KM3NeT
Opens a new window on our universe

Data Acquisition and Trigger in KM3NeT

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VLVNT 2018

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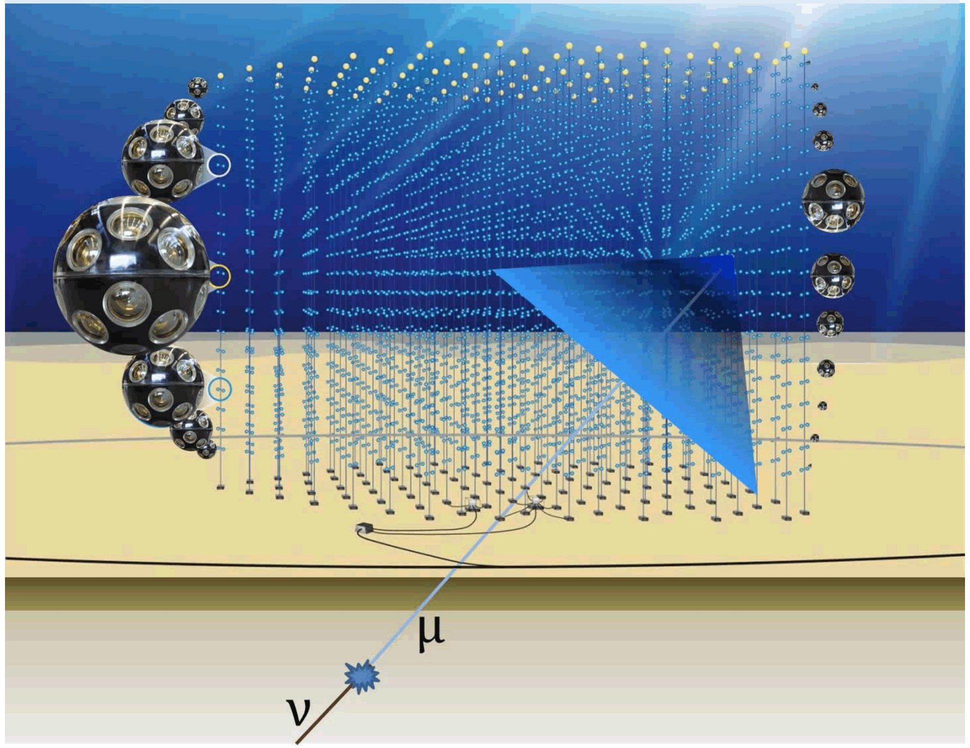
KM3NeT in short

Cherenkov light from the charged products of neutrino interactions in sea-water are detected by a sparse array of photo-multiplier tubes



31 3” PMTs in glass sphere
Multi-PMT DOM

ARCA
~ 1 km^3
Astrophysical neutrinos (TeV-PeV)
Italian Site

ORCA
~5.7 Mton
Atmospheric neutrinos (~1-100 GeV)
Neutrino mass hierarchy
French Site

DAQ Constraints & Requirements

Size :

115 Detection Units per block
18 DOMs/DU
31 PMTs/DOM

~64k PMTs

Background photons:

^{40}K decay	~7 kHz/PMT constant
Bioluminescence	~100 kHz/PMT bursts
Atmospheric muons	~100 Hz/block

Expected signal (reconstruction level) :

ARCA : 3 cosmological neutrinos/day
ORCA : 50.000 atmospheric neutrinos/year

Signal to noise
$< 10^{-6}$

Requirements:

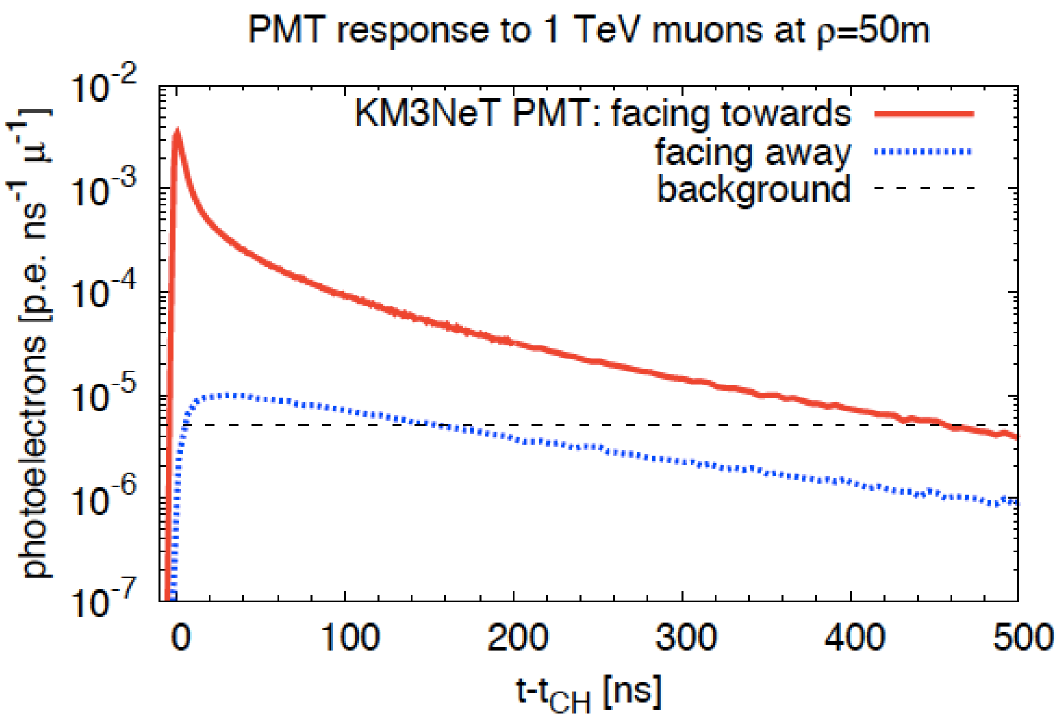
Infrastructure to transfer all data to shore for processing

Rejecting the overwhelming background

Don’t loose the sparse signals

…and do this in a hostile and dynamic environment – the Sea

But why transfer all data?? – All data to shore



Photons from neutrino interaction products have long-range nanosecond correlations , due to favorable optical properties of sea-water.

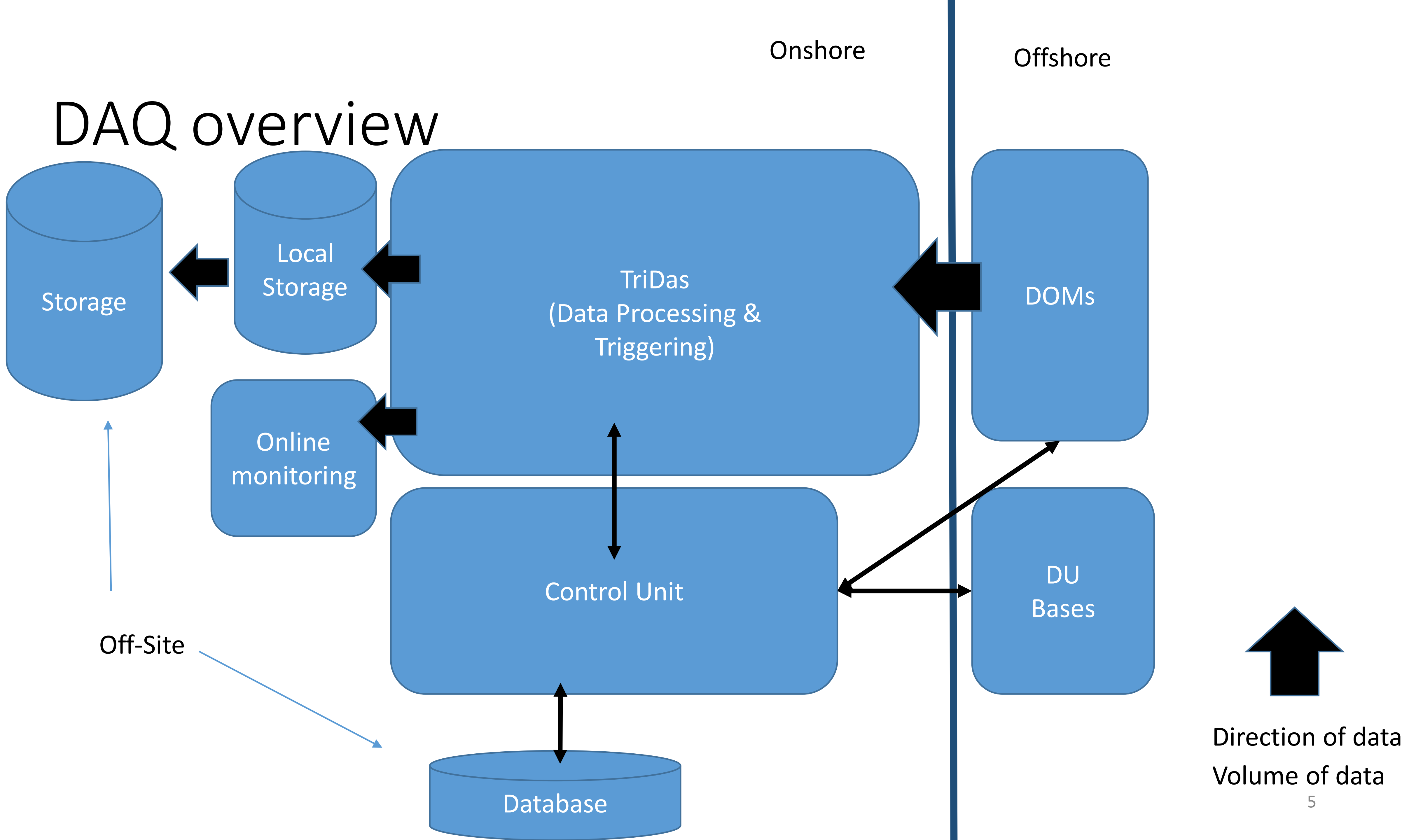
Require ns timing to exploit good water properties and suppress optical background

