Anatomy of large-volume neutrino telescopes

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Lecture 2

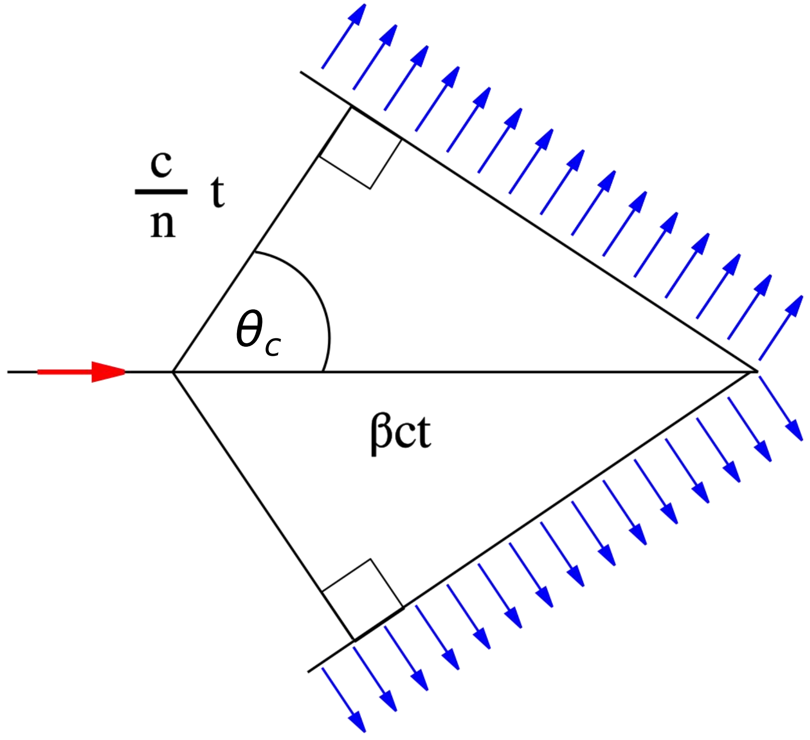
Detector response, readout and calibration

Cerenkov radiation

Charged particles moving with velocity above the speed of light in medium emit the Cerenkov radiation

Radiation intensity:

$$\frac{dN^2}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}(1 - \frac{1}{\beta^2 n^2})$$



Threshold energy

Particles above that energy emit the radiation

$$E > E_{th} = m(1 - \frac{1}{n^2})^{-1/2}$$

In water:

- electron: 775 keV
- muon: 159 MeV

Cerenkov angle

$$cos(\theta_c) = \frac{1}{n}$$

for water: ~41.2°

Cerenkov radiation

PMTs commonly used in LVNT are sensitive to ~blue region of visible spectrum

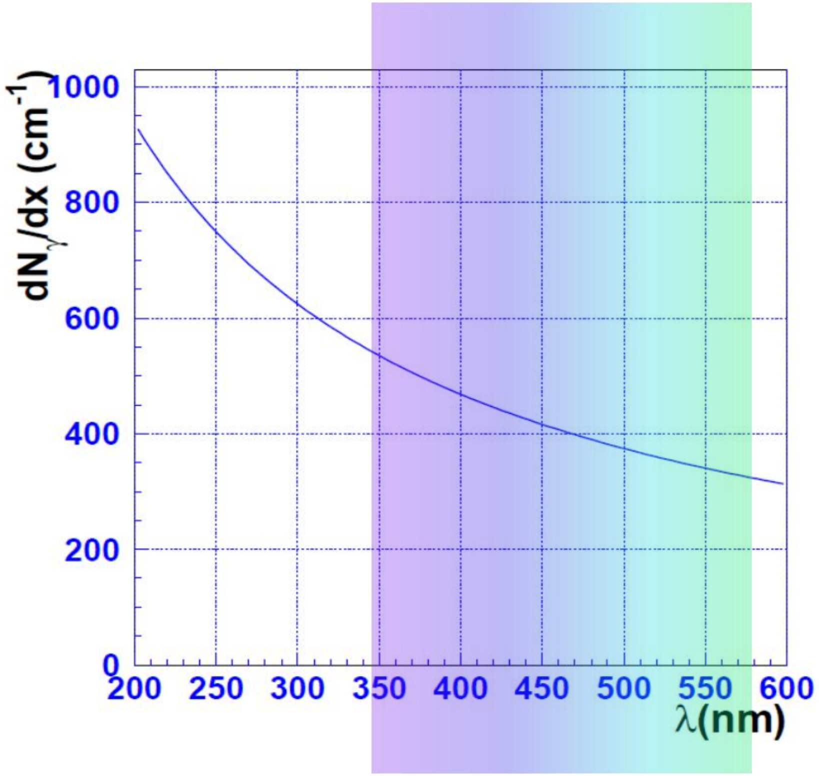
Number of photons emitted by muon or electron with β~1 per unit length in some wavelength band:

$$\frac{dN_\gamma}{dx} = 2\pi\alpha \sin^2(\theta_C)(\frac{1}{\lambda_1} - \frac{1}{\lambda_2})$$

Number of photons emitted in **320-580nm** band by β~1 charged particle 1m: **23904**

In further slides we will Cerenkov signal development for 10 TeV muon passing through the detector

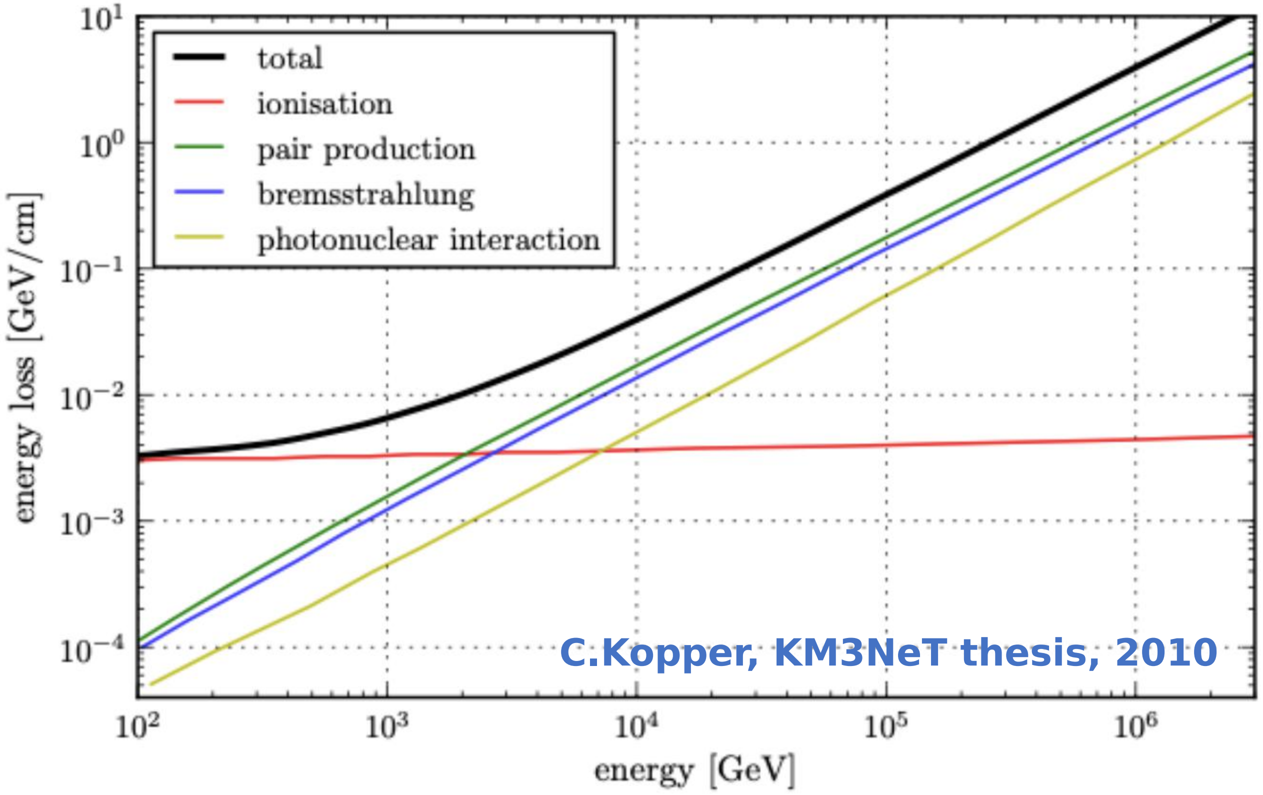
approximate photodetection band



Muon energy losses

~ Constant minimum ionizing particle (MIP) energy loss rate for low energies: ~2MeV/cm in water

High-energy muon energy loss in water



Linear stochastic energy losses starting at ~1 TeV

$$-\frac{\mathrm{d}E_\mu}{\mathrm{d}x} = a + b \cdot E_\mu$$

Losses manifest themselves as showers along the muon track

Main contribution from EM showers

- pair production
- bremsstrahlung

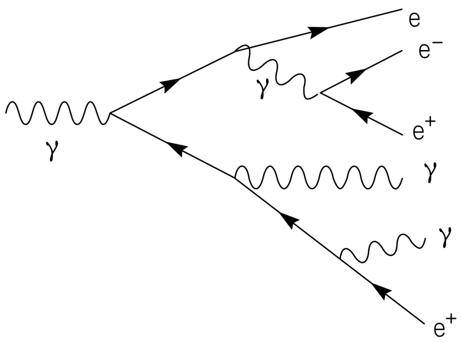
Less important HAD showering

- photonuclear interactions

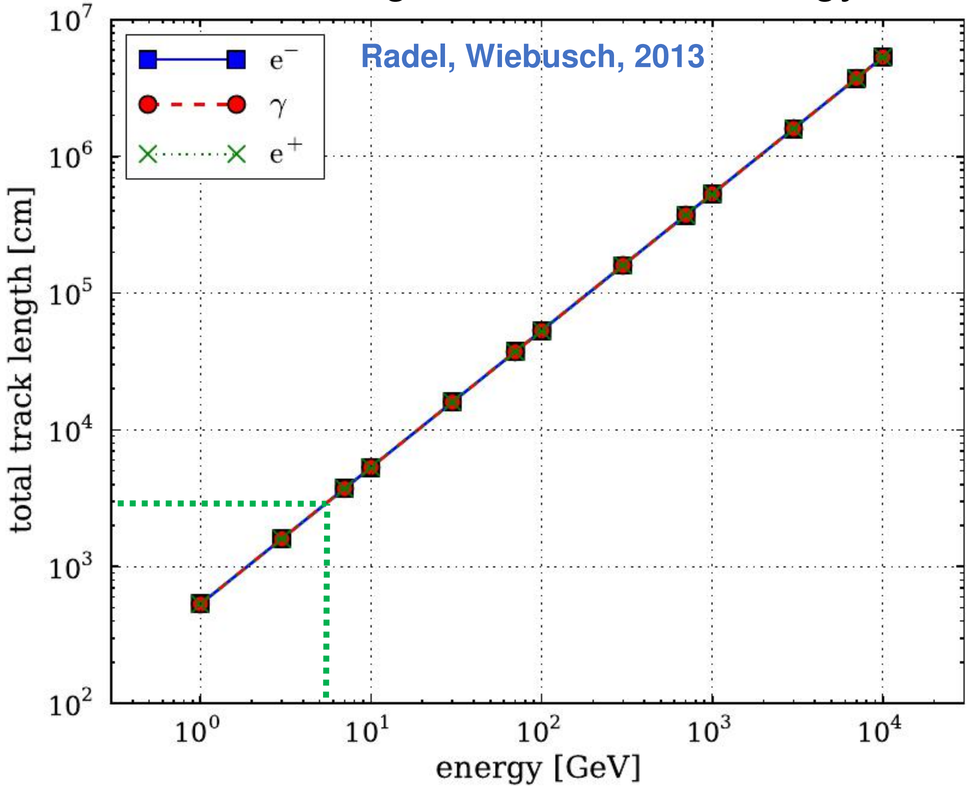
Let's consider 10 TeV muon, energy loss ~ 0.05 GeV/cm or **5 GeV/m**

Light yield due to EM energy losses

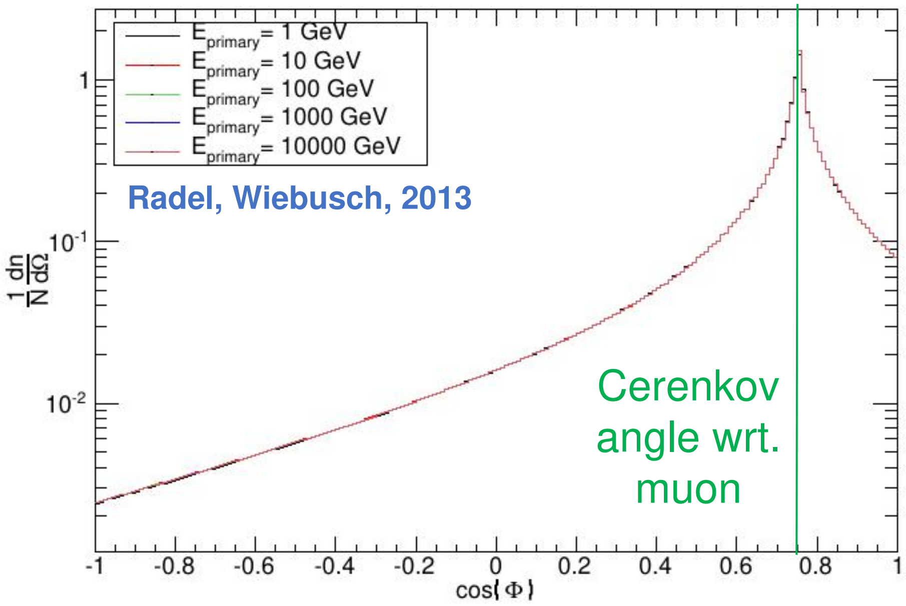
Charged particles in accompanying EM cascades emit Cerenkov light



Total Cerenkov-radiating track length vs cascade energy



Angular distribution of EM shower Cerenkov light



Assume our 10 TeV muon loose energy in one 5 GeV EM shower
It adds ~30 m of Cerenkov-emitting track length!

741024 photons per m in total

Light absorption

Light propagates to photodetector

Light absorption reduces the light intensity as follows

$$I(x,\lambda) = I_0(\lambda)e^{-x/L(\lambda)}$$

Where

- *x*: the distance from the source to the detector
- *L(λ)*: light absorption length

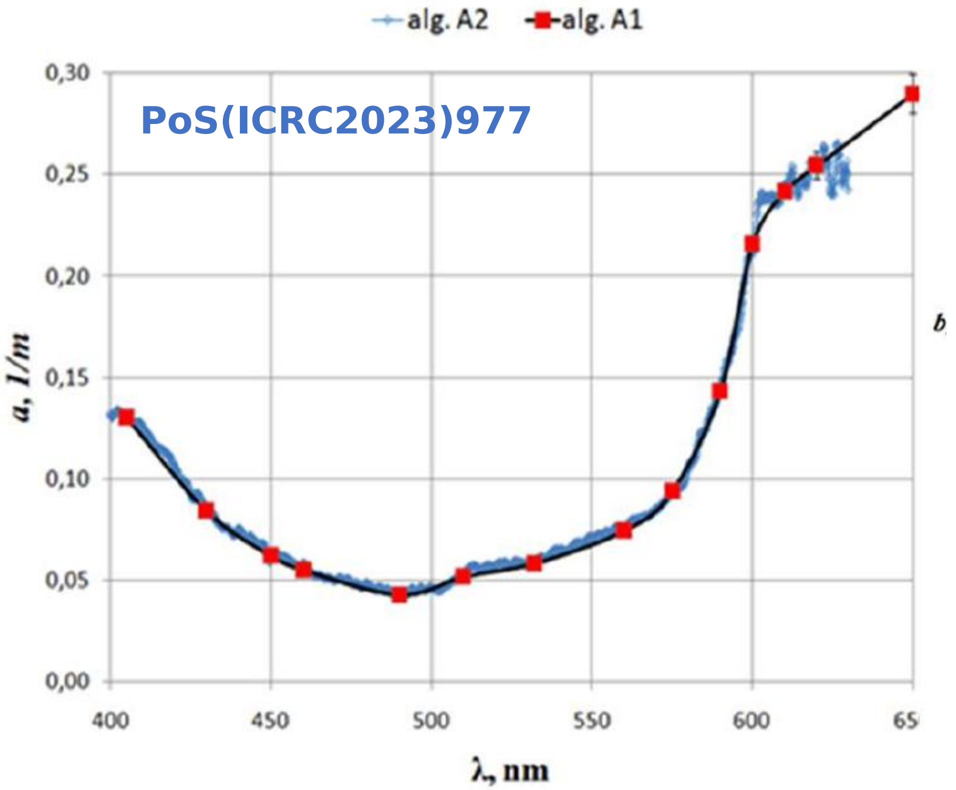
Estimate the light field for 10 TeV muon at few radii

$$\frac{dN}{dS} \sim \frac{1}{2\pi R}\frac{dN}{dx}\exp(-\frac{R}{L\sin(\theta_c)})$$

10 m : ~0.226 γ/cm²
22 m : ~0.014 γ/cm²
30 m : ~0.0027 γ/cm²

Use 10m average abs. length over the detection band

Absorption spectrum for Baikal water



Abs. length at 490 nm: ~ 22 m

Light scattering

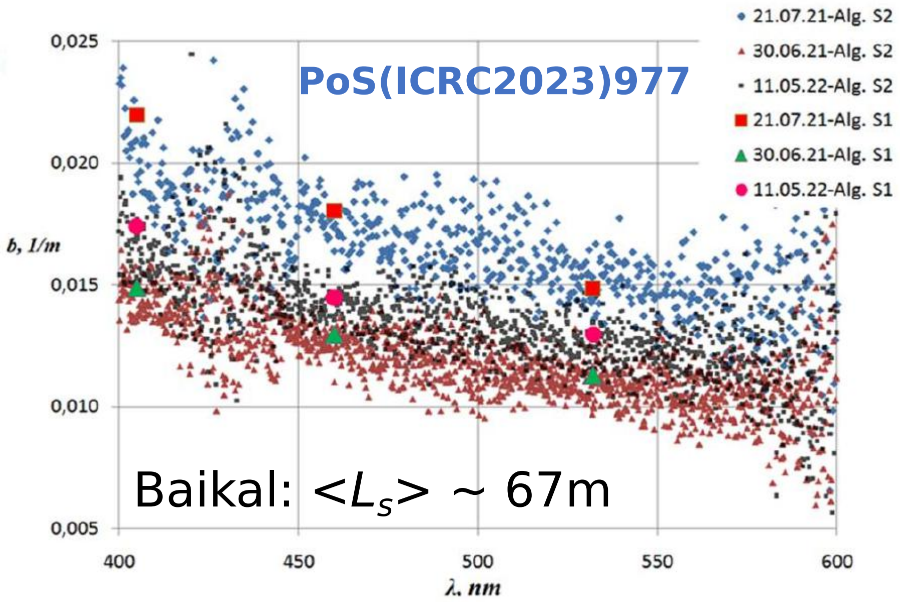
Photons propagating in media experience scattering such that a photon on average scatters at angle $\langle\cos(\theta)\rangle$ at a distance $L_s(\lambda)$

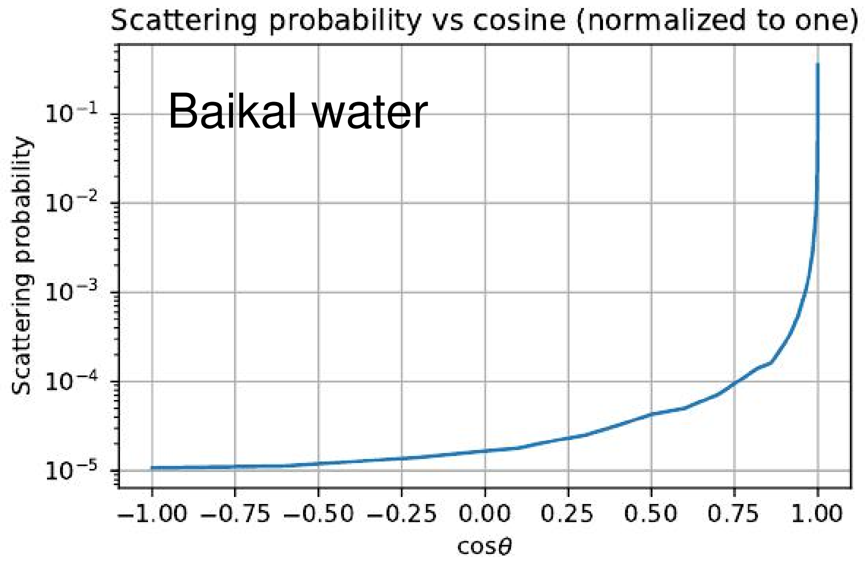
Effective scattering length takes into account scattering angle:

$$L_s^{\mathrm{eff}}(\lambda) \simeq \frac{L_s(\lambda)}{1-\langle\cos\theta\rangle}$$

For Baikal or Mediterranean water average scattering angle is close to 0°

Effective scattering length reaches hundreds of meters





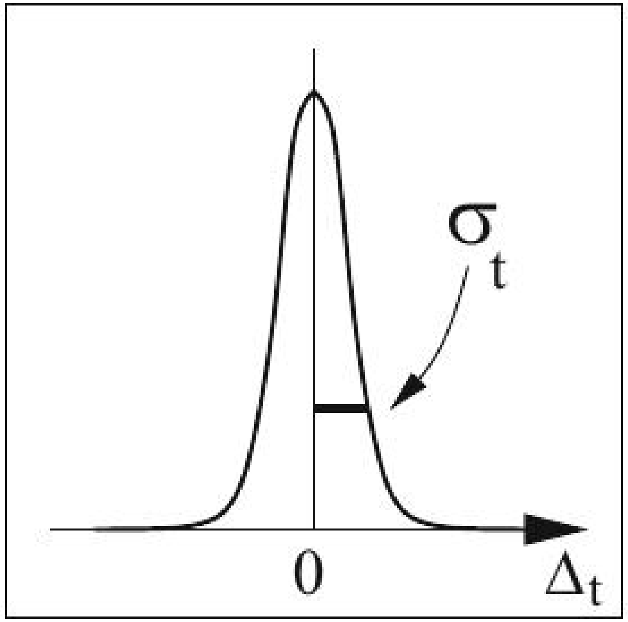
Light scattering

Light scattering causes delay of photon arrival wrt. track or cascade model

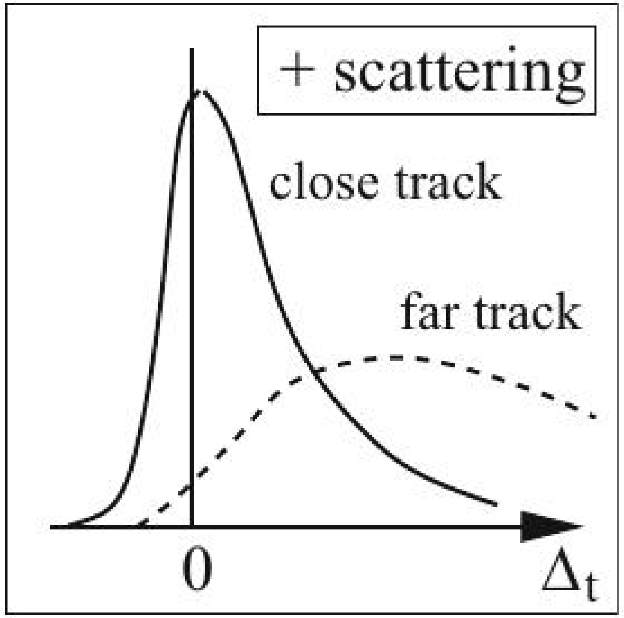
Short scattering length wrt. the absorption length causes lots of difficulties in reconstruction and analysis

