NEUTRINO TELESCOPES

Lakshmi S Mohan

1st year INO

Contents

- *Neutrino astronomy*
- *Detection techniques in neutrino telescopes*
- *Cerenkov telescopes:*

  a)under water

  b) under ice
- *Some neutrino telescopes*
- *ANTARES*
- *ICE CUBE*

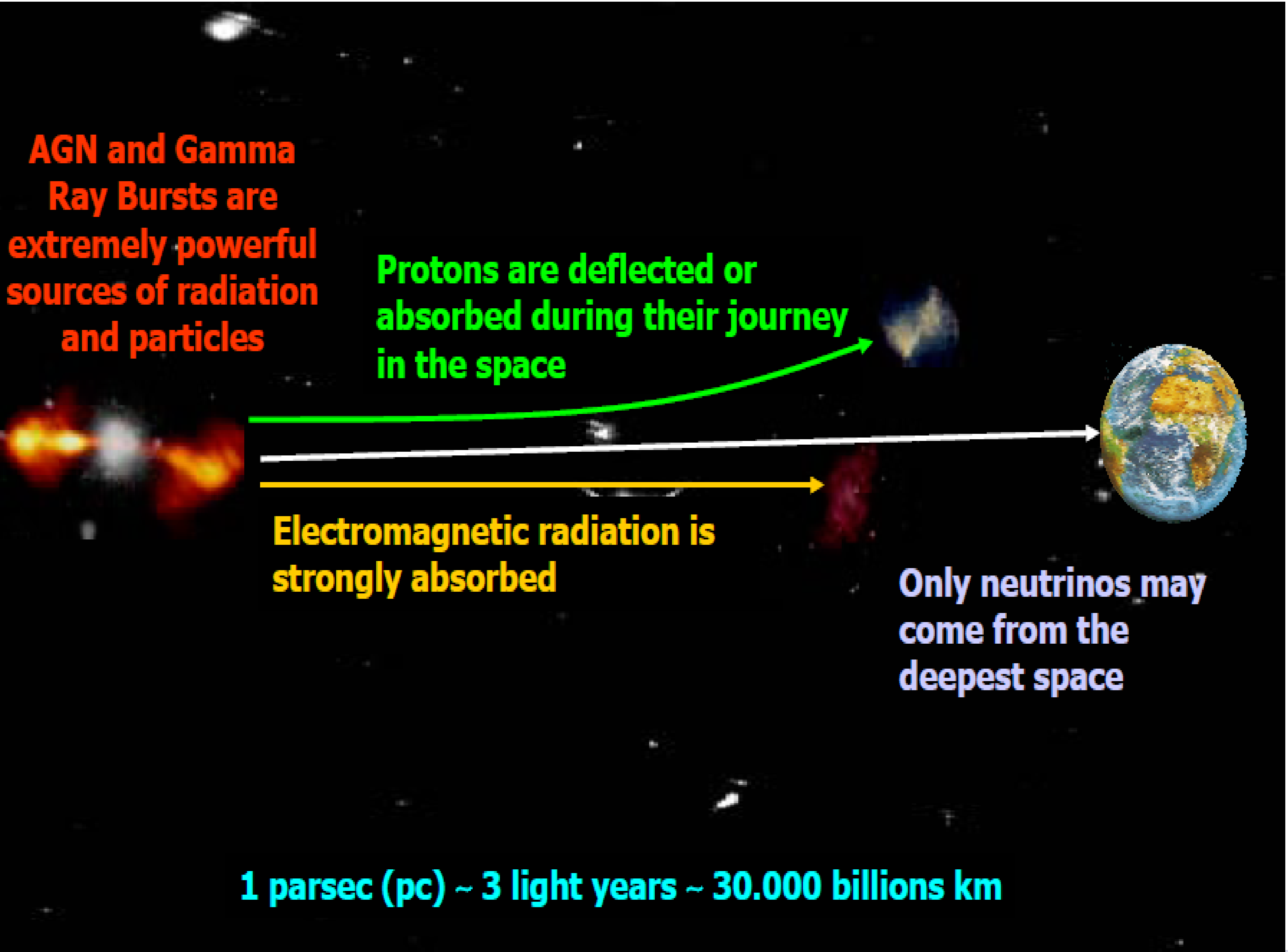
Neutrino astronomy

- A promising branch of astronomy which will help us to probe the otherwise unobservable regions of the universe.
- Main aim : the discovery and understanding of the sites of acceleration of high energy particles in the universe.
- Study of sources such as :

  * Supernova remnants (SNR)
  * Active galactic nuclei (AGN)
  * Microquasars (MQ)
  * Gamma ray bursts (GRB)

Why neutrino astronomy?

- Neutrinos interact weakly and have small cross sections.
- So can penetrate large thickness of matter with negligible attenuation.
- Enables their escape from the large matter density at the site of production and can point back to the source when detected.
- At 100GeV , neutrino interaction length $=10^8$ times that of photon.


AGN and Gamma Ray Bursts are extremely powerful sources of radiation and particles
Protons are deflected or absorbed during their journey in the space
Electromagnetic radiation is strongly absorbed
Only neutrinos may come from the deepest space
1 parsec (pc) ~ 3 light years ~ 30.000 billions km

Examples for the regions of high matter density which the neutrinos can penetrate:

- Dust clouds in the galactic plane.
- Dense accretion disks of matter around massive central sources such as black holes.
- Centers of stars and planets including the Sun and the Earth.

Neutrino production in space occurs where high energy particles or gamma rays interact with matter.