Suppress background (to "1st order") : use local coincidences

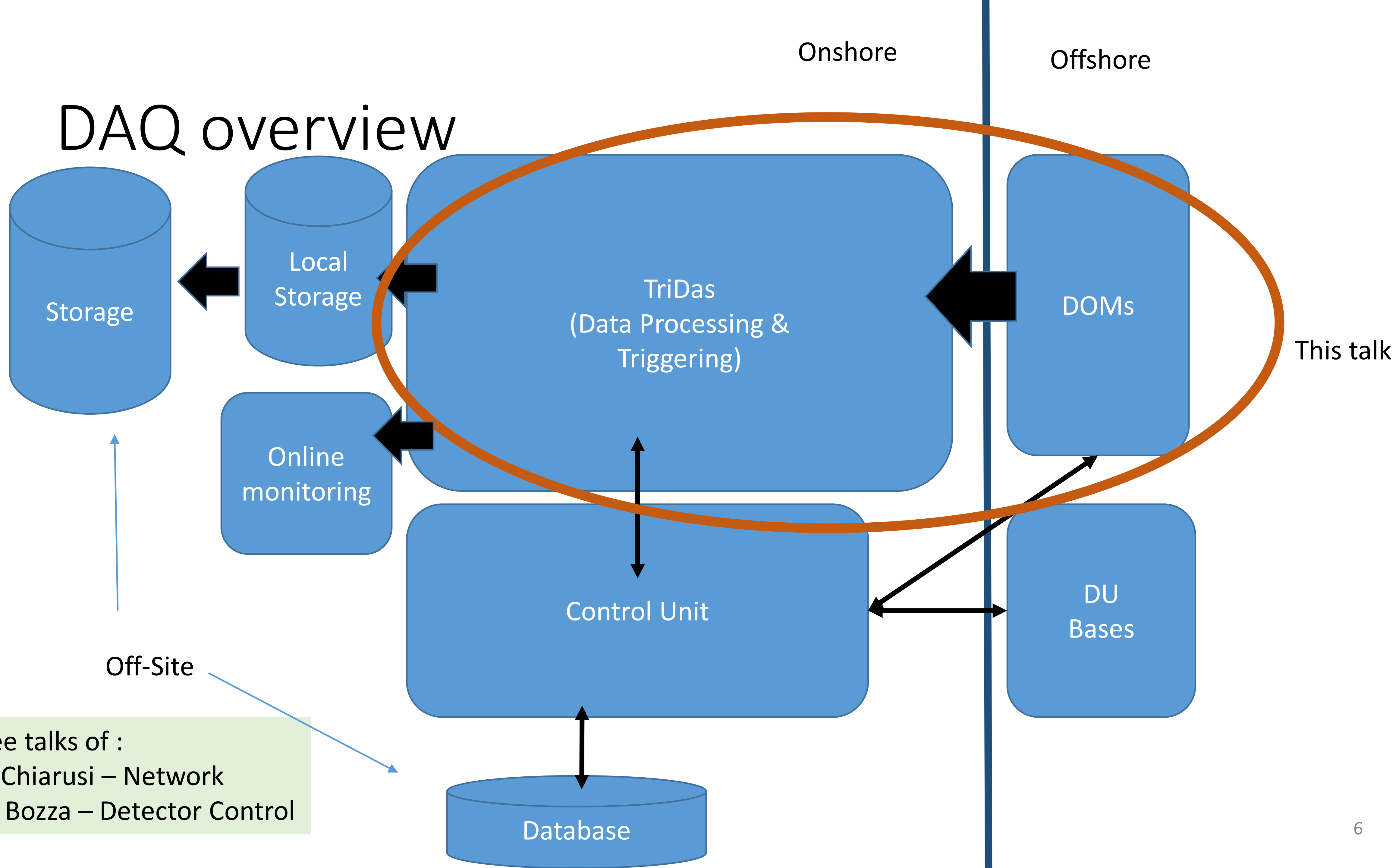
Find signal : Use long range correlations

But you cannot do this off-shore due to the detector scale!

