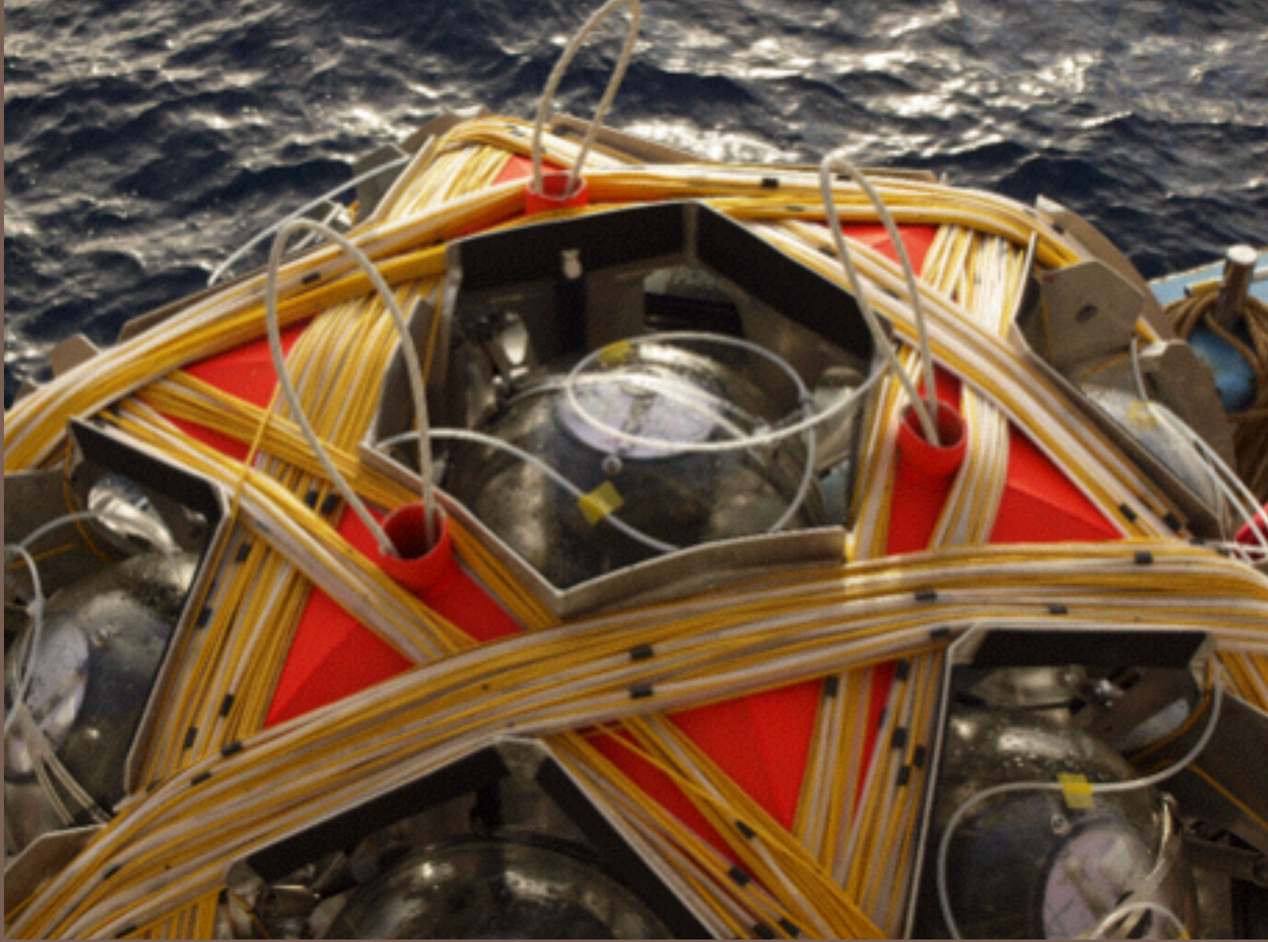
R. Coniglione
INFN-LNS - Catania
(Italy)



THE KM3NET AND ANTARES NEUTRINO TELESCOPES: CAPABILITIES AND ISSUES AT THE HIGHEST ENERGIES

Mainz - 30 September - 11 October 2019

OUTLINE

- Neutrino telescopes
- KM3NeT and ANTARES
- Issues at the highest energies
  - high energy neutrino cross section
  - atmospheric neutrino flux

What we need and what measured

The high energy neutrino telescopes

Array of optical sensors to detect neutrinos of extraterrestrial origin

Detection of the Cerenkov light produced by the particles

The faint expected fluxes and the low neutrino detection probability

↓

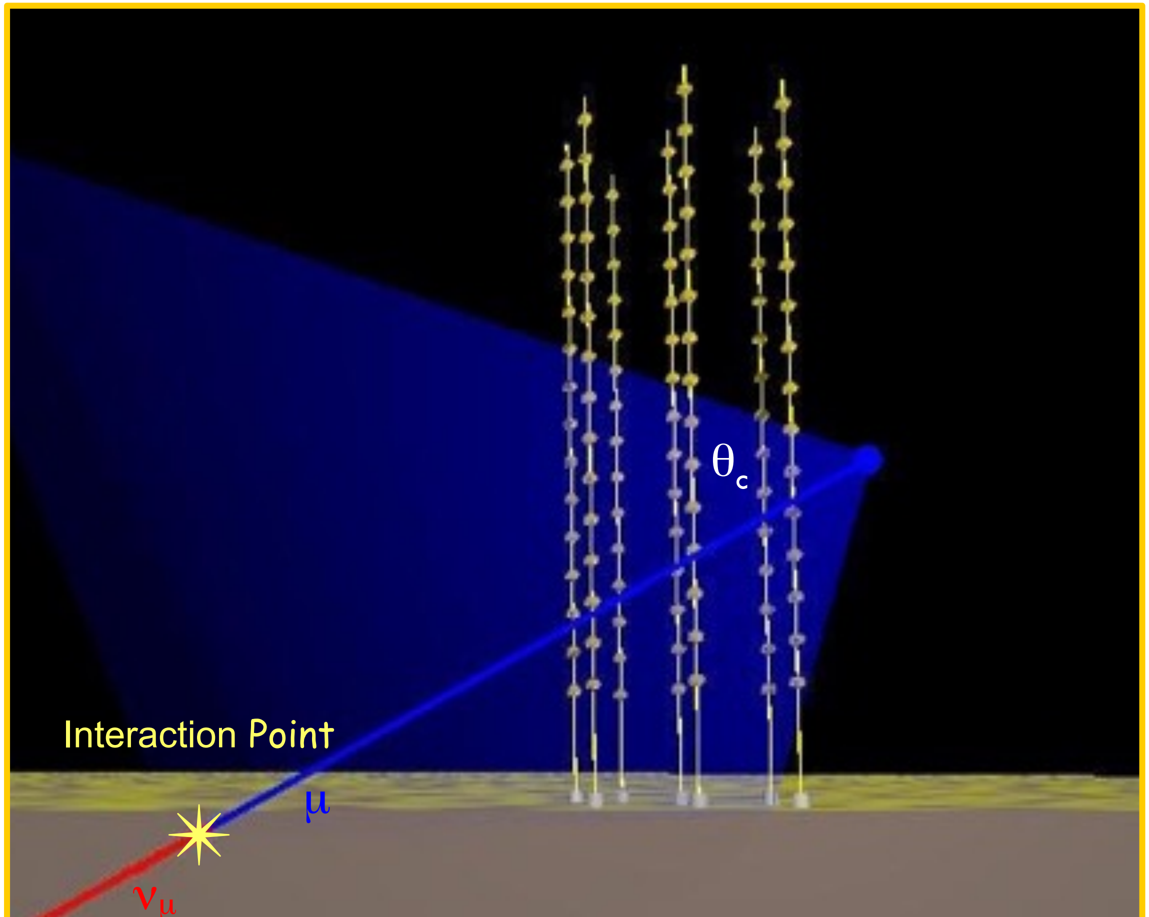
Detector with large volume (km^3) installed in deep water or ice

Idea suggested by Markov in the '60
(to use the "beam" of atmospheric neutrinos)

$\boxed{\text{High energy means} \;☞\; E_\nu \gtrsim 10^2\ \text{GeV}}$

Working detectors: ANTARES, Baikal, IceCube, KM3NeT

Detection principle

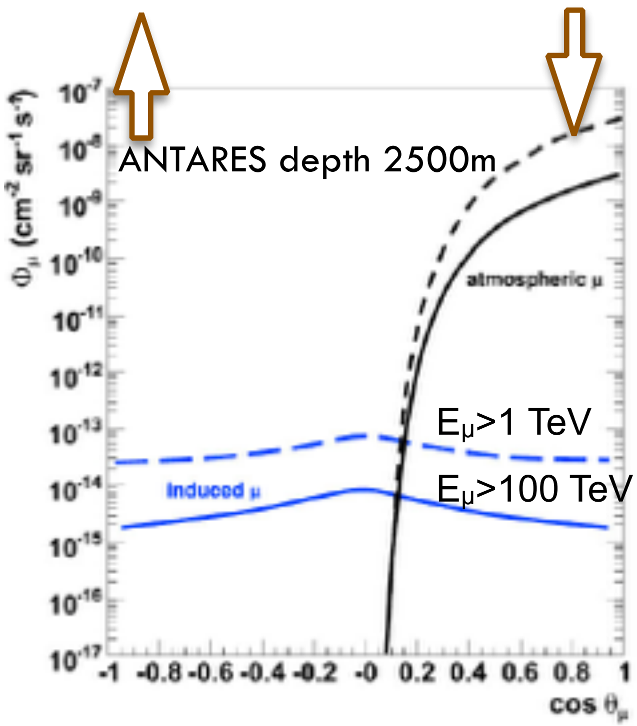


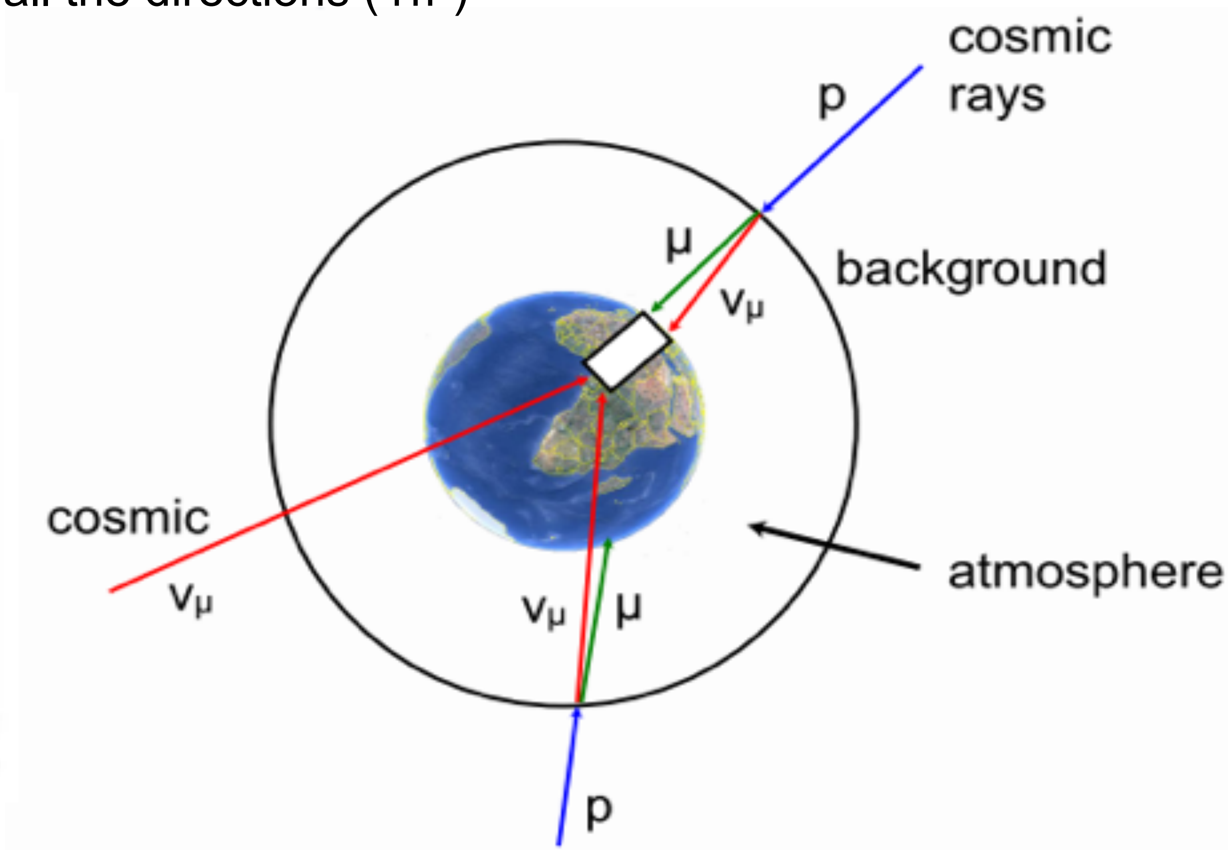
- The neutrinos interact in the water/ ice or rocks around the detector and produce secondary particles that emit Cerenkov light in a cone at 42° (in water) w.r.t the particle direction.
- Light detected by means of optical sensors (photomultipliers)
- From the arriving time of photons and from the positions of the photomultipliers is possible to determine the direction of the secondary particles. If muons, generated by ν_μ, the precision in the reconstruction of the direction is very high (0.1°-0.2°). High energy neutrinos are collinear with muons
- Possible to detect also ν_e

Background of atmospheric muons and neutrinos

From the interaction of Cosmic Ray with the atmosphere:

- Atmospheric muons only down-going (2π) …. but ….
- Atmospheric neutrinos from all the directions (4π)

