Preliminary Cosmic Ray Results from the HAWC's Eye Telescopes

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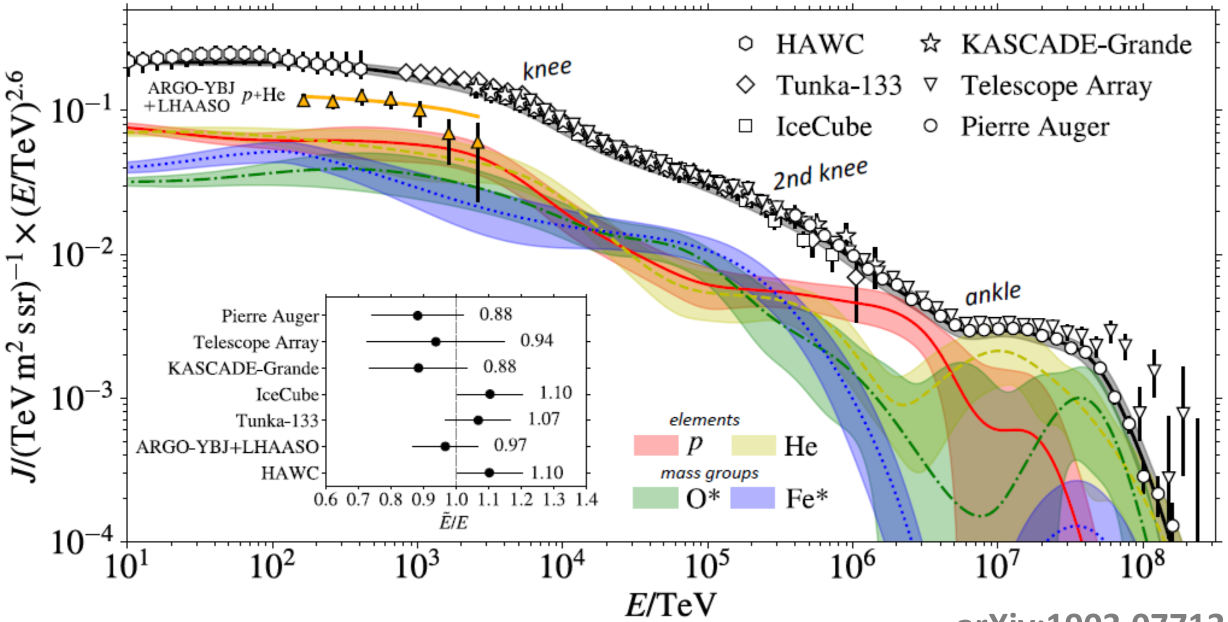
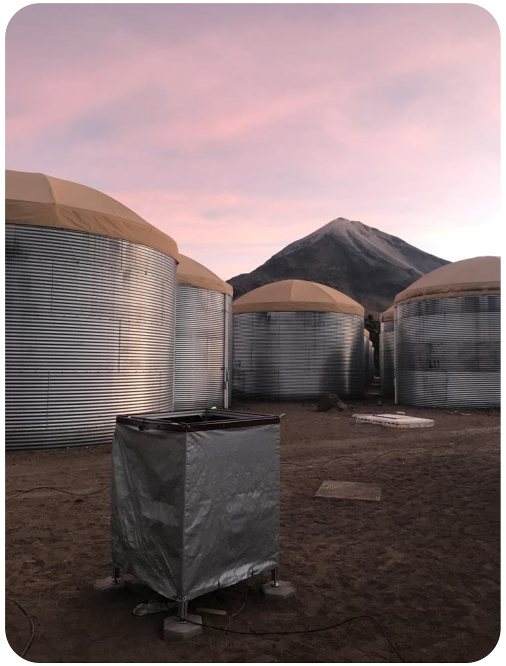
Introduction

- **Cosmic ray spectrum**
  - Sources & acceleration mechanisms → Composition & spectral features
  - 100 TeV-range: ground-based detector arrays & atmospheric Cherenkov telescopes



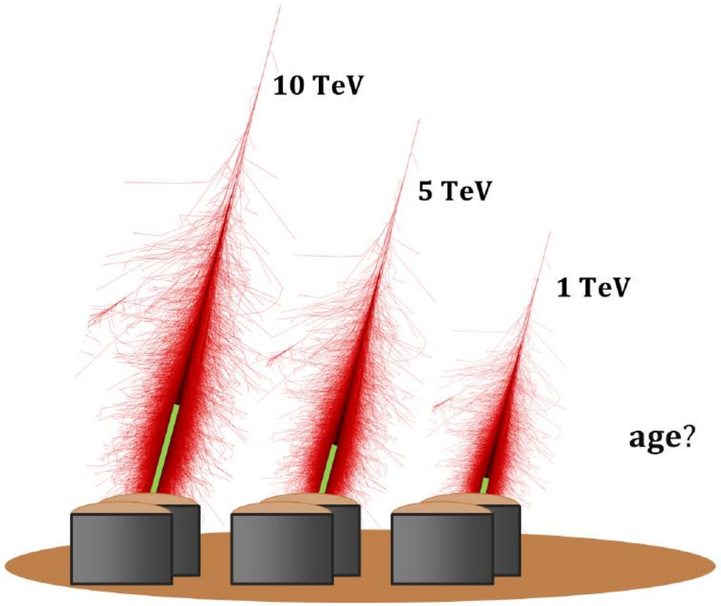
arXiv:1903.07713

1) HAWC's Eye telescopes as an extension of the HAWC observatory
2) Performance of the hybrid configuration
3) Cosmic ray measurement campaign (2019)
4) Results – Cosmic Ray Spectrum