DAQ overview

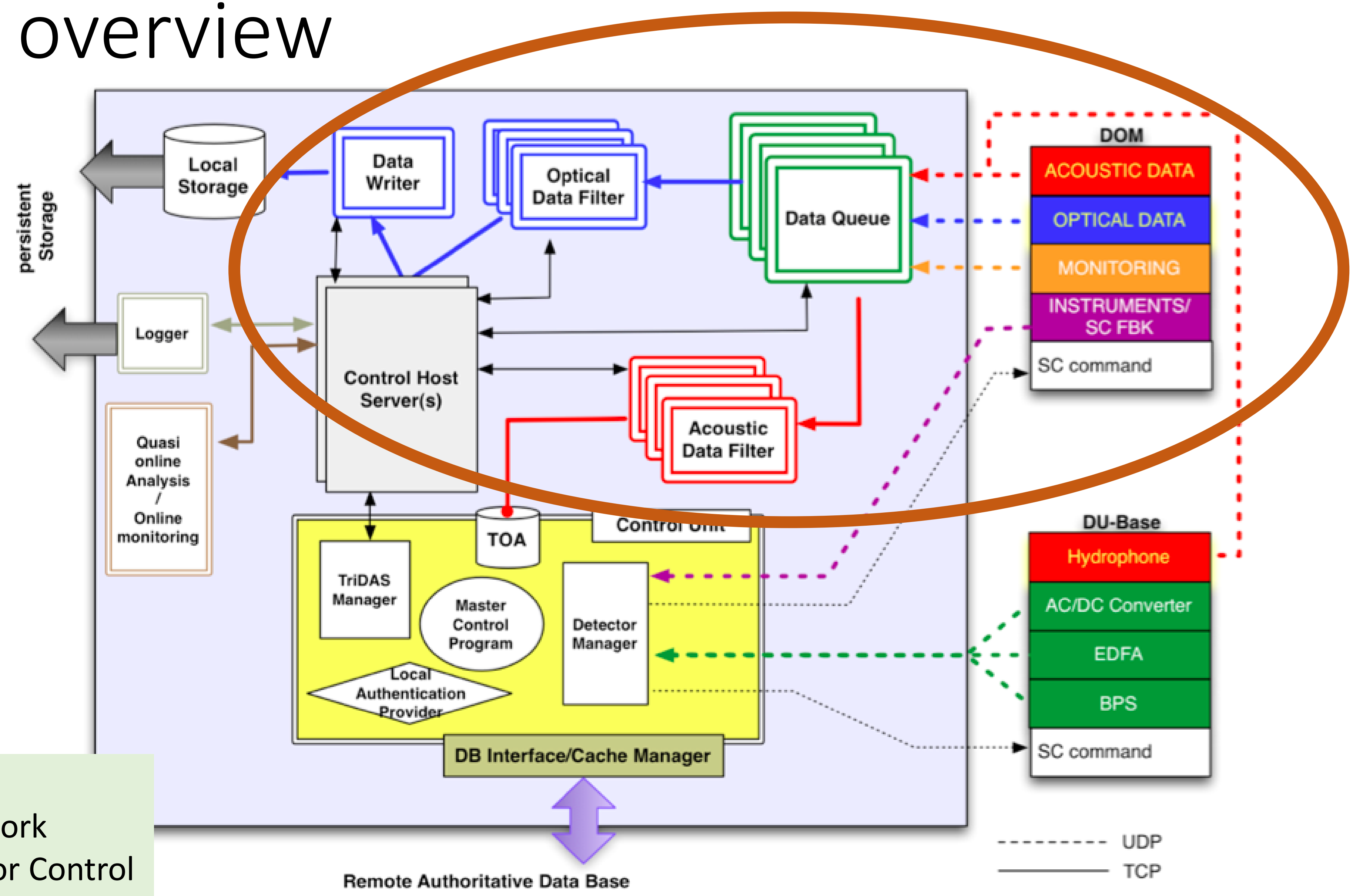


DAQ overview



See talks of :
T. Chiarusi – Network
C. Bozza – Detector Control

DAQ overview



See talks of :
T. Chiarusi – Network
C. Bozza – Detector Control

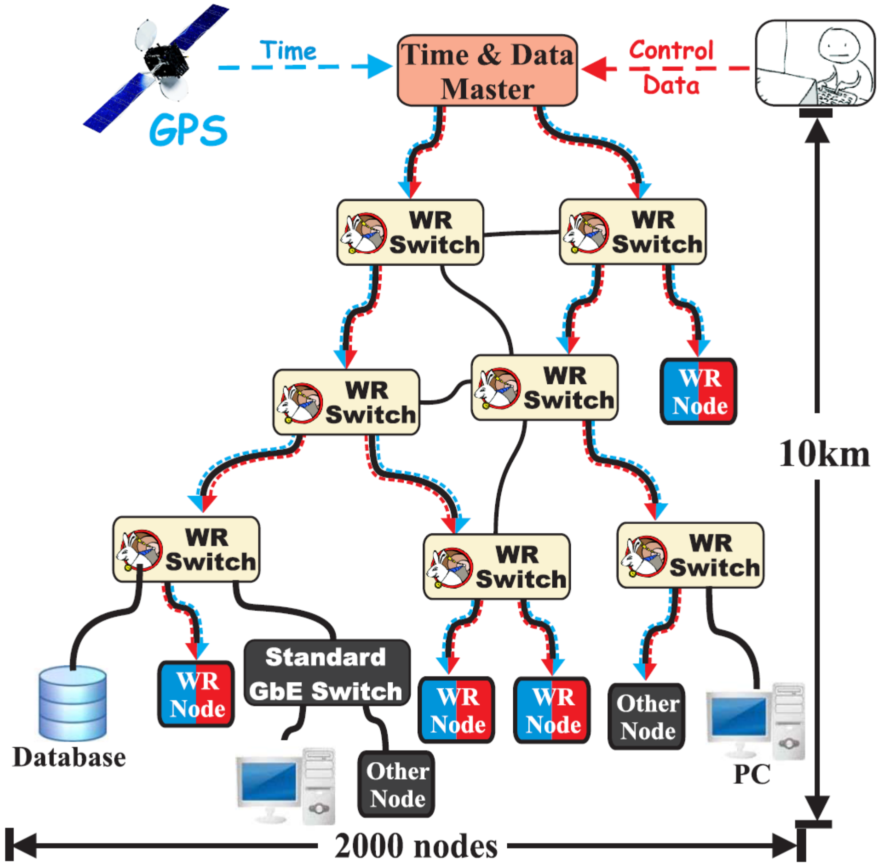
Data Streams

Type	Direction/Target	Size	Remark
Slow Control	Bidirectional, CLBs, Bases, Control Unit	minimal	To offshore : Broadcast, single channel To shore : individual channels
"Optical" Photon Hits	Unidirectional To Shore: DataQueue	11-23 Mbps/DOM	
"Acoustic" Hydrophone data	Unidirectional To Shore: DataQueue	4.6 Mbps/DOM	
"Monitoring" e.g. compass, countrates	Unidirectional To Shore: Database	minimal	
Timing	Bidirectional Bases, WR Master	minimal	White Rabbit, Part of Ethernet packets Broadcast to offshore

Time Synchronization: White-Rabbit

Enhanced Ethernet, providing:

- Synchronization: accuracy better than 1 ns precision (tens of ps stdev skew max)
- Deterministic, reliable and low-latency Control Data delivery

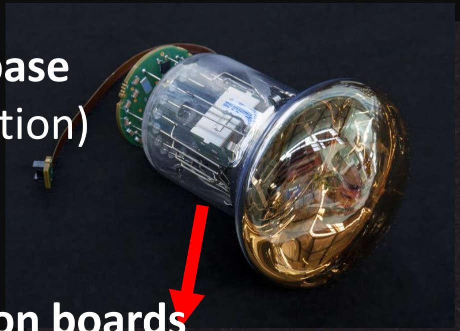


See talk of Pablo Marín JíMENEZ

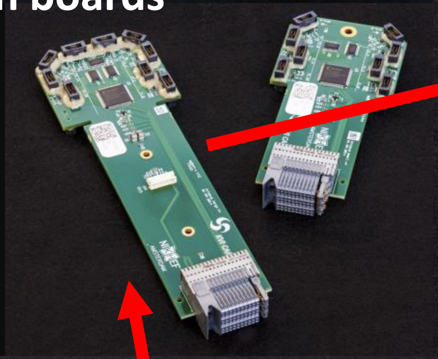
(P. Jansweijer)

DAQ/Electronics in DOM

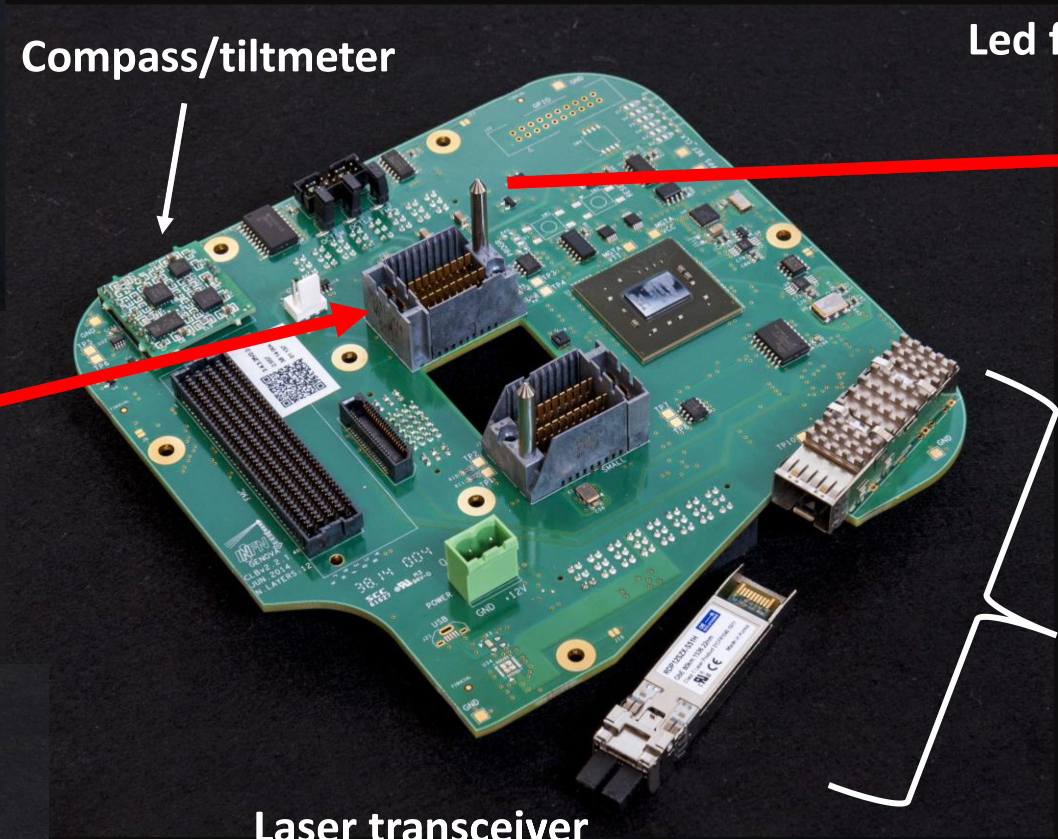
PMTs+base
(digitization)



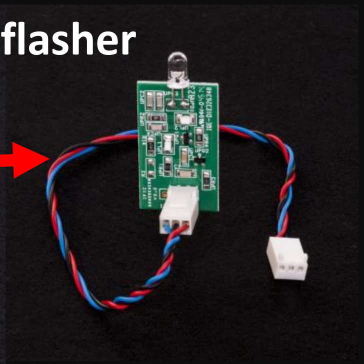
Signal collection boards
(addressing)

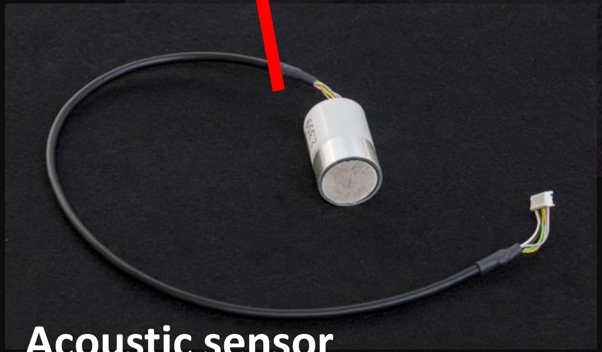


Compass/tiltmeter



Led flasher





Acoustic sensor
(Piezo, digitization in device)