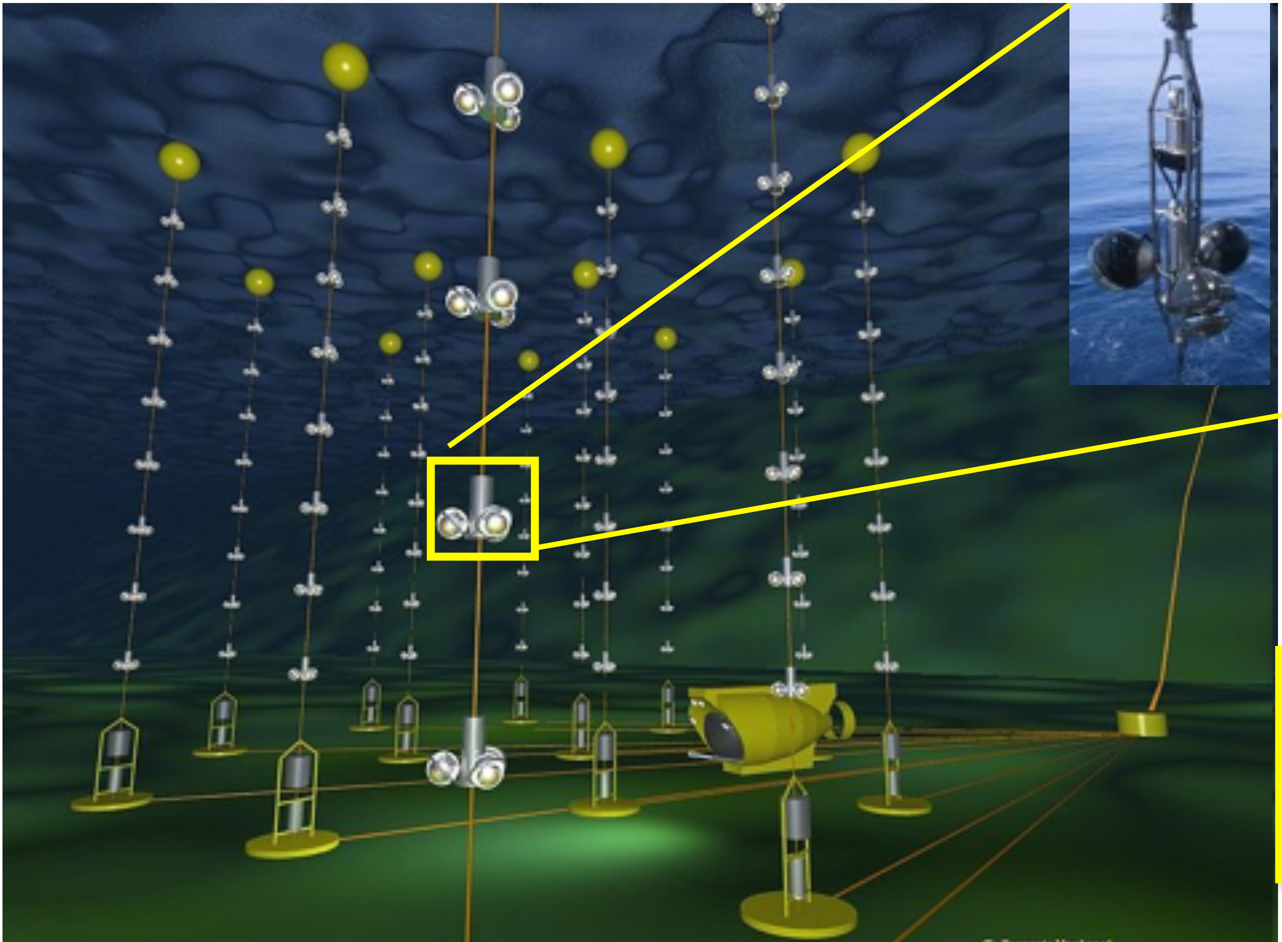




Even if the detectors are shielded by the water/ice the atmospheric muon flux is high

ANTARES

Optical sensor
1 PMT of 10 inches



Depth 2475m

12 lines of 75 PMTs
1 line for Earth and Marine sciences
25 storeys / line
3 PMTs / storey
885 PMTs
Volume 0.01 km³

Detector completed in 2008
Taking data since 11 years
with a duty cycle of ~95%

KM3NeT

KM3NeT is a research infrastructure in the Mediterranean Sea hosting neutrino detectors

- KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss)
  - observation of high energy (GeV ÷ PeV) neutrino sources ☛ a telescope offshore Capo Passero (Sicily-Italy) is in construction at a depth of 3500m
- KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss)
  - determination of the neutrino mass hierarchy ☛ a detector offshore Toulon (France) able to detect neutrinos of tens of GeV is in construction at a depth of 2500m

ORCA and ARCA same detector technology

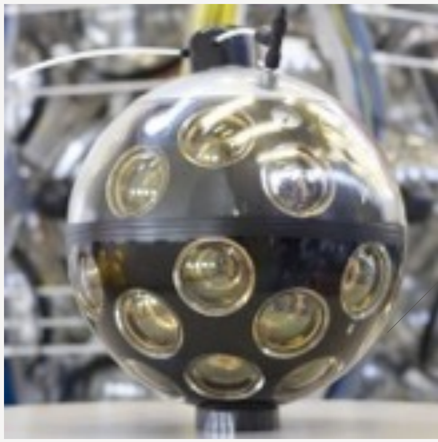
Details on the ARCA and ORCA physics performances and on the technical design in the published **Letter of Intent** ☛

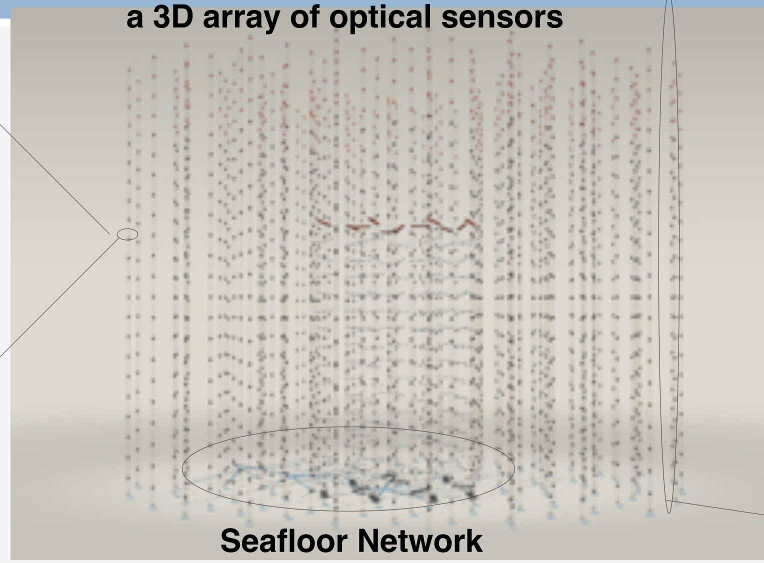
OPEN ACCESS
IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001 (130pp) doi:10.1088/0954-3899/43/8/084001

Letter of intent for KM3NeT 2.0

The KM3NeT design

The optical sensor: the Digital Optical Module (DOM)

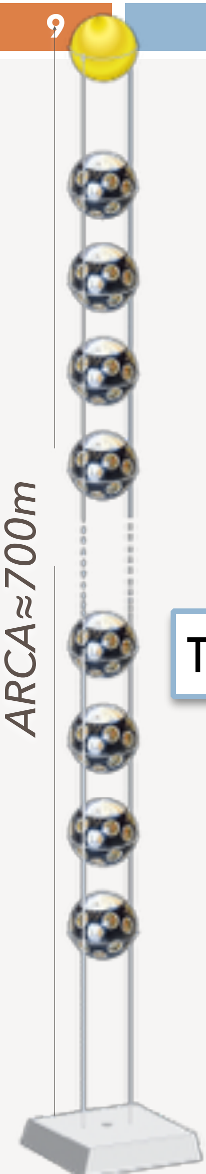


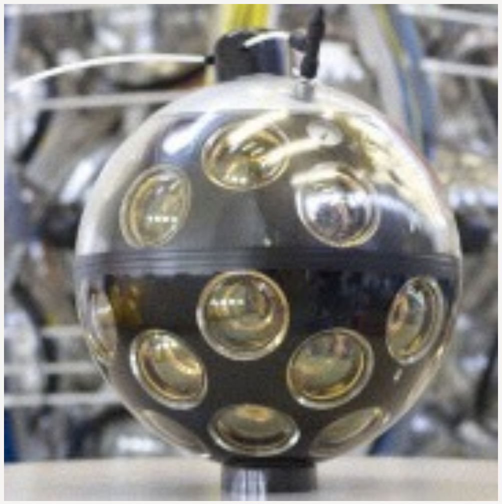


The Detection Unit (DU)

- The optical sensor is made of 31 3” PMTs (photocathode aerea ≃ 3 × 10” PMTs)
- The DU is a vertical slender string equipped with 18 Digital Optical Modules (DOM).
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Sea network of submarine cables and Junction Boxes connected to shore via a main e/o cable
- All data to shore

The Optical sensors and the Detection Unit





The DOM is a new design for optical sensors developed in the collaboration

It is a 17" glass sphere with inside:

- 31 3" PMTs (photocathode aerea ≃ 3 × 10" PMTs)
- LED and Piezo
- Front-end electronics -> FPGA

Hybrid white rabbit for time synchronization
DWDM for data transmission

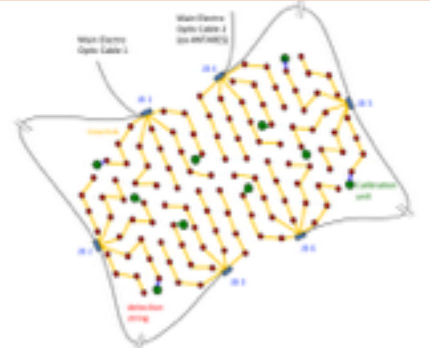
Advantages:

- increased photocathode area
- directionality
- single penetrator -> reduced risk
- Cost/photocathode area

KM3NeT

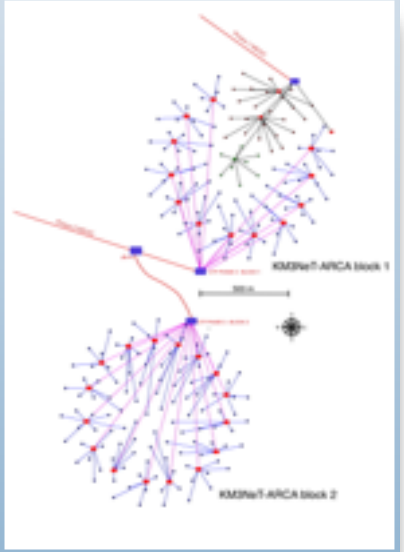
ORCA

- Depth ~2500 m
- One block of 115 DU
- Average distance between DU ~20 m
- Average vertical distance between DOMs ~9 m
- **Volume ≈ 8 Mton**



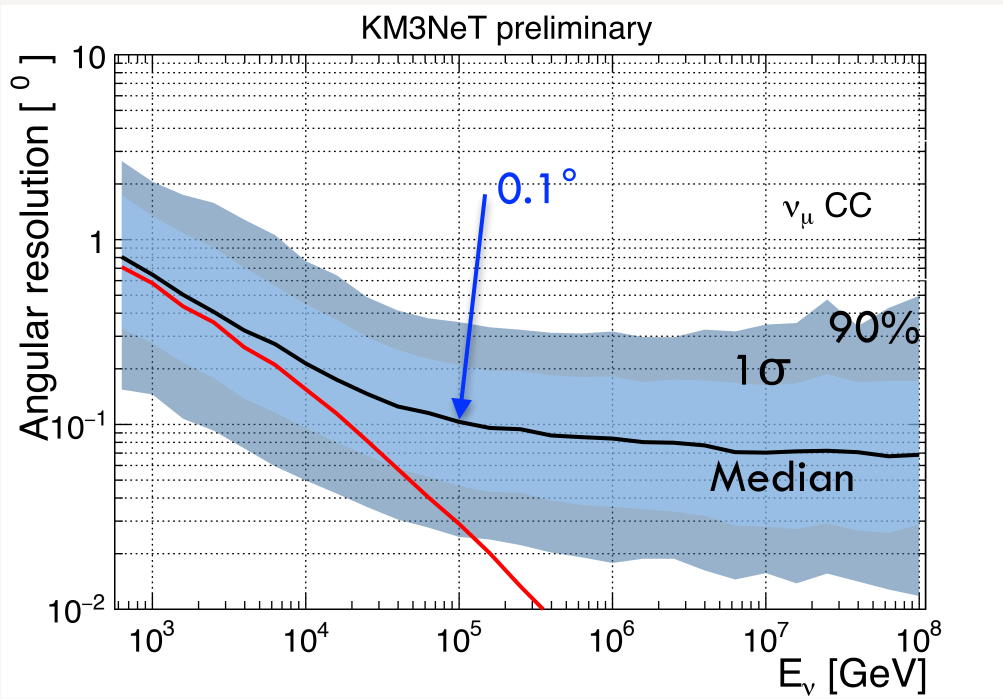
ARCA

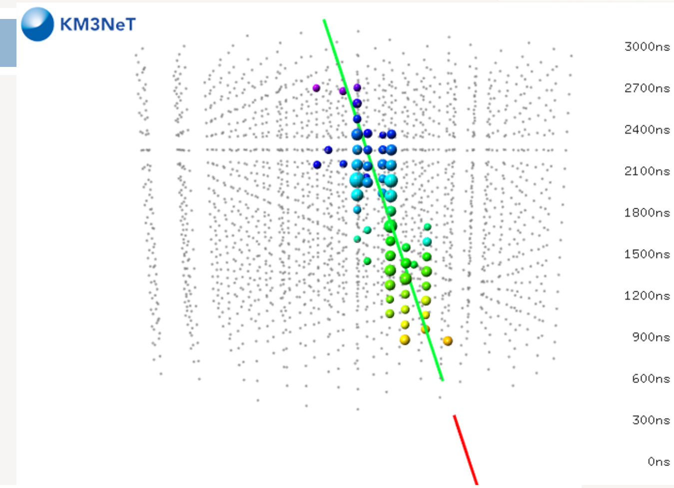
- Depth ~3500 m
- Two blocks of 115 DU each
- Average distance between DU ~90 m
- Vertical distance between DOMs ~36 m
- **Volume (0.5 × 2) km^3 ≈1 Gton**

