Monte Carlo simulations and data analysis technics for high energy neutrino detectors

ROSA CONIGLIONE

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CATANIA

Lay-out

- Introduction
  - The neutrino telescope
- Detection principle
  - The detection principle
  - Backgrounds
- The Monte Carlo simulation
  - MC codes description
- The reconstruction codes
  - Track reconstruction
  - Cascade reconstruction
- On the performance of the telescope: relevant quantities
  - Effective neutrino area
  - Sensitivity and discovery potential

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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

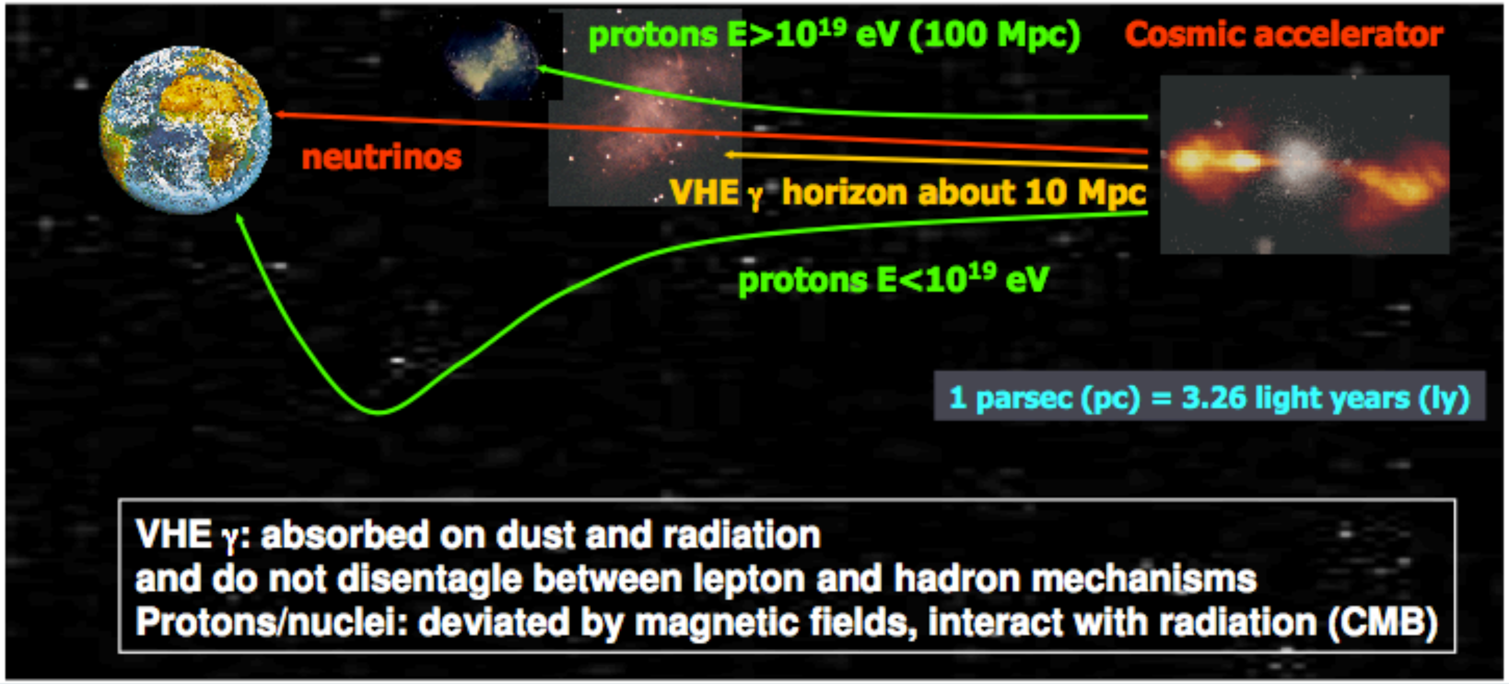
Detector with large volume (km3) installed in deep water or ice

Idea suggested by Markov in the '60

(to use the "beam" of atmospheric neutrinos)

High energy means -> from 10^2 GeV to 10^8 GeV

Why the neutrino detection?



The neutrino observation can give information on:

✓Origin of Cosmic Rays of high energies (astrophysics, cosmology and particle physics)

✓Production mechanism of high energy gammas (hadronic e/o leptonic mechanisms)

✓Properties and production mechanism in the core of sources

The observation of neutrinos is connected with the already observed gamma-ray fluxes in near low density sources and high not known high density sources.

The international context

First attempt the Dumand project – Detector located in Hawaii in the ‘90
-> failed project

Baikal telescope - lake Baikal

- NT200 working since 1998

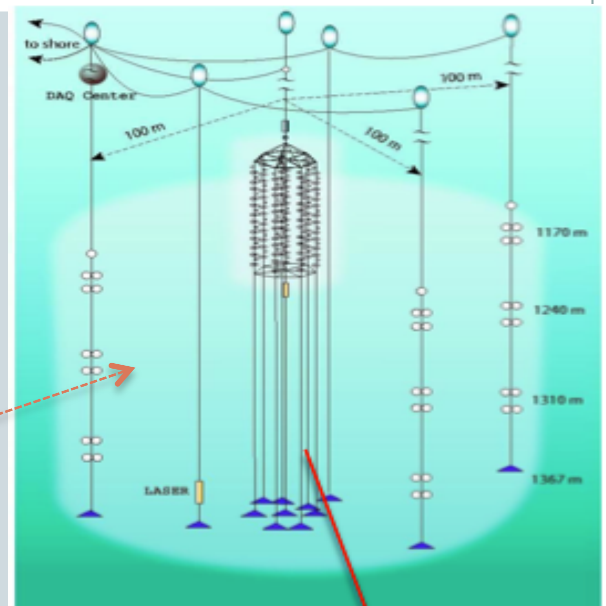
NT200: 8 strings (192 optical modules)
Height x ∅ = 70m x 40m, V_{inst}=10^5m^3
Effective area: 1 TeV~2000 m^2
Eff. shower volume: 10 TeV~ 0.2 Mton

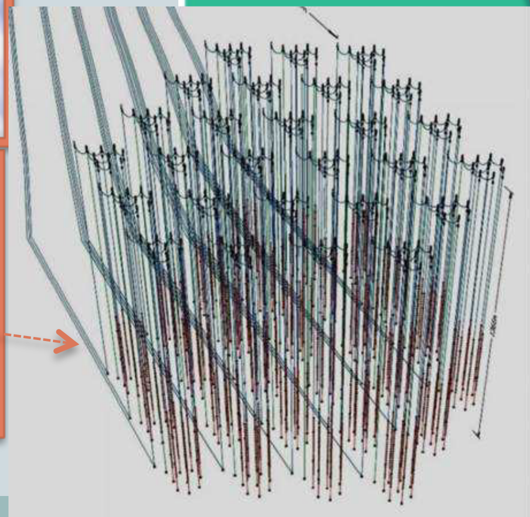
- NT200+ is taking data

NT200+ = NT200 + 3 outer strings (36 optical modules)
Height x ∅ = 210m x 200m, V_{inst} = 5×10^6m^3
Eff. shower volume: 10^4 TeV ~ 10 Mton

- GVT detector planned - Actually prototyping phase

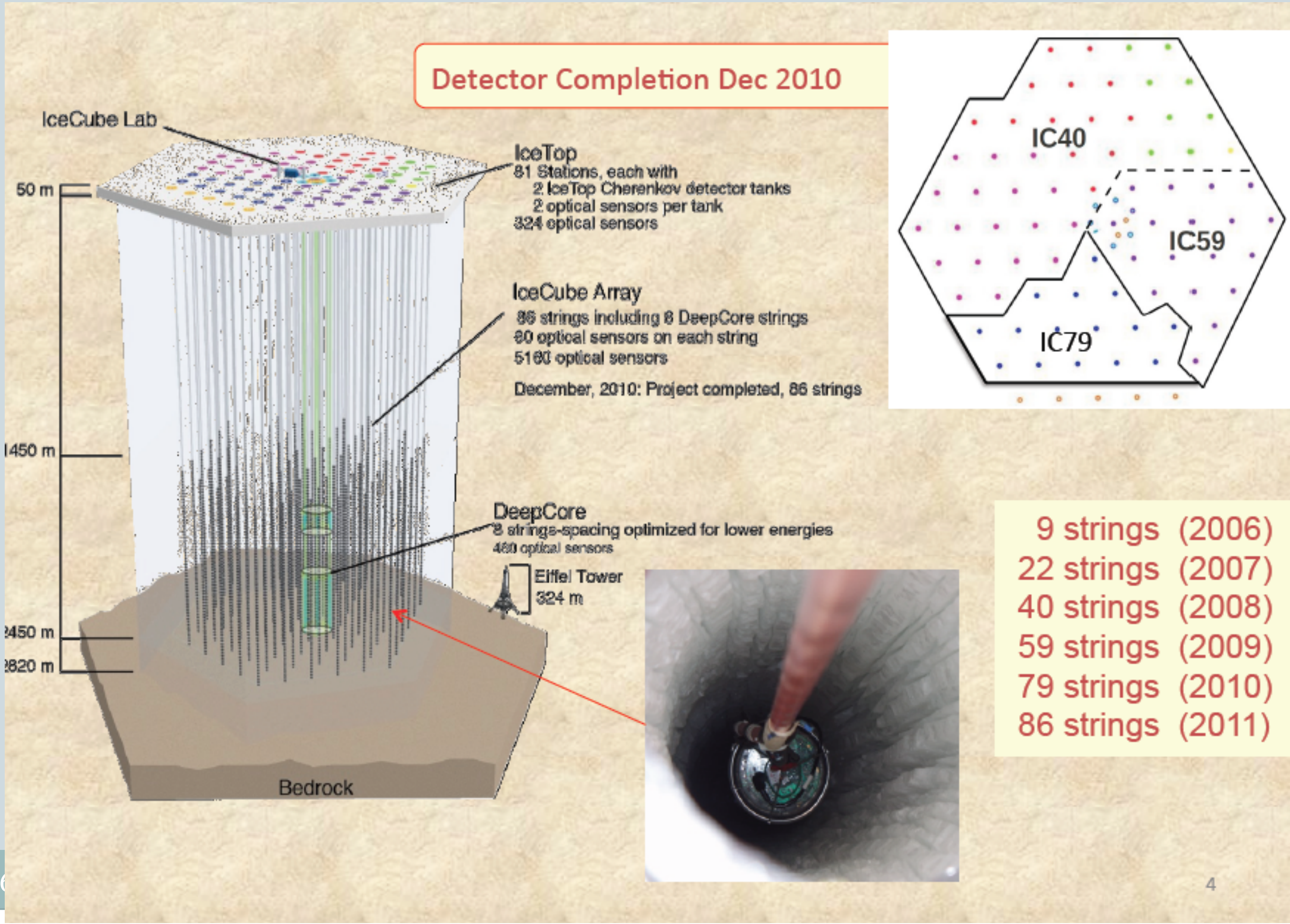
GVT = NT200+ and 27 clusters of 8 strings
Total volume 1.5 km^3





IceCube – South Pole

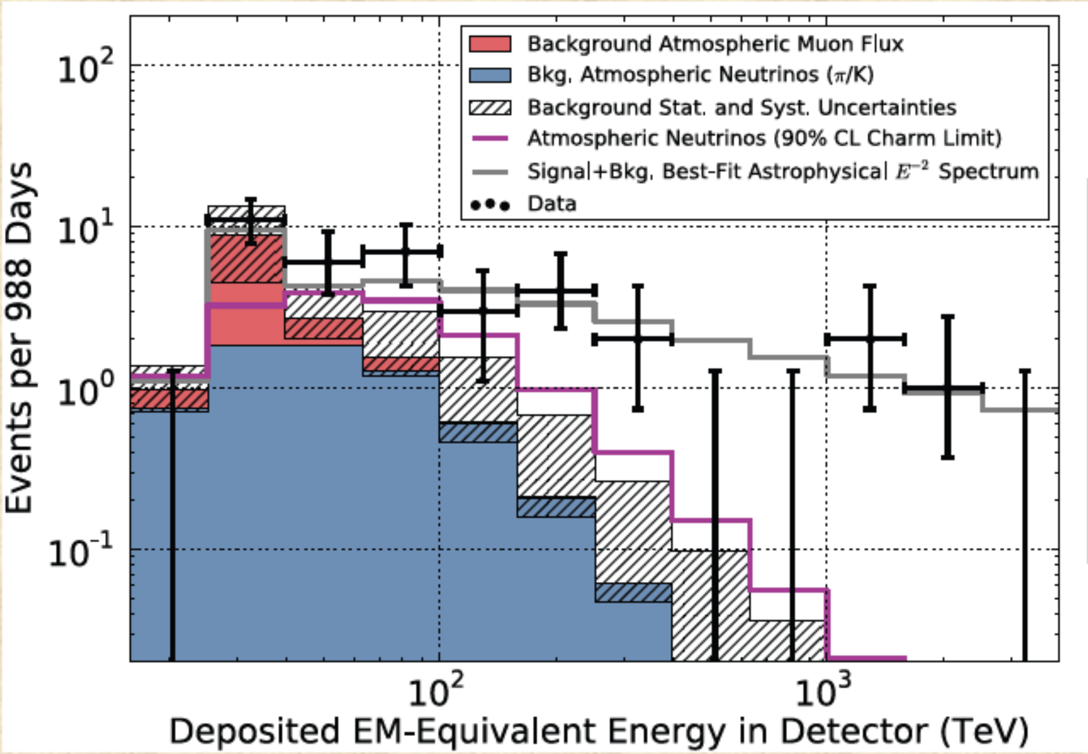
86 strings 60 PMTs each at the South Pole. Volume about 1km³. Depth 2500m



First astrophysical flux from IceCube

- Flux of astrophysical origin detected at 5.7 σ.

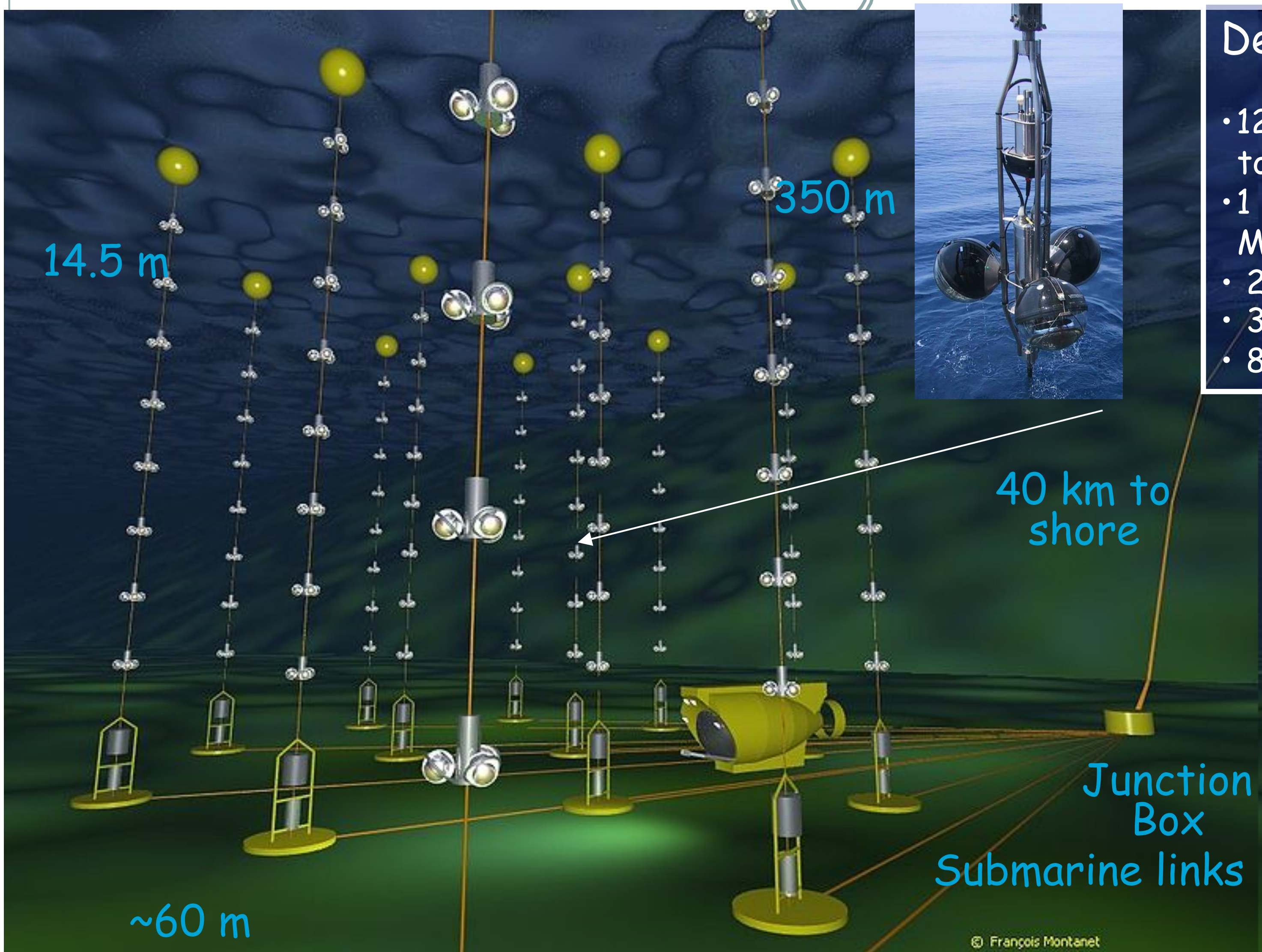
best-fit per-flavor astrophysical(E^{-2}) flux
in the energy range of 60 TeV – 3 PeV
$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}



- consistent with E^{-2}
- indication of a cutoff around 2 PeV above which 4.1 events would be expected from a flux at our best-fit level
- The range of best fit slopes of -2.0 to -2.3.

Not known the origin

ANTARES – Toulon (France)

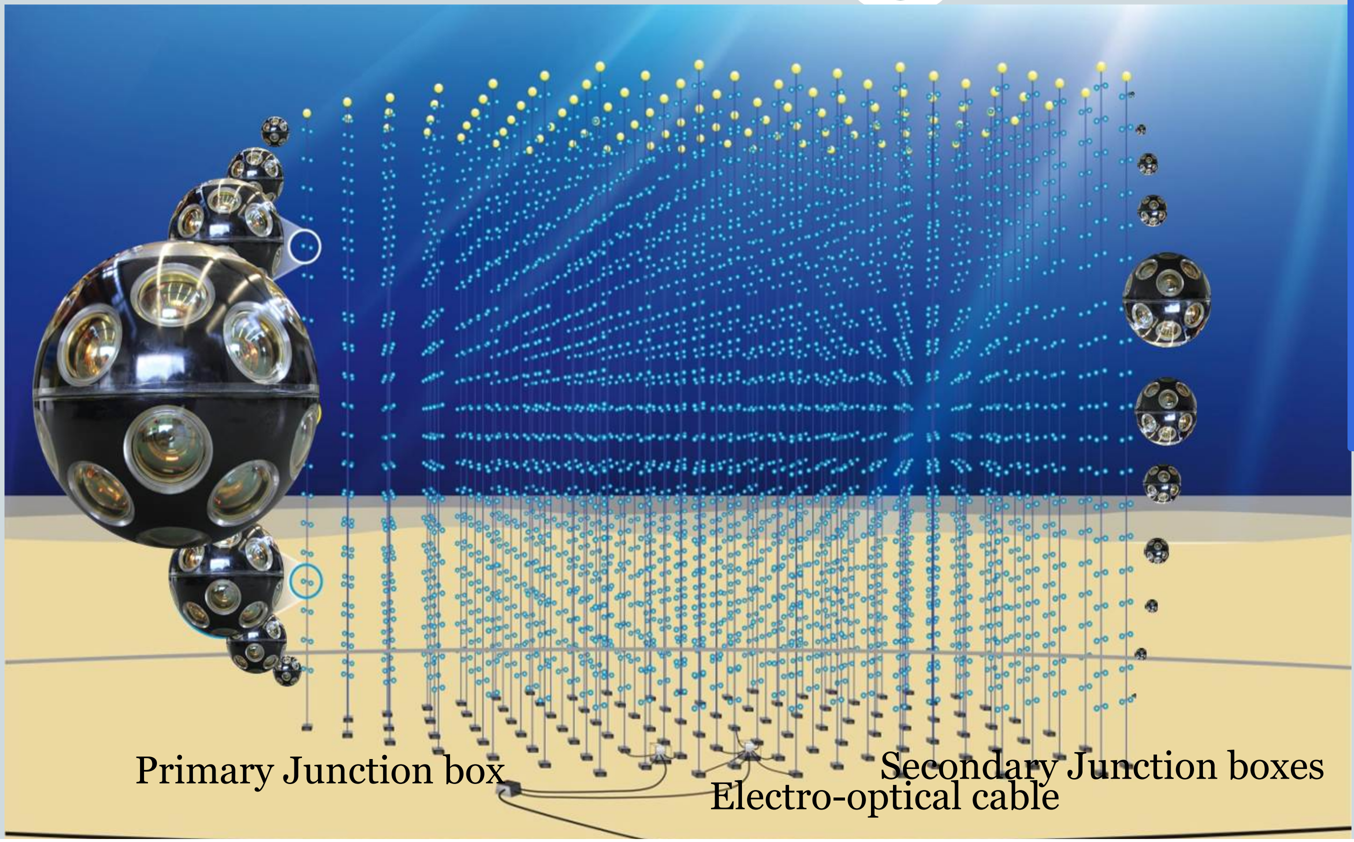


Depth 2470m

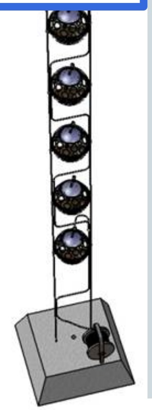
- 12 lines of 75 PMTs (885 total)
- 1 line for Earth and Marine sciences (IL07)
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

Takes data in the complete configuration since 2008.
At the moment is the largest telescope in the Mediterranean sea

KM3NeT – Mediterranean Sea



- KM3NeT in numbers (full detector)
- ~6 blocks of 115 DUs
- 18 storey/DU
- ~ 36m storey spacing
- ~700 km DU height
- ~90 m DU distance
- ~ 3 km³ volume

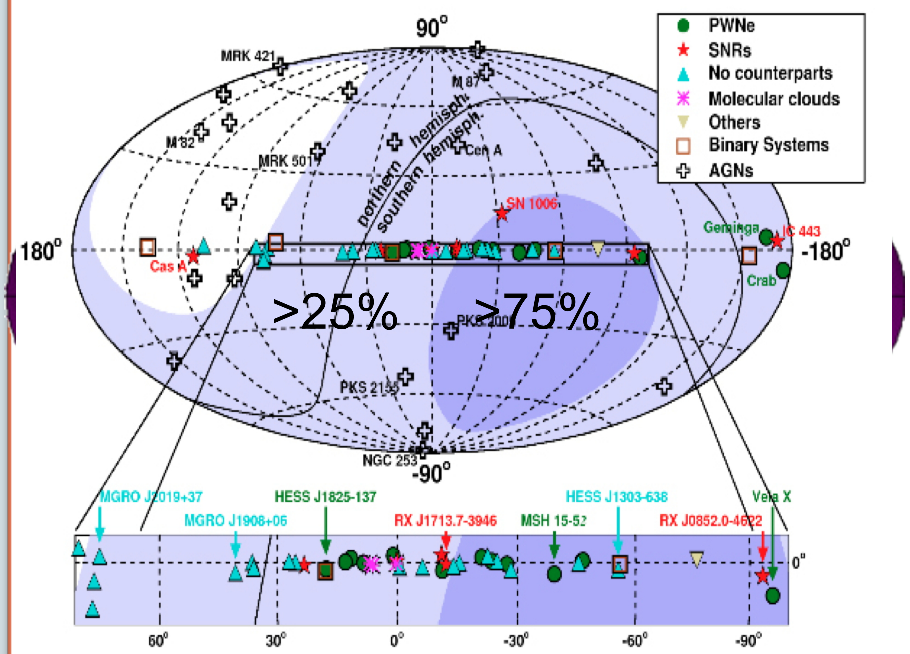


Status: funds only for Phase-1
Phase1 -> 8 towers + 24 strings in Capo Passero - construction phase started
Phase 1.5 – 2 blocks of 155 DUs (one in capo Passero and the second not yet defined)

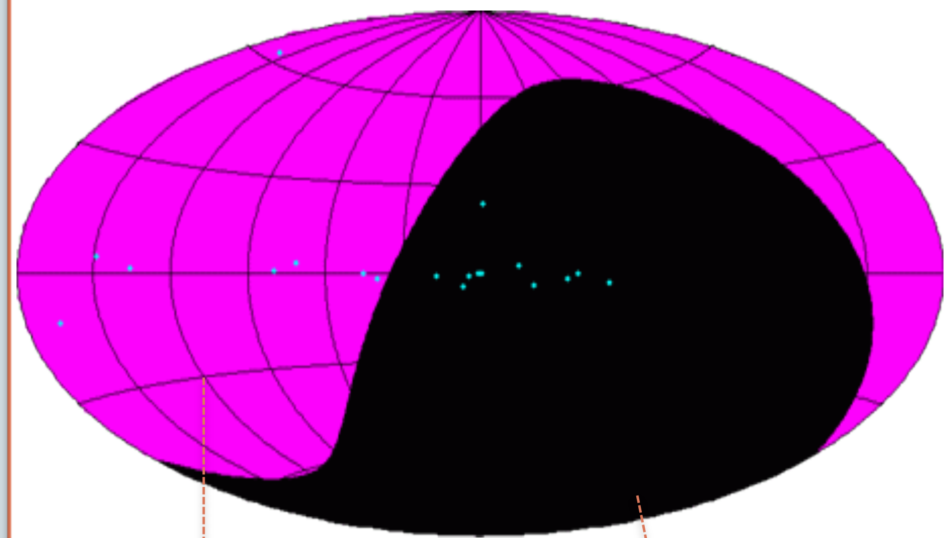
Visibility

Galactic coordinates

- ANTARES and KM3NeT



- IceCube



Northern hemisphere

Southern hemisphere

Complementary detectors

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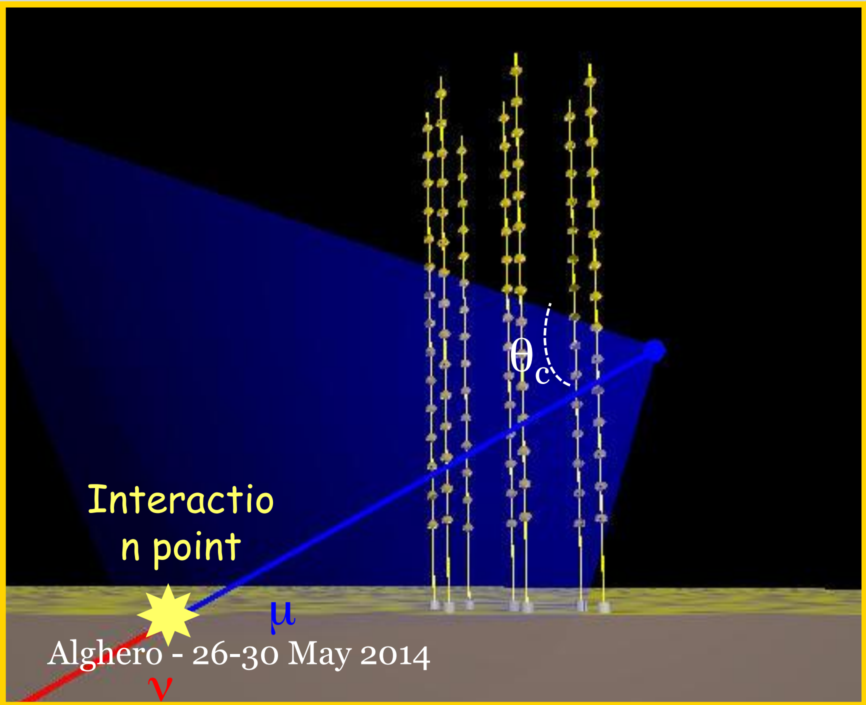
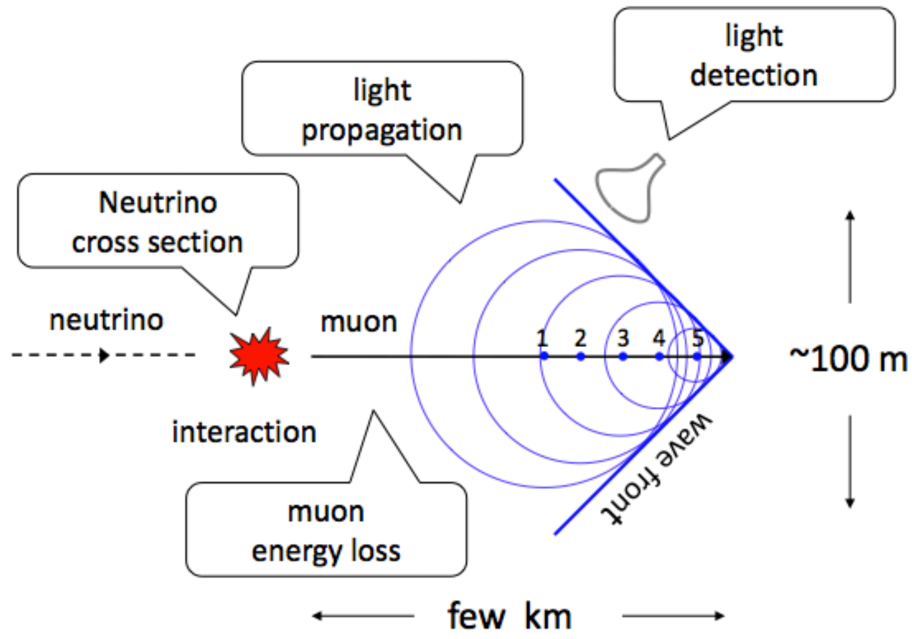
Detection principle