20.12.2019

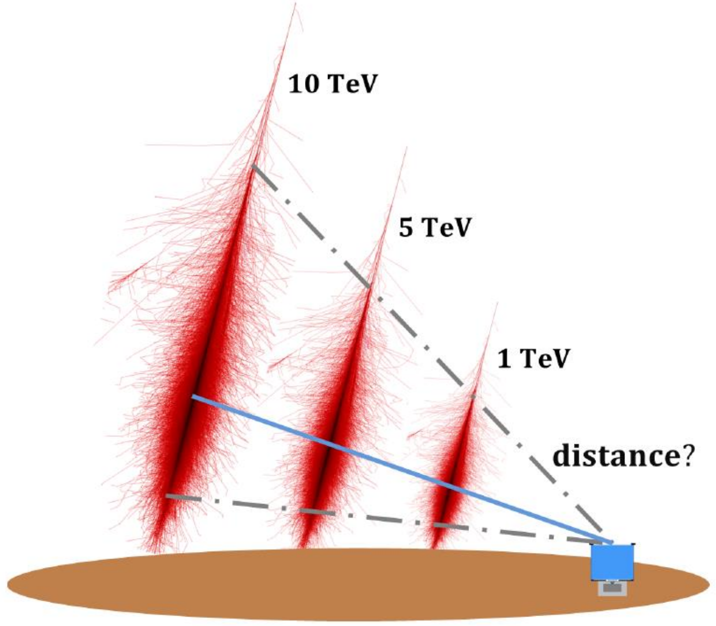
Hybrid Detection of Air Showers



Extensive Air Shower Array

Measurement of shower particles on ground

- Good shower core reconstruction
- Ambiguous shower age



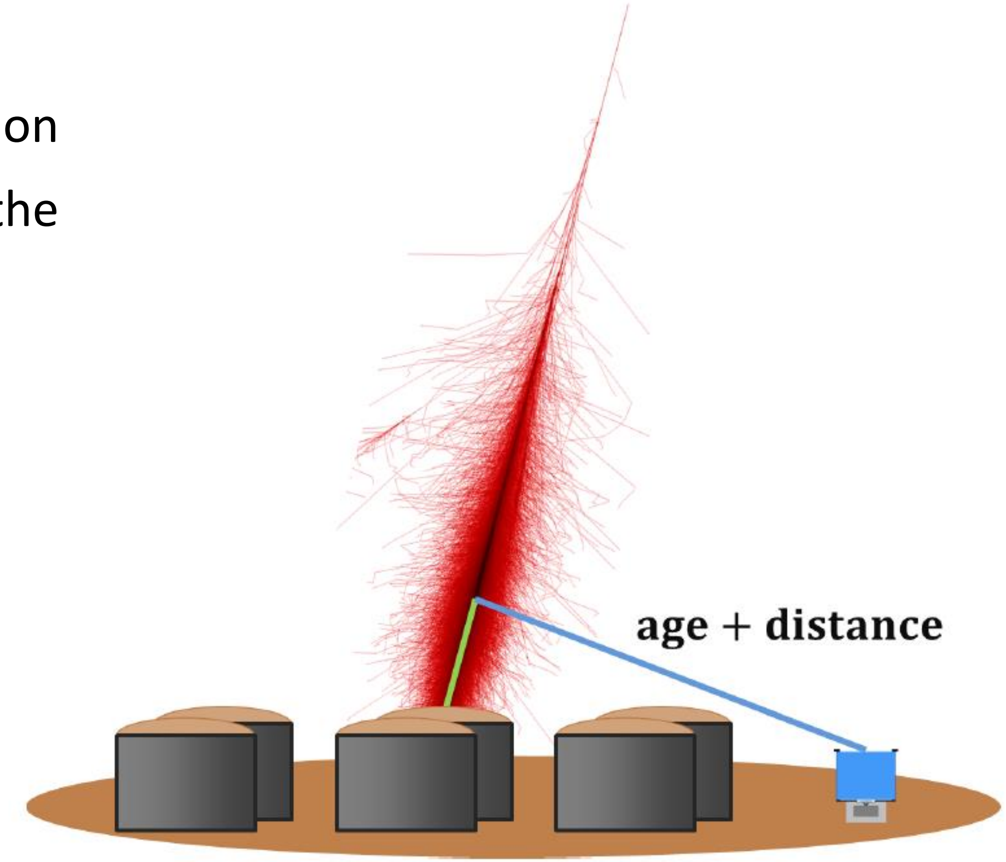
Imaging Air-Cherenkov Telescope (IACT)

Measurement of shower development through atmosphere

- Good shower age reconstruction
- Ambiguous shower core position

Hybrid Detection of Air Showers

- Combination of complementary information
- Cross-calibration and characterization of the individual detectors
- Improved performance:
  - Energy resolution
  - Angular resolution
  - Gamma/Hadron separation



HAWC - High Altitude Water Cherenkov Gamma-Ray Observatory

- 300 WCDs (200,000 L of purified water)
- Area: 22,000 m^2
- Altitude: 4100 m (Sierra Negra, Mexico)
- Energy range: 100 GeV – 100 TeV
- Field of view: 2 sr (15% sky coverage)

