Monitoring the energetic and transient Universe with the ALTO Observatory

ALTO

http://alto-gamma-ray-observatory.org

Yvonne Becherini – Linnaeus University (Sweden)

Michael Punch, Jean-Pierre Ernenwein, Satyendra Thoudam,
Mohanraj Senniappan, Tomas Bylund

Outline

- Generic information about the project
- Monte Carlo simulations and expected performance of the full array
- Prototype at Linnaeus University
- Future activities

The ALTO project

- Project born in 2014 at Linnaeus University after a research grant from the Crafoord Foundation was received

- A Wide Field-of-View (~ 2 sr) gamma-ray observatory:

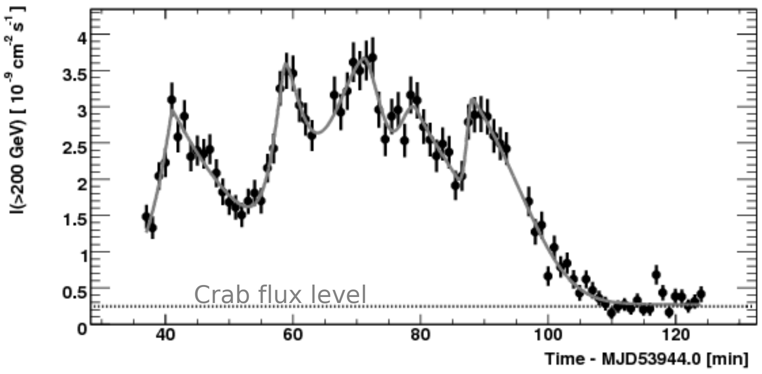
  - In the Southern hemisphere → Daily observations of Southern sources
  - At high altitude (> 5 km) → Low threshold E ≥ 200 GeV
  - Particle detectors → Observations may be done 24h per day
  - Hybrid detectors → Improved S/B discrimination
  - Excellent timing accuracy → Improved angular resolution (~ 0.1° at few TeV)
  - Modular design → Phased construction and easy maintenance
  - Simple to construct → Minimize human intervention at high-altitude
  - Long duration → Should operate for 30 years
  - “Open Observatory” → Distribute data to the community “à la Fermi-LAT”
  - Target cost → 20 M€ max

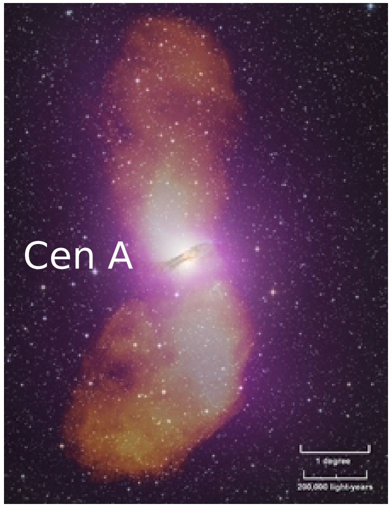
ALTO Science Goals

Daily monitoring of Southern targets:

- Transients and variable sources;
- Active Galactic Nuclei, Gamma-Ray Bursts (if spectra favourable), X-ray binaries;
- Galactic centre and central region;
- Alerts to other observatories;
- Multi-year light-curves;
- High-end of the sources' spectra;
- Search for PeVatrons;

H.E.S.S. PKS 2155-304 (blazar) flare





Study of extended sources:

Fermi Bubbles,
Vela SNR,
AGN radio lobes;

Credit: NASA/DOE/Fermi LAT Collaboration, Capella Observatory, and Ilana Feain, Tim Cornwell, and Ron Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR)

Other accessible goals:

- Search in past data if alerted to detections of:
  - gravitational waves or
  - neutrinos;
- Study of the cosmic-ray composition & anisotropy;
- Dark matter searches;
- EBL studies (if threshold low enough);
- Search for Lorentz invariance violation;
- Axion-like particles from distant AGNs.

Collaboration up to 2019

Sweden

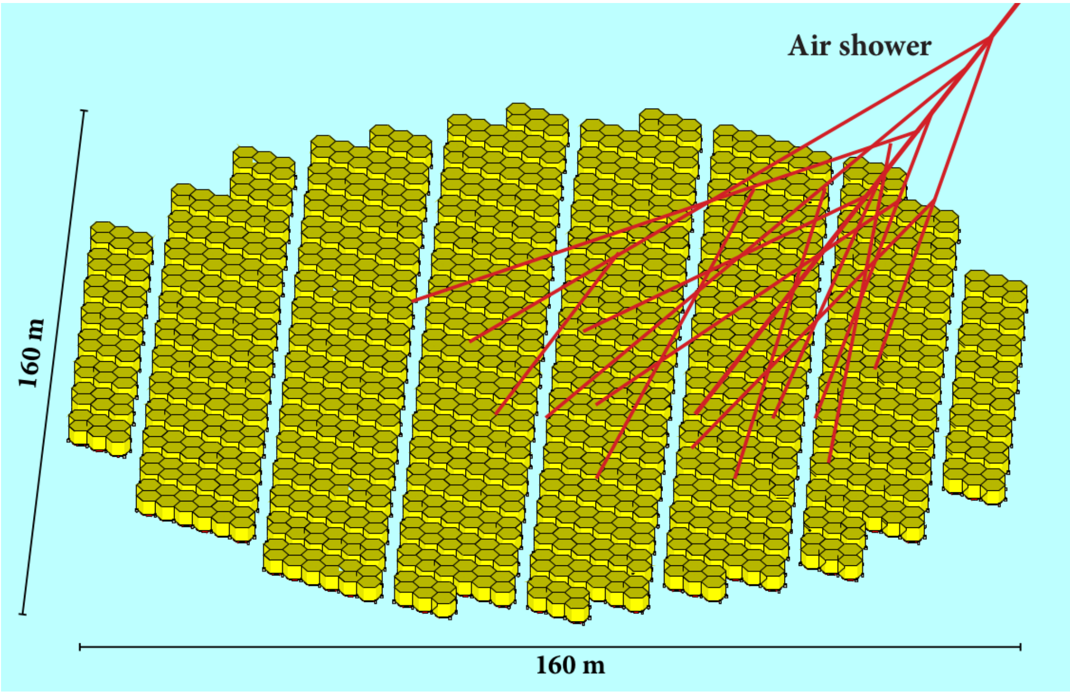
- Department of Physics and Electrical Engineering, Linnaeus University, Växjö
  - PI Yvonne Becherini
  - Post-doc Satyendra Thoudam
  - Two PhD students
- Industry: TBS Yard AB, Torsås
  - Industrial construction responsible Lars Tedehammar

France

- APC Laboratory, IN2P3/CNRS, Paris
  - Michael Punch
  - Jean-Christophe Hamilton (discussions about the site)
- Aix-Marseille University
  - Jean-Pierre Ernenwein
- LAL/Orsay
  - Dominique Breton, Jihane Maalmi (work on WaveCatcher electronics)
- CEA/Saclay
  - Eric Delagnes (past discussions on electronics)

Key design characteristics of the full array

- Key characteristics wrt HAWC:
  - Advanced electronics with sub-ns timing
  - Small-sized, closed-packed WCDs
  - Low dead-space ("packing factor" ~70%)
  - Muon detectors below the Cherenkov tanks

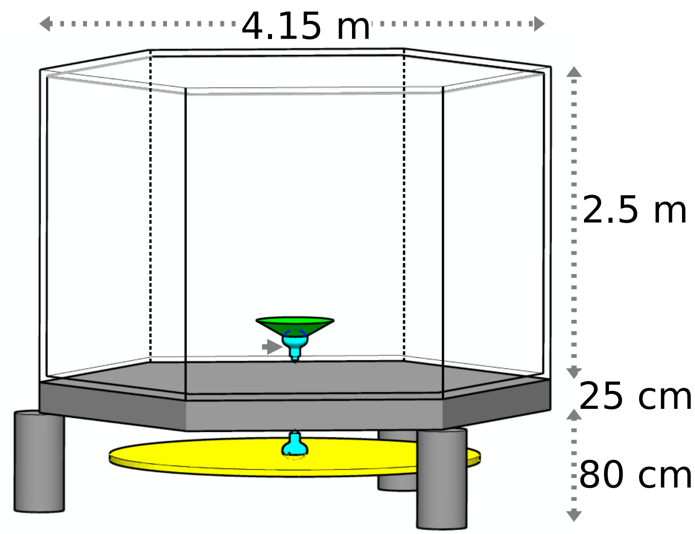


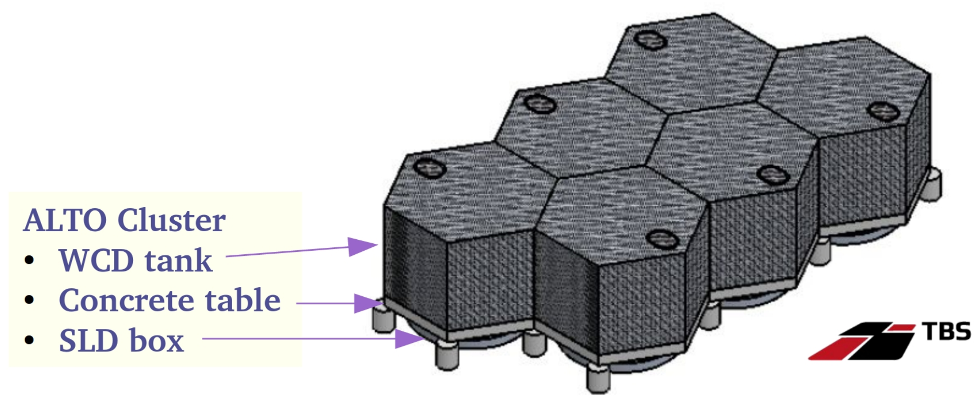
Satyendra Thoudam

ALTO detection unit & cluster

Satyendra Thoudam

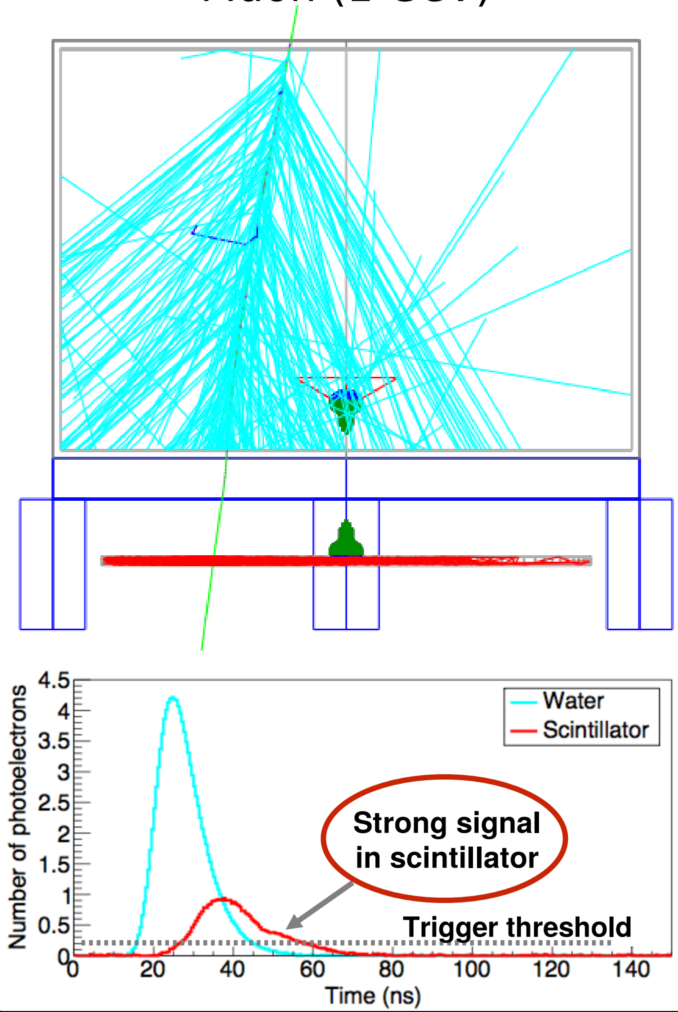
- Water Cherenkov tank:
  contains one Hamamatsu super-bialkali 8’’ PMT;
- Muon-detector scintillator tank for background rejection:
  - Liquid scintillator box (Scintillator Layer Detector, SLD) with one 8’’ standard Hamamatsu PMT;
- Advanced electronics for 6-tank “cluster”,
  WaveCatcher + White Rabbit:
  - Trigger channel precisely time-stamped with “White Rabbit” system;
  - Analogue memories + ADCs measure the waveform of the detector pulses;
  - SBC (single board computer) for local control & acquisition
  - No cables from central DAQ room, only fibres.