- 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° 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





The Cerenkov emission

The number of Cherenkov photons N emitted by a charged particle of charge ze per unit wavelength interval dλ and unit distance travelled dx

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad v > \frac{c}{n}$$

High numbers of photons at low wavelength (blue)

The number of photons in the wavelength between 300 and 600 nm and distance unit:

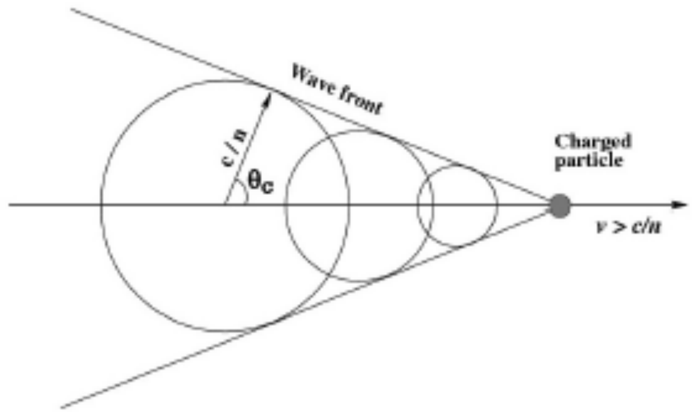
$$\frac{dN}{dx} = 76500 \cdot \sin^2\theta_{ch} \approx 34500\, fotoni/m$$

- Photons emitted at θ_{ch} w.r.t the track direction

$$\cos\theta_{ch} = \frac{1}{\beta n}$$

n water/ice refractive index

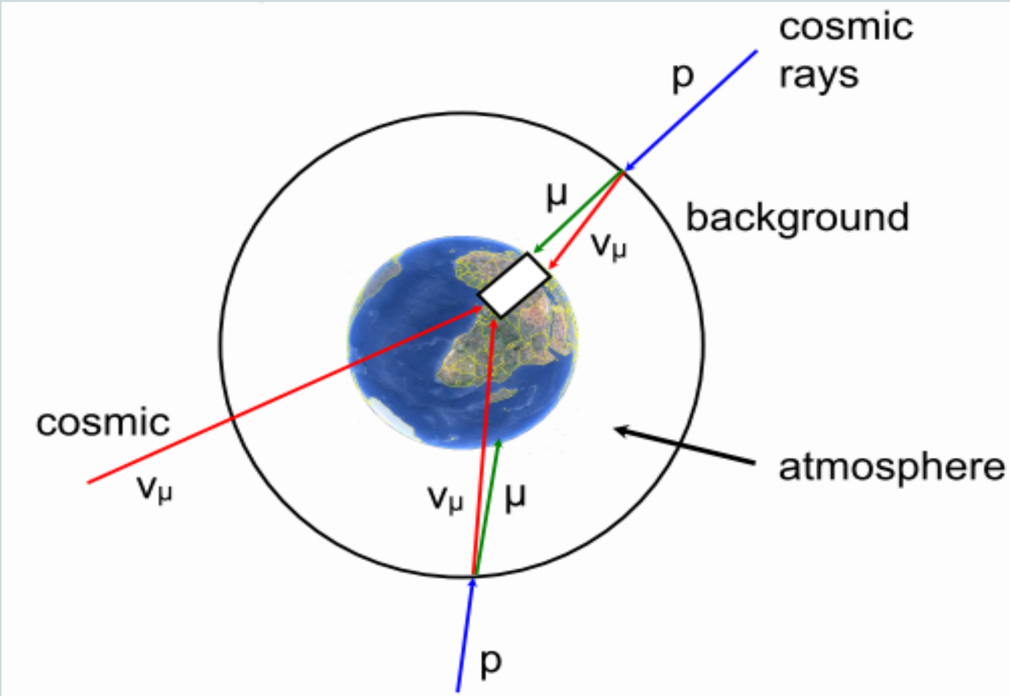
$$n = 1.35 \qquad \theta_{ch} = 42.2°$$

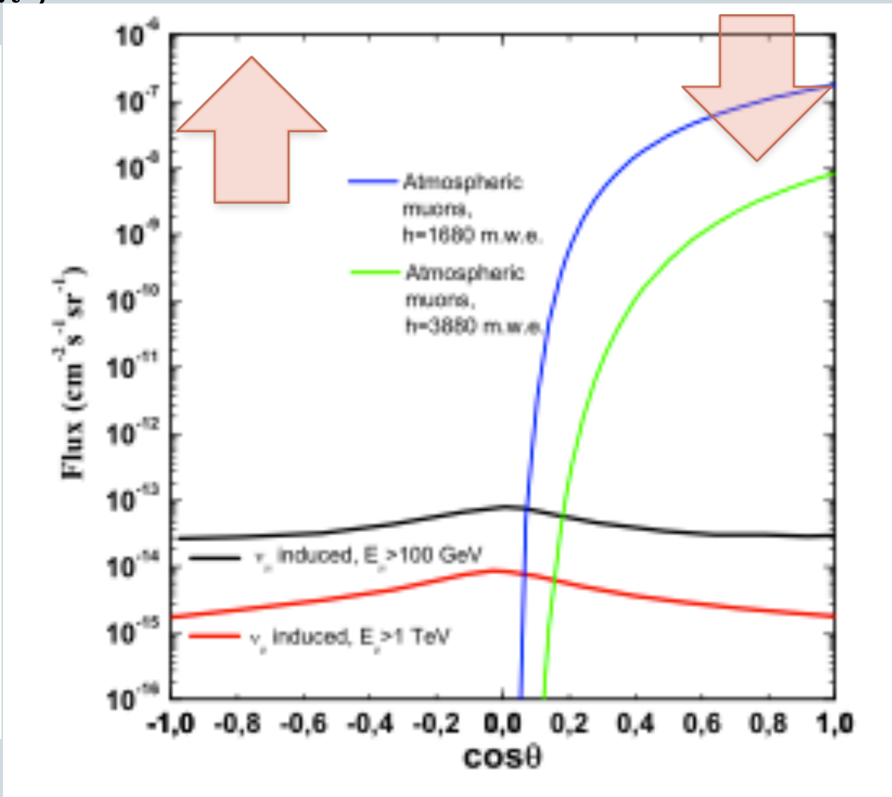


Background of atmospheric muons and neutrinos

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

Search for extraterrestrial up-going neutrinos

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Why MC simulations?

To calculate the expected number of background events

Comparisons between data and simulation: does the detector work like we think it does?

To know how many events to expect for a given signal strength

To design a new detector

To develop background suppression techniques

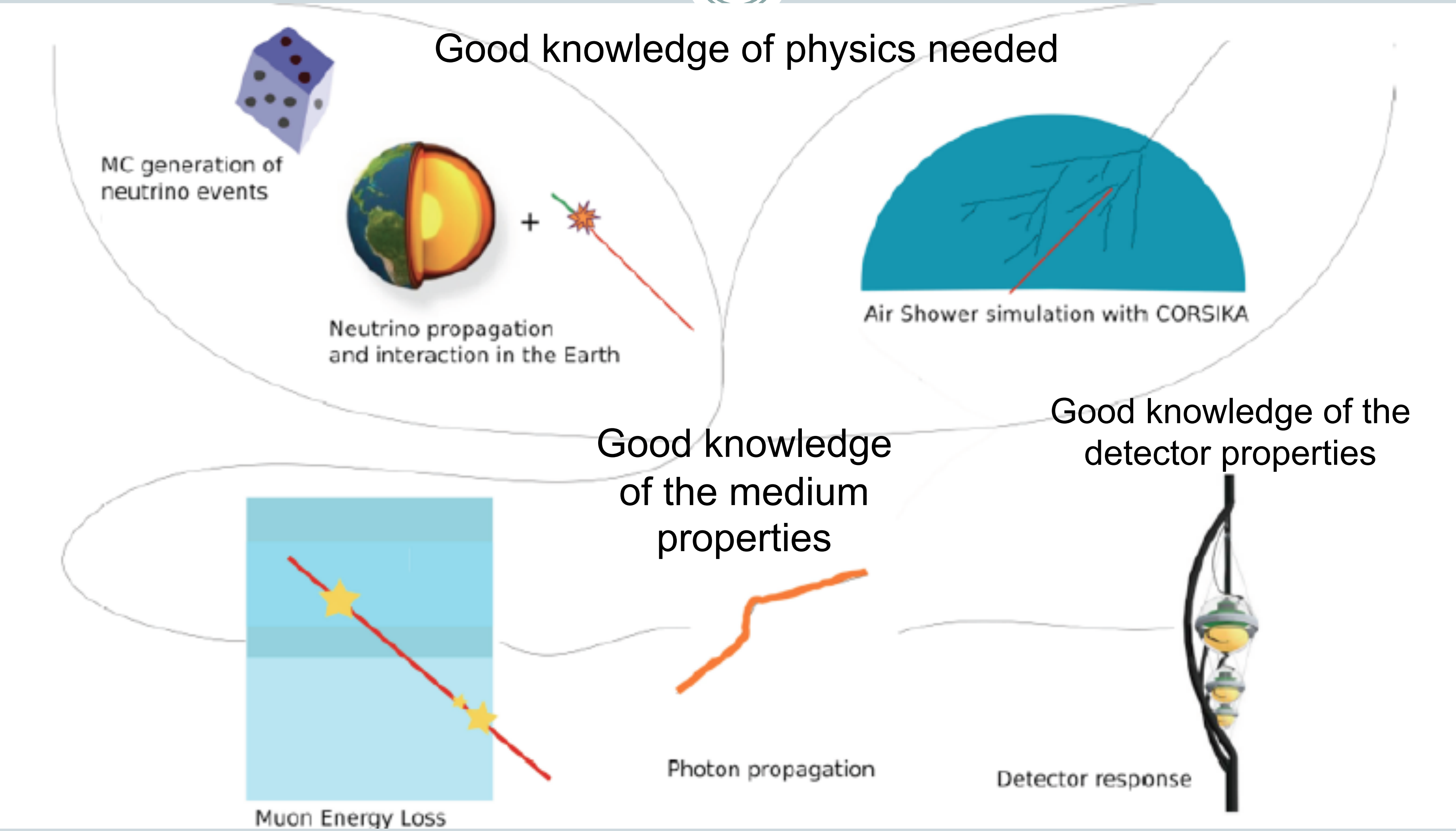
To develop and test reconstructions

To evaluate systematic uncertainties

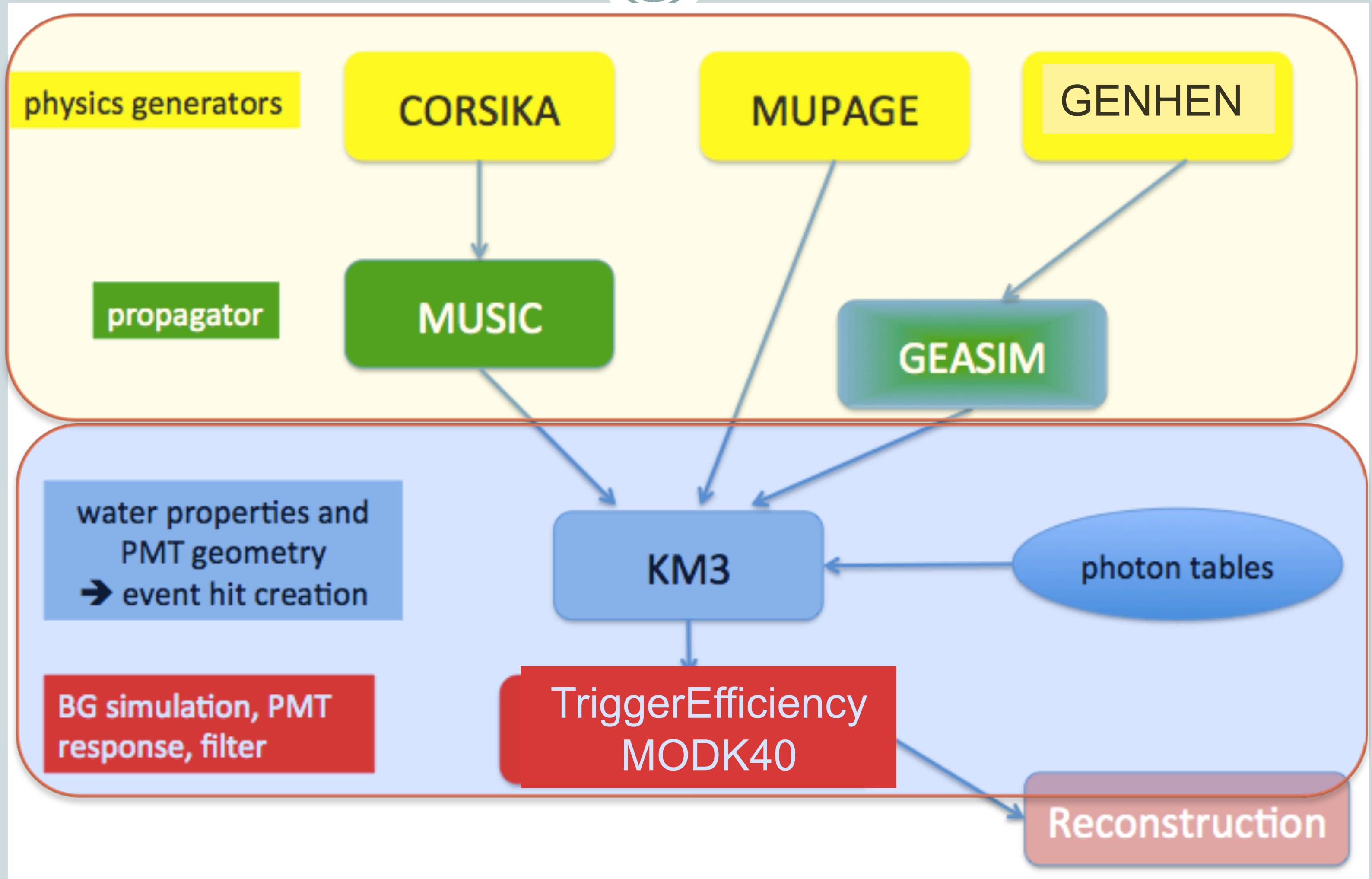
Events in neutrino telescopes

Atmospheric muons	Atmospheric neutrino	Extraterrestrial neutrino
Angular and energy distribution given by the interaction of CR in the atmosphere	Angular and energy distribution given by the interaction of CR in the atmosphere + oscillation	Angular, energy and flavour distribution given by theoretical models + oscillation
Background	Background/signal	Signal

The MC steps

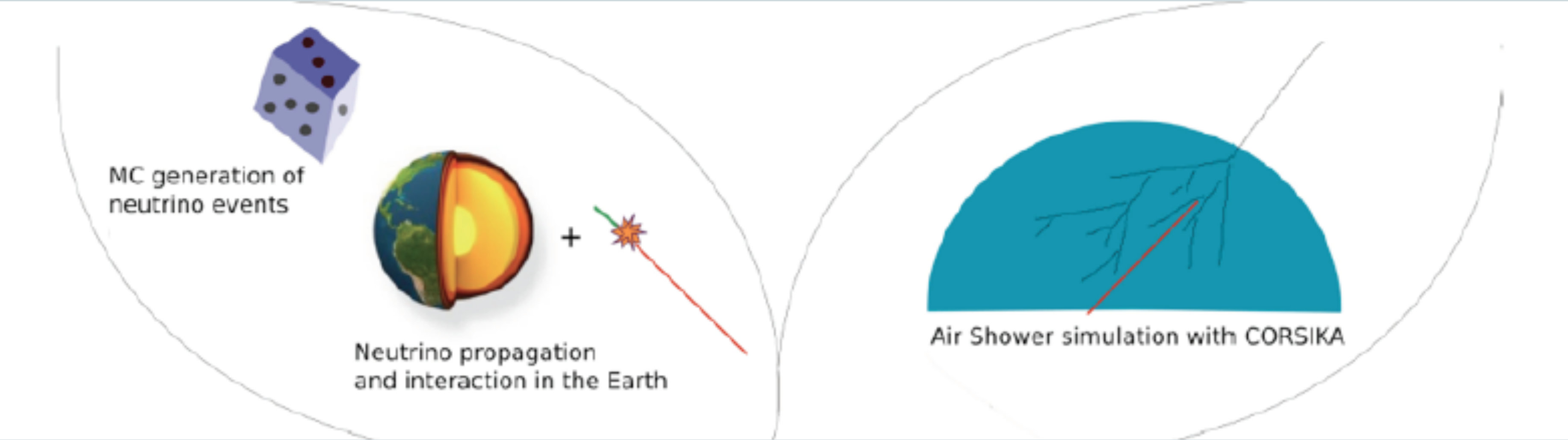

Good knowledge of physics needed
MC generation of neutrino events
Neutrino propagation and interaction in the Earth
Air Shower simulation with CORSIKA
Good knowledge of the medium properties
Good knowledge of the detector properties
Muon Energy Loss
Photon propagation
Detector response

The code chain ANTARES and KM3NeT

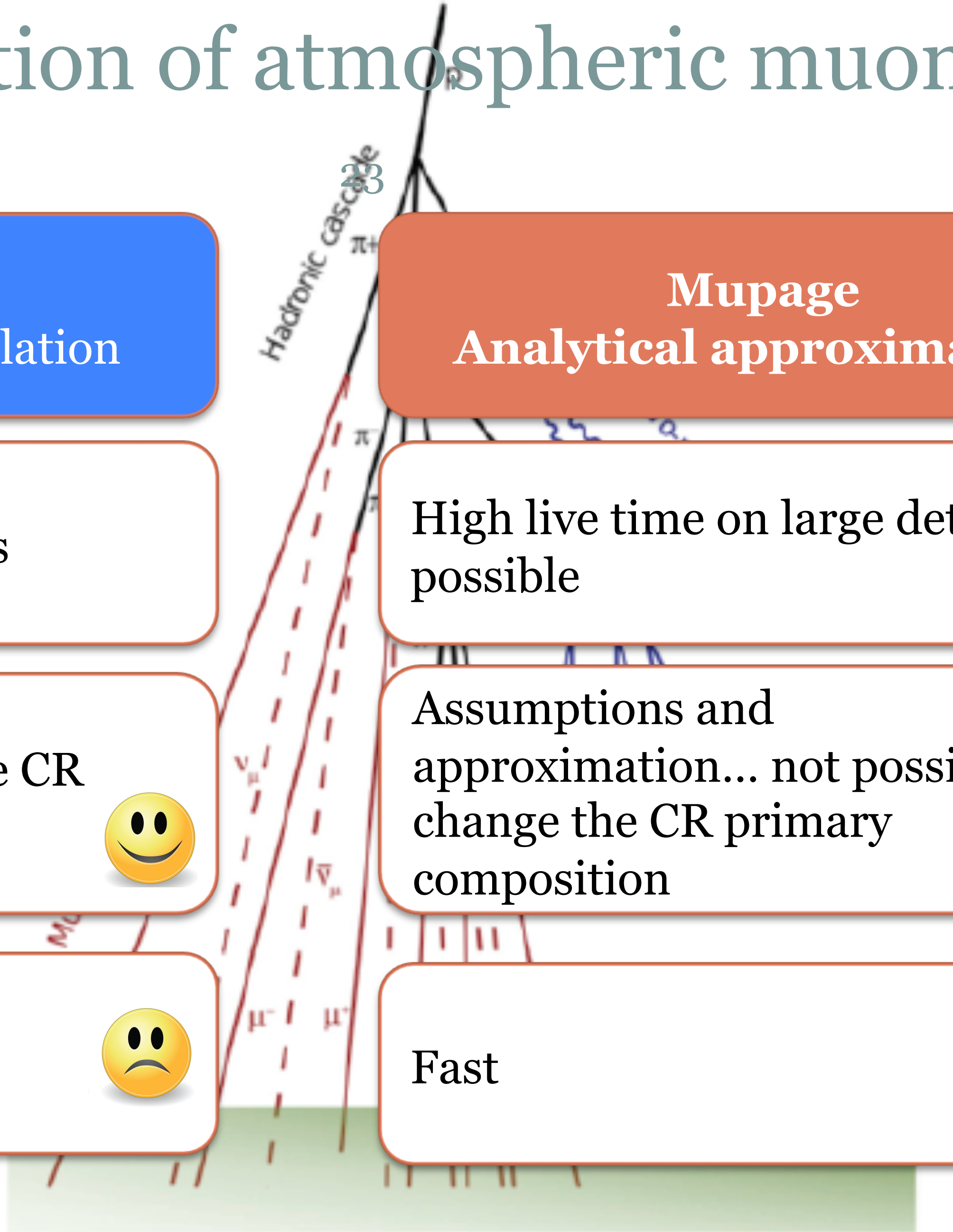


The Generators

Good knowledge of physics needed



Generation of atmospheric muons



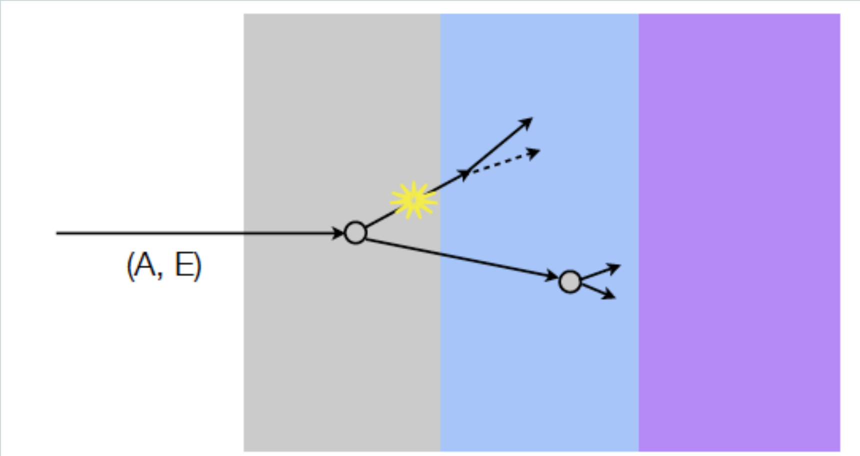
CORSIKA Full air shower simulation	**Mupage** **Analytical approximation**
Based on known models	High live time on large detector possible
The final events can be weighted- choose all the CR models (spectrum and composition)	Assumptions and approximation… not possible to change the CR primary composition
Large computing time	Fast

CORSIKA
Cosmic Ray Simulation for Kascade

http://www-ik.fzk.de/corsika

Full air shower MC simulation.

- Cross section for the interaction of primaries and secondaries.
- Knowledge of the composition of the interaction medium (Atmospheric properties tunable … 20 parameters to set the atmosphere)
- Lifetimes and decay channels for all the particles
- Energy losses of secondaries



✓ Air showers propagated up to the sea level.

✓ Primaries up to A=56

✓ CR composition models assigned aposteriori weighting the events.

Code well maintained and compared with experimental data

The interaction models

✓Based on data from beam experiments – no data at high energies-> values extrapolated

✓Collider experiments cover central region better than forward region -> values extrapolated

✓Collider data does not cover all the projectile-target possible combination -> values extrapolated

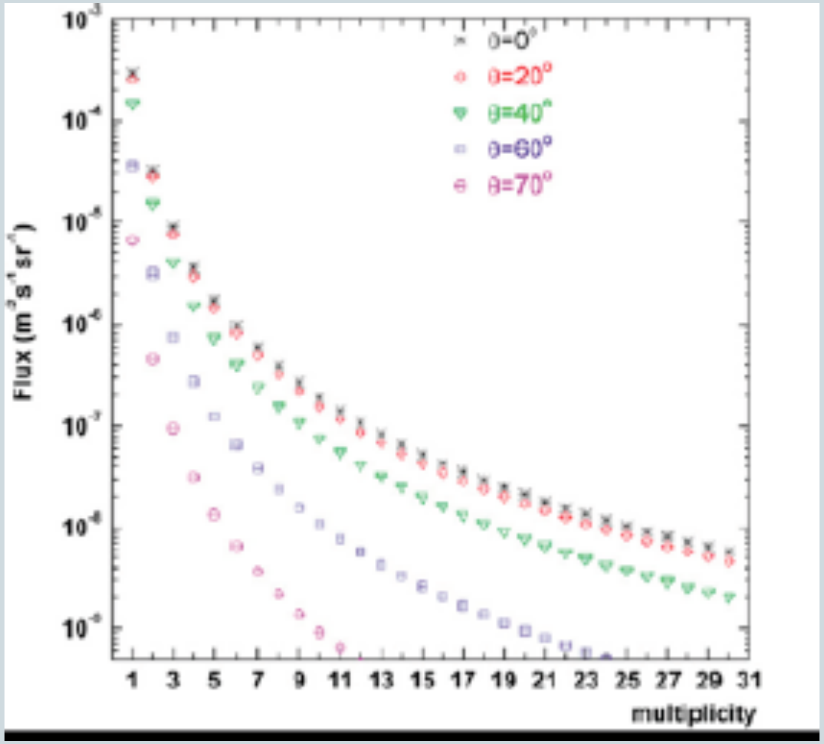
✓Many uncertainties in shower simulation for primary energies above a few TeV

✓Options for the interaction models (high energy ->VENUS, QJSJET, DPMJET, SIBYLL, low energy-> GHEISHA).

