From Prototype to Performance: Scintillation detectors of the IceCube Surface Array Enhancement

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15.1.26

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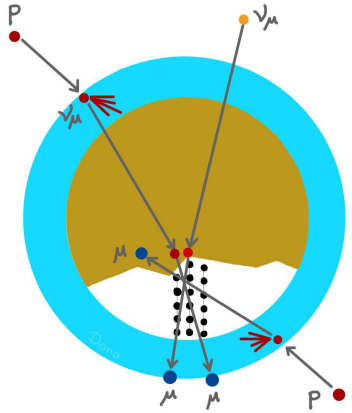
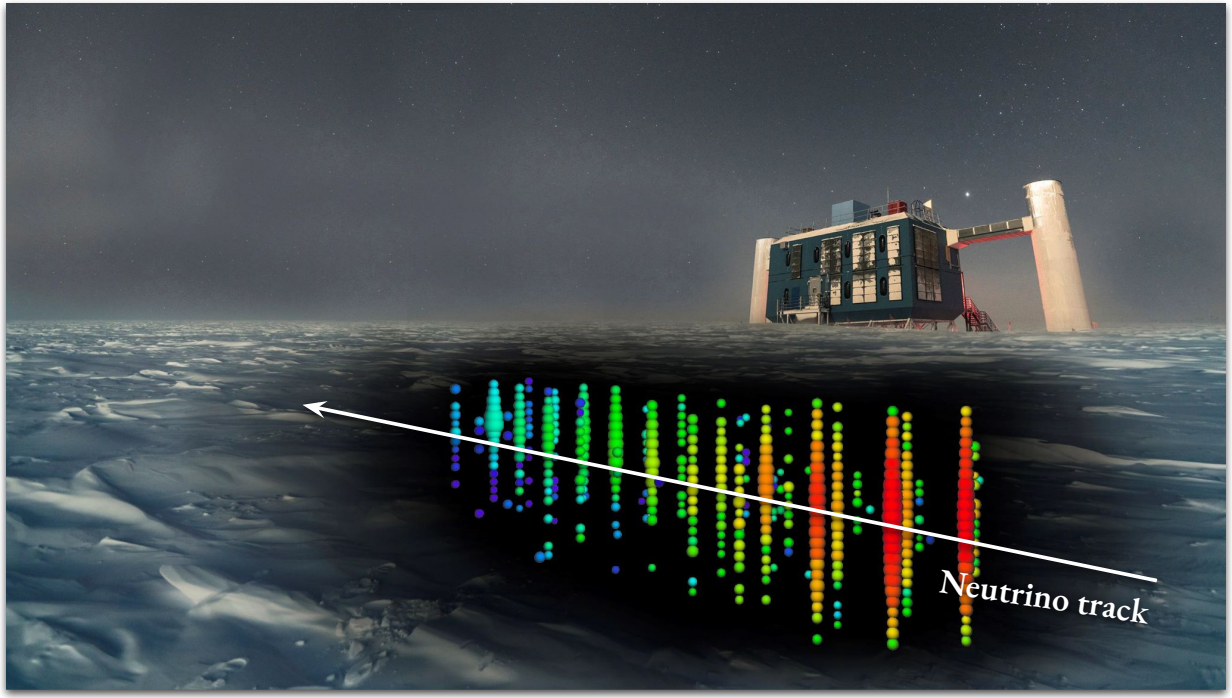
IceCube Neutrino Observatory

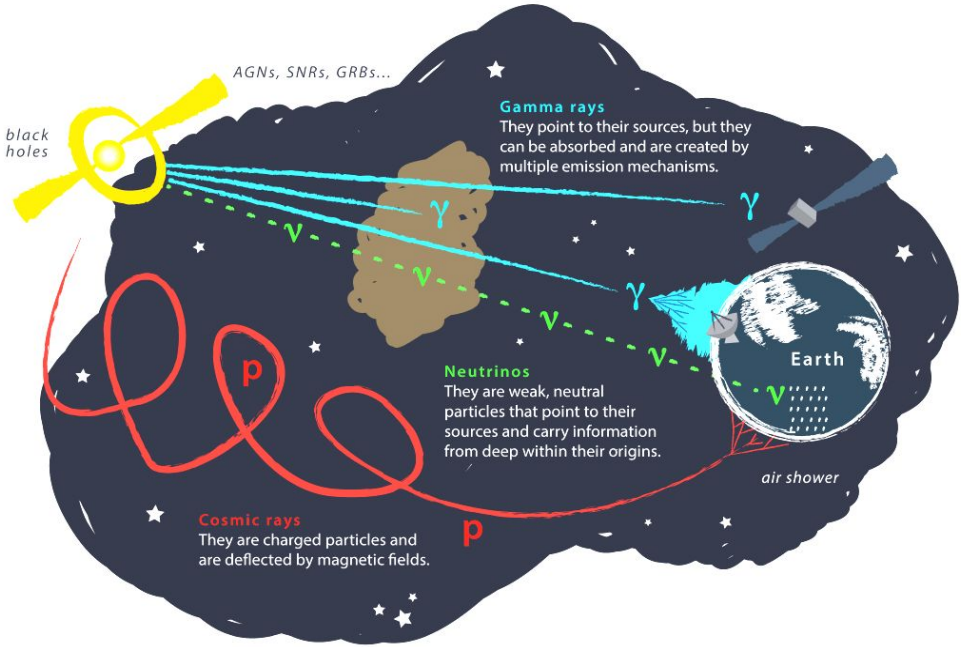
Neutrino Detection with IceCube

Signal: Astrophysical neutrinos
Background: Atmospheric neutrinos and muons (99.999% of IceCube data)



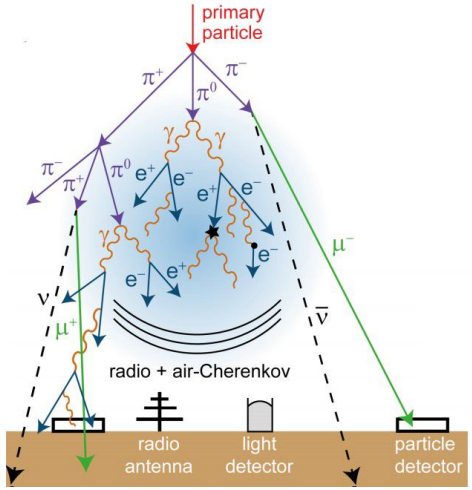


What is the origin of this background?



Cosmic Rays:

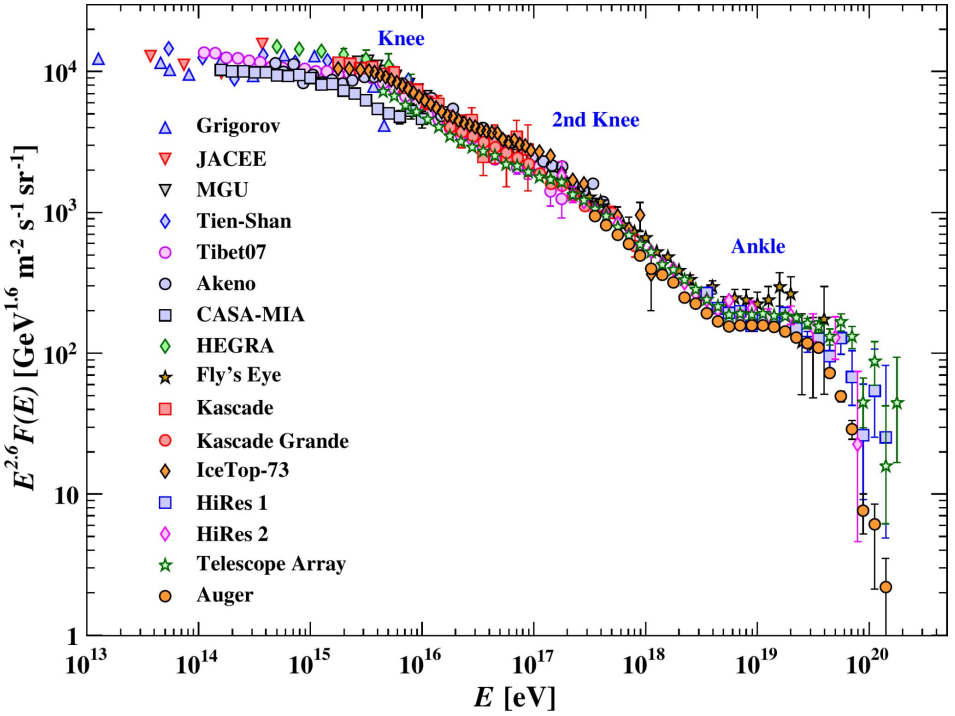
- High-energy charged particles
- ~90% protons, ~9% He nuclei and rest heavy nuclei and electrons, positrons
- Diffuse by interstellar magnetic field. On entering Earth's atmosphere lead to **Extensive Air Showers (EAS)**



Cosmic-ray spectrum

Why study Cosmic-rays?

- Probe particle acceleration & propagation in the Galaxy
- Sensitive to extreme astrophysical environments
- Key observables:
  - energy spectrum
  - mass composition
  - Anisotropy
  - multi-messenger links



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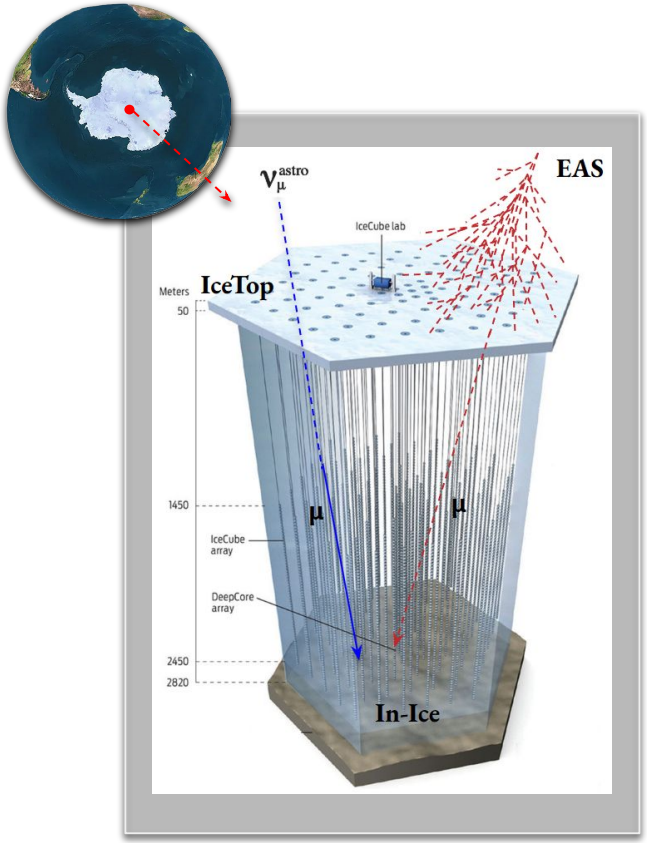
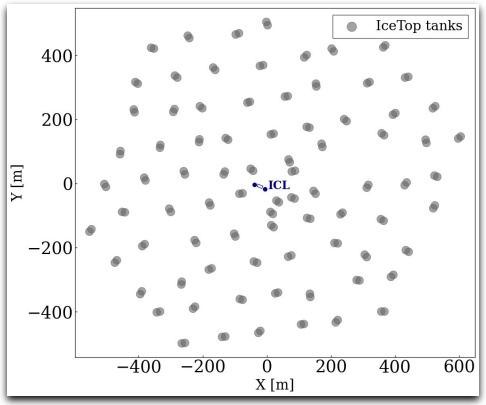
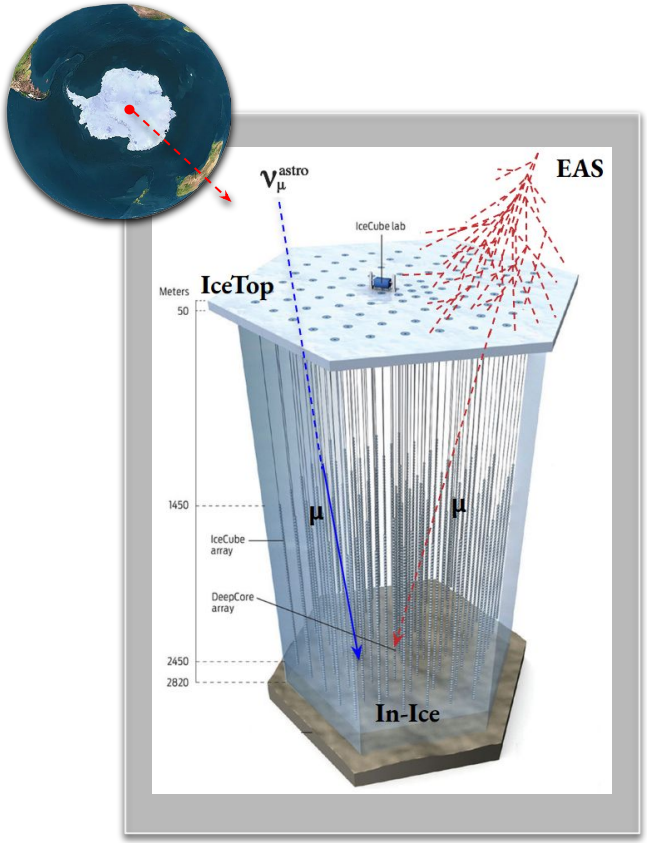


