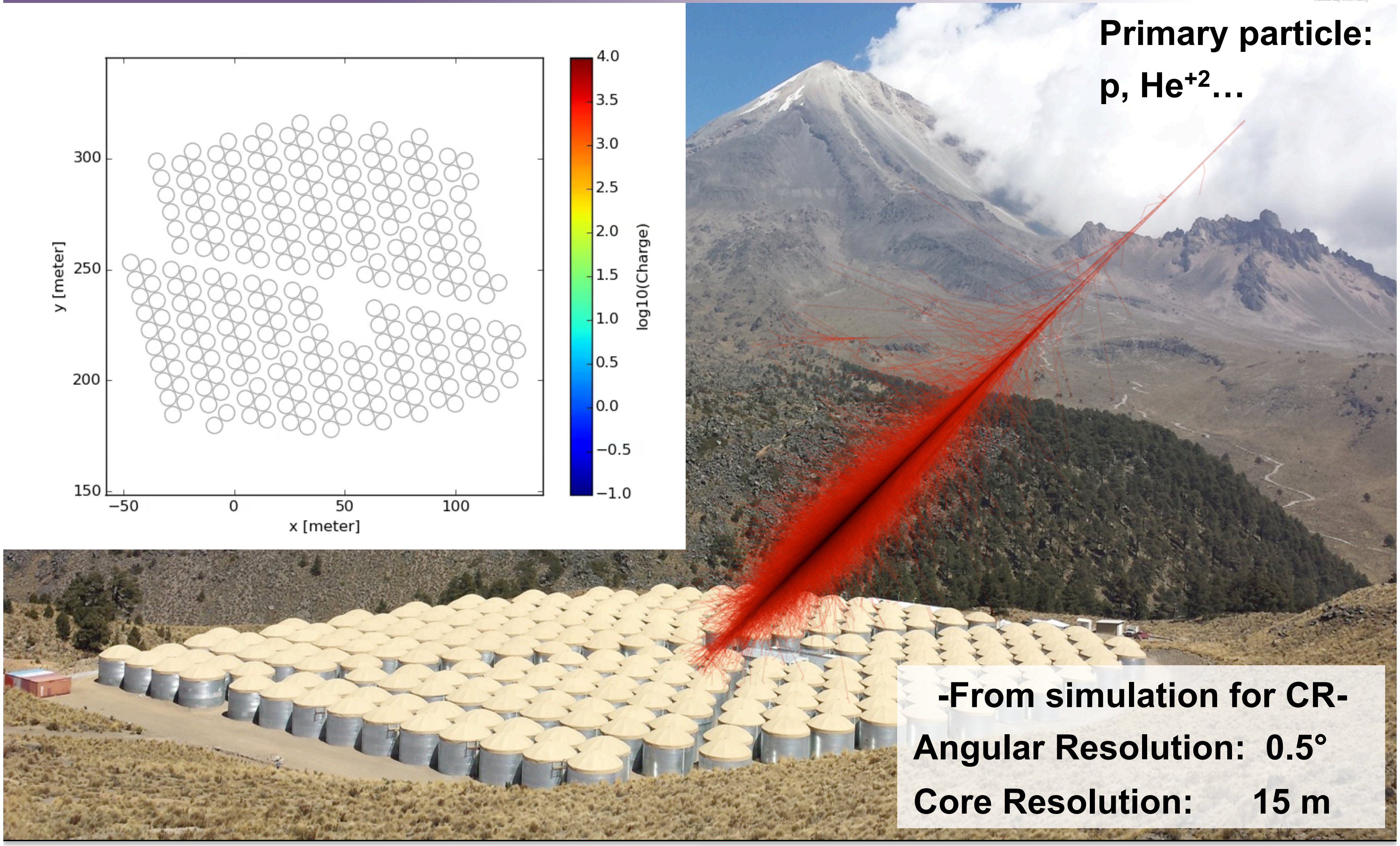
300 optically isolated water tanks
Dense 22,000 m^2 coverage

High Altitude Water Cherenkov

- 200,000 L purified water
- 4 Photomultiplier tubes (PMTs)
- Detect Cherenkov light from **relativistic** charged particles
- 95% uptime w/ data rate ~25 kHz



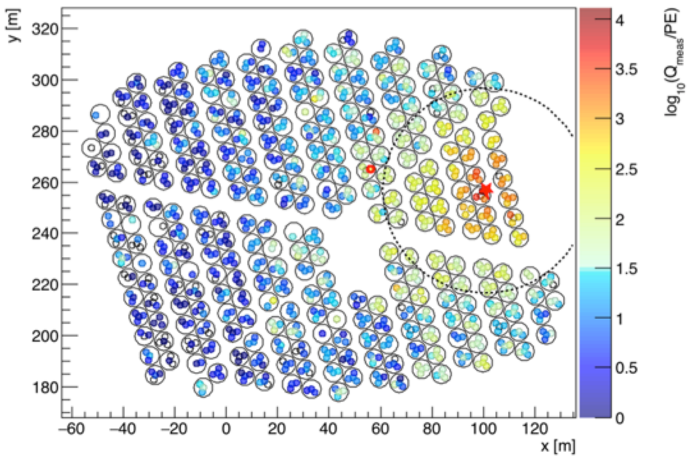
Air Showers in HAWC



Primary particle:
p, He^{+2}…

-From simulation for CR-
Angular Resolution: 0.5°
Core Resolution: 15 m

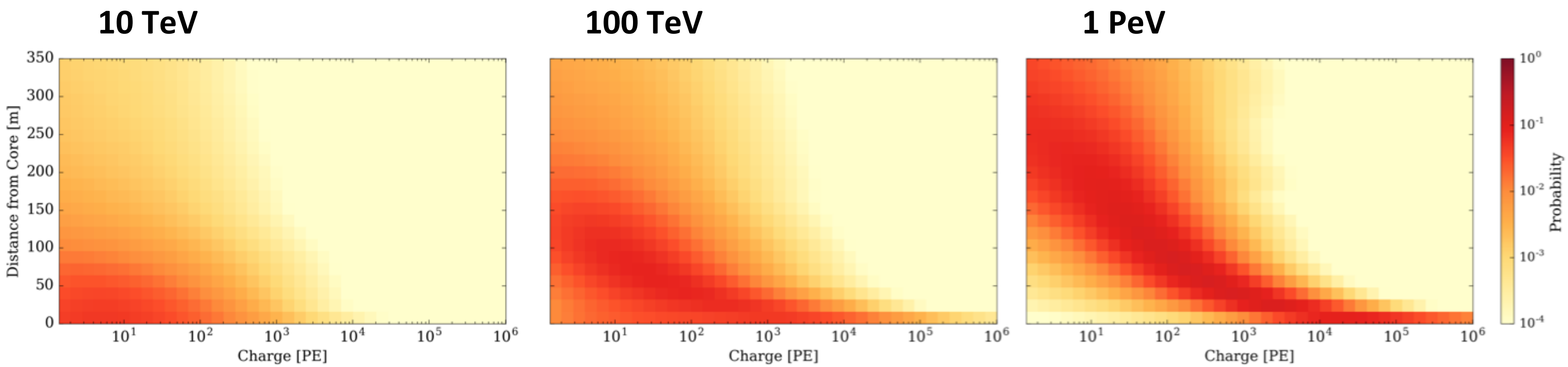
Energy Estimation



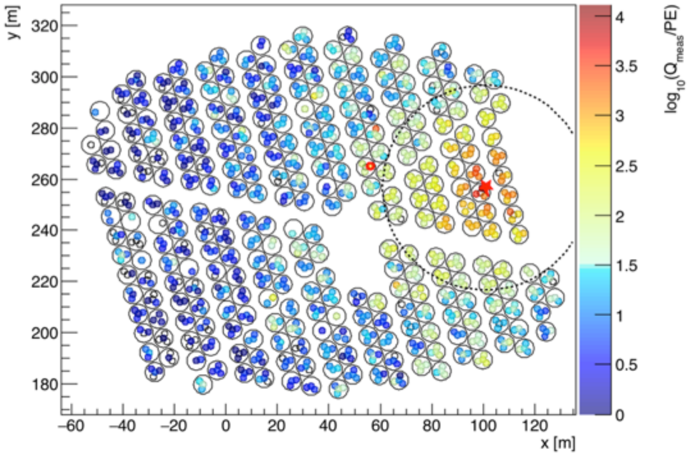
Built **lateral** distribution tables of MC **proton** shower hit patterns for range of simulated:

- Energies
- Arrival directions

Tables encode **average** shower footprint



Energy Estimation



Built **lateral** distribution tables of MC **proton** shower hit patterns for range of simulated:

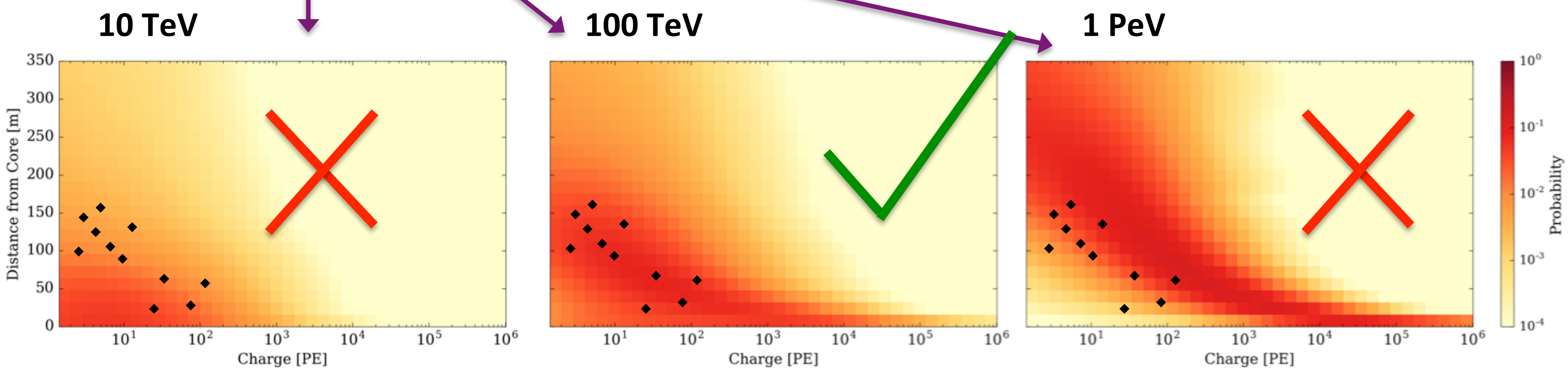
- Energies
- Arrival directions

Tables encode **average** shower footprint

Search tables to find the **<u>most likely</u> energy**

Maximum likelihood for hits to come from **distance, charge, zenith, energy** bins.