- *Extremely energetic astronomical sources : high energy neutrinos are emitted as secondary pdts in interactions of charged cosmic rays, where they are accelerated in the shock processes inside the sources. They are the interactions of:*
- *1) high energy protons with nucleons in the interstellar matter*
- *2) high energy protons with photons from the local radiation field.*
- *Decay of the charged pions produced in these hadronic interactions give neutrinos.*

$$p + N \rightarrow \pi^{\pm} + \pi^{0} + ---$$

$$p + \gamma \rightarrow \pi^{\pm} + \pi^{0} + ---$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\pi^{-} \rightarrow \mu^{-} + \overline{\nu_{\mu}}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}}$$

$$\mu^{-} \rightarrow e^{-} + \overline{\nu_{e}} + \nu_{\mu}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$

At the sources, the neutrino and gamma fluxes are almost equal, provided they come from hadronic interactions.

- $\phi_\gamma \sim \phi_\nu$ *for pp interaction*
- $\phi_\gamma \sim 4\phi_\nu$ *for* $p\gamma$ *interaction (due to dominance of* Δ *resonance)*
- *v carries only 10% of the primary proton energy.*

Relative fractions of neutrino flavours produced at the source :

$$\nu_e : \nu_\mu : \nu_\tau \cong 1 : 2 : 10^{-5}$$

After propagating ~ kpc distances to the Earth,

$$\nu_e : \nu_\mu : \nu_\tau \cong 1 : 1 : 1$$

due to $\nu_\mu \longleftrightarrow \nu_\tau$ *oscillation*

The ν_τ signature comes from the regeneration effect deriving from the τ decay in ν_τ.

- $\nu_\tau + N \longrightarrow \tau + - - -$

  $\tau \longrightarrow \nu_\tau + - - -$

- *[Double bang expected due to 1st and 2nd tau neutrinos.]*
- *The neutrinos observed from the Sun and SN1987a , in the Large Magellenic Cloud are of MeV energies.*
- *Neutrino telescopes search for TeV to PeV neutrinos form pp and proton gamma interactions.*

Why massive detectors?

- *Highly penetrating, so need massive detectors, even for very intense sources.*
- $\sigma_{\nu} \longrightarrow E_{\nu}$ *upto a few TeV*
- $\sigma_{\nu} \longrightarrow E_{\nu}^{0.4}$ *at higher energies*
- $\sigma_{\nu} \cong 10^{-34}\, cm^2$ *at 100 TeV*
- *With this crosssection, a neutrino of 100TeV energy has 63% probability to interact while crossing the Earth's diameter.*
- *Target material for neutrino telescopes ~ 1 Gigatonne*

Above 10^4 TeV , Earth becomes opaque to upgoing neutrinos. So neutrino detection depends mostly on horizontal directions.

- Event rate for different sources :

Source type	Neutrino events /km2 /year
Supernovae	50-100
Plerions	1-10
Shell SNR	40-100
Pulsars + Clouds	1-30
Binary systems	A few
Microquasars	1-300

- *km^2 aperture or km^3 volume to detect these fluxes*
- *Most suitable detection technique at this scale: underwater (deep sea, deep lakes)/under ice (deep glacier) detection of relativistic muons by means of Cerenkov radiation with the help of a matrix of light detectors (PMs) in glass spheres, optical modules hung on strings near sea bed or deep inside the ice glacier.*

Detection technique

- *Neutrino telescopes are sensitive to all the three neutrino flavours , but detection efficiency of each mode varies depending on the detection technique.*

Neutrino detection via 2^0 particles produced in interactions with matter, either inside or around the detector.

Two types of interactions :

1) Charged current interactions and

2) Neutral current interactions

Charged current : Formation of leptons corresponding to the flavour of the interacting neutrino. (Dominating mode)

$$\nu_e N \longrightarrow e^- X$$

- $\nu_\mu N \longrightarrow \mu^- X$ *(dominating mode due to long range of muon)*
- $\nu_\tau N \longrightarrow \tau^- X$
-

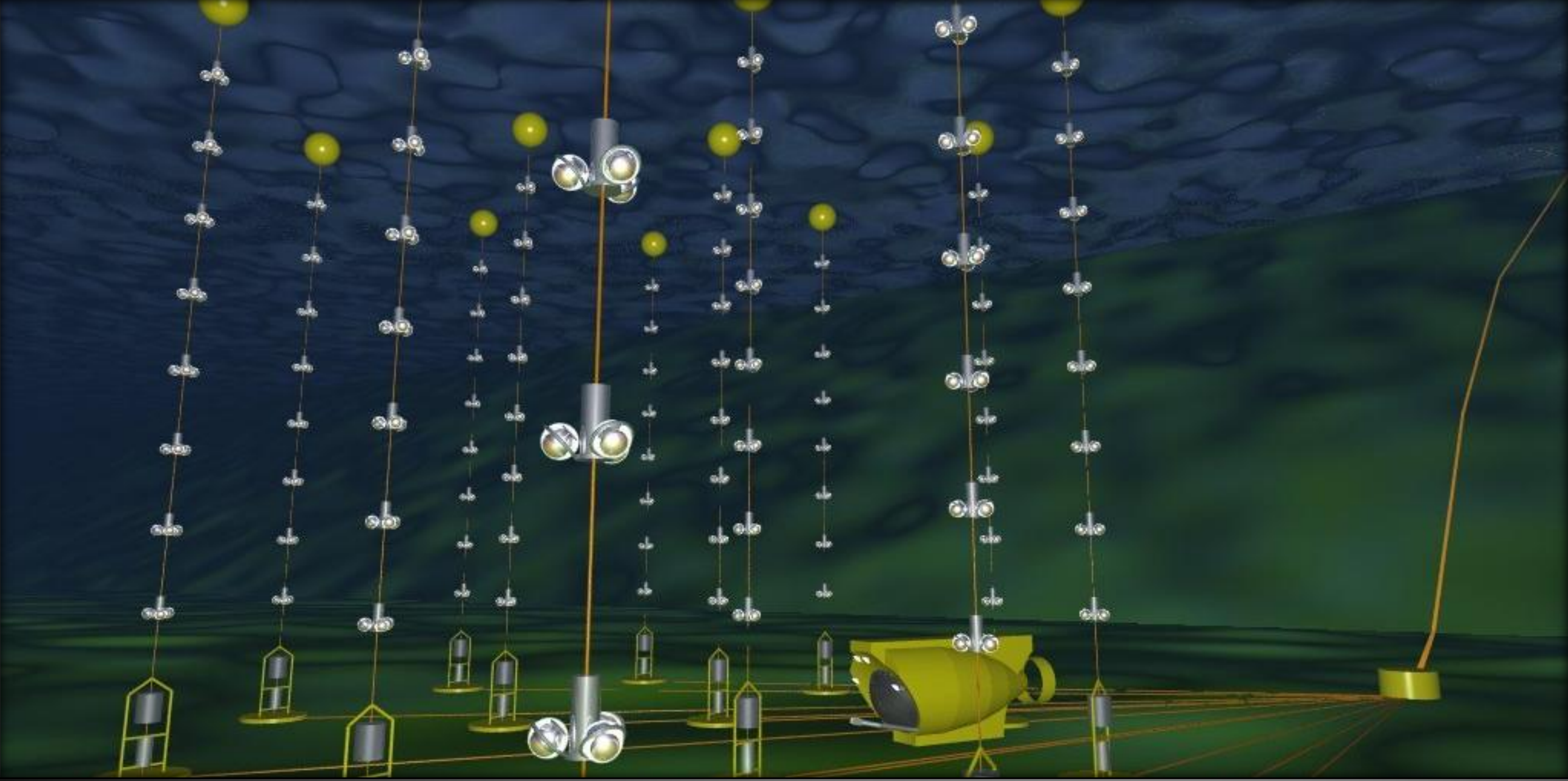
where N=nucleon and X=hadrons resulting from nucleon recoil