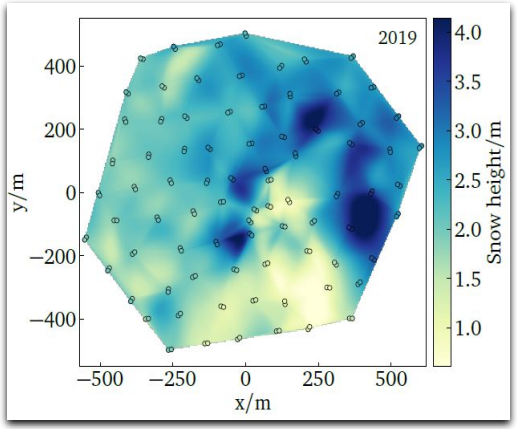


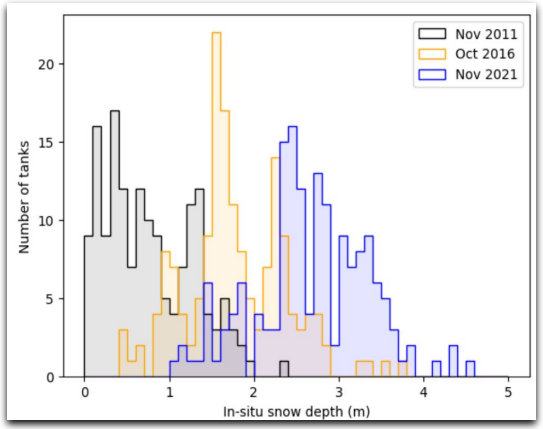
Surface Array: IceTop

- **Veto** against atmospheric background
- In-Ice background → IceTop signal: **Cosmic-Ray studies** in few PeV to EeV range

IceTop: Challenges with snow





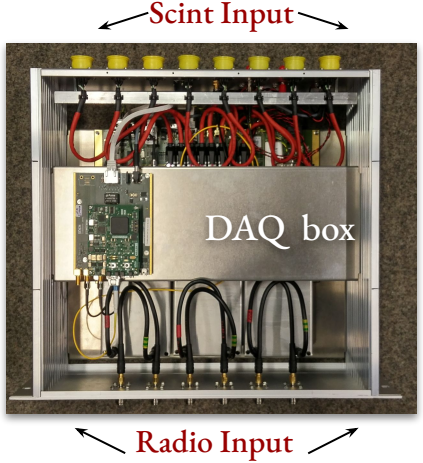


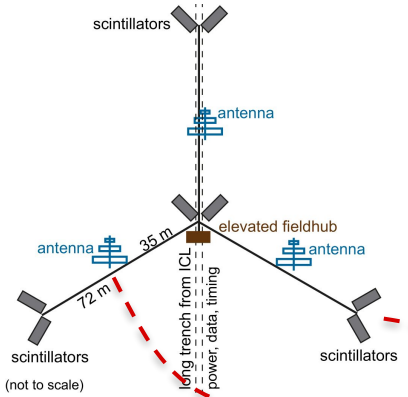
- Detector placement too sparse
- Non-uniform snow accumulation → signal attenuation:
  - increased threshold
  - Increased uncertainties

NEED FOR A BETTER VETO!

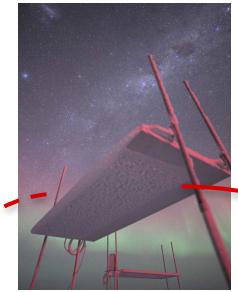
Surface Array Enhancement (SAE)

- Enhance IceTop array with 32 **hybrid elevatable detector stations**, each comprising:
  - 8 scintillation detectors
  - 3 radio antennas
  - 1 hybrid DAQ
- Radio Antennas triggered by scintillators
- Time synchronization by White Rabbit protocol

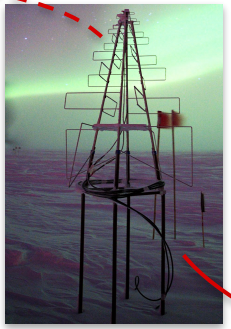




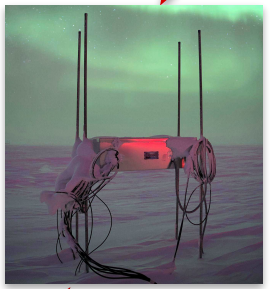
8 x Scintillation detector



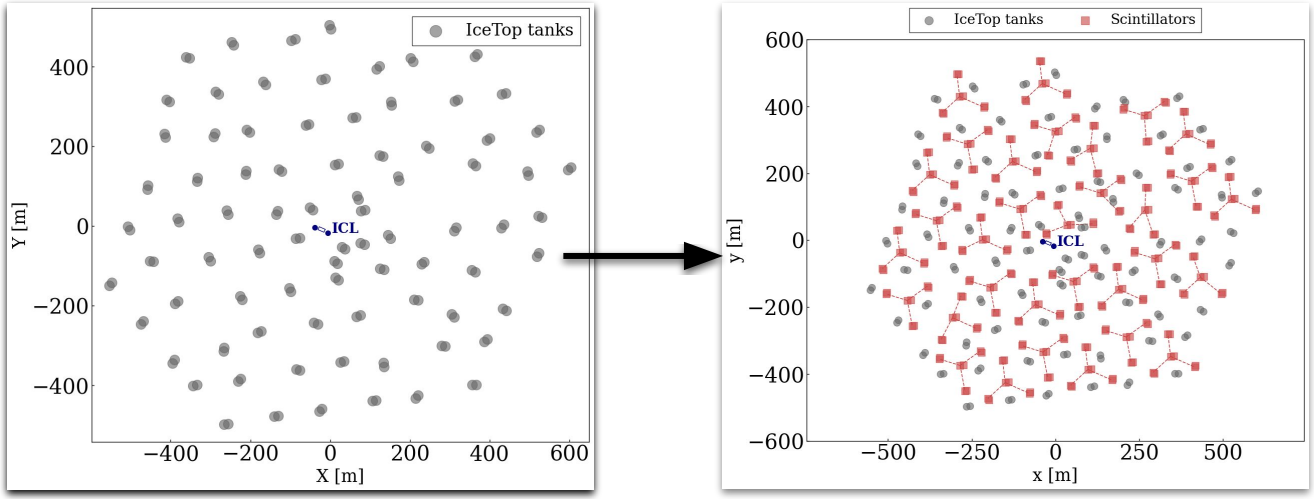
3 x Radio detector



Fieldhub



Surface Array Enhancement (SAE)

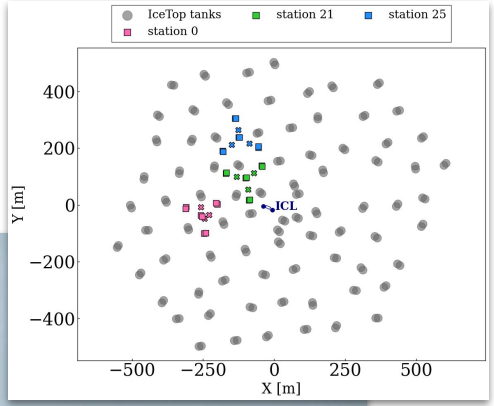


- Enhance IceTop array with **32 SAE stations.** Scintillator science cases:
  - *Improve veto for in-ice and lower detection threshold*
  - *Improve air shower reconstruction*
  - *Facilitate mass discrimination by independent detection channel*
  - *Snow monitoring and mitigation for IceTop*

SAE: Current Status

3 full stations deployed

- Prototype Station (2020) → **Station 0** (2023): First final configuration station
- **Station 21, 25** (2025): under commissioning



Note: *This talk focuses mainly on Station 0*

From Assembly to Insight: Detection of CRs

1 Production

- Component testing
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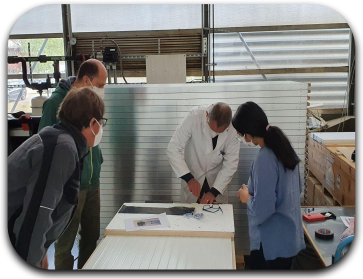
- Module Characterization

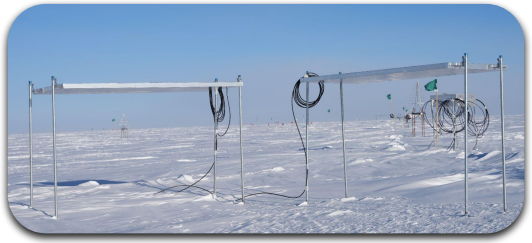
2 Data Preparation

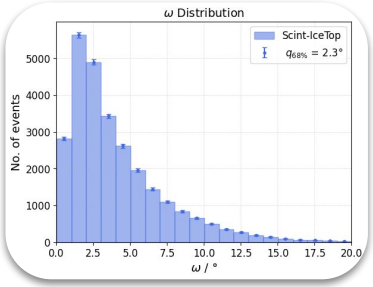
- Data Processing Pipeline
  - Calibration
  - Reconstruction

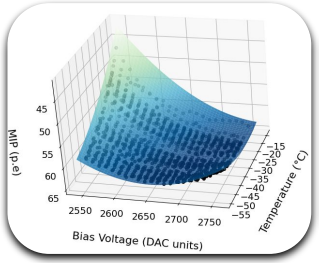
3 Performance

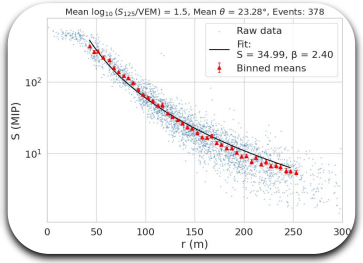
- Data Selection
- Benchmarking with respect to data / simulations