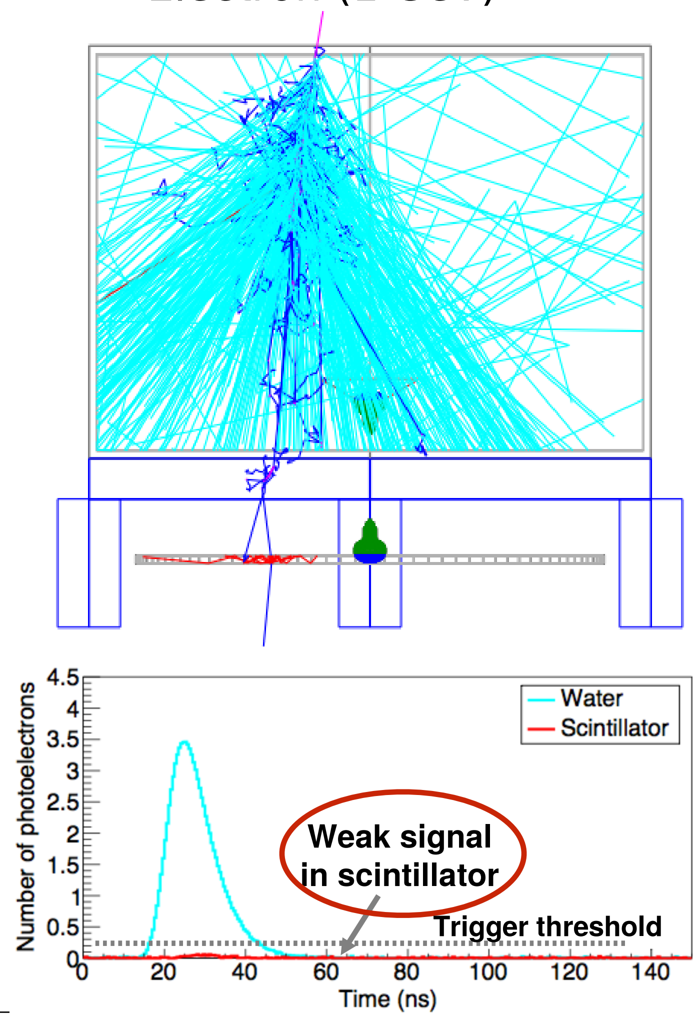


ALTO response to single particle

Muon (1 GeV)



Electron (1 GeV)



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Monte Carlo simulations, reconstruction & higher level analysis

- Corsika simulations:
  - Point-like gamma-rays
  - Diffuse protons (0-30) deg

- Geant4 simulations:
  - Cherenkov tank is black, so we track only photons which geometrically reach the PMT
  - Very CPU-consuming for ~ 1200 ALTO units

- Reconstruction of shower parameters:
  - Direction with hyperbola fit
  - Core position with NKG fit

- Muon tagging (new!):
  - Muon signal identification procedure (per unit)

- S/B discrimination with TMVA/BDT:
  - 9 parameters using:
    - Detected/expected water Cherenkov charge
    - Detected/expected scintillator charge
    - Number of triggered detectors
    - …

- High level analysis with Python Jupyter notebooks

Monte-Carlo simulations
- Shower particles with CORSIKA

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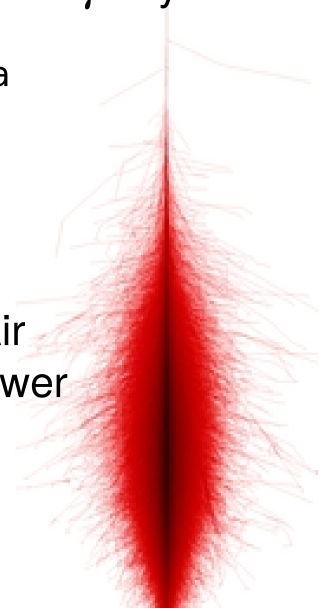

- Realistic model of Earth's atmosphere, magnetic field, refractive index, ….
- Electromagnetic and hadronic interactions based on particle physics models.

Parameter	Gamma rays	Proton
Observation height	5.1 km	Same
Energy	10 GeV-100 TeV	158 GeV-100 TeV
Spectral slope	-2.0	-2.7
Zenith angle	Fixed at 18, 32, 41° (was 18° with bug)	0-48° (was 0-30° with bug)
Azimuth angle	Fixed at 180°	0-360°
Magnetic field	ALMA site	Same
Core position (from array centre)	0-100 m (square)	Same
No. of showers	~17 million	~21 million (→ 12 minutes!)

Note:
- No reuse of Corsika showers currently

Air shower simulation:
CORSIKA (version 7.4000)

Future: with these CORSIKA simulations,
we will be able to get the instrument response up to 45°
→ **Will do "HAWC-like" moving source response per year**

Monte-Carlo simulations
- Photo-electrons at PMTs with GEANT4

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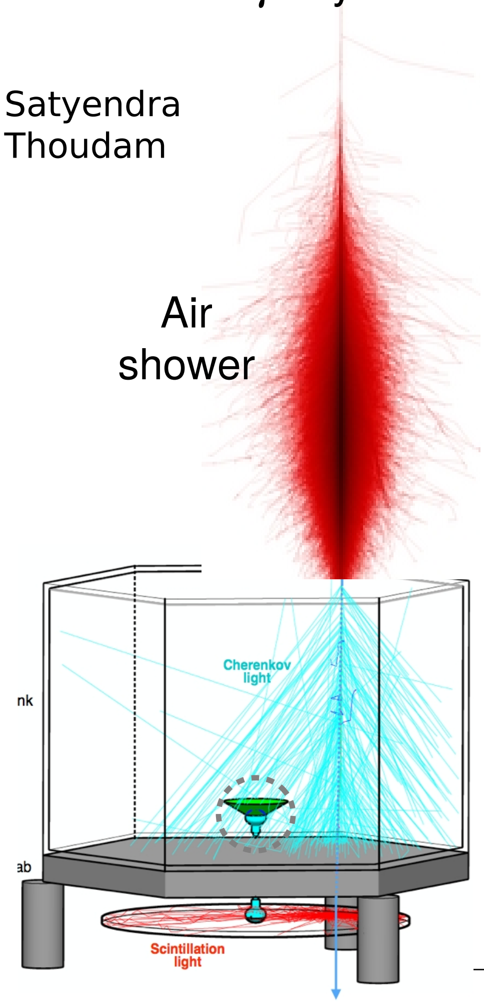

Detector simulation: GEANT4 (version 10.2)

- **All material properties included:**
  - Density, refractive index as function of wavelength.
  - Photon reflectivity, absorption and scattering coeff. as function of wavelength.
- **All important physical processes included:**
  - Electro-magnetic processes:
    - γ's: Photoelectric effect, Compton scattering, Pair production, Rayleigh scattering.
    - $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, nuclei: Multiple scattering, ionisation, bremsstrahlung, annihilation (positrons)
    - Unstable particles: Decay
  - Optical processes:
    - Cherenkov and Scintillation photons production.
    - Their emission spectrum, absorption, scattering …
- **Particle tracking**
  - All particles completely tracked by GEANT4 except for photons inside WCD.
  - ~10^5 photons (Cherenkov/Scintillation) produced in each tank.
  - For optical photons inside water tank:
    - Only those that are likely to hit the PMT are tracked.

Waveforms @ Reconstruction step

- **Signal propagation inside photomultiplier tubes:**
  - Include signal time spread (TTS) and PMT gain fluctuations.
  - Create waveforms with piled-up single-PEs

Event direction and position on the ground

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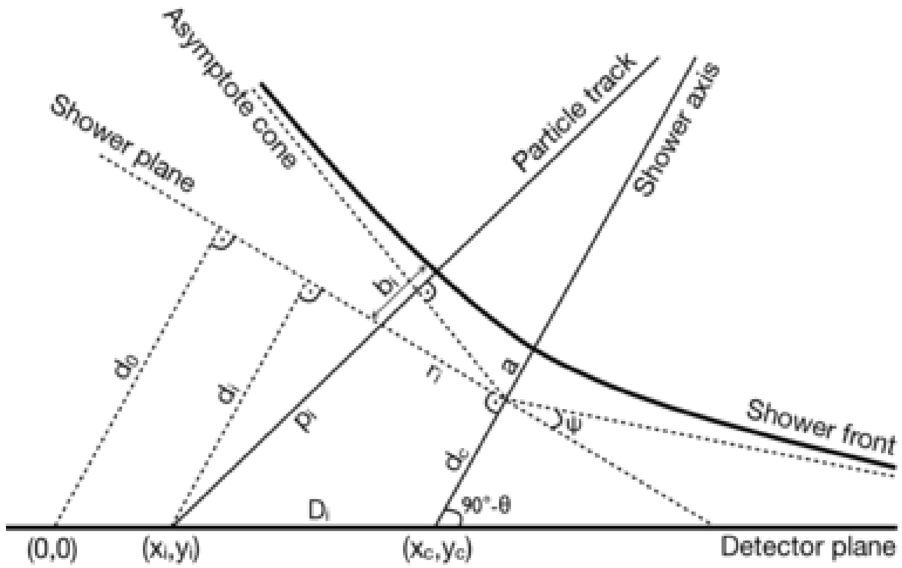
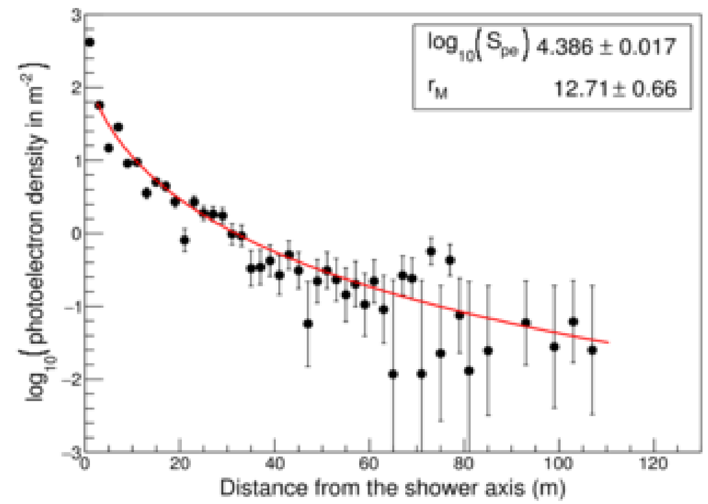
Hyperbolic fit to the wavefront



