Results and lessons learned from the ALTO prototype at Linnaeus University

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

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--- for the ALTO group ----
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Linnæus University

Current Collaboration

Sweden

- Department of Physics and Electrical Engineering, Linnaeus University (LnU), Växjö
  - PI Yvonne Becherini
  - Post-doc Satyendra Thoudam
  - Two PhD students
    - Mohanraj Seniappan: MVA Rejection
    - Tomas Bylund: DAQ & Control, Energy NN
- Industry: TBS Yard AB, Torsås
  - Industrial construction, responsible Lars Tedehammar

France

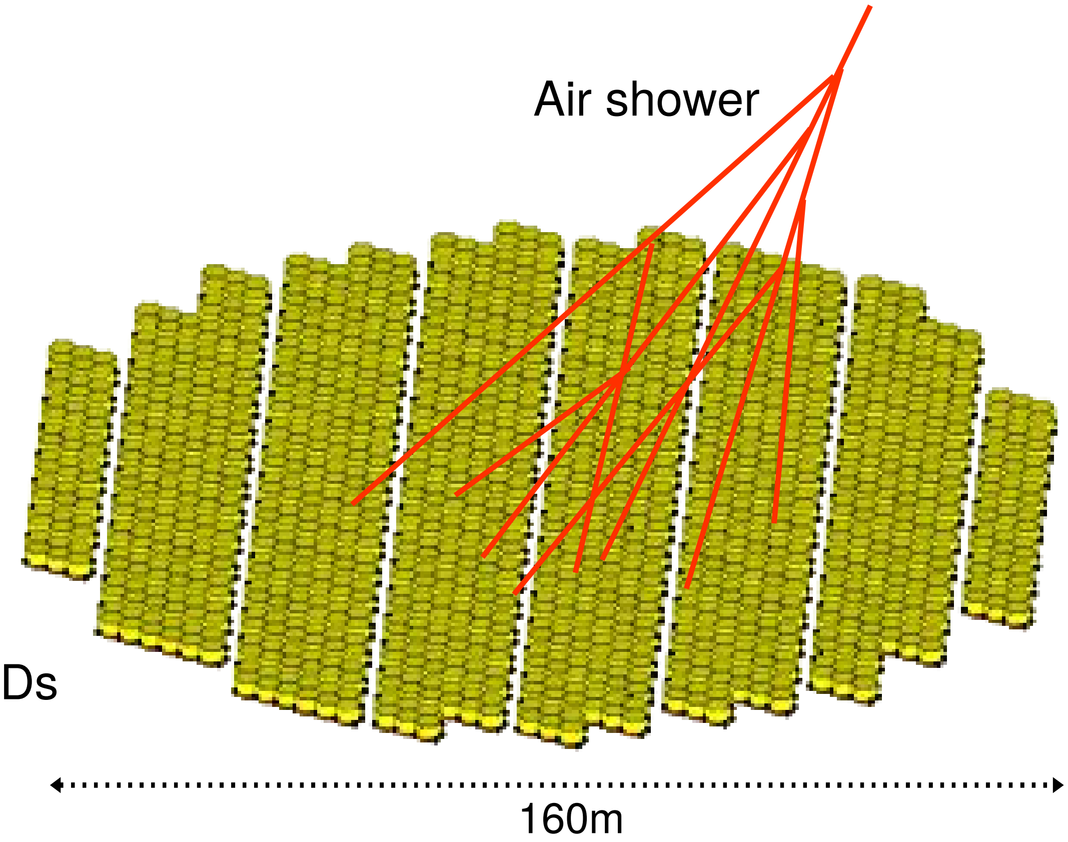
- APC Laboratory, IN2P3/CNRS, Paris
  - Michael Punch
  - Contacts with Jean-Christophe Hamilton (discussions about the site)
- Aix-Marseille University
  - Jean-Pierre Ernenwein (key work on proto, regular visits to LnU)
- LAL/Orsay
  - Dominique Breton, Jihane Maalmi (work on WaveCatcher electronics)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

ALTO
Observatory
Essentials

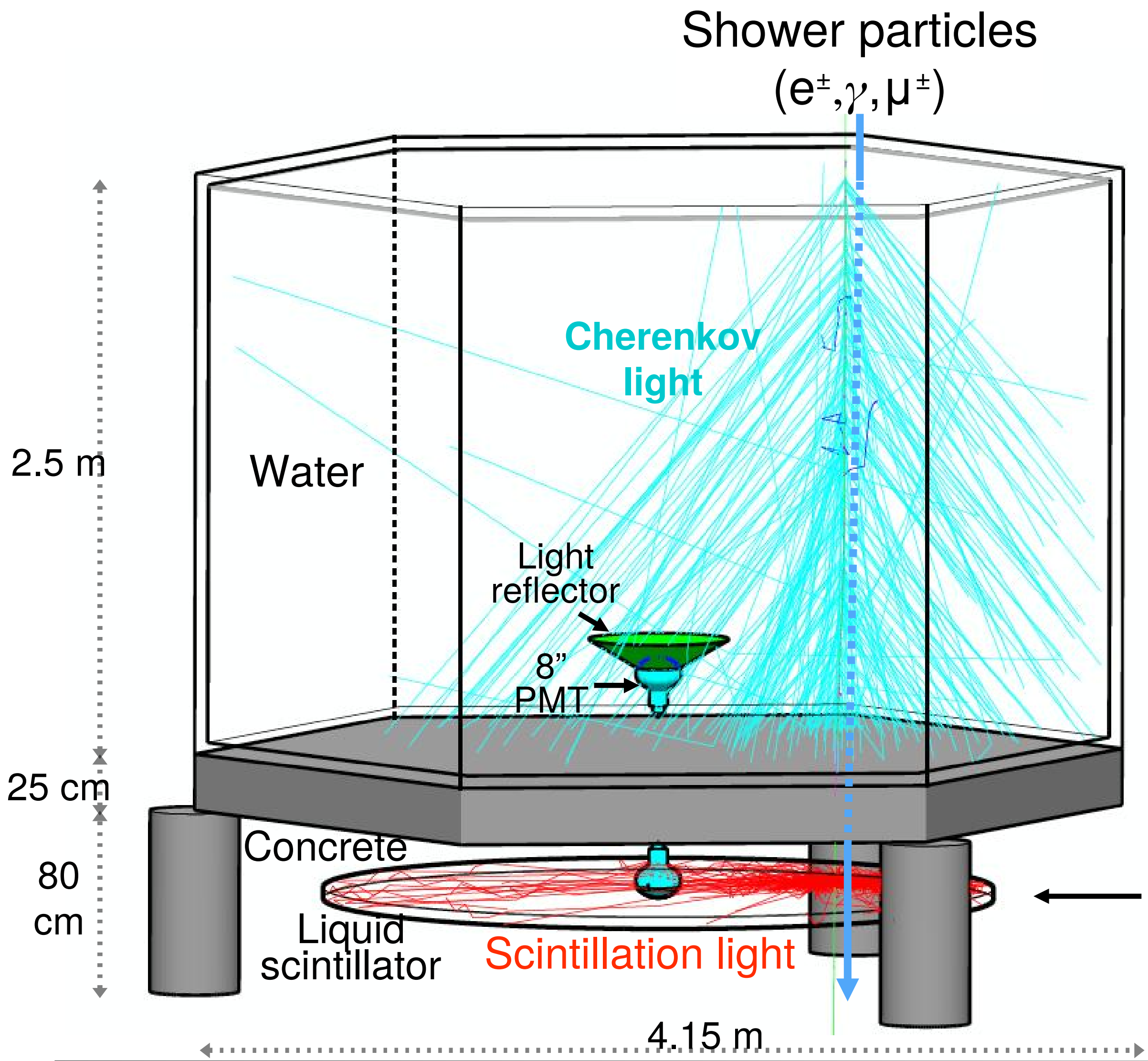
ALTO array layout and aims

- Southern Hemisphere (Chile/Argentina)
- Altitude ~5 km a.s.l
- Energy range ≳ 200 GeV
- ~1200 detector units

- Advanced electronics:
  - WaveCatcher
    + White Rabbit timing system
- Sub-ns timing
- Small-sized, closed-packed WCDs
  - Low dead-space
    (“packing factor” ~70%)
- Scintillation detectors



An ALTO detector unit



Water Cherenkov Detector

- Carbon fibre sandwich + PVC foam
- Non-reflective walls
- Sensitive to $e^{\pm}$,γ,$\mu^{\pm}$

Scintillation Detector

- Aluminium
- Highly-reflective walls
- Liquid scintillator: LAB+PPO+POPOP
- $\mu^{\pm}$ detector

An ALTO "cluster"

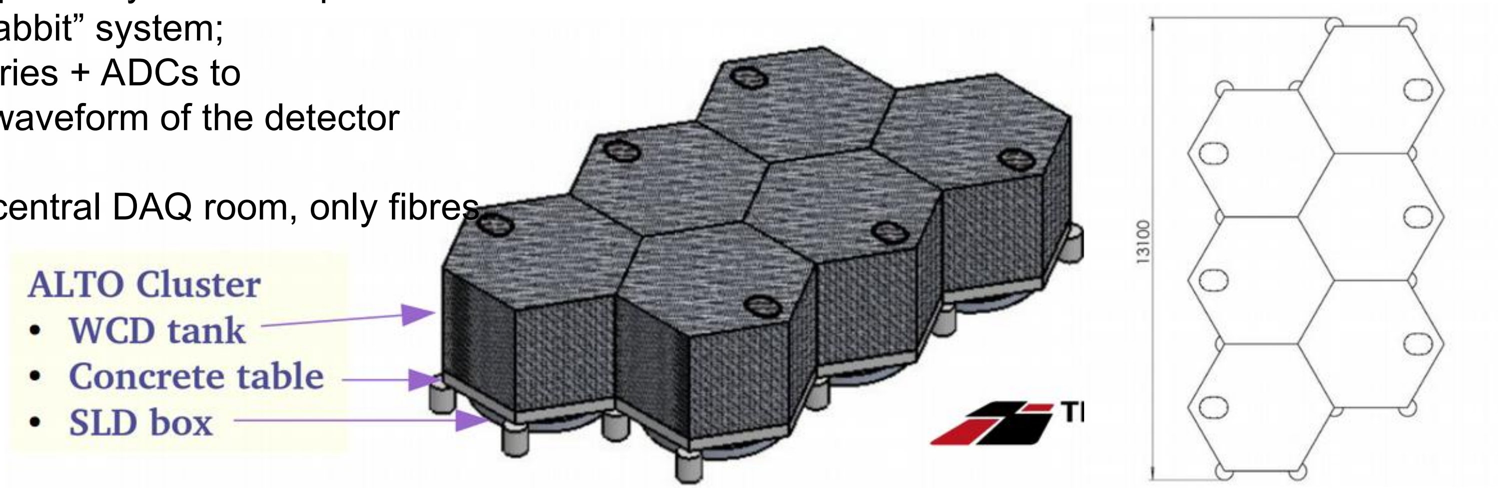
Cluster = Group of 6 Units
= 6 x (WCD + SLD)

- WCDs on concrete "table"
- SLDs below "table",
  on telescopic rails

Each cluster to have common:

- Electronics readout unit
- Solar panel + battery
- Communication/data
  to central DAQ room by fibre only

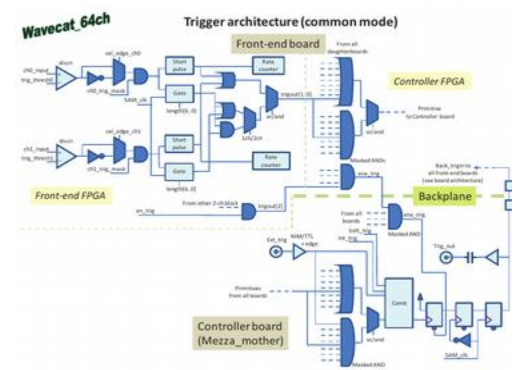
- Advanced electronics for 6-tank "cluster",
  WaveCatcher + White Rabbit:
- Trigger channel precisely time-stamped
  with "White Rabbit" system;
- Analogue memories + ADCs to
  measure the waveform of the detector pulses;
- No cables from central DAQ room, only fibres



ALTO Electronics

- Readout electronics box, to be powered by solar panels
- Communications, by fibre-optic connections only, to central DAQ

- Electronics box containing:
  - “WaveCatcher” from CEA/CNRS
    - Analogue memory
      (Switched Capacitor Array)
    - 12-bit, 0.4-3.2 GS/s fast digitizers
    - 1024 samples depth/channel
    - Includes coincidence logic to start read-out
    - 16-channel version **under test** at LnU
    - Low power consumption (~20W)
    - The WaveCatcher family of SCA-based
      12-bit 3.2-GS/s fast digitizers:
      Breton et al., Real Time Conference (RT), 2014 19th IEEE-NPSS



  - Time-stamping of Read-out trigger to ns precision
    - White Rabbit node (e.g. TiCkS-SPEC board from APC)
    - “TiCkS: A Flexible White-Rabbit Based Time-Stamping Board”,
      Champion et al., ICALEPCS2017, Barcelona, Spain, 2017

  - A Single Board Computer (e.g ML350G-10 Industrial Fanless, 64GB SDD)
    - For local control and monitoring (autonomy in case of connection loss), possible data reduction

ALTO
Prototype Status

Follow progress on the Blog!
https://alto-gamma-ray-observatory.org/blog

ALTO

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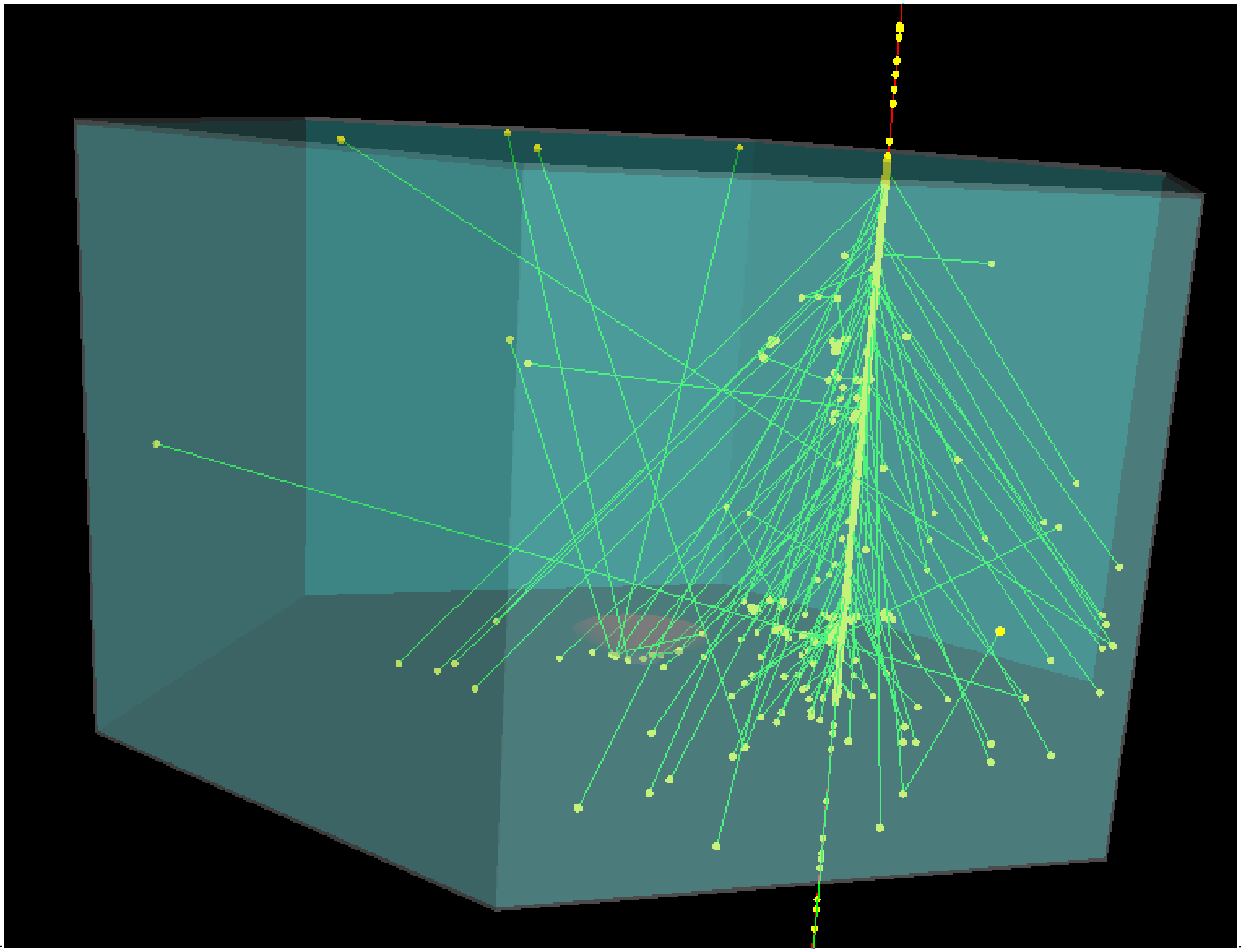
ALTO prototype construction timeline - 2018

- 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 prodution started
- Oct 7: Event display available
- Now: Waiting for muon detectors delivery!