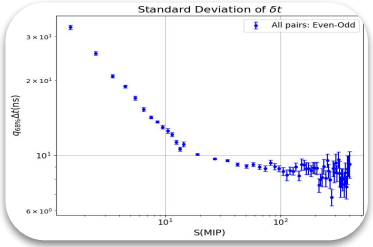












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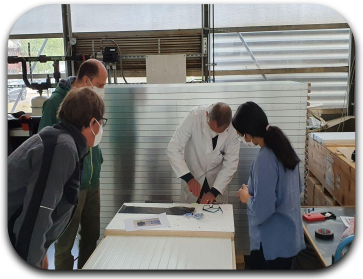
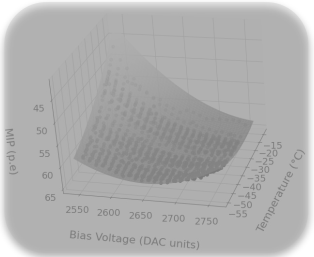
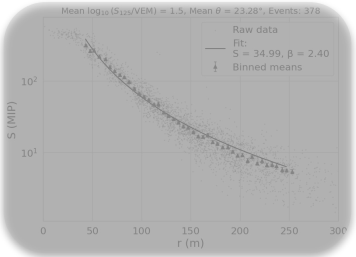
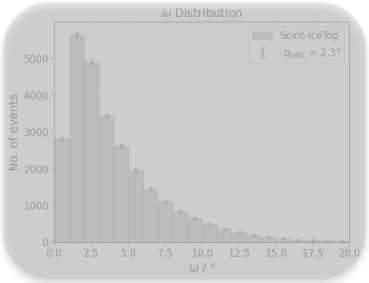
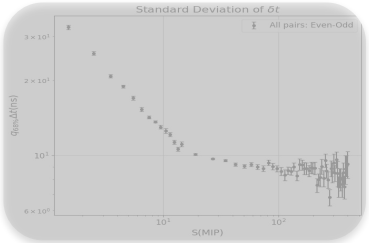






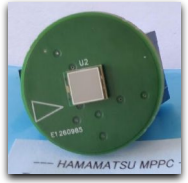




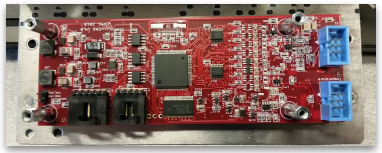
Scintillation Detectors

Minimally Ionising Particle (MIP)

Inlay: Scintillators with wavelength shifting optical fibres

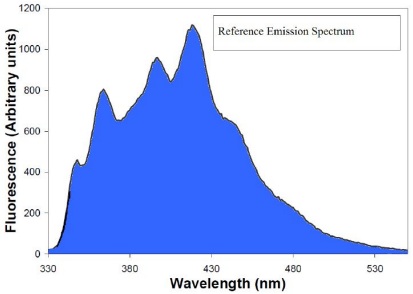


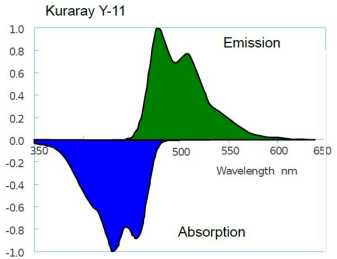
Photosensor: SiPM

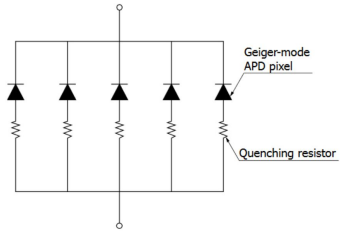


Readout board uDAQ: 3 channels

-16 plastic scintillator bars
- Wavelength shifting for readout by photosensor





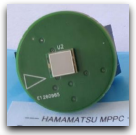


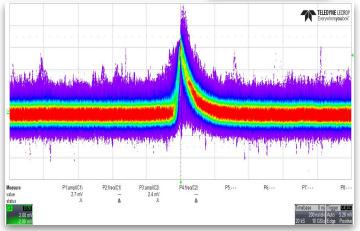
- 6 x 6 mm^2 sensitive area
- 57600 microcells, 25μm pitch
- Gain is inversely proportional to temperature

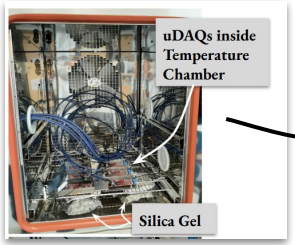
- microprocessor based readout board
- 3 gain channels for wide dynamic range
- Integrated signal output

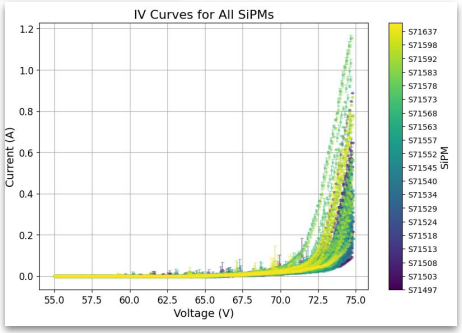
Production Chain

Component validation

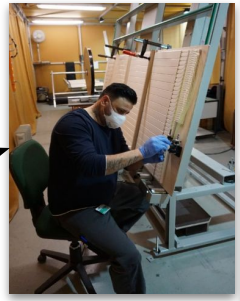








Mechanical Assembly

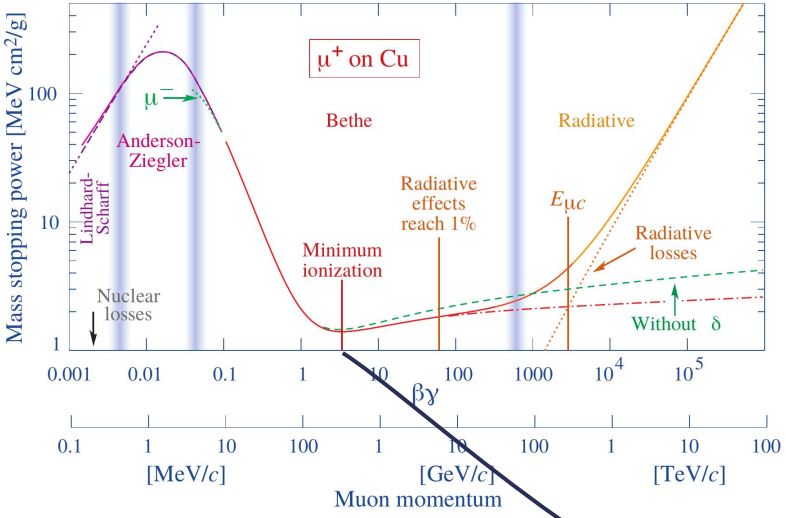


Ready for characterisation

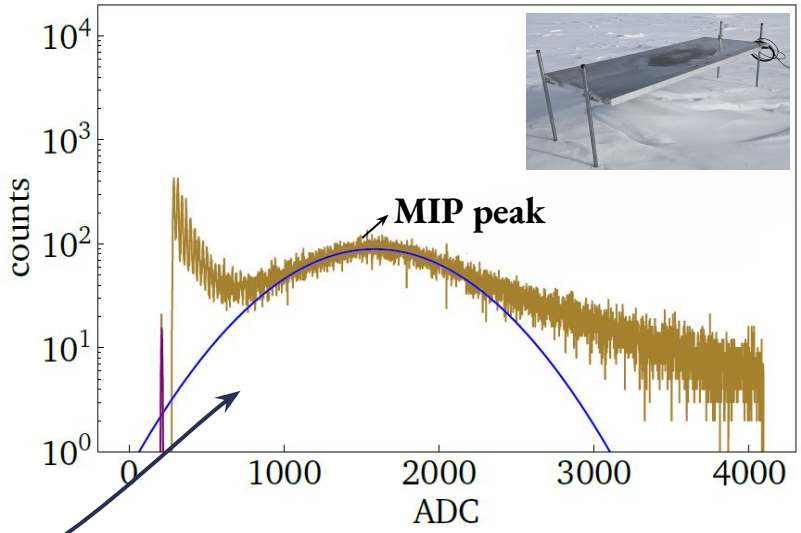
Total 99 panels produced

Scintillator panel validation

The characteristic MIP peak in the charge spectrum can be used for validation



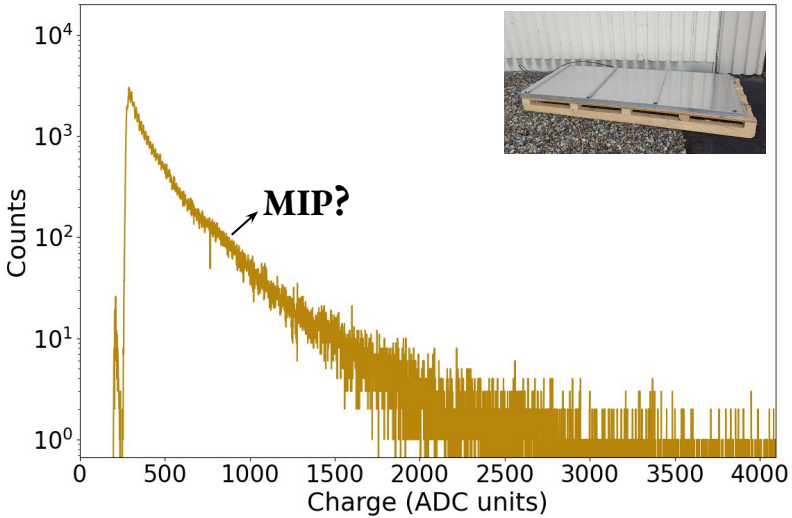
Prototype Scintillator (2020)



Measured at South Pole (-50°C)

Validation at KIT

New Scintillator (2021)



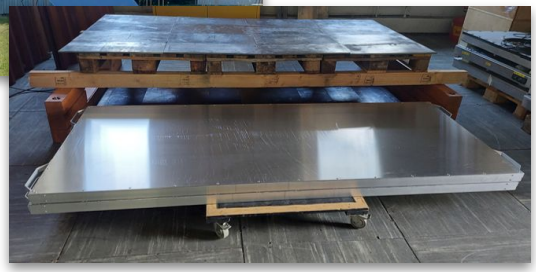
Measured at KIT (22°C)

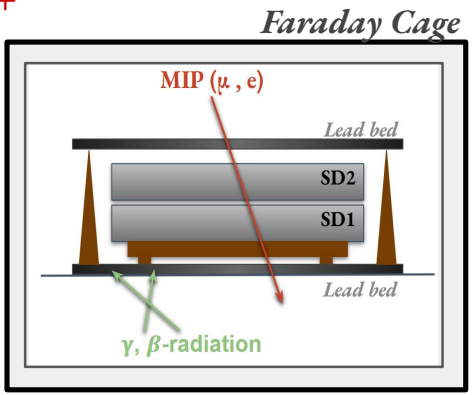
Vastly varying conditions from the South Pole

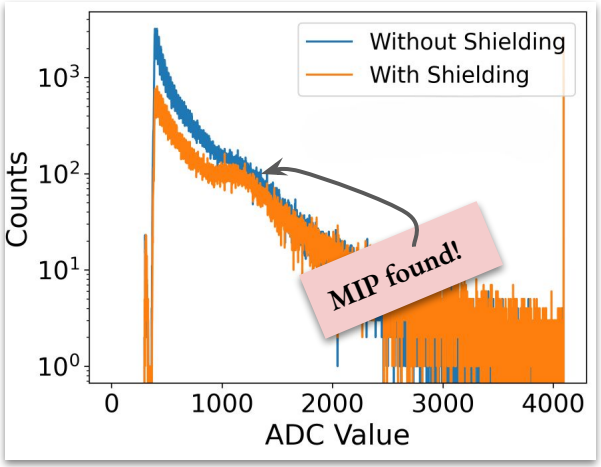
	South Pole	**Karlsruhe**
Temperature Range	-18 to -70°C	-1 to 26°C
Altitude	9000 ft	377 ft
Background Contamination	Natural Ice-shielding, limited anthropogenic background	No shielding from Natural radioactivity, High anthropogenic background