Neutral current : Inelastic scattering of neutrinos

$$\nu N \longrightarrow \nu X$$

Lepton → *Main role in detection efficiency .*

Hadrons→ *No contribution at all.*



Water Cerenkov Detection :ANTARES

Astronomy with a Neutrino Telescope and Abyss environmental RESearch

ANTARES : Mediterranian sea,near La, Seyne, France

- Area ~ 0.1km2; active height ~ 350m
- ~12 vertical strings each of 350m height , and 70m distant from one another ,with an OM which has a PMT , and other electronics enclosed in a pressure resistant glass sphere.

25 storeys; spacing 14.5m.

- OM arranged at an angle of 45^0 below the horizontal. So high detection efficiency in the lower hemisphere.
- LCM for each storey and SCM for each string.

Trigger logic in sea:

- 1st level trigger : coincidence between any two OMs in a storey.
- 2nd level trigger : combinations of 1st level triggers. Full detector will be read out following this.
- 3rd level trigger : more refined, imposing tighter time coincidences over large no:of optical modules, will be made in a farm of processors on shore .

Expected read out rate: Several kHz

Data recording rate <100 events per second

Different neutrino interactions in ANTARES

- Charged current ν_e interactions:

  - electromagnetic and hadronic showers with longitudinal dimensions < a few meters ($\because$ radiation length and nuclear interaction length of water < 1m)

  - point like events on ANTARES' scale

  - energy resolution of these events > that for muons , at E>100GeV (all energy deposited in the detector volume)

  - poor angular resolution , due to point like character of shower

  - contamination by neutral current int of both $\nu_e, \nu_\mu / \nu_\tau$

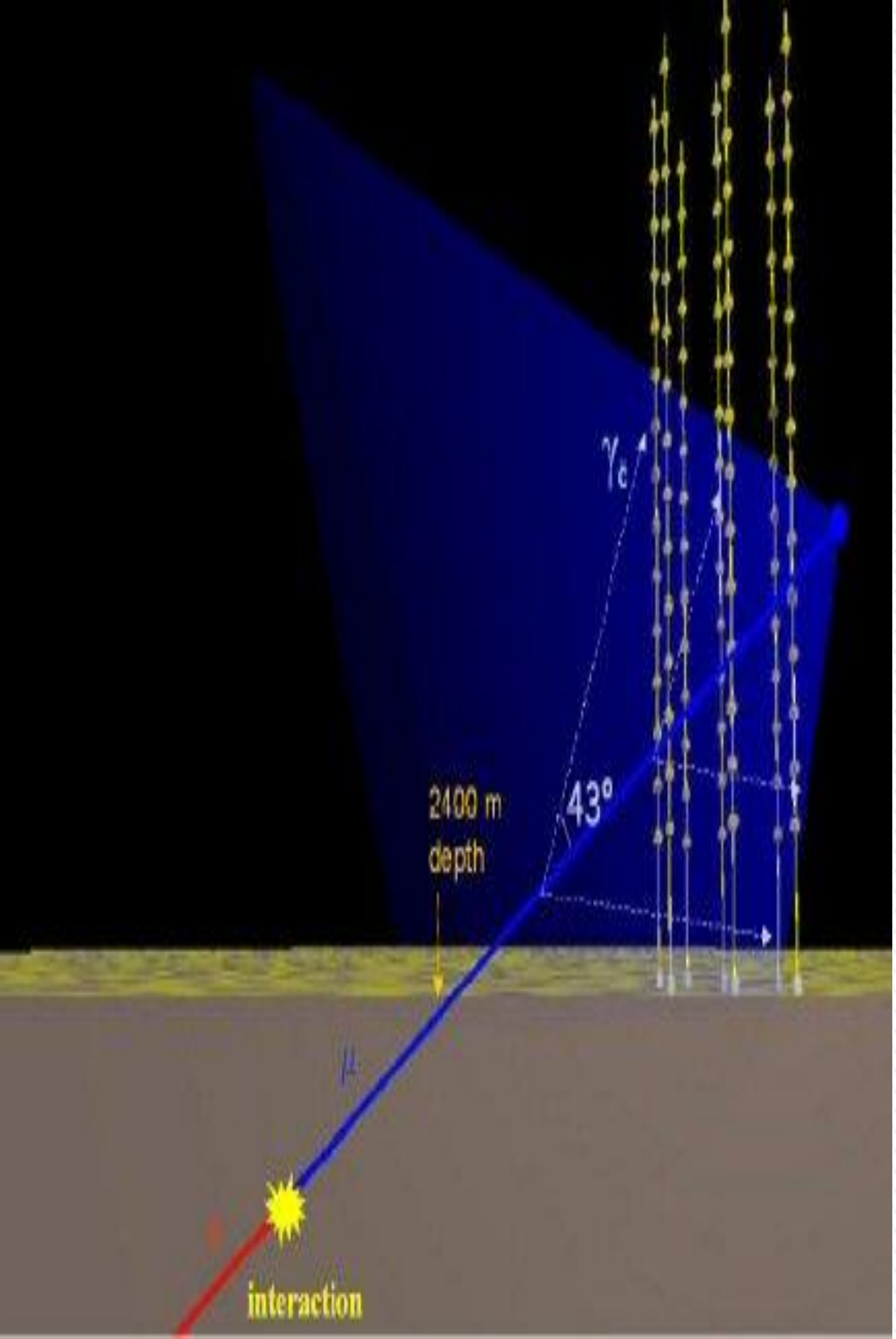
#NC int =1/3 #CC int
NC : neutrino type unidentified, poor energy resolution (final state ν missing), poor angular resolution : point like character