ALTO
Water Cherenkov Detectors

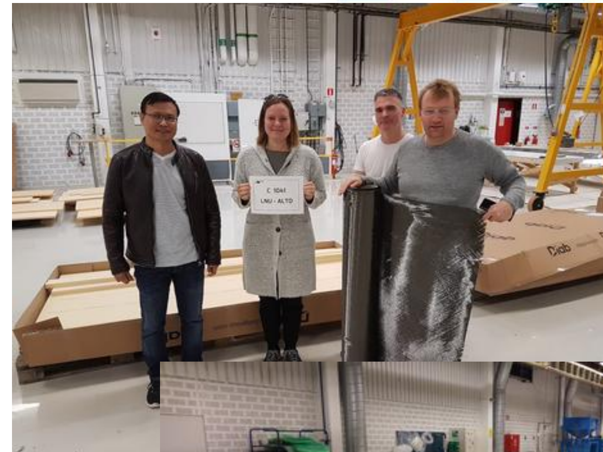
ALTO GEANT4 simulations

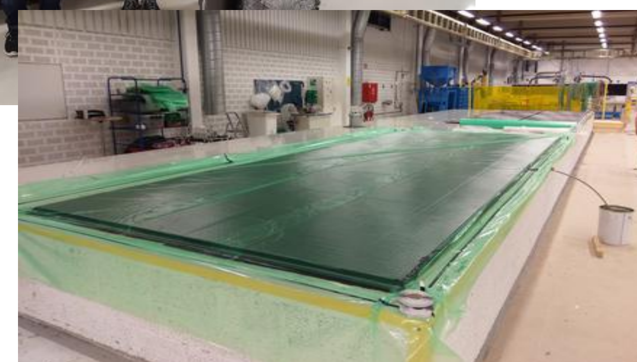
Simulation of a muon passing through the Water Tank

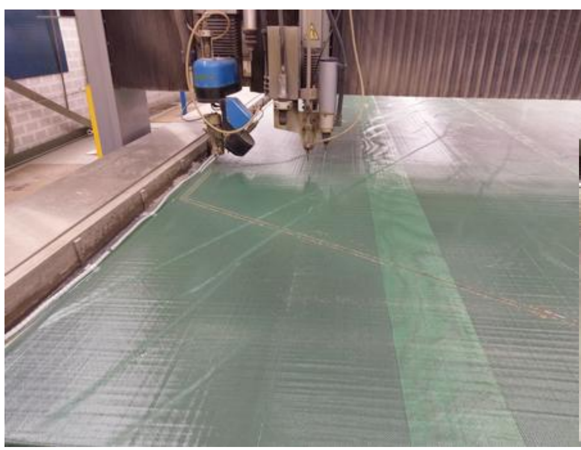


ALTO WCD Tank Construction (last year)

- 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







ALTO Site preparation and Tank delivery

- Site preparation, concrete pouring, over the winter / spring (until February)

Time-lapse video

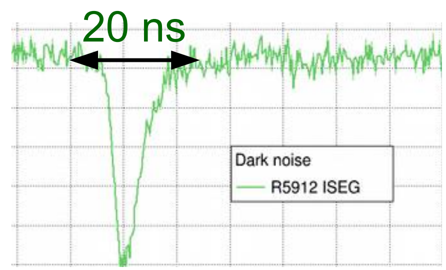
- Tank delivery

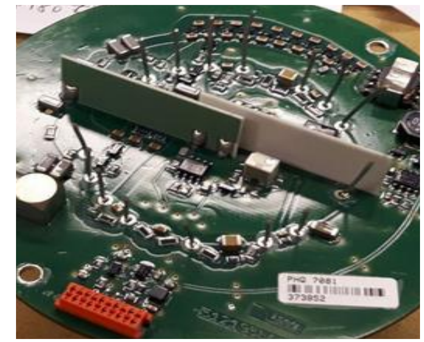
Arrival video

8” PMT

8 inch
photomultiplier
10 dynodes

Gain ~ 10^7



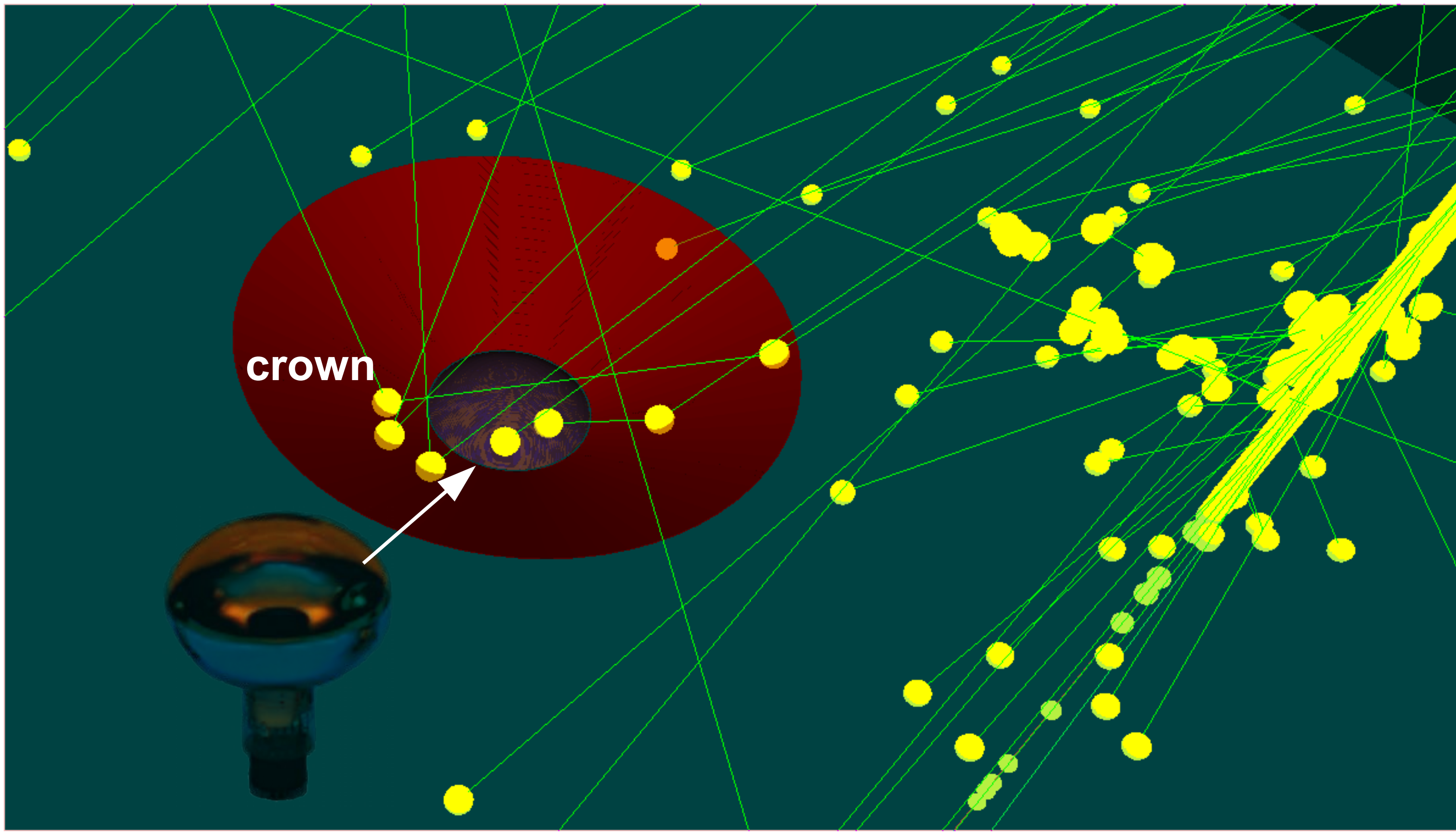


HV provided by active base ISEG PHQ 7081

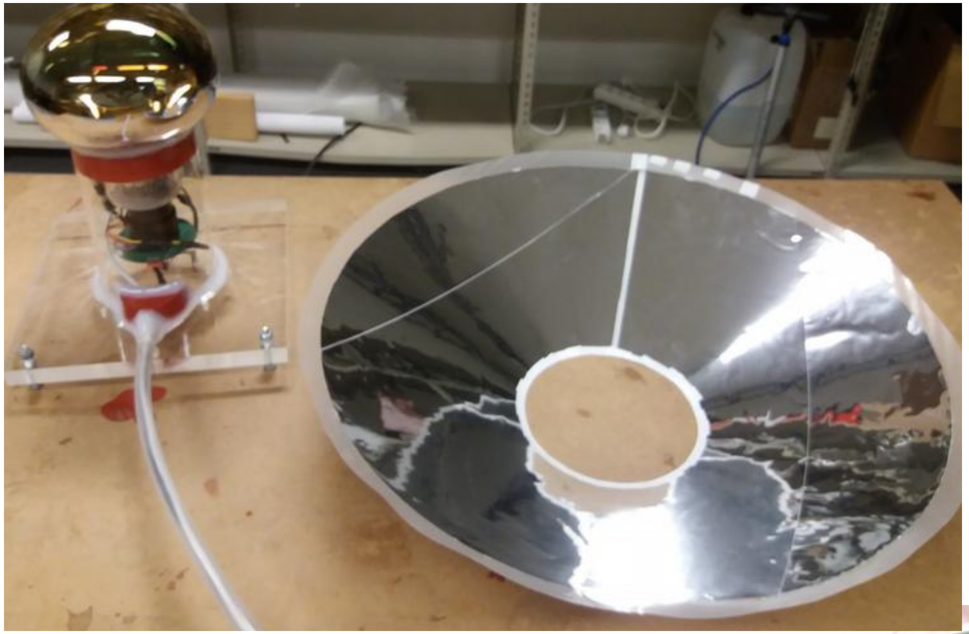
- PMT and active base
  - Encapsulated in plexiglas tube,
  - Weighted with dumbells
  - Watertightness with Wacker RTV-ME 607
  - Signal sent over ~14m RG58 cable to WaveCatcher

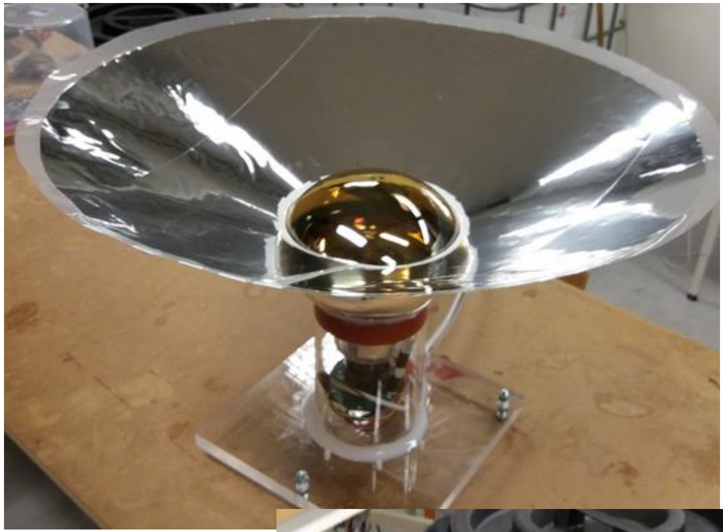
ALTO GEANT4 simulations

Optimization of light arriving at PMT with reflective crown



Encapsulated PMT
+ Crown (mylar+lamination)