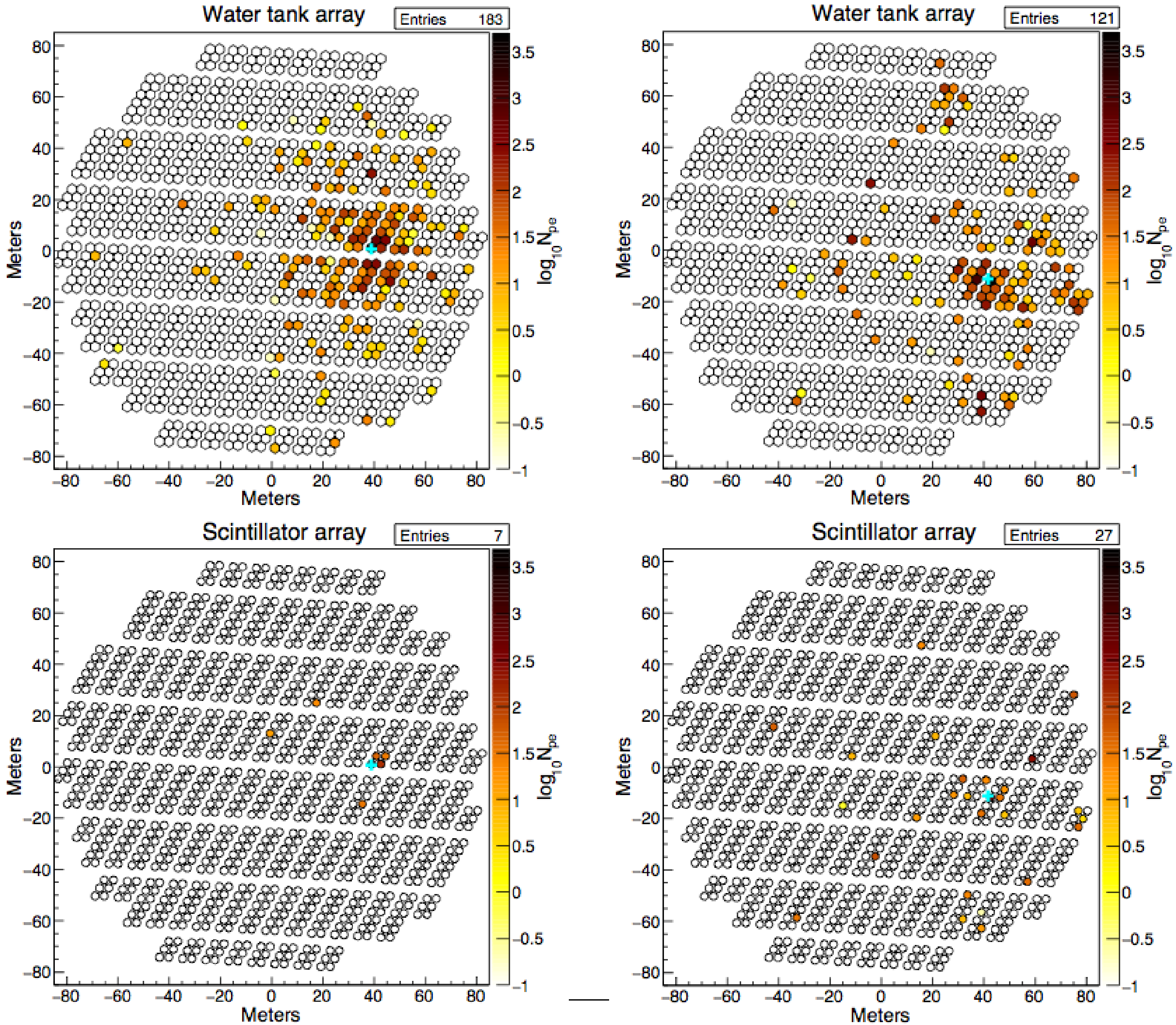
1-D Lateral distribution

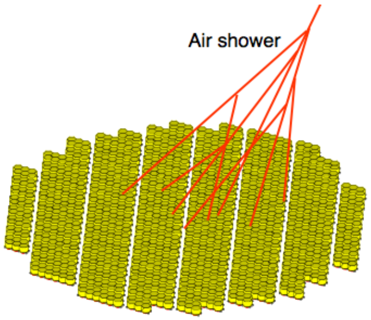


Iterative procedure between the NKG lateral-distribution fit and the particle-front timing fit

ALTO Array response to Air Showers

Gamma ray | **Cosmic-ray proton**





Gamma ray
- More compact
- Regular pattern

Cosmic ray
- Clumpy
- Hot spots in the scintillators at large distance from the core

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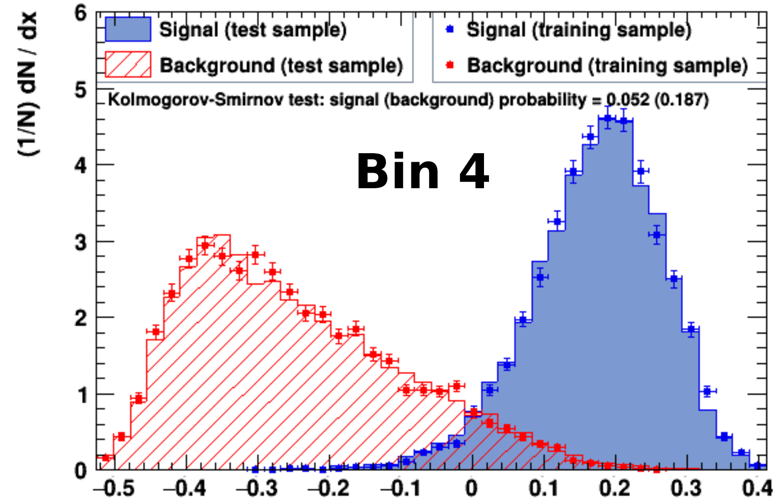
ALTO Signal over Background discrimination

- **Sample divided into 4 increasing RSize ranges (bins)**
  - Independent analysis developed for each bin (using MVA-BDT)
  - For each, a gamma efficiency was required
  - Training applied gave the proton efficiency shown.



For 32°:

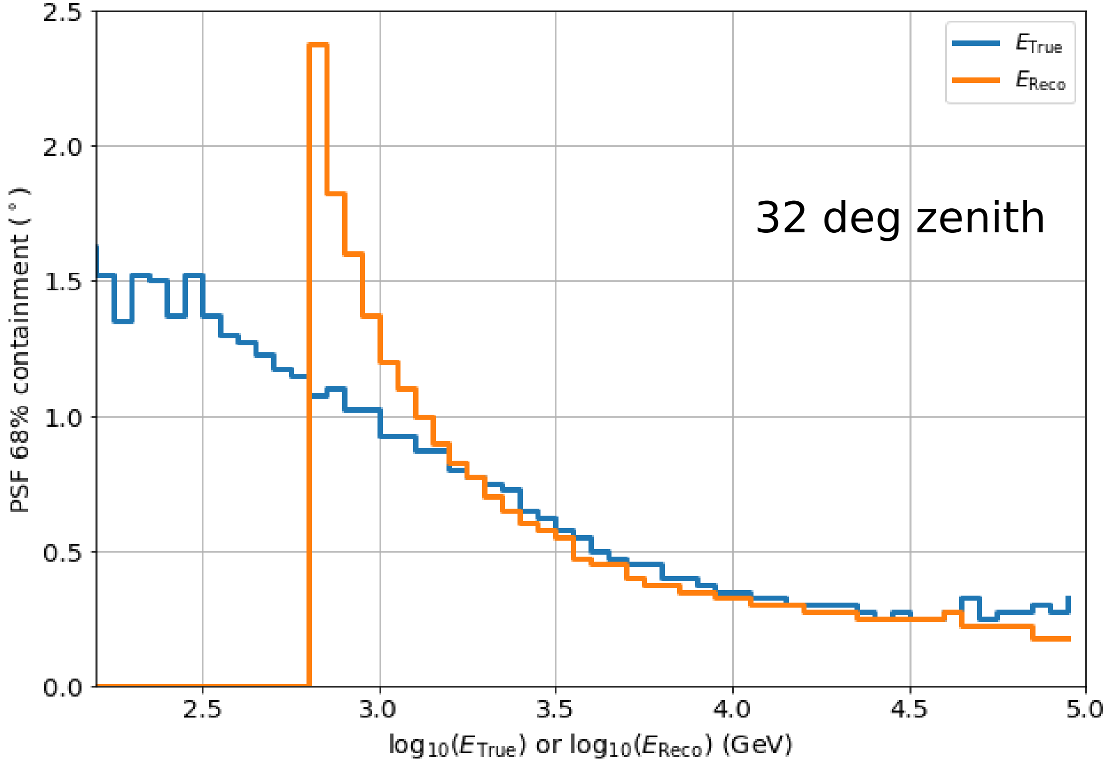
Bin No.	RSize limits (Number of events trained)	TrueEnergy Mean (in GeV)	Gamma Efficiency	Proton Efficiency
1	1.00 - 3.69 (8609)	700	0.4	0.15
2	3.69 - 4.04 (8638)	1142	0.6	0.17
3	4.04 - 4.43 (8593)	2158	0.8	0.12
4	4.43 - 7.00 (8417)	8695	0.9	0.04

Mohanraj Senniappan

Point Spread Function after all analysis cuts

- Determining cut for 68% containment of Gammas
- **NB:** Energy scale shifts by $\log_{10}(0.2)$, or ~60% from 18 → 32°

Michael Punch



Differential Sensitivity

- **Sensitivity** for 1yr live-time on a source at 32°:

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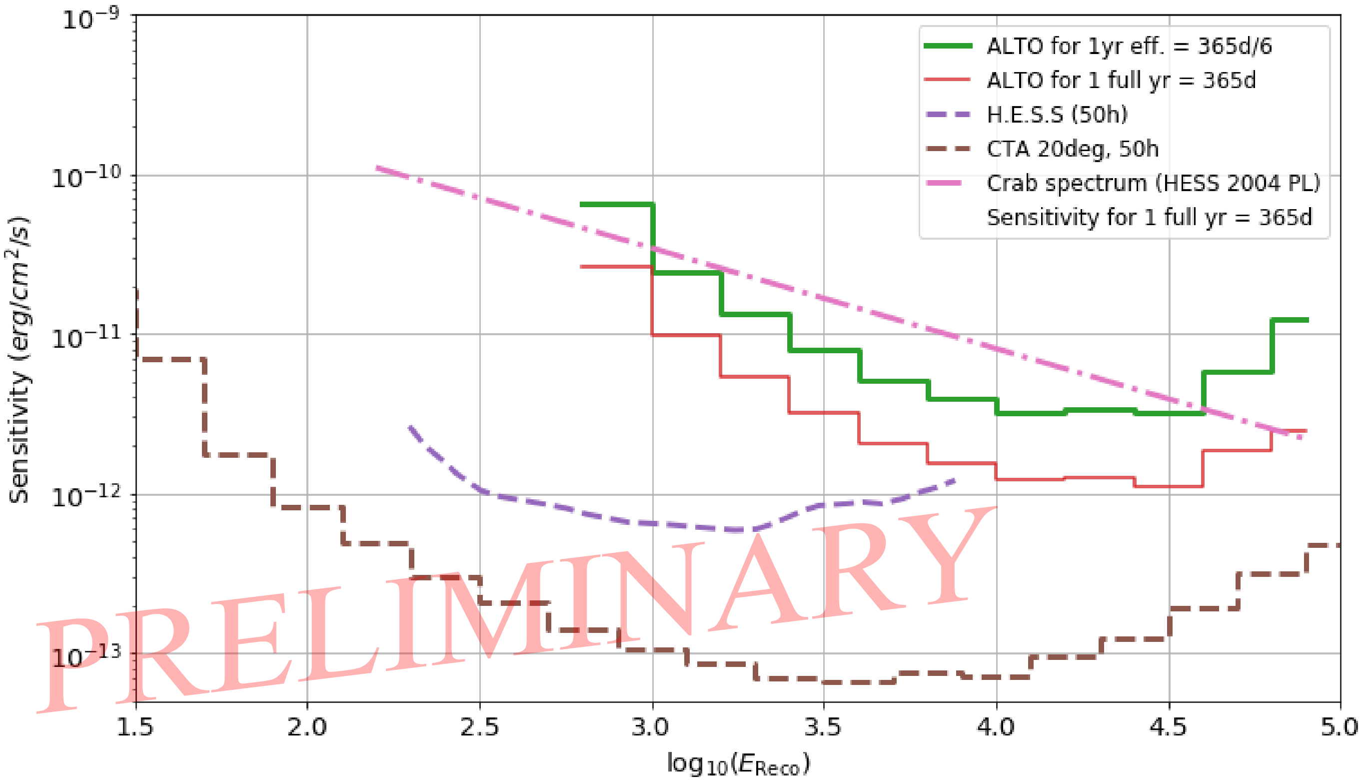
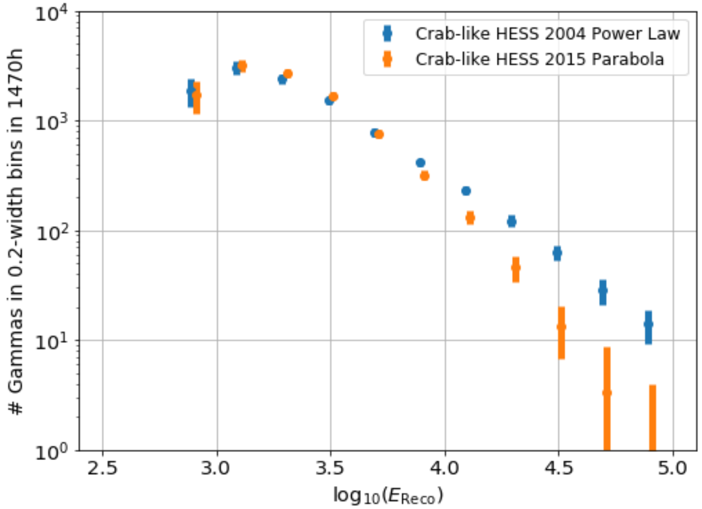
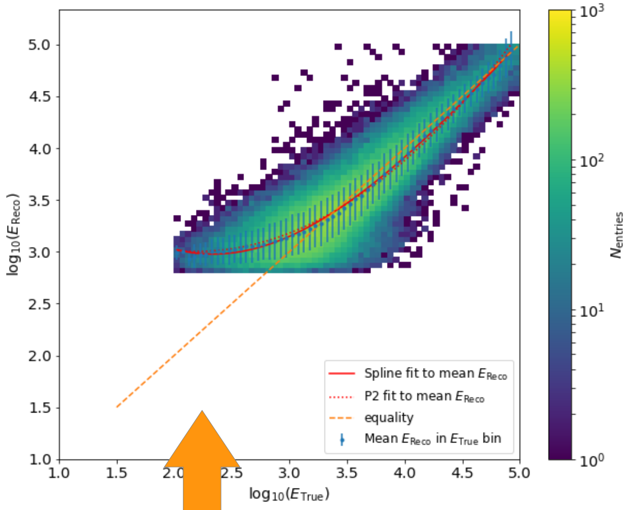


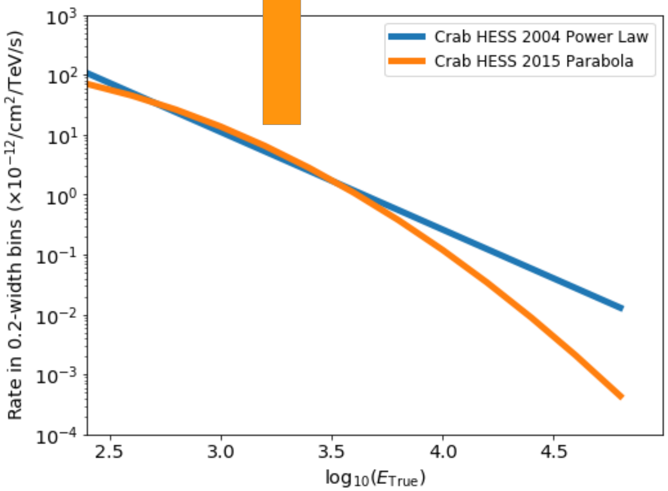
- **CAVEATs**:
  - First result at 32°, without "muon-tagging" (only some scintillator params)
  - Plan to test other layouts (e.g. graded), if faster GEANT4 available

Response to a Crab spectrum

2 months of data on-source, 75 sigmas

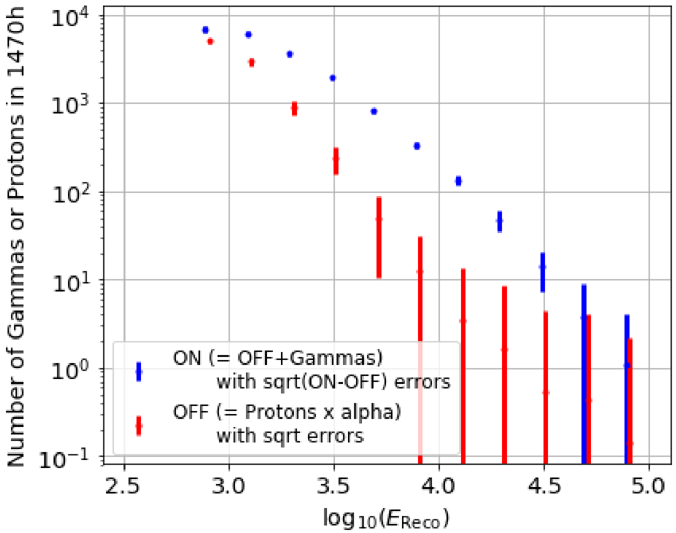


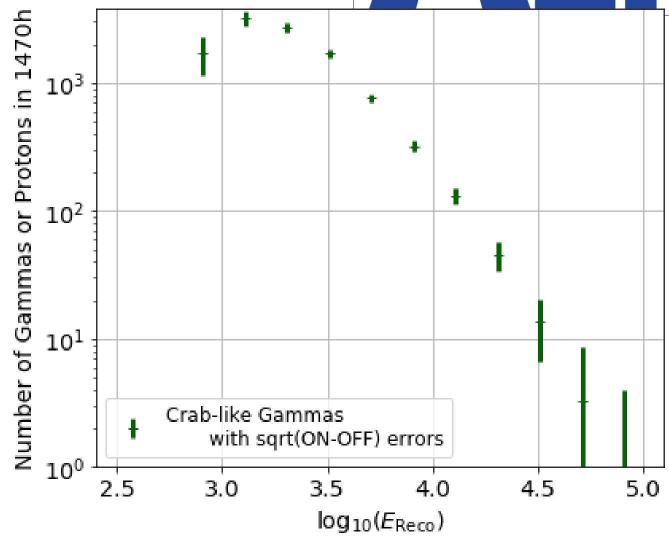




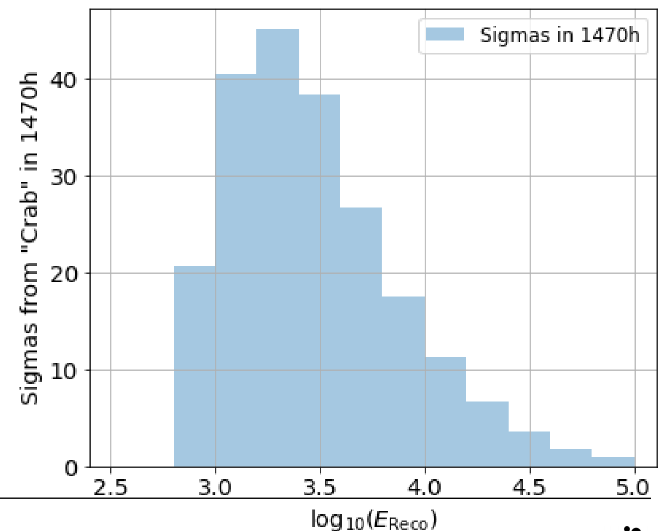
- Convolved through the effective area + energy dispersion (response matrix)
- Combined with Proton background to get realistic errors
- 2 months of data on-source
- Distinguish previous Crab-spectra at ~8 sigma

Response to a Crab spectrum





- e.g. for 1/6 of a year
  (~~ source visibility)
- For a Crab-like source at 32°
  - #Gammas: 10578
  - #Protons in PSF: 9167
  - ~ 75 sigma
- Distinguish previous Crab-spectra at ~8 sigma
- Peak of response at bin around 1.25 TeV
  - (but minimum bin around 800 GeV)



Michael Punch

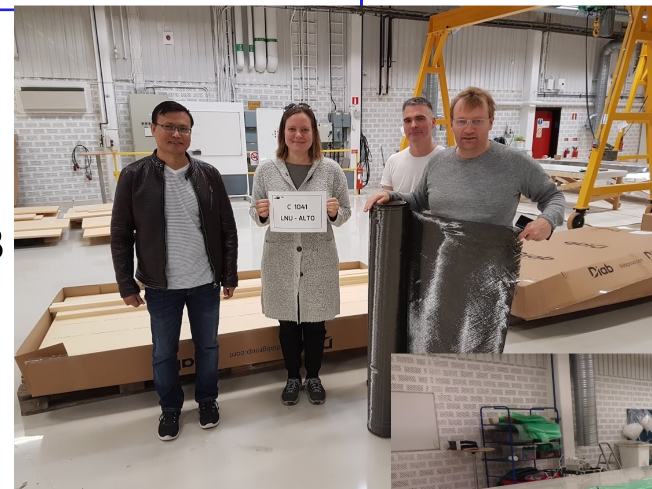
ALTO prototype construction timeline in 2018

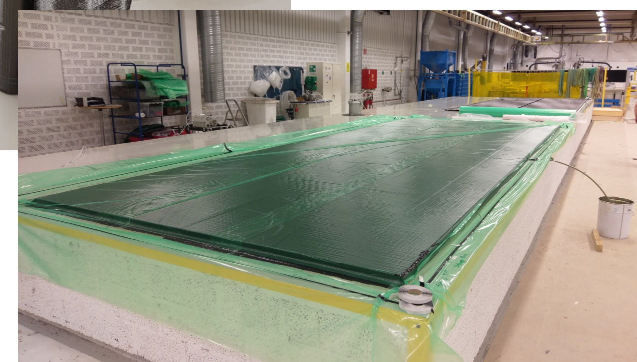
Follow our Blog on the website alto-gamma-ray-observatory.org