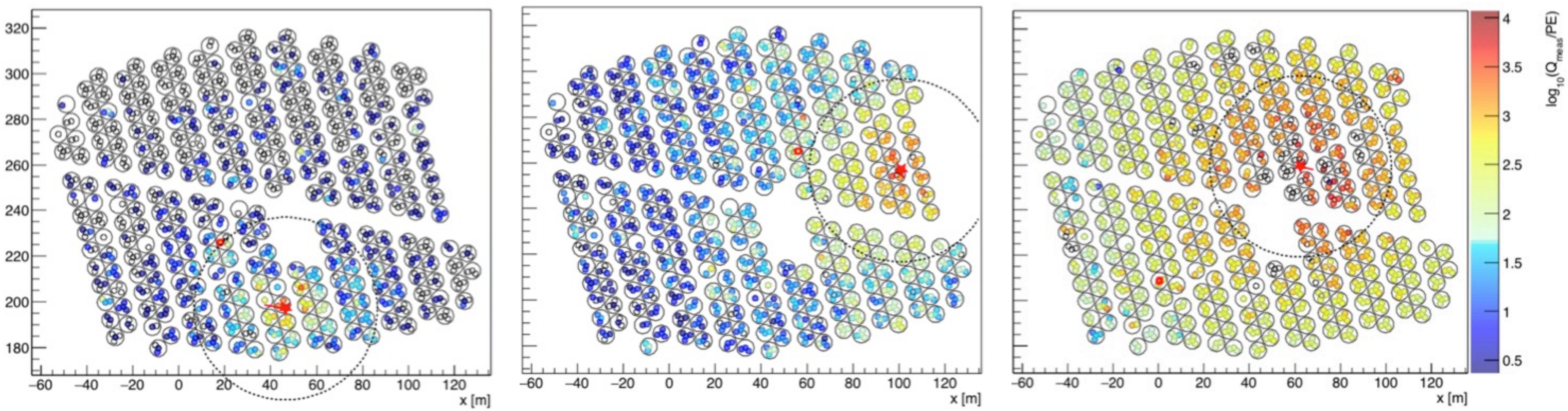
Shower of unknown energy



Example Events

Reconstructed Energy, E_{reco}

10 TeV **100 TeV** **1 PeV**



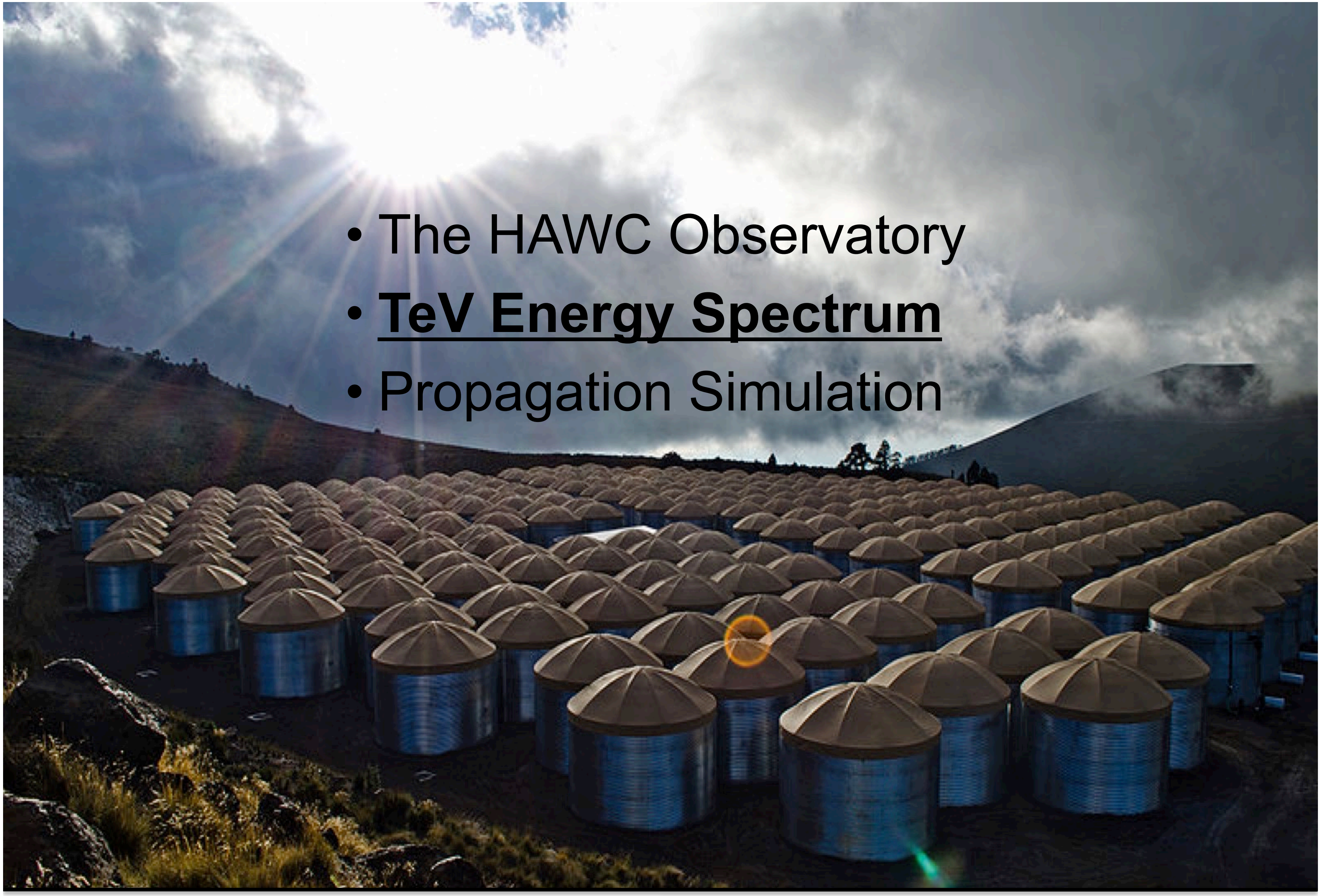
~½ the array contains signal around 10 TeV

Nearly all PMTs hit by 100 TeV

Energy resolution ~ 0.1 in log E

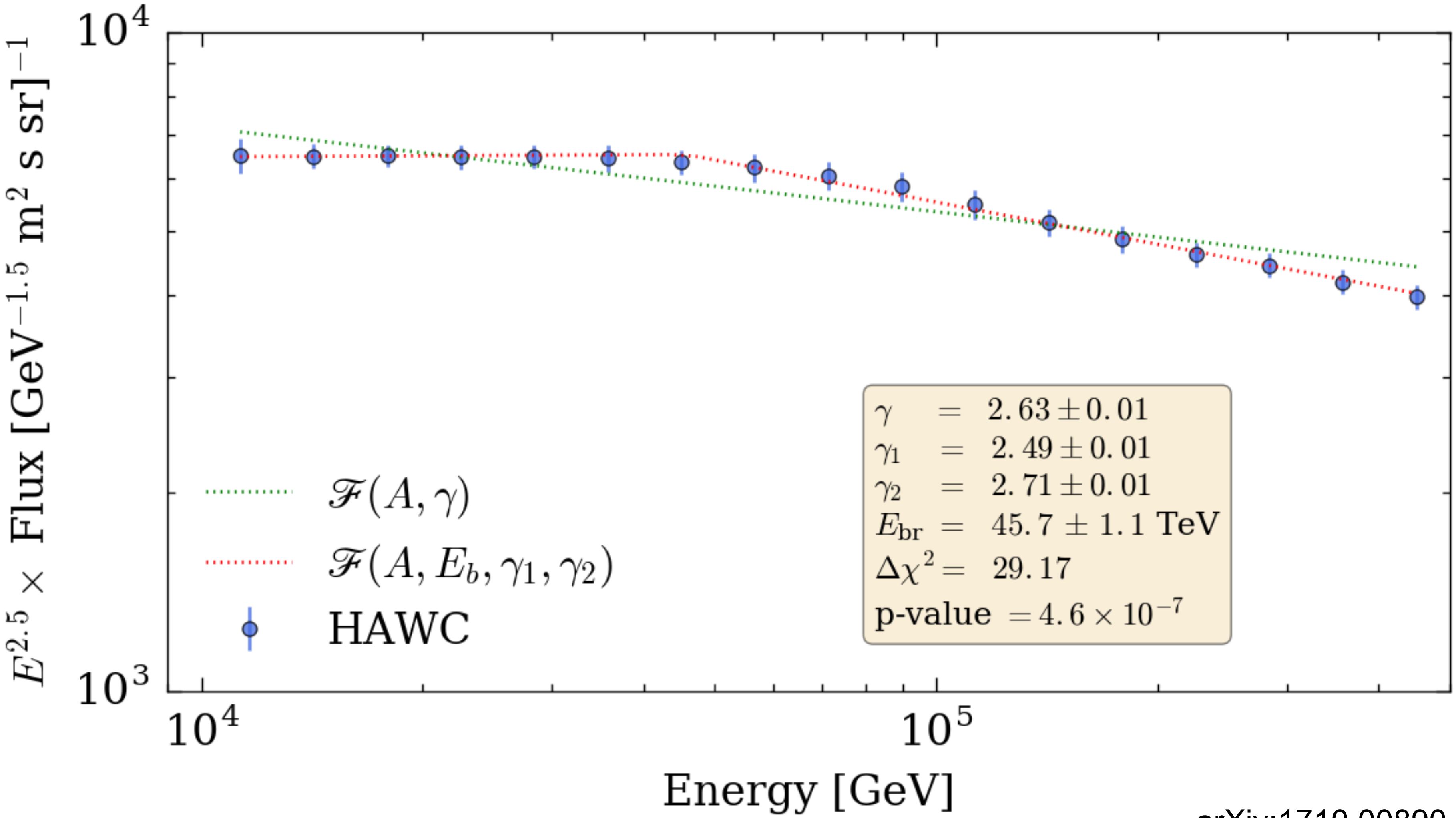
Energy scale verified by observation of cosmic-ray Moon shadow*