- CC ν_μ interactions producing $\mu^\pm$ and a point like shower.
- Estimation of ν_μ from measured $\mu^\pm$ energy.
- $\nu_\mu d \longrightarrow \mu^- u$ interactions : $E_{\mu^-} = \frac{1}{2} E_{\nu_\mu}$
- $\overline{\nu_\mu} u \rightarrow \mu^+ d$ interactions: $E_{\mu^+} = \frac{3}{4} E_{\overline{\nu_\mu}}$
- Muon energy can be determined from the range for E<100GeV or from dE/dx for E>1TeV.
- Hadronic shower gives additional information of ν_μ energy.
- ANTARES design – to detect the CC ν_μ interactions.

CC ν_τ interactions produce $\tau^\pm$ electronic, muonic and hadronic decay modes.

- The ν_τ interaction vertex and the $\tau^\pm$ decay vextex can't be separated for E<100TeV.
- The electronic and hadronic modes will look like ν_e CC or NC interactions.
- Though the muonic decays $\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$ are visible with a branching ratio 17%, they can't be distinguished from ν_μ

interactions.



Cerenkov light emission : occurs when a particle with a velocity > velocity of light in the medium passes through the medium.

- *Angle of emission of Cerenkov photons:*
- $\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$ *,where,*
- $\beta = \frac{v}{c}$ *=1 for ultra relativistic*

particles , n=refractive index of the medium.

For sea water, n=1.35

So θ_C *~*43^0 *-> half angle of the Cerenkov cone.*

Expected performance

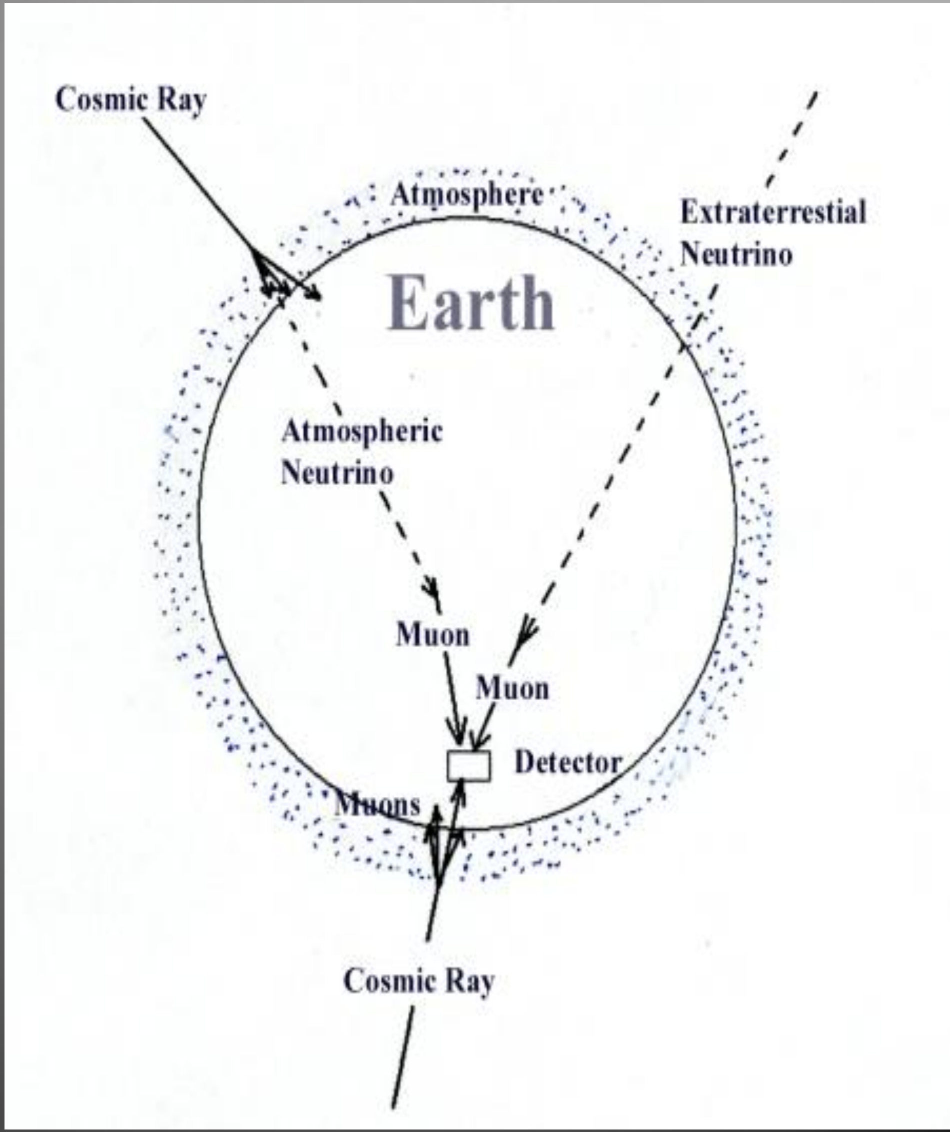
- *Pointing accuracy*
- *Effective areas for muon and neutrino*
- *Detector response to various spectral indices*
- *Energy response*

