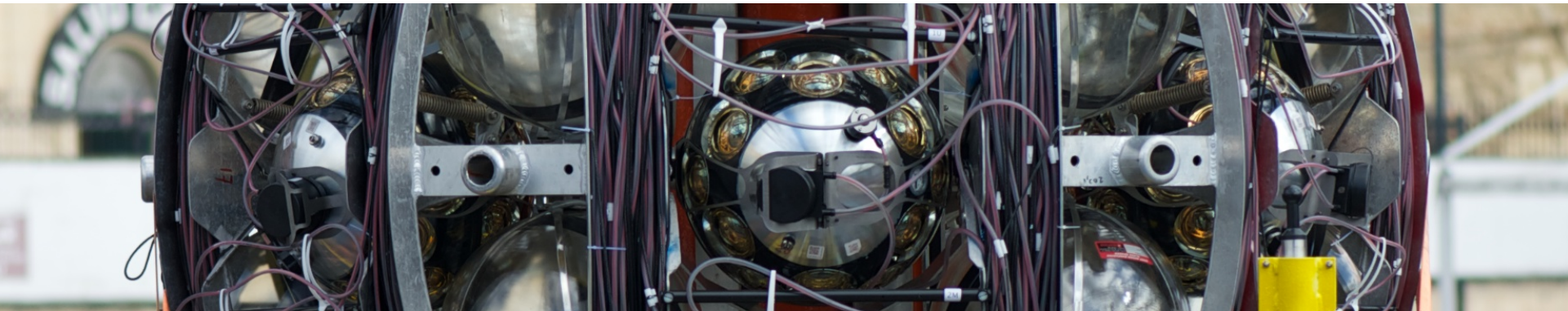
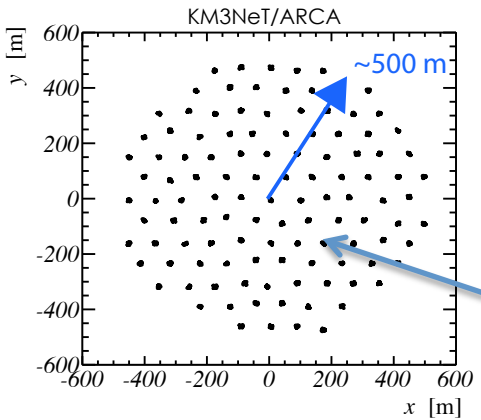
# KM3NeT Calibration

Karel Melis

Nikhef Jamboree (2017) – Amsterdam

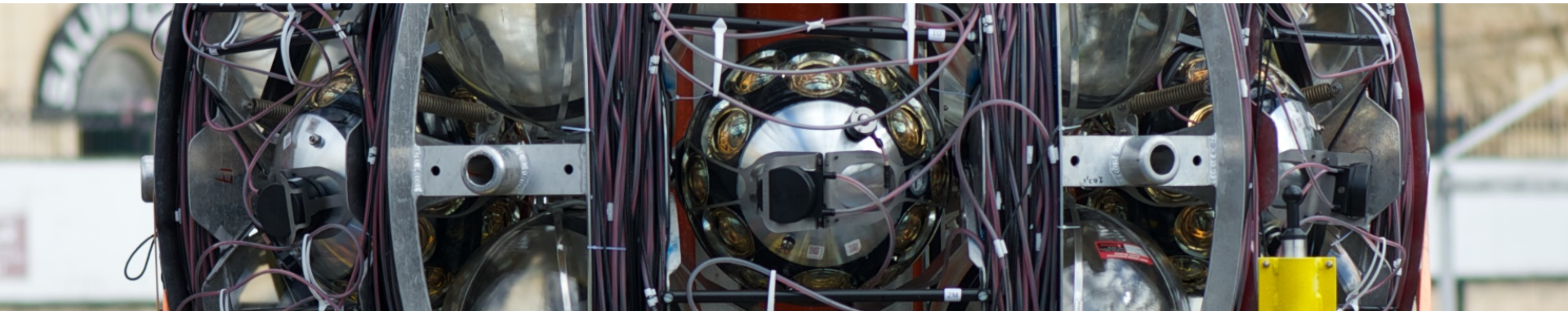


# The KM3NeT Detectors




- Digital Optical Module (DOM)
  - 31 x 3-inch PMTs
  - DAQ + Calibration devices
  - Hit times and time-over-threshold send to shore
- Detection Unit (DU)
  - 18 DOMs
  - ARCA: DOMs ~36m apart
  - ORCA: DOMs ~9m apart
- Building Block
  - 115 DUs
  - ARCA: DUs ~95m apart
  - ORCA: DUs ~ 23m apart
- Currently: 2 ARCA DUs, 1 ORCA DU

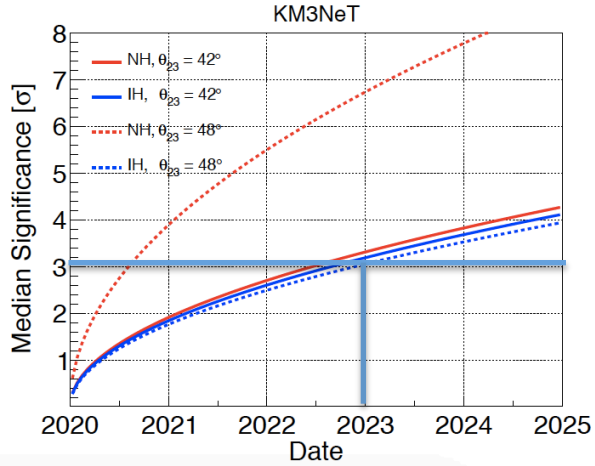
# Intro-Motivation



# Science Objectives

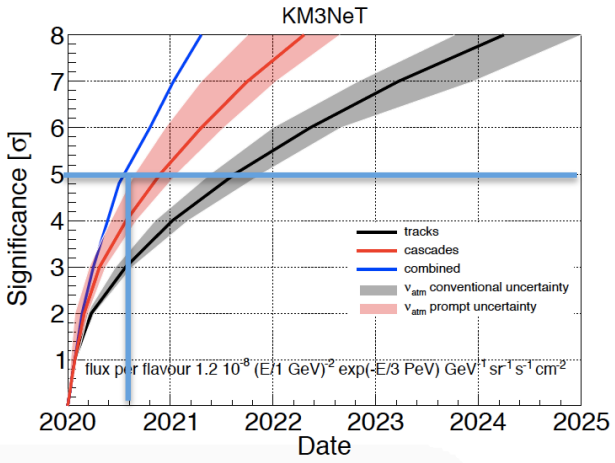
## KM3NeT/ORCA

- Neutrino mass hierarchy
- Low-energy atmospheric neutrinos
- Median sensitivity: **3 sigma in 3 years**




## KM3NeT/ARCA

- Cosmic high-energy neutrino sources
- Diffuse flux
- Median sensitivity: **5 sigma in 0.5 year**