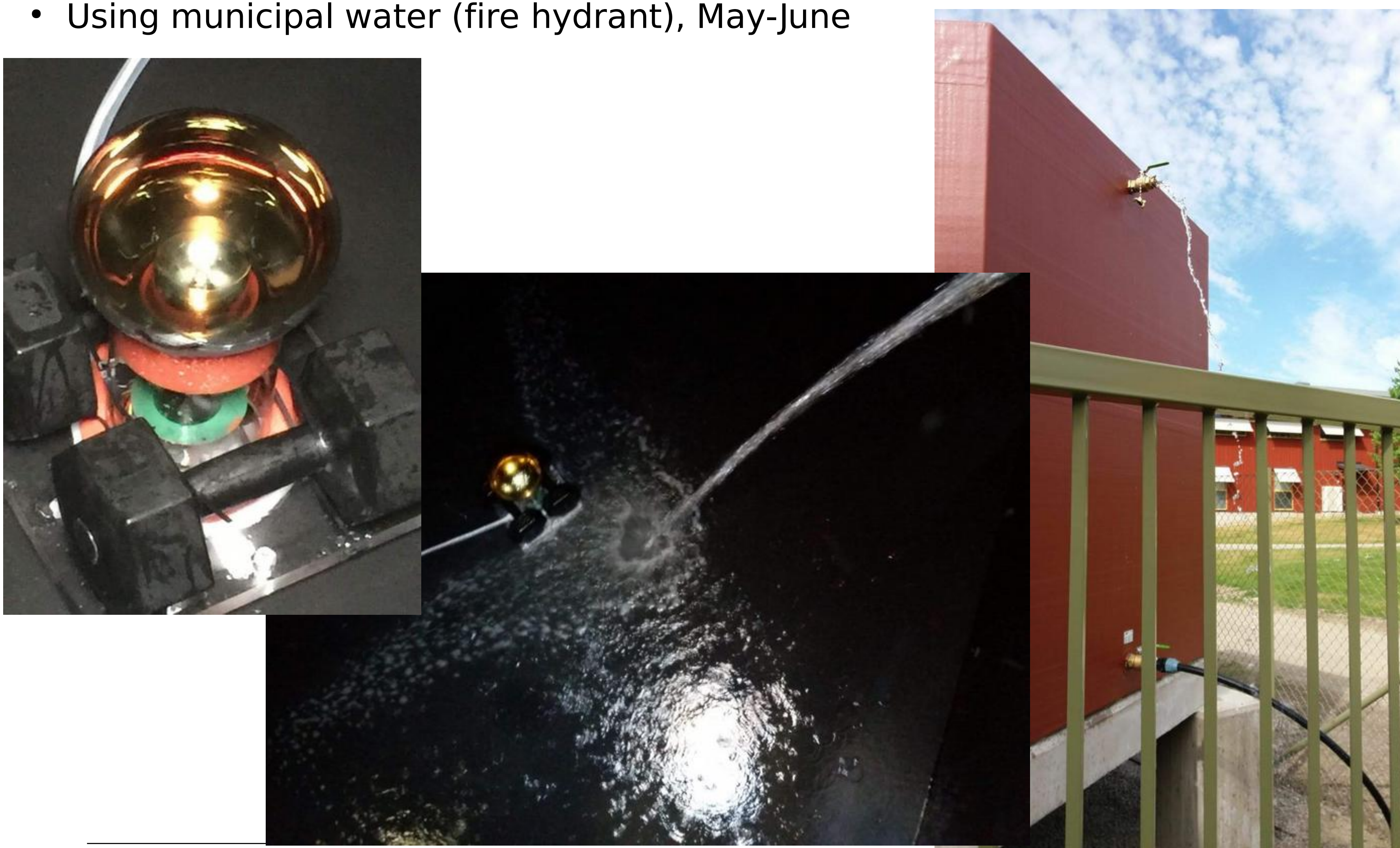




Water-tightness tests →

ALTO WCD filling

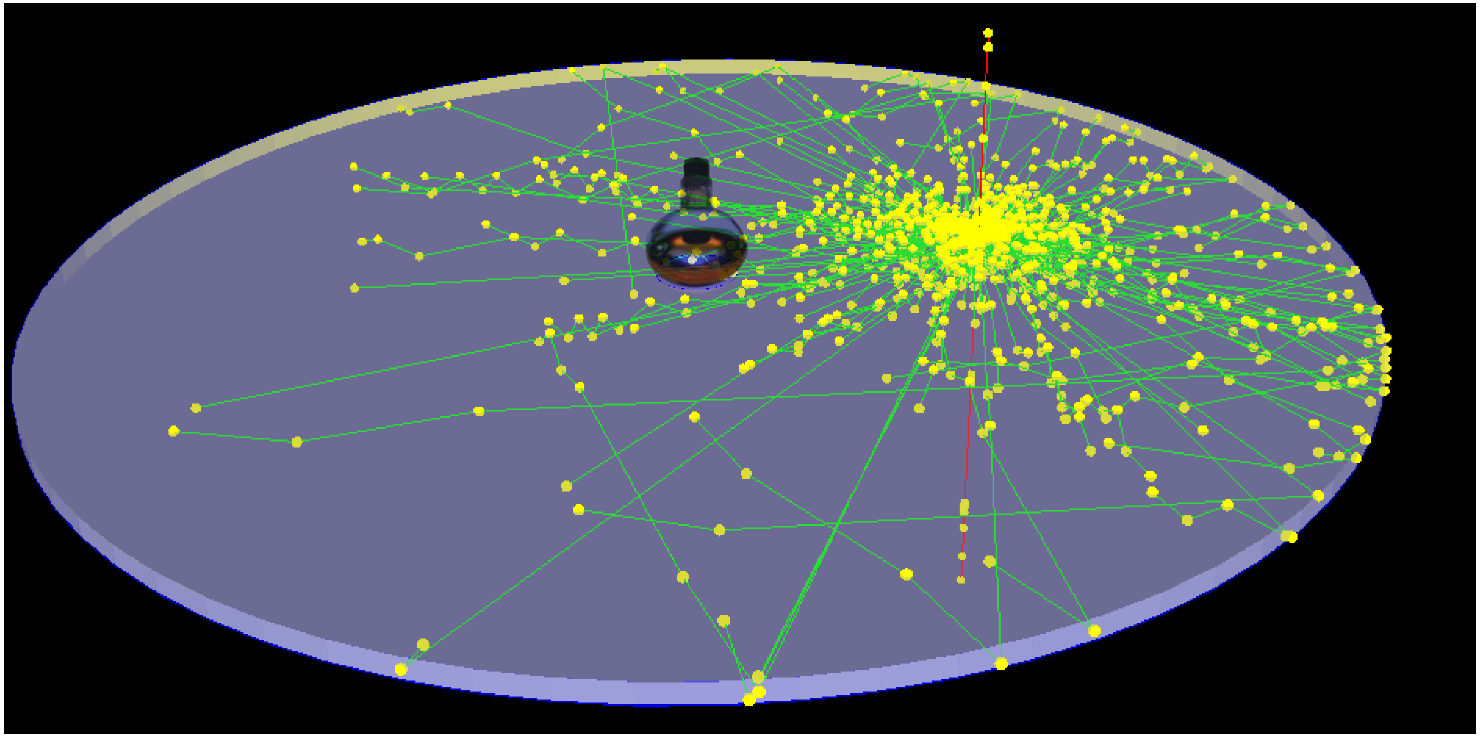
- Using municipal water (fire hydrant), May-June



ALTO
Scintillator Detectors

ALTO GEANT4 simulations

Simulation of a muon passing through the Scintillator Tank



We need to know :

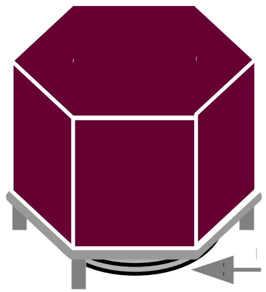
- Quantity of emitted light by the liquid
- Transparency of the liquid (to this light)
- Reflectivity of the material (aluminum)

We can predict the number of photoelectrons detected by the PMT.
According to data in literature :
> 20 photoelectrons.
Confirmed in laboratory

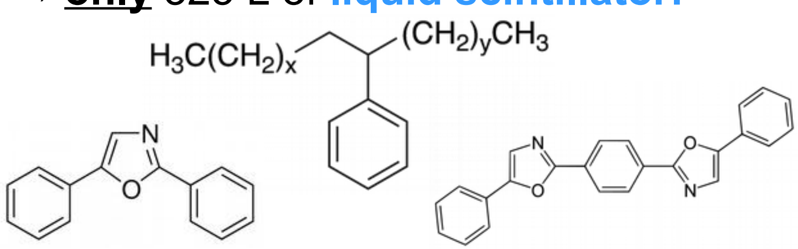
Linnæus University

ALTO Scintillator Tank

TBS YARD AB

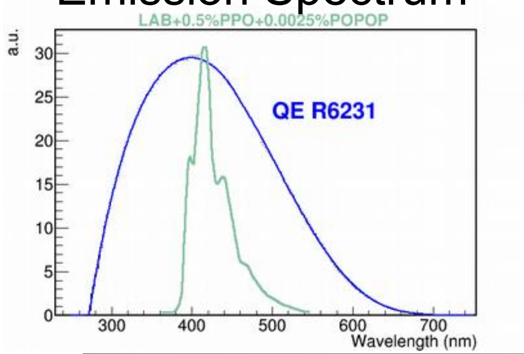


Thin box :
4.6 cm thickness for 3 m diameter:
→ **<u>only</u>** 325 L of **liquid scintillator:**

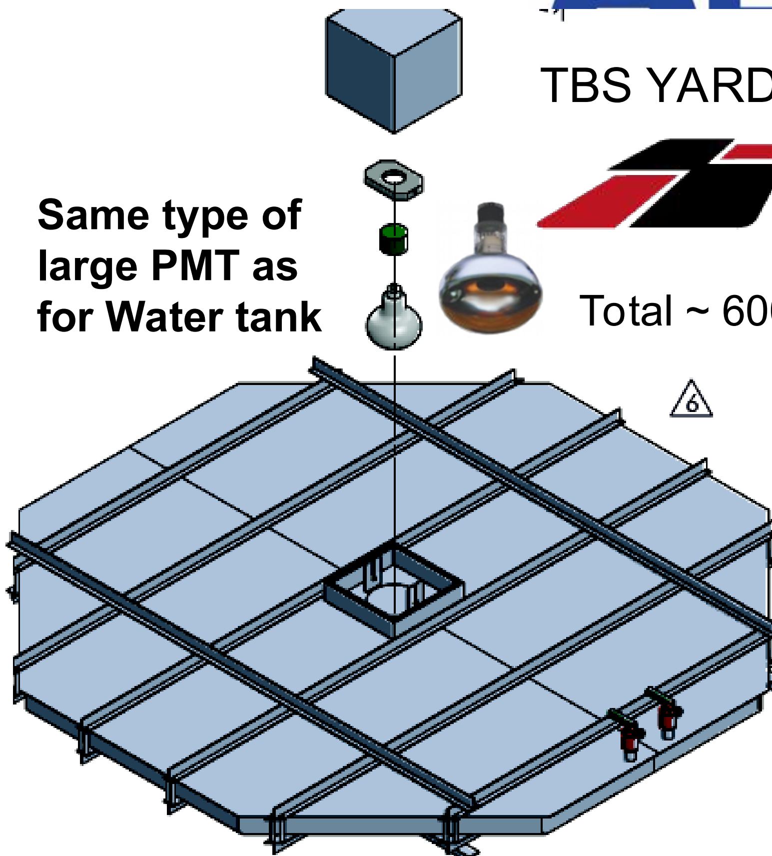


LAB + PPO + POPOP

Emission Spectrum



Same type of large PMT as for Water tank



Total ~ 600 kg (filled)

~ 330 L liquid scintillator → will try 200 L in installed version
~ 300 kg of metal.

Underneath the concrete table
Concrete + 2.5m WCD act as shielding

ALTO Scintillator Tank production

- Design finalized
  - Some delays in production
  - Hope delivery before Christmas

PROTOTYPE

→ Control Room

Inside the Control Cabinet on the Cluster

LV supply for active bases
of monitoring detectors

8-Channel WaveCatcher

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

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

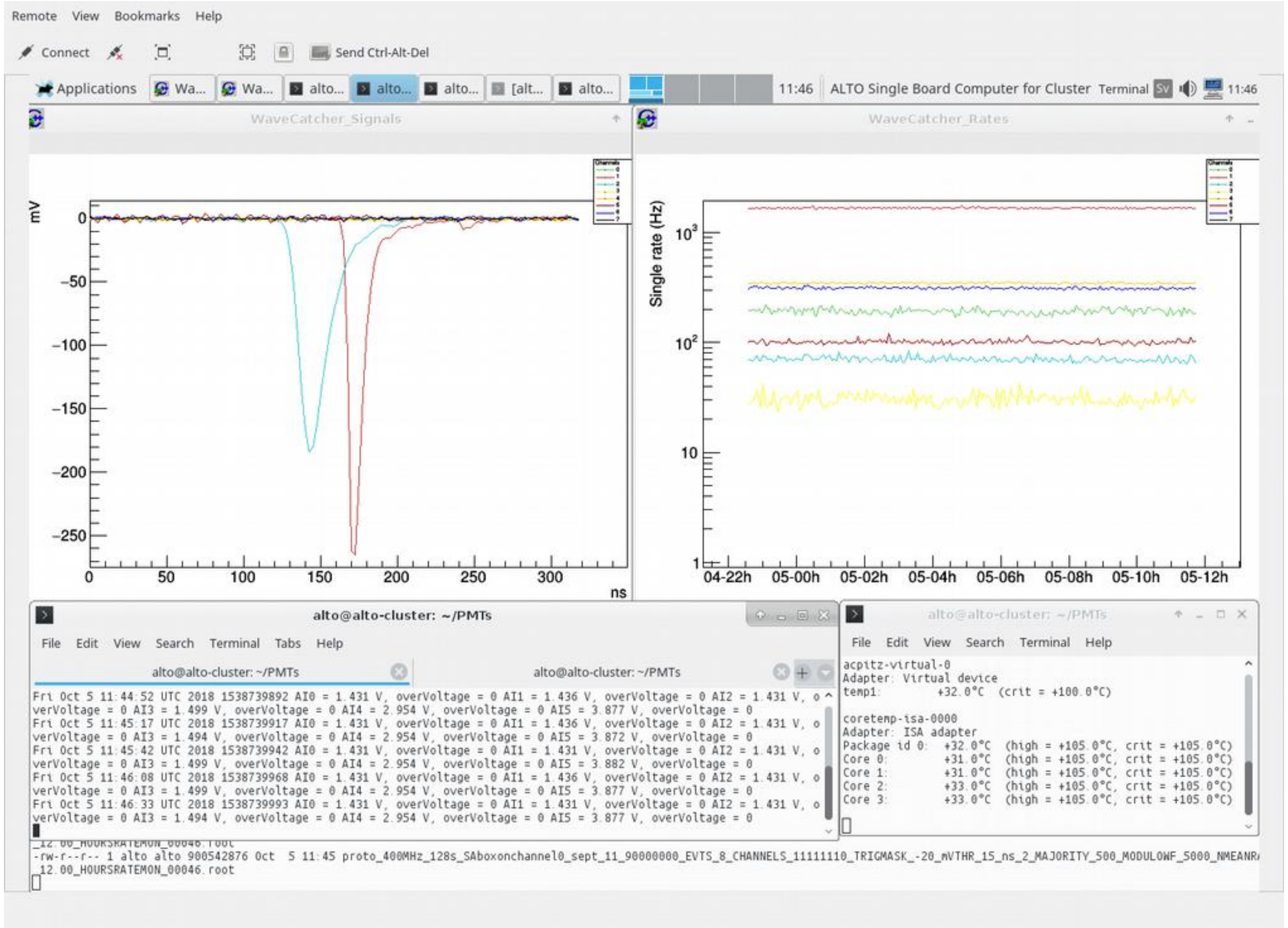
USB ↔ Fibre convertor
(to LnU network VLAN to control room)

White Rabbit Timing
(SPEC) card … to be installed

ALTO
Prototype Operation

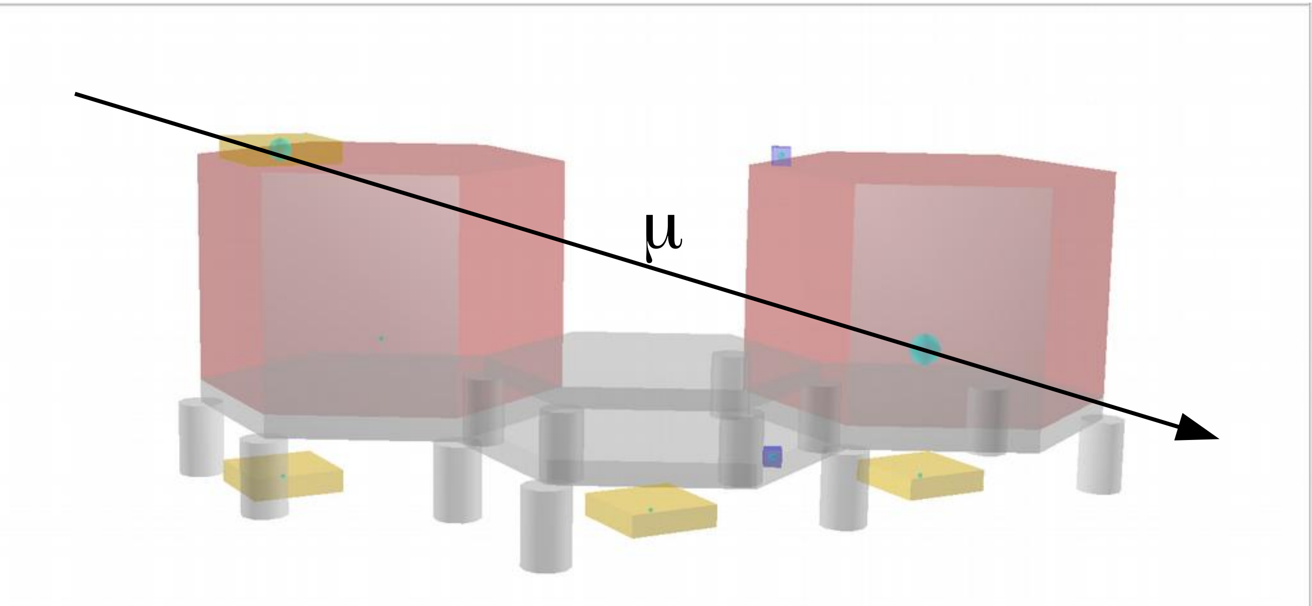
Control and Monitoring the ALTO prototype

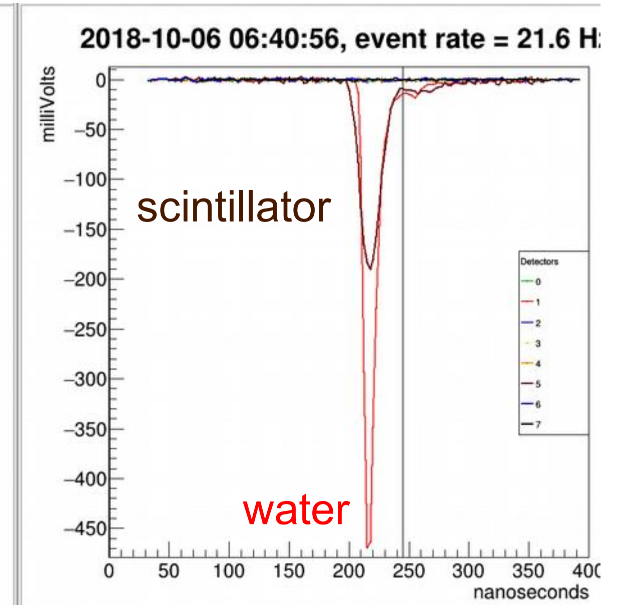
- PC in control room, with dual display
  - Monitoring and control through VNC to SBC
  - Storage of data copied from SBC
  - Analysis
  - Event Display