Test Bench at KIT

- Culprit: **Natural Radioactivity + Anthropogenic Activity**
- Test bench:
  - Faraday cage
  - Lead shielding



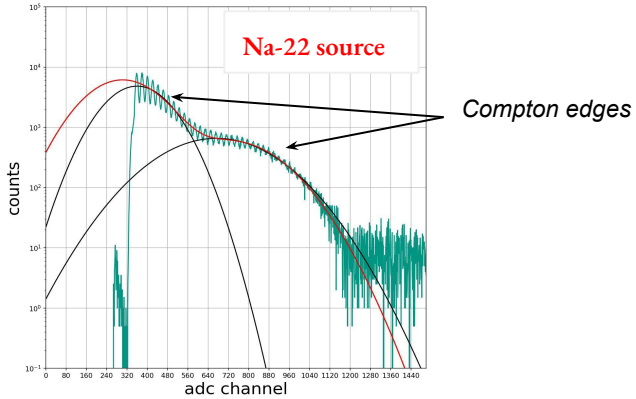


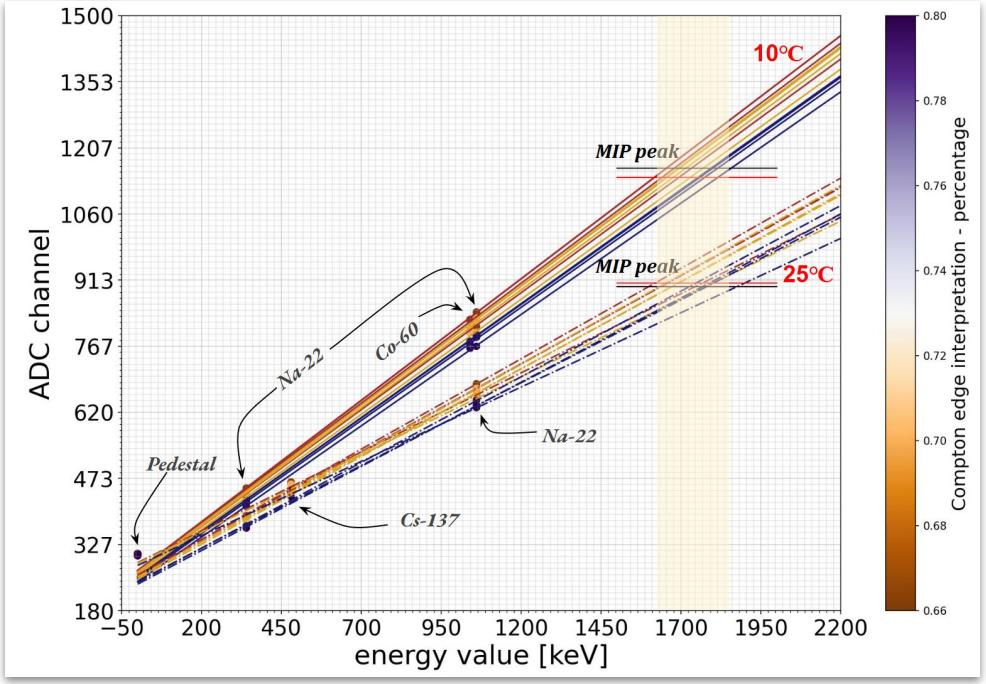


Digital Channel to Energy Calibration

Deposited energy by MIPs using radioactive sources

- Na-22, Co-60 and Cs-137
- Compton edge energy modelled with Gaussians
- 2 sets at 10℃ and 25℃
- **~1.7 MeV measured deposited energy**





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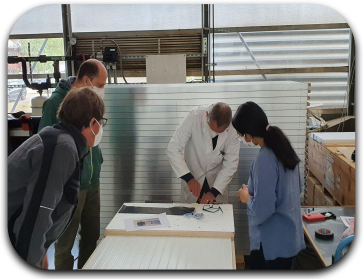
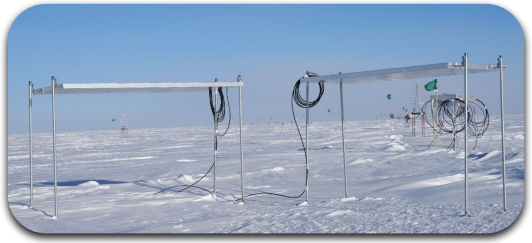
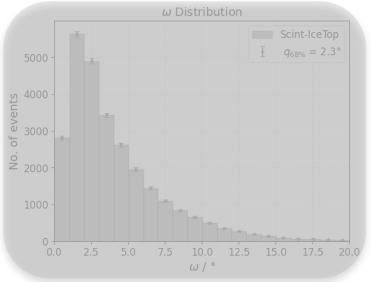
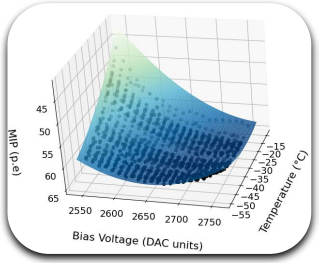
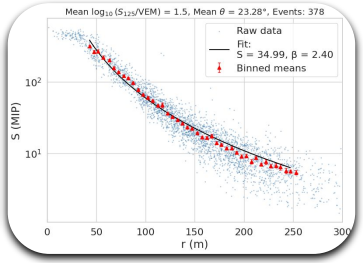
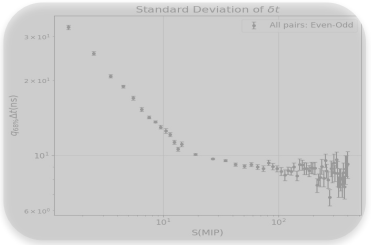






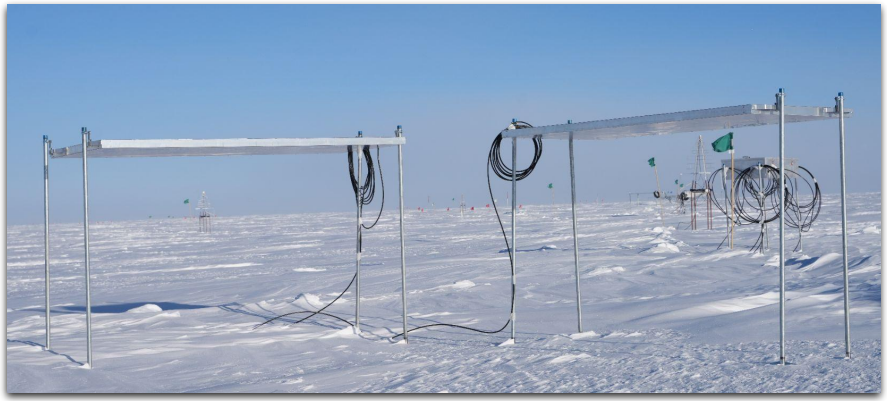


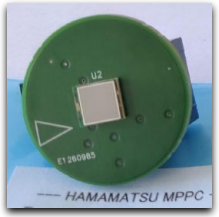


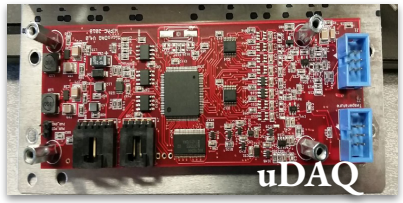


On-Ice Calibration

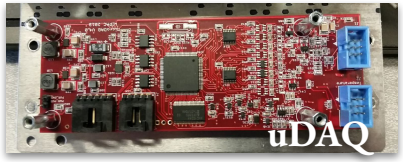
- Commissioning: calibration of detectors post deployment
- Dynamic Range: Depends on both electronic components
  - uDAQ amplification
  - SiPM light yield and PDE
  - Temperature range of operation

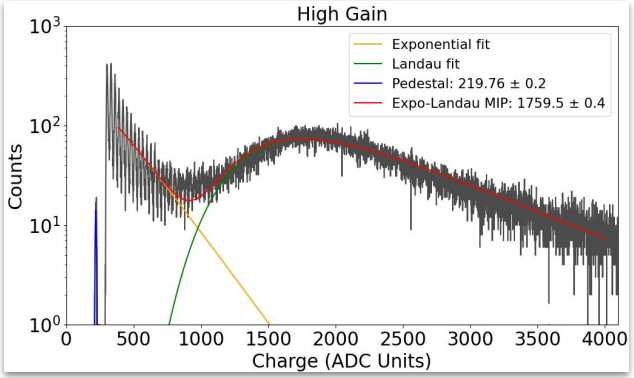


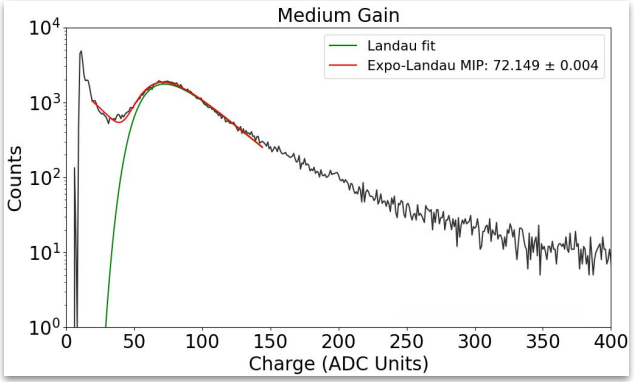


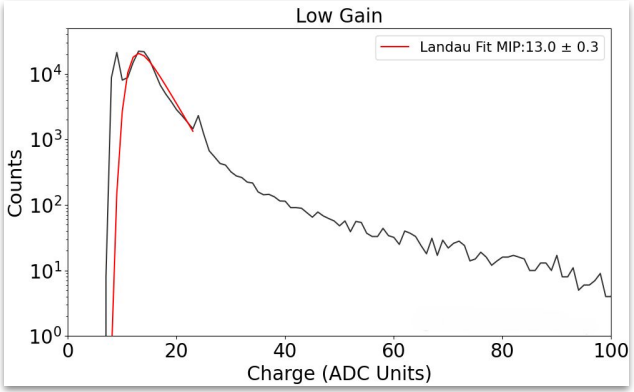


Dynamic range estimate



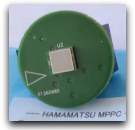




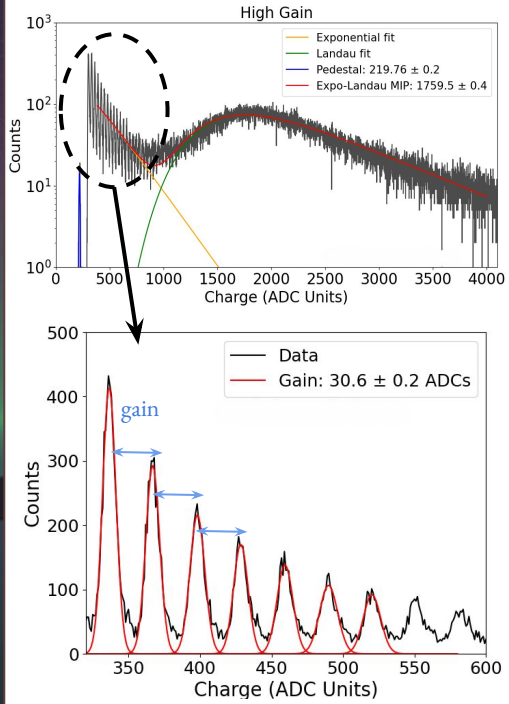


- Signal sampled by 3 12-bit channels in uDAQs : modeled by expo+landau function
- **Scaling of 280 from low to high gain**
- **Dynamic range of the uDAQ ~800 MIPs**

