Results and simulation of the prototype detection unit of KM3NeT-ARCA

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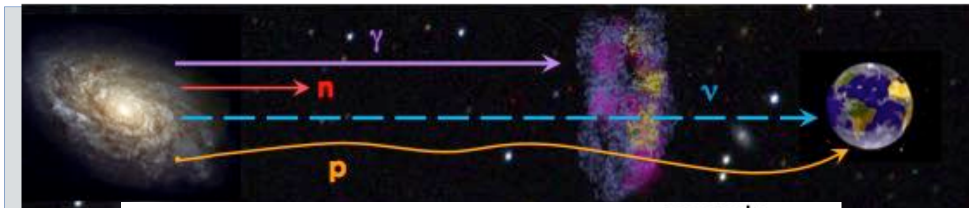
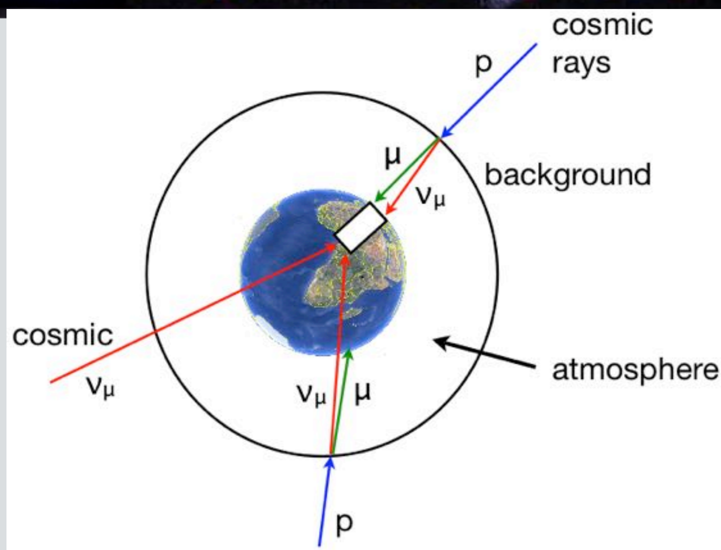
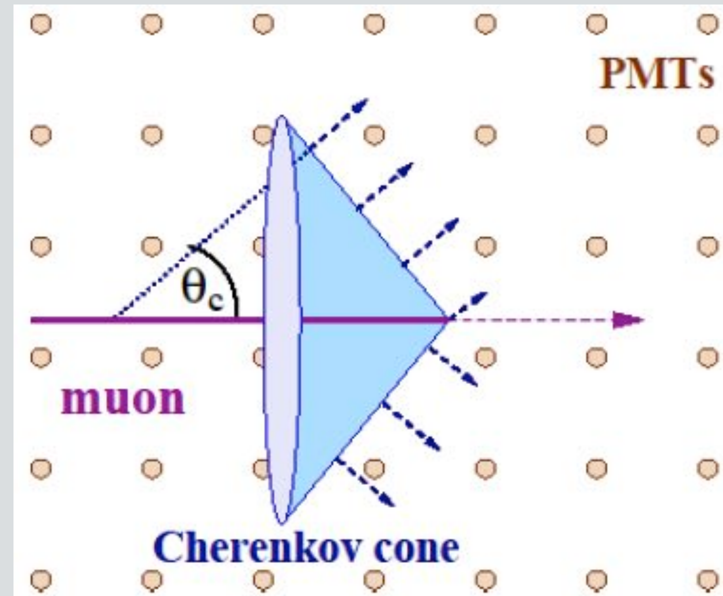
On behalf of the KM3NeT collaboration

The Neutrino telescope principle





- Main target: cosmic neutrinos going through the Earth
- Main background
  - Atmospheric muons
  - Atmospheric neutrinos



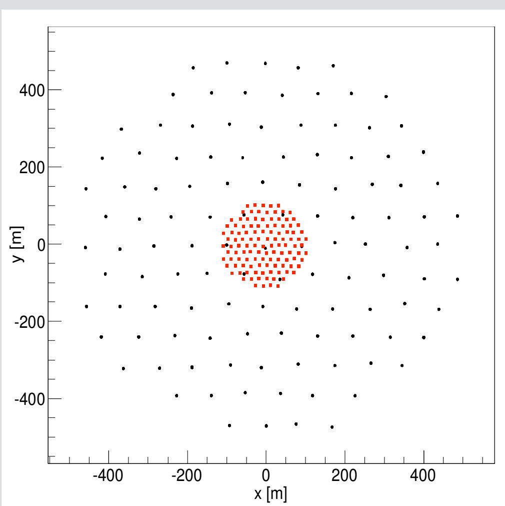
- Tcherenkov cone reconstruction thanks an array of photomultiplicator (PMT)
- Reconstitution of
  - The origin (typically 0.5 deg of resolution)
  - The energy of the event

KM3NeT the new generation of Mediterranean neutrinos telescopes

Multi-site option

Astrophysics research with cosmics in the abyss
Oscillation research with cosmics in the abyss

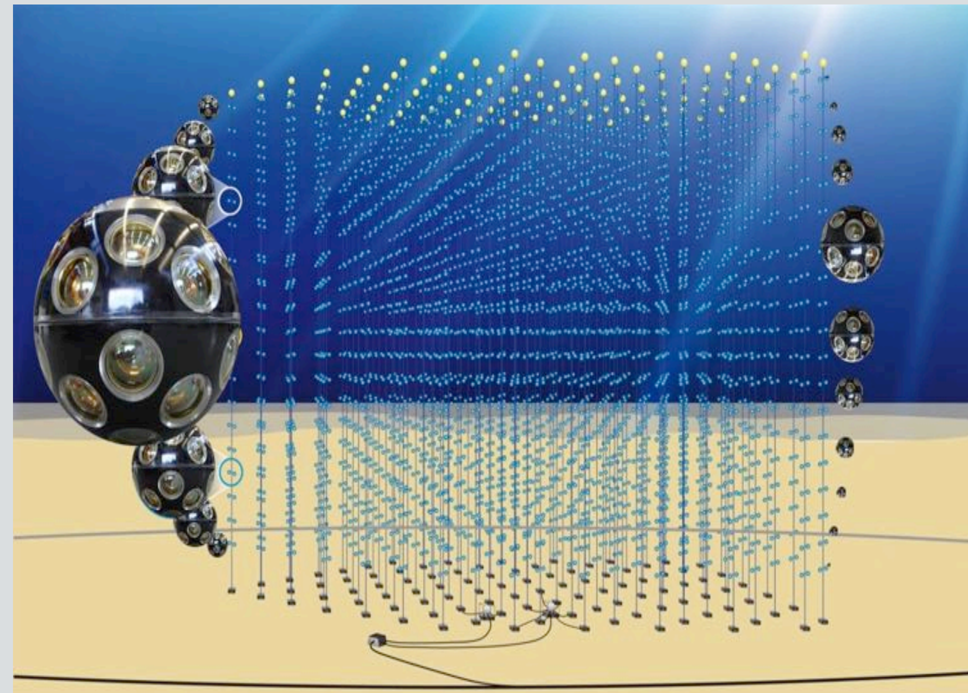
	ARCA	ORCA
Location	Italy	France
String dist. [m]	90	20
DOM spacing [m]	36	6
Volume [10^6 m^3]	~500	~3.8



<u>Multipurpose physics</u>

ORCA
100 MeV → 100 GeV
- Low energy physics
- Neutrino oscillation

ARCA
> 100 GeV
- High energy physics
- Extra-galactic physics



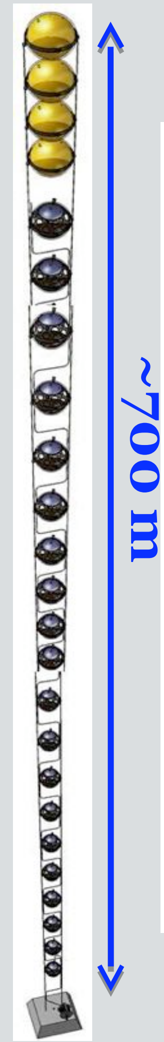
Neutrino telescope >1 km^3
Goal: extends our knowledge of the Universe

- Study of neutrino point sources
- Measurement of cosmic neutrino diffuse fluxes
- Multi-messenger approach and ‘exotics’
- Synergy with Earth and Sea sciences

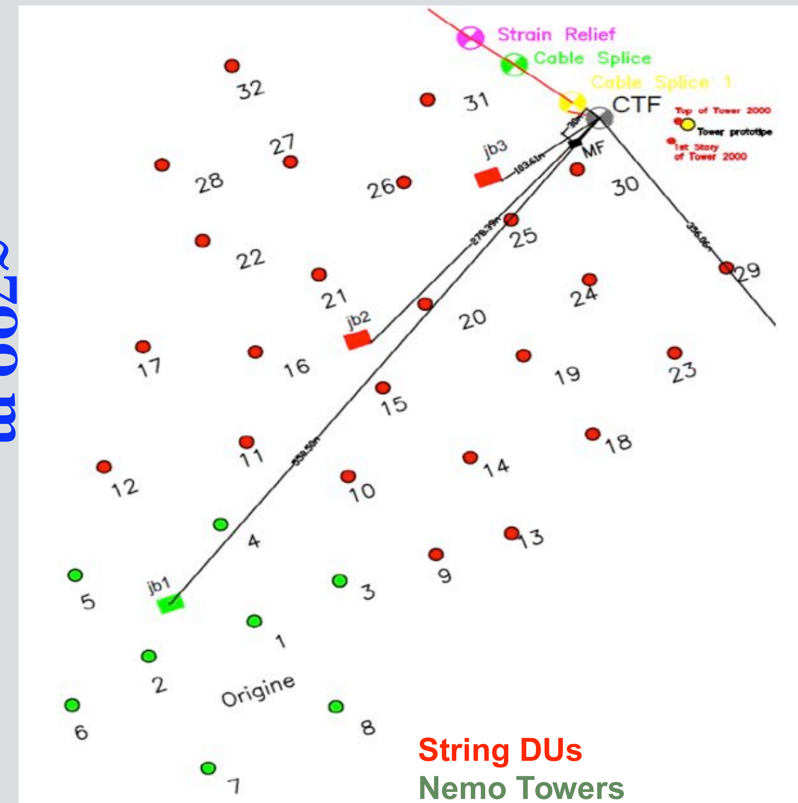
KM3NeT phase 1

- String-type with 18 optical modules
- 36 m between the optical modules

First phase
- Started in January 2014 with the first strings
- 2 strings working
- Funded with 31 million Euro
- 31 detection units will be deployed in 2015-2016
- Sites: KM3NeT-It off shore Capo Passero with 24 DUs, KM3NeT-Fr off shore Toulon with 7 DUs
- 3 times improvement in sensitivity w.r.t. Antares

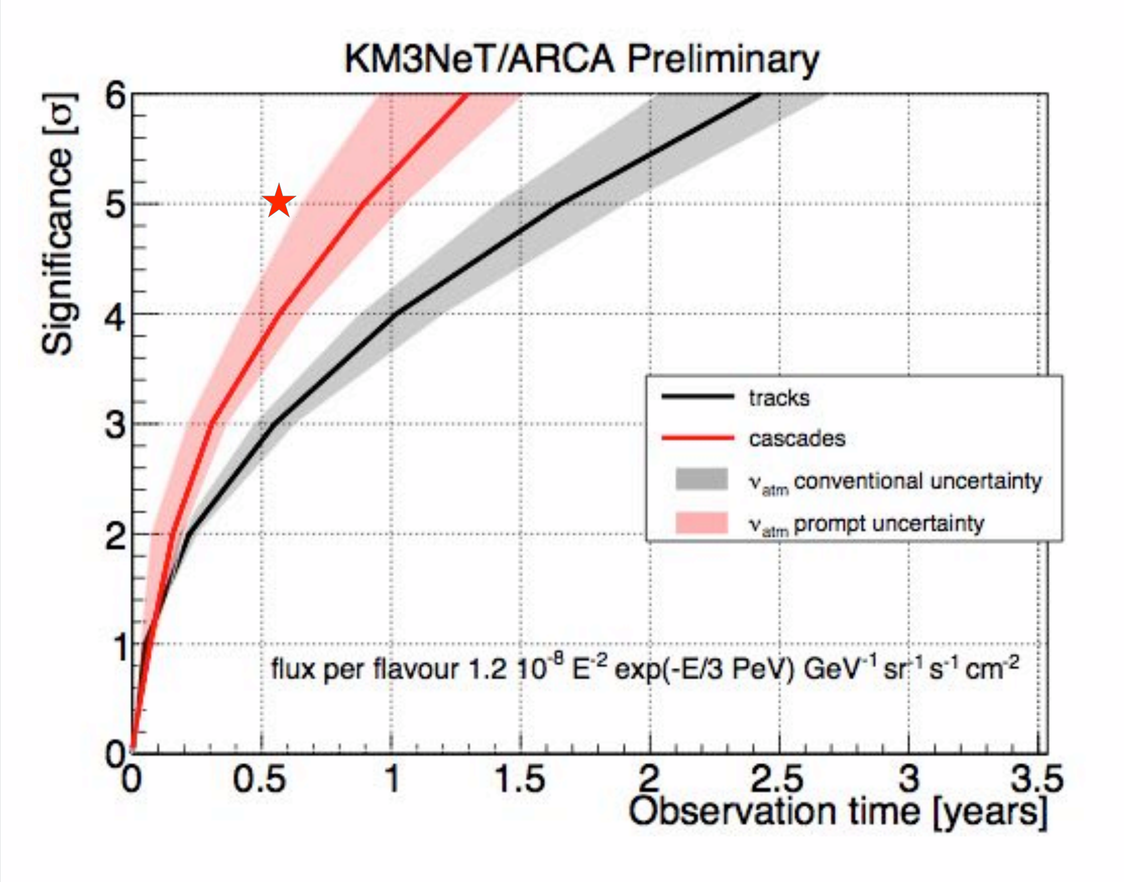


KM3NeT-it phase 1



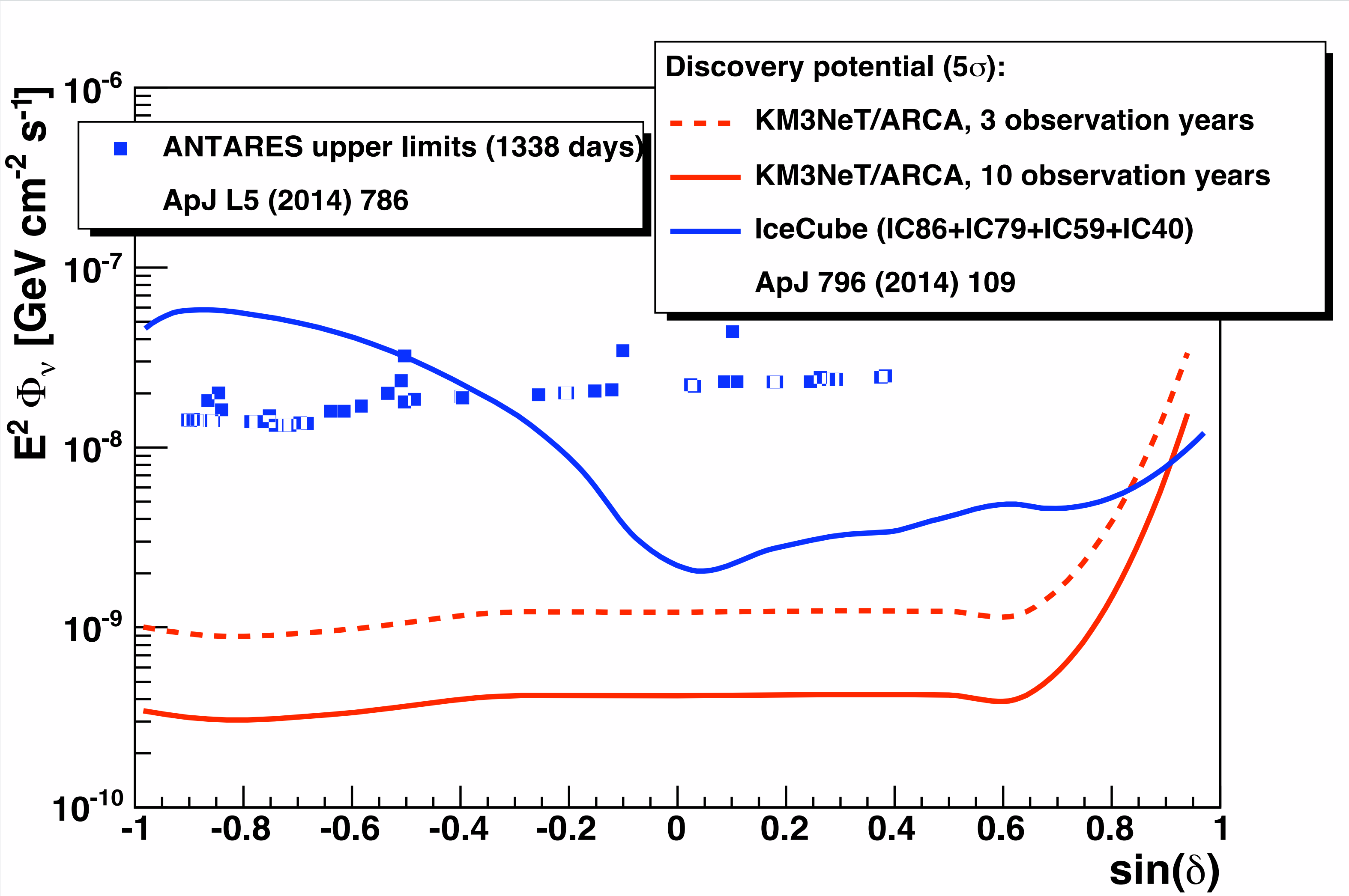
Significance for cascade and upgoing muon diffuse flux ARCA

- Contained high energy cascade events
- Up-going TRACK analisys



Flux of high energy cosmic neutrino reported by IceCube will be measured after less than one year of data taking for cascade and muons respectively with KM3NeT 2.0

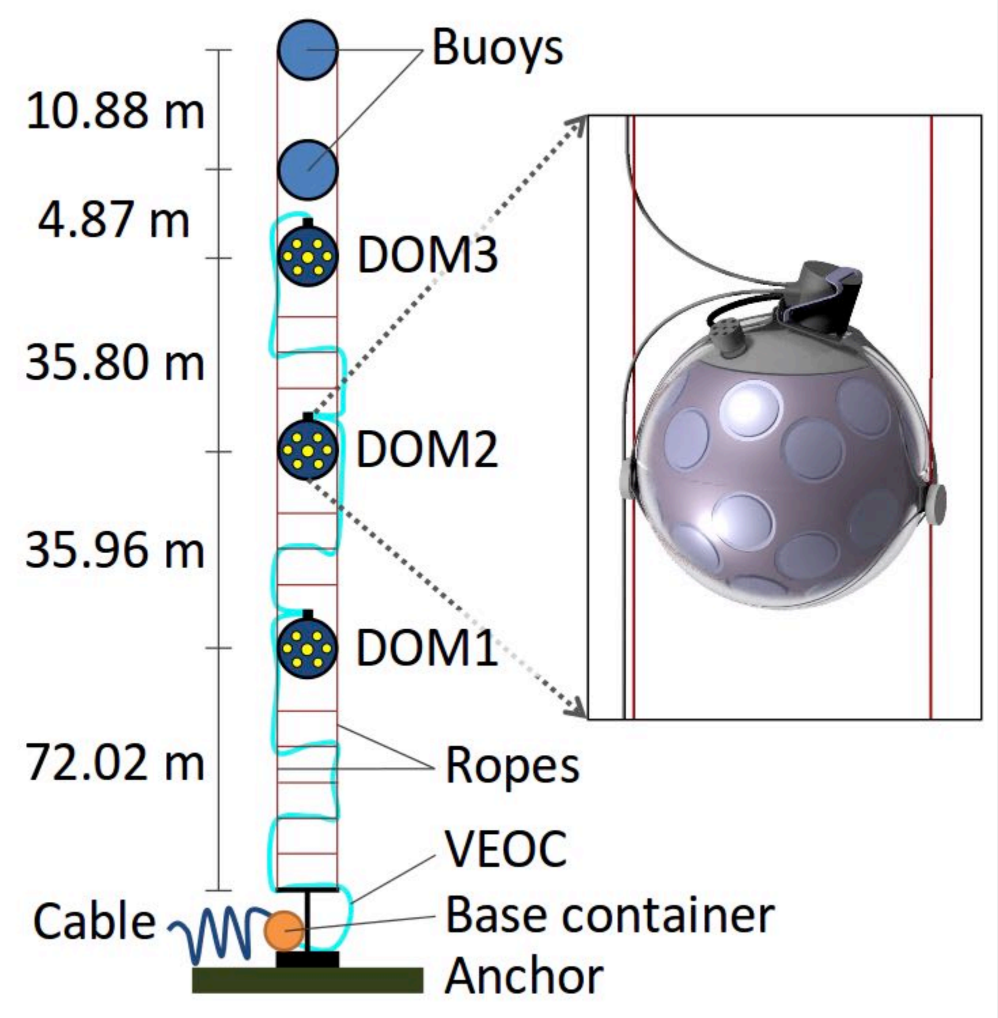
Discovery potential for point sources ∝ E^{-2} spectrum