ALTO Prototype Timing Calibration

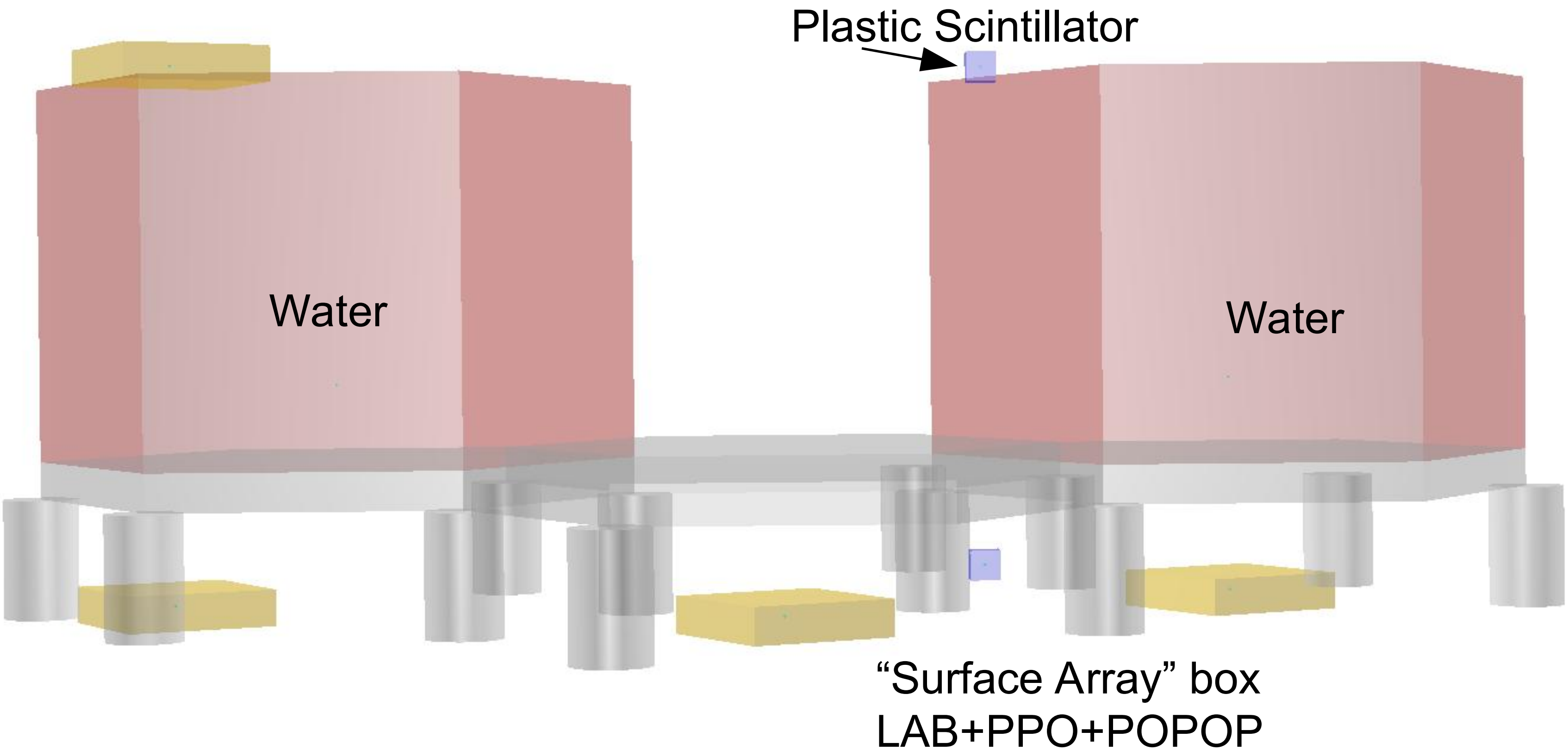
“T0s” due to cable lengths, transit times in PMTs





- From one floor to the next:
  - “skimming” muons (high charge) using the rising edges:
  - Passage threshold rather than time of maximum
- On the same level:
  - Showers

ALTO Event Display

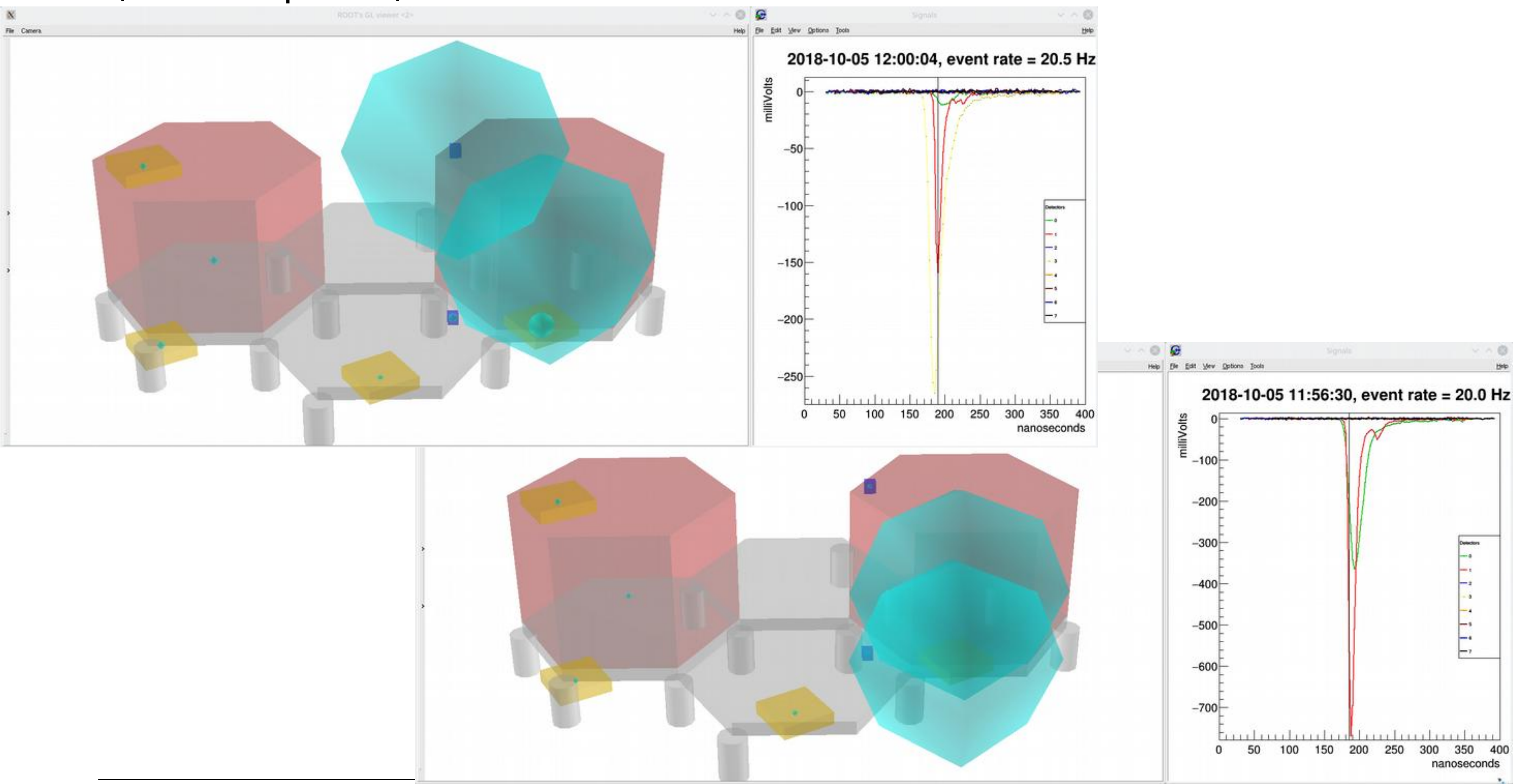


Event Display:

https://www.cppm.in2p3.fr/~rnenwein/ALTO/ALTO_PROTOTYPE.mp4

ALTO Event Display

- Sample of events in previous minute
  - (Root + OpenGL)

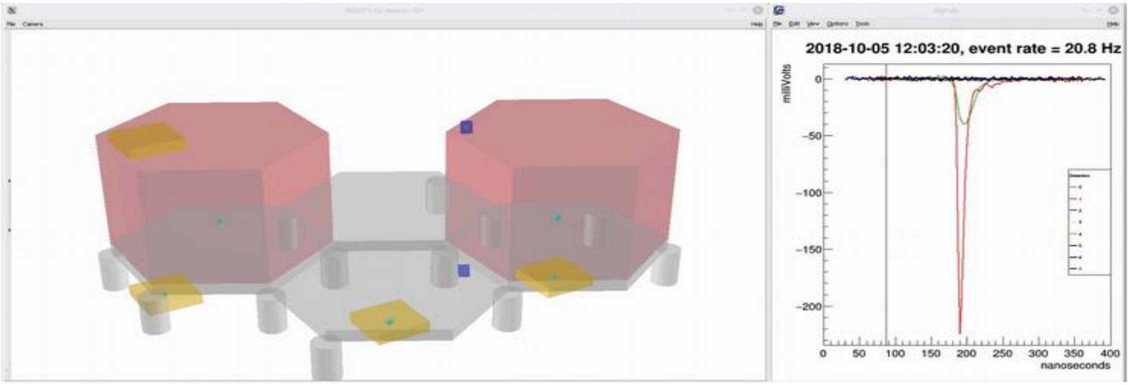


ALTO Event Display

- Sample of events in previous minute
  - (Root + OpenGL)
- Tank 0, crack developed in PMT
  - Replaced with Surface Array box
  - Hamamatsu will supply free replacement

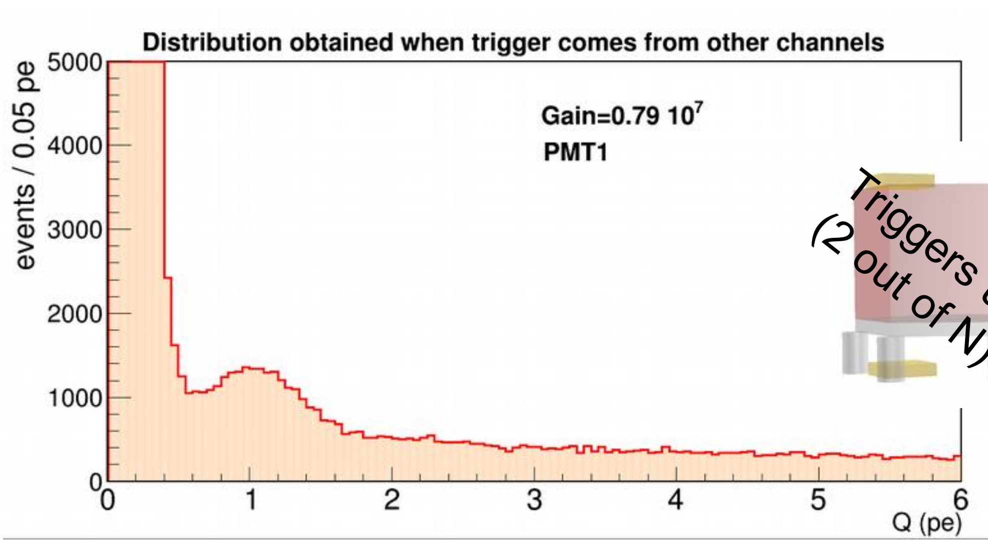
Picture taken Aug 18, 2018

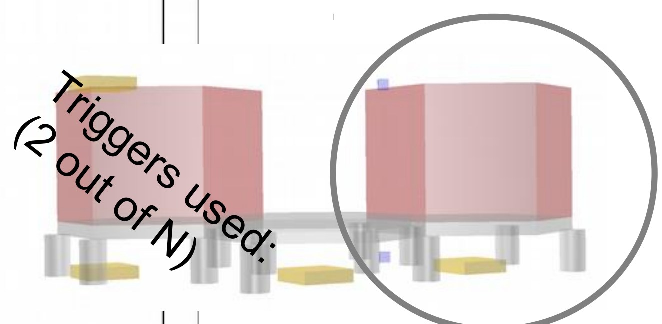
Video of interesting events



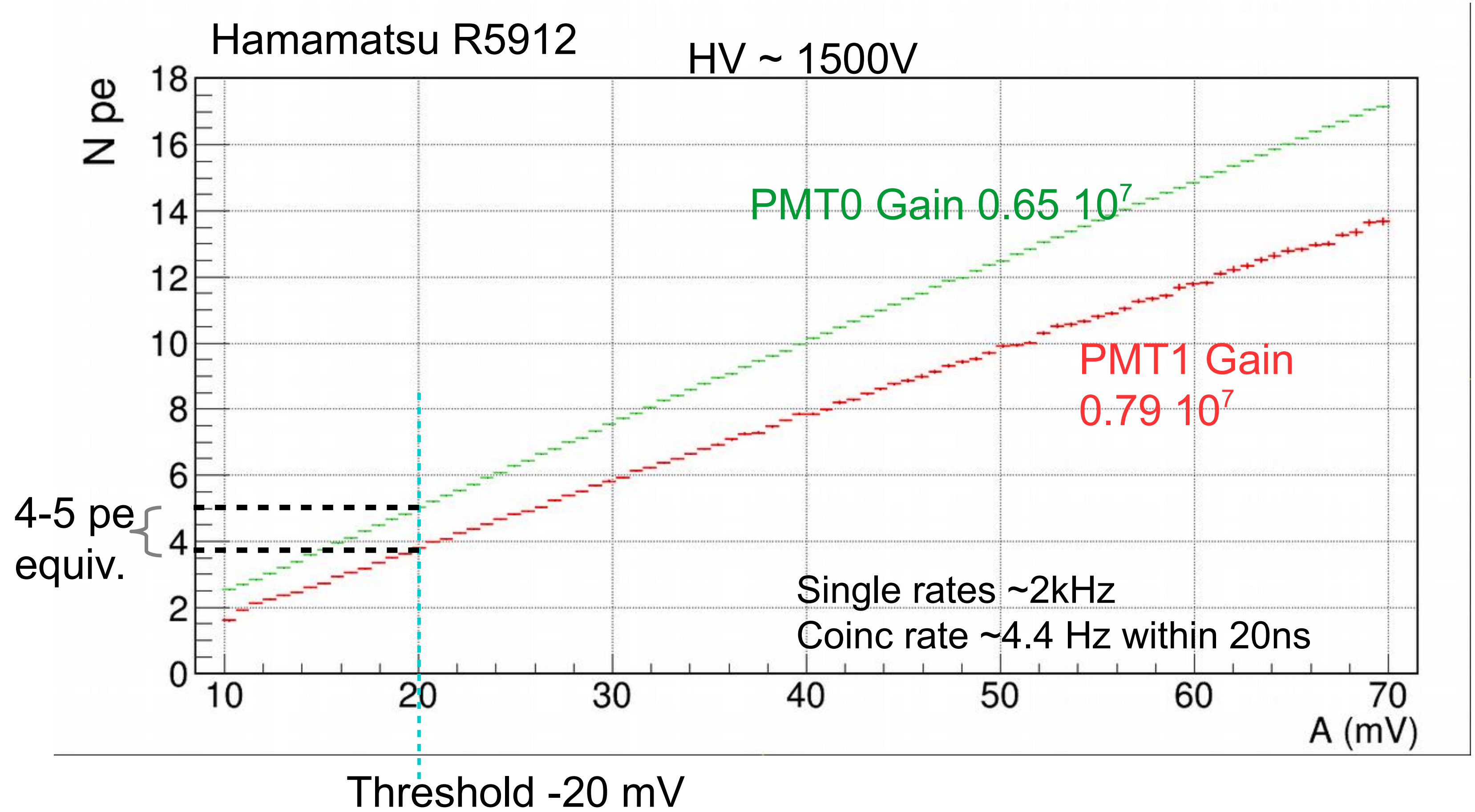
Lessons learned from Prototype: Timing, Charge calibration OK