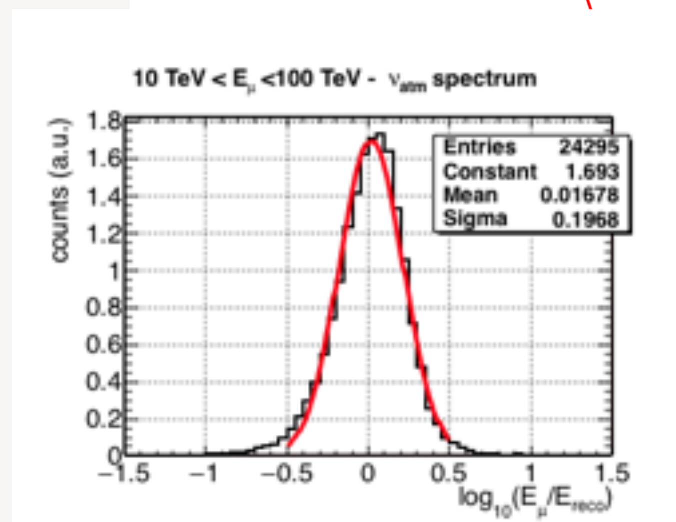


The KM3NeT/ARCA resolution for "track-like" events

"Track-like" events mainly from ν_μ CC interactions





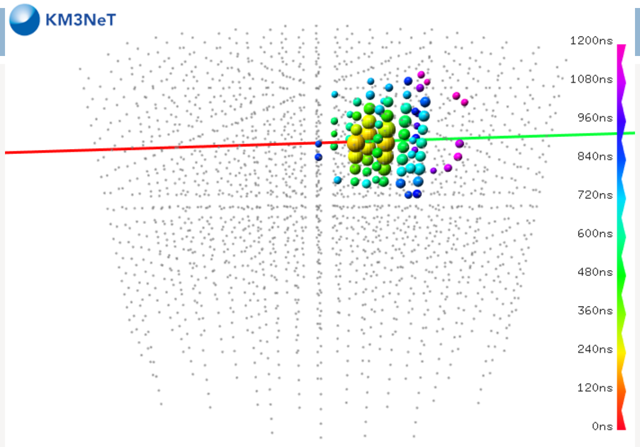


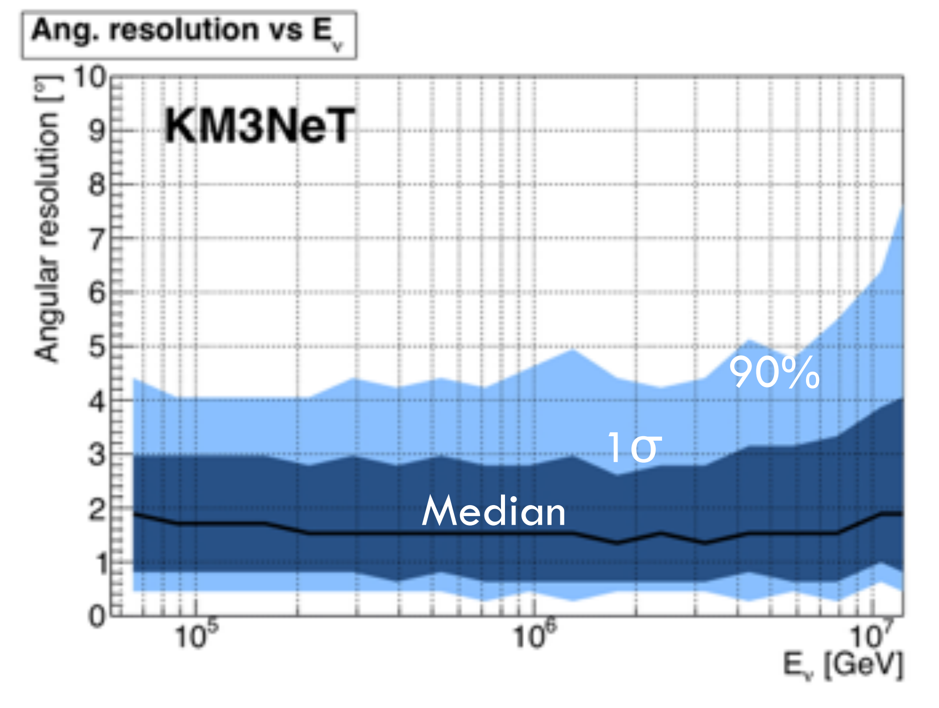
angular resolution better than 0.2° for E_ν@10 TeV and <0.1° for E_ν>100 TeV

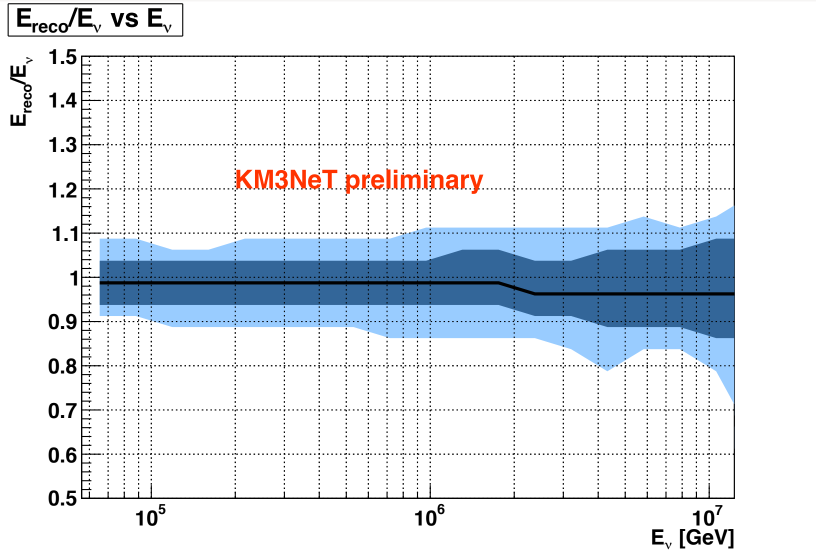
energy resolution better ≈ 20% of the $\log_{10}E_\mu$ for E_μ>10 TeV

The KM3NeT/ARCA resolution for "cascade" events

"Cascade-like" events mainly from ν_e CC and NC interactions







angular resolution better than 2°

energy resolution better ≈ 5% at 1σ

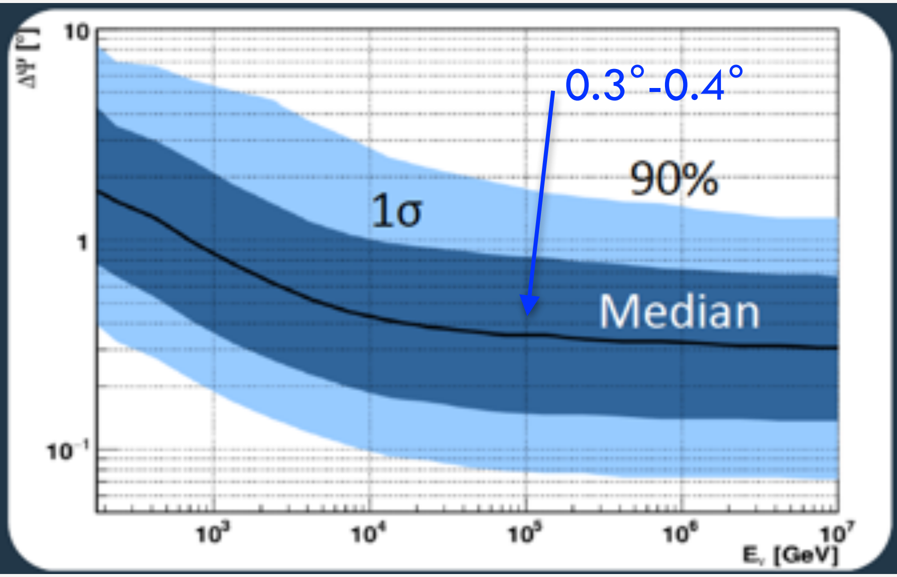
The ANTARES resolutions

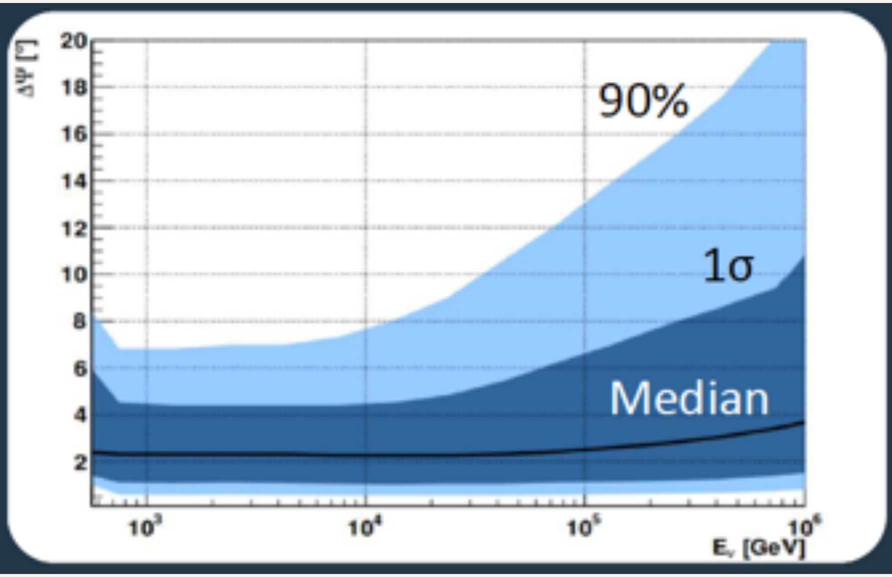
Track

Angular resolution: <0.4° @ E_ν>10 TeV
Energy resolution: <0.5 on log E_μ

Shower

Angular resolution: ~3°
Energy resolution: ~25% (<10% for ν_e-CC)





KM3NeT: status

KM3NeT is under construction

DUs currently working

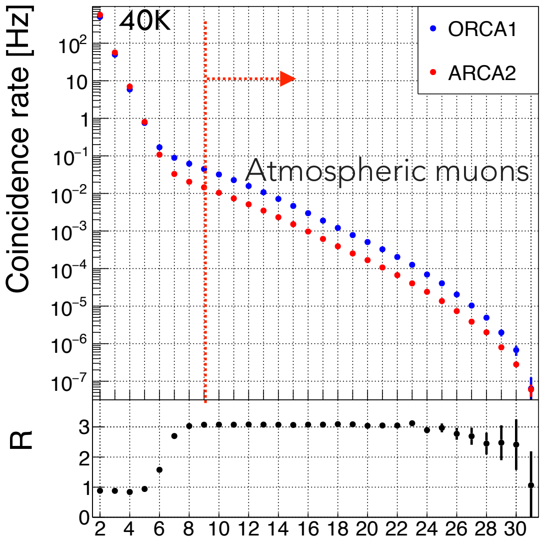
4 DUs ORCA

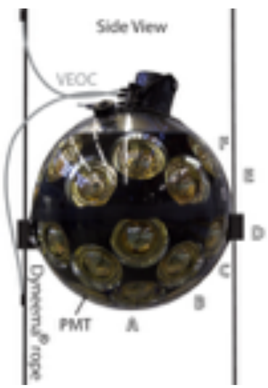
1 DU ARCA

KM3NeT: first results

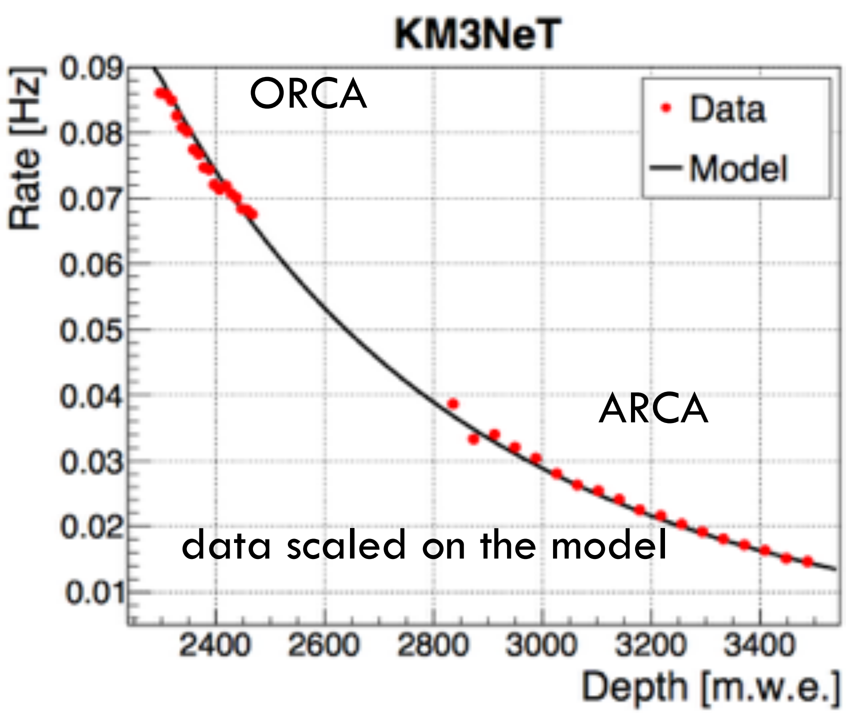
Measured the atmospheric muon depth dependence
NO track reconstruction

Results from ARCA2 (2 DU working) and ORCA1 (1 DU working)





DATA compared with a muon depth dependence model (Bugaev et al, Phys. Rev. D 58 1998 054001)