Leads to usage of complex likelihood functions in reconstruction

Deviation of time of arrival at PMT wrt. hypothesis of direct Cerenkov light from the MIP muon



Distortion introduced by light scattering



South Pole ice properties

Feature of IceCube: complex ice light propagation properties
Very small absorption and large light scattering

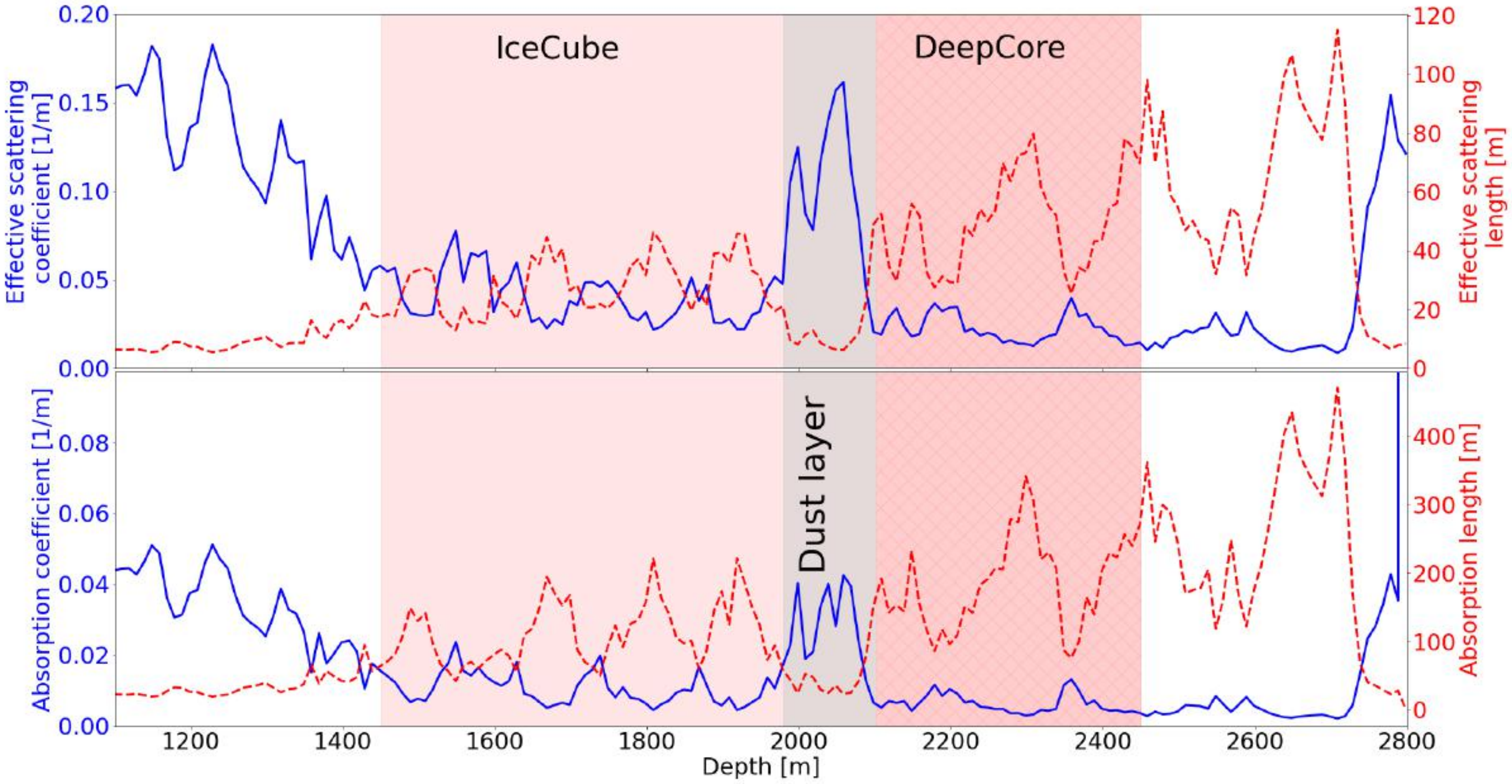
Effective scattering length is few times shorter than absorption length

Large dependence on depth of both scattering and absorption

“Dust layer” with both large absorption and scattering

More features.. (in the next lecture)

Light propagation properties at South Pole vs. depth



IC, The Cryosphere Discussions 2022 (2022) 1–48

Detection medium at various locations

location	abs. length	eff. scat. length
Baikal	max.: 22	few 100s
Mediterannean	max.: 60	few 100s
South Pole	> 100	avg. 20 - 40

Light propagation properties in water-based telescopes are very different from ice

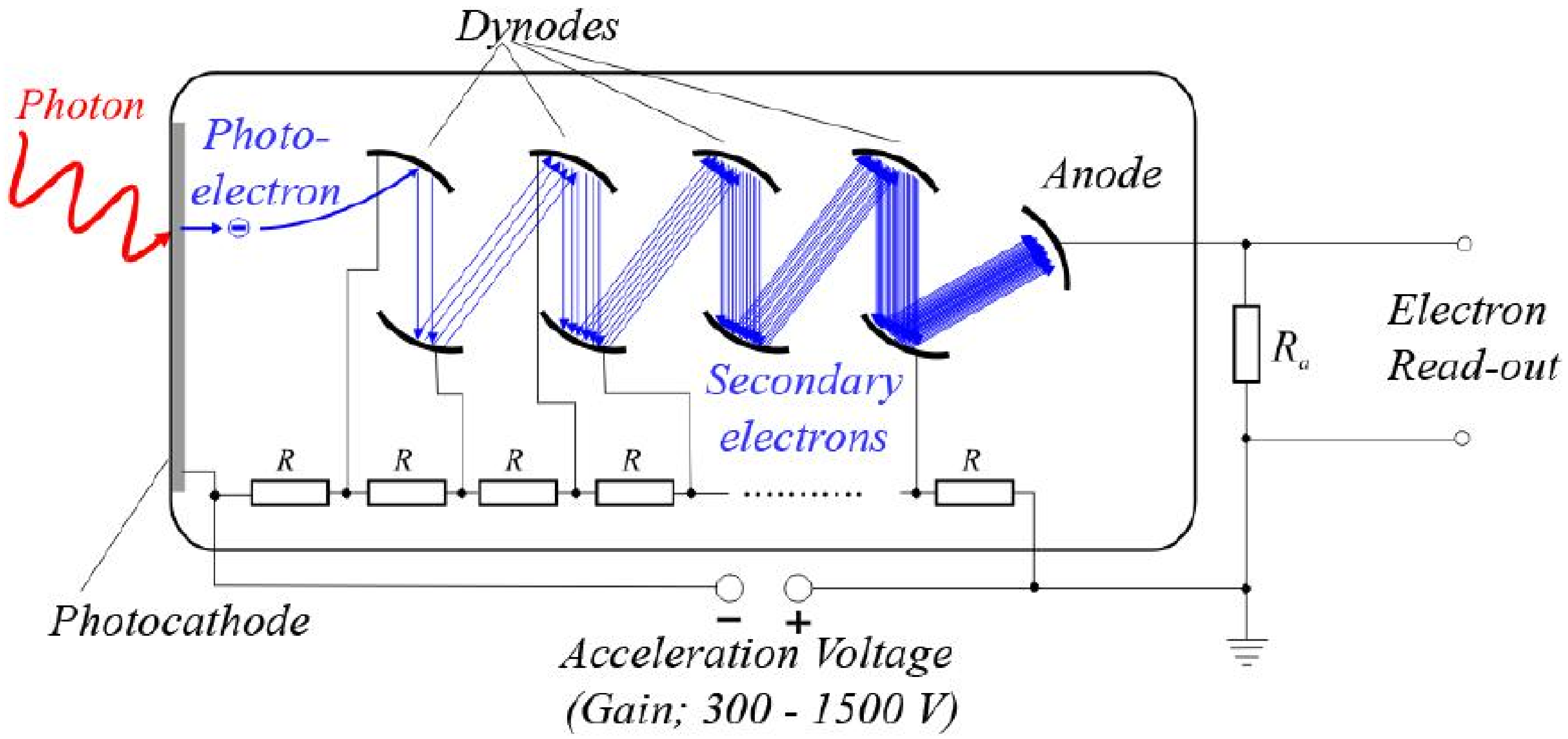
More compex Monte-Carlo simulations are needed in case of ice-based detectors

Photodetection: photomultiplier tubes

PMT principal structure

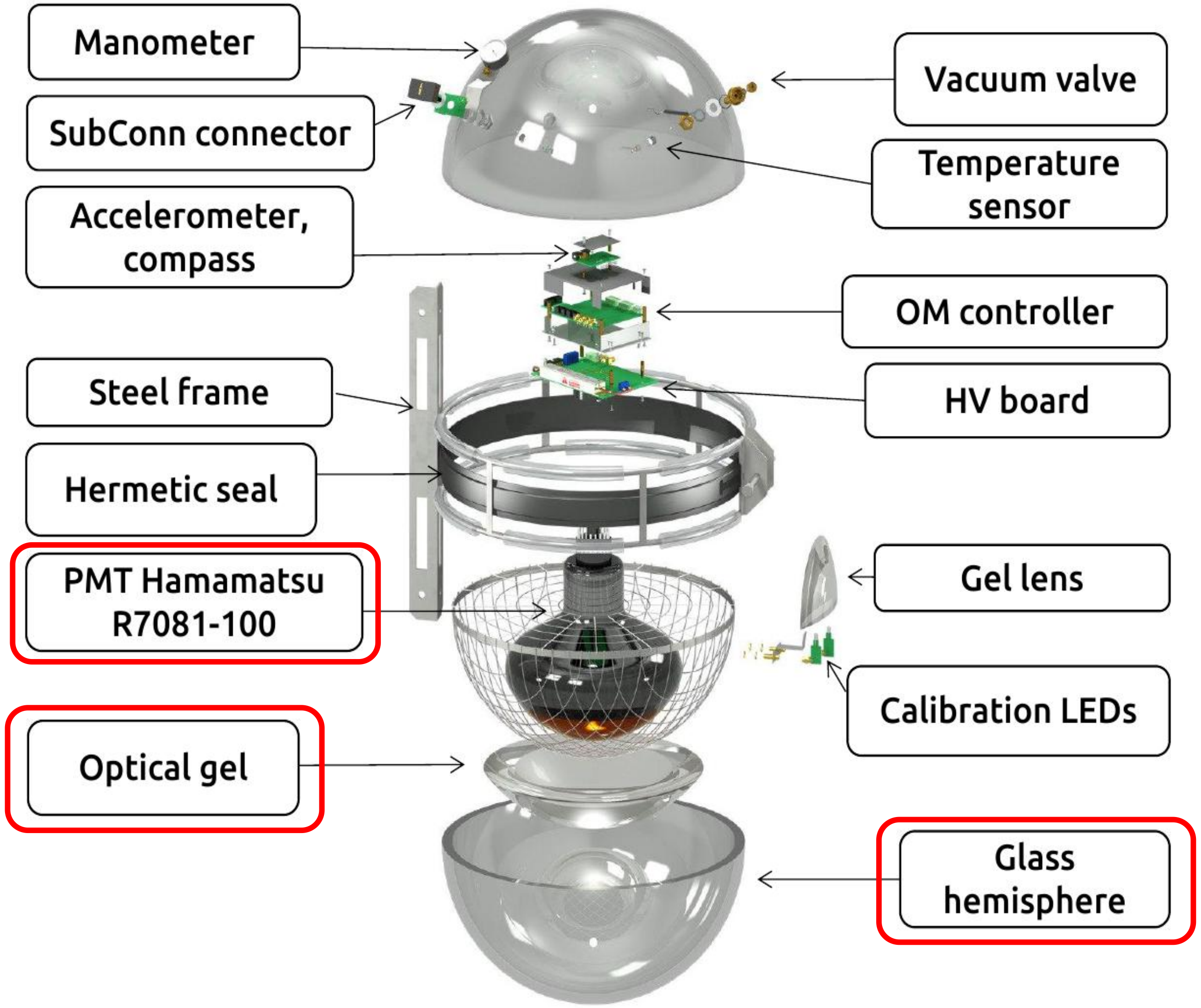
PMT features crucial for LVNT

- Photocathode area
- Photocathode quantum efficiency (probability for photon to be coverted to electron)
- Time measurement precision



Photodetection: optical module

Baikal-GVD optical module



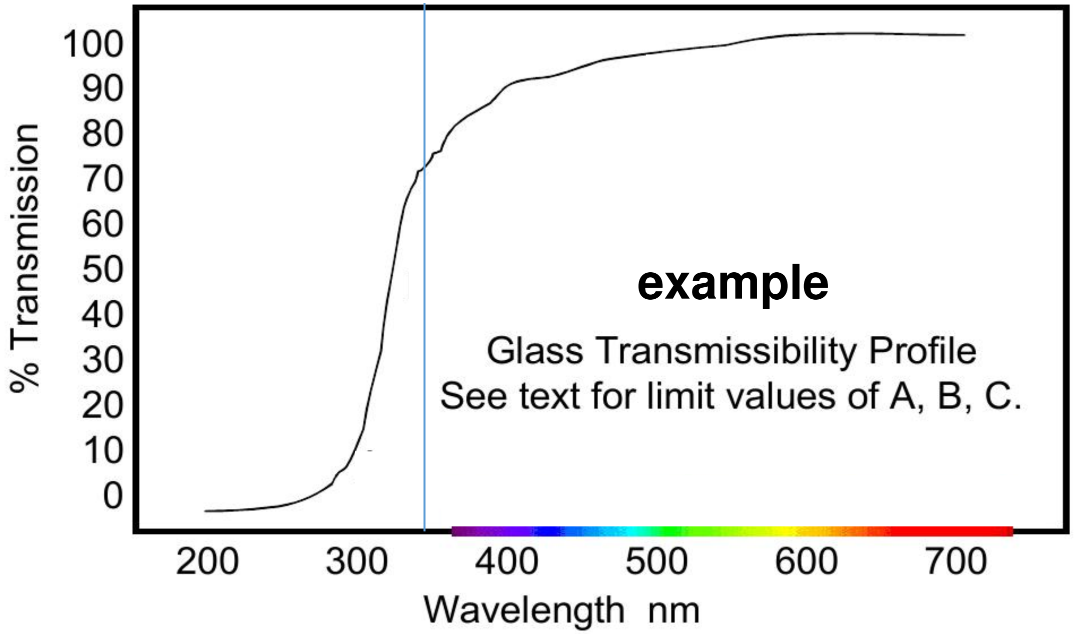
Hamamatsu R7081-100 PMT

high-quantum-efficiency
10-inch photocathode

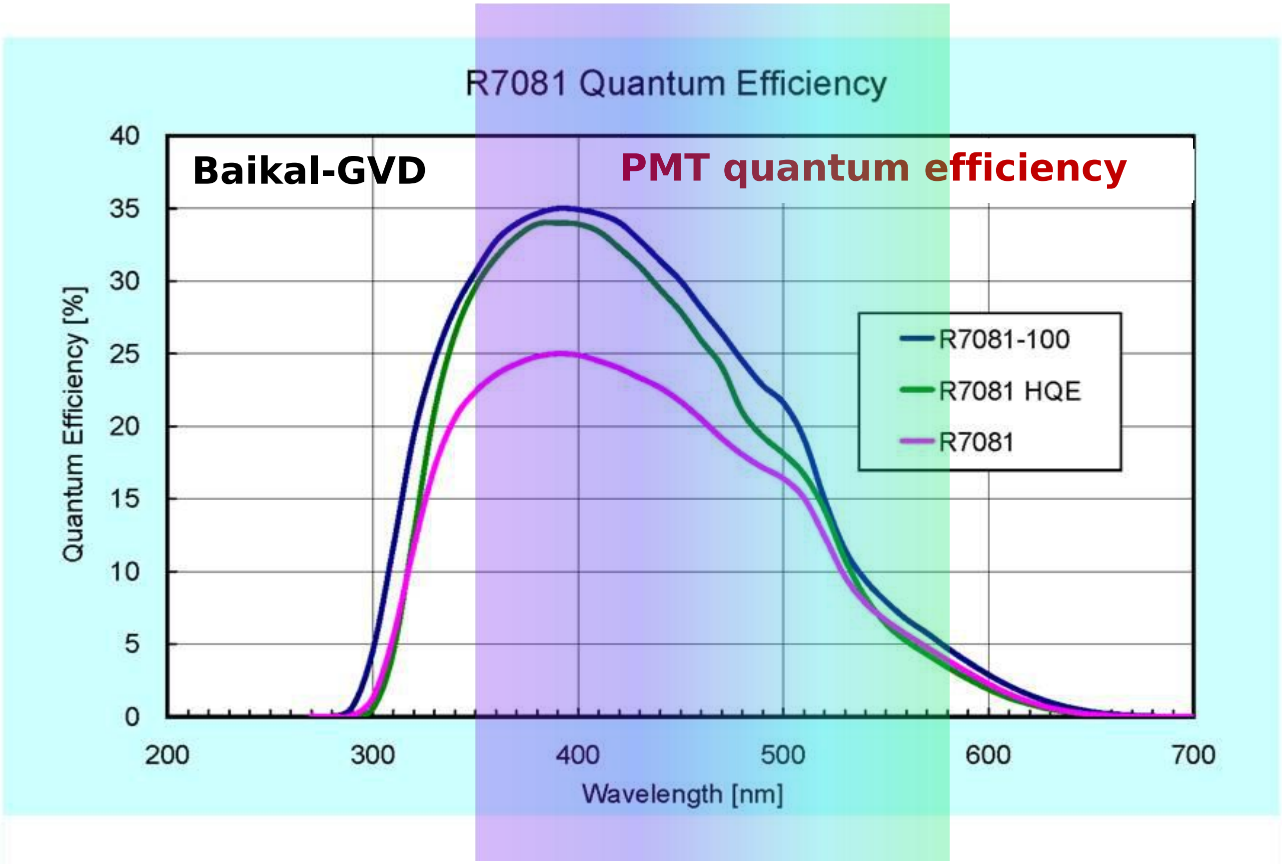
Optical contact of PMT to glass sphere is provided by optical gel lens

Photodetection efficiency

Important elements for sensitivity to incoming photons:
Glass sphere and optical gel transparency



Consider glass + gel
transparent starting ~350 nm



Quantum efficiency - probability for the photon to be converted into photoelectron

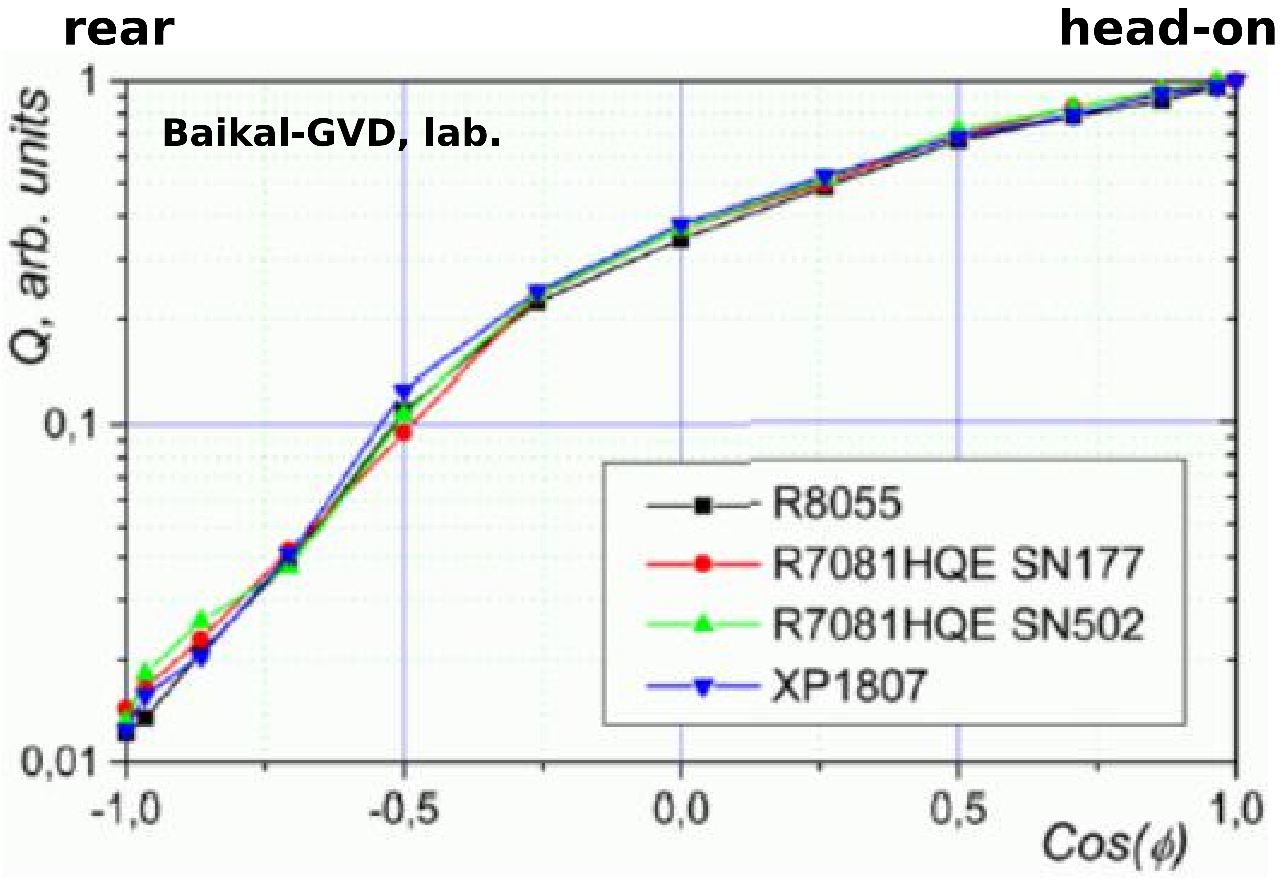
We defined optimal detection band as 350 - 580 nm

Photodetection angular sensitivity

Optical module assembly have non-uniform sensitivity depending on angle and point of entry

Usually characterized by total relative sensitivity and angular sensitivity, measured in-situ

PMTs are directed towards the lake bottom maximizing sensitivity to upgoing events



Photoelectron yield

Calculate number of photoelectrons produced at photocathode by 10 TeV muon

Consider
- Photocathode area: πR^2 ~ 506.7
- Average quantum efficiency as 0.2
- Angular sensitivity correction as 0.8

distance (m)	light field (γ/cm^2)	photoelectron yield	non-zero p.e. prob. (%)
10	0.226	18.3	~100
22	0.014	1.13	67.7
30	0.0027	0.22	19.7

Simplified calculation
- No integration over the wavelength, just averages
- Substantially dirrefent angular corrections for different OMs

Photoelectron yield

Calculate number of photoelectrons produced at photocathode by 10 TeV muon

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Simplified calculation

- No integration over the wavelength, just averages
- Substantially dirrefent angular corrections for different OMs
- Muon losses are non-uniform

With muon energy increase light field would increase ~linearly (slide 5)