KM3NeT discovery potential comparable or better than IceCube over almost whole sky

Detection Unit prototype

- 2 DOMs with 31 ETEL D783FLA PMTs
- **1 DOM with 31 Hamamatsu R12199-02 PMTs**
- LED nanobeacon and piezo
- Deployed at the KM3NeT-It site at 3500m depth, 100 km off shore
- Operational since May 2014 until july 2015



The Digital Optical Module

Segmented cathode area: 31 x 3” PMTs

Light concentrator ring

Cathode area: ~ 3 x 10-inch PMT

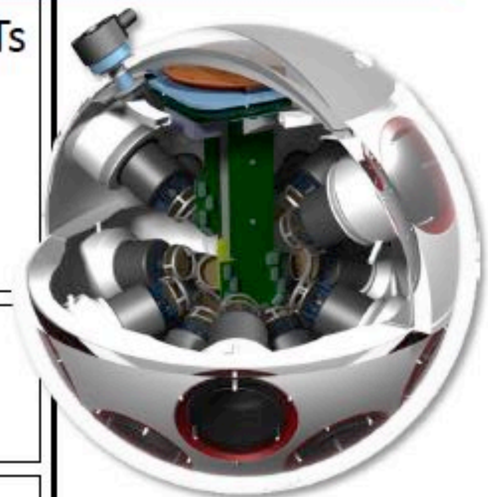
Custom low-power HV bases

LED & piezo inside

Compass and tiltmeter inside

PMT ToT measurements

FPGA readout, optical line terminator



~14000 PMTs (phase-I)

↑12 PMTs
↓19 PMTs

ETEL D792

Hamamatsu R12199

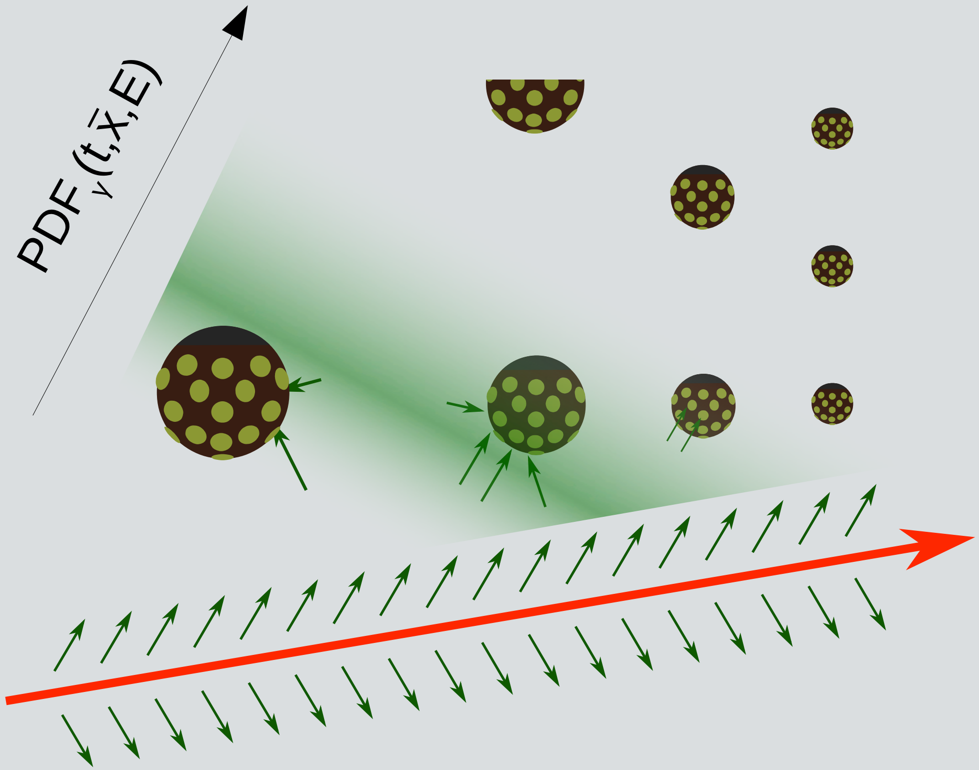
HZC XP53B20

DU prototype integration and deployment

Integrated at Nikhef (Amsterdam) and CPPM (Marseille)

Deployed at 3500 m depth at the site of Capo Passero (KM3NeT-It) in May 2014, removed in July 2015

Principle of the detector simulation



A full ray tracing simulation would be far too slow. A physics tables based simulation is used:

1) The charged lepton directionality and energy are simulated a priori, in function of the model
2) The density of the Tcherenkov photons production is calculated along the lepton (~100/cm)
3) The photon “presence” probability density in function on time is calculated along the Tcherenkov front
4) At the position of each Optical module the probability to be detected is calculated in function of
   1) The photon wavelength
   2) The photon incident point
   3) The photon incident angle

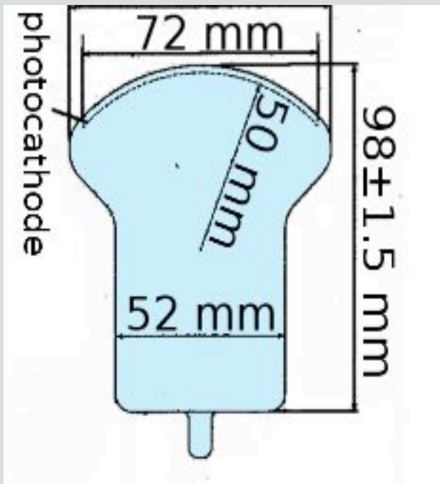
Tabulation of the angular efficiency in function of these parameters: need a ray tracing simulation (base on GEANT4)

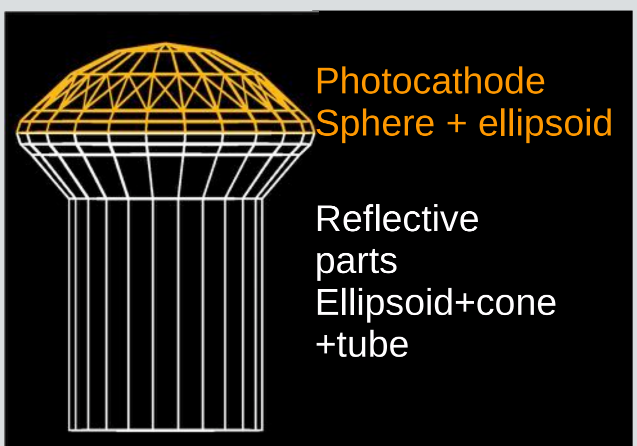
A word about the KM3NeT GEANT4 ray tracing simulation

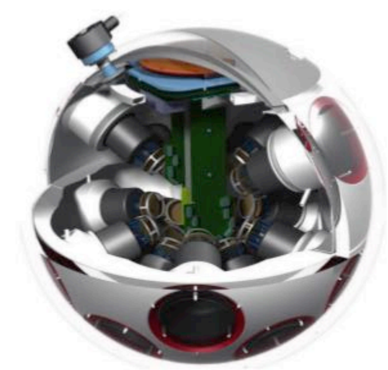
- Based on GEANT4
  - Generates the particles one by one and follows them in each processes (scatterings, decays, absorption…)
  - Works with high energy particles, but also optics (particle approach)
- Extended for Telescopes neutrino purposes
  - Not limited to KM3NeT, but also used for ANTARES, NEMO and can be used for any Tcherenkov detectors
    - First implementation in Kamland (Motta et al.)
    - Implemented for Auger (A. Creusot)
    - Implemented for ANTARES then KM3NeT
  - Added precise Smoluchowsky-Einstein scattering (based on literature and site direct measurements)
  - Added photocathode physics: Thin layer and complex index

The geometries

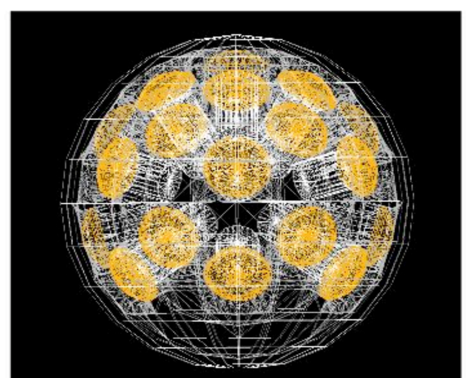
Hamamatsu R-12199







(c) Scheme of a KM3NeT DOM



(f) Simulation of the KM3NeT DOM.

The PMT

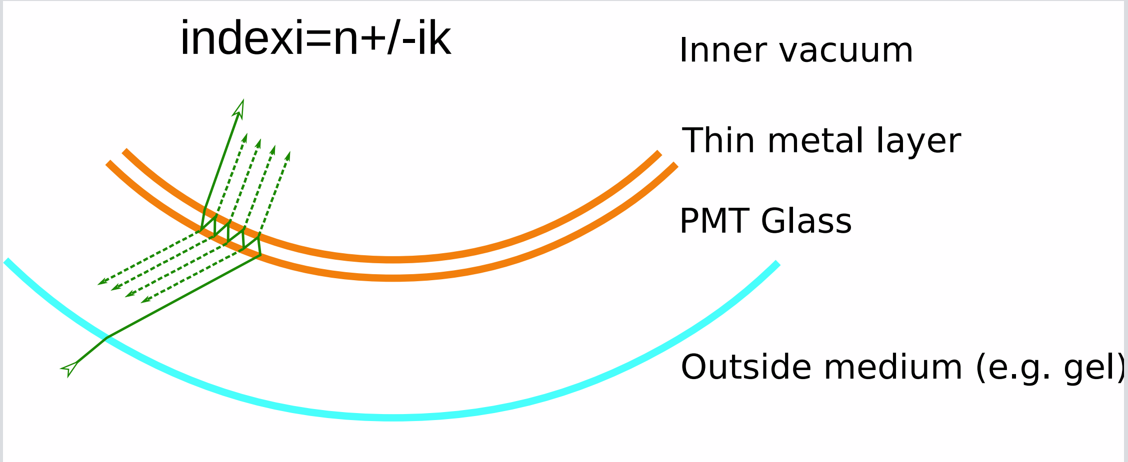
The simulation uses the main parameters given by the constructor. Can reproduce any “bulb-like” PMT. The dynods are also Taken in account, has an effect on the total efficiency.

The OMs

The simulaiton takes the number and position of PMT, the OM sizes (diameter and glass thickness.

This simulation can also reproduce OM composed of one big PMT (eg ANTARES)

Integration of the photocathode in the GEANT4 simulation

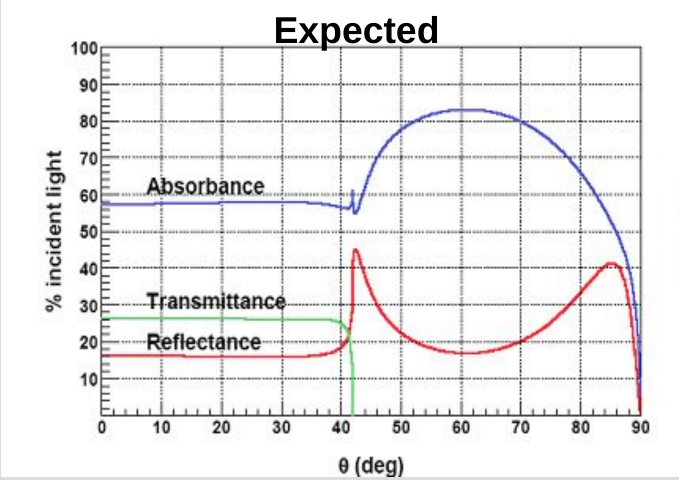


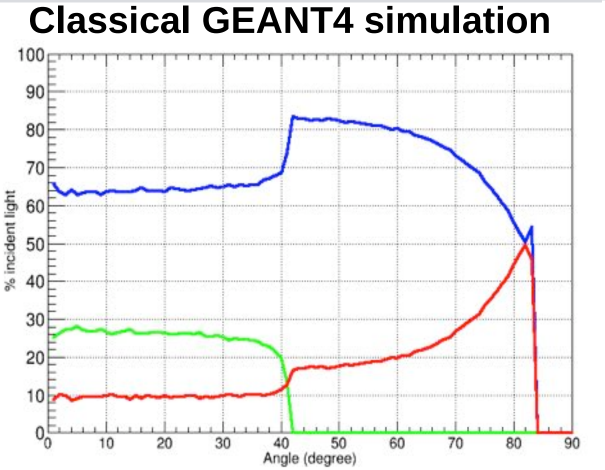
Two crucial points in the photon propagation in the photocathode:

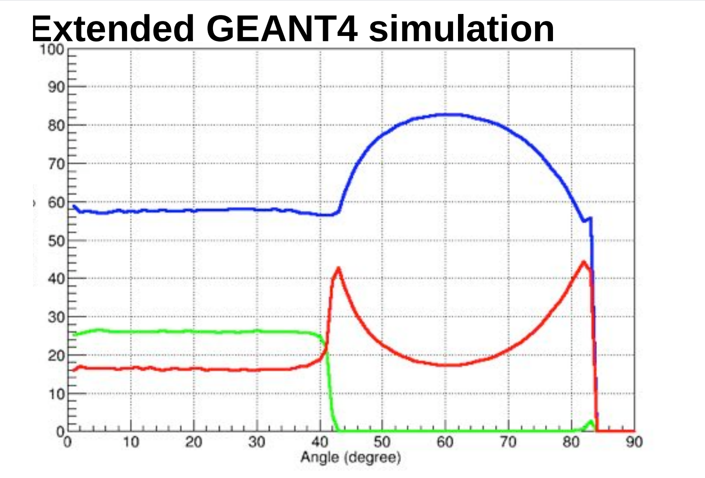
- The wave: multi-reflexion, auto-interferences
- The particle: ultimately absorbed in the thin layer, depends on he path length

The absorption length of the photocathode and the photon path are described by its complex index

New extension of the GEANT4 simulation:

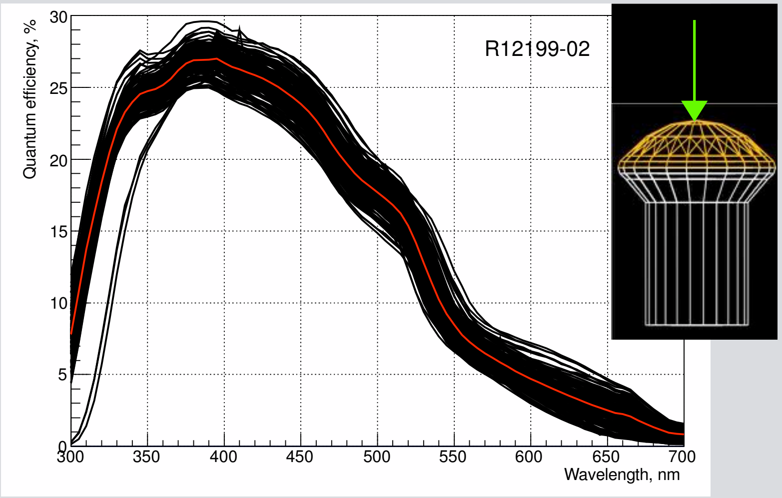




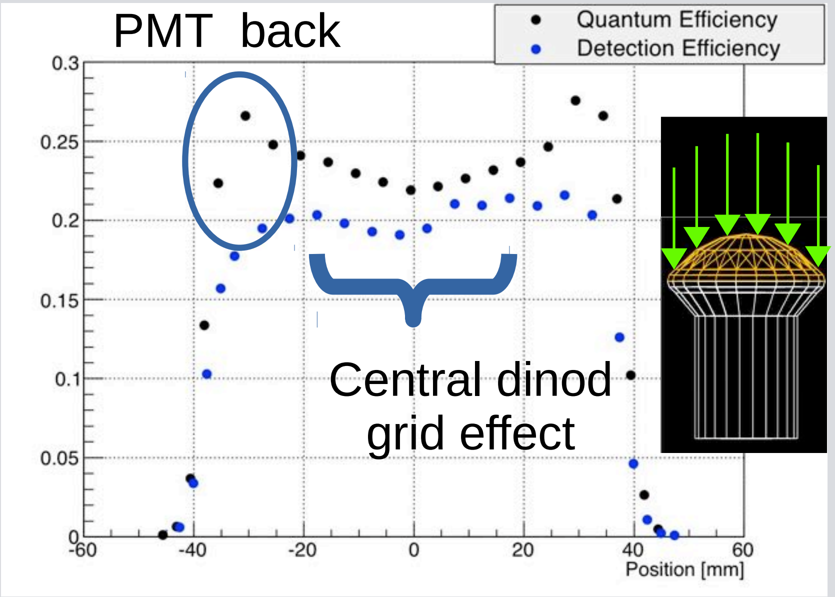


Simulation calibration

Phototube QE measurement



- PMT QE and efficiency taken from collaboration direct measurements of PMT (Erlangen's/APC):
- A system using a precisely calibrated LED can scan the PMTs to measure its QE and efficiency.
- Tens of PMTs were scanned. The mean values are used in the simulation.

