Physics Laboratory
School of Science and Technology
Hellenic Open University

KM3NeT
Opens a new window on our universe

Reconstruction efficiency and discovery potential of a Mediterranean neutrino telescope: A simulation study using the Hellenic Open University Simulation & Reconstruction (HOURS) package

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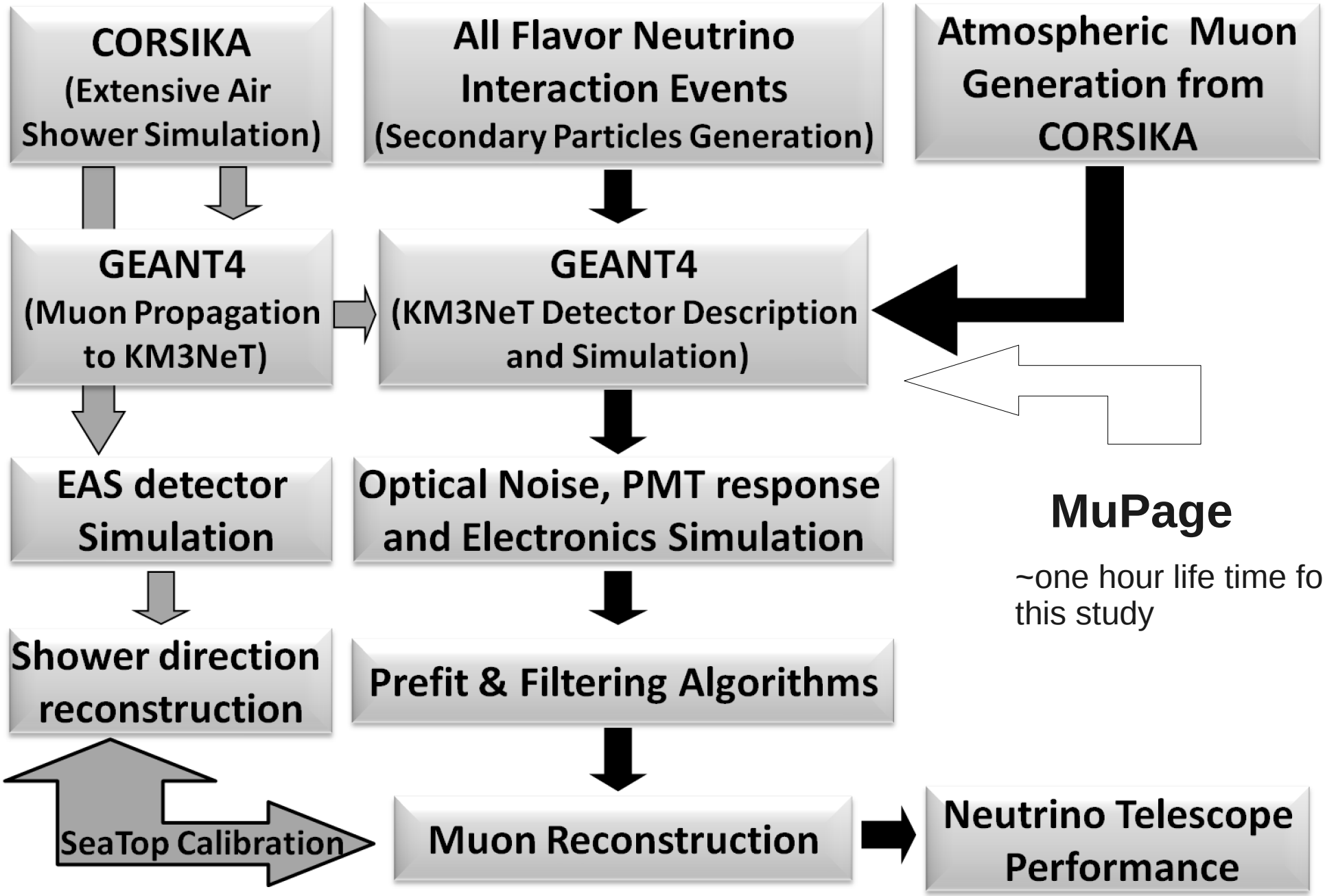
Physics Laboratory
H.O.U

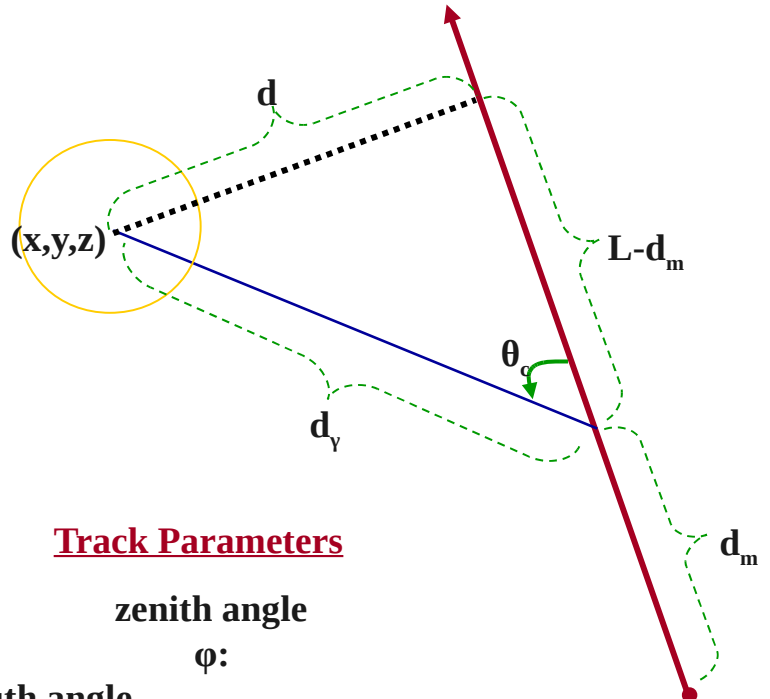
- The HOU Reconstruction & Simulation (HOURS) software package
- New tool developments
  - Advances in track reconstruction and error estimation combining Kalman Filter with a Likelihood
- Neutrino Detector performance
  - Sensitivity and discovery potential for point sources
    - Point sources discovery improvements
  - Signal from Gamma Ray Bursts & Diffuse flux sensitivity

Simulation software chain



- Prefit and Filtering based on:
  - Optical Module Hit clustering (causality) filter & clustering of candidate track segments (no apriori knowledge of the neutrino source)
  - Causality filter using the apriori known direction of the neutrino source (talk “A reconstruction method for neutrino induced muon tracks taking into account the apriori knowledge of the neutrino source” by A. Tsirigotis)

- Muon reconstruction algorithms
  - Combination of χ^2 fit and Kalman Filter is used to produce many candidate tracks
  - The best candidate is chosen using the Multi-PMT Direction and arrival time Likelihood (track quality criterion)
  - Muon energy reconstruction using the Charge Likelihood



Track Parameters

θ : zenith angle

φ: azimuth angle

(Vx,Vy,Vz): pseudo-vertex coordinates

A new tracking criterion based on the directional information offered by the Multi-PMT and the time residuals distributions

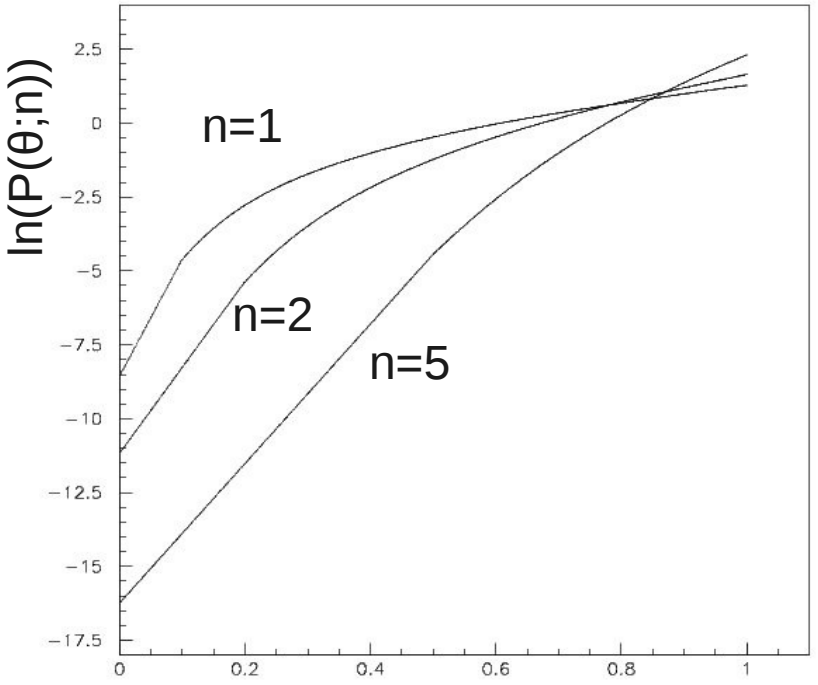
Multi-PMT direction Likelihood

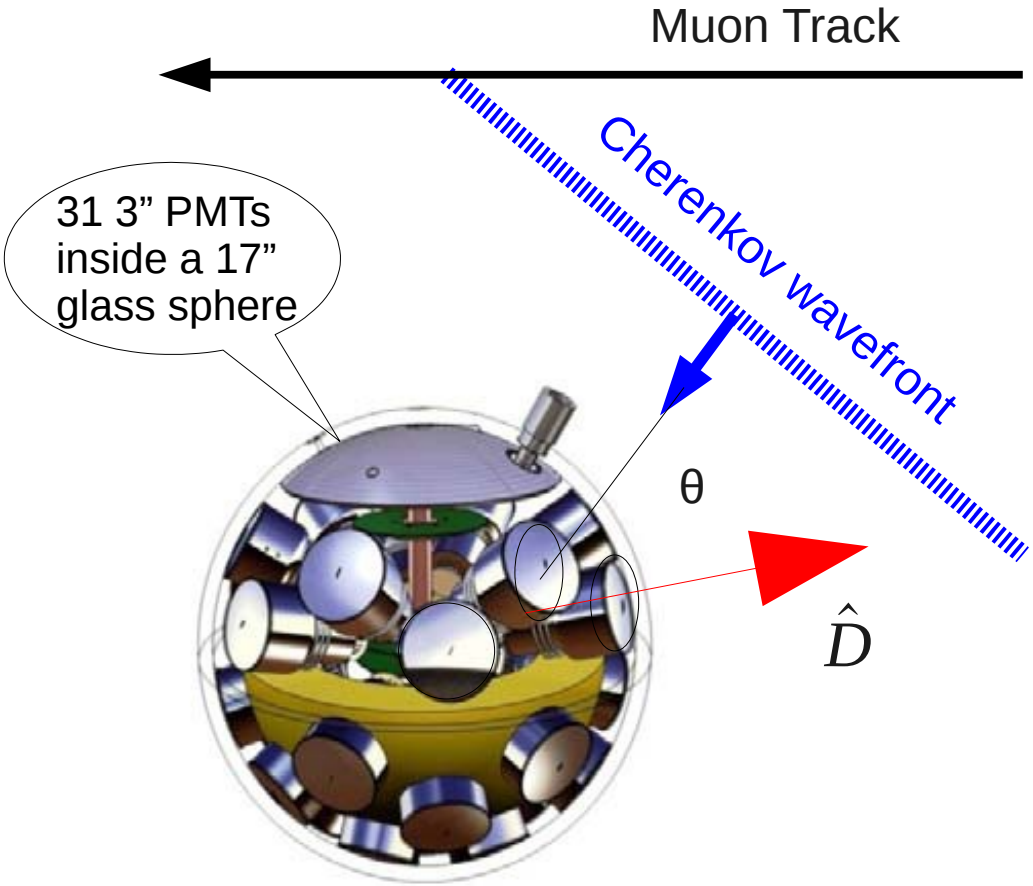
- **PDFs of the angle, θ, between the Ch wavefront direction and the active direction of the Multi-PMT**

$$PDF_{d,s}(\theta;n)$$

- **Separate parametrization for n=1,2,...18 active small pmts.**

- **For the parametrization only the angular acceptance and the directions of the small PMTs in the OM are used.**





Charge weighted averaged direction of active PMTs

$$\hat{D} = \sum_{i=1}^{N} q_i \hat{d}_i$$

The directionality criterion is used for the selection of the best track candidate.