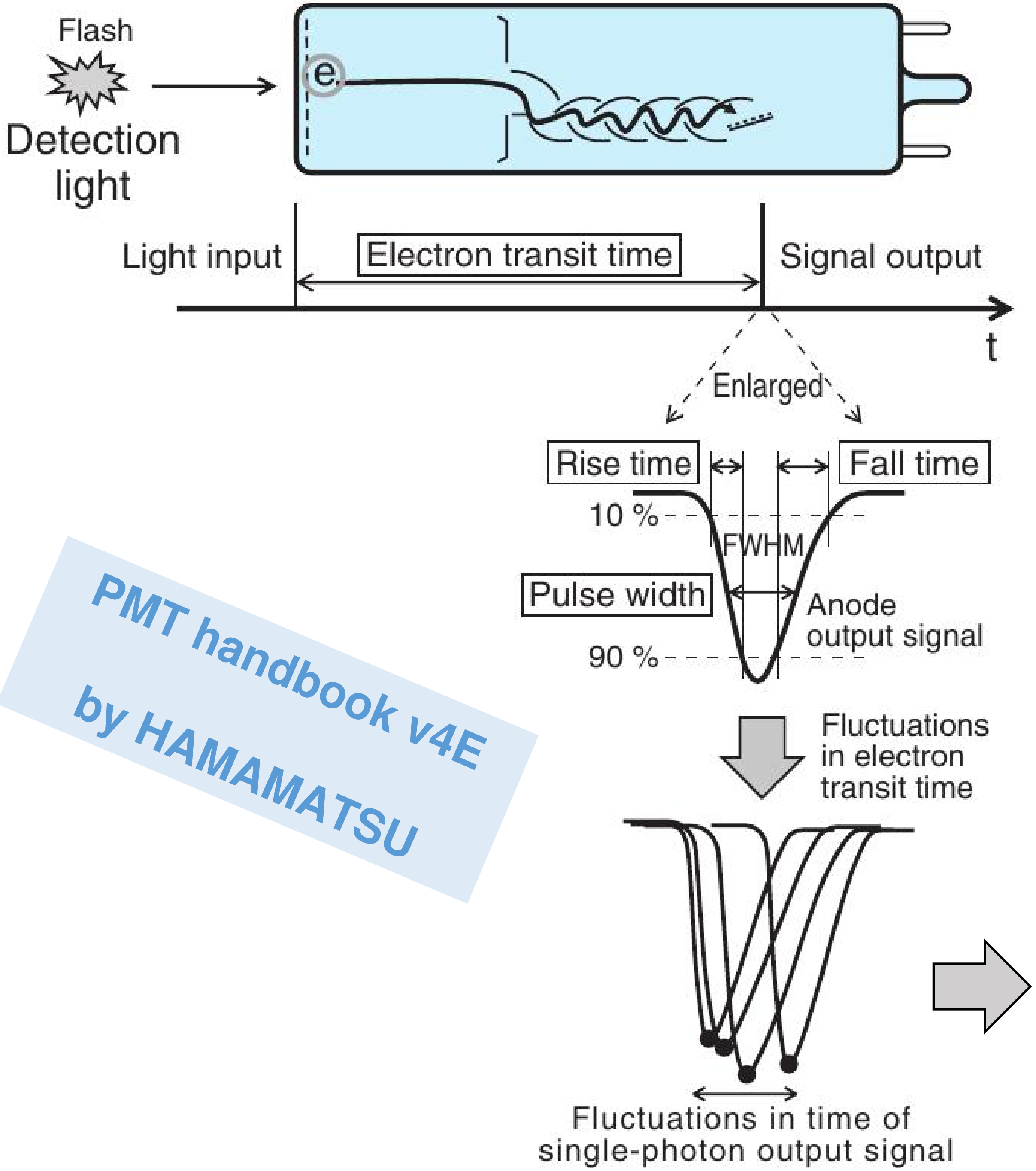
PMT signal timing

Typical large-area PMT transit time: 50-100ns

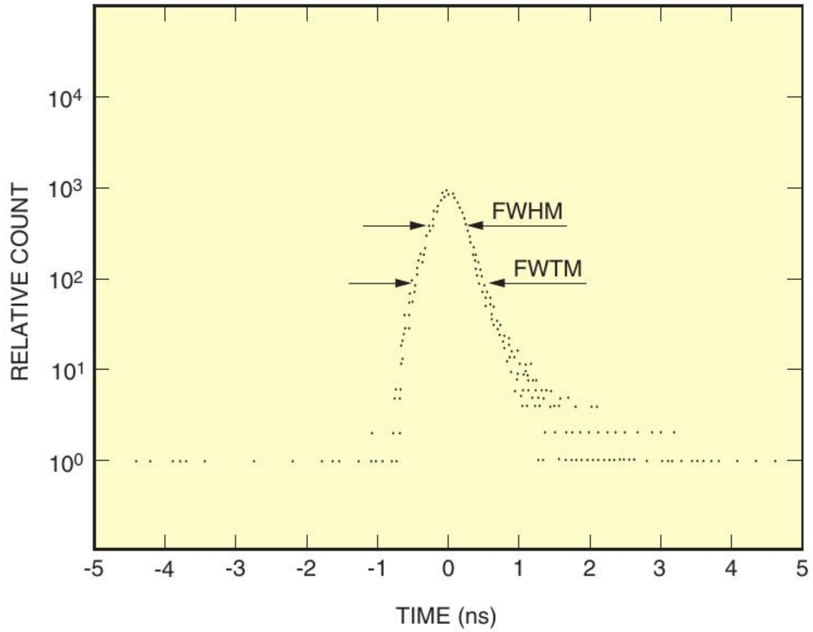
PMT transit time spread is a key component of the time measurement precision at the LVNT

IceCube and Baikal-GVD, R7081: 3.4ns

KM3NeT, R12199-02: 4.5ns



PMT handbook v4E by HAMAMATSU

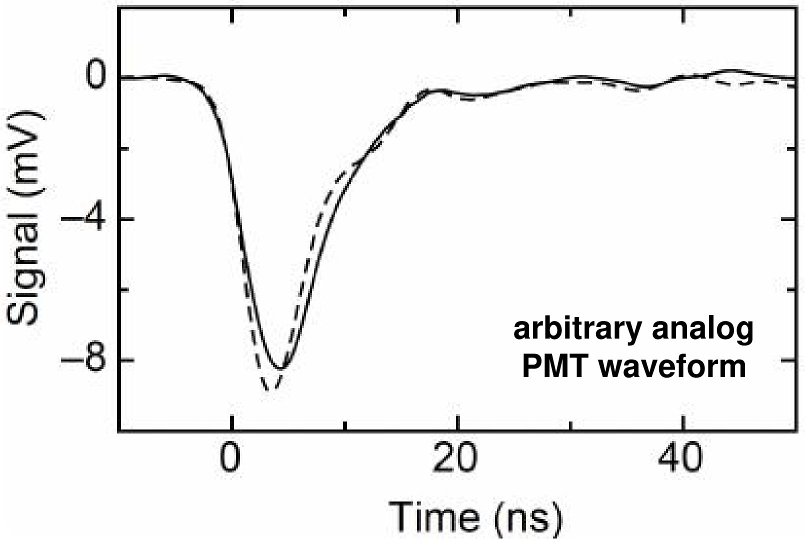


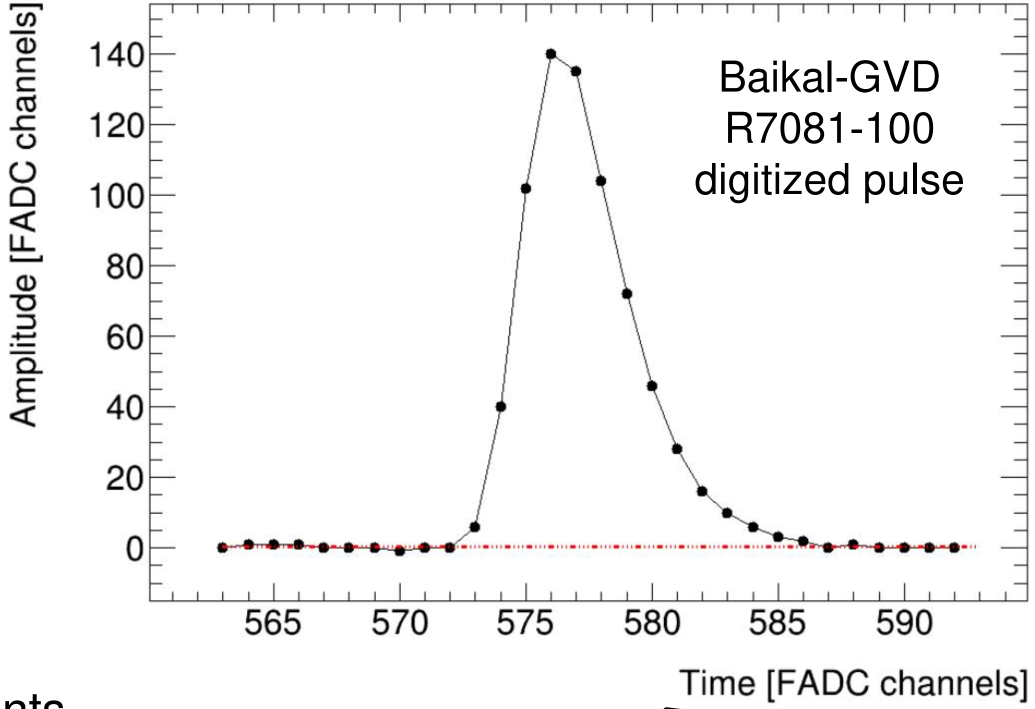
Typical single p.e. transit time distribution

PMT pulse digitization

PMT pulse is transmitted to Analog-Digital Converter (ADC),
ADC integrates and digitizes charge in time bins

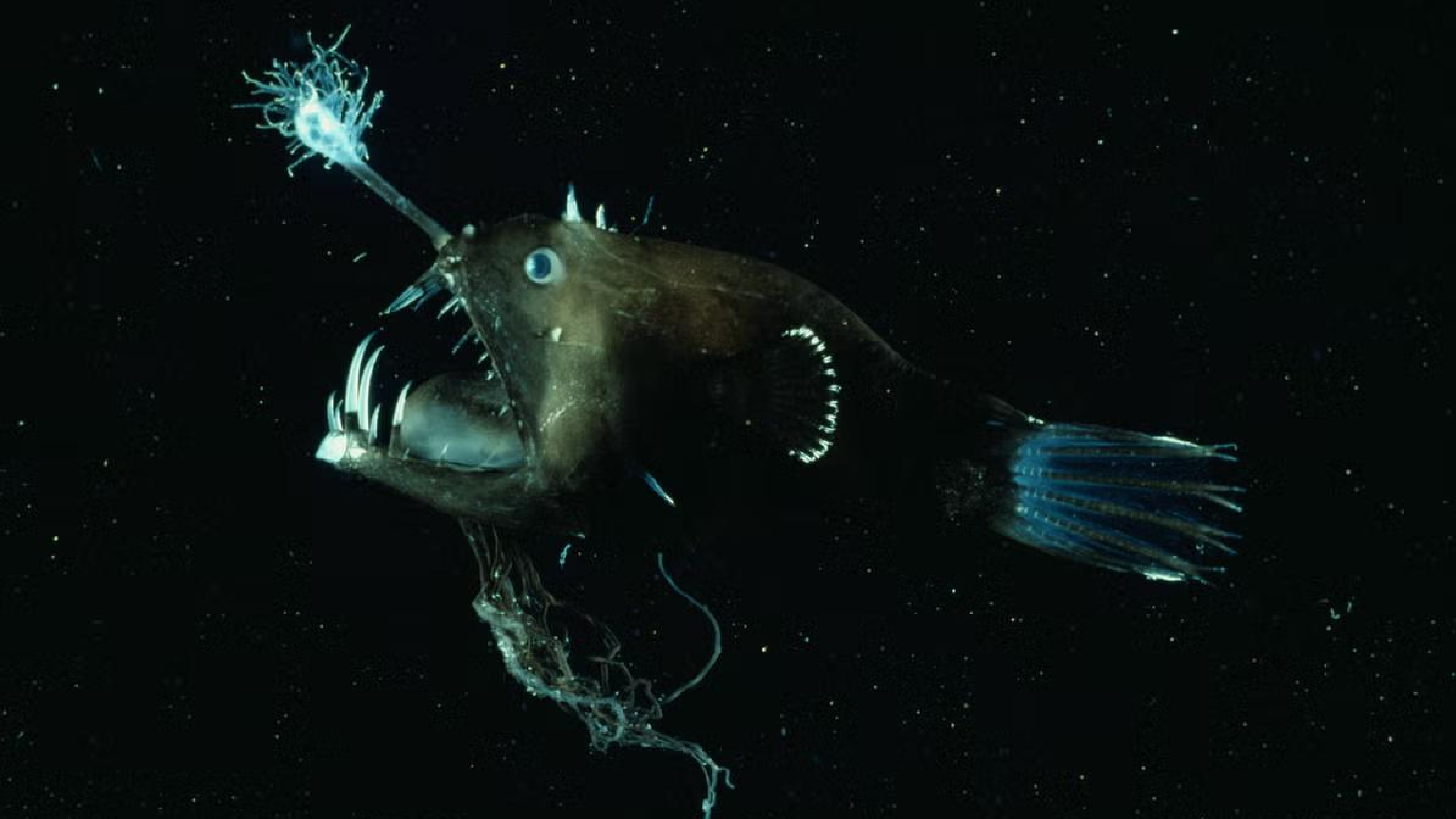
Baikal-GVD ADC integration bin: 5ns



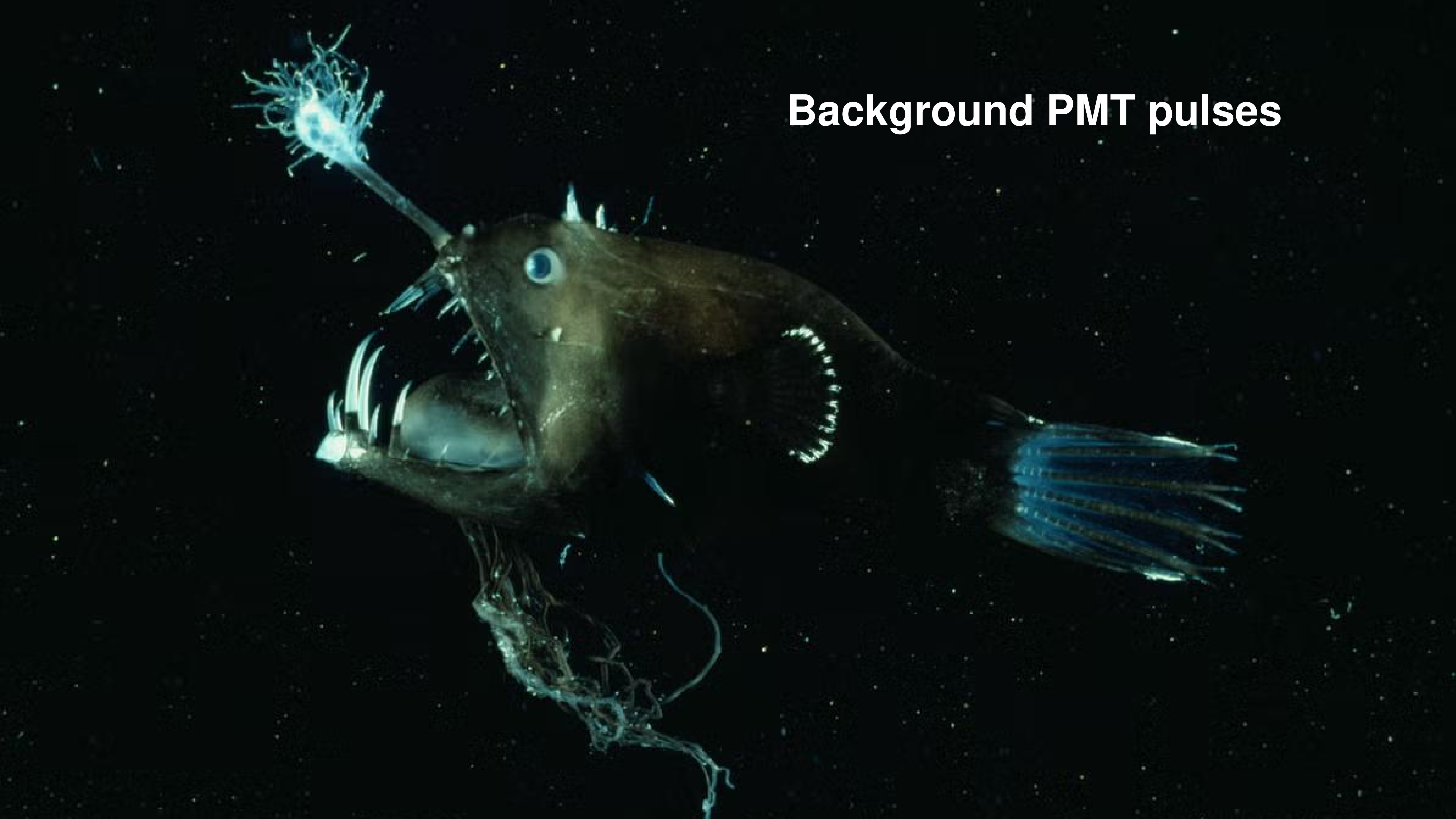


Charge in ADC counts

Time in ADC bins



Background PMT pulses



Background pulses

PMTs and detection medium always produce some background pulses

In LVNT rate of background PMT pulses is larger than atmospheric muon Cerenkov signal rate
10’s Hz vs. up to 10’s kHz

Most of the data at LVNT is produced by the background noise

PMT and electronics -generated background

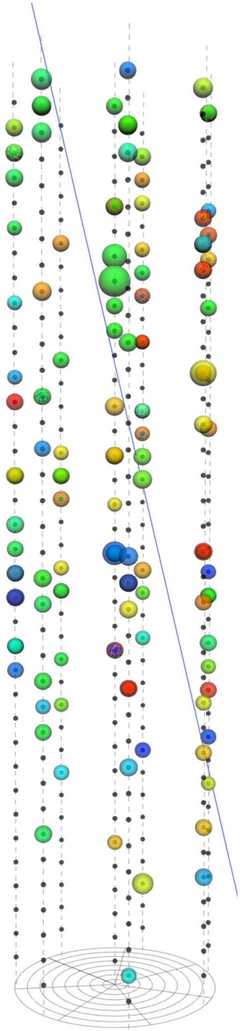
- OM dark current: O(kHz)
- PMT afterpulses, low rate but large pulse amplitude

Water background glow

- Seawater: ^{40}K decays, bioluminiscense
- Baikal Lake: Chemiluminiscense
- **Reach up to hundreds of kHz per optical module**

No chemiluminiscence, bioluminiscence or ^{40}K decays in Antarctic Ice Shield
IceCube background is only due to dark current: “background-free” detector

Background pulses in Baikal-GVD



typical event in Baikal-GVD

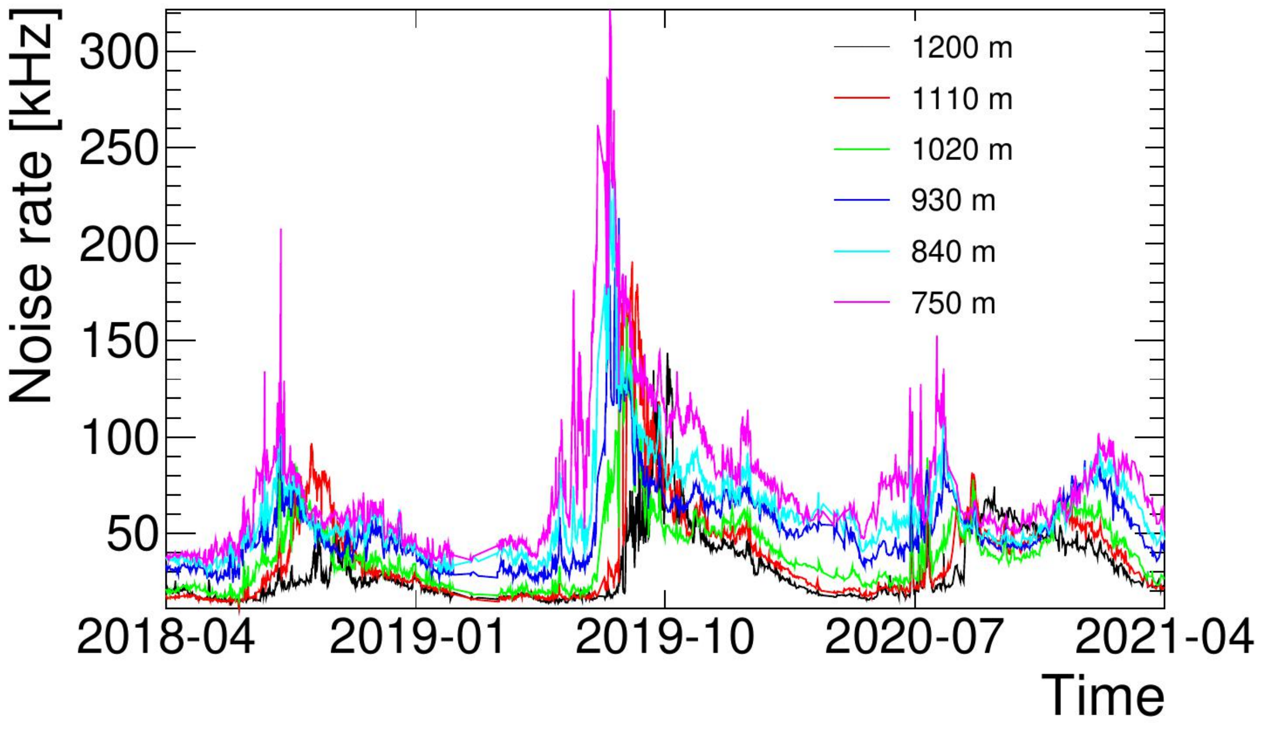
Sinking remains of algae or living organisms cause chemiluminiscence

Single p.e. -level signal with rate up to few hunderds of kHz

Substantially non-uniform rate vs. depth

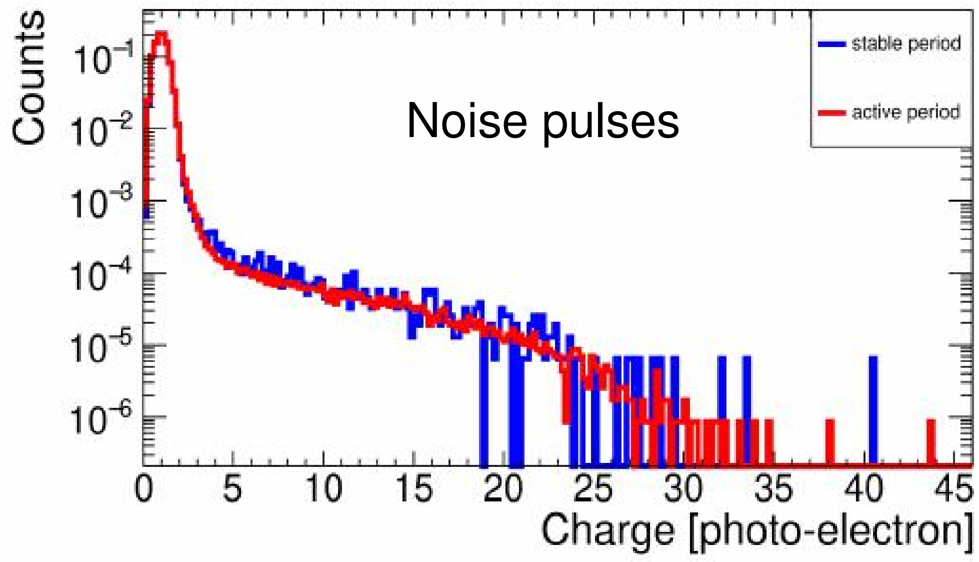
Seasonal variations
- Low noise in winter and spring
- Peak of noise in mid-summer
- Slow decrease towards winter