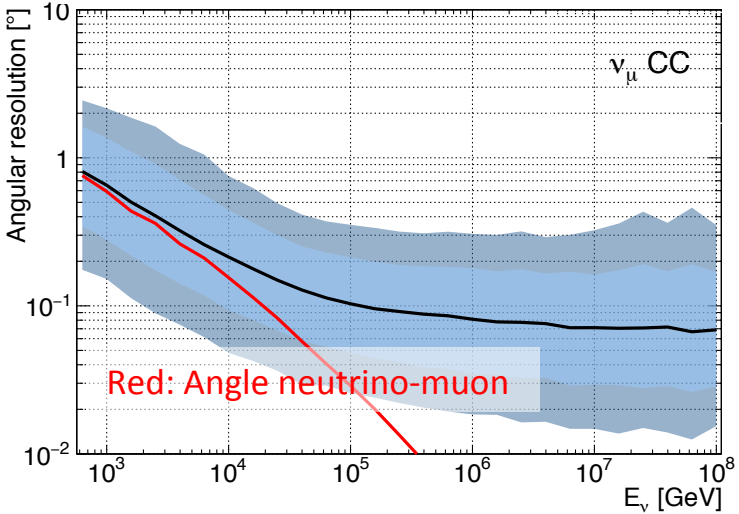



Energy and direction resolution are key ingredients

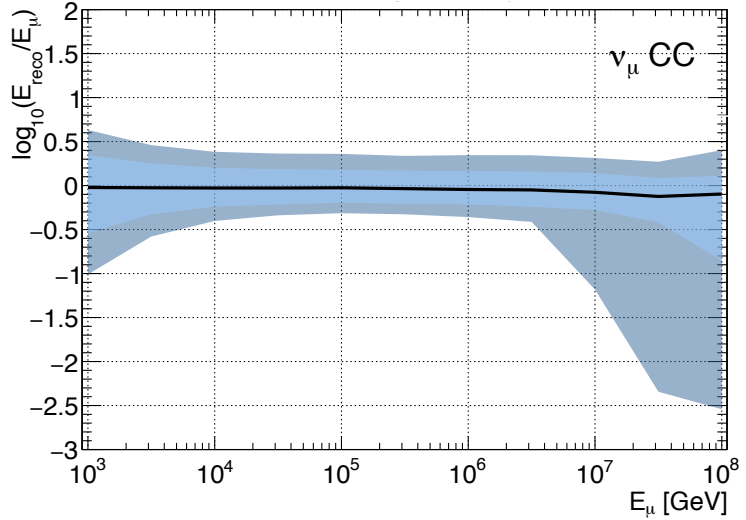
# Track Reconstruction

Hit times and PMT hit/not hit information:

**Direction resolution: < 0.1 degree**




**Energy resolution: σ < 0.3 in $\log_{10}(E_{reco}/E_{mu})$**

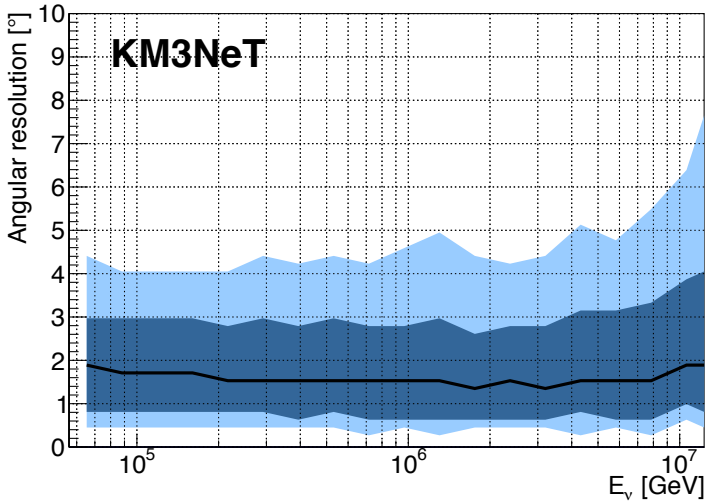



Sub-ns hit time accuracy on all PMTs leading factor

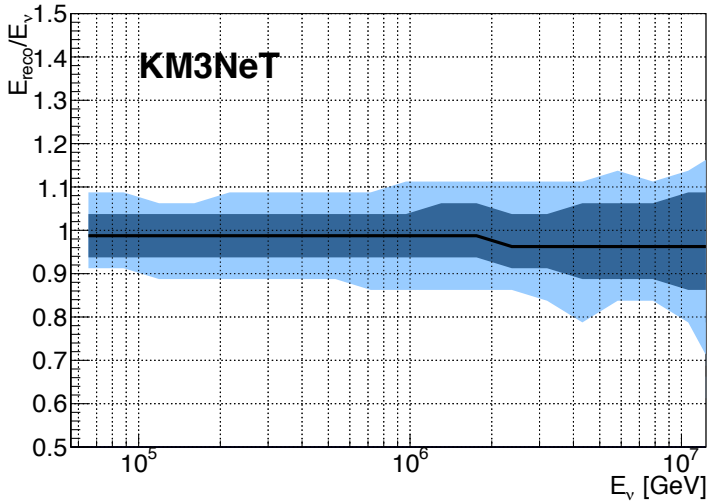
# Shower Reconstruction

Spatial distribution of PMTs hit/not hit:

**Direction resolution: ~1.5 degree**

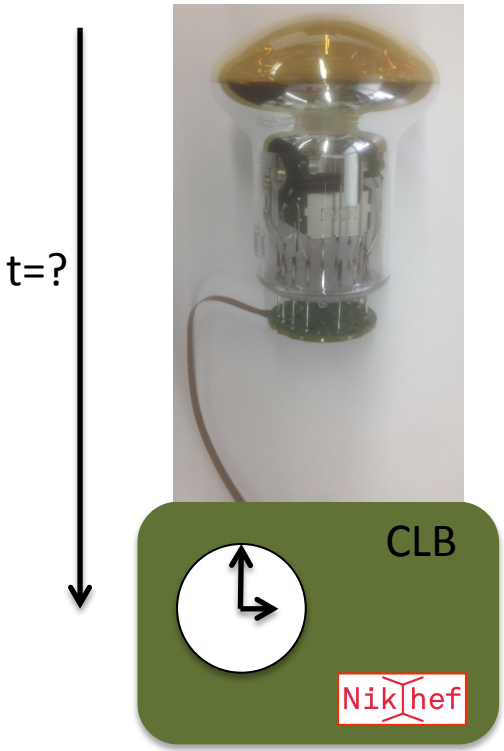


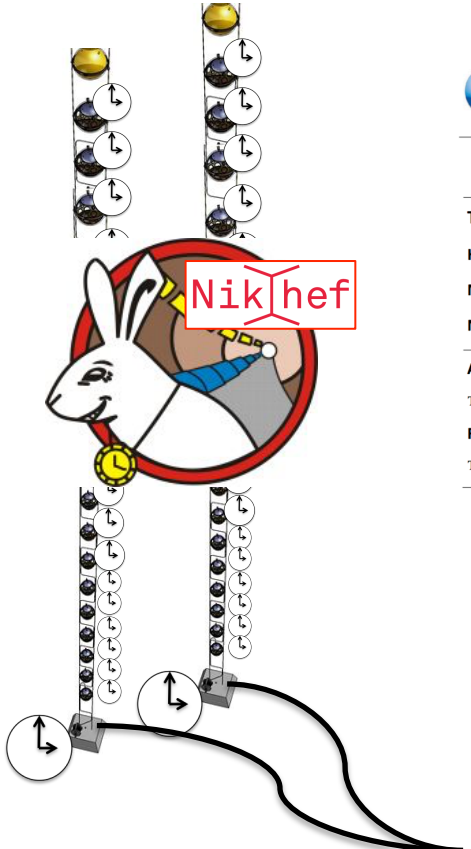

**Energy resolution: ~5%**




PMT detection efficiencies should be determined

# Time Calibration






**Technical Design Report KM3NeT Time Calibration**

**KM3NeT_CALIB_2015_010-TDR_TimeCalibration**

**Mieke Bouwhuis, on behalf of the time calibration group**

**NIKHEF**

Nikhef

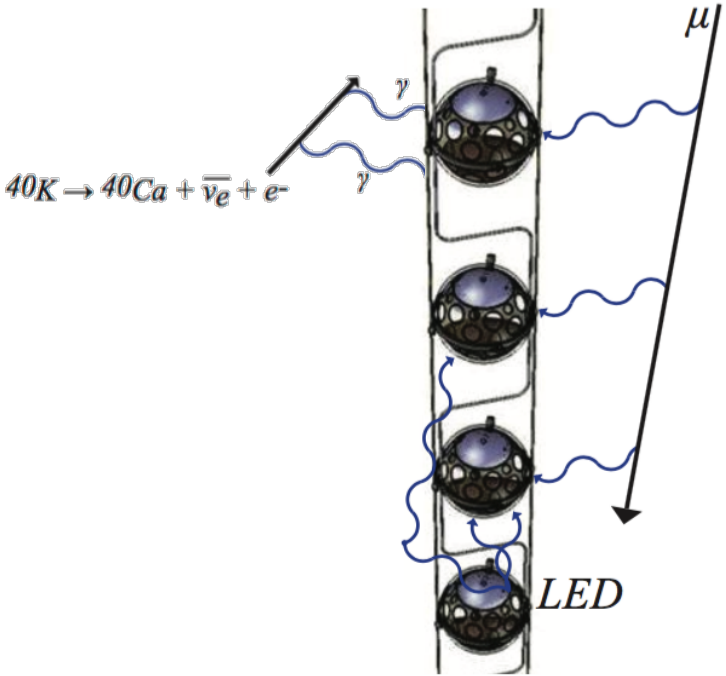
**Abstract**

This document describes the time synchronization and time calibration of the KM3NeT detector.