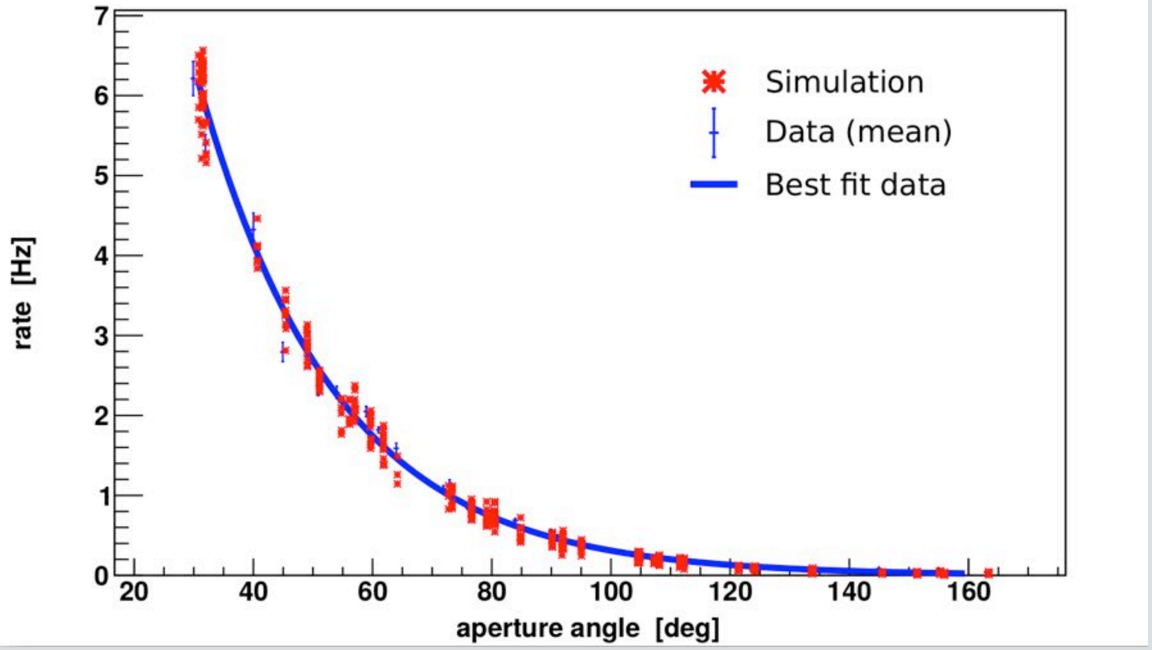


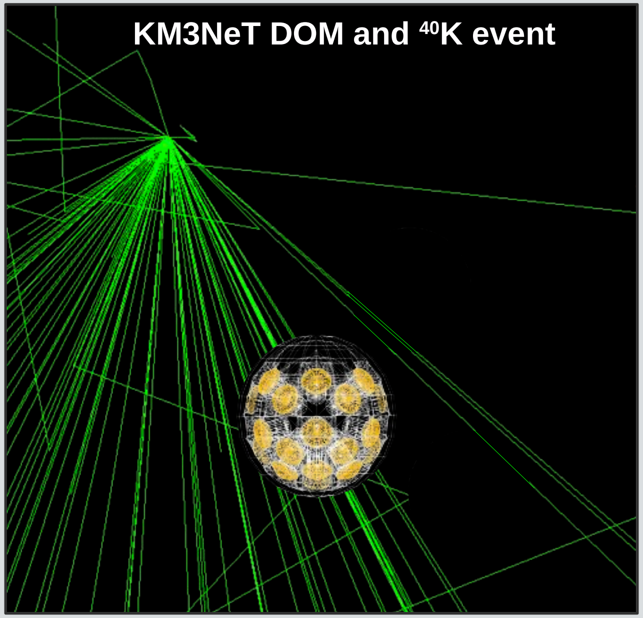
- The exact QE can be estimated thanks to a measurement of the photocathode tension
- The excess of QE on the border is due to the thin photocathode projected also on the back of the PMT
- The central lower efficiency is due to the dynods (the photons are not reflected back to the photocathode)

^{40}K data and simulation

The very constant sea salinity at these deep implies a very constant ^{40}K decay rate. This decay produce Tcherenkov photons (e^- of 1 MeV) It permits on-site calibration of the detector and cross-check with the simulation.

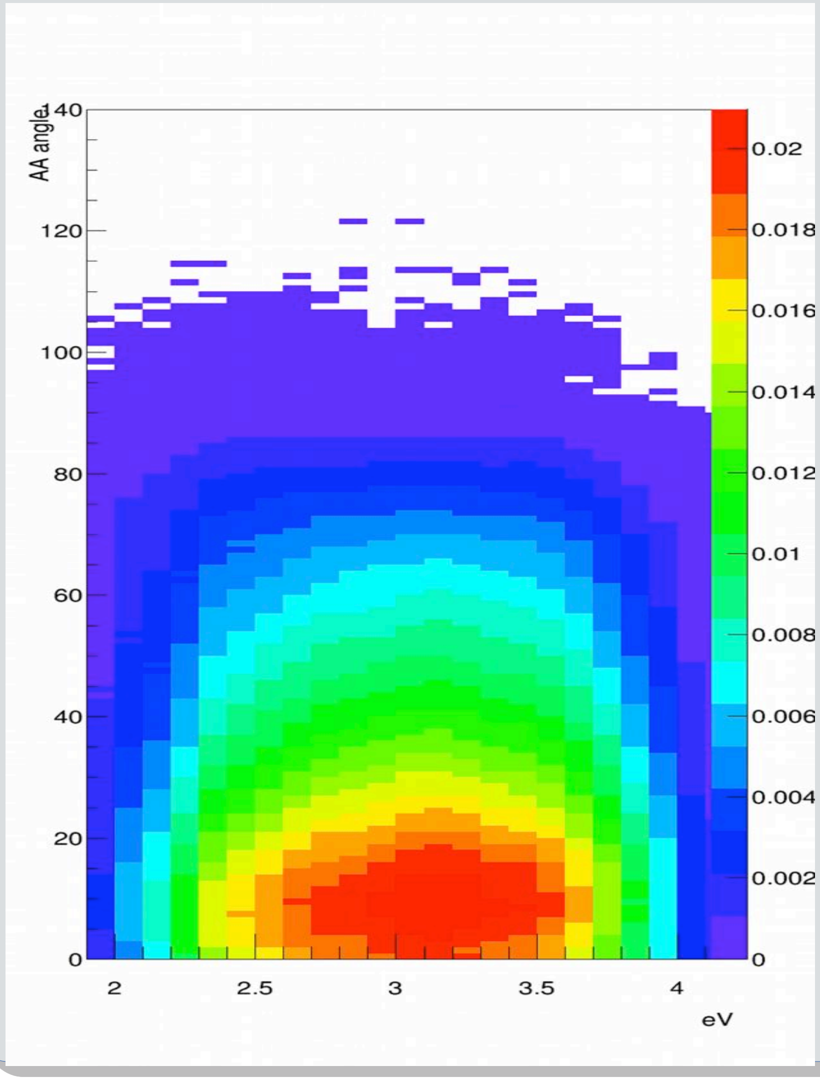
PPM-DU DOM3 rates in fonction of aperture between PMTs

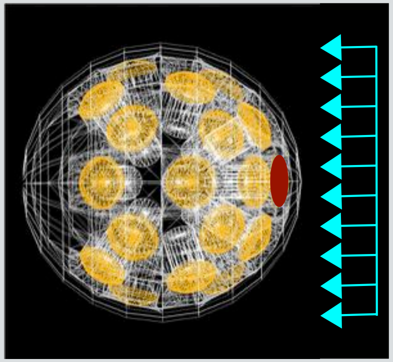




Very good accordance of expected rates from the simulation and the data

Angular efficiency function of energy



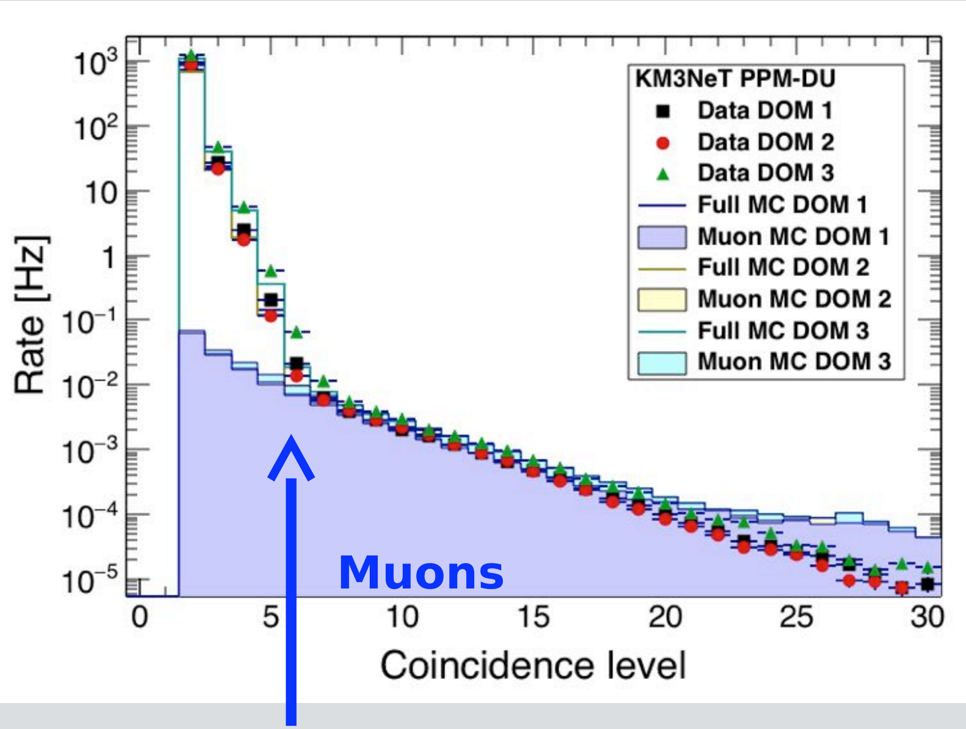


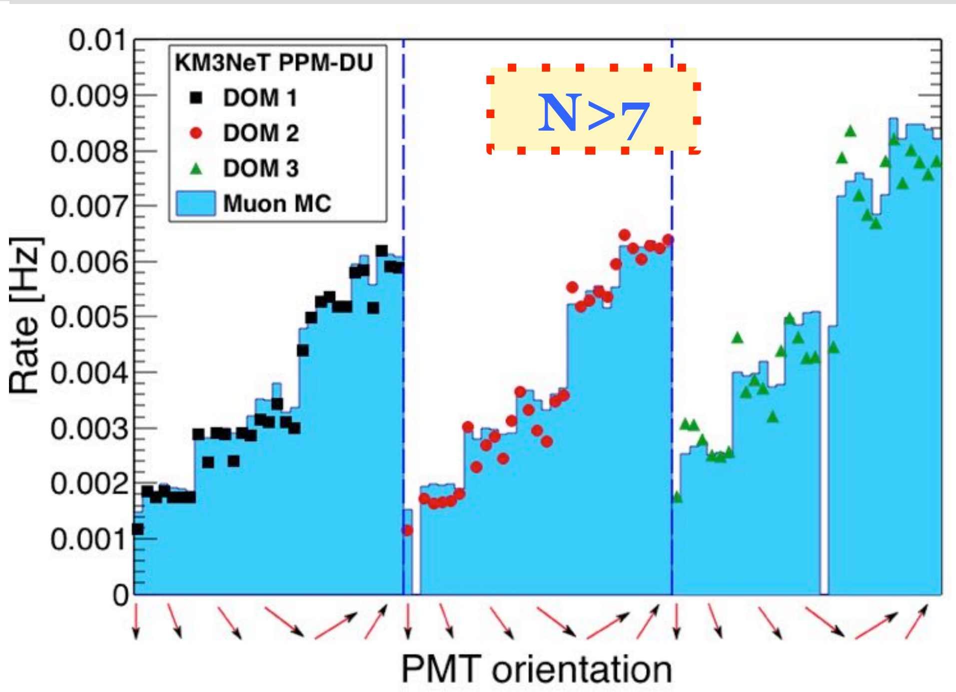
The angular acceptance corresponds to the probability that a beam of photons is detected by the optical module

The thin layer photocathode simulation allowed to take in account all the effects, to provide a precise table of angular acceptance

Tabulated for all the PMTs, angles and energy:
→ Used for the global simulation
→ Used in the the atmospheric muon simulation

PPM-DU: Searching for muons

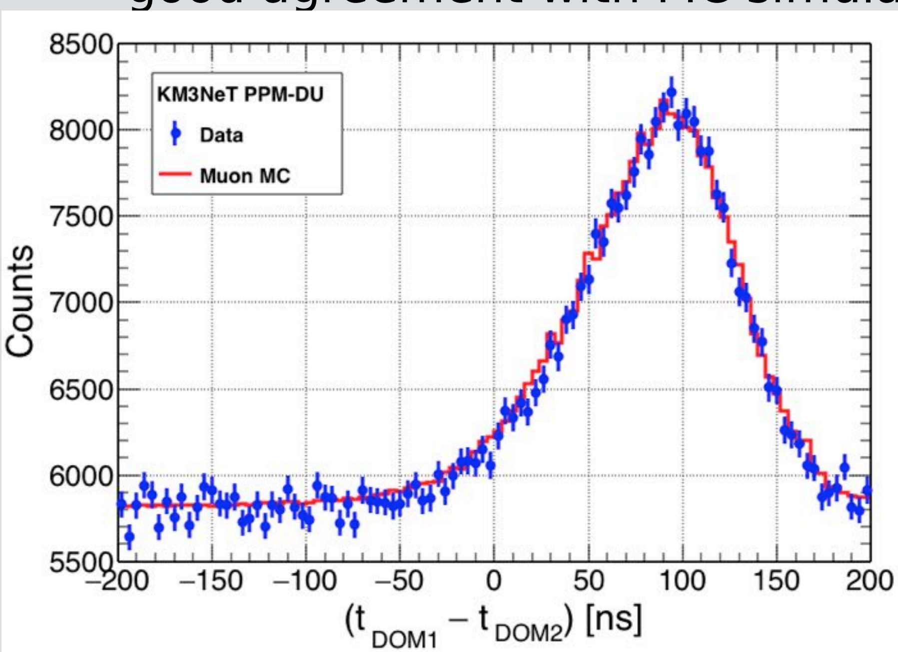




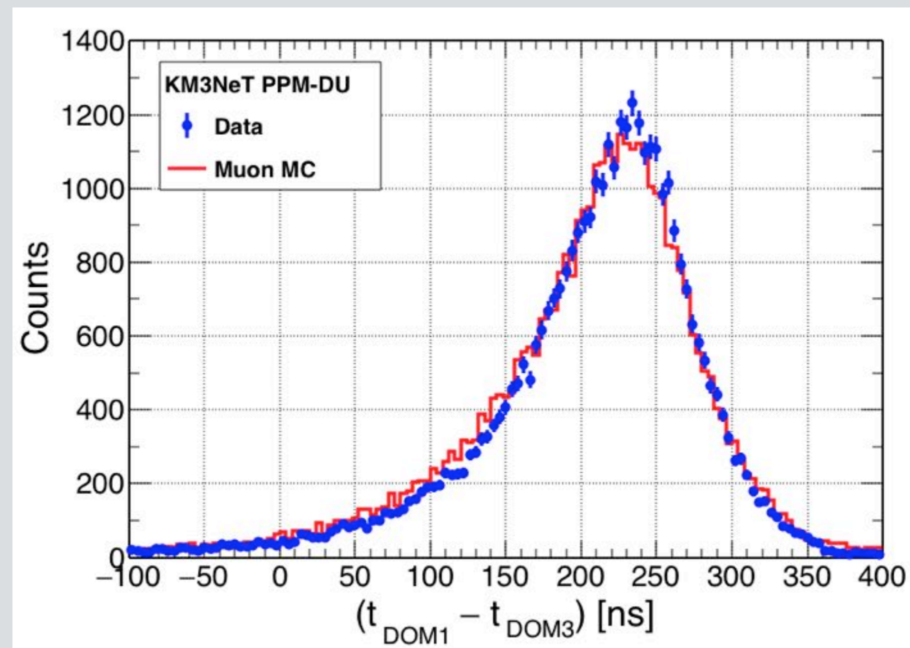
- L1 trigger = coincidence between two PMTs in 25ns; unique PMTs are selected inside the DOMs in a 130 ns time window
- The change of shape shows the region in which muons become to be dominant over the optical background
- Directionality of the DOM 3 peculiar up/down shape

Inter-DOM time calibration

- K-40 decay in sea water to calibrate Intra-DOM time offsets using local coincidences
- LED nanobeacons to calibrate Inter-DOM
- Atmospheric muons can be used to calibrate in time DOMs: very good agreement with MC simulations

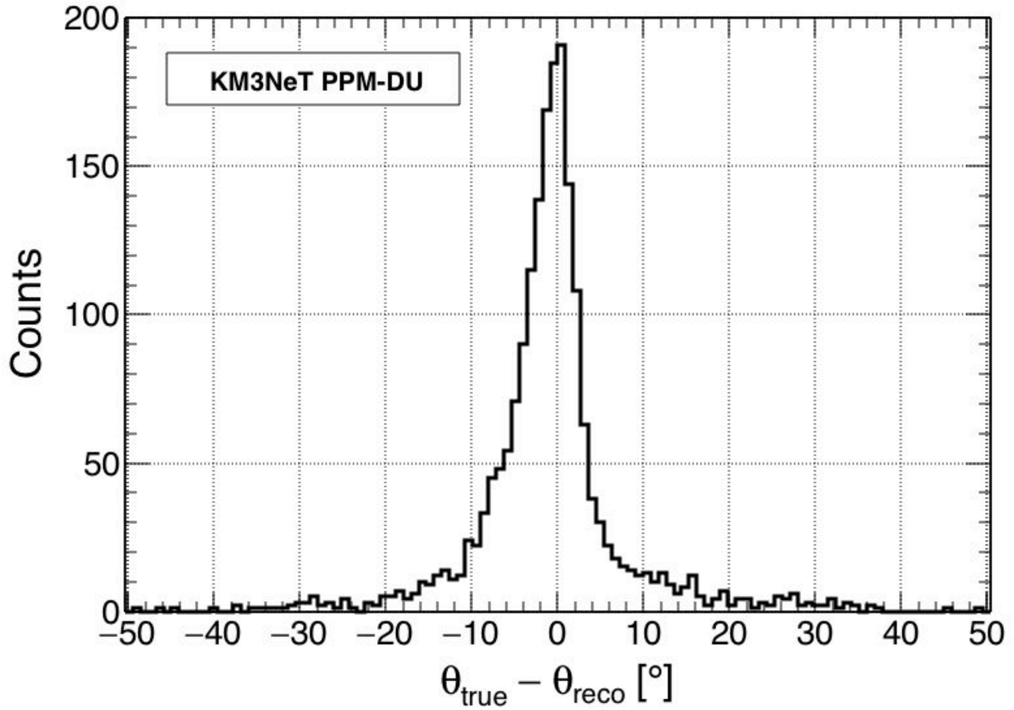


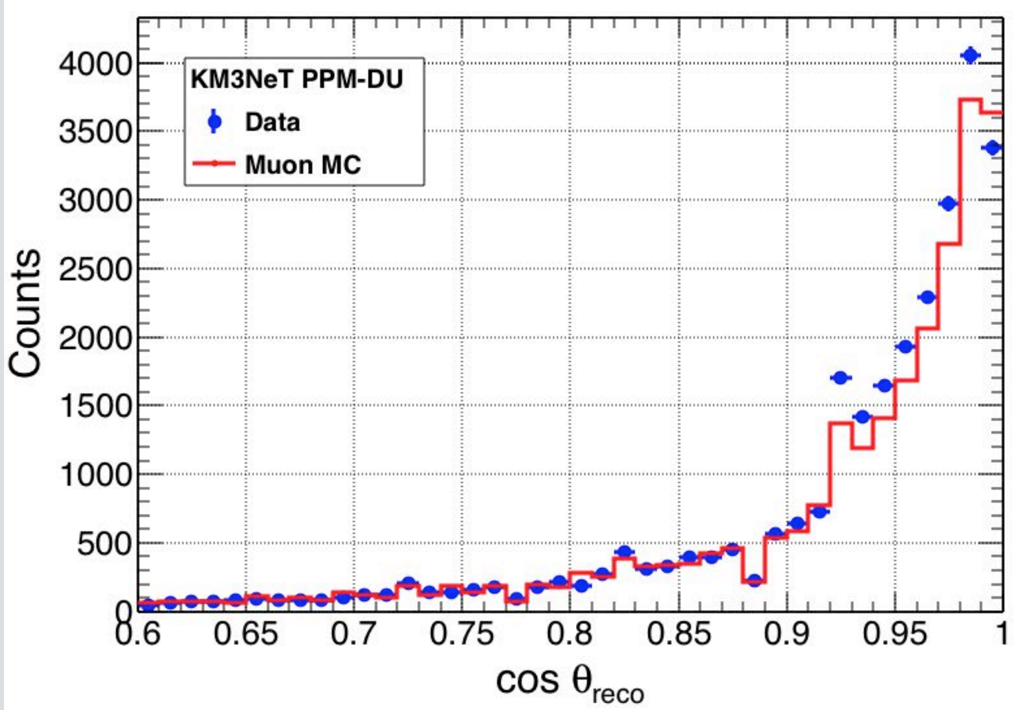
DOM1+DOM2



DOM1+DOM2+DOM 3

Zenith angle reconstruction





- Reconstruction of zenith angle of atmospheric muons
- Inputs: position of the three DOMs and time of the local coincidences
- FWHM = 7.6 degree zenith angular resolution achieved