Up to hundreds of kHz for topmost OMs



Background pulses in Baikal-GVD

Lake noise charge (p.e.) distribution



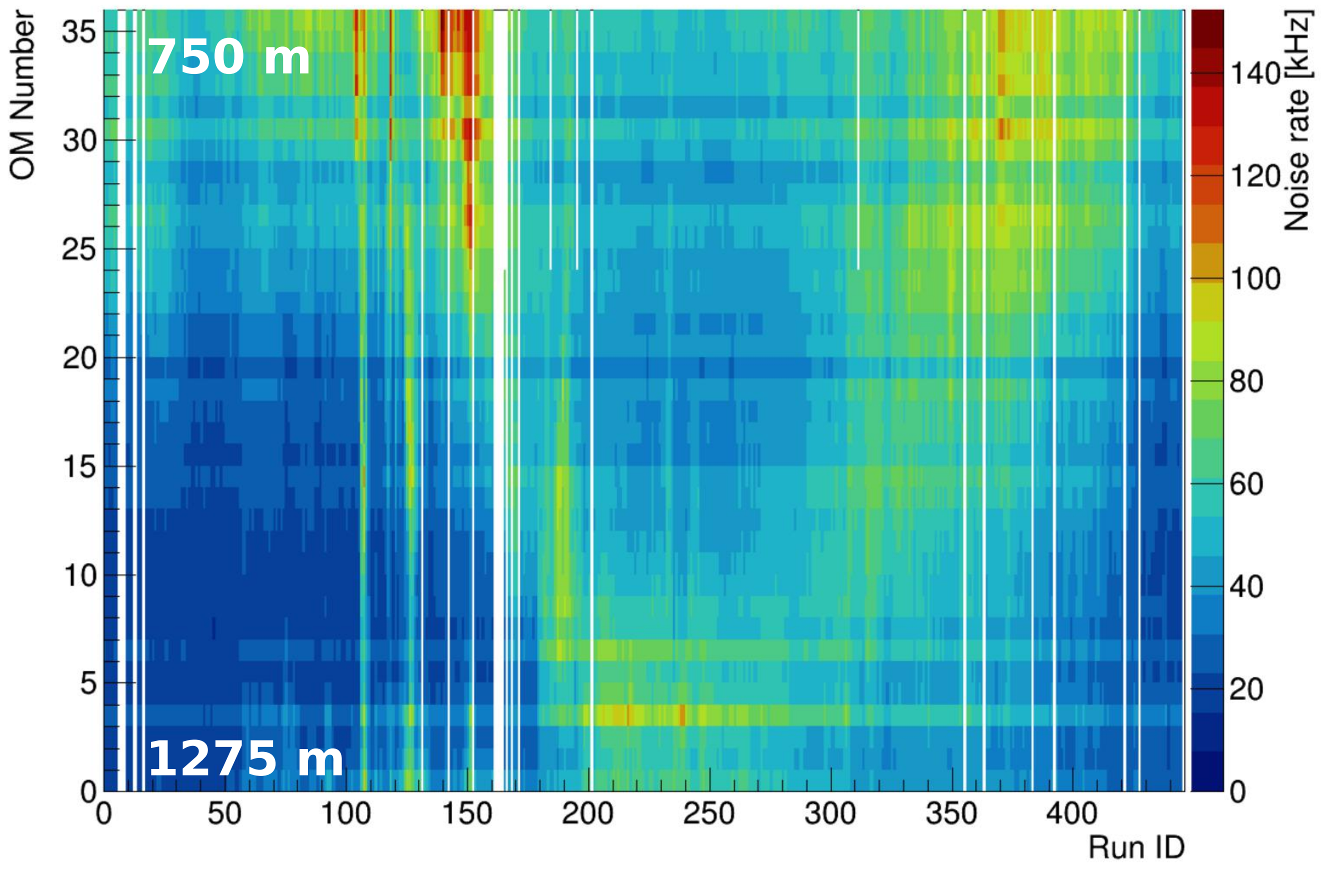
Noise at single p.e. level can be suppressed with charge cuts

But charge cuts decrease neutrino detection efficiency at low energies

Complex algorithms to suppress noise have to be developed (next lecture)

Lake noise rate dependency on depth

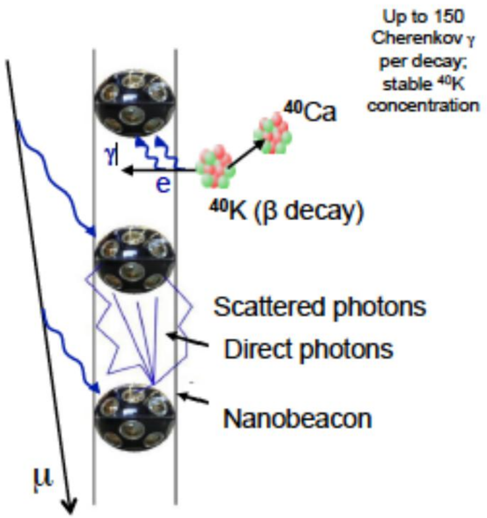
Baikal-GVD DQM data for season 2020 cluster 3, string 3



April 2020

March 2021

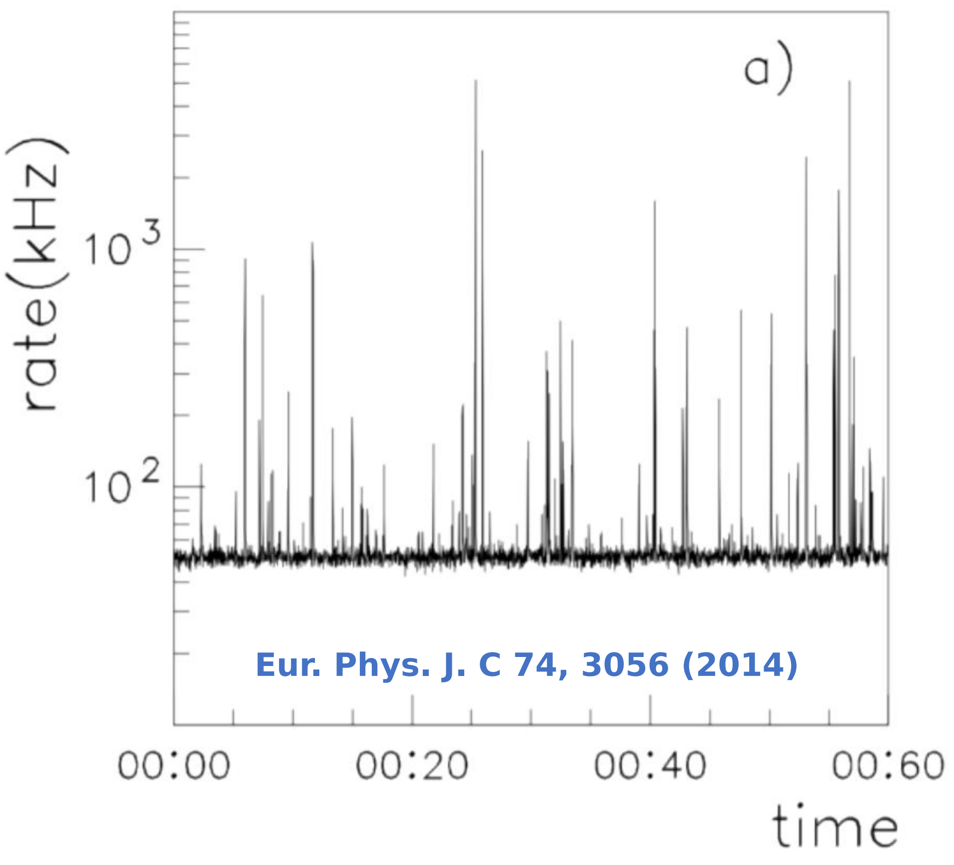
Background pulses in Mediterranean

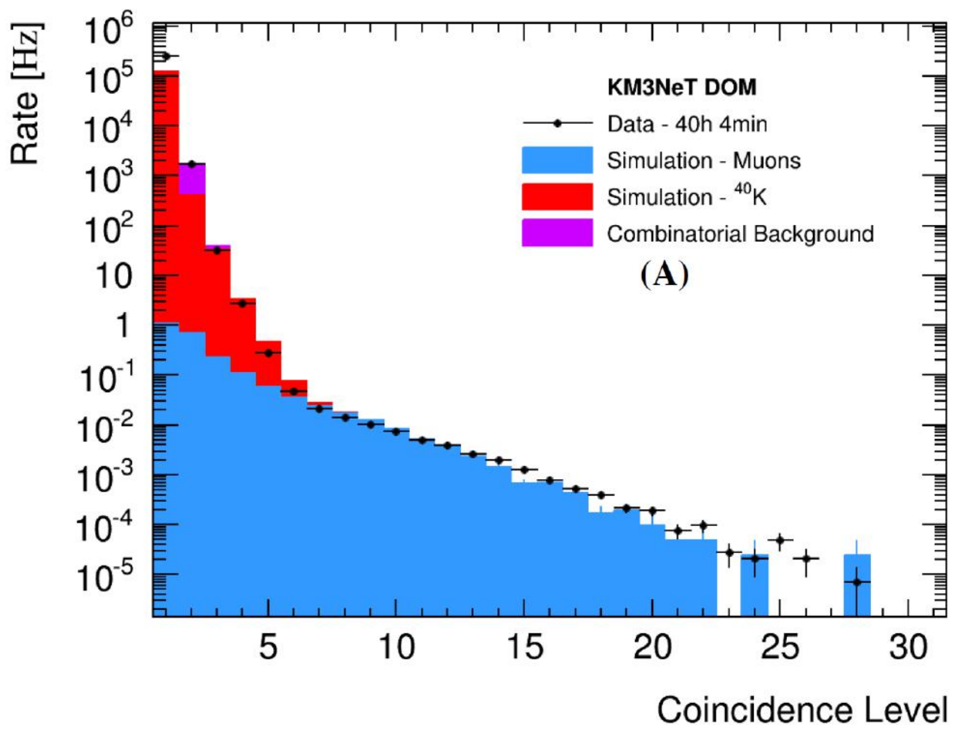


Deep sea backgrounds:

- ^{40}K decay - constant backgrount at the level of hundreds of photons per cm^2
- Bioluminiscence - very high intensity flashes
- Average rate: 7kHz per 3” PMT

10-inch PMT rate near Cape Passasero at ARCA site





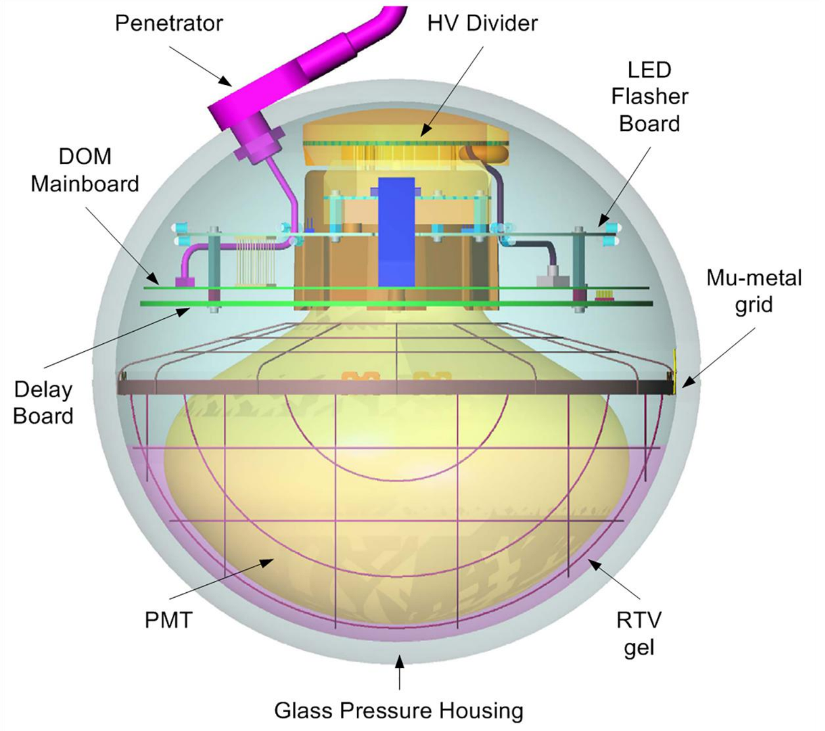
Suppressed with the coincidence counting

Triggering and readout

IceCube and KM3NeT DOMs

DOM - Digital Optical Module
In IceCube and KM3NeT PMT pulse digitization occurs in each optical module

IceCube DOM



Both IceCube and KM3Net have ADCs installed in every optical module

Data from each DOM is transmitted via optical fiber to the ice surface or seashore

KM3NeT DOM

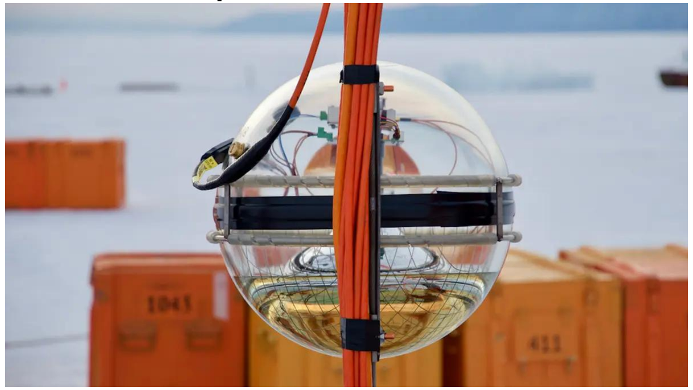
Baikal-GVD section

Section is the basic readout element

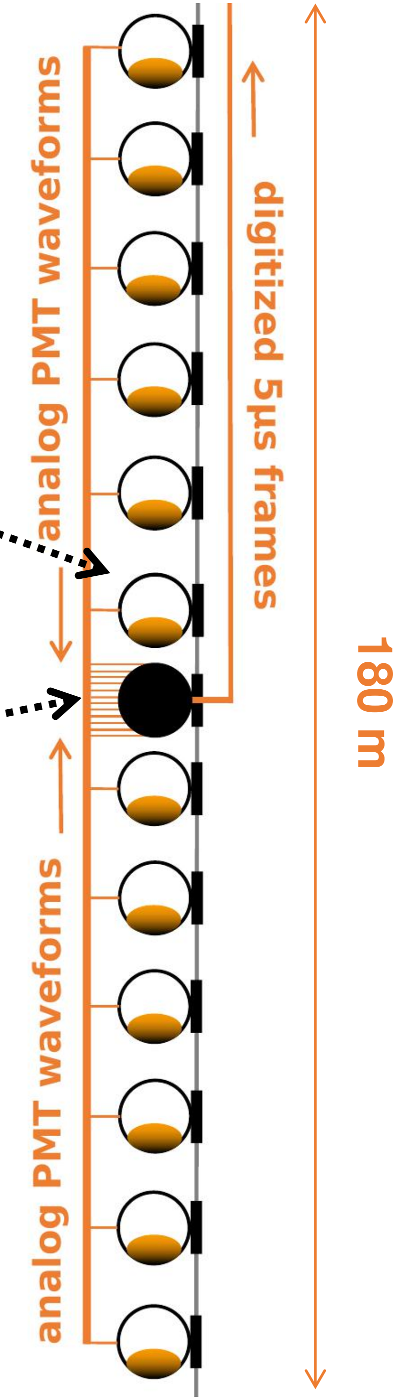
An ADC is located in section Central Module (CM)

- Receives 12 analog inputs from OMs
- Each of 12 OMs sends analog pulses via 92 m coaxial cable
- CM monitors trigger condition
- Sends digitized pulses to “cluster center”

optical module



section central module



Triggering and readout

Triggering: reduce the data rates to ones acceptable for DAQ

Baikal-GVD, underwater trigger:

- Coincident pulses at neighbouring OMs within section in 100ns window, full cluster is read out
- DAQ limitation: few 100’s Hz rate per cluster to shore

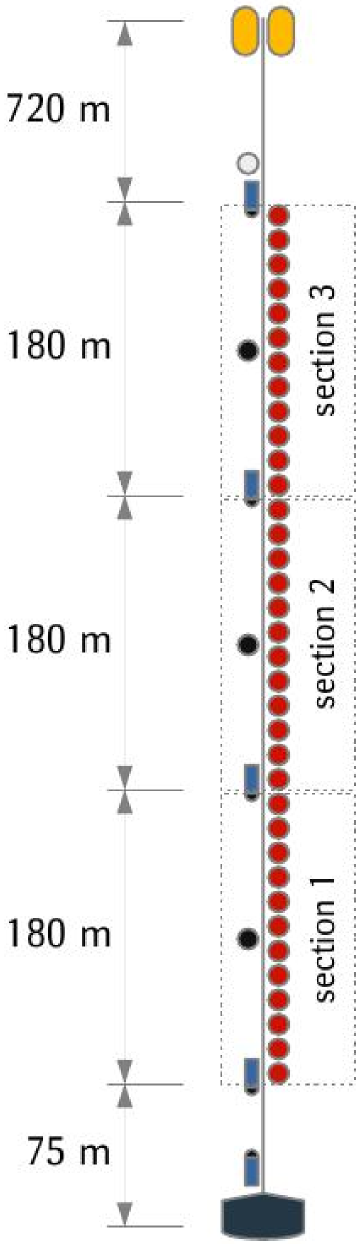
IceCube

- All data is sent to surface
- Limited waveforms around pulse maximum for all DOMs: 600Hz per DOM
- Full waveforms in case of local coincidence of pulses on +-2 DOMs: 5-15 Hz per DOM
- Complex quasi-online system of reconstruction-based events selections for prompt data transmission to Nothern Hemisphere via satellite
- Data failing these selections is stored at South Pole

KM3NeT all data to shore:

- All PMT pulses are sent to shore: ~7 kHz per PMT
- DAQ limitation: 20Mb/s per DOM
- No waveform just time and pulse shape info
- At the shore software triggers discard the data

Baikal-GVD string and cluster

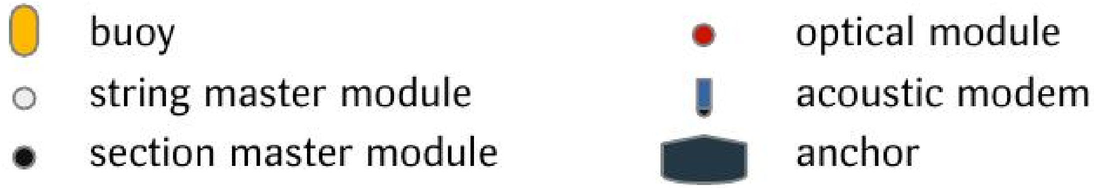


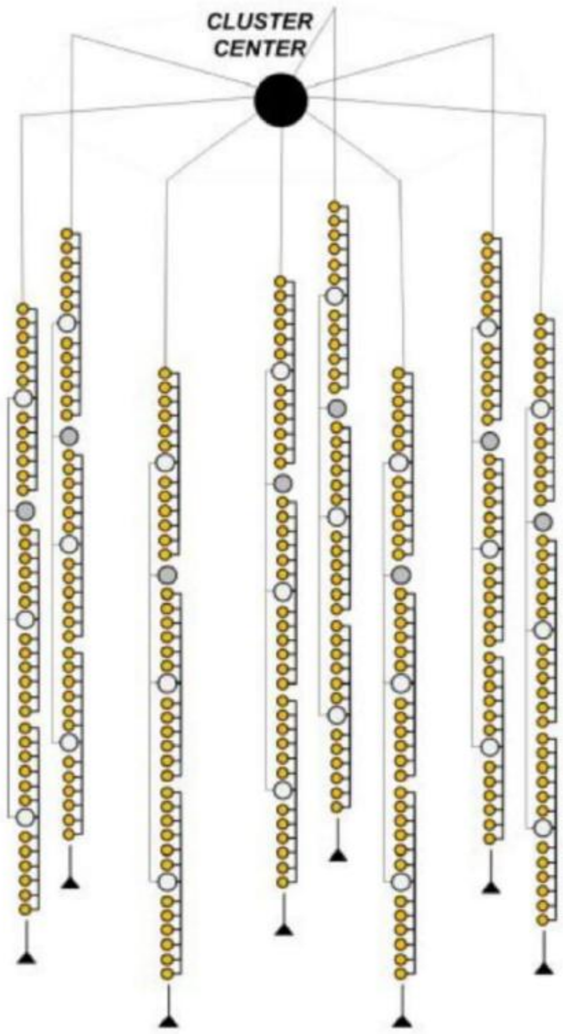
String consists of
- Anchor
- 3 OM sections
- String master module
- 3-4 acoustic modems for OM positioning
- Buoy system

Cluster consists of
- 8 or 9 strings
- Cluster center module system

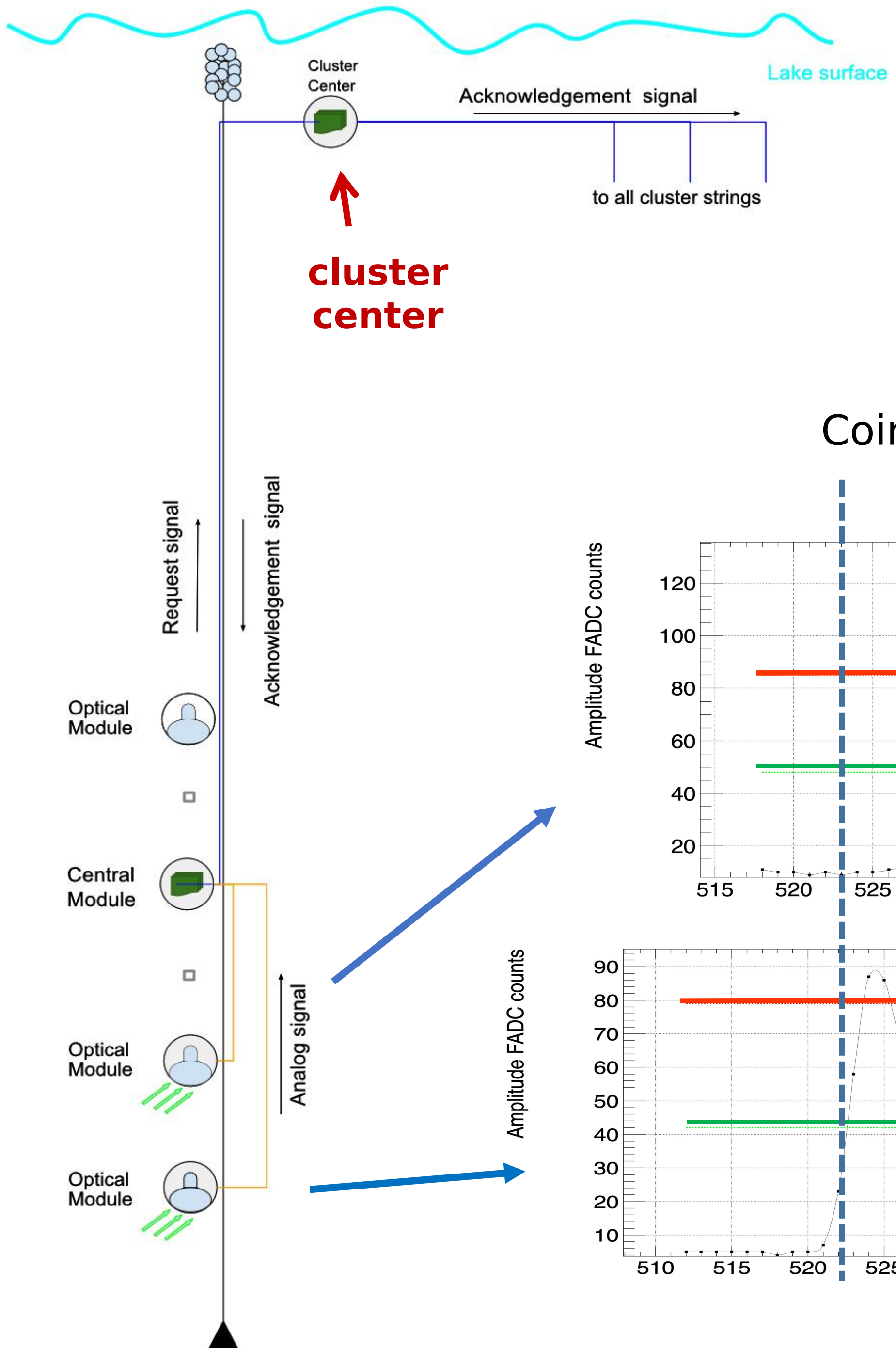
Cluster center
- Data communications with shore
- Power distribution