Signal $PDF_{d,s,i}(\theta_i; n_i)$

Noise $PDF_{d,n} = constant$

- i=1,2,...N the active Multi-PMTs
- n_i=the number of active elements in the i^{th} Multi-PMT
- θ_i=the angle between the weighted average direction of the i^{th} active Multi-PMT with the reconstructed Cherenkov wavefront

For the selection of the best candidate track also the timing likelihood is used

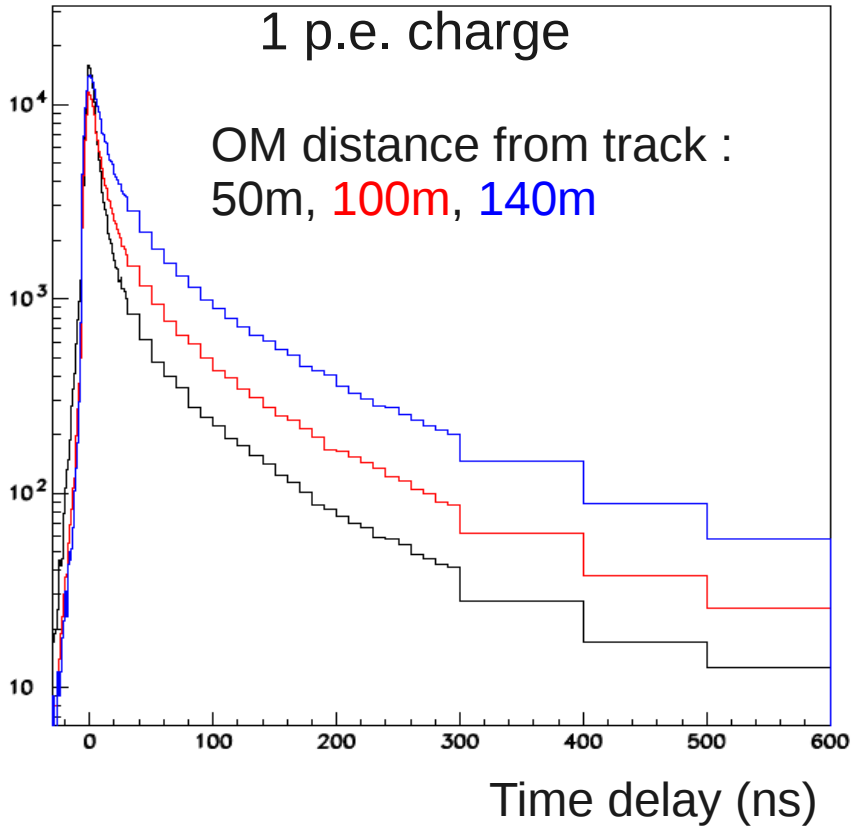
Signal $PDF_{t,s,i}(t_i - t_{exp}; q_i, d_i)$

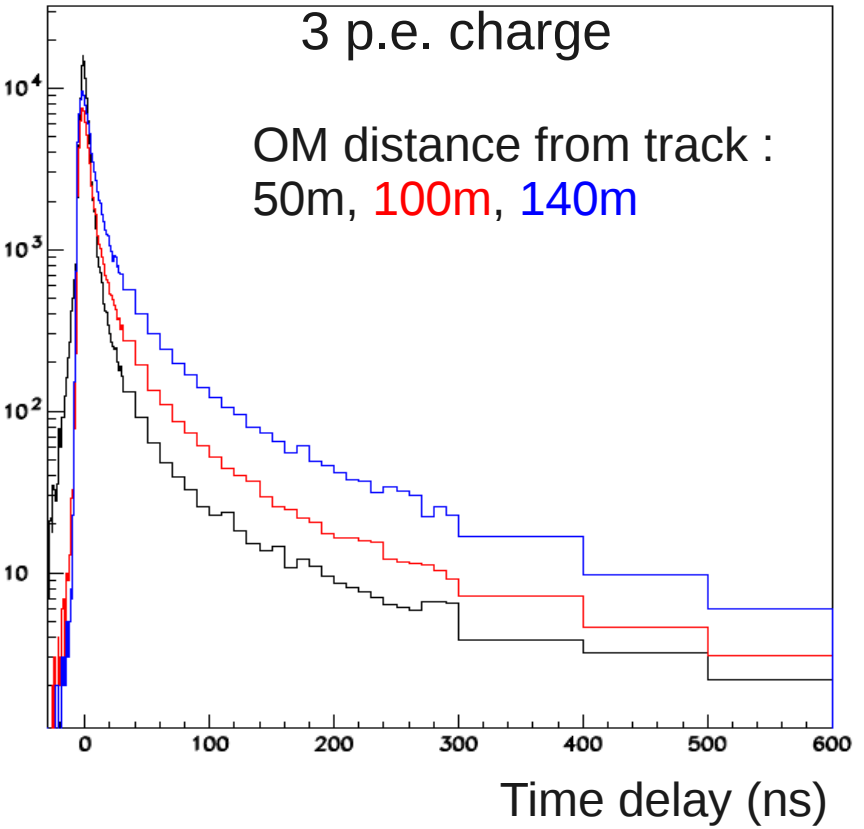
Noise $PDF_{t,n,i}(t_i - t_{exp}; d_i)$

t_i: hit arrival time,

t_{exp}:expected arrival time of direct photon

q_i: hit charge , d_i : Hit distance from track





- The timing PDFs depend on the filtering and prefit stage
- They are created for the hits that pass these stages

For all the candidate tracks form the direction*timing likelihood for all hits that pass the final filtering stage (common for all candidate tracks)

$$L_{total} = \prod [\, p_{n,i}(N_{hit}, q_i)\, PDF_{t,n,i}\, PDF_{d,n} + (1 - p_n(N_{hit}, q_i))\, PDF_{t,s,i}\, PDF_{d,s,i}]$$

$p_{n,i}(N_{hit}, q_i) \equiv$ Probability of a hit to be noise

Timing PDFs

Signal $PDF_{t,s,i}(t_i - t_{\exp}; q_i, d_i)$

Noise $PDF_{t,n,i}(t_i - t_{\exp}; d_i)$

Direction PDFs

Signal $PDF_{d,s,i}(\theta_i; n_i)$

Noise $PDF_{d,n} = constant$

- The candidate track with the largest Likelihood is chosen
- Maximize further the Likelihood for the chosen candidate track

Charge Likelihood – Used in muon energy estimation

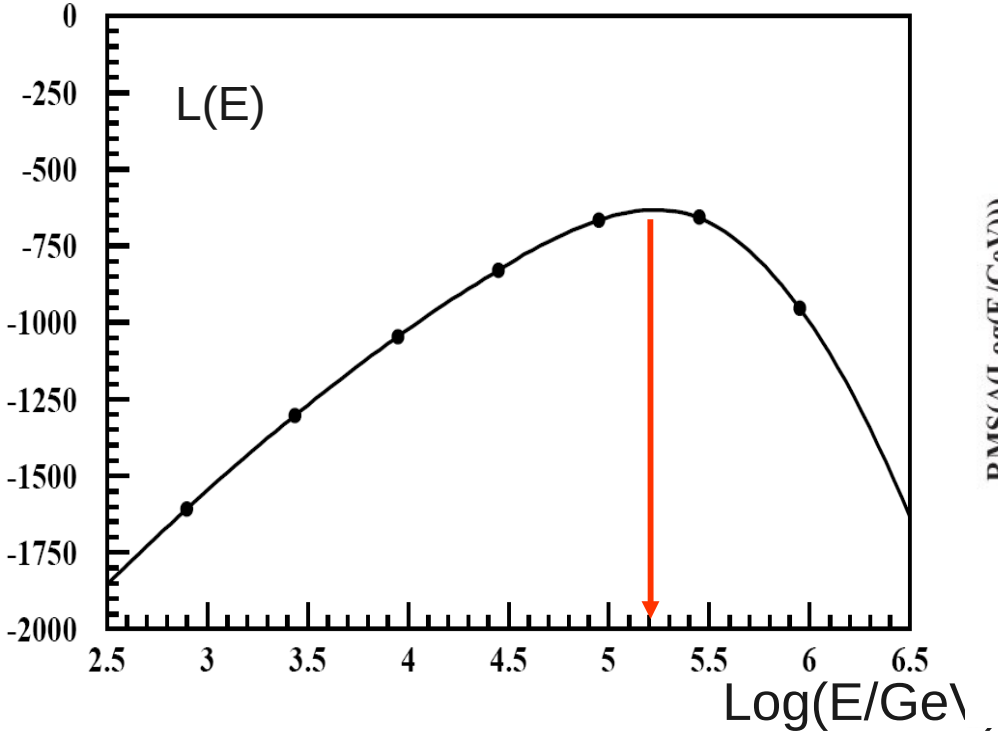
$$L(E)=\ln\left(\prod_{i=1}^{N_{hit}} P(V_{i,data};E,D,\theta)\prod_{i=1}^{N_{nohit}} P(0;E,D,\theta)\right) \qquad V_{i,data} \equiv \text{Hit charge in PEs}$$

Probability depends on muon energy, E, distance from track, D, and PMT orientation with respect to the Cherenkov wavefront:

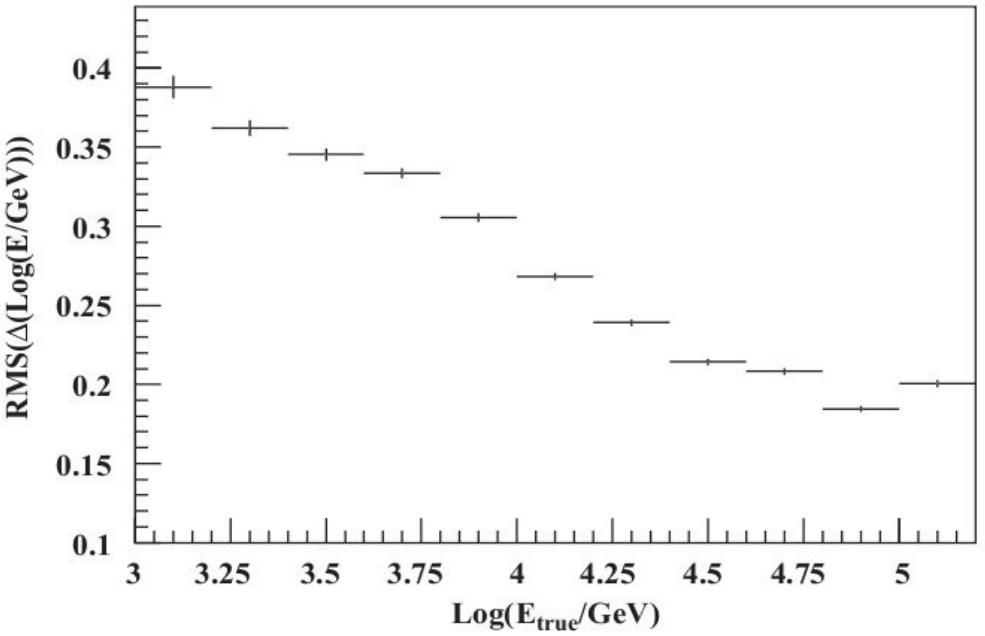
$$P(V_{i,data};E,D,\theta)=\sum_{n=1}^{\infty} F(n;E,D,\theta)\,G(V_{i,data};n,\sqrt{n}\,\sigma_{PMTresolution})$$