- Timing calibration
  - See above for prototype
  - For array, local fits on background showers give calibration in ~ minutes
- Charge calibration
  - → Single PE peak accessible



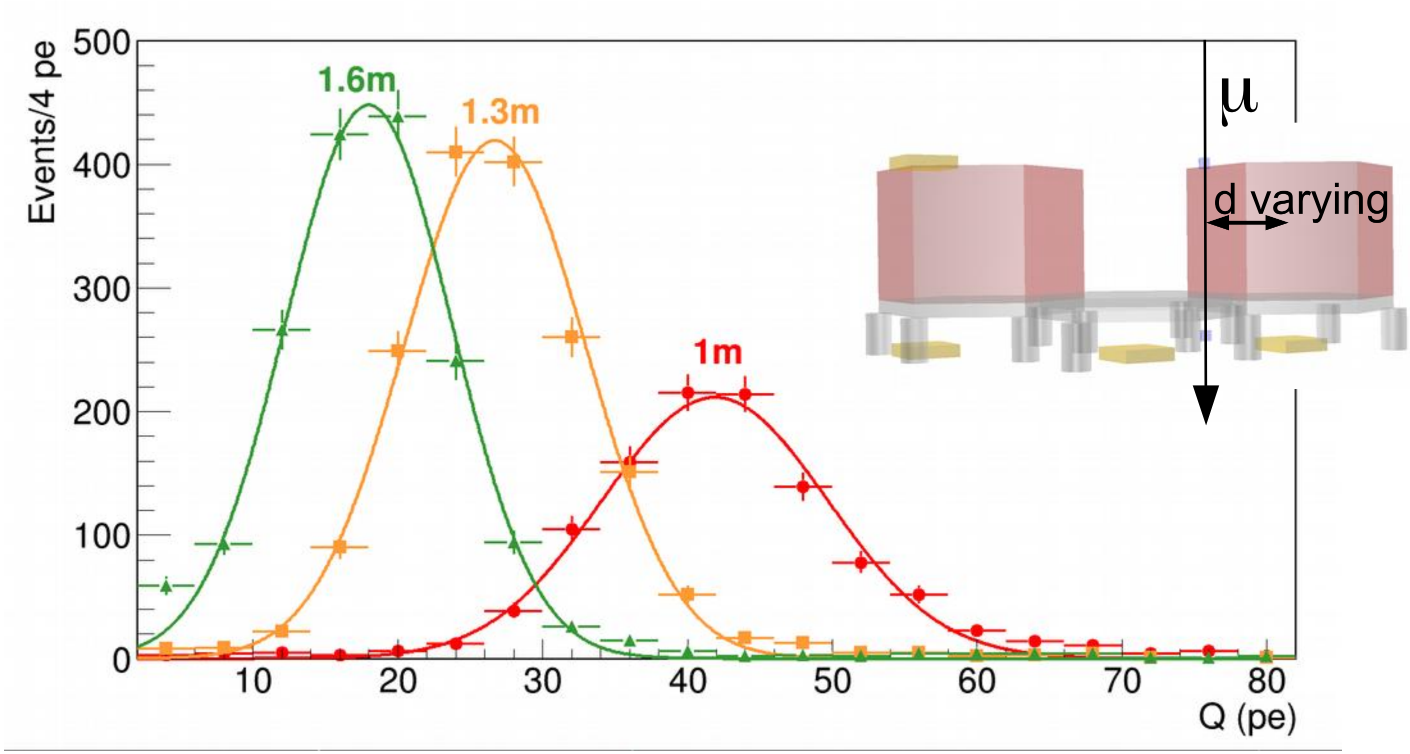


Operating conditions



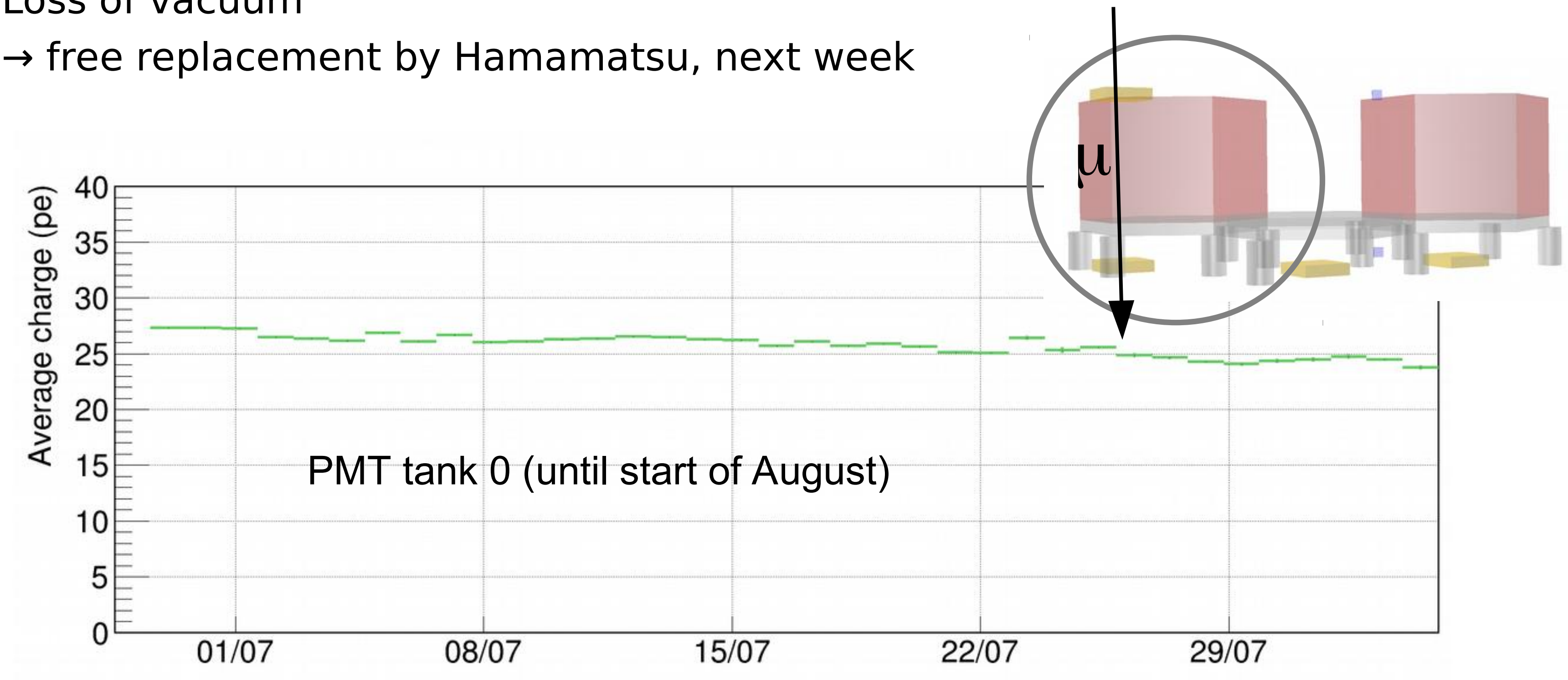
Gains measured with special runs (-3mV thr)
and in standard data (trigger originating from other DUs)

Number of PE given by a single muon



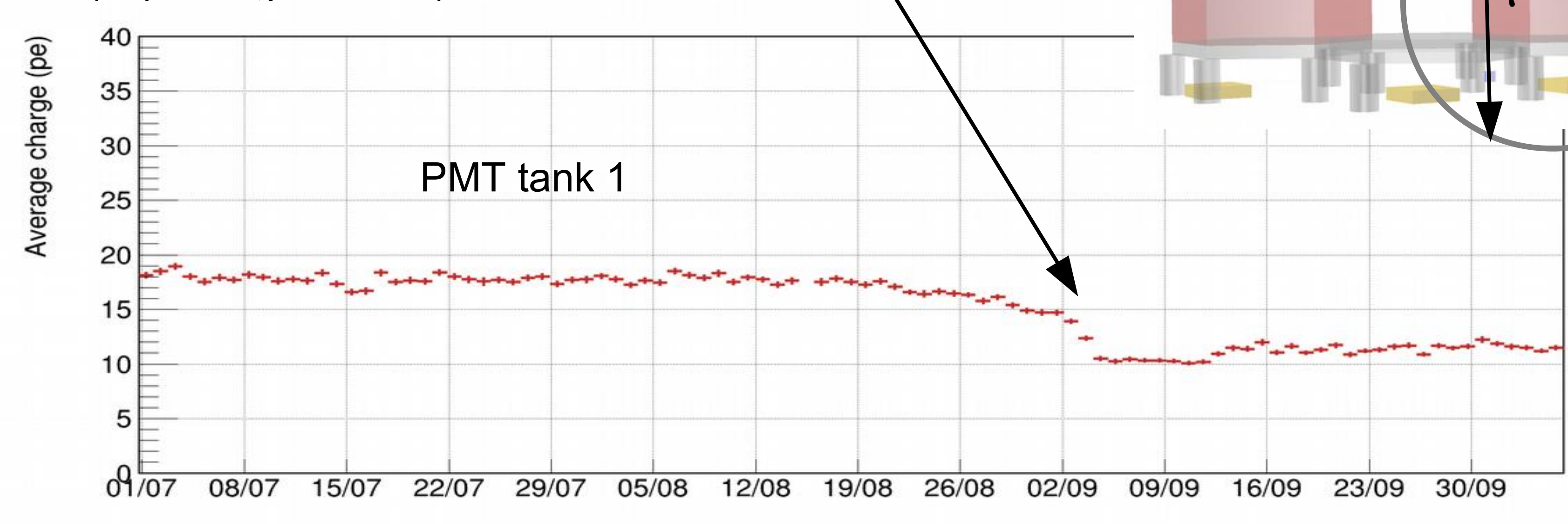
Lessons learned from Prototype: Water quality monitoring

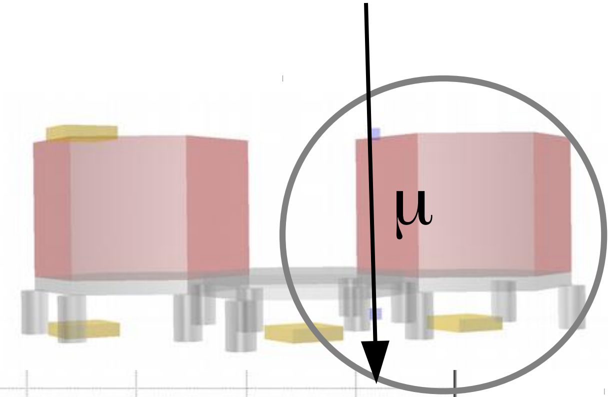
- Continuous monitoring with through-going muons
  - Tank 0, with surface array boxes coincidence
  - Interrupted run...
- PMT crack developed at beginning of August
  - Loss of vacuum
  - → free replacement by Hamamatsu, next week



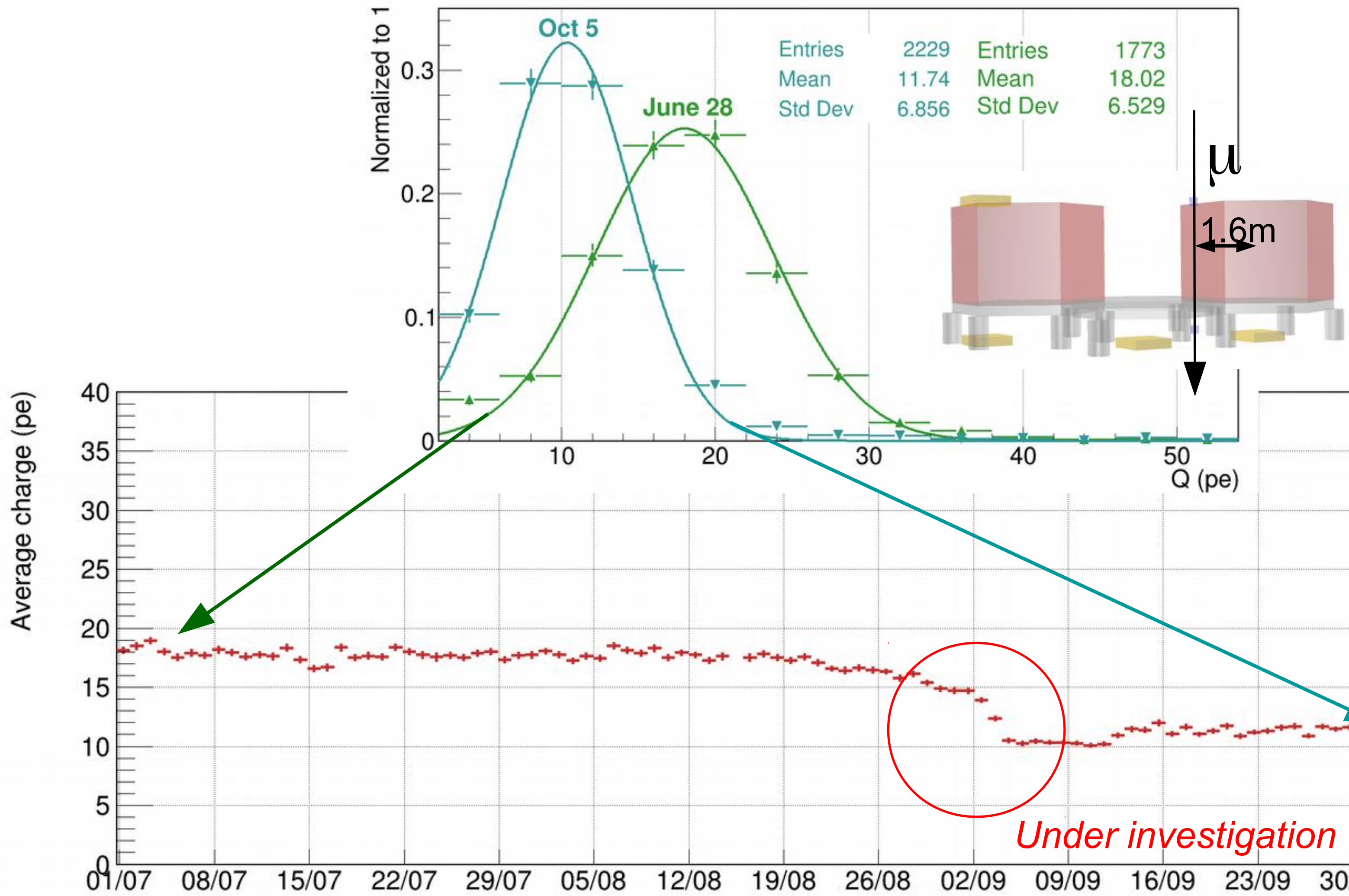
Lessons learned from Prototype: Water quality monitoring

- Continuous monitoring with through-going muons
  - Tank 1, with small plastic scintillators
- Downward jump in charge a month ago
  - Not yet understood
    - Displacement of triggers ?
    - Water ingress to crown ?
    - Development of life in the water?
  - Will examine when we replace PMT in tank 0
- → More chlorine, or UV treatment (depending on cause)





Monitoring



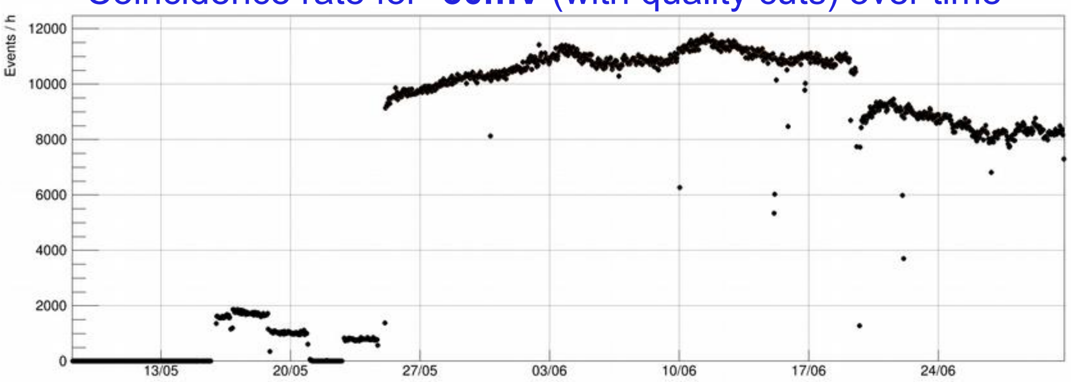
Oct 5
June 28
Entries 2229
Mean 11.74
Std Dev 6.856
Entries 1773
Mean 18.02
Std Dev 6.529
Normalized to 1
Q (pe)
μ
1.6m
Average charge (pe)
01/07
08/07
15/07
22/07
29/07
05/08
12/08
19/08
26/08
02/09
09/09
16/09
23/09
30/09
Under investigation