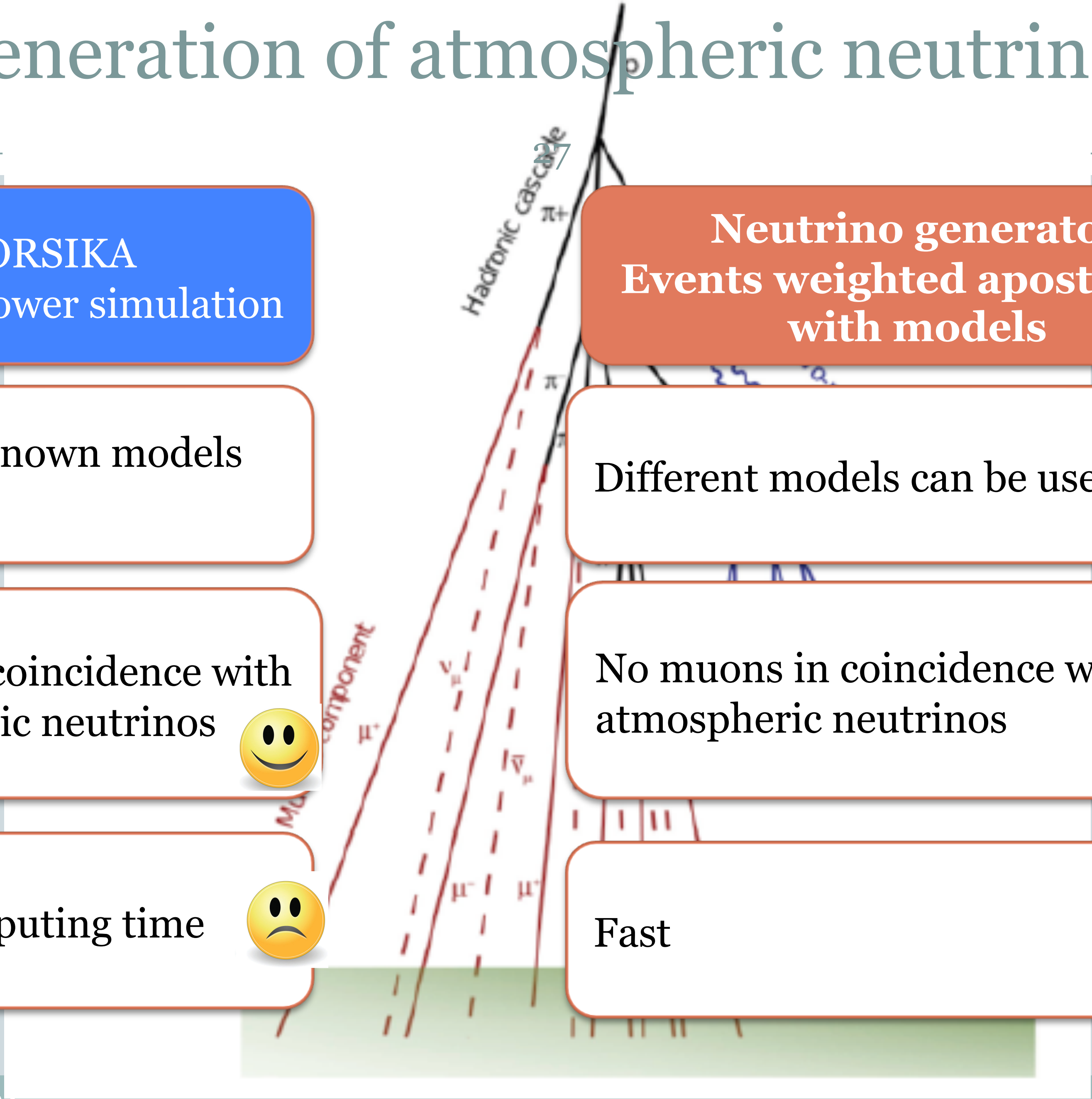
MUPAGE

Based on analytical parameterization of HEMAS (full air shower simulation).
Considered the muon bundle
Muons up to a cilinder around the detector

- Inputs:
  - Depth (1500 m <D<5000 m)
  - minimum bundle energy
  - Angular (0°<θ<85°)
  - Minimum muon energy at the cilinder
- Outputs
  - Energy and direction of each muon in the bundle
  - Live time (flux)



Generation of atmospheric neutrinos



CORSIKA
Full air shower simulation

Based on known models

Muons in coincidence with atmospheric neutrinos

Large computing time

Neutrino generator
Events weighted aposteriori with models

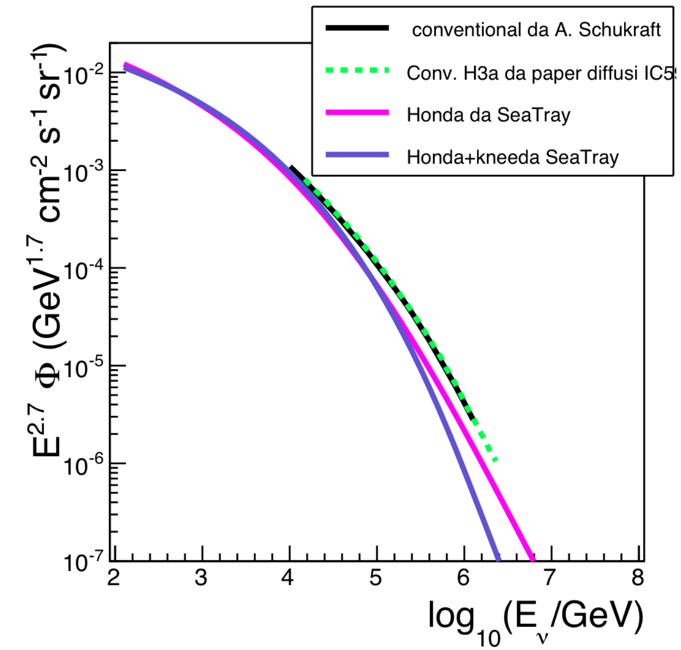
Different models can be used

No muons in coincidence with atmospheric neutrinos

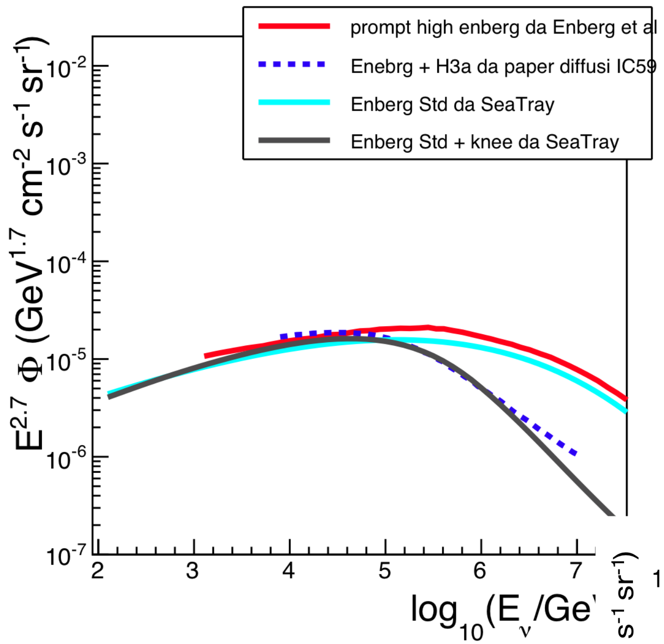
Fast

Atmospheric neutrinos

Conventional component

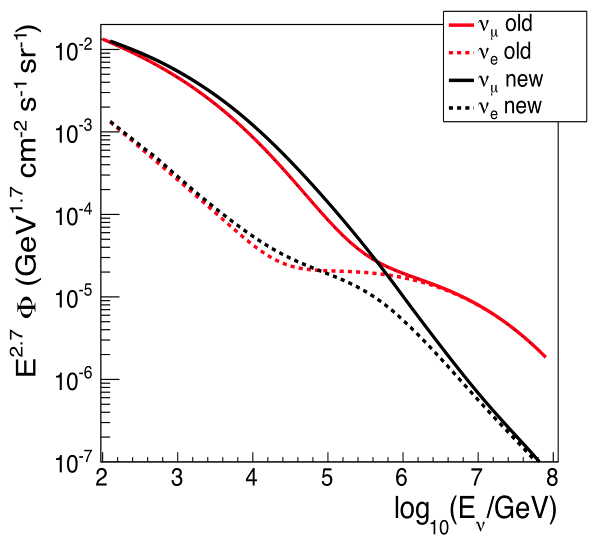


Prompt component



Spectrum proportional to $E_\nu^{-3.6}$ (100 GeV < E_ν <10 TeV)

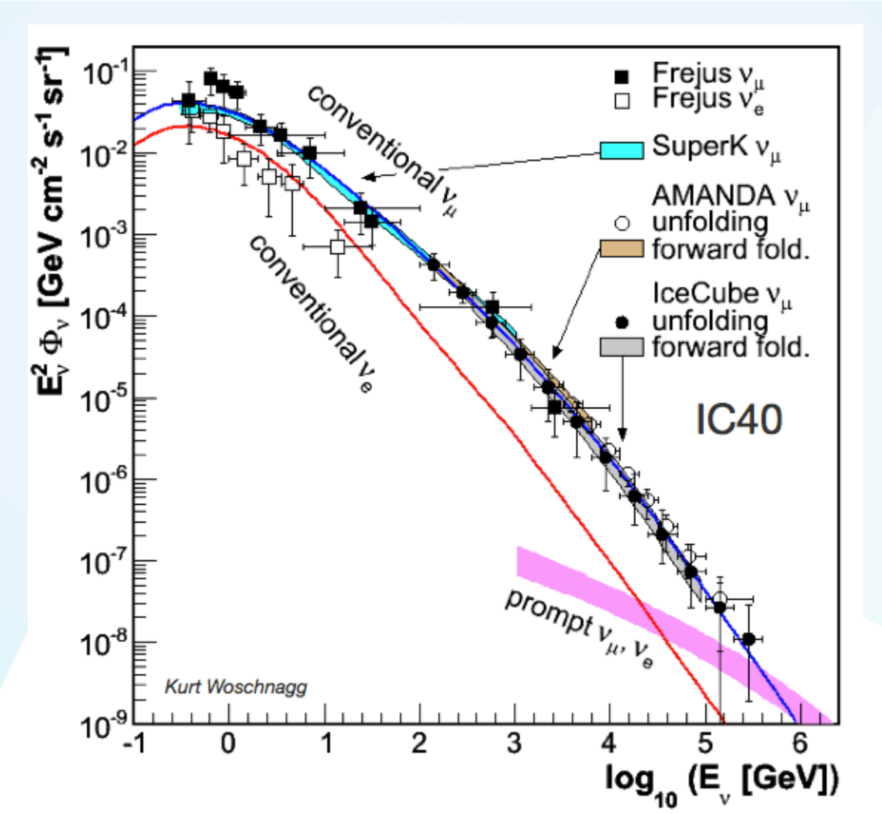
Contribution from the decay of charm meson not yet observed (prompt contribution) E_ν >10 TeV

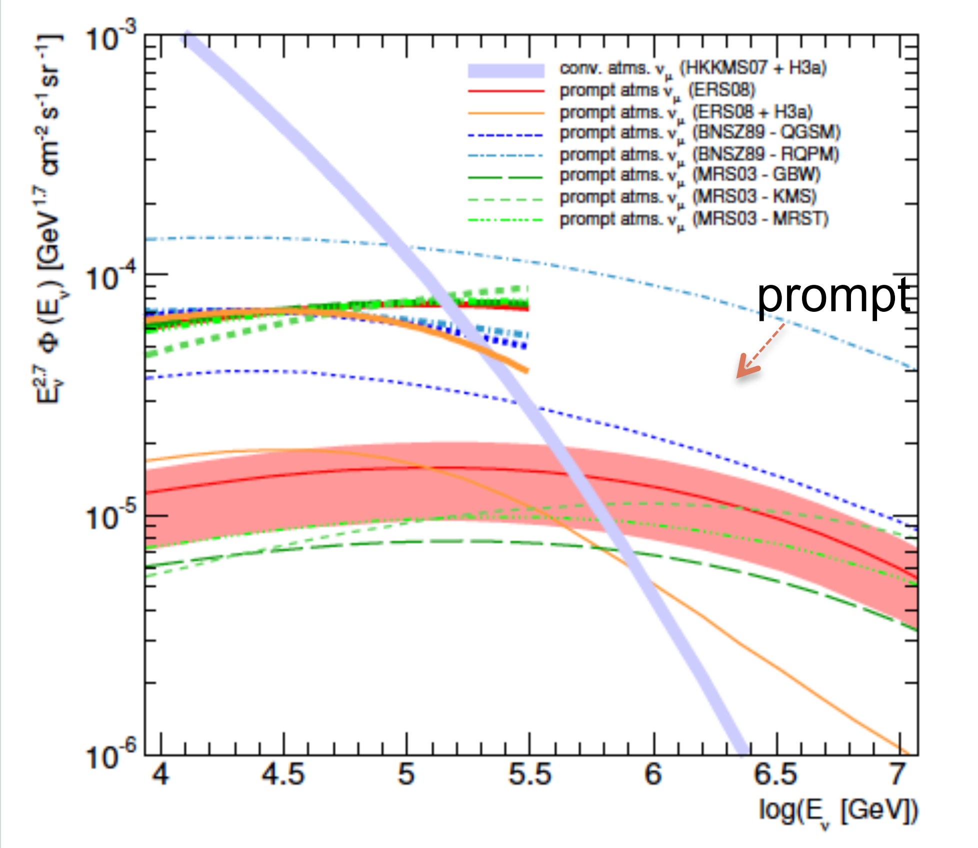


Atmospheric neutrinos

Phys. Rev. D83 012001 (2011)

Phys. Rev. D84 082001 (2011)



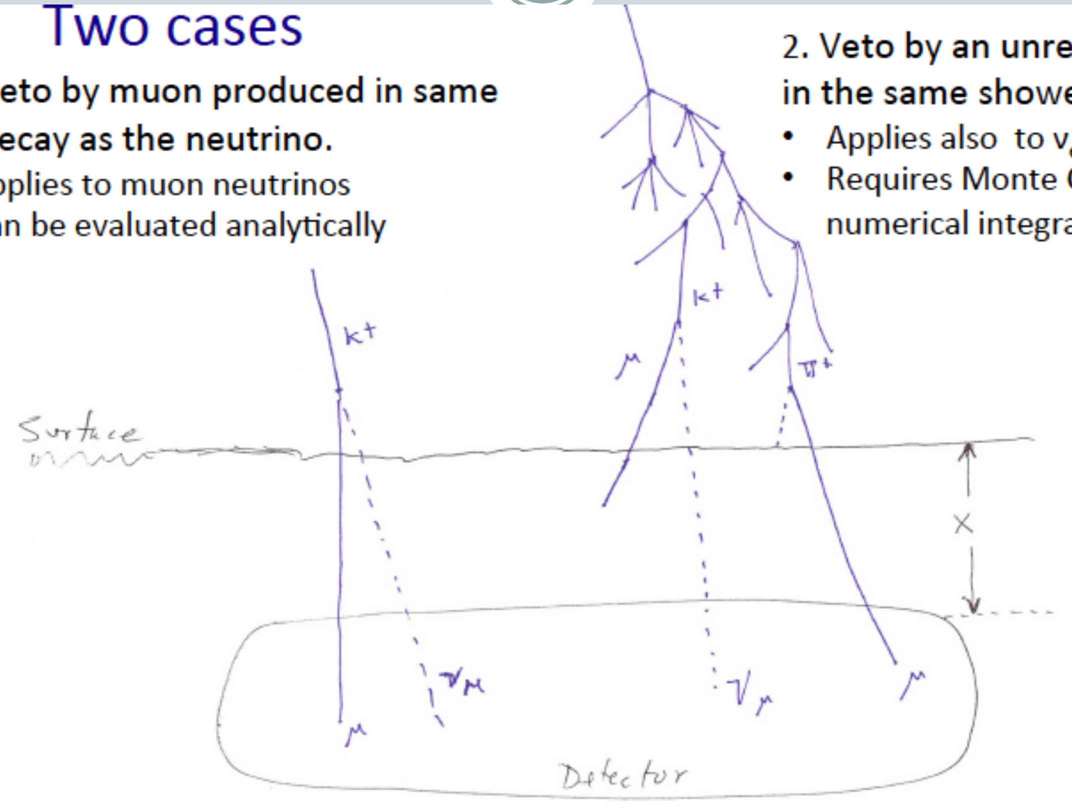


ν in coincidence with muons

Two cases

1. **Veto by muon produced in same decay as the neutrino.**
   - Applies to muon neutrinos
   - Can be evaluated analytically

2. **Veto by an unrelated μ in the same shower**
   - Applies also to ν_e
   - Requires Monte Carlo or numerical integration



MANTS 15/10/2013 Tom Gaisser 3

Vetoing the down-going muon we reduce the atmospheric neutrino background:
- depends on the arrival direction -> zenith angle
- depends on depth

Neutrino generators

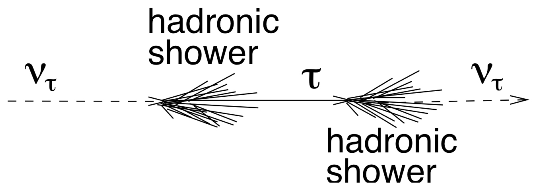
GENIE Full air shower simulation	**ANIS/NUGEN**	**GENHEN**
Low energy (100 MeV – 100 GeV)	Few 100 GeV – 10^{12} GeV	Few GeV – 10^{9} GeV
Developed for long base line experiment	Developed for Neutrino telescope	Developed for Neutrino telescope
Well maintained	Used by IceCube	Used by ANTARES/ KM3NeT

Neutrino interaction

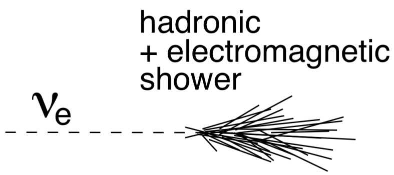
- Neutrino interaction and flavours:
  - Charged Current $\nu_{l,}$ N ->l + hadrons
  - Neutral Current ν N -> ν + hadrons

CC ν_μ interaction

CC ν_τ interaction



CC ν_e interaction



NC interaction

Muon Neutrino interaction

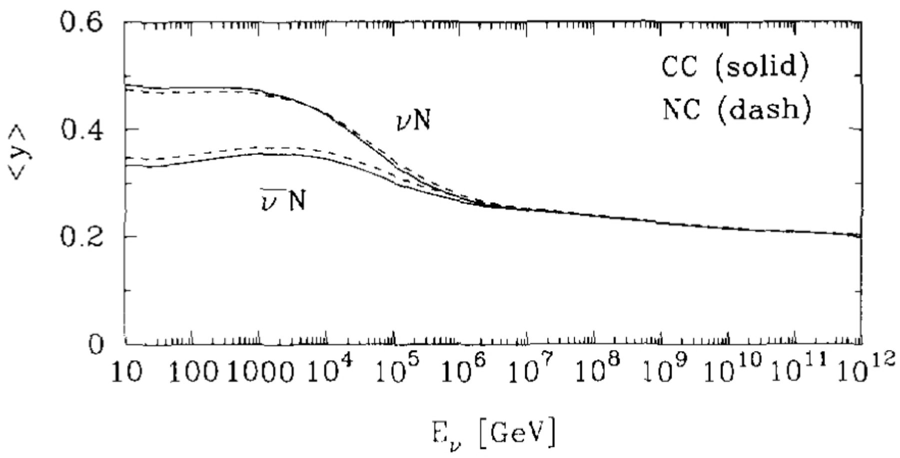
- Neutrino interaction

Charged Current $\nu_{\mu,}$ N -> μ^- + hadrons

Neutral Current ν_μ N -> ν_μ + hadrons

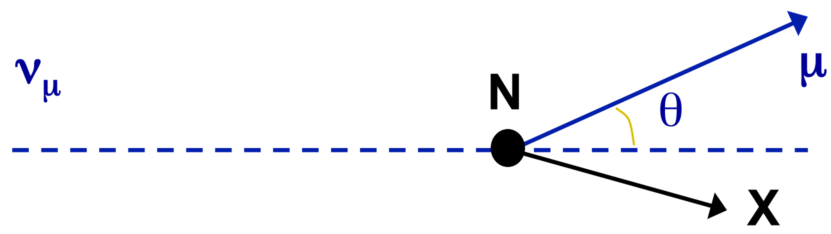
Inelasticity plot

$$\langle y \rangle = \left\langle \frac{E_\nu - E_\mu}{E_\nu} \right\rangle$$



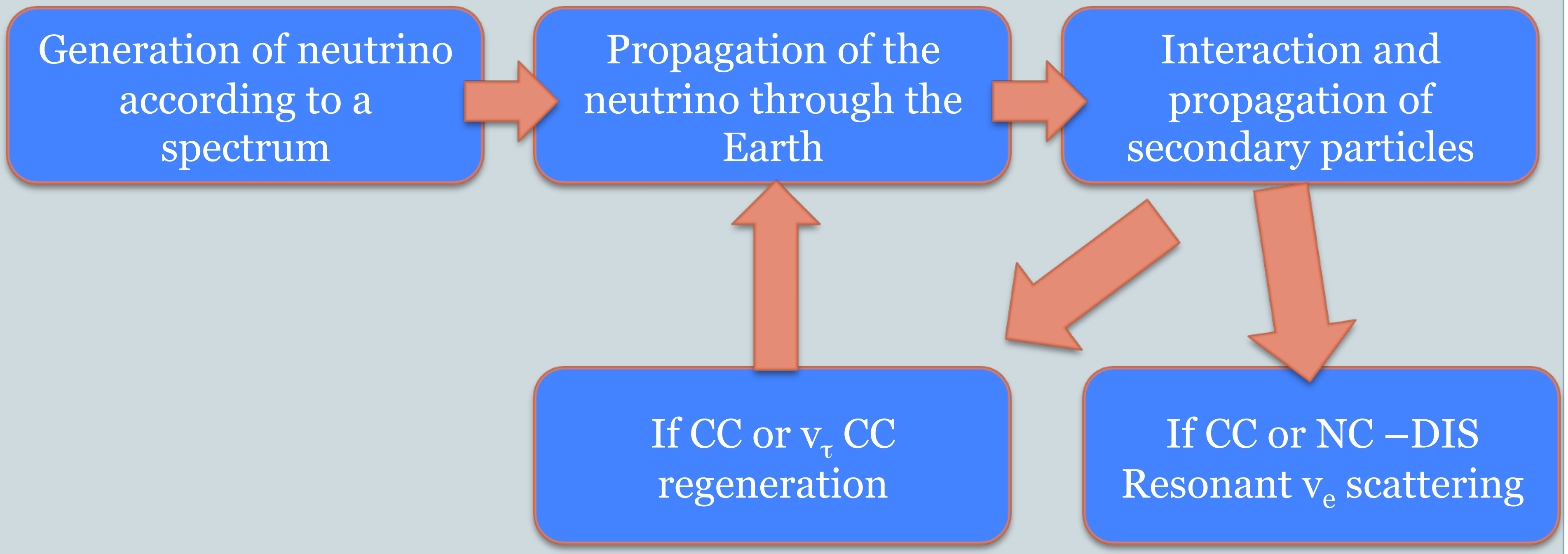
Gandhi et al. Astr.Phys. 5 (1996) 81-110

For neutrino energies >TeV neutrino and muon collinear

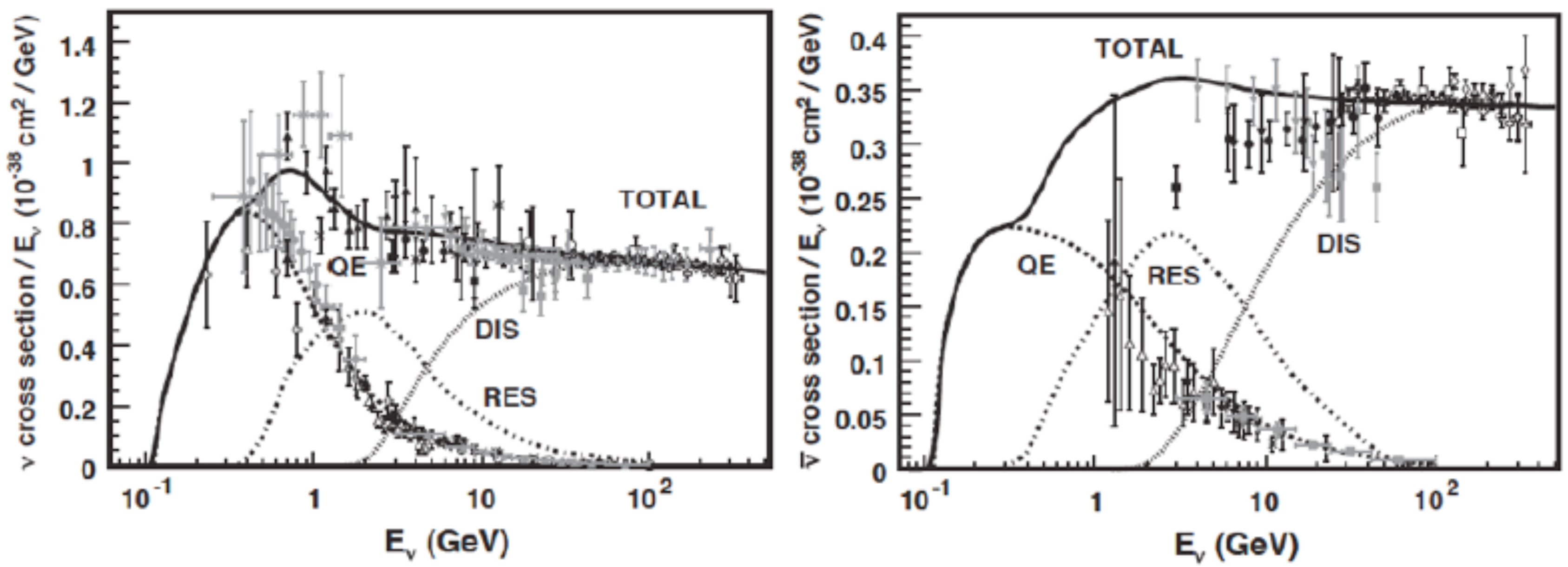


$$\langle \theta \rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu[\mathrm{TeV}]}}$$

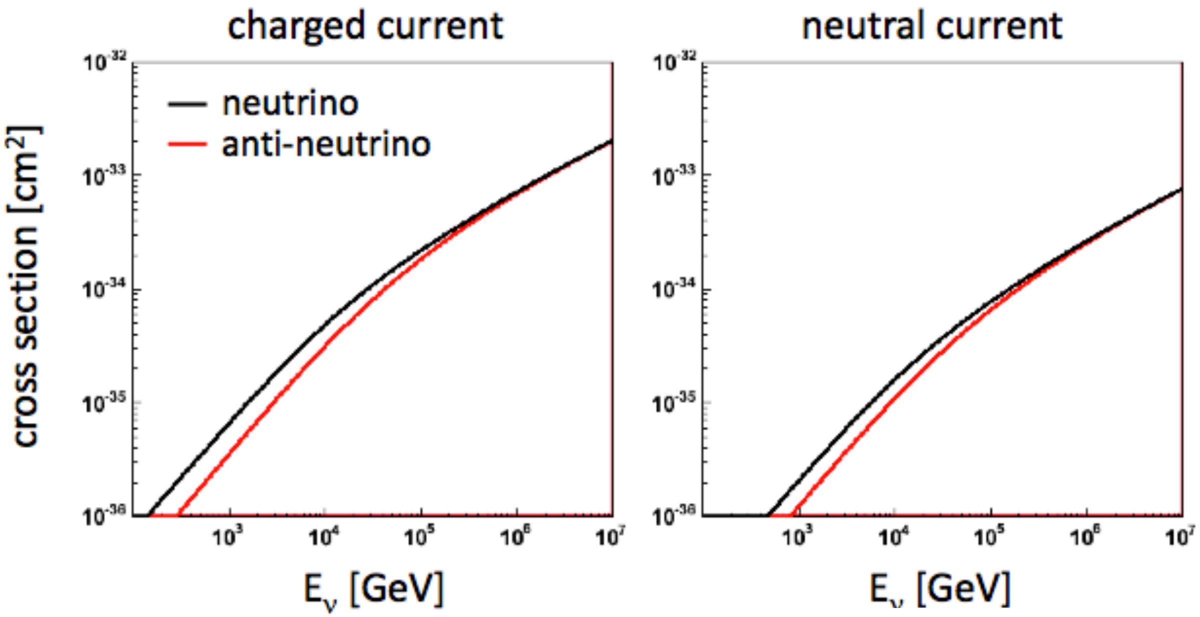
The single steps

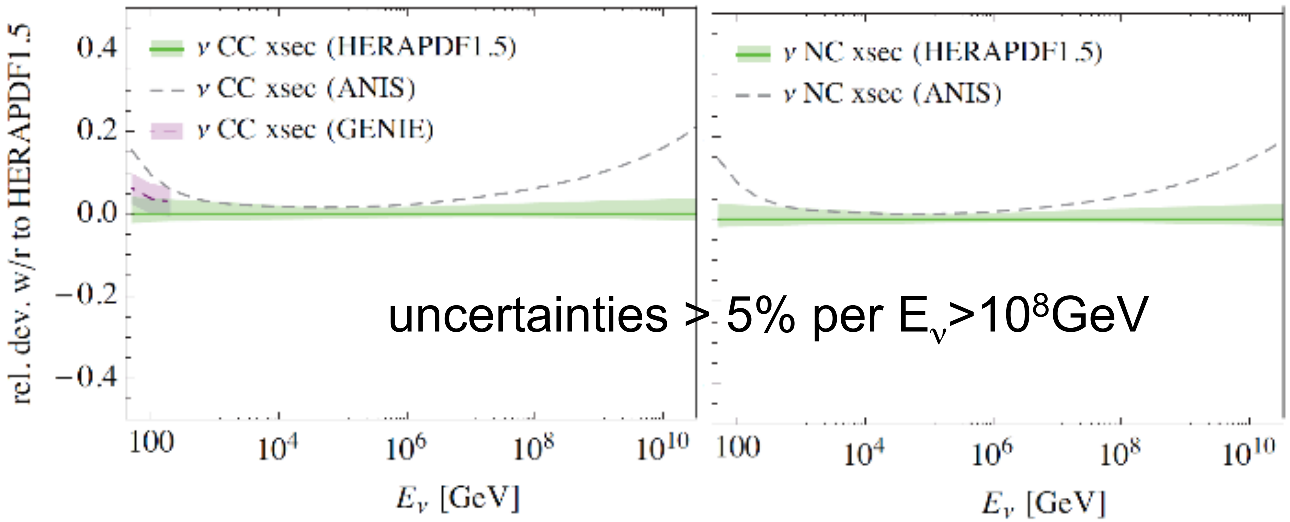


Neutrino cross section



DIS Muon Neutrino cross section





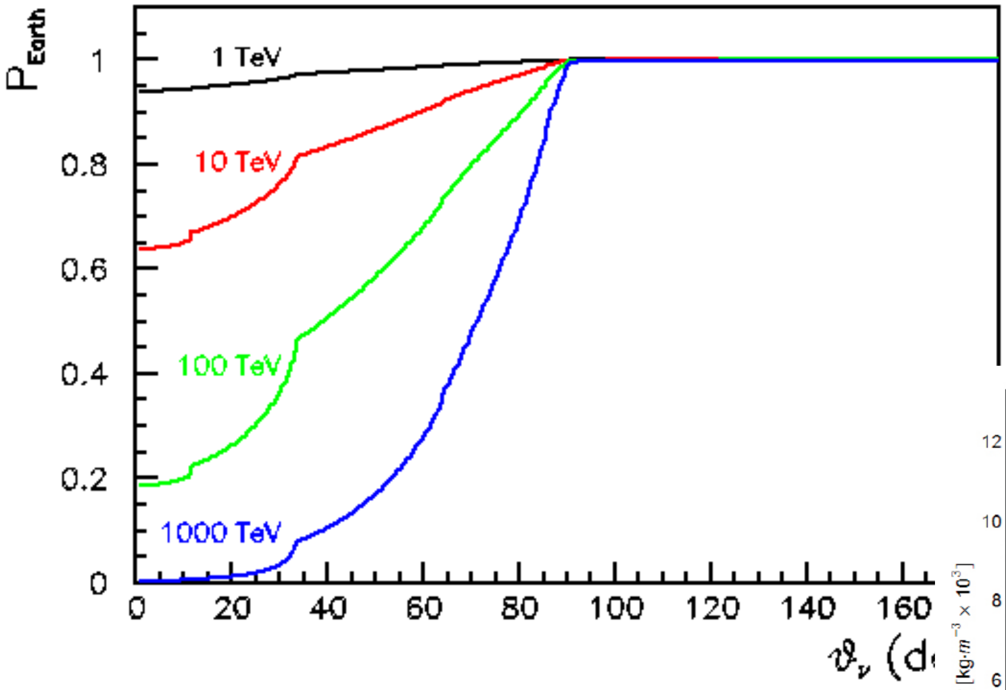
uncertainties > 5% per E_{ν}>10^8GeV

Gandhi et al. Astr.Phys. 5 (1996) 81-110
Cooper-Sarkar et al. arXiv:1106.3723v2

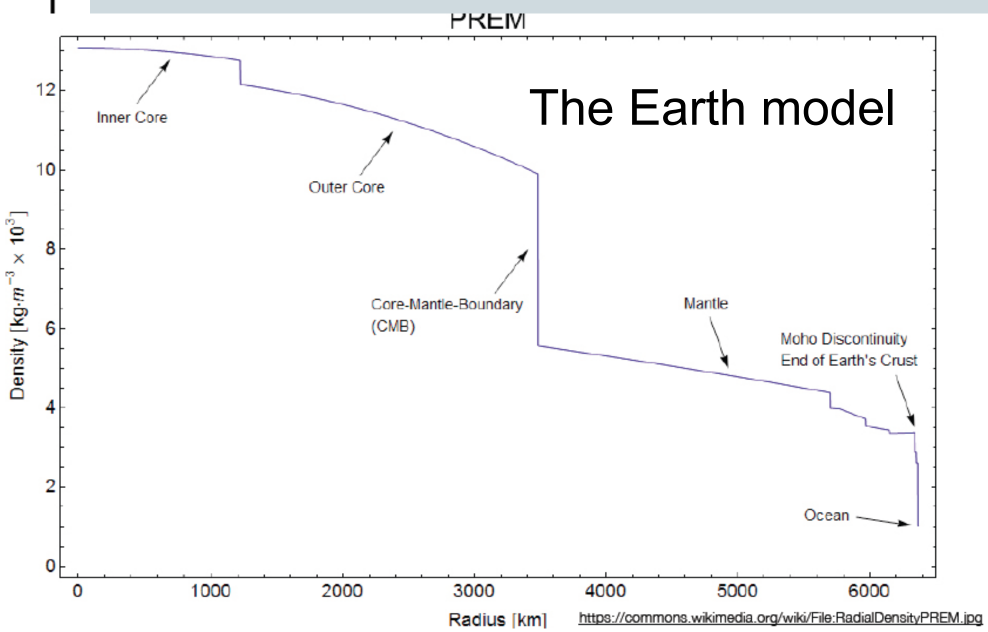
Earth transmission probability

Transmission probability:

$$P_{earth} = e^{-\sigma_{tot}(E_\nu) N_A Z(\theta)}$$



The Earth is not transparent to high energy neutrinos (>PeV)