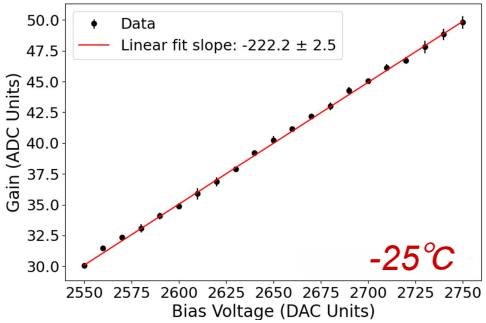
SiPM gain calibration



Single P.E peaks to determine the gain of the SiPM

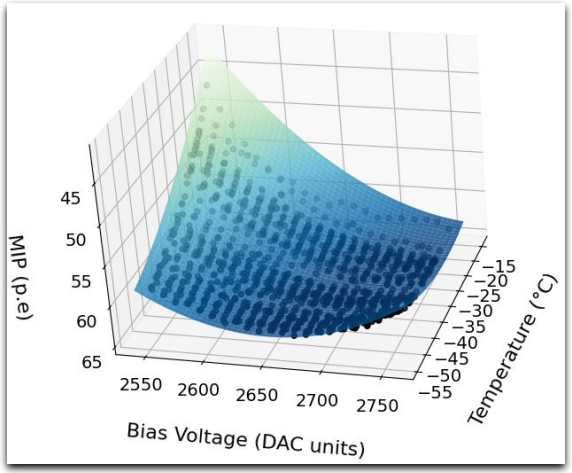


Gain versus bias voltage for each calibration run



6 months of data covering the entire temperature range at the Pole

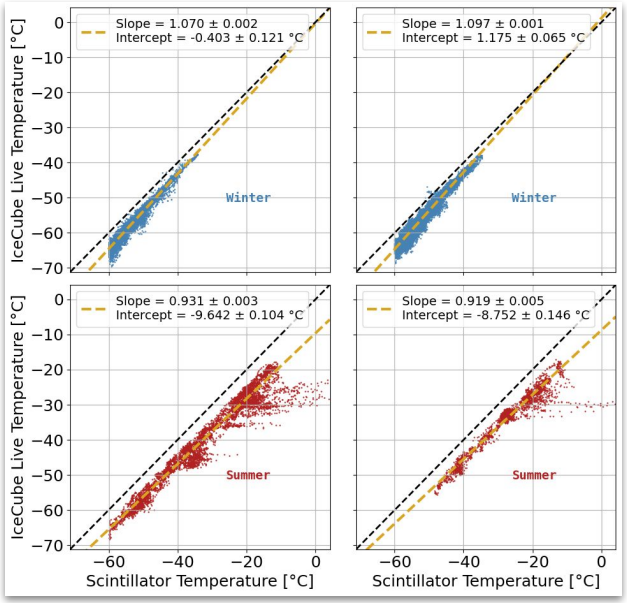
Light yield = MIP/gain

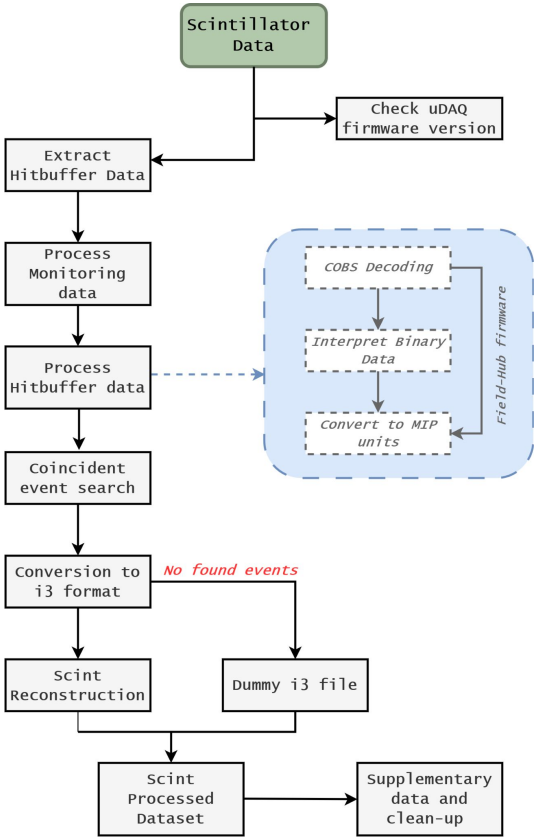


- SiPM gain linearity lost at very low temperatures
- **Dynamic range is gain dependent:** 55 - 60 p.e./MIP for 2023
- **Gain stabilization successfully applied for future firmwares**

Processing Pipeline

- Scalable pipeline for raw to reconstructed data
- Temperature calibration to ICLive for temperature corrections





Air-shower Reconstruction

Likelihood- based 3-step event reconstruction:

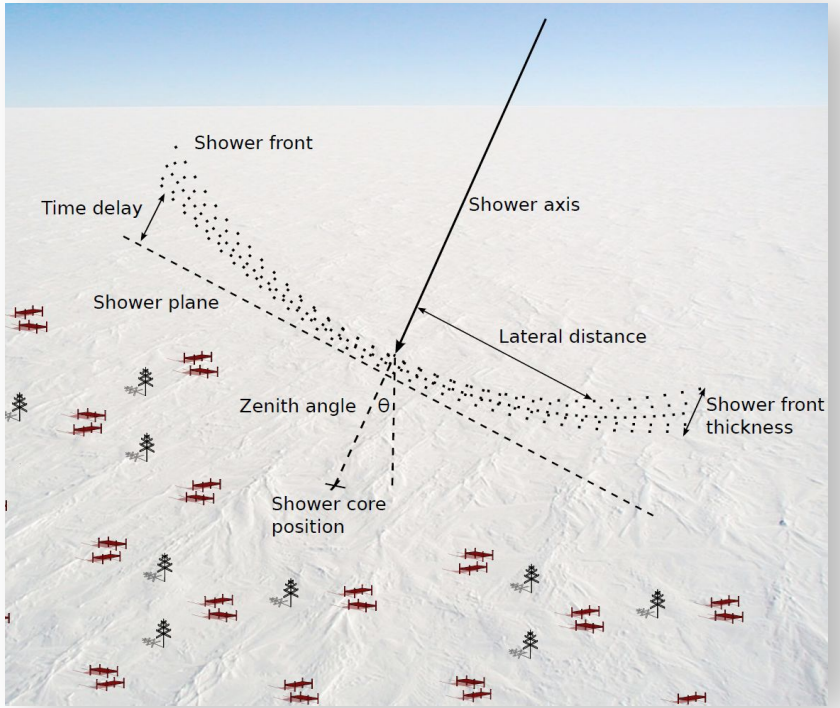
- Time front reconstruction (θ,Φ): Parabolic front

$$\Delta t(r) = ar^2 + b$$

- Lateral distribution function (LDF) (n, S): Double Logarithmic Paraboloid function

$$S(r) = S_{\text{ref}} \cdot \left(\frac{r}{R_{\text{ref}}}\right)^{-\beta-\kappa \log_{10}\left(\frac{r}{R_{\text{ref}}}\right)}$$

- For the likelihood treatment, signal and timing fluctuations needed
  - Signal fluctuations driven by shower properties as well as detector response → **data used for the signal model**



Signal Variance Model

- Neighbours sample same part of the air-shower
  - LDF shape fluctuations: S > 50 m from core
  - Threshold effects until 10 MIPs
- Power- law observed for variance :

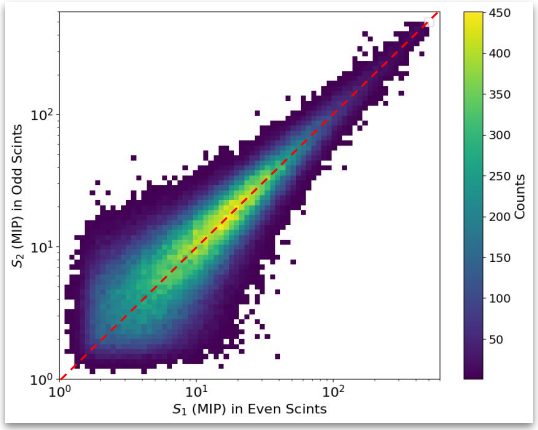
$$\sigma_{\frac{S_1 - S_2}{\sqrt{2}}} = \langle S \rangle^{\alpha}$$

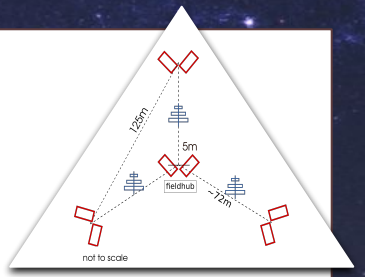
Where $\boldsymbol{\alpha}$ **~ 0.545 (~Poissonian)**

- **Data-simulations in agreement**
- Variance scaled with a spectral factor to account for zenith dependent fluctuations

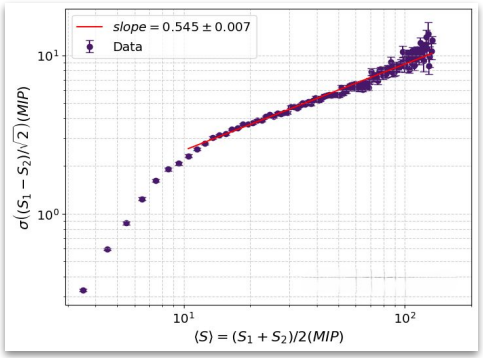
$$\sigma_{\langle S \rangle} = \langle S \rangle^{0.545} \cdot [0.39 \sin^2 \theta + 0.66]$$

Signal: S1 v/s S2

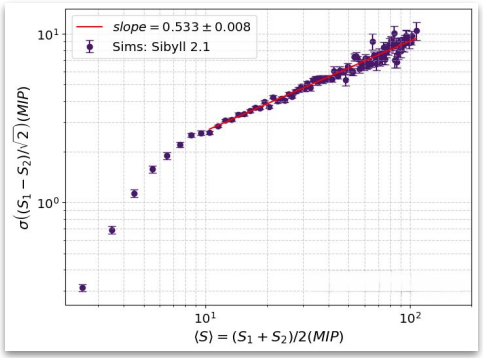




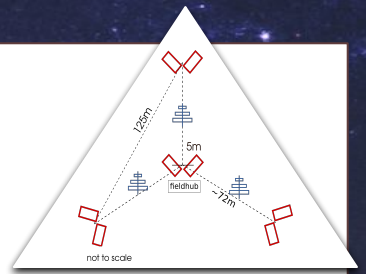
Data



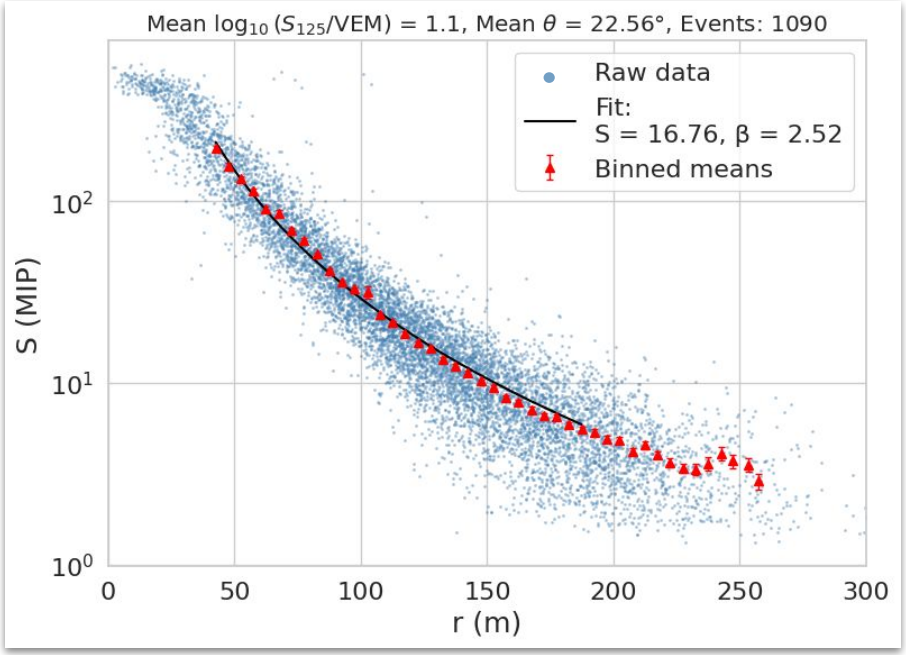
Simulations



Lateral Distribution Parameterization



- Signal variance model used for the lateral distribution fit
- Binned analysis performed to optimize the β parameter
  - Zenith (θ) and Shower size ($\log_{10}(S_{125}/\text{VEM})$)
  - Distance from the shower axis (r)