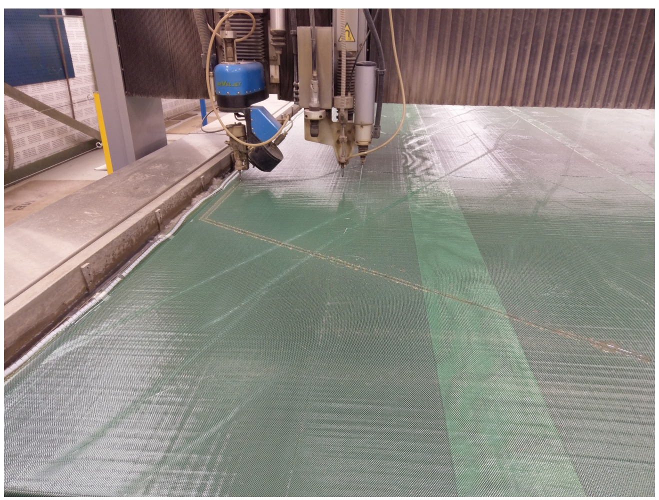
- Jan 8: Digging at the prototype site on LnU campus started
- Jan 26: Ground preparation and underground concrete base finished, columns construction well underway
- Jan 31: Concrete slab pouring
- Feb 27: Concrete structure ready, first water tank ready at TBS Yard (needed more carbon fibre for the second tank)
- Apr 7: Both water tanks ready, water resistance test
- Apr 18: Water tanks arrived at prototype site
- May 6: Photomultipliers installed in the water tanks and work on electronics and network ongoing
- May 8: First air-Cherenkov coincidence event between ALTO tanks with the full DAQ chain
- May 16: Filling of water Cherenkov tanks
- May 25: Data taking with ALTO water Cherenkov tanks started
- June 28: Added small plastic and liquid scintillators, waiting for the final ALTO scintillators
- Aug 7: Muon detectors production started
- Oct 7: Event display available
- Nov 30: First muon detector arrives at Linnaeus University
- Now: Scintillator tank inside for tests. No oil leakage, PMT installed, procedures of oil filling and installation set up
- January: Installation of the muon detectors below the water tank.
- February-March: Validation and feedback on the muon detector to Industry

ALTO WCD Tank Construction (2017)

- Composite material
  - Carbon fibre and PVC foam
  - Produced in Torsås by TBS Yard AB
- Planned for “flat-pack” shipping
  - Remote assembly
  - Gluing with Carbon fibre overlaps

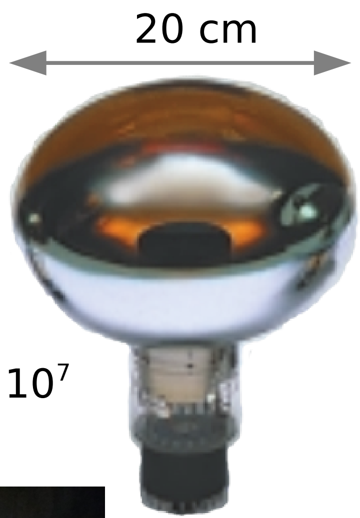




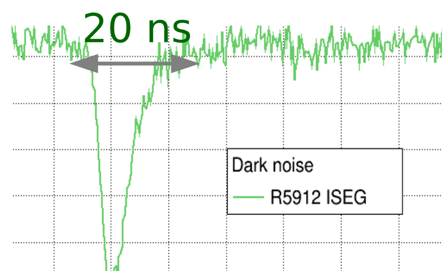


8” Hamamatsu PMT

8 inch photomultiplier
10 dynodes



Gain ~ 10^7

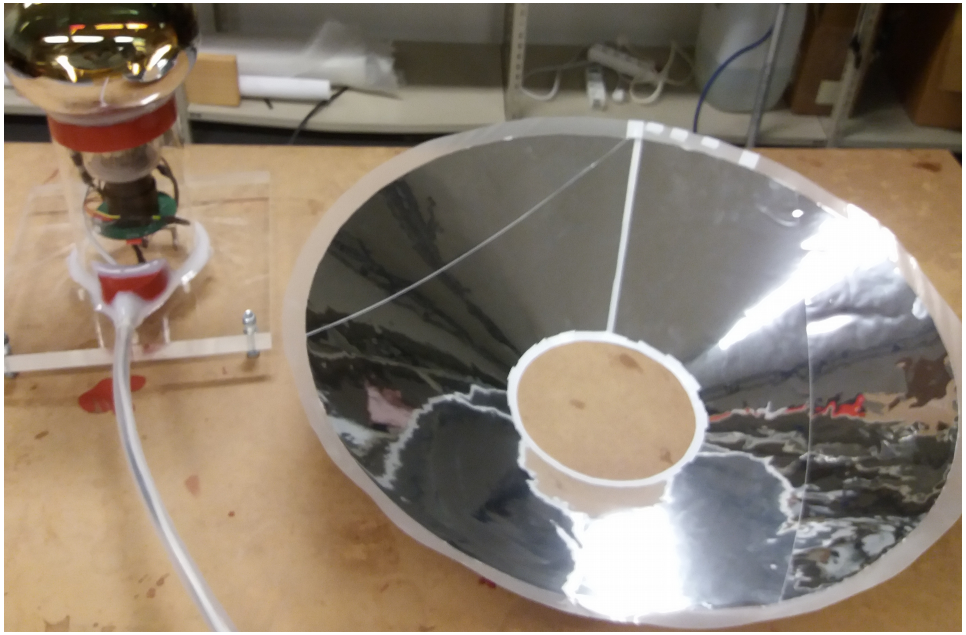


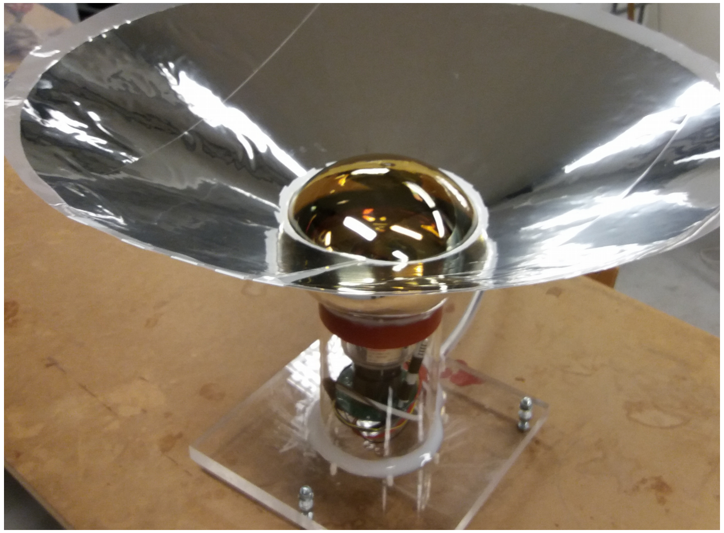
HV provided by active base ISEG PHQ 7081

- PMT and active base
  - Encapsulated in plexiglas tube
  - Watertightness with Wacker RTV-ME 607
  - Signal sent over ~14m RG58 cable to WaveCatcher

Jean-Pierre Ernenwein

Encapsulated PMT
+ Crown (mylar+lamination)



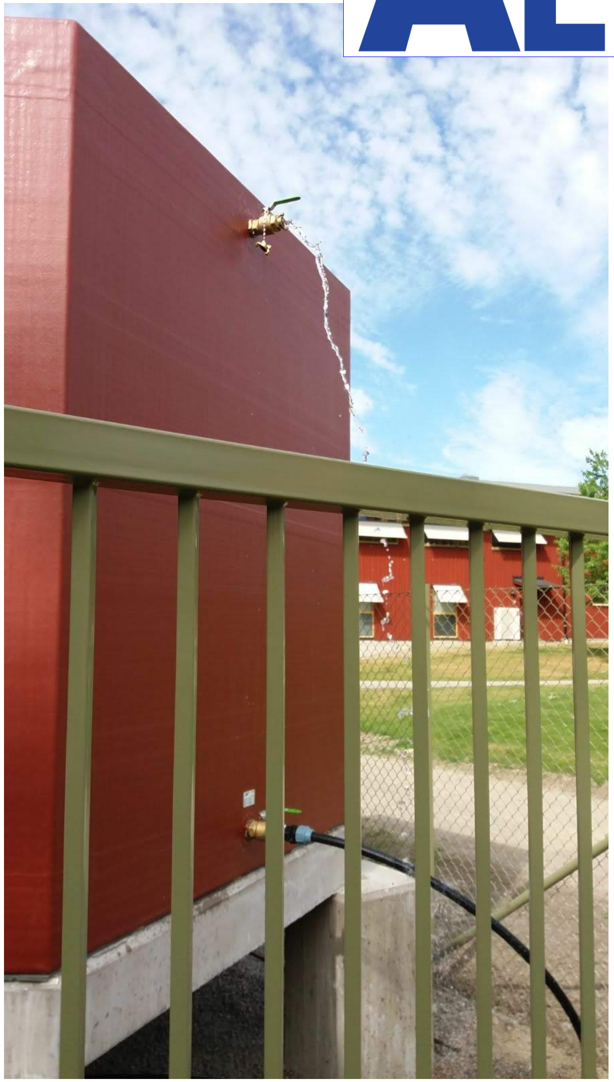


ALTO

WCD tanks delivery: April 2018

ALTO WCD filling: May-June 2018

- Using municipal water (fire hydrant)



Inside the Control Cabinet on the Cluster

LV supply for active bases of monitoring detectors

16-Channel WaveCatcher

LabJack (USB) for Slow Control of Tank PMT active bases and Sensor readout

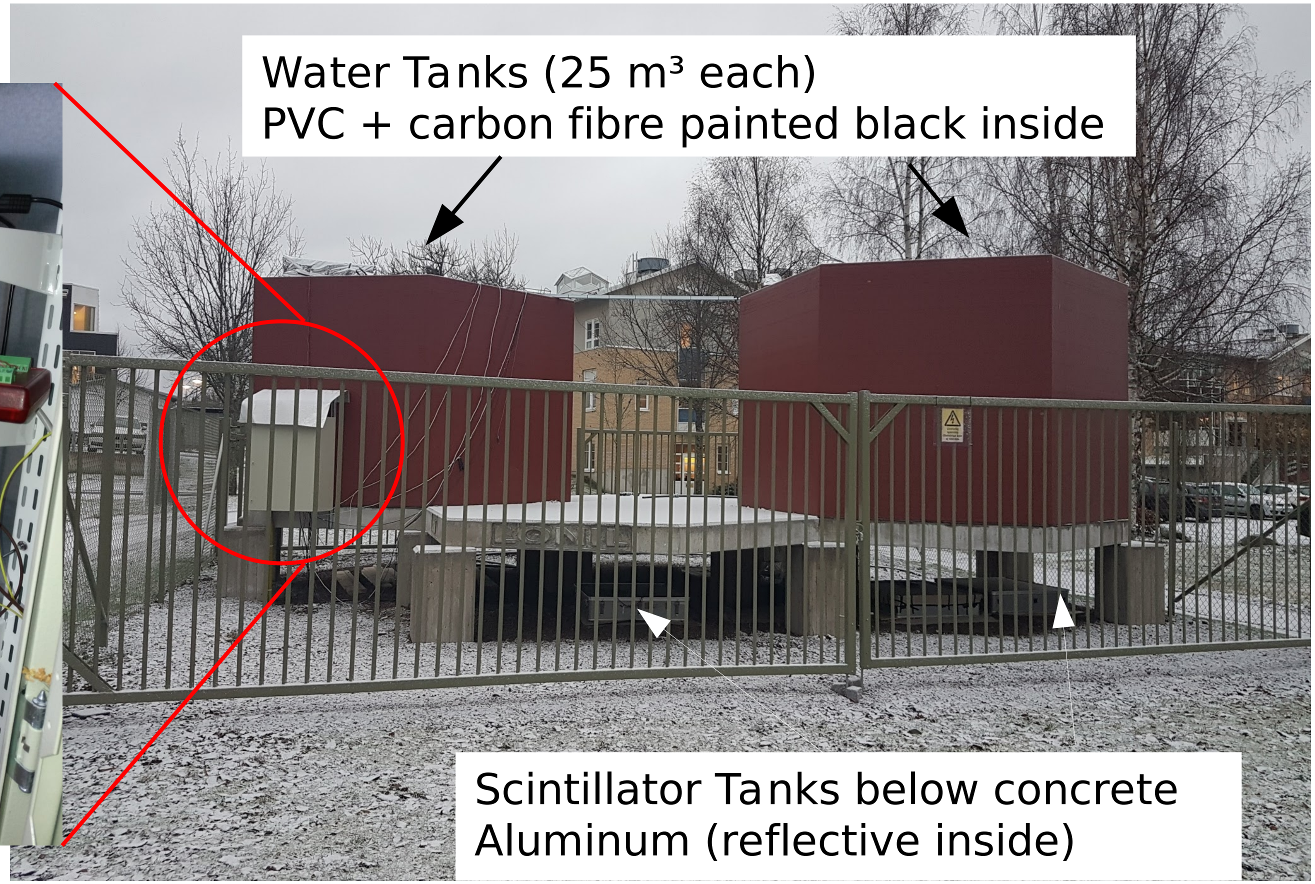
Single Board Computer (ML350G-10 Industrial Fanless, 64GB SDD)