GENHEN

GENHEN generates al flavours neutrinos (antineutrinos) (ν_e,ν_μ,ν_τ)

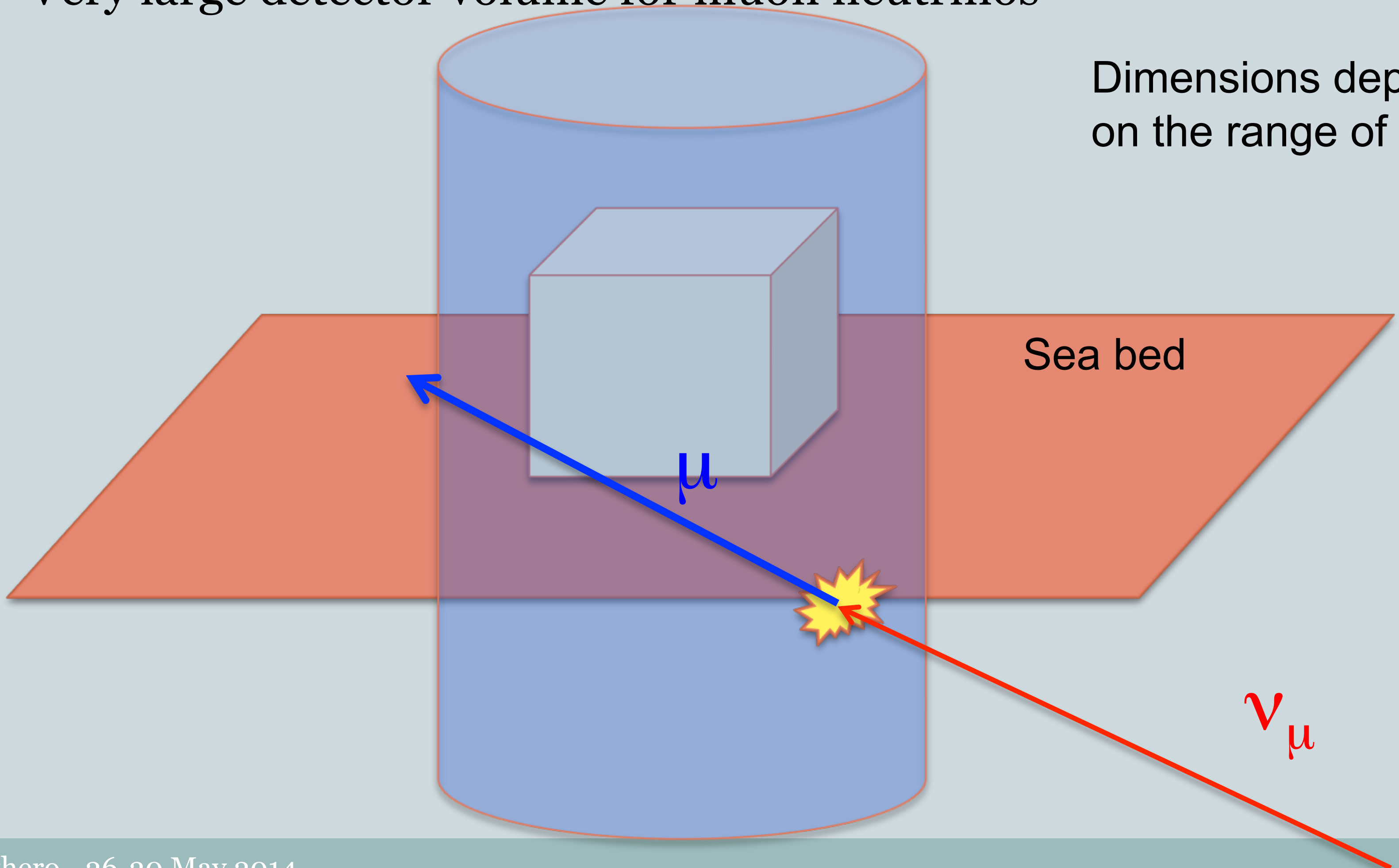
- Main inputs
  - neutrino energy range (2 GeV<E_ν<10^8 GeV)
  - neutrino angular range
  - neutrino flavour
  - Generation spectrum
- Outputs
  - Charged particles at the interaction vertex (Energy, angle and type)
  - Muons propagated up to the can level
  - Weight of the events

✓LEPTO neutrino interaction
✓CTEQ6 structure function
✓PYTHIA/JETSET for hadronization
✓DIS+RES+QE interaction (RES +QE for the low energies)

Generation volume

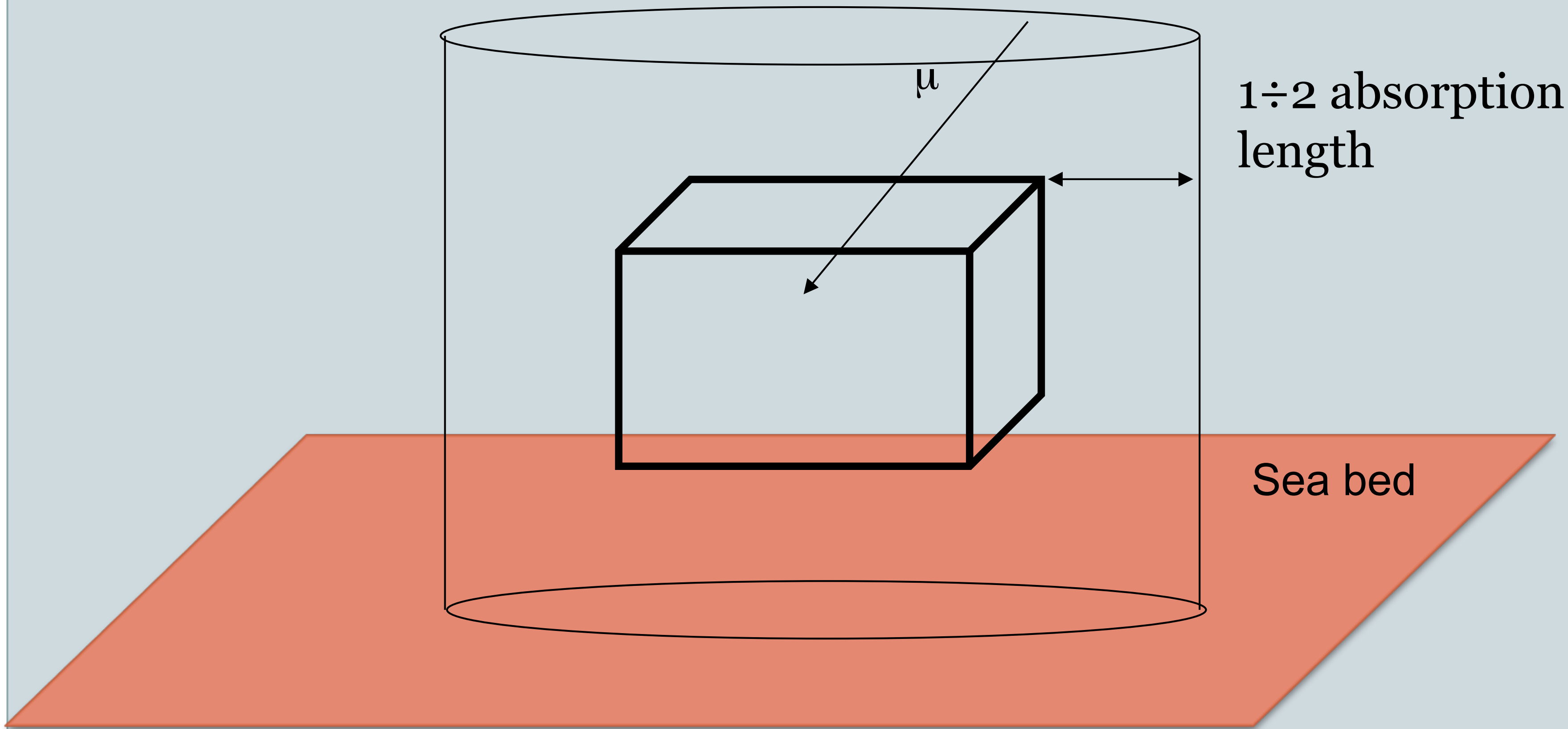
Only neutrinos inside the generation volume can reach the detector.
Very large detector volume for muon neutrinos

Dimensions dependent on the range of muons



The "can"

Only the light produced inside the cilinder around the detector can be "seen" by the optical sensors.



Event weights

- A posteriori it is possible to weight the events to change the generation spectrum

$$W_{event} = \frac{d\phi^{\mathrm{mod}\,el}}{dE_{\nu}d\Omega dSdt} \Bigg/ \frac{d\phi^{generation}}{dE_{\nu}d\Omega dSdt} = W_{generation} \cdot \frac{d\phi^{\mathrm{mod}\,el}}{dE_{\nu}d\Omega dSdt}$$

$$W_{generation} = \frac{V_{gen} \cdot I_{\theta} \cdot I_{E} \cdot E^{\gamma} \cdot \sigma(E_{\nu}) \cdot \rho N_{A} \cdot P_{Earth}(E_{\nu}, \theta_{\nu})}{N_{total}}$$

Generation Volume

Generation spectrum

Sezione d'urto

Earth transmission probability

Number of nucleons in the medium target

The GENHEN output

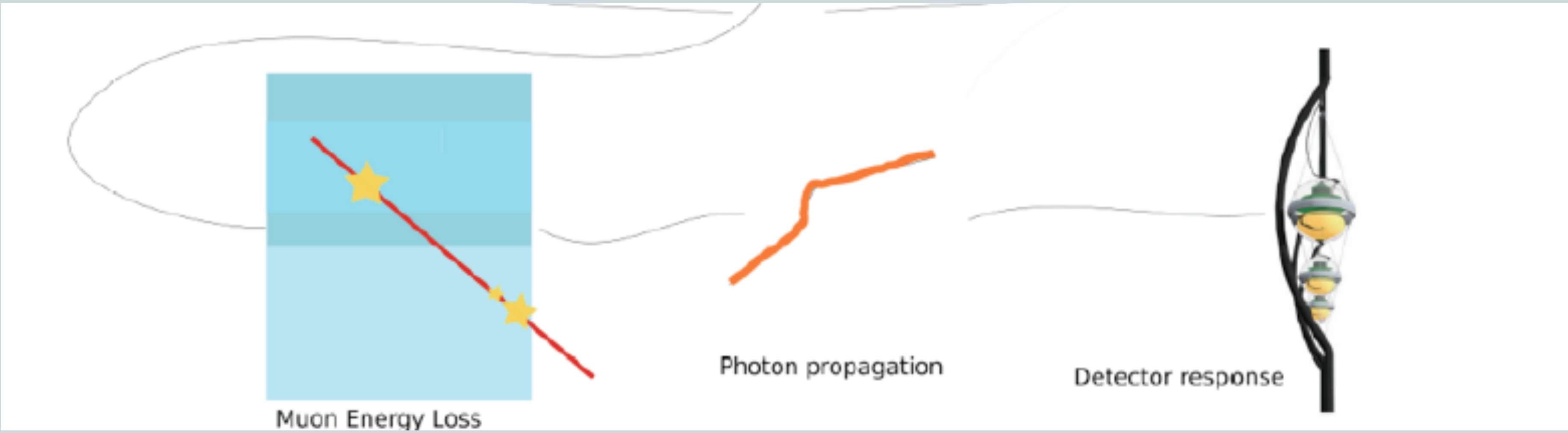

```
start_run:        1
cut_nu:  0.100E+03 0.100E+09-0.100E+01 0.100E+01
physics:  GENHEN  7.1-120213  140507 2345
drawing:  Volume
seed:  GENHEN 3       2001         0         0
spectrum:    -2.00
PDF:        4      58
model:        1       3       1       1      12
genhencut:  0.200E+04 0.000E+00
nuflux:       0       3       0 0.500E+00 0.000E+00 0.100E+01 0.300E+01
kcut:         2
target: isoscalar
xparam: OFF
sourcemode: diffuse
usedetfile: true
detector: /sps/km3net/users/coniglio/antares_seawiet/detectors/hex115_3inch31pm120_1836.det  1 1
can:    -410.69    516.71    881.43
genvol:  -25938.52   3230.71  30319.79  0.8424E+14  0.1000E+10
end_event:
```

```
start_event:       3       1
neutrino:    1    177.116    -623.566      1.810 -0.711810  0.578722 -0.398005   0.291644E+03   0.0  0.317103  0.102748  -1  14   2
track_in:    1    177.116    -623.566      1.810 -0.713400  0.585813 -0.384558   0.261678E+03      0.0  6
track_in:    2    177.116    -623.566      1.810 -0.716518  0.456275 -0.527651   0.211605E+00      0.0  8
track_in:    3    177.116    -623.566      1.810 -0.694297  0.463015 -0.550971   0.907137E+01      0.0 13
track_in:    4    177.116    -623.566      1.810 -0.686097  0.491386 -0.536481   0.721160E+00      0.0  1
track_in:    5    177.116    -623.566      1.810 -0.688330  0.515778 -0.510073   0.194797E+02      0.0  1
track_in:    6    177.116    -623.566      1.810 -0.091070  0.729955 -0.677401   0.259629E+00      0.0  8
track_in:    7    177.116    -623.566      1.810 -0.637166  0.765220 -0.091974   0.334419E+00      0.0  9
track_in:    8    177.116    -623.566      1.810 -0.759209  0.642193  0.105783   0.260022E+00      0.0  9
track_in:    9    177.116    -623.566      1.810 -0.869828  0.389872 -0.302325   0.265126E+00      0.0  8
track_in:   10    177.116    -623.566      1.810 -0.132410  0.314693  0.939913   0.111240E+00      0.0  1
track_in:   11    177.116    -623.566      1.810 -0.218302  0.940854  0.259112   0.189856E+00      0.0  1
track_earthlepton:    1    177.116    -623.566      1.810 -0.713400  0.585813 -0.384558   0.261678E+03      0.0  6
w2list:   0.2389E+37  0.8506E+05  0.1967E-39  0.7018E+10  0.1000E+01  0.8425E+03
weights:   0.8424E+14  0.3366E+16  0.5119E+11
w3list:    0  0.1521E-04  0.5119E+11
end_event:
```

The Light and hit generator

Good knowledge of the medium properties

Good knowledge of the detector responces



Light and hit generation

Full simulation based on GEANT	Code based on light tables
Each photon is tracked	Binning effect and light propagation in medium based on models
Very slow: not possible to simulate high energy events on large detector	Very fast
Used to generate the parameterizations and verify the results	

Light and hit generation

KM3 in ANTARES/ KM3NeT

Good knowledge of the medium properties required

Particle propagation into the medium inside the can	Muons E.M. showers Hadrons at the interaction vertex (One/ Many Particle Approximation)
Generation of light from particle and shower	Cerenkov light and stocastic emission of E.M. showers
PMT response simulation	Hit generation

The KM3 code

GEN HIT e KM3 used in ANTARES and KM3NeT

GEN e HIT generate light tables (based on full simulation GEANT). Optical water properties and PMTs characteristic taken into account

KM3 propagates muons and generates, from the light tables, photons and generate PMT hits

- Main inputs
  - Files optical water properties (absorption length and scattering length as a function of the wavelength)
  - PMT properties (TTS, QE(λ), photocatode area)
  - Optical properties of gel and glass of bentosphere
- Outputs
  - Hits with PMT identifier, arrival time of photons and charge

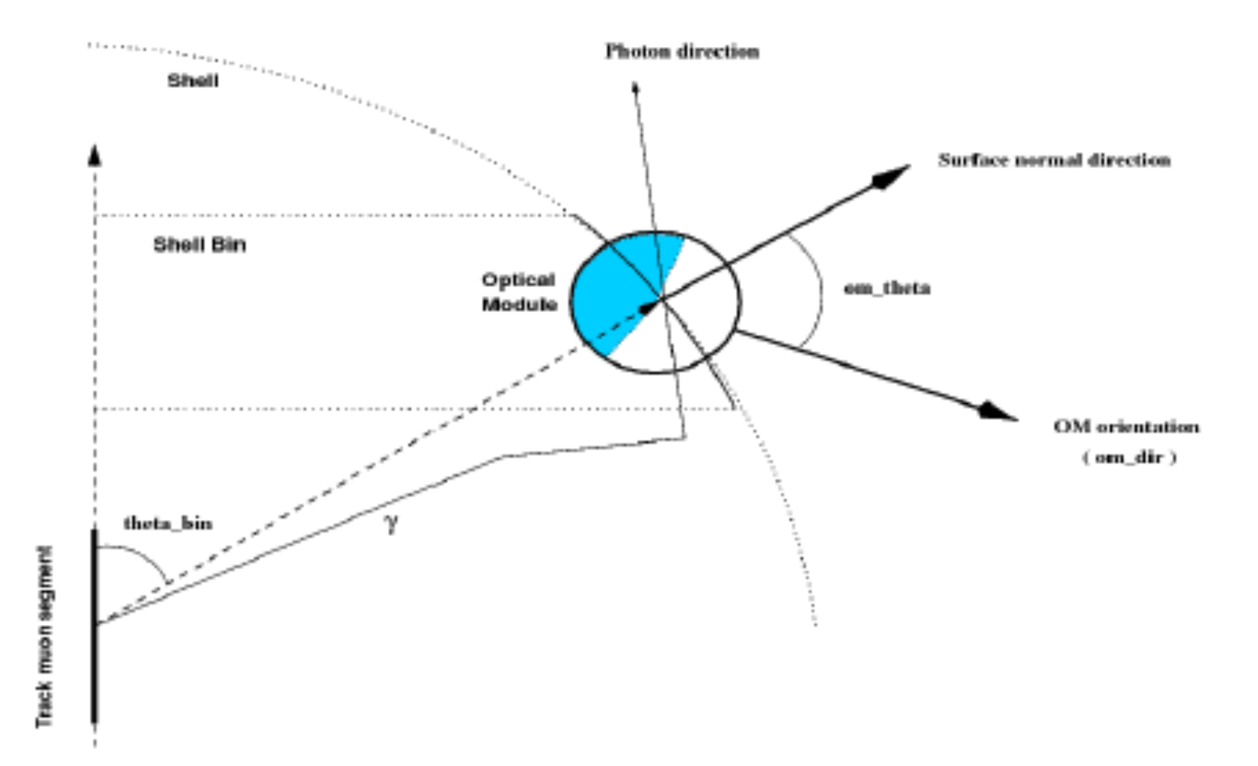
The light tables

GEN e HIT based on GEANT.
GEN generates a photon field at different radii from a segment of the track or E.M. shower. Water properties taken into account
HIT reads GEN output and generates tables with a photon probability distribution around the PMT.

Tables recreated only if water properties and PMT characteristics change

Problem of binning and interpolation

Not easy for ice



Water/ice optical properties

- The water/ice “transparency” is measured by the absorption length L_{abs} and the scattering length L_{sca}

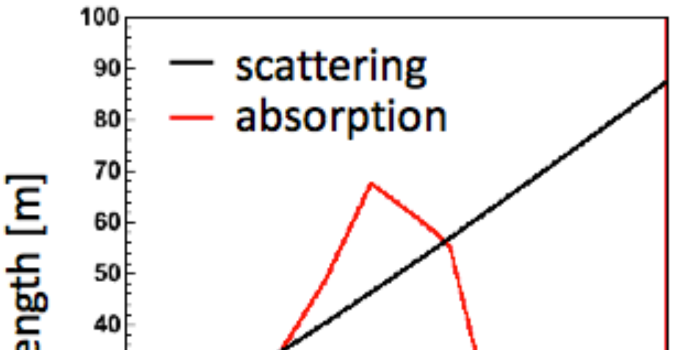
The attenuation length is :

$$\frac{1}{L_{att}(\lambda)} = \frac{1}{L_{abs}(\lambda)} + \frac{1}{L_{sca}(\lambda)}$$

Attenuation coefficient

Absorption coefficient

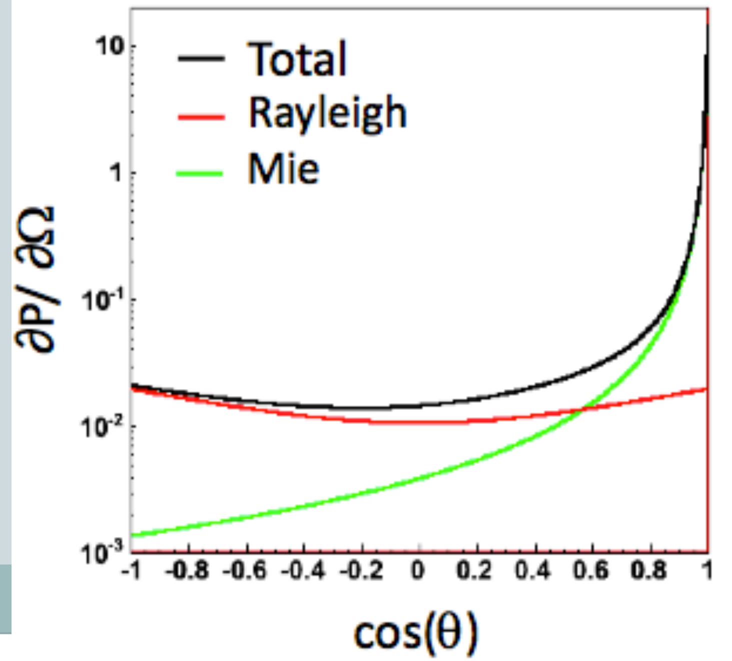
Scattering coefficient



Scattering on molecules (Rayleigh scattering) or on particles (Mie scattering)

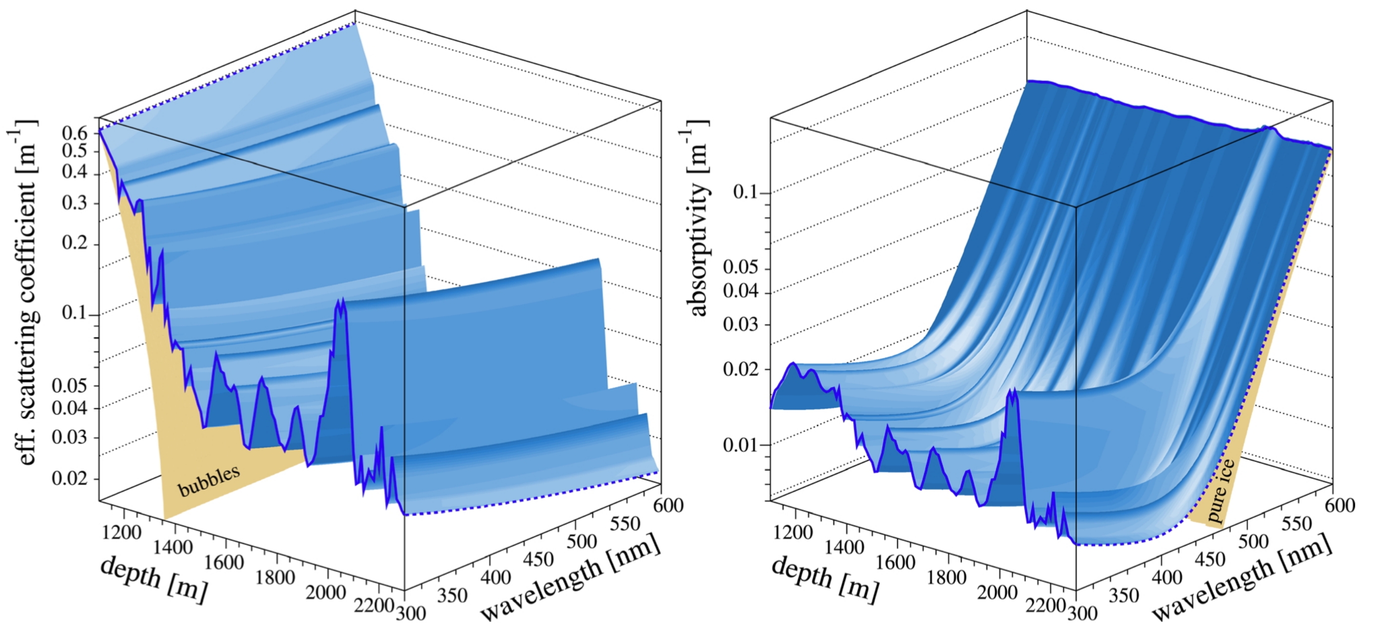
Used also the effective scattering length

$$L_{sca}^{eff} = \frac{L_{sca}(\lambda)}{1 - \langle \cos\theta_{scat} \rangle}$$