From Assembly to Insight: Detection of CRs

1 Production

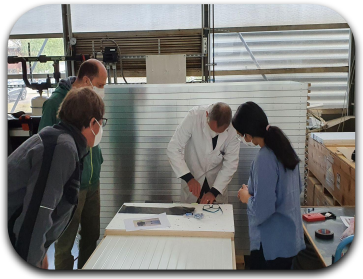
- Component testing
- Mechanical Assembly
- Module Characterization

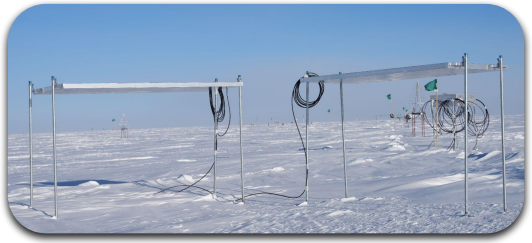
2 Data Preparation

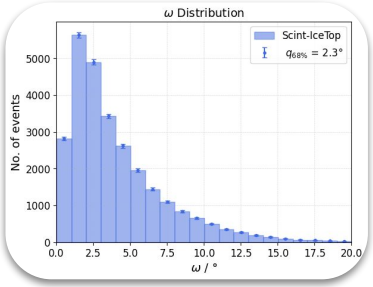
- Data Processing Pipeline
  - Calibration
  - Reconstruction

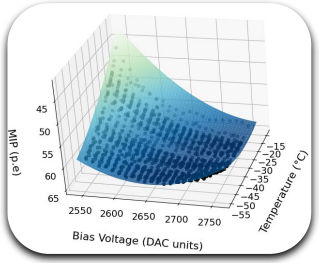
3 Performance

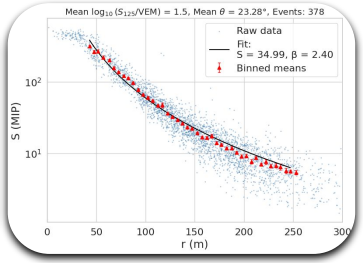
- Data Selection
- Benchmarking with respect to data / simulations

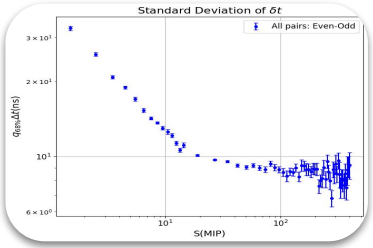






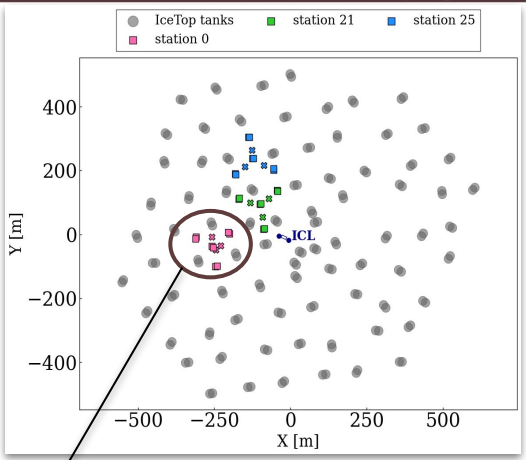




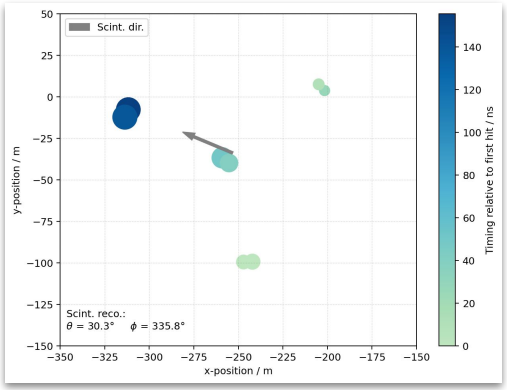


Dataset: Selection Criteria

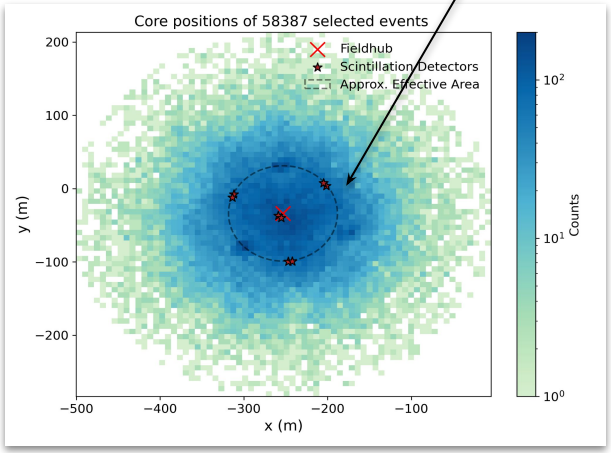
- **Benchmarking with respect to IceTop reconstructed data 2023: 58.3k events**
- Selection criteria:
  - Cores within 250m
  - IceTop reconstructed $\theta < 37°$
  - IceTop reconstructed $\log_{10}(S_{125}/\mathrm{VEM}) > 0.5$ (max efficiency)
  - Scintillator multiplicity of 8 used



Example-event with Scintillators

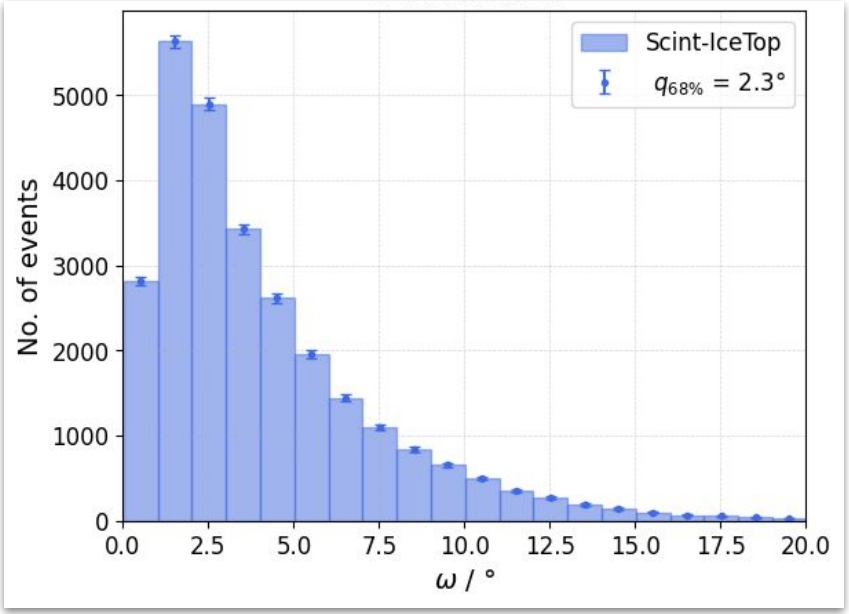


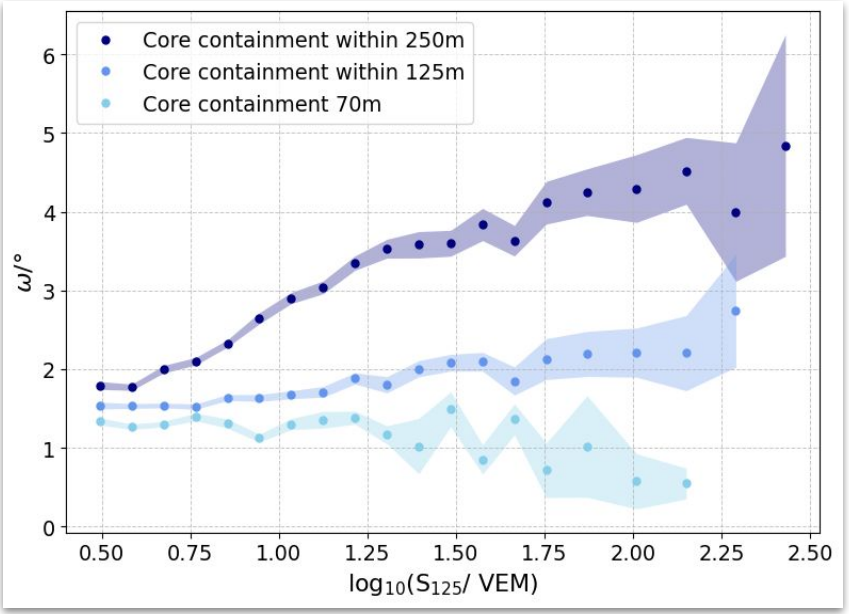
Core-Positions from IceTop



Angular Resolution

- **Combined angular resolution** with respect to reconstructed IceTop: 2.3°
  - Core-containment near the station improves the resolution to **1.3°** improving to **sub-degree for bigger shower size**

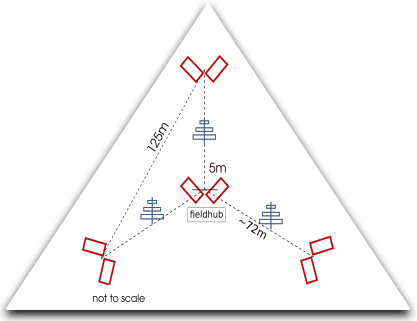


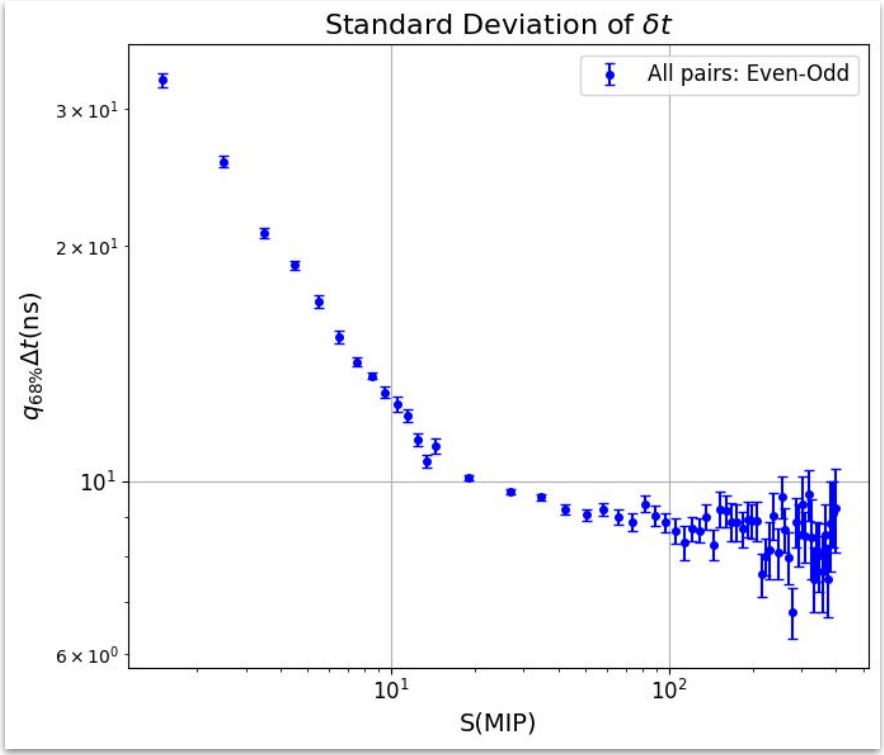


Note: *The station radius is ~70m*

Time Resolution

- Timing in neighbouring scintillators with respect to mean signal
  - Small signals: Outer fluctuations of the shower
  - Large signals: Timing resolution (indicates ~few ns)