*arXiv:1710.00890 Submitted to PRD



- The HAWC Observatory
- **<u>TeV Energy Spectrum</u>**
- Propagation Simulation

All-Particle Energy Spectrum



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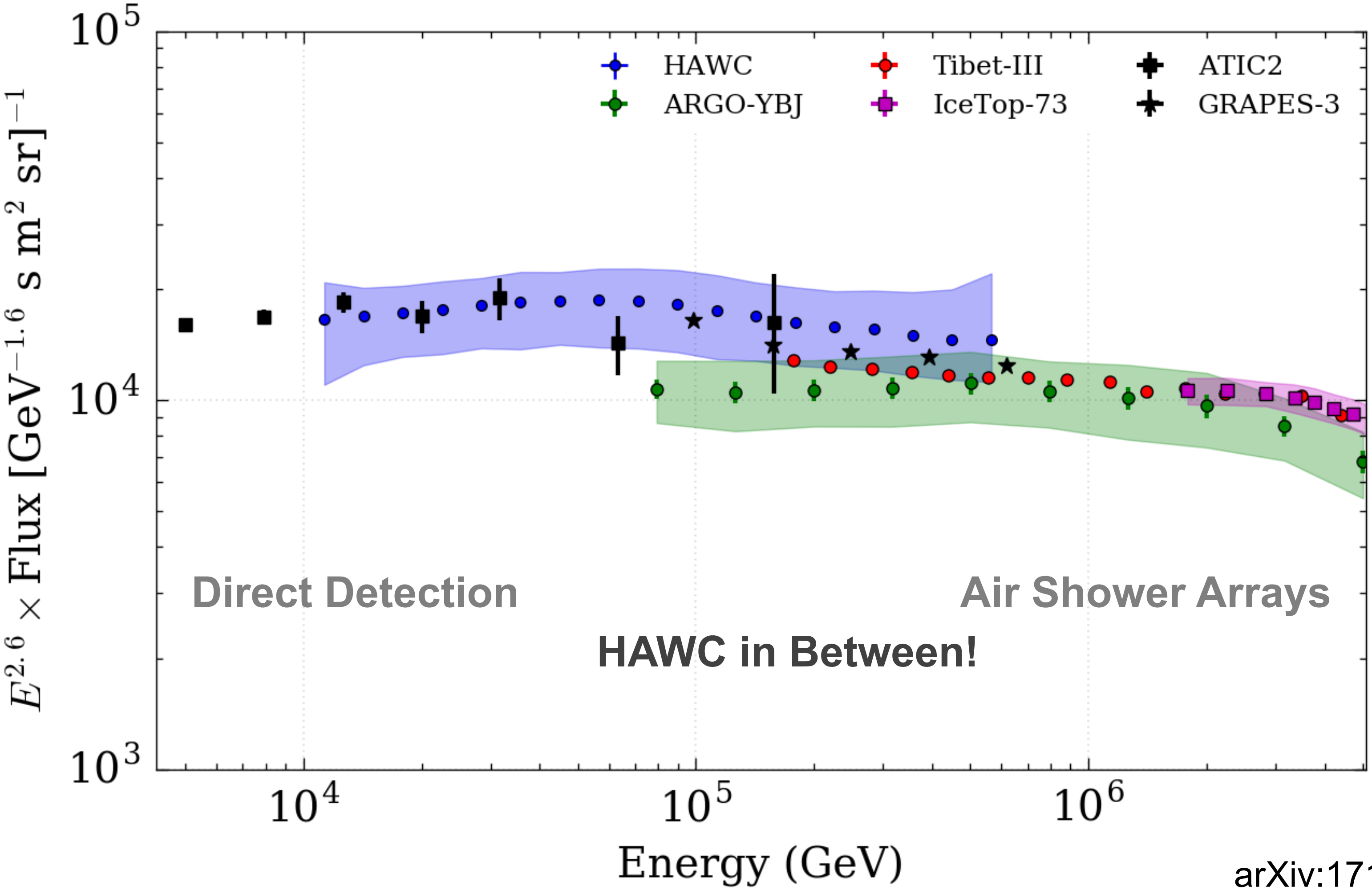
Submitted to PRD

Comparison to Other Experiments



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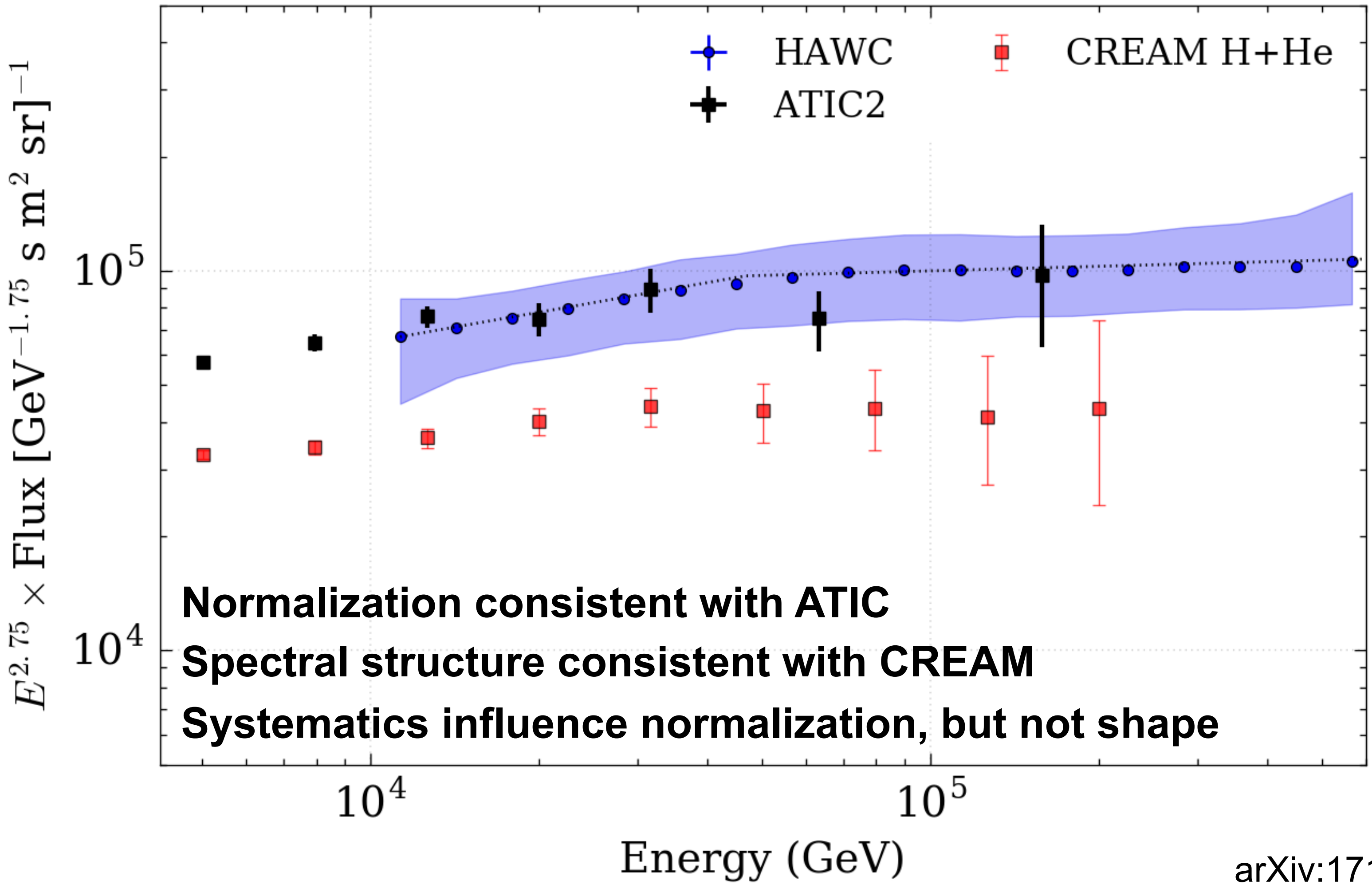
ARGO-YBJ: Frascati Physics Series Vol. **58** (2014)
ARGO: Phys. Rev. D, **88**, 10 (2013)
ATIC: Bull. Russian Acad. Sci., **73**, 564 (2009)
CREAM: Astrophys. J., **728**, 122 (2011)

GRAPES: J. Phys. G: Nucl. Part. Phys. **39** (2012)
GST4-gen: Gaisser et al 2013
IceTop: Phys. Rev. D **88**, 042004 (2013)
Poly-Gonato: Astropart. Phys. **19**, 193 (2003)
Tibet: Adv. Space Res. **42**, 467(2008)

Comparison to Other Experiments



Normalization consistent with ATIC
Spectral structure consistent with CREAM
Systematics influence normalization, but not shape

arXiv:1710.00890
Submitted to PRD

ATIC: Bull. Russian Acad. Sci., **73**, 564 (2009)
CREAM: Astrophys. J., **728**, 122 (2011)

Takeaways from All-Particle Spectrum

- Normalization is **consistent** with direct detection experiments **and** air-shower array measurements.
- Spectrum displays **structure:**

$$\boxed{\begin{aligned} \gamma_1 &= -2.5 \\ \gamma_2 &= -2.7 \\ E_{\text{br}} &= 46\ \text{TeV} \end{aligned}}$$

- Consistent with dominant **H+He spectrum** observed by CREAM balloon experiment.

arXiv:1710.00890
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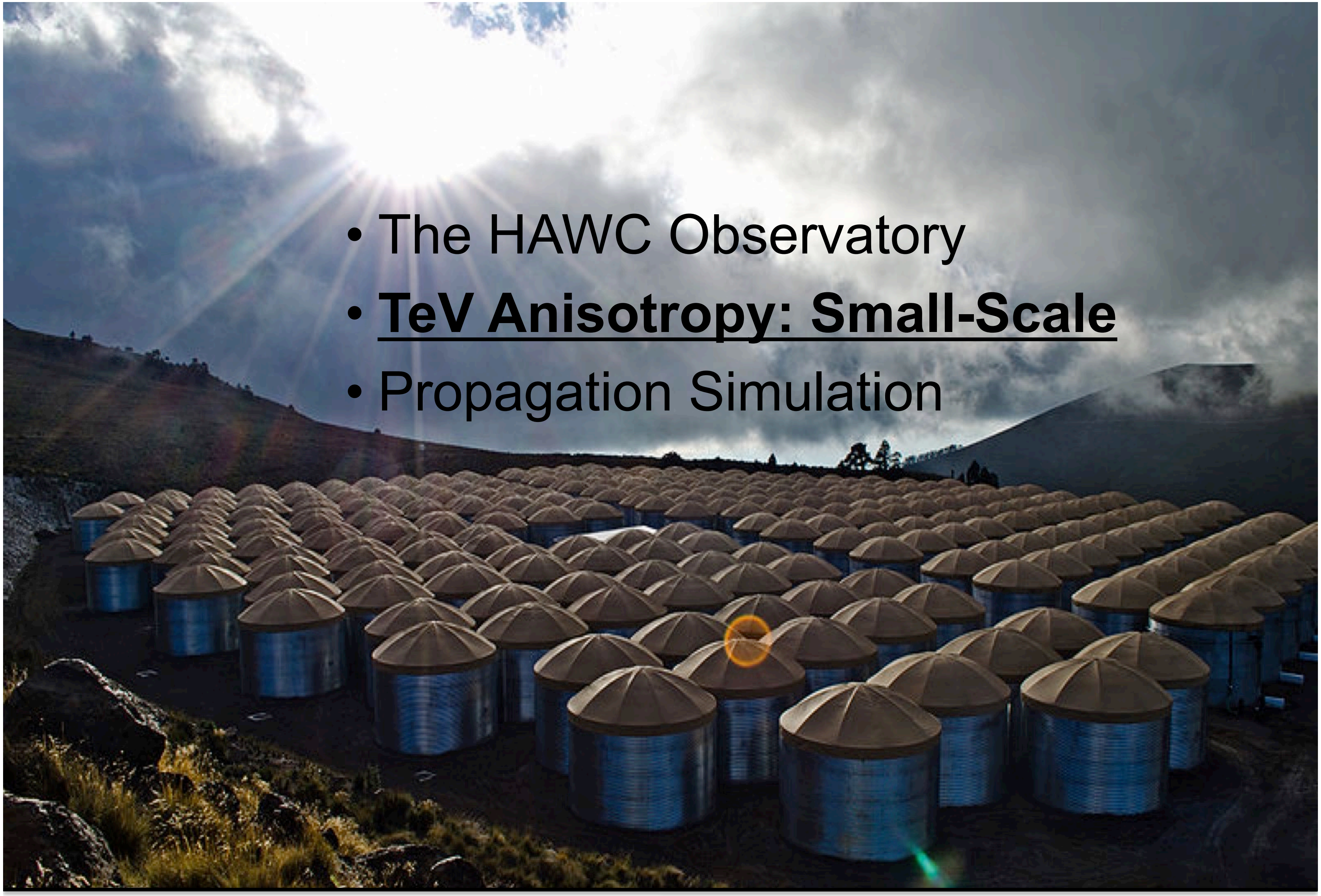