Readout results

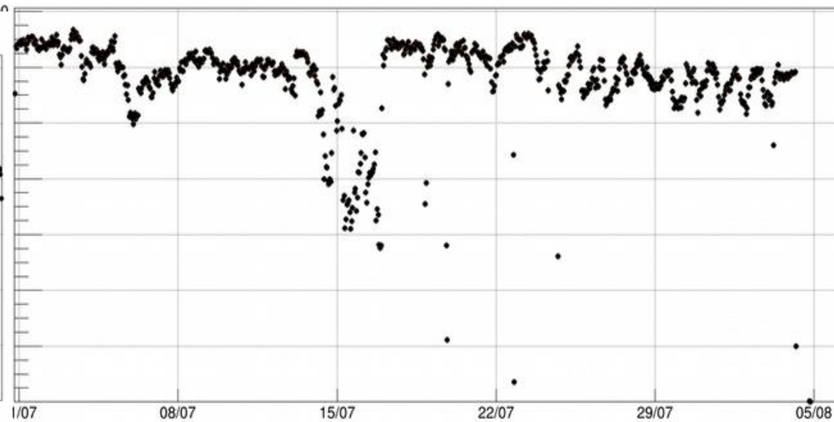
- Coincidences for 2 WCD
  - Individual tank rate < 2kHz
  - From Threshold -20mV
- Loose coincidence window 120ns in hardware to allow for different cable lengths
- Applying coincidence window of 20ns after timing calibration:
  - → 4.4 Hz
- After quality cuts on Charge, pedestal variation
  - Coinc. rate ~ 3.3Hz (12k/hr)

- Note
  - For 2kHz tank rate, 20ns window
    - Random coinc. rate: 0.16Hz
  - With 12 channels: 10Hz

Coincidence rate for **-30mV** (with quality cuts) over time



-20mV



Readout Considerations

- Wavecatcher Dead-Time (due to readout/conversion)
  - 125us for the full 1024 cells, decreasing proportionately
- Current choices:
  - Readout with 0.4GS/s (2.5ns cell size)
    - With interpolation at peak, we show little loss of precision, < **ns** okay
  - 128 samples per event
    - → 320ns, so 6us deadtime, or 5% dead-time at 3.2kHz
      - Even with 4.6kHz singles rates estimated at 5km
      - With 2/12 coincidence in 20ns window
        - → get 55Hz if uncorrelated
    - Events are contained within ~ 60ns
      - Remainder allows luxury of pedestal calculation per trace
      - Could decrease to allow lower dead-time & data-rate
        if using injected pedestals

$$R_{\mathrm{sys,acc}} = M\,{}^{N}C_{M}\,R^{M}_{\mathrm{single,acc}}\,T^{M-1}$$

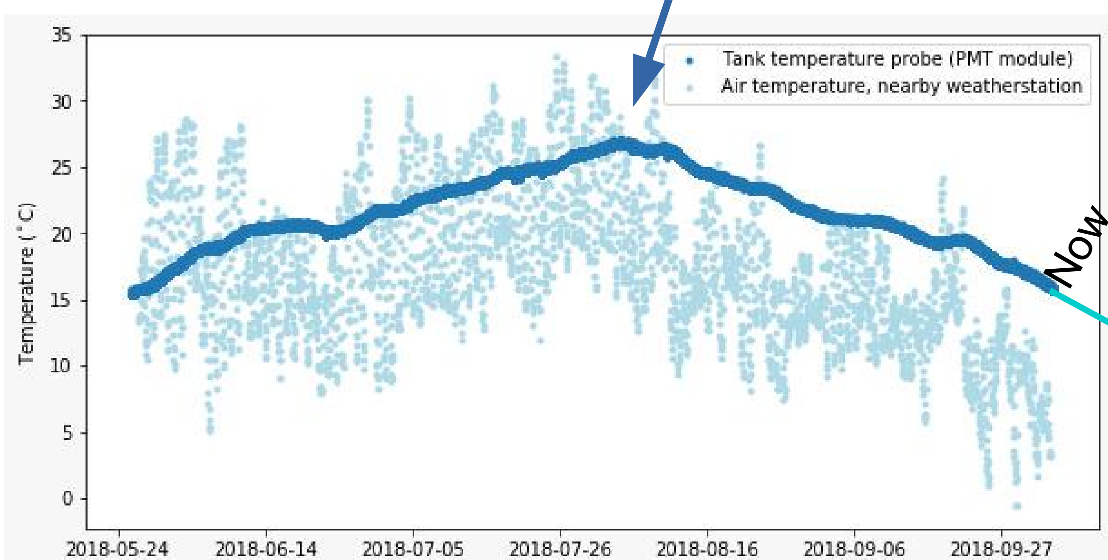
N telescopes
M-fold coinc.

Lessons (to be) learned from Prototype: Temperature response

- Temperature continually measured in the PMT assembly (plexiglass tube)
- Can be compared to measurements from nearby weather station

- Perhaps thermal inertia and sunlight (solar gain) would work in Argentina / Chile?
  - Note, PVC foam sandwich probably a good thermal insulator
  - But in Sweden, will test with -20°C winter temperatures, low sunlight, short days

Historically hot summer in Sweden



Winter is coming...

Conclusions

- 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 and
  - about behavior of water/crown/PMT encapsulation.
- Will be pursued with Scintillator tanks.

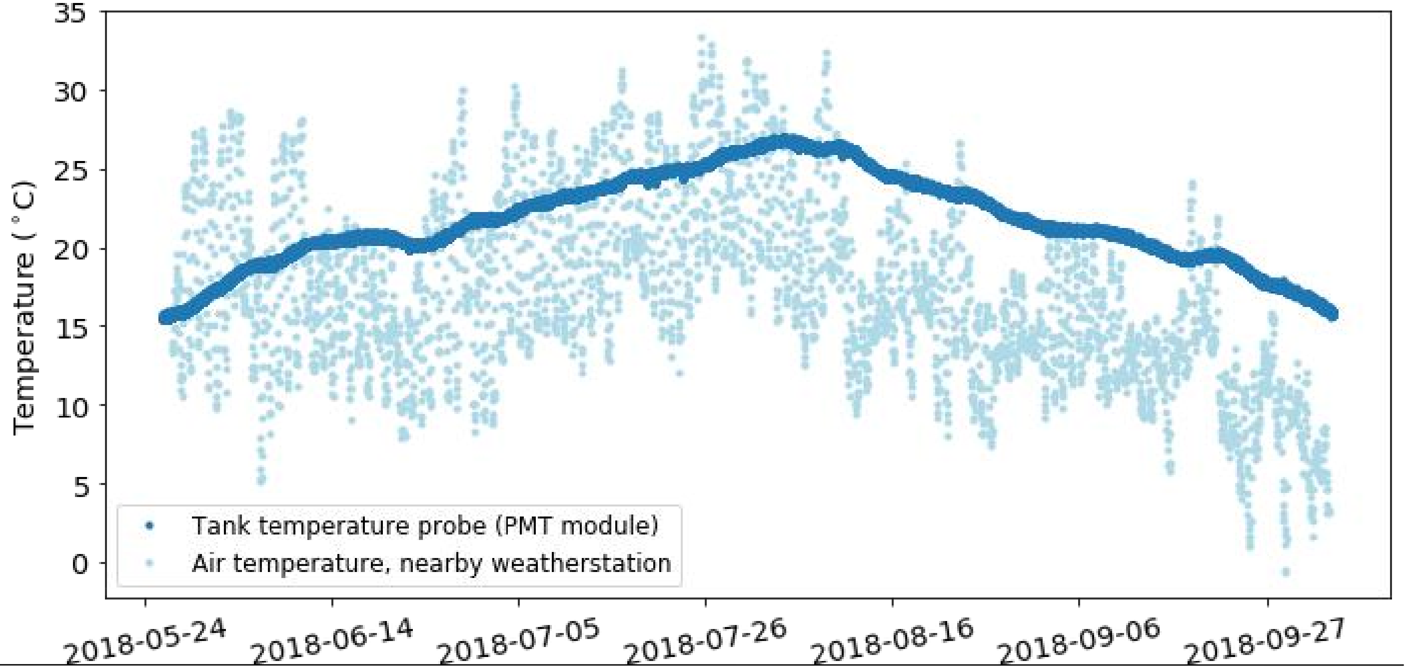
- Very fruitful interaction with local Swedish industry
- Need to work on lowering the prices (ongoing)
- Inauguration planned when ALTO scintillators are in place:
  - You are all invited! Details coming later
- Next major step: installation of protype on a high altitude site:
  - QUBIC/LLAMA site might be optimal for this

- Status of the project with further information can be found at the website:
- → http://alto-gamma-ray-observatory.org/

Backups

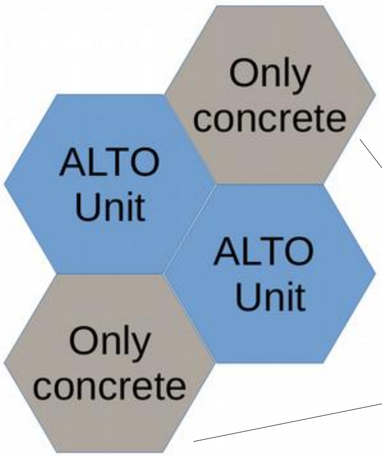
ALTO proto Environmental and Longitudinal measurements

- Temperature measurements from probe within WCD PMT module
  - Can compare with measurements from local weather station
- High thermal inertia from 25 tonnes of water evident
- Water quality / Crown / PMT measurements through Surface Array & Scintillator detectors
  - Investigating if oblique muons hitting WCD and neighbouring SD can give useful calibration signal



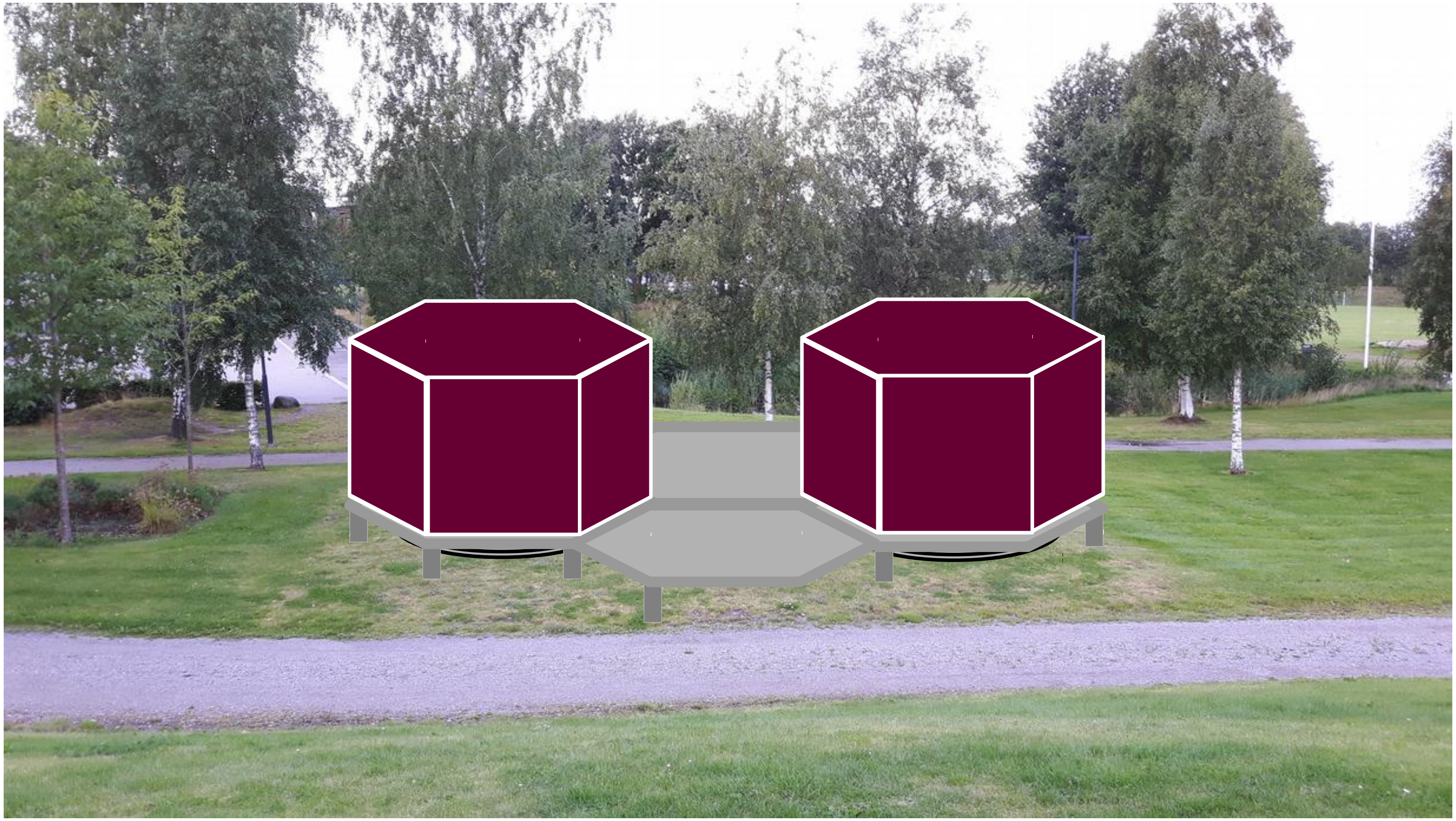
ALTO prototype at Linnaeus University in Växjö, Sweden

- Construction starts January 2nd 2018
- Several PMT solutions will be tested;
- Fully funded: construction of two full ALTO units, with 4-tank concrete layer
- The empty slots will be equipped with (smaller) additional scintillator boxes



Additional scintillator layers recycled from an on-board air-shower array used for ANTARES calibration purposes

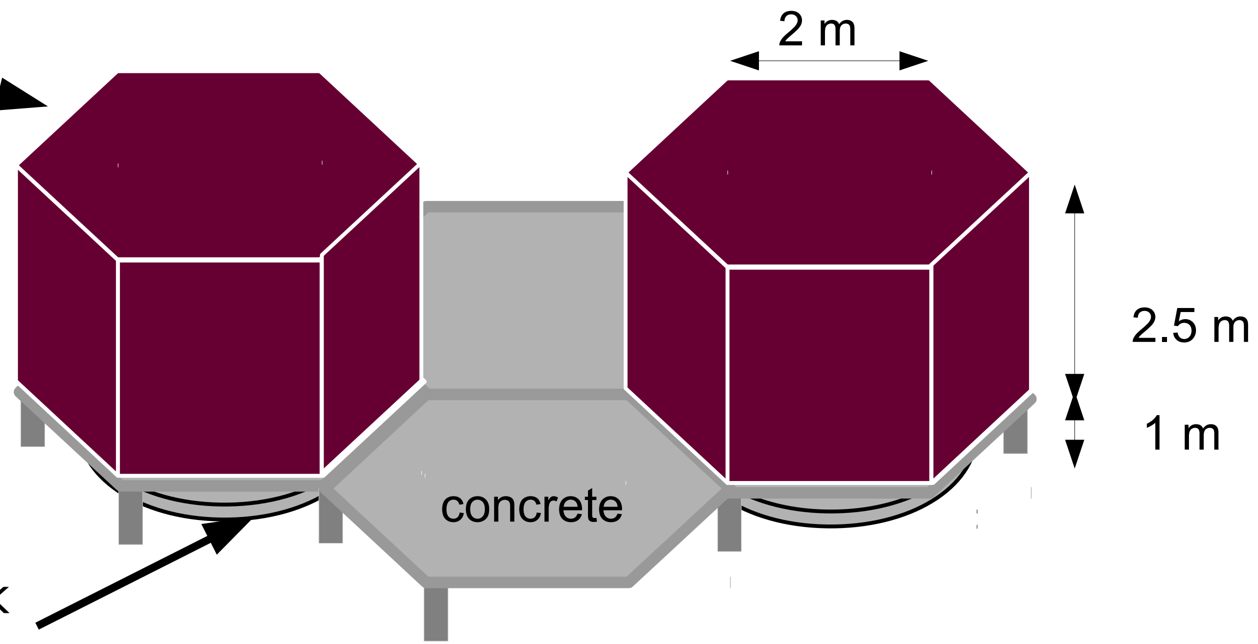
ALTO prototype setup in Växjö



ALTO prototype setup in Växjö

Water
Tank
(25 m^3)