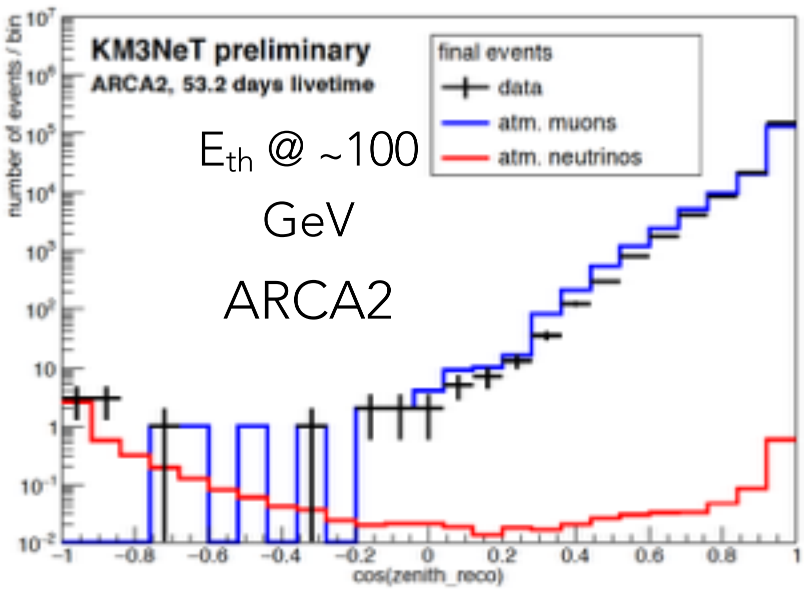
Soon the muon flux vs depth

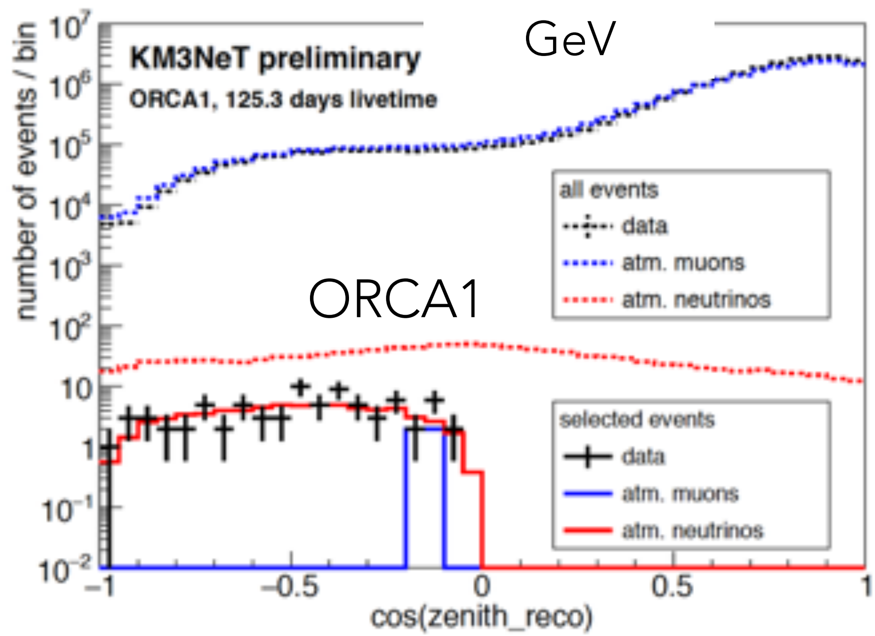
https://arxiv.org/pdf/1906.02704.pdf

KM3NeT: first results

ICRC2019 PoS 910

Selected first neutrinos





Selected ~6 neutrinos with $\cos(\theta_{rec})<-0.8$

MC: μ_{atm} 0 - ν_{atm} 3.3

Selected ~77 neutrinos

MC: μ_{atm} 4 - ν_{atm} 67.5

Good Data-MC agreement

Proved the possibility to detect neutrinos also with 1-2 DUs

Issues at high energies in a neutrino telescope

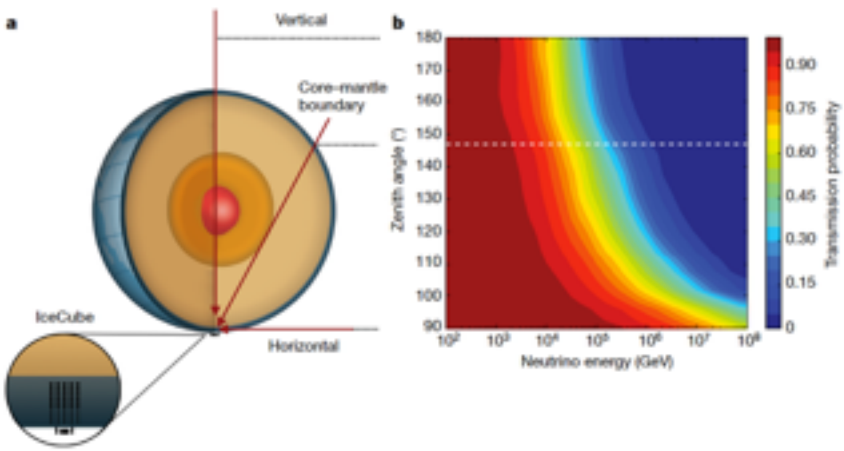
- High energy neutrino cross section 👉 Monte Carlo neutrino generators

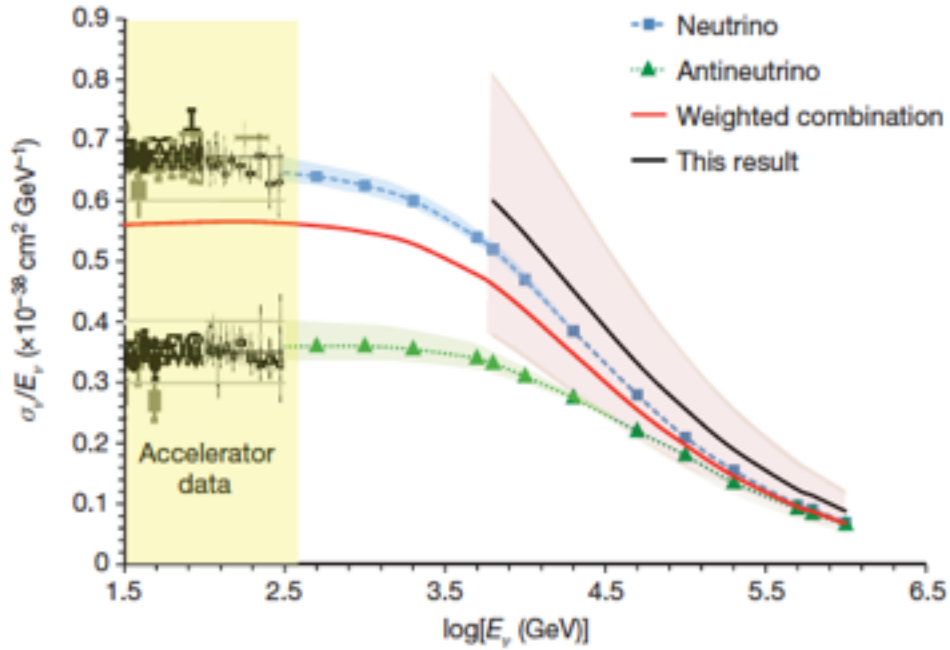
- Atmospheric neutrino flux 👉 for the estimate of KM3NeT detector performances

High energy cross section measurements

Up-going tracks selected

Measured fitting the neutrino distribution as a function of Energy and angle





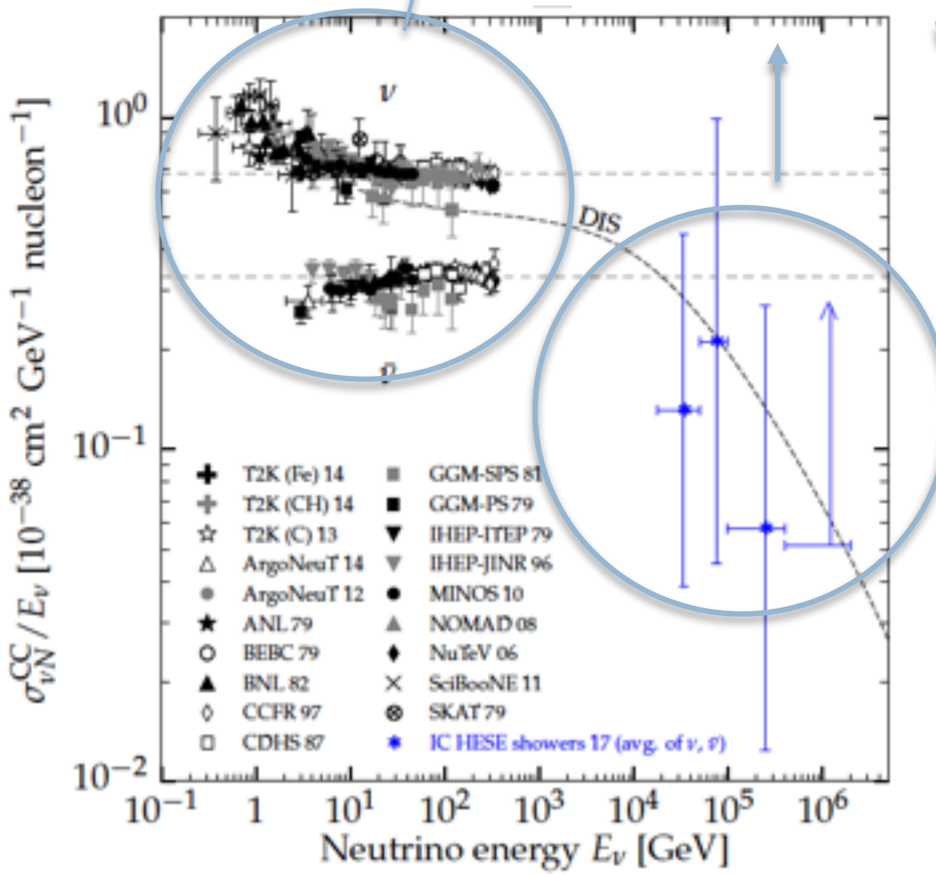
$$\sigma_{meas}/\sigma_{calc.} = 1.30^{+0.21}_{-0.19}\ \text{(statistical uncertainty)}\ ^{+0.39}_{-0.43}\ \text{(systematic uncertainty)}$$

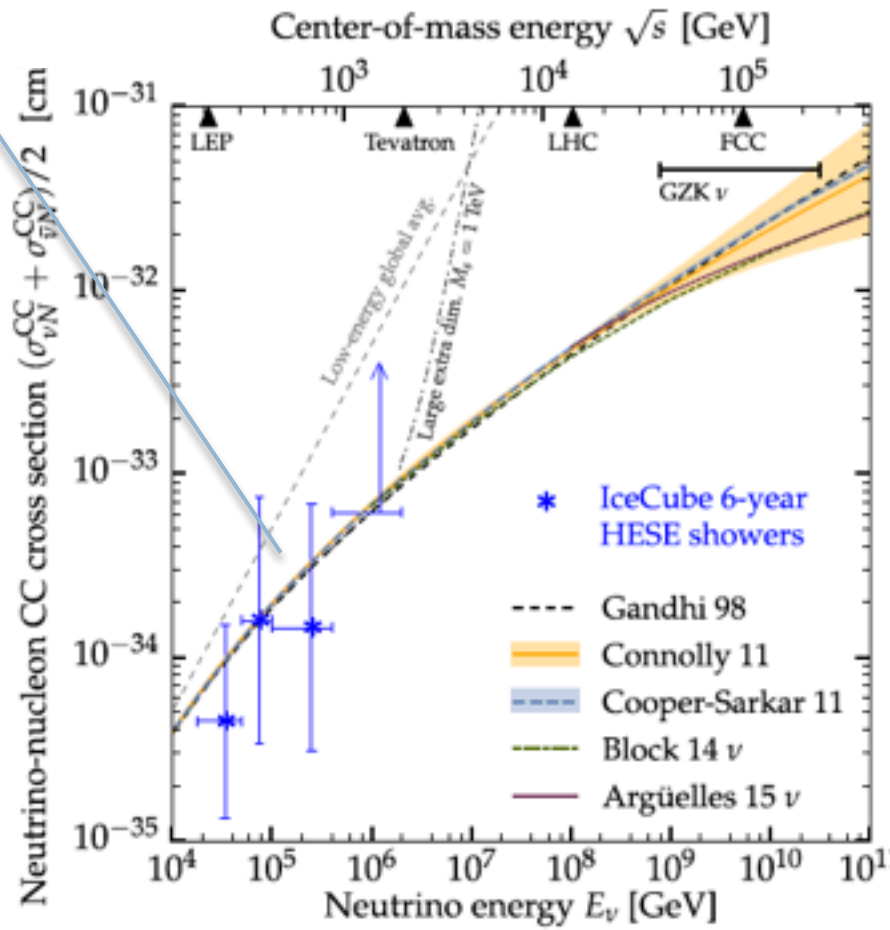
IceCube coll. - Nature, 2017. doi: 10.1038/nature24459.

High energy cross section measurements

NO measurements with accelerators above 350 GeV

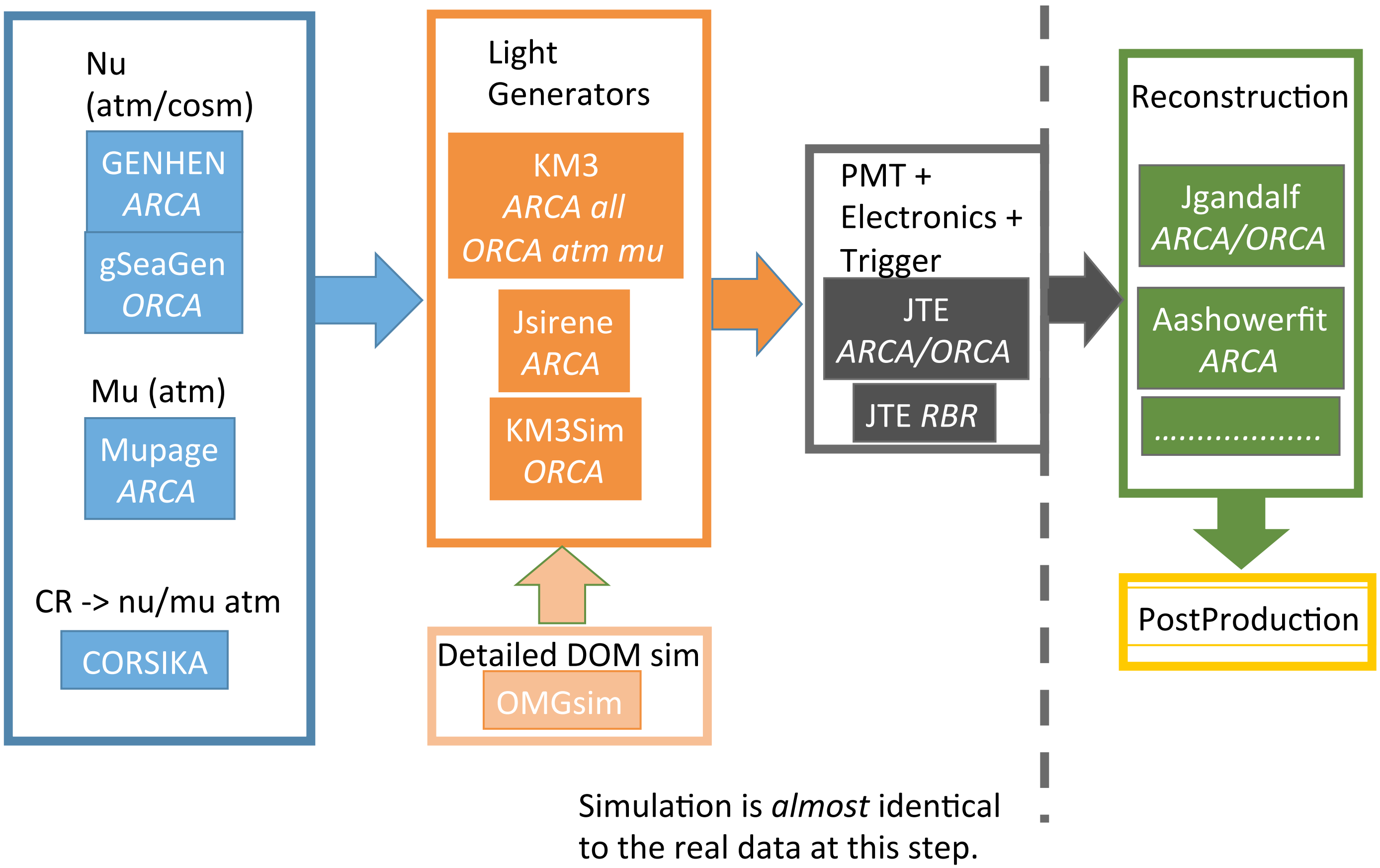
From IC HESE events





M. Bustamante and A. Connolly Phys.Rev: Lett. 122, 041101 (2019)

KM3NeT Monte Carlo scheme

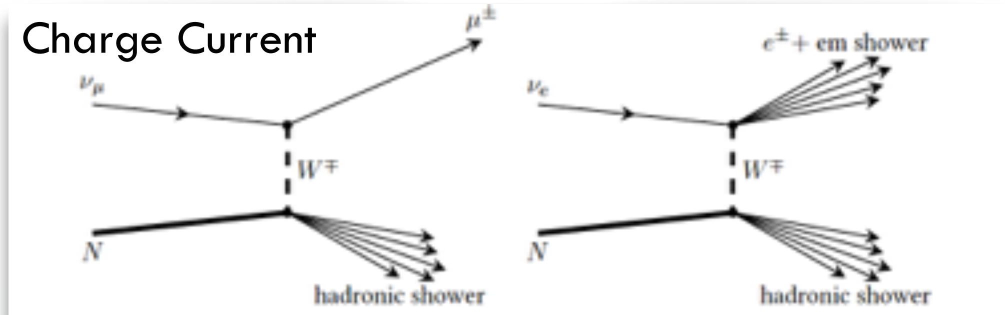


GenHen from 100 GeV up to 10^8 GeV -> LEPTO

gSeaGen from GeV up to 1 TeV -> Genie

Efforts in KM3NeT to improve high energy neutrino generator

To simulate neutrino interactions:
- Interaction probability
- Particle kinematics
- Hadronic shower