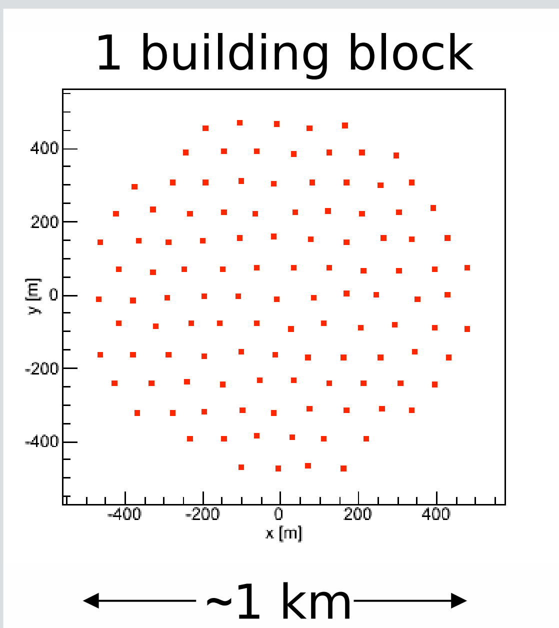
Summary and Conclusion

- The ANTARES detector proved the feasibility of undersea telescopes
- KM3NeT represents the next generation of undersea telescope for
  - HE neutrinos with ARCA
  - Low energy neutrinos and oscillations with ORCA
- The prototype of the detection units of KM3NeT showed promising results with a good reconstruction of muon an calibration
- The current status of the simulation allows to obtain very accurate results. It reproduces the ^{40}K decay and the muon reconstruction
- This simulation has been developed with the idea to be used with any neutrino telescopes. It's used with success with KM3NeT, ANTARES and NEMO

Backups

KM3NeT ARCA

- Objectives similar of ANTARES, but at bigger statistic, higher energy
- Measurements of neutrino signals reported by IceCube



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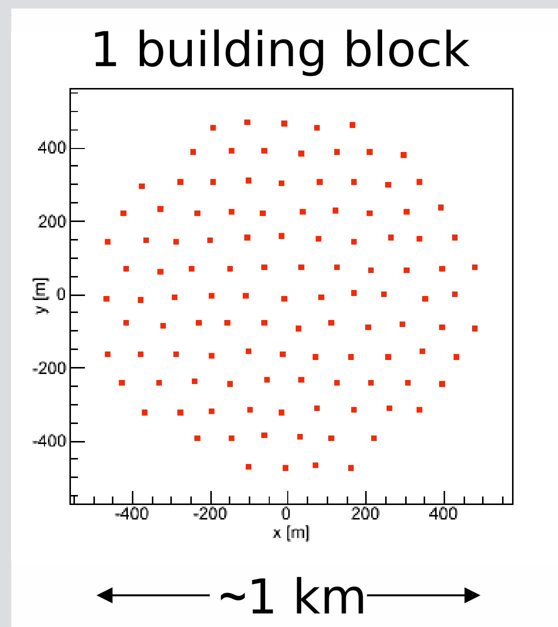
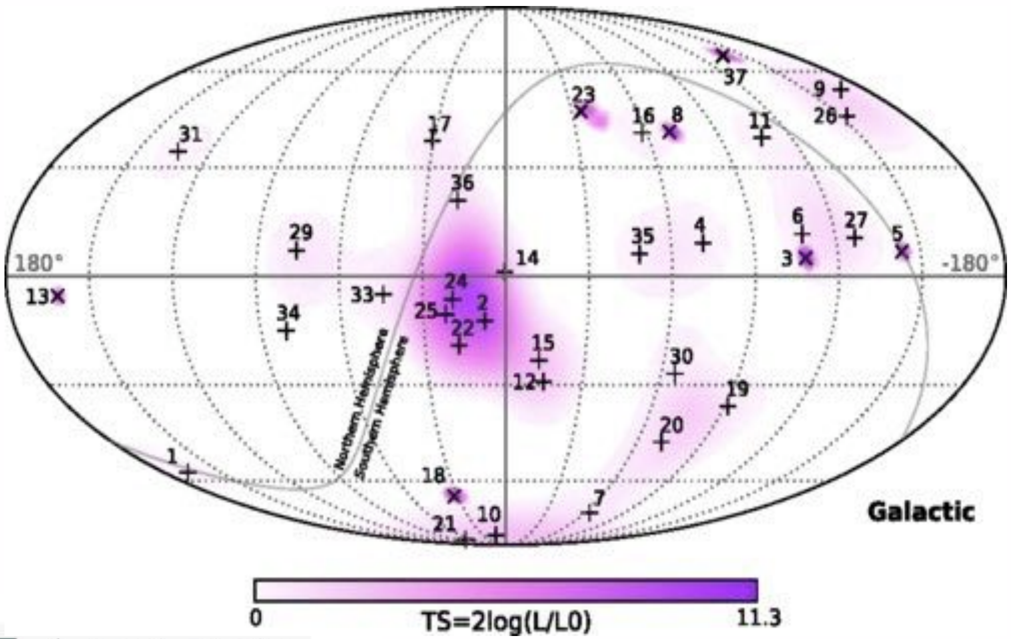
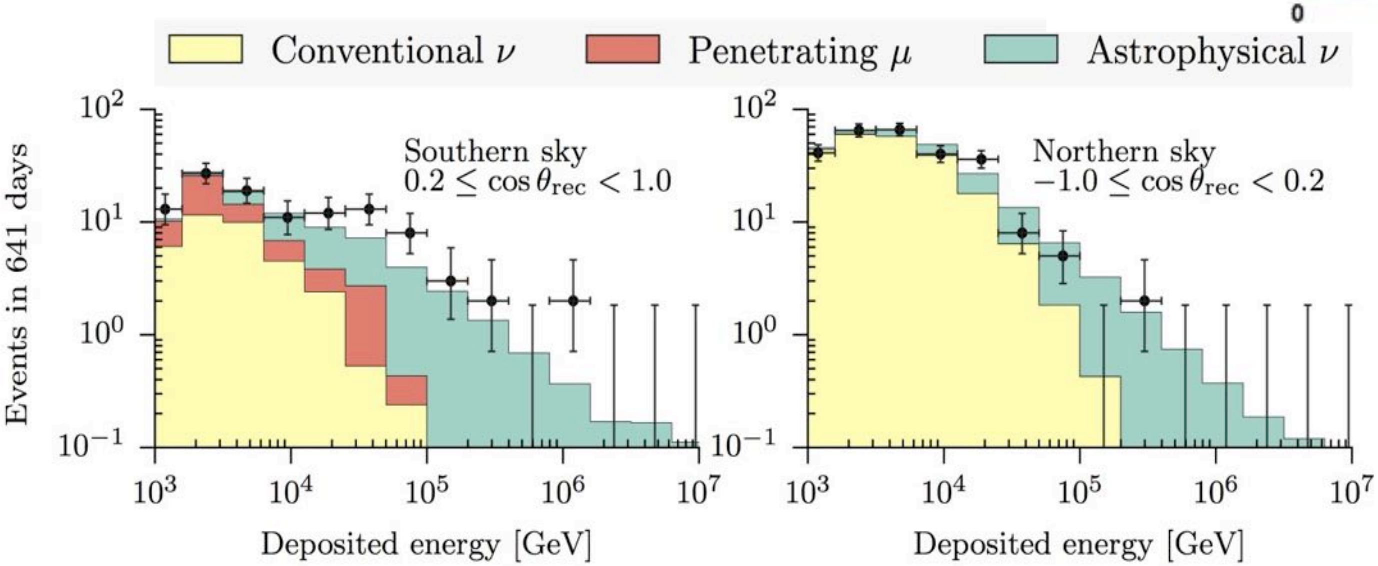


Reminder – the IC signal

Phys. Rev. Lett. 113, 01101 (2014)
HESE with 3 years of IceCube data.
'hot spot' at l = +18°, b = -9°





Phys. Rev. D 91, 022001 (2015)
$d\Phi/dE \sim E^{-2.46}$

+ flavour ratio measurement (arXiv:1502.03376, accepted PRL) also provides a fit of signal flux $d\Phi/dE \sim E^{-2.6\pm0.15}$

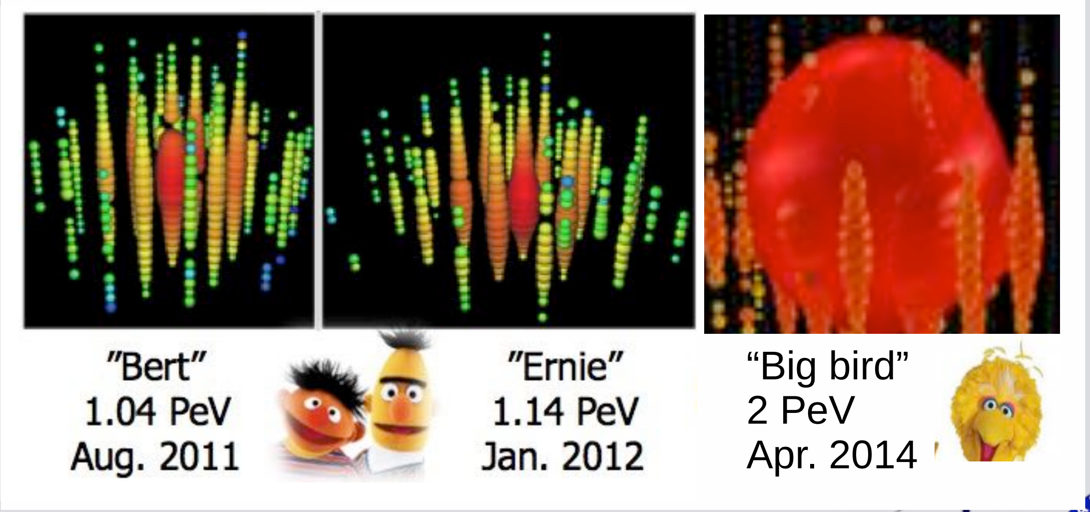
ANTARES+TANAMI paper

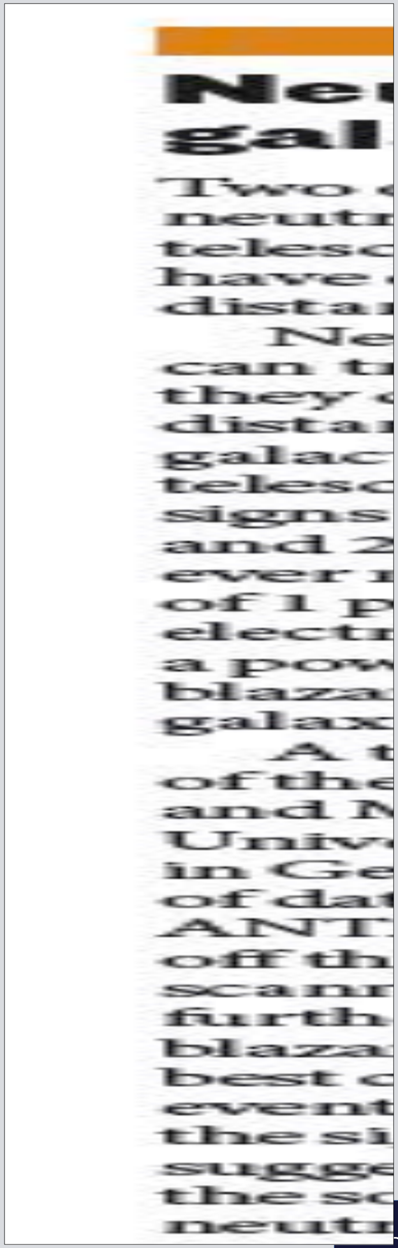
Antares+Tanami, A&A 576, L8 (2015)

ANTARES Constrains a Blazar Origin of Two IceCube PeV Neutrino Events

(highlighted in Nature vol 520, April 2015)

- Introduces method to infer events rates in ANTARES
- given IceCube observed events
- Main result:
  - 2 of 6 blazars associate with one event each in ANTARES
  - Consistent with blazar-source hypothesis (and background)

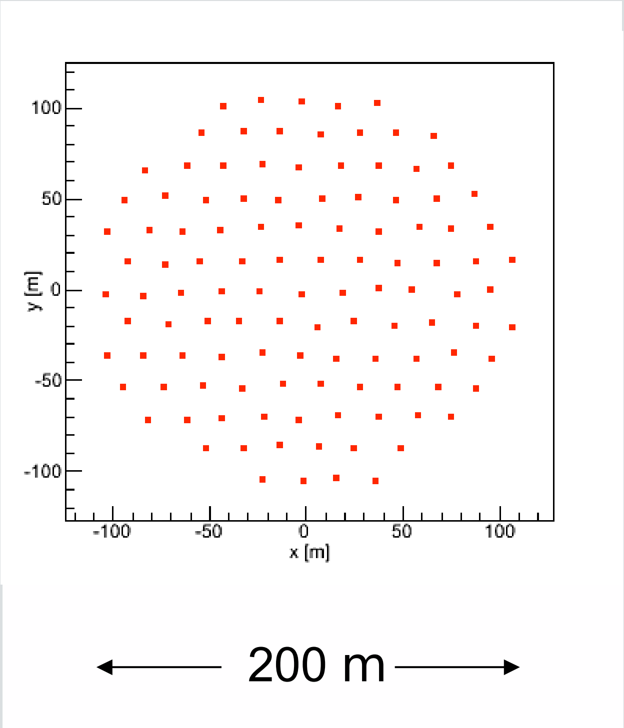




ORCA

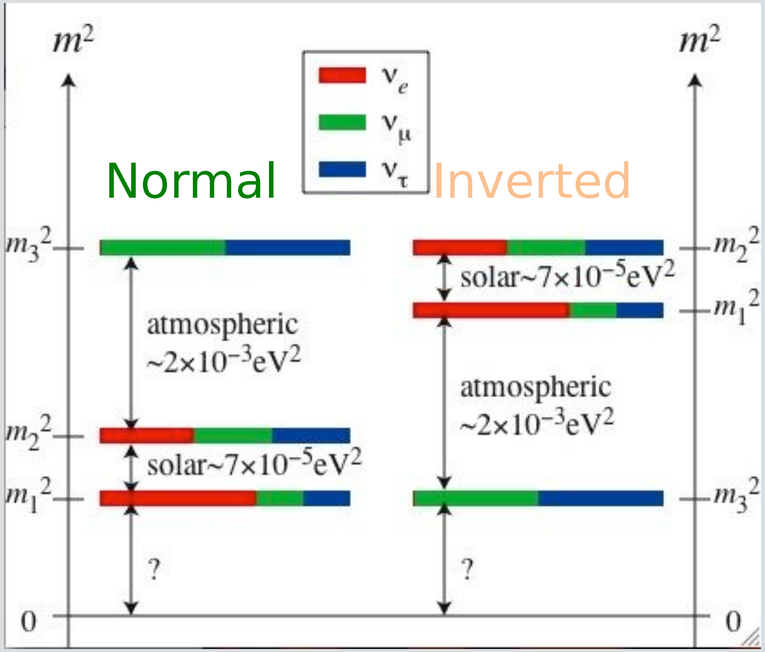
Measurement of neutrino mass hierarchy

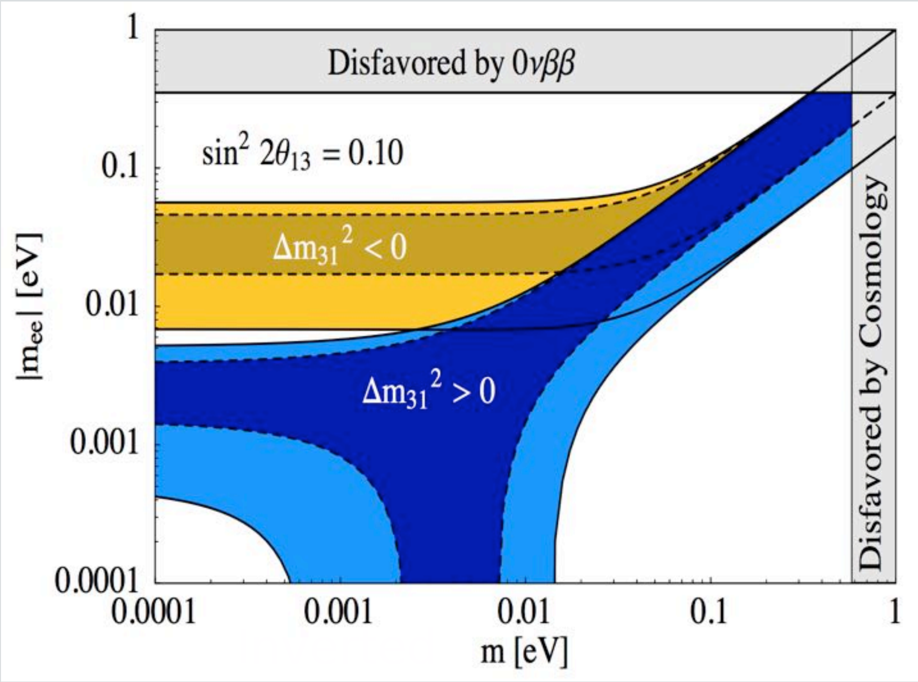
1 building block



The neutrino mass hierarchy

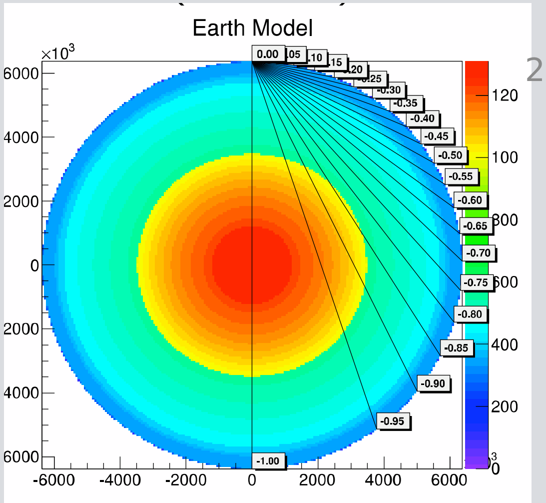
- Prime discriminator for theory models
- Origin of neutrino mass and flavour
- Help measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Core-Collapse Supernovae Physics





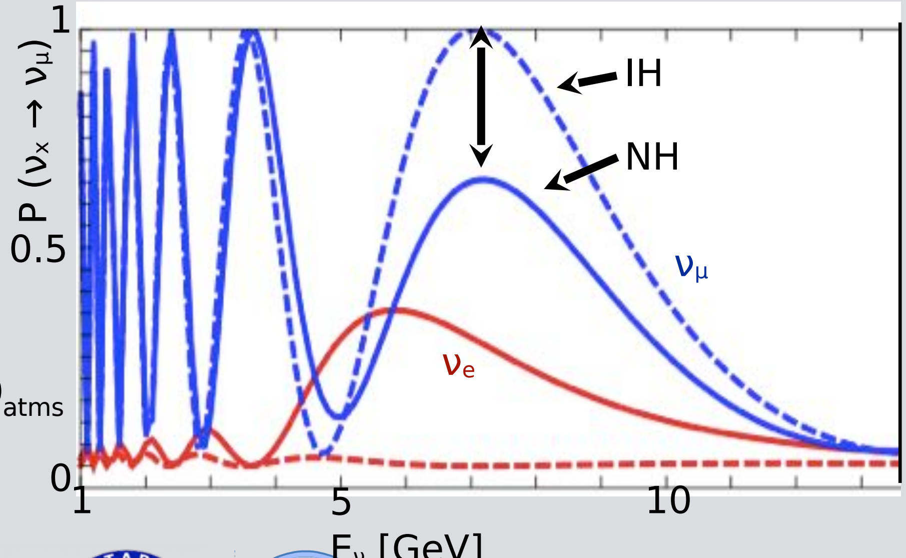
normal

Measuring the neutrino mass hierarchy with atmospheric neutrinos



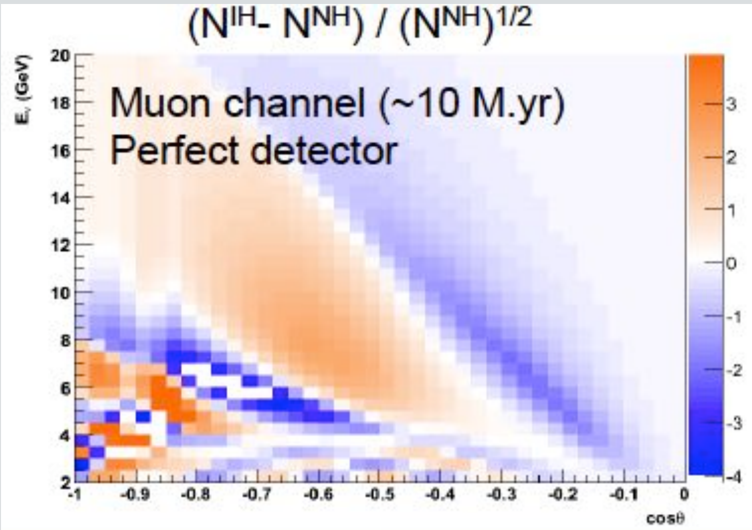
- a « free beam » of known composition (ν_e, ν_μ)
- wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- oscillation pattern distorted by Earth matter effects (hierarchy-dependent):
  maximum difference IH → NH at
  θ=130° (7645 km) and E_ν = 7 GeV
- opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
  BUT differences in flux and cross-section:
  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies
- measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos precisely, identify and count muon and electron channel events
- improve precision on measurement of ΔM^2 and θ_{atms}
- feasible now that θ_{13} is measured to be large