Each cluster delivers data to shore independently of other clusters

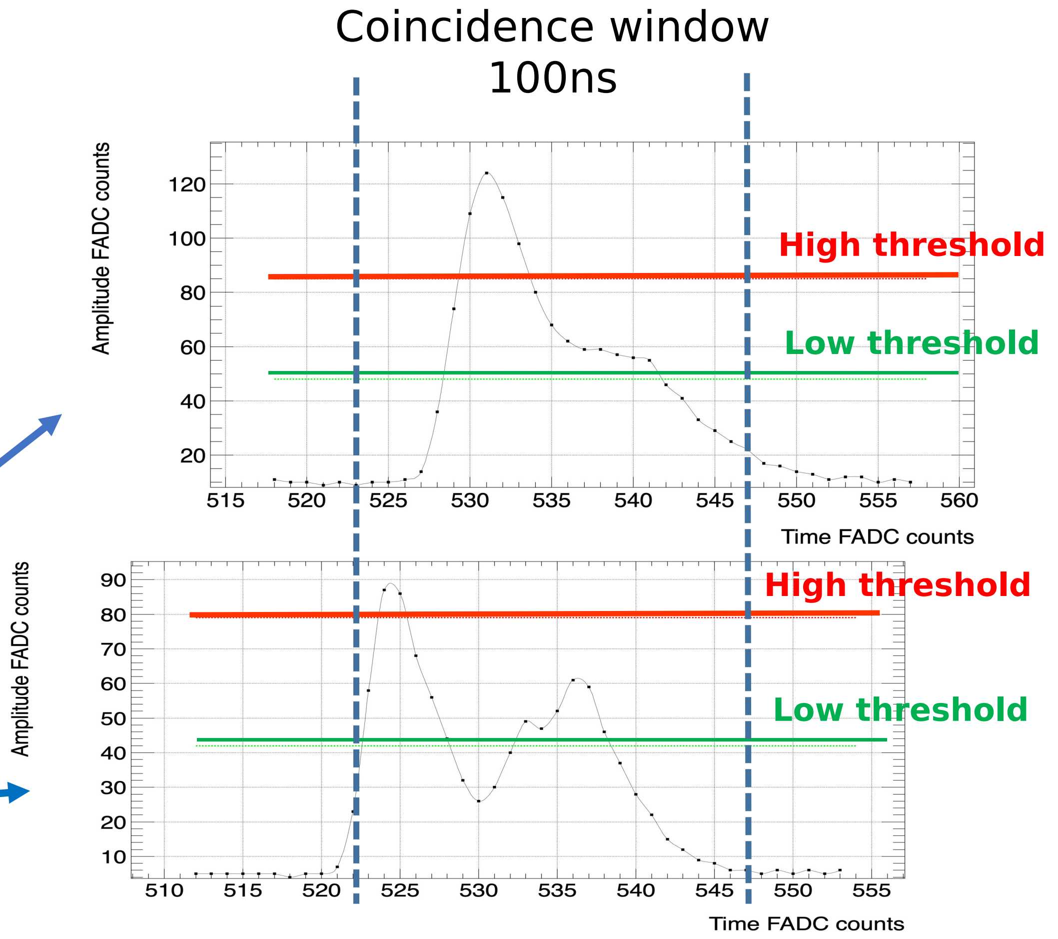




Baikal-GVD trigger



Section central modules holds digitized OM signal in buffer
Once a trigger signal is received the 5μs window is sent to shore



Baikal-GVD trigger:
coincident pulses on neighbouring channel in the same section

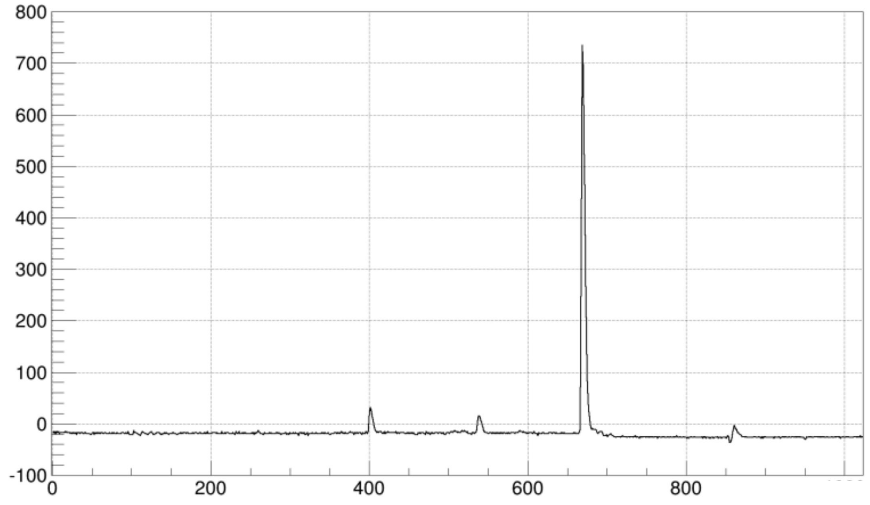
Typical trigger threshold values:

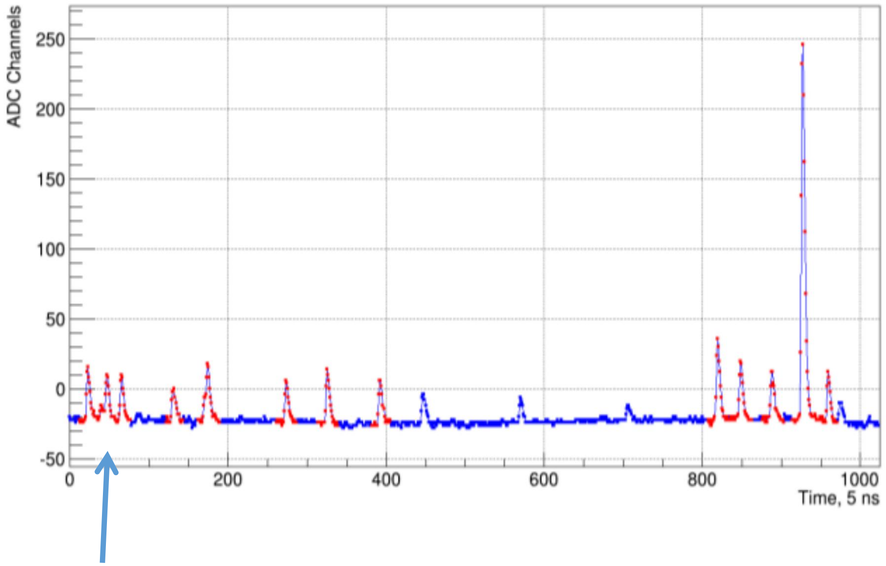
A_{low} = 1.5 p.e.

A_{high} = 4.5 p.e.

Total rate: few 100 Hz

Baikal-GVD RAW data event frame





single-p.e. level signal

Readout electronics sends event frames to the shore station

Event frame is defined wrt. the local readout electronics clock

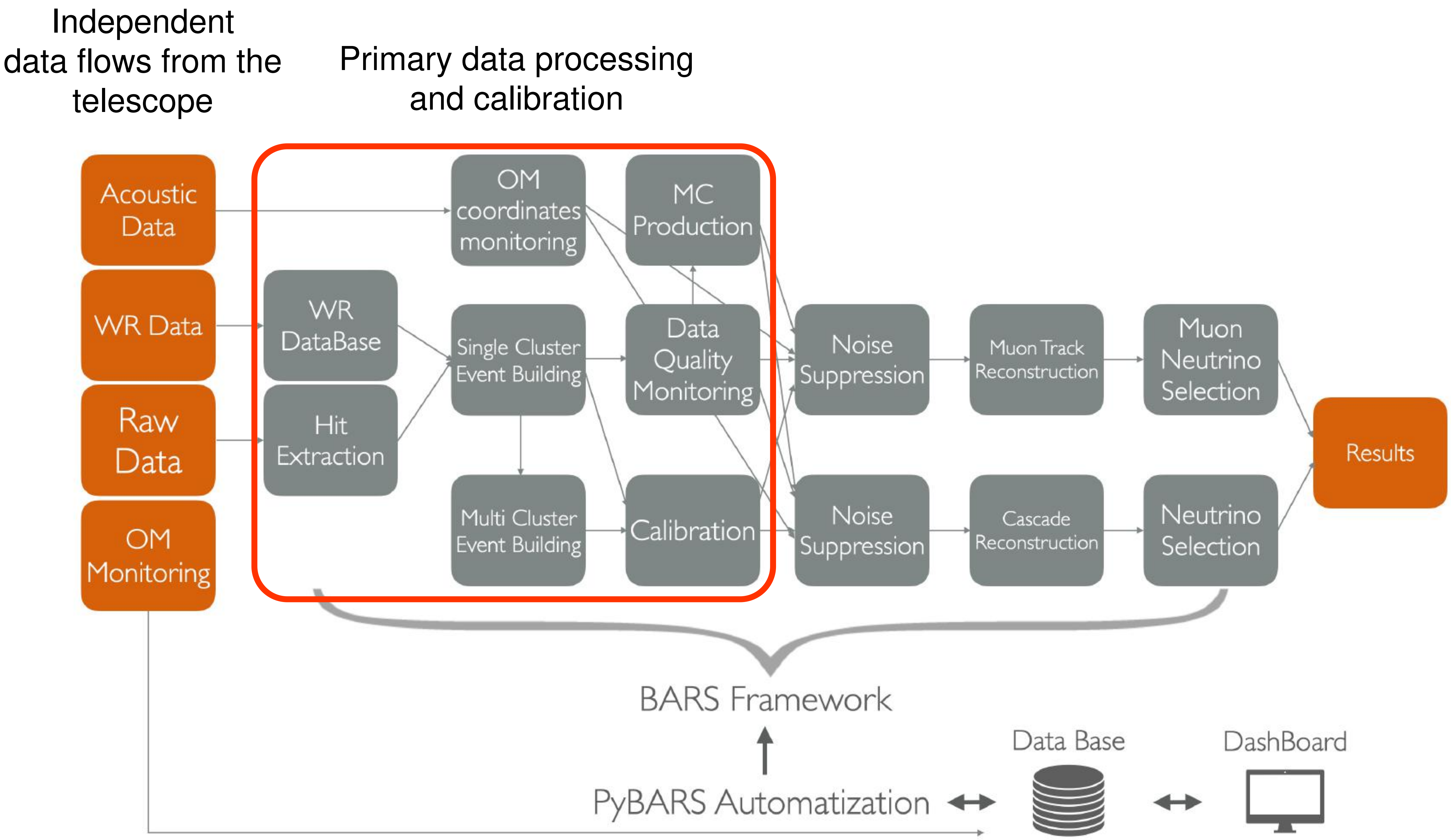
It holds digitized pulses with charge expressed in ADC counts

Typical content of the RAW data

Event builder merges event frames from different sections into single event and extracts PMT pulses time of arrival and charge info

To use this data for the event reconstruction we must perform positioning and calibration first

Baikal-GVD data processing overview



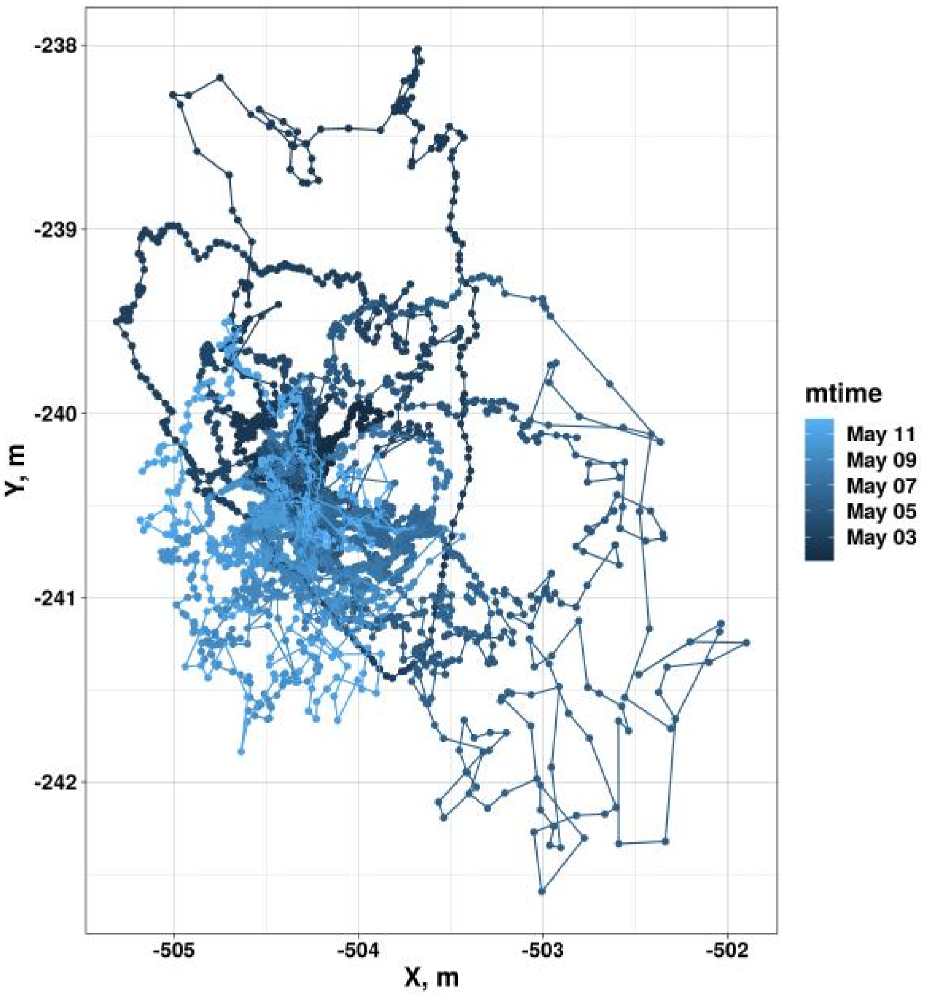
Detector positioning and calibration

Reconstruction deals with
- Coordinates of each channel
- Pulse charge
- Pulse time

To run the reconstruction we must
- Have the measurement of coordinates of each channel
- Convert ACD counts to photoelectrons
- Synchronise measurement channels to ns precision

Detector positioning

Drift of the topmost OM in Baikal-GVD over the week



Water currents cause deviations from ideally vertical detector

Drift up to 50 meters away from median position with speed up to 0.5cm/s

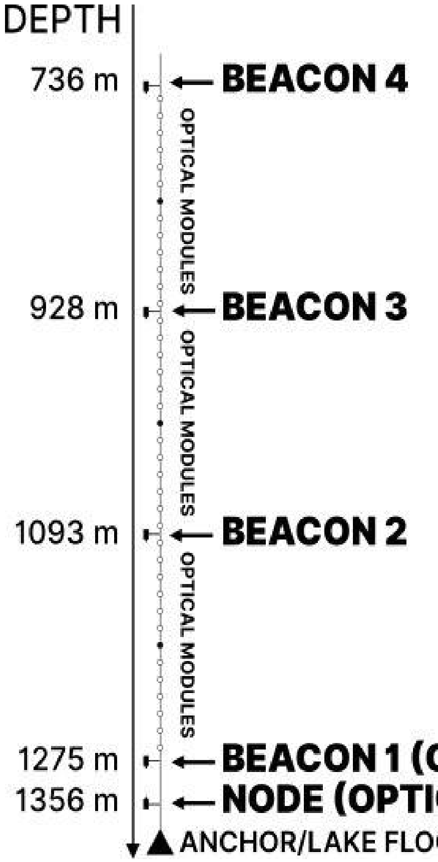
For event calibration and reconstruction it is nessesary to measure positions of all OMs in the event

Since drift occurs permanently it is nessesary to have periodic, quasi-online OM position monitoring

This is performed with acoustic calibration systems

Detector positioning

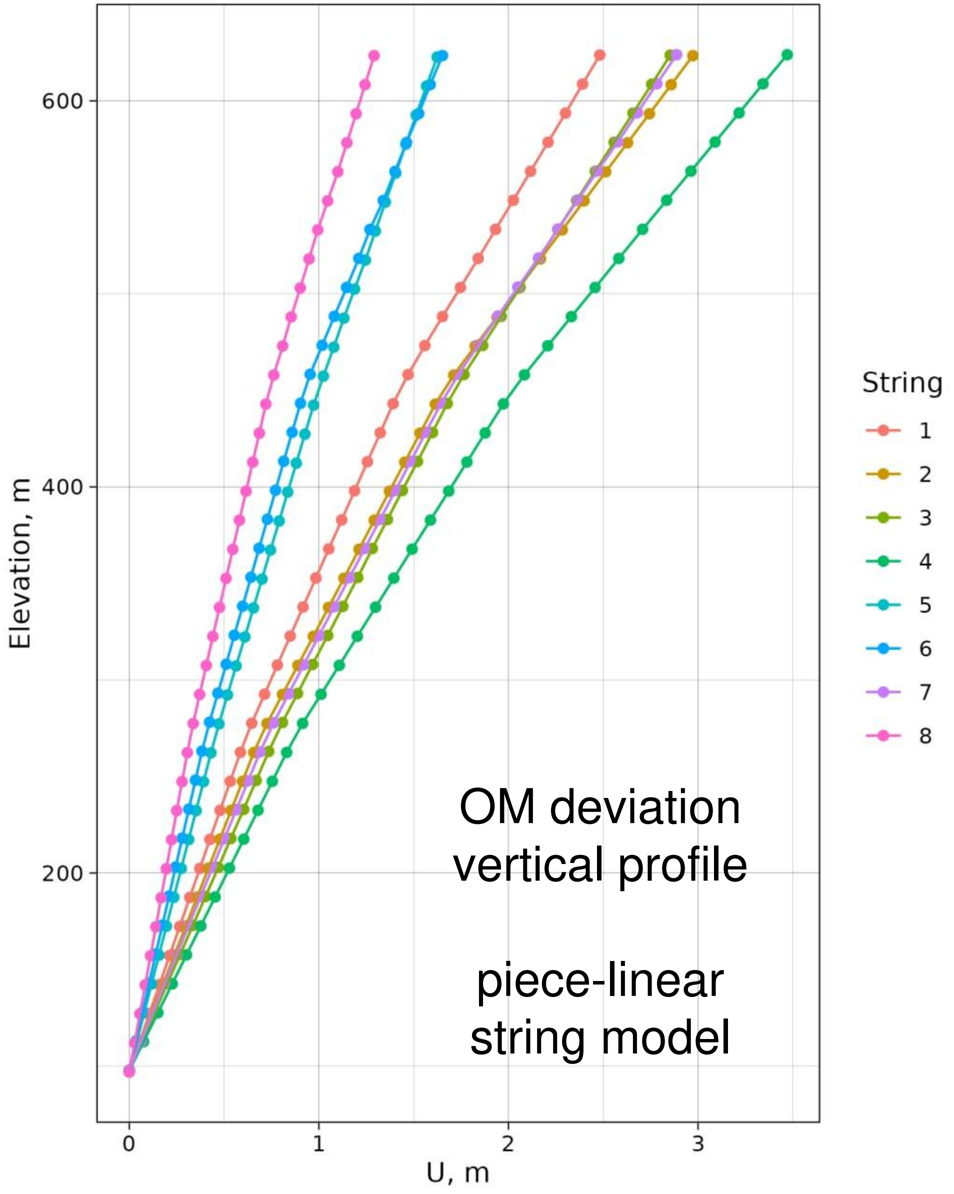
Baikal-GVD acoustic instrumentation



System of acoustic beacons at each string

- Regular acoustic poll
- Coordinates are measured by the time of acoustic signal propagation
- Position is reconstructed online for each measurement
- **The precision of OM position measurement ~40 cm**

Positioning precision corresponds to ~1.8 ns time uncertainty



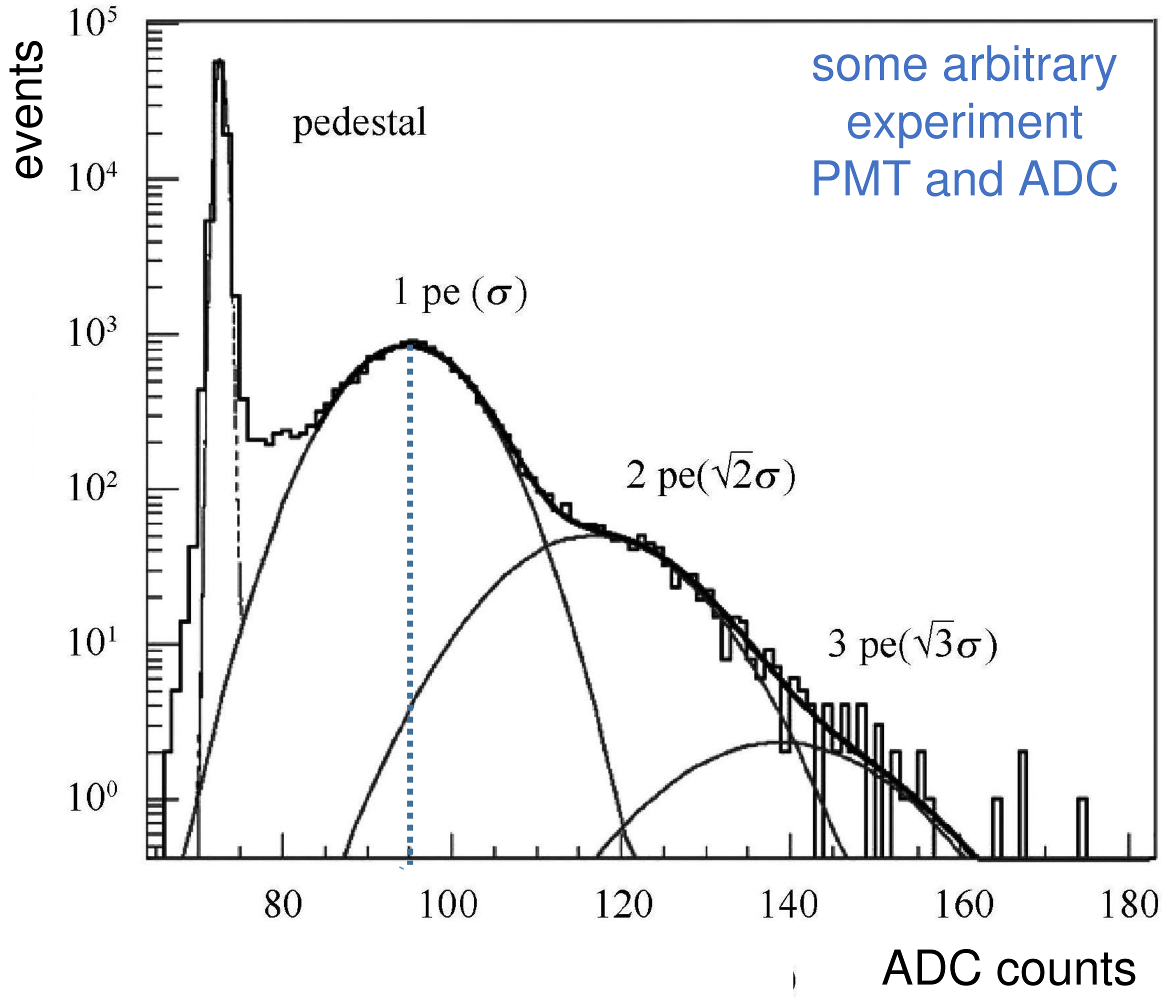
Charge calibration

ADC channels charge per count differ from each other

One need to set the uniform charge scale across the detector

Charge calibration is done by fitting the single photoelectron peak

Classical procedure used in experiments with PMTs involved



Time calibration

Time measurement precision:

$\sim \sigma_{TTS} \oplus \sigma_{unsync}$

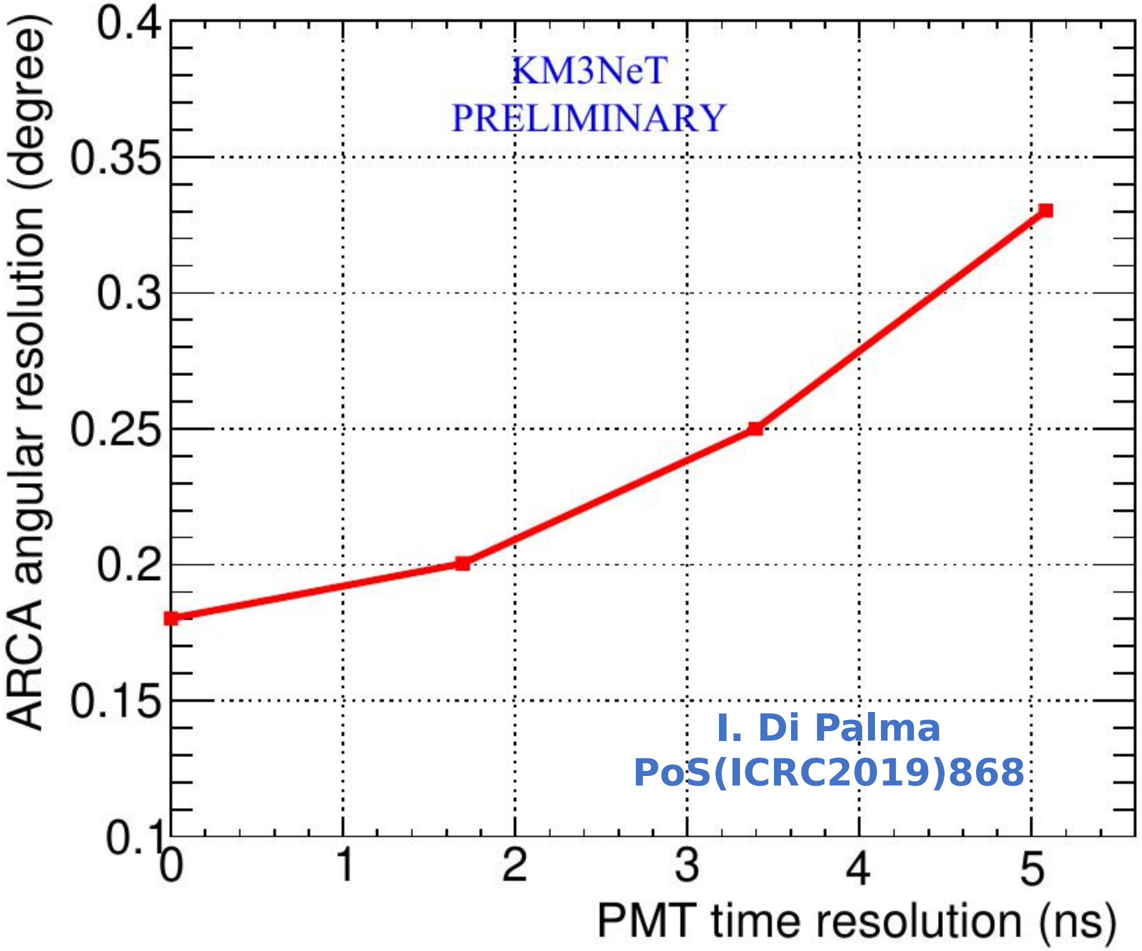
σ_{TTS} irreducible pulse time uncertainty, ~1.4ns for Baikal-GVD R7081-100

σ_{unsync} is minimised by calibration procedures

One should synchronise scales of photon arrival at the PMT photocathode to the 1-2ns level

PMT signal delays are caused by PMT channel transit time, different cable lengths, any possible delays in electronics

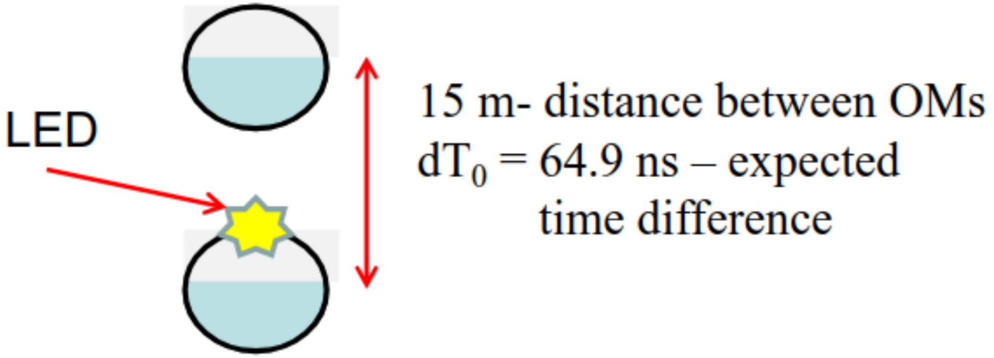
Angular resolution dependence on time measurement precision



Baikal-GVD time calibration

Main causes of unsync:

- Different PMT and front-end electronics transit time
- Coaxial cable delays



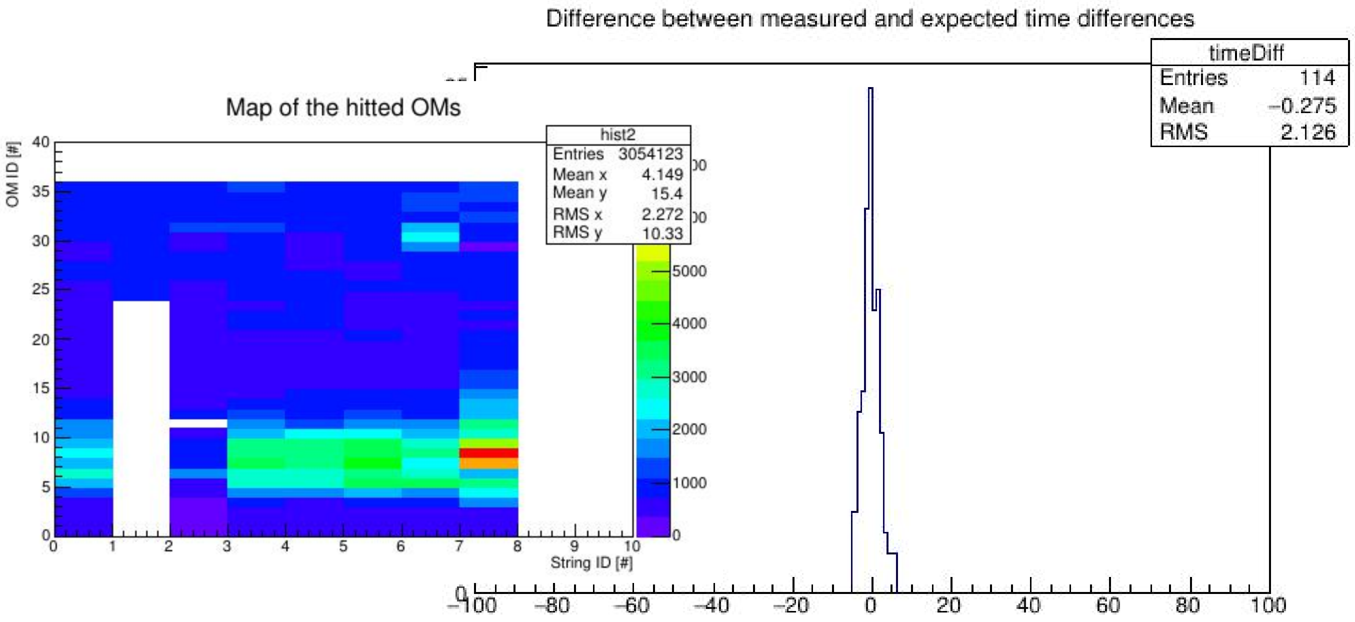
Intra-section calibration: LEDs

- Measure individual PMT delays with test pulses
- LED runs: measure delay between OM's wrt the reference

Inter-section calibration:

Strings are instrumented with LED beacons

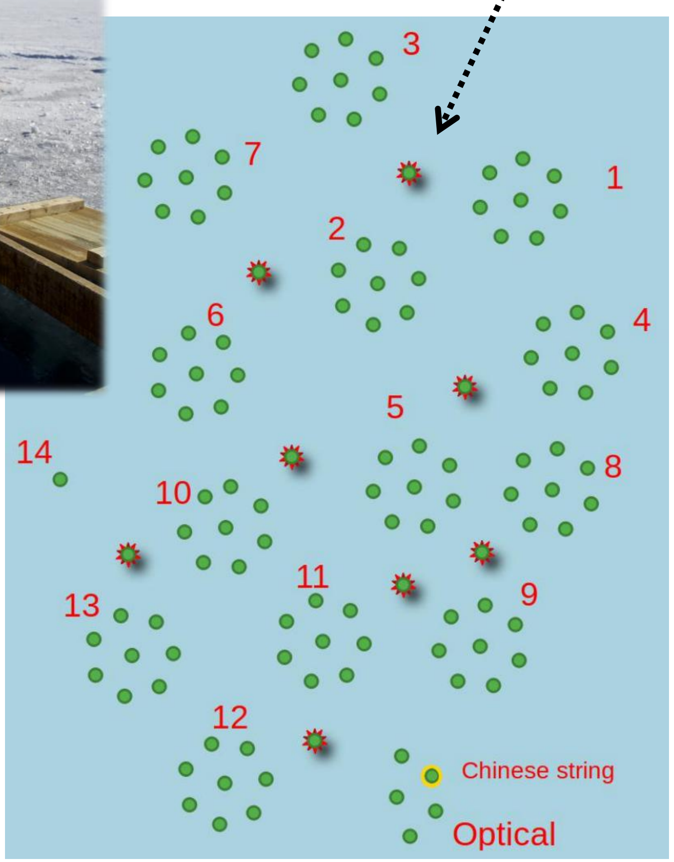
- Illuminate OM's within ~ 100m
- Delay between channels is measured and compared to the expectation



The single-cluster time calibration precision: ~ 2 ns

Time calibration

Inter-cluster synchronisation validation: system of lasers

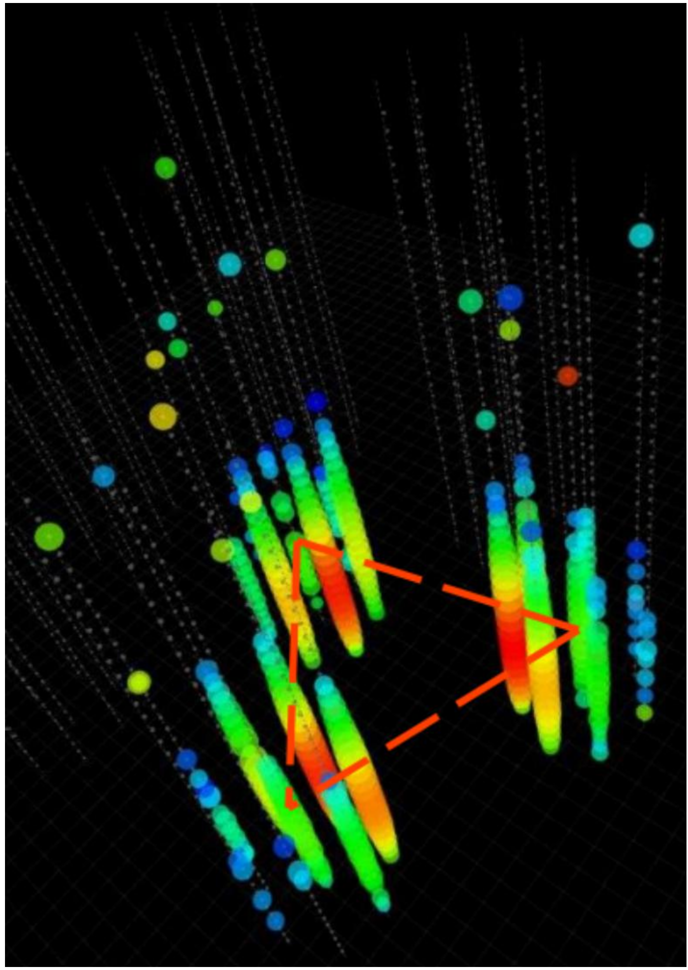


Coordinates of lasers are known with very good precision

Measure time difference between channels in different clusters

Compare to expected time difference

Calibration precision: 3ns



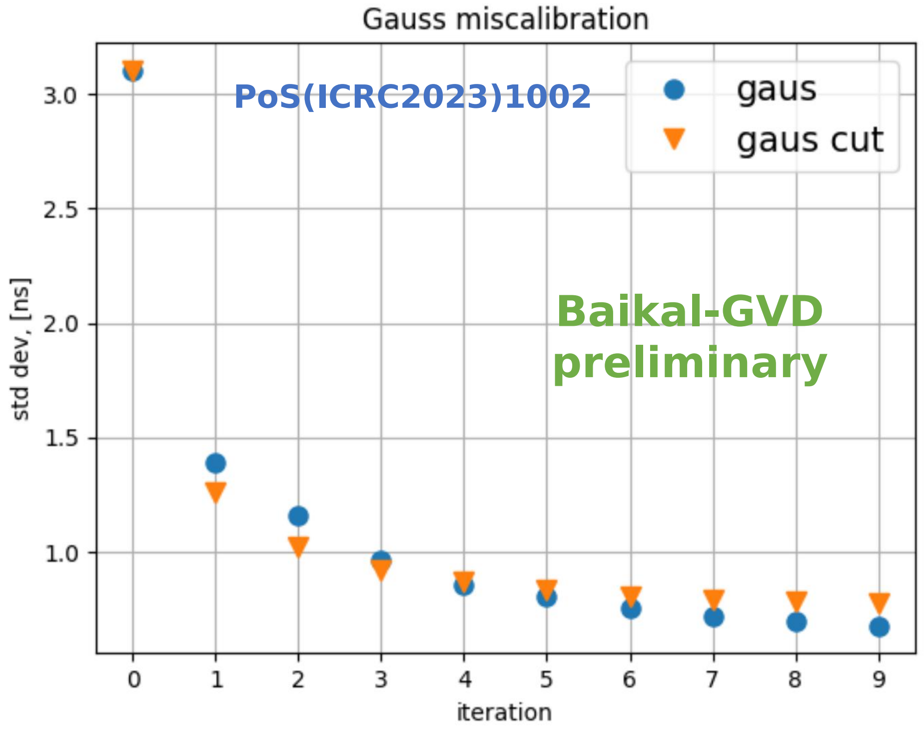
Time calibration with muons

Atmospheric muons allow to cross-check time synchronisation for well-separated parts of the detector

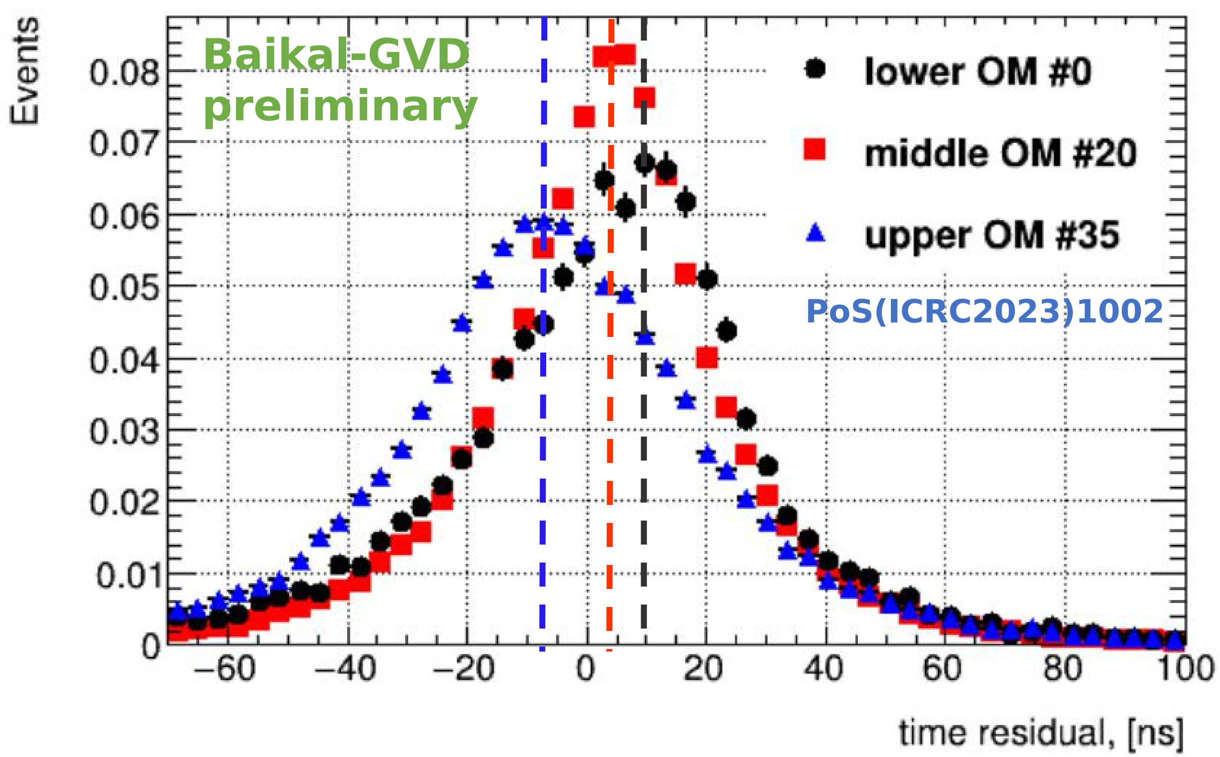
Measure for each channel i:

$\langle t_i^{res} \rangle = \langle t_i^{meas} - t_i^{th} \rangle$

where t_i^{th} is derived from reconstructed track parameters



MC channel offsets

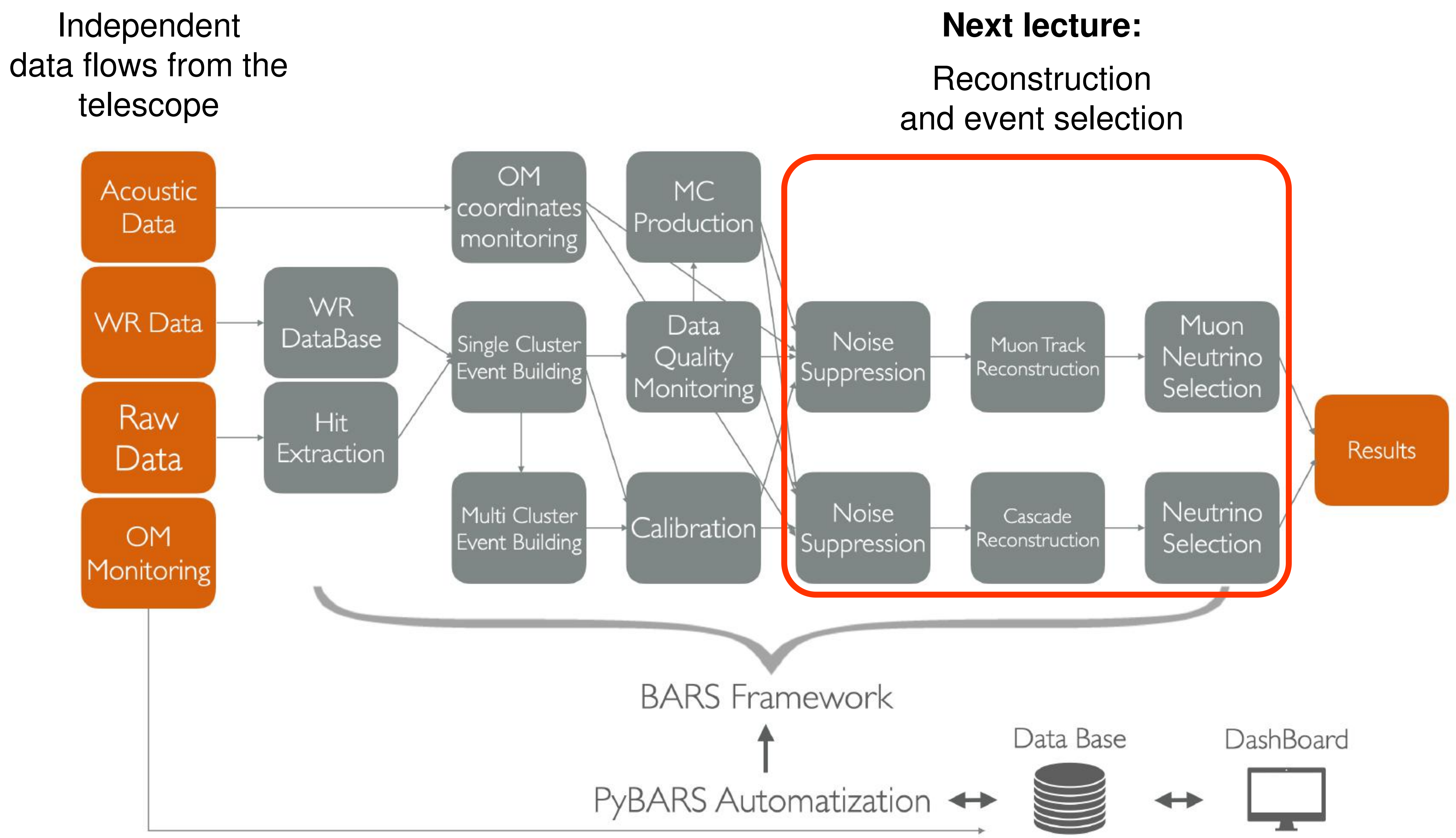


Derive correction to set each $\langle t_i^{res} \rangle$ to zero

Repeat the procedure until no further improvement in $\langle t_i^{res} \rangle$ is achieved

Iterative procedure converges to ns precision

Baikal-GVD data processing overview



BACKUP

KM3NeT calibration and positioning

Inter-PMT (intra-DOM) calibration

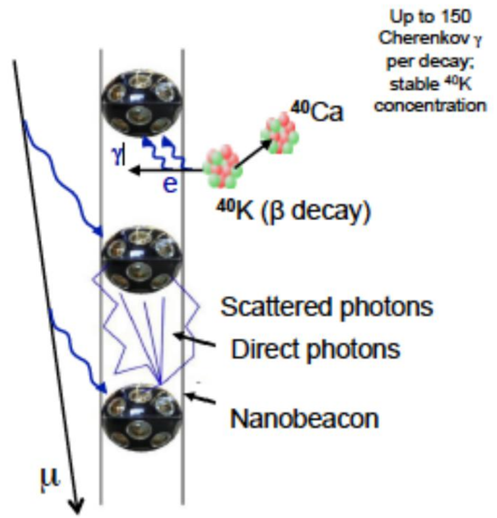
- ^{40}K in water - detection of the same flash by adjacent PMT

