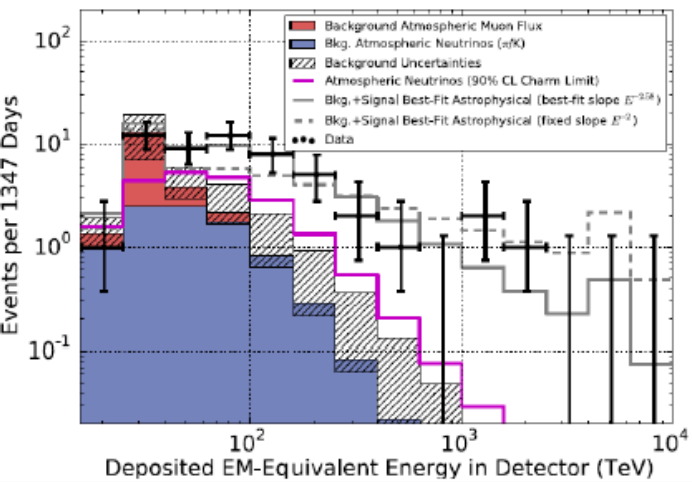
KM3NeT: neutrino astronomy and oscillation research in the Mediterranean

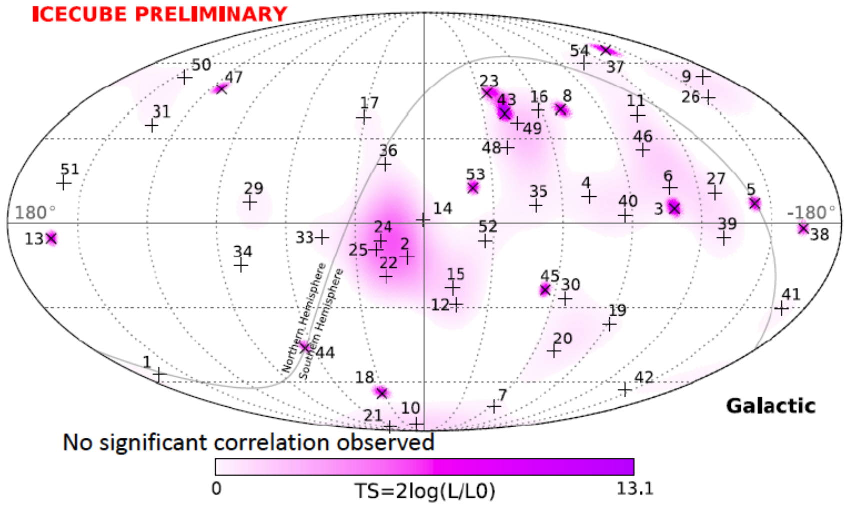
TeV Particle Astrophysics 2015
Kashiwa, Japan
October 26-30

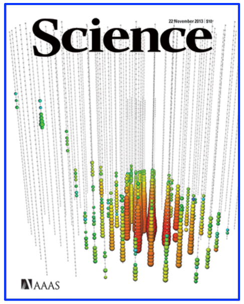
Véronique Van Elewyck
(APC & Université Paris Diderot)
on behalf of
the KM3NeT Collaboration

Neutrino astronomy

It's starting now !







… the next challenges:

? WHERE AND WHICH ARE THE SOURCES ?
main observables: spectrum – composition - anisotropies

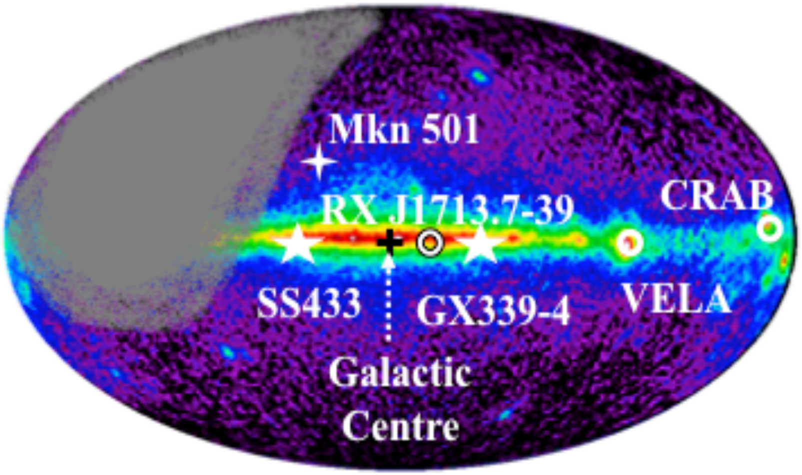
→ need good angular/energy accuracy
all-flavour astronomy
multi-messenger programs

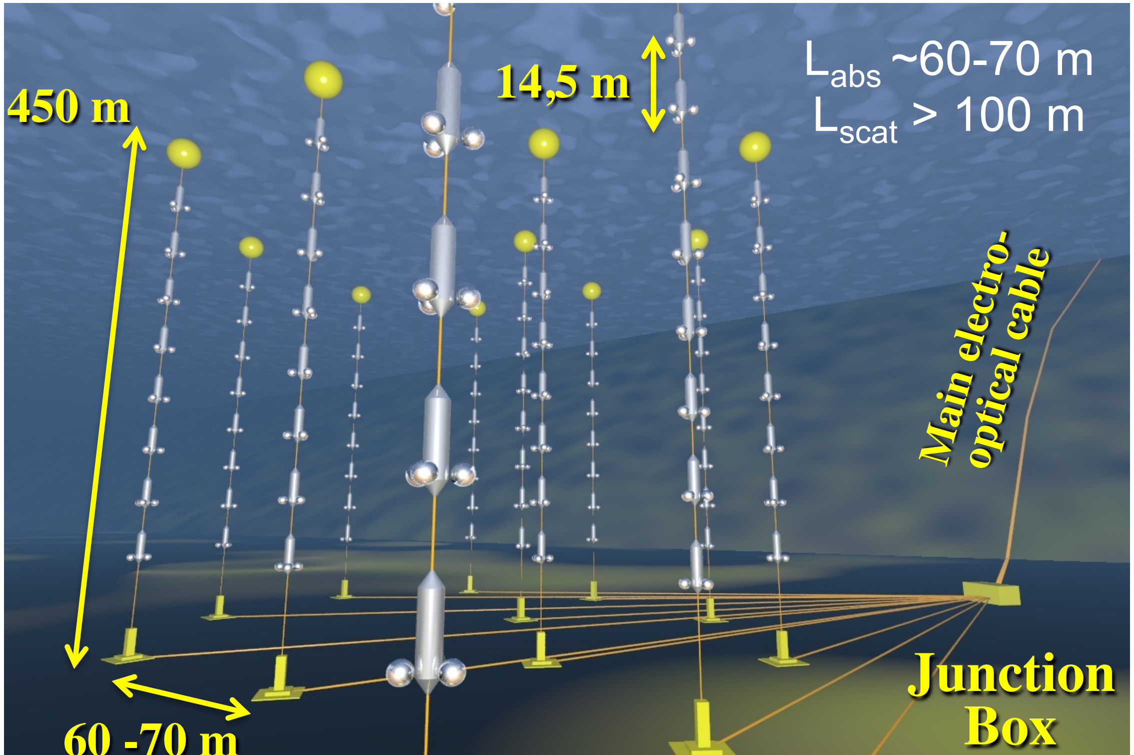
+ new opportunities in particle physics !

Deep-sea neutrino telescopes will bring new insights !

Neutrino telescopes in the Mediterranean Sea

- ✓ Complementarity to IceCube South Pole
  - ➡ excellent view of most of the Galaxy
- ✓ Long (homogeneous) scattering length
  - ➡ good pointing accuracy
- ✓ Deep sites: 2500→5000m
  - ➡ shielding from downgoing muons
- ✓ Close to shore
  - ➡ logistically attractive (deployment/repair)





ANTARES:
First undersea neutrino telescope, completed 2008 offshore Toulon (France)

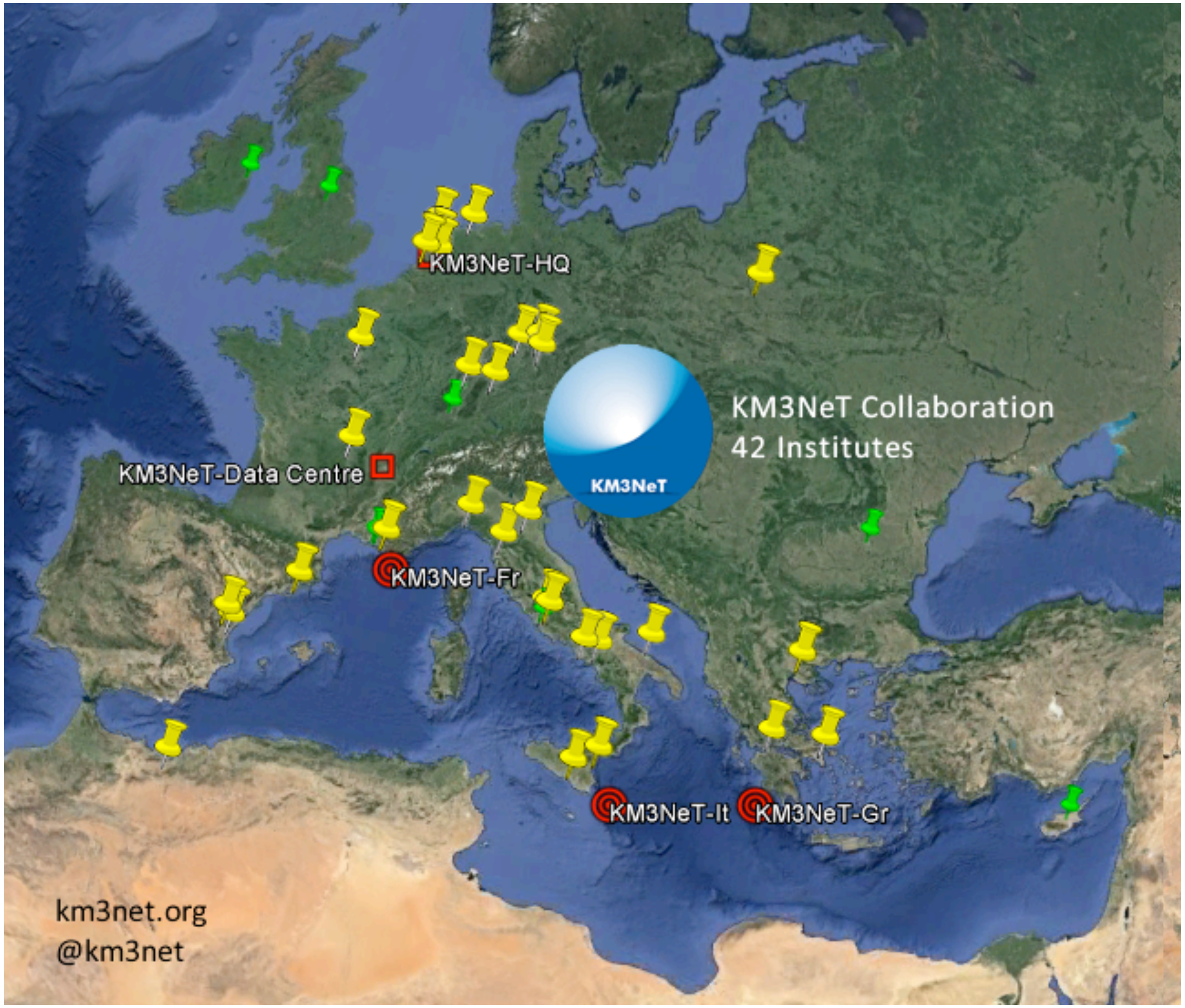
12 lines, ~0.01 km^3 instrumented

Small, but already constrains some scenarios for the IC signal…

See talk by R. Gracia
Thursday Neutrino Session

The next generation: KM3NeT

The Collaboration: 240 people, 42 institutes, 12 countries

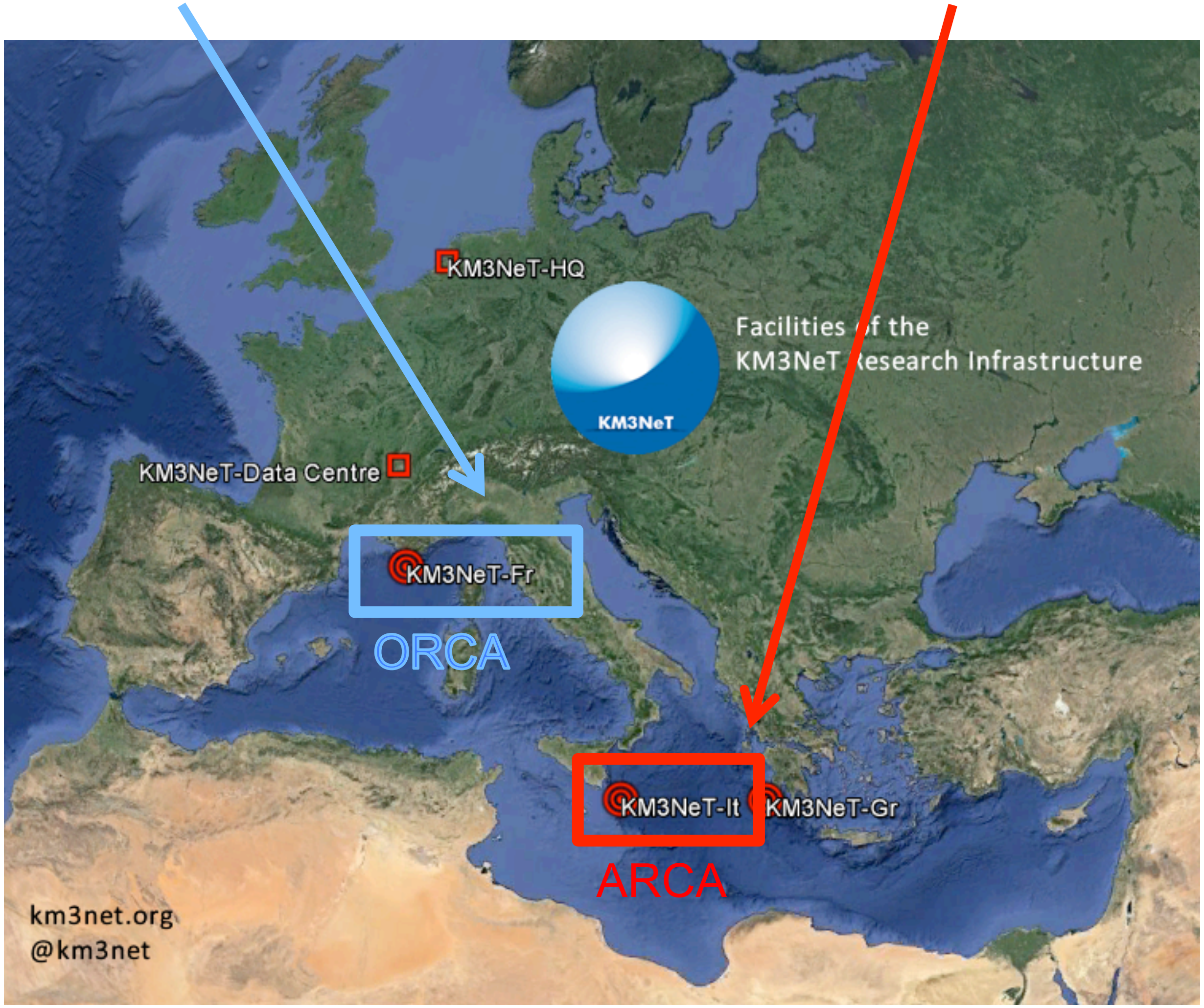


The next generation: KM3NeT

KM3NeT is a distributed research infrastructure with 2 main physics topics:

Oscillations and Astroparticle Research with Cosmics in the Abyss

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos



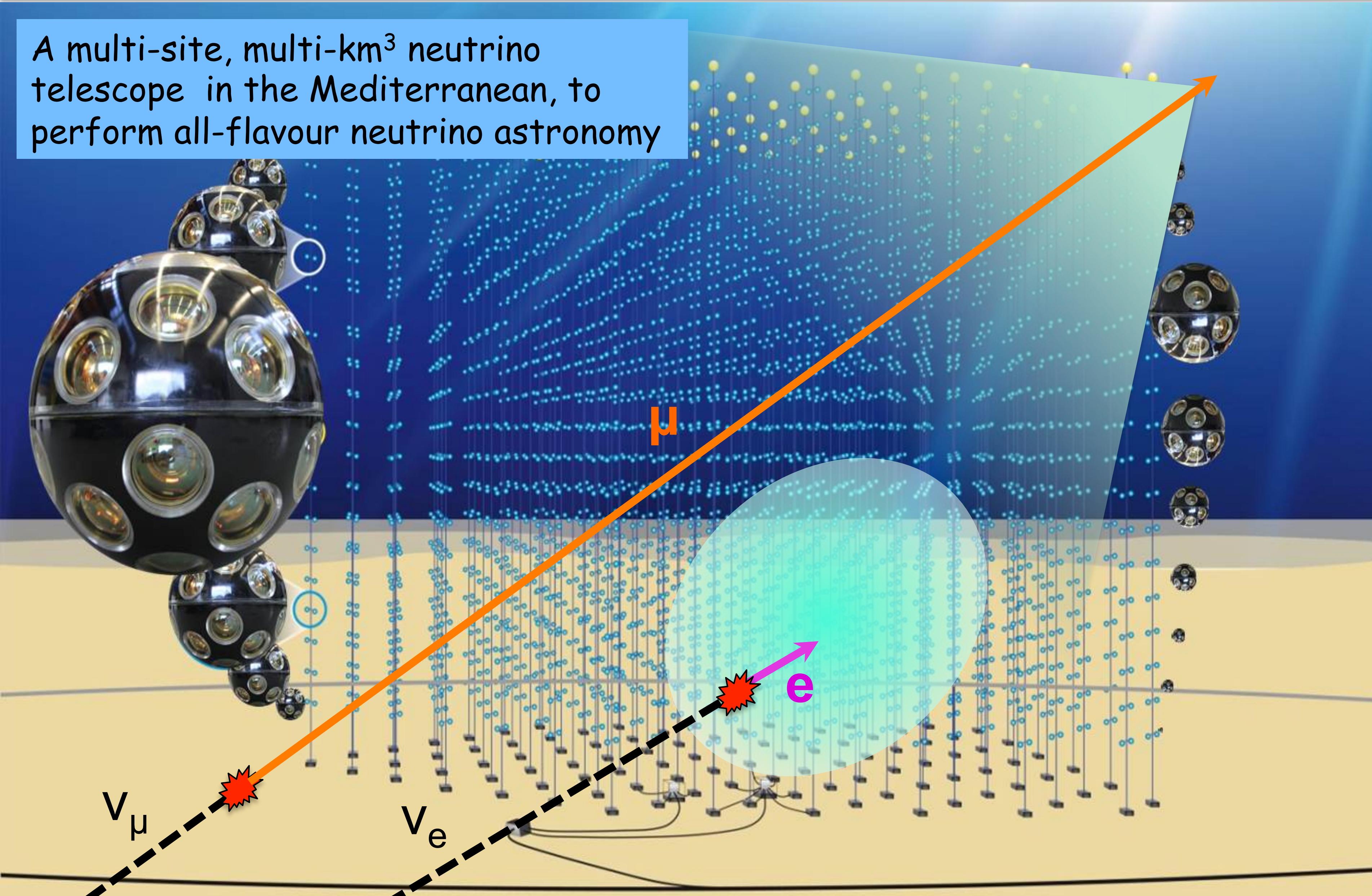
2 sites currently under construction in France and Italy:

KM3NeT-Fr (Toulon, close to ANTARES)

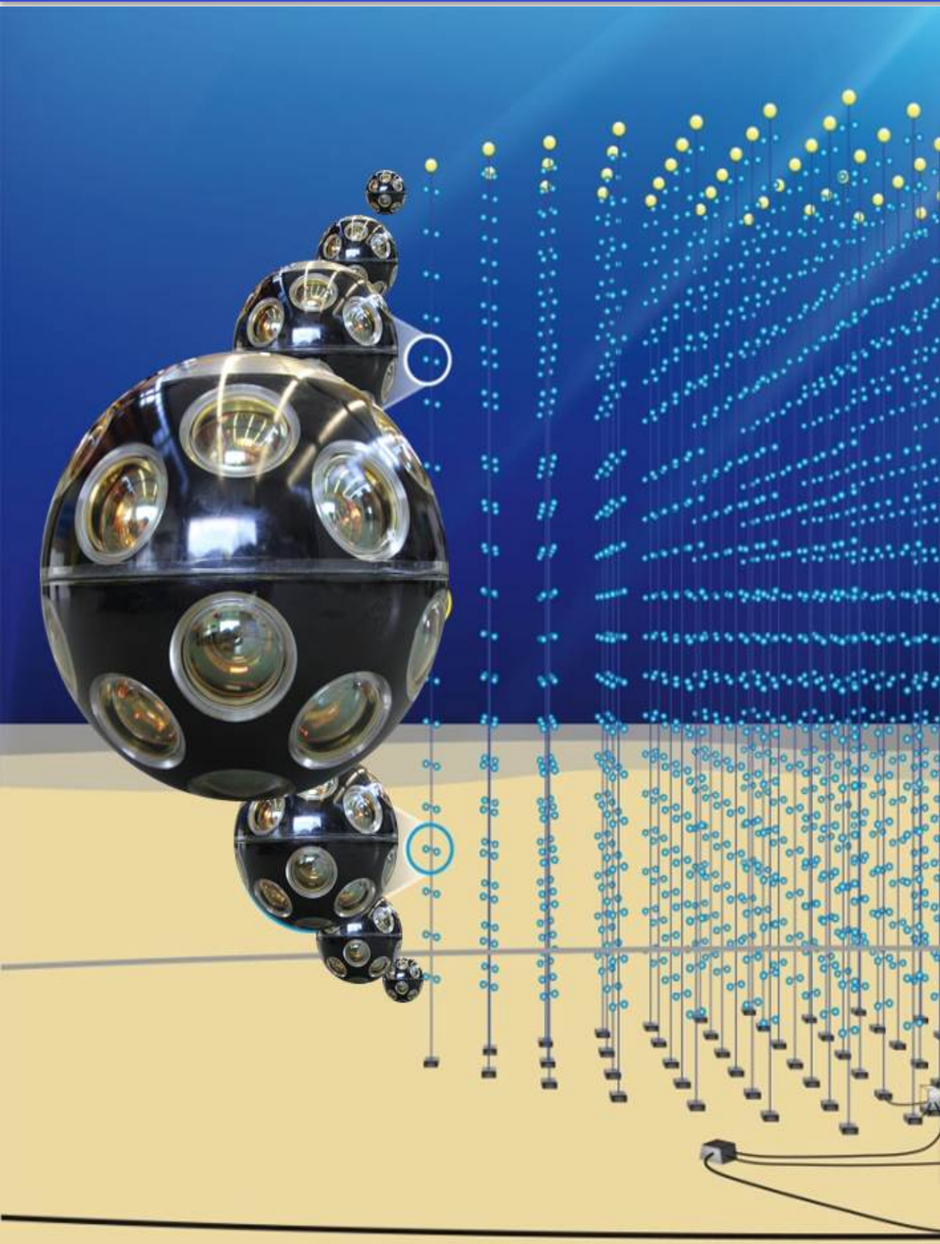
KM3NeT-It (Capo Passero, Sicily)

The next generation: KM3NeT

A multi-site, multi-km^3 neutrino telescope in the Mediterranean, to perform all-flavour neutrino astronomy



KM3NeT: design and layout



Infrastructure:

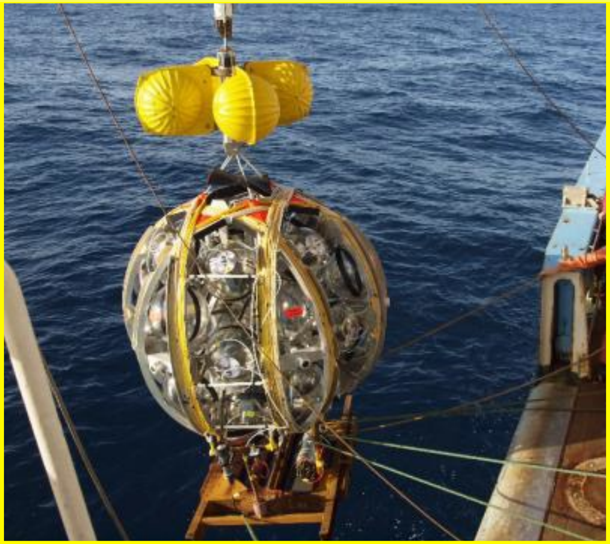
Building blocks of 115 strings anchored to sea bottom;
18 equally spaced modules per string
(~1 km^3 footprint in ARCA configuration)

- Multi-PMT digital optical modules
  31 X 3” PMTs + expansion cones
- Time synchronization
  White rabbit
- Optical data transmission
  Base module with DWDM at string anchor
- *All data to shore* concept
  Filtering/Trigger on-shore in computer farm

+ nodes for long term high-bandwidth connection for Earth and Sea sciences
Optical data transmission

KM3NeT: design and layout

Launcher vehicle:
- autonomous unfurling
- rapid deployment (several lines per campaign)
- easy recovery



Infrastructure:

Building blocks of 115 strings anchored to sea bottom;
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(~1 km^2 footprint in ARCA configuration)

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  Base module with DWDM at string anchor

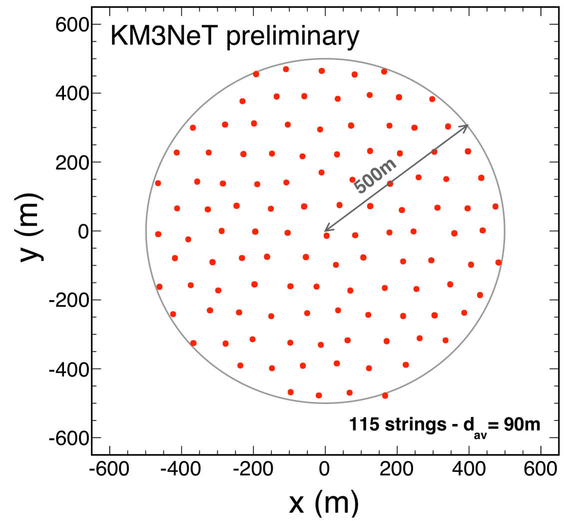
All data to shore concept
  Filtering/Trigger on-shore in computer farm

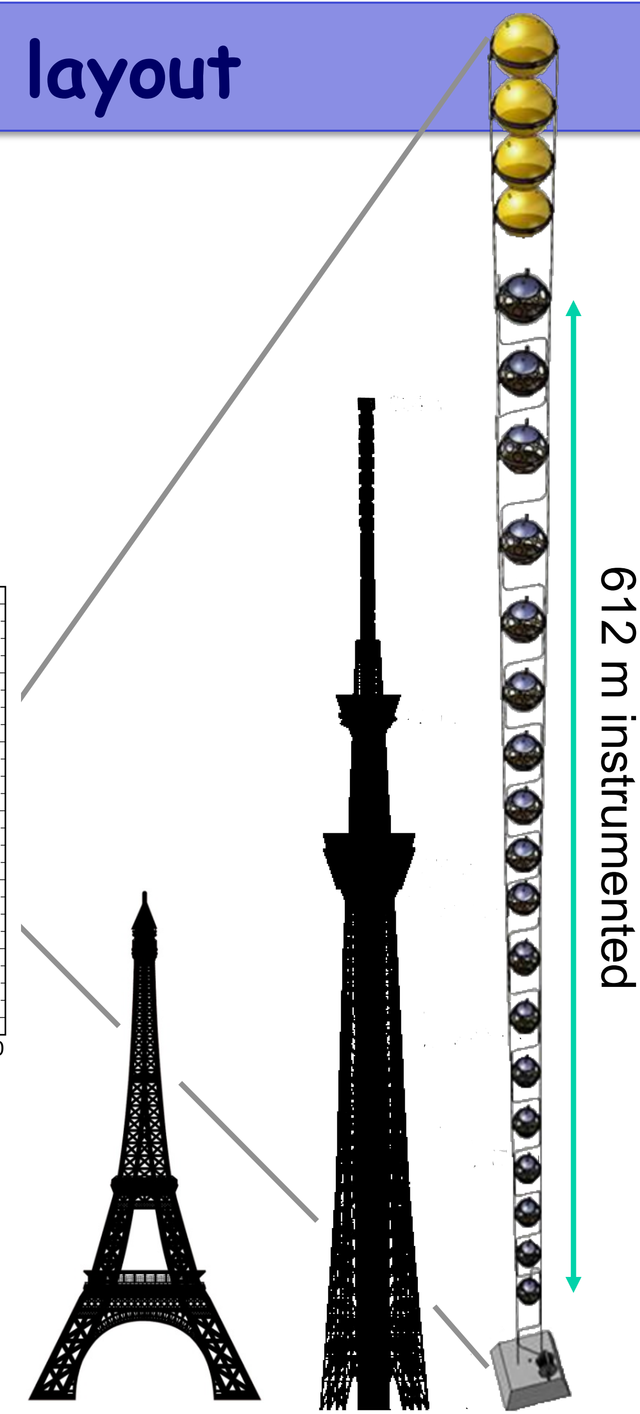
+ nodes for long term high-bandwidth connection for Earth and Sea sciences
Optical data transmission

KM3NeT design and layout

Detection Units:
18 digital optical modules per vertical string
31 3” PMTs enclosed in 17” glass sphere
Lowest optical module ~100 m above seabed
Two Dyneema® ropes + backbone cable
(2 copper conductors; 18 fibres (+spares))
Base module with DWDM at anchor

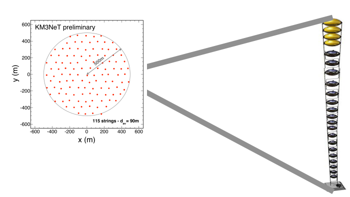
Layout optimised for
 physics goals:





ARCA blocks:
- 115 lines
- 90m horizontal
- 36m vertical

ORCA block:
- 115 lines
- 20m horizontal spacing
- 6m* vertical spacing
- 3.75 → 7 Mton instrumented



still being optimized

KM3NeT technology: the multi-PMT DOM

Segmented cathode area: 31 x 3” PMTs

- Directional Sensitivity
- 4π sr coverage
- Photon Counting

Light concentrator ring

Cathode area: ~ 3 x 10-inch PMT

Custom low-power HV bases

LED, piezo, compass and tiltmeter inside

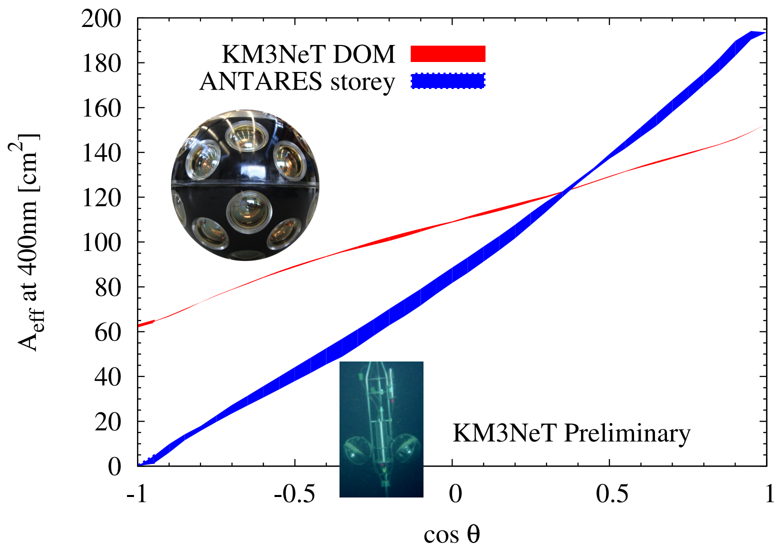
PMT Time-over-Threshold measurements

FPGA readout

ETELD792

HamamatsuR12199

HZC XP53B20



A phased implementation

	BLOCKS	PRIMARY DELIVERABLES
PHASE 1	0.25	shore and deep-sea infrastucture at KM3NeT-Fr and KM3NeT-It + 31 lines (3-4 x ANTARES) Proof of feasibility & first results
PHASE 2	2 ARCA	Measurement of IceCube signal All-flavour neutrino astronomy
	1 ORCA	Neutrino mass hierarchy
PHASE 3	6 (+1)	Neutrino astronomy including Galactic sources (…and a beam to ORCA ?)