USB ↔ Fibre convertor (to LnU network VLAN to control room)

Michael Punch
Jean-Pierre Ernenwein

ALTO Prototype array in Växjö

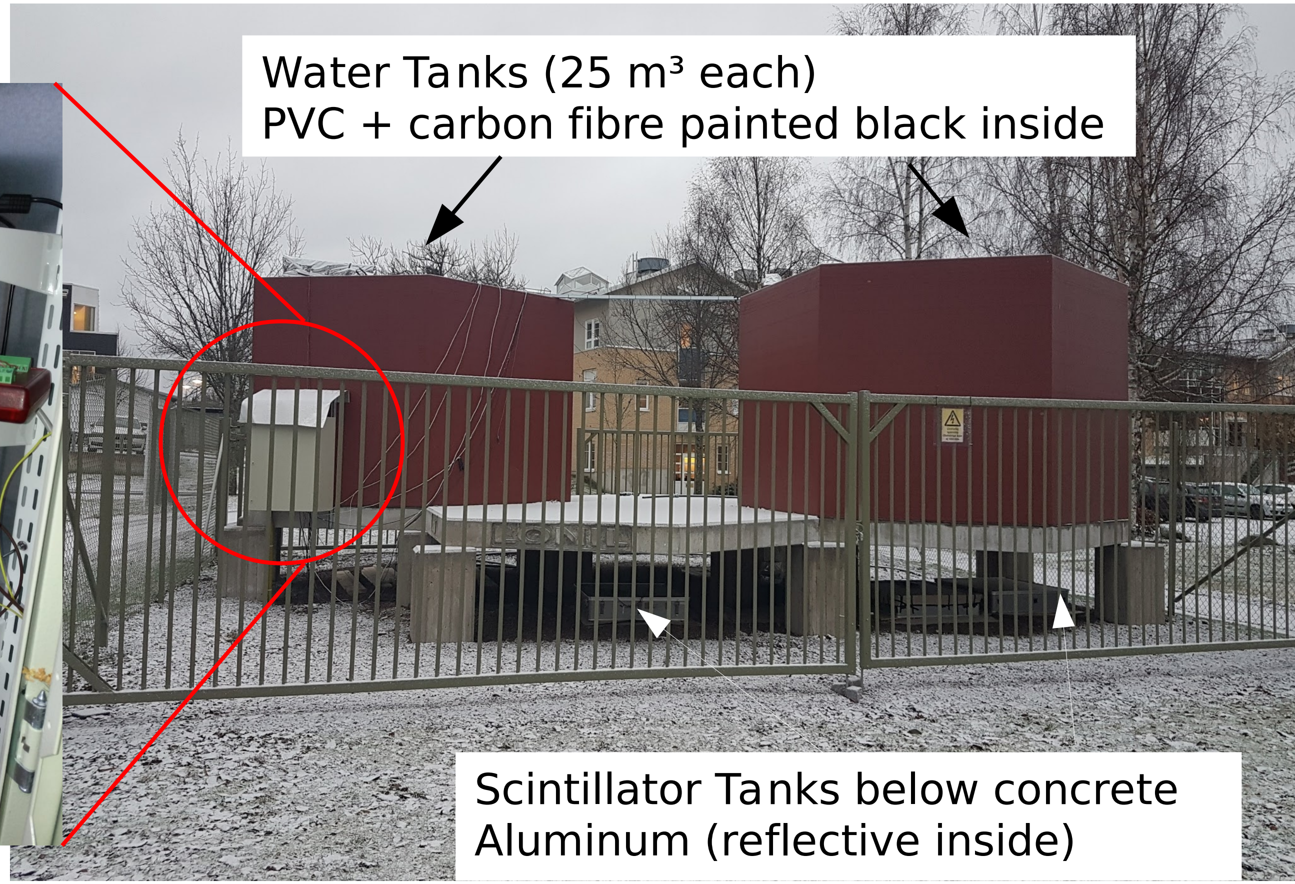
On site electronics



Control room

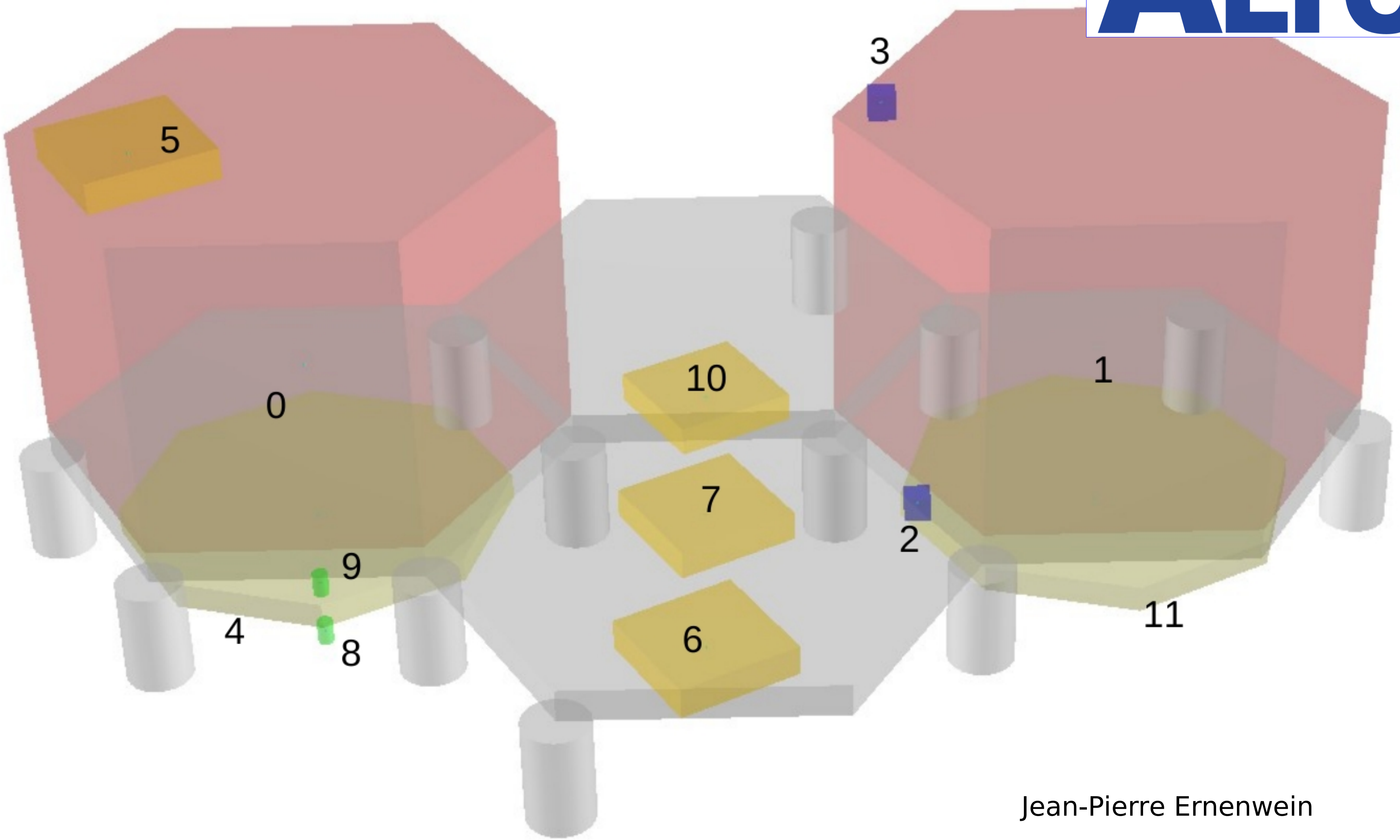
ALTO Prototype array in Växjö

On site electronics



Control room

Current configuration



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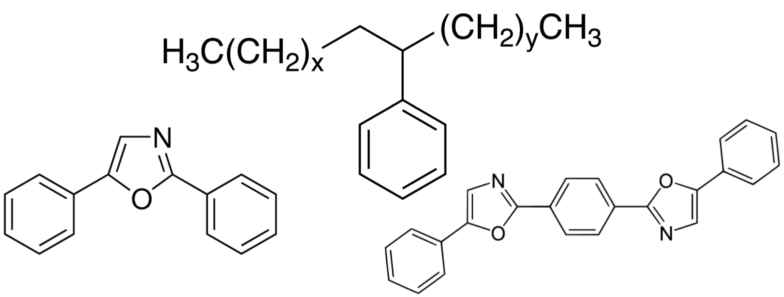
Muon detector

Thin box :
~ 3 cm liquid for 3 m diameter:
→ only 200 L of liquid scintillator:

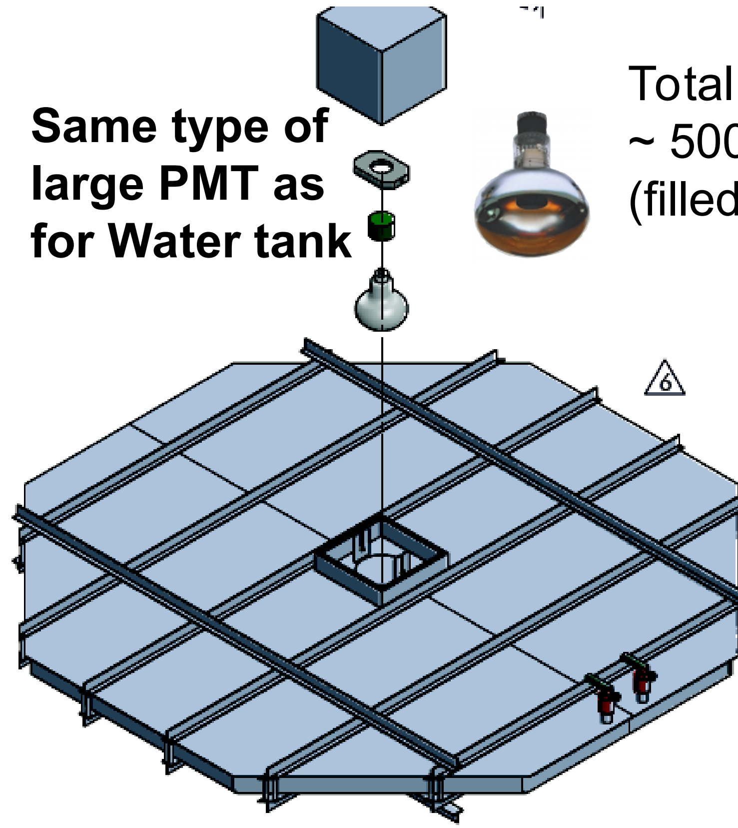


LAB + PPO + POPOP

~ 200 L of liquid scintillator
~ 300 kg for the box

Price : ~ 8 kEuros.