Laser transceiver
Each DOM has a defined outgoing wavelength
Multiplexed outside DOM
Incoming is a broadcast

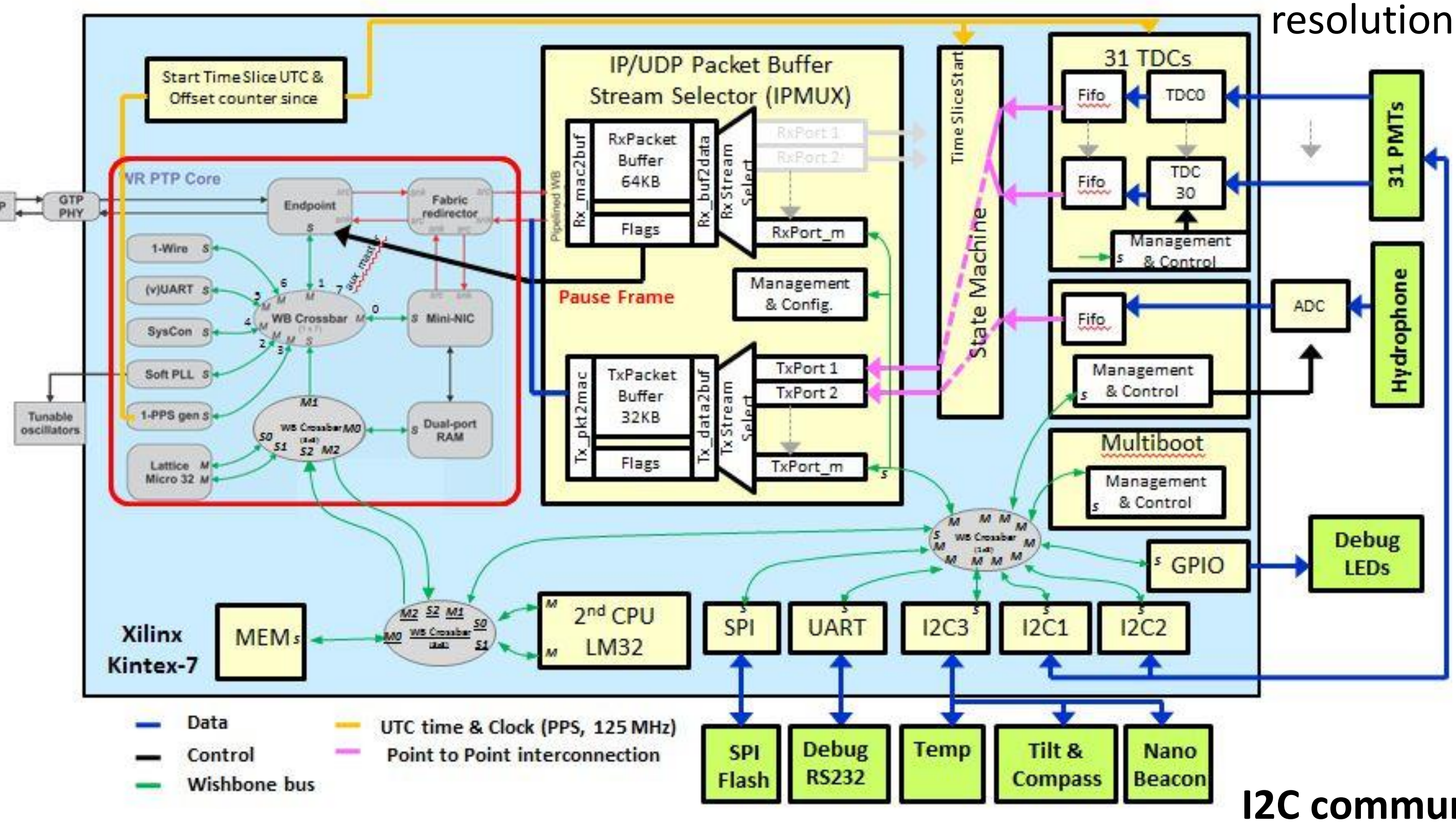
Central Logic Board (CLB)
FPGA :
- DAQ pipeline
    - Nanosecond timestamping
- Ethernet packet generation
- White-Rabbit timing
- Slow control CPU (LM32)
- Under-water reprogrammable

DOM Electronics: FPGA

IP/UDP (ethernet) packet creation
Multiple streams
(PMTs, acoustic, monitoring)

High-Speed TDCs
LVDS inputs from PMTs
Hit time and ToT. 800ps/$\sqrt{12}$ resolution

White Rabbit PTP core
for time synchronization and Ethernet over optical fibres.



Multiboot system
(fail-safe reprogramming)

LM32 CPU
Control from shore
(Slow control, DAQ pipeline, White Rabbit, other sensors)
Implements software state machine

UART
Serial terminal
Tunneled over ethernet

I2C communication
HV and thresholds
Compass/tiltmeter
Led Flasher
Temperature/Humidity

Data format

Time-multiplexing:

Frame : all data from a DOM in 100 ms
Timeslice: all frames for the same time
Remember: DOMs are synchronized!!

Time-multiplexing allows routing data with all benefits of Ethernet (addressing, load distribution, etc.)

Header of a frame :

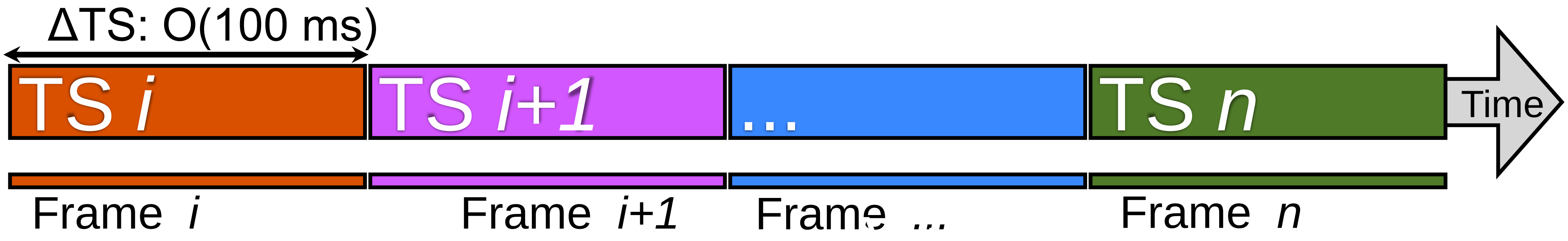
CLB Common Header

Offsets Octet		0	1	2	3
Octet	Bit	0 1 2 3 4 5 6 7	8 9 10 11 12 13 14 15	16 17 18 19 20 21 22 23	24 25 26 27 28 29 30 31
0	0	Data Type			
4	32	RunNumber			
8	64	UDP Sequence Number			
12	96	Timestamp			
16	128				
20	160	DOM Identifier			
24	192	Status I			
28	224	Status II			
32	256	Status III			
36	288	Status IV			

UDP Packet # (for timeslice)

Which DOM ?

Coarse time : seconds+16 ns ticks



Data is send over Ethernet via UDP packets

Timeslice spread out over multiple UDP packets and need reassembly (DataQueue)

Optical Data

Custom PMT bases

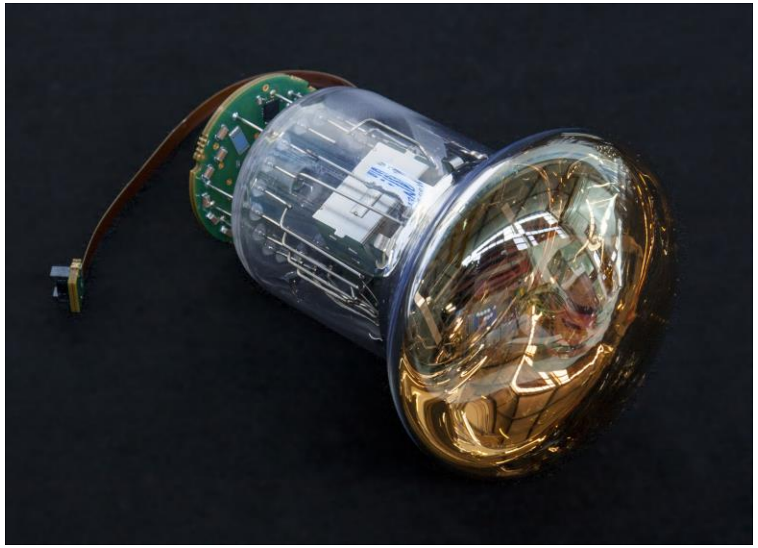
LVDS signal high as long as signal of threshold (adjustable)