31 M€
FUNDED
and
ONGOING

+95 M€

80-90 M€

Letters of Intent by end 2015

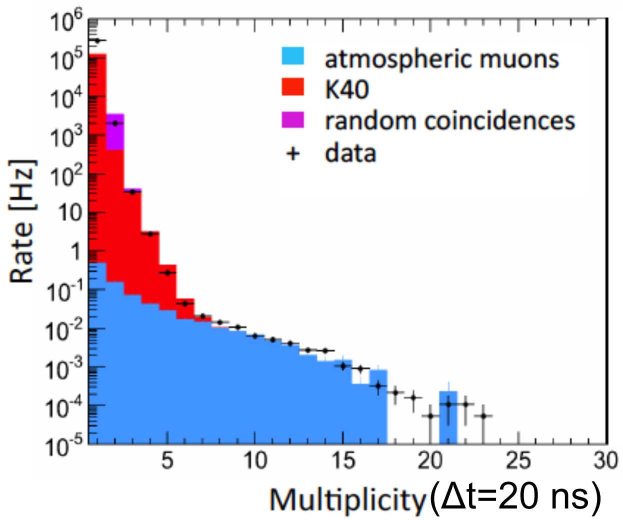
30-40 M€

+110 M€

220-250 M€
ESFRI
Roadmap

The prototypes

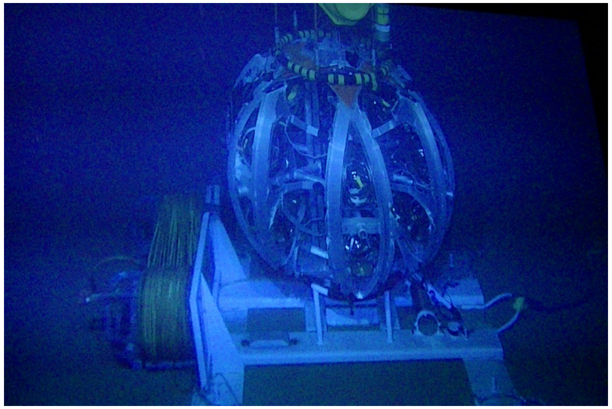
1) April 2013: Optical module deployed at ANTARES (2500 m)

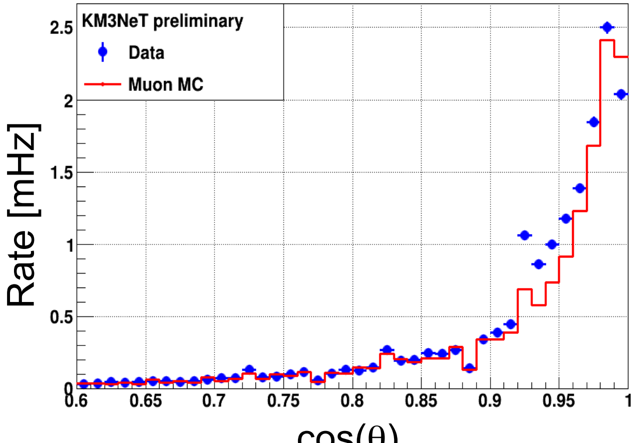


✓ Validation of photon counting & directionality performance

Eur. Phys. J. C (2014) 74:3056

2) May 2014: Mini string (3 storeys) deployed at Capo Passero





✓ First benchmark of DU integration and deployment

✓ Smooth operation and data taking

✓ Muon track reconstruction capabilities !

arXiv:1510.0156,submitted to Eur. Phys. J. C

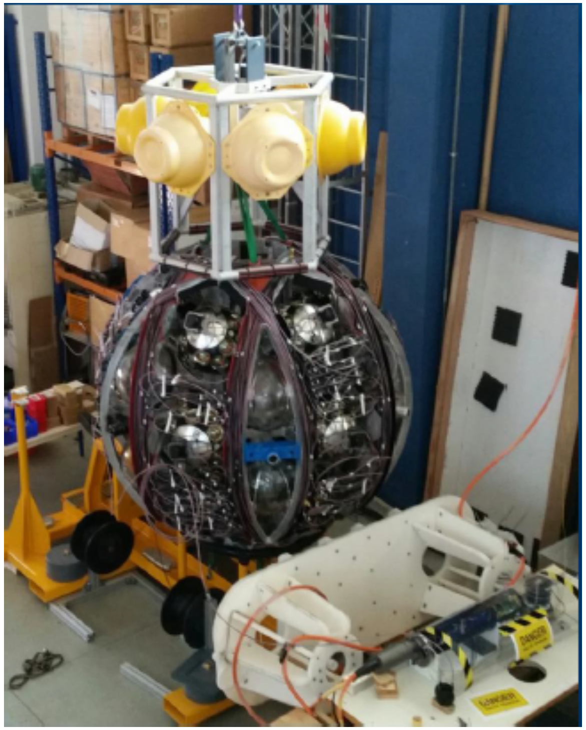
Status of Phase-1

- First string assembled, tested and integrated on the LOM @ CPPM (Marseille)

  ➡ DU-1 to be deployed at KM3NeT-Fr following node repair operation

- Second string assembled @ NIKHEF and ready to be shipped to Italy

  ➡ DU-2 to be deployed at KM3NeT-It in December 2015



Phase-1: ~0.25 building block

– 24 strings ARCA-style in KM3NeT-It
– 6 strings ORCA-style in KM3NeT-Fr

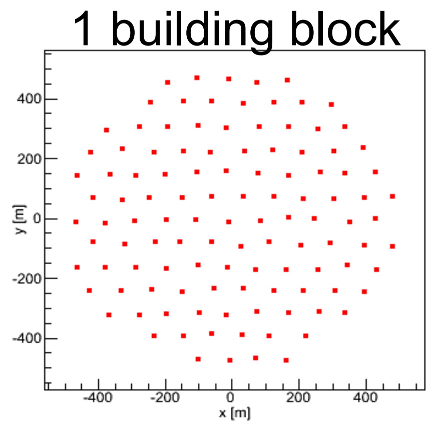
Completion expected in 2017

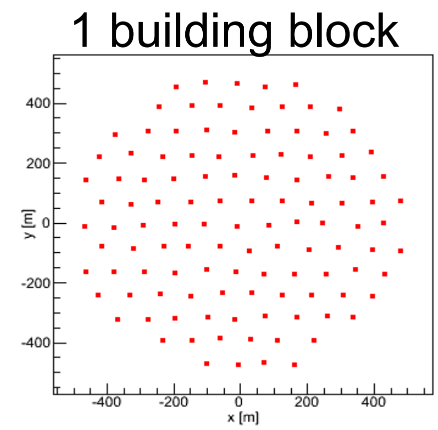
ARCA: expected performances

ARCA Phase-2:
2 building blocks
@ KM3NeT-It

Measurement of IceCube signal

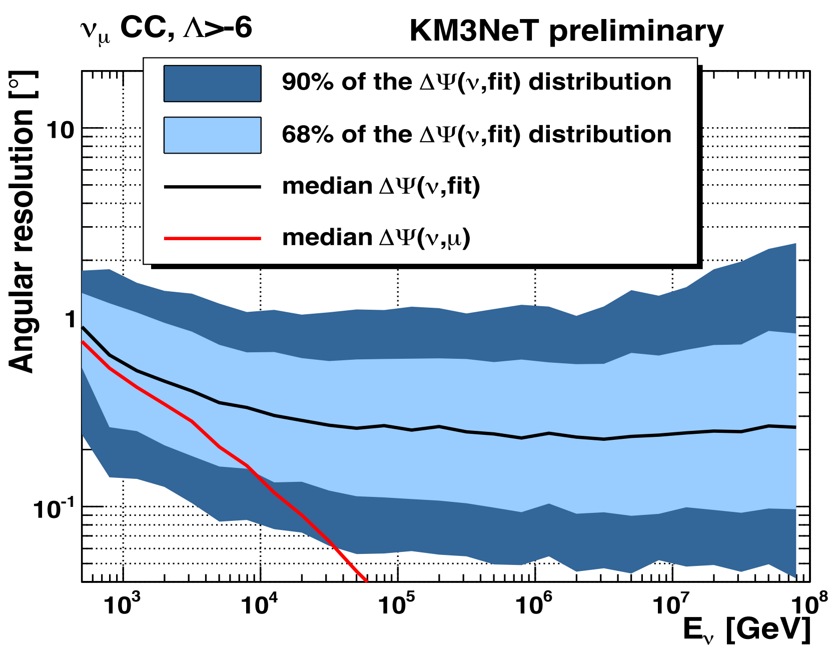
Good reconstruction performances on tracks (muon CC channel)

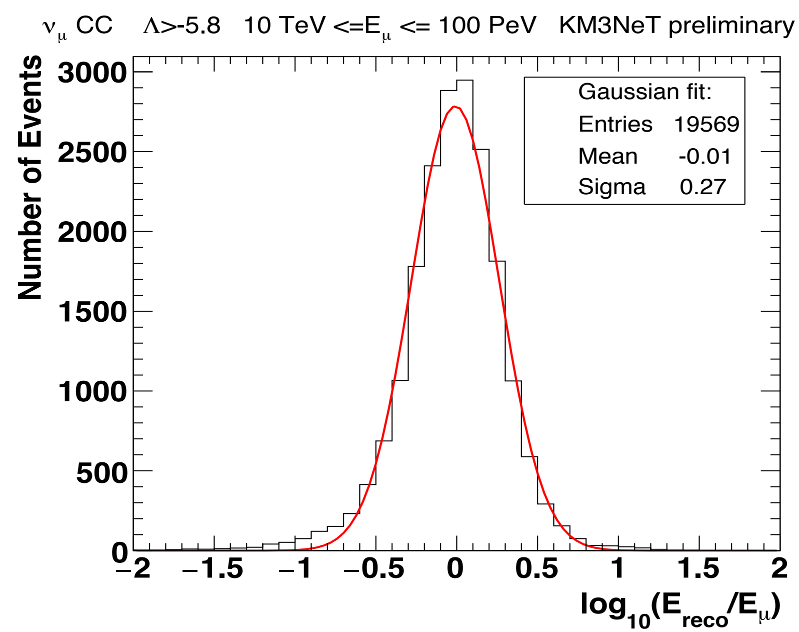




~1 km

~1 km





Neutrino direction 0.3° @ 10 TeV

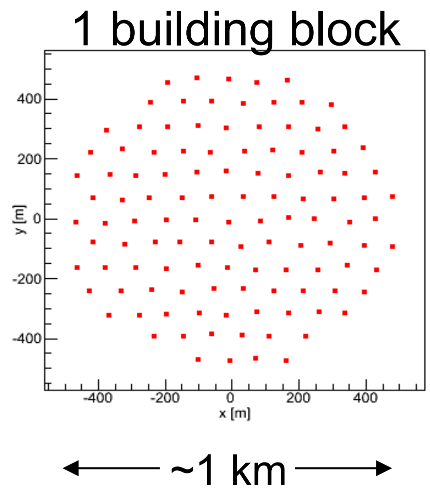
Muon energy: factor ~$2^{\pm 0.5}$ @ 10 TeV

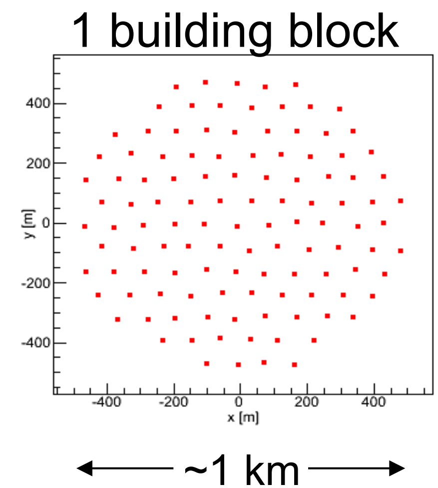
ARCA: expected performances

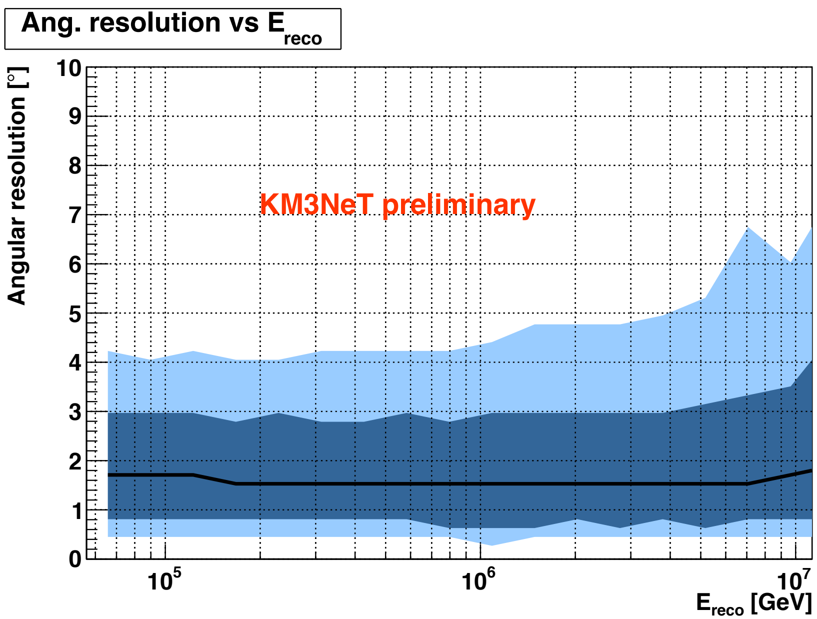
ARCA Phase-2:
2 building blocks
@ KM3NeT-It

Measurement of
IceCube signal

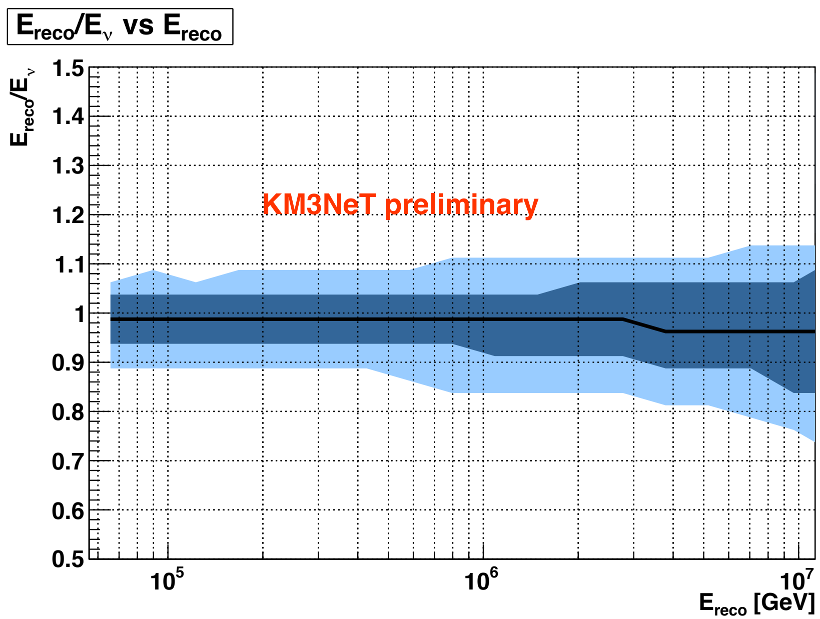
Good reconstruction performances on tracks (muon CC channel)
…and showers (here: electron CC)