Deep Inelastic Scattering

$$\frac{d^2\sigma^{CC}_{\nu-n}}{dxdy} = \frac{G_F^2}{\pi} M_N E_\nu \frac{M_W^4}{(Q^2+M_W^2)^2}\left[y^2\frac{x}{2}\mathbf{F_1(x,Q^2)} + (1-y)\,\mathbf{F_2(x,Q^2)} + y\left(1-\frac{y^2}{2}\right)\mathbf{F_3(x,Q^2)}\right]$$

$$F_i(x,Q^2) = \sum_j \int_x^1 \frac{dz}{z} f_j(z,Q^2)\, C_{i,j}(x/z,Q^2)$$

Structure Functions

=

Nucleon QCD dynamics

quark and gluon density

coefficient functions

In the existing high energy neutrino generators only Leading Order

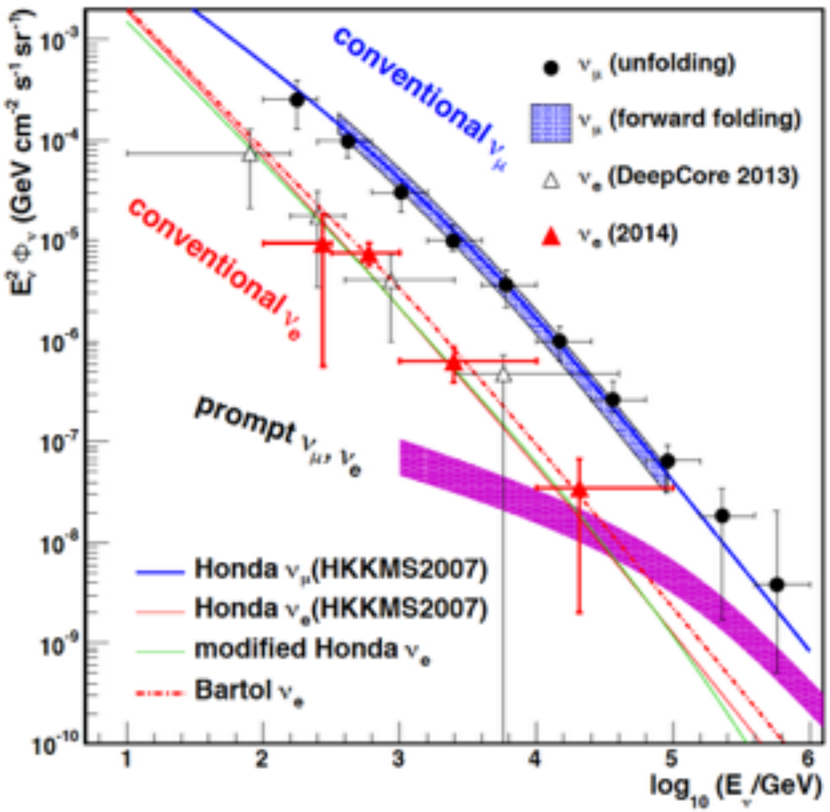
HEDIS

- HEDIS* 👉 extension of Genie at high energies
  - Newer PDFs with broader Q^2 phase space.
  - Structure Functions = C_{ij} NLO⊗PDF NLO.
  - Account for the heavy quark contributions

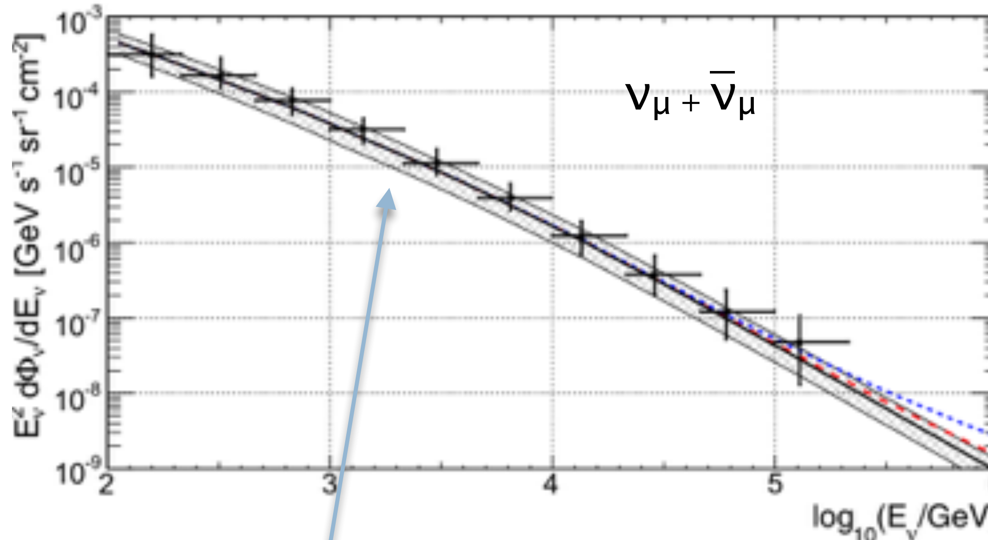
*contact: alfonsog@nikhef.nl
"High-energy neutrino event simulation at NLO in Genie for KM3NeT and other observatories" - ICRC2019 Pos895

The atmospheric neutrino flux: the conventional flux

IceCube coll., Phys. Rev. D 91, 122004 – (2015)



ANTARES coll., Eur. Phys. J. C 73 2606 (2013)
2008-2011 data



Conventional
G.D. Barr et al. Phys. Rev. D 70, 023006 (2004) and G.D. Barr et al., Phys. Rev. D 74, 094009 (2006) -> black line and band

Prompt:
A.Martin et al., ActaPhys.Pol.B34,3273(2003) -> red dashed
R.Enberg et al., Phys.Rev.D78,043005(2008) -> blue dashed

The measured conventional flux

A D Morozova et al., Journal of Physics: Conf. Series 798 (2017) 012101

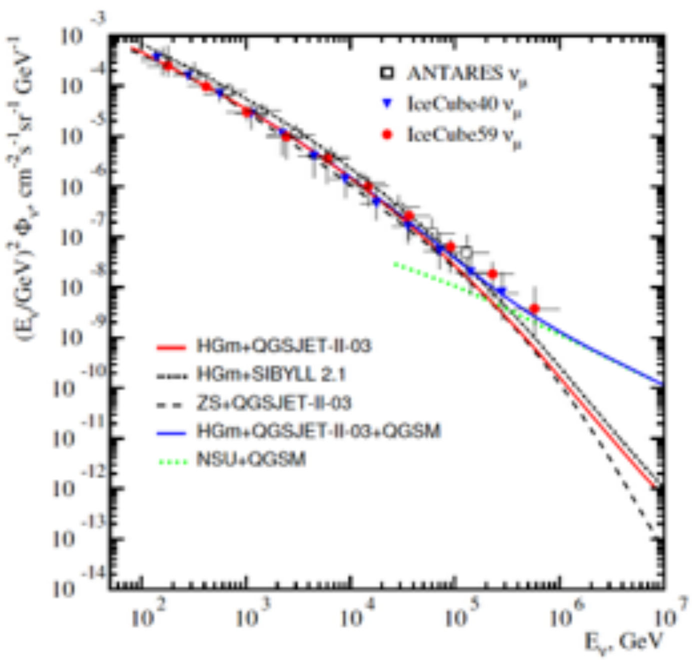


Figure 3. The $(\nu_\mu + \bar{\nu}_\mu)$ spectrum measured by IceCube [14, 15] and ANTARES [16].

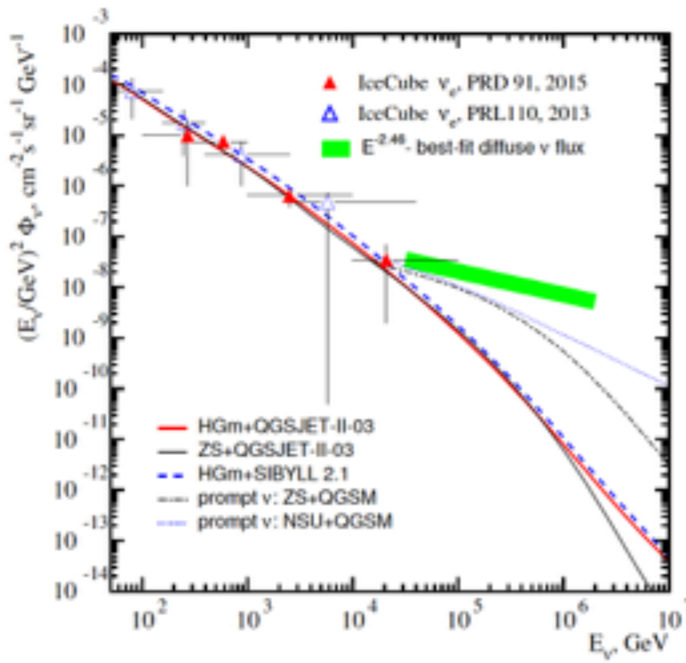


Figure 4. The atmospheric and astrophysical $(\nu_e + \bar{\nu}_e)$ fluxes measured in IceCube [13, 1, 2].

Our calculation demonstrates rather weak dependence on the model of primary cosmic-rays spectrum in the energy range of $10 - 10^5$ GeV. The major uncertainty in the calculated neutrino fluxes with energies up to 500 TeV is due to differences of hadronic interaction models, QGSJET-II, SIBYLL 2.1, which lead to significant discrepancy – up to 60% for the $(\nu_\mu + \bar{\nu}_\mu)$ flux and to $\sim 40\%$ for the $(\nu_e + \bar{\nu}_e)$ one. These differences are mainly due to the cross sections of K meson

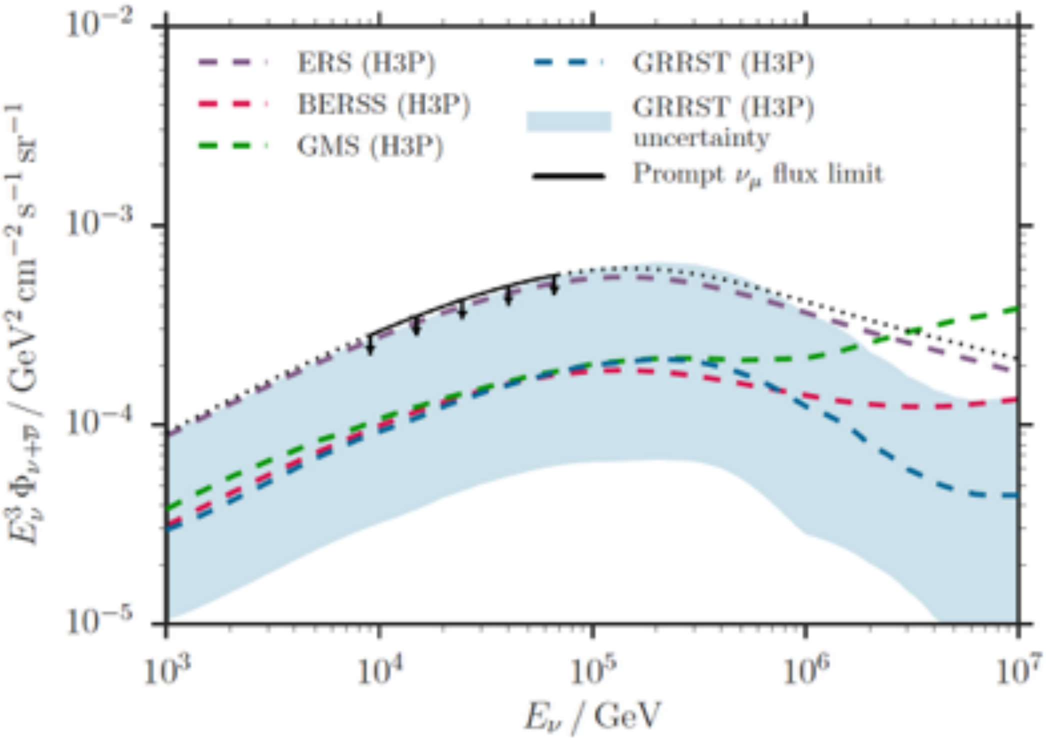
Upper limit of prompt component

IceCube 👉 from the cosmic muon neutrino flux using six years of data (track analysis)

Maximization of the likelihood of the observed data w.r.t. simulated data

ERS -> Enberg et al. 2008
GMS -> Garzelli et al. 2015
BERSS -> Bhattacharya et al. 2015
GRRST -> Gauld et al. 2016

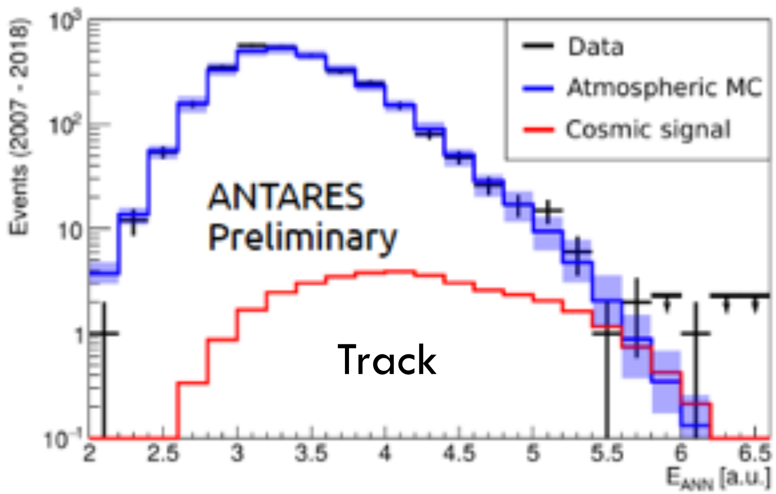
IceCube coll. The Astrophysical Journal, 833(1):3, (2016).

