Hardware development for the TERZINA and LACTEL projects

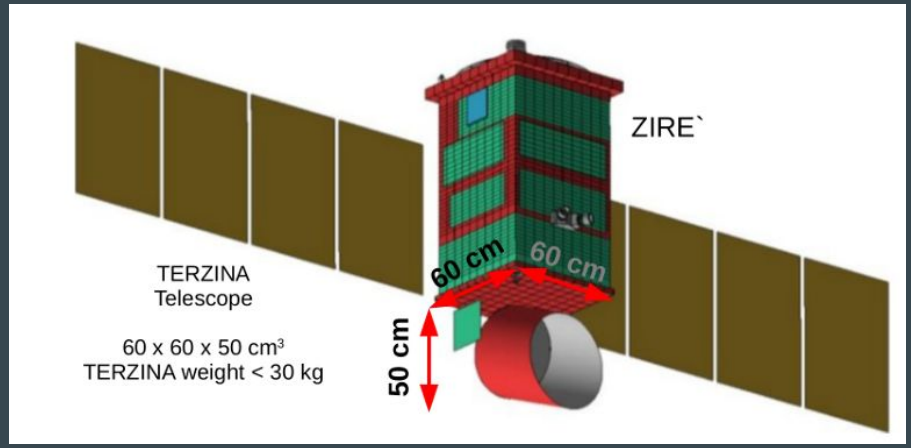
...

Christoph Tönnis
April 28th 2026

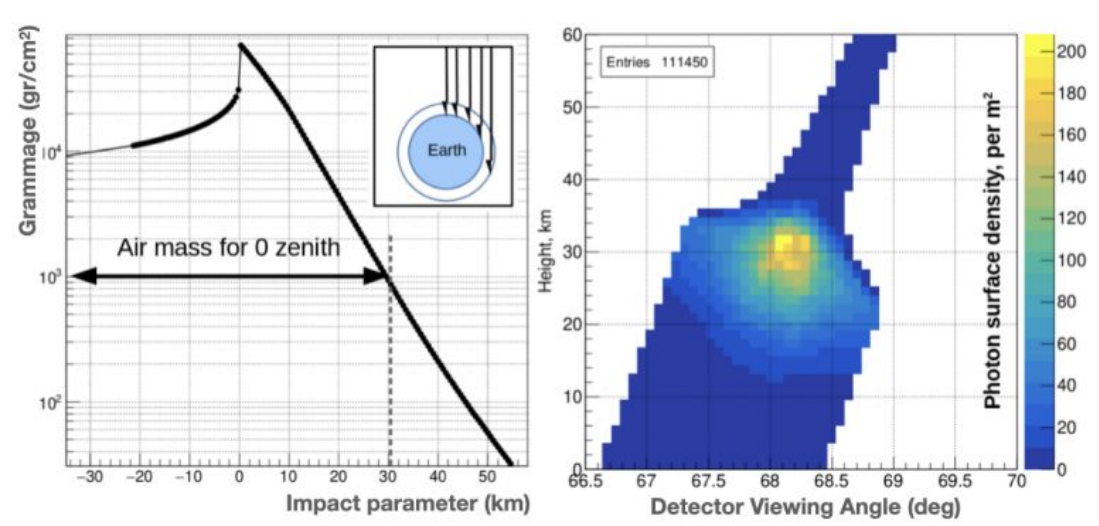
TERZINA focal plane assembly and DAQ system

The TERZINA detector aboard the NUSES satellite

- TERZINA is a planned detector using an SIPM camera to detect extensive air showers aboard the NUSES satellite
- It is intended as a pathfinder mission for future constellations of similar detectors
- The NUSES mission is planned for a total of 3 years



Looking at the limb



Left: Grammage of a cosmic particle as a function of its impact parameter. The insert at the top-right schematically shows incoming particles with different impact parameters. Right : Photon surface density (z-axis) as a function of the viewing angle and height of a UHECR

The TERZINA DAQ scheme

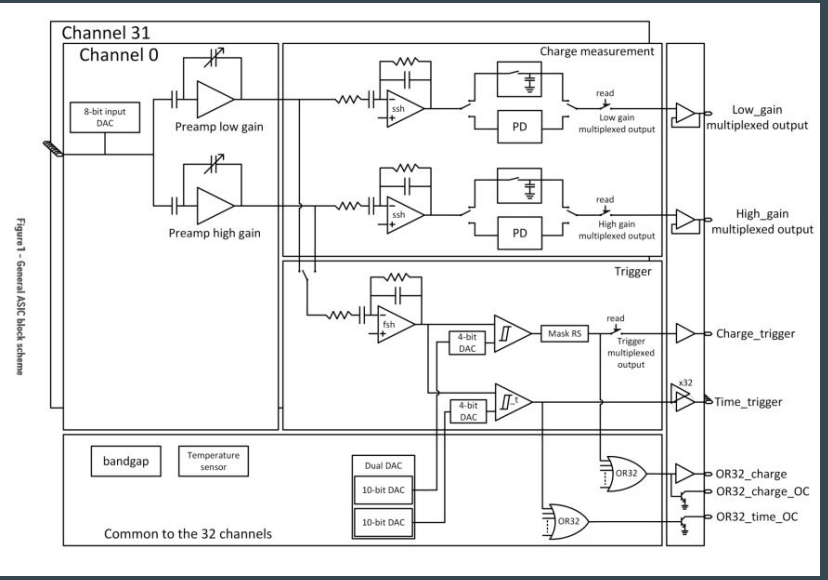
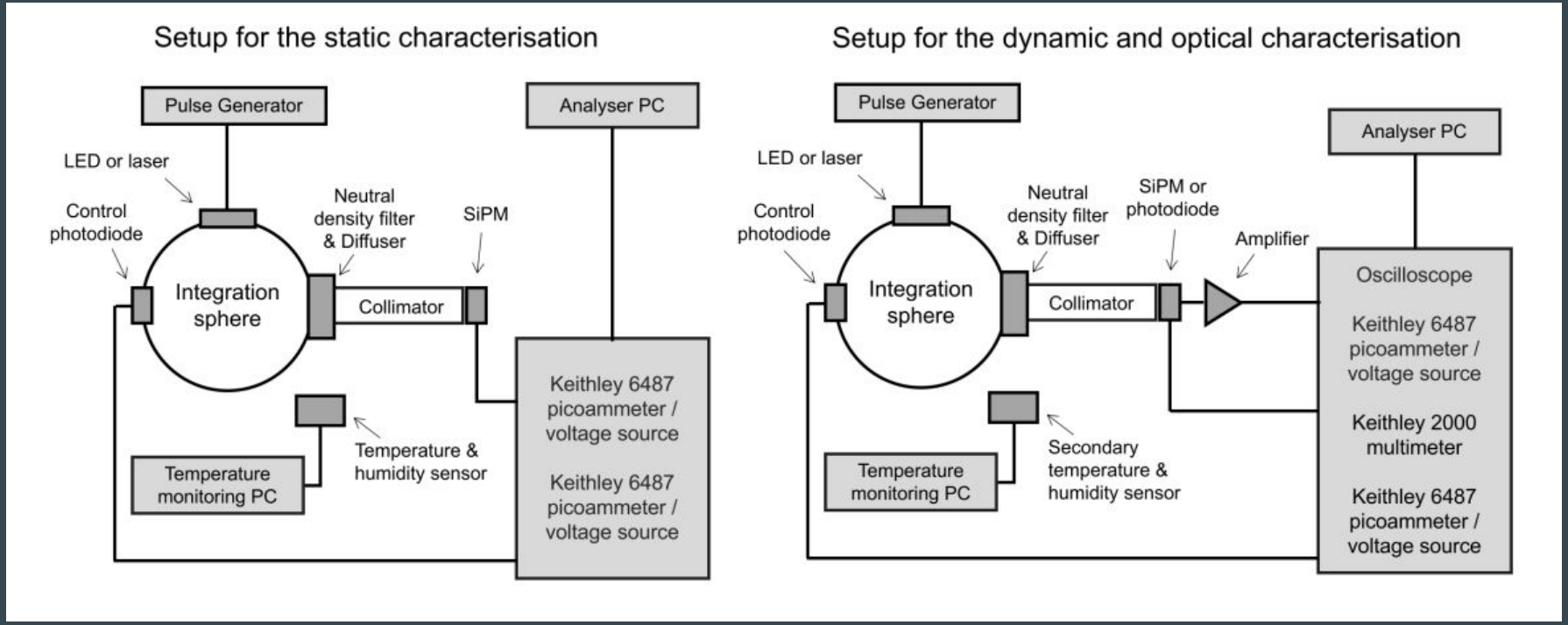


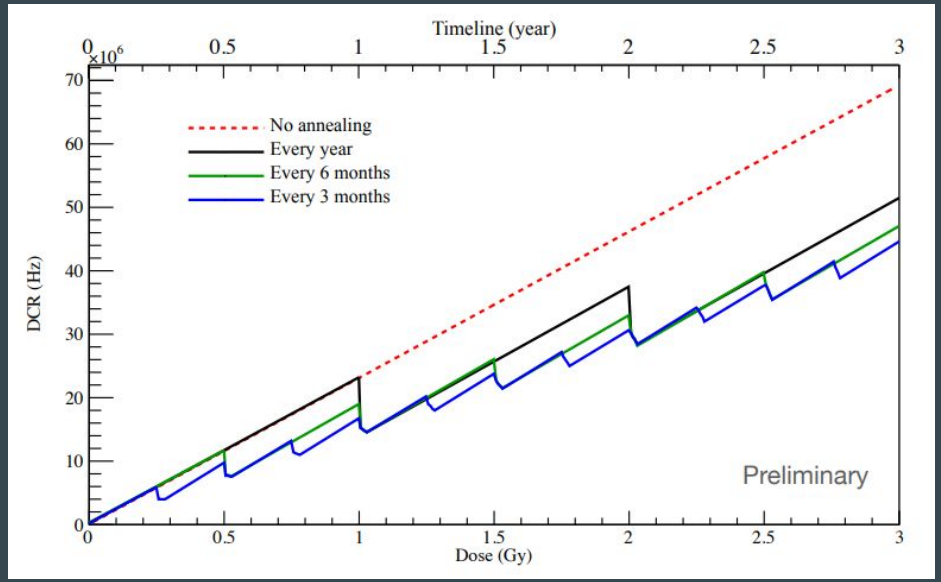
Figure 1 – General ASIC block scheme

- My work in TERZINA was focused on the development of the DAQ system and the simulation chain for the detector.
- The TERZINA DAQ system will be based on the CITIROC A1 chipset from WEROC
- This chipset is designed as a simplified readout system for SIPMs that focuses on precision timing above charge measurement
- The combined system will be able to record the peak of a waveform with a delay between the readout and the trigger shaper to manage the fast rise-times of SIPMs
- My work with this system was test the DAQ system and SIPM tiles and amplifiers