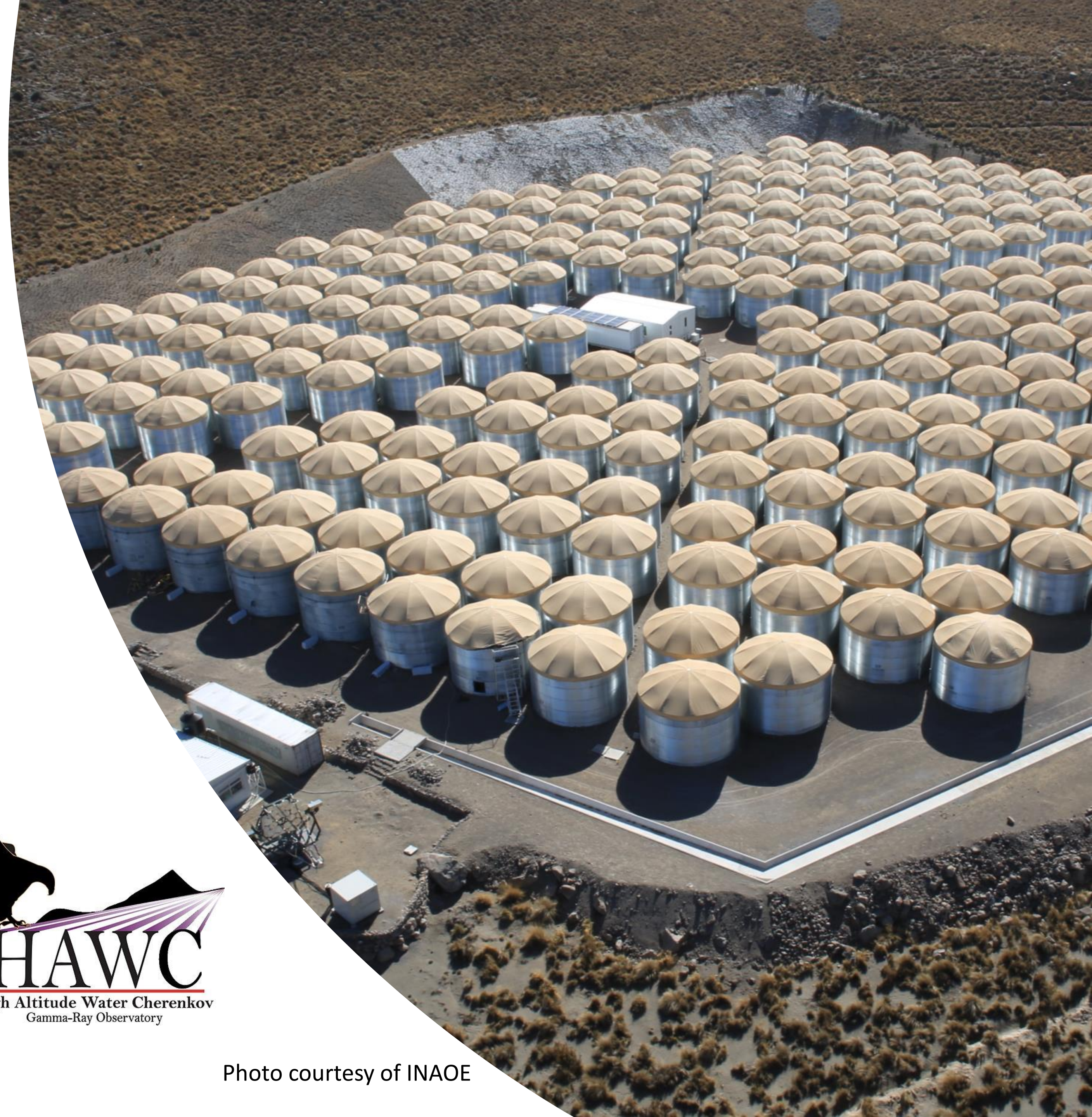
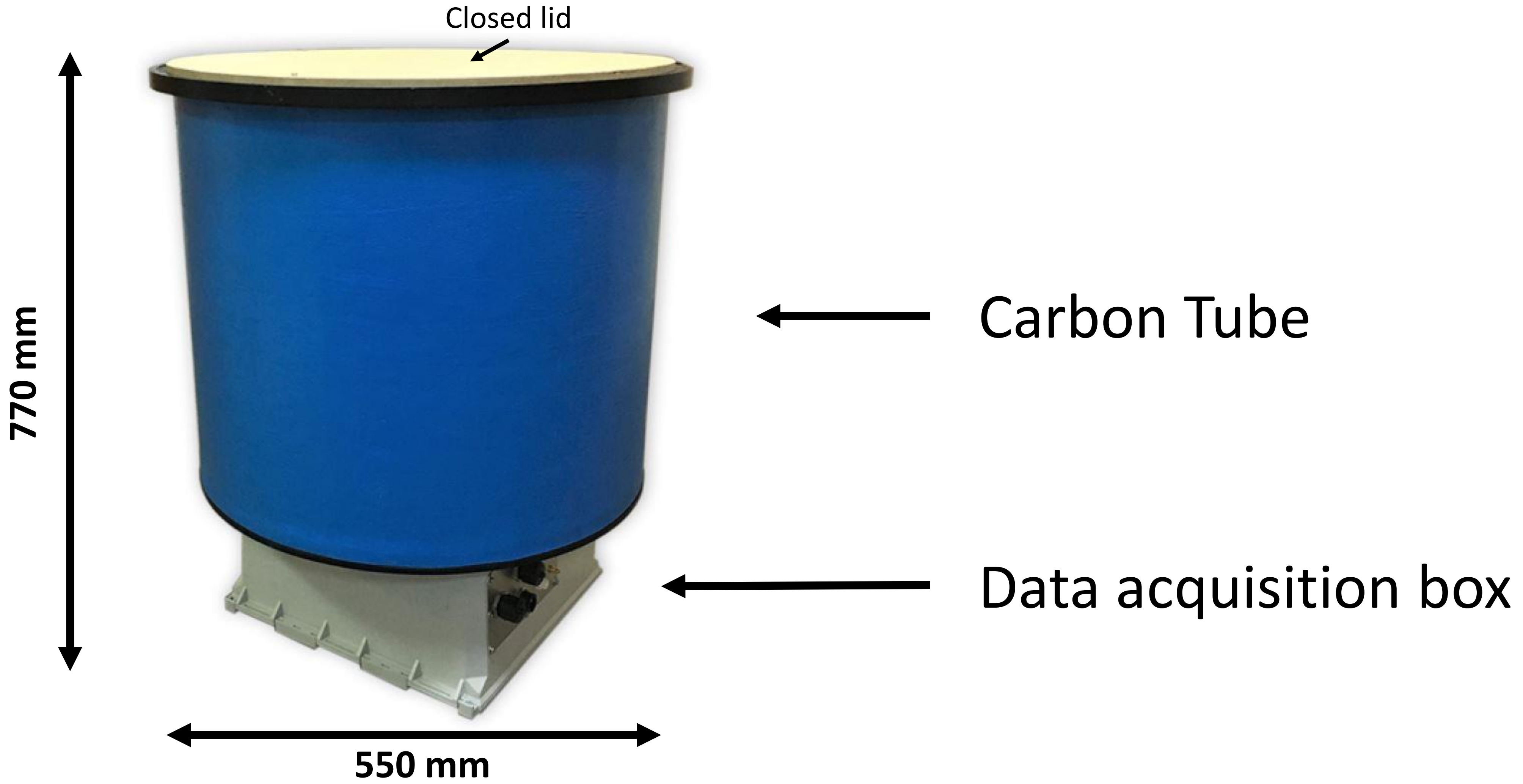