**Recipients**

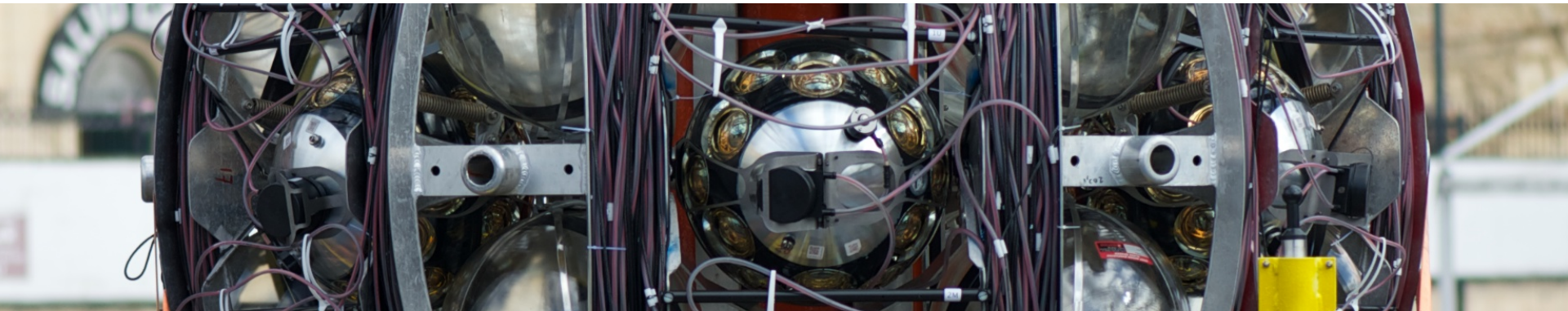
The KM3NeT Collaboration

# Calibration Sources

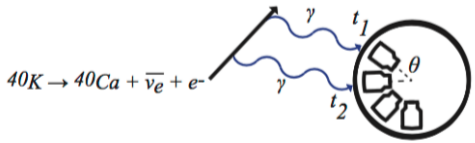


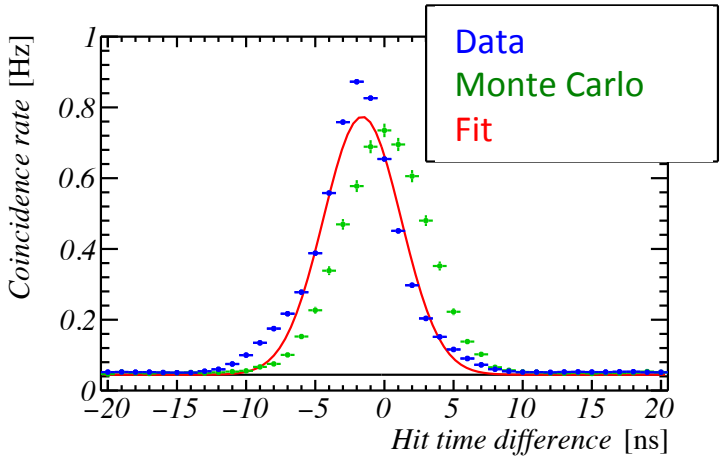

- Laboratory calibration
  - Snapshot in different environment
  - Limited accuracy
- In-situ calibration
  - Potassium-40 decays in sea salt
  - Atmospheric muons
  - LED beacons
- Continuous high-statistics monitoring
- Background sources (for free)

# Inter-PMT Time Calibration



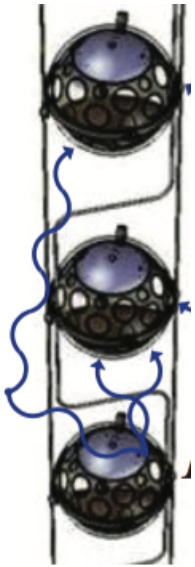
# $^{40}$K Calibration

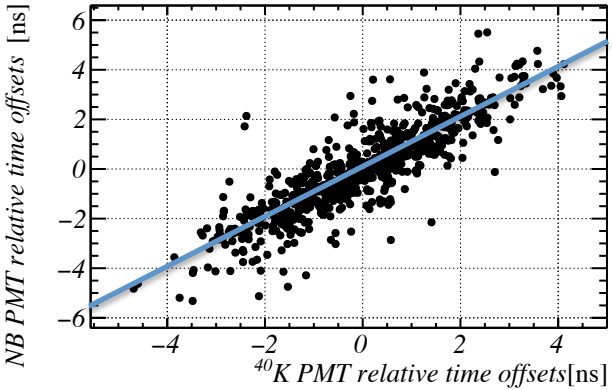


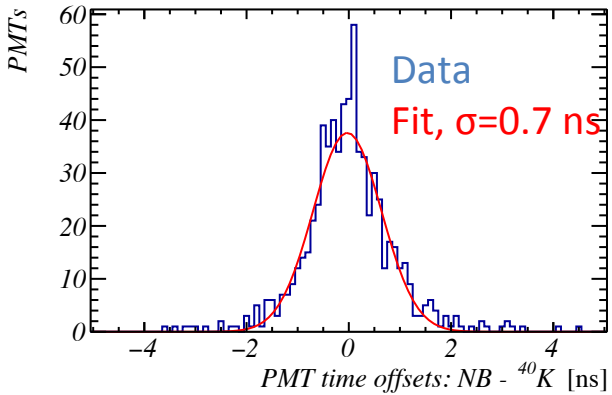




- $^{40}$K coincident light on PMT pairs in DOM
  - 456 coincidence distributions
  - Should all peak at zero
- Simultaneous fit of all pairs
  - Mean -> Time offsets
  - Width -> Transit time spreads
  - Integral -> Efficiencies

# Check with LED Beacons





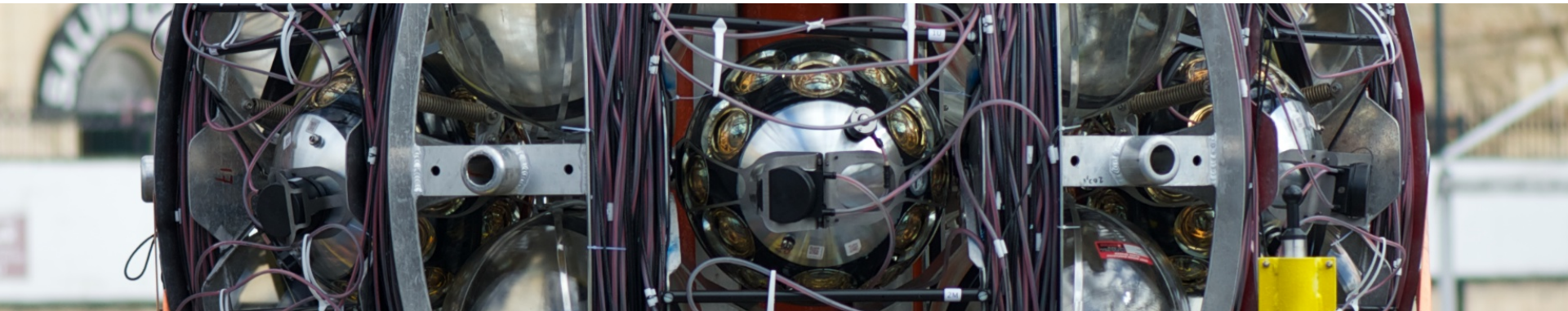




- 40K Calibration cross-checked with LED beacon data

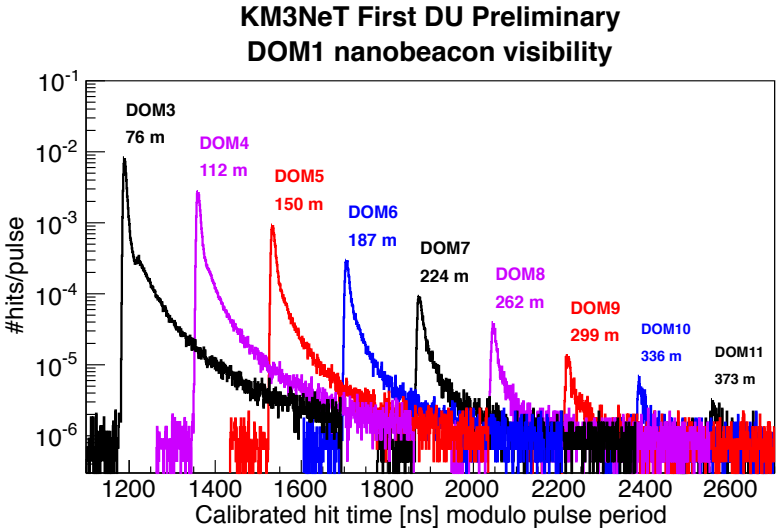
Very good agreement between methods (σ = 0.7 ns)