Lab setup

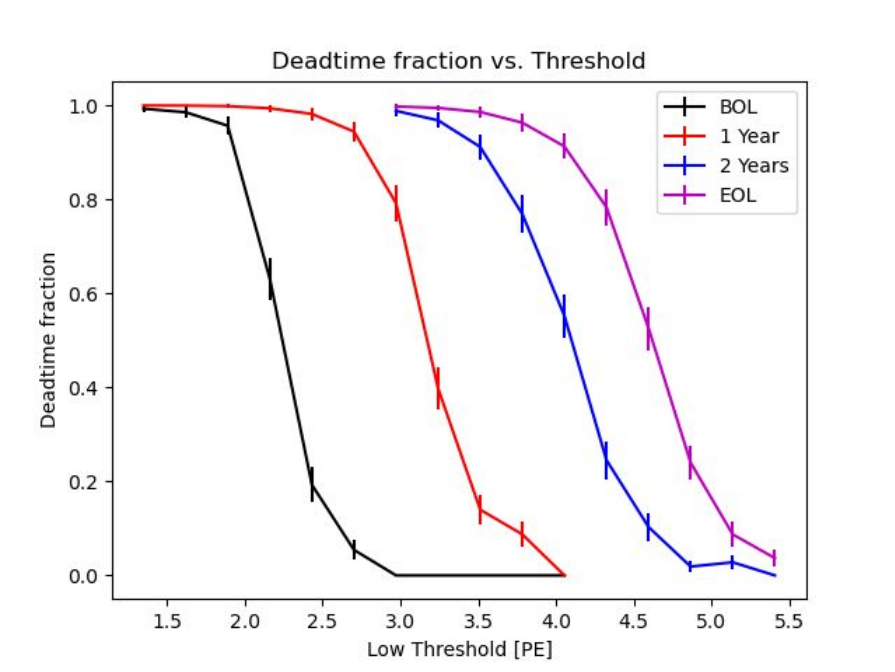

Setup for the static characterisation
Pulse Generator
Analyser PC
LED or laser
Control photodiode
Neutral density filter & Diffuser
SiPM
Integration sphere
Collimator
Keithley 6487 picoammeter / voltage source
Keithley 6487 picoammeter / voltage source
Temperature & humidity sensor
Temperature monitoring PC
Setup for the dynamic and optical characterisation
Pulse Generator
Analyser PC
LED or laser
Control photodiode
Neutral density filter & Diffuser
SiPM or photodiode
Amplifier
Integration sphere
Collimator
Oscilloscope
Keithley 6487 picoammeter / voltage source
Keithley 2000 multimeter
Keithley 6487 picoammeter / voltage source
Secondary temperature & humidity sensor
Temperature monitoring PC

Radiation damage



Development of DCR as function of time with different annealing frequencies

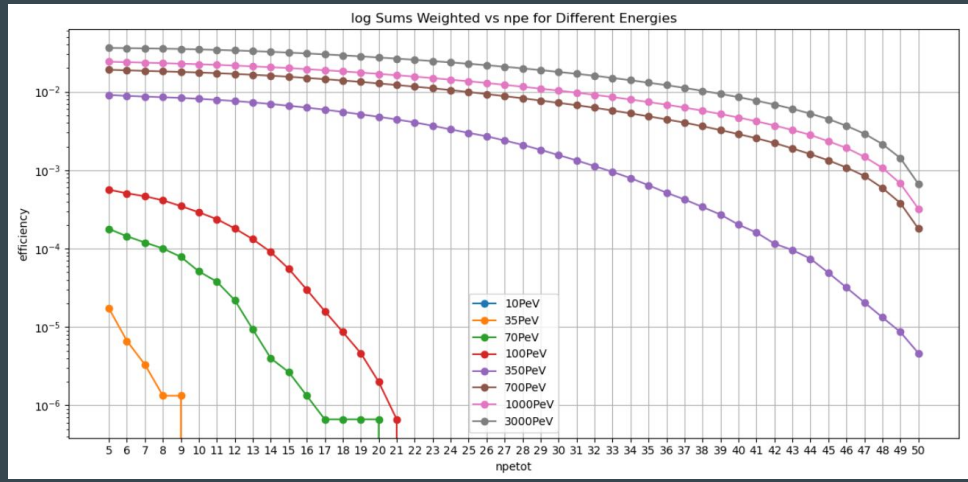
DAQ optimization



- For TERZINA I implemented a full simulation of the trigger scheme using the CITIROC chips
- This included running calculations on simulated background for different detector conditions to optimize the trigger settings (thresholds, coincidence windows, gain on different amplifiers, annealing cycles)

TERZINA simulation chain

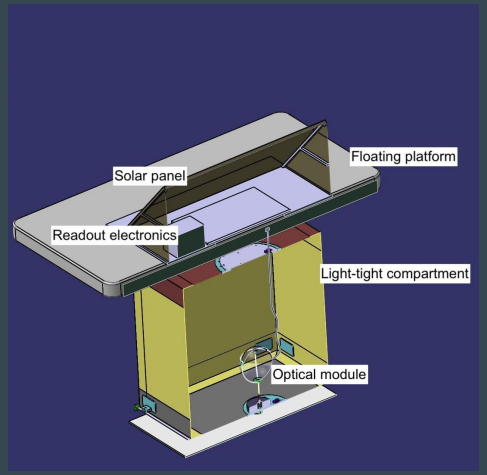
- Further work on the simulation included extensive debugging of the entire chain, containerization, optimization, documentation and developing a data model of better data access and preservation
- I also worked on tools for use with the data model to generate final results such as detector efficiency and effective area



The LACTEL detector

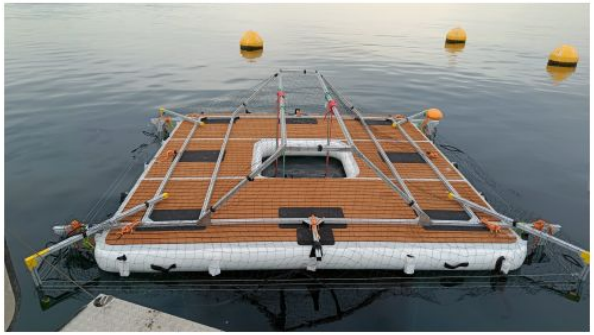
The LACTEL detector

- TheLACTEL project (LAke-based Cosmic ray electron and gamma-ray TELescope) is a new cosmic ray detector array using a novel design
- It uses two layers of water cherenkov detectors near the surface of a lake (Lake Geneva)
- The two layers will allow to cost effectively distinguish between electromagnetic and hadronic showers as muons in the shower are the only particles to produce a significant signal in the lower layer
- The array is planned to use refurbished optical modules from the ANTARES neutrino telescope



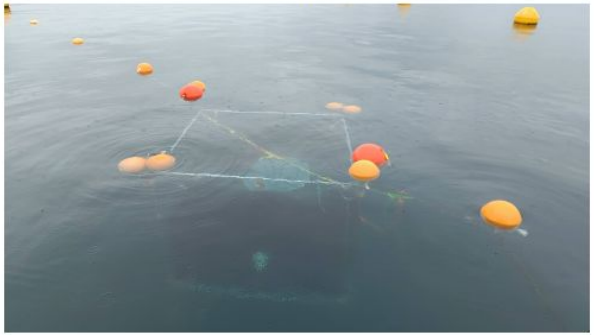
LLexplore

(a)



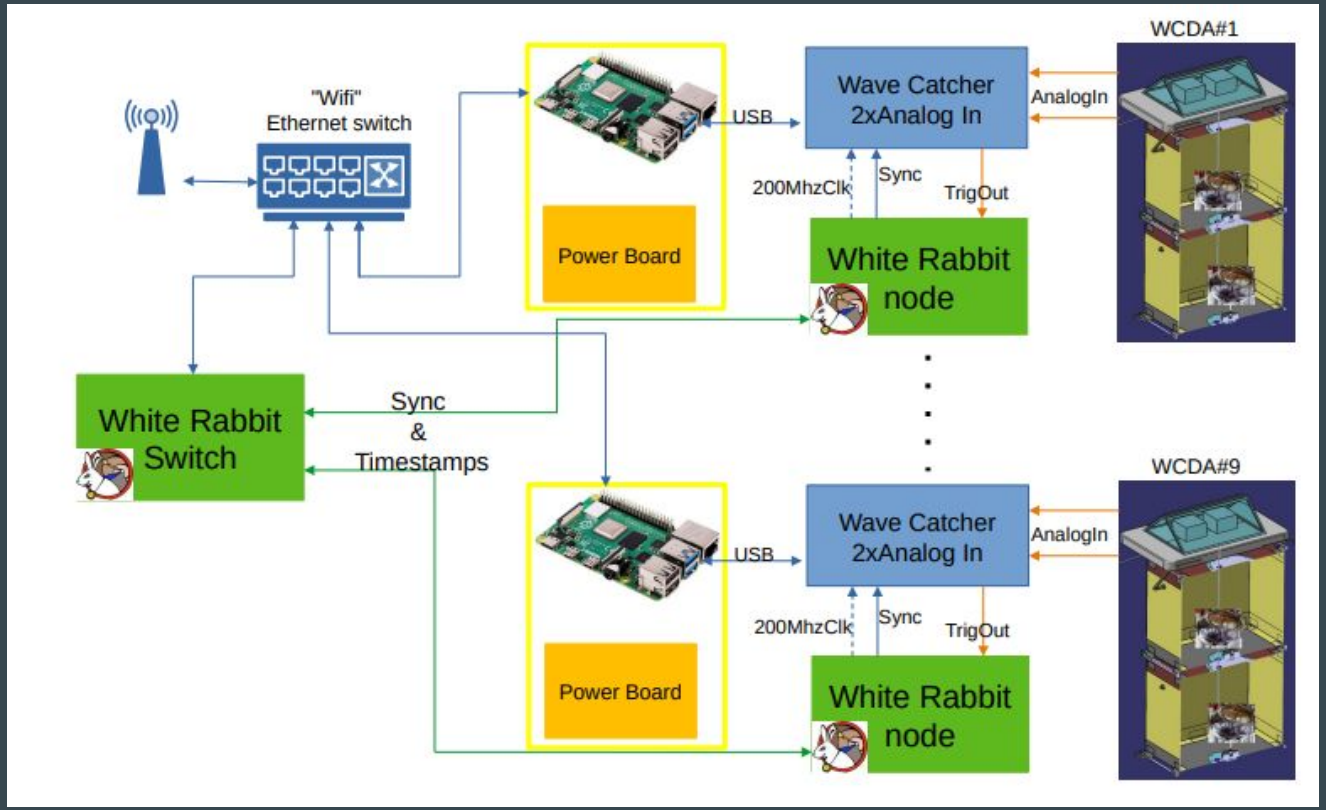
(b)