Convolution with the PMT charge response function (simplified model with Gaussian)

$F(n;E,D,\theta)$ Not a poisson distribution, due to discrete radiation processes

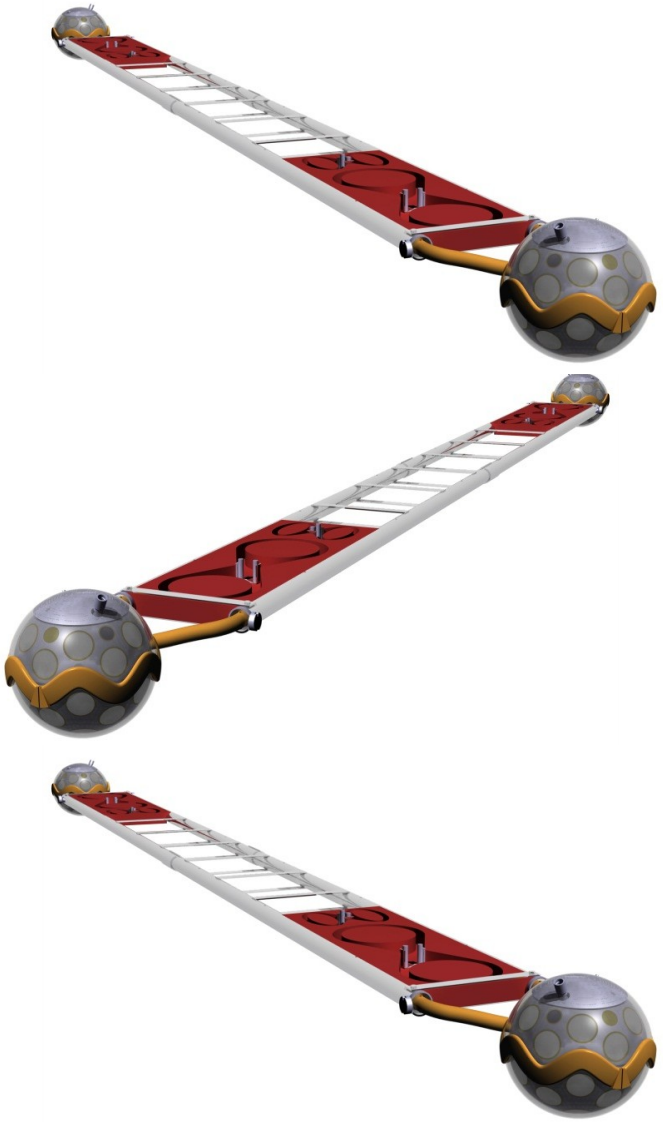


Muon energy estimation resolution

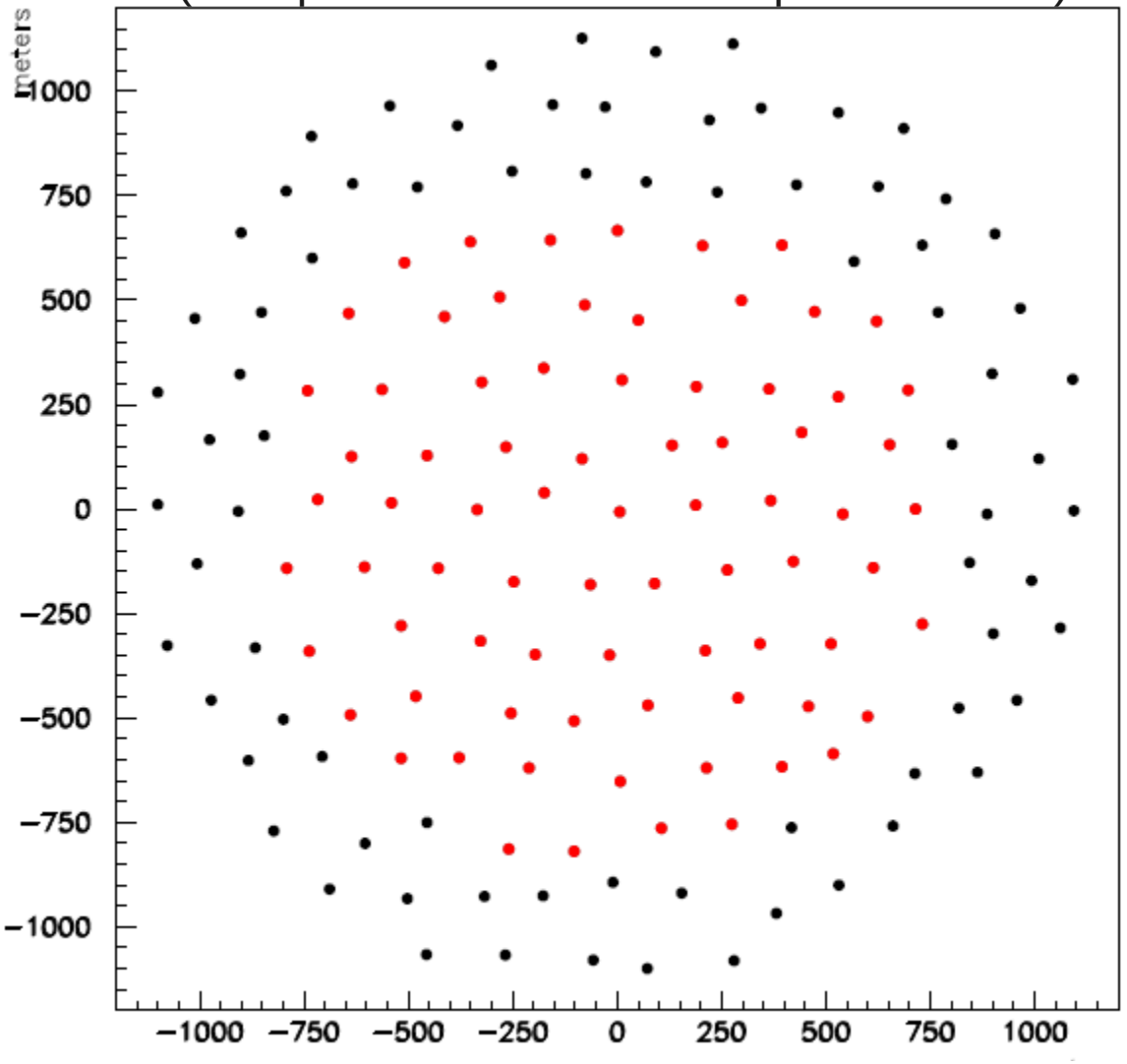


Simulated Detector Geometrical Layout

154 Towers (**Half KM3NeT detector**) with a mean distance 180m between them
Each Tower consists of 20 bars, 6m in length and 40m apart
One MultiPMT OM at each end of the bar.
Instrumented Volume ~ 2.9km^3



Detector Footprint
(not optimized for Galactic ν point sources)

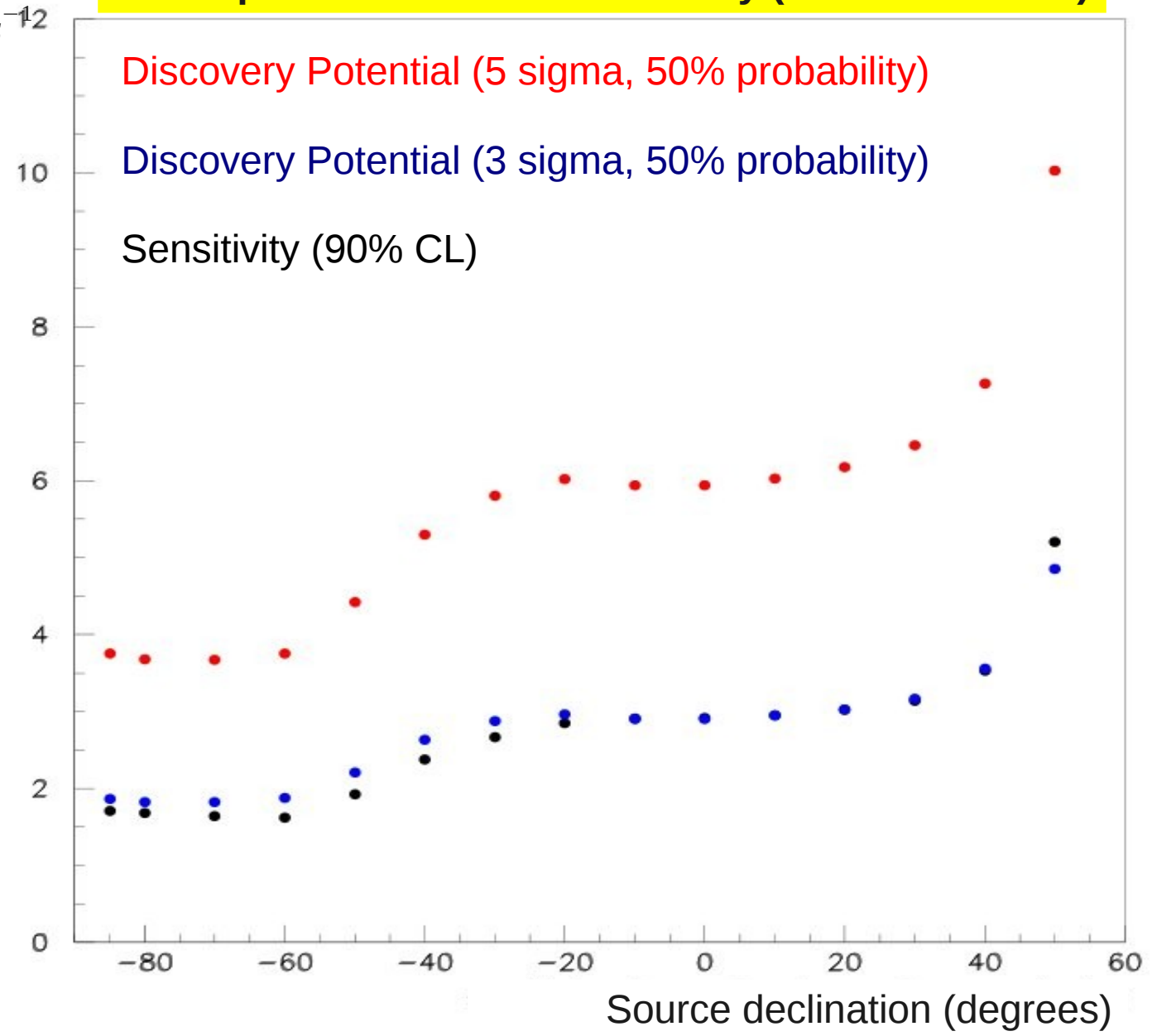


Sensitivity & Discovery Potential (**Half KM3NeT detector**)
1 year of data taking (point source with neutrino energy spectrum ~ E^{-2})