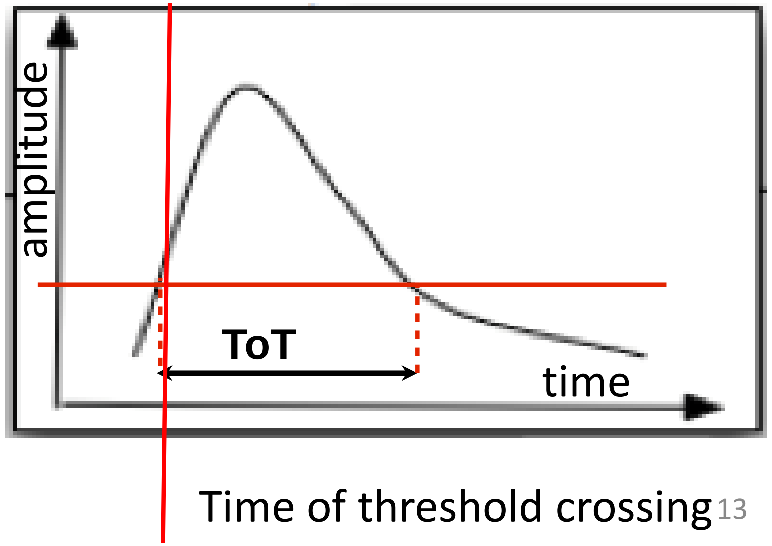
FPGA registers

- For each PMT channel
- Time of threshold crossing - “fine time”
    - nanoseconds
    - Coarse time already in header
- Duration of time over threshold

CLB Optical Format Structure

Size (bit)	Description
448	DAQ Common Header
8	TDC channel
32	Time Stamp
8	Pulse Width
8	TDC channel
32	Time Stamp
8	Pulse Width
...	...
8	TDC channel
32	Time Stamp
8	Pulse Width





Time of threshold crossing

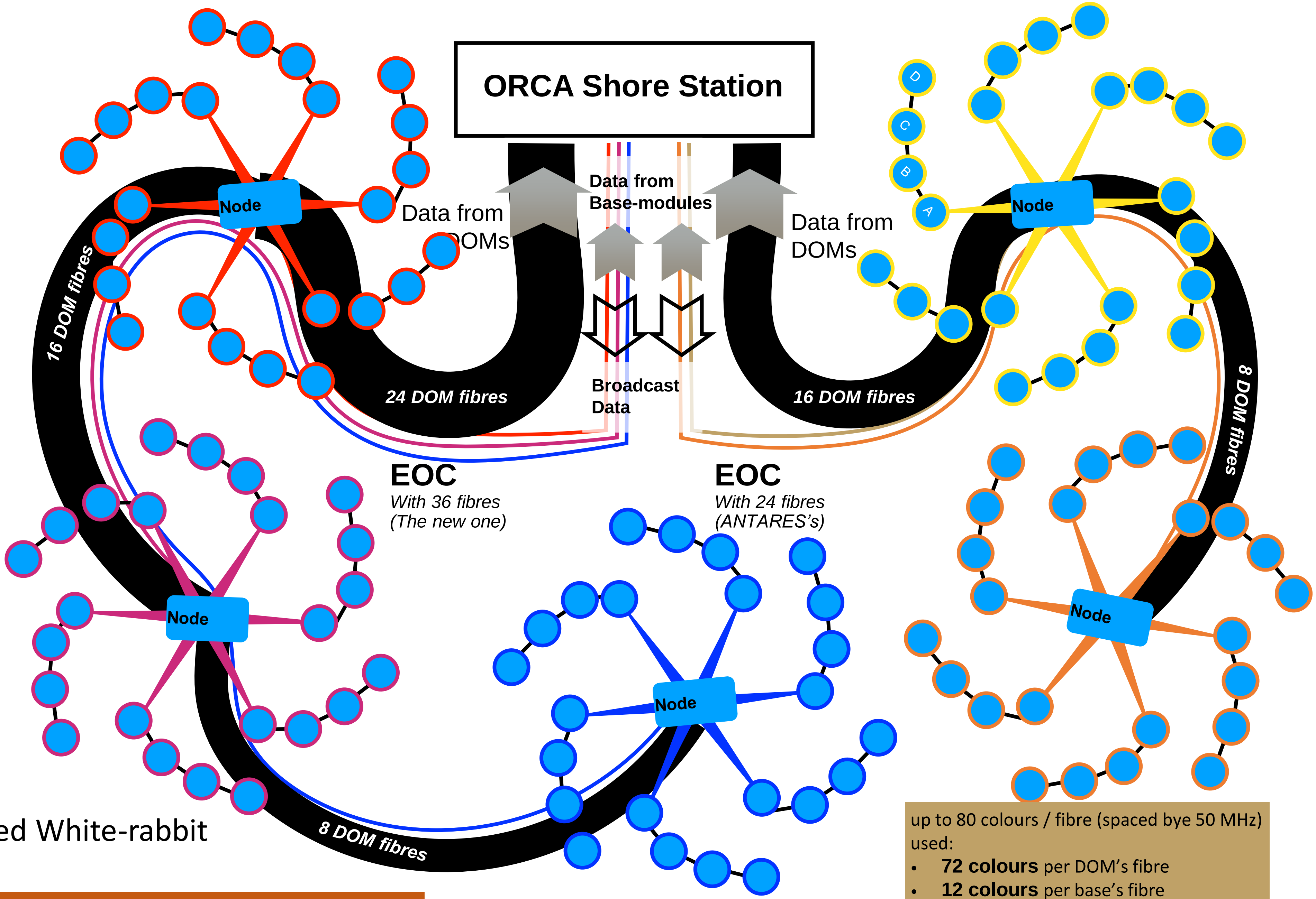
Note:
Low scattering (high information!) relaxes need for pulse shape!

KM3Net :
Asymmetric network !

Broadcast :

Single channel to DOMs
(single wavelength)

Individual channels to shore
(wavelength multiplexing!)



Datapath to shore does not need White-rabbit

up to 80 colours / fibre (spaced bye 50 MHz) used:

- **72 colours** per DOM's fibre
- **12 colours** per base's fibre

See talk of T. Chiarusi on details of the onshore infrastructure

Some words on acoustic data

Continuous data stream, but sent in timeslices

Integration time > timeslice time

Processed per DOM

193.5 kHz sampling
12 bit
1 channel

Adjustable

20% of total data stream

(positioning)