Cascade direction: median 2°



Cascade energy: 5% accuracy

ARCA: sensitivity to diffuse flux

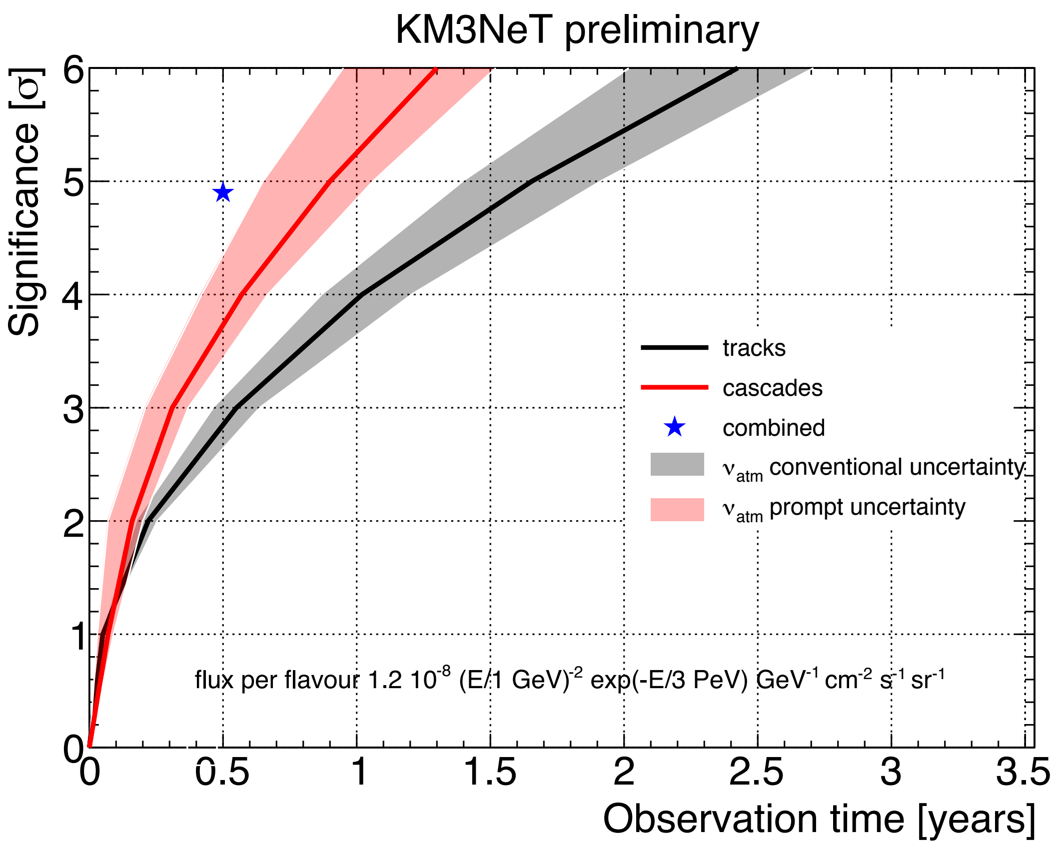
Characterised by time to re-discover nominal IceCube flux:

$$\Phi(E) = 1.2 \cdot 10^{-8} \left(E/1\ \mathrm{GeV}\right)^{-2} \exp\left(-E/3\ \mathrm{PeV}\right)\ \ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{flavour}^{-1}$$

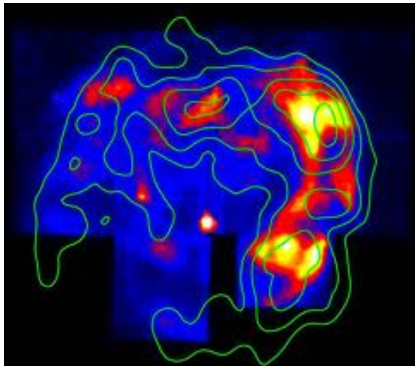
5 sigma significance:

- Tracks: 1.5-2yr
- Cascades: < 1 yr
- Combined: ~6 months

Atmospheric μ self-veto:



ARCA: sensitivity to Galactic point sources



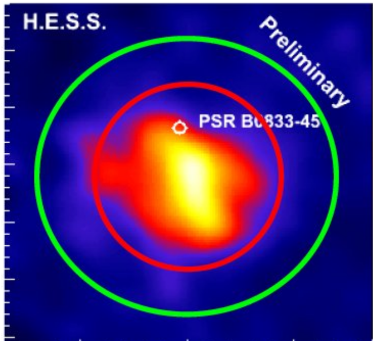
RXJ 1713:

$$\Phi(E) = 1.68\ 10^{-14} \left(\frac{E}{1\ \text{TeV}}\right)^{-1.72} \exp\left(-\sqrt{\frac{E}{2.1\ \text{TeV}}}\right) \text{GeV cm}^{-2}\ \text{s}^{-1}$$

Spectral cutoff expected at a few TeV

Point-like source: search using the muon channel

S.R. Kelner, *et al.*, Phys. Rev. D 74 (2006) 034018

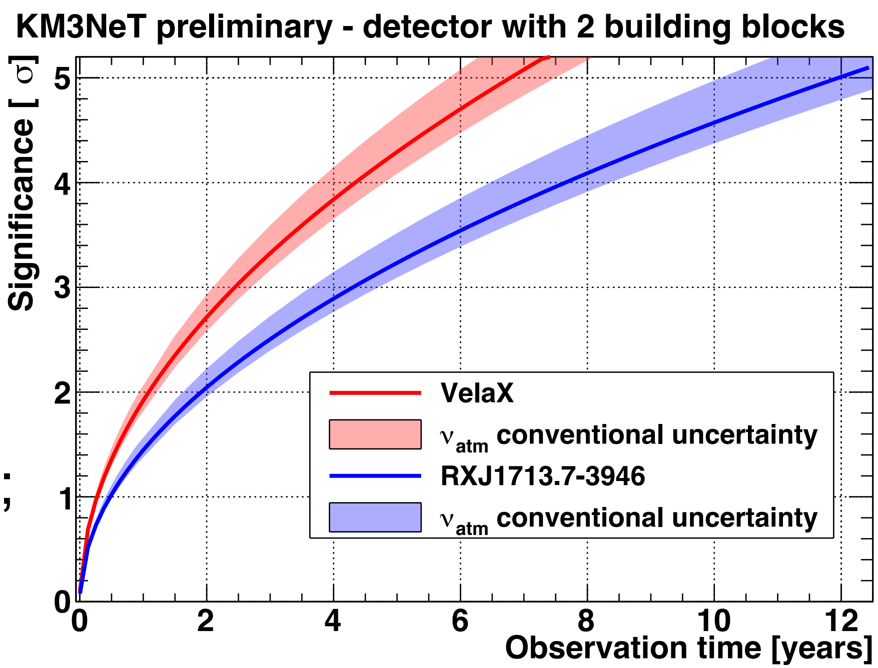


VelaX

$$\Phi(E) = 7.2\ 10^{-15} \left(\frac{E}{1\ \text{TeV}}\right)^{-1.36} \exp\left(-\frac{E}{7\ \text{TeV}}\right) \text{GeV cm}^{-2}\ \text{s}^{-1}$$

Spectrum extends to higher energies;

Sharper cutoff

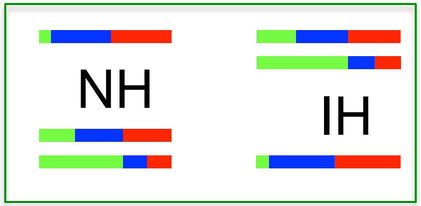


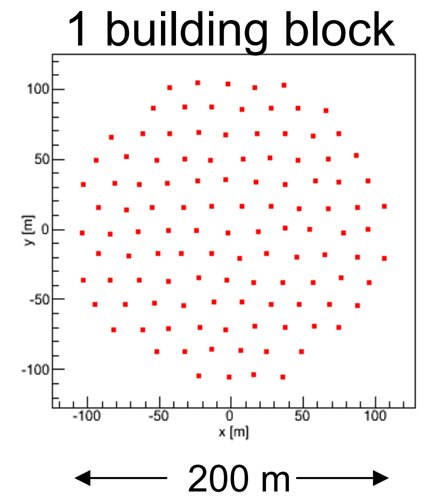
F.L. Villante and F. Vissani,
Phys. Rev. D 78 (2008) 103007

ORCA: expected performances

ORCA Phase-2: 1 building block
@ KM3NeT-Fr

Measurement of the neutrino mass hierarchy with atmospheric neutrinos in the 1 – 20 GeV energy range

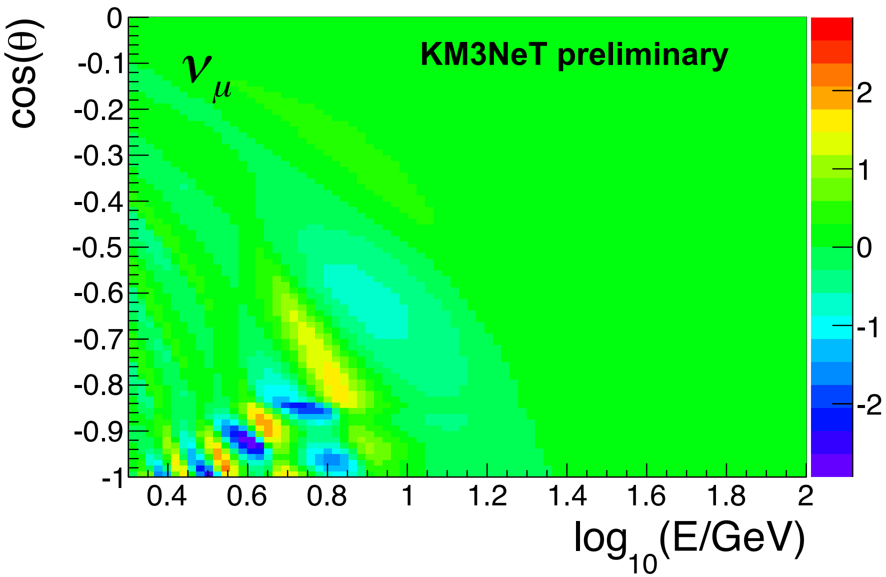


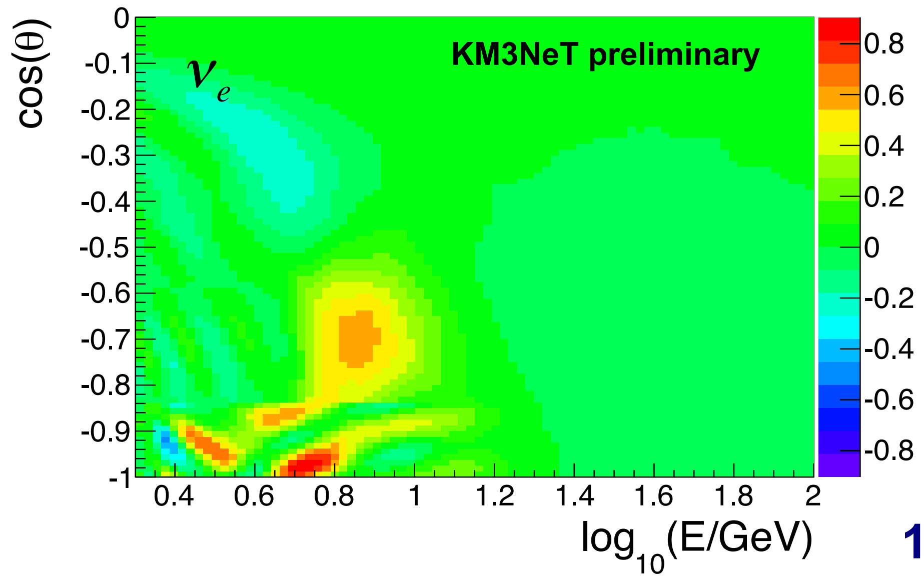


dense layout: 20m horizontal (inter-line) spacing
6 -- 12m vertical (inter-DOM) spacing
(still under optimisation)

« Significance » oscillogram: $\frac{N_{NH} - N_{IH}}{\sqrt{N_{NH}}}(E_\nu, \theta_z)$

« Perfect detector »

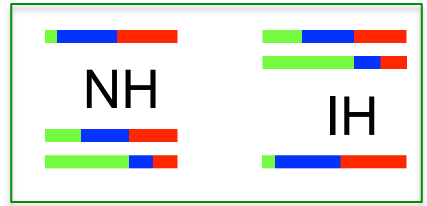


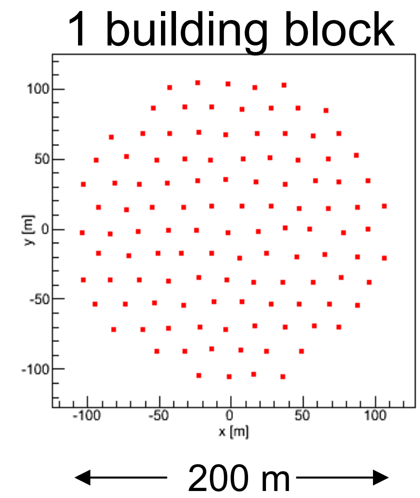


ORCA: expected performances

ORCA Phase-2: 1 building block @ KM3NeT-Fr

Measurement of the neutrino mass hierarchy with atmospheric neutrinos in the 1 – 20 GeV energy range





dense layout: 20m horizontal (inter-line) spacing
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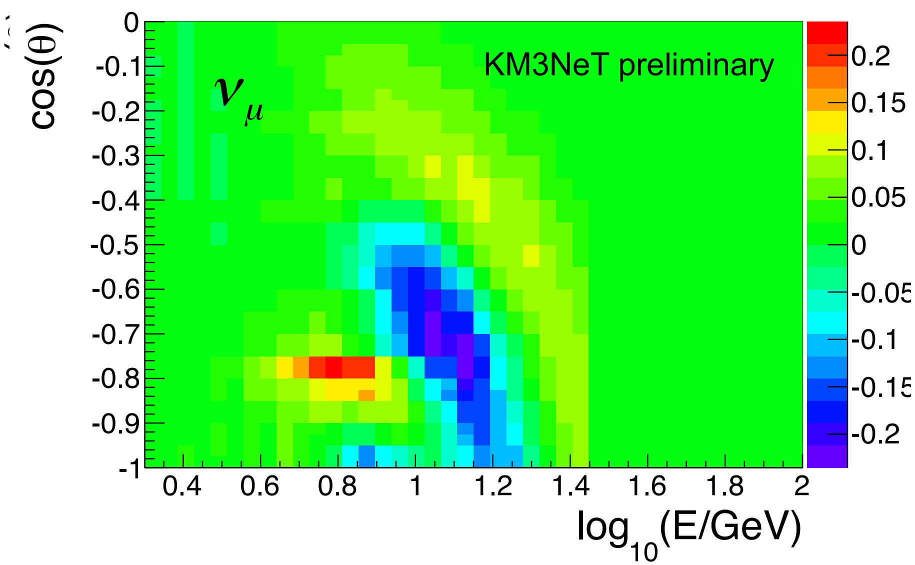
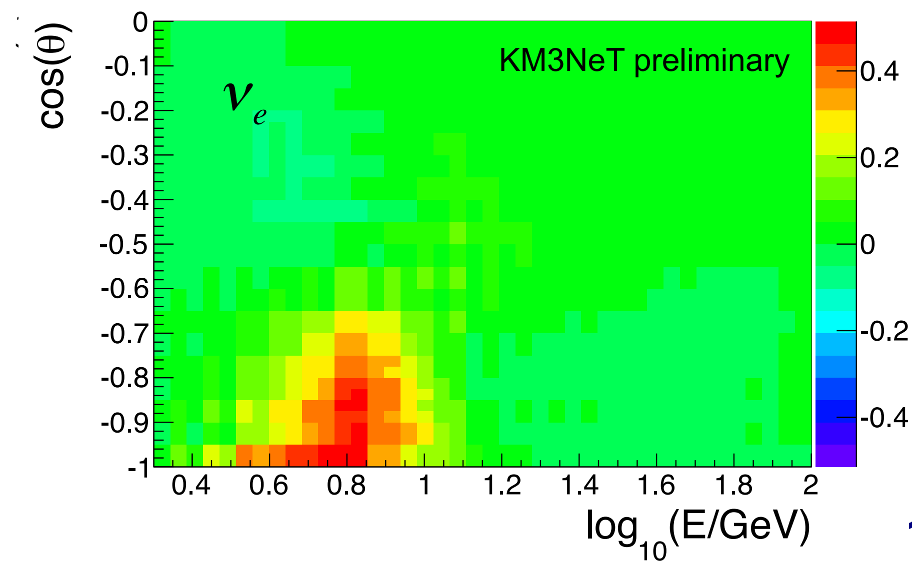
« Significance » oscillogram: $\frac{N_{NH}-N_{IH}}{\sqrt{N_{NH}}}(E_\nu,\theta_z)$