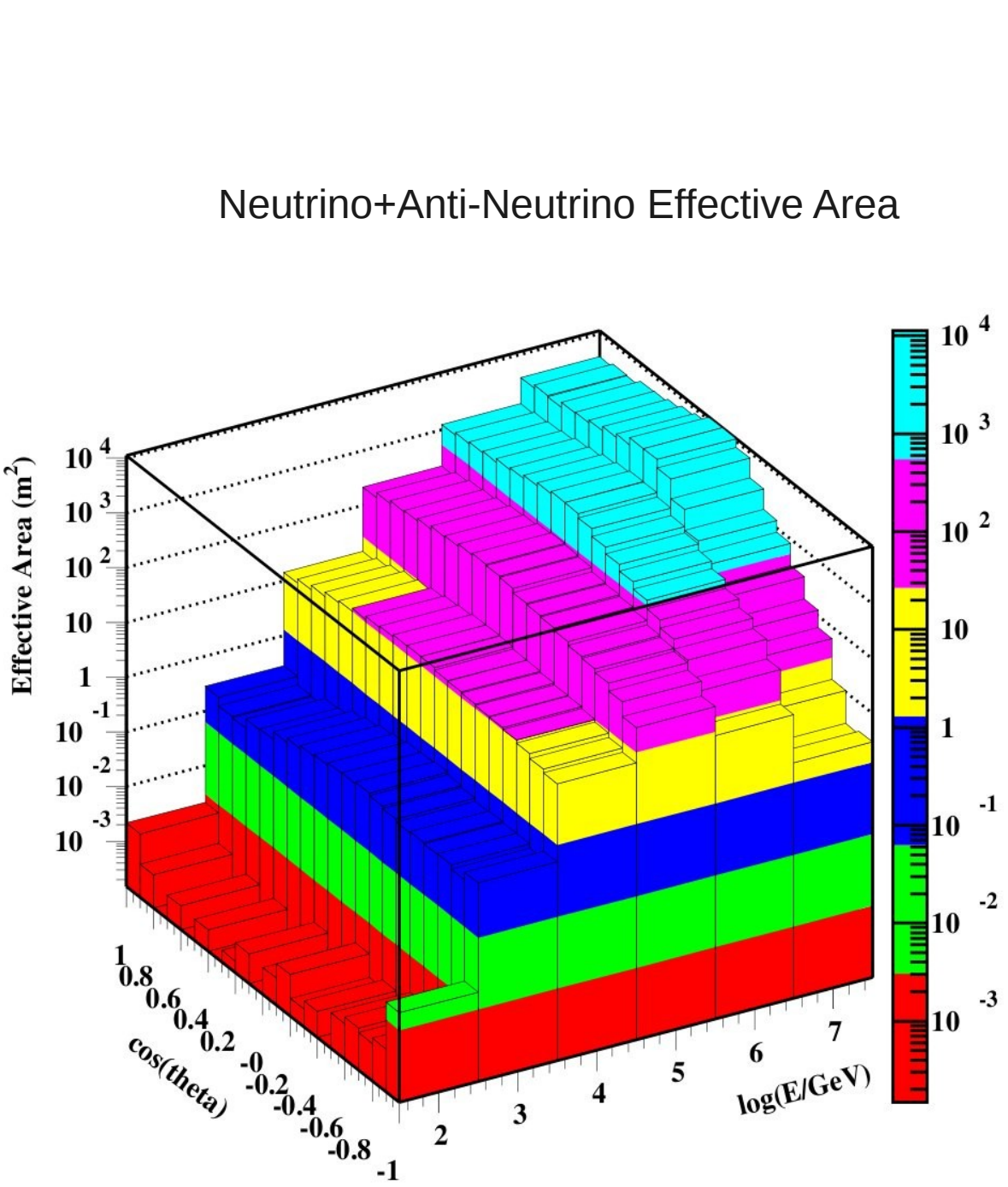
$x10^{-9} E^{-2} GeV^{-1} cm^{-2} s^{-1}$

dec	n_{bg}	n_s	sens	mdp3	mdp5
-85	0.30	1.58	1.71	1.86	3.75
-80	0.29	1.60	1.68	1.82	3.68
-70	0.33	1.66	1.64	1.83	3.67
-60	0.41	1.73	1.62	1.88	3.75
-50	0.39	1.45	1.92	2.21	4.42
-40	0.32	1.15	2.38	2.63	5.30
-30	0.28	1.01	2.67	2.88	5.81
-20	0.24	0.93	2.85	2.97	6.02
-10	0.20	0.90	2.91	2.90	5.94
0	0.20	0.90	2.92	2.90	5.94
10	0.20	0.89	2.95	2.95	6.03
20	0.20	0.87	3.02	3.02	6.18
30	0.21	0.84	3.14	3.16	6.46
40	0.21	0.74	3.53	3.56	7.26
50	0.15	0.49	5.21	4.85	10.03

Cuts optimized for best sensitivity (0.3125° bin size)



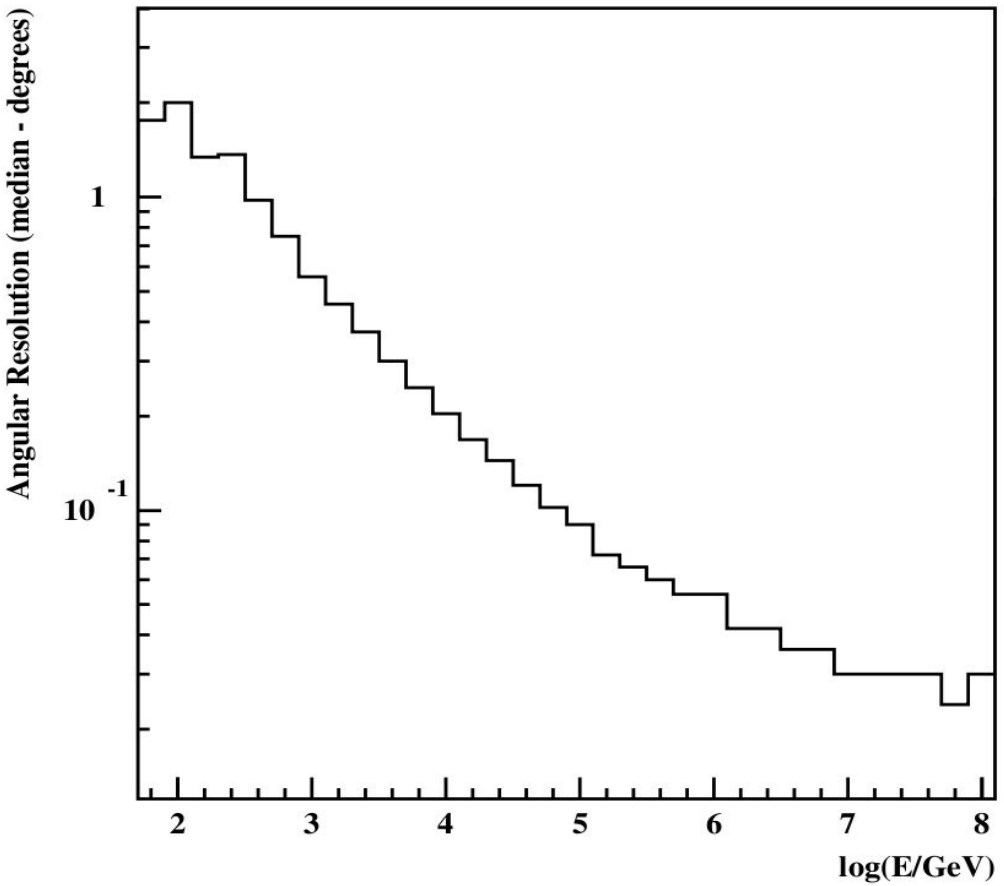
Neutrino Effective Area (**Half KM3NeT detector**)
Cuts for best sensitivity



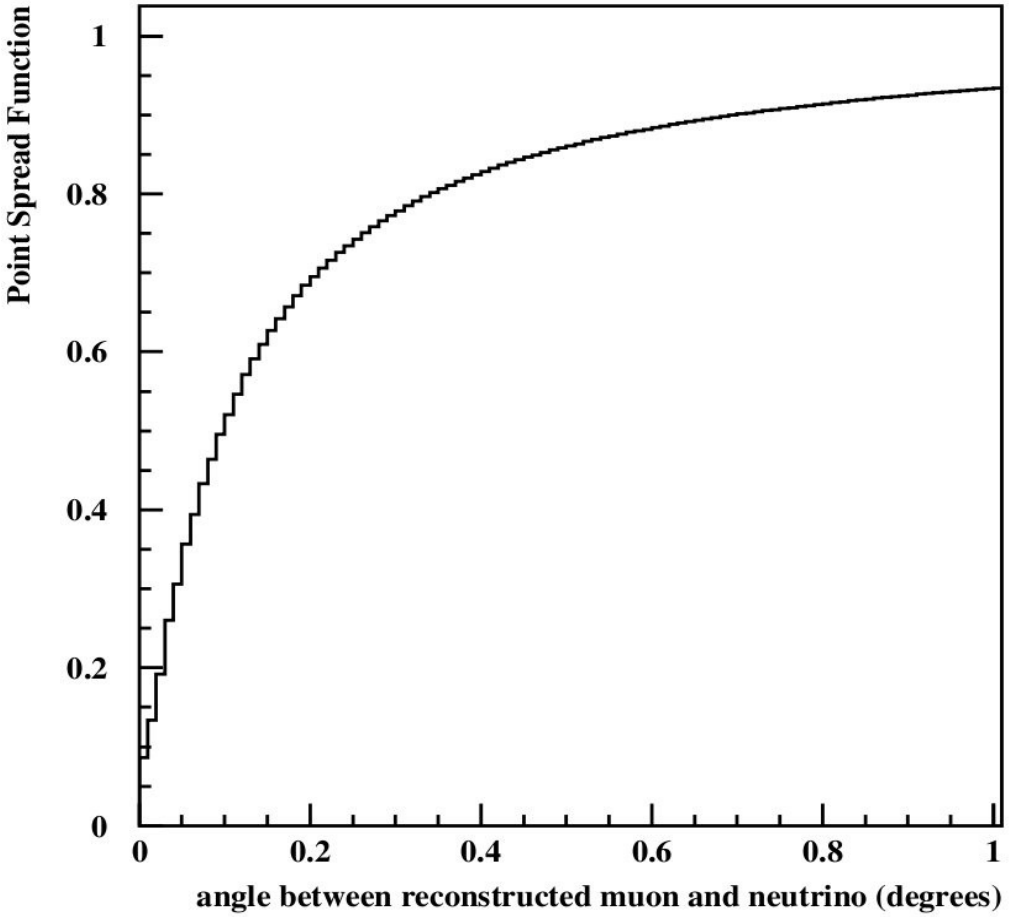
log(E) cos(θ)	2	3	4	5	6	7
-0.95	6.3E-3	6.3E-1	1.7E+1	7.6E+1	2.2E+1	3.0E+0
-0.85	8.8E-4	4.5E-1	2.0E+1	1.4E+2	9.6E+1	2.6E+0
-0.75	7.1E-4	5.4E-1	2.4E+1	2.0E+2	2.2E+2	1.1E+1
-0.65	8.6E-4	5.4E-1	2.7E+1	2.3E+2	3.4E+2	6.0E+1
-0.55	6.6E-4	5.6E-1	2.9E+1	2.5E+2	4.8E+2	1.3E+2
-0.45	0.0	5.3E-1	3.0E+1	2.9E+2	7.0E+2	3.3E+2
-0.35	4.4E-4	6.1E-1	3.2E+1	3.3E+2	9.5E+2	8.5E+2
-0.25	3.1E-4	6.6E-1	3.4E+1	3.5E+2	1.3E+3	1.4E+3
-0.15	8.5E-4	7.3E-1	3.4E+1	3.7E+2	1.6E+3	3.4E+3
-0.05	4.6E-4	6.9E-1	3.8E+1	4.5E+2	2.3E+3	7.8E+3
0.05	1.5E-4	6.7E-1	3.9E+1	4.7E+2	2.8E+3	1.1E+4
0.15	5.2E-4	6.0E-1	3.8E+1	5.0E+2	2.8E+3	1.1E+4
0.25	2.4E-4	5.5E-1	3.6E+1	4.7E+2	2.6E+3	8.4E+3
0.35	0.0	4.8E-1	3.4E+1	4.2E+2	2.3E+3	7.2E+3
0.45	3.6E-4	4.0E-1	3.0E+1	4.0E+2	1.9E+2	6.0E+3
0.55	0.0	2.9E-1	2.7E+1	3.5E+2	1.8E+2	5.4E+3
0.65	4.1E-4	2.8E-1	2.4E+1	3.2E+2	1.6E+2	5.2E+3
0.75	0.0	1.9E-1	2.0E+1	3.0E+2	1.5E+2	4.2E+3
0.85	6.0E-4	2.0E-1	1.7E+1	2.7E+2	1.4E+2	4.3E+3
0.95	2.2E-3	2.8E-1	1.4E+1	2.2E+2	1.3E+2	3.8E+3