- The HAWC Observatory
- **TeV Anisotropy: Small-Scale**
- Propagation Simulation

Small-Scale Anisotropy

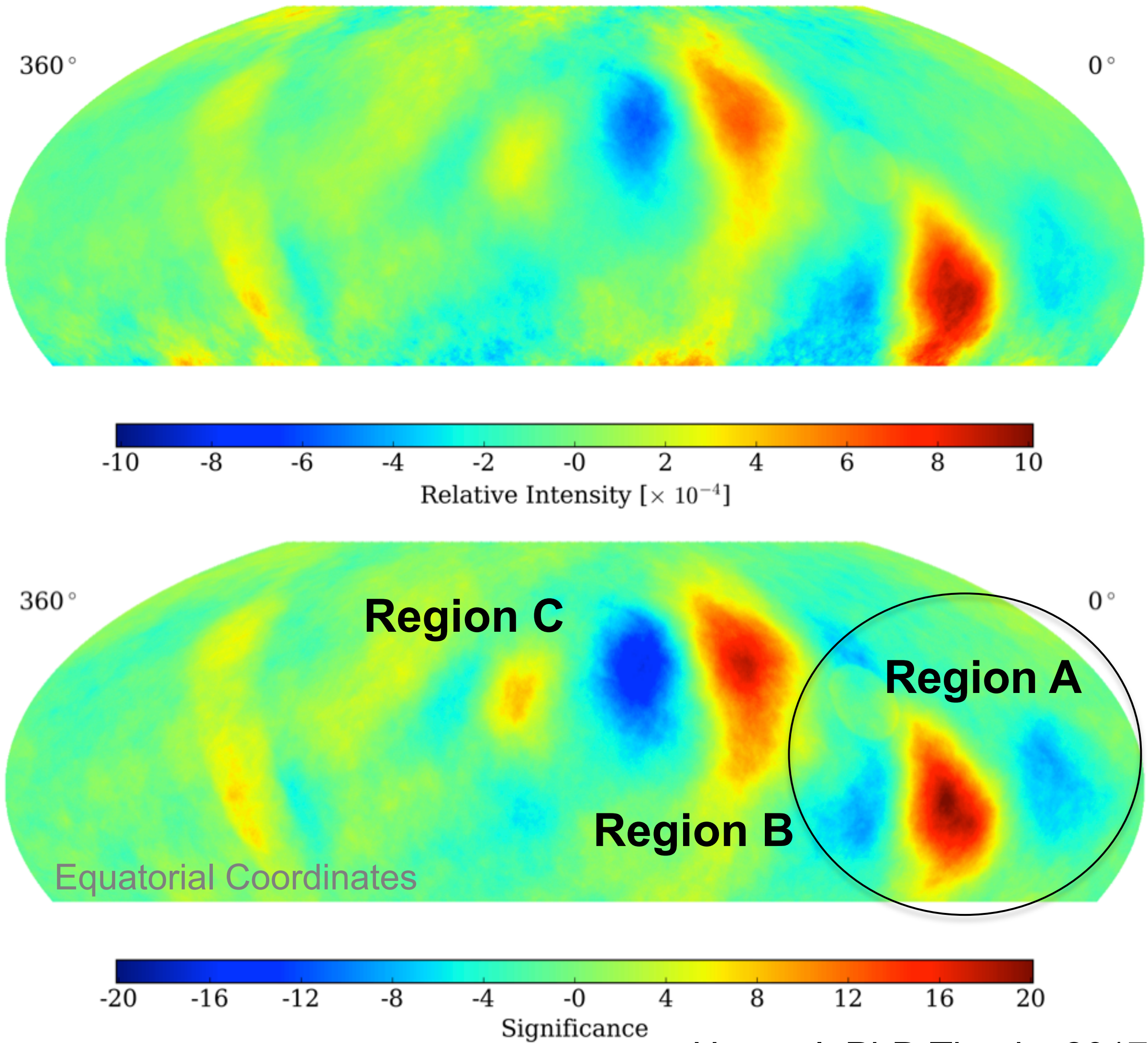
546 days live-time
6.9 x 10^{10} events
E_{med} ~ 4 TeV
10° smoothing

4 hr direct integration -> sensitive to features <60°

Usual suspects appear on small, **~10°**, angular scales

Region A of interest:

- Young, nearby sources
- Non-diff. propagation
- Heliospheric effects

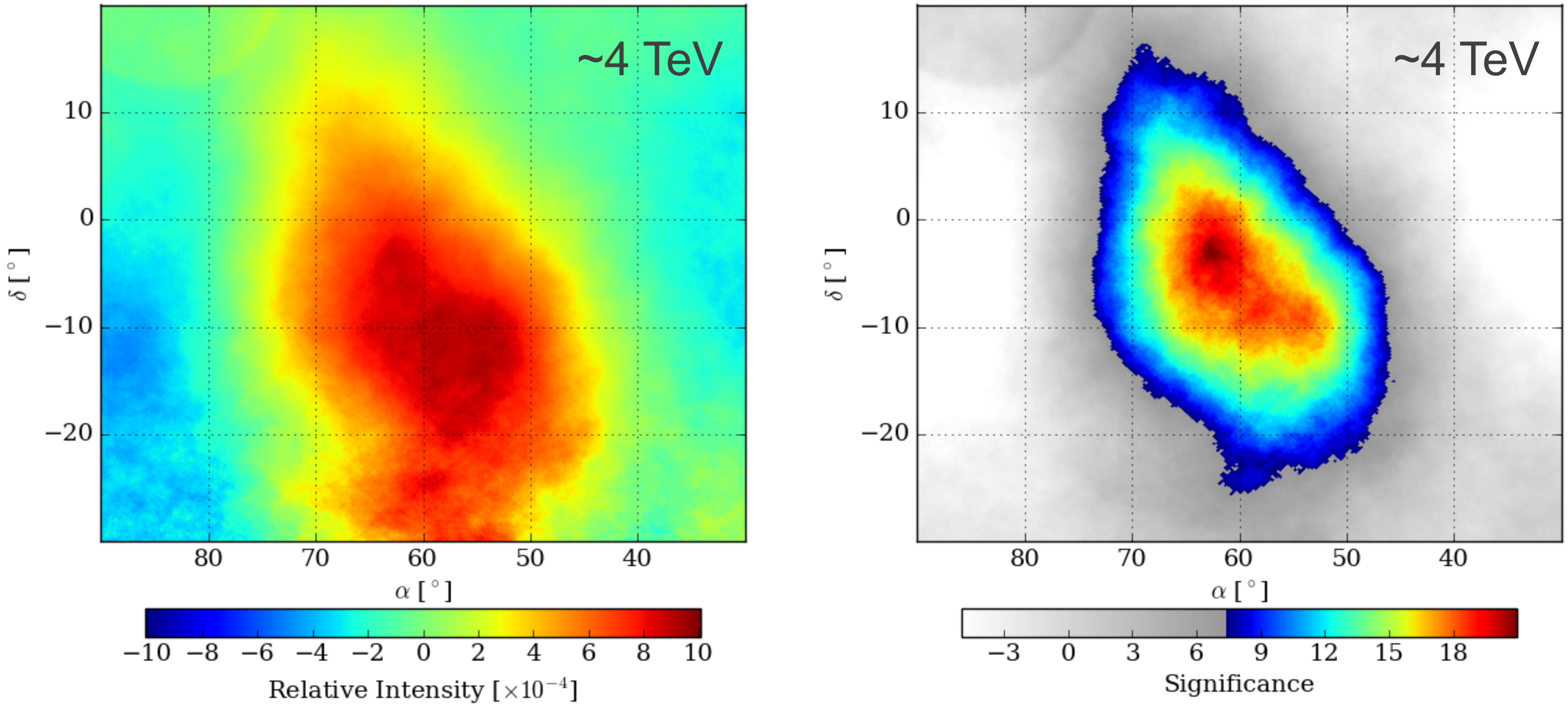


Hampel, PhD Thesis, 2017

Small-Scale Anisotropy: Region A

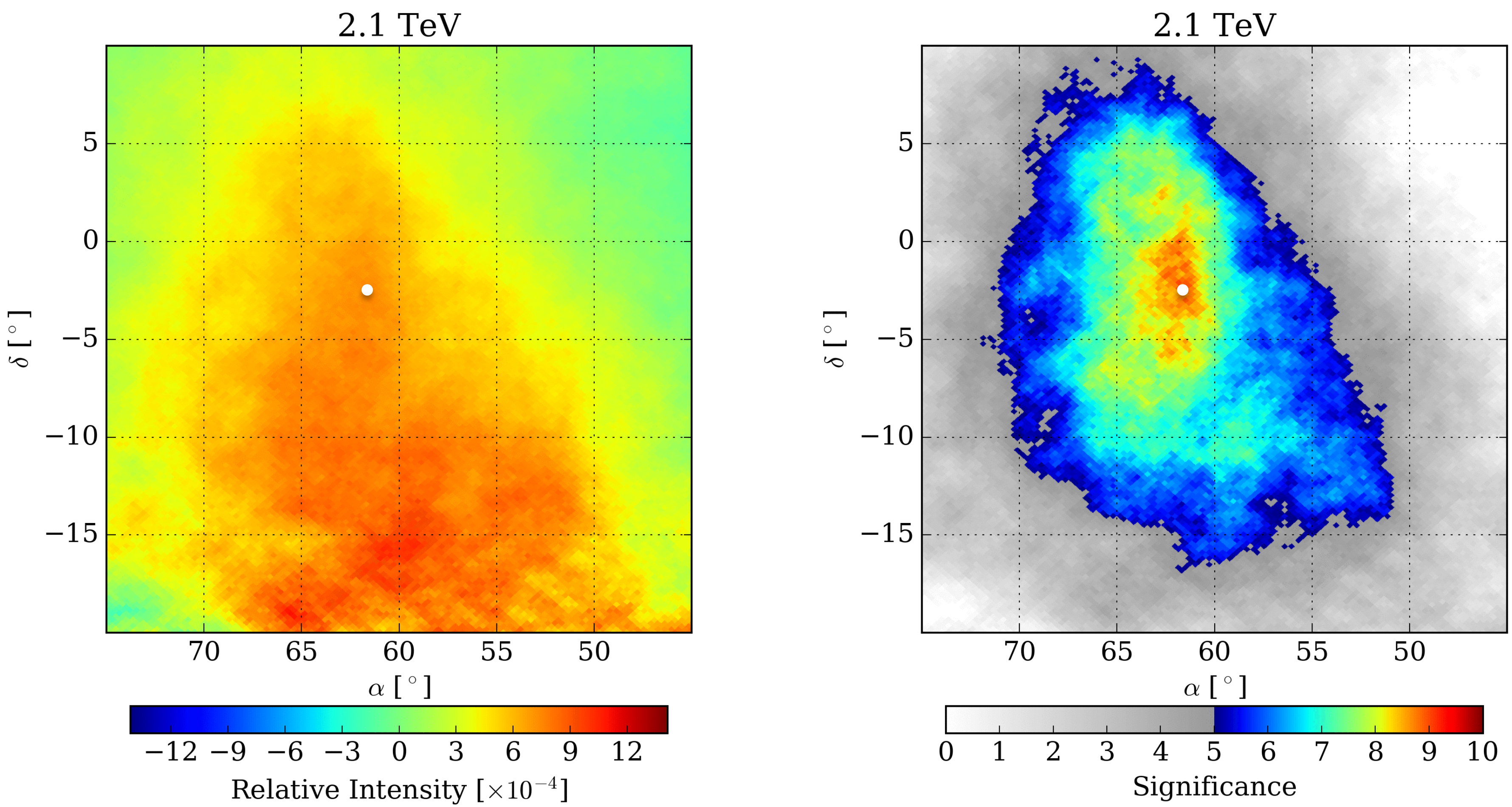
Region A extended cosmic ray excess ~30°