(c)

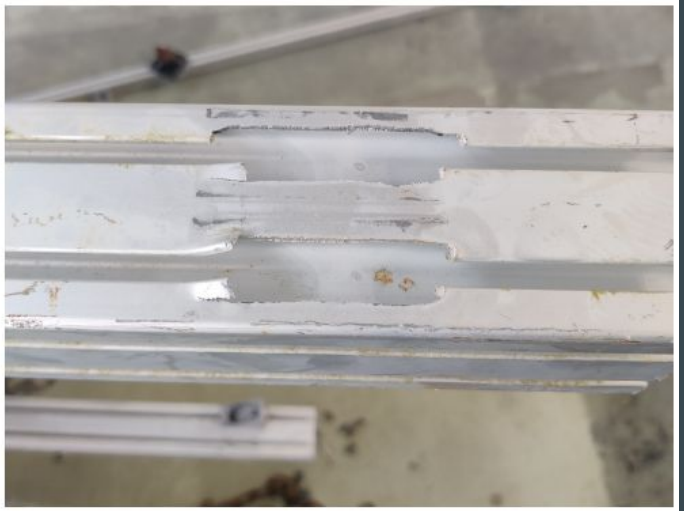


(d)

Detector scheme

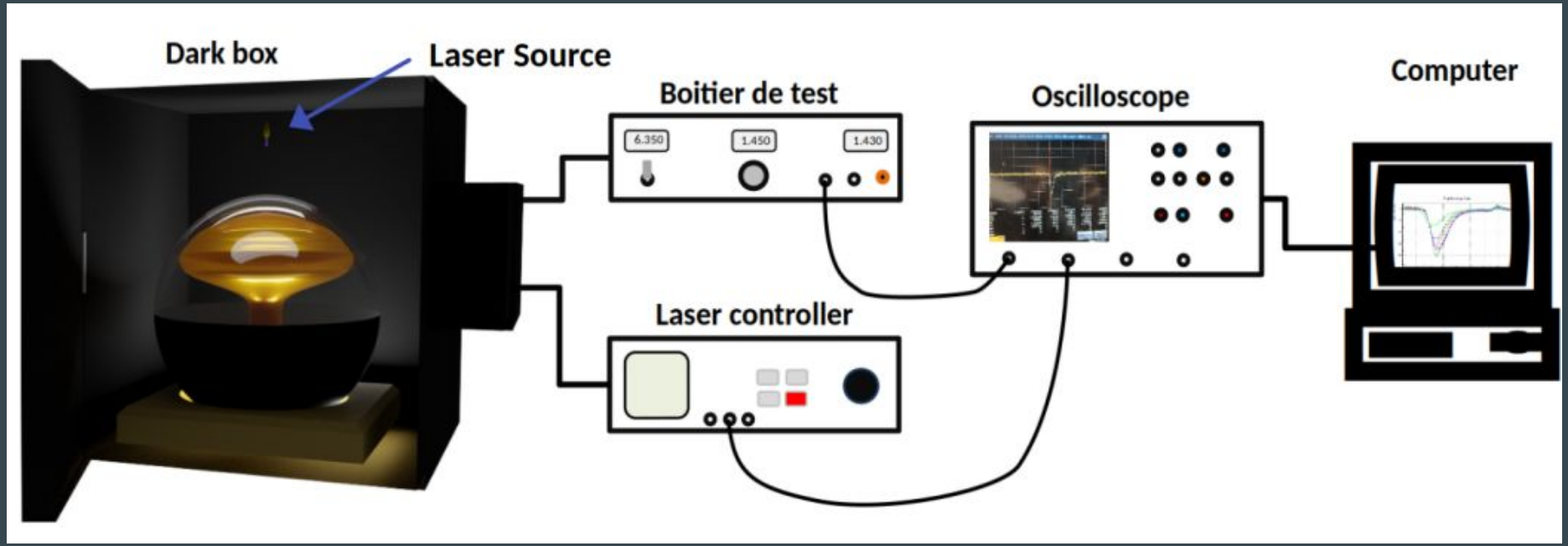


Mechanical difficulties



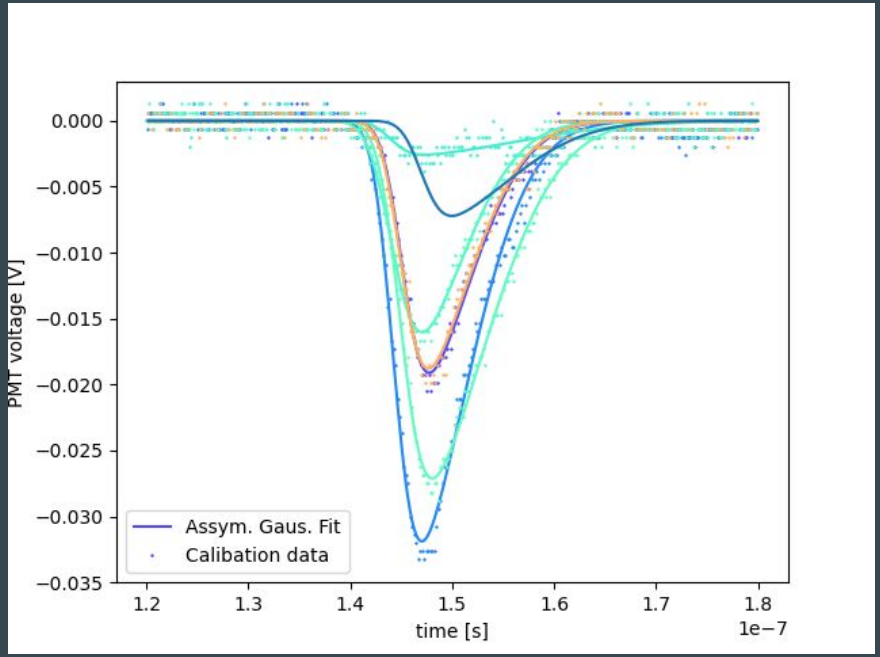
The mechanical design of the boxes is being improved. The previous design was damaged during a storm on lake geneva

OM re-qualification



OM Re-qualification

- I am involved with the qualification of the refurbished ANTARES optical modules
- The recovered optical modules are exposed with a pulsed laser at different high voltage setting to gauge the gain and quantum efficiency
- Waveforms are recorded with the same wavecatcher models used for the DAQ system
- This includes processing of the calibration data captured in Marseille to model the expected waveforms in simulation and to handle precise gain calibration and regulation

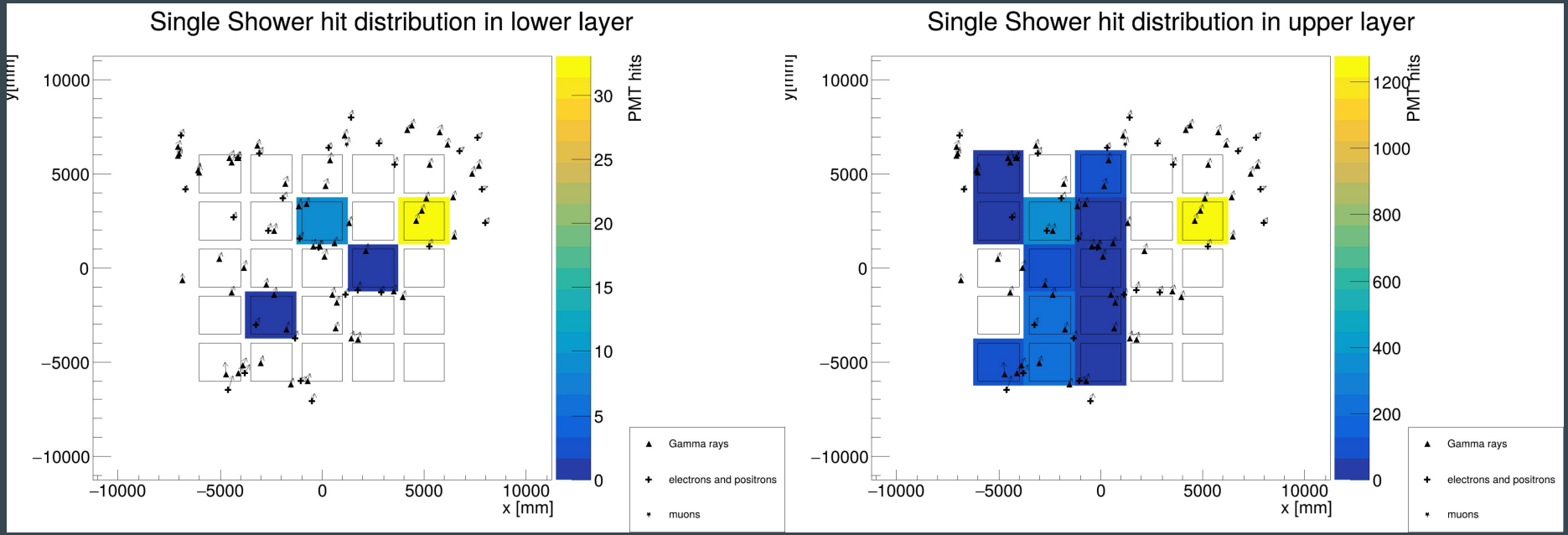


10 waveforms during calibration run with pulsed laser. Dots show data, solid lines show fitted function