Photo courtesy of INAOE

The HAWC's Eye Telescope



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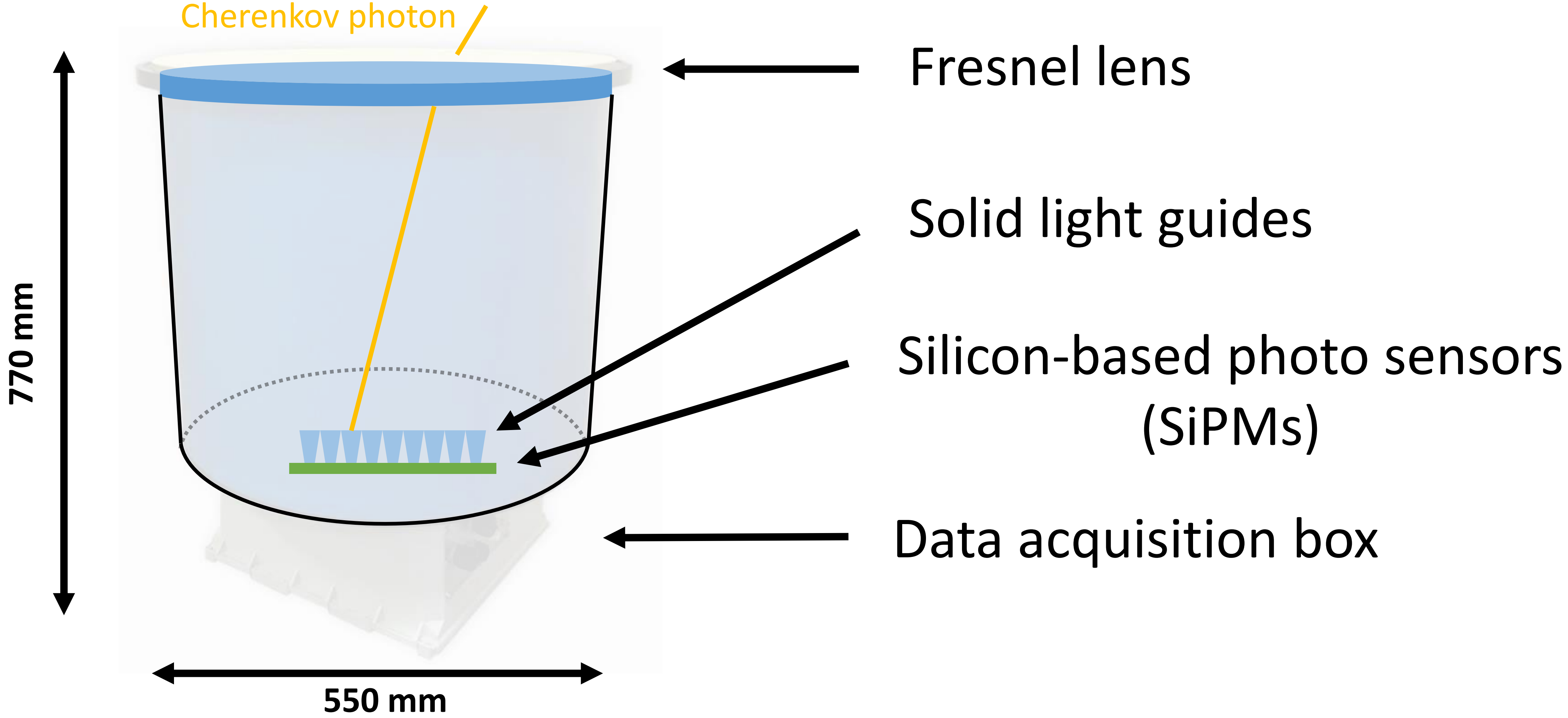