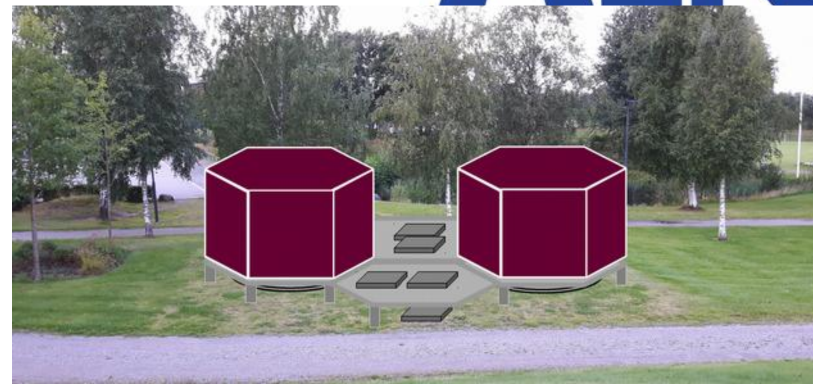
Carbon fiber
(black ”gel-coat”
painted inside)



Scintillator Tank
(0.33 m^3)
Aluminum
(reflective inside)

Project time-line & Next steps

- 2018 - Validation of prototype design;
  - At LnU campus, with "Antares Surface Array"



- 2019 - If design & funding requests successful:
  - Installation of one or more ALTO clusters at the site in the Southern hemisphere;
  - Flat-pack construction ("IKEA-type") assembly by local crew or "base camp"

2018-Q1	2018-Q2-Q4	2019?	
Prototype construction	Prototype validation and operation	Installation of one or more clusters at the final site for further validation	Full deployment

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
  - Synergies within APC lab which is working on QUBIC
- We should be in the back lobe of QUBIC in order not to disturb the QUBIC experiment data taking
- 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

Constraints and consequences

An accurate time is essential (O(ns)). Indirect late photons must not be seen in place of missed direct photons
→ reflections are strongly reduced by painting the inside of the tank in black (black gelcoat)
→ only direct light is seen by the PMT.

Only a **few tens** of **photoelectrons** are expected →

A) We use a large PMT (8 inches) with a high gain : 10^7.

B) We optimize the collection of light : next slides

Optimization of light collection

In order to avoid to buy a 10" PMT (more expensive, fewer providers), we use a reflective crown to get 10" performance with an 8" PMT.

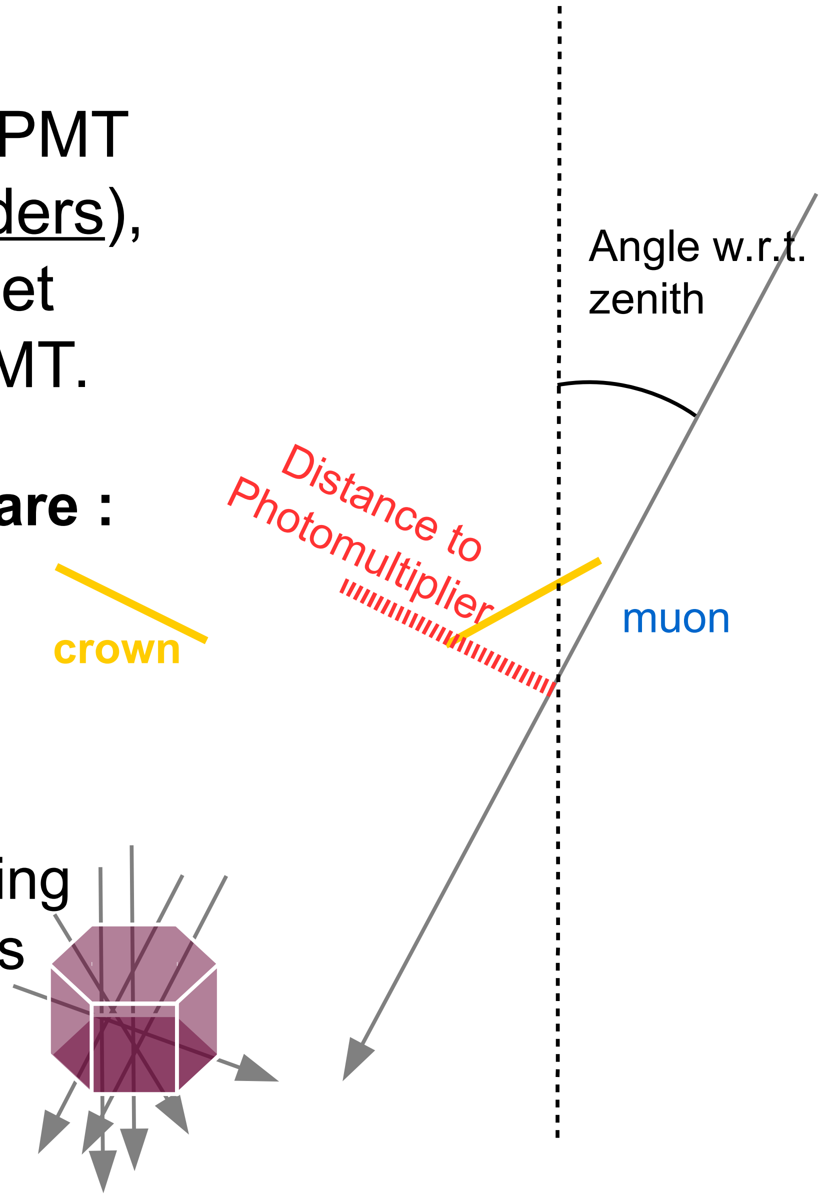
In the next pictures we compare :

bare 8" PMT / 10" PMT

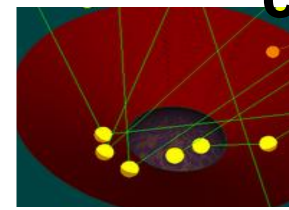
with

8" with crown / 10" PMT

using simulations of muons crossing the water tank : all possible angles and distance to PMT

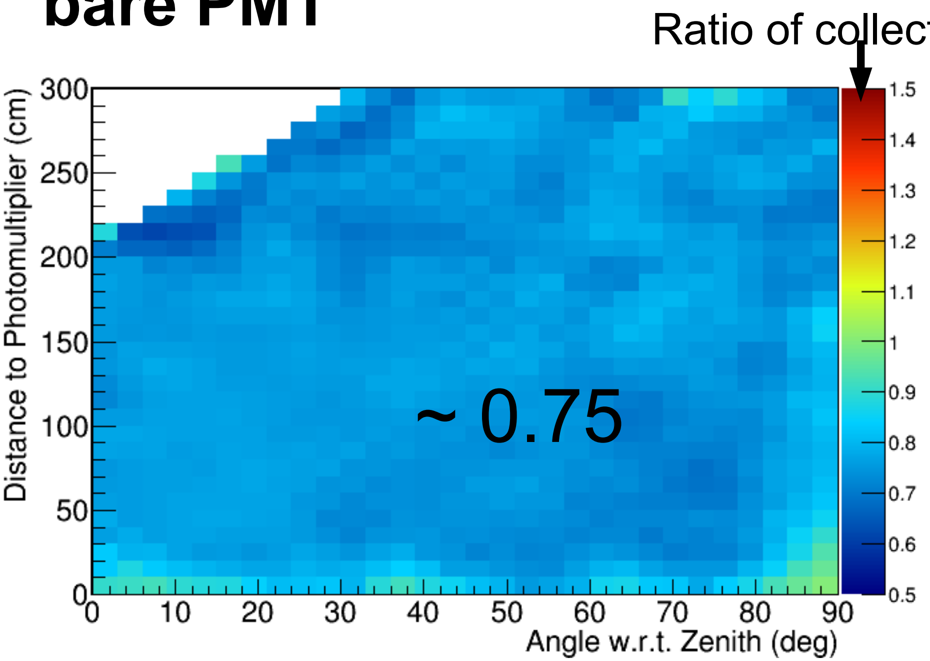


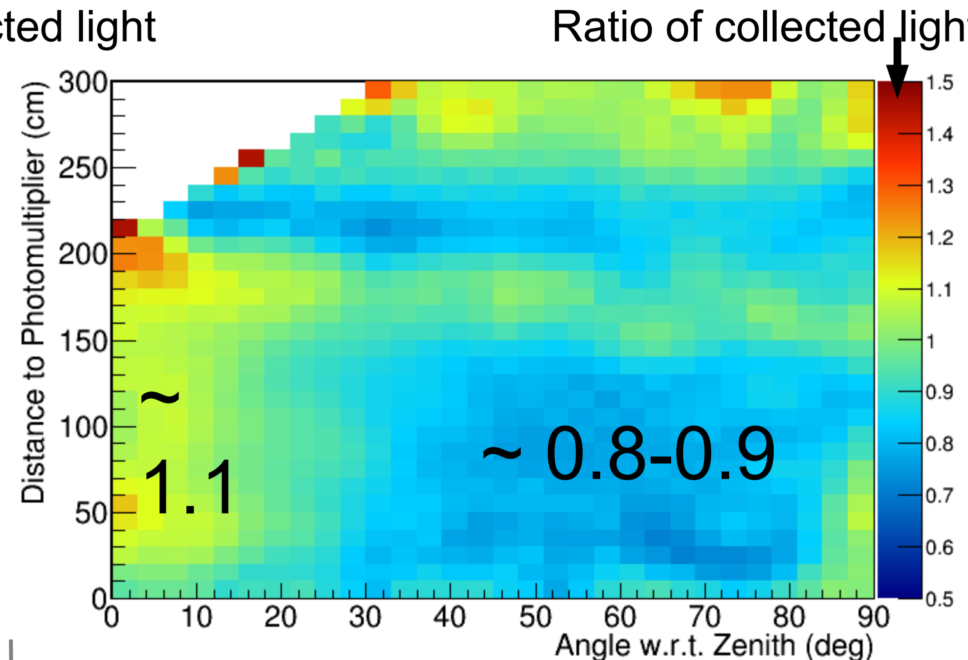
Optimization of light collection



Improvement due to the crown

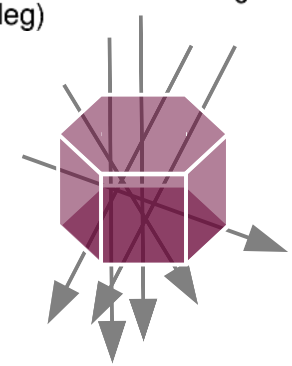
bare PMT





bare 8" PMT / 10" PMT

performance reduced = ratio of

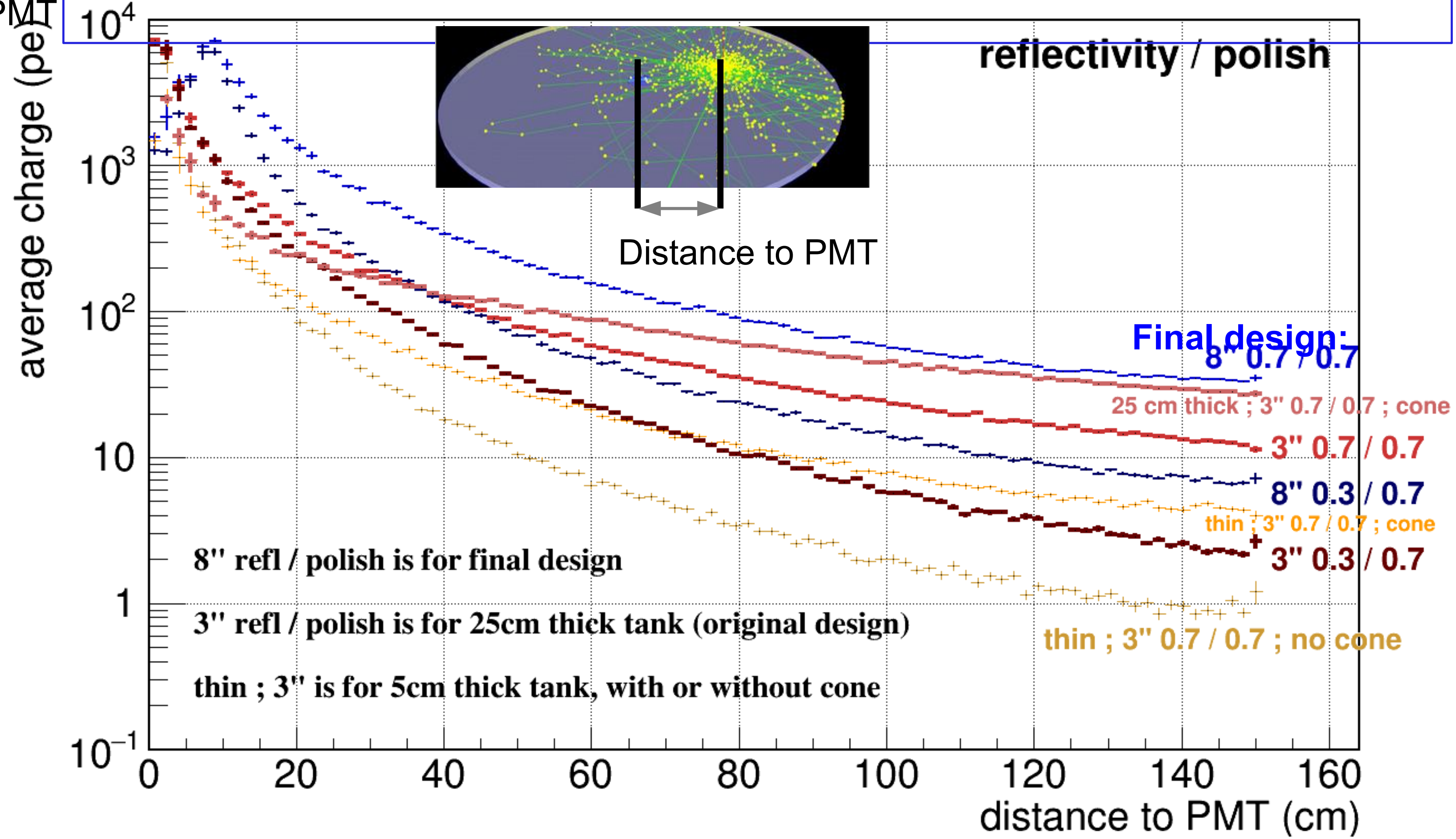


8" with crown / 10" PMT

we recover nearly all 10" performance.

History of optimisation of “scintillator tank”

Seen by PMT



Remark: “thick” is old 25cm design, central 3” PMT, et possible reflective cone below. Required 5 times more liquid than current design.
“final” design with 4.6 cm or less liquid, with 8” PMT. PMT price difference more than compensated by the decrease of liquid scintillator (+ benefit of lower weight). *Simulations Geant4.*

ALTO Pre-prototyping

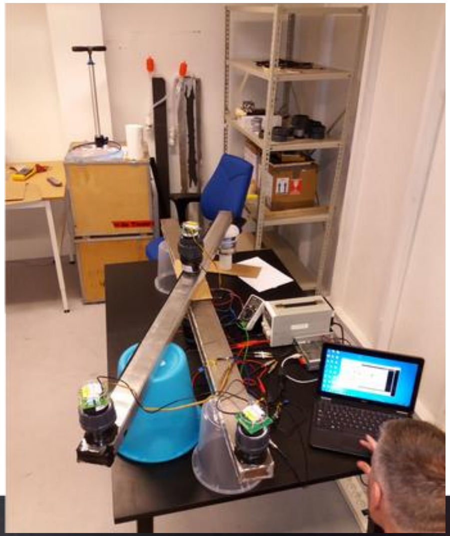
- Many test-benches, all with readout triggered
  by small (10x20cm) muon-paddles, read by "WaveCatcher"
  - All compared with GEANT4 simulations to find reflectivity, absorption, etc.