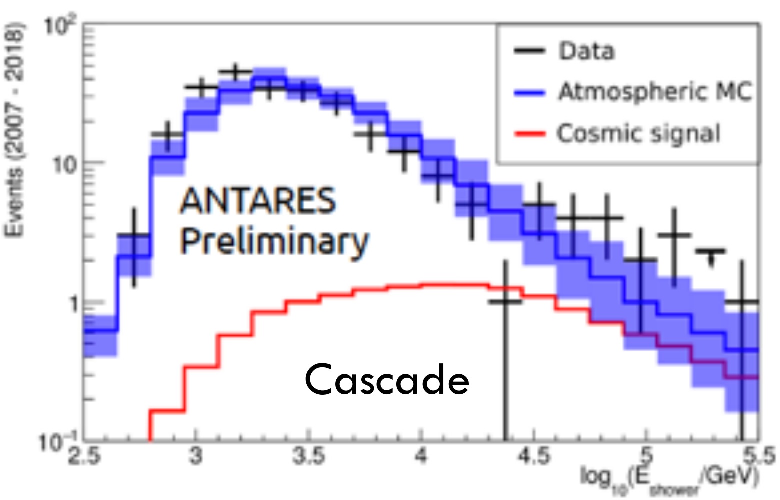


from the fit no prompt neutrino found
set upper limits

Model	Flux limit
ERS (H3p)	1.06
GMS (H3p)	$\approx$ 2.9
BERSS (H3p)	$\approx$ 3.0
GRRST (H3p)	$\approx$ 3.1

What measured by ANTARES





11 years of data

data: 50 events (27 tracks + 23 showers)
bkg MC: 36.1 ± 8.7 (19.9 tracks and 16.2 showers)

$\phi = 1.5\pm1\ 10^{-8}\ GeV^{-1} cm^{-2} sr^{-1} s^{-1}$

Γ=2.3±0.4

1.8σ excess

Atmospheric flux (Honda + Enberg together) fitted simultaneously with the cosmic flux

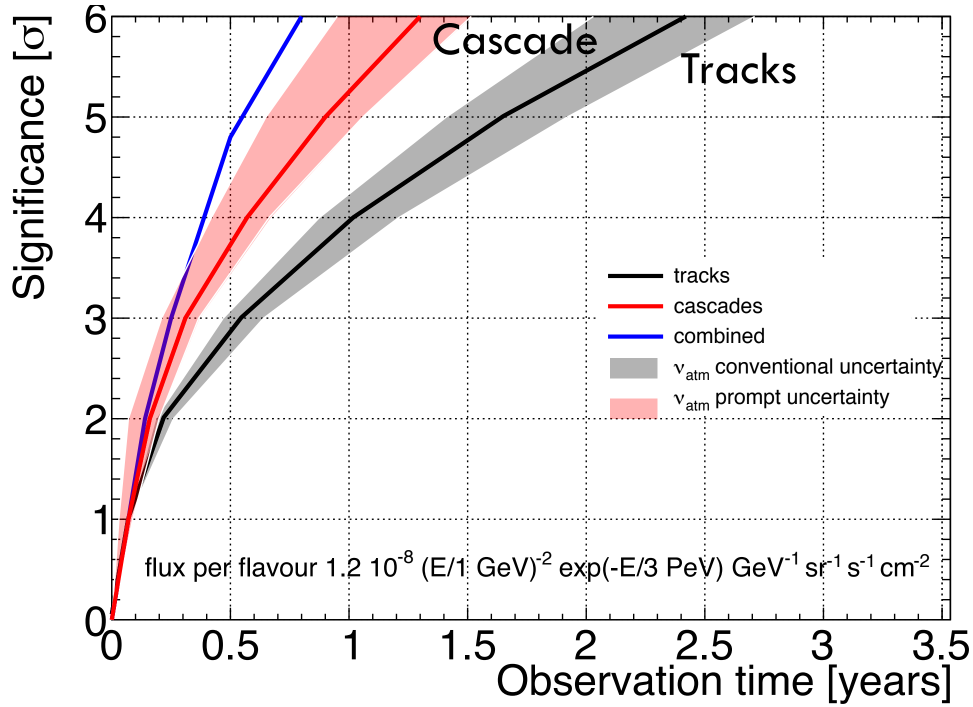
1.25 x (Honda + Enberg)

More details from L. Fusco next week

Atmospheric neutrinos

The knowledge of the atmospheric neutrino flux is the main systematic uncertainty in the estimate of KM3NeT/ARCA performances

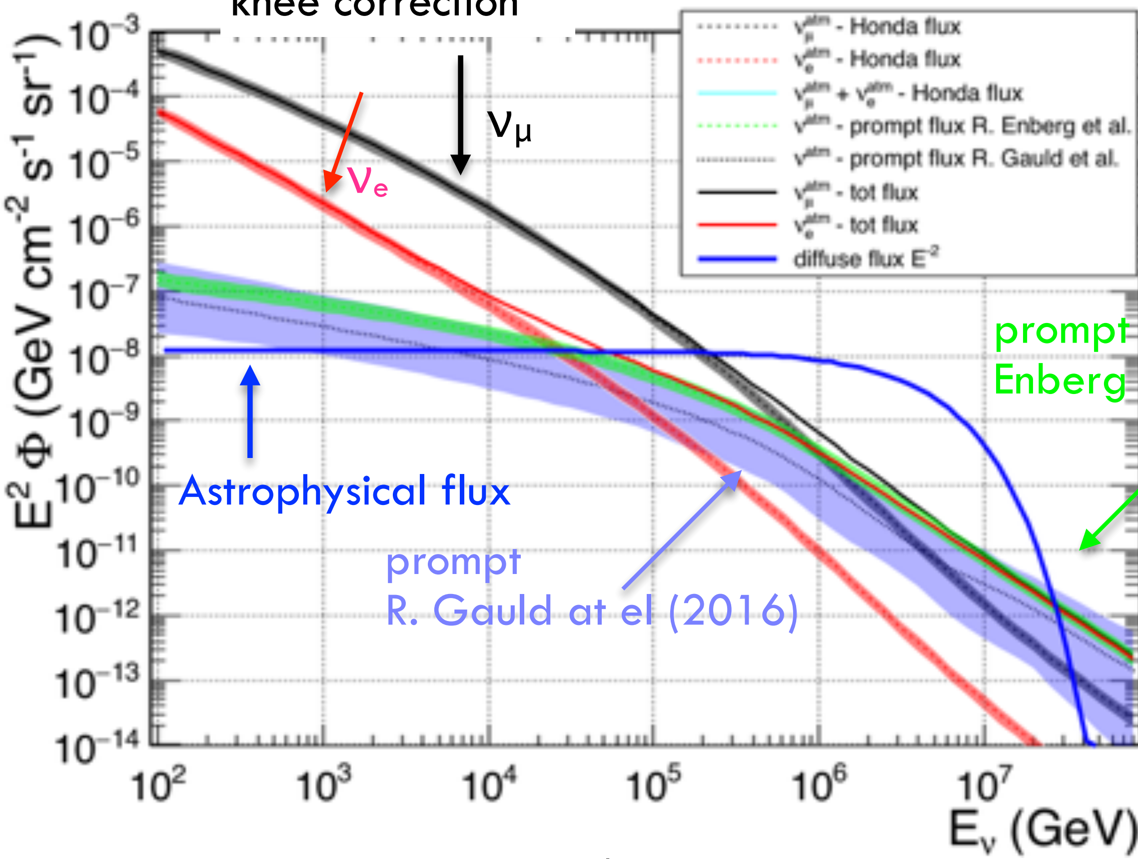
what expected for a diffuse flux



From KM3NeT LoI
Journal of Physics G: Nuclear and Particle Physics, 43 084001 (2016).

Atmospheric neutrinos in the KM3NeT LoI

Conventional Honda flux +CR knee correction

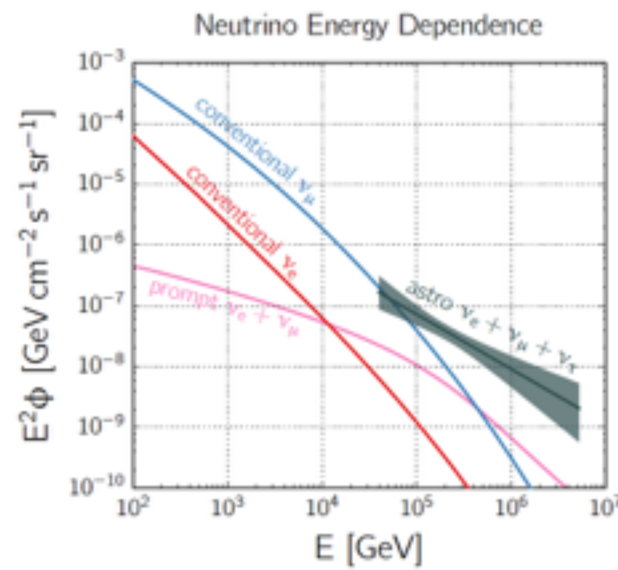


Uncertainties in the Honda flux ±25%

used Enberg et al. (ERS) for the estimates presented in the LoI

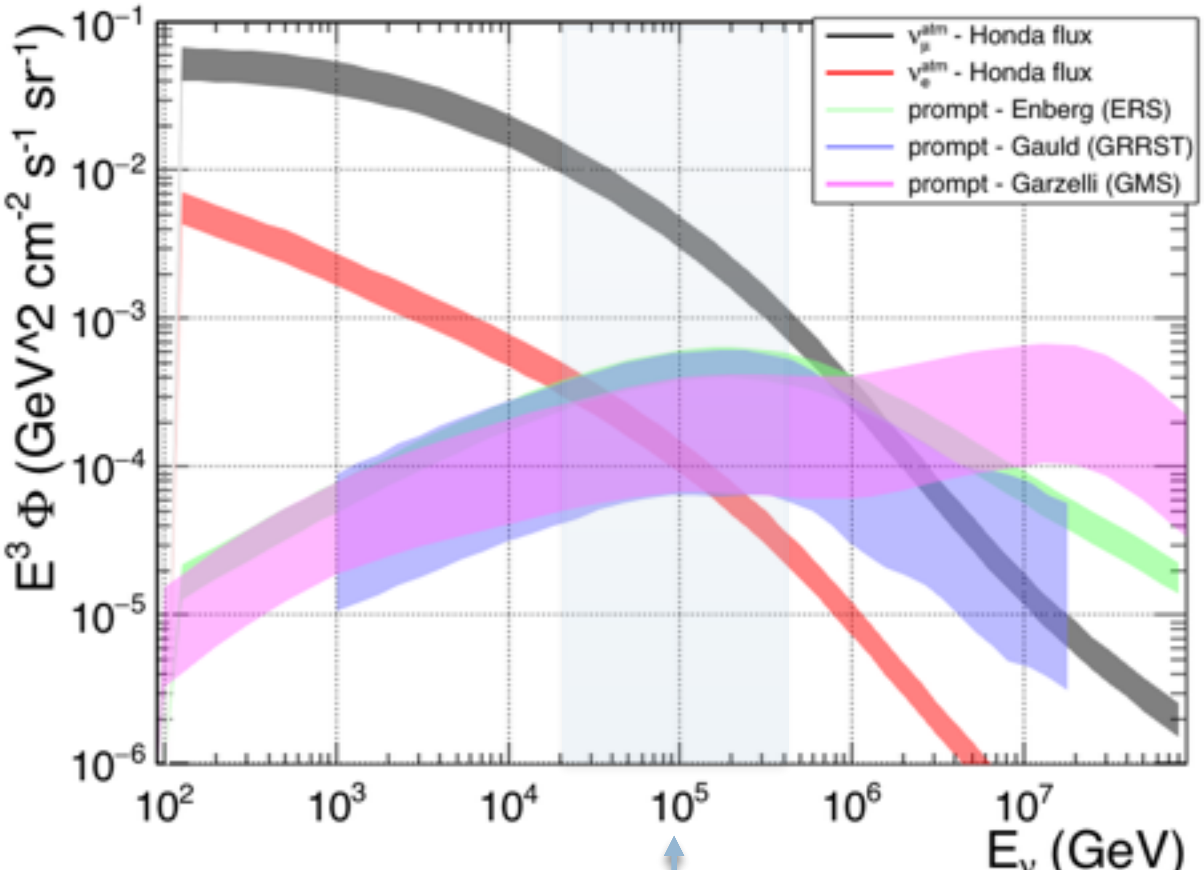
if Gauld et al. (GRRST) used 25%- 30% of variation in the discovery flux

prompt Enberg et al. (2008)



Comparison with other models

M.V. Garzelli, S. Moch, G. Sigl, et al. JHEP 1510 (2015) 115 , [arXiv:1507.01570]