a)Pointing accuracy: Llr response of detector wrt incoming ν direction .

Determining factors:

- *Lle btw ν and μ in the ν interaction*
- *Deviation of muon drn due to multiple scattering*
- *Llr resolution of detector wrt to the muon*

- *The mean angle between muon and neutrino decreases with energy like $E^{-0.5}$, with a pointing accuracy of about one degree at1 TeV.*



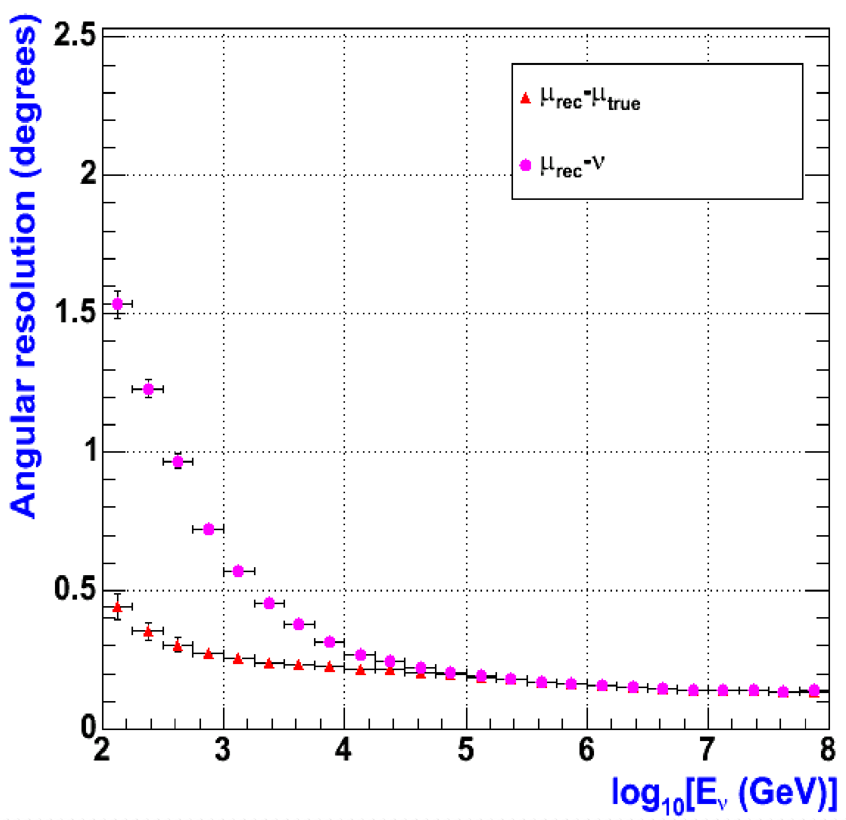
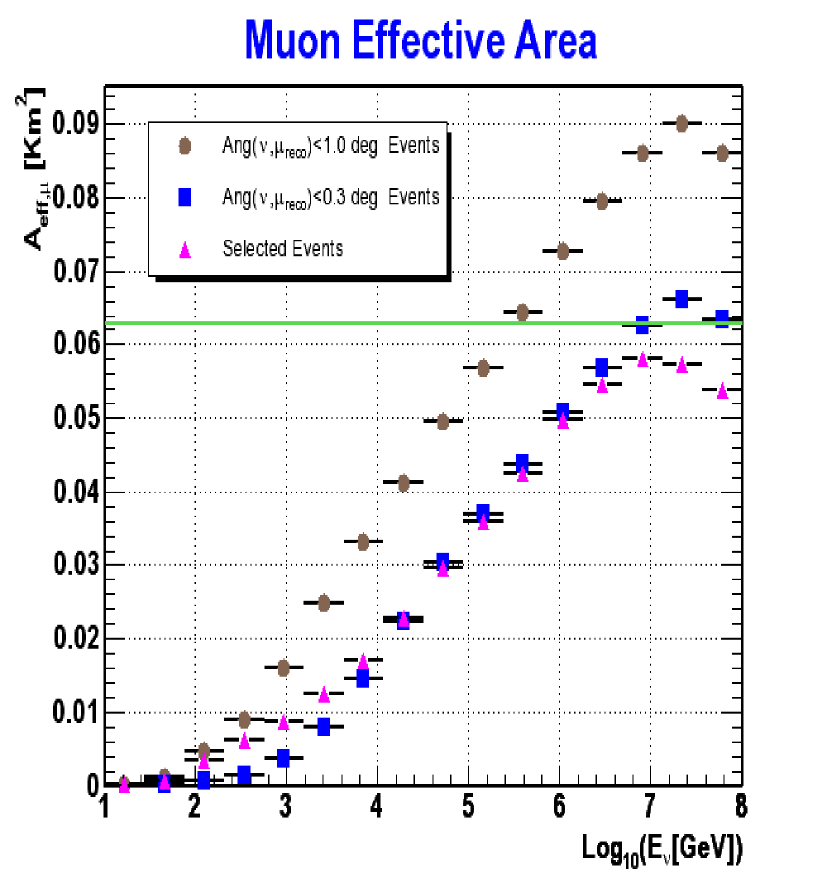