Water vs ice

- Water -> homogeneous medium:
  - Baikal water: L_{abs}=22-24m, L_{scat}=30-50m, low background
  - Sea water: L_{abs}=50-70m, L_{scat}=55m
- Ice ->not homogeneous medium :



Scattering coefficient very different (up to a factor 7)

$\langle L_{scatt} \rangle \approx 30$ m

Absorption coefficient differs of a factor 3

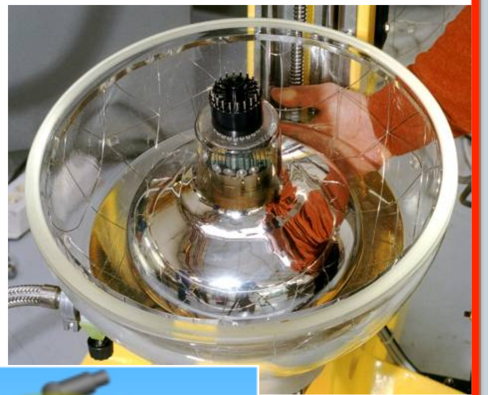
The optical sensors: PMT

Baikal

Quasar photodetector (Ø=37cm)

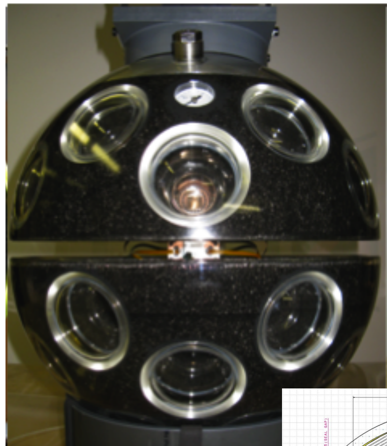
1 hibrid PMT

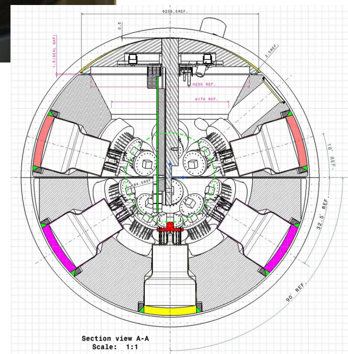
ANTARES e IceCube



1 large PMT (10”) inside a bentosphere (17”)

KM3NeT



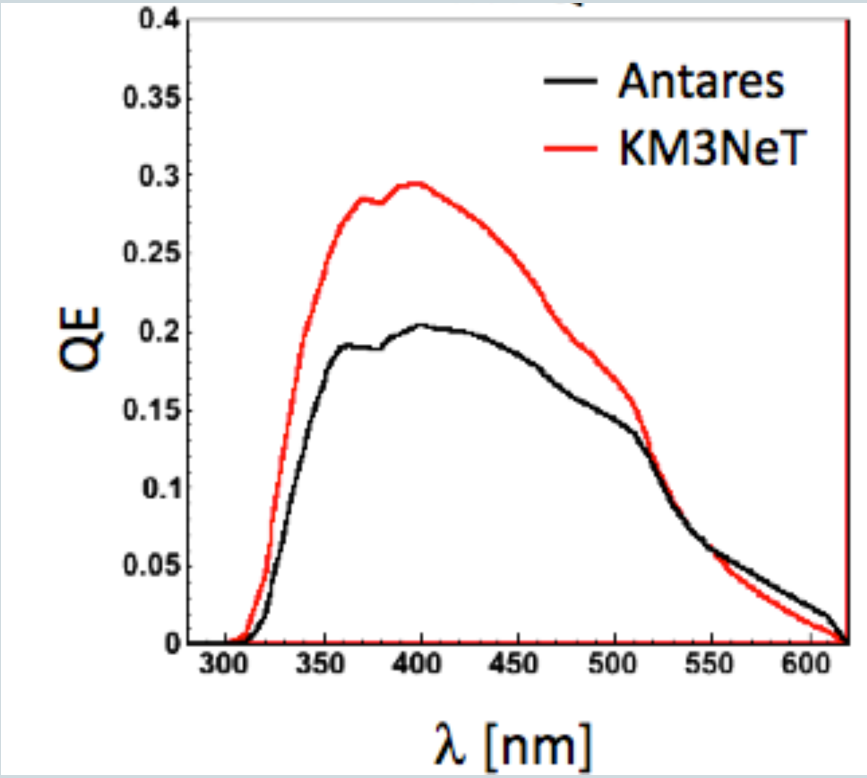


31 small PMT (3”) inside a bentosphere (17”)

PMT: the main characteristics

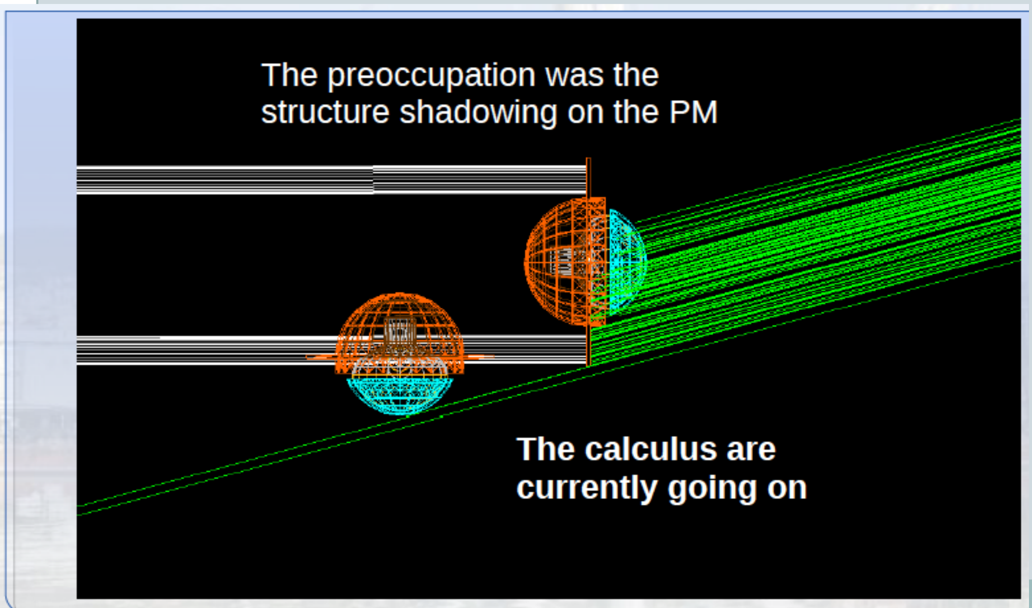
- Quantum efficiency
  - High QE required in the blue wavelength region
- Angular acceptance
  - Good precision required at backward angles
- Timing
  - Good timing required (effect on the arrivl photon tim angular track resolution)

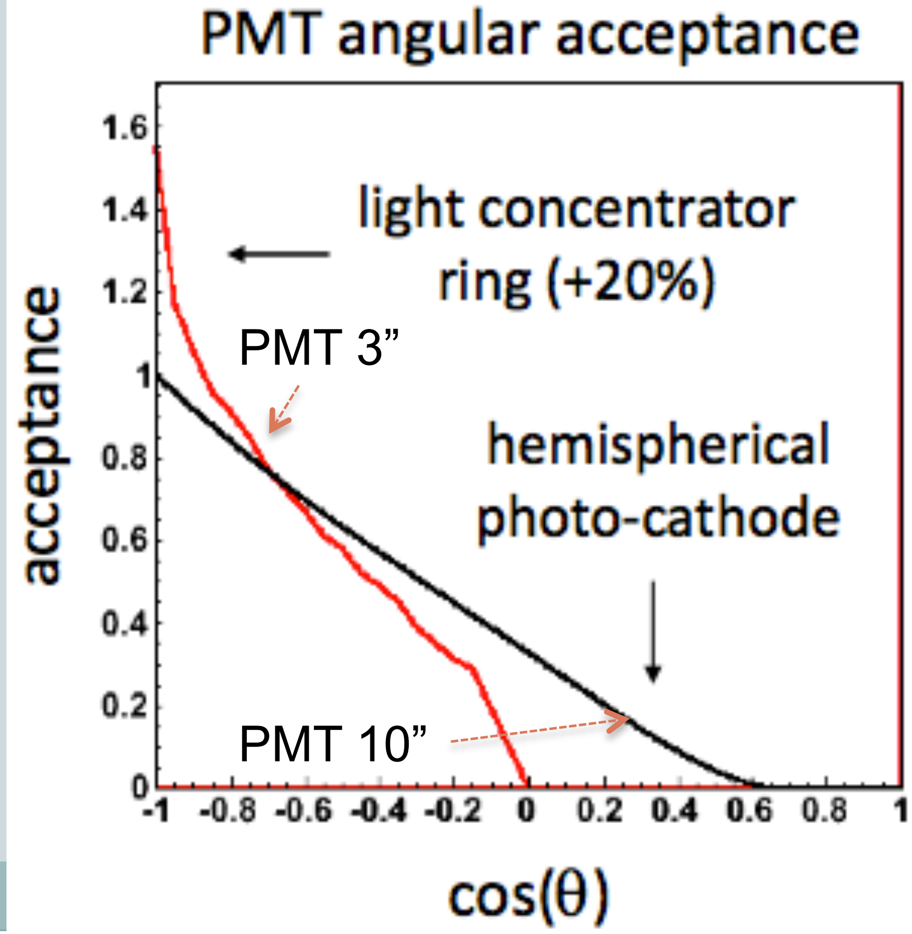
  Transit Time Spread 1 ns (sigma)
- Photocatode area



Angular PMT acceptance

- The angular acceptance estimated with GEANT4. Correctness of GEANT4 verified with laboratory measurements
  - Geometry
  - Water characteristic





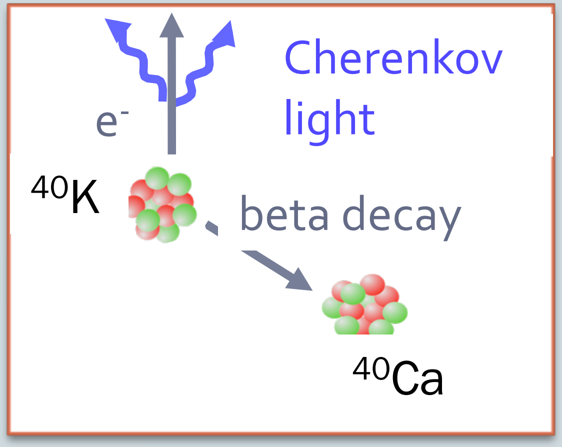
The KM3 OUTPUT

```
start_event:        3        1
neutrino: 1    177.116    -623.566      1.810 -0.711810  0.578722 -0.398005   0.291644E+03    0.0  0.317103  0.102748  -1  14    2
track_earthlepton: 1    177.116    -623.566      1.810 -0.713400  0.585813 -0.384558   0.261678E+03      0.0   6
w2list: 0.2389E+37  0.8506E+05  0.1967E-39  0.7018E+10  0.1000E+01  0.8425E+03
weights: 0.8424E+14  0.3366E+16  0.5119E+11
w3list: 0  0.1521E-04  0.5119E+11
track_in:      1    177.116    -623.566      1.810 -0.713400  0.585813 -0.384558   0.261678E+03       0.00    5    869.099
track_in:      2    177.116    -623.566      1.810 -0.716518  0.456275 -0.527651   0.211605E+00   0.000000E+00  8
track_in:      3    177.116    -623.566      1.810 -0.694297  0.463015 -0.550971   0.907137E+01   0.000000E+00 13
track_in:      4    177.116    -623.566      1.810 -0.686097  0.491386 -0.536481   0.721160E+00   0.000000E+00  1
track_in:      5    177.116    -623.566      1.810 -0.688330  0.515778 -0.510073   0.194797E+02   0.000000E+00  1
track_in:      6    177.116    -623.566      1.810 -0.091070  0.729955 -0.677401   0.259629E+00   0.000000E+00  8
track_in:      7    177.116    -623.566      1.810 -0.637166  0.765220 -0.091974   0.334419E+00   0.000000E+00  9
track_in:      8    177.116    -623.566      1.810 -0.759209  0.642193  0.105783   0.260022E+00   0.000000E+00  9
track_in:      9    177.116    -623.566      1.810 -0.869828  0.389872 -0.302325   0.265126E+00   0.000000E+00  8
track_in:     10    177.116    -623.566      1.810 -0.132410  0.314693  0.939913   0.111240E+00   0.000000E+00  1
track_in:     11    177.116    -623.566      1.810 -0.218302  0.940854  0.259112   0.189856E+00   0.000000E+00  1
track_in:     12    177.098    -623.555      1.797 -0.716518  0.456275 -0.527651   0.374415E-01   0.814696E-01 99
track_in:     13    175.562    -622.530      0.577 -0.694297  0.463015 -0.550971   0.461961E+01   0.746619E+01 99
track_in:     14    176.607    -623.201      1.412 -0.686097  0.491386 -0.536481   0.721160E+00   0.247639E+01 99
track_in:     15    175.752    -622.544      0.799 -0.688330  0.515778 -0.510073   0.194797E+02   0.661037E+01 99
track_in:     16    177.112    -623.536      1.782 -0.091070  0.729955 -0.677401   0.623910E-01   0.135488E+00 99
track_in:     17    177.082    -623.551      1.798 -0.869828  0.389872 -0.302325   0.652469E-01   0.131190E+00 99
track_in:     18    177.111    -623.554      1.846 -0.132410  0.314693  0.939913   0.111240E+00   0.127790E+00 99
track_in:     19    177.064    -623.340      1.872 -0.218302  0.940854  0.259112   0.189856E+00   0.800478E+00 99
total_hits:       19
 hit:         1   4801        1.00      645.74          5         1         1    645.74
 hit:         2  11014        1.00     1780.98          5         1         1   1780.98
 hit:         3  11063        1.00     1756.44          5         1         1   1756.44
 hit:         4  18887        1.00     2224.72          5         1         1   2224.72
 hit:         5  25085        1.00     2886.88          5         1         1   2886.88
 hit:         6  25104        1.00     2884.88          5         1         1   2884.88
 hit:         7    326        1.00     1244.84         -5         1         1   1244.84
 hit:         8   4784        1.00      645.15         -5         1         1    645.15
 hit:         9   4826        1.00      708.34         -5         1         1    708.34
 hit:        10   4826        1.00      707.39         -5         1         1    707.39
 hit:        11  16045        1.00     1703.91         -5         1         1   1703.91
 hit:        12  11051        1.00     1758.51         -5         1         1   1758.51
 hit:        13  11063        1.00     1762.66         -5         1         1   1762.66
 hit:        14  24968        1.00     3332.24         -5         1         1   3332.24
 hit:        15  25061        1.00     2940.61         -5         1         1   2940.61
 hit:        16  25097        1.00     2886.97         -5         1         1   2886.97
 hit:        17   1949        1.00      395.79         -3         5         1    395.79
 hit:        18   7054        1.00     1076.26         -3         1         1   1076.26
 hit:        19   9308        1.00     1511.82         -3         1         1   1511.82
 end_event:
```

The ^{40}K and bioluminescence

In sea water telescope photons due to the beta decay of ^{40}K are present:

- beta decay of ^{40}K presents in the salt.

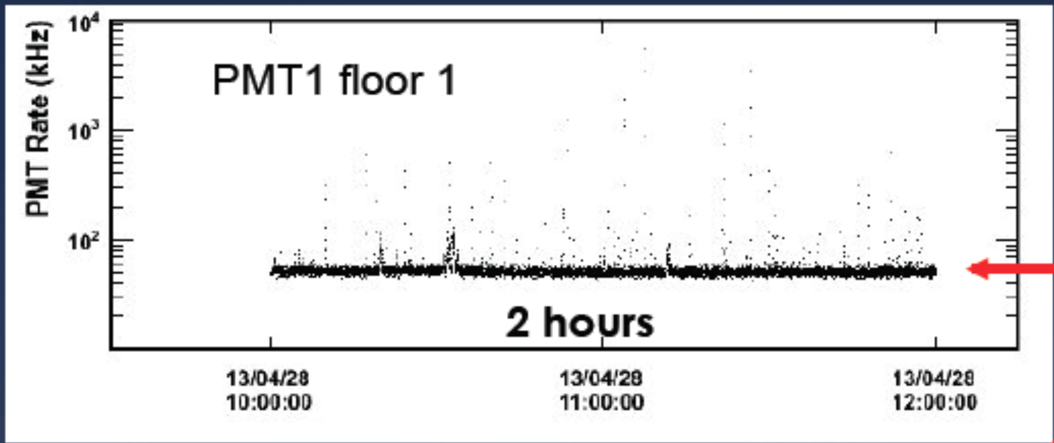


Rate of about 360 s^{-1} cm^{-2}
Baseline of about 40 kHz in8" PMT (0.3 p.e.)
And 5 kHz in 3" PMTs

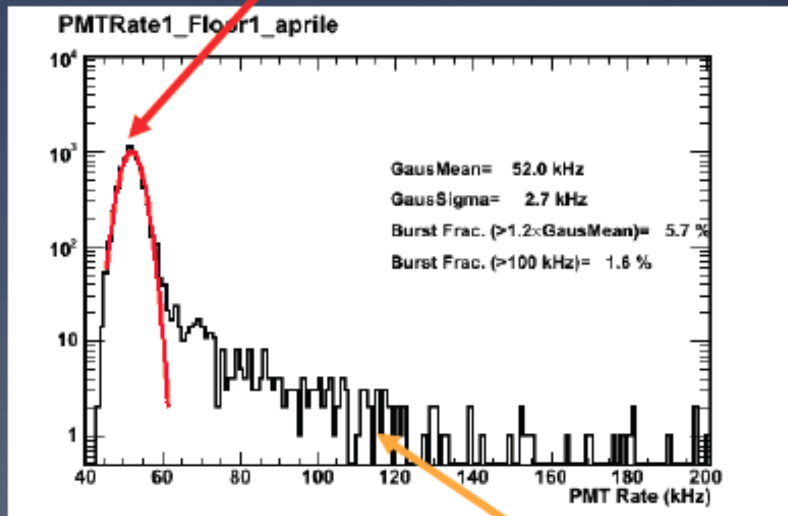
- Bioluminescence from micro-organisms (bacteria) → baseline + bursts
- Light from macro-organisms → bursts of MHz

The bioluminescence if present is strongly correlated with the sea current.

The rate in the PMTs



Baseline value = 52 kHz

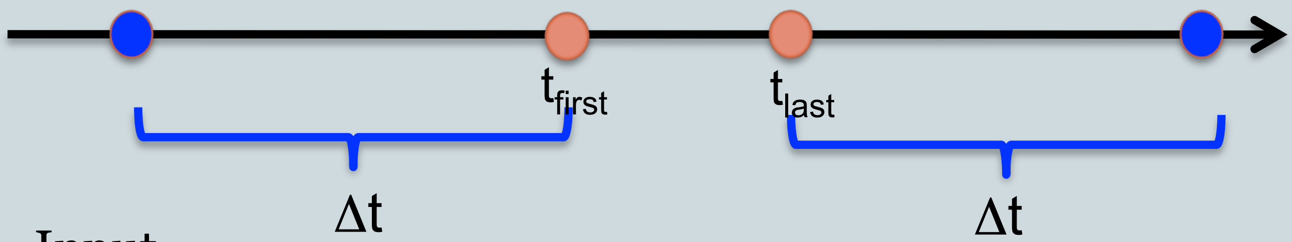


- ✓Measured optical background rate around 60 kHz for all the PMTs
  - ✓Compatible with pure 40K background
  - ✓Rare bioluminescence bursts

Burst $_{>100\ \text{kHz}}$ = 1.6%

MC generation of 40K hits and electronic simulation

- KM3NeT uses MODK40 code ->add not correlated in time due to ^{40}K inside a time window Δt (1/2 max crossing time of a muon inside the detector) around the event time window. Not included the bioluminescence



  - Input
    - 40K rate
    - Δt value
  - Output
    - Hits (PMT identifier, photon arrival time, charge
- ANTARES ->adds “run by run” the^{40}K background from the data (minimum bias) (bioluminescence automatically included)

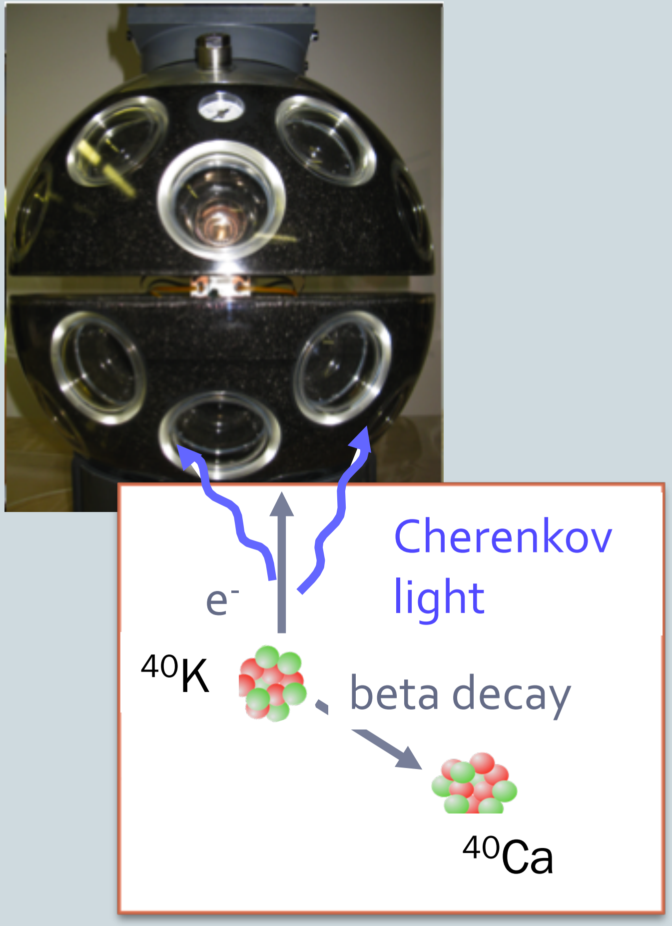
40K Coincidence rate in the multi-PMT

Probability to have time coincident hits in two PMTs inside the Multi-PMT is not negligible

Probability matrix estimated with GEANT4 and included in MODK40

$* 10^{-4}$

PMT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
2	93																													
3	93	98																												
4	93	35	98																											
5	93	24	35	98																										
6	93	35	24	35	98																									
7	93	98	35	24	35	97																								
8	33	95	26	10	10	26	95																							
9	33	95	95	26	10	10	26	45																						
10	33	26	95	95	26	10	10	8	45																					
11	33	10	26	95	95	26	10	3	8	45																				
12	33	10	10	26	95	95	26	8	3	8	45																			
13	33	26	10	10	26	95	95	45	8	3	8	45																		
14	17	65	28	8	4	8	28	95	95	12	2	2	12																	
15	17	28	65	28	8	4	8	12	95	95	12	2	2	32																
16	17	8	28	65	28	8	4	2	12	95	95	12	2	3	32															
17	17	4	8	28	65	28	8	2	2	12	95	95	12	0	3	32														
18	17	8	4	8	28	65	28	12	2	2	12	95	95	3	0	3	32													
19	17	28	8	4	8	28	65	95	12	2	2	12	95	32	3	0	3	32												
20	4	13	4	1	1	4	13	41	14	1	0	1	14	53	7	0	0	7	53											
21	4	13	13	4	1	1	4	14	41	14	1	0	1	53	53	7	0	0	7	32										
22	4	4	13	13	4	1	1	1	14	41	14	1	0	7	53	53	7	0	0	3	32									
23	4	1	4	13	13	4	1	0	1	14	41	14	1	0	7	53	53	7	0	0	3	32								
24	4	1	1	4	13	13	4	1	0	1	14	41	14	0	0	7	53	53	7	3	0	3	32							
25	4	4	1	1	4	13	13	14	1	0	1	14	41	7	0	0	7	53	53	32	3	0	3	32						
26	1	8	4	1	0	1	4	16	16	4	0	0	3	41	14	1	0	1	14	95	95	12	2	2	12					
27	1	4	8	4	1	0	1	3	16	16	3	0	0	14	41	14	1	0	1	12	95	95	12	2	2	45				
28	1	1	4	8	4	1	0	0	3	16	16	3	0	1	14	41	14	1	0	2	12	95	95	12	2	8	45			
29	1	0	1	4	8	4	1	0	0	3	16	16	3	0	1	14	41	14	1	2	2	12	95	95	12	3	8	45		
30	1	1	0	1	4	8	4	3	0	0	4	16	16	1	0	1	14	41	14	12	2	2	12	95	95	8	3	8	45	
31	1	4	1	0	1	4	8	16	3	0	0	3	16	14	1	0	1	14	41	95	12	2	2	12	95	45	8	3	8	45



MODK40 output

```
start_event:        3       1
neutrino: 1    177.116    -623.566       1.810 -0.711810  0.578722 -0.398005   0.291644E+03   0.0  0.317103  0.102748  -1  14   2
track_earthlepton: 1    177.116    -623.566       1.810 -0.713400  0.585813 -0.384558   0.261678E+03      0.0  6
w2list: 0.2389E+37  0.8506E+05  0.1967E-39  0.7018E+10  0.1000E+01  0.8425E+03
weights: 0.8424E+14  0.3366E+16  0.5119E+11
w3list: 0  0.1521E-04  0.5119E+11
track_in: 1    177.116    -623.566       1.810 -0.713400  0.585813 -0.384558   0.261678E+03       0.00    5    869.099
track_in: 2    177.116    -623.566       1.810 -0.716518  0.456275 -0.527651   0.211605E+00   0.000000E+00  8
track_in: 3    177.116    -623.566       1.810 -0.694297  0.463015 -0.550971   0.907137E+01   0.000000E+00 13
track_in: 4    177.116    -623.566       1.810 -0.686097  0.491386 -0.536481   0.721160E+00   0.000000E+00  1
track_in: 5    177.116    -623.566       1.810 -0.688330  0.515778 -0.510073   0.194797E+02   0.000000E+00  1
track_in: 6    177.116    -623.566       1.810 -0.091070  0.729955 -0.677401   0.259629E+00   0.000000E+00  8
track_in: 7    177.116    -623.566       1.810 -0.637166  0.765220 -0.091974   0.334419E+00   0.000000E+00  9
track_in: 8    177.116    -623.566       1.810 -0.759209  0.642193  0.105783   0.260022E+00   0.000000E+00  9
track_in: 9    177.116    -623.566       1.810 -0.869828  0.389872 -0.302325   0.265126E+00   0.000000E+00  8
track_in: 10    177.116    -623.566       1.810 -0.132410  0.314693  0.939913   0.111240E+00   0.000000E+00  1
track_in: 11    177.116    -623.566       1.810 -0.218302  0.940854  0.259112   0.189856E+00   0.000000E+00  1
track_in: 12    177.098    -623.555       1.797 -0.716518  0.456275 -0.527651   0.374415E-01   0.814696E-01 99
track_in: 13    175.562    -622.530       0.577 -0.694297  0.463015 -0.550971   0.461961E+01   0.746619E+01 99
track_in: 14    176.607    -623.201       1.412 -0.686097  0.491386 -0.536481   0.721160E+00   0.247639E+01 99
track_in: 15    175.752    -622.544       0.799 -0.688330  0.515778 -0.510073   0.194797E+02   0.661037E+01 99
track_in: 16    177.112    -623.536       1.782 -0.091070  0.729955 -0.677401   0.623910E-01   0.135488E+00 99
track_in: 17    177.082    -623.551       1.798 -0.869828  0.389872 -0.302325   0.652469E-01   0.131190E+00 99
track_in: 18    177.111    -623.554       1.846 -0.132410  0.314693  0.939913   0.111240E+00   0.127790E+00 99
track_in: 19    177.064    -623.340       1.872 -0.218302  0.940854  0.259112   0.189856E+00   0.800478E+00 99
hit_raw:        1       115         0.34      1891.31
hit_raw:        2       134         0.68      3875.70
hit_raw:        3       154         0.92      2768.89
hit_raw:        4       225         0.58      1979.18
hit_raw:        5       236         1.40       -84.08
hit_raw:        6       292         1.21      1387.24
hit_raw:        7       297         0.66      1763.30
```

....