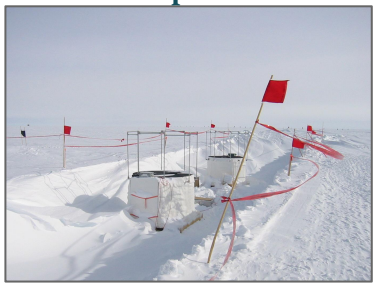




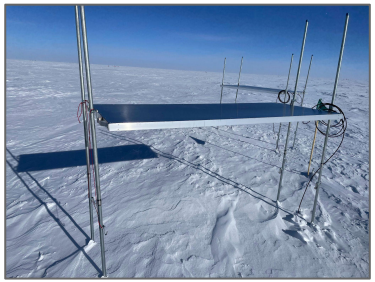
Energy Proxy with scintillators

- First estimate of the shower-size with a single station
- Expected difference in the response:
  - Can be used for improving snow model for IceTop by cross-calibrating

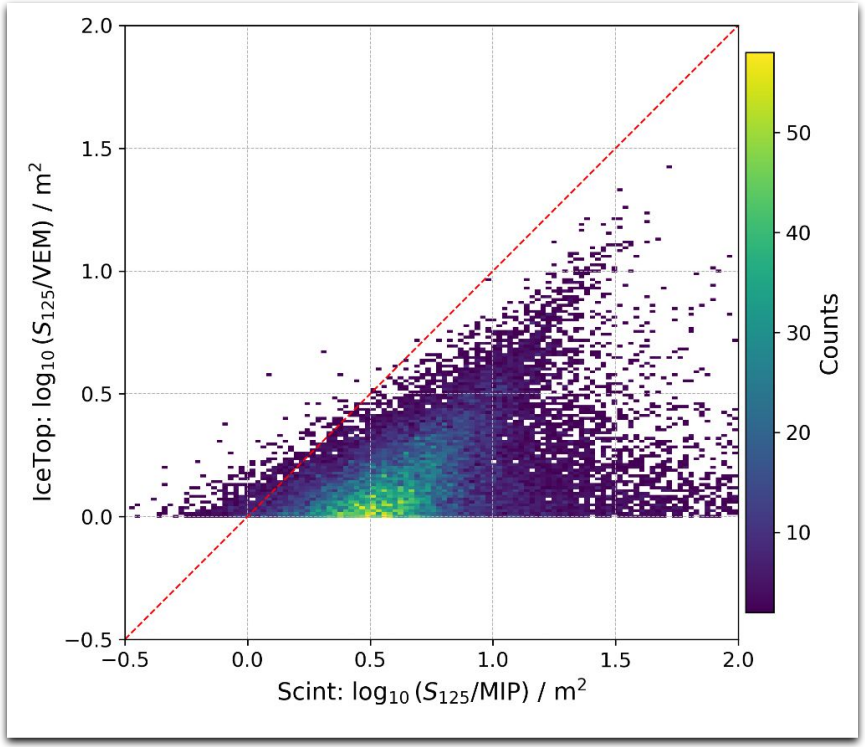
IceTop Tanks



Scintillators



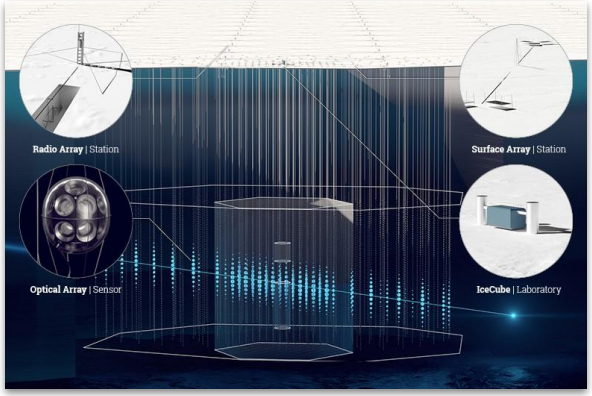
IceTop

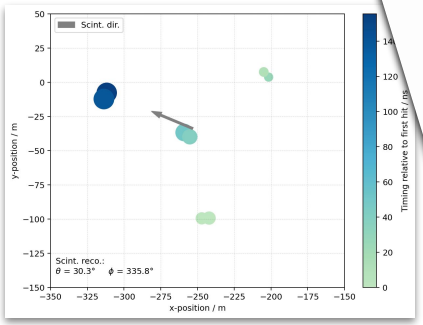


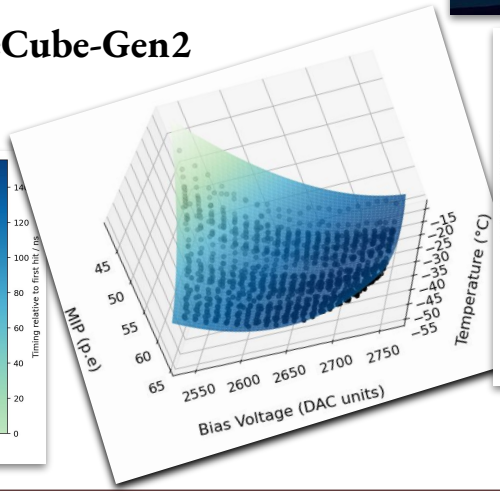
Scintillator

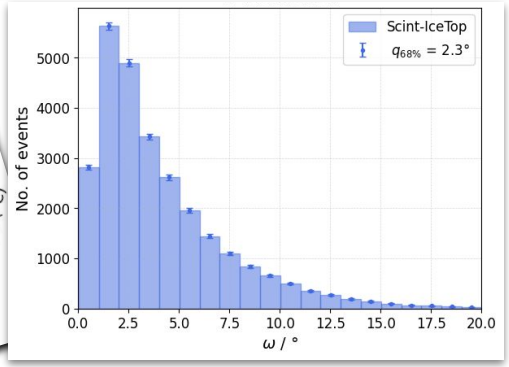
Summary

- Series production chain established for full SAE: 99 scintillators produced and validated
- Scalable data processing pipeline in place:
  - Station 0 fully calibrated. Gain stabilization implemented
  - Shower reconstruction optimized using data
- Detector performance demonstrated readiness for **Surface Array Enhancement**
- on the roadmap for the surface array of **IceCube-Gen2**
- Integrate additional stations in the future





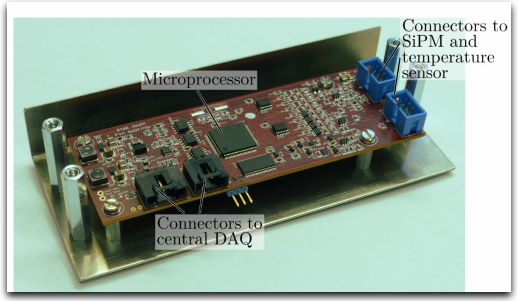


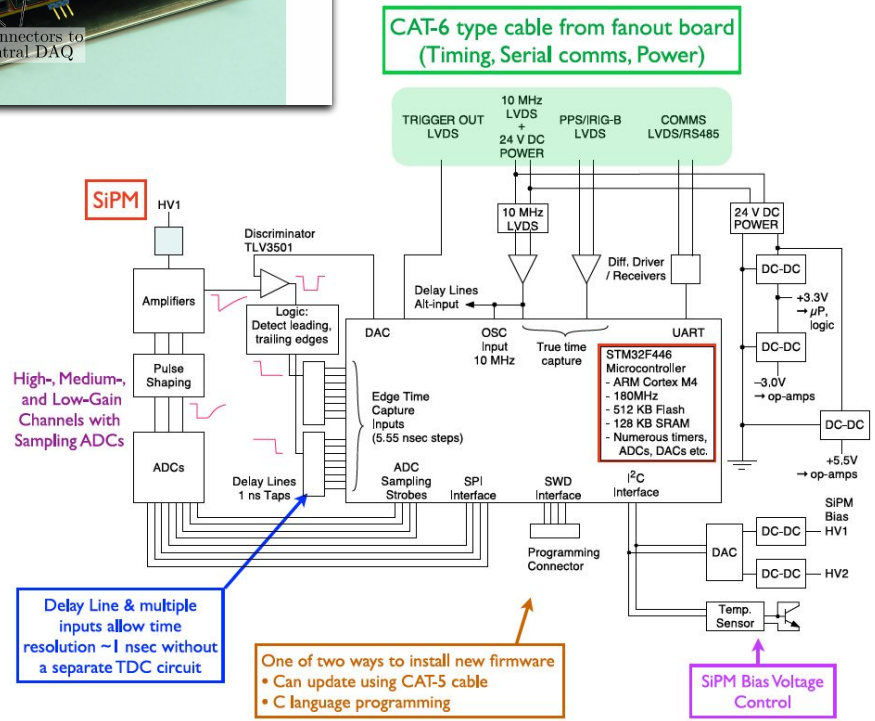


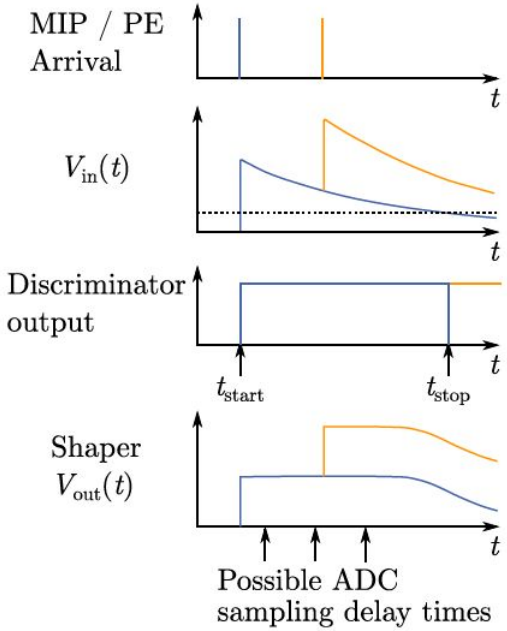
Thank You :)