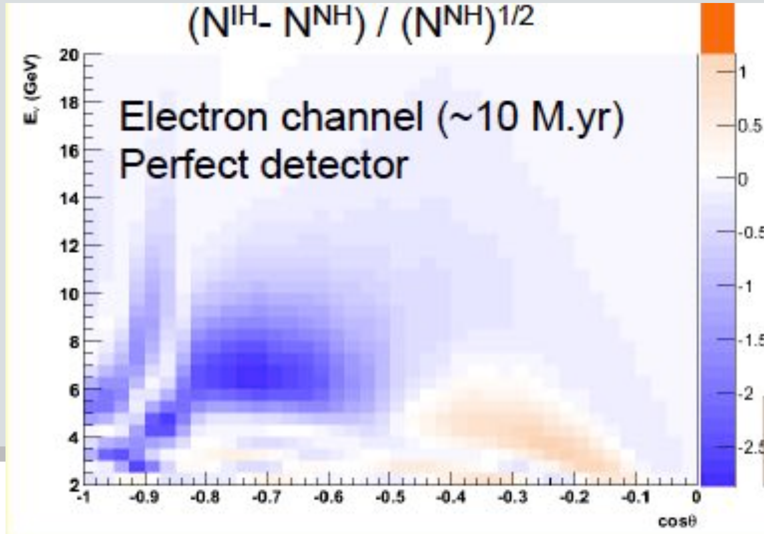
$P(\nu_\mu \to \nu_\mu)$ for θ=130º



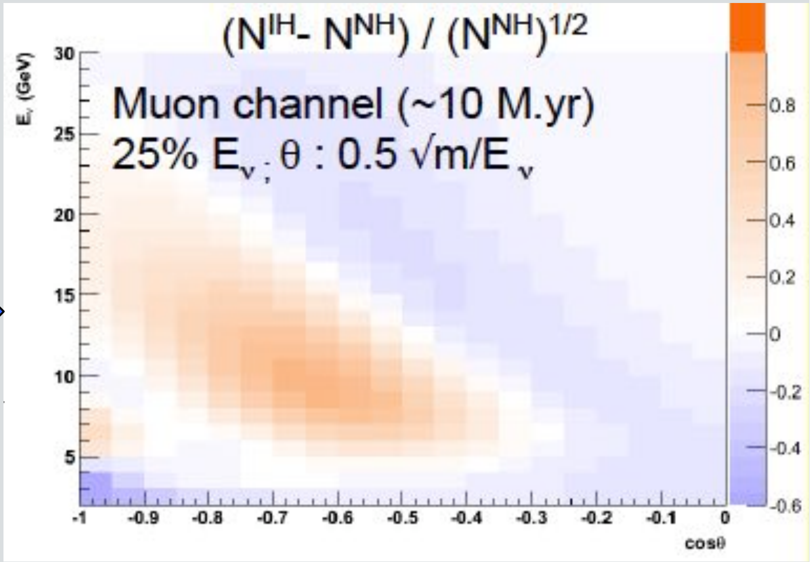
Akmedov, Razzaque & Smirnov, JHEP 02 (2013) 082

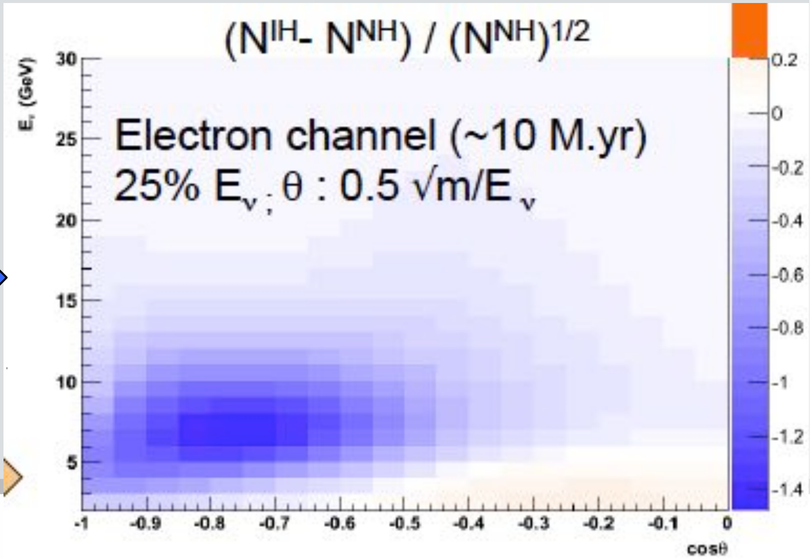
Experimental signature





E, θ smearing (kinematics + detector resolution)





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Important Ingredients

- Direction resolution (track/cascade)
- Energy resolution (track/cascade)
- Cascade versus track separation
- Atmospheric muon background rejection
- Neutral current backgrounds
- Effective volume
- Geometry optimisation
- Trigger efficiency and rates (atms mu@36Hz, K40@19Hz)
- Systematic uncertainties

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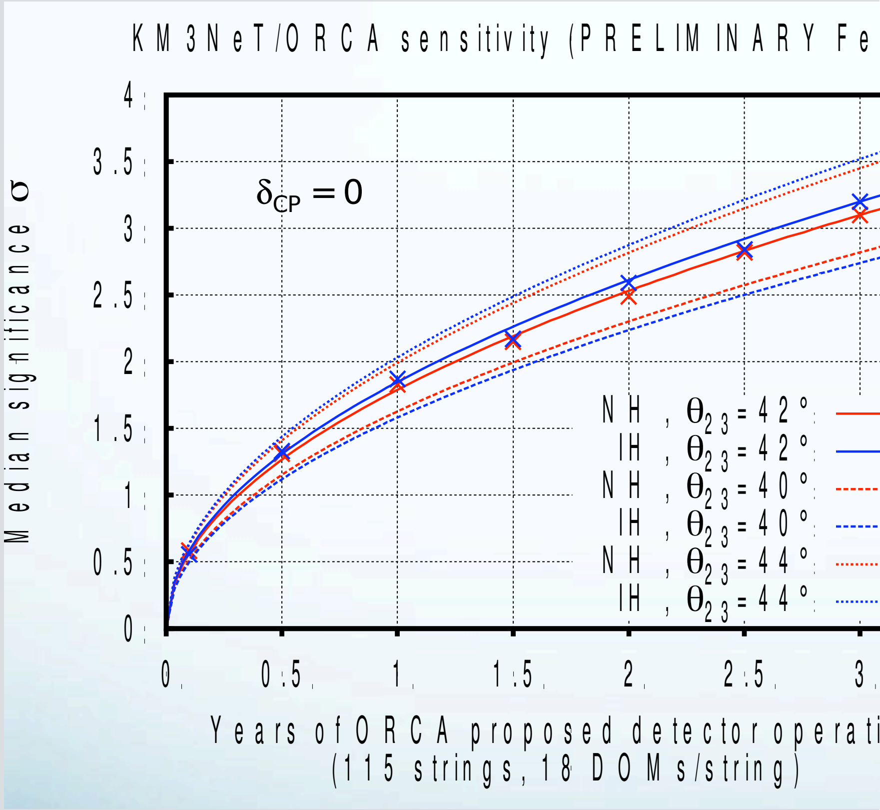
Expected NMH Sensitivity

Latest results include:
- Track vs shower event classification
- Full MC detector response matrices
- Atmospheric muon contamination
- Neutral current event contamination
- Caveat: here $\delta_{CP} = 0$ fixed to zero and fit constrained to first quadrant
- Interplay between parameters under investigation
- room for improvement:
  - combined track+shower reco,
  - Bjorken-y,
  - detector optimisation...



3 sigma in 3 years

Expected NMH Sensitivity

Latest results include:

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Atmospheric muon contamination

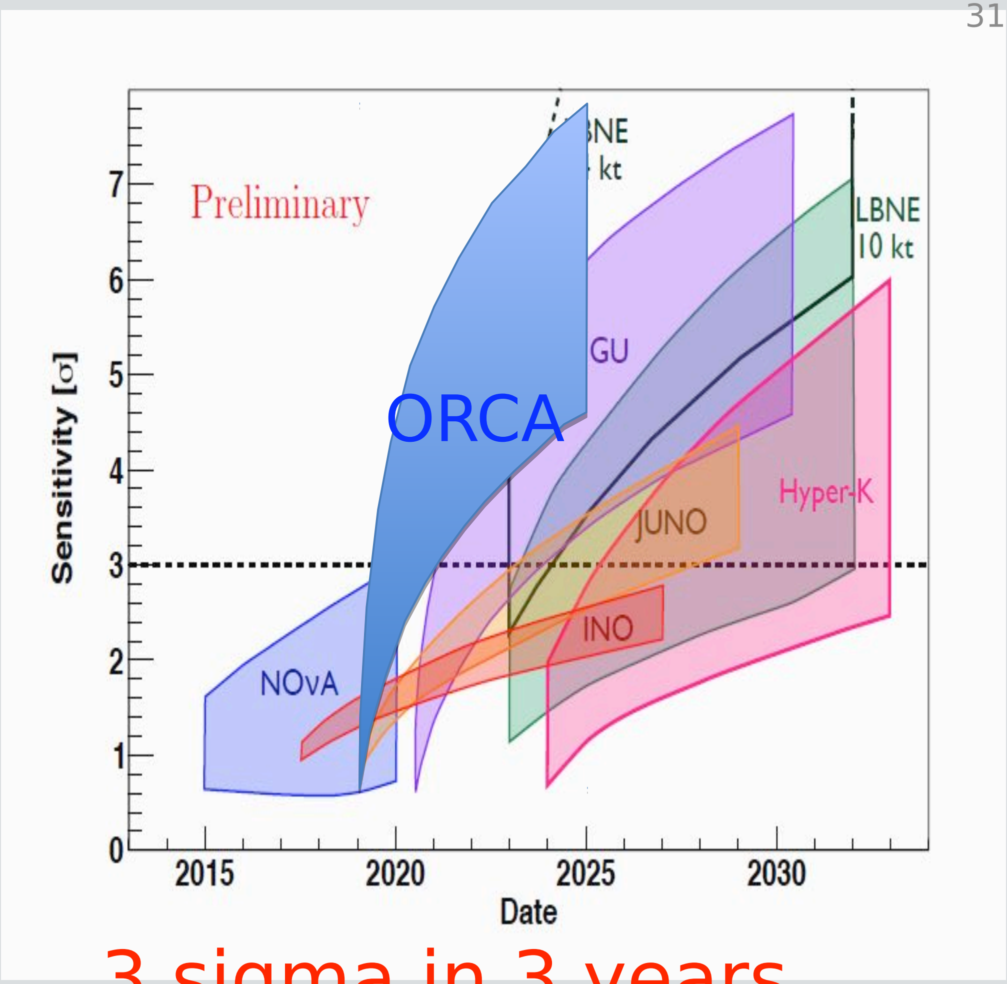
Neutral current event contamination

Caveat: here $\delta_{CP} = 0$ fixed to zero and fit constrained to first quadrant

Interplay between parameters under investigation

room for improvement:

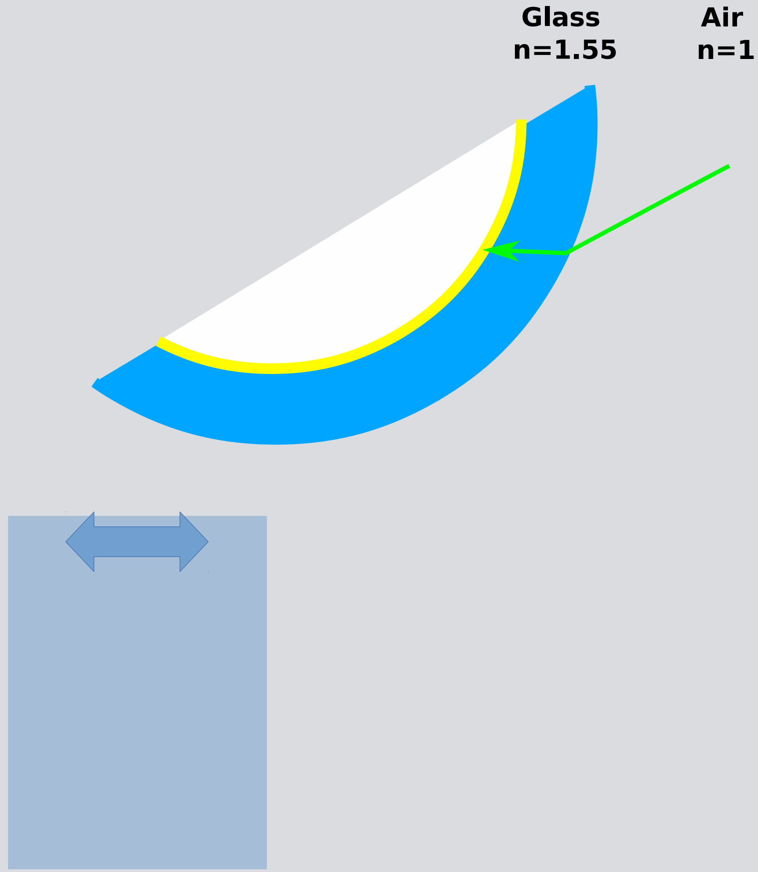
- combined track+shower reco,
- Bjorken-y,
- detector optimisation...

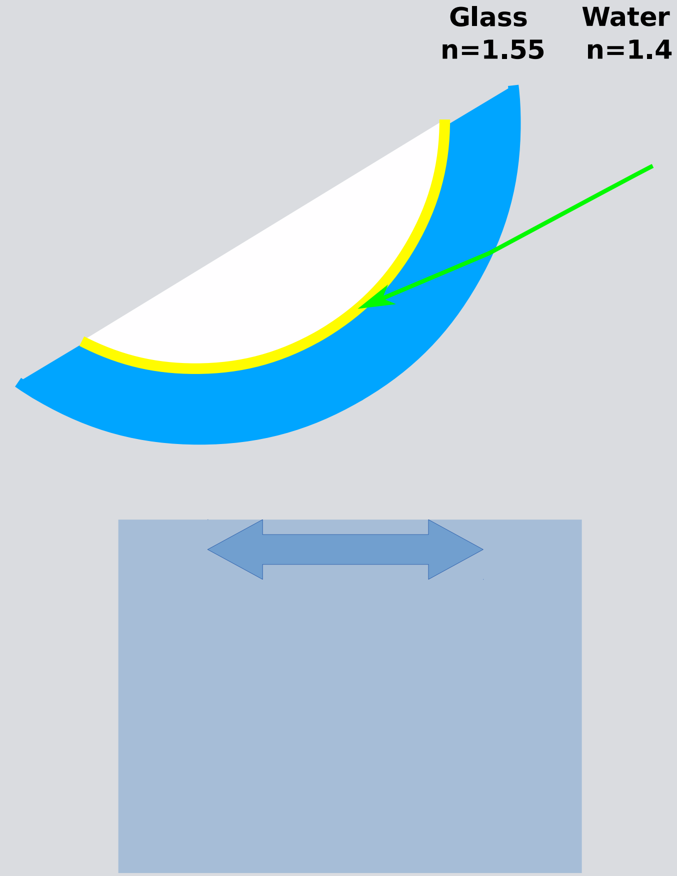


3 sigma in 3 years

Why is it important for neutrino telescopes

- Due to the refraction, the effect is negligible in air but strond in water



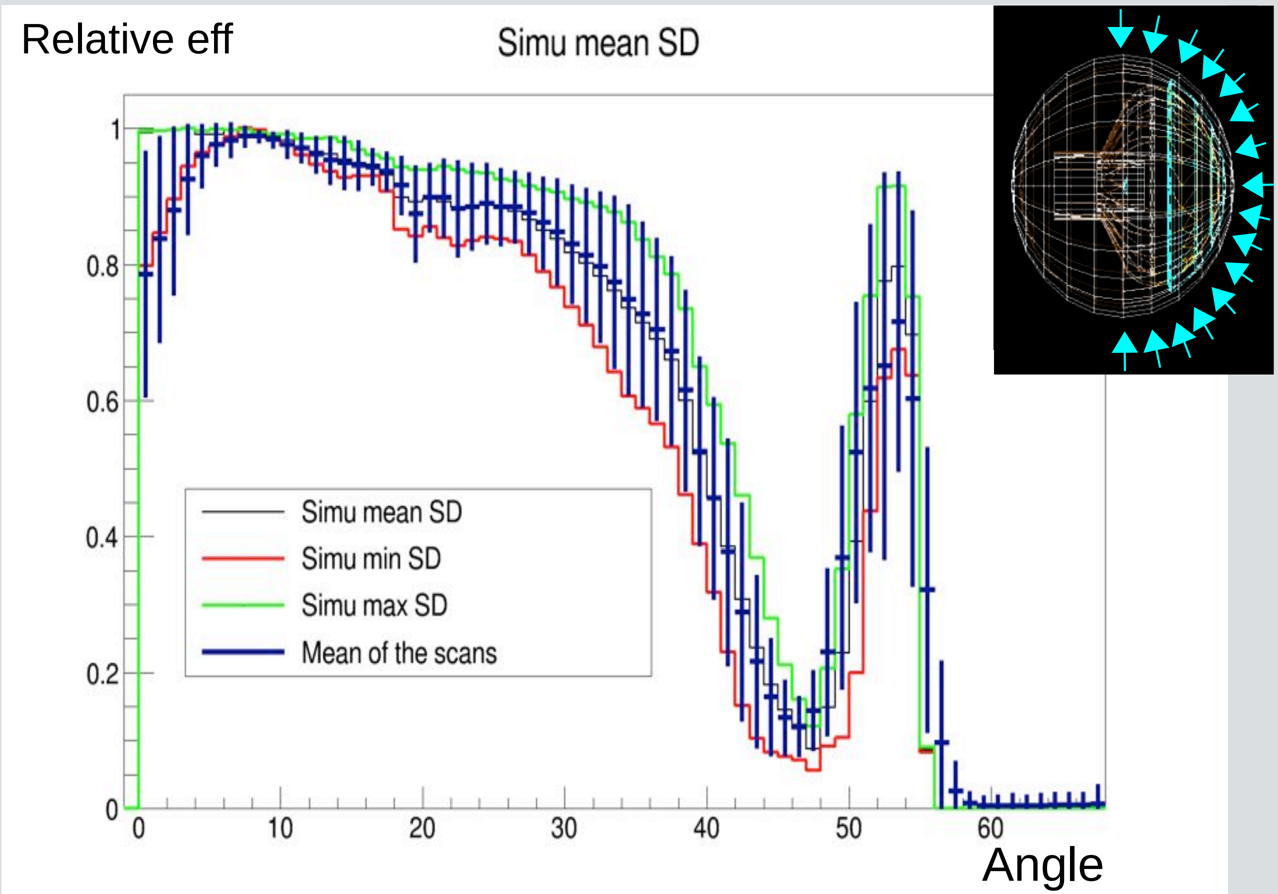


But what's about the QE in this model?