Angular resolution
Cuts for best sensitivity

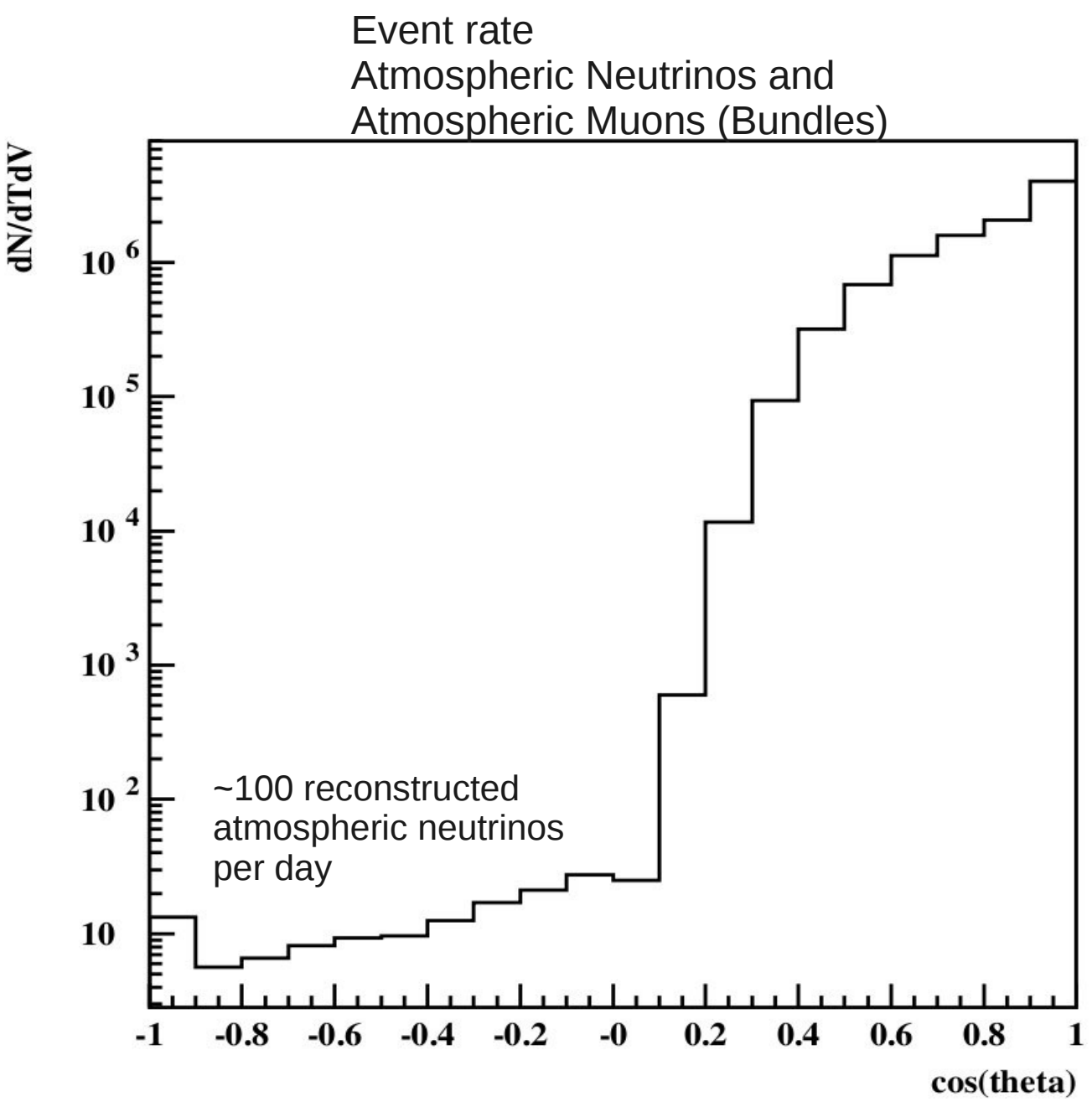
Angular resolution vs Neutrino Energy
Neutrinos and Anti-Neutrinos



Point Spread Function
Neutrinos and Anti-Neutrinos



Background event rate (**Half KM3NeT detector**)
Cuts for best sensitivity

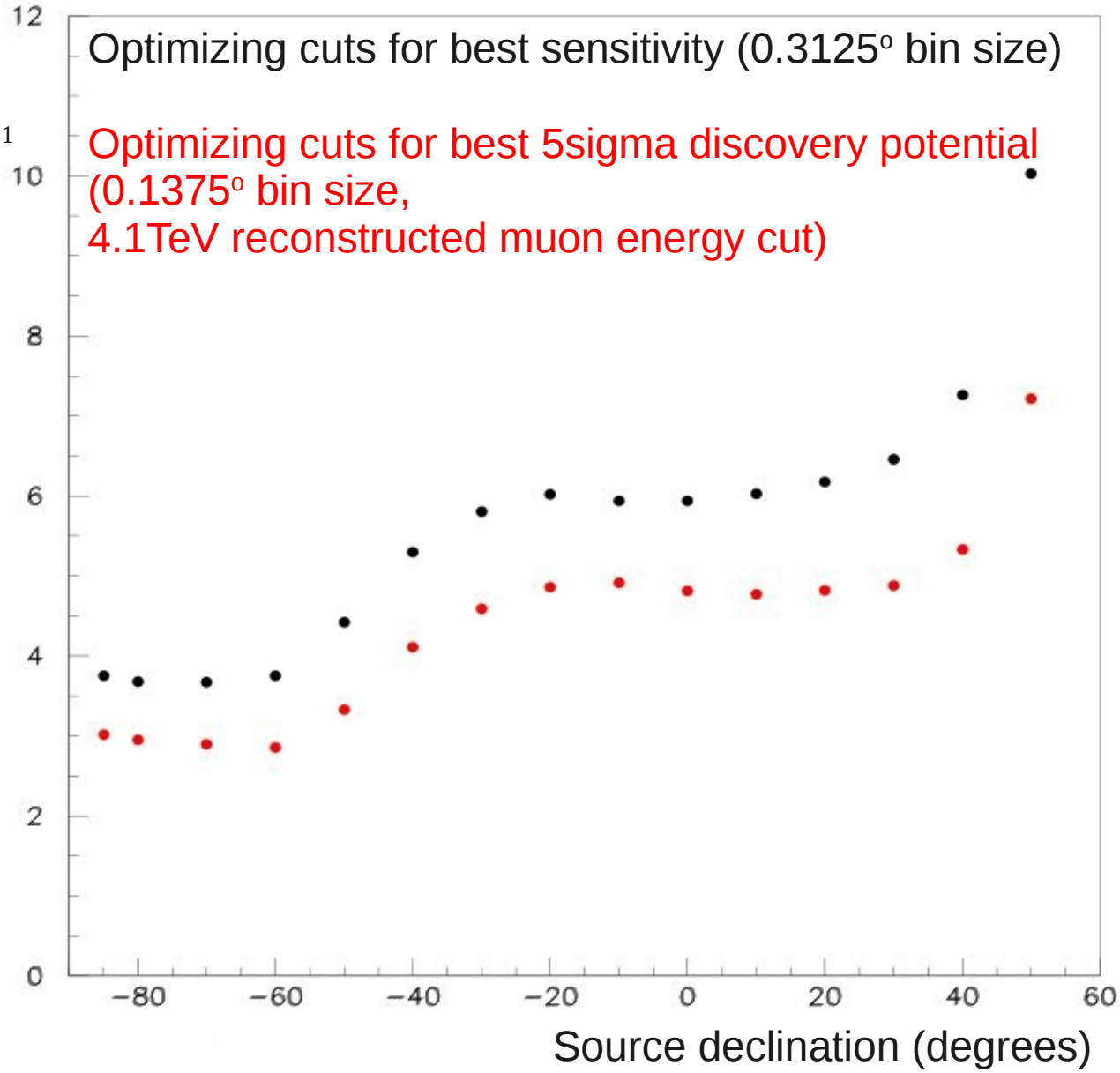


5σ discovery potential (**Half KM3NeT detector**)
1 year of data taking (point source)

Discovery Potential (5 sigma, 50% probability)

$x10^{-9}\, E^{-2} GeV^{-1} cm^{-2} s^{-1}$

dec	n_{bg}	n_s	mdp5
-85	0.0025	0.72	3.02
-80	0.0027	0.74	2.95
-70	0.0035	0.79	2.90
-60	0.0048	0.85	2.85
-50	0.0043	0.72	3.33
-40	0.0032	0.55	4.11
-30	0.0027	0.48	4.59
-20	0.0024	0.44	4.86
-10	0.0023	0.44	4.92
0	0.0024	0.45	4.81
10	0.0024	0.45	4.78
20	0.0026	0.45	4.82
30	0.0029	0.46	4.88
40	0.0031	0.42	5.33
50	0.0025	0.30	7.22



Galactic Candidate ν Sources – SNRs

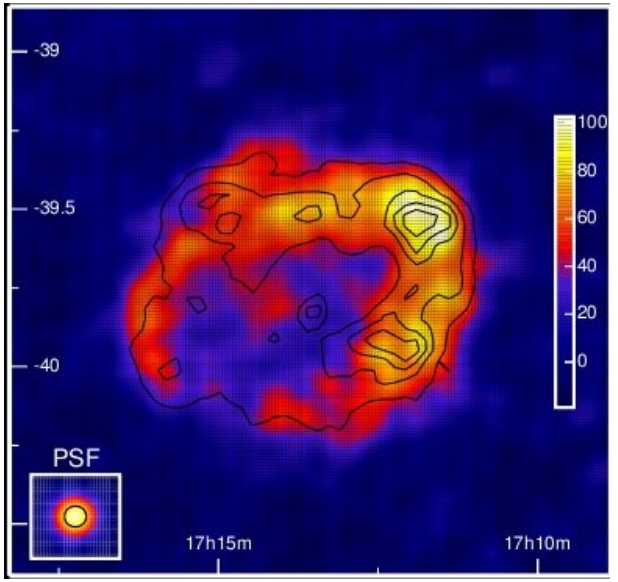
Origin of Cosmic Rays => SNR paradigm

Assuming that VHE γ emmiters are CR accelerators.