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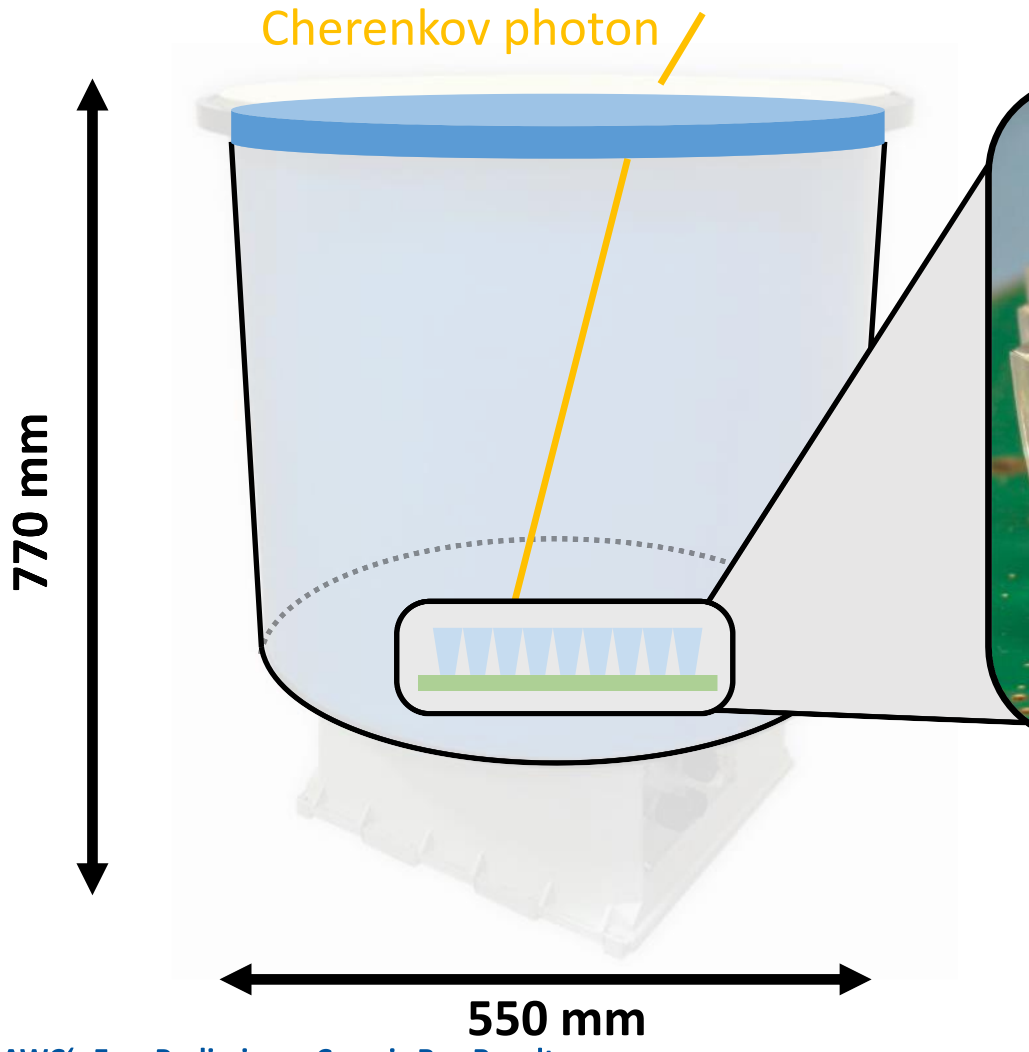
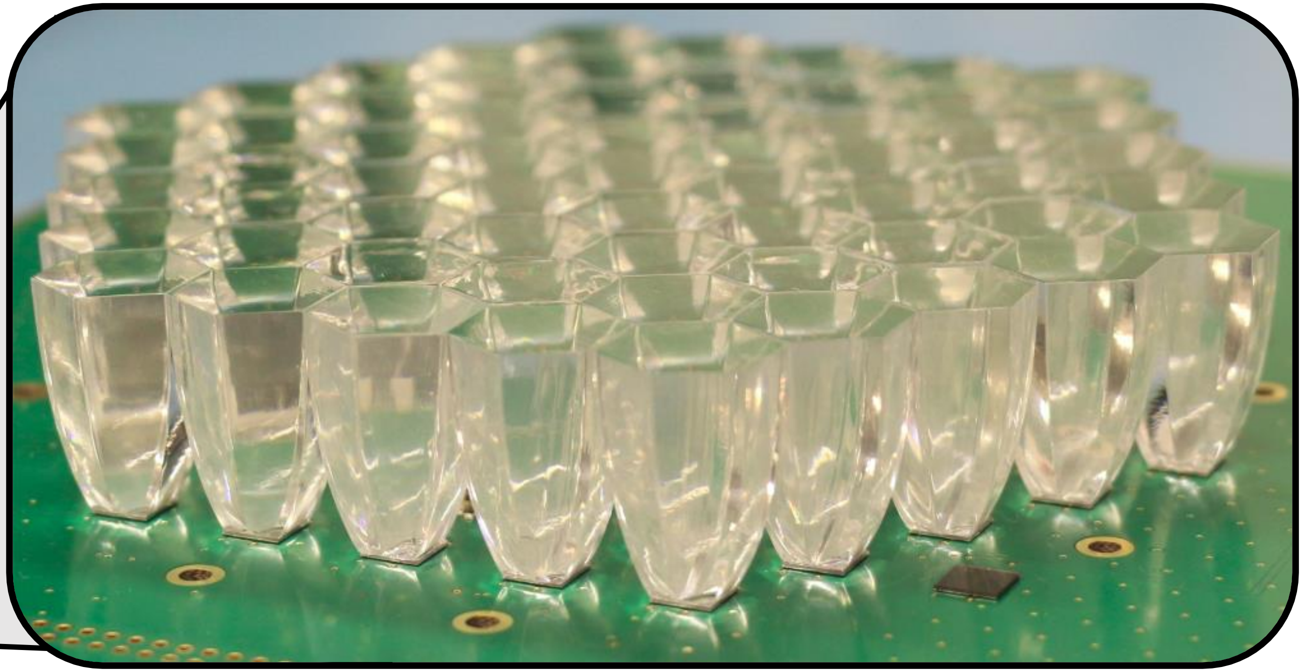
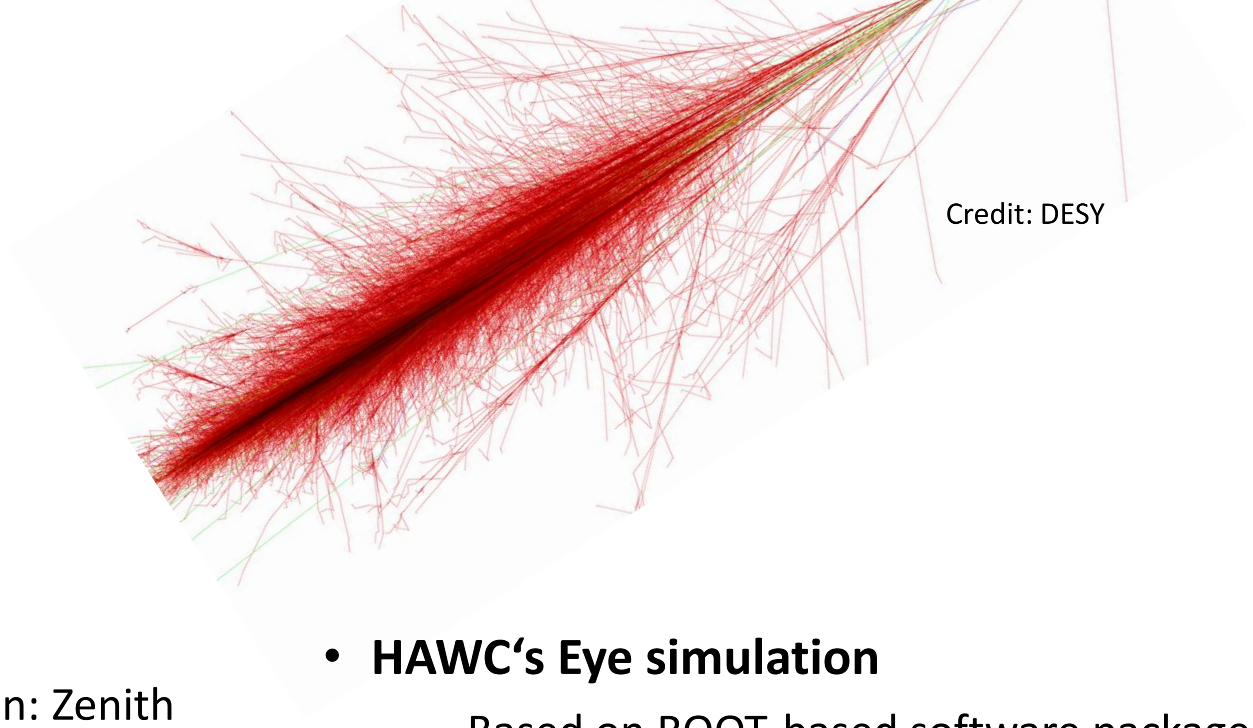