Fig: Angular resolution Vs neutrino energy in GeV (log10 scale)

- *Bottom curve: Lle difference btw reconstructed muon and simulated muon . Difference < 0.5*
- *Top curve: Llr error between reconstructed muon and simulated neutrino.*
- *Below 1TeV, kinematics dominates this error, above 1TeV, muon is emitted in the drn of parent neutrino.*
- *>10TeV , Llr resolution is better than 0.3^0 . So very good background rejection in search of point like sources.*

Effective area: area which the detector surface has, ⊥lr to the incident particle beam if the detection efficiency is 100%.

- *EA= Rate of detected events (s-1)/Incident flux (cm-2s-1)*
- *Incident muon flux at detector: EA for muon*
- *Incident ν flux at Earth's surface: EA for ν*

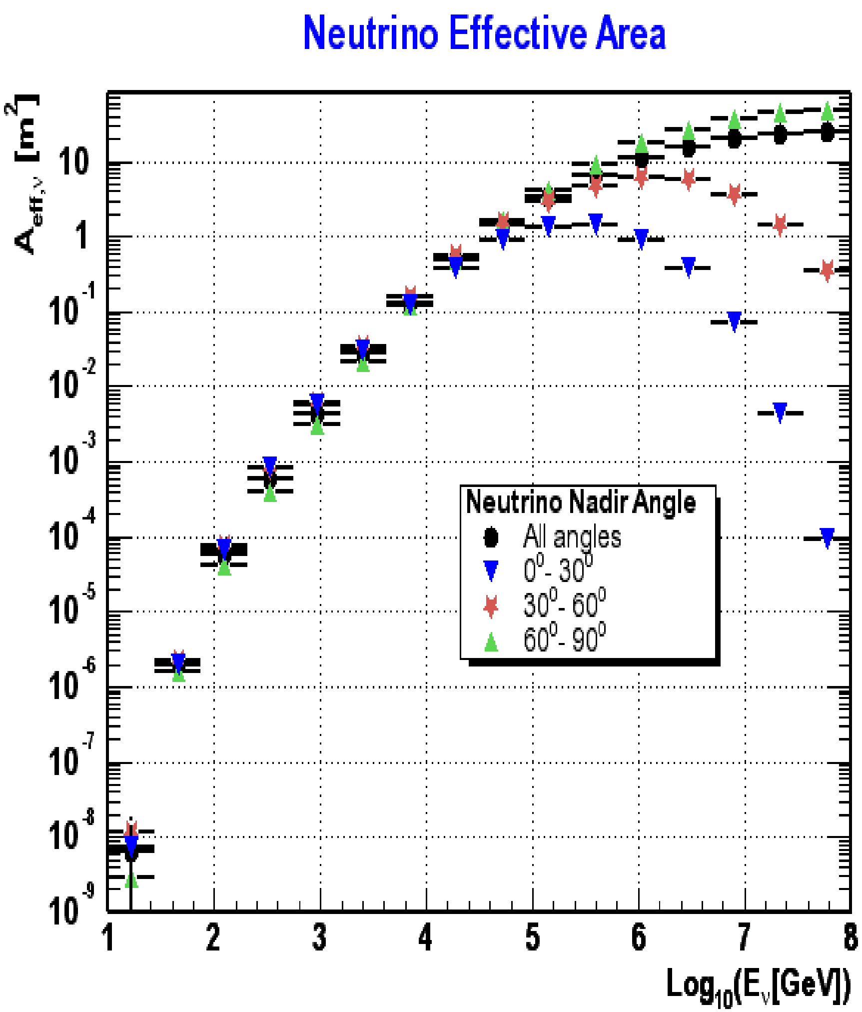


Muon effective area Vs energy

First 2curves : for reconstructed muons matching the neutrino angle at less than 1 degree and less than 3 degrees resp.