As an example, assuming that the RXJ1713.7-39.46 (the most luminous γ ray source) is a hadron accelerator then the ν spectrum can be calculated from the γ spectrum:

(S.R. Kelner, F.A. Aharonian and V.V. Bugayov Phys. Rev D 74, 034018 (2006))

Hess RXJ1713.7-39.46



$$\Phi(E) = 16.8 \times 10^{-15} \left[\frac{E}{\mathrm{TeV}}\right]^{-1.72} e^{-\sqrt{\frac{E}{2.1\ \mathrm{TeV}}}} \quad \mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$$

Discovery Potential for RXJ1713.7-3946
Sky bin search radius is 0.77 degrees
Neutrino Source Generation disk radius is 0.6 degrees

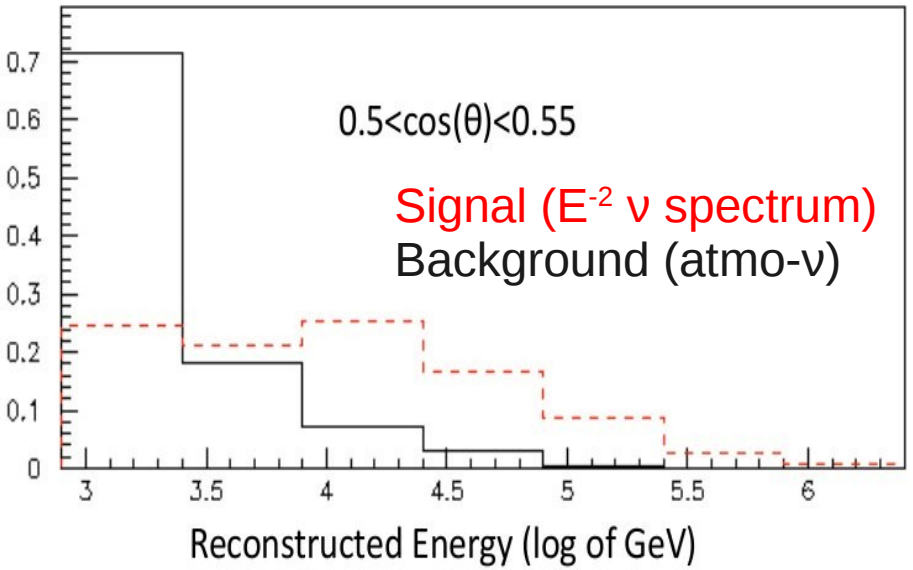
- # background/year: 1.99
- 3s Discovery Pot. (1y-Half KM3NeT): 3.85 x Φ(E)
- 8.6 y for 3s discovery (Half KM3NeT)
- 4.3 y for 3s discovery (Full KM3NeT)
- # signal/year: 1.44
- 5s Discovery Pot. (1y-Half KM3NeT): 7.39 x Φ(E)
- 24 y for 5s discovery (Half KM3NeT)
- 12 y for 5s discovery (Full KM3NeT)

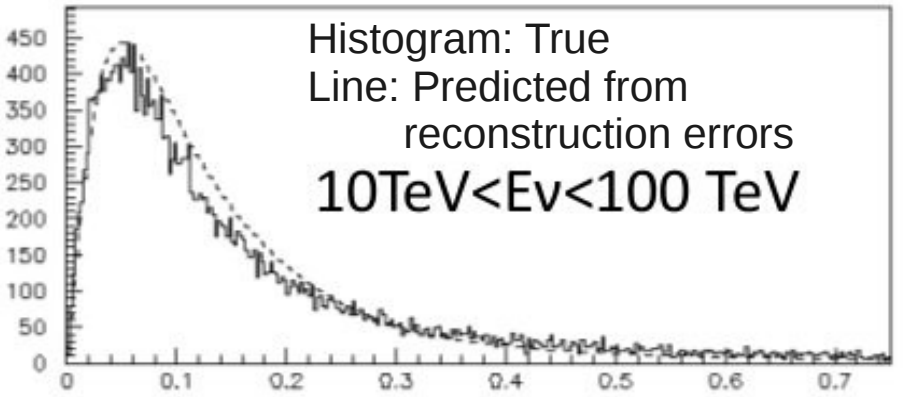
Galactic Candidate ν Sources – Discovery Improvements

Use of the full experimental information on a track by track basis:

- reconstructed muon energy, and
- track resolution (muon reconstruction parameter errors)

(Talk “Evaluation of the discovery potential of an underwater Mediterranean neutrino telescope taking into account the estimated directional resolution and energy of the reconstructed track” by A. Leisos)





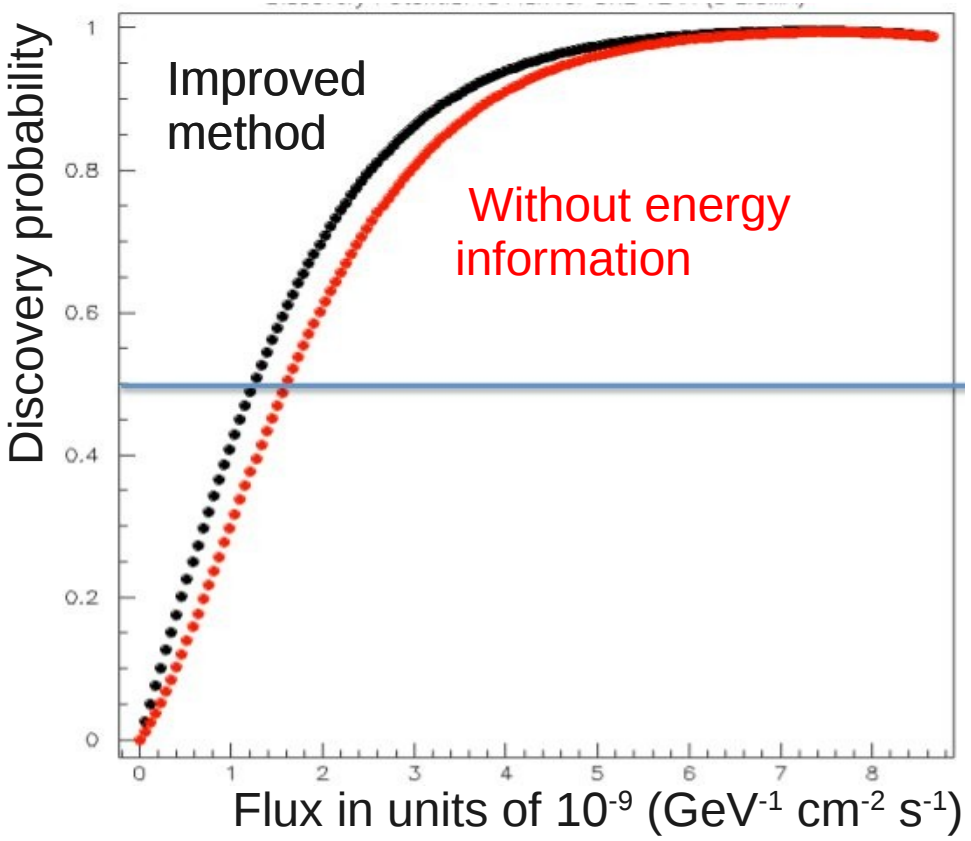
Angle between reconstructed muon track and parent neutrino (Degrees)

Galactic Candidate ν Sources – Discovery Improvements

154 DUs (half KM3NeT)

E^{-2} ν point source at -60º declination

Discovery Potential (3 sigma) vs Flux for one year of data taking

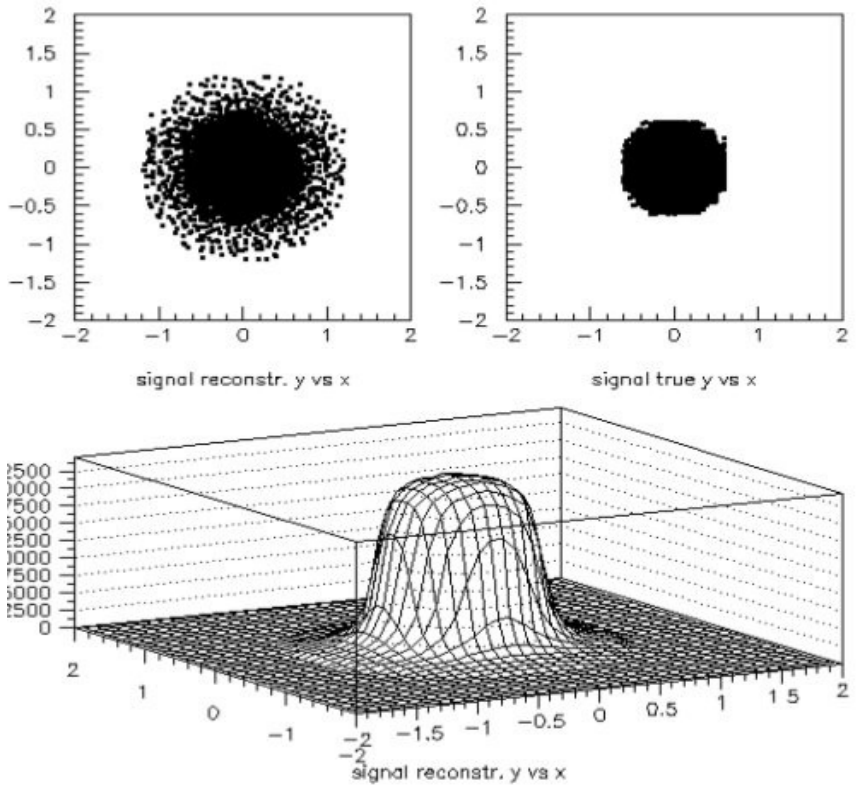


Without energy information: 1.6×10^{-9} (GeV^{-1} cm^{-2} s^{-1})

Using full exp. information: 1.2×10^{-9} (GeV^{-1} cm^{-2} s^{-1})

Binned technique: 1.9×10^{-9} (GeV^{-1} cm^{-2} s^{-1})

RXJ1713.7-39.46 (0.6º angular radius)



1y Discovery potential **WITH** energy and shape

- 3σ : 3.0 x RXJ1713 flux for 50% discovery
- 4σ : 4.1 x RXJ1713 flux for 50% discovery
- 5σ : 5.6 x RXJ1713 flux for 50% discovery

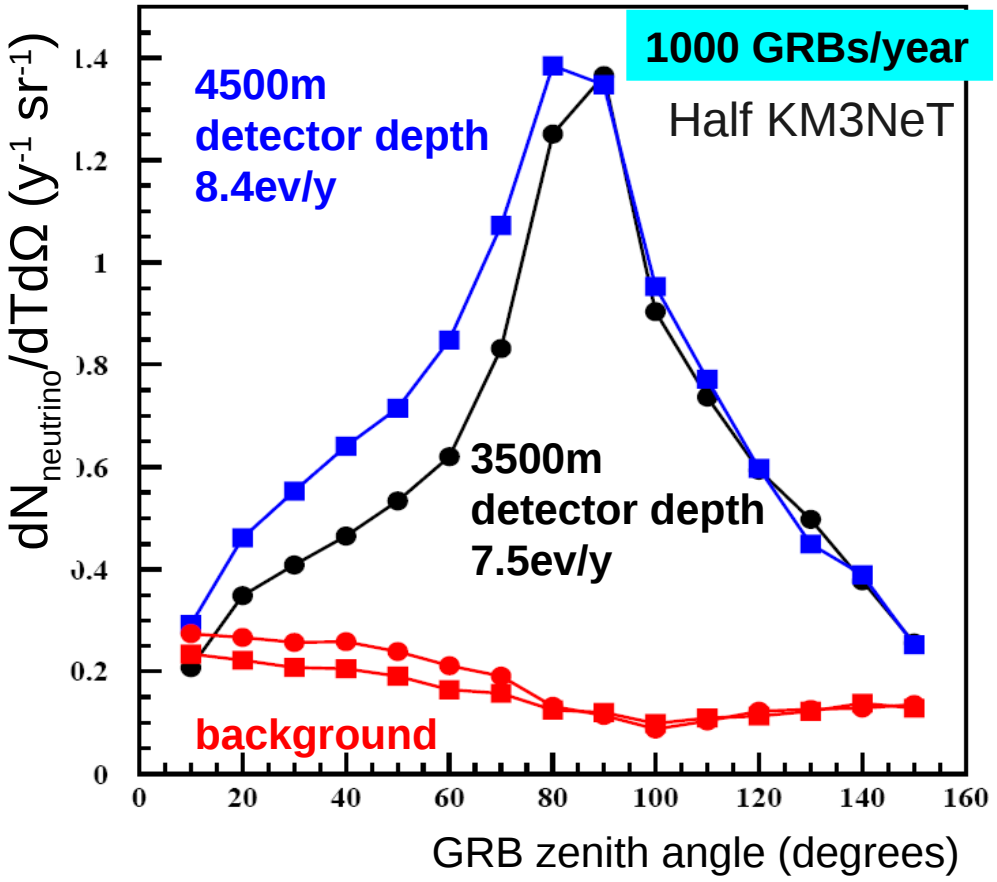
1y Discovery potential **WITHOUT** energy and shape