After reconstruction





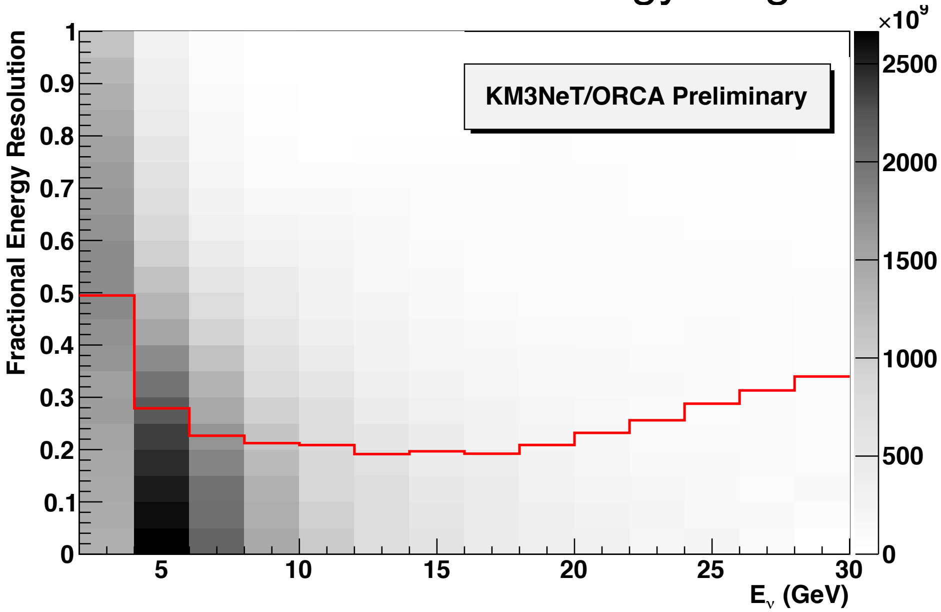
ORCA: expected performances

Track channel: target ν_μ CC events

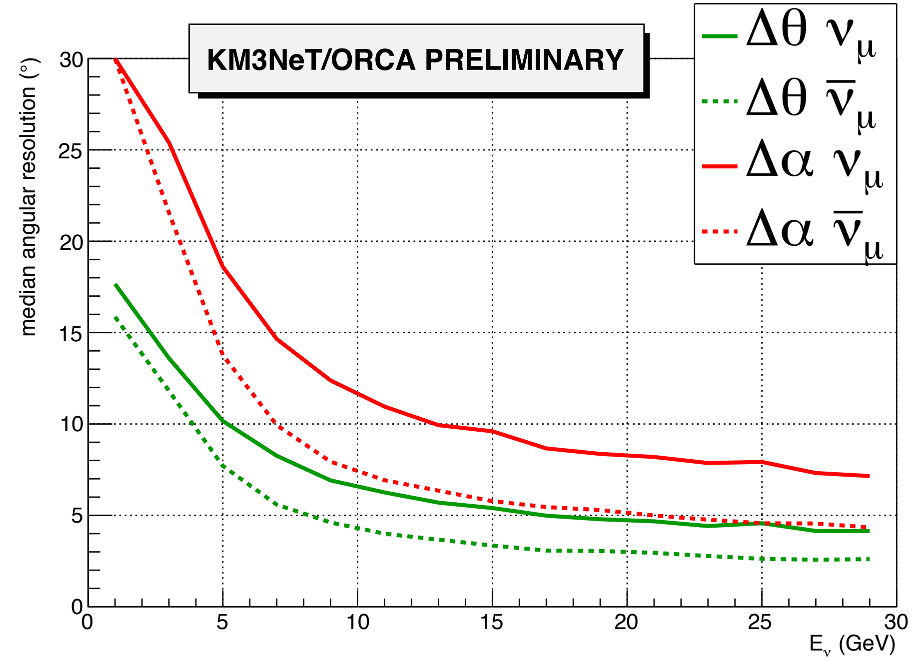
Track fit: max likelihood method based on full simulation PDFs

Neutrino energy from track length, number of hits and inelasticity

Energy resolution
~20% in relevant energy range



Angular resolution (zenith)
<10° @ 5 GeV
(dominated by kinematics)



+ sensitivity on Bjorken y ! (from hit time residuals distribution)

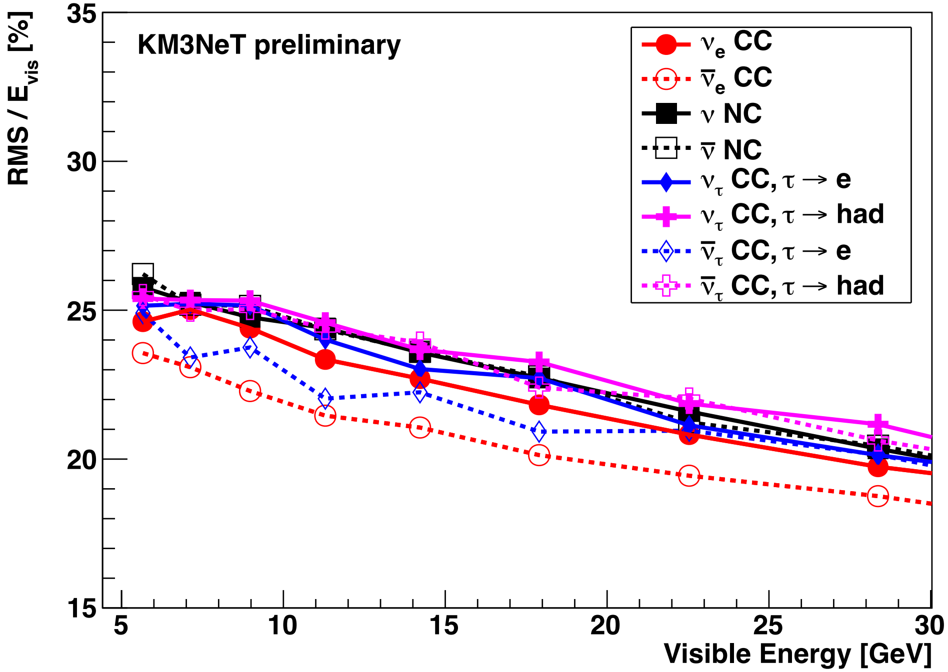
→ neutrino-antineutrino discrimination capabilities

ORCA: expected performances

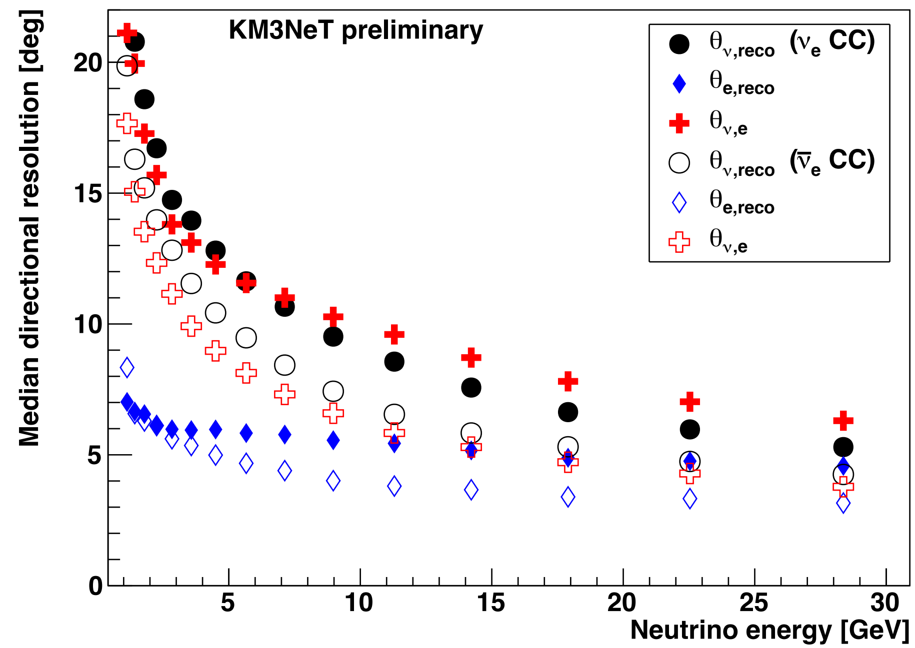
Cascade channel: target ν_e CC events

Reconstruct vertex from time residuals; then E, θ,inelasticity from max likelihood fit

Energy resolution <25%



Angular resolution<10° @ 10 GeV (dominated by kinematics)



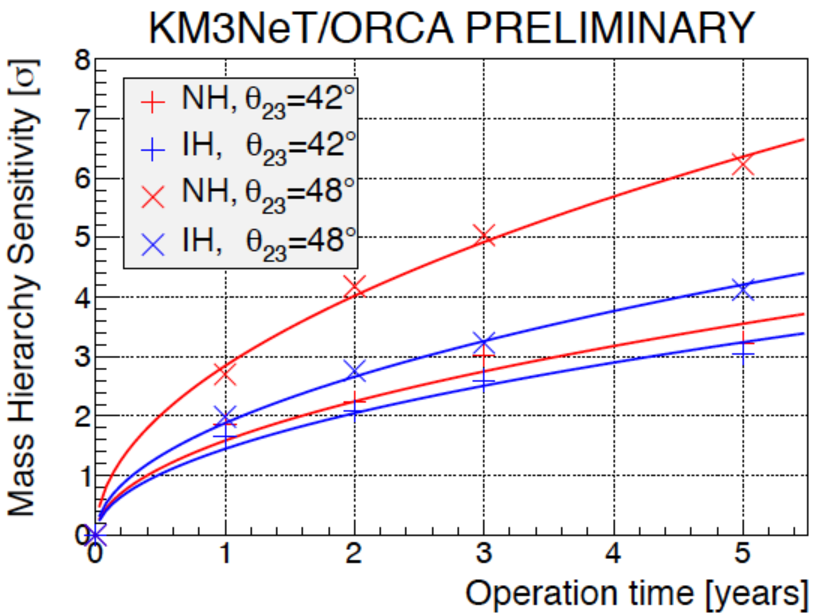
+ sensitivity on Bjorken y ! (from relative strength of Cherenkov peak)

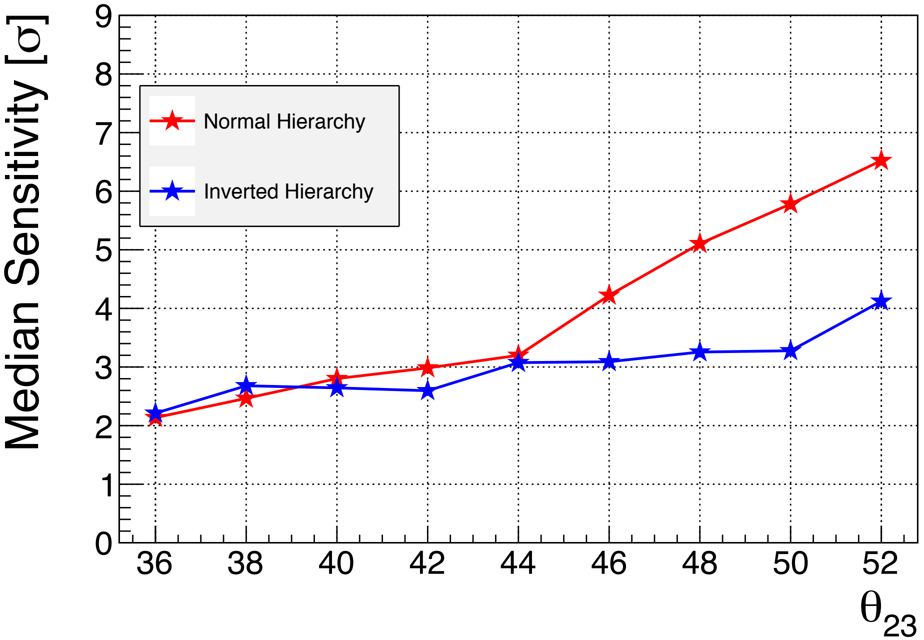
→ neutrino-antineutrino discrimination capabilities

…studies ongoing

ORCA: sensitivity to mass hierarchy

Projected sensitivity: ~3σ in 3 years, depending on true values of θ_{23} and δ_{CP}





(here: δ_{CP} fixed to 0)

- ✓ Track vs shower event classification
- ✓ Full MC detector response matrices including misidentified and NC events
- ✓ Atmospheric muon contamination
- ✓ Neutral current event contamination
- ✓ Various Systematic uncertainties

+ still room for improvement: Bjorken-y, detector optimisation…

Summary and outlook

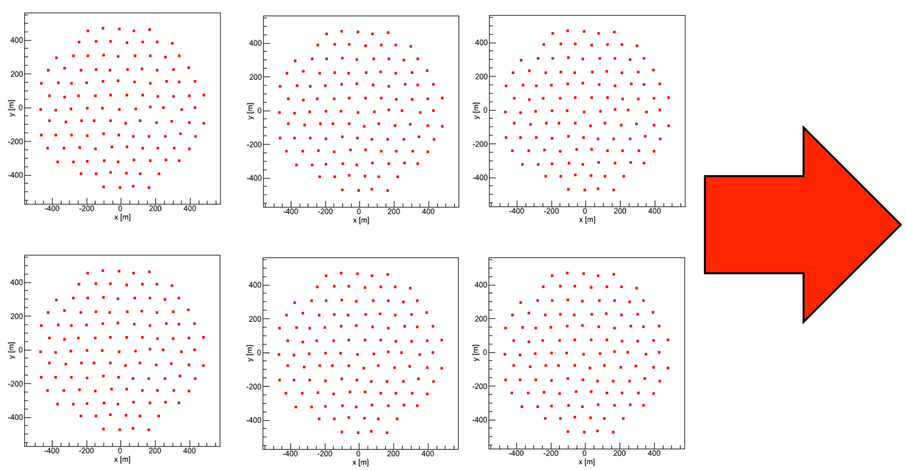
KM3NeT: phased approach to next-generation neutrino telescope
in the Mediterranean