- 61 SiPMs equipped with solid light guides
- 3 SiPMs for calibration and monitoring purposes

Simulation


Credit: DESY

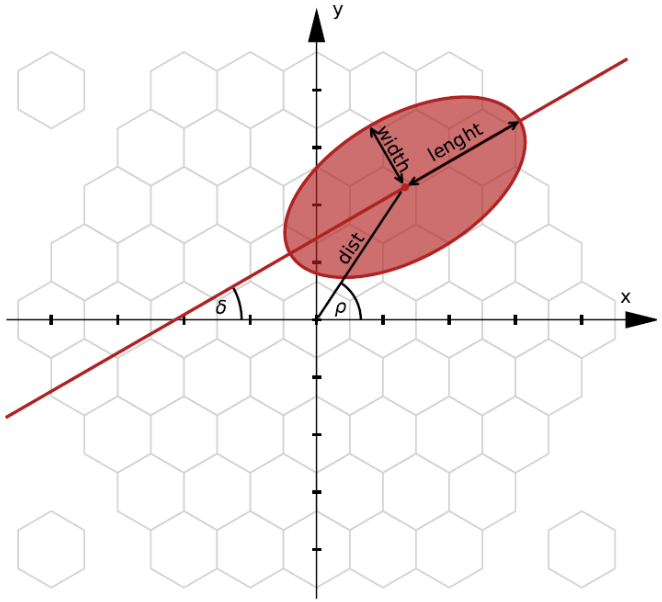
- **Air shower simulation (CORSIKA)**
  - 362,000 proton showers
  - Spectral index: -1.5
  - Energy range: 1 TeV – 100 TeV
  - View Cone: 8° → Pointing direction: Zenith
  - Area: 500 x 500 m^2

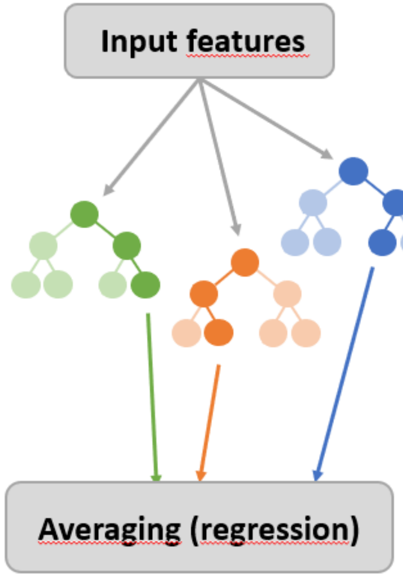
- **HAWC simulation**
  - Based on software package HAWCsim
  - Standard HAWC event selection cuts

- **HAWC's Eye simulation**
  - Based on ROOT-based software package MARS
  - Ray-tracing of Cherenkov photons and complete simulation of electronics (SiPMs, trigger, DAQ)
  - Absorption and reflection inside telescope
  - Photon detection efficiency of SiPMs
  - Angular acceptance of light guides

Hybrid energy reconstruction

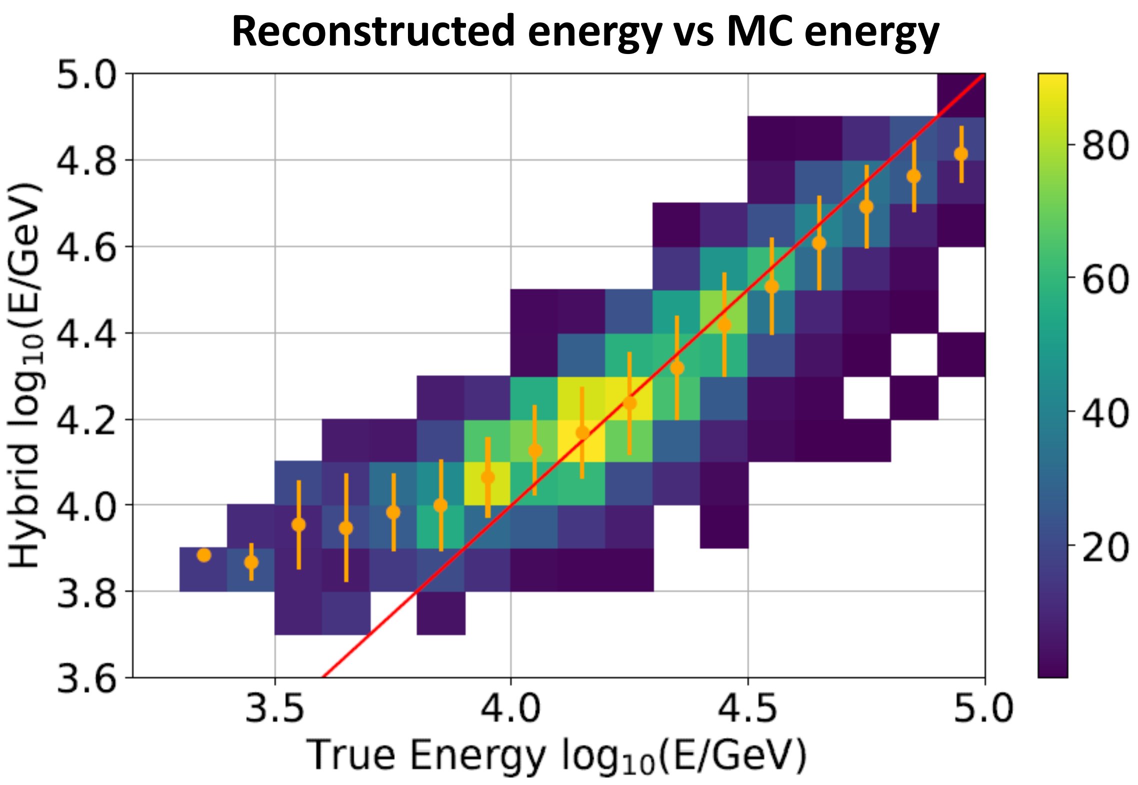
- **HAWC‘s Eye (IACT standard reconstruction)**
  - Images cleaned from night sky background
  - Cleaned signal distribution statistically analyzed and represented by a set of statistical parameters
- **HAWC (standard reconstruction)**
  - Event reconstruction using the software framework AERIE
  - Reconstruction of shower core and energy
- **Combined energy reconstruction**
  - Random Forest: machine learning algortithm based on ensemble of decision trees
  - Input features: HAWC‘s Eye image parameters + HAWC reconstruction parameters
- **In the following:**
  - HAWC reconstruction: Hybrid triggered events, only HAWC reconstruction used
  - Hybrid reconstruction: Hybrid triggered events, HAWC‘s Eye + HAWC used