Data Queue #1 → Acoustic Data Filter #1

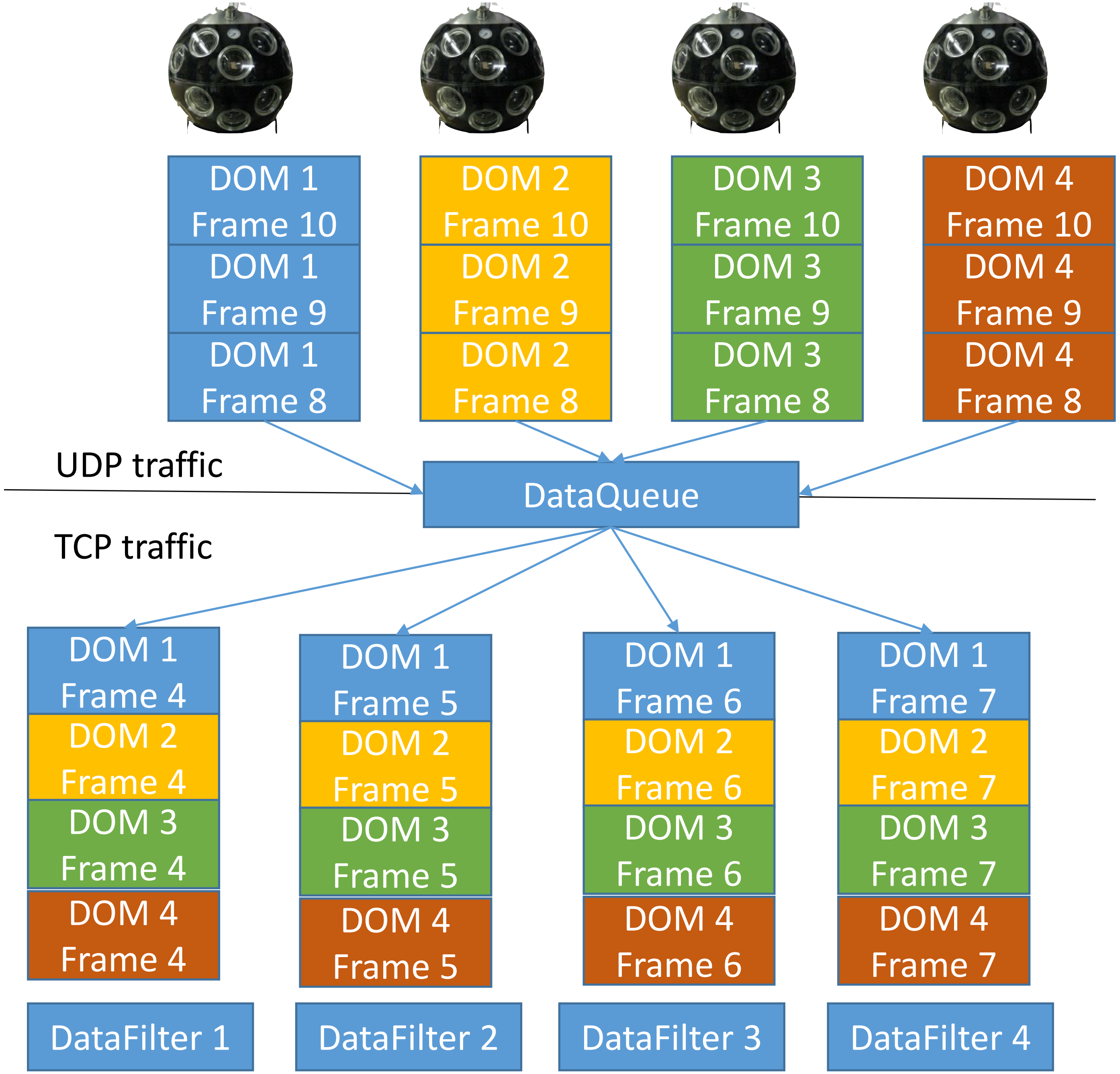
Data Queue #2 → Acoustic Data Filter #2

.
.
.

Data Queue #n → Acoustic Data Filter #n

For acoustic neutrino detection another approach is required !!!

(Optical) Datafilter



DataQueue
Assembles frames from UDP packets
Distributes all frames of a timeslice to a datafilter in a round-robin way.

More processing power required ??

Add more datafilters!!!

Datafilter sees all data(hits) in a timeslice

Flexibility of all-data-to-shore design

Design allows for multiple triggers to run in parallel and on-the-fly adjustment
(In operation for Antares, most in development for KM3NeT)

Event types:
Track
Shower
(Exotic ? (Monopole trigger))

Source Tracking
1D trigger with direction towards (lowers energy threshold)
- Sun, Galactic Center, Earth for Dark Matter
- Other potential sources

Foreseen (available in Antares)

Multi-Messenger Astronomy: Generate and receive alerts
- Supernovae

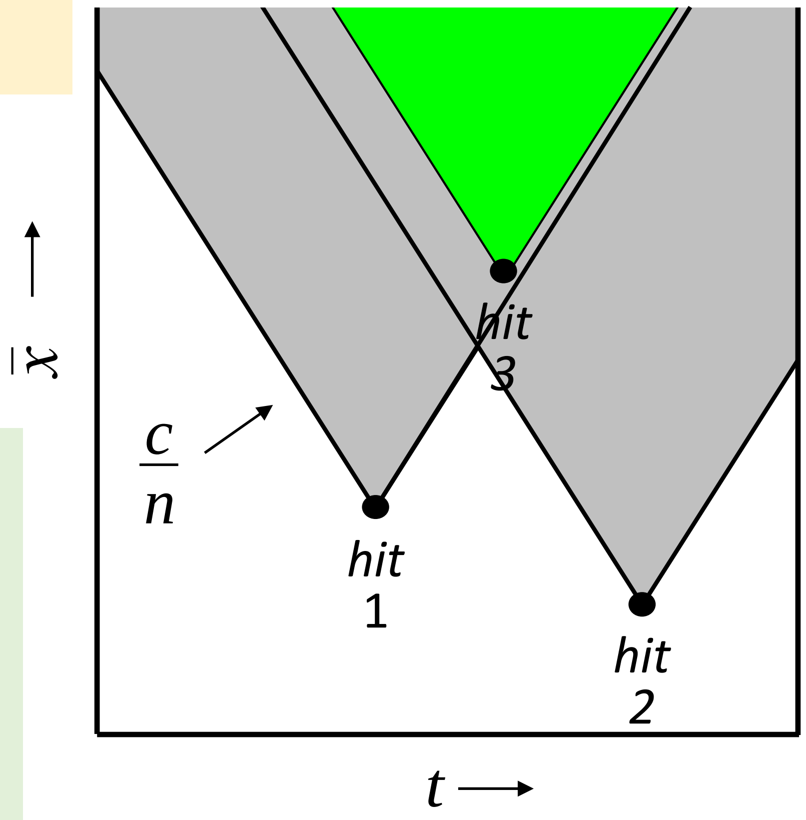
“Data-dump”
Dump all raw data memory buffers to disk
Allows to *look back* in time, depending on buffer (memory) size
e.g. GRB alerts

Implementation at DataFilter level

Trigger principles : causality & clustering

Basic condition : hits from a source must be causally connected

$$\frac{c}{n}|dt| \leq |d\overline{x}|$$



hit
≡
detected photon at position $\overline{x}$ and time t

Clustering:
Find a cluster of at least N (e.g. 5) hits that are all pair-wise causally Connected
('Clique-problem')

Non-transitive problem :
Hit (1,3) and (2,3) are causally related, but not hit (1,2)

Fine tuning example : Directional/1D causality

Assuming a direction, the causality criterion can be made more stringent

R can be constrained, as light attenuates!

R smaller than 3D distance

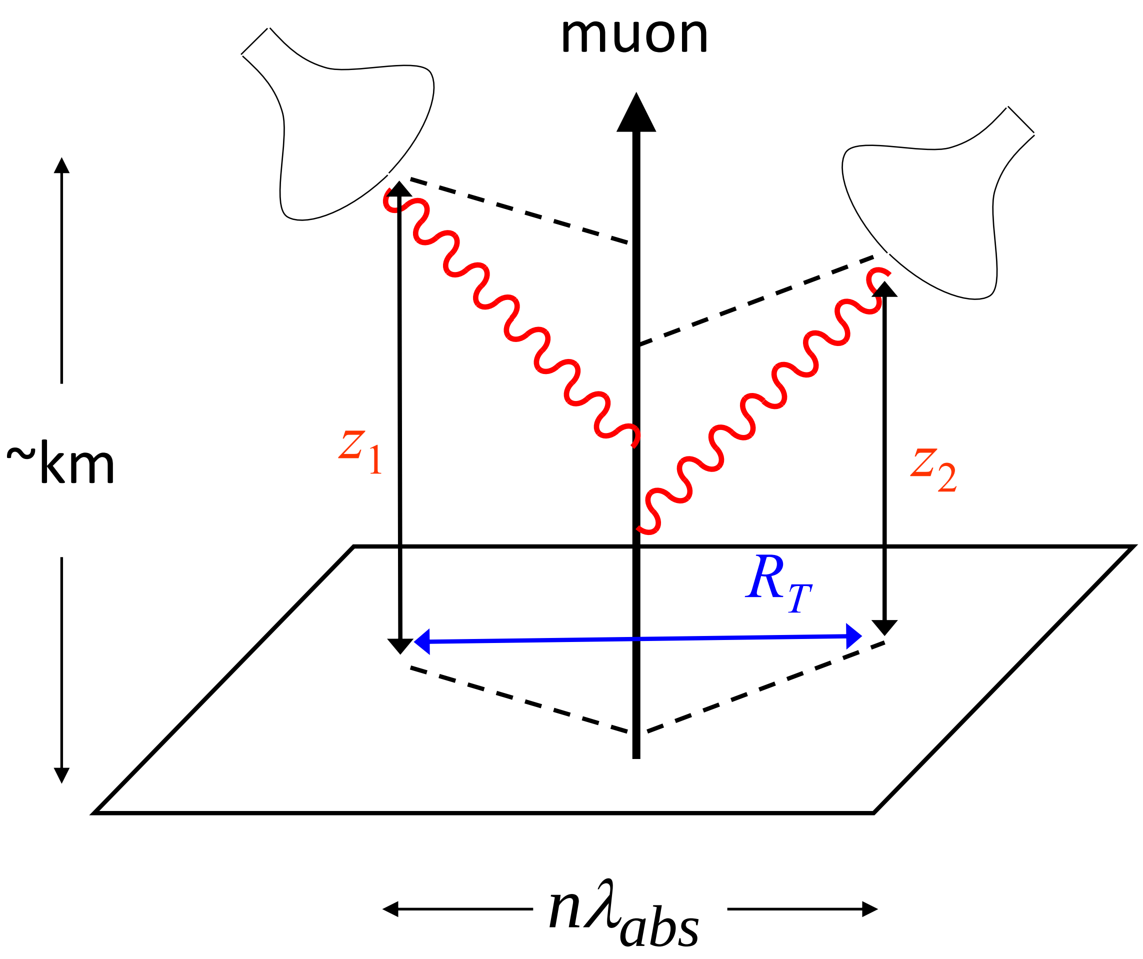
Stronger constraint on dT

$$\propto \frac{R}{D}$$

Less random noise sources (PMTs)

$$\propto \left(\frac{R}{D}\right)^2$$

Less CPU required, less chance of noise !



$$(z_1 - z_2) - R_T \tan\theta_c \le c(t_1 - t_2) \le (z_1 - z_2) + R_T \tan\theta_c$$

L0 vs L1

L0 hit : Any recorded hit ~7 kHz/**PMT**

L1 hit : 2 or more hits coincident (~20 ns) on DOM ~700 Hz/**DOM**

Sorting and cluster finding using L0 is computationally prohibitive

Using L1 hits increases energy threshold (e.g. 5 L1 hits mean >= 10 photons)

Solution (compromise?) :

Start with a L1 hit and use nearby L0 hits only

In ORCA, shower size < detector dimensions!