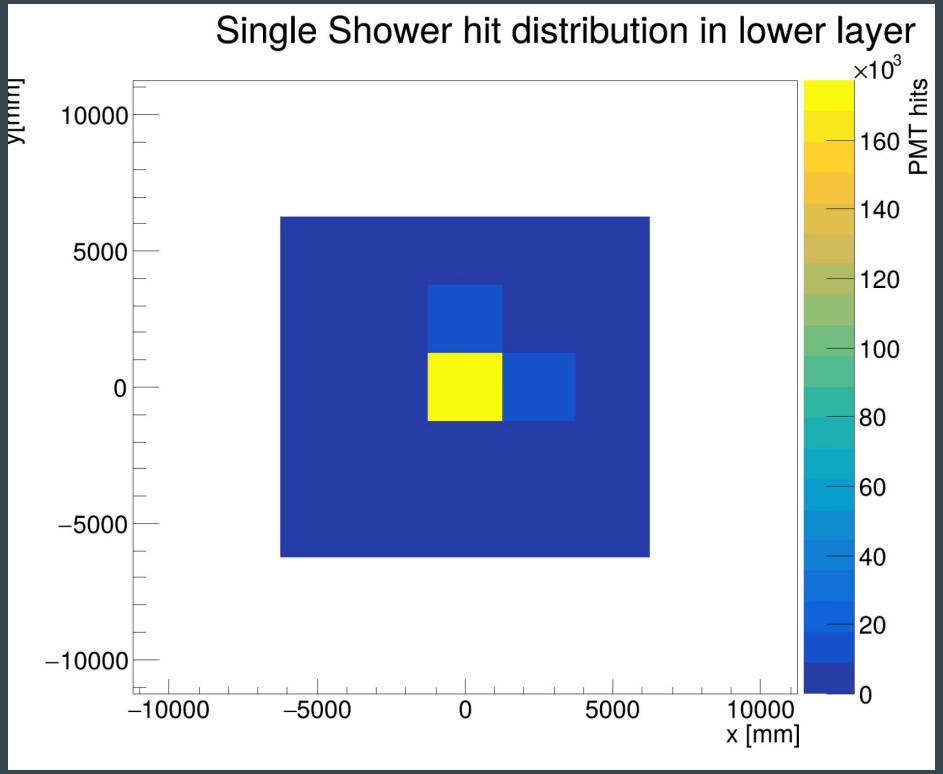
Simulation chain

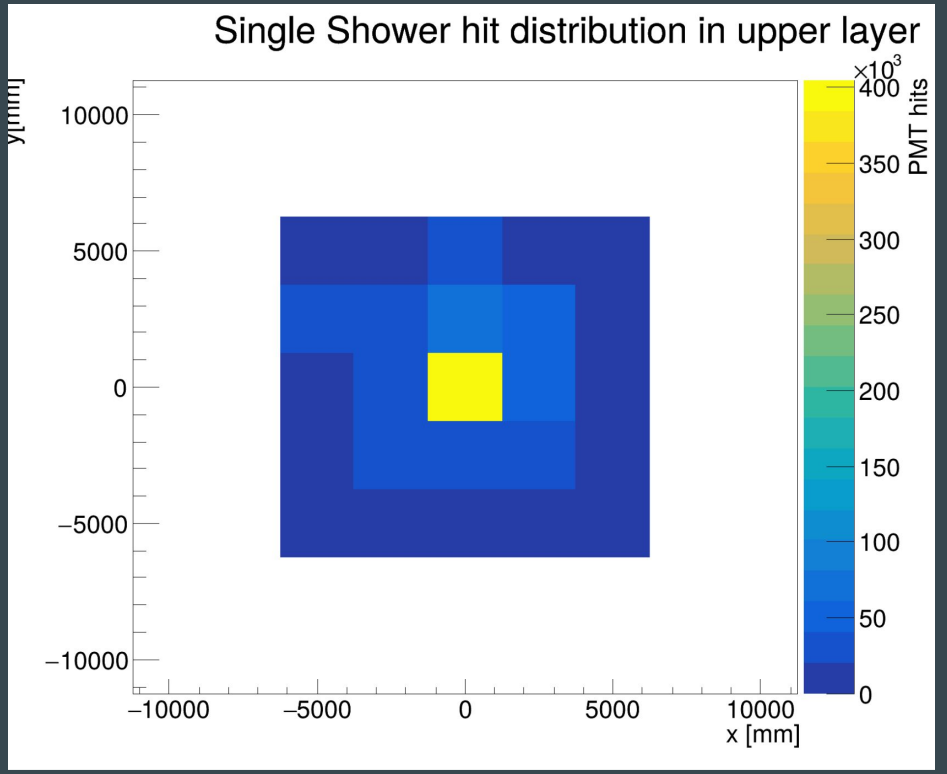
- There is now a full detector chain using the GEANT4-based OMGSim code developed for KM3Net
  - Several major adaptations had to be done to OMGSim to use it for LACTEL as it was originally designed to only handle simulating single KM3Net or ANTARES optical modules responding to passing muons
    - adding an interface to ingest CORSIKA simulation results
    - an entirely new physics list to handle hadronic interactions for hadronic shower cores
    - adding DAQ simulations based on PMT qualification data
    - updating the entire code to the most recent version of GEANT4
    - creating a new detector geometry for the full detector array
  - I am also exploring the use of SIPM modules as a cost effective option for a larger detector array and to improve angular resolution
- As of now mass simulation production is ongoing, including verification with other simulation codes

Example shower



One very bright 600 TeV near-vertical shower

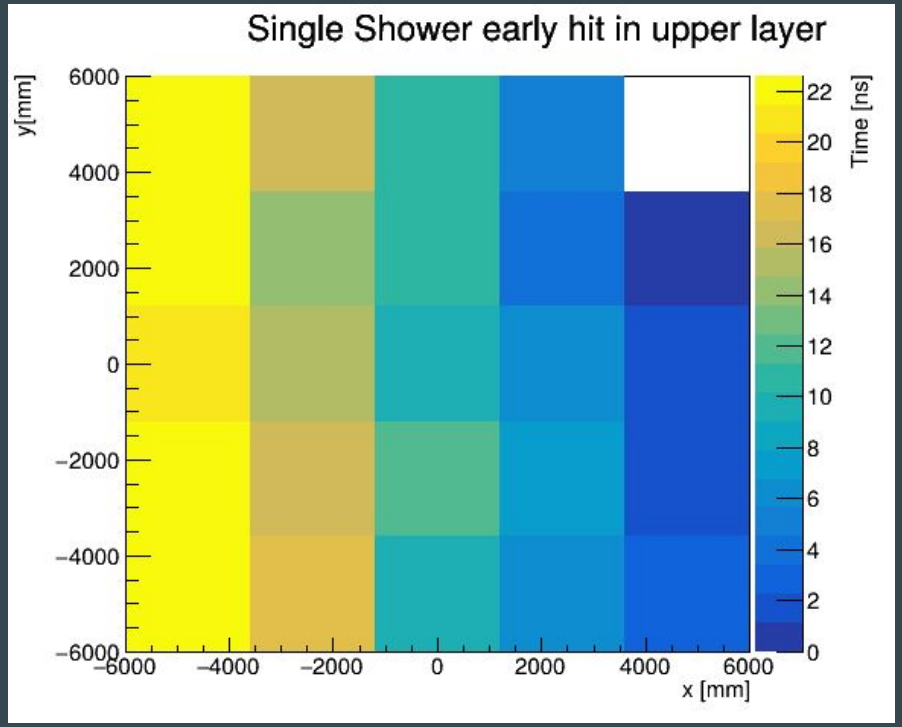


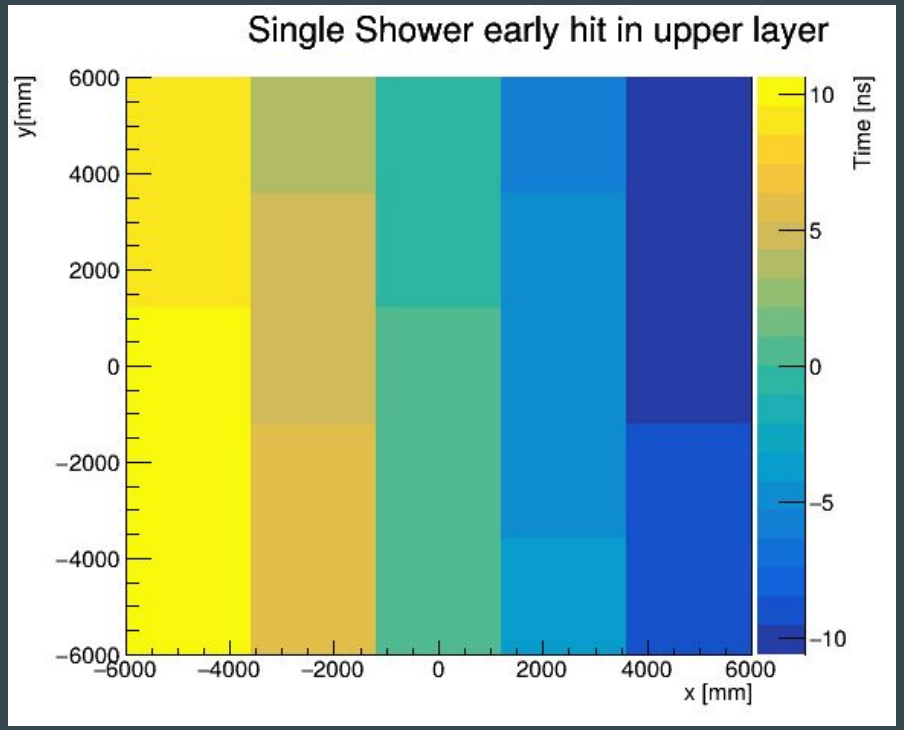


Event reconstruction

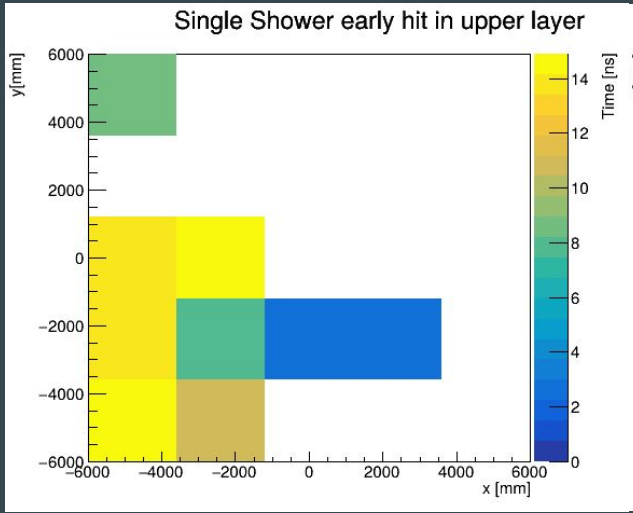
- I also worked on event reconstruction with LACTEL
- Due to the limited size of the detector energy and direction estimates are inherently limited
- For sufficiently well centered showers the data from the top layer is used to reconstruct the event direction and energy based on timing and number of hits
- First event reconstructions showed that at lower energies reconstruction becomes highly unreliable