Hybrid energy reconstruction

- Distribution re-weighted to spectral index $\gamma = -2.7$
- **Edge effects**: Trigger threshold (10 TeV) + limited simulated energy range
- **Energy resolution** in log(E): **0.12 (hybrid), 0.18 (HAWC)**



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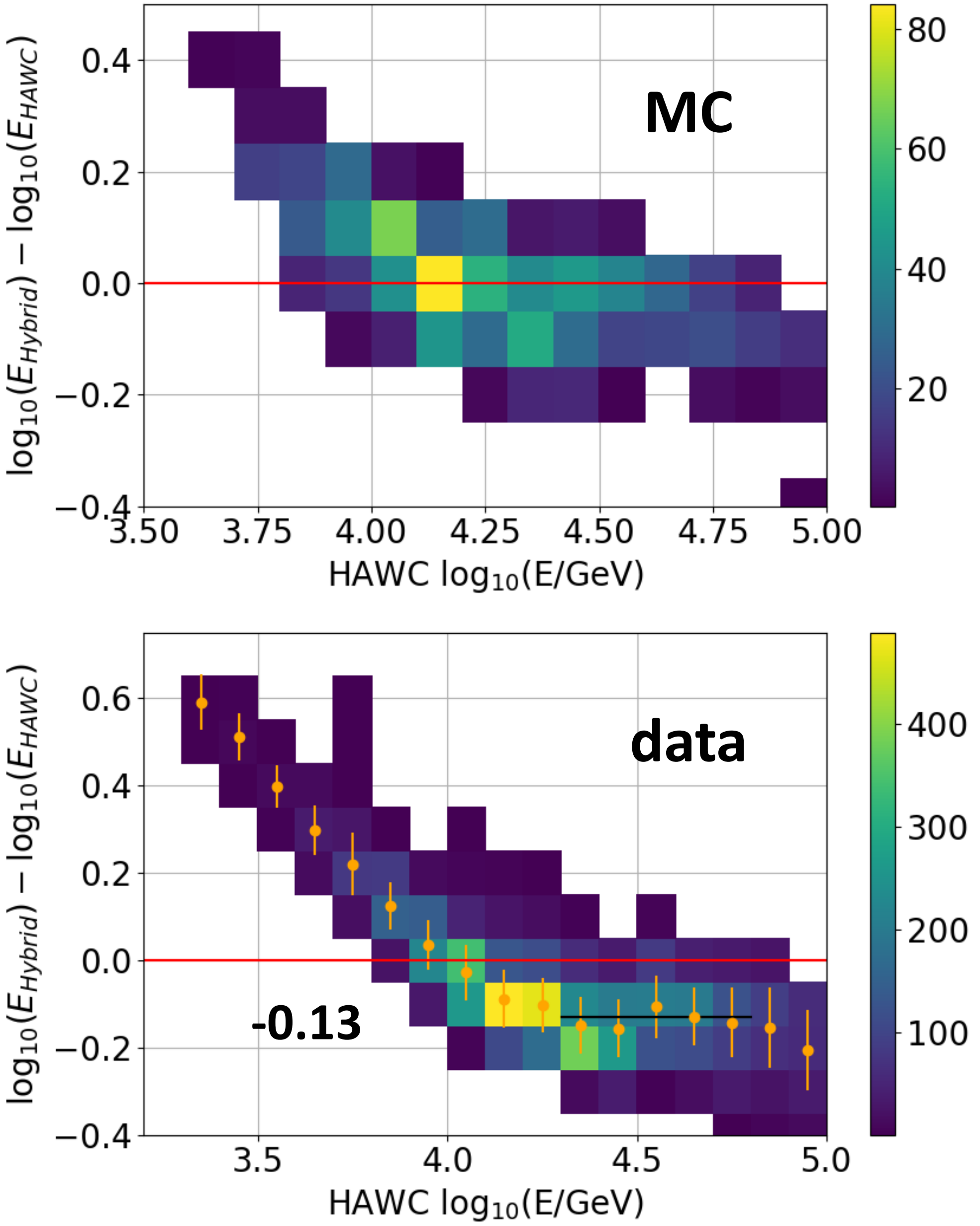
- **Energy resolution** in log(E): **0.12 (hybrid), 0.18 (HAWC)**
- **Upper plot:** HAWC reconstruction algorithm assumes mass composition but only tested with protons
- **Lower plot:** Hybrid reconstruction trained with only protons, but applied to mass composition