BACKUP SLIDES

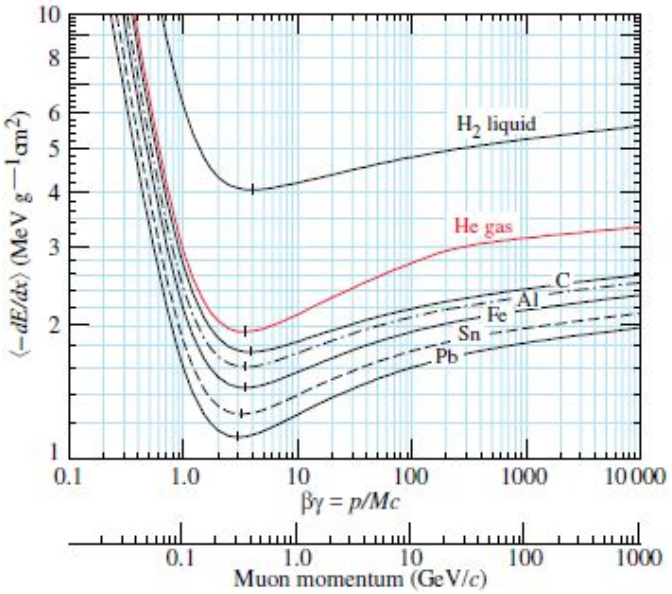
uDAQ schematic

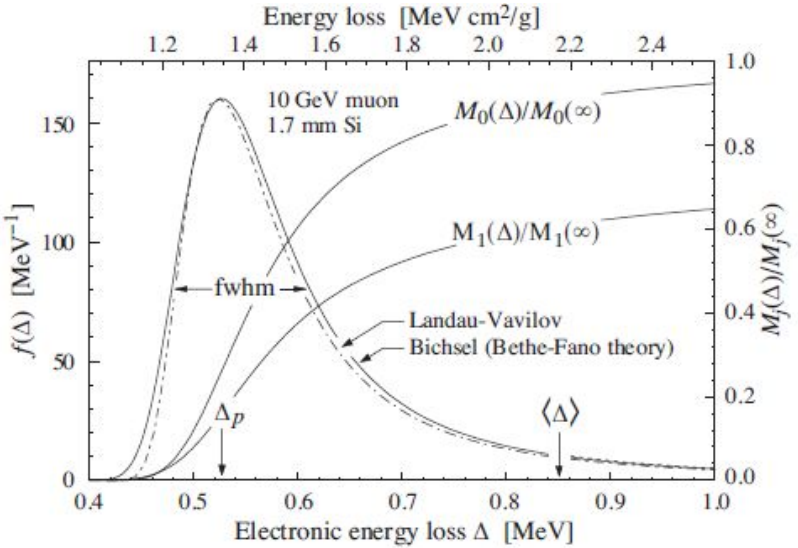






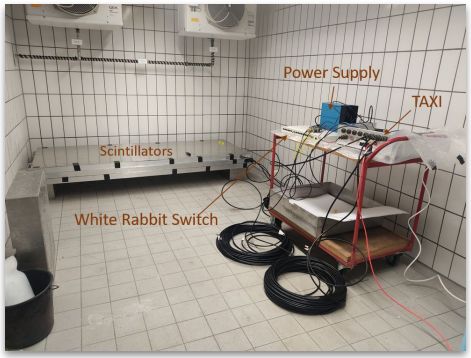
Particle energy loss in medium

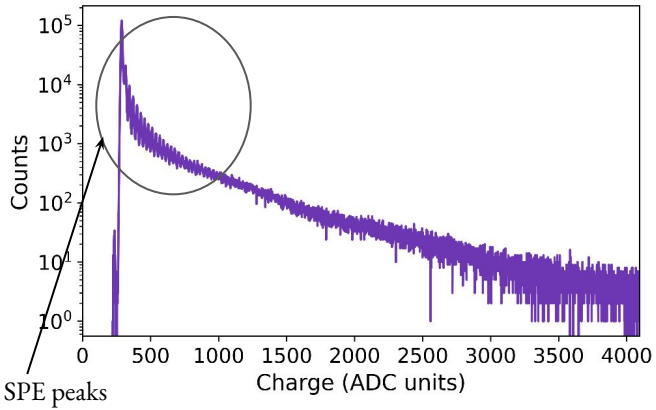




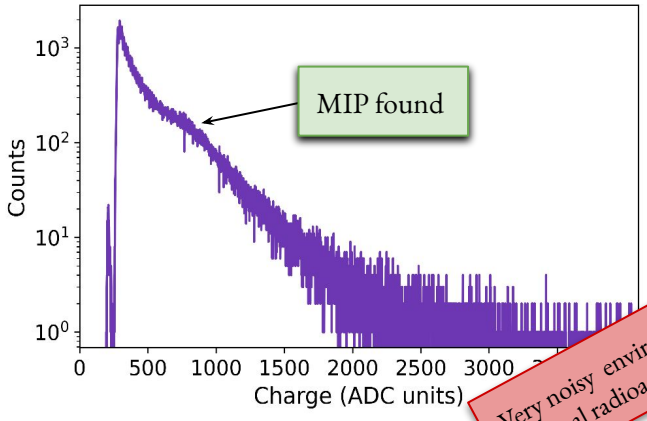
Detector Validation : Field Tests

Low Temp Measurements (-20°C)



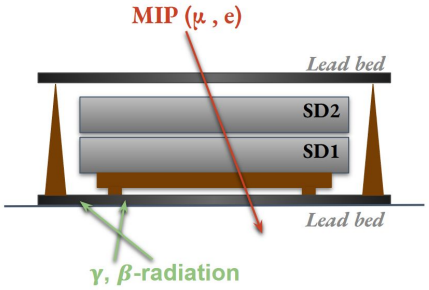


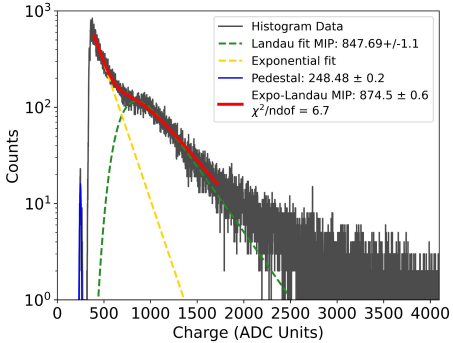
Lake Measurements (23°C)



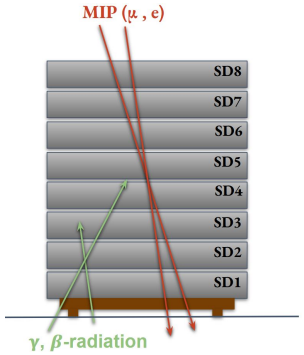
Scintillator validation

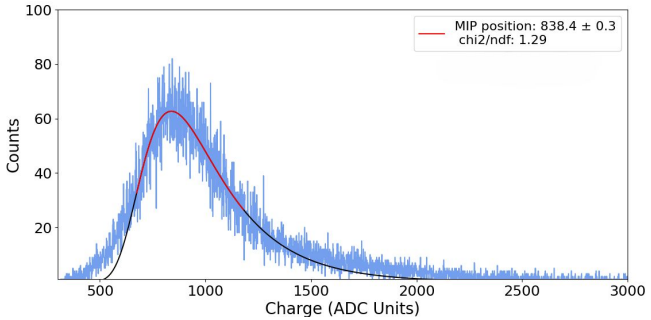
w/Lead shielding setup





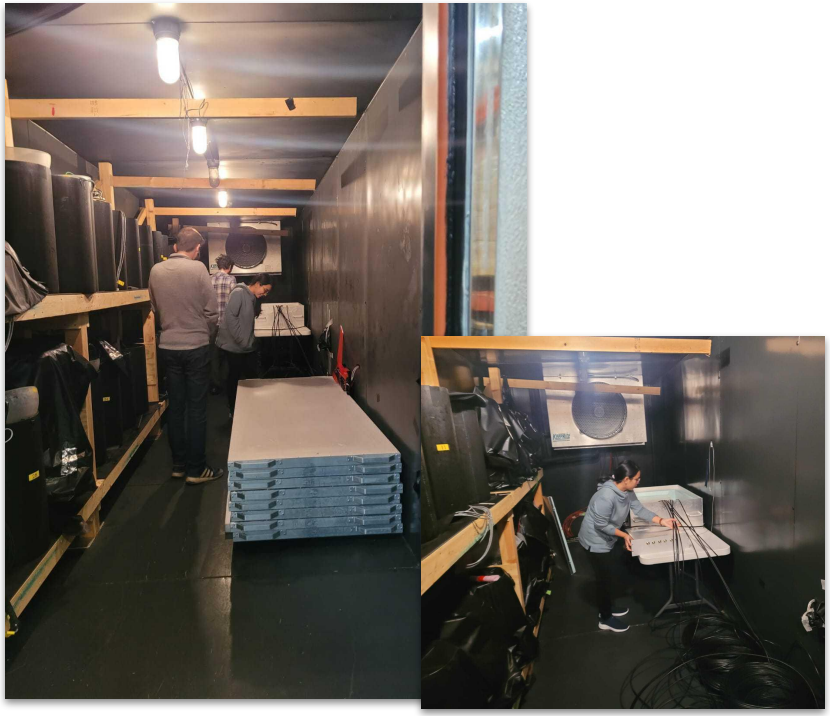
Hodoscope condition





R&D stations

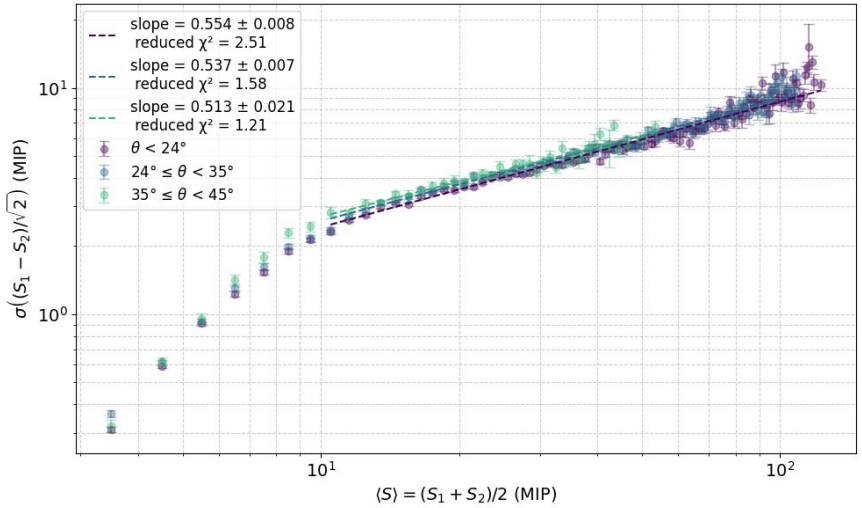
@PSL, UW-Madison

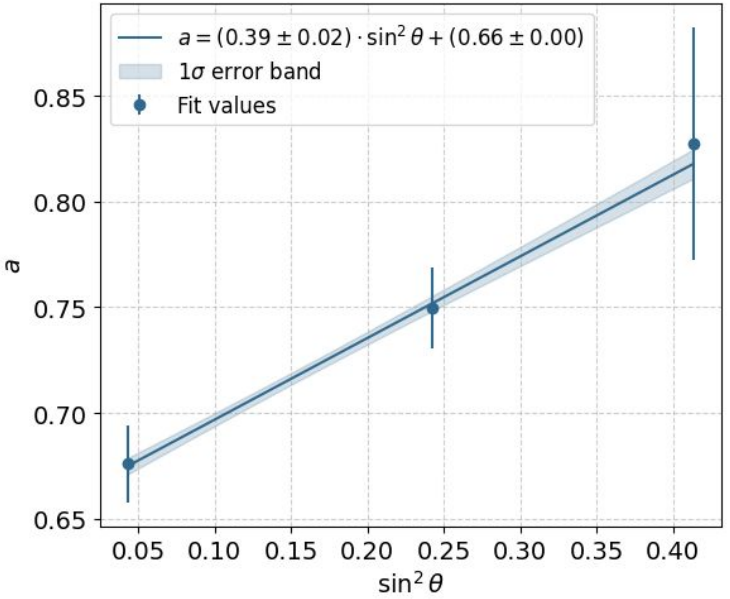


@Pierre-Auger Observatory

@Telescope Array

Signal Model : Zenith dependance

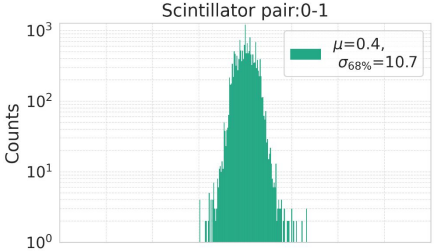




Resolution w.r.t simulations

- Not an apple to apple comparison: Data is with respect to iceTop
- Time resolution in simulations is worse than data: further investigation is required!

Data



Simulated