Most significant point is at (α=62.2°, δ=-3.3°)



Hampel, PhD Thesis, 2017

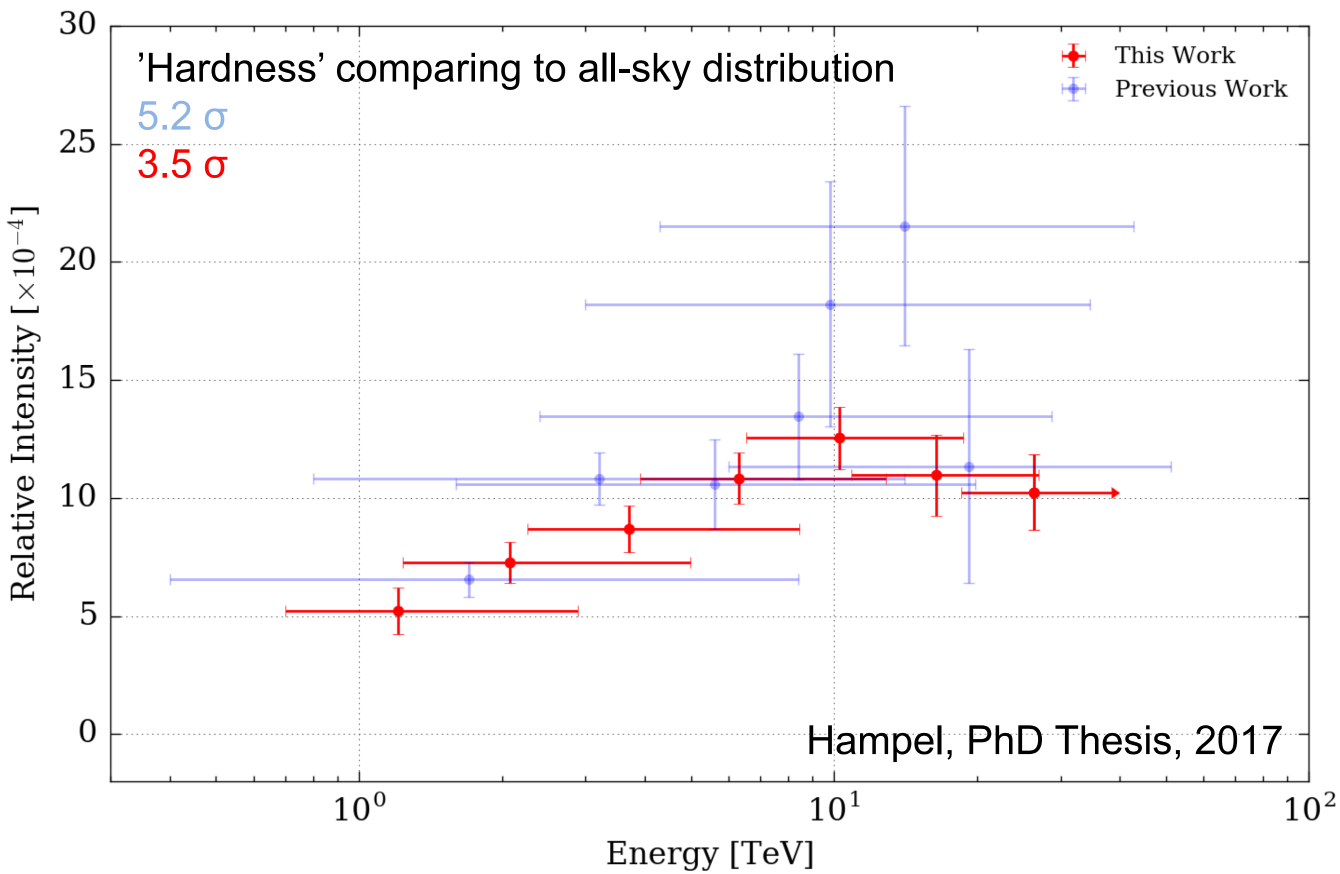
Small-Scale Anisotropy: Region A



White dot: max sig in combined map

Hampel, PhD Thesis, 2017

Region A Spectrum

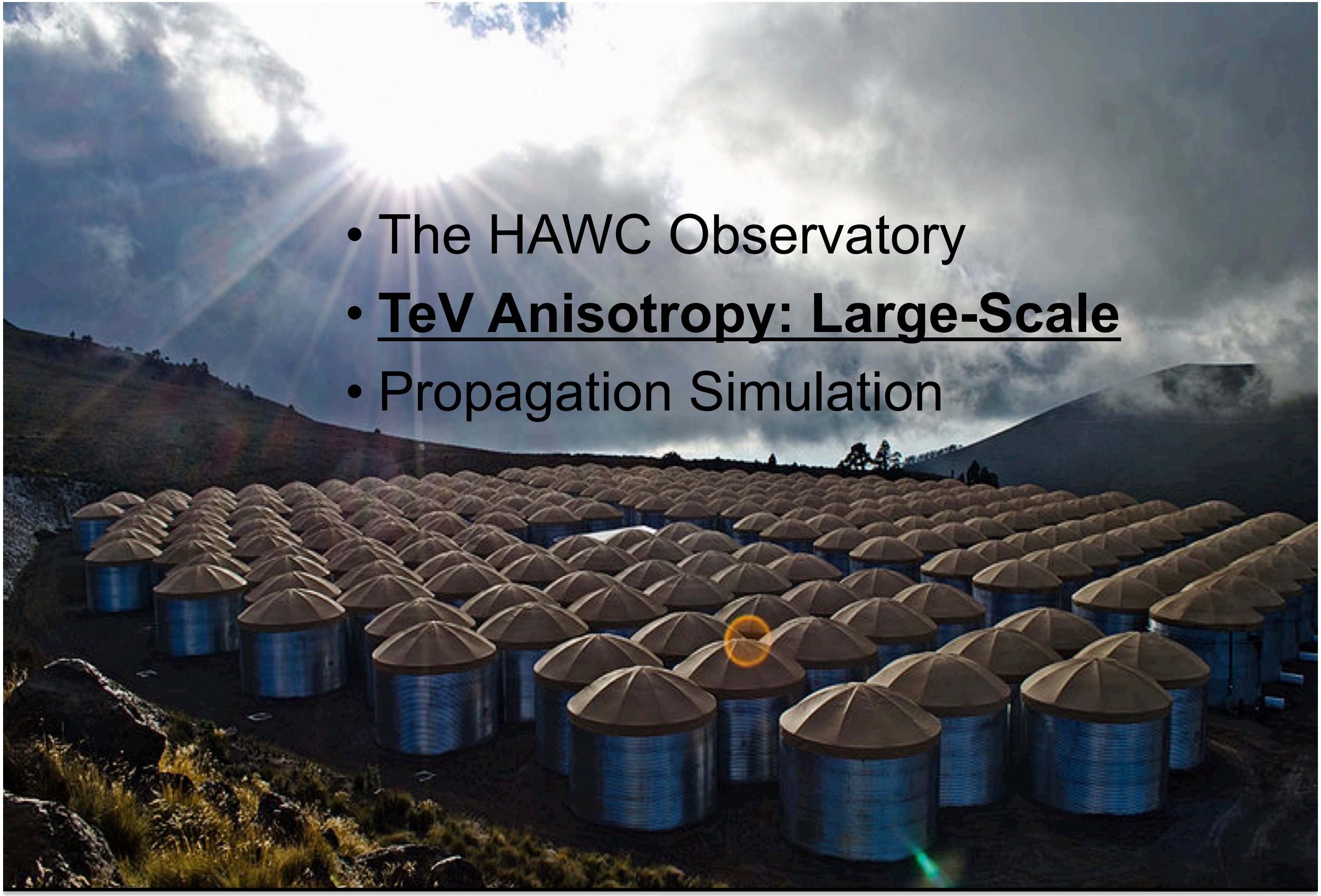


Previous work* energy estimate used multiplicity energy proxy

Larger detector & **improved energy estimation** constrains spectral shape

Statistics rapidly decreasing at highest E, more data needed to study region

*ApJ 796:108



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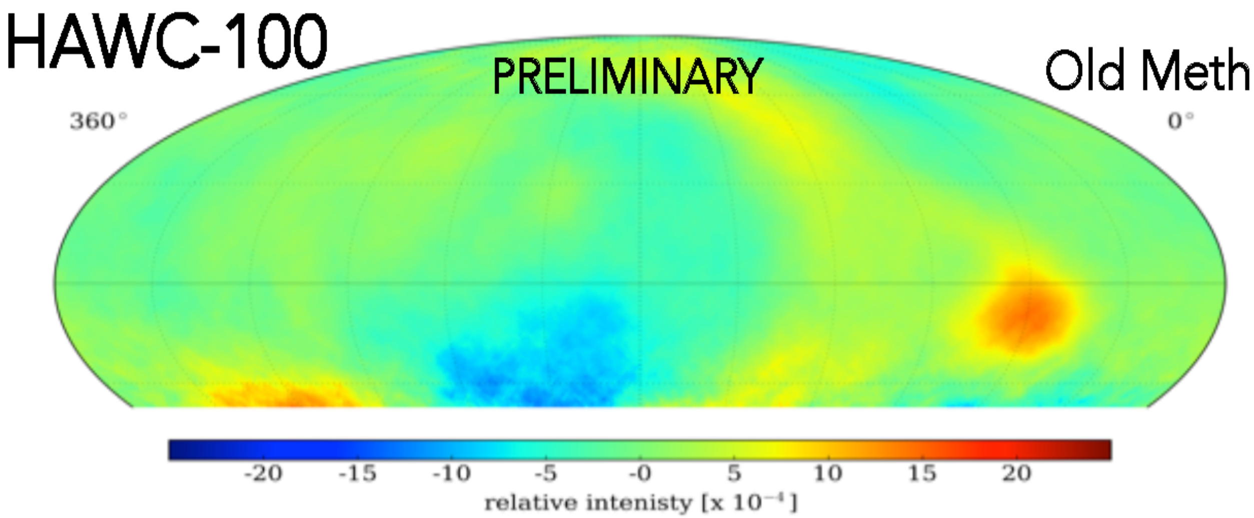
Improvements to LS Sensitivity