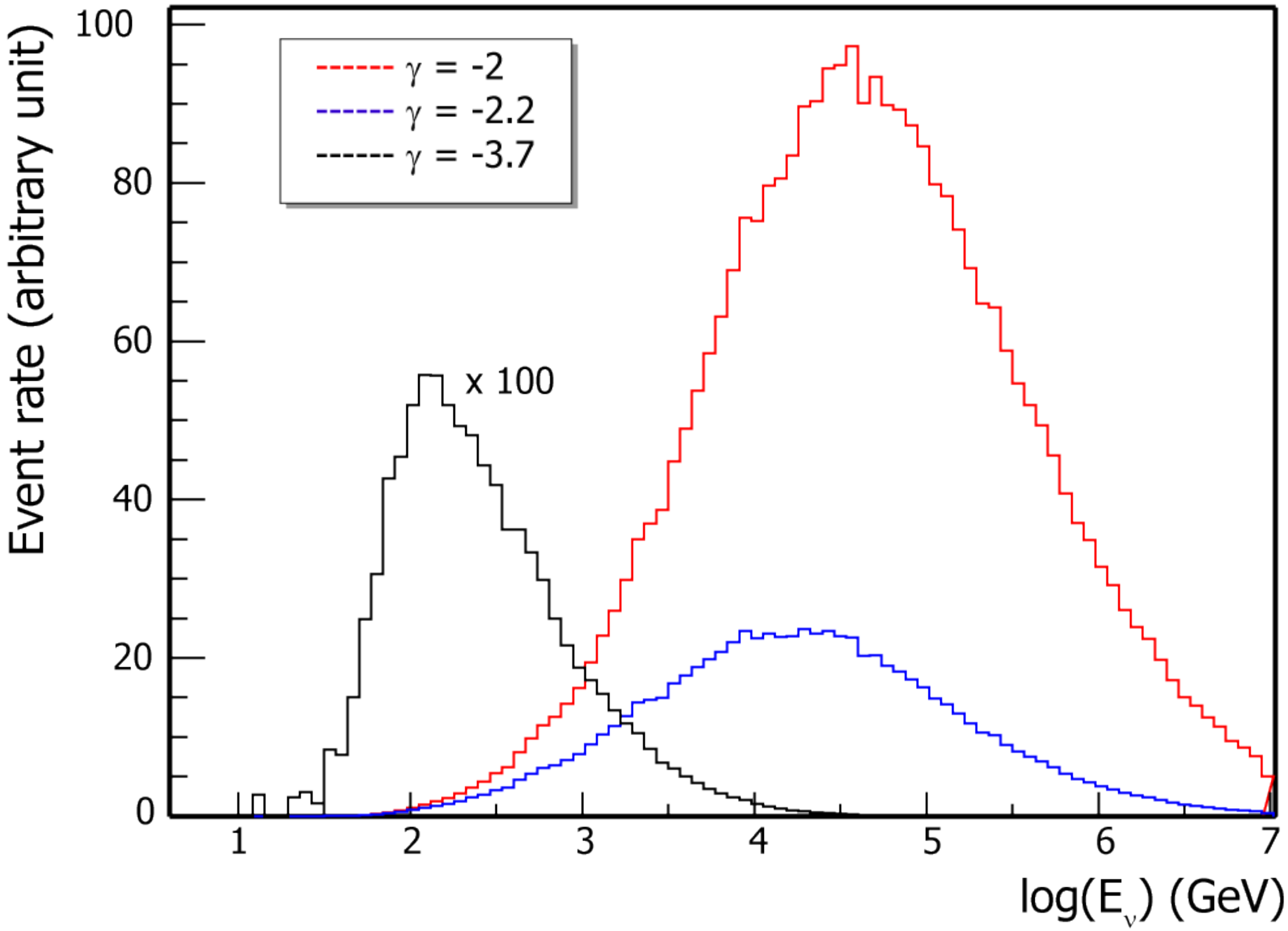
The last curve Llr resolution better than 0.3 degree above 10 TeV (so the purplee curve crosses the blue one at 10 TeV). Below 100 GeV muons don't cross the instrumented volume . Hence a drop below this energy.

Neutrino effective area: ν_μ effective area < muon effective area since it takes into account the probability for a muon neutrino to interact and give a muon that can be seen by the detector.



- *For 0-30°, blue curve and above 100 TeV, the Earth becomes opaque to neutrinos : larger cross section of ν ;early interaction so muon can't reach the detector.*
- *For larger angles and higher energies, detector is very efficient.*

Detector response to various spectral indices : differential event rates as a function of the simulated neutrino energy for three incoming neutrino spectra, obeying the power law $AE^{-\gamma}$ *, where γ =2, 2.2,3.7, represent cosmic accelerator and the atmospheric neutrino spectra resp. Enables separation of events.*



Energy response : Determining fators :- energy fraction transferred to muon in neutrino int, energy lost by the muon outside the detector, energy resolution of detector.

- *Below 100 GeV, the muons are close to minimum-ionizing ; energy of contained events, with start and end points measured inside the detector, can be determined accurately from the range.*
- *Above100 GeV, the range measurement not possible → limited size of the detector, but the visible range determines a minimum energy usable for the analysis of partially-contained events: starting events in which the vertex point is measured inside the detector, and stopping events in which the endpoint is measured.*
- *Above 1 TeV, stochastic processes are dominant, muon energy loss α energy. Increase of detection efficiency due to additional energy loss.*
- *Above 1PeV, Earth becomes opaque to upward going vertical neutrinos. Higher energies are available close to horizon. Very high energy v_τ are observable since*
- $\tau^{\pm}$ *produced in v_τ interactions decay before getting absorbed, producing v_τ of lower energies travelling along the original v_τ flight path , with decreasing interaction probability, resulting in an accumulation of events at the highest detectable energies.*

ICECUBE

- Km³ volume ; Cherenkov lights from neutrino-induced charged leptons is detected .
- An array of 4800 PMTs each enclosed in a transparent pressure

sphere → Digital Optical module (DOM).