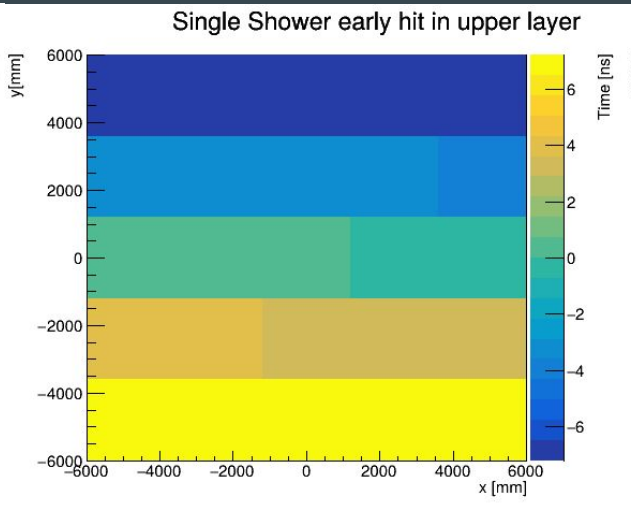
Good Hit timing

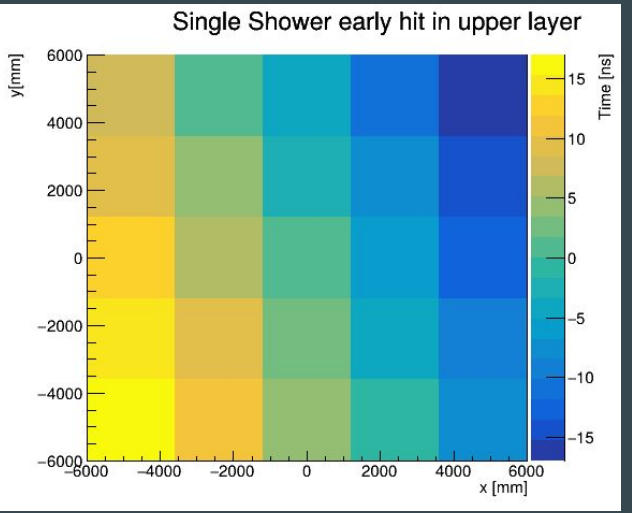




Bad Hit timing



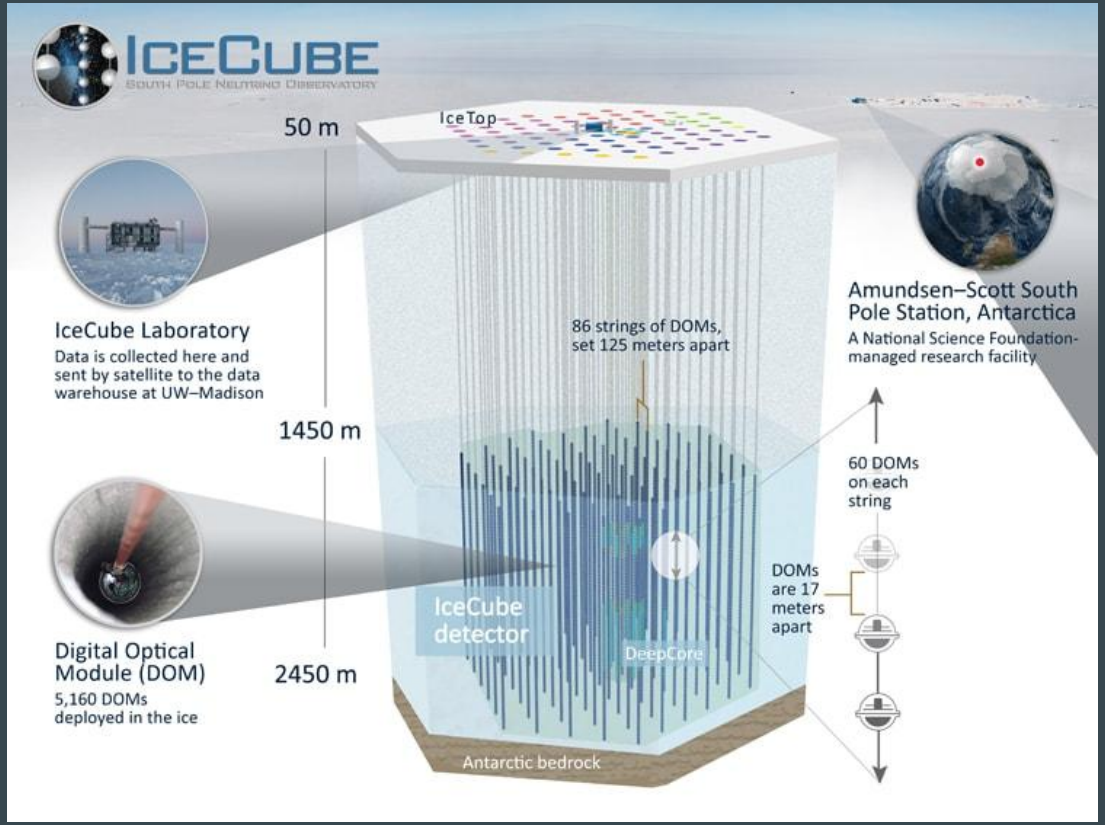




Camera based calibration of the IceCube detector

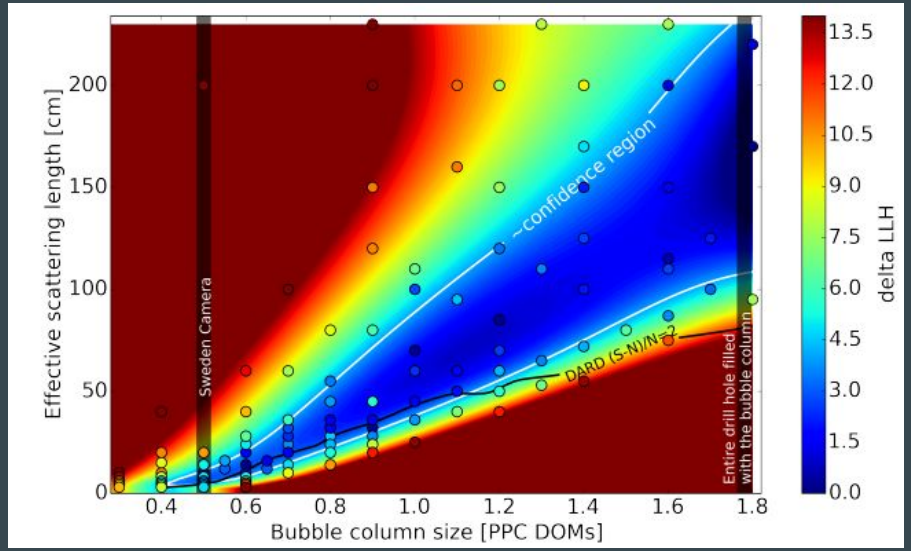
IceCube

- IceCube is the world's largest neutrino telescope
- Neutrinos are detected through the cherenkov light that is generated when relativistic particles created as a result of the neutrino interaction pass through the detector medium. Event topologies allow for the identification of the neutrino flavor:
  - Tracks indicate muon neutrinos
  - cascades indicate electron and tau neutrinos



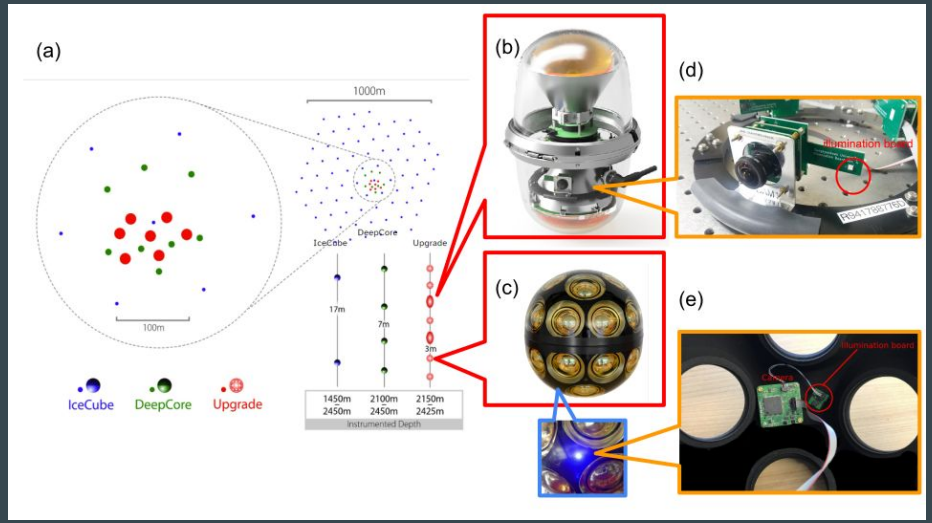
Ice property systematics

- The optical properties of the ice in the IceCube detector are a key systematic for most analyses
- There are 2 aspects to these properties that we are interested in:
  - The properties of the ice between strings (bulk ice)
  - The properties of a column of bubbles in the center of the drill holes of the IceCube strings (bubble column and hole ice)
- Current knowledge of these ice properties have been derived from measurements with the IceCube flasher LEDs and a camera system developed by the stockholm group (Sweden Camera)