- The quantum efficiency is directly derived from the complex index
  - The absorption emit an electron of a considered quasi constant energy of about 1 eV
  - The electron has a mean free path of few tens of nm
  - When the electron reach the vacuum, its immediately accelerated by the electric field
  - Then the detection probability will depend to the dinods efficiency
- Those process are taken in account, but is the complex index well defined?

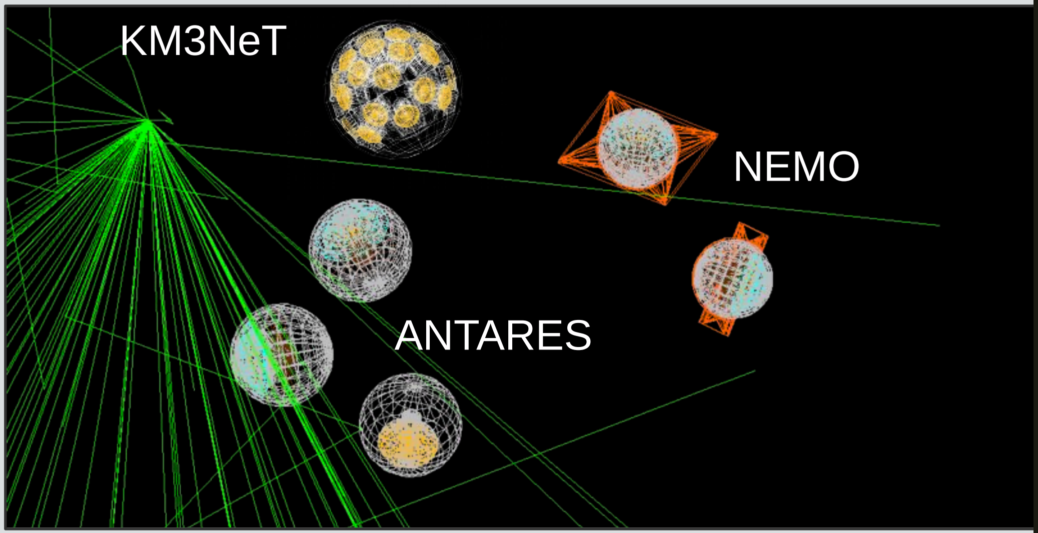
Scan fit for data and simulation

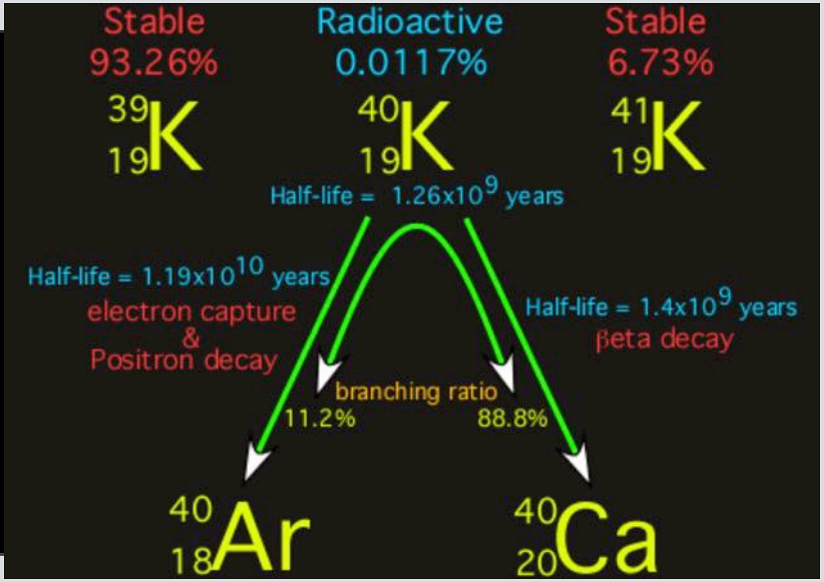
Simulation and data of OM efficiency



Very good fit between the simulation and data measurement done in laboratory on the different Optical modules

Results on ^{40}K measurements

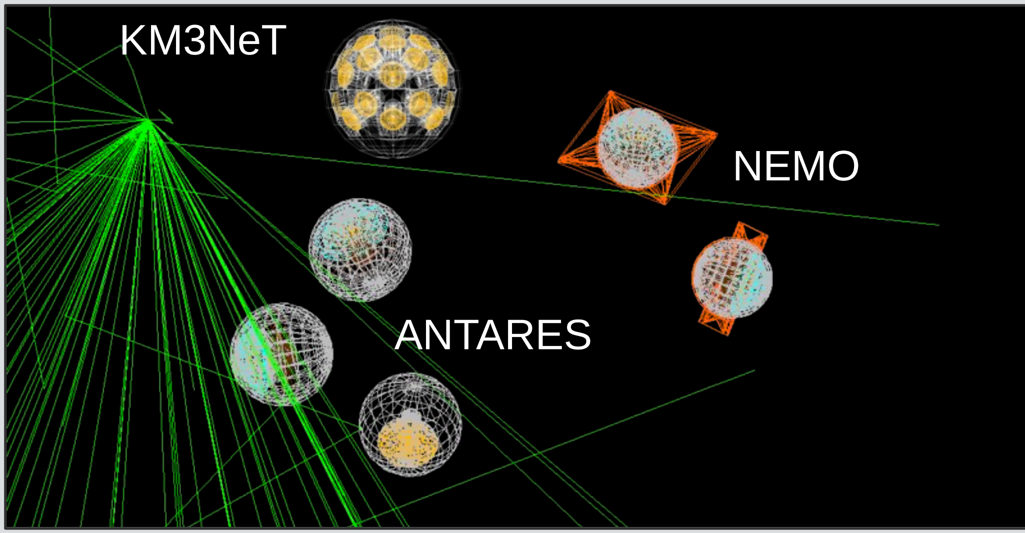


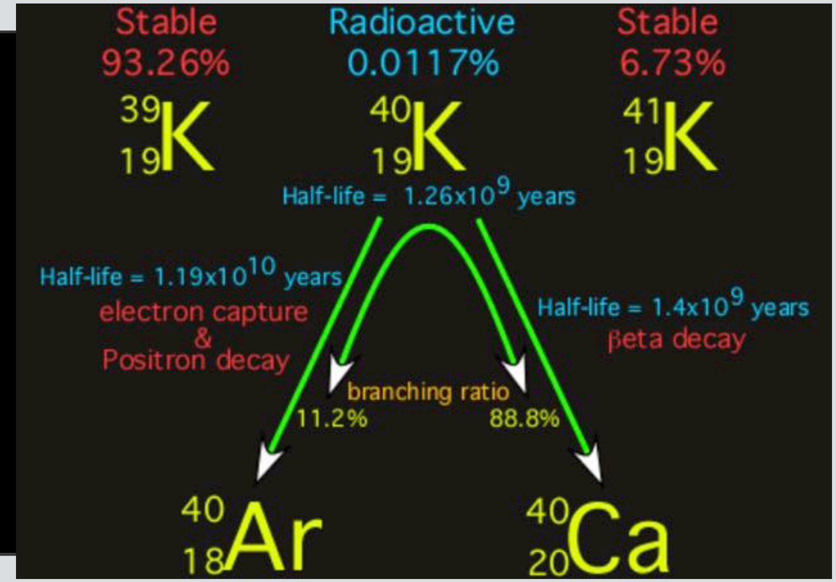


The ^{40}K natural rate is extremely stable
The coincidences rates permits to

- Calibrate the simulation and check the PMT trigger efficiency
- Evaluate the efficiency PMT per PMT/ OM per OM

Results on ^{40}K measurements

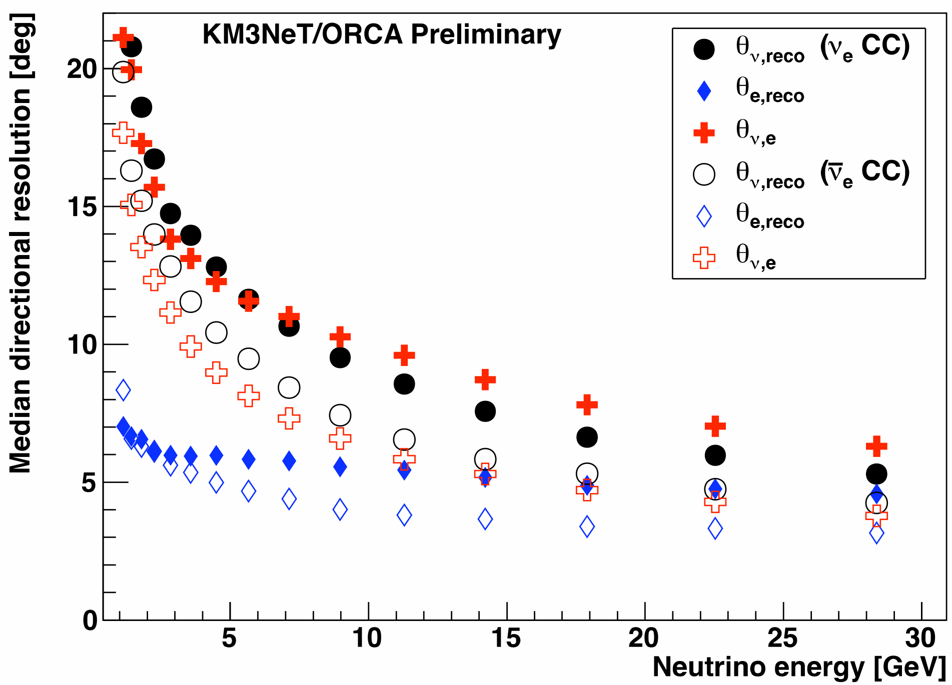


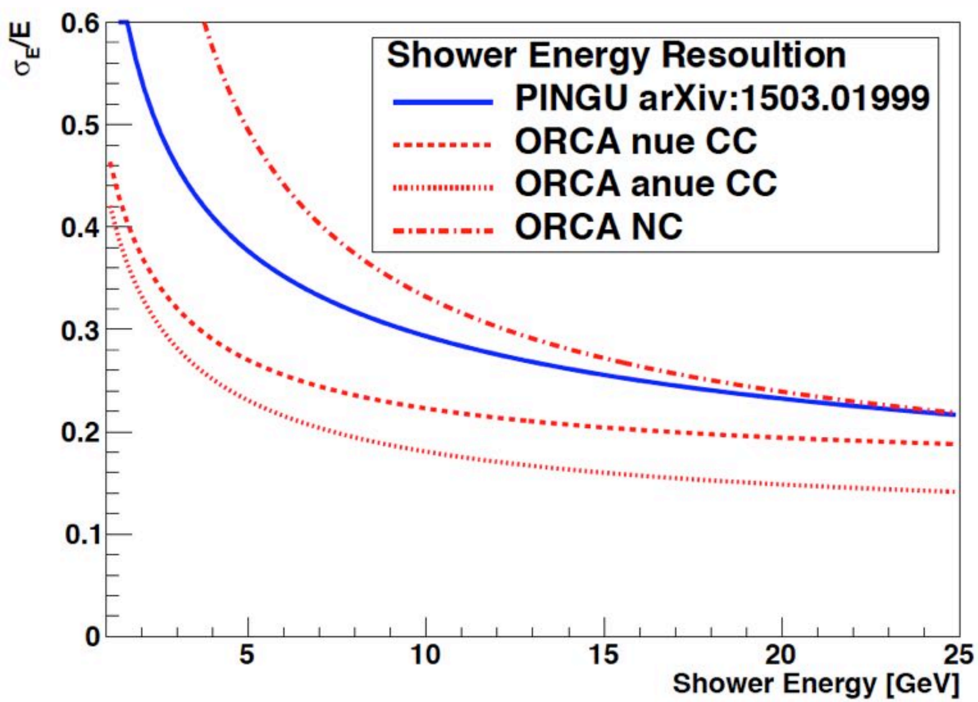


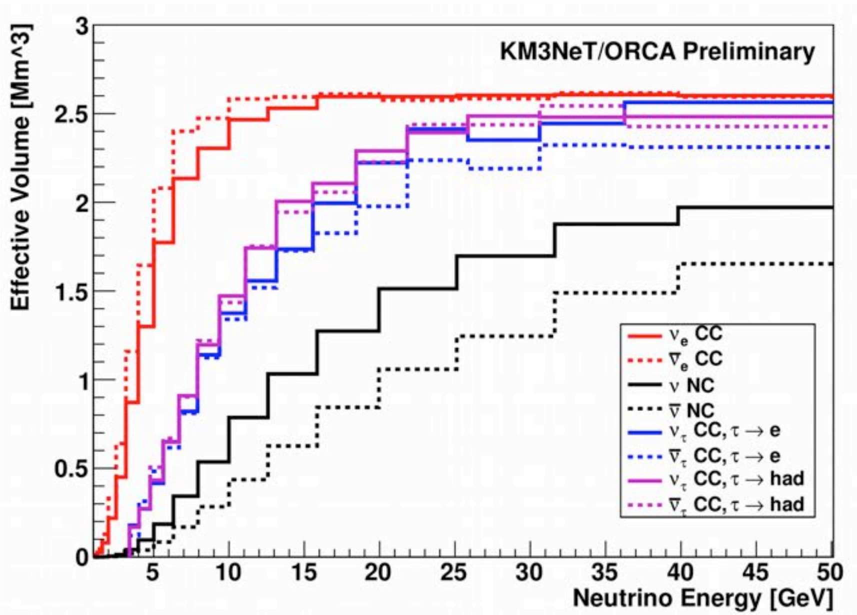
Experiment	Antares	NEMO
Experimental ^{40}K coincidences rate	15.5 Hz	21.0 Hz
Simulated ^{40}K coincidence rate	15.3 Hz	21.6 Hz

KM3NeT coincidences folds	2	3	4
Experimental ^{40}K coincidences rate	1.2 kHz	45 Hz	4.5 Hz
Simulated ^{40}K coincidence rate	1.2 kHz	50 Hz	6 Hz

ower reconstruction Performance (similar for nu mu)







Background Rejection

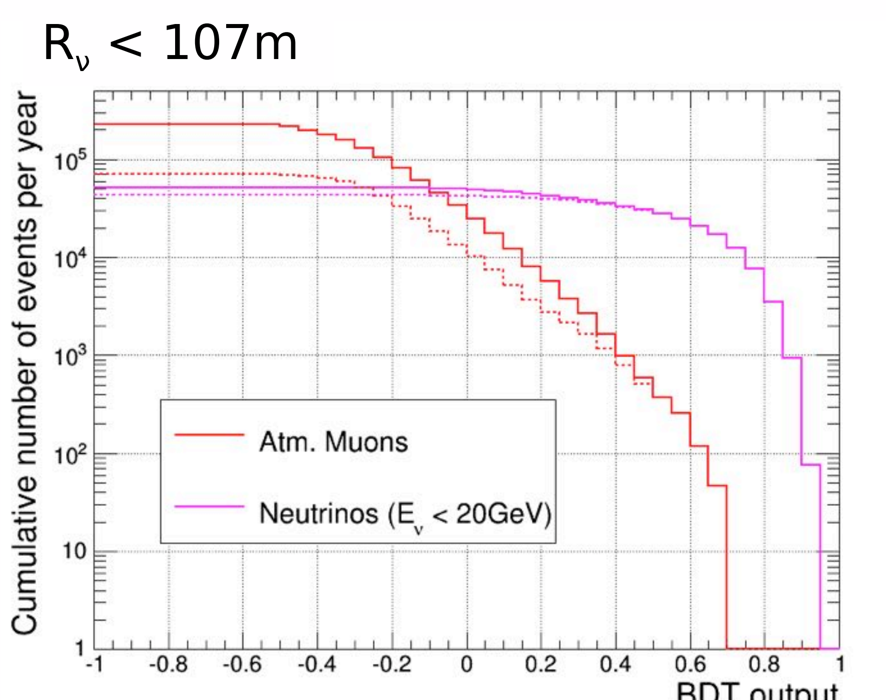
Main backgound: atmospheric muons misreconstructed as upgoing

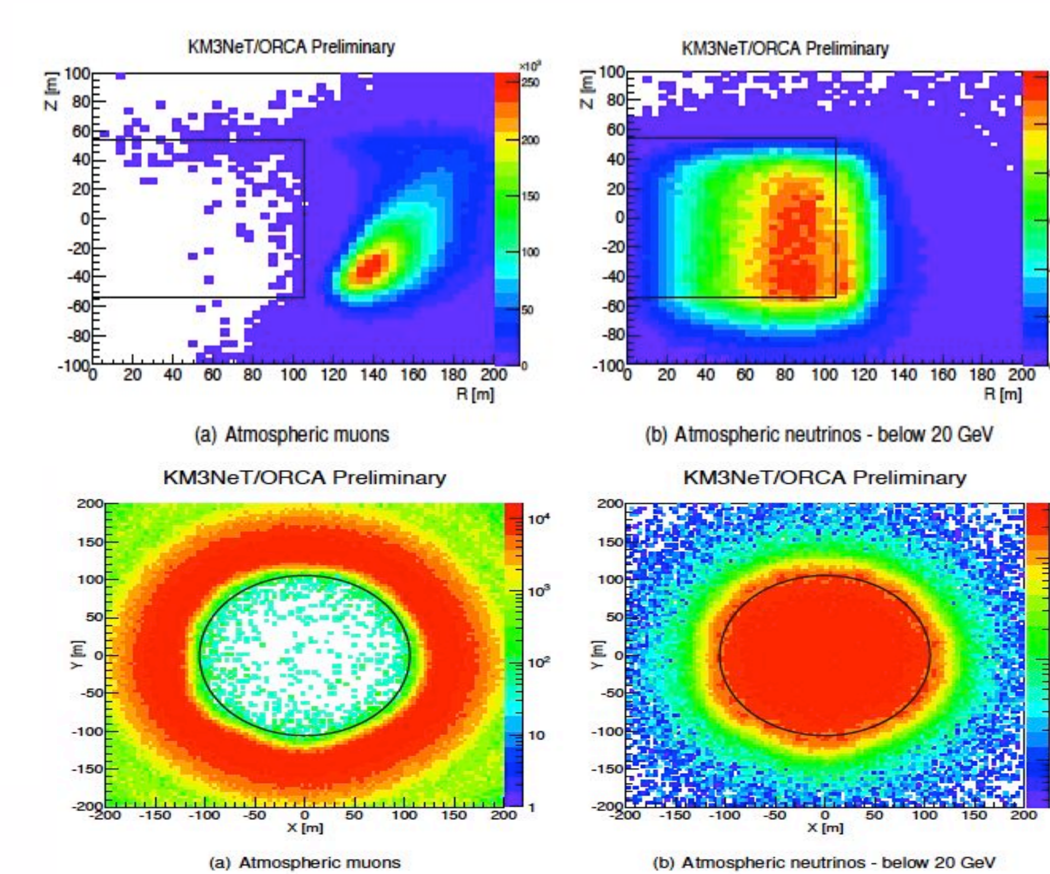
Muon contamination efficiently suppressed by cuts on

- track fit quality parameter Λ
- reconstructed position of vertex:
- R_ν inside instrumented volume