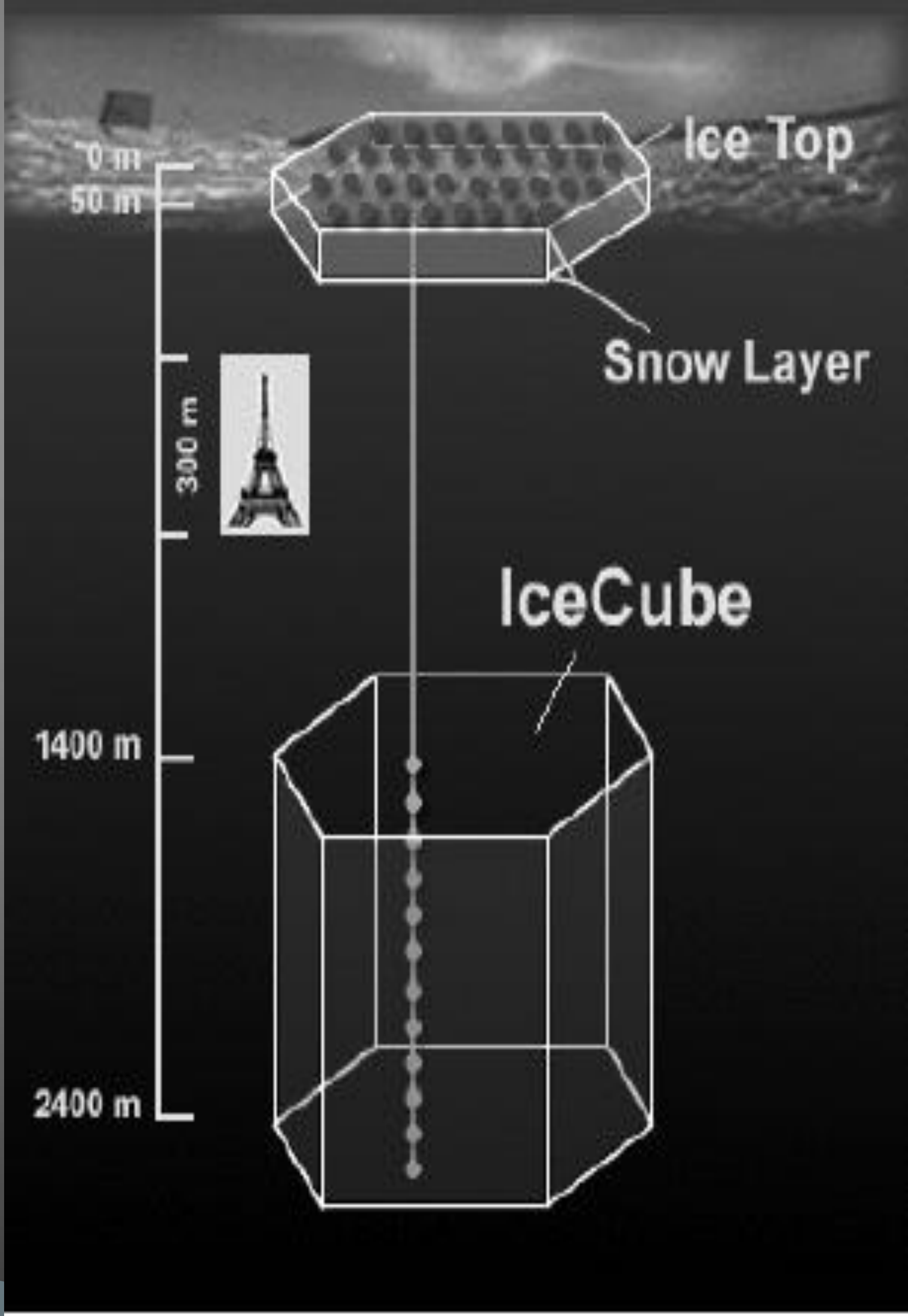
80 strings regularly spaced by 125 m over an area of ~$1km^2$

DOMs at depths of 1.4 to 2.4 km below the ice surface.

60 DOMs spaced by 17m in each string ,deployed into a hole drilled with pressurized hot water.

- IceTop : surface air shower detector with 160 Auger-style Cerenkov detectors deployed over 1km2 above IceCube, augments the deep-ice component by providing a tool for calibration, background rejection and air-shower physics

Planned operation gain t ~ 5×10^7 ,with dynamic range of ~ 200 photo-e /15 ns.



- *Possible backgrounds atmospheric muons and neutrinos produced by decay of mesons generated from cosmic ray (CR) interactions in atmosphere. Identified by down going tracks inside ice.*
- *Spectrum of UHE astrophysical neutrinos is assumed to follow* E_{ν}^{-2} *law , which is much harder than that of the background atmospheric neutrino spectrum* $E_{\nu}^{-3.7}$ *. So atms v bckgnd can be reduced by applying a channel multiplicity cut.*

Atmospheric muon background can be reduced by a factor of 10^6*.*

- *Effective area for upward moving neutrino-induced UHE muons= 1.2 km2 at 1 PeV.*
- *Pointing resolution :better than 1.0◦.*

- *Basis of discrimination of the astrophysical neutrino signals from the background :*

  - geometrical parameters obtained by the various reconstruction algorithms

  - the reduced likelihood of the reconstruction

  -number of PMT channels receiving an unscattered Cherenkov photon

  -track length

Sensitivity to astrophysical muon neutrino : Detection of

$E_\nu^2 \frac{dN_\nu}{dE_\nu} = 1 \times 10^{-8} cm^{-2} s^{-1} sr^{-1} GeV$ *in 5 years of observation.*

Observable sky

- *ANTARES: 43° North latitude , can observe upward-going neutrinos from most of the sky about 3.5π sr . Declinations below -47° are always visible, while those above +47° are never visible. Declinations between -47° and +47°are visible for part of the sidereal day .*
- *Most of the Galactic plane is visible, Galactic centre is visible most of the sidereal day.*
- *AMANDA /ICECUBE:South pole sensitive to positive declinations, the two detectors will have a reasonable area in common for cross-checks ~ 1.5π sr .*

References

1. Neutrino telescopes : C.N . DE MARZO, UTY of Bari and INFN,Italy ; Proceedings of the 6th school on non-accelerator astroparticle physics
2. Neutrino astronomy : John Carr, Centre de Physique des Particules de Marseille,France ; Proceedings of the 7th school on non-accelerator astroparticle physics
3. ANTARES ' web site
4. The IceCube High Energy Neutrino Telescope : S. Yoshida, Dept. of Physics, Chiba University , Japan
5. Presentation by Leonidas K. Resvanis NESTOR Institute for Astroparticle Physics National Observatory of Athens and Physics Department University of Athens.

THANK YOU