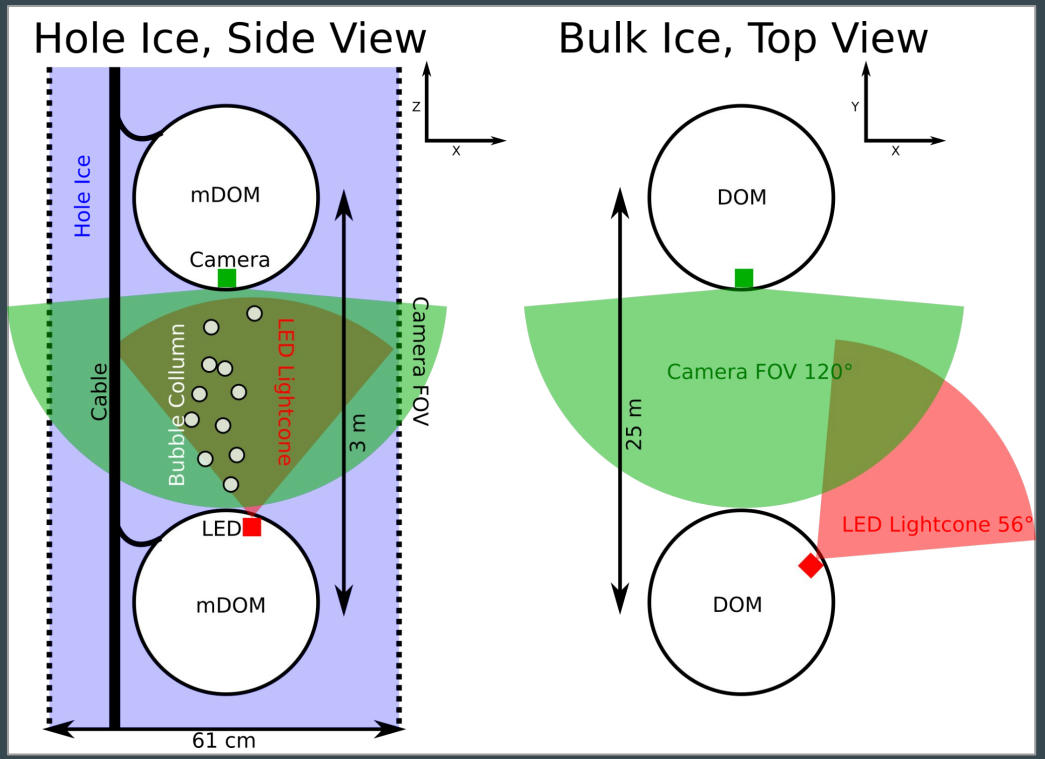
The IceCube upgrade camera system

- The IceCube upgrade camera system is a calibration device for the IceCube upgrade that aims to measure the optical properties
- It is being installed into all types of DOMs in the upgrade: the old pDOMs and the novel D-EGGs and mDOMs
- The total number of cameras and light sources in the upgrade is exceeding 2000
- On each DOM 3 cameras with one attached LED system each is installed with an additional standalone LED system in the mDOMs
- The camera system has been tested at the South Pole inside a logger system for a drillhole (more on this later) and it was part of the surveying efforts of the P-One collaboration

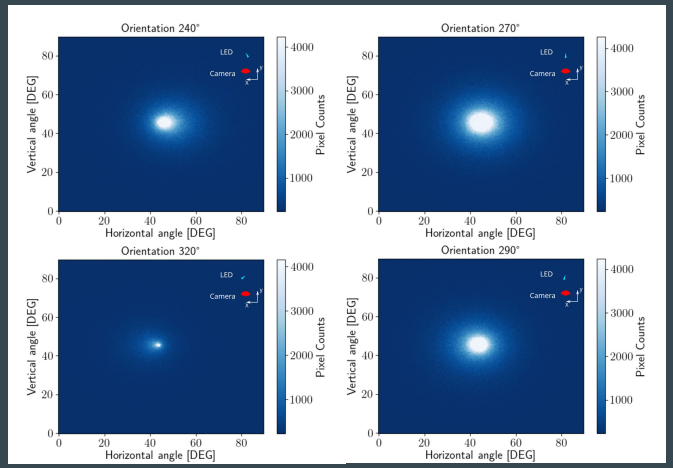


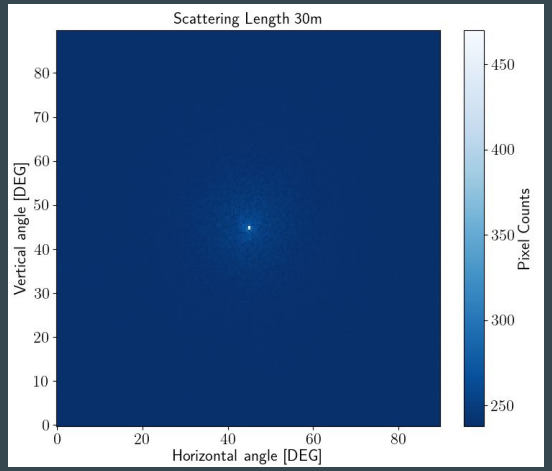
Camera measurements

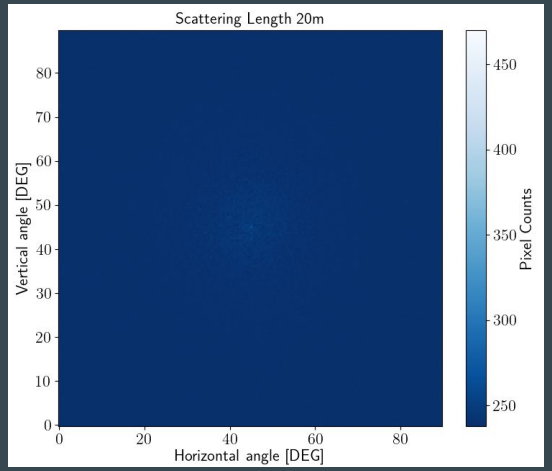
- As alluded to before there are 2 types of measurements the cameras are designed to do: bulk ice and hole ice measurements
- For the bulk ice measurements we use cameras on both mDOMs and D-EGGs to capture light from adjacent strings and measure the scattering and absorption of the ice from the intensity and distribution of light
- For the hole ice measurements we use downwards facing cameras on mDOMs to capture light from upward facing LEDs on mDOMs below or from LED next to the cameras to see the bubble column and measure its properties from the images



Camera Simulations



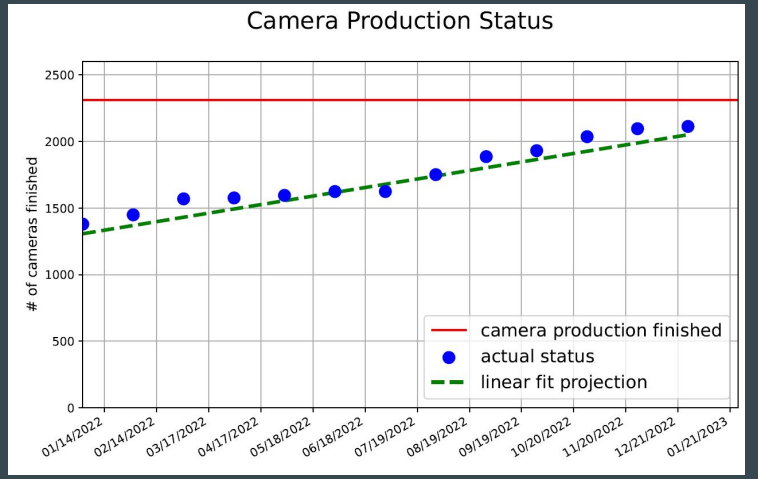




- Above some simulations done by students can be seen.
- On the left there is a series of simulations were an LED on an adjacent string was rotated to study the LED orientation as a systematic effect on the measurements
- On the left a similar simulation is shown where the scattering length was varied.
- The simulations are then used to develop analyses pipelines for the camera data.
- The simulation framework is also in use for the sweden camera and in the surveying efforts of P-One

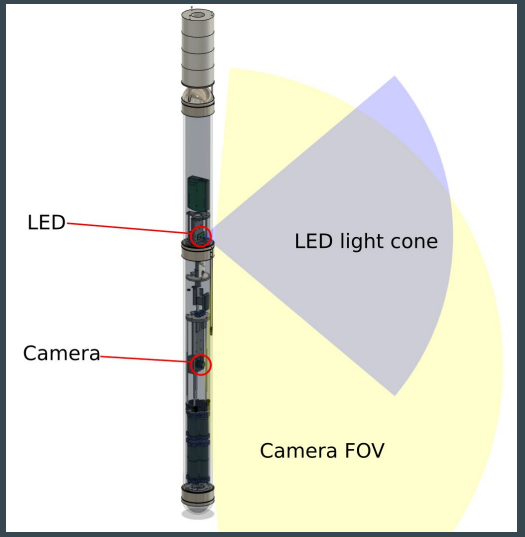
Mass production

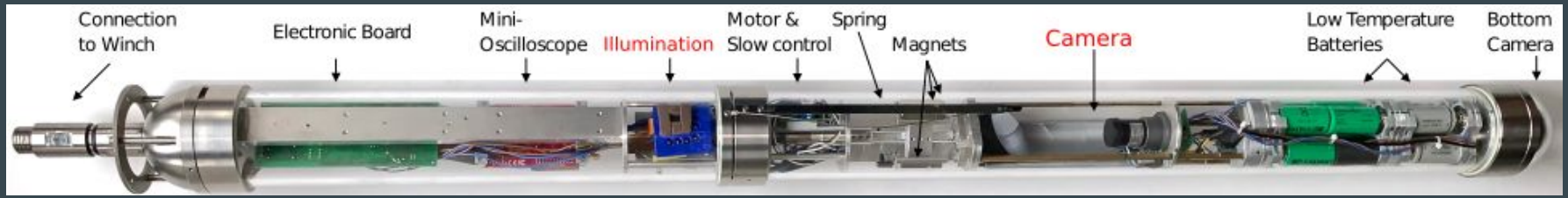
- My work included the oversight of the mass production and testing of cameras at the neutrino astroparticle physics lab at SKKU
- This included the development of mass testing setups, standard testing procedures and work on a data pipeline to process camera calibration data, storage of the data and a visual interface to evaluate camera data. This work was done with several undergraduate and graduate students who helped in the production effort and development of part of the setups and data pipeline.