Optimisation procedure based on boosted decision tree

1% contamination rate achievable, with small signal loss





(a) Atmospheric muons

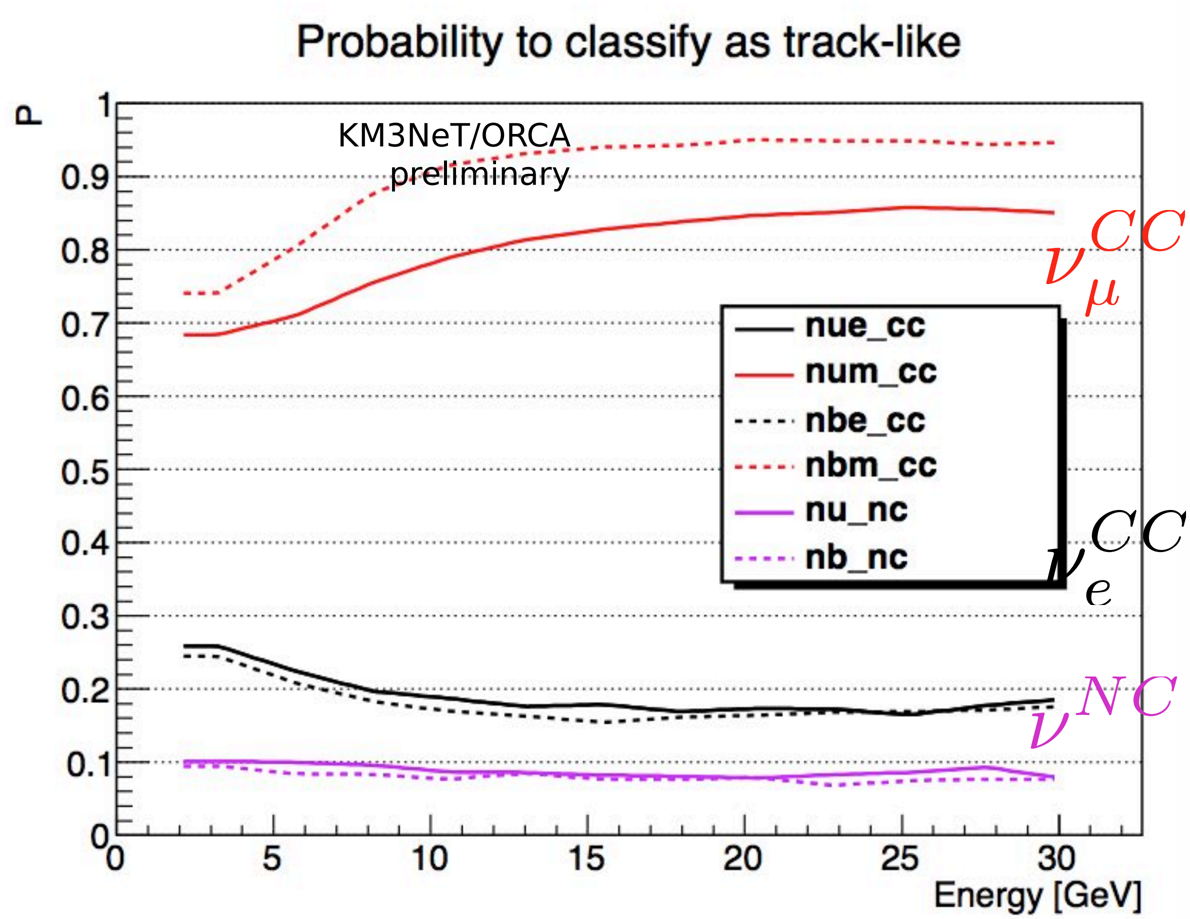
(b) Atmospheric neutrinos - below 20 GeV

(a) Atmospheric muons

(b) Atmospheric neutrinos - below 20 GeV

Flavour (mis)identification

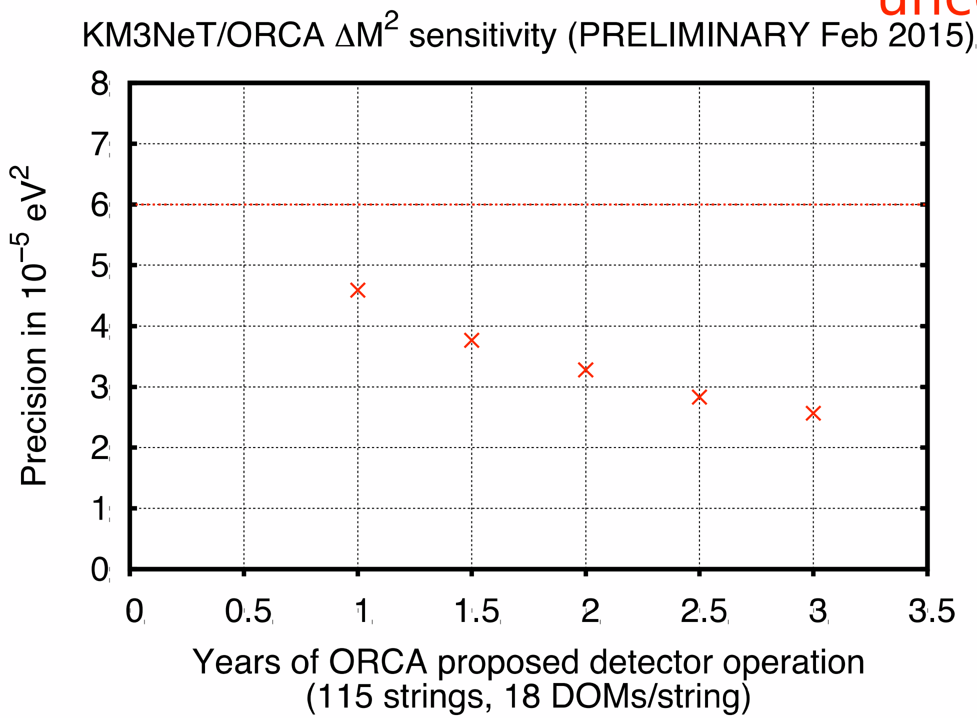
- Discrimination between 2 classes of events:
  track-like (ν_μ^{CC}) and shower-like (ν^{NC}, ν_e^{CC})
- Classification using “Random Decision Forest“ machine-learning algorithm
- Discrimination mainly due to event reconstruction observables

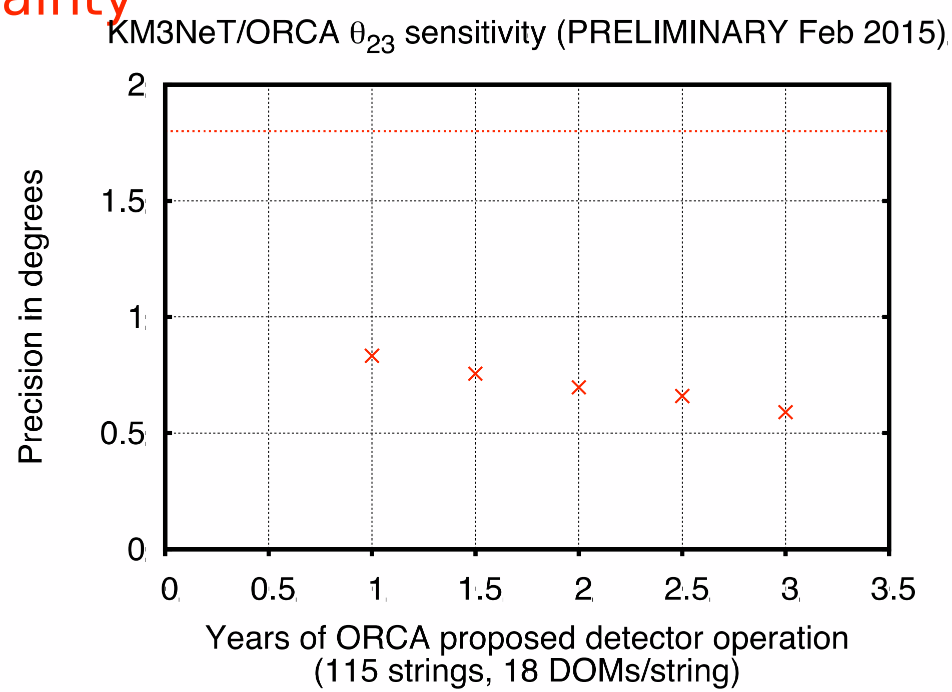


80 to 90% correct event topology identification

Sensitivity to PMNS parameters

Red dotted line: current world-average uncertainty

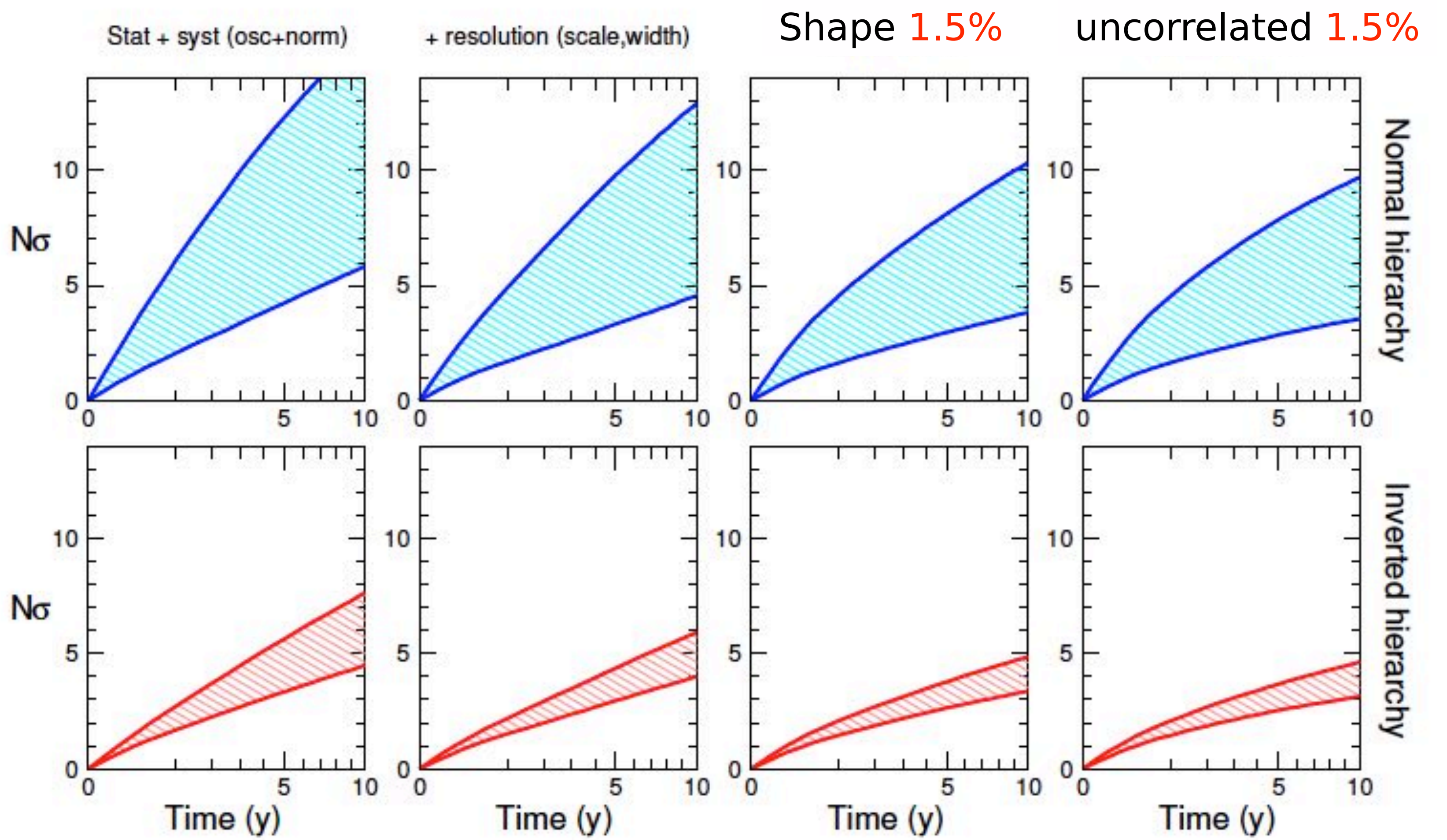




Caveat: here $\delta_{CP} = 0$ fixed to zero
and fit constrained to first quadrant

Studies of systematics

Capozzi et al. arXiv1503.01999
PINGU resolutions and effective masses



$\sin^2\theta_{23}$ in [0.4; 0.6]

Studies of Systematics (WIP)

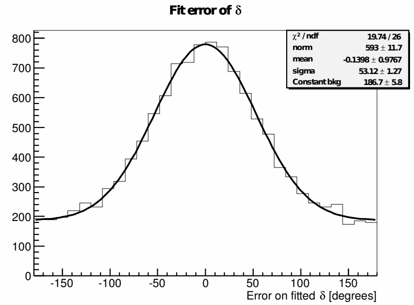
Effect	Nuisance Parameter	Default	Constraint
Normalisation	R_{Norm}	1	none
Mass difference	ΔM^2	$2.43 \cdot 10^{-3}$ eV	none
Mixing angle	θ_{13}	9°	1°
Mixing angle	θ_{23}	39°	none
CP phase	δ_{CP}	0	none
Energy slope	ϵ_E	0	3%
Energy scale	Δ_E	0	0.3 GeV
Angular slope	$\epsilon_{\cos\vartheta}$	0	1%
Angular scale	$\Delta_{\cos\vartheta}$	0	0.01
Asymmetry $\nu/\bar{\nu}$	$\varepsilon(\nu/\bar{\nu})$	0	0.03
Asymmetry μ/e	$\varepsilon(\mu/e)$	0	0.05
$track/shower$	$\varepsilon(tr/sh)$	0	0.05
NC scale	ε_{NC}	0	0.05
ν_τ scale	ε_{ν_τ}	0	0.05
$\sigma(E)$ scale	$\varepsilon_{\sigma(E)}$	0	0.05
$\sigma(\cos\vartheta)$ scale	$\varepsilon_{\sigma(\cos\vartheta)}$	0	0.05

Left free in the fit

Table 6: Summary of systematic effects

Coming soon: simultaneous minimisation with up to 7 degrees of freedc

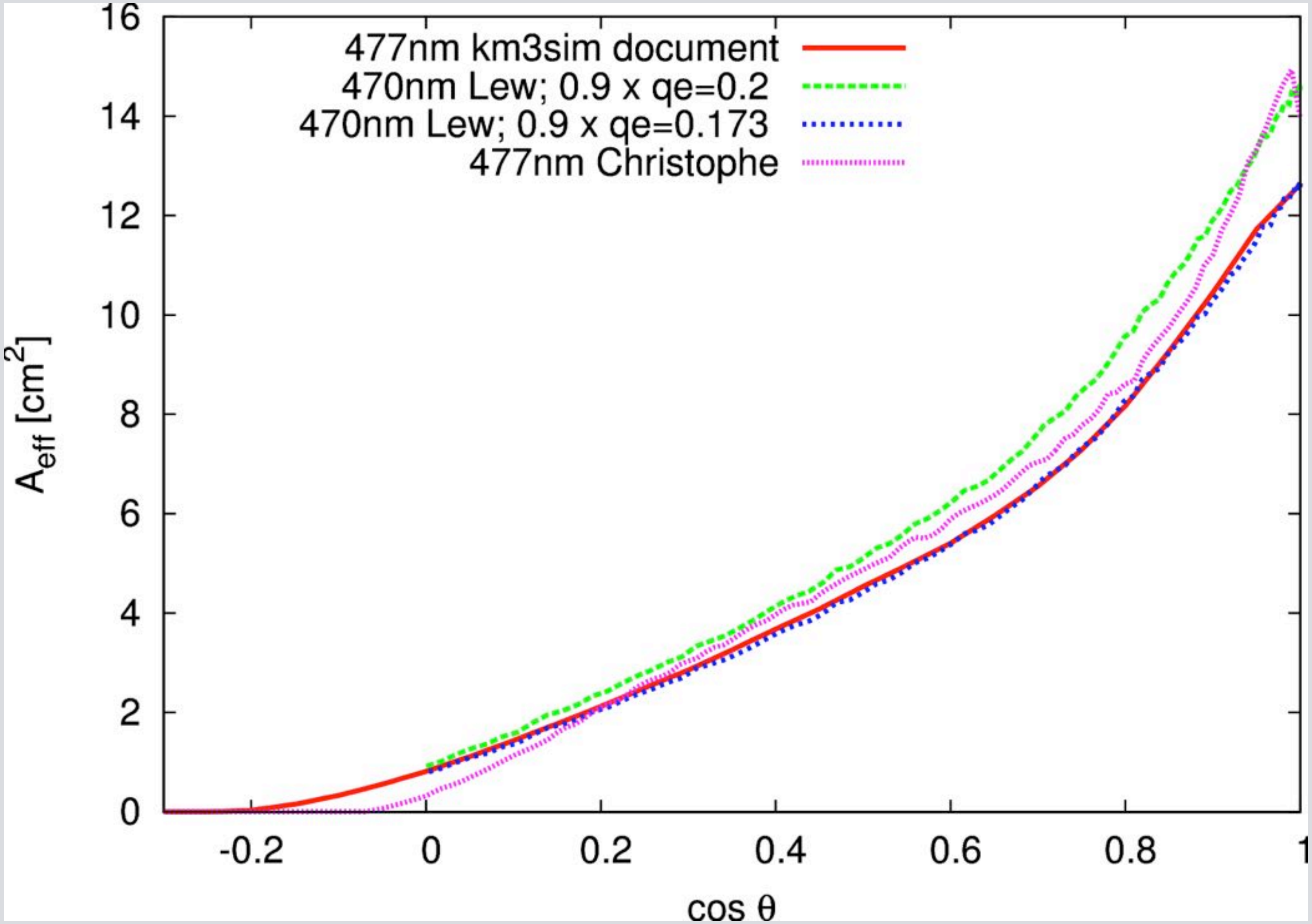
Reasonable computing time
Minimisation converges without problems
first indications-effect of new systematics small

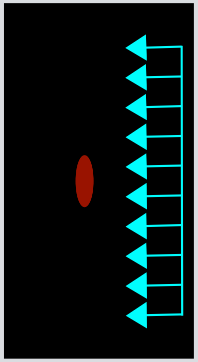


Distribution of the error on the fitted value for NH pseudo-experiments.