→ **systematic bias**

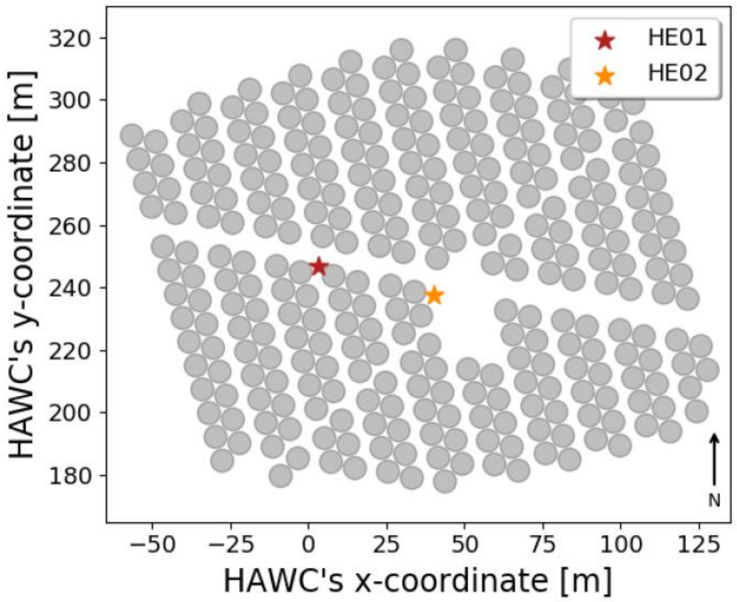
Successful hybrid reconstruction
→ apply to measurements

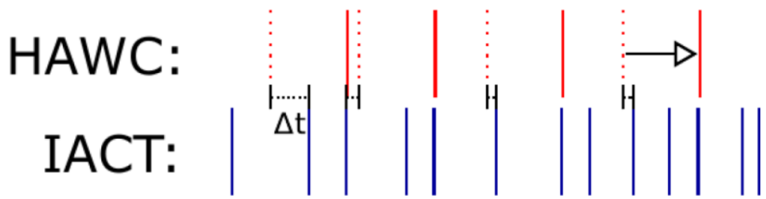
Residual hybrid reco./HAWC reco.



Hybrid Measurement Campaign

- December 2019: measurement campaign with **two telescopes in 40 meters distance**
- Only 2.5 hours of synchronized hybrid data
- **Synchronization** based on comparison of **trigger timestamps**
  - Time window of 100 µs → 10 % random coincidences remain
  - can be removed easily by low energy cut ($N_{tank} > 100$)

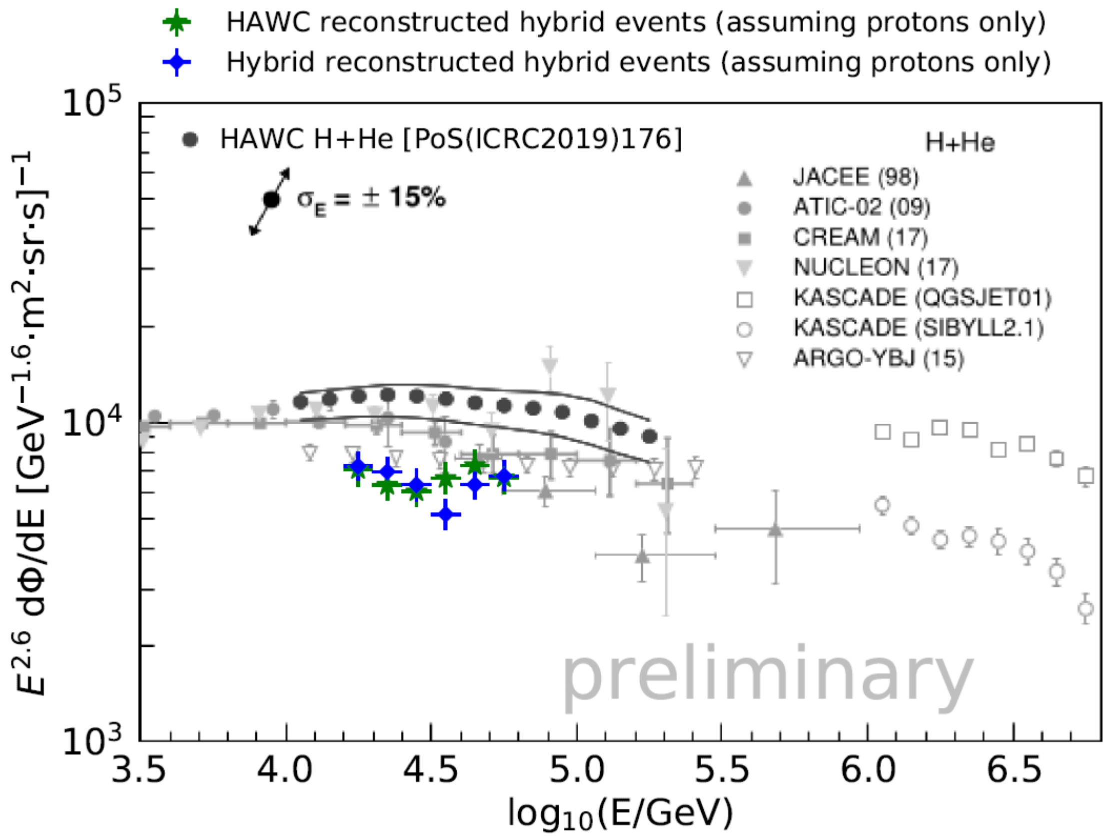




Cosmic Ray Spectrum

- Correct measured flux for detector efficiencies
  → effective aperture
- Hybrid reconstruction shifted by bias (with respect to HAWC) to account for proton-only simulation
- HAWC reconstruction is consistent with hybrid reconstruction
- Possible reasons for systematic shift:
  - Missing heavier components in simulation
  - Non-ideal Corsika configuration

→ **under investigation**



Conclusion

- Improved energy resolution due to hybrid setup
- Further improvements with stereo observation (not shown here)
- Successful hybrid measurements
- Preliminary CR spectrum from 2.5 hours of data

- Flux mismatch under investigation
- Simulation of an array of 55 telescopes ready

J Serna et al., PoS(ICRC2021)765