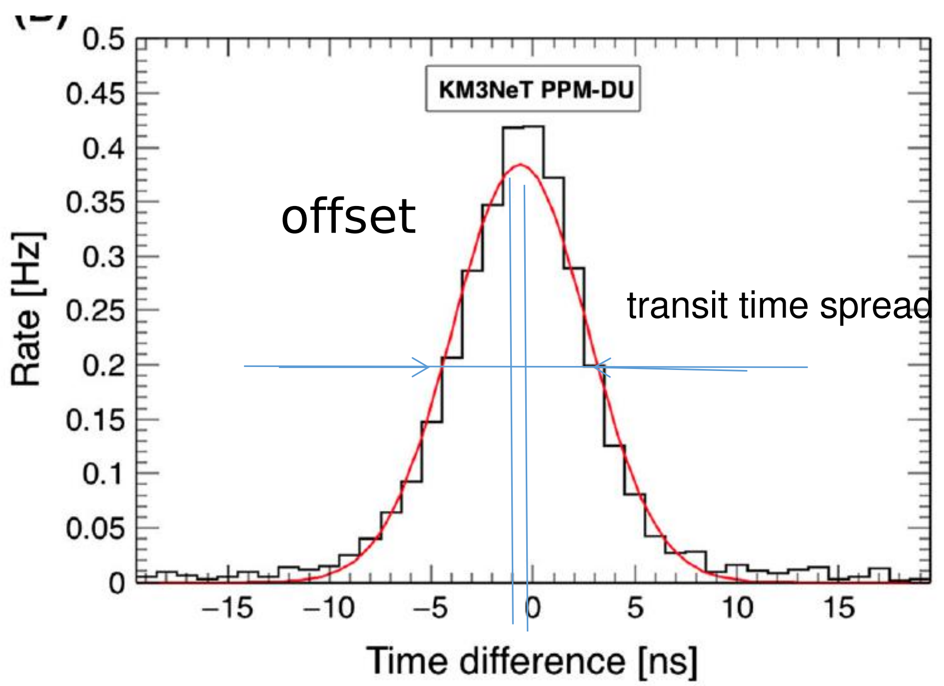
Inter-DOM calibration

- Pecalibration in laboratory during string construction
- In-situ calibration with LED sources

Inter-DU calibration

- Round-trip time for optical signal from master clock at the shore to the DU base





Calibrations are validated with down-going muons

[Eur. Phys. J C (201) 76:54]

IceCube calibration

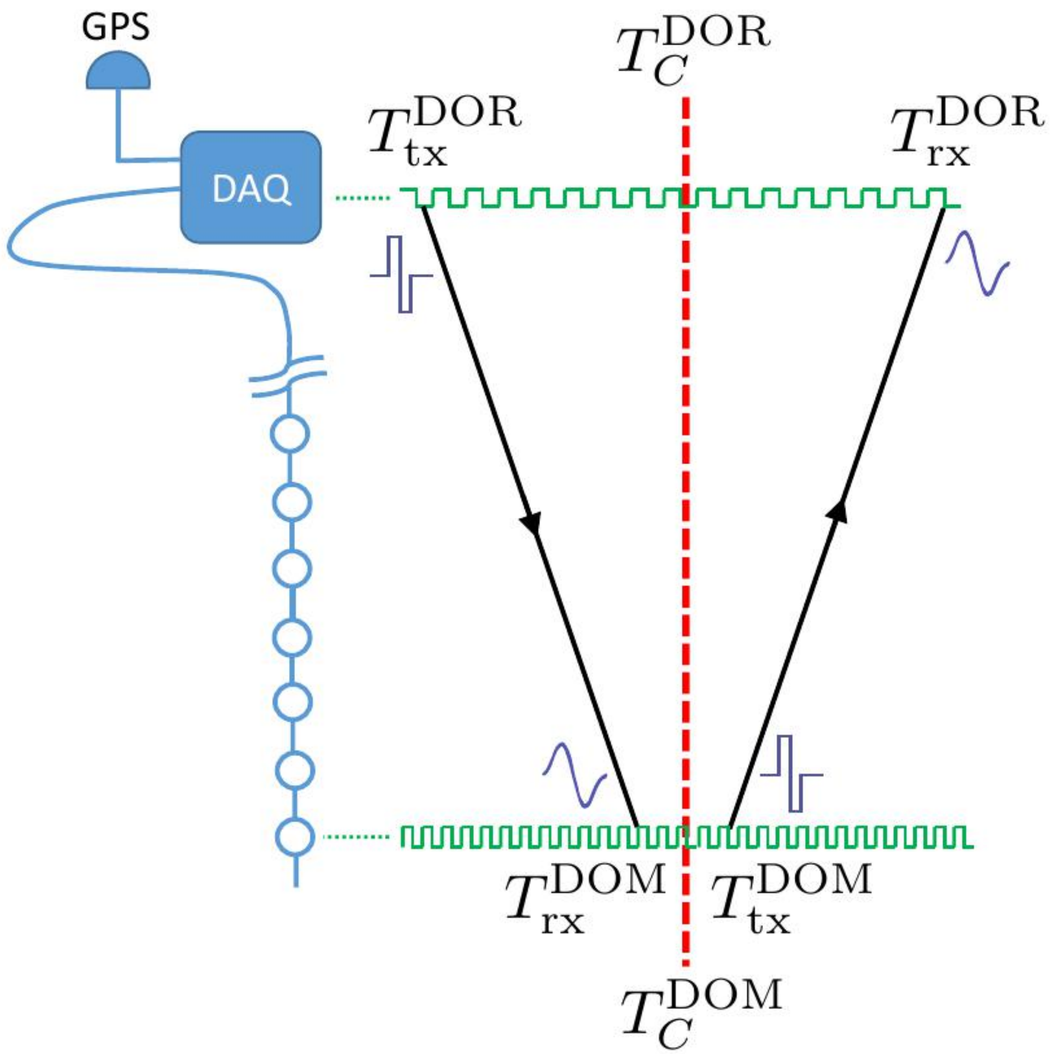
DOMCal: special board inside DOMs

- PMT signal delay calibration with local LEDs
- Charge calibration
- DOMCal runs once per year

The timestamp produced by DOM is already corrected for the PMT delay

RAPCal for DOM synchronisation

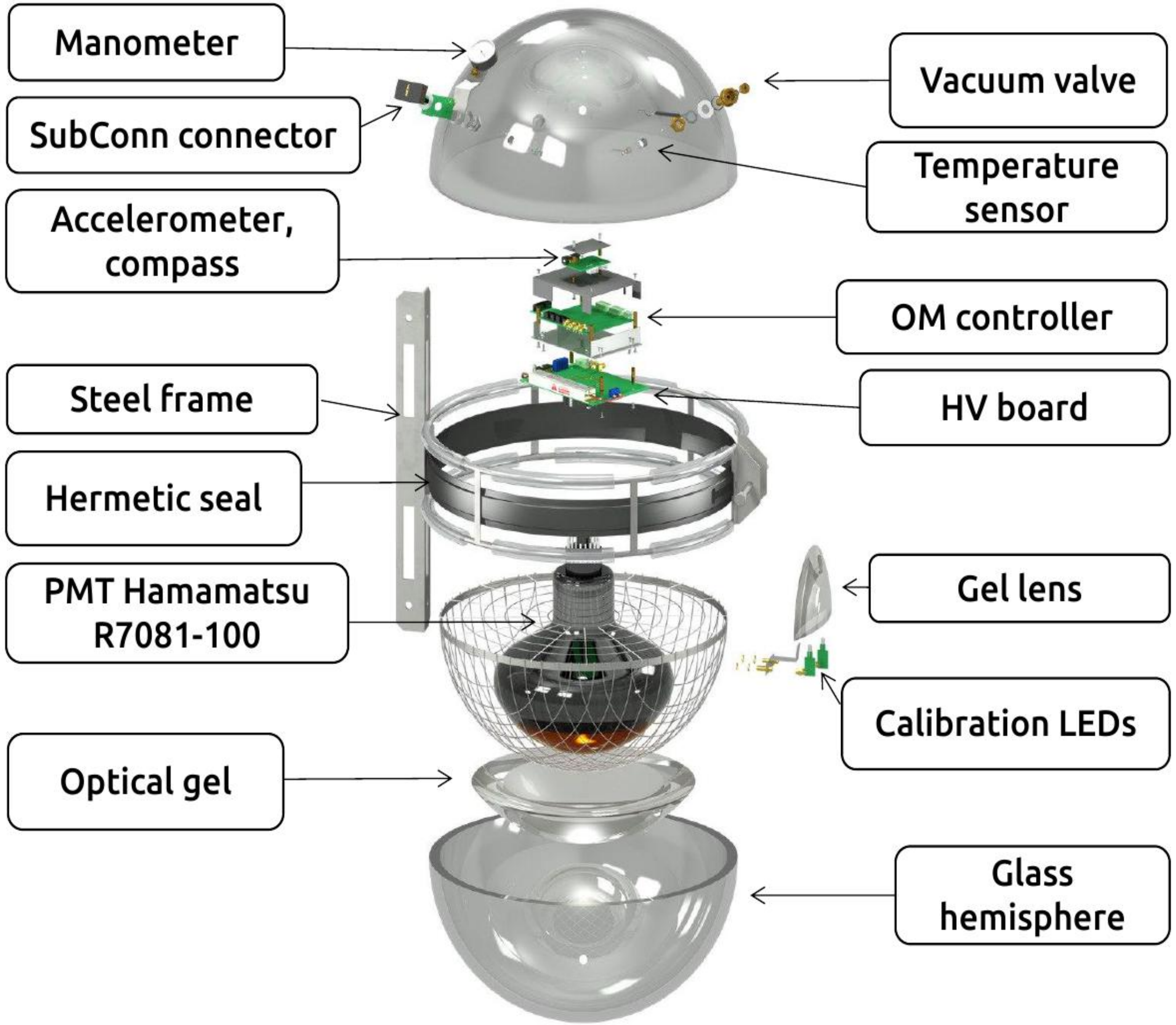
- Pulses from the surface to DOMs are sent every

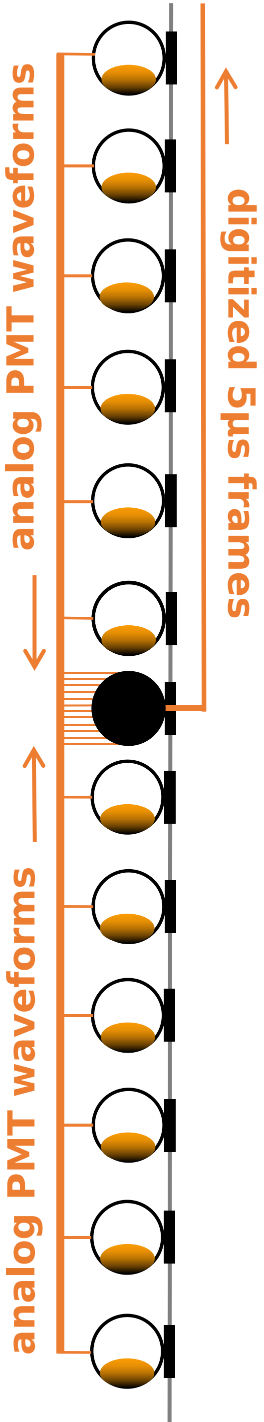


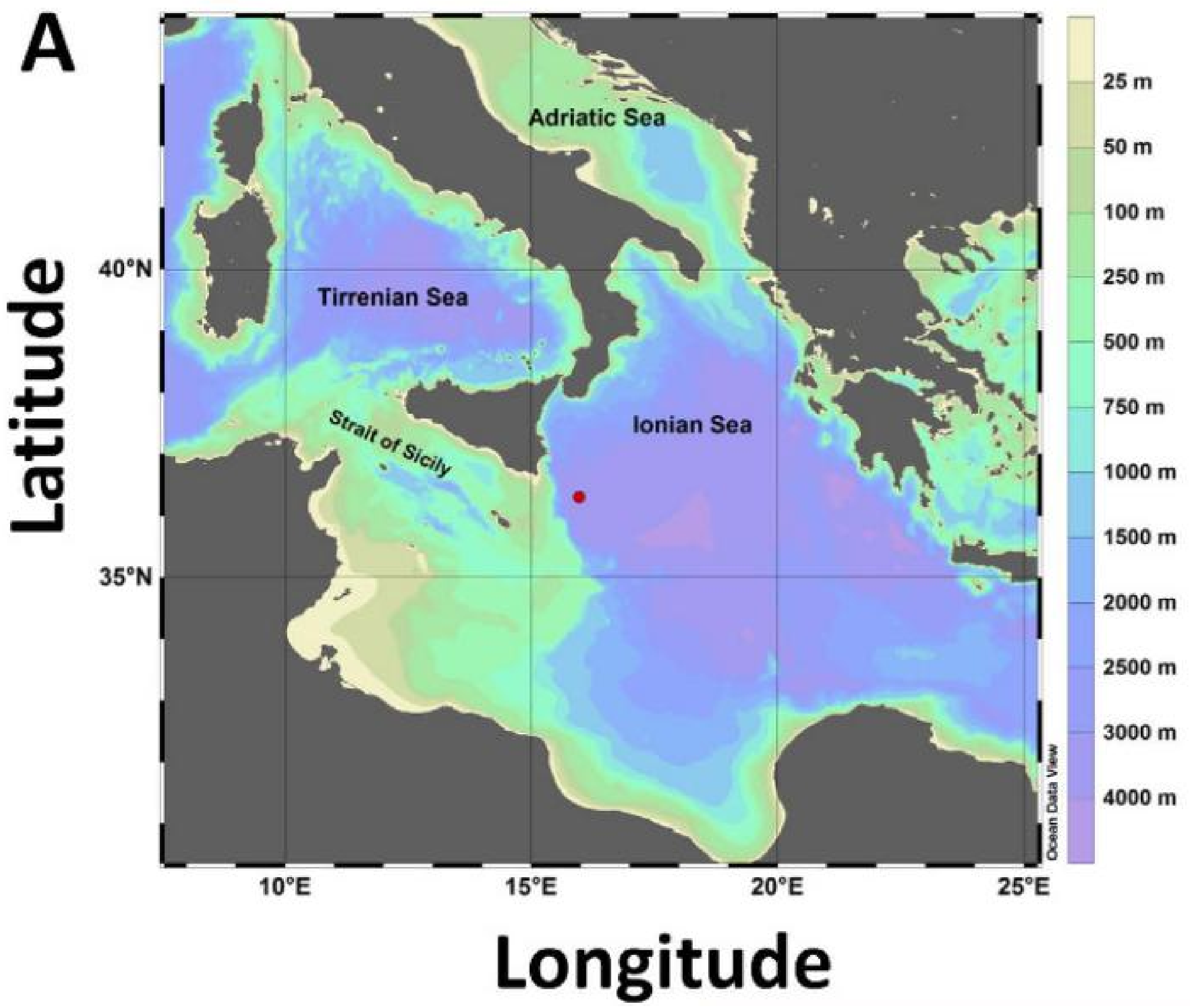
time calibration precision: 2ns precision

JINST 12 P03012 (2017)

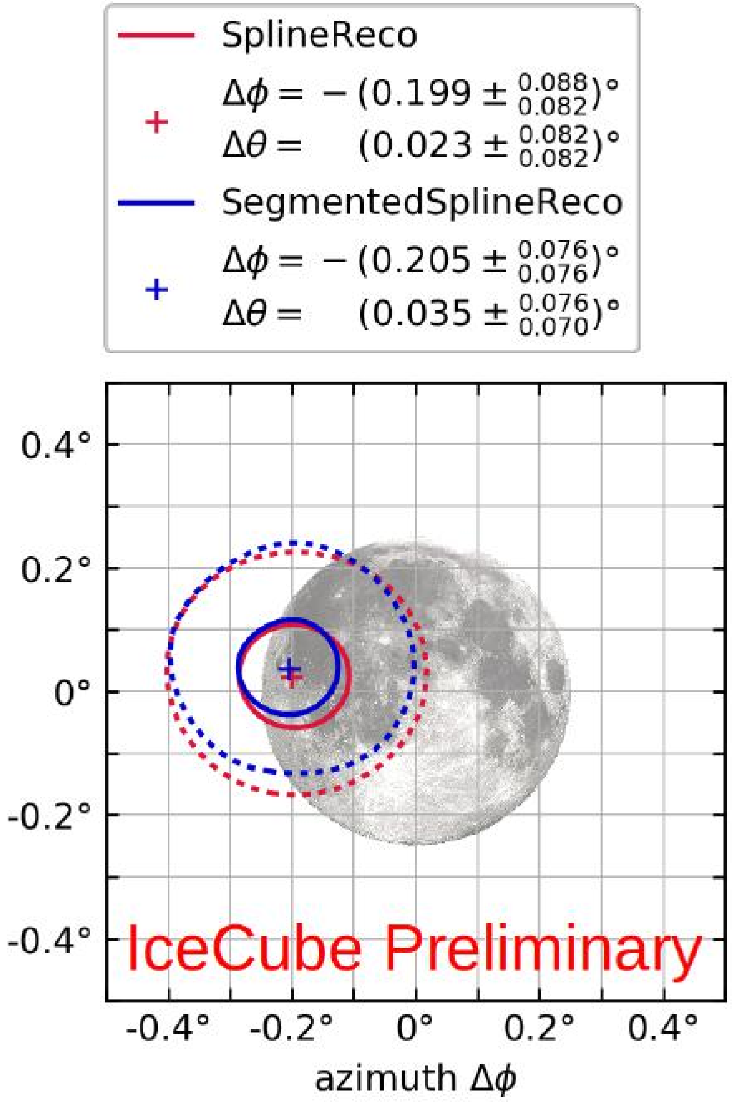
Optical modules





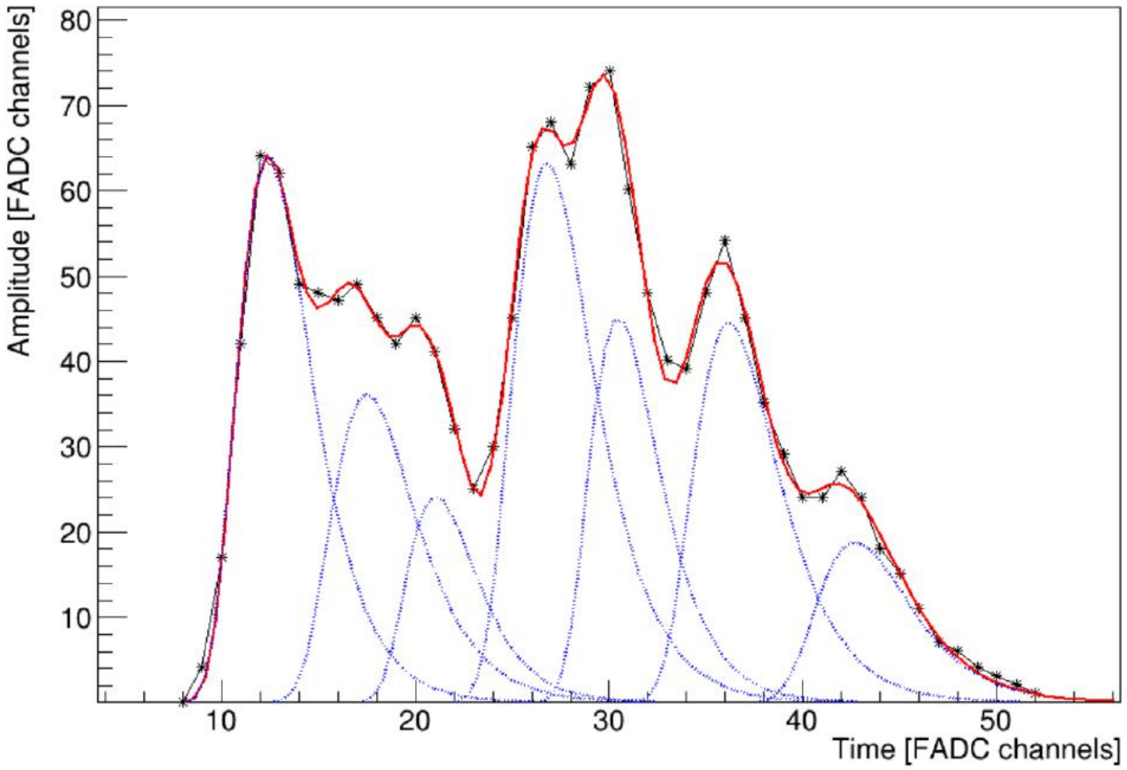

A
Adriatic Sea
Tirrenian Sea
Ionian Sea
Strait of Sicily
40°N
35°N
10°E
15°E
20°E
25°E
Latitude
Longitude
25 m
50 m
100 m
250 m
500 m
750 m
1000 m
1500 m
2000 m
2500 m
3000 m
4000 m
Ocean Data View

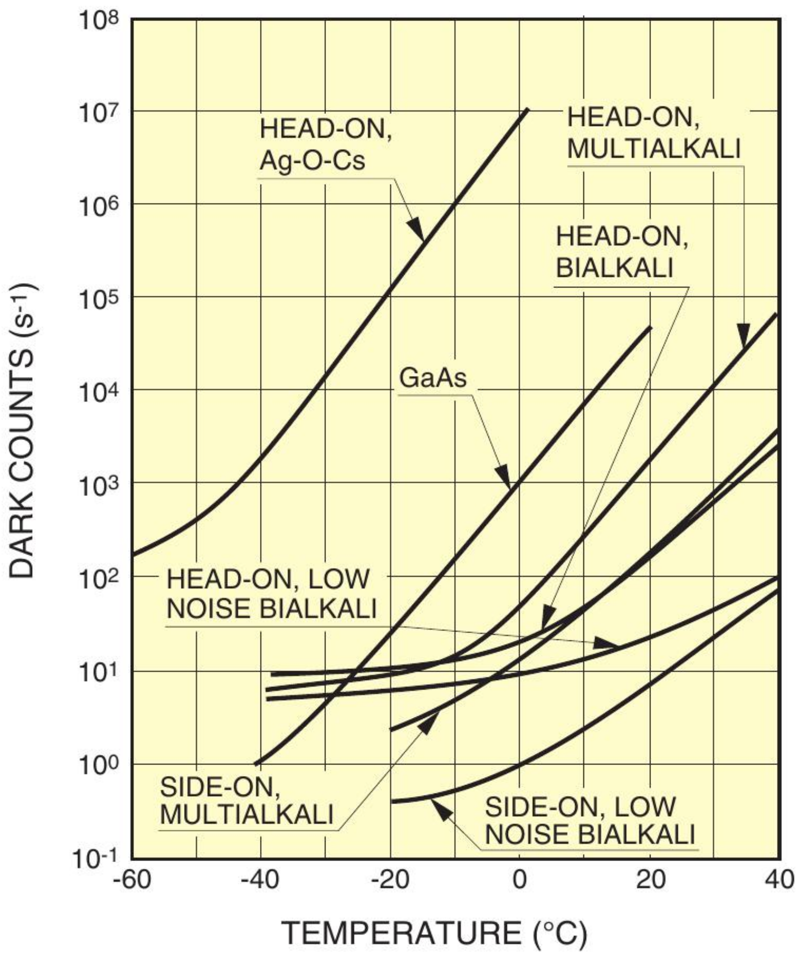
Moon shadow analysis



PMT waveforms

Pulses from photons are accumulated in complex waveforms

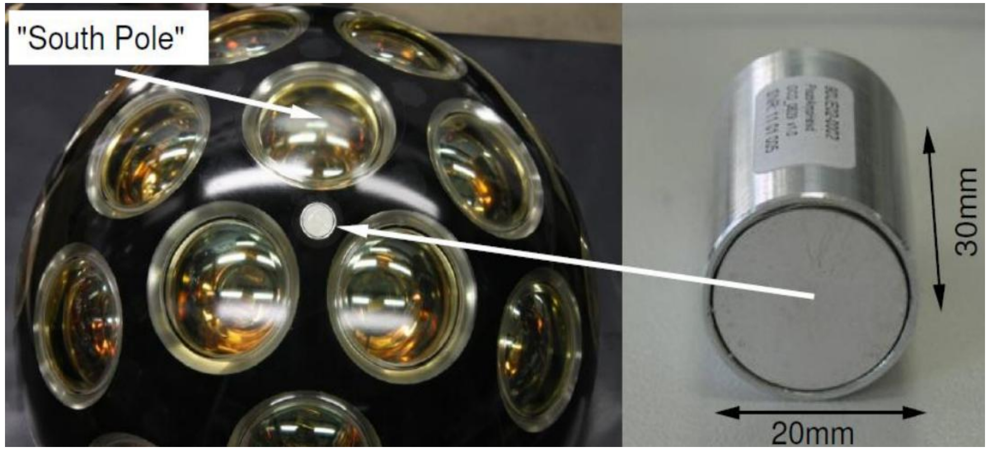




DARK COUNTS (s-1)
TEMPERATURE (°C)
10-1
100
101
102
103
104
105
106
107
108
-60
-40
-20
0
20
40
HEAD-ON, Ag-O-Cs
HEAD-ON, MULTIALKALI
HEAD-ON, BIALKALI
GaAs
HEAD-ON, LOW NOISE BIALKALI
SIDE-ON, MULTIALKALI
SIDE-ON, LOW NOISE BIALKALI