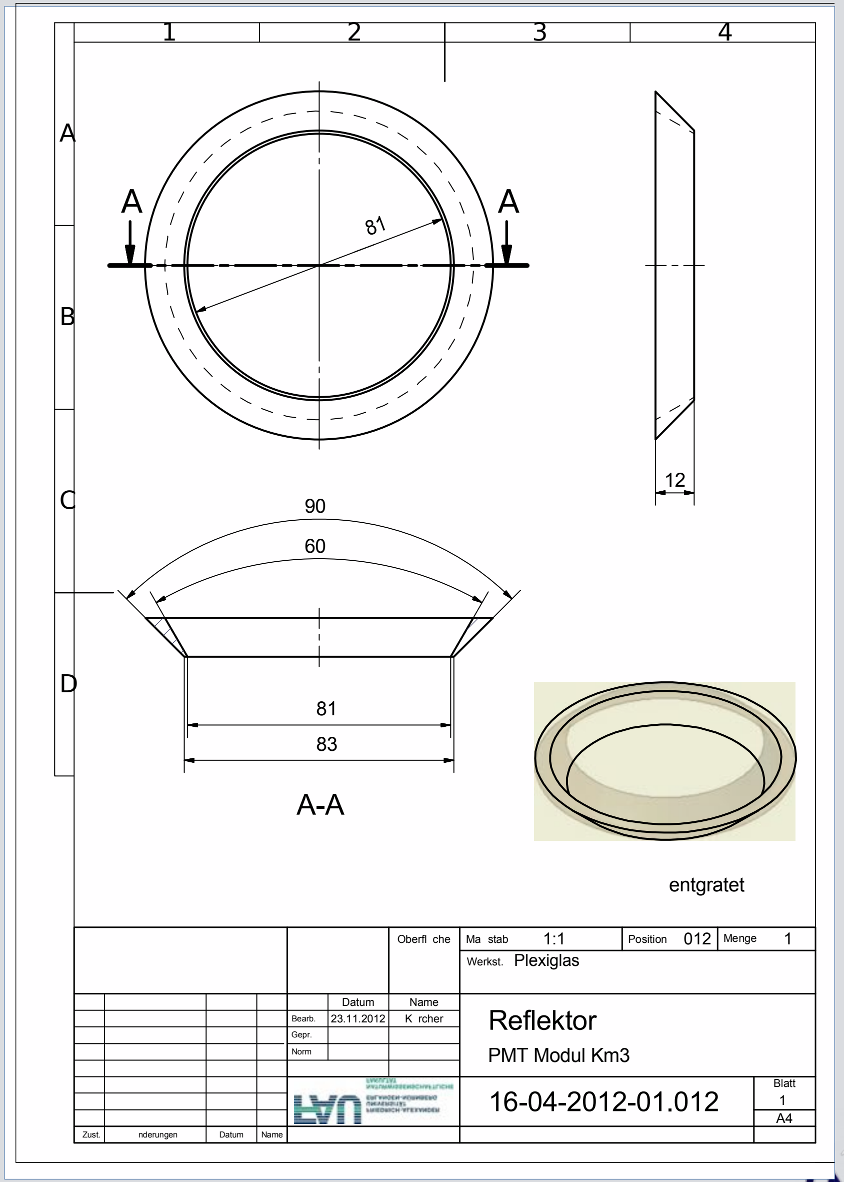
53° resolution on CP phase

Angular efficiency with comparision with the old simulation



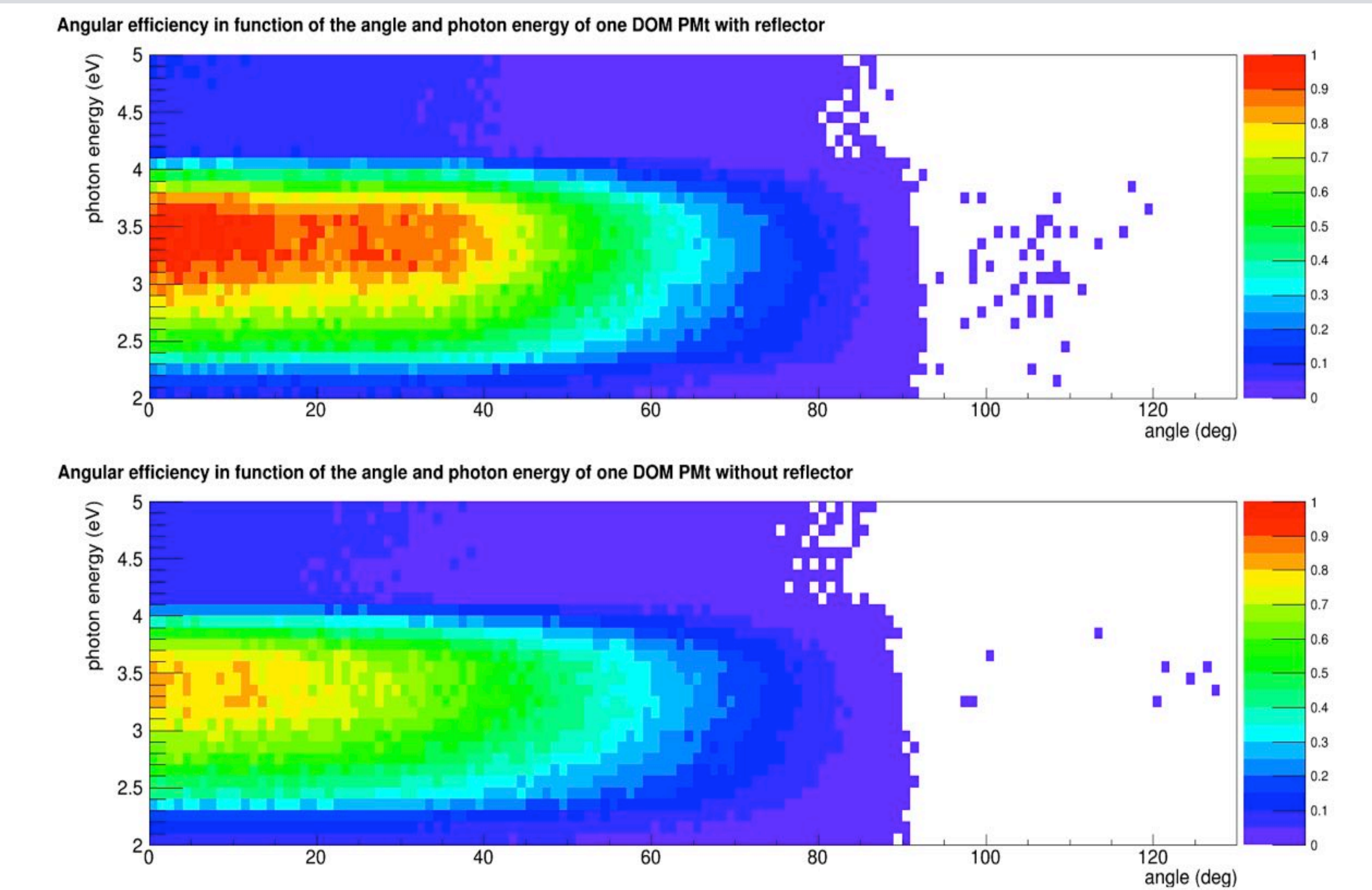


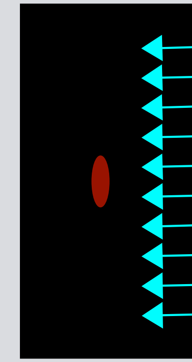
Angular efficiency, why it wasn't seen before



Simply believed that the cone angle was 30 degree from its technical design

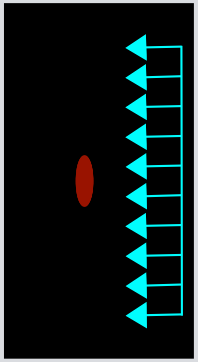
Angular efficiency, why it wasn't see before

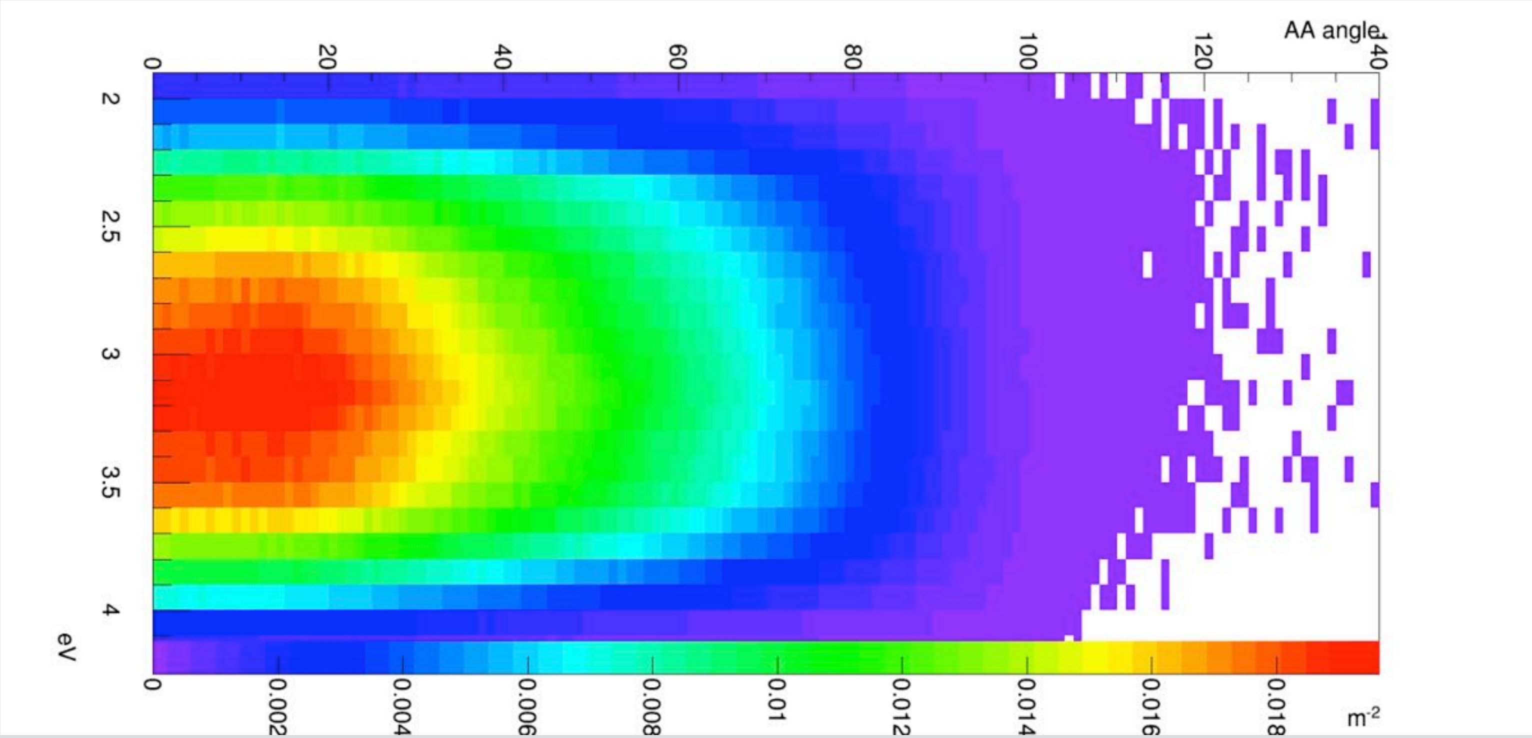




The preliminary results sounded correct

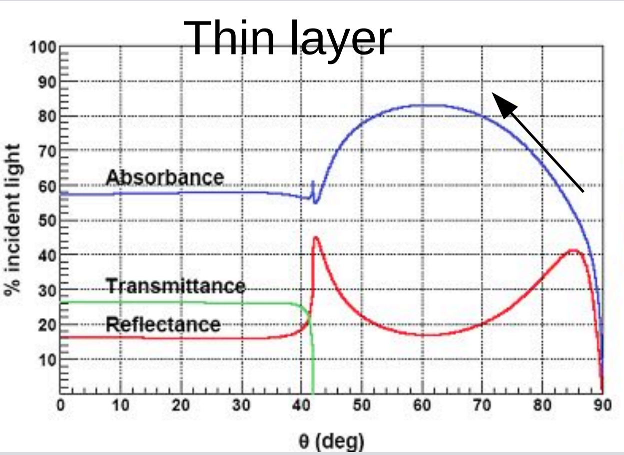
Effect in air strongly reduced

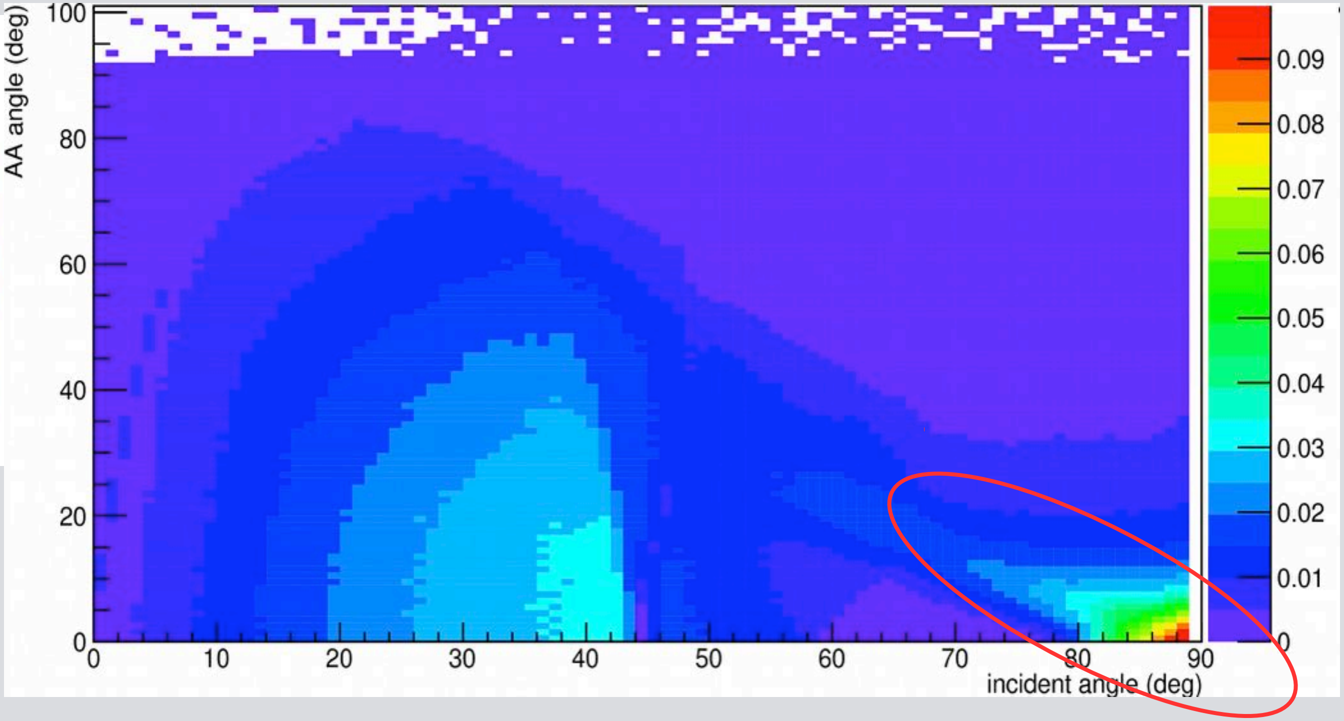




It cannot be seen in air, so experimentally hard to find out (needs measurements in water)

Where it comes from: 0 deg

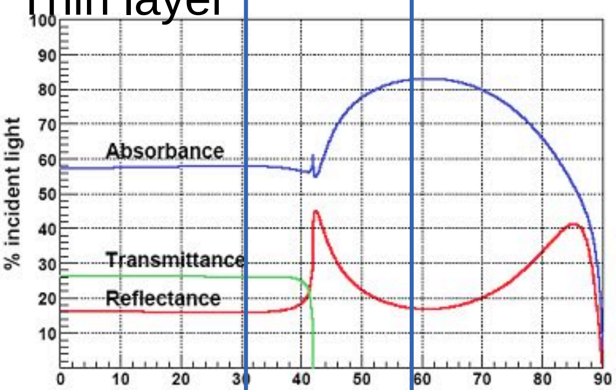




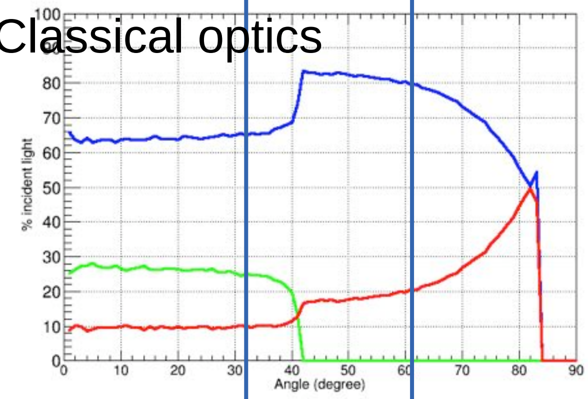
The angle of impact of a big part of events are at very big angle for small AA angle. Then it shift to higher efficiency zone.

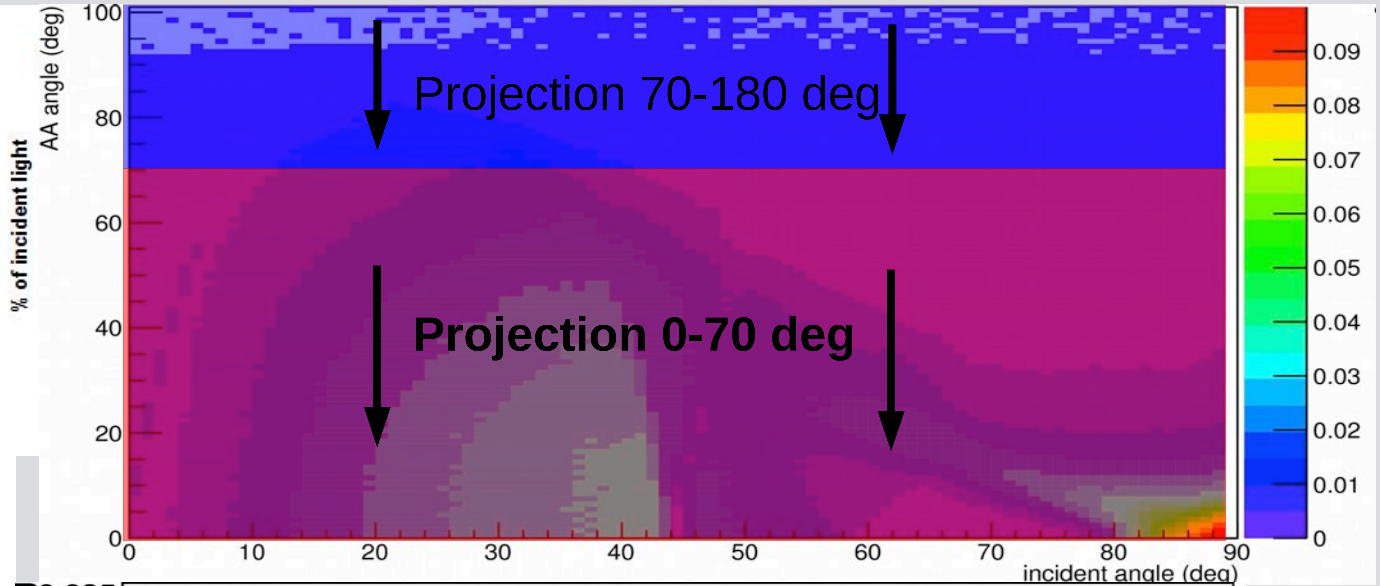
Where it comes from: 70 deg

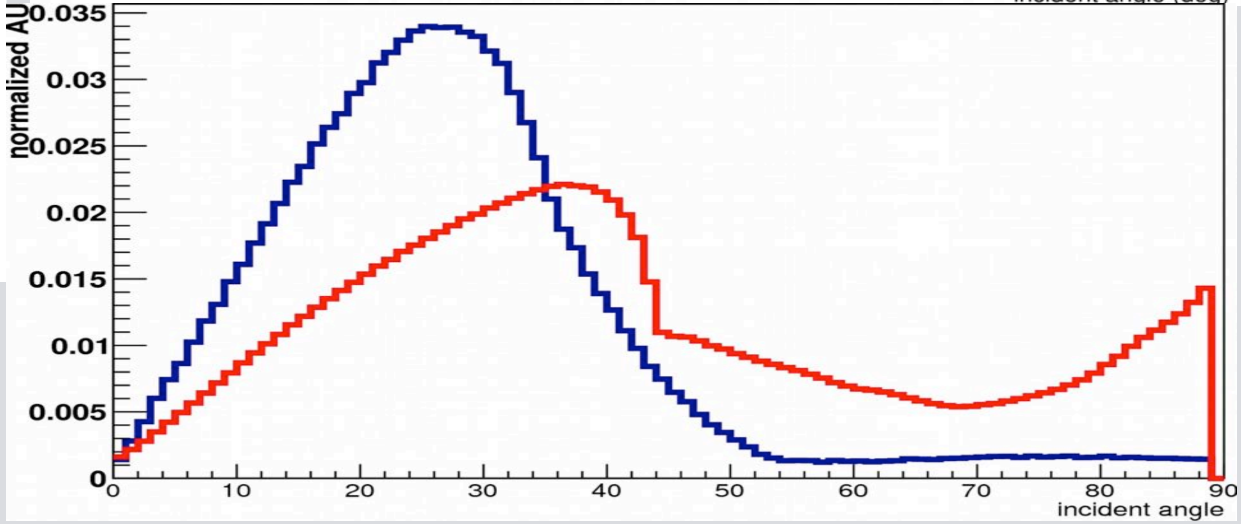
Thin layer



Classical optics







Still under investigation, the effect might be due to the 40-60 zone