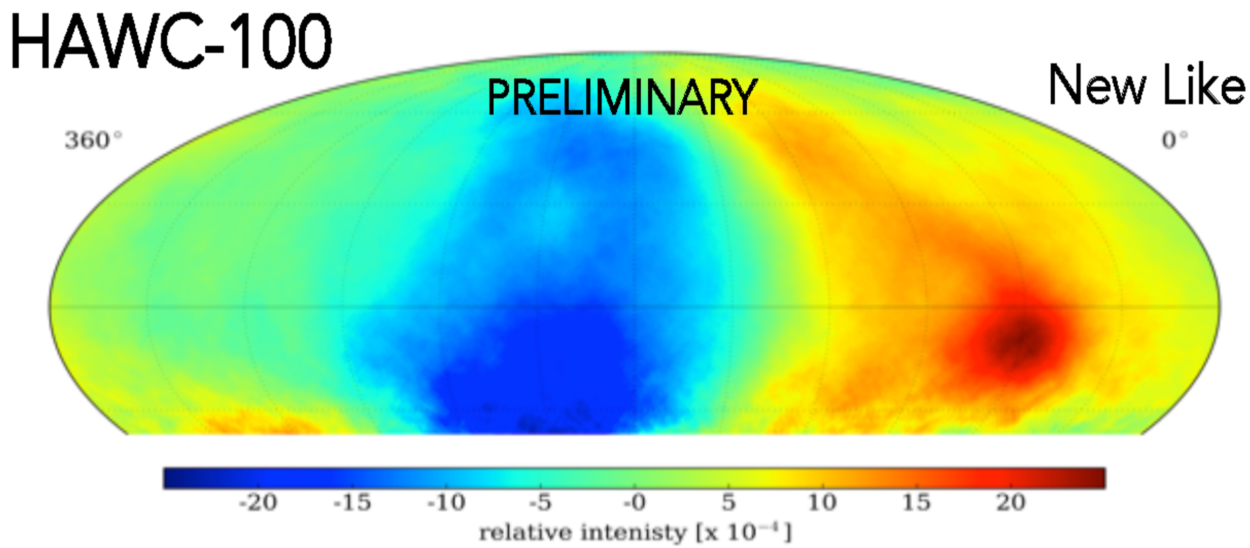


Old Method : Direct Integration

Standard method for HAWC

Sensitive only to features of scale of FOV

Ahlers, DF, et al. (2015) improved upon this algorithm by iteratively correcting the all-sky rate for the influence of the large signals



New Likelihood-based Method

Large-scale features are enhanced by over a factor of 2.

Low-moments become stronger because of correction to all-sky exposure as a function of sidereal time.

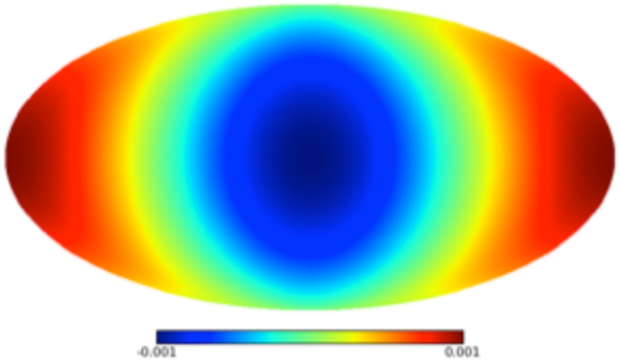
Fiorino, TeVPA 2016

*ApJ **823**:10 (2017)

Improvements to LS Sensitivity

Monte Carlo: Method Comparison

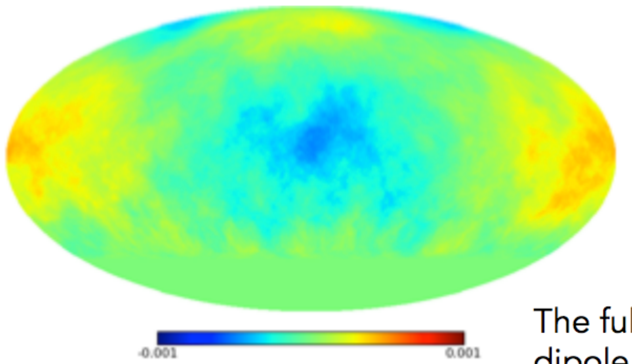
True Signal



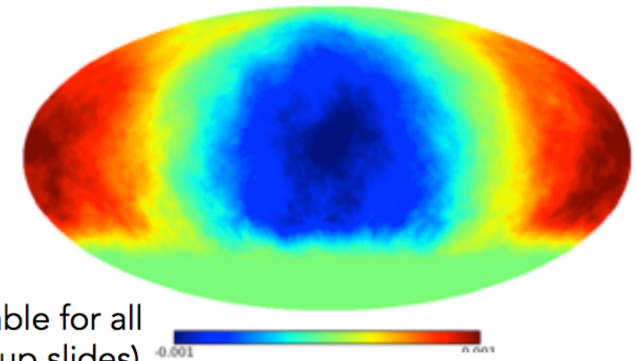
10^{-3} dipole at declination=0° for HAWC Field of View with 5x10^{10} events.

The *full signal* is recovered with the new method and greatly diminished with direct integration.

Direct Integration



Likelihood Method



The full signal is not recoverable for all dipole orientations (see backup slides)

Fiorino, TeVPA 2016

*ApJ **823**:10 (2017)

Large-Scale Maps: Rel. Int.

- Data set: 400 days

  Nov 2014 – Feb 2017

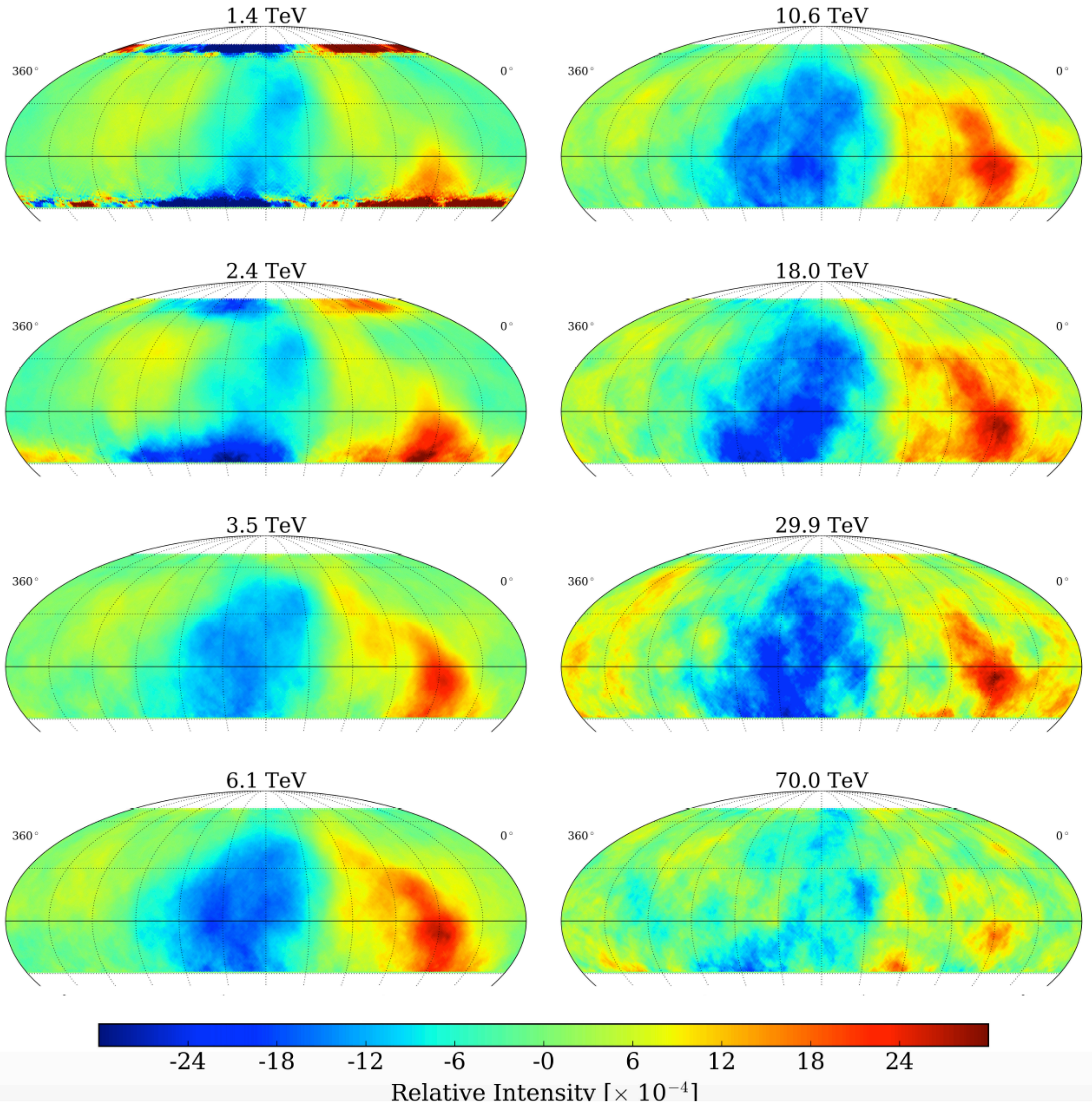
- Zenith range 0º-60º

- 4% passing rate (cuts)