- Scatter (0.7 ns) expected from beacon method inaccuracies

# Inter-DOM Time Calibration



# LED Beacons



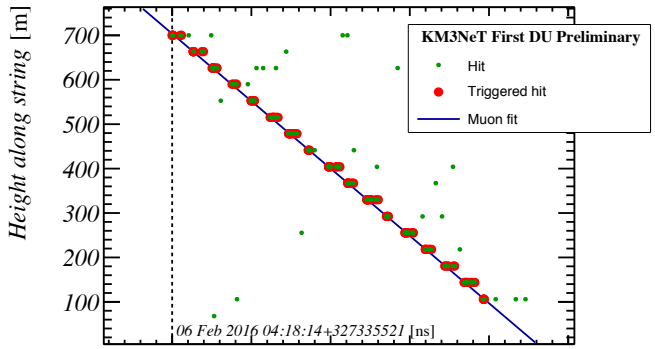

- Light can be seen up to 100's of meters
- Very sharp peak -> accurate time calib.

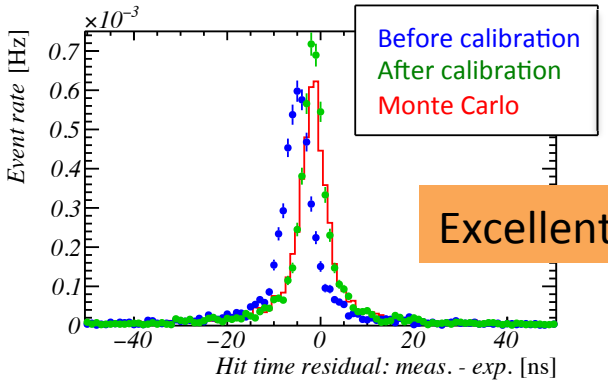
- Cross-check of laboratory calibration
- Few-nanosecond accuracy

Sub-ns calibration with atm. muons

*Work + plots by M. Jongen

# Hit Time Residuals



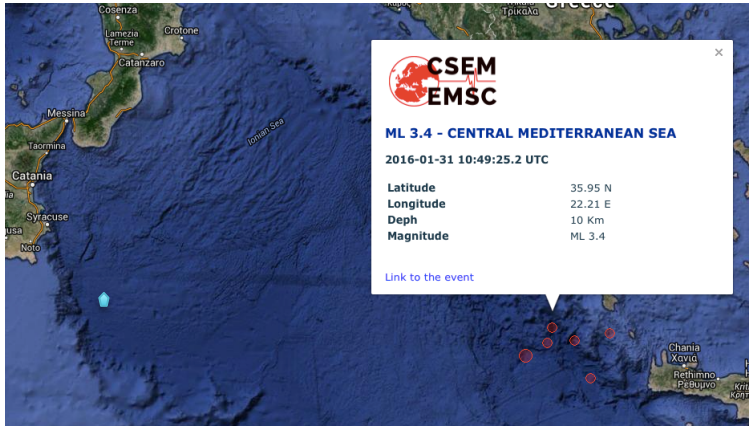

- Time between hit time and expectation of reconstructed track
  - Hit DOM excluded in fit
- Shift distribution w.r.t. MC
- Reconstruction changes -> repeat

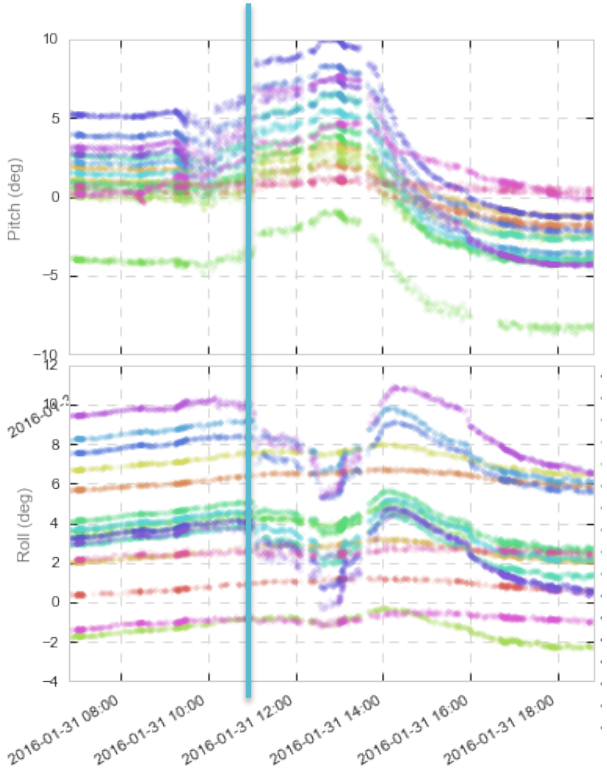
Excellent data-MC comparison

- Depends on DOM-positions

# Undersea Earthquake Observatory

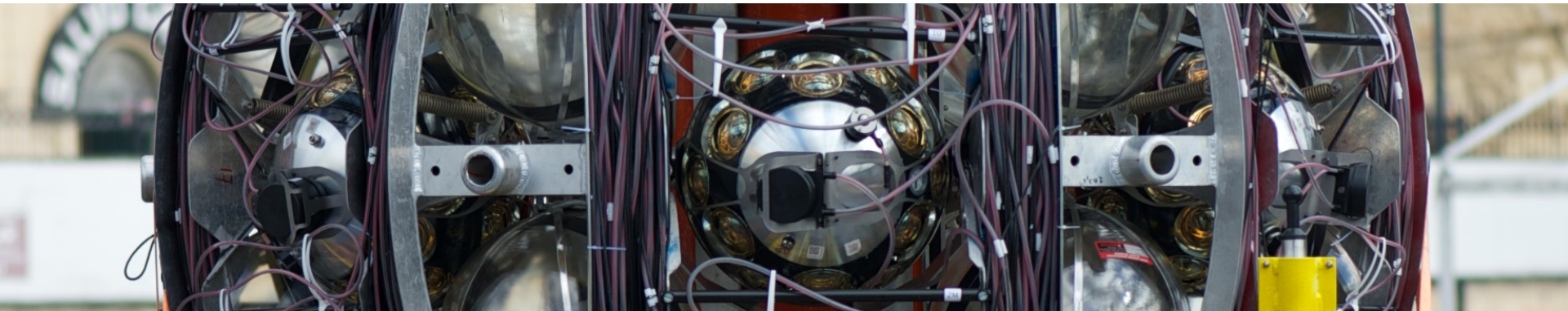
- Acoustic network + compasses
- Monitor DOM positions + orientations