....

```
hit_raw: 1603     63941          0.97      3160.19
hit_raw: 1604     63942          0.46      2426.83
hit_raw: 1605     63980          1.12       470.19
hit_raw: 1606     64112          0.60     -1188.02
hit_raw: 1607     64113          1.73     -1182.72
hit_raw: 1608     64114          0.76      3221.20
hit_raw: 1609     64116          1.12      2436.70
```

The data/MC flow

DATA	MC
Data raw acquired	Generation code
Trigger on line	Propagation and Light and hit generation
Calibration	K40 added and electronics effect simulated- >hit raw
	Trigger

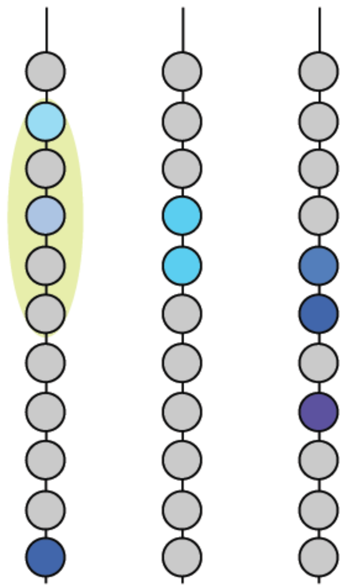
At this level Hit_Raw for MC and Data:
- PMT identifier
- Time (ns)
- Charge (photo-electrons)

Track reconstruction:
- muon track reconstruction
- cascade reconstruction
- energy reconstruction

The trigger

Applied both to date and MC

- Trigger based on time (to reject mainly the 40K background) or on geometrical issues (to reject atmospheric muons and neutrinos)
  - Local coincidence: Ex. 2 or more hits in close PMTs in a time window of 10ns
  - Coincidence in one or more floors/strings.
  - Directional trigger (Galattico center)
  - Veto on first top layers of the detector…



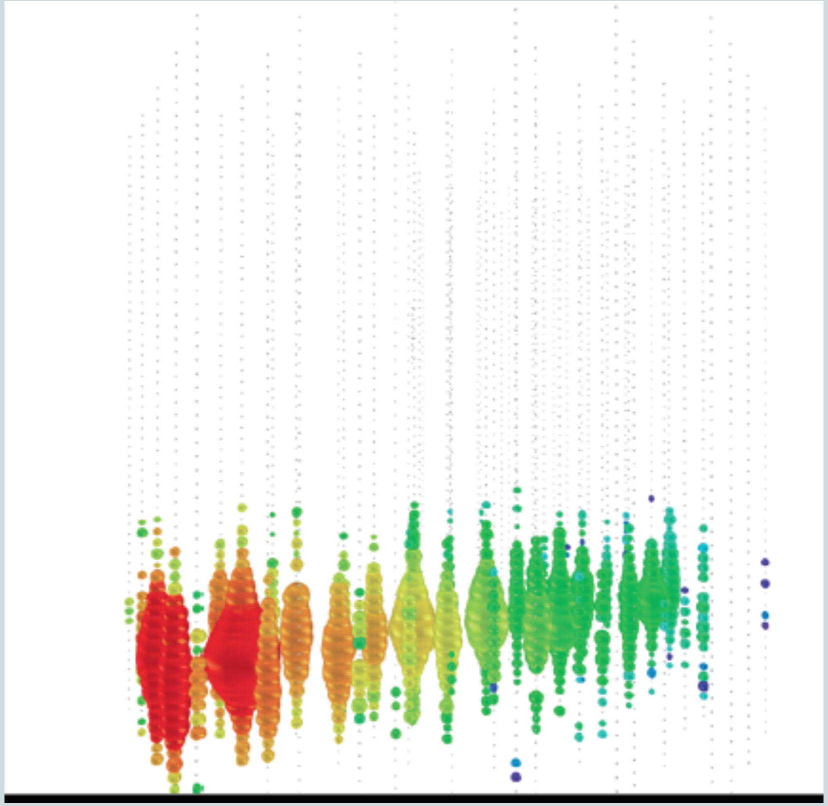
Depends on the detector geometry and on the ^{40}K rate

Lay-out

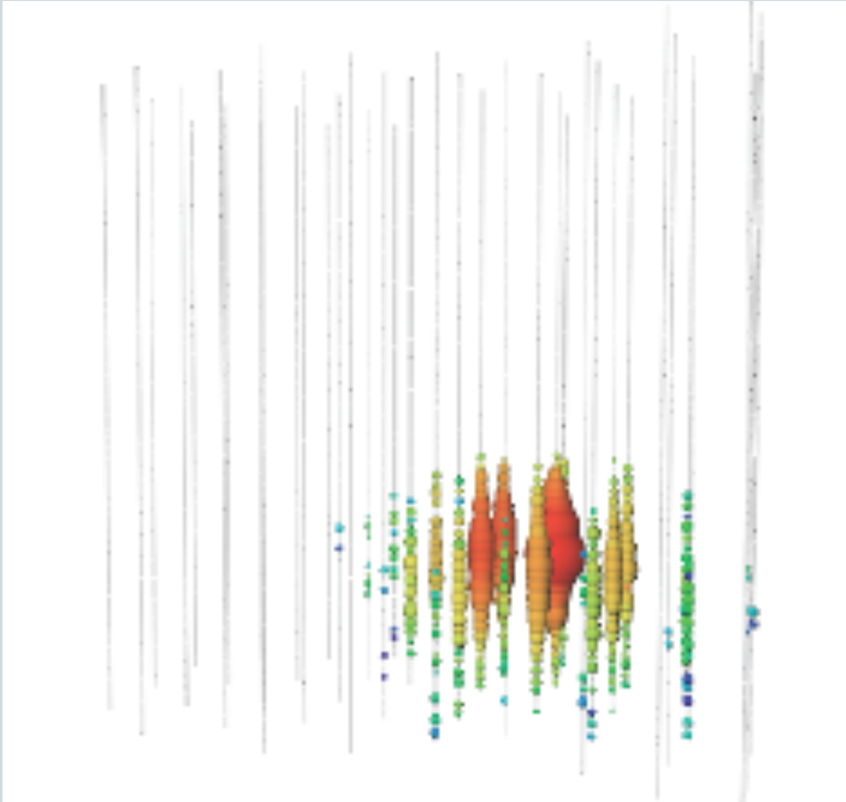
- Introduction
  - The neutrino telescope
- Detection principle
  - The detection principle
  - Backgrounds
- The Monte Carlo simulation
  - MC codes description
- The reconstruction codes
  - Track reconstruction
  - Cascade reconstruction
- On the performance of the telescope: relevant quantities
  - Effective neutrino area
  - Sensitivity and discovery potential

How muon and cascade events look like

Muon event in IceCube



Cascade event in IceCube



What do we need to reconstruct the event direction and energy

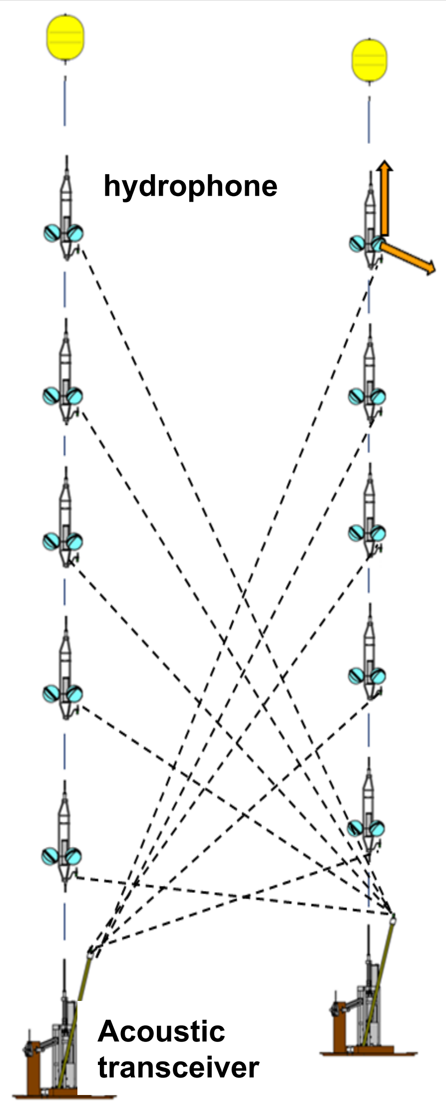
Different codes and strategies for different events: cascade or track events

Events partially cleaned

Events with soft cuts: on the geometry, on the number of hits....

Photon arrival times and PMT positions in each event

Measurement of the PMT positions in water telescope: the acoustic positioning system



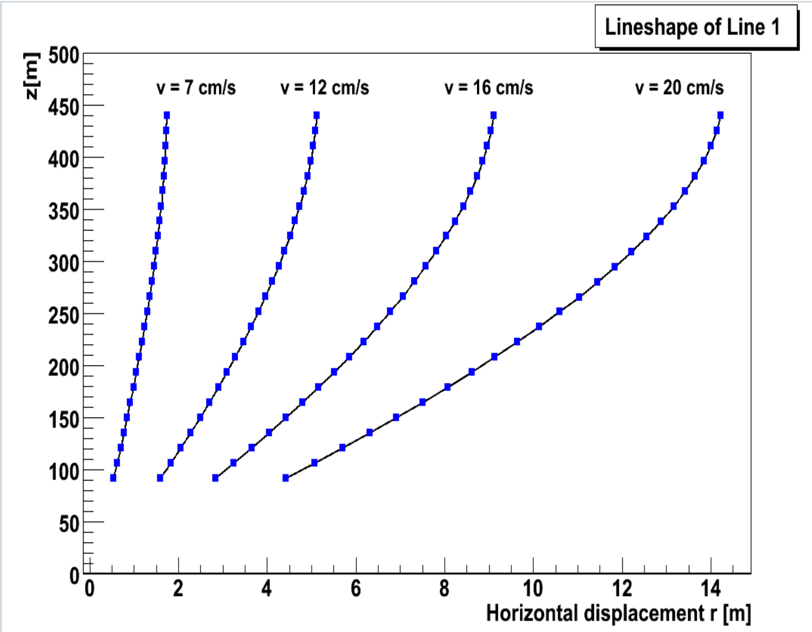
The strings are in continuous movement due to the sea currents

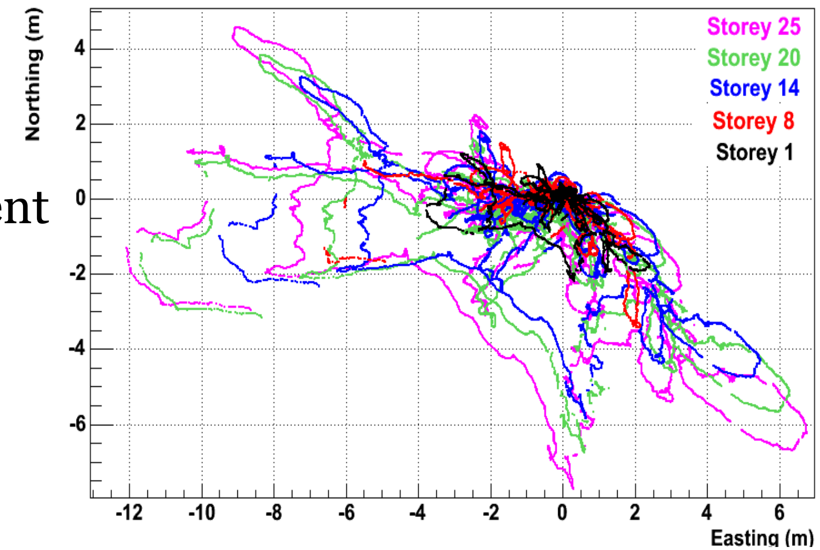
Hydrophones and transceivers located in several floors along the line

In each floor compass and tiltmeters

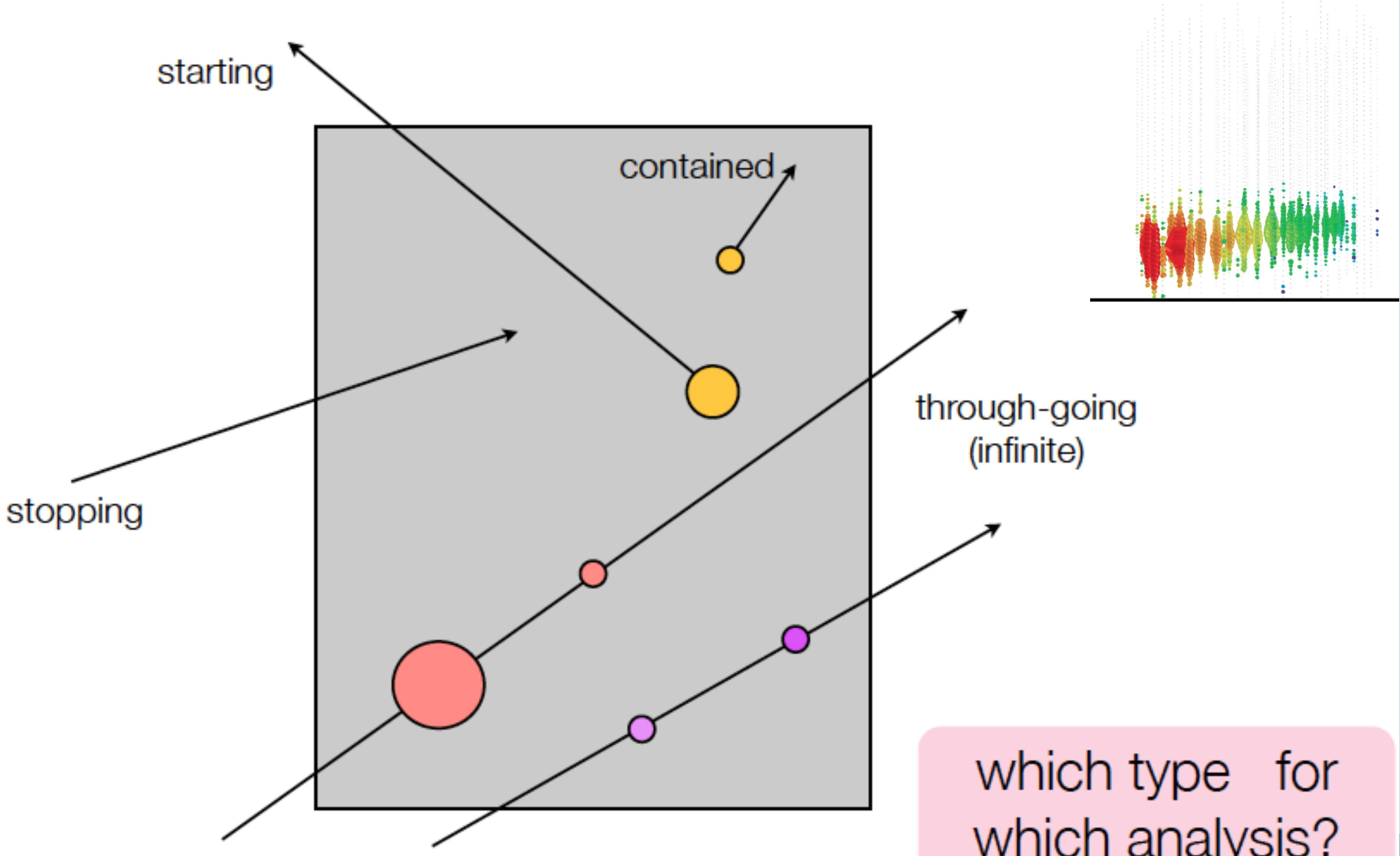
In ANTARES a measurement each 2 minutes

Position measured with an uncertainty of about 10cm





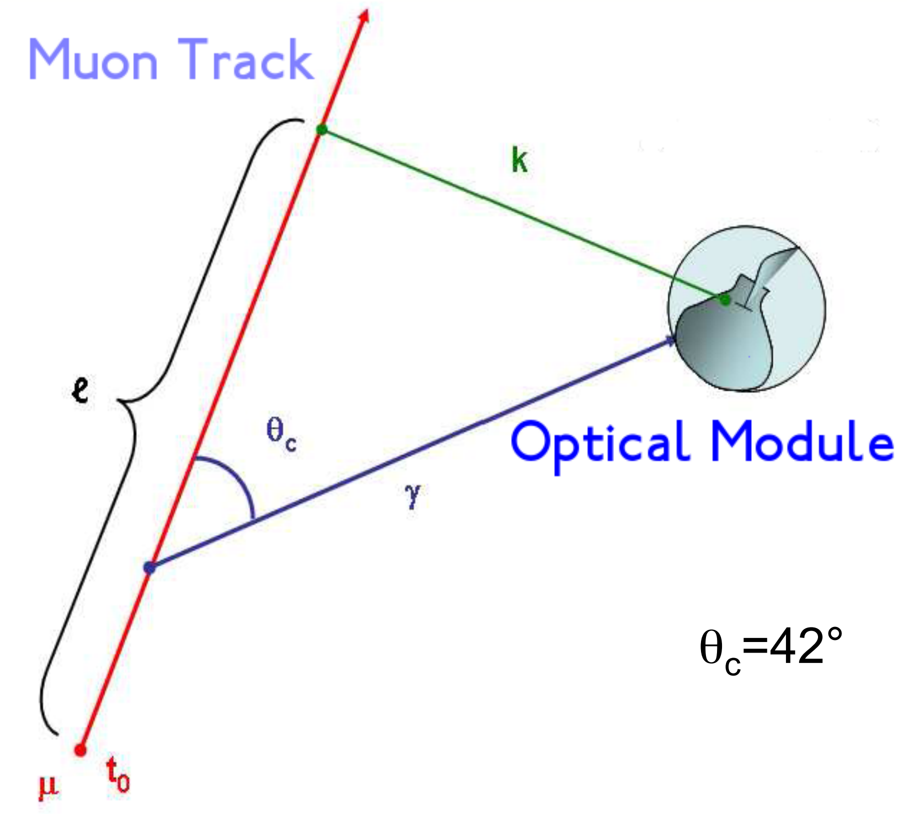
The muon tracks



which type for which analysis?

Muon track reconstruction code

Based on the relation between the track direction and photon emission angle present in the Cerenkov emission



All the code are based on the same space-time relation

$$t_{teorico} = t_0 + \frac{1}{c}\left(l - \frac{k}{\tan\theta_c}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_c}\right)$$

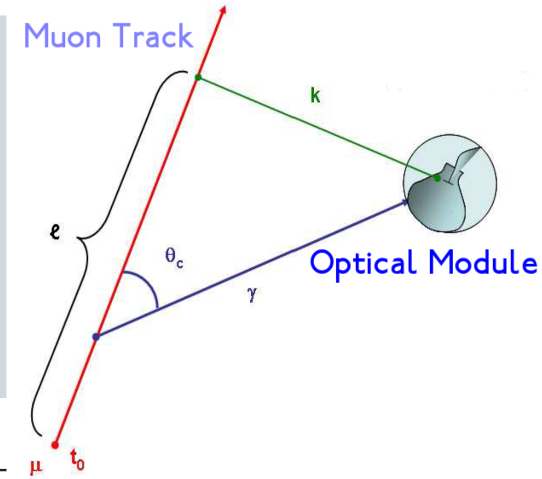
To obtain the track direction = 5 parameters θ,φ,x,y,z (x,y,z, pseudo-vertex coordinates) needed.

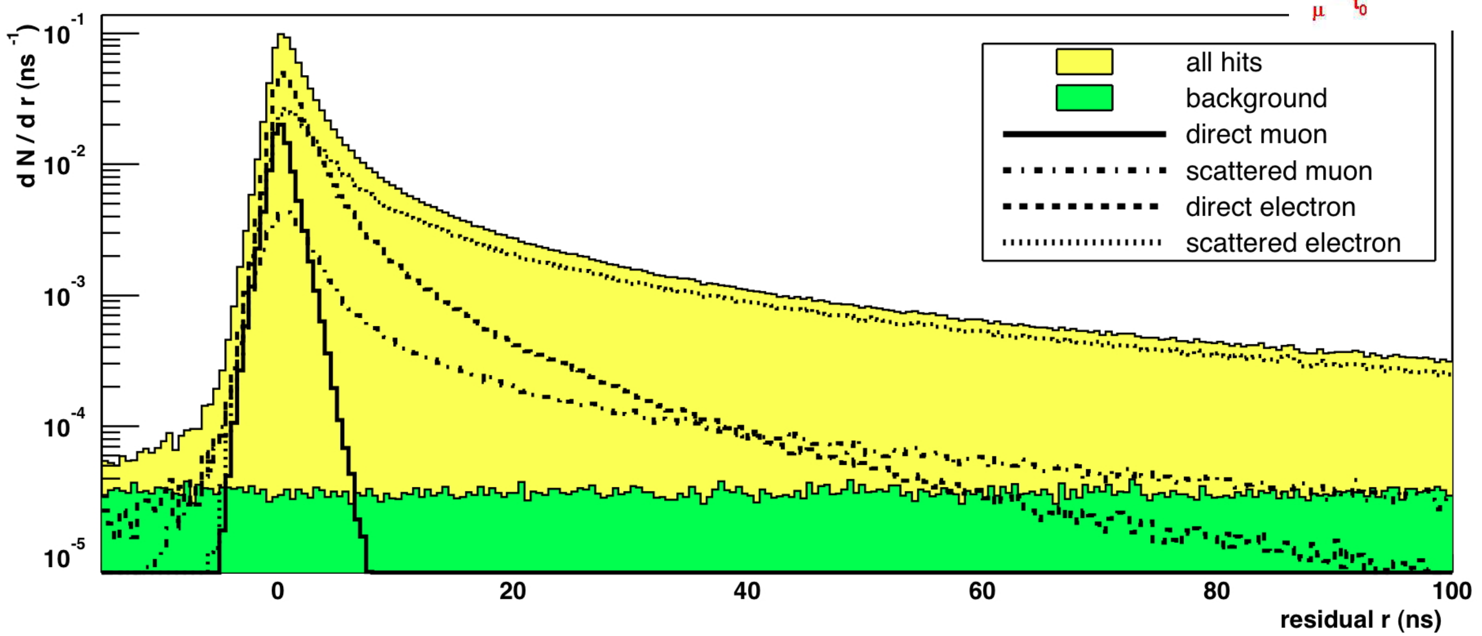
To obtain the 5 parameters we minimize

$$\Delta t_{res} = t_{teorico} - t_{\exp}$$

Time residual

- Time residual $\Delta t = t_{ph} - t_{cerenkov}^{teo}$

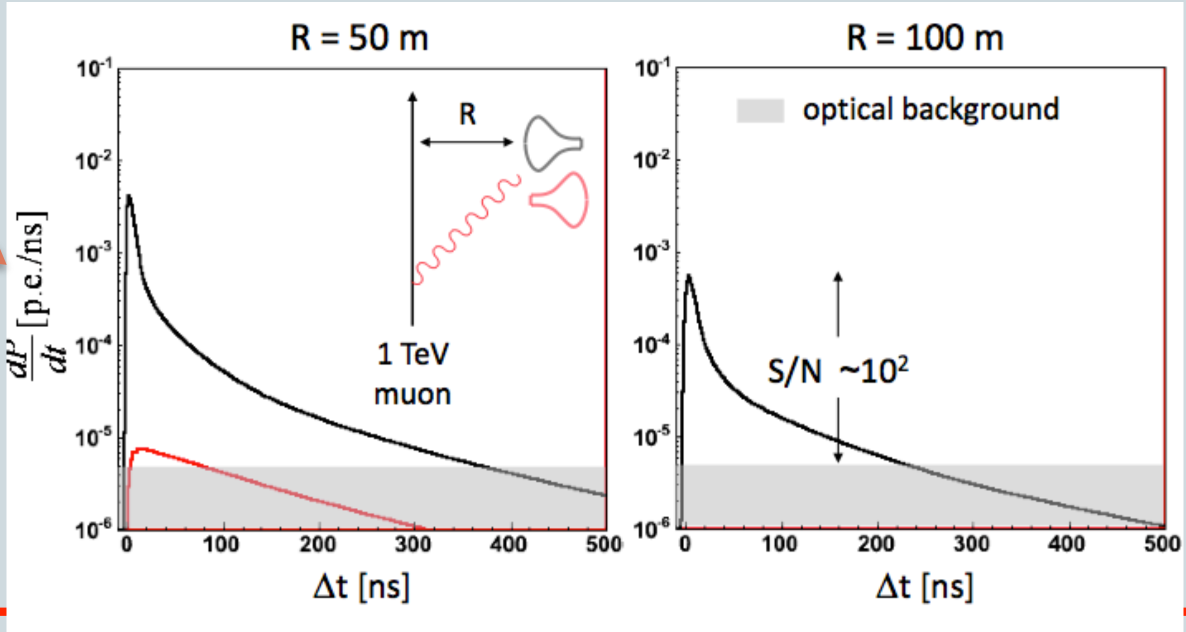




Muon track reconstruction in KM3NeT

- Code for Multi-PMT based on:
  - hit selection
  - likelihood function maxmization. Likelihood based on Probability Density Function (PDF)

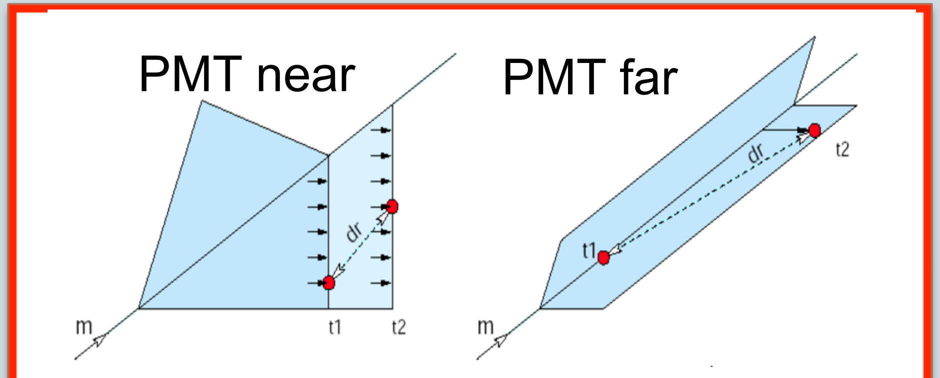
Estimate the track direction looking for the track direction that maximize the probability. The PDF is estimated parameterizing the MC expectation. Some attempts to evaluate analytically the PDF



Muon track reconstruction in KM3NeT

- Hit selection

The causality filter to remove hits due to 40K



$$|\Delta t| - \frac{\Delta r}{v} < 20ns \quad \&\& \quad \left| |\Delta t| - \frac{\Delta r}{c} \right| < 500ns$$

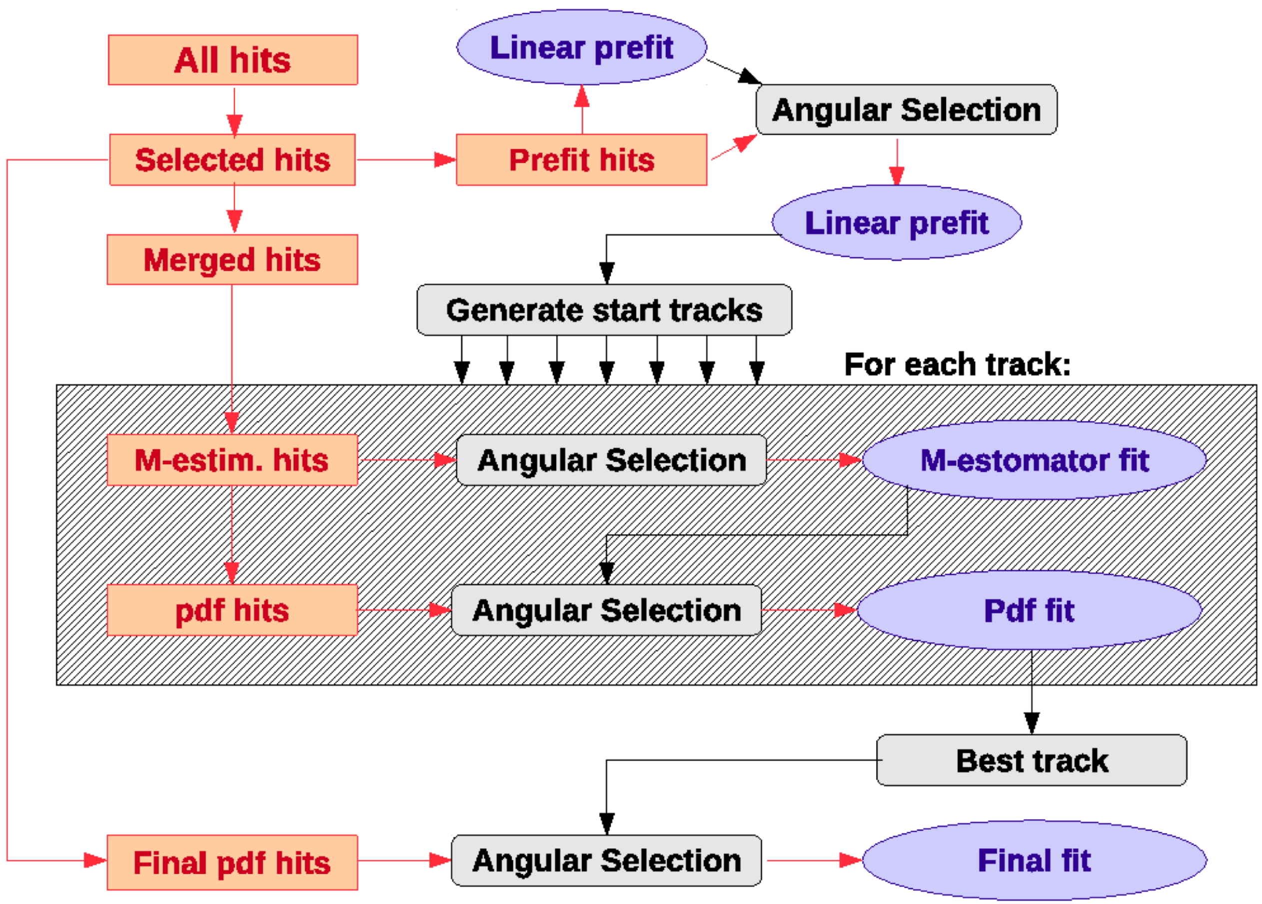
A hit "seed" is needed

Light velocity in water

Several fit steps performed: Prefit + 3 different fits
For each intermediate track a further hit selection is performed:
- Time-residual
- Angle of photons w.r.t. the PMT axis