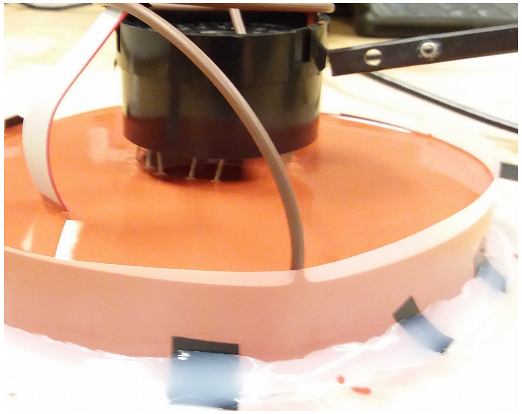
Underneath concrete slab
→ shielding → muons or “punch through”

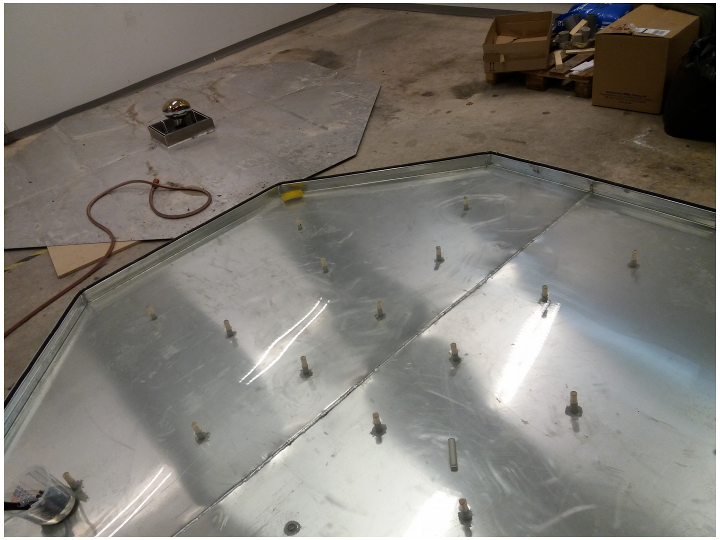


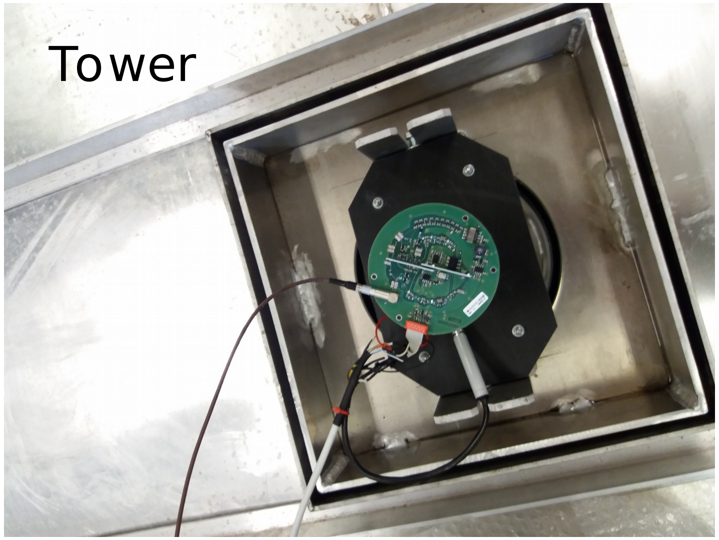
Total
~ 500 kg
(filled)

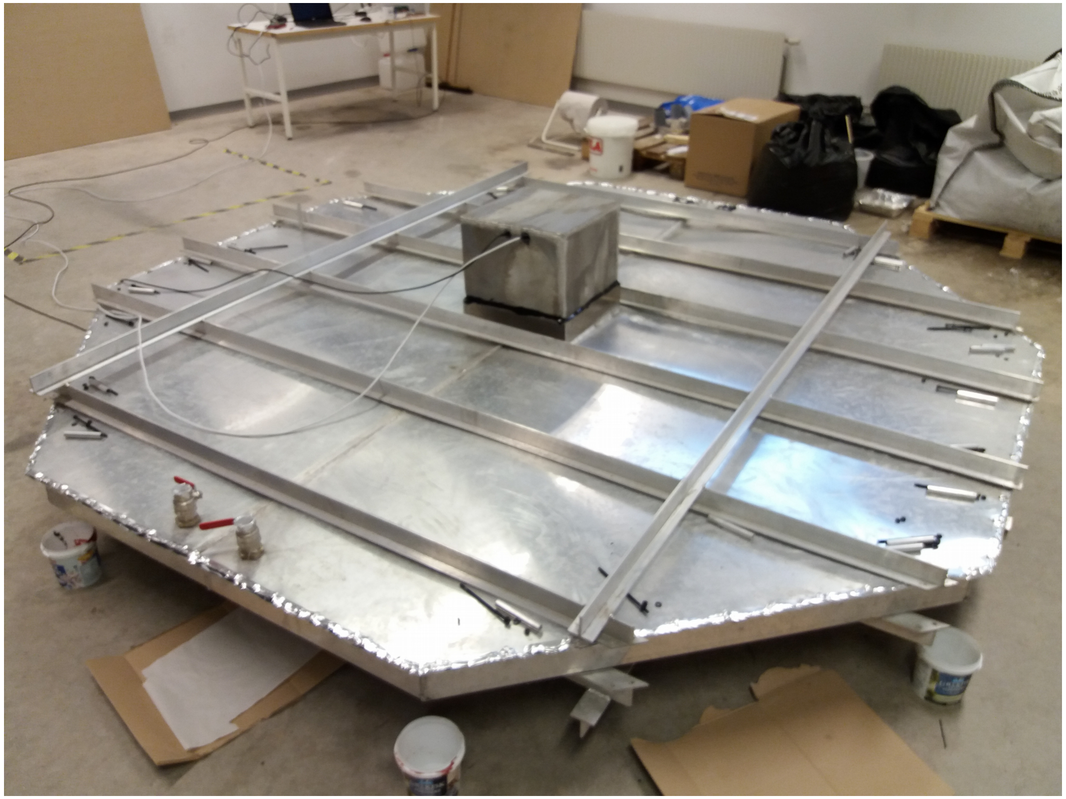
Muon detectors

Active base encapsulation (Wacker)









Muon detectors

ALTO

Charge in data

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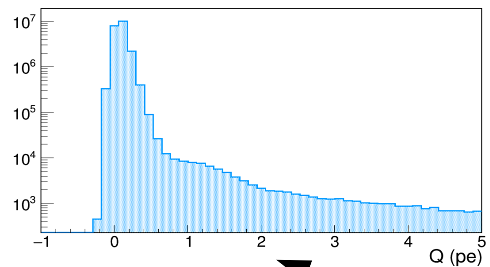
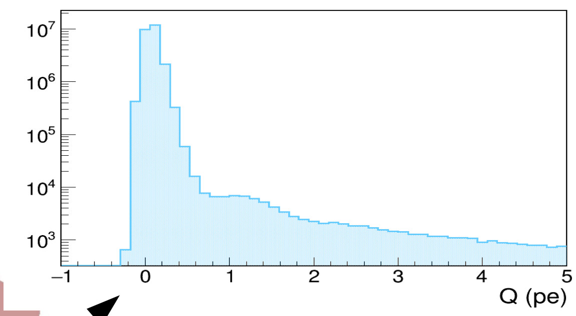
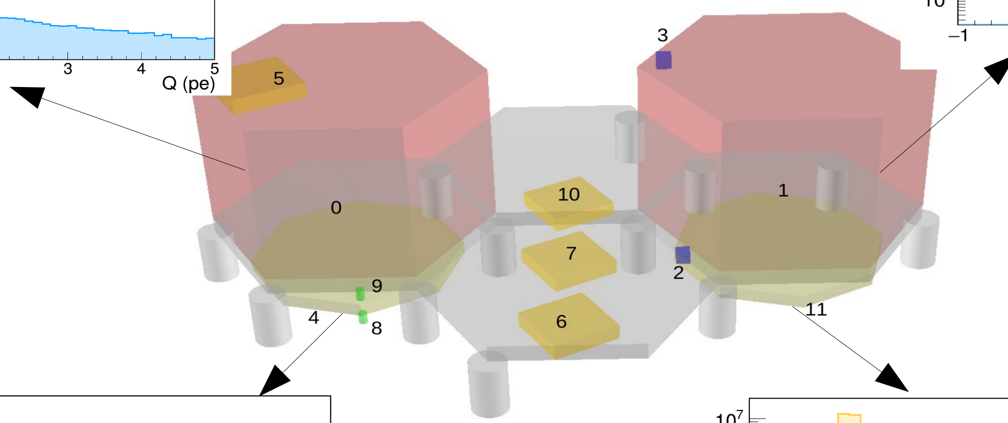
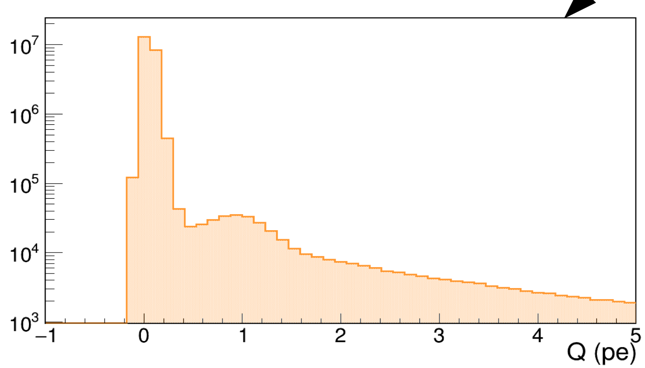
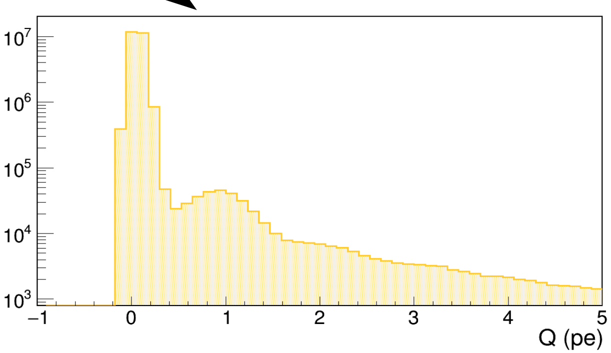
Distributions obtained when triggers originate from other channels