- 57 billion events

- Iterative method used

Preliminary



Large-Scale Maps: Significance

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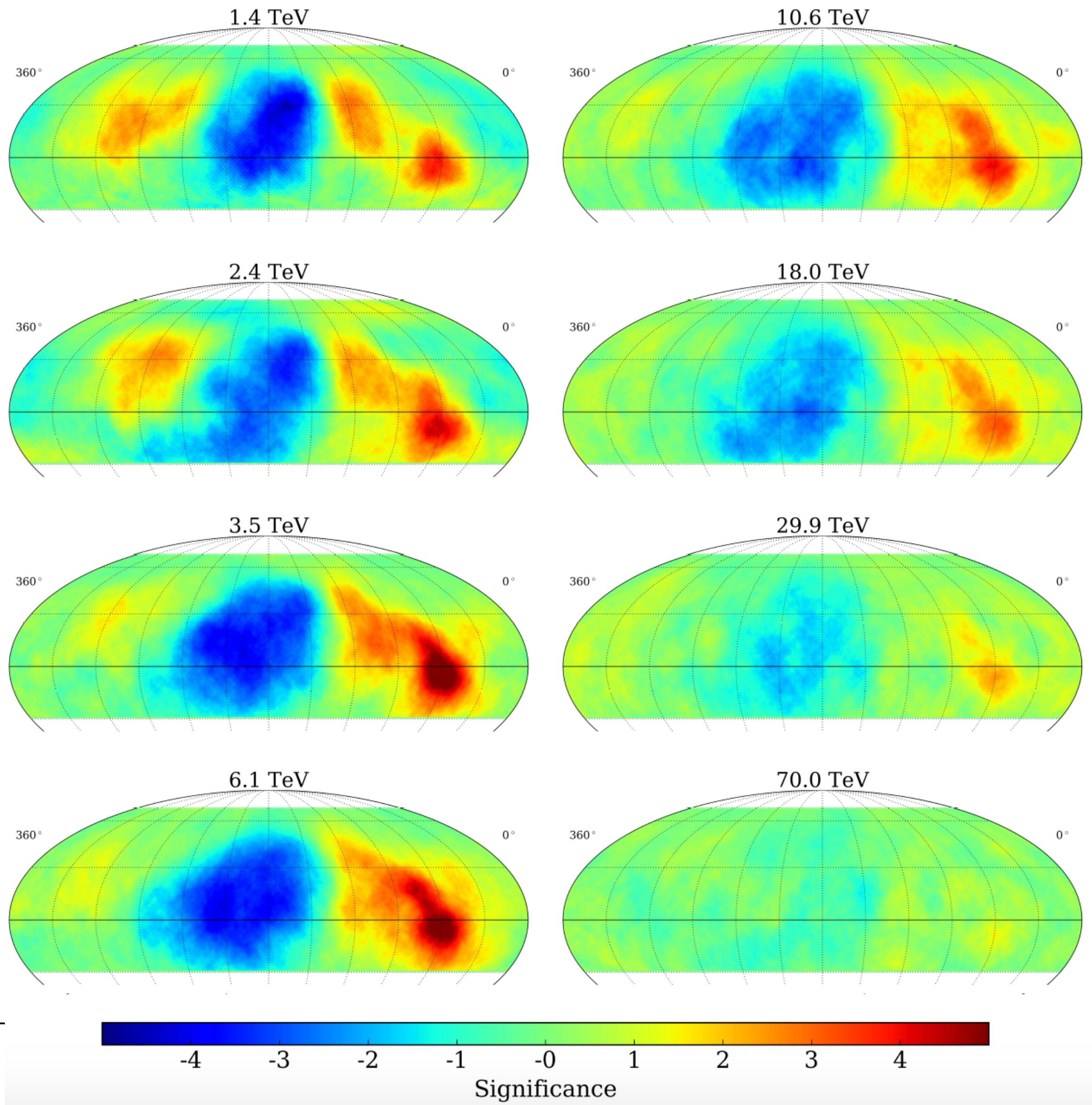
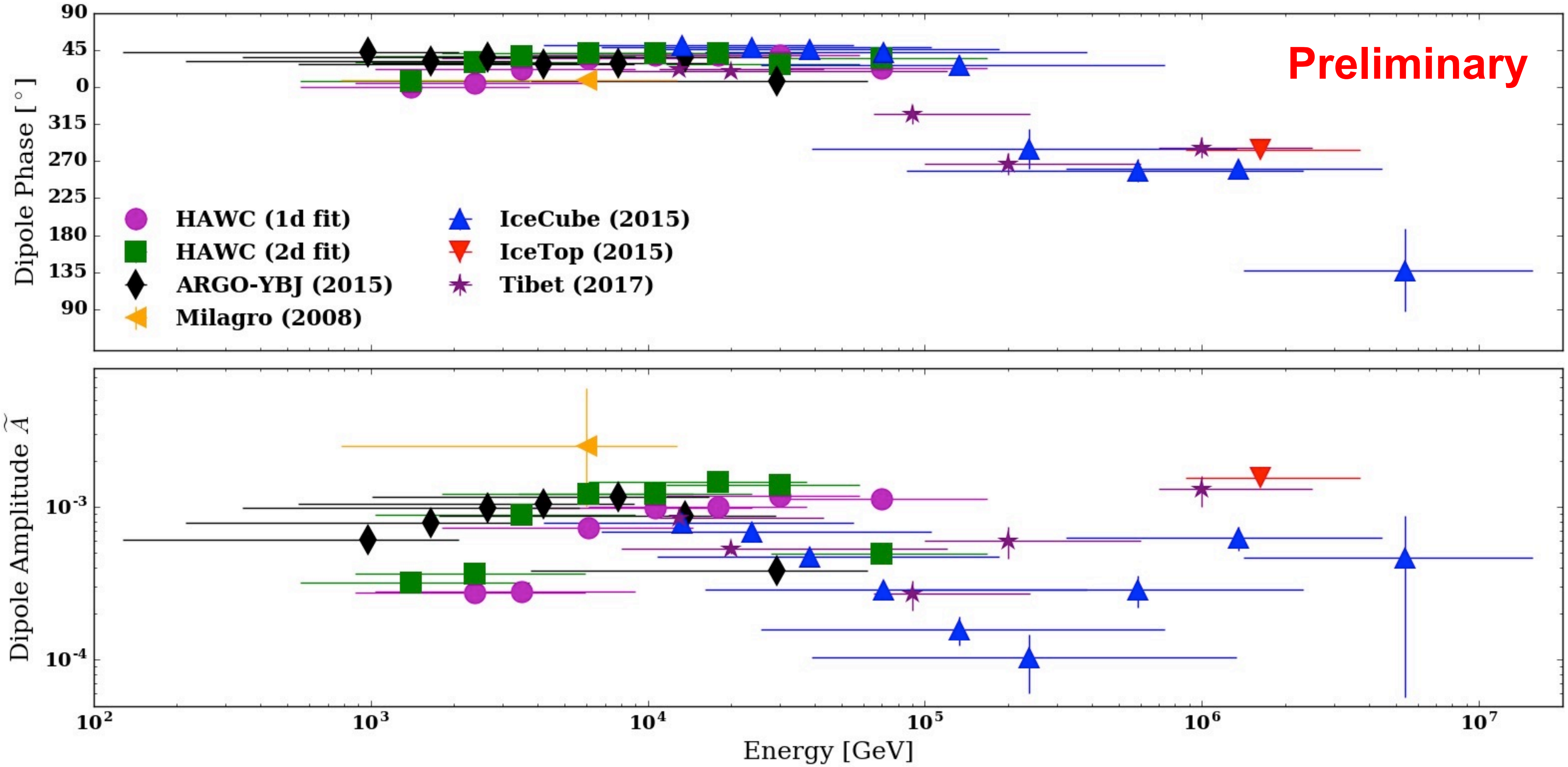


Large-Scale Maps: Dipole Fit



Consistent phase and amplitude below 100 TeV,

prior to phase flip and resurgence of amplitude.

Large-Scale Anisotropy

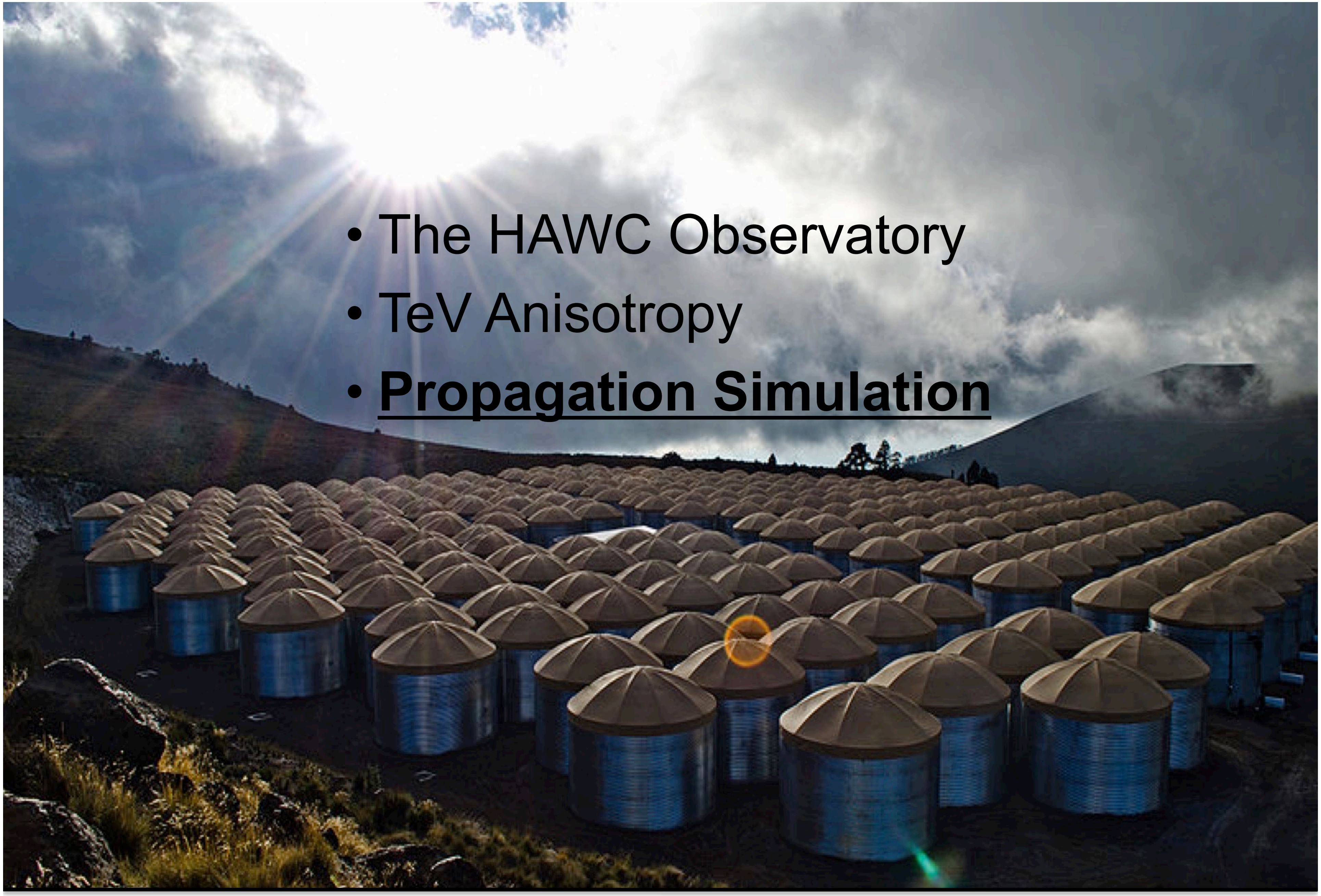
Maps have been updated with **larger data set (10x)**.

Less strict quality cuts set **passing rate to 40%** with no loss of E_{res} or dynamic range + extra 100 days of runtime.

Lowest energy bin amplitudes now **consistent** with ARGO.

Large-scale publication is currently under collaboration review.

Expect improved fits and a power spectrum.



- The HAWC Observatory
- TeV Anisotropy
- **Propagation Simulation**

Propagation Sim on GPUs

- Developed a cosmic-ray propagation GPU simulation, written in OpenCL/PyOpenCL for portability (platform independent)
- Developed to back-trace particles in geomag. field for Moon shadow studies*, 10^9 particles on 300-GPU cluster in 4 hrs (speedup of 90x over CPU cluster)
- Intend to use for fast testing magnetic field configurations, turbulence, anisotropy studies, etc.
- Implementation of Boris integrator, widely used in plasma physics

*arXiv:1710.00890
Submitted to PRD

GPU - EOM Integrator

Integration of EOM difficult in rapidly changing fields.