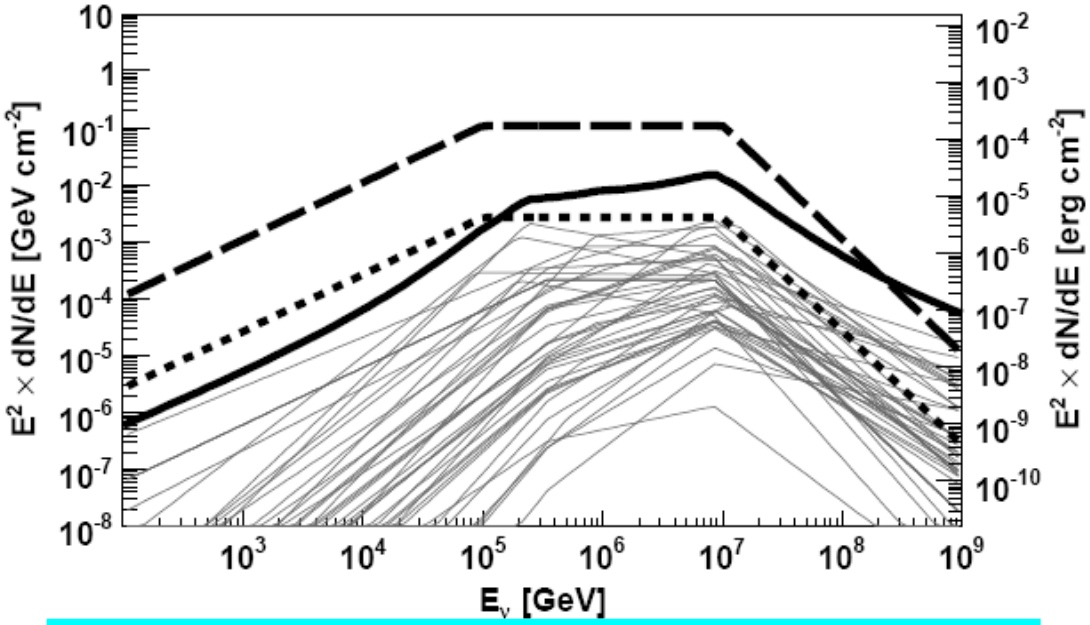
- 3σ : 3.7 x RXJ1713 flux for 50% discovery
- 4σ : 4.6 x RXJ1713 flux for 50% discovery
- 5σ : 7.4 x RXJ1713 flux for 50% discovery

Extragalactic ν Sources – GRBs

- Alert from satellite detectors (known time & direction)
- Short time window (<2h) for GRB prompt neutrino emission
- High energy neutrinos (> 100TeV)
- Application of energy cut on the reconstructed muon energy

Detection of down-going GRB neutrinos events is feasible





Expected Neutrino fluence from GRBs
R. Abbasi, et al., IceCube Collaboration,
Astrophys. J. 710 (2010) 346

The expected number of detected neutrino events from GRBs per year and steradian.

300 GRBs/year (4500m depth) Half KM3NeT

2.5 signal events/year
0.45 background events/year

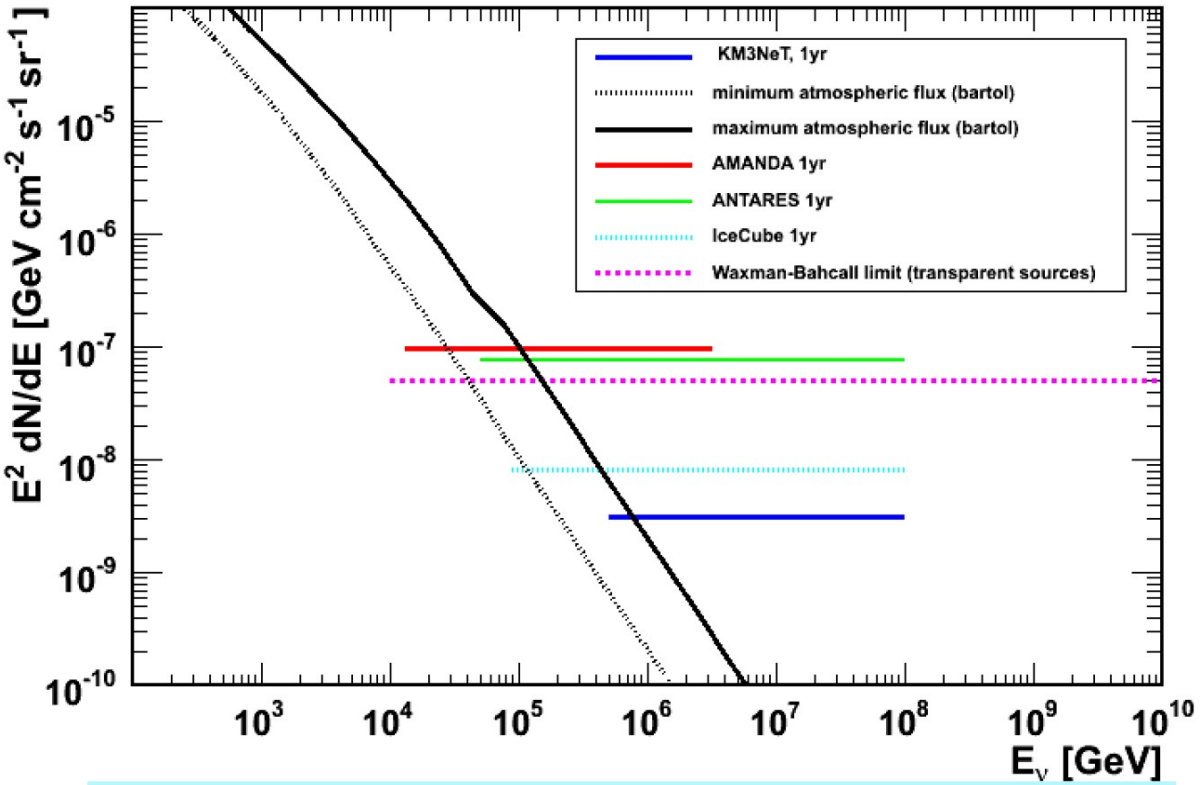
Diffuse Flux ν

Ultra high energy neutrinos from

- A multitude of objects such as Active Galactic Nuclei or GRBs
- The interaction of cosmic rays with intergalactic matter, radiation, cosmic microwave background

} isotropic diffuse flux

- No tight angular cut for reducing the background of atmospheric neutrinos
- Rely on a cut on the reconstructed muon energy.



Diffuse flux sensitivity of the KM3NeT neutrino telescope for one year of observation time.

KM3NeT (E^{-2}) diffuse ν flux sensitivity (effective energy cut $E_\nu > 500$ TeV)

$3 \cdot 10^{-9}$ (GeV^{-1} cm^{-2} s^{-1} sr^{-1})

Conclusions

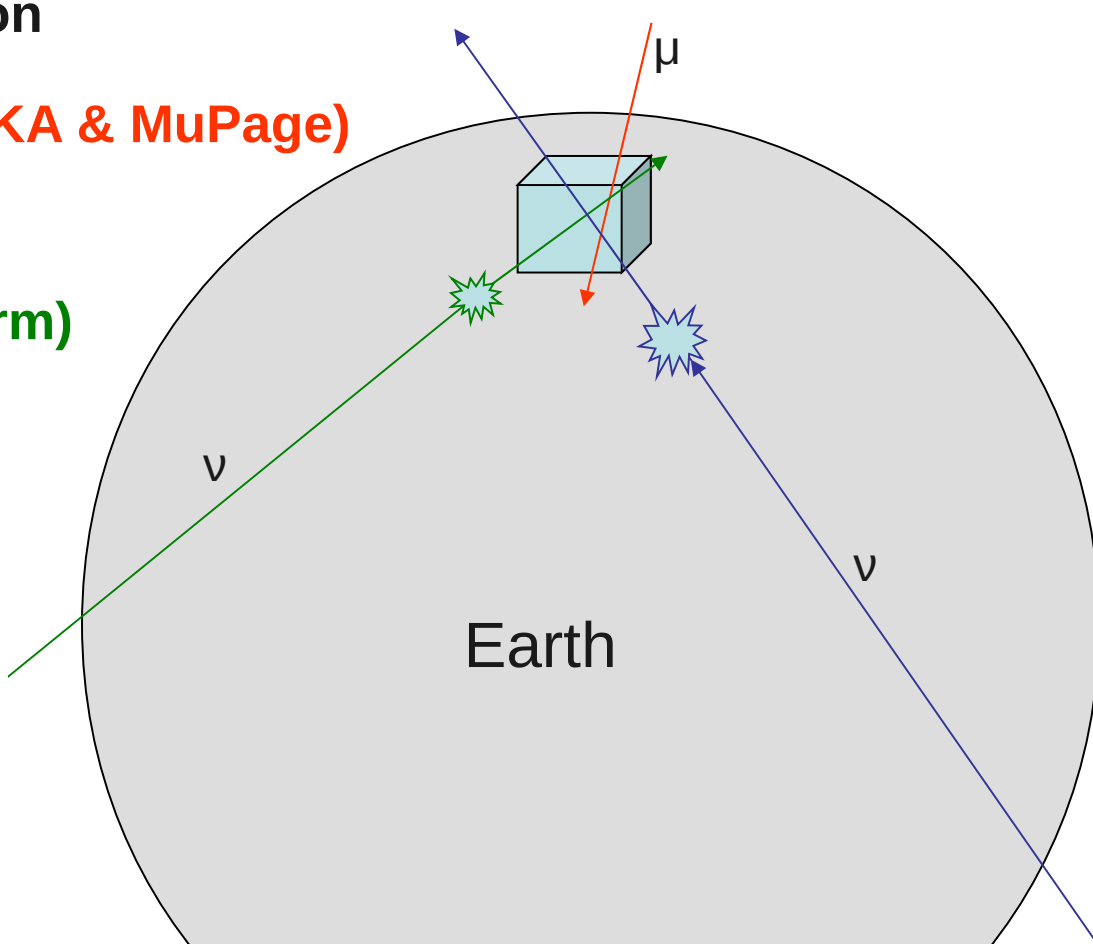
- We improved the track reconstruction and the tracking error estimation by employing a Likelihood criterion and a fit at the last stage of the tracking chain
- KM3NeT will cover most ofν sky with unprecedented sensitivity ⇨ Promising Galactic Candidate ν Sources
- Discovery potential for Galactic Candidate ν Sources can be further improved using the reconstructed energy estimation, the angular resolution on a track by track basis and the application of advanced filters using the known source's direction