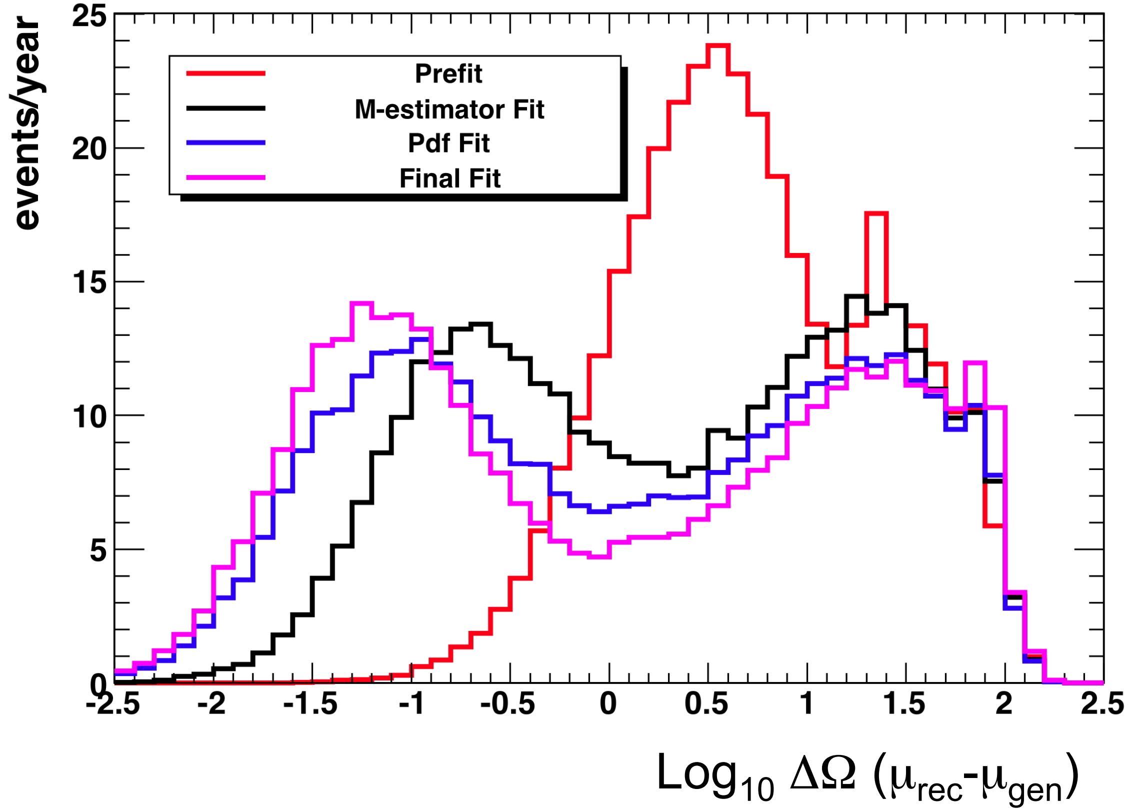
Muon track reconstruction in KM3NeT

Code optimized for high energy muon tracks



The angular resolution

Angular resolution at the different steps in the reconstruction code



The muon track reconstruction in KM3NeT

- Inputs
  - Events (hit_raw) and file with the detector geometry
  - File with parameters "hard coded" (threshold, coincidence levels...)
- Outputs
  - Track versors and pseudo vertice coordinates of the final track
  - Few tracks compatible with the last track
  - Parameter errors
  - For each track a Λ parameter (related to the reconstruction quality)

$$\boxed{\Lambda = \frac{-\log(L)}{nfit-5} + 0.1\cdot(n_{comp}-1)}$$

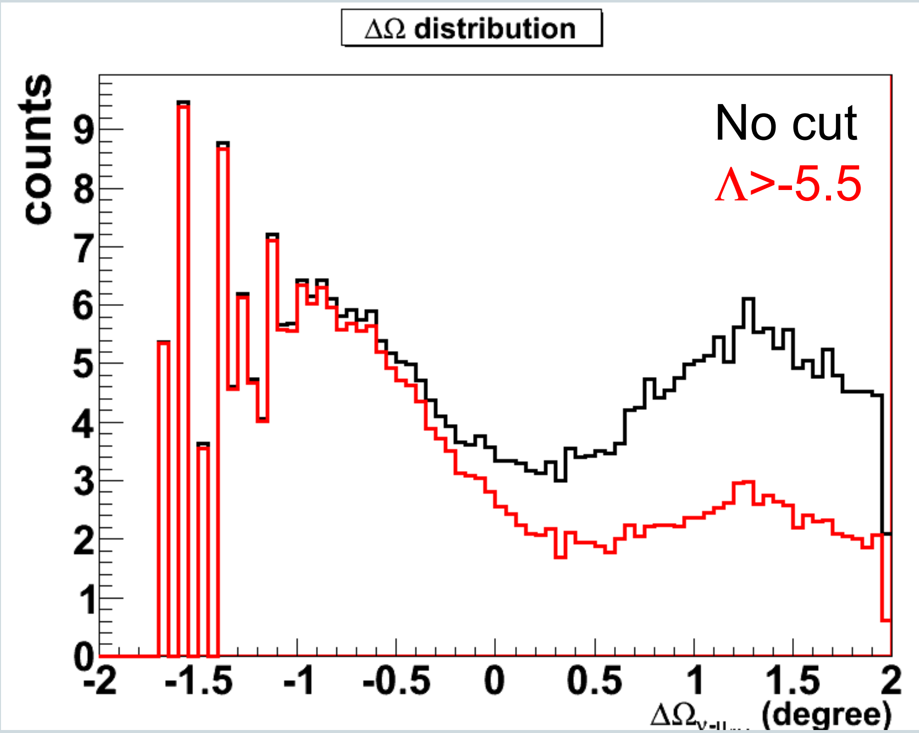
Cut on the Λ parameter rejects badly reconstructed tracks

Number of compatible tracks

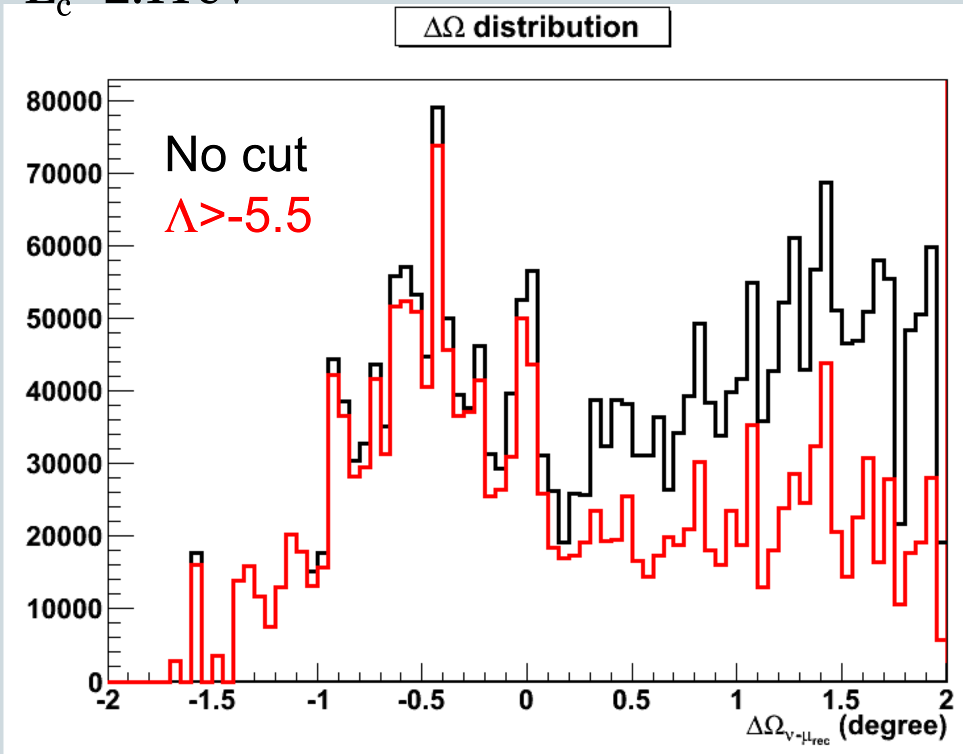
Number di hits in the final fit

Angular resolution

Source with spectrum E^{-2}

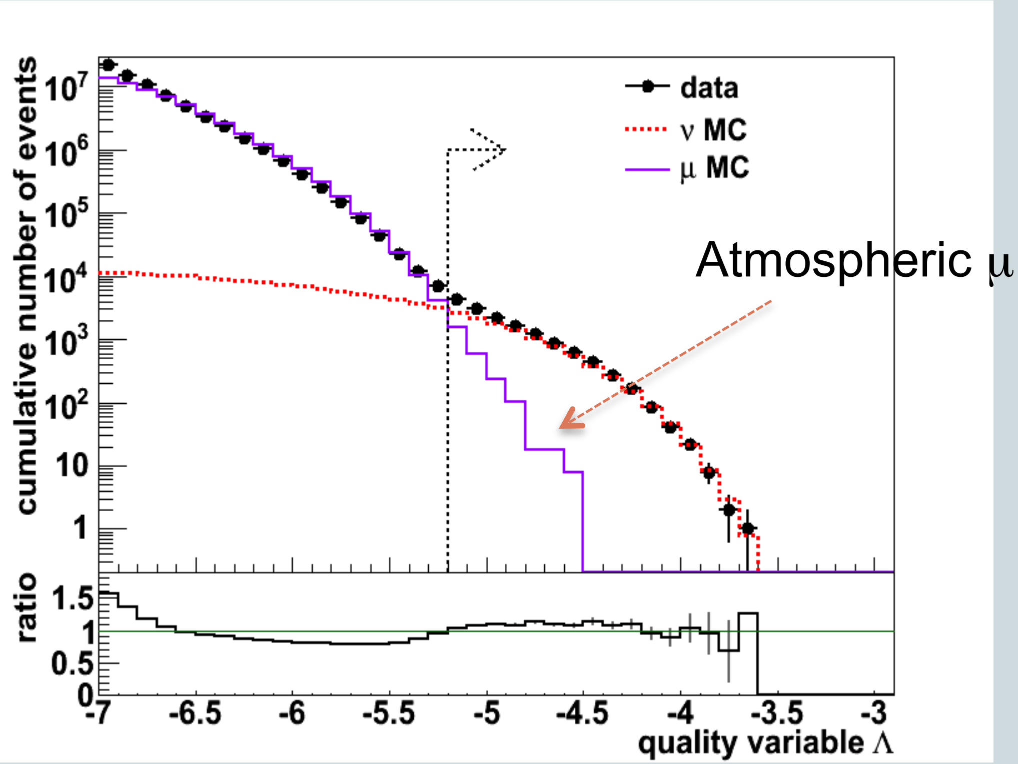


Source with spectrum E^{-2} exp-E/E_c with E_c=2.1TeV



Λ cut

up-going tracks



Atmospheric μ badly reconstructed

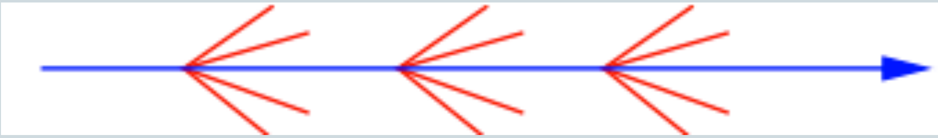
Energy reconstruction

- Based on the following relation

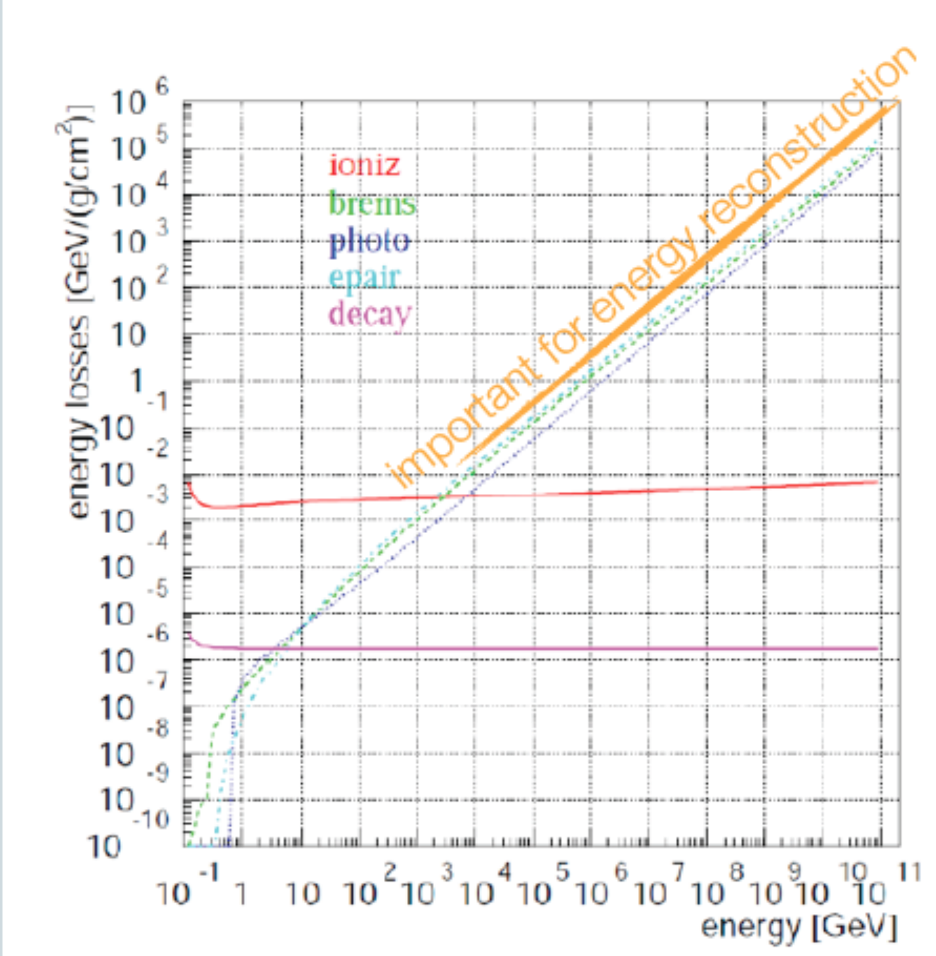
$$-\frac{dE}{dx} = a(E) + b(E)E$$

Almost constant energy loss for ionization

Stochastic energy loss above 1 TeV



- The muon energy is correlated to:
  - Number of hits per length unit
  - Total charge
  - Photon distribution
- The energy reconstruction codes need:
  - Reconstructed muon track
  - Already selected hits (no 40K hits)



Muon energy reconstruction

- Different algorithms based on different techniques (E_μ>10TeV):
  - Number of hits or Nhit/PMT (proportional to the total number of photons emitted)
  - Charge per track length

$$\boxed{\left\langle \frac{dE}{dx} \right\rangle \approx \rho = \frac{1}{L_{\det}} \frac{\sum A}{p_{acc}}}$$

A charge of the hit
L_{det} track length inside the can
P_{acc} detector acceptance

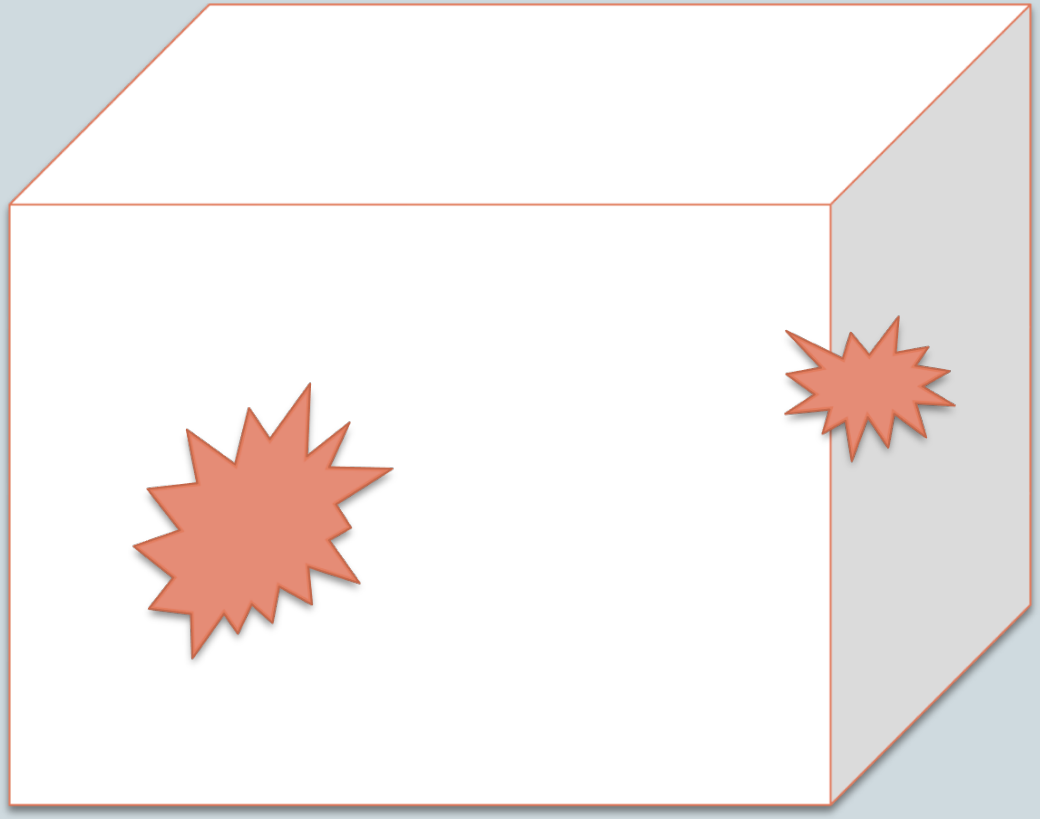
  - Neural networks (PDF used) PDF estimated using number of hits, positions, charge, time in the learning phase
  - Maximization of the likelihood (analytical PDF)

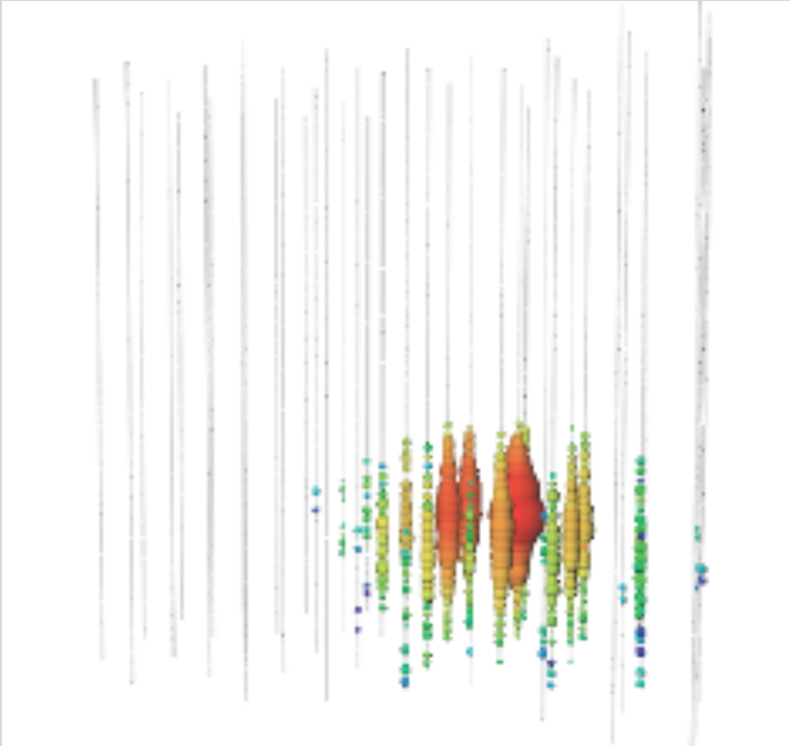
Uncertainty in the reconstructed energy 25% (at high energy) and 40% in log10 (ΔE) for E_μ>10TeV (up-going tracks)

- In IceCube maxmization of likelihood. The PDF from a model that takes into account the ice structure

Risolution between ≈1% for E_μ>1PeV and 40% in log10(ΔE) for E_μ>20GeV

Cascade events

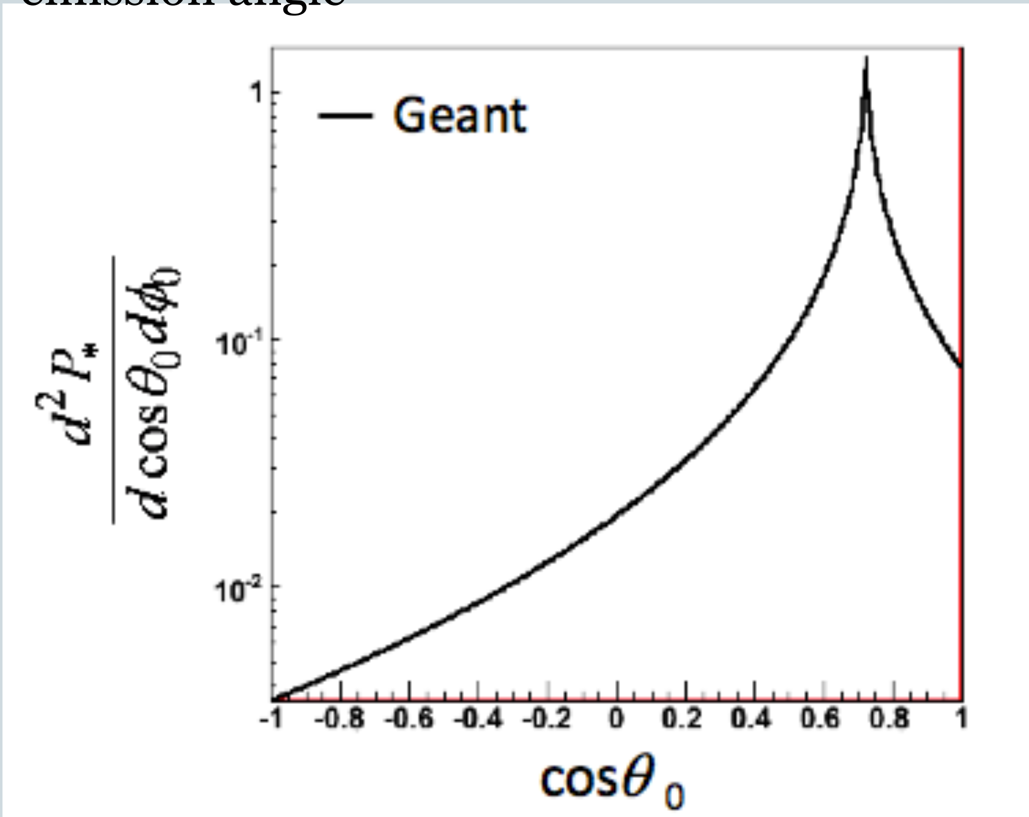




Cascade reconstruction

- Important for the detection of ν_e

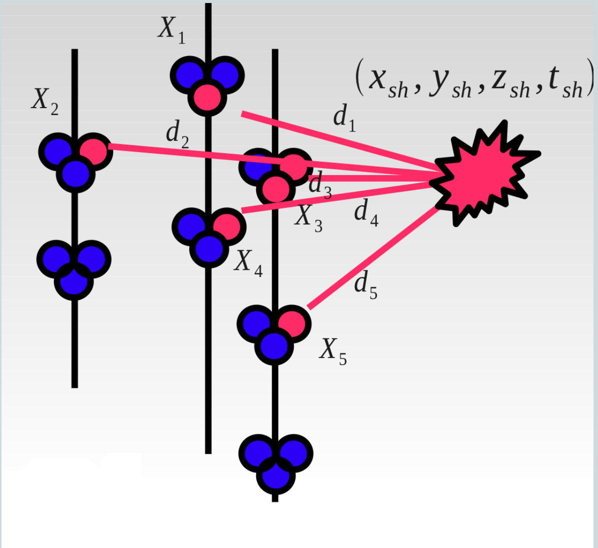
Number of e.m. photons as a function of the emission angle



- All the energy inside a small volume -> most of the light inside the detector

Shower reconstruction

- Vertex reconstruction

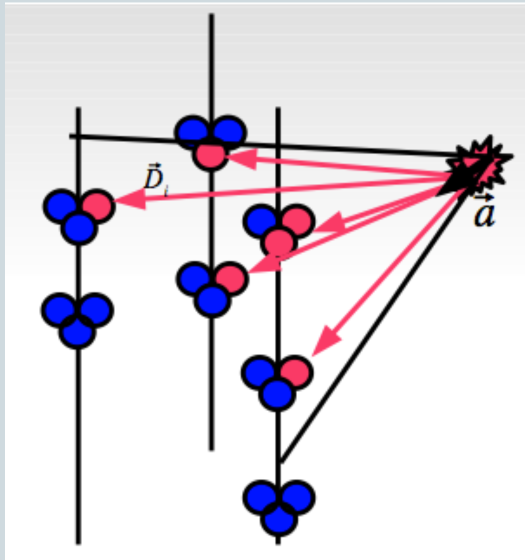


Based on the space-time relation

$$\Delta t^i_{res} = t^i_{\exp} - t^i_{th} = t^i_{\exp} - (t_{sh} + n / cd_i) = 0$$

Uncertainty on the vertex reconstruction < 5m

- Direction reconstruction



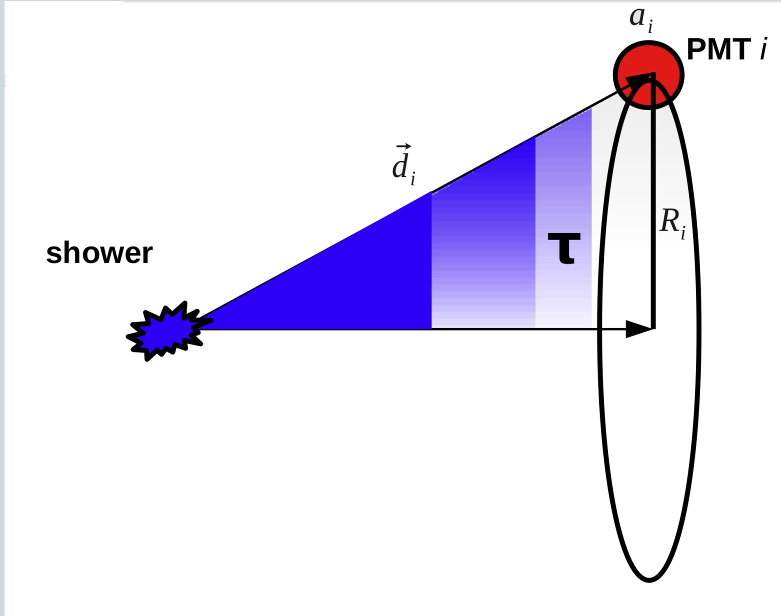
Based on the relation

$$\vec{D}_{tot} = \frac{1}{N_{hits} - 1} \sum_{i=1}^{N_{hits}-1} \vec{D}_i$$

Uncertainty in the direction reconstruction < 10°

Cascade energy reconstruction

- Energy reconstruction



Based on the relation:

$$A[pe] = \sum_{i=1}^{N} a_i R_i \exp(d_i / \tau)$$

τabsorption length
a_i amplitude of the hits

Uncertainty in the energy reconstruction of $\log(E_{shower})<0.36$

The reco output


```
hit_raw: 1607    64113         1.73    -1182.72
hit_raw: 1608    64114         0.76     3221.20
hit_raw: 1609    64116         1.12     2436.70
hit_track_fit: 312 4 120 608 611 613
hit_track_fit: 313 8 50 121 191 288 293 463 606 613
hit_track_fit: 311 12 50 118 121 191 288 289 293 457 463 606 611 613
hit_track_fit: 314 10 50 118 121 191 289 293 457 463 606 613
more_fitinf: 313 6 0 0
more_fitinf: 311 6 0 0
more_fitinf: 314 0 0.999961 0.99996 0.999995 0 0 0 5.56945e-07 0.915147
neutrino: 1    177.116   -623.566      1.810 -0.711810  0.578722 -0.398005   0.291644E+03   0.0   0.317103   0.102748   -1   14    2
total_hits: 1609
track_earthlepton: 1    177.116   -623.566      1.810 -0.713400  0.585813 -0.384558   0.261678E+03      0.0   6
track_fit:  1000 -413.19 -139.119 -314.757 -0.713914 0.587038 -0.381724 0.460143 2749.72 1 0 1.91726 0 3
track_fit:  1001 -420.639 -132.994 -318.74 -0.713914 0.587038 -0.381724 2.04405 2784.53 1 8.51688 1.91726 11.5228 3
track_fit:  1002 -420.639 -132.994 -318.74 -0.713914 0.587038 -0.381724 2.04405 2784.53 1 8.51688 1.91726 11.5228 3
track_fit:  312 -306.968 -223.137 -244.238 -0.710385 0.585987 -0.389837 0 2324.68 74714.2 0 0 0 0
track_fit:  313 179.151 -622.546 -1.13179 -0.718044 0.583906 -0.37877 0 0 11.0326 0 4.07466 0 0
track_fit:  311 179.103 -622.888 -0.153263 -0.717825 0.583446 -0.379892 0 0 -990.8 0 3.35908 0 0
track_fit:  314 175.322 -623.041 -0.0841091 -0.713914 0.587038 -0.381724 -9999 0 45.9647 10 0 0 0
track_fitter: 312 -306.968 -223.137 -244.238 1.97125 2.45186 0 0 37704.2 25655.4 11354.7 74714.2 0
track_fitter: 313 179.151 -622.546 -1.13179 1.95926 2.45886 0.740392 1.37512 1.02786 0.00254529 0.00293301 11.0326 3.49563
track_fitter: 311 179.103 -622.888 -0.153263 1.96048 2.4591 0.768795 0.915929 0.529006 0.00149109 0.00227426 -990.8 1.70983
track_fitter: 314 175.322 -623.041 -0.0841091 1.96246 2.45341 2.97548 3.89709 1.6335 0.00413976 0.0105666 45.9647 26.7092
```

Lay-out

- Introduction
  - The neutrino telescope
- Detection principle
  - The detection principle
  - Backgrounds
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- On the performance of the telescope: relevant quantities
  - Effective neutrino area
  - Sensitivity and discovery potential

The effective neutrino area
Only from MC

The effective neutrino area

- Given a source flux the expected number of event in the detector can be calculated:

$$N_\mu = \iint A_{eff}^{\nu}(E_\nu, \theta_\nu) \cdot T \cdot \frac{d\phi_\nu}{dE_\nu d\theta_\nu}$$

Numero di events at the detector

Observation time

Source spectrum

$$\begin{cases} \propto E_\nu^{-2} \\ \propto E_\nu^{-\gamma} \exp\left(-\frac{E_\nu}{E_c}\right) \end{cases}$$

Neutrino effective area

$$A_{eff}^{\nu}(\theta_\nu, E_\nu) = V_{eff}(\theta_\nu, E_\nu) \cdot (\rho N_A) \cdot \sigma(E_\nu) \cdot P_{earth}(\theta_\nu, E_\nu)$$

effective volume

Number of nucleons on the target

Neutrino cross section

Transmission Earth probability

The effective volume

$$V_{eff}^{\nu}(\theta_{\nu}, E_{\nu}) = \underbrace{\frac{N_{sel}(E_{\nu})}{N_{gen}(E_{\nu})}}_{\text{Detector efficiency}} V_{gen}$$

Generation volume

Number of selecte events

Number of generated events

Detector efficiency

WARNING: The neutrino effective area depends on the event selection : Es. Triggered events, reconstructed events, with the analysis cuts....