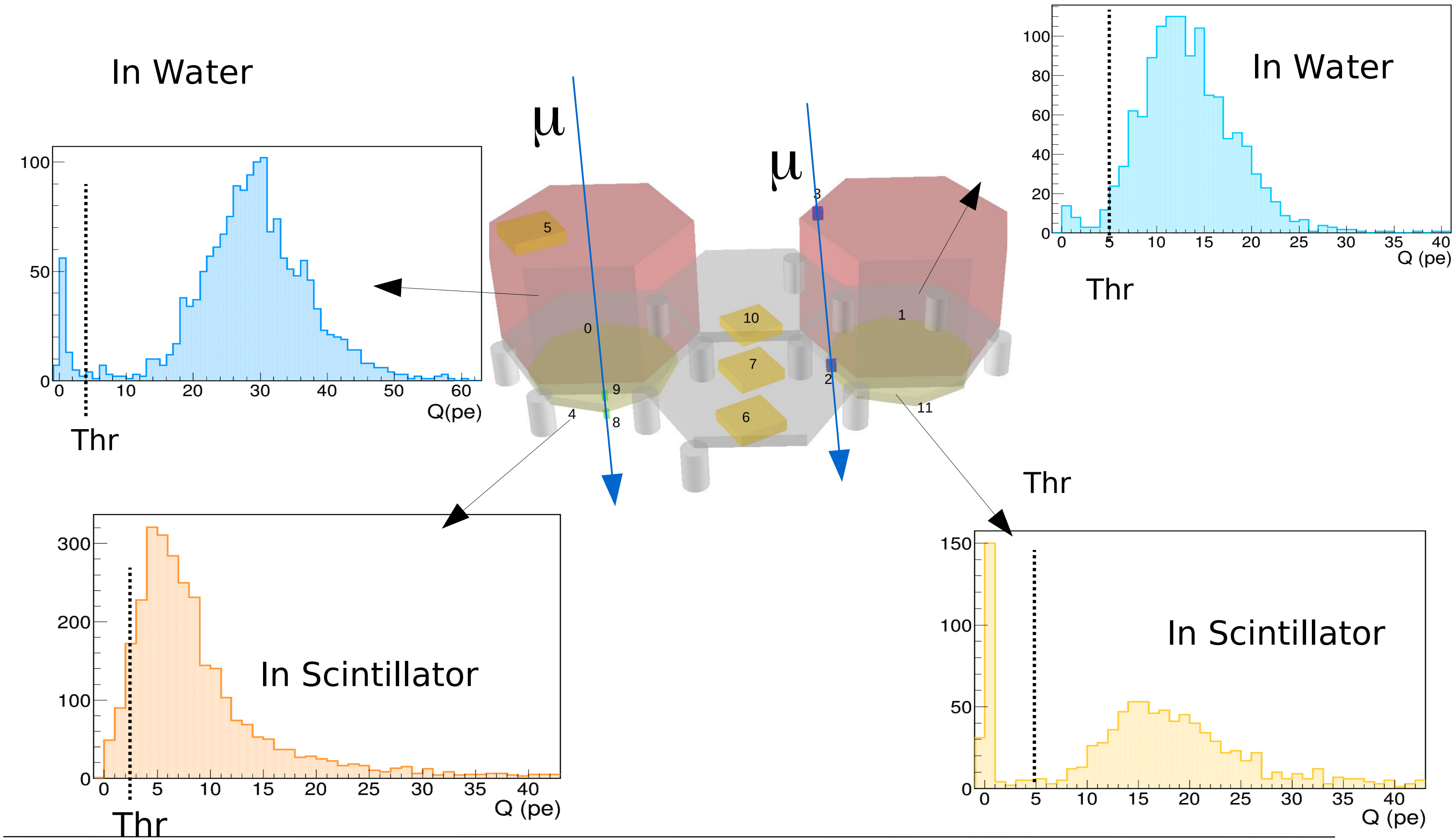




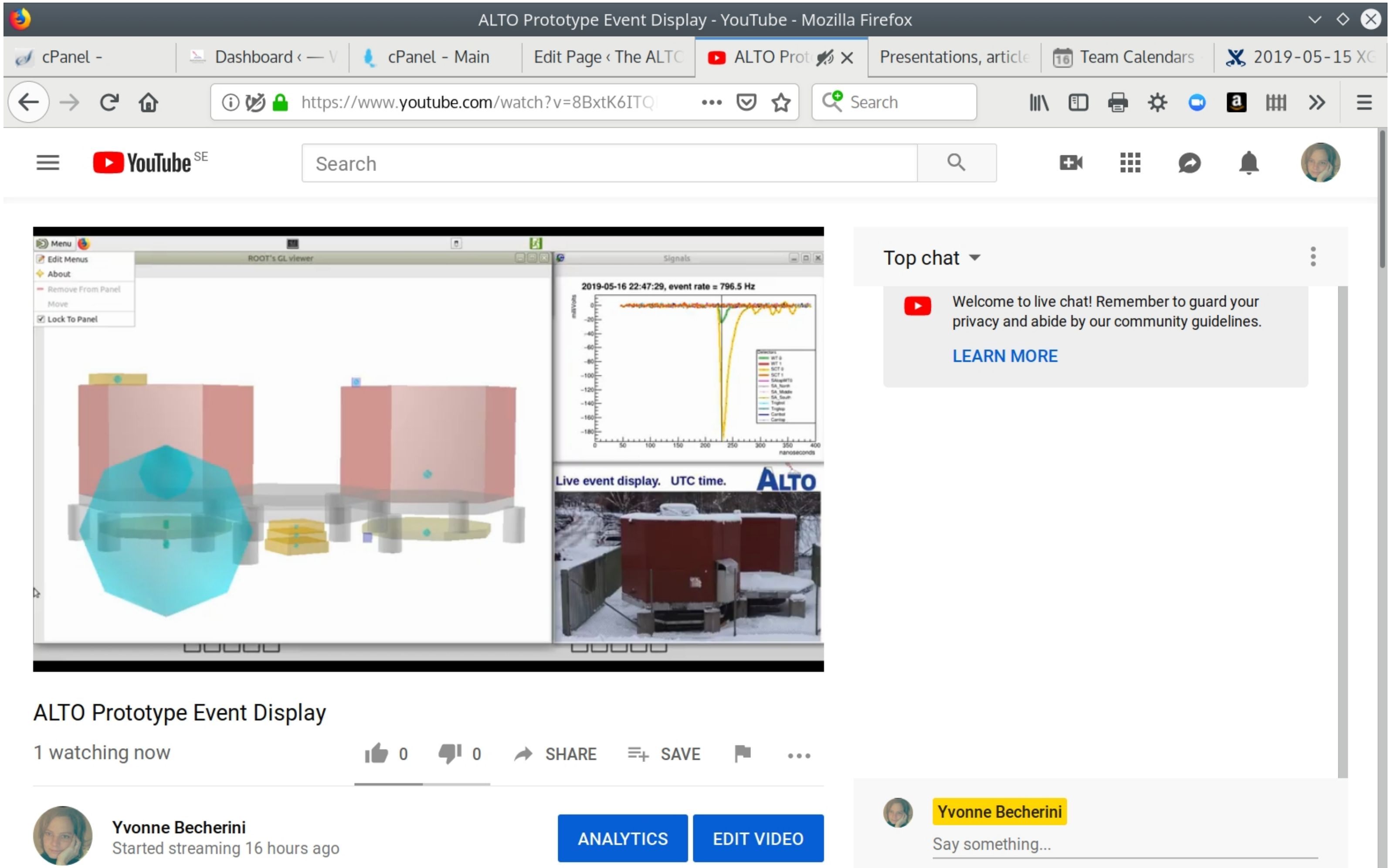


Monitoring

Jean-Pierre Ernenwein



ALTO event display on Youtube



Prototype lessons

- Running smoothly with 2 full detection units and several small detectors to monitor the behavior of ALTO units, and to crosscheck the calibration.
- Regarding temperature, this Winter, heating cables (180W) have been installed in water tanks. Temperature of water remained > 5°C. But this winter was not cold, reached only -13° C.
- Still lots of checks are possible with the small detectors surrounding the prototype.
- Investigating cheaper solutions for water tanks, and more repeatable solutions for scintillator tanks (quality, especially flatness, is not satisfactory).

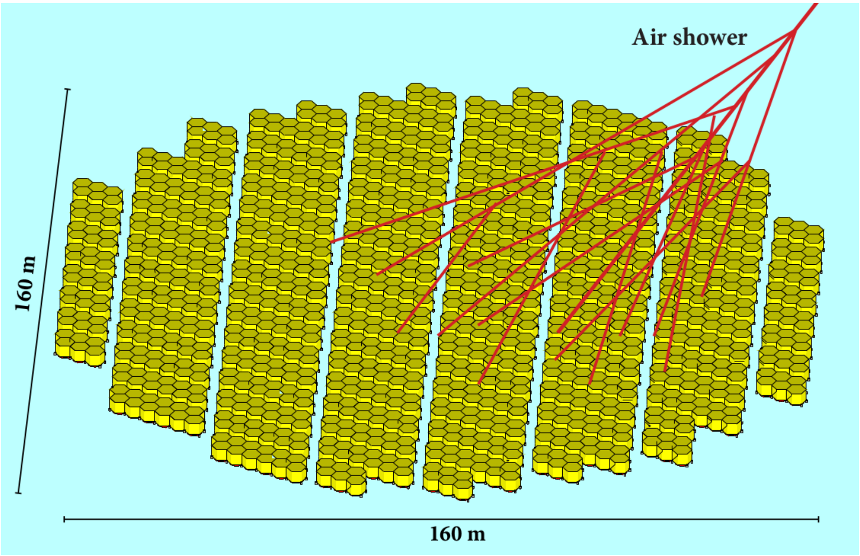
Current status of ALTO & lessons learned

- ALTO simulations and Analysis now quite mature
  - We have a complete and detailed simulation of a realizable detector
  - We have completed the full chain up to the sensitivity curves
    - Many parameters developed and tested
    - MVA - BDT machinery in place and working
    - Now, some time for optimizations based on full chain

- ALTO Prototype used to learn about
  - hardware configuration (number of samples in waveform, sampling period, thresholds, PMT gain, methods for WF integration at SBC level),
  - about self-calibration &
  - about behaviour of water/crown/PMT encapsulation.

Next steps for 2019

- Continuous monitoring of the prototype
- New cheaper version of the water tanks (some ideas already)
- Search for a site in the Southern hemisphere
- Complete the current simulations
- New simulations with a different array geometry



ALTO site in South America

- Presence of water nearby is a key factor, to lower the costs
- In order to simplify and be quick, we are aiming for the installation of 2-3 full ALTO clusters behind the site of QUBIC/LLAMA in Argentina, at an altitude of 4850 m
- Other sites possible (under investigation, discussions just started)
- There might also be the possibility to share infrastructure, power, network, roads
- The 2-3 cluster installation will allow us
  - To further test the construction feasibility at high altitude
  - To acquire further experience on singles and coincidence rates
  - To build partnerships with local industries

Conclusions

- Simple design:
  → limits costs of construction in full production phase; Prototype costs higher;
- Collaboration between Academia and Industry:
  → cost-effective solutions;
  → knowledge transfer benefiting both parties;
- Aimed investment cost for full deployment
  → ~ 20M€ excluding salaries;
- Expansion of collaboration
  - Want to visit the prototype? Contact me :)
- Status of the project with further information can be found at the website:
  → http://alto-gamma-ray-observatory.org/
- For enquiries about the project, please contact yvonne.becherini@lnu.se

Acknowledgements

ALTO

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