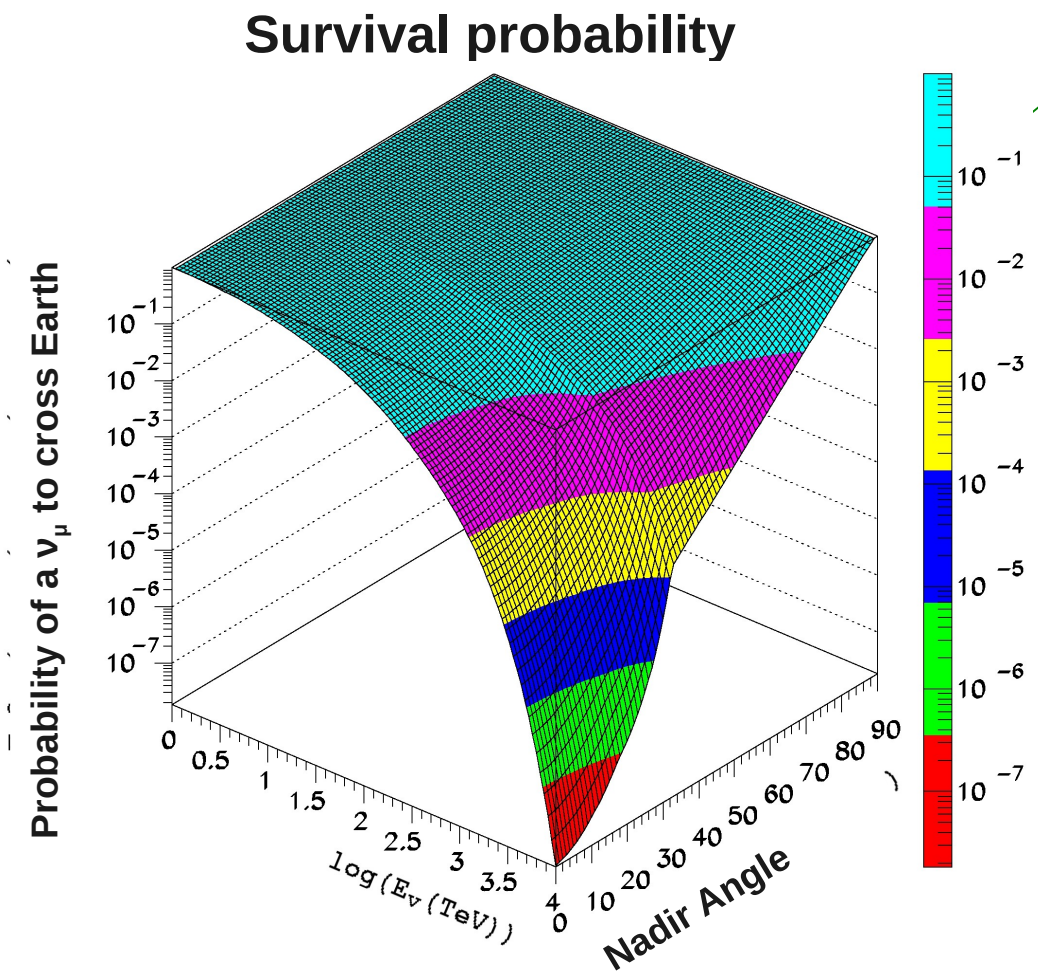
Acknowledgments
The KM3NeT project is supported by the EU in FP6 under Contract no. 011937 and in FP7 under Grant no. 212525

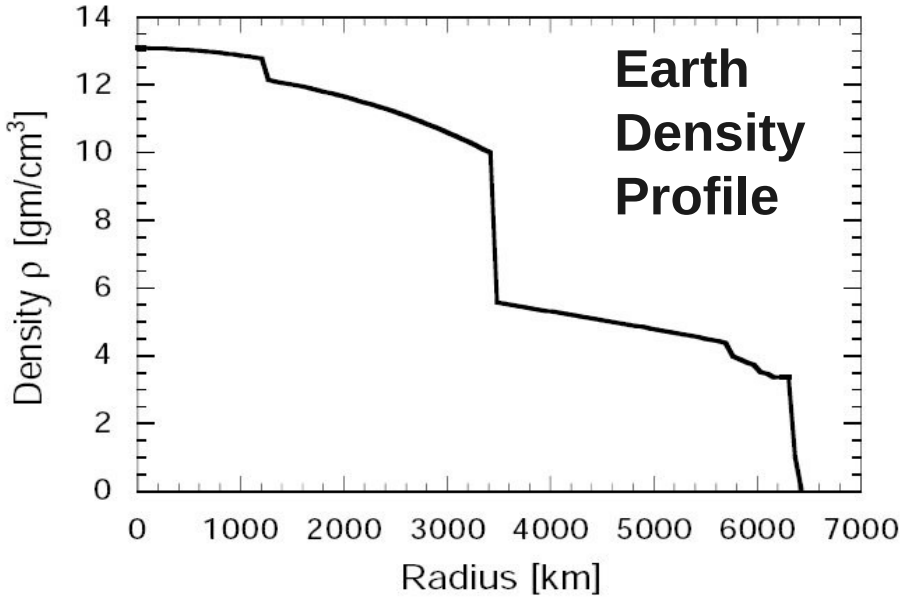
Backup slides

Event Generation – Flux Parameterization

- Atmospheric Muon Generation (CORSIKA & MuPage)
- Neutrino Interaction Events (PYTHIA)
- Atmospheric Neutrinos
(Conventional Flux+Neutrinos from charm)
- Cosmic Neutrinos
(AGN – GRB – GZK and more)







GEANT4 Simulation – Detector Description

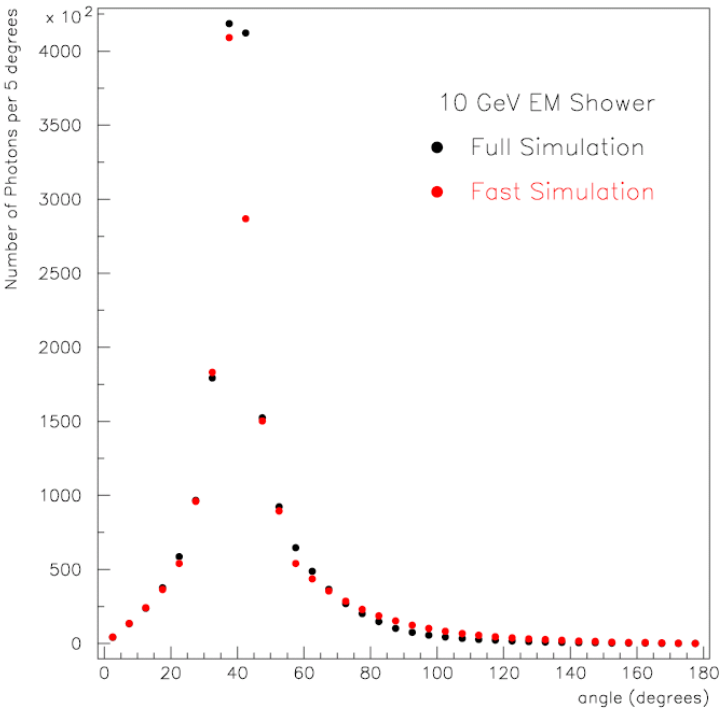
- Any detector geometry can be described in a very effective way
- All the relevant physics processes are included in the simulation

Fast Simulation

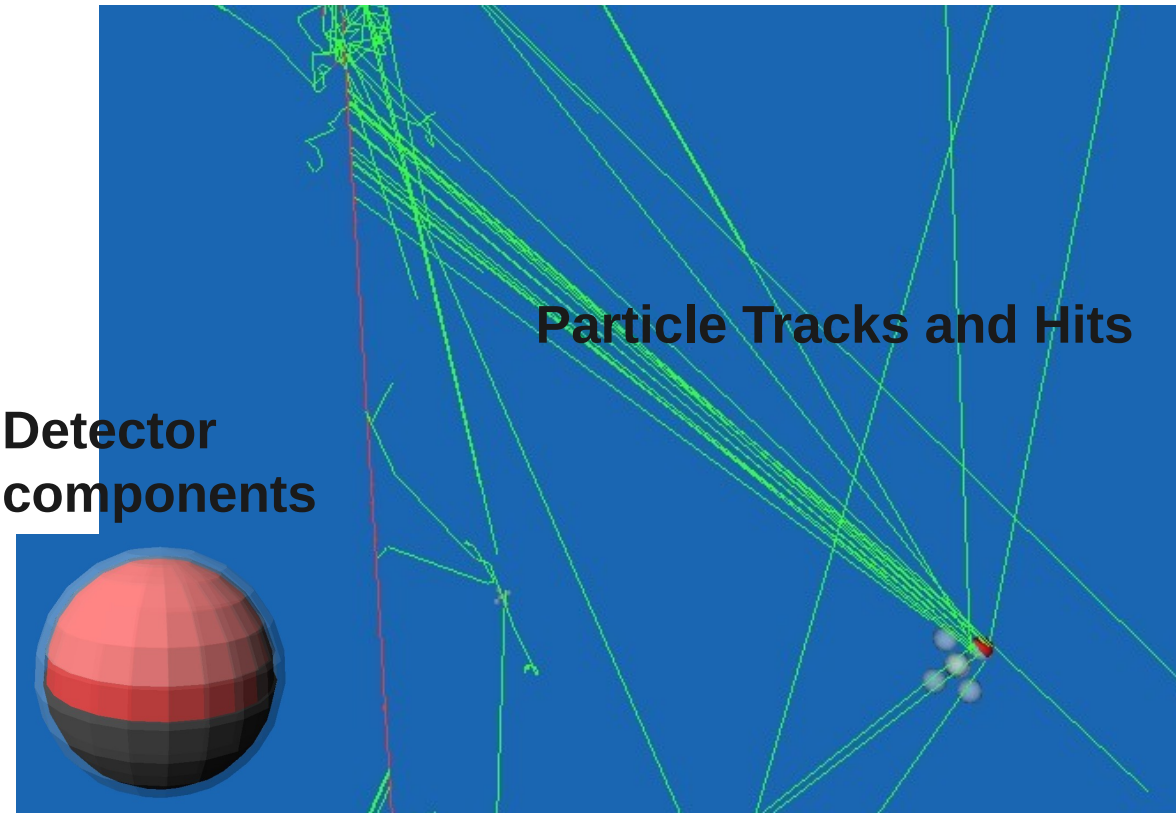
EM Shower Parameterization

- Number of Cherenkov Photons Emitted (~shower energy)
- Lateral and Longitudinal profile of emitted photons

Angular Distribution of Cherenkov Photons



Visualization



Parameters and Definitions

Neutrino Flux: $k=1.0\times10^{-9}\ E^{-2}$ ($GeV^{-1}cm^{-2}s^{-1}$)

n_{bg}=mean number of expected background events

n_s= mean number of expected signal events

Sensitivity (90% CL): $k\,\dfrac{\bar{\mu}_{90}(n_{bg})}{n_s}$

$$\bar{\mu}_{90}(n_{bg})=\sum_{N_o=0}^{\infty}\mu_{90}(N_o,n_{bg})\,P(N_o|n_{bg})$$

$$\mu_{90}(N_o,n_{bg})\equiv 90\%\,CL\ Feldman-Cousins\ Upper\ Limit$$

N_o=number of observed events

Discovery Potential (m sigma, 50%): $k\,\dfrac{d_m(n_{bg})}{n_s}$

d_m = the mean number of signal events in order to have n_0 or more observed events with probability 50%

$$0.5=\sum_{N_o=n_0}^{\infty}P(N_o|\boxed{d_m}+n_{bg})$$

n_0 = the minimum number of observed events to have a discovery of m sigma

$$\sum_{N_o=\boxed{n_0}}^{\infty}P(N_o|n_{bg})\leqslant p_m$$

$p_3=2.7\times10^{-3}$

$p_5=5.73\times10^{-7}$