Detector positioning

KM3NeT positioning system

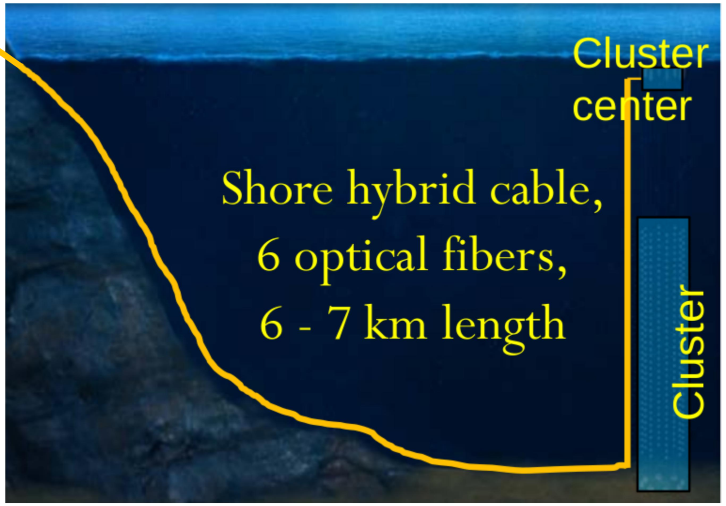


PoS(ICRC2023)1033

Data flow

Each cluster is connected to the **shore center** with opto-electric cable

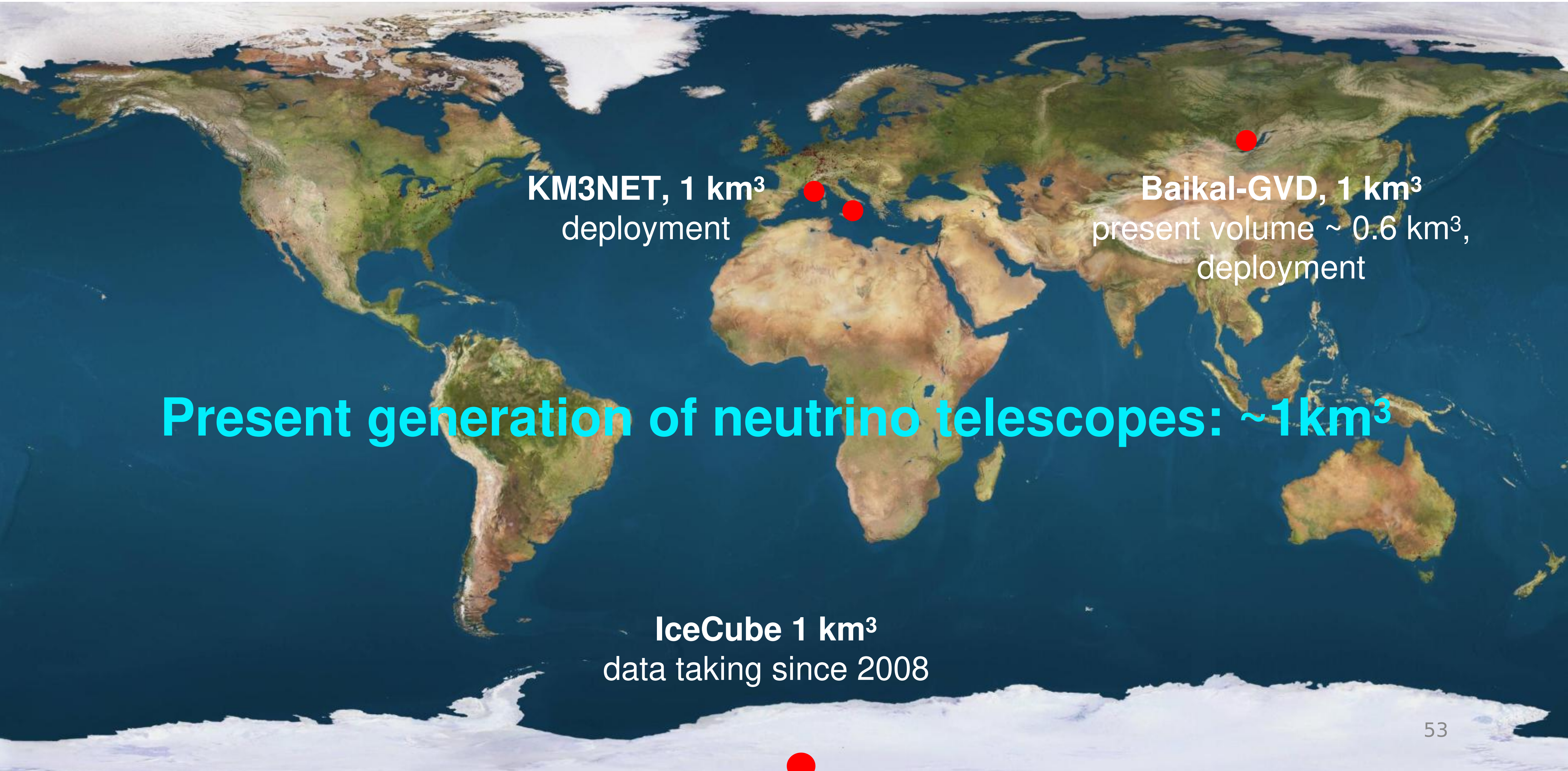
- Power distribution
- Data transmission



Baikal shore center:

- Power distrubution
- Data readout hardware/software
- Data-taking management (shifter)
- Data quality control
- Long-term storage of raw data
- Alert system (to be deployed)

Operating large-volume neutrino telescopes



Baikal-GVD neutrino telescope

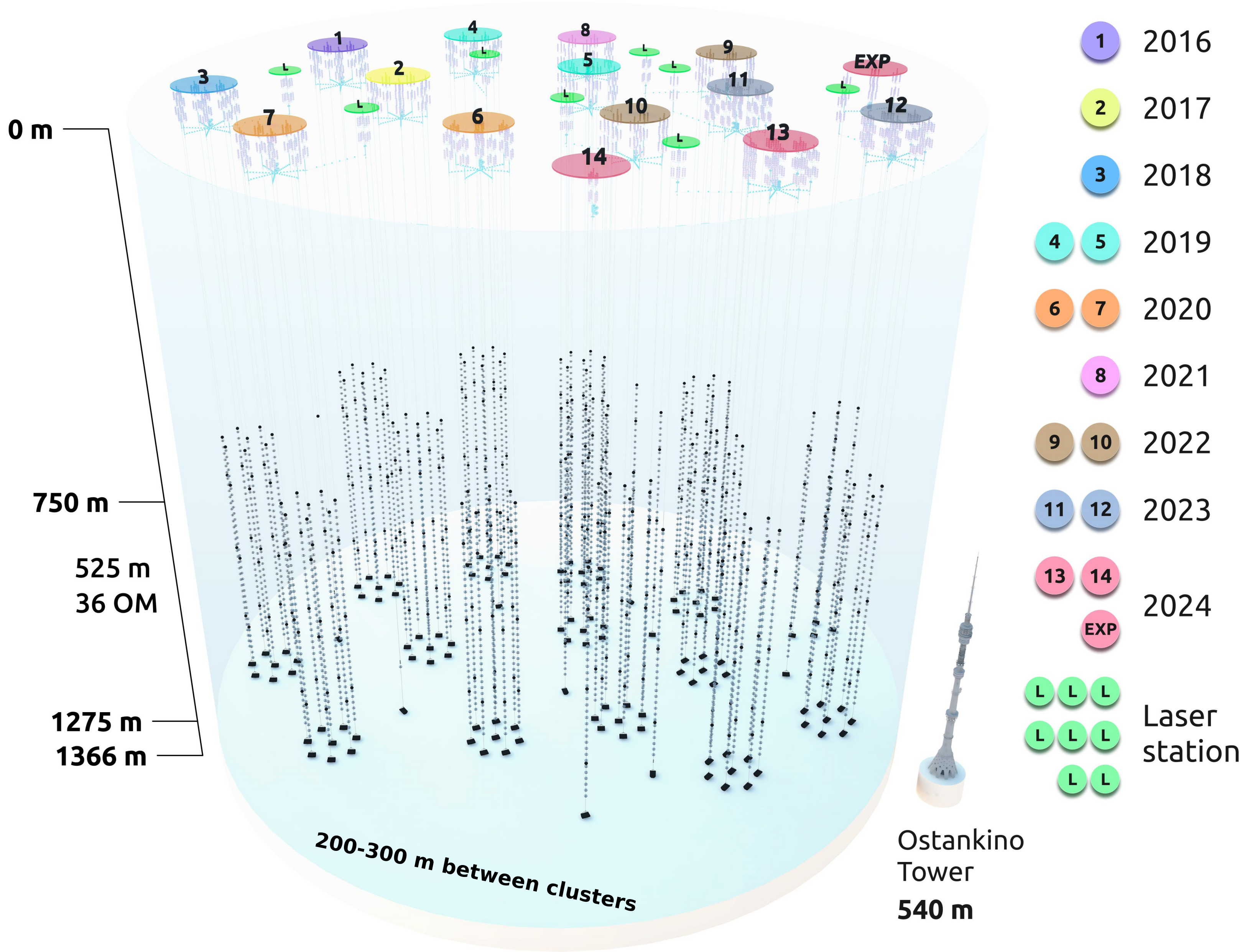
Presently detector consists of 117 strings arranged into 14 independent detectors - **clusters**

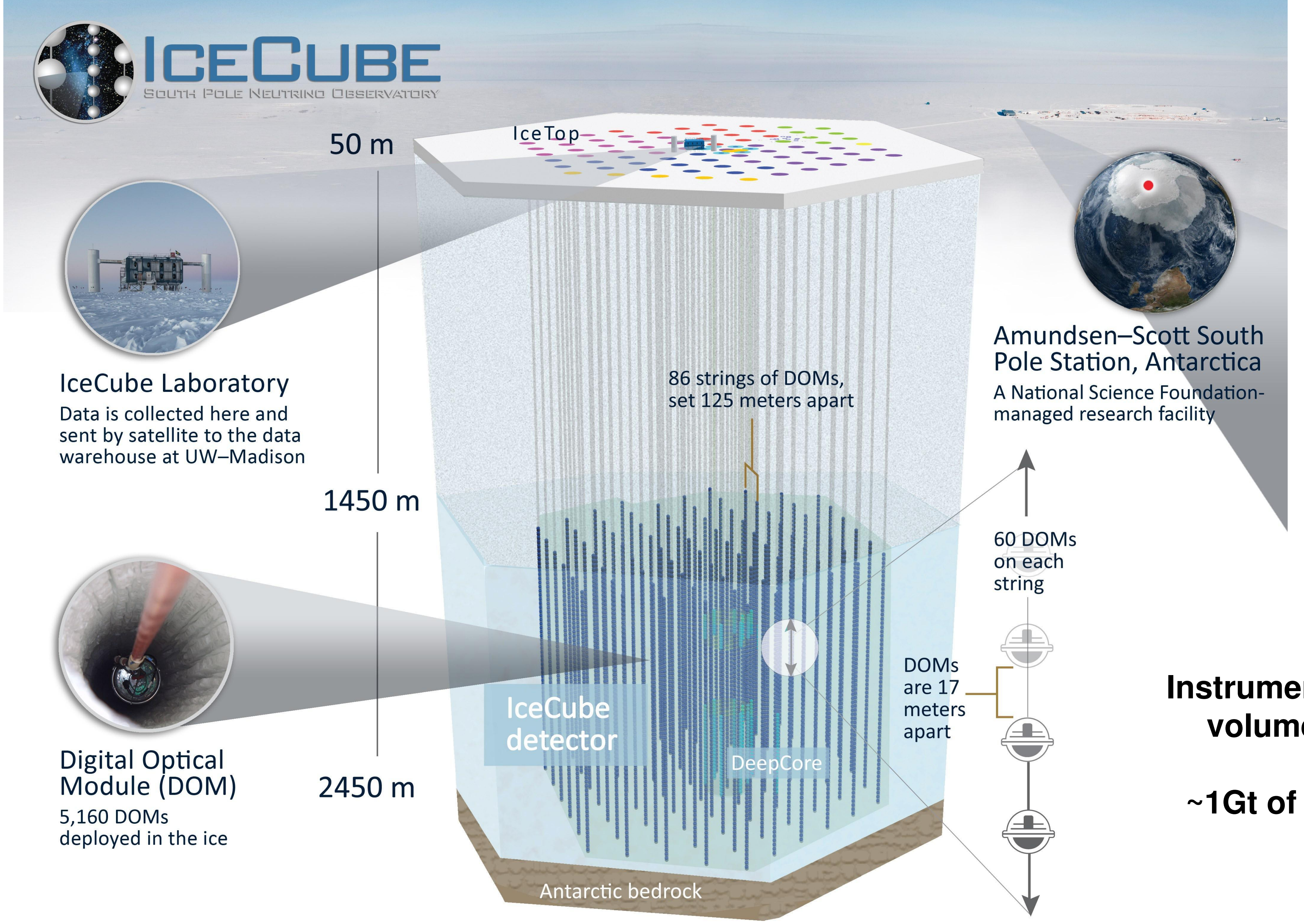
- 4212 OMs in total

Baikal-GVD cluster:

- 8 regular strings, 525 m is instrumented with optical modules (OM), 15m step between OM
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs

Detection volume: ~0.6 Gt

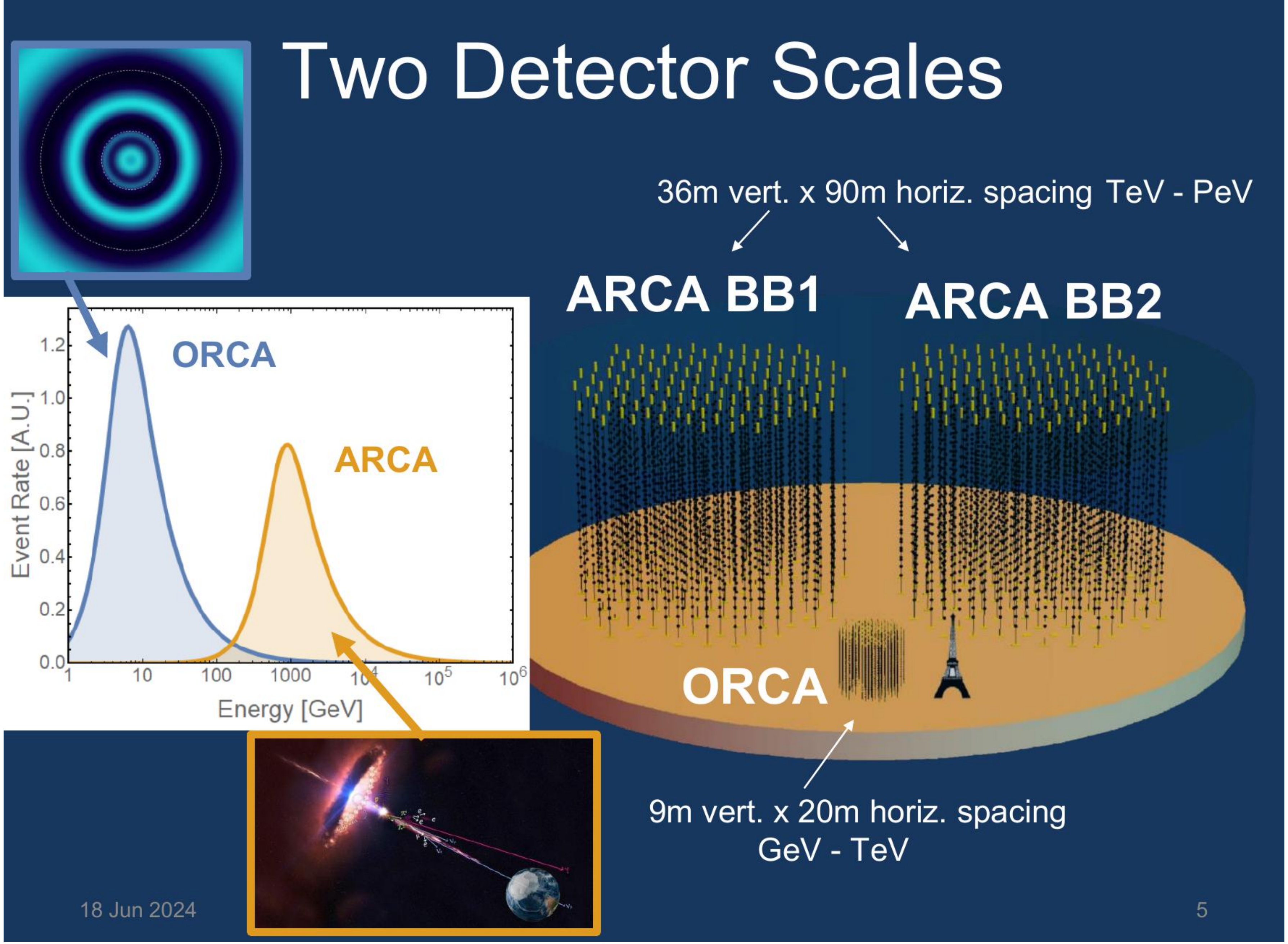




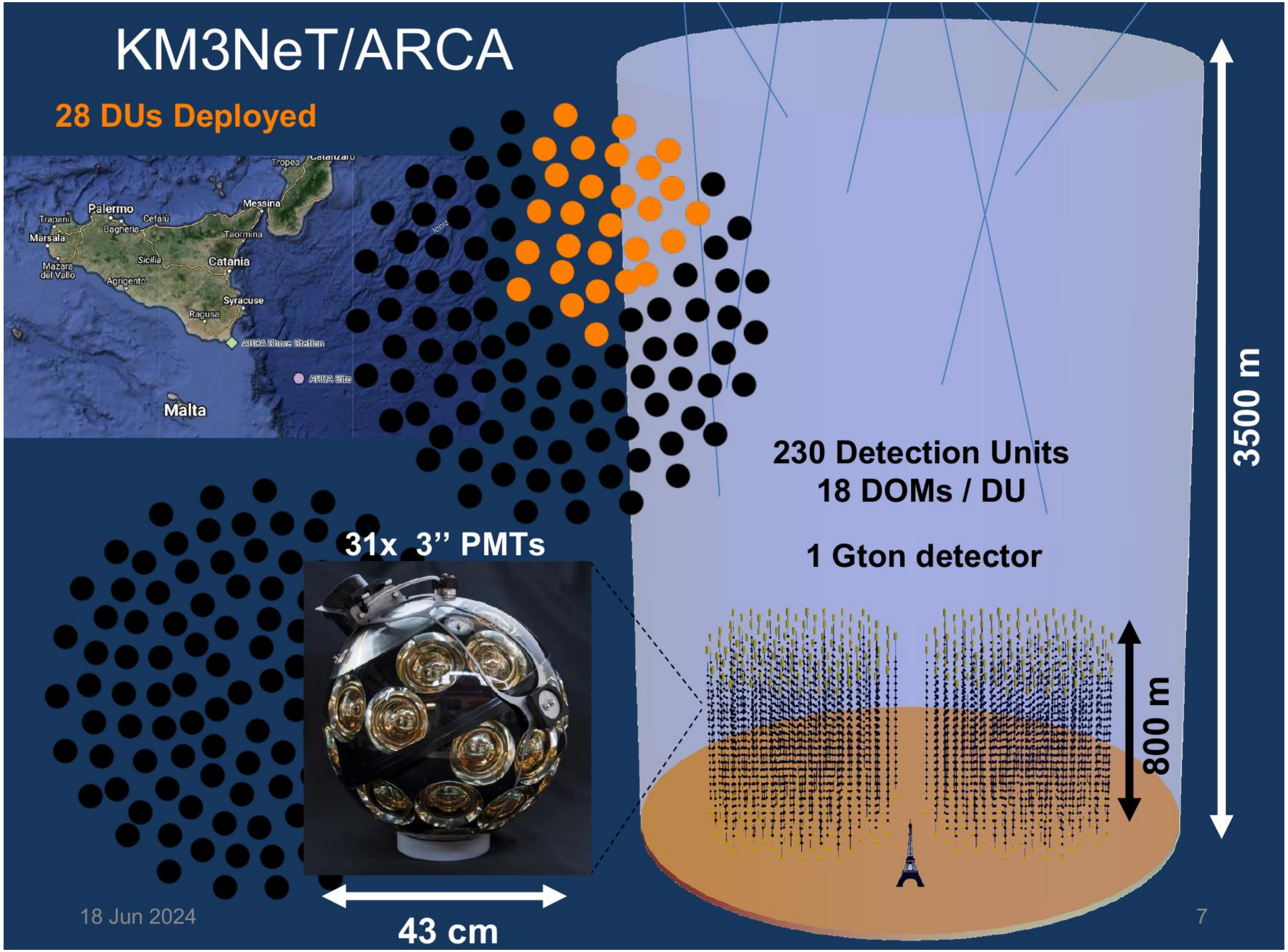
https://icecube.wisc.edu/science/icecube/

Instrumented volume:

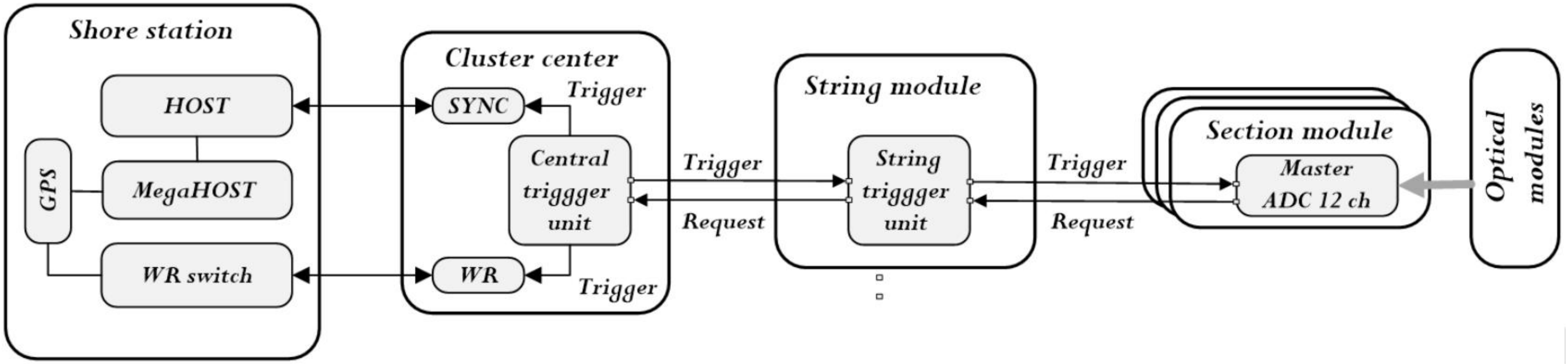
~1Gt of Ice


Two Detector Scales
36m vert. x 90m horiz. spacing TeV - PeV
ARCA BB1
ARCA BB2
ORCA
ARCA
Event Rate [A.U.]
Energy [GeV]
ORCA
9m vert. x 20m horiz. spacing
GeV - TeV
18 Jun 2024
5

5 additional DUs deployed in October 2024



15% of the detector deployed


Shore station
HOST
GPS
MegaHOST
WR switch
Cluster center
SYNC
Trigger
Central
triggger
unit
WR
Trigger
Trigger
Request
String module
String
triggger
unit
Trigger
Request
Section module
Master
ADC 12 ch
Optical
modules