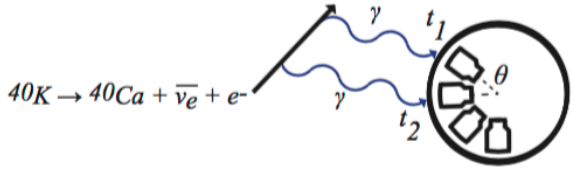



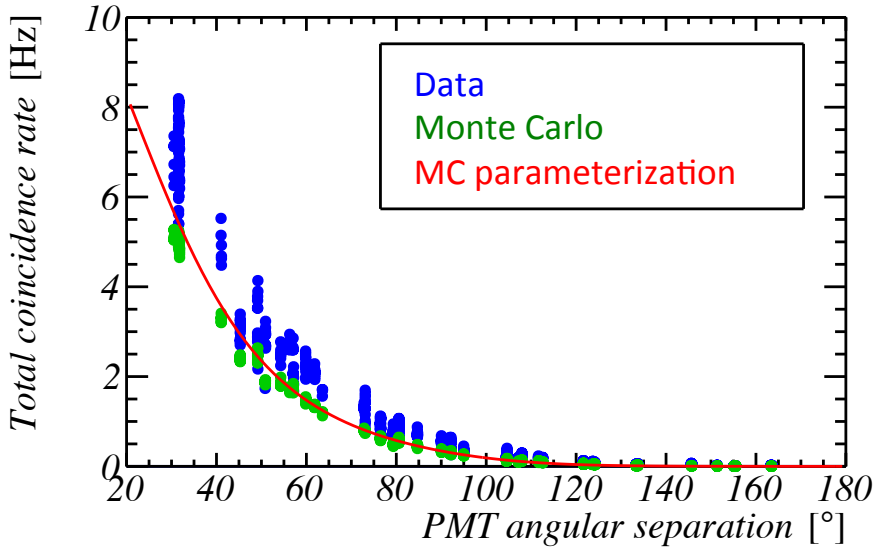

*Work + plots by D. van Eijk

# PMT Efficiencies



# PMT Efficiency Calibration

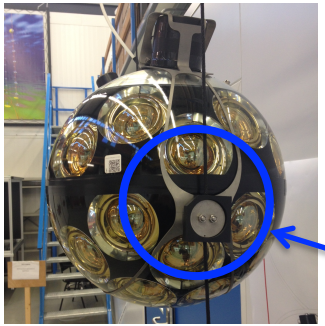


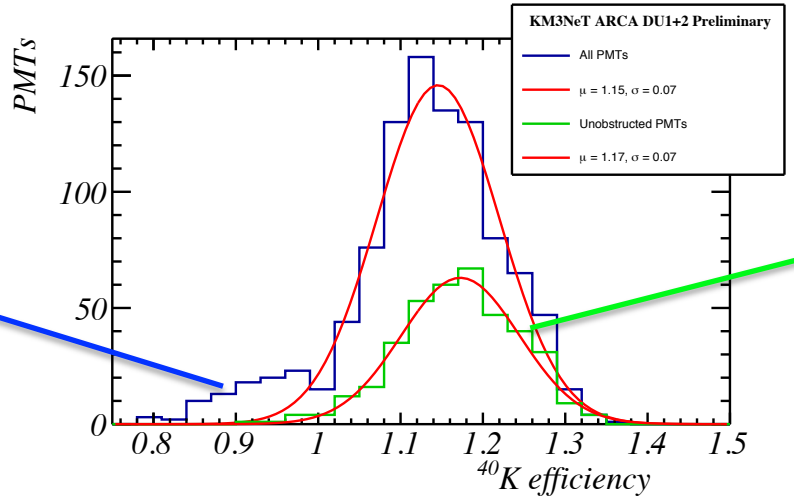




- Compare observed coincidence rates with expected $^{40}K$ rate (MC)
- Simultaneously fitted with PMT time offset and TTS (slide 10)

PMTs see more light as exp. from MC

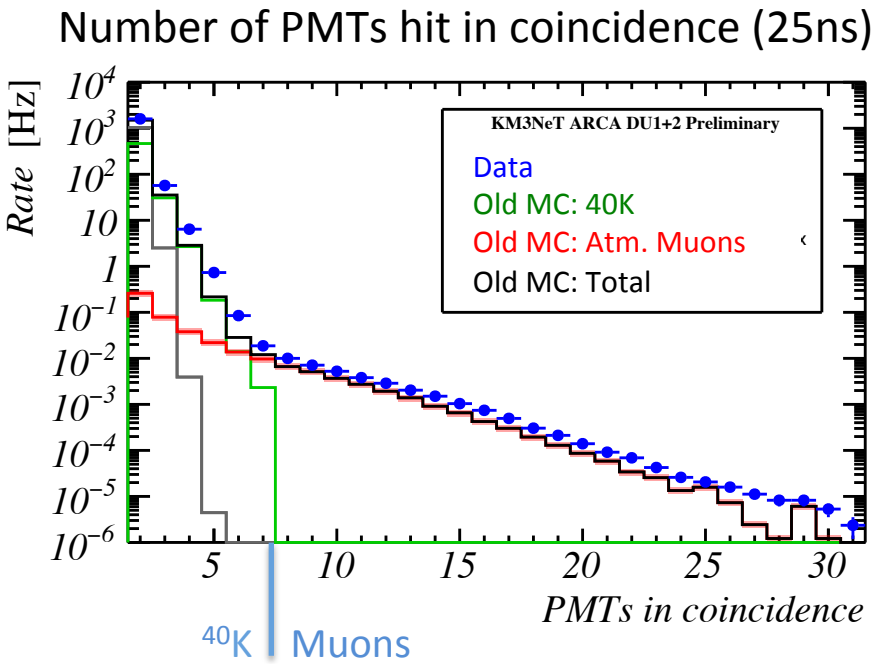
# PMT Efficiency Systematics





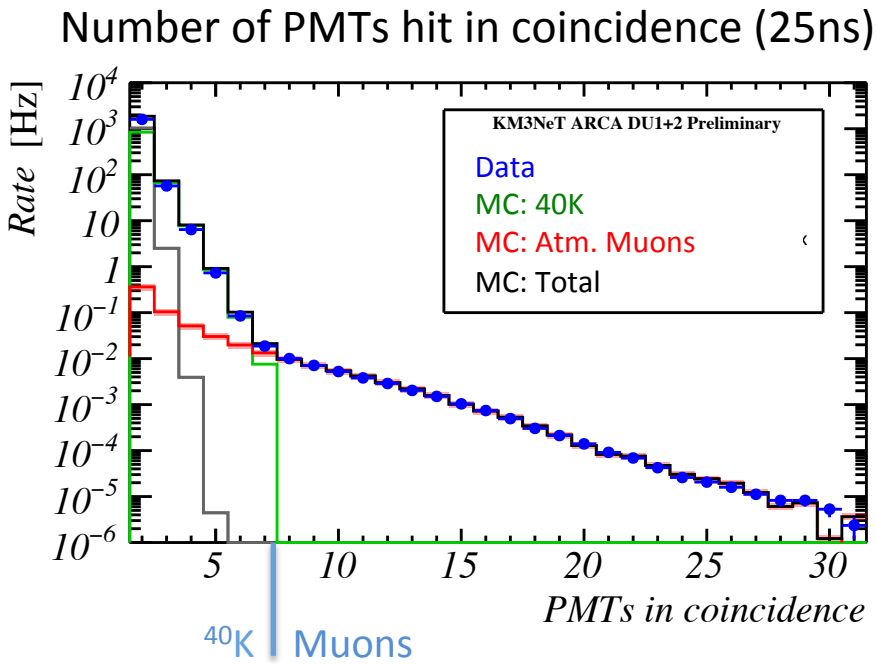

- Calibration precise enough to see support shadowing
- PMT efficiency spread: ~6%

# Old Monte Carlo




- Fitted PMT efficiencies are used in run-by-run atm. muon Monte Carlo
- Excellent data-MC-MC agreement over 9 (!) orders of magnitude