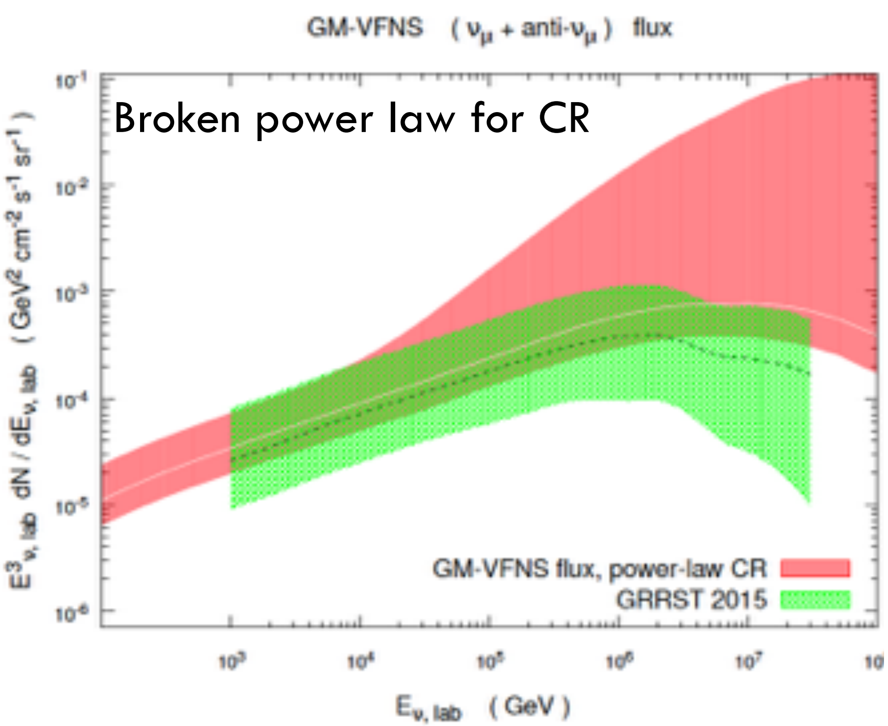


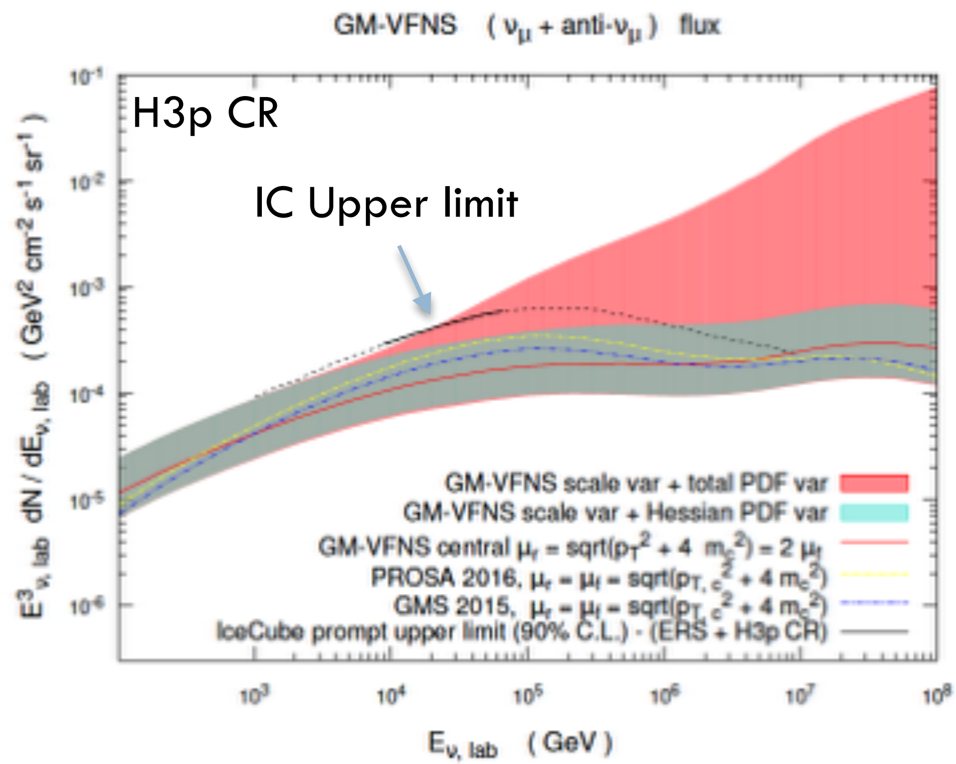
High uncertainties in the region of interest

Prompt: more recent calculations

M. Benzke, et al., JHEP12 (2017) 021

Different QCD approach w.r.t 2015 paper





Conclusion

- Cross section measurement with neutrino telescopes needs:
  - more statistics
  - events at higher energies
  - lower angular and energy resolutions
  - reduction of systematic uncertainties
- Atmospheric neutrino flux measurement needs:
  - a lower energy resolution
  - higher statistics at high energies

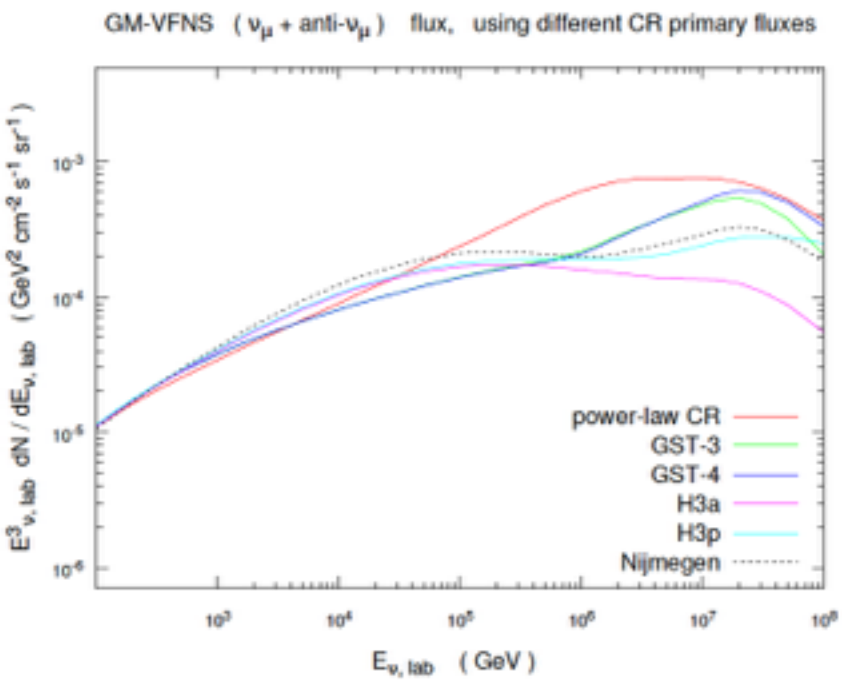
Global Neutrino Network (http://www.globalneutrinonetwork.org) aims for a closer collaboration and a coherent strategy among the neutrino telescope projects

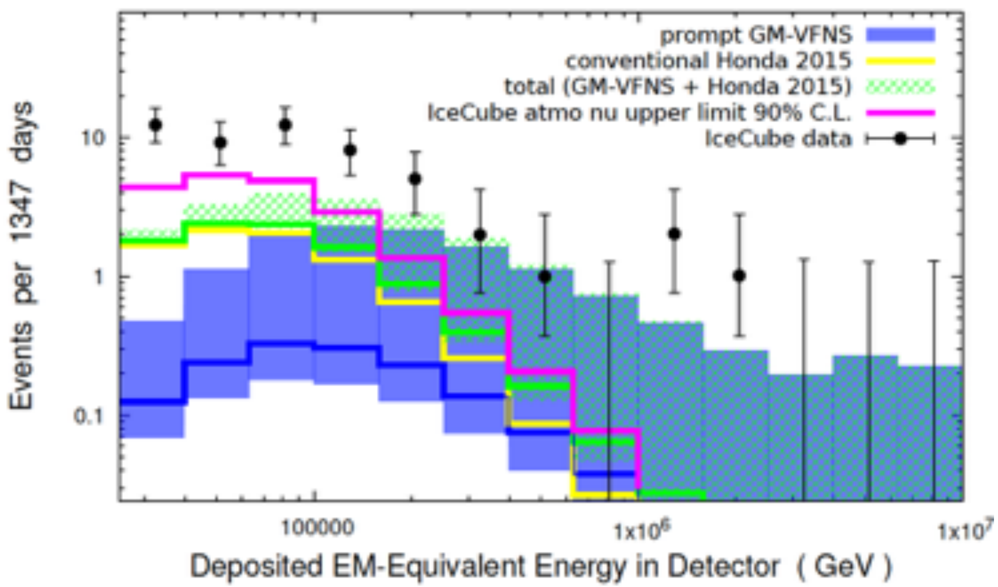
Projects participant: ANTARES, Baikal, IceCube, KM3NeT