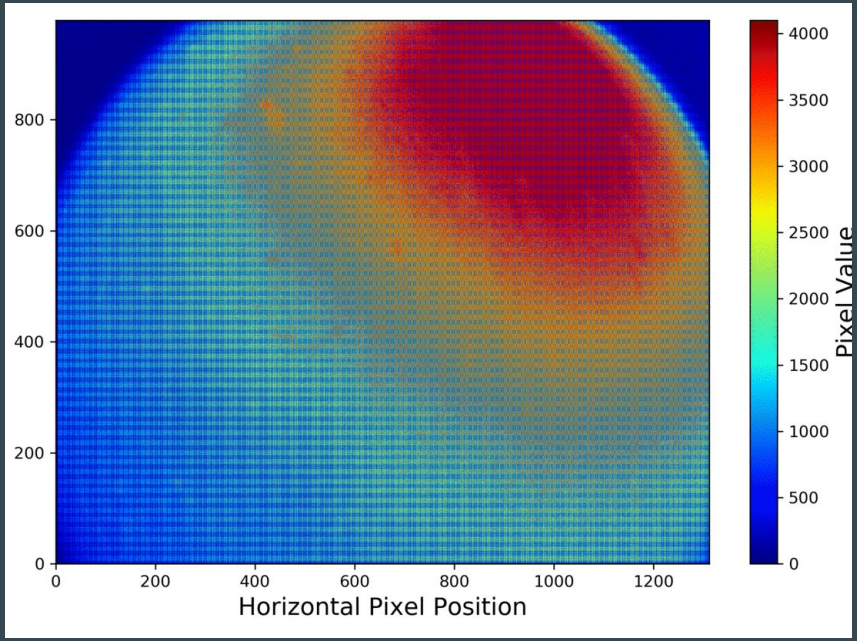
	D-Egg cameras	mDOM cameras	pDOM cameras
PRODUCTION			
commissioned	984	1320	99
produced	1017	1320	99
remaining to produce	0	0	0
amount we need to order (w/o spares)	0	0	0
SHIPMENT			
shipped to integration site	984	1320	13
total waiting to be shipped	0	0	86
--> at SKKU	0	0	86
--> at Utah	0	0	0
SPARES			
spares requested	33 (11 rings)	50	0
spares produced	33 (11 rings)	20	0
spares remaining to be produced	0	30	0
# cameras we need finish:	0	30	0

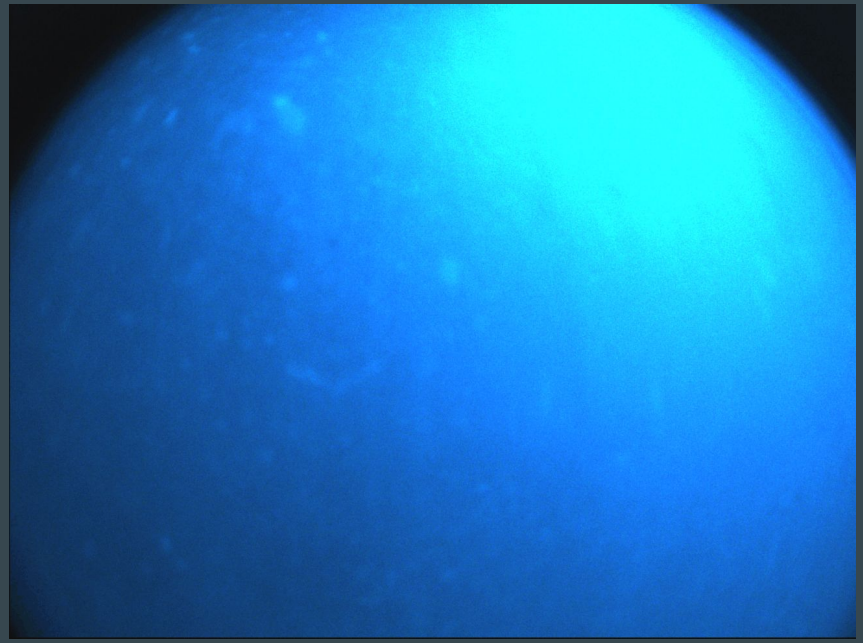
Upgrade camera deployment in the luminescence logger





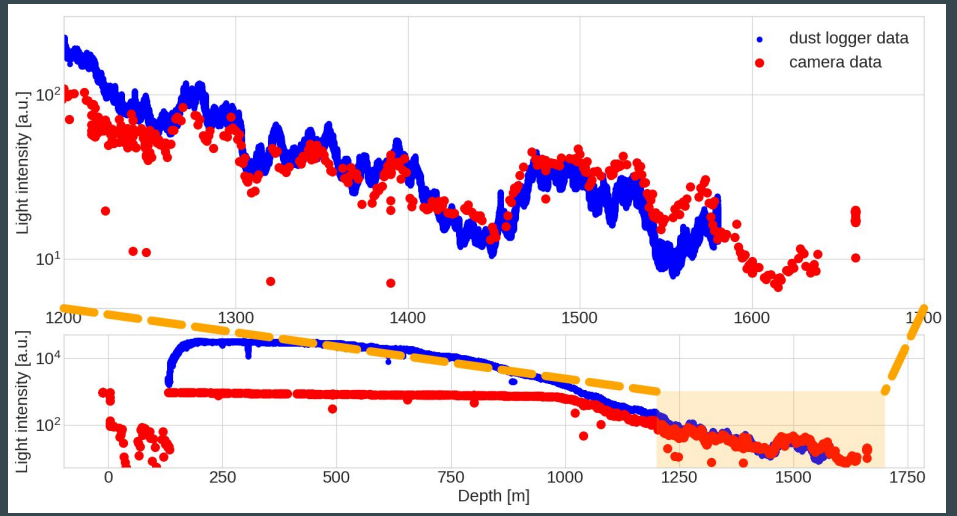
Videos from the first logger





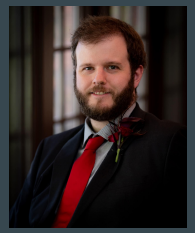
Upgrade camera deployment in the luminescence logger

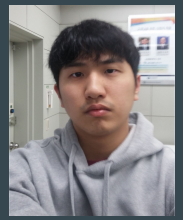
- Final results showed a nice correlation to previous measurements from the dust logger
- The second logger (upgrade camera in luminescence logger) showed much better results



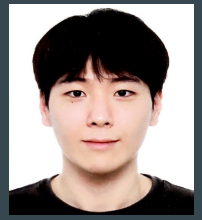
The Camera Team in 2024

Prof. Carsten ROTT





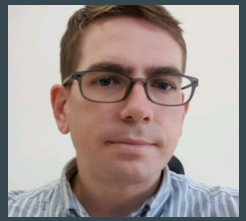
Jiwoong LEE



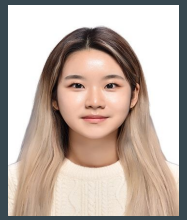
Seowon CHOI

Minyeong SEO

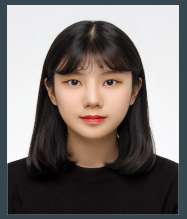
Woosik KANG



Dr. Steven RODAN



Minji SHIN



Youbin OH

Yoonyoung Kim

Gyunho YU

Summary

- I worked on the TERZINA detector and created a simulation of the DAQ system for the full simulation chain.
- I contributed to lab tests of the SIPM tiles for the final detector to evaluate radiation damage and the effectiveness of annealing
  - The end goal was to evaluate the possible detector settings as a function of time and different detector performance results for different annealing strategies
- I developed a full detector chain for the LACTEL detector based on CORSIKA and GEANT4
  - First results for the full chain were generated
  - There are ongoing comparisons to other simulation frameworks
  - First estimations of detector performance were started

Backup

Publications

1. Secluded dark matter search: PoS(ICRC2021)521
2. IceCube Upgrade Camera: PoS(ICRC2023)1037
3. Camera Simulations: PoS(ICRC2023)1071
4. DISCO device: PoS(ICRC2023)1139
5. TERZINA performance and radiation damage mitigation: JCAP (2025) 07 073
6. LACTEL publication is in preparation

References

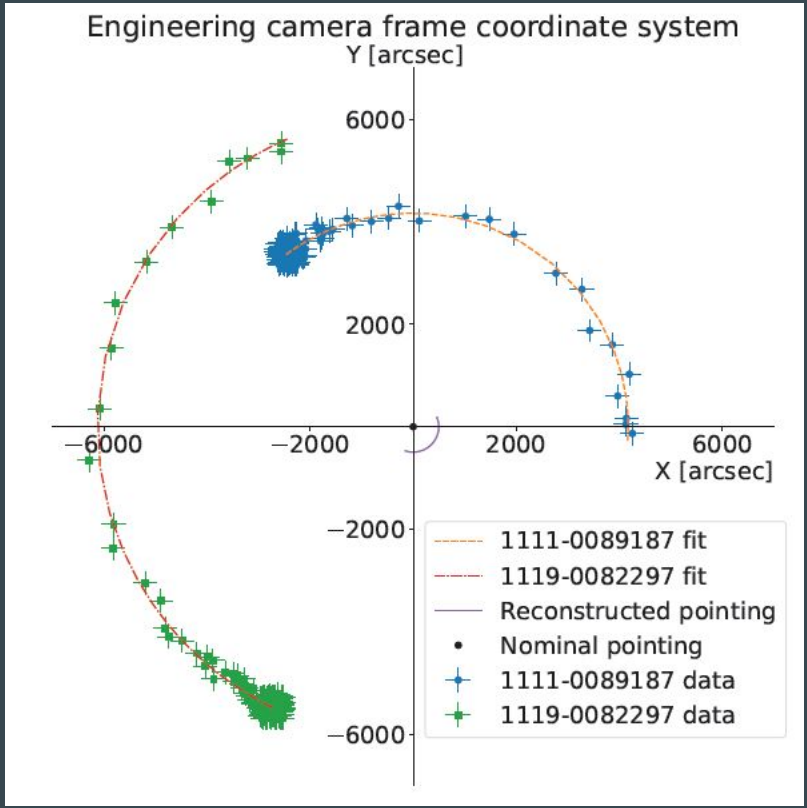
1. Secluded dark matter search: PoS(ICRC2021)521
2. IceCube Upgrade Camera: PoS(ICRC2023)1037
3. Camera Simulations: PoS(ICRC2023)1071
4. DISCO device: PoS(ICRC2023)1139
5. CTA and startracking: Astron. Astrophys., 679 A90 2023
6. TERZINA: EPJ Web of Conferences 283, 06006 (2023)
7. LACTEL: PoS ICRC2025 (2025) 443