Optical Datafilter

- Assemble timeslices from frames received from DataQueues
  - Requires buffering and logic to deal with incoming stream
- Calibrate
  - Translate DOM+PMT IDs to spatial coordinates
- Level 1
  - Build L1
    - Find >=2 coincidental hits in DOM
- Level 2
  - Build L2
    - Restrict coincidences to nearby (angular) PMTs
- Level 3
  - Muon trigger – 1D scan over N directions
  - Shower trigger – 3D causality (tuned)
  - …..
  - …..
- Merge overlapping events
- Send output to DataWriter

Requires sorting, but only at DOM level

Exploit Multi-PMT Design

Multiple triggers in parallel on same data!!

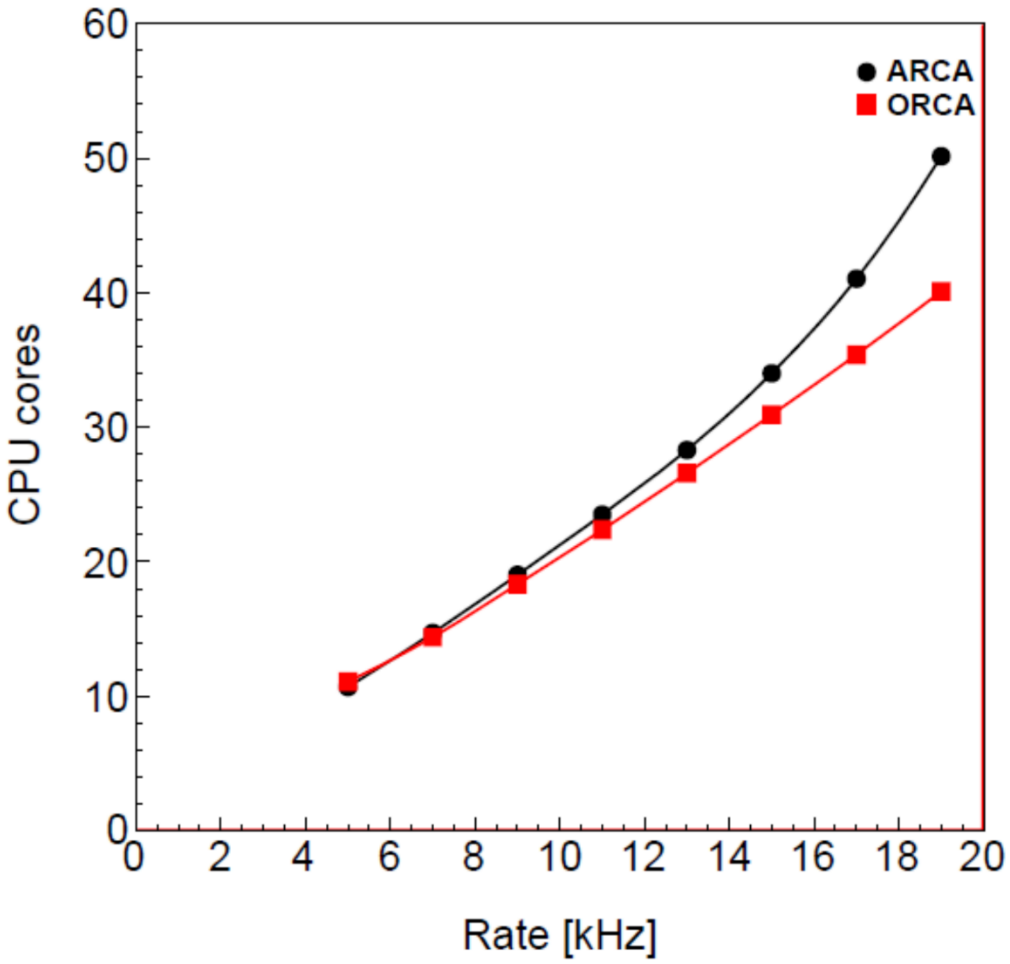
Required CPU power and performance

CPU time dominated
by sorting of hits
50 – 70 % depending on
algorithm, rates, etc.

Trigger settings optimized
by maximizing trigger efficiency
within bounds of storage/offline
processing

ORCA:
90% efficiency above 4 GeV

ARCA:
Efficiency depends on channel
(and definition)
Above 10 TeV all channels > 80 %
(>=5 hits)



ARCA
~100 Hz atm. muon events
~0 Hz pure noise

ORCA
~ 40 Hz atm. muon events
~ 20 Hz pure noise

Intel(R) Core(TM) i5-4570 CPU @ 3.20GHz

Summary

- KM3NeT has designed* a Data Acquisition system that can deal with the large data volumes and unfavorable signal to noise ratio from the medium to maximize physics potential

*: and tested – ARCA and ORCA lines operated with this system

ARCA & ORCA

High Energy Neutrino Astronomy:

ARCA: **A**stroparticle **R**esearch with **C**osmics in the **A**byss

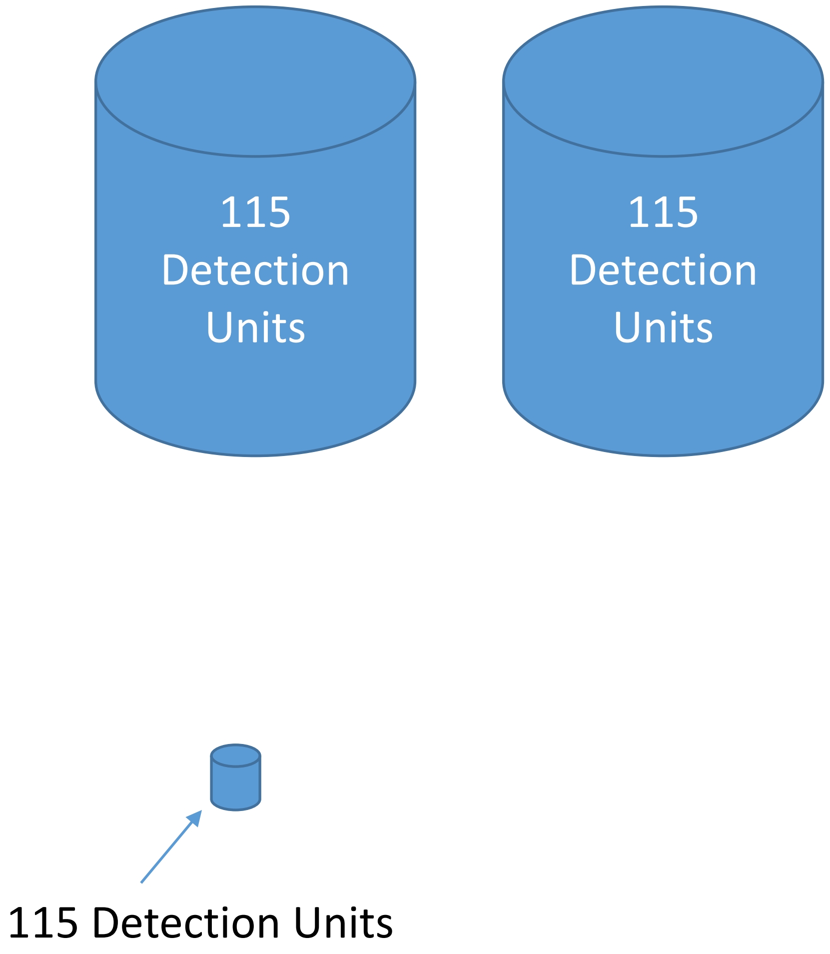
Large Detector: ~1 km^3 total
Sparsely instrumented: 36 m vertical spacing, 95 m horizontal
TeV-PeV Energies
Astrophysical Neutrinos

Same technology & layout, dimensions scaled ↕

Neutrino Physics:

ORCA: **O**scillations **R**esearch with **C**osmics in the **A**byss

´Smaller´ detector: 5.7 Mton
More densely instrumented: 9m vertical spacing, 20m horizontal
GeV energies
Atmospheric neutrinos