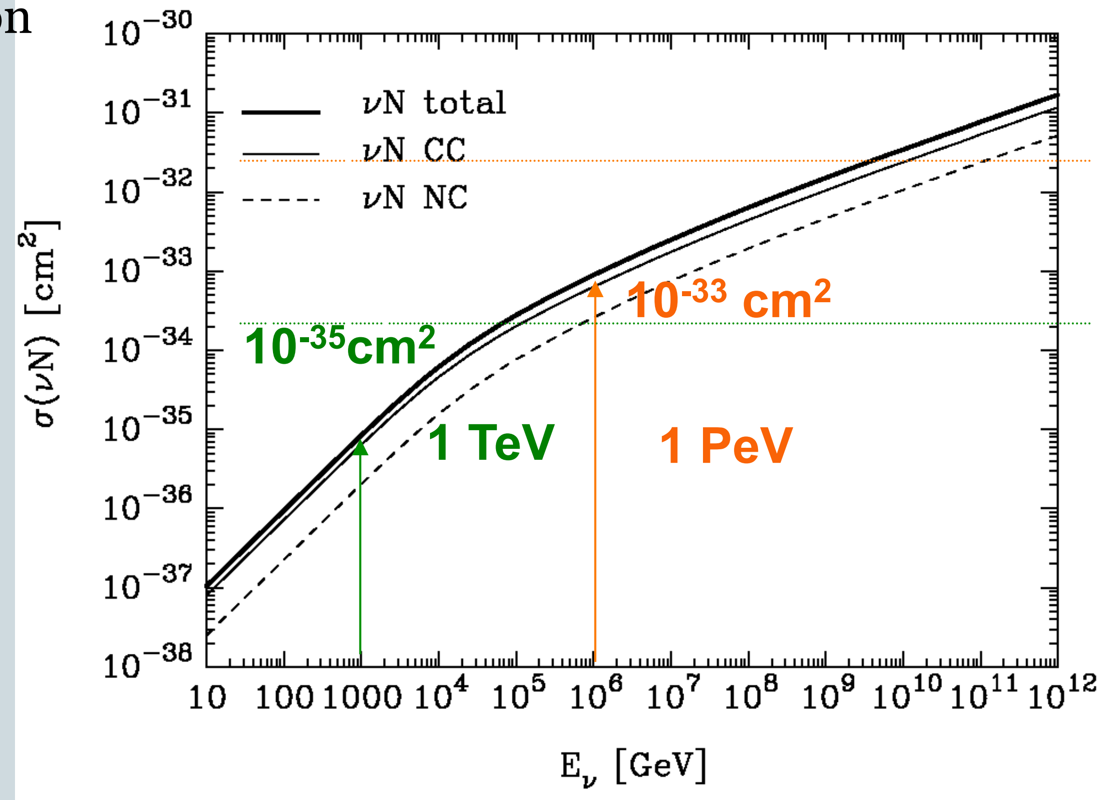
Hard to compare the performance of a detector comparing the effective area.

Neutrino cross section

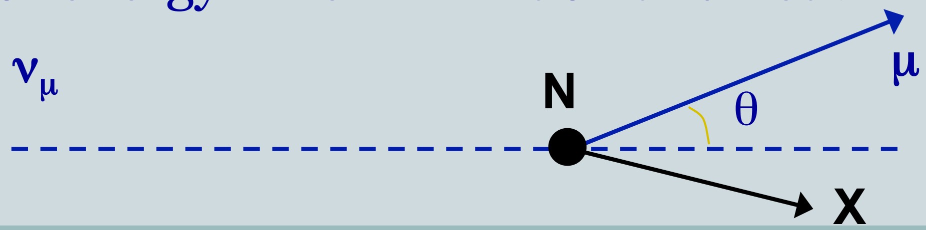
Mainly Deep Inelastic Scattering on nucleone N

$$\nu_\mu + N \rightarrow \mu + X$$

$$\sigma_{\nu N} \begin{cases} \propto E_\nu & E_\nu \leq 5\text{TeV} \\ \propto E_\nu^{0.4} & E_\nu > 5\text{TeV} \end{cases}$$



For energy >TeV -> muon and neutrino collinear

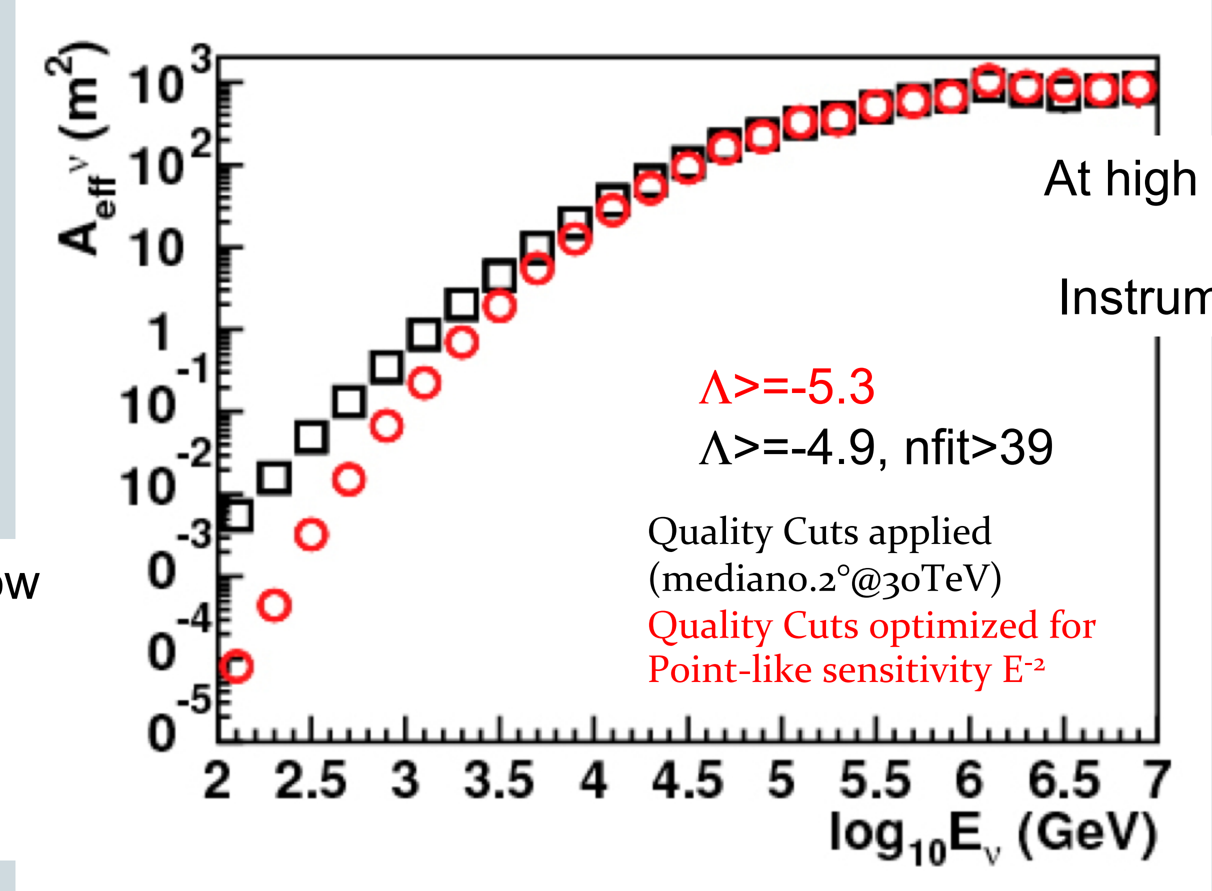


$$\langle\theta\rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu[\text{TeV}]}}$$

Effective neutrino area

- Effective neutrino area ofr KM3NeT

(TDR http://www.km3net.org/KM3NeT-TDR.pdf)

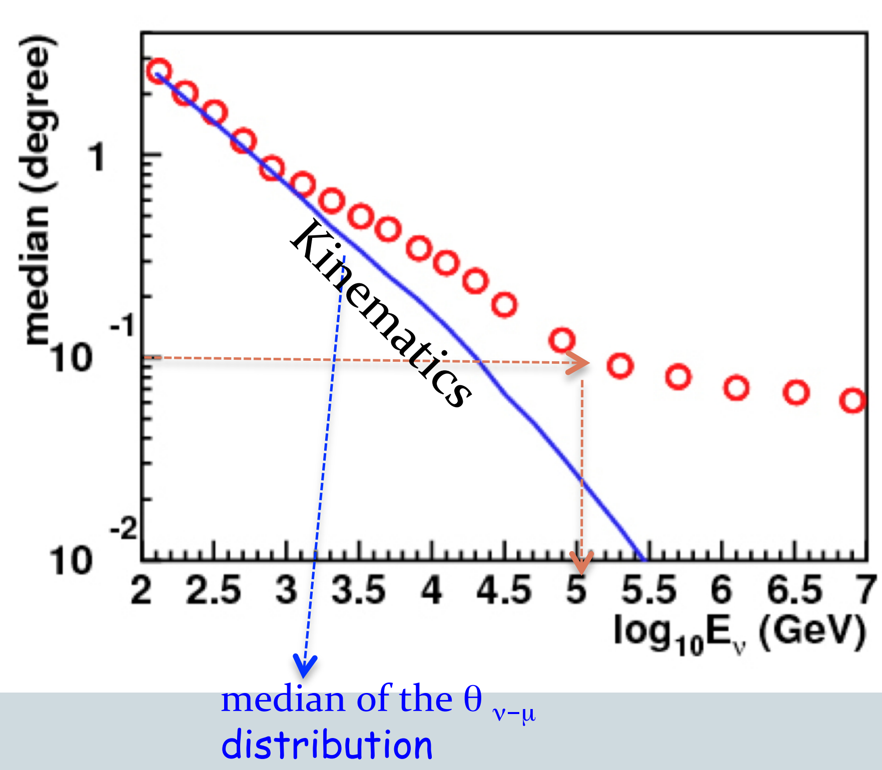


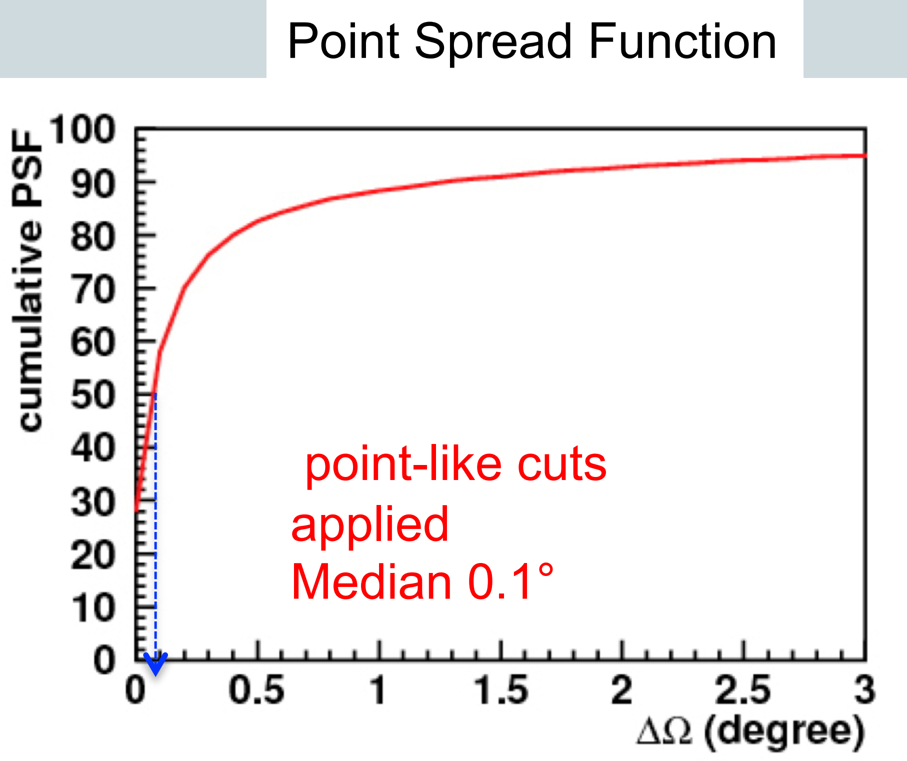
At high energy ⇩ Instrumented volume

Region at low energy ⇩ "Density" of PMTs

The angular resolution

- Angular resolution



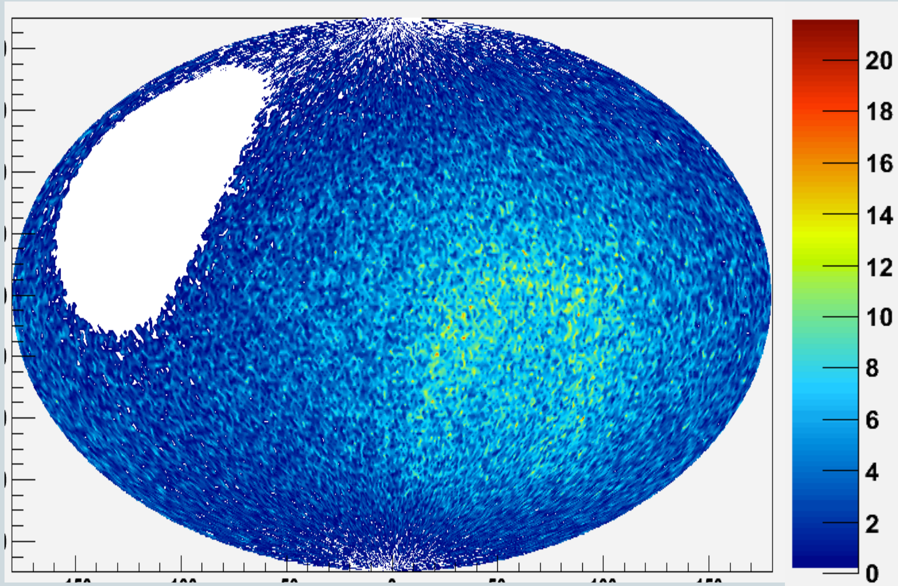


Source search

- MC after the reconstruction
  - θ,ϕ,T->δ,RA (equatorial coordinate)
  - θ,ϕ,T->b,l (galactic coordinate)

  T random

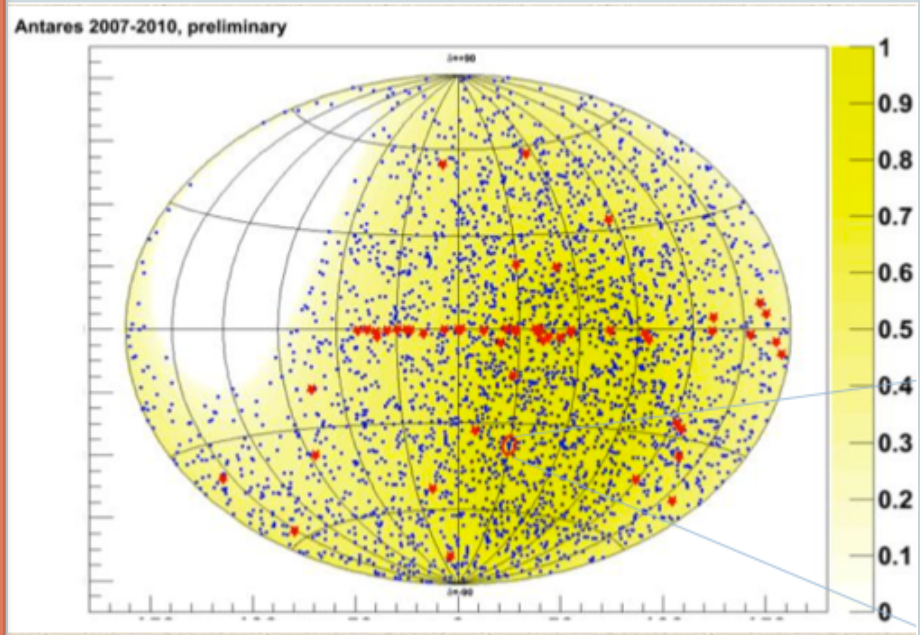
Events up-going with the cuts



- Dati after the reconstruction
  - θ,ϕ,T->δ,RA (equatorial cooridnate)
  - θ,ϕ,T->b,l (galactic coordinate)

  T absolute time of the events

Events up-going with the cuts



Source search

Search of events of neutrinos from an astrophysics source

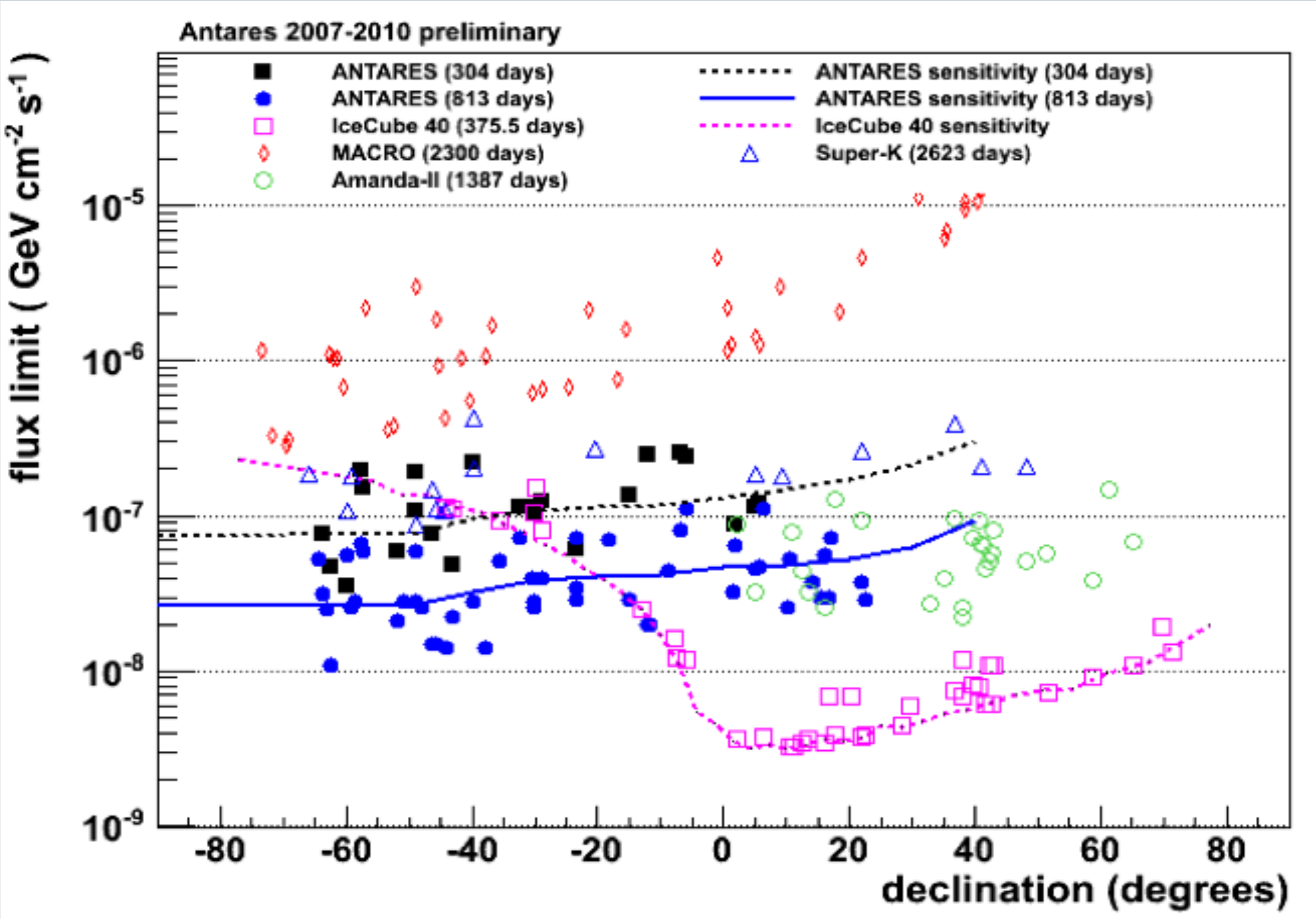
- Statistical methods applied
  - Binned method
    - Full sky search : the sky is divided in bins and in each bin an excess of events is searched.
    - Point search: for a fixed declination (known candidate source) an excess of events is searched around the known declination
  - Unbinned method
    - Full sky search: search on the full sky cluster of events and a comparison between the probabilities to have a signal or background are compared
    - Point search: around the fixed declination (known source) a comparison between the probabilities to have a signal or background are compared

Sensitivity and discovery potential

DEFINITIONS

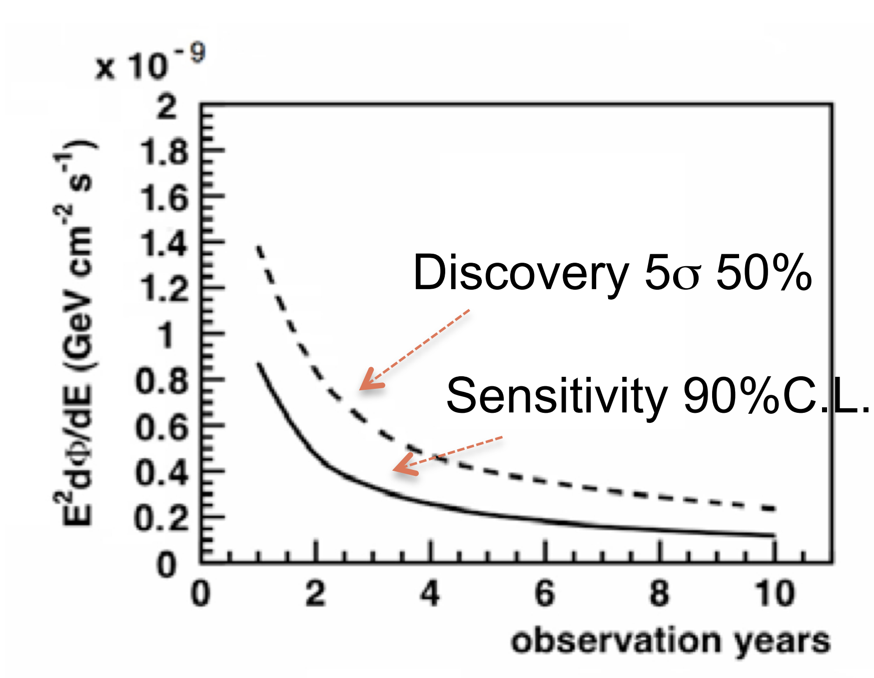
- Sensitivity: is the average upper flux limit one would get from an ensemble of experiments with the expected background and no true signal (theoretical models can be discarded if above the flux limit)
- Discovery potential: source flux required to observe, with a fixed probability, a certain number of events with a fixed value of significance above a background.
- A source can be declared "discovered" if a certain number of events are detected with a significance of 5σ above the estimated background.

Sensitivity



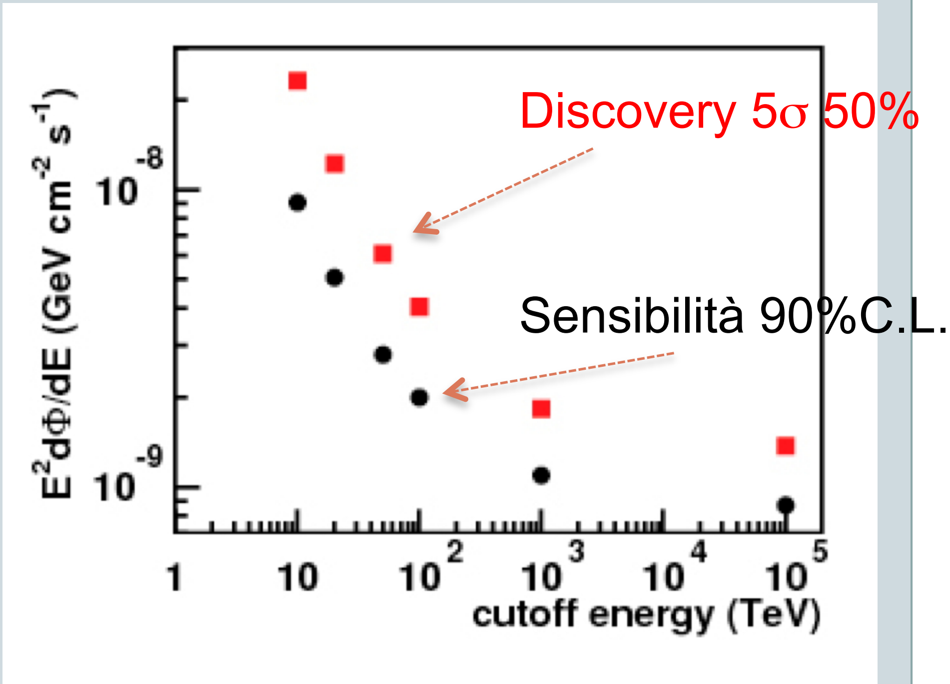
Discovery and sensitivity for KM3NeT

- As a function of the observation time



Point-like δ=-60° E^{-2}

- As a function of the cutoff



Point-like δ=-60° $E^{-2}\exp(-E/E_c)$

No conclusion……. only

thank you for the attention