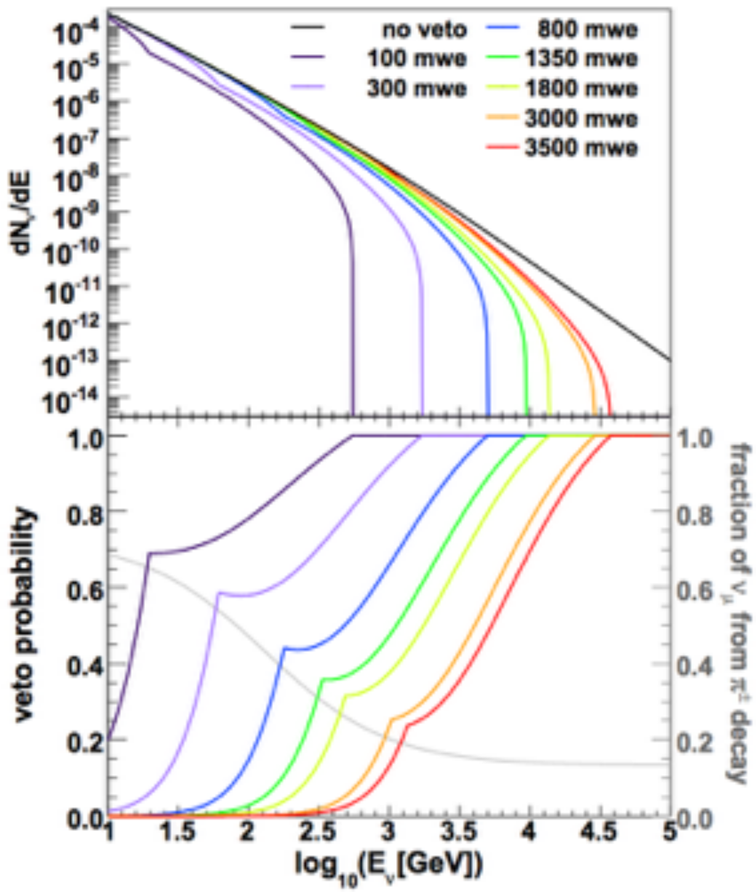
- SPARE

Prompt difference due to the different cosmic model

M. Benzke, et al., JHEP12 (2017) 021

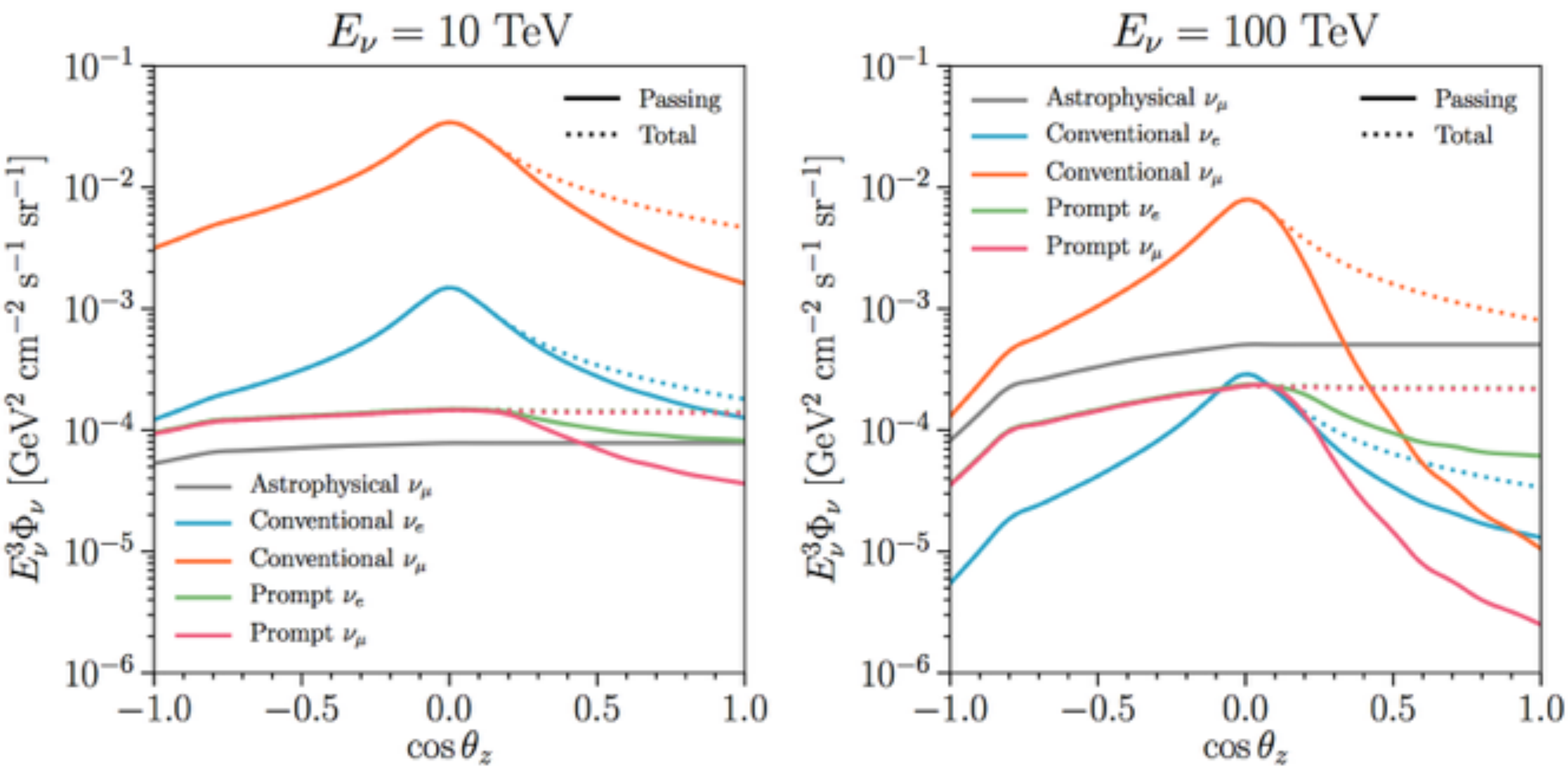






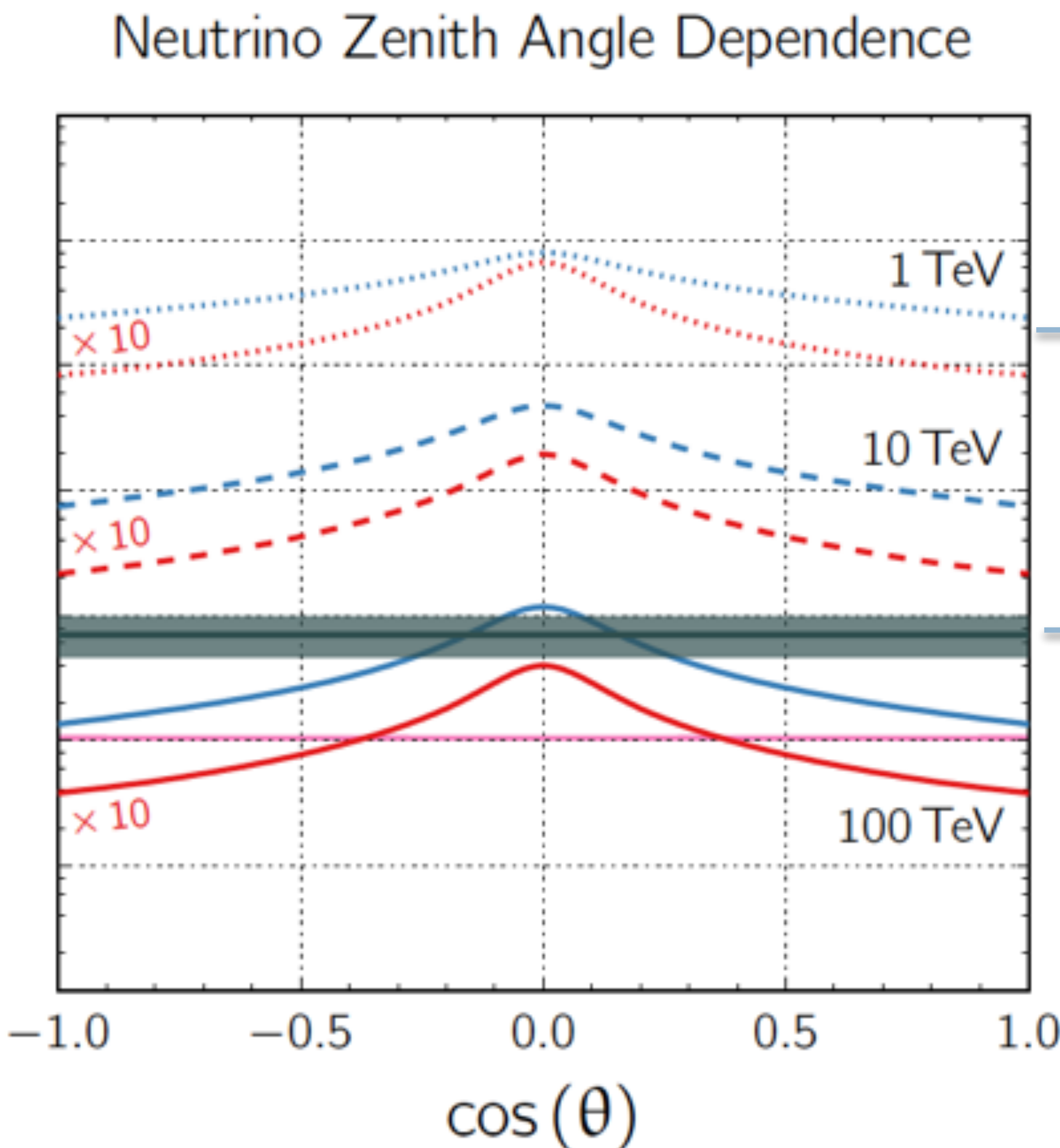
Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)

FIG. 2: Unaccompanied vertical atmospheric $\downarrow\nu_\mu$ flux (upper); probability of accompaniment (lower) for seven depths. The grey curve is the fraction of $\downarrow\nu_\mu$ from π decay.



Argüelles, Palomares-Ruiz, AS, Wille, Yuan JCAP 1807 (2018) no.07, 047

Atmospheric neutrino angular distribution



conventional Honda at 1,10,100 TeV

blue ν_μ

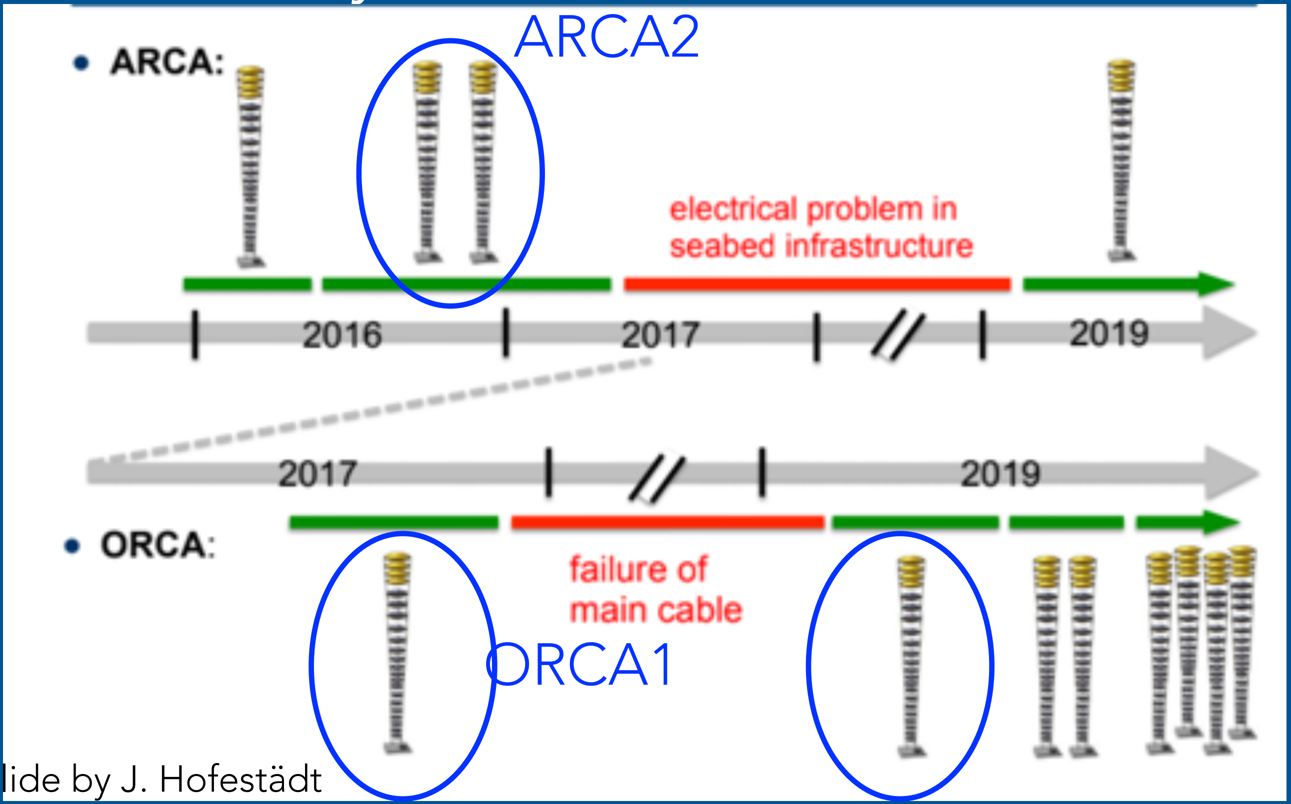
red ν_e

Astrophysical flux

prompt ERS

KM3NET: STATUS

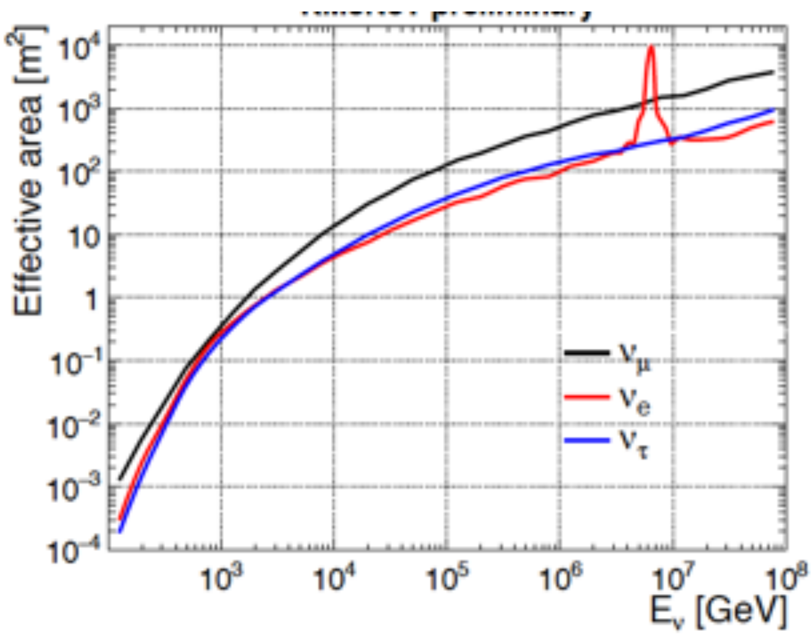
History of detector construction



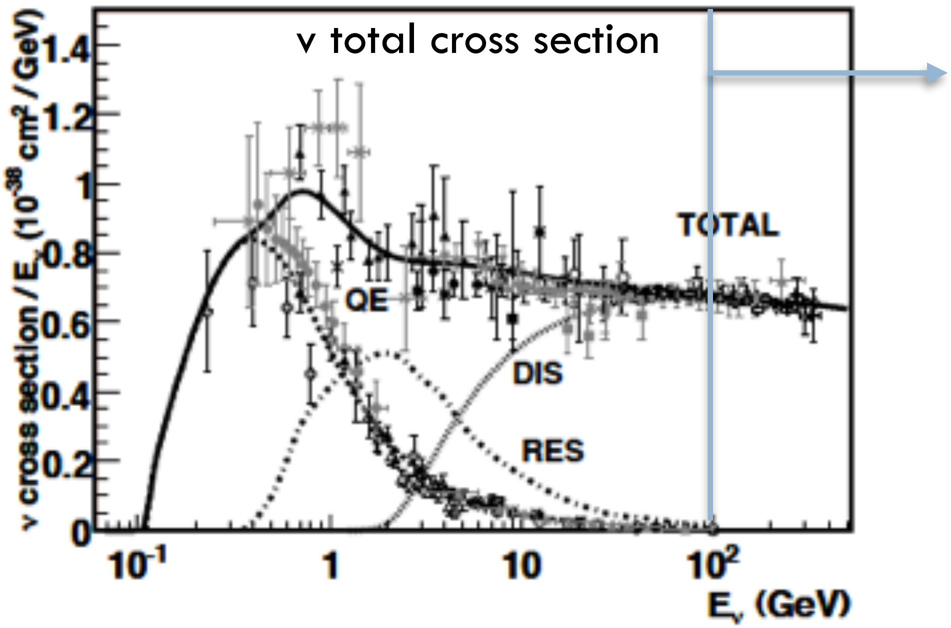
Slide by J. Hofestädt

High energy cross section

KM3NeT/ARCA effective area @ trigger level



Energy range: 100 GeV <En< 10^8 GeV

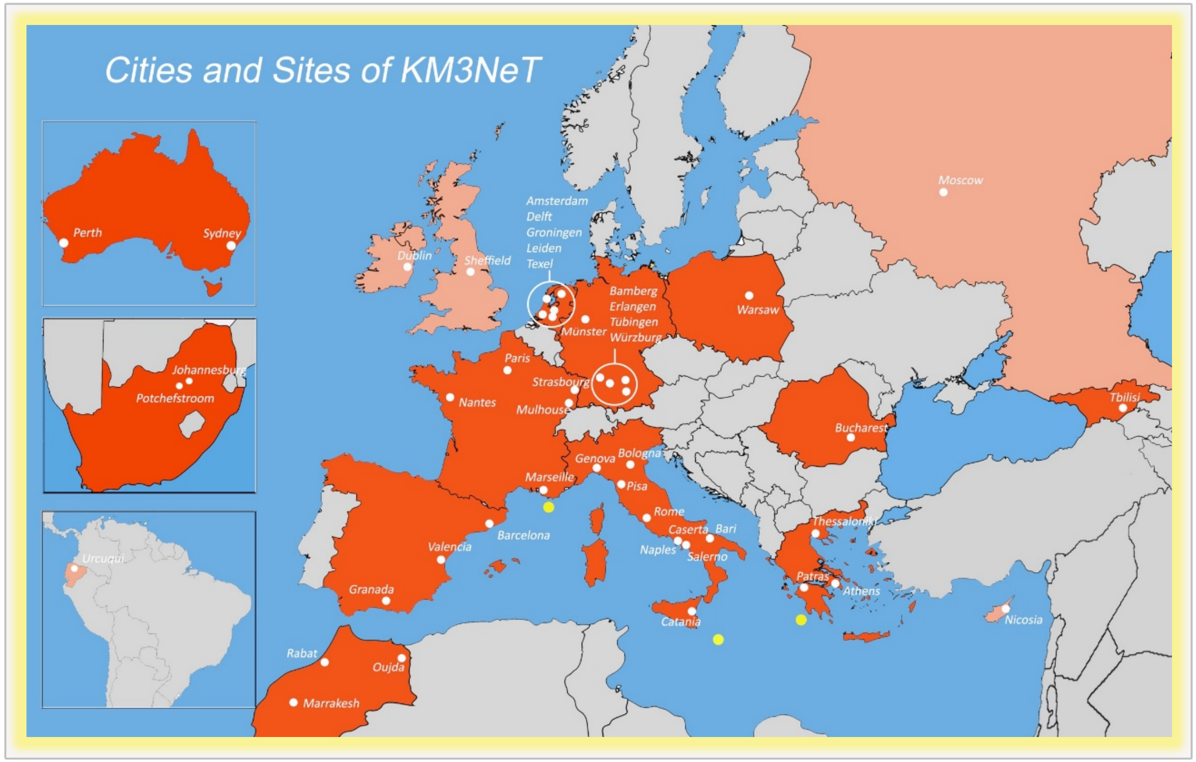


J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. 84 (2012), 1307.

above 100 GeV only DIS contributes to the total cross section
in KM3NeT no simulation above 108 GeV -> energy not available in our MC neutrino generator

The KM3NeT collaboration

- *13 countries*
- *51 institutes*



Number of Institutes and Scientists constantly increasing
New Entries: f.m. U.Johannesburg, U.Marrakech, U.Nantes; obs. LAM Marseille, U.Tbilisi, Australia Un. Perth