Multi-PMT Concept

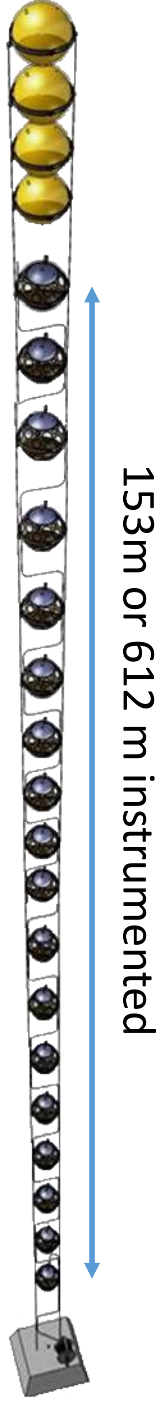
Segmented photocathode : 31 3” PMTs in a 17” sphere
(equivalent to 3 10” PMTs)

+ All front-end and digitization electronics, slow control sensors and supporting mechanics

KM3NeT
Digital **O**ptical **M**odule
(DOM)

Advantages

- Large photocathode area
- Directional Sensitivity
- Photon Counting
  (1 vs 2 vs … photons, background suppression)
- Less overhead
- Cost effective
- Minimal glass penetrations



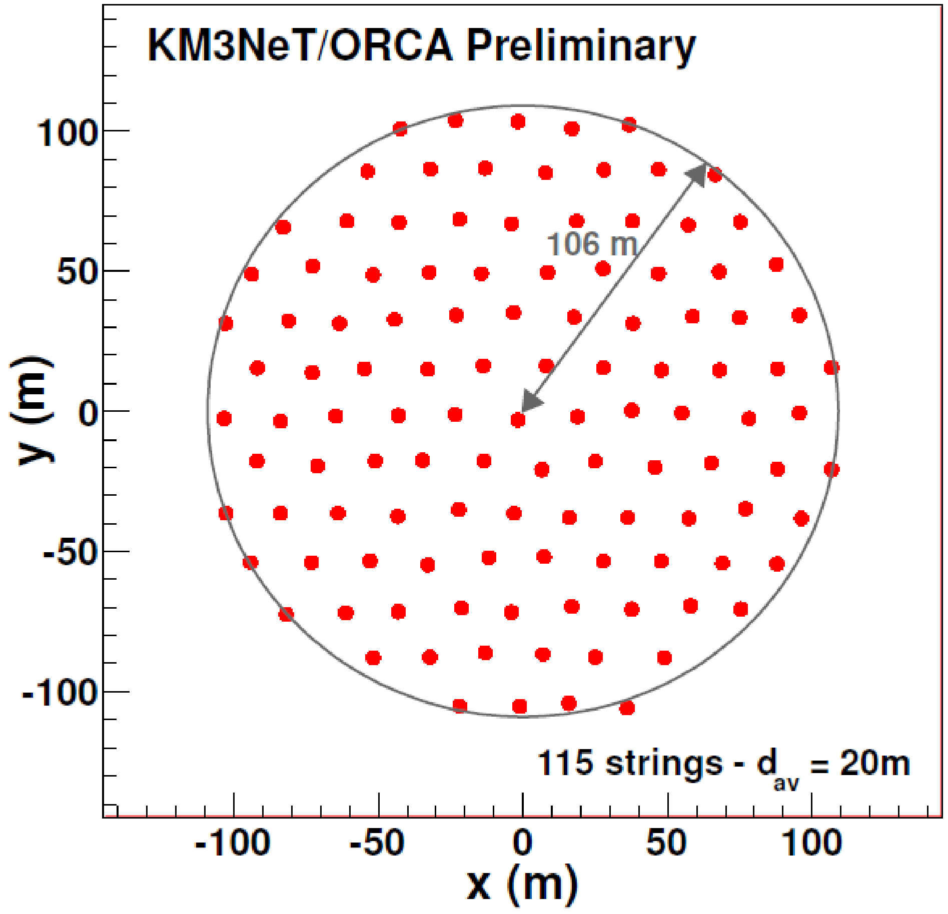
KM3NeT Design

Detection Units:

18 optical modules per vertical string
~36m or 9m between optical modules
Lowest optical module ~100m or 40m above seabed
Two Dyneema® ropes
Backbone: 2 copper conductors; 18 fibres (+spares)
Break out of cable at each optical module
Base module with DWDM at anchor
Cable for connection to seafloor network
Cost saving design

Infrastructure:

Building blocks of 115 strings
Sea-bed infrastructure
(facility for long term high-bandwidth connection for sea-science, biology etc.)
Optical data transmission
All-data-to-shore
Filtering/Trigger on-shore in computer farm



(´ORCA´ layout)

DAQ State Machine

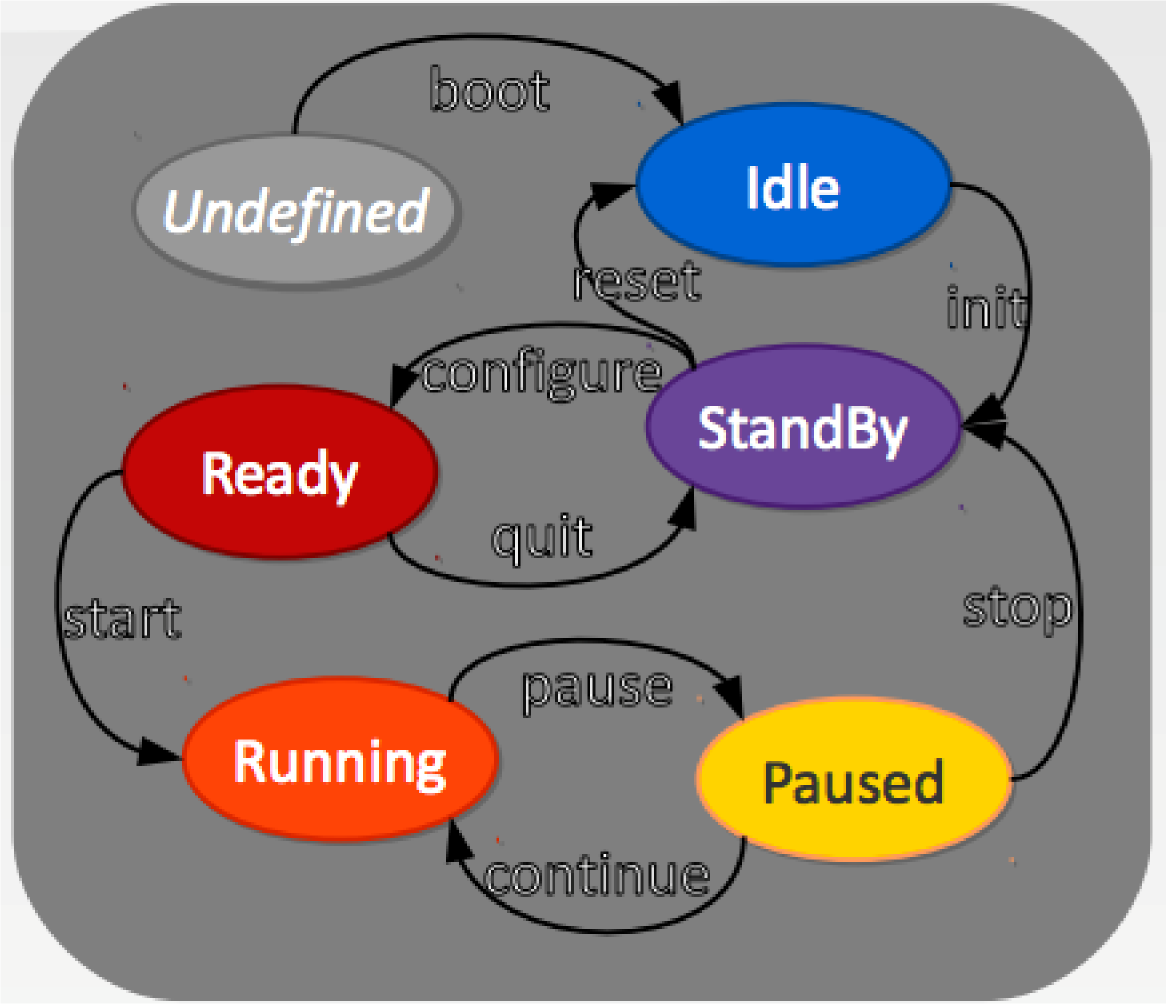
State machine implemented in all DAQ elements, off and onshore.
e.g. CLBs, DataFilters, …

Transitions distributed and monitored from Control Unit

Actions and communications at transitions are defined

User interface simple :
ON,OFF, RUN

See talk of C. Bozza for details on detector control



Random Noise

$$R(m) \cong \binom{N}{m} \times f \times (f \Delta T)^{m-1}$$