Implementation of calibration functionalities in the DPPS framework for the CTA observatory

DPPS and CTAO

- My work in the CTA observatory collaboration was focused on the data processing and preservation system (DPPS), effectively the data pipeline for the entire observatory, incorporating all planned subarrays and detector types
- I in particularly was working with others on implementing proper functionalities for calibrating cameras, including pedestals, relative gain between pixels and the camera pointing
- For the last part I am tasked porting a code over into the ctapipe framework that had been used to fit camera pointing

Startracker code

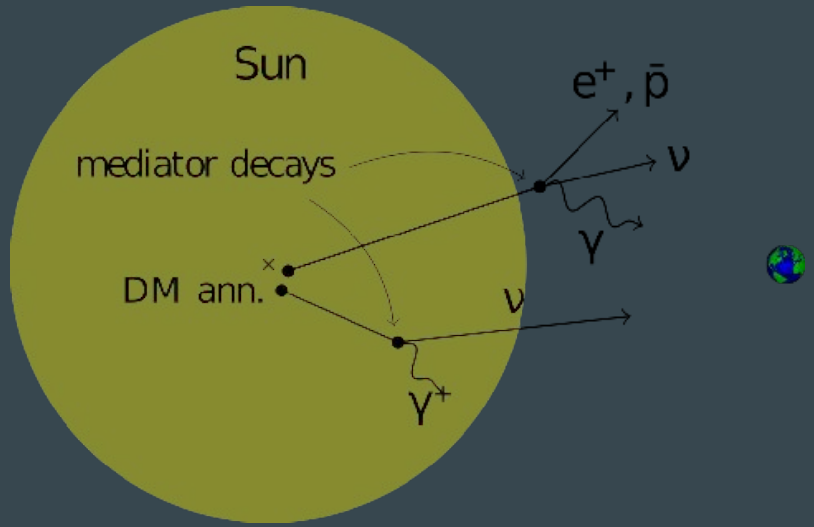


- The existing startracker code was written by Mykhailo Dalchenko and has been tested on simulations and LST data
- To use the code in the broader CTA framework a significant rewrite is necessary
- This includes changes to image calibration and relying on waveform variance to detect stars to get around the adaption to brightness of the pixels of some CTA cameras
- The ultimate goal is to have this code be usable with all telescopes and close to live during operations

Dark matter analysis

Secluded dark matter

- Secluded dark matter is a unique type of model for dark matter
- In this model Dark matter particles do not directly decay or annihilate into standard model particles
- Instead in dark matter annihilations metastable mediators are produced
- After a lifetime that can range from microseconds to 10 seconds the mediator decays into some standard model particle
- This mediator is itself not a standard model particle and can avoid interactions with baryonic matter
- In case of annihilations of dark matter accumulated in the Sun absorption in the solar plasma can be avoided



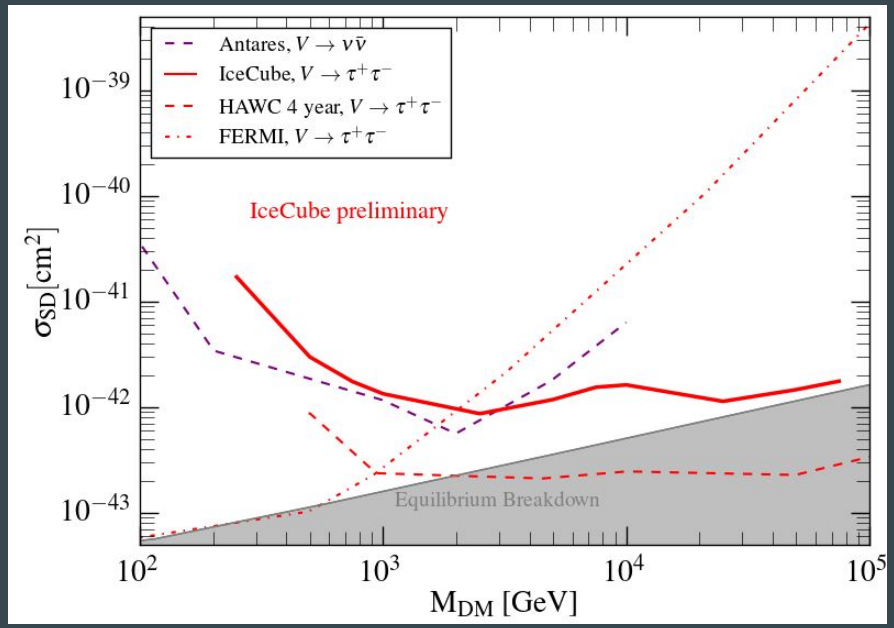
Method

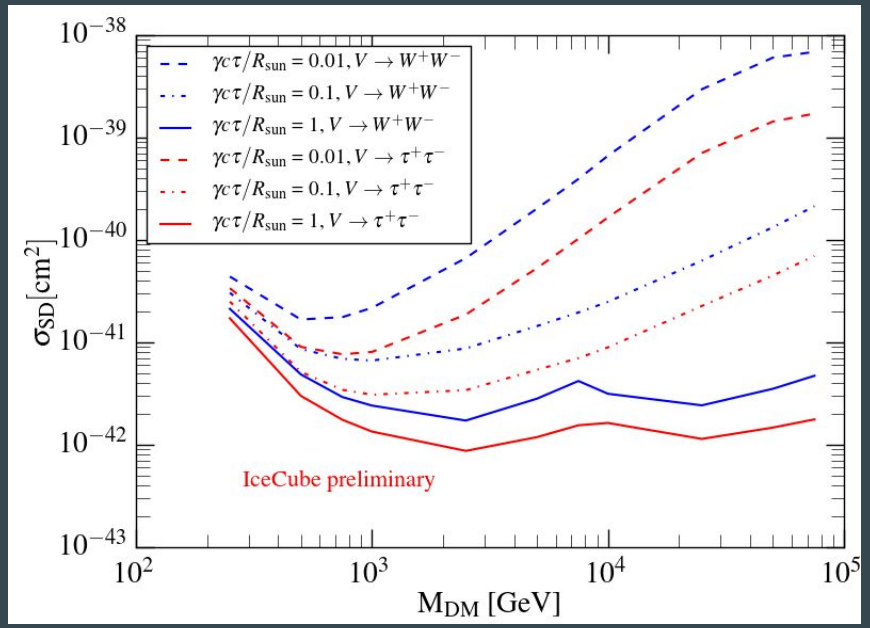
- An unbinned likelihood method is used
- The likelihood function has the following shape:

$$\mathcal{L}(n) = \prod_{i=0}^{N} \left(\frac{n}{N} S(\psi_i, E_i) + \frac{N-n}{N} B(\psi_i, E_i) \right)$$

- N is the sample size, S describes the signal behaviour as a function of the angular separation of an event to the Sun ψ_i and its energy E_i for event number i. B is the corresponding function describing the background.
- The background part of the likelihood is generated from time scrambled data
- Using this likelihood the IceCube northern tracks sample from 2011 to 2016 with 1057.8 days of livetime is being analysed

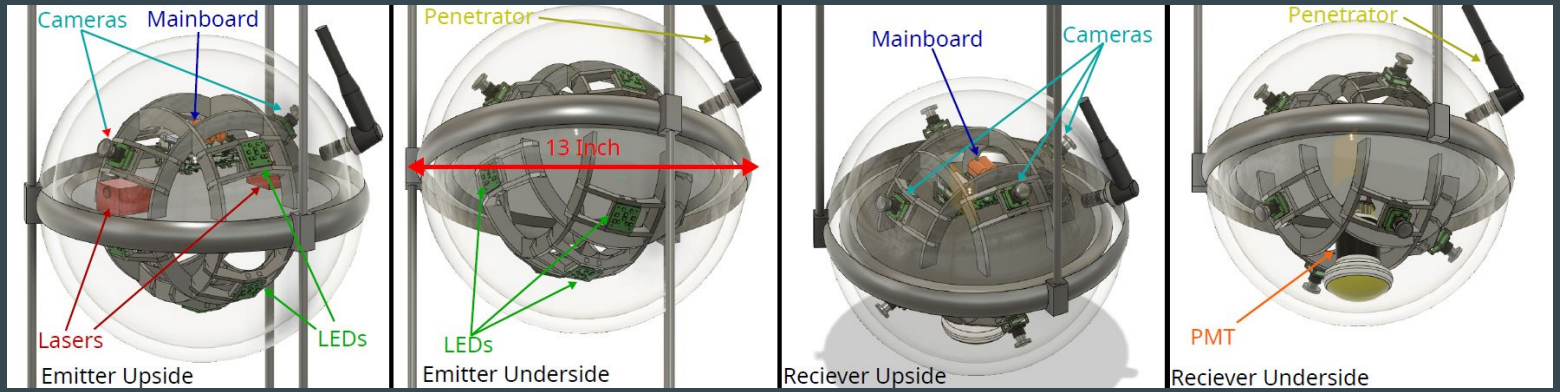
Limits





No significant excess above the expected background was found in the examined dataset. The set limits are the best of any current neutrino experiment above 3 TeV accounting for differences in mediator decay channel.

Proposal for DISCO device to US national research foundation



- I have been working on a proposed camera, laser and PMT-based calibration device called DISCO (Deep Ice and Sea Calibration Observer)
- Part of this work was running my simulation and analysis framework to study the potential sensitivity of the device and develop a proposal for a mechanical holding structure for the device
- I also organized 2 workshops on camera based calibration for astroparticle physics detectors in 2021 and 2022

South Pole Ice Core camera logger and IceCube upgrade camera test in Luminescence logger