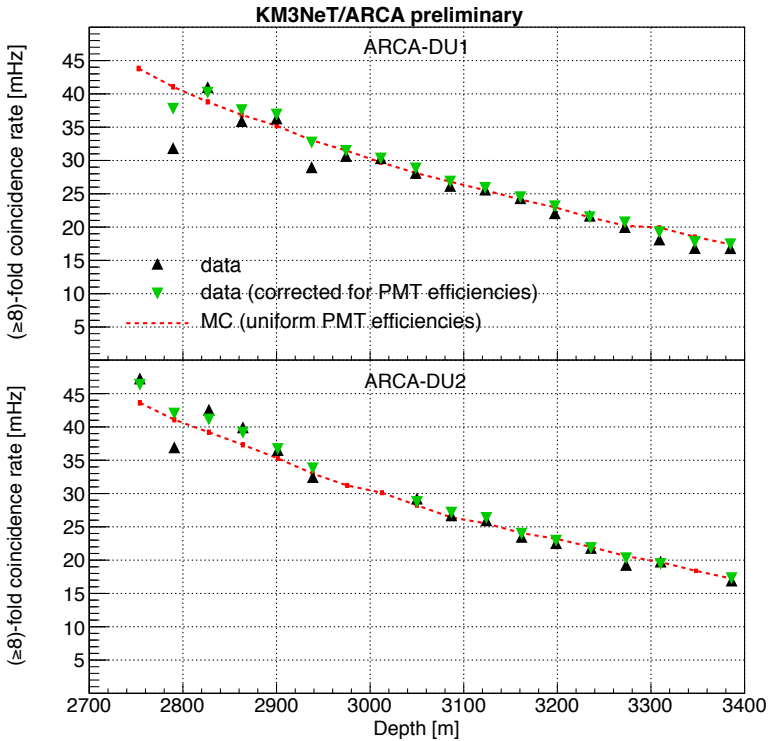
# $^{40}$K MC – Muon MC - Data




- Fitted PMT efficiencies are used in run-by-run atm. muon Monte Carlo

Excellent data-MC-MC agreement over 9 (!) orders of magnitude

# Muon Depth Dependence

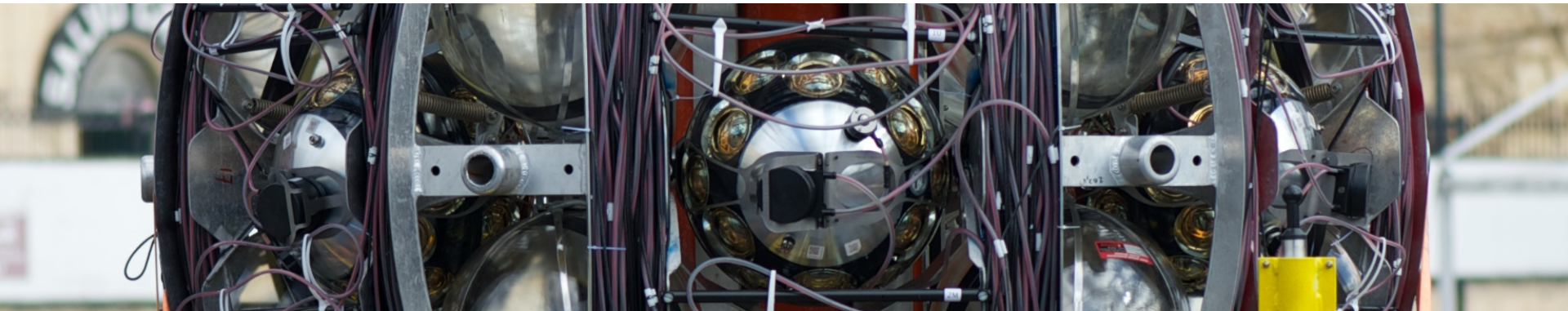



Work + plots by M. Jongen

- Multiplicity ≥8: Atmospheric muons
- Atm. muon rate decreases with depth

- Fluctuations due to different PMT efficiencies
- Rate is well-understood with PMT efficiencies from $^{40}$K fit

# Conclusions



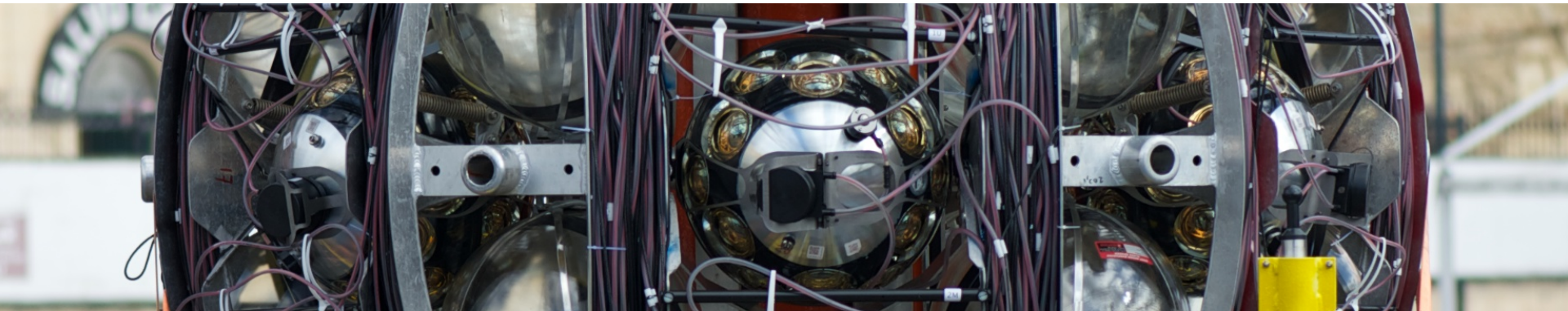
# Conclusions

- Precise, constant calibration + monitoring of PMT properties:
  - **Sub-ns** time calibration accuracy
  - PMT efficiencies fitted to **percent-level** (est.)
- Excellent data - 40K MC – atm. muon MC
  - Run-by-run simulations with fitted PMT efficiencies
- Key ingredients for neutrino source searches provided
  - (And that's exactly what I'm going to do during the last year of my PhD)

# Further Reading

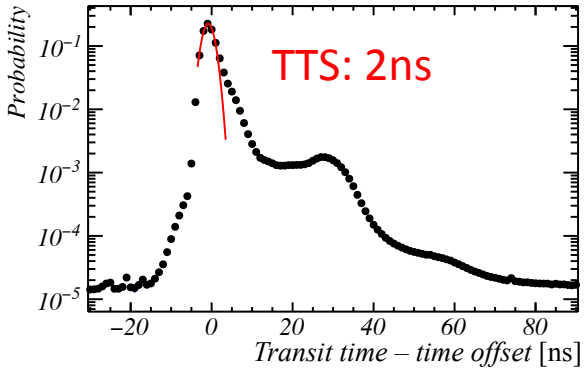
- KM3NeT Letter of Intent, J. Phys. G **43** (2016)
- In-Situ Calibration of KM3NeT, *K. Melis,* PoS(ICRC2017)1059
- All-flavour neutrino reconstruction in KM3NeT*, K. Melis, A. Heijboer & M. De Jong,* PoS(ICRC2017)950
- The KM3NeT acoustic positioning system, *S. Viola & R. Coniglione*, PoS(ICRC2017)1031
- Depth Dependence of the Atmospheric Muon Flux in KM3NeT/ARCA (in preparation)
- Characterizing the KM3NeT 3-inch Hamamatsu Photomultiplier Tube response, *A. Schermer*, master thesis