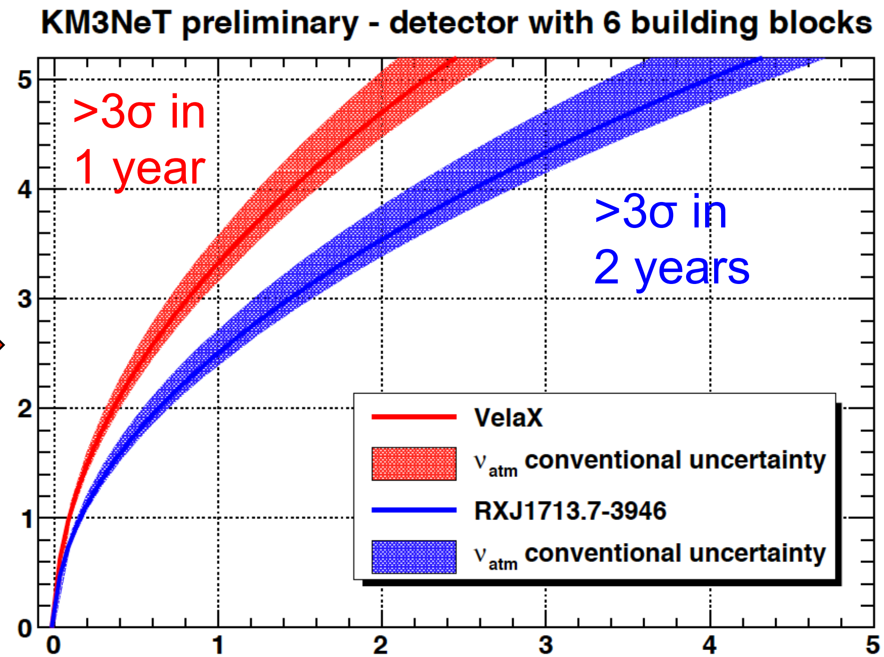
- technology and detection performances validated by prototypes
- deployment of the first detection units in upcoming months (Phase 1):
  KM3NeT-It → **ARCA**: **HE neutrino astronomy (tracks & showers!)**
  KM3NeT-Fr → **ORCA: neutrino mass hierarchy**

- Letters of Intent in preparation

- a taste of neutrino astronomy to come (Phase 3):

ARCA Phase 3

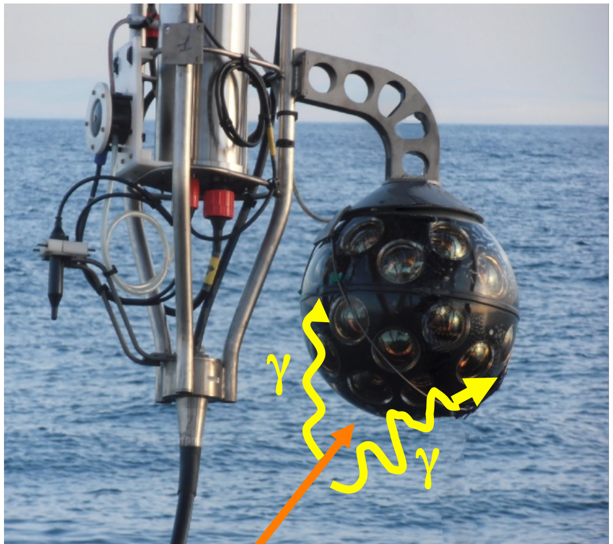


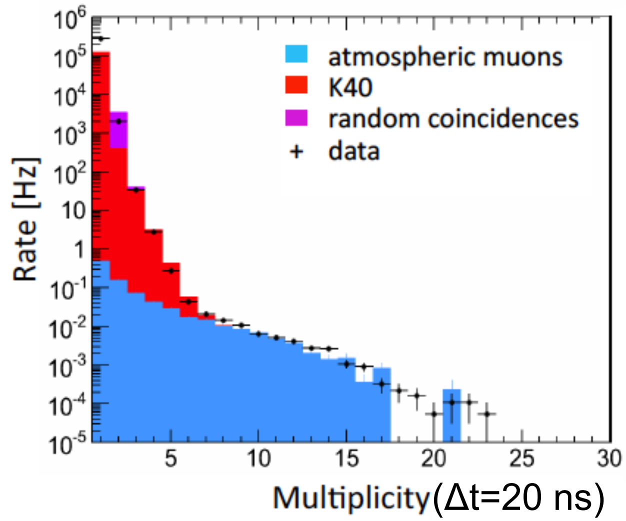


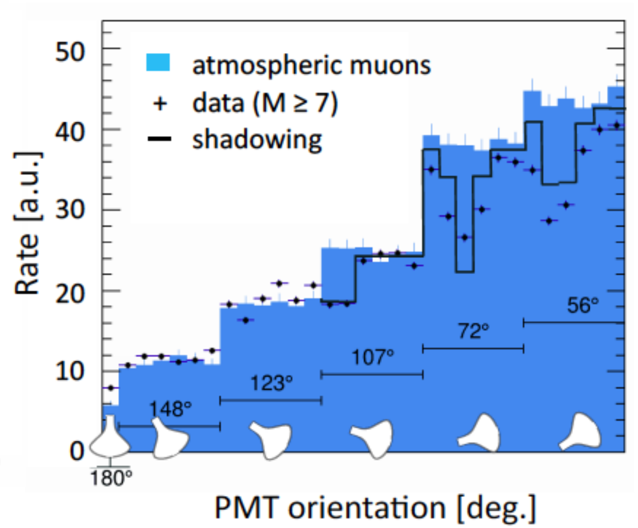
BACKUP SLIDES

KM3NeT: status of Phase-1

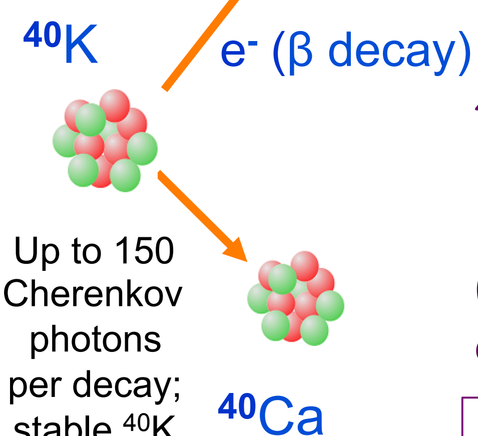
April 2013: First DOM installed on ANTARES instrumented line (KM3NeT-Fr)







Validates photon counting & directionality performances

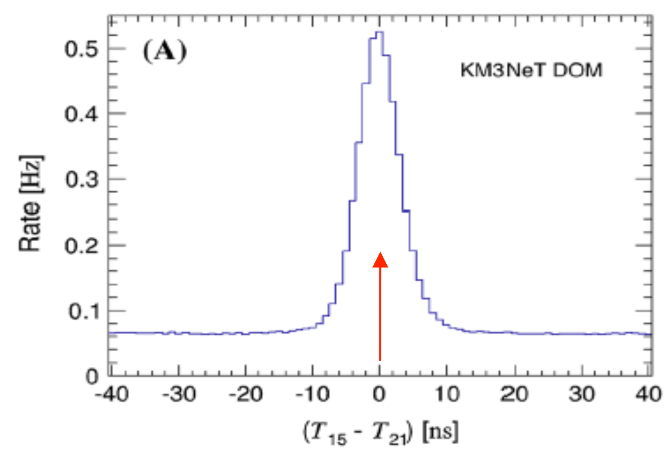


Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

^{40}K decay provides intra-DOM time calibration:

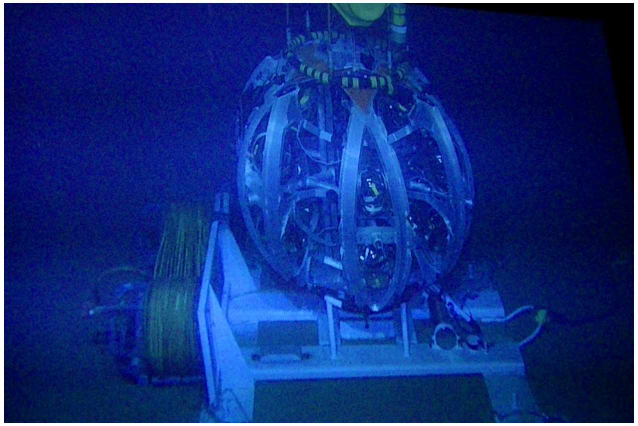
(coincidence rate ~5 Hz on neighbouring PMTs)

Eur. Phys. J. C (2014) 74:3056



KM3NeT: status of Phase-1

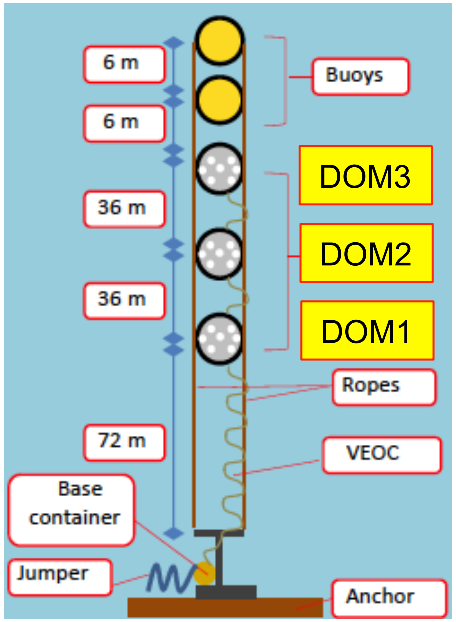
May 2014: prototype deployed at KM3NeT-It

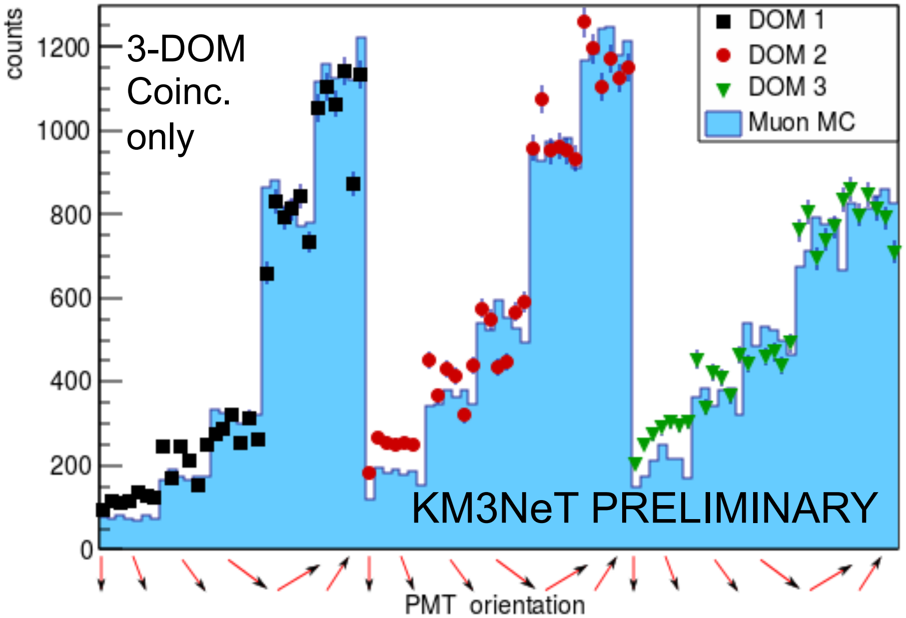


Reduced-size detection unit (DU) with 3 DOMs, equipped with Vertical Electro-Optical Cable

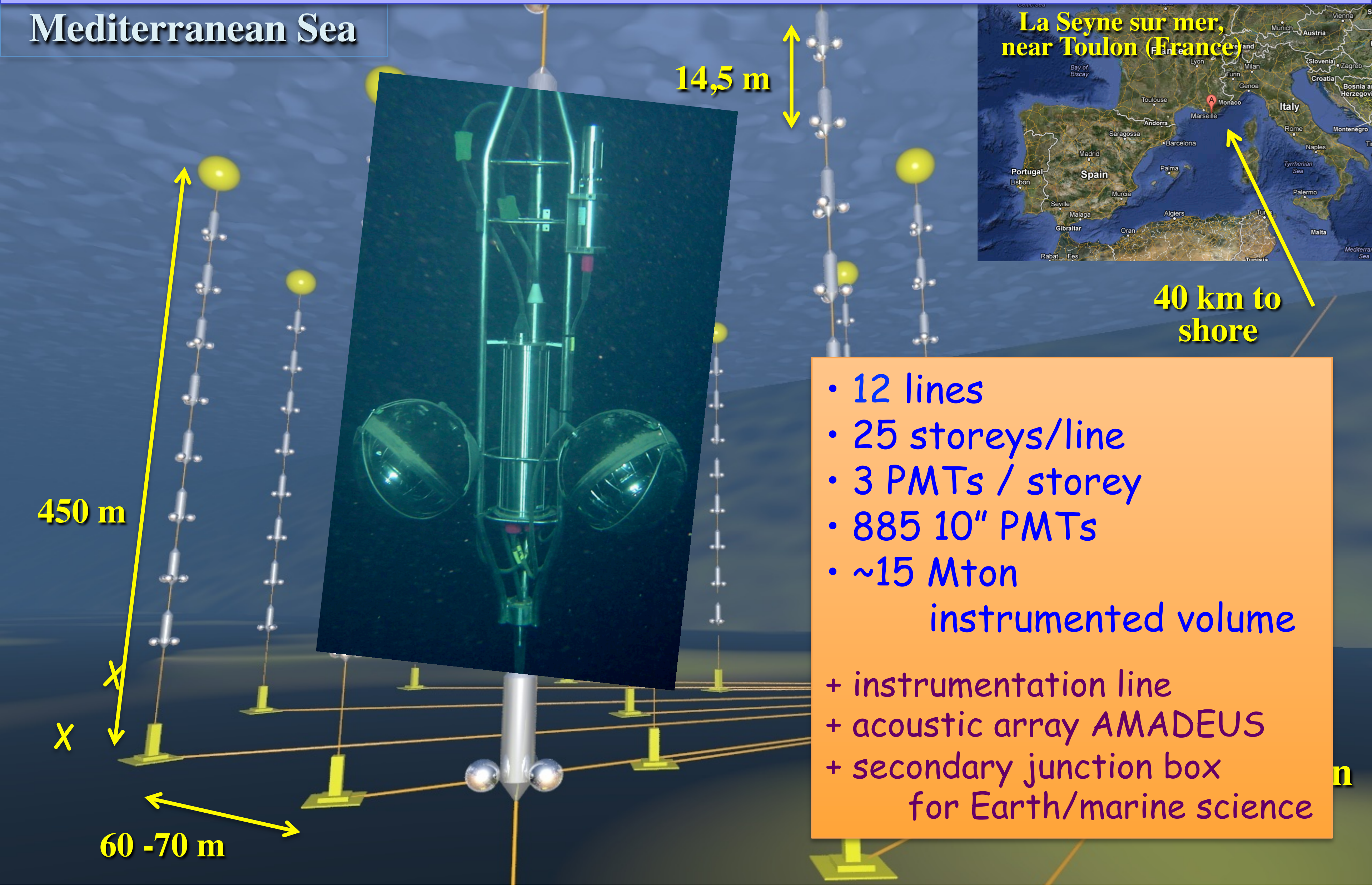
- First benchmark of DU integration and deployment
- Smooth operation and data taking

📖 *Paper in preparation!*





The ANTARES neutrino telescope



- 12 lines
- 25 storeys/line
- 3 PMTs / storey
- 885 10" PMTs
- ~15 Mton
  instrumented volume