DO NOT conserve energy for t >> δt, **DO** conserve energy

- Linear integration – Euler step
- Runge Kutta 4 – fixed / adaptive time step
- Boris – fixed / adaptive time step (symplectic, explicit)

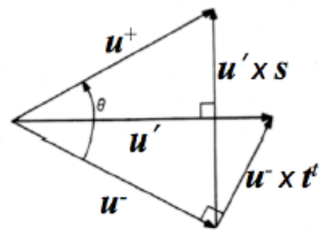
Boris Scheme* (Explicit Scheme)

$$u_{t-\Delta t/2} = u^{-} - \frac{qE}{m}\frac{\Delta t}{2}$$

$$u_{t+\Delta t/2} = u^{+} + \frac{qE}{m}\frac{\Delta t}{2}$$

$$\downarrow$$

$$\frac{u^{+} - u^{-}}{\Delta t} = \frac{q}{2m}(u^{+} + u^{-}) \times B$$



$$u^{-} = u^{t-\Delta t/2} + \frac{q\Delta t E^{t}}{2m},$$

$$u' = u^{-} + u^{-} \times t^{t},$$

$$u^{+} = u^{-} + u' \times \underbrace{\frac{2t^{t}}{1 + t^{t} \cdot t^{t}}}_{S}$$

$$u^{t+\Delta t/2} = u^{+} + \frac{q\Delta t E^{t}}{2m}$$

with $\mathbf{t}' = \dfrac{q\Delta t}{2\gamma' m}\mathbf{B}'$

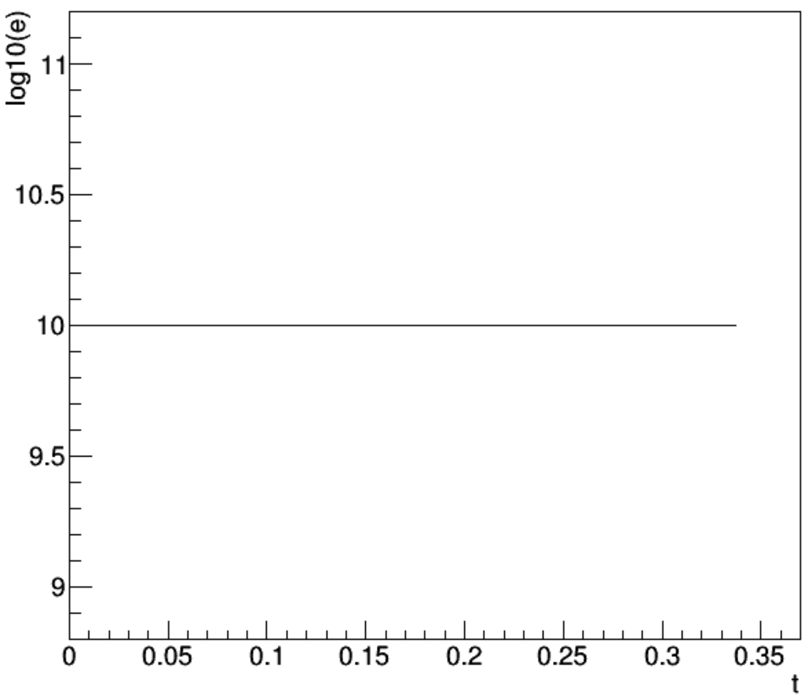
$$\theta = 2\arctan(t') = 2\arctan(qB\Delta t / 2\gamma m)$$

Fix the angular deflection per step, based on B-field evaluation.

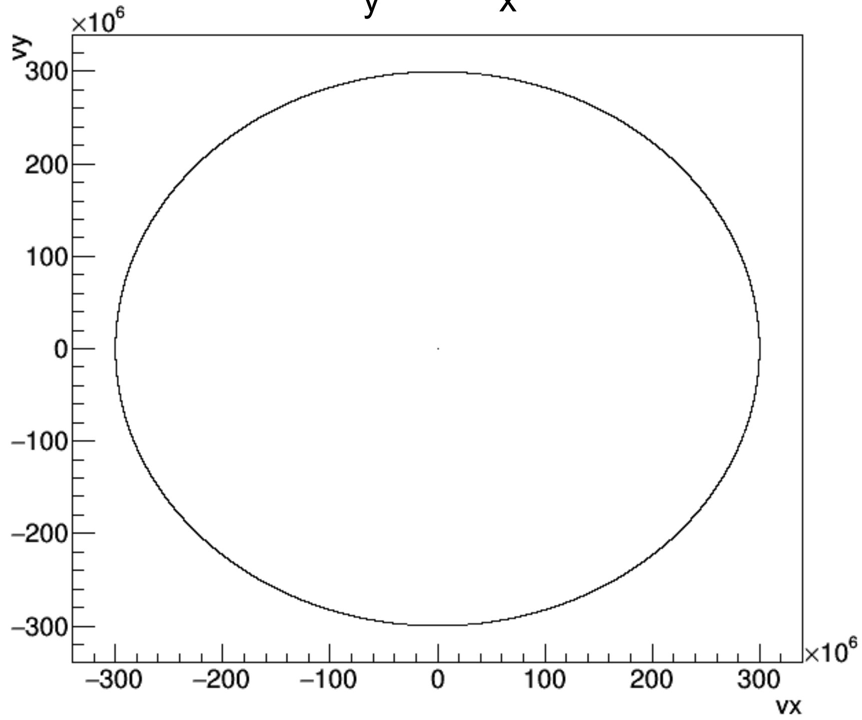
GPU Error Testing

- 10 GeV proton in **uniform** field ($|B_{Earth}|$ ~30μT) over >10^4 orbits
- Orbit phase may deviate with Boris step

Energy vs Simulation Time

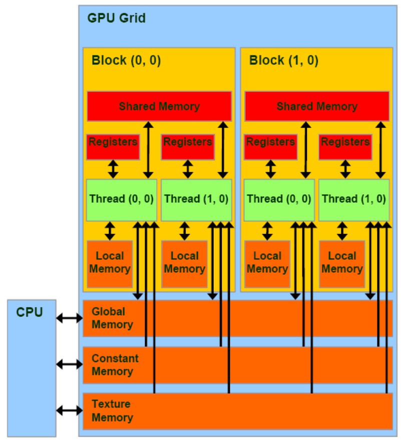


V_y vs V_x



Number of Issues to Solve

- Form of Bfield
  - Tables: GPU’s have limited storage capacity (~1 Gb)
  - Turbulence: random number generation difficult
- Verification of truncation errors for long integration periods
- But the speedups are worth it!
- Don’t want to re-invent, looking to collaborate



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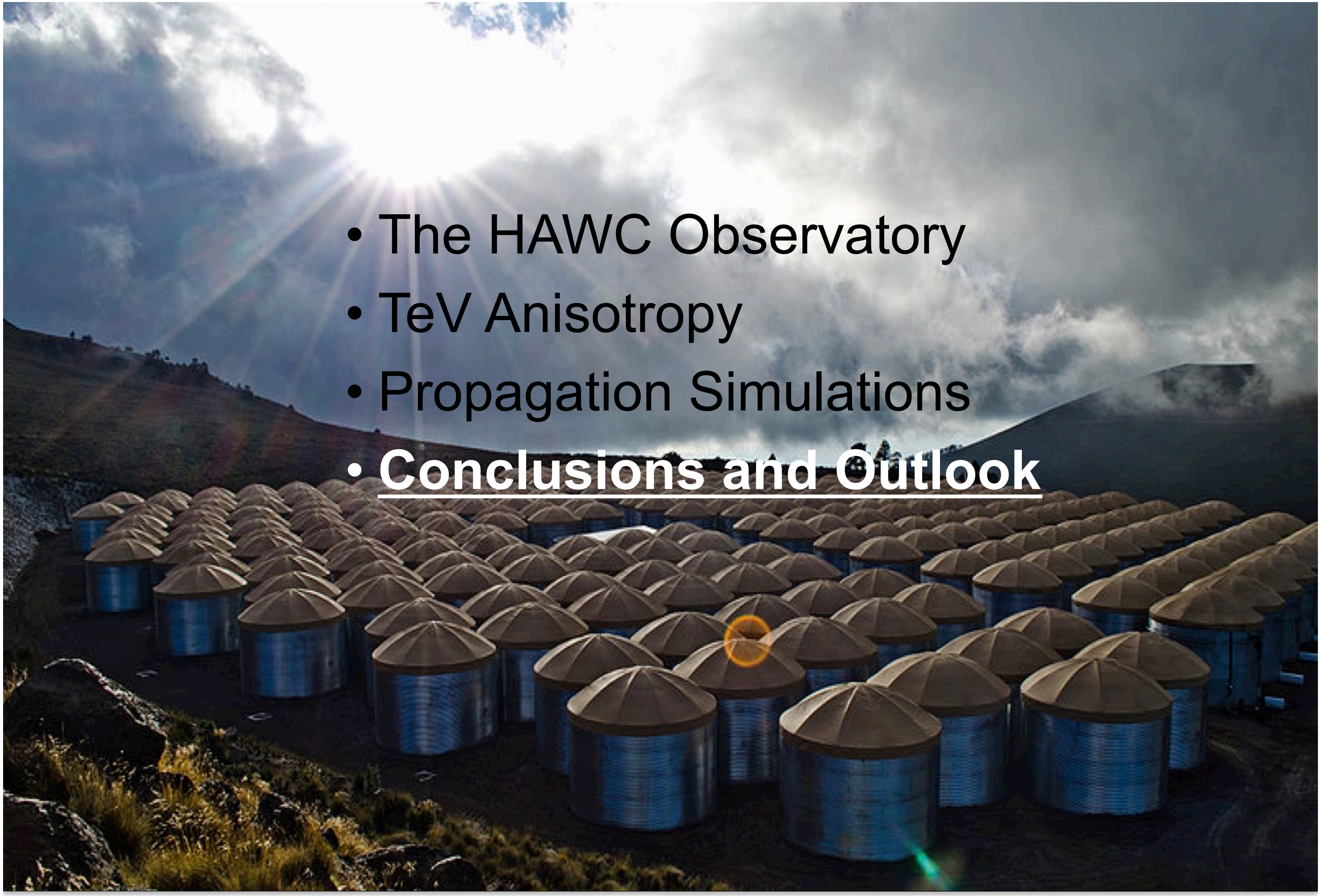
• The HAWC Observatory
• TeV Anisotropy
• Propagation Simulations
• Conclusions and Outlook

Conclusions

- HAWC is versatile TeV instrument, 1 billion events / day
- Improving upon and extending TeV studies
- Small-Scale Anisotropy
    - Region A significant excess up to 26 TeV
    - Constrained energy spectrum
- Large-Scale Anisotropy
    - Preliminary results consistent E<100 TeV
    - Updated maps coming soon including publication
- GPU cosmic-ray propagation routine
    - Promising speedups with symplectic / explicit method
    - Looking to collaborate

Thank you for your time and space!