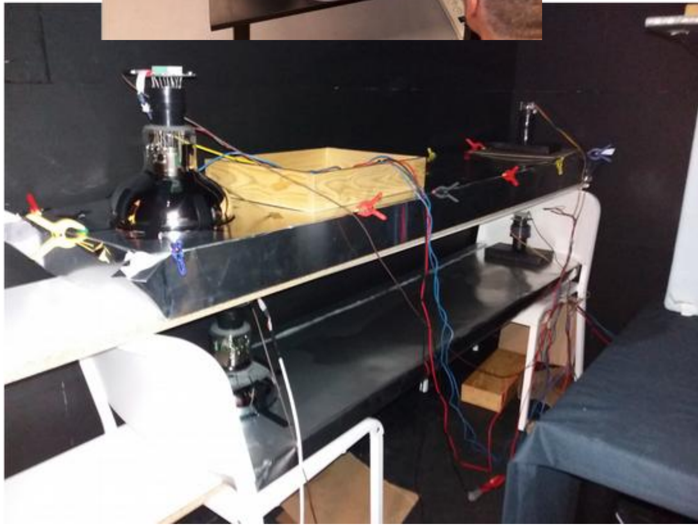
- Small water tank viewed from above by 8" PMT, to test
  - blackness of the internal "gel-coat"
  - Effects over time with strong chlorine concentration (bio-growth, leaching)
  - → 20x normal swimming pool concentration OK for now

- "Scintillator rails" read by 2" PMT
  - To test Aluminium material used in lower tank
  - Comparison of measured and expected
    (from GEANT4 simulations, adjusting reflectivity & polish)
  - → led to redesign using folded 0.5mm Al sheet
    - No welding, much simpler construction

- Large scintillator tank read by 8" PMT
  - To test aluminium material with final PMT immersed in Scintillator
  - Test of re-design → Confirmation of simplicity of construction
  - Result scalable to full-sized tank
    (factor ~x2 PE from reflections on walls)

- Comparison with a deeper (10cm) tank with Water (not scintillator)
  but with liner to replace scintillator tank, currently running
  - May be able to reduce costs, avoid some radioactivity triggers

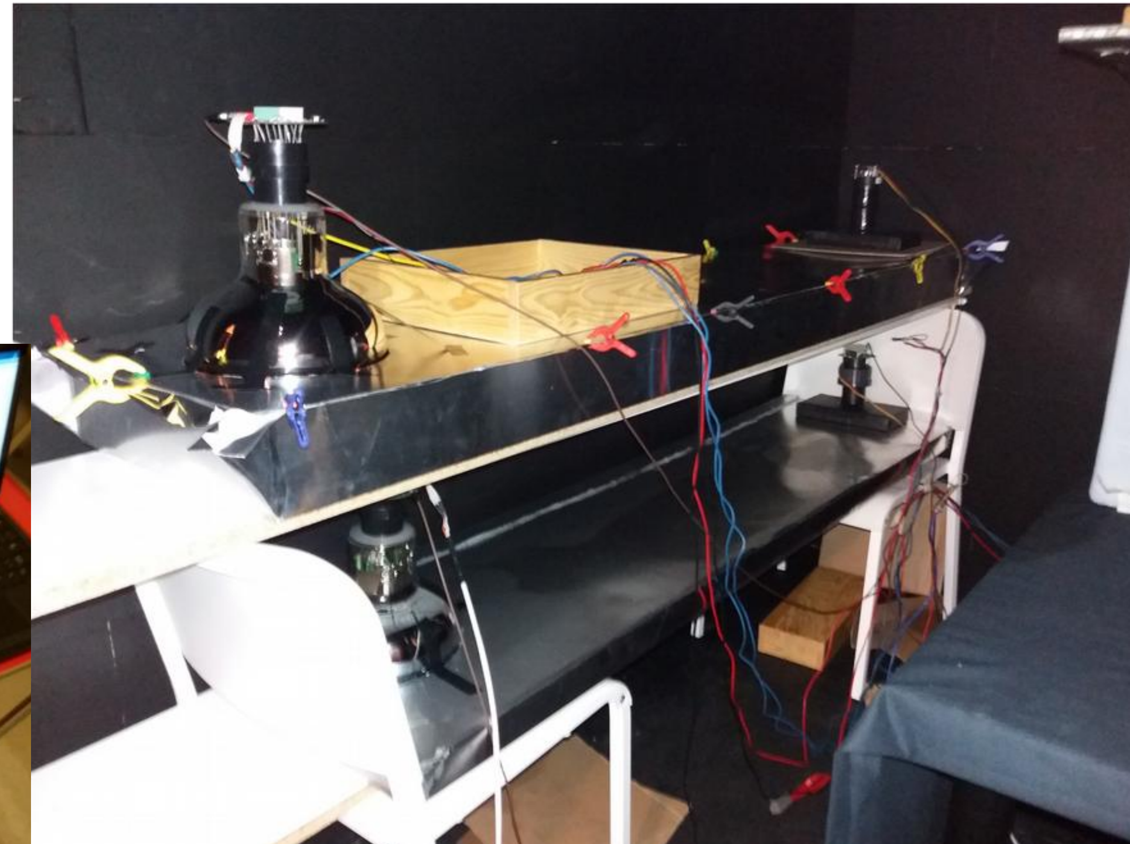


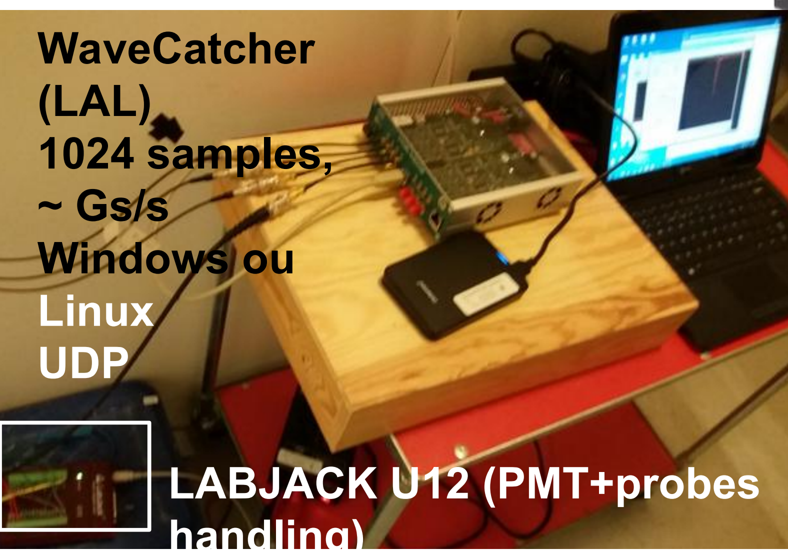


Pre-prototyping: Dark Room tests

Large scintillator tank read by 8” PMT

- To test **aluminium** material with final PMT immersed in **Scintillator (3cm)**
- Result scalable to full-sized tank

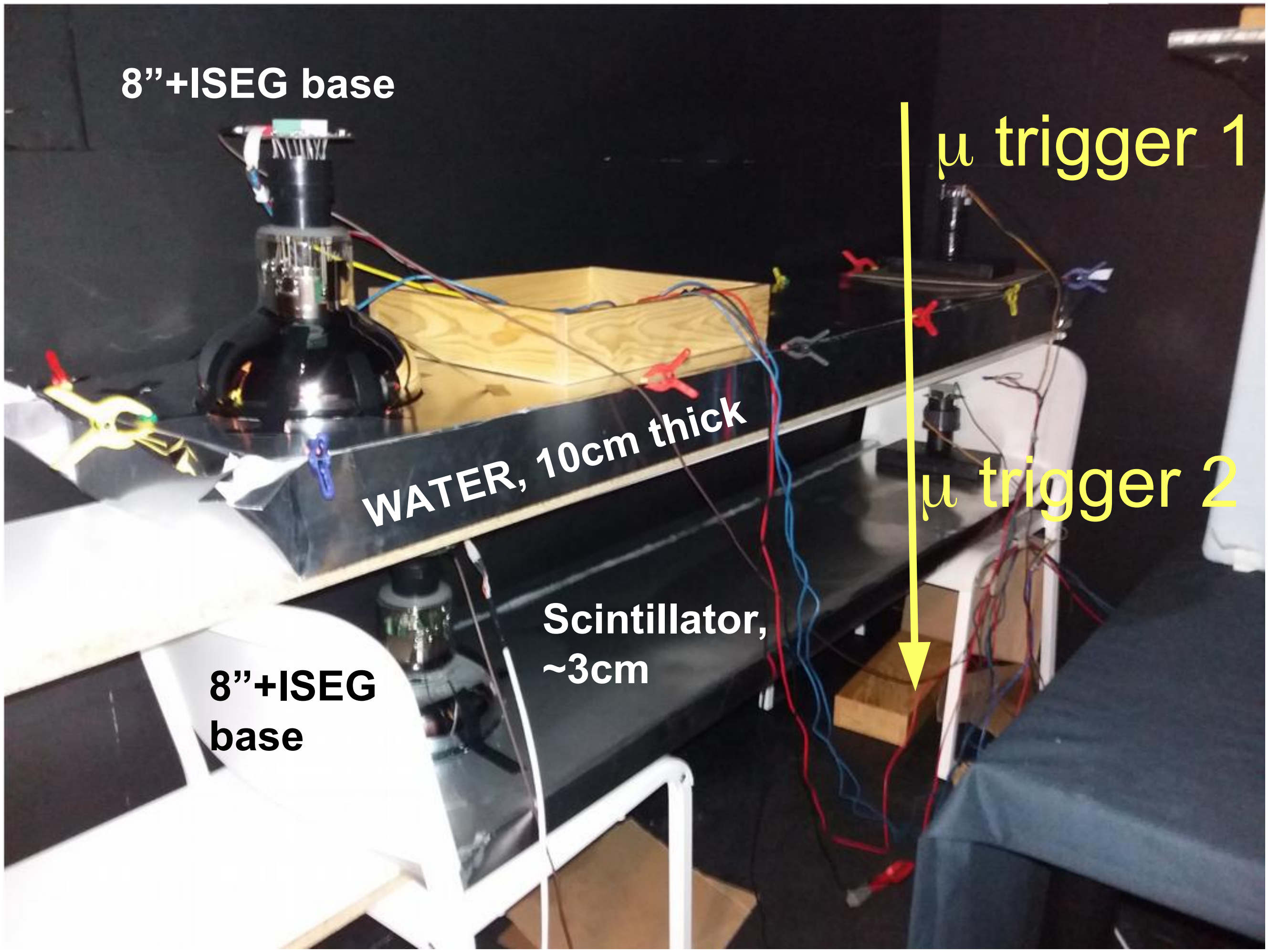




Comparison with a deeper **(10cm)** tank with **Water** (not scintillator, but **Cherenkov** effect: 20 times less photons) + **Tyvek** as reflector to replace scintillator tank, satisfactory, but freezing proplem probable: May be able to reduce costs, avoid some radioactivity triggers.

Test of small-scale bottom tank

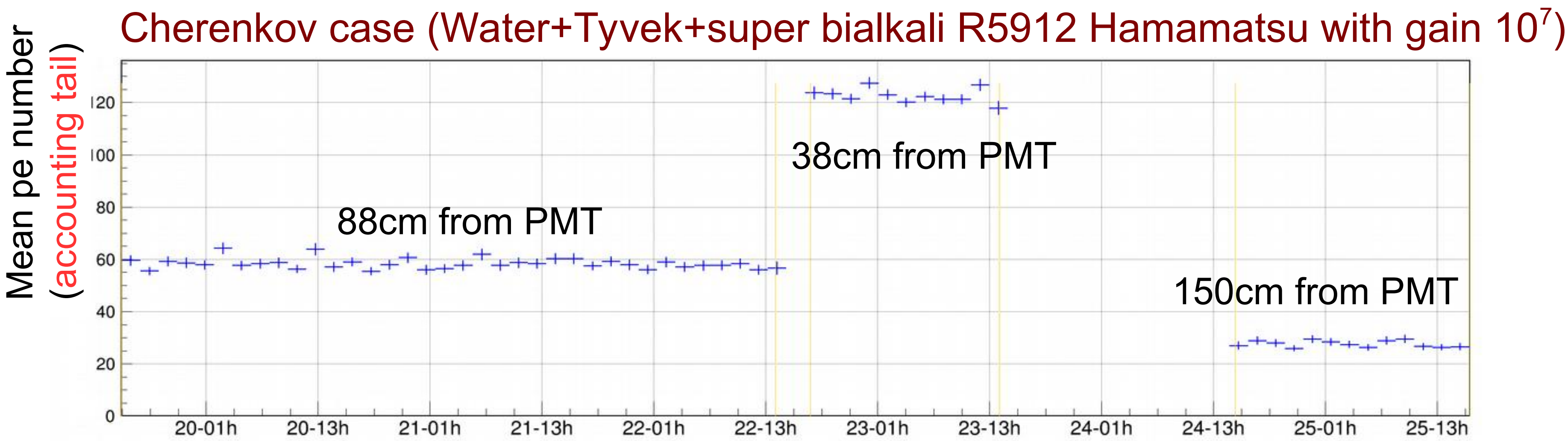
(area=area of final tank/10)

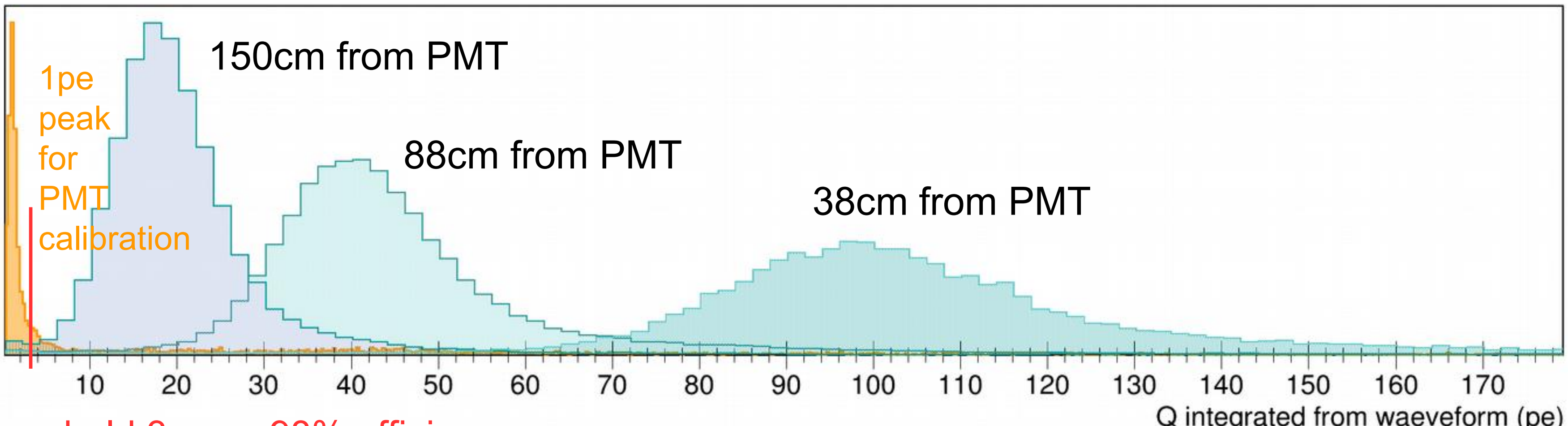


Tests of:
Water
(Cherenkov)
and
LAB+PPO+POPOP
(Scintillation)

Reflector in tanks:
aluminium,
Tyvek

Collected PEs =*f*(trigger distance from PMT center)





Threshold 3pe → 98% efficiency
and single rate 1.3 kHz