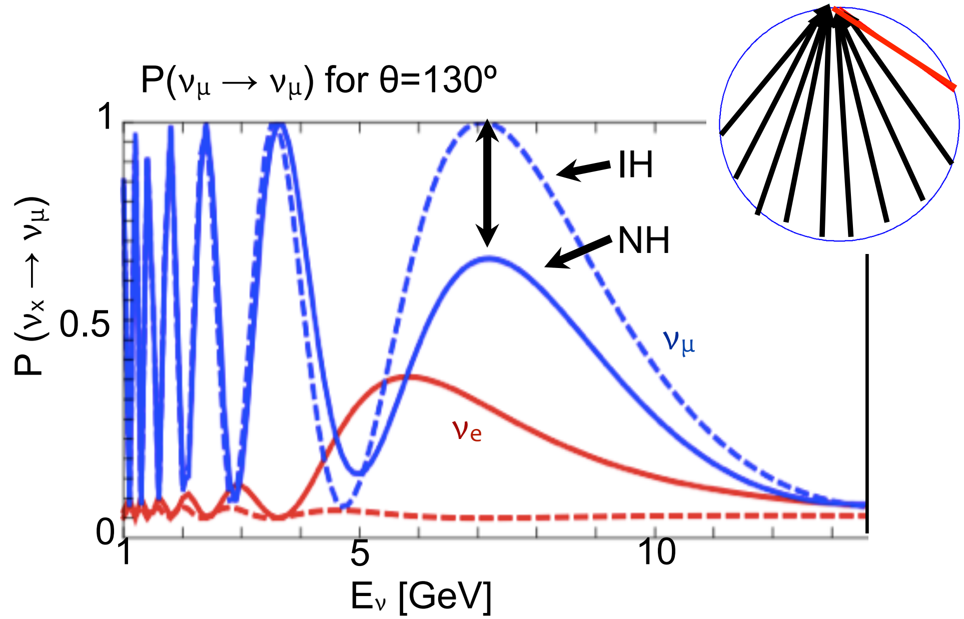
+ instrumentation line
+ acoustic array AMADEUS
+ secondary junction box
  for Earth/marine science

ORCA: Oscillation Research with Cosmics in the Abyss

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($\bar{\nu}$)

BUT differences in flux, cross-section:

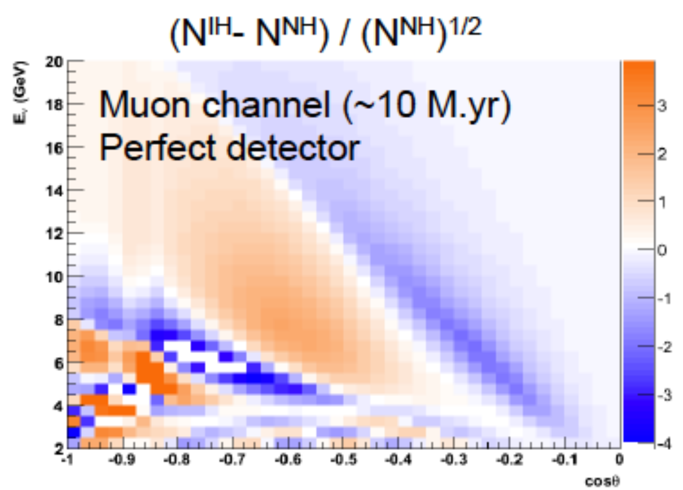
$\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\bar{\nu})$
$\sigma(\nu) \approx 2\sigma(\bar{\nu})$ at low energies

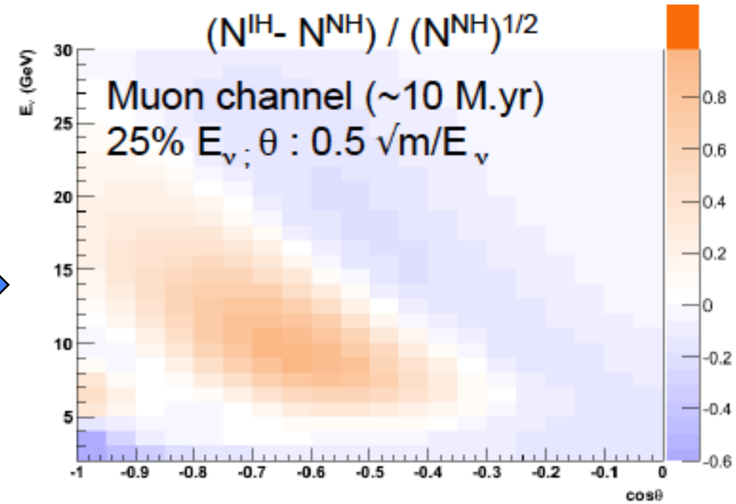
opportunity for Mton water Cherenkov detectors
(even without charge ID!)
increased case since improved knowledge of θ_{13}:

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

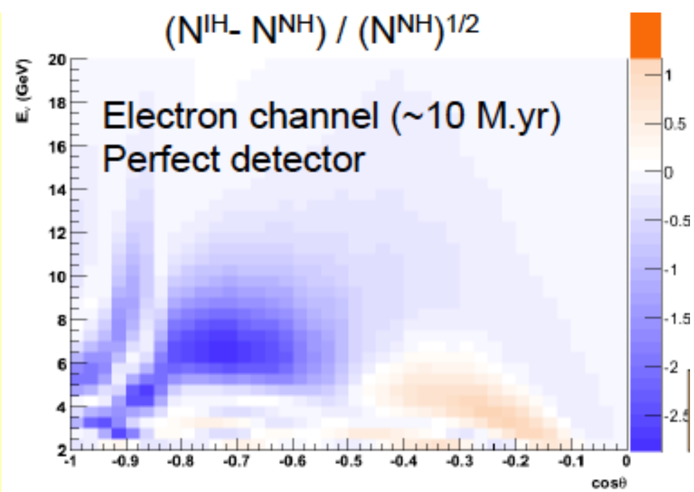
ORCA: Oscillation Research with Cosmics in the Abyss

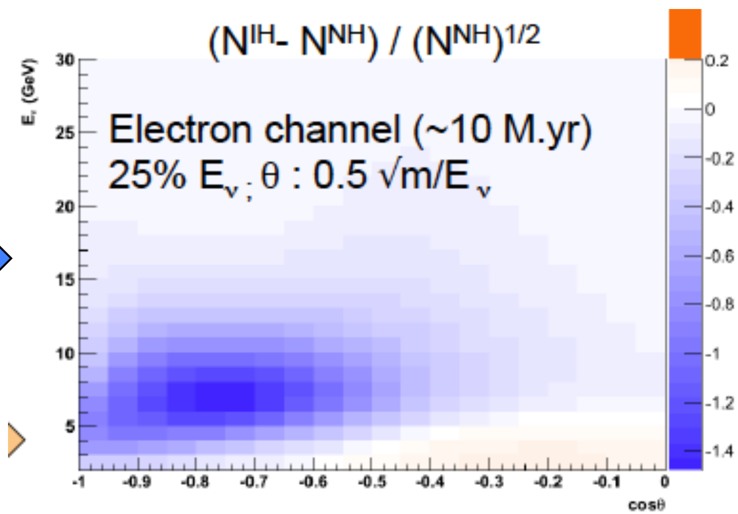
Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:



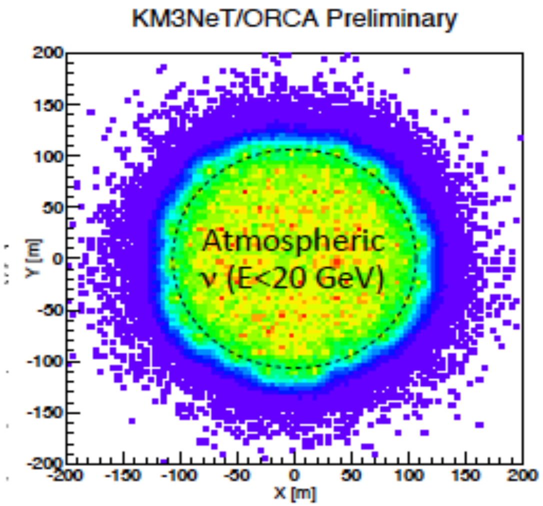


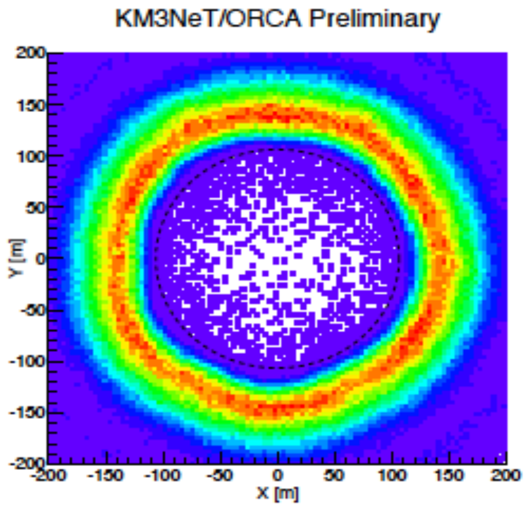
E, θ smearing (kinematics + detector resolution)



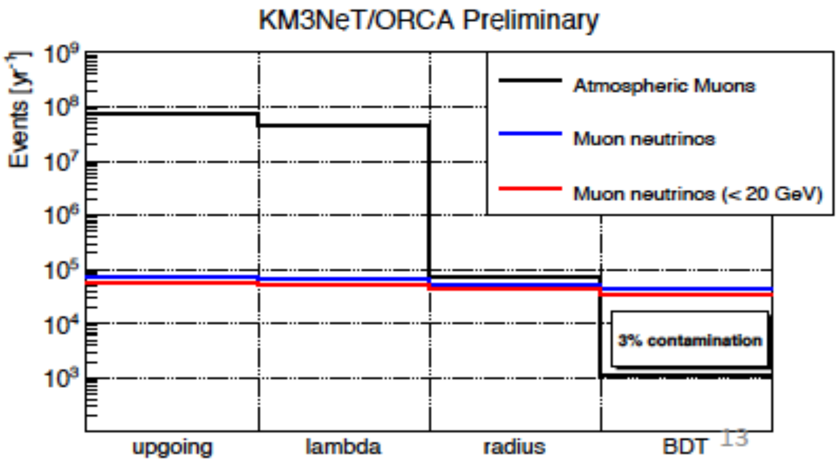


Atmospheric muon rejection



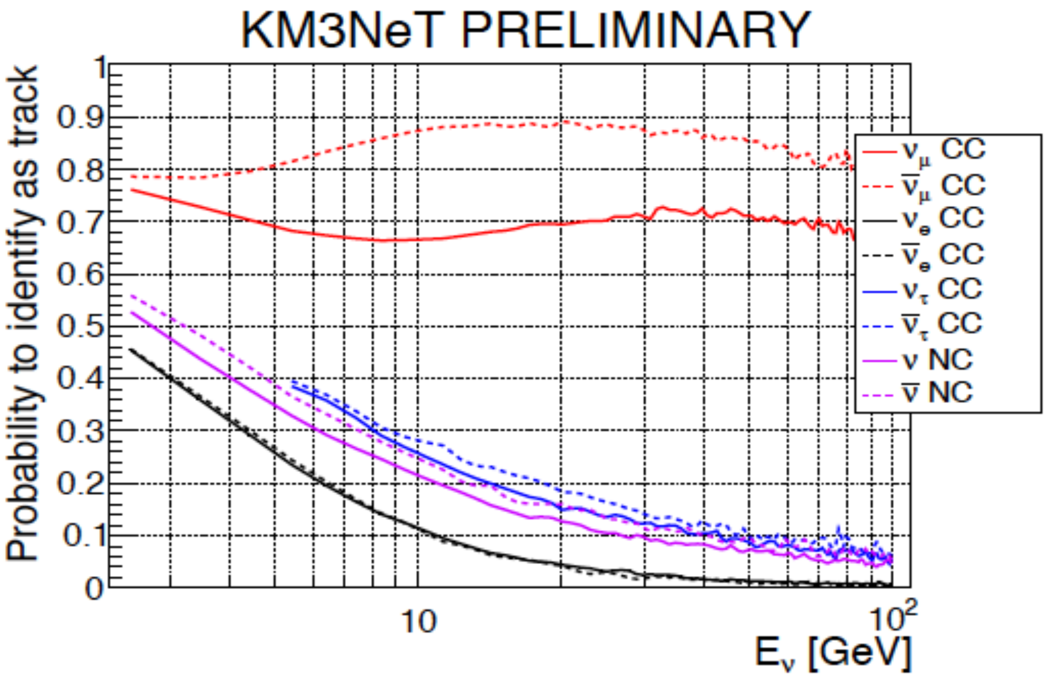


Instrumental veto not mandatory



Few % contamination achievable without too strong signal loss

Particle ID

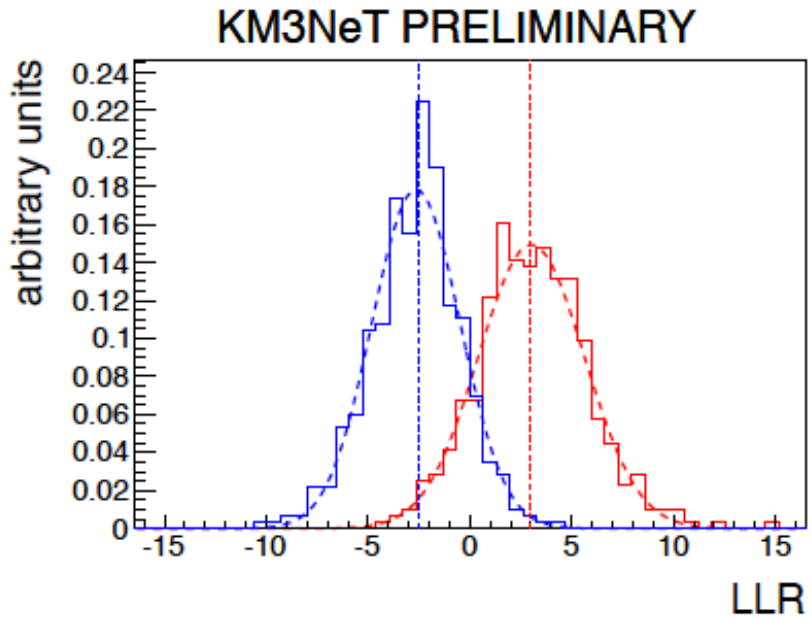


Probability that the PID algorithm identifies an event as a track as a function of the true neutrino energy. The lines denote different interaction types.

- Random Decision Forest
- Many decision trees trained on MC events
- e-like CC events better than 90% above 10 GeV
- mu-like CC events around 80% (better for $\bar{\nu}_\mu$, worse for ν_μ).