# Back-Up

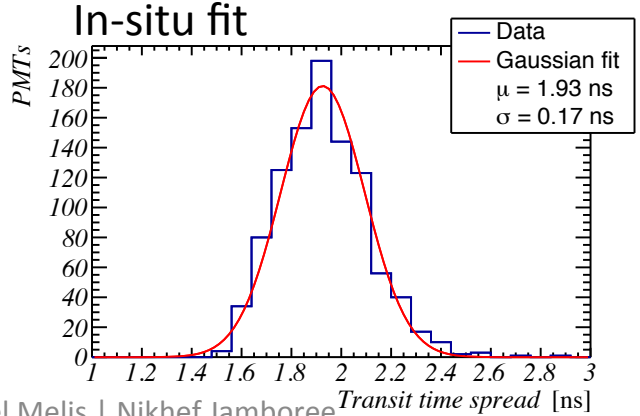


# Transit Time Spread (TTS)

Lab Measurement

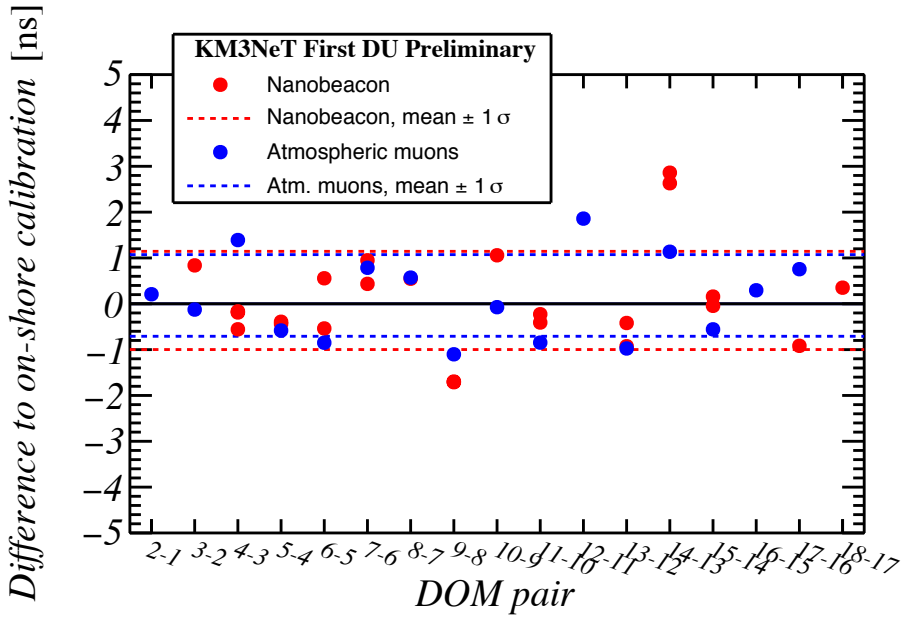



In-situ fit

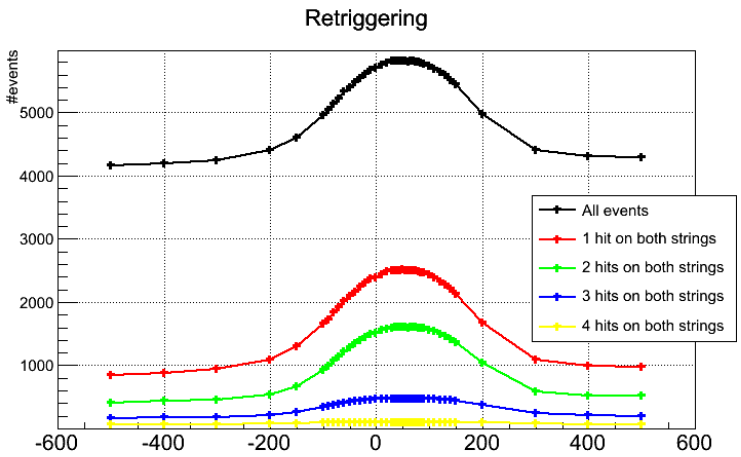



- TTS: Spread in PMT transit time
- Main factor for hit time accuracy
- In-situ fit with $^{40}$K method (slide 9)
- Mean TTS (in-situ meas.): 1.9 ns
  - Compatible with lab measurements

# DOM Time Cal. Comparison



# Trigger Rate Optimization

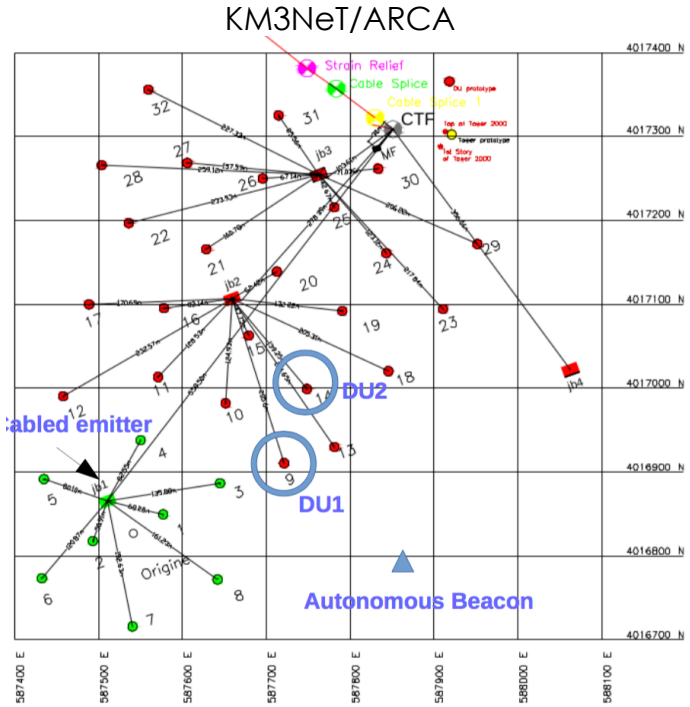



Inter-DU time offset difference – 575 [ns]

- Triggered Event:
  - At least 5 local DOM coincidences complying with track hypothesis
- Optimal DU time offset reflects in high trigger rate
- Best fit inter-DU time offset compatible with other methods (muons and LEDs)

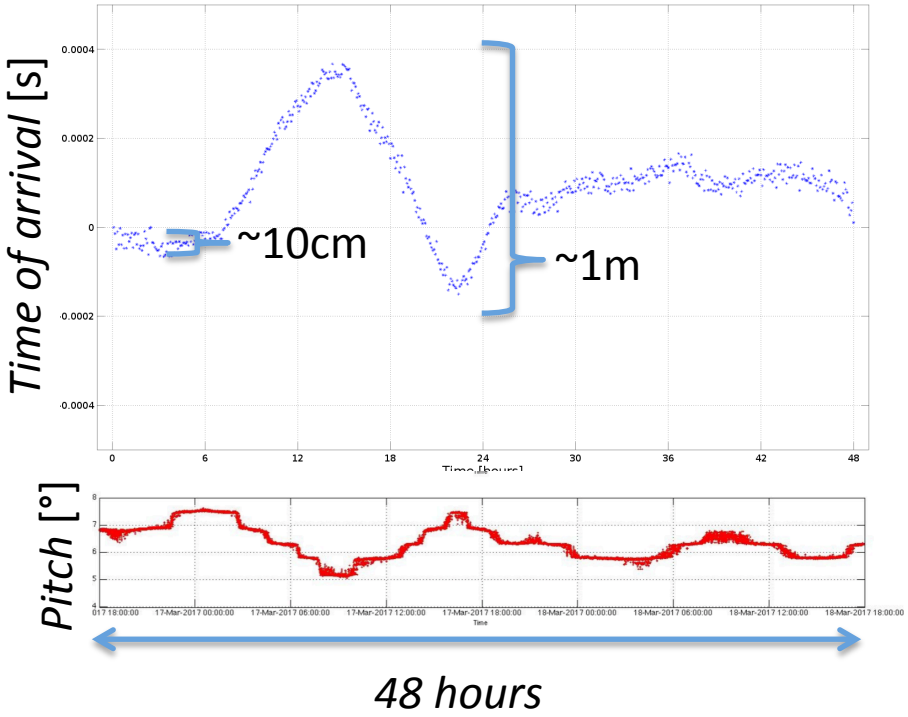
*Work + plots by M. Jongen

# Acoustic Network




- Piezo-based microphone in each DOM.
- Acoustic emitters on seabed
  - Sound range: 8km
- Distance emitter-DOM from triangulation of time-of-arrival measurements

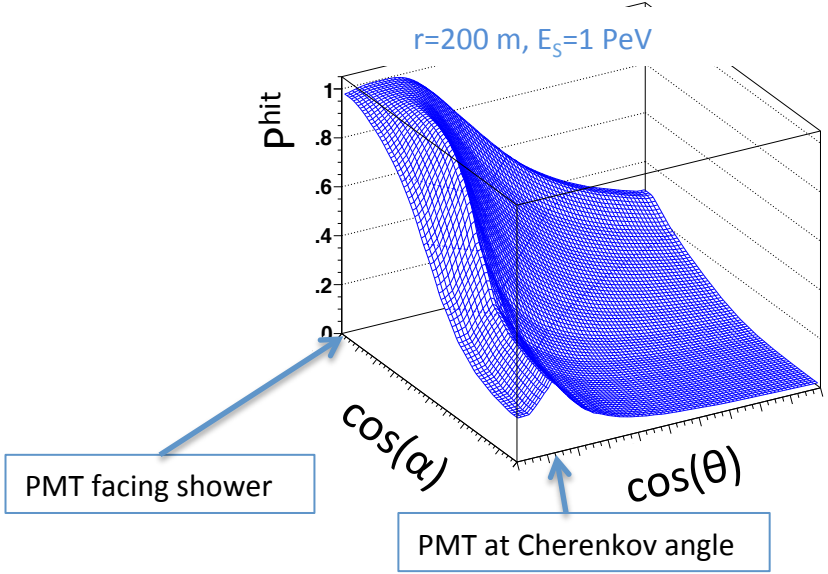
# Position Variations




*Work + plots by S. Viola

- Acoustics network to determine DOM positions with ~10cm accuracy
- ~1m position variations due to sea currents
- Also observed with DOM's compasses

# Multi-PMT Design

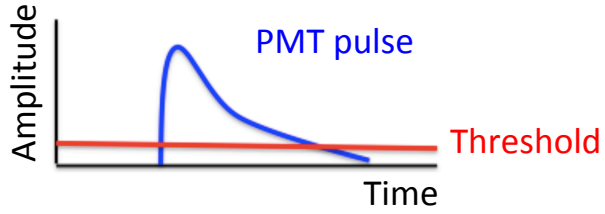


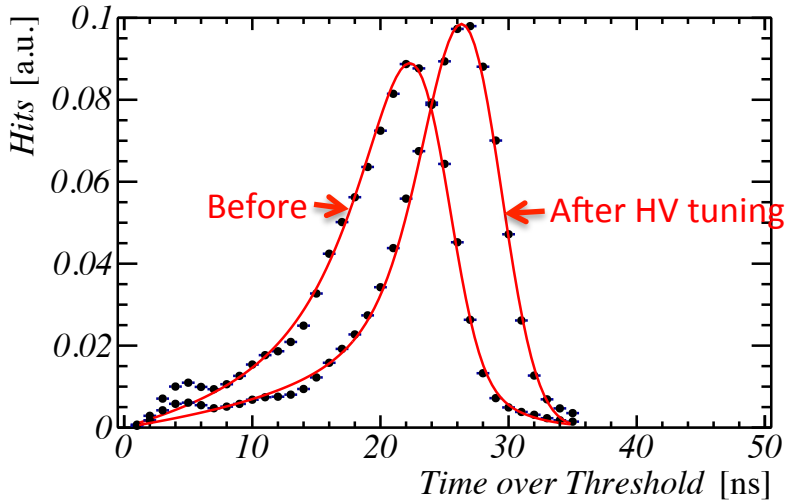

- In shower reconstruction:
  PMT hit/not information only
- Always a sensitive set of PMTs
  - Low energy: close-by PMTs facing shower
  - High energy: distant PMTs facing away

We need to know the PMT photon detection efficiencies

*Plot by A. Heijboer

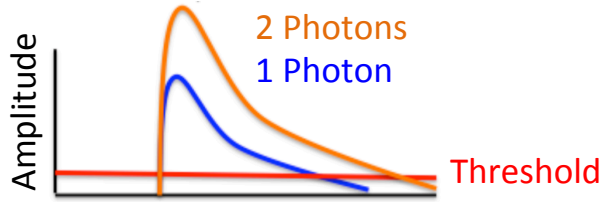
# Time over Threshold

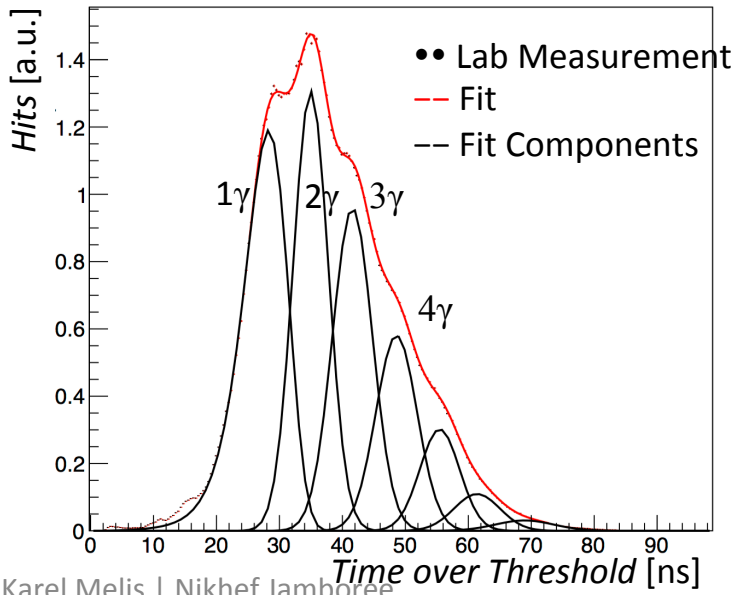



- All-data-to shore principle
  - Not feasible to store all PMT pulse
- Number of hit photons from pulse Time over Threshold (ToT)
- In-situ high voltage tuning of PMTs to give single photon ToT=26 ns.

# Photon Counting Capability



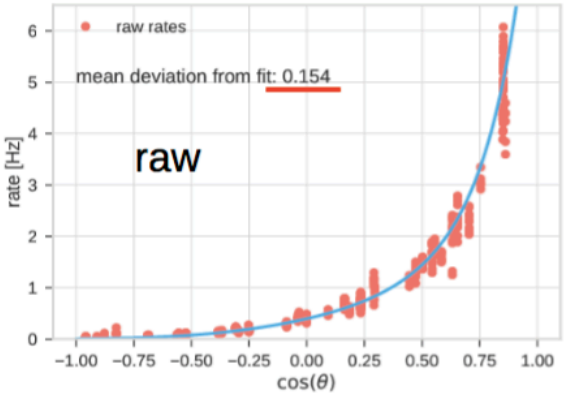



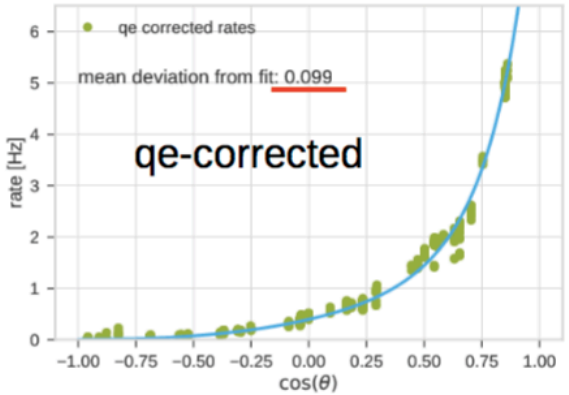

- Number of photons can be estimated from Time over Threshold (ToT)
- Fairly simple model describes data very well
  - Only sigma's and laser amplitude fitted

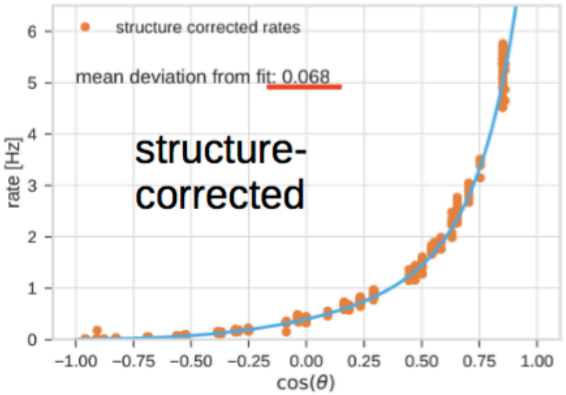
Q: What can we achieve without photon counting?

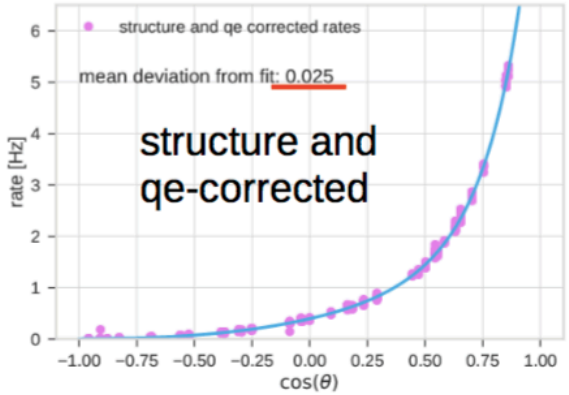
*Work + plots by B. Schermer

# PMT Systematics






*Work + plots by J. Reubelt & J. Hofestädt