Sensitivity Study - Method

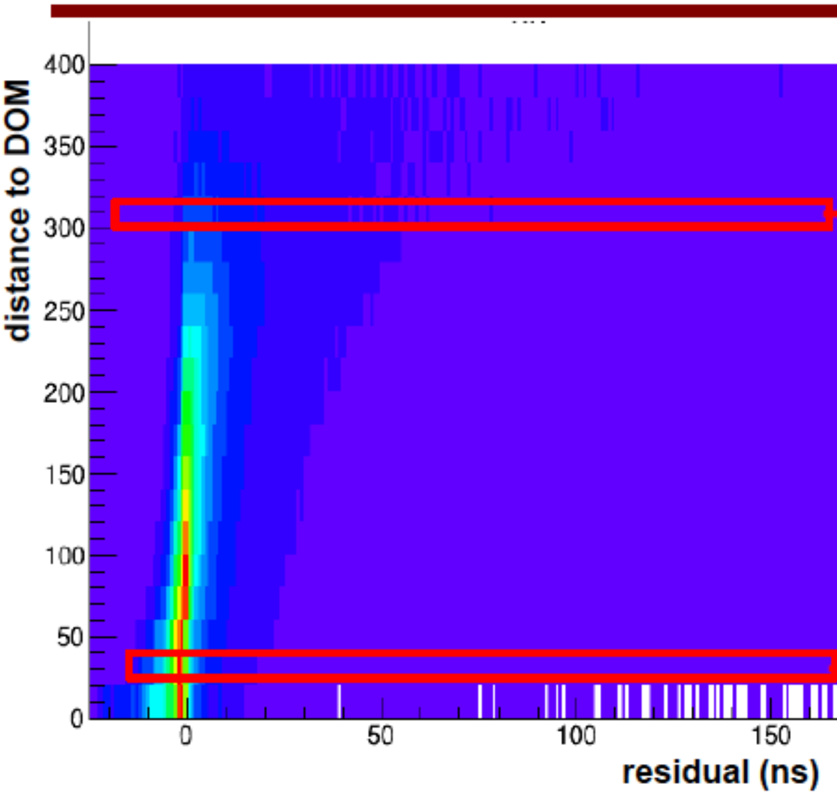
- Pseudo-experiments (PEs)
- Fit assuming NH and assuming IH
  - Maximize Likelihood of PE w.r.t. oscillation parameters and systematics
- Log likelihood ratio (LLR) $\log(L_{NH}) - \log(L_{IH})$ as discriminating variable
- LLR distributions for NH and for IH
- Figure of merit: median sensitivity = distance in σ's between the medians

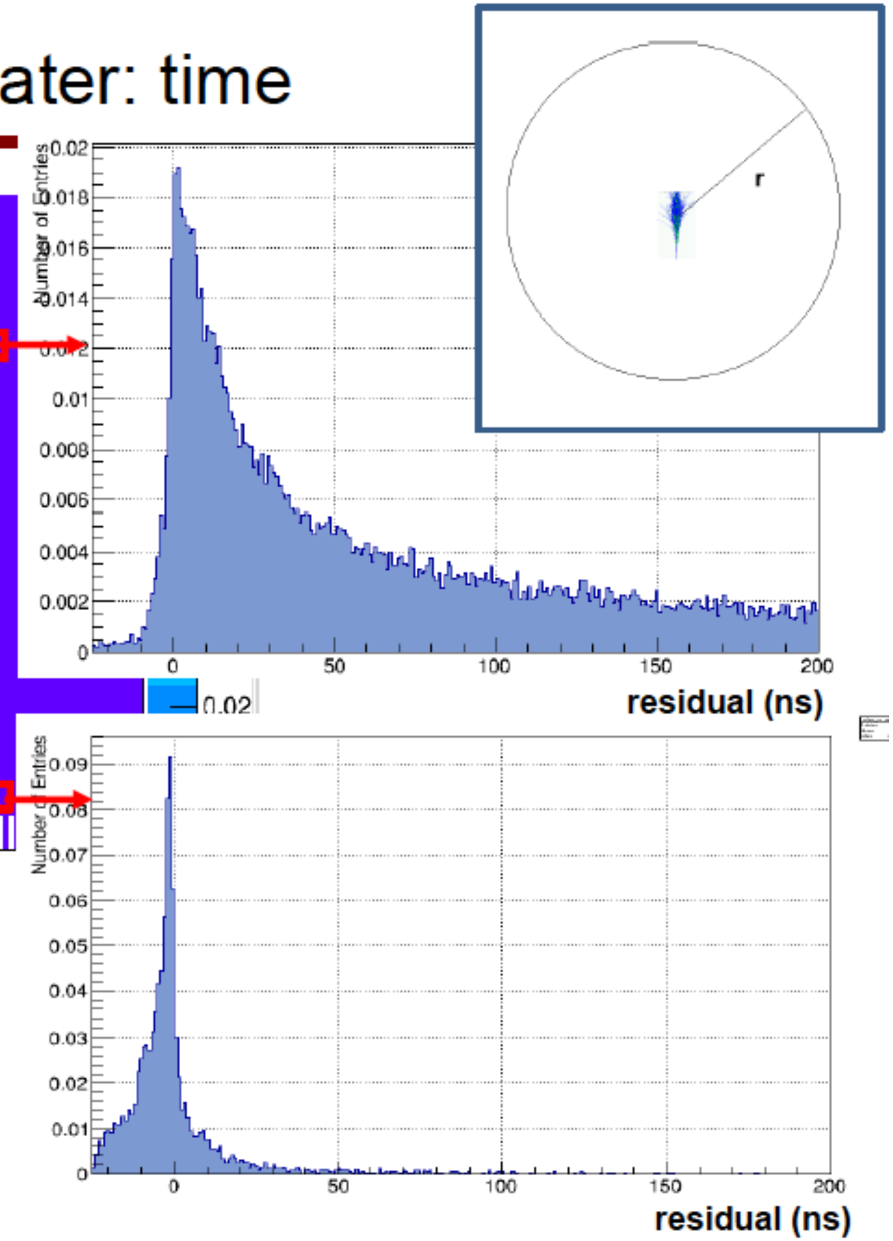


Example LLR distributions with Gaussian fits. Red (blue) shows true NH (IH) pseudo-experiments. The dashed lines indicate the medians.

ARCA: Astroparticle Research with Cosmics in the Abyss

Cascade signature in water: time



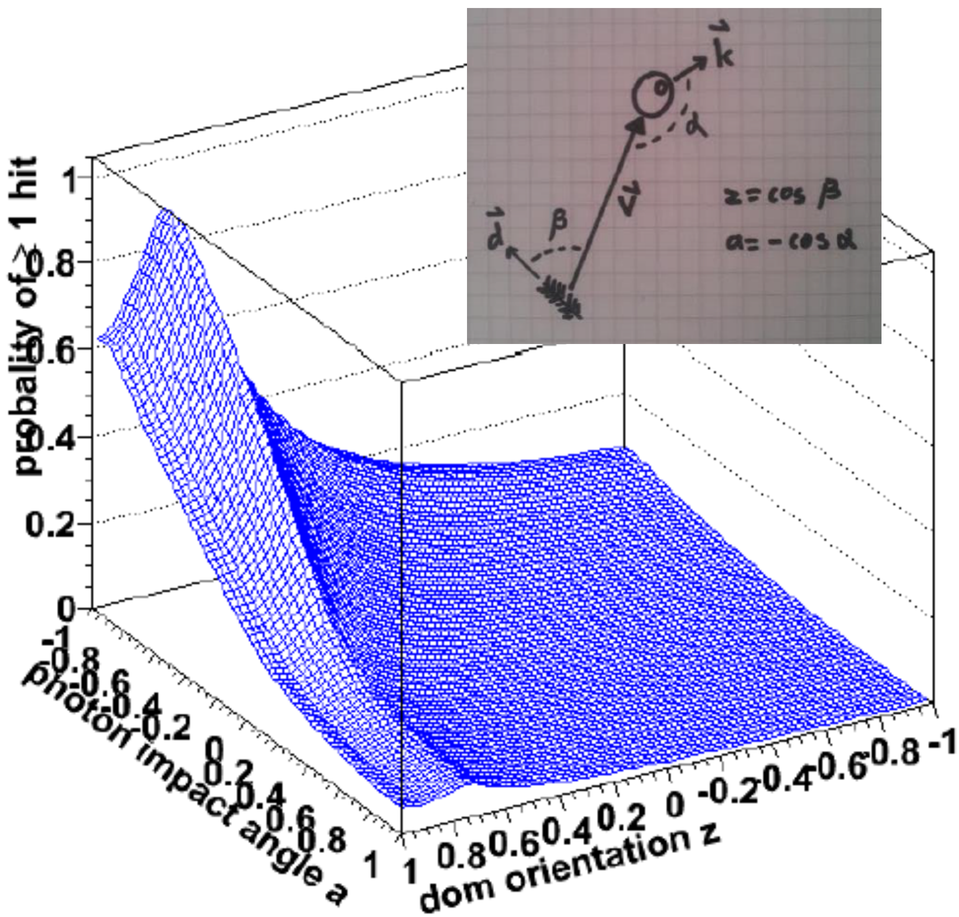


Concerning arrival times:

- spherically expanding shell of light around shower maximum
- allows accurate vertex resolution
- To first order *no direction* information in timing.

Cascade signature in water: intenstity

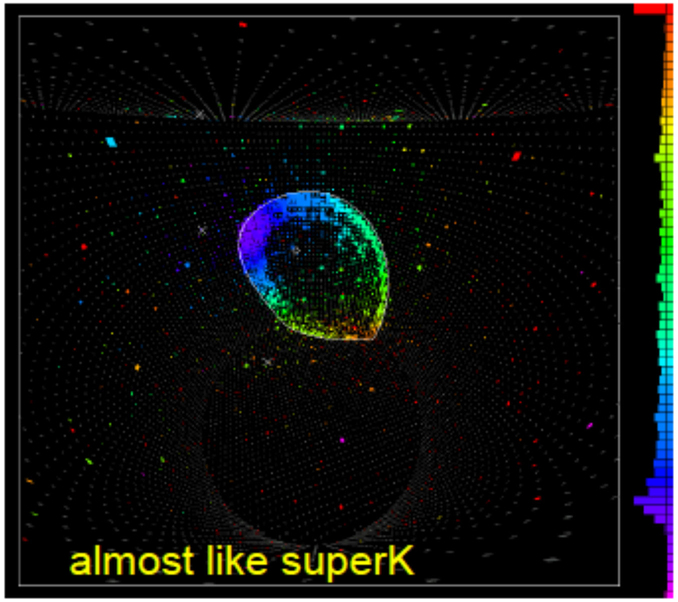
PDF for E = 1 PeV at r = 250 m



– Light is beamed in the Cherenkov direction.

– Pattern remains at large distances from the shower.

– energy independent!



need to measure the light amplitude (ToT)

KM3NeT: PMTs

3-inch PMTs

Key features:

– timing	≤ 4.5 ns (FWHM)
– QE	≥ 25-30%
– collection efficiency	≥ 90%
– photon counting purity	100% (by hits, up to 7)
– price/cm^2	≤ 10” PMT

ETEL D792

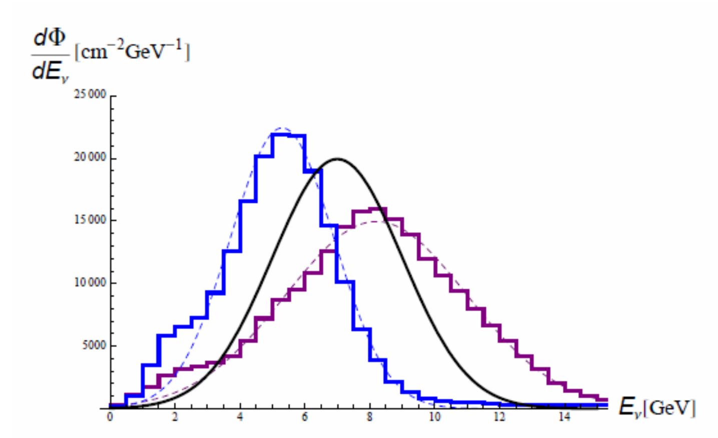
Hamamatsu R12199

HZC XP53B20

A neutrino beam to ORCA ?

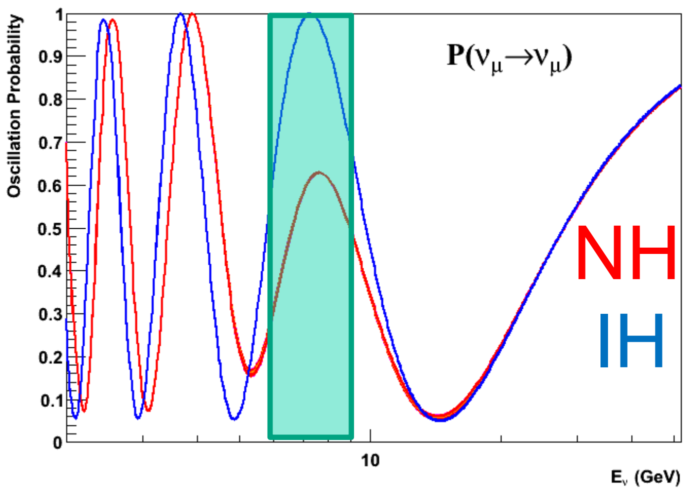
❖ Counting MUONS from a neutrino beam

F. Vissani et al., Eur.Phys.J. C73 (2013) 2439



Optimal beamline for NH/IH separation: 7000-8000 km

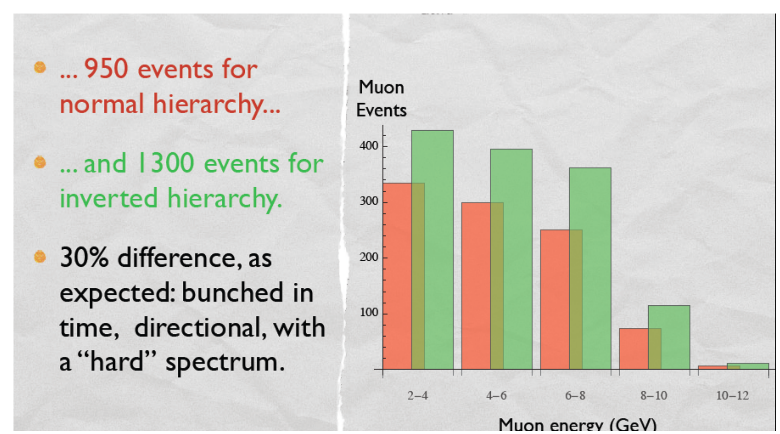
GLOBES cosθ = 0.6, baseline = 7645 km (beam inclination ~37°)



Narrow-band beam 6-9 GeV, 10^{20} pot

	Fermilab	CERN	J-PARC
South Pole	11600	11800	11400
Sicily	**7800**	1230	9100
Baikal Lake	8700	**6300**	3300

Favoured Option: FermiLab → KM3Net site in Mediterranean Sea
1300 versus 950 events for both mass hierarchy hypotheses in Mton underwater detector (ORCA)



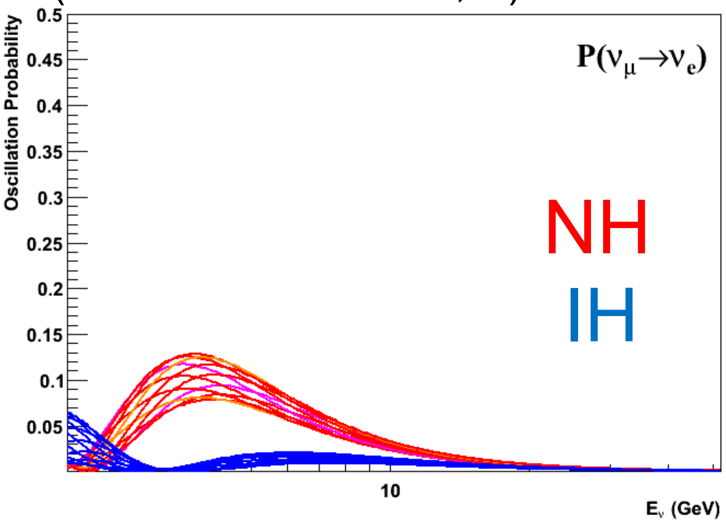
A neutrino beam to ORCA ?

❖ Counting ELECTRONS from a neutrino beam

J. Brunner, arXiv:1304.6230

Optimal beamline for NH/IH separation:
~2600 km (largest difference in event rates)

GLOBES $\cos\theta = 0.2$, baseline = 2548 km
(beam inclination ~11,5°)



- moderate inclination
- almost insensitive to δ_{CP}

A possible option: Protvino (Proton Accelerator Complex) → Toulon

L=2588 km, beam inclined 11.7°

need 1.5 10^{21} pot

From preliminary studies:
7σ discrimination in 3 yr from event counting only (3σ with 3-4% systematics)